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Chapter 8
The physics of galaxy formation and evolution

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Until recently the great majority of naturalists believed that species were immutable productions, and had been separately created. This view has been ably maintained by many authors. Some few naturalists, on the other hand, have believed that species undergo modification, and that the existing forms of life are the descendants by true generation of preexisting forms.
C. Darwin *On the origin of species.* Preface (1859)

8.1 Chapter Overview

The theoretical studies about galaxy formation and evolution are the subject of this Chapter. They started with the recognition that the Hubble sequence is not a simple morphological description of galaxies, but a possible scheme separating and characterizing the physical processes that bring galaxies to their present form. When the Hubble tuning fork reached its actual shape – around 1936 with the discovery of the S0 galaxies –, the Hertzsprung-Russell diagram that revealed the existence of the main sequence of stellar structures was already in place, but its explanation in terms of nuclear reactions was still to come (the p-p chain of Bethe appeared in 1939). Just before the end of the WWII the time was mature for the concept of stellar populations formulated by Baade, but only ~ 20 *years later appeared the first monolithic collapse model of galaxies formation by Eggen, Lynde-Bell & Sandage [115]. In 1964 Arno Penzias and Robert Woodrow Wilson measured the CMB radiation opening the way toward the current cosmological model. With the seventy the idea that merging events have produced many of the actual galaxy structures appeared in the literature with the Toomre' works. Leonard Searle and Robert Zinn proposed that galaxies form by the coalescence of smaller progenitors. At the same time the discovery of the existence of dark matter (DM) rapidly changed our idea of galaxies and how structures form in the Universe. White & Rees and Fall & Efstathiou developed the actual view of galaxy formation, in which baryons fall into* *the potential wells of hierarchically growing dark matter structures. The eighty and ninety have seen the development of Semi-Analytic Models (SAM) of galaxy formation and evolution and of numerical hydrodynamical simulations of increasing resolution and complexity. With the new century the Universe was discovered to accelerate its expansion and thanks to the big galaxy surveys the idea of the cosmic web started to be accepted. Today the dominating paradigm is that provided by the* Λ*CDM cosmology, a framework in which the Universe is believed to be made of* $\sim 70\%$ *of dark energy (DE),* $\sim 26\%$ *of cold and hot DM, and* $\sim 4\%$ *of baryons. Within this model the values of the cosmological parameters, such as the Hubble expansion rate* H_0*, are known with great accuracy. This is the precision cosmology era, a very uncomfortable situation in which the cosmological parameters are known very well, but we do not know what the Universe is made of.*

The following interviews will try to shed some light on the history of the theoretical successes in the extra-galactic domain. Sec. 8.2 deals with the first attempts to simulate the Hubble tuning fork from basic physical principles. Then, in Sec. 8.3 we better define the differences between the monolithic scenario of galaxy formation and the hierarchical scheme, introducing some hybrid versions of the two frameworks. In Sections 8.4 and 8.5 we provide a much clear view of the star formation history, i.e. of the convolution of the Initial Mass Function (IMF) and the Star Formation Rate (SFR). The role of feedback is analyzed in Sec. 8.6, that of chemical enrichment in Sec. 8.7, and that of Magnetic Fields in Sec. 8.8. We finally give a panoramic view of the comparisons between observations and models in Sec. 8.9.

8.2 The theoretical foundation of the Hubble diagram

Questions for George Lake:
you have examined several times the theoretical foundation of the Hubble diagram for the morphological classification of galaxies. Would you be so kind to summarize here for us the main conclusions coming from these studies?

The origin of the Hubble sequence has been a favorite problem of mine!

The broad brush is that galaxies come in two basic flavors, ellipticals and spirals. The elliptical galaxies are dense and slowly rotating while the spiral galaxies are more diffuse and rapidly rotating. There are numerous schemes for classifying galaxies with well-justified additional complexities. However, this simple ”theorist's cartoon” already highlights the big problem: Why do the compact ones rotate slowly while the bigger ones rotate rapidly. It takes just a few minutes of playing on a piano stool to see why this is a problem. Start rotating with your arms out. When you pull them in, you spin fast. How did elliptical galaxies become so compact without spinning rapidly?

Edwin P. Hubble's tuning-fork classification of galaxies was brilliant and insightful. He saw that there were relatively featureless galaxies that always had the same radial brightness profiles and elliptical isophotes (contours of constant surface brightness). They were distinguished only by the eccentricity of their isophotes which never got flatter than about 2:1. Spirals, with their disks and arms, show more diversity. The arms could be tightly wound or relatively open. They often had central bulges of varying prominence. The prominence of the bulge and the winding of the spirals tends to go hand in hand. The larger the bulge-to disk ratio (B/D), the more tightly wrapped are the spiral arms There is a parallel sequence of barred spiral galaxies, ones where the spiral arms seem to connect to a strong linear feature, the bar, in the center of the disk.

I would like to point out an interesting bit of history regarding the Hubble sequence. In his Annual Review article, Sandage [349] tells us that the classification be made on the basis of morphology alone, not on the basis of supposed physics that some wish to be introduced to "explain" the classification. The Hubble sequence is definitely a place where that has not been true! Galaxies that didn't have disks were classified as E0 through E7 by Jeans [181]. The number is $10*(1-b/a)$ where b/a is the ratio of the minor to major axis, so an E0 is round and E5 is flattened 2-to-1, an E7 is flattened roughly 3-to-1. Jeans was the first to propose a scheme that is close to that associated with Hubble [177, 178]. For decades, morphologists found galaxies to classify as E7. None of them really fit the part, clearly showing disks (NGC 3115 was the prototype) and modern morphologists now find ellipticals only as flat as E5.5. So, why E7? Jeans explain the transition for E7 to Spiral by noting that if you spin fluid objects, they undergo bifurcation when spun fast enough to be as flat as E7. At that point, they create bars and evolve in other ways. So, the galaxies found between E5.5 and E7 for decades owe their classification to a theoretical argument by Jeans. Just looking has lead to something different.

Around 1970, there were some first stabs at simulating galaxies. Ostriker and Peebles [296] had their famous 300 particle simulations that argued disks would be unstable if there weren't some mass than was flattened. It was another paper with Yahil that made the clearer argument that this mass should be an extended very massive dark halo. Richard Larson [227, 228] also did some simulations of galaxy formation. But, the sense was that the problem was both ill determined and ill conditioned. So, these were groundbreaking, but not compelling in their conclusions.

Back in 1984, I was at AT&T Bell Labs. Industry is very different than a University. At that time, researchers at American Universities had extremely limited access to supercomputers. The less powerful University mainframes weren't justified unless they were saturated with jobs. It was a terrible time to do large scale computing at Universities.

At Bell Labs, there was a big shiny Cray that was justified by being nearly empty. That way, when someone wanted to design a new communications processor, there were sufficient resources to get the job done in a short time. They would load the machine up for a job that took days—and they didn't have to wait a month for it to finish. The AT&T device designers were doing the job in a fraction of the time of their competitors. [The chips for the work horse switches that would take care of hundreds of homes were designed and fabricated in less than a year. Management claimed that without the ever-at-the-ready Cray it would have taken 5 years.] It made good business sense to keep a nearly empty Cray around. Basic researchers at the lab could buy ”stand-by” time for just 100/hour when the going market rate for an hour was 6,000! With the Cray being 200–600 times faster than the University VAXes, it was a great opportunity. That factor of 200–600 was the difference between walking and taking the Concorde. In absolute terms, those Crays were 35 Megaflops. Today, I use the Swiss National Supercomputer Center. Their fastest computers is 200 Million times faster. It computes in a second what the Cray took 10 years to do and the VAXes of that era needed several millennia. That Swiss computer is only the 6th fastest in the world, there are others nearly 10x faster.

For astrophysicists, the Cray was hot stuff. But, even 100/hr busted the basic science computing budget quickly. I burned up the Physical Science Research Lab allocation in a couple of weeks. A friendship with a numerical analyst (Wes Petersen, we still work together todaynow on archeological problems!) led to the cutting a deal with Nils-Peter Nelson who ran the Cray. If I stayed out of everyone’s way, I could have all the time I could eat. He called it his NSF grant–Nelson Slush Fund.

The lab got a new Cray, this one has TWO fast processors (modern supercomputers have $>$ 3 MILLION). Ray Carlberg and I jumped in and set a record for Cray time use outside of national defense. We also made some key discoveries of how to make spirals versus ellipticals.

Before our simulations, every one did galaxy formation by dropping particles from rest. We touted our cosmological conditions where we let the particles expand by a factor of 2 before collapsing. But, that little change had a real impact.

We ran a lot of simulations and found an odd thing. The main control parameter was how hot our initial conditions were. If they were cold, lumps would grow during expansion and the collapses were lumpy and chaotic. That made things that looked like ellipticals. If they were hot and small scale fluctuations didnt grow, the smooth collapses made disks. The fit to some of the gross phenomenology was amazing. We started with the same amount of specific angular momentum in both cases, but if we looked at the product of the half light radius times rotation velocity, it was 8x different in the final states of the gas that turned into stars. We found there were 3 factors of two that multiplied to make that factor of 8. The first was trivial, the different states need pre-factors that are 2x different to turn these simple numbers into specific angular momentum (while the stellar distribution of ellipticals is more compact that spirals, they also have more matter at several times their half-light radii). The next factor of 2 was that in the lumpy collapses, angular momentum was transferred from the inner parts to the outer parts. This transferred angular momentum from luminous material to the more extended dark matter. Finally, star formation was less efficient in the ellipticals and only the inner gas formed stars while the outer gas was a more effective reservoir for angular momentum. This outer reservoir of gas also fit the gross phenomenology. Ellipticals were known to have extended distributions of hot gas that didnt form stars. Although, at the time, the community was not aware that star formation was so much less efficient in ellipticals.

We finally had a physical control parameter for the Hubble sequence: the presence or absence of substructure during collapse. We executed this mechanism by changing the random motions of particles. The substructure could grow when the initial conditions were ”cold”. It was suppressed by the random motions when the protogalaxies were ”warm”. This result was published in two papers in the October 1988 issue of The Astronomical Journal [226, 225].

We still needed a cosmological context for what we thought of as hot vs. cold or quiet vs. lumpy. Back in the 1980s, it also became clear that while spirals and ellipticals overlap in luminosity, ellipticals are generally more massive then spirals and they appear preferentially in clusters.

There is the problem of missing satellites. This problem wasn’t presented in a sharp way until the 1990s [283, 199], but it was clear much earlier that a scale-free power spectrum predicted a mass spectrum such that at low mass there should be roughly 10x more galaxies every time you looked at 1/10 of the mass. But, we knew that there weren’t nearly that many dwarf galaxies. This is the mass function that emerges form the theory of Press-Schecter [331]. Something clearly suppressed dwarf galaxies that were less massive than the Magellanic Clouds. If you suppress fluctuations below a given mass scale, then things that are 10x that mass will collapse in a smooth way and things 100x that mass will be very lumpy and chaotic. Since the dwarfs were missing, suppressing lumps of a given scale seemed like the way to go.

That’s not a popular idea now. The typical phrases one here describing galaxy formation are downsizing which describes the tendency for massive galaxies to be older than less massive ones, as well as seeing massive galaxies form at modest redshifts at an accelerated rate compared to less massive galaxies.

We imagined that happening because the dark matter (DM) was still, now the dominant notion is that the baryonic component is showing a stiffness owing to energy input from supernovae and active galaxies. I’m a bit contrarian in stressing “stiffness” rather than “feedback”. I think the earliest objects preheat large volumes to create stiffness rather than feedback being a local process that can eject gas from galaxies after they’ve collapsed. I argue that preheating takes 30x less energy and you just don’t have the energy budget to eject things (I have colleagues who think that gas goes into galaxies and is ejected multiple times; you just don’t have the energy to do that).

So, the shift has been away from my early ideas that focused on the ability to make lumps in dark matter and instead quiet the formation of small things using the stiffness of energy generation.

There’s one comic aspect to our simulations. They were redone multiple times because people thought they were so poor. It was a terrible presentation on my part. When we did our simulations, we saw things that were clearly disks and even had nice spiral arms and we had dense slowly rotation things. We also had some that were hard to call. Instead of putting pictures of nice spirals into the 1988 papers, I instead put in the ones that were hard to call and was clear about how we called them. Since nobody reads papers but only figure captions, it was assumed those were the best disks we’d made. Incredibly stupid on my part and grossly lowered the impact of those papers.

The basic features of the Hubble sequence, i.e. the decreasing contribution of the bulge component with respect to the disk going from early-type to late-type galaxies, *and the evidence that the bulge contains old and metal poor stars while the disk younger and metal rich stars were modeled by Eggen, Lynden-Bell & Sandage [115] at the beginning of the sixty. Their model represents the first idea of the monolithic collapse of a galaxy. They noted that the eccentricity of the orbits of dwarf stars is correlated with the UV excess; the stars with the largest excess (i.e. the lower metal content) move in highly elliptical orbits, while those with almost no excess have generally round orbits. This result was discussed in terms of the dynamics of the collapsing proto-galaxy. The oldest stars were formed in from gas falling toward the center of the galaxy and the collapse was very rapid (*$\sim 10^8$ *yrs). The disk stars formed later when the gas was already settled in a disk structure. This model was the first picture of the galaxy formation process that interpreted coherently the various properties observed in nearby galaxies. Since then, more detailed observations of galaxy stellar populations and dynamics, the discovery of DM, and the evidence of the cosmic web structure, progressively bring researchers to prefer the hierarchical model. The next interview try to summarize the advantages and disadvantages of both ideas.*

8.3 From monolithic to hierarchical models and beyond

Questions for Cesare Chiosi:
the modern prevailing picture of galaxy formation was formulated almost 30 years ago by White & Rees [418] and Fall & Efstathiou [136]. Gas falls into the potential wells of hierarchically growing dark matter structures and is additionally governed by dissipational processes. Could you discuss the pro and cons of this theoretical picture? Which observations are in contrast with the dominating paradigm of the hierarchical merging scenario? Why has the monolithic collapse scenario been abandoned for this new paradigm? If galaxies formed by successive merging events is it possible to reproduce theoretically their stellar population content?

In a Universe containing three main components in cosmic proportions: Dark Energy (DE, 70%), Dark Matter (DM, 25%), and Baryonic Matter + Neutrinos (BM, 5%), the formation and evolution of galaxies are among the hottest topics of modern astrophysics. Current understanding of the nature of DM indicates the weak interacting massive particles (shortly named WIMPs) as the best candidates. They should have come into existence in the early Universe with a mass in the energy range GeV-TeV. The Universe is thus pervaded by slowly moving, non relativistic WIMPs, which manifest themselves only via gravitational interaction. The ratio of the total DM mass to that of BM is expected to be about 6:1 according to the present-day cosmological paradigm of the Universe. Based on this view, simulations of the cosmological growing of primordial perturbations into bigger and bigger objects under the action of gravitational interaction became the classical scenario in which the formation of galaxies was framed [417]. This view culminated in the recent spectacular Millennium Simulation [372, 373]. Very soon White, Rees, Fall and Efstathiou [418, 136] called attention on the role of BM: gas falls into the potential wells of hierarchically growing DM structures and is additionally governed by dissipational processes. The formation of true galaxies made of BM and DM is started. This view was shortly termed the ***Hierarchical Scenario*** of large scale structures and galaxies in turn. Initially, DE was not taken into consideration (Standard CDM), whereas nowadays DE and associated cosmological constant (Λ) are the leading terms of the mass-energy pattern (the so-called ΛCDM Universe). Reducing the complexity of the hierarchical scenario to a sentence: small and low mass objects come first, whereas large and massive objects come later in a hierarchy of structures of increasing size, mass and complexity as time goes by. Owing to the large DM to BM mass ratio, DM was considered to lead the game. Therefore, cosmological simulations of large scale (typically 500 Mpc on a side) have been calculated in which, owing to the huge number of DM haloes (proto-galaxies candidates) coming into existence, there was no room to include also BM and to follow the formation of real galaxies with the desired accuracy. Therefore, the large scale cosmological simulations usually left BM aside. However, since they provided the mass assembly history (MAH) of haloes (see e.g. the large scale Millennium Simulations by [372, 373] in the ΛCDM cosmology), they have been largely used as the back bone of all scenarios of galaxy formation. Given the MAH of haloes, either retrieved from cosmological simulations or built up with Monte-Carlo probabilistic techniques [224], the BM is added to haloes. Suitable prescriptions are then assumed for gas cooling and heating, star formation (often with chemical enrichment), energy feedback by SNa explosions and AGN (the central black hole), morphological transformation of disks into elliptical structures as a consequence of mergers, and population synthesis techniques to simulate luminosities, magnitudes and colors of the stellar content, *etc.* In other words, the structure and history of a galaxy are determined.

Current models of galaxy formation and evolution can be grouped in semi-analytical (SAMs) and hydrodynamical (HDMs). The latter in turn split in two categories according to the numerical technique in use: the cell-based in the modern version with adaptive meshes to follow a large range of scales (see [374], and references) and the particle-based in the modern version of smoothed particle hydrodynamics (see [374, 375, 376], and references). Over the past two decades, SAMs have been world widely adopted. Modern SAMs are very sophisticated codes (e.g., [29]), relatively easy to use, and often publicly-available together with their outputs. Using the SAMs, the importance of various physical processes can be easily tested and gauged. The weakness of SAMs is that the physics is somewhat controlled by hand and largely parameterized. The success of SAMs and the hierarchical scenario in turn generated an impressive number of studies that dominated the scene for about three decades. To mention a few we recall here [98, 4, 102, 160, 304, 103].

However, in recent times, thanks to the wealthy of data at higher and higher red-shift some failures of the hierarchical scheme became evident. A recent, critical review of the observational data and the success and drawbacks of the SAM modeling is by [364] to whom the reader should refer. The problem is further exacerbated by the nature of DM and the partial failure of the cold DM scenario itself, see [109]. In brief, the cold DM scenario agrees with the observations only on cosmological scales [2], e.g. individual haloes, groups and clusters of DM haloes, filamentary structures, whereas surprisingly fail to match the observations at small scales ($\sim$ Kpc, the scale of galaxies). According to [344] part of the problems with pure DM simulations could be solved by introducing BM. Of the body of observational data that could not be easily explained by the standard hierarchical view of galaxy formation (in the simple SAM context) we recall the rapid decrease in the cosmic start formation rate (SFR), the number of dwarf galaxies, the observed downsizing that simply opposes to the hierarchical view [50, 51, 52], the issue of gas accretion *versus* mergers in driving star formation, and the recent evidence of a systematic steepening of the initial mass function in massive early type galaxies (see [51, 364]). The frontier for high red-shift objects has been continuously and quickly extended from $z \sim 4$–5 [241, 379], and $z \sim 6$ [377, 105] to $z \sim 10$ [427, 40, 293]. According to the current view, first galaxies formed at $z \sim 10$–20 [345] or even $z \sim 20$–50 when DM haloes containing BM in cosmological proportions gave origin to the first sufficiently deep gravitational potential wells [389, 149, 150]. In addition to this, there is observational evidence for large and red galaxies already in place at very high redshift (see [248, 289]). Finally, the high redshift Universe is obscured by copious amounts of dust (see [360, 57, 341, 408, 409, 276, 277, 278]), whose origin and composition are a matter of debate [146, 147, 148, 112, 110, 113] but surely are of stellar origin thus implying star formation activity at very early (high redshift) epochs. Recent reviews of all these issues are by [338, 47, 364, 84, 163, 164, 72]. Over the years, the hierarchical scheme has been amended giving rise to two complementary alternatives known as *Dry Mergers* (fusion of gas-free galaxies to avoid star formation) and the *Wet Mergers* (the same but with some stellar activity).

In parallel, another scenario for galaxy formation and evolution has been developed. It stems from the properties of stellar populations in real galaxies, the early type ones in particular, and the pioneering studies by [115, 394, 10]. Exhaustive reviews of the many observational hints for an alternative to the hierarchical scheme are by [72, 260]. It is named ***Monolithic Scenario***: massive early type galaxies (ETGs) form at high redshift by rapid collapse and undergo a single, prominent star formation episode, ever since followed by quiescence. Over the years this view has been changed to the ***Revised Monolithic*** scheme: a great deal of the stars in massive ETGs are formed very early-on at high red-shifts and the remaining ones at lower red-shifts, and finally it incorporated the hierarchical scheme itself, generating an hybrid mode of galaxy formation and evolution named ***Early Hierarchical, Quasi Monolithic*** [274].

Combining the N-Body Tree formalism used to treat the gravitational interaction [16]) with the Smooth Hydrodynamics technique to simulate a real fluid by a discrete number of particles [375], model galaxies in the early hierarchical, quasi monolithic scenario have been presented by several authors, see [70, 186, 187, 188, 189, 270, 271, 272, 273, 274], and references therein). The merit of these models is the effort to describe the formation and evolution of individual galaxies made of DM and BM according to a given cosmological view of the Universe (e.g., S-CDM or ΛCDM) from the time of their appearance as perturbation seeds at a certain redshift to the present. The models follow (i) the growth of the initial seed by early aggregation of other seeds toward more and more distinct structures (maybe via the aggregation of many sub-lumps of matter); (ii) the cooling and collapse of baryons, and the conversion of gas into stars at a certain rate and specific efficiency; (iii) the chemical enrichment of the gas by self pollution via mass loss by stellar winds and SNa explosions; (iv) the decline of star formation both by gas heating due to energy feedback and gas consumption; (v) the interplay between gas cooling and heating and the establishment of a duty cycle among the various competing physical agents; (v) the presence of AGN phenomena (not always included because of the uncertainties and difficulties of this issue); and finally (vi) the gas ejections in form of galactic winds. The goals of all those studies are the evolutionary history of a galaxy from its initial conditions to the present situation and the comparison of the structural and physical properties of the model galaxies with their observational counterparts. To better illustrate the above issues, let us summarize the results recently achieved by Merlin and collaborators on the formation and evolution of ETGs in ΛCDM cosmology:

(1) In brief, [274] adopt the ΛCDM concordance cosmology, with values inferred from the WMAP-5 data [173]: flat geometry, $H_0 = 70.1$ km s^{-1}Mpc^{-1}, $\Omega_\Lambda = 0.721$, $\Omega_b = 0.046$ (giving a baryon ratio of $\simeq$0.1656), $\sigma_8 = 0.817$, and $n = 0.96$. The growth of primordial perturbations is followed by means of COSMICS [33] but limited to a suitably chosen portion of a standard cosmological grid ($\simeq$ 500 Mpc on a side). The sub-portion is supposed to contain perturbations with assigned over-density, mass, and dimensions chosen a priori. This means that the size of the sub-portion is fixed in such a way that the wavelength of the perturbation corresponding to the chosen over-density and mass is similar to (but suitably smaller than) the size of the sub-portion itself (about 10 Mpc on a side). Casting the problem in a different way, instead of searching the perturbation most suited to our purposes within a large scale realistic cosmological box, we suppose that a perturbation with the desired properties is already there, and derive the positions and velocities of all its DM and BM particles from a self-consistent, small-size cosmological box tailored to the perturbation we have chosen. It is known from long time that the simulation size determines the maximum perturbation wavelength. If the long wavelengths are dropped out, the strength of subsequent clustering is reduced, but at the same time the number density of intermediate mass haloes (with total mass of the order of $10^{12} - 10^{13} M_\odot$) is enhanced [330]. Since we are interested in objects with the size of galaxies and not of galaxy clusters, this is less of a problem. Furthermore, according to [330] the truncation of the initial power spectrum (*i.e.*, the small size) of the simulation has little impact on the internal properties of the haloes. Late refuelling of gas (and stars and DM) or equivalently late mergers are inhibited. This is less of a problem because [274] intended to explore the modalities of galaxy formation and evolution in alternative to the hierarchical scheme. To conclude, the above initial conditions are not in conflict with the cosmological paradigm and the halo masses that are adopted as a function of the redshift are compatible with the creation and growth of cosmological DM perturbations [238]. For all other details see [274].

(2) *Histories of Star Formation*. Using simple initial conditions, Chiosi and Carraro [70] demonstrated that at given initial over-density the SFH changes from a single dominant initial monolithic episode to a bursting-like series of events at decreasing total mass, whereas at given total mass the SFH changes from a dominant initial episode to bursting mode at decreasing initial over-density. This basic dependence of the SFH on the total galaxy mass and initial over-density (environment) has been amply confirmed over the years by many observational and theoretical studies and it is also recovered by the [274] models with cosmological initial conditions. *Downsizing and delayed star formation are naturally reproduced*. Furthermore, since the star formation rate is taken proportional to the ratio gas mass to the free-fall time scale t_{ff}, the specific star formation rate is simply the inverse of t_{ff}. All this strongly suggests that the gravitational potential well of BM + DM drives the whole process and dictates the efficiency and duration of the star formation process. A galaxy, thanks to its gravitational potential, knows in advance the kind of stellar populations (very old or spanning a large age range) it is going to build up.

(3) *Assembling the Stellar Mass*. The building up of the stellar mass of a massive galaxy as a function of the redshift is nearly completed much earlier than in the low mass ones and in any case earlier than redshift $z = 2$. Furthermore, the net efficiency of the star forming process and the duty-cycle given by gas cooling–star formation–gas enrichment–gas heating–gas cooling is such that on the average 20% of the initial BM is converted into stars, the rest is either expelled in form of galactic winds or heated up and parked away for future use.

(4) *Stellar Ages and Metallicities*. In early epochs, the stars are preferentially created in the central regions, then the star forming activity expands to larger radii (inside-out mechanism), and moving towards the present time, the stellar activity tends to shrink again towards the center. This simply mirrors the SFH and the mechanism of mass assembly above. There is a satisfactory agreement between theory and observational data concerning the mean metallicity and the metallicity gradient. Finally, the mean metallicity increases with the stellar mass of a galaxy and beyond some value tends to flattens out [398].

(5) *Mass Density Profiles*. The geometrical structure of the model galaxies is best traced by the surface mass density profiles and comparison of these with the [358] profile,

$$\sigma_S(r) = \sigma_0 \times e^{(0.324-2m)\left[\left(\frac{r}{R_e}\right)^{1/m}-1\right]}$$

where R_e is the effective radius of the galaxy (as defined by [172]), σ_0 the surface density at R_e, and m the *Sersic index* ($m = 4$ corresponds to the de Vaucouleurs profile). All profiles are computed starting at 0.2% of the virial radius of the galaxies to avoid the very central regions where softening may introduce spurious numerical effects. The best-fitting Sersic index is $m \sim 4$, $m \sim 1.5$, and $m \sim 2.5$, for high-, intermediate-, and low-mass models, respectively. In other words, high-mass models tend to have higher m, in qualitative agreement with the existence of a luminosity-Sersic index relation for ETGs [53]. However, one should notice that the most massive ellipticals in the local Universe tend to have $m \sim 8$ (e.g., [139]), while [274] find $m \sim 4$. Moreover, the intermediate-mass models have somewhat lower m than the low-mass ones. Even considering the large scatter, this is not fully consistent with the luminosity-m relation.

(6) *Core or Cuspy Luminosity (Mass) Profiles?* The overall agreement between the models and the Sersic curves is good in the external regions. However, a clear departure from the expected fits is evident in all models at small radii (some fraction of R_e). In the central regions, the model galaxies tend to *flatten out* their mass density profile. Given the adaptiveness of the force softening, this feature can hardly be ascribed to numerical artifacts. Most likely, the high value of the efficiency of star formation adopted by [274] is the cause of it. Amazingly enough, similar galaxy models by [70] with the same assumptions for the star formation rate but different initial conditions (much simpler than the present ones) yielded the opposite, *i.e.*, star dominated DM in the most central regions of the model galaxies. To single out the cause of disagreement is a cumbersome affair that cannot be discussed here (see [72] for more details on the issue).

(7) *Surface photometry and Kormendy's scale relationship*. Finally, the early hierarchical quasi monolithic scenario folded with the classical spectro-photometric synthesis technique predicts SEDs, magnitudes and colors in many photometric systems both in the rest-frame and as a function of the redshift. In particular, one may derive the structural parameters of galaxies, such as the effective radius R_e, the luminosity within R_e, the shape indices through Fourier and Sérsic analysis, the color profiles, and the radial profiles of most of the parameters that define the structure of galaxies. The luminosity profiles of the model galaxies at $z = 0$ can be reasonably fitted with a Sérsic $R^{1/n}$ law. They can be compared with the photometric data for large samples of galaxies together with the fundamental scale relations such as the Kormendy relations and the Fundamental Plane. Theory and data are in remarkable agreement (see [388].

(8) *Mass-Radius Relationship (MRR)*. The MRR of ETGs [71] stems from the action of several concurring factors: (a) the Cosmic Galaxy Shepherd (CGS) visualizing the cut-off mass of the halo mass distribution at each redshift [238]. It is set by the cosmic growing of gravitationally bounded density perturbations and associated $N(M_{DM}, z)$. The slope of the CGS goes from 0.5 to 1 as the mass increases. It is reminiscent of the slope of the MRR for dissipation-less collapse; (b) The manifold of lines of equal initial density but different redshift along which pro-haloes of any mass crowd (slope of this mass-radius relation is 1/3 by construction); (c) given the initial density, collapse redshift, and star formation efficiency, the proto-haloes of different mass filiate baryonic galaxies with certain values of M_s and $R_{1/2}$ at the present time. The baryonic components of galaxies crowd along mass-radius relations whose slope changes from 0.3 to 0.2 or less as the galaxy mass (either total or stellar) decreases. The MRR of ETGs is the locus on which the manifold of MRRs of individual BM galaxies of any mass would intersect the CGS. The galaxies at the intersection are close to the cut-mass and evolve in condition closely following the dissipation-less collapse. They trace the MRR of ETGs we observe today.

The main lesson we learn from these models of formation and evolution of galaxies is that starting from cosmological initial conditions for the perturbations one sees the aggregation of lumps of DM and BM in the common potential well and the growth of all this to the size of a real galaxy on a short time scale while star formation occurs and the stellar content of a galaxy is built up. By redshift $z = 2$ a great deal of the action is completed, even massive objects can be in place. Hierarchical aggregation has taken place within a rather short time scale, about 1–2 tenths of the Hubble time. If let evolve on its own, the resulting object will show at the present time a pattern of properties very similar to those of real galaxies. This is the main reason for naming the whole process "*early hierarchical, quasi monolithic galaxy formation*". What happens to this object if in the course of its life it undergoes later mergers with similar objects? "*The outcome depends on the relative mass of the merging galaxies and the mode of star formation*". Major mergers will greatly affect the dynamics, morphology, stellar content, and the integral SED of the resulting galaxy. Minor mergers scarcely affect the properties of receiving galaxy. The details on the outcome are not of interest here, however the signatures of the merger can be traced back in the stellar content and cannot be easily wiped out, see the discussion by [70, 387] on the age and size of mergers that are compatible with the maximum dispersion of broad band colors of ETGs. Since there is observational evidence of major and minor mergers , their occurrence cannot be excluded. What we may say is that mergers are not the only way to assembly massive galaxies, ETGs in particular. Most likely, both concur to the overall formation and evolution process of galaxies.

There is another important consideration to make, *i.e.*, the difference between the above approach and what is commonly made in classical SAMs. Quoting [364] "in SAMs, galaxies are painted on haloes built from halo merger trees or detected in cosmological dissipation-less (DM only) simulations". In other words, BM is added later to haloes, the mass assembly of which has been derived without BM. "Painting BM" is not the same as taking both DM and BM together from the very beginning. Indeed the dissipative collapse of BM and occurrence of star formation in the potential well of DM will certainly affect the dynamical behavior and hence mass assembly history of the latter. Maybe this is the simple explanation for the occurrence in Nature of early hierarchical quasi monolithic galaxy formation.

Given the achievements of the new scenario for galaxy formation, it is no longer necessary to consider mergers between proto-galaxies (or disks) as the main way in which massive ETGs are formed. Likely, Nature follows the hierarchical mode when aggregating matter on the scale of groups and clusters, and the early hierarchical quasi monolithic mode when aggregating matter on the scale of individual galaxies. On the other hand galaxy mergers cannot be completely ruled out, simply because we have direct observational evidence of their occurrence. They are beautiful, spectacular events, but not the dominant mechanism by which galaxies (the ETGs, in particular) are assembled and their main features imprinted.

The picture emerging from this analysis is that *nature* seems to play the dominant role in building up the ETGs we see today, whereas *nurture* by recurrent captures of small objects is a secondary actor of the fascinating and intriguing story of galaxy formation and evolution. In the forest of the galaxy formation theories, *ex pluribus unum.*

In this context it is important to better understand the role of SAMs and their actual limits. The next interview will clarify this aspect more precisely.

Questions for Gabriella De Lucia:
Semi-analytic models have been largely used to understand the mechanisms of galaxy formation and evolution. What is their potential and what are their limits?

The hierarchical clustering is the current paradigm of the ΛCDM cosmology. Could you discuss and explain this idea and its history? Which observational evidence support this scenario? Which are the models and simulations that have better implemented this idea? What these models and simulations are not able to explain yet?

In the last decades, a number of different observational experiments have converged to establish the ΛCDM cosmology as the *de facto* standard cosmological paradigm for structure formation. In this scenario, the mass-energy budget of the Universe is dominated by two unknown forms of matter (the 'dark matter') and energy (the 'dark energy'), while only a few per cent is composed of the (baryonic) visible matter we know.

The first observational evidence of a *missing mass* problem (that is what we now call dark matter) dates back to the 1930s, when Zwicky [431] estimated that the speeds of galaxies in the Coma cluster are too large to keep the system gravitationally bound, unless the dynamical mass is at least 100 times larger than the mass contained in galaxies. The reality of the problem, however, gained a hold upon the astronomical community only in the mid-1970s, when different studies showed that the rotation curves of spiral galaxies are either flat or rising at the optical edge of the galaxies [346], contrary to the Keplerian fall off that is expected if the visible stars and gas were the only mass in the system. In the 1980s, much work focused on the nature of the unseen dark matter component. Initially, many studies focused on neutrinos as the most likely candidates for the dark matter. It was soon realized, however, that in a neutrino-dominated Universe, structure would form by fragmentation (top-down), with the largest super-clusters forming first in a sort of flat 'pancake'-like sheets [663]. These must then fragment to form smaller structures like galaxy groups and galaxies – a picture that conflicts with observation, as shown by detailed simulations of structure formation [419]. During the same years, a number of different dark matter candidates were provided by particle physics models based on super-symmetry. These weakly interacting massive particles (WIMPs) are today considered the most likely candidates for dark matter. Because their masses are much larger (and therefore their velocities are much smaller) than those of neutrinos, these particles are said to be 'cold'. Cold dark matter (CDM) decouples from the radiation field long before recombination so that its density fluctuations can grow significantly before the baryons decouple from the radiation. When this happens, baryons are free to fall in the dark matter potential wells (the halos) that have formed. This allows structure formation to occur at a rate sufficient to be consistent with the large-scale structure observed at present [93]. In the early 1990s, measurements of galaxy clustering showed that the then 'standard CDM' model (in which the Universe was composed only of CDM and baryons) predicted less clustering on large scales than observed [242]. Several alternatives were proposed, with the ΛCDM model becoming the new concordance model after the discovery of the current acceleration of the cosmic expansion through supernovae observations [311]. In recent years, it has been shown that this model is able to match simultaneously a number of other important constraints, including the large-scale clustering of galaxies in the local Universe [309], the structure seen in the Lymanα forest at $z = 3$ [406], and the cosmic microwave background fluctuations at $z \sim 1000$ [25].

Semi-analytic models are one of the available methods to study galaxy formation and evolution in a cosmological contest. These techniques find their seeds in the 'two-stage theory' of galaxy formation proposed by [418]: dark matter halos form first, and the physical properties of galaxies are then determined by cooling and condensation of gas within the potential well of the halos. The evolution of the baryonic components is modeled using simple, yet observationally and/or theoretically motivated prescriptions. Adopting this formalism, it is possible to express the full process of galaxy formation and evolution using a set of (coupled) differential equations that describe the variation in mass as a function of time of different galactic components (e.g. stars, gas, metals). Given our limited understanding of the physical processes at play, these equations contain 'free parameters', whose values are typically chosen in order to provide a reasonably good agreement with observational data in the local Universe.

In their first renditions, semi-analytic models relied on Monte Carlo realizations of merging histories of individual halos, generated using the extended Press-Schechter theory (e.g. [184, 77]). An important advance of later years came from the coupling of semi-analytic techniques with large-resolution N-body simulations that are used to specify the location and evolution of dark matter halos – the birthplaces of luminous galaxies [185, 26]. On a next level of complexity, some more recent implementations of these techniques have explicitly taken into account dark matter substructures, i.e., the halos within which galaxies form are still followed when they are accreted onto a more massive system [370, 97]. There is one important caveat to bear in mind regarding these methods: dark matter substructures are fragile systems that are rapidly and efficiently destroyed below the resolution limit of the simulation. Depending on the resolution of the simulations used, this can happen well before the actual merger can take place. Therefore, this treatment introduces a complication due to the presence of 'orphan galaxies,' i.e., galaxies whose parent substructure mass has been reduced below the resolution limit of the simulation.

One great advantage of these hybrid methods, with respect to classical techniques based on the extended Press-Schechter formalism, is that they provide full dynamical information about model galaxies. Using realistic mock catalogues generated with these methods, accurate and straightforward comparisons with observational data can be carried out. Since N-body simulations can handle large numbers of particles, the hybrid approach can access a very large dynamic range of mass and spatial resolution, at small computational costs. In addition, since the computational times are limited, these methods also allow a fast exploration of the parameter space and an efficient investigation of the influence of specific physical assumptions. This comes at the expenses, however, of loosing an explicit description of the gas dynamics.

One common criticism to semi-analytic models is that there are 'too many' free parameters. It should be noted, however, that the number of these parameters is not larger than the number of published comparisons with different and independent sets of observational data, for any of the semi-analytic models discussed in the recent literature. In addition, these are not 'statistical' parameters but simply due to our lack of understanding of the physical processes considered. Therefore, a change in any of these parameters has consequences on a number of different predictable properties, so that often there is little parameter degeneracy for a given set of prescriptions. Finally, observations and theoretical arguments often provide important constraints on the range of values that different parameters can assume. More important than the actual value of the parameters are, in my opinion, the 'parametrizations' assumed for the physical processes at play. Also in this case, theory and observations provide important inputs. Given we lack a complete 'ab initio' theory for most (all?) of these processes, however, different parametrizations remain equally plausible.

Given the complexity of the galaxy formation process, it is not surprising that none of the methods that we use to model the formation of galaxies is able to fully and satisfactorily explain the variety of observed galaxy properties. There are, in particular, a number of 'problems' that are shared by all semi-analytic (as well as by hydrodynamical simulations) that have been recently published: (i) the number densities of low-to-intermediate mass galaxies are systematically larger than observational estimates. Efficient stellar feedback is able to bring the low mass end of the galaxy mass function in agreement with observational results in the local Universe, but does not appear to be able to solve satisfactorily the problem at higher redshift. (ii) Low-to-intermediate mass galaxies tend to be too passive with respect to observational measurements. (iii) Massive galaxies have predicted metallicities that are too low with respect to observational measurements. A detailed illustration of these problems, and more references can be found in [101]. The current wisdom is that the solution of the problem lies in a physical process that is able to break the parallelism between mass growth and halo growth, particularly for galaxies of low-to-intermediate mass. It remains to be seen if this can be achieved by simple modifications of the stellar feedback and gas recycling scheme.

The Toomre brothers were among the first to recognize that mergers can drive the evolution of galaxy types by transforming disks into objects that resemble elliptical galaxies. What are the limits of this idea? Is merging the correct solution for understanding the evolution of all galaxies? Theoreticians distinguish major and minor merging events. Would you explain why? Which observations suggest the two phenomena? How many major merging events may occur on average to a galaxy?

In the hierarchical scenario, dark matter haloes (and therefore the galaxies that reside in them) undergo frequent interactions with each other. These interactions have dramatic influence on the morphologies and star formation histories of the galaxies involved. Numerical simulations have shown that close interactions can lead to a strong internal dynamical response driving the formation of spiral arms and, depending on the structural properties of the disks, of strong bar modes. The developing non-axisymmetric structures (spiral arms and/or central bars) lead to a compression of the gas that can fuel starburst/AGN activity (see [279], and references therein). Simulations have also shown that in sufficiently close encounters between galaxies of similar mass, violent relaxation completely destroys the disk and leaves a kinematically hot remnant with photometric and structural properties that resemble those of elliptical galaxies.

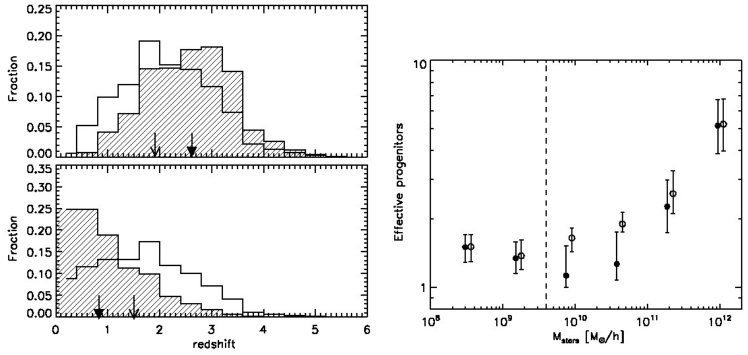

Fig. 8.1 From [98]. Left panel: Distribution of formation (top panel) and assembly redshifts (bottom panel). The shaded histogram is for elliptical galaxies with stellar mass larger than $10^{11}\,M_\odot$, while the open histogram is for all the galaxies with mass larger than $4 \times 10^9\,M_\odot$. Arrows indicate the medians of the distributions, with the thick arrows referring to the shaded histograms. Right panel: Effective number of progenitors as a function of galaxy stellar mass for model elliptical galaxies. Symbols show the median of the distribution, while error bars indicate the upper and lower quartiles. Filled and empty symbols refer to a model with and without a disc instability channel for the formation of the bulge.

The merger hypothesis for the formation of elliptical galaxies was suggested early on by [397] and later confirmed by many numerical simulations ([279, 86], and references therein). In recent years, a large body of observational evidence has been collected that demonstrates that a relatively large fraction of early-type systems show clear evidence of interactions, mergers, and recent star formation, in particular at high redshift. However, the data also seem to indicate that only a small fraction of the final mass is involved in these episodes. This observational result has often been interpreted as strong evidence against the somewhat extended star formation history naively predicted from hierarchical models. A related issue concerns the α-element enhancements observed in elliptical galaxies. The [α/Fe] ratio is believed to encode important information on the time scale of star formation, and it is a well-established result that massive ellipticals have supersolar [α/Fe] ratios, suggesting that they formed on relatively short time scales and/or have an initial mass function that is skewed toward massive stars. The inability of early renditions of the hierarchical merger paradigm to reproduce this observed trend has been pointed out as a serious problem for these models [391]. More recent work has pointed out that there is an important difference between 'formation' time of the stars in the galaxy and its 'assembly' time, which makes the observed trend of shorter star formation histories for more massive galaxies *not anti-hierarchical*. I will come back to this point below.

In order to model galaxy interactions and mergers, one needs to know what determines the structural and physical properties of a merger remnant. Numerical simulations have shown that these depend mainly on the following two factors: (1) The progenitor mass ratio. During 'major' mergers, violent relaxation plays an important role, and as a consequence, the merger remnant has little resemblance to its progenitors. On the other hand, during minor mergers, the interaction is less destructive so that the merger remnant often resembles its most massive progenitor. The exact value at which one distinguishes between minor and major mergers is somewhat arbitrary but is usually chosen to be of the order of $M_2/M_1 \sim 0.3$. (2) The physical properties of the progenitors.The structure of the galaxies involved in a merger plays an important role in determining the response to interactions: disks that are stable against the growth of instabilities (e.g., because of a central bulge or a lowered disk surface density) will be less 'damaged' than disk-dominated systems that are prone to strong instabilities. In addition, in a merger between two gas-rich progenitors, a significant fraction of the gas content can be fuelled toward the centre, triggering a starburst and/or accretion of gas onto the central black hole. Merger-driven starbursts are instead suppressed if the two merging systems are gas poor. These purely stellar mergers are often referred to as a 'dry' or 'red' and are believed to contribute significantly to the recent assembly of elliptical galaxies [98].

Naively, one expects very large number of mergers in the hierarchical scenario, where more massive systems form through the mergers of smaller units, and larger systems are expected to be made up by a larger number of progenitors. The right panel of Fig. 8.1 shows the 'effective number of stellar progenitors' of elliptical galaxies of different mass. This quantity represents a mass-weighted counting of the stellar systems that make up the final galaxy, and therefore provides a good proxy for the number of significant mergers required to assemble a galaxy of given mass. The figure shows results from a model where only mergers contribute to the formation of bulges (empty circles) and those from a model where bulges can also form through disk instability (filled symbols). The vertical dashed line indicates the threshold above which the morphology classification can be considered robust (this is set by the resolution of the parent simulation). As expected, more massive galaxies are made up of more pieces. The number of effective progenitors is, however, less than two up to stellar masses of $\sim 10^{11}\,\mathrm{M}_\odot$, indicating that the formation of these systems typically involves only a small number of major mergers. Only more massive galaxies are built thought a larger number of mergers, reaching up to ~ 5 for the most massive systems. The right panel of Fig. 8.1 shows the distribution of 'formation' (top panel) and 'assembly' (bottom panel) redshifts of model ellipticals. The former is defined as the redshift when 50 per cent of the stars that end up in ellipticals today were already formed, while the latter is defined as the redshift when 50 per cent of the stars that end up in ellipticals today are already assembled in a single objects. More massive galaxies are ‘older’, albeit with a large scatter, but assemble ‘later’ than their lower mass counterparts. Hence, the assembly history of elliptical galaxies parallels the hierarchical growth of dark matter haloes, in contrast to the formation history of the stars.

Let me finally stress that, in recent years, a large body of observational evidence has been collected that demonstrates that interactions and mergers indeed represent a common phenomenon at high redshifts, and that these processes certainly affect the population of elliptical galaxies in the local Universe. [356] found evidence for bluer colours of elliptical galaxies with an increasing amount of morphological disturbance in a study based on a small sample, with a strong bias towards isolated systems. Later studies using absorption–line indices have demonstrated that a significant fraction of cluster early–type galaxies has undergone recent episodes of star formation [15]. Signs of recent star formation activity have also been detected in a number of high redshift early–type galaxies using both colours and absorption and emission line diagnostics (e.g. [269, 399]). When using deep images, a large fraction (about seventy per cent) of local early-type galaxies show morphological signatures of tidal interactions consisting of broad fans of stars, tails, and other asymmetries at very faint surface brightness levels [405]. These results favour, at least for a part of the elliptical galaxy population, a hierarchical formation scenario.

The discovery of DM and of the Large Scale Structure of the Universe, coupled with the measurements of the CMB, progressively led astronomers toward the new paradigm of the hierarchical structure of the Universe. The next interview explains why and what is the role assigned to baryons in this game.

Questions for Jaan Einasto:
the Large Scale Structure (LSS) of the Universe contain the imprint of the physical conditions at the epoch of galaxy formation. Could you discuss what have we learned from these studies?

Let me discuss our experience step-by-step.

In early 1970’s very little was knows about the large-scale distribution of galaxies and galaxy systems. The commonly accepted picture at that time was that galaxies form a “field” in which galaxies and clusters are distributed almost randomly.

Our team started to study the distribution of galaxies in mid-1970’s when Yakov Zeldovich asked me to find an answer to the question: Can we find some observational evidence which can be used to discriminate between various structure formation scenarios? At this time there were two main scenarios of structure formation, the Peebles hierarchical clustering scenario [306], and the Zeldovich pancaking scenario [425].

When Zeldovich asked the question I had initially no idea how we could find an answer. But quite soon we understood that systems of galaxies evolve rather slowly. If there exist large-scale structures in the nearby Universe, these structures must be similar to structures during the formation of galaxies. We collected redshift data for galaxies, clusters and active galaxies and found that there exists a continuous network of galaxies and clusters we called "cell structure of the Universe" [182, 183] or the supercluster-void network [116]; presently it is called the cosmic web [38]. Dominant elements of the web are chains/filaments of galaxies and clusters. The space between filaments is almost devoid of galaxies — these regions are called cosmic voids. Superclusters are high-density regions in this network. The linear shape of filaments can be explained only in case when galaxies and clusters already form inside filaments [182]. Otherwise it is impossible to cancel galaxy velocities perpendicular to the axis of the filament, if they form randomly in space. Some filaments are rich and consists of clusters and groups of galaxies, as the main ridge of the Perseus-Pisces supercluster. Filaments of galaxies inside large voids are poor and consist only of galaxies and poor Zwicky clusters.

In summary, studies of the large-scale distribution of galaxies in late 1970's showed the presence of the cosmic web — a hierarchical network of filaments of galaxies, clusters of galaxies, superclusters and voids between them.

The connection between the structure of the cosmic web and the nature of DM particles was discussed in 1981 at two conferences, in April in Tallinn, and in September in Vatican. At the Vatican conference Joe Silk analyzed the concept of non-baryonic DM. In addition to neutrinos he considered photinos as one of the possible candidate for the DM. He concludes his analysis as follows: "It seems that the large-scale structure of the Universe is intimately related to its microscopic structure on elementary particle scales. This is perhaps not surprising if one recalls that it is the initial seed of fluctuations at the Planck epoch that are likely to determine the asymptotic growth of irregularities in the expanding Universe" [227]. These two conferences mark probably the birth of astro-particle physics. Cosmologists and particle physicists understood that properties of the micro-world and macro-world are related.

To compare the model and observed distributions of particles/galaxies we performed together with Zeldovich and his collaborators several quantitative tests [426]. We found that in most tests the pancake model is in good agreement with observations, and the hierarchical clustering model is in conflict with all tests. However, the pancake model applied by Zeldovich had one problem: it did not contain weak filaments in contrast to observations. Soon we realized that this defect is due to the fact that the model used neutrinos as DM particles.

Numerical simulations using photinos (or other Cold DM particles) were performed by Adrian Melott. In summer 1983 he visited Moscow and Tallinn to discuss his recent results. Together we performed the same quantitative tests as earlier [426]. Our conclusion was that the new CDM model is in good agreement with observations [164]. A still better agreement has the CDM model with cosmological constant (or Dark Energy) [117].

The main lesson from these studies of the cosmic web was the understanding of the presence of a close connection between the two topics — the nature of DM and the structure of the web. Secondly, we understood that both physical processes, the pancaking and the hierarchical clustering, work in nature. First DM and ordinary matter flow to form high-density regions (pancakes/filaments), thereafter in these regions the hierarchical clustering (and the merging of galaxies) starts. Thus both Zeldovich and Peebles are right.

What about the density profile of DM?

Modern simulations of the web have a very high resolution, thus it is possible to study the density profile of DM halos. These studies show that DM halos of very different mass and radius have rather similar density profiles, the NFW-profile [291]. An even better profile is given by the generalized exponential model: $\rho(a) = \rho_0 \exp\left(-(a/a_c)^{1/N}\right)$, where ρ_0 is the central density, a is the semi-major axis of the equidensity ellipsoid, a_c is the core radius, and N is the structural parameter, which allows one to vary the shape of the density profile. I introduced this profile to present the density distribution of galactic populations [189]. Presently it is called the "Einasto"-profile [292].

Why the density distributions of stellar populations and DM halos is so similar is not understood yet.

Which is the meaning of the cell structure?

Miguel Aragon-Calvo used high-resolution simulations to investigate the internal structure of voids [7]. His simulations confirmed that the cosmic web has properties of a cellular distribution. He found that all cellular systems in Nature have similar properties, depending on the number of neighbouring cells. If the number of neighbouring cells is small, then during the evolution the cell shrinks and disappears [361]. If the number of neighbours is large, then the cell expands. The most stable configuration is a cell with 8 neighbouring cells; such cells have the structure of a honeycomb. These high-resolution simulations also showed the hierarchical nature of the cellular and void structure. Within a large cell (void) there are sub-cells (sub-voids), within sub-cells there are sub-sub-cells (sub-sub-voids) etc.

When we introduced the term "cellular structure of the Universe" [182, 183], we did not guess that this term could have such a deep physical meaning. However, this hierarchical cellular structure is seen only in the distribution of DM particles. Galaxies form in high-density regions of the cellular network — filaments and knots at filament crossings. For this reason the distribution of galaxies is filamentary, and there are no continuous surfaces of cell walls, which could isolate neighbouring cells from each other [117].

Already early studies of the web showed that cosmic cells, i.e. low-density regions surrounded by superclusters, have a certain mean diameter of the order of 100 h^{-1} Mpc, where h is the Hubble constant in units of 100 km/s per Mpc [182, 183]. The dominant scale of the supercluster-void network 120 h^{-1} Mpc is very well seen in the distribution of rich Abell clusters [119].

A smaller scale has been found in the distribution of groups and clusters along filaments of galaxies. In the main filament of the Perseus-Pisces supercluster clusters and groups of galaxies are located at regular mutual distances from each other [182, 183]. Elmo Tempel developed a method how to identify galaxy filaments in the

SDSS survey. He found that galaxy filaments look like pearl necklaces [390]. The characteristic length of the pattern is around 7 h^{-1} Mpc.

The reason of the existence of both these regularities is not known.

The largest non-percolating systems of galaxies are superclusters. First supercluster catalogues were prepared using Abell clusters of galaxies [118, 120]. In the last decade large redshift surveys of galaxies have been performed. These surveys have been used to calculate the luminosity density fields of galaxies, corrected to take into account galaxies fainter than the magnitude limit used in redshift surveys. Supercluster catalogues have been prepared using the two-degree-Field (2dF) survey [121], and the SDSS survey by Liivamägi and collaborators [235].

The SDSS based supercluster catalogue has been used to investigate the morphology of superclusters using Minkowski functionals [123, 125, 126]. The superclusters can be divided into two main morphological types, spiders and filaments. Clusters in superclusters of spider morphology have higher probabilities to have substructure and larger peculiar velocities of their main galaxies than clusters in superclusters of filament morphology. Clusters in superclusters with spider morphology also contain a larger fraction of star-forming galaxies than clusters in superclusters of filament morphology. The most luminous clusters are located in the high-density cores of rich superclusters [124].

These studies show that not only the nearby environment (clusters vs. field galaxies), but also large-scale supercluster environment determines the morphological type of galaxies.

Direct observations of very distant galaxies show that first forming galaxies are irregular dwarfs. Numerical simulations suggest that galaxy formation starts in regions where the density of the pre-galactic matter is the highest — in centres of future superclusters. During the subsequent evolution pre-galactic gas (DM and baryonic) flows from low-density regions towards filaments, in such way galaxies grow steadily. Inside filaments dwarf galaxies cluster hierarchically and merge to form more massive galaxies. Along filaments galaxies and clusters move towards supercluster centres, which become great attractors. These processes — the steady inflow of matter towards galaxies, the merging of galaxies and the flow of galaxies to supercluster centres — can be followed in the nearby Universe where the velocity flows can be calculated using direct distance indicators and galaxy redshifts, combined with constrained numerical simulations of the evolution. This combined approach allowed to define the extent of our home supercluster, called Laniakea [402]. The Virgo supercluster is only a weak outlying part of the Laniakea supercluster.

The use of the velocity flows allows a physically more accurate definition of superclusters. According to [402], a supercluster is a ‘basin of attraction’ in the velocity flow field. In other words, the boundaries of a supercluster are defined by the places at which the velocity flow field points in different directions on either side of the boundary. In this way the whole space is divided between superclusters. This definition can be applied, however, only in the nearby Universe. In more distant regions the use of the luminosity density field is the best available method to define superclusters. Liivamägi and collaborators found [235], that using an adaptive threshold density limit superclusters contain 27% of all galaxies and 3.7% of the whole volume, and using a constant density threshold 5 in units of the mean luminosity density superclusters contain only 14% of galaxies, and occupy 1.3% of the whole volume. The rest is located in filaments and voids, as shown already by [182, 183].

In this way the near-field cosmology and the study of very distant objects complement each other.

What are the Baryonic Acoustic Oscillations (BAO)?

The early Universe consisted of a hot plasma of baryons, photons, and dark matter. Competing forces of gravity and pressure create oscillations: the pressure forms a spherical sound wave of baryons and photons around each over-dense region. After the decoupling (recombination) the photons no longer interact with the baryonic matter and diffuse away. The pressure vanishes and the shell of baryonic matter is left at a fixed radius, called the sound horizon. This leads to the formation of peaks in the CMB angular power spectrum, discovered by the WMAP satellite. Similar features have been found in the distribution of galaxies of the SDSS Luminous Red Giant (LRG) sample by [127] and [179], using the correlation function and the power spectrum of LRG galaxies.

Baryon acoustic structures are spherical shells of relatively small density contrast, surrounding high density central regions. Recently a new method to detect the real-space structures associated with BAO was presented [9]. The authors designed a specific wavelet adapted to search for shells, and applied this method to detect shells surrounding high-density peaks of the SDSS density field. Peaks were found using the LRG sample of galaxies; to find shells around peaks the main galaxy sample of SDSS was used. To enhance shells they were stacked around high-density peaks.

The physics of the formation of BAO cells is well understood. Presently there are numerous projects to determine redshifts of millions of galaxies in large contiguous regions of sky up to faint magnitudes. These projects have the primary goal to determine BAO cells at various redshifts, and in this way to investigate properties of the dark energy which causes the acceleration of the present-day Universe. As a by-product these projects allow to investigate the general structure of the cosmic web on largest possible scales.

Theoretical considerations suggest that all objects more distant than about 140 Mpc (as seen from a certain position) were outside the horizon after the inflation until recombination, and thus had no physical contact to each other. For this reason the skeleton of the presently visible cosmic web should be formed already during the inflation. This conclusion was confirmed by analytical calculations [202] and numerical simulations of the evolution of the cosmic web [122].

Thus the present structure of the web gives us information on physical conditions during the inflation.

Most of the present knowledge of the past history of galaxies comes from the good theoretical foundation of stellar evolution. When the concept of stellar populations *developed, was immediately followed by the ideas of star formation. Now we start to define the basic concepts associated to the star formation history of galaxies and what are the consequences of these studies for the paradigm of a hierarchical Universe.*

8.4 The initial mass function

Questions for Pavel Kroupa:
the Initial Mass Function (IMF) is one of the most important theoretical ingredients of any theory of galaxy formation and evolution. The concept of IMF was first introduced by Salpeter (1955). It provides a convenient way of parametrization of the relative number of stars as a function of their mass. The IMF has been one of the most debated issues in galaxy studies.

Measurements obtained from young clusters and associations, and old globular clusters suggested that the vast majority of their stars were drawn from a universal system IMF: a power law of Salpeter index ($\Gamma = 1.35$) above a few solar masses, and a log normal or shallower power law ($\Gamma \sim 0.25$) for lower mass stars.

The shape and the universality of the IMF is still under investigation. Could you explain us why?

The Initial Mass Function (IMF, $\xi(m)$) is one of the most important theoretical ingredients of any theory of galaxy formation and evolution. The concept of the IMF was first introduced by [348]. The IMF is defined to be the differential number of stars, dN, in the stellar mass interval m to $m+dm$, $dN = \xi(m)\,dm$. It is the distribution function of all stars formed together in one "event", and the Salpeter IMF [348] is $\xi(m) \propto m^{-\alpha}, \alpha \approx 2.3, 0.4 < m/M_\odot < 10$. It provides a convenient way of parametrization of the relative number of stars as a function of their mass. The IMF has been one of the most debated issues in galaxy studies.

Modern measurements obtained from young clusters and associations, and old globular clusters suggested that the vast majority of their stars were drawn from a universal or canonical IMF: a power law of Salpeter index ($\Gamma_2 = 1.3, \alpha_2 = 2.3$) above halve a solar mass, and a log normal or a shallower power law ($\Gamma_1 \approx 0.3, \alpha_1 \approx 1.3$) for lower mass stars (fig. 4-24 in the recent review [217] which covers much of this material).

Before continuing one needs to establish some precise vocabulary: The stellar IMF is the distribution of stellar masses formed together in one star-formation event. It is constrained by star counts in a given star-formation event. Such a population of stars is *simple* (one age, one metallicity). The IMF of a whole galaxy is a different issue, as it is deduced from the field population of stars in a galaxy, and this field population has many different ages and metallicities, it is *complex*.

Rigorous work on the IMF needs to differentiate between the true IMF of a simple population and the IMF of a complex population. Are the two the same?

The reason why the question of whether the IMF is universal or not is still being studied and debated is that the IMF is indeed such a fundamentally important distribution function, and because constraining the IMF observationally is very hard indeed and mistakes in the analysis can easily occur if the work is not highly rigorous in every respect. Any scientist attempting this task requires intimate knowledge of all aspects of astrophysics, such as pre-main sequence and post-main sequence stellar evolution, stellar birth-rate functions, the structures in which stars typically form and their dynamical evolution including gas expulsion processes, the properties and evolution of binary systems and the corrections of star counts for various biases and uncertainties. One bias, for example, often not appreciated in dealing with Galactic-field star counts, is that by the nature of the systematically changing mass-ratio of binary stars with primary mass, the photometric distance estimates suffer a systematic bias in dependence of the primary star mass [214]. It is comparatively easy to make a survey, count the "stars", and to construct a "mass" distribution. Following such a straight forward procedure, typically one obtains different mass functions for different populations (e.g. the Orion Nebula Cluster versus the Taurus-Auriga populations vs the Galactic field "IMF"). But the difficult and salient aspect of deriving the IMF is to correct the star counts for all biases and extracting the physically relevant information. And this is where some teams have progressed far, while others have not, and therefore significant discussion continues.

Essentially, the problem is so hard, but appears so easy, that mistakes are made readily leading to debates and argumentations which might not be necessary.

Any young researcher without very detailed knowledge of all the previous results and analyses, is likely to do avoidable and out-of-date errors therewith setting back progress unnecessarily.

Two cases in point exemplify this: some researchers keep insisting up until today that the IMF obtained from the Taurus-Auriga groups of very young stars is substantially different from the normal or canonical IMF or the IMF constrained for the Orion Nebula Cluster. But, taking into account the very major uncertainty in estimating stellar masses for $<$few Myr old stars and the known fact that most stars in Taurus are in binary systems while only about 50 per cent of systems in the Orion Nebula Cluster are binaries, leads to the underlying parent distribution function of individual stellar masses being consistent with the same function within the uncertainties. This has been shown a long time ago (see the review [217]), but, for some unclear reason, this is being ignored by others. Another example is the recent claim by [336] that brown dwarfs constitute a continuous extension of the stellar IMF based on the recently constrained field-star IMF by [35]. But the authors of the field-star IMF explicitly warn, in their abstract, that the functional form of the IMF they derive is only valid for a restricted mass range which excludes brown dwarfs. Ignoring this and using the functional form as a model including brown dwarfs yields wrong results. The observationally established existence of the brown dwarf desert according to which stars rarely have brown dwarfs as companions [107] is a primary issue where [336] err. All of this discussion has been occurring in the past years, although models addressing all of these issues carefully had been published many years ago (see the review [217]). It has already been shown in 2003 [216] that, treating brown dwarfs as stars in constructing binaries, leads to far too many star–brown and far too few star–star binaries, in comparison to all known populations. Brown dwarfs therefore absolutely must be treated with their own, separate, IMF, as also planets have their own IMF which is not a continuous extension of the stellar IMF.

Thus, a discussion is kept going which may not be entirely useful, rather than building upon the robust observational findings, such as the verification of the brown dwarf desert by the excellent work of Dieterich et al. [107] in combination with the known stellar and brown dwarf binary properties.

The holy grail of IMF research is extracting the expected systematic variation of the IMF with physical conditions of star formation.

A star-formation event yields a stellar population whose mass distribution is describable by the stellar IMF of a simple population (see p. 589). Such a star-formation event occurs in a molecular cloud core typically on a sub-pc-scale and on a Myr time-scale and can be referred to as an embedded cluster. The stars belonging to such an "event" can neither be counted accurately nor precisely, but such a population is mono-metallic and coeval to within a few to ten times 10^5 yr, which is the time-scale over which an embedded cluster forms. This time scale is typically a few to ten times longer than the time ($\approx 10^5\,$yr) it takes for an individual star to assemble about 90 per cent of its final mass [422]. This is seen nicely even in supposedly "distributed" or "isolated" star formation in the Taurus-Auriga clouds [159, 46, 215] and in the southern part of the L1641 Orion cloud [268, 175, 176]. In these clouds the stars and proto-stars with ages younger than about 1 Myr are distributed non-uniformly in many groups of stars clustered on $\lesssim 1$ pc scales.

Thus, the direct imaging of all very young stellar and sub-stellar objects disprove the concept that there is a distributed mode of star formation below some threshold. Star formation is organized into sub-pc-scale events, which for all practical purposes can be described as embedded clusters. Direct observations suggest that the least massive embedded cluster consists of about a dozen binaries [215].

Denser, richer embedded clusters are dynamically active and expel stars from their cores as soon as these form [294]. Extremely massive star clusters with stellar masses $\gtrsim 10^6\,M_\odot$ may retain gas for long such that their stellar populations may be complex [423]. Even modest clusters may re-accrete gas well after their formation [315] also leading to non-simple population mixtures.

According to the IMF un-measurability theorem [217] *the IMF can never be measured*. It can be stated that the IMF does not have physical reality: there is never any instant in time where $\xi(m)$ is fully assembled. $\xi(m)$ is therefore a theoretical and mathematical concept or entity.

As new binary stars form, others are ejected or broken up into their binary companions, at any instant low-mass stars have not yet reached the main sequence while massive ones have already left it and/or have been ejected from their rich embedded clusters. Thus, what an observer deduces, given an available particular survey data set, is merely a part of $\xi(m)$.

The art in the game of deducing a complete mathematical form of $\xi(m)$ and the mass range over which it is valid (assuming such a form exists as a theoretical construction) is putting together the observational clues and pieces to one functional form which can be used in theoretical work on stellar populations. Indeed, a particular stellar population constitutes merely a snapshot which is but fleeting, and the same population may appear to be described by a different mass function (MF) when viewed with a different survey at a different (astrophysical) time. Apart from the highly significant uncertainties (factors of two) in mass and age determinations of individual rapidly evolving very young stars given their photometric properties when they are younger than a few Myr, as demonstrated by the seminal work of Günther Wuchterl & Werner Tscharnuter in 2003 [422], there is patchy obscuration by dust and, very fundamentally, a time-varying population of unresolved binary stars.

Star formation typically yields binary stars, because the contracting pre-stellar molecular cloud core needs to shed and deposit its angular momentum while the formation of three- or higher-order multiple systems can only be a rare outcome [161].

Rich clusters, which partially survive the violent birth involving expulsion of their residual gas with the associated violent revirialisation (e.g. [13, 14]), will, after these events, contain a stellar mass function which has been damaged by loss of stars and this may be stellar-mass dependent if the clusters were mass segregated [249]. Star clusters evolve by evaporation preferentially of their least-massive stars and dissolve in about 20 present-day two-body relaxation times. While the initial or primordial binary population is broken up early [250], the binary fraction may increase with time as hard binaries[1] remain preferentially in a cluster because they have, on average, higher system masses than single stars.[2] Binary systems are typically unresolvable with observations. *At any time, a cluster thus has an observable stellar (system) mass function which deviates substantially from the original IMF of all its stars it was born with.* Direct star-formation simulations which are already approaching sufficient realism to reflect the real population can be used to study the time-variation of the observable MF of stars and binary systems such as demonstrated by the seminal work of Matthew Bate [19].

Therefore, the proper procedure for constraining $\xi(m)$ is to pose the hypothesis that there is a parent $\xi(m)$ from which the various observed snapshots (e.g. the individual groups in Taurus-Auriga, or a particular young or old star cluster) are drawn, thereby it being essential to take into account in the analysis *all* biases and evolution effects [217]. The mere counting-up of observed "stars" (many of which are typically unresolved binary systems) to create a histogram of masses, i.e. to obtain an estimate of the stellar mass function, suggests such mass functions to have different shapes.

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[1] Hard binaries have an absolute binding energy, $E_{\mathrm{bin}} > 0$, which is significantly larger than the mean kinetic energy of the cluster stars, E_{kin}. Soft binaries have $E_{\mathrm{bin}} \ll E_{\mathrm{kin}}$.

[2] The issue of IMF invariance is related to the important issue of whether the initial binary-star distribution functions are invariant as well. Observational evidence, analyzed carefully and taking into account the dynamical evolution properly, suggests this to be the case in present-day star-forming regions [250, 251] and in major star burst clusters a Hubble time ago [233].

But careful analysis has always yielded the result that the hypothesis that there is one invariant parent distribution cannot, in most cases, be rejected, given all the uncertainties and biases.

This statement is true for star-formation that is and has been occurring in the MW disk, including the Taurus-Auriga clouds and most globular clusters, the Galactic field and bulge and dwarf spheroidal satellite galaxies [217].

Unless the job is done extremely carefully and thoughtfully, the various outcomes of the star formation process will appear like a mess, such that somewhat careless work may imply the result "what you see is what you get", an *opinion* subscribed to by some workers. But in this light the seminal 2007 paper by de Marchi, Paresce & Pulone [104] reporting that low-concentration globular clusters have present-day stellar mass functions which are depleted in low-mass stars (i.e. they have bottom-light mass functions) came as a shock. The dynamical clock ticks slower in low-concentration clusters, such that the expectation was that these ought to, if anything, retain the IMF at the low stellar-mass end. This is nicely shown by the international collaboration led by Nathan Leigh ([232], their fig. 4). This surprising observational result can be explained if globular clusters were formed highly compact with radii smaller than about 1 pc, more massive than today and with an IMF which systematically becomes top-heavy with increasing birth density and decreasing metallicity of the cluster with significant expansion through the expulsion of residual gas [252]. The remarkable finding by this study, led by Michael Marks, is that it is consistent with the results obtained entirely independently from two studies led by Jörg Dabringhausen concerning the dynamical M/L ratios of and the X-ray sources in ultra-compact dwarf galaxies (UCDs) [88, 89, 90]. The dependency of the IMF on star-forming cloud density and metallicity is shown in fig. 3 and 4 in [252]. Furthermore, the first-ever integration of globular clusters on a star-by-star basis over a Hubble time by Akram Zonoozi et al. furthermore significantly supports these results by uncovering the initial conditions for the two clusters Pal 4 and Pal 14 after violent revirialisation through gas expulsion [428, 429]. The remaining challenge will be to see if the phase prior to violent revirialisation is consistent with the above statements. The recent constraints on the canonical shape of the low-mass stellar IMF in the Arches star-burst cluster by Shin & Kim [363] again supports these results nicely. Further independent evidence for top-heavy IMFs in extreme star-burst environments on scales of less than 100 pc is seen in the high rate of type II supernovae in e.g. Abell 220 and 299 [310, 90, 217].

Indeed, the concept of an invariant, universally valid parent IMF stands in contradiction to all predictions star-formation theory has been making over the past decades. According to even robust and fundamental arguments in star formation theory, the IMF ought to become top-heavy with decreasing metallicity and increasing gas density and temperature.[3] Cases in point of theoretical IMF work investigating

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[3] The recent much noted and important suggestion that the IMF becomes very bottom heavy with increasing mass of elliptical galaxies has been shown to be untenable (see [365, 366, 305], with a possible solution to the spectroscopic evidence being proposed by [239]). Also, no theory of the IMF has ever *predicted* such a bottom-heavy IMF, while *predictions* were always such that the IMF becomes top-heavy under extreme conditions (e.g. Larson [229] on the basis of a Jeans-

possible variations with physical conditions are [1, 229, 128, 130, 298, 18, 198, 39, 19, 171].

According to the above results gleaned largely from resolved stellar populations, the following may be stated on the IMF:

The stellar IMF can be described as an invariant canonical distribution function when the star-formation rate density (SFRD) in an embedded cluster is $\lesssim 0.1$ $M_{\odot}/(pc^3 yr)$, while it becomes progressively top-heavy with increasing SFRD [252].

Why it is so difficult to get the IMF of a galaxy?

Measuring the IMF of a simple resolved population is very challenging, but deducing the IMF of a whole star-forming galaxy is a very different problem. In a star cluster the IMF can be constrained from the count of individual stellar systems (single stars and unresolved binaries). For a galaxy this is not possible, last not least because thee are far too many stars to count, if stars can be resolved at all. Estimating the IMF of a whole galaxy, the galaxy-wide IMF (GWIMF) or the IMF of a complex population, must therefore rely on the integrated light properties of the galaxy, or on spectroscopic analysis. *The former* can yield constraints on the relative number of massive and less massive stars, since a population with a top-heavy GWIMF will be blue, while a galaxy with a top-light GWIMF will be redder. But there are degeneracies, such as younger more-metal-rich populations being as red as old metal-poor populations or populations with more bottom-heavy IMFs. *The latter* constrains the stellar population mixture more precisely from its spectral energy distribution but relies on a template library of stellar spectra which need to be combined in the correct proportions to fit the observed SED. Ideally, all different methods would be used in unison to enhance the constraints, but the workload is formidable and subject to problems such as the spectral library not being complete (if a type of star is not part of the library, other stars in the library need to compensate its contribution which can bias the result – see footnote 3 on p. 593 for a possible example of this). Also, in deriving the GWIMF it needs to be taken into account that low-mass stars have been adding up over the star formation history of a galaxy, while the massive star content is only visible as established during a time corresponding to the life time of the massive star being considered [280, 351, 217]. Normalisation issues between the low-mass end and the high-mass end thus arise, as well as systematically different spatial distributions between low-mass and massive stars. Low mass stars come in ages extending to the birth of the galaxy and have thus had many Gyr to diffuse in phase space away from their original location (e.g.

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mass argument and Adams & Fatuzzo [1] on the basis of a self-regulated star formation theory). No physical conditions are known which can generate such a bottom-heavy distribution of stellar masses (although [63] now suggest this may be possible, at least partially in highly turbulent high-Mach-number gas). Weidner et al. [414] point out the problems associated with such an IMF for the metal enrichment required to account for the observed abundances. Also, the relics of the most intense pc-scale star-burst systems known in the Local Group, the globular clusters, show bottom-light MFs [104, 232] which can be accounted for only with significant dynamical evolution as noted above. The bottom-heavy IMF case will therefore not be discussed further here.

the ancient thick disk), while those massive stars that were not dynamically ejected from their birth clusters occupy the phase-space region they were born in (e.g. the young thin disk). Similar issues are dealt with in extreme detail by the seminal work on the IMF by John Scalo [351] and Bruce Elmegreen & John Scalo [131].

How can the IMF of the MW be constrained?

The IMF of the MW disk can be constrained by carefully analyzing direct star-counts. This is a difficult endeavor prone to biases which, if not recognized, may affect the result to disadvantage. The conversion of the stellar luminosity function to the stellar mass function is proportional to the derivative of the stellar mass–luminosity relation which has substantial uncertainties [207]. One can count the stars in dependence of their absolute luminosity to construct the stellar luminosity function within a small region around the Sun for which trigonometric parallax is available. This ensemble of stars is so close by, within 5 to 20 pc depending on the brightness of the star, that all multiple systems are resolved such that an estimate of the individual stellar luminosity function becomes possible. An alternative, in order to increase the number of stars and thus the statistical significance of the stellar count per luminosity bin, is to perform thin pencil beam surveys to reach the stellar population along the line of sight out to 100 or more pc. Many such pencil beam surveys can be done, and distance measurements rely on the photometric parallax method. Multiple systems remain unresolved. The biases associated with the two methods need to be understood very well, and the structure of the Galactic disk needs to be modelled, as well as the age and metallicity distribution of the stars of different masses. Thus the Lutz-Kelker bias needs to be accounted for through measurements errors in trigonometric parallax, cosmic scatter needs to be modelled to account for Malmquist bias. The break-through seminal paper on this problem has been contributed by Stobie, Ishida & Peacock in 1989 [382]. A multi-dimensional minimisation procedure, solving simultaneously for both types of star counts, has been performed only once so far, in 1993 [214]. The resulting estimate of the IMF for main sequence stars with masses below about $1 M_\odot$ for the Galactic field population turned out to be nicely consistent with Salpeter's work [348][4], and to be remarkably robust over time and to be a good model for the parent IMF which is consistent with the resolved stellar populations seen in current star forming regions and in star clusters (see p. 589). This result by [214] deviates from the previous seminal work of Miller & Scalo in 1979 [280] and Scalo in 1986 [351] in that the mass–luminosity relation of low mass stars was modelled physically properly for the first time [207], multiple systems were taken into account for the first time [208], and both, the nearby and the pencil-beam surveys were combined consistently for the first and until now for the last time [209]. The constraints of the field-star IMF by [351] remained valid for stars more massive than $1 M_\odot$, but this regime is very hard to treat because a time-evolving star-formation history introduces structure into the observationally derived IMF, as shown for the first time by Elmegreen & Scalo in 2006 [131].

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[4] Salpeter constrained the IMF for stellar masses in the range 0.4 to $10 M_\odot$.

Nevertheless, the overall slope of the field-star IMF above about $1\,M_{\odot}$, derived by Scalo's analysis [351], turned out to be steeper with $\alpha \approx 2.7$ [214] than the massive-star IMF deduced in individual very young populations, notably by the ground-breaking work of Phil Massey (see his review [256] and fig. 2 therein), $\alpha \approx 2.3$, independently of metallicity and density for current star-forming regions [217].

This difference between the field-star IMF and the IMF deduced in star-forming regions remained unexplained for decades, and I simply thought that the Scalo index may not be correct.

What about the other galaxies?

Deducing constraints on the GWIMF in external galaxies is hard because one deals with integrated flux in various spectral pass bands, and non-uniform extinction by dust, loss of photons, scattering of photons, all play a role. Reducing the observations to a usable result is a nightmare. But a few teams in the USA and in Australia have managed break-throughs on this problem with rather dramatic results, as will be touched upon further below in this section.

Observational evidence for a systematically top-heavy IMF in star-bursting galaxies and regions therein and at larger redshift has been suggested since decades (notably by Francesca Matteucci [257], see also [217] and references therein). *But an underlying systematically varying and computable IMF model, which accounts for this observational evidence and at the same time also for the universality of the IMF in local star formation, was not available*. And, the observational evidence was based on indirect arguments, such as the dynamical M/L ratios of a region, the available gas mass and its luminosity and the metallicity distribution. A computational approach did not exist at all, except to make somewhat ad-hoc assumptions as to how the IMF may change with redshift, for example, based on a Jeans-mass argument and ambient temperature. The shape of the IMF remained unpredicted.

In any case, why should the IMF of a whole galaxy or of a large region within it differ from the IMF in actual star-forming places which are observed, wherever resolution is sufficient, to occur in pc-sized cloud cores which may not know in which type of galaxy they condense in out of a molecular cloud through self gravity?

One possible argument for a similarity between the IMF and the GWIMF would be if one assumes the IMF is a probability density distribution function. That is, in small pc-sized star-forming pockets $N_{\rm p}$ stars are drawn randomly from the same IMF as also describes the ramdom drawing process to form $N_{\rm g} \gg N_{\rm p}$ stars in a whole galaxy. Then, statistically, IMF=GWIMF.

This (naive) ansatz was favored by most researchers, including me (e.g. [128, 130, 210, 211], see also the discussion in [217]). But the computational approach has changed dramatically through the discovery of the IGIMF Theory in 2003 [213]. The generic prediction of the IGIMF theory that the GWIMF steepens at high stellar masses with decreasing galaxy-wide SFR, has been confirmed by observations of thousands of star forming galaxies [174, 231, 275, 167].

As a result, neither the IMF nor the GWIMF are scale-invariant probability density distribution functions.

Before briefly explaining this computational approach it is useful to address the perhaps most important observational evidence which unambiguously indicates a systematic change of the GWIMF from top-light at very low star formation rates (SFRs) to top-heavy at high SFRs. Surveys of hundreds and thousands of star-forming galaxies have used various photometric tracers such as Hα flux to test for the high-mass end of the GWIMF, UV flux to test for the intermediate mass stellar population and red broadband colors to test for the intermediate and lower-mass end of the GWIMF [174, 231, 275, 167]. The data analysis and the investigations of various biases such as from dust attenuation, loss of photons and others, is highly involved and reported in these works in much detail.

The result in all of these surveys has been consistent in that the GWIMF flattens progressively with increasing SFR. Modelling the GWIMF as a canonical IMF which has $\alpha_1 = 1.3$ for stellar masses $m < 0.5, M_\odot$ and $\alpha_2 = 2.3$ for $0.5 < m/M_\odot \lesssim 1$ with α_3 being the index above $\approx 1\,M_\odot$, the dependency of α_3 on the SFR as deduced from the data is shown in Fig. 8.2.

How can this result of a systematically varying GWIMF with SFR be understood in terms of the largely invariant stellar IMF deduced from individual simple stellar populations (p. 591)?

The clue comes from realizing that the GWIMF is but the result of the addition of all simple populations in a galaxy to build-up the complex population of the galaxy. Thus, in simplified notation (SP=simple population = embedded cluster = star-formation event),

$$\mathrm{GWIMF}(m) = \Sigma_{\mathrm{SP}} \xi_i(m), \tag{8.1}$$

where $\xi_i(m)$ is the stellar IMF contributed by the ith star-formation event.

How was this ansatz discovered? In 2002 I was reconsidering my old problem (p. 544 above) of how thin galactic disks might thicken with time, and since I was working as a hobby on N-body models of embedded star clusters which expel their unused gas through the action of their massive stellar content, I realized that such "popping" clusters may lead to hot kinematical components in the disk of a galaxy. Assuming all stars form in a distribution of embedded clusters, i.e. *that embedded clusters are the fundamental building blocks of galaxies* [127], I calculated the integrals and found that it was readily possible to account for the thick disk and the subsequent thinning of the MW disk as time progressed if the SFR of the MW decreased with time until the present value of a few $M_\odot$/yr [212]. This work done in 2002 constituted, without me knowing, the prediction that the MW would have been resembling a chain galaxy discovered in 2004 by Bruce Elmegreen et al. [129].

With this ansatz, a similar integral over all star formation events or all embedded clusters yielded the integrated galactic IMF (IGIMF). Together with my then PhD student Carsten Weidner we did this in 2003, finding that the Galactic-field IMF had to be steeper than the IMF [213]. This, of course, explained the result which Scalo [351] had already obtained (see Sec. 8.4). A generalization of this result to other galaxies became possible by realizing that the most-massive cluster which is forming in a galaxy depends on the SFR of the galaxy ([410], note the extension

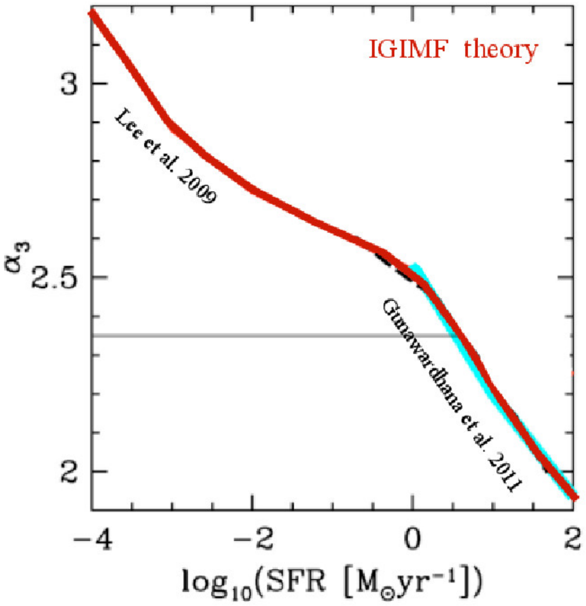

Fig. 8.2 The power-law index α_3 of the galaxy-wide IMF (GWIMF) for stars more massive than $\approx 1 M_\odot$ as a function of the galaxy-wide SFR is shown as the thick (red) solid line, as constrained by [231] for dwarf galaxies and by [167] for more massive galaxies, comparable and more massive than the MW. The solid curve coincides with the systematic variation of the IGIMF with SFR, as computed with the IGIMF Theory (adapted from fig. 1 in [415]. See also fig. 1 in Gargiulo et al. [151]. The horizontal line marks the canonical Salpeter/Massey index $\alpha = 2.35$.

to high SFRs by [332]). This allowed us to make the fundamental prediction that the IGIMF will flatten with increasing SFR [411]. This *predicted* behavior was confirmed *later* by the observational teams mentioned above. A particular success was the prediction of the Hα flux deficit over what is expected for an invariant IMF for dwarf galaxies [316], as confirmed by [231].

One shortcoming of the IGIMF Theory as known then was that it could not predict a top-heavy GWIMF, because the IGIMF could at most only become as flat as the canonical stellar IMF (i.e. Salpeter index) above $\approx 1 M_\odot$ in the “minimal scenario” of Weidner & Kroupa [411]. The knowledge of the top-heavy IMF in extreme star-burst clusters discussed below was not known then. However, including that knowledge, which was obtained entirely independently of the IGIMF Theory, into the right hand side of eq. 8.1, yielded agreement with the observed GWIMF as a function of SFR as shown in Fig. 8.2. This was published by Weidner et al. in 2013 [415]. The implication of this work is that the mass function of embedded clusters (ECMF), i.e. of star formation events, needs to also become somewhat top-heavy with an increasing galaxy-wide SFR. Galaxies with high SFRs$> 10 M_\odot$ thus also have slightly top-heavy ECMFs.

Is the IMF really a universal function?

This question can be answered readily today: *yes and no*:

The IMF within a star formation event (i.e. embedded cluster) can be taken to be a mathematically defined parent distribution function, $\xi(m)$, which follows universal rules that make it dependent on the physical boundary conditions which determine the distribution function of star formation events that are physically accessible for a galaxy.

The parent distribution function of stellar masses formed in one event (i.e. in an embedded cluster) is subject to conditions which are axioms derived empirically (for a full list see [415]):

- For a star-formation rate density on a pc-scale SFRD$\lesssim 0.1\,M_\odot/(\mathrm{pc}^3\,\mathrm{yr})$ the IMF is just the canonical form which can, for mathematical convenience, be written as a two-part power law form, or less conveniently as a log-normal part in the approximate range $0.08 - 1\,M_\odot$ (see p. 589).
- Based on independently obtained evidence from globular clusters and UCDs, the IMF becomes top-heavy when SFRD$\gtrsim 0.1\,M_\odot/(\mathrm{yr\,pc}^3)$ (p. 591).
- The IMF is truncated at the canonical maximal stellar mass $M_{\mathrm{max}*} \approx 150 M_\odot$, as deduced by different independently working groups (for the occurrence of *super-canonical stars* see [12]).
- The IMF, interpreted as an optimally sampled density distribution function [217], has a most massive star which depends on the stellar mass of the star-formation event or embedded cluster, $m_{\mathrm{max}} = \mathscr{K}_1(M_{\mathrm{ecl}}) \leq M_{\mathrm{max}*}$ (the $m_{\mathrm{max}} - M_{\mathrm{ecl}}$ relation). The function $\mathscr{K}_1(M_{\mathrm{ecl}})$ can be either fitted to the data or it may be derived independently from solving an integral equation (e.g. eq. 4-66 in [217]) and therefore directly follows from the shape of the IMF.
- The most massive embedded star cluster forming in a galaxy depends on the SFR of the galaxy, $M_{\mathrm{ecl,max}} = \mathscr{K}_2(SFR)$. Similarly to the function $\mathscr{K}_1$ above, this function $\mathscr{K}_2(SFR)$ can be fitted to data [410, 332] or it may be derived independently from solving an integral equation which expresses the stellar mass forming in embedded clusters on the time-scale, $\delta t \approx 10\,\mathrm{Myr}$, within which the inter stellar medium collapses to molecular clouds which then spawn the new population of stars (eq. 4.69 and 4.70 in [217]).
- The mass function of star formation events or embedded clusters (the ECMF) becomes slightly top heavy when the galaxy-wide SFR$> 1\,M_\odot/\mathrm{yr}$ (eq. 3 in [415]).

The *galaxy-wide IMF then follows from the above axioms* by summing together all the IMFs contributed by each star formation event over all star-formation events in a galaxy up to the most massive such event which is sustained in the galaxy, given its SFR (eq. 8.1). This is the *IGIMF Theory*. It is a theory because it is based on one principle, namely that star formation always occurs in phase-space correlated star formation events[5] and a small set of axioms derived from independent observations, and because it is predictive. That is, with the IGIMF Theory it is possible to calculate, from a few first principles deduced from observation, how galaxies evolve, enrich with metals and buildup their stellar masses (e.g. [313, 316, 198, 335, 151]).

Self-similar [67, 229, 240] star-forming disk galaxies are the by far dominant galaxy type [64] above a luminosity of $L \approx 10^{10} L_\odot$. The pronounced similarity of galaxies is not expected in the Standard Model of Cosmology [67] but is a manifestation of star formation being largely self-regulated [120], and this fundamental aspect of galactic astrophysics is captured by the IGIMF Theory. The top-heaviness of the IGIMF at very high SFRs (fig. 3 in [415]) immediately implies that elliptical galaxies formed with top-heavy IMFs, in nice agreement with the constraints on the IMF from the metal abundances brilliantly deduced by Francesca Matteucci already in 1994 [257, 154]).

Why the IMF could not be a probability distribution function?

Purely randomly sampling from a canonical IMF violates the too small spread in the IMF power-law indices deduced from many different simple populations by direct star counts (fig. 4-27 in [217]) and also the too small spread in the $m_{\rm max} - M_{\rm ecl}$ data, the spread in these data being consistent with measurement uncertainties [413]. The physical spread thus seems to be small, such that the physical constraints required to ensure the small spread implies that even a probabilistically sampled IMF becomes indistinguishable from an optimally sampled IMF. The physical interpretation of this result is that star-formation appears to be highly self-regulated, in agreement with an attractive model of star formation by Adams & Fatuzzo [1]. *Interpreting the IMF as an optimally sampled distribution function makes it mathematically convenient with the physical content of perfect self-regulation.*

Concerning the philosophical basis of the IGIMF Theory, there is a nice little episode that occurred recently involving one of the greatest minds in computational dynamics: in September 2014 I was attending the workshop held in honor of Sverre Aarseth's 80th birthday at an exclusive place in Sexten in the Dolomites. One day I was walking with Seppo Mikkola and I mentioned to him "*Nature must be surprisingly self-regulated*". He replied unhesitatingly, "*Yes, otherwise there would be complete chaos.*" Indeed a direct falsification of stochastic star formation has been achieved by an investigation of the very young cluster distribution in the galaxy M33 by Pflamm-Altenburg et al. (2013, [318]).

Despite the rather impressive quality of the IGIMF Theory, it seems to have implications which are unpalatable to parts of the community. One is that the seminal Kennicutt relation [192, 193] for calculating the SFR of a galaxy given its Hα

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[5] These are the maxima in the density fluctuations in a turbulent molecular cloud, also called embedded clusters. The least-massive examples of "embedded clusters" with a mass of about $5 M_\odot$ are what some refer to as "distributed star formation", see the individual groups or clusters in Taurus-Auriga or in the southern part of the Orion L1641 cloud discussed above.

flux needs to be corrected [312]. This centrally important relation for extragalactic studies assumed the IMF to be invariant amongst galaxies. But according to the IGIMF Theory, galaxies with a lower SFR have a comparative deficit in their massive star content while the Kennicutt relation was derived assuming an invariant ratio of massive stars to low mass stars. This has deep implications for the gas-depletion time scales and the stellar-mass buildup times of dwarf galaxies [314], which consequently do not fit the present-day models tailored within the SMoC framework. With the IGIMF Theory, a most remarkable prediction became possible, namely that dwarf galaxies must have a smaller Hα/UV flux ratio than more massive galaxies [316]. The IGIMF Theory also predicts a short radial cutoff of galactic disks in the Hα flux, the disks being much more extended in the UV [313]. Both *predictions* are confirmed by observations [231, 37].

While we now have, for the first time, a computable IMF model which encompasses universal star formation within the local smallest-groups or "distributed mode" reaching up to major starbursts, it is amusing but also frustrating to observe how parts of the community appear to invest a very major effort to show that the IGIMF Theory is not applicable. There is nothing to be written against critical tests. But too many, and it seems all published work which claims to rule out the IGIMF Theory I am aware of, has been shown to be flawed, either because newer data made the original counter argument redundant, or because the calculations are wrong. It is worth considering these reactions, since they imply that the community is now essentially largely ignoring the IGIMF Theory for interpreting extragalactic observations, rather than using the IGIMF Theory *as one possibility* to interpret the observations. For example, although [48] essentially find evidence for the IGIMF Theory by studying the stellar population in the outer region of a dwarf galaxy, the IGIMF Theory is not even mentioned, and instead stochastic star formation is used as the favored model. This is done despite the evidence that stochastic and unclustered star formation is not the appropriate description of star formation in low-density regions (see [169, 215, 300, 196], fig. 1 in [175]), and the explicit result that stochastic star formation is ruled out given data [318, 217].

A few cases in point which are fielded as arguments against the IGIMF Theory:

- In studying if a physical most-massive-star–star-cluster-mass ($m_{\rm max} - M_{\rm ecl}$) relation exists, [255] write in their abstract "Although we do not consider our compilation to be either complete or unbiased, we discuss the method by which such data should be statistically analyzed. Our very provisional conclusion is that the data are not indicating any striking deviation from the expectations of random drawing." This one last sentence, *which only expresses an opinion*, does all the damage, as this paper is being cited as evidence against the existence of a physical $m_{\rm max} - M_{\rm ecl}$ relation. But [255] culled their original data multiply times until they obtained a remnant distribution consistent with random selection of the most massive star from a model IMF, given N stars in a model. That is, their modelling did not demonstrate that stochastic sampling from the IMF is a preferred model. Further, they did not test the hypothesis whether the $m_{\rm max} - M_{\rm ecl}$ relation is ruled out by their data, and their analysis is made redundant in any case by the new data obtained by Kirk & Myers [196] which show a very small spread at the low-mass end ruling out stochastic sampling [413].

- Analyzing the spatial distribution of massive stars, [303] argue that 4 per cent of O stars which have been interpreted to have formed in isolation are consistent with stochastic/random sampling from the stellar IMF and therewith they argue against the existence of a physical $m_{\rm max} - M_{\rm ecl}$ relation. However, this exercise has become redundant because Gvaramadze et al. [168] have gathered data which show that virtually all of the previously thought 4 per cent "isolated" O stars are most likely runaways. The remaining fraction of O stars that cannot be identified as such is so small that it is not significant, but [168] demonstrate that it is consistent with the expected fraction of O stars which cannot be traced back to their birth cluster due to the *two-step ejection mechanism* [317]. This mechanism operates by a massive binary being dynamically ejected from its birth cluster, and when the primary explodes as a supernova, the secondary is launched on a ramdom trajectory depending on the phase of its orbit. Thus again, this "evidence against a physical $m_{\rm max} - M_{\rm ecl}$ relation" does not stand up to scrutiny.
- Notwithstanding the above rebuttals of the claims based on resolved populations fielded against the existence of a physical $m_{\rm max} - M_{\rm ecl}$ relation, [5] deduce, from their observations of unresolved very young clusters in a distant dwarf galaxy, that the relation is not evident and that the IMF is randomly sampled. The problems their analysis suffers from are pointed out by [416], who show that once the analysis is done correctly, the same data in actuality are consistent with the physical $m_{\rm max} - M_{\rm ecl}$ relation. Not wavering in their quest to argue that the relation does not exist, they repeat their analysis in [6] for another galaxy publishing a paper with significant text overlap with the previous one.
- There are other claims, none of which stand up to closer scrutiny, such as sometimes unwarranted criticism of the selection by Weidner et al. of the $m_{\rm max} - M_{\rm ecl}$ data: the selection is based on two criteria only, namely the very young cluster has to be of age smaller than 4 Myr and must not have evidence for a supernova explosion, and the partially very large uncertainties are carried through properly into the analysis [413]. Or, claims are put forward for cases of isolated massive star formation in nearby galaxies (such as in 2012, [45]) as an argument for stochastic star formation based on oversimplified O-star propagation times, ignoring, for the sake of the argument it seems, that a major star-forming region contains many compact embedded clusters and that the two-step ejection mechanism pointed out in 2010 [317] leads to O stars that cannot be traced back to their birth cluster. One of the authors of that study just said "Who cares?" when I pointed out that this mechanism most probably explains all their "isolated" O stars.

It is true that mistakes may happen, but these cases are mentioned here as a documentation of possible evidence as to how the scientific publications are sometimes designed in order to portray an opinion rather than from evidence. Indeed, that the natural sciences have a crisis is well known (see p. 542), and the above suggests that astronomy is not an exception.

Isolated massive star formation and the $m_{\rm max} - M_{\rm ecl}$ relation are central issues in the IGIMF Theory, because massive stars can, according to this theory, only form in embedded clusters. It is this relation which leads to galaxies with a low SFR, and which therefore form low-mass embedded clusters only, to have a deficit of massive stars compared to a statistically under-sampled IMF. Thus, if it could have been shown that the $m_{\rm max} - M_{\rm ecl}$ relation does not exist, then the IGIMF Theory with all its implications for galactic astrophysics and cosmological star formation would not be valid in the way it has been applied.[6] It is amusing to see how, as the evidence mounts which demonstrates that the relation is physical, a few teams are attempting to move their criticisms to ever more distant galaxies. For example the attempts to prove that isolated massive star formation does occur (which would violate the $m_{\rm max} - M_{\rm ecl}$ relation here) in external galaxies where such opinions (rather than robust calculations) can be barely disproven, given the extreme distances involved, are heraldic. Or, publishing opinions in the abstracts of peer-reviewed journal papers that unresolved very young (but partially shrouded) clusters in distant galaxies disprove the existence of the $m_{\rm max} - M_{\rm ecl}$ relation are comic at best. Most researchers do not have the time to analyze research papers in much detail, and all too often the contents of an abstract are adopted without careful perusal of the solidity of the contents. Thus opinions may be propagated which lack a firm scientific foundation to, with time, solidify a wrong but majority view.

At the end of the day, this situation is becoming as unsolvable as someone claiming that Newton's law of universal gravitation is falsified because in some distant apple trees there is evidence that some apples did not actually drop down, thereby ignoring that unseen animals devour the vanished apples. In this case the claim may not be falsifiable if the animals are unobservable (too small, too quick).

Does the IMF get heavier with M^*, σ and Z?

Yes, it does. There is strong evidence suggesting that the IMF in individual star formation events, i.e. in embedded clusters, becomes top-heavy with increasing density and decreasing metallicity (p. 591; see footnote 3 concerning the bottom-heavy IMF). The mathematical dependency on density is stronger though, such that in extreme galaxy-wide star bursts in which self-enrichment with metals from type II supernovae proceeds rapidly, the galaxy-wide IMF (GWIMF, eq. 8.1) becomes top-heavy in galaxies with $SFR > 1 M_\odot/yr$. Massive elliptical (E) galaxies are understood to have formed with very high SFRs ($> 10^3 M_\odot$/yr) on a short (< 1 Gyr) time scale, while lower-mass E galaxies took longer to form [334, 151].

Thus, based on the IGIMF Theory it is expected that very massive galaxies have a particularly heavy stellar population per unit light, which consists of a substantial fraction of white dwarfs, neutron stars and stellar mass black holes [151, 415].

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[6] A weaker form of the IGIMF Theory persists nevertheless if it is assumed that all stars are formed in clusters which follow a cluster mass function. Only in the trivial and unphysical case that star formation is modelled as purely stochastic drawing of stars from an invariant IMF throughout a galaxy without further constraints would the IGIMF Theory imply IMF=IGIMF [412] therewith violating the observational evidence that galaxies with a higher SFR have a systematically top-heavy IMF.

Fig. 8.3 shows the results of an IGIMF model in which the metallicity is assumed to be solar.

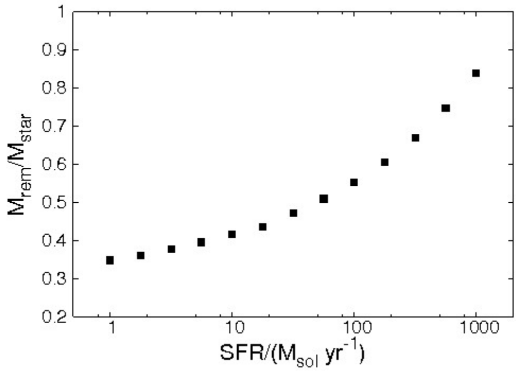

Fig. 8.3 The fraction of mass in stellar remnants (white dwarfs, neutron stars, stellar black holes), $M_{\rm rem}$ divided by the total mass in shining stars with masses smaller than $0.8 M_\odot$, as a function of the SFR of a galaxy. The IGIMF is calculated according to [415] assuming the mildly variable mass function of star formation events (i.e. of embedded clusters) and solar metallcity (see Fig. 8.2). The production of stellar remnants is treated as in Dabringhausen et al. ([88]). Kindly provided by Jan Pflamm-Altenburg.

Thus, a 10^{11} yr old massive E galaxy weighing $10^{12} M_\odot$ in stellar mass which formed within 0.5 Gyr [334, 151] would contain about as much mass in dark stellar remnants as in shining stars, while a low-mass E galaxy ($10^8 M_\odot$) which formed with a SFR of $< 1 M_\odot/\mathrm{yr}$ would only have 35 per cent mass in dark remnants in addition to its stellar mass. Detailed IGIMF results on the dynamical M/L ratios of E galaxies in comparison to observational constraints are available in [151]. Because the mass, M, metallicity, Z and velocity dispersion, σ of E galaxies are correlated positively [55, 56], a heavier IMF per unit light correlates with larger M, Z, σ. Note that the previous result reported by Cappellari [56] that more massive E galaxies need a Salpeter IMF which has more faint (essentially dark) M dwarfs rather than a canonical IMF which has fewer M dwarf stars is degenerate with the alternative IGIMF Theory, namely a top-heavy GWIMF with more dark remnants in more massive E galaxies and a GWIMF which is closer to the canonical IMF for low-mass E galaxies.

A pioneering study in which the formation and evolution of E galaxies in a SMoC Universe is studied self-consistently by employing the IGIMF Theory has been made by Gargiulo et al. (2014) [151]. Their conclusions are rather remarkable, namely that E galaxies appear to be better described by the IGIMF theory rather than the customary invariant Salpeter IMF. They emphasize in their Discussion “In general, when the argument of a variable IMF is considered to explain the [α/Fe]-stellar mass relation, the proposed IMF is treated as a free parameter . . . , or is varied with exploratory aims . . . , following no particular theory and leaving unexplored a vast region of the corresponding parameter space. In this work, we test the well defined theory regarding the integrated initial mass function of stars in galaxies with top heavy IMFs in star clusters during starbursts”.

Concerning disk galaxies, the IGIMF Theory has been shown to reproduce the observational constraints on how the GWIMF varies with SFR, as discussed at p. 596.

Why is the problem of the IMF related to the DM problem?

The IMF is related to the dark matter problem because a top-heavy IMF yields dark stellar remnants which behave dynamically like cold dark matter. Thus, as Fig. 8.3 demonstrates, a massive E galaxy which formed with a high SFR$> 1000 M_\odot/\mathrm{yr}$ would contain as much mass in dark stellar remnants as in shining stars. An astronomer analyzing the dynamical M/L ratio assuming a universal invariant IMF would wrongly conclude that the massive galaxy contains dark matter. Further, the same hypothetical astronomer may also make wrong deductions on the validity of Milgromian dynamics (Sec. 7.7).

How the galaxy-wide IMF affects fundamental physics is influenced subtly in star-forming dwarf disk galaxies (i.e. dIrrs). These are supposed to be dark matter dominated within their inner region. The large cores of their putative dark matter halos are, however, naturally and self-consistently explained in Milgromian dynamics without dark matter [137]. Now, in order to calculate the contribution by stars to the potential, a galaxy-wide IMF is required. If an invariant IMF is used for an ensemble of dIrr galaxies which have different SFRs, the contribution by dark stellar remnants would be calculated to be wrong, if instead the IGIMF Theory were the correct description. Thus, a dIrr galaxy with an extremely low SFR (say SFR$= 10^{-4} M_\odot/\mathrm{yr}$) would appear to have a redder stellar population compared to a model with a canonical IMF, because the IGIMF contains fewer massive stars at this SFR (Sec. 8.4, Fig. 8.2). This may lead to errors in the age and/or metallicity deduction, but will also affect the calculation of the potential. If this is not taken into account, it may be concluded that Milgromian dynamics does not work well in dIrr galaxies unless Milgrom's constant a_0 is adjusted systematically with the mass of dIrrs. This has indeed been found to be the case [333], but it is unclear at this stage whether using the IGIMF Theory would alleviate this possible tension of Milgromian dynamics with the data. Detailed modelling will be required to study this issue thoroughly.

This highlights how the stellar IMF in galaxies affects our ability of constraining fundamental physics.

Questions for Reinaldo de Carvalho:
you have worked a lot on the problem of the IMF. Would you present us briefly the main scientific results of your investigation on this item? What kind of observations could help to clarify the alleged universality of the IMF?

How does a galaxy form its stars? What determines the total stellar content of a galaxy? The answers to these seemingly simple questions have eluded astronomers for over half a century. Star formation starting from a cold gas cloud is an extraordinarily complex problem and probably one of the most difficult in modern astrophysics. This challenging "closed-box" scenario is further complicated by the fact that most galaxies reside in larger structures, where they interact with both their neighbors and the diffuse material present in groups and clusters. What can we do to make progress on disentangling the many processes that affect the stellar mass buildup of galaxies, and understanding which ones are dominant ?

The study of the formation and evolution of galaxies in general requires their systematic observations over a large redshift range in order to pinpoint the mechanisms responsible for the properties of galaxies as they are observed today ($z = 0$). Ensuring that the datasets for local and distant galaxies contain the same objects - or more correctly, today's galaxies and their actual progenitors - itself requires knowledge of the very evolution we are seeking to understand. Early-type galaxies (ETGs), with their predominantly old stellar populations, provide the simplest systems with which to address these questions. It is simpler to observe galaxies in the nearby Universe compared to their counterparts at high redshift. This simple fact can introduce serious biases in our interpretations when comparing different samples of galaxies from different cosmic epochs. For nearby samples, once homogeneous and high-quality data became available, the study of ETGs progressed very rapidly. Now, we can investigate in detail how these systems formed, how their stellar populations evolved, and how their structural properties are modified by the environments in which they reside [204, 223].

We embarked on a longterm project back in 2008 (myself, Dr. Francesco La Barbera, and later Dr. Ignacio Ferreras) starting with the development of a package called 2DPHOT, a multi-purpose environment for the two-dimensional analysis of wide field images [218]. This was part of a more ambitious Virtual Observatory (VO) project that is still ongoing [94]. The main goal of this project (SPIDER - Spheroids Panchromatic Investigation in Different Environmental Regions) was to coherently investigate the general properties of ETGs, like the fundamental plane and its environmental dependence, colors and color gradients, and the star formation history [219, 220, 221, 401]. We studied a sample of ~40,000 ETGs selected from SDSS-DR6, which, when matched against near infrared data from UKIRT Infrared Deep Sky Survey-Large Area Survey (UKIDSS-LAS) (DR4) comprises 5080 bright ($M_r < 20$) ETGs, in the redshift range of 0.05 to 0.095 with $grizYJHK$ photometry and spectroscopy. By conducting a systematic study of ETGs, we ended up focusing on the fundamental question of the universality of the initial mass function (IMF) - an essential component to the theory of galaxy formation.

Detailed examination of the IMF - the distribution of stellar masses in a single population at the time of birth - is a fundamental tool for understanding star formation in galaxies. In mathematical terms, the IMF expresses the distribution in mass of a newly formed stellar population as $dN/dM \propto \mathrm{m}^{-x}$, with masses in $(M, M+dM)$. Some authors adopt the logarithmic slope (as we do) $\Gamma = x - 1$. It has been usually considered a universal function, partly because of the complexities in obtaining proper observational constraints. The single power law approximation proposed by [348] has undergone numerous updates, with more complex functions that include a significant flattening of the slope for low-mass stars [351, 210, 62]. For a recent review on the IMF and its possible variations, see [17].

Studying a sample of ∼40,000 ETGS from our SPIDER project, [140] found a strong correlation between a galaxy's central velocity dispersion and the slope of the IMF, indicating an excess of low mass stars in massive ETGs. This means that low mass ETGs are well described by a Kroupa IMF, while massive ETGs require a bottom-heavier IMF. [222] analyze several spectral indices, combining gravity-sensitive features with age- and metallicity-sensitive indices, while also considering the effects of non-solar abundance variations. They conclude that central velocity dispersion, rather than alpha-enhancement, [α/Fe], drives the variation of the IMF. Although the analysis cannot discriminate between a single power-law (unimodal) IMF and a low-mass ($\leq 0.5M_\odot$) tapered (bimodal) IMF, robust constraints can be inferred for the fraction of low-mass stars at birth. Figure 8.4 shows the variation of the IMF slope unimodal distribution against central velocity dispersion, which corroborates other findings based on dynamical (e.g. [54]), stellar population analyses [80, 81], and strong gravitational lensing analysis (e.g. [400]). The shaded region corresponds to the 68% confidence level of the joint Probability Distribution Function (PDF) including spectral fitting and all three line strengths (TiO1, TiO2 and Na8190). The horizontal dashed line indicates the Salpeter case. These results expressing the non-universality of the IMF have strong implications for theories of galaxy formation and star formation.

The IMF is one of the key unknowns in modern astrophysics and there is still great debate on its universality. It is still unclear whether it varies from place to place within a galaxy and from galaxy to galaxy. In order to clarify these issues four main paths should be taken (at least):

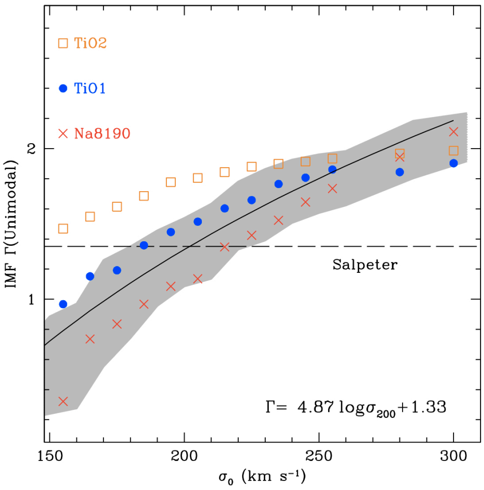

Fig. 8.4 The variation of the IMF slope vs. the central velocity dispersion, σ_0 (see text)

1. The approach of investigating the IMF through the stellar population properties of ETGS is a promising one, especially if we extend the wavelength range over which we probe the stellar content. Infrared spectroscopy out to K-band should allow us to minimize the degeneracy between true IMF variations and element abundance ratios. Along these lines, the ingredients of a Single Stellar Population (SSP) are still uncertain, deserving further detailed study (e.g. stellar evolution, stellar atmospheres, high quality stellar cluster data). In particular, theoretical and empirical work on the stellar atmospheres of cool stars is essential.
2. Originally the IMF was determined using the luminosity function of stars in the solar neighborhood plus the luminosity-mass relation and stellar lifetimes. With expanding high quality data for stars covering a much larger volume in our galaxy, we may be able to understand better the shape and variability of the IMF from place to place. Using `GAIA`'s astrometric and spectrophotometric data in our galaxy and the resolved stellar populations of nearby galaxies, we will be able to tackle the star formation history of such objects, as well as to reliably estimate their initial mass functions.
3. Observations of the cold gas in nearby galaxies reveal a more or less correlated core mass function (CMF), i.e. the masses of pre-stellar cores, and the IMF. Recent studies have investigated the relation between the CMF and the stellar IMF through numerical simulations and that is a crucial topic for the years to come - to understand what is the role of internal turbulence and external sources on the CMF by means of direct numerical simulations in grid and SPH numerical schemes.
4. The observed variations of the IMF in massive ETGs correspond to a different ISM (Inter Stellar Medium): the physical conditions of the gas in these systems (pressure, turbulence, etc.) is expected to lead to a drastically different fragmentation process. Theoretical work on this topic is of paramount importance.

The IMF is only one side of the problem of reconstructing the star formation history of a galaxy. With the next interviews we open the discussion on the physical conditions of the star formation process and on the rate with which galaxies form stars across the Hubble time.

8.5 The star formation and the rate of star formation

Questions for Cesare Chiosi:
the Schmidt-Kennicutt law, linking the star formation to the amount of gas available in a galaxy, was established on the basis of observations. Could you remind us which observations have prompted this law? Is this law valid everywhere, and if not why? Could you briefly review for us how this law has been used to understand the process of star formation in galaxies?

Let me shortly recall the main steps on the observational evidence for the dependence of the star formation rate on the gas content: long ago Maarten Schmidt [354], examining the stellar content of the solar vicinity, assumed that the rate of star formation for population I stars varies with a power n of the gas density, $d\rho_g/dt = -k\rho_g^n$, where k and n are constants to be fixed by observational data. The exponent n was derived from the relative distribution of young stars and gas perpendicular to the galactic plane. The value of n turned out to be about 2. Subsequently, Talbot and Arnett [384] set the ground for the chemical evolution of disc galaxies (like the Milky Way), presenting a model including the radial distribution of the surface mass density of gas and stars (Σ_g and Σ_s) with radial profile of the total mass Σ in agreement with the rotation curve of the disc, the Schmidt law of star formation, and the multi-zone description of chemical enrichment (in cylindrical symmetry). More relevant to our question, the [354] rate of star formation expressed by the gas volume density was translated into a new law in terms of Σ_g regulated by the balance between the gravitational settling of gas onto the equatorial plane and heating of this by the energy injection from SNa explosions. The new star formation rate is

$$\frac{1}{\Sigma(r)}\frac{d\Sigma_g(r)}{dt} = -\nu_\odot \left[\frac{\Sigma(r)}{\Sigma(r)_\odot}\right]^{2(n-1)} \left[\frac{\Sigma_g(r)}{\Sigma(r)}\right]^n$$

where the parameter k is now replaced by $\nu_\odot$.

The [384] model was extended by Chiosi [68] to the case with infall of gas (either primordial or already metal enriched). Assuming cylindrical symmetry, the mass in each cylindrical shell was supposed to increase by infall of gas from outside (whereas radial motions of gas were neglected). The rate of gas accretion included two sources. The first one with rather short time scale (say from 1 to about 3 Gyr) was meant to simulate the fast initial accumulation of gas by dynamical collapse, the second one with much longer time scale (say from 5 to 10 Gyr) was supposed to simulate the slow accretion onto the galactic disc of gas from the surrounding halo. Owing to very short time scale of energy input from short-lived stars, it was conceivable to suppose that at any time disc did not depart significantly from an equilibrium configuration and hence from the [384] scheme, the only major difference being that the surface mass density of gas is let increase with time. Under these assumptions the rate of star formation in the [68] view became

$$\frac{d\Sigma_g(r,t)}{dt} = -\tilde{\nu} \left[\frac{\Sigma(r,t)\Sigma_g(r,t)}{\Sigma(\tilde{r},t)^2}\right]^{n-1} \Sigma_g(r,t).$$

The quantities $\tilde{\nu}$ and $\Sigma(\tilde{r},t)$ are the specific star formation efficiency and the total surface mass density at some critical radial distance from the galactic centre. They are introduced for the purposes of normalization and dimensionality, however they can also assume the meaning of some physical process controlling the radial dependence of star formation, e.g. tidal interaction between the remaining gas at the distance r and the total amount of mass in stars already accumulated in the internal regions. The spatial and temporal behaviour of the above star formation rate is such that at any given time the rate is strongly inhibited at distances $r > \tilde{r}$, whereas at any distance r the star formation rate starts small, increases to a peak value and then declines, a trend that has been confirmed by the observational data not only in disc galaxies but also in spheroidal systems, e.g. [338, 72] for recent reviews of the subject.

The [68] model has been widely used for more than three decades with various degrees of complexity, it was extended to galaxies of different morphological type from irregulars to discs and spheroidals even in presence of DM (see [258, 385, 386, 259, 260] for recent reviews and referencing). It was used to study the mass to light ratios of disc galaxies [328, 329] and constrain the IMF [326]. It was taken as the backbone of many studies of population synthesis [43, 44, 385, 386, 321, 322, 322, 60]. It was extended to include the radial motions of gas [327]. Finally, it was even used to simulate the chemical evolution of the intra-cluster medium as a result of inflow of primordial gas into the gravitational well of a cluster and ejection of nuclearly processed material by galactic winds [285].

In a long series of observational studies, Robert Kennicutt (and collaborators) systematically investigated the efficiency of the star formation rate along the Hubble sequence with particular attention to the late type galaxies and the dependence of the rate on large scale quantities. To mention a few we recall here the studies [190, 191, 192, 193, 194]. Many observational indicators of stellar activity in different galaxies are considered, e.g. (i) Integral colors and spectra, and synthesis modeling; (ii) Ultraviolet continuum; (iii) Recombination lines; (iv) Forbidden lines; and (v) Far-infrared continuum. For all details see [194]. It is worth calling attention here on the fact that large-scale star formation in galaxies customarily takes place in two very distinct physical environments: one in the extended discs of spiral and irregular galaxies; the other in compact, dense gas discs in the centers of galaxies. Each of these provides an estimate of the SFR as a function of some measurable parameter for a large number of nearby galaxies, thus delineating the main trends in SFRs and star formation histories along the Hubble sequence. Comprehensive analyses of the global SFRs of galaxies have been carried out over the years (see [194] for exhaustive referencing).

The absolute SFRs in galaxies, expressed in terms of the total mass of stars formed per year, show an enormous range, from virtually zero in present-day gas-poor elliptical, S0, and dwarf galaxies to $20 M_\odot yr^{-1}$ in gas-rich spirals. Much larger values up to $100 M_\odot yr^{-1}$ are measured in star-burst galaxies, and SFRs as high as $1000 M_\odot yr^{-1}$ may be reached in the most luminous IR star-burst galaxies. Since the large range in the SFRs simply reflects the range of masses of the underlying galaxies, it is worth normalizing the SFR to the galaxy mass. Although there is a strong trend in the average SFRs with Hubble type, a dispersion of a factor of 10 is present in SFRs among galaxies of the same type. Several factors contribute to the SFR variations, including variations in gas content, nuclear emission, interactions, and possibly short-term variations in the SFR within individual objects. In any case, a robust correlation between the SFR and the galaxy type is indicated by the observational data. In the case of disc galaxies the SFR correlates with the surface mass density of gas. The dependence is $\Sigma_{SFR} = A \Sigma_g^n$, where Σ_{SFR} is the surface mass density of star formation in $M_\odot yr^{-1} kpc^{-2}$, A is a proportionality constant, and n falls in the range 1.5 to 2. Examining the typical global efficiencies of star formation and gas consumption time scales, it turns out that a average disk converts about $\sim 5\%$ of its gas every 10^8 years. Since the typical gas mass fraction in these disks is about 20%, this implies that the stellar mass of a disk grows by about 1% per 10^8 years, i.e. the time scale for building the disc (at the present rate) is comparable to the Hubble time. The efficiencies can also be expressed in terms of the average gas depletion time scale, which is about 2 Gyr. Which other global properties of a galaxy influence its SFR? It is plausible to expect the mass, bar structure, spiral arm structure, or environment to be important, and empirical information on all of these are available so that their effects can be taken into account. Following the same line of reasoning, [194] focuses on the range of star formation properties of the nuclear regions and the patterns in these properties along the Hubble sequence, highlighting the effects of the environment and of galaxy-galaxy interactions. Finally, all the observations described above can be fitted together into a coherent evolutionary picture of disk galaxies and the Hubble sequence. He summarizes the evolutionary implications of these data, taking into account the distinct patterns seen in the disks and galactic nuclei and concludes with a discussion of the critical role of the interstellar gas supply in regulating the SFR, across the entire range of galaxy types and environments, Finally the following expression for the SFR is given

$$\frac{d\Sigma_g}{dt} = -(2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_g}{1 M_\odot\, pc^{-2}} \right) M_\odot/yr/kpc^2$$

which closely resembles the SFR proposed long ago by [384]. Amazingly enough, the Schmidt-Kennicutt law of star formation was largely adopted in chemical models of galaxy evolution even before its observational discovery or confirmation.

The stellar mass of a galaxy is a key astrophysical parameter to know. There are however significant differences in the mass value coming from the different theoretical approaches. Could you tell us why? What produces such differences? Are we able to derive the mass of every kind of galaxies independently on their morphology and redshift?

Galaxy masses play a fundamental role in our understanding of structure formation models. A recent review of the subject is by [84] to whom I will refer. The review addresses the variety and reliability of mass estimators that pertain to stars, gas, and dark matter. In what follows I will focus on masses derived from stellar populations, leaving dynamical masses of gas-rich and gas-poor galaxies and masses from weak and strong lensing methods aside. The estimate of a galaxy's stellar mass heavily rests on the theory of population synthesis. In brief, the stellar content of a galaxy of age T is conceived as a manifold of stellar populations with different age [τ], chemical composition [X,Y,Z], degree of enhancement in α-elements with respect to the solar partition, initial mass function [$\phi(m)$, slope(s) x and the lower ant upper mass boundaries, m_l and m_u, respectively], this in turn determines the mass of SSP, and finally the spatial distribution of the stellar generations. Each of these SSPs is weighed on the star formation rate [$\Psi(t)$], where τ is the age of formation ($\tau = T - t$). By construction, the total mass of the stellar content of a galaxy is

$$M^*(t) = \int_0^T \Psi(t) \times M_{SSP}(\tau) dt,$$

where $M_{SSP}(\tau)$ is the current total mass of a SSP of age τ.

$$M_{SSP}(\tau) = \int_{m_l}^{m_{ev}(\tau)} m\phi(m)dm + \int_{m_{ev}(\tau)}^{m_u} m_R(m)\phi(m)dm,$$

where m_R is the remnant mass of a star of initial mass m, m_{ev} is the most evolved mass and $m_{ev} \to m_u$ for $\tau \to 0$. M_{SSP} is not constant with time because part of the initial mass in stars is lost by stellar winds and supernova explosions. Each star contributes with the mass $\Delta m = m - m_R(m)$. Only stars with lifetime shorter than the age of the Universe can contribute to ΔM, i.e. $m \simeq 0.8 M_\odot$. The evolution of stars of different mass is sufficiently well known so that the current mass of SSPs in living stars and remnants (White Dwarfs, Neutron Stars, and Black Holes) can be easily evaluated. Stars in the mass interval $0.8 \leq m \leq 6 M_\odot$ end up as WDs with mass $m_{WD} \propto m$ in the range 0.5 to 1.2 $M_\odot$. Stars in the mass interval $6 < m < 30 M_\odot$ end up as neutron stars of about $1.4 M_\odot$. Finally, stars more massive than about $30 M_\odot$ end up as Black Holes with mass greater than $1.4 M_\odot$. Stellar winds and SNa remnants refuel the interstellar medium and part of this gas may be lost by a galaxy. It is worth recalling that the mass in ejecta can be a significant fraction of the total initial SSP mass depending on the IMF.

In a similar way, with the aid of the population synthesis technique we may calculate the total SED as a function of time and hence the total luminosity (both bolometric and in any pass-band $\Delta\lambda$ according to the photometric system in use). The integrated monochromatic flux generated by the stellar content of a galaxy is defined as

$$F_\lambda(T) = \int_0^T \Psi(t,Z)\ sp_\lambda(\tau',Z)dt$$

where

$$sp_\lambda(\tau',Z) = \int_{m_l}^{m_u} \phi(m)\ f_\lambda(m,\tau',Z)dm$$

is the integrated monochromatic flux of a SSP.

In order to calculate the flux $sp_\lambda(\tau',Z)$ emitted by an SSP, we must construct isochrones in the CMD. The more accurate this calculation, the more precise are the fluxes for the whole galaxy. It is worth recalling that the precise shape of an isochrone depends on the properties of the underlying evolutionary tracks, while the relative number of stars in different portions of the isochrone is governed by the assumed $\phi(M)$ and the lifetimes of the stars present in the isochrone in different evolutionary stages.

The total luminosity of an SSP is obtained by integrating $sp_\lambda(\tau', Z)$ over the whole range of wavelengths

$$L_{SSP}(\tau', Z) = \int_0^\infty sp_\lambda(\tau', Z) d\lambda$$

from which the integrated absolute bolometric magnitude immediately follows

$$M_{bol} = -2.5 \times Log(L_{SSP}/L_\odot) + 4.72$$

Adopted a given photometric system, the integrated magnitudes $M_{\Delta\lambda}$ of SSP and of a galaxy as a whole are obtained by convolving the SED with the response functions of the pass-bands, see for instance [156, 157, 158].

Finally, we derive the mass to luminosity ratios M_*/L and $M_*/L_{\Delta\lambda}$ for SSPs and whole galaxies. It goes without saying that the galaxy mass to light ratios are in one to one correspondence with those of SSPs. Throughout the whole procedure to calculate the mass and the luminosities (both bolometric and in pass-bands) of SSPs and whole galaxies there are several points of great uncertainty, chief among which are: the isochrones, the monochromatic fluxes over the whole spectrum which requires large and complete libraries of stellar spectra at varying gravity, effective temperatures, and chemical parameters, the use of a system of pass-bands to define broad-band magnitudes and colors, the IMF, and, in the case of galaxies, the histories of star formation and chemical enrichment, i.e. $\Psi(t, Z)$ and $Z(t)$.

Since the classical IMF by [348], $dN/d\log m \propto m^{-1.35}$, many alternatives have been suggested, e.g. the multi-slopes IMFs by [351, 210, 62]. Indeed, much of the attention is paid to the slope of the IMF in the mass interval relative to stars most contributing to chemical enrichment of the ISM during the Hubble time (13.7 Gyr), e.g. $m \geq 0.8 M_\odot$, whereas the real issue with the mass determination is the portion of the IMF storing stars that live for ever (or whose lifetime is much longer than the age of the Universe. The lower mass limit m_l and slope of the IMF for $m_{\leq} 0.8 M_\odot$ drive the whole problem. The slope can be negative (as for the high mass end), zero or even positive. Therefore the mass in stars contained in this mass interval can be high, constant or small depending on the slope. [229] suggests the following simple analytic form: $dN/d\log m \propto m^{-1.35} exp(-m_1/m)$ (case a). This function has a logarithmic slope $x = 1.35 - m_1/m$, so it approaches a power law with the Salpeter slope $x = 1.35$ at large masses, peaks at a mass $m_p = m_1/1.35$, and falls off exponentially with increasingly negative x at lower masses. Since this function has a steeper fall-off at the low end than is suggested by most of the evidence mentioned above, [229] considers also the possibility that the IMF does not decline at all at the low end. If brown dwarfs are as common as is suggested by the most optimistic recent estimates, and if the IMF accordingly is approximately flat at the low end, it may be represented approximately by the following simple alternative form: $dN/d\log m \propto (1 + m/m_1)^{-1.35}$. This function is very similar to case (a) at masses above m_1 and has a logarithmic slope $x + 1.35(1 + m_1/m)^{-1}$, so that it again approaches the Salpeter form at large masses but becomes asymptotically flat with $x \simeq 0$ at the low end (case b).

Approximations (a) and (b) are thus consistent with the evidence that the IMF typically has a Salpeter form for large masses, while there is a large range of uncertainty or variability for the lower masses, and also the possibility that the mass-scale m_1 may be variable. The mass-scale m_1 might be expected to be related to a fundamental scale in the star formation process such as the Jeans mass, and evidence supporting this possibility has been discussed by [229] and references.

Along the same line of thought, using numerical simulations of star formation in the ISM, [297] suggested a universal law for the IMF whose slope and peak value (in that similar to the [229] case a) change with the physical properties of the ISM, i.e. temperature, density and velocity dispersion. [69] applied it to study a number of properties of galaxies (ellipticals in particular) that could find a coherent explanation in terms of systematic changes of the IMF from massive to low mass galaxies. In particular a top heavy IMF for stars above $1 M_\odot$ was predicted for young massive ellipticals. Indeed a top heavy IMF is suggested by [21] for high redshift massive dusty and bursty distant galaxies. All this, to remind the reader that the shape of the IMF over the mass interval in which stars are formed bears very much on the total mass of each SSP and hence the total stellar mass of a galaxy.

The second great unknown is $\Psi(t)$, for which there are ample possibilities and uncertainties. Roughly speaking, from the observational point of view $\Psi(t)$ is discontinuous, bursty and irregular in low mass galaxies (e.g. the small irregulars, the dwarf galaxies), nearly constant with mild variations in spiral galaxies, and bell-shaped, namely it start small in past grows to a peak value with a certain time scale (about a few hundred thousand years) and then it declines with a time scale from one to a few Gyr in large mass objects (e.g. ellipticals). This is possible for galaxies of the local Universe, in which the bright component of the stellar populations can be resolved into stars thus providing CMDs and LFs. In most cases $\Psi(t)$ is simply assumed to have an analytical dependence on time according to one of the three schemes above depending on the type of galaxy one tries to simulate. Alternatively, it is supposed to depend on the volume gas density to a certain power, typically $\Psi(t) = c * d\rho_g^n/dt$, where c^* is the specific efficiency that varies in range from 0.01 to 0.1, and n falls in the range 1 to 2. In the case of spiral galaxies the volume density of gas is replaced by the surface mass density of gas $\sigma_g(t)$. Via the time dependence of the gas content, the type of star formation and the temporal behaviour of $\Psi(t)$ in turn may fall in one of the above categories depending on the physical phenomena governing the formation of a galaxy out of the cosmological tissue. Good examples of it are the NB-TSPH simulations of elliptical-like galaxies of different total mass (dark and baryonic material) and different initial over-density with respect to cosmological background, in which under the same rate of star formation $d\rho_g/dt$ we end up with different $\Psi(t)$ according to the value taken by the two parameters: bell-shaped in massive and/or high over-density systems and bursty and irregular in low-mass, low over-density systems (see [70, 270, 271, 274, 72] for more details). The case of spiral and irregular galaxies can be reproduced adding some angular momentum.

The third point of great uncertainty is the theoretical SED of a galaxy, which is needed to derive the magnitudes, colors, mass to light ratios, and line absorption indices. The SED entirely rests on our ability in modelling the elemental SEDs of SSPs at varying age, metallicity and IMF. This requires accurate and complete stellar models for ample grids of initial masses and chemical abundance parameters; accurate grids of isochrones in different CMDs; and a good coverage of the stellar atmosphere parameters (effective temperature, gravity, chemical abundances). Despite the great progress made over the past two decades [30, 155, 31, 32], the present-day situation is not fully satisfactory: spectral libraries are not complete (in particular at high and low effective temperatures), the resolution of the template stellar spectra is often insufficient, and the population synthesis technique is not fully assessed. Finally, there is the long lasting question about the computational procedure that is followed to calculate the SED, i.e. the straight integration of the contribution star by star to the integral SED versus the so-called Fuel Consumption Theorem [392, 10, 337]. For recent discussions of all these issues see [78, 245, 72]. The uncertainty on the elemental SEDs of SSP immediately affects the SED of the composite stellar populations.

What is the role played by dust in this context?

The advent of modern infrared astronomy has brought into evidence the role played by the interstellar dust in galaxy formation and evolution: dust not only selectively absorbs radiation (mainly from the UV) but also re-emits it in the near (NIR) and far infrared (FIR). The detailed chemical composition of the dust and spatial distribution of this in a galaxy is of paramount importance. Therefore, to fully exploit modern data, realistic spectrophotometric models of SSPs and galaxies must include this important component of the interstellar medium (ISM). In a series of papers over the past ten years Piovan et al. [320, 321, 322, 323, 324] have addressed this issue. First they modelled the dust in the diffuse ISM and in molecular clouds (MCs), taking into account (i) three components of the dust, i.e. graphite, silicates and polycyclic aromatic hydrocarbons (PAHs); (ii) the size distribution of the dust grains; (iii) two models for the emission of the dusty ISM; (iv) reproducing the extinction curves and the emission for the Milky Way (MW) and the Large and Small Magellanic Clouds (LMC and SMC). The results are used to model the SEDs of SSPs that may be severely affected by dust at least in two types of stars: the young, massive stars while they are still embedded in their parental MCs and the intermediate- and low-mass asymptotic giant branch (AGB) stars when they form their own dust shell around. The radiative transfer problem is solved with the “ray-tracing” method, extended libraries of SSP SEDs are calculated. The theoretical SEDs successfully match the observational ones from UV to MIR and FIR [320]. Using these [321] derived the SEDs of galaxies of different morphological type and compared them with the observational data for template galaxies in the local Universe. Subsequently, [322] derived a data base of condensation efficiencies for the refractory elements C, O, Mg, Si, S, Ca and Fe in AGB stars and SNe that can be easily applied to the traditional gaseous ejecta, in order to determine the amount and kind of refractory elements locally embedded into dust and injected into the ISM. With the aid of this, [323] revised the properties and current chemical models of the solar neighborhood of the MW Disk (with infall and radial flows). Finally, [324] extended the same model to the whole galactic disk. All this provided the work bench for a detailed and sophisticated chemical, spectro-photometric models for galaxies of different morphological type. [59] using state-of-the-art models of AGB stars of low and intermediate-mass reconsidered the effect of shells of dust surrounding the AGB stars on the SED emitted by the central objects, and generated new libraries of dusty SSPs for different metallicities, ages and IMFs. The new isochrones and SSPs, have been compared with the CMDs of the field stellar populations in the LMC and SMC with particular emphasis on AGB stars, and the integrated colors of some star clusters in the same galaxies and M31. Finally, [60] generated a new library of template models of galaxies with different morphological type from spherical structures to discs with different bulge to disc ratios and provided the magnitude and color evolution in the rest-frame and as a function of the redshift for cosmological studies. Thanks to all this, *dust has become an ordinary ingredient of population synthesis*.

Given the above premises, one may eventually get the mass to light ratios of stellar populations of different complexity and with the aid of these estimate the total mass of the stellar content emitting the light. On the theoretical side the mass to light ratios as function of the isochrones, IMF, SSPs, SEDs, and chemical parameters are highly uncertain and even worst change a lot from author to author. This is perhaps the major uncertainty for which there is no physical explanation. It is indeed entirely due to unacceptable inaccuracies in the particular algorithm of population synthesis at work. On the observational side, there are several methods to derive the M_*/L ratios by fitting spectra. Both issues have thoroughly discussed by [84] and references therein. They will not be repeated here. In the case of galaxies the great villain of the whole story seems to be the rate of star formation. The only firm conclusion is that mass to light ratios from blue pass-bands seem to scatter less than the red ones, for instance M_*/L_B vs (B-R) as compared to M_*/L_B vs (I-K) and/or M_*/L_K vs (B-R) and (I-K) see (Fig. 9 in [84]). Of course the uncertainty and scatter increase when the effect of dust is included. However, contrary to what claimed by [247] neglecting dust is not a good strategy. To conclude, the mass to light ratios are not the best way of determining the mass of the stellar content in a galaxy, unless the above points of uncertainty are systematically removed, so that *concordance* mass to light ratios for SSPs are reached (I personally recommend that (i) the task is taken by people very familiar with the subtleties of stellar evolution and (ii) the direct integration of the light and spectra emitted by the stars along the isochrones is performed), and finally the star formation and chemical histories of a galaxy are estimated from independent methods.

Questions for Alvio Renzini:
the Star Formation Rate (SFR) is the key parameter for all the studies connected with stellar population analysis. Would you explain its meaning and review how the global SFRs in galaxies are measured?

Well, the meaning is simple, the SFR is the mass of gas turned into stars per unit time, and is measured in $M_\odot$/yr. A whole variety of SFR indicators are currently used. Young, just formed massive stars are powerful UV emitters, part of this light is absorbed by dust and re-emitted in the Mid- and Far-IR, ionizing photons strip electrons from hydrogen atoms, which emit Balmer lines as they recombine, relativistic electrons are generated by supernovae and upon circling magnetic fields emit synchrotron radiation, and finally young, high-mass binaries with accreting neutron stars or black holes are powerful X-ray sources. So, the UV, Hα, Mid-IR, Far-IR, radio and X-ray luminosities are all used to infer the SFR, once properly calibrated.

Which techniques are generally adopted to derive it?

They are all used, though depending on redshifts some are more practical and effective than others. In the local Universe, the Hα luminosity, corrected for extinction from the measured Balmer decrement (the Hβ/Hα ratio), is perhaps the most effective way. At higher redshifts, the most reliable measurements come from combining the UV and mid/far-IR luminosities, without correcting the UV luminosity for extinction. The problem is that quite often the infrared data are not deep enough, hence for many galaxies the SFR cannot be measured in this way. In such cases one has to rely on the UV luminosity, though the extinction correction can be quite uncertain, of one can stack the IR data in several bins of stellar mass, and construct the average main sequence in this way [343].

What are the limits of this concept and how good are the current measurements of the SFRs in galaxies?

As I said, the concept is simple and I don't see a *limit* to it. Actually, thanks to adaptive optics we are now capable of mapping the SFR surface density even in galaxies at $z \sim 2$, which is measured in $M_{\odot}$ yr^{-1} kpc^{-2}. Concerning the accuracy of SFR measurements, I would say that on average they are fairly good, probably within a factor of ~ 2. But occasionally, for a small number of objects, errors may be huge, with estimated SFRs orders of magnitude off the real ones. For example, dust extinction can be so high that most of the SFR is completely hidden at UV wavelengths, so SFR from UV, even corrected for reddening, can be off by large factors. In such cases, the far-IR, if available, gives the right answer. It can also happen that we make the opposite mistake: if the very red colors of an high$-z$ galaxy are interpreted as due to reddening then the extinction-corrected UV luminosity indicates a very high SFR, whereas the galaxy may have been red because there was no star formation at all and the galaxy was actually quenched [343].

Why do galaxies exhibit a so large dynamic range of SFRs?

At given stellar mass, most galaxies are either on/near the MS as star-forming galaxies, or are red and dead, quenched galaxies. Few galaxies lie in between, in the so-called green valley. This is illustrated by the 3D plot of Fig. 8.5, for galaxies in the local Universe. The bimodality in the SFR distribution is very evident. Besides it, the dispersion of SFRs around the main sequence central relation is about a factor of ~ 2, probably reflecting temporary up and down fluctuations in SFR due to the stochastic nature of the star formation process. Then, *starburst outliers* from the main sequence also exist, with SFRs up to 10 times higher than the mains sequence value, or even more. At redshifts ~ 2 they account for $\sim 2\%$ of all star-forming galaxies, and for $\sim 10\%$ of the global star formation density [342]. So, they play a lesser role in star formation, compared to main sequence galaxies, but certainly not a negligible one.

Is it possible to apply the locally calibrated SFRs to high-redshift galaxies or in other words could we trace the evolution of the SFR?

Oh yes! This is now common practice. So, it has been shown that the main sequence itself evolves dramatically with redshift, in such a way that for fixed stellar mass (i.e., not fixed galaxy!) the SFR increases by a factor of ~ 20 between redshift zero and ~ 2 [91]. Then measurements become a bit more uncertain, but this increase appears to continue towards higher redshifts, though with a somewhat reduced pace.

The quenching of SF is today the most popular explanation of the distribution of galaxies in the color-magnitude diagram. The analysis of the SDSS data, particularly those involving the broad-band color $g-r$, shows a bimodal distribution of galaxies. A blue and a red peaks are separated by a green valley.

In a sense, the modern interpretation of the color-magnitude diagram of galaxies, is represented by Fig. 8.5, were luminosity has been replaced by stellar mass and color by the SFR [339]. So, the blue galaxies are the star-forming ones, with most of them on the MS, and most of the red galaxies have barely detectable SFRs, i.e., they are quenched. I would say that this is the universally accepted interpretation of the color-magnitude diagram. So, I think we have a reasonable understanding of the two peaks we see in Fig. 8.5. Perhaps more intriguing is the *green valley*. It must be populated by galaxies on their way to be quenched, and therefore their number should give us insight on the quenching mechanisms. However, this green valley may also include galaxies in a temporary minimum of their SFR and will return to the main sequence in the future. Or quenched galaxies may experience a minor episode of star formation, visiting the valley for a short time. And we should not forget that a few percent of our photometric redshifts can be grossly wrong, misplacing a galaxy in the valley. So, a great deal of work may have to be done to distinguish between crossing, visiting and intruding galaxies in the green valley.

Could you summarize the problem and discuss the physical mechanisms of mass quenching and environment quenching? Can we distinguish these mechanisms observationally?

Observationally, one finds that the fraction of quenched galaxies is an increasing function of stellar mass (independently of environment) and of the local overdensity (independently of stellar mass) [308], as illustrated in Fig. 8.6. So, one speaks of

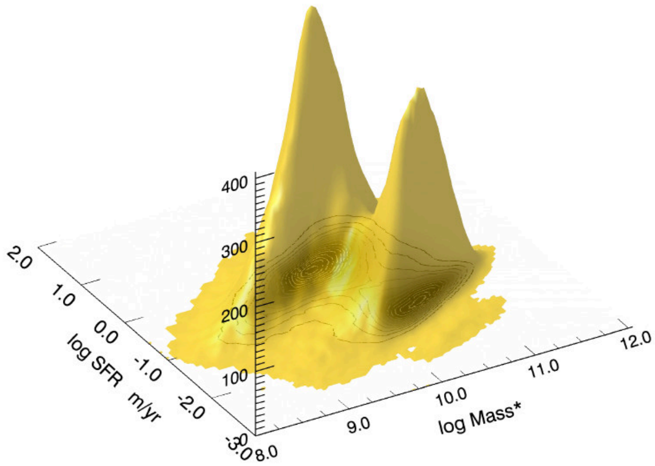

Fig. 8.5 The 3D SFR-M relation for local galaxies [339] in the SDSS database and redshift between 0.02 and 0.085. The third dimension is the number of galaxies in SFR-M bins. The drop towards lower masses is partly artificial, as no $V/V_{\rm max}$ correction has been applied. This offers a clearer vision of the 3D structure, with the two prominent peaks, one for star-forming galaxies and one for the quenched ones. Notice the sharp ridge line of the SF peak, the extremely steep fall off in the number of galaxies, either way of the ridge line, the divide, which is then been taken as the definition of the Main Sequence of star-forming galaxies. On the North-West side of the divide one also encounter the starburst outliers, whereas on the SE side of the divide is populated by a mixture of galaxies with lower SFR, with some being just in a temporary excursion below the MS band, while others are definitely on their way across the saddle, towards the peak of quenched galaxies. No $V/V_{\rm max}$ correction was applied in order to have a better visibility of the two peaks. Data are from the SDSS database.

mass quenching and environment quenching as two distinct and separable processes. But we are still struggling trying to understand what are the physical processes causing mass quenching and environment quenching. Many think environment quenching is ram-pressure stripping of gas from galaxies in groups and clusters, but the situation is far more uncertain for mass quenching and there are many candidates. A variety of radically different options are currently entertained for the mass quenching process, whereby quenching is either an *internal* or an *external* process. In one option for the former case sudden energy/momentum release from star formation and/or AGN (feedback) results in the ejection of all gas from galaxies that then turn passive, the ‘quasar mode’ quenching in current jargon [166]. Powerful AGN jets may also heat the circumgalactic medium to high temperature thus preventing further accretion of cold gas, the so-called ‘radio mode’ AGN feedback [87]. In another option for an external process, the circumgalactic gas is shock-heated to high

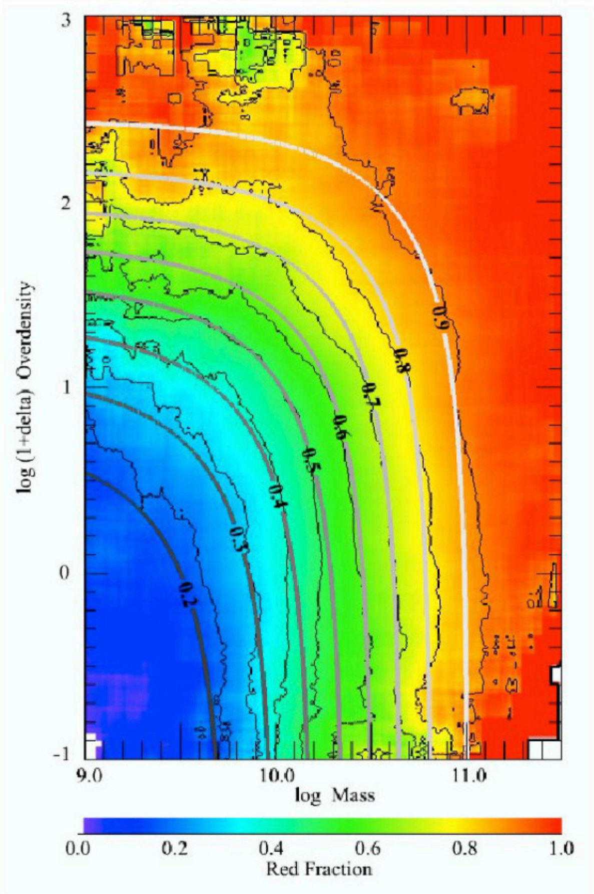

Fig. 8.6 Color-coded is the fraction of red galaxies as a function of stellar mass and local overdensity [308]. In the vast majority of such galaxies star formation is actually quenched or reduced to barely detectable levels, hence the red fraction is a fair proxy for the fraction of quenched galaxies, but a marginal number of highly dust reddened, actively star-forming galaxies may be included. Data are from the SDSS database and include galaxies in the redshift range $0.02 < z < 0.085$.

temperatures as the mass of the host dark matter halo exceeds a critical threshold (of order of $\sim 10^{12} M_\odot$) , and therefore it stops to cool and flow into the galaxy, thus discontinuing to feed star formation [95]. Finally, the growth of a central mass concentration (bulge) may *quench itself*, with increasing shear (differential rotation) suppressing the disk instability to form actively star-forming clumps, the so-called gravitational (or morphological) quenching [253]. So, we have at least four options for the physical nature of mass quenching. Actually, we don't quite know what is the mass that matters in mass quenching: is it the stellar mass? Or the mass of the host dark matter halo? Or the mass of the galactic bulge? Or that of the central supermassive black hole? Each of them suggests a totally different physical mechanism for quenching, and yet they are all tightly correlated with each other, so it gets very hard to observationally identify the culprit! Yet, it is even possible that mass and environment quenching may be two different manifestation of a same, underlying physical process [200]. I hope we can solve this problem within a few years.

What is the quenching time scale? Is it the same for all galaxies?

Many groups are trying to measure the quenching timescale, which may be different for mass and environment quenching, but there is no answer yet to this question. If quenching is due to gas ejection from the galaxy, e.g., as resulting from some sort of AGN feedback, then the quenching timescale may be quite short, of the order of the dynamical time, or $\sim 10^8$ years. If instead quenching results from cutting off gas supply from the environment, then the quenching timescale could be quite long, of the order of the gas depletion timescale, i.e., $M_{\rm gas}$/SFR, or some $\sim 10^9$ years, with $M_{\rm gas}$ being the mass of gas inside the galaxy at the beginning of the quenching process. We can gather an estimate of the quenching timescale from the number of galaxies caught in such transition, but, as I mentioned earlier, the green valley can be also populated, at all redshifts, by occasional visitors and intruders.

Which is the relation between the quenching of SF and the morphological transformation?

Empirically, we see that most quenched galaxies show an early-type morphology (i.e., they are elliptical or S0 galaxies) and most early-type galaxies are quenched. But why quenching is accompanied by morphological transformation we don't not know for sure, yet. This is indeed another open question. Integral field spectroscopy of local early-type galaxies has demonstrated that the vast majority of them ($\sim 86\%$) are fast rotators, whereas only the residual minority are slow rotators [132]. There is general consensus that the slow rotators are the result of merging, which then can be considered responsible for the morphological transformation for only a minority of galaxies. The fast rotators instead are likely to be the result of the evolution of the disk, via some kind of disk instability [96].

We examine now another aspect of galaxy evolution, that related to the so-called feedback. With this term astronomers summarize all the processes occurring in galaxies that are energetic enough to significantly affect their evolution.

8.6 The role of feedback

Questions for Luca Ciotti:

the AGN feedback is claimed to be an important physical mechanism in galaxy evolution. Could you explain why and trace a short history of this idea ? Which observations prove that such feedback indeed occurred? How is galaxy evolution affected by the feedback? Is this mechanism active in all galaxies or only in some morphological types?

The topic of AGN feedback in galaxies (in particular, in early-type galaxies, hereafter ETGs) has been, and it is right now, a relevant aspect of my research activity. As a consequence, in the following the presentation may reflect quite a personal point of view, which is not necessarily shared by all other researchers in the field. Overall, looking back over the past 25 years, since when I started to work on the subject (together with J.P. Ostriker during the sojourn at Princeton University as a PhD student), I can say that the attitude of a large part of the scientific community has been quite peculiar, ranging from initial positions like "there is no AGN feedback in ETGs", to the present "AGN feedback is the main actor in shaping the formation and evolution of ETGs, and to produce their properties as we observe them today". Well, I quite disagree with both views. I will present some arguments supporting the claim that AGN feedback *was* known to be important even 25 years ago, a necessary conclusion of elementary empirical arguments. At the same time, I claim that the main effects of AGN feedback are *not on* the galaxies, hosting at their centers the Supermassive Black Holes (hereafter SMBHs), but are essentially of more local nature, mainly affecting the growth of the SMBHs and extending at most to the galactic centers, in a $\simeq$ kpc-size region around the SMBH, and of course regulating star formation in the centers of ETGs.

In 1989-1992 I was working on my PhD thesis in an excellent research group, lead by Alvio Renzini. Annibale D'Ercole (then Astronomer at the Bologna Astronomical Observatory) and Silvia Pellegrini (also PhD student) were also in the group. Alvio was very enthusiastic about a new idea he had for the explanation of some puzzling observational property of the X-ray emission of the hot atmospheres surrounding ETGs. In particular, it was clear that, in absence of some form of heating, the gaseous halos of ellipticals, *produced by the mass ejected by the stellar mass losses of the aging stellar population* at the rate $\dot{M}_*$, i.e. the "secular evolution" of these systems, would necessarily lead to massive *cooling flows* in all elliptical galaxies, with the consequent prediction of systematically high and *unobserved* X-ray luminosities ($L_{\rm X}$). In fact, from the well established and tested theory of stellar evolution, it is known that the mass losses of an old, passively evolving stellar population of present-day total luminosity $L_{\rm B}$ (in blue solar units) can be well approximated as

$$\dot{M}_* \simeq 1.5\,10^{-11} L_{\rm B} t_{15}^{-1.35} \quad M_\odot {\rm yr}^{-1}, \tag{8.2}$$

where t_{15} is time in 15 Gyr units.

The cooling flow model [85, 135], with the prediction of high values of $L_{\rm X}$, was the paradigm at the epoch, but it is important to recall some important facts. That the stellar evolution would inject over cosmological times an *enormous* amount of mass in the host galaxies (summing up to 20 to 30 per cent of the initial stellar mass M_* of the galaxy) was so obvious that in the '70s the very important model of Supernova driven galactic wind [264] was proposed as the natural solution to the conundrum posed on one hand by the unquestioned prediction of stellar evolution about mass losses, and the apparent lack of detection of gas in ETGs on the other. The whole astronomical community was well aware that ETGs, at least from the point of view of the mass budget, are certainly not *dead and red* objects. In the '80s, the detection of X-ray emission around ETGs by *Einstein* (see, e.g., [265, 133]) finally showed that the mass *was* there, and the *cooling flow model* became the paradigm to study this kind of problems. However, it was soon realized that if the mass injected was cooling, the final state of such cooling gas should be found somewhere in the galaxy, in form of new stars, or dark objects, or free floating baryon condensations. In addition, it became also clear that the X-ray emission L_X of medium-to-low mass ellipticals was sistematically *lower* than what expected by the *standard* cooling flow model, that instead worked better (although with significant dispersion - almost two dex - in the predicted values of L_X) for massive ellipticals. Remarkably, *all* the proposed solutions attempting to reconcile the pure cooling flow scenario with observations failed, for a combination of theoretical and empirical arguments. Renzini coagulated a research group, with complementary competences, to work on the problem. In particular, by building realistic galaxy models that at the epoch were state-of-the-art (e.g., laying on the Fundamental Plane), and using the most robust prescriptions of stellar evolution, we concluded that elliptical galaxies are - from the energetic point of view - very peculiar systems, i.e., the energy needed to steadily extract the injected gas from the galaxy gravitational potential, and the energy injected per unit time in the hot ISM by SNIa explosions and thermalization of stellar motions, are *almost the same*, so that the X-ray halos are in a metastable energetic configuration. Moreover, we also found that, due to the Faber-Jackson relation, the binding energy per unit mass of the ISM (roughly proportional to the stellar velocity dispersion of the host galaxy) in large ETGs is higher than in low mass systems, so that while the latter systems should be in a global galactic wind state (in practice, mass losses from the evolving stars are ejected from the galaxy being heated to a super-virial temperatures), massive ETGs should be in the cooling flow state, with the consequent high L_X. These energy-based estimates were nicely confirmed by our hydrodynamical simulations [51] that however revealed a scenario more complicated than that depicted above (for example, the remarkable fact that the time evolution of the SNIa explosion rate is very similar to the time evolution of $\dot{M}_*$, a fact without obvious physical explanation). In summary, at that time, in addition to have learnt a lot of physics from Alvio and numerics from Annibale, I had clear in mind that 1) even in isolated ETGs (i.e., in absence of major/minor merging, cold flows, etc., objects that today would be called "red and dead"), there are internal, time-decreasing, significant sources of mass just provided by stellar evolution, and 2) while the cooling flow was not the state of the atmospheres of ETGs of low/medium mass, a large fraction of the massive ellipticals (say objects with a central velocity dispersion of the order of 250 km/s or more), should be in a cooling-flow like state (for a full account of the situation see, e.g., [307], and references therein).

In particular, while the work in our group in Bologna was clearly a significant step forward in understanding the evolution of the gaseous component of "red and dead" galaxies, yet the fate of the $\simeq 1M_{\odot}/yr$ produced internally and flowing towards the center in *massive* ETGs remained unsolved. It was exactly at this time that I started my sojourn in Princeton. After my arrival at the beginning of 1992 and a few weeks of "testing", Jerry decided that I would be assigned to study the problem of the fate of the cooling flows in big ellipticals. This was particularly timely, considering the important discovery that at the center of ETGs there are SMBHs with a mass of the order of $M_{\rm BH} \simeq 10^{-3}M_*$ [243], successively confirmed and reinforced by the discovery of the $M_{\rm BH} - \sigma$ relation (see, e.g., [138, 152, 424]). It is clear that in these systems AGN feedback is necessary, not as a consequence of complicated arguments, but just because of the extreme *smallness* of the mass of the central SMBHs. In fact, a rough calculation easily shows that the SMBH masses are approximately *two orders of magnitude* smaller than the gas made available by stellar evolution in isolated ETGs (and the argument is only reinforced in case of external accretion/merging). In practice, *AGN feedback is required by mass arguments, not by energetic arguments*. We started to work on the theory of AGN feedback, supported by numerical simulations of increasing quality (with improvements in the input physics still ongoing, thanks to the involvement over the years of several other researchers) to test observational predictions. In fact, for a mass accretion rate of $\dot{M}_{\rm BH}$, the emitted luminosity - for a given electromagnetic efficiency ε - is

$$L_{\rm BH} = \varepsilon \dot{M}_{\rm BH} c^2 \simeq \varepsilon (\dot{M}_{\rm BH}/M_{\odot} yr)\, 5.7\, 10^{46} \quad {\rm erg/s}, \tag{8.3}$$

high enough to suppress the potential cooling flow and interrupt accretion (see also [34]). The question we addressed in this first exploration of AGN feedback was why we do not observe quasars at the center of all massive ETGs as a consequence of the expected accretion. The answer was obtained and refined in a series of papers, based on numerical hydrodynamical simulations of gas flows in ETGs including radiative transport, with the spatial and temporal resolution needed to probe the resulting flows on cosmological times and on spatial scales ranging from galactic sizes down to the parsec scale near the central SMBH (well inside the Bondi radius, so that no "ad hoc" treatment for accretion, common in similar studies, was required). We showed that gas accretion on the central SMBH, due to the onset of a "cooling flow" phase, releases and transfers to the ISM enough energy to stop the cooling flow itself, and to evacuate the inner kpc-scale region around the SMBH. After a characteristic time, needed to replenish the central zone of the galaxy, and to increase the ISM to values large enough to start another "cooling catastrophe", the cycle repeats (for a full description of the simulations and the results, see [295, 52, 76]).

Quite surprisingly (for the current view), we found a strong and negative reaction to our proposal (with the exception of a few notable cases, such as Alvio Renzini and James Binney, one of the fathers of the cooling flow model then visiting Princeton, where I met him for the first time) as in general the community was fiercely defending the cooling flow paradigm (already in crisis due to SNIa heating for low/medium mass galaxies, and now also questioned for the remaining galaxies). The reactions went so far as to claim that "ETGs were lacking signs of feedback", or proposing that the SMBHs were actually steady accreting in the "obscured modality" (i.e., without emission of significant radiation, with no feedback, and so in a sense still consistent with the cooling flow paradigm). But all these criticisms missed the point, i.e., that the low mass of central SMBHs *is* a clear observational signature of feedback, and that obscured accretion *cannot* be the solution, because the SMBH mass would grow to unobserved values (in fact, that obscured accretion cannot be used to reconcile the cooling flow model with the physics of SMBH accretion is also proved beyond discussion by the Soltan argument, coupled with the well known theoretical upper bounds on accretion efficiency of compact objects, see e.g., see e.g. [424]).

A few important aspects of AGN feedback should be considered. First, the time interval from the beginning of central accretion, to its shutdown due to AGN feedback, is found to be of the order of 10^7 yrs, in nice accordance with observational estimates of the "on" phase of quasars. Second, in the simulations these feedback events becomes more and more rare as the galaxy age increases (see Fig. 8.7), because the stellar mass losses need longer and longer time to produce the critical density required for a global ISM cooling event (see eq. 8.2). Third, as the major feedback events in the life of a galaxy are just a few, it results that the *duty-cycle* of AGN activity (i.e., the time fraction so that the AGN luminosity is above some fraction of the Eddington luminosity) is much less than unity ($\simeq 10^{-2}$ or even less), thus explaining why we do not see quasars in galaxies in the local Universe, i.e., because the probability to catch a SMBH in the "on" phase is very small, and it decreases with increasing cosmic time.

As already stressed, an important aspect of the AGN feedback physics - not always appreciated - is that the main issue of the problem is not whether there is enough energy to stop a cooling flow (see eq. 8.3), but *how much* of the energy emitted in a given accretion event can be transmitted to the ISM in the host galaxy. Theoretical estimates and physically based numerical simulations of AGN feedback show that in fact the fraction of energy transferred to the ISM (and so able to stop gas cooling) is *very small*. In other words, the energy emitted by the AGN in a given accretion event is very large (much bigger than the energy required to eject all the ISM from the galaxy in the intergalactic space), but the captured fraction (both as radiation and kinetic coupling with the conical nuclear wind launched by the AGN) is only able to momentarily stop the gas cooling.

This is a very interesting fact, as nowadays AGN feedback, after having been initially ignored or even discarded as an important aspect of the evolution of ETGs, is invoked as the final explanation of why ETGs are the systems with the characteristics we observe. For example, AGN feedback is considered the main actor in quenching star formation at the epoch of galaxy formation. My impression is that this is more an expectation than a proved statement. In fact, numerical simulations in spherical symmetry (when feedback effects are maximum for geometric reasons), and with realistic coupling between radiation and matter (obtained by solving radiative transport equations) are systematically found unable to eject from massive galaxies the ISM produced by stellar evolution, even worse if we imagine the galaxy

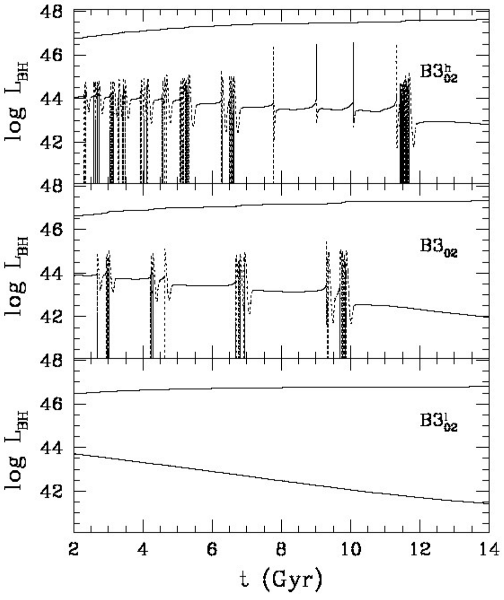

Fig. 8.7 Dotted lines are the optical SMBH luminosity corrected for absorption (i.e, as would be observed from infinity) for three galaxy models with central velocity dispersion of 280 km/s ($B3^h_{02}$), 260 km/s ($B3_{02}$), and 240 km/s ($B3^l_{02}$). The almost horizontal solid line represents the Eddington luminosity. Note how the less massive galaxy is in a state of SNIa driven permanent galactic wind, and the AGN accretion luminosity remains low (Adapted by permission of the AAS from Ciotti et al. 2010).

filled with all the gas needed for star formation, and a more realistic (and less efficient) non-spherical feedback geometry.

Another related interesting result that emerged from our work [75], was the fact that actually AGN feedback can *induce* star formation, at the beginning of each major feedback event. In fact, each event (of a total duration of $\approx 10^7$ yrs), when observed at sufficiently high time resolution, is made of a series of sub-burst of increasing intensity (e.g., see the last burst in the top panel of Fig. 8.7), due to a complex hydrodynamical structure of the ISM in the $\simeq 300-500$ pc around the SMBH. In this region, the sequence of shock waves (direct and reflected) leads to the formation of a gaseous cold shell, with a few hundred parsecs radius, that in turns form stars at peak rates of $10^2 M_\odot/yr$ or more. The final sub burst in the series finally ends the sequence, and stops star formation: therefore, we found that AGN feedback is - at the same time - able to *induce* and *suppress* star formation. We also found that the new stars produced by the periodic central starbursts are distributed in the central regions of the models with a profile remarkably similar in shape and values to the observed stellar cusps in the central regions of ETGs ([162], see also [52, 74], and references therein). It is interesting to speculate that the so-called "E+A galaxies" may be somewhat related to this recurrent activity.

In the spirit of this book, I conclude presenting a list of major results about AGN feedback that I think are quite robust, followed by a list of points that I feel should be the focus of future investigations, theoretical and observational.

R1) AGN feedback in galaxies is required by simple mass arguments, not by energy arguments: the mass of SMBHs at the center of big ETGs is approximately two orders of magnitude smaller than the gas that would be accreted by a non-impeded cooling flow. Therefore, obscured /or radiatively inefficient accretion is not a solution to the problem of missing quasars in massive ETGs.

R2) Sporadic quasar activity *is* present in ETGs, even in perfect isolation, due to the immense amount of material secularly injected in the galaxy by stellar evolution. Therefore, quasar statistics cannot be straighforwardly used as a measure of frequence of gas-rich ("wet") merging events, as it can be produced purely by secular internal evolution of "red and dead" galaxies.

R3) AGN feedback is, *empirically*, fundamental to maintain the mass of SMBHs "small", however it is unable to fully evacuate the host galaxy by the mass injected by the aging stars. SNIa heating, being distributed over the galaxy body, and released at a continuous rate, is much more important. All the available indications from numerical simulations where the feedback is calculated from first principles seem to suggest that the effects at early times can be similarly small, in absence of some additional physical effects. Possibly, SNII are more important in terminating star formation at early times.

R4) Stellar evolution has the nice property that the amount of material injected *scales linearly* with the stellar mass of the galaxy, so that the accretion of some fraction of this material on the central SMBH does not destroy (or even improves) a proportionality possibly established at the end of the period of galaxy formation.

R5) The efficiency of AGN feedback and the rates of gas injection and cooling are essentially *unrelated* phenomena: a long-time balance between the two is impossible, so that steady-state configurations are practically impossible in massive ETGs. A possible exception is represented by low mass ellipticals, where SMBHs accretion proceeds at very low L_{BH}, with Bondi-like accretion from hot and low-density atmosphere, as the galaxies are in SNIa assisted global winds.

Among the questions that I would like to see addressed (and solved!) in a near future:

Q1) What is the role of angular momentum in the structure and evolution of gas flows in galaxies with some rotation? It is known that in these systems, in absence of additional heating phenomena, gas cooling would lead to the formation of massive, centrifugally-supported, kpc-size disks of cold gas, unable to reach the center. What happens of these disks? Are they consumed by star formation? Are they massive enough to become self-gravitating and unstable? If yes, will they develop non axysimmetric features, break angular momentum conservation and collapse toward the center fueling the SMBH? What kind of feedback the AGN will produce when fed by such disks?

Q2) How can we describe in acceptable physical terms the “granularity” of the galaxy stellar distribution within the inner tens of parsec around the SMBH? Of course, a spatial and temporal smooth description of the stellar distribution and of the mass and energy injection becomes more and more unrealistic as the number of stars involved decreases.

Q3) What is the relative role of radiative and kinetic energy in AGN feedback? What are the observational signatures of AGN induced and suppressed star formation (the so-called positive and negative feedback)? What is the relative importance for feedback of the starburst energy compared to the AGN energy?

Q4) The contribution of AGN feedback to quench star formation at the epoch of galaxy assembly was really fundamental? Or it was just an additional contribution to SNII and SNIa activity?

Questions for Francesca Matteucci:
SNe have been indicated as possible sources of feedback mechanisms. Could you explain why? Which is the role of SNe in galaxy evolution? Which observations confirm these ideas?

As already mentioned, supernovae influence galaxy evolution through chemical enrichment and energy feedback, namely the energy that they can transfer into the ISM. The explosion energy of SNe is large, although in some cases most of it can be lost via cooling, and clearly contributes to increase the thermal energy of the ISM. Because of this, the interstellar gas can reach the escape velocity and escape from the potential well of the galaxy and in this case we speak of galactic wind, but the gas can also be temporarily removed and fall back again, in such a case we speak of galactic fountains [42, 368]. These fountains are likely to occur in spiral disks and are triggered by multiple explosions of massive stars. The evidence of galactic winds is given by the metals found in the ICM and IGM and they have also been observed in dwarf irregular galaxies. In particular, the observations of dwarf starburst galaxies indicate that these winds are linked to SN explosions. [254] reported `Chandra` observations of the dwarf starburst galaxy NGC 1569 in the Local Group showing the gas which is escaping from the galaxy at a rate which is a factor of a few of the star formation rate. The same author reported observations made with FUSE of other dwarf galaxies such as NGC 4214 , NGC 5253 and NGC 1705 also showing that they are suffering galactic winds outflowing at a rate which varies from 1 to 5 times the star formation rate.

Stars have progressively enriched the interstellar medium of metals. In the next interviews we examine with more detail this process and its consequences, as well as how this idea has been encoded in modern numerical simulations.

8.7 The chemical enrichment

Questions for Francesca Matteucci:
how has the idea of the chemical enrichment of galaxies developed? What have been the main theoretical progresses in this field? Which physical mechanisms govern the chemical evolution of galaxies? Are observations in agreement with the theoretical models?

The idea of the chemical enrichment of galaxies developed in the 1970s and it was led by researchers such as W.D. Arnett, J.W. Truran, J. Audouze, B.E.J. Pagel and, in particular, B.M. Tinsley. The basic idea is simple: stars transform light elements into heavier ones in their interiors and when they die the new elements are restored into the ISM. The following stellar generation will then form out of enriched gas and the process will go on until all the gas is consumed or lost via winds. Beatrice Tinsley developed most of the analytical formulas for computing chemical evolution of galaxies. These formulas are very important and useful but their limit is related to the hypothesis of instantaneous recycling approximation (IRA), necessary to obtain analytical solutions to the equations of chemical enrichment. The IRA approximation states that *all stars with* $M < 1 M_{\odot}$ *live forever and that stars with* $M \geq 1 M_{\odot}$ *die instantaneously*; while the first sentence is correct, the second is incorrect and does not allow one to compute in detail the evolution of those chemical elements that are produced on the timescales of billion years, such as, for example, iron and nitrogen. One of first interesting topics dealing with galactic chemical evolution was the so-called *G-dwarf problem*: it consists in the fact that the Simple Model of chemical evolution could not reproduce the distribution of the G-dwarfs as a function of metallicity in the solar vicinity, as first discovered by van den Bergh [404] and Schmidt [355]. In particular, the Simple Model predicts too many low metallicity stars relative to what is observed. The main assumptions of the Simple Model are: a) the system evolves as a closed box, with no infall nor outflow, b) the IMF is constant in time, c) there is instantaneous mixing at any time, d) the chemical composition of the gas out of which the system forms stars is primordial. The G-dwarf problem can be solved in several ways: i) by assuming that the gas which formed the Galactic disk was pre-enriched, ii) by assuming an IMF variable in time and favoring high mass stars at early times, iii) by assuming that the Galactic disk formed by infall of gas. These solutions were discussed in important papers such as Tinsley [393], Talbot & Arnett [384] and Pagel & Patchett [299]. It has been since long concluded that infall of primordial gas (hypothesis iii) seems the most promising solution and it has been assumed in the majority of chemical evolution models. After these pioneering papers, several numerical models of galactic chemical evolution relaxing IRA were developed ([68, 262, 66, 36], plus many others), thus starting new developments. [262] in particular, were the first introducing a detailed calculation of the rate of SNe Ia originating in white dwarfs in binary systems[7]: this is fundamental

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[7] Tinsley [395] had already suggested the Type Ia SNe as possible Fe producers on long timescales but before the [262] paper, no precise calculation had been performed.

in order to correctly follow the evolution of Fe and to correctly interpret the [X/Fe] vs. [Fe/H] observed relations. Later on, [92] introduced in a chemical evolution model also the chemical enrichment from nova systems, which can be important for computing the evolution of elements such as Li and some C,N,O isotopes. [8] and, more recently, [263] included in the chemical evolution of the Milky Way also the chemical enrichment from merging neutron stars, which seem to be very promising producers of r-process elements, such as Eu.

Other interesting developments in galactic chemical evolution arose from the hypotheses about the formation of the various Galactic components: halo, thick-, thin-disk and bulge. The two-infall model for the Milky Way [66] tried to explain the different evolution of the halo and disk by separating their formation and assuming that two main infall episodes gave rise to the two components, respectively. Several other authors assumed the two-infall concept for treating the evolution of the Milky Way [65, 3].

The main physical mechanisms governing chemical evolution of galaxies are: the process of star formation which means either the rate at which the gas is transformed into stars or the distribution of the stellar masses at birth. Then the stellar nucleosynthesis, which determines the amounts of newly created elements in stars of different mass. Then gas flows, which can be entering or leaving the galaxy, as well as radial gas flows. Finally, also stellar migration can influence the chemical evolution since stars born at a given Galactocentric distance can move, during their lives, and land at a different distance.

However, taking into account gas and star flows would require a dynamical approach besides a chemical one. Chemical evolution models can take into account these phenomena only in a parametric way. Chemo-dynamical models, where chemical enrichment and gas and stellar dynamics are present should represent one of the main future goals in studying galaxy evolution. Recently, an example of such chemo-dynamical models was presented by [281], who included stellar dynamics in a detailed chemical evolution model.

However, the already existing detailed chemical models can reproduce many chemical patterns observed in galaxies and they have allowed us to even predict what should have been observed ahead of time. As an example, [261] predicted, since no observations existed yet, that the stars in the Milky Way bulge should show high [α/Fe] ratios for a large range of metallicities and this was indeed observed by [267] and by many subsequent authors. The [261] prediction is shown in Fig. 4.20 in Chapter 4 (curve labelled Bulge). However, we are still far from having understood the mechanisms of formation of the various Galactic components: the chemical abundances can only suggest the timescales on which the various Galactic components have formed, but they cannot tell us the details of how they formed. A lot of work is still necessary to answer to the still many open questions concerning the Milky Way and external galaxies. For example: is the IMF universal or it does it vary from galaxy to galaxy? Did the spiral disks form by accretion of cold gas occurring inside-out, as suggested by chemical models? How did the thick-disk stars form, in situ or they were accreted from the dwarf satellites? How did the bulge of the Milky Way form? Are the more massive galaxies older than the smaller

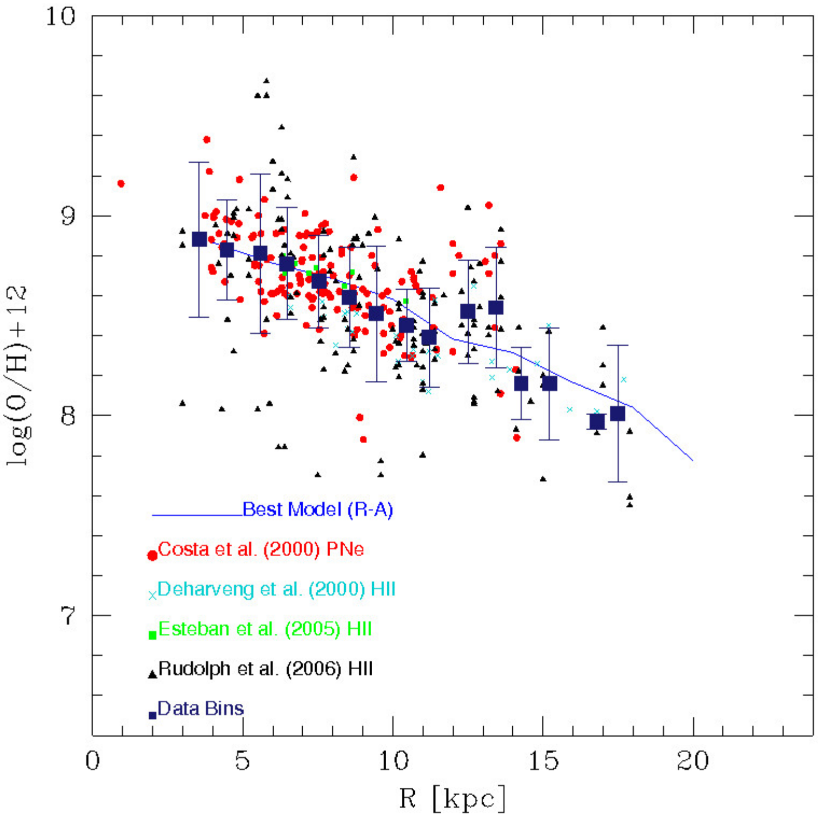

Fig. 8.8 The abundance gradient of oxygen along the Galactic thin disk. The data are HII regions and planetary nebulae. For references see [290]. The model assumes inside-out formation of the Galactic thin disk, a threshold in the gas density for star formation, and radial inflow of gas with the velocity pattern suggested by [369]. Figure from [290], where the references to the data can be found.

ones, as chemical models suggest for ellipticals and spirals? Is the efficiency of star formation a function of the galactic mass (stars plus gas), as suggested by several chemical constraints? As a final example of observations in good agreement with chemical models, we show in Fig. 8.8 the measured abundance gradient of oxygen along the Galactic thin-disk, compared to the predictions of a chemical evolution model including radial gas flows and assuming an inside-out formation of the disk as a result of accretion of cold gas [290].

More recently, there has been an attempt at computing Galactic chemical evolution in the framework of cosmology. In particular, models following the hierarchical galaxy formation paradigm, where massive objects should have formed by merging of smaller units. Among those we recall the work of [201] who included detailed nucleosynthesis prescriptions in cosmological simulations of galaxy formation. At the preset time there are still two different approaches to galaxy formation and galactic chemical evolution: a) the astro-archaeological approach and b) the cosmological approach. In the former, which is expressed by the chemical evolution models described before, one starts from the observed chemical abundances and tries to reconstruct, by means of a chemical model, the history of star formation, gas accretion and/or gas outflow that has created the observed abundance pattern. In the cosmological approach instead, the history of galaxy formation is given by the hierarchical paradigm which descents from the ΛCDM cosmological scenario. However, this last approach, although continuously improving, has not yet allowed one to reproduce very realistic galaxies. One argument of debate among the two approaches is, for example, the formation and evolution of elliptical galaxies. In fact, observational data for these galaxies suggest that the average $< [\alpha/Fe] >$ ratio in their dominant stellar population increases with the stellar mass. This can be nicely explained if we assume that the most massive ellipticals formed their stars first and on a shorter timescale than less massive ones. This is called *down-sizing in star formation* and it predicts the contrary of what is expected in the hierarchical scenario for galaxy formation, where the most massive objects should assemble on a longer timescale than the less massive ones and should have formed stars for a longer period. In order to have a high $< [\alpha/Fe] >$ ratio in massive ellipticals instead, their star formation should have been intense and short to avoid that too many Type Ia SNe exploded and polluted the ISM with Fe.

Questions for Gabriella De Lucia:
the Milky Way and the Local Group galaxies are today the only objects of the Universe for which we are able to determine the ages and the chemical composition of their individual stars. May you summarize how these data have been used in the framework of the hybrid models of galaxy formation? Could you compare these results with those based on hydrodynamical simulations?

Our own galaxy - the Milky Way - is a fairly large spiral galaxy consisting of four main stellar components: a *thin disk* that contains most of its stars, a *thick disk*, a *bulge*, and a *stellar halo* that contains only a tiny fraction of the total stellar mass. The stars in the thick disk are old, have on average lower metallicity than those of similar age in the thin disk, and are on orbits of lower angular momentum. The bulge is dominated by old and metal-rich stars, with a tail with lower abundances. Finally, the stellar halo is dominated by old and metal poor stars with low angular momentum orbits [145].

Historically, chemical and kinematic information provided the basis for the first galaxy formation models. Eggen, Lynden-Bell & Sandage [115] studied a sample of local dwarf stars and found that those with lowest metal abundance were moving on highly elliptical orbits and had small angular momenta. The data were interpreted as evidence that the oldest stars in the galaxy were formed out of gas collapsing from the halo onto the plane of the galaxy, on a relatively short time-scales. About one decade later, Searle & Zinn [357] found no radial abundance gradient in a sample of red giants and globular clusters. These observations led them to formulate the hypothesis that the stellar halo (particularly its outer region) formed through the agglomeration of subgalactic fragments, that may be similar to the surviving dwarf spheroidal satellites (dSphs) of the Milky Way.

The Searle and Zinn scenario appears to be in qualitative agreement with expectations from the hierarchical CDM scenario. Evidence in support of this picture includes the detection of significant clumpiness in the phase space distribution of halo and disk stars (e.g. [244, 67, 24]), and the detection of satellite galaxies caught in the act of tidal disruption (e.g. [180, 430]). The debate between a rapid collapse and a sequence of accretion events is, however, not settled. One difficulty was pointed out by [362] who obtained high resolution spectra for stars in three dSph galaxies and noted that these tend to have lower alpha abundances than stars in the stellar halo. These results, later confirmed with larger samples, suggest that the Galactic stellar halo cannot result from the disruption of satellite galaxies similar to those observed in the Local Group. The counter-argument is that the *surviving* satellites might be intrinsically different from those that contributed stars to the stellar halo. Another problem with the Searle & Zinn scenario was pointed out by [170] who found a significant difference between the metal-poor tail of the dSph metallicity distribution and that of the Galactic halo, suggesting that the progenitors of present day dSphs are fundamentally different from the building blocks of our Galaxy, even at earliest epochs. Recently, however, different groups have detected very metal-poor stars both in classical and in ultra-faint dwarf satellites [195, 144]. Finally, a classical element of crisis with respect to the current cosmological paradigm is the so called *missing satellite problem*, i.e. the finding that substructures resolved in galaxy-size DM haloes significantly outnumber the satellites observed around the Milky Way [199, 284]. Early studies based on semi-analytic models of galaxy formation focused on this particular aspect, and showed that the presence of a strong photoionizing background, possibly associated with the reionization of the Universe, can suppress accretion and cooling in low-mass haloes thereby suppressing the formation of small galaxies [114, 184, 27]. The discovery of a new population of ultra-faint satellites in recent years has led to a renewed interest in the physics of dwarf galaxy formation[8]. New impetus to the field has also been given by the completion of extremely high resolution N-body simulations of galaxy size haloes [371, 106].

In the last decade, different groups have taken advantage of these simulations to study the formation of the Milky Way and its satellites in a cosmological context. [49] combined mass accretion histories of galaxy-size haloes constructed using an analytic (the extended Press-Schechter) formalism with a detailed chemical evolution model that considers both Type II and Type Ia supernovae. For each accretion event, they run N-body simulations following the dynamical evolution of the accreted satellites, placed on orbits consistent with those found in cosmological simulations. [142] analysed the build up and chemical properties of the stellar halo in these models. The simulations reproduce the systematic differences between

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[8] It should be noted that this discovery did not alleviate the original missing satellite problem, as all the newly discovered satellites are fainter than the classical ones.

the chemical abundances of stars in satellite galaxies and those in the Milky Way. This results from the fact that the stellar halo originates from a few relatively massive satellites, accreted early on, and enriched in α elements by Type II supernovae. The model surviving satellites are accreted later, have more extended star formation histories and stellar population enriched to solar level by both Type II and Type Ia supernovae. While the approach provides a high numerical resolution for each accreted galaxy, the stellar distribution of the galaxies is not modelled self-consistently during the N-body simulation.

In a recent study [99], I applied a hybrid model of galaxy formation to a series of N-body simulations with increasing numerical resolution. We showed that our model was able to reproduce reasonably well both the estimated physical properties of our own Galaxy (its stellar mass, gas content, present star formation rate) and the metallicity distribution of its different stellar component (although the modelled bulge is more metal poor than the Galactic bulge). In this study, we also analysed the formation and structure of the stellar halo, under the working hypothesis that it is built from the cores of the satellite galaxies that merged with the Milky Way over its lifetime. In order to identify the stars that end up in the stellar halo, the full merger tree of the model Milky Way galaxy was constructed, and the galaxies that merge onto the main branch of the galaxy identified. These galaxies were then traced back to the time they were about to become satellite, and a fixed fraction (ten per cent in our fiducial model) of the most bound particles of their parent haloes were *tagged* with the stellar metallicity of the galaxies residing at their centre. Our results were in qualitative agreement with those by [142]: only a few satellites make most of the stellar mass in the halo, and most of them are accreted early on. The halo has a steeper profile and is more centrally concentrated than the dark matter profile. In addition, we found that high-metallicity star particles are more centrally concentrated than star particles of lower abundances, in qualitative agreement with observational measurements [58].

A more sophisticated tagging scheme has been recently used by [82] who take advantage of the higher resolution simulations from the Aquarius project [371]. In their study, Cooper et al. assume that the energy distribution of newly formed stars traces that of the dark matter. They then order the particles by binding energy and select some fraction (f_{MB}) of these most bound particles to be tagged. f_{MB} is treated as a free parameter, and is fixed by comparing model predictions with observational measurements of the structure and kinematics of the Milky Way satellites. Fig. 8.9 shows a projected surface brightness map of the stellar halo, for the six Aquarius dark matter haloes. Substantial diversity among the haloes is apparent. A few haloes (e.g. Aq-B and Aq-E) are characterized by strong central concentrations, while others show extended envelopes out to $75-100$ kpc. Each envelope is the superposition of streams and shells that are phase-mixed to varying degrees. Most haloes exhibit a strongly prolate distribution of stellar mass, particularly in the inner regions. The brightest and most coherent structures visible can be associated with the most recent accretion events. The model stellar haloes span a wide range of accretion histories, ranging from a gradual accretion of many progenitors to one or two significant accretions.

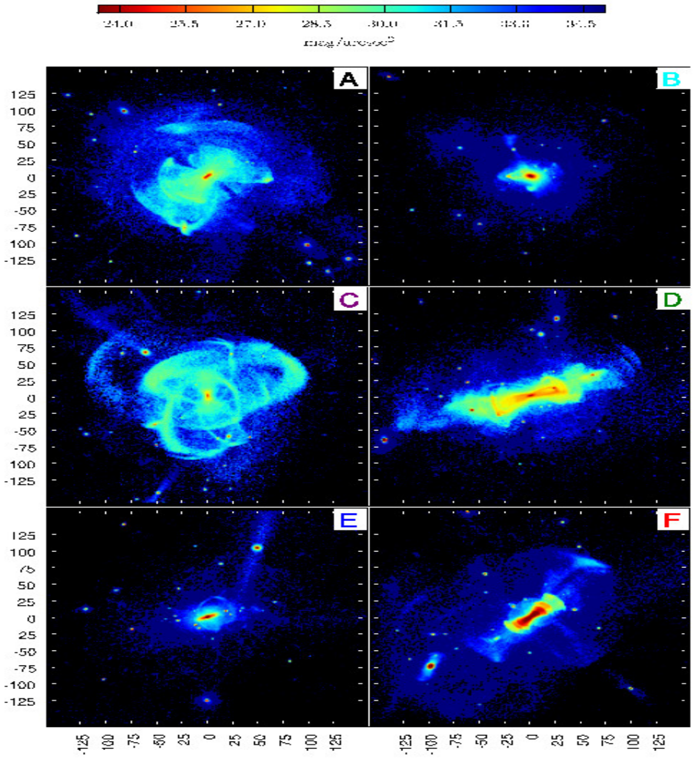

Fig. 8.9 From [82]: V-band surface brightness of model stellar haloes (and surviving satellites), to a limiting depth of 35 mag/arcsec^2. The axis scales are in kiloparsec.

The latest incarnations of semi-analytic models have been applied to high-resolution simulations also to study the number density and physical properties of satellite galaxies of the Local Group. These studies have confirmed that, combining a sufficiently high redshift reionization with a relatively strong feedback from supernovae, it is possible to bring the predicted number of luminous satellites in agreement with the most recent observational results [234, 240, 143, 378]. The same models provide a relatively good agreement with some basic physical properties measured for the Milky Way satellites, as well as an explanation for the weak dependence of M_{300} on the virial mass of the substructures hosting luminous galaxies [383]. In fact, models predict a weak increase of M_{300} for increasing luminosity which will be testable once more accurate measurements are available.

One strong limitation of all models mentioned above is that they are all based on an instantaneous recycling approximation (i.e. the models do not account for the finite lifetime of stars and its dependence on stellar mass). This is clearly inappropriate for iron-peak elements, mainly produced by supernovae Type Ia. In a recent study, we have developed a new method to trace individual abundances within a semi-analytic model [100], and applied it to the Aquarius simulations. The model reproduces the [Fe/H] distributions of the stars in the disc component, as well as the global physical properties of the Milky Way. For the spheroid component (whose formation we model only through mergers), the metallicity distributions are offset low with respect to observational measurements for the Milky Way bulge. This is a consequence of narrow star formation histories, with relatively low rates of star formation. It remains to be seen if the same model is able to reproduce also the vast amount of chemical data available for the more general galaxy population, both in the local Universe and at higher redshift.

As discussed above, hydrodynamical simulations have generally had problems reproducing disk-dominated galaxies in typical dark matter haloes, when taking into account the cosmological setting. Because of these difficulties, most of the focus so far has been on reproducing thin disks similar to that of the Milky Way, rather than reproducing its detailed chemical properties. Very recent studies have started using also the detailed information available on the age and chemical properties of the Milky Way and its satellites.

Sawala et al. [350] studied the formation and evolution of dwarf galaxies with halo masses in the range of $\sim 2 \times 10^8$ to $10^9\,\mathrm{M}_\odot$ in cosmological simulations including cooling, SN feedback and UV radiation. Their simulated galaxies span a range of luminosity and metallicity in good agreement with Local Group dSphs. However, the observed dwarf sample is more diverse (in terms of star formation histories) than the simulated sample. For example, simulations do not include a system as luminous and extended, or with such a large age spread as Fornax. The same code and feedback scheme employed in this study had been used in [352] and, more recently, in [353] to study the formation of Milky-Way like galaxies. As mentioned above, the latter study compared results of 13 cosmological gas-dynamical codes run on the same initial conditions. The different implementations of star formation and feedback led to a large variations in the predicted stellar mass, size, morphology, and gas content. No code resulted in a simulated galaxy that resembles our own Milky Way. In particular, most codes tend to produce galaxies more massive, smaller and less rich than typical spirals, with a relatively massive bulge. The chemical properties of simulated Milky Way galaxies, based on the same code, were analysed in [396]. Simulated disks are found to be more chemically enriched than the stellar halo but slightly less enriched than the central spheroids. Central spheroids are formed mainly by old stars most of which have been formed *in situ* with contributions of less than ~ 20 per cent of stars formed in satellites. The stars in the outer halo are mostly accreted by satellites and are less enriched than those in the inner halo, in qualitative agreement with observational measurements.

Aumer et al. [11] presented an update to the numerical scheme adopted in the studies mentioned above that include a more elaborate treatment of the production of metals, cooling, and a scheme for turbulent diffusion of metals. Their simulated galaxies show realistic morphologies, circular velocity curves and stellar metallicities, but overly flat metallicity gradients. Contrasting results were presented in [381] that is based on a different numerical code. In their simulations, the old stars lie in a thickened distribution with a short scalelength, while the young stars form a thinner disc, with scalelengths decreasing, as [Fe/H] increases. This translates into a metallicity gradient that is in quite good agreement with that observed for the Milky Way. Also in this case, the simulated galaxy has a prominent thick disc that is not seen in the Milky Way.

A solid theory of galaxy formation should reproduce the fundamental scaling relations of galaxies and their scatter as a function of redshift and environment, in the high dimensional space of observed galaxy properties. Unexplained scatter, or discrepancies in the scaling relations, indicates missing physics and or flows in the model. Do we have a theoretical explanation of the most important scaling relations ?

Future surveys, e.g. from LSST, will produce much better defined relations and consequently outliers. Will current models survive?

Galaxies span a wide range in physical properties (masses, morphologies, sizes). However, their structural parameters obey a number of scaling relations, some of which, as you say, are remarkably tight. These relations likely hold important information on the physical processes that drive them. Therefore, a successful theory of galaxy formation needs to explain their origin.

Elliptical galaxies are concentrated on a plane in the three-dimensional space spanned by surface brightness, size, and velocity dispersion [108, 111], termed the 'Fundamental Plane'. Projections of this relationship form the Faber-Jackson relation [134] between luminosity and velocity dispersion, and the Kormendy relation between luminosity and radius [203]. Spiral galaxies also obey a well-defined scaling relation between the luminosity L and their rotation velocity (usually taken as the maximum of the rotation curve well away from the centre, V_{max}). This is known as the TullyFisher relation [403].

The origin of the Fundamental Plane is usually interpreted in terms of the virial theorem ($GM/ < R > = < v^2 >$), but the plane observed is 'tilted' with respect to that expected on the basis of the virial theorem, suggesting a variation of the mass-to-light ratio or non-homology in the class of the elliptical galaxies. There is still no consensus on what is setting the tilt of the Fundamental Plane, with some studies arguing that non-homology is responsible for large part of the observed tilt [165], and other studies claiming that influence of non-homology is not significant [54]. Another challenge is that of understanding why the scatter in this relation is so small. At face value, this seems difficult to explain in the framework of the current standard cosmological paradigm (the *Cold Dark Matter* - CDM - scenario) where larger systems form from mergers and accretion of smaller ones. Detailed controlled merger simulations have demonstrated that gas dissipation is a crucial ingredient in order to reproduce the observed Fundamental Plane in the framework of the hierarchical merging scenario [340]. In these simulations, the tilt of the Fundamental Plane arises primarily by variations in the M/L ratio. Simulations have also shown that mergers between gas-poor galaxies (sometimes referred to as *dry mergers*) maintain the tilt. It should be noted that these simulations are not embedded in a cosmological context, and that initial conditions are often idealized and likely not representative of the range of orbital distributions and physical parameters of the merging systems occurring in the real Universe.

Various attempts have been made to include detailed prescriptions for modelling galaxy sizes in theoretical models of galaxy formation of the kind I describe below. These are coupled to cosmological simulations but rely on prescriptions based on the simulations mentioned above (therefore often extrapolated to higher redshift and/or outside the range of parameters directly probed) to model galaxy sizes. Early models used simple formulae based on the virial theorem and conservation of energy, that are appropriate for dissipationless gas-poor mergers. More recent implementations have taken advantage of results of hydro-simulations to include the energy dissipated in gas-rich major mergers in the energy budget. This modification reduces the sizes of less massive ellipticals, bringing the predicted mass-size relation in quite good agreement with observational data (see e.g. [359, 325]). Predictions from different models, however, differ in the detail (unsurprisingly) so that, in a few cases, contradicting conclusions are drawn. For example, [359] find that the scatter in sizes of elliptical galaxies at fixed stellar mass is larger than the observed one, while [325] claim that their model correctly predicts the normalization, slope *and scatter* of the low redshift size-mass relation for elliptical galaxies. The latter study finds a curvature in the Faber-Jackson relation that is not observed locally and that they claim could be alleviated if more massive ellipticals have more bottom heavy initial mass functions. The observed tilt of the Fundamental Plane is also reproduced in these models, and it results from the decrease of gas fraction with increasing progenitor mass that leads to a varying central dark matter fraction [83]. It will be interesting to see how model predictions compare to better defined local relations, and to more detailed observations at higher redshift. When comparing data with models, however, one should keep in mind that these models do not resolve the internal structure of galaxies: they only provide a ‘bulge-to-total’ parameter, that is used to assign model galaxies to different morphological classes. ‘Standard’ mass/light distributions are also assumed in order to estimate galaxy sizes.

Let’s now turn to disk dominated galaxies. The observed Tully-Fisher relation implies a close relation between the total gravitational mass and the total amount of stars. The relation is surprisingly tight, particularly at long wavelengths [421], and has long provided a major challenge for modern theories of galaxy formation. From the theoretical point of view, such a relation can arise as a natural consequence of the correspondence between mass and circular velocity [282]. A scaling similar to that observed can be obtained if the disk rotation speeds and the luminosities (that are the observables entering the Tully-Fisher relation) are proportional to the circular velocity of the halo and to the mass of the halo, respectively. In practice, these assumptions are not valid: disk rotation speeds depend in a non trivial fashion on the contribution of gas, stars, and dark matter within the optical radius of the galaxy, and the luminosity results from the entire star formation history of the galaxy, that is not uniquely determined by the mass of the parent halo.

Early N-body simulations reproduced the slope of the relation, but had difficulties in matching its zero-point [380]. These were just a manifestation of the so-called 'angular momentum catastrophe': baryons condense early in clumps that then fall into larger haloes and merge via dynamical friction. This produces a net and significant transfer of angular momentum from the baryons to the dark matter, with the result that simulated disks are generally too compact and with up to ten times less angular momentum than real disk galaxies. The formation of a realistic rotationally supported disk galaxy in a cosmological context is still an open problem. Numerical work has shown that this is in part due to limited resolution and related numerical effects that cause artificial angular momentum loss and spurious bulge formation (for a detailed discussion, see e.g. [266]). The physics of galaxy formation during the merger of the most massive protogalactic lumps at high redshift and, in particular, the feedback due to supernovae are, however, also playing a very important role ([353] and references therein).

Fig. 8.10 shows the results from a recent work by [353] that has compared various cosmological gas-dynamical codes used to simulate the formation of a disk-like galaxy. The runs differ in their numerical treatment but use the same initial conditions. The figure shows that there is a clear discrepancy between the observed Tully-Fisher relation and simulated galaxies, that tend to have significantly larger velocities at fixed stellar mass. Models with more efficient stellar feedback come closer to match the observed scaling laws, but the same models often have a significant central component (i.e. the efficient feedback damages the disk).

In the framework of semi-analytic models of galaxy formation, matching the zero-point and slope of the Tully-Fisher relation is 'easier'. It remains, however, a long standing problem that of matching the zero-point of this relation and reproducing at the same time the observed galaxy luminosity function. It remains unclear if this difficulty is related to some approximation in the size calculation, or to more fundamental shortcomings of the CDM model [20].

Of course the fact that models are not in perfect agreement with the data does not mean that the models have to be killed. It is actually from these disagreements that we learn more about the physics that is at play!

The last aspect to examine in the problem of galaxy formation is that related to the role of magnetic fields.

8.8 The role of magnetic fields

Questions for David Moss:
could contemporary galactic fields trace their origin back to the era before galaxy formation?

Perhaps the conceptually simplest explanation of the fields we see today is that fields with spatial scales greater than that of protogalaxies are created in the early stages

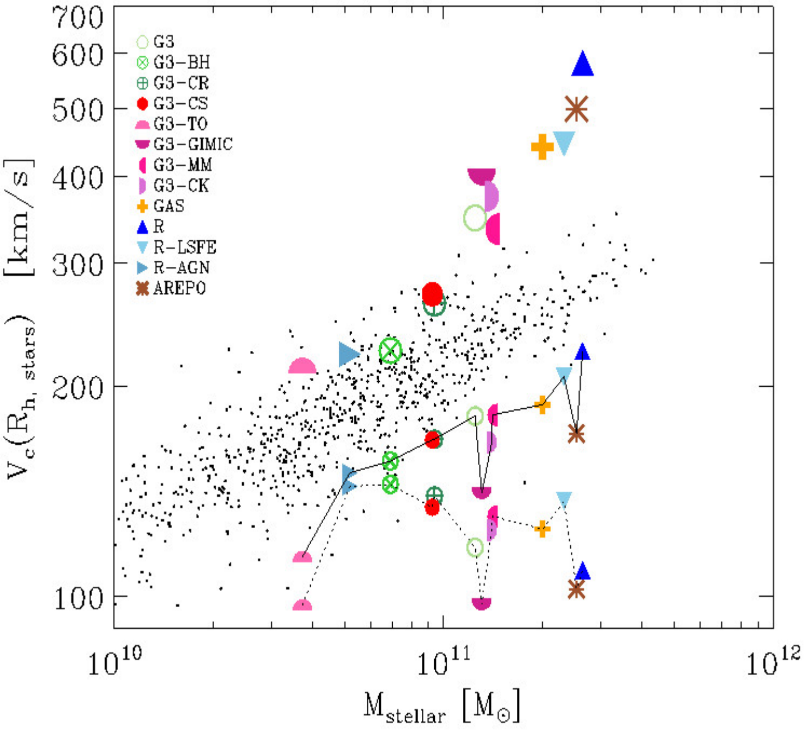

Fig. 8.10 From [353]: The circular velocity at the stellar half-mass radius of simulated galaxies plotted as a function of stellar mass. Small black dots correspond to data for nearby spiral galaxies. Symbols connected by a solid line show the contribution of dark matter to the circular velocity at the same radius. A dotted line shows the same but for a dark matter only simulation. The difference between solid and dotted curves indicates the degree of 'contraction' of the halo.

of the Universe, and then evolve to become the fields seen today. The physics of the origin of any such field is still unclear, and presents a possibly important gap in our understanding. A number of possibilities have been proposed, including phase transitions in the very early Universe (see, e.g. [420]), and instabilities and fluctuations after reionization [230]. Any such primordial fields would be compressed during galaxy formation and subsequently stretched and distorted by differential rotation, large-scale non-circular motions, interstellar turbulence and other flows, once galaxies have formed.

There are several basic difficulties with this scenario. Perhaps the most fundamental is the "winding problem". A generous upper limit for the strength of the primordial field is $O(10^{-12})$G – some estimates are much smaller. If this field is to be amplified to the observed microgauss strengths, even after allowing for compression during the collapse of the protogalaxy, this would require so much winding by the differential rotation that the resulting pitch angles p ($\tan p = B_r/B_\phi$), would have $p \lesssim 1^\circ$. In contrast, typical observed values are around 20°. Additionally, such a field is rapidly expelled to near the perimeter of the galaxy (the ”MHD flux expulsion effect”), and would then be inconsistent with observed RM measures.

Conversely, if there is sufficient field dissipation (reconnection) to restrict the field winding sufficiently to yield the desired pitch angles, the fields will be much too weak.

There is also a ”parity problem”. The parity of a magnetic field is a measure of its symmetry with respect to a plane, often the rotational equator. In galactic terms, axisymmetric fields with both azimuthal component and poloidal component (lying in meridian planes) having even symmetry with respect to the plane, are described as being of even parity, $P = +1$. Fields with the opposite symmetry properties have odd parity, $P = -1$. Of course, intermediate (”mixed”) parities are possible. A component of a primordial field that is parallel to the disc plane will have even parity with respect to the plane, but we have just seen that this component cannot be expected to survive the winding process. A component parallel to the rotation axis will have odd parity, which will be subsequently preserved. In contrast, galaxy fields appear to have even symmetry with respect to the plane – see [367].

This all suggests that large-scale field of observed strengths cannot be directly inherited from pre-galactic fields, and that detailed consideration of *in situ* generation mechanisms is required.

So if the contemporarily observed fields are not the direct descendants of pregalactic fields, how can they be explained?

It is now widely accepted that galactic discs are suitable sites for large-scale dynamos to operate. In particular, galactic dynamo theory generally predicts fields of even parity with respect to the disc plane, and that field vectors near the disc are offset from the gas flow vectors – both features are in agreement with observations. In its simplest form, a dynamo is a mechanism by which an infinitesimally small ”seed” magnetic field can be amplified to finite magnitude, and maintained indefinitely against decay. The possible origins of such seed fields merit some attention, but let us assume that they can be found. The most readily accessible formulation of dynamo theory is MFD theory, but note that less restrictive approaches are also being developed.

The gas in a galactic disc is turbulent. The turbulence is driven by injection of energy from supernovae (SN) explosions, winds from hot stars and dynamical instabilities. Whilst the turbulence (on scales typically of 100 pc) causes modelling problems, it is a key ingredient of the dynamo action that is believed to create and maintain the large-scale field.

In its modern form, astrophysical dynamo theory began with the seminal paper of Parker [301]. He showed that mirror antisymmetric cyclonic turbulence together with differential rotation can drive dynamo action. This paper was addressed to explaining the magnetic field in the solar convective envelope. It was soon recognized that the mechanism could also operate in galactic discs [302]. In order to tackle the dynamo problem in full it would be necessary to solve not only the basic MHD equation

$$\frac{\partial \mathbf{B}^*}{\partial t} = \nabla \times (\mathbf{u}^* \times \mathbf{B}^* - \eta_{\mathrm{m}} \nabla \times \mathbf{B}^*) , \qquad (8.4)$$

but also the hydrodynamic equations, and possibly the thermodynamic equations. A wide range of spatial and temporal scales, spanning many orders of magnitude are involved, and there is no prospect of solution of this ”full” problem without substantial approximation and simplification. In Eq. 8.4, $\mathbf{u}^*$ is the total fluid velocity (rotation, large-scale streaming and small-scale turbulence), $\mathbf{B}^*$ is the total magnetic field and η_{m} is the microscopic diffusivity. The most dramatic, and most accessible and fruitful, simplification is the MFD theory, in which Eq. (8.4) becomes

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\alpha \mathbf{B} + \mathbf{u} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) . \qquad (8.5)$$

In deriving Eq. 8.5, Eq. (8.4) has been averaged over some scale, and **B**, **u** are now the resulting *mean fields*, representing averages over these scales. α, which parameterizes the generative effects of cyclonic turbulence, is the key quantity in MFD theory; η is the turbulent resistivity. η and α thus represent sub-grid modelling; both may be tensor quantities. In galactic MFDs, differential rotation plays a key role in generating large-scale magnetic field by twisting and stretching poloidal field. In order to close the cycle, and maintain the overall field against decay, the alpha-effect (or something analogous) is required to create poloidal field from toroidal. In the MFD equation, in axisymmetric models toroidal (azimuthal) field is predominantly created from poloidal field (in meridian planes) by the differential rotation, whereas the converse step, poloidal to toroidal field, is achieved via the α-effect. Without such a loop, dissipation processes would dominate and the field would eventually disappear. The solution $\mathbf{B}(\mathbf{r},\mathrm{t})$ of Eqn. (8.5) is usually interpreted as corresponding to the observed *regular* fields, and the small scales are subsumed into the coefficient α.

Differential rotation is one of the two essential ingredients of the operation of large-scale galactic dynamos. Its absence in elliptical, dwarf and irregular galaxies provides a natural explanation for the absence of large-scale magnetic fields in these objects.

This approach was pioneered in Jena and Potsdam in the 1960s and 1970s; a comprehensive treatment is given in [205]. Early investigations were followed by an interval during which the basic concept of a significant α-effect was rigorously challenged (e.g. [61] and many subsequent papers). Now both theoretical studies and the results of detailed modelling of small ”boxes” of gas lend support to the basic validity of the MFD approach and this ”catastrophic quenching” does not occur. The basic concern was that an accumulation of small-scale field could ”strangle” dynamo action, limiting large-scale fields to irrelevantly small amplitudes. Now it it is generally agreed that various transport mechanisms exist that can alleviate this problem (for example, [197, 407, 41, 287, 64] and many others). The simplest forms of galactic dynamos are driven by the joint effects of cyclonic turbulence (in this approximation, the alpha-effect) and differential rotation. These are conveniently summarized by dynamo numbers $R_\alpha = \alpha_0 L/\eta_0$ and $R_\omega = (rd\Omega/dr)_0 L^2/\eta_0$, where r is cylindrical radius, L is a suitable length scale and subscript zero denotes a representative value. In many cases these can be combined into a single dynamo number $D = R_\alpha R_\omega$. In most physically relevant examples dynamo action occurs when $|D|$ exceeds some threshold value. When applied to galactic discs, even simple models give results that are broadly consistent with observations – see e.g. [347, 23]. Some form of nonlinear back reaction of the magnetic fields onto the gas motions is necessary to limit fields at finite magnitude. Other gas motions, such as large-scale non-circular streaming, outflows from the disc – galactic winds and fountains – probably play an important role in some galaxies. Refinements can be added to models, including several explicit formulations of nonlinear dynamical feedback, such as buoyancy, cosmic rays and galactic winds. The latter, besides taking part in the basic dynamo action, may influence field structure in the halo regions above and below the galactic disc.

The MFD model is quite robust, in the sense that truncation to two or even one spatial dimension can yield useful results.

It has also become apparent that a full understanding of dynamo action cannot be attained without consideration of the properties of *magnetic helicity*, a property of the small-scale fields, that controls the α-effect. Crudely speaking, magnetic helicity is a measure of the degree of linkage of magnetic field lines. It is defined as the volume integral $\int \mathbf{B} \cdot \mathbf{A} dV = \int \nabla \times \mathbf{A} \cdot \mathbf{A} dV$, where $\mathbf{A}$ is the magnetic vector potential. (There is a clear analogy with the kinematic helicity, $\int \mathbf{v} \cdot \nabla \times \mathbf{v} dV$.) Magnetic helicity is a conserved quantity, so increase in large-scale field (e.g. by dynamo action) increases large-scale helicity, and thus small-scale helicity of the opposite sign. Dynamical feedback from the latter can strangle the dynamo action – the catastrophic quenching referred to above – unless a mechanism exists to remove the small-scale helicity.

Plausible and useful results in modelling spiral galaxies can be obtained by taking the simplest form of MFD theory, whilst bearing in mind that additional effects may need to be included, for example the effects of buoyant motions in the disc driven for example by "bubbles" from sites of multiple supernovae explosions (e.g. [141]), or by inflation of bubbles by cosmic rays. In a first approximation, these models can also be studied by a quantity analogous to the alpha effect (see, e.g., [286]). MFD modelling has the advantage that substantial exploration of parameter space can be made with limited computational resources. Of course, this efficiency and convenience is paid for by accepting the uncertainties of parametrization of small-scale processes.

An alternative approach is known as Direct Numerical Simulation (DNS), which attempts to model more-or-less explicitly some smaller-scale dynamical and thermodynamical processes. Very substantial computing resources are required. Even so, parametrization of transport processes at small scales is still needed. DNS in relatively small "boxes" has been used to provide direct estimates of the turbulent transport coefficients α and η, and to study the evolution of statistical properties of the small-scale fields and how nonlinear feedback on the α-effect evolves. Gent [153] gives a comprehensive review. DNS in a box has also been coupled to studies parametrizing the effects of cosmic ray heating from SN in driving the rise of bubbles from the galactic disc; this can be an effective contribution to the α-effect. At the moment, even accepting sub-grid parametrizations, adequate DNS of an entire galaxy presents very substantial computational problems. For the forseeable future the most promising approach may be to use computationally intensive DNS in local boxes to estimate transport coefficients, and to use these estimates in global mean field models.

When discussing both observations and dynamo theory you mentioned small-scale fields. How do these arise? Also seed fields are clearly important to initiate large-scale dynamo action. What can you say about them?

Small-scale fields are known to be ubiquitous (e.g. from the observed depolarization of synchrotron radiation) and to be at least as strong as the large-scale fields. Typical length scales are of order 100 pc, compared with the several kpc scales of large-scale fields, and O(10) kpc for galactic radii. There are two potential sources of these fields. They arise naturally from the tangling of large-scale fields by the disc turbulence. There is also the possibility of *small-scale dynamo action*, in which small-scale turbulent motions can maintain small-scale fields, in approximate energy equipartition with the gas motions. The highly turbulent vicinities of groups of supernovae may be particularly favourable for this mechanism to operate.

For a dynamo to operate, a ”seed field” must be initially present; dynamos do not create magnetic field *ab initio*. Large-scale dynamos amplify a seed field, organize it and maintain it against decay. It follows that discussion of the origin of galactic fields is incomplete without consideration of possible seed fields. Galactic MFDs have typical growth times (e-folding times) of about $5 \times 10^8 - 10^9$ yr, so a primordial field can only be amplified to contemporary strengths in the available time if it is near its rather optimistic upper limit of $O(10^{-12})$G. The detection of strong organized fields out to redshifts in excess of unity provides an even stronger constraint on the necessary strength of primordial seed fields. On the other hand, turbulence will rapidly (timescale $O(10^6)$ yr in a galactic disc) drive small-scale dynamo action. This generates disordered fields at the scale of the turbulence and in approximate equipartition with the kinetic energy of the turbulent motions – i.e. at least $O(10^{-6})$G. Large-scale dynamo action (as described e.g. by a MFD) can then organize such a small-scale field into contemporary structures. In models, signs of such organization typically appear after a few galactic rotations – $1 \sim 2$ Gyr say [22, 288], when this field is already of microgauss strength. Additionally turbulence, perhaps augmented by the magnetorotational instability (MRI), may tangle and amplify a weak relic field, in this way also providing a strong small-scale seed field. Another possibility is that weak fields could be generated by the Biermann ”battery” mechanism, or even by a dynamo, in the first generation of stars and subsequently ejected into the ISM where small-scale and then large-scale dynamo action can operate, as outlined above; a more detailed discussion is given in [367]. Thus there may not be such a fundamental distinction between these various scenarios, and finding a suitable source of seed fields may not be a problem.

To what extent our ability in modeling the various processes occurred during galaxy formation and subsequent evolution is in agreement with the observational data? We explore now this aspect of the problem.

8.9 Confronting model predictions with observations

Questions for Malcolm Longair:
the physics of baryons is certainly the most difficult part of galaxy formation models. Could you sketch the main processes that see baryons are the most visible ingredients of galaxies? Why is it so difficult to model these phenomena? Which processes dominate during this epoch?

The reason that the behavior of the baryons is so difficult is because baryonic matter is dissipative. This means that it can lose energy by radiation, unlike, say, the dark matter. The good news is that, because baryonic matter can lose energy by radiation, stars can condense from regions of high interstellar gas density leading to high temperatures in their cores which enable the nuclear processing of material to take place. In turn, this leads to the synthesis of the heavy elements which are necessary for organic and inorganic chemistry and so ultimately to human life. From the point of view of understanding the astrophysics of galaxies, these processes lead to the huge variety of astrophysical phenomena which all need to built into a self-consistent picture of galaxy evolution, taking into account with the vast amount of information now available on galaxy populations. We know that there must be feedback mechanisms between star formation, supernova explosions, the enrichment of the interstellar medium with heavy elements, and so on, each of which is a complex discipline in its own right.

The most ambitious supercomputer simulations nowadays aim to build realistic astrophysics into the models of galaxy formation and evolution, but there remain considerable uncertainties in key aspects of the simulations. For example, the star formation history of galaxies is an essential part of the story and yet we do not have a mature enough theory of the star formation process and its dependence upon local physical conditions to include this process in a purely physical manner – some reasonable empirical approximations have to be made. To circumvent these difficulties, semi-empirical models of galaxy formation and evolution have been constructed, in the hope that these will provide guidance about how secure the various empirical assumptions of the models really are. But this is very different from predictive astrophysics. So, galaxy formation and evolution are hard.

Notice that this necessarily complex problem contrasts strongly with the evolution of the dark matter in galaxies. Assuming the dark matter is some sort of ultra-weakly interacting particle, the evolution of the dominant dark matter in galaxies can be simulated in considerable detail and with a good deal of confidence. The structures which form under gravitational collapse and the subsequent evolution of the dark matter under two-body processes and dynamical phenomena such as violent relaxation result in structures which can account for the observed statistical properties of the Universe of galaxies in a general way. These dark matter structures provide the framework within which baryonic processes lead to the optical appearance of galaxies. To put it crudely, the baryonic matter falls into the pre-existing gravitational potential wells created by the dark matter. Then, the full panoply of dissipative phenomena come into play - star formation, stellar evolution, the deaths of stars, supernova explosions, the formation of neutron stars and black holes, stimulated star formation and many more astrophysical phenomena. Not surprisingly, the results are sensitive to the input assumptions.

But there is also a lot of good news as well, much of it coming from the availability of new data from the very large galaxy surveys and from new and future instruments for large telescopes. My own view is that one of the most important developments of the last decade has been the quantification of the properties of vast numbers of galaxies in terms of simply quantifiable physical quantities. The various correlation diagrams which have been derived from the SLOAN surveys of galaxies put the whole question of the physical and chemical evolution of galaxies on a new quantitative footing.[9] These diagrams represent global average properties of galaxies and so cannot be expected to account for the myriad of detailed features which real galaxies exhibit – but this is real progress. What I like about these studies is that, although classification decisions still have to be made, they involve objective criteria and can therefore be compared quantitatively with theory. So, despite the intrinsic complexity of the baryonic Universe, I am optimistic that much deeper insights will be forthcoming. But it will require a very major effort to get to the next step of understanding these aspects of the physics of galaxies.

Questions for Alvio Renzini:
Would you discuss the main difficulties encountered in modeling the stellar population of galaxies and their evolution?

Well, in principle there are no great difficulties. We have the ingredients from stellar evolution and from libraries of stellar spectra, so putting them together is not such a great effort after all. The question is, in case, the reliability of the results. In practice, the synthetic stellar population models cannot be perfect, hence when used to derive galaxy properties, they will imprint in the results their mismatch with reality. This clearly leads to systematic errors, which in some instances may be more important than observational errors and much more difficult to control. Derived trends of one observable versus another, such as age vs. mass, of IMF vs. velocity dispersion and the like, may be real, may be not real. They result from models giving us a somewhat distorted image of reality and therefore we should resist the temptation to soon build physical interpretations of trends that may just be an artifact of

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[9] For many examples of the remarkable results of these surveys, see the relevant chapters of my books *Galaxy Formation* [236] and *High Energy Astrophyscs* [237].

some subtle mismatch between our model stellar populations and those in the sky. I am especially concerned for models for super-solar metallicities, as we lack adequate calibrators in this regime. A long standing debate concerns the contribution of asymptotic giant branch (AGB) stars to the near-IR luminosity of stellar populations, especially relevant when measuring mass and ages of quenched galaxies at high redshifts [73, 79, 206, 246, 319].

What is in your opinion the most productive approach to gain significant theoretical improvements in this field?

I dont expect theoretical improvements. In case, observational ones. New insight may be gathered by comparing synthetic stellar population models with the integrated spectra of stellar systems for which age and metallicity distributions and the stellar mass function are known independently. Globular clusters and the Galactic bulge offer the best available *calibrators* for this purpose. Unfortunately, they do not cover the full parameter space occupied by the stellar populations of galaxies at large. So, in several instances we have to work in a risky, extrapolating regime.

You have mentioned the IMF, do you think it is universal or does it depend on “space and time”?

A variable IMF is often invoked as an *had hoc* fix to specific discrepancies that may emerge here or there, which however may have other origins. For example, an evolving IMF with redshift has been sometimes invoked to ease a perceived discrepancy between the cosmic evolution of the stellar mass density and the integral over the cosmic time of the star formation rate. In other contexts it has been proposed that the IMF may be different in starbursts as opposed to a more steady star formation regime, or in disks vs. spheroids. Sometimes one appeals to a top-heavy IMF in one context, and then to a bottom-heavy one in another, as if it was possible to have as many IMFs as problems to solve. Honestly, we dont know whether there is one and only one IMF, but if appealing to a different IMF to solve one problem, at the same time one should check whether the new IMF does not destroy agreements elsewhere, or if it is not conflicting with other astrophysical constraints. I think it is perfectly legitimate to contemplate IMF variations from one situation to another, but should be mandatory to explore all consequences of postulated variations, well besides the specific case one is attempting to fix. This kind of sanitary check is most frequently neglected in the literature appealing to IMF variations.

What will be the contribution in this scientific area expected from large 30m+ ground based telescopes?

Wow, I dont know! My dream is to see galaxies at high redshifts with so much detail as we used to have, in the era of photographic plates, for local galaxies (such as Andromeda, M33, etc.). And make posters with them. I wish we could see forming/young globular clusters around galaxies beyond redshift ~ 3. I would love to see stellar color-magnitude diagrams within the effective radius of giant ellipticals such as M87, and measure their metallicity distribution function. What else? See the very first, Population III stars, or at least the first mini-galaxies at redshift beyond ~ 10, perhaps in sufficient number to make sure they are re-ionizing the Universe. But, who knows? I just wish I will still be around to enjoy the spectacle.

What do you think of our ability to model galaxy evolution from first physical principles, i.e., either constructing semi analytic models or hydrodynamical simulations?

We all believe that galaxies form within dark matter halos that grow from initial cosmological fluctuations as mapped by the cosmic microwave background. Over the past three decades this paradigm has informed virtually all our attempts at understanding how galaxies form and evolve, a paradigm which has scored great success in accounting for the growth of large scale structures (LSS) as we see them in our Local Universe. This was indeed achieved with a remarkable economy of means, as dark matter particles interact only gravitationally and N-body simulations have been able to deal with millions of such particles. This success is a result of the simplicity of the physics involved: the mere two-body gravitational interaction, over and over again, millions of times.

But galaxies as we see them are also made of baryons, and baryons give rise to a frightening variety of physical processes and phenomena. On the scale of galaxies, such phenomena include star formation, galactic winds launch and fallback, formation of supermassive black holes and active galactic nuclei (AGN), supernova explosions and their feedback, dust formation, AGN feedback, gas accretion from the circumgalactic and intergalactic media via cooling inflows and/or cold streams, ram pressure, heating and cooling of a multiphase ISM, disk instabilities and clump formation, merging and starbursts, tidal interactions, etc. We know that all such processes must be at work inside and/or around galaxies and must play a role in shaping them and in driving their evolution. Baryon physics comes indeed with a great deal of *complexity*.

Attempts at modeling all this from first principles has come in two flavors, semi-analytic models (SAM) and hydrodynamical simulations. In SAM the hierarchical growth of dark matter halos within very large cosmological volumes is taken from state-of-the-art N-body calculations, and the behavior of baryons within them is conveniently parametrized, rendering in some plausible way the physical processes mentioned above. This approach has the advantage that whole populations of galaxies can be modeled as they form and evolve from the early Universe to the present. But each galaxy is represented by a small number of quantities, such as mass, star formation rate (SFR), stellar ages and a few others. In hydrodynamical simulations the computational effort is intensive rather than extensive. Only few individual galaxies can be modeled, but this is done in great detail producing model galaxies that once conveniently visualized may appear indistinguishable from real ones. Yet, the current spatial resolution of the simulations is far from covering the huge dynamical range, from sub-parsec to megaparsec scales, at which physical processes operate. Once more, *sub-grid physics* needs to be parametrized, not unlike in the case of the SAM approach.

In the early years of the SAM practice (the 1980s and 1990s) relatively few free parameters were sufficient to construct mock galaxy populations meeting several properties of galaxies in the local Universe. A fully theoretical creation of the realm of galaxies started to be produced, predicting in great detail how galaxies would have evolved through cosmic times. Theory was enjoying an enormous success, a cultural dominance at a time when data were still scanty and we all got mesmerized, as we saw movies showing to us plausible lives of galaxies, from their first seeds to full grow. Then a flood of data started to arrive, invalidating earlier predictions, as new large facilities came on line, ensuring a continuous multiwavelength coverage from X-rays to radio and probing ever further in the distant Universe.

This has forced models to incorporate new processes, thus inflating the number of free parameters. For example, the authors of a recent set of SAMs carefully list 29 adjustable parameters of their models, with five of them fixing the cosmological model according to the current concordance cosmology, and the other 24 being needed to describe baryon physics [28], or gastrophysics as it is called sometimes. These sheer numbers give a vivid impression of the inherent complexity of galaxies as evolving physical systems and of the quandaries one may encounter in navigating a 29-dimensional parameter space. Yet, in spite of these complexities, three remarkable *simplicities* have emerged directly from the observations. I have already mentioned two of them, the existence of the main sequence of star-forming galaxies and mass and environment quenching as two *separable* processes. The third is the evolution of the mass function of star forming galaxies, which is well reproduced by a Schechter function with constant faint-end slope α and characteristic mass M_* [308].

Thus, a sort of phase transition has taken place, and this is where we stand today: theoretical modeling of galaxy evolution has lost its early predictive power and now struggles to adjust to the data. For this reason I think that, at least in the short term, a fully phenomenological approach is more rewarding.

Based on these three simplicities a fully phenomenological model has been developed that provides a comprehensive *description* of the evolution of galaxies from high redshift to the present [308]. This includes the mass growth of galaxies and the quenching of their star formation, as a function of time, stellar mass and environment. By applying simple growth and quenching rules the result is a perfect match with the mass functions of the star-forming and quenched galaxies in the local Universe. This phenomenological models has provided to me, and I hope to many others, my currently *best understanding* of galaxy evolution, though it is still a very incomplete one.

So, what do you believe are the next most pressing questions? and how much it may take before we get the answers?

The phenomenological model does not contain much physics at all. But certainly we will not be satisfied until we understand the physics. So, to me these are the most pressing questions: what are the physical mechanisms responsible for mass and environment quenching? Can they be *unified* into a single underlying mechanism? What fraction of the stellar mass of local, massive galaxies formed *in situ* and how much was accreted? How did galactic bulges form? Was the growth of bulges synchronous with the growth of their central black holes, or did they preced/follow the others? How did the metal production in galaxies proceed and how metals have circulated out of them into the intergalactic space? But I should stop here, as the list may easily diverge. For the rest, I'm optimistic. If we look back we can appreciate the enormous progress that has been made in this field in the last ten years . So, I am confident that at least the questions above will be answered within the next decade, if not before.

8.10 To Summarize

The spectrum of theoretical efforts realized up to now to explain the complex nature of galaxies is so wide that in this Chapter we have only rapidly discussed the most accredited ideas about galaxy formation and evolution, together with the main concepts that have been developed to model such evolution. Our interviews were designed to point out the qualities and failures of each model as well as the comparison with the observational data. The key point behind the whole discussion is the gradual passage from the idea of galaxies as Island Universes to that of cells of the cosmic web. Today it is no more possible to simulate the formation and evolution of galaxies without setting the right cosmological context, the right environment, and the correct energy feedback. The consequence of this increased complexity is that we cannot follow the entire process without posing a number of constraints in terms of fixed parameters and adopted scaling laws. The most important difficulties are to follow the dissipative behavior of baryons inside the DM halos, the details of the star formation process, the coupling between dark and baryonic matter in terms of angular momentum, the feedback of stars and nuclei, the yields from stars ejected in the ISM, and the frequency of merging and gravitational interactions.

The modeling of galaxies now starts with the development of the dark matter halos and proceed through the dark and subsequent re-ionization era of the Universe and the collapse of the baryons in the DM halos. In this context looking at the high redshift galaxies has certainly improved our knowledge of several phenomena, but at the same time has provided new inputs in terms of complexity. We realized that the physical processes at work in shaping the actual form of galaxies are so many that is almost impossible to identify the early progenitors of today objects.

Galaxies live in a complex and evolving society within which they form and evolve. We have only started to understand the large messy of phenomena involved in this process.

As for the other Chapters, the following items are intended to summarize the key points of each interview.

- *Numerical simulations are now able to reproduce the main features of the Hubble sequence. The key parameters are set by the initial conditions of the proto-galaxy in terms of angular momentum and random motions. Another important thing is the presence or absence of substructures during the collapse: these grow when the initial conditions are "cold" and are suppressed when the proto-galaxies are "warm". The cosmological context is still one of the problems of such simulations for what concern the power spectrum of the various galaxies, but it is also not yet clear the effective role of DM, in particular in exchanging angular momentum with the baryonic component.*
- *In the hierarchical scheme of galaxy formation today largely accepted, small and low mass objects come first, whereas large and massive objects come later in a hierarchy of structures of increasing size, mass and complexity as time goes by. The most used technique in numerical simulations is to reconstruct the mass assembly history of the DM component and later on add the dissipative BM that collapse into each halo with suitable prescriptions for gas cooling and heating, star formation and chemical enrichment, as well as energy feedback by SNe and AGN. The first failures of this scheme came when it was recognized that the CDM does not reproduce correctly the structures observed on small scales. Further problems are the interpretation of the rapid decrease of the cosmic start formation rate (SFR), the number of dwarf galaxies, and the observed downsizing that is anti-hierarchical. Alternative approaches to the pure hierarchical framework have been developed, such as the Revised Monolithic and the Early Hierarchical-Quasi Monolithic scenarios. In these model the keyword is to follow the evolution of the BM within each halo provided by a given cosmological context, adding all the recipes for the gas cooling, feedback, and so on. In this framework the action of merging is less important, at least for the more massive ellipticals that are formed very early in single collapse events.*
- *Semi-analytic models of galaxy formation are able to follow the variation in mass as a function of time of the various galaxies components (stars, gas, metals) with few equations and some free parameters. Today semi-analytic techniques are coupled with large-resolution N-body simulations that are used to specify the location and evolution of dark matter halos. Using mock catalogs generated by these models straightforward comparisons with observational data can be obtained. The method suffers the big number of free parameters used and the parametrization of the physical processes. The encountered difficulties are: 1) the number densities of low-to-intermediate mass galaxies that are systematically larger than observational estimates; 2) low-to-intermediate mass galaxies tend to be too passive with respect to observational measurements; 3) massive galaxies have predicted metallicities that are too low with respect to observational measurements. The solution of these problems probably lies in a physical process that is able to break the parallelism between mass growth and halo growth, particularly for galaxies of low-to-intermediate mass. An important thing to keep in mind in this context is that there is an important difference between 'formation' time of the stars in the galaxy and its 'assembly' time.*

- *The big redshift campaigns have today definitively established the cosmic web nature of the Universe. Dominant elements of the web are chains/filaments of galaxies and clusters. The space between filaments is almost devoid of galaxies – the cosmic voids, while super-clusters are high-density regions of this network. The nature of the connection between the cosmic web and the DM is still highly debated, and can be considered as the nucleus of the problem of astro-particle physicists. There is clearly a link between the large scale of the Universe we see today and the small scale phenomena that originated the density perturbations at the beginning of the Universe. The lack of detections of the WIMPs particles up to now poses several questions on this side. There are several arguments which lead to think that the skeleton of the present structure of the Universe should be connected with the epoch of inflation.*
- *The Initial Mass Function (IMF) is one of the most important ingredients of any theory of galaxy formation and evolution. Conceptually the IMF is the distribution of stellar masses formed together in one star-formation event, while the IMF of a whole galaxy is a different issue, as it is deduced from a field population that can have many different ages and metallicities. The study of the IMF is biased by several difficulties: it requires an intimate knowledge of the pre and post main sequence stellar evolution, of the stellar birth-rate function, of the structures in which stars typically form and their dynamical evolution including gas expulsion processes, of the properties and evolution of binary systems, etc. Furthermore, corrections for various biases and uncertainties must be taken correctly into account. The single star-formation event described by the IMF occurs in a molecular cloud core typically on a sub-pc-scale and on a Myr time-scale. The IMF is a theoretical concept, there isn't an instant of time in which the full IMF can be determined: as new binary stars form, others are ejected or broken up into their binary companions, and at any instant of time low-mass stars have not yet reached the main sequence while massive ones have already left it and/or have been ejected from their rich embedded clusters. Direct star-formation simulations are now used to approach the time-variation of the observable MF of stars and binary systems. Despite these difficulties up to now the hypothesis that in the MW there is one invariant IMF cannot be rejected, given all the uncertainties and biases. The concept of an invariant, universally valid parent IMF stands however in contradiction to all predictions star-formation theories, according to which the IMF ought to become top-heavy with decreasing metallicity and increasing gas density and temperature. For galaxies the determination of the IMF is much more complex since only the integrated properties of the stellar population are available. In general, a galaxy with a top-heavy IMF will appear blue, while a galaxy with a top-light IMF will appear red, but degeneracies can occur. The IMF of galaxies should be normalized because the low-mass and the high-mass stars have systematically different time evolution and spatial distribution. The determination of the IMF for galaxies is hampered by many sources of errors and we do not have yet a theoretical approach for this difficult problem. In this context the assumption that the IMF measured for the resolved stellar population in the MW and that of external galaxies are equal is based on statistical*

arguments. Recent theoretical works seem to indicate that neither the IMF of the MW that those of galaxies are scale-invariant probability density distribution functions. There are also observational evidence which indicates a systematic change of the IMF of galaxies from top-light at very low star formation rates (SFRs) to top-heavy at high SFRs. The current idea is that the IMF of a galaxy can be obtained by summing together all the IMFs contributed by each star formation event over all star-formation events up to the most massive one sustained in the galaxy, given its SFR. There are also now strong evidence suggesting that the IMF in individual star formation events, i.e. in embedded clusters, becomes top-heavy with increasing density and decreasing metallicity. The IMF is related to the dark matter problem because a top-heavy IMF yields dark stellar remnants which behave dynamically like cold dark matter. Therefore by analyzing the dynamical M/L *ratio assuming a universal invariant IMF one would wrongly conclude that massive galaxy contains dark matter.*

- *The SFR of galaxies is the mass of gas turned into stars per unit time. The absolute SFR spans a wide range of values, from virtually zero in present-day gas-poor elliptical, S0, and dwarf galaxies up to* $1000 M_\odot yr^{-1}$ *in the most luminous IR star-burst galaxies. For this reason it is often normalized to the galaxy mass and we speak of specif SFR. In any case the spread at each galaxy mass is quite large (nearly a factor of 10). A robust correlation is observed between the SFR and the galaxy type. The galaxy emissions in the UV,* $H\alpha$*, Mid-IR, Far-IR, radio and X-ray are often used to infer the SFR. Each method needs a proper calibration and has its own advantages and disadvantages. In the modern interpretation of the color-magnitude diagram the blue galaxies are the star-forming ones, while the red galaxies have barely detectable SFRs, i.e. are quenched objects. Galaxies can also populate the green valley, the region between red and dead objects and those still star forming. Several phenomena might produce a crossing of the green valley in both directions. Observations suggest that the fraction of quenched galaxies is an increasing function of stellar mass (independently of environment) and of the local overdensity (independently of stellar mass). There is not however a clear theoretical understand of the physical processes causing the mass quenching and the environment quenching. The same happens for the quenching time scale since we dot know yet whether the end of star formation is caused by a feedback mechanisms or by a stop in the gas fueling from the cosmic filaments.*
- *The AGN feedback problem has seen in these years a true revolution. Antithetic positions have been expressed on this question, ranging from the null effect of the feedback to a very significant role for galaxy evolution. In between the main effects of AGN feedback are believed to be relevant not for the whole galaxy, hosting at their centers the Supermassive Black Holes, but for the local environment surrounding the galactic centers, a* $\simeq$ *kpc-size region around the SMBH. The AGN feedback is connected with the so-called cooling flow problem in massive E galaxies. The feedback appears necessary not for an energetic balance but for the simple reason that SMBH masses are approximately two orders of magnitude smaller than the gas made available by stellar evolution in isolated ETGs.*

For a typical mass accretion rate the emitted AGN luminosity is sufficiently high to account for the stop of the cooling flow. The time interval from the beginning of central accretion, to its shutdown due to AGN feedback, is found to be of the order of 10^7 *yrs, in nice accordance with observational estimates of the "on" phase of quasars. This problem is currently highly debated because many questions are still open.*

- *Supernovae influence galaxy evolution through chemical enrichment and energy feedback, namely the energy that they can transfer into the ISM. Unfortunately the exact amount of energy transferred to the ISM is still poorly known. The interstellar gas can then reach the escape velocity and escape from the potential well of the galaxy (in particular in dwarf objects) and in this case we have a galactic wind. The evidence of this is given by the metals found in the ICM and IGM. These metals have also been observed in dwarf irregular galaxies.*
- *Stars transform light elements into heavier ones in their interiors and when they die the new elements are restored into the ISM. The following stellar generation will then form out of enriched gas and the process will go on until all the gas is consumed or lost via winds. The detailed balance of the various elements produced is still not well known, in particular because we have a limited knowledge of the stellar ejecta. Chemo-dynamical models are now used to reconstruct the whole history of star formation and chemical enrichment. These take into account the rate of stellar ejecta coming from SN explosion and mass loss, but also the stellar migration. The chemical abundances can only suggest the timescales on which the various Galactic components have formed, but they cannot tell us the details of how they formed. A lot of work is still necessary to answer many open questions.*
- *The debate between the monolithic scenario of galaxy formation and the idea that galaxies form by the progressive accretion of small clumps has been very large up to now. Contrasting positions have been expressed in particular on the metallicity content of the halo stars. These data suggest that the Galactic stellar halo cannot result from the disruption of satellite galaxies similar to those observed in the Local Group. However, the surviving satellites might be intrinsically different from those that contributed stars to the stellar halo.*
- *The "missing satellite problem", i.e. the finding that substructures resolved in galaxy-size DM halos significantly outnumber the satellites observed around the Milky Way, is another element of crisis for the current cosmological model. However, semi-analytic models have shown that the presence of a strong photoionizing background, possibly associated with the reionization of the Universe, can suppress accretion and cooling in low-mass halos thereby suppressing the formation of small galaxies.*
- *N-body simulations have reproduced the slope of the TF relation, but had difficulties in matching its zero-point. This failure is attributed to a net and significant transfer of angular momentum from the baryons to the dark matter, with the result that simulated disks are generally too compact and with up to ten times less angular momentum than real disk galaxies. In a similar way difficulties are encountered in modeling other scaling relations, such as the FP, that will be the*

results of the dissipative processes occurred in the gas during the galaxy formation.

- *Magnetic field were certainly present since the first epochs of galaxy formation, but several arguments lead to say that the large-scale field observed today in galaxies cannot be directly inherited from pre-galactic fields. The most diffuse opinion is that a dynamo action produce the fields we see in galaxies. A dynamo is a mechanism by which an infinitesimally small "seed" magnetic field can be amplified to finite magnitude, and maintained indefinitely against decay. The turbolent status of the gas in the ISM of a galaxy disk, due to the SN explosions, is the key ingredient of the dynamo theory. The differential rotation of the disk contribute to the formation of the large scale fields. The magnetic field modeling has reached a good level, but several problems are still open, in particular for explaining the fields on small scales.*

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