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Invited Review Talk in Plenary Session

PARTICLE PHYSICS AND COSMOLOGY

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ABSTRACT

In this talk I will review the present status of inflationary cosmology and its emergence as the basic paradigm behind the Standard Cosmological Model, with parameters determined today at better than 10% level from CMB and LSS observations.

1 Introduction

In this short review I will outline the reasons why the inflationary paradigm ^{1, 2)} has become the backbone of the present Standard Cosmological Model. It gives a framework in which to pose all the basic cosmological questions: what is the shape and size of the universe, what is the matter and energy content of the universe, where did all this matter come from, what is the fate of the universe, etc. I will describe the basic predictions that inflation makes, most of which

have been confirmed only recently, while some are imminent, and then explore the recent theoretical developments on the theory of reheating after inflation and cosmological particle production, which might allow us to answer some of the above questions in the future.

Although the simplest slow-roll inflation model is consistent with the host of high precision cosmological observations of the last few years, we still do not know what the true nature of the inflaton is: although there are many possible realizations, there is no unique particle physics model of inflation. Furthermore, we even ignore the energy scale at which this extraordinary phenomenon occurred in the early universe; it could be associated with a GUT theory or even with the EW theory, at much lower energies.

2 Basic Predictions

Inflation is an extremely simple idea based on the early universe dominance of a vacuum energy density associated with a hypothetical scalar field called the inflaton. Its nature is not known: whether it is a fundamental scalar field or a composite one, or something else altogether. However, one can always use an effective description in terms of a scalar field with an effective potential driving the quasi-exponential expansion of the universe. This basic scenario gives several detailed fundamental predictions: a flat universe with nearly scale-invariant adiabatic density perturbations with Gaussian initial conditions.

2.1 A flat and homogeneous background

Inflation explains why our local patch of the universe is spatially flat, i.e. Euclidean. Inflation does, provides an approximately constant energy density that induces a tremendous expansion of the universe. Thus, an initially curved three-space will quickly become locally indistinguishable from a “flat” hypersurface. Moreover, this same mechanism explains why we see no ripples, i.e. no large inhomogeneities, in the space-time fabric, e.g. as large anisotropies in the temperature field of the cosmic microwave background when we look in different directions. The expansion during inflation erases any prior inhomogeneities. These two are very robust predictions of inflation, and have been confirmed to high precision by the detailed observations of the CMB, first by COBE (1992) for the large scale homogeneity, to one part in 10^5 , and recently

by BOOMERanG ³⁾ and MAXIMA ⁴⁾, for the spatial flatness, to better than 10%.

2.2 Cosmological perturbations

Inflation also predicts that on top of this homogeneous and flat space-time background, there should be a whole spectrum of cosmological perturbations, both scalar (density perturbations) and tensor (gravitational waves). These arise as quantum fluctuations of the metric and the scalar field during inflation, and are responsible for a scale invariant spectrum of temperature and polarization fluctuations in the CMB, as well as for a stochastic background of gravitational waves. The temperature fluctuations were first discovered by COBE and later confirmed by a host of ground and balloon-borne experiments, while the polarization anisotropies have only recently been discovered by the CMB experiment DASI ⁵⁾. Both observations seem to agree with a nearly scale invariant spectrum of perturbations. It is expected that the stochastic background of gravitational waves produced during inflation could be detected with the next generation of gravitational waves interferometers (e.g. LISA), or indirectly by measuring the power spectra of polarization anisotropies in the CMB by the future Planck satellite ⁶⁾.

Inflation makes very specific predictions as to the nature of the scalar perturbations. In the case of a single field evolving during inflation, the perturbations are predicted to be adiabatic, i.e. all components of the matter and radiation fluid should have equal density contrasts, due to their common origin. As the plasma (mainly baryons) falls in the potential wells of the metric fluctuations, it starts a series of acoustic compressions and rarefactions due to the opposing forces of gravitational collapse and radiation pressure. Adiabatic fluctuations give a very concrete prediction for the position and height of the acoustic peaks induced in the angular power spectrum of temperature and polarization anisotropies. This has been confirmed to better than 1% by the recent observations, and constitutes one of the most important signatures in favor of inflation, ruling out a hypothetically large contribution from active perturbations like those produced by cosmic strings or other topological defects.

Furthermore, the quantum origin of metric fluctuations generated during inflation allows one to make a strong prediction on the statistics of those per-

turbations: inflation stretches the vacuum state fluctuations to cosmological scales, and gives rise to a Gaussian random field, and thus metric fluctuations are in principle characterized solely by their two-point correlation function. Deviations from Gaussianity would indicate a different origin of fluctuations, e.g. from cosmic defects. Recent observations by BOOMERanG in the CMB and by gravitational lensing of LSS indicate that the non-Gaussian component of the temperature fluctuations and the matter distribution on large scales is strongly constrained, and consistent with foregrounds (in the case of CMB) and with non-linear gravitational collapse (in the case of LSS).

Of course, in order to really confirm the idea of inflation one needs to find cosmological observables that will allow us to correlate the scalar and the tensor metric fluctuations with one another, since they both arise from the same inflaton field fluctuations. This is a daunting task, given that we ignore the absolute scale of inflation, and thus the amplitude of tensor fluctuations (only sensitive to the total energy density). The smoking gun could be the observation of a stochastic background of gravitational waves by the future gravitational wave interferometers and the subsequent confirmation by detection of the curl component of the polarization anisotropies of the CMB. Although the gradient component has recently been detected by DASI, we may have to wait for Planck for the detection of the curl component.

3 Recent Cosmological Observations

Cosmology has become in the last few years a phenomenological science, where the basic theory (based on the hot Big Bang model after inflation) is being confronted with a host of cosmological observations, from the microwave background to the large scale distribution of matter, from the determination of light element abundances to the detection of distant supernovae that reflect the acceleration of the universe, etc. I will briefly review here the recent observations that have been used to define a consistent cosmological standard model.

3.1 Cosmic Microwave Background

The most important cosmological phenomenon from which one can extract essentially all cosmological parameters is the microwave background and, in particular, the last scattering surface temperature and polarization anisotropies.

Since they were discovered by COBE in 1992, the temperature anisotropies have lived to their promise. They allow us to determine a whole set of both background (0-th order) and perturbation (1st-order) parameters – the geometry, topology and evolution of space-time, its matter and energy content, as well as the amplitude and tilt of the scalar and tensor fluctuation power spectra – in some cases to better than 10% accuracy.

At present, the forerunners of CMB experiments are BOOMERanG and MAXIMA (balloons), and DASI, VSA and CBI (ground based interferometers). Together they have allowed cosmologists to determine the angular power spectrum of temperature fluctuations down to multipoles 1000 and 3000, respectively, and therefore provided a measurement of the positions and heights of at least 3 to 7 acoustic peaks. A combined analysis of the different CMB experiments yields convincing evidence that the universe is flat, with $|\Omega_K| = |1 - \Omega_{\text{tot}}| < 0.05$ at 95% c.l.; full of dark energy, $\Omega_\Lambda = 0.66 \pm 0.06$, and dark matter, $\Omega_m = 0.33 \pm 0.07$, with about 5% of baryons, $\Omega_b = 0.05 \pm 0.01$; and expanding at a rate $H_0 = 68 \pm 7$ km/s/Mpc, all values given with 1σ errors, see Table 1. The spectrum of primordial perturbations that gave rise to the observed CMB anisotropies is nearly scale-invariant, $n_s = 1.02 \pm 0.06$, adiabatic and Gaussian distributed. This set of parameters already constitutes the basis for a truly Standard Model of Cosmology, based on the Big Bang theory and the inflationary paradigm. Note that both the baryon content and the rate of expansion determinations with CMB data alone are in excellent agreement with direct determinations from BBN light element abundances ¹³⁾ and HST Cepheids ¹⁴⁾, respectively.

In the near future, a new satellite experiment, the Microwave Anisotropy Probe (MAP) ¹⁵⁾, will provide a full-sky map of temperature (and possibly also polarization) anisotropies and determine the first 2000 multipoles with unprecedented accuracy. When combined with LSS and SN measurements, it promises to allow the determination of most cosmological parameters with errors down to the few% level.

Moreover, with the recent detection of microwave background polarization anisotropies by DASI ⁵⁾, confirming the basic paradigm behind the Cosmological Standard Model, a new window opens which will allow yet a better determination of cosmological parameters, thanks to the very sensitive ($0.1\mu\text{K}$) and high resolution (4 arcmin) future satellite experiment Planck ⁶⁾. In prin-

Table 1: *Estimates of the cosmological parameters that characterize a minimal adiabatic inflation-based model. From Ref. 12).*

Priors	CMB	CMB+LSS	CMB+LSS+SN	CMB+LSS+SN+HST
Ω_{tot}	$1.05^{+0.05}_{-0.05}$	$1.03^{+0.03}_{-0.04}$	$1.00^{+0.03}_{-0.02}$	$1.00^{+0.02}_{-0.02}$
n_s	$1.02^{+0.06}_{-0.07}$	$1.00^{+0.06}_{-0.06}$	$1.03^{+0.06}_{-0.06}$	$1.04^{+0.05}_{-0.06}$
$\Omega_b h^2$	$0.023^{+0.003}_{-0.003}$	$0.023^{+0.003}_{-0.003}$	$0.024^{+0.003}_{-0.003}$	$0.024^{+0.002}_{-0.003}$
$\Omega_{\text{cdm}} h^2$	$0.13^{+0.03}_{-0.02}$	$0.12^{+0.02}_{-0.02}$	$0.12^{+0.02}_{-0.02}$	$0.12^{+0.01}_{-0.01}$
Ω_Λ	$0.54^{+0.12}_{-0.13}$	$0.61^{+0.09}_{-0.10}$	$0.69^{+0.04}_{-0.06}$	$0.70^{+0.02}_{-0.03}$
Ω_m	$0.52^{+0.15}_{-0.15}$	$0.42^{+0.12}_{-0.12}$	$0.32^{+0.06}_{-0.06}$	$0.30^{+0.02}_{-0.02}$
Ω_b	$0.080^{+0.023}_{-0.023}$	$0.067^{+0.018}_{-0.018}$	$0.052^{+0.011}_{-0.011}$	$0.049^{+0.004}_{-0.004}$
h	$0.55^{+0.09}_{-0.09}$	$0.60^{+0.09}_{-0.09}$	$0.68^{+0.06}_{-0.06}$	$0.69^{+0.02}_{-0.02}$
Age	$15.0^{+1.1}_{-1.1}$	$14.7^{+1.2}_{-1.2}$	$13.8^{+0.9}_{-0.9}$	$13.6^{+0.2}_{-0.2}$
τ_c	$0.16^{+0.18}_{-0.13}$	$0.09^{+0.12}_{-0.07}$	$0.13^{+0.14}_{-0.10}$	$0.13^{+0.13}_{-0.10}$

The age of the Universe is in Gyr, and the rate of expansion in units of 100 km/s/Mpc. All values quoted with 1σ errors.

inciple, Planck should be able to detect not only the gradient component of the CMB polarization, but also the curl component, if the scale of inflation is high enough. In that case, there might be a chance to really test inflation through cross-checks between the scalar and tensor spectra of fluctuations, which are predicted to arise from the same inflaton potential.

The observed positions of the acoustic peaks of the CMB anisotropies strongly favor purely adiabatic density perturbations, as arise in the simplest single-scalar-field models of inflation. These models also predict a nearly Gaussian spectrum of primordial perturbations. A small degree of non-gaussianity may arise from self-coupling of the inflaton field (although it is expected to be very tiny, given the observed small amplitude of fluctuations), or from two-field models of inflation. Since the CMB temperature fluctuations probe directly primordial density perturbations, non-gaussianity in the density field should lead to a corresponding non-gaussianity in the temperature maps. However, recent searches for non-Gaussian signatures in the CMB have only given stringent upper limits, see Ref. 17).

One of the most interesting aspects of the present progress in cosmolog-

ical observations is that they are beginning to probe the same parameters or the same features at different time scales in the evolution of the universe. We have already mentioned the determination of the baryon content, from BBN (light element abundances) and from the CMB (acoustic peaks), corresponding to totally different physics and yet giving essentially the same value within errors. Another example is the high resolution images of the CMB anisotropies by CBI¹²⁾, which constitute the first direct detection of the seeds of clusters of galaxies, the largest gravitationally bound systems in our present universe. In the near future we will be able to identify and put into one-to-one correspondence tiny lumps in the CMB with actual clusters today.

3.2 Large Scale Structure

The last decade has seen a tremendous progress in the determination of the distribution of matter up to very large scales. The present forerunners are the 2dF Galaxy Redshift Survey¹⁸⁾ and the Sloan Digital Sky Survey (SDSS)¹⁹⁾. These deep surveys aim at 10^6 galaxies and reach redshifts of order 1 for galaxies and order 5 for quasars. They cover a wide fraction of the sky and therefore can be used as excellent statistical probes of large scale structure^{16, 20)}.

The main output of these galaxy surveys is the two-point (and higher) spatial correlation functions of the matter distribution or, equivalently, the power spectrum in momentum space. Given a concrete type of matter, e.g. adiabatic vs. isocurvature, cold vs. hot, etc., the theory of linear (and non-linear) gravitational collapse gives a very definite prediction for the measured power spectrum, which can then be compared with observations. This quantity is very sensitive to various cosmological parameters, mainly the dark matter content and the baryonic ratio to dark matter, as well as the universal rate of expansion; on the other hand, it is mostly insensitive to the cosmological constant since the latter has only recently (after redshift $z \sim 1$) started to become important for the evolution of the universe, while galaxies and clusters had already formed by then. Together, 2dFGRS, plus CMB, weak gravitational lensing and Lyman- α forest data, allow us to determine the power spectrum with better than 10% accuracy for $k > 0.02 h \text{ Mpc}^{-1}$, which is well fitted by a flat CDM model with $\Omega_m h = 0.20 \pm 0.03$, and a baryon fraction of $\Omega_b/\Omega_m = 0.15 \pm 0.06$, which together with the HST results give values of the parameters that are compatible with those obtained with the CMB, see

Table 1. It is very reassuring to note that present parameter determination is robust as we progress from weak priors to the full cosmological information available, a situation very different from just a decade ago, where the errors were mostly systematic and parameters could only be determined with an order-of-magnitude error. In the very near future such errors will drop again to the 1% level, making Cosmology a mature science, with many independent observations confirming and further constraining previous measurements of the basic parameters.

An example of such progress appears in the analysis of non-Gaussian signatures in the primordial spectrum of density perturbations. The tremendous increase in data due to 2dFGRS and SDSS has allowed cosmologists to probe the statistics of the matter distribution on very large scales and infer from it that of the primordial spectrum. Recently, both groups have reported non-Gaussian signatures (in particular the first two higher moments, skewness and kurtosis), that are consistent with gravitational collapse of structure that was originally Gaussianly distributed ^{21, 22}). Moreover, weak gravitational lensing also allows an independent determination of the three-point shear correlation function, and there has recently been a claim of detection of non-Gaussian signatures in the VIRMOS-DESCART lensing survey ²³), which is also consistent with theoretical expectations of gravitational collapse of Gaussianly distributed initial perturbations.

The recent precise catalogs of the large scale distribution of matter allows us to determine not only the (collapsing) cold dark matter content, but also put constraints on the (diffusing) hot dark matter, since it would erase all structure below a scale that depends on the free streaming length of the hot dark matter particle. In the case of relic neutrinos we have extra information because we know precisely their present energy density, given that neutrinos decoupled when the universe had a temperature around 0.8 MeV and cooled down ever since. Their number density today is around 100 neutrinos/cm³. If neutrinos have a significant mass (above 10⁻³ eV, as observations of neutrino oscillations by SuperKamiokande ²⁴) and Sudbury Neutrino Observatory ²⁵) seem to indicate), then the relic background of neutrinos is non-relativistic today and could contribute a large fraction of the critical density, $\Omega_\nu = m_\nu/92 h^2 \text{ eV} \geq 0.001$, see Ref. ²⁶). Using observations of the Lyman- α forest in absorption spectra of quasars, due to a distribution of intervening clouds, a limit on the

absolute mass of all species of neutrinos can be obtained ²⁷⁾. Recently, the 2dFGRS team ²⁸⁾ have derived a bound on the allowed amount of hot dark matter, $\Omega_\nu < 0.13$ $\Omega_m < 0.05$ (95% c.l.), which translates into an upper limit on the total neutrino mass, $m_{\nu, \text{tot}} < 1.8$ eV, for values of Ω_m and the Hubble constant in agreement with CMB and SN observations. This bound improves several orders of magnitude on the direct experimental limit on the muon and tau neutrino masses, and is comparable to present experimental bounds on the electron neutrino mass ²⁹⁾.

3.3 Cosmological constant and rate of expansion

Observations of high redshift supernovae by two independent groups, the Supernova Cosmology Project ³⁰⁾, and the High Redshift Supernova Team ³¹⁾, give strong evidence that the universe is accelerating, instead of decelerating, today. Although a cosmological constant is the natural suspect for such a “crime”, its tiny non-zero value makes theoretical physicists uneasy ³²⁾. A compromise could be found by setting the fundamental cosmological constant to zero, by some yet unknown principle possibly related with quantum gravity, and allow a super-weakly-coupled homogeneous scalar field to evolve down an almost flat potential. Such a field would induce an effective cosmological constant that could in principle account for the present observations. The way to distinguish it from a true cosmological constant would be through its equation of state, since such a type of smooth background is a perfect fluid but does not satisfy $p = -\rho$ exactly, and thus $w = p/\rho$ also changes with time. There is a proposal for a satellite called the Supernova / Acceleration Probe (SNAP) ³³⁾ that will be able to measure the light curves of type Ia supernovae up to redshift $z \sim 2$, thus determining both Ω_X and w_X with reasonable accuracy, where X stands for this hypothetical scalar field. For the moment there are only upper bounds, $w_X < -0.6$ (95% c.l.) ³⁴⁾, consistent with a true cosmological constant, but the SNAP project claims it could determine Ω_X and w_X with 5% precision.

Fortunately, the SN measurements of the acceleration of the universe give a linear combination of cosmological parameters that is almost orthogonal, in the plane $(\Omega_m, \Omega_\Lambda)$, to that of the curvature of the universe ($1 - \Omega_K = \Omega_m + \Omega_\Lambda$) by CMB measurements and the matter content by LSS data. Therefore, by combining the information from SNe with that of the CMB and LSS, one can significantly reduce the errors in both Ω_m and Ω_Λ , see Table 1. It also allows

an independent determination of the rate of expansion of the universe that is perfectly compatible with the HST data¹⁴). This is reflected on the fact that adding the latter as prior does not affect significantly the mean value of most cosmological parameters, only the error bars, and can be taken as an indication that we are indeed on the right track: the Standard Cosmological Model is essentially correct, we just have to improve the measurements and reduce the error bars.

4 Conclusions

Inflation is nowadays a robust paradigm with a host of cosmological observations confirming many of its basic predictions: large scale spatial flatness and homogeneity, as well as an approximately scale-invariant Gaussian spectrum of adiabatic density perturbations.

It is possible that in the near future the next generation of CMB satellites (MAP and Planck) may detect the tensor or gravitational wave component of the polarization power spectrum, raising the possibility of really testing inflation through the comparison of the scalar and tensor components, as well as determining the energy scale of inflation.

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