Gauging the inner mass power spectrum of early-type galaxies

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Summary

A brief history of the early universe

According to the hot Big Bang cosmology, 13.8 billion years ago, our very own universe started its journey of expansion, from a very high temperature ($\sim 10^{32}$ K) and very high density state ($\sim 10^{19}$ GeV). At this very early stage the average energy of the universe was so high that none of our everyday subatomic particles could manage to form and exist. Even the four fundamental forces of nature, namely gravitational, strong and weak nuclear force, and electromagnetic – all were unified in one combined force. As this just born universe started expanding and cooling, the fundamental forces started separating from each other, and subsequently it went through a very sudden and rapid expansion of the spacetime fabric, which is termed as *inflation*. All these happened within the first picosecond (10^{-12} second) of cosmic time.

After the cosmic inflation, universe was filled with a hot quark-gluon plasma, which subsequently led to the genesis of baryons (such as protons and neutrons, which are made of three quarks), and their anti-baryons. Due to an asymmetry between the matter and the antimatter – a result of the earlier phases of the cosmic evolution – far more number of baryons were formed, compared to anti-baryons. The phase between 10^{-6} second to 1 second after the big bang is called the *Hadron epoch*. Hadrons are particles formed by two or three quarks, bound together by the strong nuclear force (mentioned above). Although initially the matter and the anti-matter were in thermal equilibrium, as the temperature continued to go down, no new

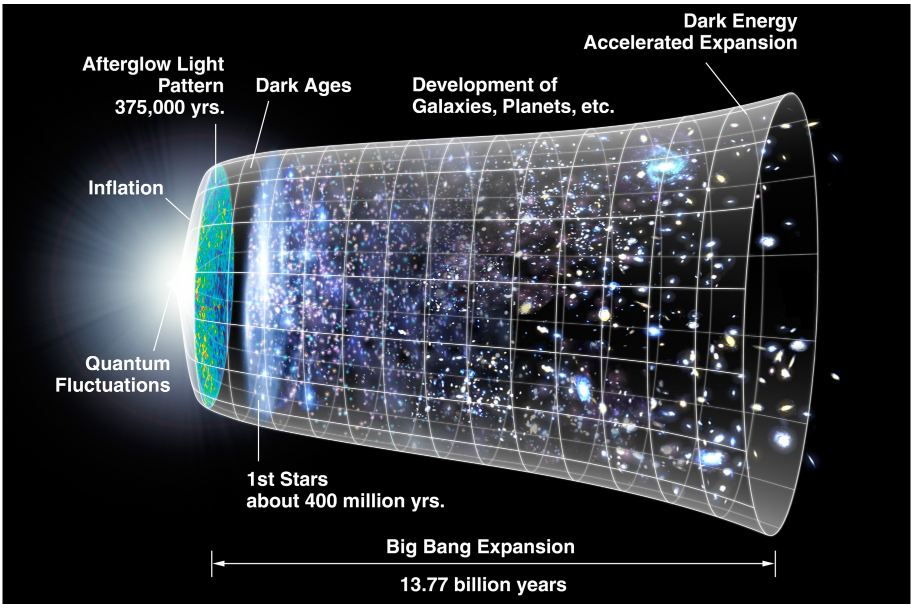

Figure 7.5: Timeline of the universe – a diagrammatic representation of the observable universe from the Big Bang (left) to the present. Courtesy: NASA/WMAP Science Team.

hadron and anti-hadron pairs were being created. Most of the pre-existed, just formed hadron pairs got annihilated, and this process produced pairs of high energy photons. Due to the slightly lower mass, the equilibrium was shifted in favour of the protons compared to the neutrons, and this epoch ended with a neutron to proton ratio of 1:7, and the lepton anti-lepton pairs; particles such as electrons, muons, neutrinos, and their anti-particles.

At an age of 1 second after the big bang, when the temperature of the baby universe fell down to 10^{10} K (1 MeV), neutrinos decoupled from the baryons and started their 'free travel through the space', creating the *Cosmic Neutrino Background* (CNB). The phase between 1 and 10 seconds after the Big Bang, is called the *Lepton epoch* and just like the hadron epoch, this phase left residues of non-annihilated leptons, and most of the mass-energy of the universe in the form of photons (radiation).

In the following phase starting from 10 seconds till 377,000 years after the Big Bang, these photons continue interacting with electrons, protons,

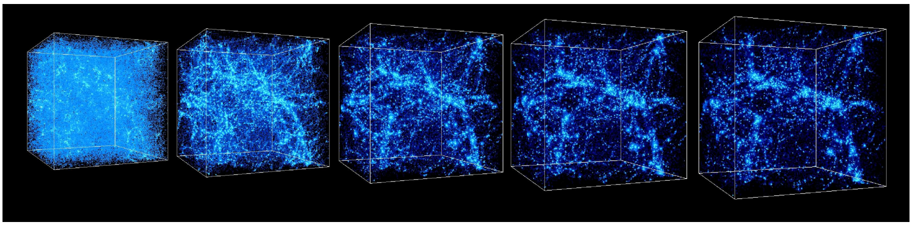

Figure 7.6: Formation and evolution of clusters and the filament structures of the universe in 43 Mpc box, from redshift, z=10 to the present epoch following Lambda-CDM cosmological model, simulated at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University).

and with the nuclei of deuterium, helium-4, and lithium-7 etc, which are formed during the age range of 2 to 20 minutes of the universe. This epoch of synthesising the nucleus of light elements is called as *Big bang Nucleosynthesis*. As the temperature kept on falling down, this phase was just right (10^9 K $\sim$ 10^7 K corresponding to 100 keV $\sim$ 1 keV) to create stable nuclei of hydrogen isotope deuterium. But as most deuterium fuses to helium-4 quickly, at the end of this phase, the resulting matter of the universe consisted of about 75% hydrogen nuclei and 25% helium nuclei.

Matter dominated era and the large scale structures

When the universe was about 47,000 years old (redshift, z=3600), it started becoming more matter dominated instead of radiation, because the matter energy density started exceeding both the vacuum energy and the radiation energy densities. Also at this stage, the densities of atomic nuclei (non-relativistic matter) and that of the photons (relativistic radiation) become equal. Consequently, through a competition of pressure and gravitational pulls, smallest structures of the cosmos started forming. These perturbations began to grow in their amplitudes, and following the Lambda-CDM cosmological model, at this epoch, universe was already dominated by 84.5% cold dark matter (CDM), and 15.5% baryonic matter.

Since this point of the cosmic evolution, dark matter started gathering hierarchically and eventually formed filamentary structures under the influence of gravitational force (see figure 7.6). The inhomogeneities or perturbations in the density of the universe — the imprints of the cosmic inflation — started getting amplified too. Slightly dense regions started getting denser and denser, and slightly emptier regions started to be be rarefied. Smaller dark matter structures started clustering and merging together, to form bigger, massive haloes. Subsequently in the later phase of the cosmic evolution, these dark matter filaments provide the gravitational potential wells, which eventually dictate and direct the ordinary matter (gas) to cool down, collapse faster (at around 150 million years of age), and furthermore to form stars and give rise to galaxies (from around 400 to 700 million years after the Big bang) as we see in our universe today.

Epoch of recombination, dark ages and reionization

Around 377,000 years after the Big Bang (z=1100), when the temperature of the universe was 4000 K (0.4 eV), free electrons and the nuclei started binding together to form first neutral atoms. This is called as *epoch of recombination.* During the pre-recombination phase, universe was opaque – photons (light) were tightly coupled and in thermal equilibrium with the ionised matter. At this point of time, photons for the first time get decoupled from the matter and the universe becomes transparent. These photons start free streaming through the transparent, weakly perturbed, homogeneous and isotropic cosmos, which is called as the *Cosmic Microwave Background* (CMB).

Soon after the photon decoupling and the recombination epoch, as the universe kept on expanding and cooling, CMB photons got redshifted to infrared within 3 million years, and as there were no stars or galaxies, during the phase starting from 377,000 years till the formation of the first stars at around 400 million years after the Big Bang, the universe was devoid of visible light. This is termed as *Dark Ages.* The only sources of photons during this age are the faint 21-cm spin line radio emissions from the neutral hydrogen atoms. During the dark ages, universe cooled down from 4000 K to about 60 K. Starting from around 150 million to 1 billion years after the Big Bang, gradually the first stars (also known as population-III stars), dwarf galaxies and quasars started forming. During this era, a second phase transition of the gas happened, when the strong radiation emitted from these earliest cosmic structures ionised the baryonic matter present in the universe, mostly in the form of hydrogen and helium. This phase is called the *epoch of reionization.*

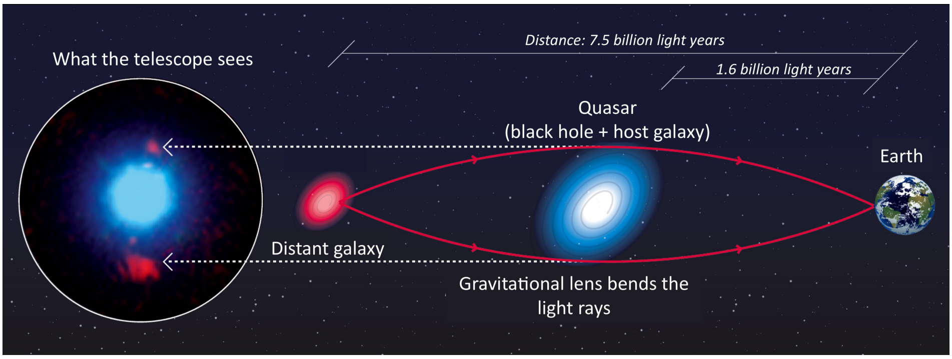

Figure 7.7: A geometrical representation of gravitational lensing. The image shows a schematic diagram of a background distant galaxy, sitting at 7.5 billion light years away, being gravitationally lensed by a foreground quasar at a distance of 1.6 billion light years from the earth. Image credit: F. Courbin, S. G. Djorgovski, G. Meylan, et al., Caltech/EPFL/WMKO

Galaxies, dark-matter, gravitational lensing

Starting from an age of 1 billion year till around 10 billion years after the Big Bang, gravitationally bound systems like galaxies – which are mostly made of stars, interstellar dust, gas and dark matter – continued forming. Due to the gravitational pull towards each other, galaxies gradually started forming groups, clusters and superclusters as well. Since the age of around 9.8 billion years, the universe started accelerating again, ending its matter dominated phase of decelerated expansion; which lasted since the end of the radiation dominated era of early universe. This new age is called the *dark energy dominated era* in cosmic evolution – as we experience the present appearance of the universe.

Dark energy is believed to constitute about 68.3% (while the dark matter constitutes 26.8%) of the entire mass-energy of the universe. As mentioned before, although dark matter alone constitutes 84.5% of the total mass of the universe, but it does not interact with electromagnetic radiation, such as light. So, we can not 'see' it. However, as it does interact gravitationally, one of the novel ways to detect dark matter is therefore via an astrophysical phenomenon called *'gravitational lensing'*.

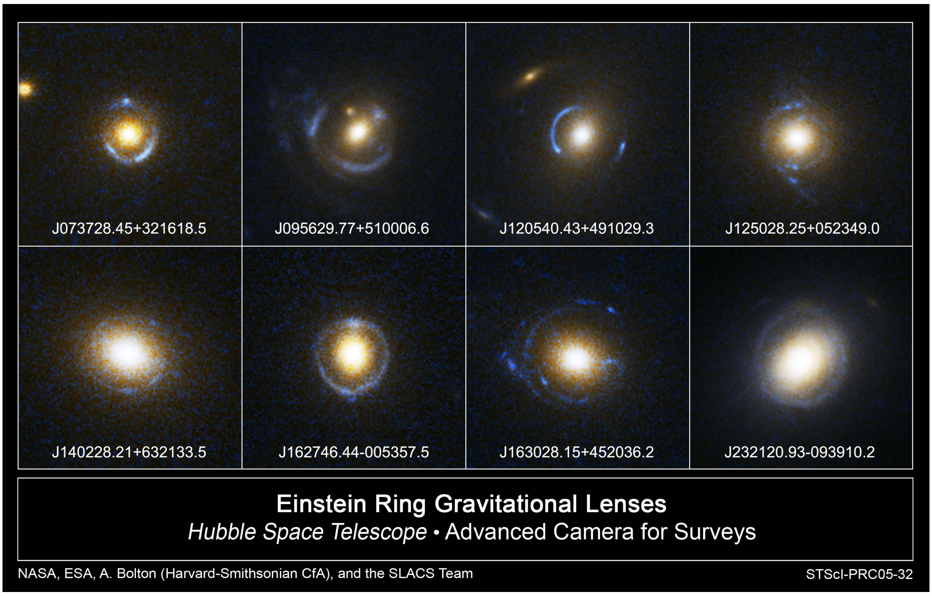

Figure 7.8: Einstein rings (thin blue bull's-eye patterns), observed between August 2004 and March 2005, via *Hubble Space Telescope*'s Advanced Camera for Surveys. The yellow blobs are massive foreground elliptical galaxies, situated roughly from 2 to 4 billion light-years away from us. Credits: NASA, ESA, and the SLACS survey team.

One of the most profound predictions of Einstein's general theory of relativity is that, light rays (or photons) get deflected due to the presence of the gravitating objects. Matter that is concentrated in galaxies or in clusters of galaxies, situated between an observer (like us on earth) and a distant source (like another galaxy in the background), can act similar to a 'lens', and is able to gravitationally deflect the trajectory of light that travels from the source to the observer (see figure 7.7). Depending on the relative position and distance between the source and the lens, and the way mass is distributed in the lensing galaxy, observer can see multiple images or arcs or rings of the source (see figure 7.8). Although the dark matter present in the galaxies can not be 'seen', but by measuring how much the lights coming from the distant background sources are being bent by these invisible stuff, one can indirectly detect the presence and the distribution of this dark matter.

This thesis

The research presented in this thesis attempts to quantify the distribution of the mass in the galaxies using gravitational lensing, especially the presence of this mysterious dark matter on small sub-galactic scales, as well as other contributions that play their role as 'gravitational lens', but which are difficult or almost impossible to detect otherwise. This thesis mostly focuses on the massive elliptical galaxies – containing older stars and with almost no gas – and which have evolved relatively more, compared to the spiral ones. Due to the various physical processes through which they have undergone, these galaxies have lost most of their interesting structures, e.g. spiral arms, bars etc, and became more 'boring' in shape and form. But within our current understanding, a complete picture of galaxy formation and evolution is still lacking. We know that the various feedback processes coming from the star formation, accretion of gas, supernovae etc play significant roles in shaping the mass distribution of these galaxies. But can these imprints be detectable and distinguishable from these massive elliptical galaxies? Or in other words, how can these physical processes shape the mass distribution in these galaxies?

To answer the above questions, one needs to develop robust statistical estimators so that the sub-galactic mass fluctuations can be detected, which in terms of the order-of-magnitude, can be relatively comparable to the noise present in the observed images. This research reports the development of novel statistical techniques to quantify the mass distributions (Chapter 3), and also computational frameworks for simulating artificial images of 'lensed' galaxies (Chapter 2). The underlying idea is to 'model' the surface-brightness of the lensed images of the background source, and therefore to infer the majority of the mass distribution present in the foreground lens galaxies. The 'residuals' which are left over after modelling, are analysed statistically to quantify the mass profile at small sub-galactic scales, which can be theorised to be originating from low mass dark matter subhaloes present in the foreground galaxy.

This theoretical research has also been connected and applied to real astronomical observations, coming from the *Hubble Space Telescope* (HST, Chapter 4) and the Kilo Degree Survey (KiDS, Chapter 2). Besides these, the simulations and the statistical framework developed in this Ph.D. thesis have also been applied to artificial intelligence to find gravitational lenses (Chapter 2), and to a quantitative analysis of the biases and the dependencies in gravitational lens modelling systematics (Chapter 5).

As described before, since the epoch of first stars and galaxies, the process of structure formation in universe has become very nonlinear in nature, which makes our lives harder to calculate these phenomena analytically. So, we take helps from computers and super-computers to simulate these various scenarios (see for example figure 7.2). One major benefit of using numerical simulations is that, one can fine-tune the parameters corresponding to the underlying sub-grid physics and various physical processes, and thus alternate scenarios of the universe can be generated. This thesis uses one such state-of-the-art cosmological simulation, named EAGLE, and attempts to find the imprints of the hitherto physical processes in the mass distribution of the simulated galaxies, at sub-galactic scales (Chapter 6) using the statistical framework developed throughout the thesis.