Kavli Institute for Cosmology, Cambridge

Cosmology@KICC – Talks

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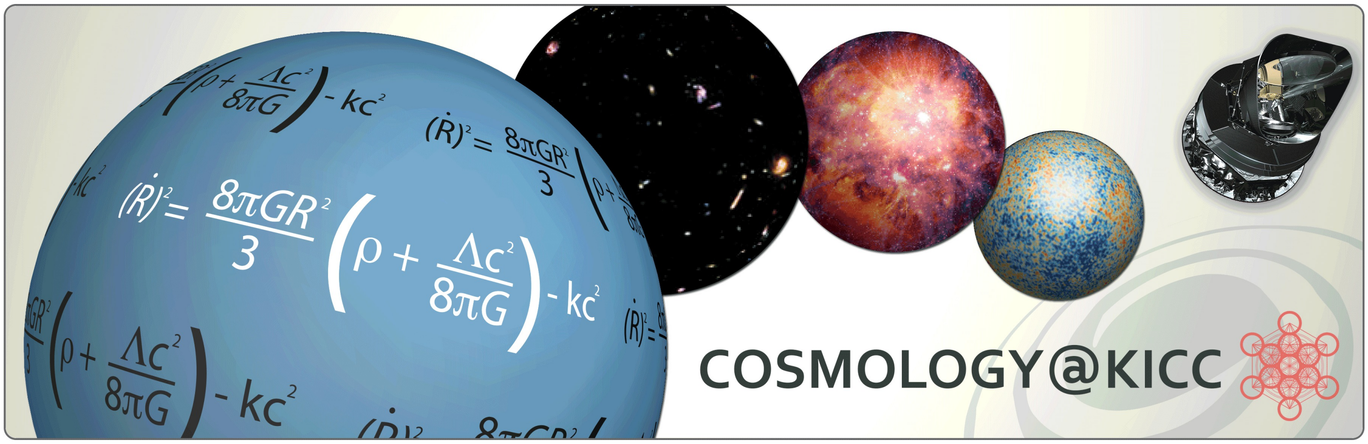
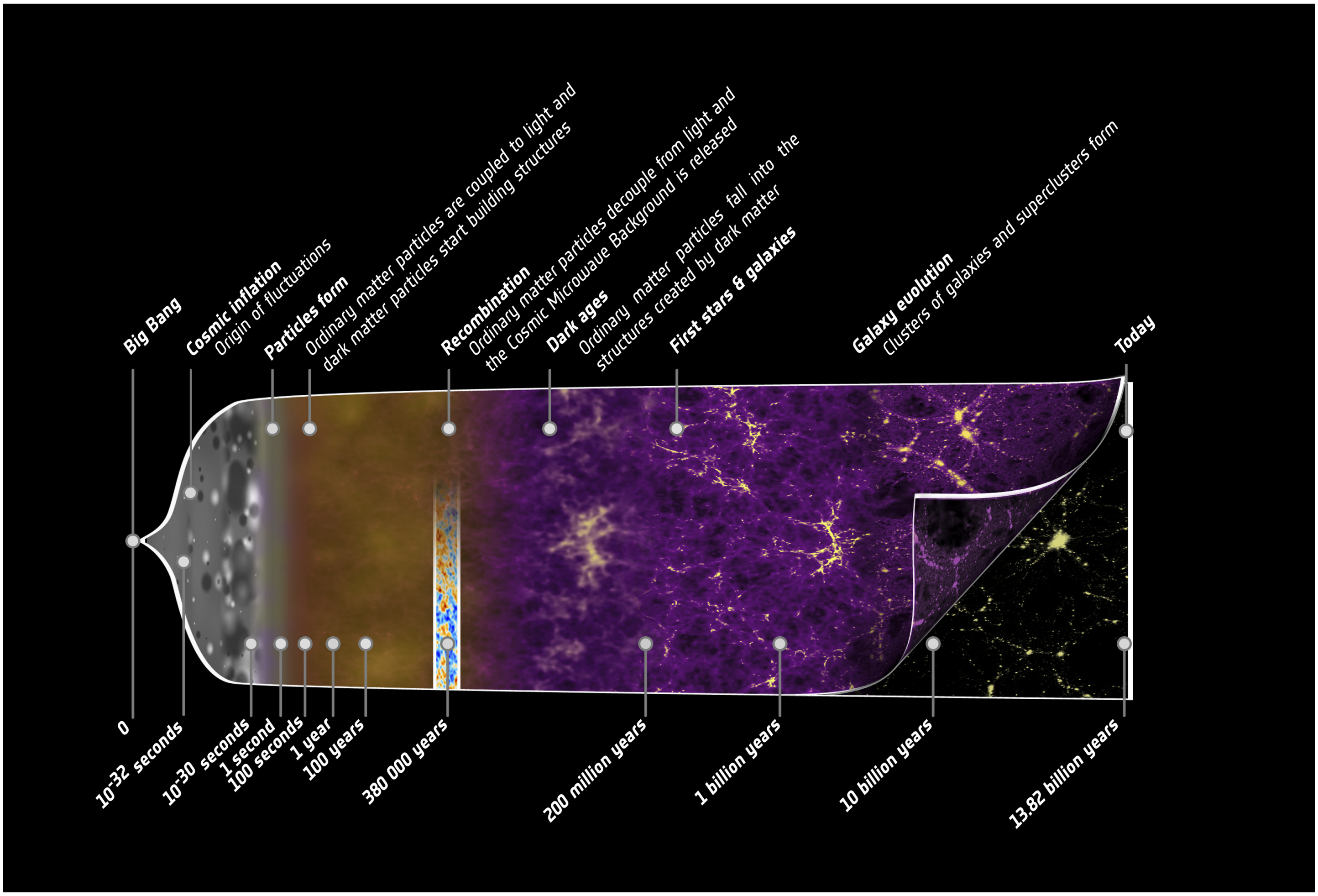


Overview



Astronomers are in the very fortunate position of having a natural time machine. As they observe ever deeper into the cosmos using ever more powerful telescopes, they see the history of the Universe laid out. In the last century our observations and deductions have resulted in cosmology moving from the realm of speculation to firm foundations. Observations of receding galaxies and the cosmic microwave background, with the parallel theoretical development of general relativity, combine to give us our present picture of the Big Bang origin of the Universe. Today we exist in an era of precision cosmology with satellite missions, such as NASA's COBE and WMAP, the recent ESA's Planck and Gaia missions, and the future ESA Euclid mission and the ground-based Square Kilometre Array (SKA) observatory.

All the data gathered so far have resulted in today's ΛCDM model (pronounced Lambda CDM, where Λ represents dark energy and CDM is the acronym for cold dark matter), our current best picture of the origin and evolution of the Universe, succinctly shown in the figure above. Starting from the Big Bang, as the origin of space and time, the Universe undergoes an incredibly brief period of inflationary expansion, followed by the synthesis of the light elements, such as hydrogen and helium. The formation of hydrogen atoms decouples matter and radiation and the Universe glows with the light of the Big Bang, visible today as the cosmic microwave background. With time, and the process of gravity, other luminous sources emerge but remain hidden as their intense ultraviolet radiation is strongly absorbed by the neutral hydrogen, in an era called the Dark Ages. Initially slowly, but gaining pace as more and more luminous sources appear, this gas is increasingly photo-ionised, until finally we are able to see the emergence of the first stars and galaxies by about 1 billion years.

The results of analysis with the Planck data, released in 2013, revealed that our Universe is 13.82 billion years old and only 4% of its content is composed of matter that we know. This ultimate step in the Copernican revolution means that not only are we not at the centre of anything; we're not even made of the same stuff as most of the rest of everything. Our part of the Universe could be thought of as little more than trace elements, and if removed by taking away all the ordinary matter, from which we are made, then the universe would continue largely undisturbed. The remaining 96% is dark matter about which we understand some things, and dark energy which we understand hardly at all. The following talks at **Cosmology@KICC** will shed further light on specific aspects of this incredible picture of the early Universe.

Big Bang and Inflation

By reversing the expansion of the Universe, observed by Edwin Hubble in 1929, we can conclude it emerged from a state of extremely high density at all the points of space, such that the Universe must have been born from an inconceivably dense, hot fireball in which all space, matter and time were created. As this cosmic fireball expanded it would take another billion years before the hot gas cooled sufficiently to condense into the stars and galaxies we observe all around us today. Proposed by Friedmann and Lemaitre in 1929 as a solution to Einstein's equations of general relativity, this 'Big Bang', a term coined by Fred Hoyle, is supported by three main pillars of evidence: the observation of galaxies flying apart as determined by their redshift, known as the Hubble flow; the detection of the after-glow of the Big Bang in the form of cosmic microwave background radiation that fills the sky; and the quantities of light elements in the Universe.

The imprint of the seeds, or density variations, that went on to form the galaxies and clusters of galaxies, were expected and finally detected in the cosmic microwave radiation by the COBE mission in the early 1990s as temperature variations across the sky with some regions one-thousandth of 1 percent hotter than other regions. Such small density variations, which grow in time as regions of higher than normal density variations would have exerted a gravitational attraction on other matter in their vicinity, pulling in yet more surrounding matter and thus becoming denser still. This is all that is required to explain the overall featureswe observe today in the cosmos, and it is clear that the events of the first few seconds after the Big Bang left a permanent imprint on the cosmos.

In 1981 Alan H. Guth proposed the inflation concept as an add-on, or elaboration, to the Big Bang theory in order to help explain certain puzzling features of the present-day Universe. He proposed that about a trillionth of a trillionth of a trillionth of a second after its birth our Universe went through a super-rapid, or exponential, expansion taking an infinitesimally small patch of space to something about the size of a marble, before then continuing to coast outwards. Note, this faster-than-light expansion speed does not contravene relativity as it is space itself, and not the objects within it, that is moving faster than light! This theory can then explain why the Universe looks so smooth on the largest scales, as inflation would have stretched away any unevenness. Also, it could explain the structure we see in the Universe which arose from the original density fluctuations as random quantum fluctuations that existed during inflation would have been amplified to provide the seeds for everything that came after.

This exquisite tying together of the very very large to the very very small, also allowed astronomers to look back to a time so close to the beginning that some now speculate about the events which caused the Universe to come into being, and also about the possible existence of other universes, linked together in a multiverse.

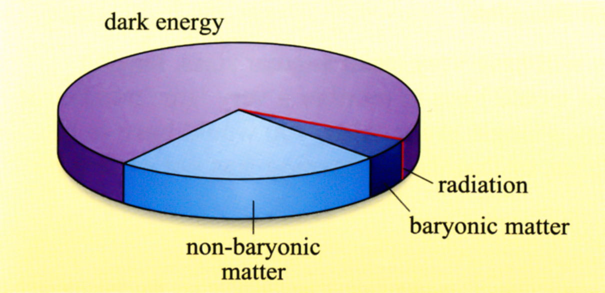
The Big Bang and Inflation

Will Handley

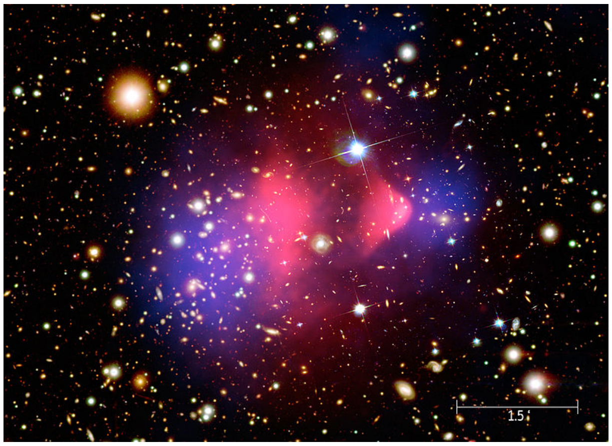
We now know that the universe began around 13.8 billion years ago. At the beginning of the universe the entirety of creation was a seething soup of energy and particles which we call 'The Big Bang'. We also have strong evidence that in the very earliest moments the universe underwent an extremely rapid expansion, termed 'Cosmic Inflation'. In this talk I will discuss these ideas and the evidence underlying them, as well as the direction of current research in this field.

Dark matter

From modelling the CMB using data from the recent Planck satellite mission, and WMAP preceding it, we can deduce the current composition of our Universe:



(a) Contributions to total (energy) density of the Universe from various sources: 68.3% dark energy; 26.8% dark matter and 4.9% normal matter



(b) The Bullet Cluster

A crucial component that is required if we are to observe the current structure of the Universe within its current timescale is dark matter, which forms more than 83% of all the matter (from the ratio of 6:1). This is not non-luminous normal baryonic matter (neutrons and protons), which is attributable to stellar remnants or bodies that have masses lower than that of main sequence stars, such as brown dwarfs, planets, asteroids etc and accounts for only $\sim 4\%$, but is non-baryonic dark matter. This non-luminous matter, which does not interact with light and is made from something else, is only observable via its gravitational effects.

In fact dark matter was proposed by Fritz Zwicky as long ago as the 1930s from work with the nearby Coma cluster of galaxies, where the observed behaviour required a mass significantly greater than that attributable to all the stars, gas and dust within the cluster and its component galaxies. Similarly, work by Vera Rubin in the 1970s also showed the need for dark matter in order to explain the rotation speeds of stars within individual galaxies, which rotated much faster than they should based on the combined mass of stars within it. Mapping dark matter shows that not only is it spread throughout galaxies, but extends by a factor of 10 beyond the limit of the outer-most stars forming a halo around every galaxy.

The most direct observational evidence to date for dark matter, as against modified theories of gravity, is in a system known as the Bullet Cluster. Typically, dark matter and baryonic (visible) material are found together because of their mutual gravitational attraction, but the collision between two clusters in the Bullet Cluster appears to have caused a separation of the the two. X-ray observations show that much of the baryonic matter (hot gas plasma) is concentrated in the centre of the system as it is slowed down by interaction, while weak gravitational lensing observations of the same system show that much of the mass resides outside of the central region of baryonic gas, because dark matter would remain unaffected by the types of interaction experienced by baryonic matter, accounting for the separation.

The race is on to the determine the nature of dark matter. **MACHOs** (Massive Astrophysical Compact Halo Objects), objects listed above that emit little/no radiation, so only detectable by their gravitational effect, have fallen out of favour as evidence from gravitational micro-lensing has shown insufficient numbers to fully account for dark matter, leaving **WIMPs** (Weakly Interacting Massive Particles) which are new kinds of subatomic particles as now the focus of research. Neutrinos make up some small fraction, but the main component of non-baryonic matter is likely to be some other exotic particle such as neutralinos associated with super-symmetry theories. Proposing particles, with their subsequent detection is nothing new, as was the case with the neutron, or antimatter, and the search is on at CERN's Large Hadron Collider, or in mines deep underground so as to exclude cosmic rays.

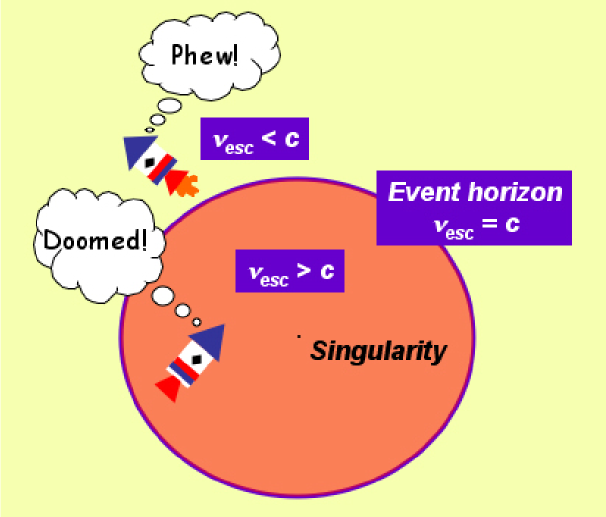
Exploring the Dark Universe: "Seeing" the Invisible

Mustafa A. Amin

Over the past few decades, cosmologists have discovered that the stuff you, I and even the stars and galaxies are made up of, only makes up $\sim 4\%$ *of the matter in our universe. The rest is a bit of a mystery. We know that the rest of the stuff does not emit or absorb light in currently detectable amounts, it is dark. In this talk I will highlight, how we have reached this seemingly incredible conclusion and what properties this dark stuff must have. I will highlight some of the exciting attempts, past, present, and future to understand this dark side of our universe.*

Supermassive Black Holes

In Einstein's theory of gravity, called general relativity and applied to modelling the whole Universe, Einstein melded space-time together into a single metric (or measure), and it is this metric that distorts as you move or accelerate which maintains the fixed speed of light. Objects bend space-time around themselves, and gravity is then experienced as a result of objects being accelerated by this curved space. This warping of space-time also results in the bending of light forming gravitational lenses, and also in the formation of black holes, which are super-dense objects from which even light may not escape. The escape velocity increases as you increase the mass of the object, so for example the speed required by a rocket to escape the Earth for a moon-bound journey must exceed a speed of 11 km/s (or 25000 mph). However, for very massive objects, such as black holes, this escape velocity would exceed the speed of light, so not even light could escape its gravitational pull!



(c) Guide to a black hole

(d) The centre of an active galaxy

The concept of black holes has a long history originating in the 18th century from the work of John Michell and Pierre-Simon Laplace, and subsequently found as a solution by Karl Schwarzschild to Einstein's equations of relativity, in which the 'event horizon' marks the boundary around the black hole from which even light may not escape. A limit due to Chandrasekhar shows objects with masses greater than 3 solar masses will go on to form a black hole. These were first observed in the 1960s, and although we cannot see the black hole we can infer its existence from its effects on the environment around itself. For example, in the very high speeds of stars in orbit around the centres of galaxies or from the intense radiation, as seen in Quasars, emitted by gas and dust as it spirals into the black hole outside of the event horizon and is heated up by frictional forces to a temperature of millions of degrees.

Some simple arguments show that the energy output of such active galaxies, that constitute about 10% of all galaxies, is best explained by the existence of a super-massive black hole of the order of 100 million solar masses residing at the core of these objects, and today it is thought likely all galaxies contain at least a dormant super-massive black hole. For example, the Milky Way is estimated to contain an object of four million solar masses within a size that is a small fraction of the size of the Solar System.

As yet we don't know how they formed, perhaps by the merger of small black holes into larger ones, but they strongly influence the growth of the galaxies they inhabit, as perhaps indicated by close relationship between the size of the central black hole and the size of the galactic bulge that it inhabits. Maybe these massive objects create the galaxy, or grow with the galaxy as it evolves, but nevertheless they play a crucial goal with respect to creation of structure in the Universe.

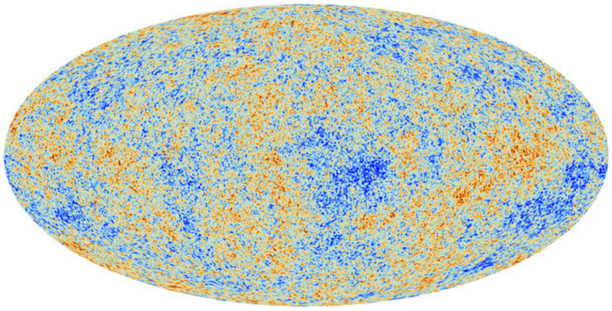
Supermassive Black Holes: Monsters lurking in the hearts of galaxies

Ewald Puchwein

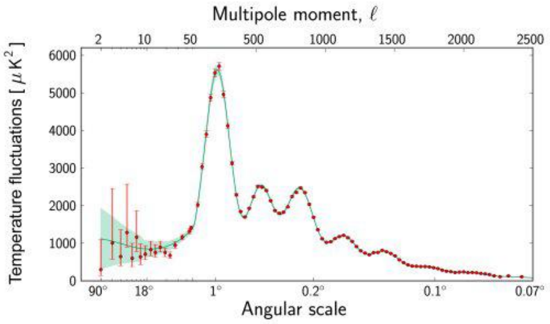
A few decades ago black holes from which not even light can escape were mostly considered a theoretical curiosity that was allowed by the equations of Einstein's general relativity theory. Nowadays, we not only have convincing evidence that they actually exist in nature, and are rather abundant in fact, but also that they influence profoundly how galaxies form and evolve. The extremely energetic events by which they interact with their surroundings are a fascinating topic of ongoing research.

Future of cosmology

Much of the attention in cosmology over the past couple of decades has been focused on the study of the cosmic microwave background. This is the remnant of the heat of the Big Bang cooled by the expansion of the universe in the intervening period, so now its light washes over the Earth at microwave frequencies. Recent CMB results were released by the Planck mission in 2013.

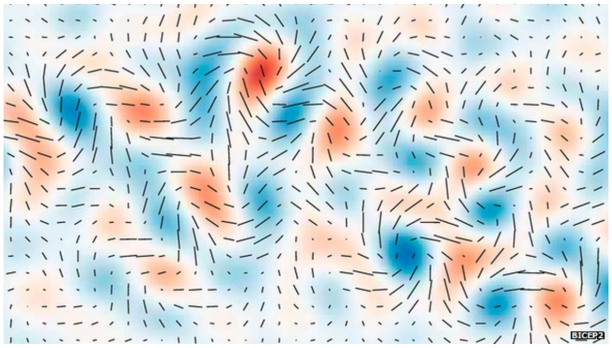


(e) Planck CMB Map



(f) Planck power spectrum of the CMB

In addition the Planck satellite also observed the CMB in polarisation, which can be used to test the inflation model, discussed earlier. This model predicts that the waves of gravitational energy that would have accompanied this violent growth spurt would have left their imprint as swirls in the CMB polarisation, otherwise known as B-modes.



(g) CMB polarization B-modes

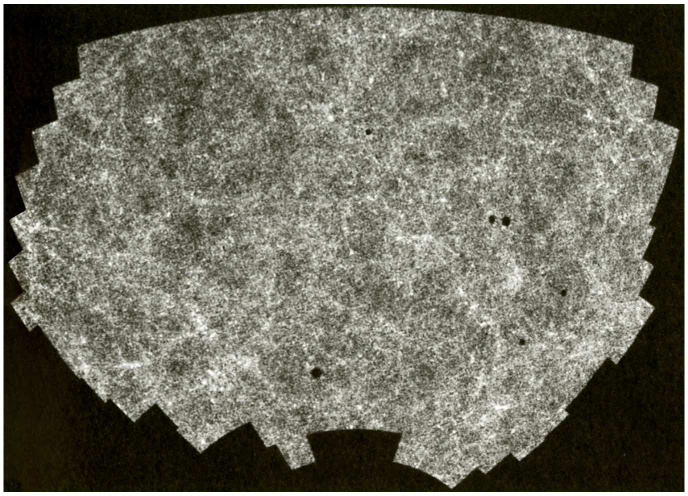
This pattern, or additional evidence for cosmic inflation, has apparently now been seen when in March 2014 the BICEP2 team announced its discovery with its South Pole telescope. This result may yet be ruled out as arising from dust, which also produces the same effect and which may not have been accurately removed from the signal. Besides reinforcing the inflation model, this result, if confirmed, would be a huge result as it represent our most direct detection yet of gravitational waves. Future CMB missions are now being proposed to specifically search for this extremely weak signal.

The cosmic microwave background only provides a snapshot of the Universe at an age of 380,000 years, when the recombination of protons and electrons into neutral hydrogen allowed the trapped radiation from the Big Bang to escape, as the close relationship between matter and radiation ended. Following this decoupling and with no luminous sources present all of space would have seemed filled with a softly glowing fog.

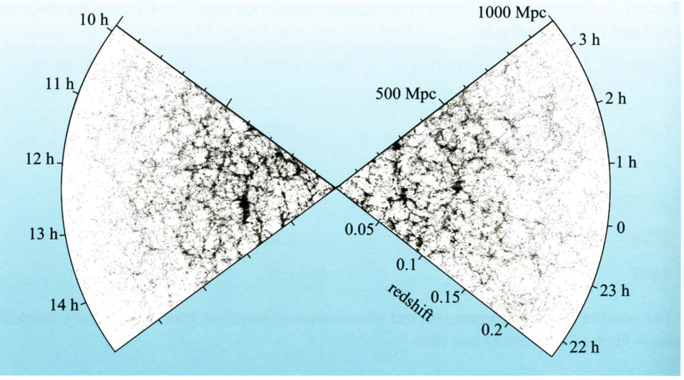
The small density fluctuations visible in the cosmic microwave background map of the early universe are then amplified by gravity and into these regions sank first the dark matter, forming halos, followed later by ordinary matter in the form of gas, which as it cooled by emitting radiation sinks into the centres of the halos. As these halos cooled they would start to become dense enough to form stars, and star formation begins about 150 million years after the Big Bang. Models predict that these first generation stars, called Population III stars, would be massive and their intense ultraviolet radiation, or that from the super-massive black holes at the centres of Quasars, would be blocked by the all-pervading medium of hydrogen atoms which strongly absorbs ultraviolet light, and as a result they are lost to our sight. Hence, this period is referred to as the Dark Ages, lasting up to a billion years! During that time intense ultraviolet radiation begins to photo-ionise the hydrogen atoms, filling the universe with ionised hydrogen. This process is completed between 500 million years to 1 billion years after the Big Bang, and optical light is now free to travel without being absorbed. Optical observations are now pushing back to the boundary with recent Hubble Space Telescope observations that show large galaxies having been formed by the time re-ionisation is completed at 1 billion years, and future radio observations, with the Square Kilometre Array, will push observations into the dark period using observations at 21cm wavelength where the first stars and galaxies arose in the early universe.

Modern survey techniques and very large telescopes have enabled us to measure large numbers of galaxy redshifts giving us a 3-D picture of the local Universe, for example with the automated Sloan Survey (SDSS), and what we then find on very large scales (100s of Mpc) is a 3-dimensional network in which regions of high galaxy density are connected by filaments and sheets, surrounding voids containing few galaxies.

These maps of a web-like cosmic network have spurred on decades of work in the running of computer simulations, with models that encapsulate all the relevant laws of physics governing the formation of galaxies, in an attempt to build accurate computer simulations of the development of the Universe. The most recent simulation, Illustris, tracks the development of the Universe from 12 million years after the Big Bang up to the present, with results released in May 2014, showing 41,000 galaxies in a cube of simulated space 350 million light years on each side. Illustris yields a realistic mix of spiral galaxies like

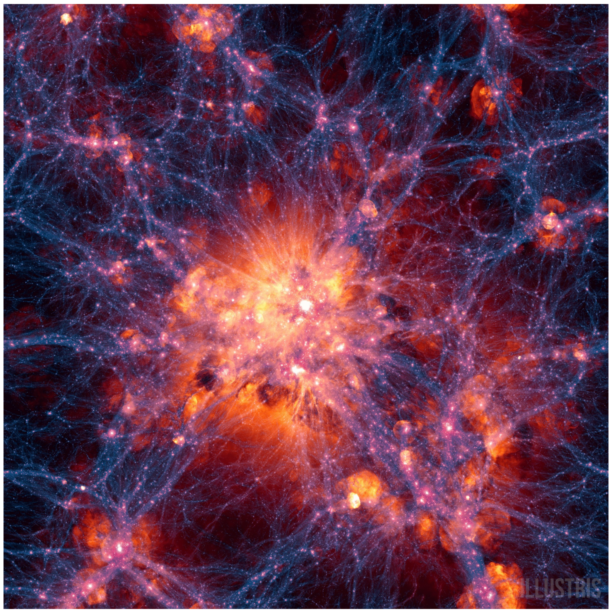


(h) APM map of galaxy positions



(i) 2-degree Field Galaxy Redshift Survey

the Milky Way and giant elliptical galaxies, but also recreated the large-scale structures like galaxy clusters and the bubbles and voids of the cosmic web.



(j) The Illustris simulation

Cosmology in the Future: Surveying the Sky Across the Electromagnetic Spectrum

Manda Banerji

Observational studies of cosmology require us to survey the sky across the electromagnetic spectrum in order to build up a full understanding of the different components that make up our Universe. Experiments such as Planck and BICEP have revealed in exquisite detail the nature of the cosmic microwave background: the relic thermal radiation left over from the Big Bang. At the same time, new sensitive cameras on some of the world's largest telescopes, have allowed us to image remote galaxies in the optical and infrared wavelengths out to the distant reaches of our Universe. These galaxies are not randomly distributed on the sky but instead seem to exist in complex filamentary structures. I will discuss how these observations from the current generation of survey experiments have shaped our understanding of cosmology and highlight some new experiments, that are coming up within the next decade, that will enable us to take the next step forward in our quest to better understand the Universe we live in.

The fate of the Universe?

As we have followed the origin of the Universe and its development in the early phase, some of you may wonder about the ultimate fate of the Universe. How will it end? Obviously, it depends on determining the nature of dark energy, this mysterious anti-gravity type of force, as to the final outcome, but what we do know is that in about 5 billion years the Milky Way will collide with the Andromeda galaxy, although it is unlikely the Earth will be around to see this having long been vaporized by the expansion of the Sun. Some stars will be hurled out into intergalactic space, while others will fall into the embrace of the combined supermassive black hole that will emerge. With time, dark energy will cause all others galaxies to leave our horizon, leaving us visibly alone. In 100 trillion years all the gas in the Universe will have been converted into stars and new star formation will cease, such that all light will fade as stellar evolution also comes to end. On even longer time-scales galaxies will collapse onto their central black holes as stellar orbits decay, which in turn will effectively evaporate as they radiate away their energy via Hawking radiation, followed eventually by the probable disintegration of matter as protons may decay on the timescale of a googol ($\sim 10^{100}$) years. But perhaps this story is for another day.