Origin and evolution of cosmic structure

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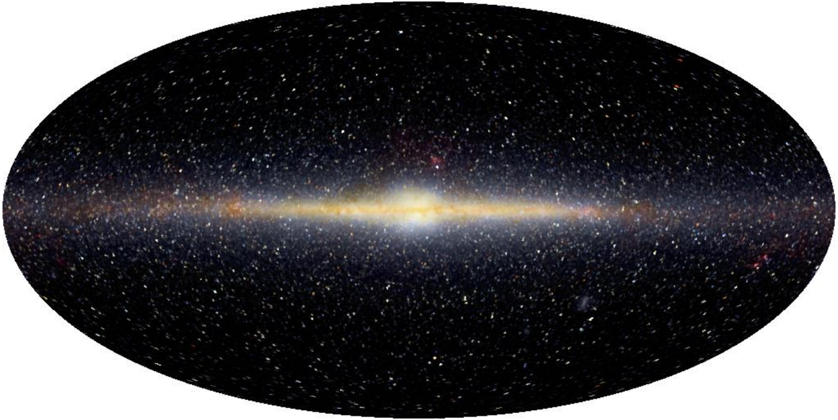
Plan of the talk

Plan of the talk

An infrared image of our galaxy



Our galaxy – the Milky Way – as observed by the COsmic Background Explorer (COBE) satellite at the infrared wavelengths[1]. The diameter of the disc of our galaxy is, approximately, $45 \times 10^3\,\mathrm{ly}$ or $15\,\mathrm{kpc}$ (*i.e.* a kilo parsec, with $1\,\mathrm{pc} \simeq 3.26\,\mathrm{ly}$). It contains about 10^{11} stars such as the Sun, and its mass is about $2 \times 10^{12}\,\mathrm{M}_{\odot}$.

[1] Image from http://aether.lbl.gov/www/projects/cobe/cobe_pics.html.

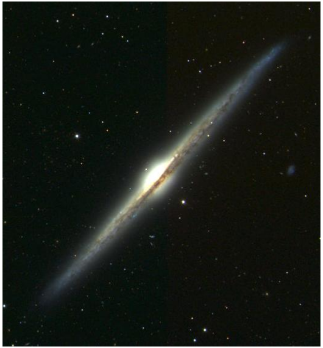
Our galactic neighbors and the local group[2]

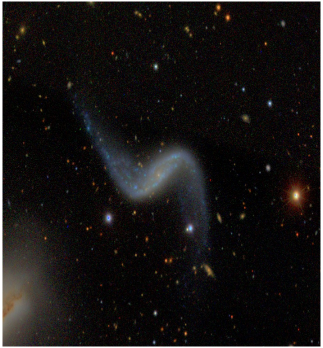
Left: The Andromeda galaxy and its two companion galaxies. The Andromeda galaxy is very similar to our galaxy and is located at a distance of about $700\ \mathrm{kpc}$.

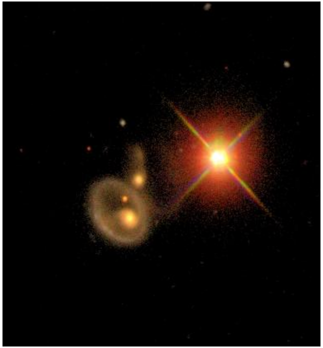
Right: The Triangulum galaxy M33. These galaxies, along with our galaxy, are major members of a local group of about 30 galaxies that are bound gravitationally. The size of the local group is estimated to be about $1.3\ \mathrm{Mpc}$.

[2]Images from http://www.seds.org/messier/m/m031.html and http://www.seds.org/messier/m/m033.html.

Varieties of galaxies[3]



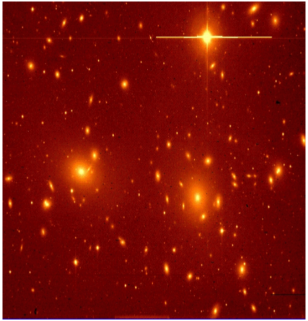




Left: The disk galaxy NGC 4565 seen edge on in this image from the Sloan Digital Sky Survey (SDSS). The galaxy has a clear bulge, but little light can be seen from its halo.
Center: An image of the spiral galaxy NGC 3187 from SDSS.
Right: CGCG 180-023 is a superb example of a ring galaxy. Ring galaxies are believed to form when a compact smaller galaxy plunges through the center of a larger more diffuse rotating disk galaxy.

[3] Images from http://www.sdss.org/iotw/archive.html and http://cosmo.nyu.edu/hogg/rc3.

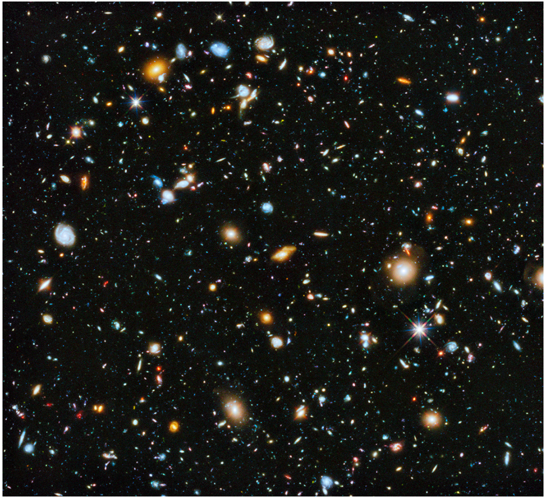
The Virgo, the Coma and the Hercules cluster of galaxies[4]


Left: The Virgo cluster, whose center is considered to be located at a distance of about $20\ \mathrm{Mpc}$. Consisting of over 100 galaxies, it strongly influences the nearby galaxies and galaxy groups gravitationally due to its enormous mass.
Center: The Coma cluster of galaxies, which contains more than 1000 bright galaxies. It is about $20\ \mathrm{Mpc}$ across, and is located at a distance of about $100\ \mathrm{Mpc}$.
Right: An SDSS image of the Hercules galaxy cluster that is located at a distance of about $100\ \mathrm{Mpc}$ from us.

[4] Images from http://apod.nasa.gov/apod/ap000220.html, http://www.astr.ua.edu/gifimages/coma.html and http://www.sdss.org/iotw/archive.html.

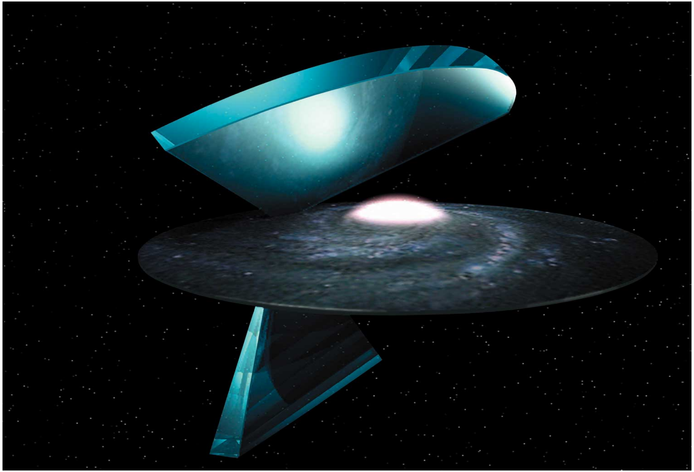
Deepest views in space



An ultra deep field image from the Hubble Space Telescope (HST). The image contains a bewildering variety of galaxy shapes and colors[5].

[5]Image from http://hubblesite.org/newscenter/archive/releases/2014/27.

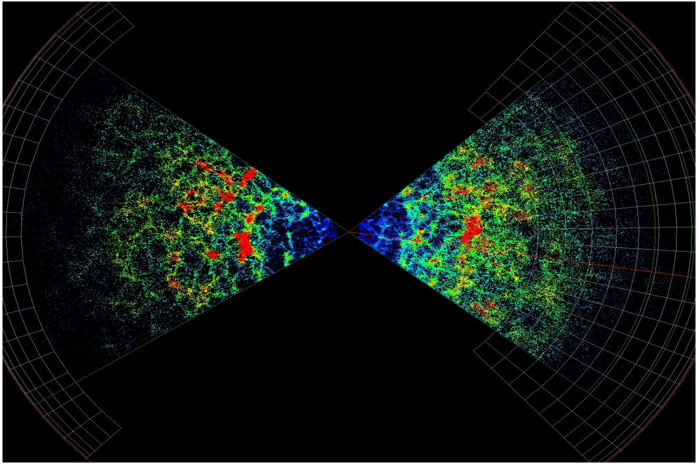
Surveying the universe



A schematic drawing showing the directions of the regions observed by the 2 degree field (2dF) redshift survey with respect to our galaxy[6]. The survey regions actually extend more than 10^5 times further than shown here.

[6] Image from http://magnum.anu.edu.au/~TDFgg/Public/Pics/2dF3D.jpg.

Distribution of galaxies in the universe



The distribution of more than two million galaxies as observed by the 2dF redshift survey[7]. (Note that each dot in the picture represents a galaxy.) The density and the 'radius' of the universe are estimated to be about $10^{-28}\ \mathrm{kg/m^3}$ and $3000\ \mathrm{Mpc}$, respectively.

[7] Image from http://magnum.anu.edu.au/~TDFgg/Public/Pics/2dFGRS_top_view.gif.

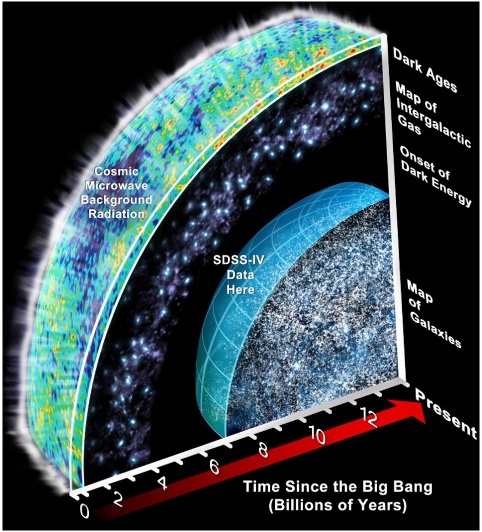
The Sloan digital sky survey

- The Sloan Digital Sky Survey (SDSS) is one of the most ambitious and influential surveys in the history of astronomy[8].
- Over eight years of operations, it has obtained deep, multi-color images covering more than a quarter of the sky and created three-dimensional maps containing more than $930,000$ galaxies and more than $120,000$ quasars.

Play SDSS movie

[8] See http://www.sdss.org/.

The region surveyed by SDSS



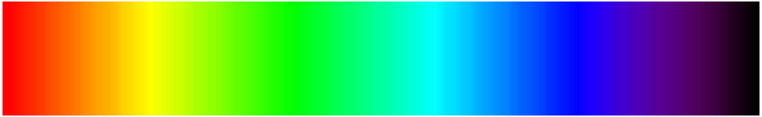
A perspective of the region surveyed by SDSS[9].

9 Image from https://medium.com/starts-with-a-bang/ask-ethan-how-far-is-the-edge-of-the-universe-from-the-farthest-galaxy-f3a4b4fc85d4.

Plan of the talk

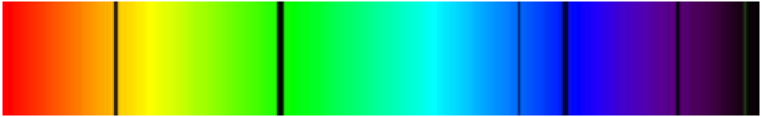
Continuous, emission and absorption spectra[10]

A typical continuous spectrum from an opaque hot body:



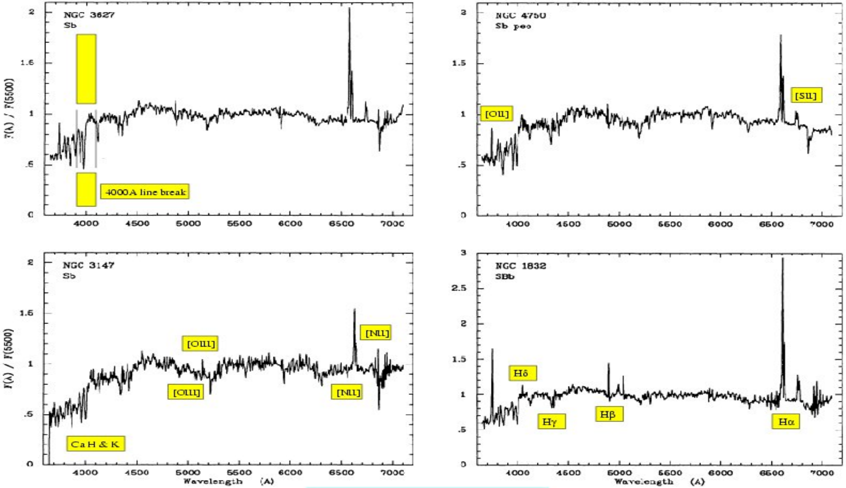
Emission spectrum, as from a given element:

Absorption spectrum, as due to an intervening cool gas:



[10] Images from http://hea-www.harvard.edu/~efortin/thesis/html/Spectroscopy.shtml.

Typical spectra of galaxies[11]

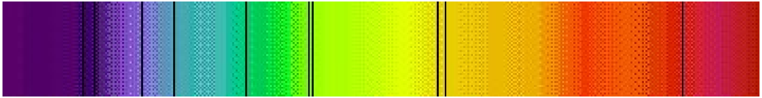


Spectra of some spiral galaxies. The spectra usually contain characteristic emission and absorption lines.

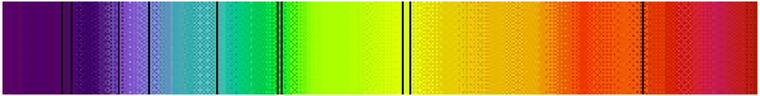
[11] Image from http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html.

The 'Doppler effect' and redshift[12]

If the source is receding, the spectrum will be red-shifted



when compared to the spectrum in the source's frame



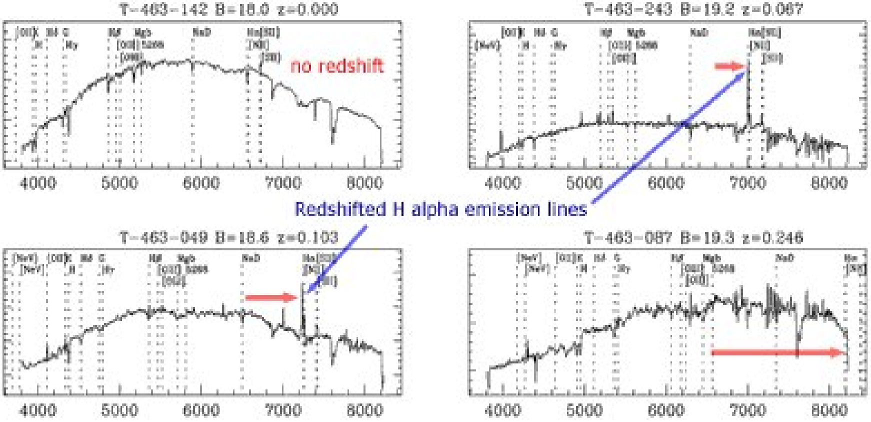
The redshift z of the receding source is defined as:

$$1 + z = \frac{\lambda_{\rm O}}{\lambda_{\rm E}} = \frac{\omega_{\rm E}}{\omega_{\rm O}},$$

where $\lambda_{\rm O}$ and $\omega_{\rm O}$ denote the observed wavelength and frequency of the source, while $\lambda_{\rm E}$ and $\omega_{\rm E}$ denote its emitted wavelength and frequency, respectively.

[12] Images from http://www.astronomynotes.com/light/s10.htm.

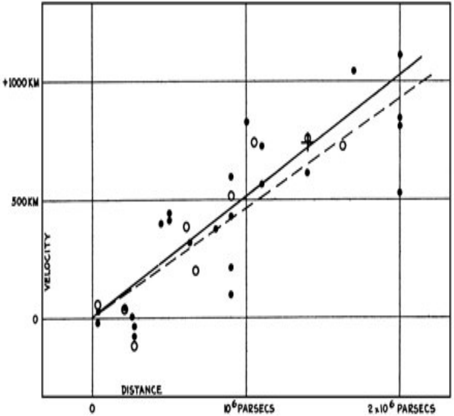
Runaway galaxies[13]

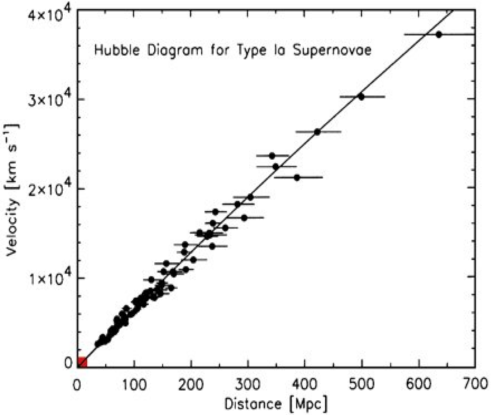


Spectra of four different galaxies from the 2dF redshift survey. On top left is the spectrum of a star from our galaxy, while on the bottom right we have the spectrum of a galaxy that has a redshift of $z = 0.246$. The other two galaxies show prominent Hα emission lines, which have been redshifted from the rest frame value of 6563 Å.

[13] Image from http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.

Relation between the velocity and the distance of galaxies[14]



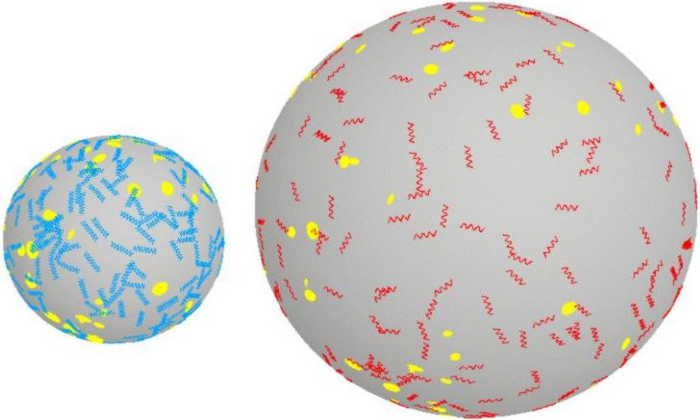


Left: The original Hubble data. The slope of the two fitted lines are about $500\ \mathrm{km/sec/Mpc}$ and $530\ \mathrm{km/sec/Mpc}$.

Right: A more recent Hubble diagram. The slope of the line is about $72\ \mathrm{km/sec/Mpc}$. The small red region in the lower left marks the span of Hubble's original diagram.

[14] R. Kirshner, Proc. Natl. Acad. Sci. USA **101**, 8 (2004).

Visualizing the expanding universe

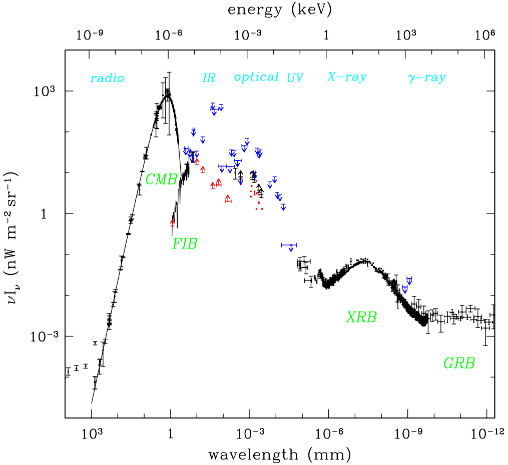


A two-dimensional analogy for the expanding universe[15]. The yellow blobs on the expanding balloon denote the galaxies. Note that the galaxies themselves do not grow, but the distance between the galaxies grows and the wavelengths of the photons shift from blue to red as the universe expands.

[15] Image from http://www.astro.ucla.edu/~wright/balloon0.html.

Plan of the talk

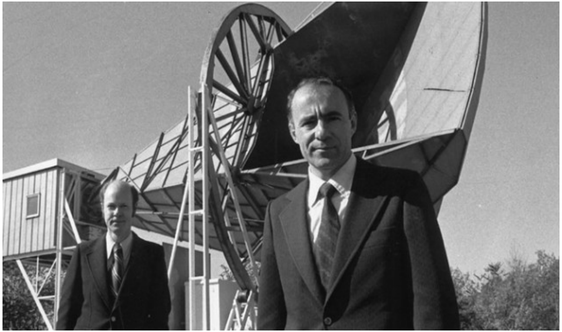
The Cosmic Microwave Background (CMB)

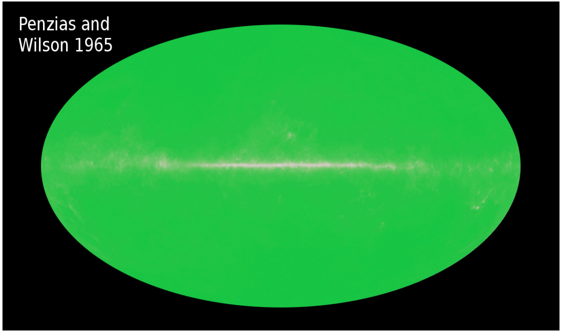


The energy density spectrum of the cosmological background radiation has been plotted as a function of wavelength[16]. Note that the CMB contributes the most to the overall background radiation.

[16] Figure from D. Scott, arXiv:astro-ph/9912038.

Discovery of the CMB[17]



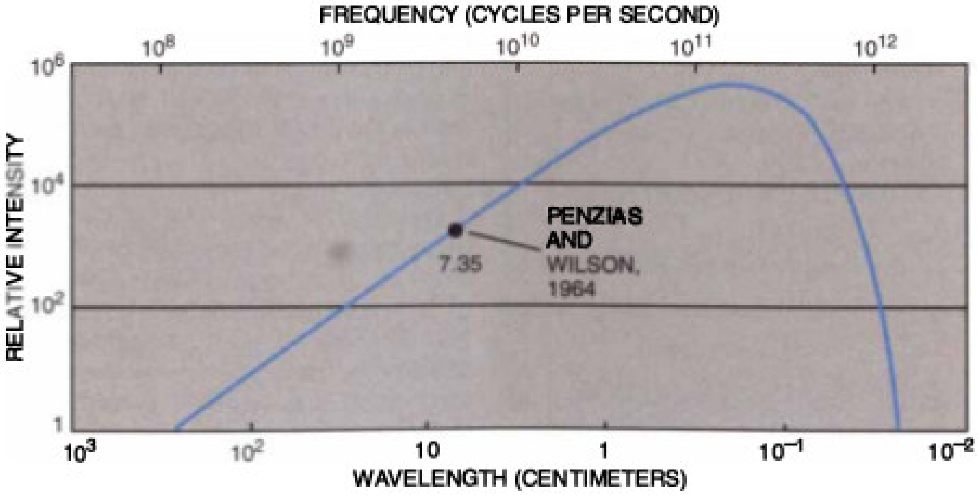


The horn antenna used by Penzias and Wilson (on the left) and the CMB as observed by them (on the right).

Anisotropies observed by COBE

[17] In this context, see, for instance, S. G. Brush, Sci. Am. **267**, 62 (1992).

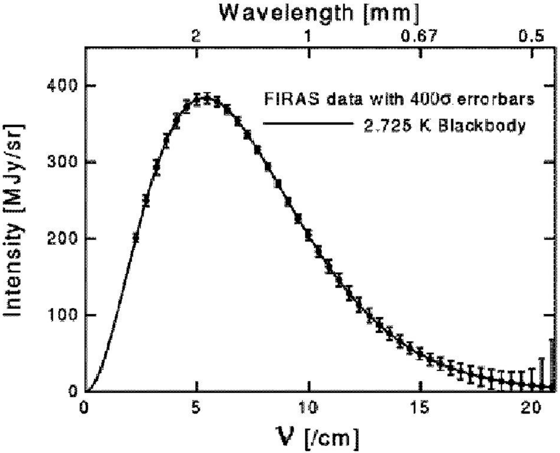
The thermal nature of the CMB



The region of the thermal spectrum observed by Penzias and Wilson[18]

[18] Image from, S. G. Brush, Sci. Am. **267**, 62 (1992).

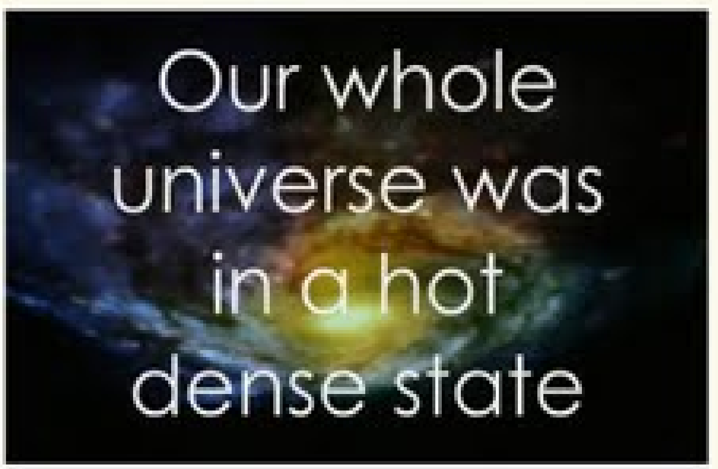
Spectrum of the CMB



The spectrum of the CMB as measured by the COBE satellite[19]. It is a perfect Planck spectrum (corresponding to a temperature of 2.725° K) which is unlikely to be bettered in the laboratory. The error bars have been amplified 400 times so that they are visible!

[19] Image from http://www.astro.ucla.edu/~wright/cosmo_01.htm.

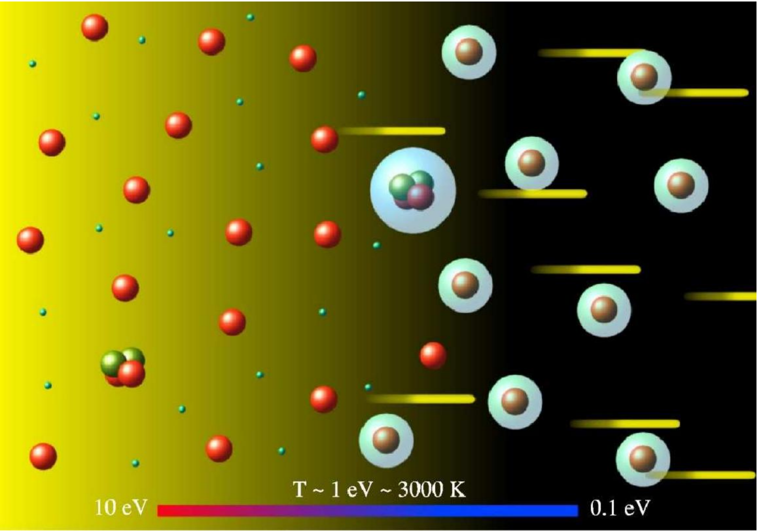
The big bang model seems popular!



The current view of the universe, encapsulated in the hot big bang model, seems popular. The above image is a screen grab from the theme song of the recent American sitcom 'The Big Bang Theory'[20]!

[20] See http://www.cbs.com/shows/big_bang_theory/.

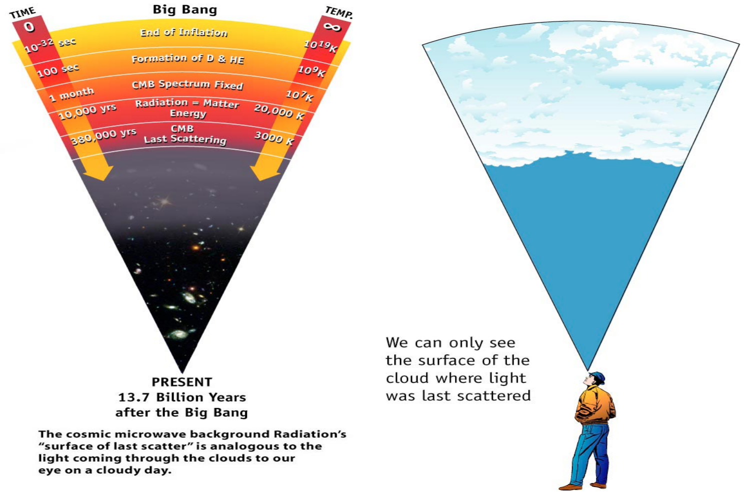
Decoupling of matter and radiation



The CMB arises because matter and radiation cease to interact at an early time[21].

[21] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

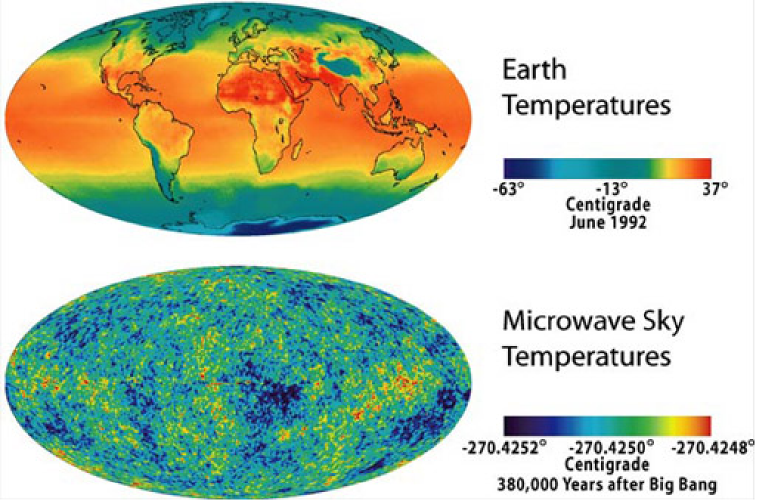
The last scattering surface and the freestreaming CMB photons



The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter[22].

[22] Image from http://map.gsfc.nasa.gov/media/990053/990053.jpg.

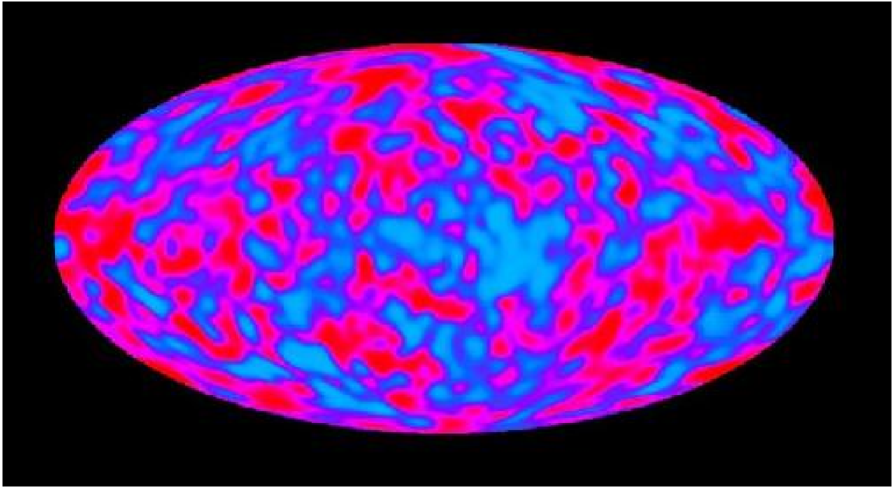
Projecting the last scattering surface



The temperature of the CMB on the last scattering surface can be projected on to a plane as the surface of the Earth is often projected[23].

[23] Image from http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html.

Anisotropies in the CMB



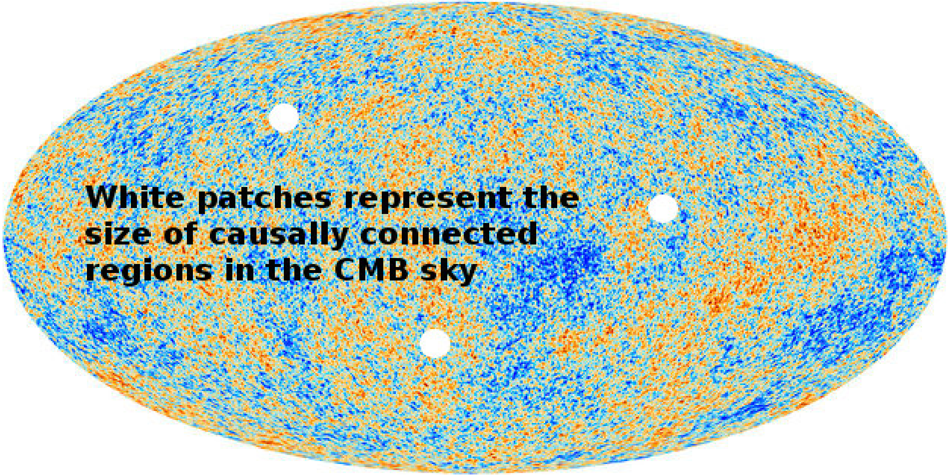
The fluctuations in the temperature of the CMB as seen by COBE[24]. The CMB turns out to be isotropic to one part in 10^5.

▸ The smooth CMB ▸ WMAP and Planck

[24] Image from http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html.

Plan of the talk

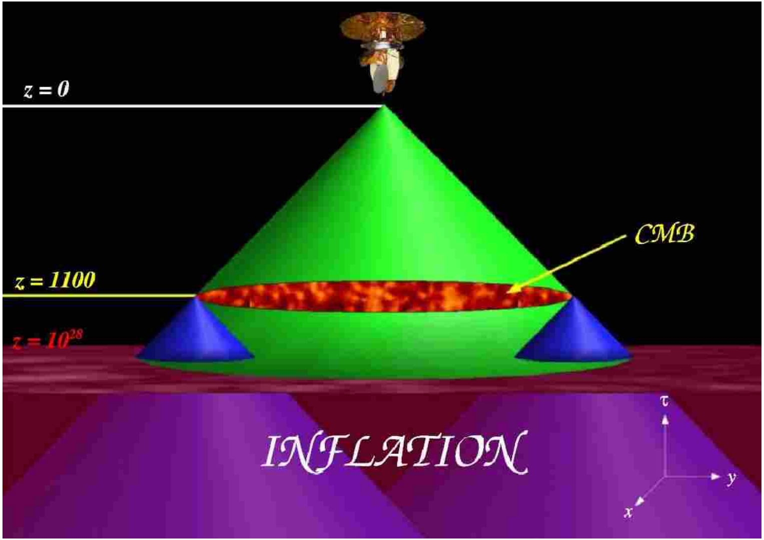
The horizon problem



The radiation from the CMB arriving at us from regions separated by more than the Hubble radius at the last scattering surface, which subtends an angle of about 1° today, could not have interacted before decoupling[25].

[25] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

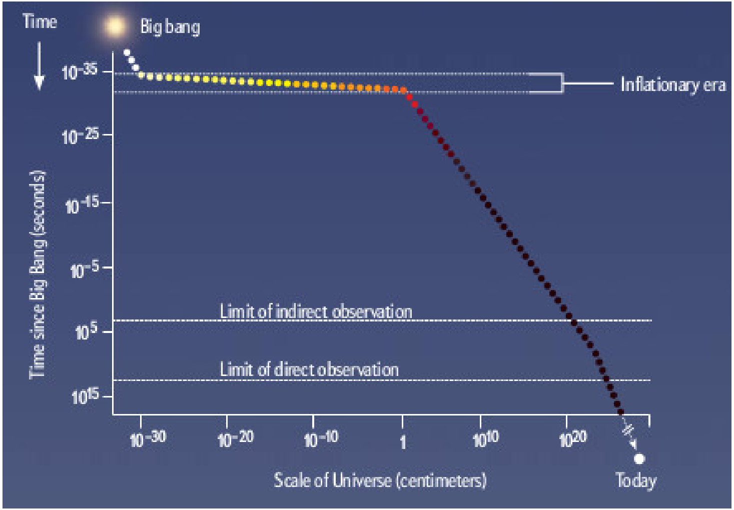
Inflation resolves the horizon problem



An early and sufficiently long epoch of inflation resolves the horizon problem[26].

[26] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

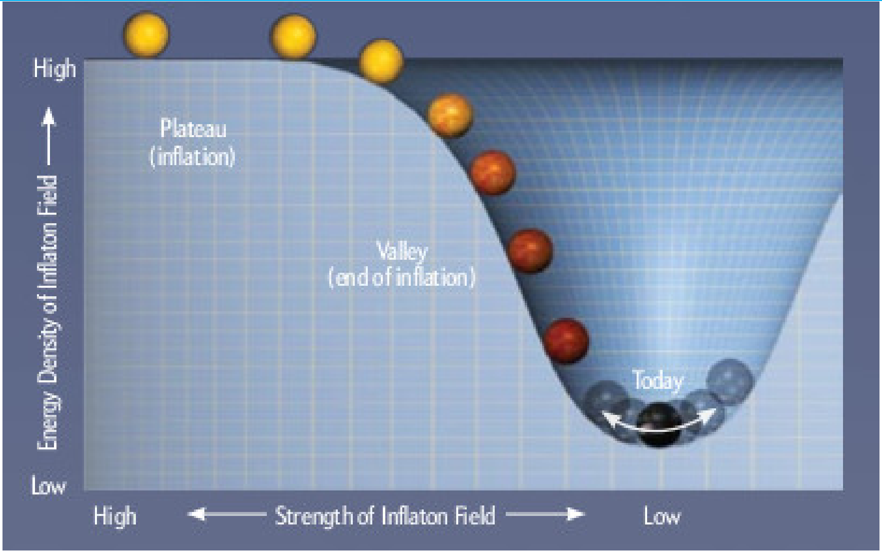
The time and duration of inflation



Inflation – a brief period of accelerated expansion – is expected to have taken place during the very stages of the universe[27].

[27] Image from P. J. Steinhardt, Sci. Am. **304**, 18 (2011).

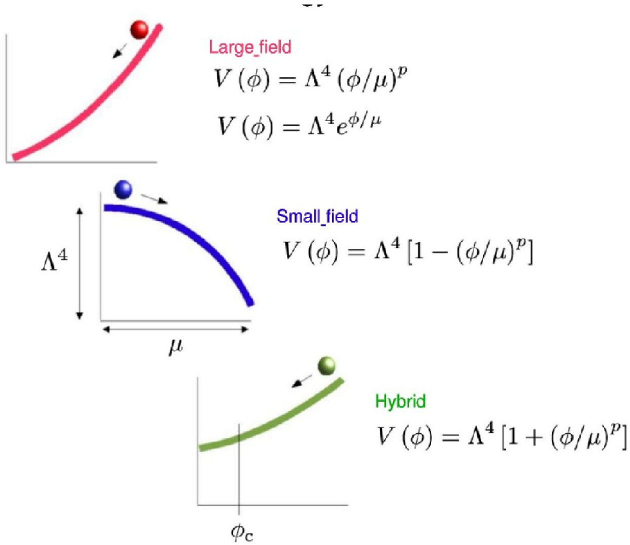
Driving inflation with scalar fields



Inflation can be achieved with scalar fields encountered in high energy physics[28].

[28] Image from P. J. Steinhardt, Sci. Am. **304**, 34 (2011).

A variety of potentials to choose from



A variety of scalar field potentials are considered to drive inflation[29].

[29] Image from W. Kinney, astro-ph/0301448.

Plan of the talk

Origin and evolution of the perturbations

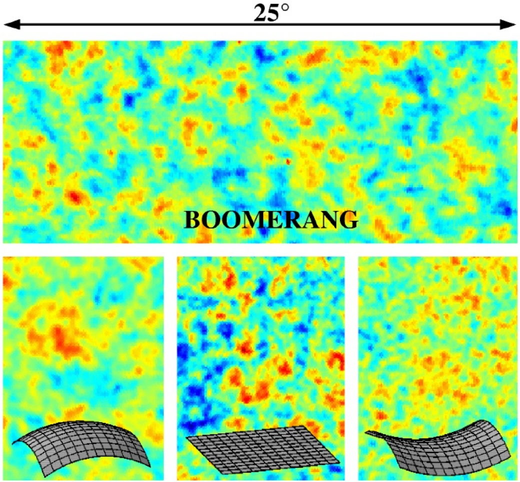
- Inflation is typically driven with the aid of scalar fields. It is the quantum fluctuations associated with these scalar fields that are responsible for the origin of the perturbations.
- These perturbations are amplified during the inflationary epoch, which leave their imprints as anisotropies in the CMB.

Play movie

- The fluctuations in the CMB in turn grow in magnitude due to gravitational instability and develop into the structures that we see around us today.

Play movie

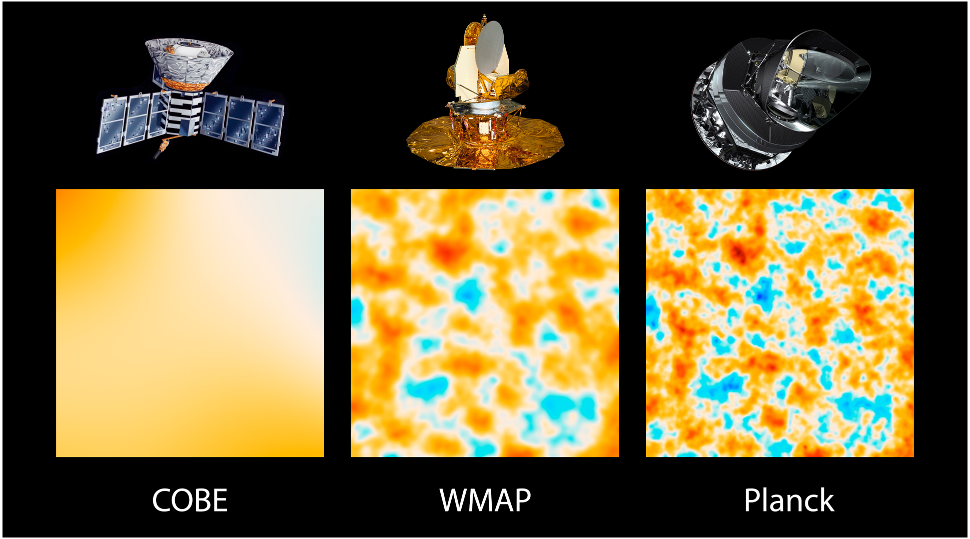
BOOMERANG and the spatially flat universe



It was observations by balloon borne BOOMERANG that had first revealed that the universe is very nearly spatially flat[30].

[30] Images from http://oberon.roma1.infn.it/boomerang/pressrelease/illustrations/index.html.

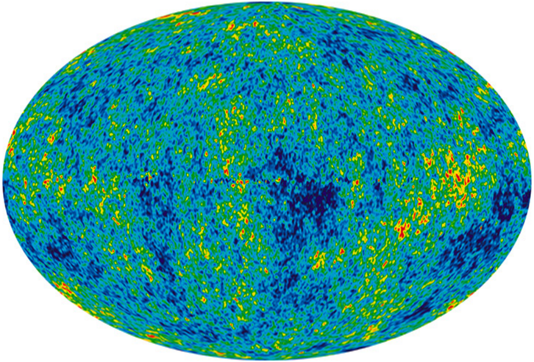
Satellite missions that brought the CMB into sharper focus

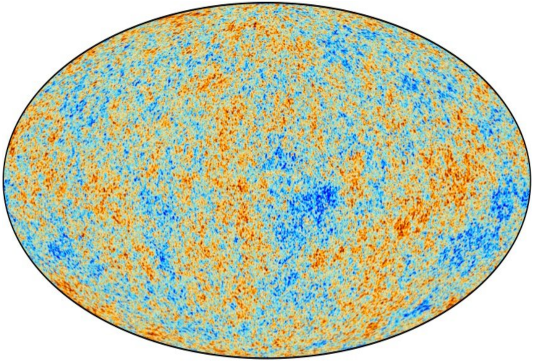


COBE, WMAP and Planck observed the CMB with ever increasing resolution[31].

[31] Image from https://www.nasa.gov/sites/default/files/images/735694main_pia16874-full_full.jpg.

CMB anisotropies as seen by WMAP and Planck

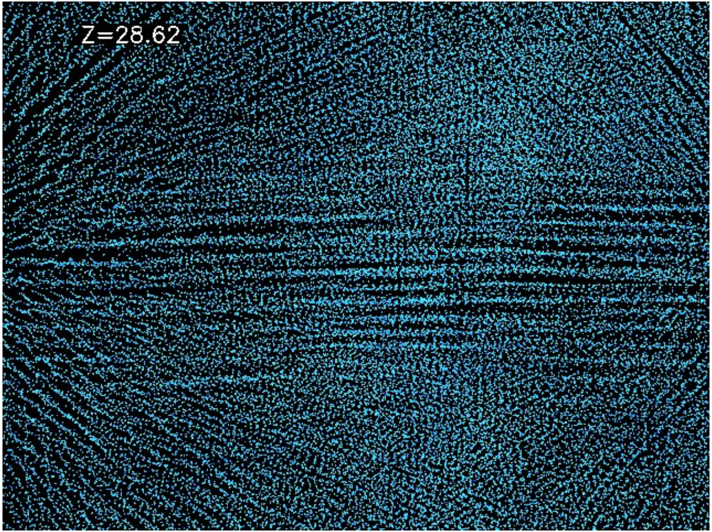




Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[32].
Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\ \mathrm{MHz}$ observations[33]. The above images show temperature variations (as color differences) of the order of $200^\circ\ \mu\mathrm{K}$.

[32] Image from http://wmap.gsfc.nasa.gov/media/121238/index.html.
[33] P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].

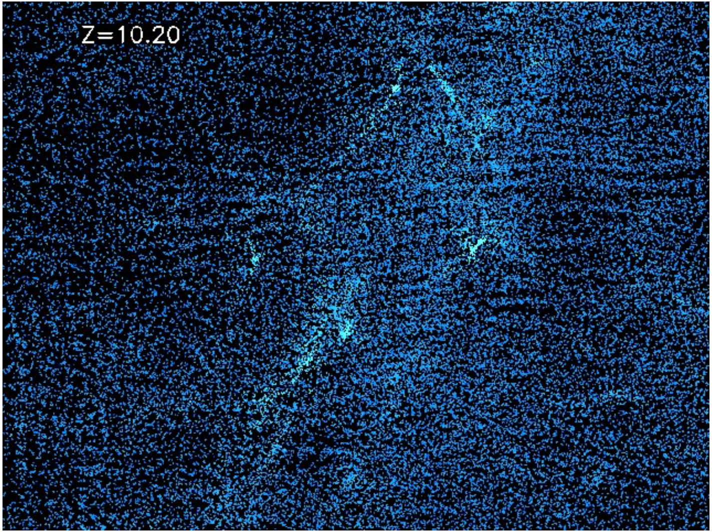
Formation of structures due to gravitational instability



Simulation illustrating the formation of structures due to gravitational instability[34].

[34] Images from http://cfcp.uchicago.edu/lss/group.html.

Formation of structures due to gravitational instability



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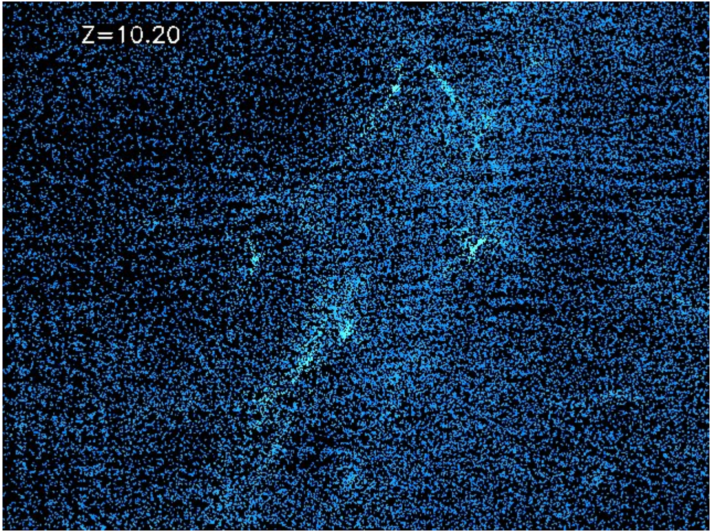

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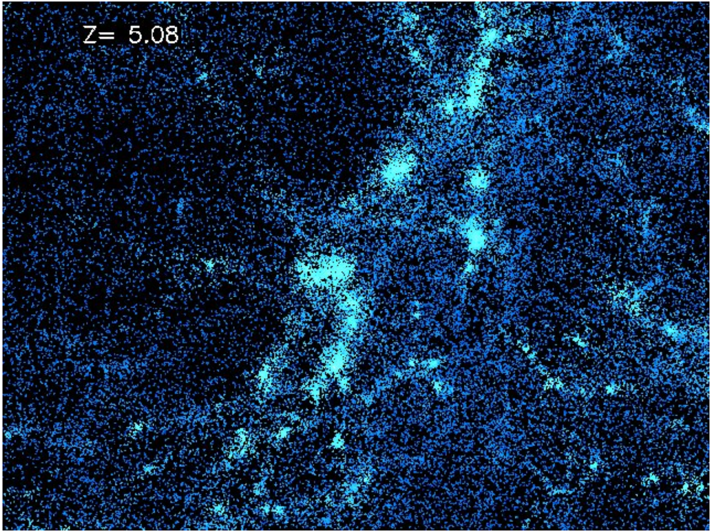

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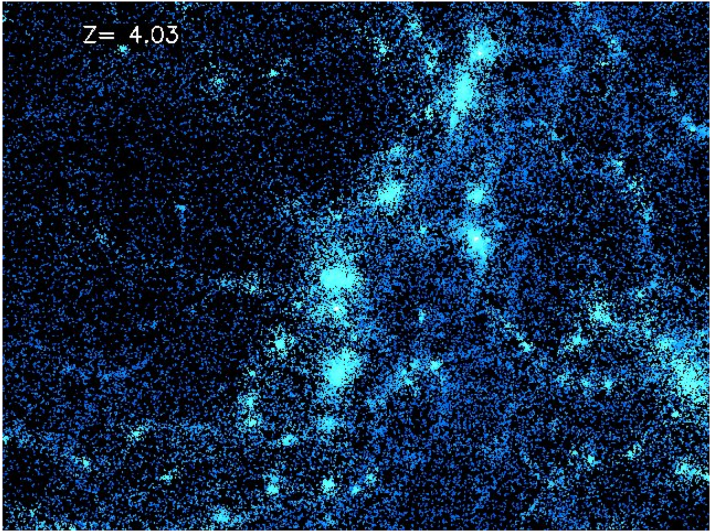

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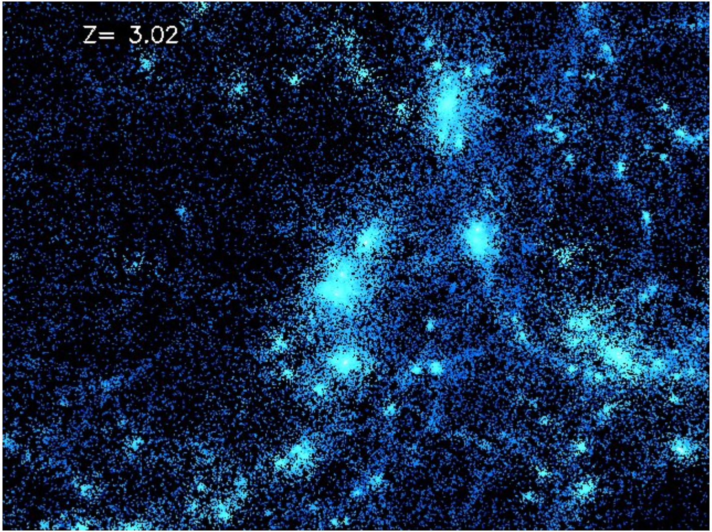

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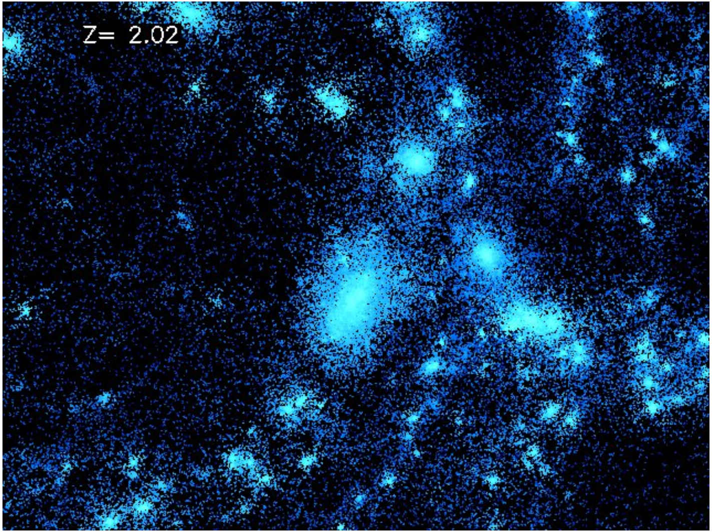
[34] Images from http://cfcp.uchicago.edu/lss/group.html.

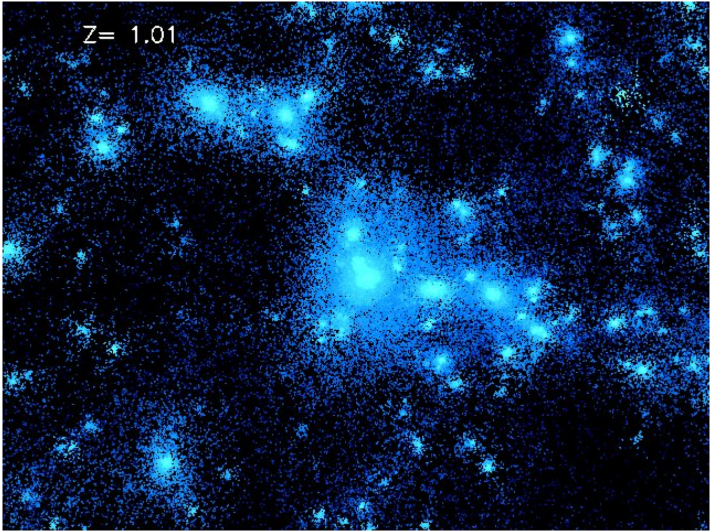
Formation of structures due to gravitational instability



Simulation illustrating the formation of structures due to gravitational instability[34].

[34] Images from http://cfcp.uchicago.edu/lss/group.html.

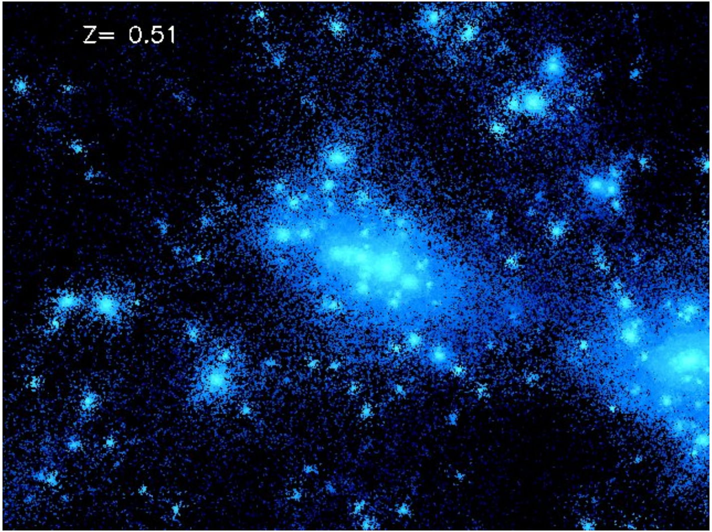
Formation of structures due to gravitational instability



Simulation illustrating the formation of structures due to gravitational instability[34].

[34] Images from http://cfcp.uchicago.edu/lss/group.html.

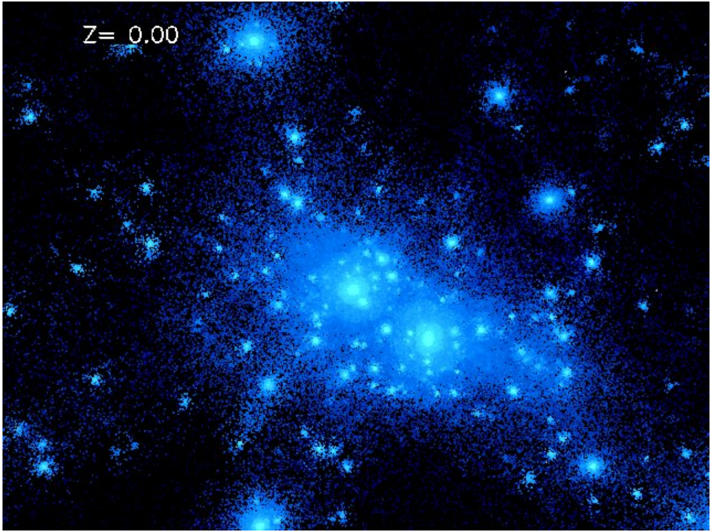
Formation of structures due to gravitational instability



Simulation illustrating the formation of structures due to gravitational instability[34].

[34] Images from http://cfcp.uchicago.edu/lss/group.html.

Formation of structures due to gravitational instability



Play again

Simulation illustrating the formation of structures due to gravitational instability[34].

[34] Images from http://cfcp.uchicago.edu/lss/group.html.

The millennium simulation

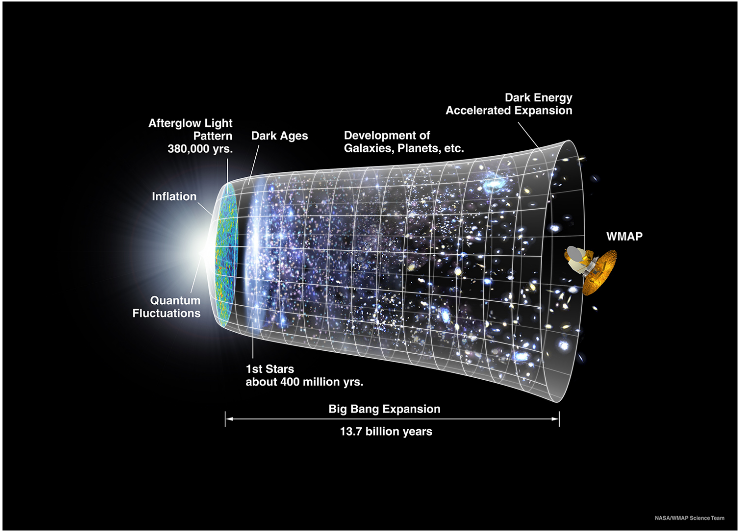
- The Millennium Run used more than 10 billion particles to trace the evolution of the matter distribution in a cubic region of the universe over 2 billion light years on a side[34].
- It kept busy the principal supercomputer at the Max Planck Society's Supercomputing Centre in Garching, Germany for more than a month.

Play movie

[34] See http://www.mpa-garching.mpg.de/galform/virgo/millennium/.

Plan of the talk

The timeline of the universe



A pictorial timeline of the universe[35].

[35] See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

Summary

- According to the currently prevalent view, the inflationary epoch magnifies the tiny fluctuations in the quantum fields present at the beginning of epoch and converts them into classical perturbations.
- These inhomogeneities leave their imprints as anisotropies in the CMB.
- Gravitational instability then takes over, and converts the small anisotropies in the CMB into the large scale structures that we see around us today as galaxies and clusters of galaxies.
- Increasingly precise observations of the anisotropies in the CMB and the distribution of the large scale structure allow us to reconstruct the physics of the early universe.

Ongoing and future missions

The BICEP (top left), Euclid (top right), Square Kilometer Array (bottom left) and the Dark Energy Survey (bottom right) missions are expected to provide unprecedented amount and quality of cosmological data that can help us unravel the mysteries of the universe.

Thank you for your attention