Cosmic structure: Its origins and history

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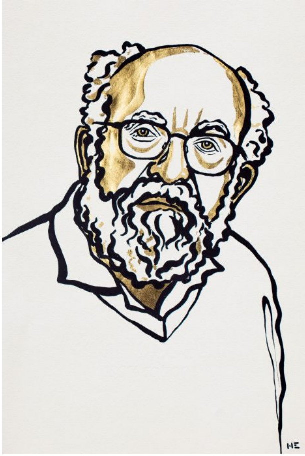
James Peebles of Princeton University, New Jersey, USA, was awarded half of the Nobel Prize in Physics for the year 2019 '*for theoretical discoveries in physical cosmology*'.

Tamilnadu Science and Technology Centre
Chennai
February 12, 2020

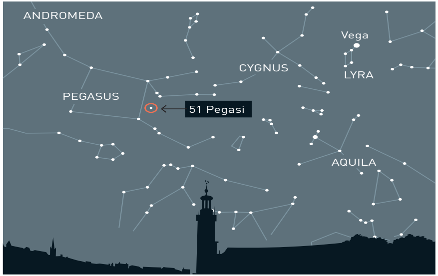
Nobel prize in Physics 2019[1]



The other half of the Nobel Prize in Physics 2019 was awarded jointly to Michel Mayor (on the left) and Didier Queloz (on the right) '*for the discovery of an exoplanet orbiting a solar-type star*'.

[1] Images from https://www.nobelprize.org/prizes/physics/2019/press-release/.

Discovery of the first exoplanet: 51 Pegasi b



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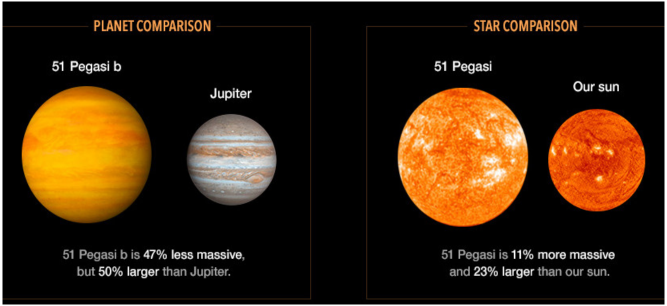


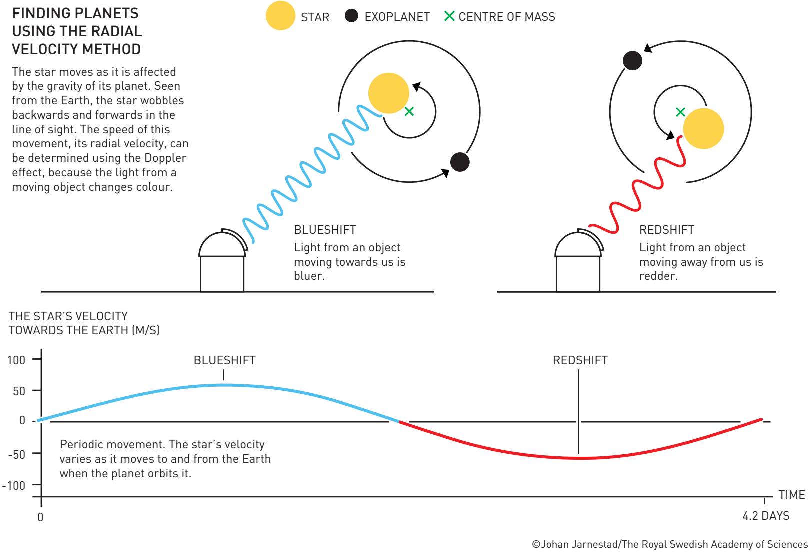
At an observatory in southern France, using custom-made instruments, in 1995, Mayor and Queloz had discovered planet 51 Pegasi b (at the location in the star chart on the left[2]), a gaseous ball comparable with the solar system's biggest gas giant, Jupiter (as illustrated in the image on the right[3]).

The discovery of Mayor and Queloz started a revolution and since then more than 4000 exoplanets have been discovered in our galaxy.

[2] Image from https://www.nobelprize.org/prizes/physics/2019/press-release/.

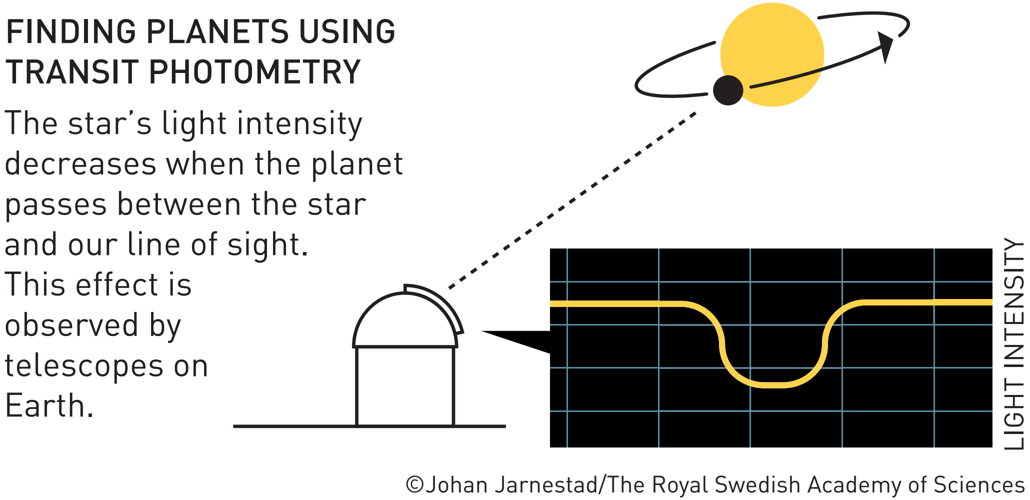
[3] Image from https://exoplanets.nasa.gov/resources/289/infographic-profile-of-planet-51-pegasi-b/.

Discovering exoplanets: Method I[4]



[4] Image from https://www.nobelprize.org/prizes/physics/2019/press-release/.

Discovering exoplanets: Method II[5]



[5] Image from https://www.nobelprize.org/prizes/physics/2019/press-release/

Plan of the talk

1. The universe at large

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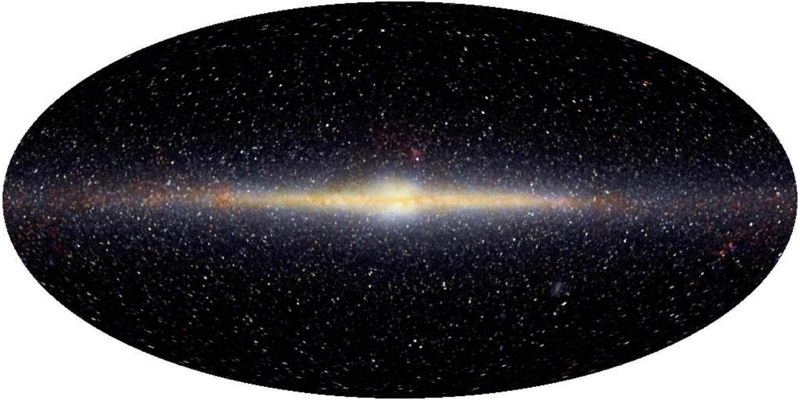
An infrared image of our galaxy



Our galaxy – the Milky Way – as observed by the COsmic Background Explorer (COBE) satellite at the infrared wavelengths[6]. 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 $2 \times 10^{12}\,\mathrm{M}_{\odot}$.

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

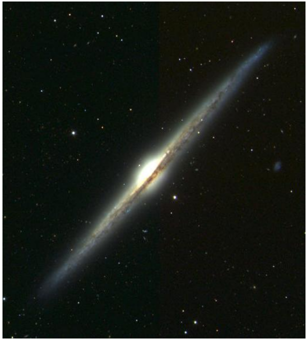
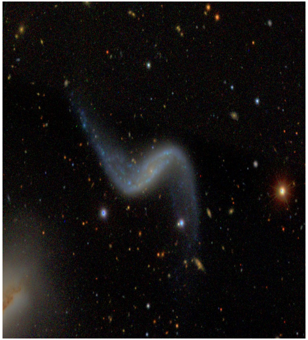
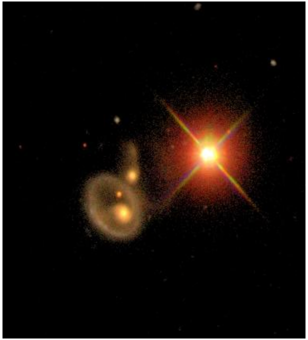
Our galactic neighbors and the local group[7]

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 $1.3\ \mathrm{Mpc}$.

▸ Rotation curves of spiral galaxies

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

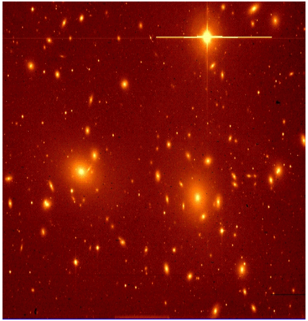
Varieties of galaxies[8]

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.

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

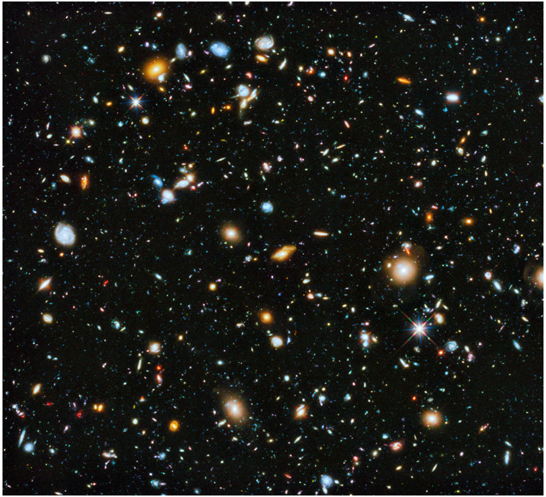
The Virgo, the Coma and the Hercules cluster of galaxies[9]


Left: The Virgo cluster, whose center is considered to be located at a distance of about 20 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 Mpc across, and is located at a distance of about 100 Mpc.
Right: An SDSS image of the Hercules galaxy cluster that is located at a distance of about 100 Mpc from us.

[9] 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.

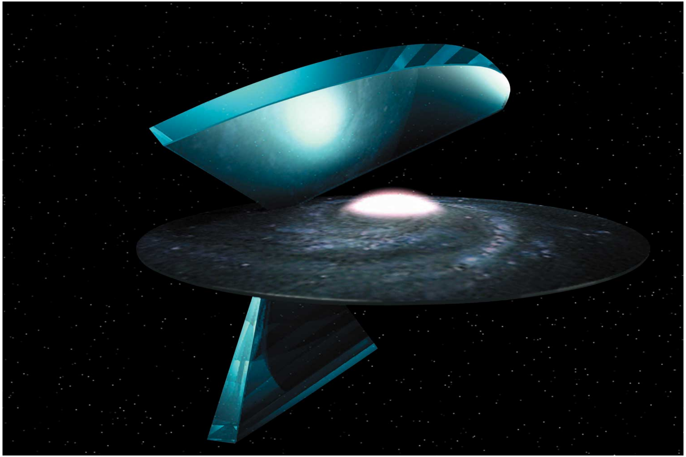
Deepest views in space



An ultra deep field image from the Hubble Space Telescope (HST). The image contains a bewildering variety of galaxy shapes and colors[10].

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

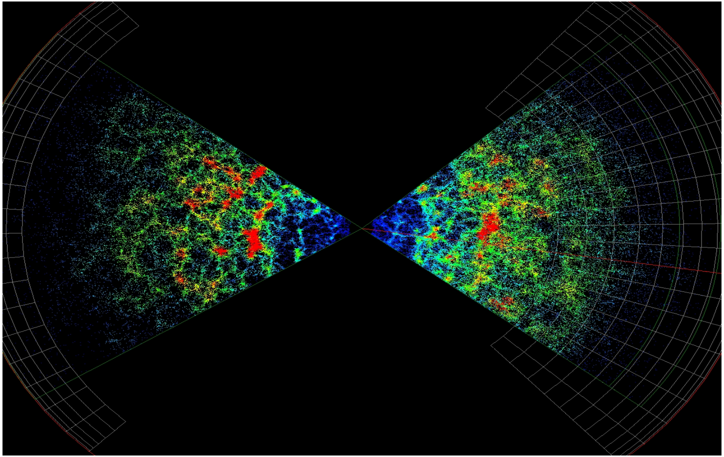
Surveying the universe



A schematic drawing showing the directions of the regions observed by the 2 degree field (2dF) redshift survey with respect to our galaxy[11]. The survey regions actually extend more than 10^5 times further than shown here.

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

Distribution of galaxies in the universe



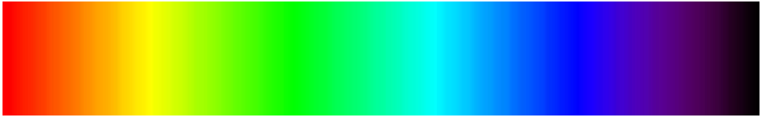
The distribution of more than two million galaxies as observed by the 2dF redshift survey[12]. (Note that each dot in the picture represents a galaxy.) The density and the 'radius' of the universe are estimated to be about $10^{-28}\ \mathrm{kg/m^3}$ and $3000\ \mathrm{Mpc}$, respectively.

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

Plan of the talk

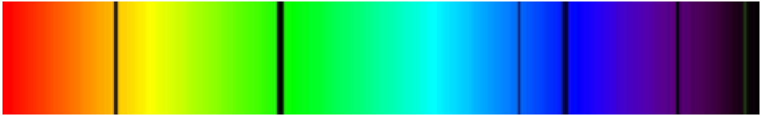
Continuous, emission and absorption spectra[13]

A typical continuous spectrum from an opaque hot body:



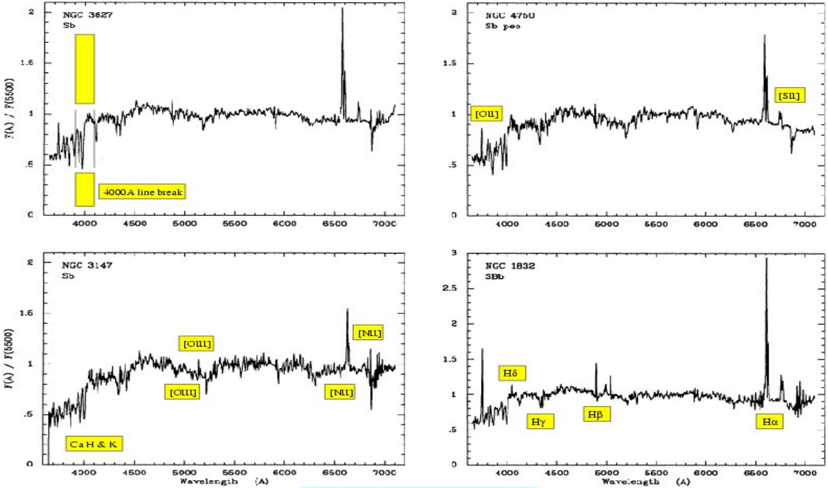
Emission spectrum, as from a given element:

Absorption spectrum, as due to an intervening cool gas:



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

Typical spectra of galaxies[14]

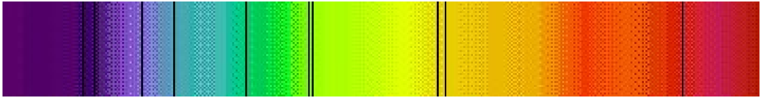


Spectra of some spiral galaxies. The spectra usually contain characteristic emission and absorption lines.

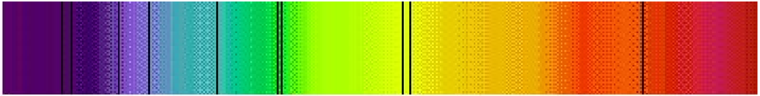
[14] Image from http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html.

The 'Doppler effect' and redshift[15]

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



when compared to the spectrum in the source's frame



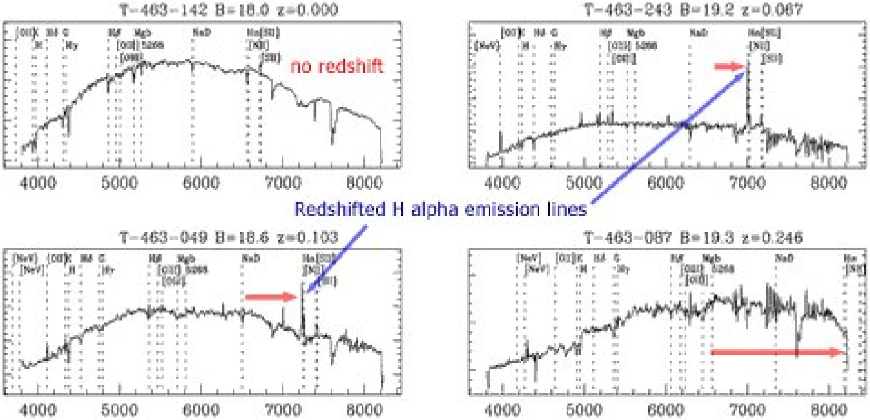
The redshift z of the receding source is defined as:

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

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.

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

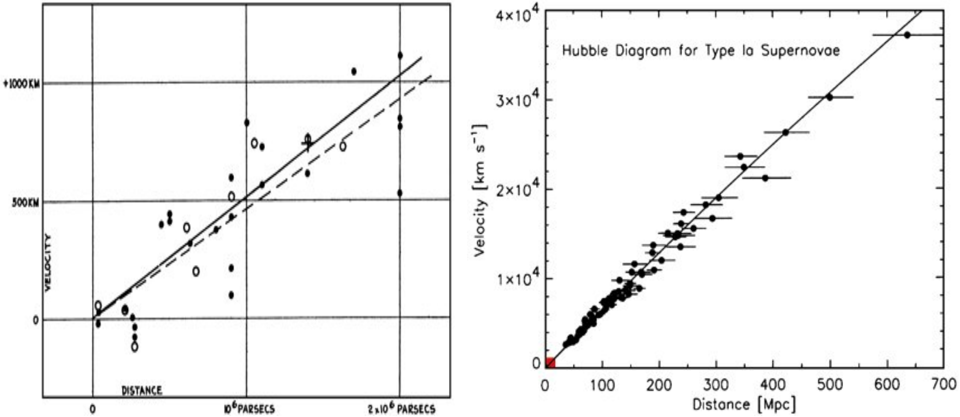
Runaway galaxies[16]



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.

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

Relation between the velocity and the distance of galaxies[17]

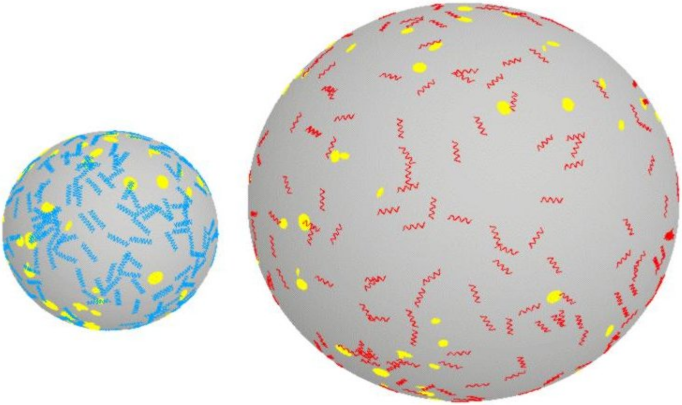


Left: The original Hubble data. The slope of the two fitted lines are about $500\ \mathrm{km/sec/Mpc}$ and $530\ \mathrm{km/sec/Mpc}$.

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

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

Visualizing the expanding universe

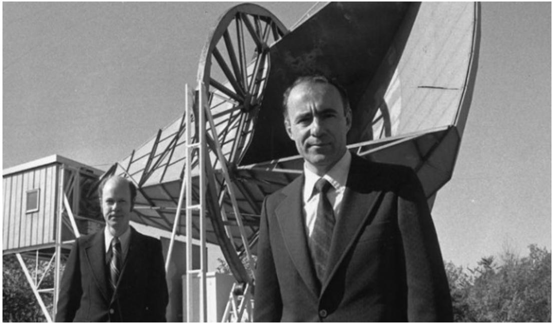


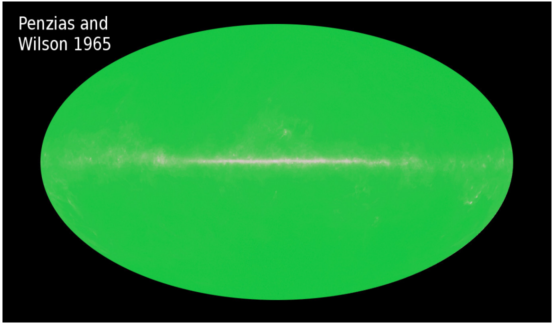
A two-dimensional analogy for the expanding universe[18]. The yellow blobs on the expanding balloon denote the galaxies. Note that the galaxies themselves do not grow, but the distance between the galaxies grows and the wavelengths of the photons shift from blue to red as the universe expands.

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

Plan of the talk

Discovery of the Cosmic Microwave Background (CMB)[19]



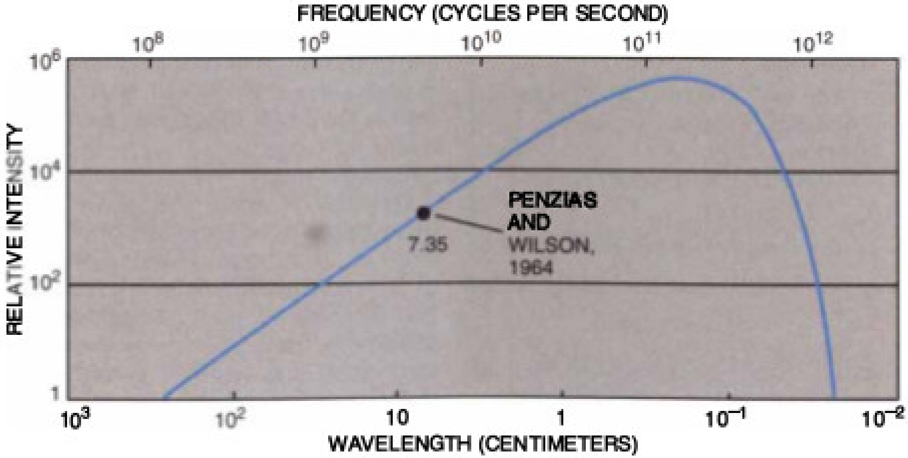


The horn antenna used by Penzias and Wilson (on the left) and the CMB as observed by them (on the right).

Anisotropies observed by COBE

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

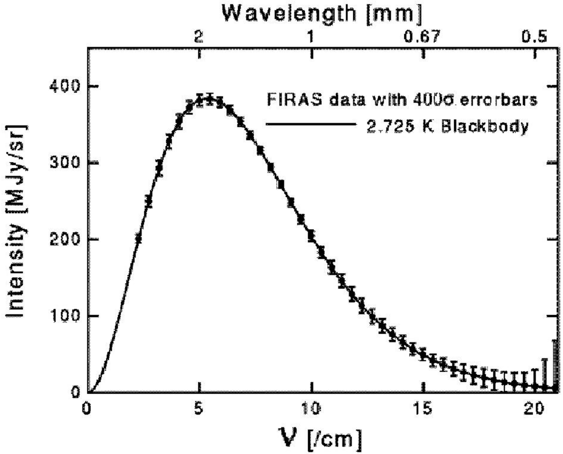
The thermal nature of the CMB



The region of the thermal spectrum observed by Penzias and Wilson[20]

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

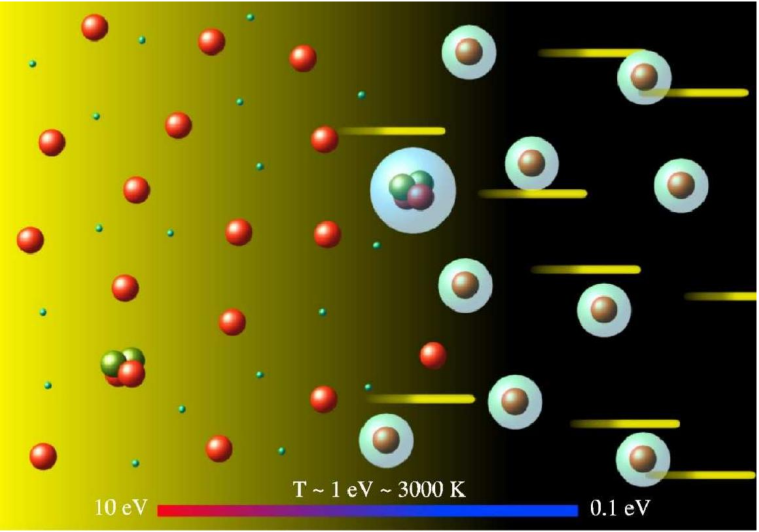
Spectrum of the CMB



The spectrum of the CMB as measured by the COBE satellite[21]. 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!

[21] Image from http://www.astro.ucla.edu/˜wright/cosmo_01.htm.

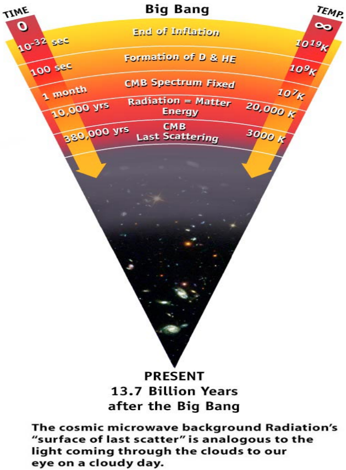
Decoupling of matter and radiation

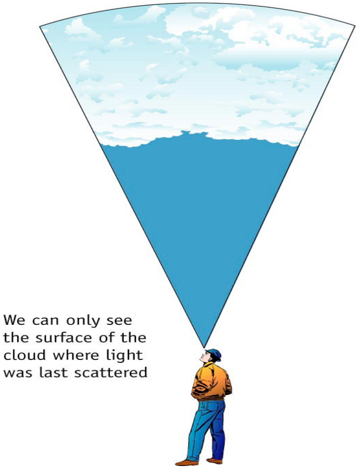


The CMB arises because matter and radiation cease to interact at an early time[22].

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

The last scattering surface and the freestreaming CMB photons

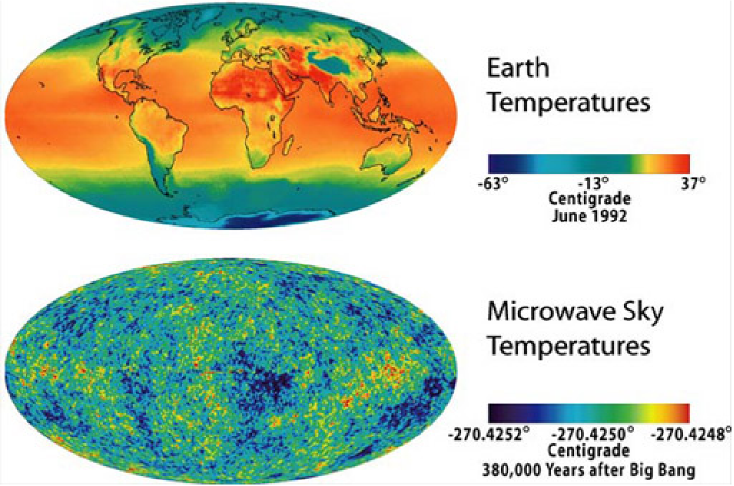




The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter[23].

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

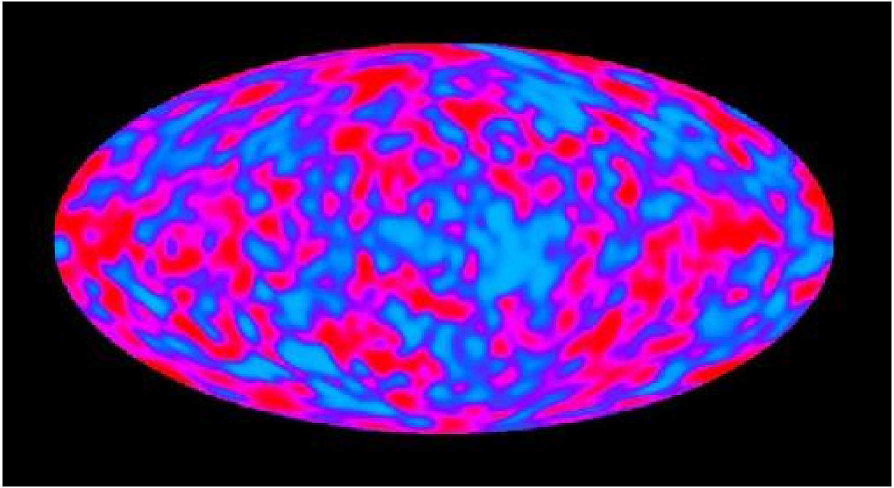
Projecting the last scattering surface



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[24].

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

Anisotropies in the CMB



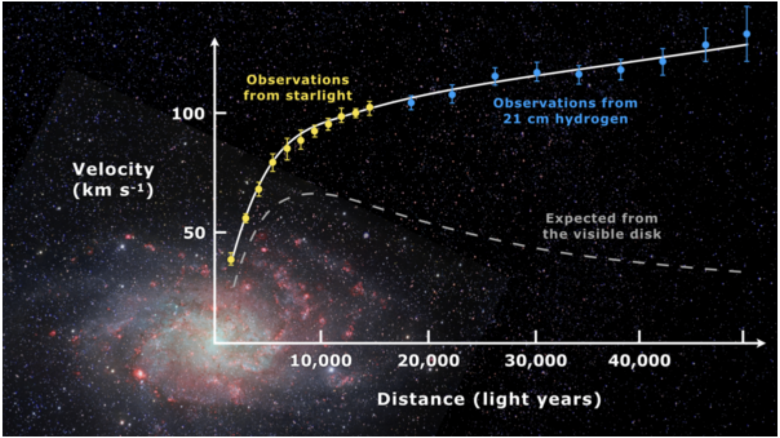
The fluctuations in the temperature of the CMB as seen by COBE[25]. The CMB turns out to be isotropic to one part in 10^5.

▸ The smooth CMB ▸ WMAP and Planck

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

Plan of the talk

Rotation curves of spiral galaxies

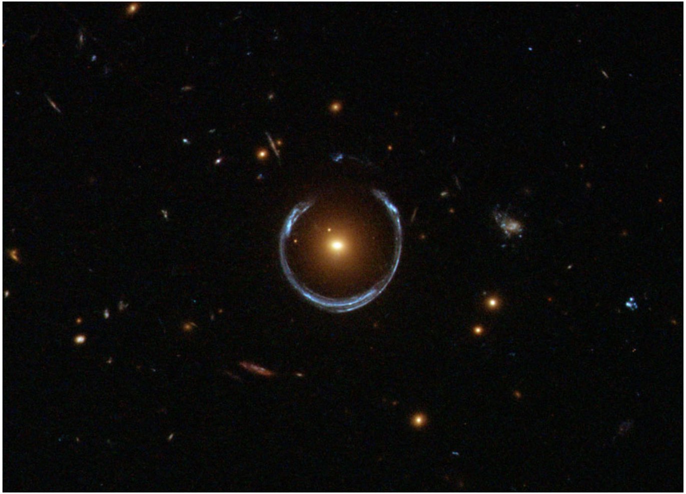


The M33 galaxy

The observed rotation curve of the spiral galaxy M33 (yellow and blue points with error bars), and the predicted curve from the distribution of visible matter (gray line). The observed curve can be accounted for by embedding the galaxy in a dark matter halo[26].

[26] Image from https://en.wikipedia.org/wiki/Galaxy_rotation_curve.

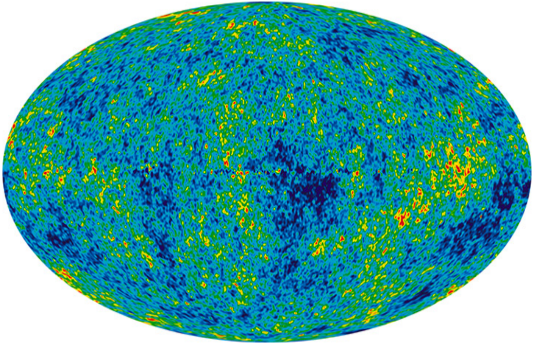
Gravitational lensing reveals the distribution of matter

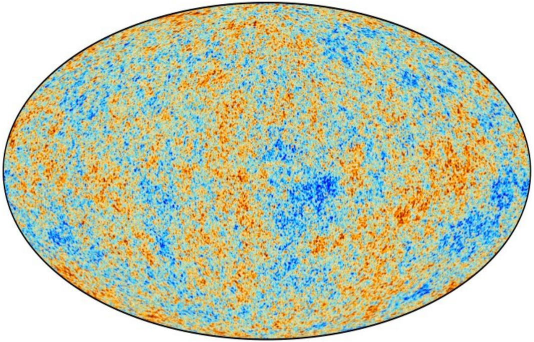


A near perfect Einstein ring! The ring is formed due to the gravitational field of the foreground luminous red galaxy which distorts the light from a more distant blue galaxy[27].

[27] Image from https://apod.nasa.gov/apod/ap111221.html.

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[28]. ▸ COBE

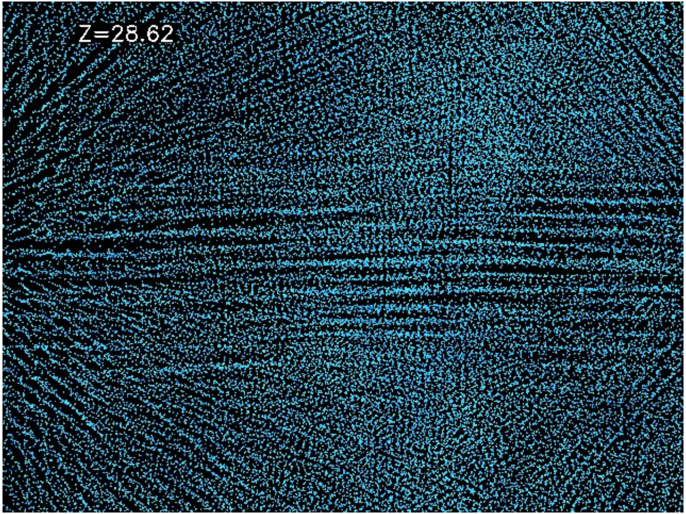
Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\ \mathrm{MHz}$ observations[29]. The above images show temperature variations (as color differences) of the order of $200^\circ\ \mu\mathrm{K}$.

[28] Image from http://wmap.gsfc.nasa.gov/media/121238/index.html.

[29] P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].

Plan of the talk

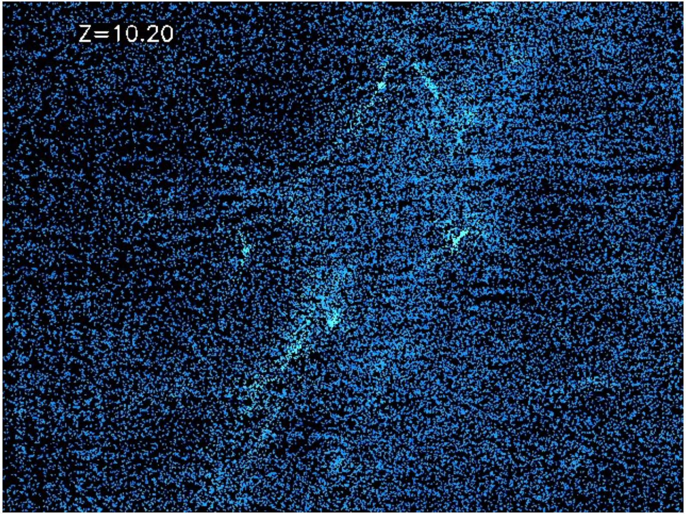
Formation of structures due to gravitational instability



Simulation illustrating the formation of structures due to gravitational instability[30].

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

Formation of structures due to gravitational instability



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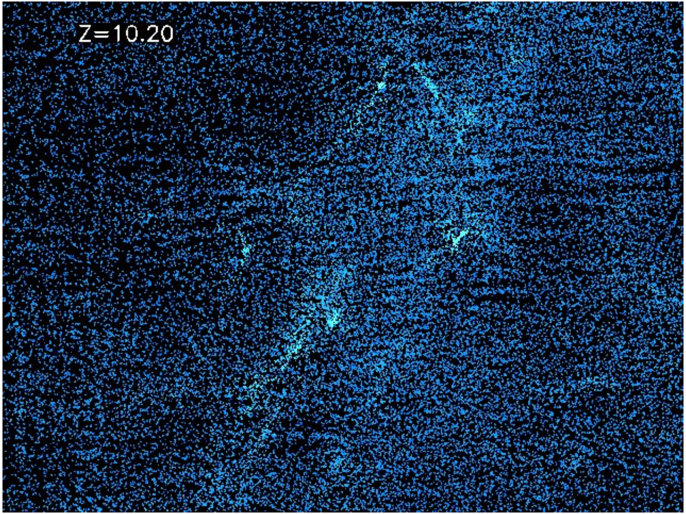

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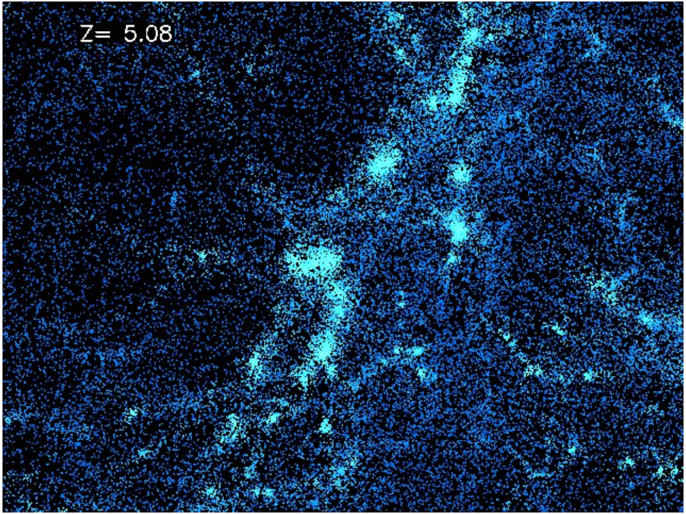

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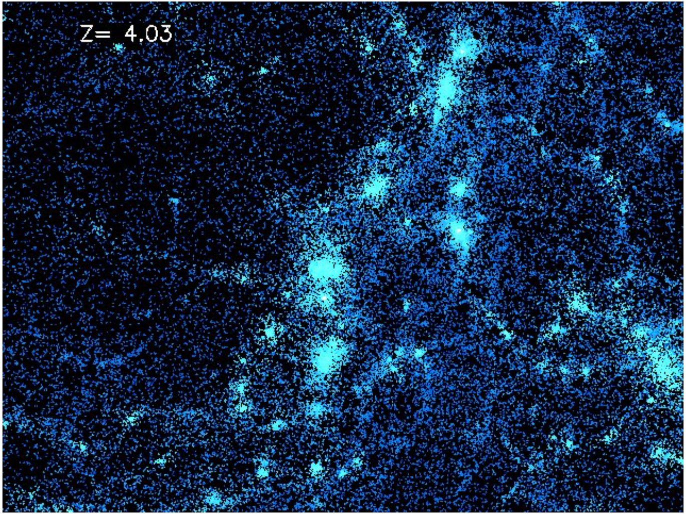

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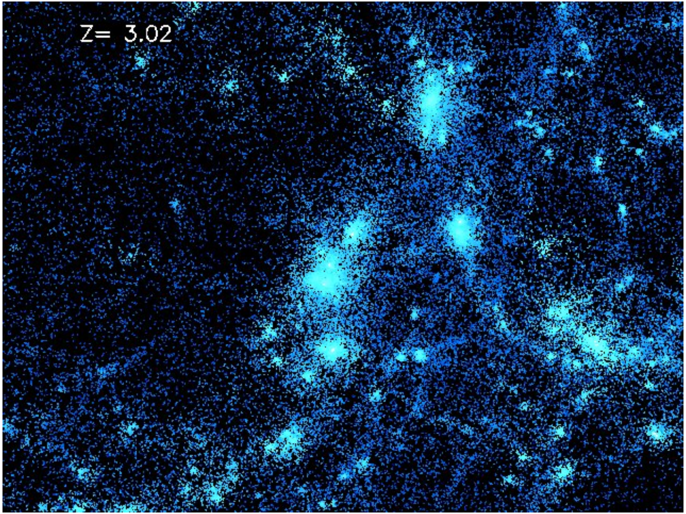

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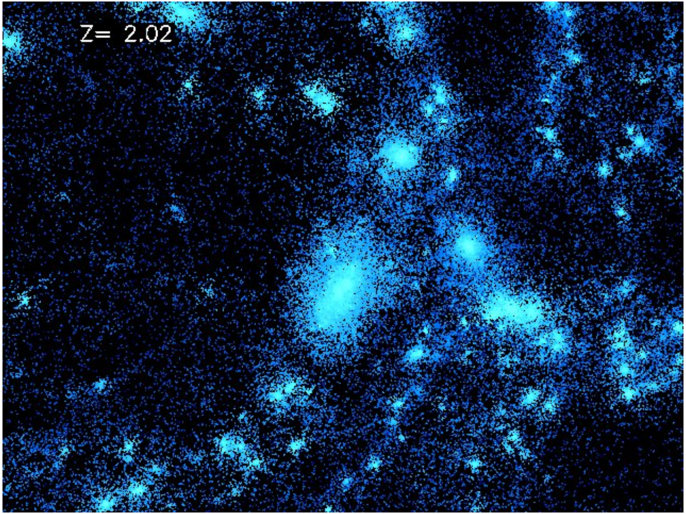

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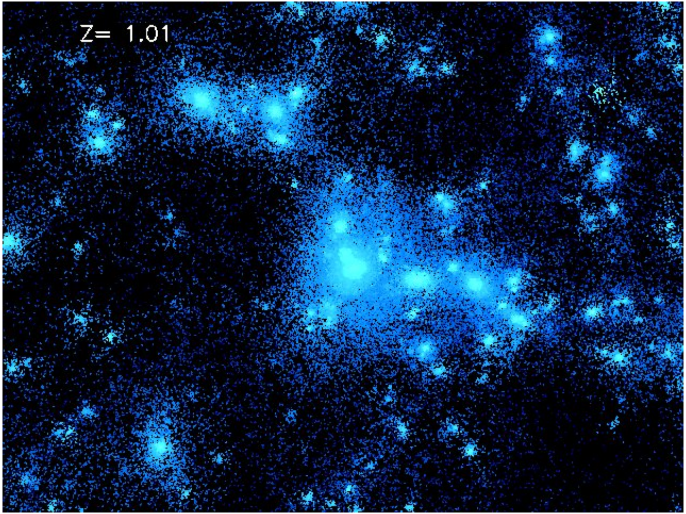

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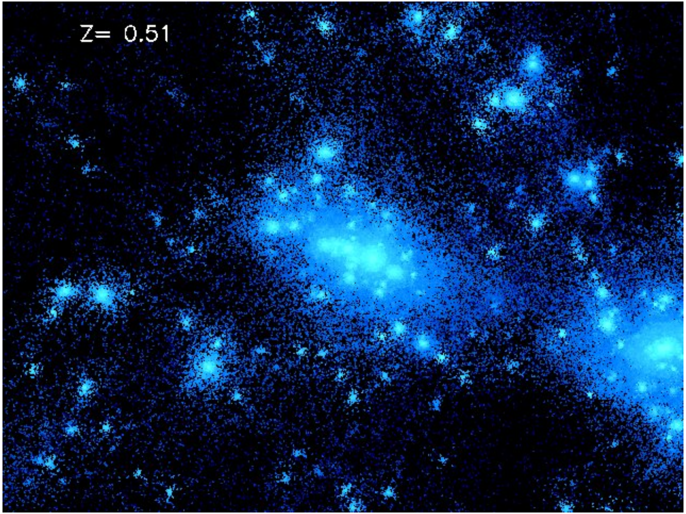

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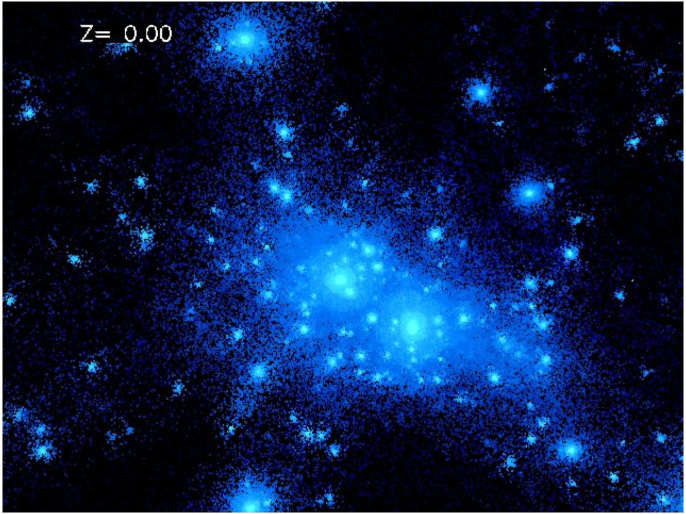


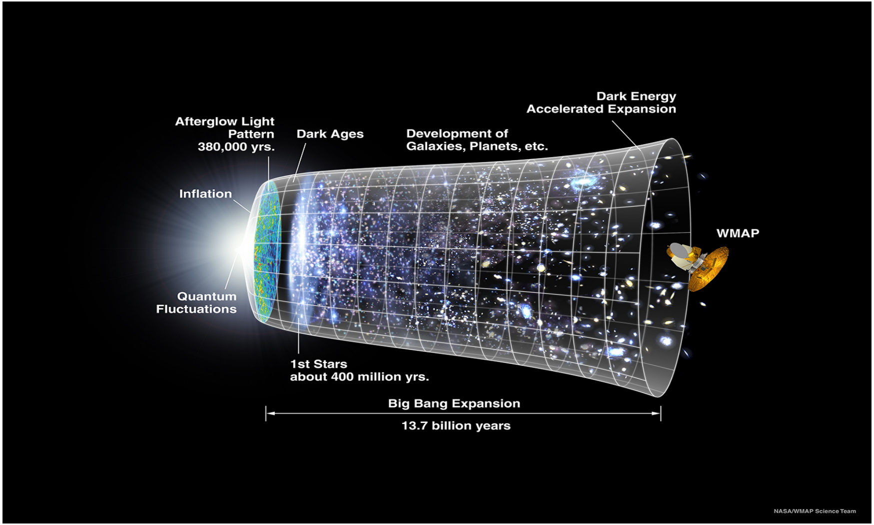
▸ Play again

Simulation illustrating the formation of structures due to gravitational instability[30].

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

Plan of the talk

The timeline of the universe



A pictorial timeline of the universe[30].

[30] Image from http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

Thank you for your attention