

Cosmic structure: Its origins and history

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January 23, 2023

Plan of the talk

1 The universe at large



Plan of the talk

- 1 The universe at large
- 2 The expanding universe



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- 3 The cosmic microwave background



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- 2 The expanding universe
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- 4 The need for dark matter
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- 6 Summary

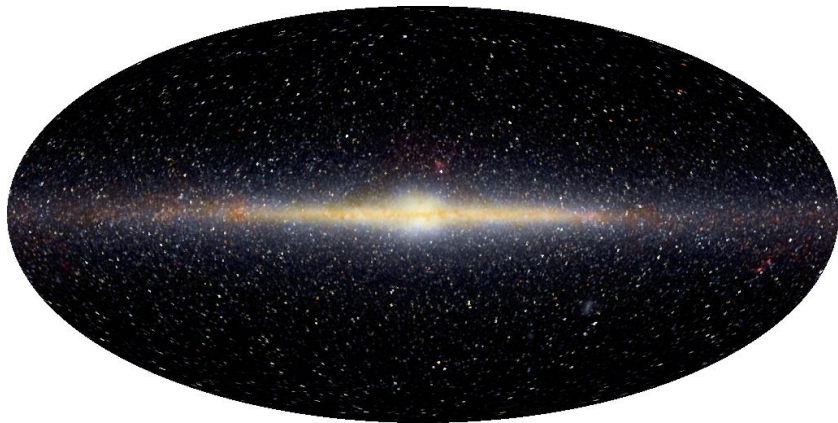


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An infrared image of our galaxy

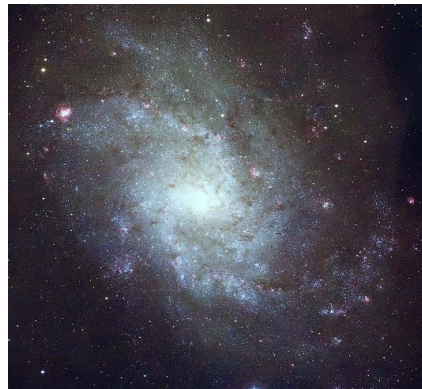


Our galaxy – the Milky Way – as observed by the COsmic Background Explorer (COBE) satellite at the infrared wavelengths¹. The diameter of the disc of our galaxy is, approximately, 45×10^3 ly or 15 kpc (*i.e.* a kilo parsec, with $1 \text{ pc} \simeq 3.26 \text{ ly}$). It contains about 10^{11} stars such as the Sun, and its mass is about $2 \times 10^{12} M_{\odot}$.

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



Our galactic neighbors and the local group²



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** kpc.

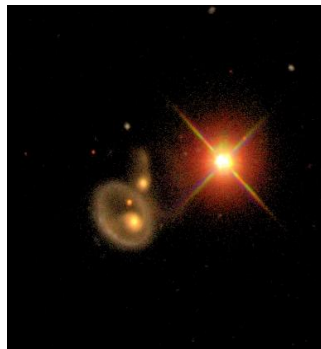
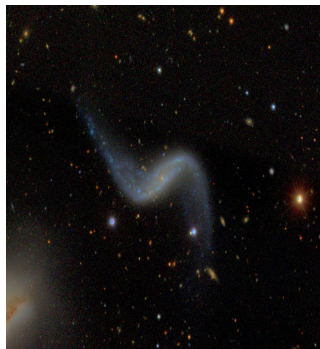
Right: The Triangulum galaxy M33. These galaxies, along with our galaxy, are major members of a local group of about **30** galaxies that are bound gravitationally. The size of the local group is estimated to be about **1.3** Mpc.

▶ Rotation curves of spiral galaxies



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

Varieties of galaxies³



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.

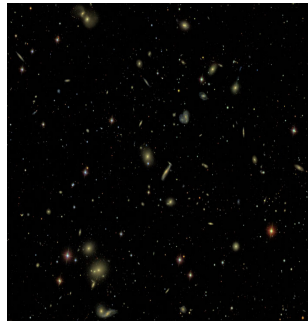
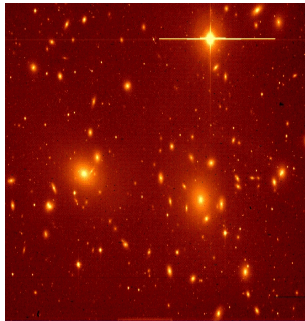
Center: An image of the spiral galaxy NGC 3187 from SDSS.

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.

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



The Virgo, the Coma and the Hercules cluster of galaxies⁴



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.

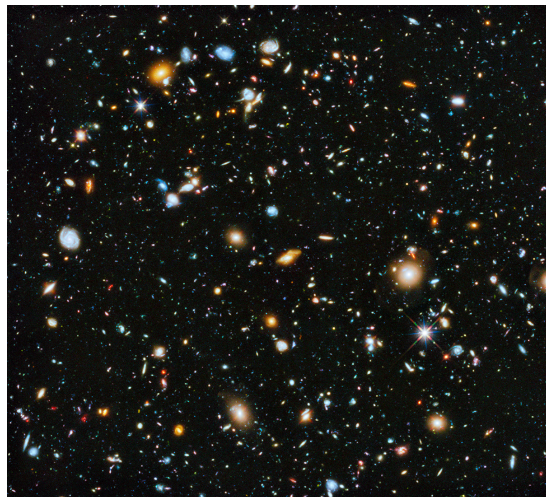
Center: The Coma cluster of galaxies, which contains more than 1000 bright galaxies. It is about 20 Mpc across, and is located at a distance of about 100 Mpc.

Right: An SDSS image of the Hercules galaxy cluster that is located at a distance of about 100 Mpc from us.

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

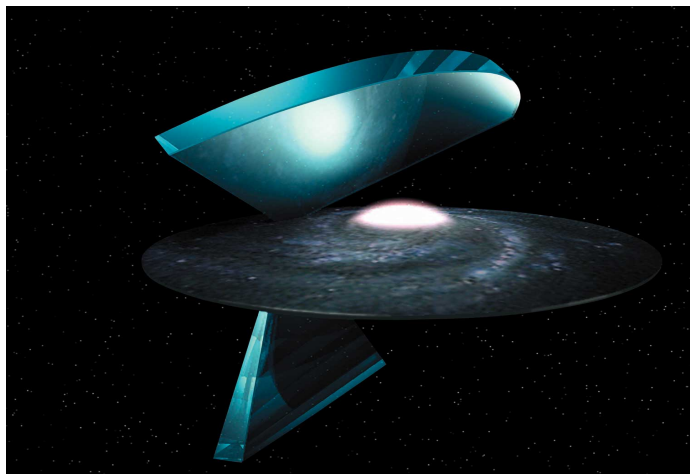


An ultra deep field image from the Hubble Space Telescope (HST). The image contains a bewildering variety of galaxy shapes and colors⁵.

⁵Image from <http://hubblesite.org/newscenter/archive/releases/2014/27>.



Surveying the universe

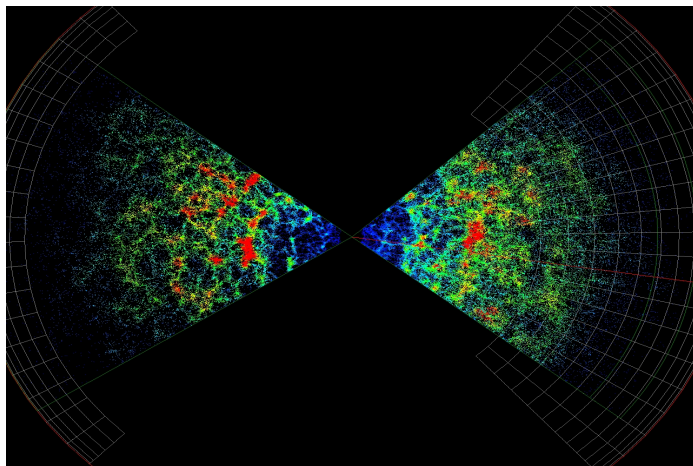


A schematic drawing showing the directions of the regions observed by the 2 degree field (2dF) redshift survey with respect to our galaxy⁶. The survey regions actually extend more than 10^5 times further than shown here.

⁶Image 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 survey⁷. (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} kg/m³ and 3000 Mpc, respectively.

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



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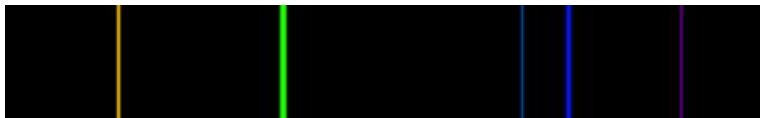


Continuous, emission and absorption spectra⁸

A typical continuous spectrum from an opaque hot body:



Emission spectrum, as from a given element:



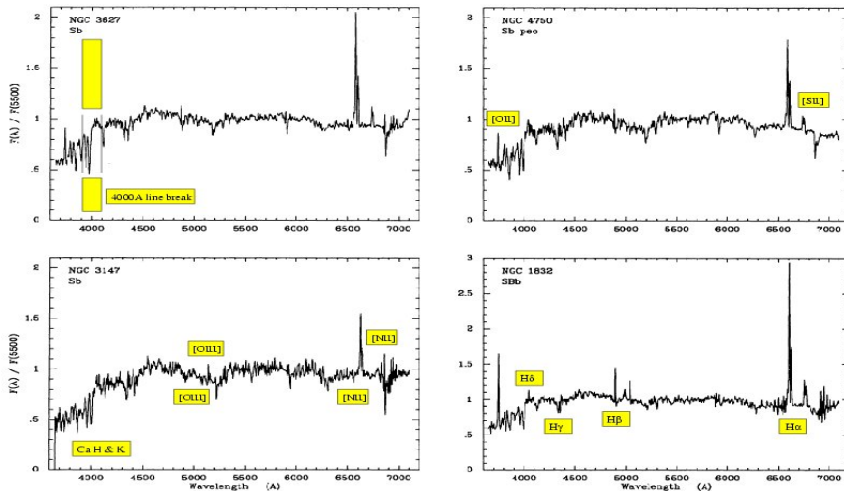
Absorption spectrum, as due to an intervening cool gas:



⁸Images from <http://hea-www.harvard.edu/~efortin/thesis/html/Spectroscopy.shtml>.



Typical spectra of galaxies⁹



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

⁹Image from <http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html>.



The 'Doppler effect' and redshift¹⁰

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



when compared to the spectrum in the source's frame



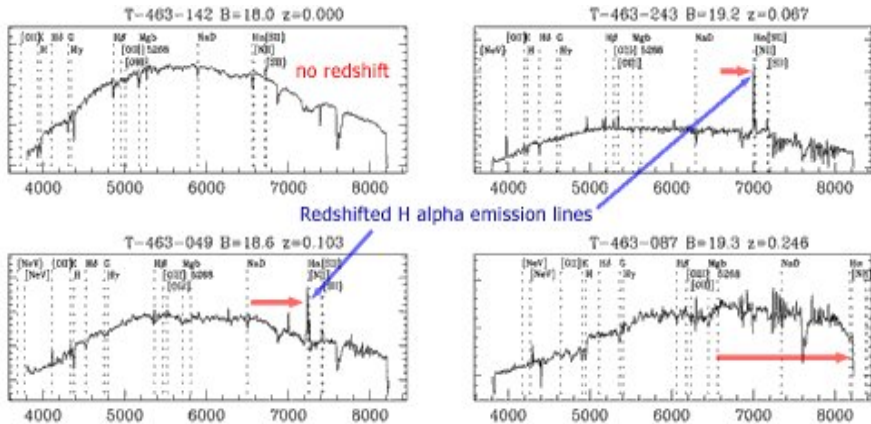
The redshift z of the receding source is defined as:

$$1 + z = \frac{\lambda_O}{\lambda_E} = \frac{\omega_E}{\omega_O},$$

where λ_O and ω_O denote the observed wavelength and frequency of the source, while λ_E and ω_E denote its emitted wavelength and frequency, respectively.

¹⁰Images from <http://www.astronomynotes.com/light/s10.htm>.



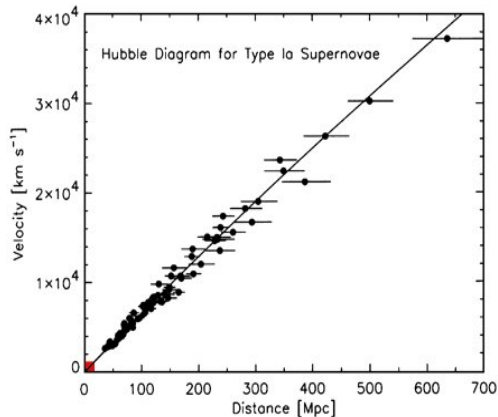
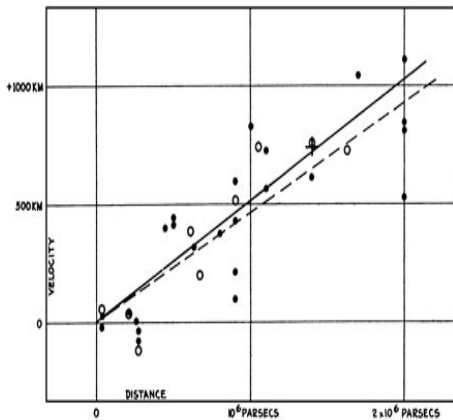
Runaway galaxies¹¹

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 H α emission lines, which have been redshifted from the rest frame value of 6563 \AA .

¹¹Image from http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.



Relation between the velocity and the distance of galaxies¹²



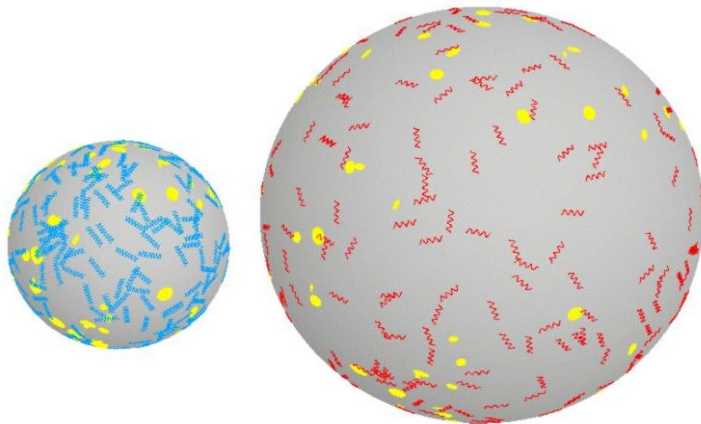
Left: The original Hubble data. The slope of the two fitted lines are about **500** km/sec/Mpc and **530** km/sec/Mpc.

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

¹²R. Kirshner, Proc. Natl. Acad. Sci. USA **101**, 8 (2004).



Visualizing the expanding universe



A two-dimensional analogy for the expanding universe¹³. 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.

¹³Image from <http://www.astro.ucla.edu/~wright/balloon0.html>.

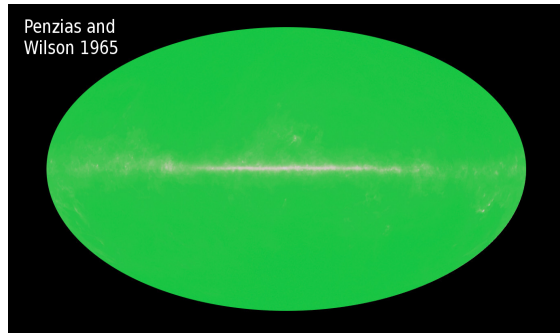
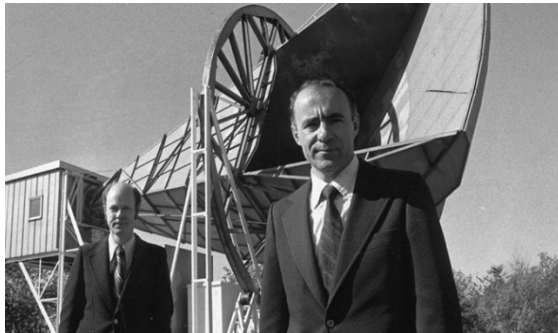


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Discovery of the Cosmic Microwave Background (CMB)¹⁴



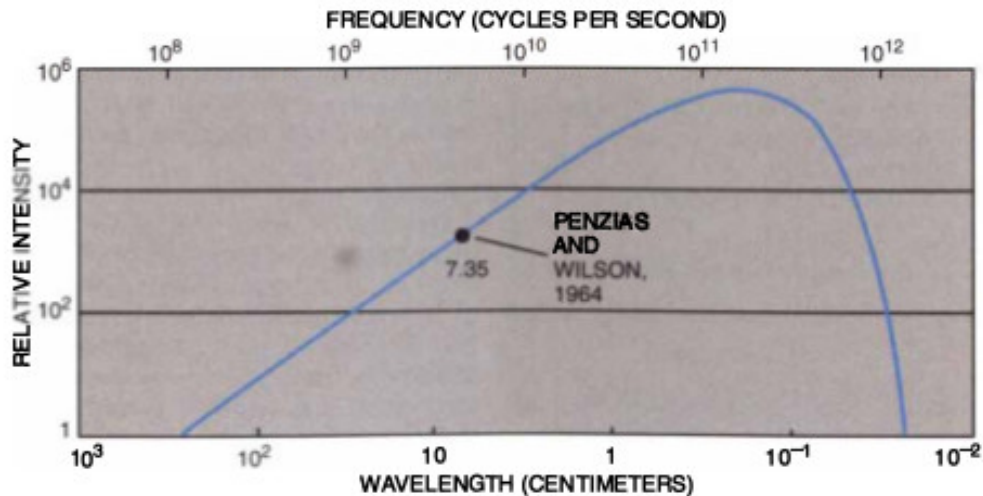
The horn antenna used by Penzias and Wilson (on the left) and the CMB as observed by them (on the right).

► Anisotropies observed by COBE

¹⁴In this context, see, for instance, S. G. Brush, *Sci. Am.* **267**, 62 (1992).



The thermal nature of the CMB

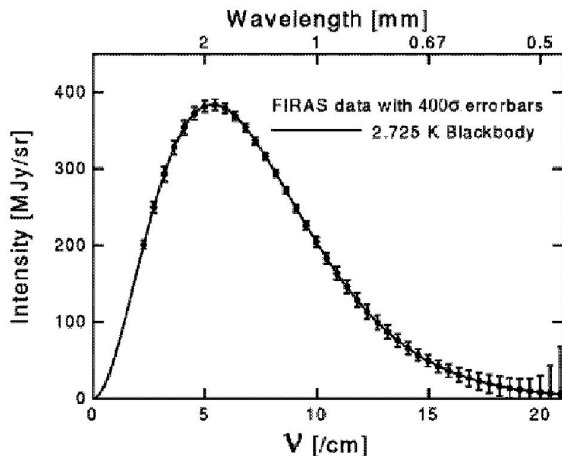


The region of the thermal spectrum observed by Penzias and Wilson¹⁵

¹⁵Image from, S. G. Brush, *Sci. Am.* **267**, 62 (1992).



Spectrum of the CMB

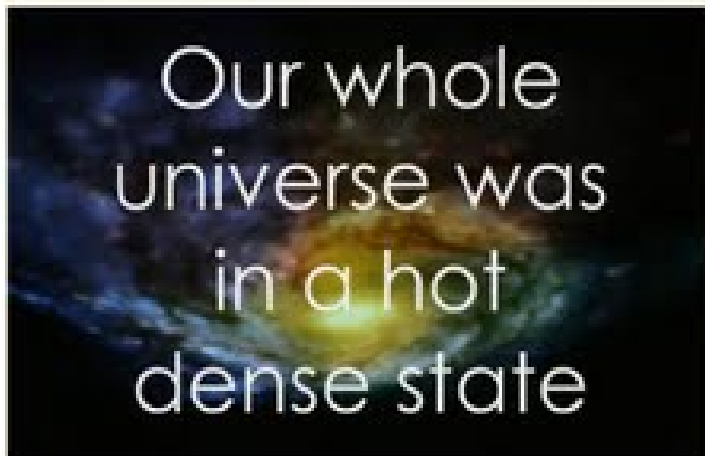


The spectrum of the CMB as measured by the COBE satellite¹⁶. It is a perfect Planck spectrum (corresponding to a temperature of 2.725°K) which is unlikely to be bettered in the laboratory. The error bars have been amplified 400 times so that they are visible!

¹⁶Image from http://www.astro.ucla.edu/~wright/cosmo_01.htm.



The big bang model seems popular!

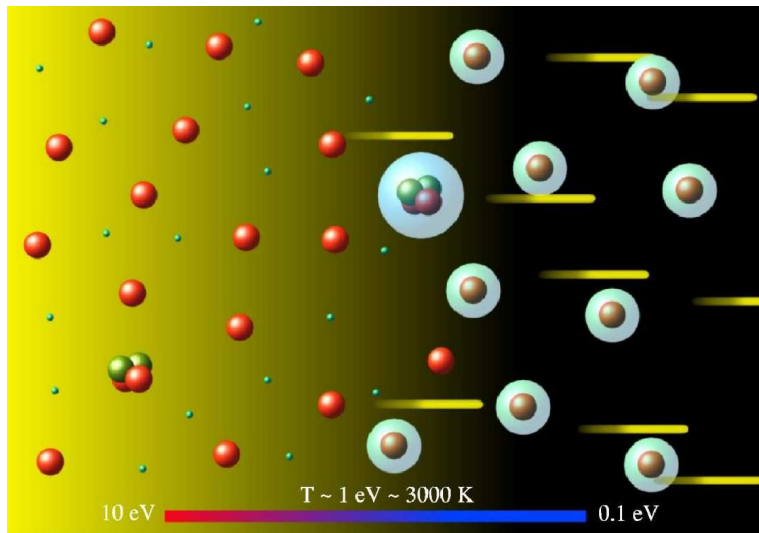


The current view of the universe, encapsulated in the hot big bang model, seems popular. The above image is a screen grab from the theme song of the recent American sitcom 'The Big Bang Theory'¹⁷!

¹⁷See http://www.cbs.com/shows/big_bang_theory/.



Decoupling of matter and radiation

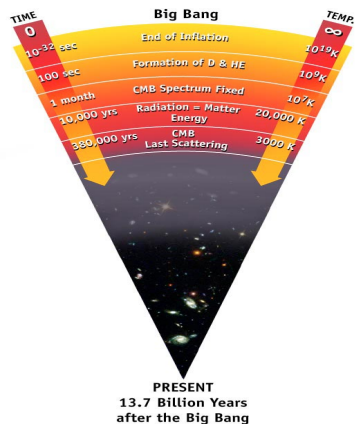


The CMB arises because matter and radiation cease to interact at an early time¹⁸.

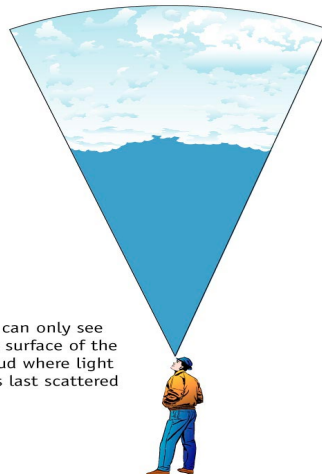
¹⁸Image from W. H. Kinney, [arXiv:astro-ph/0301448v2](https://arxiv.org/abs/astro-ph/0301448v2).



The last scattering surface and the freestreaming CMB photons



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



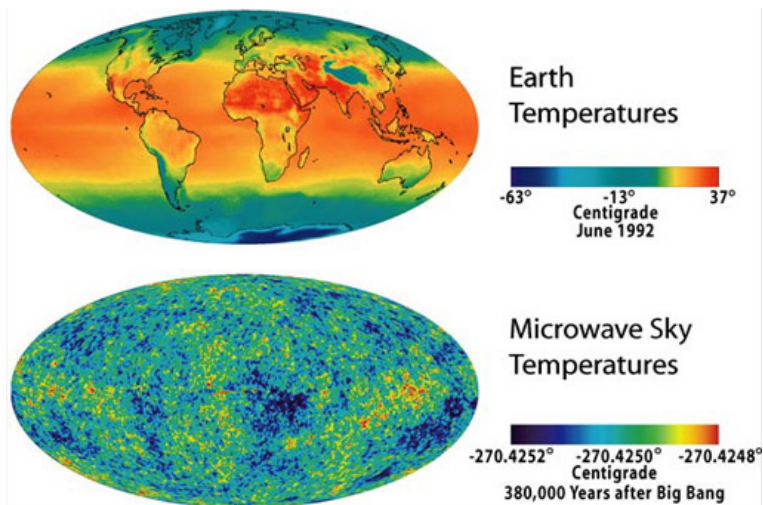
We can only see the surface of the cloud where light was last scattered

The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter¹⁹.

¹⁹Image from <http://map.gsfc.nasa.gov/media/990053/990053.jpg>.



Projecting the last scattering surface

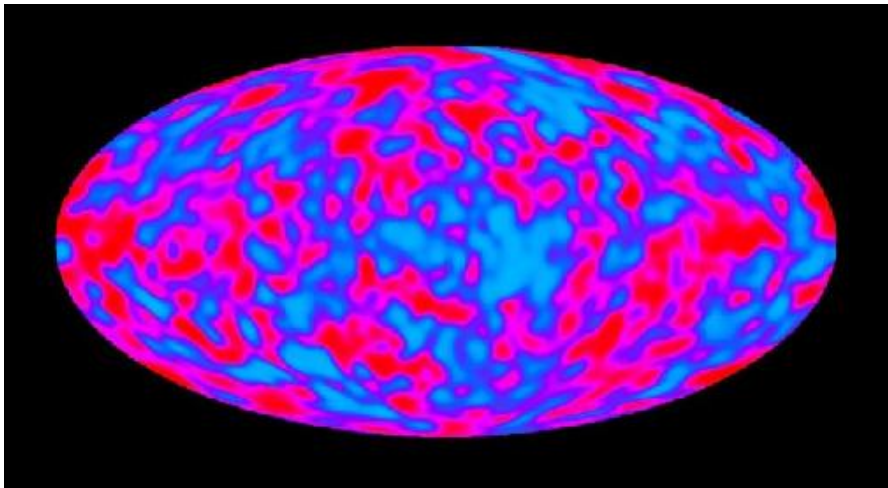


The temperature of the CMB on the last scattering surface can be projected on to a plane as the surface of the Earth is often projected²⁰.

²⁰Image 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 COBE²¹. The CMB turns out to be isotropic to one part in 10^5 .

▶ The smooth CMB

▶ WMAP and Planck



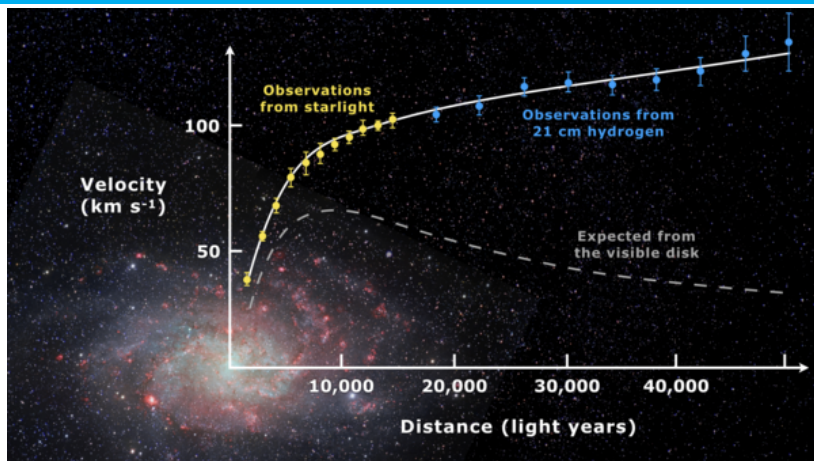
²¹Image from http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html.

Plan of the talk

- 1 The universe at large
- 2 The expanding universe
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Rotation curves of spiral galaxies



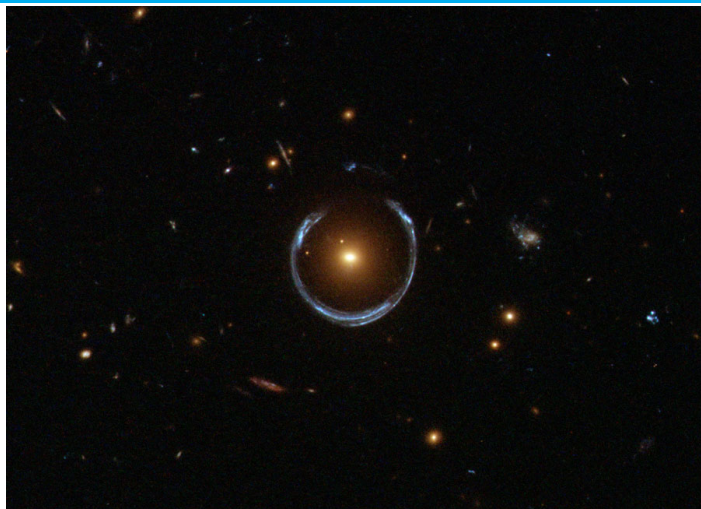
► The M33 galaxy

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 halo²².

²²Image from https://en.wikipedia.org/wiki/Galaxy_rotation_curve.



Gravitational lensing reveals the distribution of matter

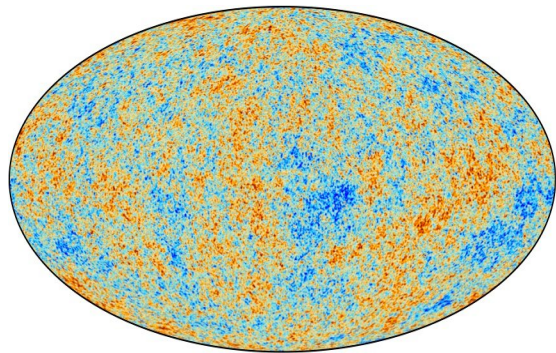
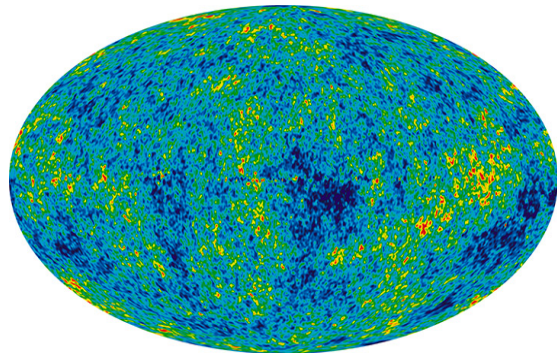


A near perfect Einstein ring! The ring is formed due to the gravitational field of the foreground luminous red galaxy which distorts the light from a more distant blue galaxy²³.

²³Image 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) data²⁴.

► COBE

Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and 408 MHz observations²⁵. The above images show temperature variations (as color differences) of the order of $200^\circ \mu\text{K}$.

²⁴Image from <http://wmap.gsfc.nasa.gov/media/121238/index.html>.

²⁵P. A. R. Ade *et al.*, [arXiv:1502.01582 \[astro-ph.CO\]](https://arxiv.org/abs/1502.01582).

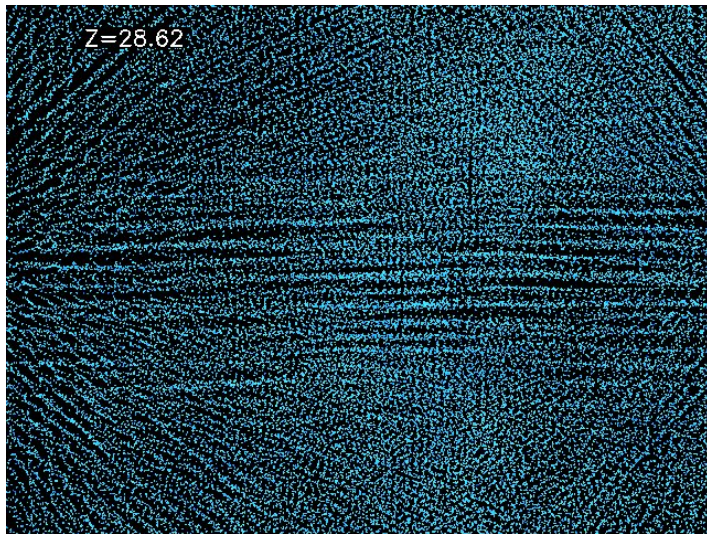


Plan of the talk

- 1 The universe at large
- 2 The expanding universe
- 3 The cosmic microwave background
- 4 The need for dark matter
- 5 Formation of large scale structure**
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Formation of structures due to gravitational instability

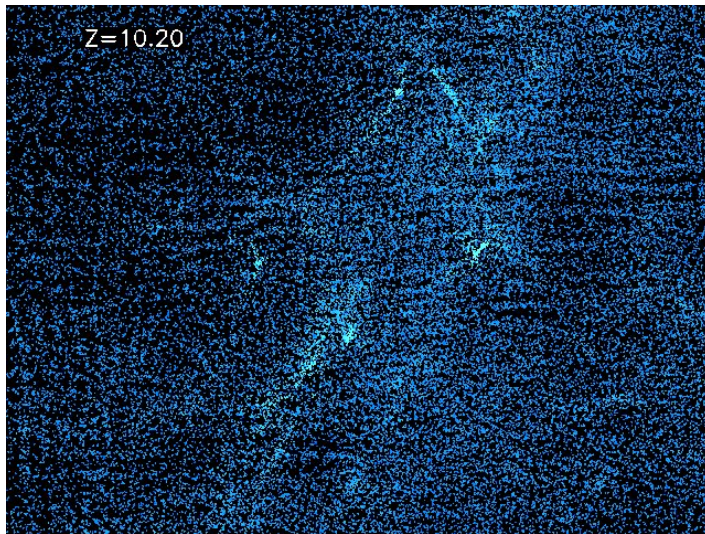


Simulation illustrating the formation of structures due to gravitational instability²⁶.

²⁶Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

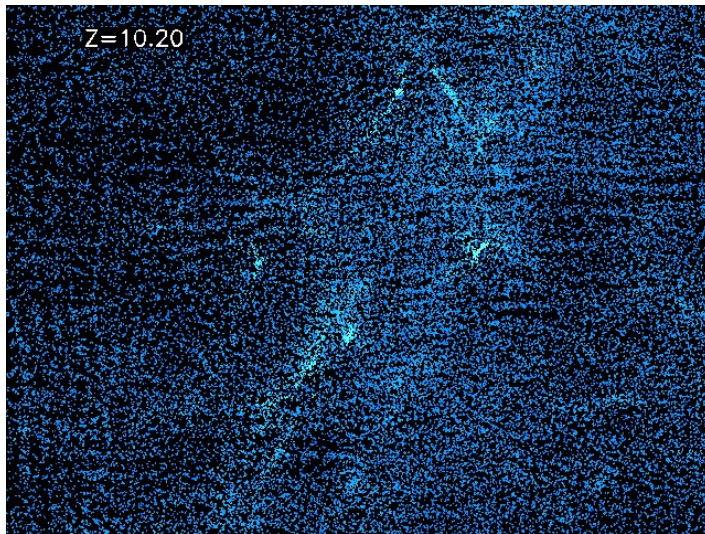


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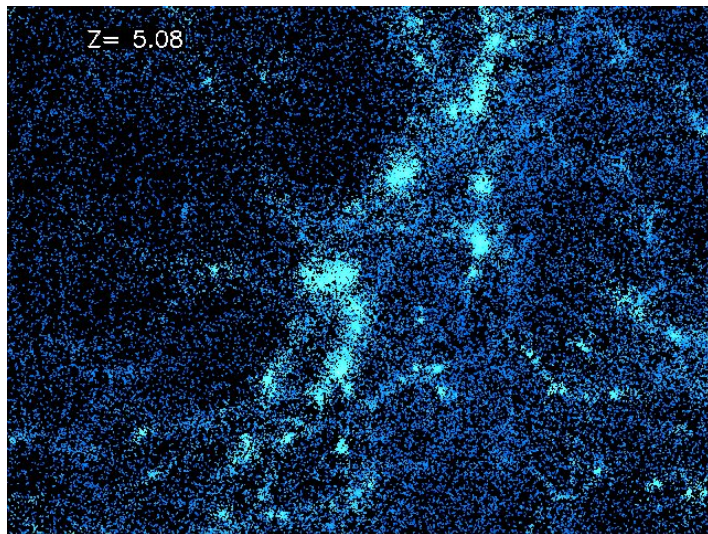


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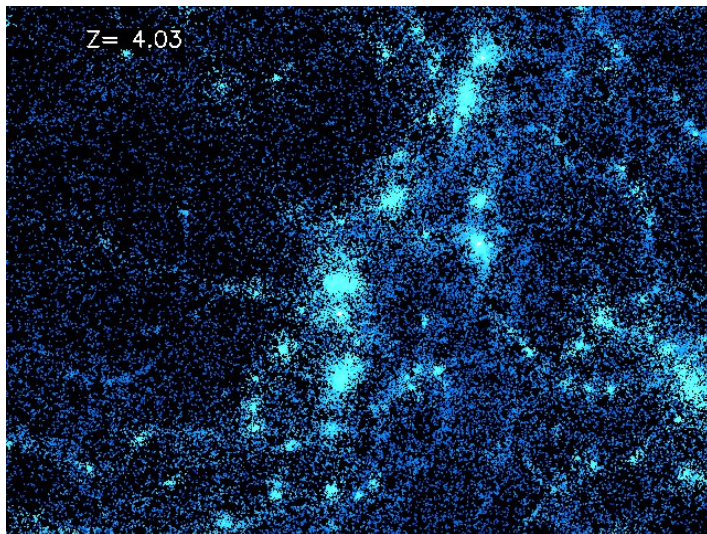


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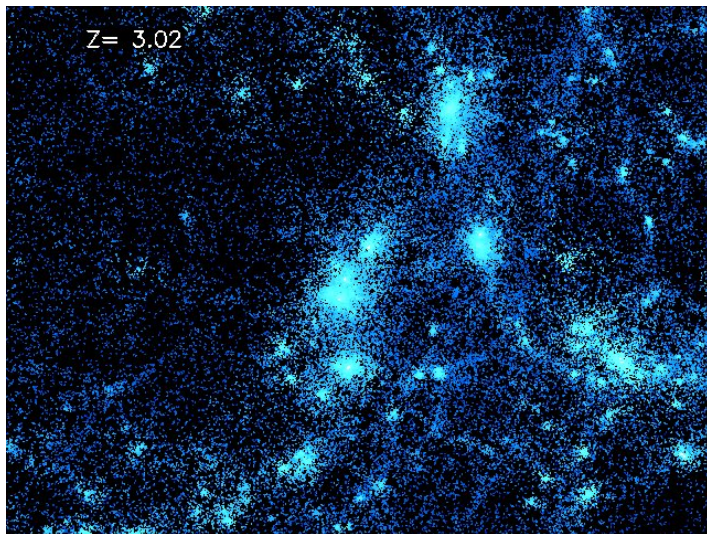


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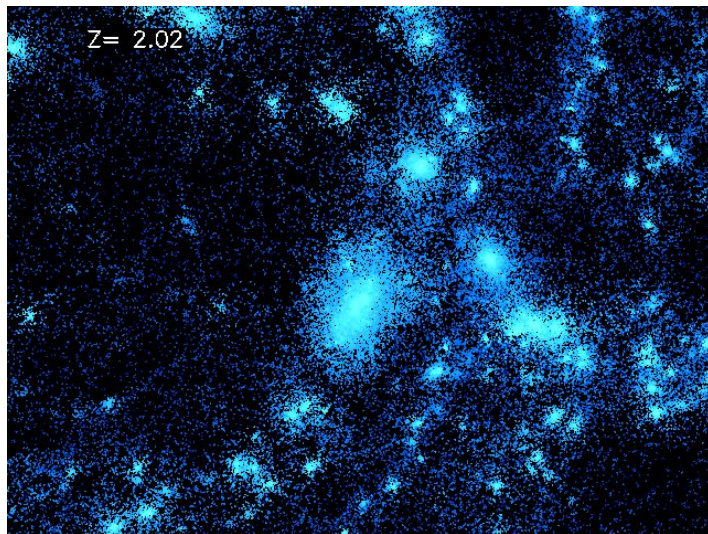


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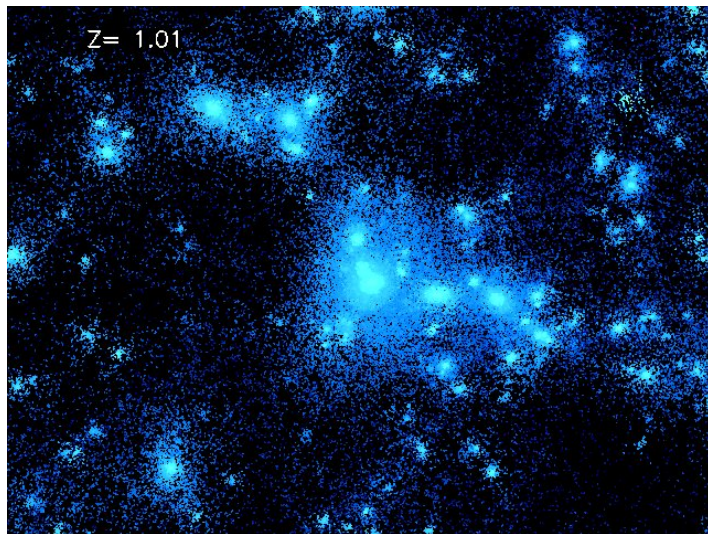


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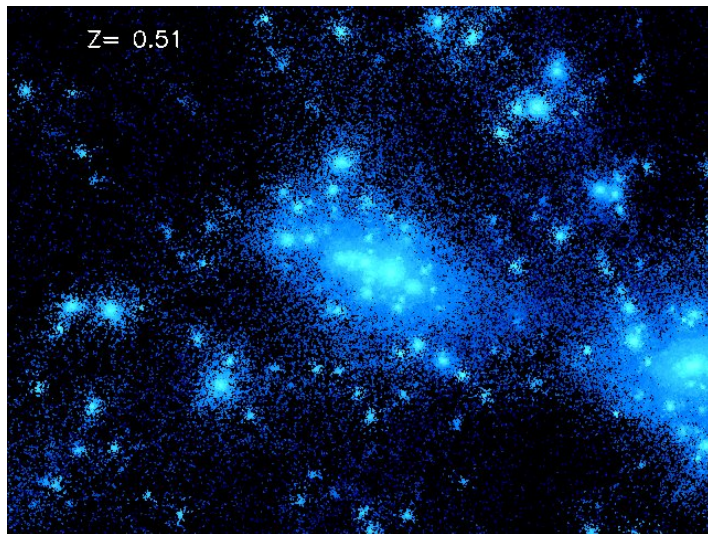


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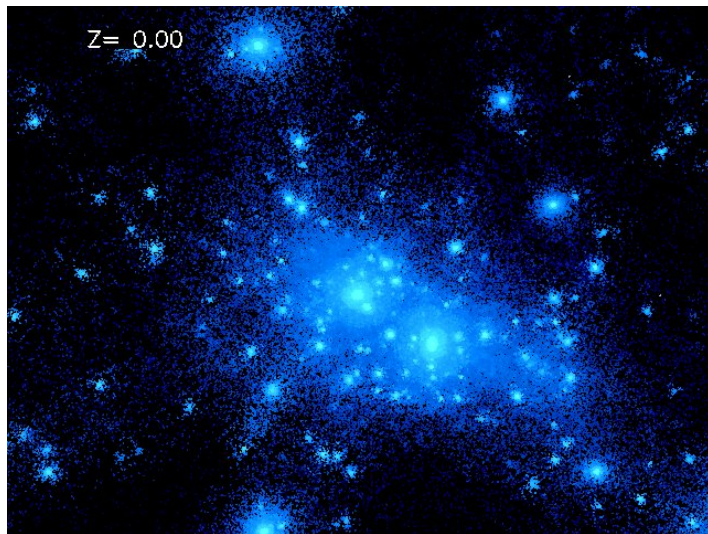


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Formation of structures due to gravitational instability



▶ Play again

Simulation illustrating the formation of structures due to gravitational instability²⁶.

²⁶Images from <http://cfcp.uchicago.edu/lss/group.html>.

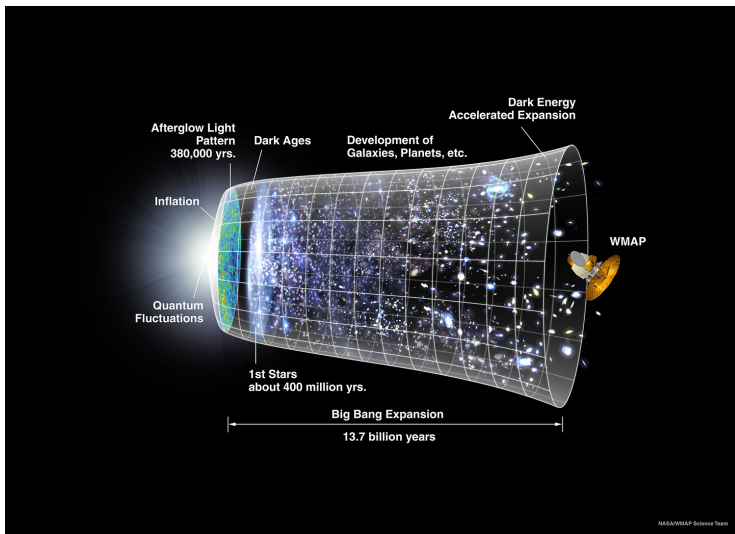


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- 1 The universe at large
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- 6 Summary



The timeline of the universe



A pictorial timeline of the universe²⁶.

²⁶Image from http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.



Thank you for your attention