

A brief history of the universe

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Plan of the talk

- 1 Universe at large
- 2 Expanding universe
- 3 Cosmic microwave background
- 4 Inflationary scenario
- 5 Origin and formation of structures in the universe
- 6 Summary

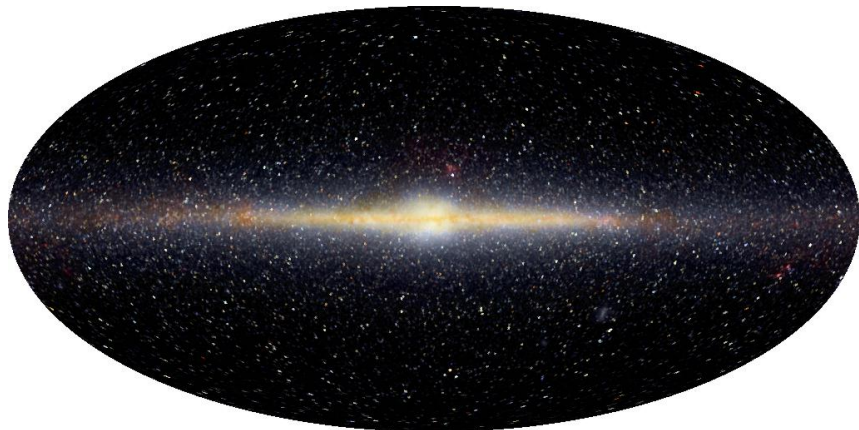


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An infrared image of our galaxy

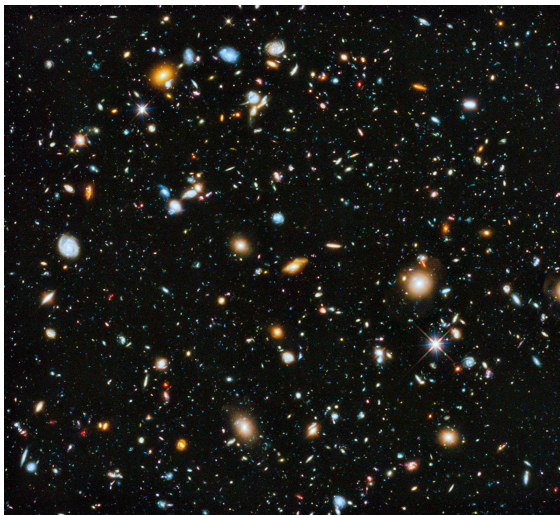


Our galaxy — the Milky Way — as observed by the COsmic Background Explorer (COBE) satellite at the infrared wavelengths¹. The diameter of the disc of our galaxy is, approximately, 45×10^3 ly or 15 kpc (*i.e.* a kilo parsec). It contains about 10^{11} stars such as the Sun, and its mass is about $2 \times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

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



Deepest views in space

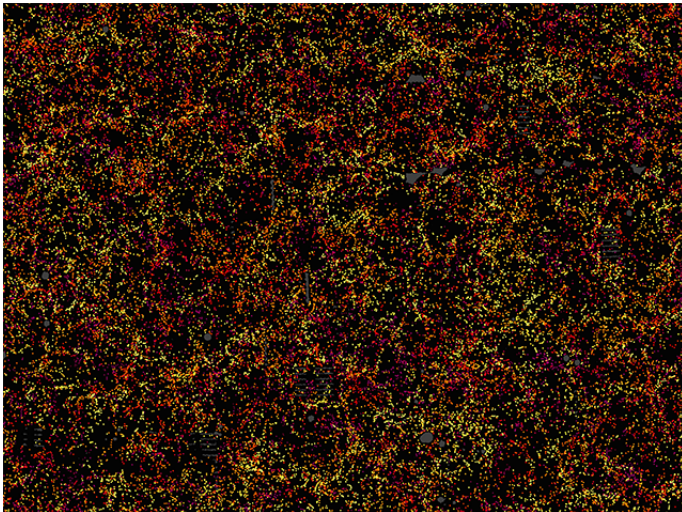


An ultra deep field image from the Hubble Space Telescope. The image contains a bewildering variety of galaxy shapes and colors².

²Image from <http://hubblesite.org/newscenter/archive/releases/2014/27>.



Surveying the universe



The Sloan Digital Sky Survey has obtained images covering more than a quarter of the sky and created three-dimensional maps containing more than a million galaxies³.

³See <http://www.sdss.org/>.

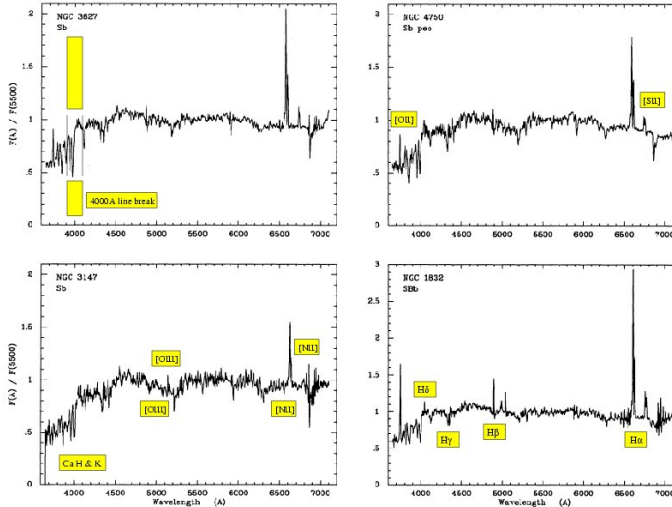


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Typical spectra of galaxies⁴

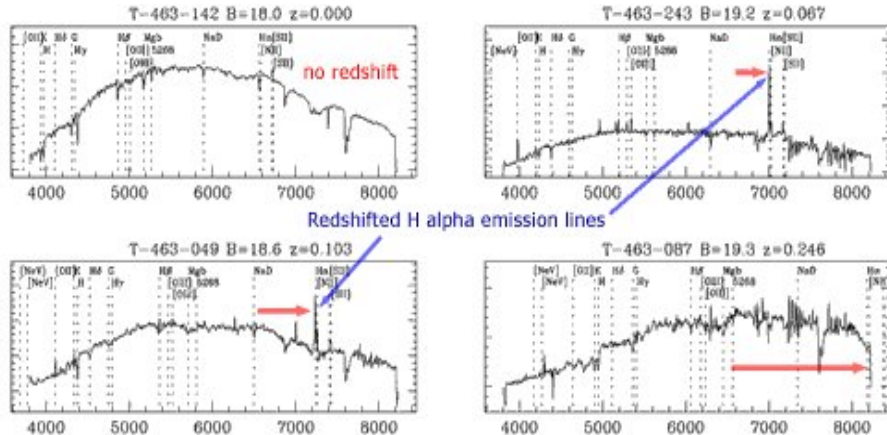


Spectra of some spiral galaxies, which usually contain characteristic emission and absorption lines.

⁴Image from <http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html>.



Runaway galaxies!

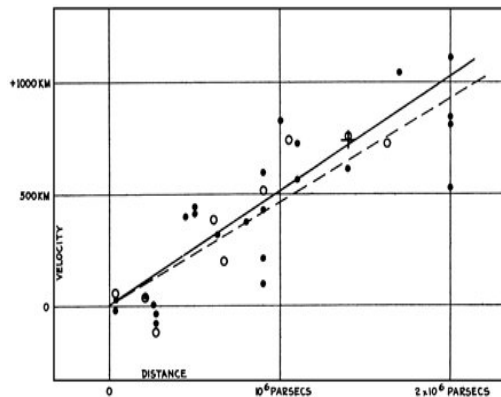


Spectra of four different galaxies from the 2dF redshift survey⁵. On top left is the spectrum of a star from our galaxy, while on the bottom right we have the spectrum of a galaxy that has a redshift of $z = 0.246$. The other two galaxies show prominent H α emission lines, which have been redshifted from the rest frame value of $6563 \text{ \AA}$.

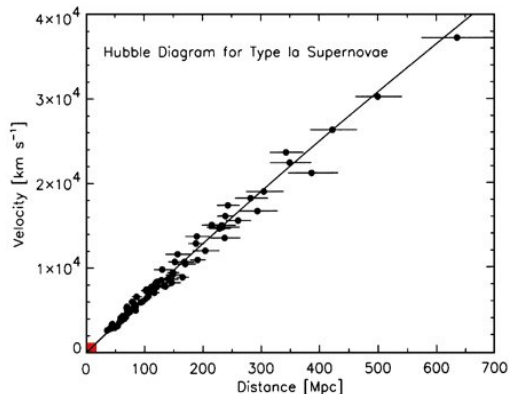
⁵Image from http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.



Hubble's law⁶



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

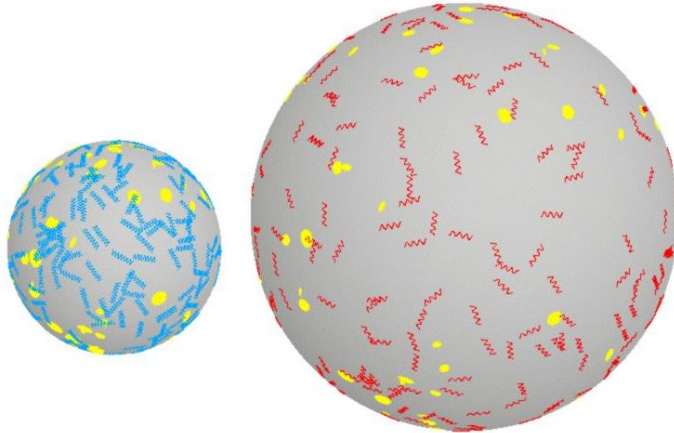


Right: A more recent Hubble diagram. The slope of the straight line is found to be about 72 km/sec/Mpc. The small red region in the lower left marks the span of Hubble's original diagram.

⁶R. Kirshner, Proc. Natl. Acad. Sci. USA **101**, 8 (2004).



Visualizing the expanding universe



A two-dimensional analogy for the expanding universe⁷. 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.

⁷Image from <http://www.astro.ucla.edu/~wright/balloon0.html>.

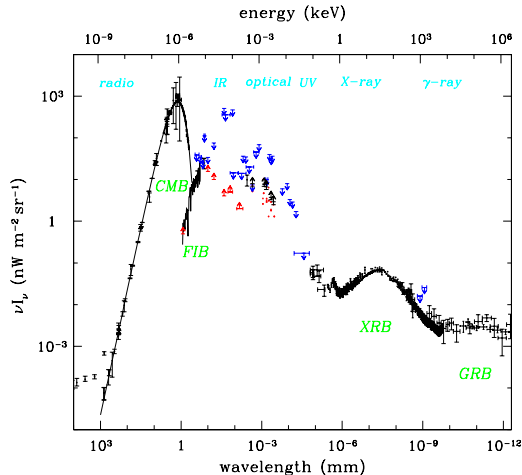


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Spectrum of radiation in the universe

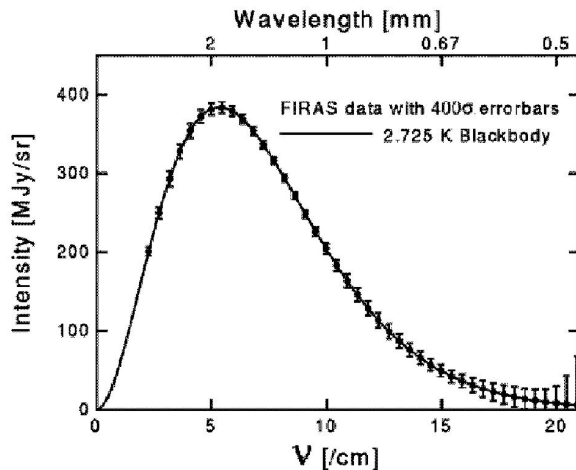


The spectrum of the energy density of the cosmological background radiation has been plotted as a function of wavelength⁸. Note that the Cosmic Microwave Background (CMB) contributes the most to the overall background radiation.

⁸Figure from, D. Scott, [arXiv:astro-ph/9912038](https://arxiv.org/abs/astro-ph/9912038).



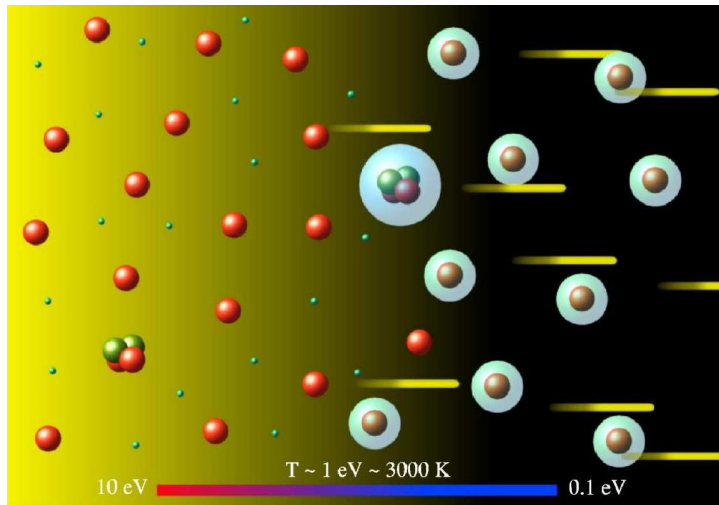
Spectrum of the CMB



Spectrum of the CMB as measured by COBE⁹. It is such a perfect Planck spectrum (corresponding to a temperature of 2.725° K) that it is unlikely to be bettered in the laboratory. The error bars in the graph above have been amplified 400 times so that they can be seen.

⁹Image from http://www.astro.ucla.edu/~wright/cosmo_01.htm.

Decoupling of matter and radiation¹⁰

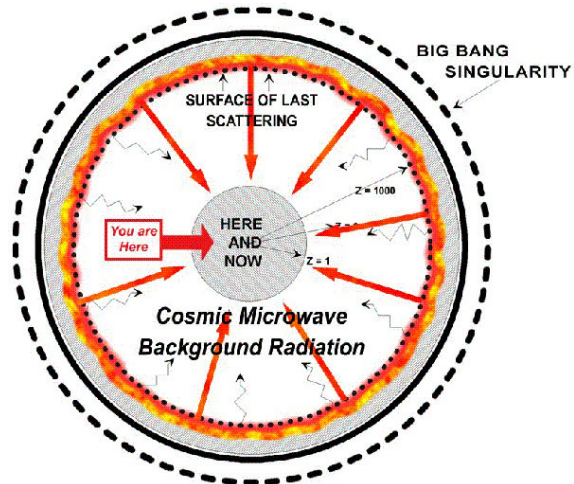
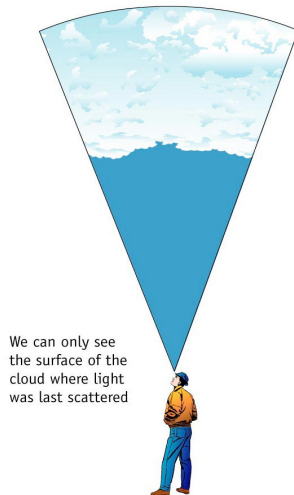


Matter and radiation cease to interact at a temperature of about $T \simeq 3000^\circ \text{ K}$, which corresponds to a redshift of about $z \simeq 1000$.

¹⁰Image from W. H. Kinney, arXiv:astro-ph/0301448v2.



Last scattering surface and freestreaming CMB photons

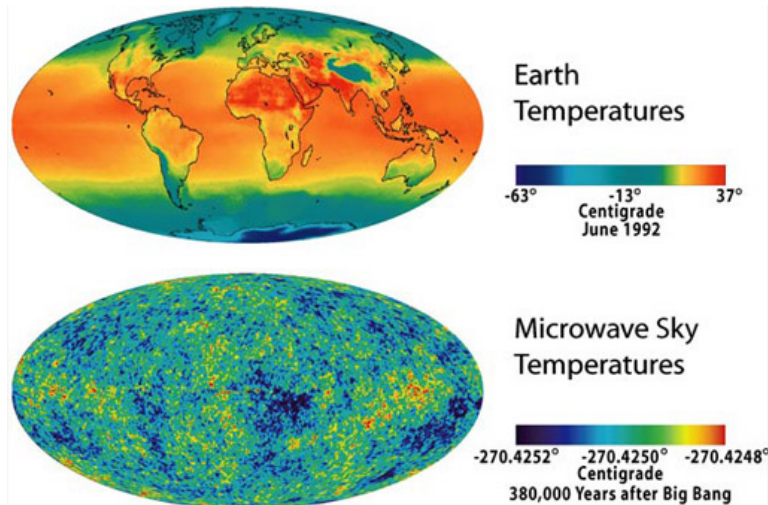


The CMB photons stream to us freely from the last scattering surface when radiation decoupled from matter¹¹.

¹¹Image from <http://planck.caltech.edu/epo/epo-cmbDiscovery4.html>.



Projecting the last scattering surface

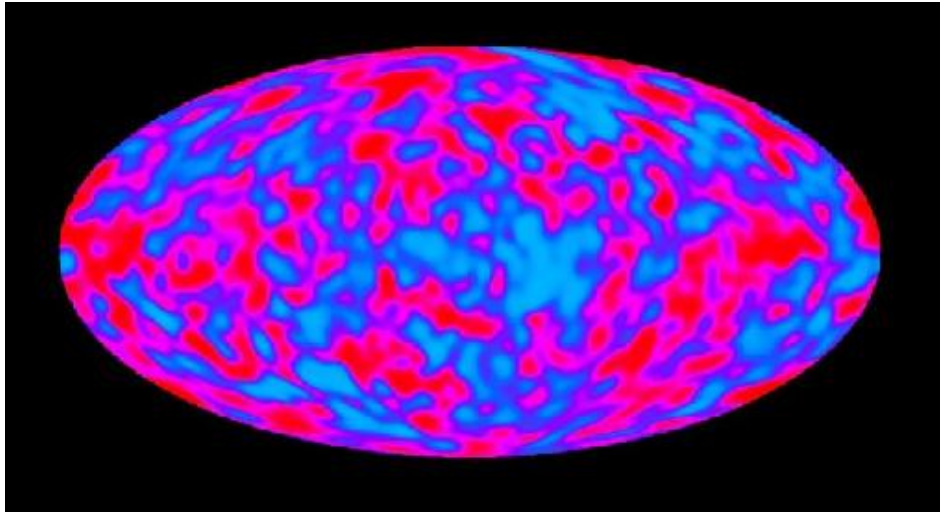


The temperature of the CMB on the last scattering surface can be projected on to a plane as the surface of the Earth is often projected¹².

¹²Image from <http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html>.



Extent of isotropy of the CMB

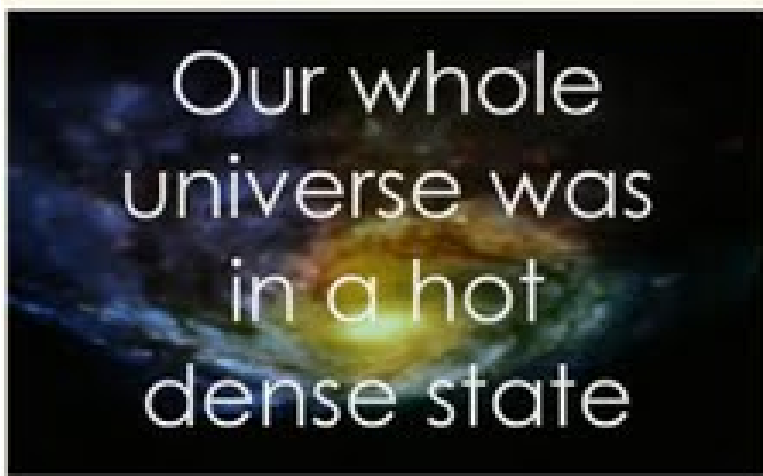


The fluctuations in the temperature of the CMB as seen by COBE¹³. The CMB turns out to be isotropic to one part in 10^5 .

¹³Image from http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html.



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'¹⁴!

¹⁴See http://www.cbs.com/shows/big_bang_theory/.

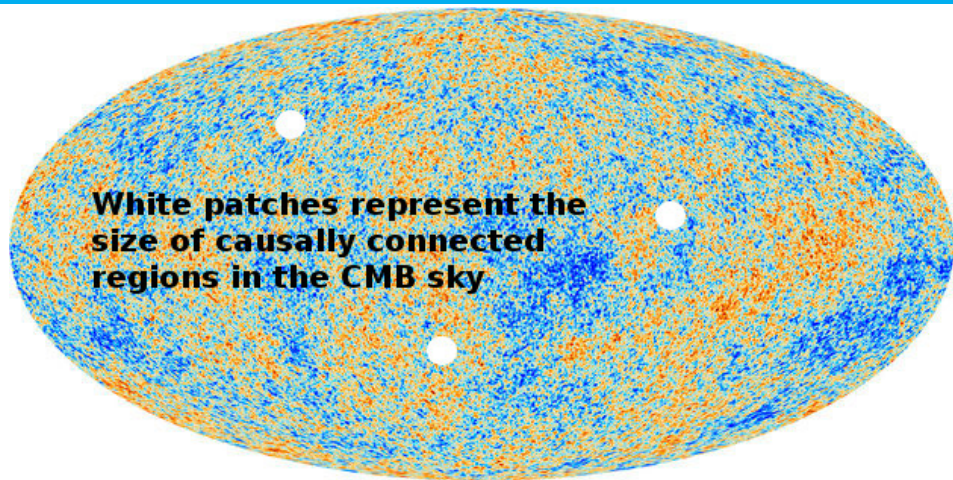


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The horizon problem

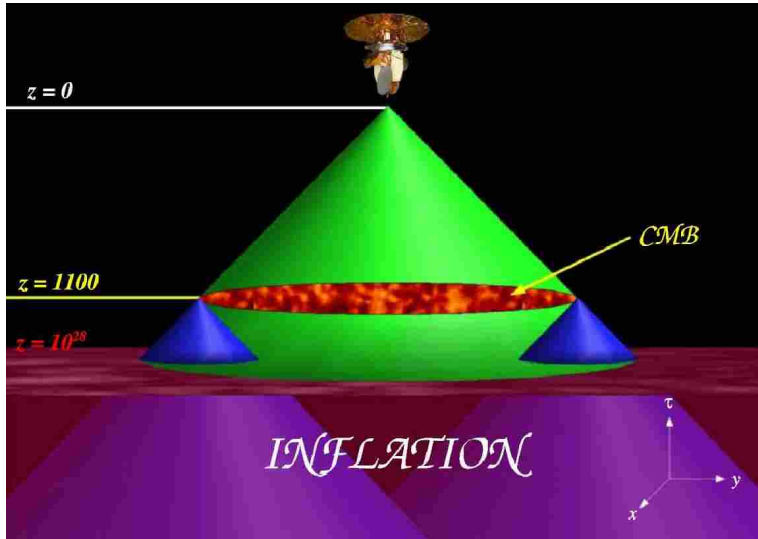


The radiation from the CMB arriving at us from regions separated by more than the 'horizon' at the last scattering surface, which subtends an angle of about 1° today, could not have interacted before decoupling¹⁵.

¹⁵Image from [W. H. Kinney, arXiv:astro-ph/0301448v2](#).



Inflation resolves the horizon problem

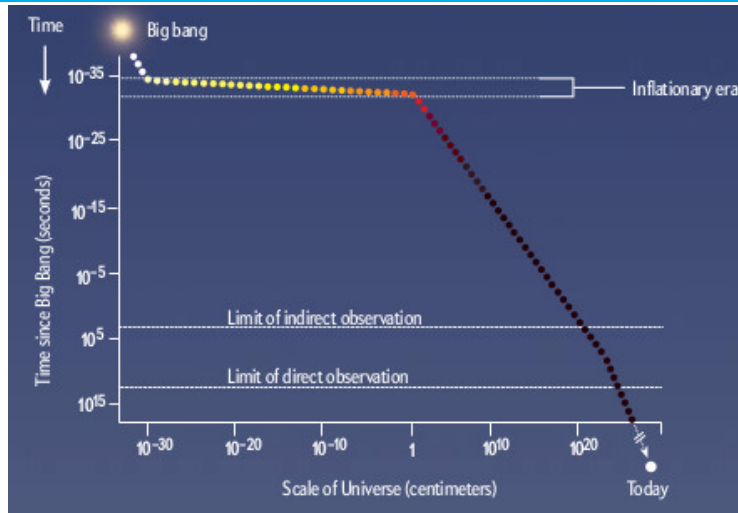


An early and sufficiently long epoch of inflation resolves the horizon problem¹⁶.

¹⁶Image from W. H. Kinney, [arXiv:astro-ph/0301448v2](https://arxiv.org/abs/astro-ph/0301448v2).



Time and duration of inflation

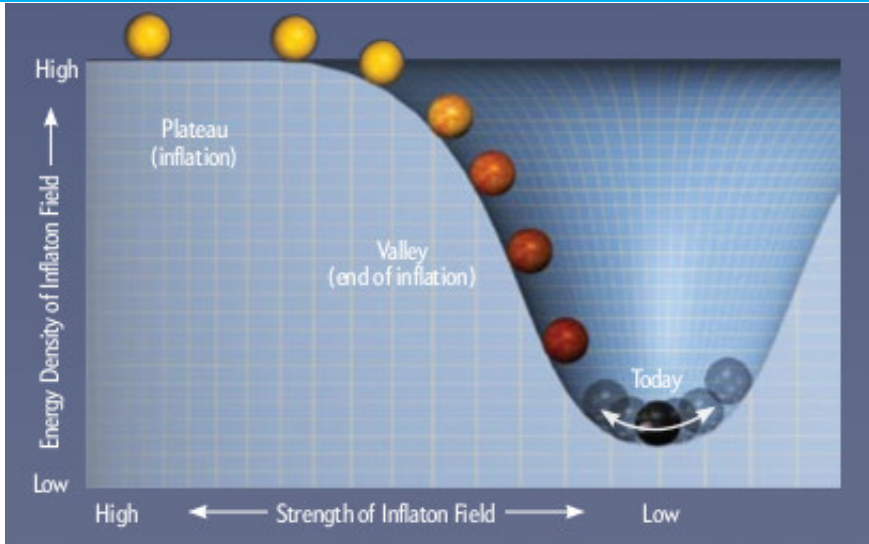


Inflation — a brief period of accelerated expansion — is expected to have taken place during the very stages of the universe¹⁷.

¹⁷Image from P. J. Steinhardt, *Sci. Am.* **304**, No. 4, 36 (2011).



Achieving inflation with scalar fields

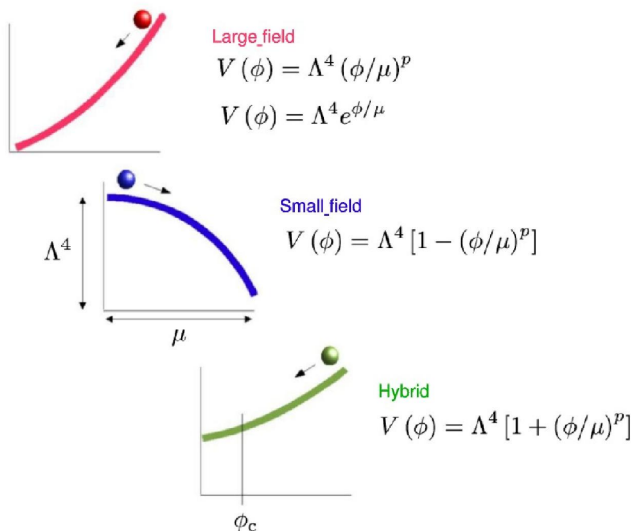


Inflation can be achieved with scalar fields encountered in high energy physics¹⁸.

¹⁸Image from P. J. Steinhardt, *Sci. Am.* **304**, No. 4, 36 (2011).



A variety of potentials to choose from



A variety of scalar field potentials have been considered to drive inflation¹⁹.

¹⁹Image from W. Kinney, astro-ph/0301448.

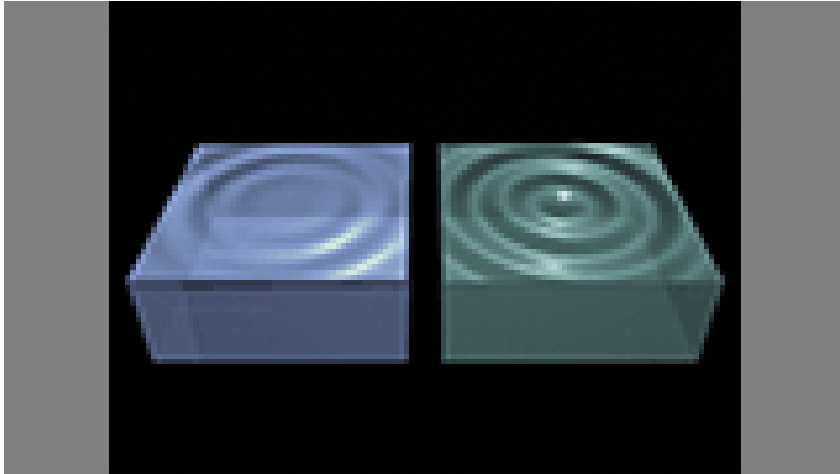


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Generation of the primordial fluctuations

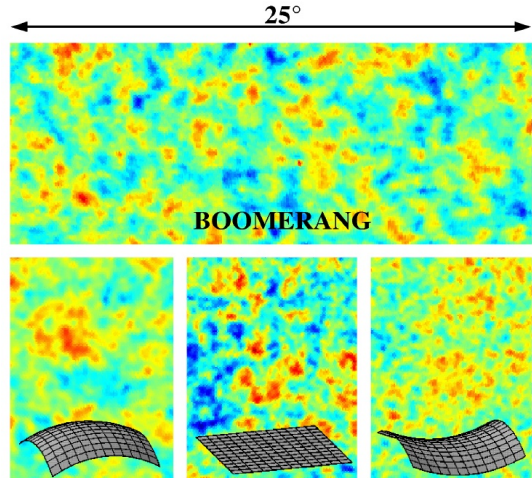


It is the quantum fluctuations associated with the scalar fields driving inflation which are responsible for the origin of the perturbations. These perturbations are amplified during the inflationary epoch, which leave their imprints as anisotropies in the CMB²⁰.

²⁰Movie from <https://wmap.gsfc.nasa.gov/resources/animconcepts.html>.



BOOMERANG and the spatially flat universe

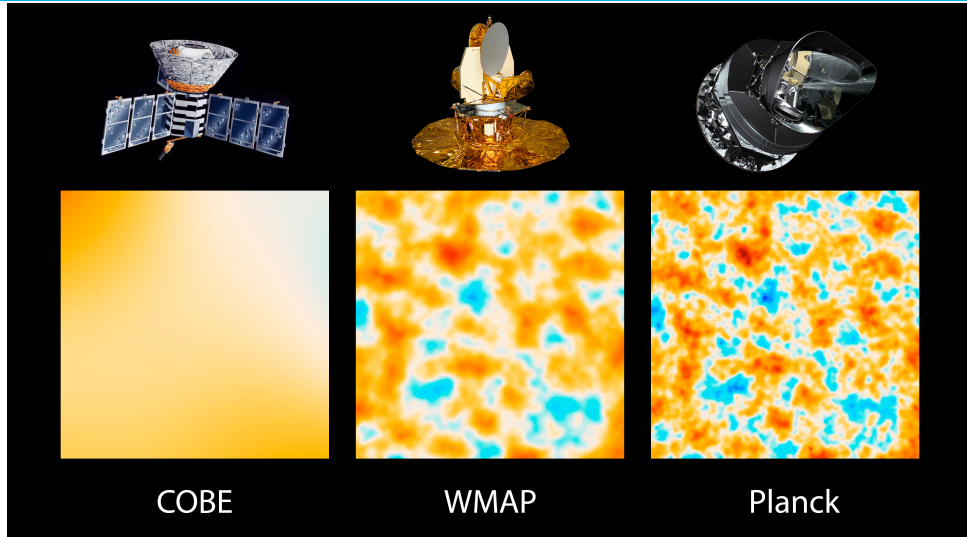


It was observations by balloon borne BOOMERANG that had first revealed that the universe is very nearly spatially flat²¹.

²¹ Images from <http://oberon.roma1.infn.it/boomerang/pressrelease/illustrations/index.html>.



Satellite missions that brought the CMB into sharper focus

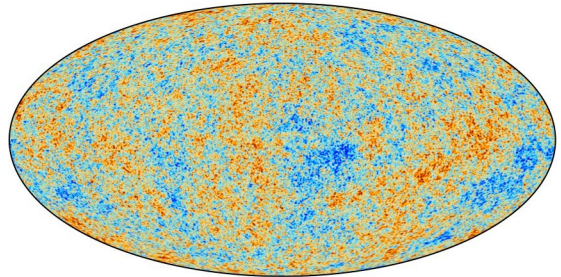
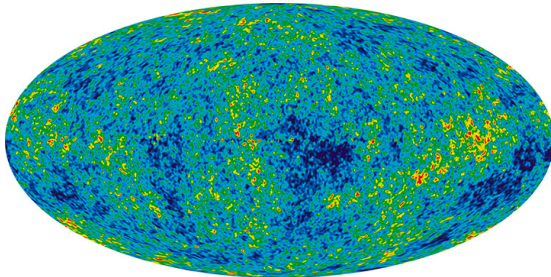


COBE, WMAP and Planck observed the CMB with ever increasing resolution²².

²²Image 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) data²³.

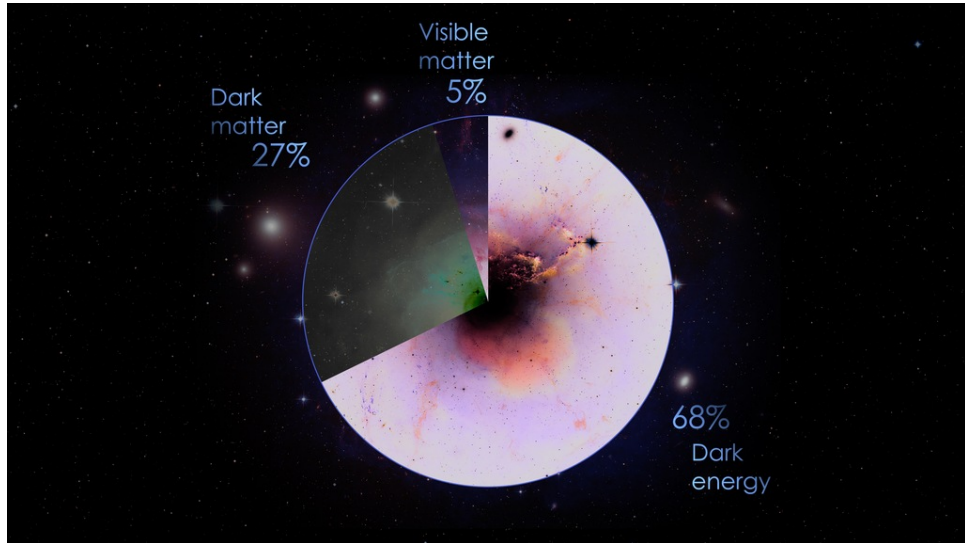
Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and 408 MHz observations²⁴. The above images show temperature variations (as color differences) of the order of $200^\circ \mu\text{K}$. These temperature fluctuations represent the seeds of all the structure around us today.

²³Image from <http://wmap.gsfc.nasa.gov/media/121238/index.html>.

²⁴P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].



Matter content of the universe

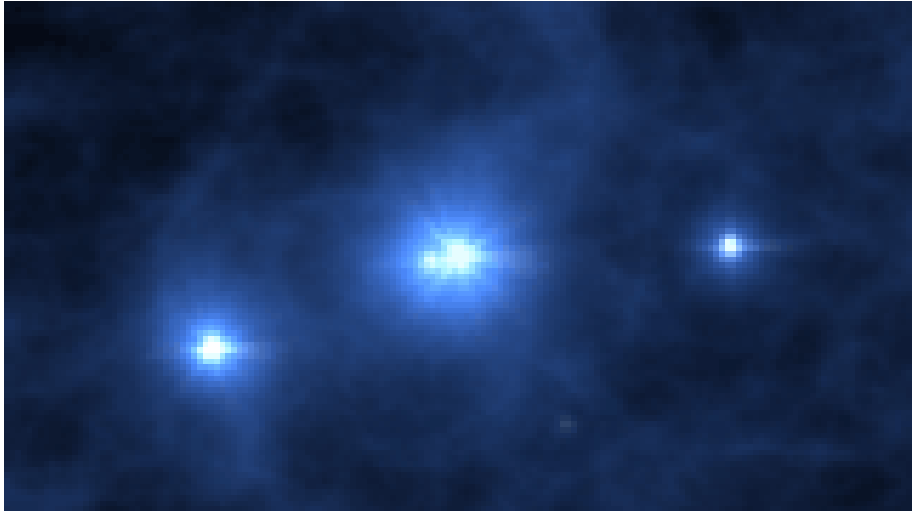


A pie chart of the matter content of the universe today²⁵.

²⁵Movie from <https://svs.gsfc.nasa.gov/12307>.



Evolution of the primordial fluctuations

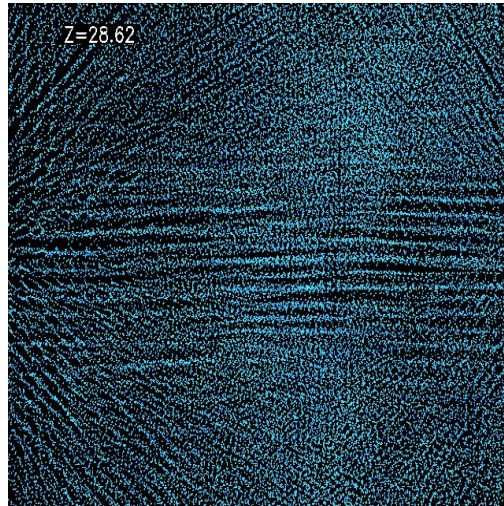


The fluctuations in the CMB grow in magnitude due to gravitational instability and develop into the structures that we see around us today²⁶.

²⁶Movie from <https://svs.gsfc.nasa.gov/12307>.



Formation of structures due to gravitational instability

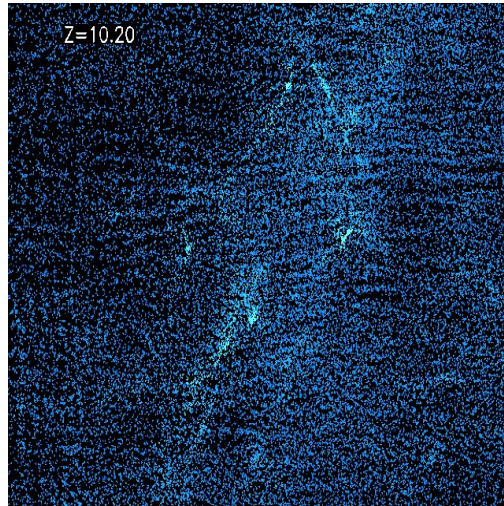


A numerical simulation illustrating the formation of large scale structures due to gravitational instability²⁷.

²⁷Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

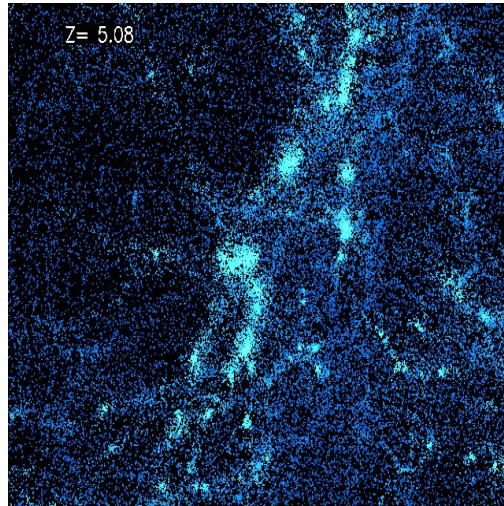


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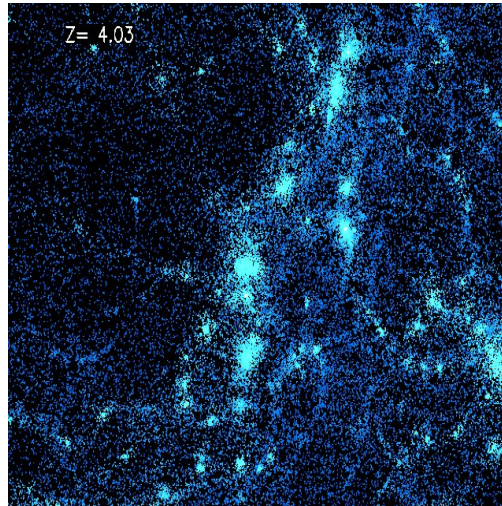


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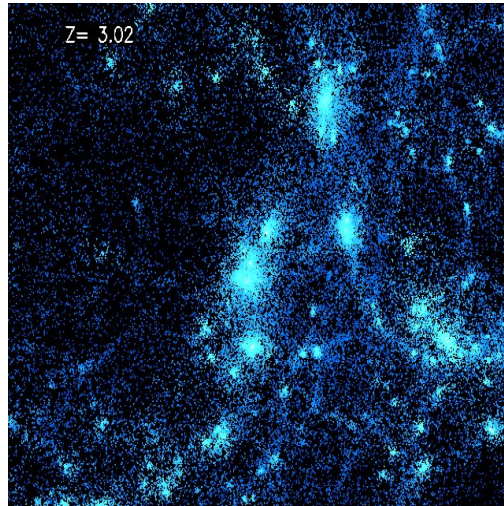


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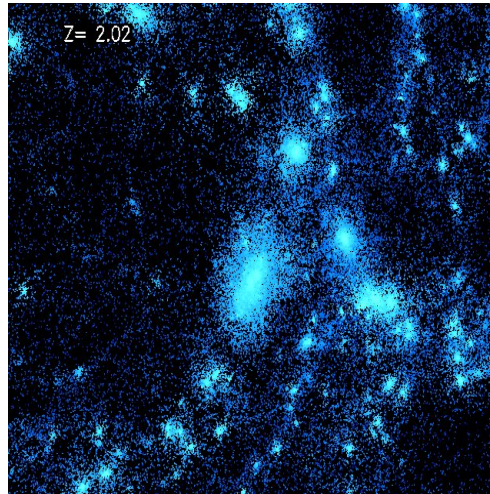


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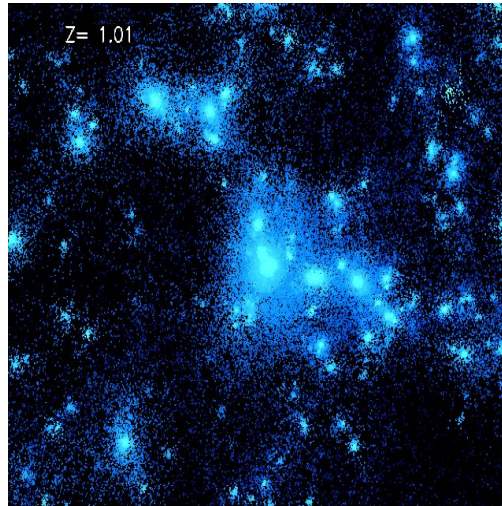


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Formation of structures due to gravitational instability

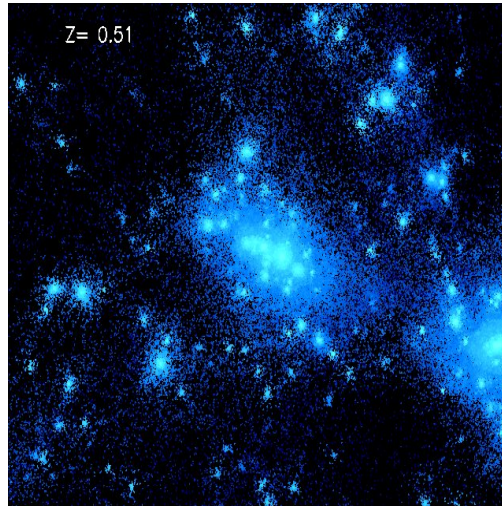


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²⁷Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

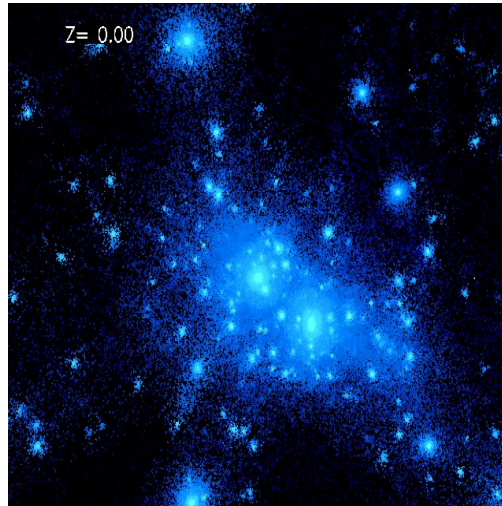


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Formation of structures due to gravitational instability



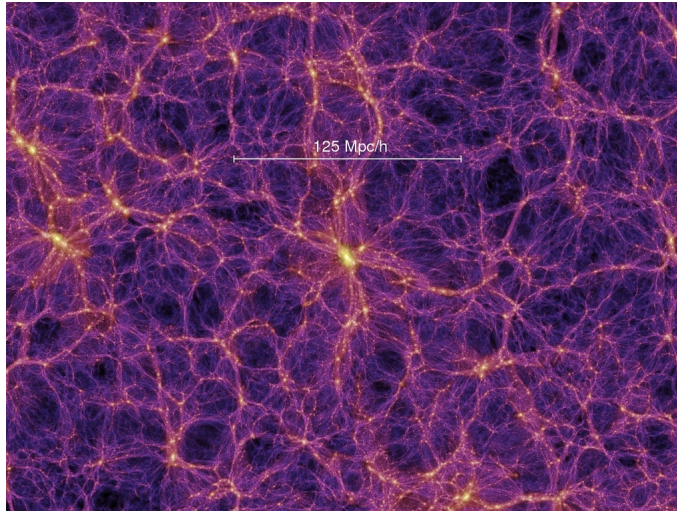
A numerical simulation illustrating the formation of large scale structures due to gravitational instability²⁷.

► Play again



²⁷Images from <http://cfcp.uchicago.edu/lss/group.html>.

The millennium simulation



The results from the Millennium Run which traced the evolution of the matter distribution in a cubic region of the universe over 2 billion light years on a side²⁷.

²⁷See <http://www.mpa-garching.mpg.de/galform/virgo/millennium/>.

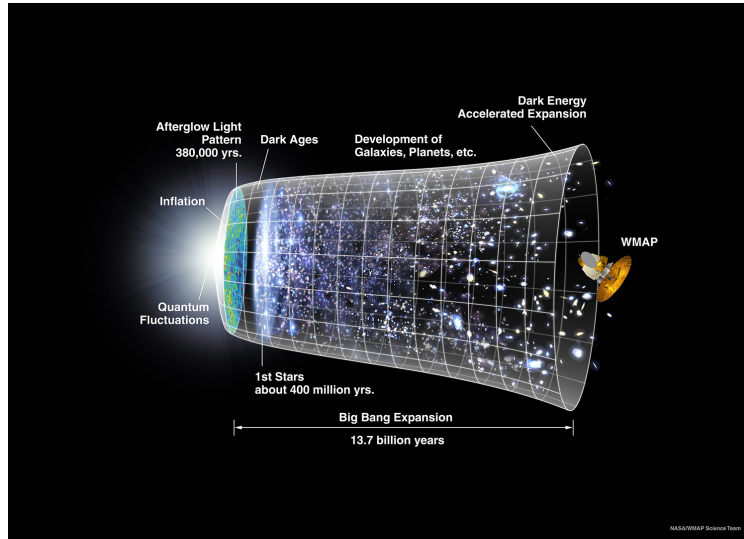


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Timeline of the universe



A pictorial timeline of the universe²⁸.

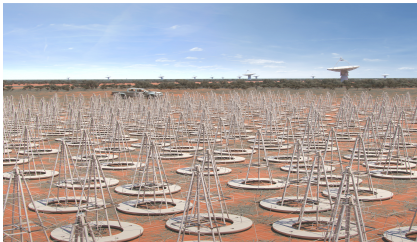
²⁸See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

Standard model of cosmology

- ◆ The universe is homogeneous and isotropic at length scales of the order of 100 Mpc and above.
- ◆ Baryons, *i.e.* matter as we know it, contribute less than 5% to the total density of the universe today. Most of the matter today is, in fact, dark and dominated by dark energy. Dark energy and pressureless (*i.e.* cold) dark matter contribute about 70% and 25% to the the density today, respectively.
- ◆ The inflationary epoch magnifies the tiny fluctuations in the quantum fields present at the beginning of epoch into classical perturbations.
- ◆ These inhomogeneities leave their imprints as anisotropies in the CMB.
- Gravitational instability then takes over, and converts the tiny perturbations in the CMB into the large scale structures that we see around us today as galaxies and clusters of galaxies.



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