A brief history of the universe

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The Guru Talks

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Plan of the talk

1. The universe at large

Plan of the talk

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2. The expanding universe

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3. The cosmic microwave background

Plan of the talk

1. The universe at large
2. The expanding universe
3. The cosmic microwave background
4. The inflationary scenario

Plan of the talk

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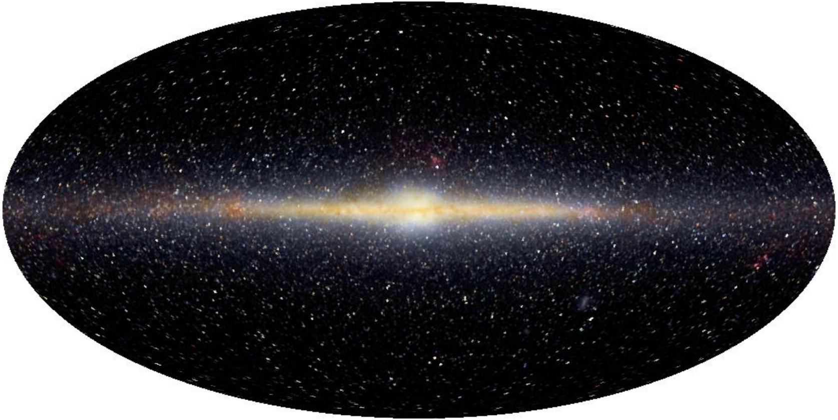
Plan of the talk

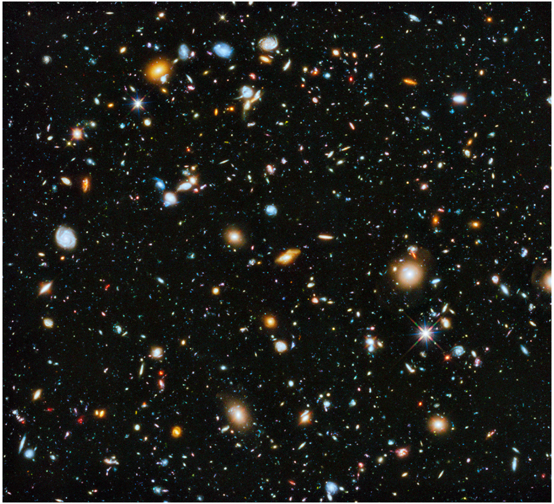
An infrared image of our galaxy



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, 45×10^3 ly or 15 kpc (*i.e.* a kilo parsec). It contains about 10^{11} stars such as the Sun, and its mass is about $2 \times 10^{12}\ \mathrm{M}_{\odot}$.

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

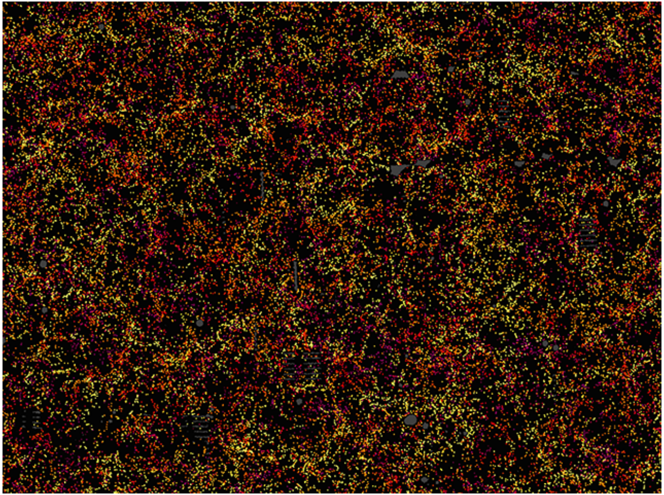
Deepest views in space



An ultra deep field image from the Hubble Space Telescope. The image contains a bewildering variety of galaxy shapes and colors[2].

[2]Image 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 galaxies[3].

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

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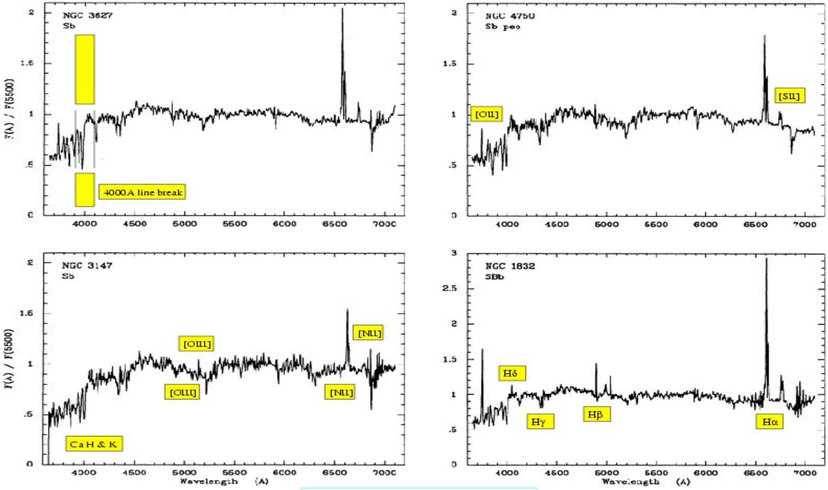
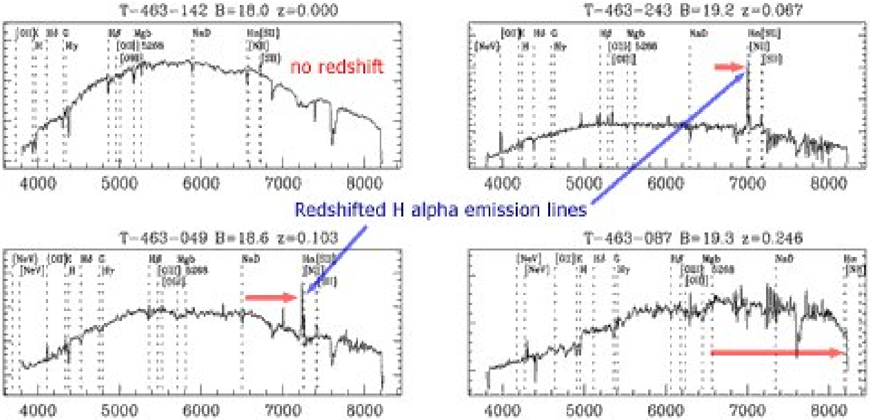
Typical spectra of galaxies[4]



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

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

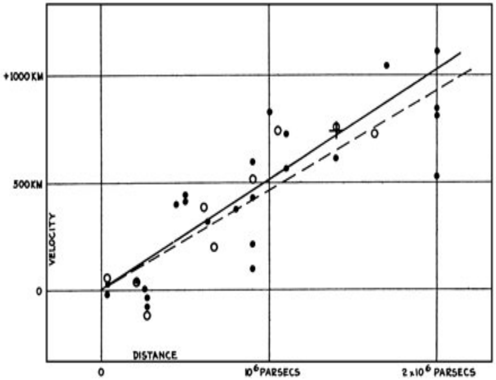
Runaway galaxies!

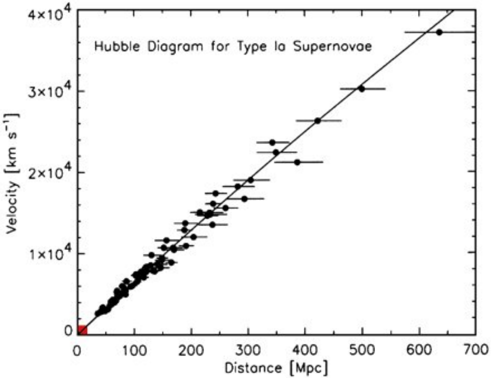


Spectra of four different galaxies from the 2dF redshift survey[5]. On top left is the spectrum of a star from our galaxy, while on the bottom right we have the spectrum of a galaxy that has a redshift of $z = 0.246$. The other two galaxies show prominent Hα emission lines, which have been redshifted from the rest frame value of 6563 Å.

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

The Hubble's law[6]



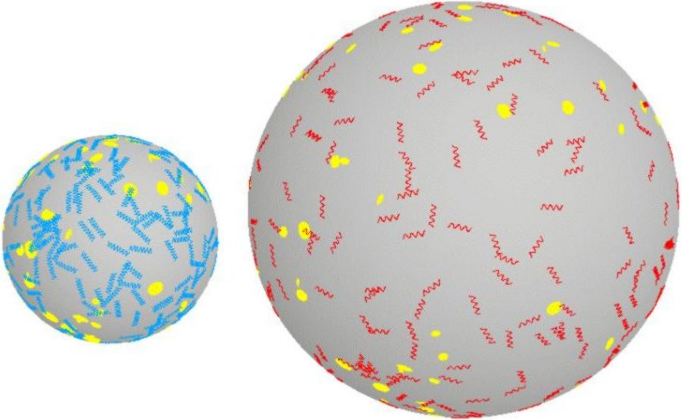


Left: The original Hubble data. The slope of the two fitted lines are about $500\ \mathrm{km/sec/Mpc}$ and $530\ \mathrm{km/sec/Mpc}$.

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

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

Visualizing the expanding universe

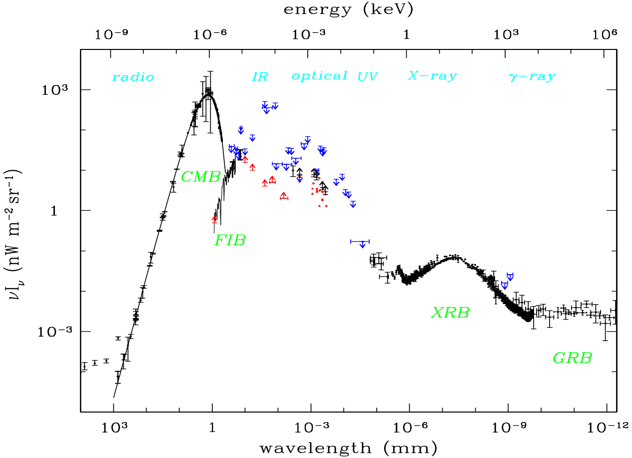


A two-dimensional analogy for the expanding universe[7]. The yellow blobs on the expanding balloon denote the galaxies. Note that the galaxies themselves do not grow, but the distance between the galaxies grows and the wavelengths of the photons shift from blue to red as the universe expands.

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

Plan of the talk

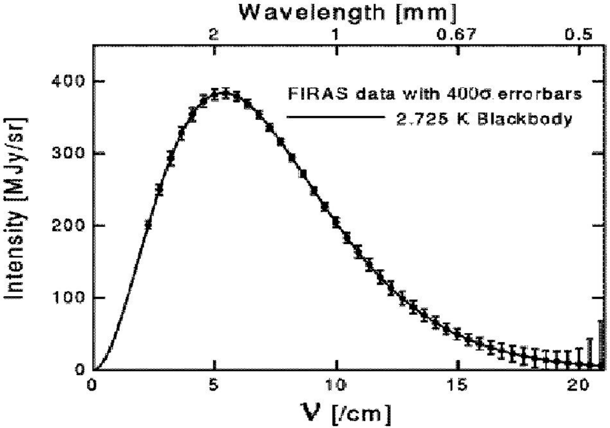
The spectrum of radiation in the universe



The energy density spectrum of the cosmological background radiation has been plotted as a function of wavelength[8]. Note that the Cosmic Microwave Background (CMB) contributes the most to the overall background radiation.

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

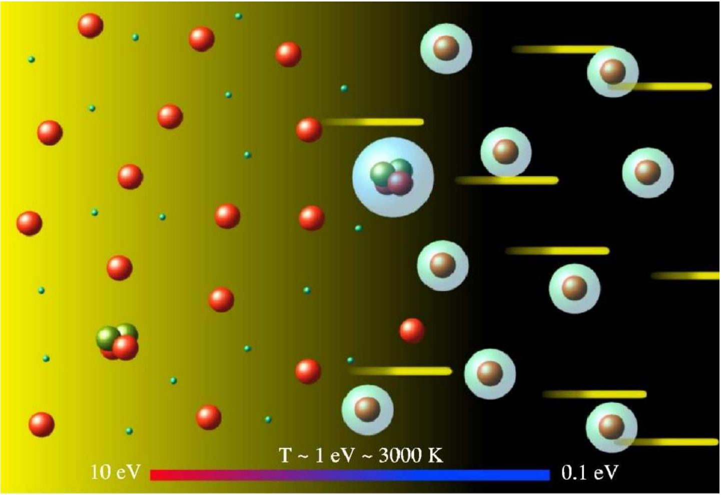
The spectrum of the CMB



The spectrum of the CMB as measured by COBE[9]. 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!

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

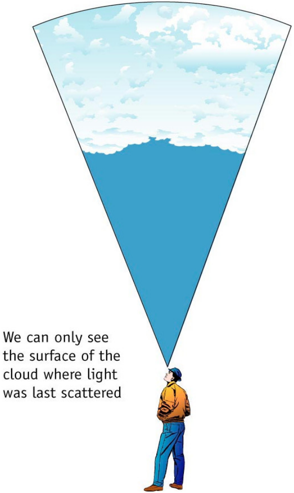
Decoupling of matter and radiation[10]

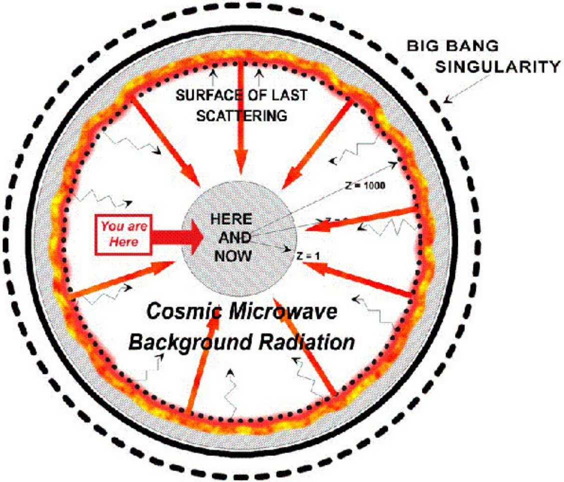


Matter and radiation cease to interact at a temperature of about $T \simeq 3000^\circ\ \mathrm{K}$, which corresponds to a redshift of about $z \simeq 1000$.

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

The last scattering surface and the freestreaming CMB photons

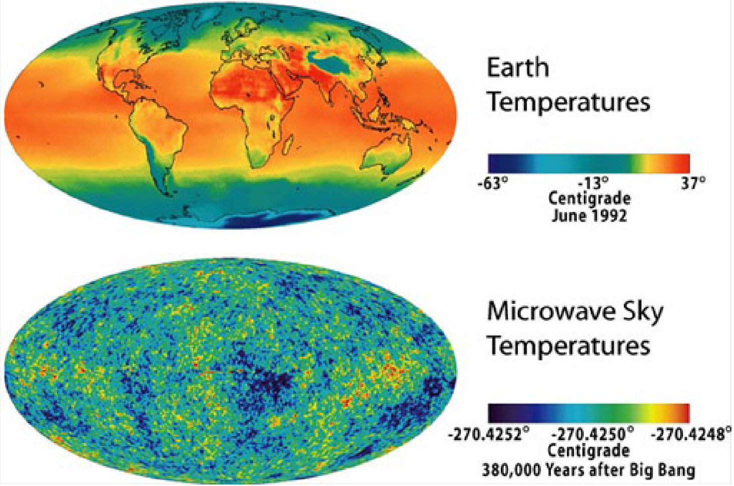




The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter[11].

[11] Image from http://planck.caltech.edu/epo/epo-cmbDiscovery4.html.

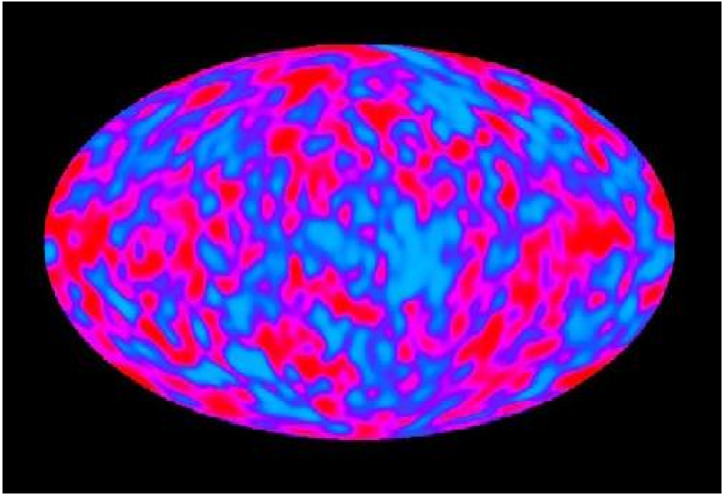
Projecting the last scattering surface



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 projected[12].

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

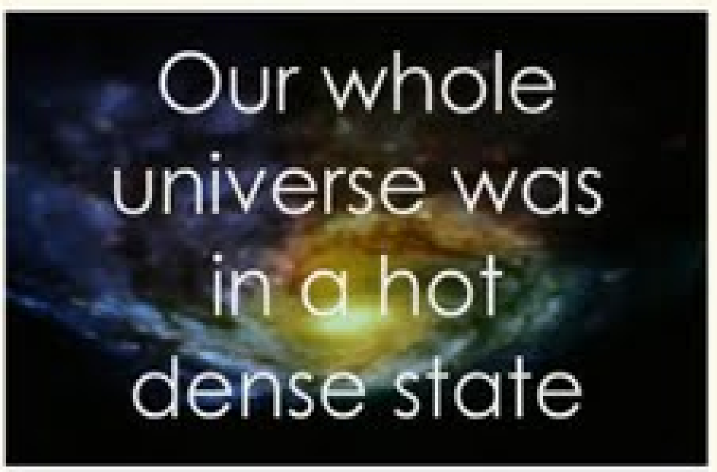
The extent of isotropy of the CMB



The fluctuations in the temperature of the CMB as seen by COBE[13]. The CMB turns out to be isotropic to one part in 10^5.

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

The big bang model seems popular!

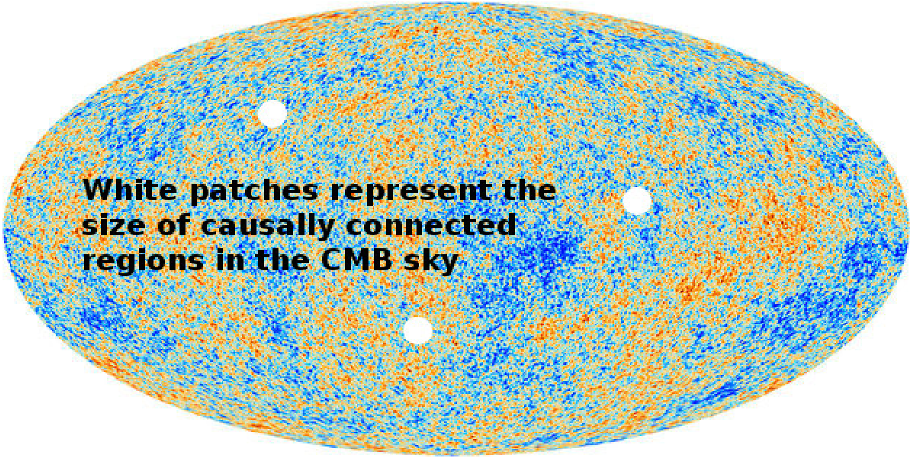


The current view of the universe, encapsulated in the hot big bang model, seems popular. The above image is a screen grab from the theme song of the recent American sitcom 'The Big Bang Theory'[14]!

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

Plan of the talk

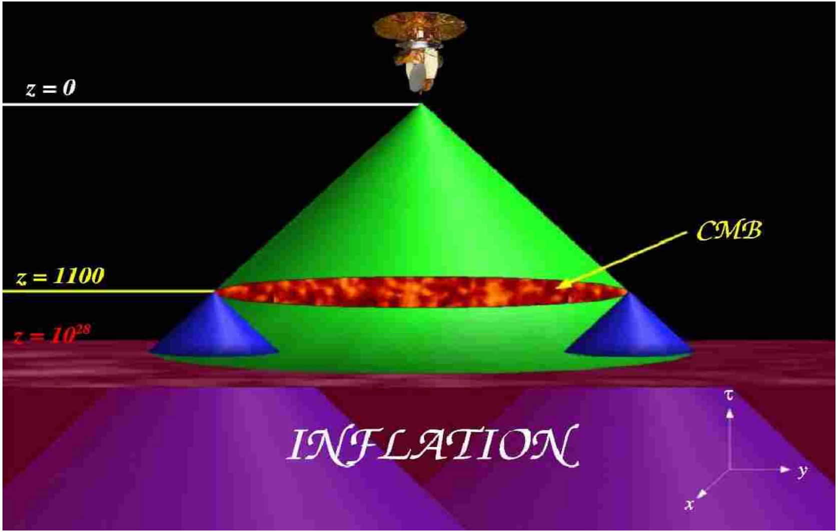
The ‘horizon’ problem



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 decoupling[15].

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

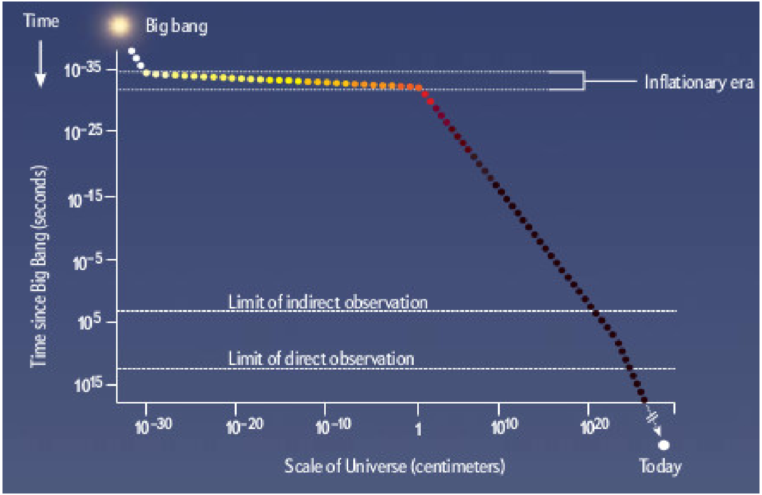
Inflation resolves the horizon problem



An early and sufficiently long epoch of inflation resolves the horizon problem[16].

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

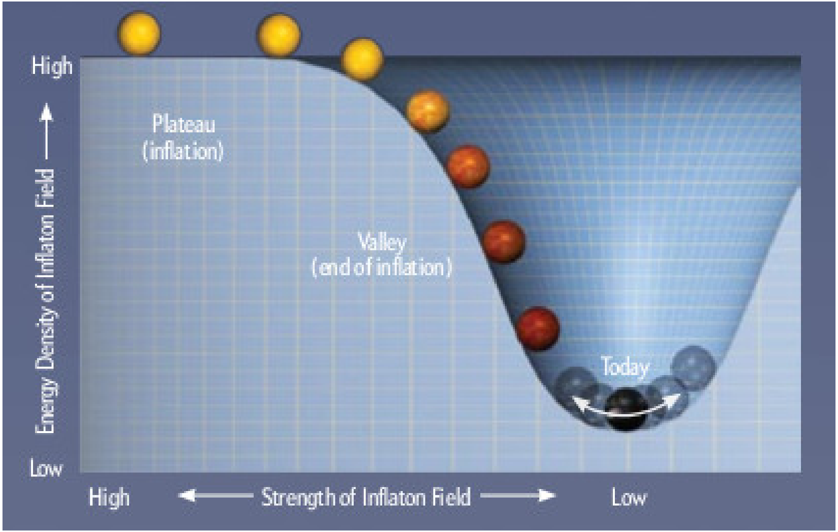
The time and duration of inflation



Inflation — a brief period of accelerated expansion — is expected to have taken place during the very stages of the universe[17].

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

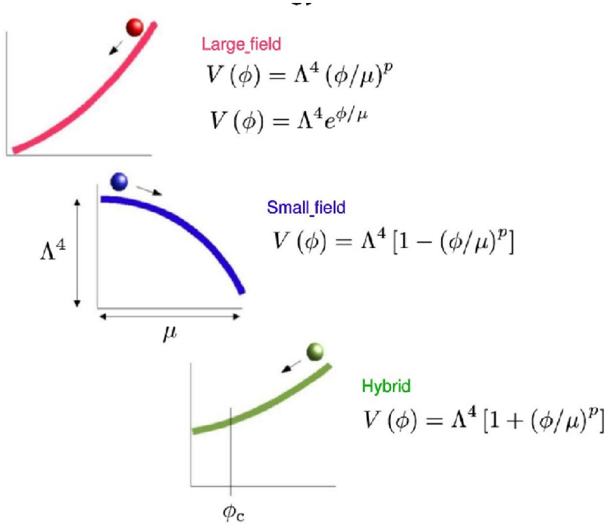
Achieving inflation with scalar fields



Inflation can be achieved with scalar fields encountered in high energy physics[18].

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

A variety of potentials to choose from

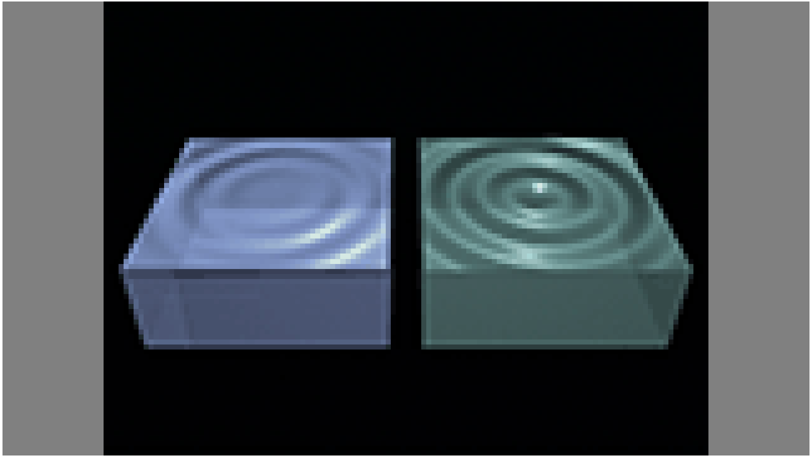


A variety of scalar field potentials have been considered to drive inflation[19].

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

Plan of the talk

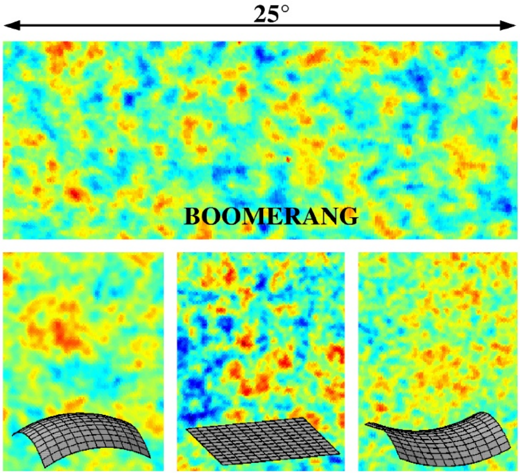
Generation of the primordial fluctuations



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 CMB[20].

[20]Movie from https://wmap.gsfc.nasa.gov/resources/animconcepts.html.

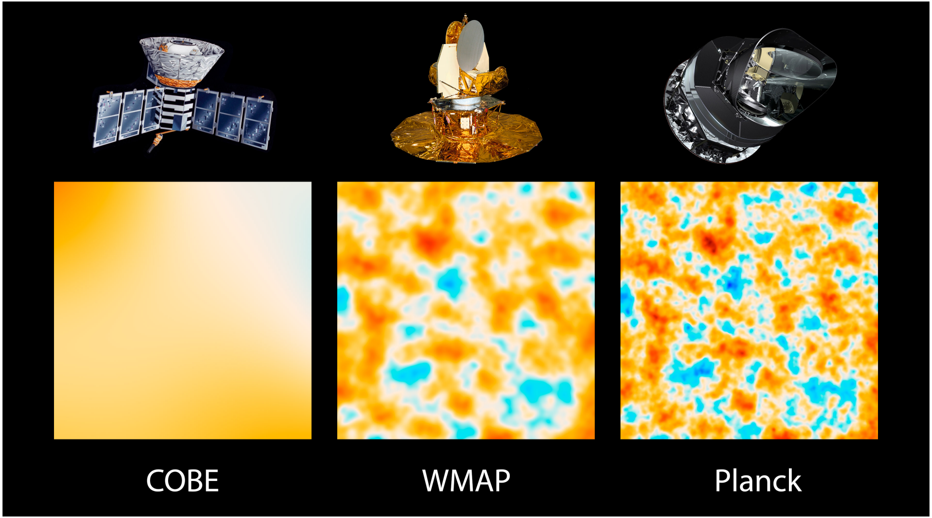
BOOMERANG and the spatially flat universe



It was observations by balloon borne BOOMERANG that had first revealed that the universe is very nearly spatially flat[21].

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

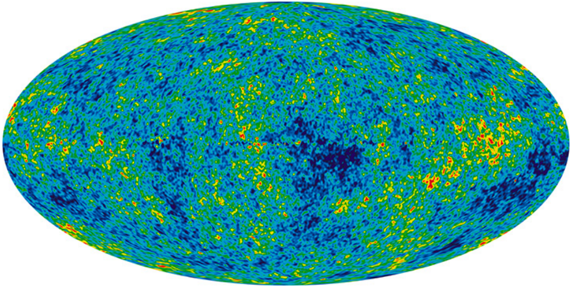
Satellite missions that brought the CMB into sharper focus

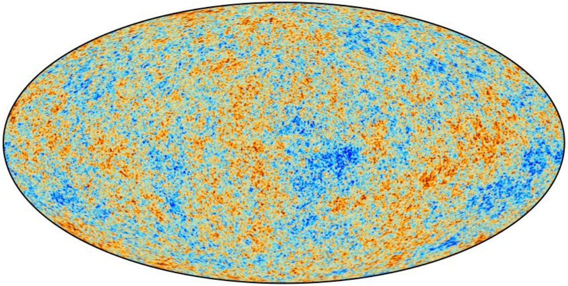


COBE, WMAP and Planck observed the CMB with ever increasing resolution[22].

[22] 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[23].

Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[24]. The above images show temperature variations (as color differences) of the order of $200^\circ\,\mu\mathrm{K}$. These temperature fluctuations represent the seeds of all the structure around us today.

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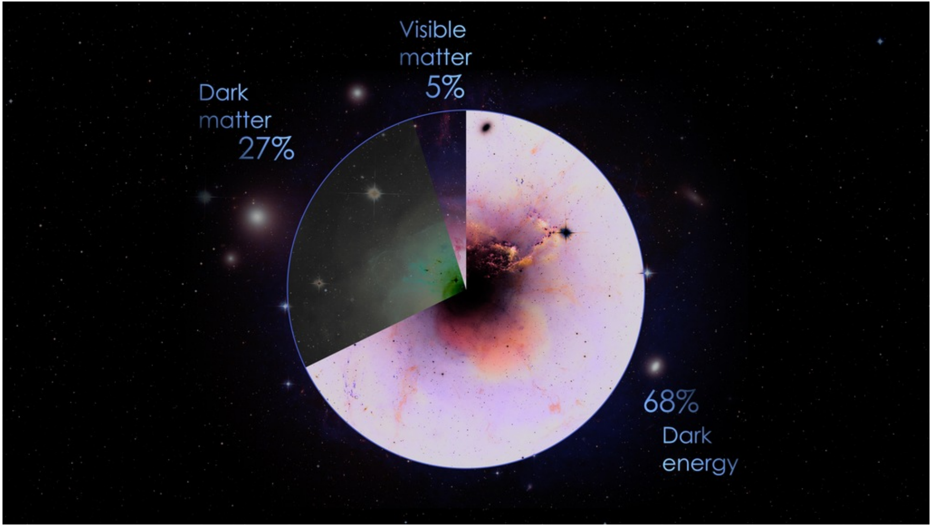
[23] Image from http://wmap.gsfc.nasa.gov/media/121238/index.html.

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

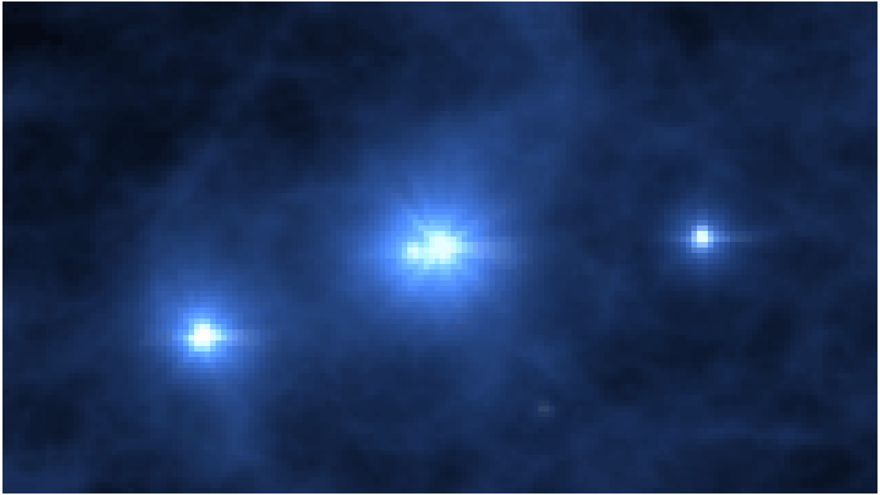
Matter content of the universe



A pie chart of the matter content of the universe today[25].

[25]Movie 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 today[26].

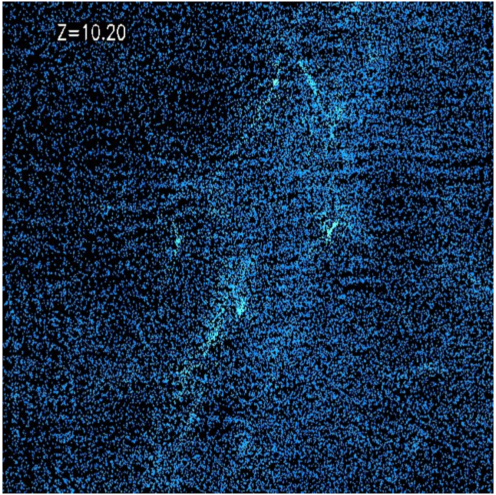
[26] Movie from https://svs.gsfc.nasa.gov/12307.

Formation of structures due to gravitational instability

A numerical simulation illustrating the formation of large scale structures due to gravitational instability[27].

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

Formation of structures due to gravitational instability



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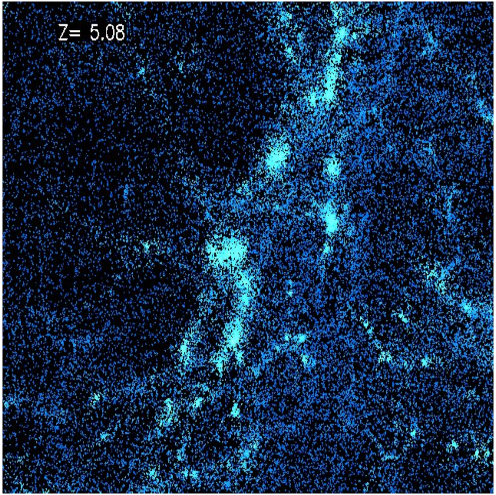

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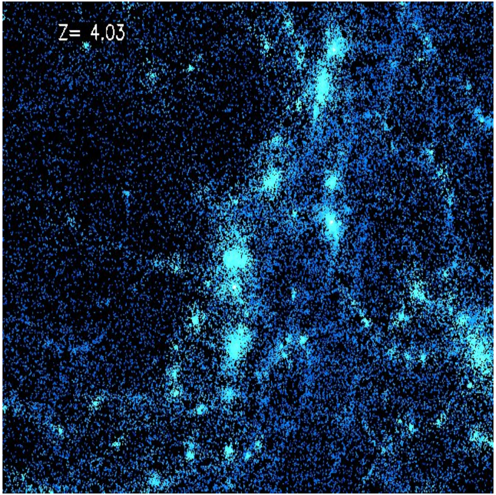

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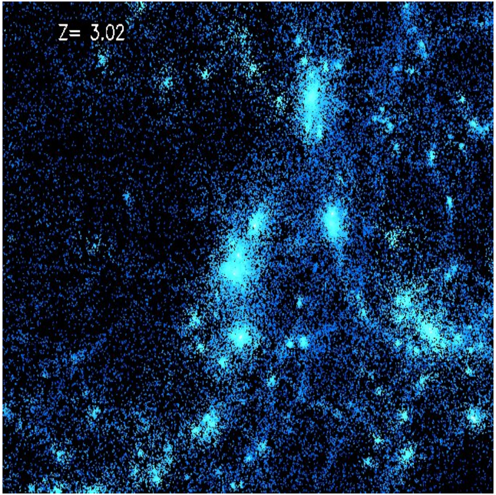

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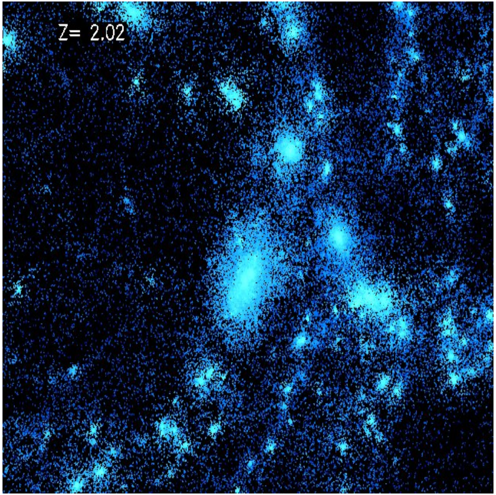

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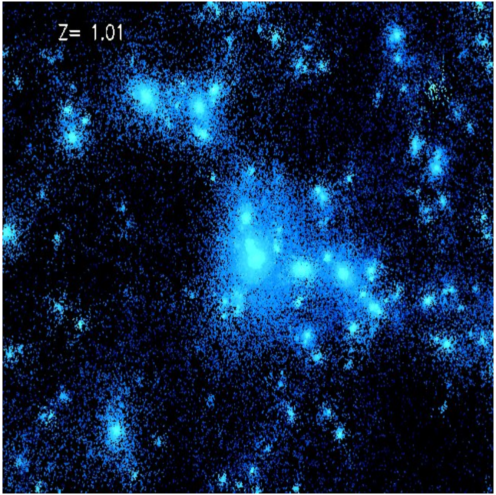

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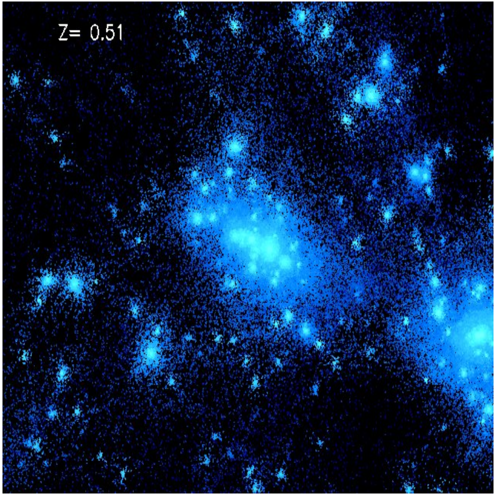

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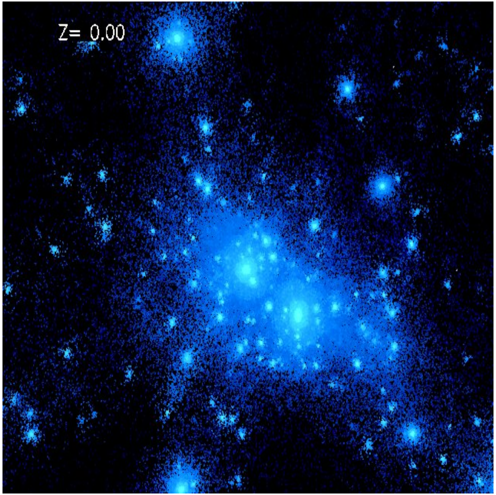
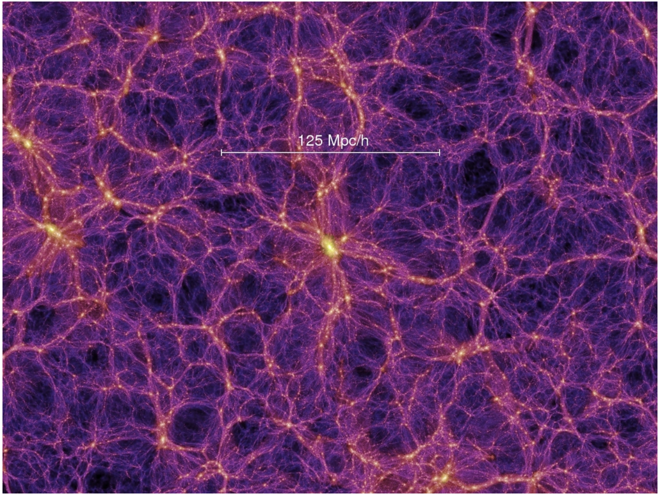


A numerical simulation illustrating the formation of large scale structures due to gravitational instability[27].

Play again

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

The millennium simulation

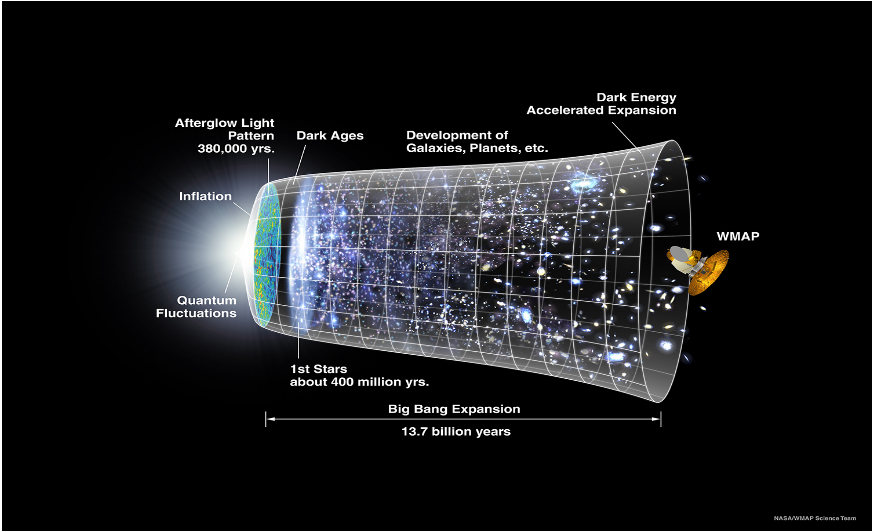


The results from the Millennium Run which traced the evolution of the matter distribution in a cubic region of the universe over 2 billion light years on a side[27].

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

Plan of the talk

The timeline of the universe



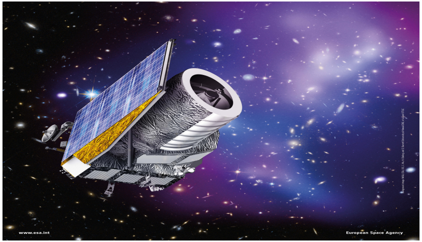
A pictorial timeline of the universe[28].

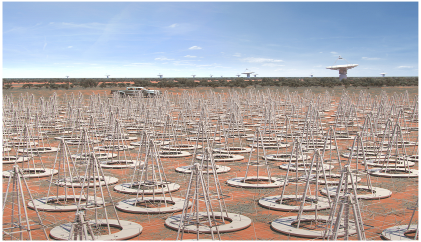
[28] See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

The standard model of cosmology

- The universe is homogeneous and isotropic at length scales of the order of $100\ \mathrm{Mpc}$ 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