The standard model of cosmology

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100 years of General Relativity: Where do we stand?

Indian Institute of Technology Guwahati, Guwahati

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Plan of the talk

1. The smooth universe

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2. The hot big bang model

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3. Origin and imprints of perturbations

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5. Summary and open issues

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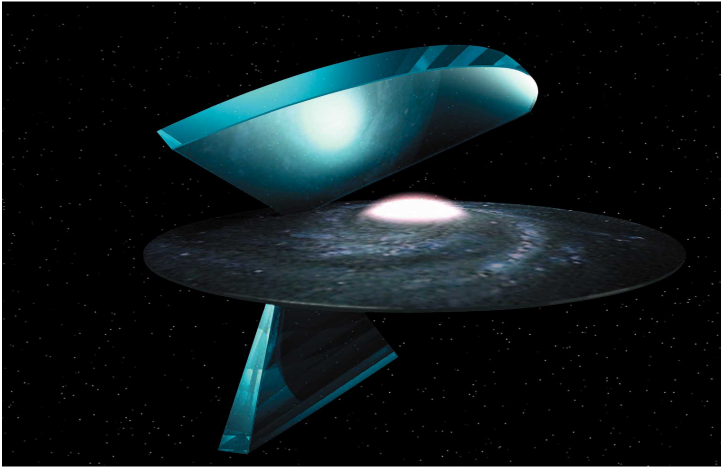
1. The smooth universe
   - Distribution of matter in the universe
   - The cosmic microwave background
   - Hubble's law
   - Describing the smooth universe
2. The hot big bang model
3. Origin and imprints of perturbations
4. Formation of structure
5. Summary and open issues

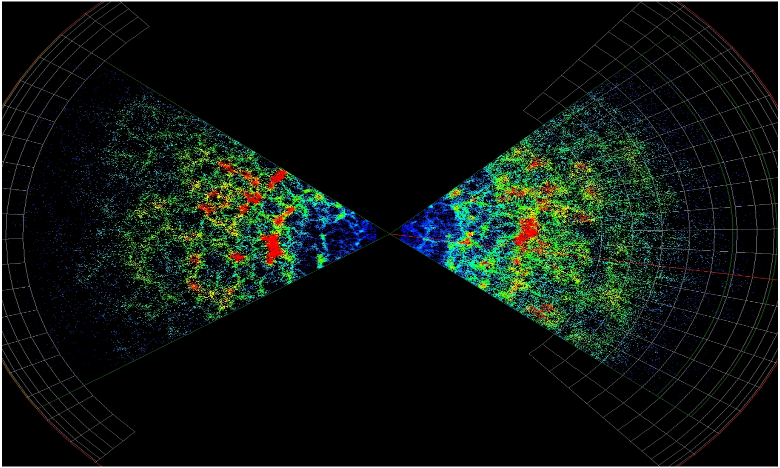
Surveying the universe



A schematic drawing showing the directions of the regions observed by the 2 degree field (2dF) redshift survey with respect to our galaxy[1]. The survey regions actually extend more than 10^5 times further than shown here.

[1] 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[2]. (Note that each dot in the picture represents a galaxy.) It is evident that the universe is homogenous on a suitably large scale.

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

The Sloan digital sky survey

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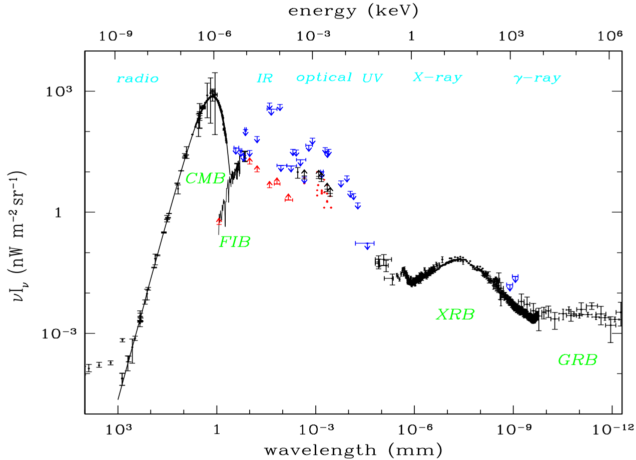
- Over eight years of operations, it has obtained deep, multi-color images covering more than a quarter of the sky and created three-dimensional maps containing more than $930,000$ galaxies and more than $120,000$ quasars.

Play SDSS movie

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

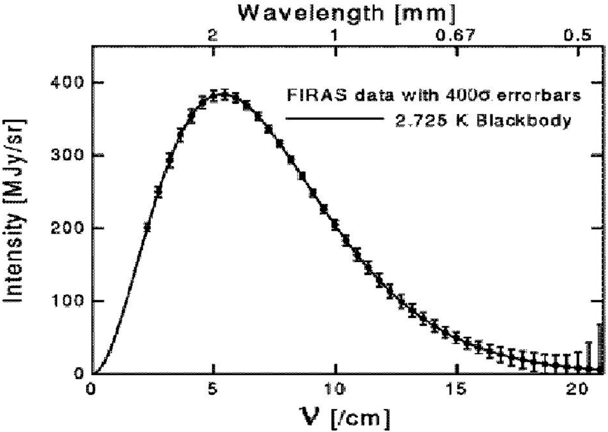
Radiation in the universe



The energy density spectrum of cosmological background radiation has been plotted as a function of wavelength[4]. Note that the Cosmic Microwave Background (CMB) contributes the most to the overall background radiation.

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

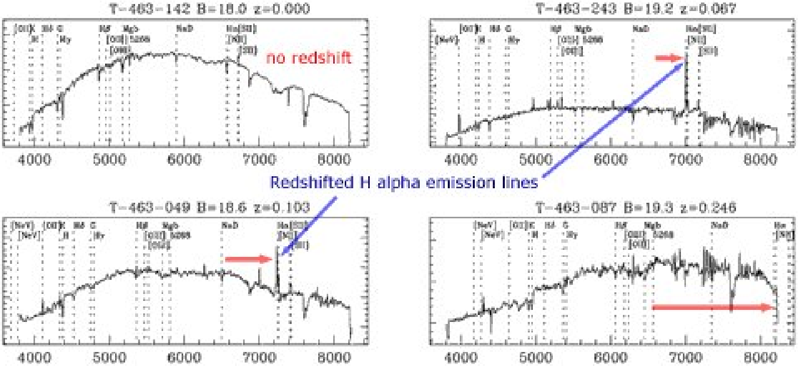
The spectrum of the CMB



The spectrum of the CMB as measured by the COBE satellite[5]. 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!

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

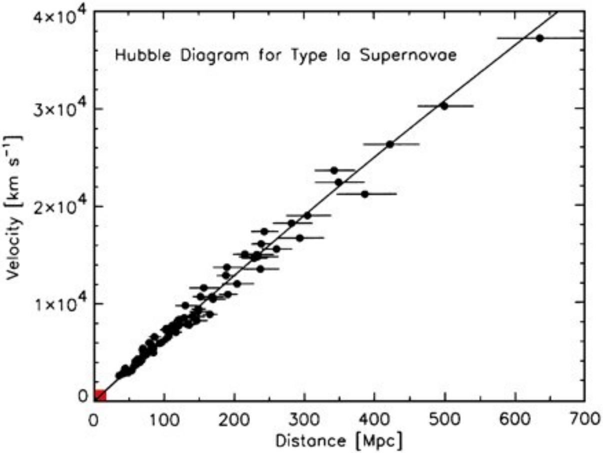
Runaway galaxies and the expanding universe



Spectra of four different galaxies from the 2dF redshift survey[6]. 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 red-shifted from the rest frame value of $6563\ \text{Å}$. The red-shift arises due to the expansion of the universe.

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

Relation between the velocity and the distance of galaxies



A modern Hubble diagram[7]. The slope of the straight line is found to be about $72\ \mathrm{km/s/Mpc}$. The small red region in the lower left marks the span of Hubble's original diagram.

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

The Friedmann-Lemaître-Robertson-Walker metric

The homogeneous, isotropic and expanding universe can be described by the following Friedmann-Lemaître-Robertson-Walker (FLRW) line element:

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\left[\frac{\mathrm{d}r^2}{(1-\kappa\, r^2)} + r^2\,\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right)\right],$$

where t is the cosmic time and $a(t)$ denotes the scale factor, while $\kappa = 0, \pm 1$.

[8] Image from http://abyss.uoregon.edu/~js/lectures/cosmo_101.html.

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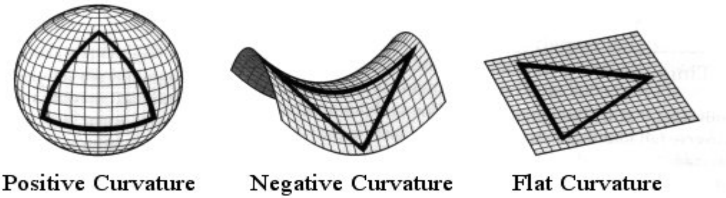
where t is the cosmic time and $a(t)$ denotes the scale factor, while $\kappa = 0, \pm 1$.

The quantity κ denotes the spatial geometry of the universe. It can be flat ($\kappa = 0$), closed ($\kappa = 1$) or open ($\kappa = -1$) depending on the total energy density of matter present in the universe[8].



[8]Image from http://abyss.uoregon.edu/~js/lectures/cosmo_101.html.

The Friedmann equations

If ρ and p denote the energy density and pressure of the smooth component of the matter field that is driving the expansion, then the Einstein's equations for the FLRW metric lead to the following equations for the scale factor $a(t)$:

$$\begin{aligned} H^2 + \frac{\kappa}{a^2} &= \frac{8\pi\, G}{3}\,\rho, \\ \frac{\ddot{a}}{a} &= -\frac{4\pi\, G}{3}\,(\rho + 3\,p)\,, \end{aligned}$$

where $H = \dot{a}/a$ is the Hubble parameter.

The cosmological redshift

In a FLRW universe, the frequency of electromagnetic radiation decreases with the expansion as follows:

$$\omega(t) \propto \frac{1}{a(t)},$$

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Therefore, in terms of the scale factor, the cosmological redshift z is given by

$$\frac{a_0}{a(t)} = 1 + z,$$

where a_0 denotes the value of the scale factor *today* (*i.e.* at $t = t_0$).

The cosmological parameters

In terms of the redshift z, the first of the Friedmann equations can be written as

$$\left[\frac{H(z)}{H_0}\right]^2 = \Omega_{\rm NR}\,(1+z)^3 + \Omega_{\rm R}\,(1+z)^4 + \Omega_{\Lambda} - (\Omega - 1)\,(1+z)^2\,,$$

where $H_0 \equiv (\dot{a}/a)_{t=t_0}$ is the Hubble constant, $\Omega_i = \rho_i/\rho_{\rm C}$ with $\rho_{\rm C}$ being the critical density given by

$$\rho_{\rm C} = \frac{3\,H_0^2}{8\,\pi\,G}$$

and $\Omega = \Omega_{\rm NR} + \Omega_{\rm R} + \Omega_{\Lambda}$.

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The Hubble constant H_0 is usually expressed as $H_0 = 100\,h\;{\rm km/s/Mpc}$.

Plan of the talk

Equilibrium between matter and radiation at early epochs

In an evolving universe, the temperature of the CMB goes as

$$T \propto \frac{1}{a(t)},$$

so that the energy density of radiation behaves as

$$\rho_{\mathrm{R}} \propto \frac{1}{a^4(t)}.$$

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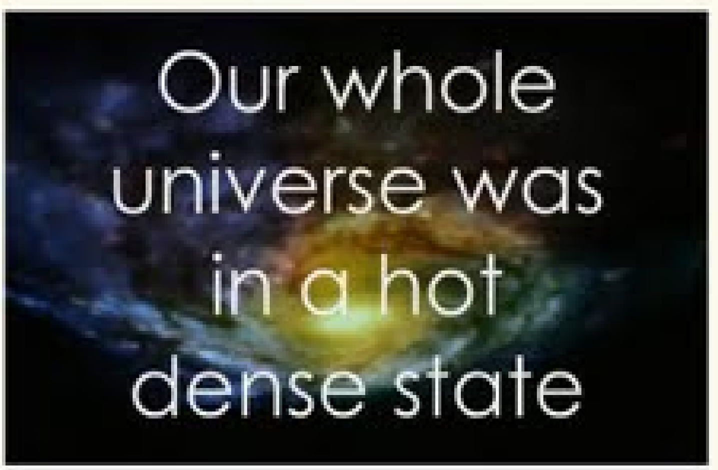
Observations indicate that, today,

$$\rho_{\rm R} \simeq \frac{\rho_{\rm NR}}{10^4}.$$

This points to the fact that matter and radiation would have interacted strongly and, hence would have been in thermal equilibrium, when the universe was about 10^4 times smaller.

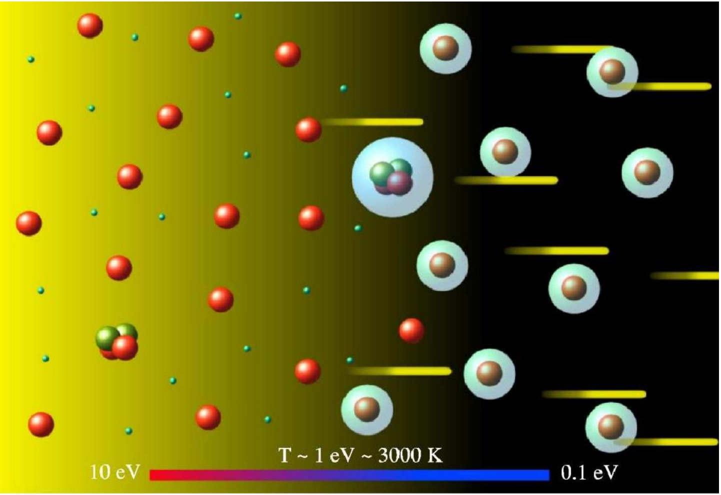
The big bang model seems popular!



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'[9]!

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

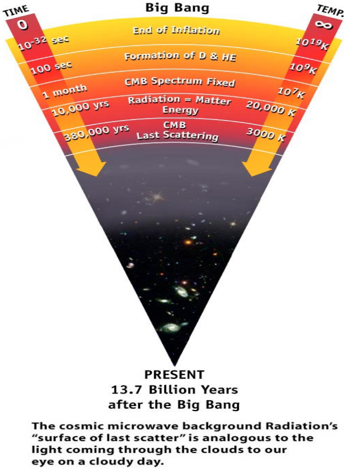
Decoupling of matter and radiation[10]

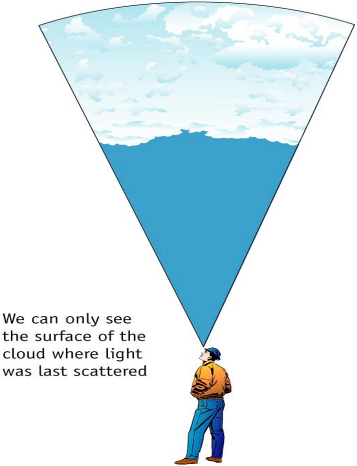


Radiation ceases to interact with matter at a temperature of about $T \simeq 3000^\circ\ \mathrm{K}$, which corresponds to a redshift of about $z \simeq 1000$.

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

Last scattering surface and freestreaming CMB photons

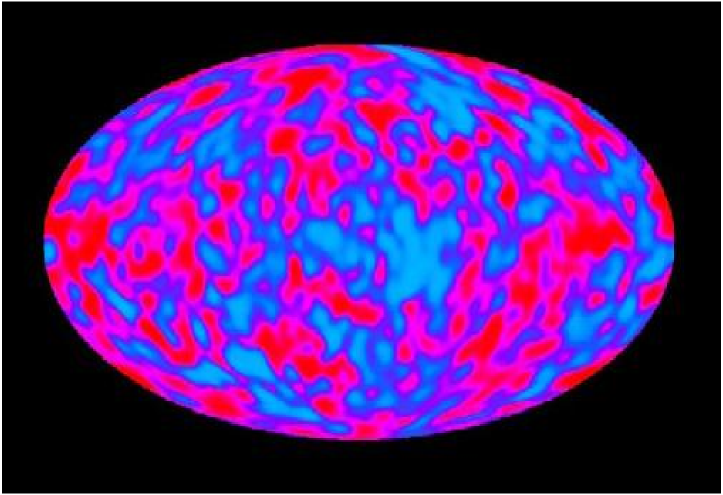




The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter[11].

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

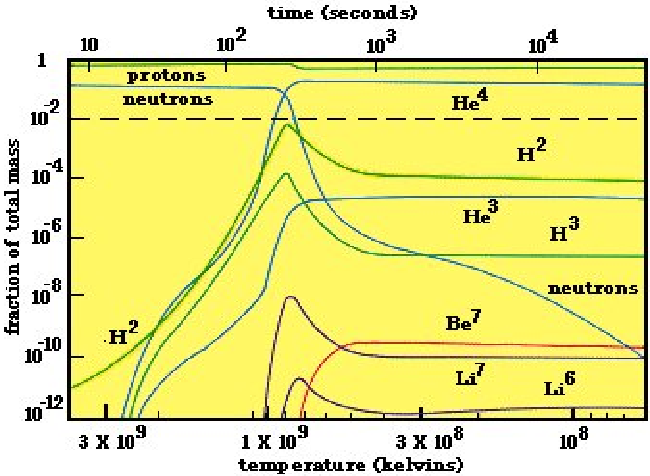
Extent of isotropy of the CMB



The fluctuations in the temperature of the CMB as seen by COBE[12]. The CMB turns out to be isotropic to one part in 10^5.

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

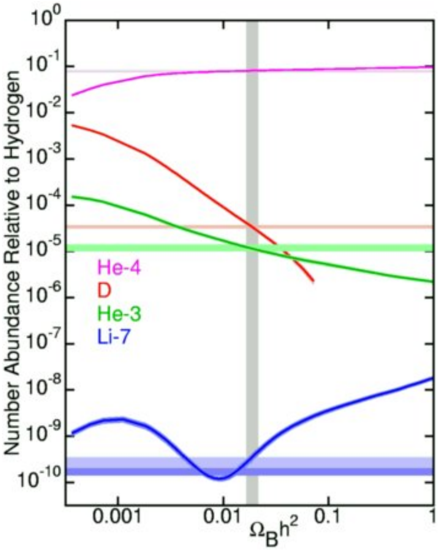
Abundance of light elements – Theory



The relative abundances of the light elements in the early radiation dominated epoch have been plotted as a function of temperature[13].

[13] Image from http://www.astro.ucla.edu/~wright/BBNS.html.

Abundance of light elements – Observations[14]



The graph to the left contains the theoretically predicted abundance versus the density for the light elements as curves, the observed abundances as horizontal stripes and the derived baryon density as the vertical stripe. Note that a single value of the baryon density fits all the four abundances, and it is found that $\Omega_{\rm B}\, h^2 \simeq 0.022$, where $H_0 = 100\, h\, {\rm km/sec/Mpc}$.

[14] Image from http://www.astro.ucla.edu/~wright/BBNS.html.

Supernovae can be as bright as the host galaxy[15]

Supernova 1994D, visible as the bright spot on the lower left, occurred in the outskirts of disk galaxy NGC 4526.

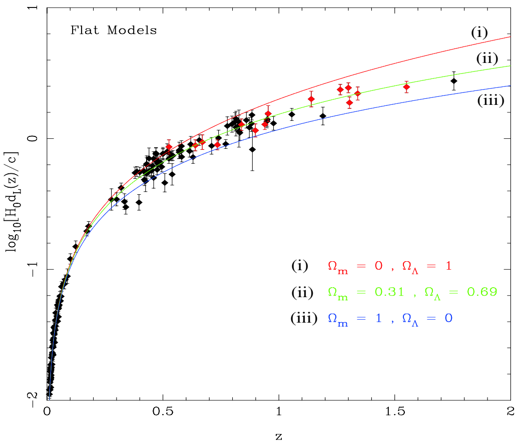
[15] Image from http://apod.nasa.gov/apod/ap981230.html.

A supernova explosion in a distant galaxy

Left: A supernova at the redshift of 0.28 caught at maximum light by the Supernova Legacy Survey (SNLS).
Right: The supernova after it had faded[16].

[16] Images from C. J. Pritchet *et. al.*, arXiv:astro-ph/0406242v1.

Supernovae data and the need for a cosmological constant

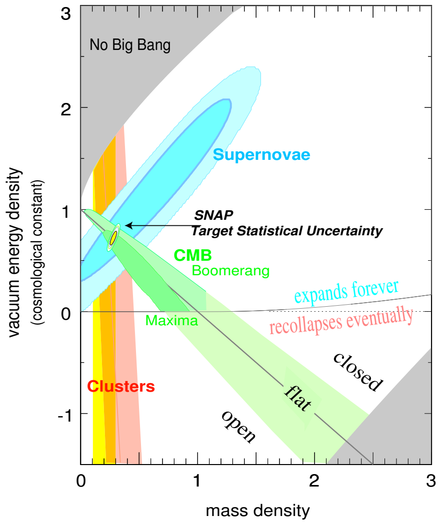


The luminosity distance $H_0\, d_{\rm L}$ plotted as a function of the redshift z for spatially flat cosmological models[17]. The black points are from the 'Gold' data sets and the red points are the data from the Hubble Space Telescope[18].

[17] Figure from T. R. Choudhury and T. Padmanabhan, Astron. Astrophys. **429**, 807 (2005).

[18] R. A. Knop *et. al.*, Astrophys. J. **598**, 102 (2003); A. G. Riess *et. al.*, Astrophys. J. **607**, 665 (2004).

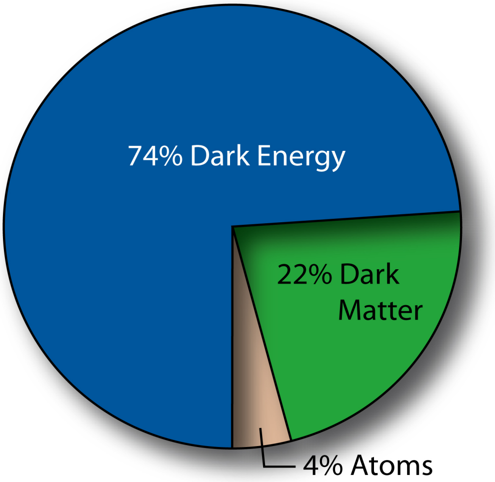
Joint constraints on $\Omega_{\rm NR}$ and Ω_{Λ}[19]



Joint constraints on $\Omega_{\rm NR}$ and Ω_{Λ} from the observations of supernovae, CMB and galaxy clustering. Note that a cosmology with $\Omega_{\rm NR} = 1$ and $\Omega_{\Lambda} = 0$ is ruled out to 99% confidence level, while a universe with $\Omega_{\rm NR} \simeq 0.3$ and $\Omega_{\Lambda} \simeq 0.7$ proves to be a good fit to the data. The figure also contains the constraints that can be expected from the planned Supernova/Acceleration Probe (SNAP).

[19] Figure from G. Aldering *et. al.*, arXiv:astro-ph/0209550v1.

Matter content of the universe

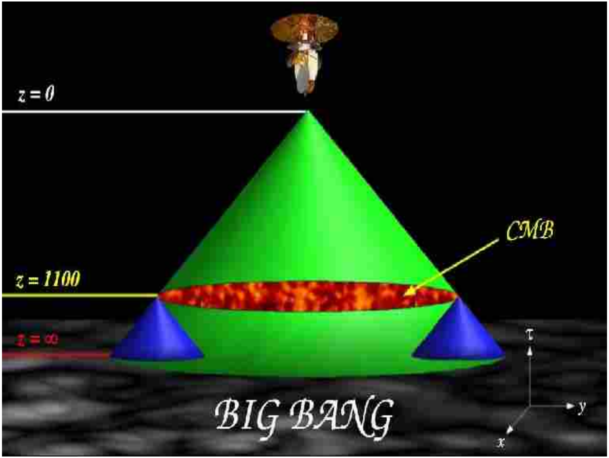


A pie chart of the matter content of the universe today[20].

[20] Image from http://map.gsfc.nasa.gov/media/060916/060916_UniversePie300.jpg.

Plan of the talk

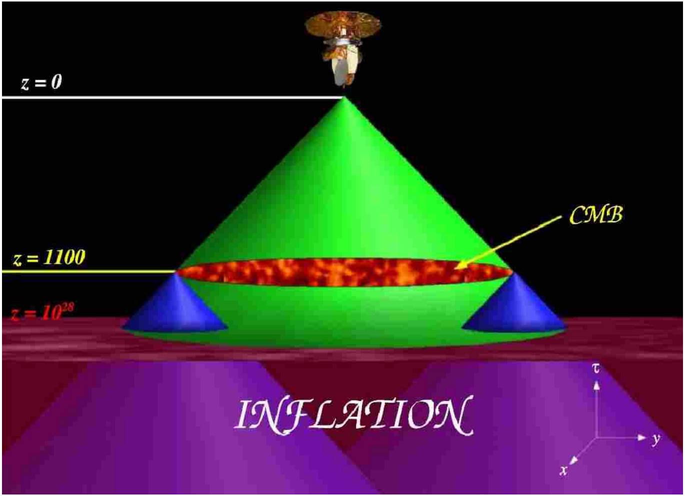
The horizon problem



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[21].

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

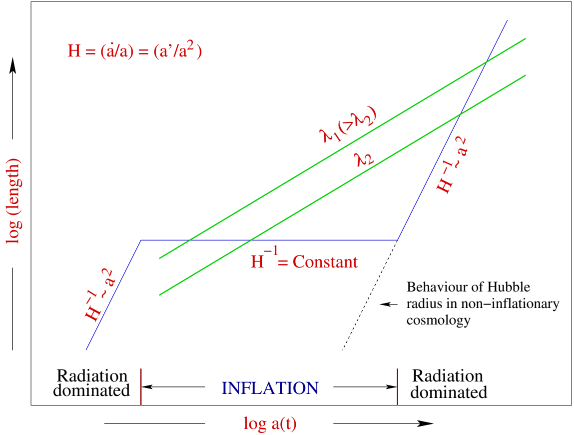
Inflation resolves the horizon problem



An illustration of how an early and sufficiently long epoch of inflation (*viz.* a phase when $\ddot{a} > 0$) resolves the horizon problem[22].

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

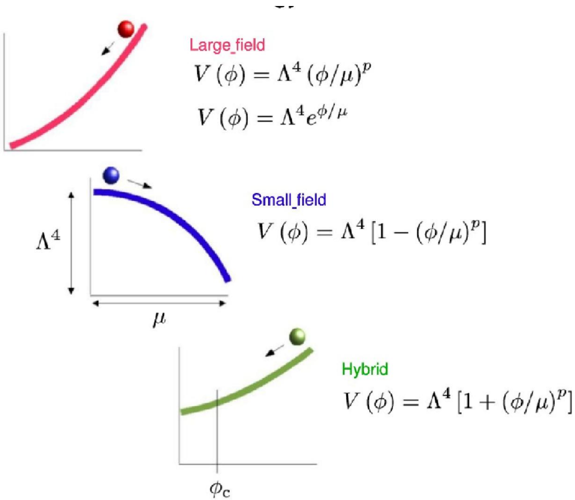
Bringing the modes inside the Hubble radius



A schematic diagram illustrating the behavior of the physical wavelength $\lambda_{\rm P} \propto a$ (the green lines) and the Hubble radius $d_{\rm H} = H^{-1}$ (the blue line) during inflation and the radiation dominated epochs[23].

[23] See, for example, E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley Publishing Company, New York, 1990), Fig. 8.4.

Driving inflation with scalar fields



A variety of scalar field potentials have been considered to drive inflation[24]. These potentials are classified as small field, large field and hybrid models.

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

Origin and evolution of perturbations

- It is the quantum fluctuations associated with these scalar fields which are responsible for the origin of the perturbations.

Origin and evolution of perturbations

- It is the quantum fluctuations associated with these scalar fields 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.

Play movie

The character of perturbations

In a Friedmann universe, the perturbations in the metric and the matter can be classified according to their behavior with respect to local rotations of the spatial coordinates on hypersurfaces of constant time as follows[25]:

- Scalar perturbations – Density and pressure perturbations
- Vector perturbations – Rotational velocity fields
- Tensor perturbations – Gravitational waves

The metric perturbations are related to the matter perturbations through the first order Einstein's equations.

The scalar perturbations leave the largest imprints on the CMB, and are primarily responsible for the inhomogeneities in the distribution of matter in the universe.

In the absence of sources, vector perturbations decay rapidly in an expanding universe.

Whereas, the tensor perturbations, *i.e.* the gravitational waves, can be generated even in the absence of sources.

[25] See, for instance, L. Sriramkumar, Curr. Sci. **97**, 868 (2009).

Primordial perturbation spectra[26]

When comparing with the observations, for simplicity, one often uses the following power law, template scalar and tensor spectra:

$$\mathcal{P}_{\rm S}(k) = \mathcal{A}_{\rm S}\,\left(\frac{k}{k_\ast}\right)^{n_{\rm S}-1} \quad \text{and} \quad \mathcal{P}_{\rm T}(k) = \mathcal{A}_{\rm T}\,\left(\frac{k}{k_\ast}\right)^{n_{\rm T}},$$

where $\mathcal{A}_{\rm S}$ and $\mathcal{A}_{\rm T}$ denote the scalar and tensor amplitudes, $k_\ast$ represents the so-called pivot scale at which the amplitudes are quoted, while the spectral indices $n_{\rm S}$ and $n_{\rm T}$ are assumed to be constant.

The tensor-to-scalar ratio r is defined as

$$r(k) \equiv \frac{\mathcal{P}_{\rm T}(k)}{\mathcal{P}_{\rm S}(k)}$$

and, often, the dependence of r on the wavenumber of k is assumed to be very weak.

[26] See, for instance, L. Sriramkumar, Curr. Sci. **97**, 868 (2009).

Definition of the CMB angular power spectrum[27]

The deviation from the mean value of the CMB temperature in a given direction of the sky, say $\hat{\boldsymbol{n}}$, can be expanded in terms of the spherical harmonics as follows:

$$\frac{\Delta T\,(\hat{\boldsymbol{n}})}{T} = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{m=\ell} a_{\ell m} Y_{\ell m}\,(\hat{\boldsymbol{n}})\,.$$

The correlation function of the deviations is defined as

$$C(\theta) \equiv \langle [\Delta T\,(\hat{\boldsymbol{n}}_1)\ \Delta T\,(\hat{\boldsymbol{n}}_2)]\,/T^2\rangle,$$

where $\cos\theta = \hat{\boldsymbol{n}}_1 \cdot \hat{\boldsymbol{n}}_2$ and the average is taken across all the pairs of points in the sky.

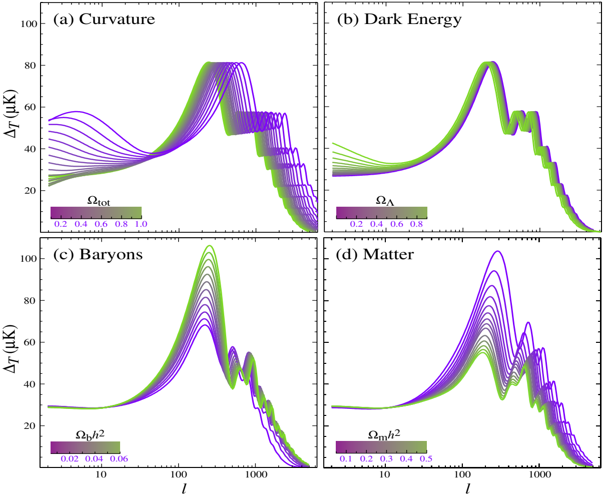
As there is no preferred direction, we have $\langle a_{\ell m}^{*}\, a_{\ell' m'}\rangle = C_\ell\, \delta_{\ell\ell'}\, \delta_{mm'}$ so that

$$C(\theta) = \frac{1}{4\,\pi} \sum_{l=2}^{\infty} (2\,\ell+1)\ C_\ell\, P_\ell\,(\cos\theta)\,,$$

where $P_\ell\,(\cos\theta)$ are the Legendre polynomials and C_ℓ are the observed quantities known as the multipole moments.

[27] See, for example, S. Weinberg, *Cosmology* (Oxford University Press, Oxford, England, 2008), Sec. 2.6.

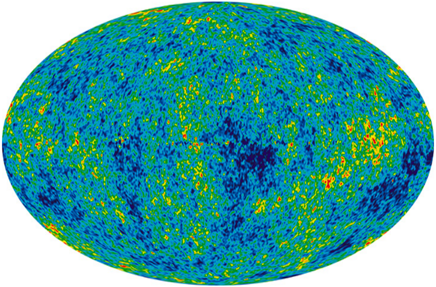
'Effects' of the cosmological parameters on the CMB[28]

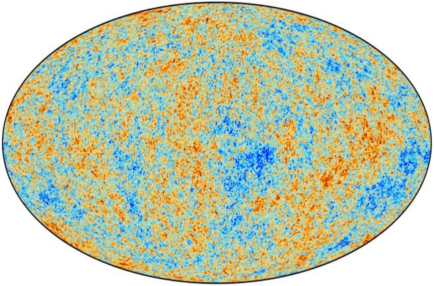


Sensitivity of the CMB angular power spectrum to the four cosmological parameters: Ω, Ω_Λ, $\Omega_{\rm B}\, h^2$ and the non-relativistic matter density $\Omega_{\rm NR}\, h^2$.

[28]Figures from W. Hu and S. Dodelson, Ann. Rev. Astron. Astrophys. **40**, 171 (2002).

CMB anisotropies as seen by WMAP and Planck



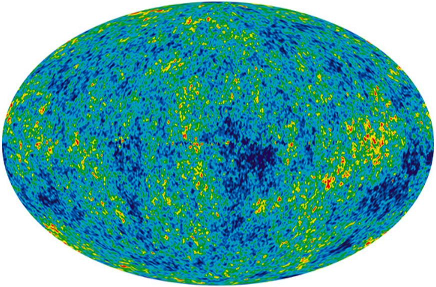


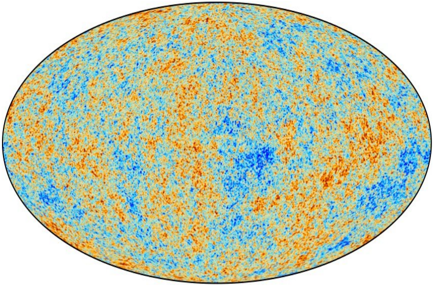
Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[29].

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

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

CMB anisotropies as seen by WMAP and Planck





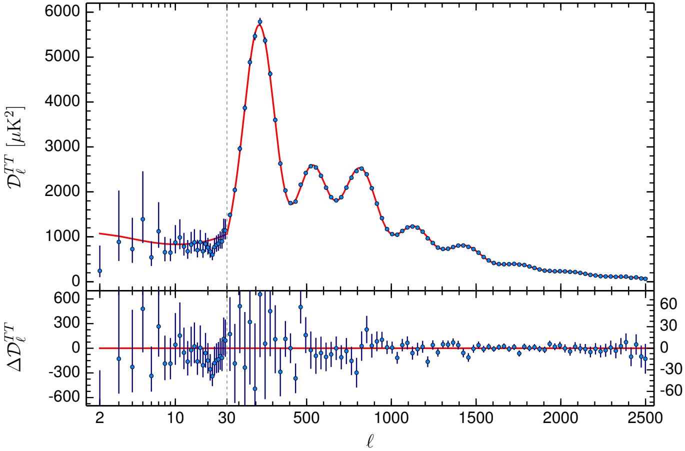
Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[29].

Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[30]. The above images show temperature variations (as color differences) of the order of $200^\circ\,\mu\mathrm{K}$. The angular resolution of WMAP was about 1°, while that of Planck was about $5'$. These temperature fluctuations correspond to regions of slightly different densities, and they represent the seeds of all the structure around us today.

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

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

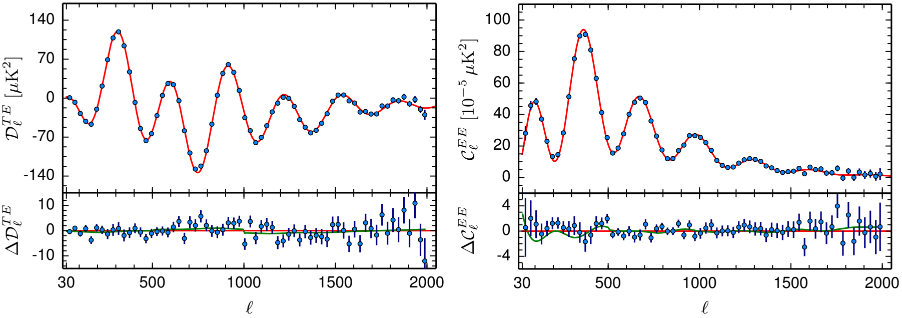
CMB TT angular power spectrum from Planck[31]



The CMB TT angular power spectrum from the Planck 2015 data (the blue dots with error bars) and the theoretical, best fit ΛCDM model with a power law primordial spectrum (the solid red curve).

[31] P. A. R. Ade *et al.*, arXiv:1502.02114 [astro-ph.CO].

CMB TE and EE angular power spectra from Planck[32]



The CMB TE (on the left) and EE (on the right) angular power spectra from the Planck 2015 data (the blue dots with error bars) and the theoretical, best fit ΛCDM model with a power law primordial spectrum (the solid red curves).

[32] P. A. R. Ade *et al.*, arXiv:1502.02114 [astro-ph.CO].

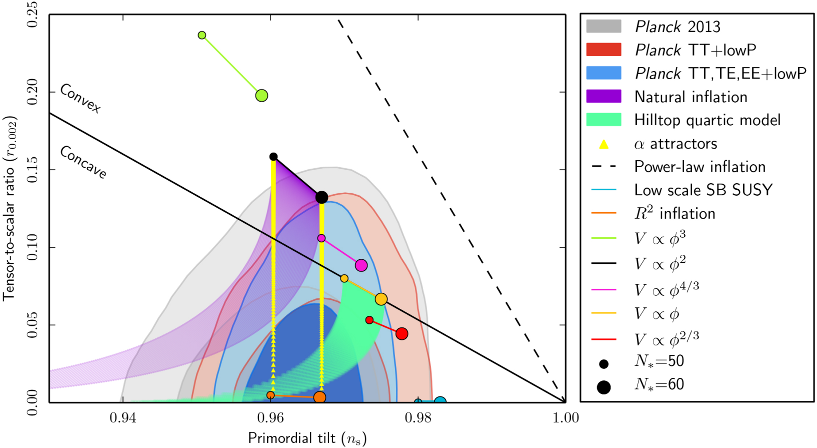
Best fit values of the cosmological parameters[33]

Parameter	TT+lowP	TT+lowP+lensing	TT+lowP+BAO	TT,TE,EE+lowP
$\Omega_{\rm b}h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02226 ± 0.00020	0.02225 ± 0.00016
$\Omega_{\rm c}h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1190 ± 0.0013	0.1198 ± 0.0015
$100\theta_{\rm MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04095 ± 0.00041	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.066 ± 0.016	0.080 ± 0.017	0.079 ± 0.017
$\ln(10^{10}A_{\rm s})$	3.089 ± 0.036	3.062 ± 0.029	3.093 ± 0.034	3.094 ± 0.034
$n_{\rm s}$	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9673 ± 0.0045	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.81 ± 0.92	67.63 ± 0.57	67.27 ± 0.66
$\Omega_{\rm m}$	0.315 ± 0.013	0.308 ± 0.012	0.3104 ± 0.0076	0.3156 ± 0.0091

Confidence limits on the parameters of the base ΛCDM model, for various combinations of the Planck 2015 data, at the 68% confidence level.

[33] P. A. R. Ade *et al.*, arXiv:1502.02114 [astro-ph.CO].

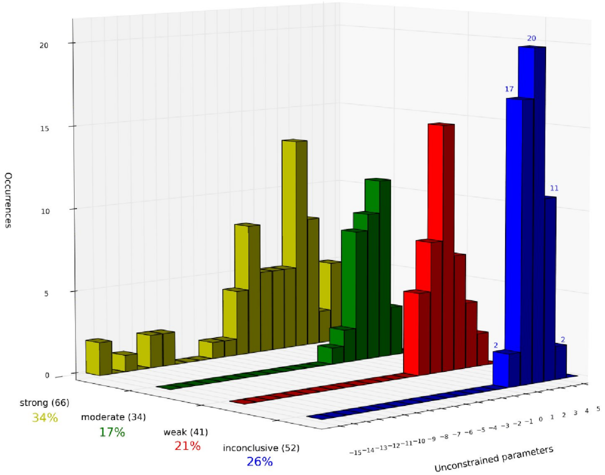
Inflationary models in the n_s-r plane[34]



Marginalized joint $68\,\%$ and $95\,\%$ CL regions for n_s and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

[34] P. A. R. Ade *et al.*, arXiv:1502.02114 [astro-ph.CO].

Performance of inflationary models



The efficiency of the inflationary paradigm leads to a situation wherein, despite the strong constraints, a variety of models continue to remain consistent with the data[35].

[35] J. Martin, C. Ringeval, R. Trotta and V. Vennin, JCAP **1403**, 039 (2014).

Plan of the talk

Formation of large scale structure

- 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.

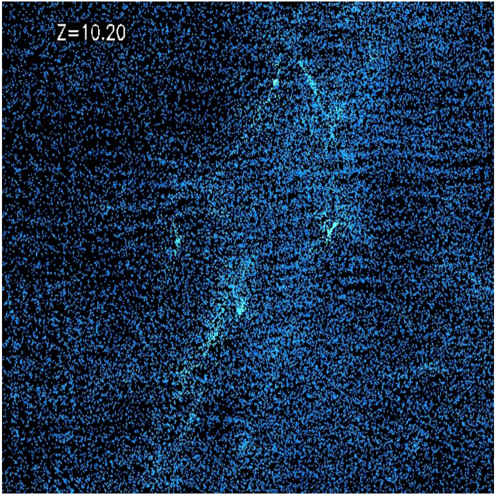
Play movie

Formation of structures due to gravitational instability

A numerical simulation illustrating the formation of large scale structures due to gravitational instability[36].

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

Formation of structures due to gravitational instability



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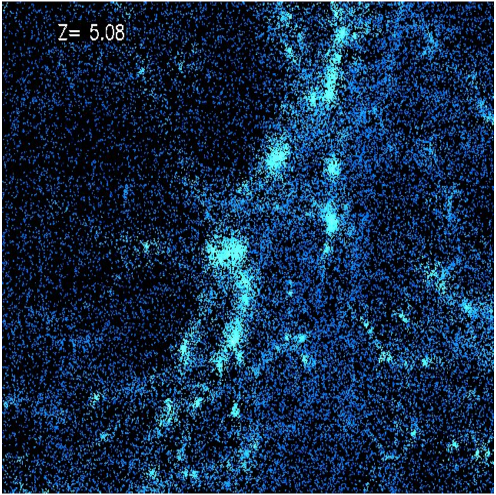

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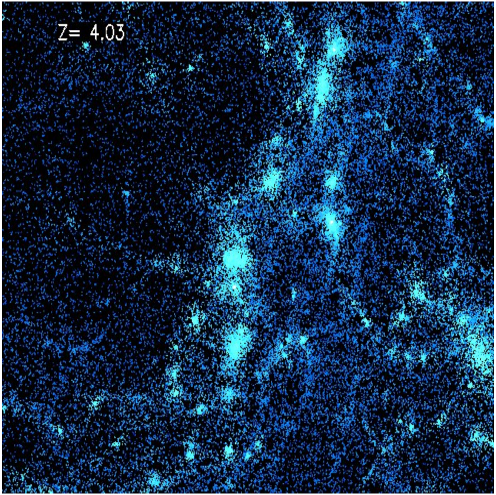

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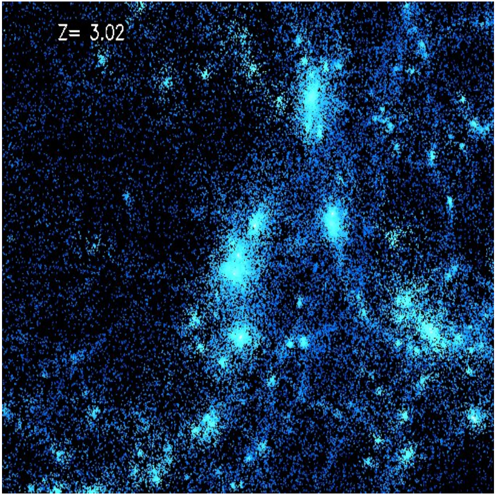

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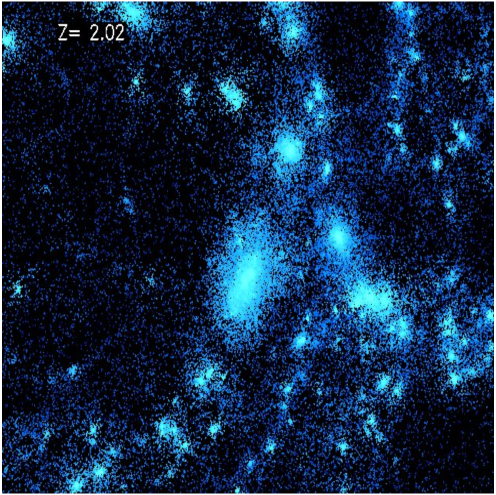

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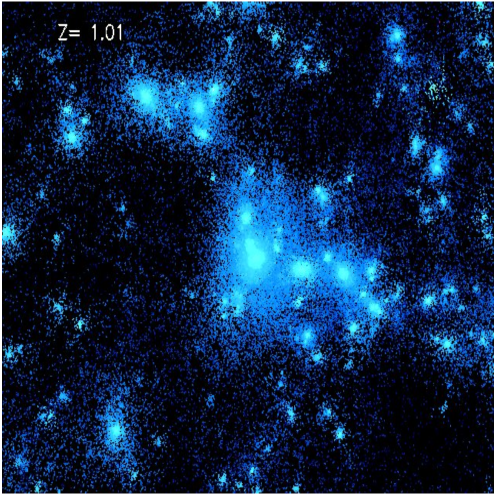

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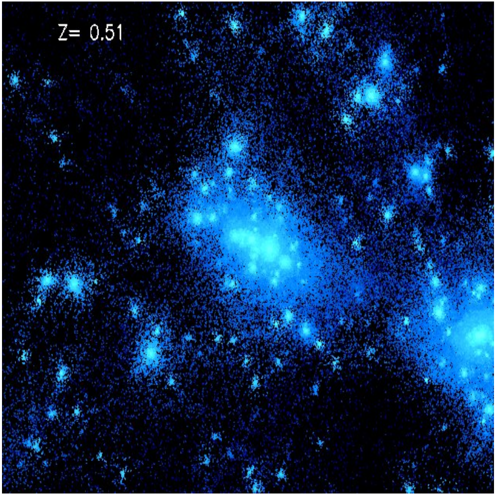

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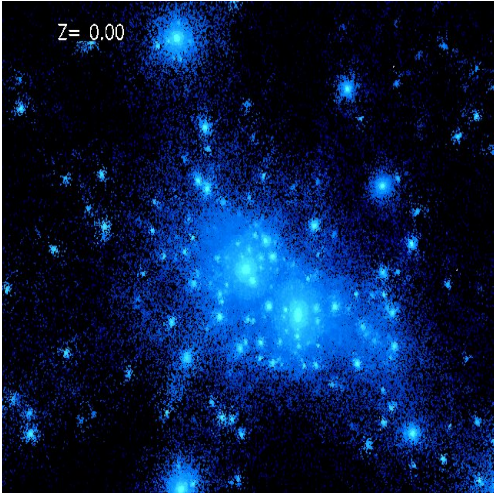

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Play again

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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[36].

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

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- It kept busy the principal supercomputer at the Max Planck Society's Supercomputing Centre in Garching, Germany for more than a month.

Play movie

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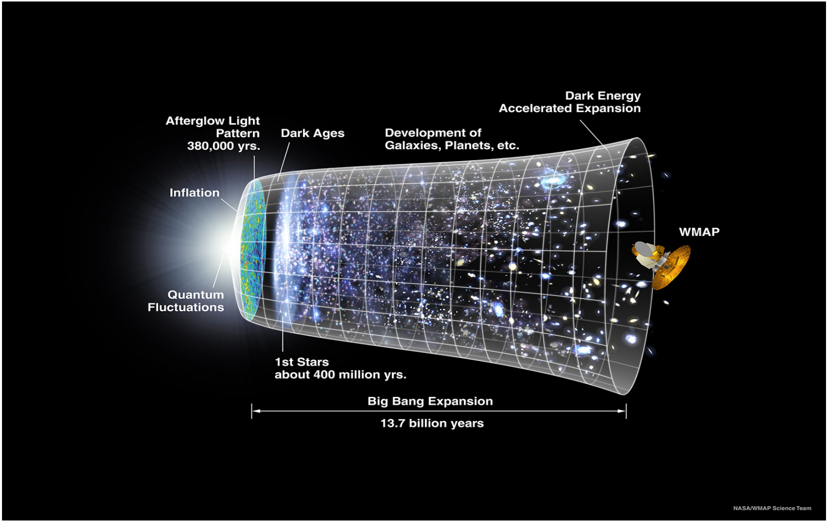
Plan of the talk

Timeline of the universe



A pictorial timeline of the universe – from the big bang until today[37].

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

Summary

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

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- 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.

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- 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.

Open issues

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- Is gravity described by the general theory of relativity?
- Are the primordial perturbations adiabatic? Are they Gaussian?

Thank you for your attention