Understanding our universe
– From the early epochs to late times –

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Plan of the talk

1. A survey of the universe

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2. The composition and evolution of the smooth universe

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3. The origin and evolution of perturbations

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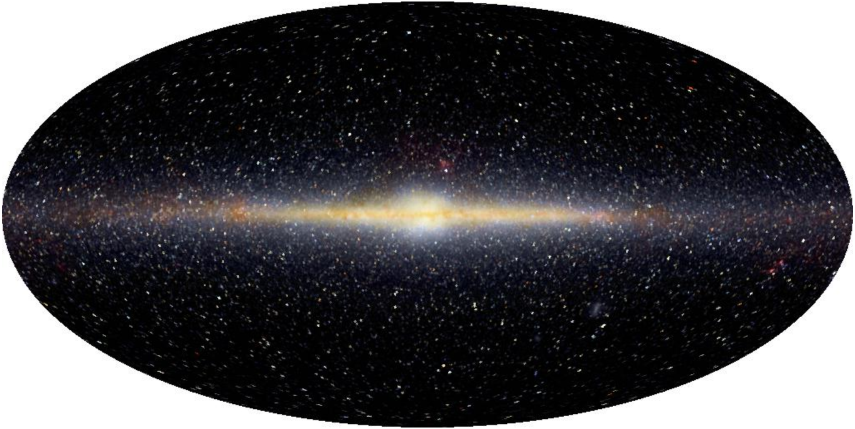
3. The origin and evolution of perturbations
4. The standard model of cosmology

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

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

Our galactic neighbors and the local group[2]

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 $700\ \mathrm{kpc}$.

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

Our galactic neighbors and the local group[2]

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. 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 $1.3\ \mathrm{Mpc}$.

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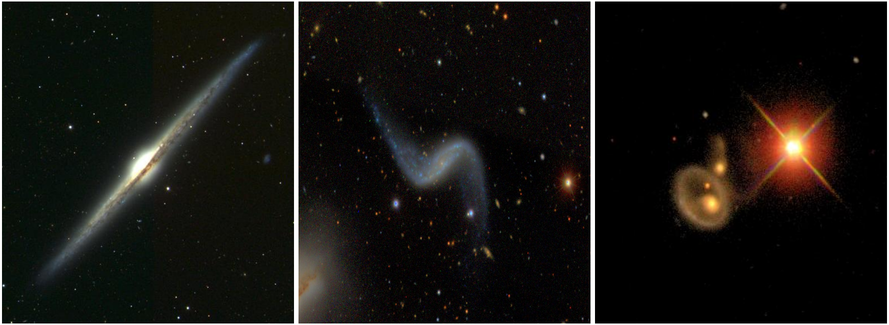
[2] Images from http://www.seds.org/messier/m/m031.html and http://www.seds.org/messier/m/m033.html.

Varieties of galaxies[3]



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.

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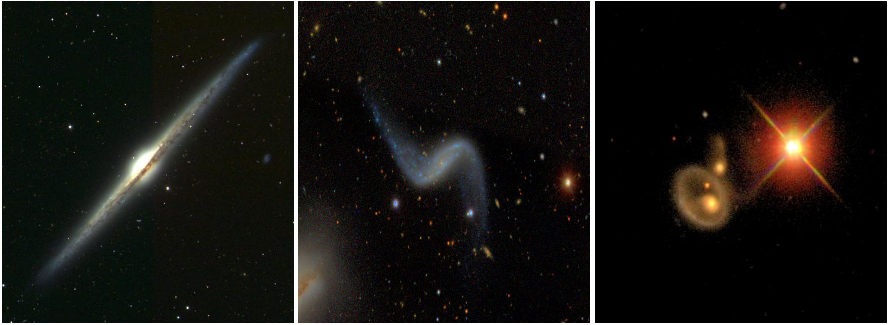

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Center: An image of the spiral galaxy NGC 3187 from SDSS.

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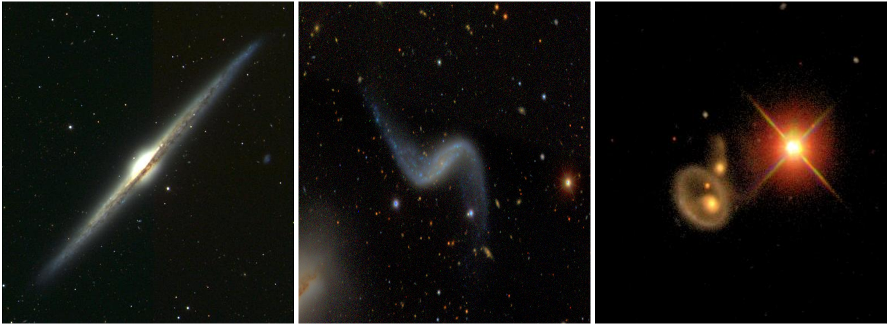

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Center: An image of the spiral galaxy NGC 3187 from SDSS.

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.

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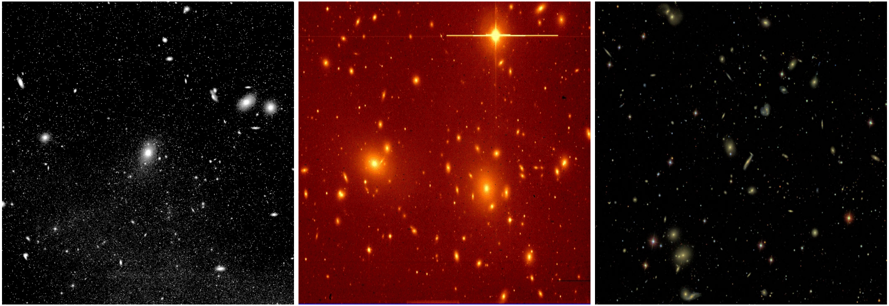
[3] Images from http://www.sdss.org/iotw/archive.html and http://cosmo.nyu.edu/hogg/rc3.

The Virgo, the Coma and the Hercules cluster of galaxies[4]



Left: The Virgo cluster, whose center is considered to be located at a distance of about $20\ \mathrm{Mpc}$. Consisting of over 100 galaxies, it strongly influences the nearby galaxies and galaxy groups gravitationally due to its enormous mass.

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[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.

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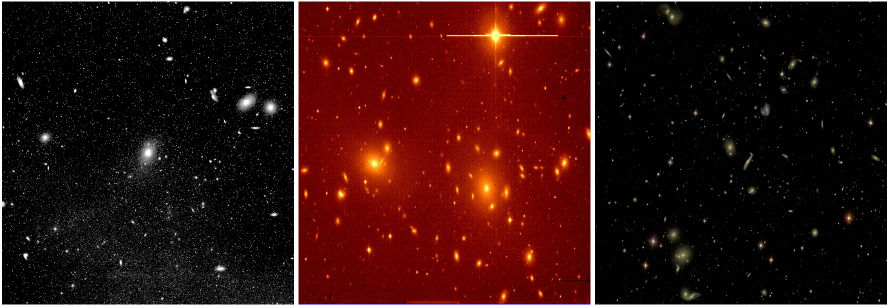

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Center: The Coma cluster of galaxies. The cluster is nearly spherical in shape and contains more than 1000 bright galaxies. It is about $20\ \mathrm{Mpc}$ across, and is located at a distance of about $100\ \mathrm{Mpc}$.

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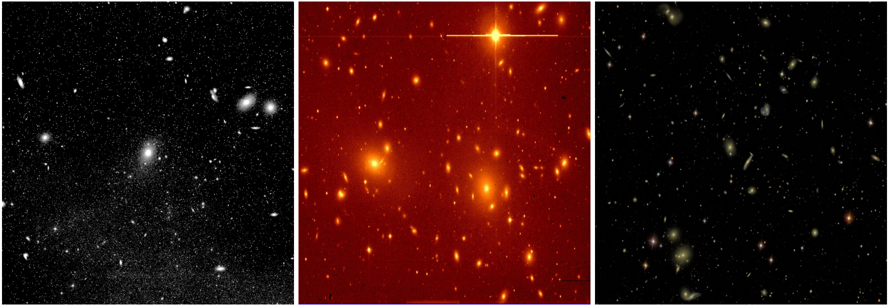

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Right: An SDSS image of the Hercules galaxy cluster that is located at a distance of about $100\ \mathrm{Mpc}$ from us.

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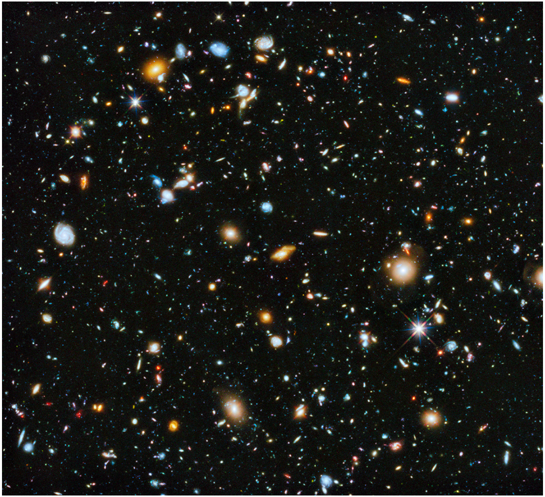
Deepest views in space



An ultra deep field image from the Hubble Space Telescope (HST). The image contains a bewildering variety of galaxy shapes and colors[5].

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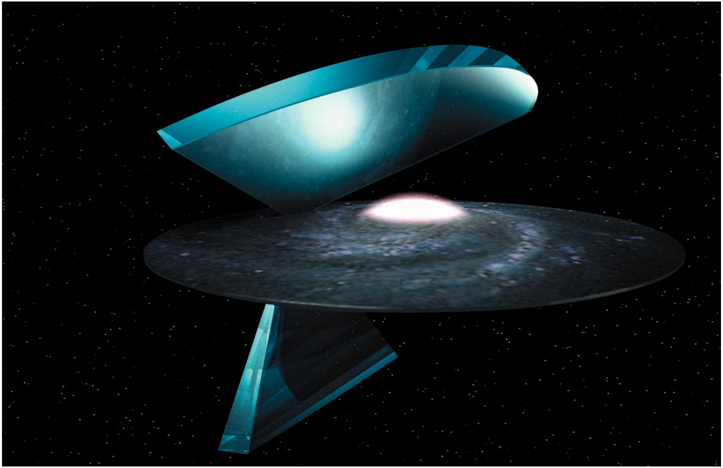
[5] Image from http://hubblesite.org/newscenter/archive/releases/2014/27.

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[6]. The survey regions actually extend more than 10^5 times further than shown here.

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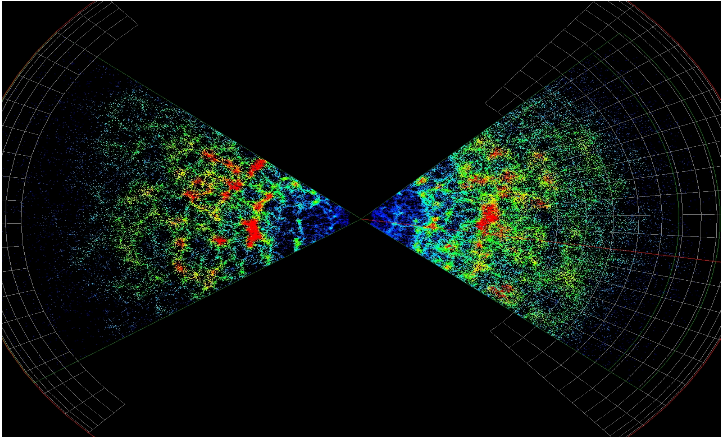
[6] Image from http://magnum.anu.edu.au/˜TDFgg/Public/Pics/2dF3D.jpg.

Distribution of galaxies in the universe



The distribution of more than two million galaxies as observed by the 2dF redshift survey[7]. (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.

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

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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.

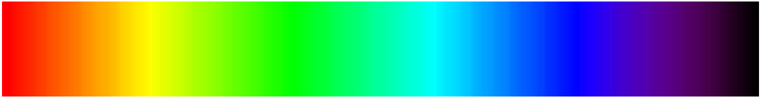
▸ Play SDSS movie

Plan of the talk

1. A survey of the universe
2. The composition and evolution of the smooth universe
    - The expanding universe and the Hubble's law
    - Describing and characterizing the universe
    - The cosmic microwave background
    - The hot big bang model
    - Decoupling of matter and radiation
    - The baryon content of the universe
    - Why do we require dark energy?
    - The composition of the universe
3. The origin and evolution of perturbations
4. The standard model of cosmology

Continuous, emission and absorption spectra[8]

A typical continuous spectrum from an opaque hot body:



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

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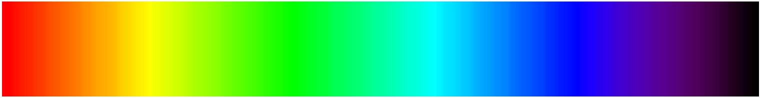

Emission spectrum, as from a given element:

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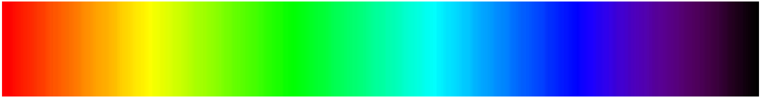
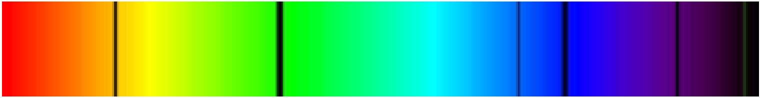


Emission spectrum, as from a given element:

Absorption spectrum, as due to an intervening cool gas:



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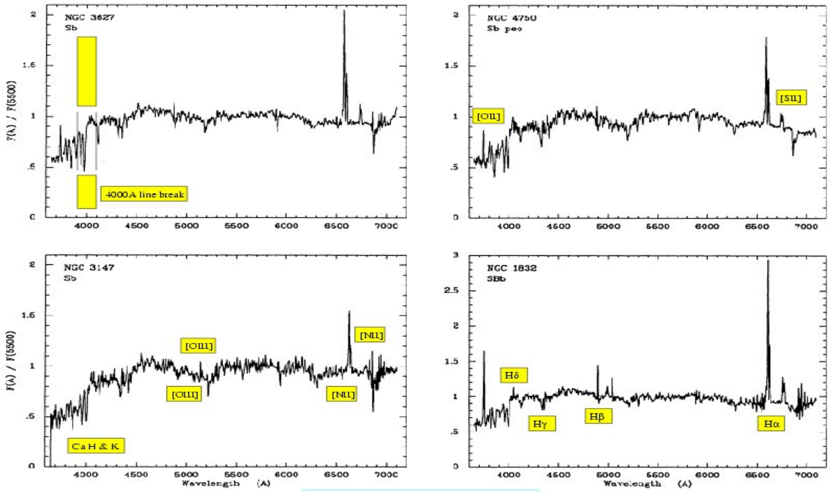
Typical spectra of galaxies[9]



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

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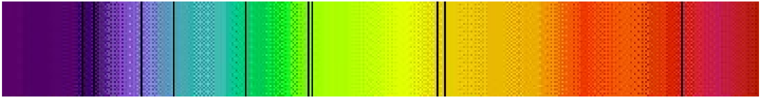
[9] Image from http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html.

The 'Doppler effect' and redshift[10]

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



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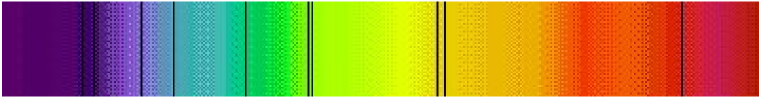
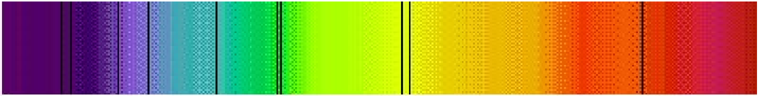


when compared to the spectrum in the source's frame



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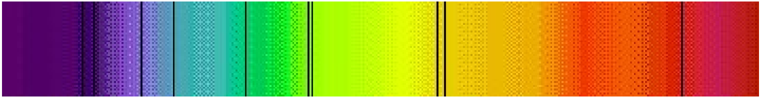

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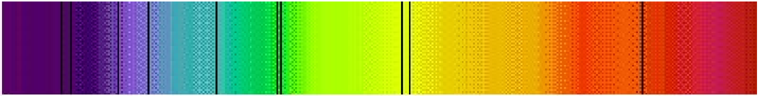

The redshift z of the receding source is defined as:

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

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.

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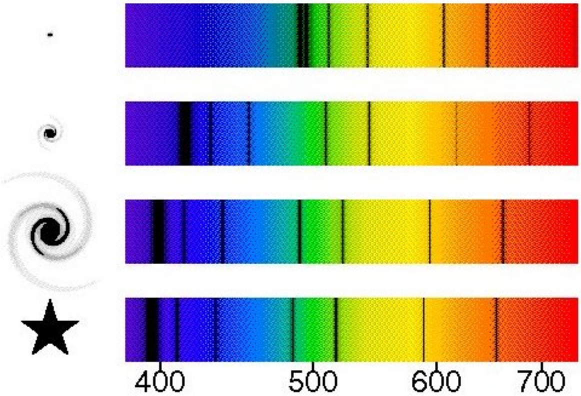
Runaway galaxies – A schematic diagram[11]



A distant galaxy, $z = 0.25$

A farther galaxy, $z = 0.05$

A nearby galaxy, $z = 0.01$

A galactic star, $z = 0$

In the above spectrum of the galactic star, the wavelengths of the absorption lines are 393 and $397\ \mathrm{nm}$ from Ca II (ionized calcium); 410, 434, 486 and $656\ \mathrm{nm}$ from H I (atomic hydrogen); $518\,\mathrm{nm}$ from Mg I (neutral magnesium); and $589\ \mathrm{nm}$ from Na I (neutral sodium).

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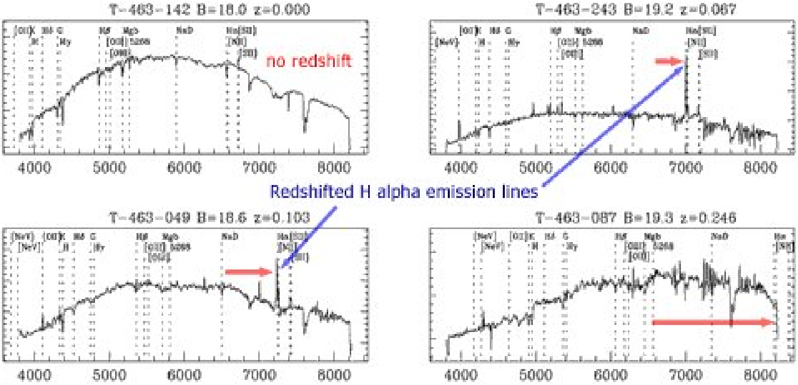
[11] Image from http://www.astro.ucla.edu/˜wright/doppler.htm.

Runaway galaxies – Actual observations[12]



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.

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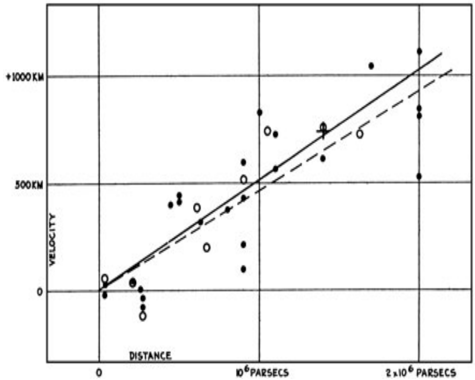
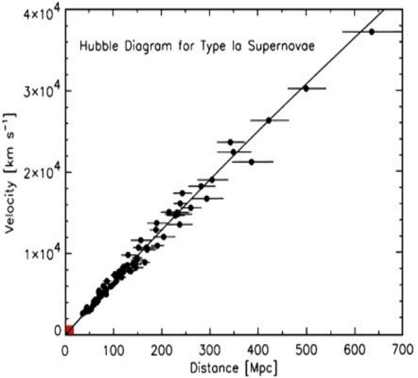
[12] Image from http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.

Relation between the velocity and the distance of galaxies[13]





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

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

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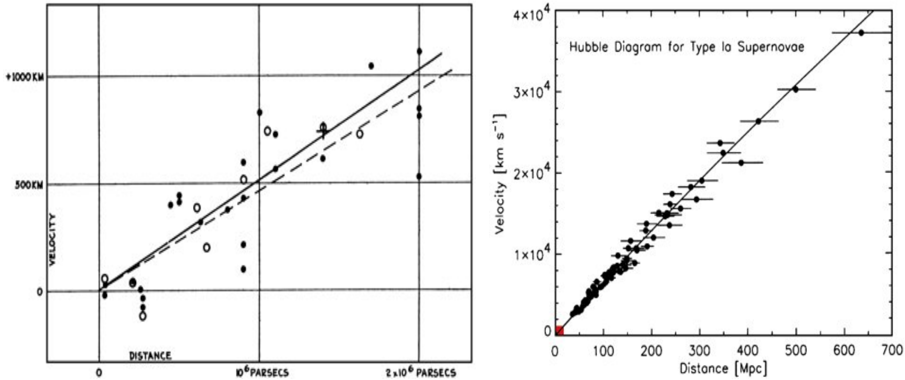

Left: The original Hubble data. The slope of the two fitted lines are about $500\ \mathrm{km/sec/Mpc}$ and $530\ \mathrm{km/sec/Mpc}$.

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.

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[13] 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 $\kappa = 0, \pm 1$.

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[14] Image from http://abyss.uoregon.edu/˜js/lectures/cosmo_101.html.

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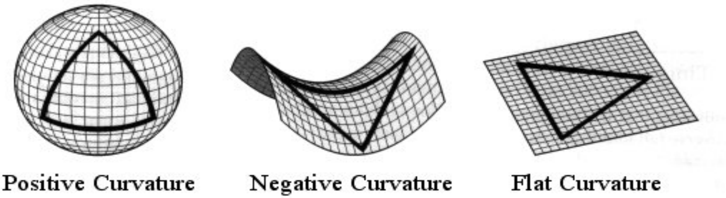
where t is the cosmic time and $a(t)$ denotes the scale factor, while $\kappa = 0, \pm 1$.

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[14].



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

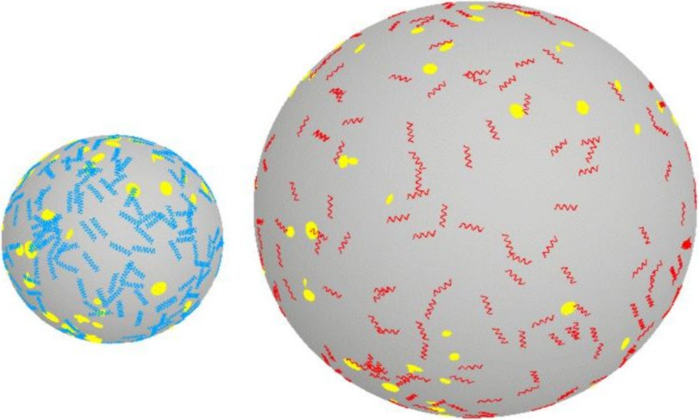
The Friedmann equations

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 $a(t)$:

$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi G}{3}\,\rho \quad \text{and} \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\,(\rho + 3\,p)\,,$$

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

Visualizing the expanding universe



A two-dimensional analogy for the expanding universe[15]. 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.

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[15] Image from http://www.astro.ucla.edu/˜wright/balloon0.html.

The cosmological redshift

Recall that, we had defined the redshift z of a receding source as follows:

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

where $\omega_{\rm O}$ and $\omega_{\rm E}$ denote the observed and emitted frequencies, respectively.

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In an expanding universe, it can be shown that the frequency of electromagnetic radiation decreases with the expansion as follows:

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

where $a(t)$ is the scale factor that characterizes the expansion.

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where $a(t)$ is the scale factor that characterizes the expansion.

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

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

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

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

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

The cosmological parameters

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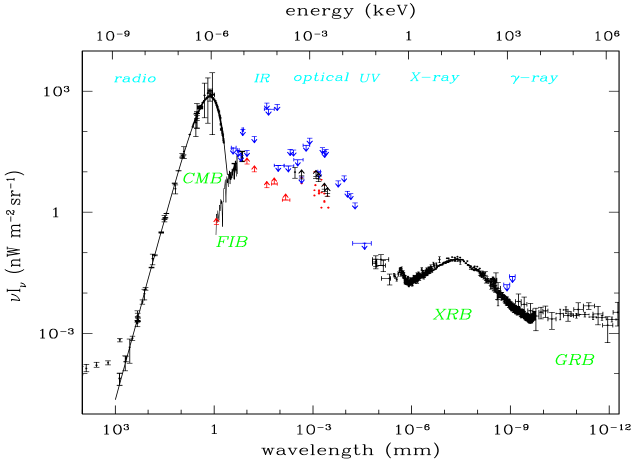
and $\Omega = \Omega_{\rm NR} + \Omega_{\rm R} + \Omega_{\Lambda}$.

The quantities H_0, $\Omega_{\rm NR}$, $\Omega_{\rm R}$ and Ω_{Λ} are four of the cosmological parameters that are to be determined by observations.

The Cosmic Microwave Background (CMB)



The energy density spectrum of cosmological background radiation has been plotted as a function of wavelength[16]. Note that the CMB contributes the most to the overall background radiation.

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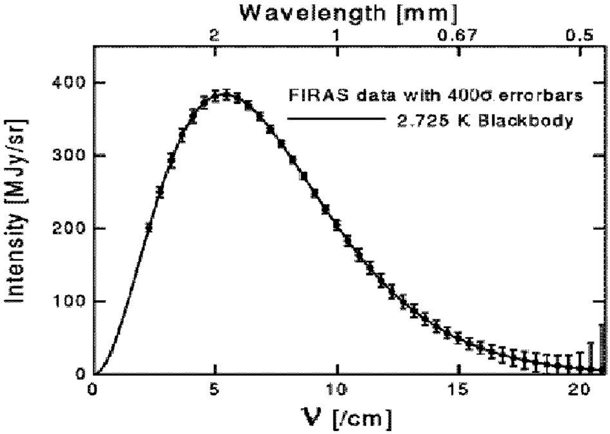
[16] Figure from, D. Scott, arXiv:astro-ph/9912038.

The spectrum of the CMB



The spectrum of the CMB as measured by the COBE satellite[17]. It is such a perfect Planck spectrum (corresponding to a temperature of $2.725^\circ\ \mathrm{K}$) 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!

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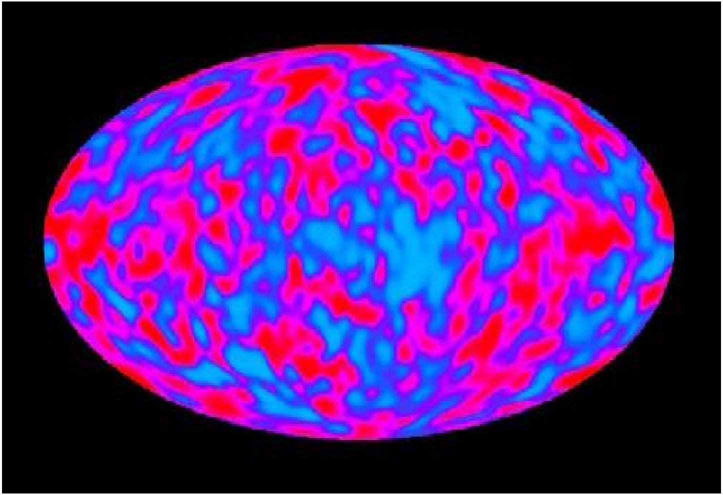
[17] Image from http://www.astro.ucla.edu/˜wright/cosmo_01.htm.

The extent of isotropy of the CMB



The fluctuations in the temperature of the CMB as seen by COBE[18]. The CMB turns out to be isotropic to one part in 10^5.

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

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

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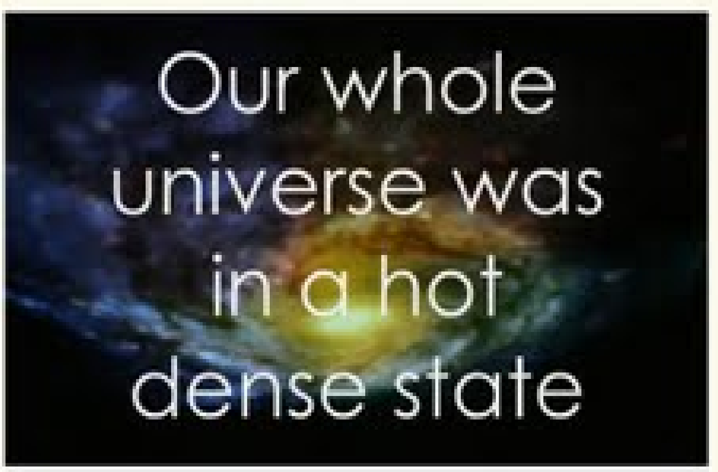
This points to the fact that matter and radiation would have interacted strongly and, hence would have been in thermal equilibrium, when the universe was about 10^4 times smaller.

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’[19]!

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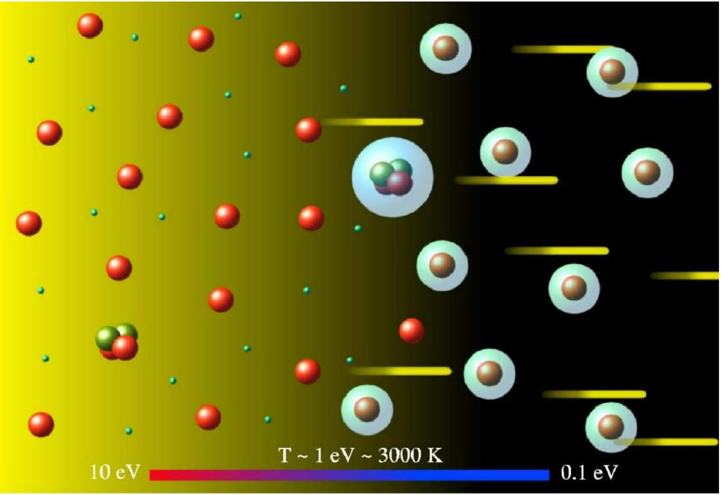
[19] See http://www.cbs.com/shows/big_bang_theory/.

Decoupling of matter and radiation[20]



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

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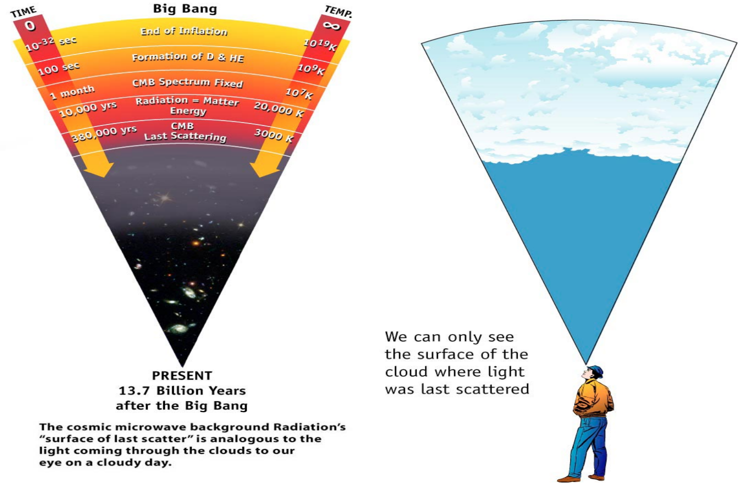
[20] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

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.

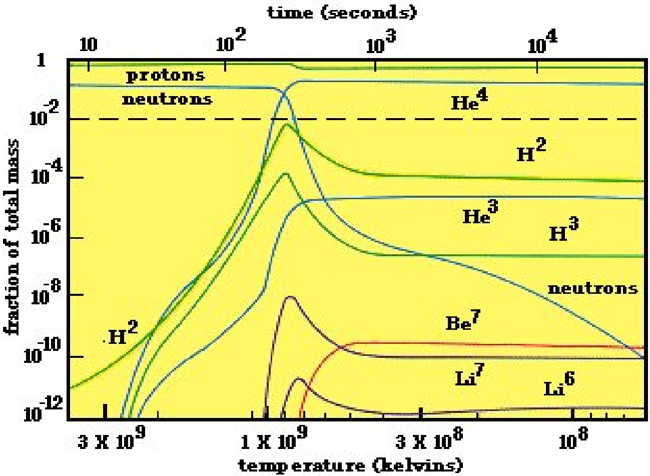
We can only see the surface of the cloud where light was last scattered

The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter[21].

---

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

The abundance of light elements – Theory

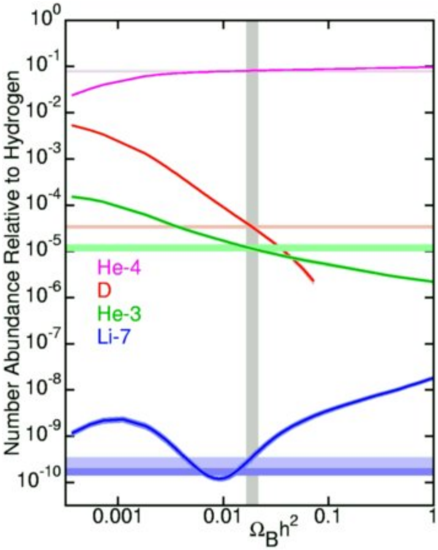


The relative abundances of the light elements in the early radiation dominated epoch have been plotted as a function of temperature[22].

---

[22] Image from http://www.astro.ucla.edu/˜wright/BBNS.html.

Abundance of light elements – Observations[23]



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 $H_0 = 100\, h\, {\rm km/sec/Mpc}$.

---

[23] Image from http://www.astro.ucla.edu/˜wright/BBNS.html.

Supernovae can be as bright as the host galaxy[24]

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

---

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

A supernova explosion in a distant galaxy[25]

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

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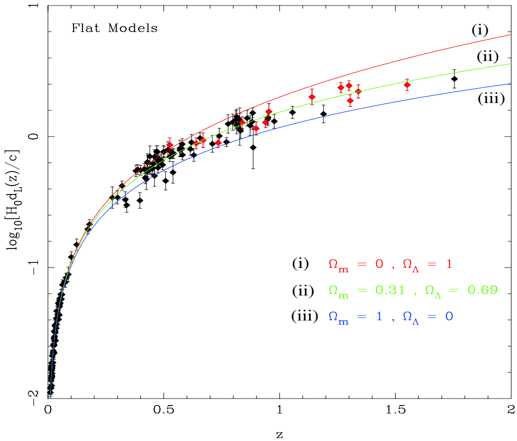
[25] Images from C. J. Pritchet *et. al.*, arXiv:astro-ph/0406242v1.

Supernovae data and the need for a cosmological constant



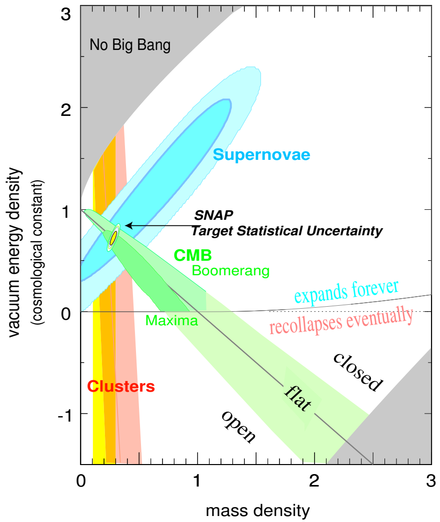
The luminosity distance $H_0\, d_L$ plotted as a function of the redshift z for spatially flat cosmological models[26]. The black points are from the 'Gold' data sets and the red points are the data from the Hubble Space Telescope[27].

---

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

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

Joint constraints on Ω_{NR} and Ω_{Λ}[28]



Joint constraints on Ω_{NR} and Ω_{Λ} from the observations of supernovae, CMB and galaxy clustering. Note that a cosmology with $\Omega_{\mathrm{NR}} = 1$ and $\Omega_{\Lambda} = 0$ is ruled out to 99% confidence level, while a universe with $\Omega_{\mathrm{NR}} \simeq 0.3$ 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).

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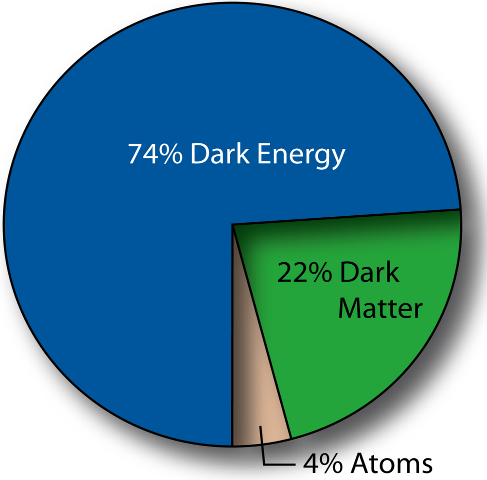
[28] Figure from G. Aldering *et. al.*, arXiv:astro-ph/0209550v1.

Matter content of the universe



A pie chart of the matter content of the universe today[29].

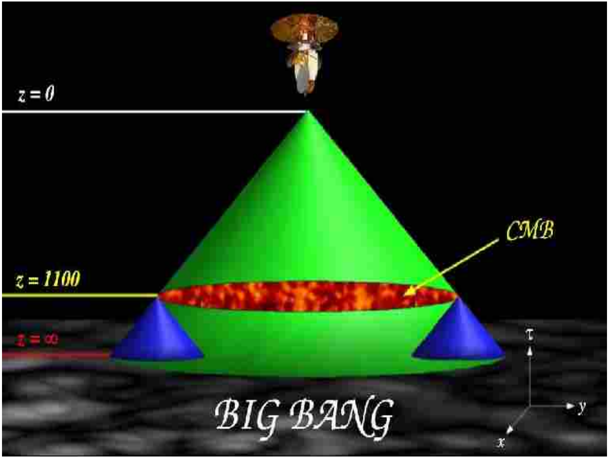
---

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

Plan of the talk

1. A survey of the universe
2. The composition and evolution of the smooth universe
3. The origin and evolution of perturbations
    - The need for an inflationary epoch
    - The generation and the evolution of perturbations
    - The universe according to WMAP and Planck
    - The formation of large scale structures
4. The standard model of cosmology

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[30].

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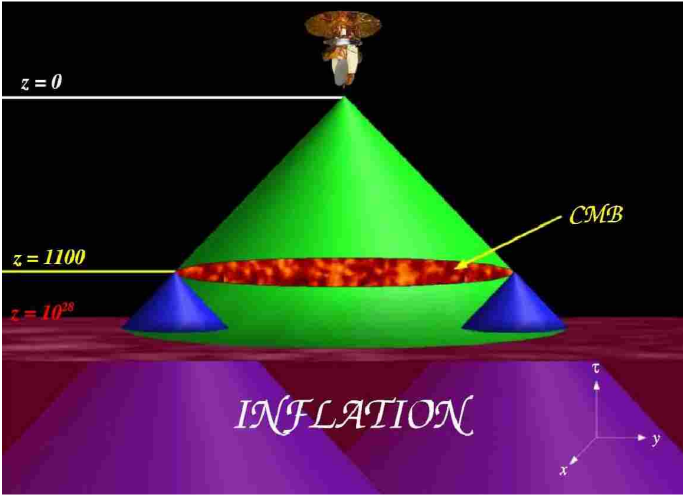
[30] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

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[31].

---

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

The origin and the evolution of the perturbations

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

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▸ Play movie

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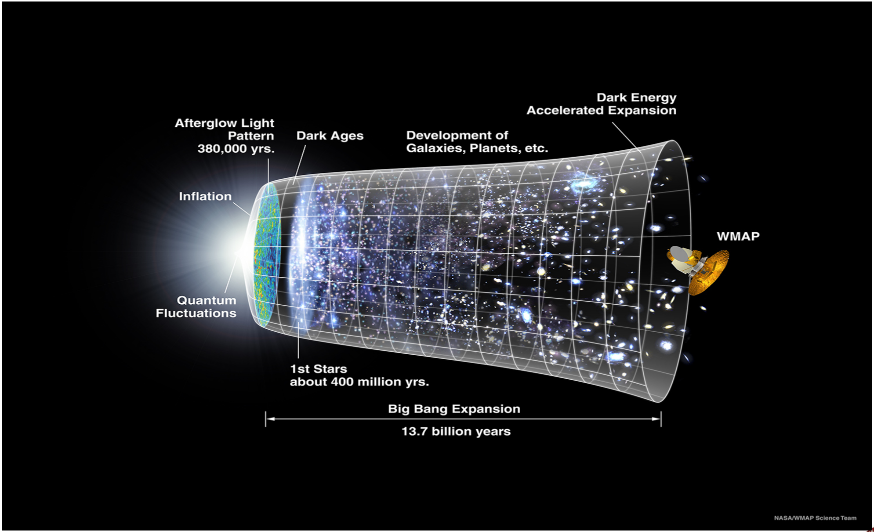
- These perturbations are amplified during the inflationary epoch, which leave their imprints as anisotropies in the CMB.

▸ Play movie

- 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

The timeline of the universe



A pictorial timeline of the universe[32].

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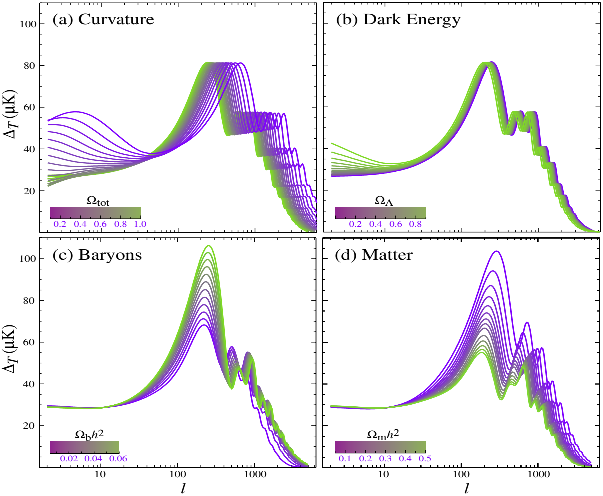
[32] See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

‘Effects’ of the cosmological parameters on the CMB[33]



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 $\Omega_{\rm NR}\, h^2$.

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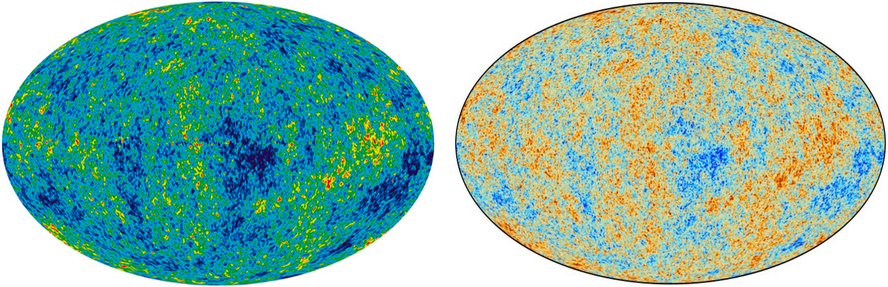
[33] Figures from W. Hu and S. Dodelson, Ann. Rev. Astron. Astrophys. **40**, 171 (2002).

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[34].

---

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

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

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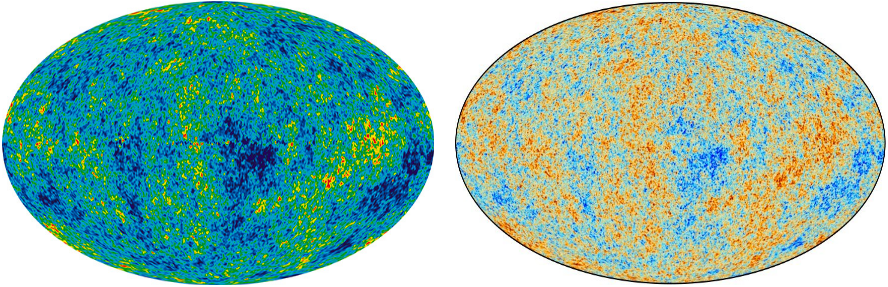


Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[34].

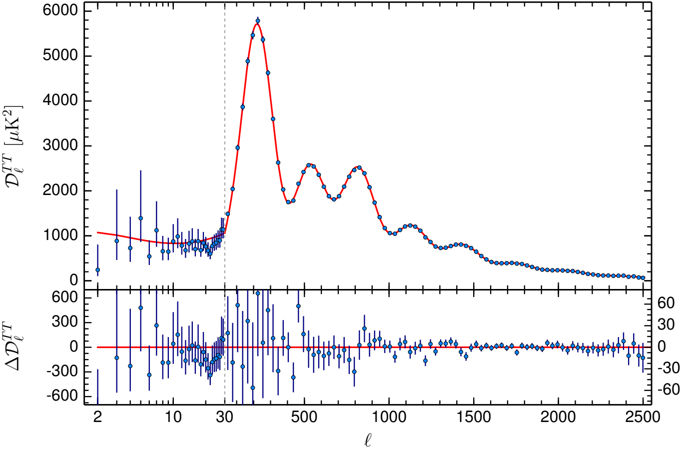
Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[35]. The above images show temperature variations (as color differences) of the order of $200^\circ\ \mu\mathrm{K}$. The angular resolution of WMAP was about 1°, while that of Planck was about $5'$. These temperature fluctuations correspond to regions of slightly different densities, and they represent the seeds of all the structure around us today.

---

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

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

The CMB angular power spectrum from Planck



The CMB 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)[36].

---

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

Formation of structures due to gravitational instability

A numerical simulation illustrating the formation of large scale structures due to gravitational instability[37].

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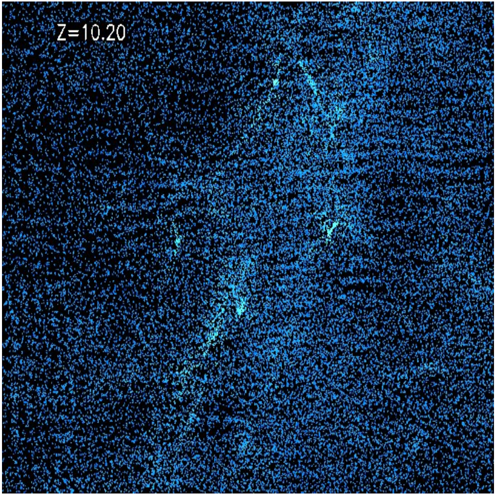
[37] Images from http://cfcp.uchicago.edu/lss/group.html.

Formation of structures due to gravitational instability



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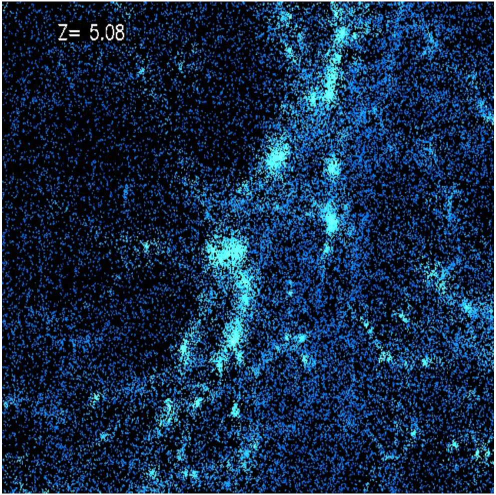

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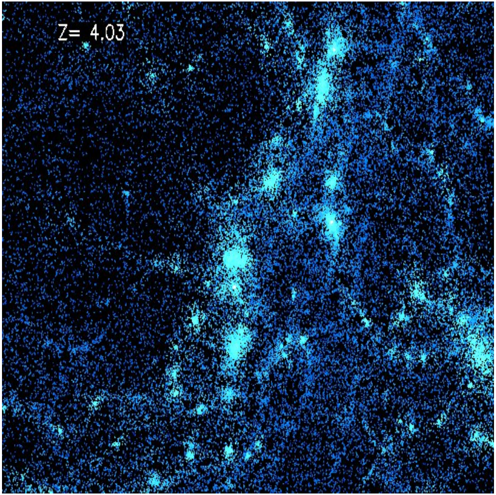

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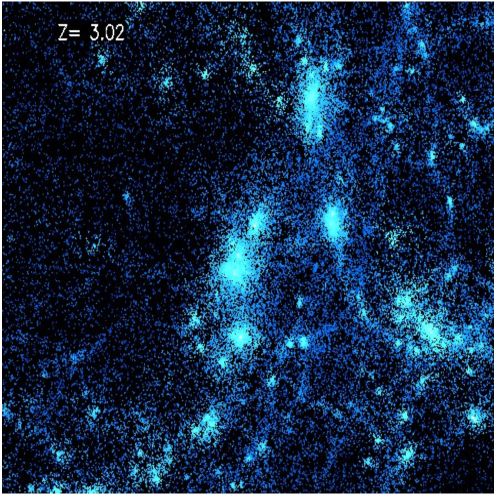

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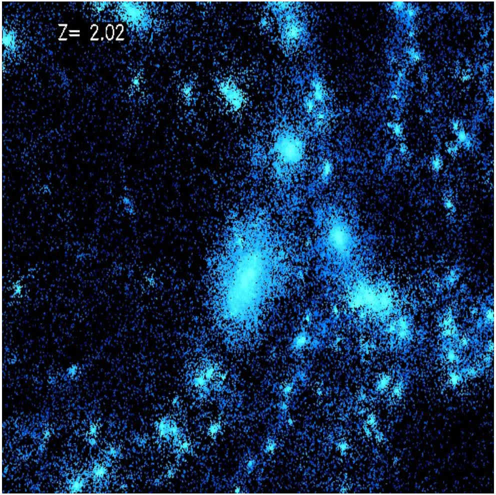

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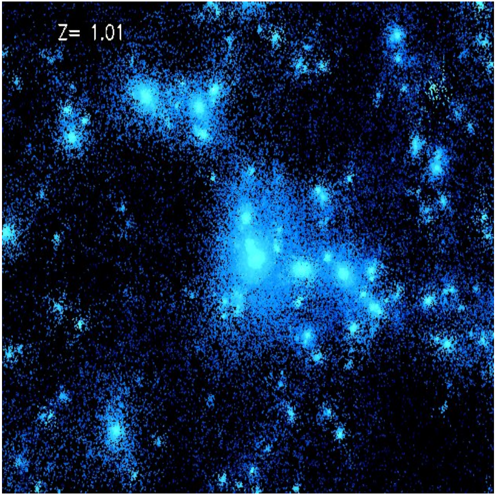

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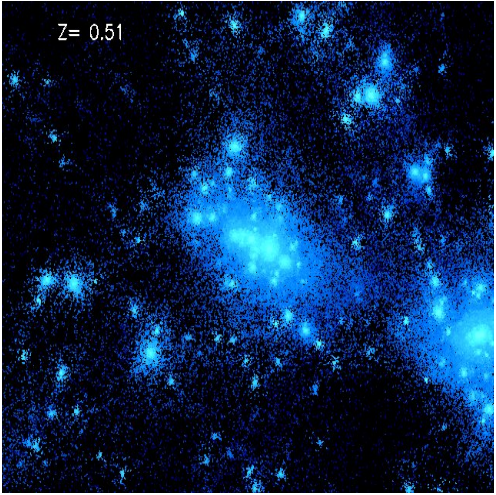

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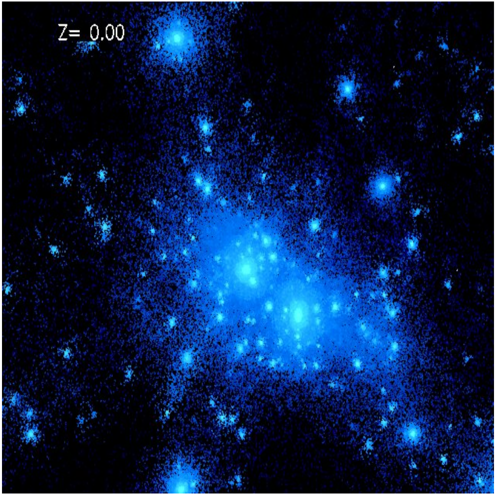

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▸ Play again

---

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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[37].

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[37] 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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- 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.

Popular books

1. S. Weinberg, *The First Three Minutes* (Bantam, New York, 1977).
2. J. Silk, *The Big Bang* (W. H. Freeman, San Francisco, 1988).
3. S. Singh, *Big Bang* (Harper Collins, New York, 2004).

Thank you for your attention