Distant supernovae and the accelerating universe

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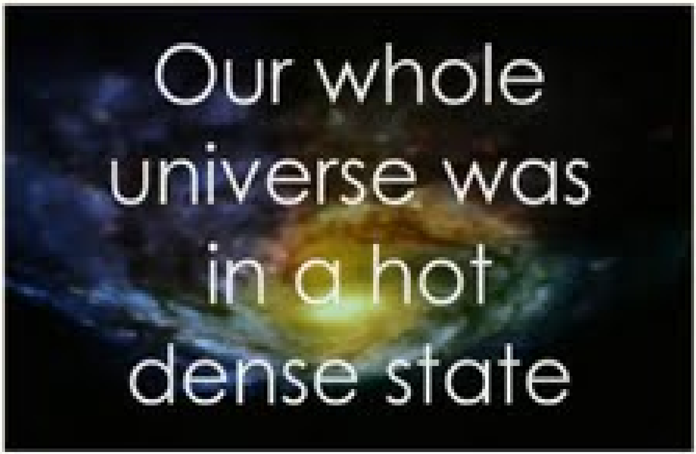
Science club meet, Chennai

November 12, 2011

The hot big bang model



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'[1]!

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

The 2011 Nobel prize in physics[2]



The 2011 Nobel prize in physics was awarded to Saul Perlmutter of the University of California, Berkeley, U.S.A. (on the left), Brian P. Schmidt of the Australian National University, Weston Creek, Australia (in the middle) and Adam G. Riess of the Johns Hopkins University, Baltimore, U.S.A. (on the right) *for the discovery of the accelerating expansion of the universe through observations of distant supernovae*.

[2] See http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/.

Outline

1. Runaway galaxies and the Hubble's law

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2. The cosmological distance ladder

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3. Implications of the supernovae observations
4. Other supporting evidence
5. Summary and further reading

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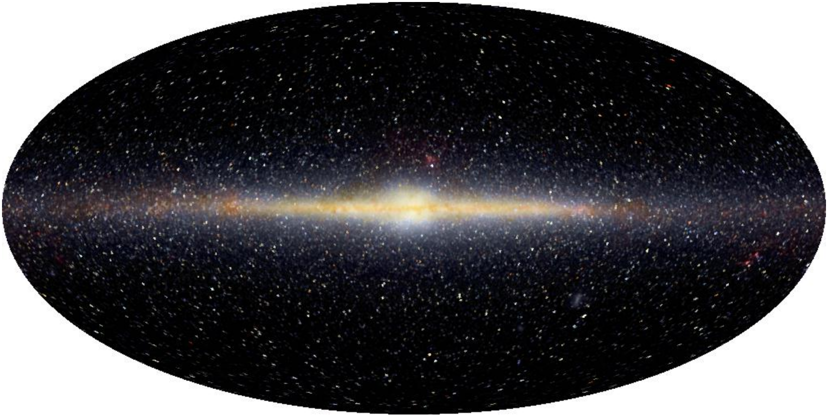
An infrared image of our galaxy



Our galaxy – the Milky Way – as observed by the COsmic Background Explorer (COBE) satellite at the infrared wavelengths[3]. 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 $2 \times 10^{12}\ \mathrm{M}_\odot$.

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

Our galactic neighbors and the local group[4]

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 $700\ \mathrm{kpc}$.

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

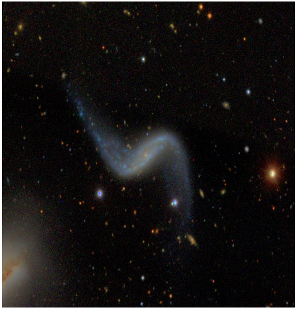
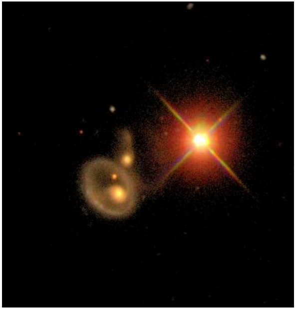
Our galactic neighbors and the local group[4]


Left: The Andromeda galaxy and its two companion galaxies. The Andromeda galaxy is very similar to our galaxy and is located at a distance of about 700 kpc.

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

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

Varieties of galaxies[5]

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.

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

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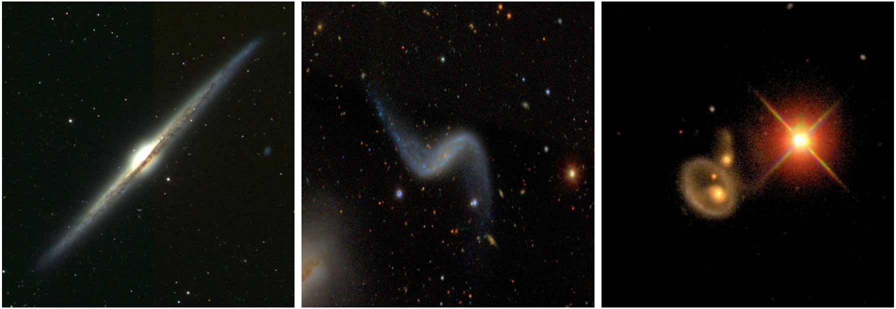

Left: The disk galaxy NGC 4565 seen edge on in this image from the Sloan Digital Sky Survey (SDSS). The galaxy has a clear bulge, but little light can be seen from its halo.

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

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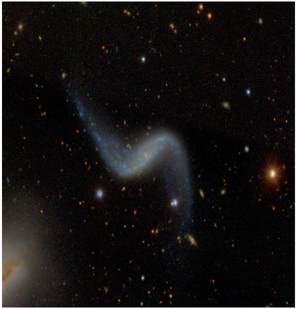
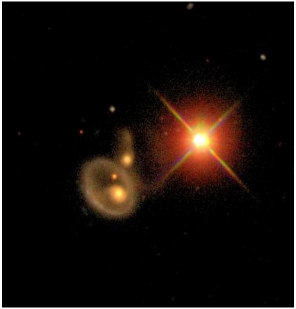

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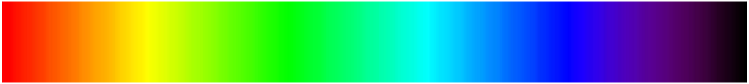
Center: An image of the spiral galaxy NGC 3187 from SDSS.

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.

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

Continuous, emission and absorption spectra[6]

A typical continuous spectrum from an opaque hot body:



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

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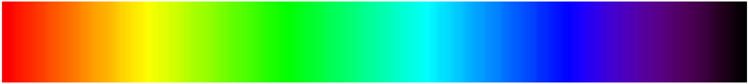

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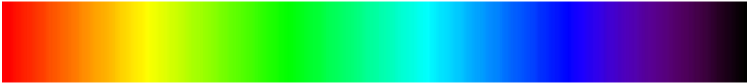
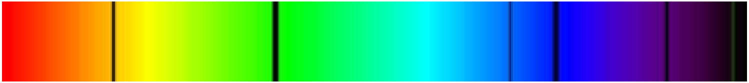


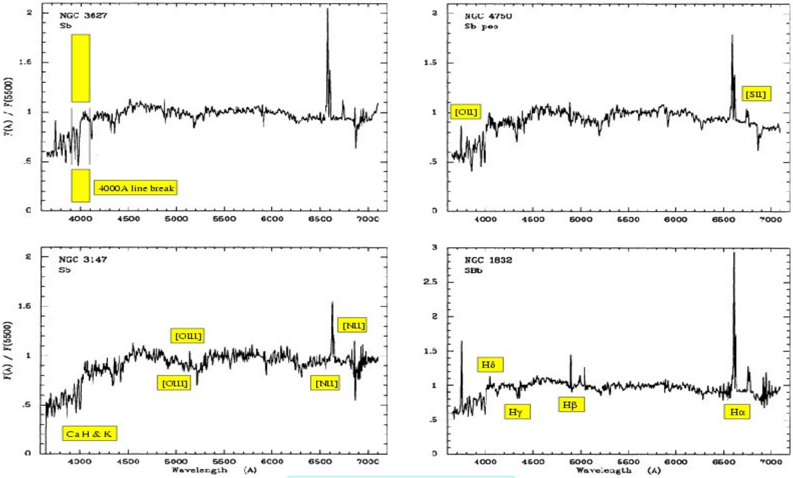
Emission spectrum, as from a given element:

Absorption spectrum, as due to an intervening cool gas:



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

Typical spectra of galaxies[7]



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

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

The 'Doppler effect' and redshift[8]

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

[8] Images from http://www.astronomynotes.com/light/s10.htm.

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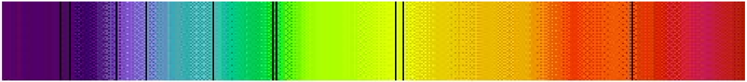

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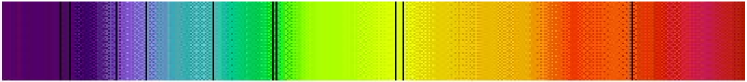


The redshift z of the receding source is defined as:

$$(1+z) = (\lambda_{\rm O}/\lambda_{\rm E}) = (\omega_{\rm E}/\omega_{\rm O}),$$

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.

[8] Images from http://www.astronomynotes.com/light/s10.htm.

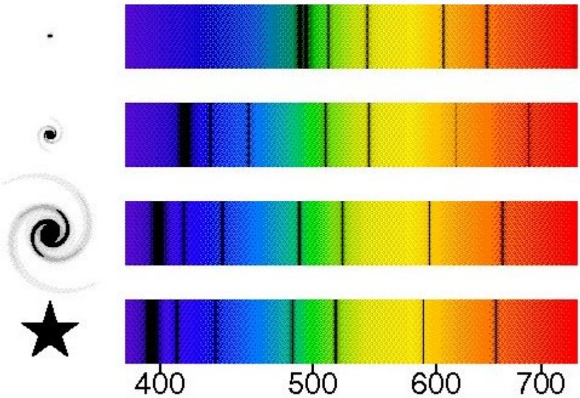
Runaway galaxies – A schematic diagram[9]

A distant galaxy, $z = 0.25$

A farther galaxy, $z = 0.05$

A nearby galaxy, $z = 0.01$

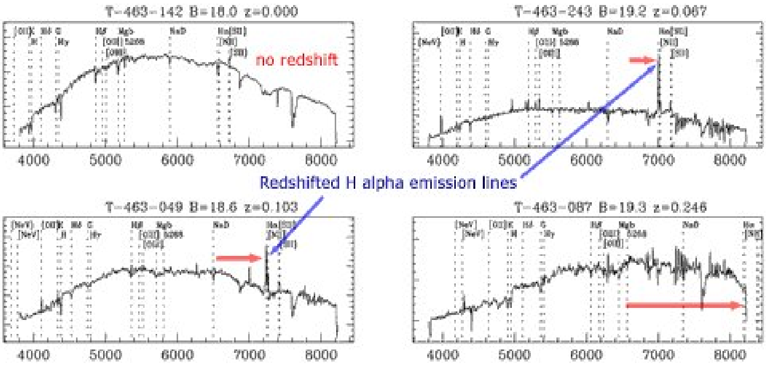
A galactic star, $z = 0$



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).

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

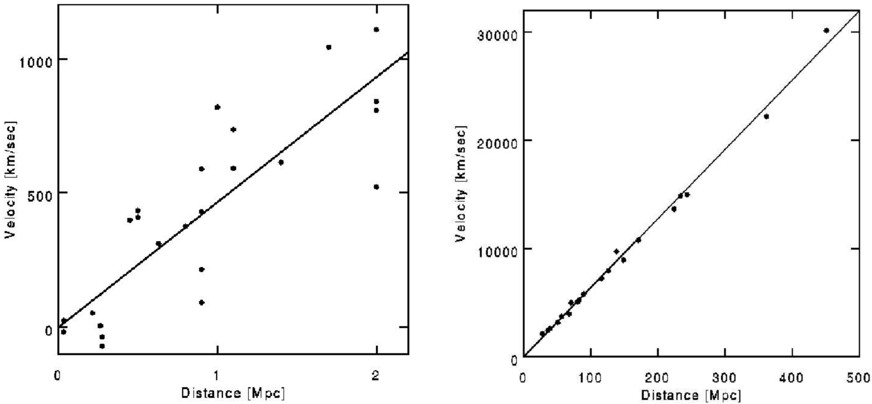
Runaway galaxies – Actual observations[10]



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.

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

Relation between the velocity and the distance of galaxies[11]



Left: The original Hubble data. The slope of the fitted line is 464 $\mathrm{km/sec/Mpc}$.

[11] Plots from http://www.astro.ucla.edu/˜wright/cosmo_01.htm.

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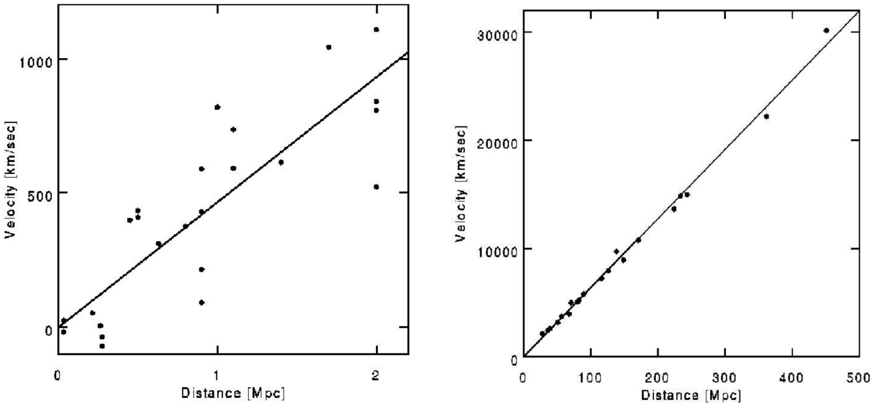
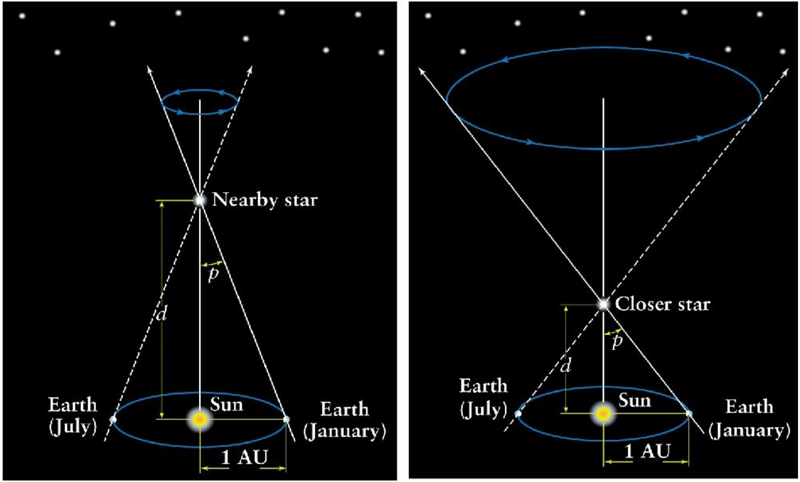


Left: The original Hubble data. The slope of the fitted line is 464 km/sec/Mpc.
Right: A more recent Hubble diagram. The slope of the straight line is found to be 64 km/sec/Mpc.

[11] Plots from http://www.astro.ucla.edu/~wright/cosmo_01.htm.

Outline

Stellar parallax[12]



The baseline of the earth's orbit of 2 Astronomical Units (AU) can be used to determine the distances of nearby stars through trigonometric parallax.

[12] Image from http://find.uchicago.edu/~pryke/compton/slides2/mgp00007.html.

The parsec

- Parsec (pc): The distance to an object whose parallax is $1''$ due to the baseline of the earth's orbit of 2 AU.

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From the figure in the previous slide, it is clear that

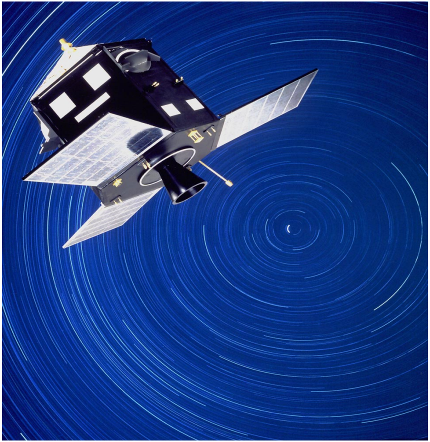
$$d = (1\ \mathrm{AU}/\tan p) \simeq (1/p)\ \mathrm{AU},$$

where we have assumed that the angle p is small. If p is expressed in units of *arcseconds*, we find that

$$d = \left(\frac{2.063 \times 10^5}{p''}\right)\ \mathrm{AU}.$$

Note that for $p = 1''$, $d = 2.063 \times 10^5\ \mathrm{AU} = 1\ \mathrm{pc} = 3.26\ \mathrm{ly} = 3.0857 \times 10^{16}\ \mathrm{m}$.

Astrometry with Hipparcos[13]



An image of the Hipparcos satellite which was the very first space mission for measuring the positions, distances, motions and brightness of stars. While distances up to $30\,\mathrm{pc}$ were measurable from Earth using parallax, Hipparcos allowed determination of distances up to $100\,\mathrm{pc}$ using the same method.

[13] Image from http://www.rssd.esa.int/Hipparcos.

The concept of a standard candle

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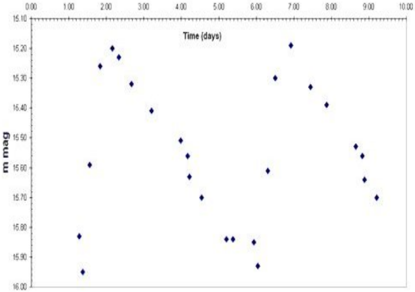
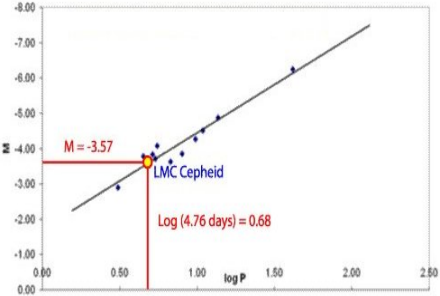
- The term standard candle applies to celestial objects with well-defined absolute brightness. If the intrinsic brightness of objects are known, the observed brightness then allows us to determine the distance to the objects, since the brightness falls as the inverse square of the distance.
- Possible correlations between the intrinsic brightness and one or more easily observable properties of distant objects can help us arrive at their intrinsic brightness.

Cepheid variables – An important early rung[14]





Left: Cepheid variables are stars whose outer atmospheres pulsate with periods of about 2-100 days. The observed magnitude of a Cepheid in the nearby Large Magellanic Cloud has been plotted as a function of time.

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

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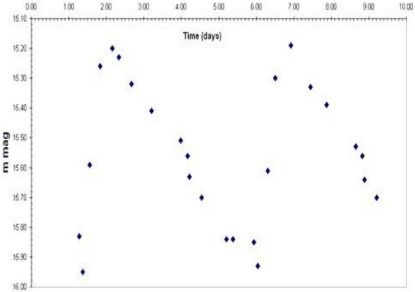

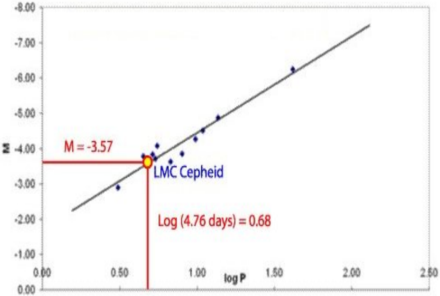

Left: Cepheid variables are stars whose outer atmospheres pulsate with periods of about 2-100 days. The observed magnitude of a Cepheid in the nearby Large Magellanic Cloud has been plotted as a function of time.

Right: The period of the oscillations of the Cepheids are found to exhibit a strong correlation with their intrinsic magnitudes. Such a correlation is initially established using nearby Cepheids whose parallaxes are known. Cepheids further away can then be utilized to determine distances up to a few Mpc.

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

Galaxies themselves as standard candles

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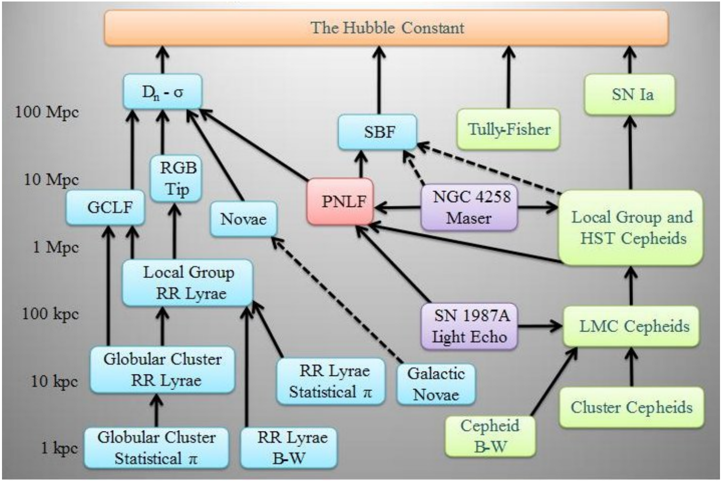
- Also, in the case of elliptical galaxies, it is known that there exists a specific relationship between the mean brightness of the galaxies and the dispersion in their velocities.
- These properties can be used to determine distances of the order of $100\,\mathrm{Mpc}$.

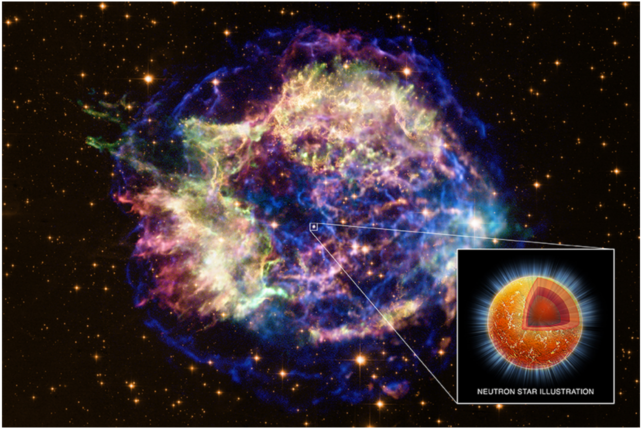
Construction of the cosmological distance ladder



Assembling the cosmological distance ladder. A variety of well-established properties of stars and galaxies are used to construct the ladder[15].

[15] Image from http://upload.wikimedia.org/wikipedia/en/1/13/Extragalactic_distance_ladder.JPG.

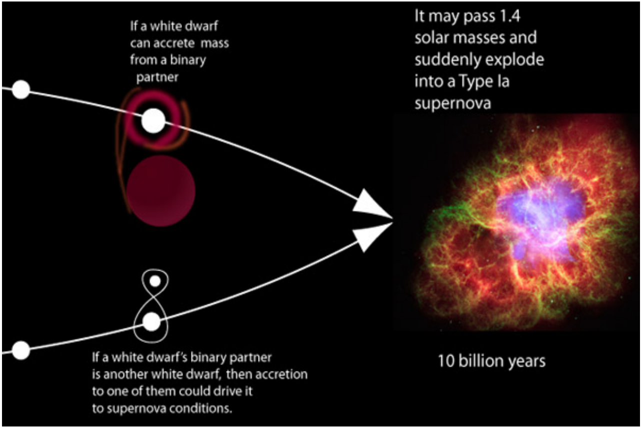
What is a supernova?



A supernova is an explosion of a massive, supergiant star, which may shine with the brightness of 10 billion suns! The above image is a composite optical and x-ray image of the supernova remnant Cassiopeia A, and the bright source near the center is a neutron star, i.e. the incredibly dense, collapsed remains of the stellar core[16].

[16] Image from http://apod.nasa.gov/apod/ap110305.html.

Type Ia supernovae[17]



Type Ia supernovae are produced when material accrete on to a white dwarf from an evolving star as a binary partner. If the accreted mass causes the white dwarf mass to exceed the Chandrasekhar limit, it will catastrophically collapse to produce the supernova.

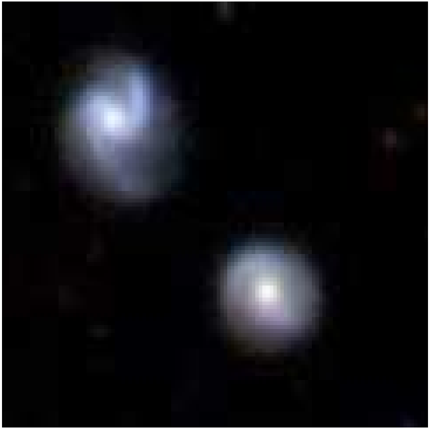
[17] Image from http://hyperphysics.phy-astr.gsu.edu/hbase/astro/snovcn.html

Supernovae can be as bright as the host galaxy[18]

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

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

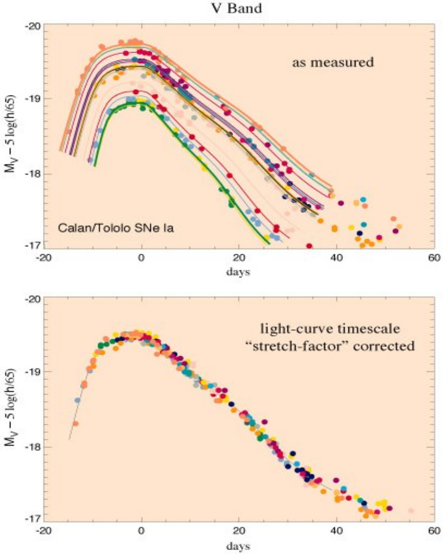
A supernova explosion in a distant galaxy[19]

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.

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

Light curves of type Ia supernovae[20]



Top: Absolute magnitude, an inverse logarithmic measure of intrinsic brightness, is plotted against time (in the stars rest frame) before and after peak brightness. The great majority fall neatly onto the yellow band.

[20] Image from http://www-supernova.lbl.gov/public/papers/aasposter198dir/aaasposter.html.

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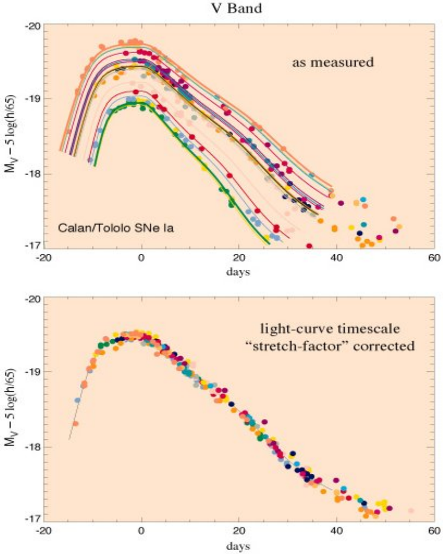
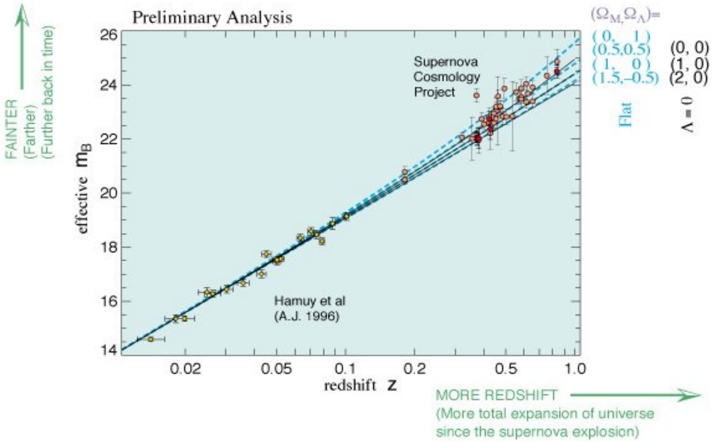


Top: Absolute magnitude, an inverse logarithmic measure of intrinsic brightness, is plotted against time (in the stars rest frame) before and after peak brightness. The great majority fall neatly onto the yellow band.

Bottom: Simply by stretching the time scales of individual light curves to fit the norm, and then scaling the brightness by an amount determined by the required time stretch, one gets all the type Ia light curves to match, suggesting a standard candle. These supernovae can be used to determine distances in excess of 1000 Mpc.

[20] Image from http://www-supernova.lbl.gov/public/papers/aasposter198dir/aaasposter.html.

Beyond the Hubble's law[21]



Determining luminosity distances of galaxies further away permits us to understand their behavior at large redshifts which, in turn, allows us to determine the matter content of the universe.

[21] Image from http://hyperphysics.phy-astr.gsu.edu/hbase/astro/snovcn.html.

Outline

Distribution of galaxies in the universe

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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

The Friedmann-Robertson-Walker metric

The homogeneous, isotropic and expanding universe can be described by the following Friedmann-Robertson-Walker 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 $\kappa = 0, \pm 1$.

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

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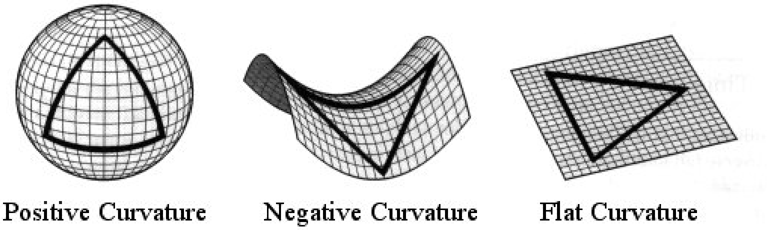
where t is the cosmic time and $a(t)$ denotes the scale factor, while $\kappa = 0, \pm 1$.

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[22].



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

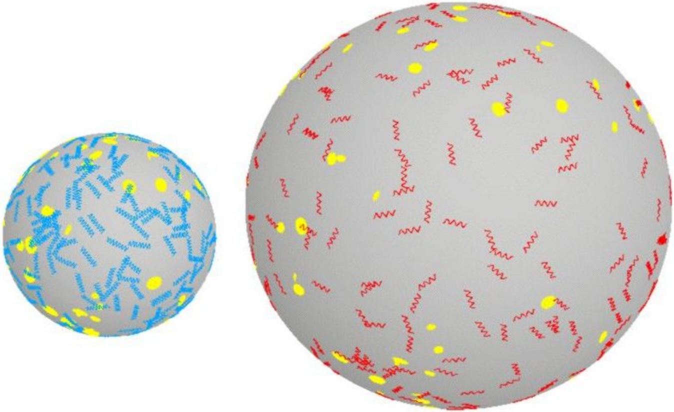
The Friedmann equations

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 Friedmann-Robertson-Walker metric lead to the following equations for the scale factor $a(t)$:

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

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

Visualizing the expanding universe[23]



A two-dimensional analogy for the expanding universe. 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.

[23] 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:

$$(1+z) = (\omega_{\mathrm{E}}/\omega_{\mathrm{O}}),$$

where ω_{O} and ω_{E} denote the observed and emitted frequencies, respectively.

The cosmological redshift

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

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

In an expanding universe, by solving the geodesic equation, it can be shown that the frequency of photons decreases with the expansion as follows:

$$\omega(t) \propto [1/a(t)]\,.$$

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

$$[a_0/a(t)] = (1+z),$$

where a_0 denotes the value of the scale factor today.

It is important to appreciate that the redshift is *not* due to Doppler effect, but is cosmological in origin, arising due to the expansion of the universe.

The background cosmological parameters

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

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

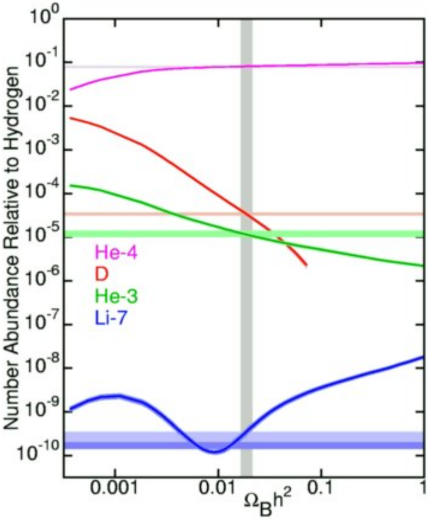
where $H_0 \equiv (\dot{a}/a)_{t=t_0}$ is the Hubble constant, $\Omega_i = (\rho_i/\rho_{\rm C})$ with $\rho_{\rm C}$ being the critical density given by

$$\rho_{\rm C} = \left(3\,H_0^2/8\pi\,G\right)$$

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.

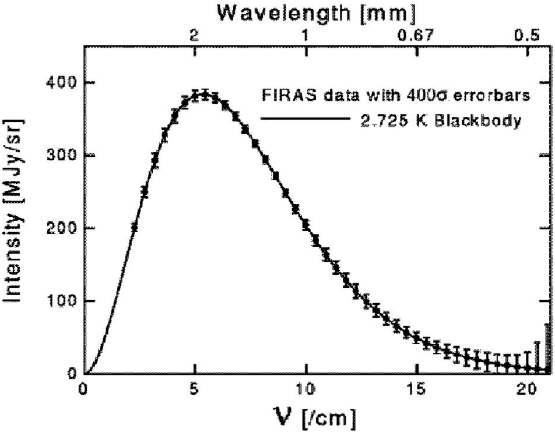
Abundance of light elements[24]



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 $(\Omega_{\rm B}\, h^2) \simeq 0.022$, which corresponds to only about 5% of the total amount of matter in the universe!

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

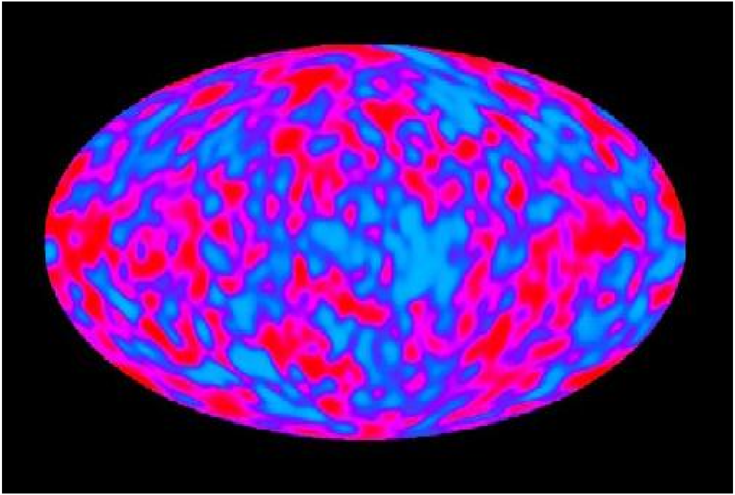
The spectrum of the cosmic microwave background



The spectrum of the Cosmic Microwave Background (CMB) as measured by the COBE satellite[25]. 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!

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

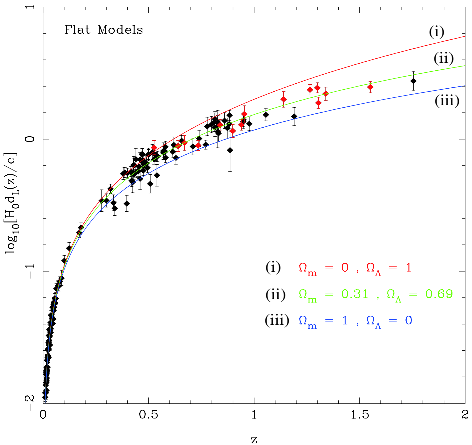
The extent of isotropy of the CMB



The fluctuations in the CMB as seen by COBE[26]. The CMB turns out to be isotropic to one part in 10^5.

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

Implications of the supernovae observations

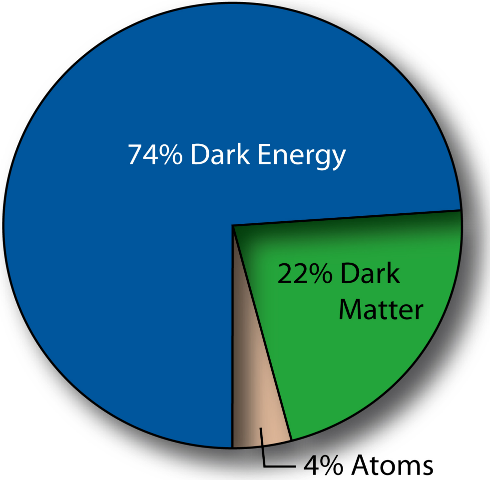


The luminosity distance $(H_0\, d_L)$ plotted as a function of the redshift z for spatially flat cosmological models[27]. The black points are from the 'Gold' data sets and the red points are the data from the Hubble Space Telescope[28].

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

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

The cosmic pie chart[29]

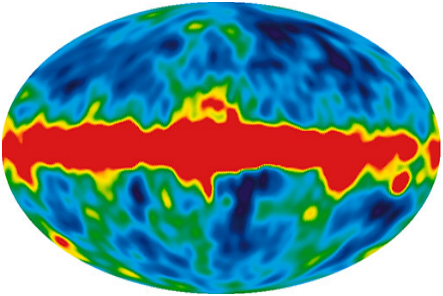


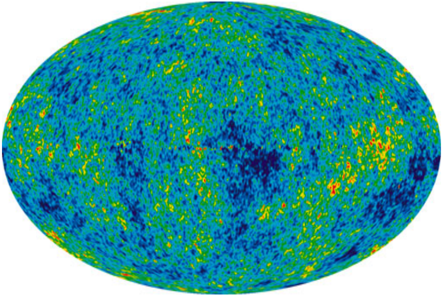
A pie chart of the matter content of the universe.

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

Outline

CMB anisotropies as seen by COBE and WMAP



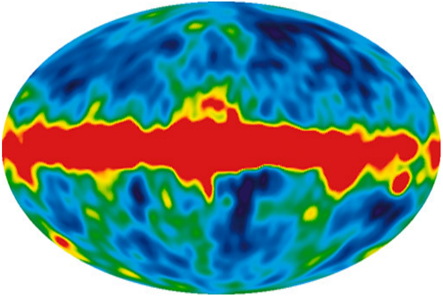


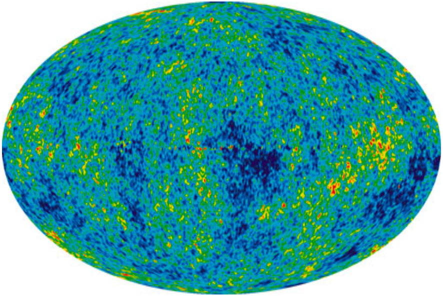
Left: All-sky map of the anisotropies in the CMB at the frequency of 53 GHz constructed from four years of data collected by COBE[30]. (The central red region is the emission from our galaxy.) COBE had an effective angular resolution of 7°, and it had found the deviations from the mean temperature to be one part in 10^5.

[30] Image from http://map.gsfc.nasa.gov/media/990166/990166_512.jpg.

[31] Image from http://map.gsfc.nasa.gov/media/101080/101080_7yrFullSky_WMAP_512W.jpg.

CMB anisotropies as seen by COBE and WMAP





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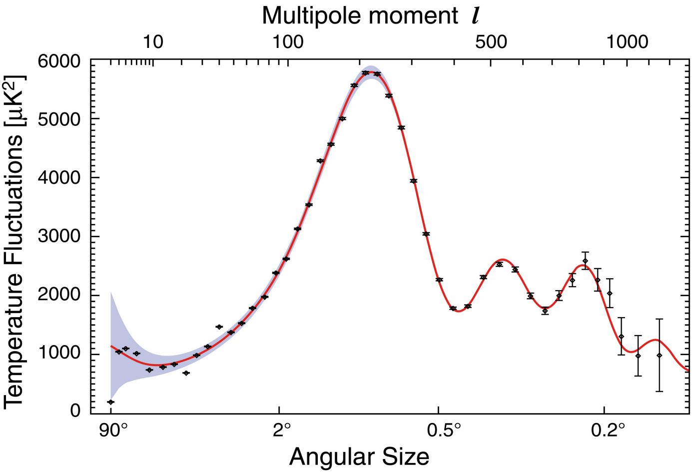
Right: All-sky map of the CMB anisotropies constructed from seven years of the Wilkinson Microwave Anisotropy Probe (WMAP) data collected in the following five frequency bands: 23, 33, 41, 61 and $94\ \mathrm{GHz}$[31]. The image shows temperature variations of the order of $200^\circ\ \mu\mathrm{K}$. The angular resolution of WMAP is 1°.

[30] Image from http://map.gsfc.nasa.gov/media/990166/990166_512.jpg.

[31] Image from http://map.gsfc.nasa.gov/media/101080/101080_7yrFullSky_WMAP_512W.jpg.

The CMB angular power spectrum from WMAP[32]



The CMB angular power spectrum from the WMAP seven-year data (the black dots with error bars) and the best-fit ΛCDM model with a nearly scale invariant primordial spectrum (the red curve). The blue band denotes the cosmic variance.

[32] Image from http://map.gsfc.nasa.gov/media/111133/111133_7yr_PowerSpectrumL.jpg.

Summary

- The supernovae observations point to the fact that the cosmological constant (or, in general, dark energy) and pressureless (i.e. cold) dark matter contribute about 70% and 25% to the density of the universe today, respectively.

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Summary

- The supernovae observations point to the fact that the cosmological constant (or, in general, dark energy) and pressureless (i.e. cold) dark matter contribute about 70% and 25% to the density of the universe today, respectively.
- These conclusions are independently supported by the observations of the anisotropies in the CMB.
- A dominant dark energy implies an accelerating universe.

For further reading

- S. Perlmutter, *Supernovae, dark energy, and the accelerating universe*, Physics Today **56**, 53–62 (2003).

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Thank you for your attention