Dark Energy: The Cosmological Enigma

CHIPP winter school 2010

Ruth Durrer

Department of Theoretical Physics
Geneva University
Switzerland

UNIVERSITÉ DE GENÈVE

Ascona, January 19, 2010

- PART I Dark energy
- PART II Cosmology and fundamental physics:
  dark matter, neutrini, phase transitions, inflation

Content

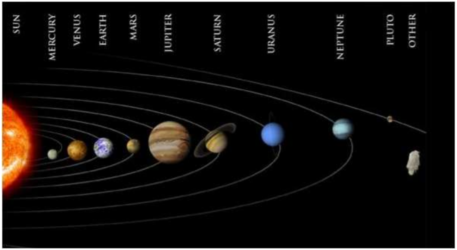
1. The size of the Universe
2. Expansion of the Universe
3. The thermal history of the Universe
4. Structure formation
5. Evidence for dark energy
6. Models for dark energy
7. Conclusions

Distances

The radius of the earth $\simeq$ 6000km

Distances

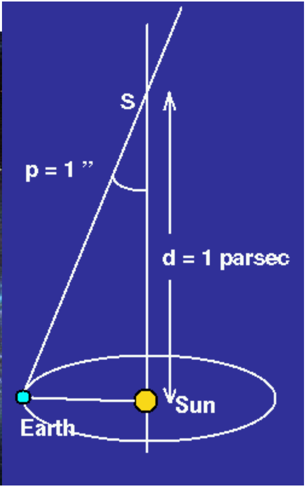
The solar sytem $\simeq 7 \times 10^9$km ($\simeq$ 50au)
1 au $\simeq 150 \times 10^6$km is the mean distance between earth and sun.



Distances

The (visible part of the) milky way $\simeq 10^{18}$km $\simeq 30'000$parsec

The (luminous part of the) milky way $\simeq 10^{18}$km $\simeq 30'000$parsec

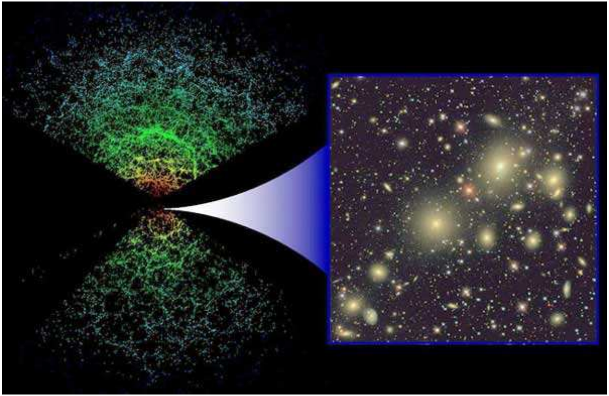


$$1'' = 1^o/3600 = 1\text{arc second}$$

$$1\text{parsec} \simeq 3.26 \text{ light years}$$

Distances

The size of the observable Universe (Hubble scale) $\simeq 4000\text{Mpc} = 4 \times 10^9$parsec
(Contains about 10^{11} galaxies like the milky way)



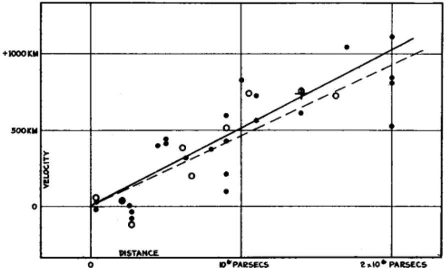
Each point is a galaxy
(Sloan digital sky survey, SDSS)

The Universe is expanding

Newtonian gravity is attractive, each mass attracts every other mass.

Newtonian gravity is attractive, each mass attracts every other mass.
Nevertheless, observations show that the Univers is expanding. Galaxies fly apart with a speed which is proportional to their distance,

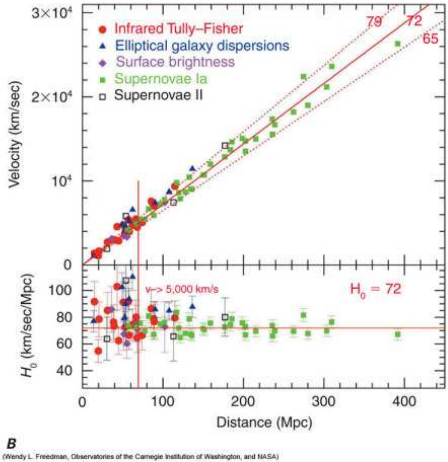
$$v = \dot{a} = H_0 \cdot a \qquad \text{(Hubble law)}$$



$H_0 \simeq 72$km/s/Mpc

(Hubble 1932)

The Universe is expanding



$v = H_0 a$, $H_0 \simeq (72 \pm 7)$km/s/Mpc, W. Freedman et al. 2003.

$H_0 = h100$km/s/Mpc, $h = 0.72 \pm 0.07$.

The Universe is expanding

To determine the 'Hubble diagram' we have to measure two quantities: the velocity and the distance of distant galaxies.

The Universe is expanding

To determine the 'Hubble diagram' we have to measure two quantities: the velocity and the distance of distant galaxies.

- To determine the velocity one measures the redshift.

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = v/c \,, \qquad \text{if } \; z \ll 1 \,.$$

The Universe is expanding

To determine the 'Hubble diagram' we have to measure two quantities: the velocity and the distance of distant galaxies.

- To determine the velocity one measures the redshift.

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = v/c\,, \qquad \text{if } \; z \ll 1\,.$$

- Measuring the redshift is relatively easy, but to measure distances is difficult. One needs 'standard candles' (or 'standard rulers').

The Universe is expanding

To determine the 'Hubble diagram' we have to measure two quantities: the velocity and the distance of distant galaxies.

- To determine the velocity one measures the redshift.

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = v/c\,, \qquad \text{if } z \ll 1\,.$$

- Measuring the redshift is relatively easy, but to measure distances is difficult. One needs 'standard candles' (or 'standard rulers').

- In cosmology, looking far means looking into the past.
(We see Andromeda as it has been 2 million years ago.)

The Universe is expanding

To determine the 'Hubble diagram' we have to measure two quantities: the velocity and the distance of distant galaxies.

- To determine the velocity one measures the redshift.

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = v/c\,, \qquad \text{if } z \ll 1\,.$$

- Measuring the redshift is relatively easy, but to measure distances is difficult. One needs 'standard candles' (or 'standard rulers').
- In cosmology, looking far means looking into the past.
  (We see Andromeda as it has been 2 million years ago.)
- A moment in the past can be parameterized by its redshift. z.

The Universe is expanding

To determine the 'Hubble diagram' we have to measure two quantities: the velocity and the distance of distant galaxies.

- To determine the velocity one measures the redshift.

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = v/c\,, \qquad \text{if } \; z \ll 1\,.$$

- Measuring the redshift is relatively easy, but to measure distances is difficult. One needs 'standard candles' (or 'standard rulers').

- In cosmology, looking far means looking into the past.
(We see Andromeda as it has been 2 million years ago.)

- A moment in the past can be parameterized by its redshift. z.

- The expansion velocity of the Universe which is presently $H_0 \simeq 72$km/s/Mpc has been different in the past. We want to measure it as function of the redshift, $H(z)$. For this we have to measure the redshift z and the distance d of far away galaxies.

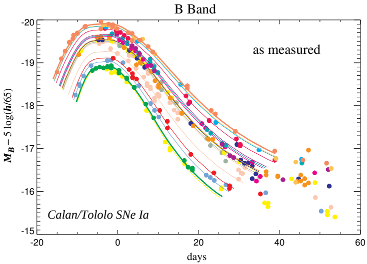
Standard candles

The most powerful standard candles are supernovae type Ia.

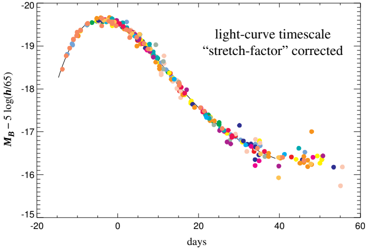
(SN1994D)

SNIa courbe de lumière

After correction by a 'stretch factor' the maximum of the light curve, i.e. the maximal luminosity is nearly identical for all supernovae.

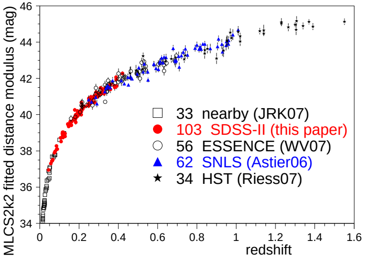


Without correction.

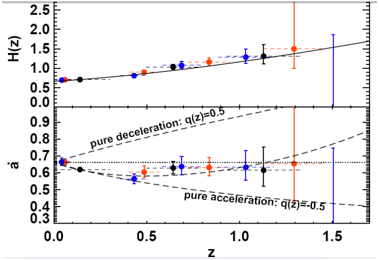


With correction.

The expansion of the Universe accelerates



(Kessler et al. 2009)



(Riess et al. 2007)

Distance modulus
$\propto \log(\text{apparent luminosity})$

$$\propto \log(1/d_L^2)$$

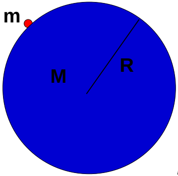
$$d_L(z) \propto f_K\left(\int_0^z \frac{dz'}{H(z')}\right)$$

$$H = \frac{\dot a}{a} = (1+z)\dot a(z)$$

$$\dot a(z)$$

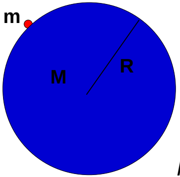
An expanding Universe within Newtonian gravity

Consider a test mass m at the surface of a sphere of homogeneous mass density ρ, expanding with velocity v.



$$M = (4\pi/3)a^3\rho$$

Consider a test mass m at the surface of a sphere of homogeneous mass density ρ, expanding with velocity v.

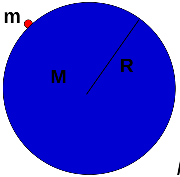


$M = (4\pi/3)a^3\rho$

Its energy is

$$E = \frac{m}{2}v^2 + U = \frac{m}{2}v^2 - \frac{mMG}{a} = \frac{m}{2}v^2 - \frac{4\pi}{3}m\rho a^2 G$$

Consider a test mass m at the surface of a sphere of homogeneous mass density ρ, expanding with velocity v.



$M = (4\pi/3)a^3\rho$

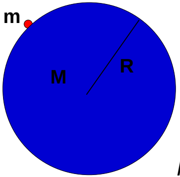
Its energy is

$$E = \frac{m}{2}v^2 + U = \frac{m}{2}v^2 - \frac{mMG}{a} = \frac{m}{2}v^2 - \frac{4\pi}{3}m\rho a^2 G$$

Hence $2E/m =: -K = \text{constant} = \dot{a}^2 - 8\pi G\rho a^2/3$. With $H^2 = \left(\frac{\dot{a}}{a}\right)^2$ we obtain

$$H^2 + \frac{K}{a^2} = \frac{8\pi G}{3}\rho$$

Consider a test mass m at the surface of a sphere of homogeneous mass density ρ, expanding with velocity v.



$M = (4\pi/3)a^3\rho$

Its energy is

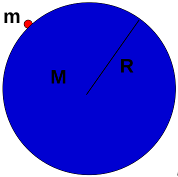
$$E = \frac{m}{2}v^2 + U = \frac{m}{2}v^2 - \frac{mMG}{a} = \frac{m}{2}v^2 - \frac{4\pi}{3}m\rho a^2 G$$

Hence $2E/m =: -K = \text{constant} = \dot{a}^2 - 8\pi G\rho a^2/3$. With $H^2 = \left(\frac{\dot{a}}{a}\right)^2$ we obtain

$$H^2 + \frac{K}{a^2} = \frac{8\pi G}{3}\rho$$

This is the Friedmann equation (1922).

Consider a test mass m at the surface of a sphere of homogeneous mass density ρ, expanding with velocity v.



$M = (4\pi/3)a^3\rho$

Its energy is

$$E = \frac{m}{2}v^2 + U = \frac{m}{2}v^2 - \frac{mMG}{a} = \frac{m}{2}v^2 - \frac{4\pi}{3}m\rho a^2 G$$

Hence $2E/m =: -K =$ constant $= \dot{a}^2 - 8\pi G\rho a^2/3$. With $H^2 = \left(\frac{\dot{a}}{a}\right)^2$ we obtain

$$H^2 + \frac{K}{a^2} = \frac{8\pi G}{3}\rho$$

This is the Friedmann equation (1922).
It is valid also of the exterior of the sphere is filled homogeneously.

The density is diluted by the expansion

$$\rho = \frac{M}{\frac{4\pi}{3}a^3}\,, \qquad \dot\rho = -3\rho\frac{\dot a}{a}$$

The density is diluted by the expansion

$$\rho = \frac{M}{\frac{4\pi}{3}a^3}\,, \qquad \dot\rho = -3\rho\frac{\dot a}{a}$$

Inserting this in the derivative of the Friedmann equation we find

$$\frac{d}{dt}\left[\left(\frac{\dot a}{a}\right)^2 + \frac{K}{a^2}\right] = \frac{8\pi G}{3}\dot\rho = -8\pi G\rho\frac{\dot a}{a}$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\rho < 0\,.$$

An expanding Universe within Newtonian gravity

The density is diluted by the expansion

$$\rho = \frac{M}{\frac{4\pi}{3}a^3}\,, \qquad \dot\rho = -3\rho\frac{\dot a}{a}$$

Inserting this in the derivative of the Friedmann equation we find

$$\frac{d}{dt}\left[\left(\frac{\dot a}{a}\right)^2 + \frac{K}{a^2}\right] = \frac{8\pi G}{3}\dot\rho = -8\pi G\rho\frac{\dot a}{a}$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\rho < 0\,.$$

This is the 2nd Friedmann equation (1922). It requires that expansion decelerates!

The density is diluted by the expansion

$$\rho = \frac{M}{\frac{4\pi}{3}a^3}, \qquad \dot\rho = -3\rho\frac{\dot a}{a}$$

Inserting this in the derivative of the Friedmann equation we find

$$\frac{d}{dt}\left[\left(\frac{\dot a}{a}\right)^2 + \frac{K}{a^2}\right] = \frac{8\pi G}{3}\dot\rho = -8\pi G\rho\frac{\dot a}{a}$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\rho < 0 \,.$$

This is the 2nd Friedmann equation (1922). It requires that expansion decelerates! Within general relativity these equations are somewhat modified:

$$\begin{aligned}\left(\frac{\dot a}{a}\right)^2 + \frac{K}{a^2} &= \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}\\ \frac{\ddot a}{a} &= -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}\end{aligned}$$

Here P is the pressure and Λ is a new constant, the cosmological constant. In addition, K has a different interpretation. It is the curvature of space:

An expanding Universe

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{K}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

Deriving the first eqn and inserting $\ddot{a}$ from the second eqn. one also finds

$$\frac{\dot{\rho}}{\rho} = -3(\rho + P)\frac{\dot{a}}{a}$$

An expanding Universe

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{K}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

Deriving the first eqn and inserting $\ddot{a}$ from the second eqn. one also finds

$$\frac{\dot{\rho}}{\rho} = -3(\rho + P)\frac{\dot{a}}{a}$$

This last equation is easily solved if the equation of state parameter $w = \frac{P}{\rho}$ = constant. Then

$$\rho \propto a^{-3(1+w)} = \begin{cases} a^{-3} & \text{for dust, } w = 0 \\ a^{-4} & \text{for radiation, } w = 1/3 \\ \text{const.} & \text{for a cosmological constant, } w = -1 \end{cases}$$

$$\left(\frac{\dot a}{a}\right)^2 + \frac{K}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$
$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

Deriving the first eqn and inserting $\ddot a$ from the second eqn. one also finds

$$\frac{\dot\rho}{\rho} = -3(\rho + P)\frac{\dot a}{a}$$

This last equation is easily solved if the equation of state parameter $w = \frac{P}{\rho}$ = constant. Then

$$\rho \propto a^{-3(1+w)} = \begin{cases} a^{-3} & \text{for dust, } w = 0 \\ a^{-4} & \text{for radiation, } w = 1/3 \\ \text{const.} & \text{for a cosmological constant, } w = -1 \end{cases}$$

Inserting this in the Friedmann eqn. for $K = 0$ we find

$$a(t) \propto \begin{cases} t^{2/3} & \text{for dust, } w = 0 \\ t^{1/2} & \text{for radiation, } w = 1/3 \\ \exp(Ht) & \text{for a cosmological constant, } w = -1 \end{cases}$$

Accelerated expansion

We introduce the parameters

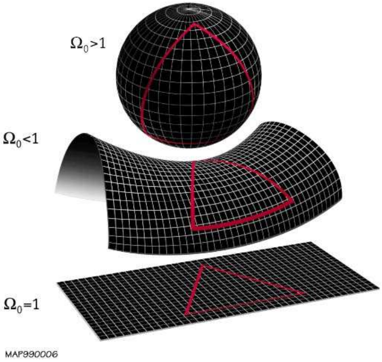
$$\Omega_m = \frac{8\pi G\rho}{3H^2}\,, \qquad \Omega_K = -\frac{K}{a^2H^2}\,, \qquad \Omega_\Lambda = \frac{\Lambda}{3H^2}\,,$$

so that the first Friedmann eqn. becomes $\Omega_m + \Omega_\Lambda + \Omega_K = 1\,.$

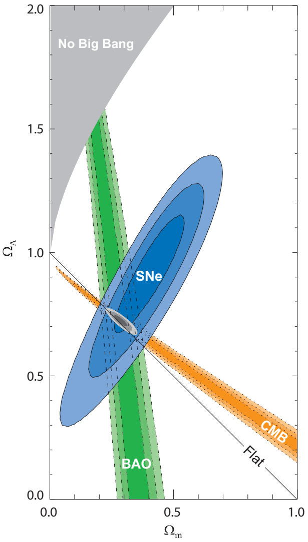
$K > 0$ ($\Omega_K < 0$): spherical space,

$K < 0$ ($\Omega_K > 0$): pseudo-sphere (saddle),

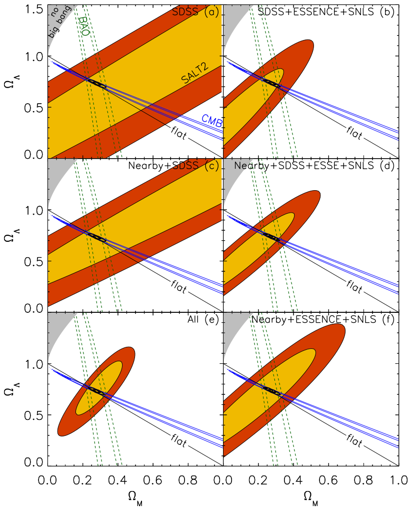
$K = 0$ ($\Omega_K = 0$): flat space.



Matter density, Ω_m, and cosmological constant, Ω_Λ (dark energy).



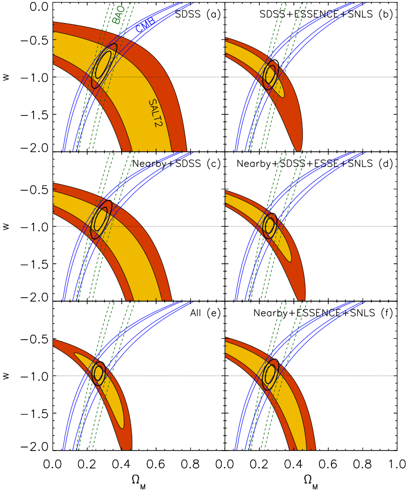
Matter density and cosmological constant
(Kessler et al. ’09).



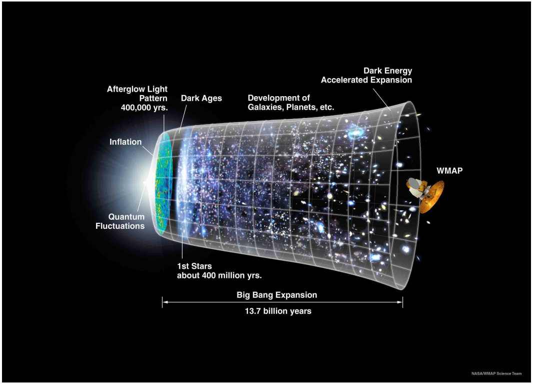
The expansion of the Universe is accelerated

If the pressure is very negative, $P = w\rho$ with $w < -1/3$ one can have accelerated expansion without cosmological constant. Such a component is called dark energy. A cosmological constant corresponds to dark energy with $w = -1$.

The matter fraction and the parameter w of the dark energy (Kessler et al. '09).



In the past the Universe was not only much denser but also much hotter.

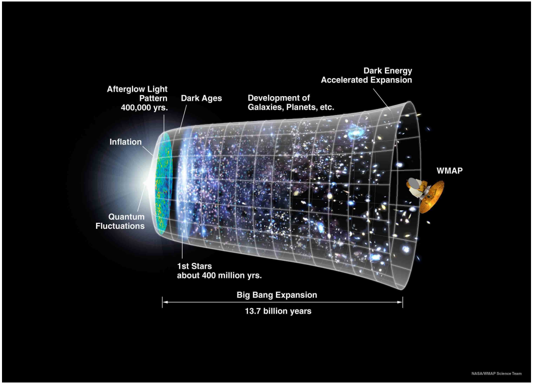


Age of the Universe: $t_0 \simeq 1.37 \times 10^{10}$years.

Events.

- Recombination (electrons and protons combine to neutral hydrogen).

In the past the Universe was not only much denser but also much hotter.

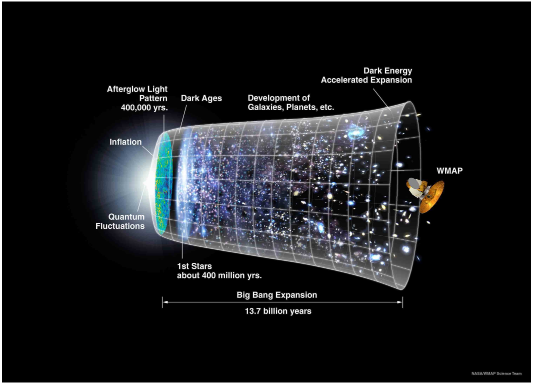


Age of the Universe: $t_0 \simeq 1.37 \times 10^{10}$years.

Events.

- Recombination (electrons and protons combine to neutral hydrogen).
- Nucleosyhthesis (formation mainly of helium,...)

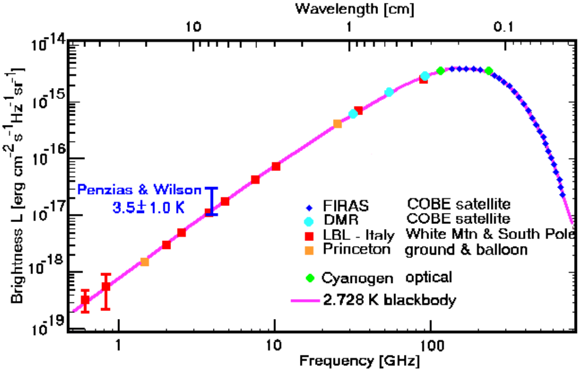
In the past the Universe was not only much denser but also much hotter.



Age of the Universe: $t_0 \simeq 1.37 \times 10^{10}$years.

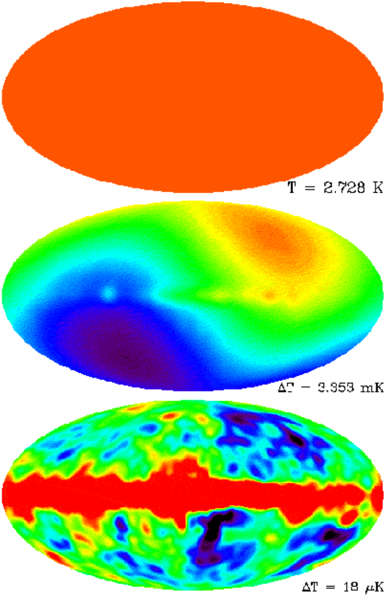
Events.

- Recombination (electrons and protons combine to neutral hydrogen).
- Nucleosyhthesis (formation mainly of helium,...)
- Inflation ?



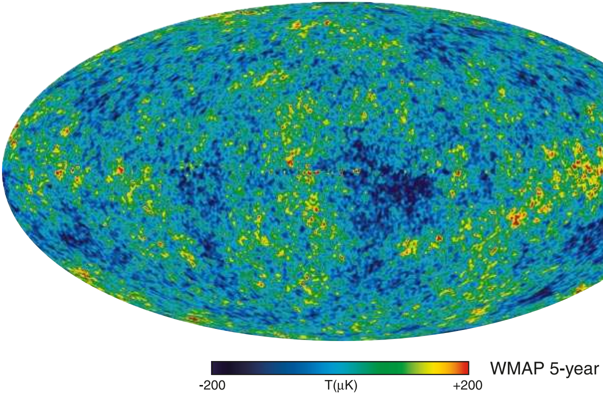
Fixen et al. (1996) Nobel Prize 1978 pour Penzias et Wilson and 2006 for Mather

$$T_0 = 2.728\text{K} \simeq -270.5^o\text{C}$$

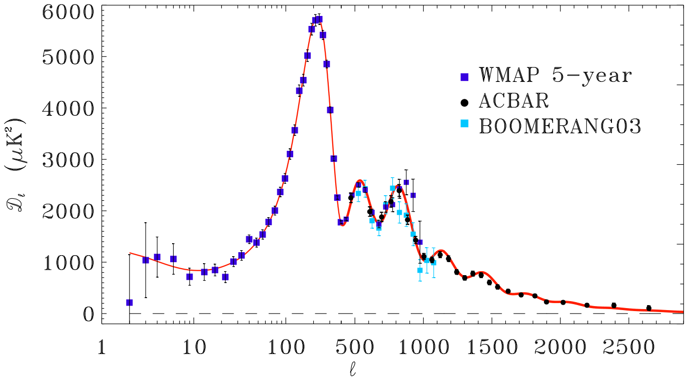


Smoot et al. (1999), Nobel Prize 2006

The cosmic micro wave background: anisotropies



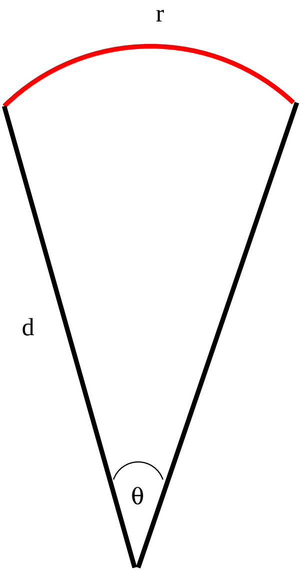
Hinshaw et al. (2008)

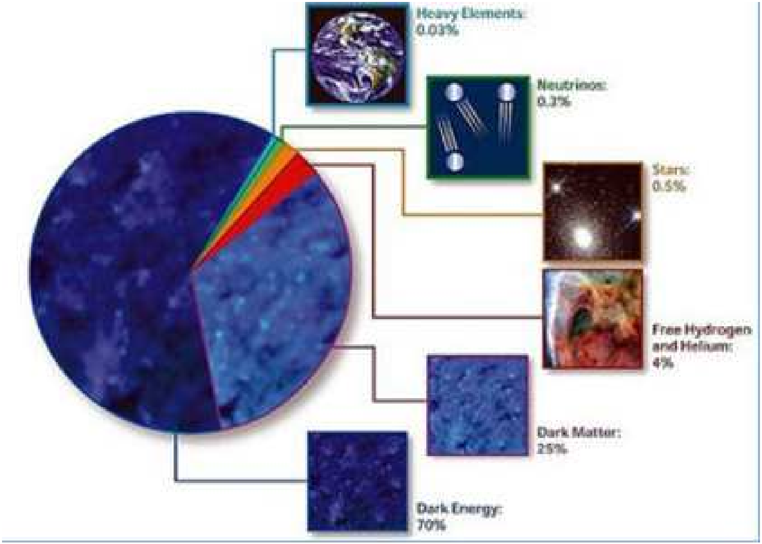


Reichhardt et al. (2008) $\ell = 200$ corresponds to about 1^o.
(This is roughly the double of the angular size of the full moon (and of the sun).)
$\Rightarrow$ 'acoustic peaks'. ($\theta \simeq 180^o/\ell$)

The physical size of the patches which correspond to acoustic peaks are standard rulers. Their size is fixed by the age of the Universe at the moment of decoupling (recombination). The angle under which they appear determines the distance to the surface of last scattering ($z = z_{\rm dec} \simeq 1100$), $d = r/\theta$.
The amplitude of the peaks is a measure for the matter density, $\rho_m \propto \Omega_m H_0^2$ and the difference in amplitude of even and odd peaks relates directly the baryon density, $\rho_b \propto \Omega_b H_0^2$.

$\Omega_m h^2 = 0.13 \pm 0.006$
$\Omega_b h^2 = 0.022 \pm 0.002$
$\Omega_\Lambda = 0.73 \pm 0.1$
$\Omega_K = 0 \pm 0.02$
More details in the student talk by
Marc Vonlanthen




Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
Dark Matter:
25%
Dark Energy:
70%

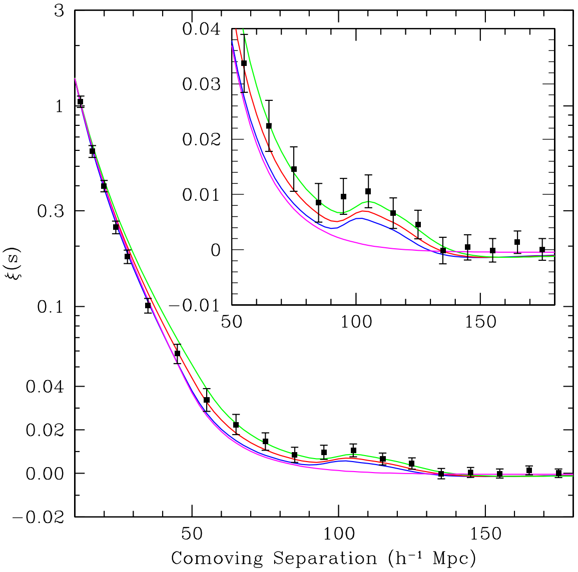
- The supernovae distances $\Rightarrow H(z)$ $(0 < z < 1.7)$

Evidence for dark energy

- The supernovae distances$\Rightarrow H(z)$ $(0 < z < 1.7)$
- The acoustic peaks in the CMB anisotropies $(z = 1100)$

- The supernovae distances$\Rightarrow H(z)$ $(0 < z < 1.7)$
- The acoustic peaks in the CMB anisotropies $(z = 1100)$
- The acoustic oscillations in the galaxy correlation function (BAO) $(z \simeq 0.2 \quad z \simeq 0.35)$

Evidence for dark energy: baryon acoustic oscillations BAO

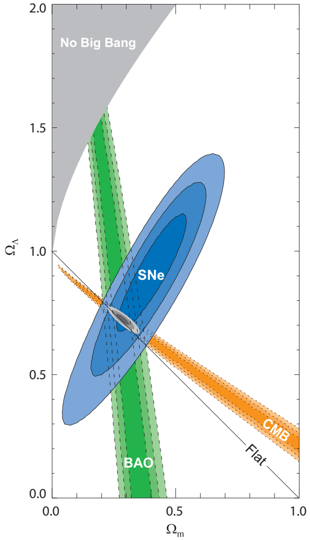


(Eisenstein et al. 2005)

Evidence for dark energy

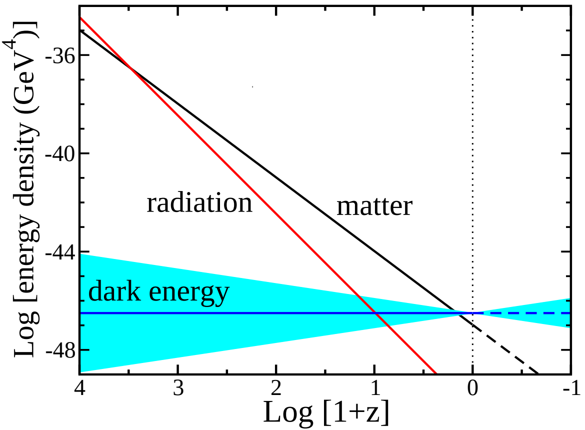
- The supernovae distances $\Rightarrow H(t)$ $(0 < z < 1.7)$
- The acoustic peaks in the CMB anisotropies $(z = 1100)$
- The acoustic oscillations in the galaxy correlation function (BAO) $(z \simeq 0.2 \quad z \simeq 0.35)$
- Abundance of galaxy clusters $\Rightarrow \quad \Omega_m \simeq 0.3$.

The expansion of the Universe is accelerated



Fraction of matter and dark energy.

- Cosmological constant / vacuum energy
  Fits most of the data but we do not understand its amplitude (fine tuning problem) neither why it comes to dominate right now (coincidence problem).

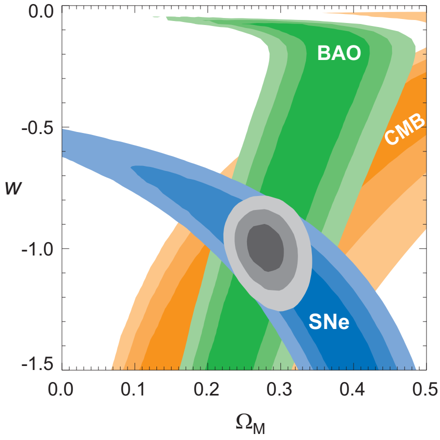


Models for dark energy

- Quintessence
  A scalar field ϕ can show so called ’tracker behavior’ so that it represents always a small fraction of the radiation and matter background density. By ’some mechanism’ it can come to dominate.

- Quintessence
  A scalar field ϕ can show so called 'tracker behavior' so that it represents always a small fraction of the radiation and matter background density. By 'some mechanism' it can come to dominate.
- Can reproduce the data if it behaves today nearly like a cosmological constant...

- **Quintessence**
  A scalar field ϕ can show so called 'tracker behavior' so that it represents always a small fraction of the radiation and matter background density. By 'some mechanism' it can come to dominate.
- Can reproduce the data if it behaves today nearly like a cosmological constant...



$$w = \frac{P}{\rho} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}$$

Models for dark energy

- Modification of general relativity at large distance, extra dimensions (DGP).

- Modification of general relativity at large distance, extra dimensions (DGP).
- Backreaction: If structure formation leads to important modifications of the geomety such that perturbation theory is no longer sufficient, this could modify the redshift – distance relation...

Conclusions

- SN observations
  Ten years after the discovery of accelerated expansion, observations of several hundred supernovae confirm it strongly (more than 7σ).

Conclusions

- SN observations
  Ten years after the discovery of accelerated expansion, observations of several hundred supernovae confirm it strongly (more than 7σ).
- Additional data
  Other observations (CMB, BAO, ...) also require a dominant component with strong netiative pressure.

Conclusions

- SN observations
  Ten years after the discovery of accelerated expansion, observations of several hundred supernovae confirm it strongly (more than 7σ).
- Additional data
  Other observations (CMB, BAO, ...) also require a dominant component with strong netiative pressure.
- Cosmological constant
  A cosmological constant or vacuum energy which contributes about 75% of the energy density of the Universe is in good agreement with all data.

Conclusions

- SN observations
  Ten years after the discovery of accelerated expansion, observations of several hundred supernovae confirm it strongly (more than 7σ).
- Additional data
  Other observations (CMB, BAO, ...) also require a dominant component with strong netiative pressure.
- Cosmological constant
  A cosmological constant or vacuum energy which contributes about 75% of the energy density of the Universe is in good agreement with all data.
- Negative pressure
  The dark energy must have large netative pressure $P = w\rho$ with $w = -1 \pm 0.2$. It comes to dominate at a redshift of about $z \simeq 0.4$ before roughly 4 billion years.

Conclusions

- SN observations
  Ten years after the discovery of accelerated expansion, observations of several hundred supernovae confirm it strongly (more than 7σ).
- Additional data
  Other observations (CMB, BAO, ...) also require a dominant component with strong netiative pressure.
- Cosmological constant
  A cosmological constant or vacuum energy which contributes about 75% of the energy density of the Universe is in good agreement with all data.
- Negative pressure
  The dark energy must have large netative pressure $P = w\rho$ with $w = -1 \pm 0.2$. It comes to dominate at a redshift of about $z \simeq 0.4$ before roughly 4 billion years.

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.
- Dark theory
  There exist many models of dark energy but none of them is convincing.

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.
- Dark theory
  There exist many models of dark energy but none of them is convincing.
- Dark destiny
  The future of the Universe depends crucially on the nature of dark energy. If it is truly a cosmological constant, all galaxies not gravitationally bound to us will speed away outside of our visible Universe (horizon) and in about hundred billion years astronomers can only observe the local group of galaxies.

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.
- Dark theory
  There exist many models of dark energy but none of them is convincing.
- Dark destiny
  The future of the Universe depends crucially on the nature of dark energy. If it is truly a cosmological constant, all galaxies not gravitationally bound to us will speed away outside of our visible Universe (horizon) and in about hundred billion years astronomers can only observe the local group of galaxies.

The observations are clear and convincing, but not understood:

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.
- Dark theory
  There exist many models of dark energy but none of them is convincing.
- Dark destiny
  The future of the Universe depends crucially on the nature of dark energy. If it is truly a cosmological constant, all galaxies not gravitationally bound to us will speed away outside of our visible Universe (horizon) and in about hundred billion years astronomers can only observe the local group of galaxies.

The observations are clear and convincing, but not understood:

- Indication of quantum gravity?

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.
- Dark theory
  There exist many models of dark energy but none of them is convincing.
- Dark destiny
  The future of the Universe depends crucially on the nature of dark energy. If it is truly a cosmological constant, all galaxies not gravitationally bound to us will speed away outside of our visible Universe (horizon) and in about hundred billion years astronomers can only observe the local group of galaxies.

The observations are clear and convincing, but not understood:

- Indication of quantum gravity?
- Extra dimensions?

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.
- Dark theory
  There exist many models of dark energy but none of them is convincing.
- Dark destiny
  The future of the Universe depends crucially on the nature of dark energy. If it is truly a cosmological constant, all galaxies not gravitationally bound to us will speed away outside of our visible Universe (horizon) and in about hundred billion years astronomers can only observe the local group of galaxies.

The observations are clear and convincing, but not understood:

- Indication of quantum gravity?
- Extra dimensions?
- 'Back reaction' ?

Conclusions

- Dark value
  All estimates of the vacuum energy from quantum field theory give results which are many orders of magnitude larger than the measured value.
- Dark theory
  There exist many models of dark energy but none of them is convincing.
- Dark destiny
  The future of the Universe depends crucially on the nature of dark energy. If it is truly a cosmological constant, all galaxies not gravitationally bound to us will speed away outside of our visible Universe (horizon) and in about hundred billion years astronomers can only observe the local group of galaxies.

The observations are clear and convincing, but not understood:

- Indication of quantum gravity?
- Extra dimensions?
- 'Back reaction' ?