Cosmology II: The CMB, dark matter and dark energy

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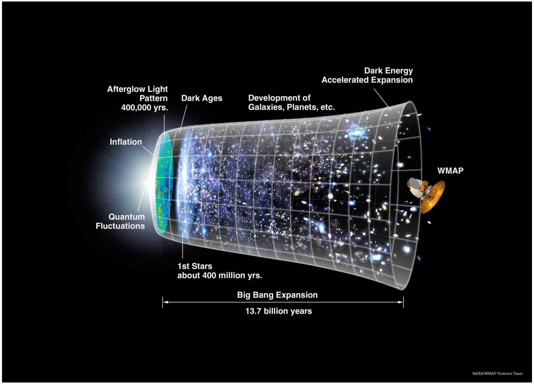
Contents

Thermal history

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



Age of the Universe: $t_0 \simeq 13.7$ billion years

The most remarkable events of the hot Universe:

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

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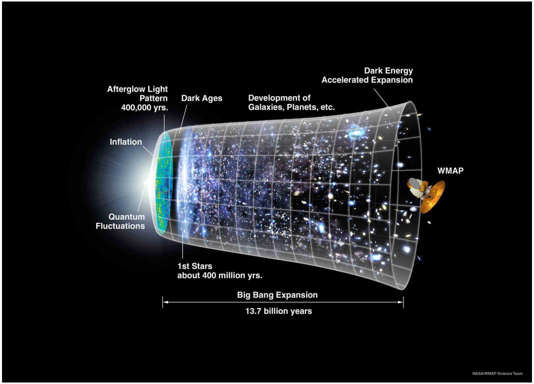

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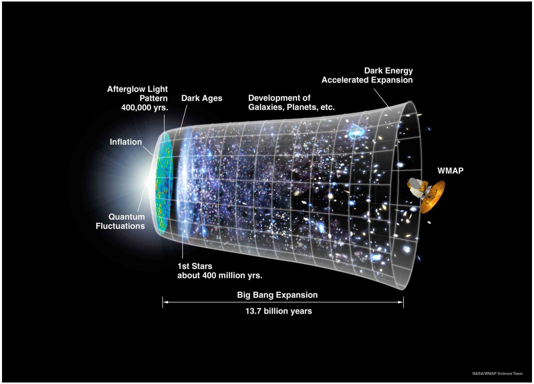

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- Inflation ?

Recombination

- Since the photon (radiation) energy density scales like $T^4 \propto R^{-4} \propto (z+1)^4$ while the matter density scales like $mn \propto R^{-3} \propto (z+1)^3$, at very early time, the Universe is radiation dominated ($z \gtrsim 4000$, $t \lesssim 10^4$ years).

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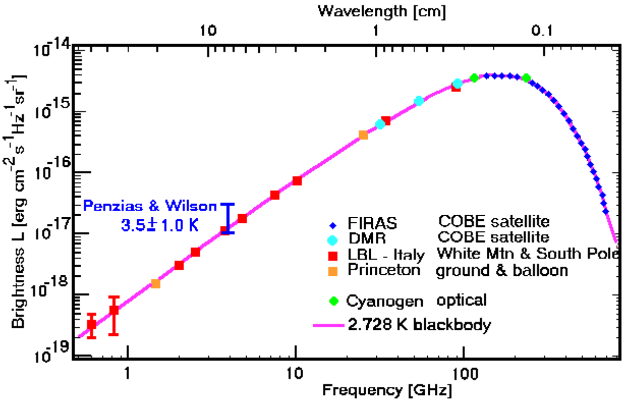
- It represents a 'photo' of the Universe when it was about 300'000 years young, corresponding to a redshift of $z \simeq 1100$.

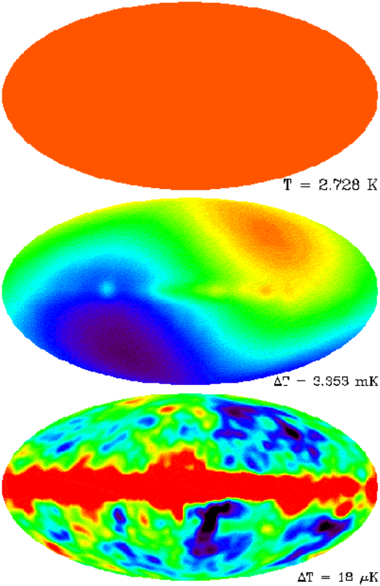


(Fixen et al. 1996)

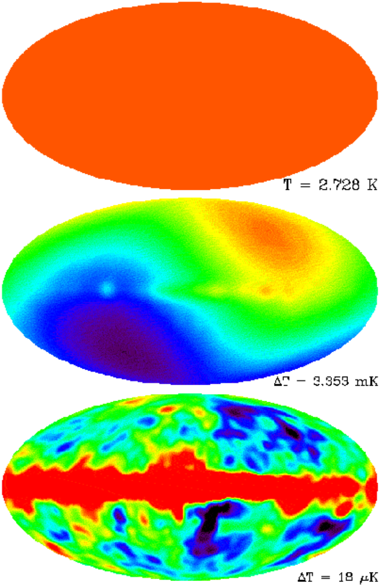
Nobel Prize 1978 for Penzias and Wilson,
Nobel Prize 2006 for Mather

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

The cosmic microwave background: anisotropies



Map of the CMB temperature: perfectly isotropic.



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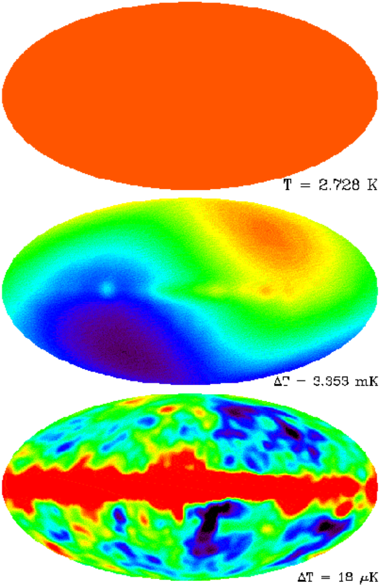

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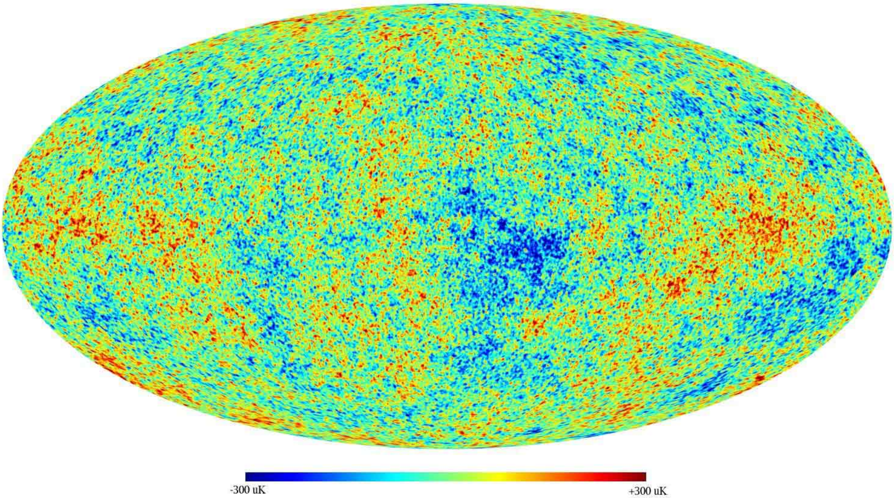
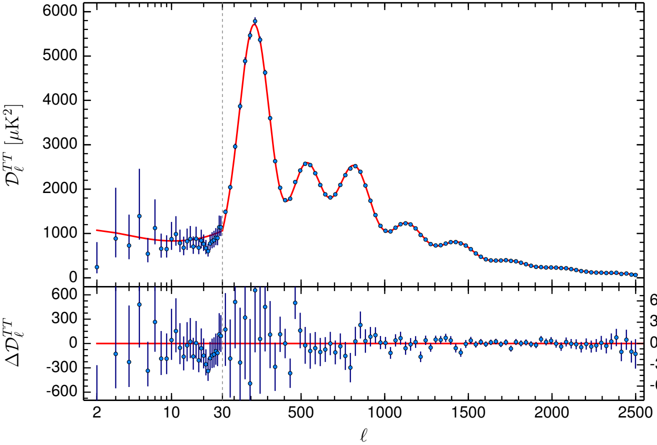
And what is this? Left over after subtracting the dipole. Fluctuations of amplitude $\sim 10^{-5}$.



ESA/Planck (2015)

The cosmic microwave background: anisotropies



$$\frac{\Delta T}{T}(\mathbf{n}) = \sum a_{\ell m} Y_{\ell m}(\mathbf{n})$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

$$\mathcal{D}_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell$$

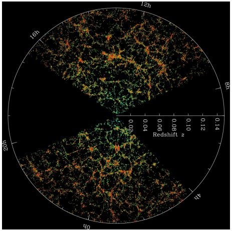
$$\frac{\Delta T}{T} \simeq 2 \times 10^{-5}$$

ESA/Planck (2015)

$\ell = 200$ corresponds to about 1^o. $\Rightarrow$ 'acoustic' peaks. $(\theta \simeq 180^o/\ell)$

(This is roughly the double of the angular size of the full moon (or of the sun).)

The matter distribution in the observed Universe is not very homogeneous and isotropic. It is in form of galaxies, clusters, filaments, voids.
The idea is that these large scale structures formed by gravitational instability from small initial fluctuations which have been set up very early in the Universe (during inflation).



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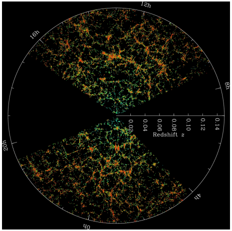

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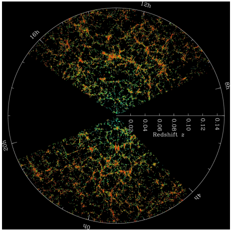

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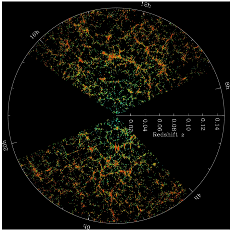

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- The second peak peak corresponds to fluctuations which have had time to make exactly 1 contraction and 1 expansion since horizon entry until decoupling (under density).

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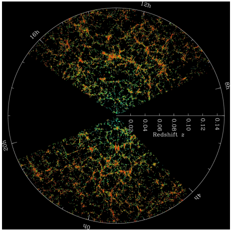

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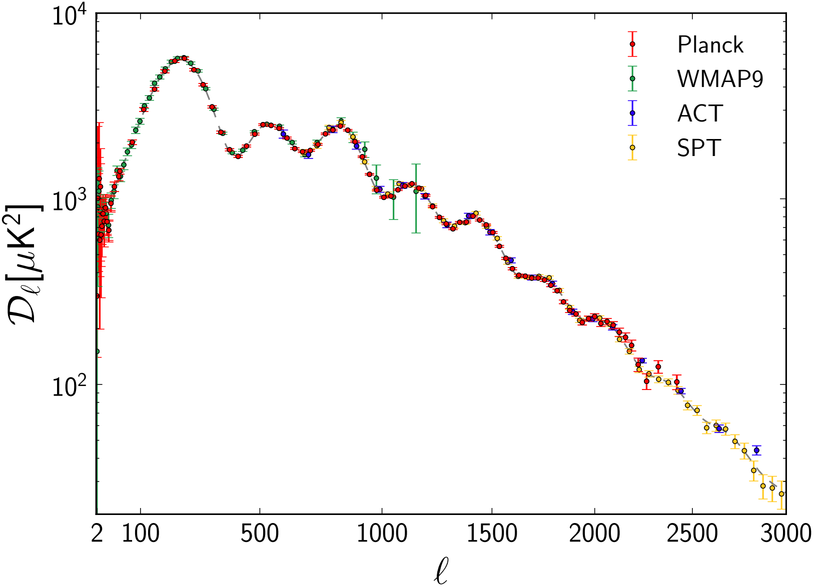
- The second peak peak corresponds to fluctuations which have had time to make exactly 1 contraction and 1 expansion since horizon entry until decoupling (under density).
- The third peak corresponds to fluctuations which have had time to make exactly 2 contractions (and 1 expansion) since horizon entry until decoupling. $\cdots$


Planck
WMAP9
ACT
SPT
10^4
10^3
10^2
$\mathcal{D}_\ell[\mu K^2]$
2
100
500
1000
1500
2000
2500
3000
ℓ

The patches of peak amplitude temperature fluctuations are standard rulers. Their size is given by the age of the Universe at the time of decoupling (recombination). The angle under which we see these patches determines the distance to the surface of last scattering. ($z = z_{\rm dec} \simeq 1100$), $d = r/\theta_p$.

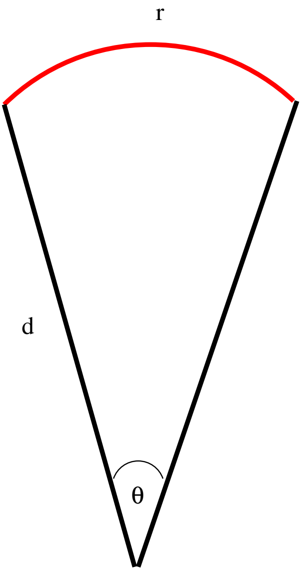
The amplitude of the peaks depends on the matter density ($h = H_0/100$km/s/Mpc)

$$\rho_m \propto \Omega_m h^2 = 0.1417 \pm 0.00097$$

and the difference of the amplitude of even and odd peaks depends strongly on the density of electrons and hence baryons,

$$\rho_b \propto \Omega_b h^2 = 0.02230 \pm 0.00014 \ll \Omega_m h^2$$

Most of the matter in the Universe is dark and non-baryonic!



The cosmic microwave background: parameters from Planck (2015)

The angle subtended by the 1st peak is (together with the CMB temperature) the best measured number in cosmology,

$$\theta_s = \frac{r_s}{d_A(z_s)} = (1.04093 \pm 0.00030) \times 10^{-2} \qquad \delta\theta_s/\theta_s = 2.8 \times 10^{-4}$$

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$$r_s = \frac{2h/H_0}{\sqrt{3(1+z_s) r\omega_m}} \log\left(\frac{\sqrt{1+z_s+r} + \sqrt{\frac{(1+z_s)r\omega_r}{\omega_m} + r}}{\sqrt{1+z_s}\left(1+\sqrt{\frac{r\omega_r}{\omega_m}}\right)} \right), \qquad r = \frac{3\omega_b}{4\omega_\gamma}.$$

$(\Omega_x h^2 \equiv \omega_x)$

$$r_s = (144.81 \pm 0.24)\mathrm{Mpc}.$$

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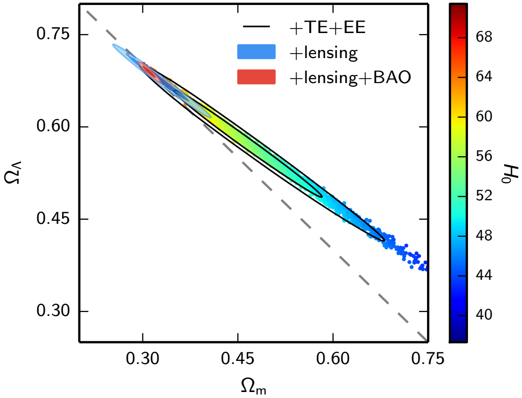
$$\frac{r_s}{\theta_s} = d_A(z_s) = \int_0^{z_s} \frac{dz}{H(z)} = \frac{1}{H_0}\int_0^{z_s} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda}}$$

$$H_0 = (67.74 \pm 0.46)\ \text{km/s/Mpc}$$

(Local measurements find $H_0 = (73 \pm 1.5)$km/s/Mpc, Riess et al. 2016)

Combining CMB temperature anisotropies, polarisation and lensing breaks degeneracies.

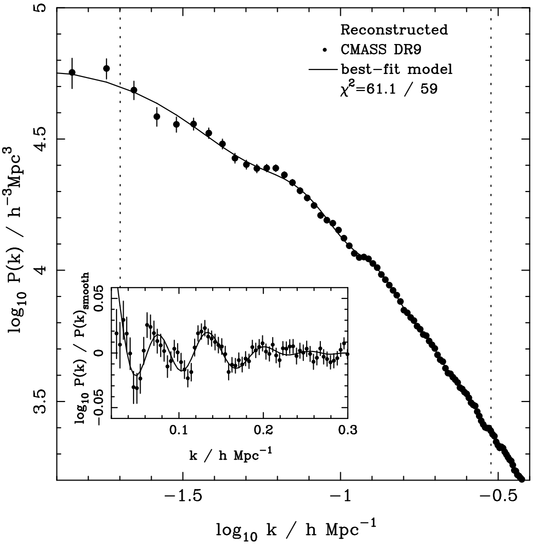


(Planck 2015)

$$\Omega_K = 0.000 \pm 0.005 \qquad \text{at } 95\%$$

Baryon acoustic oscillations

The acoustic peaks are also visible in the matter power spectrum. (= The mean square amplitude of fluctuations of a given size.)



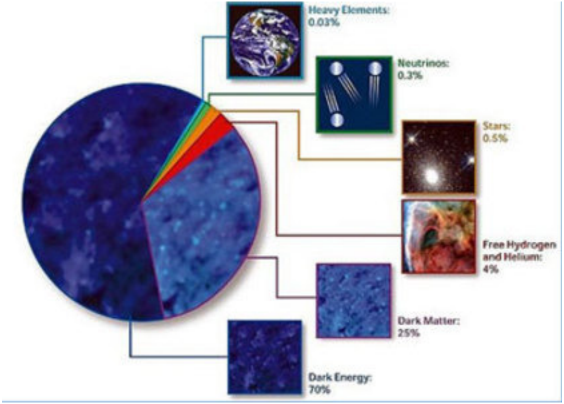
from Anderson et al. '12

SDSS-III (BOSS)
power spectrum.

$H_0 = (68.11 \pm 0.86)$km/s/Mpc

(Cheng & Huang, 2014)

The cosmological composition



Data: CMB + BAO + SN Ia

$$
\begin{aligned}
H_0 &= (67.7 \pm 0.5)\text{km/s/Mpc} \\
&= h100\text{km/s/Mpc} \\
\Omega_m &= 0.3 \pm 0.01 \\
\Omega_b h^2 &= 0.0223 \pm 0.00016 \\
\Omega_K &= 0.00 \pm 0.005 \quad (95\%) \\
\Omega_\Lambda &= 0.7 \pm 0.01 \\
\Omega_{\rm rad} h^2 &= 0.48 \times 10^{-5} \\
\text{age} &= (13.81 \pm 0.026)\text{Gyr}
\end{aligned}
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Dark matter

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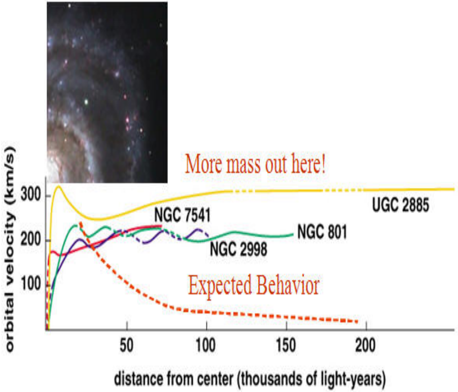
- Also most of the baryonic matter is in the form of gas which does not emit visible light.
- The first to postulate dark matter was the Swiss astronomer Fritz Zwicky. He realized that binding galaxy clusters gravitationally, requires about 100 times more mass than the mass of all its stars (HPA, 1933).
- In the 70ties, the American astronomer Vera Rubin has shown that also galaxies are dominated by dark matter which contributes about 10 times more to their mass than the stars.

Dark matter

Rubin found that the rotation curves of test particles (stars, hydrogen atoms) rotating around galaxies do not show the expected decay of the velocity,

$$v^2 = \frac{GM}{r}, \quad v \propto \frac{1}{\sqrt{r}}$$

but have $v =$ constant. Kepler's law then requires that $M \propto r$.



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- Estimations of cluster masses (and CMB and LSS observations) yield $\Omega_m h^2 \simeq 0.14$
- CMB anisotropies (and nucleosynthesis) require $\Omega_b h^2 \simeq 0.02$
- Hence most of dark matter (env. 85%) is non-baryonic.

Dark matter : Candidates

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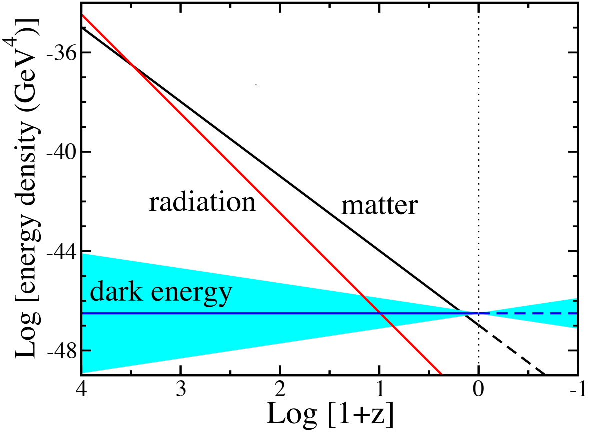
All these candidates require physics beyond the standard model!

- Cosmological constant / vacuum energy
  Provides a good fit to the data, but nobody understands its value and which it comes to dominate exactly 'now'.



Dark energy models

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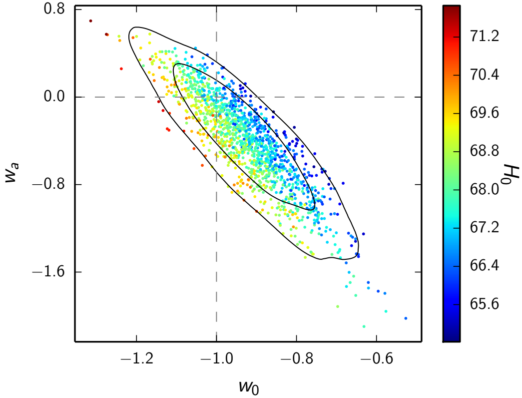

$$w = P/\rho_E = -1 \pm 0.08$$
$$= \text{pressure/(energy density)}$$

$$w(z) = w_0 + \frac{z}{1+z} w_a$$

Planck (2015)

Dark energy models

- Modification of gravity at large scales, e.g. massive gravity, degravitation, extra dimensions.

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- Backreaction: If structure formation leads to relevant modifications of the geometry, this could modify the relation between distance and redshift...

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- Other data also require dark energy
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- Cosmological constant
  A cosmological constant or vacuum energy which contributes about 70% to the energy density of the Universe is in good agreement with data.
- Dark matter
  25% of the energy density of the Universe is in the form of non-baryonic dark matter. Even if several reasonable candidates exist, we still have not been able to identify dark matter 80 years after it has been first postulated by Fritz Zwicky.

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- Observations SN
  15 years after the discovery of the accelerated expansion of the Universe, observations of several 100 supernovae of type Ia confirm it at more than 7σ.
- Other data also require dark energy
  CMB, BAO, ...
- Cosmological constant
  A cosmological constant or vacuum energy which contributes about 70% to the energy density of the Universe is in good agreement with data.
- Dark matter
  25% of the energy density of the Universe is in the form of non-baryonic dark matter. Even if several reasonable candidates exist, we still have not been able to identify dark matter 80 years after it has been first postulated by Fritz Zwicky.
- Baryons
  Only about 5% of the energy density of the present Universe is in the form of matter as we find it in our solar system, ordinary atoms made out of baryons and electrons.