Cosmology II: The thermal history of the Universe

Ruth Durrer

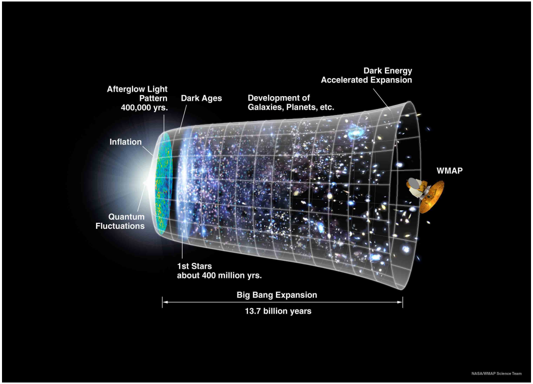
Département de Physique Théorique et CAP
Université de Genève
Suisse

August 6, 2014

Contents

Thermal history

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

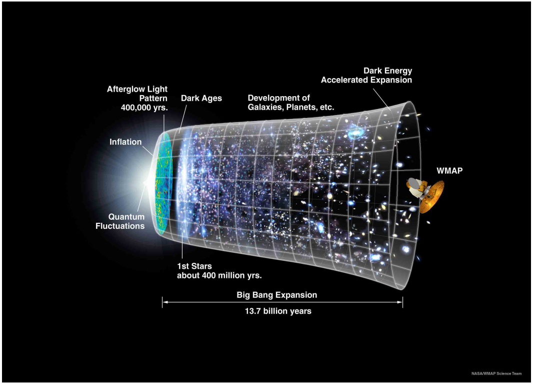


Age of the Universe: $t_0 \simeq 13.7$ billion years

The most remarkable events of the hot Universe:

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

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



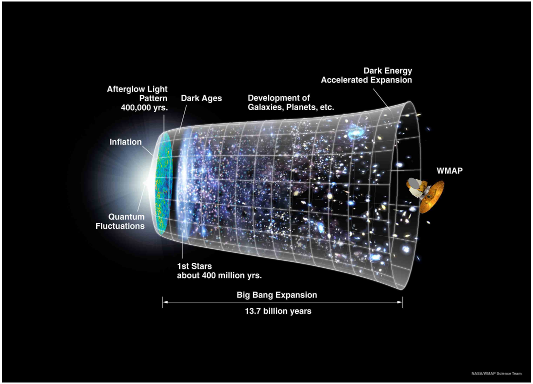
Age of the Universe: $t_0 \simeq 13.7$ billion years

The most remarkable events of the hot Universe:

- Recombination (electrons and protons combine to neutral hydrogen).
- Nucleosyhthesis (the formation of Helium, Deuterium, ...)

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).
- Nucleosyhthesis (the formation of Helium, Deuterium, ...)
- Inflation ?

- 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).

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).

- At $T \simeq 3000$K ($t \simeq 300'000$years) the Universe is 'cold' enough that protons and electrons can combine to neutral hydrogen.

Recombination

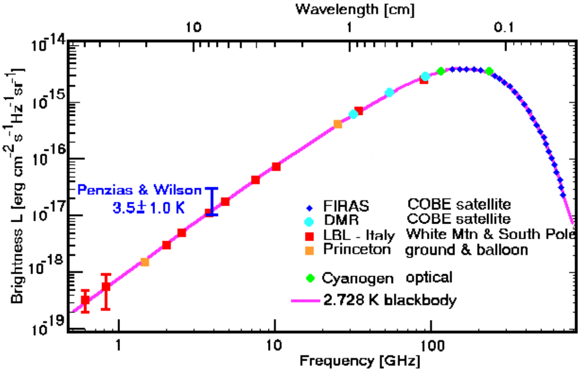
- Since the photon (radiation) energy density scales like $T^4 \propto R^{-4} \propto (z+1)^4$ while the matter density scales like $mn \propto R^{-3} \propto (z+1)^3$, at very early time, the Universe is radiation dominated ($z \gtrsim 4000$, $t \lesssim 10^4$ years).
- At $T \simeq 3000$K ($t \simeq 300'000$years) the Universe is 'cold' enough that protons and electrons can combine to neutral hydrogen.
- After this, photons no longer scatter with matter but propagate freely. Their energy (and hence the temperature) is redshifted to $T_0 = 2.728$K today, corresponding to a density of about 400 photons per cm^3.

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).
- At $T \simeq 3000$K ($t \simeq 300'000$years) the Universe is 'cold' enough that protons and electrons can combine to neutral hydrogen.
- After this, photons no longer scatter with matter but propagate freely. Their energy (and hence the temperature) is redshifted to $T_0 = 2.728$K today, corresponding to a density of about 400 photons per cm^3.
- This cosmic microwave background can be observed today in the (1– 400)GHz range. It has a perfect blackbody spectrum.

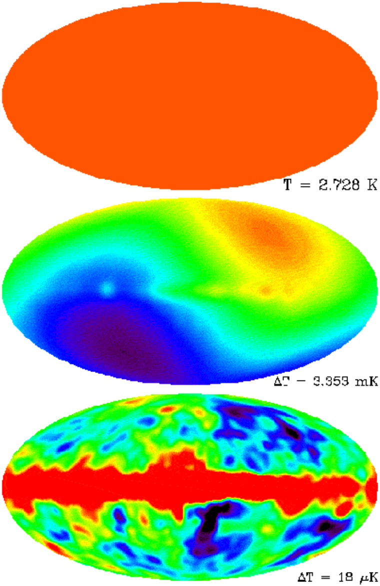
Recombination

- 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).
- At $T \simeq 3000$K ($t \simeq 300'000$years) the Universe is 'cold' enough that protons and electrons can combine to neutral hydrogen.
- After this, photons no longer scatter with matter but propagate freely. Their energy (and hence the temperature) is redshifted to $T_0 = 2.728$K today, corresponding to a density of about 400 photons per cm^3.
- This cosmic microwave background can be observed today in the (1– 400)GHz range. It has a perfect blackbody spectrum.
- It represents a 'photo' of the Universe when it was about 300'000 years old, corresponding to a redshift of $z \simeq 1100$.



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

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



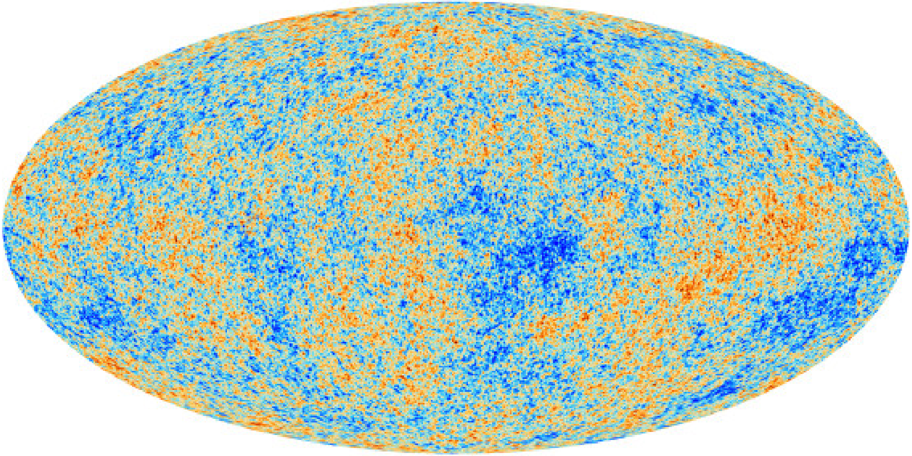
Smoot et al. (1999), Nobel Prize 2006

Map of the CMB temperature: perfectly isotropic.

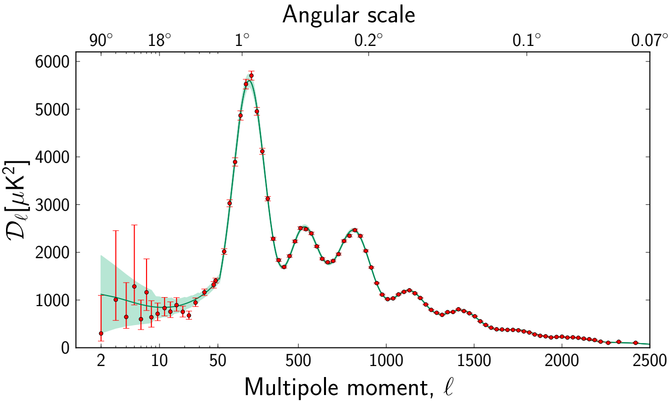
Subtracting the monopole a dipole of amplitude $\sim 10^{-3}$ becomes visible. It is mainly due to the motion of the solar system with respect of the sphere of emission (last scattering surface).

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

The cosmic microwave background: anisotropies



ESA/Planck (2013)

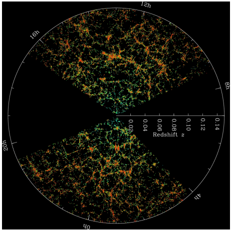


ESA/Planck (2013)

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

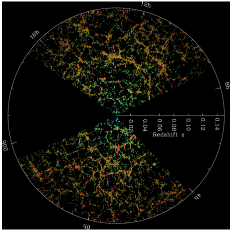
(This is roughly the double of the angular size of the full moon (or of the sun).)

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 during inflation.



The cosmic microwave background: anisotropies

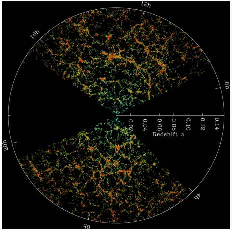
The matter distribution in the observed Universe is not very homogeneous and isotropic. It is in form of galaxies, clusters, filaments, voids.
The idea is that these large scale structures formed by gravitational instability from small initial fluctuations which have been set up during inflation.



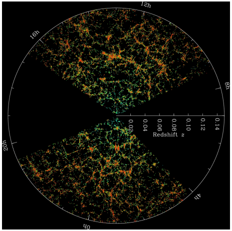
- These initial fluctuations are also imprinted in the CMB.

The cosmic microwave background: anisotropies

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 during inflation.



- These initial fluctuations are also imprinted in the CMB.
- Once a given scale enters the horizon, fluctuations on this scale begin to oscillate like acoustic waves (sound). The first peak corresponds to fluctuations which have had time to make exactly 1 contraction since horizon entry until decoupling.

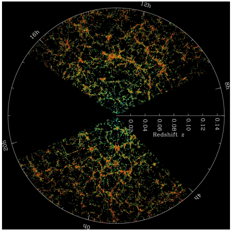


The matter distribution in the observed Universe is not very homogeneous and isotropic. It is in form of galaxies, clusters, filaments, voids.
The idea is that these large scale structures formed by gravitational instability from small initial fluctuations which have been set up during inflation.

- These initial fluctuations are also imprinted in the CMB.
- Once a given scale enters the horizon, fluctuations on this scale begin to oscillate like acoustic waves (sound). The first peak corresponds to fluctuations which have had time to make exactly 1 contraction since horizon entry until decoupling.
- 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).

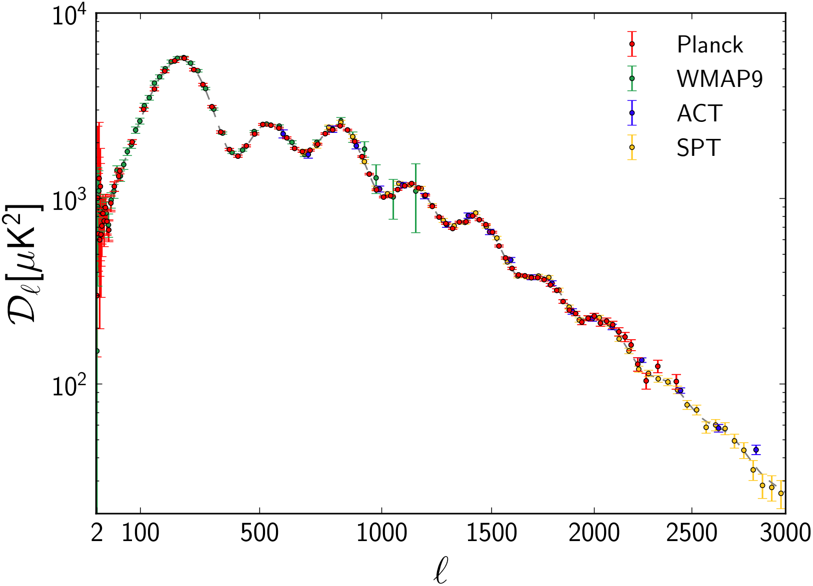
The cosmic microwave background: anisotropies

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 during inflation.



- These initial fluctuations are also imprinted in the CMB.
- Once a given scale enters the horizon, fluctuations on this scale begin to oscillate like acoustic waves (sound). The first peak corresponds to fluctuations which have had time to make exactly 1 contraction since horizon entry until decoupling.
- 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. $\cdots$

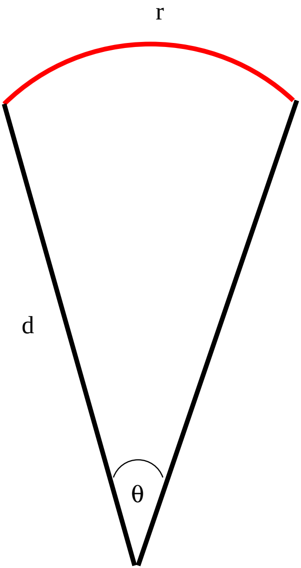
Combined CMB data



The cosmic microwave background: anisotropies

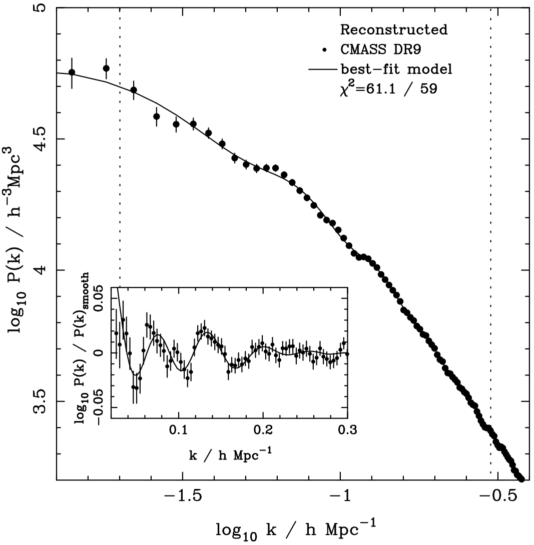
The patches which have of peak amplitude temperature fluctuations are standard rulers. Their size is given by the age of the Universe at the time of decoupling (recombination). The angle under which we see these patches determines the distance to the surface of last scattering.
$(z = z_{\rm dec} \simeq 1100)$, $d = r/\theta$.
The amplitude of the peaks depends on the matter density
$\rho_m \propto \Omega_m H_0^2 = (13 \pm 2) \times 100(\text{km/s/Mpc})^2$
and
the difference of the amplitude of even and odd peaks depends strongly on the density of electrons and hence baryons,
$\rho_b \propto \Omega_b H_0^2 = 2.2 \pm 0.3 \times 100(\text{km/s/Mpc})^2 \ll \Omega_m H_0^2$.

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



Baryon acoustic oscillations

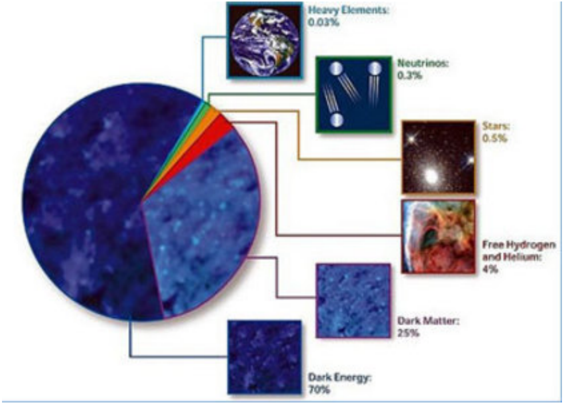
The acoustic peaks are also visible in the matter power spectrum. (= The mean square amplitude of fluctuations of a given size.)



from Anderson et al. '12

SDSS-III (BOSS) power spectrum.

The cosmological composition



Data: CMB + BAO + SN Ia

$$
\begin{aligned}
H_0 &= 67.8 \pm 1\text{km/s/Mpc} \\
&= h100\text{km/s/Mpc} \\
\Omega_m &= 0.31 \pm 0.01 \\
\Omega_b h^2 &= 0.0221 \pm 0.0002 \\
\Omega_K &= -0.0005^{+0:0065}_{-0.0066} \\
\Omega_\Lambda &= 0.69 \pm 0.01 \\
\Omega_{\rm rad} h^2 &= 0.48 \times 10^{-5} \\
\text{age} &= 13.80 \pm 0.04\text{Gyr}
\end{aligned}
$$

Dark matter

- Most of the matter in the Universe is in the form of an unknown non-baryonic component which does not interact with photons (dark).

Dark matter

- Most of the matter in the Universe is in the form of an unknown non-baryonic component which does not interact with photons (dark).
- Also most of the baryonic matter is in the form of gas which does not emit light.

Dark matter

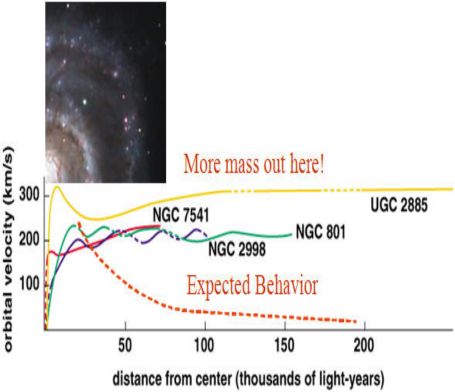
- Most of the matter in the Universe is in the form of an unknown non-baryonic component which does not interact with photons (dark).
- Also most of the baryonic matter is in the form of gas which does not emit light.
- The first to postulate dark matter was the Swiss astronomer Fritz Zwicky. He realized 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 $M \propto r$.



Dark matter is non-baryonic

- These original discoveries do not shed any light on the nature of dark matter except that it does not emit visible photons.

- These original discoveries do not shed any light on the nature of dark matter except that it does not emit visible photons.
- X ray observations show that a part (about 10%) of dark matter in clusters is in the form of hot gas emitting X rays.

Dark matter is non-baryonic

- These original discoveries do not shed any light on the nature of dark matter except that it does not emit visible photons.
- X ray observations show that a part (about 10%) of dark matter in clusters is in the form of hot gas emitting X rays.
- Estimations of cluster masses (and CMB and LSS observations) yield $\Omega_m h^2 \simeq 0.14$

Dark matter is non-baryonic

- These original discoveries do not shed any light on the nature of dark matter except that it does not emit visible photons.
- X ray observations show that a part (about 10%) of dark matter in clusters is in the form of hot gas emitting X rays.
- Estimations of cluster masses (and CMB and LSS observations) yield $\Omega_m h^2 \simeq 0.14$
- CMB anisotropies (and nucleosynthesis) require $\Omega_b h^2 \simeq 0.02$

Dark matter is non-baryonic

- These original discoveries do not shed any light on the nature of dark matter except that it does not emit visible photons.
- X ray observations show that a part (about 10%) of dark matter in clusters is in the form of hot gas emitting X rays.
- 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.

What could this dark matter be?

Dark matter : Candidates

What could this dark matter be? A stable particle which do not couple to photons.

What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$

What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$
- Sterile Neutrino which is more massive but less abundant ?

Dark matter : Candidates

What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$
- Sterile Neutrino which is more massive but less abundant ?
- Neutralino (stable particle in most simple models of super-symmetry $\Rightarrow$ LHC) ?

Dark matter : Candidates

What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$
- Sterile Neutrino which is more massive but less abundant ?
- Neutralino (stable particle in most simple models of super-symmetry $\Rightarrow$ LHC) ?
- Axion (Hypothetical stable particle required to solve the 'strong CP problem') ?

What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$
- Sterile Neutrino which is more massive but less abundant ?
- Neutralino (stable particle in most simple models of super-symmetry $\Rightarrow$ LHC) ?
- Axion (Hypothetical stable particle required to solve the 'strong CP problem') ?
- Primordial black holes ?

What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$
- Sterile Neutrino which is more massive but less abundant ?
- Neutralino (stable particle in most simple models of super-symmetry $\Rightarrow$ LHC) ?
- Axion (Hypothetical stable particle required to solve the 'strong CP problem') ?
- Primordial black holes ?
- Wimpzillas ?

Dark matter : Candidates

What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$
- Sterile Neutrino which is more massive but less abundant ?
- Neutralino (stable particle in most simple models of super-symmetry $\Rightarrow$ LHC) ?
- Axion (Hypothetical stable particle required to solve the 'strong CP problem') ?
- Primordial black holes ?
- Wimpzillas ?
- Gravitinos ?

Dark matter : Candidates

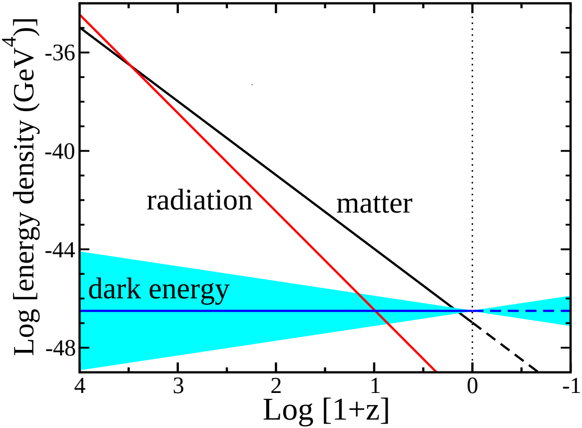
What could this dark matter be? A stable particle which do not couple to photons.

- Neutrino (cannot be bound in dwarf galaxies, too little small scale structure). $\lightning$
- Sterile Neutrino which is more massive but less abundant ?
- Neutralino (stable particle in most simple models of super-symmetry $\Rightarrow$ LHC) ?
- Axion (Hypothetical stable particle required to solve the 'strong CP problem') ?
- Primordial black holes ?
- Wimpzillas ?
- Gravitinos ?

All these candidates require physics beyond the standard model!

Dark energy models

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

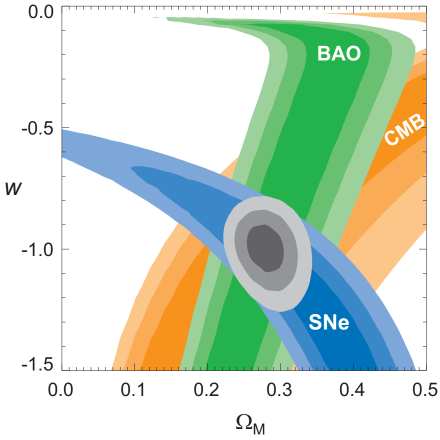


- Quintessence
  A scalar field which first follows the scaling of matter and radiation and has started to dominate recently.

Dark energy models

- Quintessence
  A scalar field which first follows the scaling of matter and radiation and has started to dominate recently.
- Can reproduce the data if its behavior is close to a cosmological constant.

- Quintessence
  A scalar field which first follows the scaling of matter and radiation and has started to dominate recently.
- Can reproduce the data if its behavior is close to a cosmological constant.



$w = P/\rho_E$
$=$pressure/(energy density)

Dark energy models

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

Dark energy models

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

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

Conclusions

- 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.

Conclusions

- 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, ...

Conclusions

- 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.

Conclusions

- 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.

Conclusions

- 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.