The Universe as laboratory for fundamental physics

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Introduction

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- Phase transitions at high temperature
- Baryogenesis
- Inflation

Dark matter

- Dark matter had been postulated originally by the Swiss astronomer Fritz Zwicky. Studying the relative velocities of galaxies in clusters, he had realized that clusters can be gravitationally bound only if their total mass is about 100 times more than the mass coming from the lumnious galaxies (Helv. Phys. A. 1933). For this he has used the virial theorem:

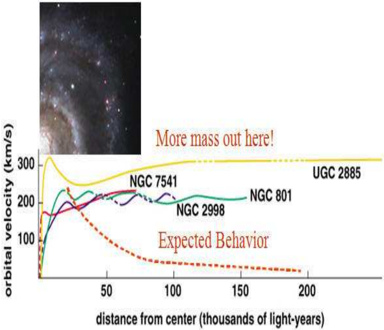
$$v^2 = \frac{GM}{R} .$$

- In the 70ies and 80ies, the American astronomer Vera Rubin has shown that also the individual a galaxies are dominated by dark matter which contributes about 10 times more than the mass of the stars.

Rubin has found that the rotation curves of test particles (star, hydrogen atoms) around galaxies do not exhibit the expected decay law

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

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



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- On the other hand, nucleosynthesis calculations and the mesured anisotropies of the cosmic microwave background require $h^2\Omega_b \simeq 0.02$
- Hence a large part (about 85%) of the matter in the Universe is non-baryonic.

Dark matter candidates

These have to be stable particles which do not couple to the photon.

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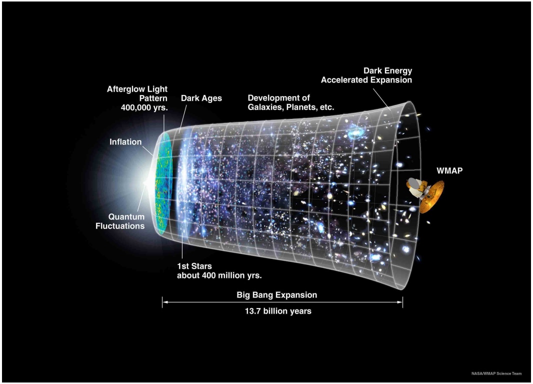
All these candidates rely on physics beyond the standard model.

Thermal history

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



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

Main events in the hot Universe:

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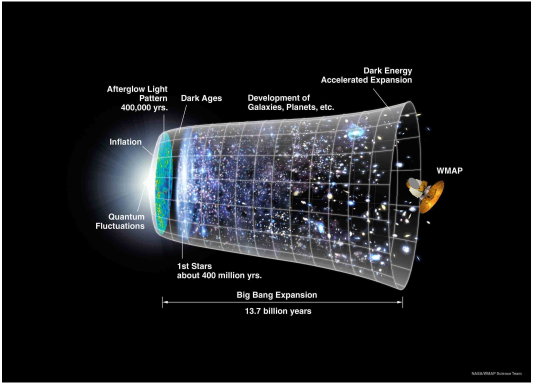

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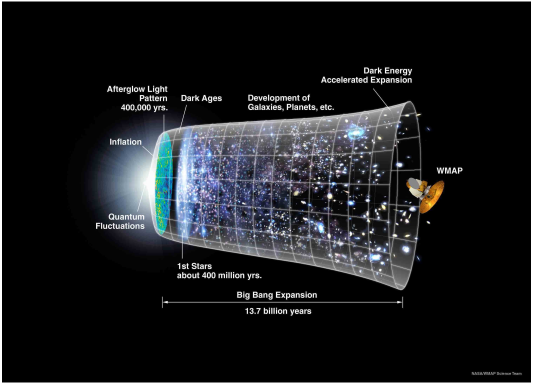

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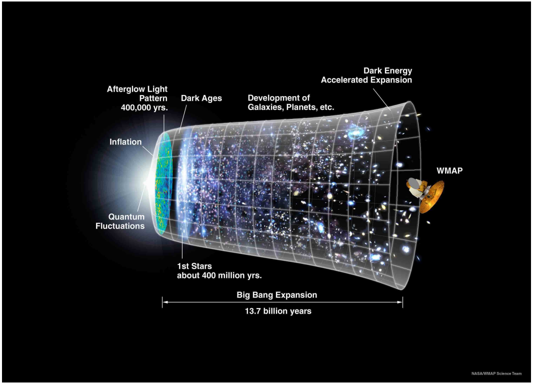

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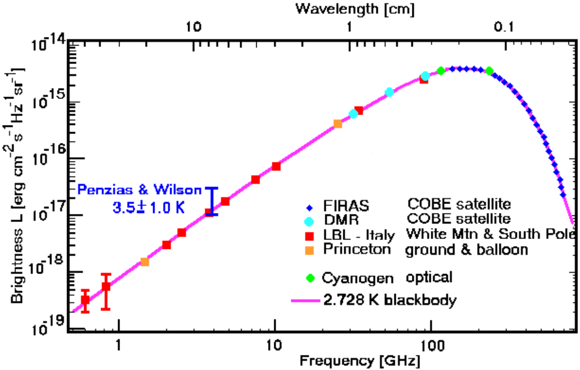
The Universe then becomes transparent to the cosmic photons.

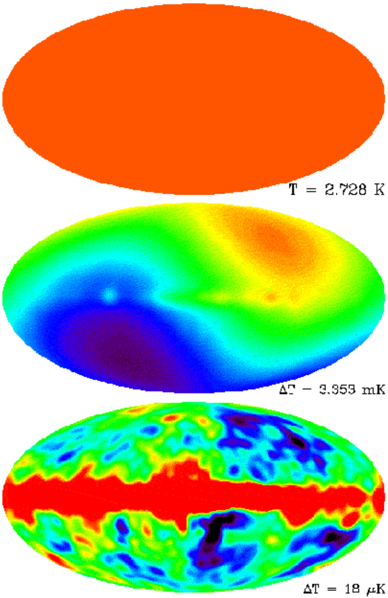
Subsequently the thermal photon spectrum is modified only by cosmic expansion,

$$\nu_0 = \nu_{\rm dec}/(1+z_{\rm dec}) \quad \Rightarrow \quad T_0 = T_{\rm dec}/(1+z_{\rm dec})$$

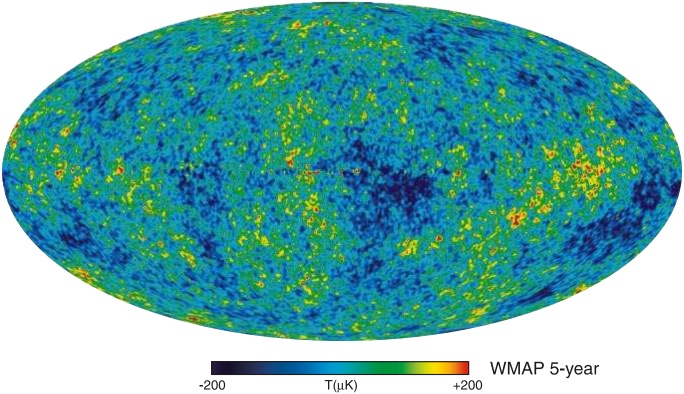


Fixen et al. (1996). Nobel Prize 1978 Penzias et Wilson; 2006 Mather

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



Smoot et al. (1992), Nobel Prize 2006

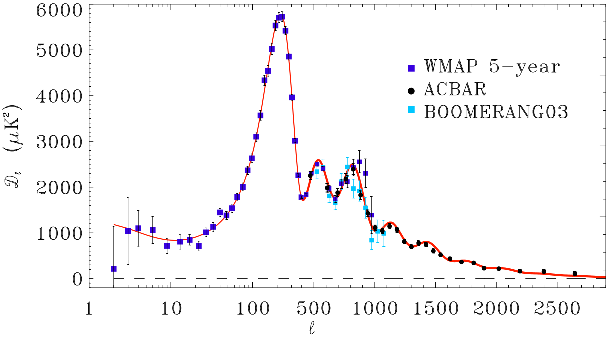


Hinshaw et al. (2008)

The fluctuations are a function on the sphere and can be developed in spherical harmonics:

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

Statistical isotropy implies $\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'}\delta_{mm'} C_\ell$.
The C_ℓ's are the angular power spectrum. $\ell(\ell+1)C_\ell \simeq \langle (\Delta T)^2 \rangle (\theta \simeq \pi/\ell)$



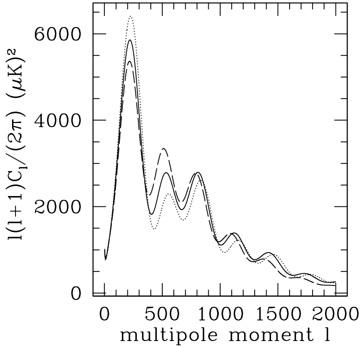
Reichhardt et al. (2008)

$\ell = 200$ corresponds to about 1^o. (twice the angular scale of the full moon.)

The baryon density affects the acoustic oscillations of the photon-baryon plasma prior to recombination which are imprinted in the CMB anisotropies in various ways:

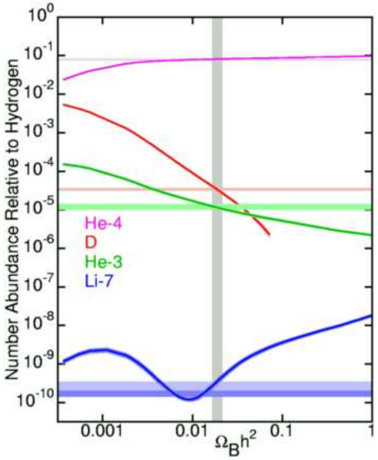
- Baryons as they are massive enhance the the contraction peaks (odd) and reduce the expansion peaks (even).
- Baryons reduce the sound speed and thereby the sound horizon which is related to the scale of the acoustic peaks.
- The baryon density determines the Silk damping scale.

More details on the parameter dependence of CMB anisotropies will be discussed in the student talk by Marc Vonlanthen



$$h^2\Omega_b = \begin{cases} 0.02 & \text{solid} \\ 0.03 & \text{dotted} \\ 0.01 & \text{dashed} \end{cases}$$

- At $T \sim 0.1$MeV the Universe is sufficiently cool for deuterium to become stable.
- Most of the deuterium is immediately burned into He^4 and only very little remain in the form of deuterium or formed He^3. Some of these primordial nuclei go on to form Li^7. (No stable nuclei with $A = 5, 6$ do exist.)
- The abundances of these light elements, especially of deuterium and He^3 but also of Li^7 are extremely sensitive to the baryon density.



Neutrino decoupling

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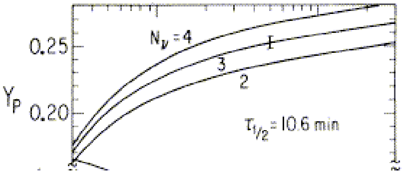
- Even if these neutrini have a density of about 336/cm^3, since they interact so weakly, they have not been detected directly (so far).

Neutrini are observed' indirectly by their gravitational effects:

- They contribute to the expansion of the early Universe which is mainly relevant for the helium-4 abundance
  $\Rightarrow$ N_ν (number of species of relativistic neutrini at $T \simeq 0.1$MeV).



(Sarkar et al. '06)

Abundance of relativistic particles relativiste

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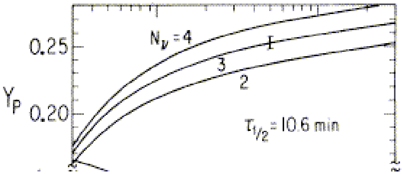

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$$\Rightarrow \quad \boxed{N_\nu \simeq 3 \pm 1}$$

- This limit applies to any species of relativistic particles with thermal abundance at $T \simeq 0.1$MeV.

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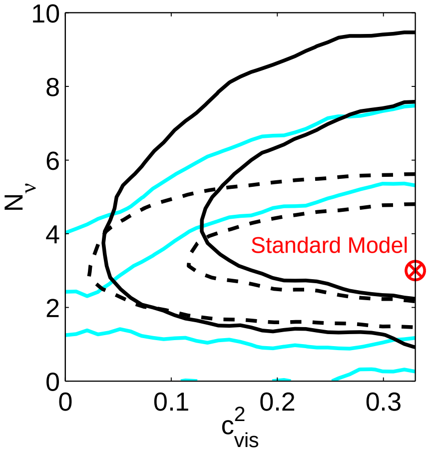
($c_{vis} = 0$ fluide parfait, $c_{vis}^2 = 1/3$, collisionless relativistic particles.)



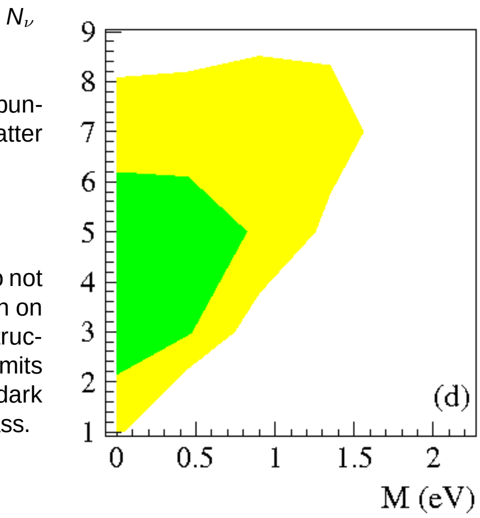
(Melchiorri & Trotta, 2004)

Massive neutrini with thermal abundance contribute to the dark matter density,

$$\Omega_{m\nu} h^2 = N_\nu \frac{m_\nu}{94\mathrm{eV}.}$$

Since they are very light, they do not participate to structure formation on small scales. Observations of structure at small scales therefore limits the contribution of neutrini to dark matter which constains their mass.

$$m_\nu \leq 1\mathrm{eV}$$



(Crotty et al. 2004)

Phase transitions: confinement, electroweak transition

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Observational consequences (so far unconfirmed):
If the transitions are second order or only a cross over, as is expected in the standard model, they probably do not leave observable traces in the Universe. However, if they are first order (e.g. if the neutrino chemical potential is large (QCD) or if the Higgs sector is non-standard (EW)), the transition proceeds via bubble nucleation leading to MHD turbulence in the ambient plasma (very high conductivity and Reynolds numbers).

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- magnetic fields

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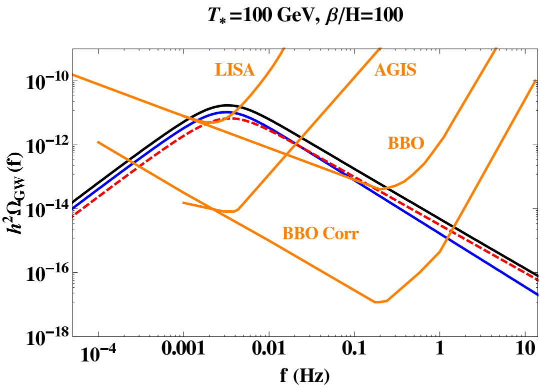
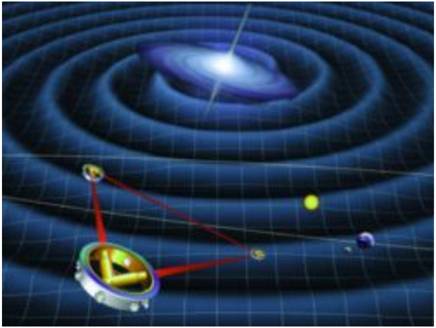
Parity violation during the transition can lead to helical magnetic field which can become large scale coherent seeds for the observed magnetic fields in galaxies and clusters (see student talk by Elisa Fenu).

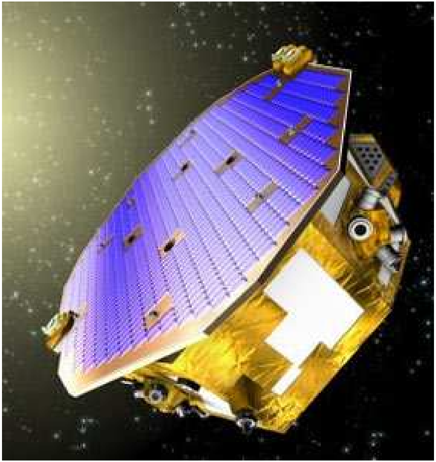
The gravitational wave background generated by MHD turbulence during a first order phase transition might be observable with LISA.
(Caprini, Durrer & Servant, 2009)



The satellite LISA



Le LISA satellite projet (artistic impression). Launch >2017.



The LISA pathfinder satellite (the real thing). Launch planned 2011.

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With small variations of the standard model of particle physics one can obtain that the EW phase transition is first order and therefore proceeds out of thermal equilibrium (in the bubble walls). This can yield a baryon-asymmetry of the right order of magnitude:

$$\frac{n_B - \bar{n}_B}{n_B}(t_{ew}) \simeq \frac{n_B(t_0)}{n_\gamma(t_0)} \simeq 10^{-10}$$

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But inflation has also other consequences:

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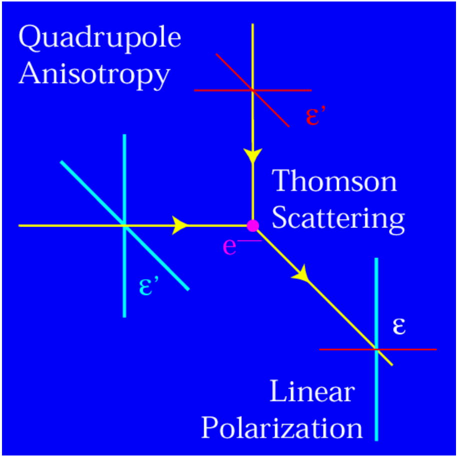
Density perturbations produce only one type of polarisation (E) while gravitational waves produce also a second type (B).

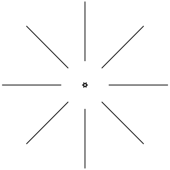
Polarization of the CMB

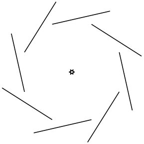


For photons with polarisation in the scattering plane the cross section is suppressed by a factor $\cos^2\theta$.

$\Rightarrow$ A quadrupole anisotropy in the photon distribution leads to polarisation.

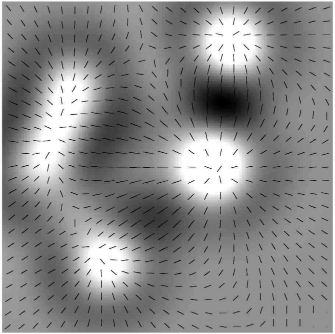
The Planck satellite

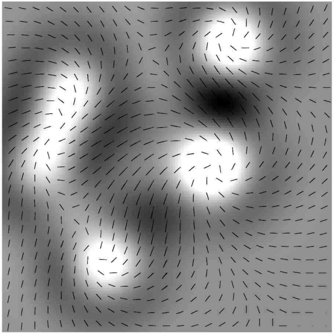




pure E-polarisation (scalar perts. & grav. waves)

pure B-polarisation (only grav. waves)





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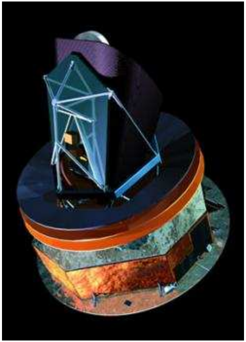
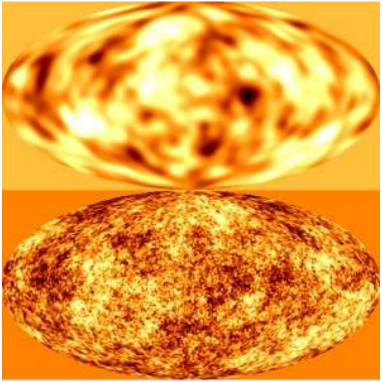
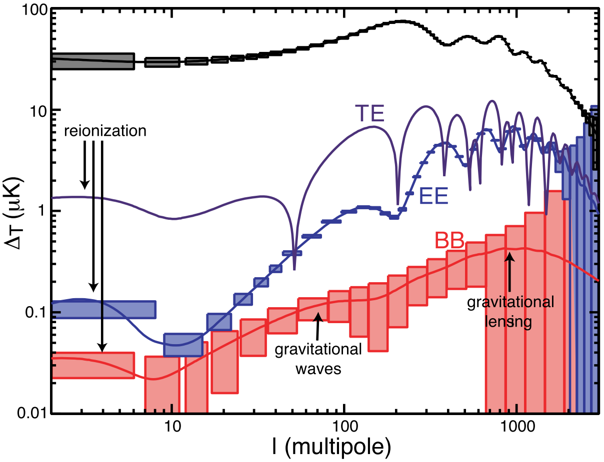
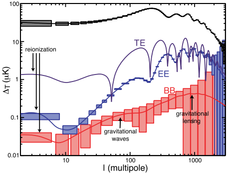


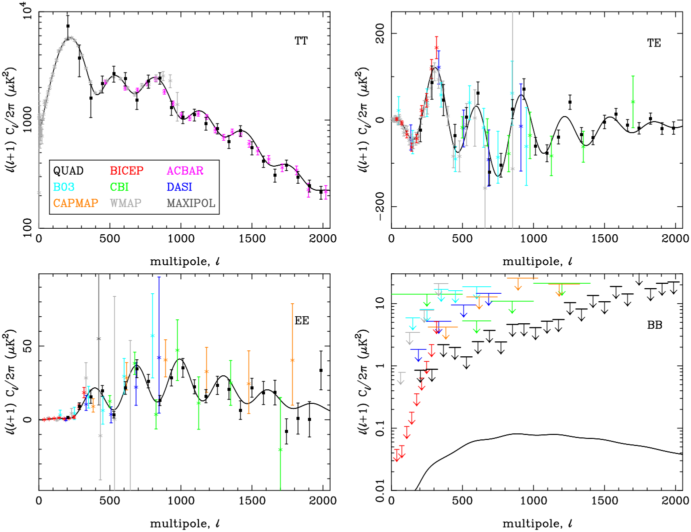


The resolution of Planck compared to COBE.



Planck forecast





Planck forecast

Present data (Pryke et al., 2009).

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