Cosmology III : The Universe as a high energy physics laboratory

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Contents

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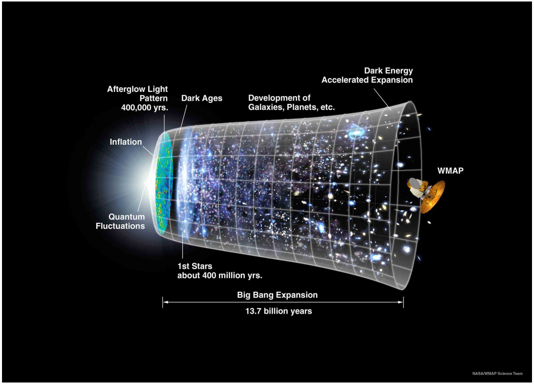

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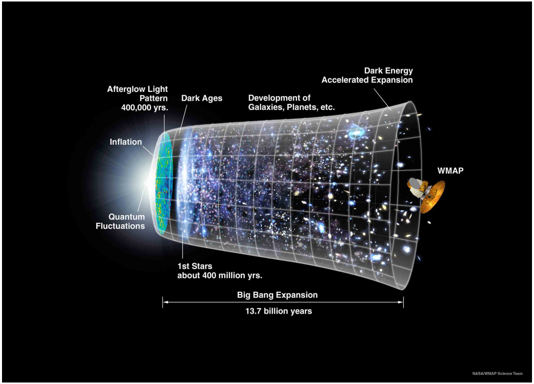

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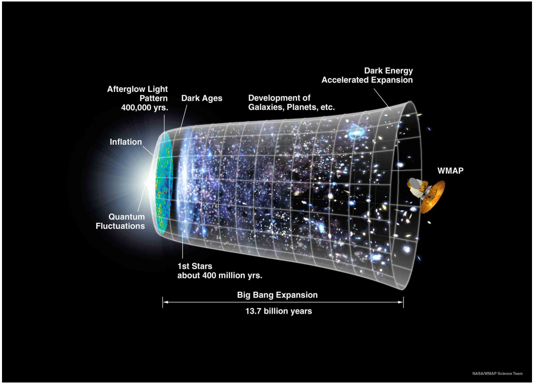

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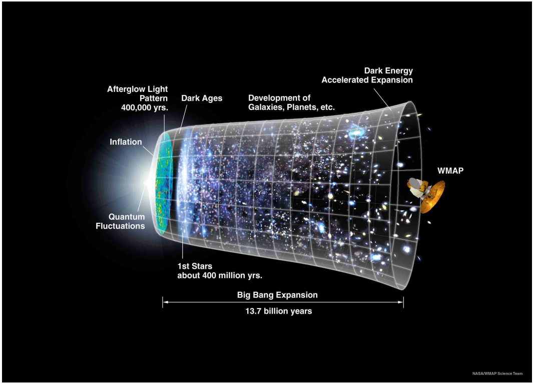

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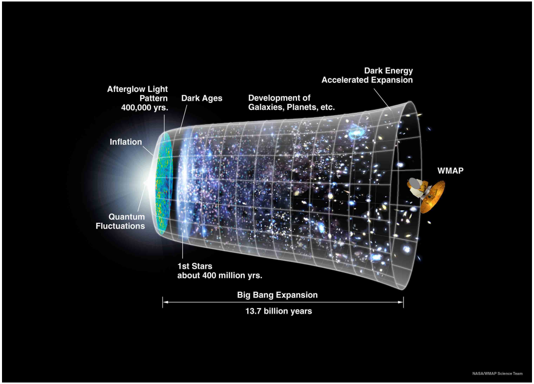

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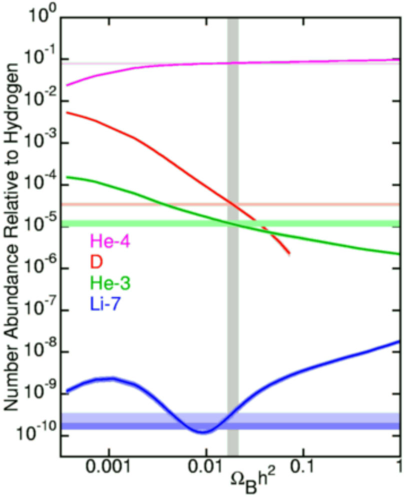
A $T_{\rm nuc} \simeq 0.08$MeV $\simeq 10^9$K Deuterium $(p + n)$ becomes stable. At this moment virtually all the neutrons present in the Universe are 'burned' into He^4. Only traces of Deuterium, Helium^3 and Lithium^7 remain. Their abundance depends strongly on the baryon density.



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- Later, at $T \simeq 0.5\text{MeV}$, electrons and positrons decay into photons and heat up the photons but not the decoupled neutrinos.
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- But even if these neutrinos have a density of about 300 particles per cm^3 they have not been detected directly so far due to their extremely weak interaction.

Abundance of relativistic particles

Neutrinos are however 'observed' indirectly by their gravitational effects:

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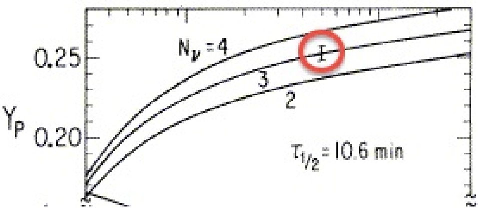

(Sarkar et al. '06)

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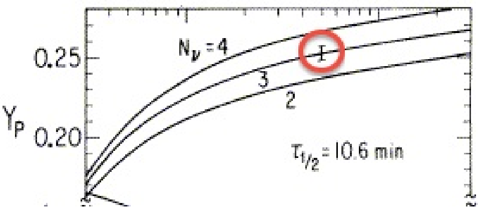

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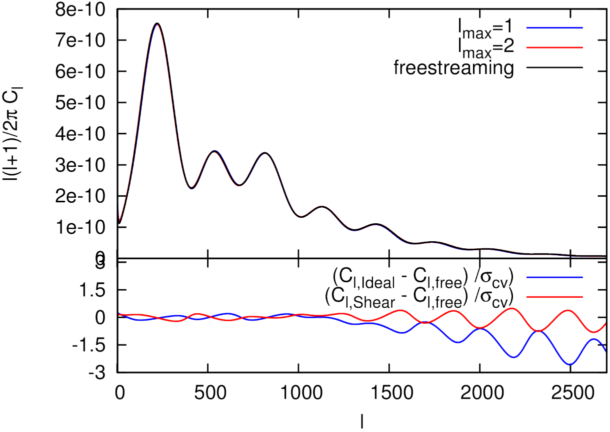
$$\Rightarrow \quad \boxed{N_\nu \simeq 3 \pm 1}$$

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

Neutrinos in the CMB

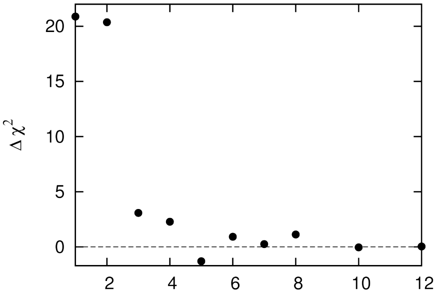
Neutrinos also contribute to the anisotropies of the CMB where one can even mesure the consequence of the fact that neutrinos are not a perfect fluid but collisionless particles.



(Sellentin & Durrer, 2015)

Neutrinos in the CMB

The CMB cannot be fit with neutrino's which are either a perfect fluid or a fluid with anisotropic stress.



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The probability that the fluid model is described by this data is

$$\exp(\Delta\chi^2/2) \simeq 3.7 \times 10^{-5}$$

times smaller than the probability that the data is described by free streaming neutrinos.

Neutrino mass

Oscillation experiments request (see course by B. Kayser): $\sum_{\nu_i} m_{\nu_i} > 0.057\text{eV}$.
Oscillation experiments measure mass differences; cosmological observations are mainly sensitive to the sum neutrino masses.
Massive neutrinos contribute to the dark matter density,

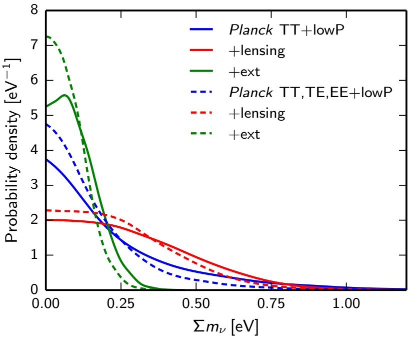
$$\Omega_{m\nu} h^2 = \frac{\sum_{\nu_i} m_{\nu_i}}{94\text{eV}.}$$

As they are very light, the cannot form small scale structure: Observations of small scale structure limit neutrinos masses.

$\sum m_\nu < 0.49\text{eV}$ (95%)
(Planck only)

$\sum m_\nu < 0.194\text{eV}$ (95%)
(Planck +BAO + SN1a+H_0)

$\sum m_\nu < 0.15\text{eV}$ (95%)
(SDSSIII/BOSS (Ly-α)
+Planck (2013))



Neutrino number, sterile neutrinos

The number of relativistic degrees of freedom, $N_{\rm eff}$ which decouple before $e^\pm$ annihilation is defined by

$$\rho_{\rm rel} = \left[N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} + 1\right]\rho_\gamma$$

In the standard model $N_{\rm eff} = 3.046$. The Planck + BAO data requires

$$N_{\rm eff} = 3.04 \pm 0.18 \qquad (68\%)$$

Even with the Planck data alone, $\Delta N_{\rm eff} \geq 1$ is excluded at more than 4σ.

An additional sterile neutrino with $\Delta N_{\rm eff} \simeq 0.3$ and mass $0.5\ {\rm eV} \lesssim m_{\nu {\rm sterile}} \lesssim 5\ {\rm eV}$ can actually reduce the tension of Planck with lensing data (which has a lower σ_8).

A much heavier, $\sim$ keV, sterile neutrino could be warm dark matter.

Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

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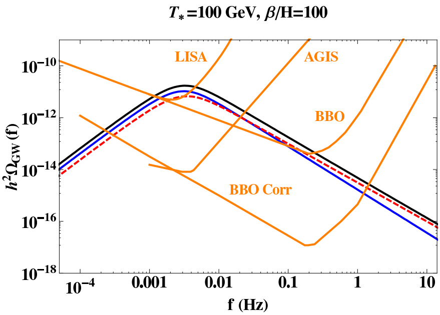
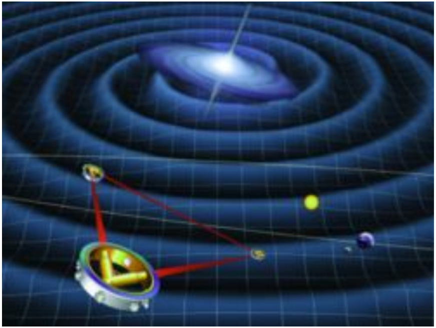


(Caprini, Durrer & Servant, 2009)

The satellite eLISA



The eLISA satellite projet (artist's impression). Launch >2018.

The LISA pathfinder satellite (the real thing). Scheduled for launch later this year.

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With small variations of the standard model particle physics can obtain a 1st order electroweak phase transition which would lead to out of equilibrium processes and allow the generation of a baryon asymmetry.

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But an inflationary phase has also other consequences...

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Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

But a quantum field fluctuates a bit even in vacuum (i.e. in absence of particles).

During an inflationary phase, these quantum fluctuations are excited (enhanced) by the rapid expansion of the Universe when they become larger than the Hubble scale during inflation.

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The large scale structure of the Universe has been initiated by quantum fluctuations.

Fluctuations from inflation in the CMB

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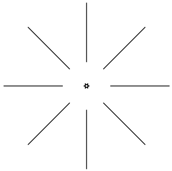
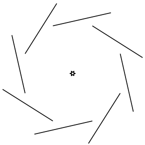
Density perturbations (scalars) generate only one type of polarisation (E) while gravitational waves (tensor perturbations) generate also a second type (B).



pure E-polarisation (scalars and grav. waves)



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Polarisation of the CMB

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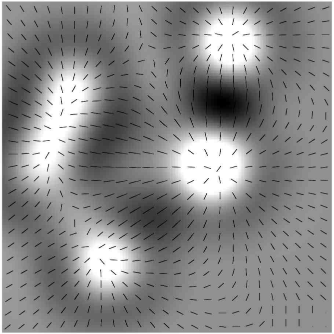

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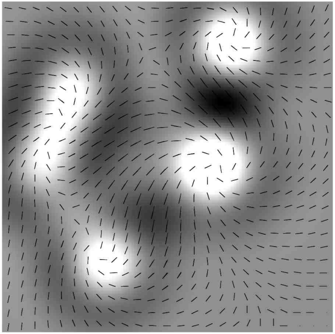
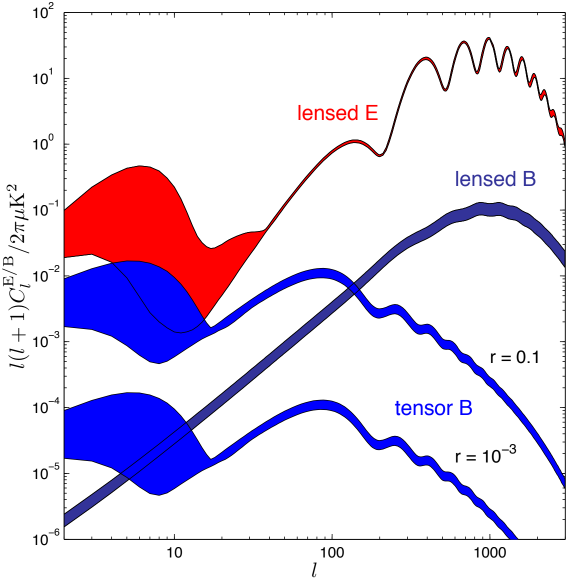


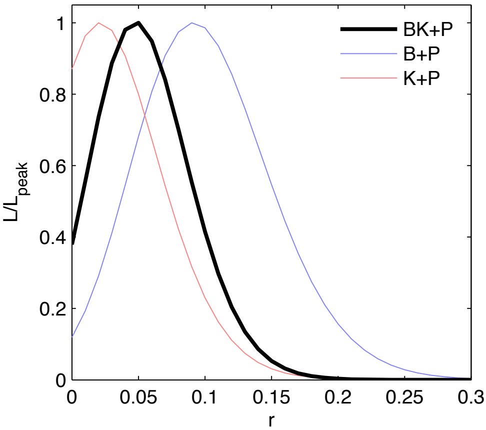
The discovery of B-polarisation is considered the 'holy grail' of inflation. It determines the energy scale of inflation.

B-polarisation in the CMB from tensors & lensing



Challinor & Lewis (2006)

Experimental limits



(Bicep-Keck-Planck, 2015)

Limits on the tensor to scalar ratio $r = A_T/A_S$ from observations.

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- And we would see a quantum effect of the gravitational field,
  $\Rightarrow$ a 'glimpse' of quantum gravity.

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Cosmology seems to be one of the most promising directions to give us access to the physics at very high energies, $E \gg 10\text{TeV}$.