The CMB and Particle Physics

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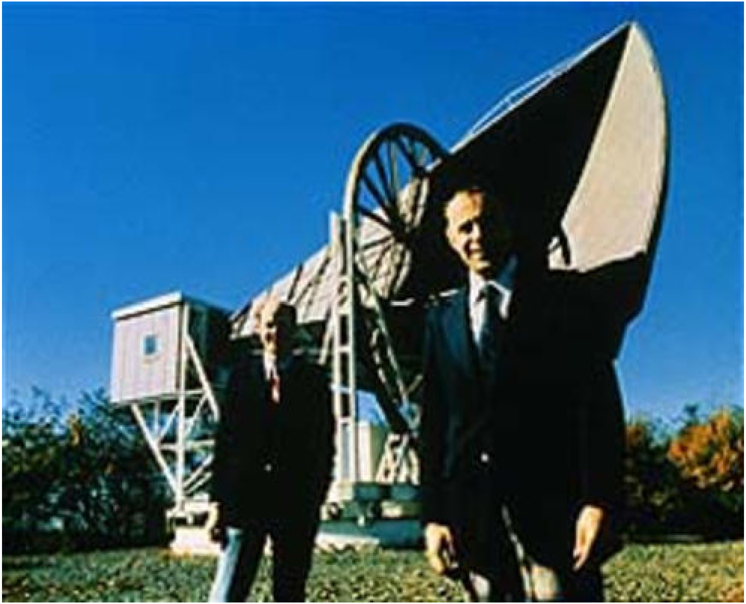
- Dark matter , dark energy
- Neutrinos
- Contains the cleanest information about inflation, the ultimate high energy laboratory
- The CMB is a beautiful immensely rich dataset which every real physicist must admire.

The cosmic microwave background discovery 1965 by Penzias & Wilson



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- This corresponds to about 400 photons per cm^3 with typical energy of $E_\gamma = kT_0 \simeq 2.3 \times 10^{-4}$eV $\simeq$ 150GHz ($\lambda \simeq 0.2$cm). This is the observed CMB.
- At $T > 9300$K$\simeq 0.8$eV the Universe was 'radiation dominated', i.e. its energy density was dominated by the contribution from these photons (and 3 species of relativistic neutrinos which made up about 35%). Hence initial fluctuations in the energy density of the Universe should be imprinted as fluctuations in the CMB temperature.

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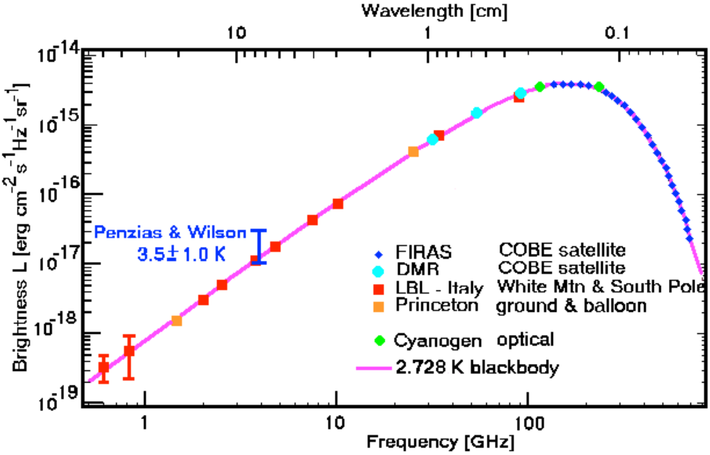
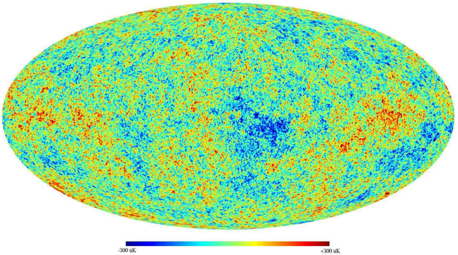
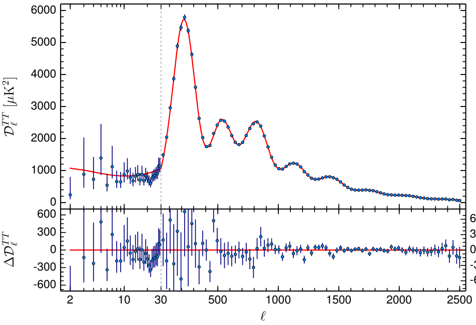
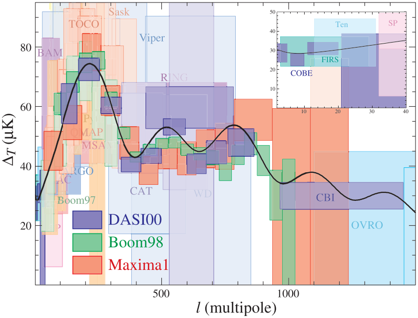




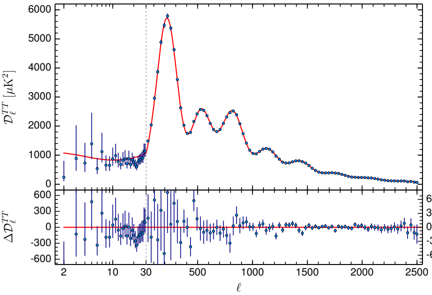
$T_0 = 2.7255K$
$\Delta T(\mathbf{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{n})$
$C_\ell = \langle |a_{\ell m}|^2 \rangle,$
$D_\ell = \ell(\ell+1)C_\ell/(2\pi)$



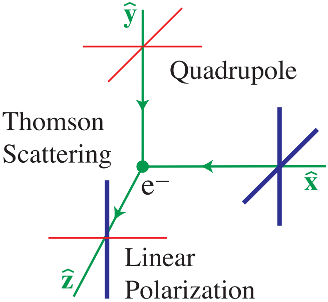
From the Planck Collaboration
Planck Results XIII (2015)
arXiv:1502.01589

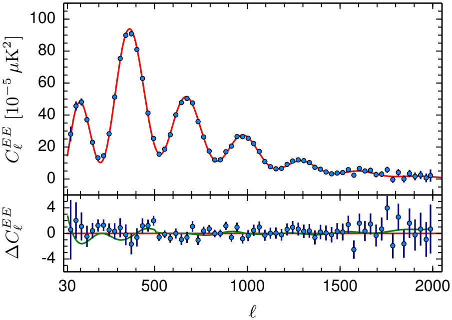


(Hu & Dodelson, 2002)



(Planck Collaboration 2015)





Thomson scattering depends on polarisation.
A local quadrupole induces linear polarisation, $Q \neq 0$ and $U \neq 0$.

The physics of CMB fluctuations

- In the radiation dominated Universe small density fluctuations perform acoustic oscillations at constant amplitude, $\delta \propto \cos(k \int c_s d\tau)$. On large scales, the gravitational potential (metric fluctuation) is constant, on 'sub-Hubble scales', $k\tau > 1$ it decays like a^{-2}.

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- The wavelength corresponding to the first acoustic peak is $\lambda_* = 2\pi/k_*$ with $k_*\int_0^{\tau_*} c_s d\tau = \pi$. In a matter-radiation Universe this gives ($\omega_x = \Omega_x h^2$)

$$\frac{H_0}{h}(1+z_*)\lambda_* = \frac{4}{\sqrt{3r\omega_m}}\log\left(\frac{\sqrt{1+z_*+r}+\sqrt{\frac{(1+z_*)r\omega_r}{\omega_m}+r}}{\sqrt{1+z_*}\left(1+\sqrt{\frac{r\omega_r}{\omega_m}}\right)}\right), \qquad r = \frac{3\omega_b}{4\omega_\gamma}.$$

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- On small scales fluctuations are damped by free streaming (Silk damping).
- In a Λ-dominated Universe δ is constant and the gravitational potential decays.

The angle onto which the scale k_* is projected depends on the angular diameter distance to the CMB, $\theta_* = \lambda_*/(2d_A(z_*))$ This is the best measured quantity of the CMB, with a relative error of about 3×10^{-4}

$$\theta_s = \frac{r_s}{d_A(z_s)} = (1.04077 \pm 0.00032) \times 10^{-2} .$$

(Planck Collaboration: Planck results 2015 XIII)

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The distance to the CMB is given by

$$(1+z_*)d_A(z_*) = \int_0^{z_*} H(z)^{-1} dz = \frac{h}{H_0}\int_0^{z_*} \frac{1}{\sqrt{\omega_m(1+z)^3 + \omega_K(1+z)^2 + \omega_x(z)}} dz$$

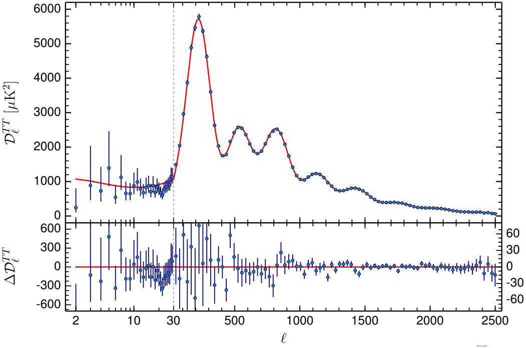
Cosmological parameters

The CMB fluctuations into a direction **n** in the instant decoupling approximation are given by

$$\frac{\Delta T}{T}(\mathbf{n}) = \left[\frac{1}{4}D_g + \mathbf{n}\cdot\mathbf{V} + \Psi + \Phi\right](\mathbf{n},\tau_*) + \int_{\tau_*}^{\tau_0}\partial_\tau(\Psi+\Phi)ds\,.$$

The power spectrum C_ℓ of CMB fluctuations is given by

$$\left\langle \frac{\Delta T}{T}(\mathbf{n})\frac{\Delta T}{T}(\mathbf{n}')\right\rangle = \frac{1}{4\pi}\sum_\ell(2\ell+1)C_\ell P_\ell(\mathbf{n}\cdot\mathbf{n}')$$



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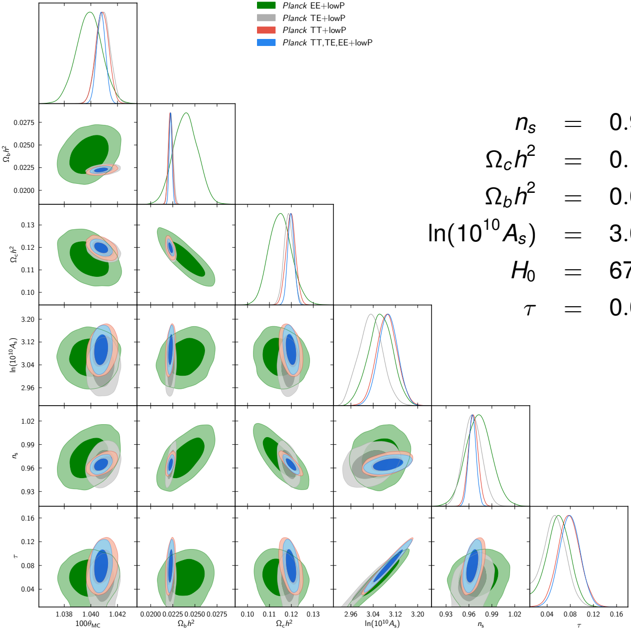
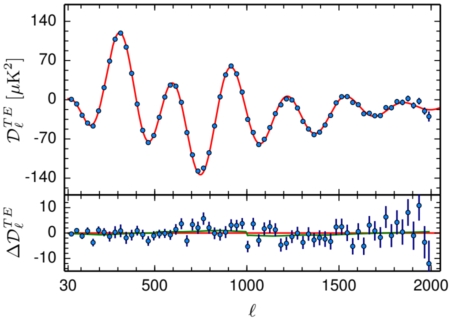
- optical depth to reionization τ

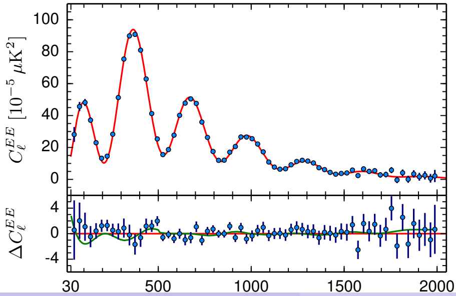


$$n_s = 0.9645 \pm 0.0049$$
$$\Omega_c h^2 = 0.1198 \pm 0.0015$$
$$\Omega_b h^2 = 0.02225 \pm 0.00016$$
$$\ln(10^{10} A_s) = 3.094 \pm 0.034$$
$$H_0 = 67.27 \pm 0.66$$
$$\tau = 0.079 \pm 0.017$$



T-E correlation

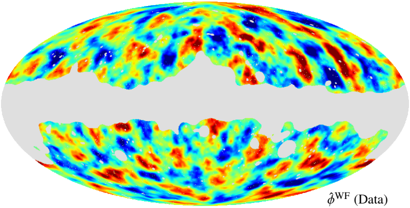
$$\mathcal{D}_\ell^{TE} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{TE}$$

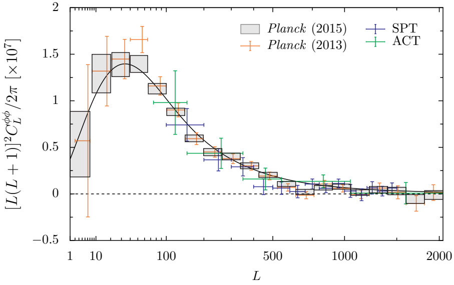


E-E spectrum

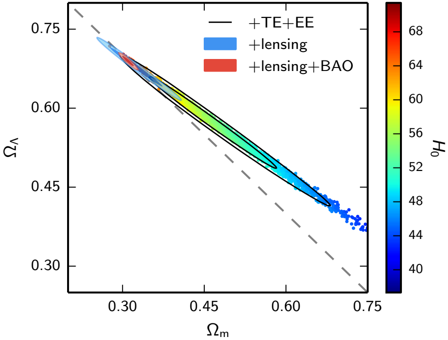
$$\mathcal{D}_\ell^{EE} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{EE}$$

$$\phi(\mathbf{n}) = -2\int_0^{r_*} dr \frac{(r_* - r)}{r_* r}\Psi(r\mathbf{n}, \tau_0 - r)$$





Lensing breaks degeneracies

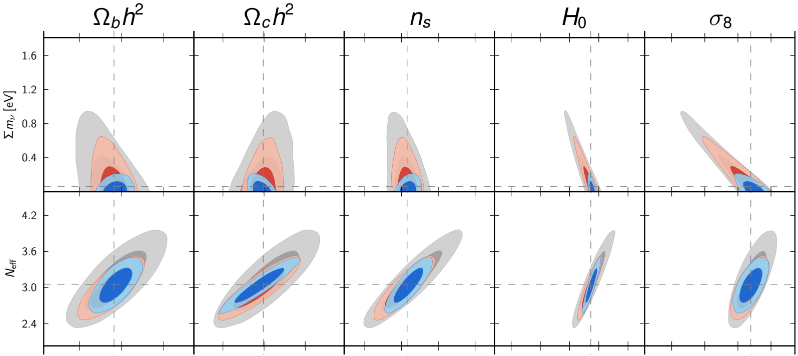


(Planck 1502.01589)

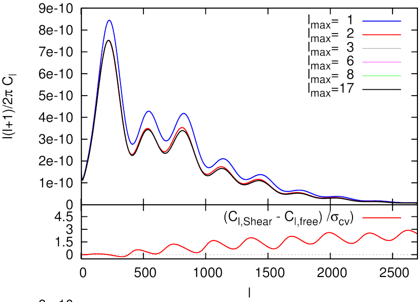
$$\Omega_K = \begin{array}{lll} -0.040 \pm 0.04 & \text{(TT,EE,TE)} & \\ -0.005 \pm 0.016 & \text{add lensing} & 95\% \\ -0.000 \pm 0.005 & \text{add BAO's} & \end{array}$$

Single extension best constraints:

$$N_{eff} = 3.04 \pm 0.2\ (0.18) \qquad \text{Planck (+ BAO)}$$
$$\Sigma_i m_i = 0.49\ (0.17)\ \mathrm{eV} \qquad 95\% \quad \text{Planck (+ BAO)}$$

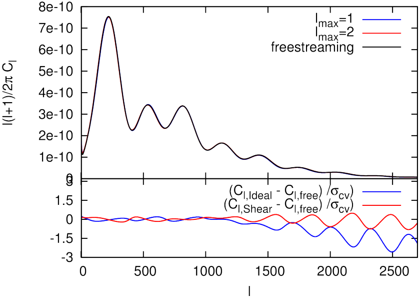


Cosmic neutrinos are collisionless (E. Sellentin & RD arXiv:1412.6427)

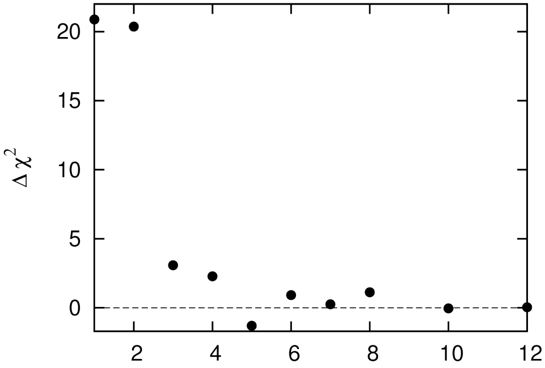


Treating neutrinos as perfect fluid or viscous fluid affects CMB spectra significantly.

(Here fixing the other parameters.)



Marginalizing over the other parameters



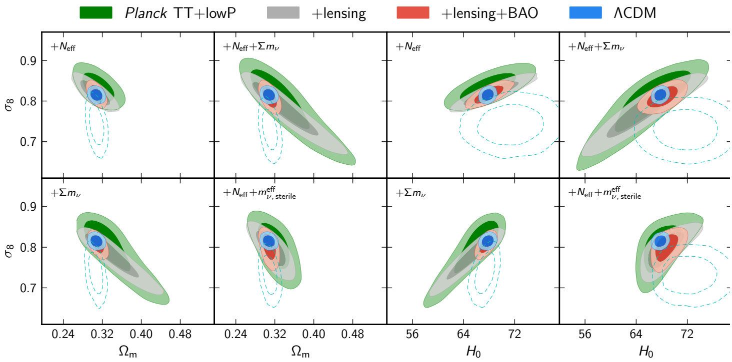
20
15
10
5
0
$\Delta\chi^2$
2
4
6
8
10
12

Sterile neutrinos

$$m_{\nu,\mathrm{sterile}}^{\mathrm{eff}} = 94.1\Omega_{\nu,\mathrm{sterile}}\mathrm{eV}.$$

$$m_{\nu,\mathrm{sterile}}^{\mathrm{eff}} = \Delta N_{\nu,\mathrm{sterile}}^{\mathrm{eff}} m_{\nu,\mathrm{sterile}}^{\mathrm{thermal}}, \text{ cut: } m_{\nu,\mathrm{sterile}}^{\mathrm{thermal}} < 10\mathrm{eV}.$$

$$\begin{array}{lcr} \Delta N_{\nu,\mathrm{sterile}}^{\mathrm{eff}} & < & 0.7 \\ m_{\nu,\mathrm{sterile}}^{\mathrm{eff}} & < & 0.52 \end{array} \quad 95\% \quad (\mathit{Planck} + \mathit{gal.} - \mathit{lensing} + \mathit{BAO})$$



Inflation

The fluctuations in the CMB stem from a very early phase of inflationary expansion of the Universe. They contain inform,ation on the physics of this very hot early phase.

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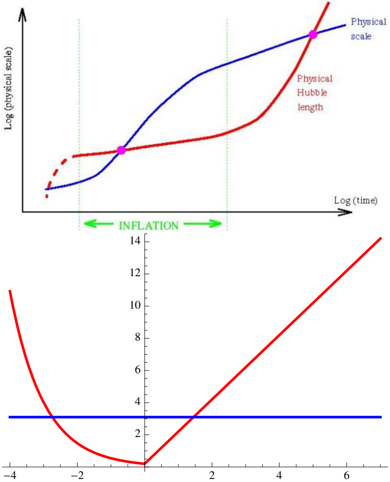
- When inflation ends the inflaton field decays into the standard model particles which thermalize and generate a hot thermal Universe.
- During inflation quantum fluctuations of both, the inflaton and of the metric are stretched and amplified.

Inflation

Once a quantum mode 'exits the horizon' $\lambda > H_*^{-1}$, they 'freeze in' as classical fluctuations of the energy density and of the metric with a nearly scale invariant spectrum.

Or even simpler: A wave function scatters at a time dependent potential and gets amplified.

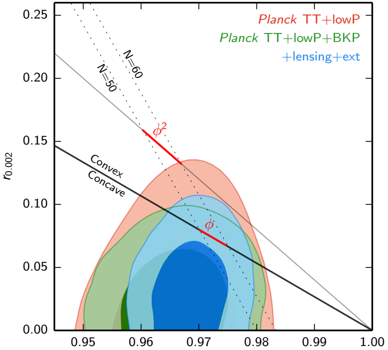


Inflation

Slow-roll inflationary models can be described with a few (mainly 2) slow-roll parameters and the Hubble scale during inflation, H_*. The scalar and tensor spectra from inflation are given by

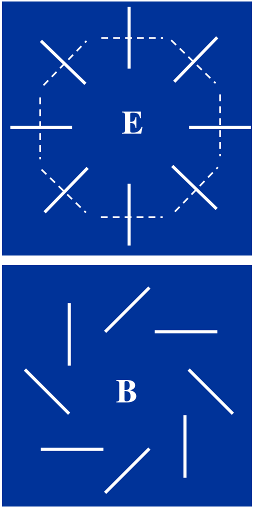
$$P_\zeta(k) \simeq \frac{H_*^2}{\epsilon M_p^2} k^{-6\epsilon+2\eta} \simeq 12.2 \times 10^{-9} \qquad P_h \simeq \frac{H_*^2}{M_p^2} k^{-2\epsilon} \simeq \left(\frac{E_*}{M_p}\right)^4$$

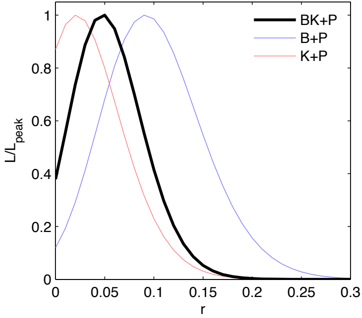
$$E_* = \left(\frac{r}{0.1}\right)^{1/4} 1.7 \times 10^{16}\mathrm{GeV}$$



Tensor to scalar ratio

Tensor perturbations can generate B-polarisation.





Bicep2 – KeckArray – Planck
arXiv:1502.00612

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