The CMB and Particle Physics

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Why is the cosmic microwave background of interest for particle physicists?
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- Dark matter, dark energy
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- Neutrinos
Introduction

Why is the cosmic microwave background of interest for particle physicists?

- Dark matter, dark energy
- Neutrinos
- Contains the cleanest information about inflation, the ultimate high energy laboratory
Why is the cosmic microwave background of interest for particle physicists?

- 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
The cosmic microwave background (CMB)

- The Universe is expanding. In the past it was much denser and hotter.
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At $T \simeq 3000\text{K}$ protons and electrons combined to neutral hydrogen. The photons became free and their distribution evolved simply by redshifting of the photon energies to a thermal distribution with $T_0 = 2.7255 \pm 0.0006\text{K}$ today.
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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 $\simeq 150$GHz ($\lambda \simeq 0.2$cm). This is the observed CMB.
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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 $\simeq 150$GHz ($\lambda \simeq 0.2$cm). This is the observed CMB.
- At $T > 9300K \simeq 0.8$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.
The cosmic microwave background (CMB)

Penzias & Wilson
3.5 ± 1.0 K

Brightness $L$ [erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$]

Wavelength [cm]

Frequency [GHz]

COBE satellite
DMR
LBL - Italy
Princeton
Cyanogen

FIRAS
White Mtn & South Pole
ground & balloon

$2.728$ K blackbody
Fluctuations in the CMB

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

From the Planck Collaboration
Planck Results XIII (2015)
arXiv:1502.01589
The cosmic microwave background (CMB)

(Hu & Dodelson, 2002)  (Planck Collaboration 2015)
Polarisation of the CMB

Thomson scattering depends on polarisation. A local quadrupole induces linear polarisation, $Q \neq 0$ and $U \neq 0$. 
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{3} r \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), \quad r = \frac{3\omega_b}{4\omega_\gamma}.
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The physics of CMB fluctuations

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- In the matter dominated Universe density fluctuations grow $\delta \propto a$ and the gravitational potential remains constant.

- On small scales fluctuations are damped by free streaming (Silk damping).

- In a $\Lambda$-dominated Universe $\delta$ is constant and the gravitational potential decays.
The distance to the CMB

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 $3 \times 10^{-4}$

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

(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 \( \mathbf{n} \) in the instant decoupling approximation are given by

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

The power spectrum \( C_\ell \) of CMB fluctuations is given by

\[
\left\langle \frac{\Delta T}{T}(\mathbf{n}) \frac{\Delta T}{T}(\mathbf{n}') \right\rangle = \frac{1}{4\pi} \sum_\ell (2\ell + 1) C_\ell P_\ell(\mathbf{n} \cdot \mathbf{n}').
\]
The Planck ’base’ model

- Curvature $K = 0$

- No tensor perturbations, $r = 0$

- Three species of thermal neutrinos, $N_{\text{eff}} = 3.046$ with temperature $T_{\nu} = \left(\frac{4}{11}\right)^{1/3} T_{0}$

- 2 neutrino species are massless and the third has $m_3 = 0.06\text{eV}$ such that $\sum_i m_i = 0.06\text{eV}$.

- Helium fraction $Y_p = \frac{n_{\text{He}}}{n_{\text{b}}}$ is calculated from $N_{\text{eff}}$ and $\omega_b$.
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- Baryon density $\omega_b = \Omega_b h^2$
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- Baryon density \( \omega_b = \Omega_b h^2 \)
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- Present value of Hubble parameter \( H_0 = 100h \text{km/sec/Mpc} \) \( (\Omega_\Lambda = 1 - (\omega_b + \omega_c)/h^2) \).
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- Present value of Hubble parameter $H_0 = 100 h \text{km/sec/Mpc}$ ($\Omega_\Lambda = 1 - (\omega_b + \omega_c) / h^2$).
- Optical depth to reionization $\tau$
$n_S = 0.9645 \pm 0.0049$

$\Omega_c h^2 = 0.1198 \pm 0.0015$

$\Omega_b h^2 = 0.02225 \pm 0.00016$

$\ln(10^{10} A_S) = 3.094 \pm 0.034$

$H_0 = 67.27 \pm 0.66$

$\tau = 0.079 \pm 0.017$
Polarization spectra (Planck 2015 arXiv:1502.01589)

Fig. 3. Frequency-averaged TE and EE spectra (without fitting for T-P leakage). The theoretical TE and EE spectra plotted in the upper panel of each plot are computed from the Planck TT + lowP best-fit model of Fig. 1. Residuals with respect to this theoretical model are shown in the lower panel in each plot. The error bars show ±1 errors. The green lines in the lower panels show the best-fit temperature-to-polarization leakage model of Eqs. (11a) and (11b), fitted separately to the TE and EE spectra.

T-E correlation

\[ D_\ell^{TE} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{TE} \]

E-E spectrum

\[ D_\ell^{EE} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{EE} \]
\[ \phi(n) = -2 \int_0^{r_*} dr \frac{(r_* - r)}{r_* r} \psi(r_n, \tau_0 - r) \]
Lensing breaks degeneracies

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

(Planck 1502.01589)
Single extension best constraints:

\[ N_{\text{eff}} = 3.04 \pm 0.2 \ (0.18) \quad \text{Planck (+ BAO)} \]
\[ \Sigma_i m_i = 0.49 \ (0.17) \text{ eV} \quad 95\% \quad \text{Planck (+ BAO)} \]
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
Cosmic neutrinos are collisionless

(E. Sellentin & RD arXiv:1412.6427)
Sterile neutrinos

\[ m_{\nu, \text{sterile}}^{\text{eff}} = 94.1 \Omega_{\nu, \text{sterile}} \text{eV}. \]

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

\[ \Delta N_{\nu, \text{sterile}}^{\text{eff}} < 0.7, \quad 95\% \quad (\text{Planck} + \text{gal.} - \text{lensing} + \text{BAO}) \]

\[ m_{\nu, \text{sterile}}^{\text{eff}} < 0.52 \]

\[ \sigma_8 \]

\[ \Omega_m \]

\[ H_0 \]

\[ \Lambda \text{CDM} \]

\[ \text{Planck TT+lowP} \]

\[ +N_{\text{eff}} \]

\[ +N_{\text{eff}} + \Sigma m_{\nu} \]

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

- Inflation is a phase of very fast expansion during which the Universe becomes large and flat. This can be achieved with the energy density of a scalar field if it is dominated by the scalar field potential, $V$. 
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- During inflation quantum fluctuations of both, the inflaton and of the metric are stretched and amplified.
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

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

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

![Diagram showing CMB anisotropies with curves for different models and parameters.](image-url)
Tensor to scalar ratio

Tensor perturbations can generate B-polarisation.

Bicep2 – KeckArray – Planck
arXiv:1502.00612
Conclusion

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Apart from addressing the above questions it can also be used to test the cosmic neutrinos.
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- Cosmological perturbations are generated by quantum excitation in a time dependent background.