The theory of the Cosmic Microwave Background, CMB

Ruth Durrer

Département de Physique Théorique and CAP, Université de Genève

UNIVERSITÉ DE GENÈVE

Center for Astroparticle Physics GENEVA

Mainz, March 2017

The theory of the CMB is quite simple and elegant. But the most amazing success story is how it helped us to determine the parameters describing the present Universe with 1% precision. Virtually all precise numbers in cosmology come from CMB observations.

Introduction

The theory of the CMB is quite simple and elegant. But the most amazing success story is how it helped us to determine the parameters describing the present Universe with 1% precision. Virtually all precise numbers in cosmology come from CMB observations.

Basic physics determining CMB anisotropies:

- Decoupling and photon propagation in a perturbed Friedmann universe

Introduction

The theory of the CMB is quite simple and elegant. But the most amazing success story is how it helped us to determine the parameters describing the present Universe with 1% precision. Virtually all precise numbers in cosmology come from CMB observations.

Basic physics determining CMB anisotropies:

- Decoupling and photon propagation in a perturbed Friedmann universe
- Polarization

The theory of the CMB is quite simple and elegant. But the most amazing success story is how it helped us to determine the parameters describing the present Universe with 1% precision. Virtually all precise numbers in cosmology come from CMB observations.

Basic physics determining CMB anisotropies:

- Decoupling and photon propagation in a perturbed Friedmann universe
- Polarization
- Lensing

Introduction

The theory of the CMB is quite simple and elegant. But the most amazing success story is how it helped us to determine the parameters describing the present Universe with 1% precision. Virtually all precise numbers in cosmology come from CMB observations.

Basic physics determining CMB anisotropies:

- Decoupling and photon propagation in a perturbed Friedmann universe
- Polarization
- Lensing
- Parameter dependence

Introduction

The theory of the CMB is quite simple and elegant. But the most amazing success story is how it helped us to determine the parameters describing the present Universe with 1% precision. Virtually all precise numbers in cosmology come from CMB observations.

Basic physics determining CMB anisotropies:

- Decoupling and photon propagation in a perturbed Friedmann universe
- Polarization
- Lensing
- Parameter dependence
- Beyond present analyses

Introduction

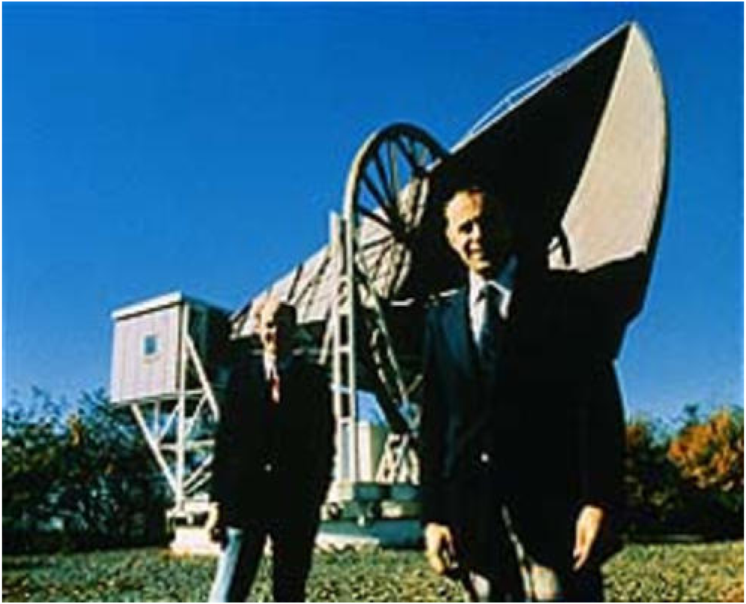
The theory of the CMB is quite simple and elegant. But the most amazing success story is how it helped us to determine the parameters describing the present Universe with 1% precision. Virtually all precise numbers in cosmology come from CMB observations.

Basic physics determining CMB anisotropies:

- Decoupling and photon propagation in a perturbed Friedmann universe
- Polarization
- Lensing
- Parameter dependence
- Beyond present analyses

Ruth Durrer, The Cosmic Microwave Background, Cambridge University Press, 2008

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.

The cosmic microwave background (CMB)

- The Universe is expanding. In the past it was much denser and hotter.
- At $T > 3000$K hydrogen was ionised and the 'cosmic plasma' of protons, electrons and photons was strongly coupled by Thomson scattering and in thermal equilibrium.

The cosmic microwave background (CMB)

- The Universe is expanding. In the past it was much denser and hotter.
- At $T > 3000$K hydrogen was ionised and the 'cosmic plasma' of protons, electrons and photons was strongly coupled by Thomson scattering and in thermal equilibrium.
- At $T \simeq 3000$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 $T_0 = 2.7255 \pm 0.0006$K today.

The cosmic microwave background (CMB)

- The Universe is expanding. In the past it was much denser and hotter.
- At $T > 3000$K hydrogen was ionised and the 'cosmic plasma' of protons, electrons and photons was strongly coupled by Thomson scattering and in thermal equilibrium.
- At $T \simeq 3000$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 $T_0 = 2.7255 \pm 0.0006$K today.
- This corresponds to about 400 photons per cm^3 with typical energy of $E_\gamma = kT_0 \simeq 2.3 \times 10^{-4}$eV $\simeq 140$GHz ($\lambda \simeq 0.25$cm). This is the observed CMB.

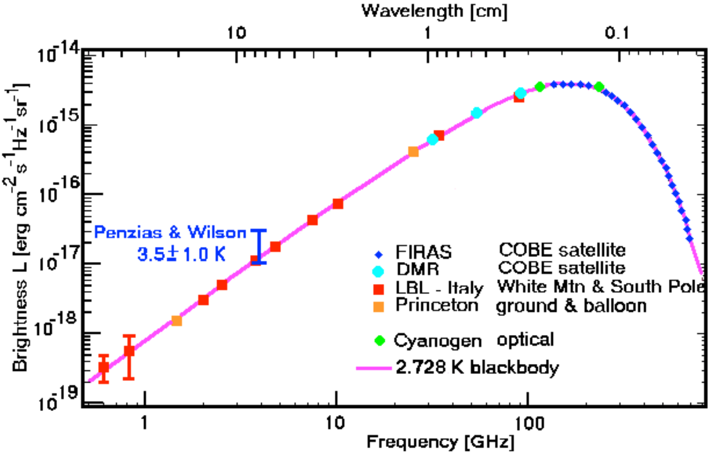
The cosmic microwave background (CMB)

- The Universe is expanding. In the past it was much denser and hotter.
- At $T > 3000$K hydrogen was ionised and the 'cosmic plasma' of protons, electrons and photons was strongly coupled by Thomson scattering and in thermal equilibrium.
- At $T \simeq 3000$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 $T_0 = 2.7255 \pm 0.0006$K today.
- This corresponds to about 400 photons per cm^3 with typical energy of $E_\gamma = kT_0 \simeq 2.3 \times 10^{-4}$eV $\simeq 140$GHz ($\lambda \simeq 0.25$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.

The cosmic microwave background (CMB)

- The Universe is expanding. In the past it was much denser and hotter.
- At $T > 3000$K hydrogen was ionised and the 'cosmic plasma' of protons, electrons and photons was strongly coupled by Thomson scattering and in thermal equilibrium.
- At $T \simeq 3000$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 $T_0 = 2.7255 \pm 0.0006$K today.
- This corresponds to about 400 photons per cm^3 with typical energy of $E_\gamma = kT_0 \simeq 2.3 \times 10^{-4}$eV $\simeq$ 140GHz ($\lambda \simeq 0.25$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.
- Much later, at $z \sim 7$–8 the Universe was re-ionized (probably due to uv radiation from star formation.

The cosmic microwave background (CMB)



Calculating CMB anisotropies

They are determined within linear perturbation theory. After decoupling, CMB photons move along perturbed geodesics:

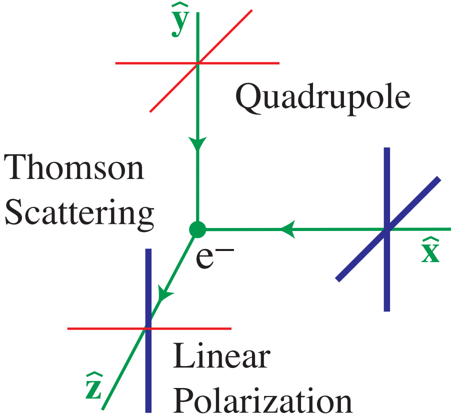
$$\delta n^0 = [h_{00} + h_{0j} n^j] - \frac{1}{2}\int_i^f \dot{h}_{\mu\nu} n^\mu n^\nu d\lambda$$

To first order in linear perturbation theory their energy shift (temperature shift) is (scalar perts.)

$$\frac{E_f}{E_i} = \frac{T_f}{T_i} = \frac{(n\cdot u)_f}{(n\cdot u)_i} = \frac{T_0}{T_{\rm dec}}\left\{1 + \left[\frac{1}{4}D_g^{(r)} + V_j^{(b)} n^j + \Phi + \Psi\right](x_{\rm dec}) + \int_{t_{\rm dec}}^{t_0} \partial_t(\Psi+\Phi)dt\right\}$$

To treat decoupling correctly one has to solve the perturbed Boltzmann equation for the photon distribution function, taking into account Thompson scattering. The main additional effects are:

- Silk damping on small scales
- Polarisation



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}.

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}.
- 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 ($\omega_x = \Omega_x h^2$)

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

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}.
- 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 ($\omega_x = \Omega_x h^2$)

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

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

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}.
- 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 ($\omega_x = \Omega_x h^2$)

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

- 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).

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}.
- 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 ($\omega_x = \Omega_x h^2$)

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

- 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 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 in cosmology, with a relative error of about 3×10^{-4}

$$\theta_s = \frac{r_s}{d_A(z_s)} = (1.04069 \pm 0.00031) \times 10^{-2} .$$

(Planck Collaboration: Planck results 2016 XLVI [1605.02985])

The distance to the CMB

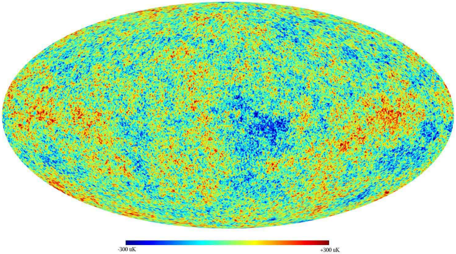
The angle onto which the scale k_* is projected depends on the angular diameter distance to the CMB, $\theta_* = \lambda_*/(2d_A(z_*)$ This is the best measured quantity in cosmology, with a relative error of about 3×10^{-4}

$$\theta_s = \frac{r_s}{d_A(z_s)} = (1.04069 \pm 0.00031) \times 10^{-2} \,.$$

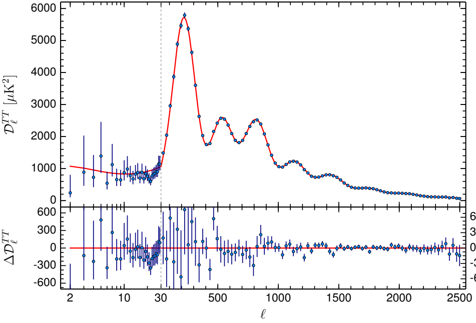
(Planck Collaboration: Planck results 2016 XLVI [1605.02985])

The distance to the CMB is given by

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



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



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

Polarisation

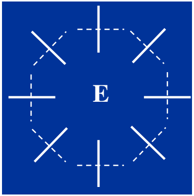
Polarisation defines a vector field on the CMB sky which is split into a gradient component called E-polarisation and a curl component called B-polarisation.

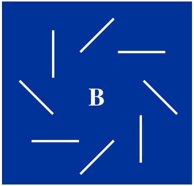
At first order, scalar perturbations only generate E-polarisation.

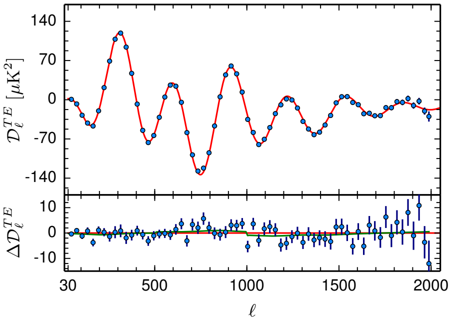
B-polarisation is generated by vector and tensor perturbations and by higher order scalar perturbations.

E-polarisation is correlated with temperature anisotropies.

B-polarisation has opposite parity to E polarisation and temperature anisotropies, hence in a parity conserving Universe $\langle EB \rangle = \langle TB \rangle = 0$

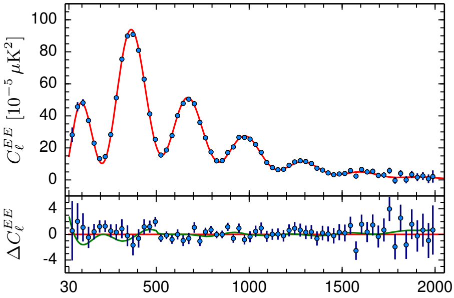






T-E correlation

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



E-E spectrum

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

CMB lensing

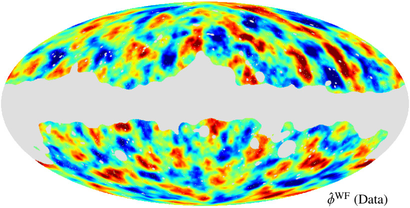
Due to the foreground gravitational potential the CMB temperature anisotropies and polarisation are lensed:

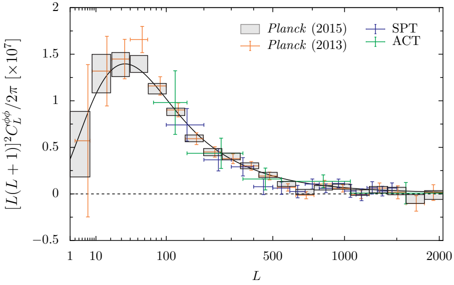
$$T_{\rm obs}(\mathbf{n}) = T(\mathbf{n} + \delta\mathbf{n}), \qquad \delta\mathbf{n} = \nabla\phi,$$

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

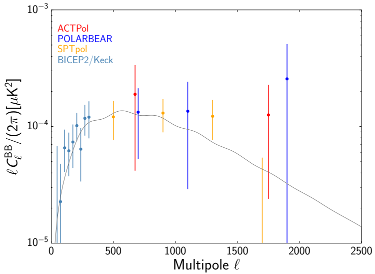
Lensing of the CMB is a second order effect. Lensing E polarisation induces B polarisation.

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

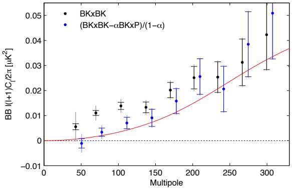


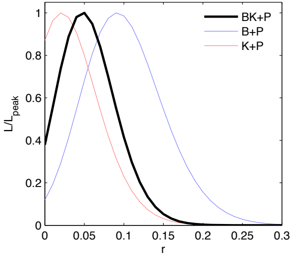


Lensing B modes



Atacama telescope array [arXiv:1610.02360]





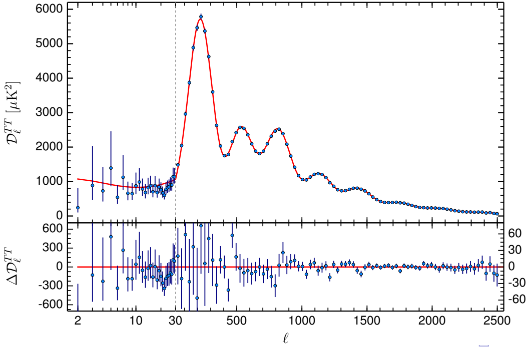
Bicep2 – KeckArray – Planck [arXiv:1502.00612]

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

$$T_0^2\left\langle\frac{\Delta T}{T}(\mathbf{n})\frac{\Delta T}{T}(\mathbf{n}')\right\rangle = \frac{1}{4\pi}\sum_\ell(2\ell+1)C_\ell P_\ell(\mathbf{n}\cdot\mathbf{n}')$$



The Planck 'base' model

- Curvature $K = 0$

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\rm He}/n_b$ is calculated from $N_{\rm eff}$ and ω_b.

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\rm He}/n_b$ is calculated from $N_{\rm eff}$ and ω_b.

Parameters

- Amplitude of curvature perturbations, A_s

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\rm He}/n_b$ is calculated from $N_{\rm eff}$ and ω_b.

Parameters

- Amplitude of curvature perturbations, A_s
- Scalar spectral index, n_s

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\rm He}/n_b$ is calculated from $N_{\rm eff}$ and ω_b.

Parameters

- Amplitude of curvature perturbations, A_s
- Scalar spectral index, n_s
- Baryon density $\omega_b = \Omega_b h^2$

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\rm He}/n_b$ is calculated from $N_{\rm eff}$ and ω_b.

Parameters

- Amplitude of curvature perturbations, A_s
- Scalar spectral index, n_s
- Baryon density $\omega_b = \Omega_b h^2$
- Cold dark matter density $\omega_c = \Omega_c h^2$

The Planck 'base' model

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\rm He}/n_b$ is calculated from $N_{\rm eff}$ and ω_b.

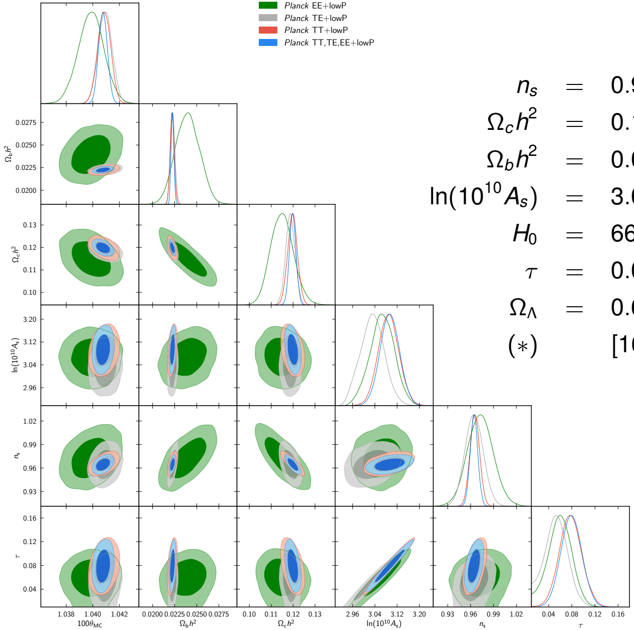
Parameters

- Amplitude of curvature perturbations, A_s
- Scalar spectral index, n_s
- Baryon density $\omega_b = \Omega_b h^2$
- Cold dark matter density $\omega_c = \Omega_c h^2$
- Present value of Hubble parameter $H_0 = 100h$km/sec/Mpc $(\Omega_\Lambda = 1 - (\omega_b + \omega_c)/h^2)$.

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\rm eff} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\rm He}/n_b$ is calculated from $N_{\rm eff}$ and ω_b.

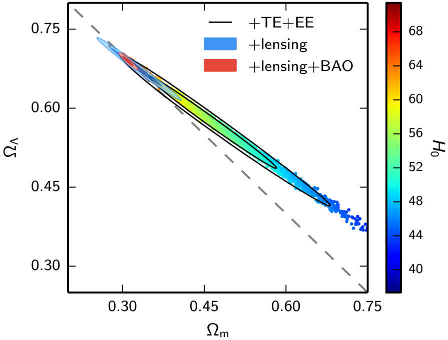
Parameters

- Amplitude of curvature perturbations, A_s
- Scalar spectral index, n_s
- Baryon density $\omega_b = \Omega_b h^2$
- Cold dark matter density $\omega_c = \Omega_c h^2$
- Present value of Hubble parameter $H_0 = 100h$km/sec/Mpc ($\Omega_\Lambda = 1 - (\omega_b + \omega_c)/h^2$).
- optical depth to reionization τ



$$
\begin{aligned}
n_s &= 0.9619 \pm 0.0045 \quad (*) \\
\Omega_c h^2 &= 0.1205 \pm 0.0014 \quad (*) \\
\Omega_b h^2 &= 0.02218 \pm 0.00015 \quad (*) \\
\ln(10^{10} A_s) &= 3.056 \pm 0.018 \quad (*) \\
H_0 &= 66.93 \pm 0.62 \quad (*) \\
\tau &= 0.055 \pm 0.009 \quad (*) \\
\Omega_\Lambda &= 0.688 \pm 0.0087 \\
(*) & \quad [1605.02985]
\end{aligned}
$$

Lensing breaks degeneracies



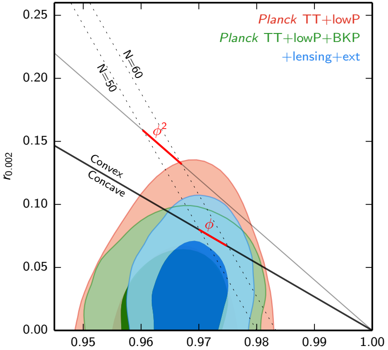
(Planck 1502.01589)

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

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

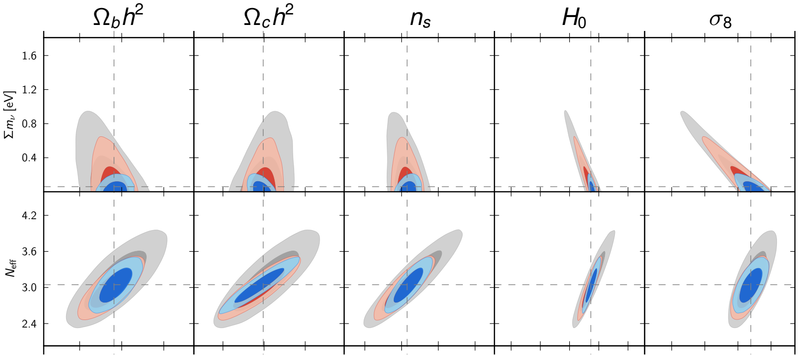
$$P_\zeta(k) \simeq \frac{H_*^2}{\epsilon M_p^2} k^{-6\epsilon+2\eta} \simeq 12.2 \times 10^{-9} \qquad P_h \simeq \frac{H_*^2}{M_p^2} k^{-2\epsilon} \simeq \left(\frac{E_*}{M_p}\right)^4$$

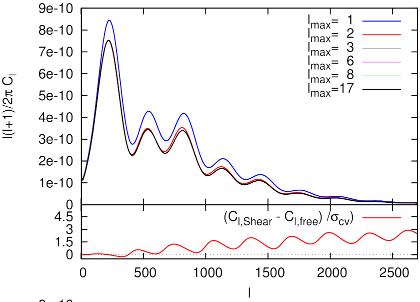
$$E_* = \left(\frac{r}{0.1}\right)^{1/4} 1.7 \times 10^{16}\,\mathrm{GeV}$$



Single extension best constraints:

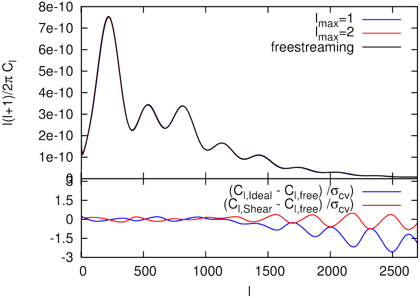
$$
\begin{array}{llll}
N_{eff} & = 3.04 \pm 0.2\ (0.18) & & \text{Planck (+ BAO)} \\
\Sigma_i m_i & = 0.49\ (0.17)\ \mathrm{eV} & 95\% & \text{Planck (+ BAO)}
\end{array}
$$





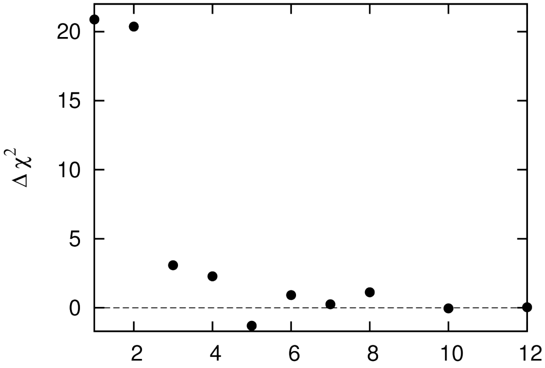
Treating neutrinos as perfect fluid or viscous fluid affects CMB spectra significantly.

(Here fixing the other parameters.)



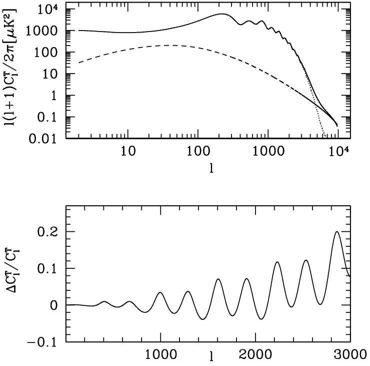
Marginalizing over the other parameters

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



Lensing beyond the Born approximation

The effect of lensing is very strong, especially on small scales.



In this lensing signal the effect of the first order deflection angle is fully resummed. This resummation is required at the present accuracy of data.

This prompted us to study the effects of second and third order lensing:

$$\tilde{\mathcal{M}}(x^a) = \mathcal{M}\left(x^a+\delta\theta^a\right) \simeq \mathcal{M}(x^a)+\sum_{i=1}^{4}\theta^{b(i)}\nabla_b\mathcal{M}(x^a)+\frac{1}{2}\sum_{i+j\le 4}\theta^{b(i)}\theta^{c(j)}\nabla_b\nabla_c\mathcal{M}(x^a)$$

$$+\frac{1}{6}\sum_{i+j+k\le 4}\theta^{b(i)}\theta^{c(j)}\theta^{d(k)}\nabla_b\nabla_c\nabla_d\mathcal{M}(x^a)+\frac{1}{24}\theta^{b(1)}\theta^{c(1)}\theta^{d(1)}\theta^{e(1)}\nabla_b\nabla_c\nabla_d\nabla_e\mathcal{M}(x^a)\,.$$

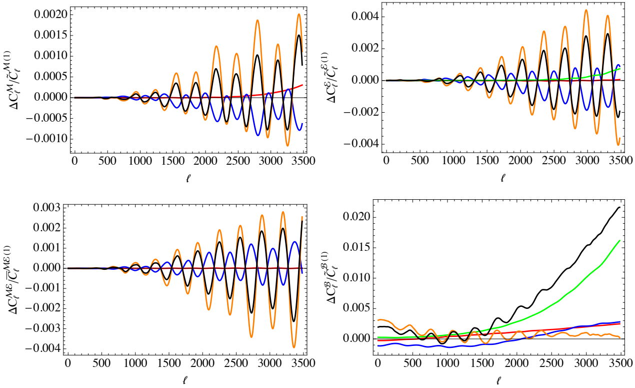
$$\theta^{a(1)} = -2\int_0^{r_s}dr'\,\frac{r_s-r'}{r_s\,r'}\nabla^a\Phi_W(r')\,,$$

$$\theta^{a(2)} = -2\int_0^{r_s}dr'\,\frac{r_s-r'}{r_s\,r'}\nabla_b\nabla^a\Phi_W(r')\theta^{b(1)}(r')\,,$$

$$\theta^{a(3)} = -2\int_0^{r_s}dr'\,\frac{r_s-r'}{r_s\,r'}\left[\nabla_b\nabla^a\Phi_W(r')\theta^{b(2)}(r')+\frac{1}{2}\nabla_b\nabla_c\nabla^a\Phi_W(r')\theta^{b(1)}(r')\theta^{c(1)}(r')\right].$$

The vector part of second order perturbations leads to rotation of the polarisation tensor: This induced more *B*-modes from *E* polarisation.

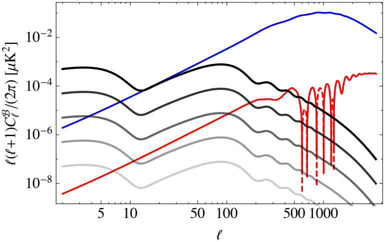
$$\tilde{\mathcal{P}}(x^a) = e^{-2i\beta}\mathcal{P}(x^a + \delta\theta^a) \qquad \beta = -\frac{1}{2}\Delta\Omega$$

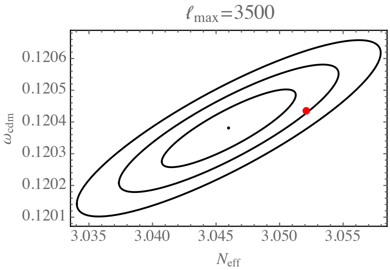


Marozzi, Di Dio, Fanizza & RD, arXiv:1612.07263

Lensing beyond the Born approximation

Despite the fact that these terms are significantly smaller than cosmic variance for each fixed ℓ. They have to be taken into account for the nest generation of CMB experiments (S4).





Marozzi, Di Dio, Fanizza & RD, arXiv:1612.07650

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.
- It may be used in the future for non-trivial tests of General Relativity on cosmological scales (frame dragging, gw's).

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.
- It may be used in the future for non-trivial tests of General Relativity on cosmological scales (frame dragging, gw's).
- It can also be used to test the nature of cosmic neutrinos.

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.
- It may be used in the future for non-trivial tests of General Relativity on cosmological scales (frame dragging, gw's).
- It can also be used to test the nature of cosmic neutrinos.
- Cosmology provides the strongest (only?) experimental evidence for physics beyond the standard model.

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.
- It may be used in the future for non-trivial tests of General Relativity on cosmological scales (frame dragging, gw's).
- It can also be used to test the nature of cosmic neutrinos.
- Cosmology provides the strongest (only?) experimental evidence for physics beyond the standard model.
  - What is dark matter?

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.
- It may be used in the future for non-trivial tests of General Relativity on cosmological scales (frame dragging, gw's).
- It can also be used to test the nature of cosmic neutrinos.
- Cosmology provides the strongest (only?) experimental evidence for physics beyond the standard model.
    - What is dark matter?
    - What is dark energy ?

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.
- It may be used in the future for non-trivial tests of General Relativity on cosmological scales (frame dragging, gw's).
- It can also be used to test the nature of cosmic neutrinos.
- Cosmology provides the strongest (only?) experimental evidence for physics beyond the standard model.
  - What is dark matter?
  - What is dark energy ?
  - What is the inflaton?

Conclusion

- The CMB is the most precious cosmological dataset. It is very precisely observed and very well understood.
- Nearly all precision information on cosmological parameters so far stems form the CMB.
- It may be used in the future for non-trivial tests of General Relativity on cosmological scales (frame dragging, gw's).
- It can also be used to test the nature of cosmic neutrinos.
- Cosmology provides the strongest (only?) experimental evidence for physics beyond the standard model.
  - What is dark matter?
  - What is dark energy ?
  - What is the inflaton?
- Cosmological perturbations are generated by quantum excitation in a time dependent background.