Exploring the Early Universe with the Cosmic Microwave Background

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Contents

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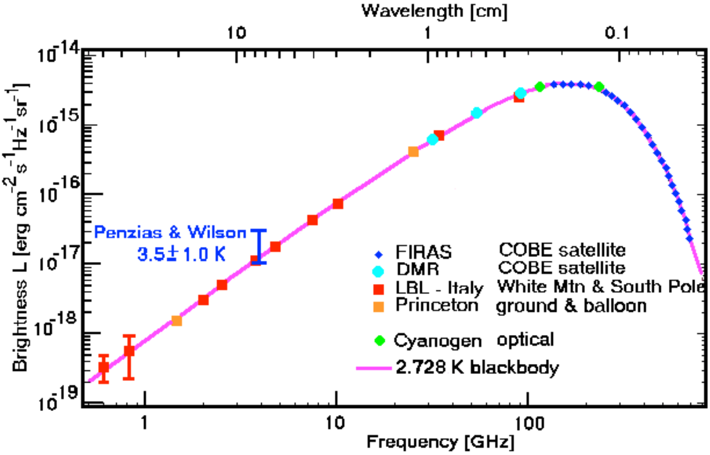
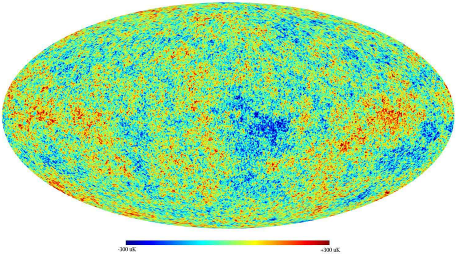
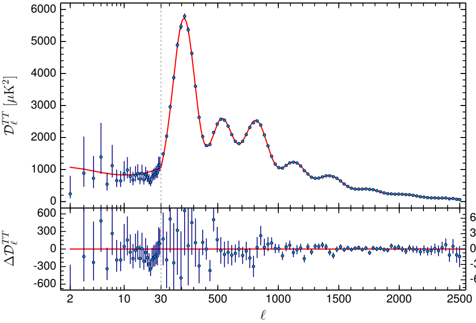
- At $T > 8300\text{K} \simeq 0.8\text{eV}$ the Universe was 'radiation dominated', i.e. its energy density was dominated by the contribution from these photons (and 3 types of relativistic neutrinos which made up about 35%). Hence initial fluctuations in the energy density of the Universe should be imprinted as fluctuations in the CMB temperature.


Wavelength [cm]
10
1
0.1
Brightness L [erg cm^{-2}s^{-1}Hz^{-1}sr^{-1}]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
Penzias & Wilson
3.5± 1.0 K
FIRAS COBE satellite
DMR COBE satellite
LBL - Italy White Mtn & South Pole
Princeton ground & balloon
Cyanogen optical
2.728 K blackbody
1
10
100
Frequency [GHz]

Fluctuations in the CMB



$$T_0 = 2.7363K$$
$$\Delta T(\mathbf{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{n})$$
$$C_\ell = \langle |a_{\ell m}|^2 \rangle,$$
$$D_\ell = \ell(\ell+1)C_\ell/(2\pi)$$



From the Planck Collaboration 2015

Quantum fluctuations from inflaton I

Our present understanding is that these fluctuations stem from quantum fluctuations imprinted on the space-time metric during a phase of very rapid expansion called 'inflation'.

We consider a homogeneous and isotropic Universe with vanishing spatial curvature. The metric is

$$ds^2 = -dt^2 + a^2(t)\delta_{ij}dx^i dx^j \ .$$

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It is well known that coupling a quantum field to a time dependent external classical field can lead to particle creation. The energy of the modes which can be generated is determined by the kinetic energy in the time dependence of the external field. In an expanding universe, this is determined by the Hubble parameter $H(t)$ which is nearly constant during inflation,

$$H^2 = \frac{8\pi G}{3}\left(\dot{\phi}^2 + V(\phi)\right) \simeq \frac{8\pi G}{3}V, \qquad \dot{\phi}^2 \ll V(\phi) \quad \text{(slow roll)}$$

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Let us consider small fluctuations of the metric in ADM form,

$$ds^2 = -N^2dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

There is one scalar and two tensor degrees of freedom.

In comoving gauge

$$\begin{aligned} \phi(t,x) &= \phi_0(t), \\ h_{ij}(t,x) &= a^2(t)e^{2\zeta(t,x)}\hat{h}_{ij}, \quad \hat{h}_{ij} = \exp\left[\gamma_{ij}\right] \qquad \gamma^i_i = \partial_i\gamma^i_j = 0 \end{aligned}$$

where γ^i_j is (transverse traceless) graviton, and ζ is the comoving curvature perturbation. On a quasi de Sitter background,

$$\epsilon \equiv \epsilon_1 := \frac{\dot{\phi}_0^2}{2H^2M_{\rm pl}^2} = -\frac{\dot{H}}{H^2} \ll 1\,, \qquad \epsilon_{i+1} = \frac{\dot{\epsilon}_i}{H\epsilon_i}\,,$$

the second order action is

$$S_2 = M_{\rm pl}^2\int d^4x\, a^3\, \left\{\epsilon\left[\dot{\zeta}^2 - \frac{1}{a^2}(\partial\zeta)^2\right] + \frac{1}{8}\left[\dot{\gamma}_{ij}\dot{\gamma}_{ij} - \frac{1}{a^2}\partial_k\gamma_{ij}\partial_k\gamma_{ij}\right]\right\}$$

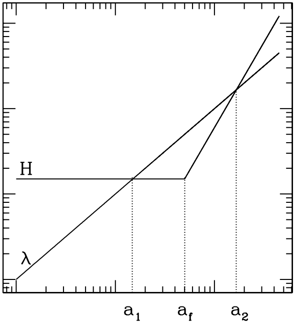
Quantum fluctuations from inflaton III

Quantizing ζ and γ_{ij}, one finds that the coupling of the vacuum fields to the expansion of the Universe generates the following spectra of scalar and tensor modes out of an initial (Bunch Davis) vacuum state.

$$\langle \zeta(\mathbf{k},t)\zeta^*(\mathbf{k}',t)\rangle = \delta(\mathbf{k}-\mathbf{k}')(2\pi)^3 P_\zeta(k)$$

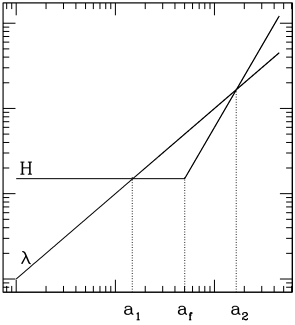
$$\begin{aligned}
P_\zeta(k) &= \frac{H^2}{8\pi^2\epsilon_1 M_{\rm pl}^2}\left(\frac{k}{k_\star}\right)^{n_s-1}, \quad n_s-1 = -2\epsilon_1-\epsilon_2\,, && \text{(Mukhanov \& Chibisov, 1982)}\\
P_\gamma(k) &= \frac{2H^2}{\pi^2 M_{\rm pl}^2}\left(\frac{k}{k_\star}\right)^{n_T}, \quad n_T = -2\epsilon_1\,, && \text{(Starobinskii, 1979)}\\
r &= \frac{P_\gamma(k_*)}{P_\zeta(k_*)} = 16\epsilon_1 = -8n_T\\
\text{for } k &\ll aH\,.
\end{aligned}$$

One can show that the long duration of inflation leads to squeezed states so that denoting the canonically normalized field operator by $y(\mathbf{k},t)$ and its canonically conjugate momenta by $p(\mathbf{k},t)$, we obtain $p \to \alpha(k,t)y$, where α is a function, so that $[p,y] \to 0$ and the field becomes a classical stochastic field (Kiefer & Polarski, 2009).



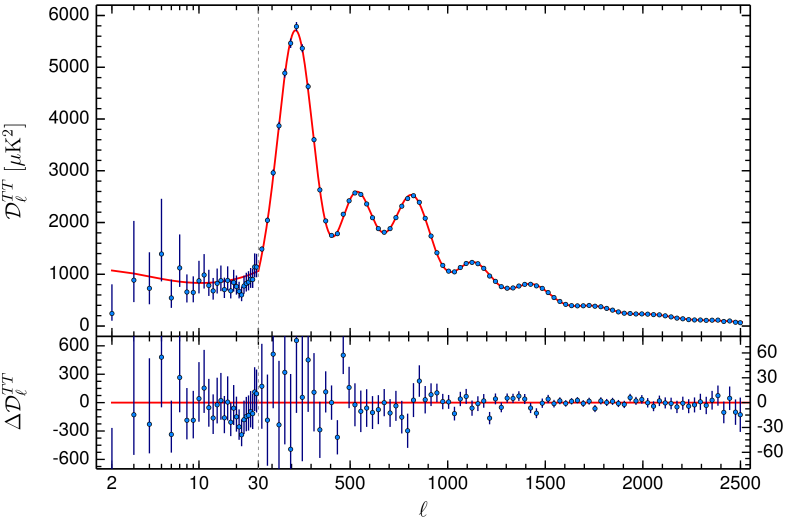
The physical wavelength λ (inverse of frequency) of a mode is growing faster than the Hubble scale H^{-1} during inflation.

Quantum fluctuations from inflaton: resumé



The physical wavelength λ (inverse of frequency) of a mode is growing faster than the Hubble scale H^{-1} during inflation.

After inflation, the Universe 'reheats' into a thermal bath of relativistic particles. In the radiation phase, $\lambda \propto a \propto \sqrt{t}$ while $H^{-1} \propto t$, the Hubble scale catches up.
Due to the relativistic pressure, $P = \rho/3$, scalar perturbations undergo acoustic oscillations, $\zeta(\mathbf{k}) = A(\mathbf{k}) \cos(c_s k \tau)$,
at fixed wave number k they are all in phase.
These are the acoustic peaks we see in the CMB.

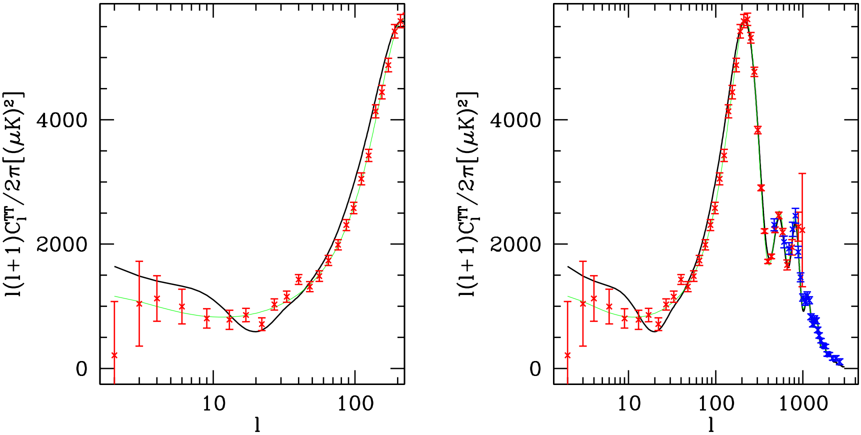

6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

A non inflationary toy model

Is inflation really needed to generate such a fluctuation spectrum?

To test this we considered a model of rapidly expanding thin spherical shells of energy (rapid explosions) in a radiation dominated universe.

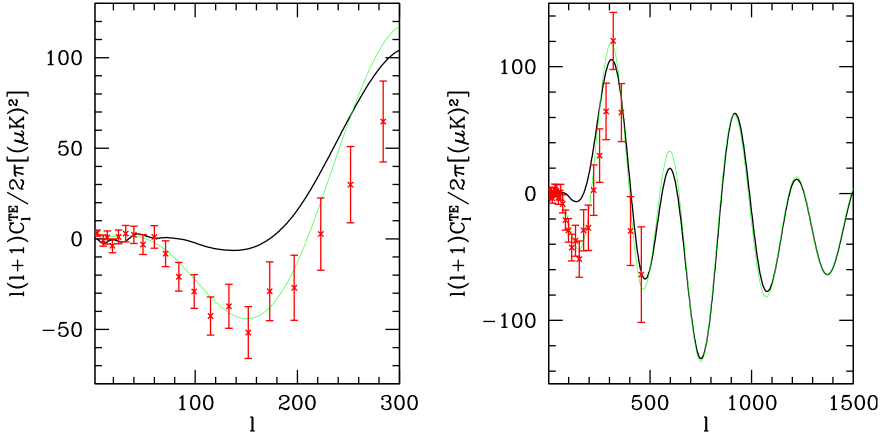
A non inflationary toy model



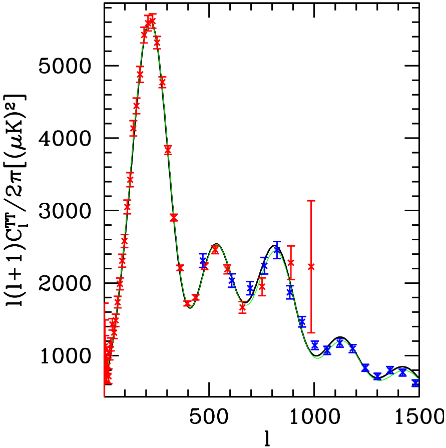
(from Scodeller, Kunz & RD, '09)

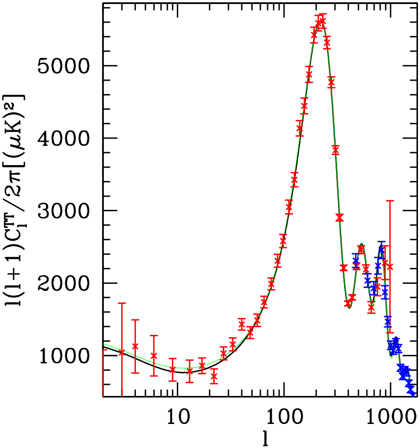
The best fit CMB anisotropies from a causal model of expanding shells (fat black line) compared with the data from WMAP and ACBAR, and to the best fit ΛCDM model (thin green line). Left: the rise to the first peak, $\ell \leq 200$ which can not be fitted satisfactorily by this model. Right: the spectrum up to $\ell = 2500$. The secondary peaks are well fitted.

A non inflationary toy model



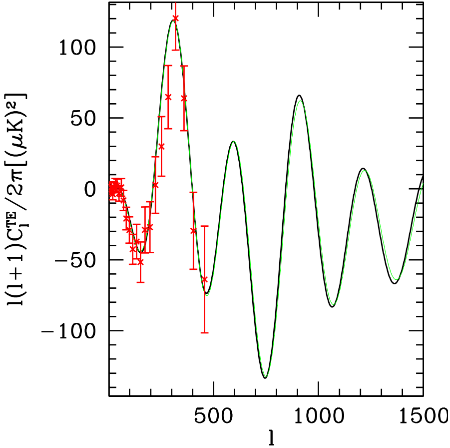
(from Scodeller, Kunz & RD, '09)
The best fit T-E correlation spectrum from a causal model of expanding shells (fat black line) compared with the data from WMAP and with a standard ΛCDM model (thin green line). Left: the first acausal anti-correlation peak, at $\ell \simeq 150$ which is absent in the causal model (as predicted by Spergel & Zaldarriaga, '97). Right: the spectrum up to $\ell = 1500$. The secondary peaks are very similar to the inflationary case.



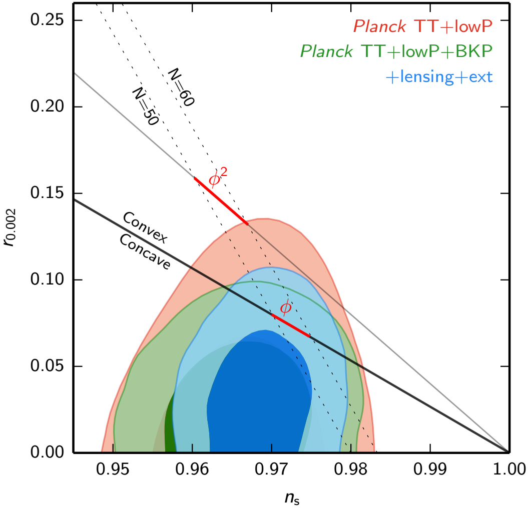


(from Scodeller, Kunz & RD, '09)

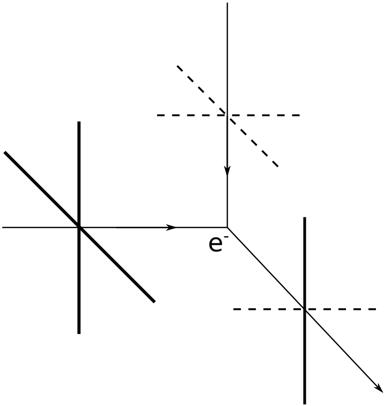
The best fit CMB anisotropies from an a-causal seed model ($\nu_1 \simeq 2$, $\nu_2 \simeq 1.5$, fat black line) are compared with the data from WMAP and ACBAR and to a standard ΛCDM model (thin green line).



(from Scodeller, Kunz & RD, '09)
The best fit CMB temperature–polarization cross correlation from an acausal seed model ($v_1 \simeq 2$, $v_2 \simeq 1.5$, fat black line) are compared with the data from and to a standard ΛCDM model (thin green line).

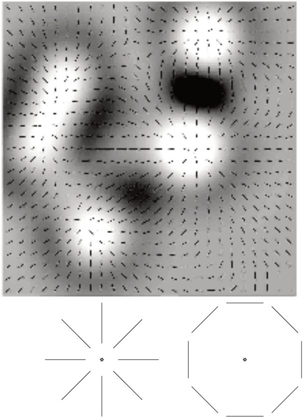


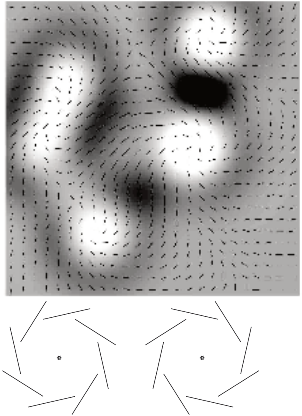
2D marginalized limits (68% and 95% CL) for the tensor-to-scalar ratio r, and the scalar spectral index n_s, for Planck data. The predicted values for a chaotic inflationary model with inflaton potential $V(\phi) \propto \phi^p$ with 60 e-folds are shown for $p = 2,\ 1$;
$p > 1$ is disfavored at $> 80\%$ CL.
The Planck Collaboration 2015.



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

Polarisation of the CMB

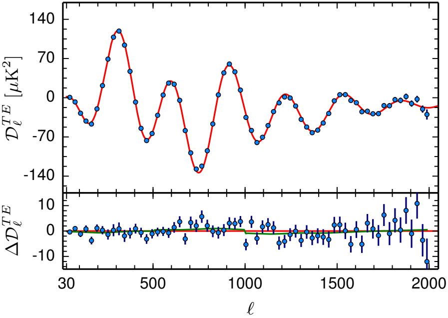




Left: E-polarisation is pure gradient or pure curl, $\epsilon(\mathbf{n}) = \nabla\phi(\mathbf{n})$ or $\epsilon(\mathbf{n}) = \nabla \wedge \psi(\mathbf{n})$
Right: B-polarisation is a mixture , $\epsilon(\mathbf{n}) = \nabla\phi(\mathbf{n}) + \nabla \wedge \psi(\mathbf{n})$.
A rotation by $\pi/4$ turns pure E-modes into pure B-modes and vice versa.

Scalar perturbations only generate E-polarisation.

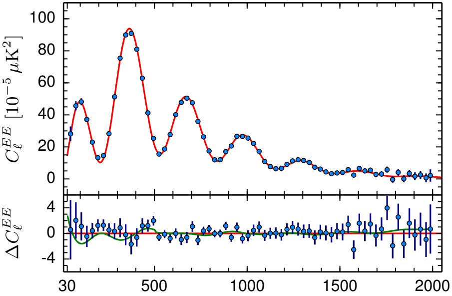
The CMB polarization spectra



T-E correlation

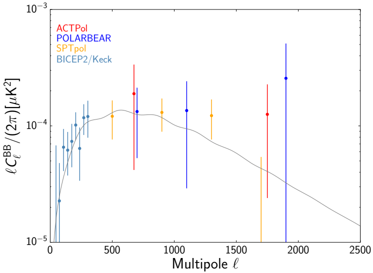
$$\mathcal{D}_\ell^{TE} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{TE}$$

(The Planck Collaboration 2015)

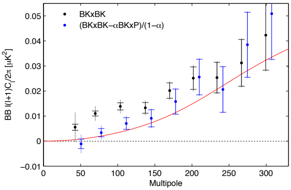


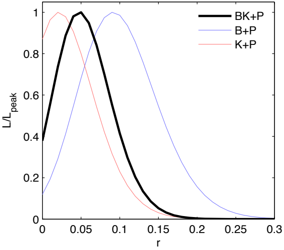
E-E spectrum

The B polarisation spectrum



Atacama telescope array
ACTPOL Collaboration, 2017



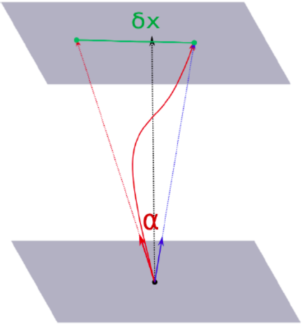


Bicep2-Keck-Planck
BICEP2 and Planck Collaborations, 2016

$r < 0.11$ at 90% confidence (in the minimal model with tensors).

CMB lensing induces B-polarisation

The presence of foreground structure deflects photon geodesics from a straight line.



$$\mathbf{x} \mapsto \mathbf{x} + \delta\mathbf{x}$$

$$\mathbf{n} = (\theta^1, \theta^2) \mapsto \mathbf{n} + \alpha$$

The Jacobian of this lens map is given by

$$\begin{aligned} A_{ab} &= \delta_{ab} + \nabla_b \alpha_a \\ &= \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2+\omega \\ -\gamma_2-\omega & 1-\kappa+\gamma_1 \end{pmatrix} \end{aligned}$$

κ describes magnification, γ is the shear and ω a rotation.

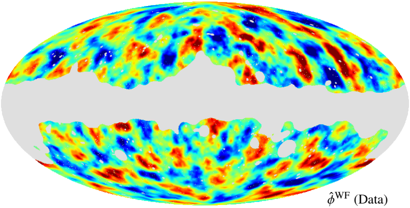
(Figure by M. Vanvasselaer)

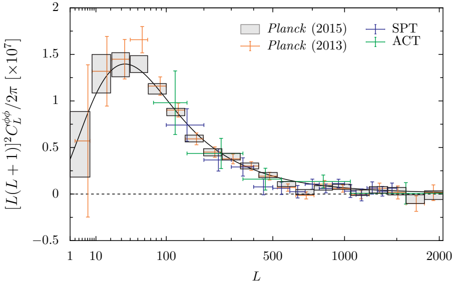
In a 'quasi Newtonian' situation the deflection angle is the gradient of the lensing potential,

$$\psi(\mathbf{n}, t_*) = -2\int_0^{\lambda_*} d\lambda \frac{\lambda_* - \lambda}{\lambda_* \lambda} \Phi(\lambda\mathbf{n}, t_0 - \lambda) \qquad A_{ab} = \delta_{ab} + \nabla_b \nabla_a \psi \quad \Rightarrow \quad \omega = 0\,.$$

The lensing spectrum

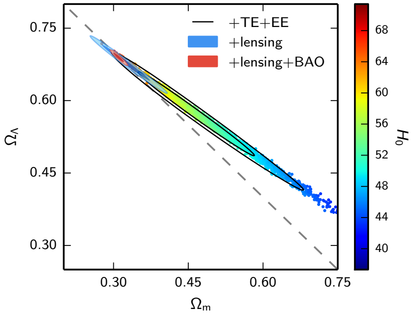
$$\psi(\mathbf{n}) = -2\int_0^{r_*} dr \frac{(r_* - r)}{r_* r}\Phi(r\mathbf{n}, t_0 - r)$$



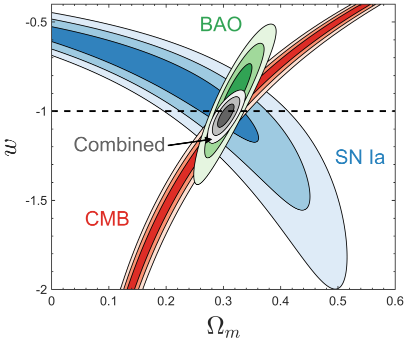


(Planck Collaboration 2015)

Cosmological parameters

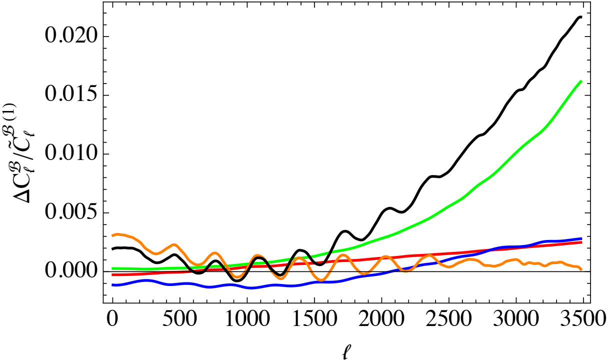


(Planck Collaboration, 2015)



(Huterer et al., 2017)

Second order lensing and B-polarisation

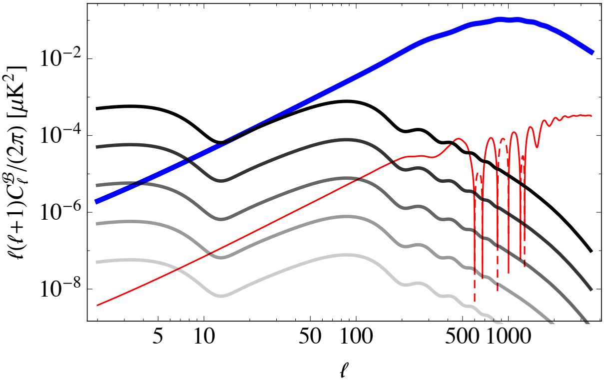


(Figure from Marozzi, Fanizza, Di Dio, RD, 2016).

Different contributions to the higher order lensing B-mode spectrum. The contribution from the rotation ω is green, the sum in black.

Why should we care

Not correctly subtracted B-modes from lensing (incorrect 'delensing') can mimic primordial B-modes from inflation.



(Figure from Marozzi, Fanizza, Di Dio, RD, 2016).

Blue: first order lensing B-modes. Red: B-modes from higher order lensing (rotation). Grey-tones: primordial B-modes from inflation, $r = (10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6})$.

Conclusions

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Thank You

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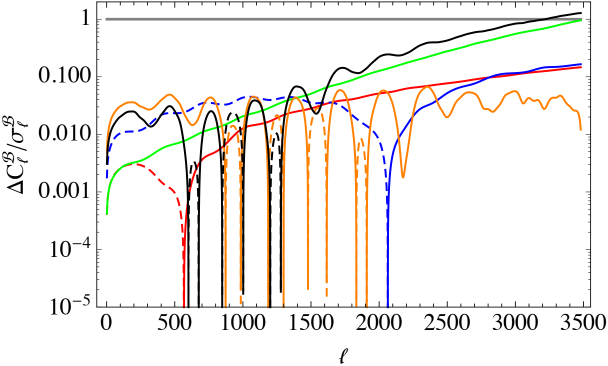

(figure from Marozzi, Fanizza, Di Dio, RD, 2017)