The Cosmic Microwave Background and Quantum Physics

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MITP Workshop

Quantum Vacuum and Gravitation

Contenu

1. Introduction
2. Fluctuations in the CMB
3. Why inflation
4. Evidence for Λ
5. Conclusions

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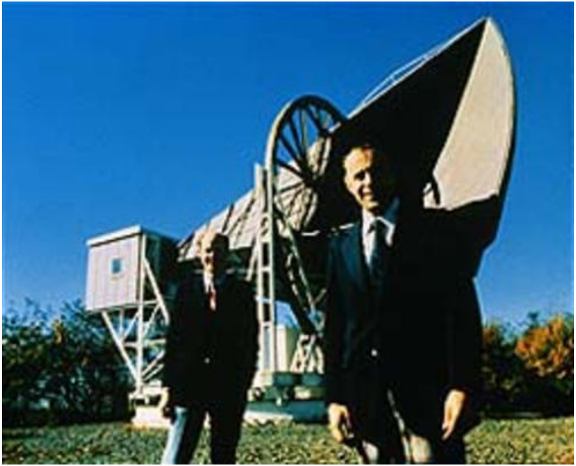
  How sure are we?

Accidental discovery of the CMB by Arno Penzias and Robert Wilson 50 years ago (Nobel Prize 1978)



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Gamov has predicted the existence of the CMB already in 1948.

Here with Alpher and Hermann.

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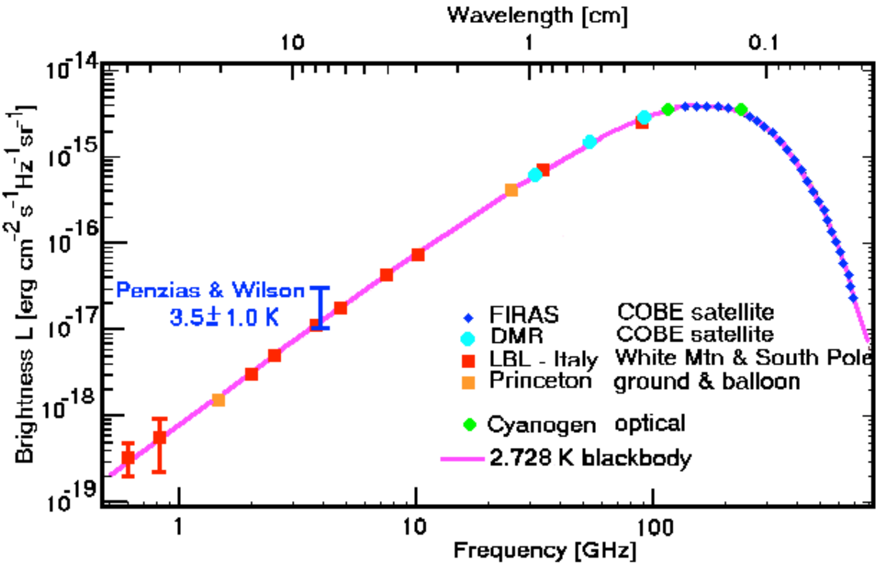
- This corresponds to about 400 photons per cm^3 with typical energy of $E_\gamma = kT_0 \simeq 2.3 \times 10^{-4}$eV $\simeq 150$GHz ($\lambda \simeq 0.2$cm). This is the observed CMB.
- At $T > 9300$K$\simeq 0.8$eV the Universe was 'radiation dominated', i.e. its energy density was dominated by the 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 frequency spectrum of the CMB



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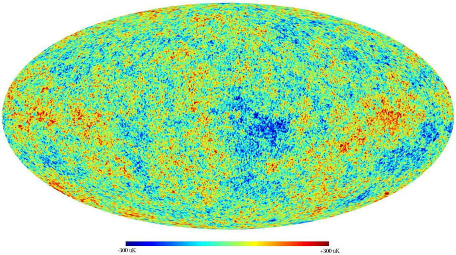
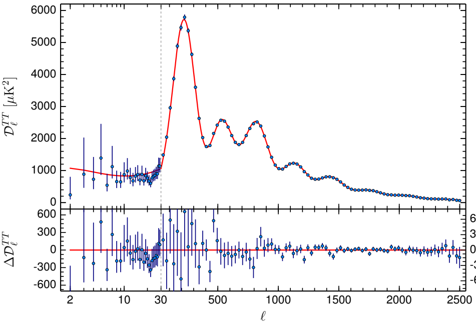
- Immediately after its discovery, astrophysicists began to search for fluctuations in the CMB. The found them in 1992 with the COBE satellite (Nobel Prize 2006).

Fluctuations in the CMB



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



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

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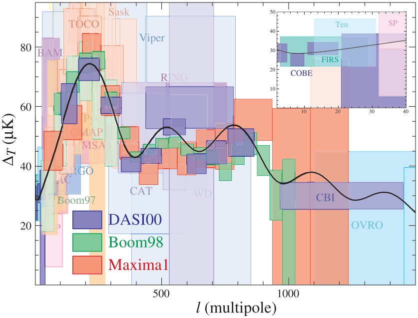

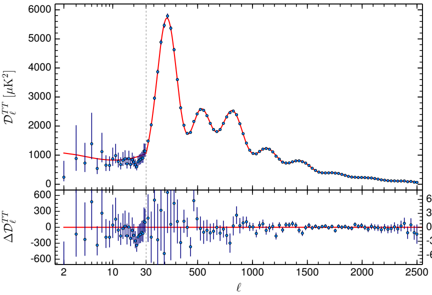

(Hu & Dodelson, 2002) (Planck Collaboration 2015)

The physics of CMB fluctuations

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

$$\frac{\Delta T}{T}(\mathbf{n}) = \left[\frac{1}{4}D_g + \mathbf{n}\cdot\mathbf{V} + \Psi + \Phi\right](\mathbf{n},\tau_*) + \int_{s_*}^{s_0} \partial_\tau(\Psi+\Phi)ds\,.$$

(RD 1991)

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

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- On small scales fluctuations are damped by free streaming (Silk damping).
- The fluctuations are lensed by foreground structures.

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 3×10^{-4}

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(Planck Collaboration: Planck results 2015 XIII [arXiv:1502.01589])

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The distance to the CMB is given by

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

Coherence

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- They have a nearly scale invariant, slightly red spectrum.
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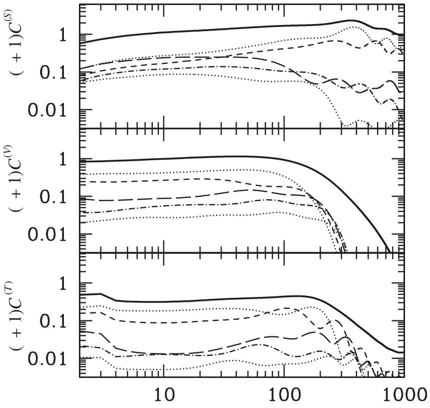
- they are coherent: all fluctuations of a given wave number are in phase.



RD, Kunz & Melchiorri, 2001

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- Fluctuations on very large scales, $\ell < 150$ were super-Hubble at the time of decoupling and therefore, without invoking a period of inflation, there cannot be any structure in the CMB on these scales.
- In a 'causally generated' CMB spectrum the first acoustic peak in the T-E correlation spectrum must be absent. (Spergel & Zaldarriaga 1997)

Polarisation

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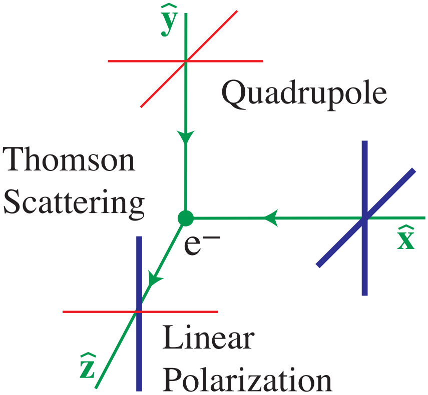
$\Rightarrow$ A quadrupole anisotropy in the intensity (temperature) introduces linear polarisation.



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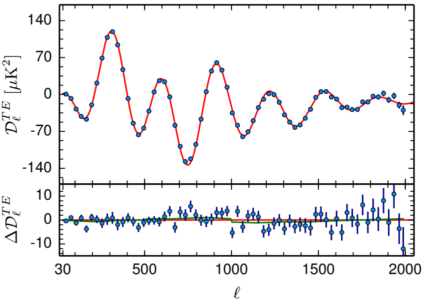
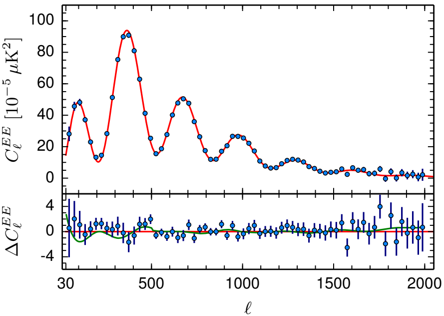
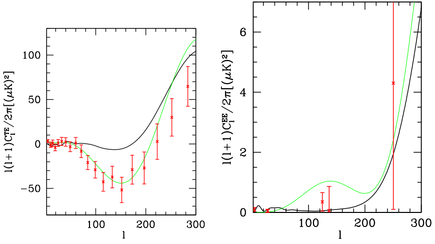




(The Planck Collaboration 2015)

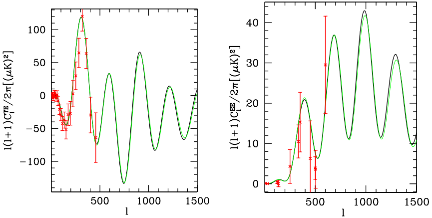
Acausality

We have considered a model with relativistic exploding shells leading to a scale invariant spectrum of fluctuations (Scodeller, Kunz & RD 2009)



T-E spectrum　　E-E spectrum

causal



T-E spectrum　　E-E spectrum

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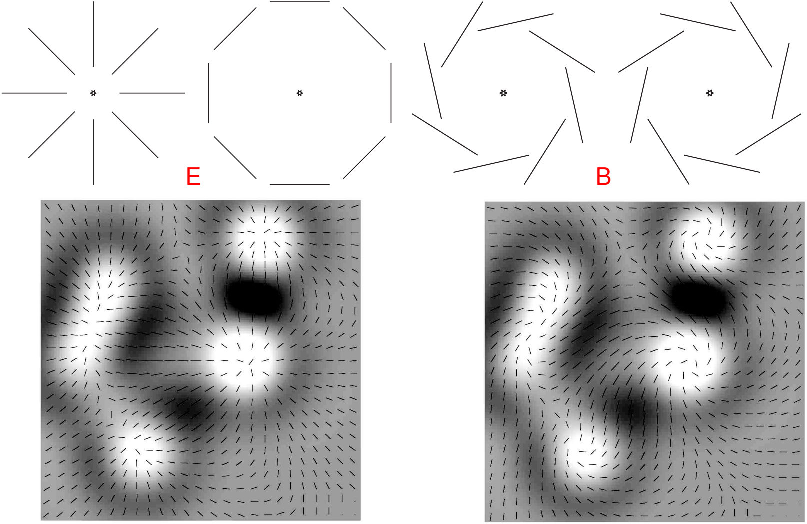
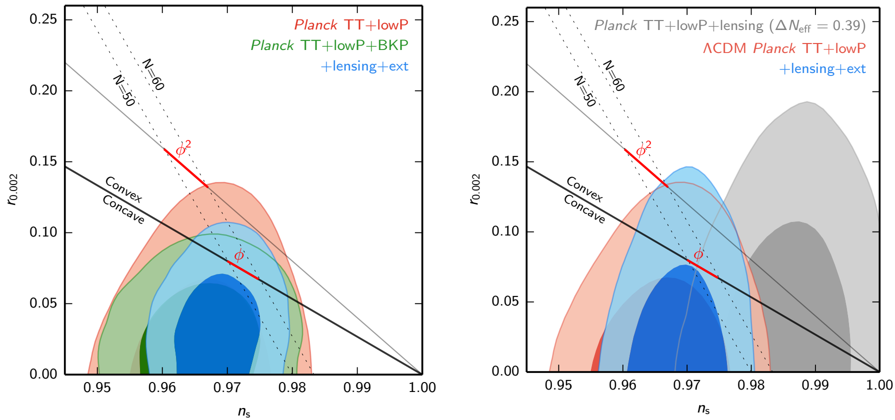
$v_1 = 1.65, \;\; v_2 = 2.4$

(From Scodeller, Kunz, RD 2009)

Only tensor (and vector) perturbations can generate *B* polarisation.





The tensor to scalar ratio is $r \lesssim 0.1$.

If $r \neq 0$ we might be able to test the slow roll consistency relation, $r = -8n_t$.

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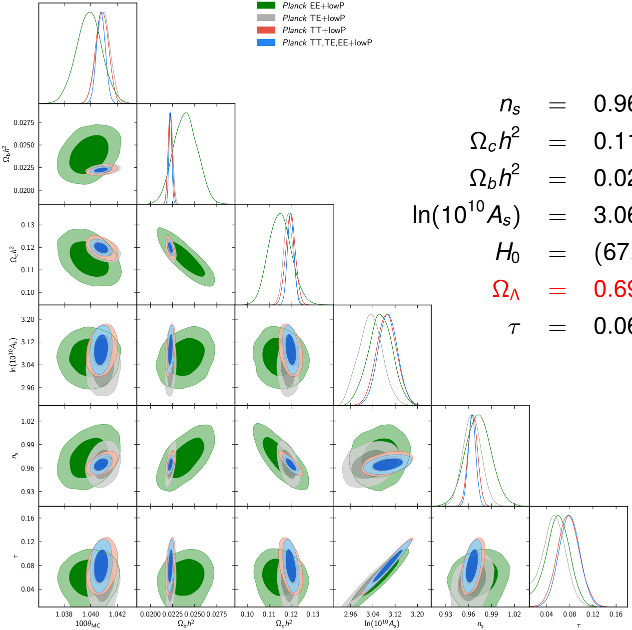
- optical depth to reionization τ

Cosmological parameters from Planck 2015 arXiv:1502.01589



$$n_s = 0.9653 \pm 0.0048$$

$$\Omega_c h^2 = 0.1188 \pm 0.0010$$

$$\Omega_b h^2 = 0.0223 \pm 0.00011$$

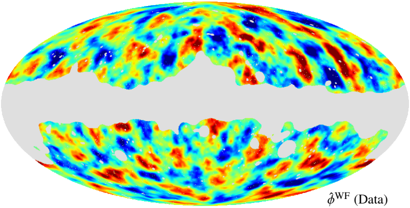
$$\ln(10^{10}A_s) = 3.064 \pm 0.023$$

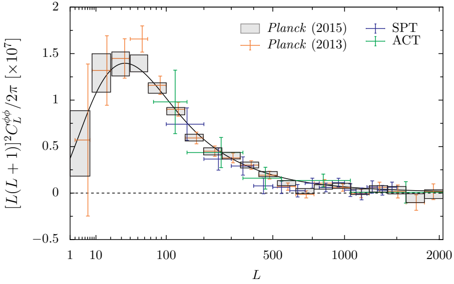
$$H_0 = (67.74 \pm 0.46)\text{km/sec/Mpc}$$

$$\Omega_\Lambda = 0.6911 \pm 0.0062$$

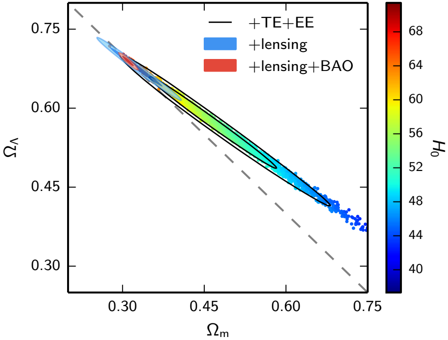
$$\tau = 0.066 \pm 0.012$$

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





Lensing breaks degeneracies

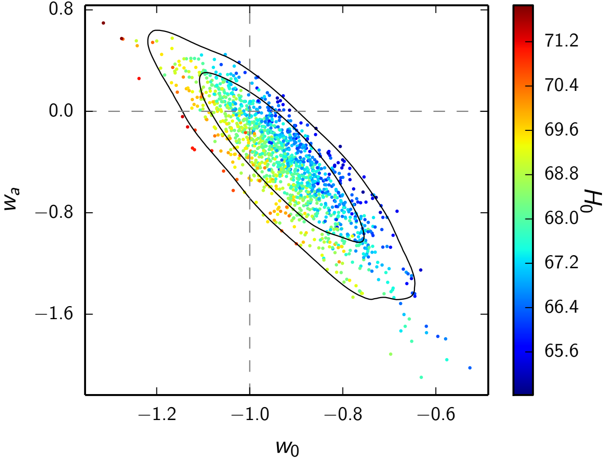


(Planck 1502.01589)

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

Dark energy models

A simple Taylor expansion, $$\frac{P_{DE}}{\rho_{DE}} = w = w_0 + (1-a)w_a$$



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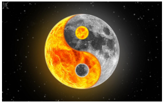
In this picture

- The biggest structures in the Universe have been generated by small quantum fluctuations.



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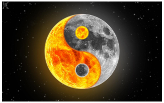

- If we ever find B polarisation it probably originates from quantum fluctuations of the gravitational field.

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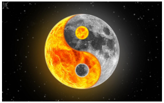
- The biggest structures in the Universe have been generated by small quantum fluctuations.



- If we ever find B polarisation it probably originates from quantum fluctuations of the gravitational field.
- The energy density in the Universe is at present and for all future times dominated by vacuum energy.