Cosmology with Planck: exploring the early universe via the CMB

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Workshop on (Super)Gravity, Strings and related matters
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Planck is a 3rd generation ESA satellite devoted to CMB
Ultimate characterization of the temperature anisotropies
74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz
angular resolution between 30’ and 5’, $\Delta T/T \sim 2 \times 10^{-6}$
Final (legacy) release expected later this year
May 2009: Launched from Kourou

Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data

Oct 2013: Planck ‘Shut Down’

Feb 2015: Data Release and Cosmology Results
Full Mission Temperature and (preliminary) Polarization data

2017: Legacy Data & Paper Release
THE SKY AS SEEN BY PLANCK

30 GHz

44 GHz

70 GHz

100 GHz

143 GHz

217 GHz

353 GHz

545 GHz

857 GHz

European Space Agency
UNVEILING THE CMB SKY

The *ultimate* measurement of the CMB temperature anisotropy field

Planck unveils the Cosmic Microwave Background

![Graphs showing the Rms brightness temperature (μK) vs Frequency (GHz) for different components: CMB, Thermal dust, Spinning dust, Free-free, CO 1-0, Sum fg, Synchrotron.](image-url)
Definitive measurement of the CMB temperature anisotropies
PLANCK: POLARIZATION ANISOTROPIES
Two independent components: a grad-like (E) and a curl-like (B) mode. Different behaviour under parity.
Two independent components: a grad-like (E) and a curl-like (B) mode
Different behaviour under parity

Still a wealth of information to be extracted
*Planck* has just scratched the surface
The CMB is polarized

- CMB polarization is unavoidable if
  - Photons scatter off (free) electrons
  - Electrons are surrounded by anisotropic (quadrupolar) radiation
The Thomson scattering cross section depends on photon polarization:

\[
\frac{d\sigma_T}{d\Omega} \propto |\vec{\varepsilon} \cdot \vec{\varepsilon}'|^2
\]

CMB polarization is created only by a local temperature quadrupole anisotropy. This is generated only when the photon diffusion length grows enough to reveal higher order moments in the brightness distribution (e.g. at recombination).
Origin of quadrupole anisotropy

• We see anisotropy in the CMB density perturbation and in the matter distribution (large scale structure)

• These two things barely talk each other today, but were tightly connected in the early universe.

• Perturbations to smooth background metric $g_{\mu \nu}$ must have existed in the early universe.

• Standard paradigm says that they origin in quantum fluctuation amplified by the cosmic inflation. Two kinds of perturbations:
  
  – Scalar perturbations: these can grow under self gravity
  
  – Tensor perturbations: gravitational waves
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB.
Gravitational Lensing

The gravitational tug of the intervening large scale structure distorts photon paths. Deflections \( \sim 2 \) arcmin, coherent over 2 degree scales. A subtle effect that may be measured statistically with high angular resolution, low-noise observations of the CMB, like those from Planck.
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PLANCK: LENSING POTENTIAL
Most significant detection on CMB lensing to date
Reconstructed from the temperature and polarization maps
Most significant detection on CMB lensing to date
Reconstructed from the temperature and polarization maps

Measures deflection of light due to intervening structures
(average deflection angle is \sim 2.5 \text{ arcmin})
Gives integrated information about the matter distribution between us and the last scattering surface
The information in the maps can be compressed by computing the 2-point correlation functions (i.e., spectra)
STATISTICAL DESCRIPTION

\[ \hat{\gamma} = (\theta, \varphi) \]

**CORRELATION FUNCTIONS**

\[ \left\langle \frac{\Delta T}{T} (\bar{\gamma}) \frac{\Delta T}{T} (\gamma') \right\rangle \quad \text{from Inflation} \]

\[ \left\langle \frac{\Delta T}{T} (\bar{\gamma}) \frac{\Delta T}{T} (\gamma') \frac{\Delta T}{T} (\gamma'') \right\rangle \]

\[ \left\langle \frac{\Delta T}{T} (\bar{\gamma}) \frac{\Delta T}{T} (\gamma') \frac{\Delta T}{T} (\gamma'') \frac{\Delta T}{T} (\gamma''') \right\rangle \]

\[ \ldots \]

**POLARIZATION**

\[ \mathbf{P} (\hat{\gamma}) = \nabla \mathbf{E} + \nabla \times \mathbf{B} \]

- **E-modes**: even under parity
- **B-modes**: odd under parity

Density perturbations -> E-modes
Gravitational Waves -> E- and B-modes
E-mode and B-mode

- Polarization is a spin 2 tensor, can be decomposed in parity even and parity odd component (“E” and “B”)

- Gravitational potential (density perturbation, parity even) can generate the E-mode polarization, but not B-modes because CMB physics is electromagnetic (parity conserving)

- Primordial Gravitational waves from inflation can generate both E- and B-modes!
The red curve is a fit of the 6-parameters $\Lambda$CDM model to the TT data only.
Planck baseline cosmological dataset uses the full TT spectrum + large scale (l < 30) polarization (not shown) (PlanckTT+lowP)
Can be extended to include the full polarization information 
(PlanckTTTEEE+lowP)  
Less conservative: high-ell polarization could be affected by residual systematics
All the previous can be complemented by the lensing power spectrum (+Planck lensing)
**Base $\Lambda$CDM**

Good fit to the data

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-> Fully described by 6 parameters
**Base ΛCDM**

Good fit to the data

High precision parameter estimates even better than 1%

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Sub-% precision ~ 6 - 7σ from scale invariance -> Inflationary Paradigm

Improves on pre-Planck constraints by a factor 1.5 - 2
Base $\Lambda$CDM

Good fit to the data
High precision parameter estimates even better than 1%

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Sub-% precision \(\sim 6 - 7\sigma\) from scale invariance --> Inflationary Paradigm

Improves on pre-Planck constraints by a factor 1.5 - 2

Almost independent determinations from polarized spectra - good consistency
TT $\rightarrow$ EE at most 1$\sigma$ shifts
TT $\rightarrow$ TE at most 0.5$\sigma$ shifts
TE results are already almost as powerful as TT
Base $\Lambda$CDM

Good fit to the data

Bernal et al 2016
**Base $\Lambda$CDM**

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Optical death to last scattering surface
**POLARIZATION AND REIONIZATION**

\[ \tau = \int_{\eta}^{\eta_0} \sigma T n_e a(\eta) d\eta \]

Planck – LFI polarization data

Planck TT + lowP + lensing + BAO

\[ \tau = 0.066 \pm 0.013 \quad z_{\text{re}} = 8.8^{+1.3}_{-1.2} \]

Planck – HFI polarization data

Planck TT + SimLow (Planck intermediate results. XLVI.)

\[ \tau = 0.058 \pm 0.009 \quad z_{\text{re}} = 8.11 \pm 0.93 \]

Optical depth and reionization redshift lower than for WMAP polarization (2013)

\[ \tau = 0.089^{+0.012}_{-0.014} \quad z_{\text{re}} = 11.1 \pm 1.1 \]

and in better agreement with astrophysical observations and galaxy formation models.
The presence of a background of relic neutrinos \((\mathbf{C}_{\nu} B)\) is a basic prediction of the standard cosmological model

- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until \(T \sim 1\) MeV \((z \sim 10^{10})\);
- Below \(T \sim 1\) MeV, neutrino free stream keeping an equilibrium spectrum:
  \[
  f_\nu(p) = \frac{1}{e^{p/T} + 1}
  \]
- Today \(T_\nu = 1.9\) K and \(n_\nu = 113\) part/cm\(^3\) per species
THE COSMIC NEUTRINO BACKGROUND

This picture is consistent with current CMB observations:

\[ \rho_{\text{rad}} = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma \]

\[ n_\ell^2 = -\log_{10} \frac{C_\ell}{2\pi} \left[ 10^9 \mu K^2 \right] \]

\( N_{\text{eff}} = 2.5 \)
\( N_{\text{eff}} = 2.75 \)
\( N_{\text{eff}} = 3.046 \)
\( N_{\text{eff}} = 3.25 \)
\( N_{\text{eff}} = 3.5 \)

(note I am showing \( \sim \ell^4 C_\ell \), not \( \ell^2 C_\ell \))
THE COSMIC NEUTRINO BACKGROUND

This picture is consistent with current CMB observations:

\[ l^2(l+1)C_l/(2\pi) \, [10^9 \mu K^2] \]

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Energy density in units of “standard” neutrino density (thermally distributed with \( T=1.9 \) K)

(note I am showing \( \sim l^4 C_l \), not \( l^2 C_l \))
**The Cosmic Neutrino Background**

This picture is consistent with current CMB observations:

\[ \rho_{\text{rad}} = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_{\gamma} \]

Due to non-instantaneous decoupling, the standard expectation is \( N_{\text{eff}} = 3.046 \)

(note I am showing \( \ell^4 C_\ell \) not \( \ell^2 C_\ell \))

Energy density in units of "standard" neutrino density (thermally distributed with \( T=1.9 \) K)

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This picture is consistent with current CMB observations:

\[ N_{\text{eff}} = 3.15 \pm 0.23 \quad \text{(Planck TT+lowP+BAO)} \]
Higher values of $N_{\text{eff}}$ can help relieve the tension with astrophysical measurements of $H_0$. However, they imply a larger $\sigma_8$ and thus worsen the tension with LSS probes.

(Planck 2015 XIII)
Effective number of neutrino families

Planck constraints on $N_{\text{eff}}$ alone (can be regarded as a massless limit for the sterile)

$N_{\text{eff}} = 3.13 \pm 0.32$ (PlanckTT+lowP)

$N_{\text{eff}} = 3.15 \pm 0.23$ (PlanckTT+lowP+BAO)

$N_{\text{eff}} = 2.99 \pm 0.20$ (PlanckTT,TE,EE+lowP)

$N_{\text{eff}} = 3.04 \pm 0.18$ (PlanckTT,TE,EE+lowP+BAO)

(uncertainties are 68% CL)

$N_{\text{eff}} = 4$ (i.e., one extra thermalized massless neutrino) is excluded at between $\sim 3$ and 5 sigma.
**Background:** change in MR equality, angular-diameter distance to LSS

$H_0$ and $\Omega_\Lambda$ are varied to keep $z_{eq}$ and $\theta_s$ constant.

- $\Sigma m_\nu = 0.06 \text{ eV}$
- $\Sigma m_\nu = 0.2 \text{ eV}$
- $\Sigma m_\nu = 0.4 \text{ eV}$
- $\Sigma m_\nu = 0.6 \text{ eV}$
- $\Sigma m_\nu = 0.8 \text{ eV}$
How heavy?

Background: change in MR equality, angular-diameter distance to LSS can be mostly compensated by acting on other parameters (e.g. $H_0$)

$H_0$ and $\Omega_\Lambda$ are varied to keep $z_{eq}$ and $\theta_s$ constant

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Perturbations: free streaming, damping of small-scale perturbations.
HOW HEAVY?

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Net effect is to decrease lensing

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Perturbations: free streaming, damping of small-scale perturbations
- proportional to the neutrino energy density
- the effect is larger for larger masses
HOW HEAVY?

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Perturbations: free streaming, damping of small-scale perturbations
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95% constraints on total mass

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<th>\textit{PlanckTTTEEE}</th>
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</thead>
<tbody>
<tr>
<td>+lowP</td>
<td>&lt;0.72 eV</td>
<td>&lt;0.49 eV</td>
</tr>
<tr>
<td>+lowP+lensing</td>
<td>&lt;0.68 eV</td>
<td>&lt;0.59 eV</td>
</tr>
<tr>
<td>+lowP+BAO</td>
<td>&lt;0.21 eV</td>
<td>&lt;0.17 eV</td>
</tr>
<tr>
<td>+lowP+ext</td>
<td>&lt;0.20 eV</td>
<td>&lt;0.15 eV</td>
</tr>
<tr>
<td>+lowP+lensing+ext</td>
<td>&lt;0.23 eV</td>
<td>&lt;0.19 eV</td>
</tr>
</tbody>
</table>

Larger mass can partly alleviate the tension with LSS probes (smaller $\sigma_8$) but increases tension with direct measurements of the Hubble constant.
Power asymmetries in Planck data
Suppose now that this is not a statistical fluke and that we are seeing hints of new physics. What are the mechanisms that can provide such an effect? If we want to accommodate it in the primordial Universe, in general a transition FAST-SLOW roll of the inflaton can provide that.

Are we seeing relics of the onset of the slow-roll inflation via the power anomaly?

Destri, De Vega, Sanchez (2010)
Dudas, Kitazawa, Patil, Sagnotti JCAP 2012
Kitazawa, Sagnotti JCAP 2014
✓ String Theory and Supergravity may provide hints on the transition of the inflation from a pre-inflationary to an inflationary phase.

✓ This introduces an infrared depression in the power spectrum of primordial perturbations that can be modeled extending $\Lambda$CDM model with a new scale $\Delta$ (infrared depression).

$$\mathcal{P}(k) = A \left( \frac{k}{k_0} \right)^{n_s - 1}$$

$$\mathcal{P}(k) = \frac{A \left( \frac{k}{k_0} \right)^3}{\left[ \left( \frac{k}{k_0} \right)^2 + \left( \frac{\Delta}{k_0} \right)^2 \right]^{\nu}}, \quad \nu = 2 - \frac{n_s}{2}$$

Exact solution
Dudas, Kitazawa, Patil, Sagnotti JCAP 2012
✓ Performing a MCMC analysis we can constrain this new parameter Delta

✓ Results depend on the considered Galactic mask. With an extended mask, the detection is significant at 99% C.L..

This analysis indicates that the CMB anisotropy pattern at large angular scale exhibits some more power around the Galactic area. Is this power coming from last scattering surface or it is not of cosmological origin? Further investigations are needed.

Posterior probabilities of $\Delta$, in Mpc$^{-1}$, (solid line for the standard mask with fsky $\approx 90\%$, and dashed line for an extended mask with fsky $\approx 40\%$).

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This analysis will benefit from updated polarization measurements, from Planck 2017 and... beyond!
But there is more!

- Science targets exist that are polarization specific:
- Despite polarization is a generated at recombination [and later], we can use it to probe inflation
What is inflation?

• Inflation => sustained accelerating expansion in the early universe
• Has to be sustained, or we cannot explain why the universe is spatially flat
• How can we prove that it happened?
Where is the evidence?

- Existence of perturbations and CMB anisotropy is a hint. But this is not enough, other mechanism can explain their existence.
- CMB polarization gives more solid arguments
Temperature anisotropy and polarization from scalar fluctuations are anticorrelated!

• We observe anticorrelation on superhorizon scales.
• This is very difficult to cook outside of inflationary models.
• Can be seen on the maps!
Planck 2015 hot/cold spot stacking
Have a closer look

- Necessary and sufficient condition for inflation = sustained accelerating expansion in the early universe
- Expansion rate: $H = (da/dt)/a$
- Accelerating expansion: $(d^2a/dt^2)/a = dH/dt + H^2 > 0$
- Implying: $-(dH/dt)/H^2 < 1$
- Therefore, we prove inflation by showing $\varepsilon = - (dH/dt)/H^2 < 1$
- Sustained $\Rightarrow \varepsilon$ has to be small, $\sim \mathcal{O}(N^{-1}) << 1$, $N$ being the number of e-folds from the end of inflation

$$N \equiv \ln \frac{a_{\text{end}}}{a} = \int_t^{t_{\text{end}}} dt' H(t') \approx 50$$
Have can we “see” the inflation

• Show that $\varepsilon = - \frac{(dH/dt)/H^2}{H^2}$ is small.
• This is equivalent to “mapping” $H$
• You have to build a sort of “Hubble diagram” during inflation
Line element:

\[ d\ell^2 = a^2(t)[1 + 2\zeta(x, t)][\delta_{ij} + h_{ij}(x, t)]dx^i dx^j \]

Fluctuations have quantum origin, boosted by inflation. Ultra-long gravitational waves (also stretched by inflation) are just another kind of fluctuations.
Fluctuations are proportional to H

• True both for $\zeta$ and $h_{ij}$!
  – Quantum origin $\Rightarrow$ uncertainty principle ($H^{-1}$ is Hubble time):

$$\delta E \delta t \sim \frac{\delta E}{H} \Rightarrow \text{conserved!}$$

– Longer wavelength, larger angle on the sky, older fluctuation: by looking at different angular scales on the CMB power spectra, we can look at $H$!
Wavelengths

Multipole moment, $\ell$

Temperature fluctuations [\(\mu K^2\)]

Angular scale

Long

Short
"Primordial" power spectrum

\[ \ell \approx \ell^{n_s - 1} \]
Power spectrum tilt

- In 2013 Planck provided the first CMB only 5 sigma measurement of the departure of $n_s$ from 1
  
  \[ n_s = 0.960 \pm 0.007 \]

- This is a key prediction of inflation: it occurs because inflation has to end at some point
- So $1 - n_s << 1$. Does this imply $\varepsilon << 1$? NO!
- $H$ and $\zeta$ are proportional, but the factor may depend on time, and on the properties of matter.
- Need a probe which is disentangled by matter
Gravitational waves!

- Their amplitude is proportional to $H$ during inflation, and the constant is really a constant! (does not depend on time)
- So if you observe them, you have mapped $H$ during inflation!
- But *how* can we observe them?
- They contribute to CMB anisotropy, but are obscured by scalar anisotropy, which is much more intense.
- Need a clean channel!
Measuring tensor fluctuations brings:

• A “smoking gun” of inflation through direct mapping of $H$.

• A probe of the energy scale of inflation, can be directly linked to the “tensor to scalar ratio” $r = \frac{A_T}{A_S}$
  – current upper limits around $r < 0.07$ at 95% CL from combined analysis of Bicep/Keck and Planck

• A complementary probe of the primordial power spectrum for tensors, to check if it is also nearly scale invariant, i.e. $\approx \ell^{n_T}$ with $|n_T| << 1$ (in most models, $n_T = -2\varepsilon$)
Scalar spectral index and tensor fluctuations

Planck TT + lowP
\[ r_{0.002} < 0.10 \]

Planck TT + lowP + BKP
\[ r_{0.002} < 0.07 \]

+ lensing + ext
\[ r_{0.002} < 0.09 \]
Upper limits on primordial tensor modes. The constraints from Planck are already cosmic variance limited. They are also model dependent.

To improve we need direct detection of primordial B-modes.
**Inflationary Gravitational Waves**

The B-modes era has begun!

Bicep2/Keck Array + Planck BB
\[ r_{0.05} < 0.09 \text{ @95\% CL} \]

constraints from B-modes alone are already stronger than temperature

Bicep2/Keck Array + Planck BB & TT
\[ r_{0.05} < 0.07 \text{ @95\% CL} \]

PRESENT AND FORTHCOMING CMB PROBES

Ground

ACTPol

POLARBEAR

In addition, ABS, CLASS, POLARBEAR-2, Simons Array, Adv-ACTPol, ...

Atacama, Chile

BICEP1 DASI KECK QUAD

SPTPol BICEP2

South Pole

In addition, BICEP3, POLAR, QUBIC, ...

In addition, QUIJOTE in Canary island, AMiBA in Hawaii

Balloon

EBEX

Satellite

WMAP (obs. end in 2010)

Planck

SPIDER

LiteBIRD

LSPE

PIXIE

PIPER

COrE+
Not funded!

PRESENT AND FORTHCOMING CMB PROBES

Ground

Polarbear

ACTPol

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In addition, ABS, CLASS, POLARBEAR-2, Simons Array, Adv-ACTPol, ...

Atacama, Chile

In addition, BICEP3, POLAR, QUBIC, ...

South Pole

BICEP1

BICEP2

DASI

QUAD

KECK

In addition, QUIJOTE in Canary island, AMiBA in Hawaii

Balloon

EBEX

Spider

Satellite

WMAP (obs. end in 2010)

Planck

Retired

Almost- Retired

LiteBIRD

Not funded!

LSPE

PIPER

CORe+
The figure shows the angular power spectrum of different components of the cosmic microwave background (CMB) radiation as a function of multipole moment $\ell$. The spectrum is plotted on both a logarithmic and linear scale.

- The CMB spectrum is plotted up to multipole moment $\ell \approx 3500$.
- The spectrum includes contributions from various sources, including Galactic radiation, dust, synchrotron, and lensing, as well as contributions from different surveys and experiments.

The figure highlights the following components:

- **Galaxy (100 GHz)**
- **Galaxy (353 GHz)**
- **Galaxy (70 GHz)**
- **Galaxy (44 GHz)**
- **Galaxy (150 GHz)**

The figure also indicates the sky coverage ($f_{\text{sky}} = 73\%$) and includes data from different experiments and surveys:

- **Planck (2015)**
- **ACTpol (2014)**
- **SPTpol (2013/2014)**
- **BICEP2/Keck/Planck (2015)**
- **PolarBear (2014)**

The multipole moment $\ell$ is plotted on a logarithmic scale on the x-axis and on a linear scale on the right side of the graph.
Conclusions

- Planck is quickly approaching its final (legacy) release
- It has provided the ultimate (cosmic variance limited) measurement of CMB anisotropy
- ... But just opened the door of CMB polarization (which was never designed to measure, by the way)
- It has already fulfilled its promise of measuring the fundamental cosmological parameters to percent accuracy
- And brought remarkable constraints on particle physics parameters as well, excluding a fourth fully thermalized neutrino and constraining the total neutrino masses in the range of 0.2 eV
- Has measured well one relevant inflationary parameter, the primordial spectral index, allowing constraints on the inflationary paradigm
- Yet has uncovered several tensions with astrophysical measurements, which may or may not hint at new physics.
- Primordial gravitational waves remain unseen.
- To exploit the wealth of information that still is in the CMB, we need to cope with the extraordinary complexity of the sky. This can be credibly done only with a space mission.