Planck recent cosmological results

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Particle Physics and COsmology
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Outline

- Introduction
- The Planck mission
- CMB anisotropies analysis: temperature & polarization
- Adding more datasets
- The B mode saga
- Conclusions
Cosmology

- GR (isotropy & homogeneity) $\rightarrow$ concordance $\Lambda$CDM model: $\sim 7$ parameters
- Inflation paradigm $\Rightarrow$ origin of anisotropies
- CMB $\Rightarrow$ “snapshot” of density field $\sim 380,000$ y after BB
Cosmological parameters

“vanilla” $ΛCDM$ (Planck T + polar):

- primordial spectrum: normalisation $A_s$, spectral index $n_s$
  $\left( P_k = A_s (k/k_0)^{n_s-1} \right)$
- present expansion rate $H_0$ ($h = (H_0/100\text{km/s/Mpc})$)
- energy densities: $Ω_b h^2$, $Ω_{CDM} h^2$
- reionisation optical depth $τ$ (low $ℓ$ polarization)

Assumptions (addressed using extensions, including more data sets):

- flat universe
- light neutrinos: $\sum M_ν = 0.06$eV
- 3 families of $ν$ ($N_{eff} = 3.05$)
- no tensor modes ($r = A_t/A_s = 0$)

NB Results depend on fitted model + dataset(s) ⇒ check their compatibility!
The Planck mission

ESA mission project started 1992
launched on 15/05/2009 (with Herschel)
orbit around L2 (1.5Mkm)
guaranteed duration : 14 months (2 surveys)
extended till mid January 2012 (HFI) / mid 2013 (LFI)

1. Telescope (1.5m) - danish consortium
2. LFI (HEMTs 30-70GHz, 20 K, 15-30 arcmin beams) - consortium coordinated by Bologna Univ. (+US, Sp, It,...)
3. HFI (bolometers 100-857 GHz, 100 mK, 10-5 arcmin beam) - coordinated by Orsay+Paris; institutes from Ca, CH, Ge, Fr, Irl, It, NL, Sp, US, UK,...

“early results” 2011
first CMB results 2013 (T only, 1/2 mission)
second release 2014/5 (T+P, full dataset)
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Planck at L2

Continuous observations (7 months → all sky)
redundancies on different timescales (systematics)

2014-5 improvements: full mission T+P data, better control of instrumental systematics, absolute & more accurate calibration (no mismatch wrt WMAP)
The sky as seen by Planck
Planck physics

- primary objective(s): CMB anisotropies (T and polarization)
  photon noise limited for T and E modes
- many astrophysical components observed together with CMB:
  - Solar system: planets, asteroids, zodiacal light ...
  - Galactic: dust, synchrotron, free-free
  - extragalactic: clusters (SZ), CIB, radio sources, ...
- different frequency dependence $\Rightarrow$ component separation
- first full sky maps at 200-800 GHz
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different frequency dependence ⇒ component separation

first full sky maps at 200-800 GHz
Cosmological parameters from CMB (temperature) in a nutshell

- CMB map $\rightarrow$ spherical harmonic decomposition ($\ell \sim 1/\text{angle}$):

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{\ell} \sum_{m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

- general assumption $\Rightarrow a_{\ell m}$ are random variables (gaussian p.d.f.); $\langle a_{\ell m} \rangle_m = 0$; all information contained in their variance (=model prediction)

$$C_{\ell} = \frac{1}{2\ell + 1} \sum_{m} a_{\ell m} a_{\ell m}^\dagger$$

- only one realization is observable $\Rightarrow$ intrinsic dispersion wrt model ("cosmic variance")

- Planck analysis: 100, 143 and 217 GHz maps cross spectra (suppression of instrumental noise) with masks ($\Rightarrow$ low foregrounds contamination) (high $\ell$); CMB map ML (low $\ell$ I); 70GHz cleaned Q,U maps (low $\ell$ P)

- fit cosmological parameters using a likelihood function (accounting for CMB, residual foregrounds, instrumental nuisance parameters - $\sim$ 20 parameters)
CMB polarization analysis

- CMB is (weakly) polarized
- polarization = vector field \(\Rightarrow\) use Stokes parameters \(Q\) and \(U\)
- decompose \(Q + iU\) in the (spinned) spherical harmonics basis

\[
Q + iU = \sum \pm 2 a_{lm} \pm 2 Y_{lm}(\theta, \phi)
\]

- transform into parity even (E) and odd (B) components:

\[
\pm 2 a_{lm} = a_{lm}^E \pm i a_{lm}^B
\]

- As for temperature, all information contained in variances \(C_{\ell}^{XY}\) (\(X, Y = T, E, B\))
- in general 6 power spectra but symetries \(\Rightarrow C_{\ell}^{TB} = C_{\ell}^{EB} = 0\)
- one (ideal) detector at orientation \(\psi\) measures

\[
m = I + Q \cos 2\psi + U \sin 2\psi
\]

\(\Rightarrow\) needs several orientation/detector or several detectors (Planck)
CMB polarization

- Mecanism: temperature quadrupolar anisotropies + Thomson scattering on $e$

- Origins:
  - primordial tensor modes (GW) → B modes
  - plasma dynamics (correlation with temp. anisotropies) → E modes
  - late time re-ionisation ($z \sim 10$) → E modes (low $\ell$)
  - gravitational lensing transforms (part of) E into B modes

- very low amplitude signals ($\sim 10^{-2} - 10^{-4}$ temperature)

- amplitude of primordial B modes power spectrum measures $r = A_t/A_s$ ($\propto$ inflation energy scale)
Planck TT power spectra

output of Planck likelihood - foregrounds subtracted

Hybrid method: map based ML (low \( \ell \)) / pseudo-spectra (high \( \ell \)) of masked raw maps
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Planck 2014 CMB polarization

- High $\ell$ (>50) : 100-217 GHz

- Low $\ell$ : HFI 70 GHz (residual systematics in HFI polar maps)
CMB lensing by Large Scale Structures

LSS distortion of the CMB photons’ paths →
- small “smearing” of the $C_\ell$ spectra
- non gaussian distortion of the CMB images
- E→B leakage
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- $E \rightarrow B$ leakage
Mapping the lensing structures

CMB anisotropies 4 points statistics ⇒ Power spectrum of the deflexion field (integrated information on LSS @ $z \approx 2.5$)

2014-5 : more null tests, T+P...

used in cosmological parameter fits together with $C_\ell$
Planck 2014 (CMB only) ΛCDM parameters constraints

Polarization only agrees with T only
Non-CMB datasets

Nice agreement between CMB & BAO usefull for e.g. $\nu$ properties

Looking for extensions (Planck 2014/5 + external datasets)

- - - Λ CDM values
not much room for extensions
especially when combining with BAO
Neutrino sector constraints

\[\Sigma m^r \leq 0.21 \text{ (95\% C. L.)}\]

+ not much room for sterile \( \nu \) ...

number of relativistic species: \( N_{\text{eff}} = 3.15 \pm 0.23 \)
(standard value: 3.046)
DM annihilation ⇒ energy injection ⇒ changes the $e$ fraction ⇒ effect on CMB power spectra:
- suppression of amplitude
- enhancement of polar ($\ell \sim 300$)

Planck constraints

Thermal relic
Planck TT,EE,TE+lowP
WMAP9
CVL
Possible interpretations for:
AMS-02/Fermi/Pamela
Fermi GC
B modes with Keck/Bicep2

Planck 353 GHz ⇒ non-negligible dust contribution in B2/Keck data:

Constraints on $r$: B2K and Planck TT agree
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Constraints on $r$ : B2K and Planck TT agree

- Planck TT + lowP
- Planck TT + lowP + BKP + lensing + ext
Planck 2014-5 delivery is out: full dataset, better calibration, polar (high $\ell$)

$\Lambda$ CDM model better fitted than ever by CMB (+ BAO, SN1a) data: no strong need for extension

neutrino updated constraints

tighter DM annihilation constraints from CMB

dust contribution to B mode B2K result non negligible - key ingredient to measure $r$

no evidence for non gaussianities or scale on invariance (updated results)

CMB cosmology: uncertainties now dominated by systematics: beware before combining!

mild tension (O(2$\sigma$)) with astrophysical measurements involving amplitude of matter anisotropies (e.g. weak lensing, RSD)

more “in the can” (low $\ell$ polar/systematics control in HFI) - stay tuned! last release next year (TBC)

all planck papers (and more) are available here: http://www.cosmos.esa.int/web/planck
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
mild disagreement between Planck $H_0$ and local measurements: systematics?
both measurements depend on precise accounting for matter local anisotropies amplitude $\sigma_8$ (non linear + complex)
tensions with WL ...

... are hard to solve with extensions!