Toward primordial CMB B-modes observation

Sylvain Vanneste
Laboratoire de l’Accélérateur Linéaire, Orsay

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• Introduction:
  - The cosmological model and CMB
  - Inflation
  - B-modes of CMB

• B-modes analysis:
  - Foregrounds cleaning
  - CMB polarisation spectrum estimator

• Conclusion
Three pillars:

1. Universe expansion
2. Big Bang Nucleosynthesis
3. Cosmic Microwave Background (CMB)
• Standard cosmological model: \( \Lambda CDM \) (\( \Lambda \) + Cold Dark Matter)

• 6 parameters:
  - 2 for the primordial matter spectrum
    \[
    P_R(k) = (A_s) \left( \frac{k}{k_0} \right)^{n_s - 1}
    \]
    (primordial matter fluctuations induced by inflation)
  - 1 for the Universe expansion rate \( H_0 \)
  - 2 parameters for baryonic and dark matter densities \( \Omega_b \), \( \Omega_c \)
  - reionization parameter \( \tau \)
    (describes universe reionization epoch after Big-Bang)

• Cosmic Microwave Background (CMB) traces the distribution of matter at the early Universe (13 billions years ago).

→ Good probe for cosmology physics!
+ many other ground telescopes or balloon experiments...
Anisotropies power spectrum

- Spherical harmonics decomposition of temperatures anisotropies $\frac{\Delta T}{T}$:

$$\frac{\Delta T}{T} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^{T}_{\ell m} Y_{\ell m}$$

with spherical harmonics functions $Y_{\ell m}$

$$a^{T}_{\ell m} = \int \frac{\Delta T}{T} (\vec{n}) Y_{\ell m}^* (\vec{n}) d\vec{n}$$

$C^T_{\ell} = \langle a^{T}_{\ell m} a^{T}_{\ell m}^* \rangle$ is the temperature anisotropies power spectrum (two points correlation function)

- Compresses CMB data
- Retains all the cosmological statistics informations
• We fit for the 6 $\Lambda$CDM parameters
Precise constraints on $\Lambda$CDM from PLANCK data:

\[
\begin{array}{|c|c|}
\hline
\Omega_b & 0.0486 \pm 0.0010 \\
\Omega_c & 0.2589 \pm 0.0057 \\
H_0 & 67.3 \pm 1.20 \\
\tau & 0.089 \pm 0.014 \\
n_s & 0.960 \pm 0.007 \\
10^9 A_s & 2.196 \pm 0.06 \\
\hline
\end{array}
\]

- Dark energy?
- Dark matter?
- Inflation?
- ....

Universe matter density distribution:
- 69% Baryon matter
- 26% Dark energy
- 5% Dark matter
Inflation: huge and brief Universe expansion after ‘Big-Bang’

Eventual location of the Milky Way Galaxy

Edge of the observable universe

(a) Before inflation   (b) After inflation   (c) Today

10^{24} m = 30 Mpc

10^{-26} m

10^{-23} m

10^4 Mpc

‘Problems’ of cosmology:
- Horizon ?
- Flatness ?
- Primordial fluctuations ?

Inflation:
- Former causal contact. ✓
- Flattens the Universe. ✓
- Quantum fluctuations → macroscopic scales ✓
Inflation predictions

Inflation origin?
→ Simplest mechanism: a scalar field, the ‘inflaton’.
→ Open questions: nature of the inflaton? shape of its potential?

Hints for inflation:
• Already measured:
  ✦ $n_s < 1$ from PLANCK.
• Predicts gaussian and adiabatic fluctuations of initial densities (PLANCK).

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Inflation validation:
• Inflation generates primordial gravitational waves $\rightarrow$ visible in CMB?
  $\rightarrow$ B modes!
CMB polarisation

- CMB photons are polarised.
- Decomposition in two patterns (as in EM): E modes and B modes.

Primordial BB spectrum:
- Produced by inflation only (via primordial gravitational waves).
- Directly validates inflation theory. ✓
- Measures the inflation energy. ✓
- At least 1000 times weaker than temperature. ✗
Things are not so simple

**CMB Temperature** (expected)

**CMB Polarisation** (expected)

-500 µK  500 µK

-5 µK  5 µK
Things are not so simple

**CMB Temperature** (expected)

-500 µK 500 µK

**CMB Polarisation** (expected)

-5 µK 5 µK

**CMB Polarisation**

(what we actually see)

-5 µK 5 µK
Things are not so simple

CMB Temperature (expected)

-500 µK  500 µK

CMB Polarisation (expected)

-5 µK  5 µK

CMB maps contaminated by:

- Galactic foregrounds:
  - Synchrotron
  - Dust
- Instrumental noise

→ Tools to handle contaminations (my work)
Foregrounds signals

Different signal behaviours as a function of photons frequency (or wavelength):

- 100 GHz
- 217 GHz
- 353 GHz
- 143 GHz
First approximation: Linear

\[ \text{Map (100 GHz)} = \text{CMB} + \alpha \times \text{Dust Template} + \text{Noise} \]

\[ \text{Dust Template} \approx \text{Map (353 GHz)} \approx \text{Dust} + \text{CMB} + \text{Noise} \]

\[ \hat{\alpha} = \frac{\sum n_{\text{pix}} (\alpha T^2 + \sigma_c^2)}{\sum n_{\text{pix}} (T^2 + \sigma_c^2 + \sigma_t^2)} \cdot \]

Map cleaning:

\[ \text{CMB estimation} = \left( \text{Map} - \alpha \times \text{Dust} \right) \bigg/ (1 - \alpha) \]

- \( T \) = Template
- \( \sigma_c^2 \) = CMB variance
- \( \sigma_t^2 \) = template noise variance
• Dust properties on the sky not sufficiently modelled yet.

• Goal: test $\alpha$ coefficients variations over the sky for PLANCK maps.

• Cut sky into patches:

• Linear regression result over whole sky (1 patch):

\[
\text{Dust} \quad \alpha = 0.0183 \pm 0.0004
\]

• Linear regression results for 700 patches:

→ Given PLANCK noise level, no variation of the dust coefficient $\alpha$ over the sky.
• Initial PLANCK map

• Foreground subtraction

• Masking eventual foreground residuals
Treated CMB map

Power spectra estimation $C_\ell$

Model ($\Lambda$CDM)

Cosmological parameters

- $\Omega_c$
- $\Omega_b$
- $H_0$
- $\tau$
- $n_s$
- $10^9 A_s$
EE - BB mixing
- **B patterns** ↔ **E patterns** hard to distinguish near mask → mixed signal
• **B patterns** ↔ **E patterns** hard to distinguish near mask → mixed signal

→ E-B mixing must be handled!
**Power spectra estimators**

**Pseudo spectrum:**
- Direct estimation of pseudo-spectra $C_\ell$ from data.
- Near optimal variance ✓
- Possible E-B mixing ✗
- Cross-spectrum ✓
- Computationally fast ✓
- Less efficient for large angular scale ✗ (most BB signal)

**Approximation of maximum likelihood (QML):**
- From pixel-pixel correlation.
- Optimal variance ✓ → especially required for B-modes
- Less E-B mixing effect ? → my work
- Cross-spectrum ? → my work
- Computationally expensive ✗
- Efficient for large angular scale ✓
Cross-spectrum

Auto-correlation

\[ C_\ell = \langle a_{\ell m}^X a_{\ell m}^{X*} \rangle \]

Requires perfect noise knowledge for de-biasing

\[ \langle \text{noise}_X, \text{noise}_X \rangle = \sigma_X^2 \]

Cross-correlation

\[ C_\ell = \langle a_{\ell m}^X a_{\ell m}^Y \rangle \]

Unbiased!

\[ \langle \text{noise}_X, \text{noise}_Y \rangle = 0 \]
Preliminary results

Approximation of maximum likelihood (QML):

- Less E-B mixing effect ✓
- Cross-spectrum ✓
- Efficient for large angular scale ✓
- Optimal variance ✓

→ Next step:
Apply on Planck maps!
• B-modes are keys for understanding the primordial Universe and nature of inflation

• Challenging to measure, requires lot of efforts in next decades:
  - State-of-the-art technology
  - Precise astrophysics and cosmology models
  - Optimised data analysis

Thank you
CMB today and tomorrow

- Goal: precise polarisation measurements.
- Next generation of experiments:
  - SPT3G, Advanced ACTPol, Simons Array, BICEP3 & Keck Array, QUBIC, LiteBird …

Stages IV, ground based:
- Lots of detectors (>100 000).
- Located in South Pole, and on Atacama plateau in Chilean.
- Testing inflation, neutrinos, dark energy, general relativity, …