

Toward primordial CMB B-modes observation



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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**

Universe history

Three pillars :

1. Universe expansion
2. Big Bang Nucleosynthesis
3. **Cosmic Microwave Background (CMB)**



Cosmological Standard Model

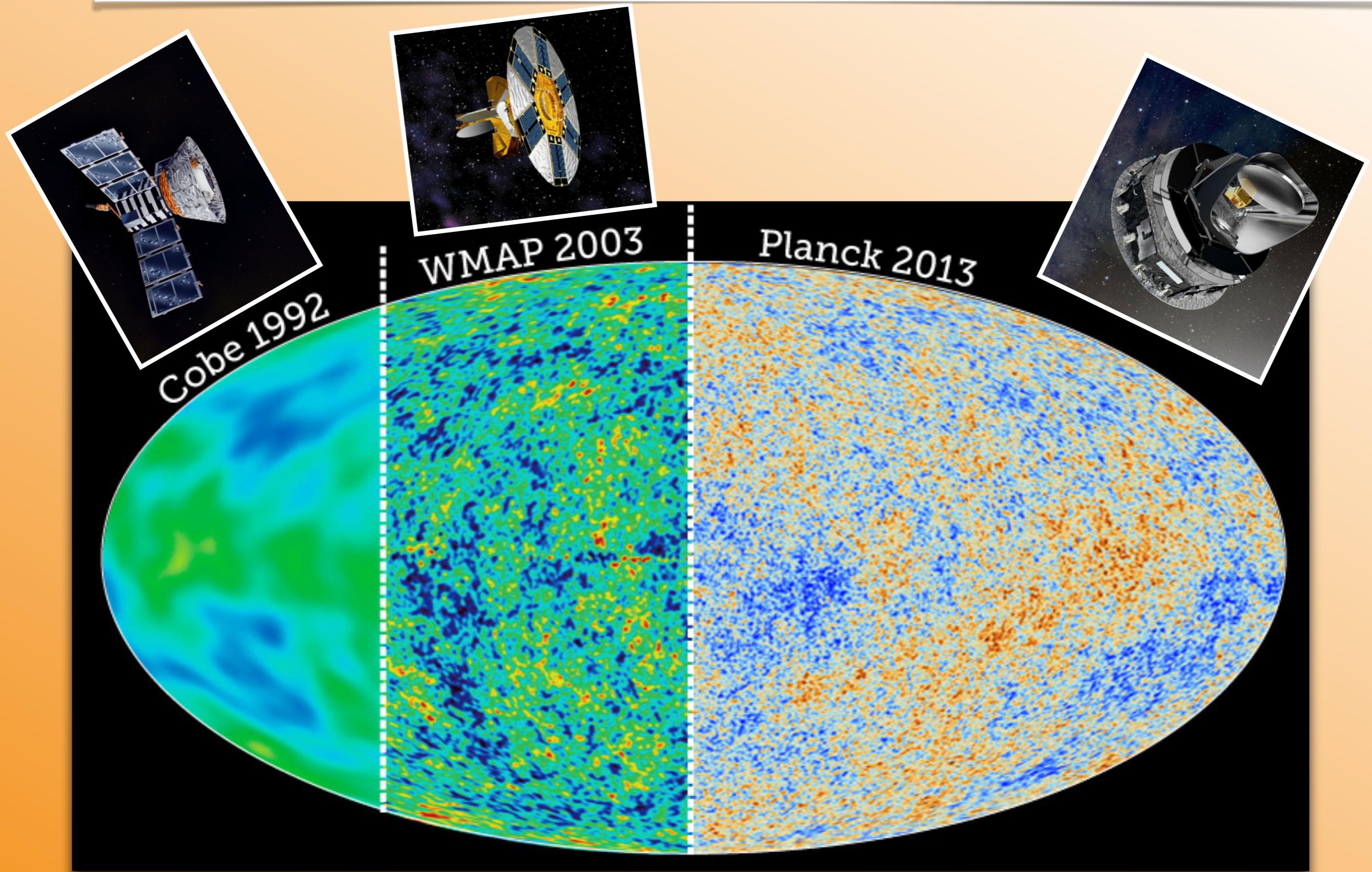
- Standard cosmological model : ΛCDM (Λ + Cold Dark Matter)
- 6 parameters :

- 2 for the primordial matter spectrum $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$
(primordial matter fluctuations induced by inflation)
- 1 for the Universe expansion rate H_0
- 2 parameters for baryonic and dark matter densities Ω_b Ω_c
- reionization parameter \mathcal{T}
(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 !

Cosmic Microwave Background anisotropies



+ many other ground telescopes or balloon experiments...

Anisotropies power spectrum

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

$$\frac{\Delta T}{T} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^T Y_{\ell m} \quad \text{with spherical harmonics functions } Y_{\ell m}$$

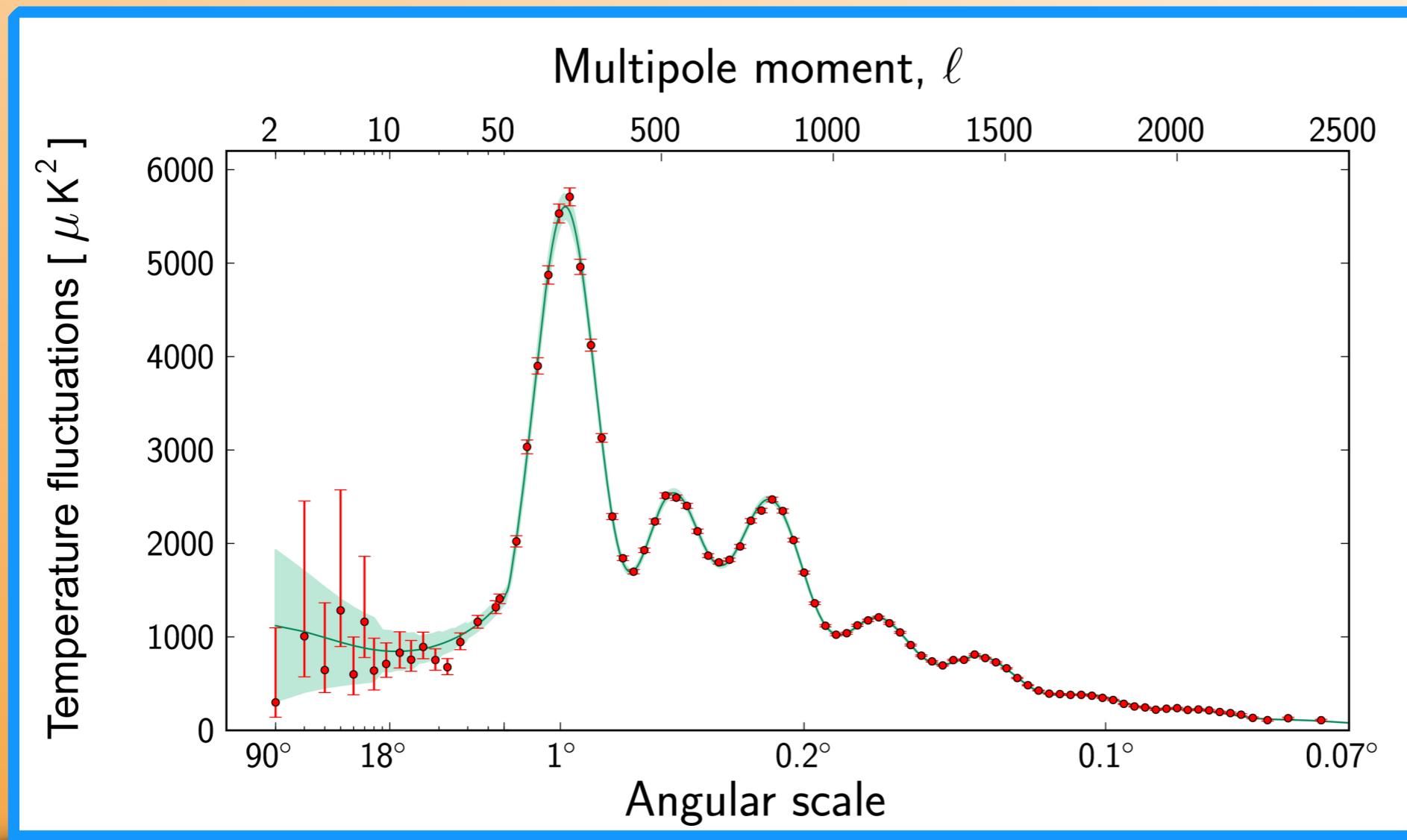
$$a_{\ell m}^T = \int \frac{\Delta T}{T}(\vec{n}) Y_{\ell m}^*(\vec{n}) d\vec{n}$$

$$C_\ell^T = \langle a_{\ell m}^T a_{\ell m}^{T *} \rangle$$

is the temperature anisotropies **power spectrum** (two points correlation function)

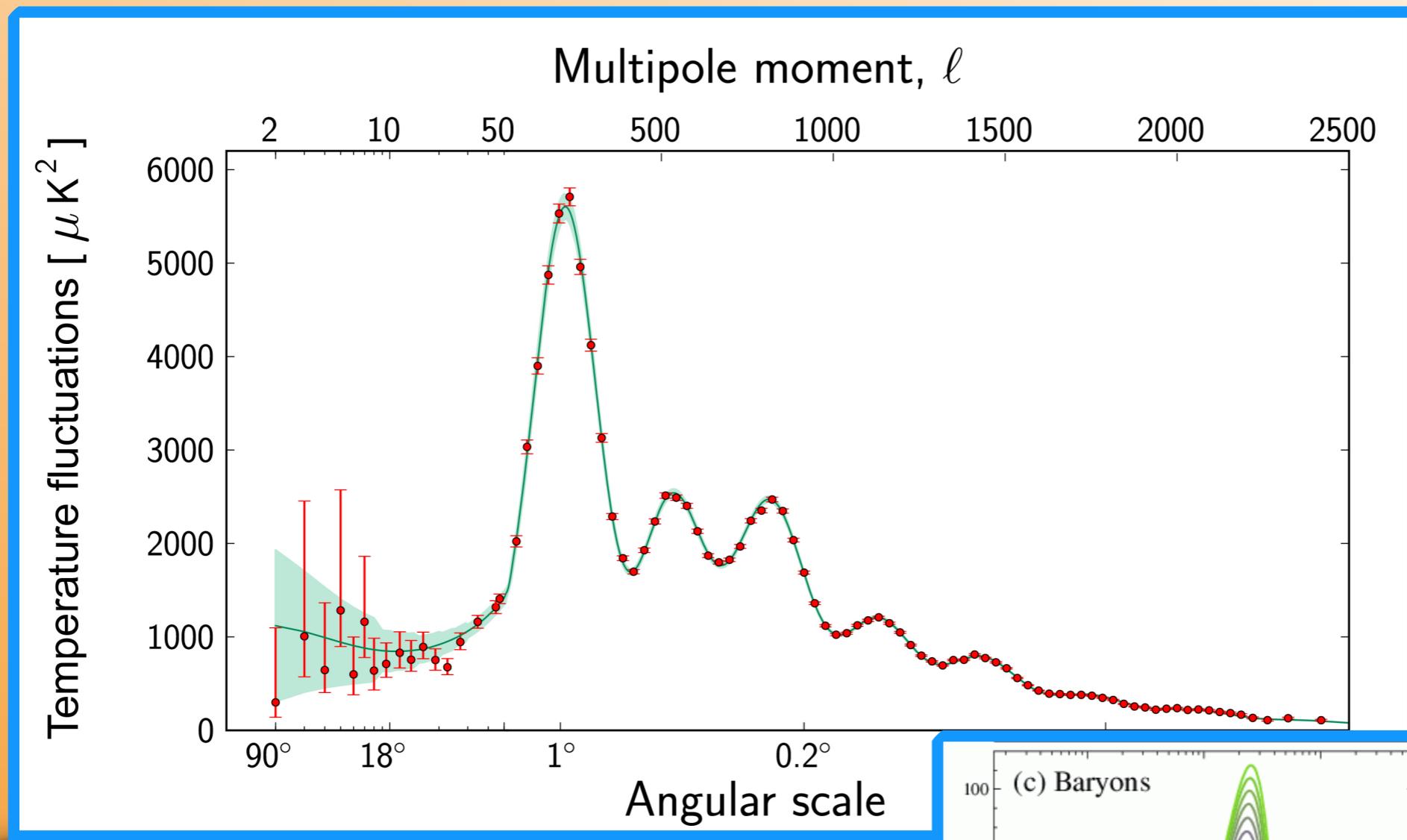
- Compresses CMB data
- Retains all the cosmological statistics informations

PLANCK power spectrum

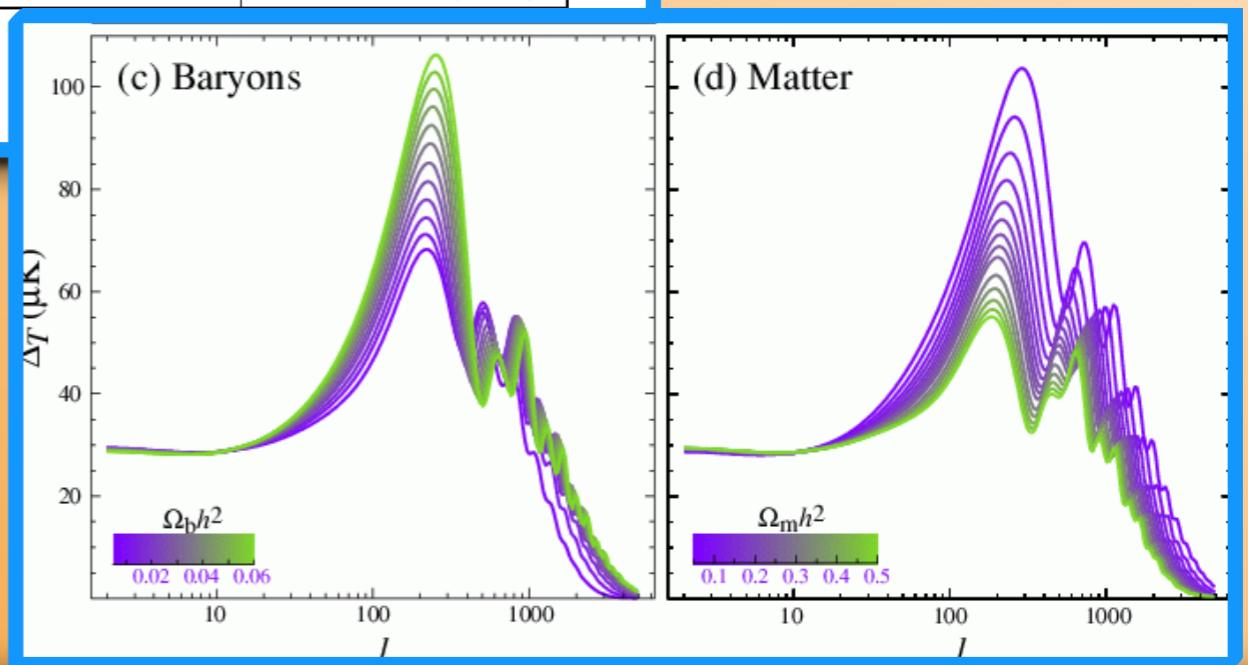


- We fit for the 6 ΛCDM parameters :

PLANCK power spectrum



- We fit for the 6 ΛCDM parameters :

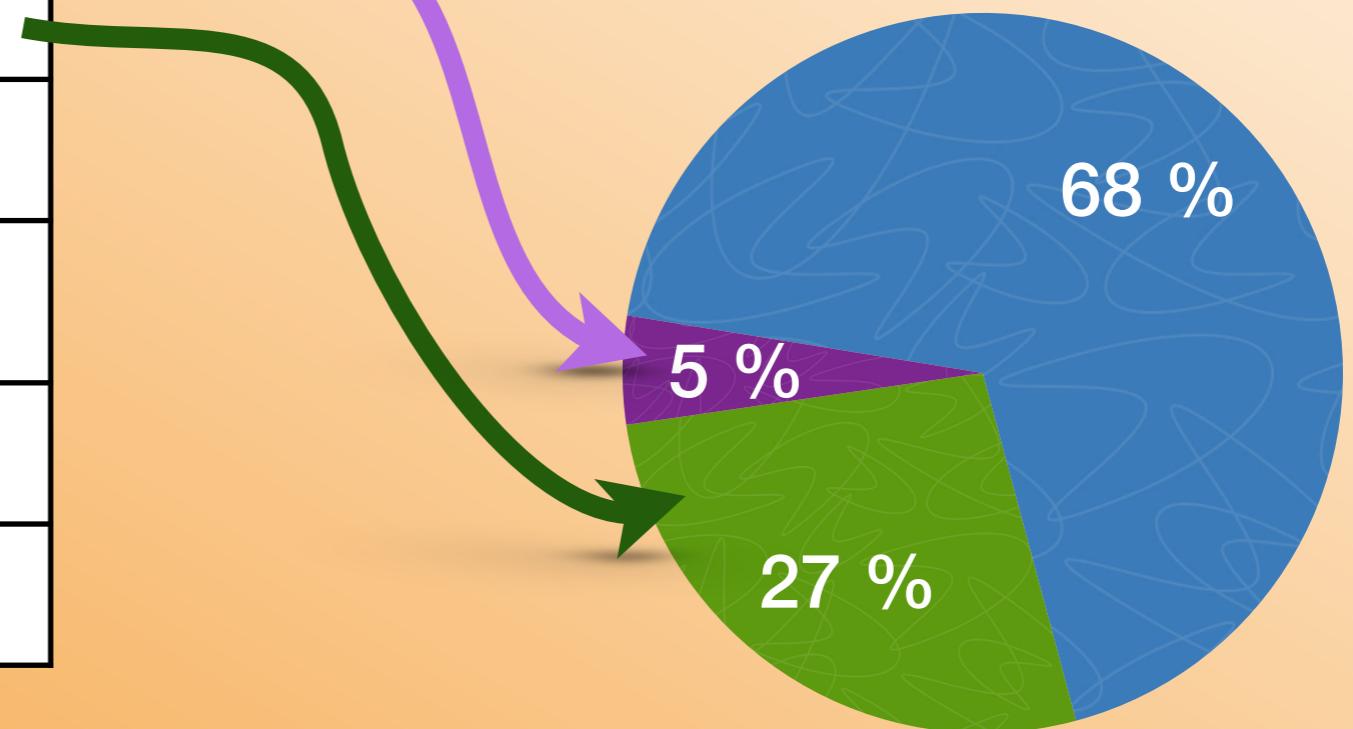


Parameters measurements

- Precise constraints on Λ CDM from PLANCK data :

Ω_b	0.0486 ± 0.0010
Ω_c	0.2589 ± 0.0057
H_0	67.3 ± 1.20
τ	0.089 ± 0.014
n_s	0.960 ± 0.007
$10^9 A_s$	2.196 ± 0.06

Universe matter density distribution

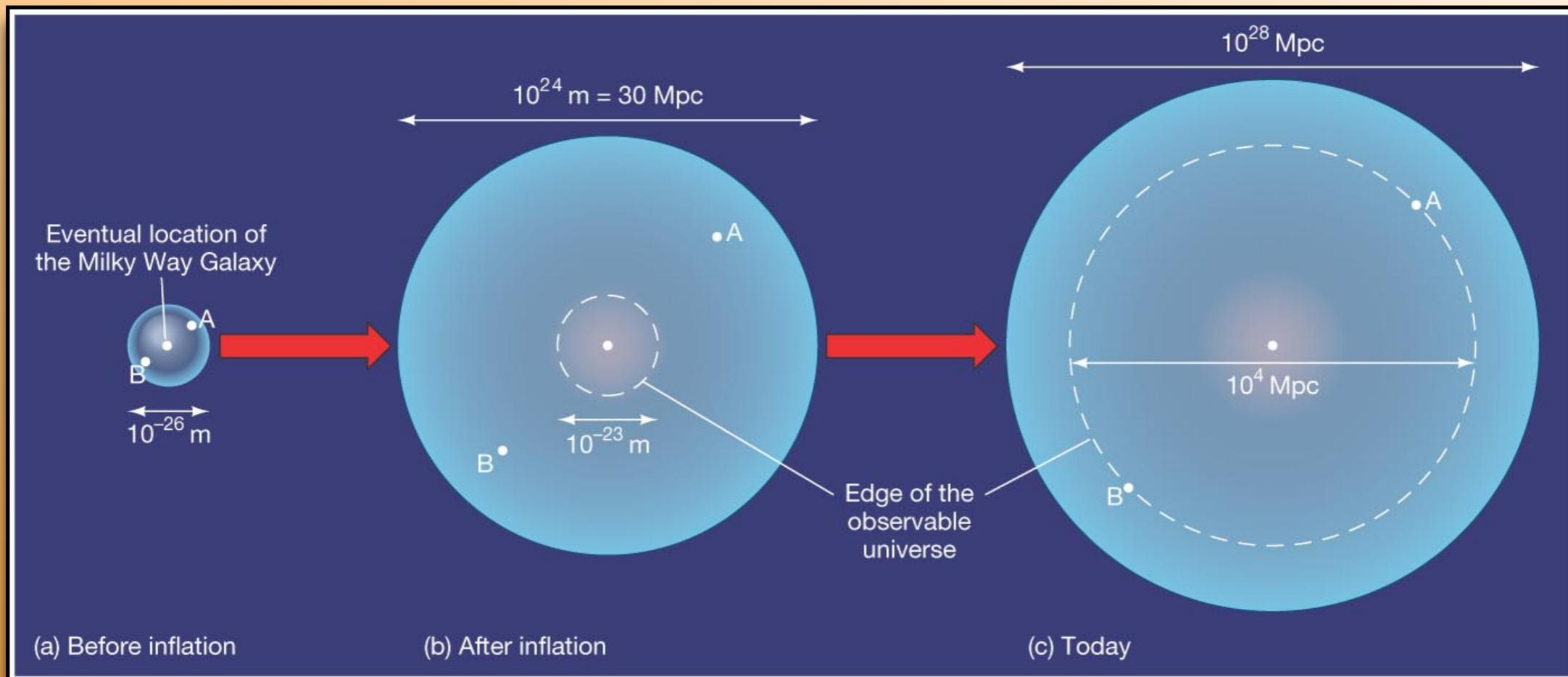


- Dark energy ?
- Dark matter ?
- Inflation ?
-

- Baryon matter
- Dark energy
- Dark matter

Inflation

Inflation : huge and brief Universe expansion after ‘Big-Bang’



‘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 ‘*inflation*’.
- Open questions : nature of the inflaton ? shape of its potential ?

Hints for inflation :

- Already measured :
 - ◆ **n_s < 1** from PLANCK. ✓

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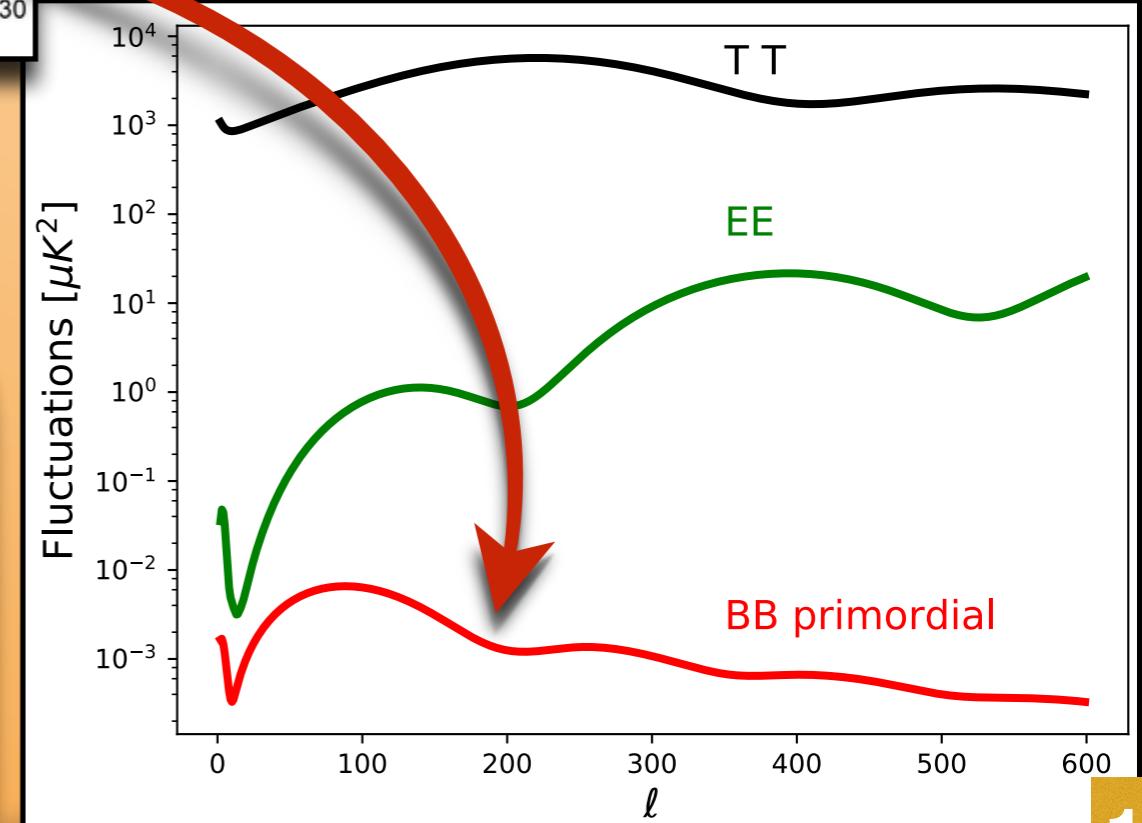
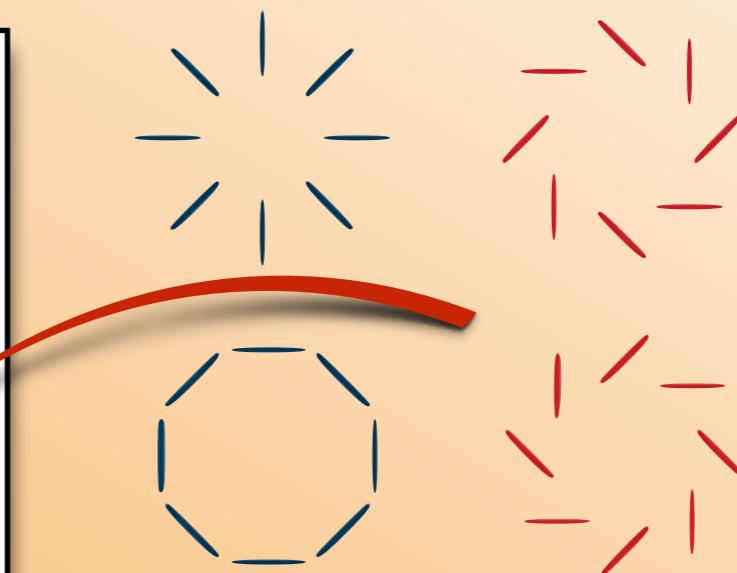
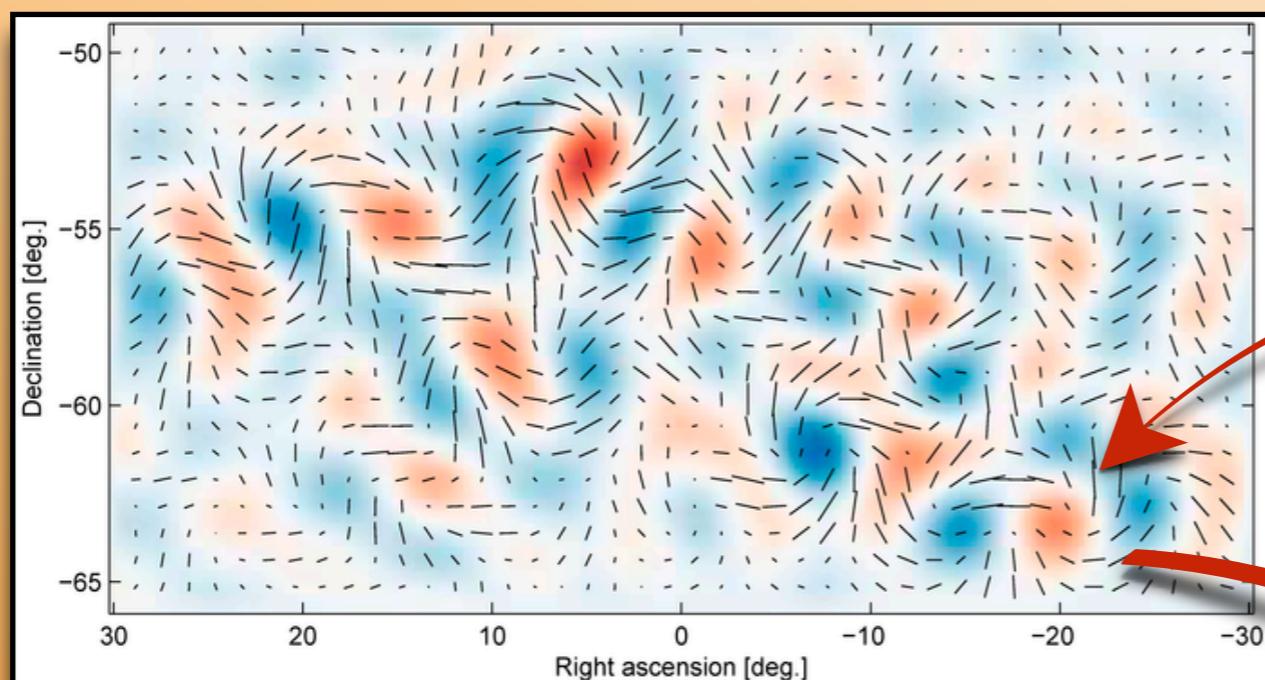
- ◆ Predicts *gaussian* and *adiabatic* fluctuations of initial densities (PLANCK). ✓

Inflation validation :

- Inflation generates primordial gravitational waves → visible in CMB ?
 - **B modes !**

CMB polarisation

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

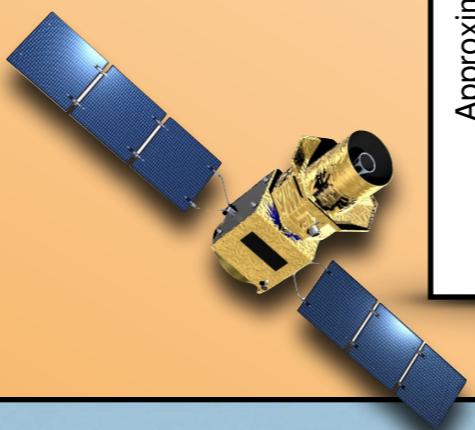


Primordial BB spectrum :

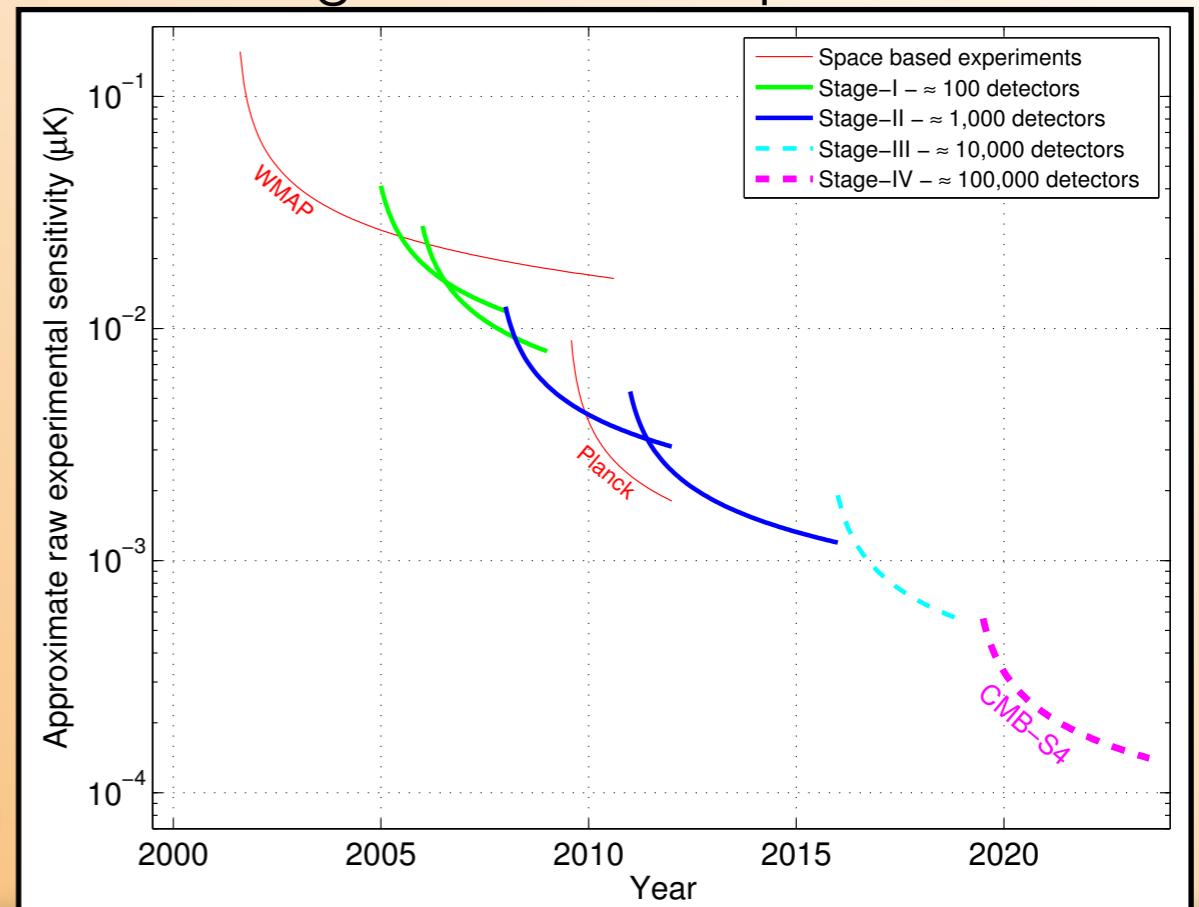
- Produced by **inflation** only
(via primordial gravitational waves).
- Directly validates inflation theory. ✓
- Measures the inflation energy. ✓
- At least 1000 time weaker than temperature. ✗

CMB today and tomorrow

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



Stages of CMB experiments



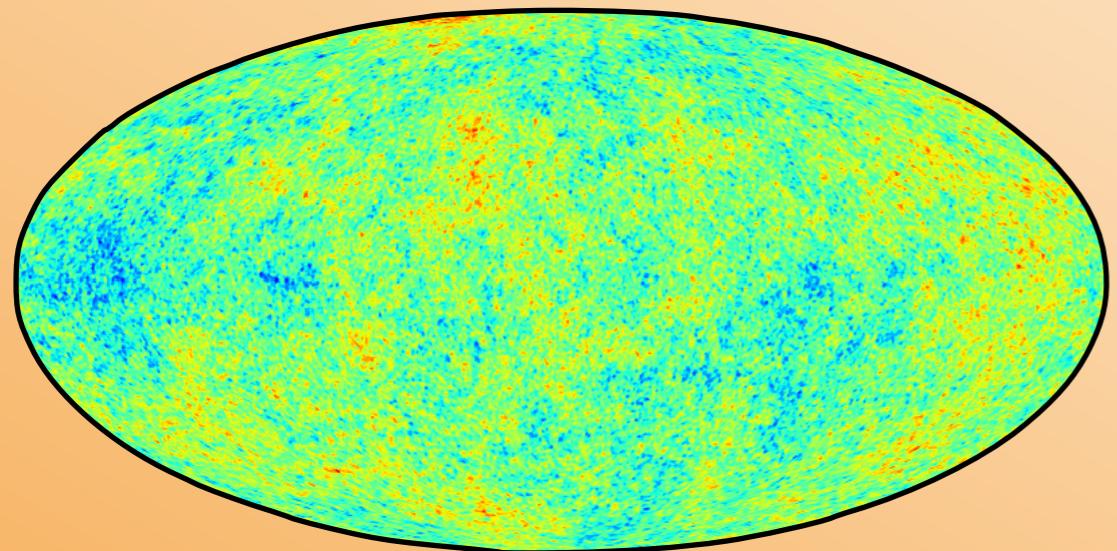
Stages IV , ground based :

- Lots of detectors ($>100\,000$).
- Located in South Pole, and on Atacama plateau in Chilean.
- Testing inflation, neutrinos, dark energy, general relativity, ...



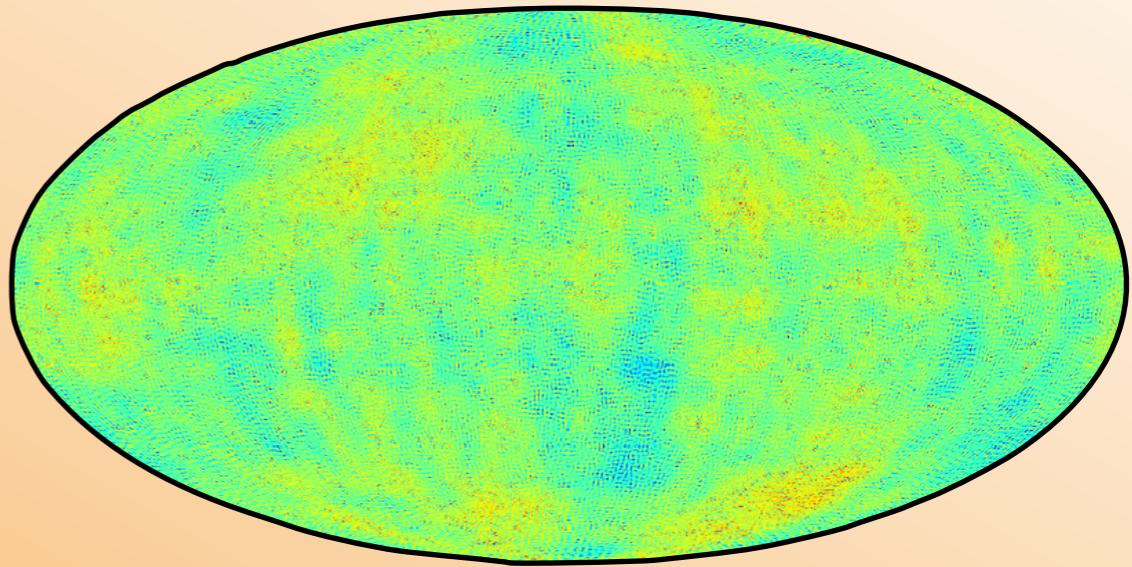
Things are not so simple

Temperature (expected)



-500 μK ————— 500 μK

Polarisation (expected)



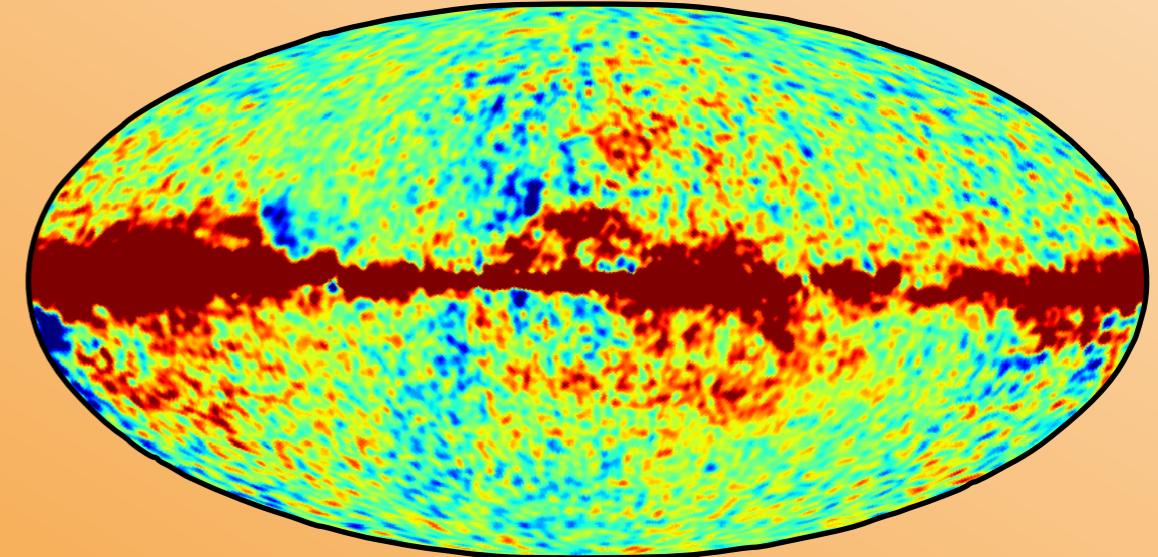
-5 μK ————— 5 μK

CMB maps contaminated by :

- Galactic foregrounds :
 - ◆ Synchrotron
 - ◆ Dust
- Instrumental noise

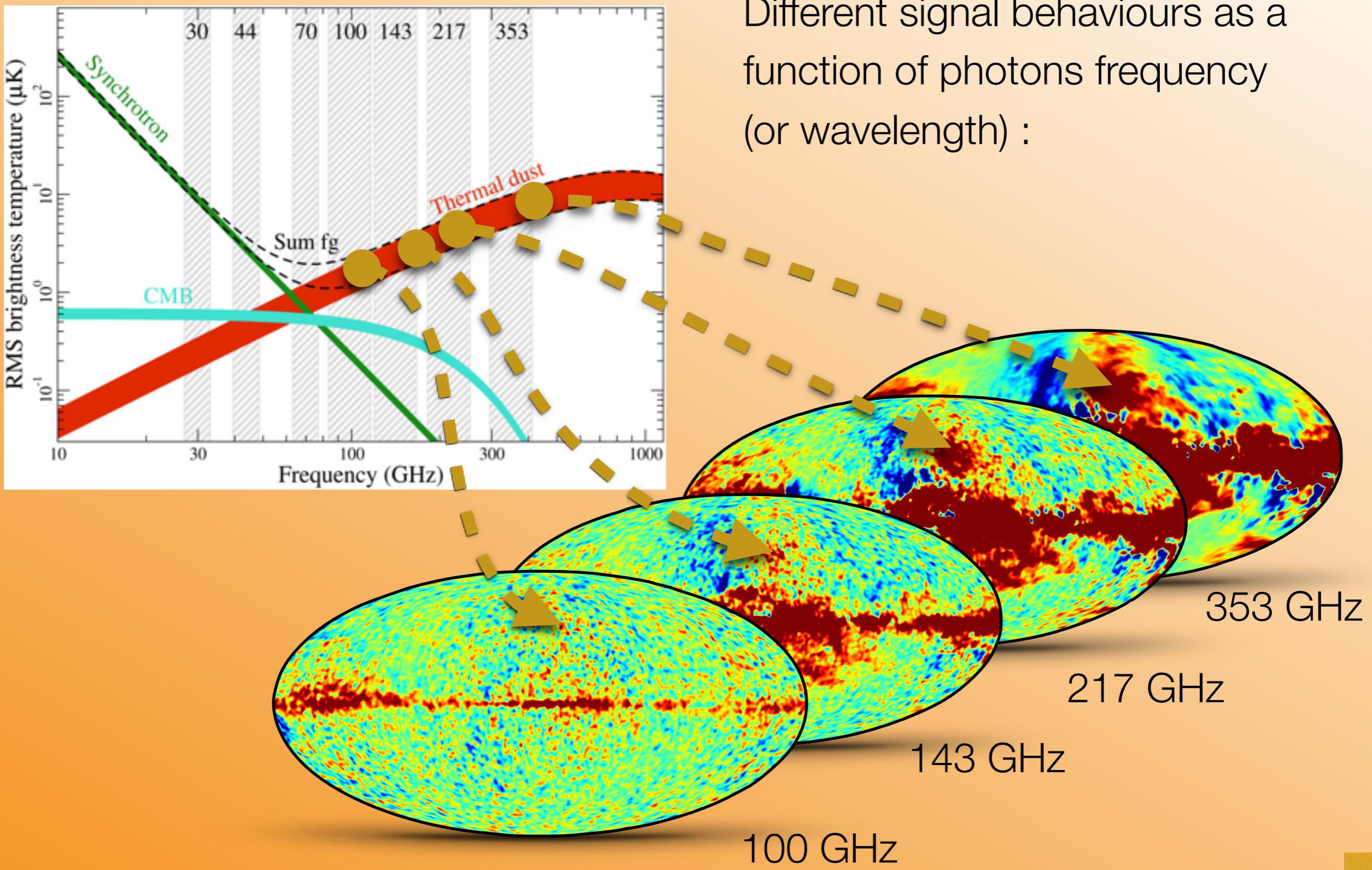
→ *Tools to handle contaminations
(my work)*

Polarisation (what we actually see)



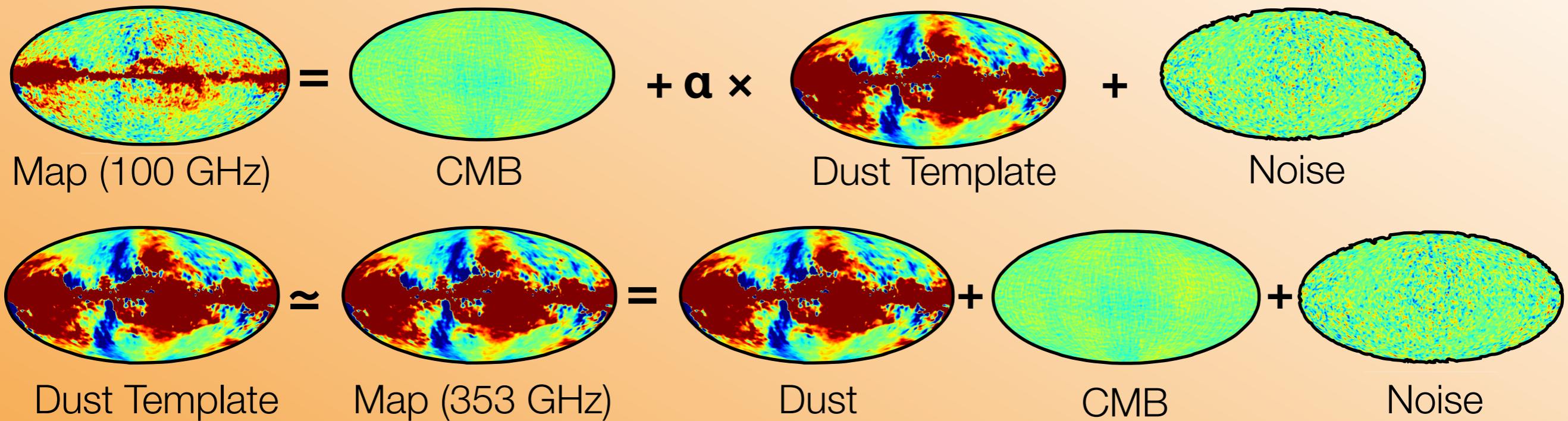
-5 μK ————— 5 μK

Foregrounds signals



Template cleaning

- First approximation : Linear



$$\rightarrow \hat{\alpha} = \frac{\sum n_{pix} (\alpha T^2 + \sigma_c^2)}{\sum n_{pix} (T^2 + \sigma_c^2 + \sigma_t^2)}.$$

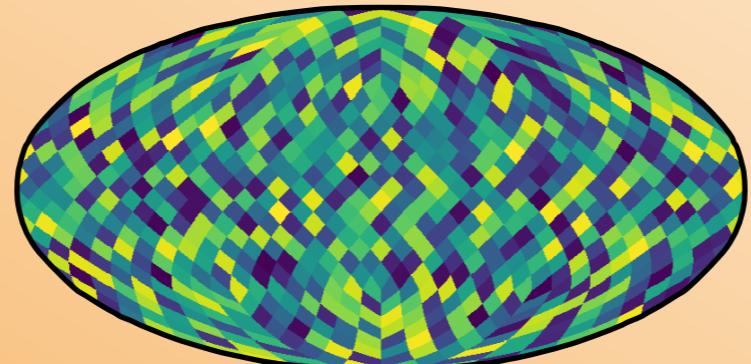
- T = Template
- σ_c^2 = CMB variance
- σ_t^2 = template noise variance

- Map cleaning :

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

Variation over the sky

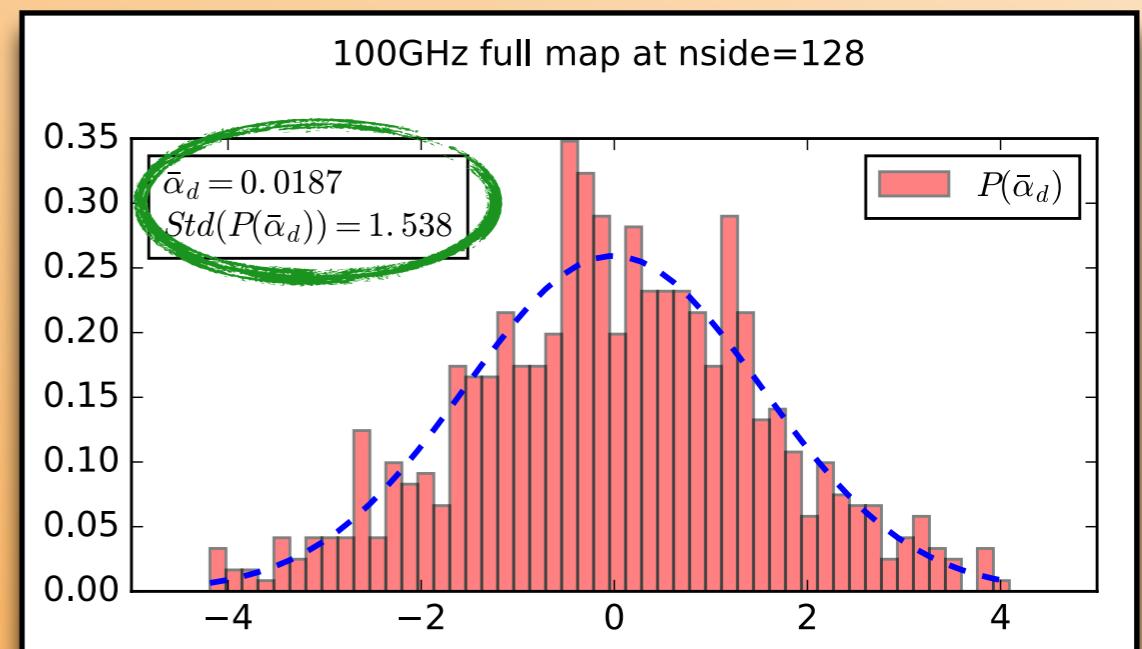
- Dust properties on the sky not sufficiently modelled yet.
- Goal : test α coefficients variations over the sky for PLANCK maps.



- Cut sky into patches :

Map	100GHz
Dust	$\alpha = 0.0183 \pm 0.0004$

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

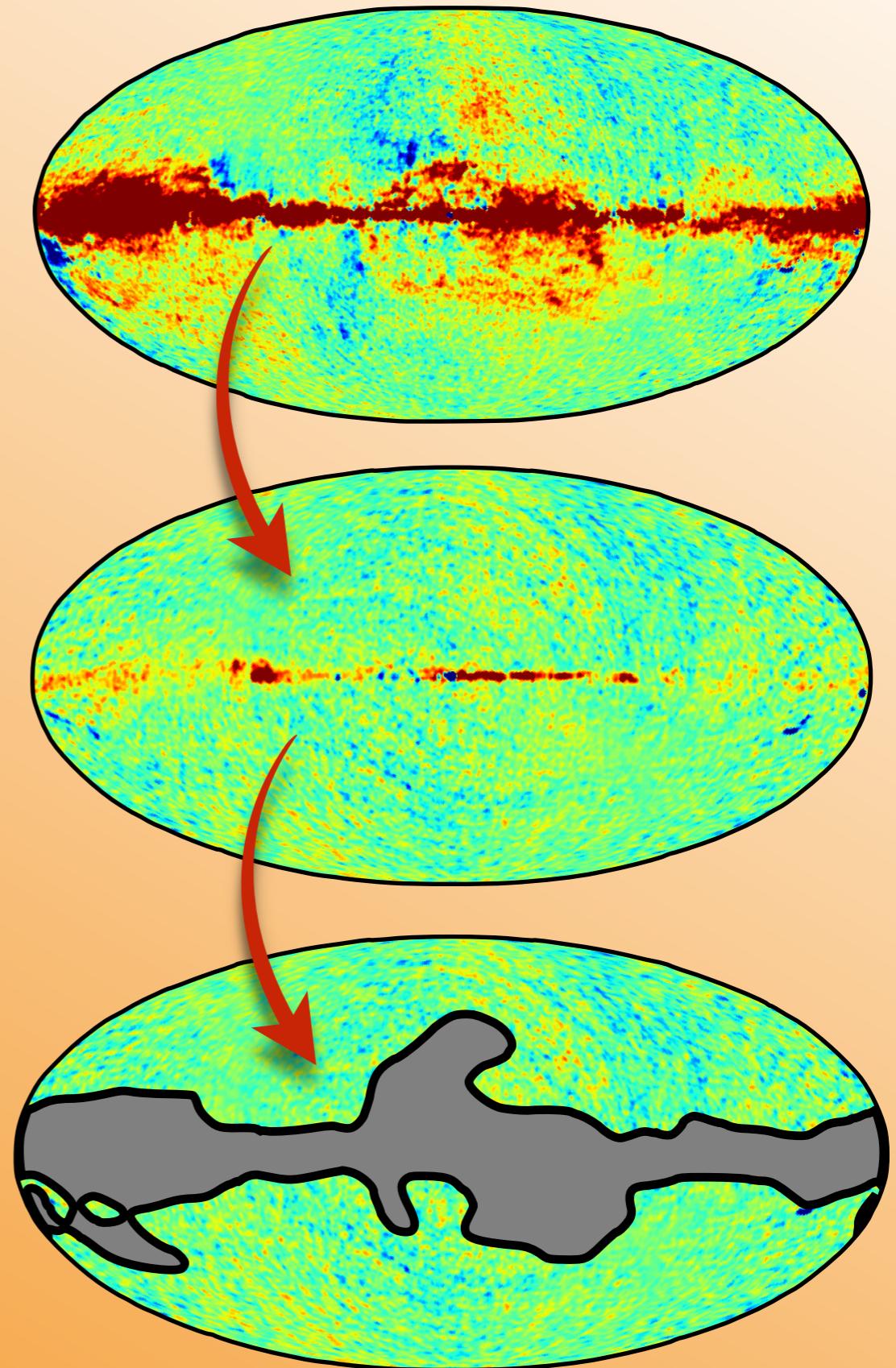


- Linear regression results for 700 patches :

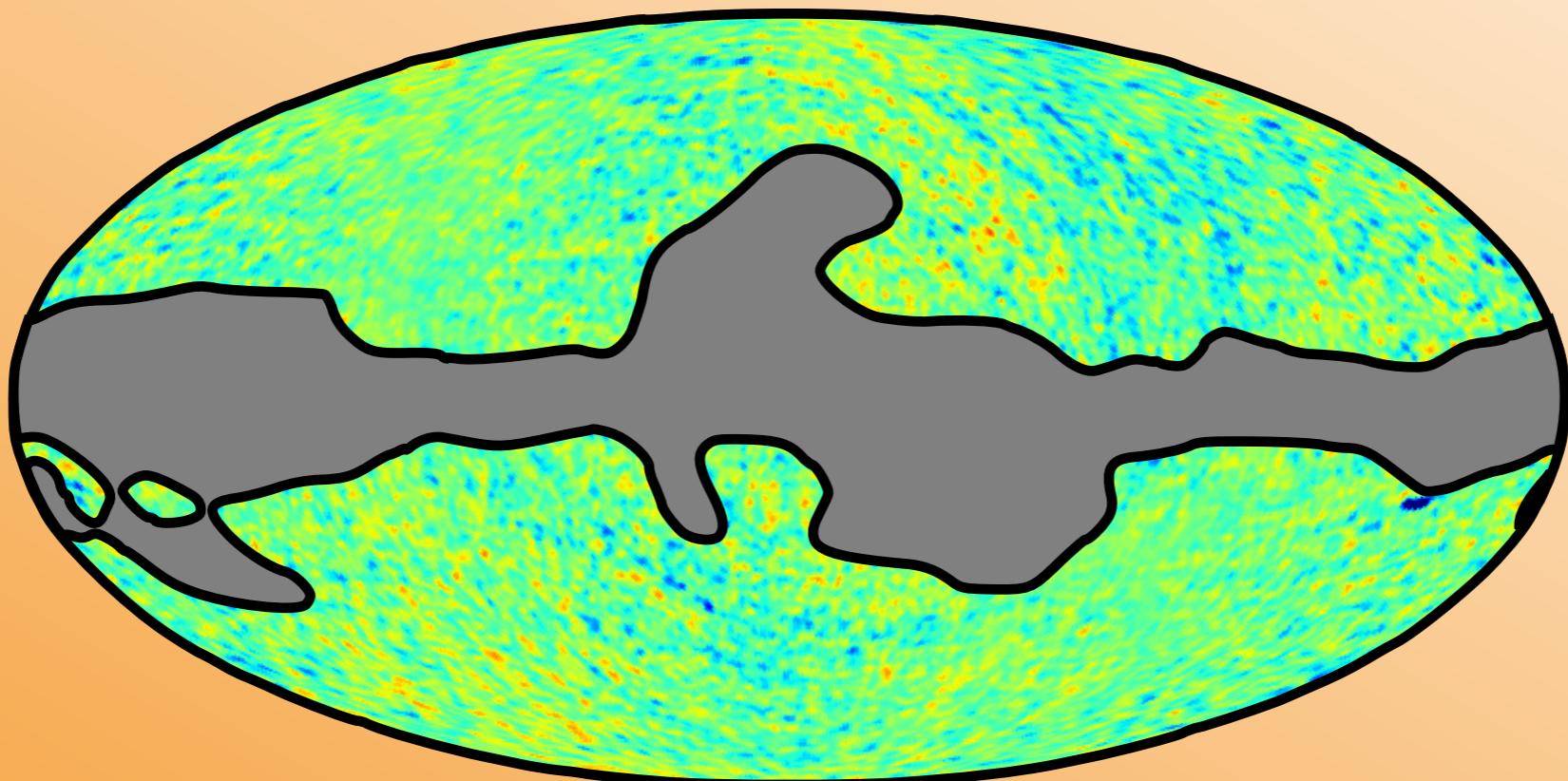
→ Given PLANCK noise level, no variation of the dust coefficient α over the sky.

Map cleaning steps

- Initial PLANCK map
- Foreground subtraction
- Masking eventual foreground residuals

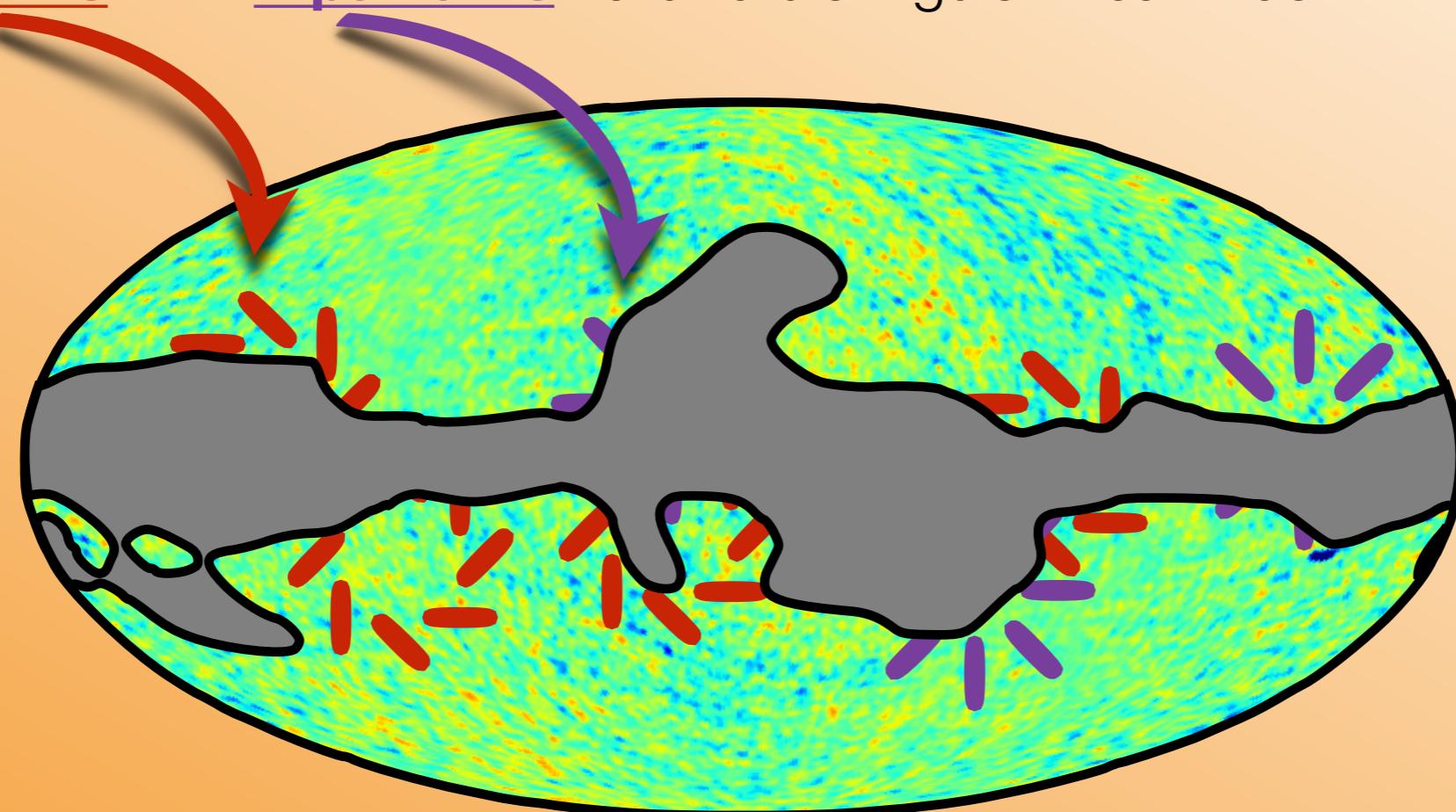


EE - BB mixing



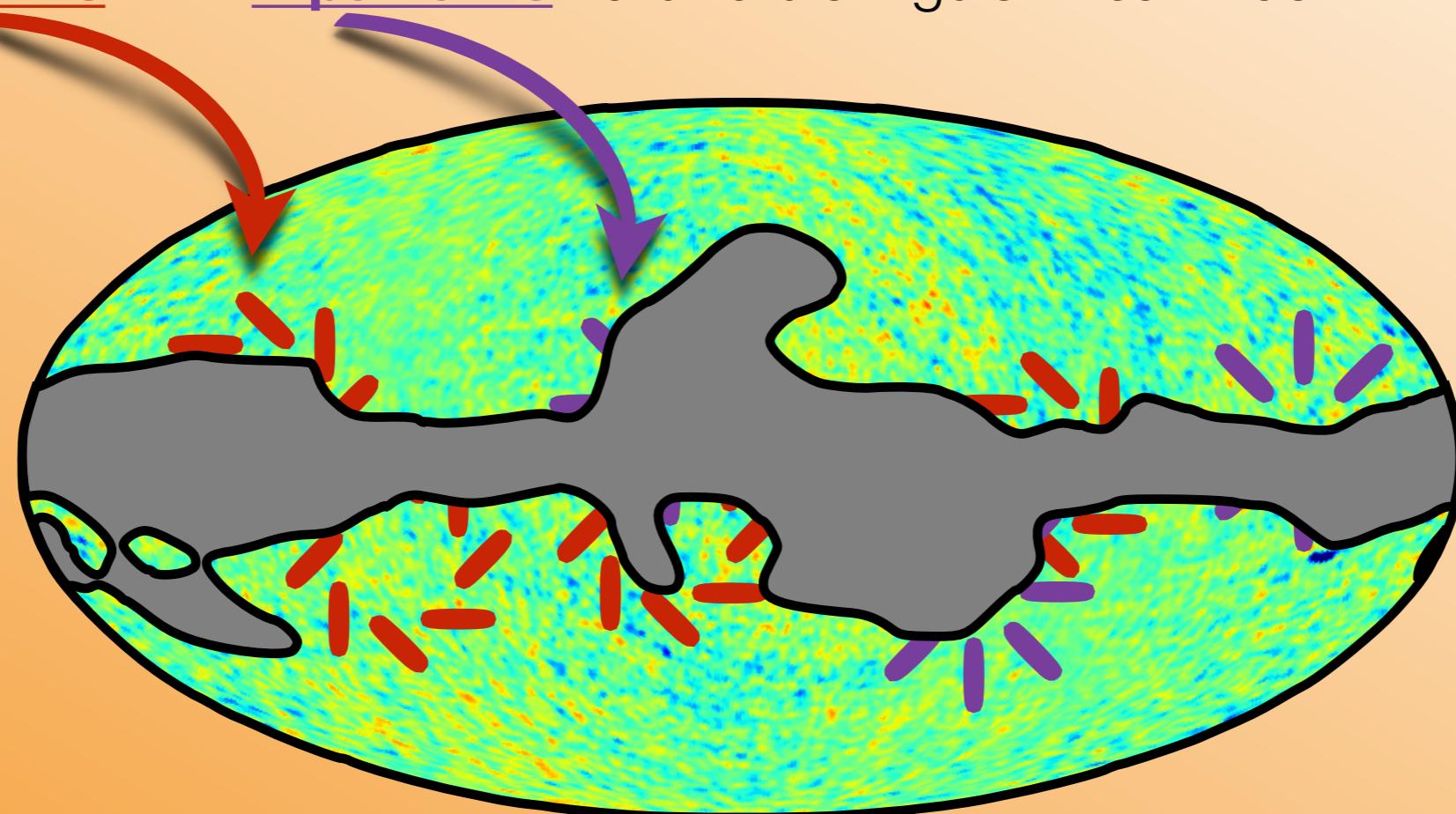
EE - BB mixing

- **B patterns** ↔ **E patterns** hard to distinguish near mask → mixed signal



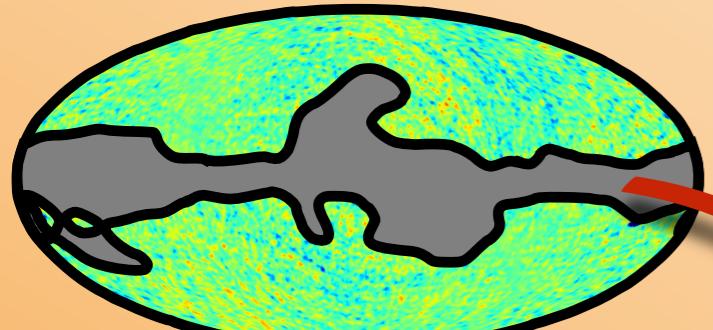
EE - BB mixing

- **B patterns** ↔ **E patterns** hard to distinguish near mask → mixed signal

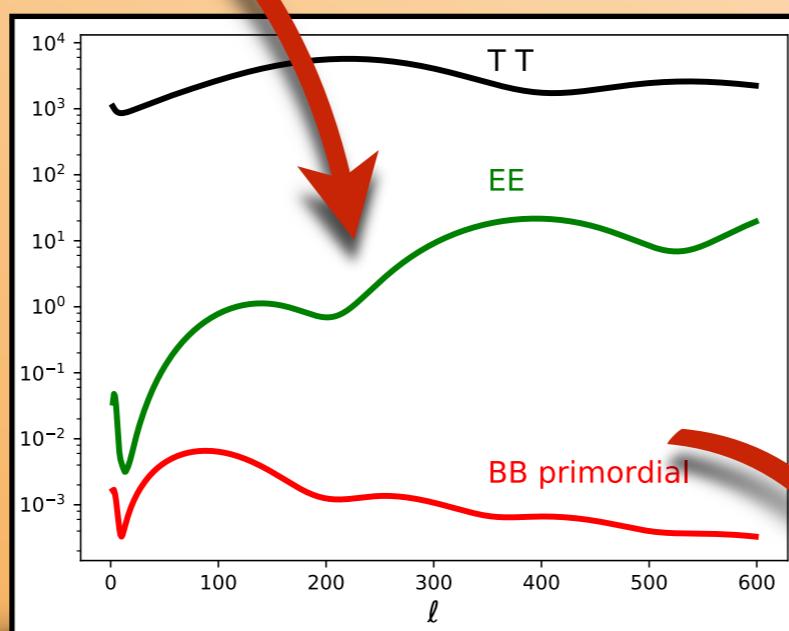


→ E-B mixing must be handled !

Data analysis



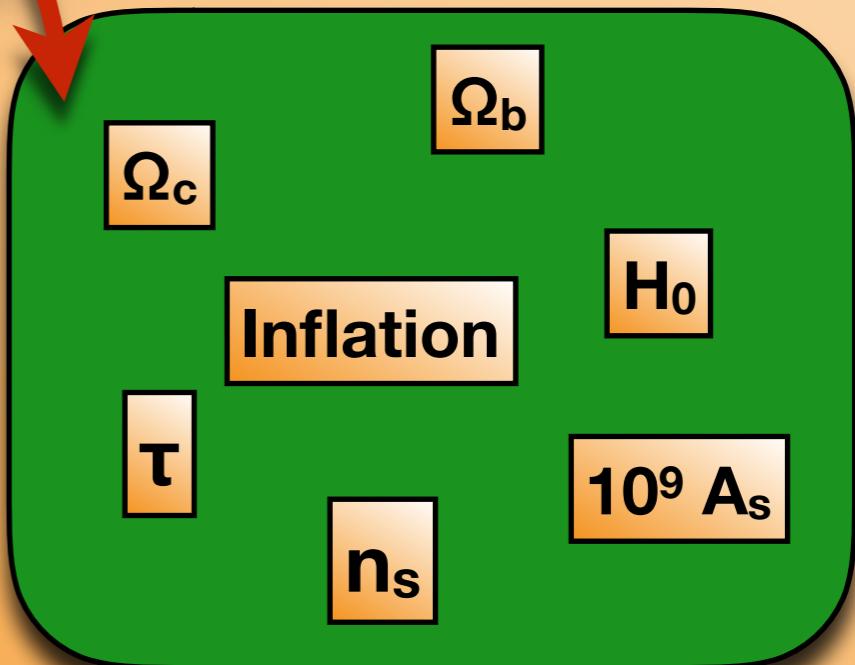
Treated CMB map



Power spectra
estimation C_ℓ

Model
(Λ CDM)

Cosmological parameters

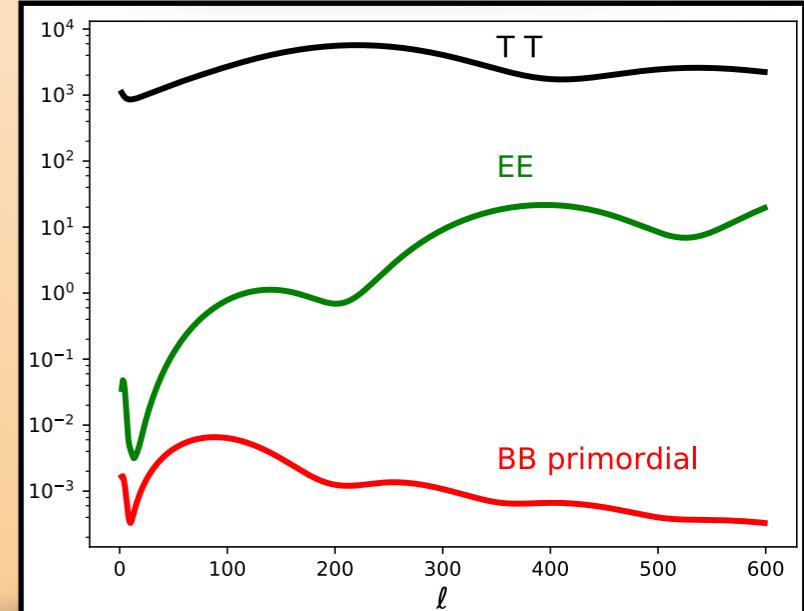


Power spectra estimators

Pseudo spectrum :

- Direct estimation of pseudo-spectra C_ℓ from data.
- Near optimal variance ✓
- Possible EE-BB mixing ✗
- Cross-spectrum ✓
- Computationally fast ✓

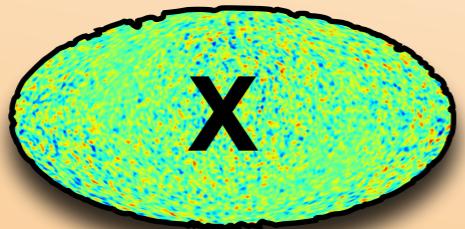
Power spectra
estimation C_ℓ



Approximation of maximum likelihood :

- From pixel-pixel correlation.
- Optimal variance ✓ → **especially required for B-mode**
- Less E-B mixing ? → **my work**
- Cross-spectrum → **my work**
- Computationally expensive ✗

Cross-spectrum

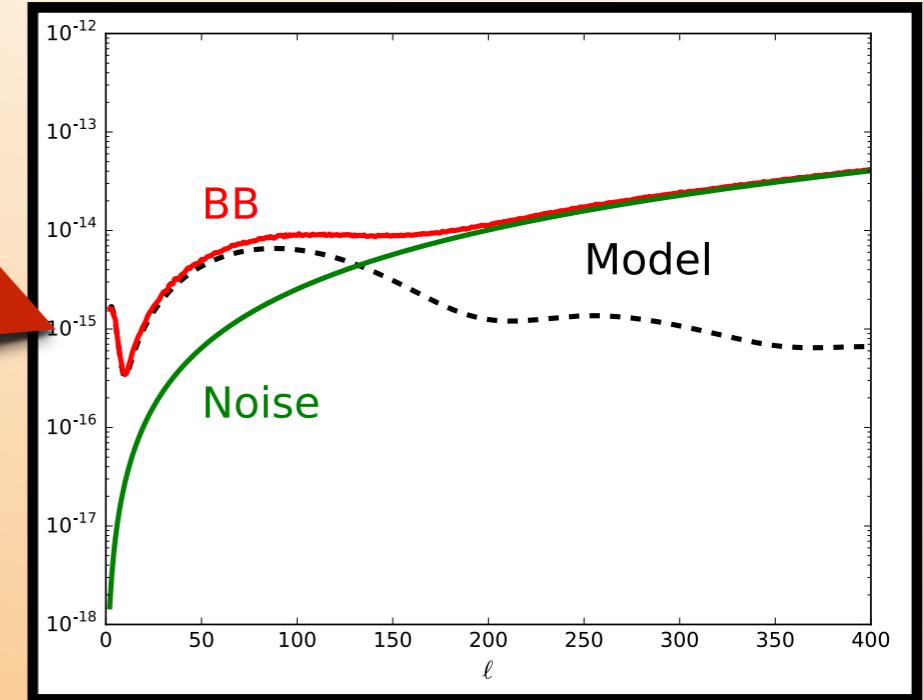


CMB + noise X

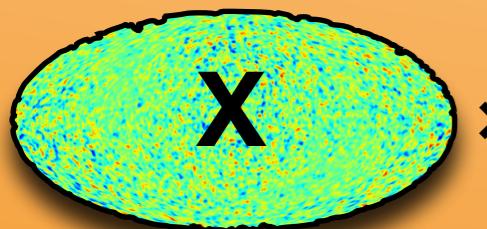
$$C_\ell = \langle a_{\ell m}^X a_{\ell m}^{X *} \rangle$$

Auto-correlation

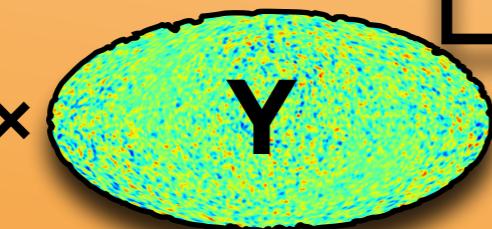
$$\langle \text{noise}X, \text{noise}X \rangle = \sigma_X^2$$



Requires perfect noise knowledge for de-biasing



CMB + noise X

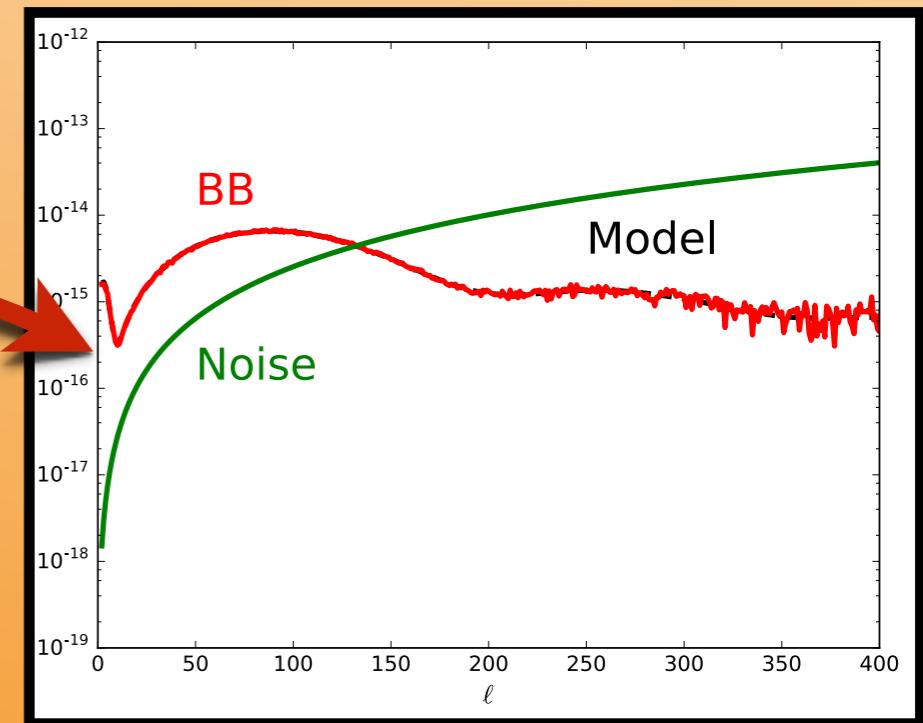


CMB + noise Y

$$C_\ell = \langle a_{\ell m}^X a_{\ell m}^{Y *} \rangle$$

Cross-correlation

$$\langle \text{noise}X, \text{noise}Y \rangle = 0$$



Unbiased !

Conclusion

- B-modes are keys for understanding the primordial Universe and nature of inflation
- Challenging to measure, require lot of efforts in next decades :
 - State-of-the-art technology
 - Precise astrophysics and cosmology models
 - Optimised data analysis

Thank you

LIGO/CITA doc