Toward primordial CMB B-modes observation

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Outline

- **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

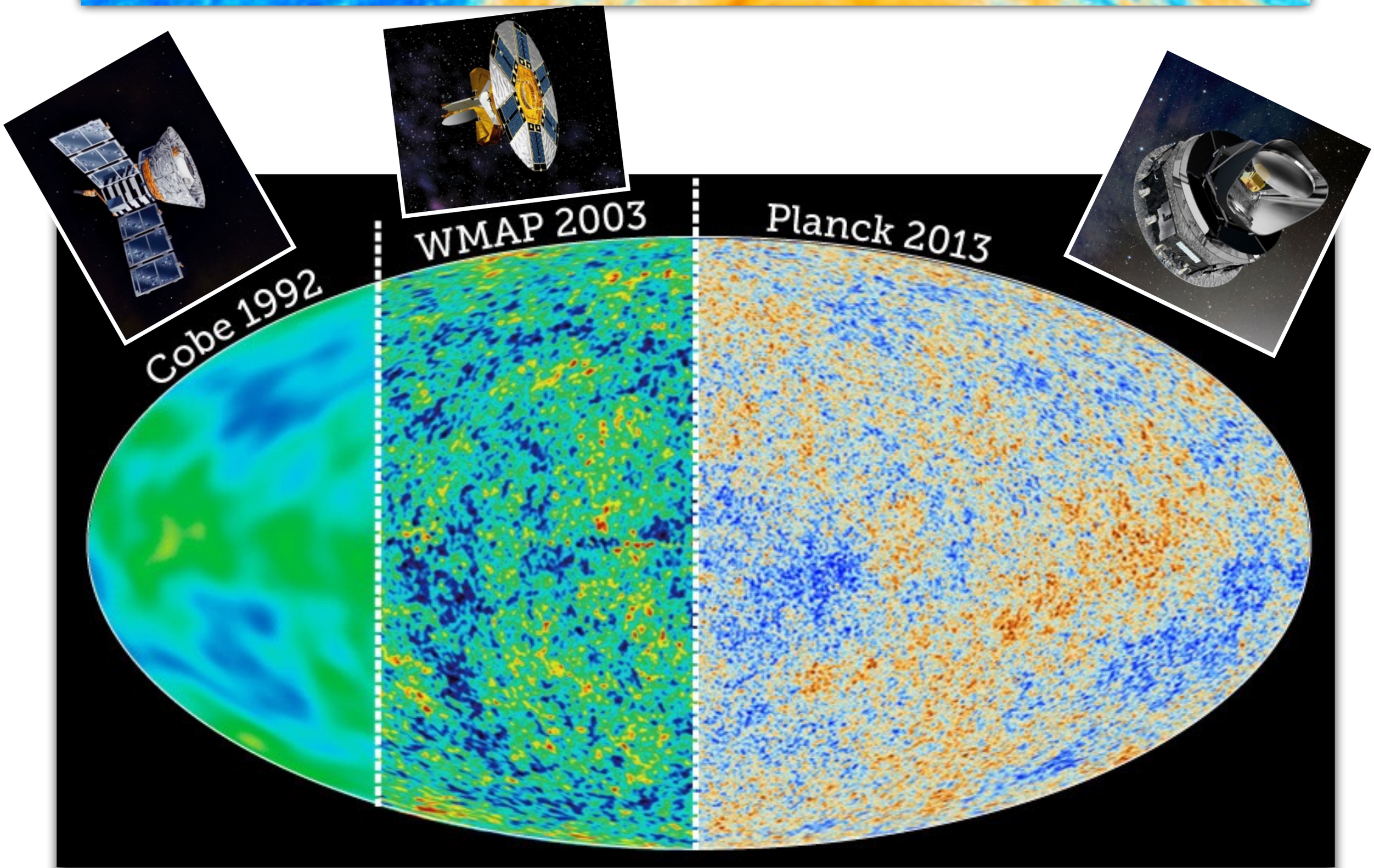
  - reionization parameter τ

    (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 $\frac{\Delta T}{T}$:

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

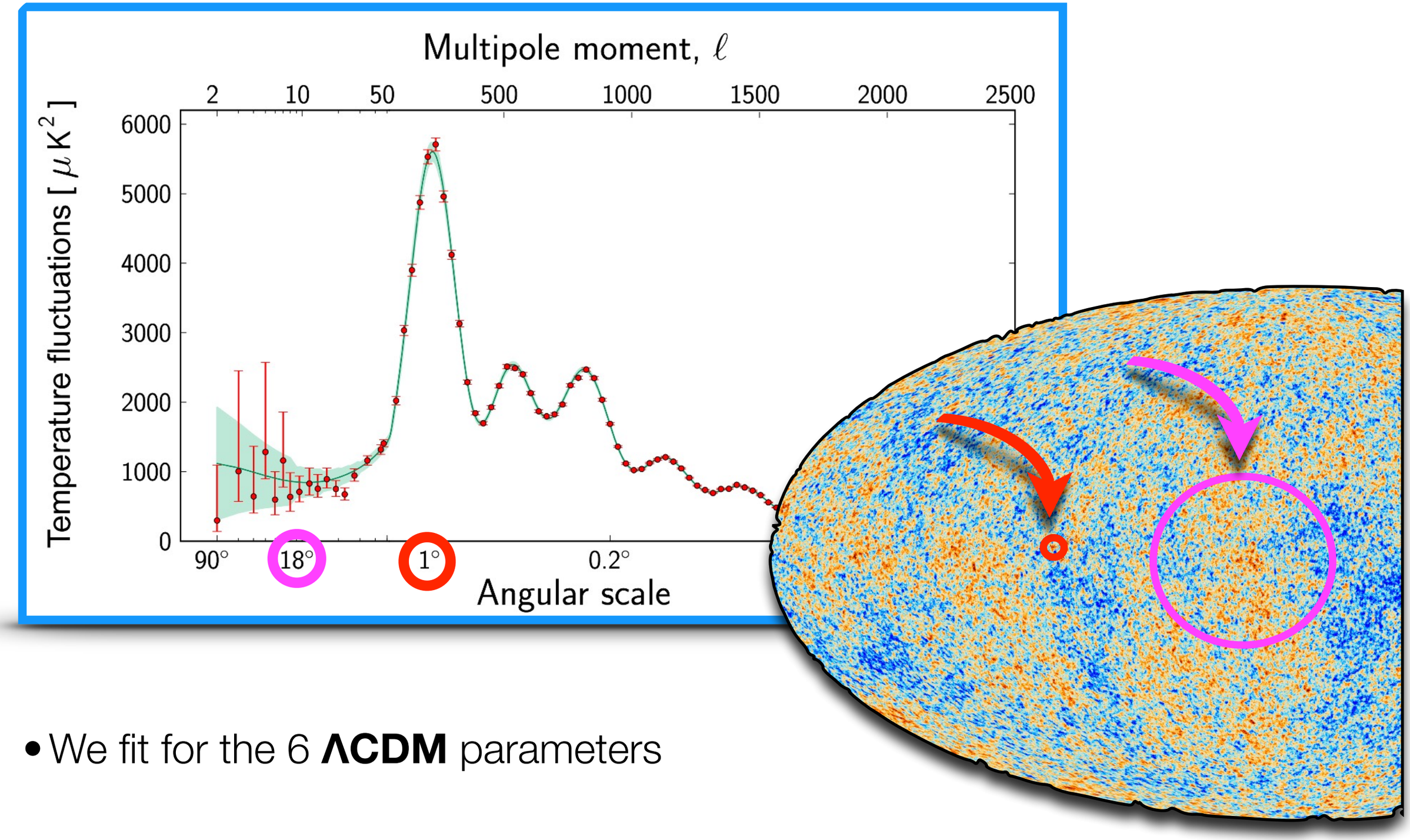
$$a^T_{\ell m} = \int \frac{\Delta T}{T}(\vec{n}) Y^*_{\ell m}(\vec{n}) d\vec{n}$$

$$\boxed{C^T_\ell = \langle a^T_{\ell m} a^T_{\ell m}{}^* \rangle}$$

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

- Compresses CMB data
- Retains all the cosmological statistics informations

PLANCK power spectrum



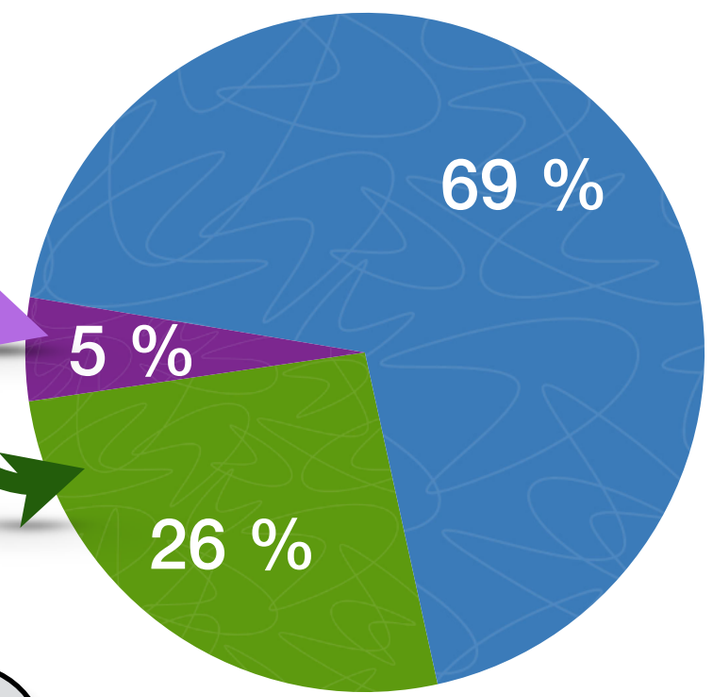
- We fit for the 6 **ΛCDM** parameters

Parameters measurements

- Precise constraints on ΛCDM 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

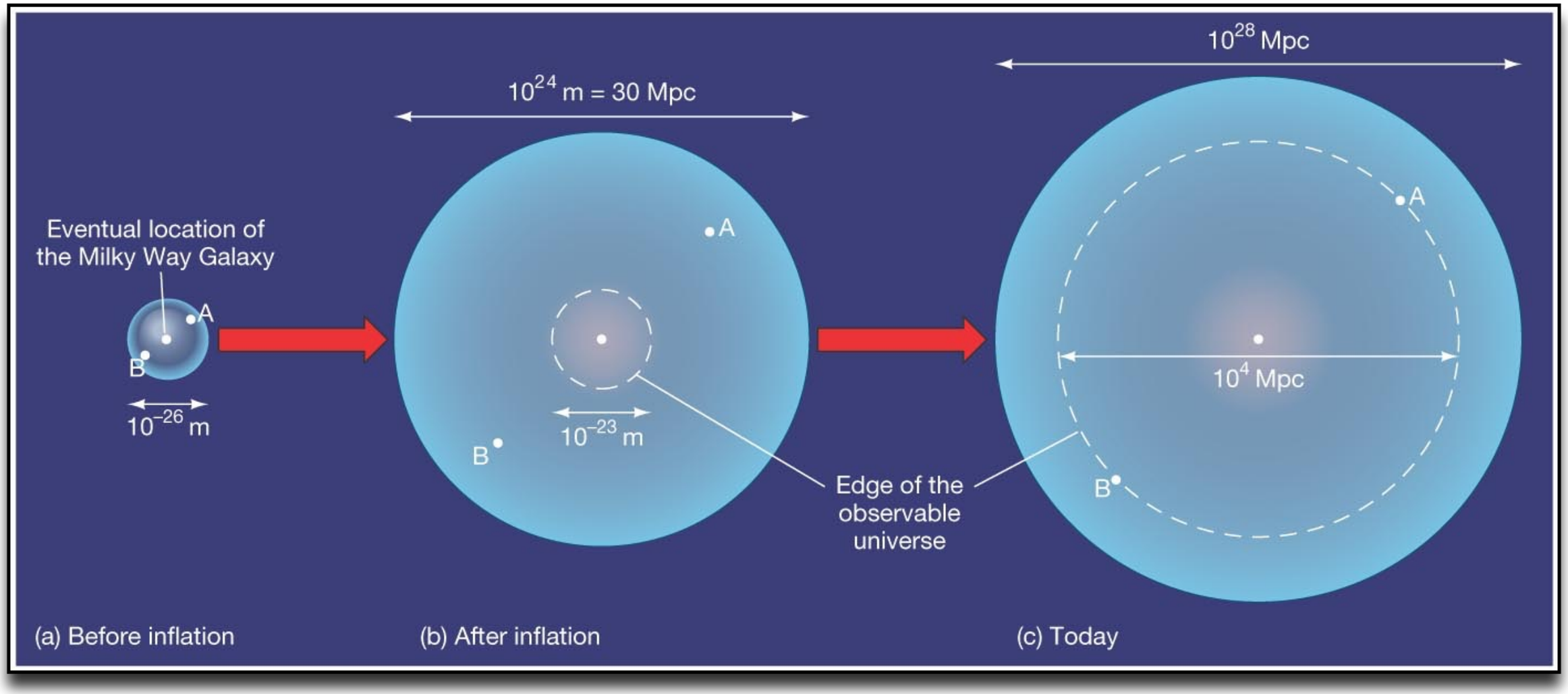


- Baryon matter
- Dark energy
- Dark matter

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

Inflation

Inflation *: huge and brief Universe expansion after 'Big-Bang'*



'Problems' of cosmology : → **Inflation :**

- Horizon ?
- Flatness ?
- Primordial fluctuations ?

- 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 ?

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

Hints for inflation :

- Already measured :
  - ✦ **$n_s < 1$** from PLANCK. ✓
  - ✦ Predicts *gaussian* and *adiabatic* fluctuations of initial densities (PLANCK). ✓

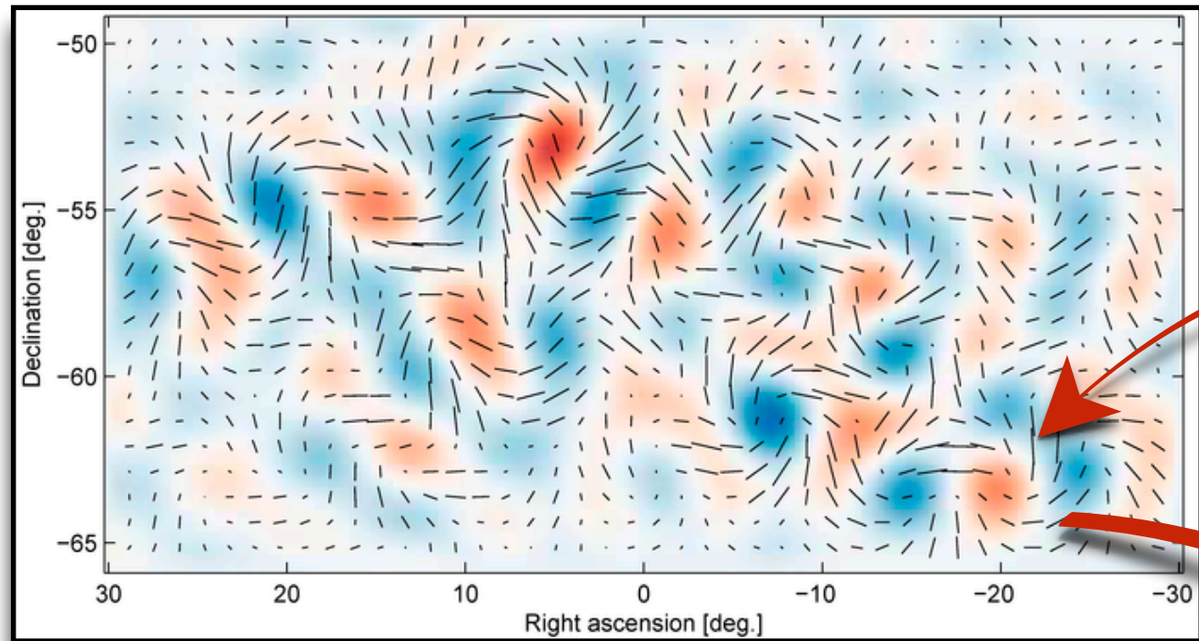
Inflation validation :

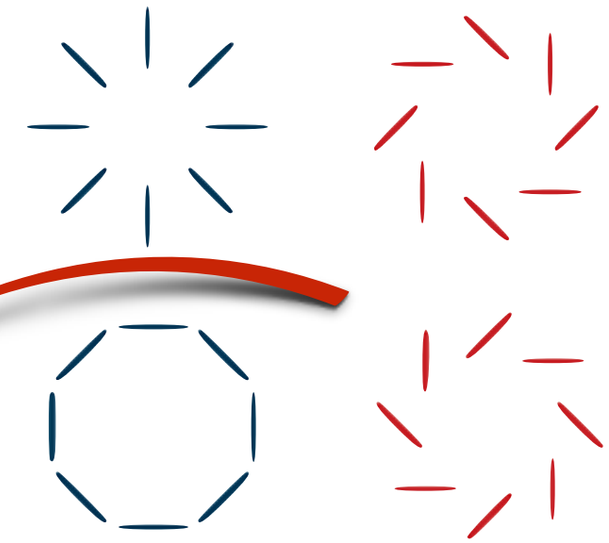
- Inflation generates primordial gravitational waves → visible in CMB ?

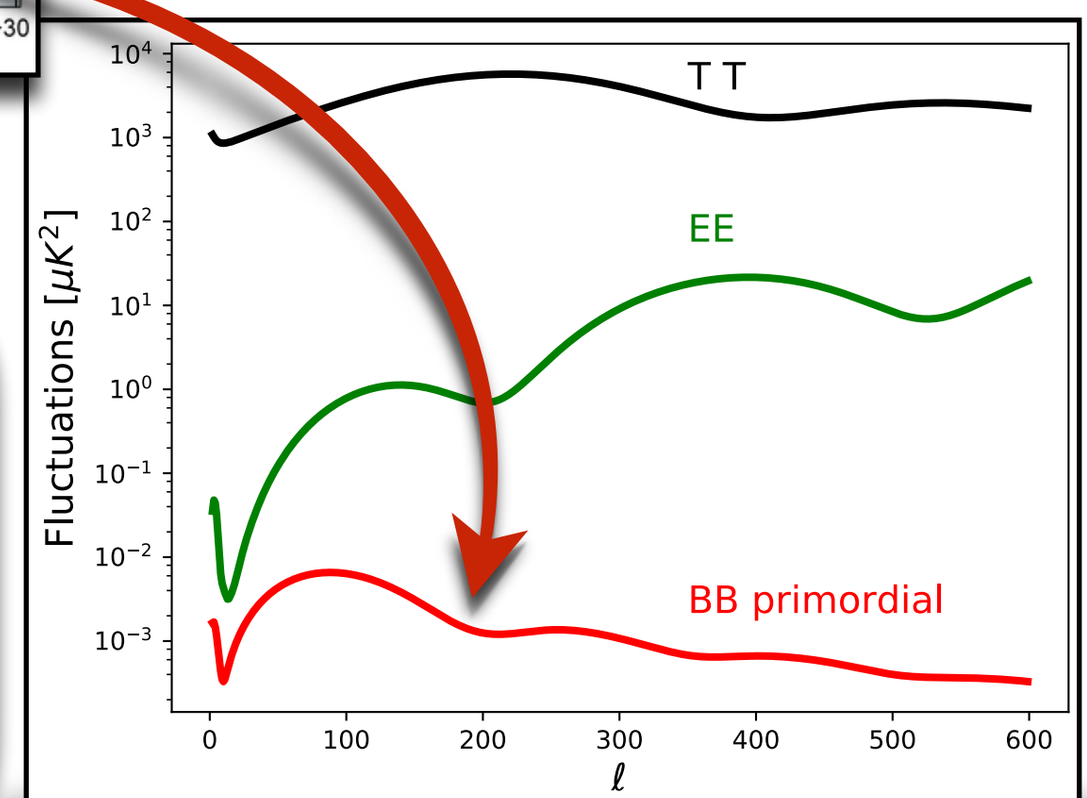
  → **B modes !**

CMB polarisation

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





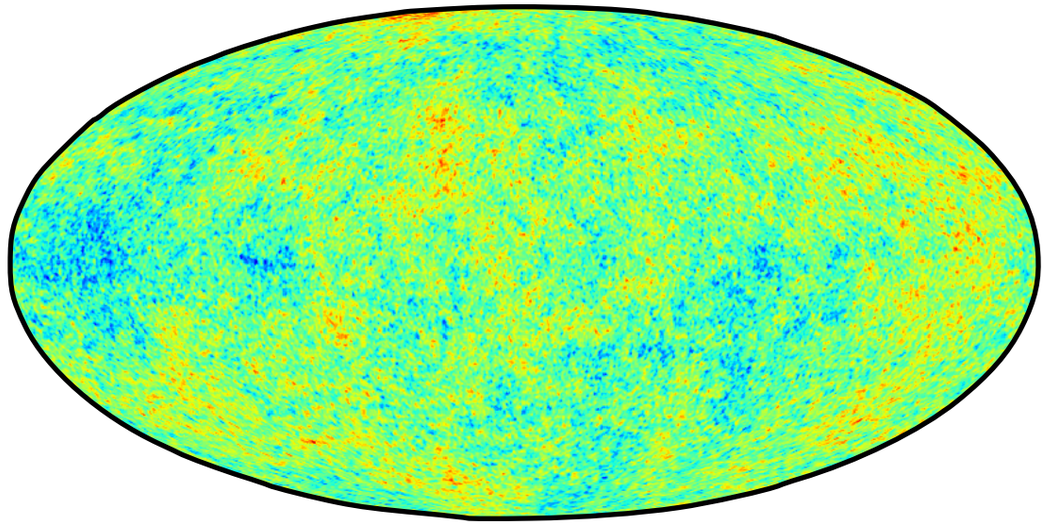


Primordial BB spectrum :

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

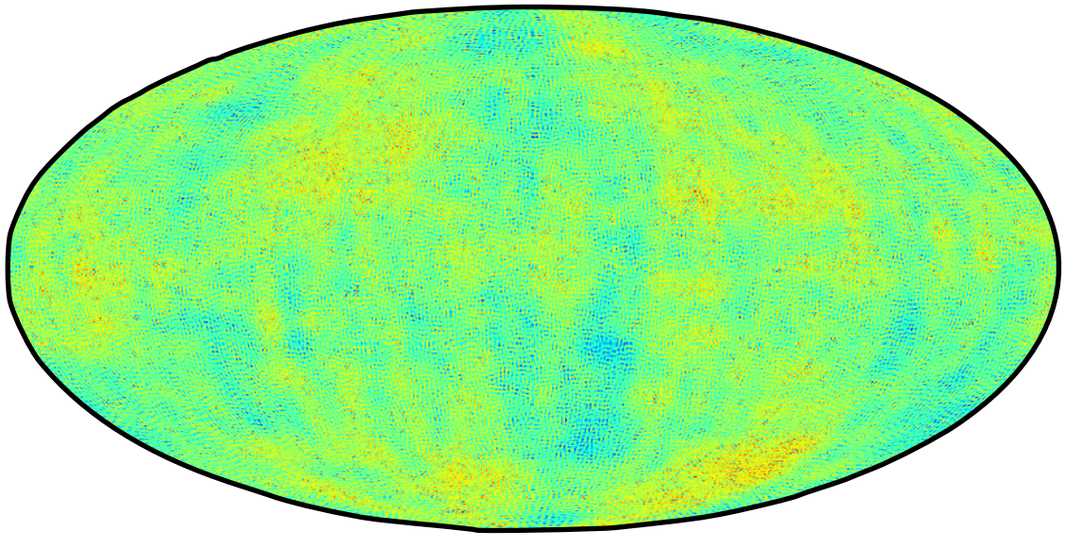
Things are not so simple

CMB Temperature (expected)



-500 μK 500 μK

CMB Polarisation (expected)



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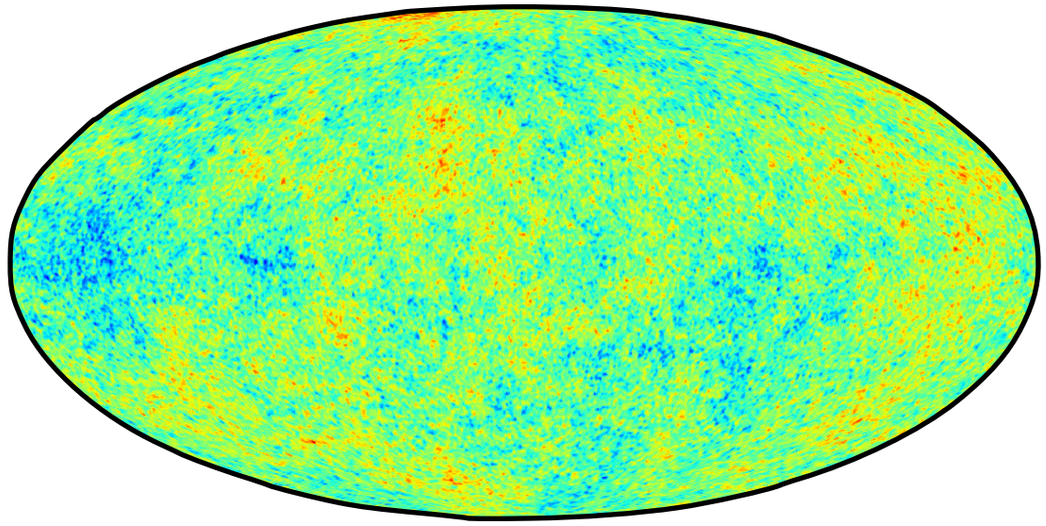

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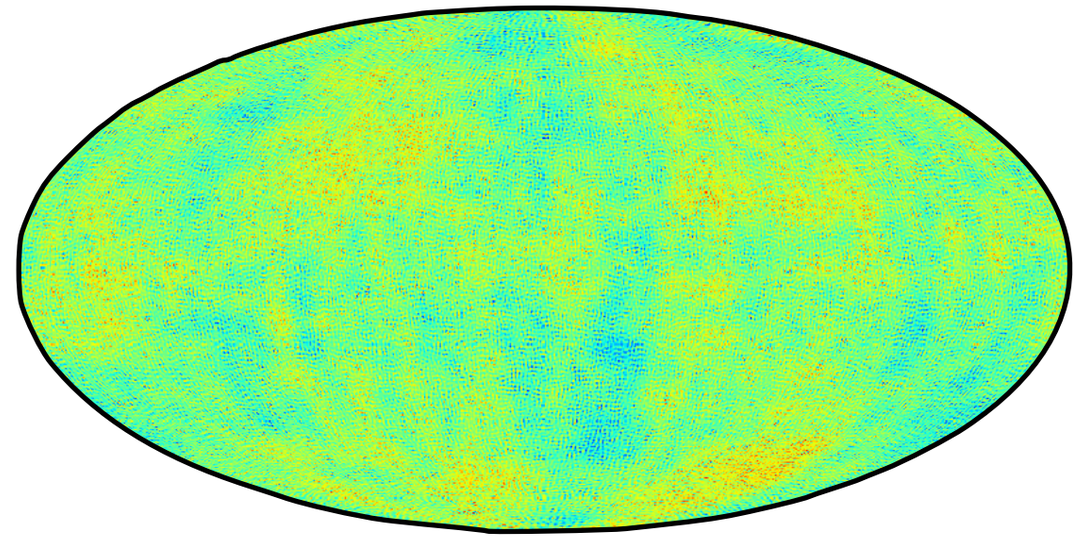
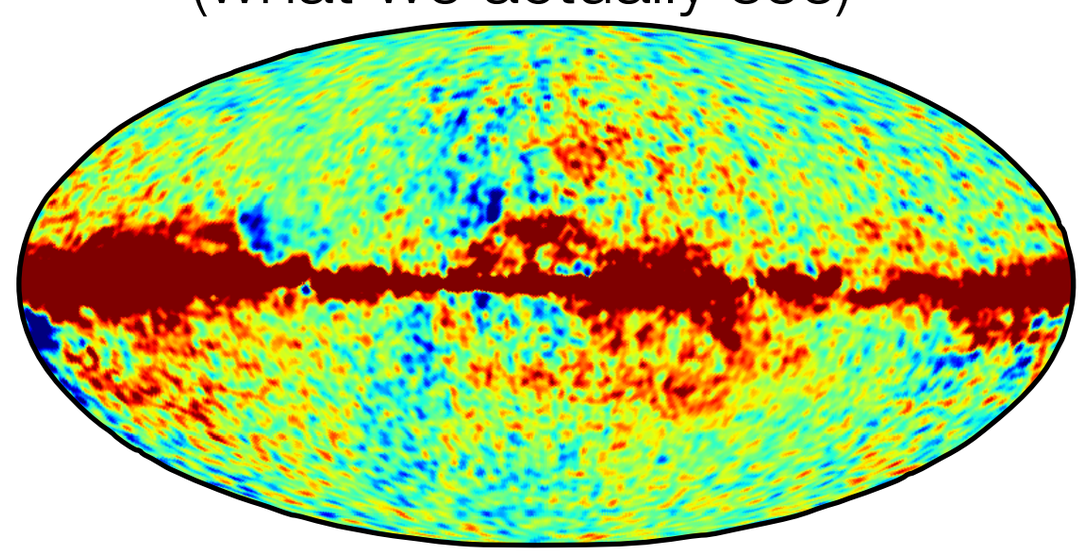
CMB Polarisation (expected)



-5 μK 5 μK

CMB Polarisation

(what we actually see)



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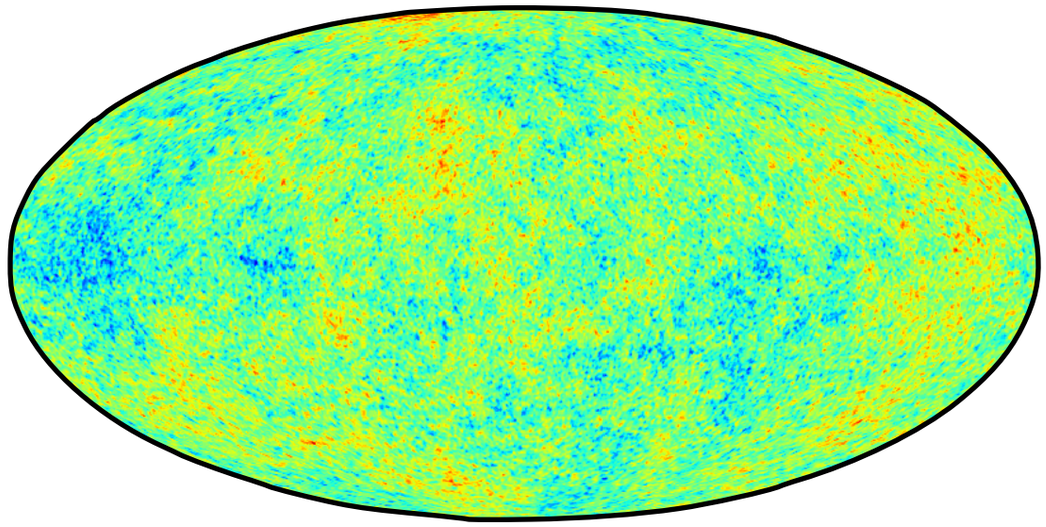
Things are not so simple

CMB Temperature (expected)



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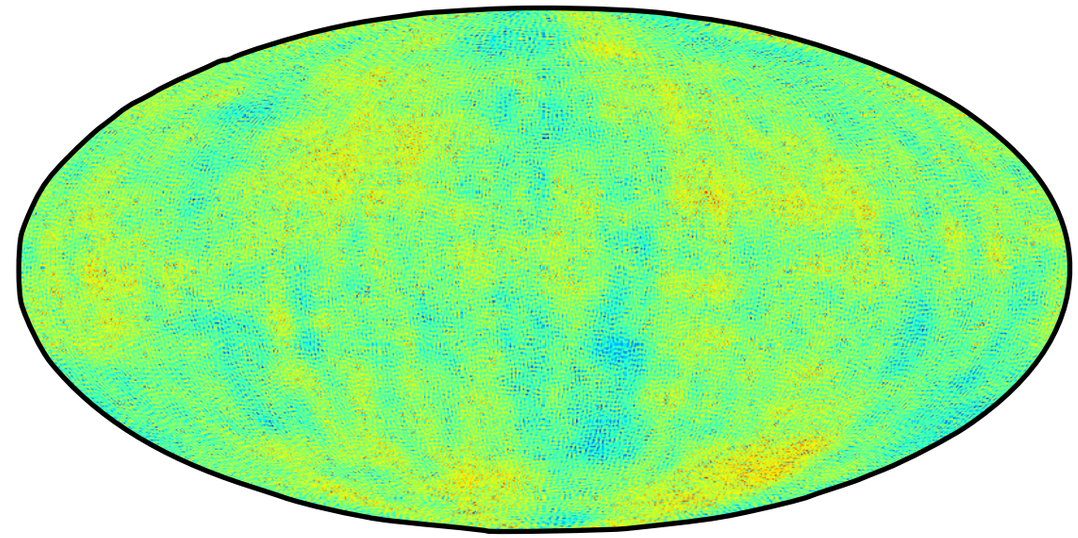
CMB Polarisation (expected)



-5 μK 5 μK

CMB Polarisation

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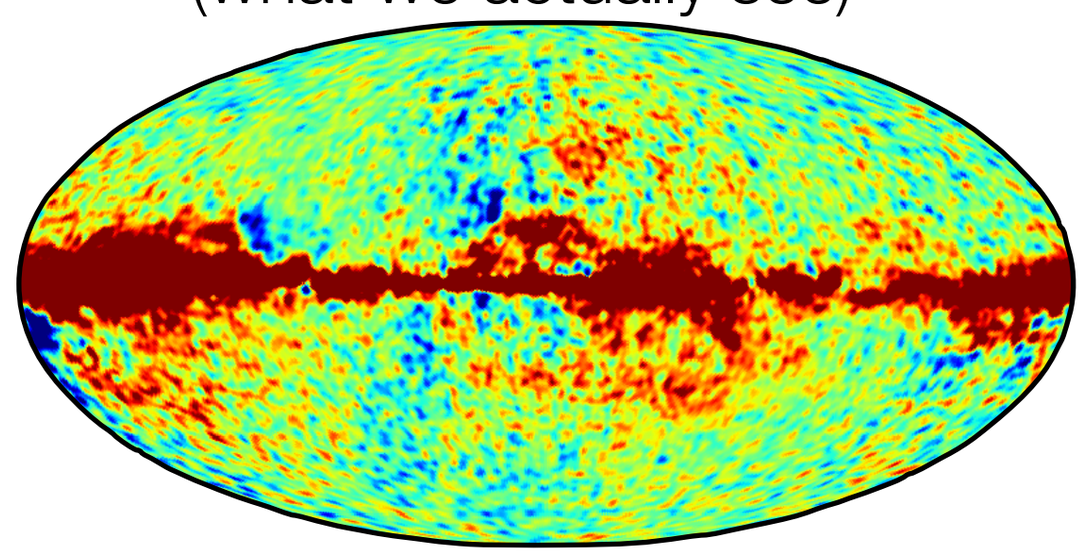


-5 μK 5 μK

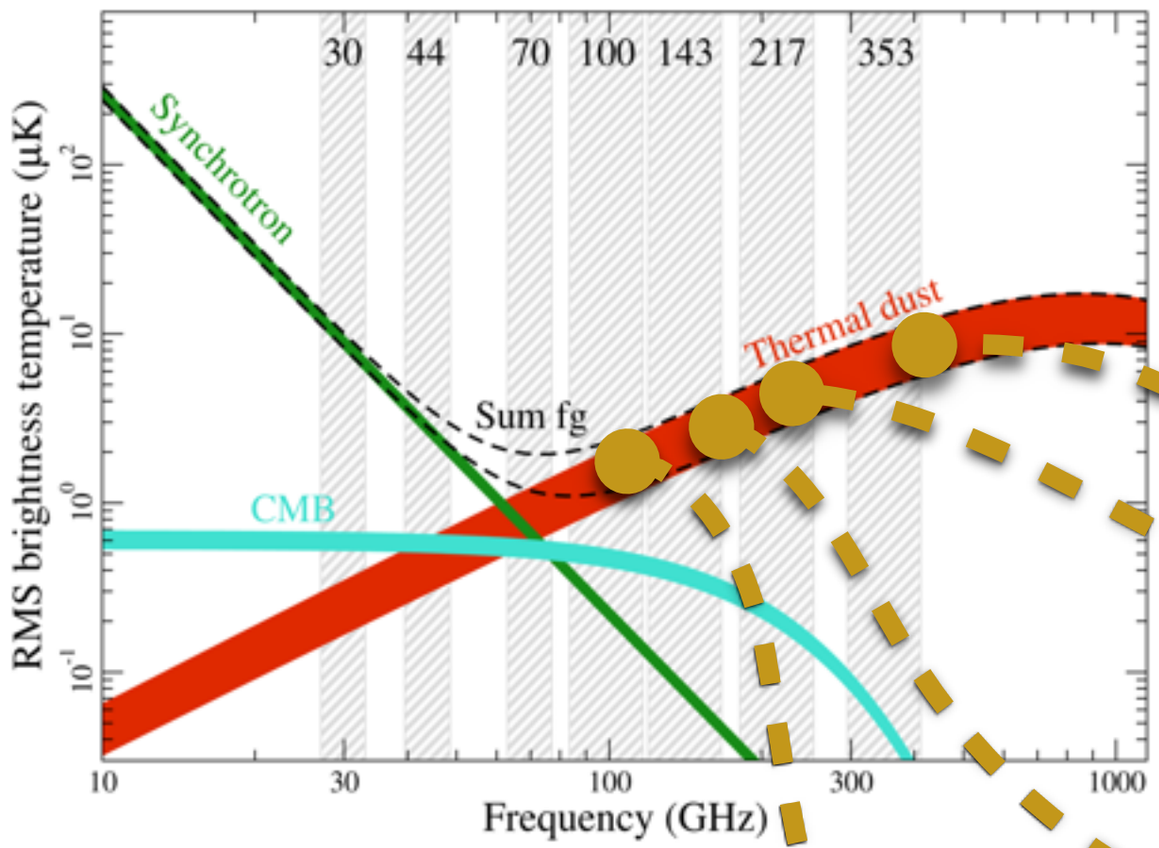
<u>CMB maps contaminated by :</u>

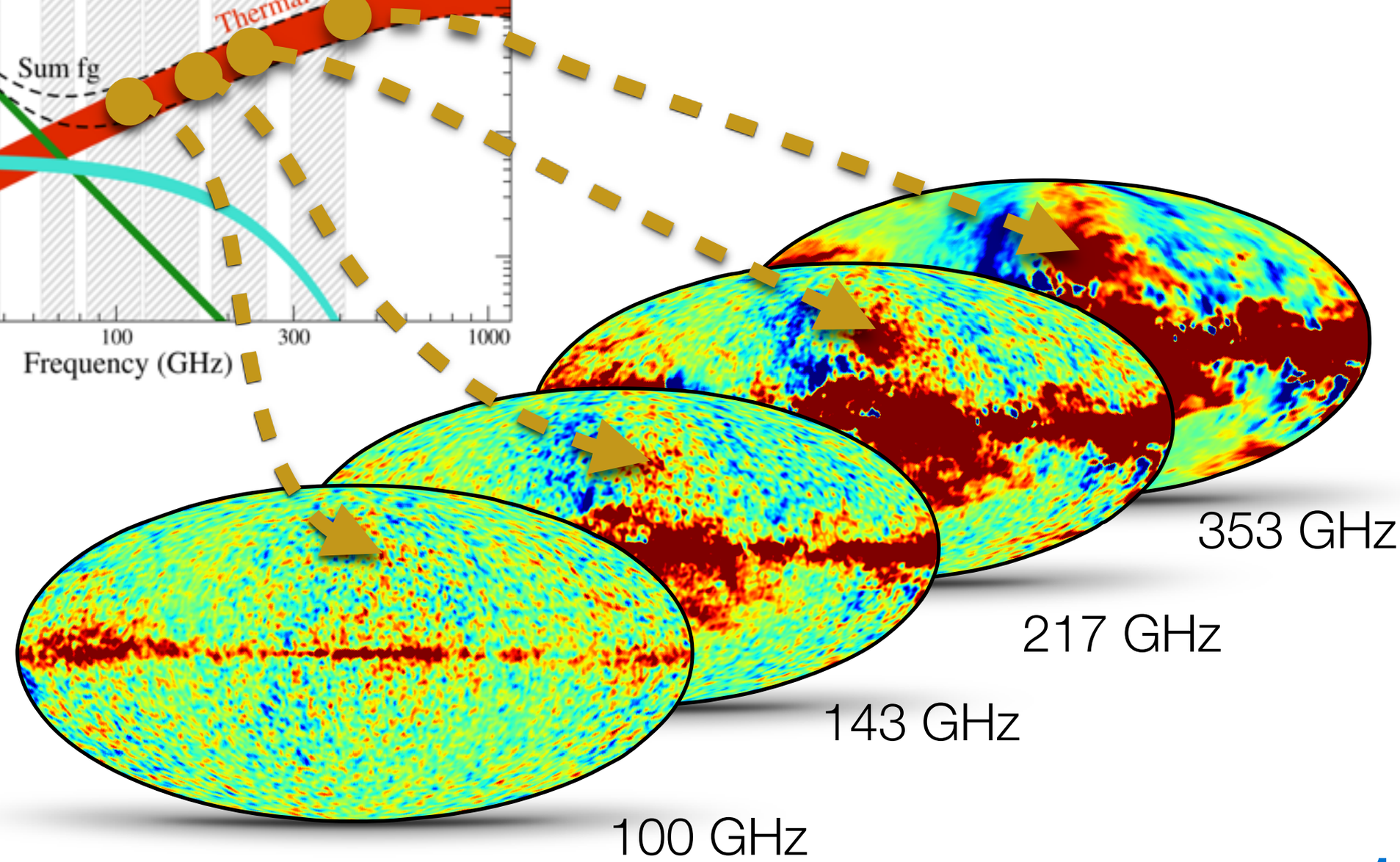
- Galactic foregrounds :
  - ✦ Synchrotron
  - ✦ Dust
- Instrumental noise

→ *Tools to handle contaminations (my work)*

Foregrounds signals

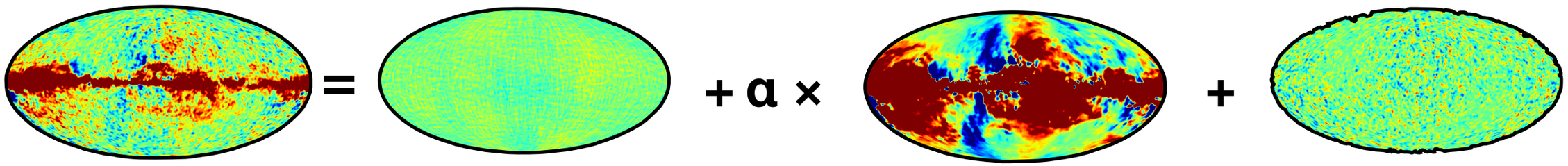
Different signal behaviours as a function of photons frequency (or wavelength) :



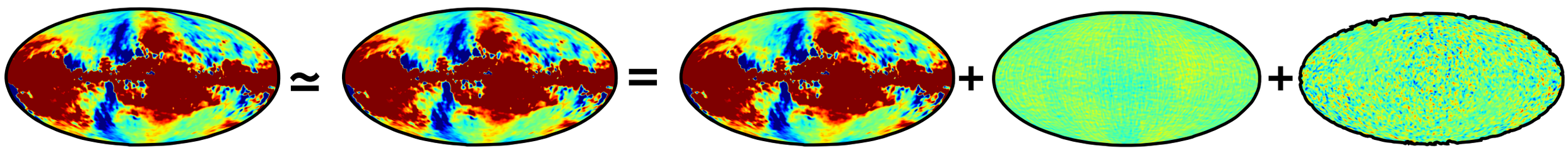


Template cleaning

- **First approximation : Linear**



Map (100 GHz) | CMB | Dust Template | Noise

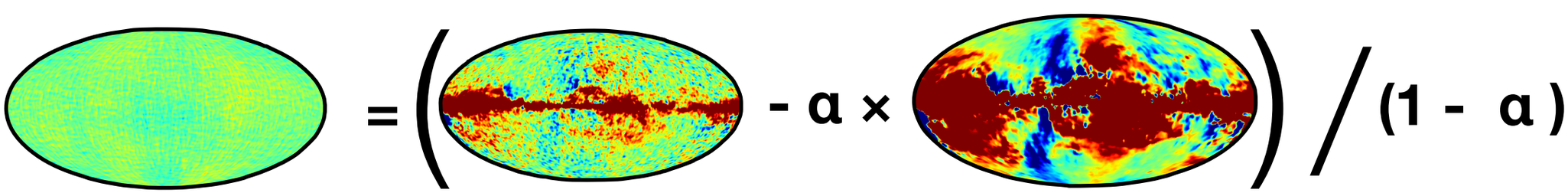


Dust Template | Map (353 GHz) | Dust | CMB | Noise

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

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

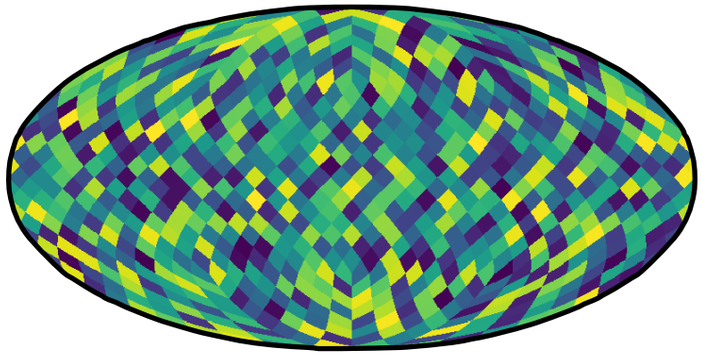
- **Map cleaning :**



CMB estimation | Map | Dust

Variation over the sky

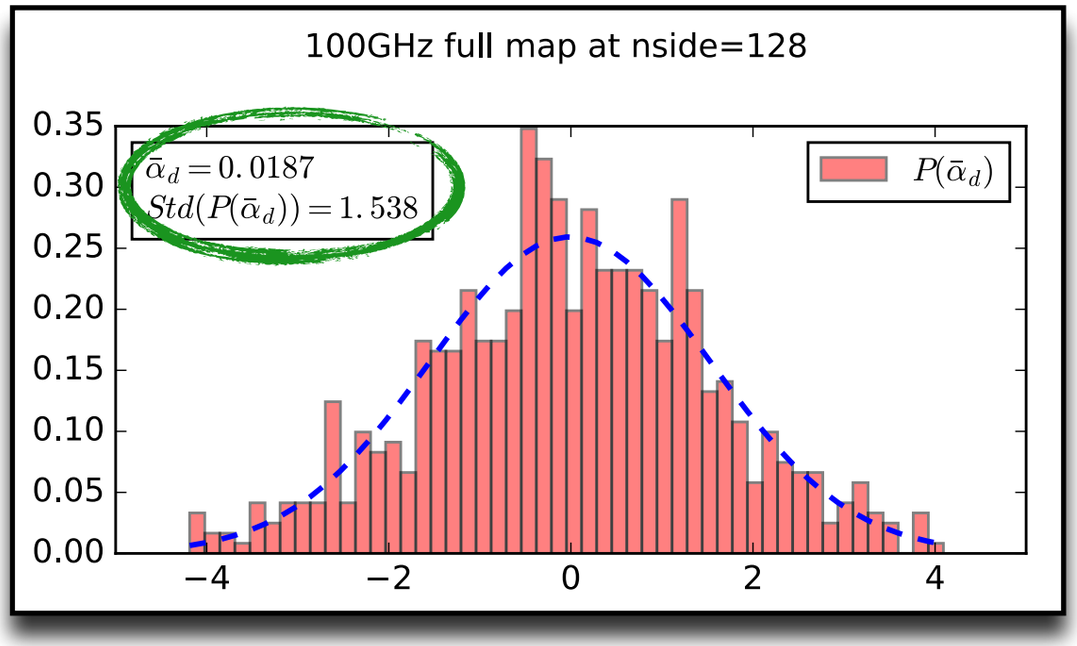
- Dust properties on the sky not sufficiently modelled yet.
- Goal : test **α** coefficients variations over the sky for PLANCK maps.
- Cut sky into patches :



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

Map	100GHz
Dust	α =0.0183±0.0004

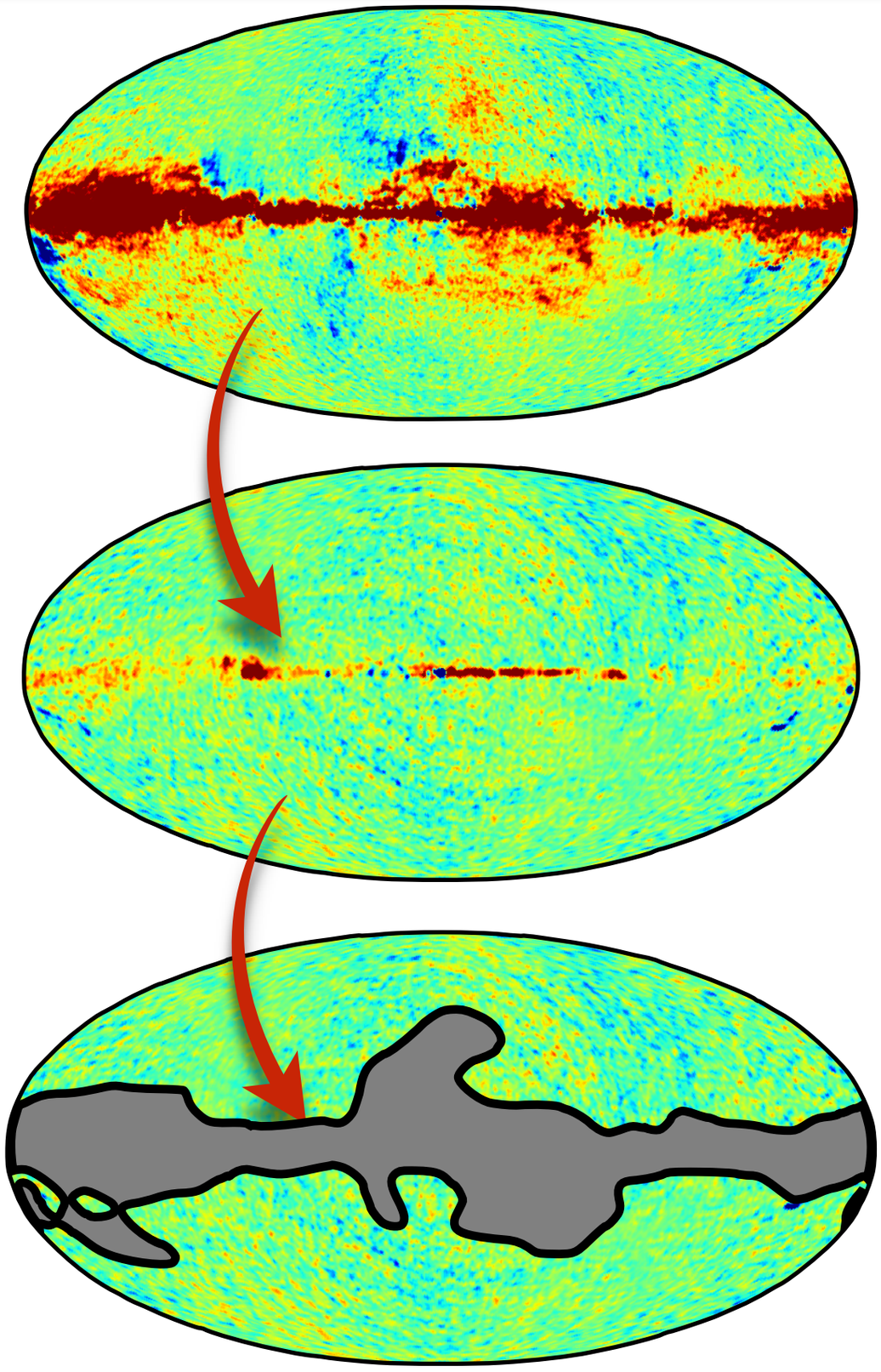
- Linear regression results for 700 patches :



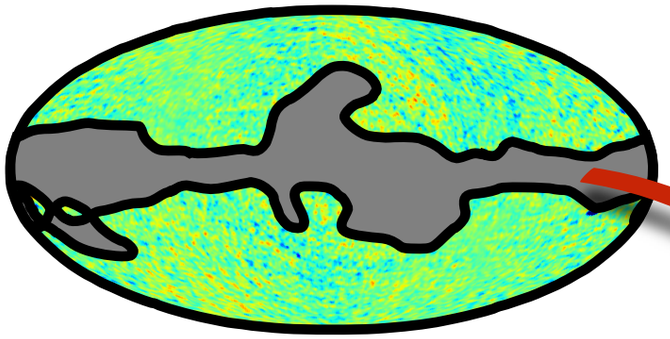
→ Given PLANCK noise level, no variation of the dust coefficient **α** over the sky.

Map cleaning steps

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

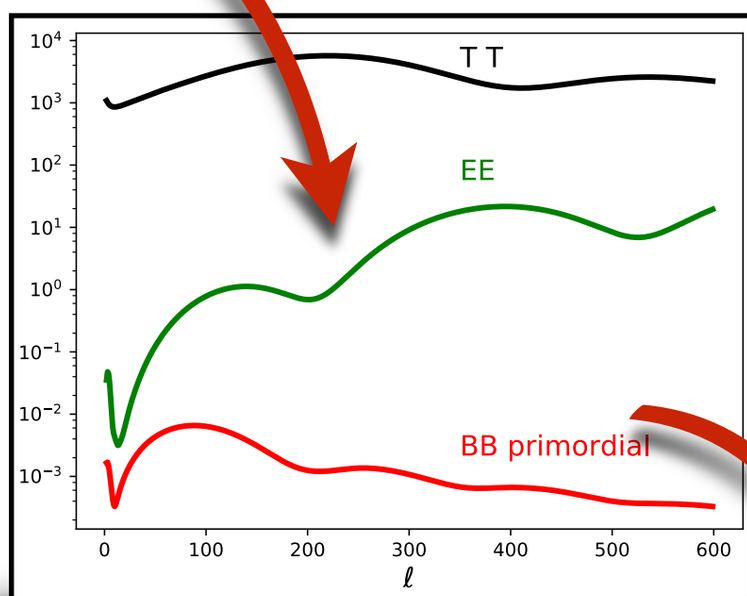


Data analysis



Treated CMB map

Power spectra estimation C_ℓ



Model (ΛCDM)

Cosmological parameters

Ω_b

Ω_c

H_0

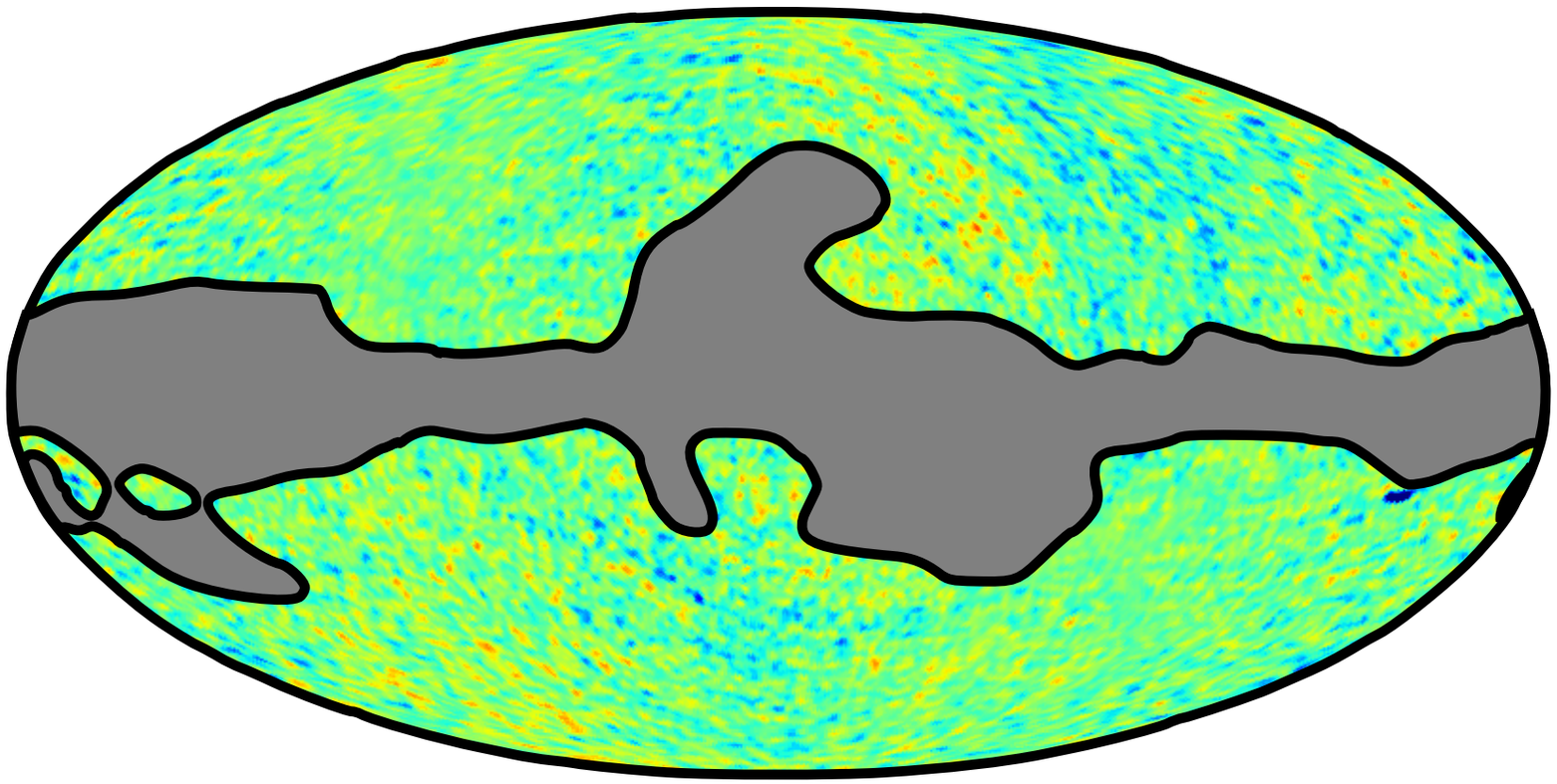
Inflation

τ

$10^9 A_s$

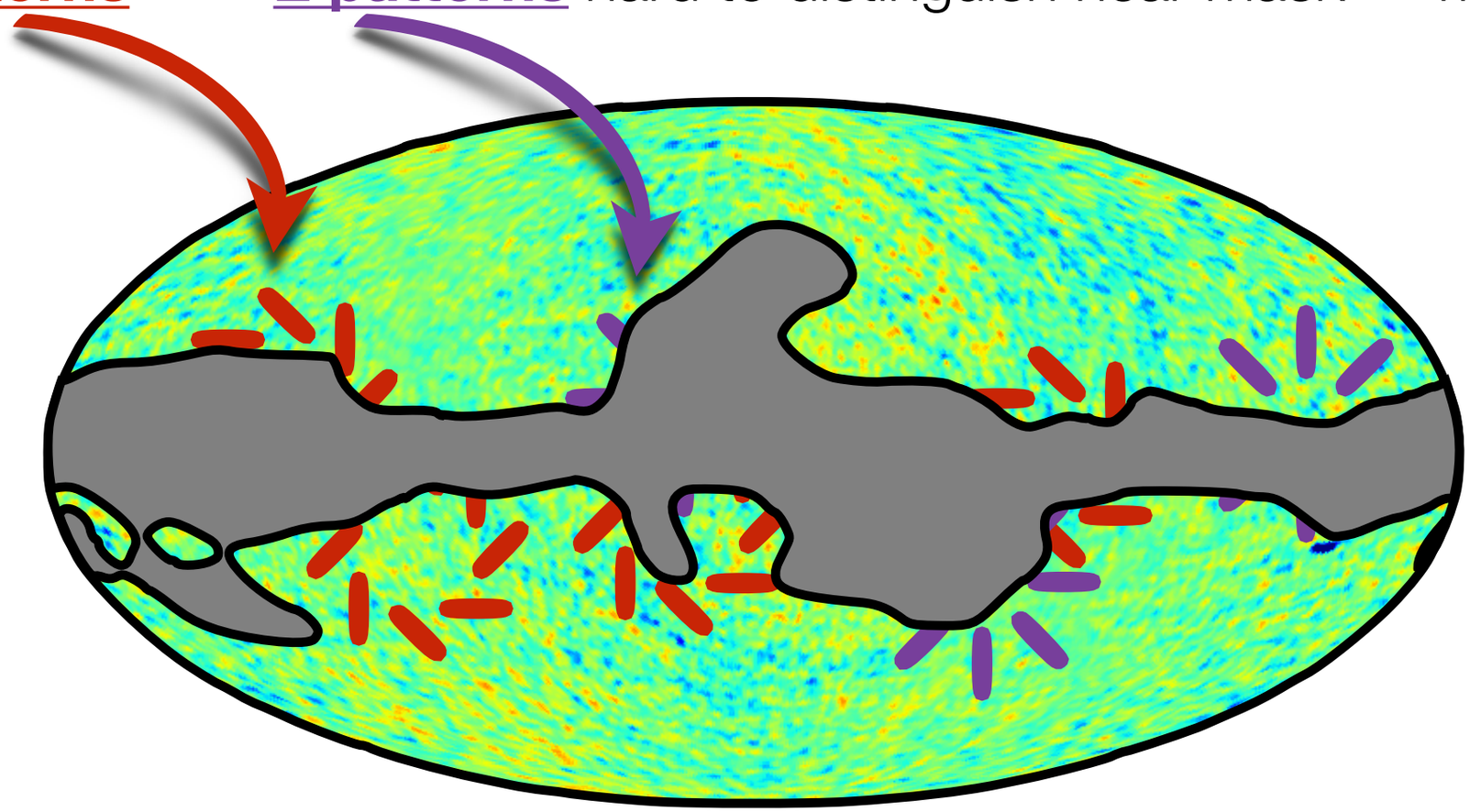
n_s

EE - BB mixing



EE - BB mixing

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



EE - BB mixing

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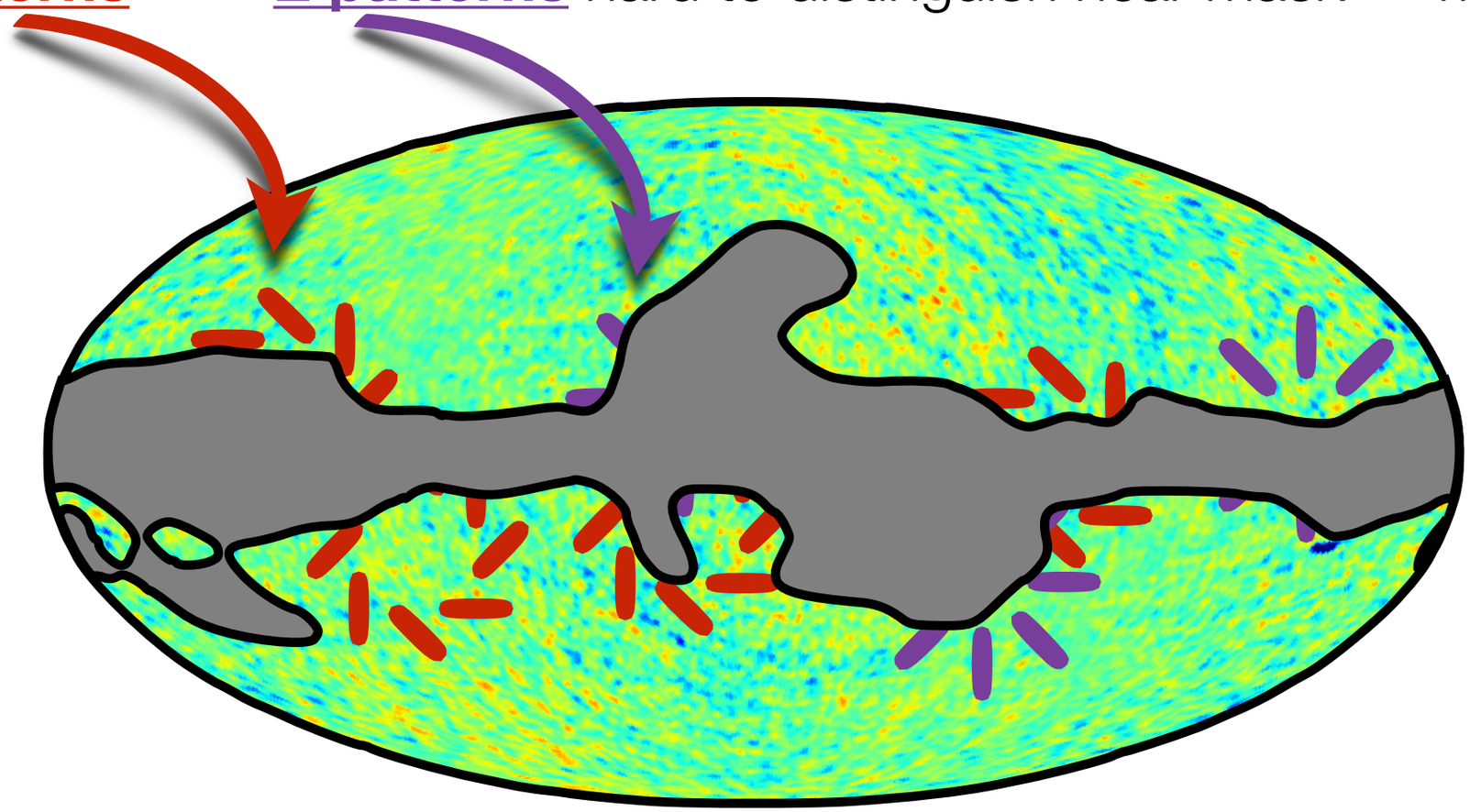


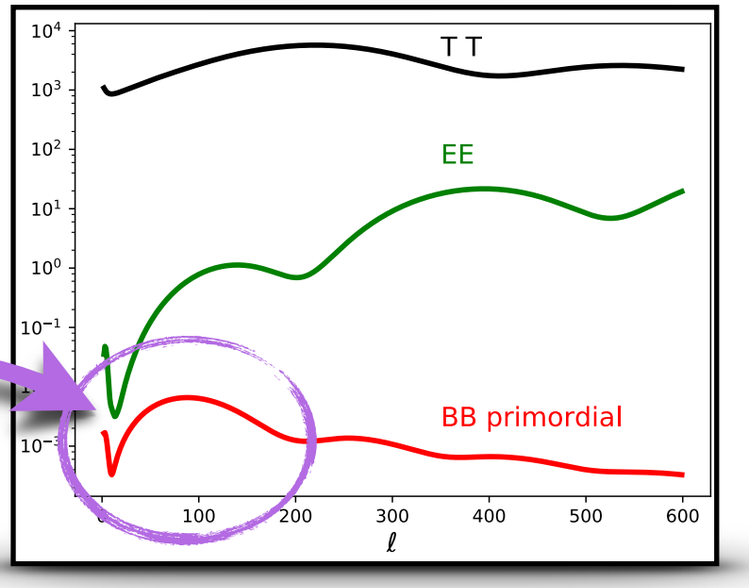
→ **E-B mixing must be handled !**

Power spectra estimators

Power spectra estimation C_ℓ

Pseudo spectrum :

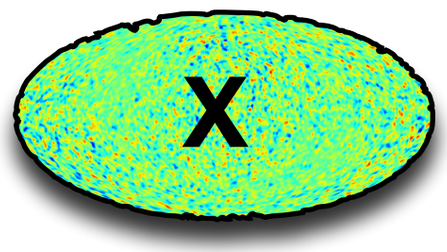
- Direct estimation of pseudo-spectra C_ℓ from data.
- Near optimal variance ✓
- Possible E-B mixing ✗
- Cross-spectrum ✓
- Computationally fast ✓
- Less efficient for large angular scale ✗ (most BB signal)



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

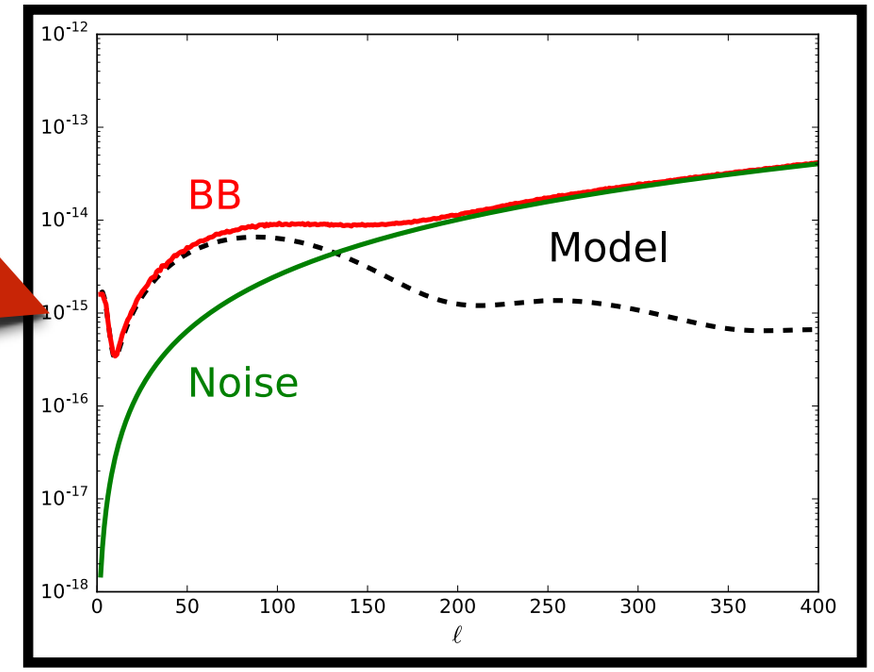


CMB + noise X

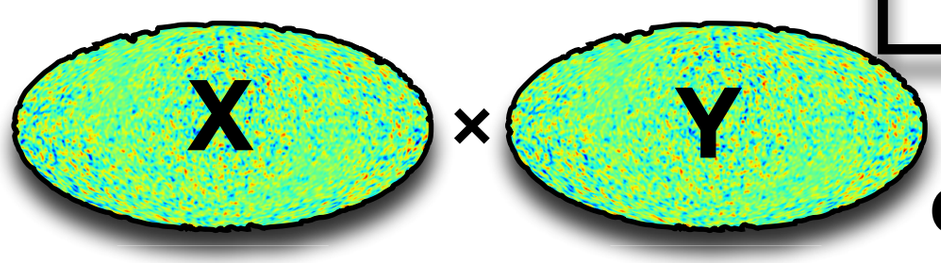
$$C_\ell = \langle a^X_{\ell m} a^X_{\ell m}{}^* \rangle$$

Auto-correlation

$$\langle noiseX, noiseX \rangle = \sigma^2_X$$



Requires perfect noise knowledge for de-biasing

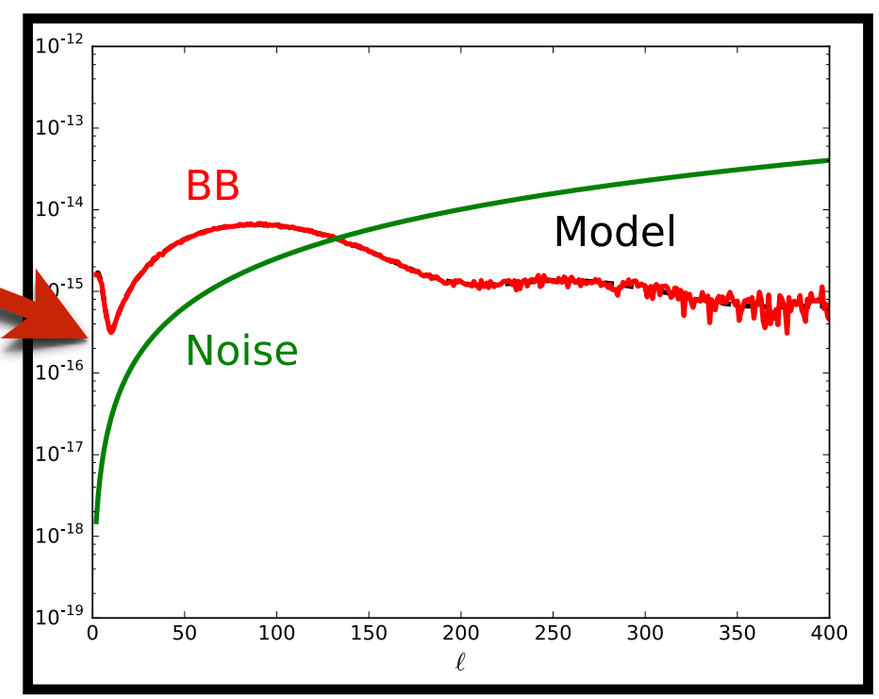


CMB + noise X CMB + noise Y

$$C_\ell = \langle a^X_{\ell m} a^Y_{\ell m}{}^* \rangle$$

Cross-correlation

$$\langle noiseX, noiseY \rangle = 0$$



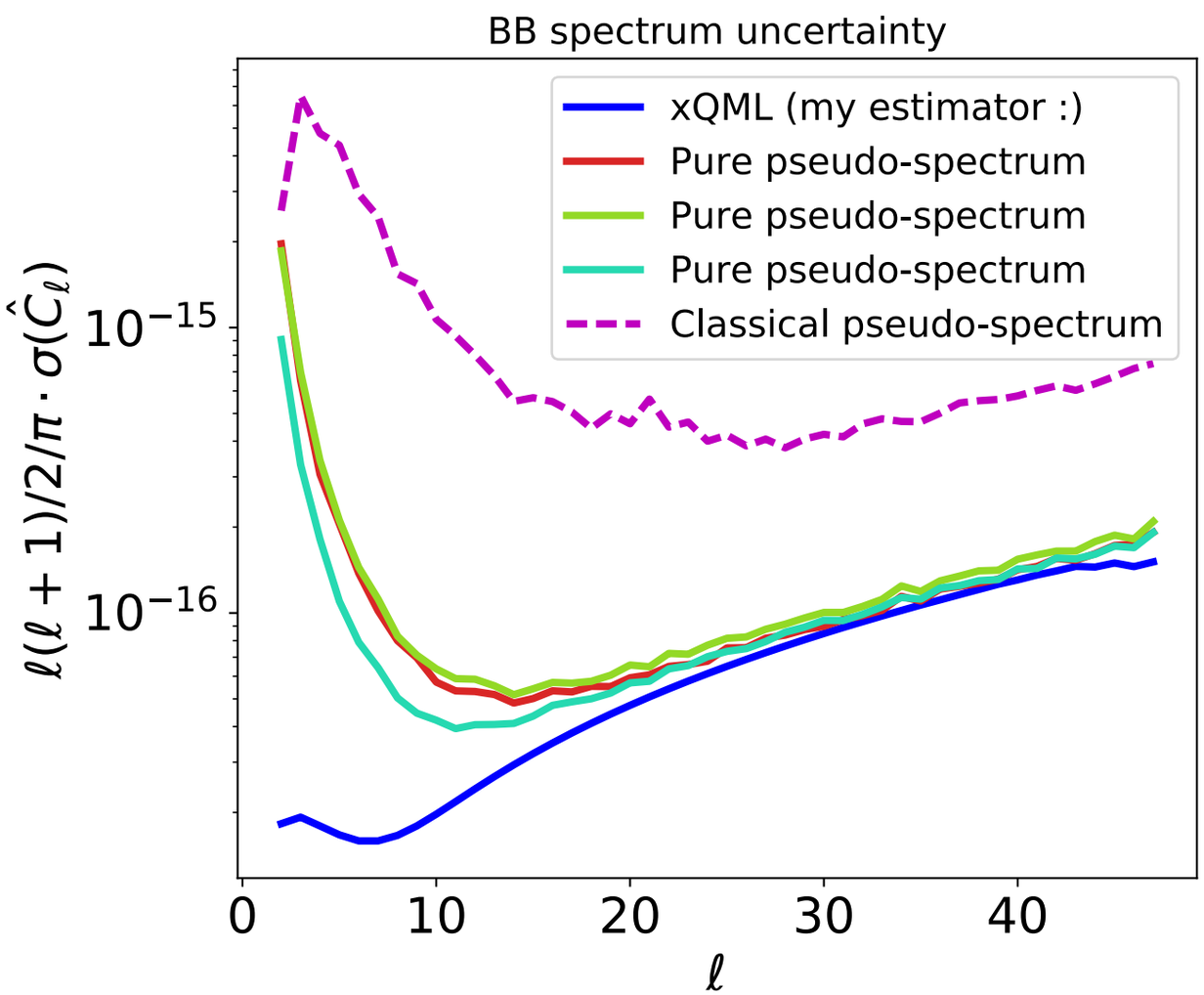
Unbiased !

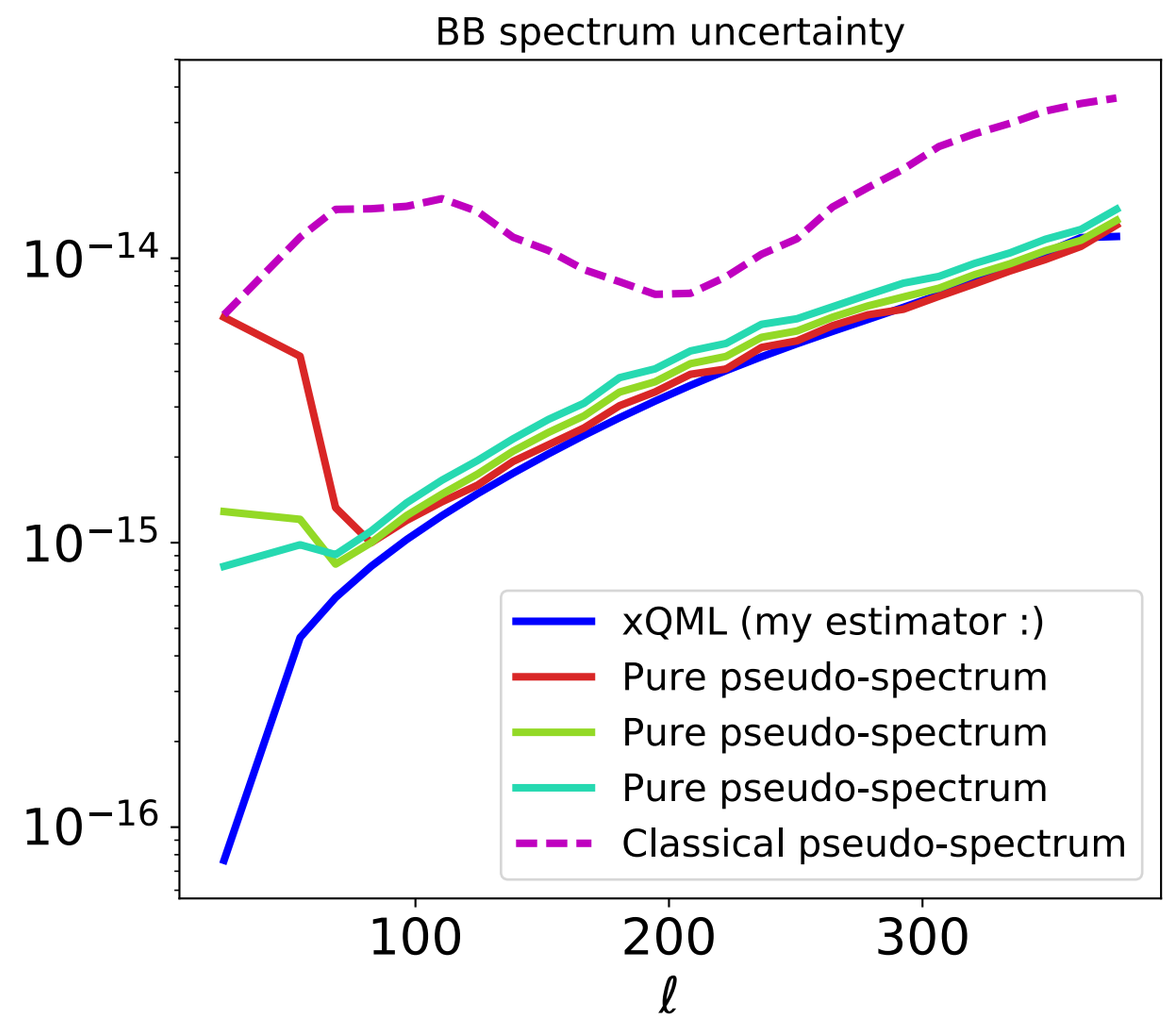
Preliminary results

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 !





Conclusion

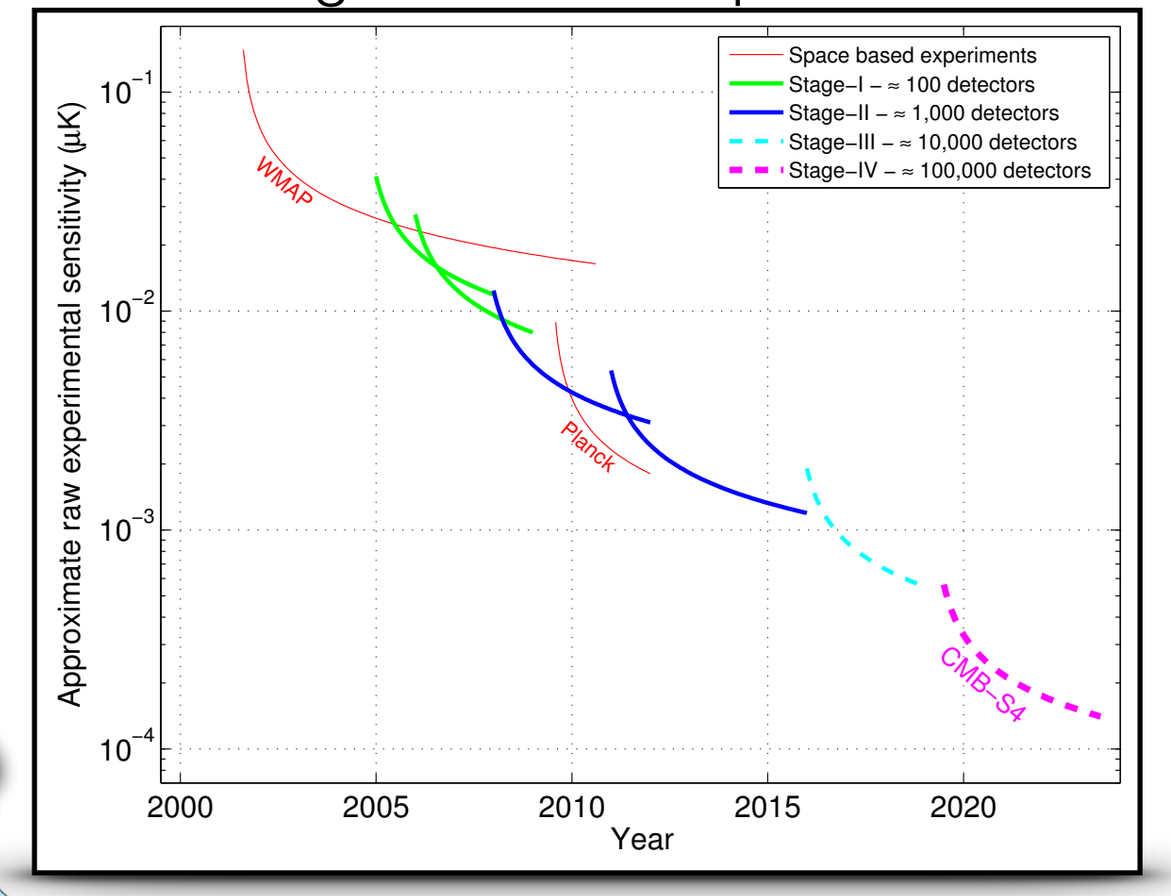
- B-modes are keys for understanding the primordial Universe and nature of inflation

- 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

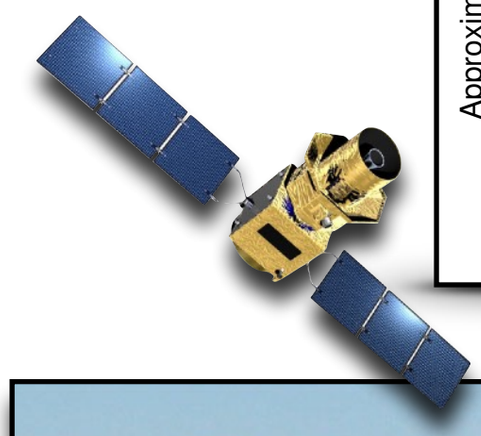
CMB today and tomorrow

Stages of CMB experiments



- Goal : precise polarisation measurements.
- Next generation of experiments :

  SPT3G, Advanced ACTPol, Simons Array, BICEP3 & Keck Array, QUBIC, LiteBird …



<u>Stages IV , ground based :</u>

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