Reconstruction of Inflationary CMB B-mode Signal in the Presence of Instrumental Effects and Galactic Foreground Emissions

Julien TANG

École Polytechnique
KAVLI Institute for the Physics and Mathematics of the Universe

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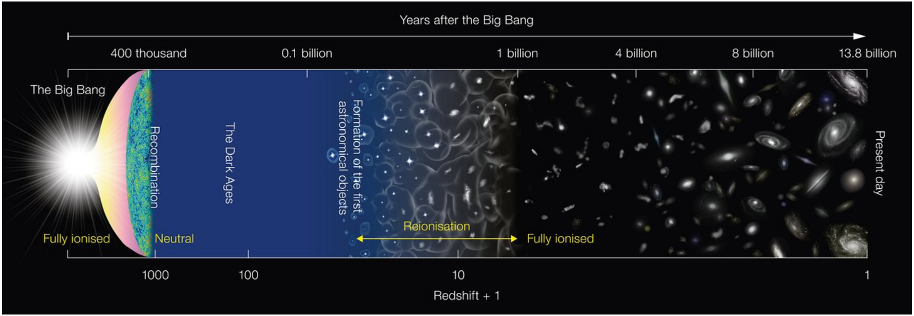
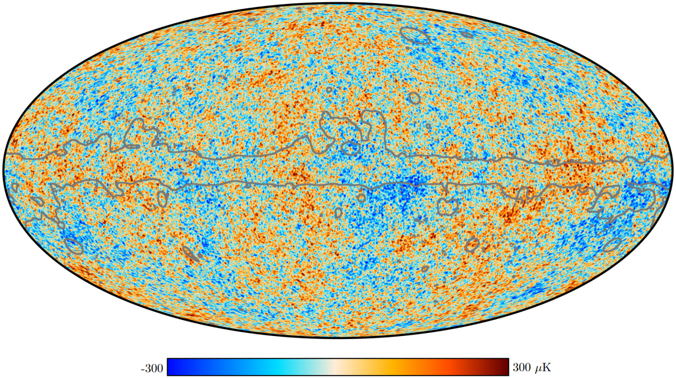
ILANCE International Laboratory for Astrophysics, Neutrino and Cosmology Experiments

Modern cosmology in a nutshell



Credits : NAOJ/ESO

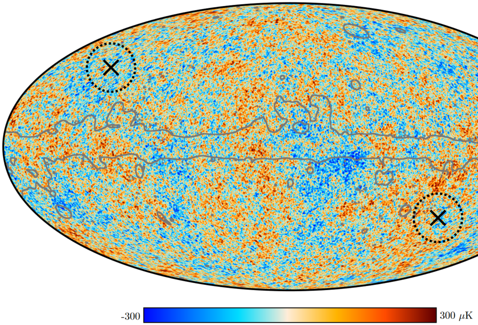
Cosmic Microwave Background (CMB)



2018 Planck map of the temperature anisotropies of the CMB

- CMB : oldest light in the universe, originating from the time of recombination (370 000 years after the Big Bang).
- Very homogeneous (black-body power spectrum) with very faint anisotropies.

Two cosmology problems and Cosmic Inflation

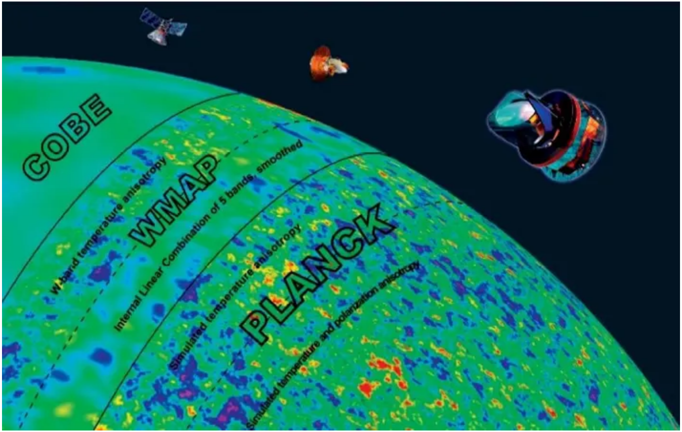


Horizon problem in the CMB

- Two cosmology puzzles :
  1. **Flatness problem :** Why is the Universe so flat?
  2. **Horizon Problem :** Why is the CMB so homogeneous?
- Problem with initial conditions in standard cosmology.
- **Cosmic inflation** provides an explanation for both problems and a mechanism for production of primordial perturbations.

CMB surveys

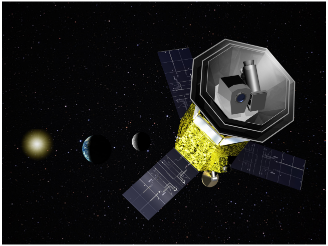
To this day, COBE,WMAP and Planck have already observed the CMB. CMB temperature is well known.

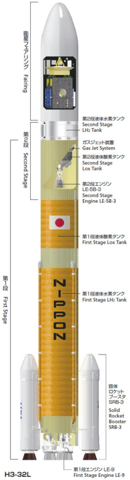


Credits : NASA/ESA and the COBE, WMAP and Planck teams

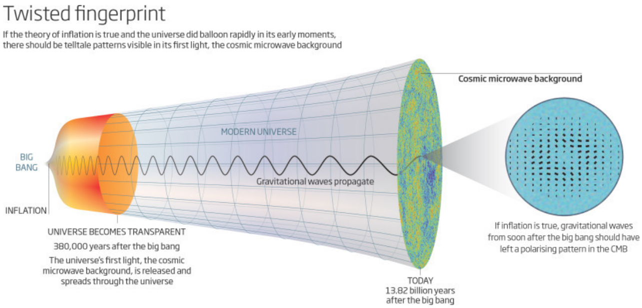
CMB surveys and LiteBIRD

- Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in late 2029 with JAXA's H3 rocket
- All-sky 3-year survey, from Sun-Earth Lagrangian point L2





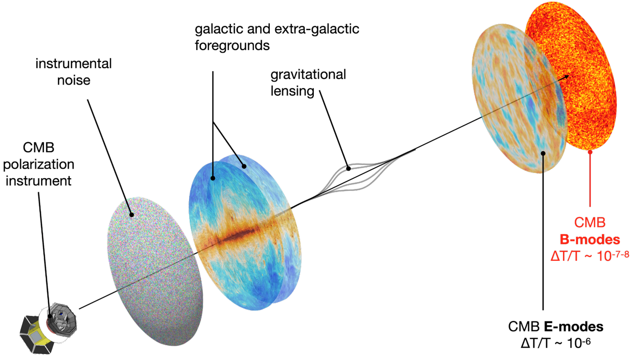
JAXA's H3 rocket



Credits : New Scientist

- Search for gravitational waves in the CMB polarization as a probe of cosmic inflation .
- The magnitude of primordial gravitational waves is proportional to the tensor-to-scalar ratio, r.
- Current best constraint: $r < 0.032$ (95 % C.L.). (Tristram et al. 2021, combining BK18 and Planck PR4)

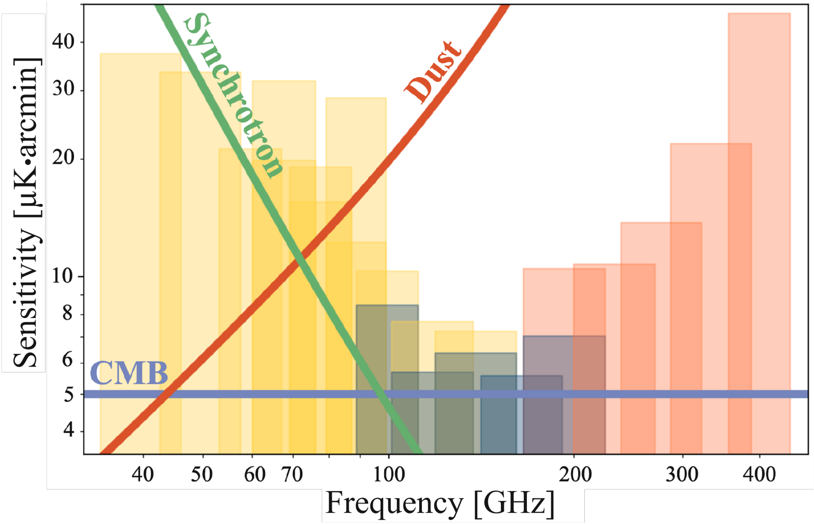
Foreground emissions & Instrumental effects



Credits : Josquin Errard

- Two main polarized foreground components :
  1. Galactic dust
  2. Synchroton emission

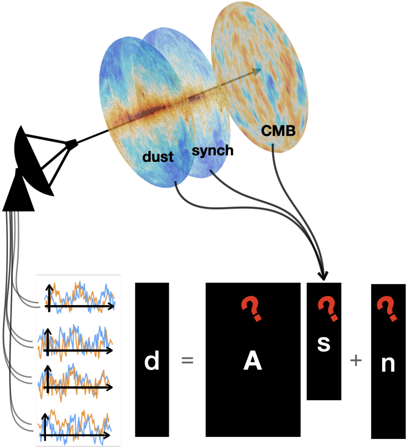
Foreground emissions & Instrumental effects

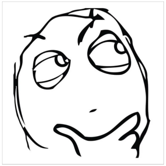


- Large frequency coverage (34–448 GHz in 15 bands).

Component separation formalism

Model of the multi-frequency sky signal





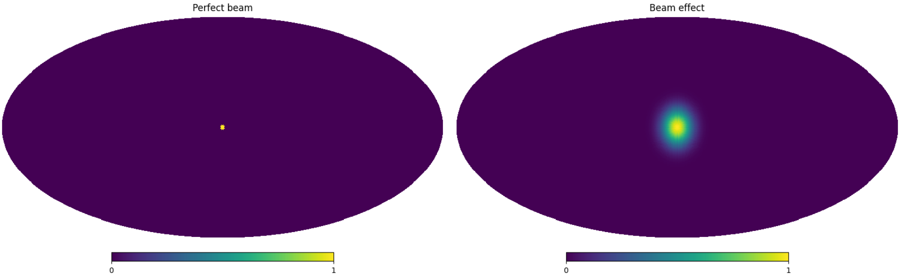
Stivoli et al. (MNRAS, 2010)
JE, Stivoli and Stompor (PRD, 2011)
JE and Stompor (PRD, 2012)
JE, Feeney, Peiris, Jaffe (JCAP, 2016)
Stompor, JE and Poletti (PRD, 2016)
JE and Stompor (PRD, 2019)
Poletti and JE (in prep)

Credits : Josquin Errard

Power spectrum C_ℓ of CMB B-modes

1. Produce maps and add instrumental noise (component model for each pixel : $\mathrm{d}_p = \mathrm{A}_p \mathrm{s}_p + \mathrm{n}_p$).
2. Fit foreground scaling laws to separate components(CMB, Dust, Synchrotron).
3. Compute power spectrum of retrieved CMB for B-modes.
4. Compare with power spectrum of gravitational waves for different values of r (maximization of cosmological likelihood).

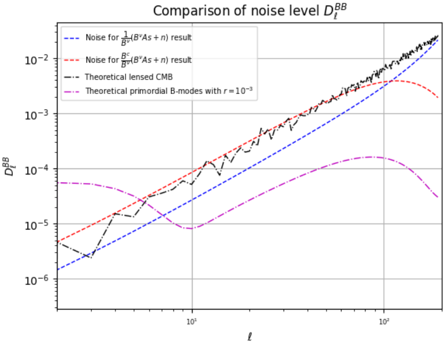
Instrumental effects : beam management



- Received signal is convolved by the beam :

$$d_p = [B(\alpha, \vec{r}) * A(\beta)s(\vec{r})]_p + n_p$$

Influence of the beam



Deconvolving the signal is necessary to avoid mismatch with model but it amplifies noise. Reconvolution by a common beam (of width 80')is necessary to avoid the noise increasing at high ℓ.

My internship

- Understand the context and bibliographical work.
- Reproduce existing results
- Modify the mixing matrix to incorporate the beam.
- Adapt existing component separation code to include the beam.
- **Goal :** Probing CMB B-modes at higher ℓ.

Questions

Backup Slide 1 : Galactic Foreground emission

1. The CMB angular power spectra correspond to the *Planck* 2018 best-fit parameters. With lensing and no tensor i.e. r = 0.
2. Synchrotron dominate at frequencies lower than 70 GHz. Stokes parameters are modeled as :

$$[Q_s, U_s](\hat{n}, \nu) = [Q_s, U_s](\hat{n}, \nu_\star) \left(\frac{\nu}{\nu_\star}\right)^{\beta_s(\hat{n})}$$

3. Thermal dust dominate at frequencies higher than 70 GHz. Stokes parameters are modeled as :

$$[Q_d, U_d](\hat{n}, \nu) = [Q_d, U_d](\hat{n}, \nu_\star) \left(\frac{\nu}{\nu_\star}\right)^{\beta_d(\hat{n})-2} \frac{B\left[\nu, T_d(\hat{n})\right]}{B\left[\nu_\star, T_d(\hat{n})\right]}$$

Backup Slide 2 : Log-likelihoods

- Single pixel log-likelihood :

$$-2 \ln \mathcal{L}_{data}(s_p, \beta_i) = C + (d_p - A_p s_p)^t N_p^{-1} (d_p - A_p s_p) \qquad (1)$$

$N_p \in S_{n_s \times n_f}(\mathbb{C})$ is a noise matrix defined for each pixel p.

- Multi-pixel log-likelihood :

$$-2 \ln \mathcal{L}_{data}(s, \beta) = C + (\mathrm{d} - \mathrm{As})^t N^{-1} (\mathrm{d} - \mathrm{As}) \qquad (2)$$

Here all the matrices and vectors now span over many pixels.

- Block-diagonal N case :

$$-2 \ln \mathcal{L}_{data}(s, \beta) = C + \sum_p (d_p - A_p s_p)^t N_p^{-1} (d_p - A_p s_p) \qquad (3)$$

Backup Slide 3 : Beam management in the log likelihood

$$\mathrm{d}_p = [\mathrm{B}(\alpha, \vec{r}) * \mathrm{A}(\beta)s(\vec{r})]_p + \mathrm{n}_p \tag{4}$$

- Introducing the modified mixing matrix :

$$\widetilde{\mathrm{A}}^{\nu}_{\ell(m),n} \equiv \mathrm{B}^{\nu}_{\ell(m)}\mathrm{A}^{\nu}_{n} \tag{5}$$

  where n could be either CMB, dust or synchrotron.
- The new spectral likelihood reads :

$$-2\ln\mathcal{L}_{\text{spec}} = -\sum_{\ell m} d^{\dagger}_{\ell m}\mathcal{N}^{-1}_{\ell(m)}\widetilde{\mathrm{A}}_{\ell m}\left(\widetilde{\mathrm{A}}^{\mathrm{T}}_{\ell m}\mathcal{N}^{-1}_{\ell(m)}\widetilde{\mathrm{A}}_{\ell m}\right)^{-1}\widetilde{\mathrm{A}}^{\mathrm{T}}_{\ell m}\mathcal{N}^{-1}_{\ell(m)}\mathrm{d}_{\ell m}$$

Backup Slide 4: Mission CMB - COBE/WMAP/Planck and LiteBIRD

- Cosmic Background Explorer (COBE) (Nobel Prize 2006) provided further support for the Big Bang theory of the universe: CMB has a near-perfect black-body spectrum and very faint anisotropies.
- Wilkinson Microwave Anisotropy Probe (WMAP). The WMAP measurements support the cosmic inflation paradigm in several ways, including the flatness measurement.
- Planck
- ... Lite BIRD

Backup Slide 5 : Numbers for cosmological puzzles

- **Flatness problem :** Our universe shows no sign of spatial curvature. Flat space is an unstable fixed point of the dynamics. At the time of the electroweak phase transition ($z \approx 10^{15}$) ([1]), curvature is bound : mod $\Omega_k(t_{EW}) \leq 10^{-30} \ll 1$. This is very small!!!
- **Horizon problem :** The CMB is almost perfectly uniform and isotropicn with temperature 2.725 K. With our standard cosmology, causally connected patches are within $\theta \approx 1.7$. How could thermal equilibrium be reached for parts of the Universe never in causal contact?