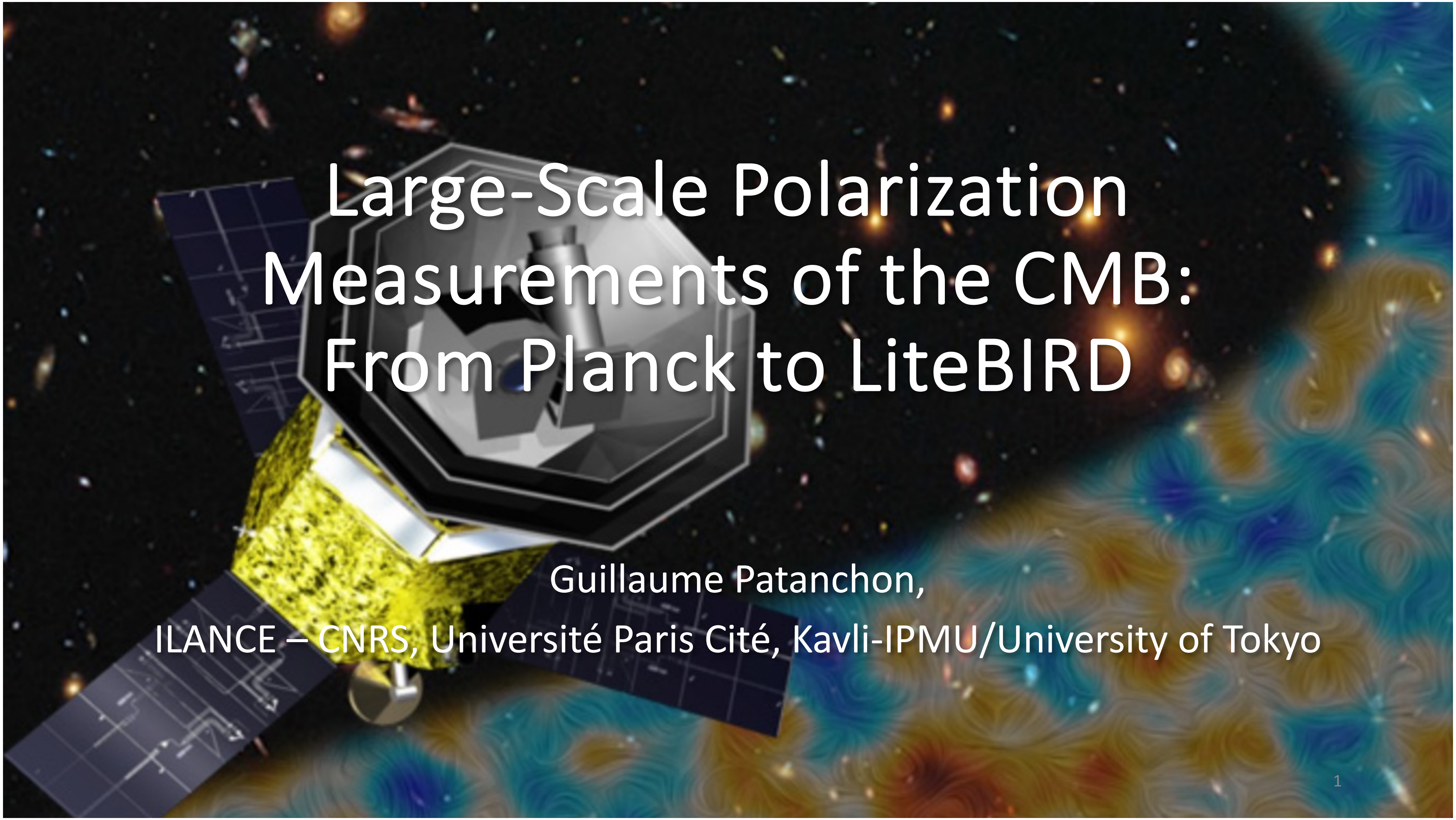
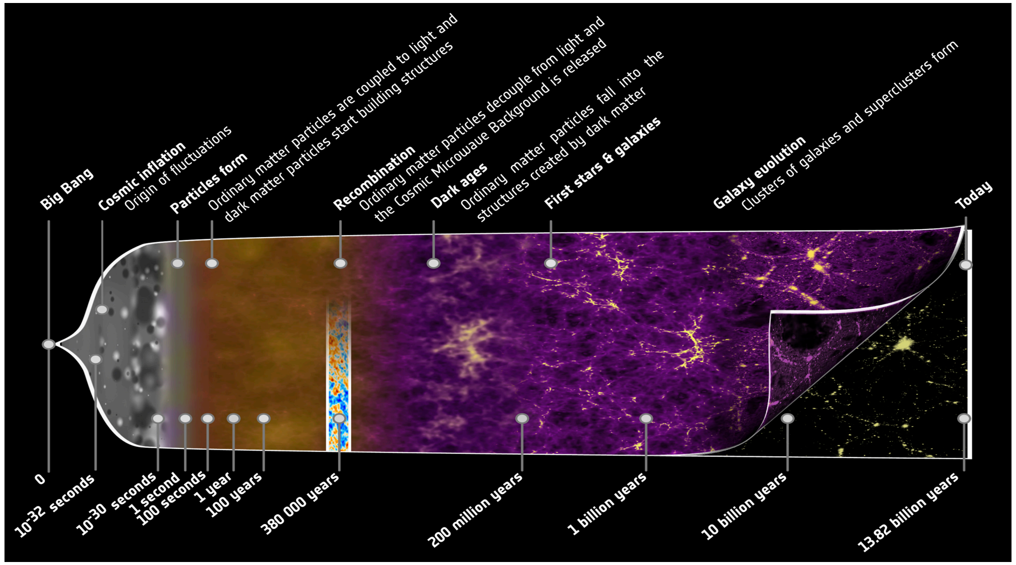


Large-Scale Polarization Measurements of the CMB: From Planck to LiteBIRD

Guillaume Patanchon,

ILANCE – CNRS, Université Paris Cité, Kavli-IPMU/University of Tokyo

The primordial Universe



Questions in cosmology:

❑ **Nature of dark energy and dark matter**

❑ **Inflation** (~10^{-34} s) **Accelerated expansion phase**

- Mechanism for the generation of structures:

scalar

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

tensor

$$P_T(k) = A_T \left(\frac{k}{k_0}\right)^{n_t}$$

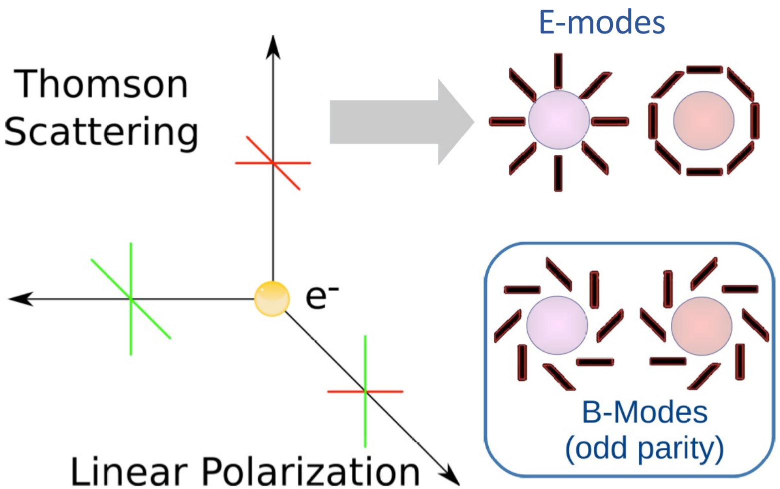
Simplest inflation model:
a single scalar field:

New physics
$E \sim 10^{16}$ GeV

$$V^{1/4} \sim \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\,\mathrm{GeV}$$

signatures on the CMB

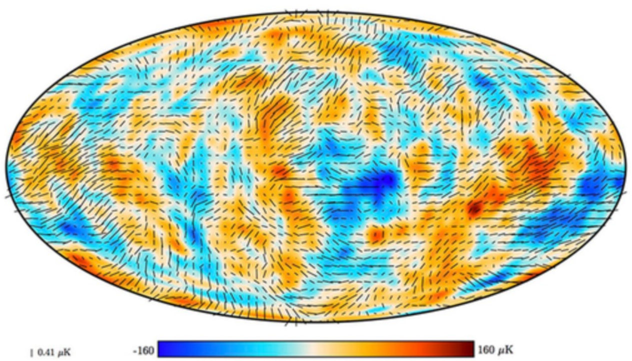
CMB polarisation



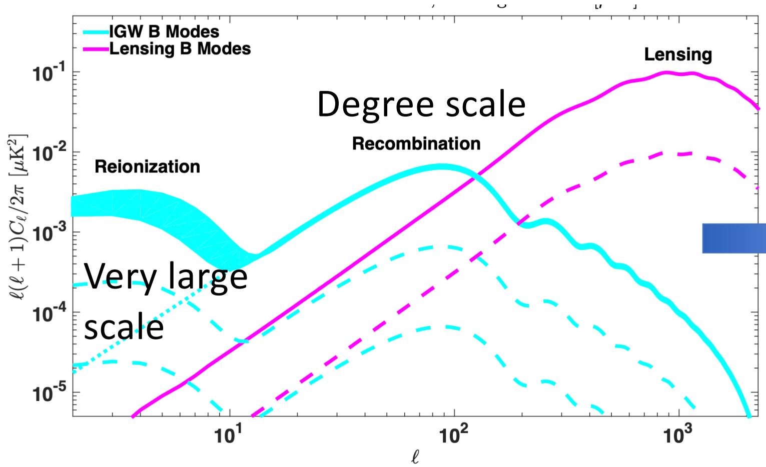
Tensor modes (GW) only!

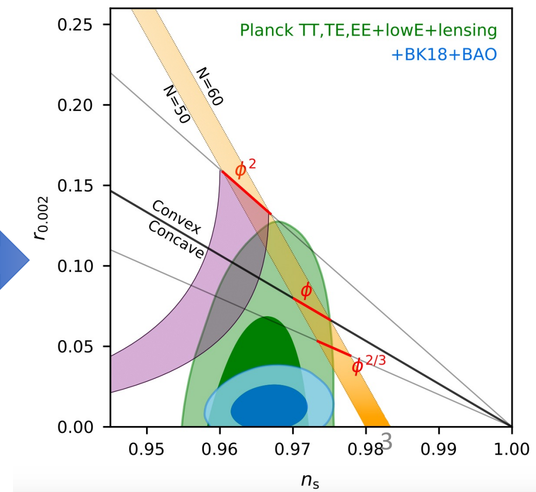
With E-modes:

- Neutrino mass
- Dark energy eq. of state
- Nb. of types of relat. particles
- τ reionisation



B-mode power spectra: **Measurement of r**



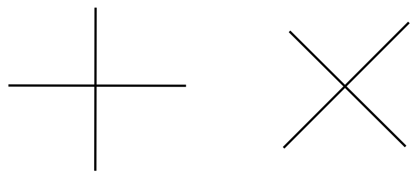


Complexity of the CMB polarisation measurement

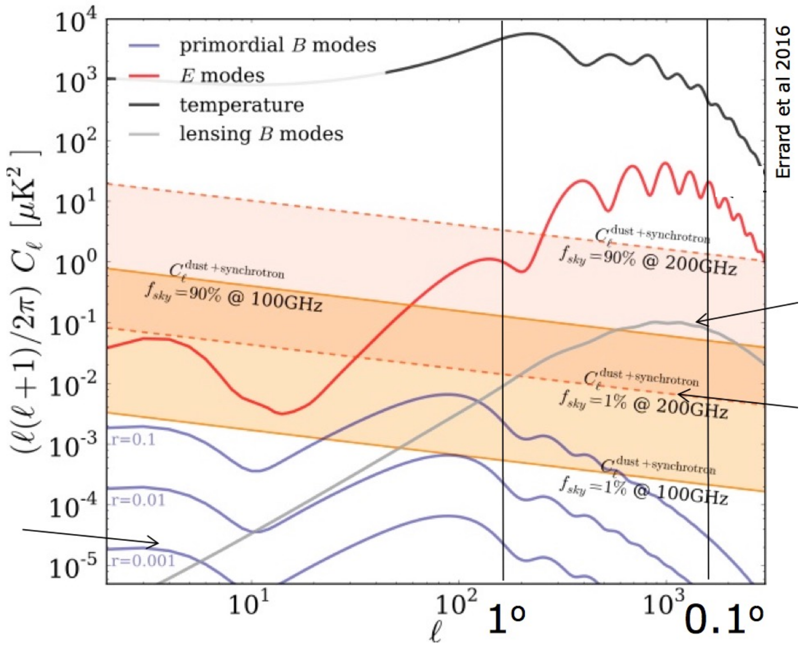
❑ **Presence of complex systematic effects in data : Ex. Planck 10 years of analysis**

Stokes parameters Q and U are obtained by linear combinations differentiating measurements

Ex : $S_A - S_b$ gives Q or U



Cancellation non-polarized signal



Large dynamics between I and Q, U:
➡ **Any small difference between detectors produces a leakage from intensity to polarization**

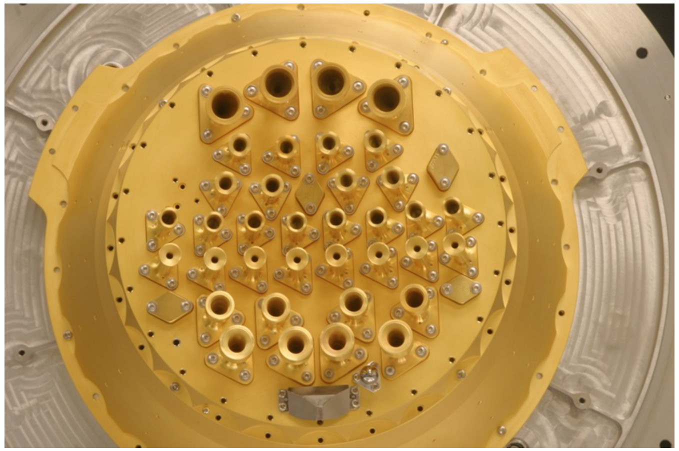
Systematic effects must be controlled to an unprecedented precision.

❑ **Polarized galactic emissions have an amplitude higher than the searched signal**

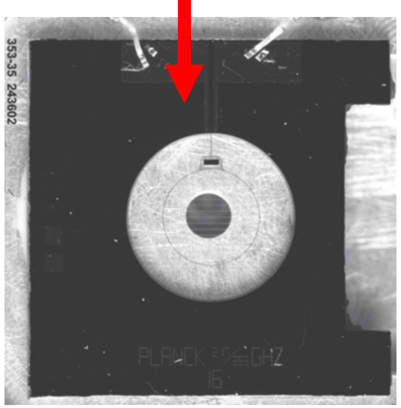
The Planck satellite of ESA

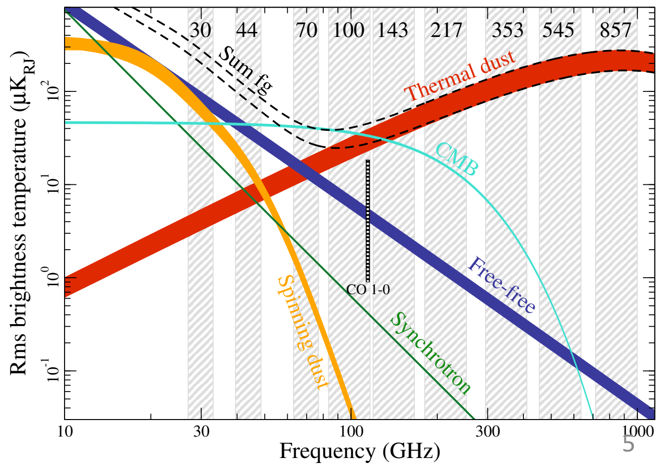
- 1.5 m off-axis Gregorian telescope, 2 instruments: LFI (20K) HFI (0.1K)
- Frequency coverage from 30 to 857 GHz.
  Angular resolution from 30’ to 5’
- Launched in 2009, last publications 2018!
- Reference maps for the next decade: cosmic variance limited temperature map.

HFI focal plane



Polarization sensitive bolometers





esa

planck

cnes

agenzia spaziale italiana

NASA

CNRS

DTU Space
National Space Institute

INAF Istituto Nazionale di Astrofisica

Science & Technology Facilities Council

CSIC
Consejo Superior de Investigaciones Científicas

National Research Council of Italy

Gobierno de España
Ministerio de Ciencia e Innovación

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK

PLANCK LFI

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ipac
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Helsinki Institute of Physics

Instituto de Astrofísica de Canarias

IFCA
Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG

ISDC
Data Centre for Astrophysics

JPL

LAL
Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris
LERMA

LPSC Grenoble

MilliLab

Max-Planck-Institut für Astrophysik

NUI Maynooth

INAF
Osservatorio Astronomico di Padova

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esa

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University of Toronto

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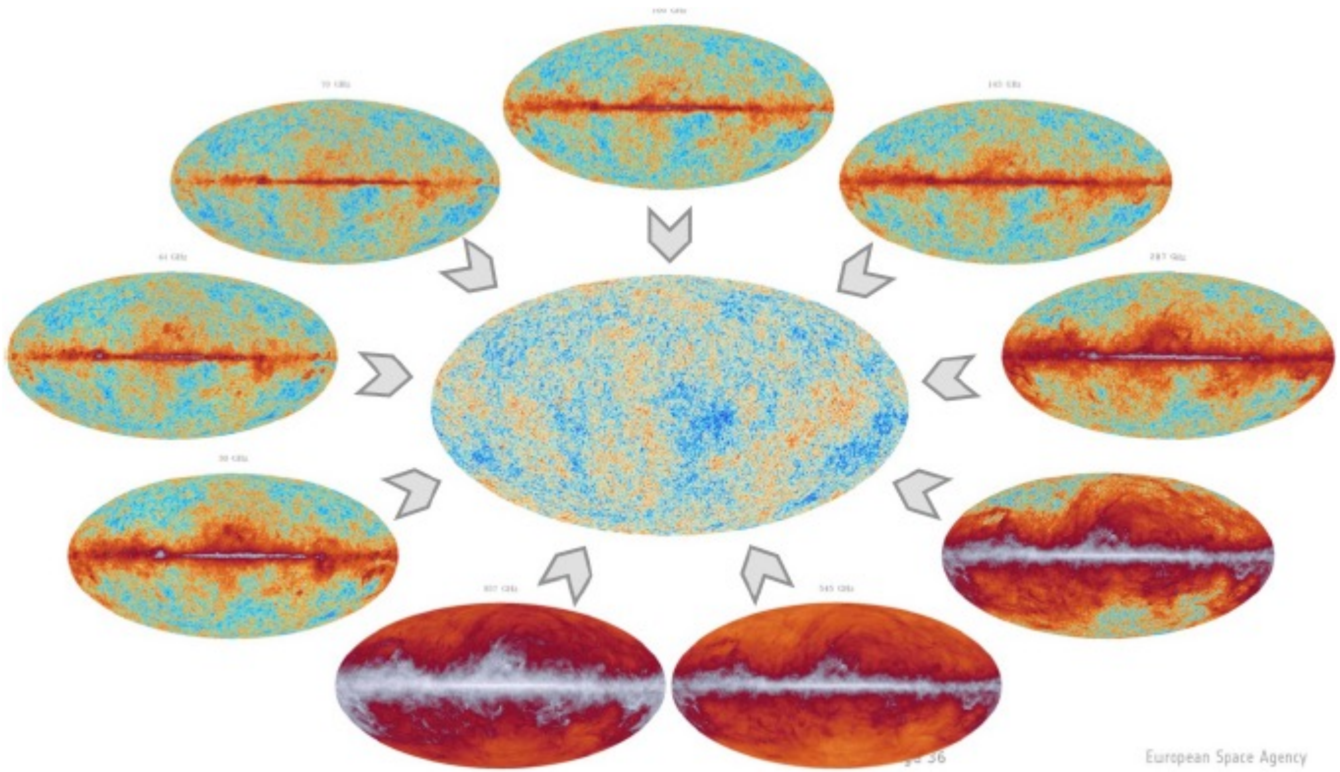
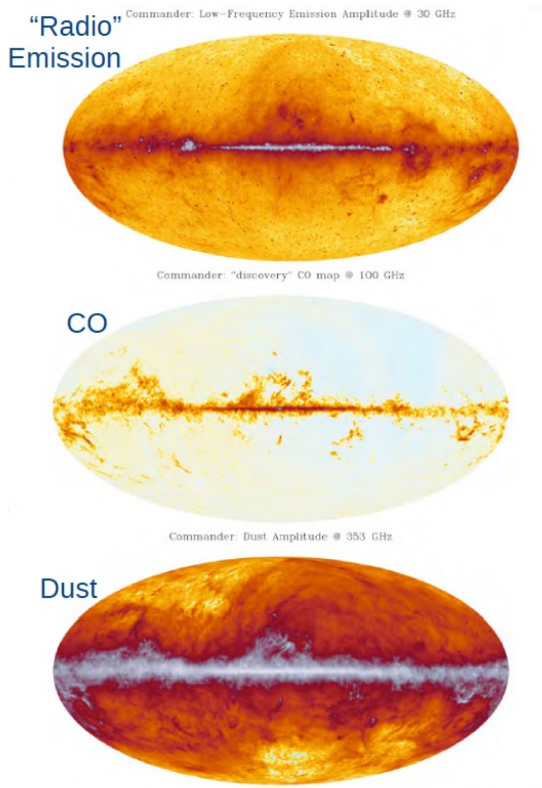
asdc

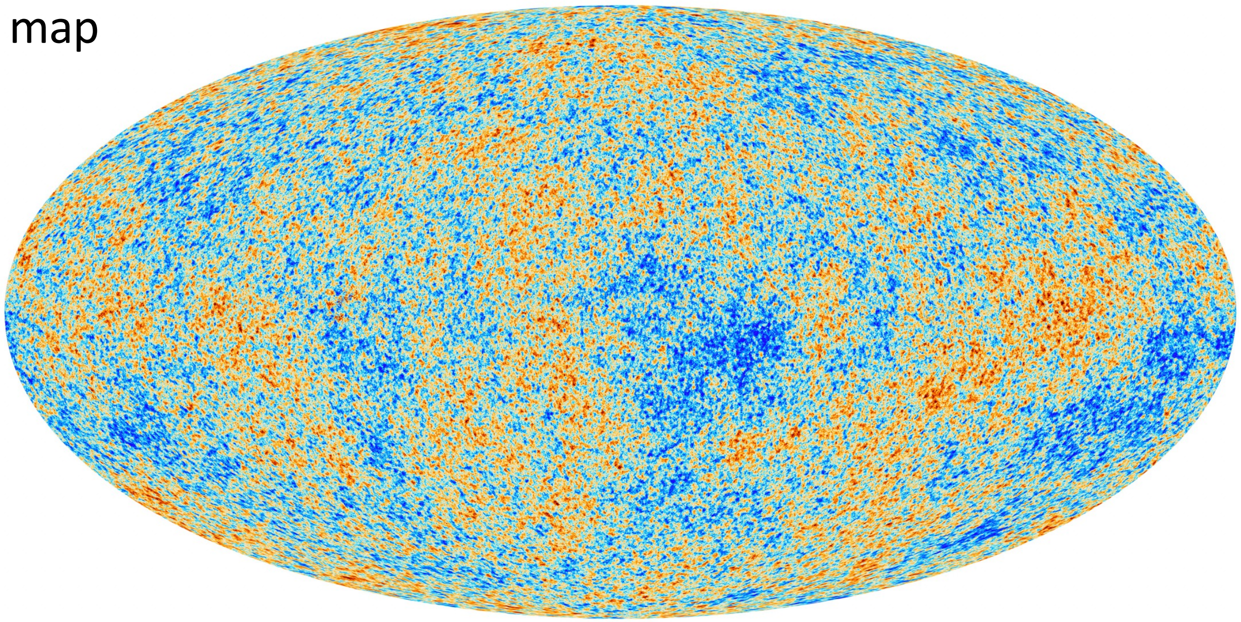
Frequency maps and component separation





CMB map measured by Planck

Full sky temperature map

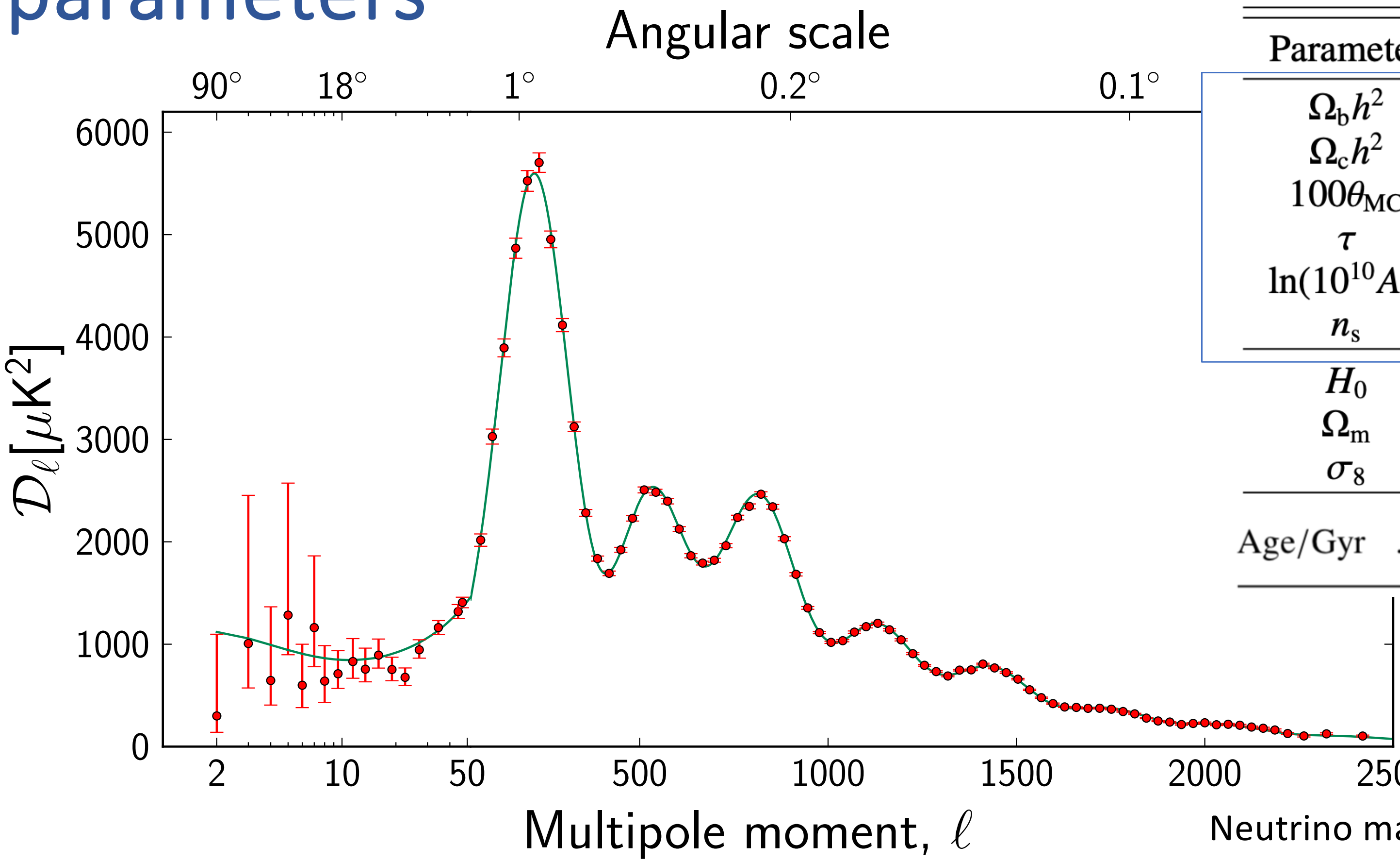


Many other data products:

- full sky polarisation maps
- foreground maps used for galactic studies and prediction for the preparation of future CMB missions
- lensing potential map

…

Temperature power spectrum – cosmological parameters



Parameter	TT,TE,EE+lowE+lensing
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_m	0.3153 ± 0.0073
σ_8	0.8111 ± 0.0060
Age/Gyr	13.813 ± 0.038

Remarquable fit
only 6 parameters

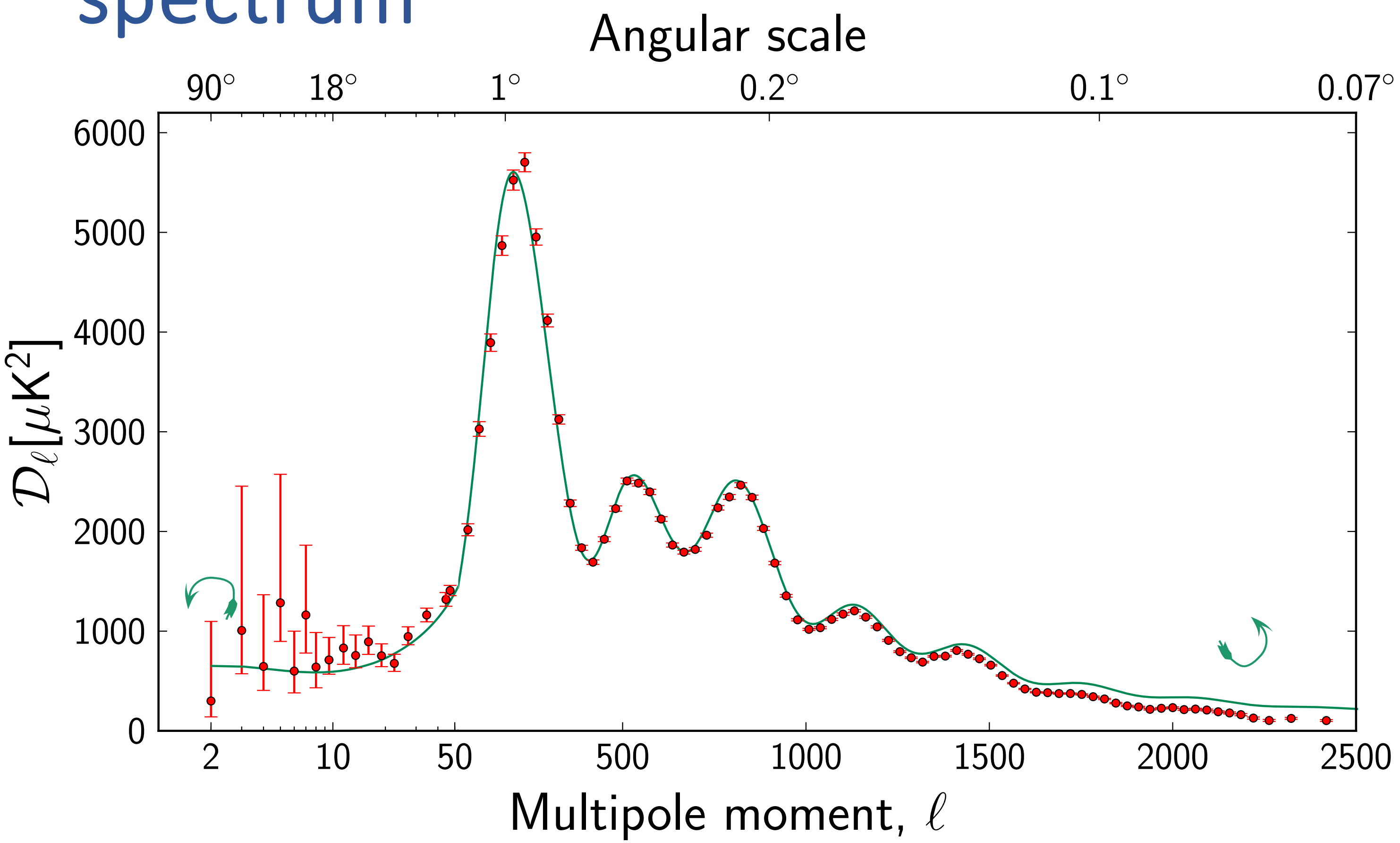
Neutrino masses: $\sum m_\nu < 0.23$ eV

DE eq. of state: $w = -1.019^{+0.075}_{-0.080}$

Curvature: $\Omega_K = 0.000 \pm 0.005$ (95%,

Nb. of relat. species: $N_{\rm eff} = 3.04 \pm 0.18$

Temperature power spectrum – primordial spectrum



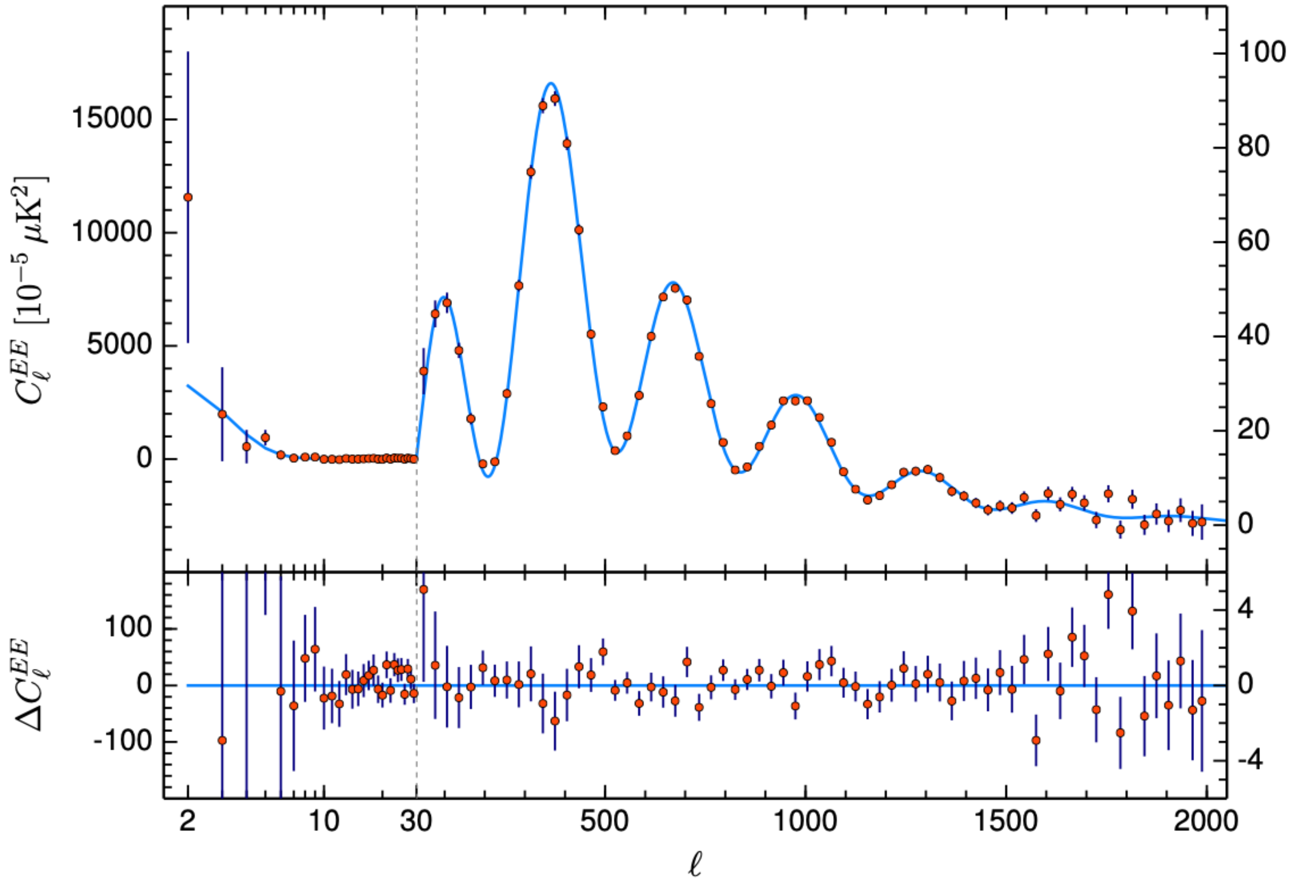
Constraint on primordial spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

$n_s = 0.9649 \pm 0.0042$

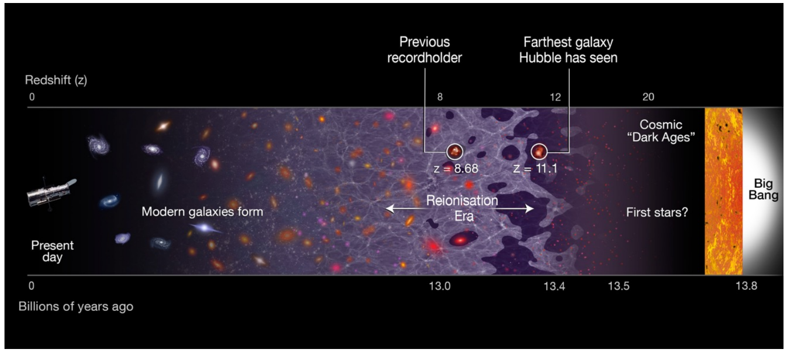
Departure from invariant spectrum. One important prediction from inflation

E-mode polarization

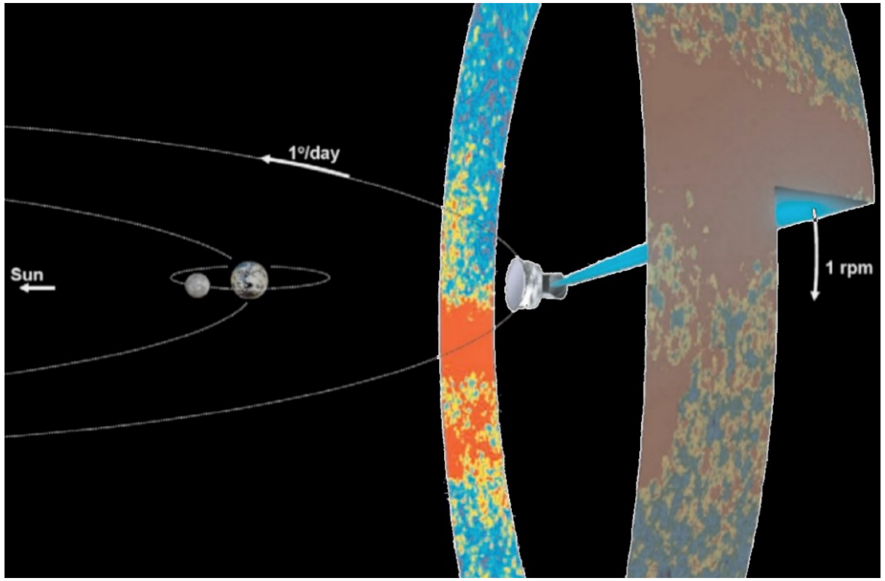


Constraints on reionisation parameter in the Universe history

$$\tau = 0.0544 \pm 0.0073$$



Planck scanning strategy

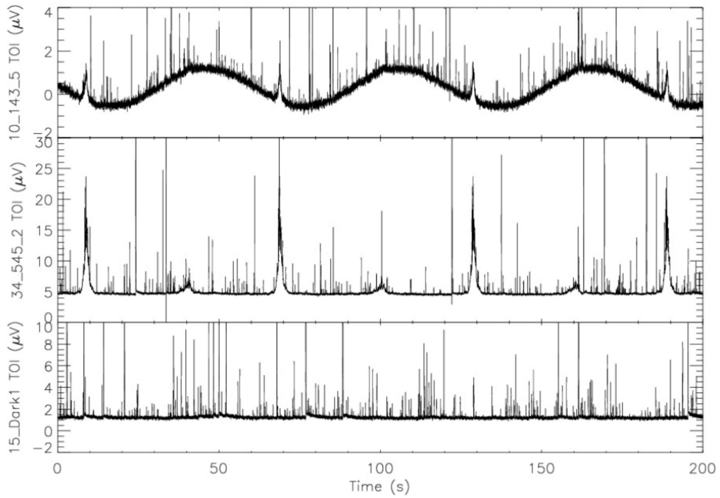


- One circle observed every minute
- Each circle is observed ~ 50 times
- Precession of 7 degrees
- One full survey every 6 month (5 surveys total for HFI and 8 for LFI)

143 GHz

545 GHz

“dark”



Systematic effects and data reduction

Model of the raw data:

Electronic response

4K lines (A_k, w_k, …)

$$d_i(t) = g_i \int R_i(t - t') W(t') \left[X_i(t') + \sum_j T_{ij}(t') \right] \mathrm{d}t' + Q_i(t) + n_{Ji}(t) + \sum_c F_{ic}(t).$$

Gain

Transfer function

(A, τ, …)

$$X_i(t') = \left[\int H_i(t' - t'') \left(\{ B_{i;\psi_{it''}} * [S_i + o] \}(\vec{r_{t''}}) + n_{si}(t'') \right) \mathrm{d}t'' \right]$$

Lobes

Data are digitized, averaged over 40 samples, and compressed on board

Systematic effect due to:

- mismodeling
- unknown parameter
- No correction

Data processing: compression

Symmetrized lobe

$$d_i(t_p) = \{ B_{\psi_{itp}} * [S_i + o] \}(\vec{r_{t_p}}) + n_{i;\mathrm{total}}(t_p).$$

Final objective

Noise in HFI time ordered data

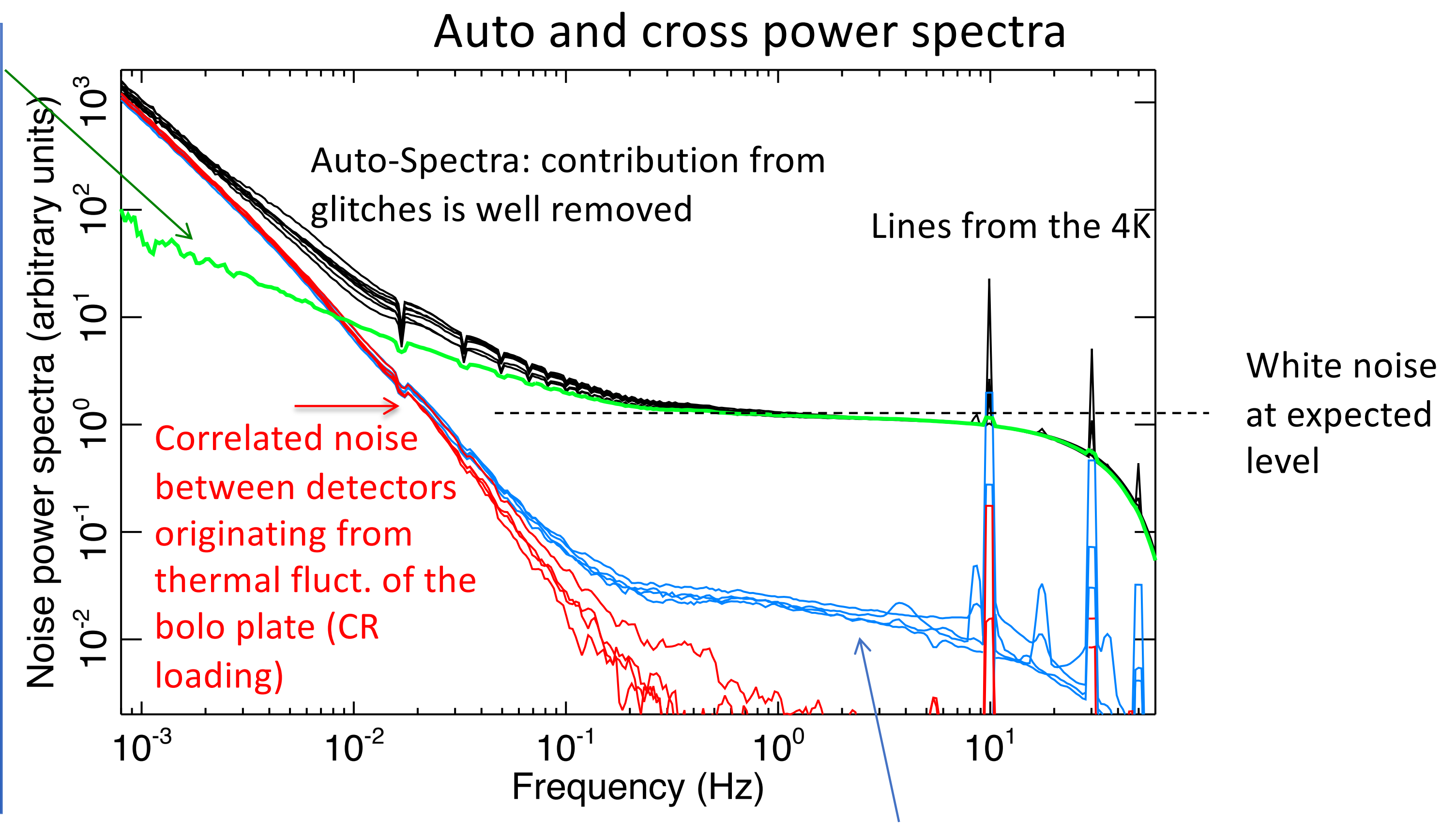
Uncorrelated noise

Not observed at that level on the ground

f_{knee}~ 0.15 Hz

No clear explanation, probably not due to CRs since not modulated as glitch rate

Fundamental limit after removal of systematics



Glitches below the detection threshold common between PSB-a and PSB-b
Provide a limit on the level of remaining glitches in data

Main systematic effects in Planck

- Additive effects : Cosmic ray events, unexpected 1/f noise, microphonic noise

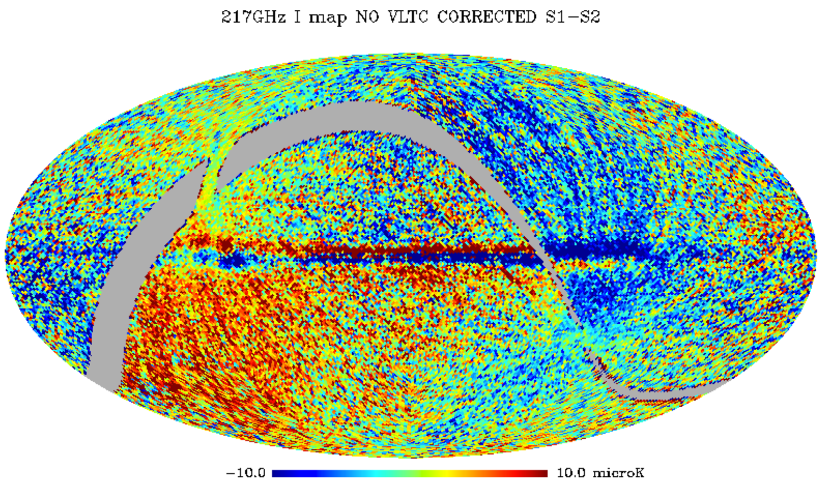
- Main effects I to P leakages, different detectors had to be combined to estimate Q and U Stokes parameters
  - ADC non-linearities
  - Band-pass mismatch
  - Long time constants

- Other systematics
  - Beam + time constants

- Use of redundancies of observations and of the strong dipole signal to calibrate and correct the data : Surveys with opposite scanning directions allowed optimization of parameters and correction of many systematic effects.

Use of redundancies

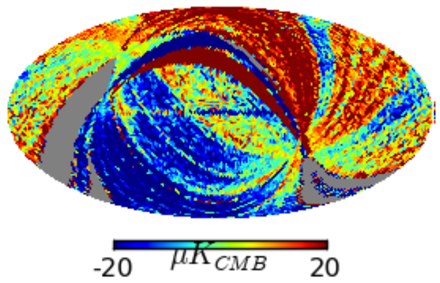
Survey difference maps were useful to track and characterize systematic effect



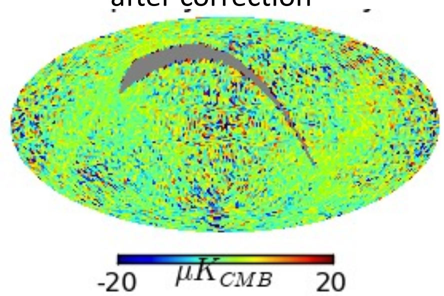
- Uncorrected **long time constants** slightly shift the galaxy
- **ADC non-linearitie**s creates residual dipole seen in the difference

Effect of long time constants is corrected after optimization at the map-making level by template fitting

1 detector before

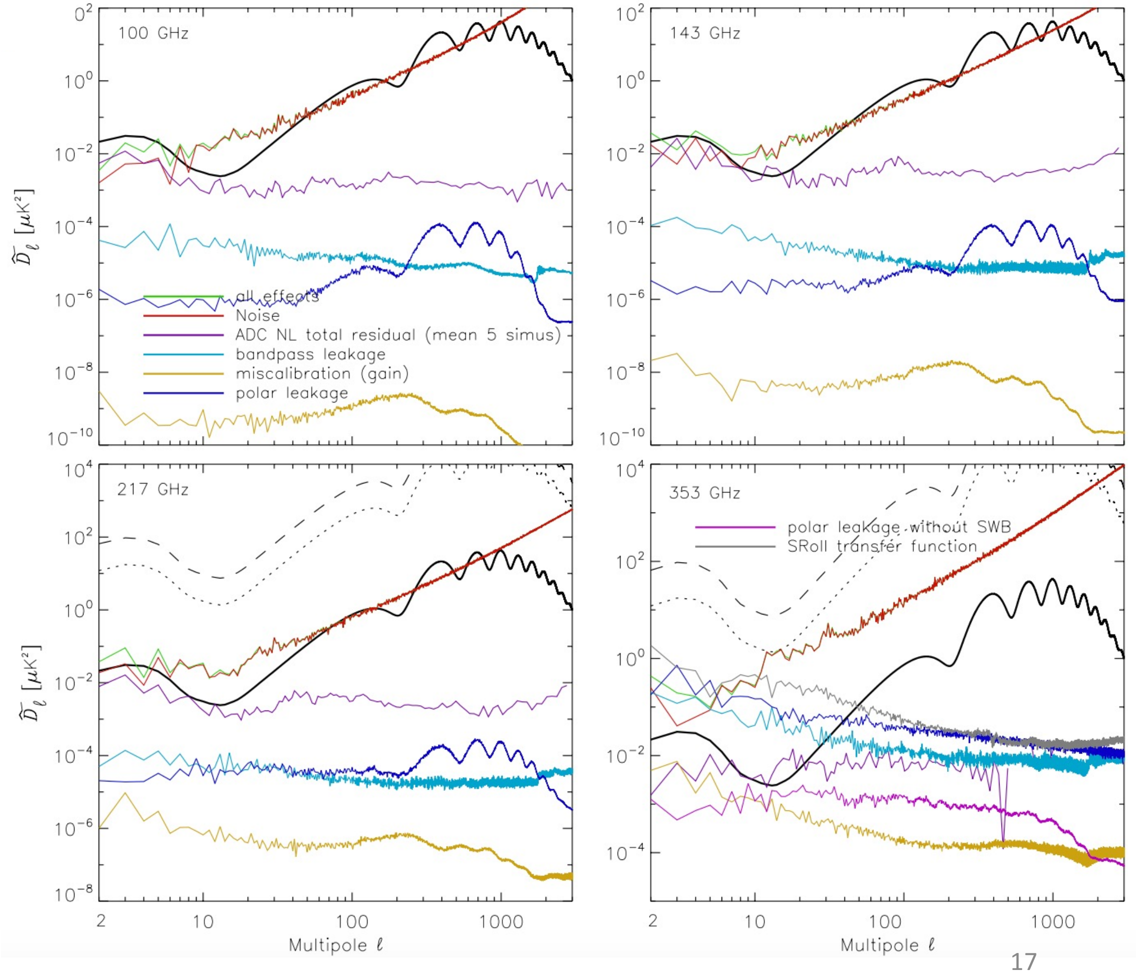


after correction



Summary of systematic effects (HFI)

- ADC is the dominant systematic effect
- Its contribution is at the level of the noise at low ells after intensive corrections



Towards B-mode measurements from space

- Increase the number of detectors (Planck-HFI detector are photon noise limited):

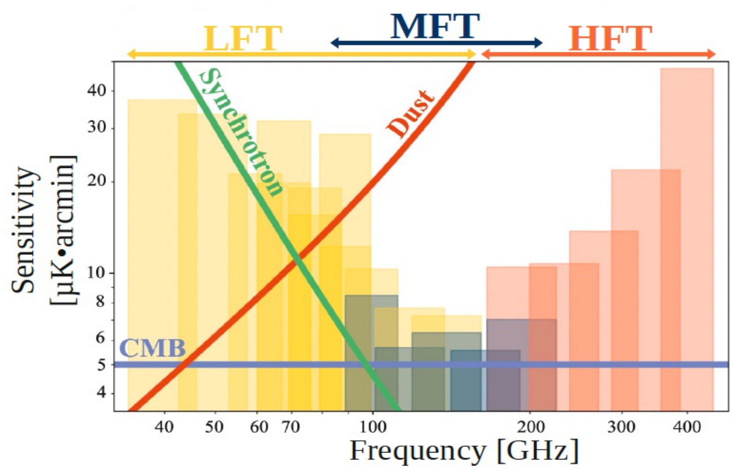
➡ ~5000 detectors for LiteBIRD
~13000 " " for PICO

- More frequency bands of observation to capture foreground complexity:

➡ 15 bands for LiteBIRD
21 " " for PICO (21 to 800 GHz)

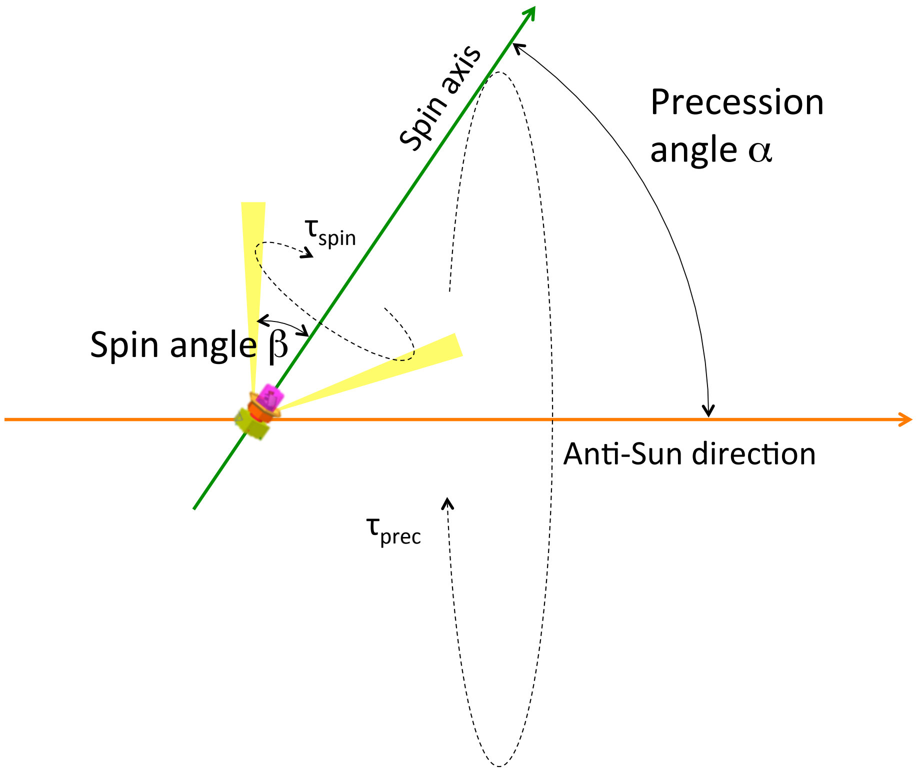
- Increased scanning redundances: scanning angles, polarisation angles:

➡ Large precession angle (37.5 degrees for LiteBIRD)
➡ Use of an HWP for instantaneous separation of I,Q,U



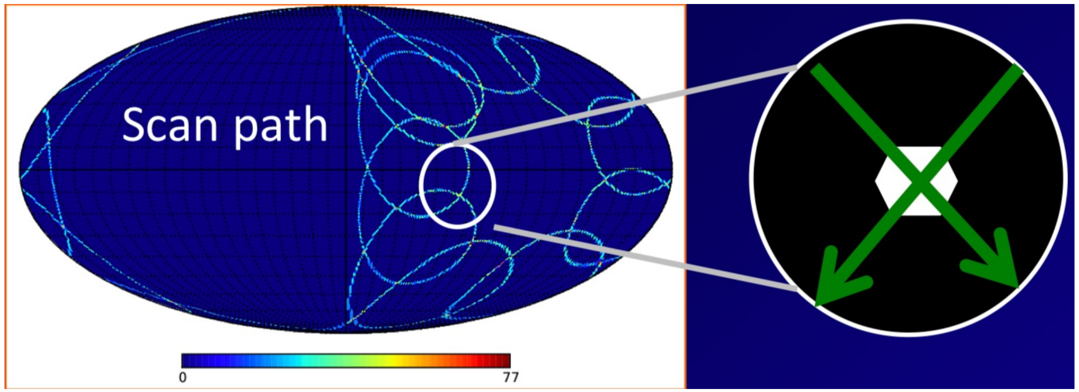
Systematics mitigation by scanning strategy

Rotation and precession



Large precession angle:
allows detector cross-linking

LiteBIRD nominal: $\alpha = 37.5^{o}$; $\beta = 57.5^{o}$

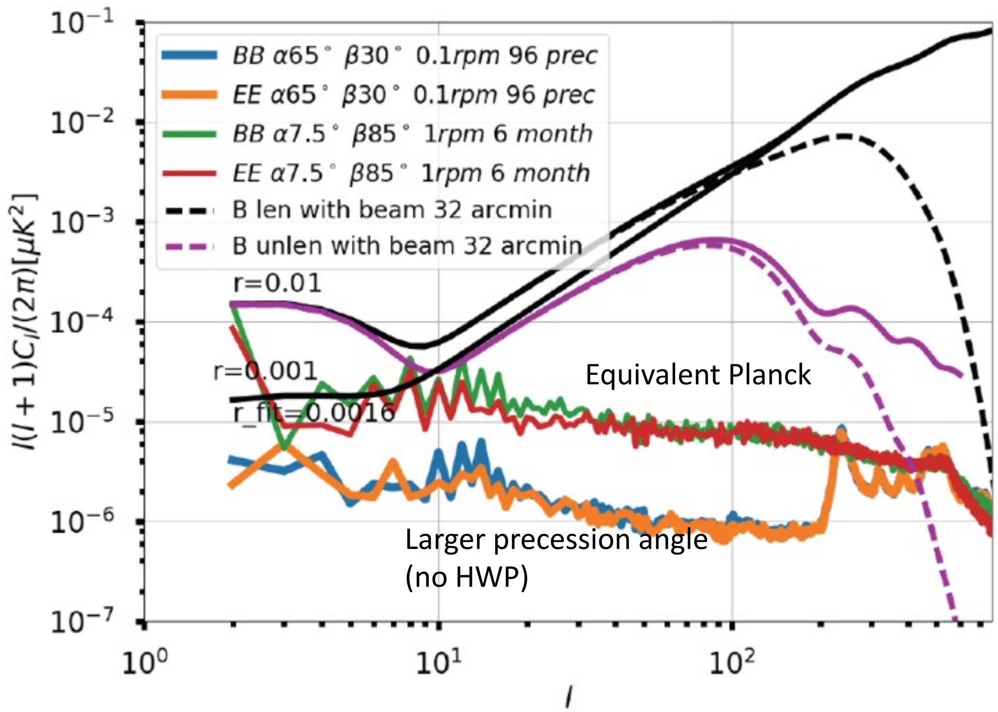


Cross-linking, redundances and systematics

- Many effects scale with <cos 2Ψ> and <sin 2Ψ>. The use of a HWP and better angle redundancies as planned for LiteBIRD help.

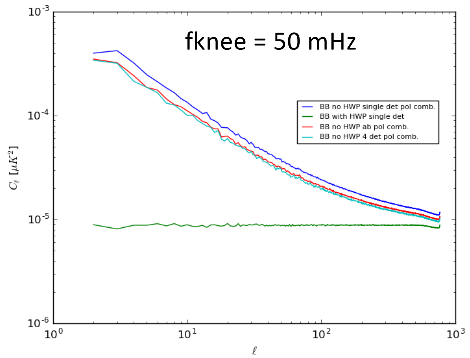
- Redundances are important to
  - separate instrumental effects from the sky signal
  - Find unexpected instrumental effects

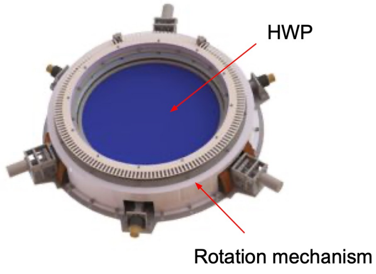
Effect of band-pass mismatch, Hoang Duc Thuong 2017

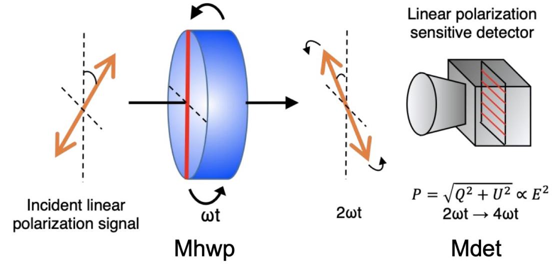


Advantages of an HWP

- 1/f reduction

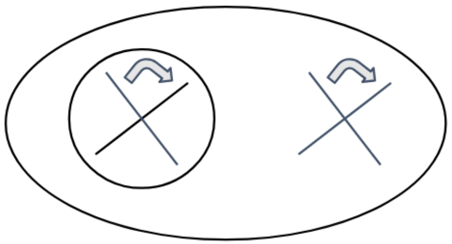




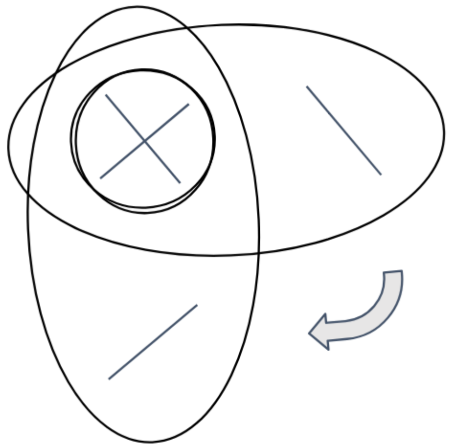


- Systematic effect reduction

With HWP

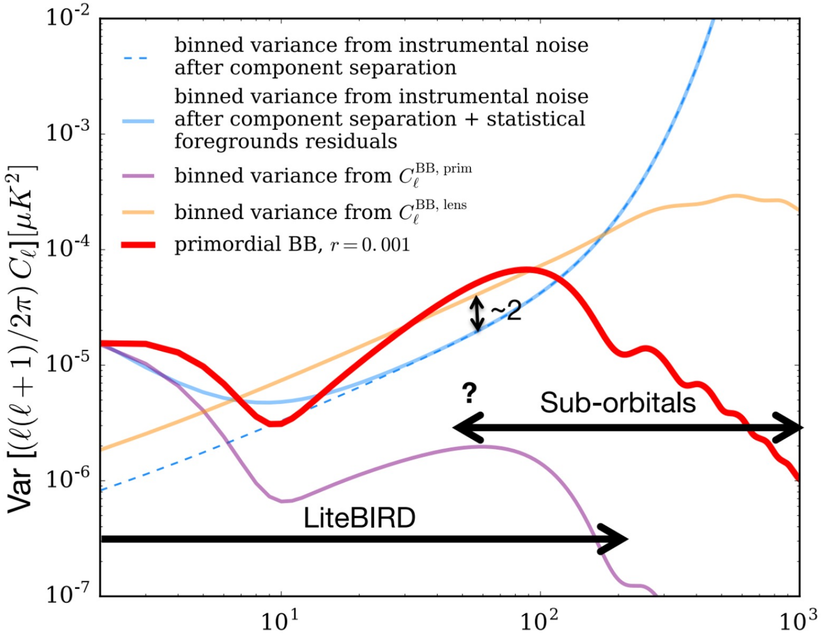


Without HWP

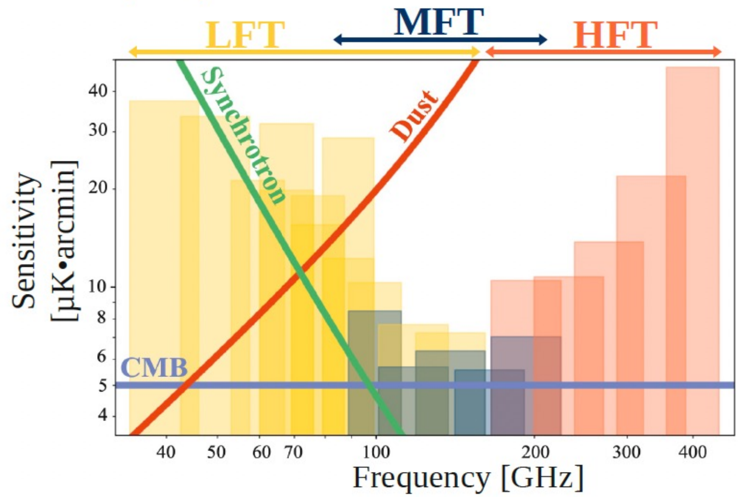


LiteBIRD sensitivity to B-modes

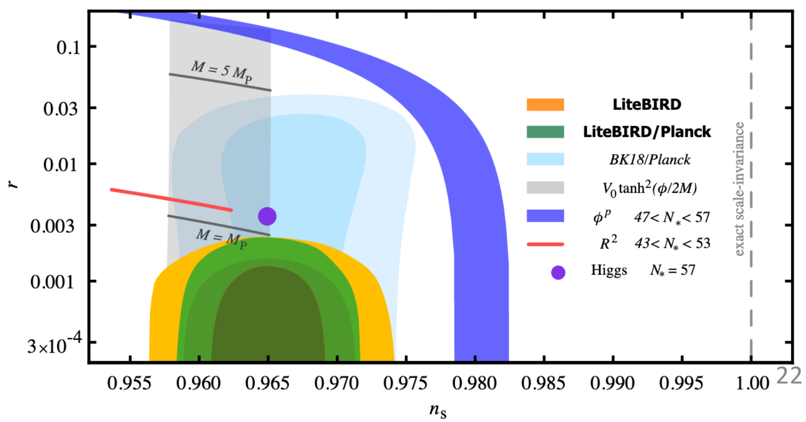
Measurement of the tensor-to-scalar ratio with the sensitivity: σ(r) < 10[-3]



Efficient component separation



Constraints on inflation



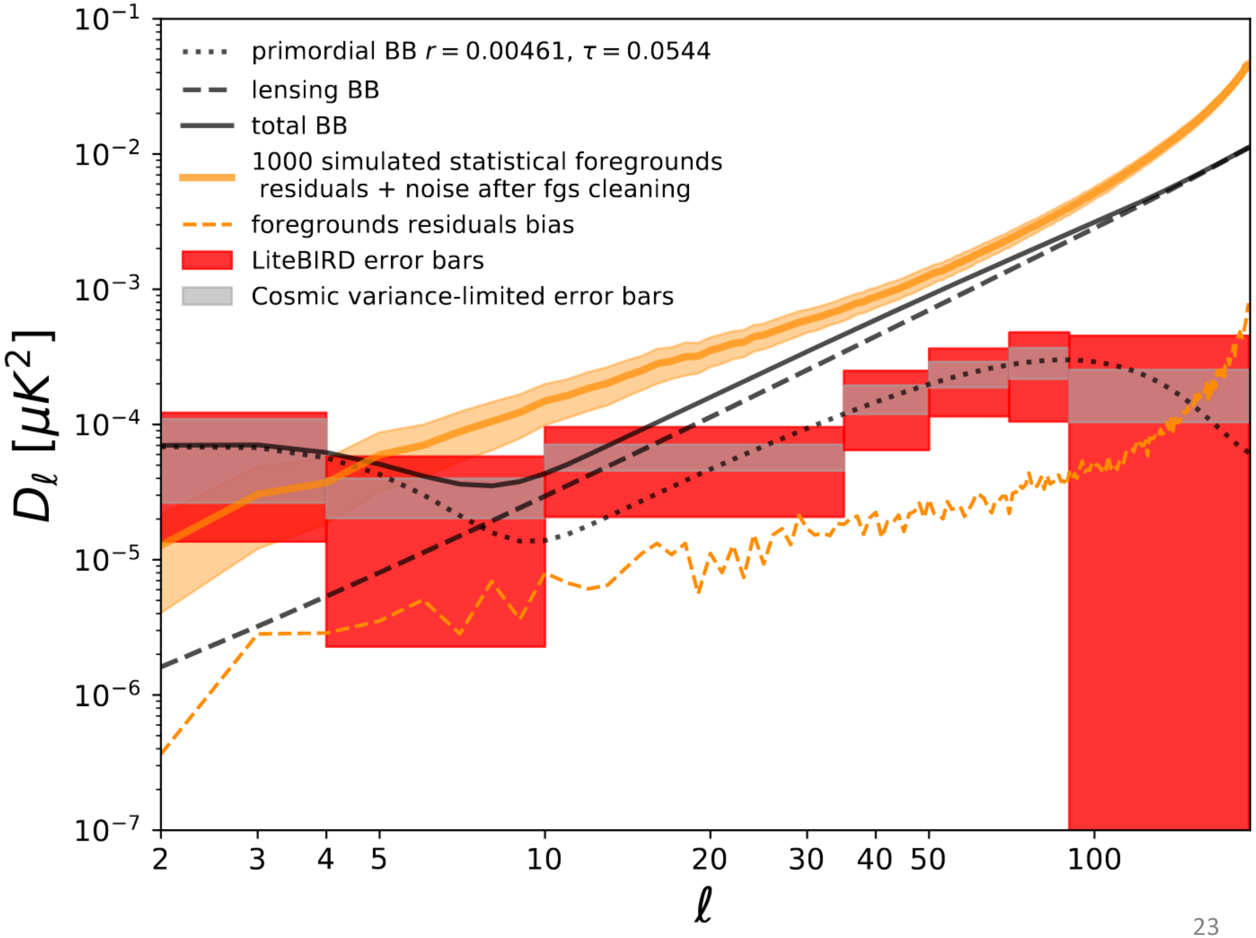
Uncertainty budget

Combination of:

- noise
- foreground residuals after component separation
- systematic effects

We assign a third of the error budget for the evaluation of **r** to systematics

LB collab, PTEP, 2023

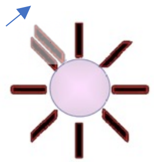


Sources of systematics

Nearly 70 possible sources of systematics have been identified

Those either produce:

- I to P leakages
- E to B leakages



- Pure B effect without mixing: mostly induced galactic foreground leakages due to mismatch in component separation

The main identified effect is **beam mismatches**

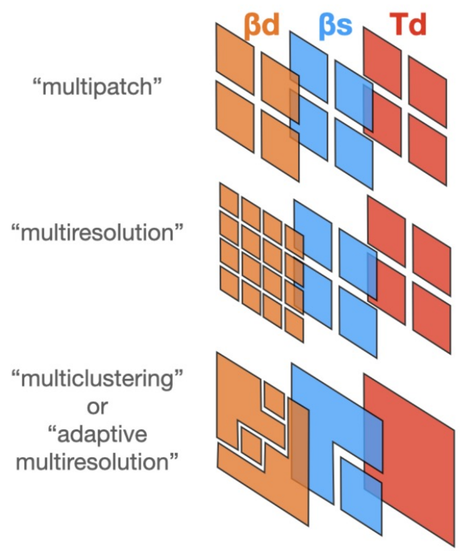
Category	Systematic effect	Δr	Source	Type
Beam	Far sidelobes	4.4×10^{-5}	$B \to B,\ E \to B$	R
	Near sidelobes	5.7×10^{-6}	$B \to B,\ E \to B$	R
	Main lobe	$< 10^{-6}$	$E \to B$	E
	Ghost	5.7×10^{-6}	$E \to B$	R
	Polarization and shape in band	$< 10^{-6}$	$E \to B$	R
Cosmic ray	Cosmic-ray glitches	Noise	Power to B, E	E
HWP	Instrumental polarization	$< 10^{-6}$	$T \to B$	E
	Transparency in band	5.7×10^{-6}	$E \to B$	R
	Polarization efficiency in band	5.7×10^{-6}	$B \to B$	R
	Polarization angle in band	5.7×10^{-6}	$E \to B$	R
Gain	Relative gain in time	5.7×10^{-6}	$E \to B$	R
	Relative gain in detectors	5.7×10^{-6}	$E \to B$	R
	Absolute gain	1.9×10^{-6}	$B \to B$	E
Polarization	Absolute angle	9.1×10^{-6}	$E \to B$	E
angle	Relative angle	5.7×10^{-6}	$E \to B$	E
	HWP position	1.0×10^{-6}	$E \to B$	E
	Time variation	$< 10^{-7}$	$E \to B$	E
Pol. efficiency	Efficiency	5.6×10^{-6}	$B \to B$	E
Pointing	Offset	5.7×10^{-6}	$E \to B$	R
	Time variation	$< 10^{-6}$	$E \to B$	E
	HWP wedge	5.7×10^{-6}	$E \to B$	R
Bandpass	Bandpass efficiency	5.3×10^{-6}	$E \to B$	R
Transfer	Crosstalk	5.7×10^{-6}	$B \to B$	R
function	Detector time constant knowledge	5.7×10^{-6}	$E \to B$	R

Component separation and systematic effects

$$d_\nu = A_\nu s + n_\nu$$

- Advanced developments are made with two types of methods for the preparation of LiteBIRD
  - Parametric methods: FGBUSTER. (Leloup, Rizzieri, Errard) ➡ $A(\beta(p))$
  - Blind or semi-blind methods: MC-NILC. Carones et al. 2023 ➡ use the statistics of s

  Other hybrid methods are under development (Moment expansion, MICMAC, SMICA, delta-map)



Credits: Josquin Errard

Main difficulty: spatial variations of physical properties

- Many (most) instrumental systematics come from the interplay with component separation. E.g. systematics at high freq. introduce distortion of the dust map and errors in separation

Systematic effect bias evaluation

Systematics induce a bias on r and additional uncertainty

- evaluate the contribution to B-mode for each effects. With or wo correction.
- calculate the additional bias and uncertainty on r after likelihood maximization
- evaluate the additional uncertainty, eventually after marginalisation

Example simple likelihood:

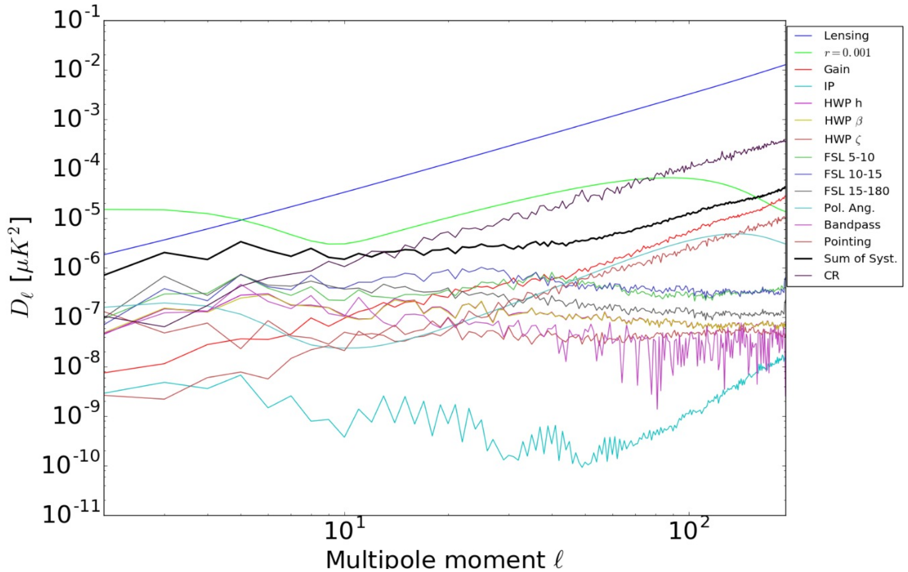
$$\log P_\ell(r) = -f_{\rm sky}\frac{2\ell+1}{2}\left[\frac{\hat{C}_\ell}{C_\ell} + \log C_\ell - \frac{2\ell-1}{2\ell+1}\log \hat{C}_\ell\right]$$

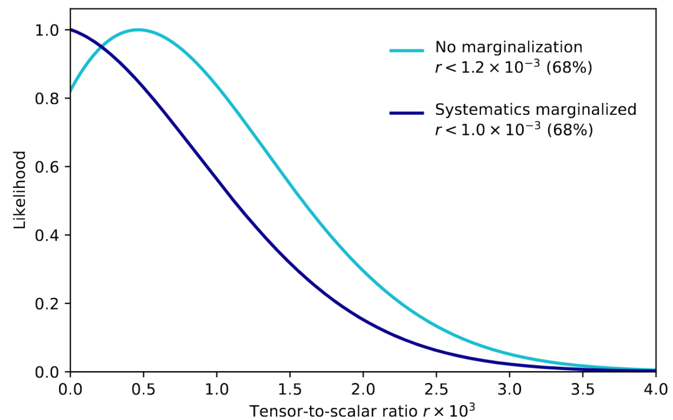
$$C_\ell = rC_\ell^{\rm tens} + C_\ell^{\rm lens} + N_\ell$$

$$\hat{C}_\ell = C_\ell^{\rm sys} + C_\ell^{\rm lens} + N_\ell$$

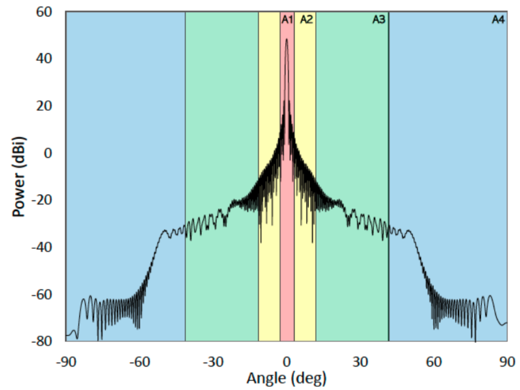
$$\left.\frac{dL(r)}{dr}\right|_{r=\Delta r} = 0 \qquad \frac{\int_0^{\delta r} L(r)dr}{\int_0^{\infty} L(r)dr} = 0.68$$

Realistic likelihood accounting for cut sky are now being used and developed





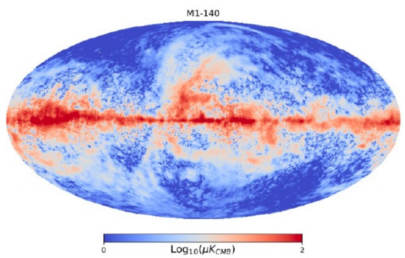
Beam systematics

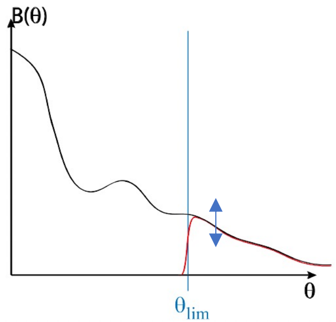


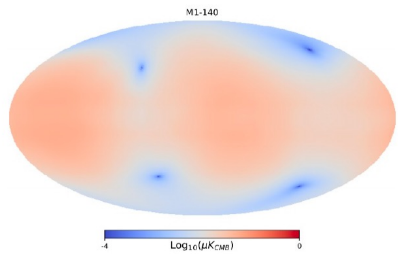
Diffraction and reflection on the instrument generates far side lobes:

Error in the model of the beam shapes induce **errors on the component separation** which translate into **a bias on r**

Leloup et al. 2023, with FGBuster
Carralot et al. 2025, with NILC







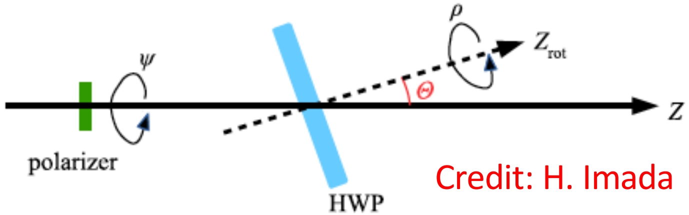
Requirements on the precision knowledge for the amplitudes of the beam in each band are derived (FGBuster):

ν (GHz)	LFT										
	40	50	60	68		78		89		100	119
4 deg $< \theta <$ 8 deg	-42.55	-34.09	-39.46	-36.70	-30.45	-42.82	-39.42	-48.56	-38.84	-51.80	-54.82
7 deg $< \theta <$ 12 deg	-46.62	-38.35	-43.67	-41.38	-35.62	-45.87	-42.48	-51.75	-42.04	-54.98	-57.91
11 deg $< \theta$	-66.40	-57.98	-63.20	-61.52	-56.00	-61.76	-59.07	-68.70	-59.51	-72.09	-75.00

ν (GHz)	LFT	MFT					HFT				
	140	100	119	140	166	195	195	235	280	337	402
4 deg $< \theta <$ 8 deg	-51.25	-50.65	-54.58	-49.55	-60.87	-63.56	-59.01	-62.92	-60.57	-70.48	-67.91
7 deg $< \theta <$ 12 deg	-54.11	-53.91	-57.78	-52.45	-64.07	-66.58	-62.38	-66.07	-63.60	-73.57	-70.77
11 deg $< \theta$	-74.60	-69.44	-73.96	-75.36	-80.06	-80.69	-78.63	-81.55	-75.23	-86.41	-88.72

HWP Systematics : Instrumental Polarization

- EM propagation simulations through a realistic HWP (H. Imada):

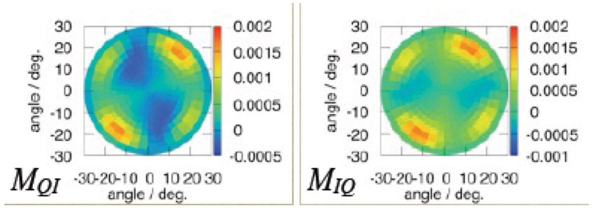


Credit: H. Imada

- Mueller matrix coefficients are estimated from the simulations. Decomposed in three terms:

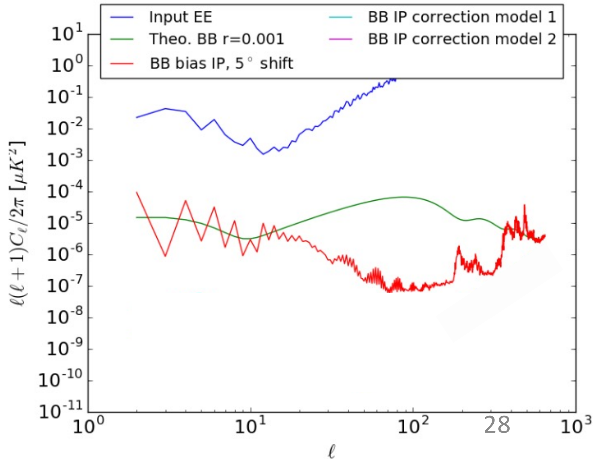
$$M = \begin{pmatrix} M_{II} & M_{QI} & M_{UI} & M_{VI} \\ M_{IQ} & M_{QQ} & M_{UQ} & M_{VQ} \\ M_{IU} & M_{QU} & M_{UU} & M_{VU} \\ M_{IV} & M_{QV} & M_{UV} & M_{VV} \end{pmatrix}$$

$$M(\Theta, \rho - \psi) = A + B_0(\Theta)\cos(2\rho - 2\psi + \phi_B) + C_0(\Theta)\cos(4\rho - 4\psi + \phi_C)$$



The 4f terms are potentially biasing the B-mode spectra since they are modulated as the polarization signal. IP Imperfections at $4f_{HWP}$ of the order of 5. 10^{-5}

Data simulation + Map-making



Correction methods at the map-making level

- **Systematic effect correction methods are being developed and relax the requirements on their amplitude**
- **Use of observation redundances to distinguish between instrument related params and sky map params**

- **Correction of the instrumental polarization:**
- Model: $$d_{it} = \bar{\mathcal{M}}^{pc}_{it}\, m_{pc} + T_{itc}\lambda^{(c)}_{i} + \alpha_i o_t + n_{it}$$

Mueller/pointing matrix
without the IP terms

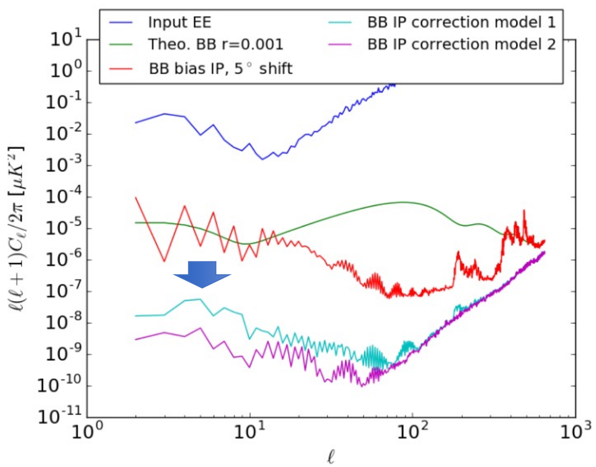
$$T_{tc=1} = I_t \cos\alpha_t\,;\; T_{tc=2} = I_t \sin\alpha_t;\; T_{tc=3} = \cos\alpha_t\,;\; T_{tc=4} = \sin\alpha_t$$

- Estimate λ_i for each detector as well as the maps m

$$\frac{\partial \mathcal{L}}{\partial m}_{|\hat{\lambda}} = 0;\; \frac{\partial \mathcal{L}}{\partial \lambda_i}_{|\hat{m}} = 0$$

$$\hat{m} = \left[\sum_i \mathcal{M}_i(\hat{\lambda}_i)^t N_i^{-1} \mathcal{M}_i(\hat{\lambda}_i)\right]^{-1} \sum_i \mathcal{M}_i(\hat{\lambda})^t N_i^{-1}(d_i - \alpha_i o)$$

$$\hat{\lambda}_i = [T^T N_i^{-1} T]^{-1} T^T N_i^{-1}(d_i - \alpha_i o - \bar{\mathcal{M}}_i \hat{m}),$$



Conclusion

- Given the incredible sensitivity of future missions, need to avoid leakage from a huge signal background

- The systematic effect studies have an impact on both the instrument design and the calibration setting. Crucial studies in the early phase of LiteBIRD preparation. Main effect: beam near and far side lobes.

- Use of Planck experience for future satellite mission. Planck strategy was adapted for CMB intensity measurement.

- LiteBIRD takes advantage of a highly cross-linked scanning strategy as compared to Planck, as well as a polarisation modulator (HWP)

- The HWP has its own systematics. Modelling and simulation is an on-going activity. Several studies have provided requirements