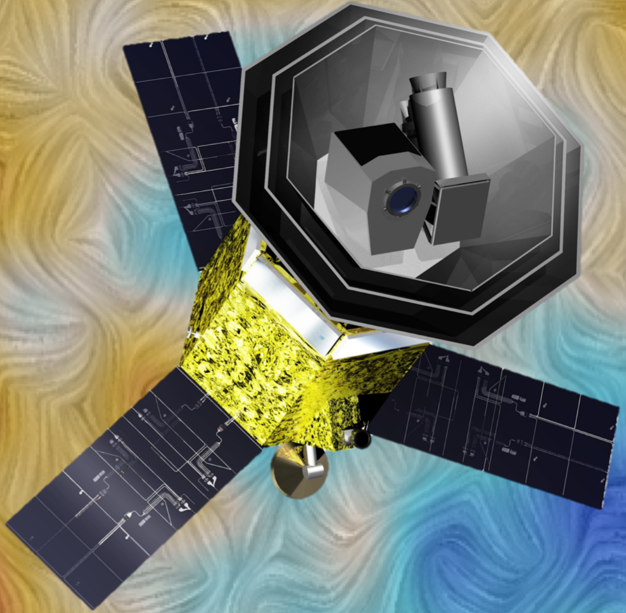
B-modes from space 2019



The challenges of ground calibration and systematics

in the light of LiteBIRD

Sophie Henrot-Versillé (IJL Lab) on behalf of the LiteBIRD collaboration

Systematics and the Planck data: an example

The A_L parameter, 3 high-l likelihoods, with different foreground modellings:

$$A_{\rm L} = 1.243 \pm 0.096 \quad (68\,\%\,, \mathrm{TT+lowE\ [Plik]})$$

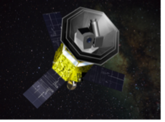
$$A_{\rm L} = 1.246 \pm 0.095 \quad (68\,\%\,, \mathrm{TT+lowE\ [CamSpec]})$$

$$A_{\rm L} = 1.160 \pm 0.075 \quad (68\,\%\,, \mathrm{TT+lowE\ [Hillipop]})$$

=> reveals the impact of remaining systematics

=> they may come from fg model or instrumental syste which is catched differently by the different fg modellings parameters

F. Couchot et al. A&A 597, A126 (2017) **[Planck 2018 results. VI]**



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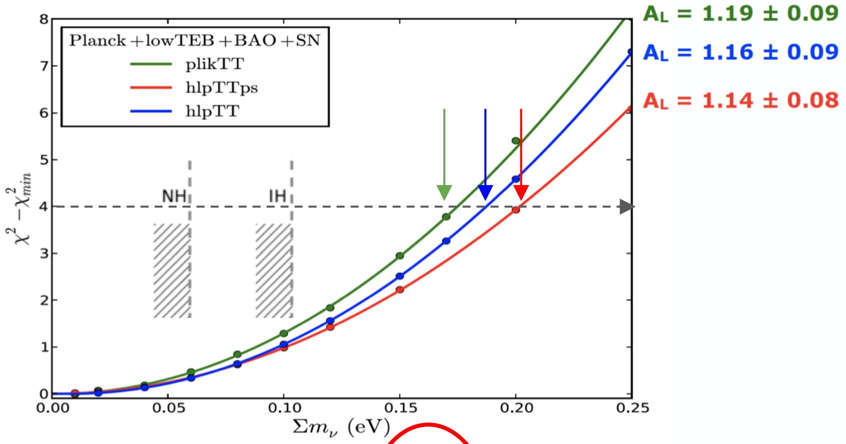
Why do we care ?

because we want to constrain the physics of the Universe in an unbiased way eg: Sum of the neutrino mass

- high value for A_L → **artificially tighter constraints** on Σm_ν



PLANCKTT+lowTEB BAO+SNIa 2015	ΛCDM+ Σm_ν limit (eV)	ΛCDM+ A_L
hlpTT	0.18	1.16±0.09
hlpTTps	0.20	1.14±0.08
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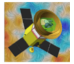
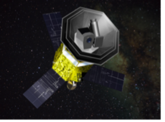
??!!

F. Couchot et al. A&A 606, A104 (2017)





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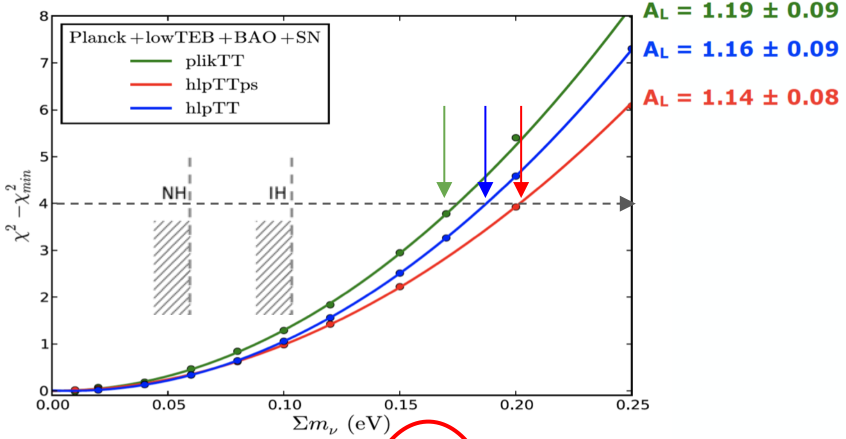

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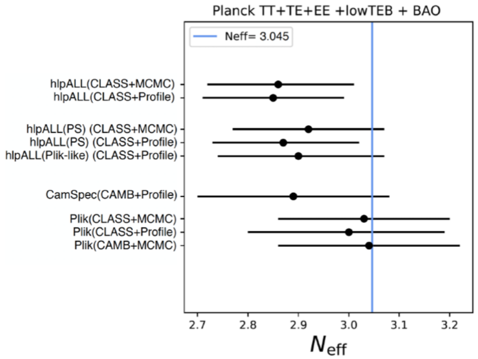
F. Couchot et al. A&A 606, A104 (2017)

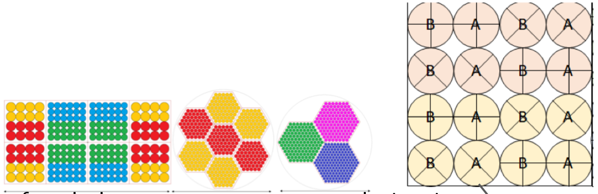
Another example: The effective number of relativistic species comparisons of results from :

- high-l likelihoods
- CAMB/CLASS
- Bayesian vs. frequentist

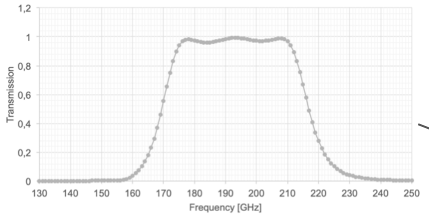


S. Henrot-Versille et al. A&A 623 (2019) A9

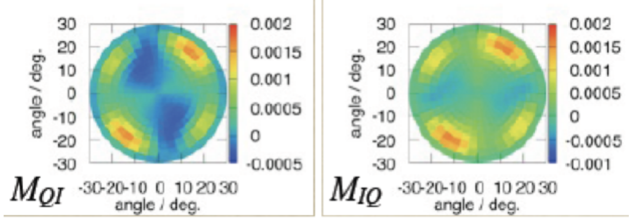
To get to r we need to know our instruments



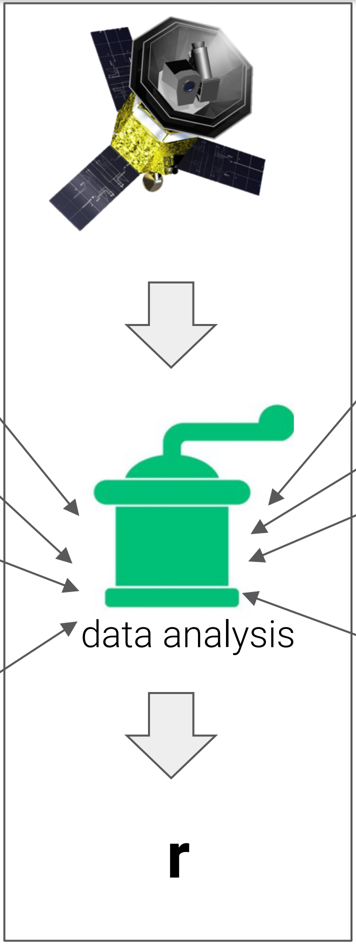
focal plane arrangement + polarisation
(credit: Toki)



Bandpass (credit: Toki)

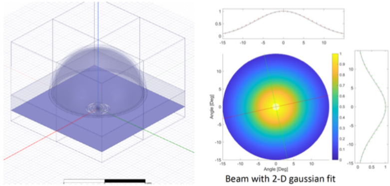


HWP (credit: Hiroaki)

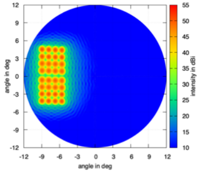


data analysis

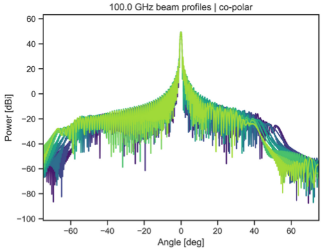
r



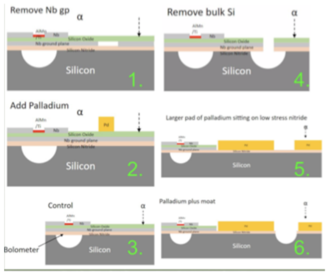
beam former (credit: Aritoki)



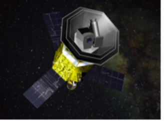
beams (credit: Hiroaki)



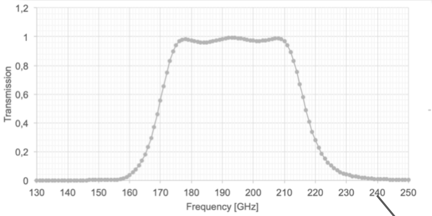
beams (credit: Jon)

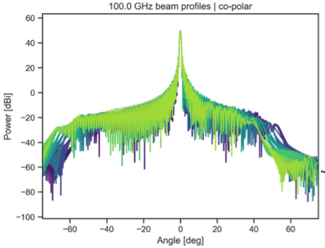


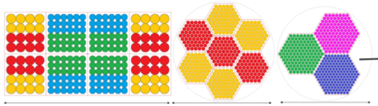
Cosmic Rays
(credit: S. Beckman, A. Lee)

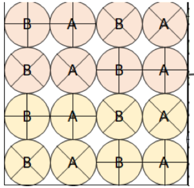


Otherwise, if we use a wrong description….

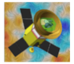




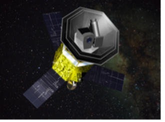




Name	Origin	Description	Major mode of Leakage
Bandpass Mismatch	Spectral Filters	Edges and shape of the spectral filters vary from detector to detector.	I -> P
Beam Mismatch and Asymmetry	Optical beams	Beam shape differs from an ideal Gaussian form.	I -> P E -> B
Pointing Uncertainty	Attitute control, pointing reconstruction	Detector pointing at location different from that given by reconstructed pointing data.	I -> P E -> B
Polarisation Misalignment	Detectors	Uncertainty in polarisation calibration. Polarisation axis misaligned with measured direction.	E -> B
Gain mismatch and stability	Detectors and Calibration	Gain calibration mismatch between detectors. These could also be variable over time	I -> P



From Ranajoy Banerji



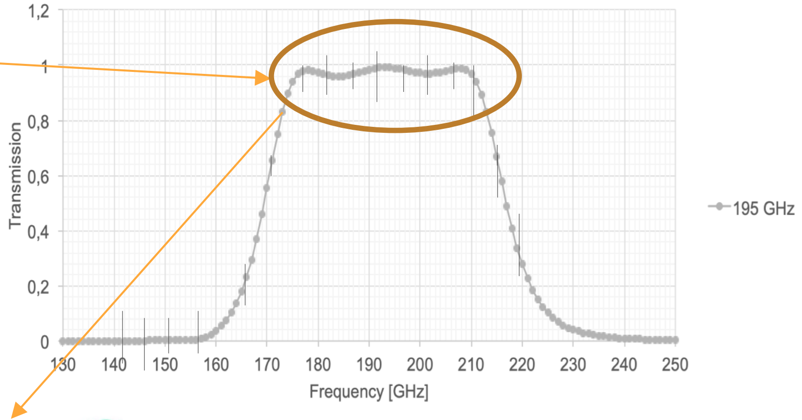
But more than that !

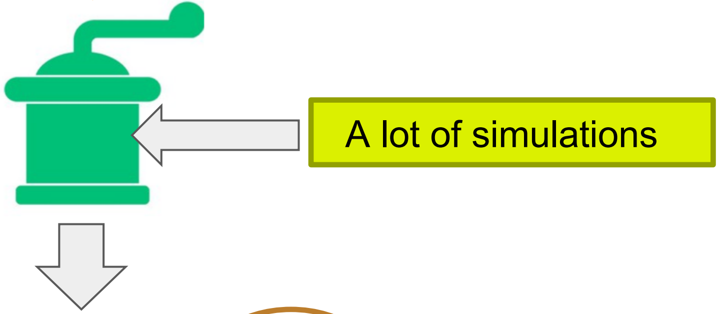
BUT: even we have a good description of our instruments,

We will know the instrumental parameters up to a certain level.

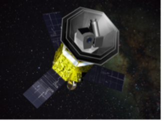
Those uncertainties will need to be propagated to the end-results (cosmology!)

=> the resulting errors on cosmological parameters is what is called instrumental systematic error !





$$r \pm \sigma_{stat} \pm \sigma_{syst}$$



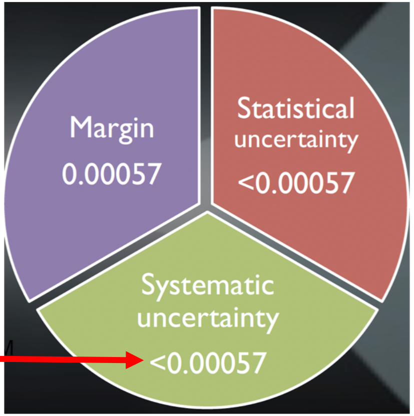
Up to which level ?

We want to measure r with an accuracy of (68%CL):

$$\sigma_r = 0.001$$

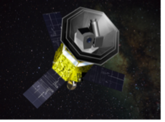
Assuming:

$$(\sigma_r = 0.001)^2 = \boxed{\sigma^2_{\mathbf{syst}}} + \sigma^2_{\mathbf{fg}} + \sigma^2_{\mathbf{margin}}$$



For each potential source of instrumental systematics:

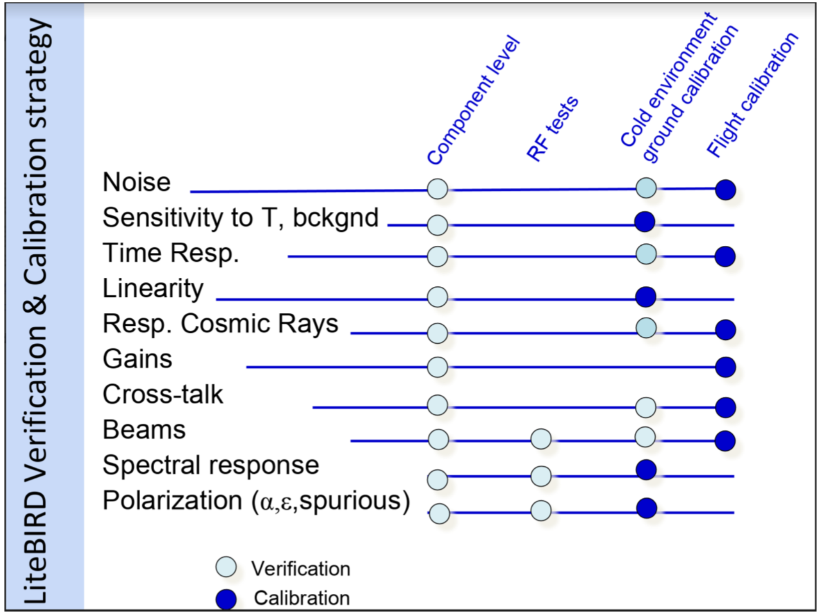
1. We assign an error budget:
   $\sigma(r)_{sys} < 5.7 \times 10^{-6}$ as the budget (1% of total budget for systematic error)
2. From this we derive a requirement on the knowledge of the underlying instrumental parameters.
3. Those requirements are used to best define the calibration method.



How ? verification and calibration strategy

To reach the required accuracies the calibration strategy is setup in several steps. We will rely on measurements:

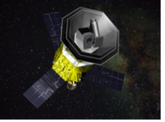
- on the ground and in-flight
- from component level to full integrated instruments



LiteBIRD Verification & Calibration strategy

	Component level	RF tests	Cold environment ground calibration	Flight calibration
Noise	○		○	●
Sensitivity to T, bckgnd	○		●	
Time Resp.	○		○	●
Linearity	○		●	
Resp. Cosmic Rays	○		○	●
Gains	○			●
Cross-talk	○		○	●
Beams	○	○	○	●
Spectral response	○	○	●	
Polarization (α,ε,spurious)	○	○	●	

○ Verification
● Calibration



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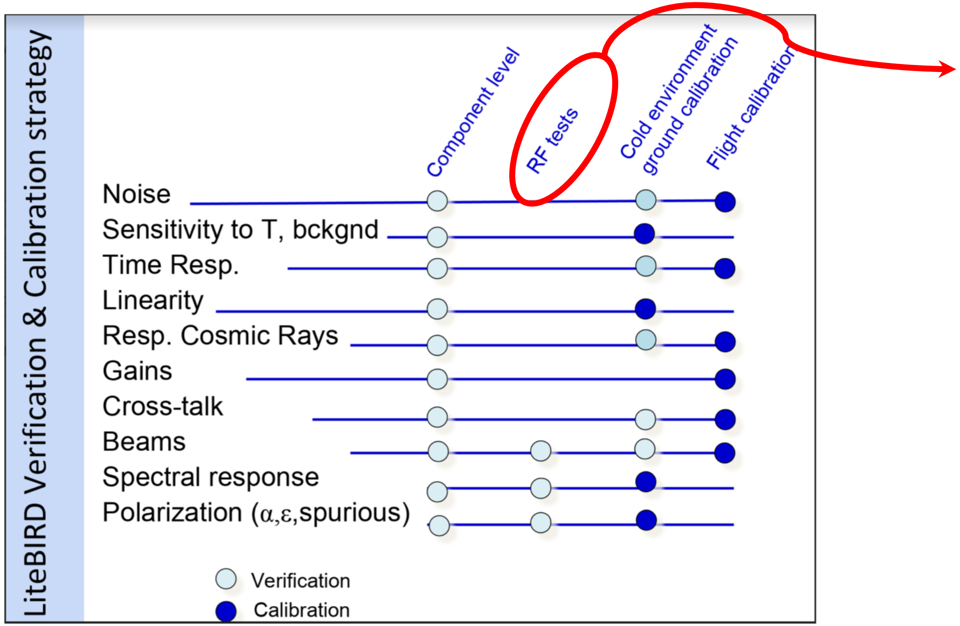

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RF measurements for beam characterization

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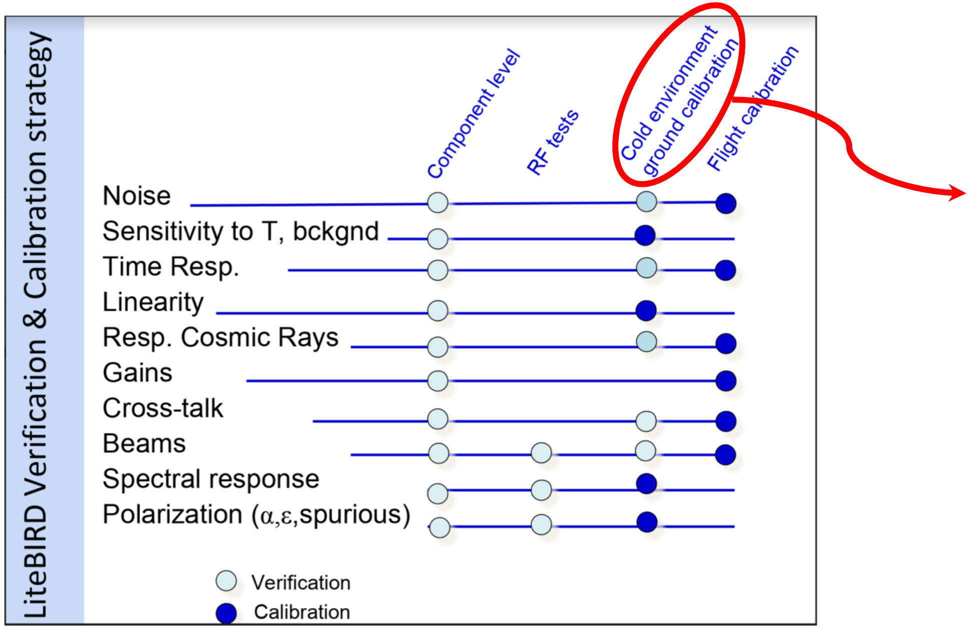

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Cold environment “flight-like” loading conditions on the instruments+calibration sources in a big cryogenic facility

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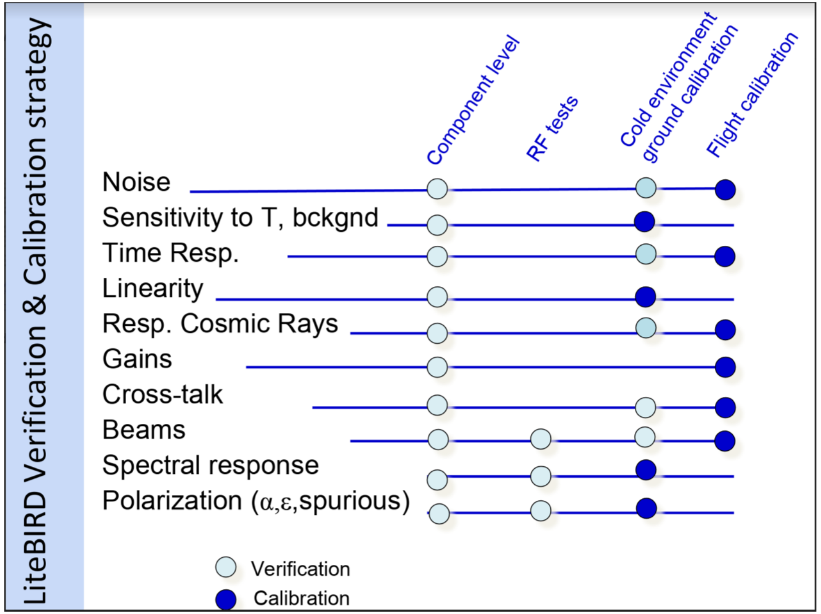

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RF measurements for beam characterization

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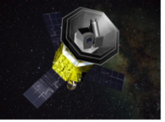
=> In this talk I will focus on:

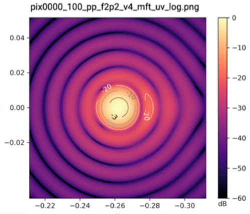
- Beams
- Spectro-polarimetry

(and will not address component level tests)

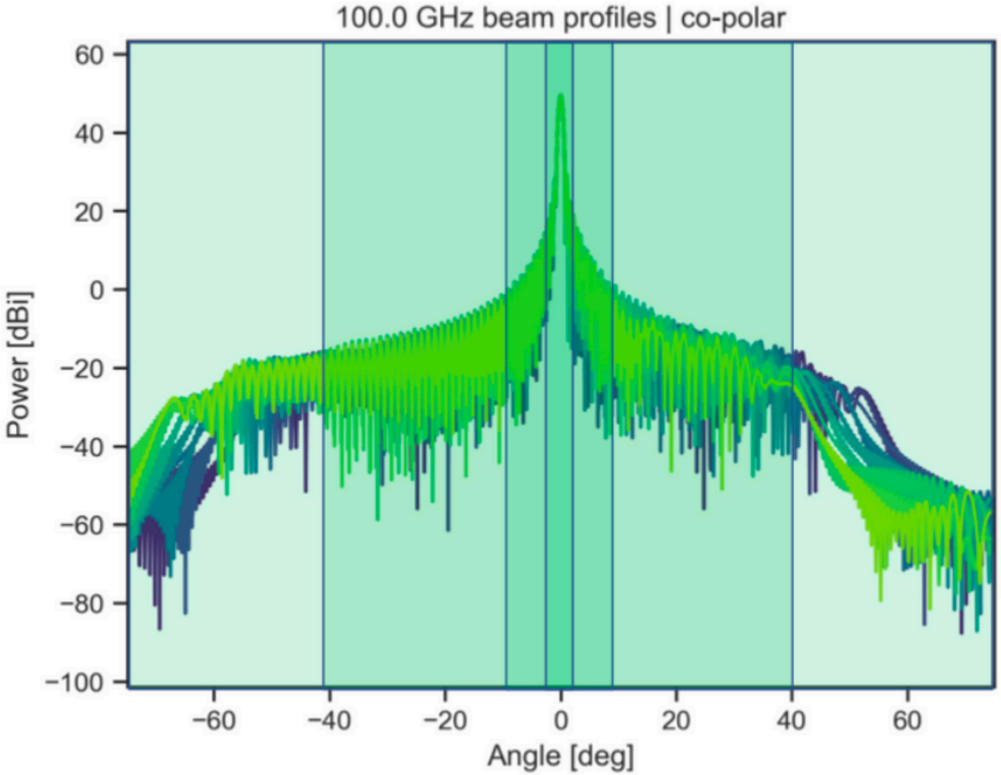


Beams requirements

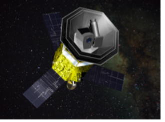
credit: Ryo Nagata, Davide Maino



credit: the MHFT Optics working group (Jon JGudnmunsson et al.)



credit:: M De Petris



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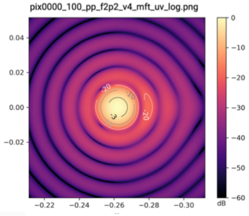

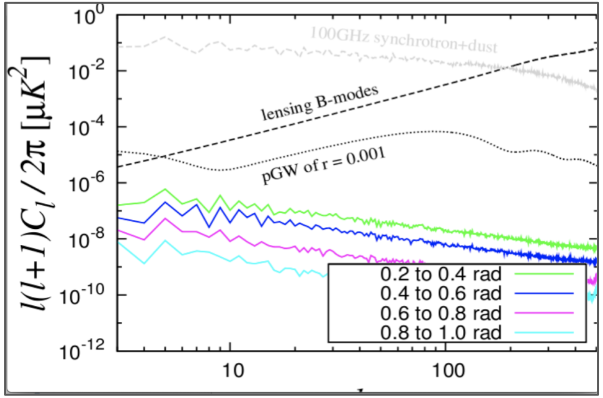

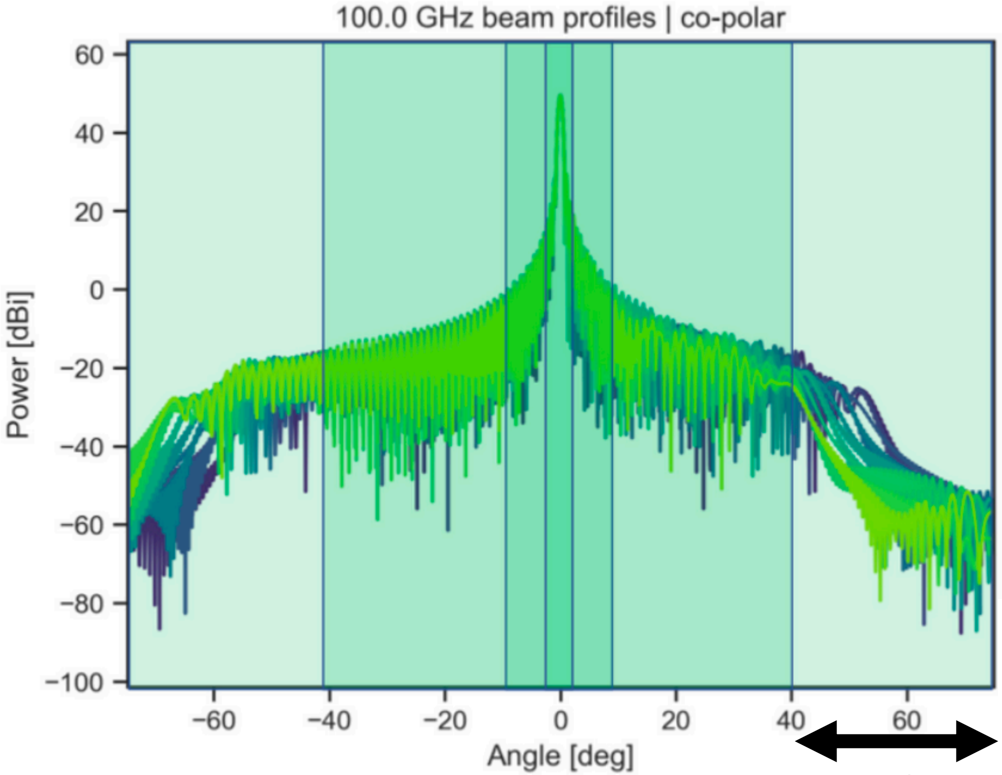

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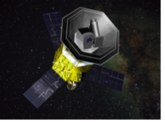
credit:: M De Petris

Verification regime

We need to know the beam down to the -57dB level (by design)



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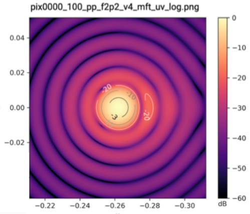

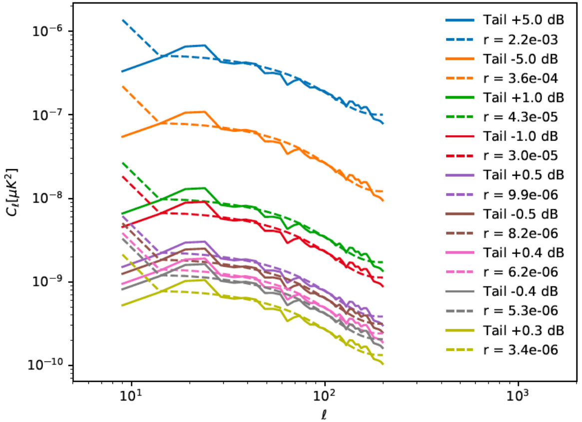

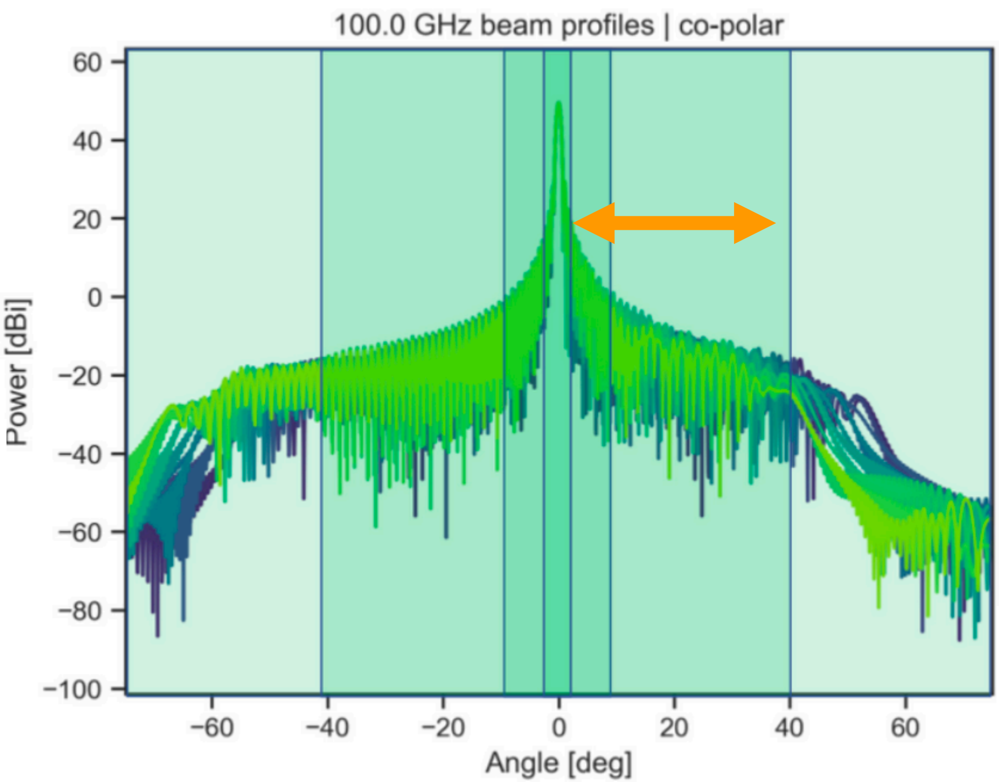

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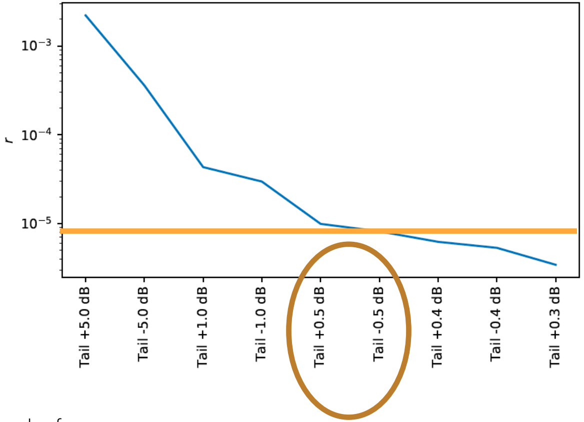
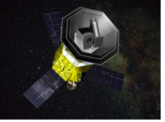


the regime between -20 and -35 dB
has to be determined to better than 10%.

B-modes from
space -2019



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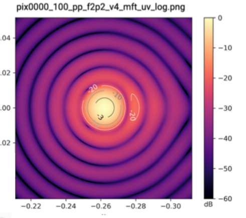

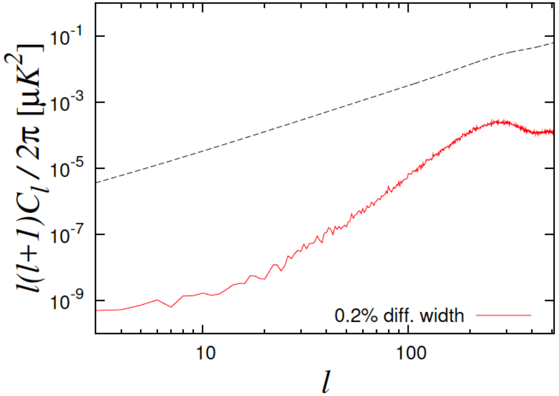

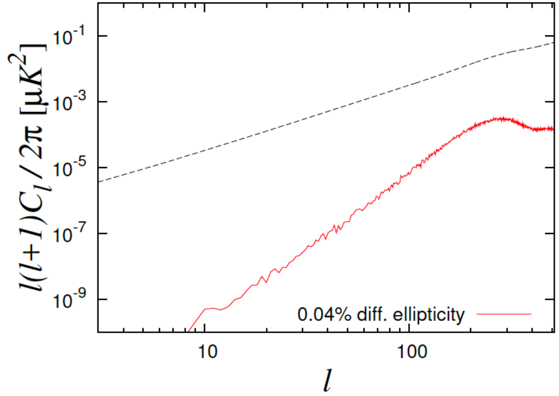

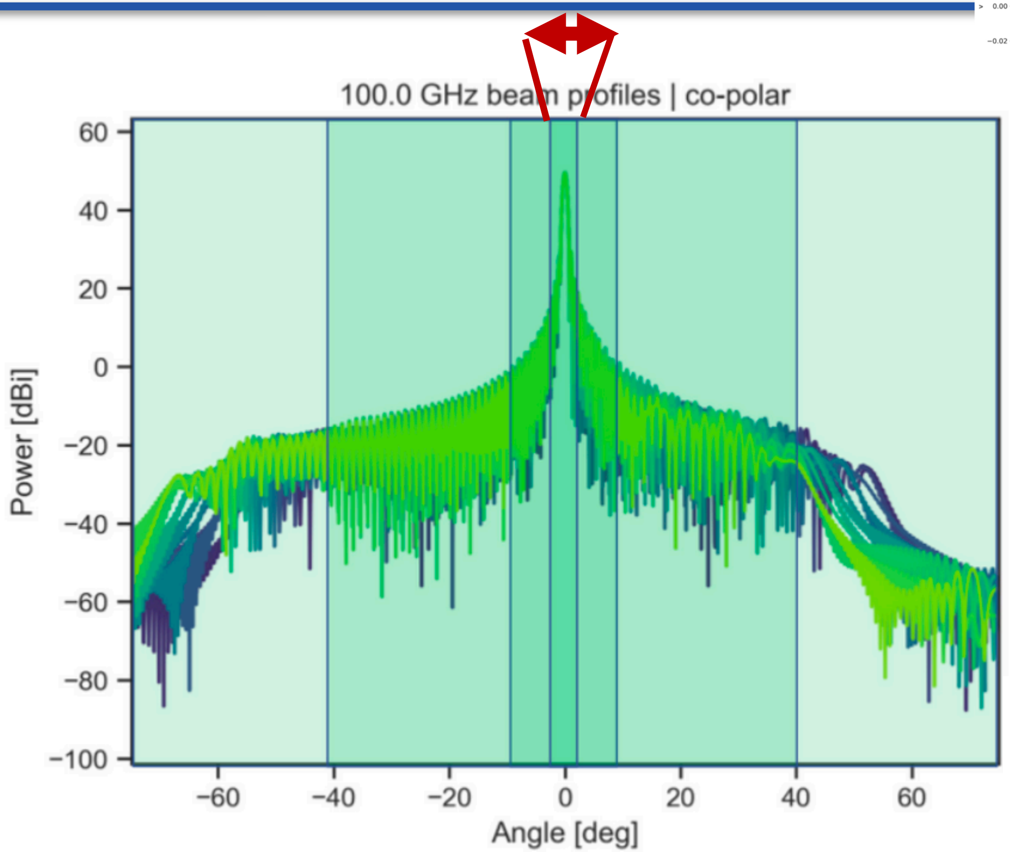

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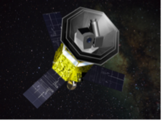
credit:: M De Petris

B-modes from space -2019

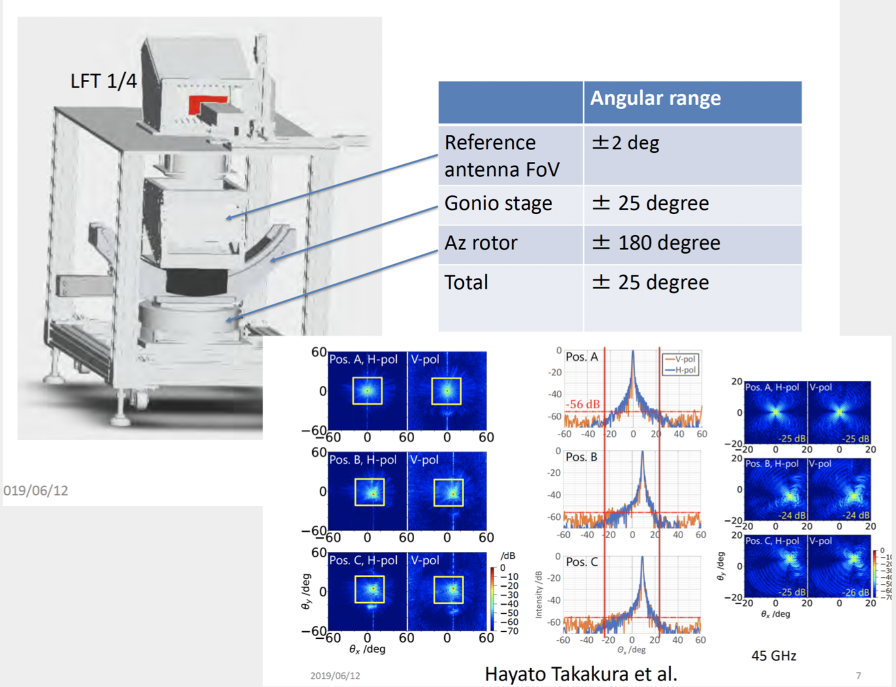
Main beam requirement: 0.65% level,
beam ellipticity requirement 0.086%



RF ground measurements for LFT

The full strategy is being addressed and further refined with on-going measurements in Japan

In the last months: **very successful** measurements of beams at warm temperature on a small scale LFT model



	Angular range
Reference antenna FoV	±2 deg
Gonio stage	± 25 degree
Az rotor	± 180 degree
Total	± 25 degree

019/06/12

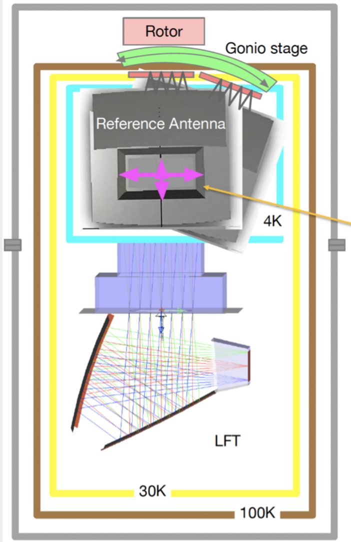
2019/06/12

Hayato Takakura et al.

7

=> Next steps: cold measurements

Reference antenna + Gonio + Az rotor



	Angular Range
Reference antenna FoV	±10 deg x ±2 deg
Gonio stage	-1 ~ +15 degree
Az rotor	± 180 degree
Total	± 25 degree

2019/06/12

credit: Yutaro Sekimoto

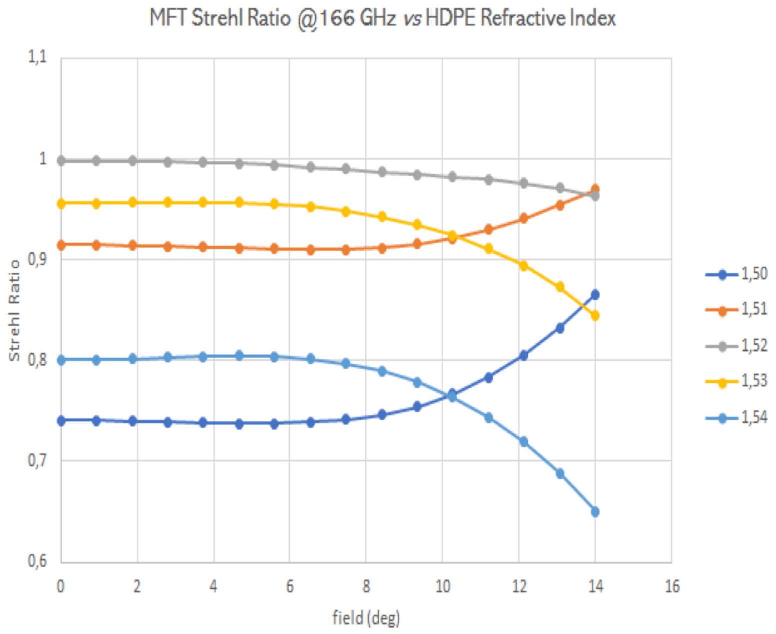
Challenges of the RF measurements for MHFT

The properties of the lenses (indices of refraction) depends on the temperature

AND

the beam shape depends on the properties of the lenses

we need to cool down the instrument to measure the beams ! ...



Eg: Strehl ratio for various refraction indices of lenses (typical of cold->warm variations)

credit: the MHFT Optics working group (Jon Gudmundsson et al.)

RF ground measurements for MHFT

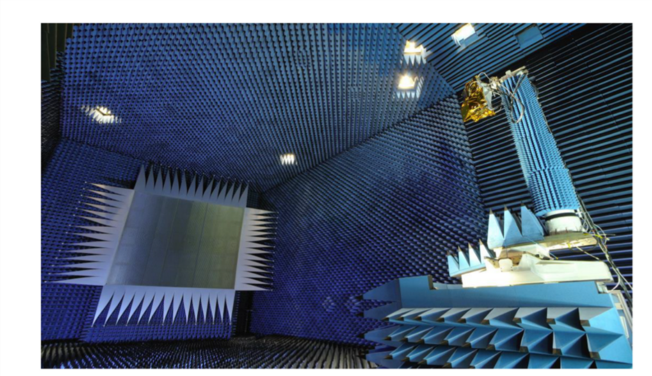
credit: the MHFT RF working group (Cristian Franceschet, Jon Gudmundsson, Bruno Maffei et al) +CNES CATR team

We are currently studying the best strategy, to build up a model fed with:

- sub-system, semi-integrated and integrated level measurements
- warm/cold measurements

On-going work at CNES/Toulouse:

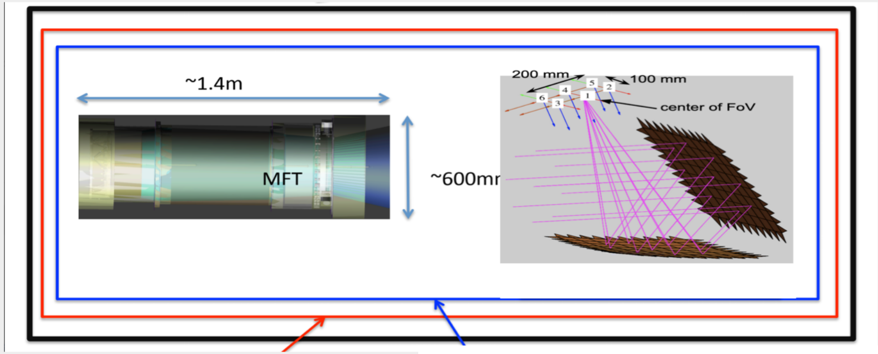
Antenna models will be built on the basis of MHFT beam simulations (optics group) for 100 to 402 GHz => to be further characterized with the use of submm source in the CATR to perform a feasibility study in CNES facilities.



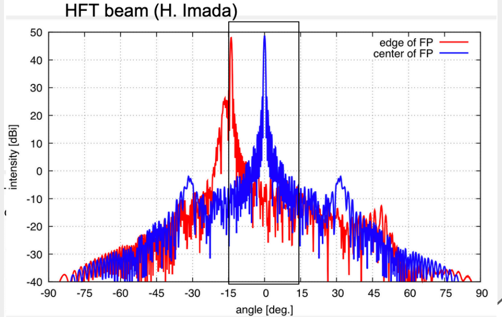
Modèle de vol de Saphir, instrument du satellite Megha-Tropiques, en essais en BCMA.

Cryo tests far field study

Hiroaki Imada, M. De Petris, C. Franceschet, M. Bersanelli



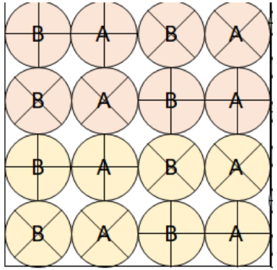
Far field measurements are what we need at the end !
⇒ several configurations are under study



Spectro-polarimetry requirements

credit: Patricio Vielva, Enrique Martinez Gonzalez, Tommaso Ghigna

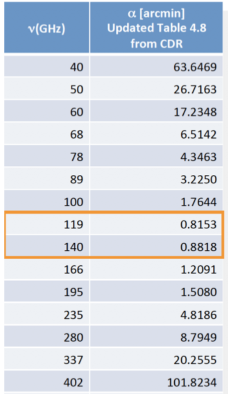
Polarisation angle



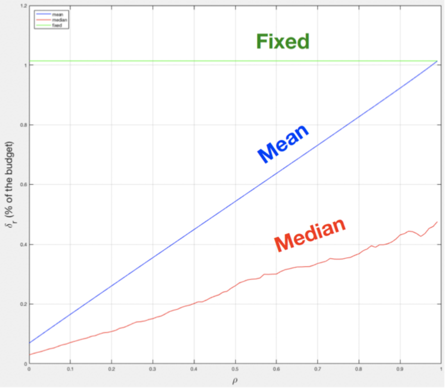
Absolute polarisation angle uncertainty must be ≲ 1arcmin to meet $\delta_r \sim 5.77\ 10^{-6}$

(less stringent on relative angle per frequency)

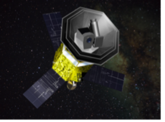
Note: Planck HFI ~60 arcmin/detector preflight



ν(GHz)	α [arcmin] Updated Table 4.8 from CDR
40	63.6469
50	26.7163
60	17.2348
68	6.5142
78	4.3463
89	3.2250
100	1.7644
119	0.8153
140	0.8818
166	1.2091
195	1.5080
235	4.8186
280	8.7949
337	20.2555
402	101.8234



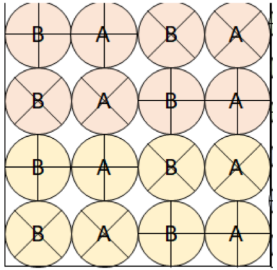
The requirements are driven
by the 119 and 140GHz frequency bands



Spectro-polarimetry requirements

credit: Patricio Vielva,
Enrique Martinez Gonzalez,
Tommaso Ghigna

Polarisation angle



Absolute polarisation angle uncertainty must be ≲ 1arcmin to meet δ_r ~ 5.77 10^{-6}

(less stringent on relative angle per frequency)

Note: Planck HFI ~60 arcmin/detector preflight

ν(GHz)	α [arcmin] Updated Table 4.8 from CDR
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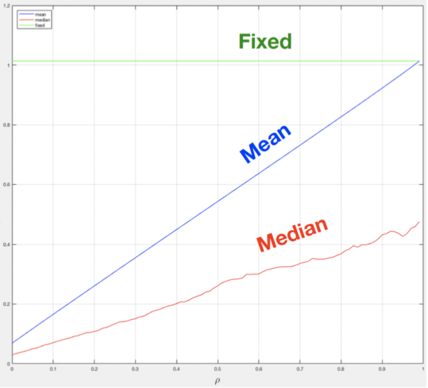
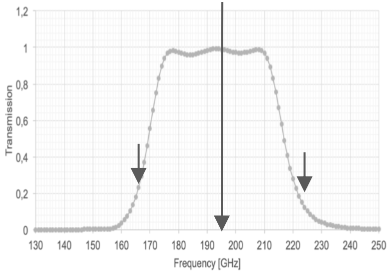


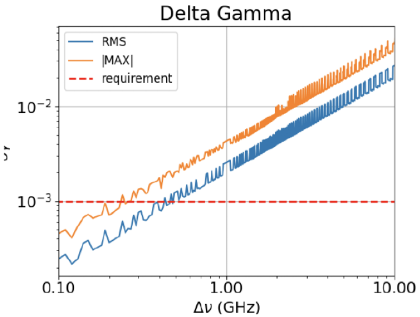
The requirements are driven
by the 119 and 140GHz frequency bands

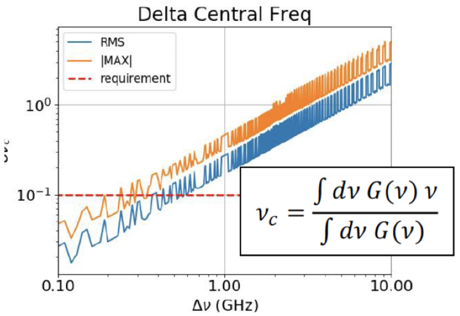
Bandpass knowledge and gain calibration



If g can be calibrated well enough using Dipole, δ_g is dominated by δ_γ. We need to determine a bandpass measurement resolution that satisfies the requirement.

$$\gamma_d = \frac{I_{cmb}(\nu_0)}{I_d(\nu_0)} \frac{\int d\nu\, G(\nu) I_d(\nu)}{\int d\nu\, G(\nu) I_{cmb}(\nu)} \rightarrow \delta\gamma = \frac{\gamma_{\Delta\nu} - \gamma_0}{\gamma_0}$$





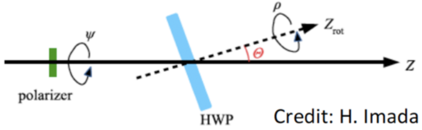
$$\nu_c = \frac{\int d\nu\, G(\nu)\, \nu}{\int d\nu\, G(\nu)}$$

Worst case scenario (top hat function):
=> measurement resolution of the order of 0.5GHz
(driven by the 337 and 402GHz channels).

Instrumental polarisation (HWP)

credit: Hiroaki Imada,
Guillaume Patanchon

- Electromagnetic propagation simulations through the HWP are performed (H. Imada):
  - include realistic anti-reflection coating
  - computed at many frequencies
  - computed for many incident angles



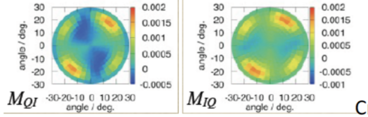
Credit: H. Imada

Tilted HWP to reduce reflexions and ghosts

- 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}

At 140 GHz, for $\Theta = 9^{\circ}$ (extreme case)

$$(C_{XY}) = \begin{pmatrix} 1.492\times10^{-6} & 5.471\times10^{-5} & 5.496\times10^{-5} & 1.586\times10^{-6} \\ 5.262\times10^{-5} & 9.769\times10^{-1} & 9.766\times10^{-1} & 2.422\times10^{-2} \\ 5.295\times10^{-5} & 9.767\times10^{-1} & 9.764\times10^{-1} & 2.421\times10^{-2} \\ 1.420\times10^{-6} & 2.099\times10^{-2} & 2.098\times10^{-2} & 5.204\times10^{-4} \end{pmatrix}$$

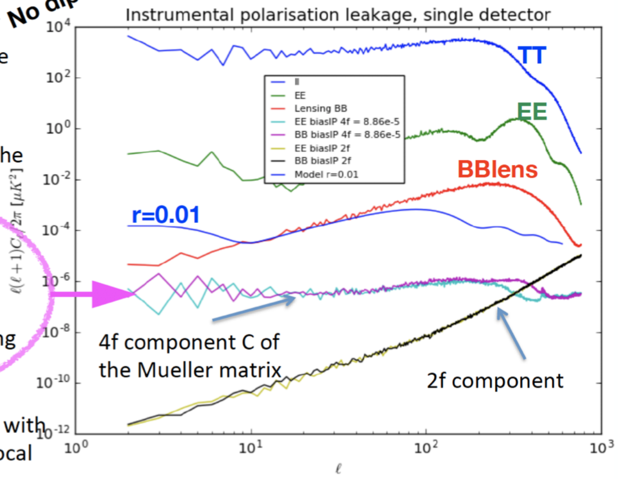
Credit: H. Imada

- Simulations with CMB only **No dipole**
- Single detector, edge of the focal plane
- Use the full M matrix
- Assume an ideal HWP for the reconstruction

→ 4f components have more impact on the sky

→ Instr. polar. of 5. 10^{-5} gives roughly 1% of the BB lensing signal

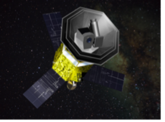
→ Having a scanning strategy with many orientations of the focal plane reduces the effect



4f component C of the Mueller matrix

2f component

→ Combining several detectors at different locations of the focal plane reduces the effect since it is observed with different phases



Spectro-polarimetry ground measurements

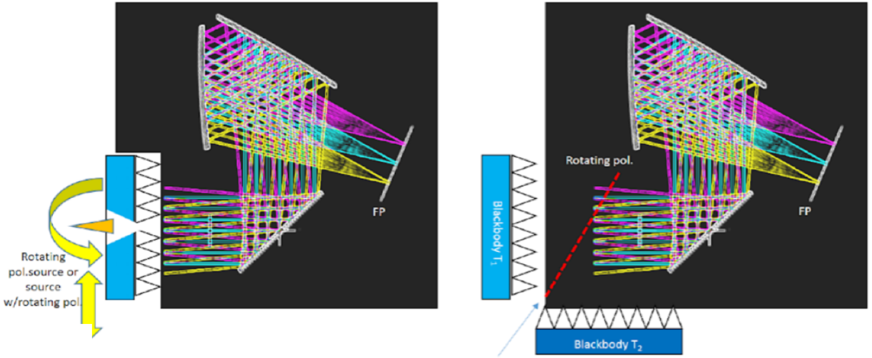
credit: Giorgio Savini

The presence of a polarization modulator couples the two tests:

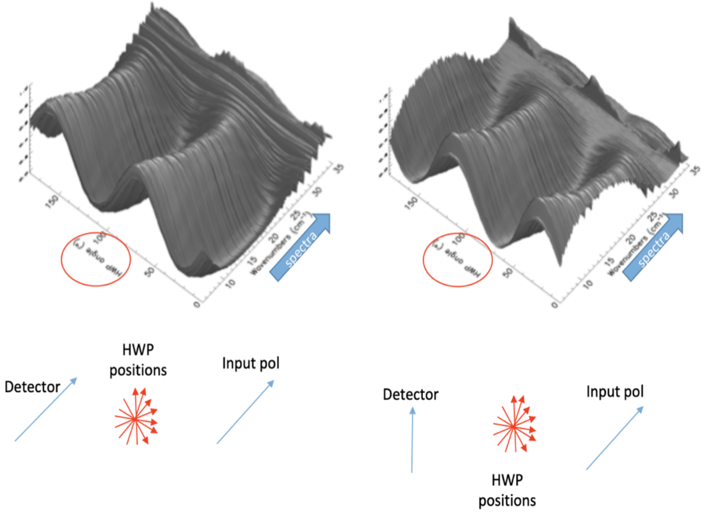
- Spectral Response
- Polarimetric sensitivity

=> the instrument needs to be cold

=> within a cold “flight-like” environment

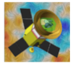


foreseen output : the datacube



The combination of these two sets provides a complete set of information

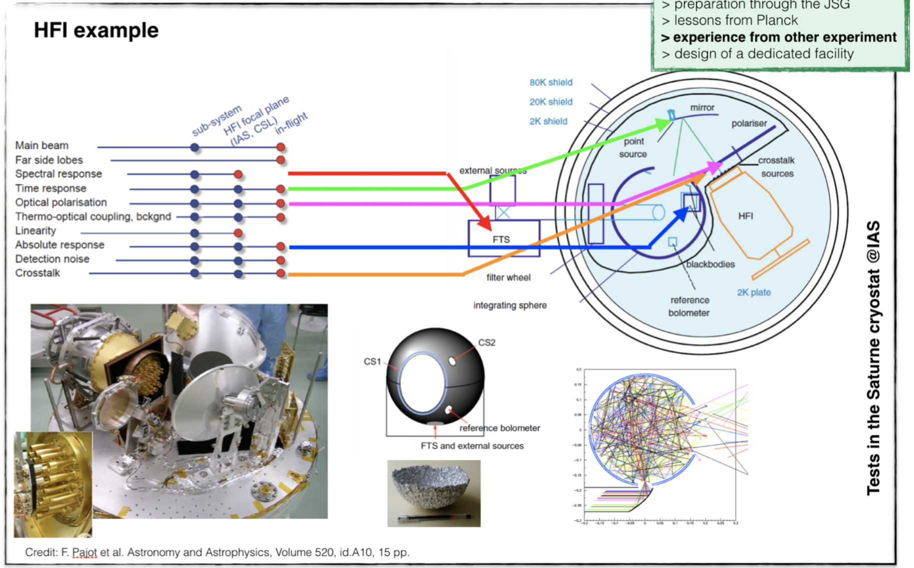
Rotate the input pol by 90 degree and you have the same sets by exchanging surfaces and adding a 90 degree offset.



Cryogenic facilities for RF&flight-like calibration

“a la Planck-HFI” strategy:

Fully integrated HFT calibration
> preparation through the JSG
> lessons from Planck
> experience from other experiment
> design of a dedicated facility

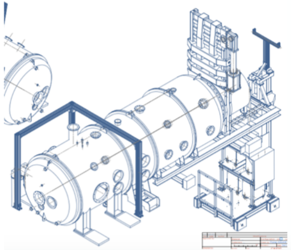


Credit: F. Pajot et al. Astronomy and Astrophysics, Volume 520, id.A10, 15 pp.

LFT
in Japan
@ KEK and
@ JAXA

credit: Masashi

MHFT
In France..and in Europe…



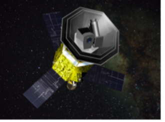
Jupiter @IAS/Orsay

Erios @LAM/Marseille

NB: both need an upgrade

CSL/Liege
or even ESA …

-> on-going discussions & feasibility studies



...Into the future

B-modes experiments calibration operations are very challenging to reach the systematics error budget !

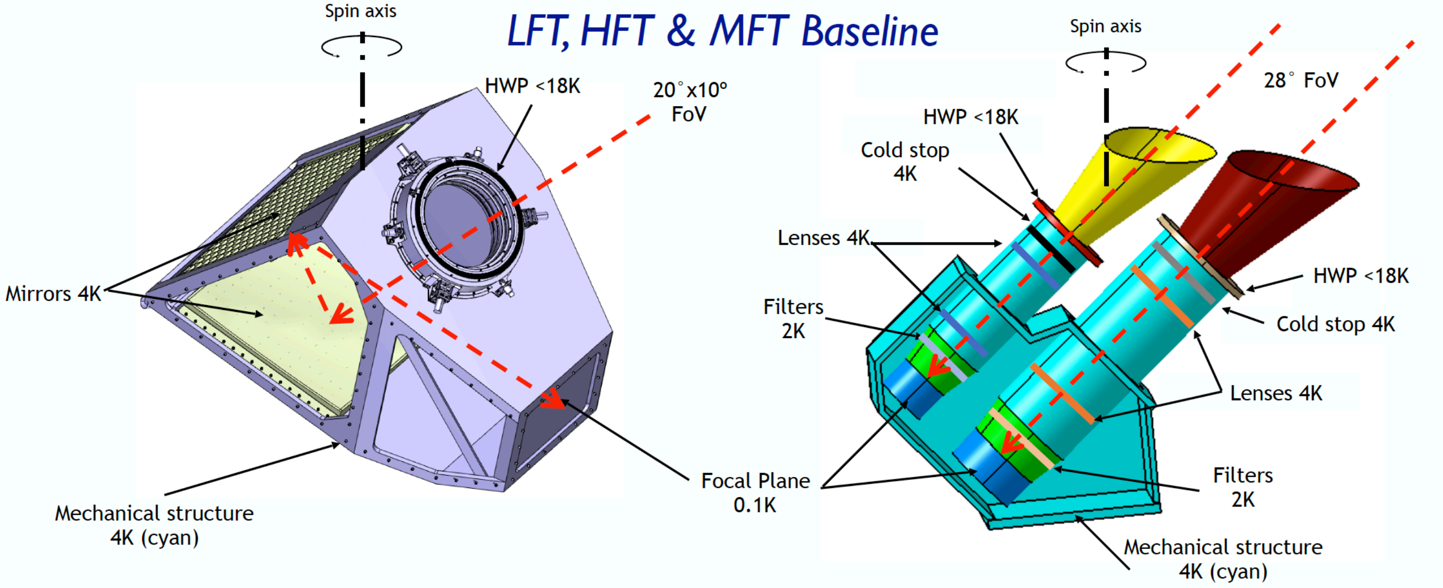
- The Systematics JSG(*) teams in LiteBIRD are working hard to update the requirements for each frequency bands. Next step will be to couple systematic effects and further refine the analysis in collaboration with the foreground JSG, and perform joint simulations.
- The Calibration JSG teams are deeply involved in defining the best strategy to meet the requirements, as well as to prepare the calibration devices and the facilities.
- This is only a status report: more work is needed on all sides, this is a huge effort in the LiteBIRD collaboration !

(*) JSG stands for Joint Study Group

Backups

Instrumental design Overview

LFT, HFT & MFT Baseline



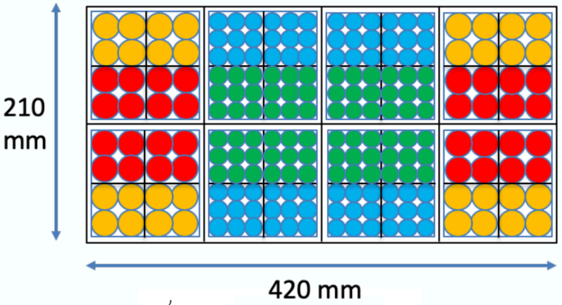
L-M-HFT concept

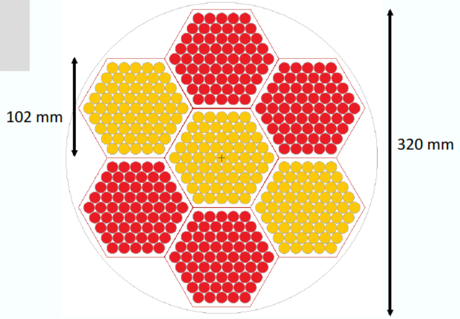
- LFT => Crossed Dragone
  - Aperture ø : 400 mm
- MFT => Transmissive
  - Aperture ø : 300 mm
- HFT => Transmissive
  - Aperture ø : 200 mm

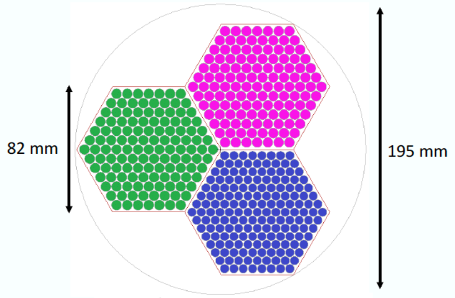
- Continuously rotating HWP
- Cryogenic temperature telescopes 4K
- Focal plane at 100mK

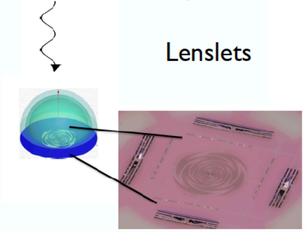
Focal plane configuration

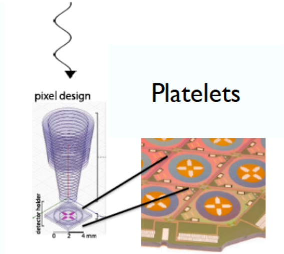
Number of detectors: 4676
Overlap between instruments











89GHz **MFT** (2.5:1) 224 GHz

2074 detectors
366 Trichroic TES
488 Dichroic TES

100 119 140 166 195

LFT (4.7:1)

40 50 60 68 78 89 100 119 140

1248 detectors
2 x (64 + 144) Trichroic TES

34GHz 161 GHz

HFT (2.7:1)

195 235 280 337 402

1354 detectors
2 x 254 Dichroic TES
338 Monochromatic TES

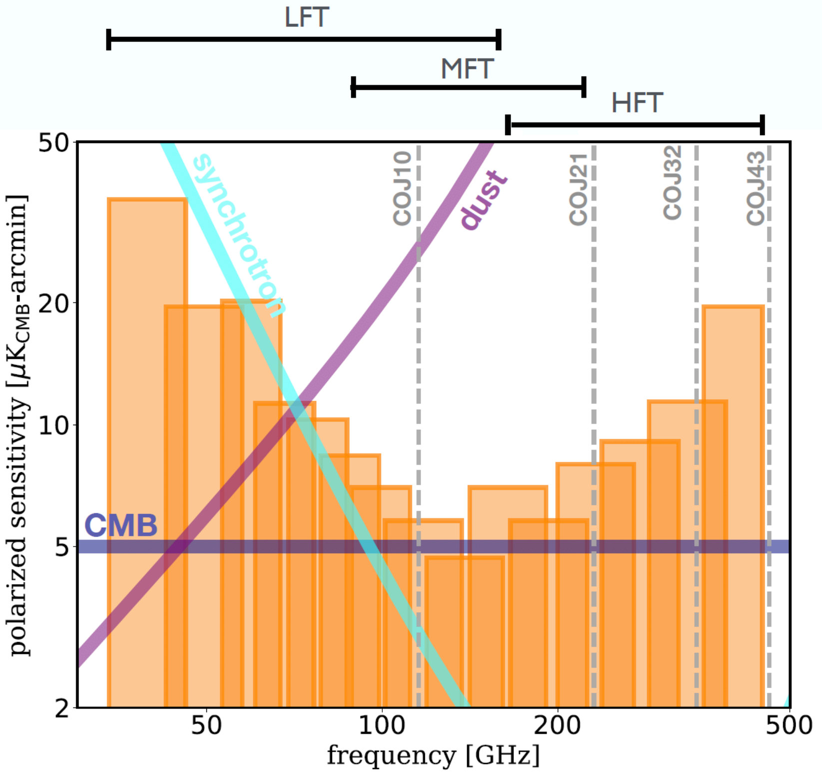
166 GHz 448 GHz

LiteBIRD Mission

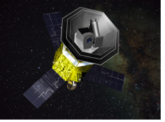
Frequency coverage

15 bands
from 34GHz
to 448GHz

4676
detectors



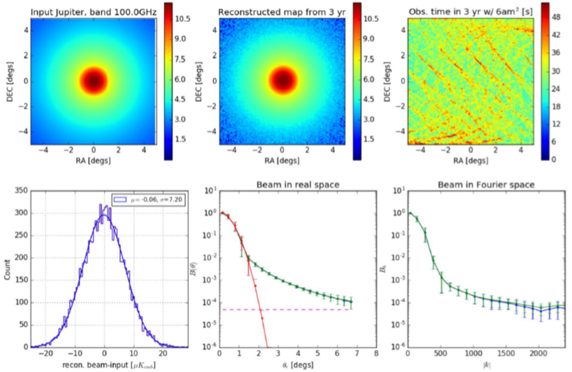
9 bands LFT
5 bands x 2 MHFT
+
4 bands
overlapping



flight calibration

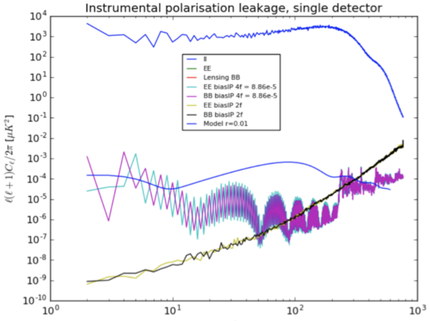
not exhaustive...

Main beam reconstruction from planets (Tomo Matsumura)

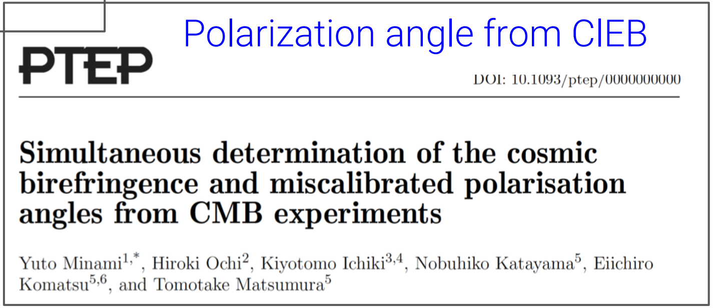


Instrumental Polarization from the dipole signal (Guillaume Patanchon)

- The dipole is a strong signal and also leaks into the polarization
- Again detector averaging will reduce the effect as 1/Ndet
- Since the dipole can be predicted, the signal can be used to fit the IP parameters



Polarization angle from CIEB



PTEP

DOI: 10.1093/ptep/0000000000

Simultaneous determination of the cosmic birefringence and miscalibrated polarisation angles from CMB experiments

Yuto Minami[1,*], Hiroki Ochi[2], Kiyotomo Ichiki[3,4], Nobuhiko Katayama[5], Eiichiro Komatsu[5,6], and Tomotake Matsumura[5]