Evaluation of beam far sidelobes systematic effect on the future LiteBIRD satellite mission

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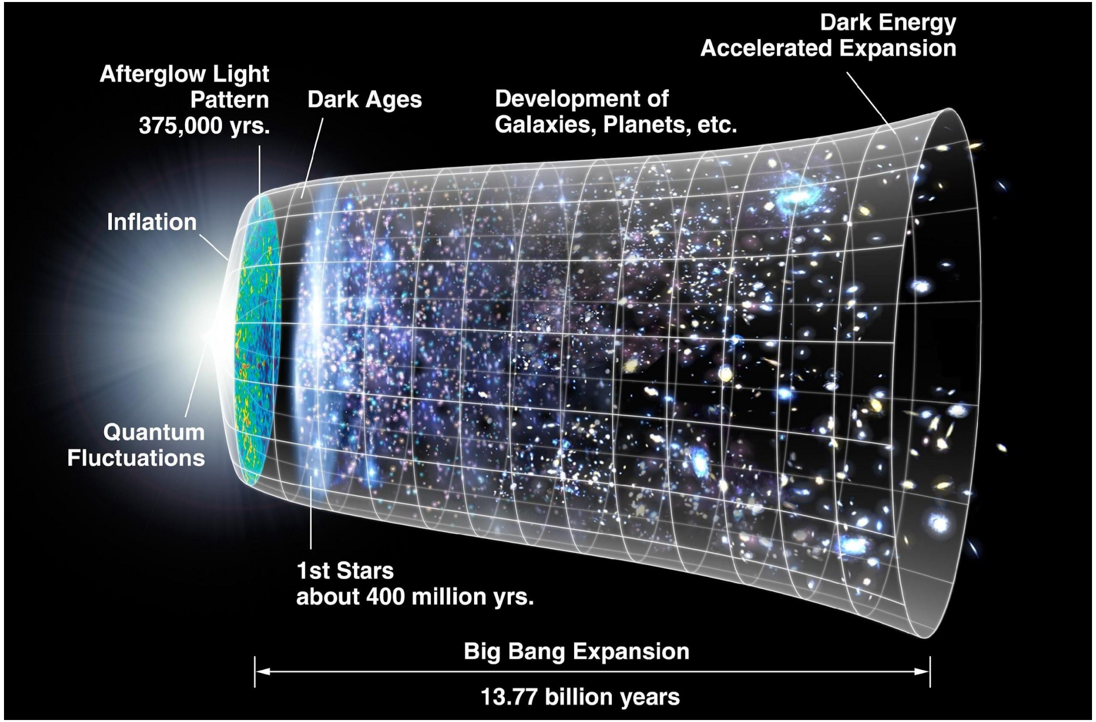
Journées de Rencontre des Jeunes Chercheurs 2022

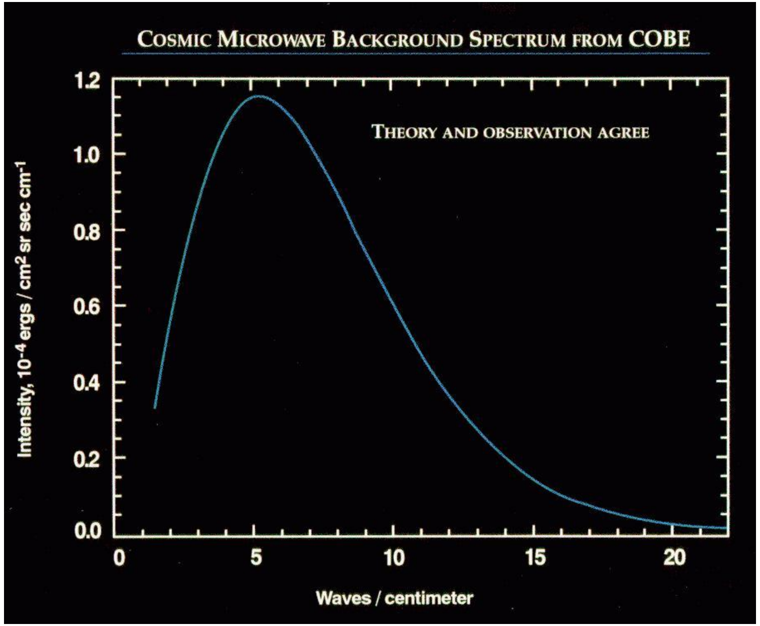
The history of the universe

The discovery and confirmation of the CMB: secure the Big Bang as the best theory of the origin and evolution of the universe.



Cosmic Microwave Background

- Monopole: Blackbody, T = 2.725K
- Dipole: v_{LG}= 627±22 km/s in CMB rest frame



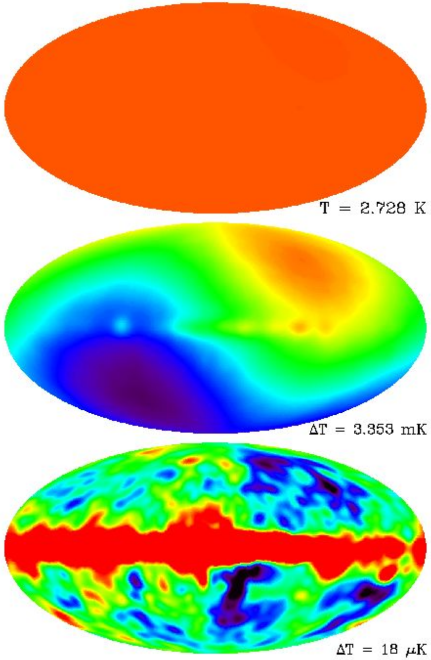
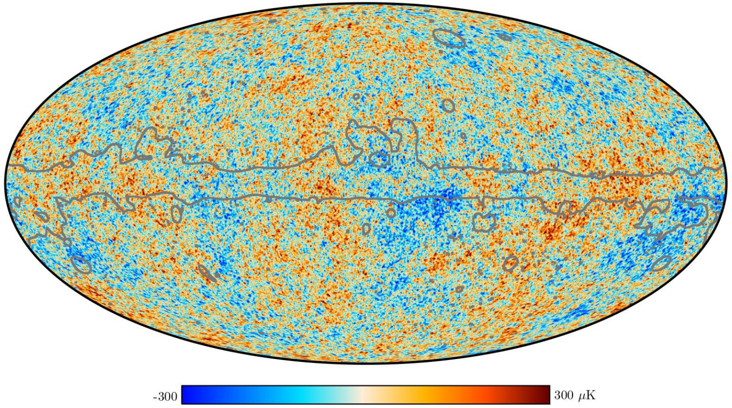


Image Credit: NASA / COBE Science Team

Cosmic Microwave Background

Era of Precision Cosmology:

- Multipole and angular power spectrum



$$\Delta_T(\vec{x},\hat{\gamma}) = \sum_{\ell\geq 2}^{\infty}\sum_{m=-\ell}^{\ell} a_{\ell m}^{\mathrm{T}}(\vec{x})Y_{\ell m}(\hat{\gamma})$$

$$C_\ell^{\mathrm{TT}} = \left\langle \left| a_{\ell m}^{\mathrm{T}}(\vec{x})\right|^2 \right\rangle ,$$

$$\mathcal{D}_\ell^{\mathrm{TT}} = [\ell(\ell+1)/2\pi]C_\ell^{\mathrm{TT}}$$

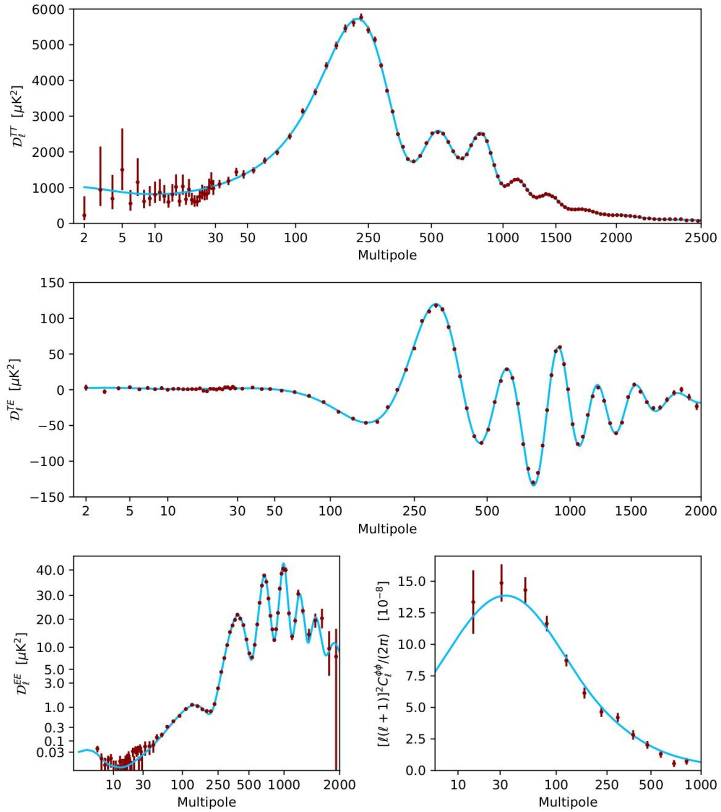


Image credit: ESA and the Planck Collaboration

ΛCDM model

ΛCDM model: the most successful phenomenological cosmological model under a set of assumptions

Main Composition: Dark Energy, Dark Matter, Baryonic Matter and Electromagnetic Radiation.

- Parameters in base ΛCDM model

$$\{\omega_b, 100\theta_s, A_s, n_s, \tau, \omega_{cdm}\}$$

ω_b: Physical baryon density parameter

ω_{cdm}: Physical dark matter density parameter

θ_s: Angular scale of acoustic oscillations

A_s: amplitude of scalar fluctuation

n_s: Scalar spectral index

τ : Reionization optical depth

- Possible extensions: curvature Ω_k, tensor-to-scalar ratio r, etc.
- Accelerating expansion: Hubble constant $v = H_0\, D$

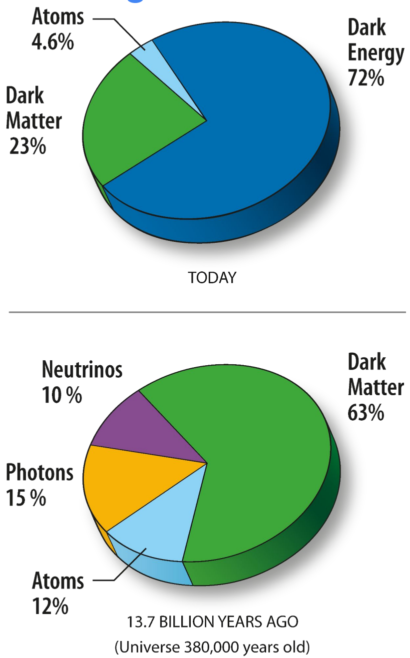


Image Credit: NASA/WMAP Team

Inflation

The Big Bang theory also leads to some problems, two main problems are:

- **Horizon problem**: the Universe appears statistically homogeneous and isotropic in accordance with the cosmological principle when two regions with big enough distances should be unconnected.
- **Curvature/Flatness problem**: the contribution of curvature to the Universe must be extremely small at big bang nucleosynthesis.

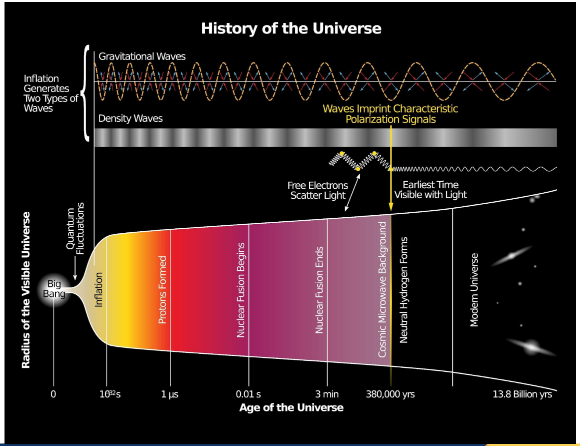
Inflation: a postulated period of accelerated expansion in the early Universe (10^{-33} s)

The details of this epoch is UNKNOWN

Inflation generates

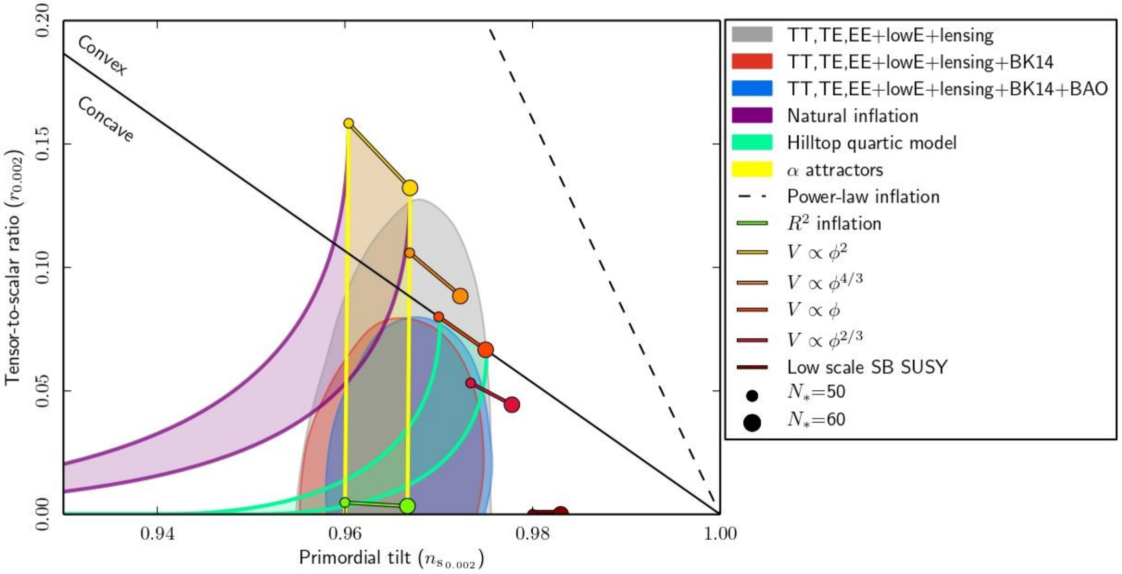
- Primordial density perturbations: $\Delta^2_\zeta(k)$
- Primordial gravitational waves: $\Delta^2_h(k)$

The GW amplitude is often reported as a tensor-to-scalar ratio: $r \equiv \frac{\Delta^2_h}{\Delta^2_\zeta}$



Inflation models

The measurement of r is important for the study of inflation models.



- Different inflation models predict different value of r generated in the epoch of inflation.
- A higher precision of the measurement is required to better constrain r.

GW detectors

pGWs cover a wide range of frequency

- Terrestrial interferometers, Pulsar Timing:
  Challenging, not enough sensitivity

- Space interferometers:
  possible, LISA (planned for 2035)

Eyes on CMB polarization! (ongoing)

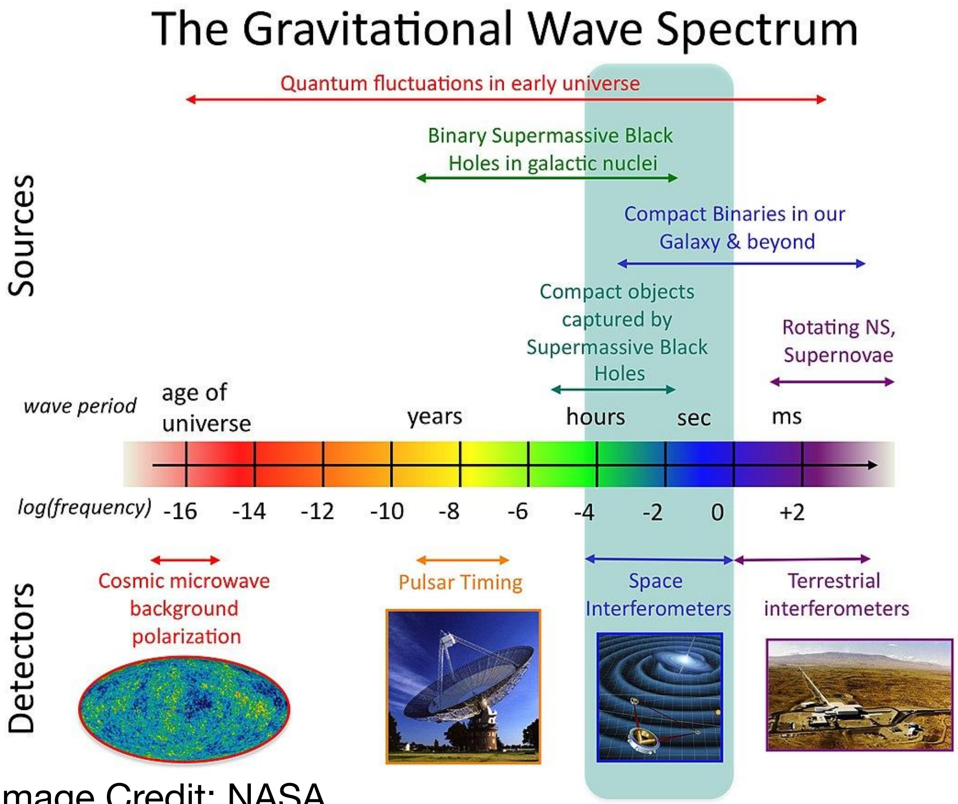
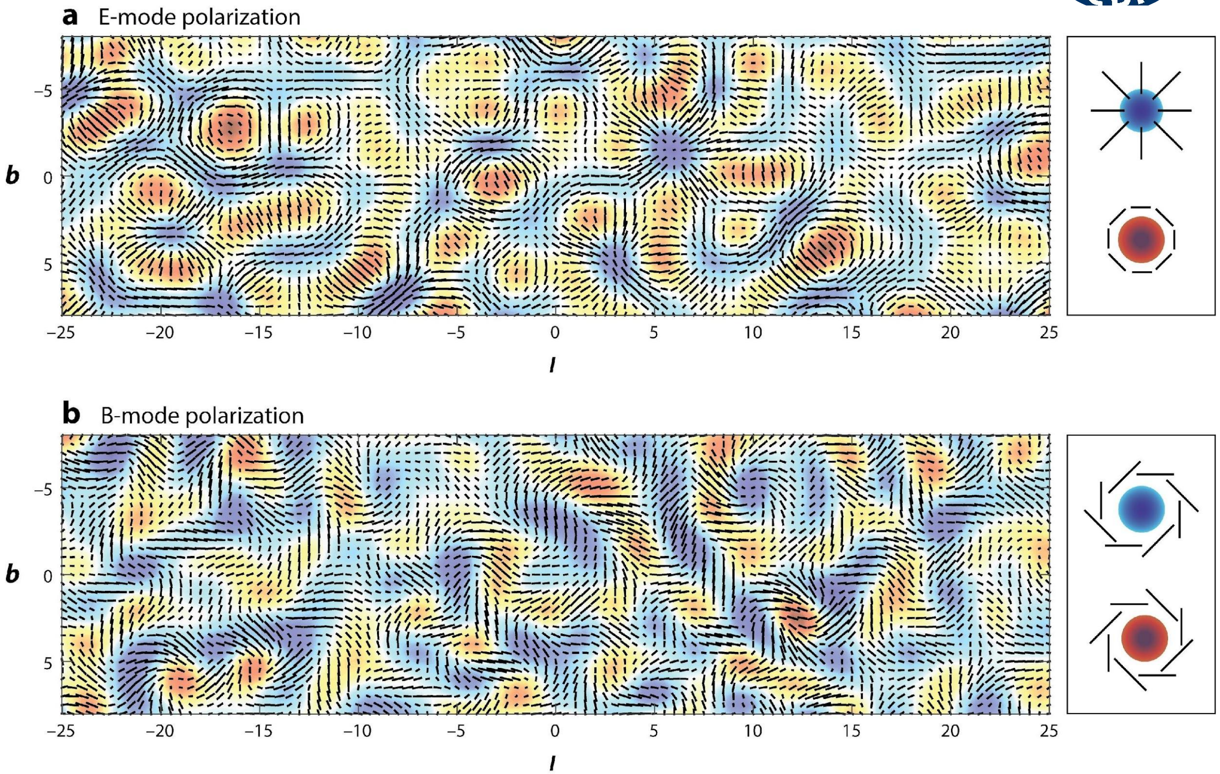


Image Credit: NASA

CMB polarization

The density perturbations:
Only create E-modes.

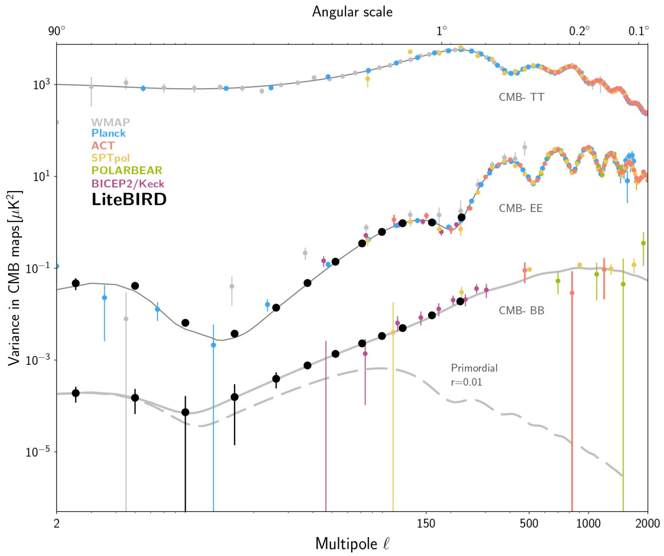
Gravitational waves:
can source B-mode
(Weak Gravitational Lensing of the CMB as well)



Kamionkowski M, Kovetz ED. 2016.
Annu. Rev. Astron. Astrophys. 54:227–69

Polarized CMB anisotropies

The B-mode power is proportional to the tensor-to-scalar ratio, r



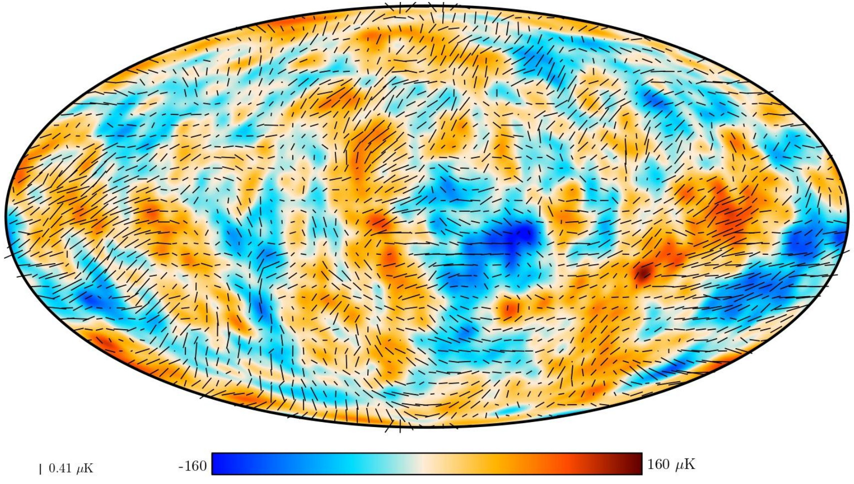


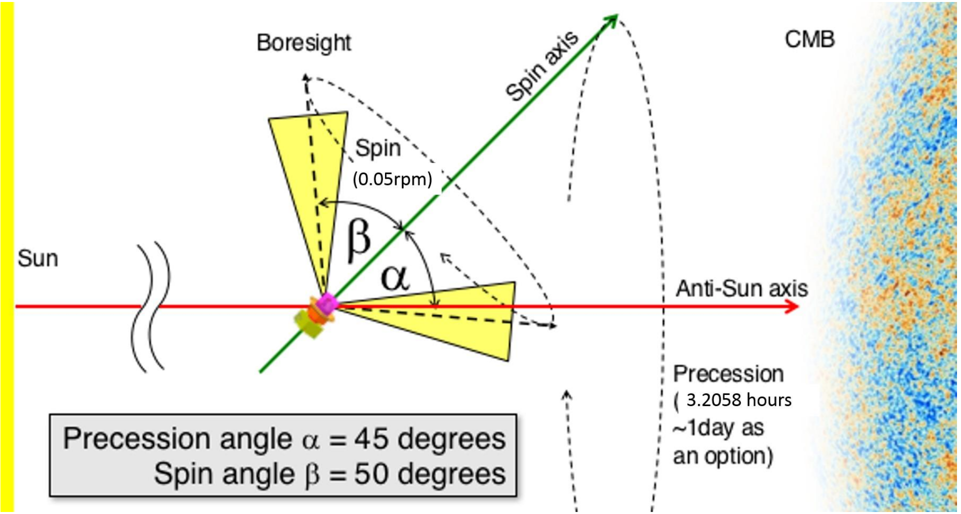
Image credit: ESA and the Planck Collaboration, LiteBIRD collaboration

Challenge: The B-mode power is much lower than temperature and E-mode.

- Planck constraints on the tensor-to-scalar ratio, r<0.044 (Planck PR4 release)
- Need to go to space for low l.

LiteBIRD overview

- Expected launch in late 2020s
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- All sky surveys (34 – 448 GHz, 15 bands) at 70–20 arcmin.



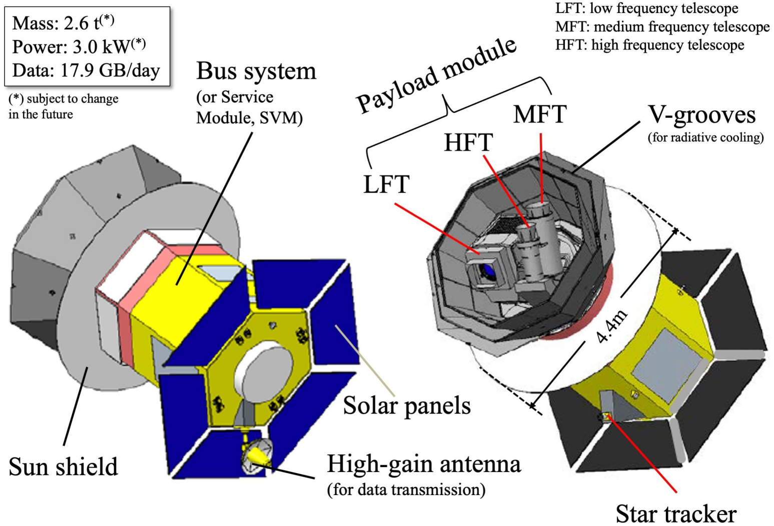


Image credit: LiteBIRD collaboration

Science goal of LiteBIRD

The primary goal of liteBIRD:

- Mission: δr < 0.001 in $2 \leq l \leq 200$

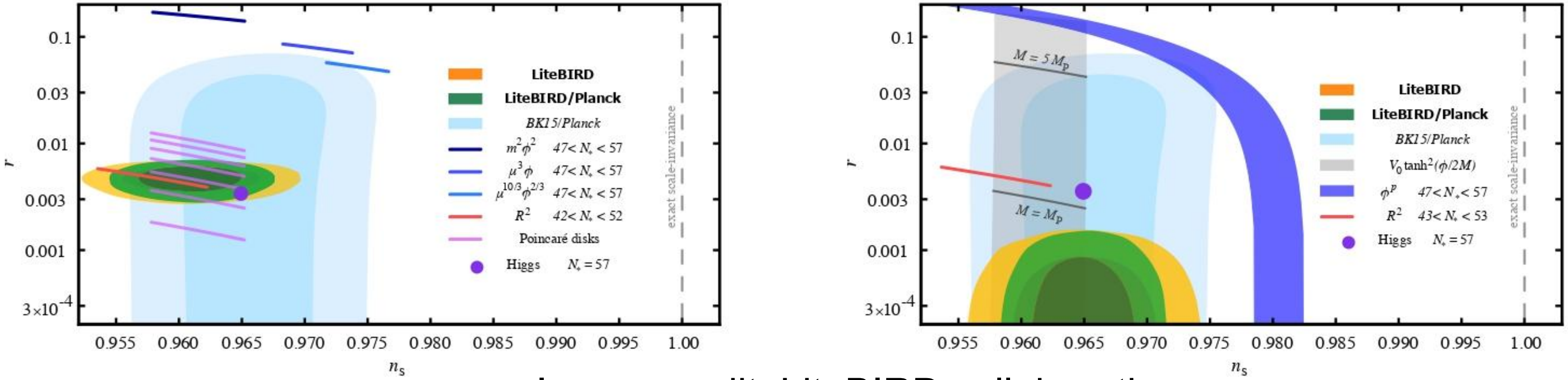


Image credit: LiteBIRD collaboration

- Making a discovery or ruling out well-motivated inflationary models. E.g., Starobinsky model; Poincare disk models; models that invoke the Higgs field as the inflation

Systematic effect

Systematic effects give rise to the leakage from temperature to polarization, from E-mode to B-mode.

Sources of systematic effects：

- Beam
- Cosmic ray
- HWP
- Gain
- Polarization angle
- Pol. efficiency
- Pointing
- Bandpass
- Transfer function

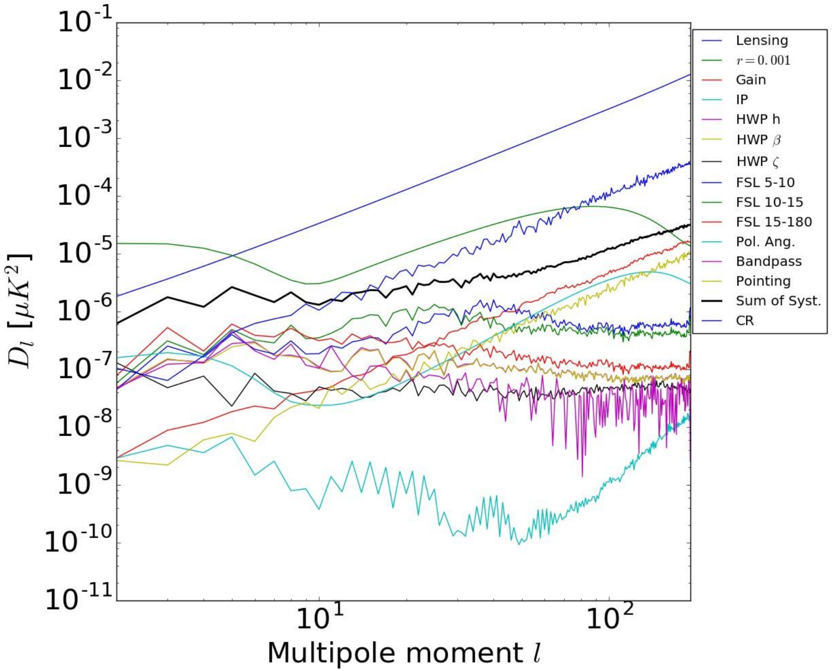


Image credit: LiteBIRD collaboration

Beam

The power received: convolution of the ske signal and the beam

$$dW_{\rm tot} \propto \langle|\varepsilon \cdot \tilde{\varepsilon}|^2\rangle d\Omega$$

For a polarized beam, with Stocks parameters

$$W_{\rm tot} \propto \frac{1}{2}\int (I\tilde{I} + Q\tilde{Q} + U\tilde{U} - V\tilde{V})d\Omega$$

In harmonic space, the convolution is written as

$$W_{\rm tot}(\phi,\theta,\psi) \propto \sum_{\ell m m'} \left[\frac{1}{2}\left(a^{I*}_{lm} b^{I}_{lm'} - a^{V*}_{lm} b^{V}_{lm'}\right) + \sum_{P} a^{P*}_{lm} b^{P}_{lm'}\right] D^{\ell}_{mm'}(\phi,\theta,\psi)$$

The final observed map of I, Q, U is produced given the data and hit angle ψ via mapmaking. It is much simplified in the case of axi-symmetric beam

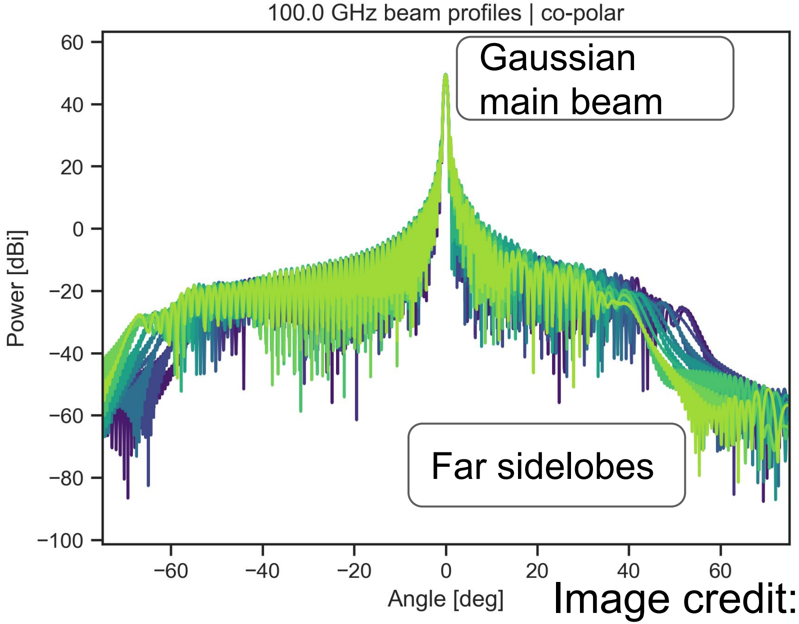
$$I_{\rm eff}(\theta,\phi) = \sum_{\ell m}\left(\sqrt{\frac{4\pi}{2\ell+1}} b^{\rm I}_{\ell 0}\right) a^{\rm I}_{\ell m} Y_{\ell m}(\theta,\phi)$$

$$\frac{1}{\sqrt{2}}(Q_{\rm eff} \pm iU_{\rm eff}) = \sum_{\ell m}\left(-2\sqrt{2}\sqrt{\frac{4\pi}{2\ell+1}} b^{\rm E}_{\ell 2}\right)(a^{\rm E}_{\ell m} \mp i a^{\rm B}_{\ell m})\,_{\mp 2}Y_{\ell m}(\theta,\phi)$$

Beam profile

The current available beam profile:

- Basic physical optics (PO) simulations
- the azimuthal symmetry of the beams breaks closer to the edge of the field



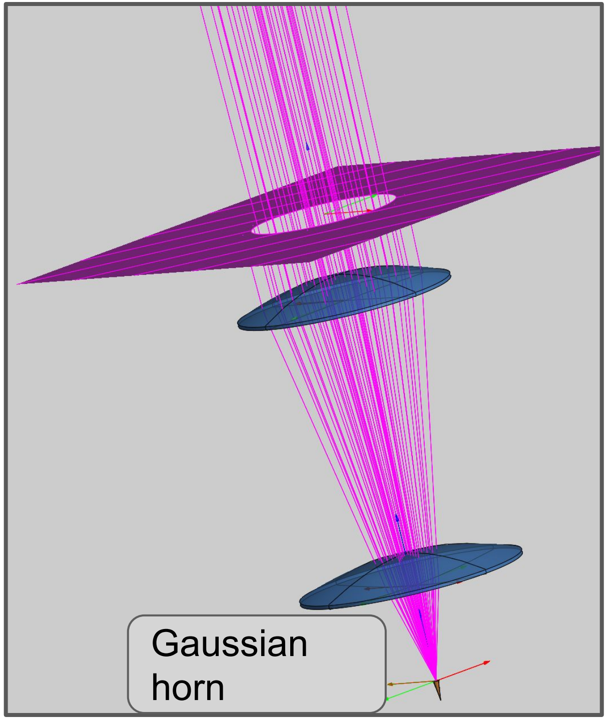


Image credit: LiteBIRD collaboration

Foregrounds

Foreground is a problem…

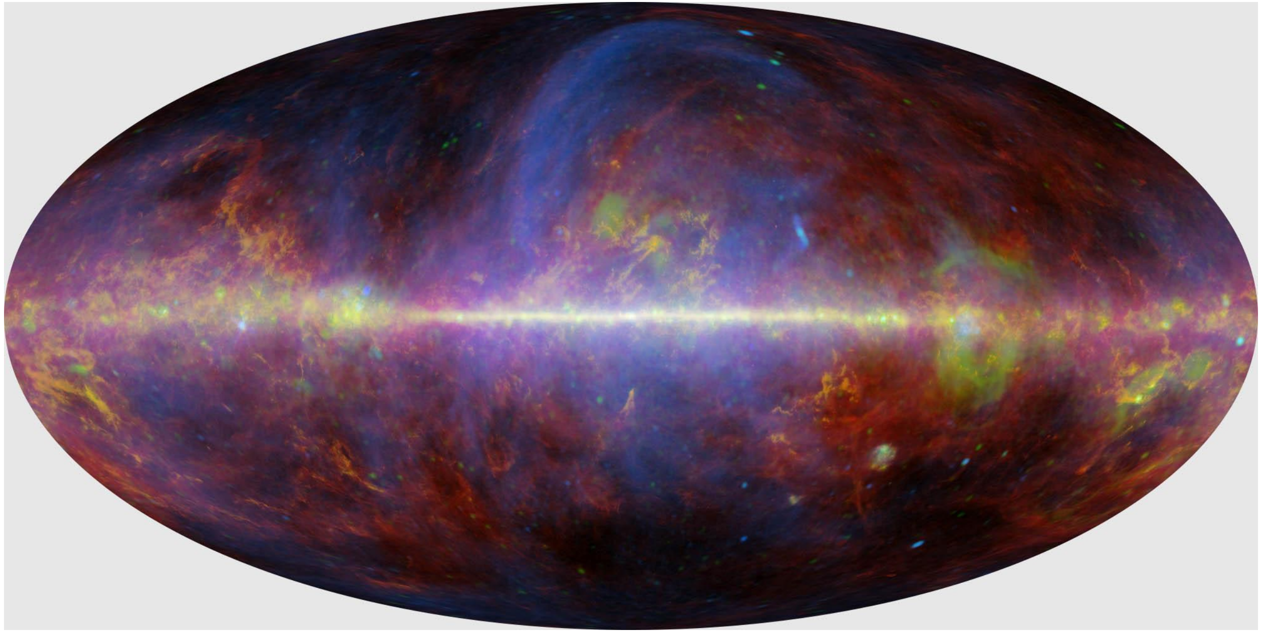


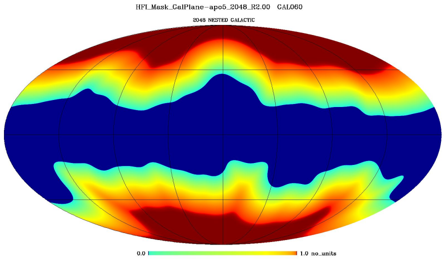
Image credit: Planck collaboration

Foregrounds

Foreground is a problem…

Solution:

1. mask the Galactic plane



2. Component separation:

- Parametric: FGBuster, Commander3, etc.
- Non-blind: HILC,NILC, SMICA, etc.

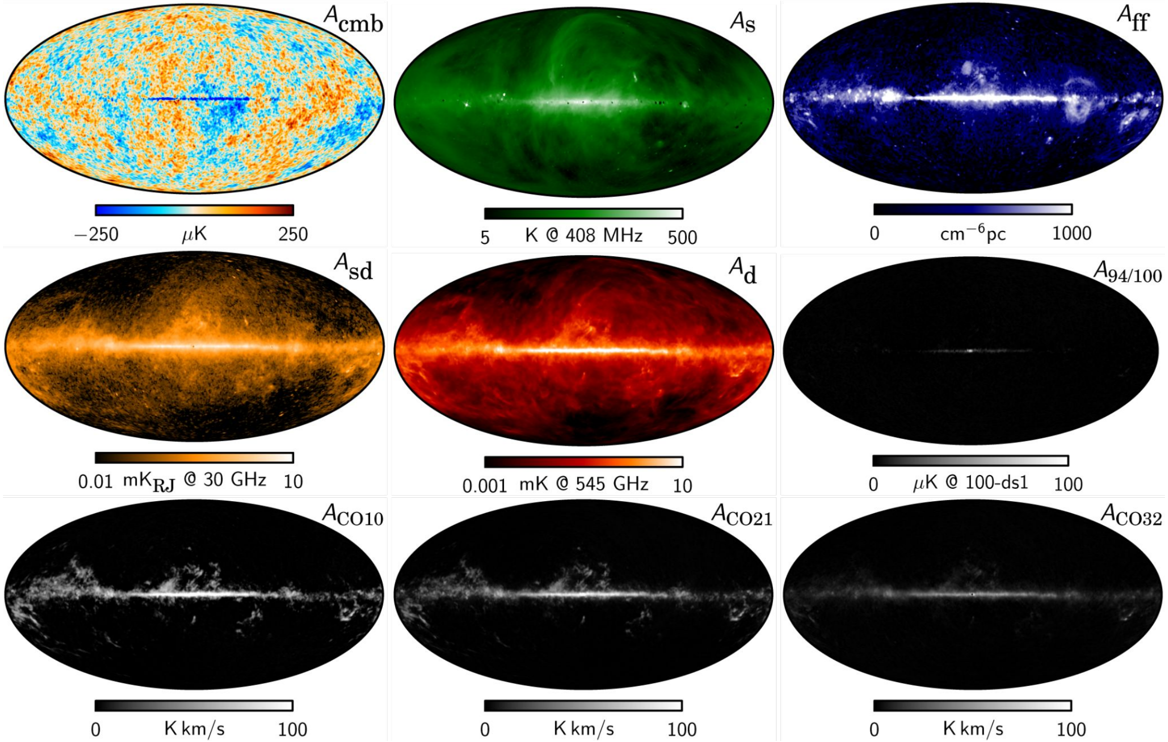


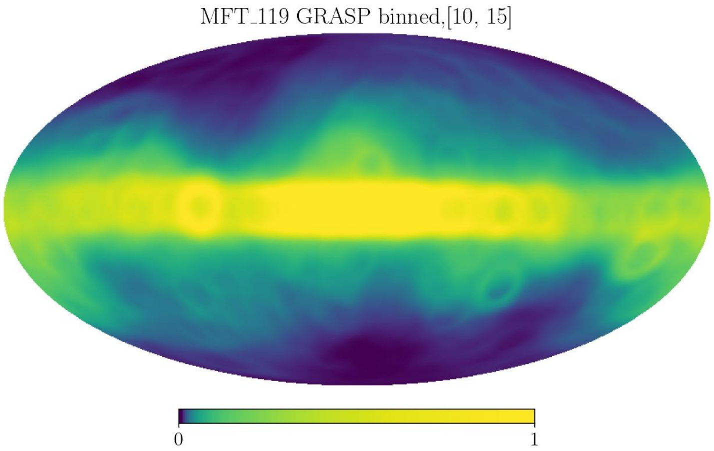
Image credit: Planck collaboration

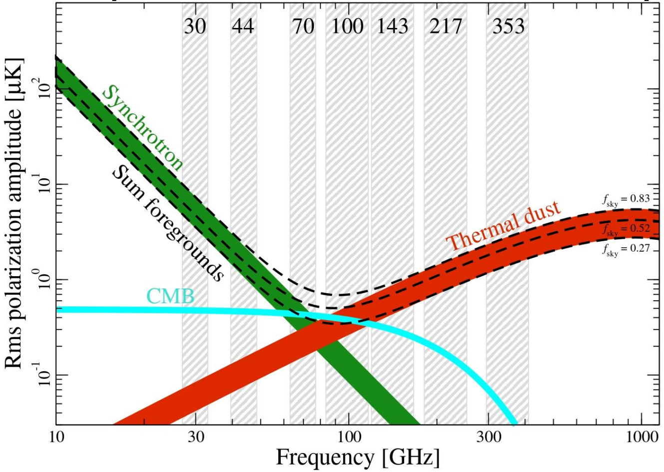
Systematic effect from beam far sidelobes

The sky in the pixel domain is modeled as:

$$\mathbf{d}_p = \mathbf{A}_p \mathbf{s}_p + \mathbf{n}_p$$

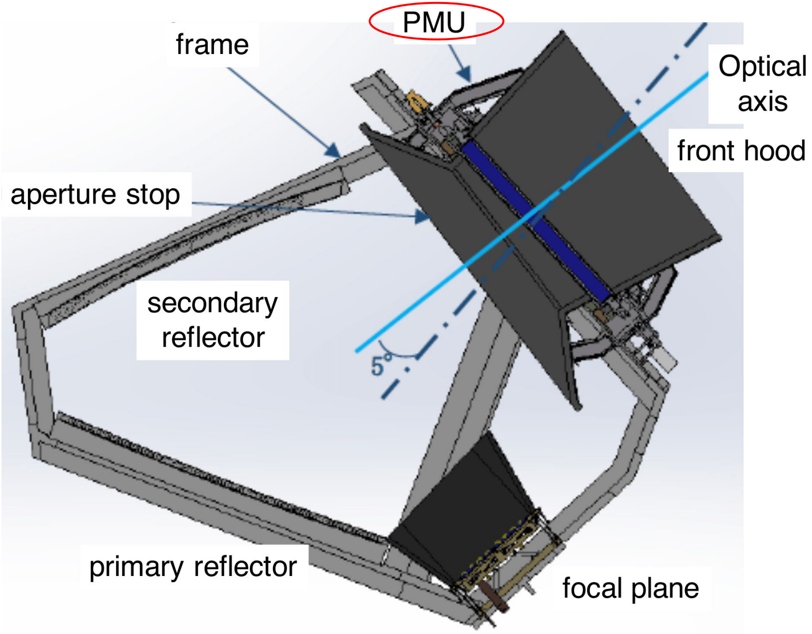
The far sidelobes will pick up the Galactic plane emission and contaminate the ‘clean’ high galactic latitude area of the sky;
The mismatch of our knowledge on beam far sidelobes will cause an incorrect estimate of the foregrounds and further affect the recovery of the CMB B-mode map.





Optical system

Rotating HWP is adopted to reduce systematic effects



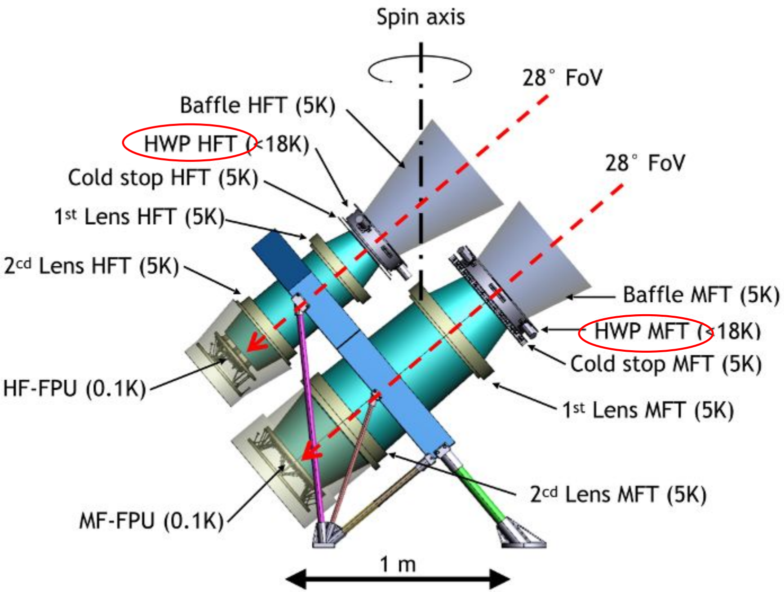
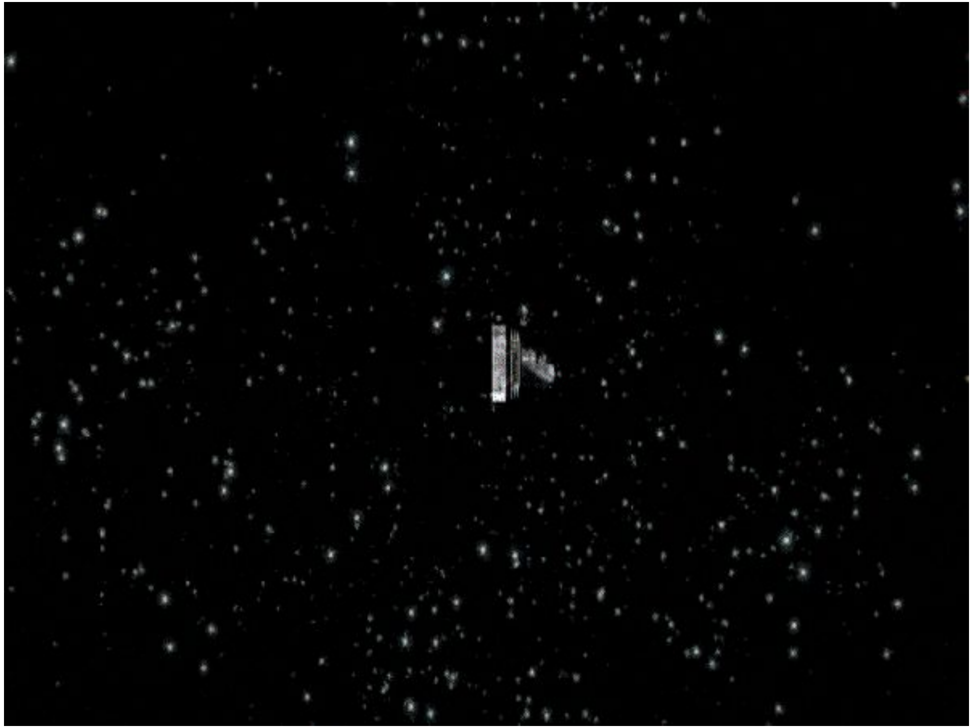
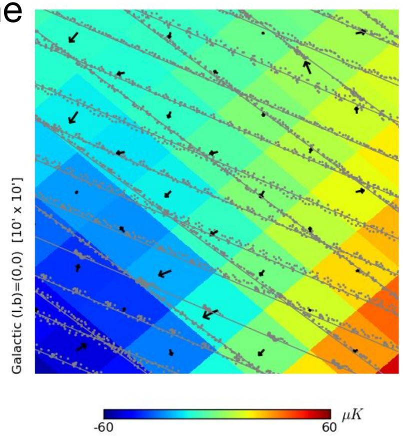


Image credit: LiteBIRD collaboration

Hit angle distribution



At Galactic plane
Planck:



LiteBIRD:

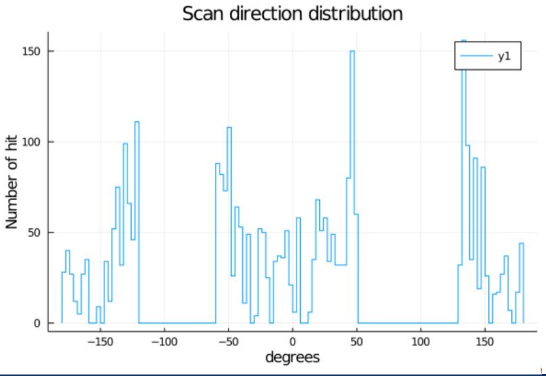


Image credit: Planck, LiteBIRD collaboration

Motivation

Goals with the beam far sidelobes study (biggest source of systematics):

- Study the systematic error caused by the beam fsl mismatch in different angular ranges (P1.1)
  $\longrightarrow$ A flexible approach with the feasibility of perturbing beam fsl in arbitrary angular range
  $\longrightarrow$ A fast pipeline to estimate the bias on cosmological parameter δr from beam fsl mismatch
    $\longrightarrow$ Assuming the effective beams are unpolarized and symmetrized
    $\longrightarrow$ Perturbing the transfer function

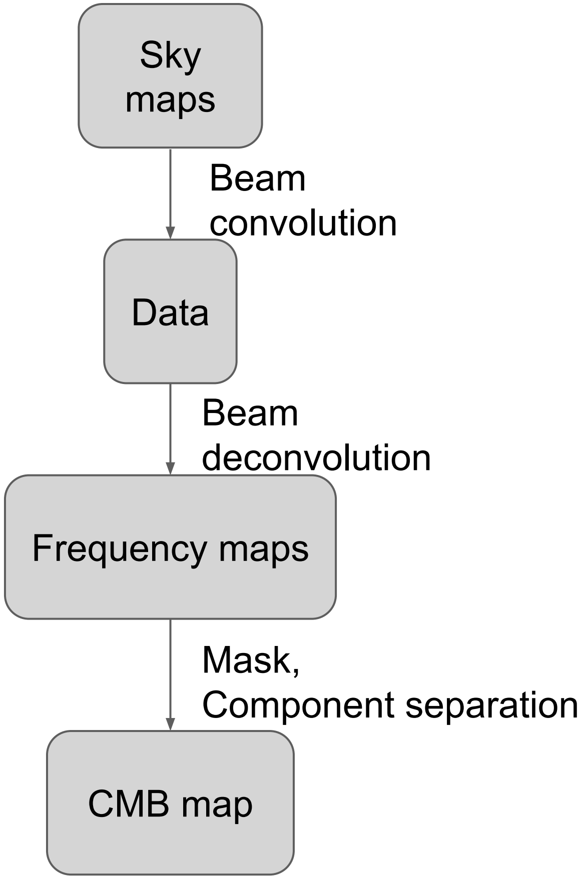
- Setting the requirement for the calibration of beam far sidelobes (P1.2)
  $\longrightarrow$ Modeling of the calibration uncertainty and propagating to the bias on δr

- Study the detailed feature of the beam far sidelobes (P2.1)
  $\longrightarrow$ Studying beam fsl asymmetries and its effect on effective beam
  $\longrightarrow$ Studying the polarized beam

- The fact that it is challenging to calibrate the beam to the required precision (P2.2)

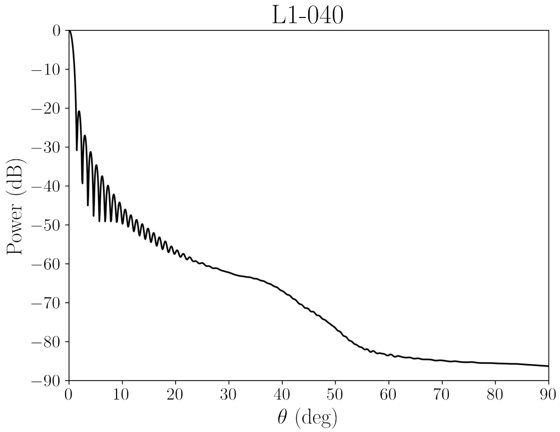
  $\longrightarrow$ Mitigating the effect of beam fsl mismatch in the analysis pipeline, namely component separation

P1.1 Setup: Pipeline for analysis

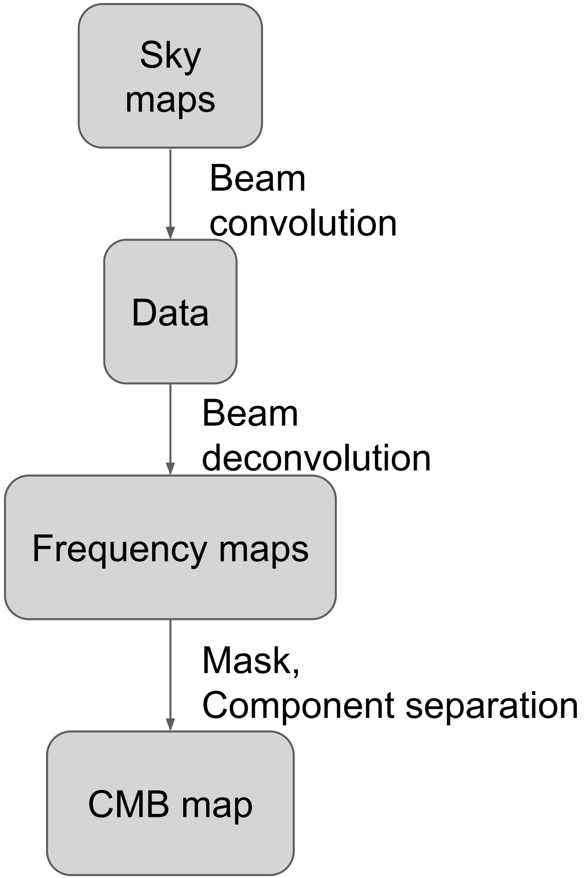


The choice of input map and beam:

- Original sky: bandpass integrated d0s0 sky maps (same input maps as PTEP simulations).
- Beam: averaged and symmetrized GRASP beams.
- Mask: HFI Galactic mask, 60% sky.
- Component separation: fgbuster in pixel domain.



P1.1 Setup: Pipeline for analysis



Residual: the recovered CMB B-mode multipoles in reference case and in perturbed case

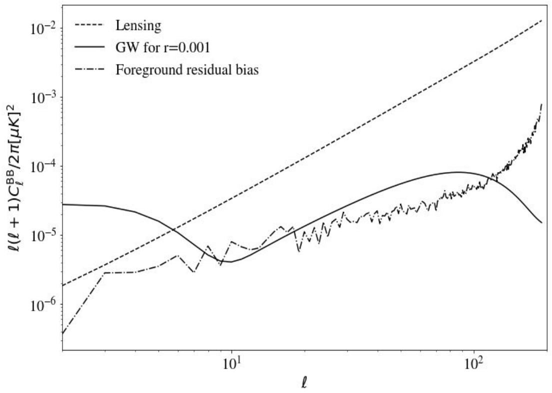
$$\delta \mathbf{res}_{\ell m} = \bar{\mathbf{s}}_{\ell m} - \bar{\mathbf{s}}^{\text{ref}}_{\ell m}$$

The bias on tensor-to-scalar ratio δr: by maximizing the likelihood

$$-2\ln\mathcal{L}_{cosmo} = f_{sky}\sum_{\ell}(2\ell+1)\left(\ln C_\ell^{\text{th}}(r) + \frac{C_\ell^{\text{th}}(r=0)+C_\ell^{\text{res}}}{C_\ell^{\text{th}}(r)}\right)$$

Here $C_\ell^{\text{th}} = rC_\ell^{GW} + C_\ell^{\text{lens}} + N_\ell$

with primordial CMB BB power-spectrum, gravitational lensing and foreground residuals from statistical uncertainties



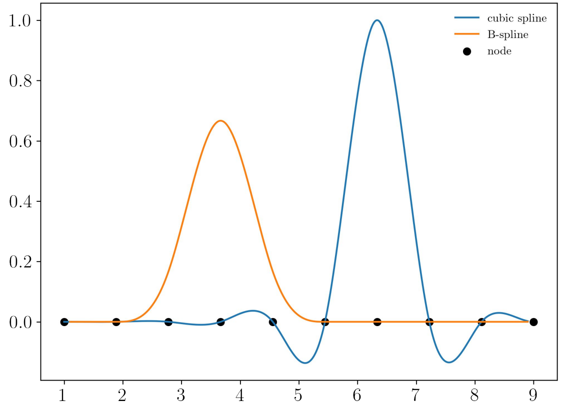
P1.1 Cubic splines as basis function

In Planck, B-spline basis functions are used to reconstruct the main beam and near sidelobe (Planck Collaboration VII. 2014):
The time ordered data (Mars observation) are used to fit a two dimensional B-Spline surface

- a least square minimization;

$$S = \sum_i \left[y_i - \mathbf{B}(t, x_i) \cdot \mathbf{c}\right]^2$$

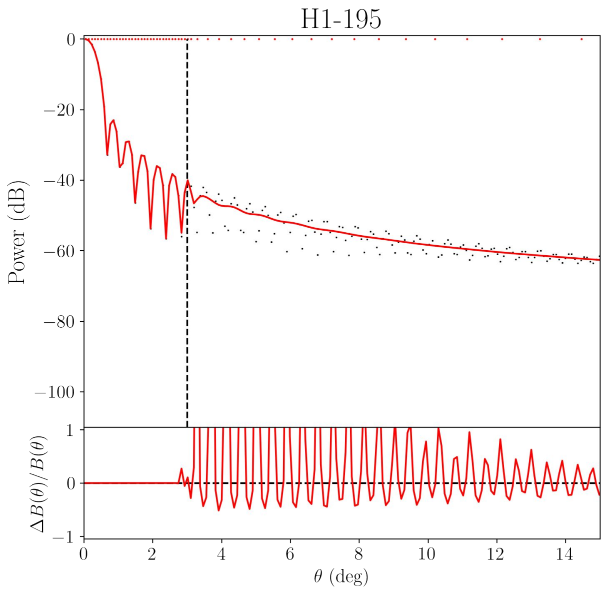
- a smoothing criterion to minimize the effects of high spatial frequency variations.

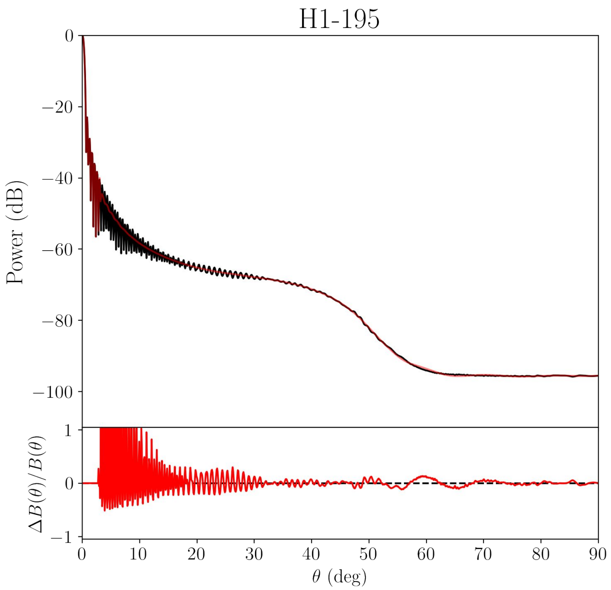


We extend this to far sidelobe, with a different choice of cubic spline basis function.

P1.1 Beam reconstruction with cubic spline

Data: averaged and symmetrize GRASP beams (currently 1D); Node: 40 nodes between 3° and 90°, log scale



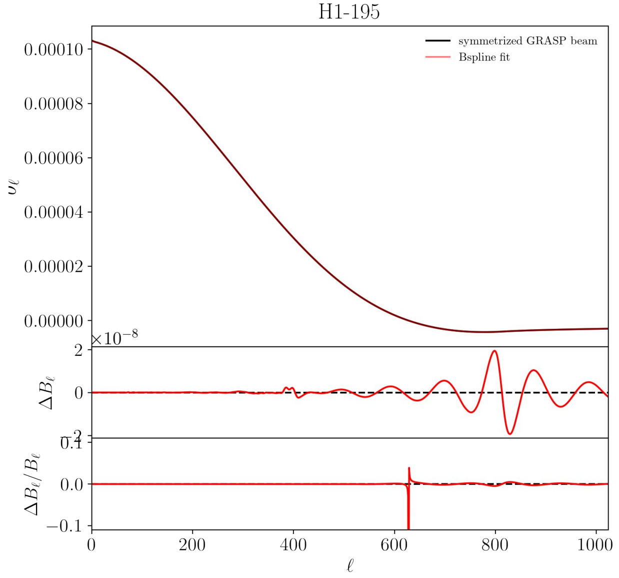


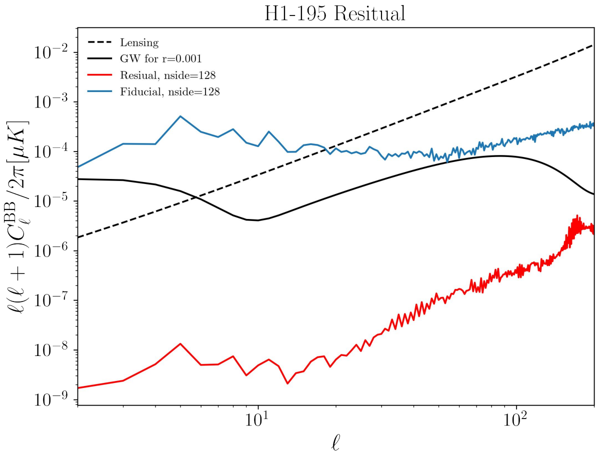
Link to calibration:

Position of the nodes→ resolution.

P1.1 Beam reconstruction with cubic spline

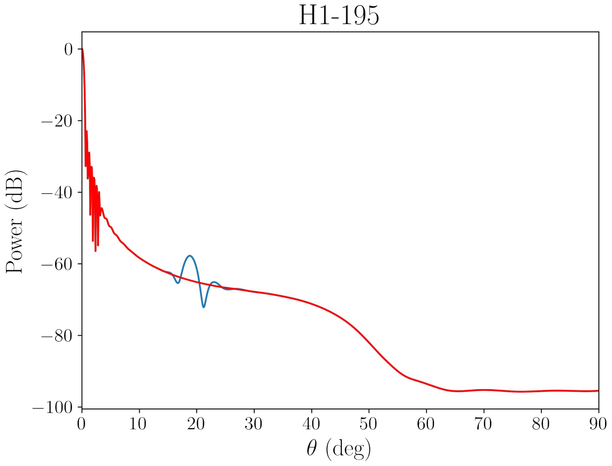
b_l and the residual recovered CMB after component separation

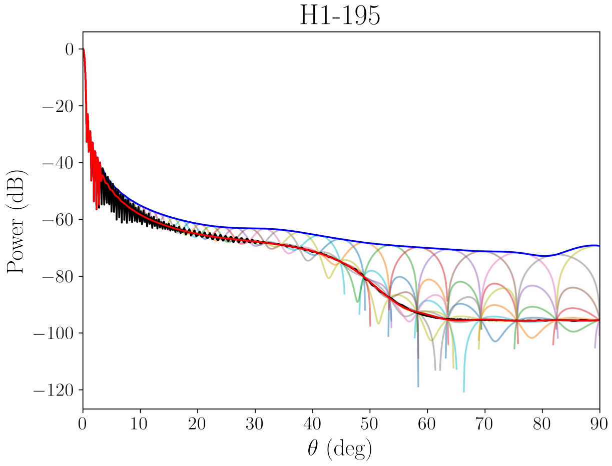




P1.1 Requirement on beam fsl knowledge

1. fit the beam with given spline basis functions,
2. each time perturb the beam by varying the value of one coefficient $\boldsymbol{c}$.





In total, there are 39 theta range. The budget is set to be δr = 5.7 × 10^{-5}/22/39.

P1.2 Calibration:

Following the PTEP analyses with $\Delta\Omega_{Pixel}$, $\Delta\theta$

Grid:

The value of $\Delta\varphi$ is determined by

$\Delta\varphi = \Delta\Omega_{Pixel}/(\Delta\theta \sin\theta)$

Beam	θ range (°)	φ range (°)	Δθ (°)		Δφ (°)		N. pts θ		N. pts φ	
			Req	Goal	Req	Goal	Req	Goal	Req	Goal
LFI 27	[140,180]	[0,360]	5	2	5	2	9	21	73	181
LFI 24	[140,180]	[0,360]	5	2	5	2	9	21	73	181
LFI 18	[140,180]	[0,360]	5	2	5	2	9	21	73	181
$\sum_\nu$ N. pts = 1971 (Req) – 11403 (Goal)										

Table 7 Angular region and angular step for the straylight region measurements.

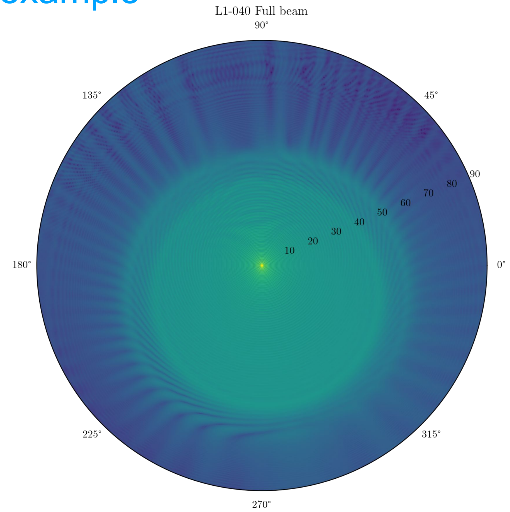
L1-040 channel as an example

PTEP GRASP beam

tp_grid

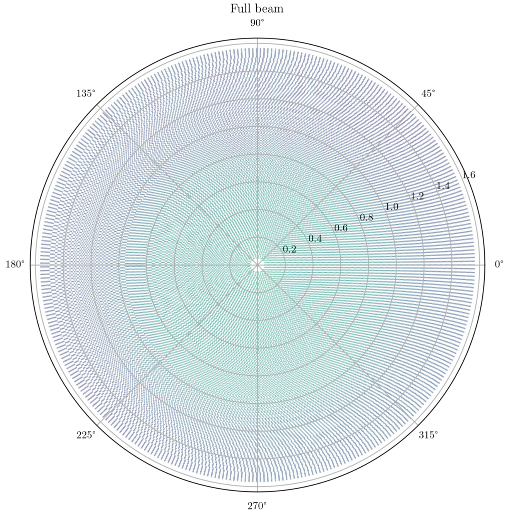
Ntheta = 1001

Nphi = 1000



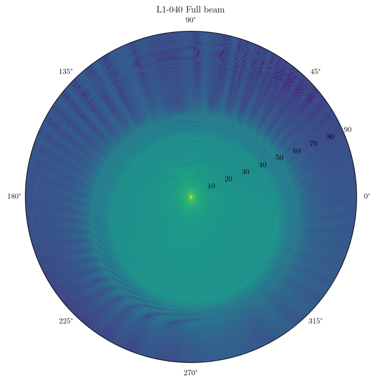
Sampled beam

Bilinear interpolation for collecting data

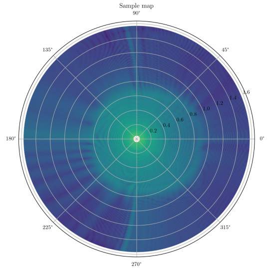


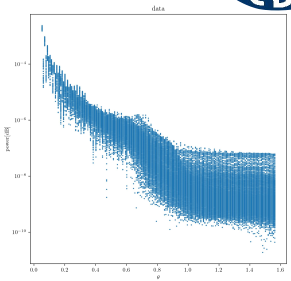
P1.2 Sampling

Requirement is derived with
$\Delta\theta$ =0.5°
$\Delta\Omega_{\mathrm{Pixel}}$ =0.25□

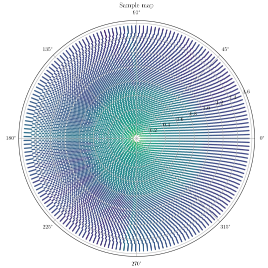


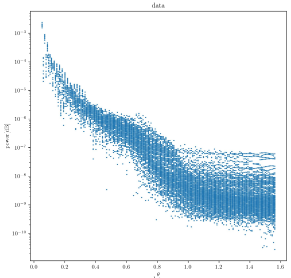
$\Delta\theta$ =0.5°
$\Delta\Omega_{\mathrm{Pixel}}$ =0.5□



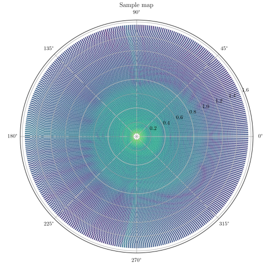


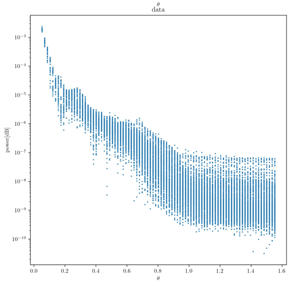
$\Delta\theta$ =0.5°
$\Delta\Omega_{\mathrm{Pixel}}$ =1.0□





$\Delta\theta$ =1.0°
$\Delta\Omega_{\mathrm{Pixel}}$ =1.0□





$\Delta\theta$: Resolution at 1D (symmetrized beam)
$\Delta\Omega_{\mathrm{Pixel}}$ density of measure measurement

P1.2 Uncertainty in the calibration

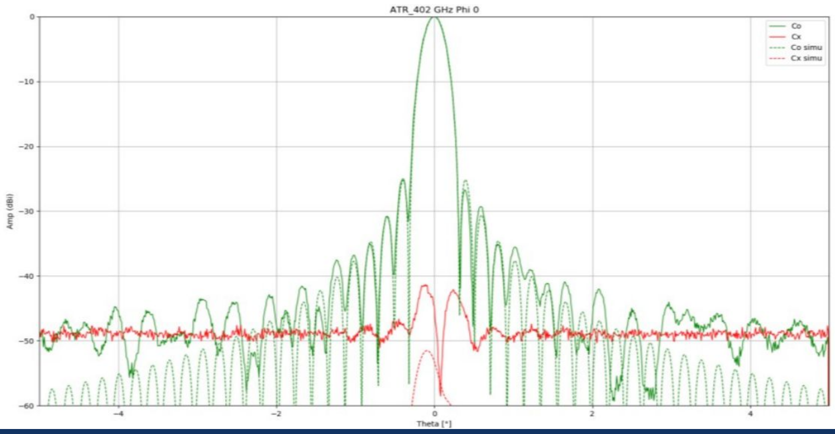
Possible source of error

- Pointing: negligible

- Power:

1. Uncertainty at power

2. Systematic in the measurement



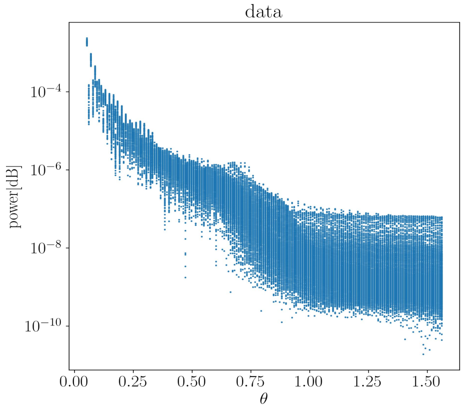
Modeling

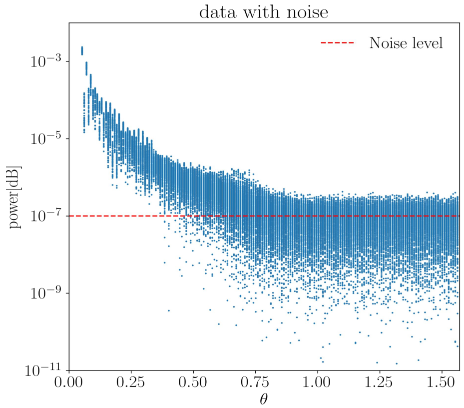
- No pointing errors

- Power:

1. Uncorrelated Gaussian noise for each data point, $\sigma_{\text{Uncertainty}}$

2. Keep negative points assuming the systematic can be removed





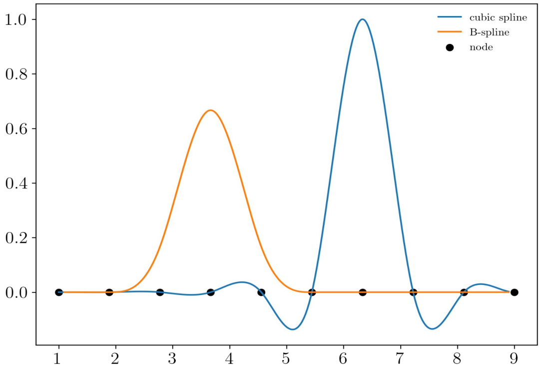
P1.2 Reconstructing the beam

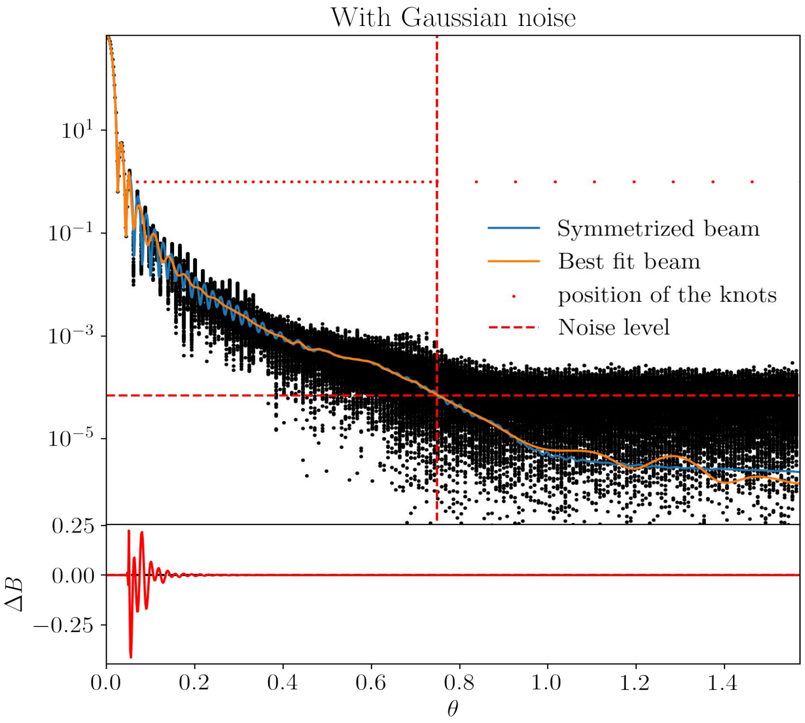
A least square minimization:

$$S = \sum_i [y_i - \mathbf{B}(t, x_i) \cdot \mathbf{c}]^2$$

Spline: with nodes separation same as $\Delta\theta$

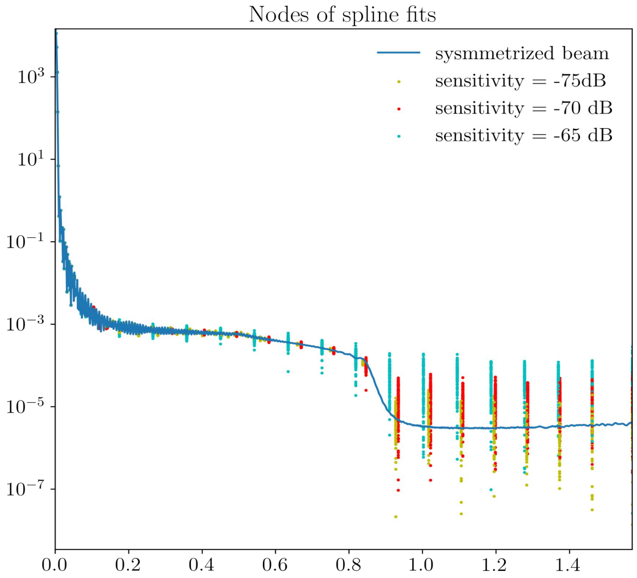
The larger nodes separation at region below the noise level



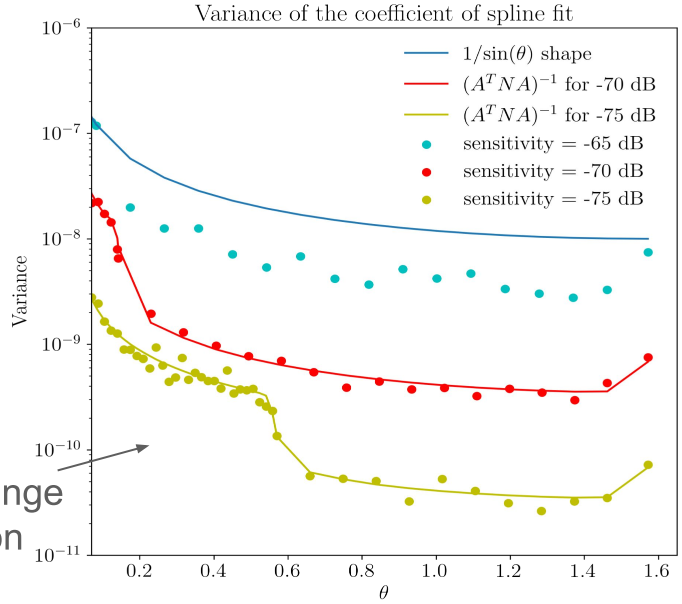


P1.2 Monte Carlo run

100 realizations for each frequency
$\Delta\theta$ =0.5°
$\Delta\Omega_{\text{Pixel}}$ =0.25□
Uncertainty:
3 closest multiple of five of value below beam at 3 degree



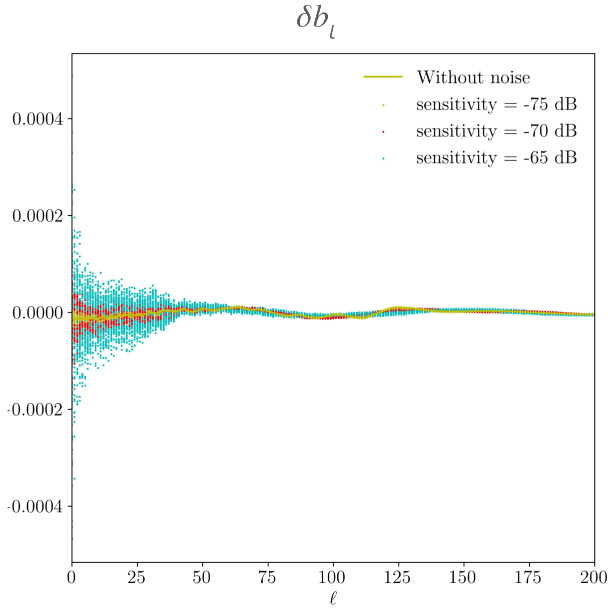
Uncorrelated noise:
$\Delta\varphi \propto 1/\sin\theta$
Variance following $(A^TNA)^{-1}$

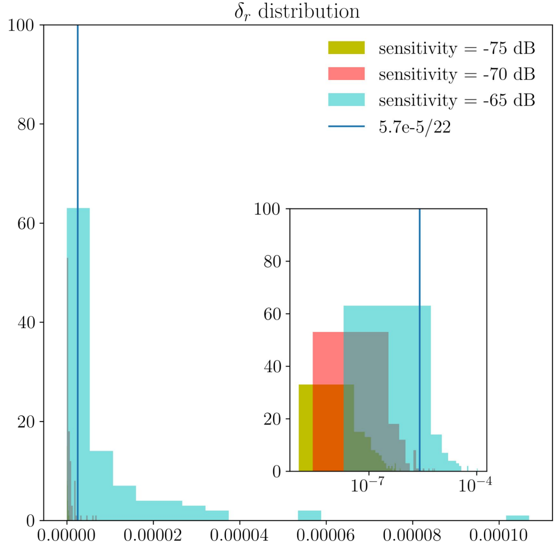


P1.2 Result δr: 402GHz

The bias on knowledge of beam is limited by
1. Angular resolution
2. Noise

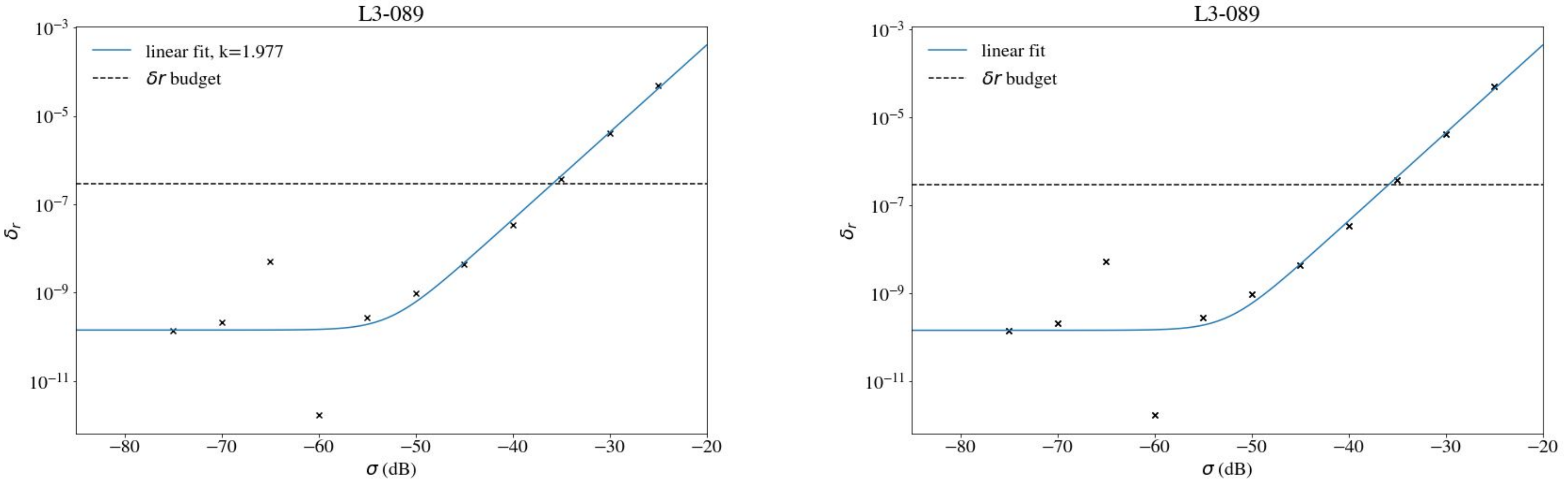
Mean δr		
-65 dB	-70 dB	-75 dB
8.42×10^{-6}	7.08×10^{-7}	1.33×10^{-7}





P1.2 Analysis method

1. 10 realizations for each sigma for each frequency channel, calculate the average value δr
2. Fit with a power law $\delta r = a \cdot \sigma^k + \delta r_{\text{offset}}$ (varying k and fixed k=2)
3. Set error budget $\boldsymbol{\Delta r}$ and read corresponding σ_{lim} from the curve for given $\boldsymbol{\Delta\theta}$ and $\Delta\Omega_{\text{Pixel}}$



P1.2 Crosscheck: calibration requirement

Clément's approach

GRASP beam → Perturbed beam → $\boldsymbol{\alpha}_{\rm lim}$ → $\boldsymbol{\sigma}_{\rm Calib}$

Certain shape of perturbation

$$B^{\nu}_{\rm pert}(\theta,\phi) = \mu_{\nu}(1+\alpha_{\nu}W(\theta))\,B^{\nu}_{0}((\theta,\phi),$$

Budget
$\Delta r = 1.9\times 10^{-5}/66$

$\Delta\theta = 0.5^{\circ}$

$\Delta\Omega_{\rm pix} = 0.25^{\square}$

$$\sigma_{\rm Calib} = \frac{\int W(\theta){\rm d}\Omega}{\sqrt{\sum_{ij} W^2(\theta_{ij})\Delta\Omega_{\rm pix}}}\delta\overline{B}_{\rm lim}$$

Wang's approach

GRASP beam → Sampled data → Perturbed beam → $\boldsymbol{\sigma}_{\rm lim}$

$\Delta\theta = 0.5^{\circ}$

$\Delta\Omega_{\rm pix} = 0.25^{\square}$

Random Gaussian noise, reconstruction

$$\delta B_i \sim N(0,\sigma^2)$$

Budget
$\Delta r = 1.9\times 10^{-5}/66$

P1.2 Result

Set up:

- Pixel $\Delta\theta$ =0.5°, $\Delta\Omega_{\text{Pixel}}$ =0.25□
- Perturbation in window [5, 10] deg
- Budget Δr = (1.9/66) ×10^{-5}

Conclusion:

- Consistent value with Clément's result
- The small structure of the beam is negligible.

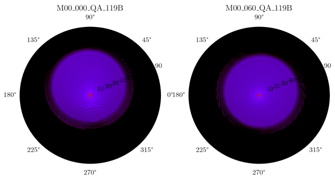
Further study with Clément et al.

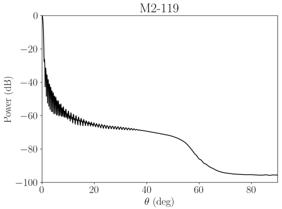
- The bias on δr not sentitive to the shape of perturbation
- δr can be well characterized by only one parameter, the residual beam power between the "actual" beam and the model in far sidelobes

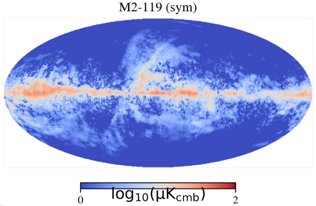
beam	σ_{lim}(dB)		σ_{Clement}(dB)
	Varying k	k = 2	
L1-040	-35.23	-35.92	-28.20
L2-050	-21.22	-21.28	-19.73
L1-060	-26.50	-26.43	-25.11
L3-068	-23.62	-24.05	-22.34
L2-068	-15.78	-18.34	-16.10
L4-078	-30.08	-30.34	-28.46
L1-078	-27.18	-26.42	-25.07
L3-089	-35.91	-35.92	-34.20
L2-089	-26.54	-25.72	-24.49
L4-100	-38.90	-39.18	-37.45
L3-119	-41.15	-41.11	-40.47
L4-140	-36.16	-35.83	-36.90
M1-100	-37.16	-37.78	-36.30
M2-119	-40.97	-41.51	-40.23
M1-140	-35.01	-34.79	-35.20
M2-166	-47.81	-47.69	-46.52
M1-195	-50.17	-50.05	-49.20
H1-195	-46.23	-46.29	-44.65
H2-235	-50.04	-49.68	-48.57
H1-280	-44.98	-45.19	-46.22
H2-337	-56.49	-56.18	-56.12
H3-402	-52.36	-52.61	-53.56

P2.1 Flowchart: beam asymmetry

With assumption:



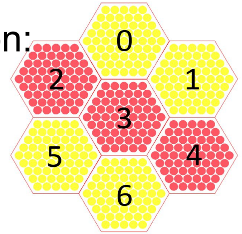


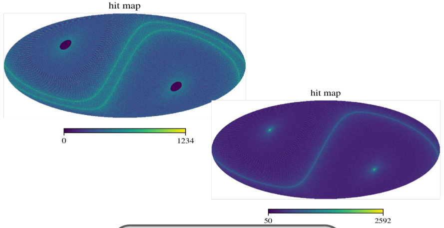


GRASP beams → Averaged symmetric beam → (Transfer function) → Observed maps(sym)

Observed maps(sym) → Bias from asymmetry: δr

Without assumption:





Focalplane → (Detector locations)

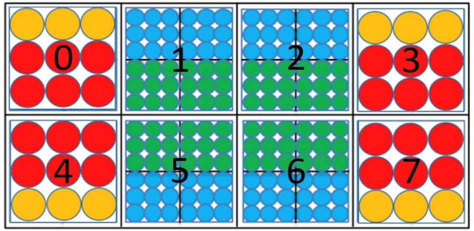
Scanning HWP → (Hit angle ψ)

GRASP beams → TOD: Effective beam → (Transfer function) → Observed maps(asy)

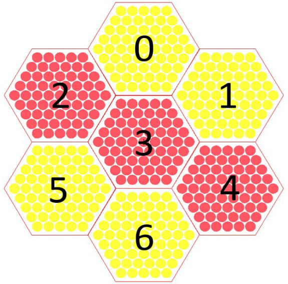
Observed maps(asy) → Bias from asymmetry: δr

P2.1 Setup: focalplane

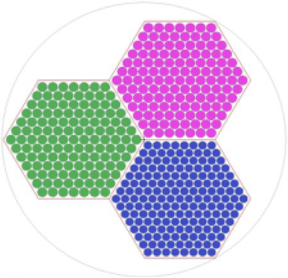
To isolate the effect of beam sidelobes with scanning strategy, selecting one detector for each frequency band



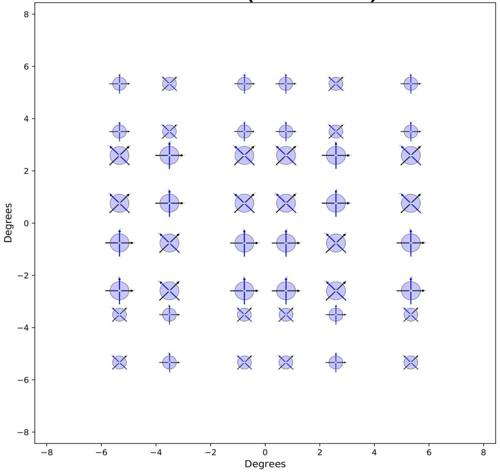
Focal plane for PTEP simulation:
LFT(16 mm)

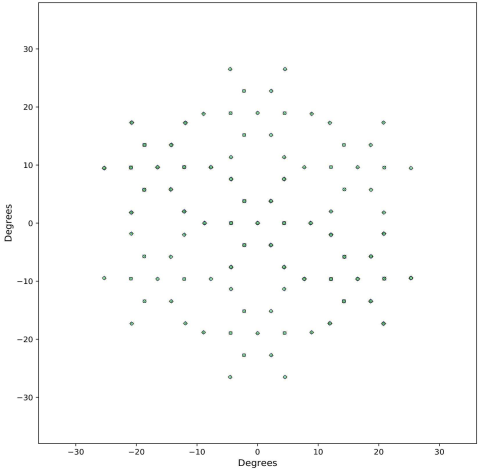


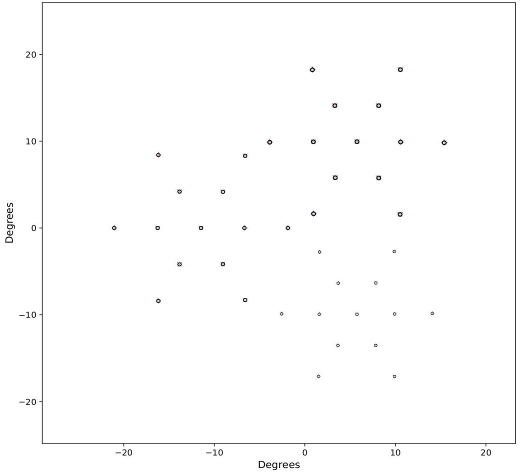
MFT



HFT







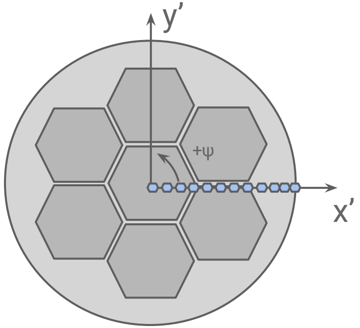
P2.1 Setup: beam

- 12 beam maps for each of the MFT band

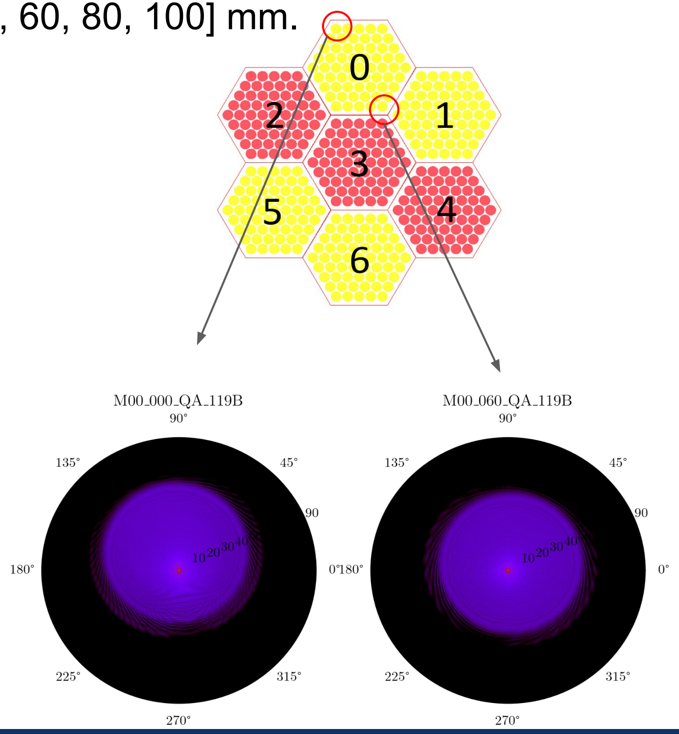
radial coordinate of r = [0, 20, 40, 60, 80, 100, 120, 140, 160, 170, 175, 180] mm

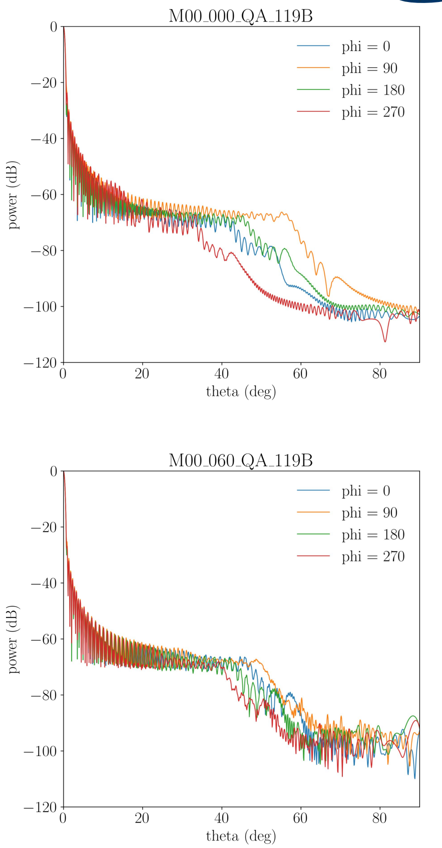
- 6 beam maps for each of the HFT band

radial coordinate of r = [0, 20, 40, 60, 80, 100] mm.



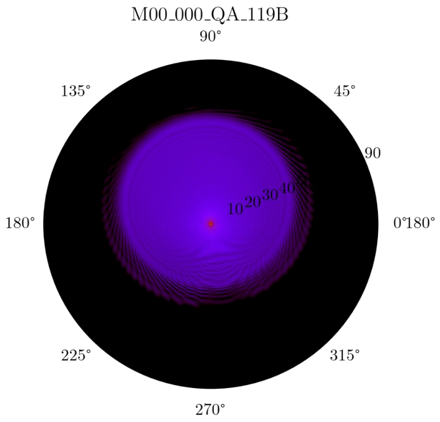
View from sky
down to FPU (MFT)
Image credit: Jon

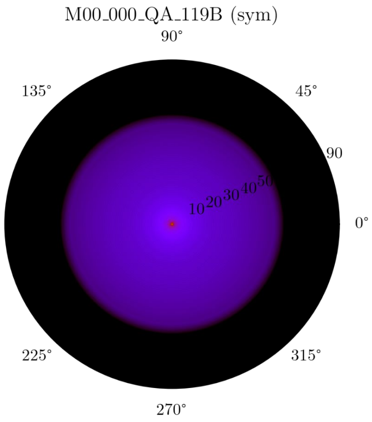


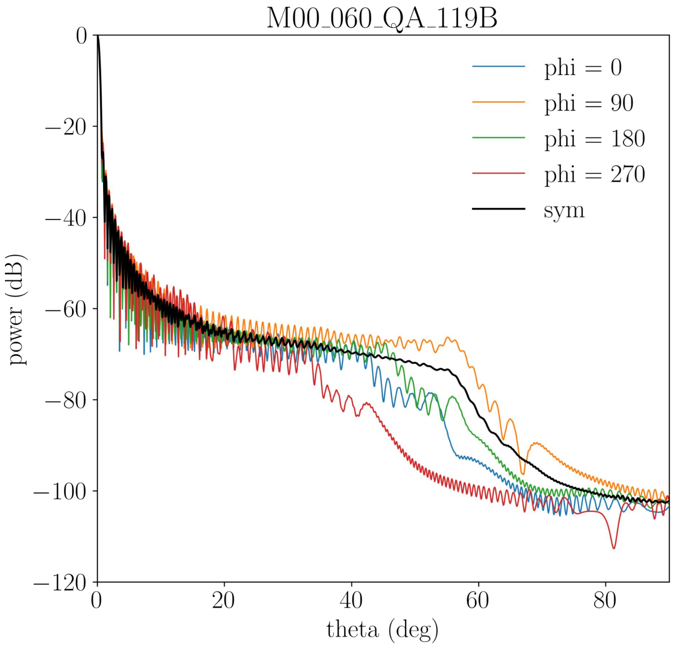


P2.1 Setup: beam

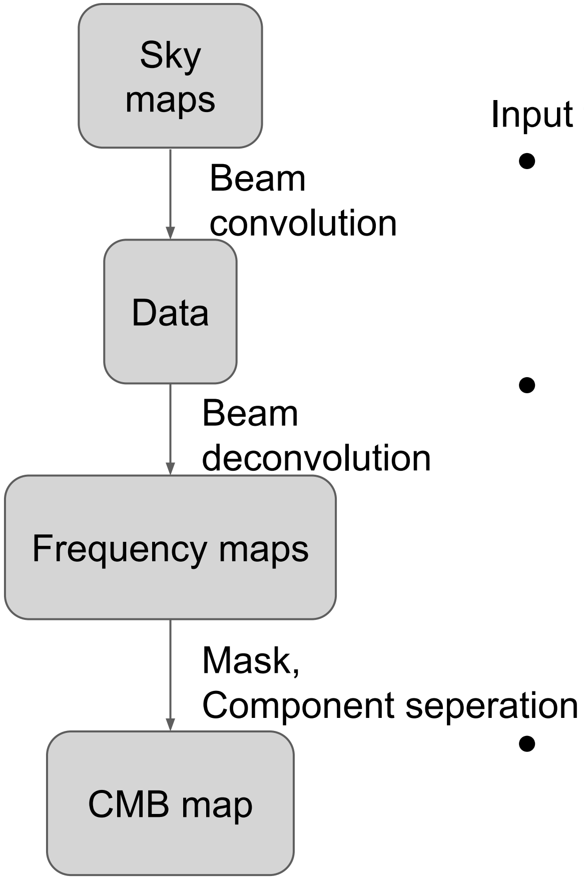
- the beam employed for the convolution of the polarization signals Q and U is assumed to be the same as the one adopted for unpolarized part of the signal
- Libconviqt: spinning HWP included





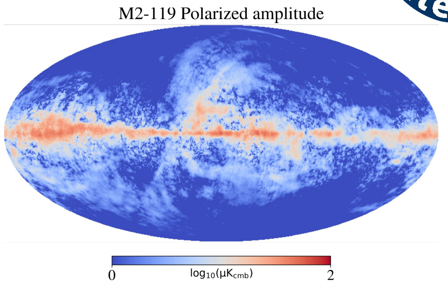


P2.1 Setup: Pipeline for analysis

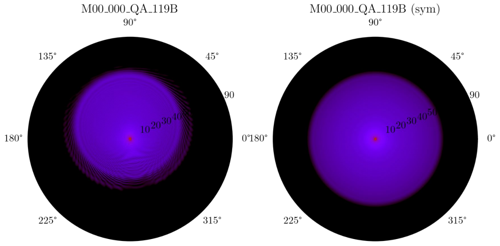


Input for TOAST

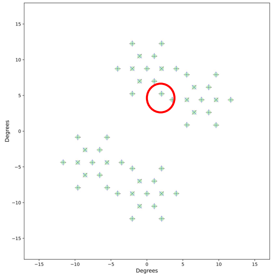
- Sky maps: d0s0, healpy.map2alm
  alm, lmax = 1536, mmax = 1536



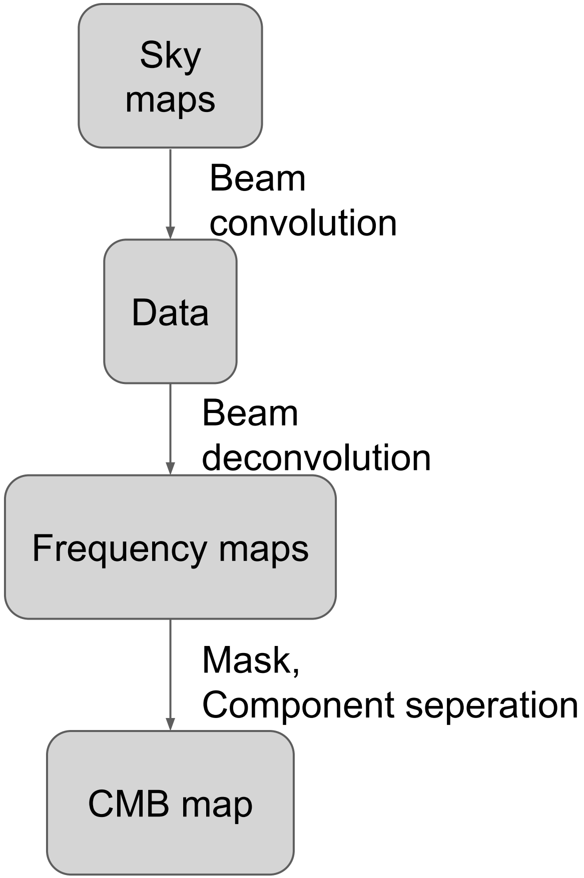
- Beam: LevelS.beam2blm
  blm, lmax = 1024, mmax = 140
  Asymmetric and symmetrized beam



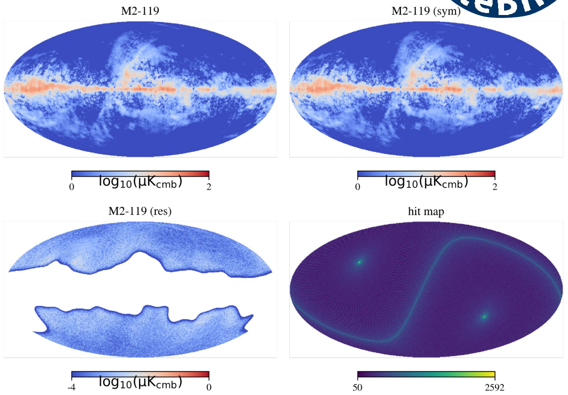
- Focalplane: TOAST-litebird
  The nearest detector to the center



P2.1 Setup: Pipeline for analysis



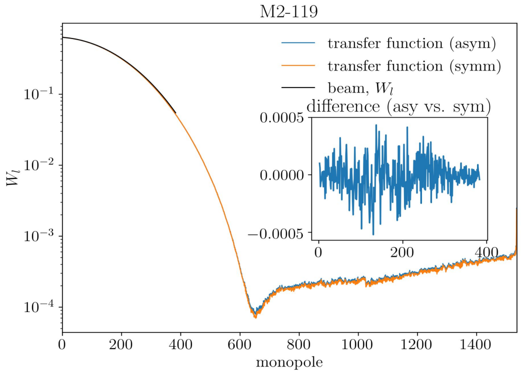
- Mask:
  Planck HFI Galactic mask, 60%



- Transfer function:
  Window function for symmetrized beam B mode

$$W_{\ell,\mathrm{eff}} = \sqrt{\frac{C_\ell^{\mathrm{sym}}}{C_\ell^{\mathrm{sky}}}}$$

Here we use a truncated a_{lm} in the following analysis. (lmax = 383)



- Component separation:
  Fgbuster in pixel domain

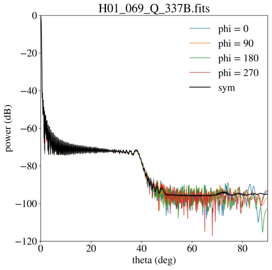
P2.1 Intermediate results

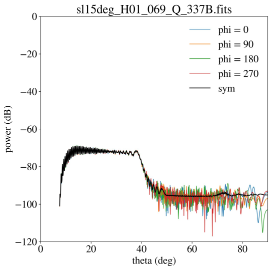
The output map of full beam and fsl [15, 90] (biggest bias channel) (beam file at center)

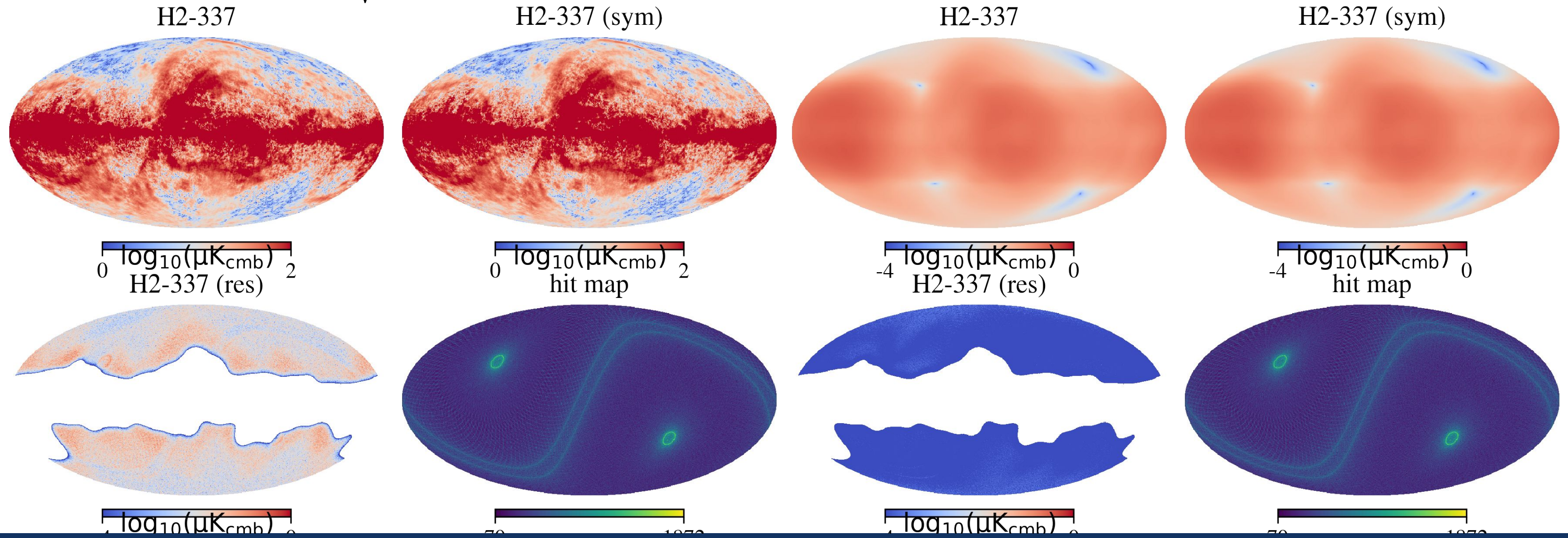
As we expect to calibrate main beam and near sidelobe to a good precision, the bias from beam asymmetry may main on the far sidelobes.

$$\text{polarization amplitude} = \sqrt{Q^2 + U^2}$$

$$\text{res} = \sqrt{(\Delta Q)^2 + (\Delta U)^2}$$

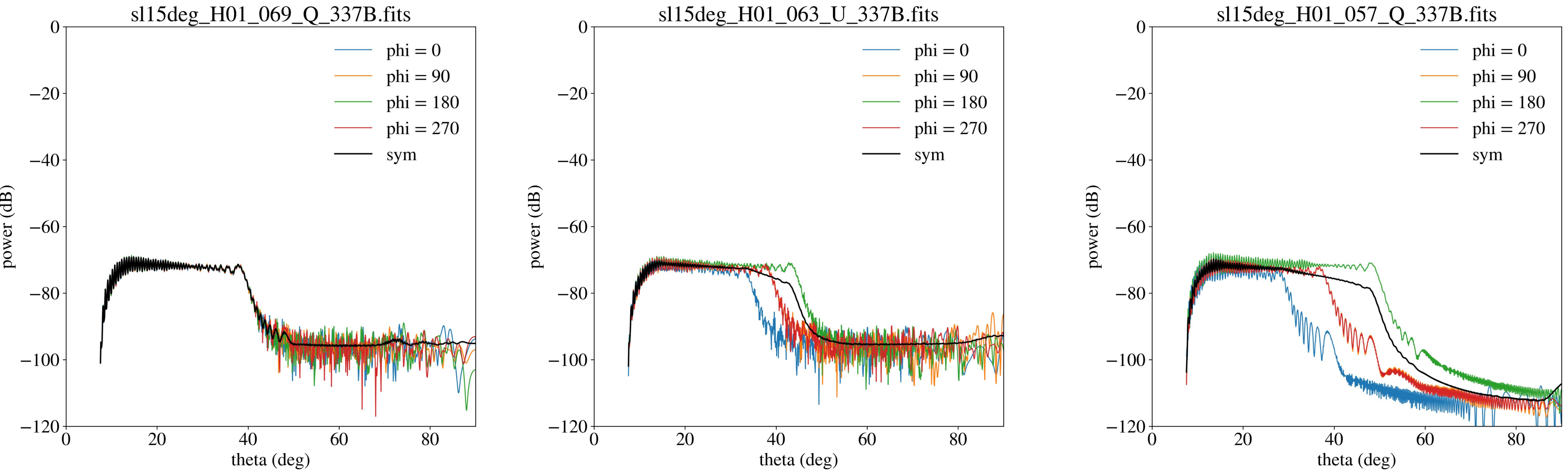






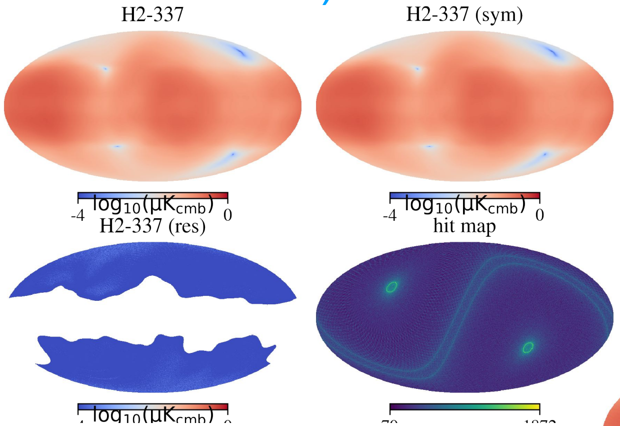
P2.1 Intermediate results

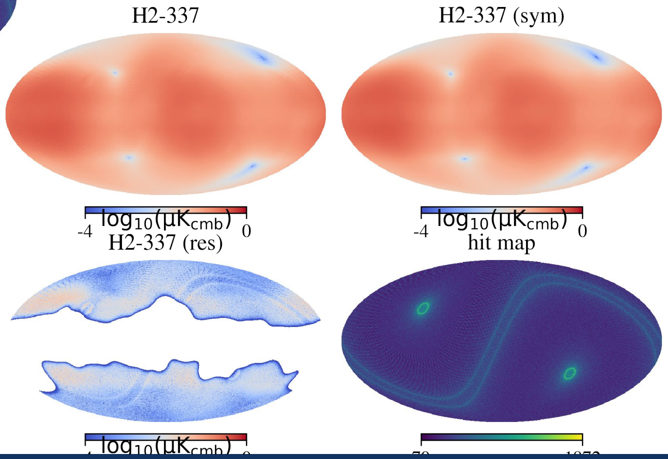
Beam fsl [15, 90] at center vs. middle vs. edge of focalplane (biggest bias channel)

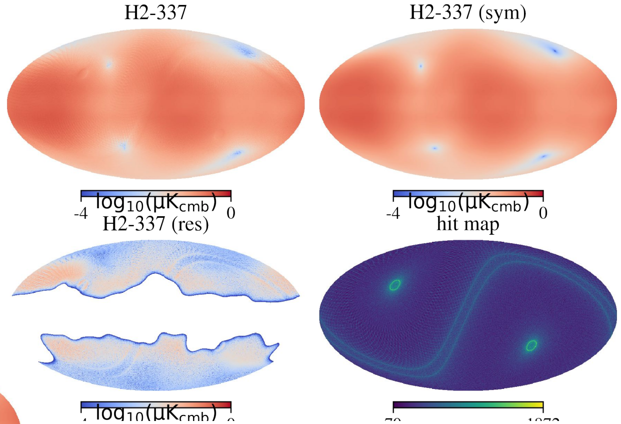


P2.1 Intermediate results

Observed maps at center vs. middle vs. edge of focalplane (fsl [15, 90]) (biggest bias channel)







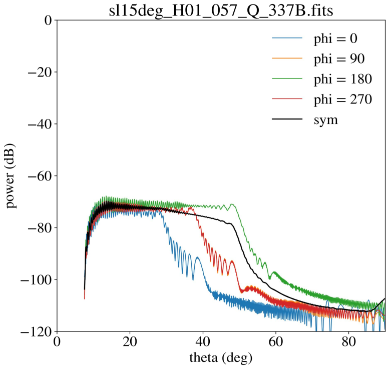
P2.1 Intermediate results

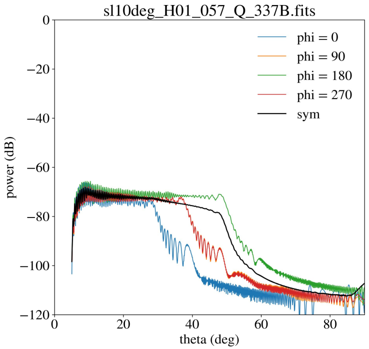
δr at center vs. middle vs. edge of beam file (fsl [15, 90])

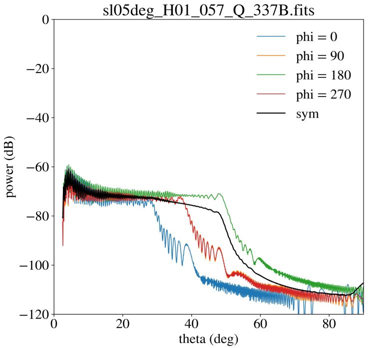
beam	δr			beam	δr		
	center	middle	edge		center	middle	edge
L1-040	3.18e-10	2.38e-10	3.78e-10	M1-100	1.83e-11	6.72e-09	5.95e-08
L2-050	2.05e-11	3.01e-11	4.07e-11	M2-119	1.42e-08	2.58e-08	9.74e-08
L1-060	<1.00e-11	<1.00e-11	2.10e-11	M1-140	1.90e-11	3.13e-08	2.43e-07
L3-068	7.42e-11	5.76e-11	6.82e-11	M2-166	8.41e-08	8.80e-08	1.68e-07
L2-068	<1.00e-11	1.71e-11	<1.00e-11	M1-195	<1.00e-11	2.31e-07	1.83e-06
L4-078	<1.00e-11	1.20e-11	<1.00e-11	H1-195	9.65e-10	1.60e-08	1.03e-07
L1-078	<1.00e-11	<1.00e-11	<1.00e-11	H2-235	1.53e-10	1.54e-07	5.10e-07
L3-089	7.77e-11	8.84e-11	1.21e-10	H1-280	<1.00e-11	8.22e-09	4.52e-08
L2-089	<1.00e-11	<1.00e-11	<1.00e-11	H2-337	5.04e-10	2.63e-06	8.74e-06
L4-100	3.82e-11	3.59e-11	2.50e-10	H3-402	<1.00e-11	9.67e-07	2.83e-06
L3-119	1.97e-10	1.98e-10	2.50e-10				
L4-140	3.45e-11	3.35e-11	2.93e-11				

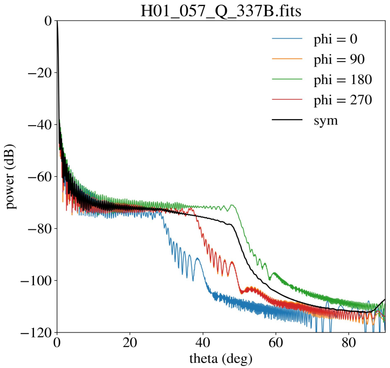
P2.1 Intermediate results

Beam maps at fsl [15, 90] vs. fsl [10, 90] vs. fsl [5, 90] vs. full beam at edge of FP



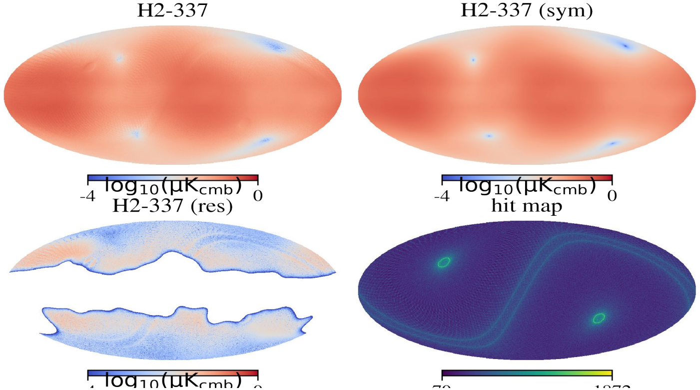


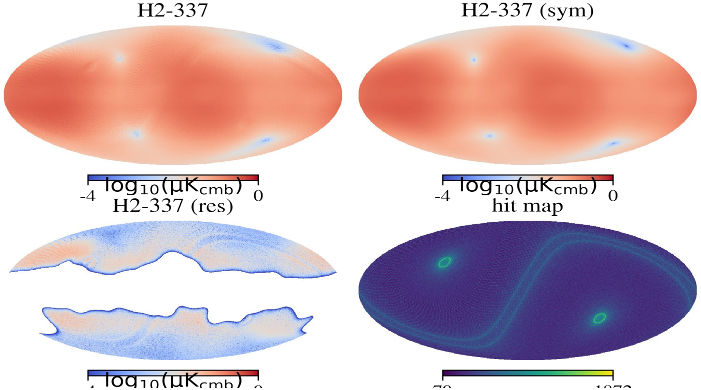


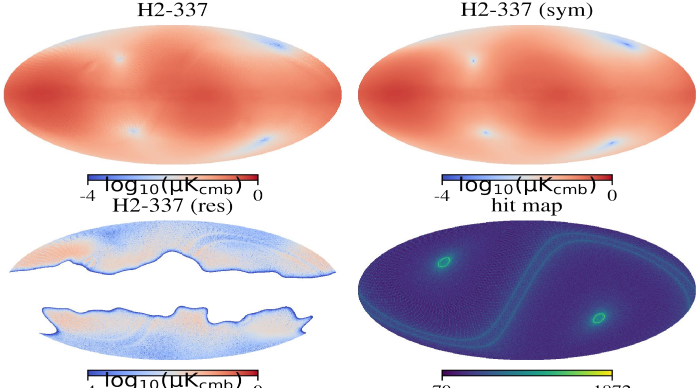


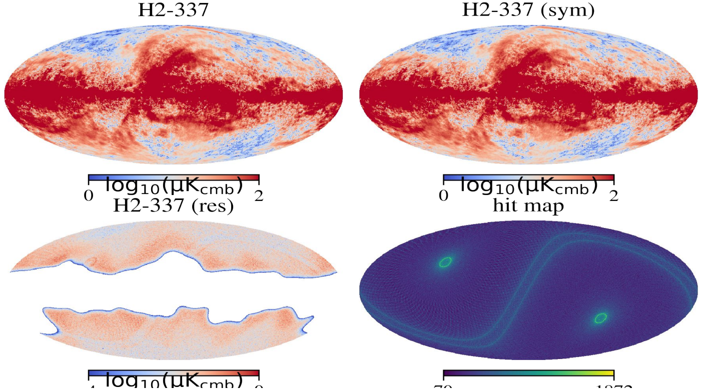
P2.1 Intermediate results

Observed maps at fsl [15, 90] vs. fsl [10, 90] vs. fsl [5, 90] vs. full beam at edge of FP









P2.1 Intermediate results

δr at fsl [15, 90] vs. fsl [10, 90] vs. fsl [5, 90] vs. full beam for edge beam file

beam	δr				beam	δr			
	[15, 90]	[10, 90]	[5, 90]	Full		[15, 90]	[10, 90]	[5, 90]	Full
L1-040	3.78e-10	5.58e-10	1.26e-09	6.55e-08	M1-100	5.95e-08	5.89e-08	5.94e-08	7.83e-08
L2-050	4.07e-11	7.22e-11	1.66e-10	4.47e-10	M2-119	9.74e-08	9.85e-08	1.00e-07	1.57e-07
L1-060	2.10e-11	2.31e-11	7.95e-11	6.72e-10	M1-140	2.43e-07	2.45e-07	2.47e-07	3.24e-07
L3-068	6.82e-11	1.48e-10	3.04e-10	7.63e-10	M2-166	1.68e-07	1.69e-07	1.69e-07	2.85e-07
L2-068	<1.00e-11	<1.00e-11	<1.00e-11	1.58e-10	M1-195	1.83e-06	1.84e-06	1.85e-06	4.51e-06
L4-078	<1.00e-11	4.21e-11	9.63e-11	2.36e-10	H1-195	1.03e-07	1.05e-07	1.08e-07	1.43e-07
L1-078	<1.00e-11	<1.00e-11	<1.00e-11	<1.00e-11	H2-235	5.10e-07	5.18e-07	5.31e-07	9.52e-07
L3-089	1.21e-10	2.00e-10	2.83e-10	6.64e-10	H1-280	4.52e-08	4.56e-08	4.62e-08	7.91e-08
L2-089	<1.00e-11	<1.00e-11	<1.00e-11	6.15e-11	H2-337	8.74e-06	8.82e-06	8.88e-06	1.85e-05
L4-100	2.50e-10	1.16e-10	2.83e-10	2.93e-10	H3-402	2.83e-06	2.85e-06	2.86e-06	4.41e-06
L3-119	2.50e-10	3.96e-10	5.72e-10	4.89e-09					
L4-140	2.93e-11	2.50e-11	4.13e-11	8.01e-09					

P2.1 Parameterization of asymmetry(R)

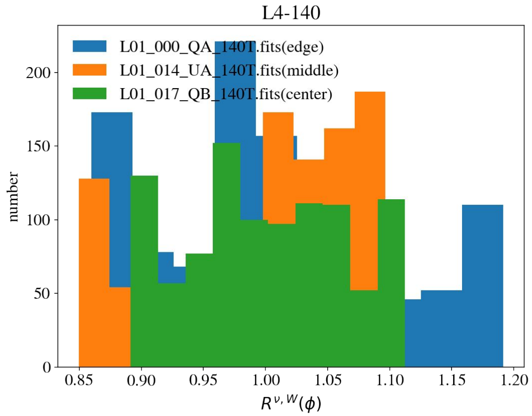
Read B(θ, φ) of the given beam and calculate the beam power $R^{\nu,W}(\varphi)$ for each direction φ in a given angular range W.

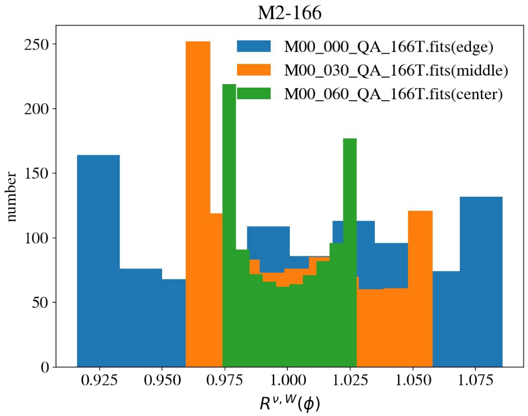
$$R^{\nu,W}(\phi) \equiv \frac{\int B^{\nu,W}(\theta,\phi)\, W(\theta)\, 2\pi \sin\theta d\theta}{\int \overline{B_0^{\nu}}(\theta)\, d\Omega}.$$

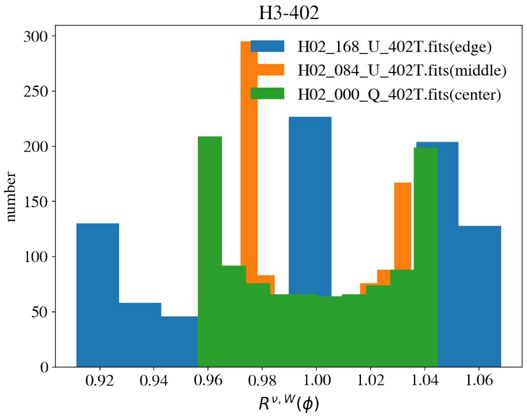
Here I have calculated 4 W ranges: full beam, [5, 90], [10, 90], [15, 90].
And I calculate the average beam power $\overline{R^{\nu,W}}$ for the corresponding symmetrized beam.
Attempt: we use the standard deviation of R for the degree of asymmetry

$$\mathrm{da}^{W} \equiv \sigma_{R^{W}} = \sqrt{\frac{\sum_{\phi}\left(R^{\nu,W}(\phi) - \overline{R^{\nu,W}}\right)^2}{N_{\phi} - 1}}$$

Full beam:



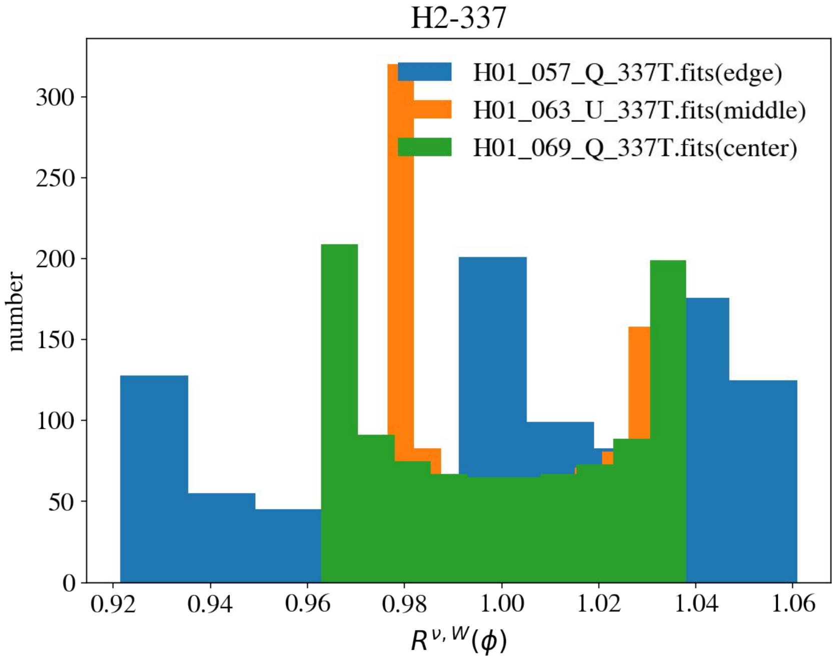




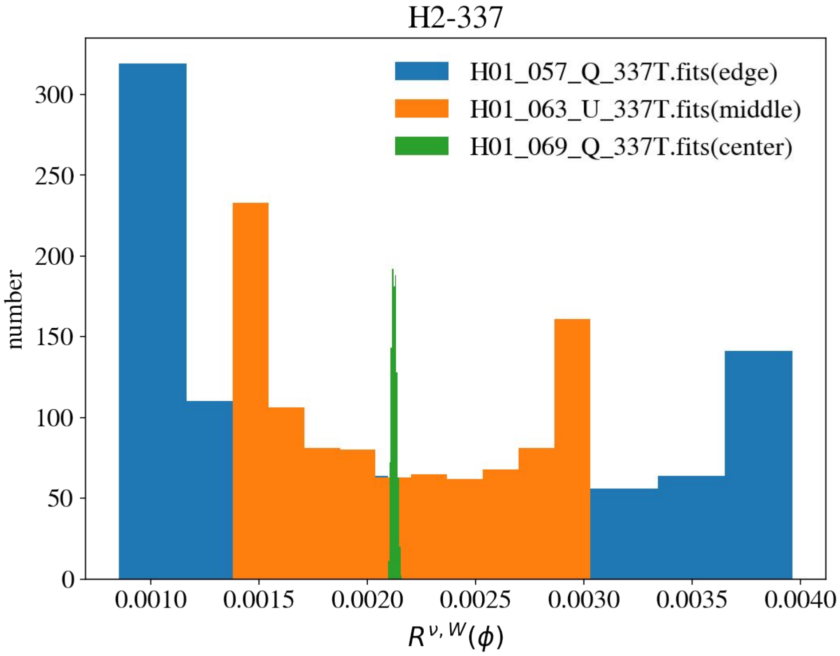
P2.1 Parameterization of asymmetry(R)

Full beam vs. the [5,90]deg far sidelobes:
The main beam of the beam profile at the center has higher degree of asymmetry

Full beam:

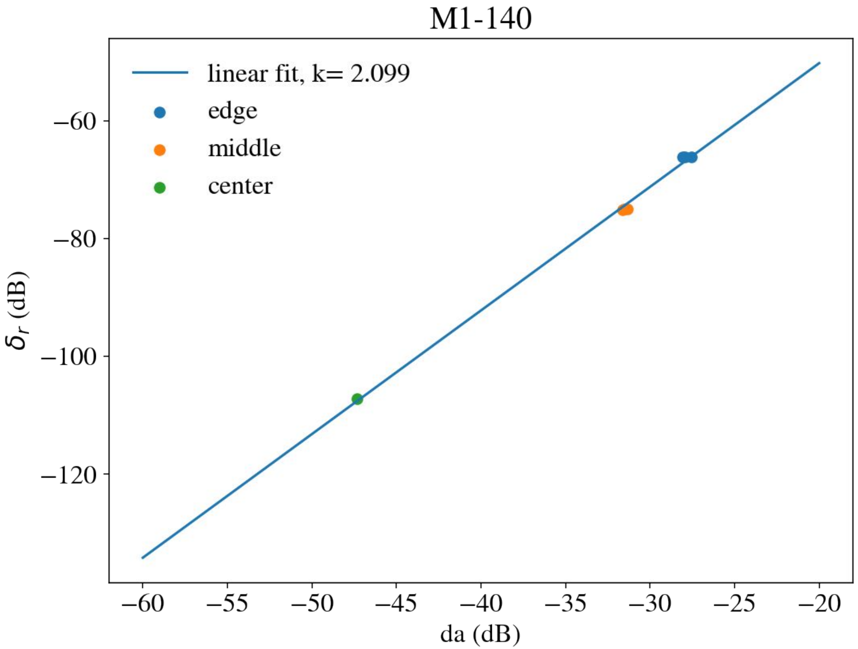


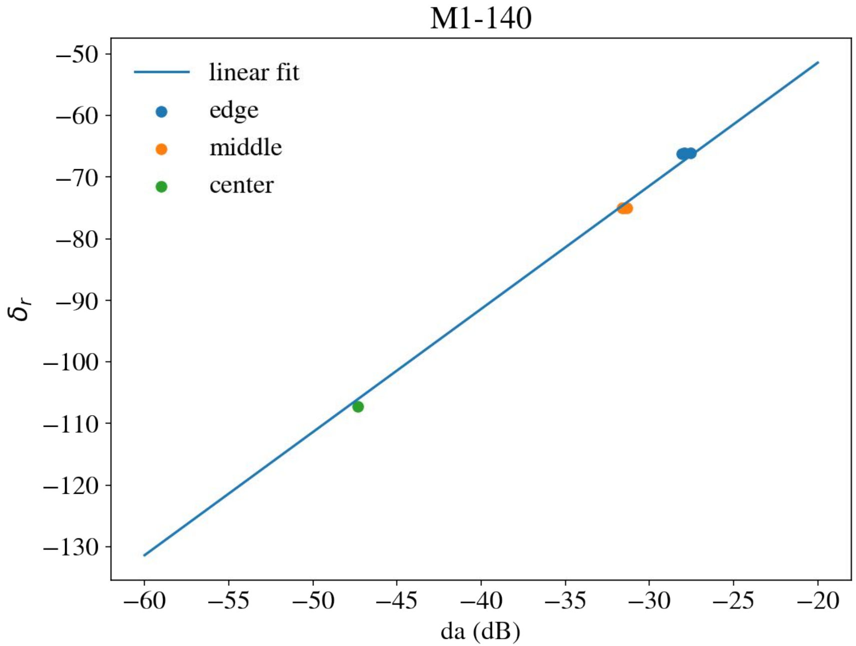
[5, 90]deg far sidelobes:



P2.1 Parameterization of asymmetry(R)

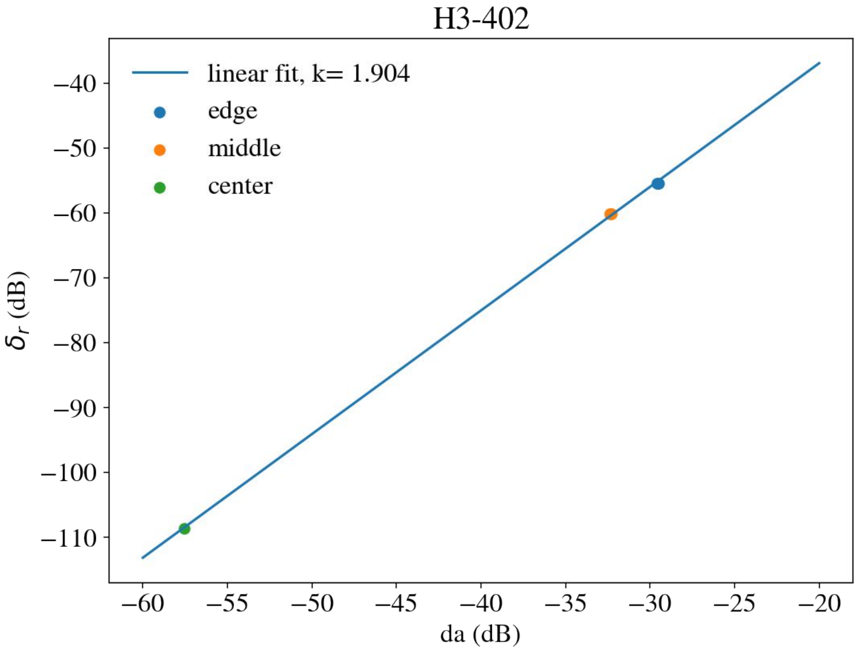
Degree of asymmetry — δr:
For quadratic relation k=2.000

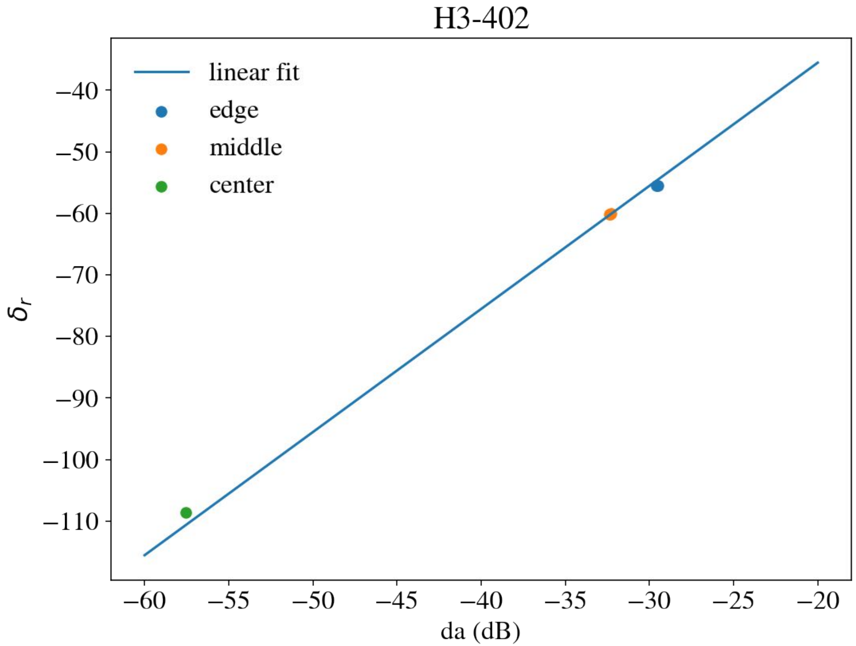




P2.1 Parameterization of asymmetry(R)

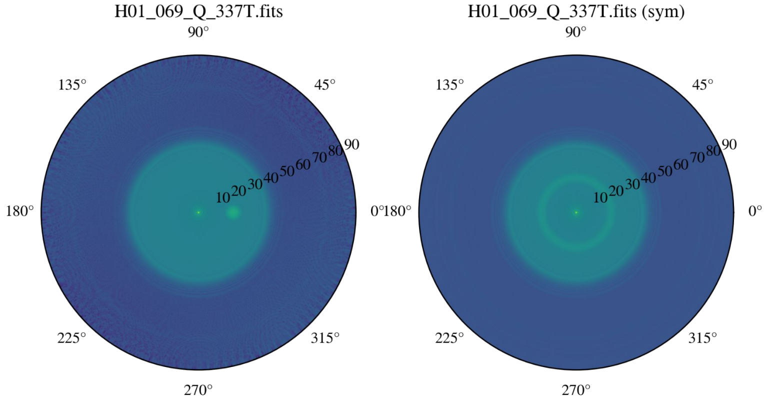
Degree of asymmetry — δr:
For quadratic relation k=2.000

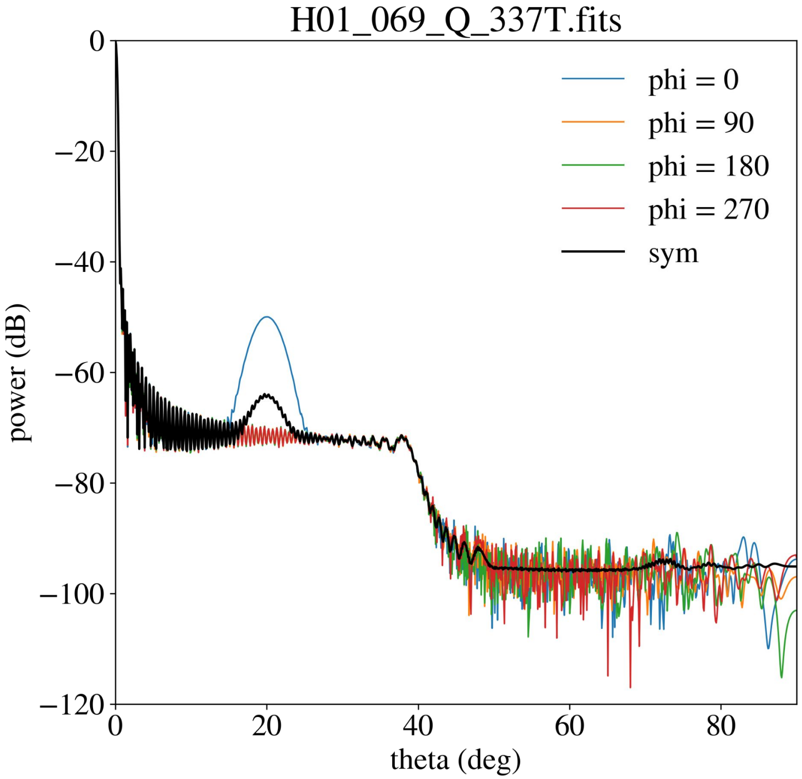




P2.1 Intermediate results (beam + bump)

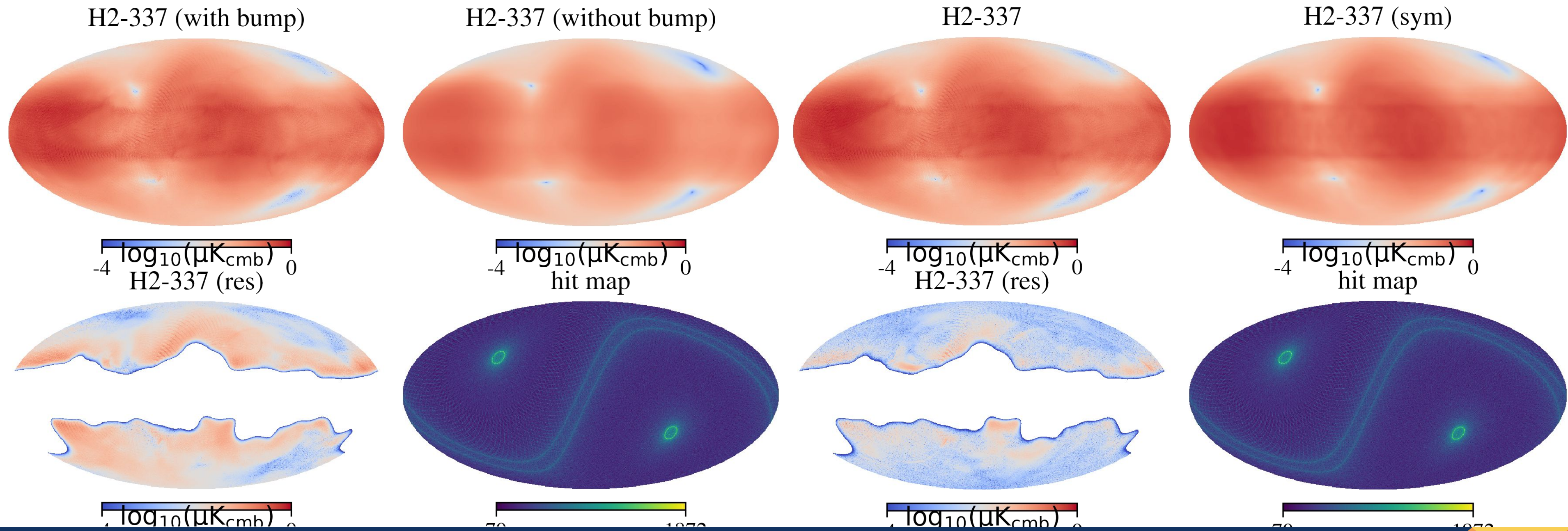
Center beam + Gaussian bump: a = -50dB, b = (20, 0)deg, FWHM = 5 deg





P2.1 Intermediate results (beam + bump)

Center beam + Gaussian bump: a = -50dB, b = (20, 0)deg, FWHM = 5 deg



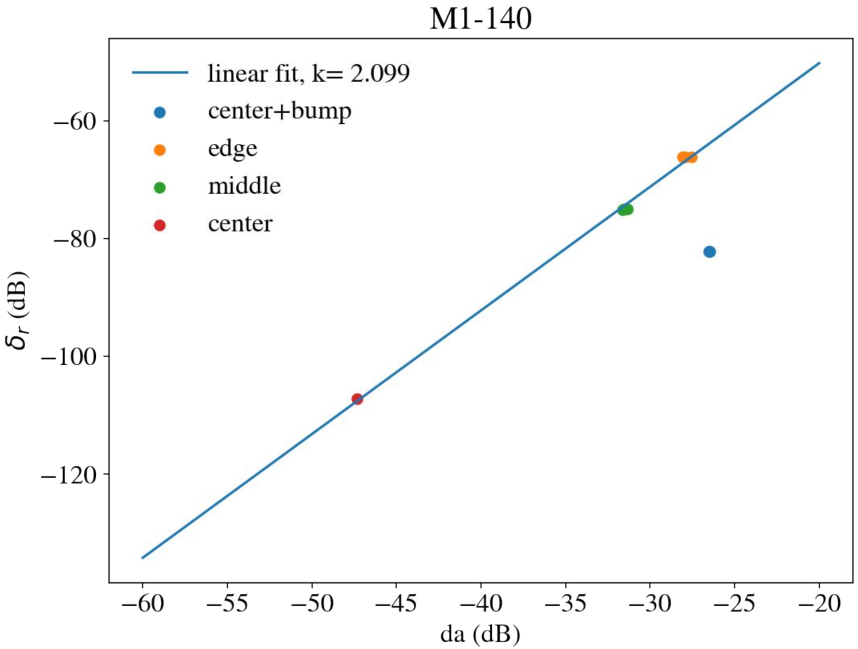
P2.1 Intermediate results (beam + bump)

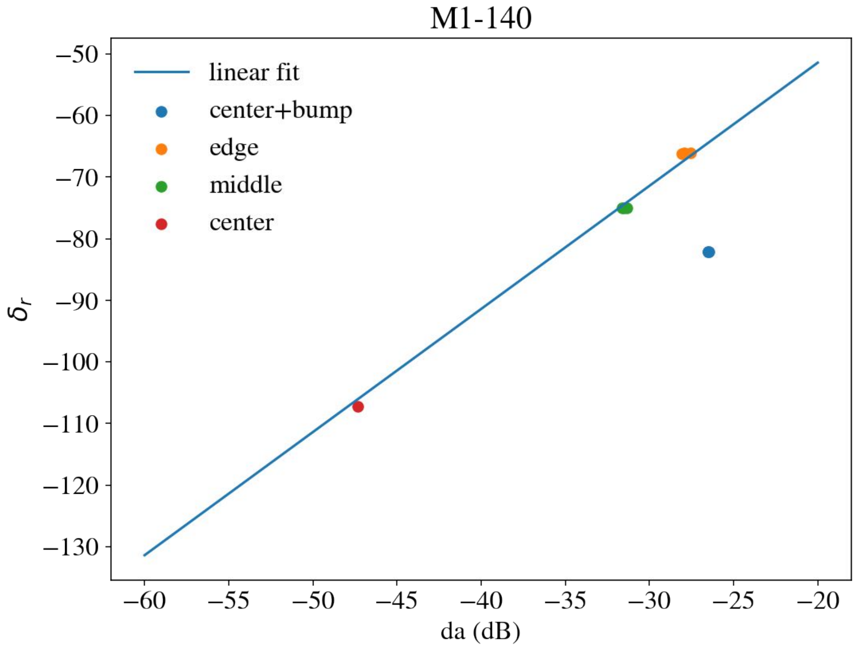
δr at fsl [15, 90] vs. fsl [10, 90] vs. fsl [5, 90] vs. full beam for center beam + bump profile

beam	δr				beam	δr			
	[15, 90]	[10, 90]	[5, 90]	Full		[15, 90]	[10, 90]	[5, 90]	Full
L1-040	3.00E-10	4.88E-10	8.25E-10	1.24E-08	M1-100	1.09E-09	1.09E-09	1.08E-09	3.72E-09
L2-050	2.90E-11	6.55E-11	1.59E-10	<1.00E-11	M2-119	3.88E-08	3.89E-08	3.92E-08	5.48E-08
L1-060	<1.00E-11	2.89E-11	2.56E-11	<1.00E-11	M1-140	6.17E-09	6.18E-09	6.17E-09	1.32E-08
L3-068	1.02E-10	1.51E-10	2.00E-10	7.04E-10	M2-166	2.36E-07	2.36E-07	2.36E-07	2.93E-07
L2-068	<1.00E-11	<1.00E-11	<1.00E-11	4.49E-11	M1-195	2.53E-07	2.53E-07	2.53E-07	5.56E-07
L4-078	6.00E-11	9.57E-11	1.40E-10	6.09E-10	H1-195	3.27E-08	3.28E-08	3.30E-08	5.37E-08
L1-078	1.26E-11	<1.00E-11	<1.00E-11	<1.00E-11	H2-235	2.38E-07	2.38E-07	2.37E-07	8.74E-08
L3-089	3.82E-10	4.49E-10	5.07E-10	1.03E-09	H1-280	1.61E-07	1.61E-07	1.61E-07	2.23E-07
L2-089	<1.00E-11	1.15E-11	<1.00E-11	1.11E-10	H2-337	1.20E-05	1.20E-05	1.20E-05	5.91E-06
L4-100	2.08E-09	2.28E-09	2.40E-09	9.04E-09	H3-402	1.14E-05	1.14E-05	1.14E-05	1.26E-05
L3-119	1.02E-08	1.07E-08	1.11E-08	2.20E-08					
L4-140	1.39E-08	1.40E-08	1.41E-08	2.64E-08					

P2.1 Parameterization of asymmetry(R)

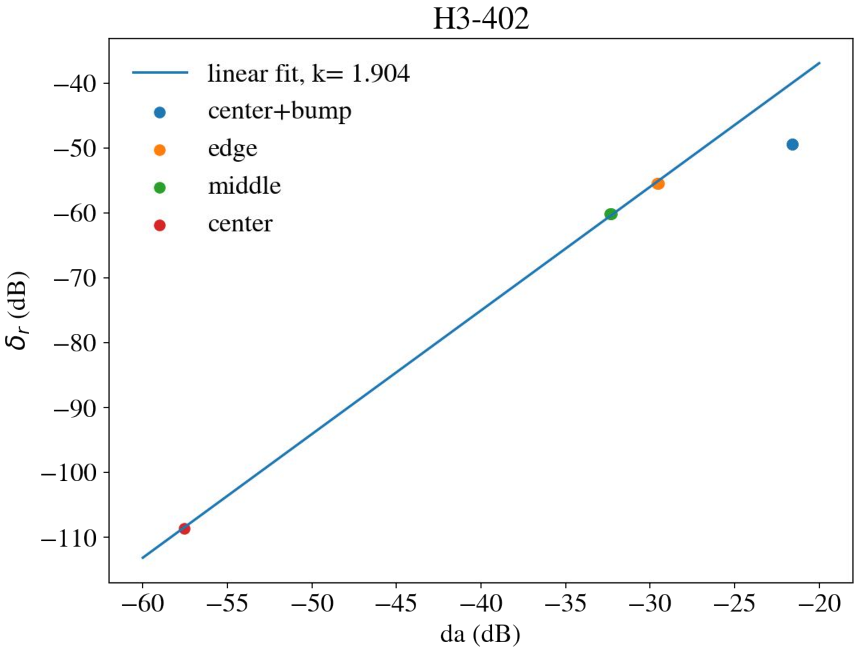
Degree of asymmetry — δr:
For quadratic relation k=2.000

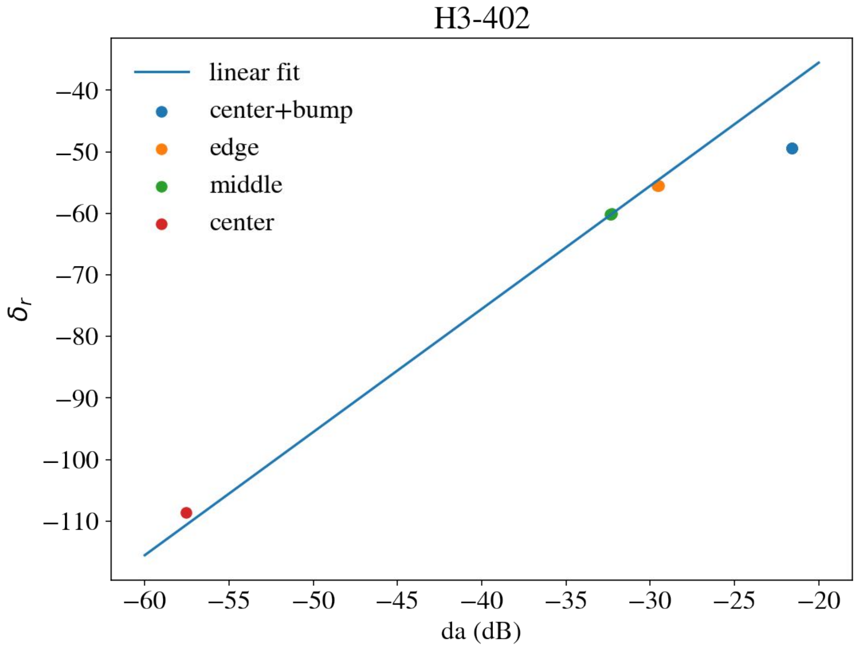




P2.1 Parameterization of asymmetry(R)

Degree of asymmetry — δr:
For quadratic relation k=2.000





P2.1 Scanning strategy and hit angle

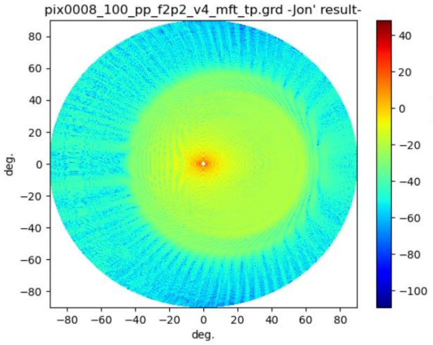
Yusuke 's idea: Calculate the effective beam (link). Lighter code compared to TOAST, TO DO:

1. make convolution check with TOAST.
2. Extend to multi-detectors

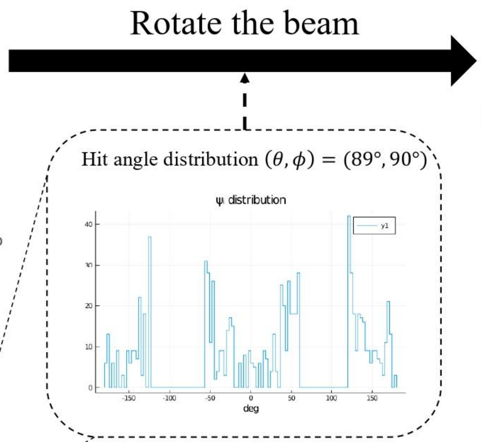
Yusuke's slide:

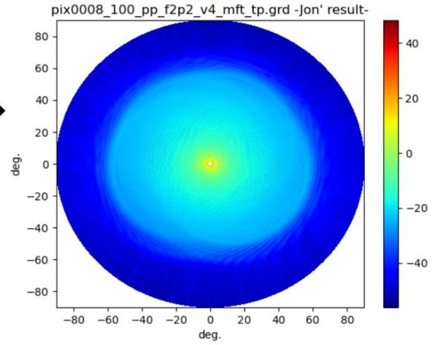
How to make effective beam

- Different scan directions cause the beam to rotate in the pixel, and as the observation progresses, it is symmetrized and can be viewed as an effective beam.



Original beam @ IMo





Symmetrized beam

	ψ_1	ψ_2	…	ψ_{hit}
$\theta = 90°$	50°	−120°	…	40°

From scan direction database at $\phi = 90°$

Side lobes are averaged!

Conclusion and future work

- Analysis pipeline under the assumption of symmetrization is built
  - Arbitrary beam shape can be tested
  - Requirement for calibration can be obtained given the calibration resolution

  conclusion:
  - Consistent value with two approach
  - The small structure of the beam is negligible.

  Further study with Clément et al.
  - The bias on δr not sentitive to the shape of perturbation
  - δr can be well characterized by only one parameter, the residual beam power between the "actual" beam and the model in far sidelobes

- Study of the beam asymmetry pipeline is under construction

  Conclusion:
  - An empirical power law relation is found between da of local beam and δr
  - Further study on effective beam is ongoing

- The current requirement on calibration is challenging to reach
  - Method of mitigating the effect of beam far sidelobes via data analyse pipeline is being study

P2.2 Beam modeling

Primary conclusion from Clément's study:

The cosmological parameter tensor-to-scalar ratio r is weakly dependent on the shape of the beam, and the bias on r can be well characterized by only one parameter, the residual beam power between the "actual" beam and the model in far sidelobes.

Assumptions:

- The effective beams of LiteBIRD are symmetrized by the scanning strategy and rotating half-wave plate
- the mismatch has the same shape as the far sidelobes.

Modeling:

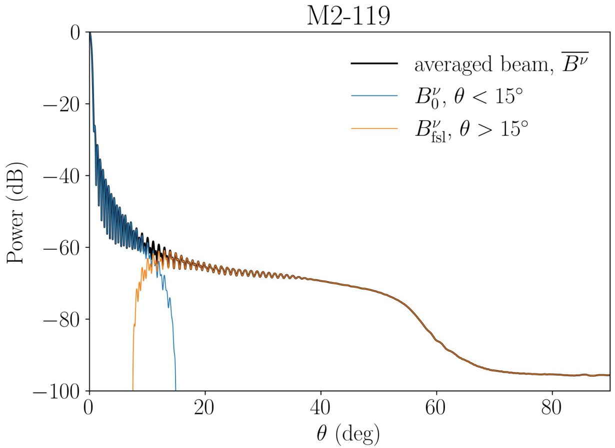
One parameter for each frequency band:

$$B^{\nu}_{\text{model}}(\theta) = B^{\nu}_{0}(\theta) + \alpha_{\nu} B^{\nu}_{\text{fsl}}(\theta).$$

The transfer function is:

$$b^{\nu}_{\ell} = b^{0,\nu}_{\ell} + \alpha_{\nu} b'^{\nu}_{\ell}$$

Plan: We will extend existing parametric component separation approach and include α.



P2.2 Future plan and challenge

With the asi-symmetric unpolarized beams, A signal measured in each pixel p is given by:

$$\boldsymbol{d}_p = \left[\boldsymbol{B}(\boldsymbol{\alpha}, \vec{r}) * \boldsymbol{A}(\boldsymbol{\beta})\boldsymbol{s}(\vec{r})\right]_p + \boldsymbol{n}_p.$$

Assuming the spectral parameters does not vary on the sky as a start.

Parameters in component separation:

- Beam: 22 αs from far sidelobes mismatch
- Foreground: spectral parameters and component amplitude

Spectral Likelihood with fgbuster aprroach:

$$-2\ln\mathcal{L}_{spec} = -\sum_{\ell,m} \boldsymbol{s}^{\dagger}_{\ell m}\mathcal{N}_\ell^{-1}\widetilde{\boldsymbol{A}}_{\ell m}\left(\widetilde{\boldsymbol{A}}^{\mathrm{T}}\mathcal{N}_\ell^{-1}\widetilde{\boldsymbol{A}}\right)^{-1}\widetilde{\boldsymbol{A}}^{\mathrm{T}}_{\ell m}\mathcal{N}_\ell^{-1}\boldsymbol{s}_{\ell m} + \sum_i \frac{(\alpha_i - \alpha^{\mathrm{calib}})^2}{(\sigma^{\mathrm{calib}})^2}.$$

A prior on α may be added to break the degeneracy.

THANK YOU