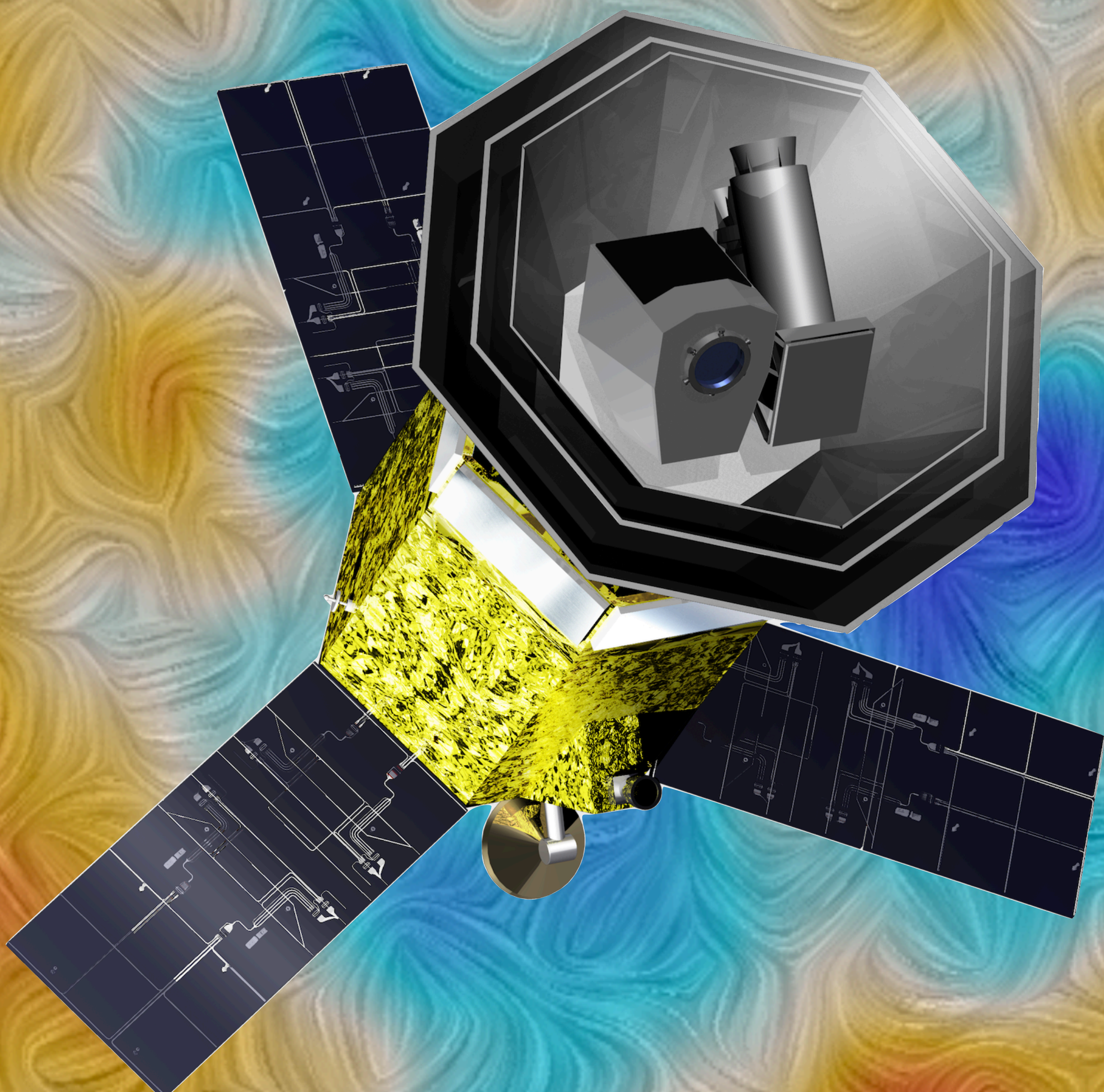


LiteBird Challenges II: Systematic effects

E. Hivon on behalf of
Systematics Joint Study Group

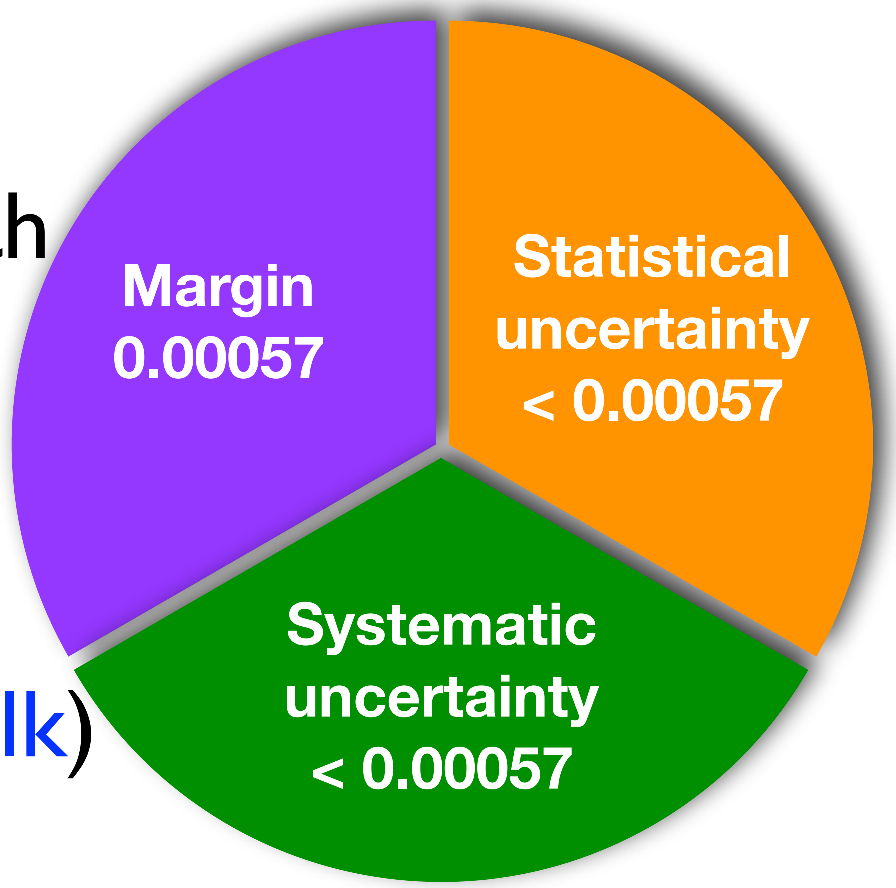
LiteBird error budget

- LiteBird designed to measure *r* at $\sigma(r) = 10^{-3}$ (68% CL) for full success with

  $$\sigma(r)^2 = \sigma^2_{\mathrm{syst.}} + \sigma^2_{\mathrm{stat.}} + \sigma^2_{\mathrm{margin}}$$

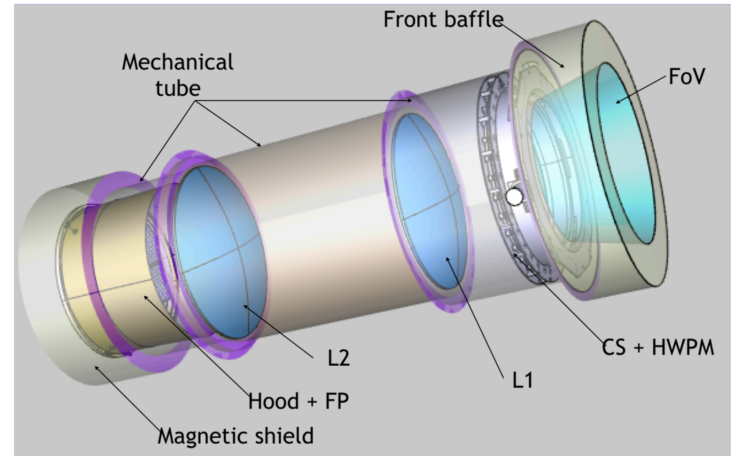
  $$\sigma_{\mathrm{syst.}} \sim \sigma_{\mathrm{stat.}} < \sigma_{\mathrm{margin}} = 0.577\ 10^{-3}$$

  σ_{stat} includes FG residuals (see Josquin's talk) + lensing + 1/f noise



- Each systematic effect must contribute at most $\delta_r < 0.01\ \sigma_{\mathrm{syst.}} = 5.77\ 10^{-6}$
  This sets the requirements on the instrument design and mitigation measures (Baptiste's talk, and this one), and calibration requirements (see Sophie's talk)

LiteBird Systematics



- More than 70 systematic effects in 14 categories, to name a few:
  - ✦ Refractive optics for MFT and HFT (reflective optics with LFT) → Flares and ghosts, will depend on lenses and inner tube AR coating
  - ✦ Beam measurements: outer planets scans during flight + pre-flight measurements? + simulations? → final accuracy of the beam knowledge ?
  - ✦ Side lobes → bias FG cleaning
  - ✦ Beam non-circularity + beam mismatch → leak T into Q&U, mitigated with rotating HWP and optimised scanning strategy
    - Impact of HWP ?
  - ✦ Band-passes → bias FG cleaning
  - ✦ Angle of polarisation (EE to BB leakage)
  - ✦ Stability of detectors, including gain stability
  - ✦ Polarisation efficiency
  - ✦ Sinuous antennas → Frequency dependent rotation of polarisation → E to B leakage mitigated via modelling and/or simulations ?

Scanning strategy

f_{samp} = 22Hz(?), T_{HWP} < 1s

β_{spin}= 50deg, T_{spin}= 20mn

$\alpha_{precess}$= 45deg, $T_{precess}$=1.51h(*)

(*): Thuong Hoang++, 2017

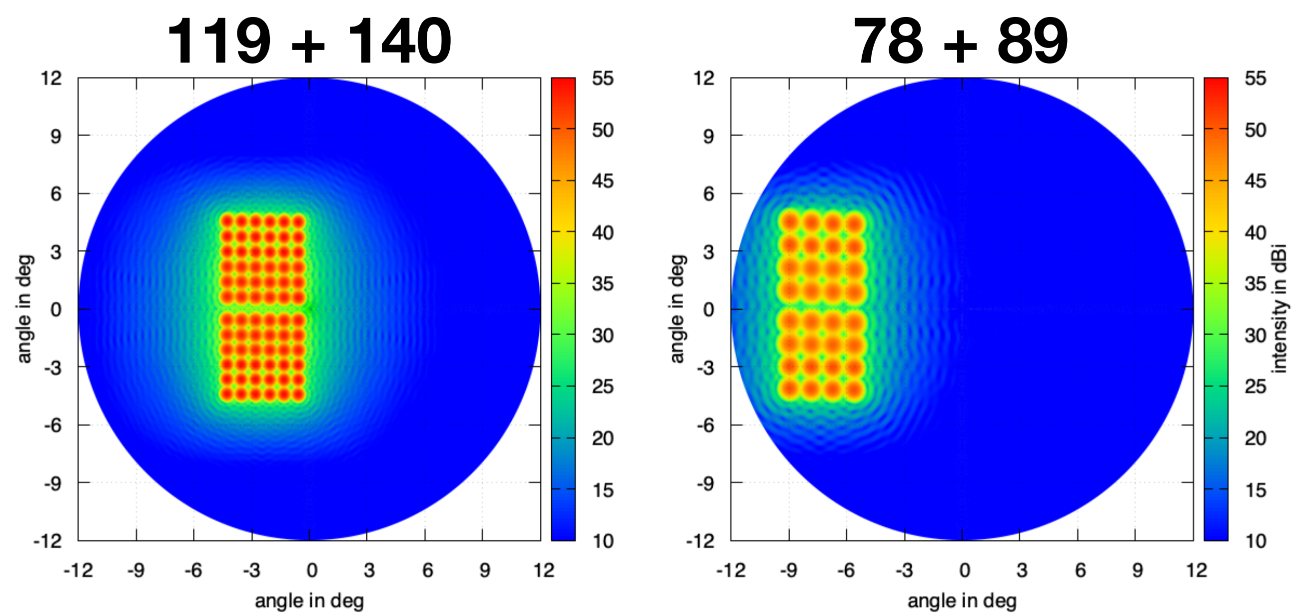
Beam simulations on going

- *3 focal planes, 4636 detectors, 19 channels @ 15 frequencies, $40 \leq \nu_0 \leq 402$GHz, $\Delta\nu/\nu_0 = 0.23$ or 0.3*

- Optical simulations, mostly using GRASP (with PO, MoM, …)

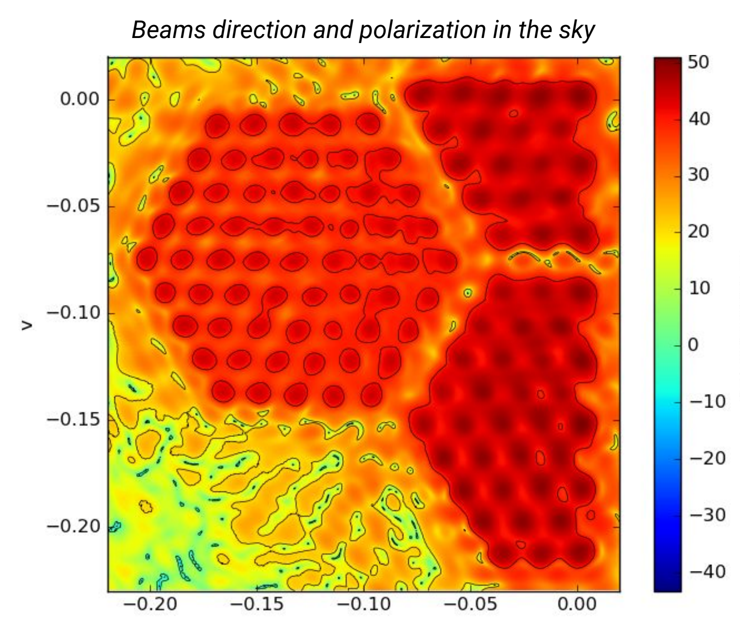
$70' \geq \theta_{FWHM} \geq 18'$

$1.004 \leq \theta_{Maj} / \theta_{min} \leq 1.02$



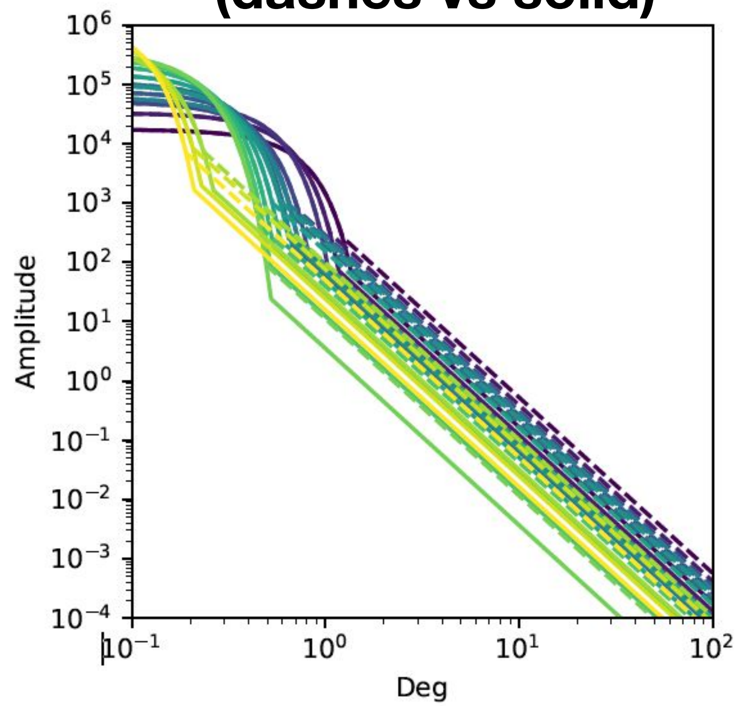
- ✦ LFT: H. Imada (LAL)

- ✦ MFT +HFT: J. Gudmundsson (SU) as of June 2019:
  - MFT: 12 pixels x 5 central frequencies
  - HFT: 6 pixels x 5 central frequencies

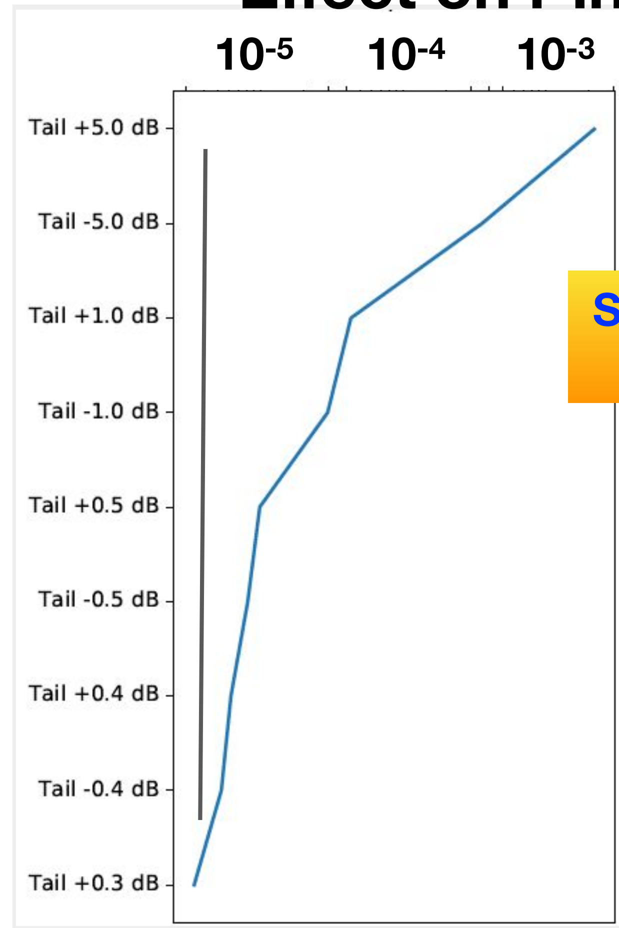


Beam knowledge

Mismatch in beam tail (dashes vs solid)



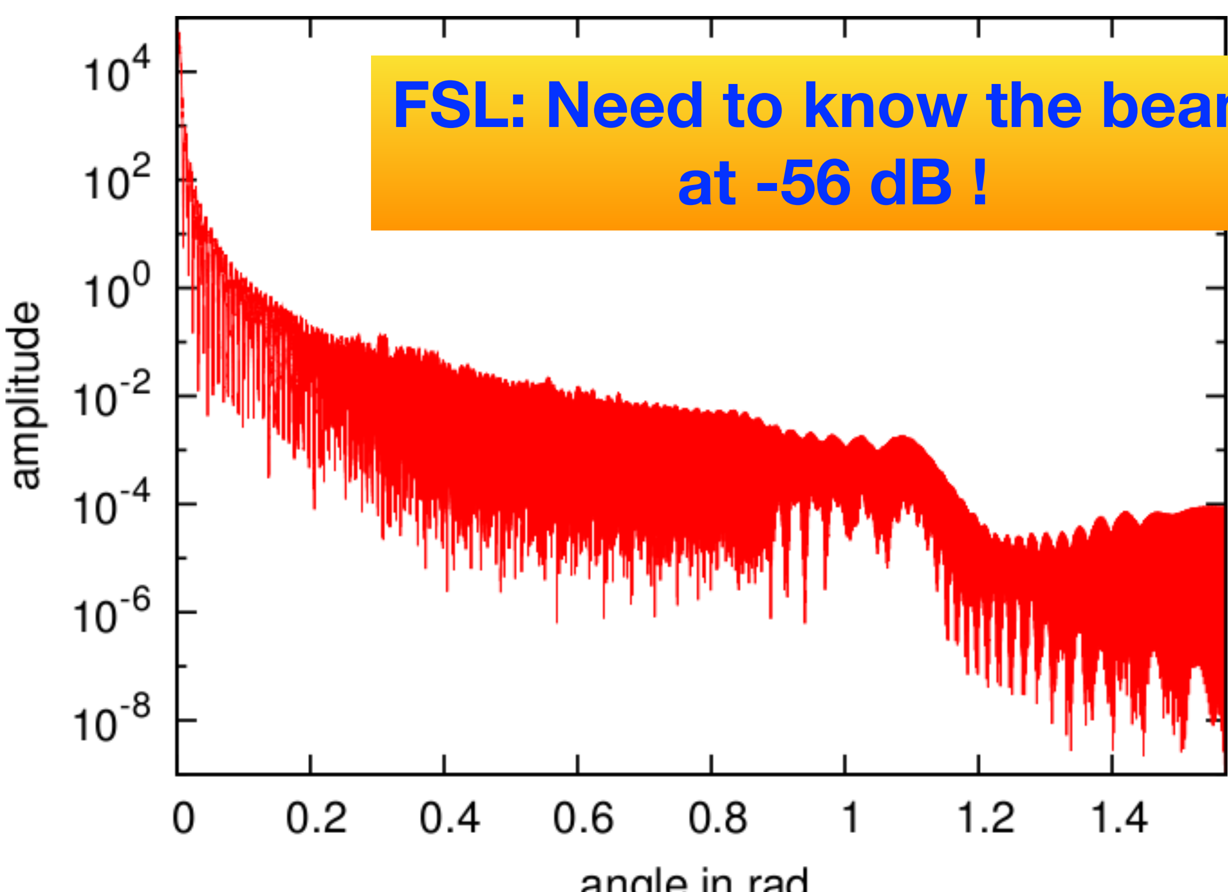
Effect on r in presence of foreground



SL:The regime between -20 and -35dB has to be known at < 10%

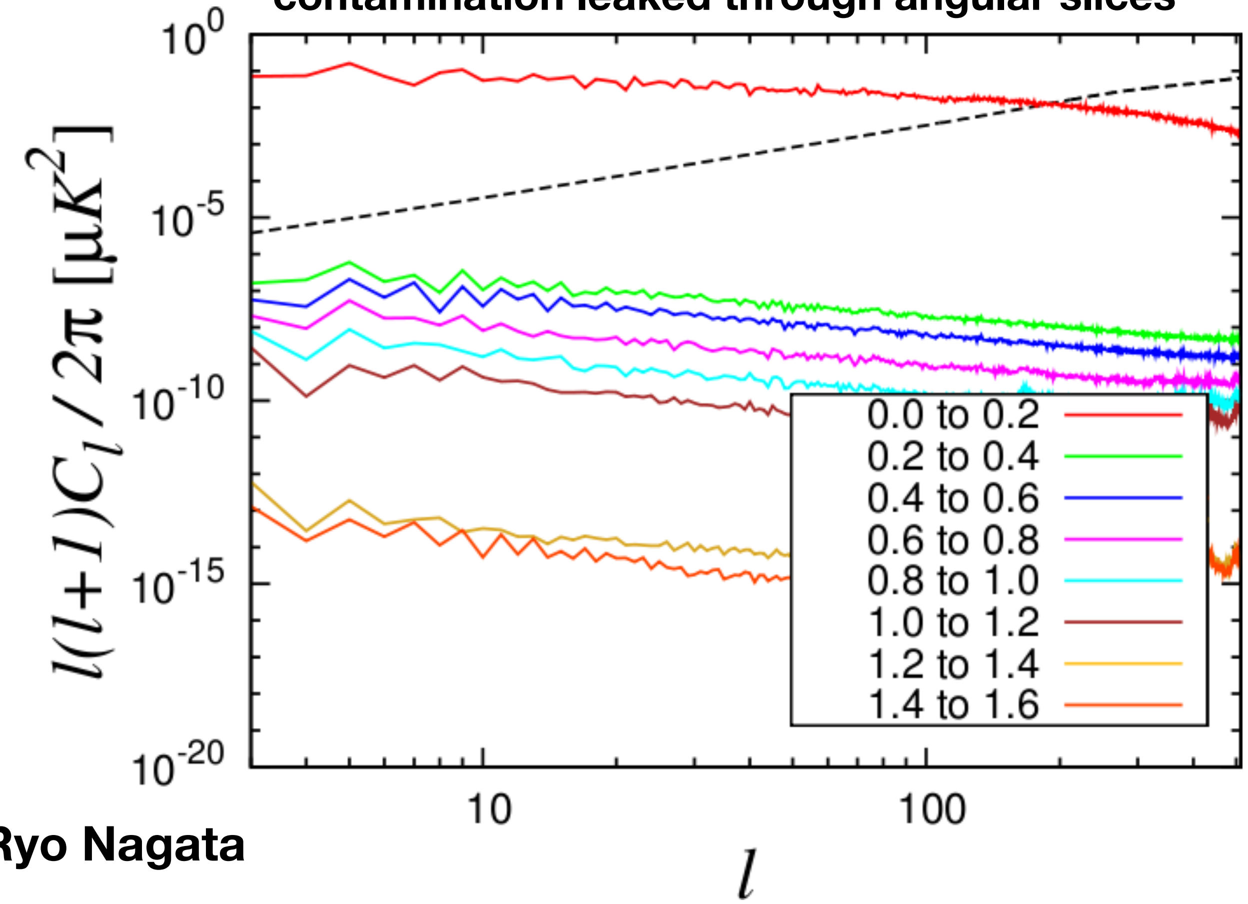
Done for CMB channels, to be checked at other frequencies

Beam radial profile at 100GHz

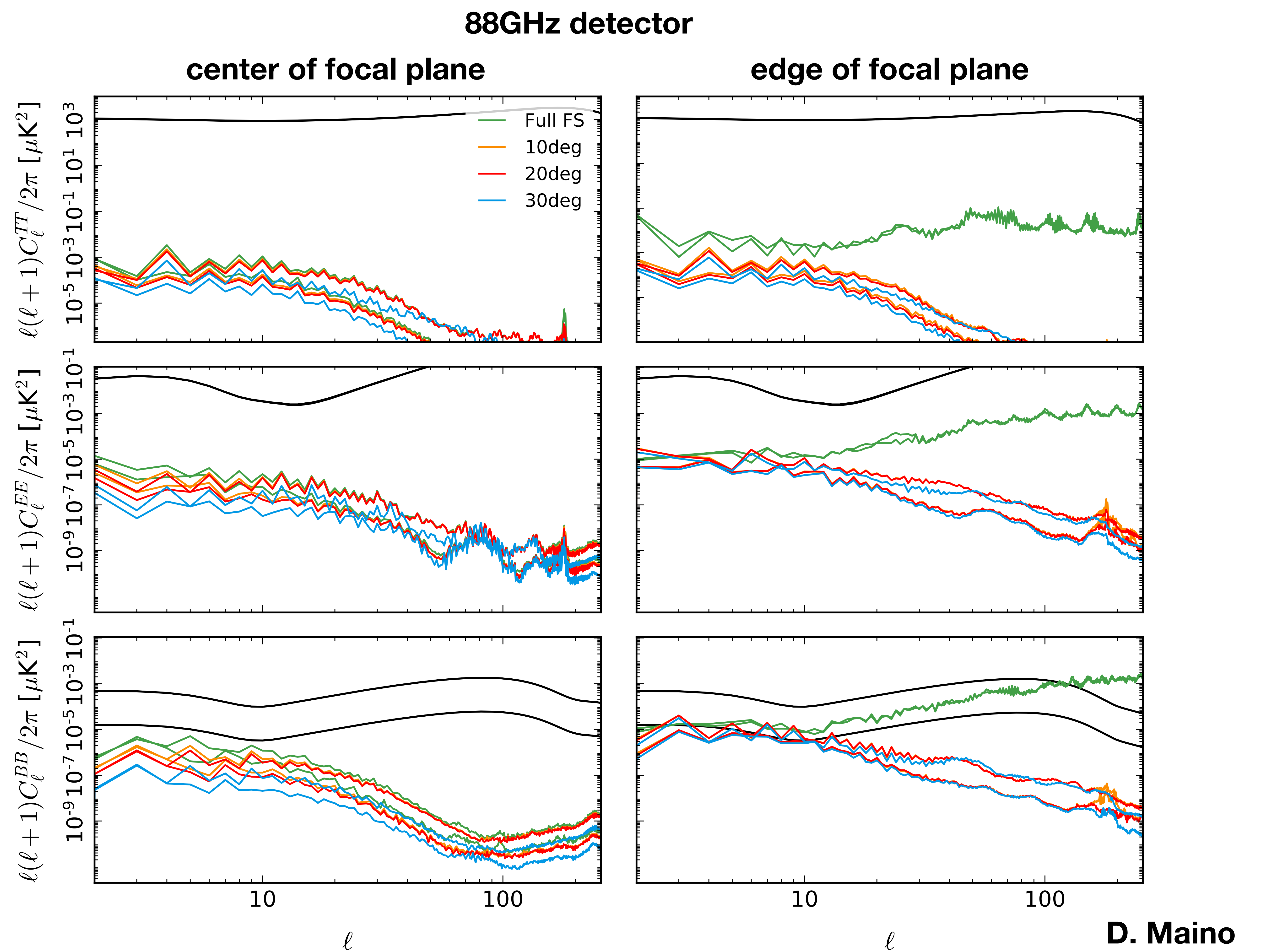


FSL: Need to know the beam at -56 dB !

Angular power spectra of 100GHz foreground contamination leaked through angular slices



Ryo Nagata



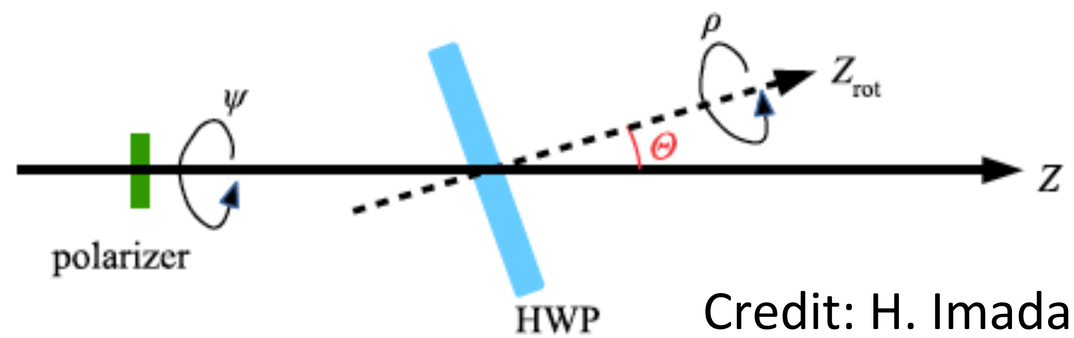
88GHz detector
center of focal plane
edge of focal plane
Full FS
10deg
20deg
30deg
$\ell(\ell+1)C_\ell^{TT}/2\pi$ [μK^2]
$\ell(\ell+1)C_\ell^{EE}/2\pi$ [μK^2]
$\ell(\ell+1)C_\ell^{BB}/2\pi$ [μK^2]
10
100
ℓ
D. Maino

Rotating Half Wave Plates: 1/3

- Half Waves Plates (HWP, made of birefringent material) rotating at f_{HWP} are used to modulate polarisation, allowing the full measurement of polarisation (*Q*&*U*) by a single detector
  - no need to differentiate detectors:
    → lesser sensitivity to detector mismatch, beam mismatch, beam elongation
    → lesser contamination of *B* by *I* and *E*
  - modulation of polarisation at 4 f_{HWP}
    → lesser sensitivity to low-frequency noises
  - …
- But refractive rHWP have downsides:
  - mobile pieces,
  - can be heavy → weight, thermal, microphonic problems
  - limit bandpass,
  - …
- Do rHWP create systematics of their own ?
  - only looking here at Instrumental Polarisation created by rHWP

Rotating Half Wave Plates: 2/3

- 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

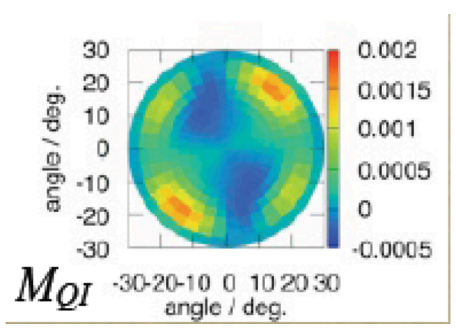
Tilted HWP to reduce reflexions and ghosts

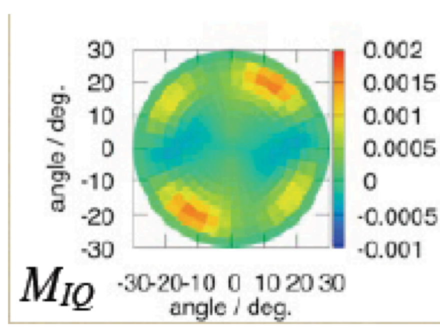
- Mueller matrix coefficients are estimated from the simulations. Decomposed in three terms:

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

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

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}





Credit: H. Imada

At 140 GHz, for $\Theta = 9^o$ (extreme case)

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

H. Imada & G. Patanchon

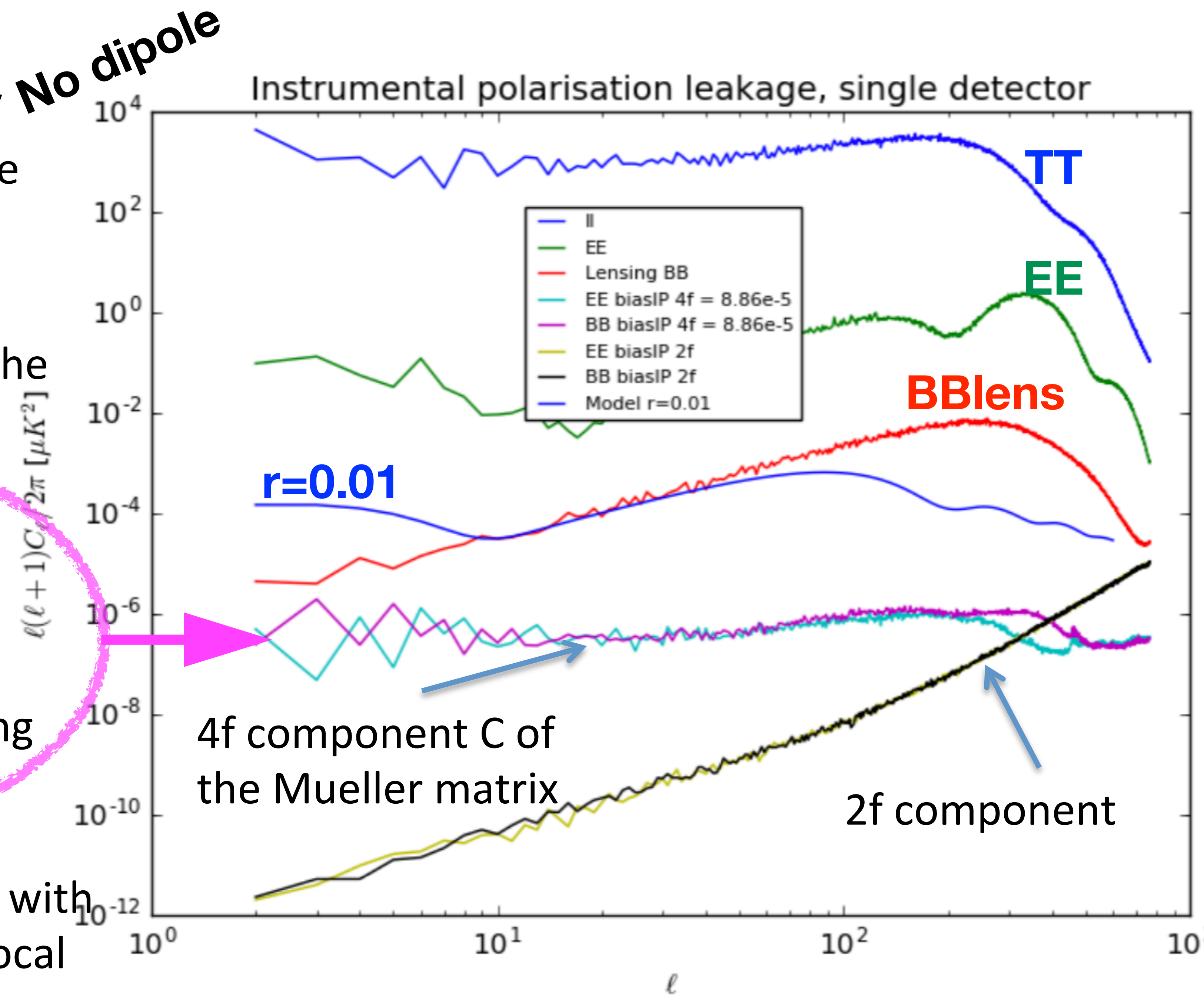
Rotating Half Wave Plates: 3/3

- Simulations with CMB only
- 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



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

H. Imada & G. Patanchon

Polarisation angles

- The component separation process mixes frequency maps (or power spectra) *and therefore systematics* with frequency dependent weights

  $$s(p) = \Sigma\, w_\nu\, d_\nu(p)$$

  For polarisation angle α, bias on r is $\delta_r \sim (\Sigma\, \alpha_\nu\, w_\nu)^2$

  The final impact will depend on the correlation of systematics across frequencies

For inverse variance weights

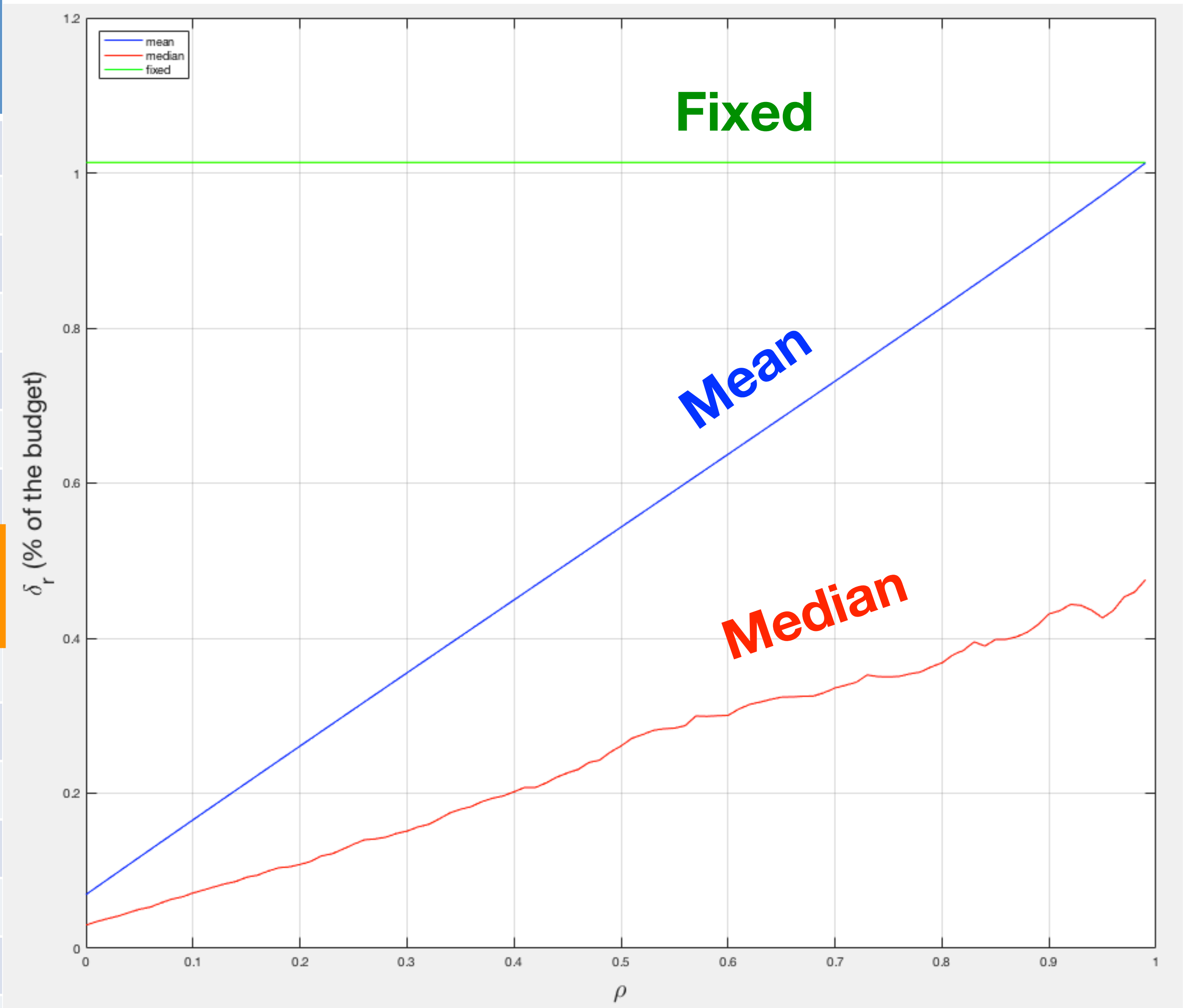
ν(GHz)	α [arcmin] Updated Table 4.8 from CDR
40	63.6469
50	26.7163
60	17.2348
68	6.5142
78	4.3463
89	3.2250
100	1.7644
119	0.8153
140	0.8818
166	1.2091
195	1.5080
235	4.8186
280	8.7949
337	20.2555
402	101.8234
δ_r (% sys.)	1.014

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

δ_r as a function of the correlation degree



P. Viela & E. Martinez-Gonzalez

Gains and Bandpasses

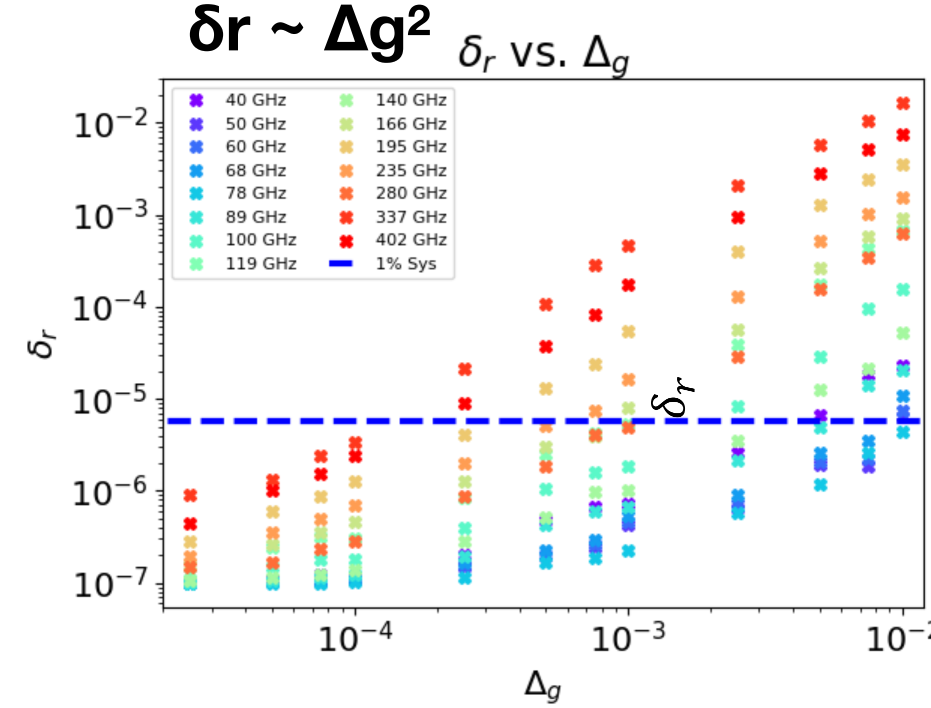
CMB + dust + synchrotron

$$d = \boldsymbol{g}(I_{cmb} + \boldsymbol{\gamma_d} I_d + \boldsymbol{\gamma_s} I_s)$$
$$\pm \boldsymbol{g}\varepsilon[(Q_{cmb} + \boldsymbol{\gamma_d} Q_d + \boldsymbol{\gamma_s} Q_s)cos2\varphi + (U_{cmb} + \boldsymbol{\gamma_d} U_d + \boldsymbol{\gamma_s} U_s)sin2\varphi] + n$$

γ_x = relative calibration of foreground x wrt CMB

error on gain will affect BB measurement

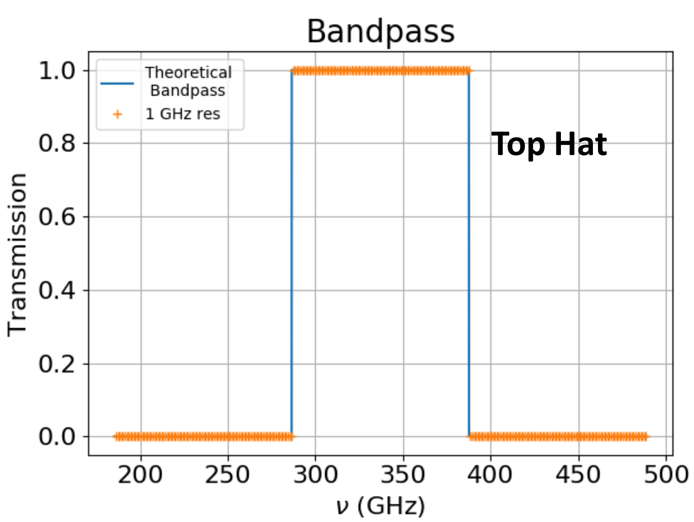
$\delta r \sim \Delta g^2$

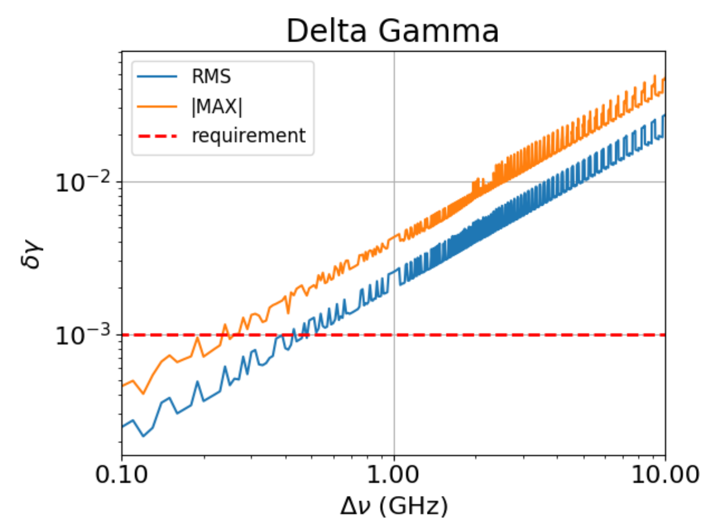


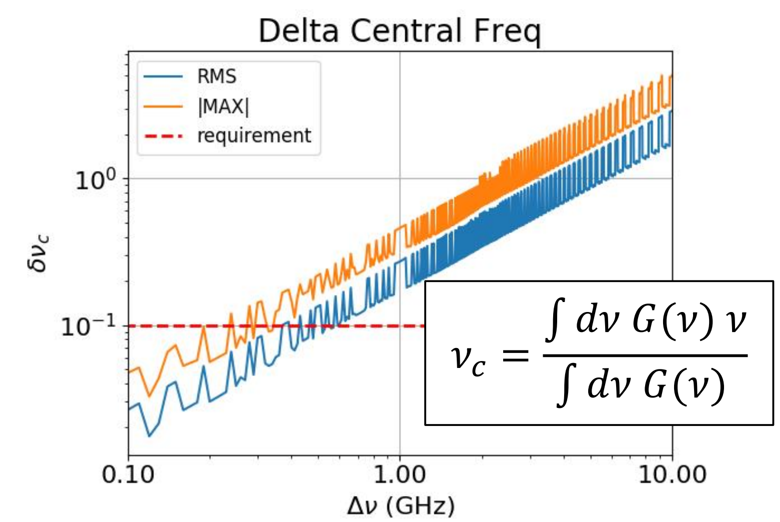
If $\boldsymbol{g}$ can be calibrated well enough using Dipole, $\boldsymbol{\delta_g}$ is dominated by $\boldsymbol{\delta_\gamma}$. We need to determine a bandpass measurement resolution that satisfies the requirement.

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

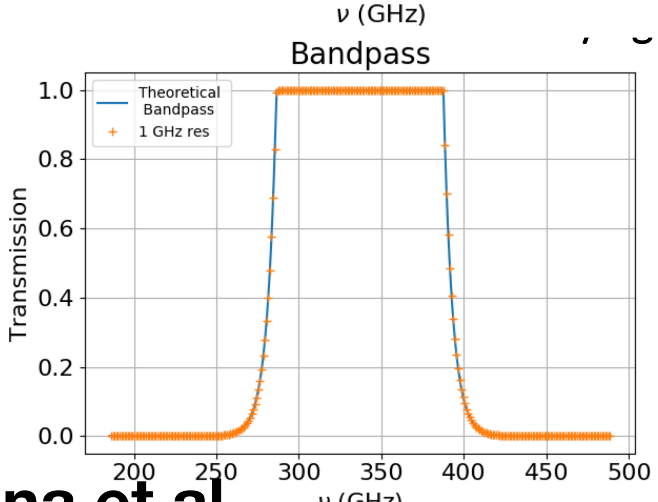
Most stringent requirement is coming from channel 337 GHz (dust dominated): $\boldsymbol{\delta_g \sim 0.001}$.

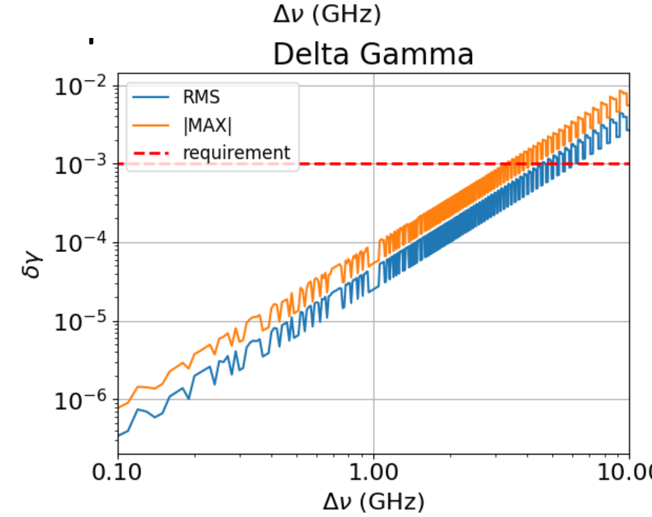






$$\nu_c = \frac{\int d\nu\, G(\nu)\, \nu}{\int d\nu\, G(\nu)}$$





Worst case scenario: top hat bandpass @ 337 and 402GHz (dust dominated)
→ meas. resolution ~ 0.5GHz

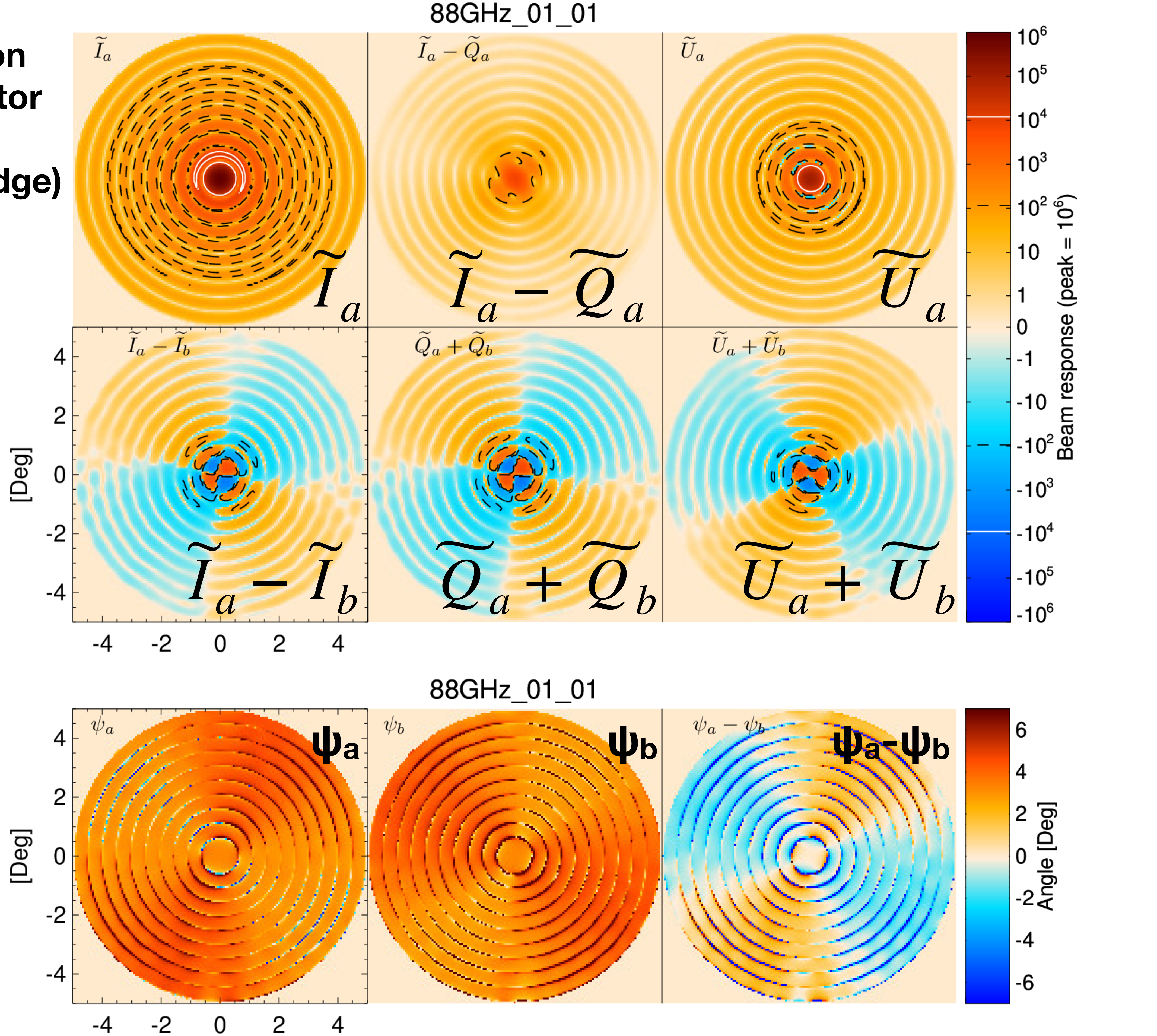
T. Ghigna et al

Optics induced rotation of polarisation

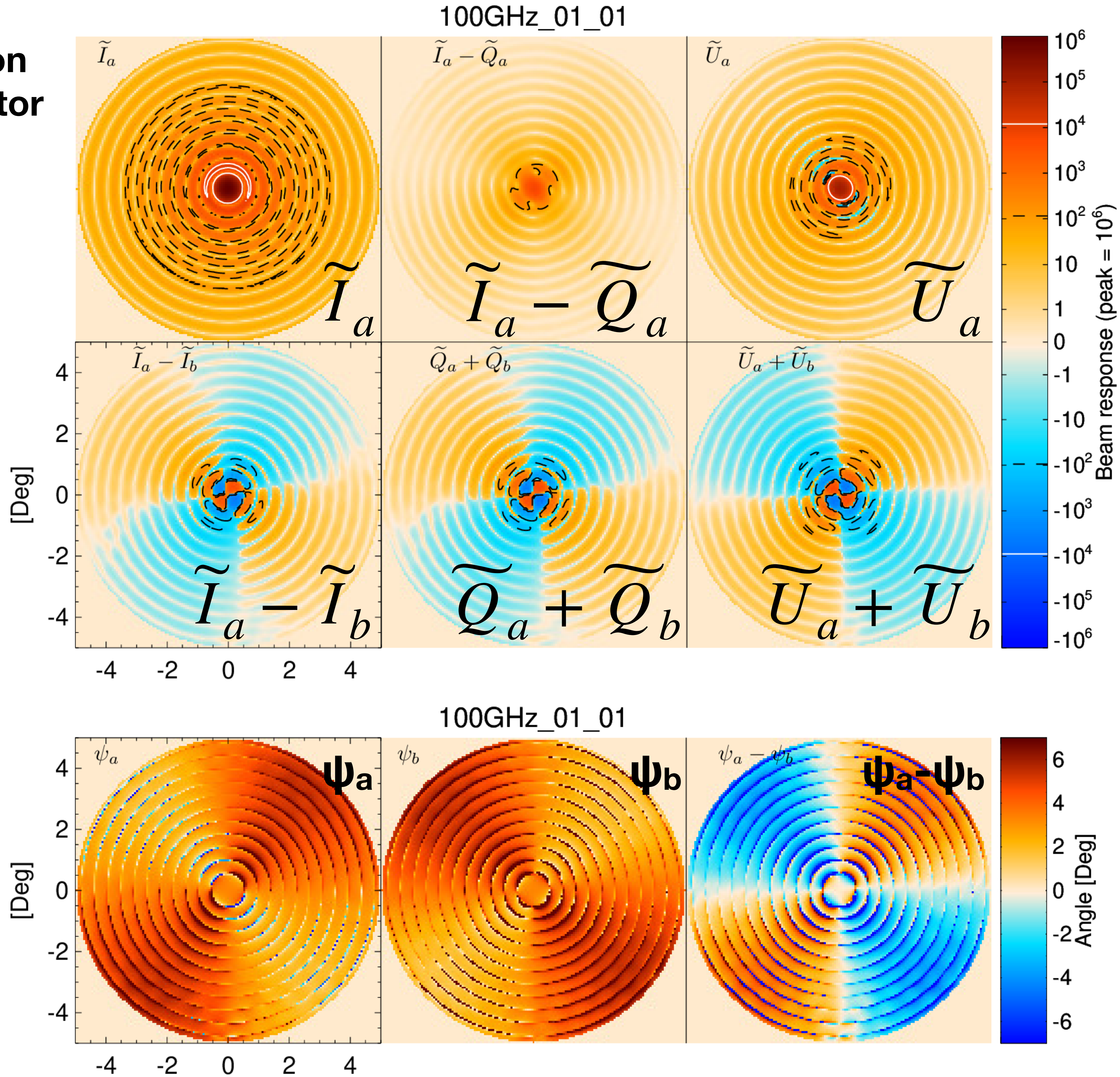
- Lenslets + sinuous antennas + bandpass filters + TES detectors used for LFT and MFT (horns + OMTs for HFT)
  - ✦ almost scale free structure → broad band for dichroic and trichroic detectors (used in PolarBear, SA, SPT-3G, SO, …)
  - ✦ dual polarisation with limited cross-polarisation
    - but polarisation tilt angle ψ varies with frequency ("wobbling") and with position in focal plane
    - for perfectly co-polar beam, with polarisation rotated by ψ: $\tilde{Q} = \tilde{I} \cos 2\psi, \quad \tilde{U} = \tilde{I} \sin 2\psi$
    - will also be present with rHWP
  - ✦ GRASP simulations:
    - at 34 and 42 GHz: $\max(|\tilde{U}|)/\max(\tilde{I}) = 0.013 = \sin 2\psi \rightarrow \psi = 22.3'$
    - at 88 GHz: $\max(|\tilde{U}|)/\max(\tilde{I}) = 0.1 = \sin 2\psi \rightarrow \psi = 2.86^\circ$
- Rotation of polarisation → EE to BB leakage : $C_{BB}' = \cos^2 2\psi \, C_{BB} + \sin^2 2\psi \, C_{EE}$
- This rotation will have to be
  - included in the definition of the effective angle of polarisation, using optics simulations, and/or, calibrated out with Crab measurements, or using TB and EB spectra, … in order to reach the requirement of a few arcmin residual error
  - can it be reduced by co-analysing the signal from an antenna (tilt = ψ(ν)) with the one of its mirror image (tilt = -ψ(ν)) ?

E.H. & H. Imada

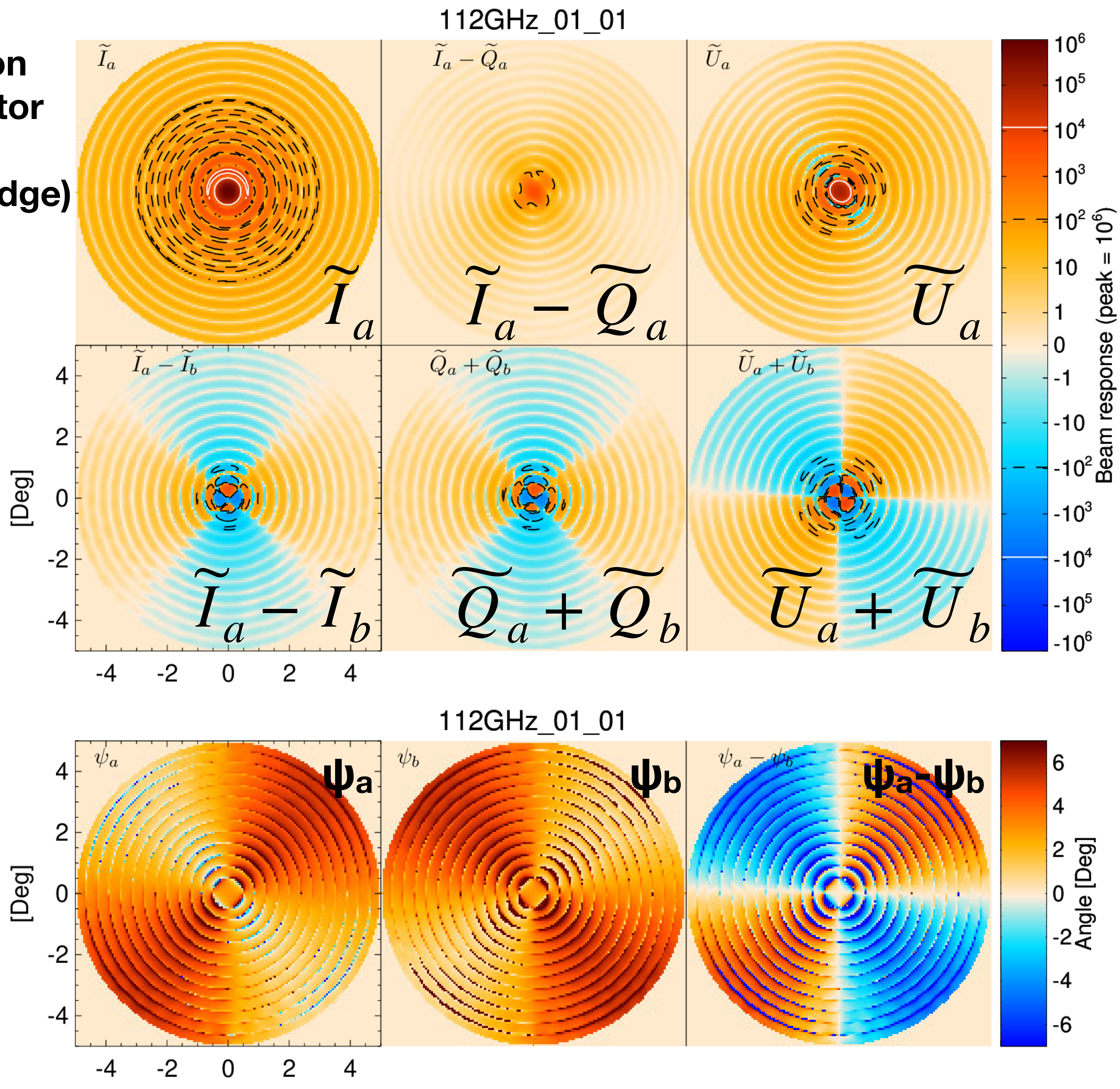
GRASP simulation for 100GHz detector @88GHz (lower bandpass edge)



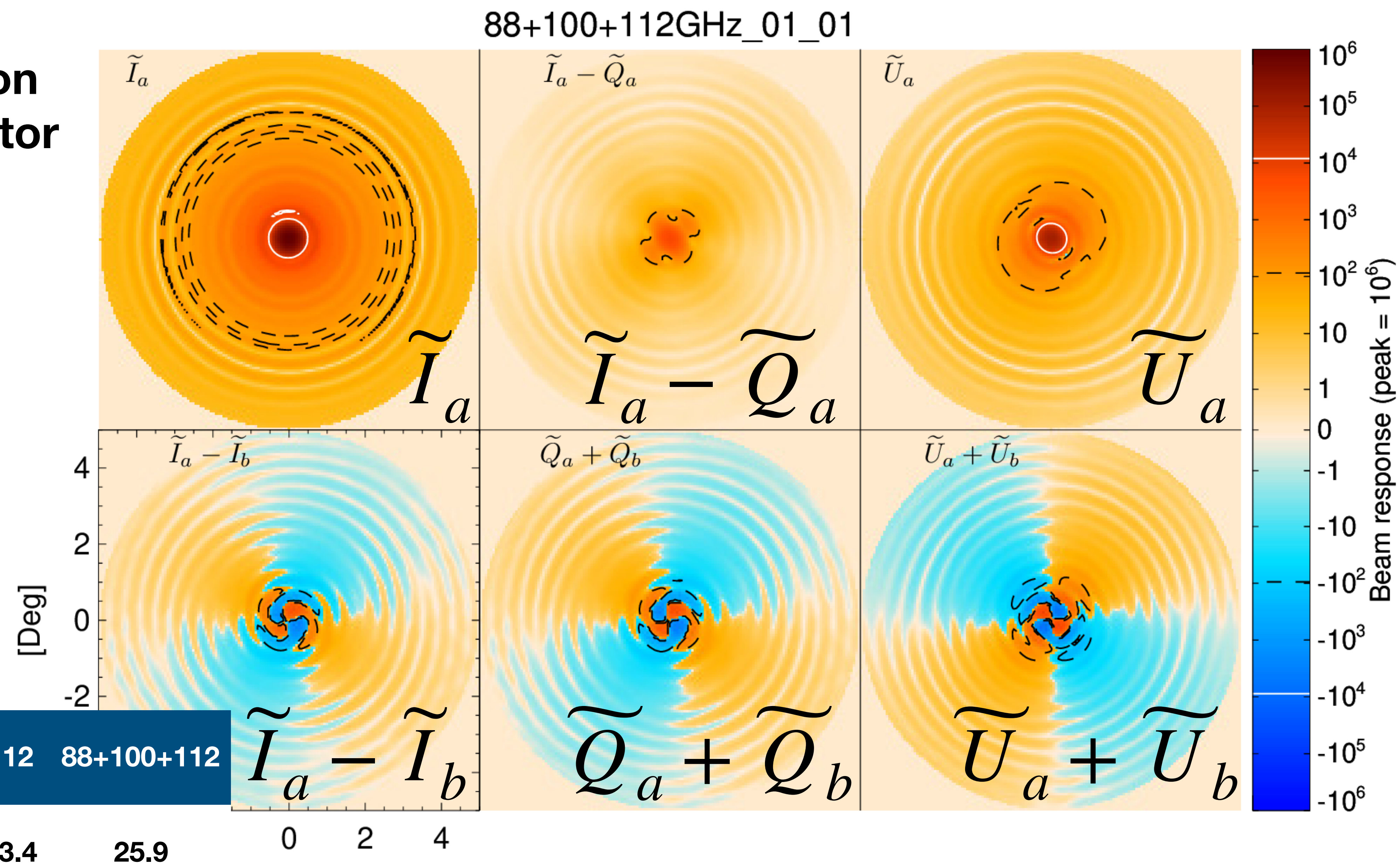
GRASP simulation for 100GHz detector @100GHz



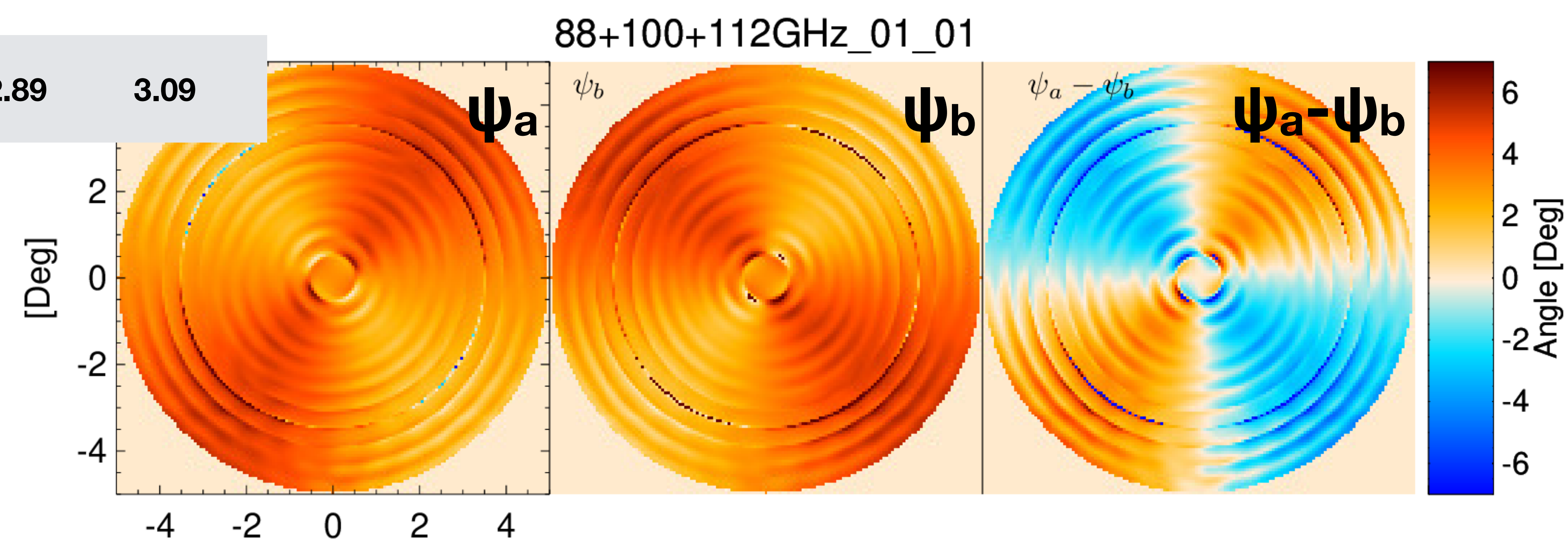
GRASP simulation for 100GHz detector @112GHz (higher bandpass edge)

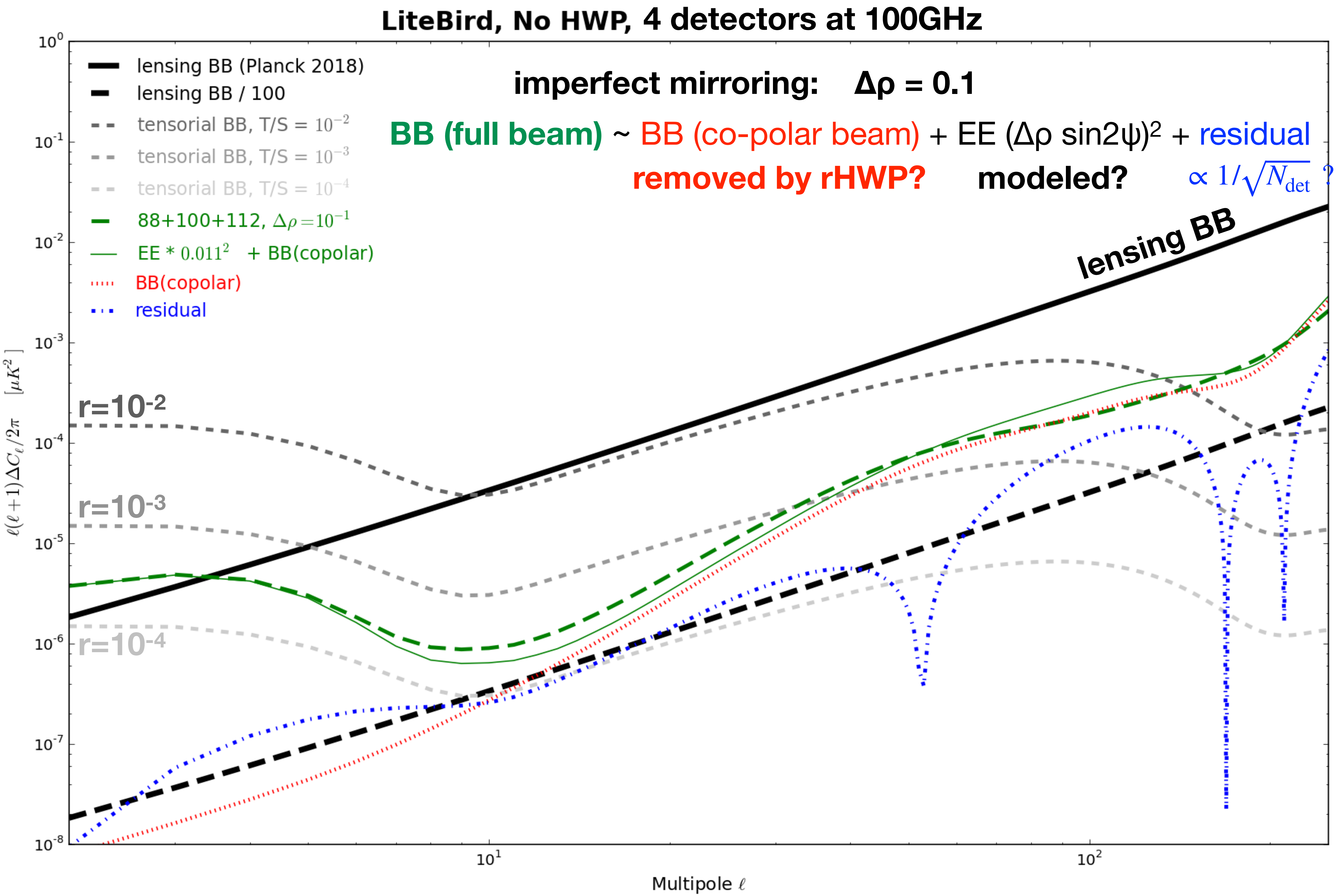


GRASP simulation for 100GHz detector "integrated"

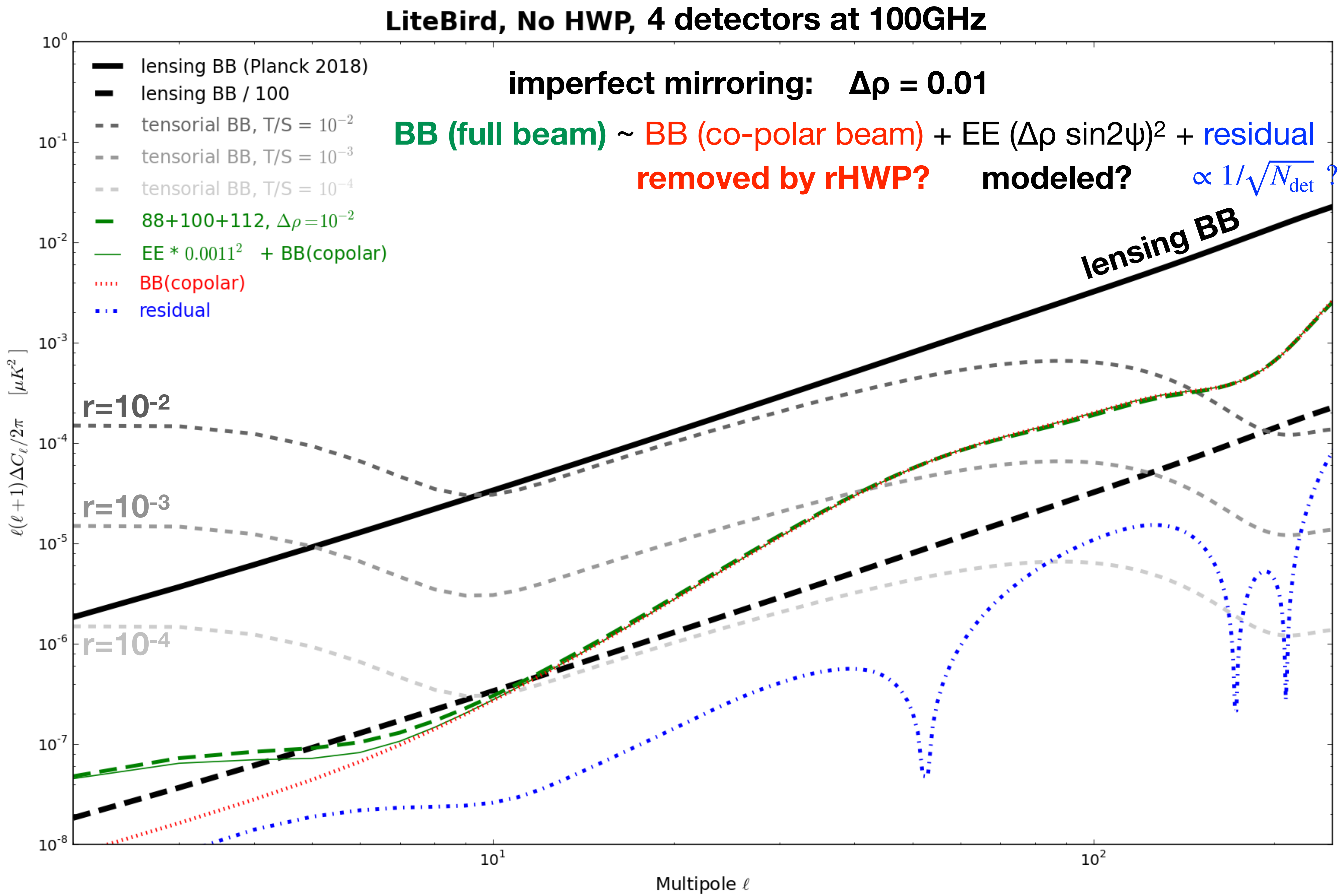


Freq [GHz]	88	100	112	88+100+112
FWHM [arcmin]	29.8	26.2	23.4	25.9
ψ at beam center [Deg]	3.29	3.27	2.89	3.09

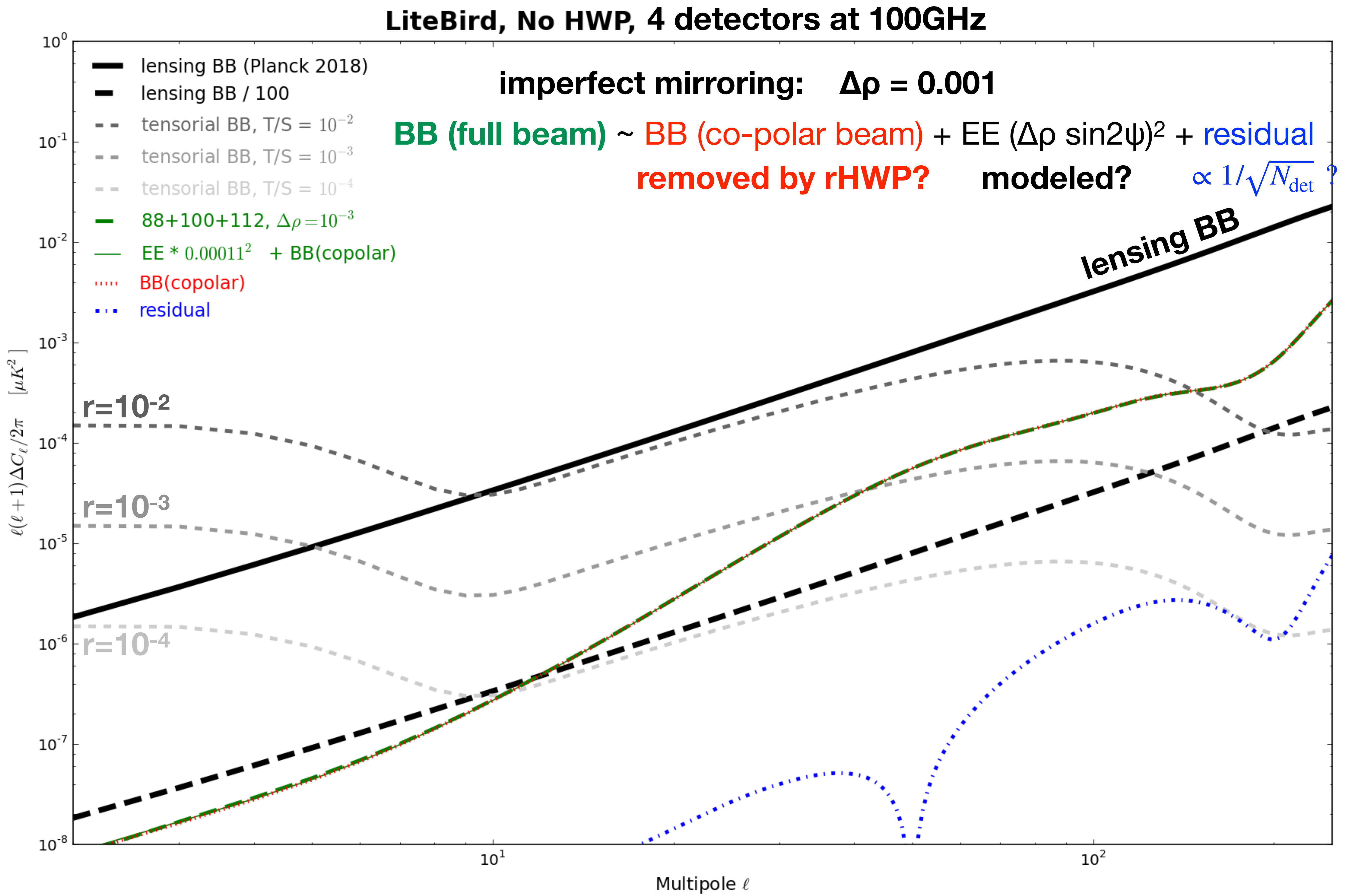




LiteBird, No HWP, 4 detectors at 100GHz
lensing BB (Planck 2018)
lensing BB / 100
tensorial BB, T/S = 10^{-2}
tensorial BB, T/S = 10^{-3}
tensorial BB, T/S = 10^{-4}
88+100+112, $\Delta\rho = 10^{-1}$
EE * 0.011^2 + BB(copolar)
BB(copolar)
residual
imperfect mirroring: Δρ = 0.1
BB (full beam) ~ BB (co-polar beam) + EE (Δρ sin2ψ)^2 + residual
removed by rHWP?
modeled?
$\propto 1/\sqrt{N_{\rm det}}$?
lensing BB
r=10^{-2}
r=10^{-3}
r=10^{-4}
$\ell(\ell+1)\Delta C_\ell/2\pi \quad [\mu K^2]$
Multipole ℓ



LiteBird, No HWP, 4 detectors at 100GHz
lensing BB (Planck 2018)
lensing BB / 100
tensorial BB, T/S = 10^{-2}
tensorial BB, T/S = 10^{-3}
tensorial BB, T/S = 10^{-4}
88+100+112, $\Delta\rho = 10^{-2}$
EE * 0.0011^2 + BB(copolar)
BB(copolar)
residual
imperfect mirroring: Δρ = 0.01
BB (full beam) ~ BB (co-polar beam) + EE (Δρ sin2ψ)^2 + residual
removed by rHWP? modeled? $\propto 1/\sqrt{N_{\rm det}}$?
lensing BB
r=10^{-2}
r=10^{-3}
r=10^{-4}
$\ell(\ell+1)\Delta C_\ell/2\pi \quad [\mu K^2]$
Multipole ℓ



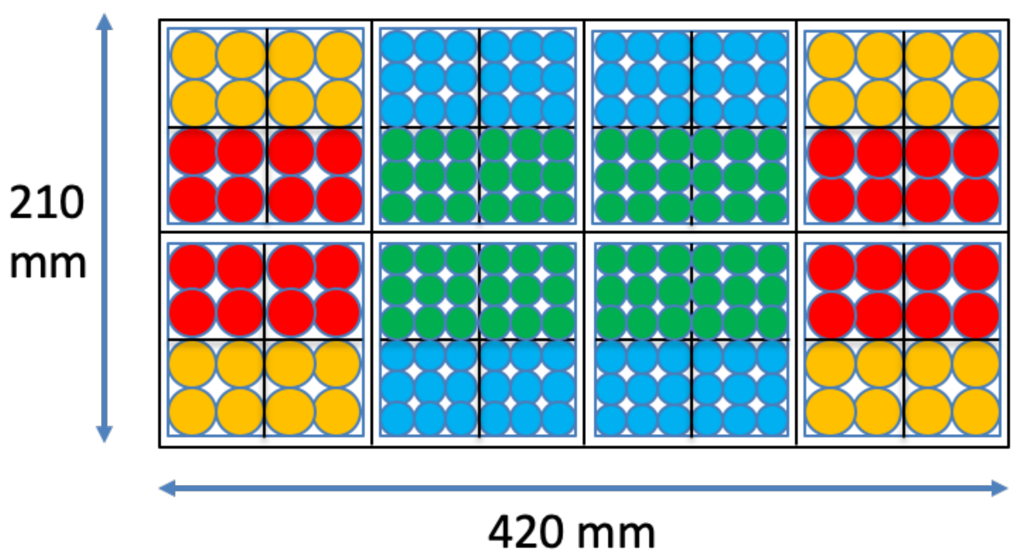
LiteBird, No HWP, 4 detectors at 100GHz
imperfect mirroring: Δρ = 0.001
BB (full beam) ~ BB (co-polar beam) + EE (Δρ sin2ψ)² + residual
removed by rHWP?
modeled?
$\propto 1/\sqrt{N_{det}}$?
lensing BB (Planck 2018)
lensing BB / 100
tensorial BB, T/S = 10^{-2}
tensorial BB, T/S = 10^{-3}
tensorial BB, T/S = 10^{-4}
88+100+112, $\Delta\rho = 10^{-3}$
EE * 0.00011^2 + BB(copolar)
BB(copolar)
residual
lensing BB
r=10^{-2}
r=10^{-3}
r=10^{-4}
$\ell(\ell+1)\Delta C_\ell/2\pi \quad [\mu K^2]$
Multipole ℓ

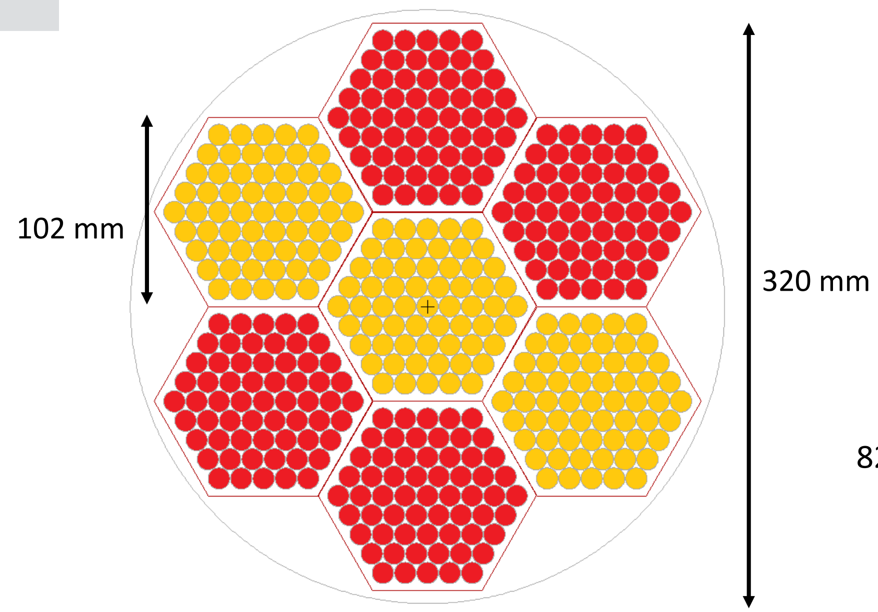
Conclusions

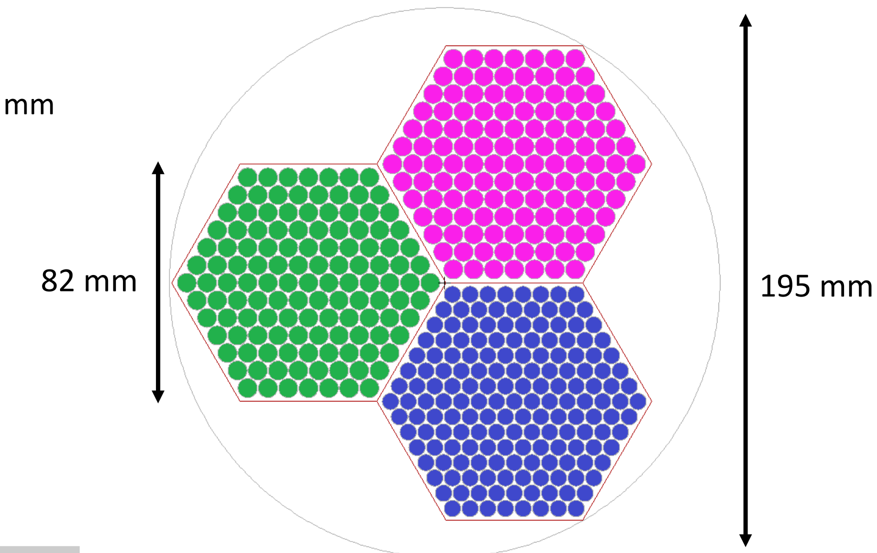
- Many systematics can affect the accuracy with which *r* is measured or constrained ($<5.77\ 10^{-6}$)
    - instrumental polarisation (including HWP)
    - beam mismatch, beam side lobes
    - detector gain, orientation, band-width
  - ✦ No major show-stopper so far, but some simulation work to do, for instance
    - coupling of systematics
- Many features of LiteBird detection chain must be calibrated very precisely.

Extra slides

Number of detectors: 4636







MFT (2.5:1)

89GHz — 224 GHz

2134 detectors
386 Trichroic TES
488 Dichroic TES

100 | 119 | 140 | 166 | 195

LFT (4.7:1)

40 | 50 | 60 | 68 | 78 | 89 | 100 | 119 | 140

1248 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

Y. Sekimoto

- Electric field $\mathbf{e}_{\text{in}} = (E_x(\mathbf{r},t), E_y(\mathbf{r},t))$ of (sky emitted) incoming radiation has the Stokes parameters

$$\begin{cases} I = & \langle E_x^2 + E_y^2 \rangle \\ Q = & \langle E_x^2 - E_y^2 \rangle \\ U = & 2 \ \mathrm{Re} \ \langle E_x E_y^* \rangle \\ V = & 2 \ \mathrm{Im} \ \langle E_x E_y^* \rangle = 0 \end{cases}$$

- Optical system outputs $\mathbf{e}_{\text{out}} = \mathbf{J}_{\text{opt}} \, . \, \mathbf{e}_{\text{in}}$

  with Jones matrix $\mathbf{J}_{\text{opt}}$ such that $\mathbf{J}_{\text{opt}}^{\dagger}\mathbf{J}_{\text{opt}} = \begin{bmatrix} \tilde{I} + \tilde{Q} & \tilde{U} + i\tilde{V} \\ \tilde{U} - i\tilde{V} & \tilde{I} - \tilde{Q} \end{bmatrix}$

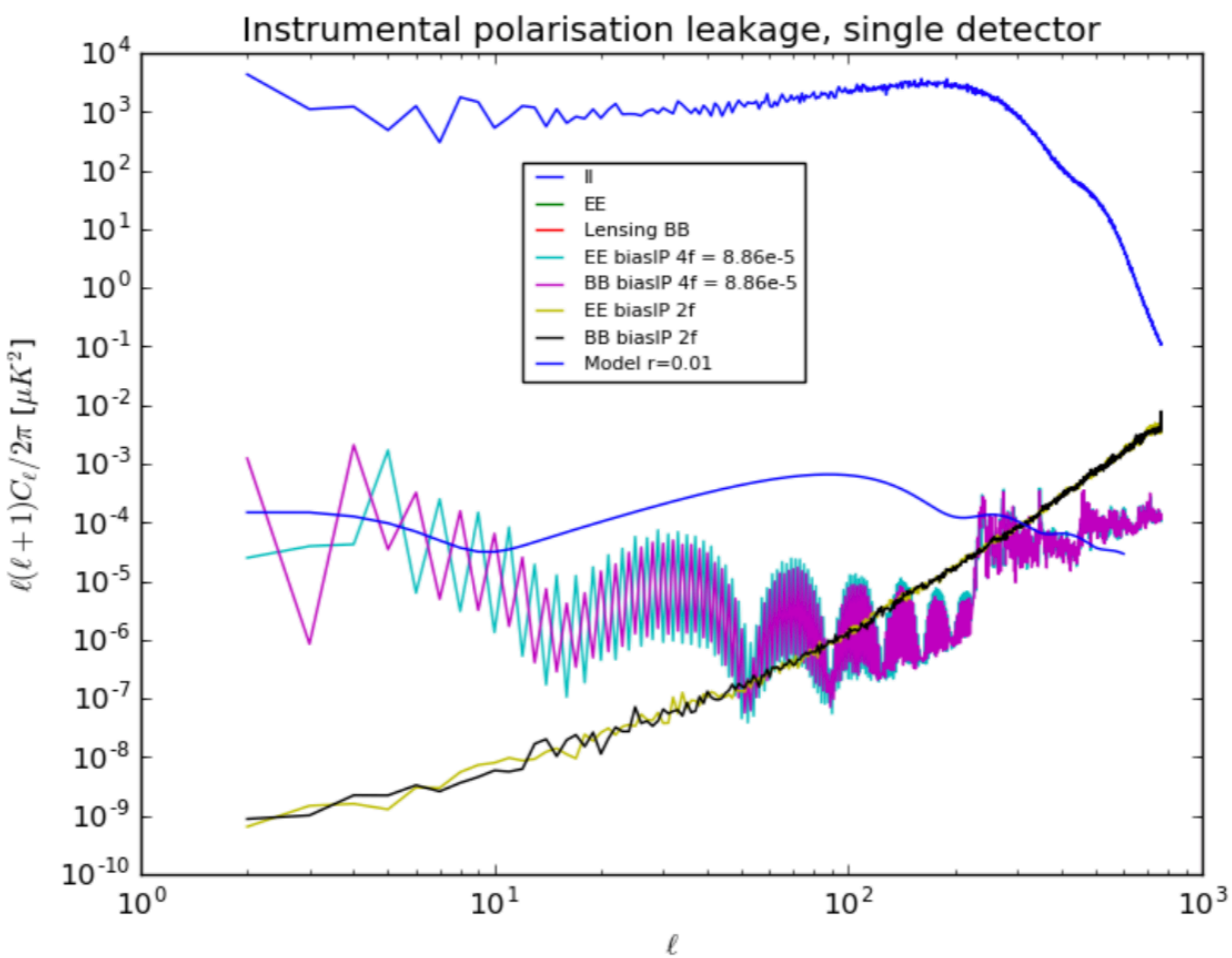
- Measured signal $d = \langle \mathbf{e}_{\text{out}}^{\dagger} \mathbf{e}_{\text{out}} \rangle$ integrated over all incoming radiations

$$d = \frac{1}{2} \int \mathrm{d}\mathbf{r} \left[\tilde{I} I \ + \ \left(\tilde{Q} \cos 2\psi - \tilde{U} \sin 2\psi \right) Q \ + \ \left(\tilde{Q} \sin 2\psi + \tilde{U} \cos 2\psi \right) U \ - \ \tilde{V} V \ \right]$$

  when the instrument is rotated by angle ψ

Effect of the IP on the dipole

- 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



The leakage on maps can be predicted analyticaly by propagating the expression of the IP through the map-making equations