CALIBRATION STRATEGY FOR THE ATACAMA COSMOLOGY TELESCOPE

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ATACAMA COSMOLOGY TELESCOPE

Altitude of 5200 m in the Atacama desert in northern Chile

- Access to ~70% of the sky (ACT maps ~40%)

6 m telescope

- ~5 times *Planck* resolution

PI: Suzanne Staggs, Co-Director: Mark Devlin

image credit: Debra Kellner

ATACAMA COSMOLOGY TELESCOPE

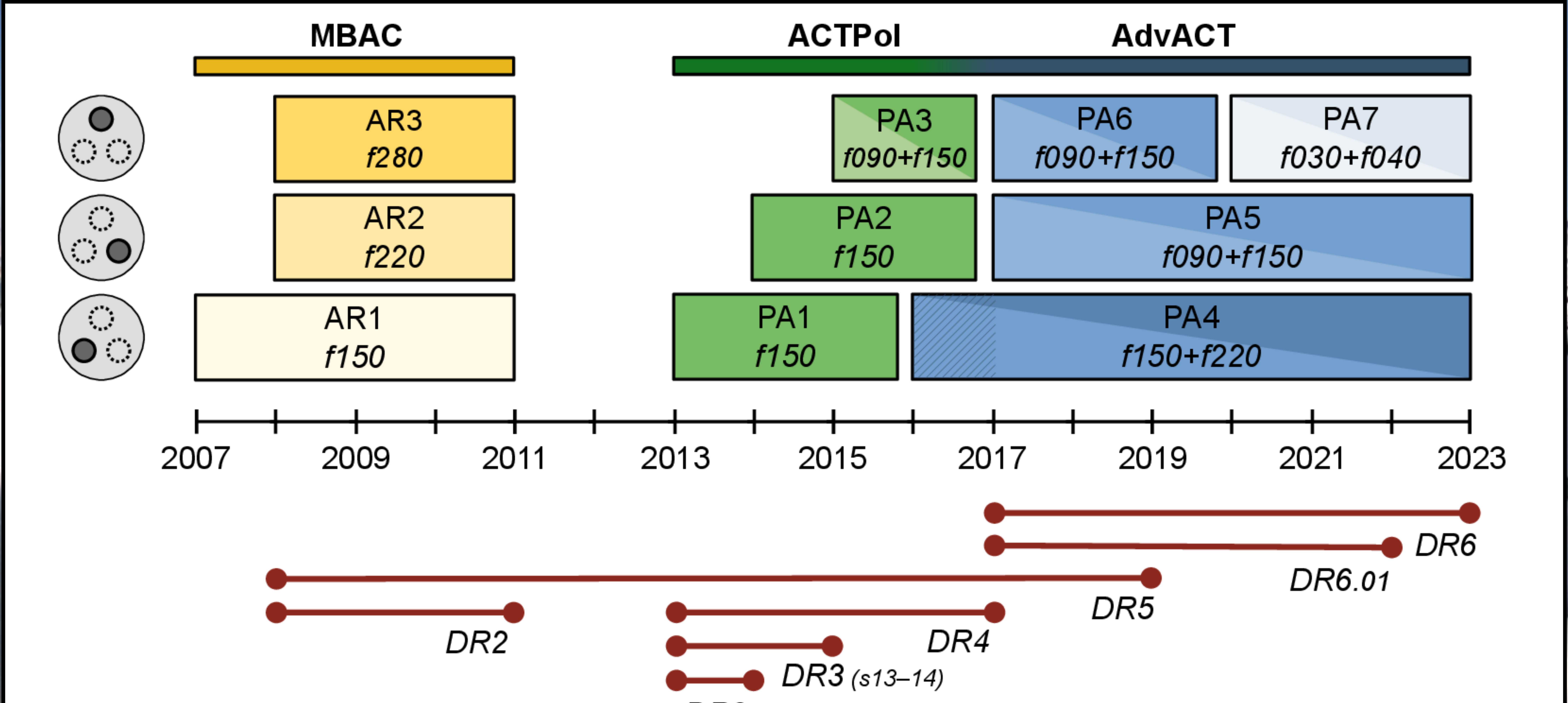
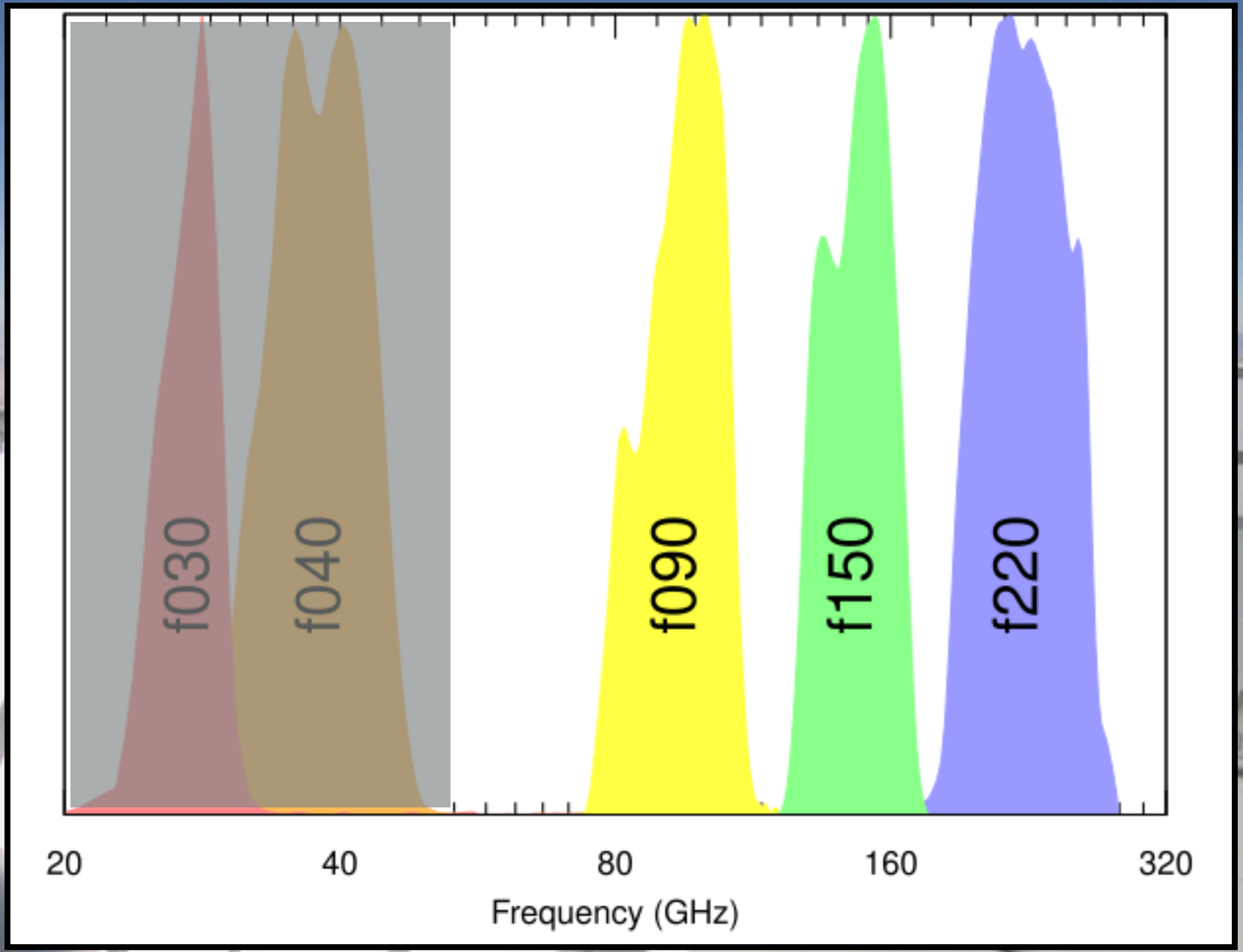
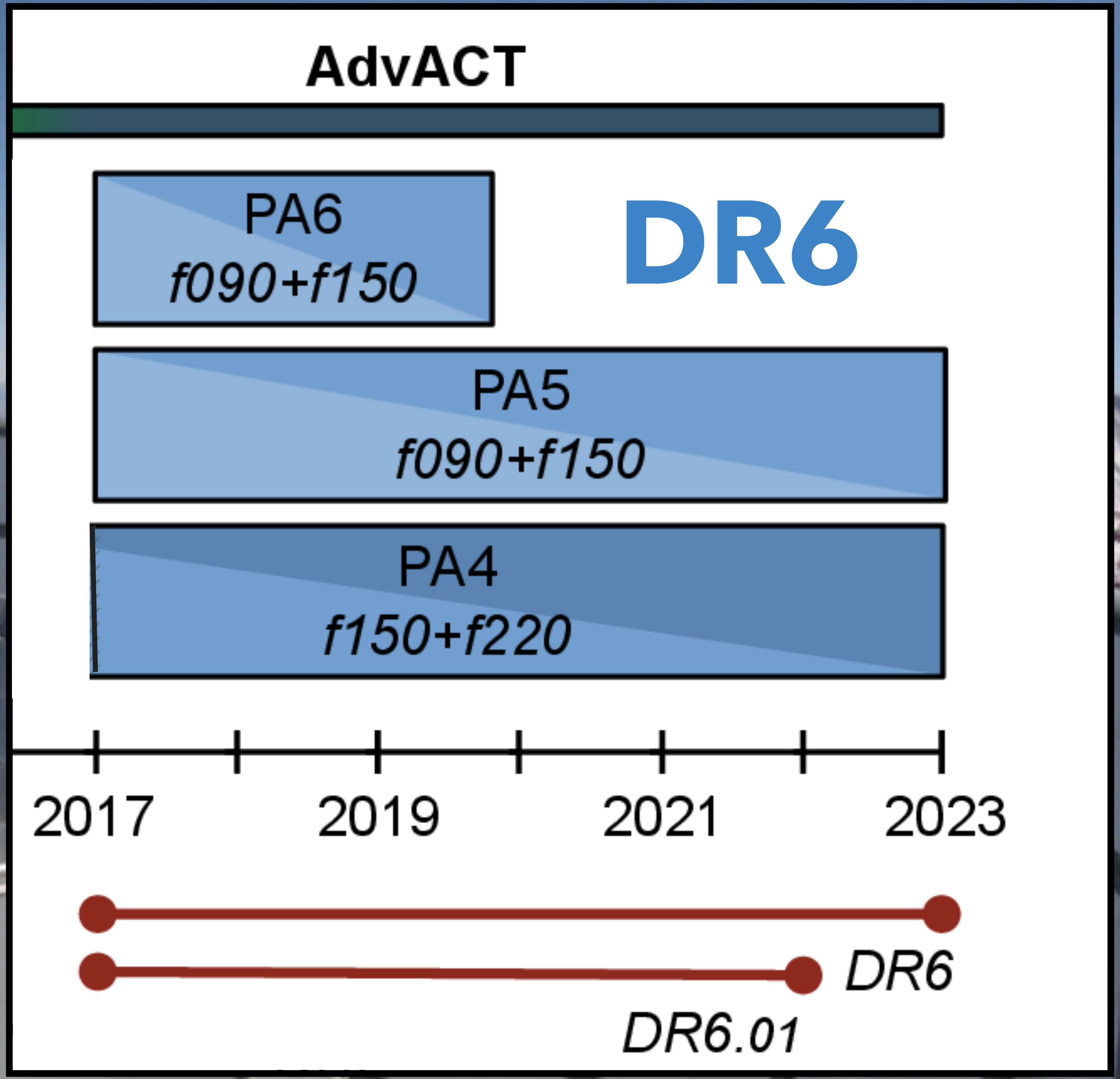


Figure: Adam Hincks

ATACAMA COSMOLOGY TELESCOPE, DR6





RELATIVE CALIBRATION

$$d^{\mathrm{pW}} = R f d^{\mathrm{DAQ}}$$

- R : hourly bias step measurements
- f : monthly atmospheric flatfield
  - Common mode in 0.01-0.1 Hz range, using Morris et al, 2022 (2111.01319) to identify atmosphere-dominated chunks of data
- Initially used Uranus-based flatfielding, but inaccurate due to strong dependence on detector beam variations
- Final detector gains accurate to few percent, suffers from detector passband mismatches

TRANSFER FUNCTION FROM GAIN ERRORS

Naess, Louis, 2023 (2210.02243)

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- 1D toy model with 2 detectors
  - $N_f = A_f \begin{pmatrix} 1 & \alpha_f \\ \alpha_f & 1 \end{pmatrix}, \; G = \begin{pmatrix} g_1 & 0 \\ 0 & g_2 \end{pmatrix}$

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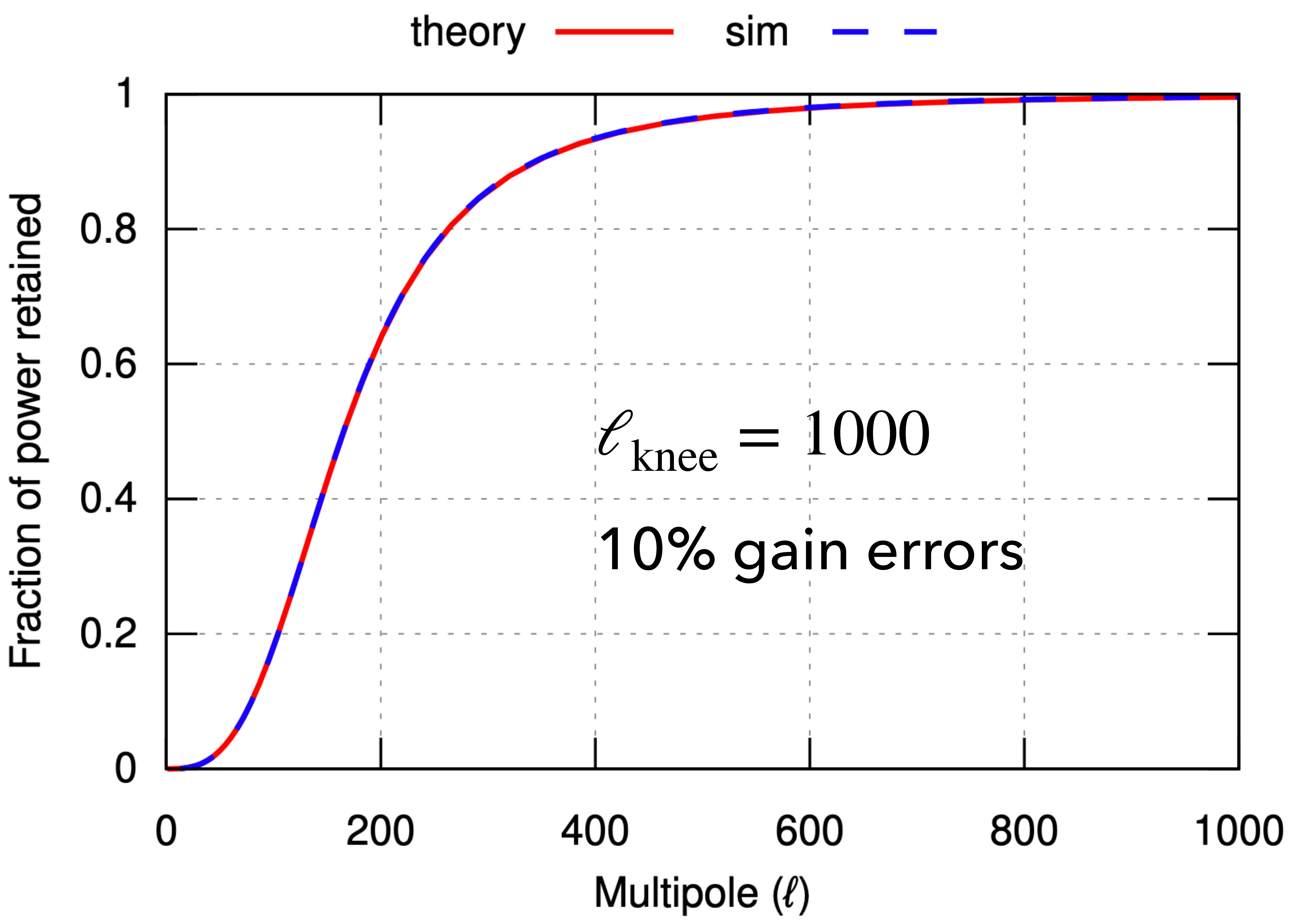

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ABSOLUTE CALIBRATION

- Uranus observations to get time-dependent absolute calibration from pW to $\mu\mathrm{K}_{\mathrm{CMB}}$
- $g(w, \theta) = c \exp\left(\frac{\tau w}{\sin\theta}\right)$
  - c and τ fitted per season to individual gain measurements: $g_i = \frac{T}{A_i}$ using model for T from Hasselfield et al, 2013 (1303.4714)
  - Significant not-understood scatter around best fit: **f090**:1-3%, **f150**: 2-8%, **f220**: 4-12%, Hervías-Caimapo et al, 2024 (2301.07651)

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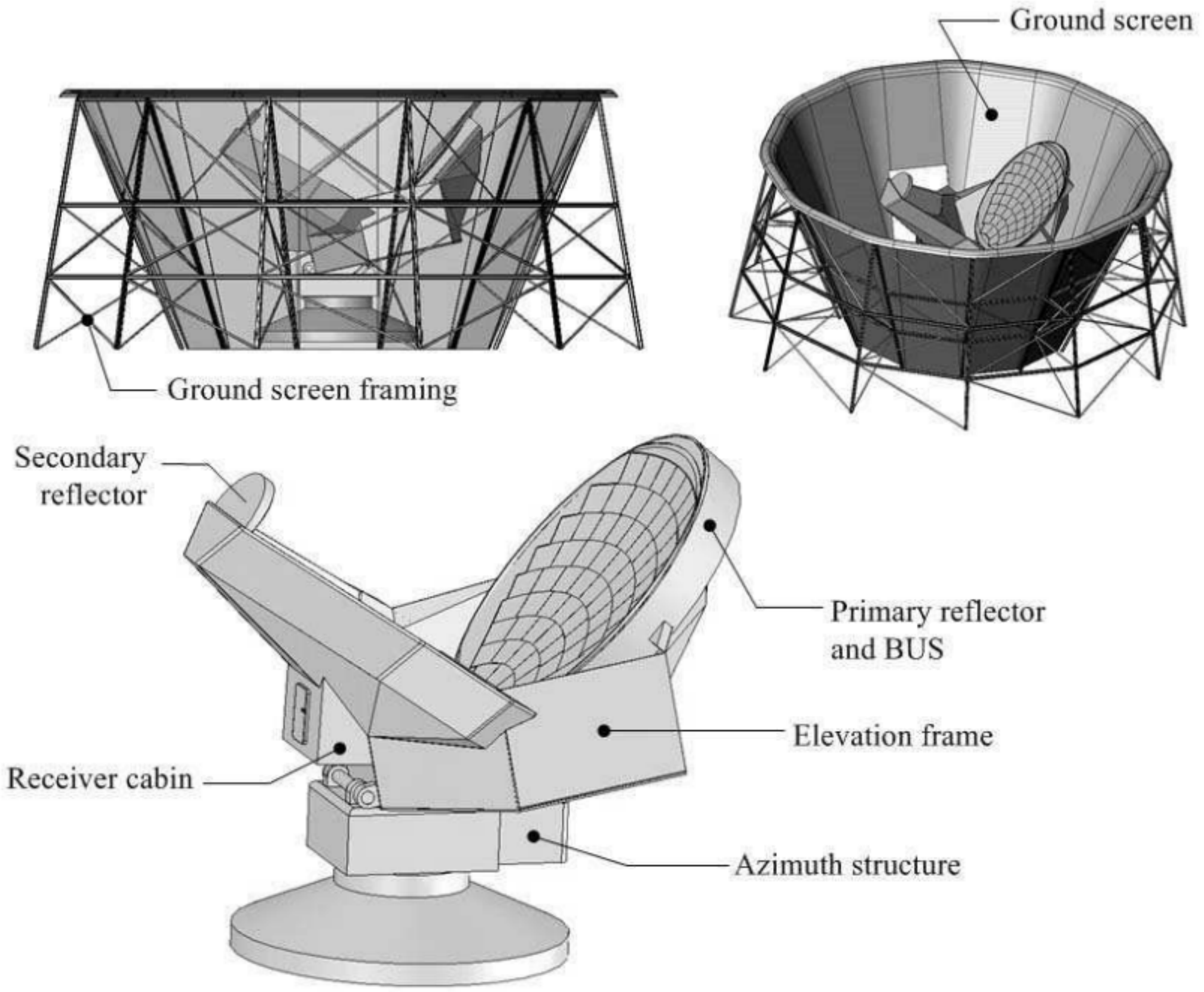
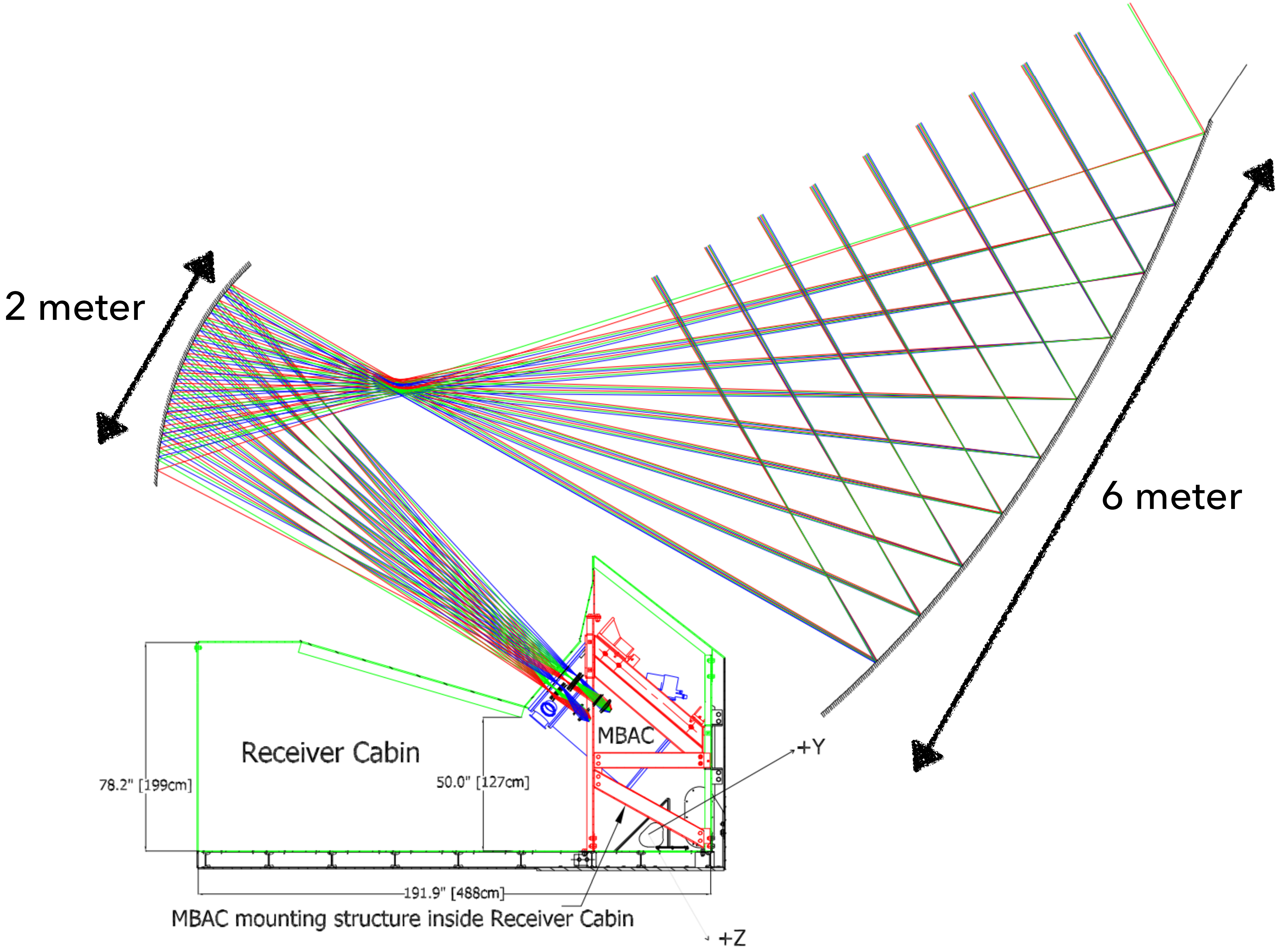
  - Significant not-understood scatter around best fit: **f090**:1-3%, **f150**: 2-8%, **f220**: 4-12%, Hervías-Caimapo et al, 2024 (2301.07651)
- Final calibration to *Planck* TT spectrum, $\mathcal{O}(1\%)$ correction
  - Requires overlapping scales. One reason to worry about low-multipole transfer function

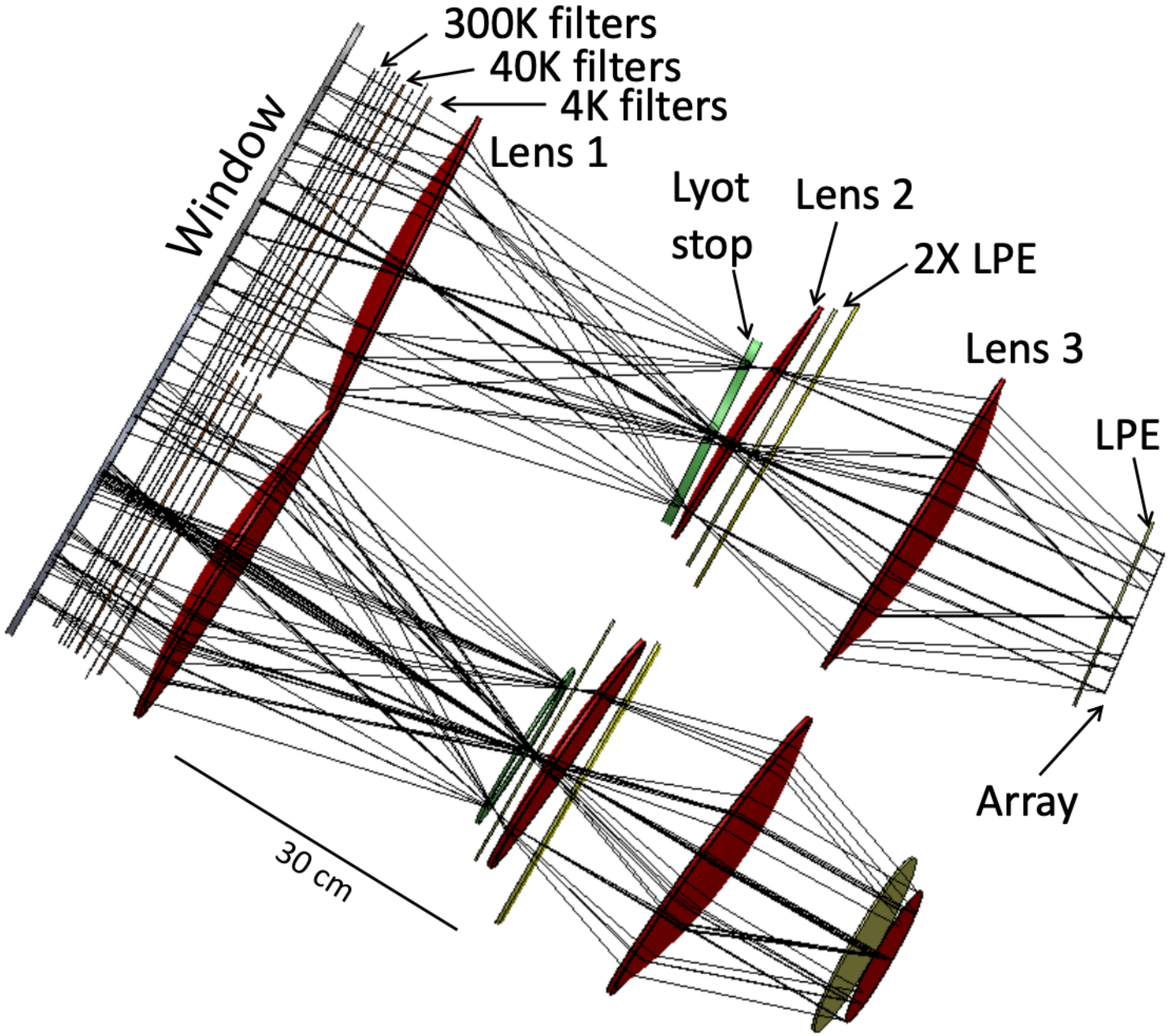
ATACAMA COSMOLOGY TELESCOPE





See Fowler et al., 2007 (0701020) and Swetz et al., 2011 (1007.0290)

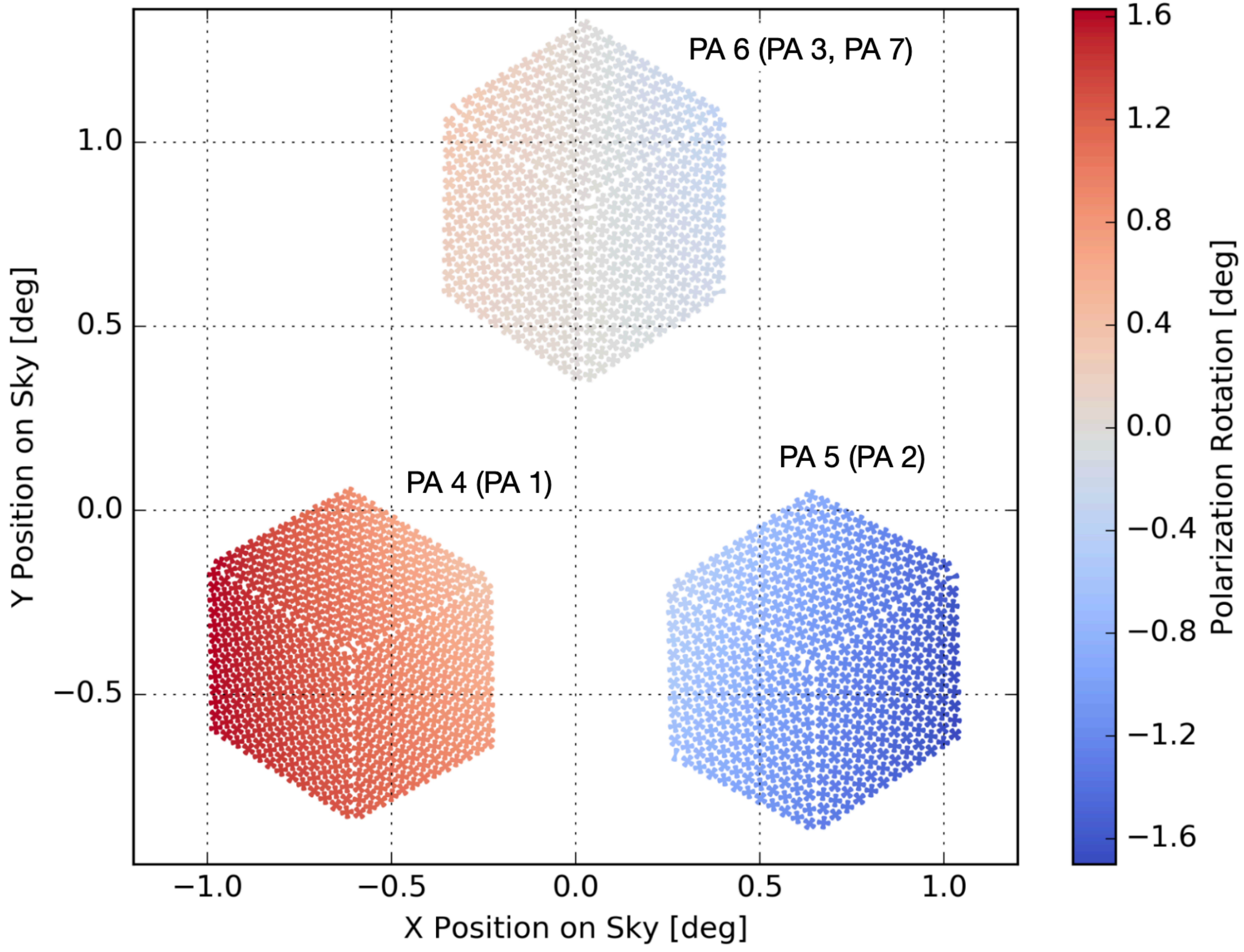
ATACAMA COSMOLOGY TELESCOPE



See Fowler et al., 2007 (0701020) and Swetz et al., 2011 (1007.0290)

POLARIZATION ANGLE

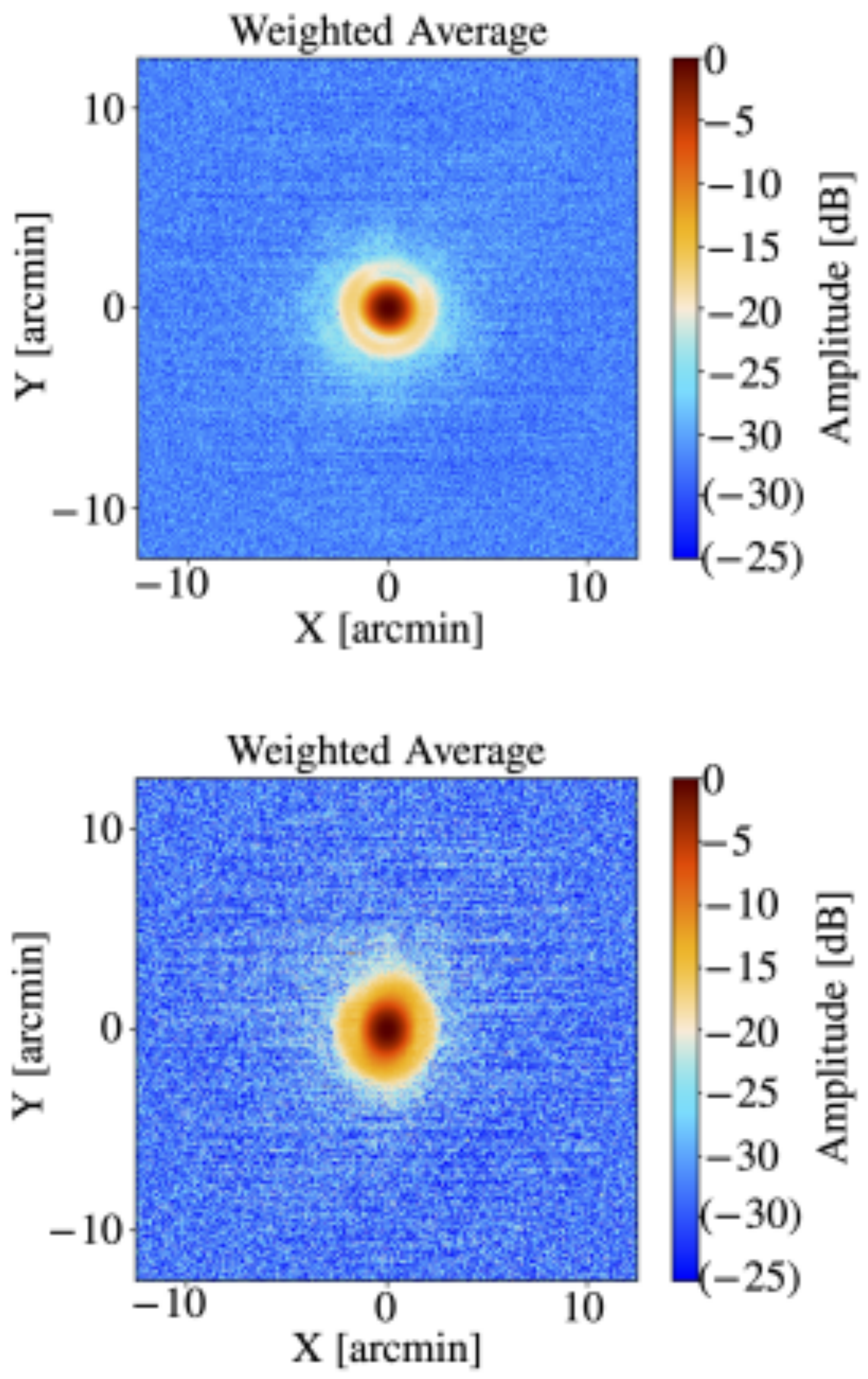
- Detector polarization angles determined from polarized raytracing model
  - Koopman et al, 2016 (1607.01825)
  - Murphy et al, 2024 (2403.00763)
- Point sources constrain overall rotation of each array to ≲0.05 deg
  - Choi et al, 2020 (2007.07289)

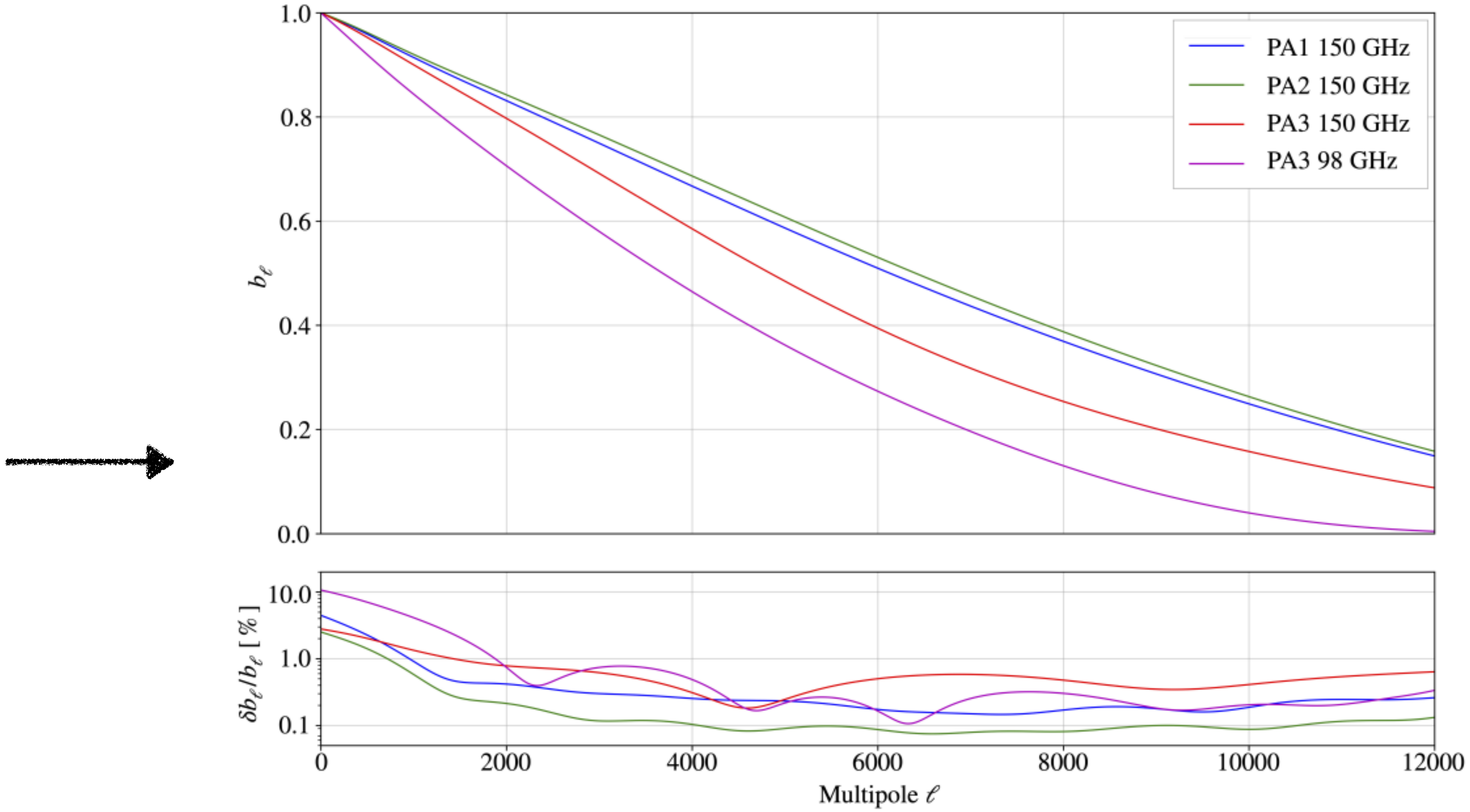


Murphy et al, 2024 (2403.00763)

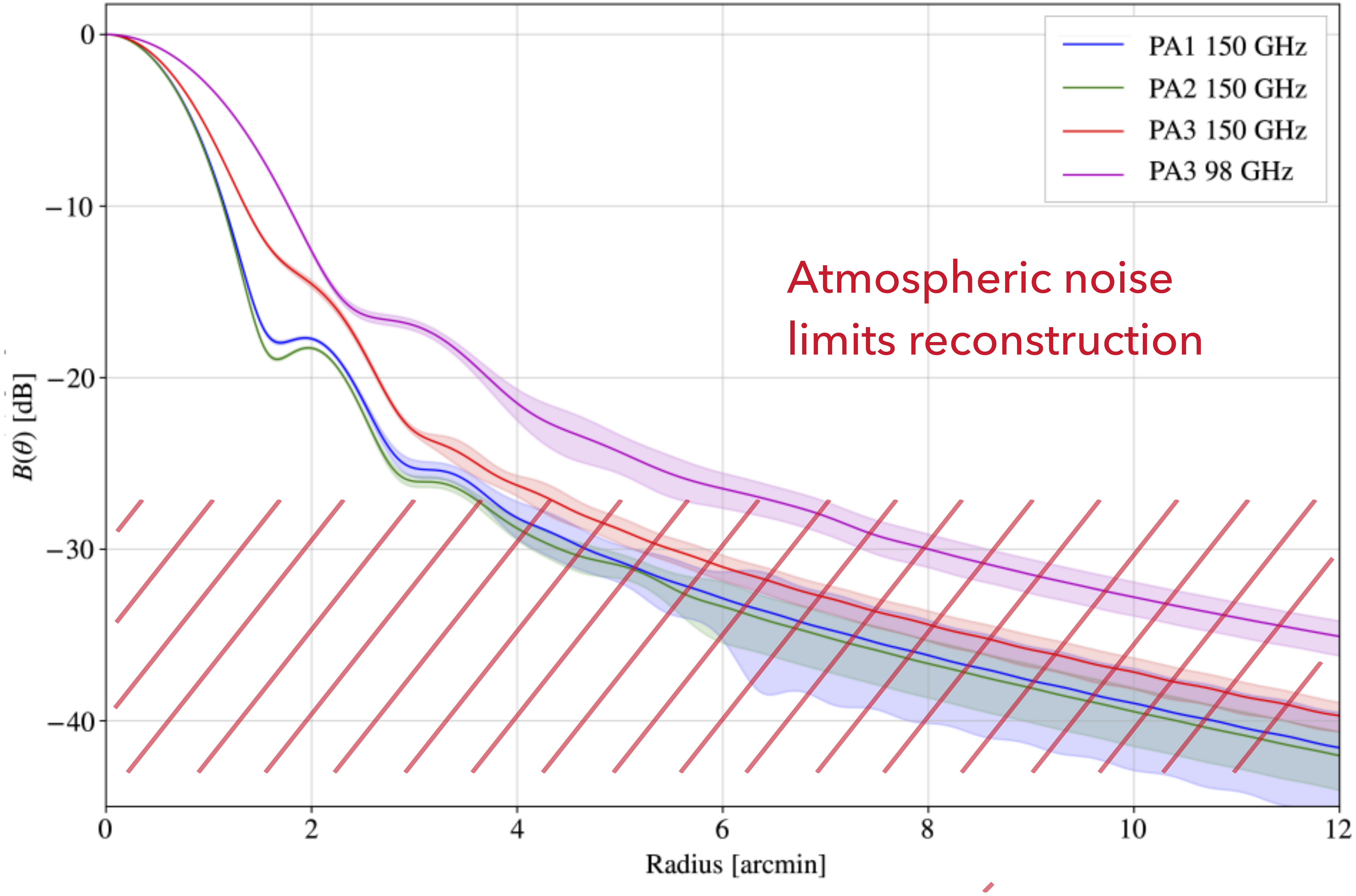
MAIN BEAM

- ACT's beam estimation pipeline summarized in Lungu et al, 2022 (2112.12226)





ATMOSPHERIC NOISE



From Lungu et al, 2022 (2112.12226)

PLANET MAPMAKING

- Atmospheric noise is optimally suppressed in ACT's CMB maps using maximum likelihood mapmaking
- $\hat{m} = (P^\top N^{-1} P)^{-1} P^\top N^{-1} d$
  - N^{-1} : inverse noise covariance matrix modeled as **stationary** in time (N^{-1} only depends on $t_1 - t_2$, not t_1, t_2 individually)

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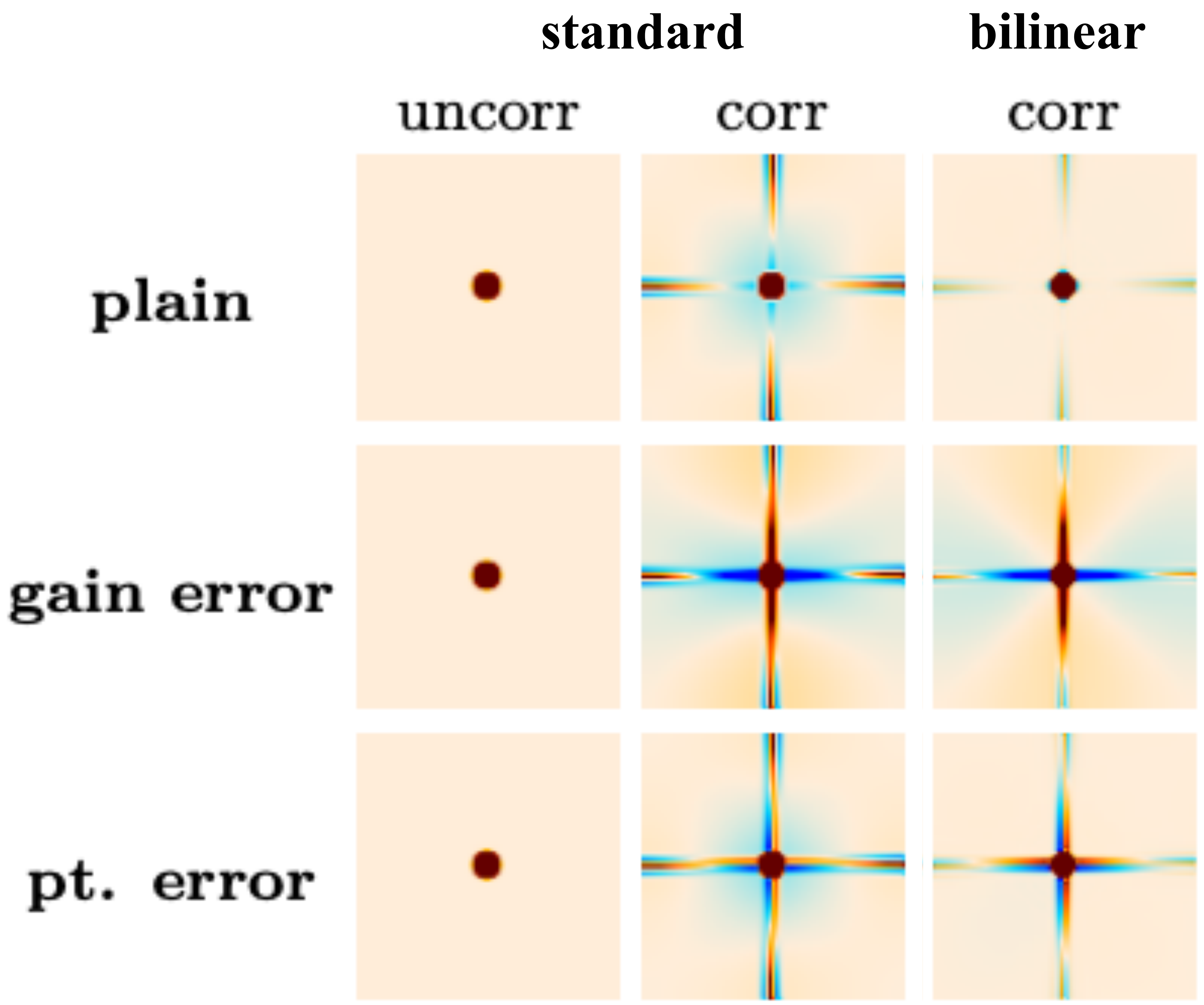
← This is a bad approximation for planet observations

PLANET MAPMAKING

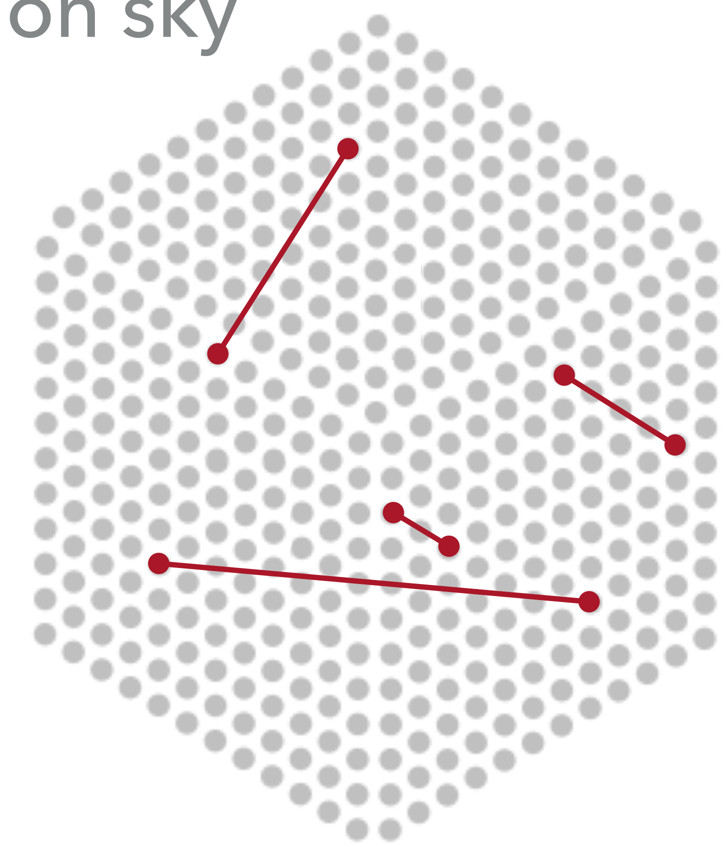
- In presence of correlated noise, maximum-likelihood mapmaking is **not** a good tool for bright point sources
  - Errors between data and model (pixelization, gain, pointing) localized at source get spread out along scan direction based on the noise correlation length
  - In addition to the low-multipole transfer function discussed before



Naess, 2019 (1906.08030)

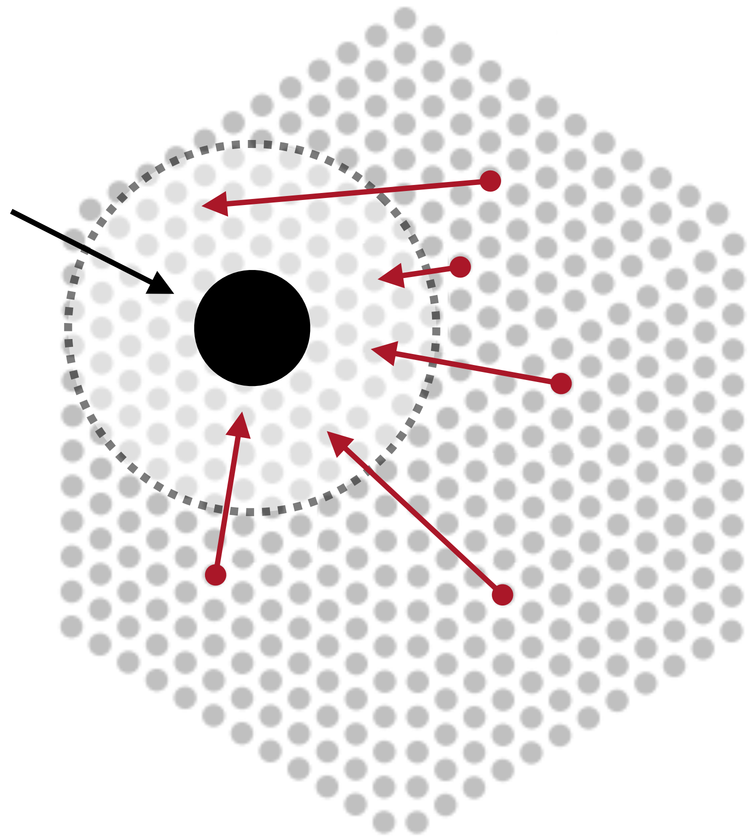
PLANET MAPMAKING

Focal plane on sky

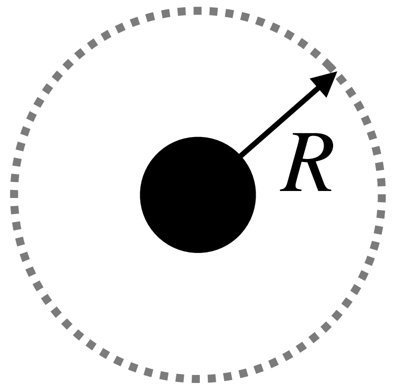


1. Estimate detector-detector noise covariance matrix

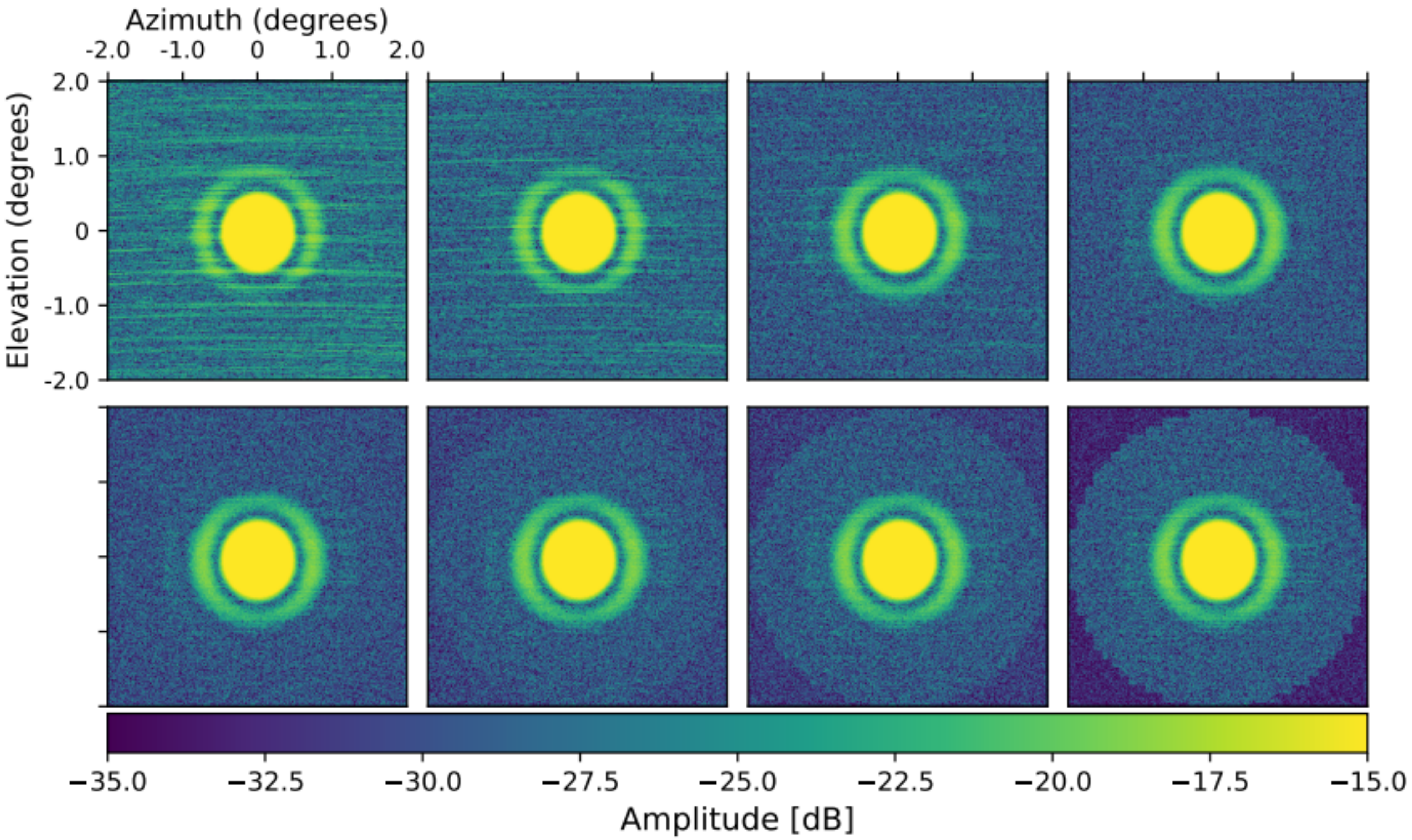
Planet



2. Subtract best estimate of correlated noise around the planet



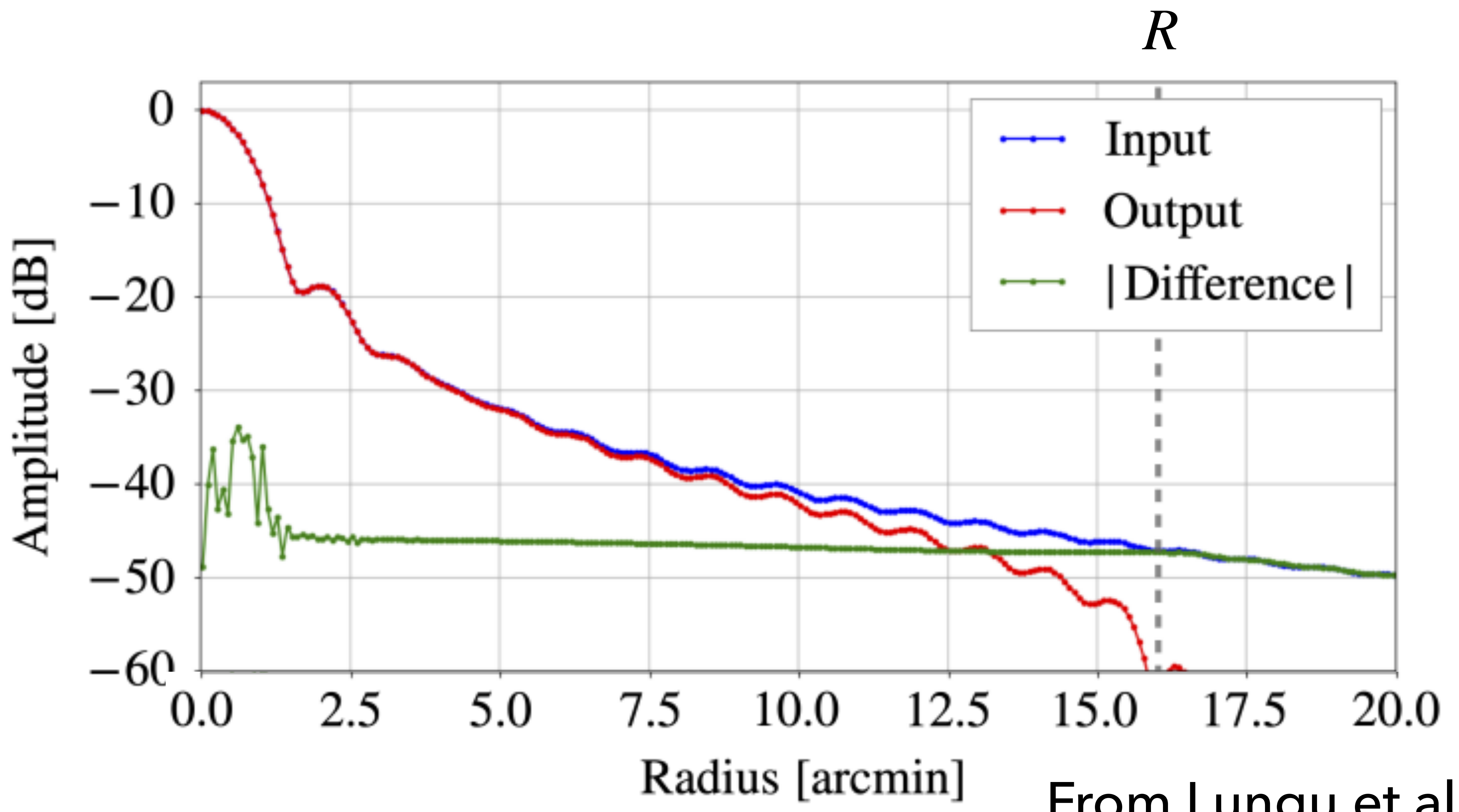
3. Map remaining signal assuming white noise



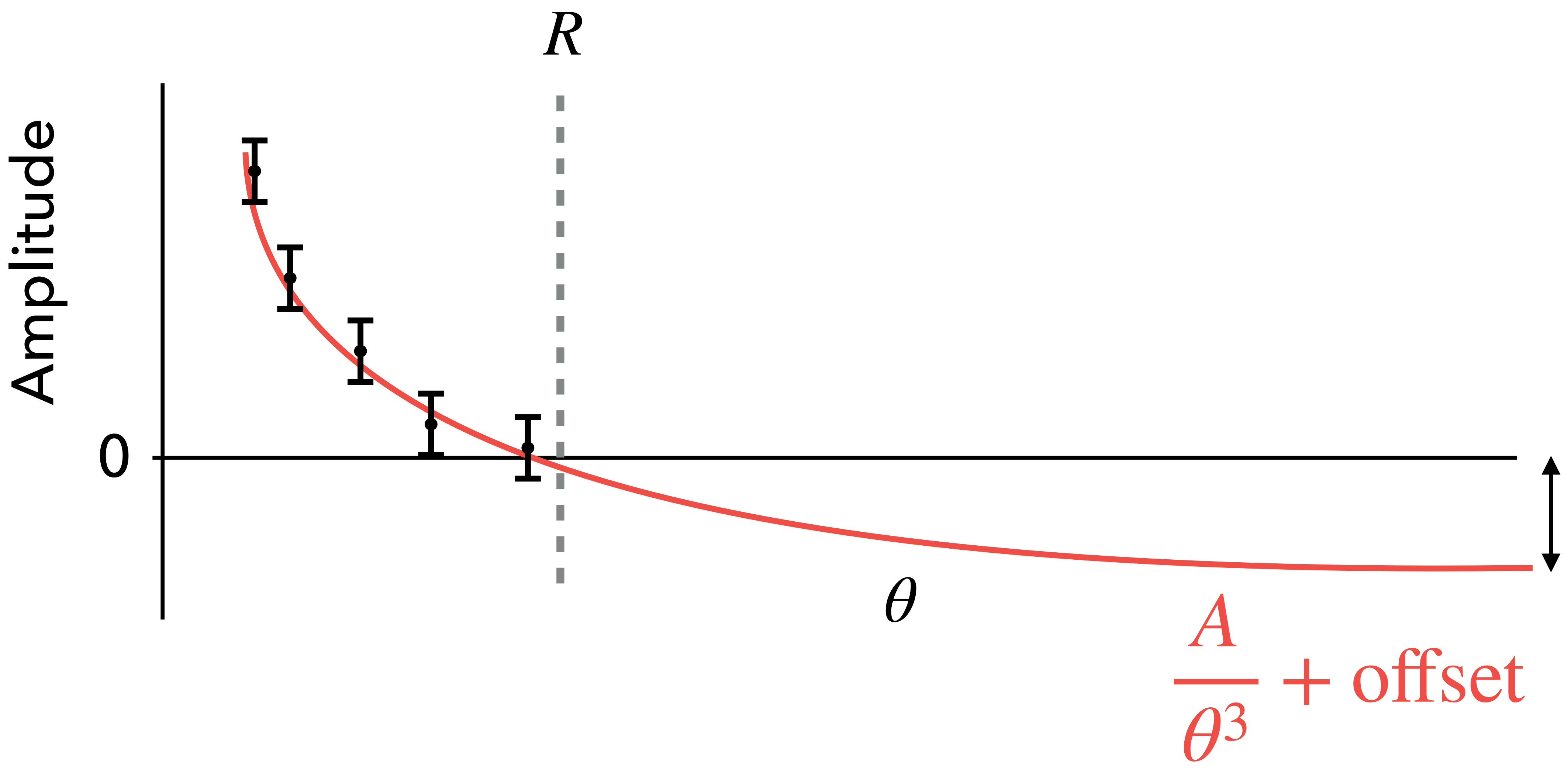
Dachlythra et al, 2023 (2304.08995)

PLANET MAPMAKING

- Resulting maps are slightly biased
  - Any beam power outside radius R is interpreted as correlated noise and subtracted
  - Manifests (to good approximation) as constant offset
  - We add this offset back in by fitting an $\frac{A}{\theta^3} + \text{offset}$ model to the outer region of the beam profile



From Lungu et al, 2022



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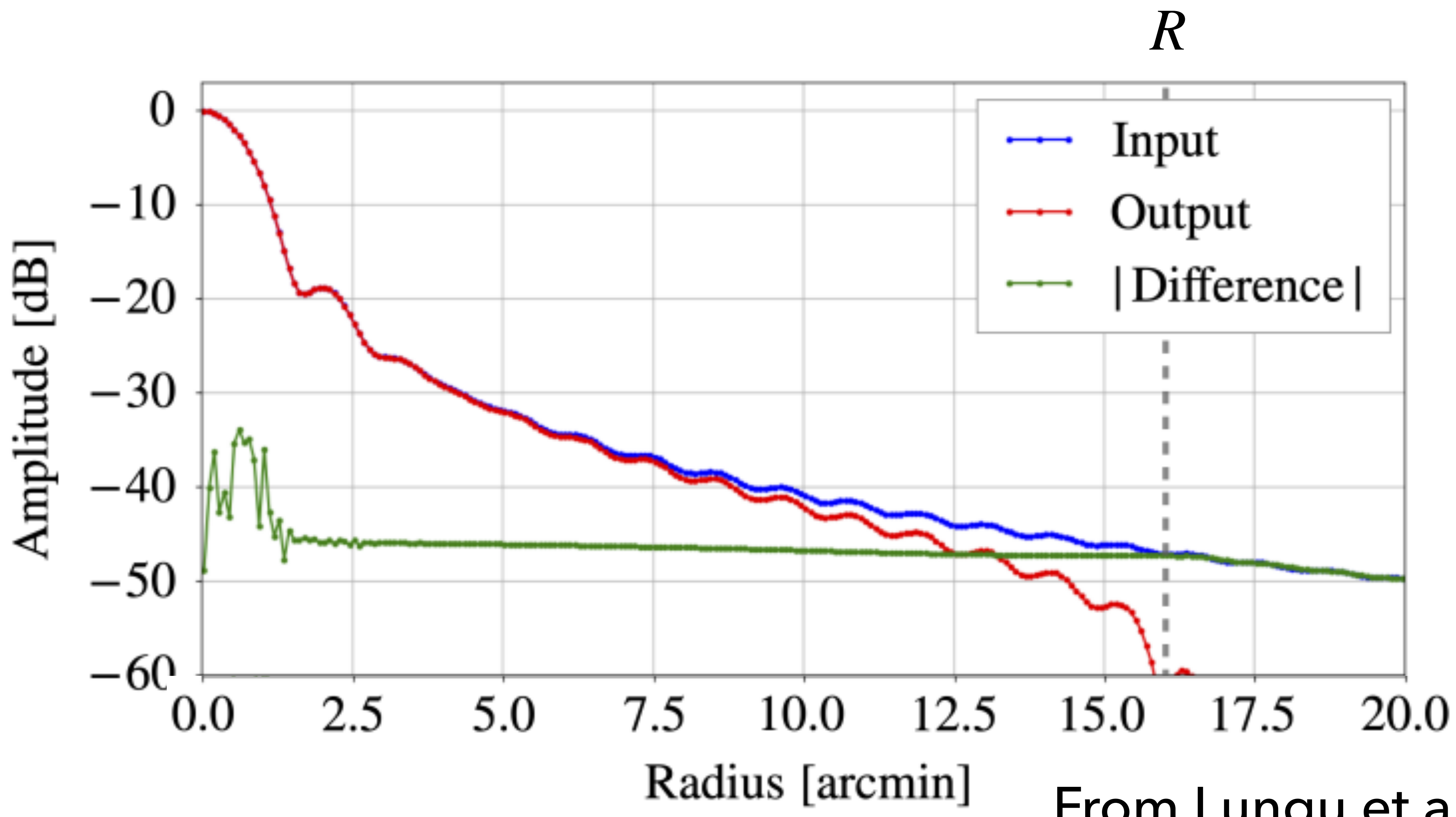

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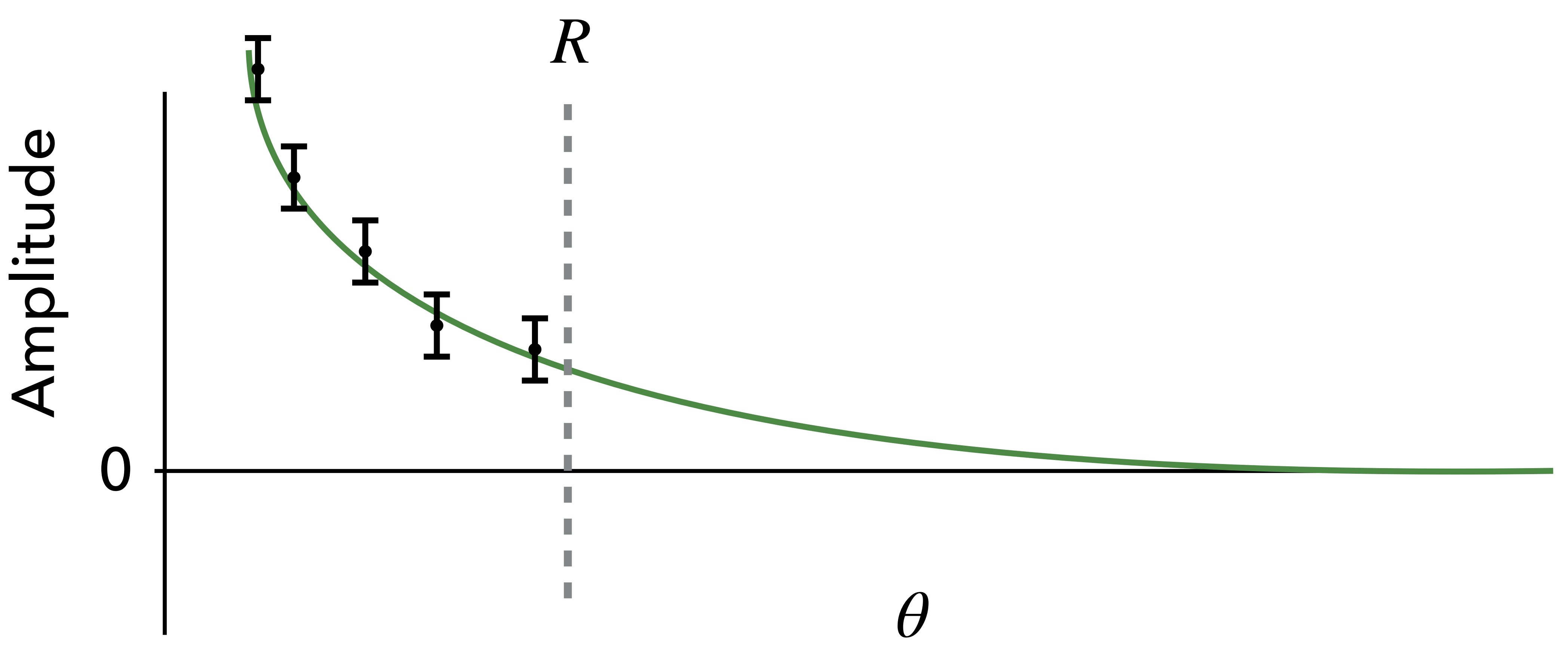
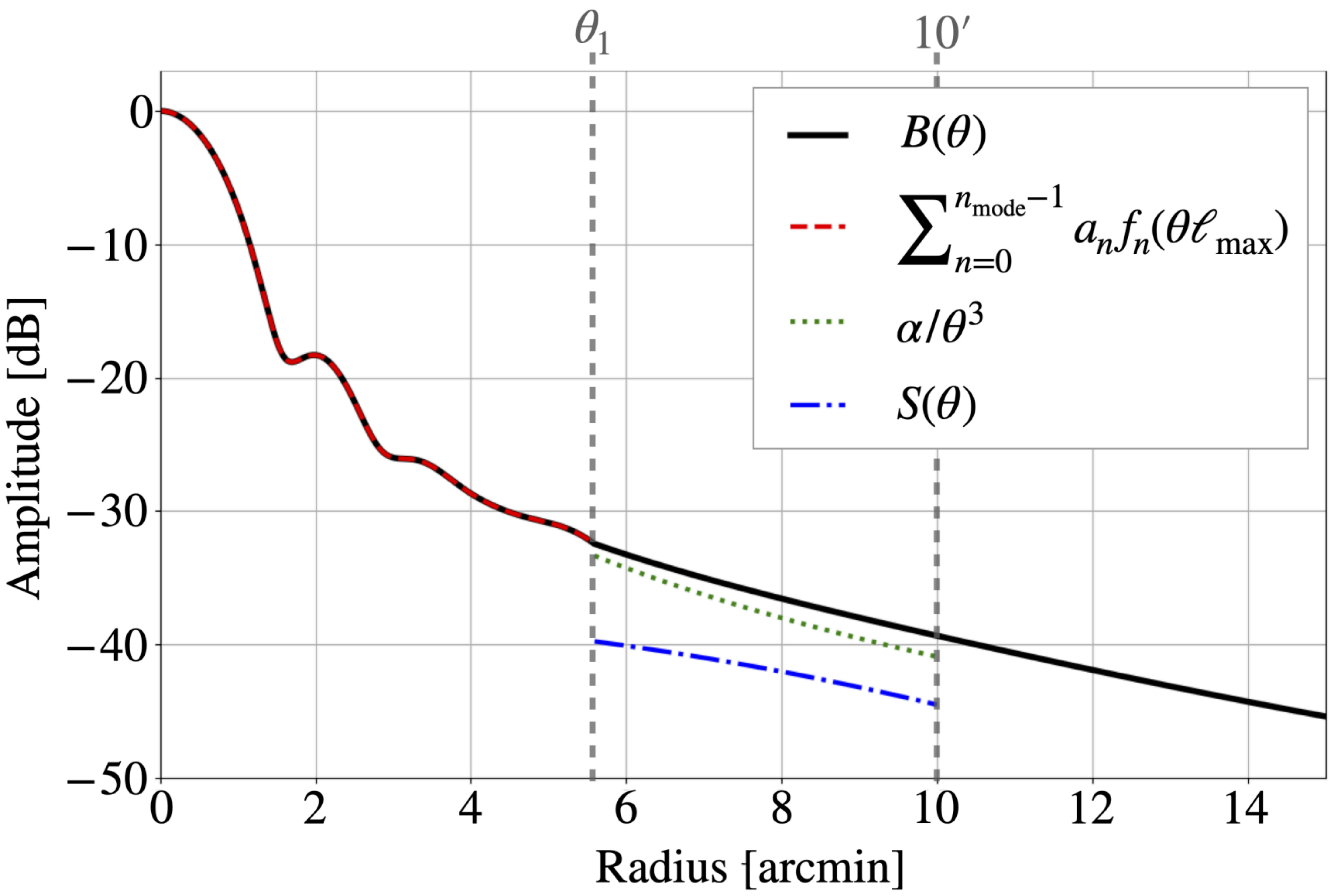


BEAM MODEL



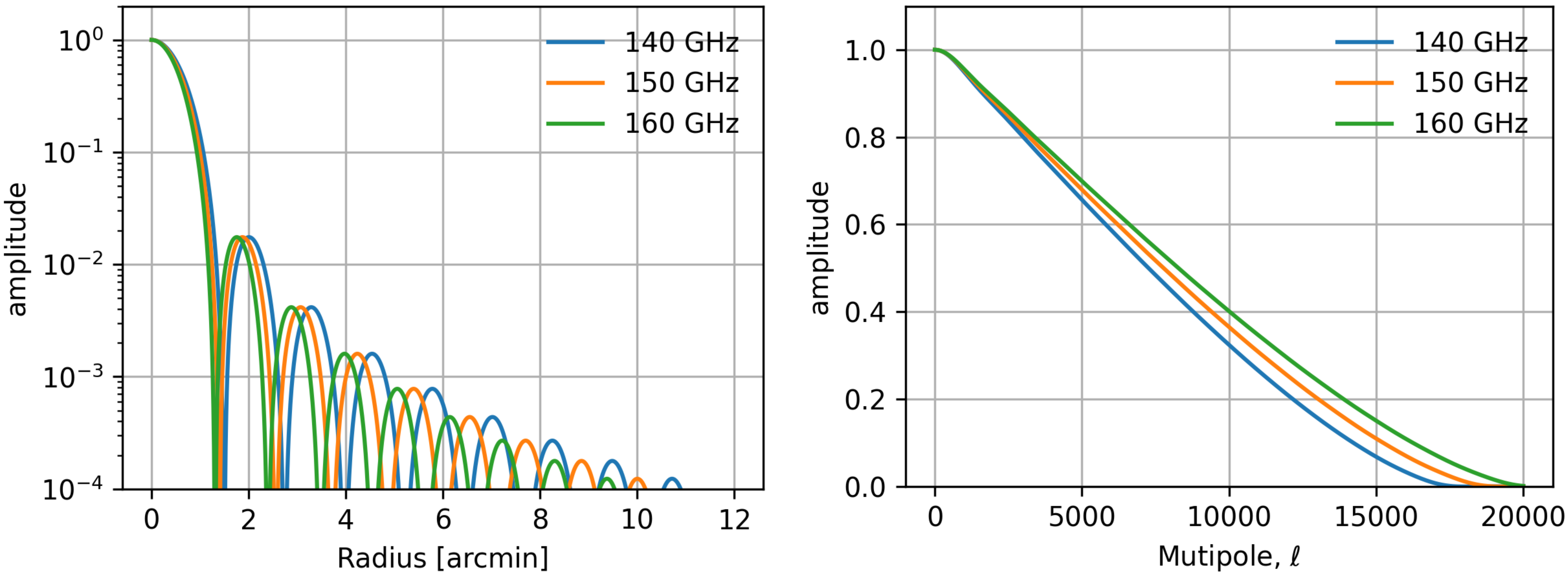
- Core fitted by $f_n(\theta) = \dfrac{J_{2n+1}(\theta\ell_{\mathrm{max}})}{\theta\ell_{\mathrm{max}}}$
- Outer region: $\dfrac{\alpha}{\theta^3}$
- Scattering term $S(\theta)$ to account for roughness of the primary's surface

From Lungu et al, 2022 (2112.12226)

COLOR CORRECTIONS

- Example: Airy disk for $D = 6$ meter telescope

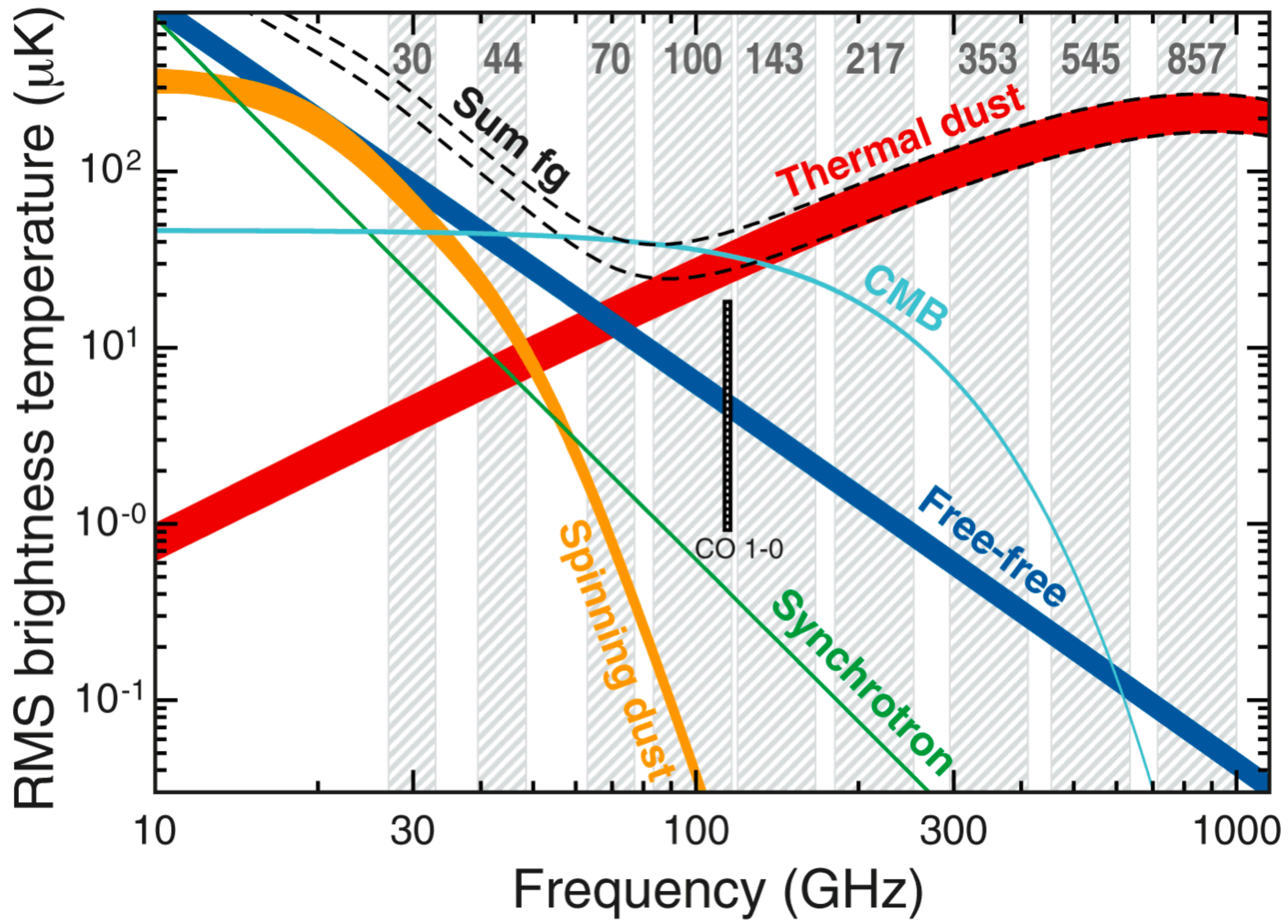
$$B(\theta) = \left[\frac{2J_1[k(D/2)\sin\theta]}{k(D/2)\sin\theta}\right]^2$$



COLOR CORRECTIONS

- Equation for general beam convolved signal calibrated in CMB temperature units

- $d_{\ell m} = \dfrac{\int B_\ell(\nu)\, s_{\ell m}(\nu)\, \nu^{-2}\, \tau(\nu)\, \mathrm{d}\nu}{\int b'_\nu\, \nu^{-2}\, \tau(\nu)\, \mathrm{d}\nu}$
  - $d_{\ell m}$: data
  - $B_\ell(\nu)$: monochromatic beam
  - $s_{\ell m}(\nu)$: signal (surface brightness in $\mathrm{W/m^2/Hz/sr}$)
  - $b'_\nu = \left.\dfrac{\partial B_\nu}{\partial T}\right|_{T_{\mathrm{CMB}}}$
  - $\tau(\nu)$: passband



ESA/Planck

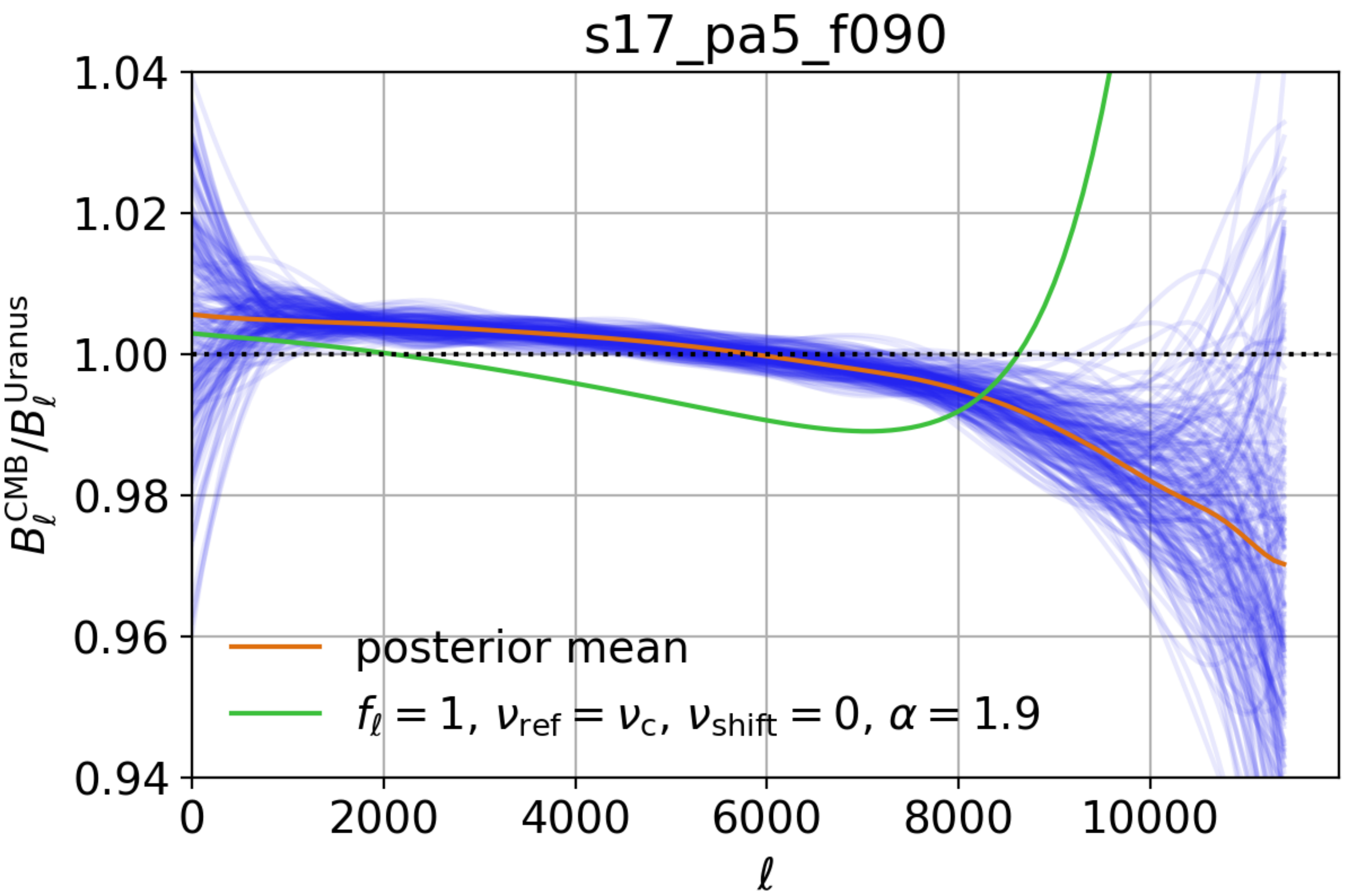
FREQUENCY DEPENDENCE OF BEAM

- Infer what $B_\ell(\nu)$ is from the data
- Ansatz: $B_\ell(\nu) = (f\,B^{\mathrm{Uranus}})_{\ell(\nu/\nu_r)^{-\alpha/2}}$
  - $f: \mathcal{O}(1\%)$ correction that is slowly varying over multipoles
  - (Reasonable) reference frequency ν_r can be picked freely (choice will be absorbed in f_ℓ)

FREQUENCY DEPENDENCE OF BEAM

- Ansatz: $B_\ell(\nu) = (f\,B^{\text{Uranus}})_{\ell(\nu/\nu_r)^{-\alpha/2}}$
- Find f_ℓ such that forward-modeled Uranus beam $\frac{\int B_\ell(\alpha, f, \nu)\,\nu^2\,\nu^{-2}\tau(\nu)\mathrm{d}\nu}{\int \nu^2\,\nu^{-2}\tau(\nu)\mathrm{d}\nu}$ best approximates measured Uranus beam B_ℓ^{Uranus}
- Place prior on α centered on GRASP results and impose $\alpha < 2$
- Jointly sample f_ℓ, α, beam measurement uncertainty and passband frequency shifts

FREQUENCY DEPENDENCE OF BEAM

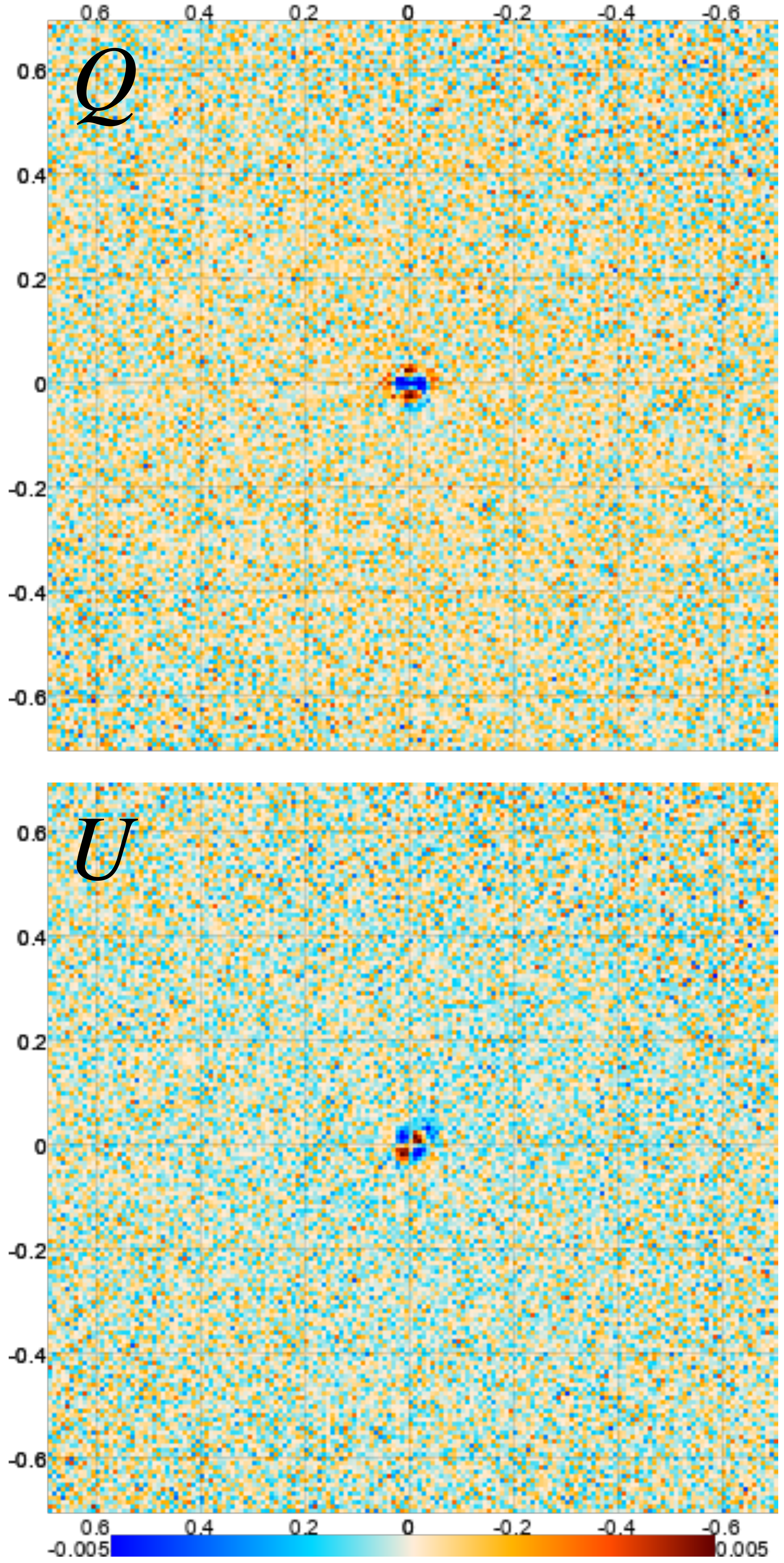


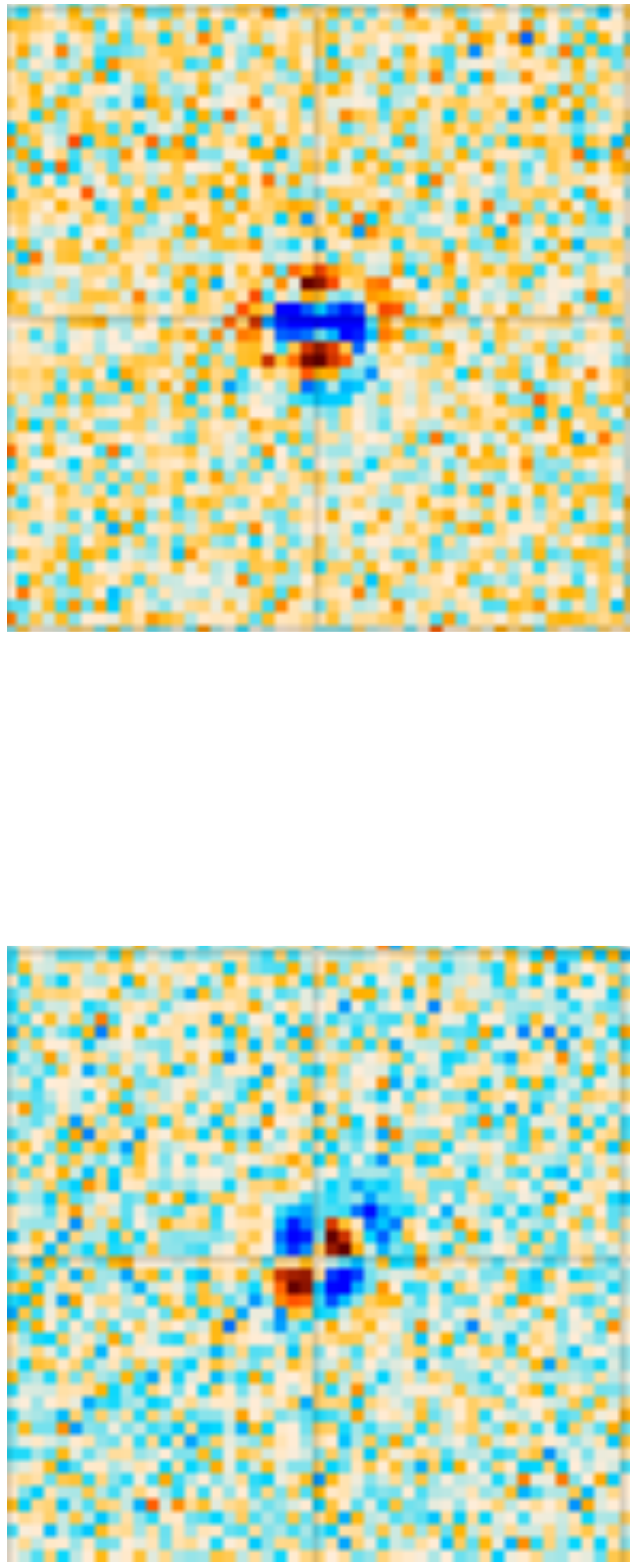
LESSONS LEARNED – COLOR CORRECTIONS

- Frequency dependence of beam is an important effect for ACT
  - ~1% effect at $\ell \sim 3000$, ~10% corrections at ACTs angular band limit
  - Implemented in ACT's sky component separation methods
    - Madhavacheril et al, 2020 (1911.05717) and Coulton et al., 2023 (2307.01258)
  - Implemented in ACT DR6 power spectrum likelihood. Important for extragalactic foregrounds
- Crucial to have a good prior on the frequency dependence of the beam. This is where e.g. GRASP simulations can play an important role

TEMPERATURE-TO-POLARIZATION LEAKAGE

- Power spectrum null tests detect non-zero T->E leakage at $\ell < 1500$
    - Planet mapmaker does not suffice (maps too small) → go back to maximum likelihood maps





0.7 $\deg^2$ maximum-likelihood maps of ~ 25 Uranus observations

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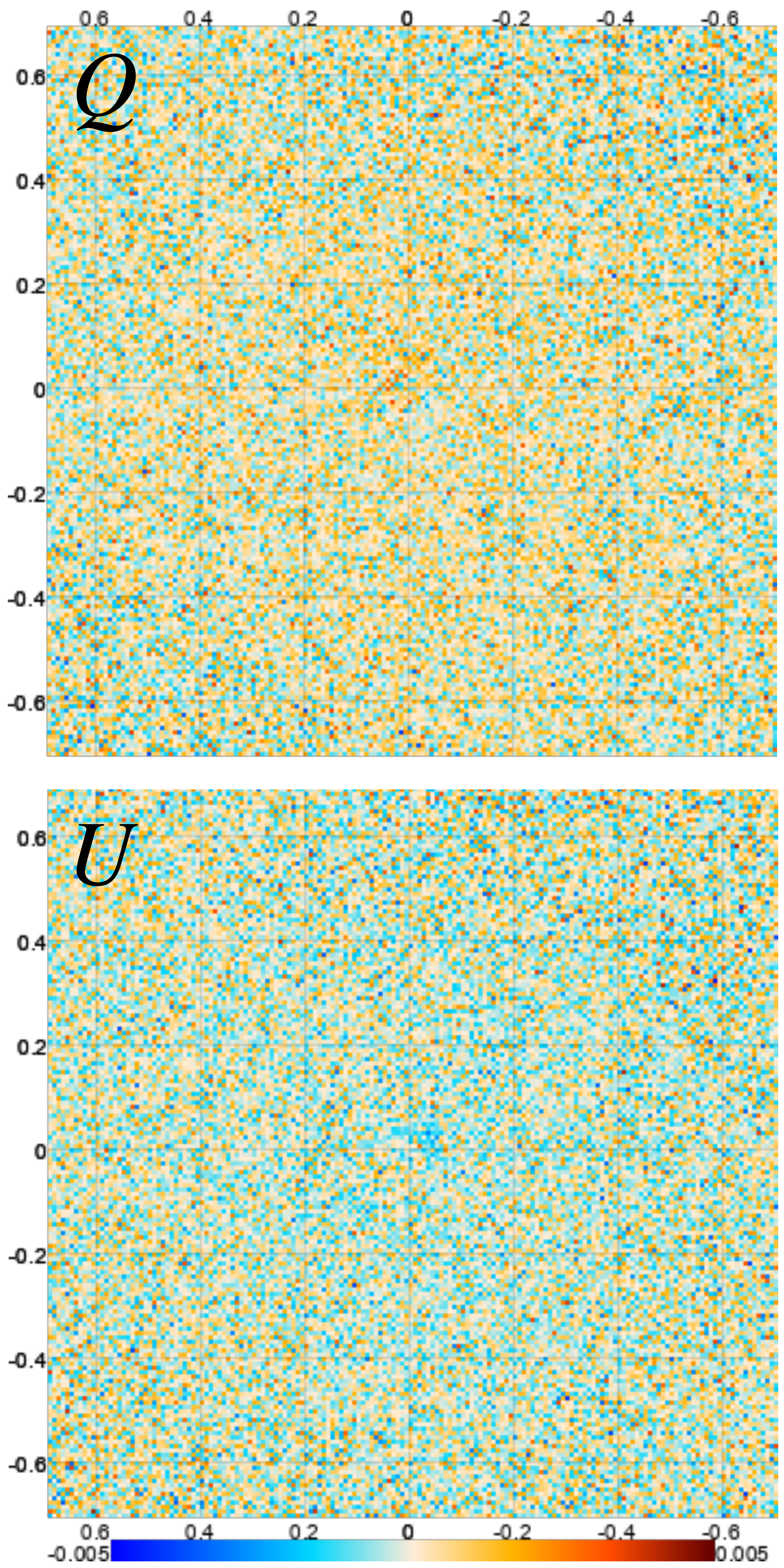

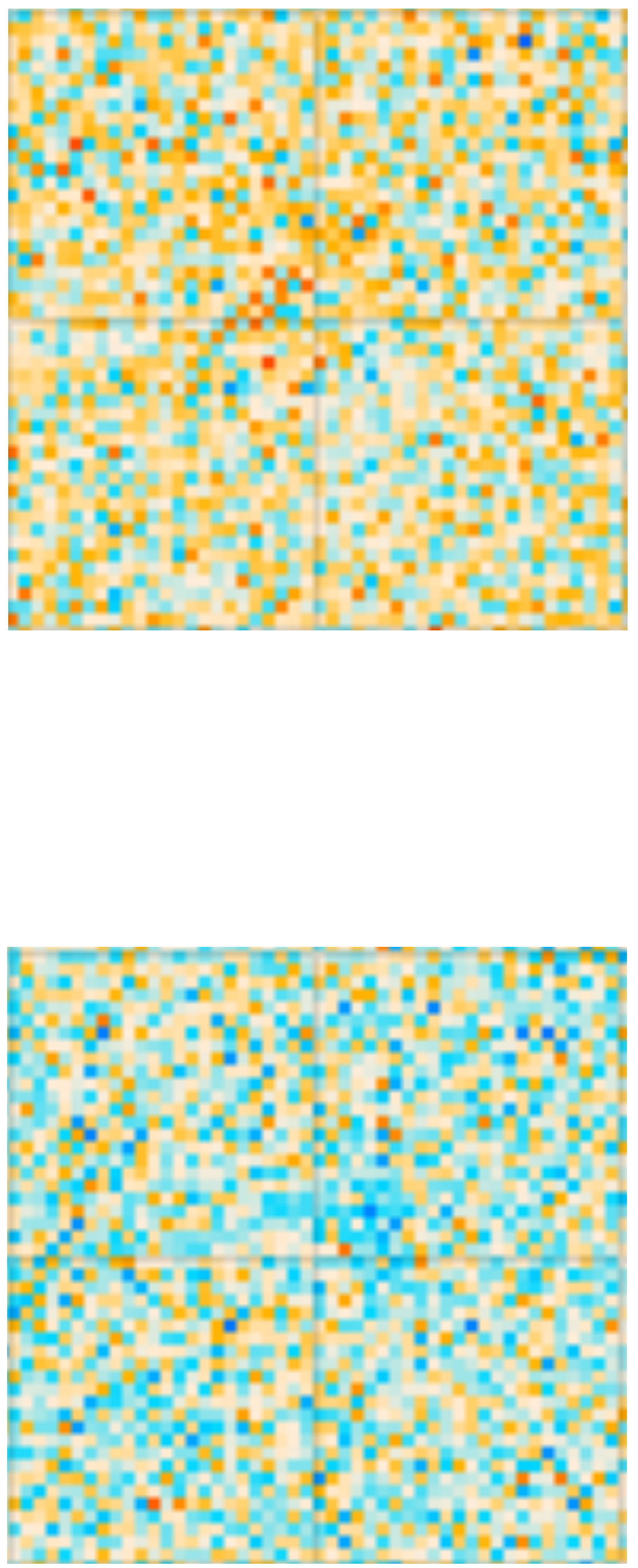

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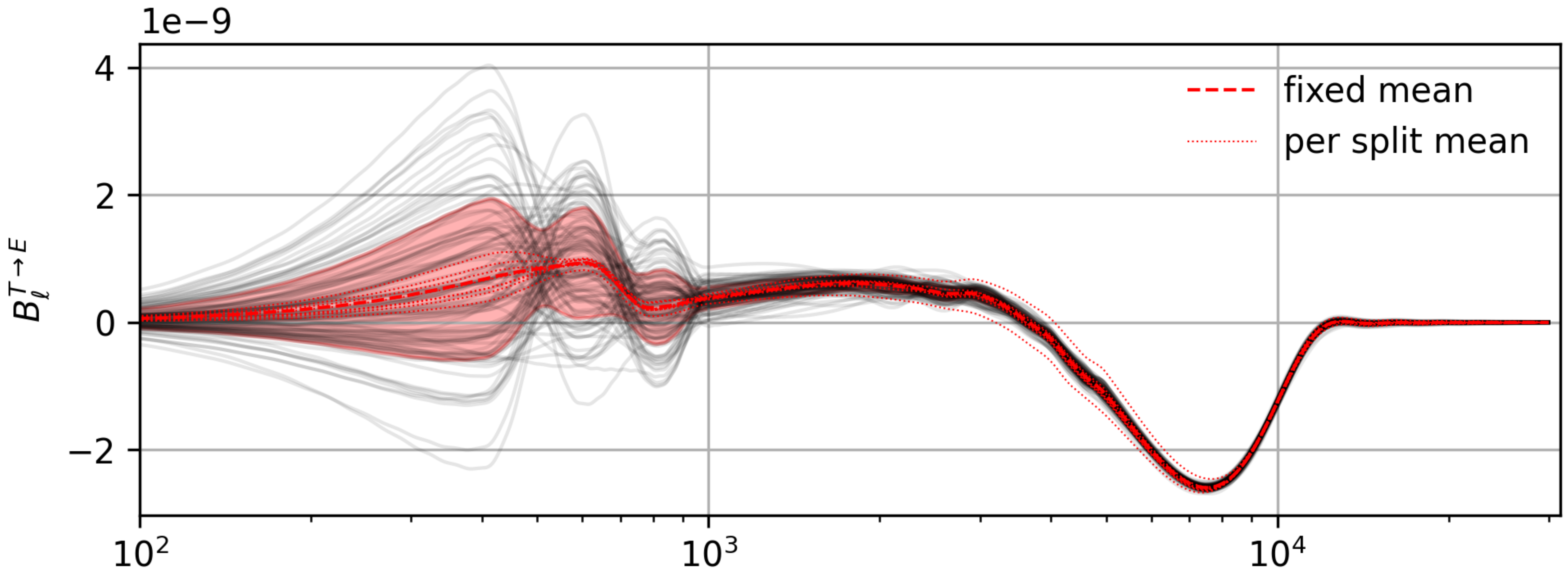
SIMPLE GAUSSIAN LIKELIHOOD

- $\bar{B}(\hat{\mathbf{n}}) = W \sum_i \bar{\alpha}_i f_i(\hat{\mathbf{n}})$
  - W : pixel window function
  - $\bar{\alpha}_i, f_i(\hat{\mathbf{n}})$: coefficients and beam basis functions
- $-2 \log P(\bar{\alpha}_i \,|\, d) \propto \sum_{j \in \text{splits}} \left[d^j(\hat{\mathbf{n}}) - W \sum_i \bar{\alpha}_i f_i(\hat{\mathbf{n}}) \right]^\top N_j^{-1} \left[d^j(\hat{\mathbf{n}}) - W \sum_i \bar{\alpha}_i f_i(\hat{\mathbf{n}}) \right] - 2 \log P(\bar{\alpha}_i)$

SIMPLE GAUSSIAN LIKELIHOOD

- Uncertainty due to atmosphere + instrumental noise does not fully explain scatter from different splits → Leakage beam is not quite stable in time



BAYESIAN HIERARCHICAL MODEL

- $P(\bar{\alpha}_i \,|\, d) \propto \prod_{j \in \text{splits}} P(d^j \,|\, \bar{\alpha}_i) P(\bar{\alpha}_i)$

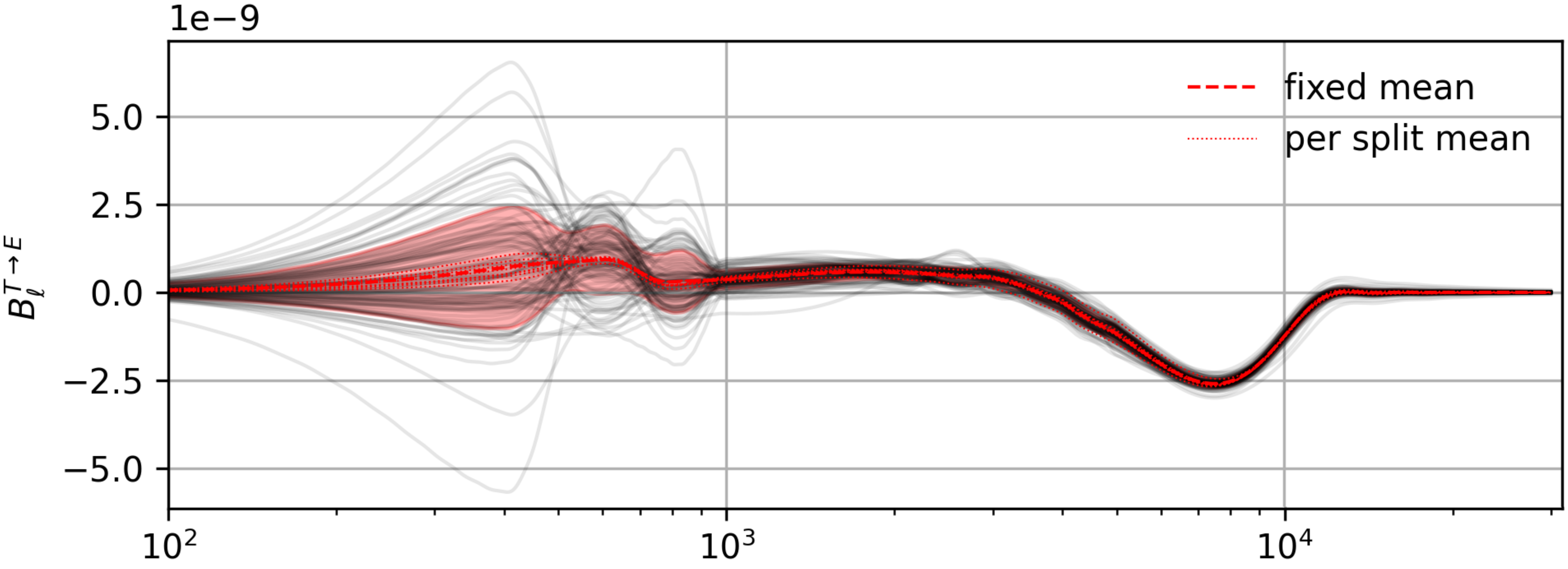
- $P(\bar{\alpha}_i, C \,|\, d) \propto \int \mathrm{d}\alpha_i^j \prod_{j \in \text{splits}} P(d^j \,|\, \alpha_i^j) P(\alpha_i^j \,|\, \bar{\alpha}_i, C) P(\bar{\alpha}_i) P(C)$

- Jointly estimate covariance matrix C that describes the scatter between observations

- Sampling ~1000 parameters with MCMC. Done using differentiable posterior (JAX) and Microcanonical Langevin Monte Carlo, Robnik, Seljak, 2024 (2303.18221)
  - Sampling takes a few minutes on single GPU

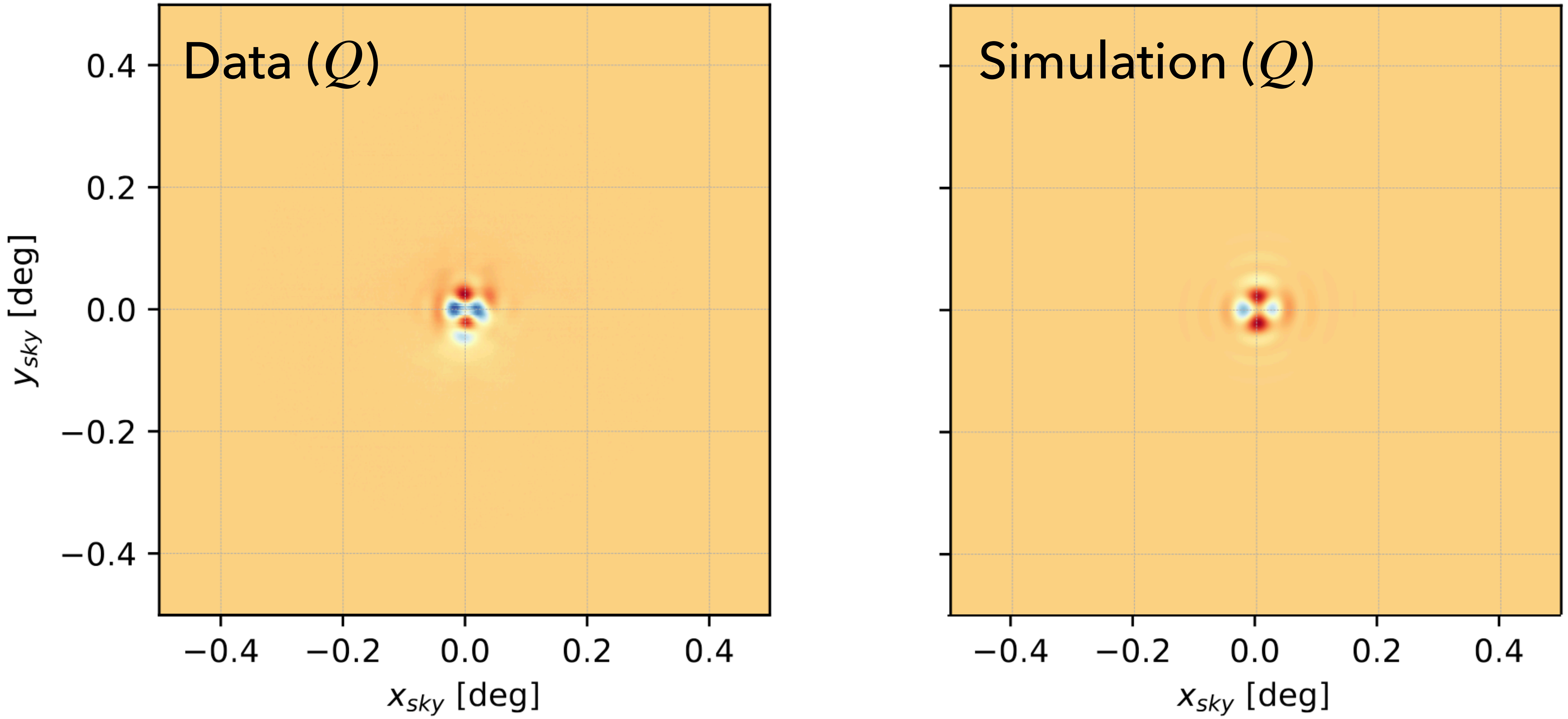
TEMPERATURE-TO-POLARIZATION LEAKAGE BEAMS

- Leakage estimates good enough to pass power spectrum null tests
- Uncertainty is significant part of power spectrum error budget at $\ell < 1500$



COMPARED TO SIMULATIONS

- Ongoing work by Roberto Puddu (Pontificia Universidad Católica de Chile)



GRASP simulation of single detector on the center of the focal plane

No gain errors simulated, just the mirrors and lenses

LESSONS LEARNED – CALIBRATION

- Difficult to get sub-percent gain errors with atmosphere flatfielding
  - Requires accurate per-detector passbands
- Few percent relative errors in detector gains cause low-ell transfer function
  - Strong case for dedicated gain calibration hardware
- Systematic error from uncertainties on passband shifts already exceed statistical errors for studies of the thermal Sunyaev-Zeldovich effect, e.g. Coulton, Duivenvoorden et al, 2024 (2410.19046)

LESSONS LEARNED - BEAMS

- Modeling errors during mapmaking have to be carefully dealt with when making maps of bright sources (in combination with atmospheric noise)
- Scale-dependent color-corrections are important, especially for studies of extragalactic secondaries
  - Difficult to get good estimate of $B_\ell(\nu)$. Future beam pipelines should jointly fit planets and point sources to make use of the different SEDs
- Optical simulations (or lab measurements) are required for frequency scaling beams and understanding of temperature-to-polarization leakage