Constraints on isotropic and anisotropic cosmic birefringence with POLARBEAR and future experiments

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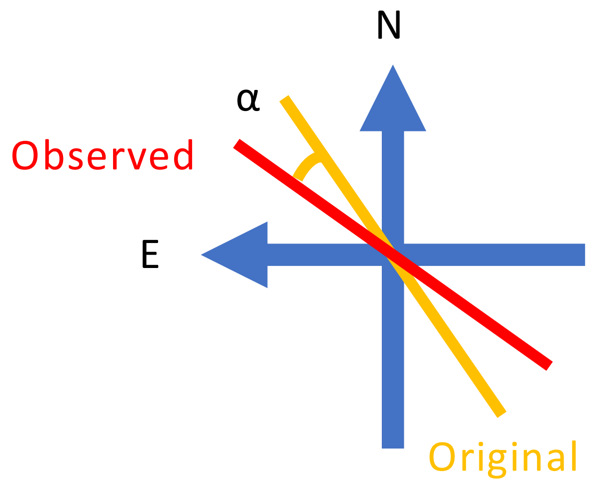
Outline

- General introduction to cosmic polarization rotation
- Isotropic rotation
- Anisotropic rotation
- Calibration methods and proposals
- Preliminary forecasts and final remarks

Cosmic polarization rotation (CPR)

- Photon's original polarization angle at the surface of last scattering gets rotated along a line of sight by some angle α
- CPR can occur in the Standard Model Extension (SME) with Lorentz-violating terms
- CPR can also occur due to Faraday rotation through magnetic fields (Galactic or primordial)

$$\begin{pmatrix} Q' \\ U' \end{pmatrix} = \begin{pmatrix} \cos(2\alpha) & -\sin(2\alpha) \\ \sin(2\alpha) & \cos(2\alpha) \end{pmatrix} \begin{pmatrix} Q \\ U \end{pmatrix}$$



General reference on SME and cosmic birefringence: Kostelecky and Mewes, PRD - 0905.0031

Isotropic rotation

- Every line of sight rotates by the same angle, related to one of the SME free parameters.
- Very easy to write down effect on the angular power spectrum
- Unfortunately, it is completely degenerate with a mis-calibration of the receiver’s polarization axes.

$$\alpha = \frac{k^{(3)}_{(V)00}}{\sqrt{4\pi}} \int_0^z \frac{dz'}{(1+z')H_{z'}}$$

$$\left\langle C_\ell^{TT,obs} \right\rangle = C_\ell^{TT} + N_\ell^{TT}$$

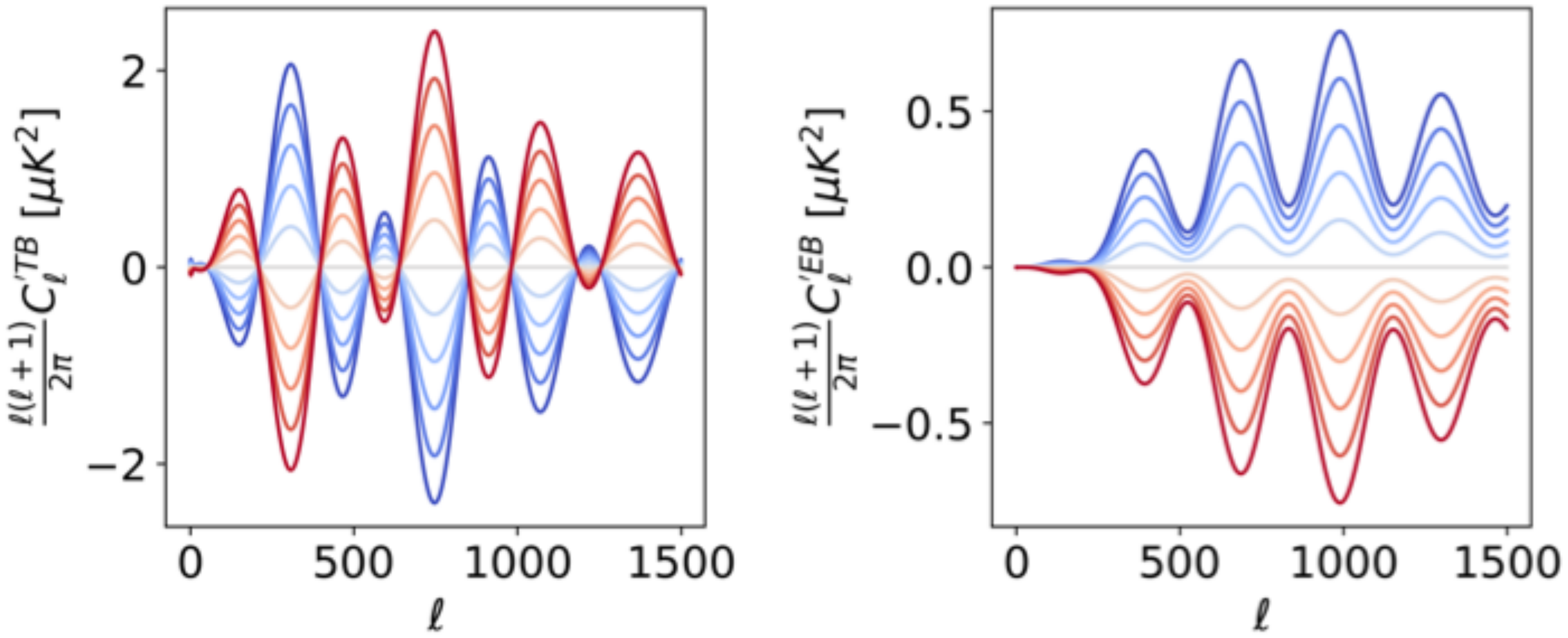
$$\left\langle C_\ell^{TE,obs} \right\rangle = C_\ell^{TE} \cos(2\alpha)$$

$$\left\langle C_\ell^{TB,obs} \right\rangle = -C_\ell^{TE} \sin(2\alpha)$$

$$\left\langle C_\ell^{EE,obs} \right\rangle = C_\ell^{EE} \cos^2(2\alpha) + C_\ell^{BB} \sin^2(2\alpha) + N_\ell^{PP}$$

$$\left\langle C_\ell^{BB,obs} \right\rangle = C_\ell^{BB} \cos^2(2\alpha) + C_\ell^{EE} \sin^2(2\alpha) + N_\ell^{PP}$$

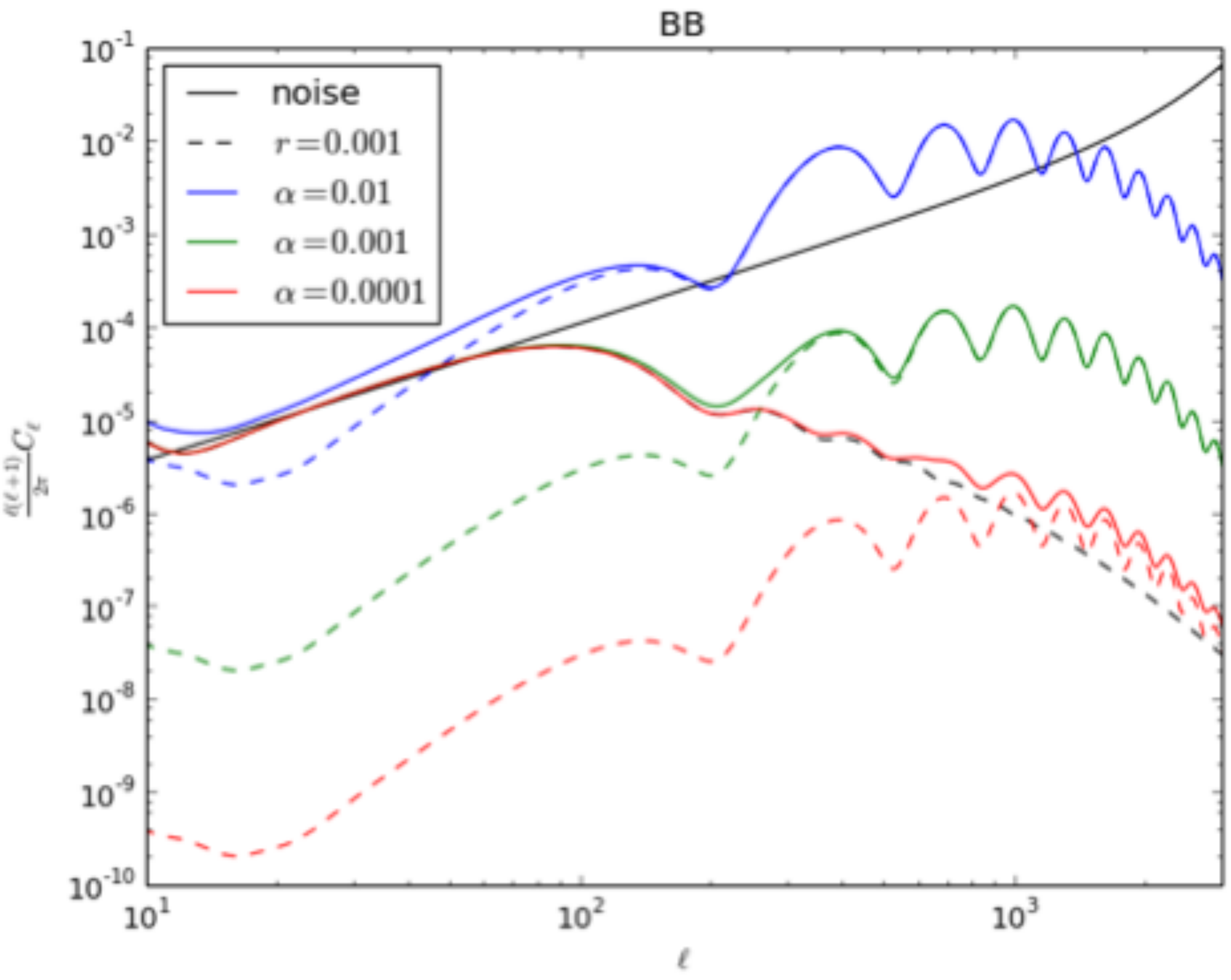
$$\left\langle C_\ell^{EB,obs} \right\rangle = -\frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right) \sin(4\alpha)$$



Effect of -2.5° (darkest blue) to +2.5° polarization rotation in 0.5° steps

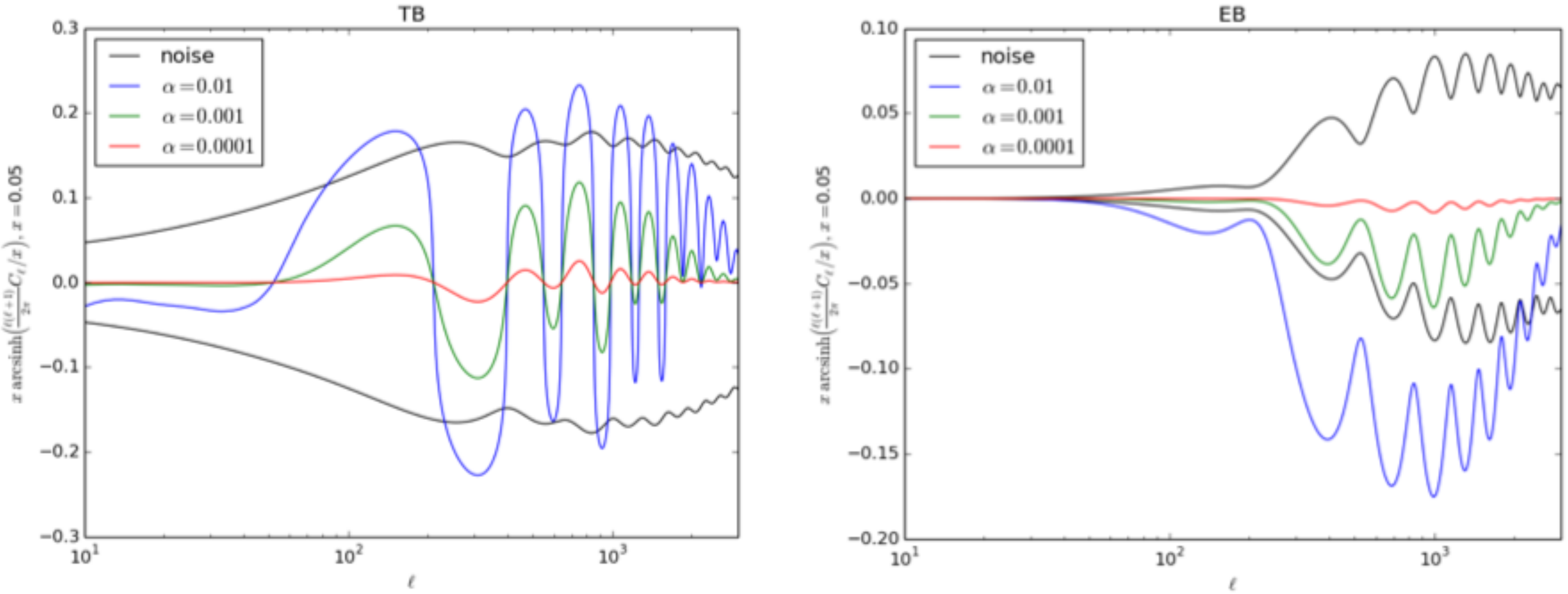
Plots by M. Navaroli

Assume a generic, idealized, future experiment with FWHM 2 arcmin beams and a noise level scaled to match the delensed BB spectrum of r=0.001 at l~80.



Plot by D. Leon

A rotation of α=0.01 radians (34 arcmin) would be detected in TB and EB, but this is the limit of calibration systematics of current experiments.



Plots by D. Leon

Note: The unusual sinh(x) scale of the y-axis in these plots provide a kind of signed logarithm that crosses zero linearly.

D-estimators

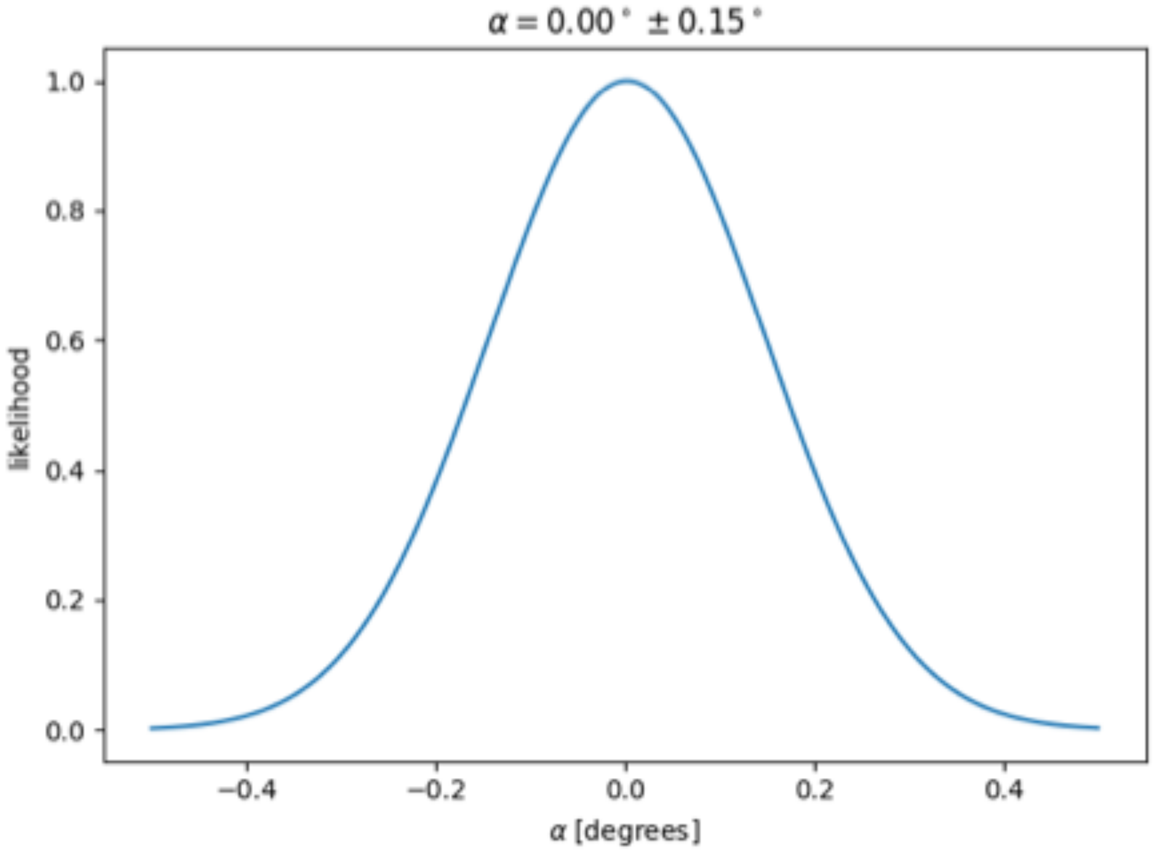
- It is possible to define a pair of estimators which should be zero (up to noise) for ANY input cosmology.
- Unbiased even with lensing
- Since the D-estimators are linear in the C_l, their covariance can also be expressed in terms of covariances of C_l, i.e. no need to run additional simulations.

$$D_\ell^{TB} = C_\ell^{TB,obs} \cos(2\alpha) + C_\ell^{TE,obs} \sin(2\alpha)$$
$$D_\ell^{EB} = C_\ell^{EB,obs} \cos(4\alpha) + \frac{1}{2}\left(C_\ell^{EE,obs} - C_\ell^{BB,obs}\right) \sin(4\alpha)$$

References:
Zhao et al., JCAP - 1504.04507
Gruppuso et al., JCAP - 1604.05202
Molinari et al., Physics of the Dark Universe - 1605.01667

POLARBEAR self-calibration

- POLARBEAR rotates the apparent rotation until the χ^2 is minimized.
- This means that the experiment is insensitive to isotropic rotation, but there is no risk of mis-calibration.



Plot by D. Leon

$$\chi^2 = \begin{pmatrix} D_\ell^{TB} & D_\ell^{EB} \end{pmatrix} \begin{pmatrix} \mathrm{cov}\left(D_\ell^{TB}, D_{\ell'}^{TB}\right) & \mathrm{cov}\left(D_\ell^{TB}, D_{\ell'}^{EB}\right) \\ \mathrm{cov}\left(D_\ell^{EB}, D_{\ell'}^{TB}\right) & \mathrm{cov}\left(D_\ell^{EB}, D_{\ell'}^{EB}\right) \end{pmatrix}^{-1} \begin{pmatrix} D_{\ell'}^{TB} \\ D_{\ell'}^{EB} \end{pmatrix}$$

Anisotropic rotation

- Rotation angle varies along different lines of sight.
- Associated with axion-like pseudoscalars or primordial magnetic fields
- Constraints come from both direct stress-energy contribution to C_l and from reconstructed angle (similar to lensing).

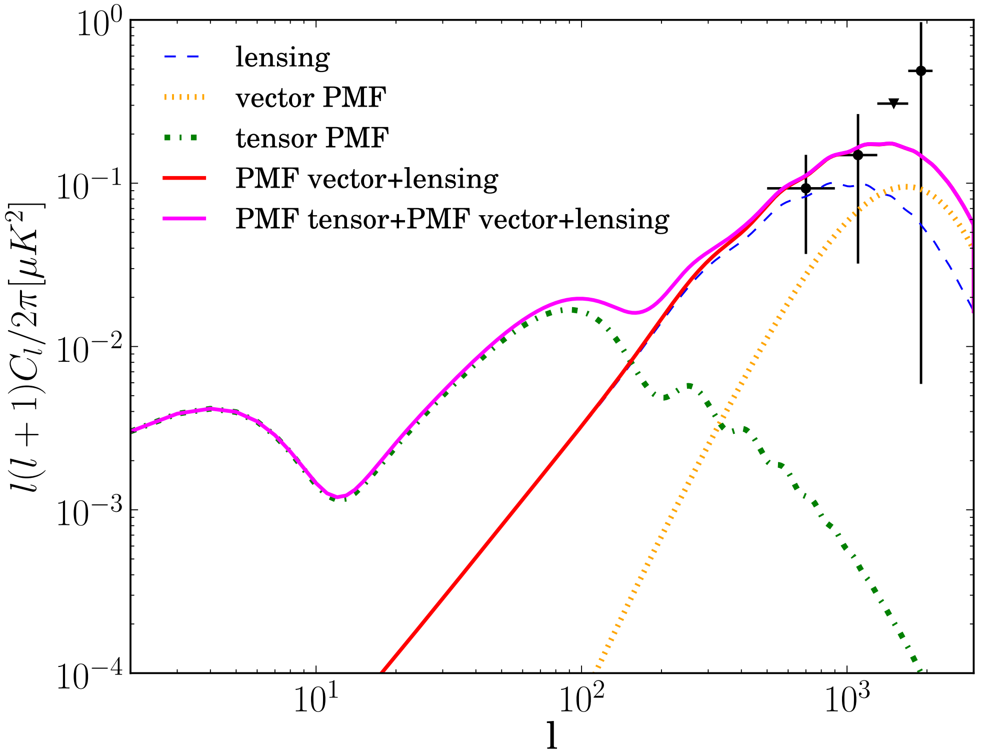
$$\mathcal{L} = \frac{\phi}{2M} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \alpha = \frac{1}{M}\int \dot{\phi}\, d\eta$$

$$\alpha(\hat{\mathbf{n}}) = \frac{3c^2}{16\pi^2 e}\nu^{-2}\int \dot{\tau}\,\mathbf{B}\cdot d\mathbf{l}$$

$$\alpha_{EB}(\mathbf{L}) = A_{EB}(L)\int E(\mathbf{l})B(\mathbf{l}')\frac{2\tilde{C}_l^{EE}\cos 2\phi_{\mathbf{l}\mathbf{l}'}}{C_l^{EE}C_{l'}^{BB}}\frac{d^2\mathbf{l}}{(2\pi)^2}$$

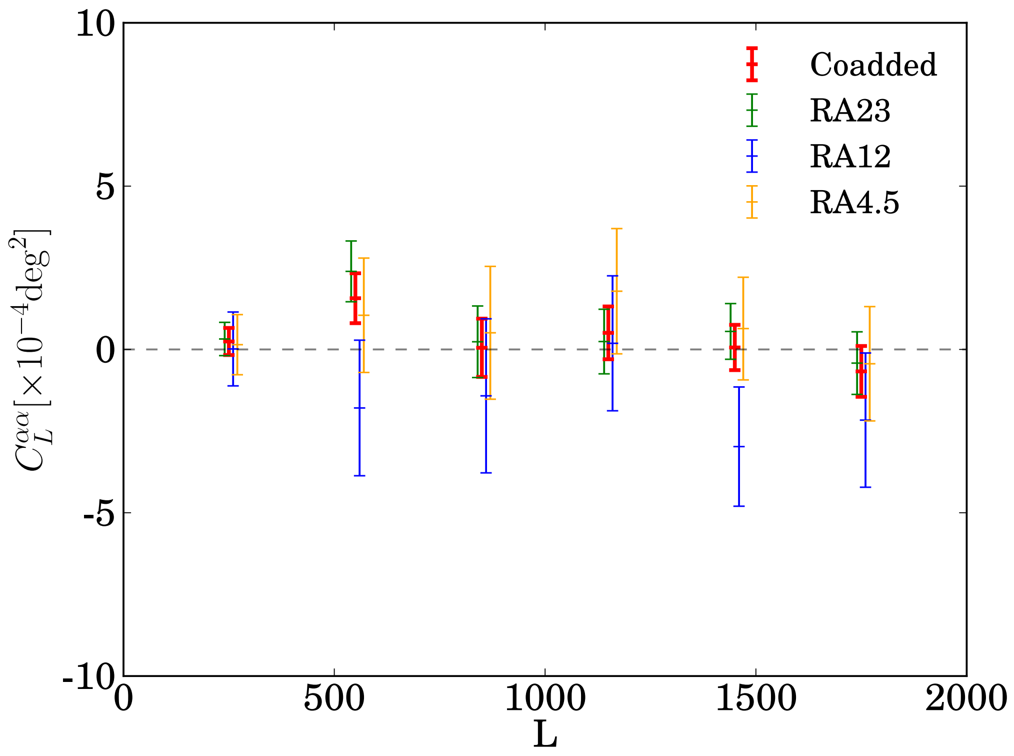
Constraints from BB

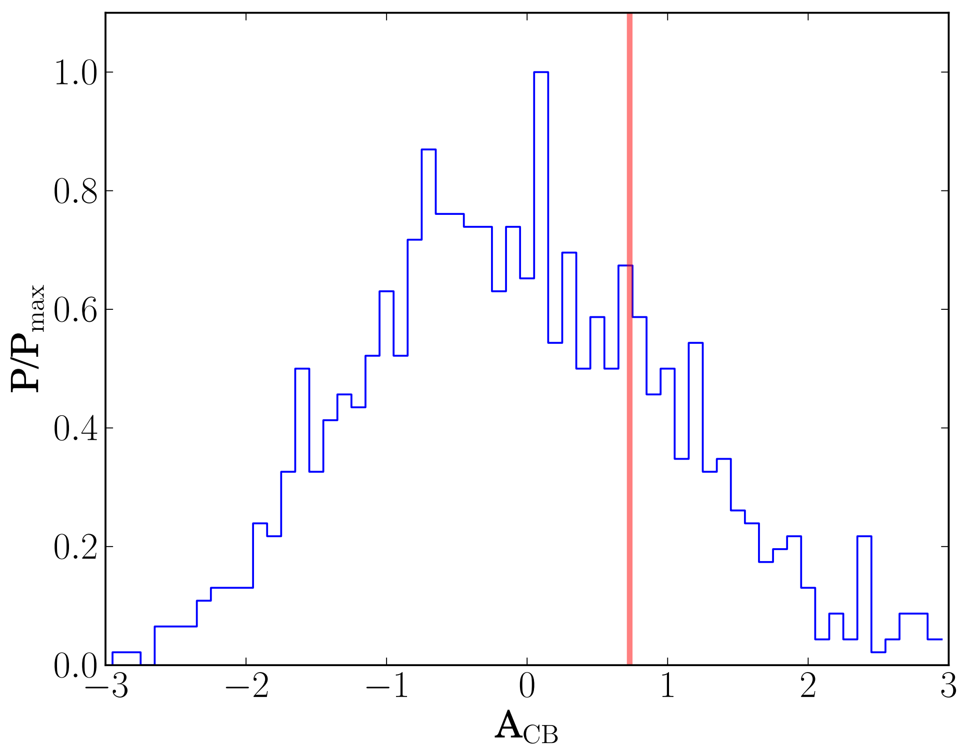
- The best constraints come from regular, on-diagonal measurement of BB.
- Tensor contribution from PMF would look just like r.
- Constraint corresponds to PMF of **B<3.9 nG** on 1 Mpc scales (or B<4.5 nG with different prior).
- Effect scales as ~B^4, so this method is mostly exhausted.



POLARBEAR Collaboration (corresp. C. Feng) - 1509.02461

Constraints from α reconstruction



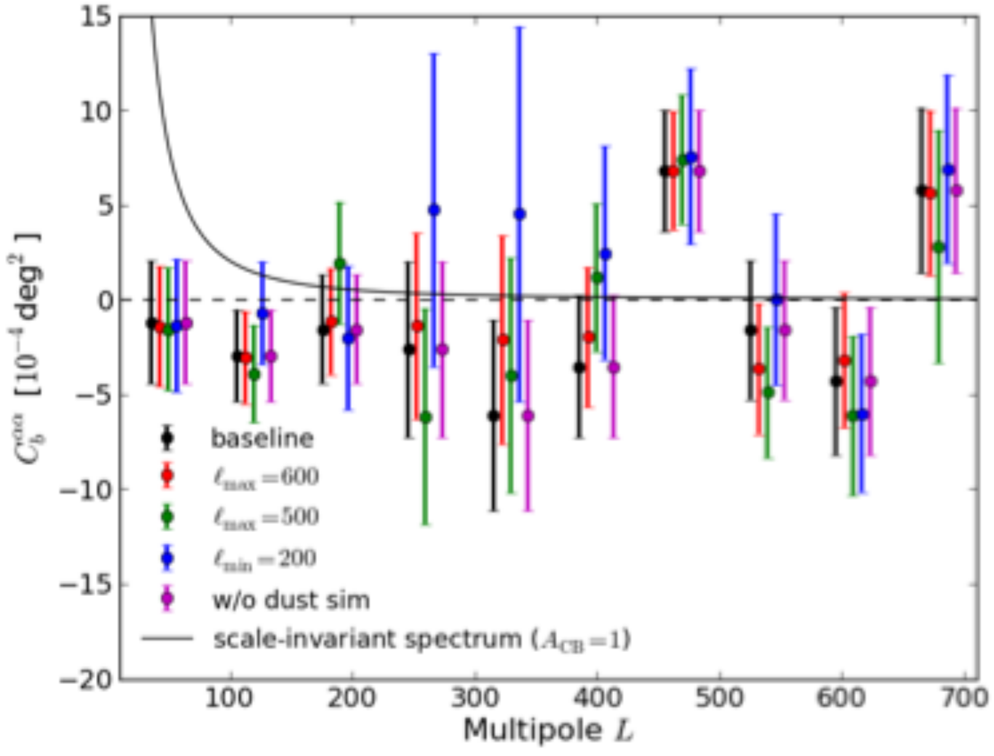


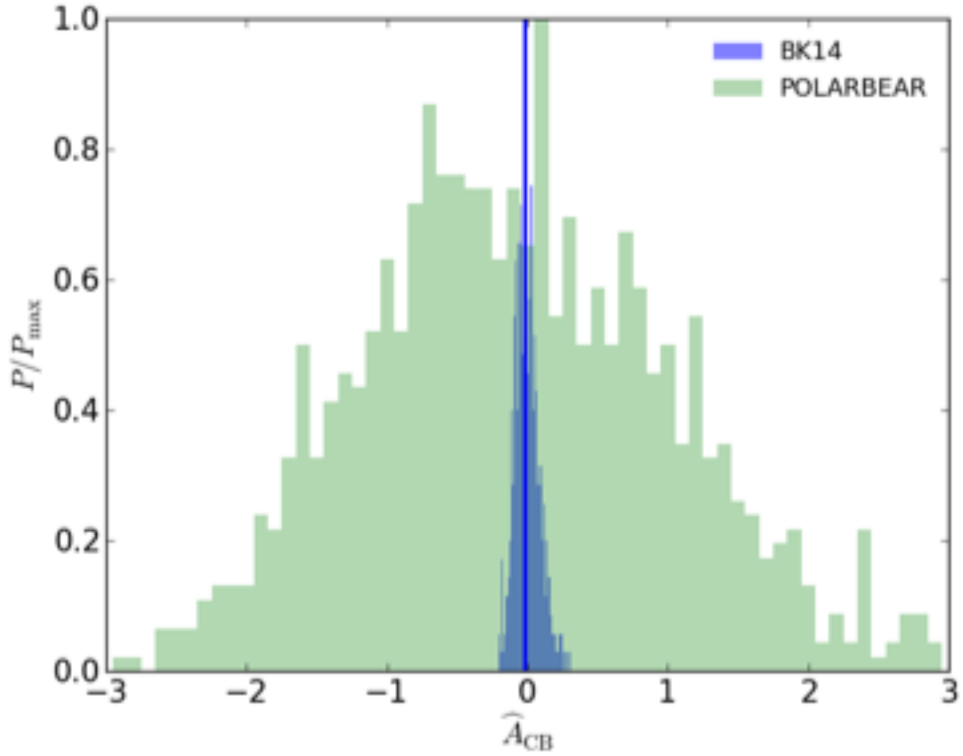
PMF **B<93 nG** on 1 Mpc scales

POLARBEAR Collaboration (corresp. C. Feng) - 1509.02461

Scales as ~B^2, so room to improve

Constraints from α reconstruction





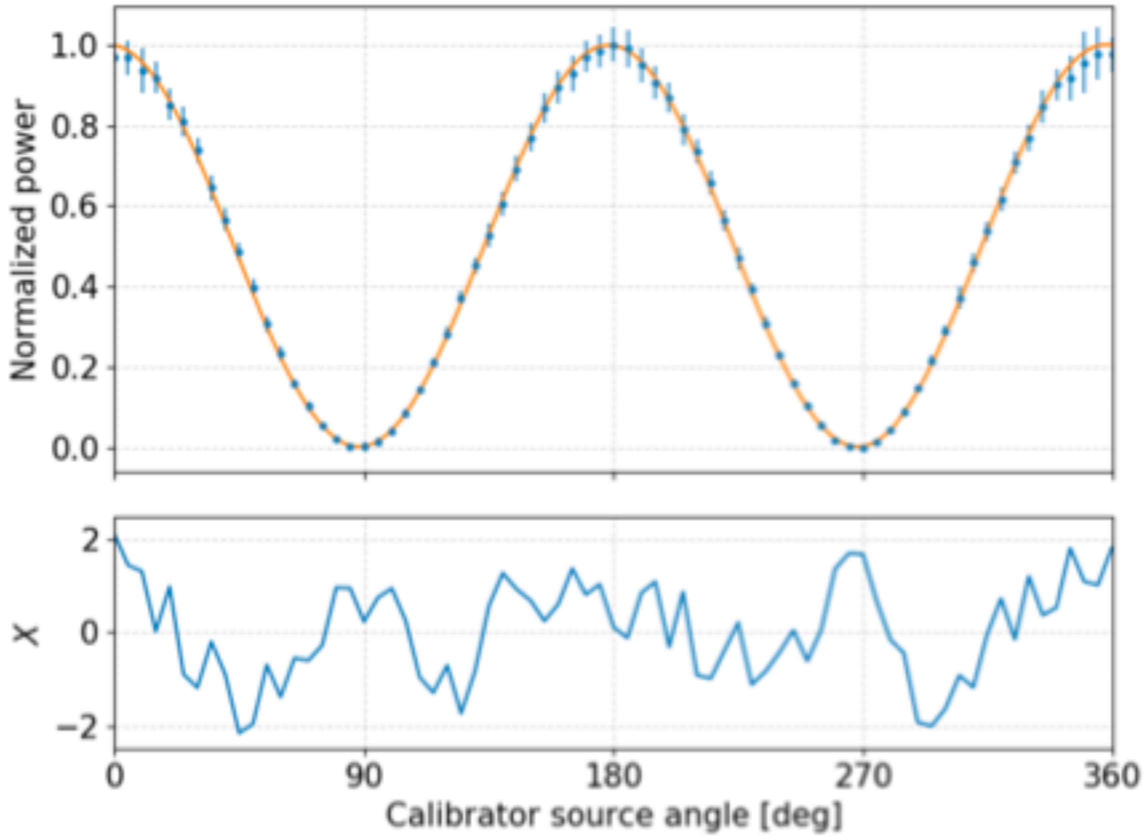
PMF **B<30 nG** on 1 Mpc scales

BICEP2 / Keck Array (corresp. T. Namikawa) - 1705.02523

Scales as ~B^2, so room to improve

Angle calibration

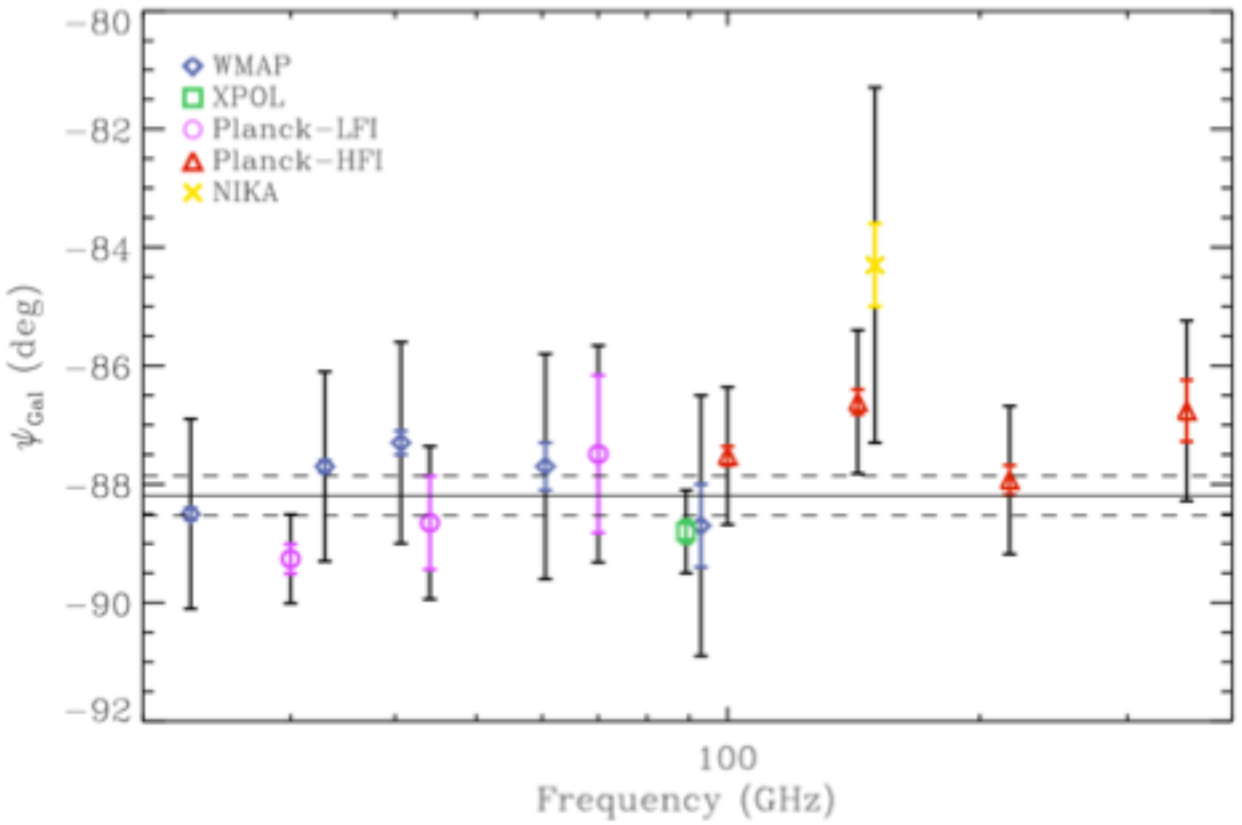
- No published constraints better than ~0.5° because multiple calibration methods often disagree
- Ideal calibrations would reference to a controlled, far field point source.
- Ground-based rotating polarized source demonstrated in lab to ~0.1° but not field proven.



Plot by M. Navaroli

Tau A as a reference calibrator

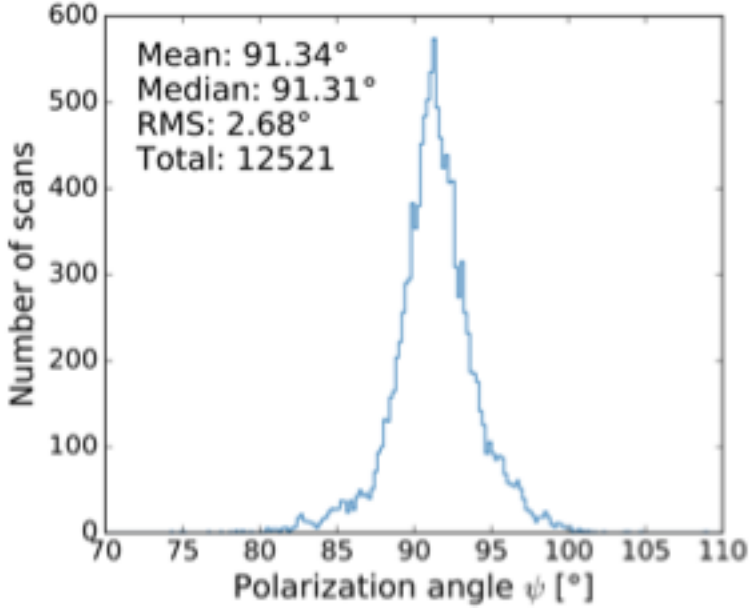
- Multiple microwave telescopes with independent, controlled ground calibrations have measured Tau A.
- Combining them results in an overall uncertainty of ±0.33°.
- Tau A can help cross-calibrate Chilean telescopes but is below the horizon at South Pole.



Aumont et al., submitted to A&A - 1805.10475

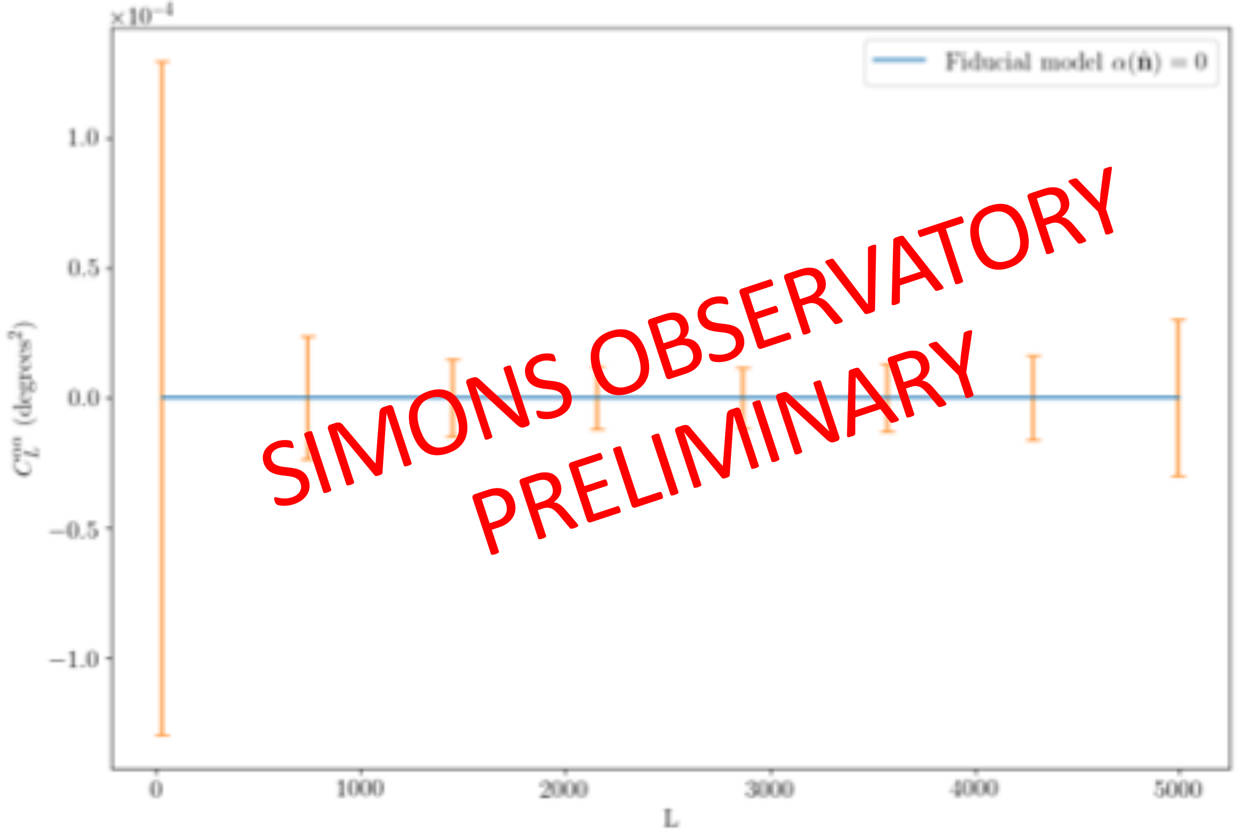
Future calibrations

- Proposal for drone or balloon-based calibrator referenced by a star camera instead of gravity: Nati et al., J. Astron. Instrum. - 1704.02704
- Polarbear with a half-wave plate detects nearly horizontally polarized clouds (in prep, led by S. Takakura).



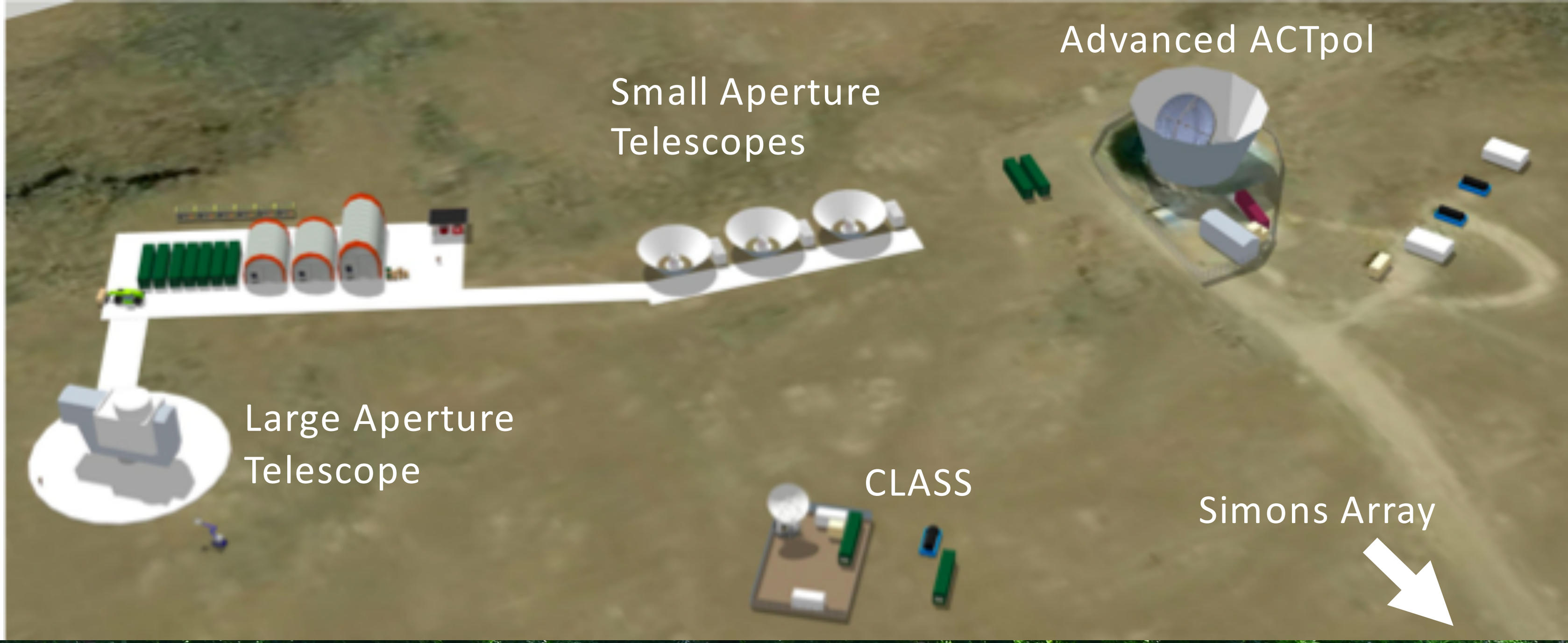
Final remarks, forecasts

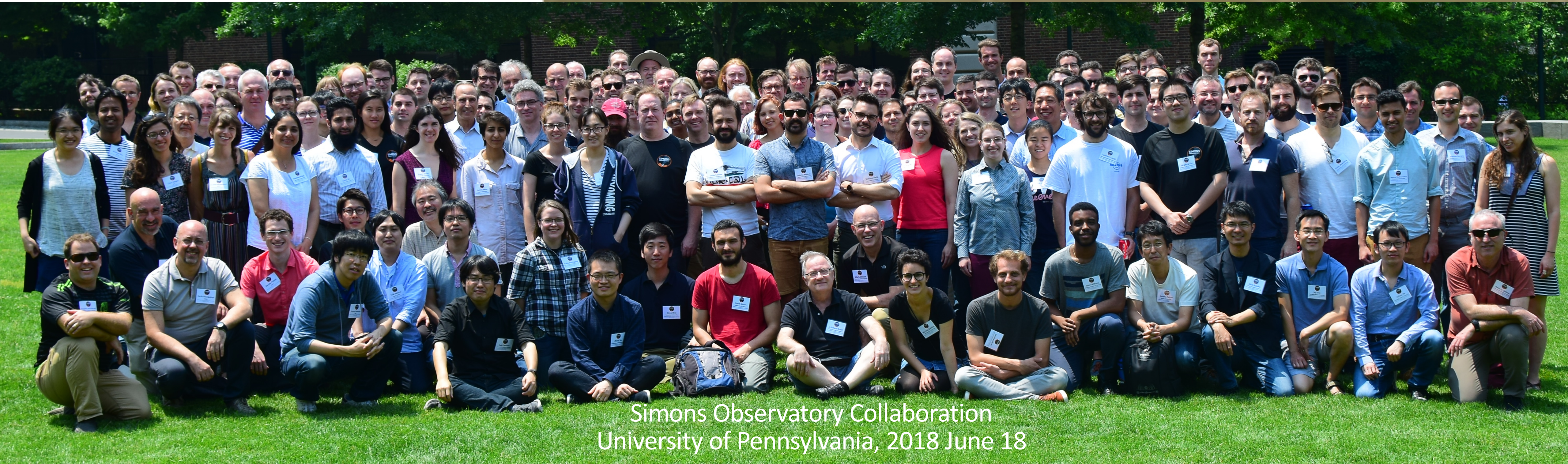
- Simons Observatory noise studies are ongoing, but ~10x improvement to σ(α) plausible.
- Calibration uncertainties must improve below <0.1° to continue probing α≠0.
- Errors on anisotropic rotation also likely to improve by ~10x.
- We need more study in relation to lensing and foregrounds.



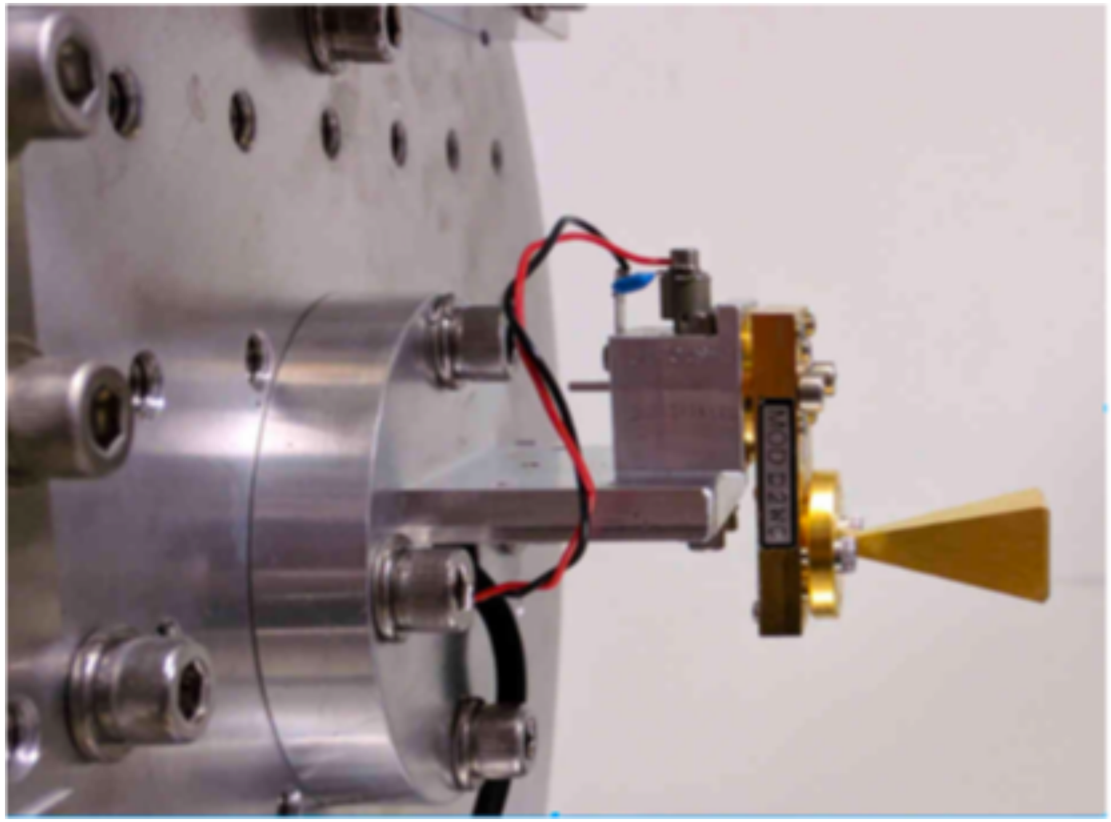
Preliminary plot by C. J. Williams

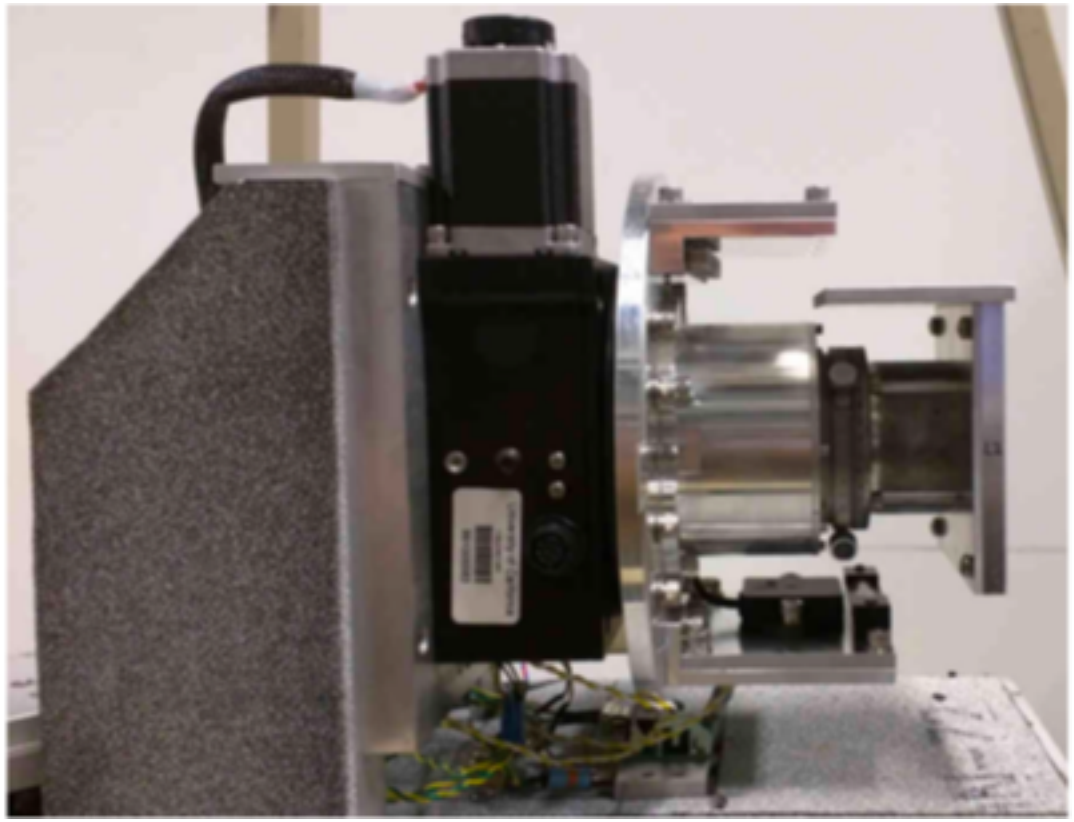
Thank you, and stay tuned!

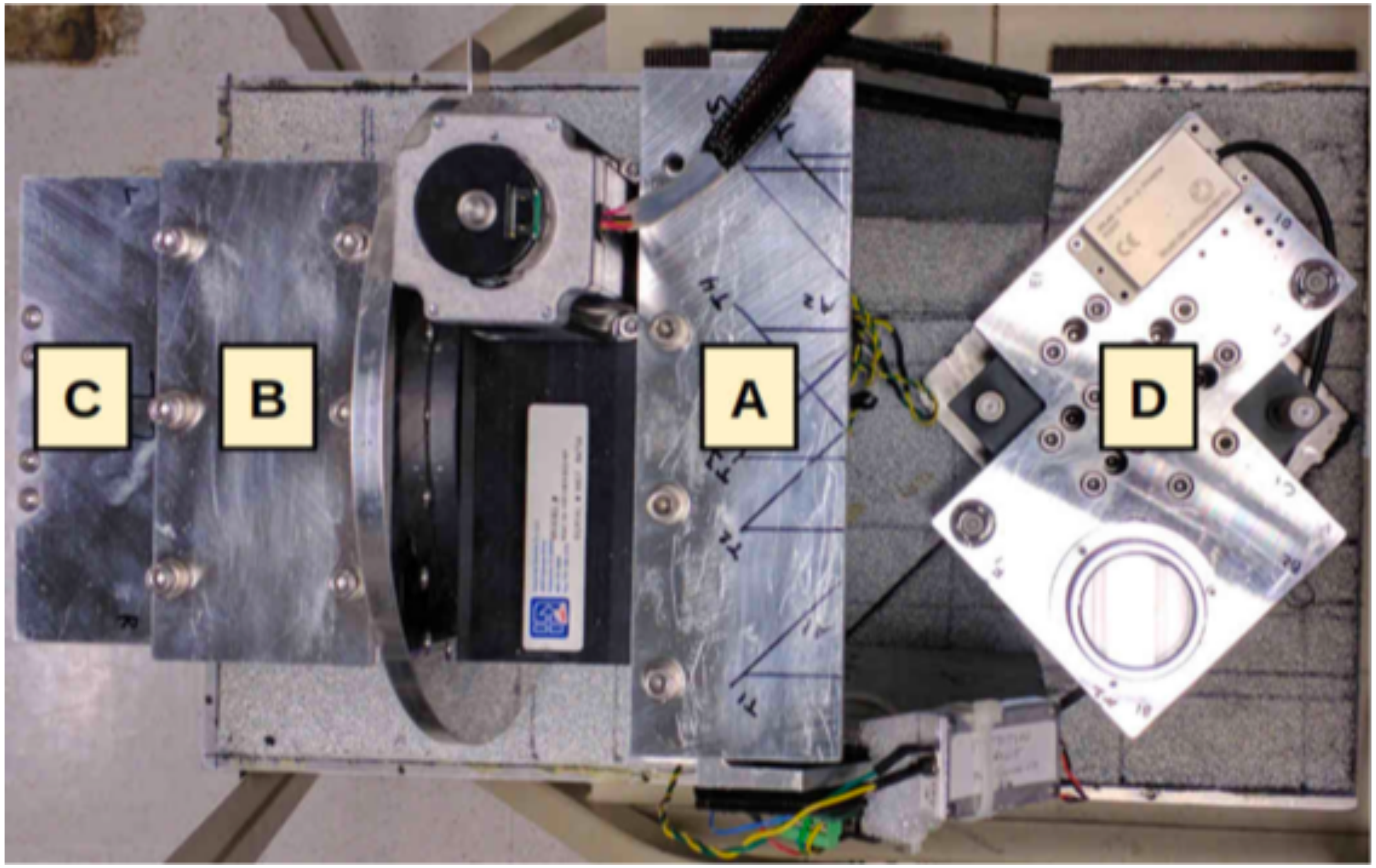


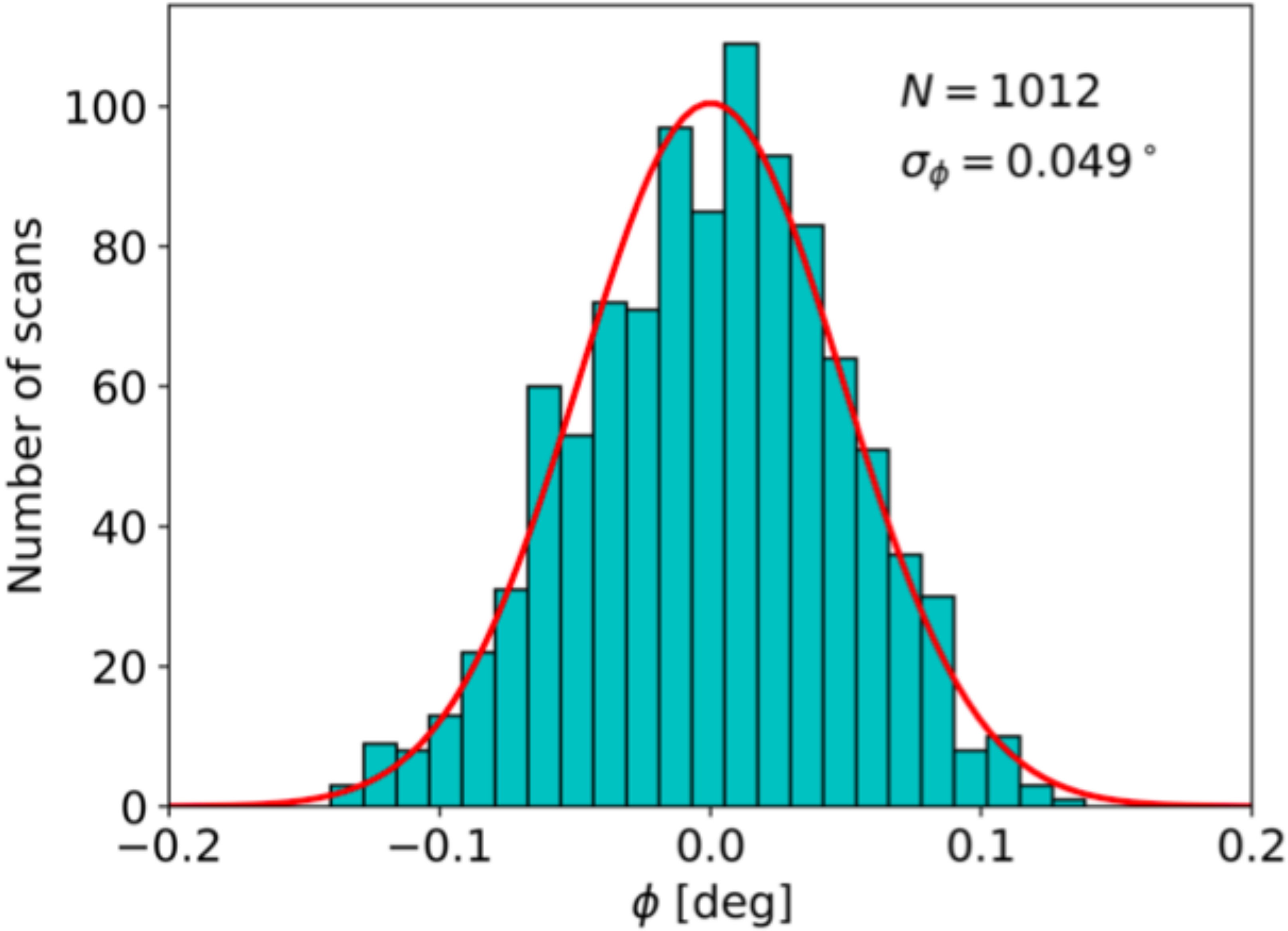


Backup






C
B
A
D

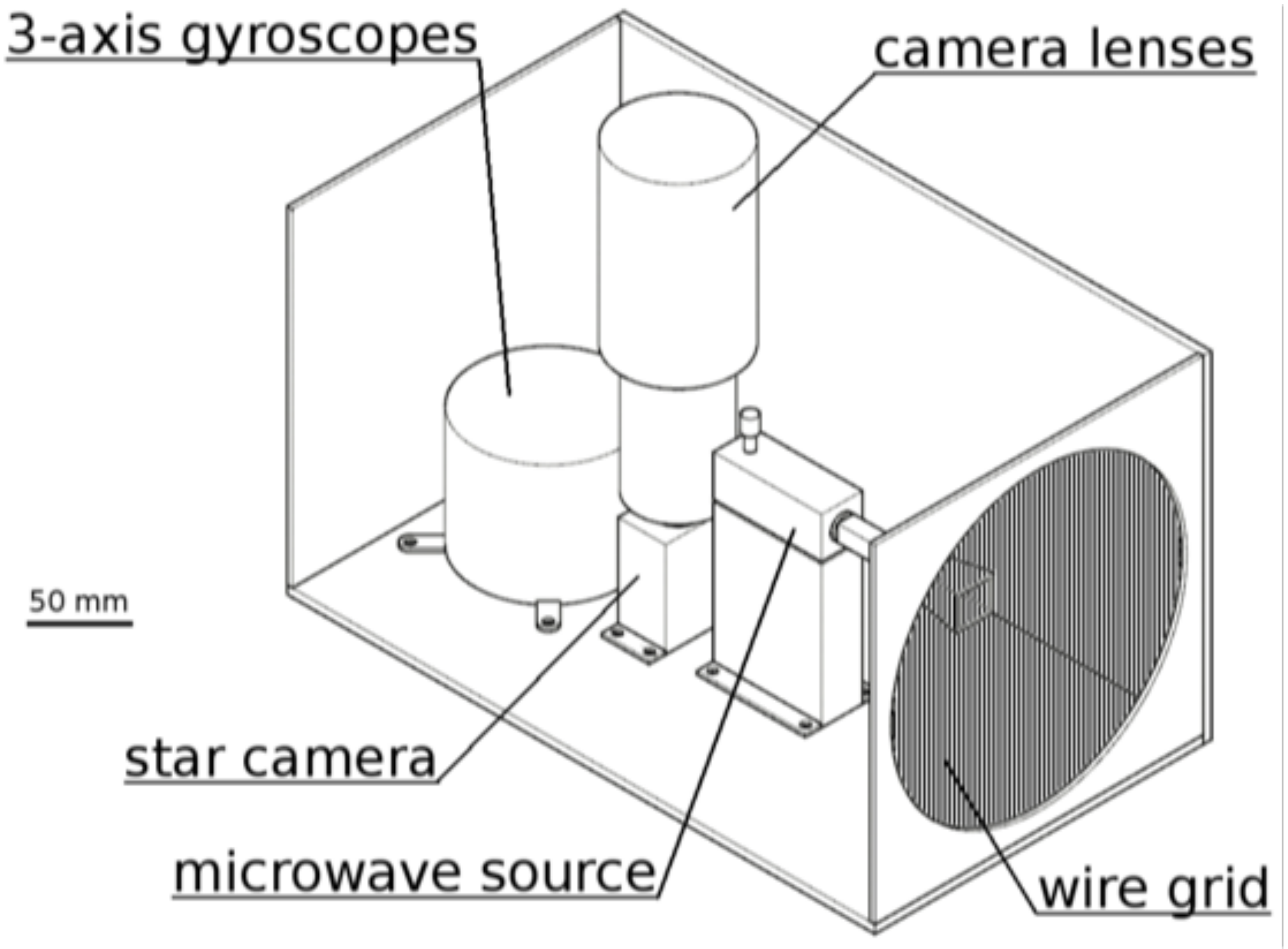


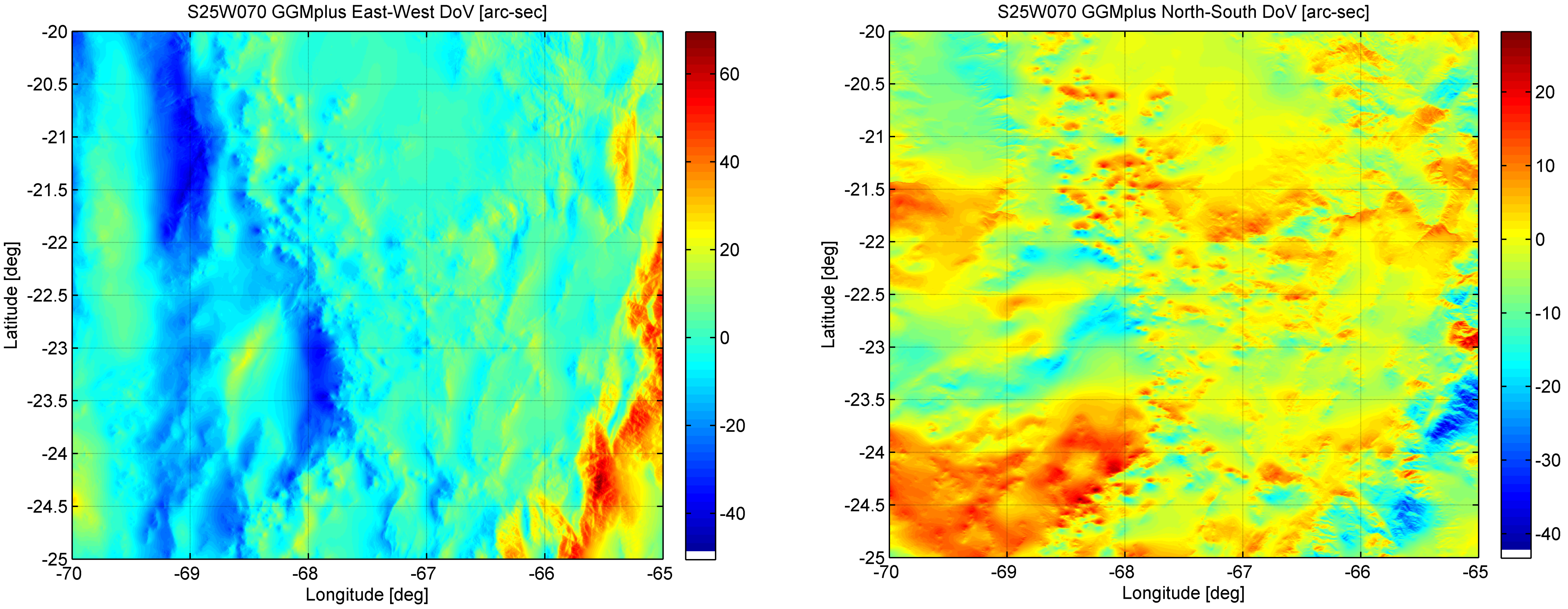
N = 1012
σϕ = 0.049 °
Number of scans
0
20
40
60
80
100
−0.2
−0.1
0.0
0.1
0.2
ϕ [deg]

Table 1. Calculated and estimated statistical and systematic errors.

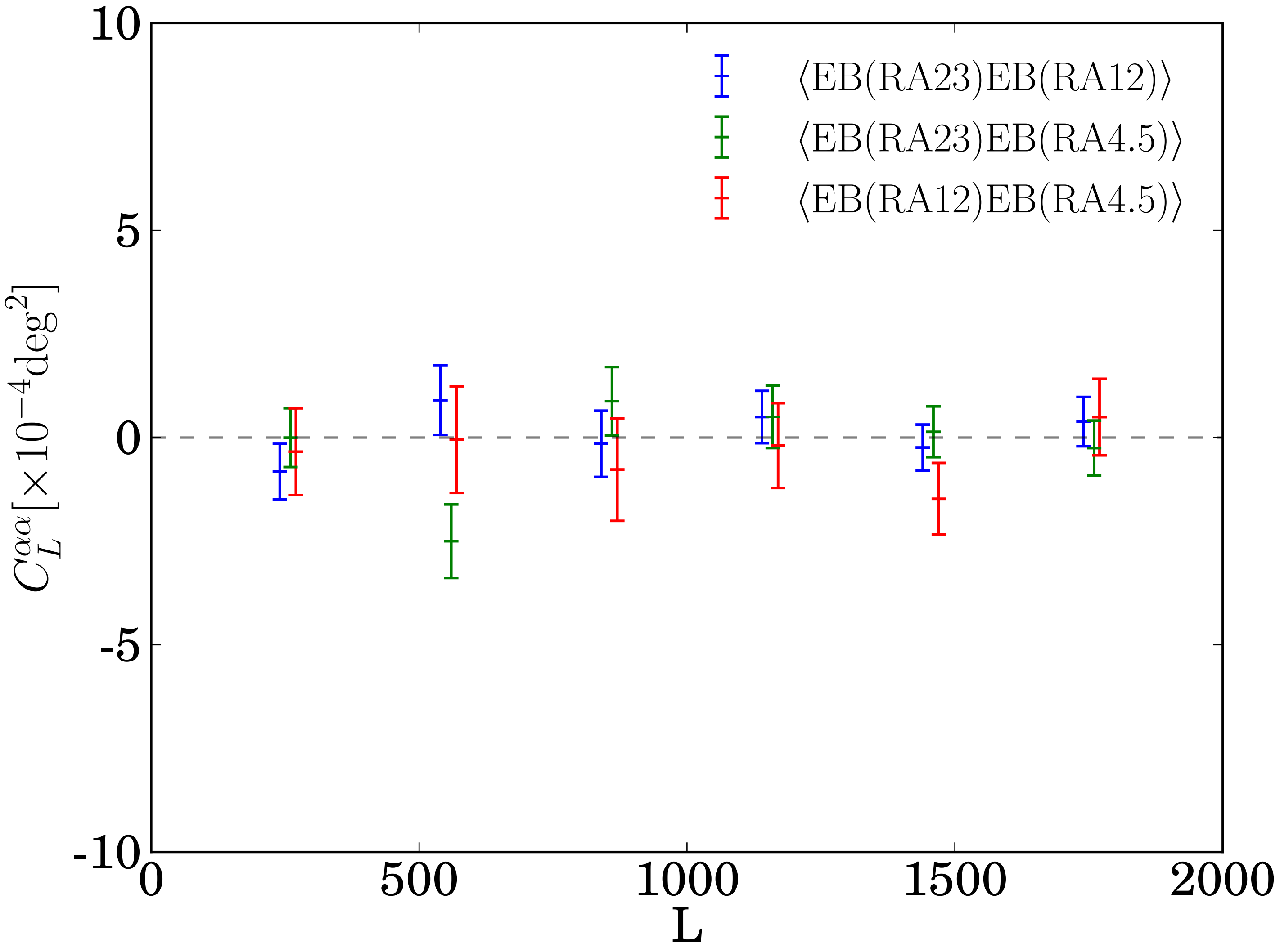
Statistical uncertainties	**Angle**
Wire-grid wire wrapping	0.02°
Wire-grid misalignment	0.006°
Rotation stage backlash	0.006°
Pre-pointing gravity vector leveling	0.006°
Post-pointing	0.006°
Total	**0.025°**

Systematic uncertainties	**Angle**
Electrical crosstalk	0.05°
Ground reflections	0.015°
Calibrator beam deformities	<0.01°
Gunn diode temperature stability	<0.01°
Birefringent MF-110 attenuators	<0.01°
Total	**0.055°**

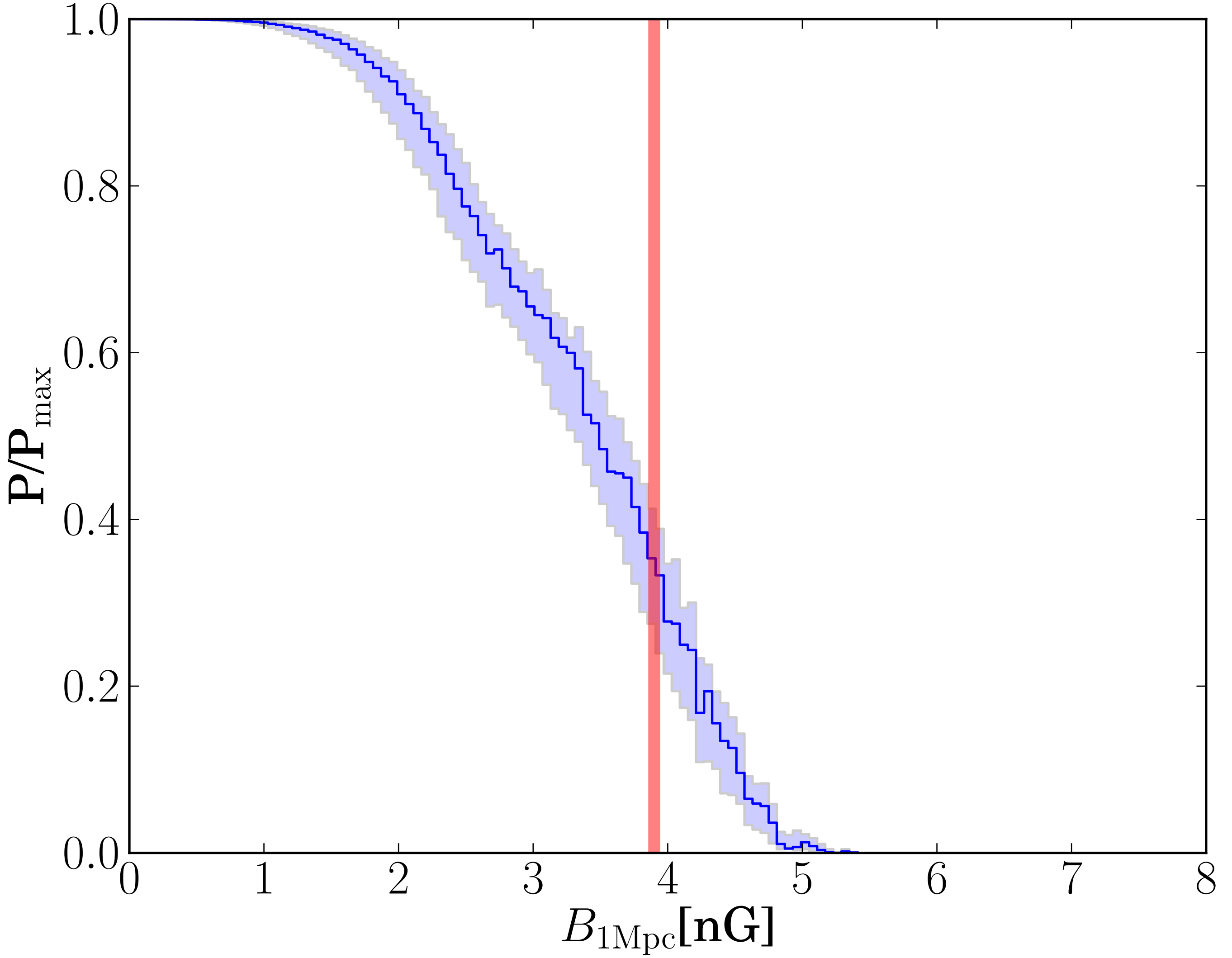

3-axis gyroscopes
camera lenses
50 mm
star camera
microwave source
wire grid



Model of the deviation of gravity vector around the Chilean observing site
Hirt et al. - doi:10.1002/grl.50838



⟨EB(RA23)EB(RA12)⟩
⟨EB(RA23)EB(RA4.5)⟩
⟨EB(RA12)EB(RA4.5)⟩
10
5
0
-5
-10
0
500
1000
1500
2000
L
$C_L^{\alpha\alpha}[\times 10^{-4}\mathrm{deg}^2]$


1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
$\mathbf{P/P_{max}}$
$B_{1\mathrm{Mpc}}$**[nG]**