Constraining cosmic birefringence with CMB polarisation experiments

Measurement of BICEP3 polarization angles and consequences for constraining cosmic birefringence and inflation (BICEP Collaboration, PRD 2025)

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+ James Cornelison, Annie Polish & the BICEP collaboration

mm Universe 2025 – June 26

Overview

What is cosmic birefringence and how can we constrain it?

What can we achieve with BICEP data?

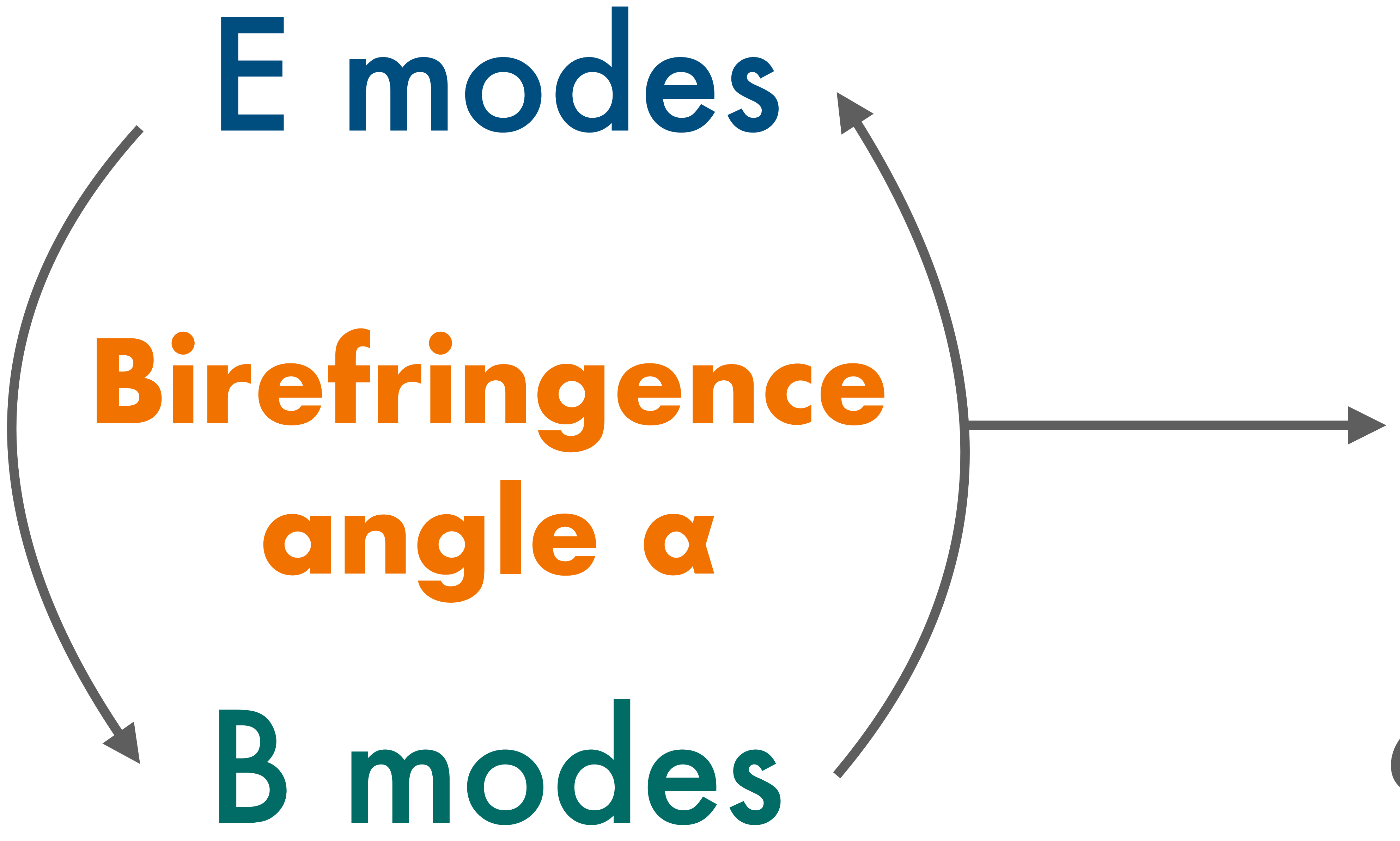
What can we do to improve our expected performance?

Cosmic birefringence

Parity-violating field interacting with the electromagnetic field
→ **polarisation rotation angle α**
aka "cosmic birefringence"

Coupling effect integrates over the line of sight
→ **the CMB is the best place to look for the signal!**

Impact on the CMB



EB signal*

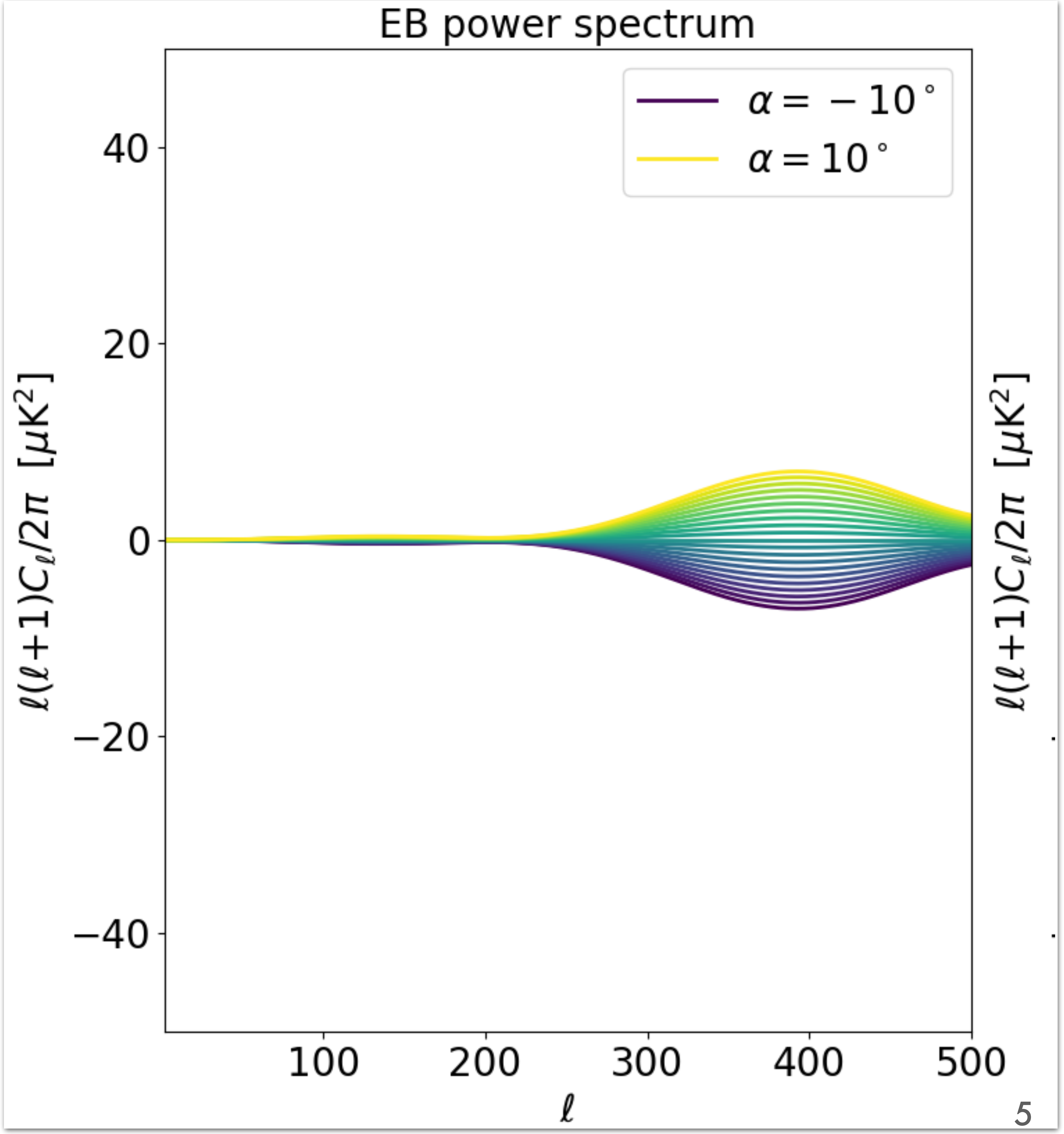
$$C_\ell^{EB} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\alpha)$$

*also produces TB but not used in this analysis because it contains no additional constraining power

Measurement challenges

Degenerate with instrumental polarisation
→ absolute calibration of individual detector polarisation angles

Low amplitude
→ high instrumental sensitivity
→ control of systematics



State of the art

ACT DR6: 0.2° ± 0.08° (stat + optics) ± 0.03° (pointing)
Celestial sources + optics metrology and modelling

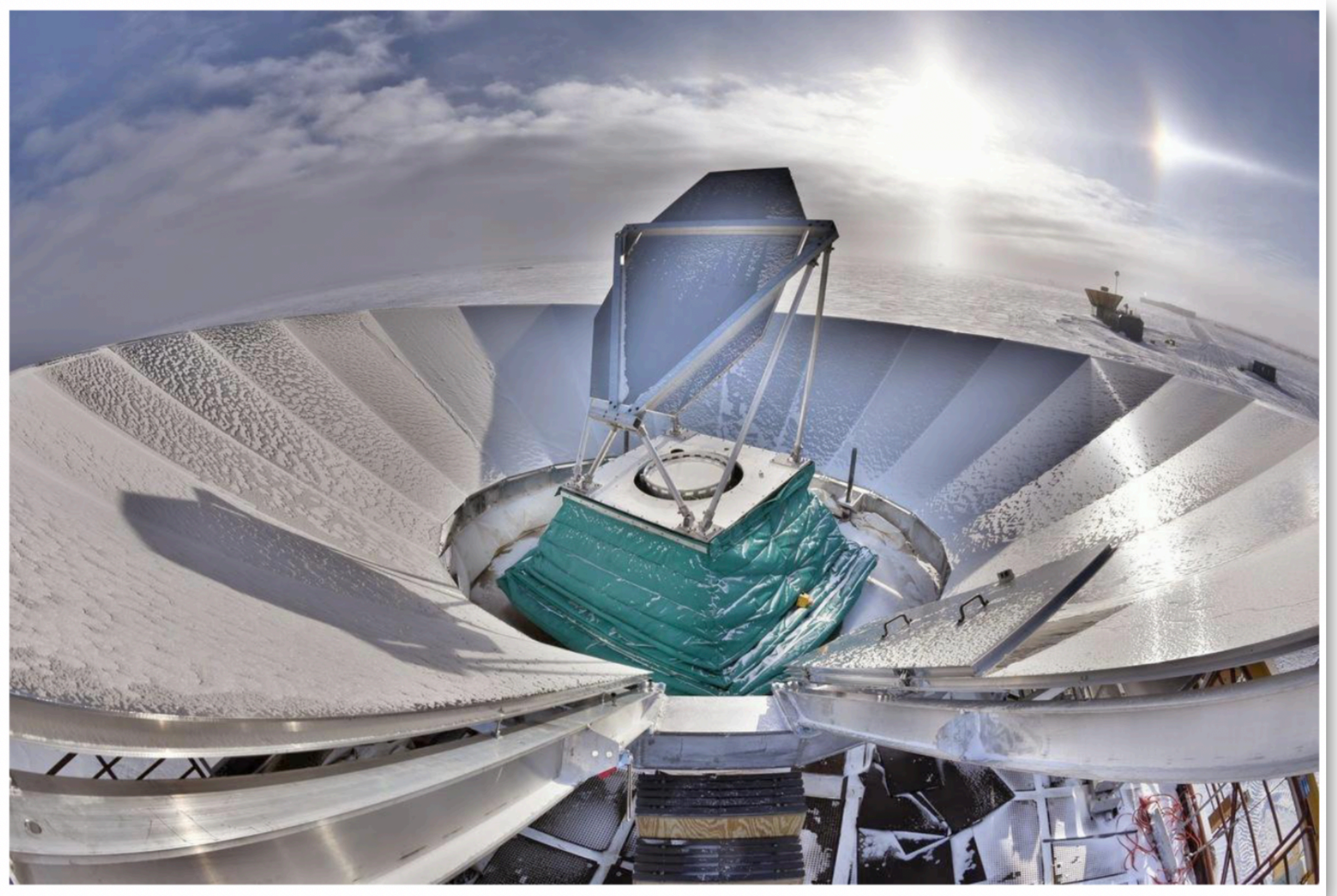
Planck/WMAP reanalysis: ~ 0.3° ± 0.1°
Assumes model for foreground EB emission

What can we achieve with absolute calibration of BICEP maps?

BICEP3 2-year data set (2017 + 2018)

2400 detectors @ 95GHz

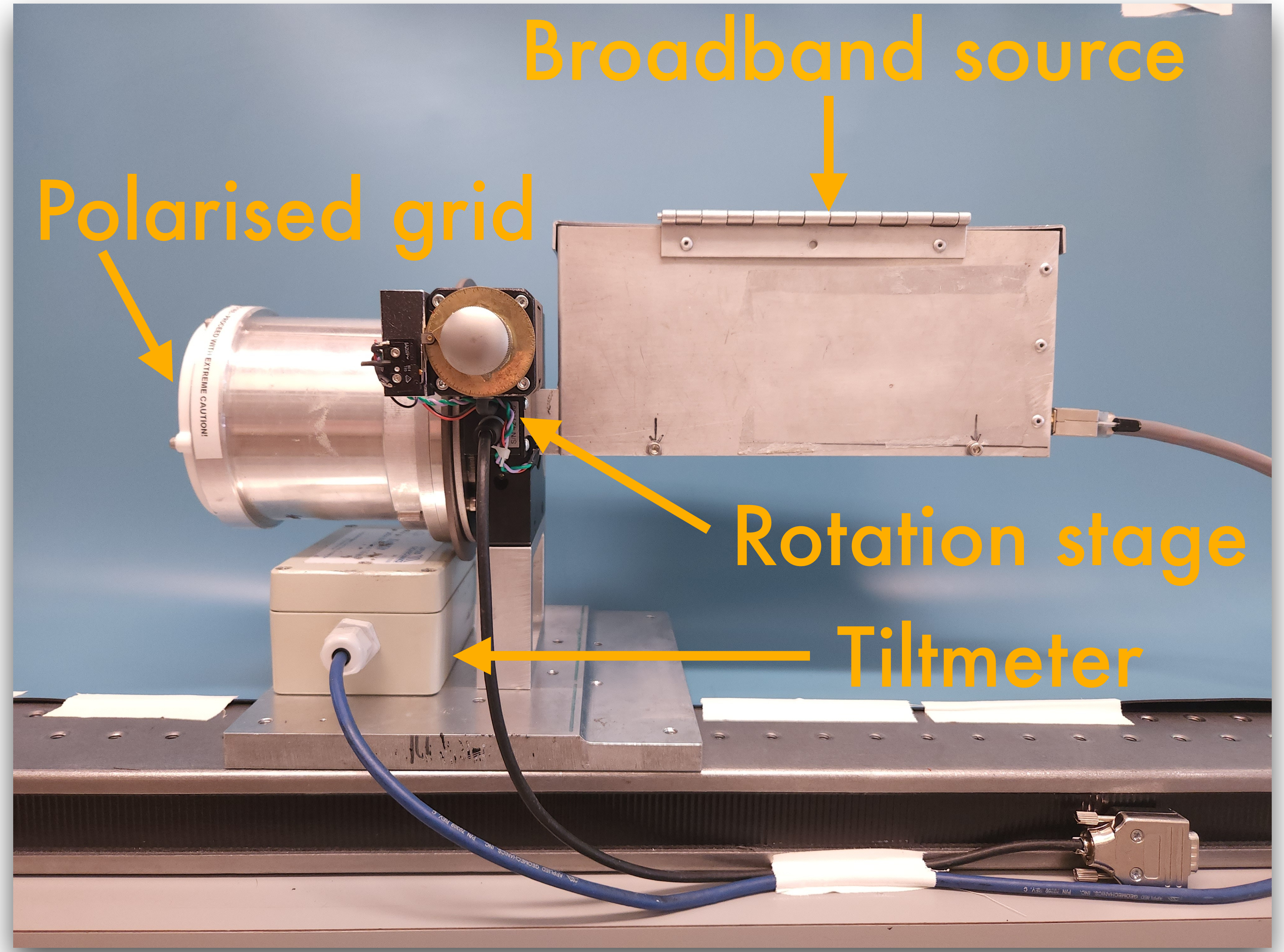
3.3 μK.arcmin over ~600 sq deg



BICEP Collaboration

Calibrating BICEP3

Rotating Polarised Source (RPS)



2022 RPS calibration campaign

1-month campaign

Measured angles for 1800 detectors in BICEP3, 10 times

BICEP Collaboration/J. Cornelison

Error budget

	Calibration	Sky signal
Statistical uncertainty	How repeatable is the angle measurement?	How well do we measure the EB signal from the sky?
Systematic uncertainty	Is the angle measurement biased?	Is the EB signal biased by another sky signal?

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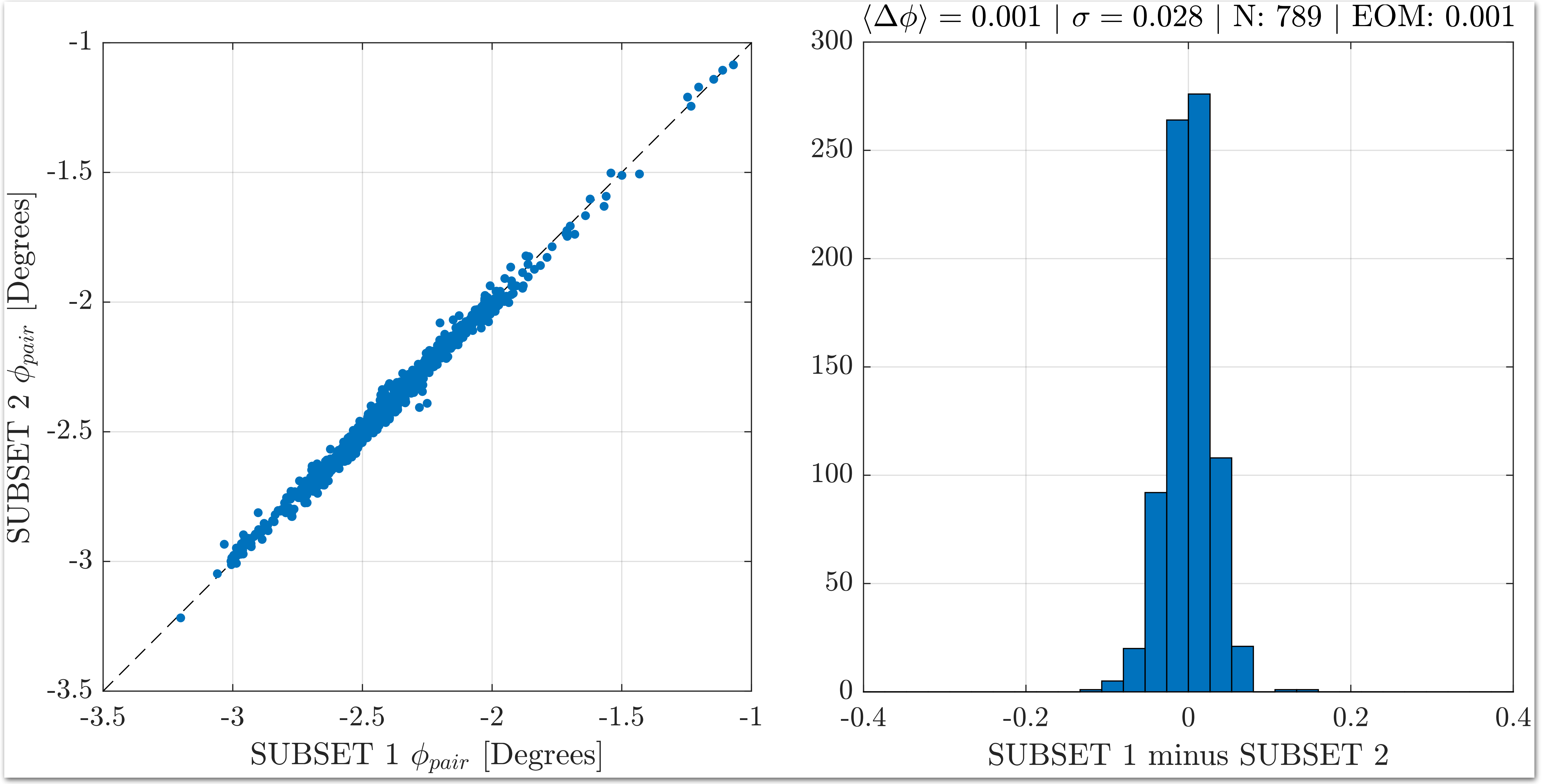
Calibration – statistical uncertainty



$\sigma(\alpha) = 0.02°$

This is the **most precise direct measurement** of polarisation angles for a CMB experiment

+ passed consistency checks on real data, blind to systematics uncertainty

Error budget

	Calibration	Sky signal
Statistical uncertainty	0.02 °	**How well do we measure the EB signal from the sky?**
Systematic uncertainty	Is the angle measurement biased?	Is the EB signal biased by another sky signal?

Sky signal – statistical uncertainty

Breakdown of contributions

- noise only: $\sigma(\alpha) = 0.061°$
- only lensed-ΛCDM: $\sigma(\alpha) = 0.035°$ (vs unlensed-ΛCDM $\sigma(\alpha) = 0.004°$)
- **lensed-ΛCDM + noise + Gaussian dust: $\sigma(\alpha) = 0.078°$**

Competitive with other CMB experiments

Error budget

	Calibration	Sky signal
Statistical uncertainty	0.02°	0.078°
Systematic uncertainty	Is the angle measurement biased?	**Is the EB signal biased by another sky signal?**

Sky signal – dust systematics?

Dust models (Gaussian, MKD, Vansyngel, MHD)
→ no bias and no significant impact on statistical uncertainty

Maximally correlated dust toy model $\mathscr{C}_\ell^{EB} = \sqrt{\mathscr{C}_\ell^{EE} \times \mathscr{C}_\ell^{BB}}$
→ **maximum bias of 0.027°**

Dust B-modes x CMB E-modes
→ **maximum bias of 0.016°**

Additional **σ(α) = 0.02°** to account for dust contribution

Beam systematics

TP leakage from main beam mismatch: ~ 0.03°
Due to T-to-B leakage correlating with TE in the CMB

Beam window function errors: 10% multiplicative error on α

Error budget

	Calibration	Sky signal
Statistical uncertainty	$0.02°$	$0.078°$
Systematic uncertainty	**Is the angle measurement biased?**	$\lesssim 0.04°$

Calibration – systematic uncertainty

Category	Amplitude	$\sigma(\phi_{pair})$
RPS performance		
Mechanical repeatability	$0.006°$	$0.006°$
Tiltmeter calibration	$0.014°$	$0.014°$
Rotation stage backlash	$0.06°$	$0.06°$
Pointing model		
Focal plane residual rotation	$0.012°$	$0.012°$
Measurement uncertainties		
Pair anticorrelations	1.3%	$0.019°$
Alignment error (model)	$1° Az/5° El$	$0.035°$
Alignment error (measured)		$\sim 0.3°$

Diffraction on the rim of the wire grid generating spatially varying cross-polar response

→ Manifests as sensitivity to alignment

→ Mitigation strategy in progress (shielding, different horn, etc.)

Check out Annie Polish' poster on RPS performance & upgrades!

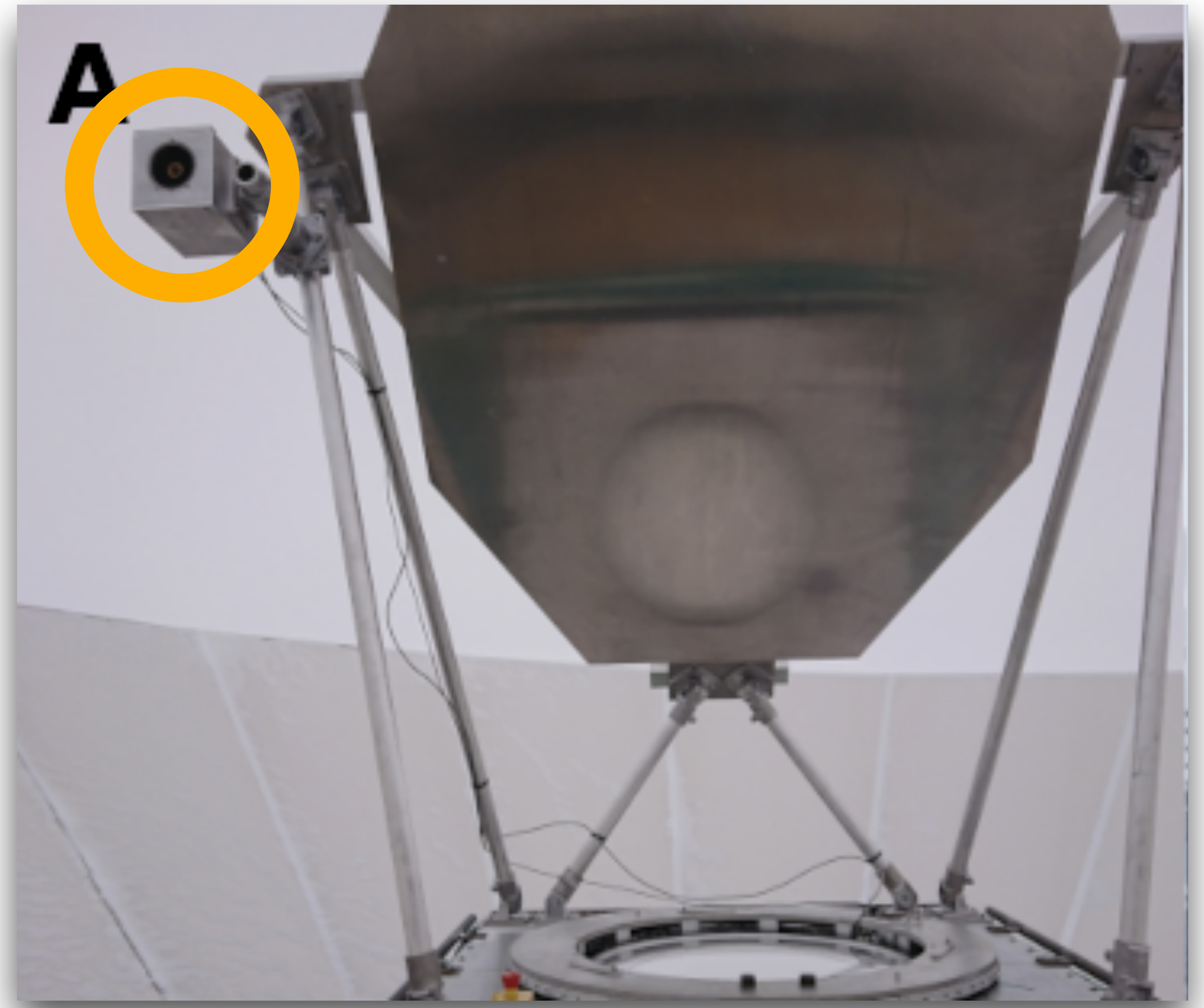
Error budget

	Calibration	Sky signal
Statistical uncertainty	0.02°	0.078°
Systematic uncertainty	**> 0.3°**	≲0.04°

Looking ahead

Improve calibration procedure (Annie's poster)

- Mitigate cross-polar response
- Improve RPS performance
- Check RPS performance in real time



M. Echter

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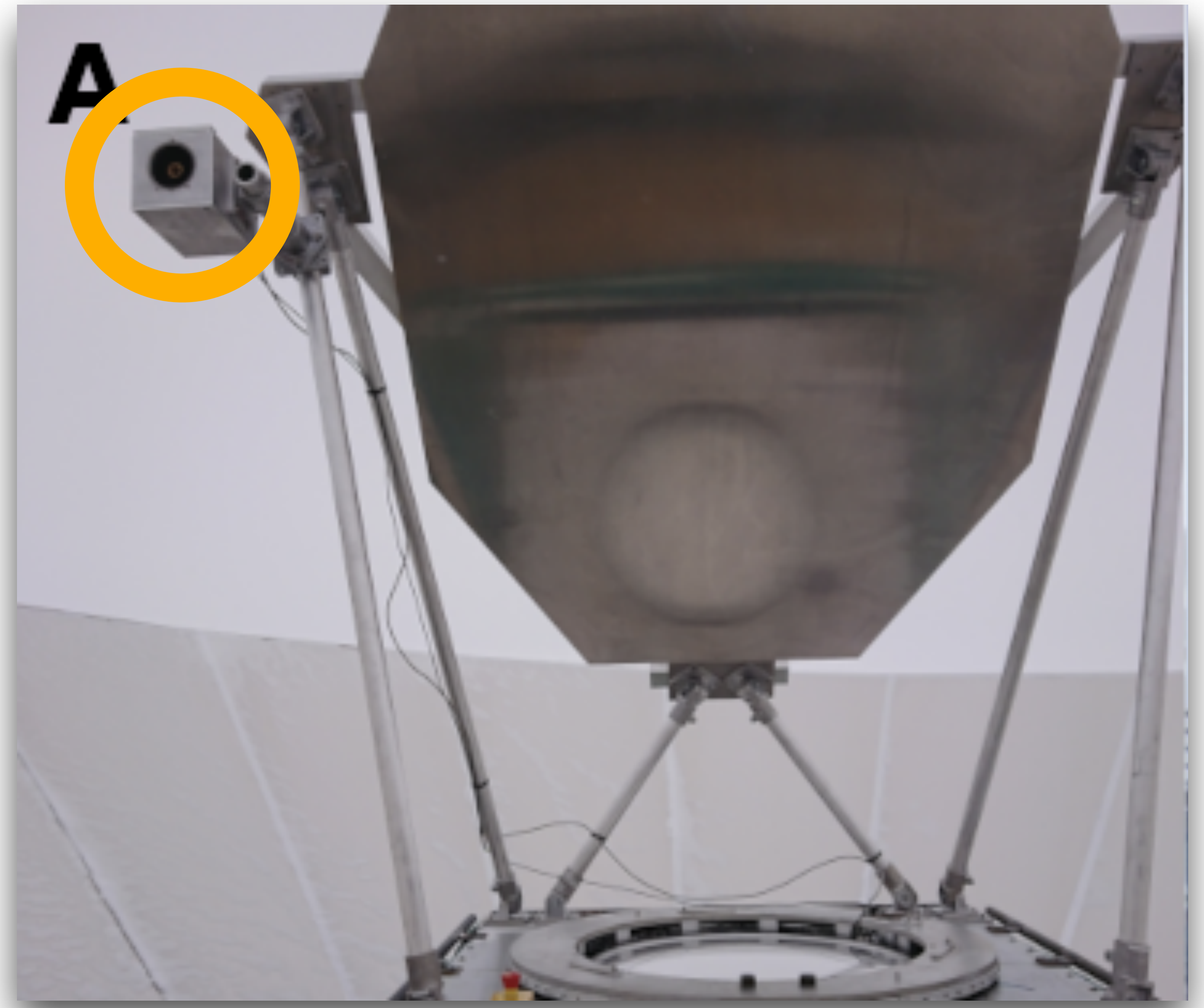

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Increase sensitivity

- Go from 2-year to 7-year data set
- Multifrequency analysis
- Use external data sets to extend multipole range and/or delens

Signal	σ_{noise}	$\sigma_{lensing}$	$\sigma_{\mathbf{tot}}$
B3 2 years (this work)	0.061°	0.035°	**0.078°**
B3 7 years	0.035°	0.035°	**0.055°**
B3 2 years + delensing	0.061°	0.024°	**0.073°**
B3 7 years + delensing	0.035°	0.024°	**0.048°**

Conclusion

Demonstrated field performance of calibration source

✅ Most precise measurements of polarisation angles for a CMB experiment

Detailed constraining power for BICEP3 2-year data set

✅ Competitive with other measurements (Planck/WMAP, ACT)

No cosmic birefringence constraint derived from real data so far but…

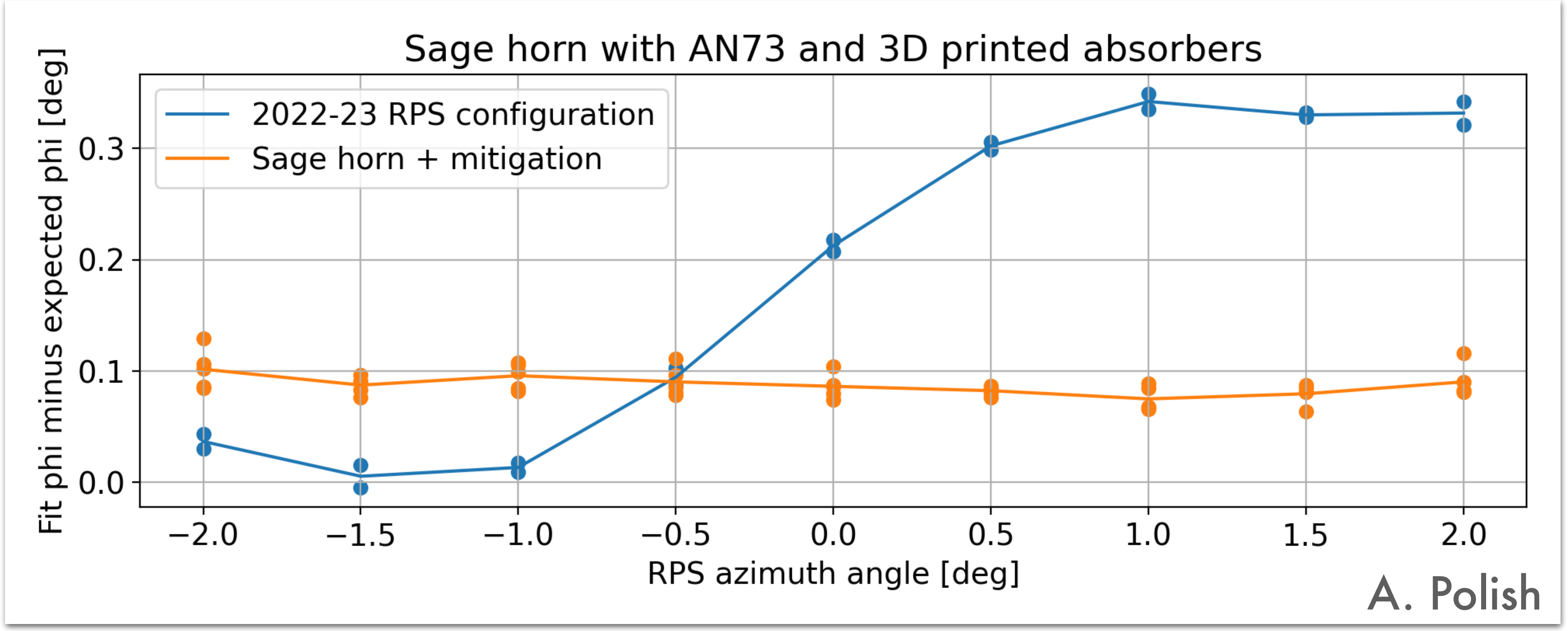
→ On-going improvement of RPS operations for future calibration campaigns

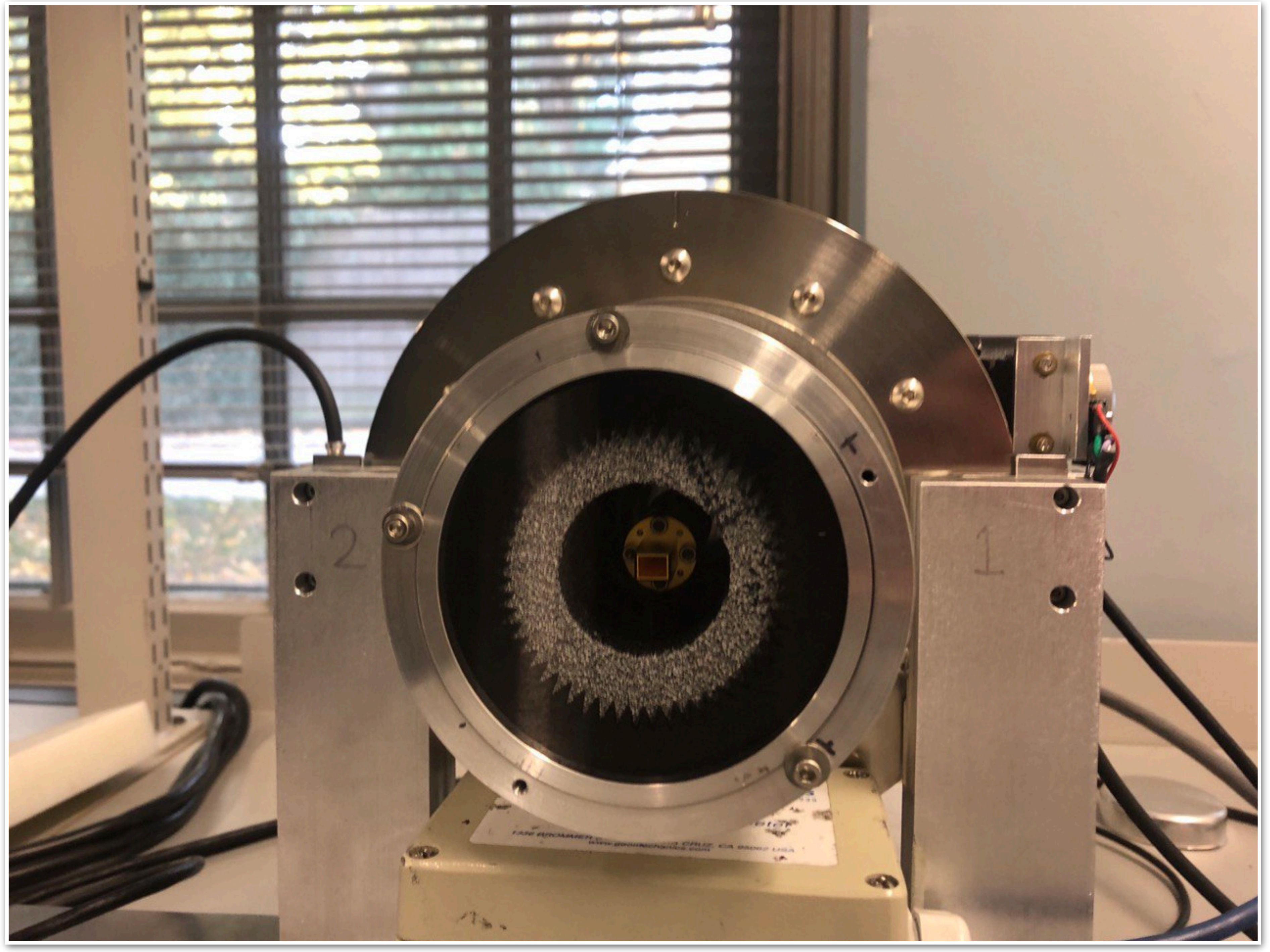
→ More data is already available to increase sensitivity

Targeting $0.05° < \sigma(\alpha) < 0.1°$

All the details (and more!) in *BICEP/Keck XVIII: Measurement of BICEP3 polarization angles and consequences for constraining cosmic birefringence and inflation*, PhysRevD.111.063505

Calibration bias





Sensitivity to alignment is due to previously unmitigated electromagnetic effects in the calibration source itself