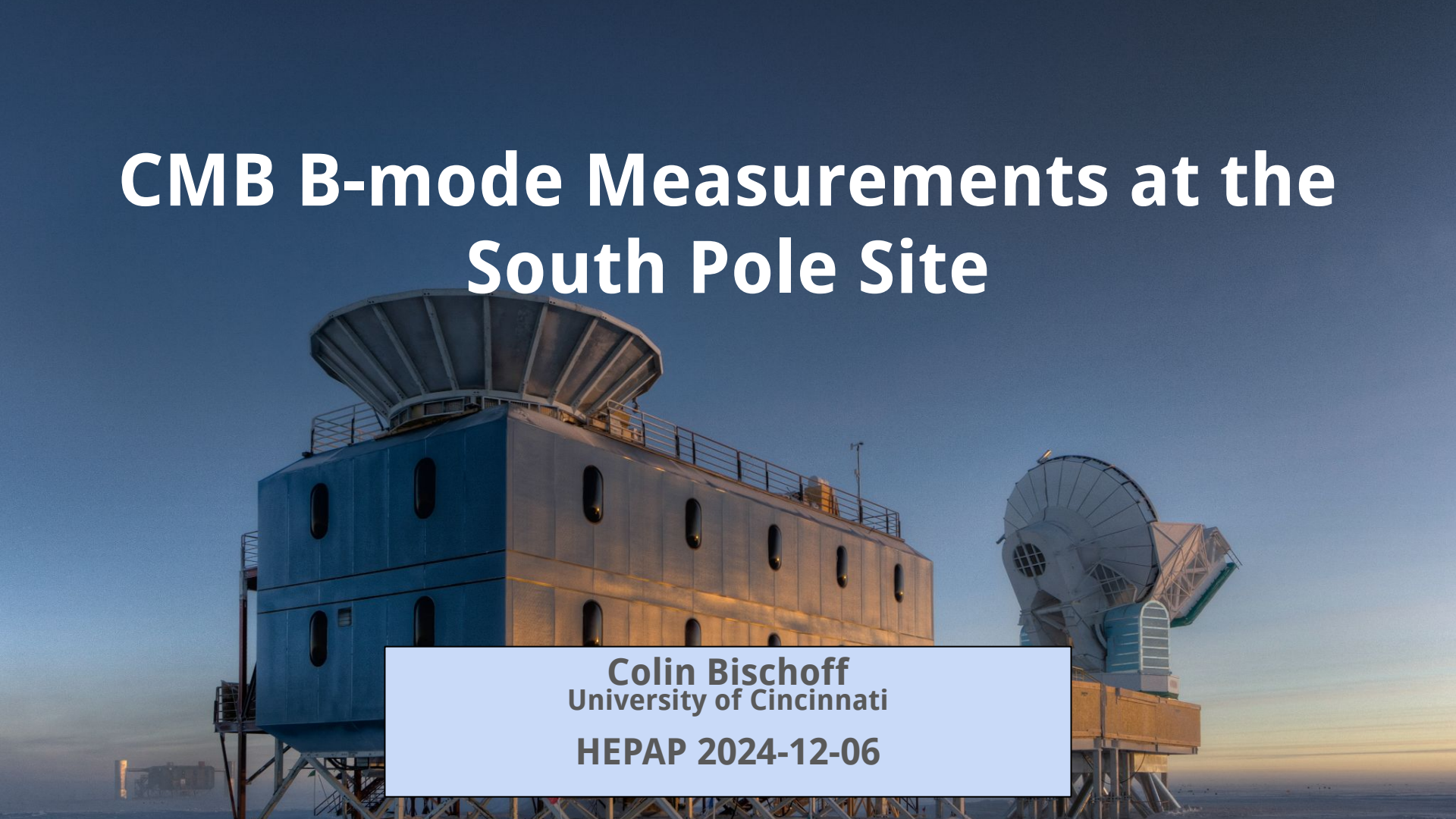
CMB B-mode Measurements at the South Pole Site



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Who am I

- Associate professor, University of Cincinnati
- BICEP/SPO Collaboration senior member
- CMB-S4 member, Science Council co-chair
- 20+ years of experience in instrumentation, calibration, instrumental systematics, and data analysis for CMB polarization experiments

Talk outline

- Inflation science with CMB polarization
- History of B-mode limits from South Pole
- Why the South Pole is an exceptional place to make these measurements
- Path forward for CMB observations from South Pole

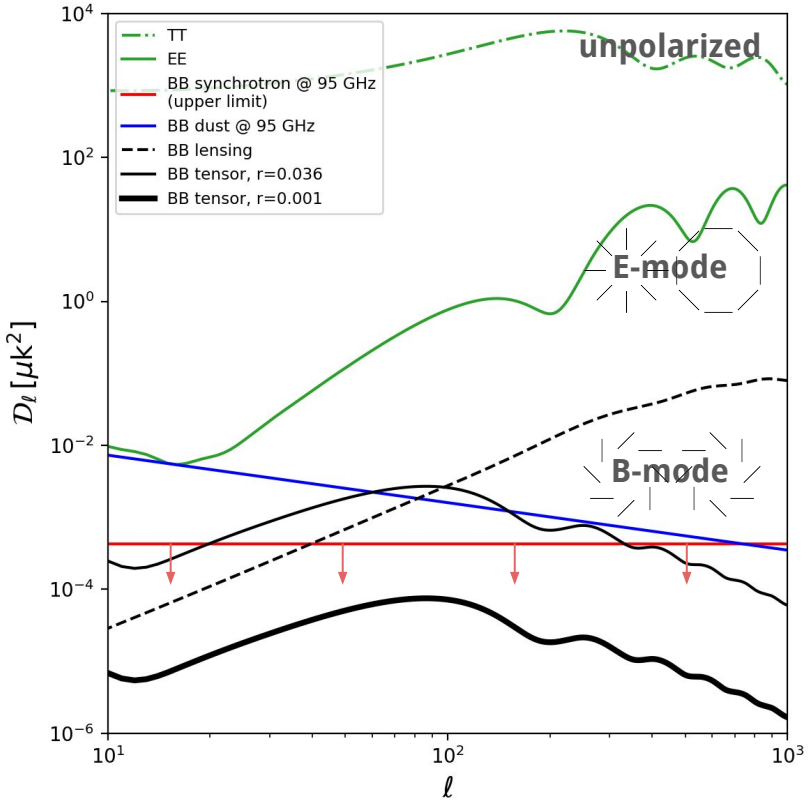
B-mode searches for inflation science

Inflation models predict the existence of a primordial gravitational wave (PGW) background, which imprints a B-mode (parity odd) signature on the polarization of the CMB at degree angular scales.

From P5 Report: "the discovery of gravitational waves produced by inflation in the extremely early universe would provide a direct window to this previously inaccessible epoch in cosmic history, and to the highest energy scales in the universe"

Current upper limit on tensor (PGW) to scalar ratio, r, from BICEP, Planck, and WMAP data is r < 0.036 at 95% confidence.

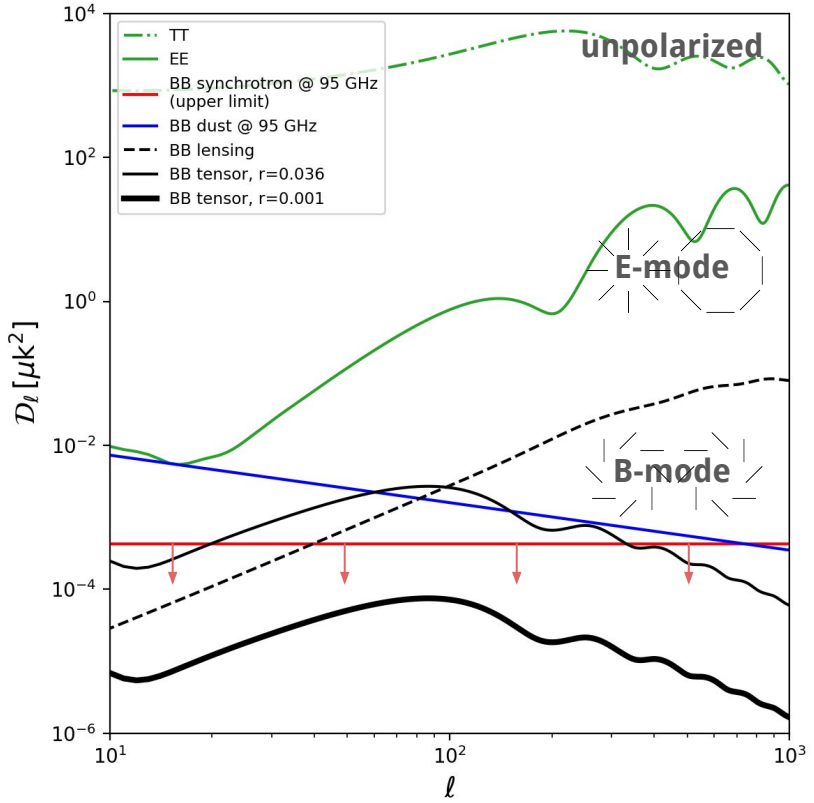
Target for CMB-S4 is r < 0.001 at 95% confidence or 5-sigma detection for r ≥ 0.003.



B-mode searches for inflation science

To push beyond current limits on r, CMB polarization experiments need:

- **High sensitivity, achieved by operating large numbers of detectors over many years with high observing efficiency**
- **Observations at multiple frequencies to separate CMB from Galactic foregrounds**
- **High signal-to-noise and moderately high resolution data from large aperture telescopes for delensing**
- **Excellent control of systematic errors, which bias the BB spectrum. Note that CMB TT/EE, lensing BB, and foregrounds are all much larger than r=0.001 PGW signal.**

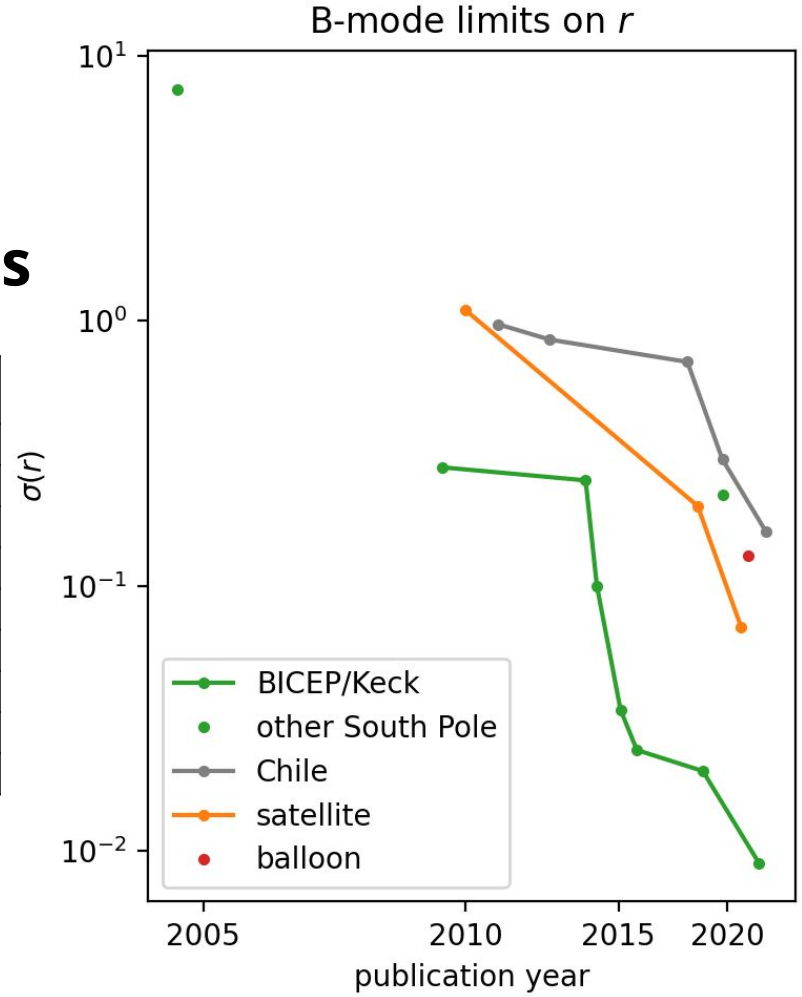


Observations from South Pole have produced the leading r constraints for the past 10+ years

Experiment	arxiv post	σ(r)
DASI	0409357	7.5
BICEP1 2yr	0906.1181	0.28
WMAP 7yr	1001.4538	1.1
QUIET-Q	1012.3191	0.97
QUIET-W	1207.5034	0.85
BICEP1 3yr	1310.1422	0.25
BICEP2	1403.3985	0.10
BK13 + Planck	1502.00612	0.034
BK14 + WP	1510.09217	0.024

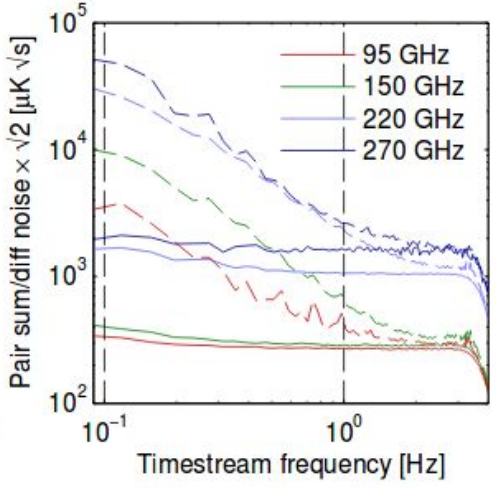
Experiment	arXiv post	σ(r)
ABS	1801.01218	0.7
Planck	1807.06209	~0.2
BK15 + WP	1810.05216	0.020
Polarbear	1910.02608	0.3
SPTpol	1910.05748	0.22
Planck/Tristram	2010.01139	0.07
SPIDER	2103.13334	0.13
BK18 + WP	2110.00483	0.009
Polarbear	2203.02495	~0.16

Green = South Pole
Grey = Chile
Orange = satellite
Red = suborbital balloon



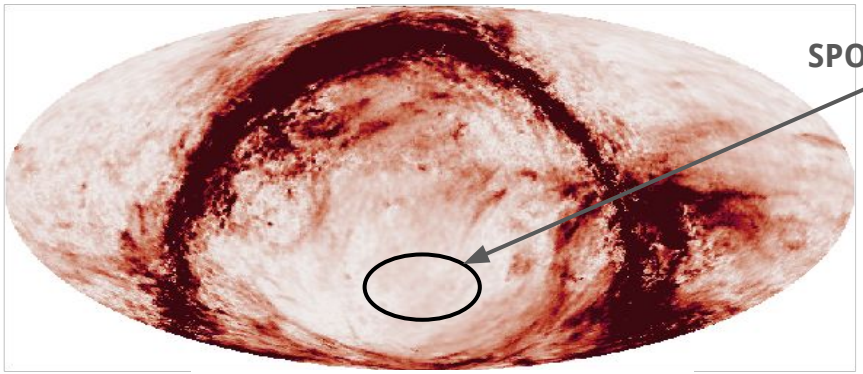
What features of the South Pole site enable B-mode measurements?

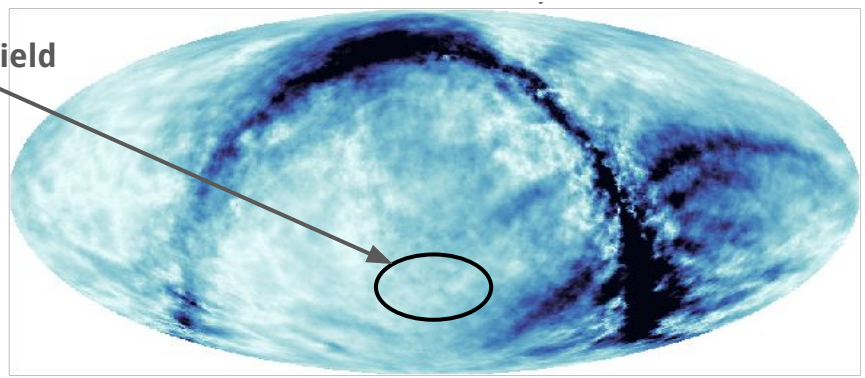
1. Atmospheric properties
    - Very low precipitable water vapor, which decreases atmospheric loading on detectors (especially at high frequency), and minimizes “sky noise”, i.e. emission from clumps of water vapor.
    - One diurnal cycle per year and extremely flat terrain contributes to a very stable atmosphere, especially in deep winter.
    - Taking the difference of orthogonally polarized detector pairs (solid lines) is highly effective at reducing South Pole sky noise (dashed lines) to achieve good noise properties over the range of frequencies relevant for B-mode measurements, without the need for polarization modulators.



What features of the South Pole site enable B-mode measurements?

2. **The ability to integrate deeply on a small, clean field**
    - From the South Pole the sky simply rotates overhead so the “Southern Hole”, a field with very low foreground levels, is *always* observable.
    - In contrast, observing strategies from Chile must focus on multiple fields, some of which have brighter foregrounds, that are spaced apart in right ascension since they rise and set.





353 GHz polarized intensity (dust)

30 GHz polarized intensity (synchrotron)

What features of the South Pole site enable B-mode measurements?

2. The ability to integrate deeply on a small, clean field

- The angular power spectrum is the sample variance of measured mode amplitudes at each angular scale. Follows chi-squared statistics.
  For a noise-dominated measurement*, sensitivity to the BB spectrum scales as

$$\sigma(r) \sim N_\ell \, f_{\rm sky}^{-1/2}$$

  where N_ℓ is noise power and $f_{\rm sky}$ is sky area (effective number of modes).
  For fixed instrumental sensitivity, i.e. a certain number of detector-years, there is a trade-off between survey depth and area, so

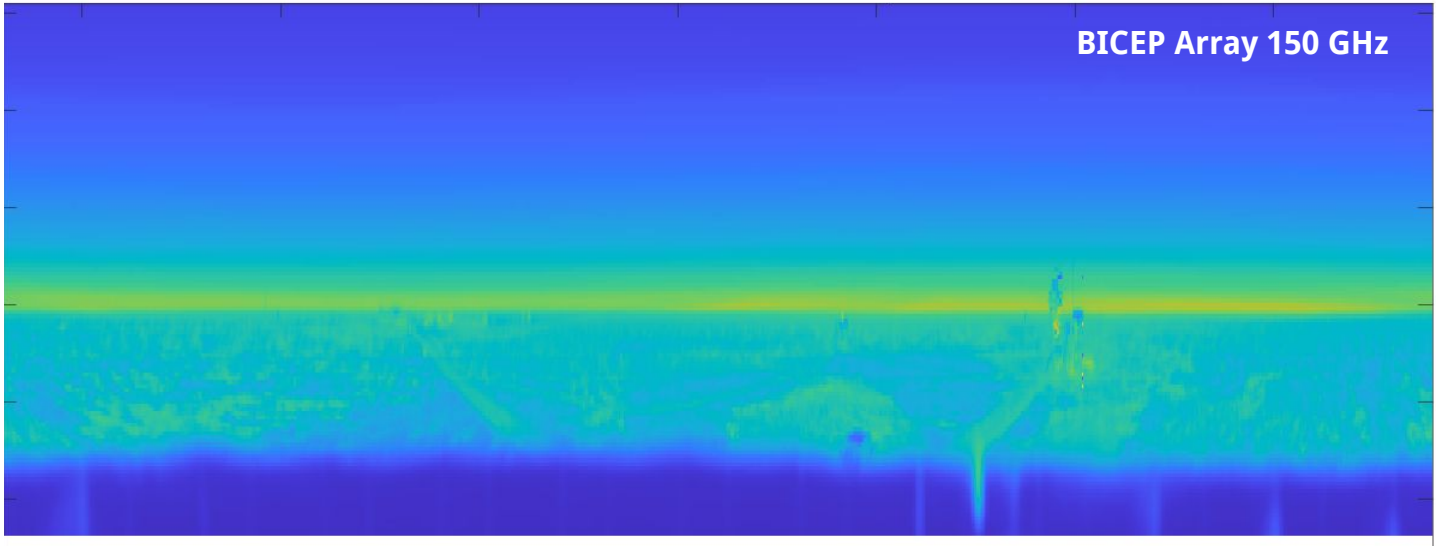
$$N_\ell \, f_{\rm sky}^{-1} \sim \text{const} \rightarrow \boxed{\sigma(r) \sim f_{\rm sky}^{1/2}}$$

- Minimum survey area for small aperture telescopes in Chile is 3-4x larger than SPO field, which yields 1.7-2x larger σ(r) for the same total sensitivity (if noise dominated).

*noise-dominated implies that we have done a good job of foreground cleaning and delensing (and we haven't detected r!)

What features of the South Pole site enable B-mode measurements?

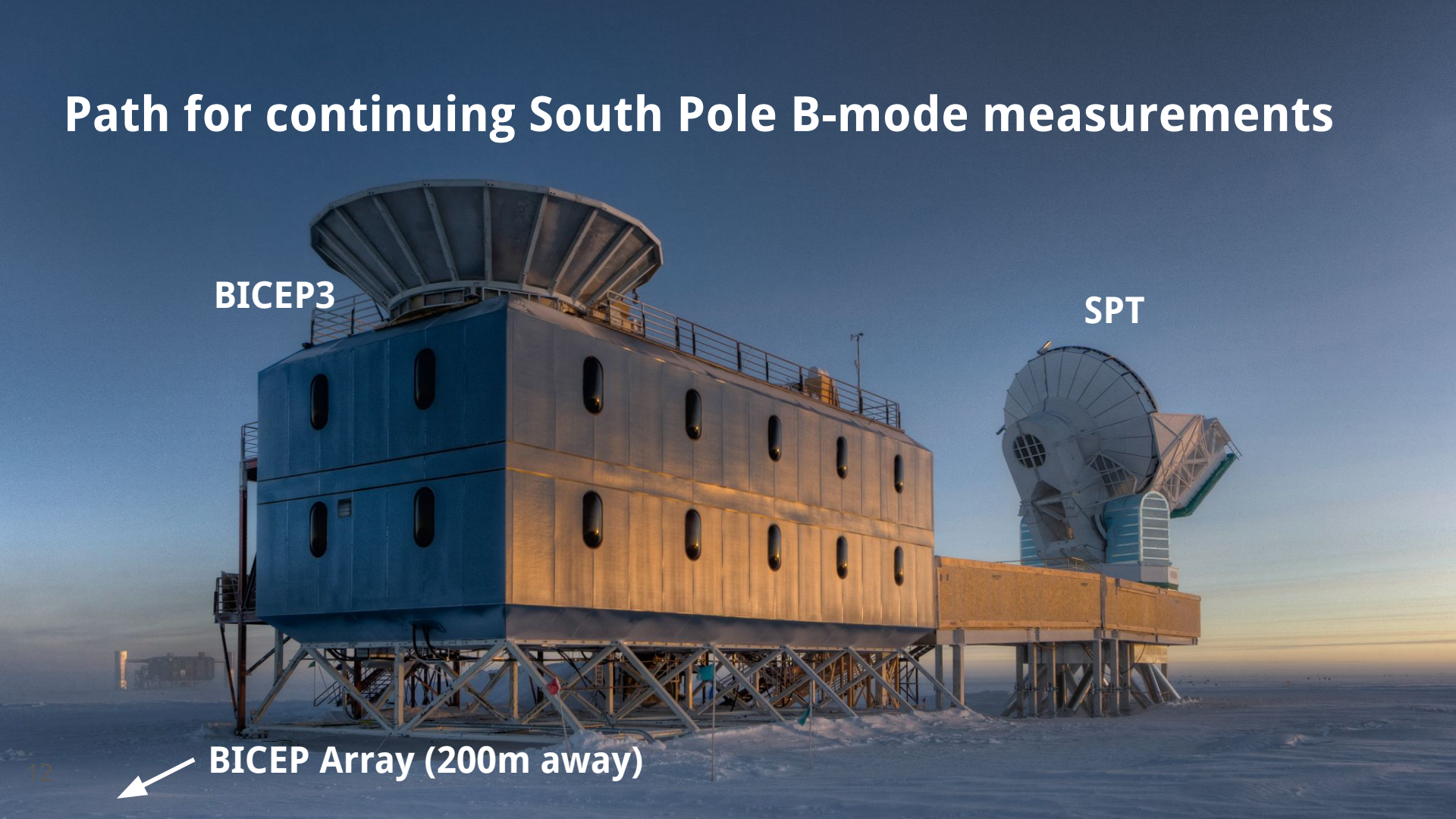
3. Clean environment for systematics control
    - CMB small aperture telescopes have multiple levels of shielding/baffling to prevent bright emission from the ground from diffracting into the telescope. This strategy is aided by the simple and featureless horizon, with no diurnal cycle, at the South Pole.



What features of the South Pole site enable B-mode measurements?

4. **Minimal solar contamination and heating**
    - **The Sun is below the horizon continuously for six months and never rises above 23°. Even with the Sun at a low, constant elevation and fixed distance from our observing field, we detect subtle effects in BICEP summer data due to heating of the telescope forebaffle. This experience highlights the importance of a six month night.**

Path for continuing South Pole B-mode measurements



Path for continuing South Pole B-mode measurements

South Pole Observatory is a collaboration between BICEP and SPT to measure B modes from joint analysis of a common survey field.

BICEP small aperture telescopes provide degree angular scales. SPT provides arcminute scales for delensing.

Telescopes currently operating at South Pole:

- **BICEP3: 2560 detectors @ 95 GHz, deepest degree-scale CMB polarization maps ever**
- **BICEP Array (four BICEP3-scale telescopes): two already operating, third deploying now, frequency coverage from 30 to 270 GHz**
- **SPT-3G: 16000 detector camera on 10-meter SPT, frequency coverage from 90 to 220 GHz, observing since 2018**

Path for continuing South Pole B-mode measurements

Planned upgrades to BICEP Array and SPT, aligned with NSF intention to continue support for existing South Pole projects and sustain CMB research at the Pole without expanding logistical footprint while infrastructure improvements are addressed

- **PreSAT project to deploy 4th BICEP Array telescope (90/150 GHz dichroic) using CMB-S4 prototype optics and detector technology**
  - **Partially funded through NSF MRI. Needs additional funding for detectors and readout.**
- **SPT-3G+ is an upgrade to the SPT camera that will increase mapping speed by factor of 7**
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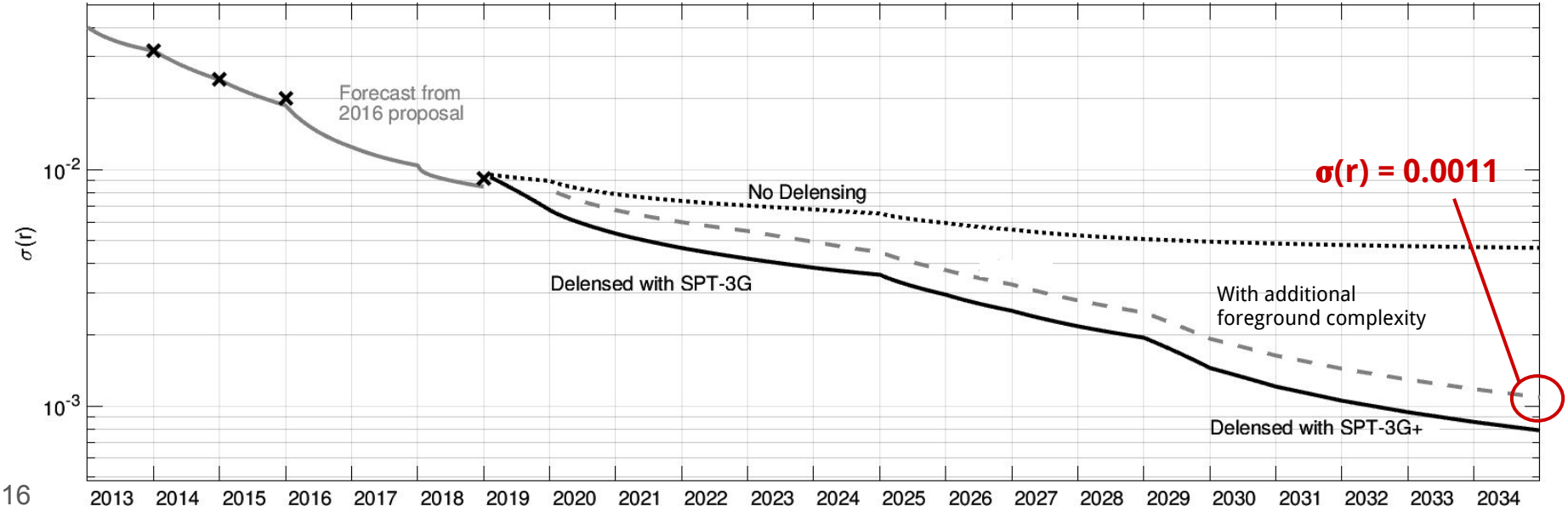
Shown here are conservative forecasts based on scaling of past performance achieved by BICEP/Keck telescopes. Demonstrates what we are confident we can do from the South Pole site.

BICEP operations currently funded through 2027, renewal award required starting 2028.

SPT renewal award required starting 2030.

Note the black x marks, which indicate published results.
(x-axis marks when data are acquired, not publication year)



Path for continuing South Pole B-mode measurements

Modest investment to complete PreSAT and SPT-3G+, as well as extending SPO operations through 2034, can achieve 8x improvement over current best inflation constraints, building on a program with demonstrated deep CMB B-mode measurements.