Title: Improved constraint on primordial gravitational waves with delensing

Speakers: Kimmy Wu

Series: Cosmology & Gravitation

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Abstract: Inflation generically predicts a background of primordial gravitational waves, which generate a primordial B-mode component in the polarization of the cosmic microwave background (CMB). The measurement of such a B-mode signature would lend significant support to the paradigm of inflation. Observed B modes also contain a component from the gravitational lensing of primordial E modes, which can obscure the measurement of the primordial B modes. We reduce the sample variance in the BB spectrum contributed from this lensing component by a process called 'delensing.' In this talk, I will show results from the first demonstration in an improved constraint on primordial gravitational waves with delensing using data from BICEP/Keck, the South Pole Telescope (SPT), and Planck. In addition, I will provide an outlook of joint-analysis efforts of the BICEP/Keck and the SPT collaborations (the South Pole Observatory) to constrain primordial gravitational waves.

Improved constraint on primordial gravitational waves with delensing

W.L. Kimmy Wu
Associate Scientist | Panofsky Fellow
SLAC National Accelerator Laboratory

May 11, 2021
Perimeter Institute Seminar

Outline

- Inflation, the cosmic microwave background (CMB), and CMB lensing
- The BICEP/Keck Array and South Pole Telescope (SPT)
- Improving constraints of inflation from BICEP/Keck through "delensing"
- The Future: from BICEP/Keck + SPT to CMB-S4

Background: the South Pole Telescope
and double sun dog (credit: A. Lowitz)

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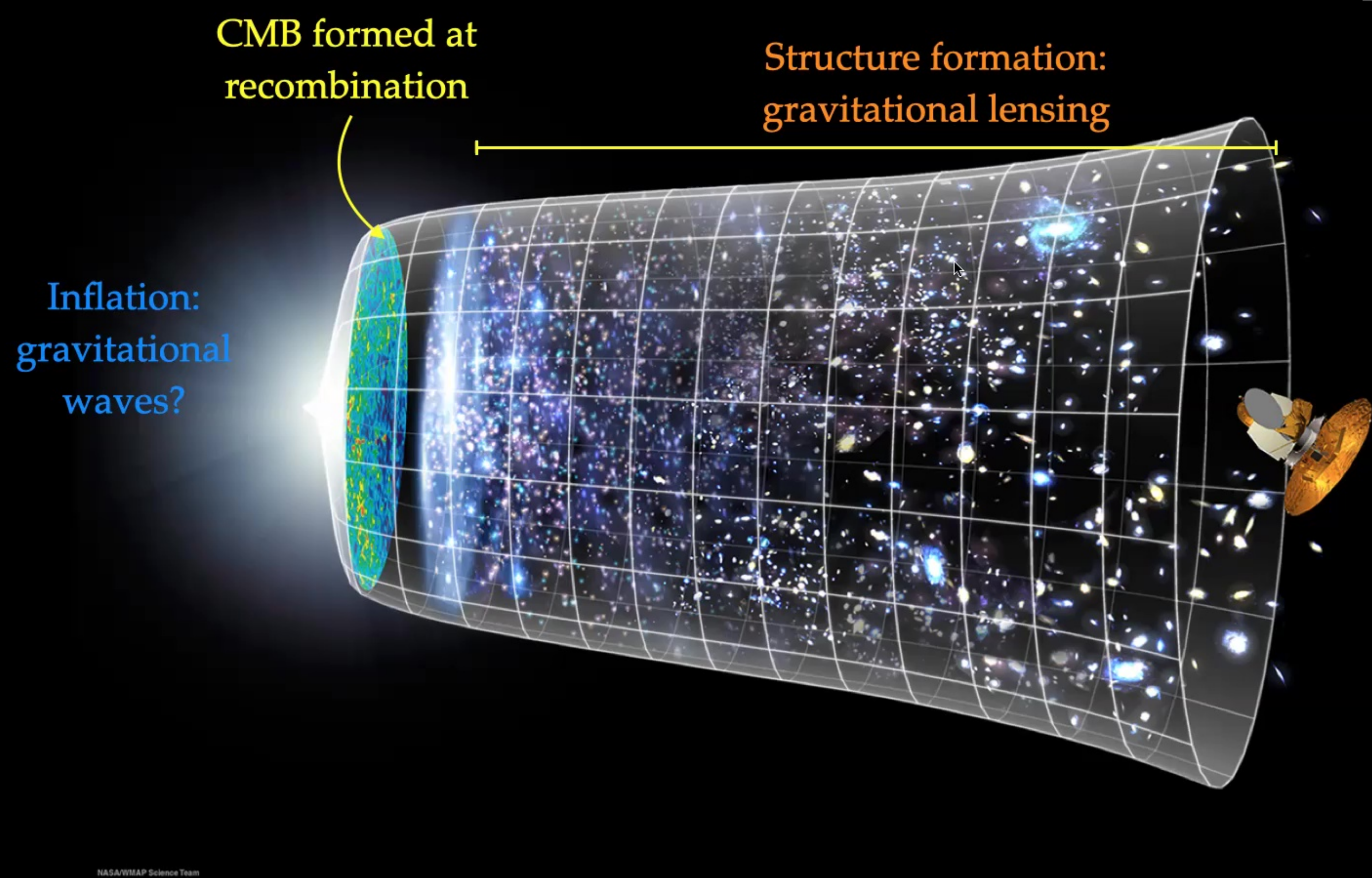
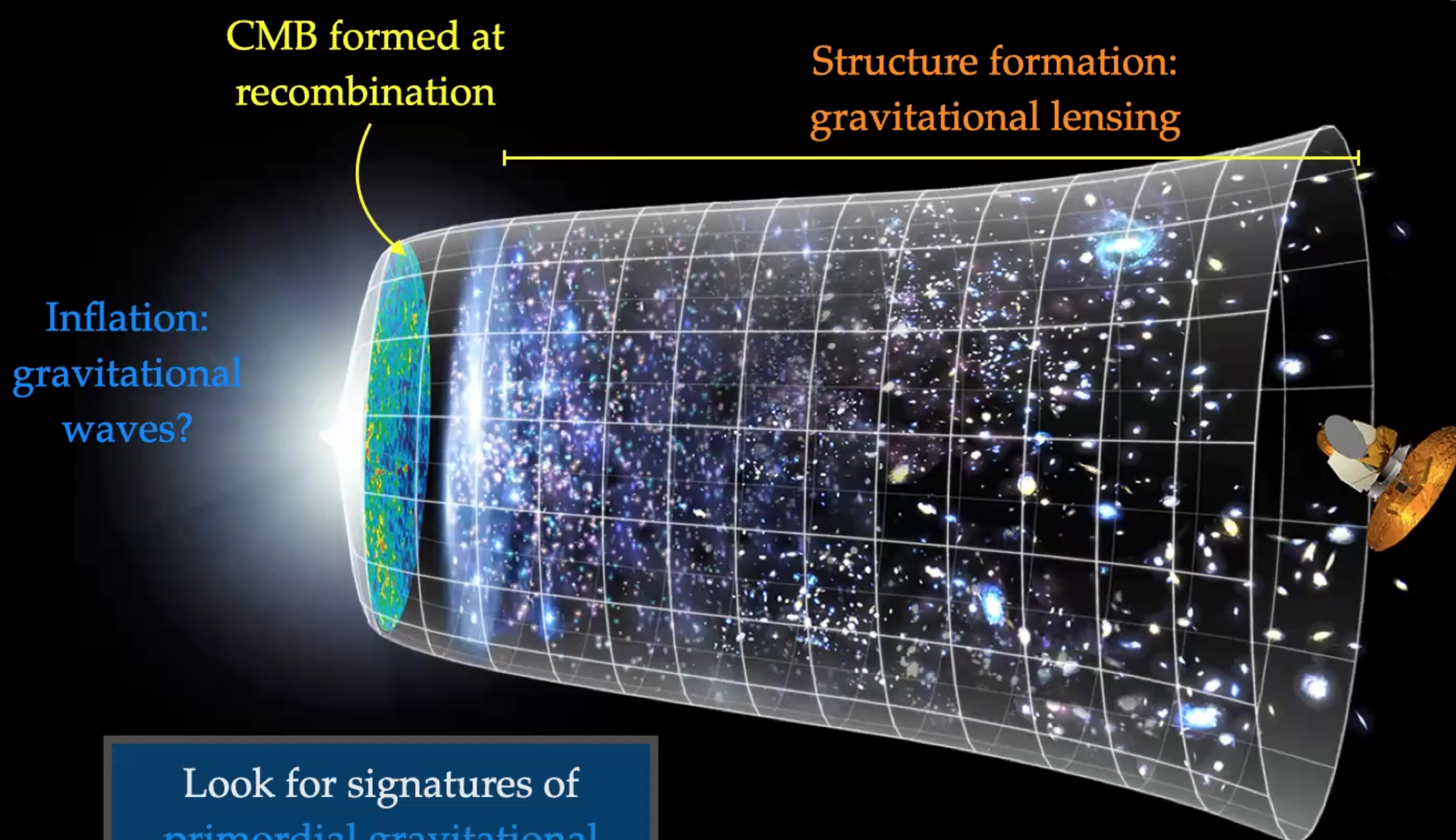
CMB: sensitive to physics of the early and late univ



CMB: sensitive to physics of the early and late univ

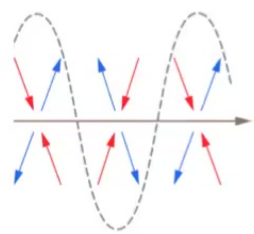
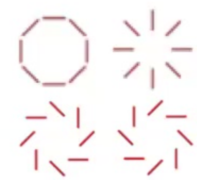
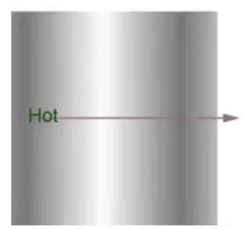


Look for signatures of primordial gravitational waves on CMB B-mode polarization.

delensing ⟷

CMB lensing

Inflation generically predicts PGW exist; B-mode polarization at recombination is window to PGW.

Perturbation of metric at inflation	Classical waves generated	Polarization type generated at the CMB
tensor perturbations		E B 
scalar perturbations		E 

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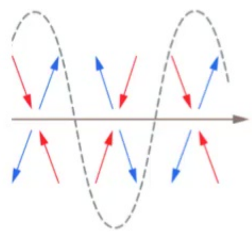
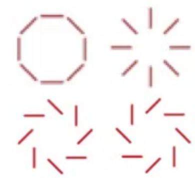
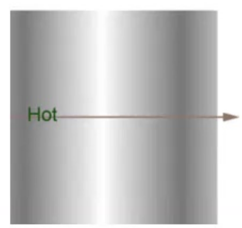
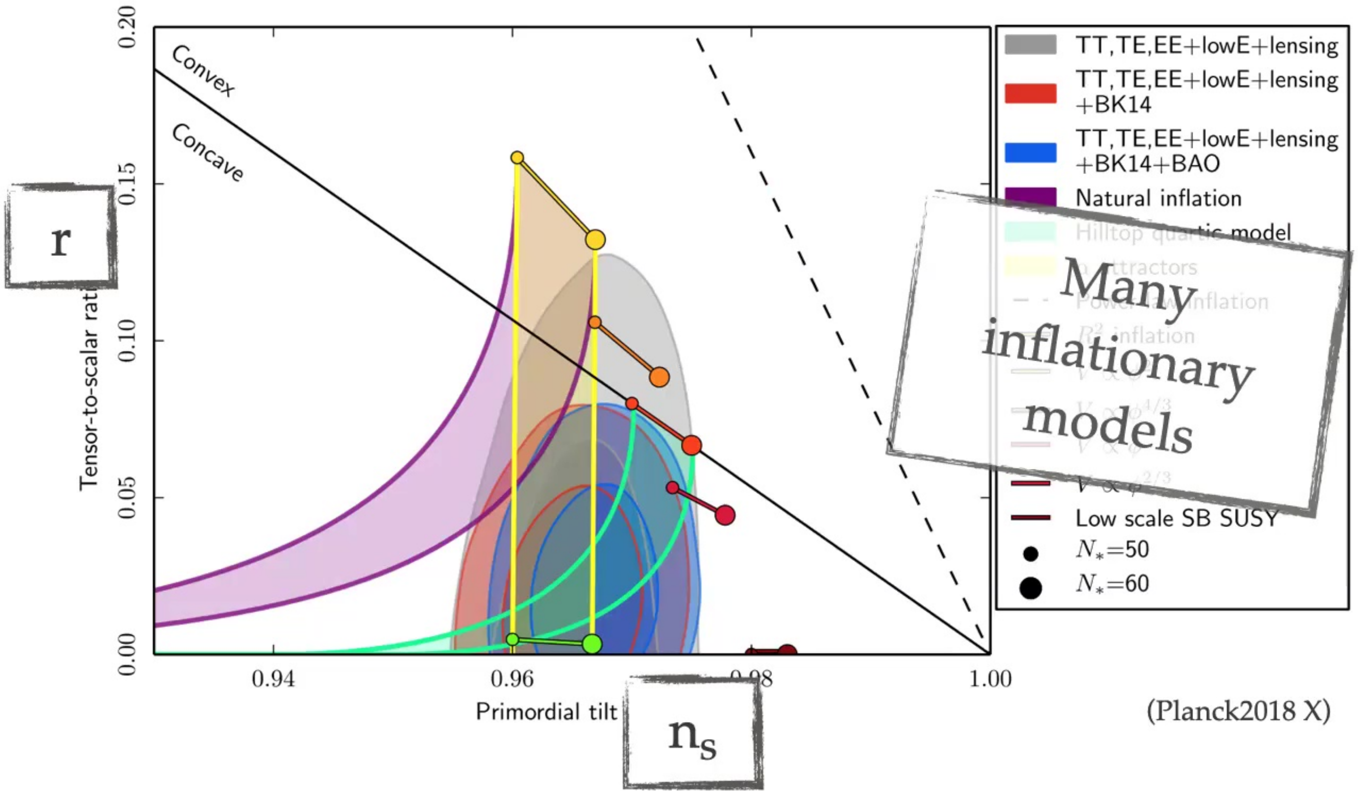
Inflation generically predicts PGW exist; B-mode polarization at recombination is window to PGW.

Perturbation of metric at inflation	Classical waves generated	Polarization type generated at the CMB
tensor perturbations		E, B 
scalar perturbations	 	E 

*r = tensor spectrum/scalar spectrum at k**

Inflation generically predicts PGW exist; B-mode polarization at recombination is window to PGW.



(Planck2018 X)

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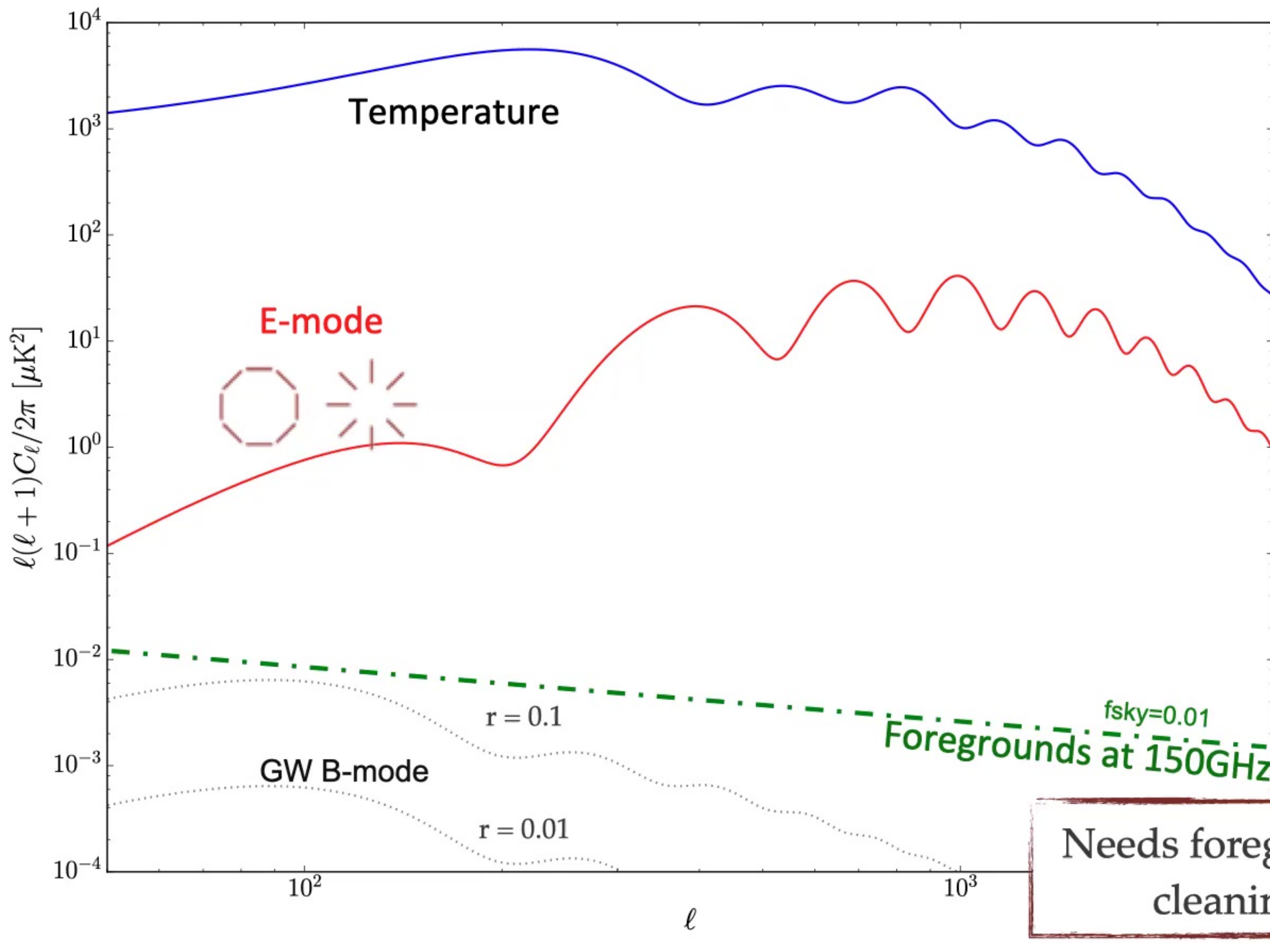
The challenges of measuring PGW B modes

- Extremely faint signal (T ~ 300uK, B (r=0.1, ℓ~100) ~ nK)
  - Build more sensitive instruments
- Polarized Galactic foregrounds
  - Observe in multiple mm-wave bands
- Lensing B modes —> delensing

Galactic foregrounds drown the faint signa



Needs foreground cleaning

CMB lensing

$$\text{lensed field}(\hat{n}) = \text{unlensed field}(\hat{n} + \nabla\phi)$$

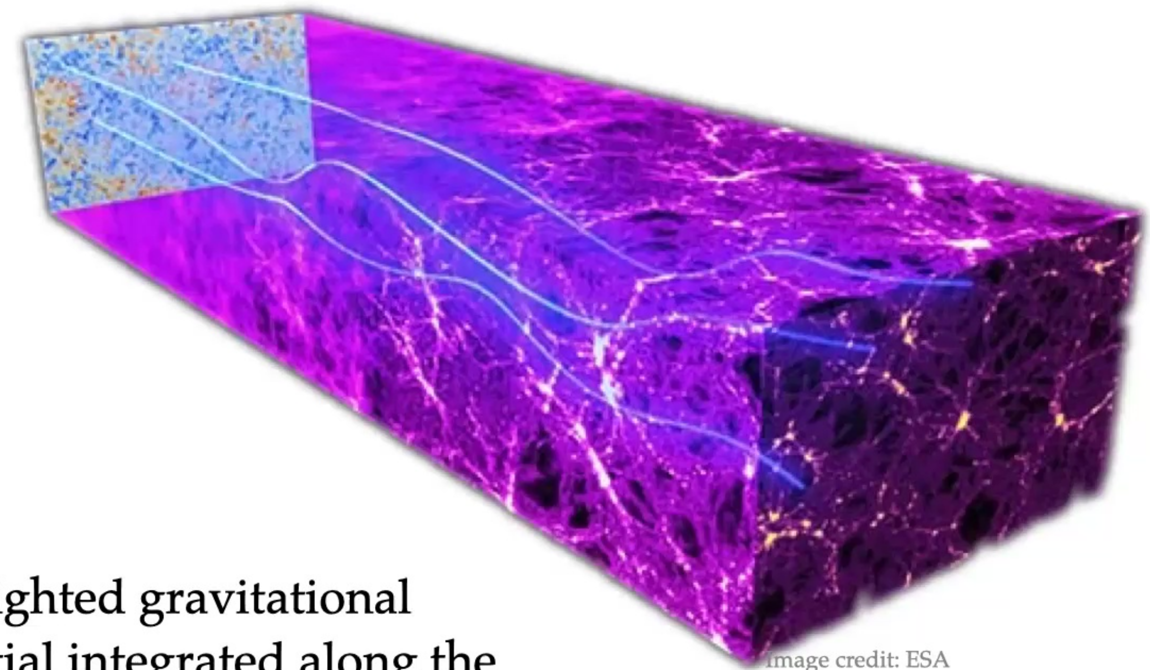
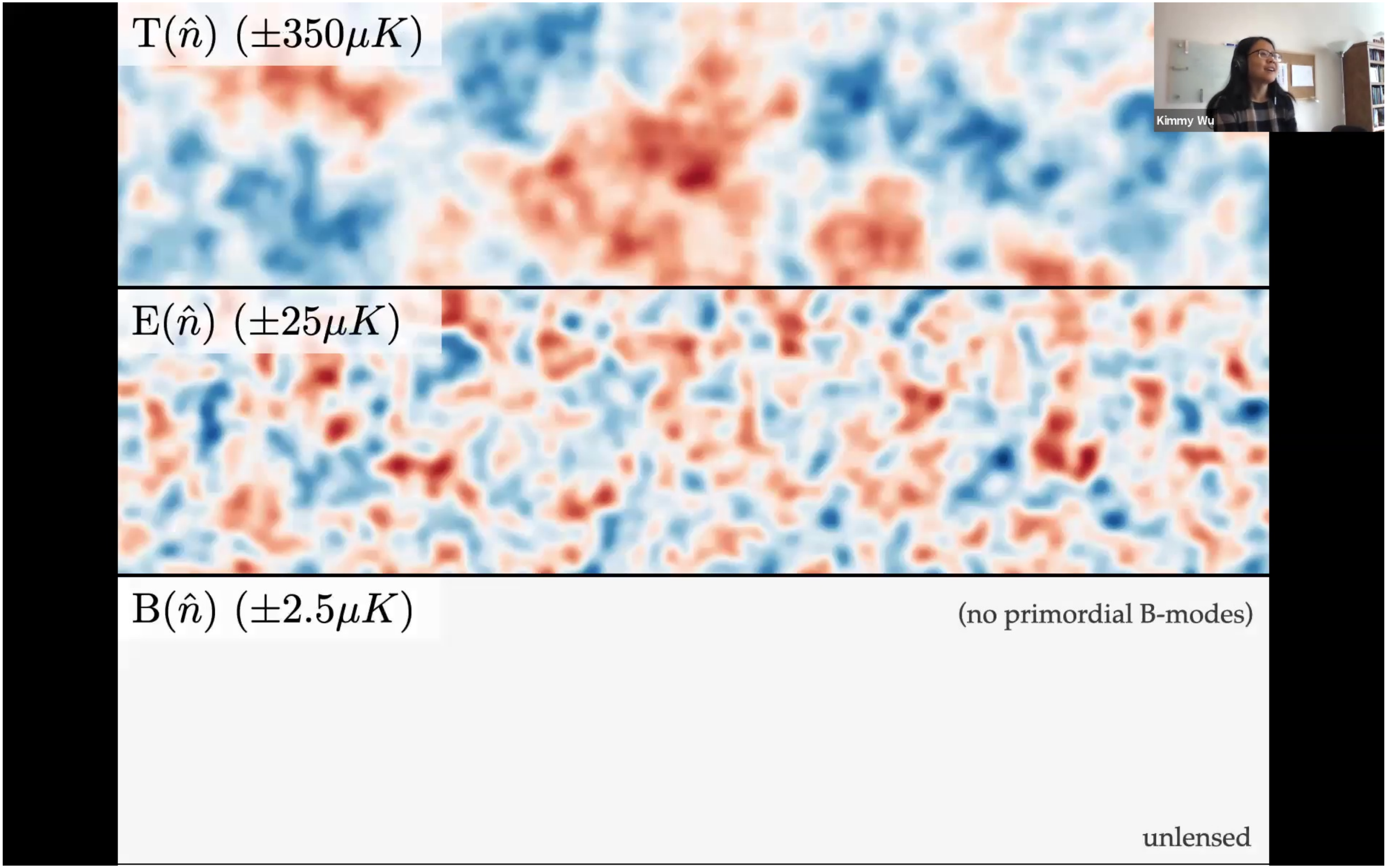
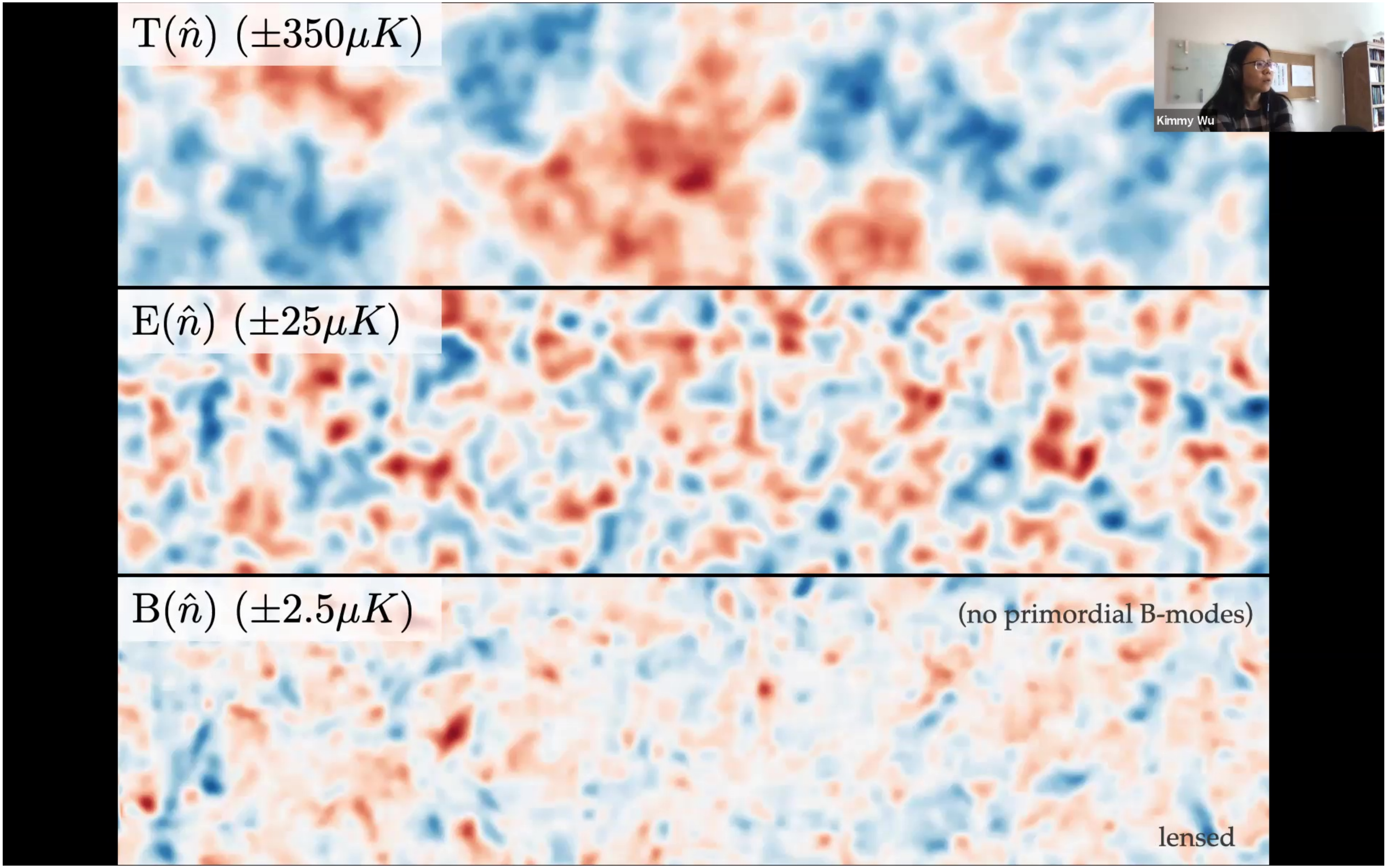


image credit: ESA

ϕ: weighted gravitational potential integrated along the line of sight



$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
(no primordial B-modes)
unlensed
Kimmy Wu


$T(\hat{n})$ $(\pm 350\mu K)$
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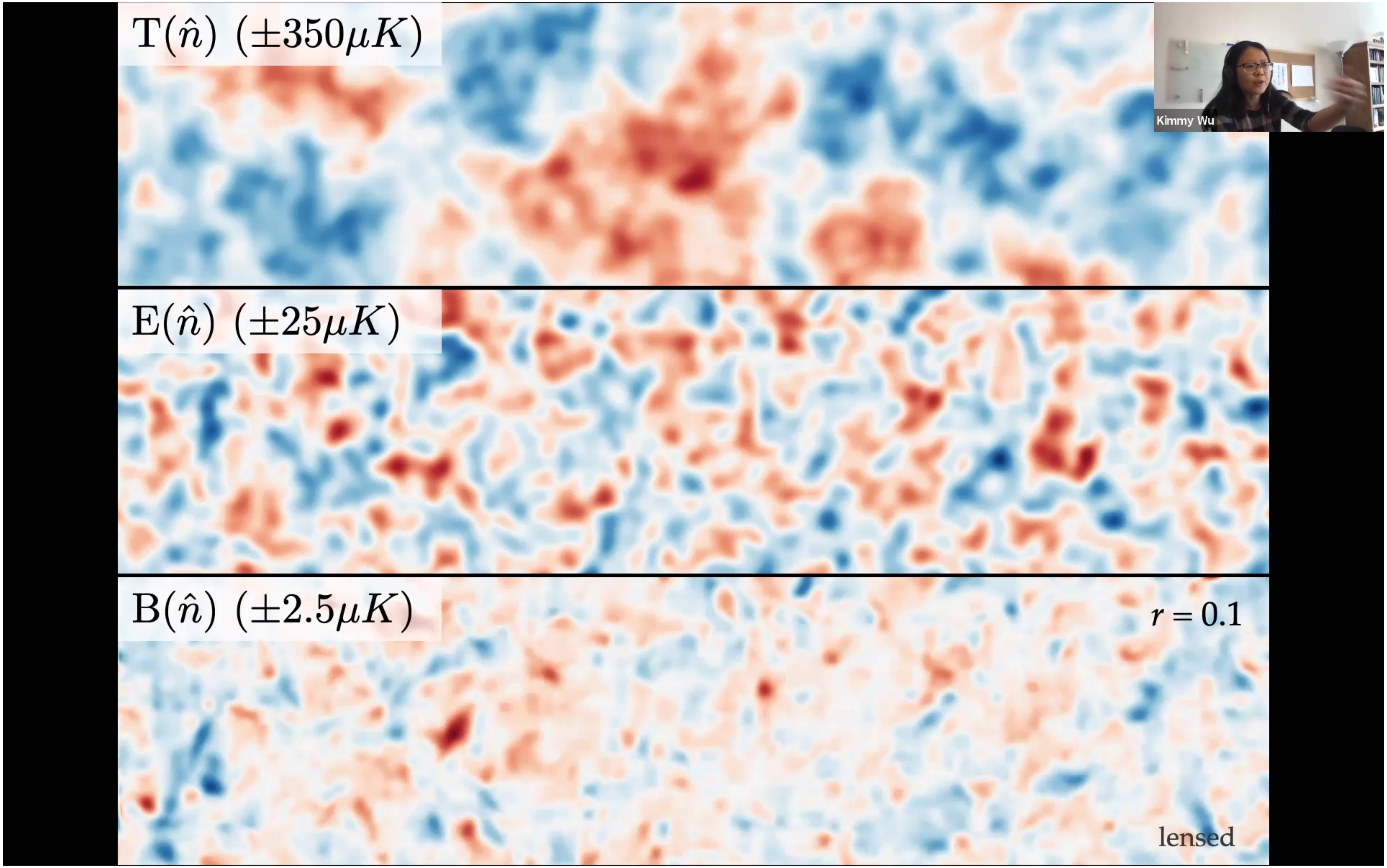
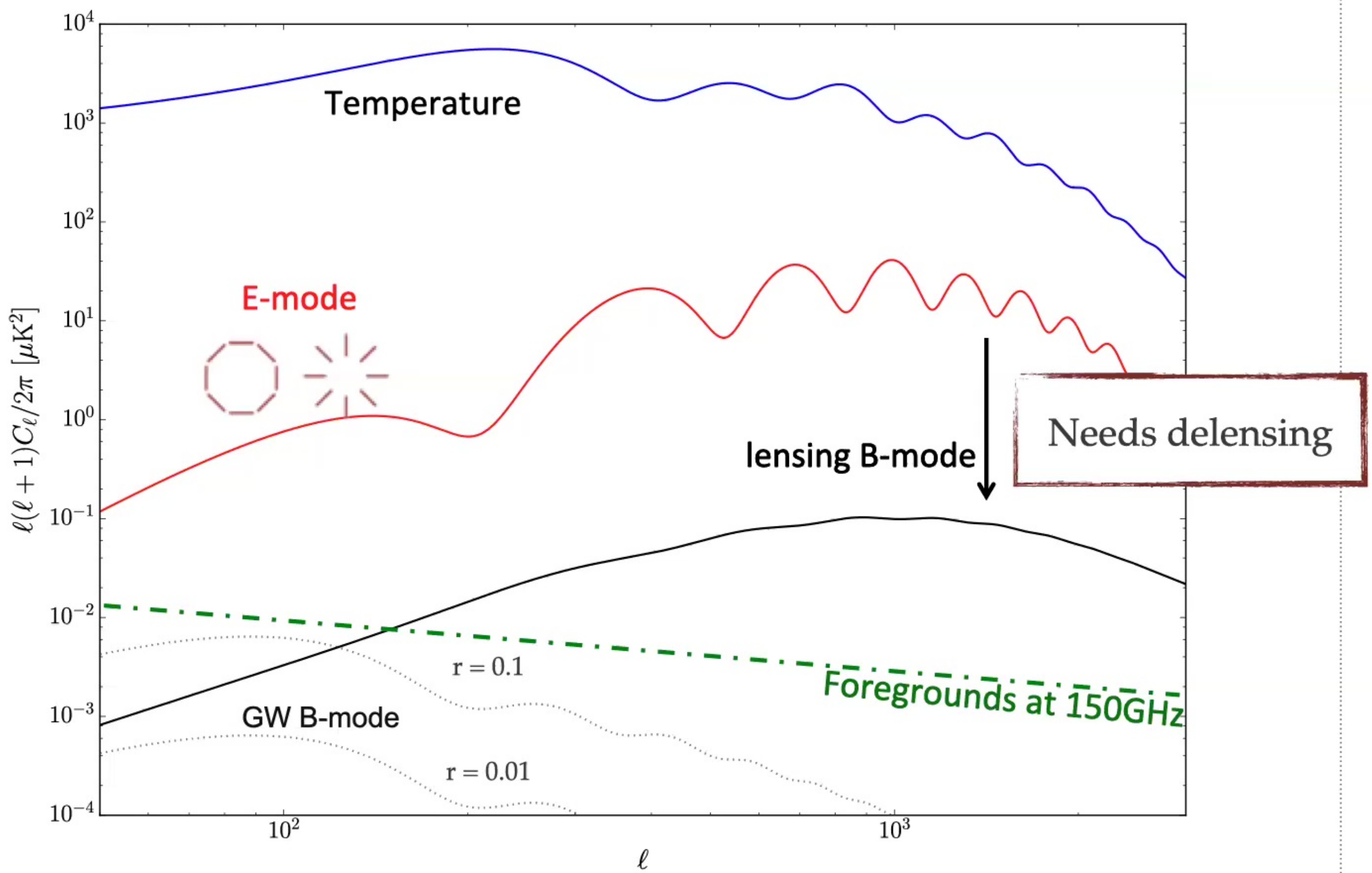
(no primordial B-modes)
lensed
Kimmy Wu



$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
$r = 0.1$
lensed
Kimmy Wu

Lensing B modes add fuel to the fire



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The telescopes


The South Pole has excellent conditions for
mm-wave observations
South Pole
Station
Keck
BICEP3, SPT
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Kimmy Wu

What make the South Pole a great site for mm-wave observations?

A. It is a desert.

B. It has high elevation

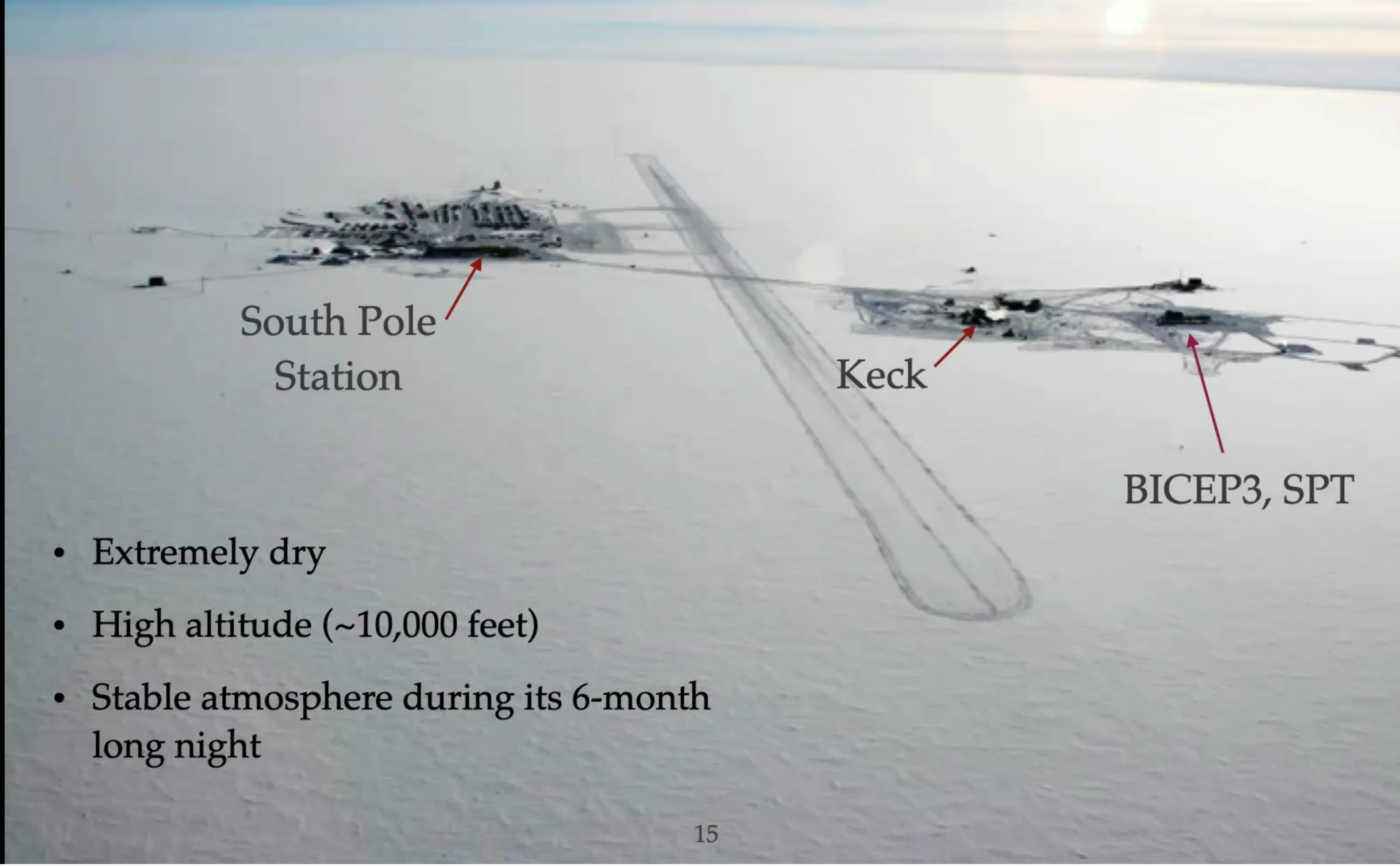
C. It has little light pollution.

D. The sun only rises and sets once every year

E. It has great seeing.

F. Penguins.

The South Pole has excellent conditions for mm-wave observations



- Extremely dry
- High altitude (~10,000 feet)
- Stable atmosphere during its 6-month long night

The South Pole has excellent conditions for mm-wave observations

- Extremely dry
- High altitude (~10,000 feet)
- Stable atmosphere during its 6-month long night

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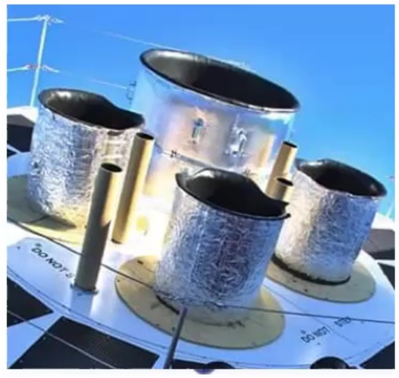
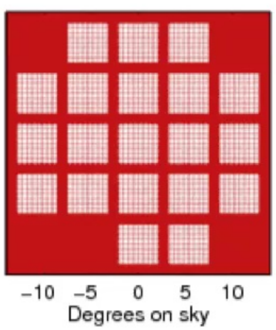
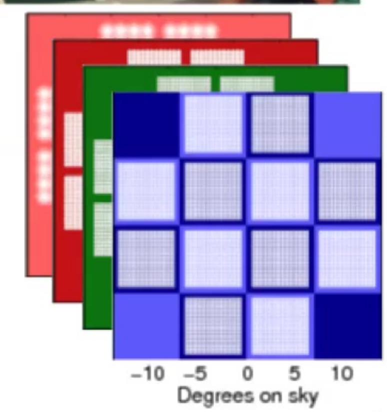
BICEP3
(2016-)

BICEP Array
(2020-)







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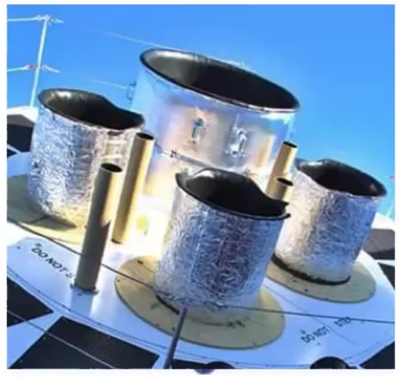
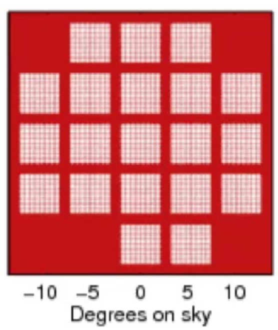
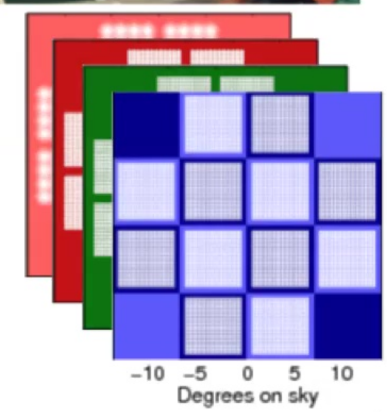
BICEP3
(2016-)

BICEP Array
(2020-)

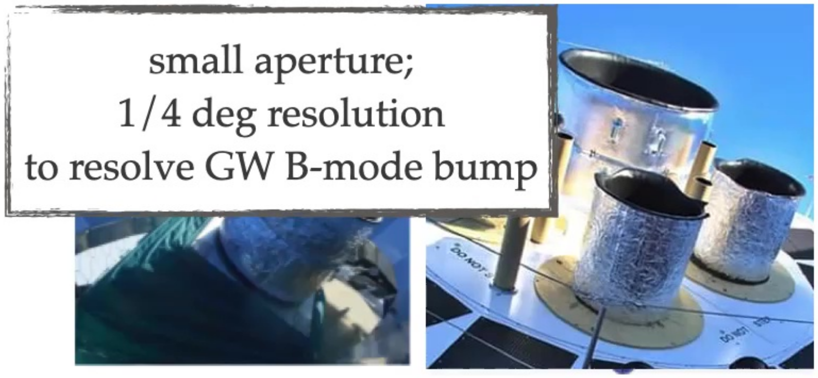




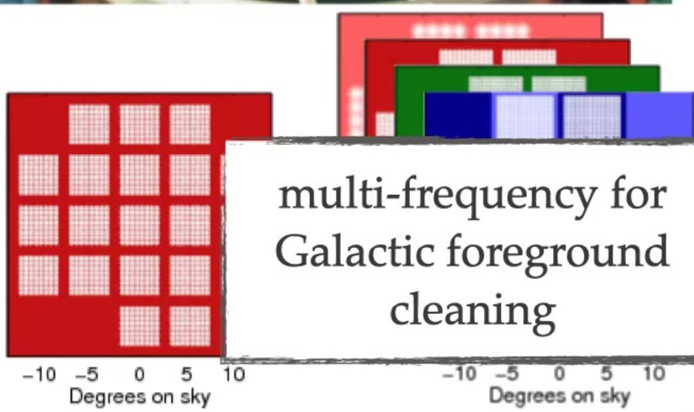


BICEP3 (2016-)

BICEP Array (2020-)

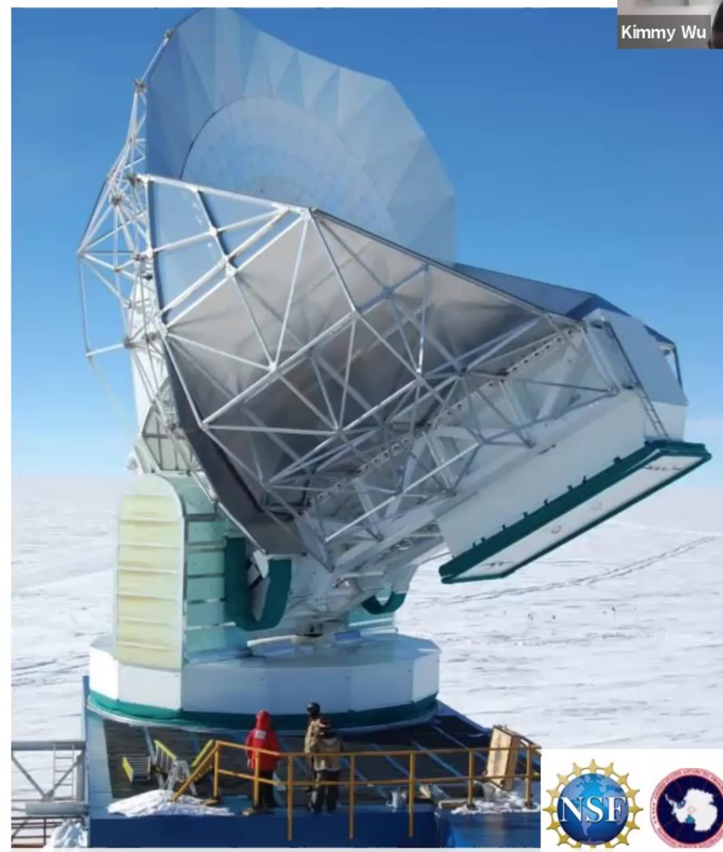


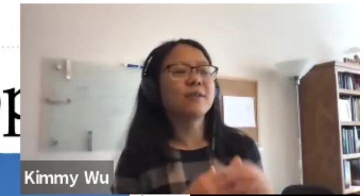
small aperture;
1/4 deg resolution
to resolve GW B-mode bump



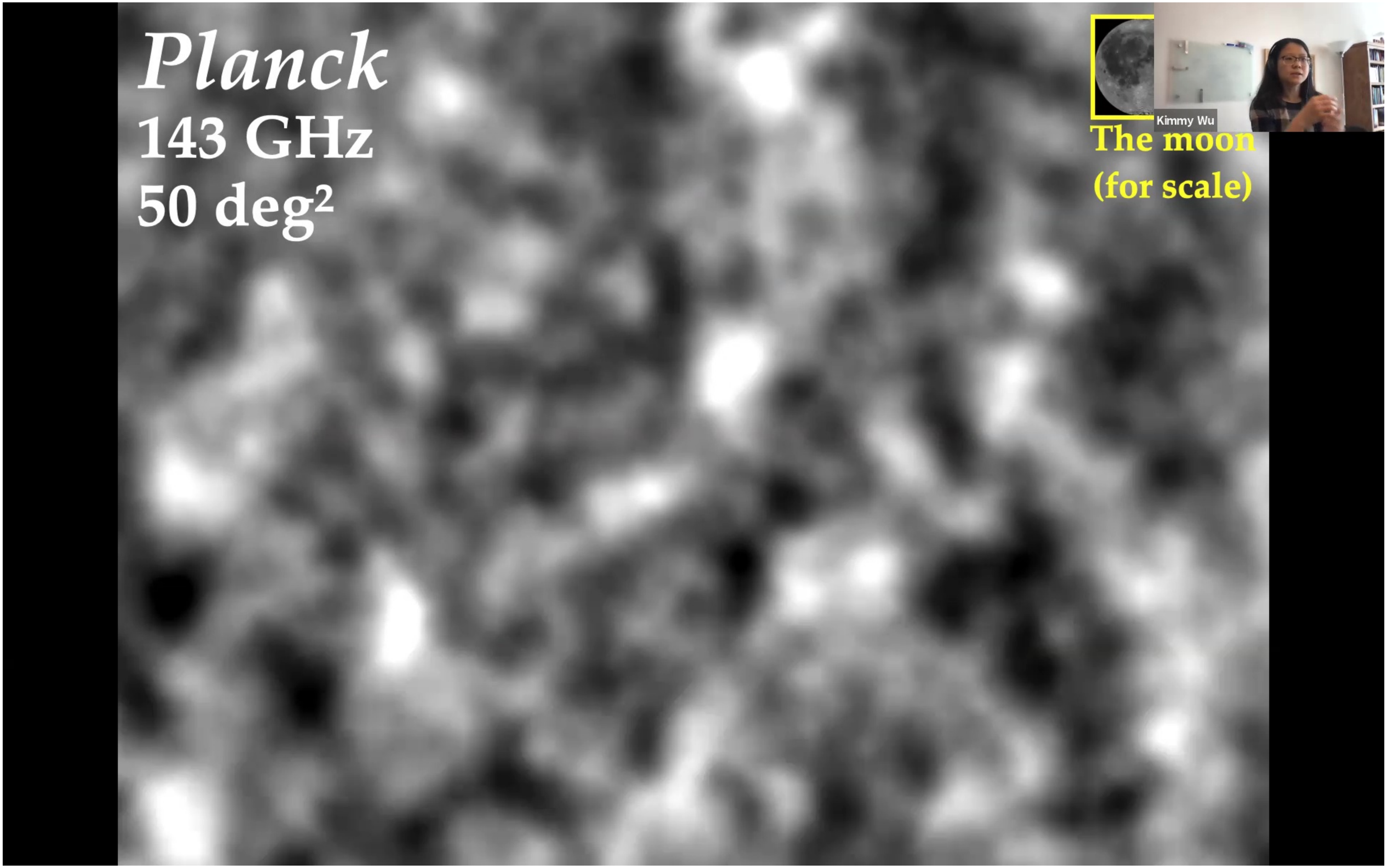
multi-frequency for
Galactic foreground
cleaning

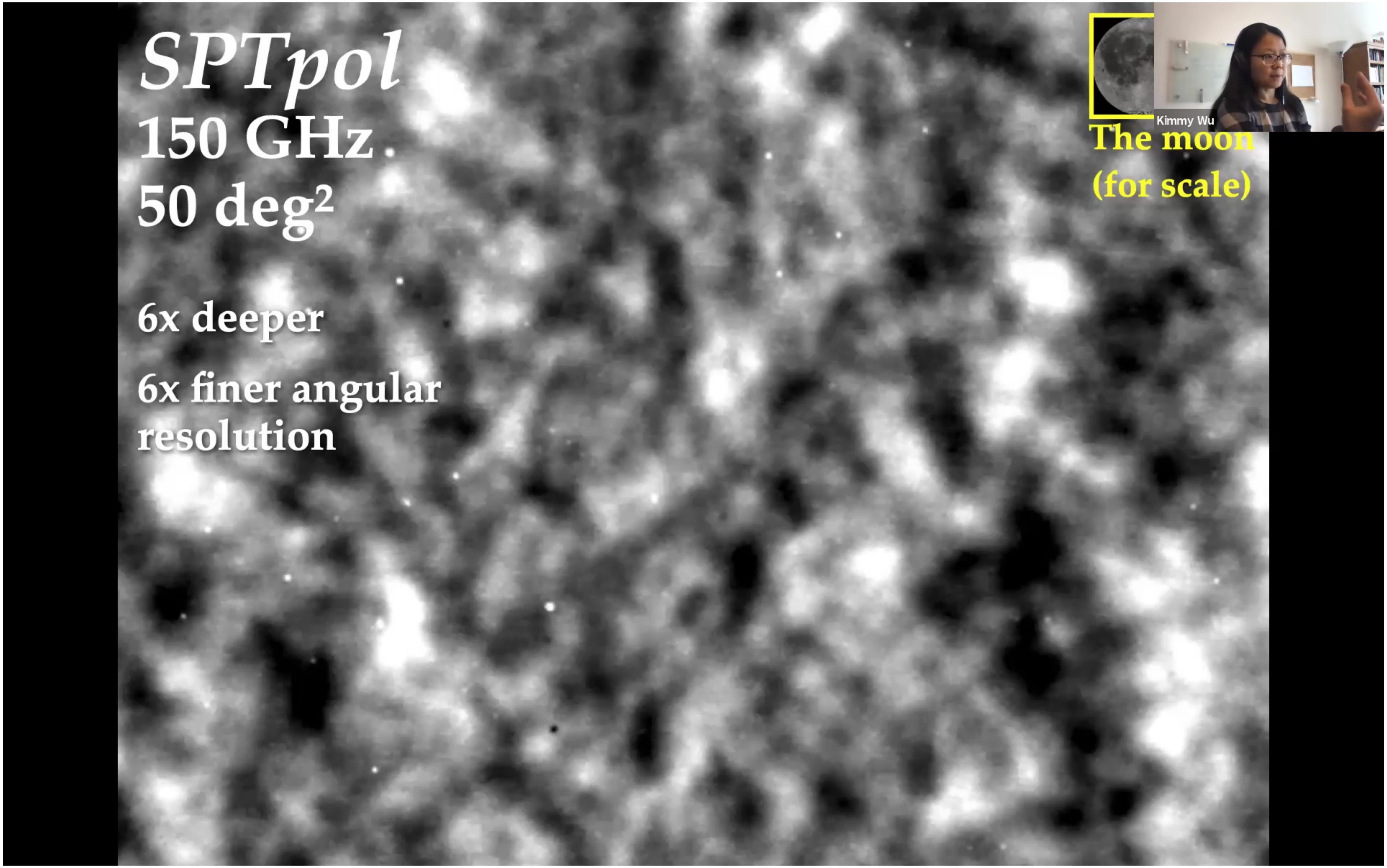
South Pole Telescop



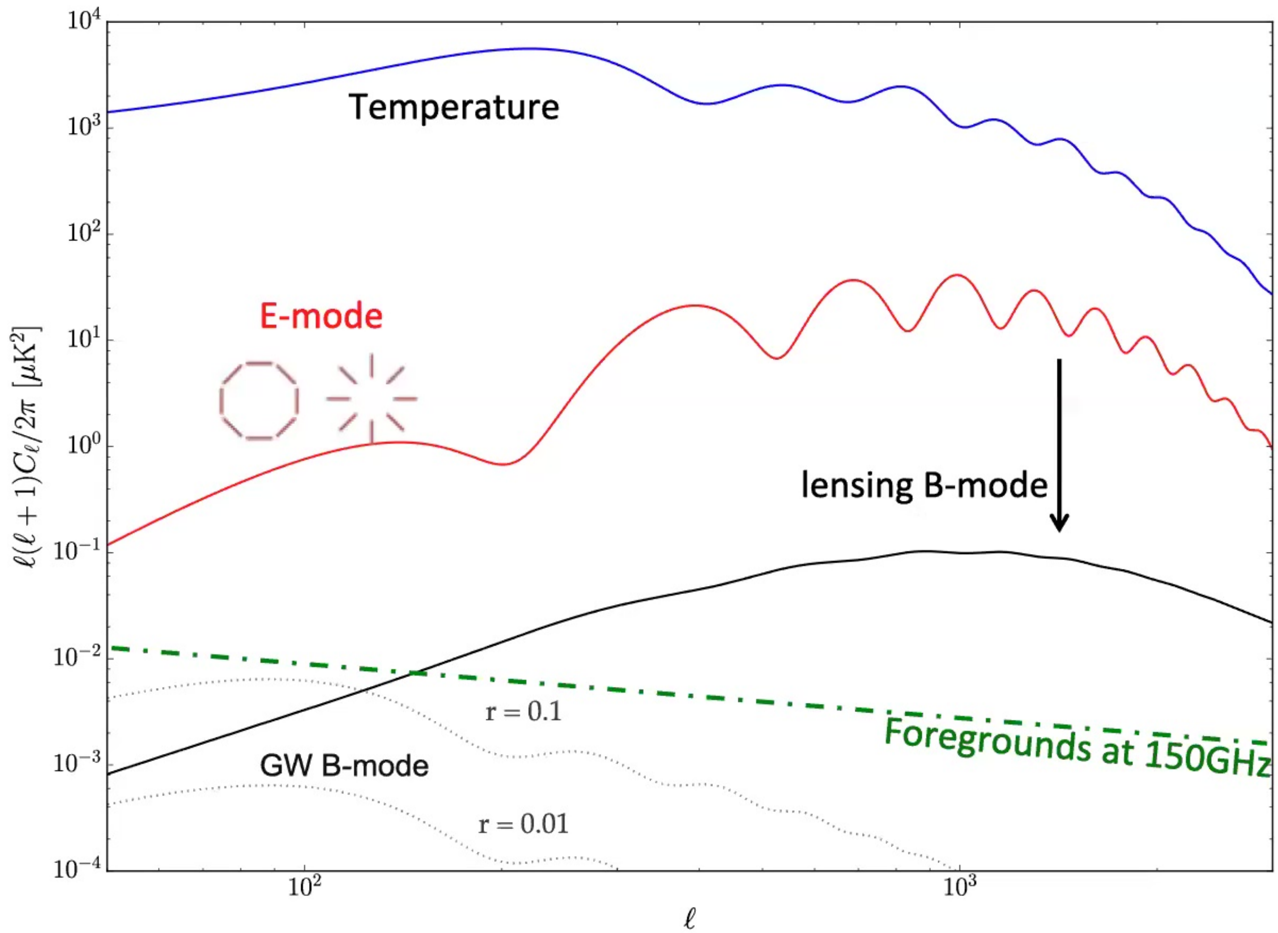


- Highest resolution CMB Telescope (1′).
- Produced the largest deep CMB polarization maps in sub-degree scales


Planck
143 GHz
50 deg²
The moon
(for scale)
Kimmy Wu


SPTpol
150 GHz
50 deg²
6x deeper
6x finer angular resolution
The moon
(for scale)
Kimmy Wu

High resolution: small angular scales



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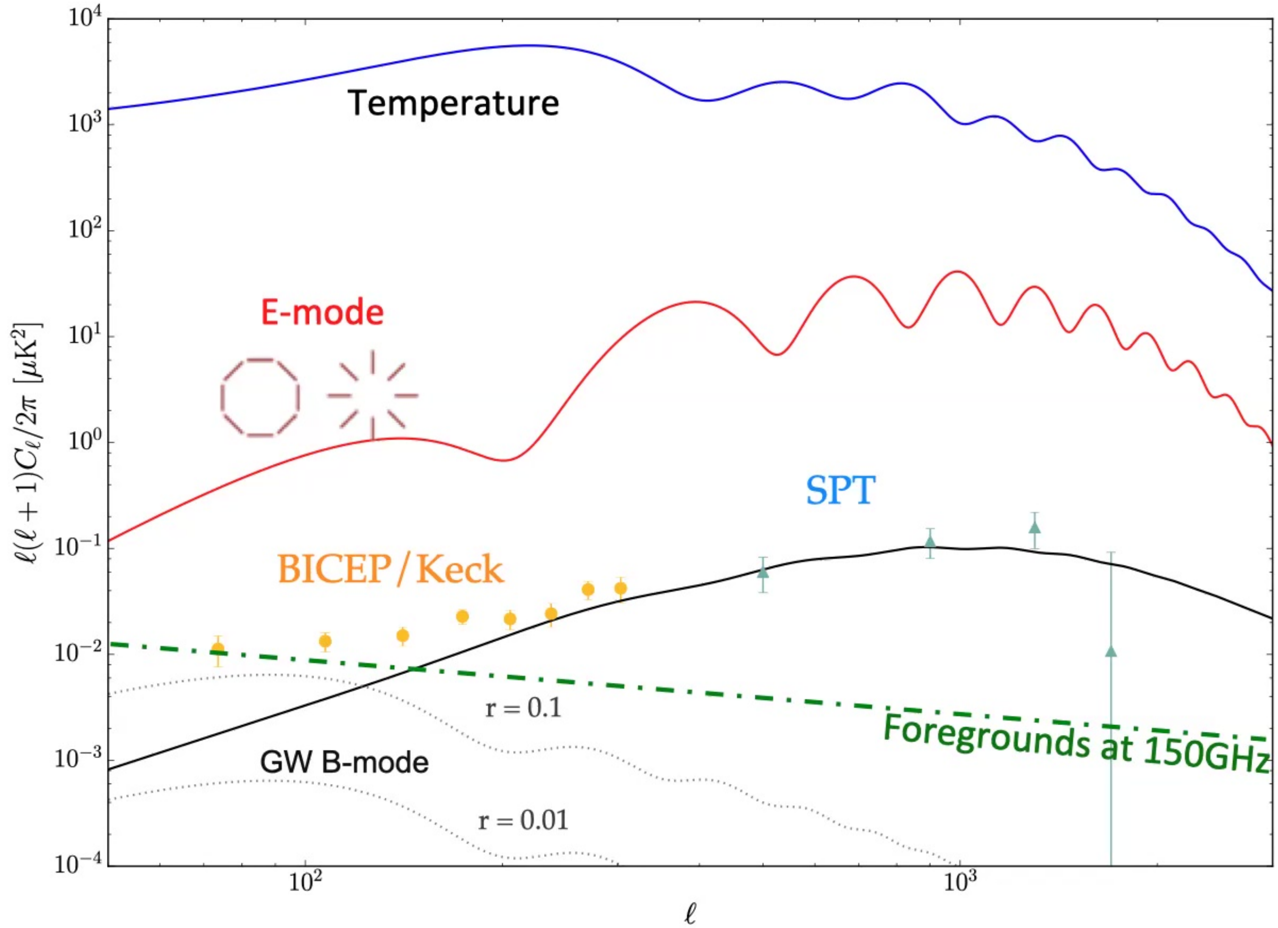
High resolution: small angular scales



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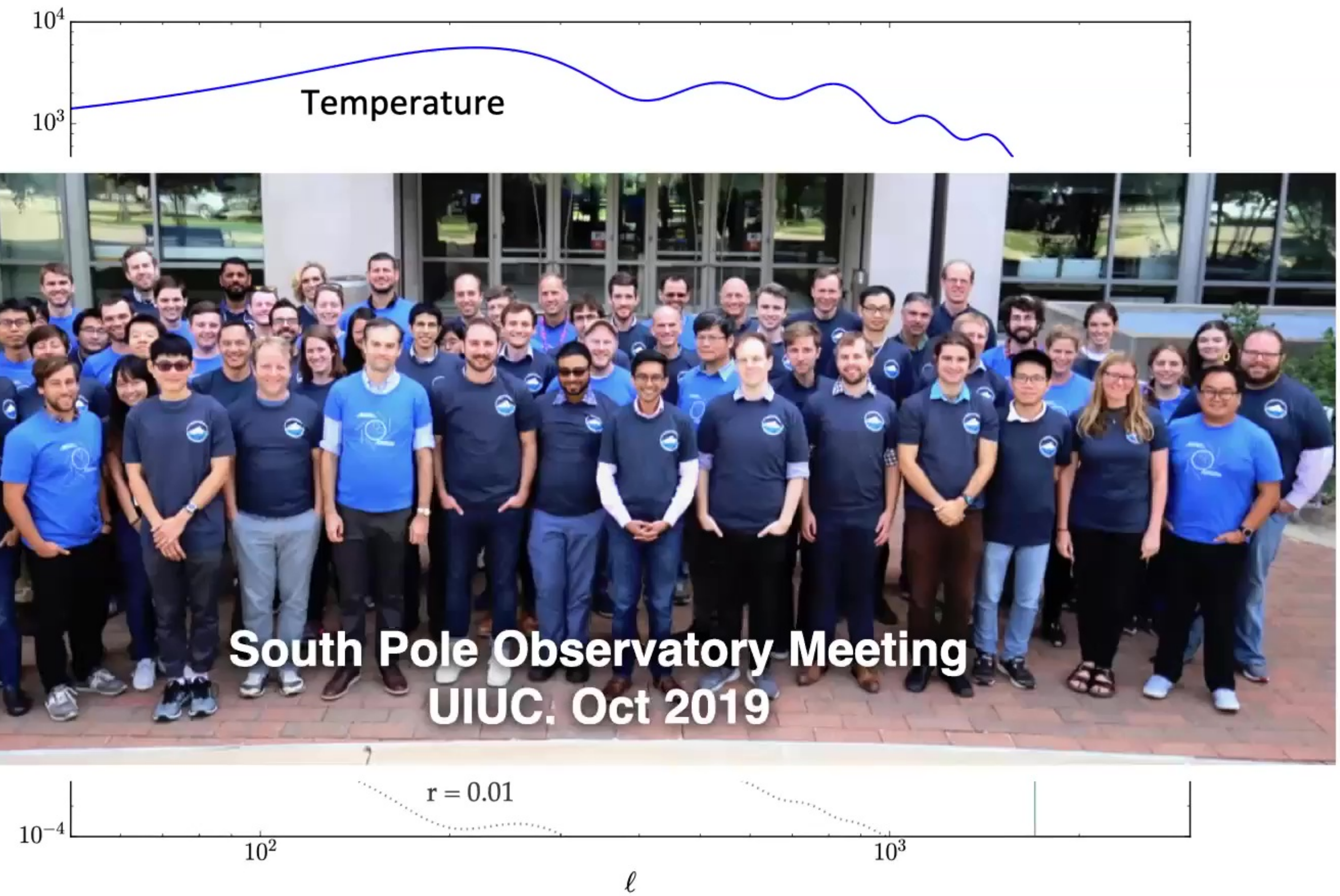
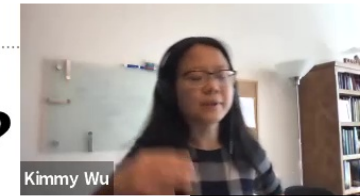
Complementary information from BK and S



Delensing BICEP / Keck B-mode maps



How does lensing degrade the r estimate?

Lensing, foreground, (PGW B-modes)

Instrument noise

$$\sigma(r)^{*} \propto C_\ell^{\mathrm{BB}} + N_\ell$$

Delensing for *r* = reduce the sample variance contributed by lensing when measuring *r*

*assuming diagonal covariance & brutally simplified

$$\sigma(r) \propto \sum_\ell \sqrt{\frac{1}{\#\,\text{of modes}}} \left(\frac{C_\ell^{BB} + N_\ell}{\partial C_\ell^{BB}/\partial r} \right)$$

Why now for BICEP/Keck?

Contributions to σ(r): $C_\ell^{\mathrm{BB,fg}} + C_\ell^{\mathrm{BB,lens}} + N_\ell$

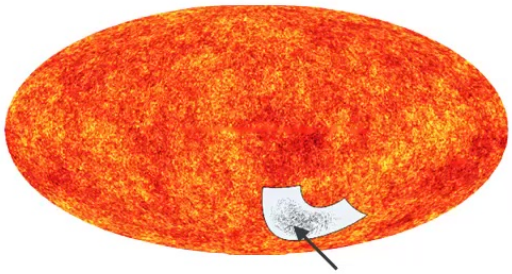
For current BICEP/Keck data set:

Foregrounds becoming sample-variance limited

Noise variance becoming comparable/ lower than lensing variance at 90/150 GHz

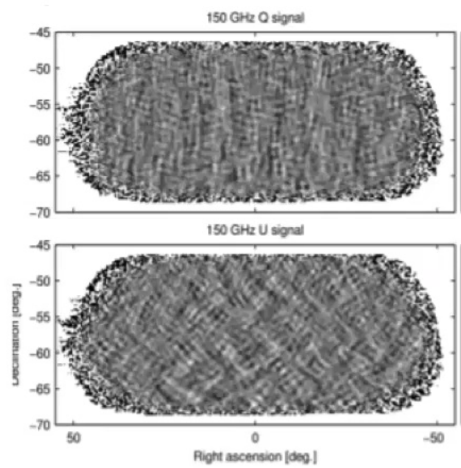
In regime where delensing can begin to improve $\sigma(r)$

Reminder of the BICEP/Keck r analysis: input map

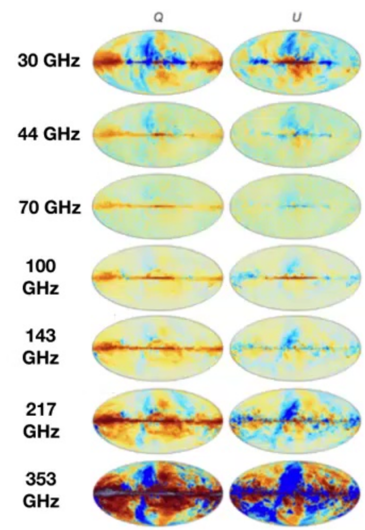


BK/SPTpol patch; ~500 deg^2

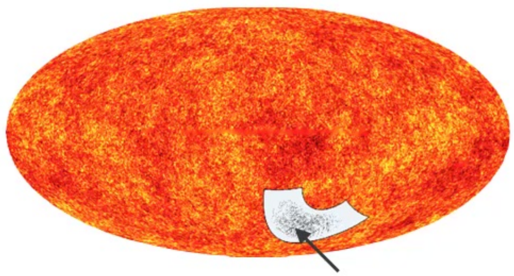
Maps from BICEP/Keck (95/150GHz)



Maps from Planck/WMAP

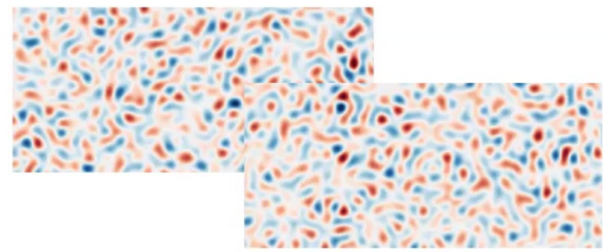


Reminder of the BICEP/Keck r analysis: input map

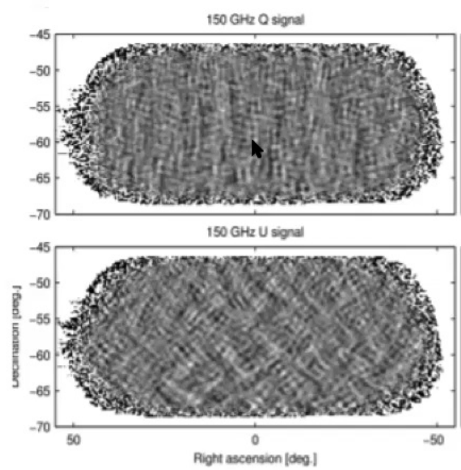


BK/SPTpol patch; ~500 deg^2

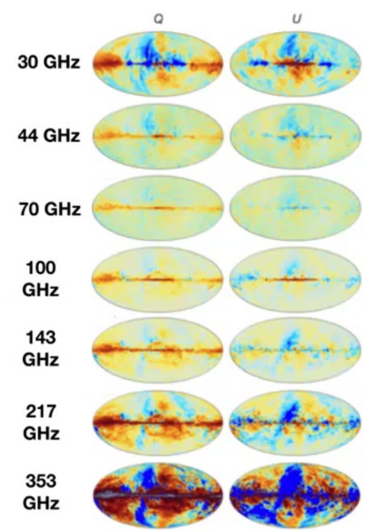
+ lensing template



Maps from BICEP/Keck (95/150GHz)

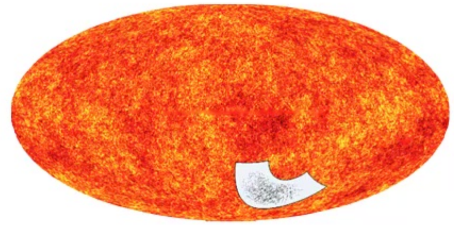


Maps from Planck/WMAP

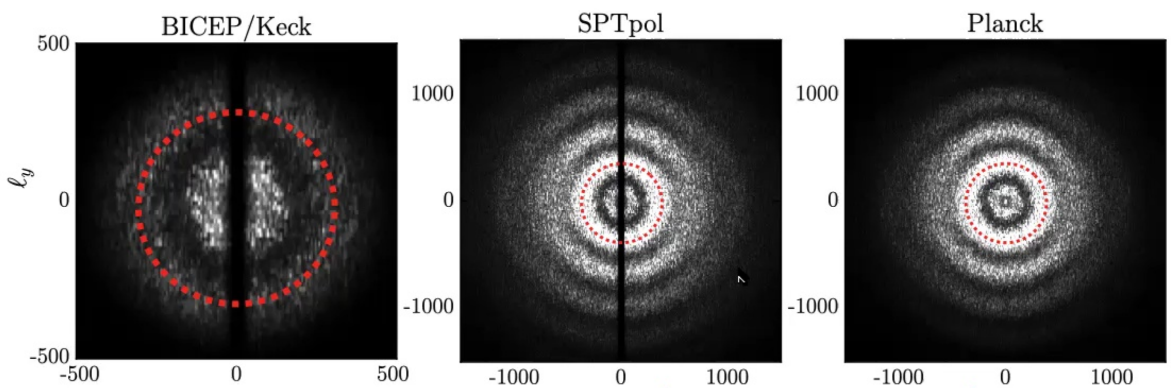


Lensing template inputs: Q/U maps for E mode

E modes: combine Q/U maps from BICEP/Keck 150GHz, SPTpol 150GHz, and *Planck* 143GHz



E mode 2D angular power spectra (signal simulation)



Cover broader multipole range than BK;
SPTpol contributes most S/N to the final lensing template.

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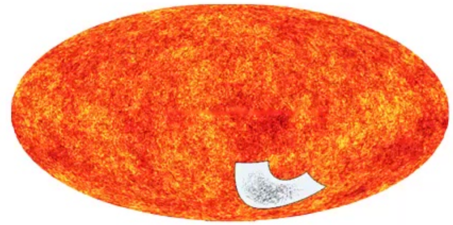
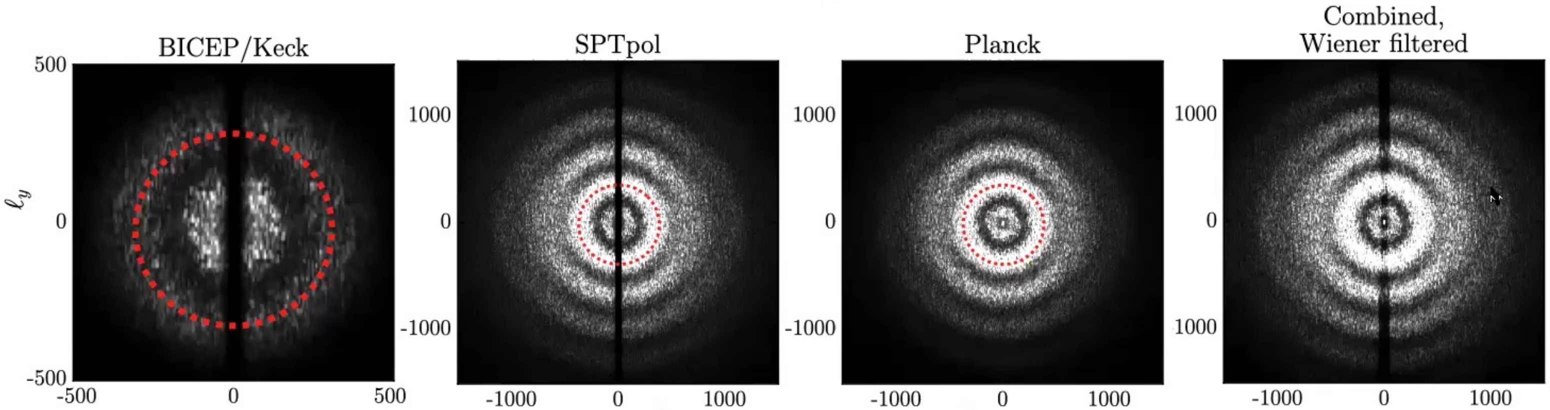
Lensing template inputs: Q/U maps for E mode

E modes: combine Q/U maps from BICEP/Keck 150GHz, SPTpol 150GHz, and *Planck* 143GHz



E mode 2D angular power spectra (signal simulation)



Cover broader multipole range than BK;
SPTpol contributes most S/N to the final lensing template.

Lensing template inputs: CIB for ϕ tracer

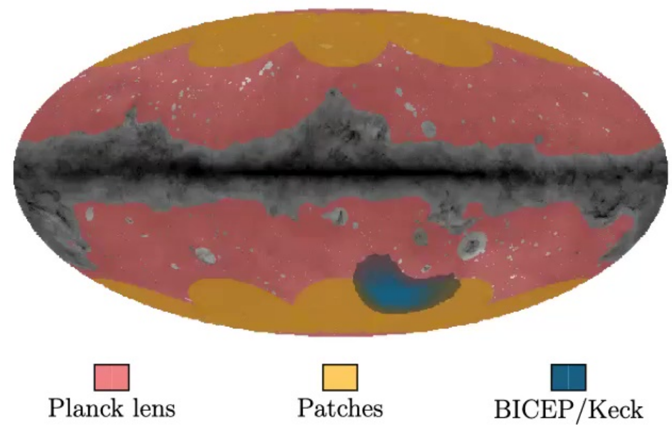
- CIB map: Planck GNILC

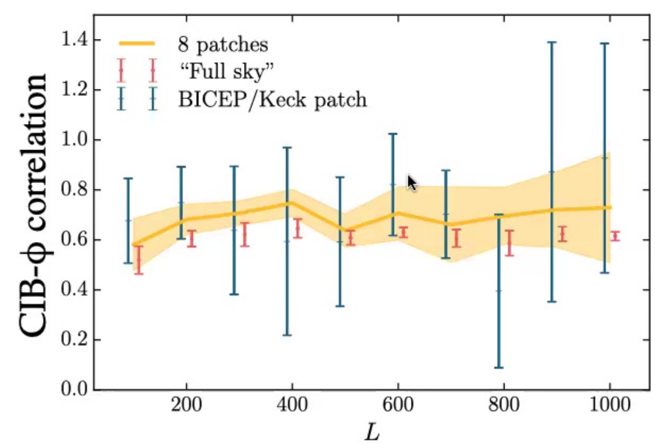
- Need CIB auto-spectrum and CIBxϕ for filtering and generating simulated CIB realizations.

  - CIBxϕ measure with Planck ϕ reconstruction.

- Use high Galactic latitude areas to estimate the CIB auto-spectrum and CIBxϕ to ensure similar levels of dust contamination.

- Generate CIB realizations by rescaling the simulated ϕ and adding Gaussian noise given the CIB auto-spectra and CIBxϕ; distribution drawn from the covariance of the spectra measured from the 8 patches.





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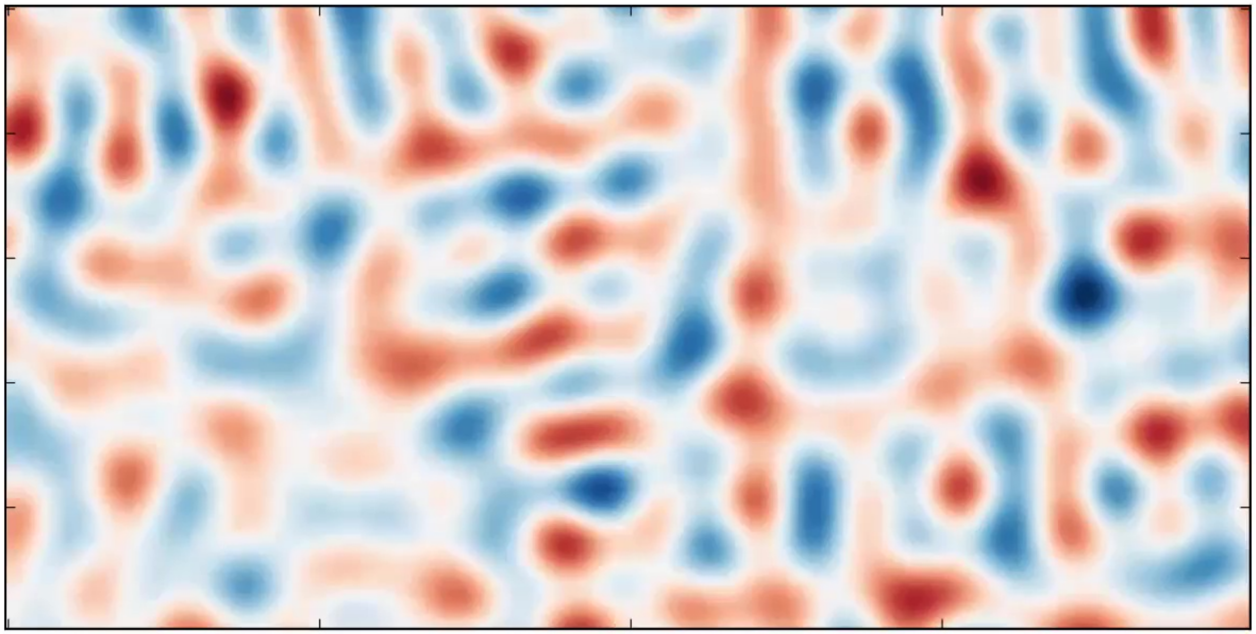
Making the lensing template: undeflect-and-differenc

$\pm 3.5 \mu K$

Undeflect by $-\nabla\hat{\phi}$



Sim

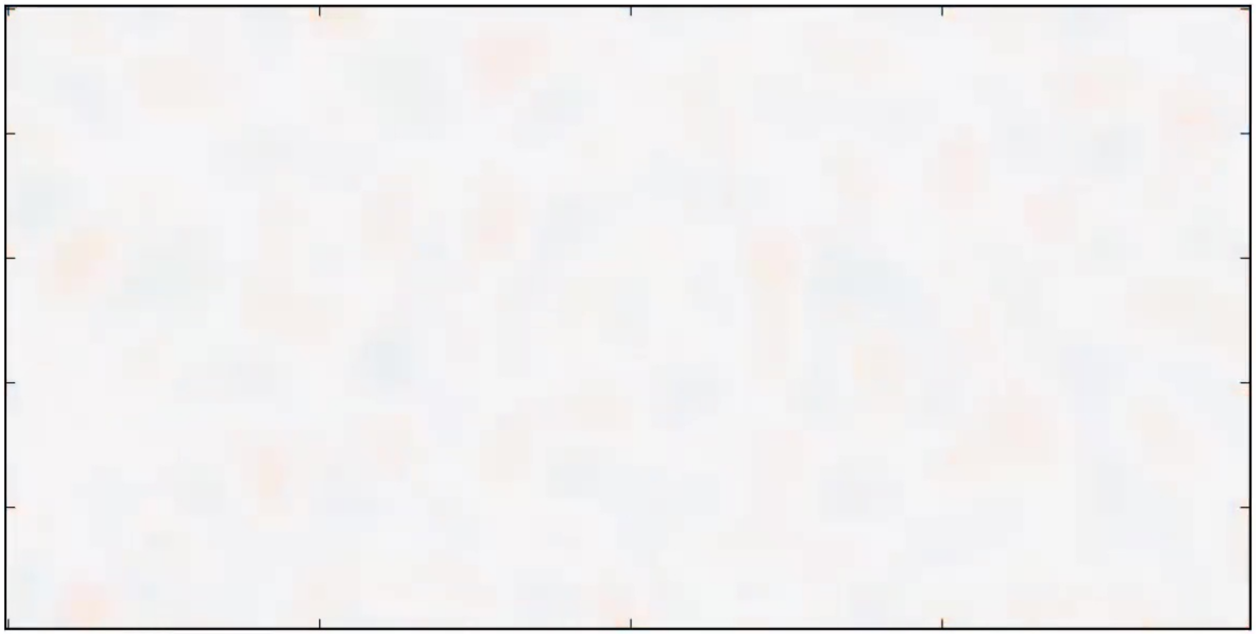
1) Lensed Q map; 2) Undeflected Q map; 3) Lensed-Undeflected Q map

Same for U map

Making the lensing template: undeflect-and-differenc

$\pm 3.5 \mu K$

Undeflect by $-\nabla\hat{\phi}$



Sim

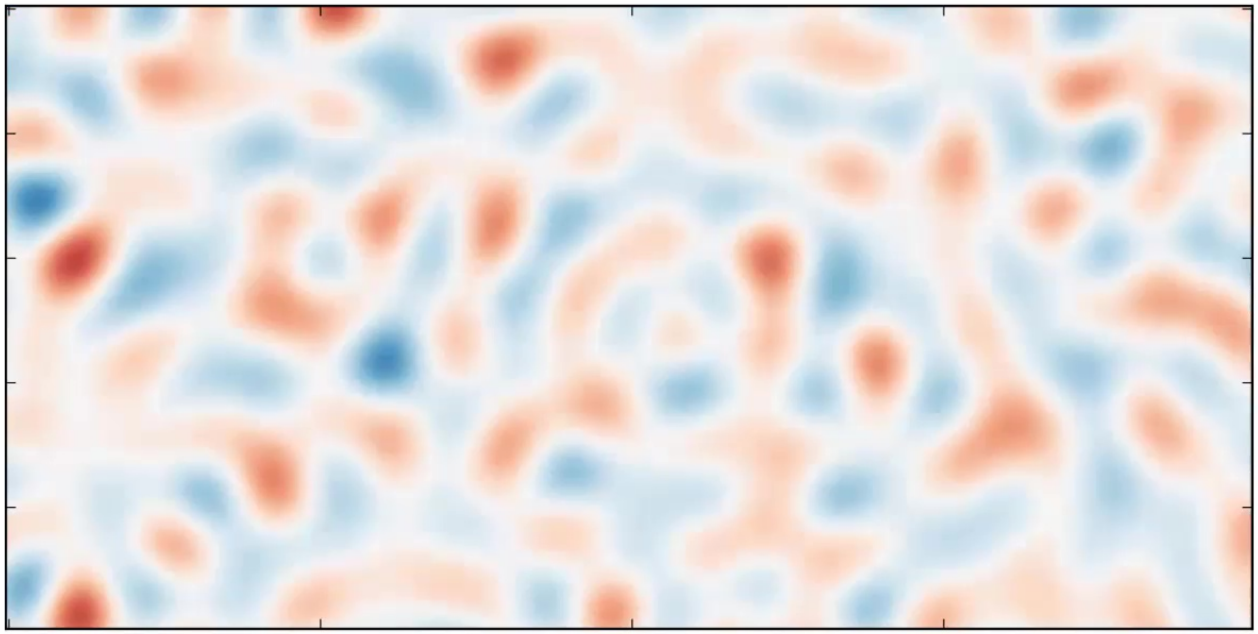
1) Lensed Q map; 2) Undeflected Q map; 3) Lensed-Undeflected Q map

Same for U map

Making the lensing template: undeflect-and-differenc

$\pm 0.35 \mu K$

Undeflect by $-\nabla\hat{\phi}$

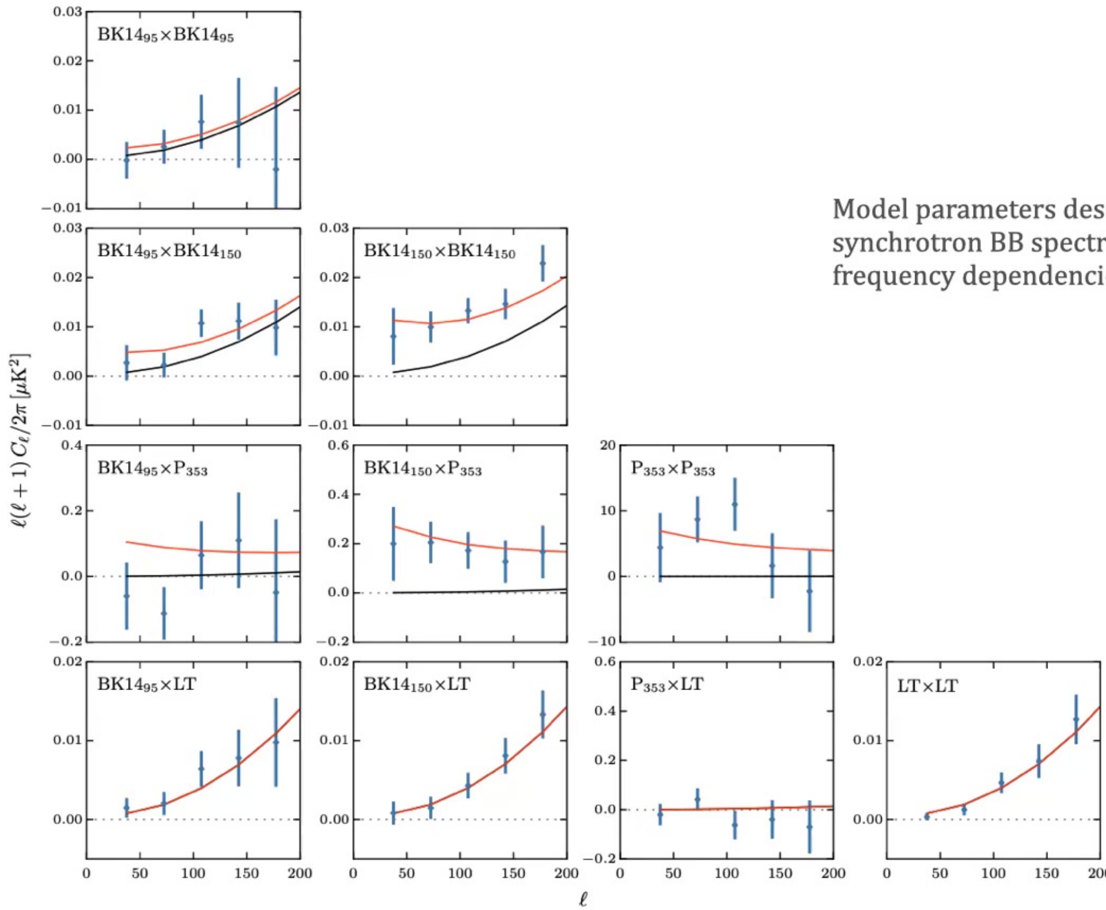


Sim

1) Lensed Q map; 2) Undeflected Q map; 3) Lensed-Undeflected Q map

Same for U map

Reminder of the BICEP/Keck r analysis: spectr



Model parameters describe r, lensing, dust and synchrotron BB spectrum amplitudes, shapes, frequency dependencies, and correlations.

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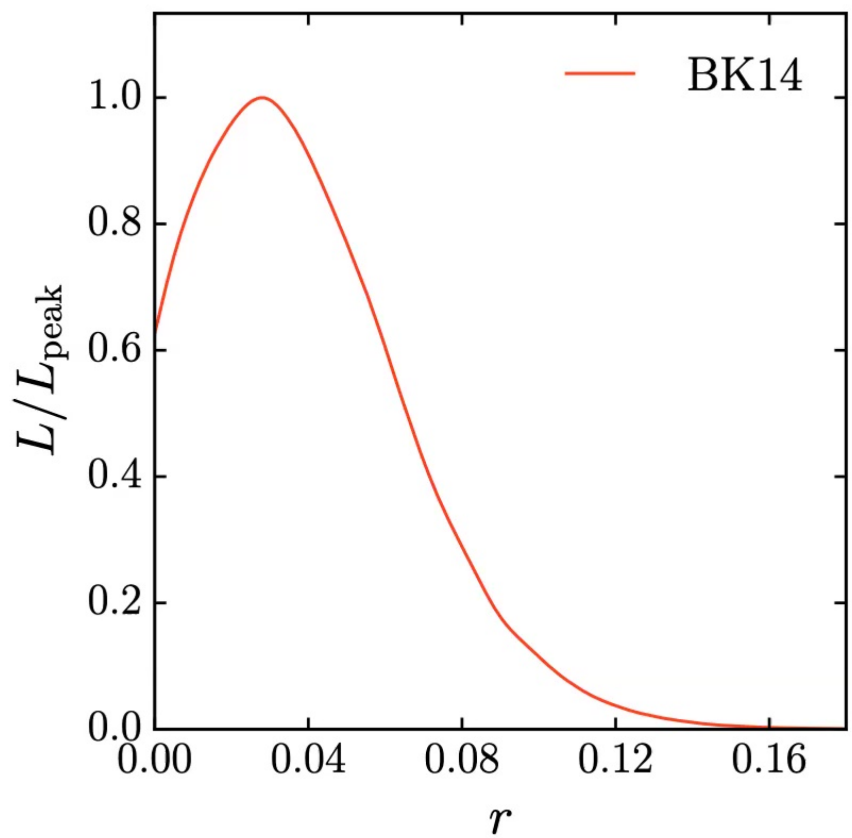
r posterior without delensing



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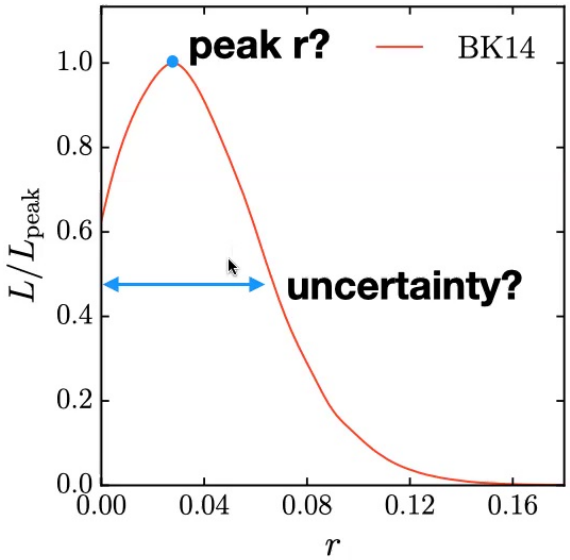
Which of the following you think best describe the post-delensing marginalized r posterior?

A. reduced uncertainty, lower peak r;

B. reduced uncertainty, higher peak r;

C. increased uncertainty, lower peak r;

D. increased uncertainty, higher peak r.



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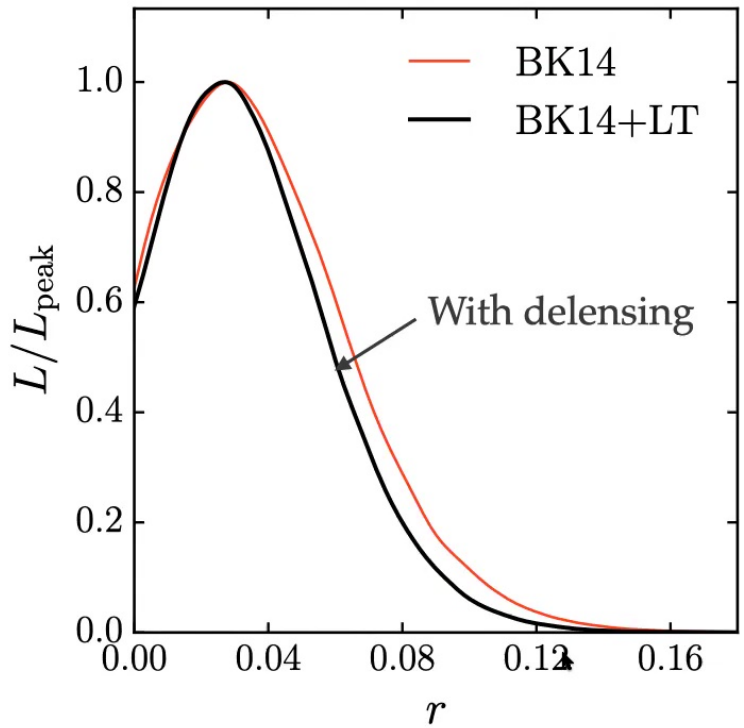
r posterior with and without delensing



The 95% C.L. upper limit on r is reduced from r<0.090 to r<0.082.

(K. Wu; BK+SPTpol Collaborations; arXiv:2011.08163)

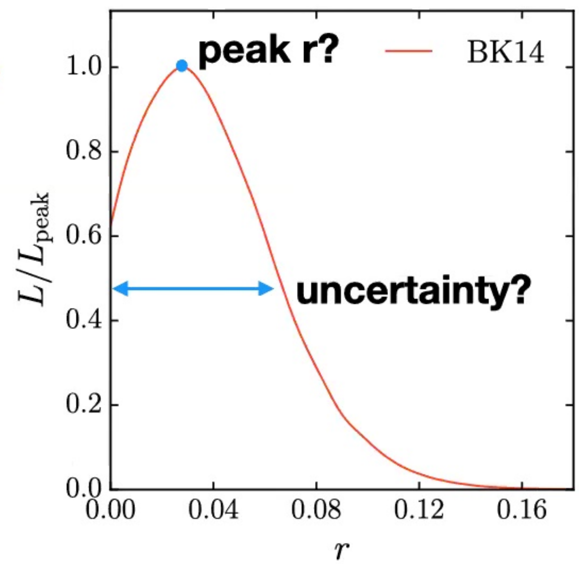
Which of the following you think best describe the post-delensing marginalized r posterior?

A. reduced uncertainty, lower peak *r*; ✓

B. reduced uncertainty, higher peak *r*;

C. increased uncertainty, lower peak *r*;

D. increased uncertainty, higher peak *r*.



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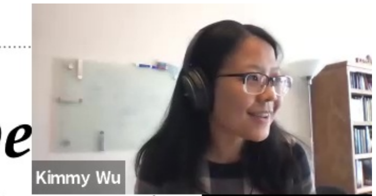
Which of the following you think best describe the post-delensing marginalized r posterior?

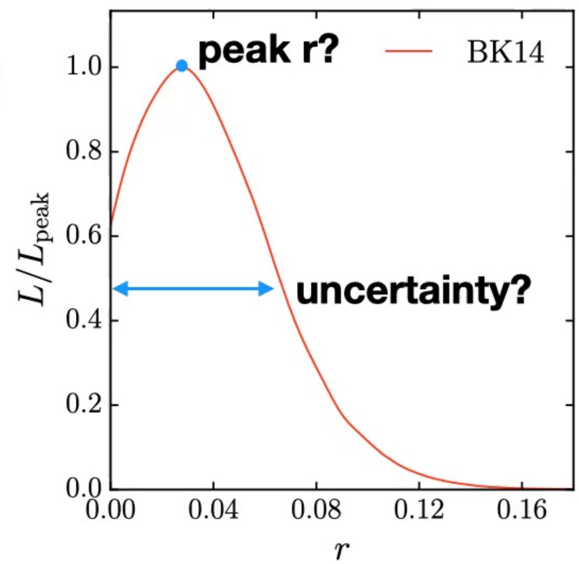


A. reduced uncertainty, lower peak r; ✓

B. reduced uncertainty, higher peak r;

C. increased uncertainty, lower peak r;

D. increased uncertainty, higher peak r.



~30% probability this data set gives higher peak r.

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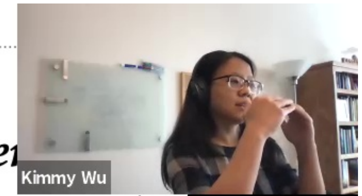
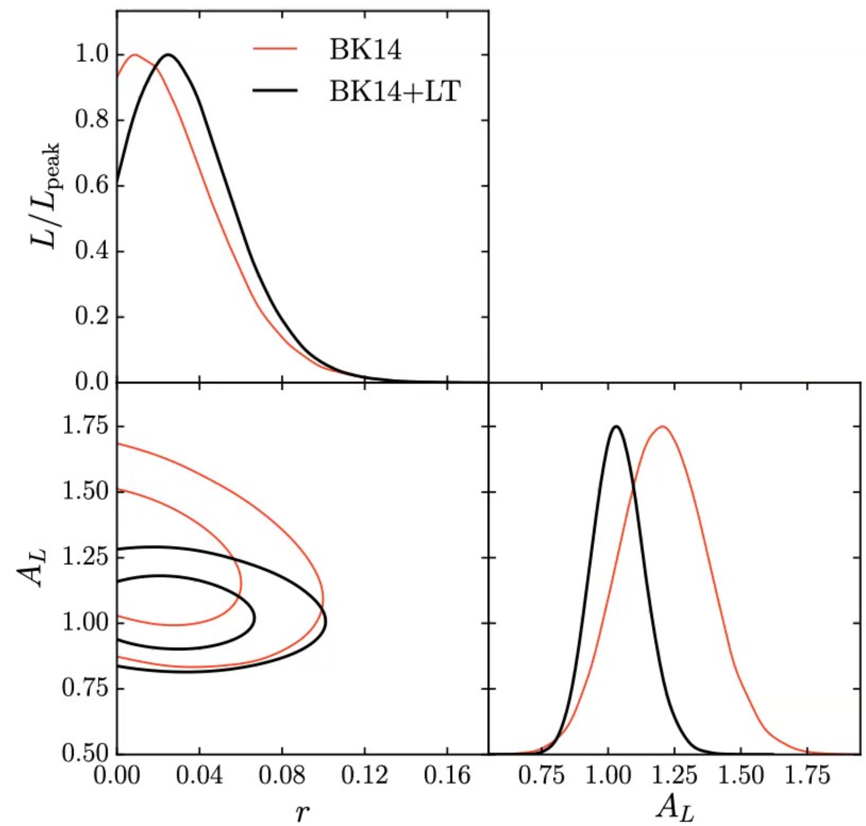
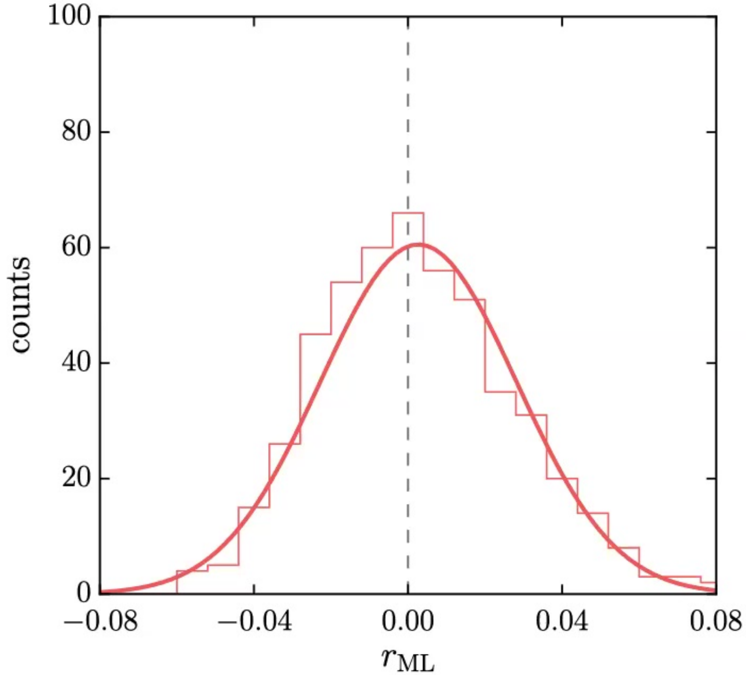
Lensing template breaks r degeneracy with A_{le}





(K. Wu; BK+SPTpol Collaborations; arXiv:2011.08163)

How much do we improve σ(r)?



No delensing
Perfect delensing
This analysis

- With perfect φ map and E modes, adding a lensing template to the BK14 data set improves σ(r) from 0.024 to 0.018.
  - ~26 % of C_ℓ^{BB} variance is from lensing
- Using CIB φ tracer to form the lensing template, σ(r) improves by ~10% from BK14 to 0.022.
- Template from SPTpol Q/U map alone gives σ(r) = 0.022.

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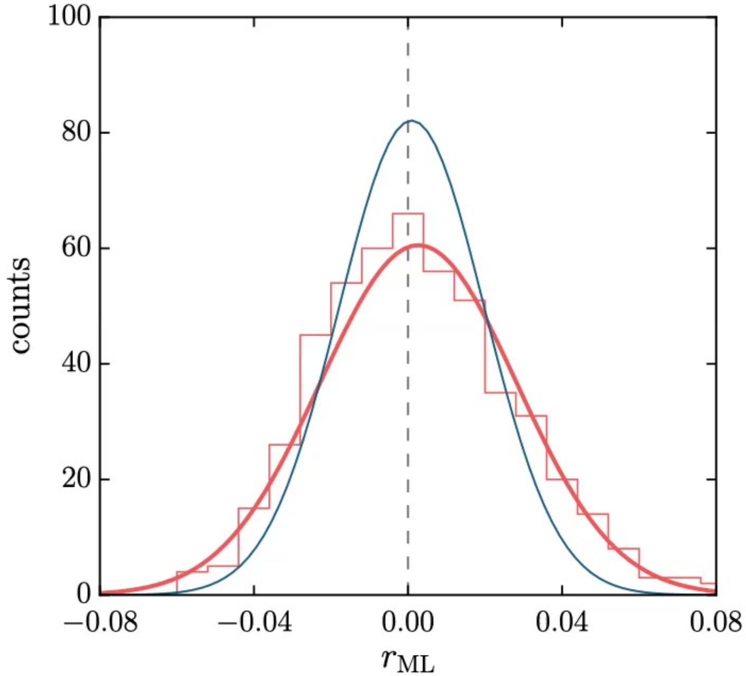

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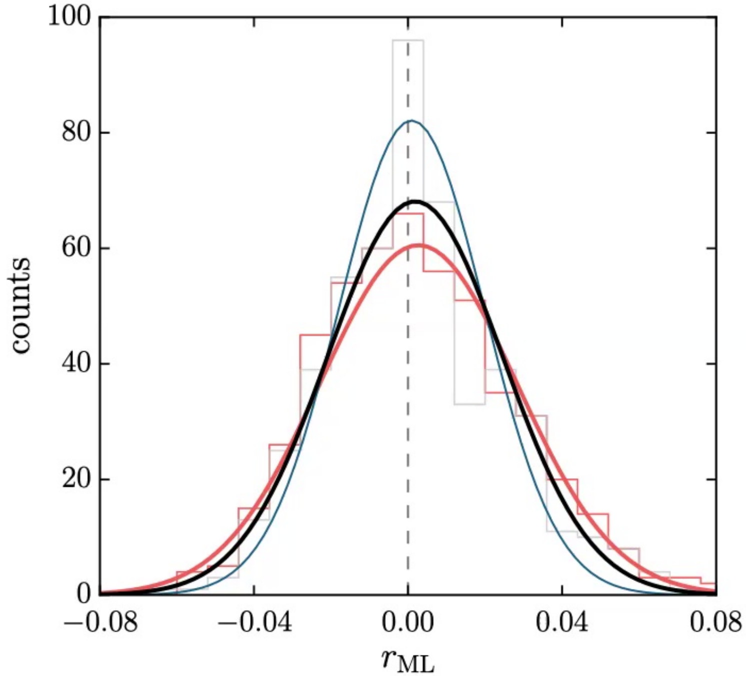

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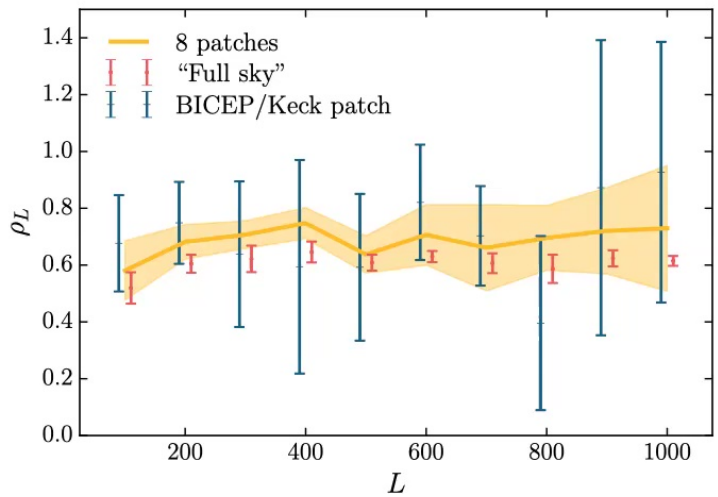
First demonstration of σ(*r*) reduction through delensing!

Systematics considerations

- CIB-phi cross-correlation
- CIB non-Gaussianity
- Galactic dust contamination in Q/U maps and in CIB map

Misestimation in CIB-ϕ correlation

- Analyze simulations generated with $0.5\sigma_{sp}$ shift in CIB-ϕ cross-power as if they were the baseline.
- End-to-end result shows a bias on r by 0.2σ.
- $0.5\sigma_{sp}$ shift is expected to be larger than what the ϕ field and the CIB map could have, given that ϕ comes from a component separated map.
- Future delensing with CIB combined with CMB-ϕ would have less contribution from CIB; smaller impact.
- Can marginalize over this uncertainty.



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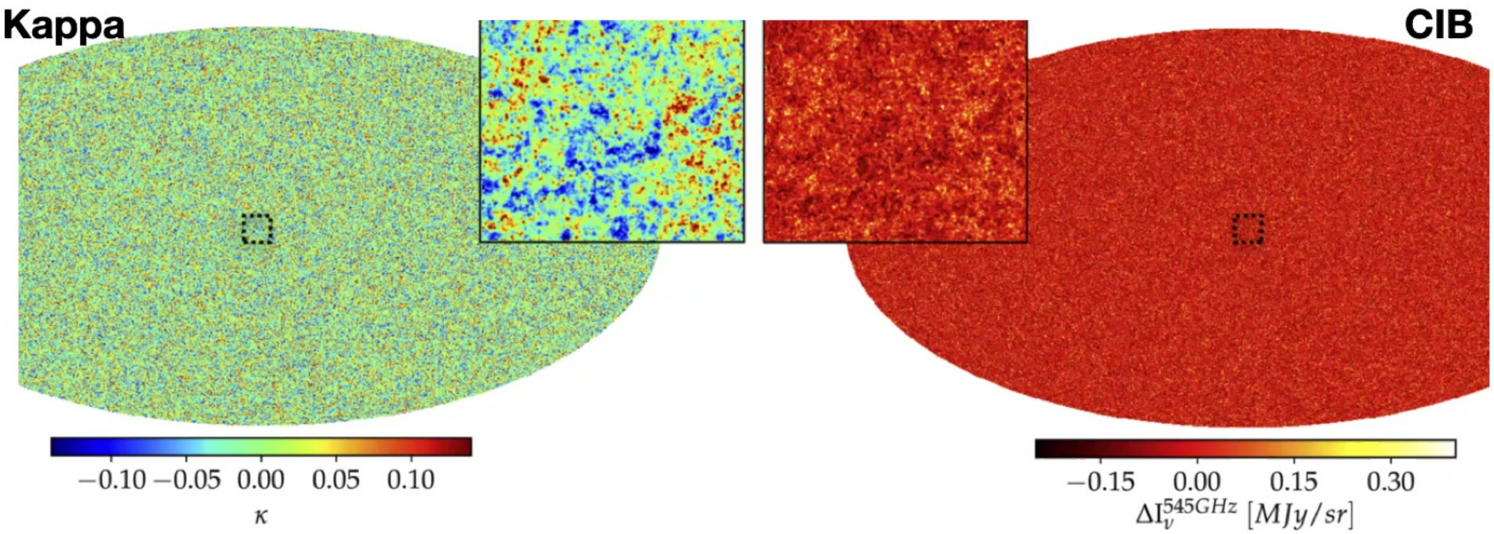
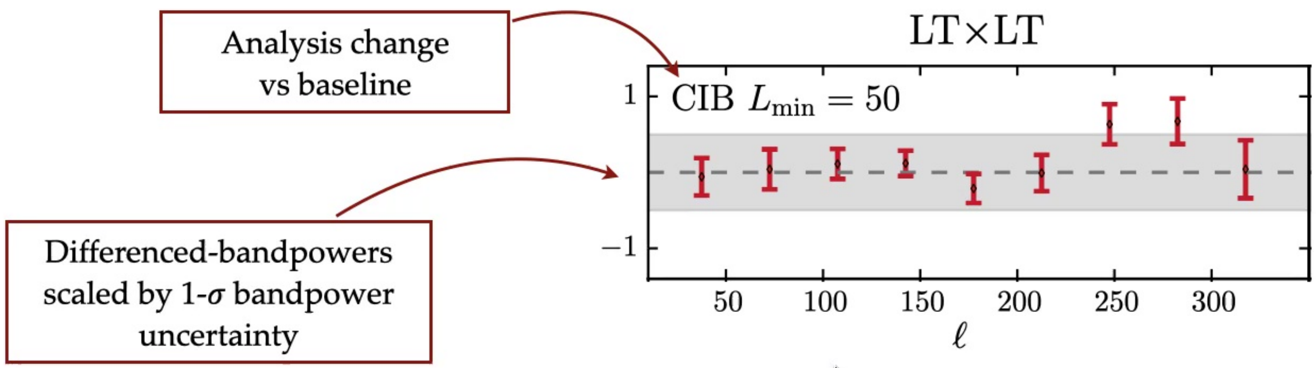
CIB non-Gaussianity



Websky sims

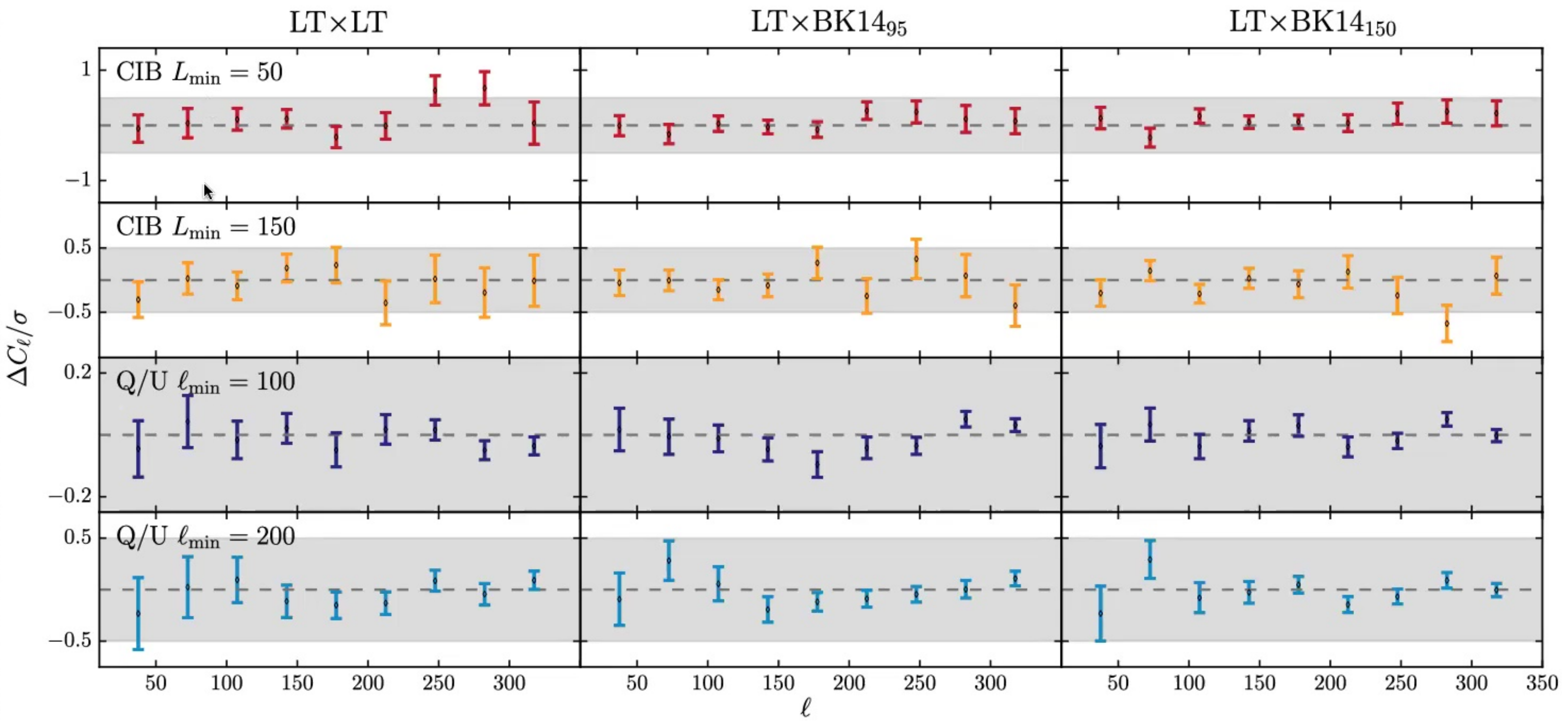
- Model CIB signal (part that correlates with ϕ) and noise (part that does not correlate with ϕ) to be both Gaussian;
- Compare lensing template bandpower variance given Gaussian vs non-Gaussian CIB simulations (from Websky); find no statistically distinguishable difference between the two.
- Artificially increase the lensing template bandpower variance in the covariance matrix and find negligible difference in σ(r).

Galactic dust in Q/U and CIB maps



- Unmodelled non-Gaussian Galactic dust fluctuations could exist in Q/U maps and in CIB map
- Are they large enough to alter the lensing template auto- and cross-spectra beyond what is expected from noise?
- Test: cut out scales below L_{min} and form difference-spectra with baseline; Galactic dust dominates large angular scales and this test would be pick them out if they are large.

Galactic dust in Q/U and CIB maps



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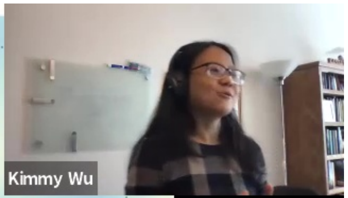

Current limitation to delensing

- B mode variance is dominated by galactic foregrounds; even with perfect delensing we do not improve $\sigma(r)$ very significantly.
- Need better ϕ tracer: CIB map we use has cross-correlation with underlying ϕ at 60-80%. CMB-derived ϕ from upcoming CMB experiments will do better!

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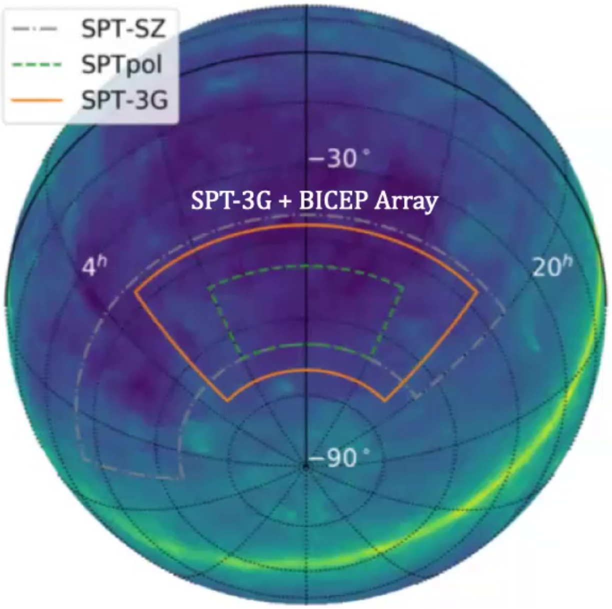
How to get better ϕ?

- ϕ reconstructed from lensed CMB will give better signal-to-noise (compared with e.g. using CIB) in the near future

    1) Make deeper high-res CMB polarization maps

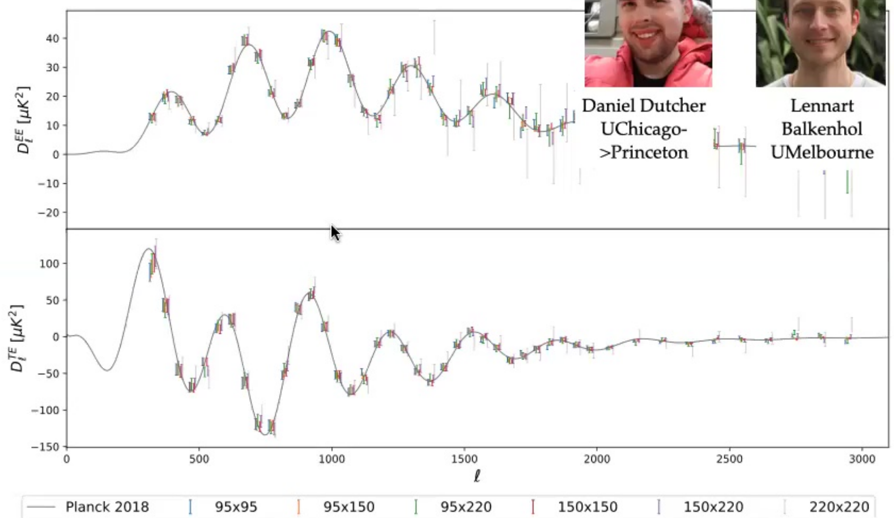
    2) Extract lensing information more optimally

SPT-3G status



Daniel Dutcher
UChicago->Princeton

Lennart Balkenhol
UMelbourne

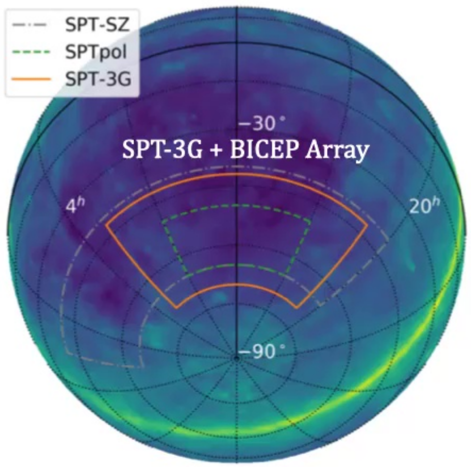


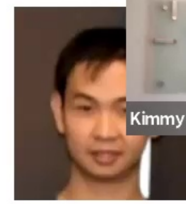
On-going observations on main CMB-field; noise levels on track to match projections; 1st science results out!

H_0 = 68.8 ±1.5 km/s/Mpc; similar to most recent ACT DR4 release. Independent measurement of H0 from Planck. Explored LCDM model extensions.

(Dutcher & Balkenhol et al.; SPT3G Collaboration; arXiv:2101.01684/2103.13618)

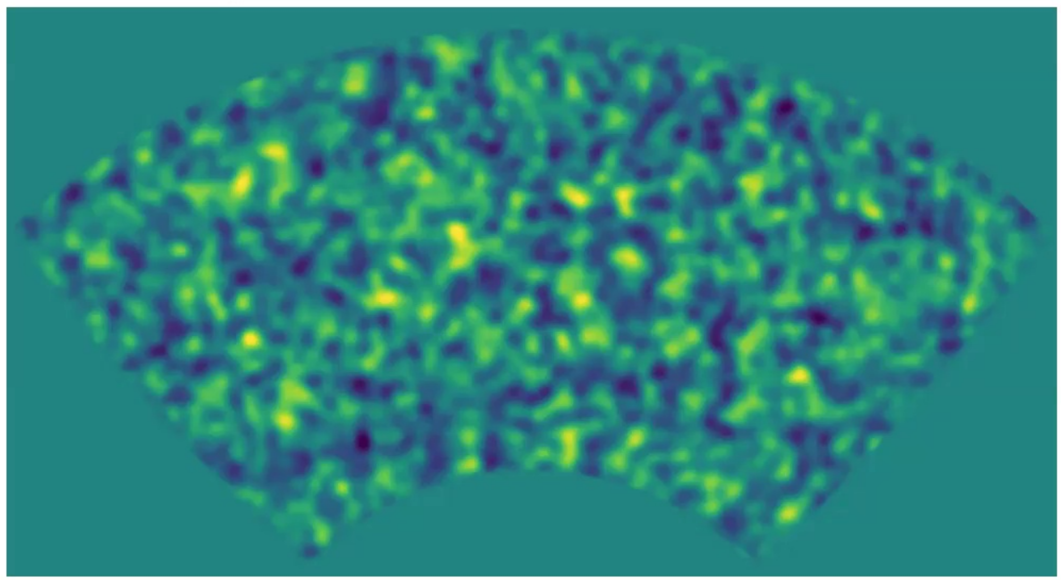
SPT-3G lensing





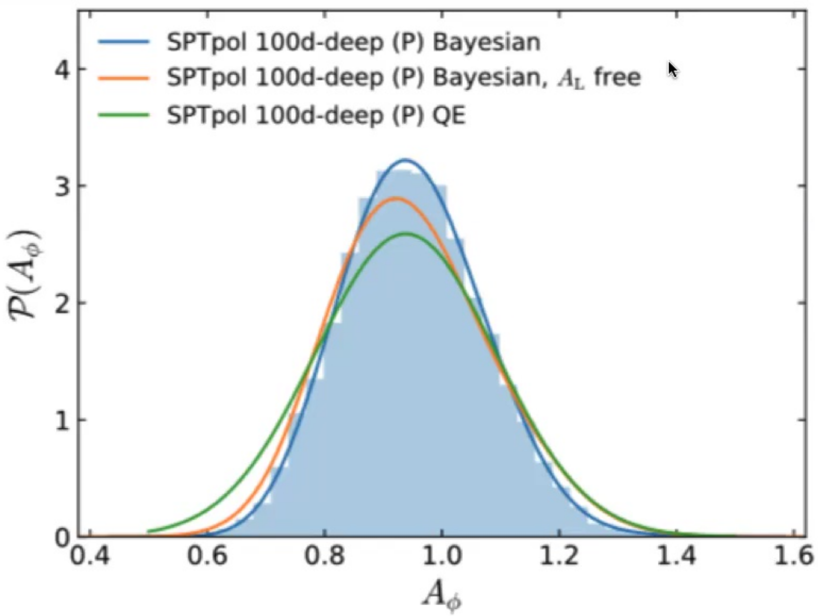
Zhaodi Pan
UChicago->
Argonne

MV reconstruction on 1500 sq. deg. SPT3G footprint, 2018 noise level (simulation)



Bayesian (optimal) lensing estimate on SPTpol data

Marius Millea
Berkeley



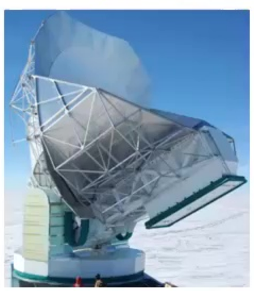
(Millea et al.; SPTpol Collaboration; arXiv:2012.01709)

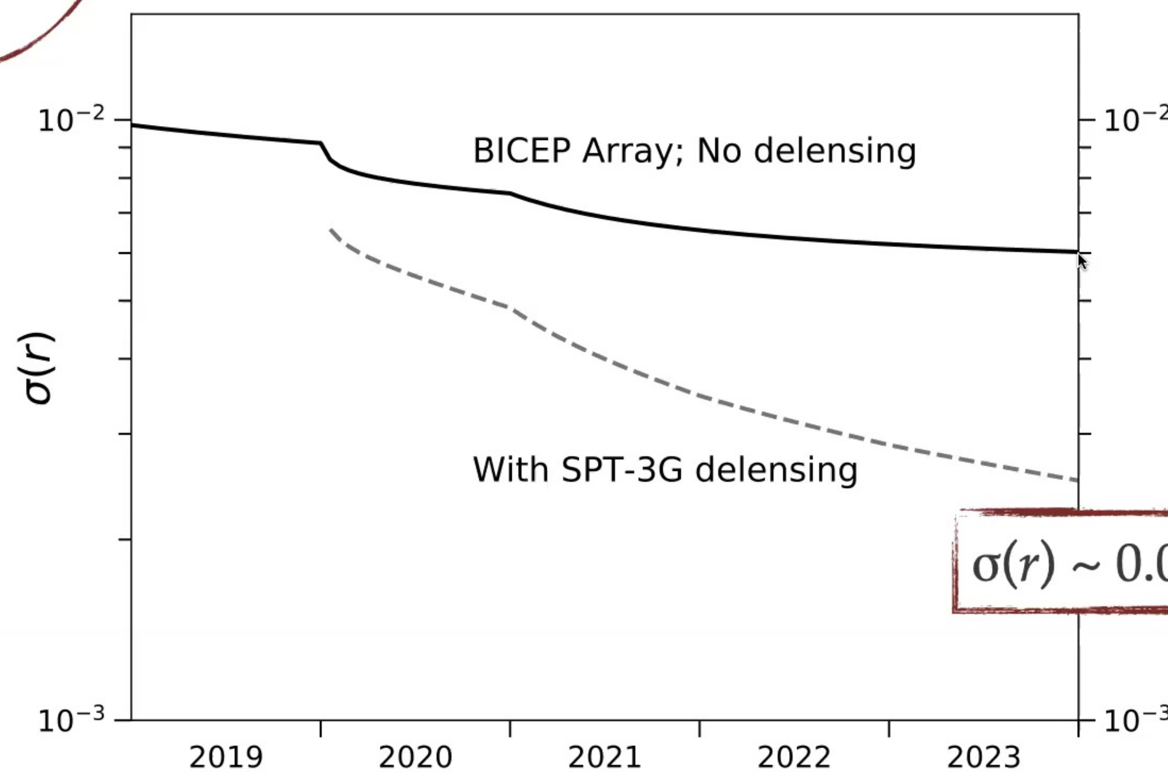
- Bayesian analysis improves constraint on lensing amplitude by ~20% compared with standard methods on same SPTpol data set.
- Optimal reconstruction of lensing essential for next-generation CMB experiment CMB-S4 to achieve *r* goal.

Delensing BICEP/Keck B-mode maps using SPT-3G φ improve r constraint

Current $\sigma(r) = 0.02$
(BK15)

BICEP Array
(2018-)





$\sigma(r) \sim 0.003$

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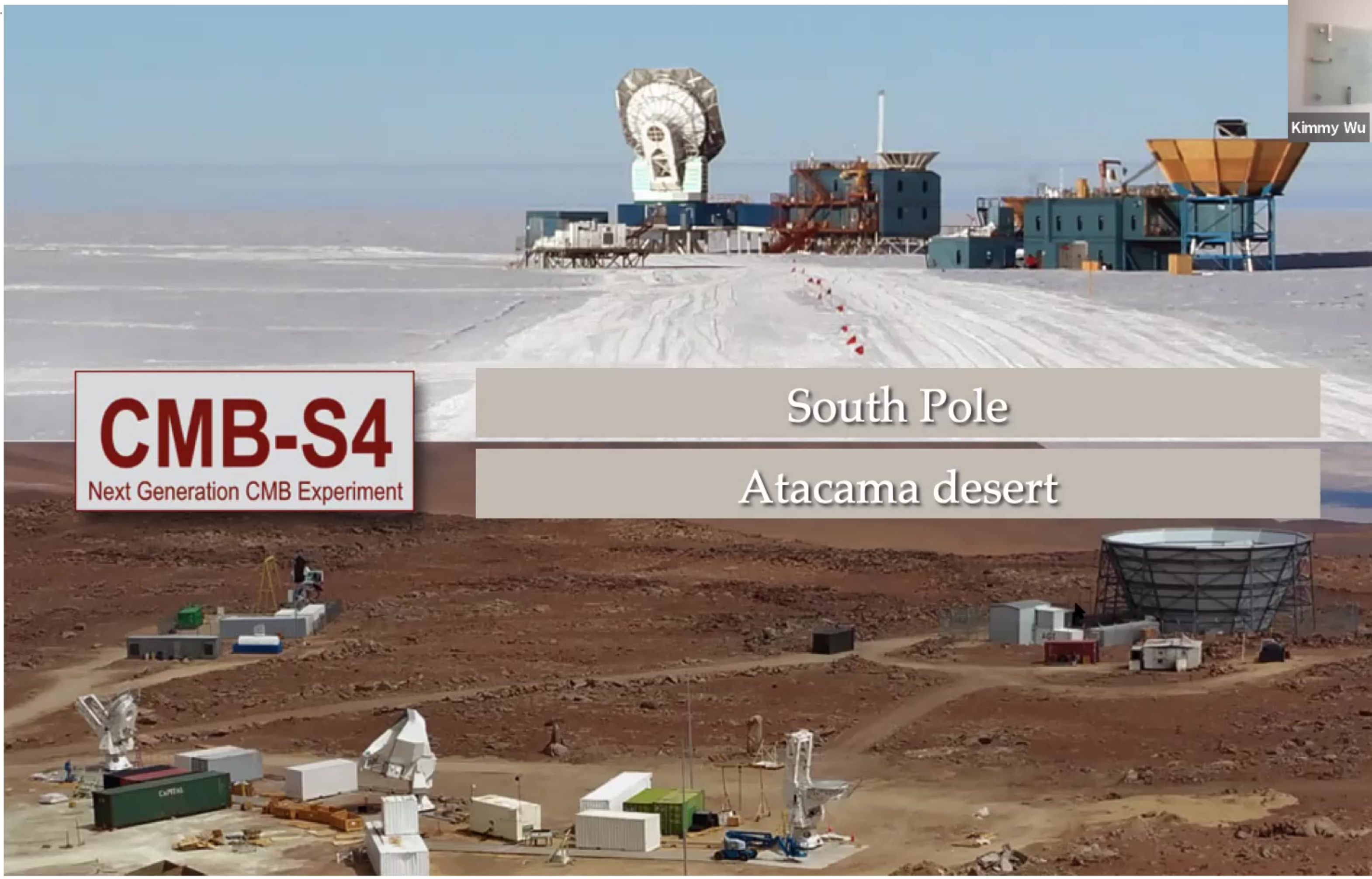

CMB-S4 Science Book (incl. KW)

- ~500,000 detectors; begin survey in late 2020s
- deep survey (~3% sky) for r; wide survey (> 40% sky) for lensing, cross-correlations, and multi-messenger
- $\sigma(r) \sim 0.0005$; $\sigma(\sum m_\nu) < 20$ meV (joint with BAO)

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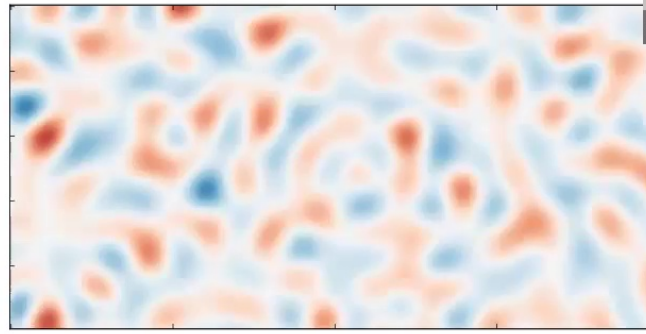
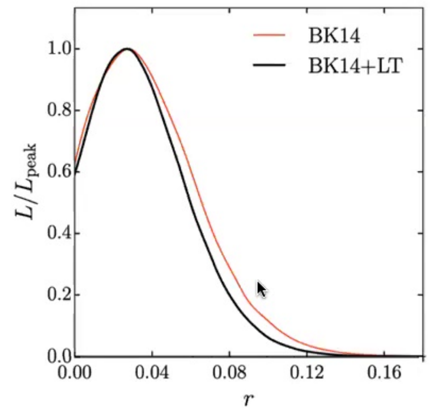
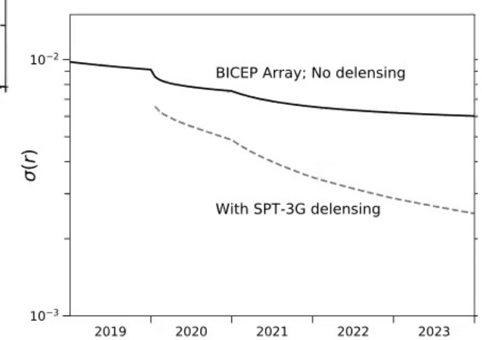
Summary

- CMB B modes provide a unique window to early universe physics; e.g. tensor perturbation amplitude —> energy scale of inflation.
- Lensing B modes are one of the foregrounds of primordial B-mode measurements, and will be limiting the uncertainty of the r measurement $\sigma(r)$ in the next 2-3 years.
  - We have demonstrated improved r constraints when delensing BICEP/Keck maps.
- Delensing of BICEP Array maps using SPT-3G lensing potentials improves $\sigma(r)$ by 2-3x.
- More optimal techniques of lensing reconstruction/delensing are required to reach next-generation CMB experiment CMB-S4 $\sigma(r)$.







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