Cosmology with Large-Scale CMB Polarimetry

Cyndia Yu

2022 November 1

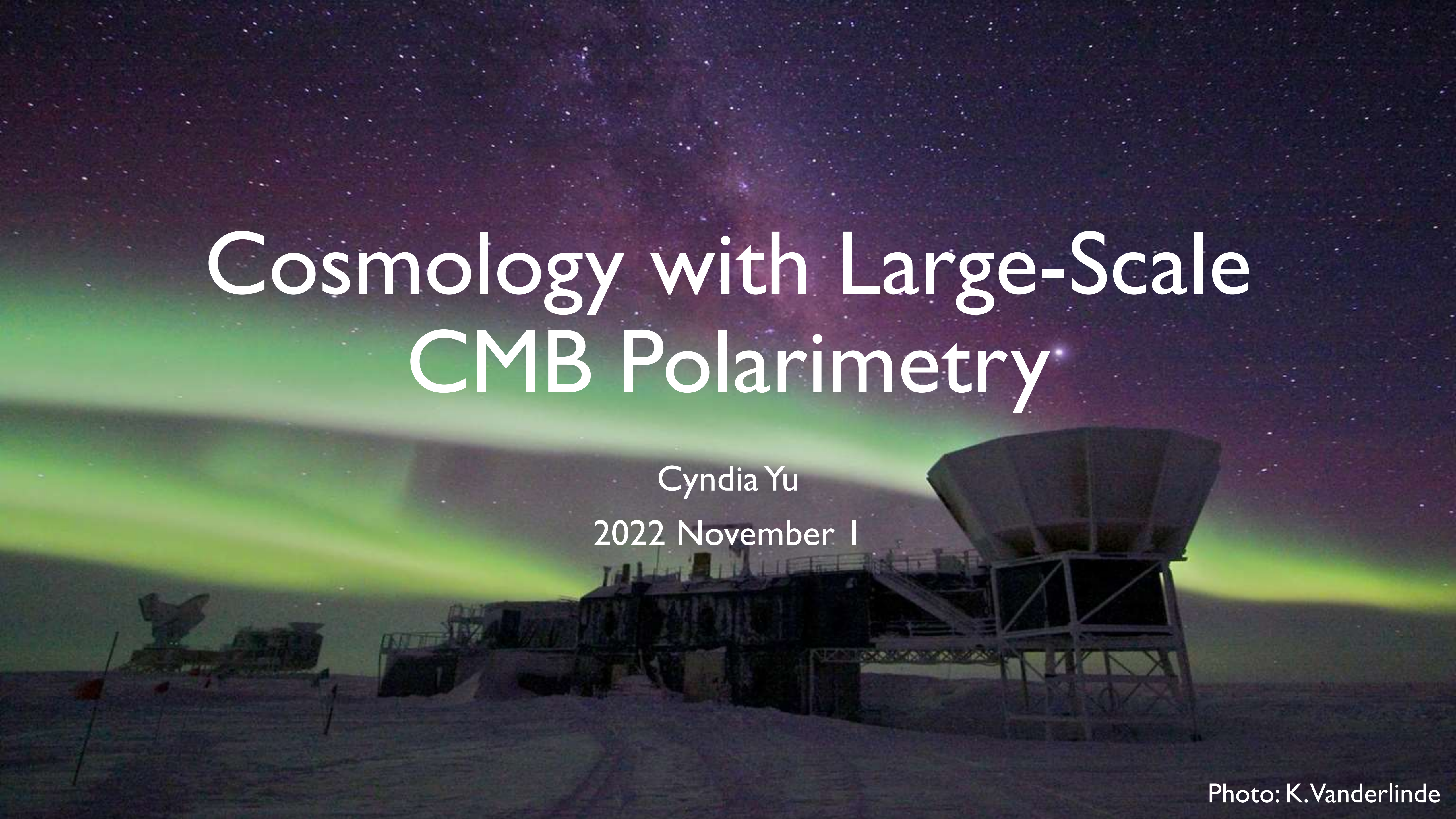


Photo: K. Vanderlinde

Outline

- Crash course on CMB cosmology
- The BICEP/Keck experiment and latest constraints on inflation
- Beyond inflation: cosmology with (other) large-scale CMB polarization
- Looking forward

Please stop me with questions!!

Crash course: CMB Cosmology

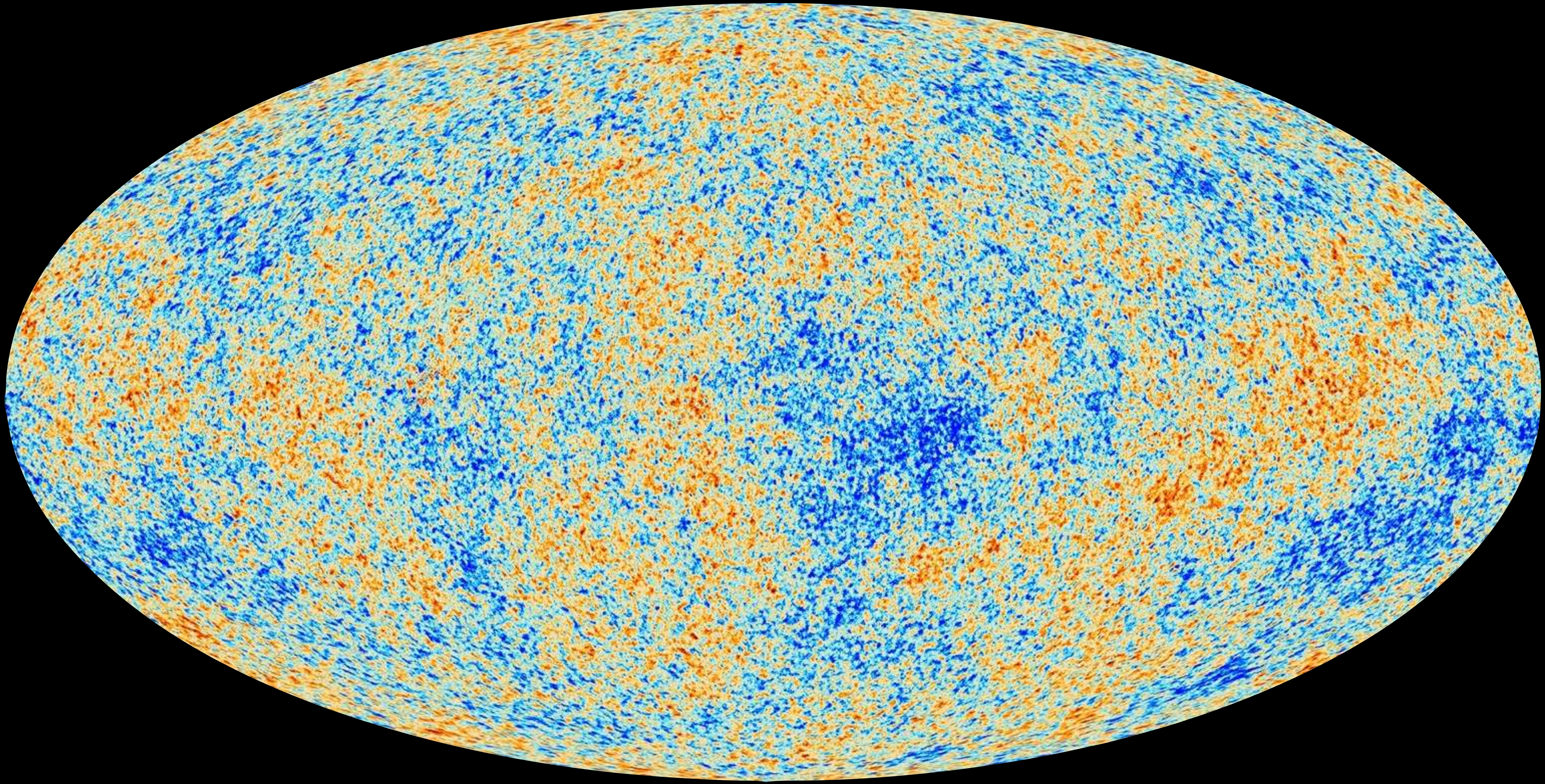
Modern cosmology in a nutshell

Edwin Hubble

1. The universe is expanding. (Hubble, 1920s)
2. It was once hot and dense, like the inside of the Sun. (Alpher, Gamow, Herman, 1940s)
3. You can still see the glow!

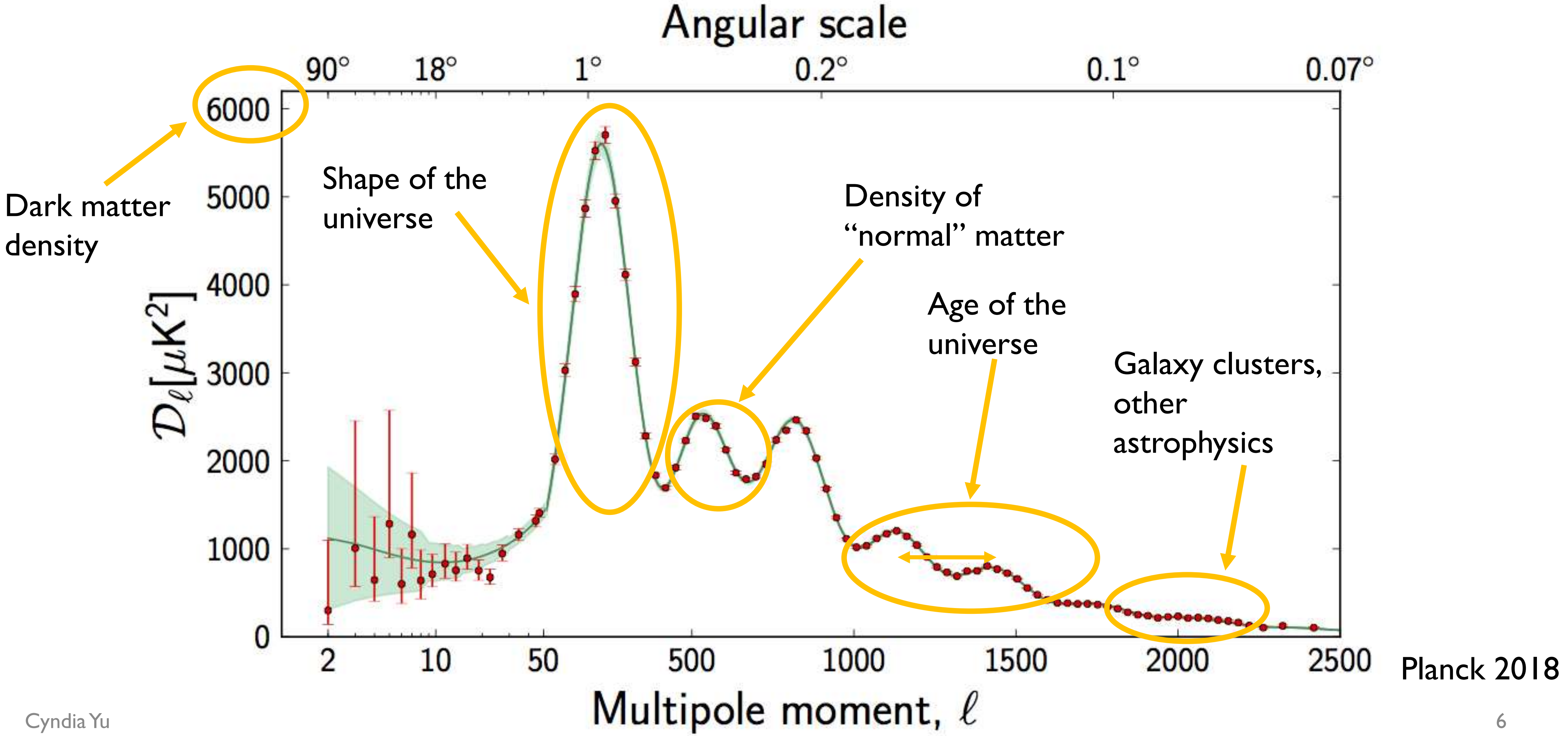
→ Acceptance of the "HOT BIG BANG"

Bob Wilson + Arno Penzias



Planck

The Standard Model of Cosmology

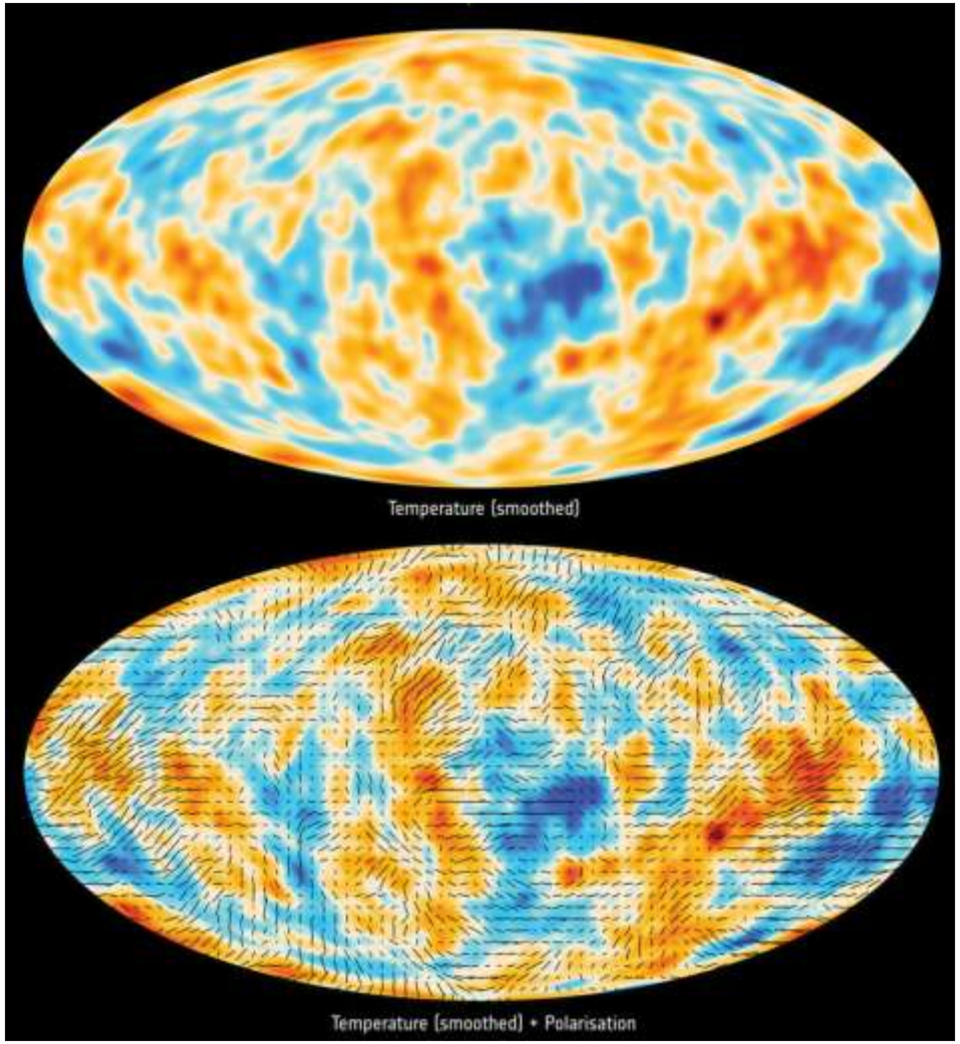


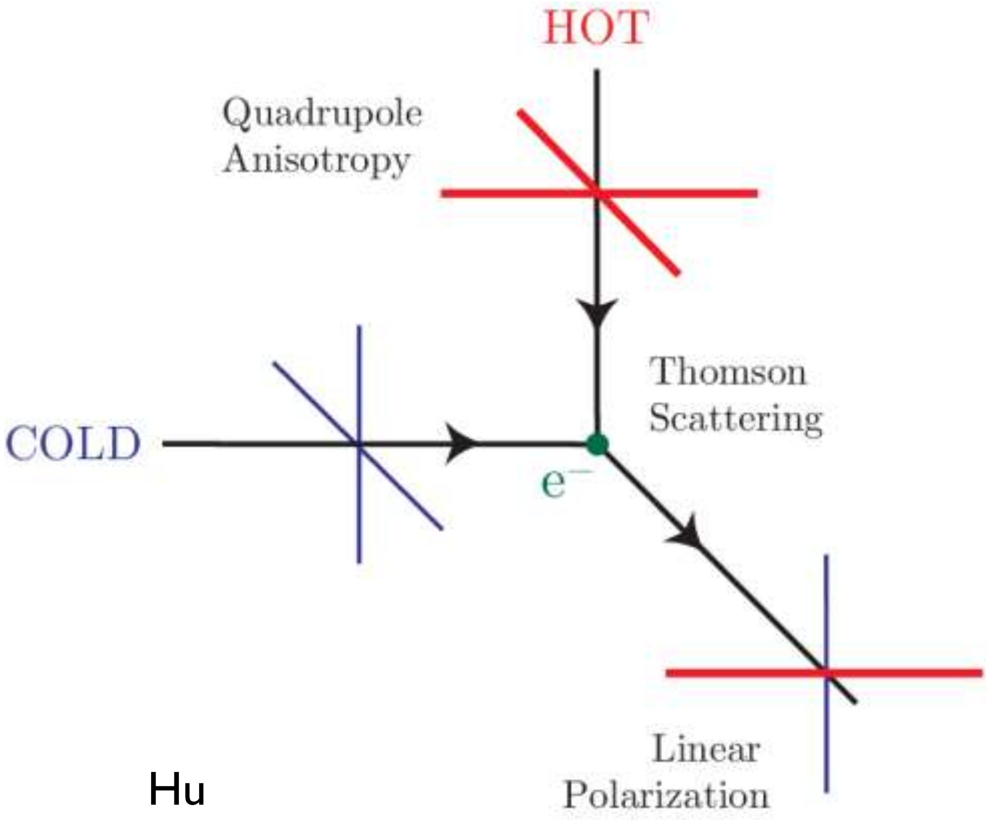
Open questions within

The Standard Model of Cosmology

- What's Lambda?
- What's CDM?
- Where did the initial conditions come from?
- …plus some disagreement on the exact parameter values…

CMB Polarization

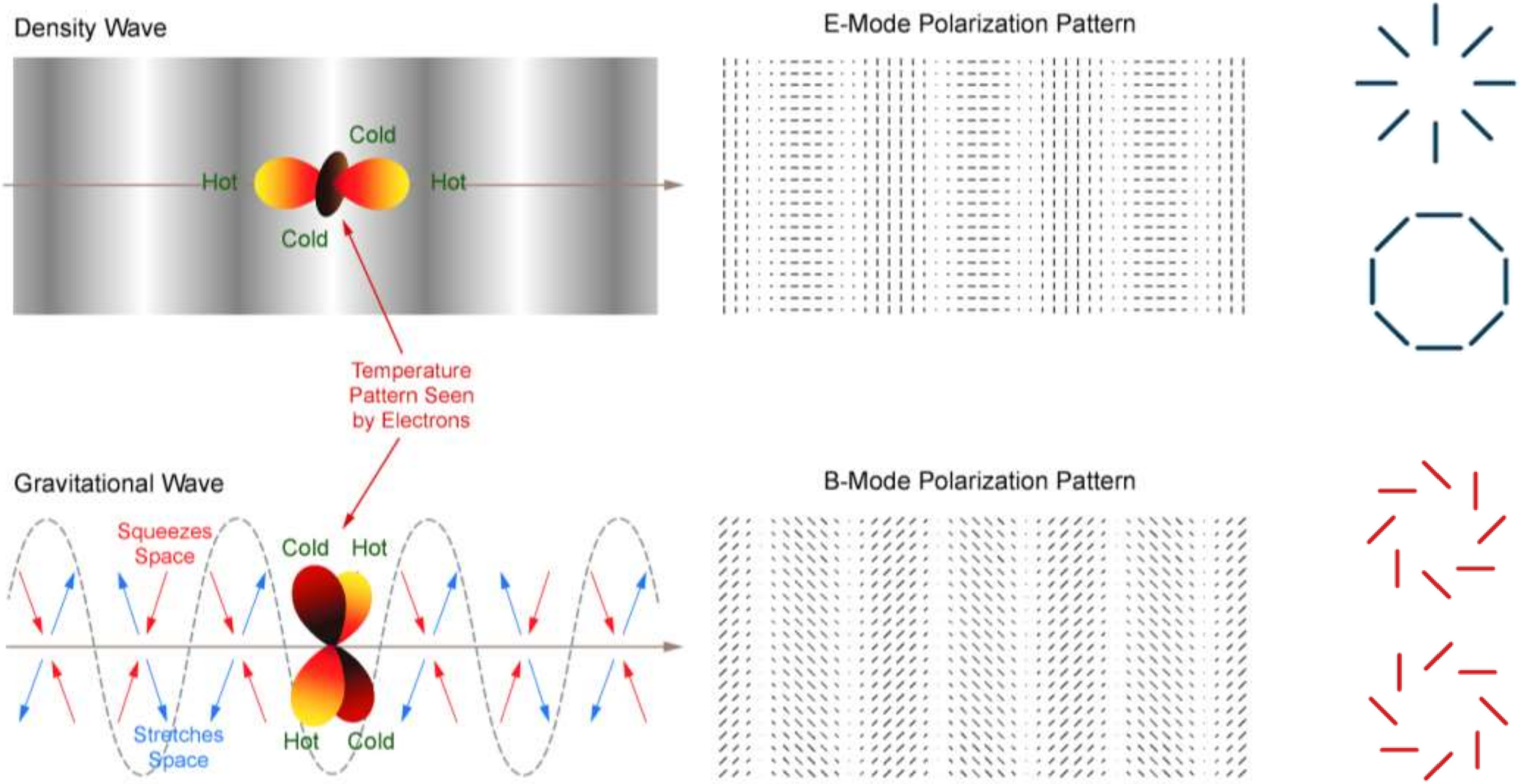




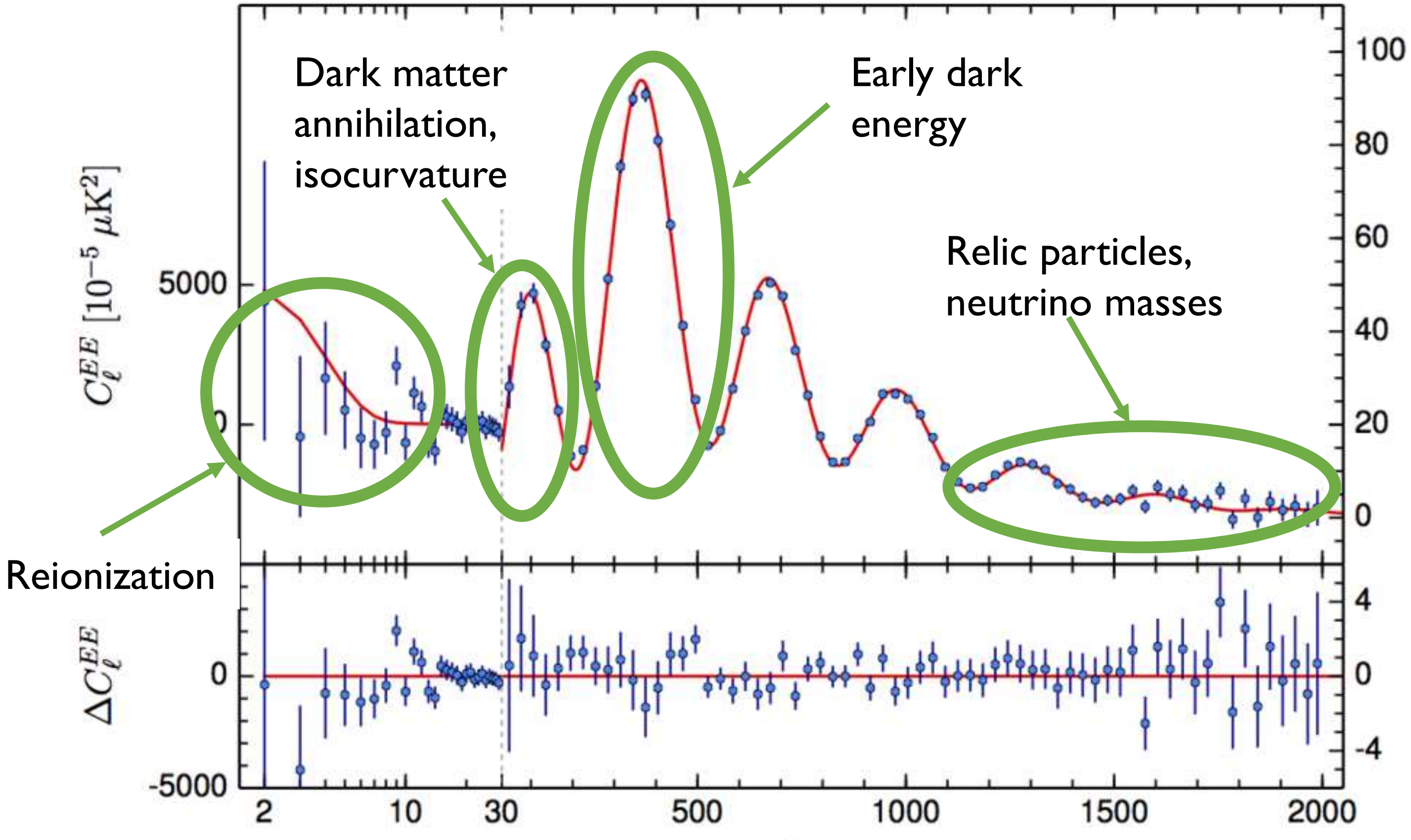
Hu

CMB polarization offers an additional window into our universe!

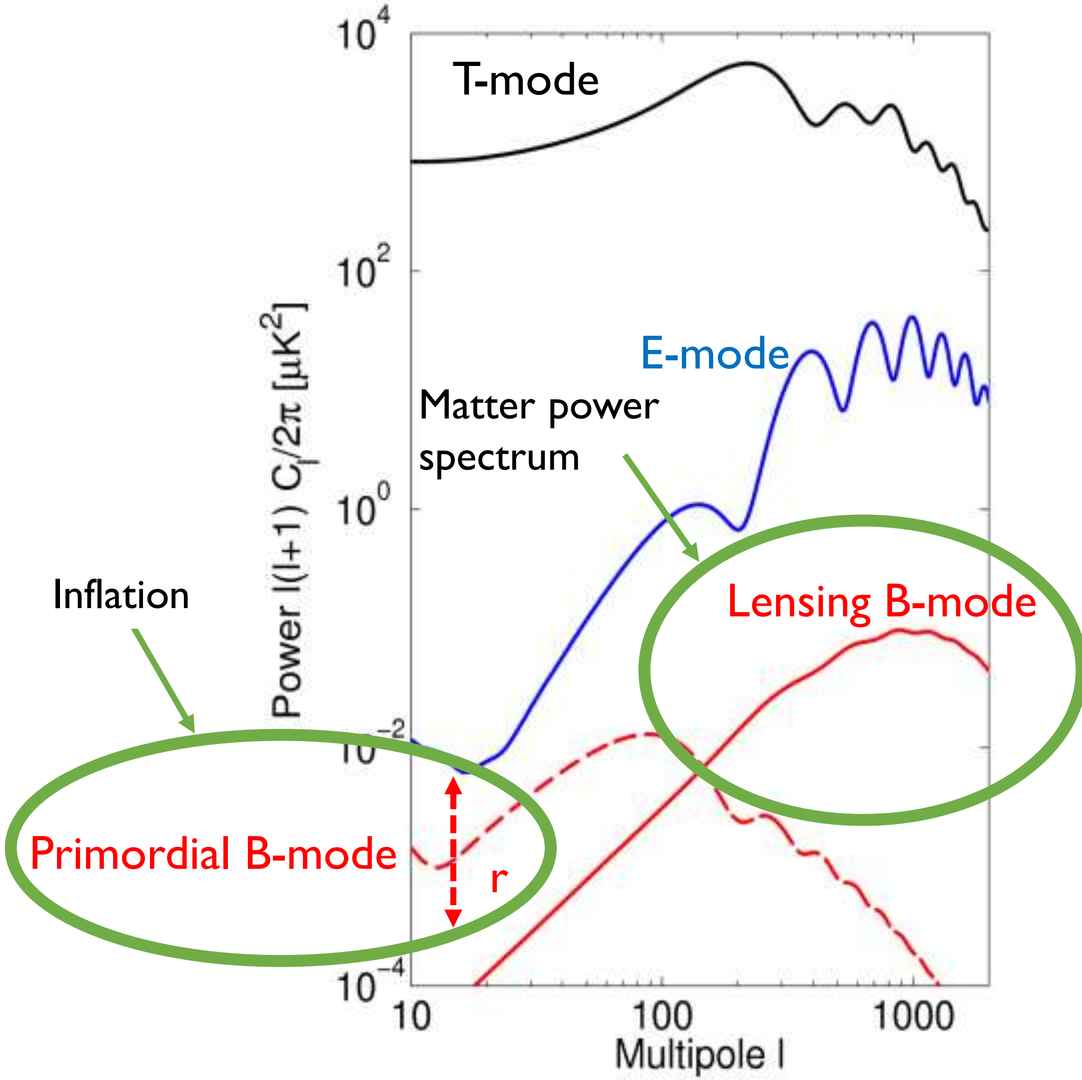
CMB polarization offers insights beyond temperature



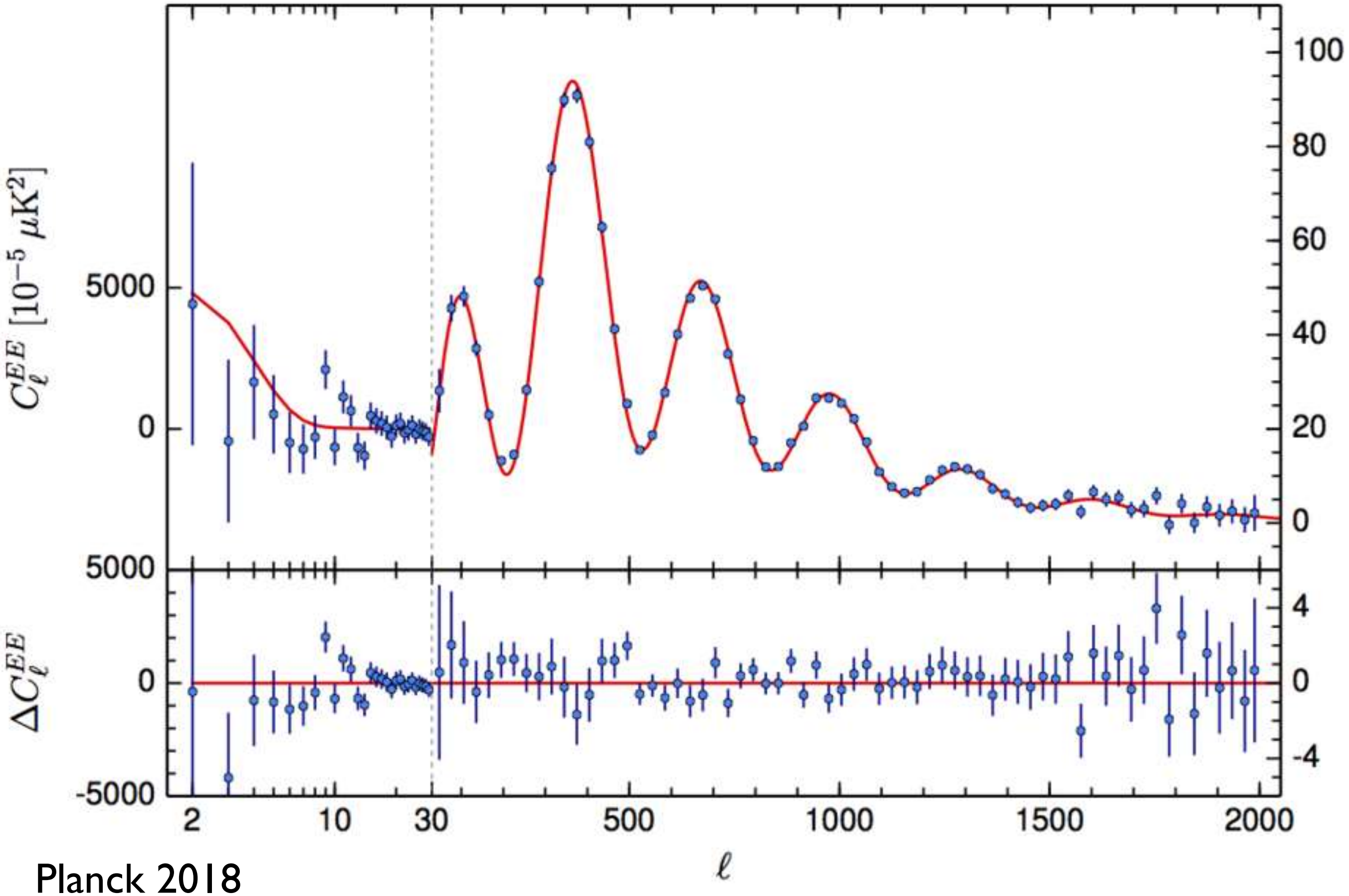
Cosmology in CMB Polarization



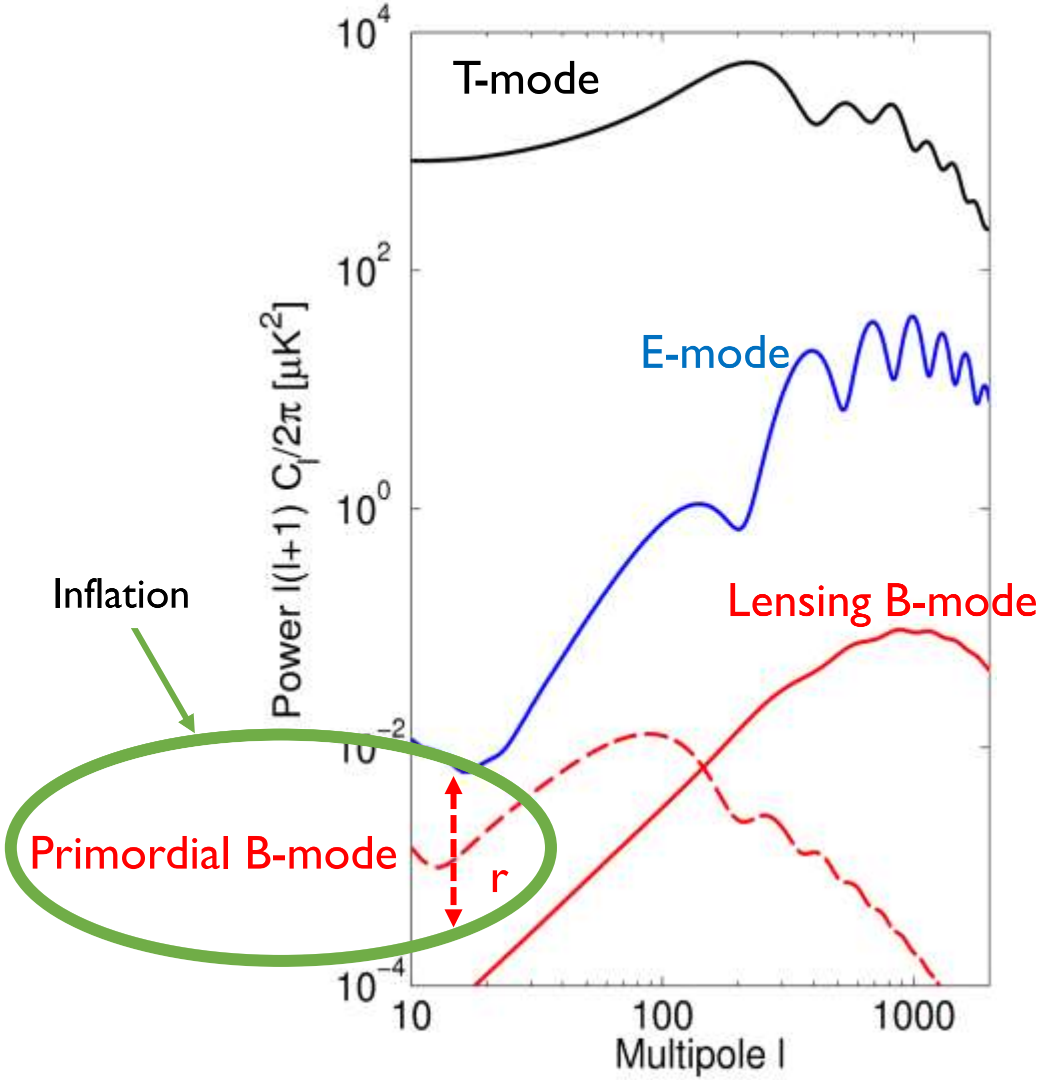
Planck 2018



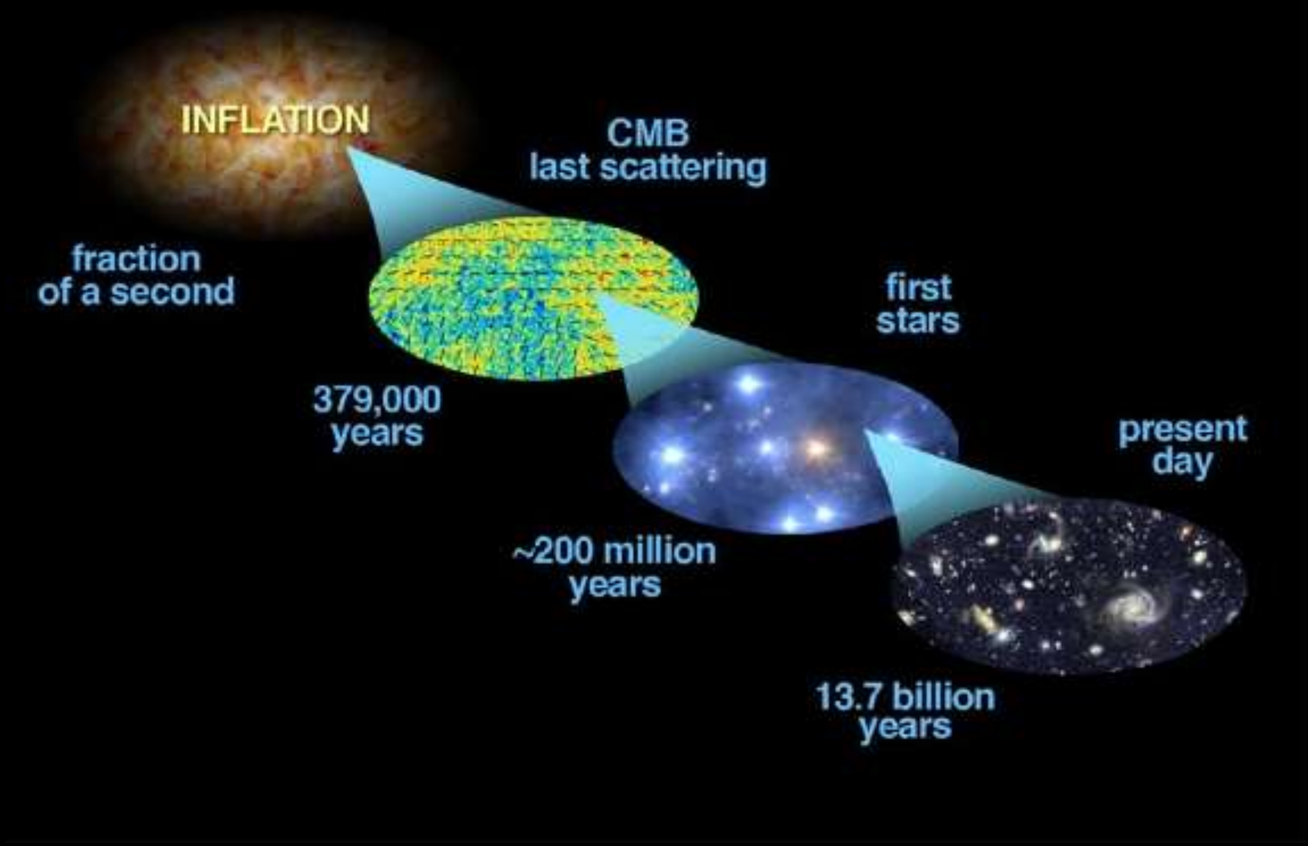
Cosmology in CMB Polarization



Planck 2018

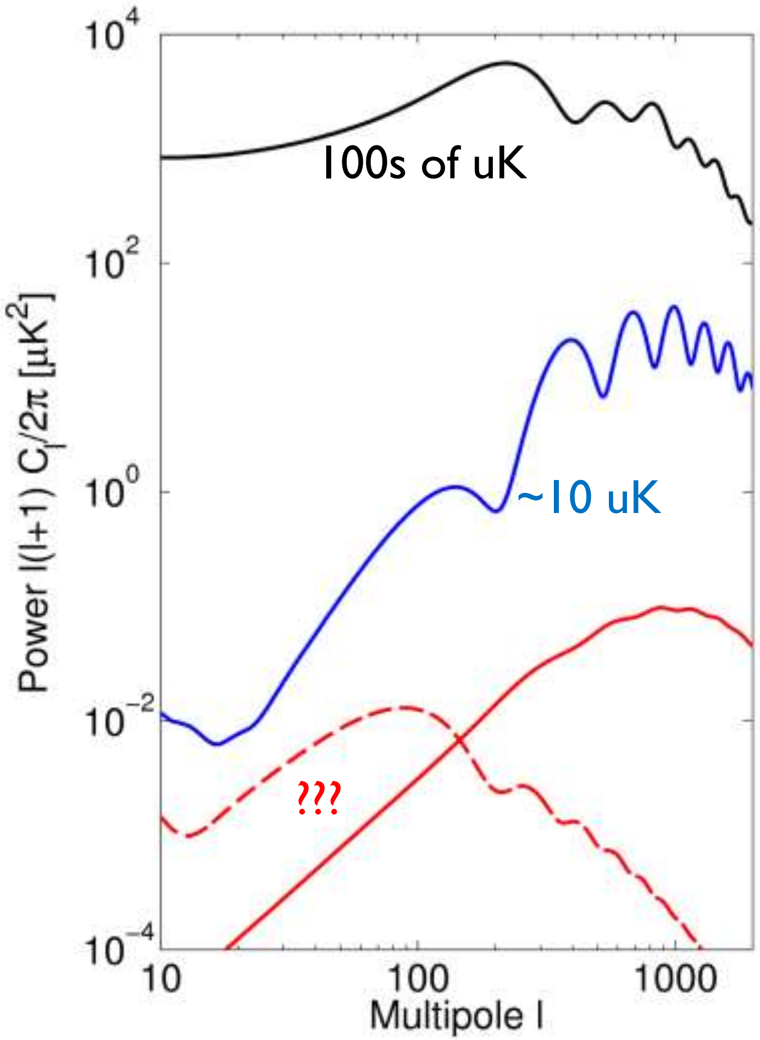


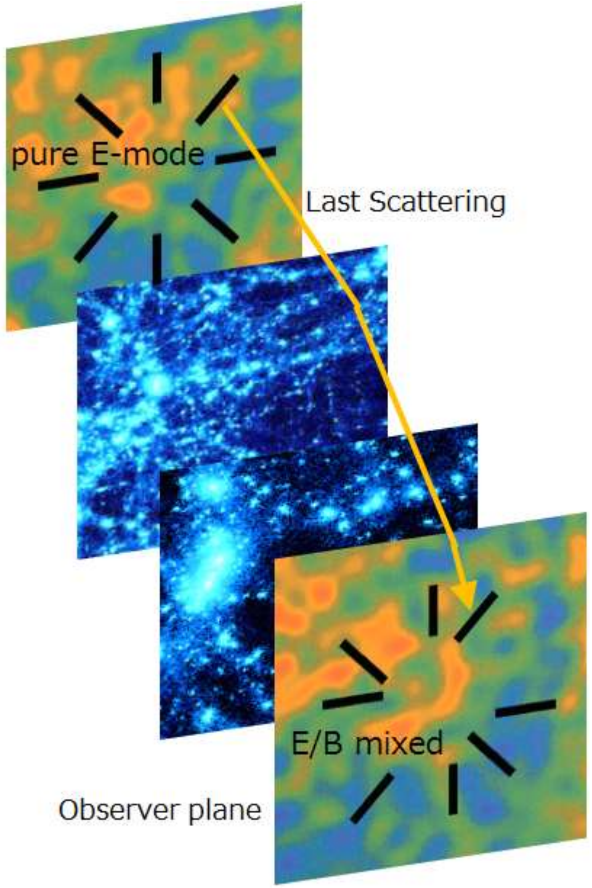
Inflation!

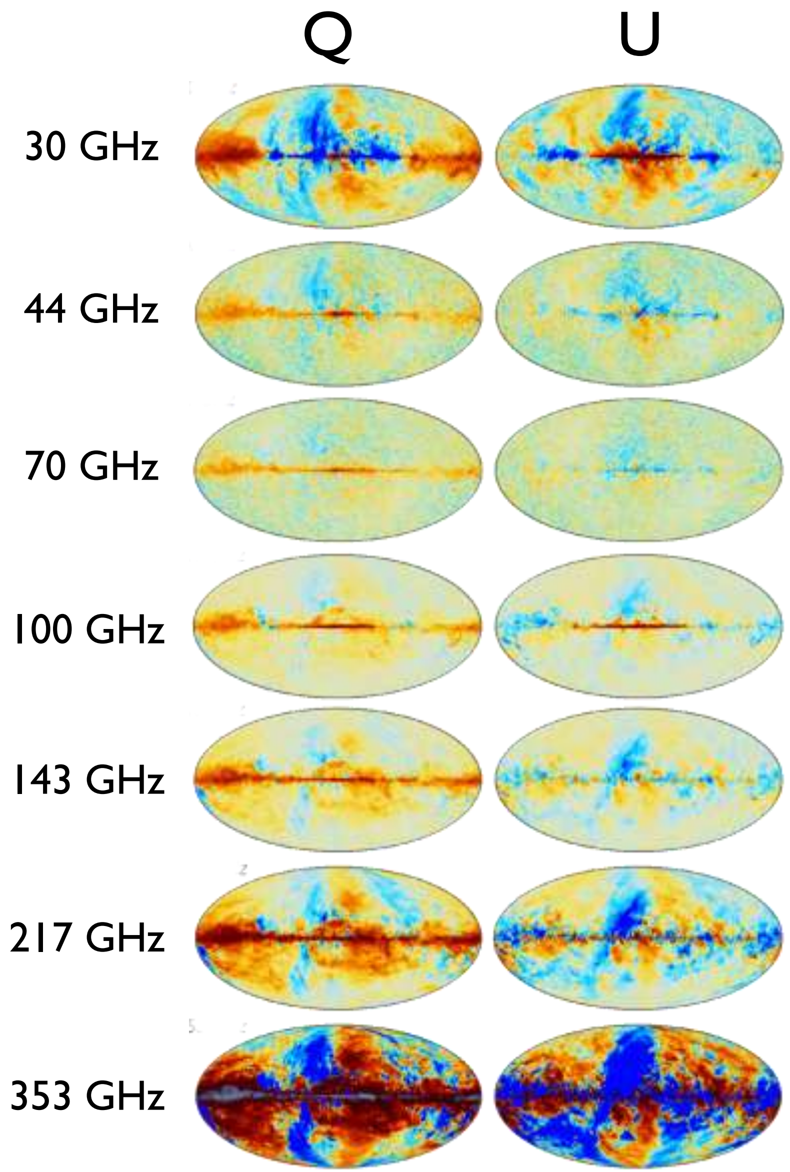


- Solves the flatness, horizon, exotic relics problems
- Period of rapid, accelerated expansion drive small initial state apart
- Quantum fluctuations in initial plasma seed anisotropies that eventually produce large-scale structure
- New physics at very high-energy scales
- Generically produces **primordial gravitational waves**

Experimental challenges



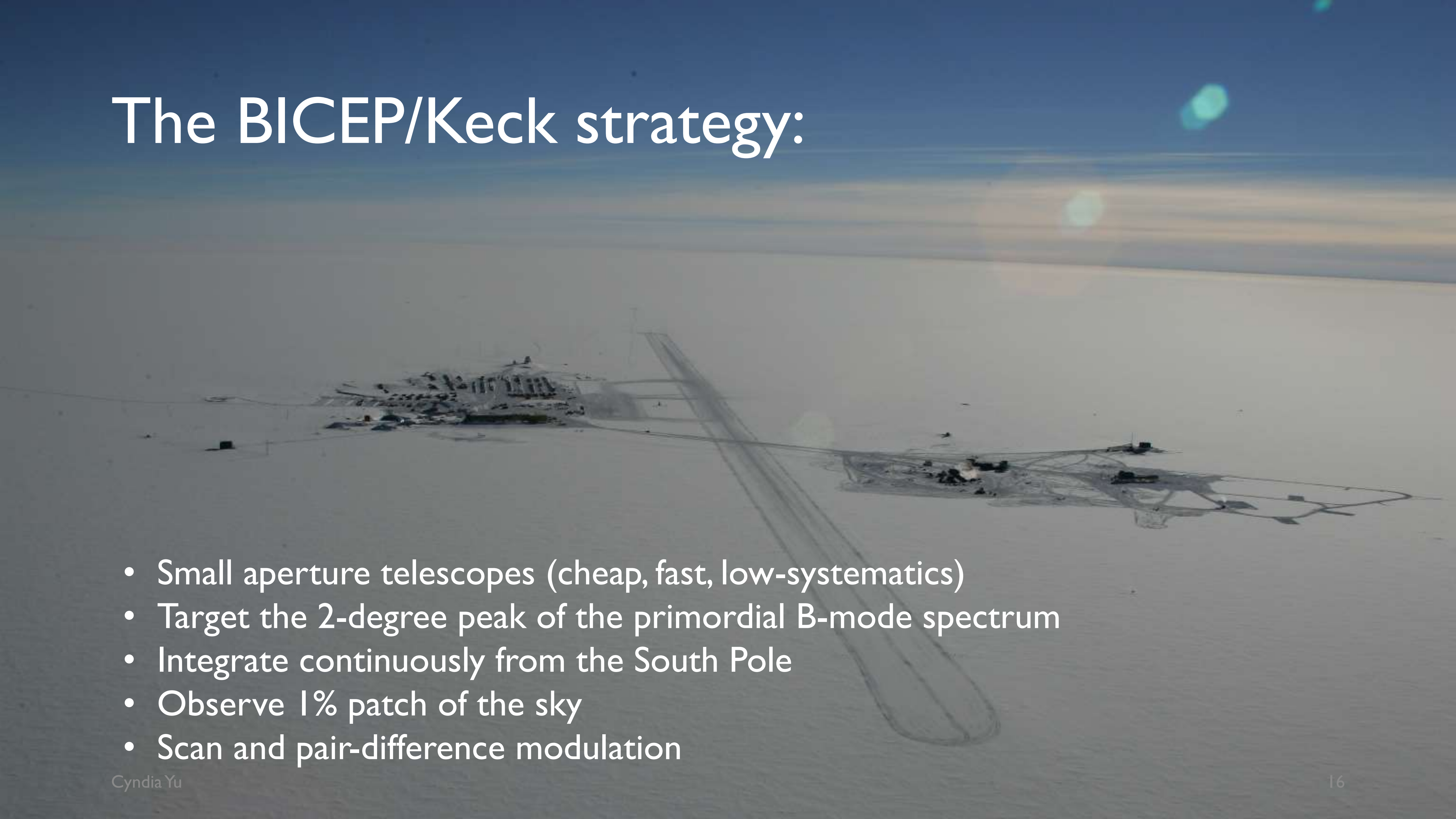




The BICEP/Keck Program

Searching for primordial gravitational waves with CMB B-modes

The BICEP/Keck strategy:



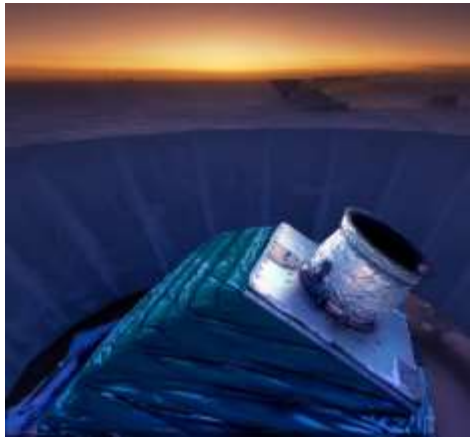
- Small aperture telescopes (cheap, fast, low-systematics)
- Target the 2-degree peak of the primordial B-mode spectrum
- Integrate continuously from the South Pole
- Observe 1% patch of the sky
- Scan and pair-difference modulation

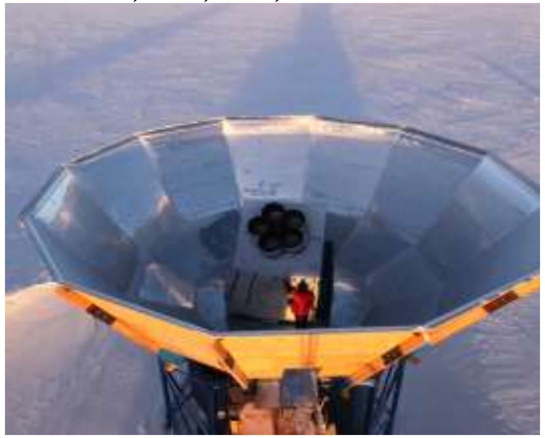
BICEP2
(2010-2012)
150GHz

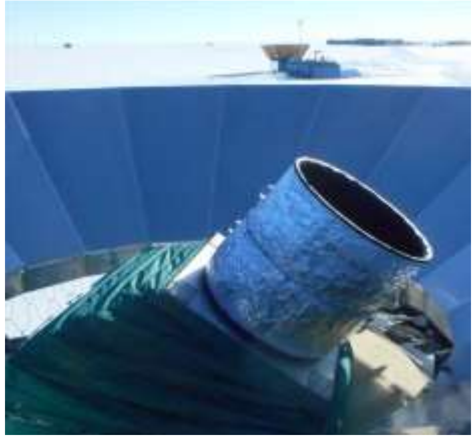
Keck Array
(2012-2019)
95, 150, 220, 270GHz

BICEP3
(2015-)
95GHz

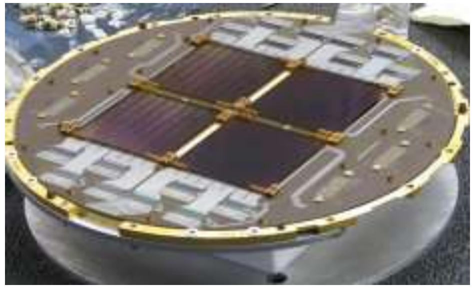
Telescope and Mount

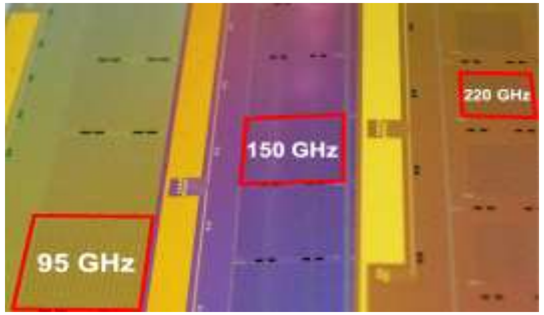


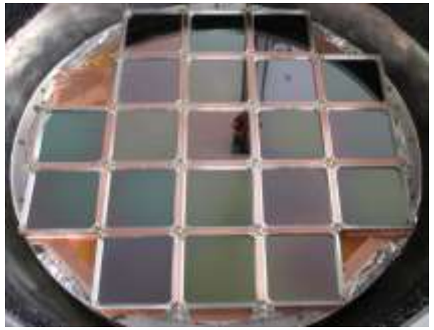




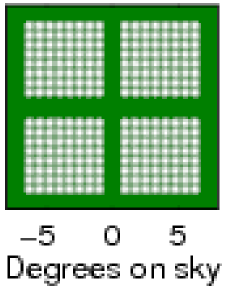
Focal Plane



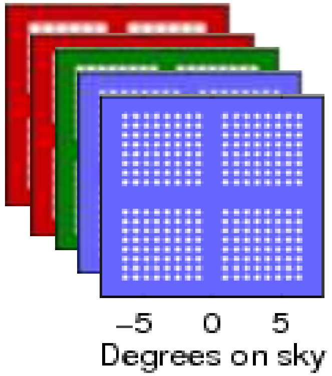




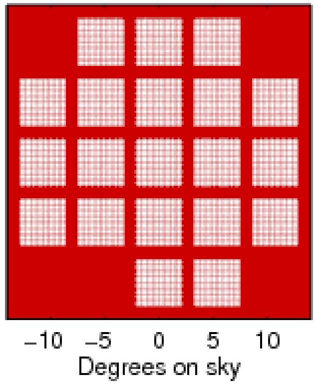
Beams on Sky



~500 sensors



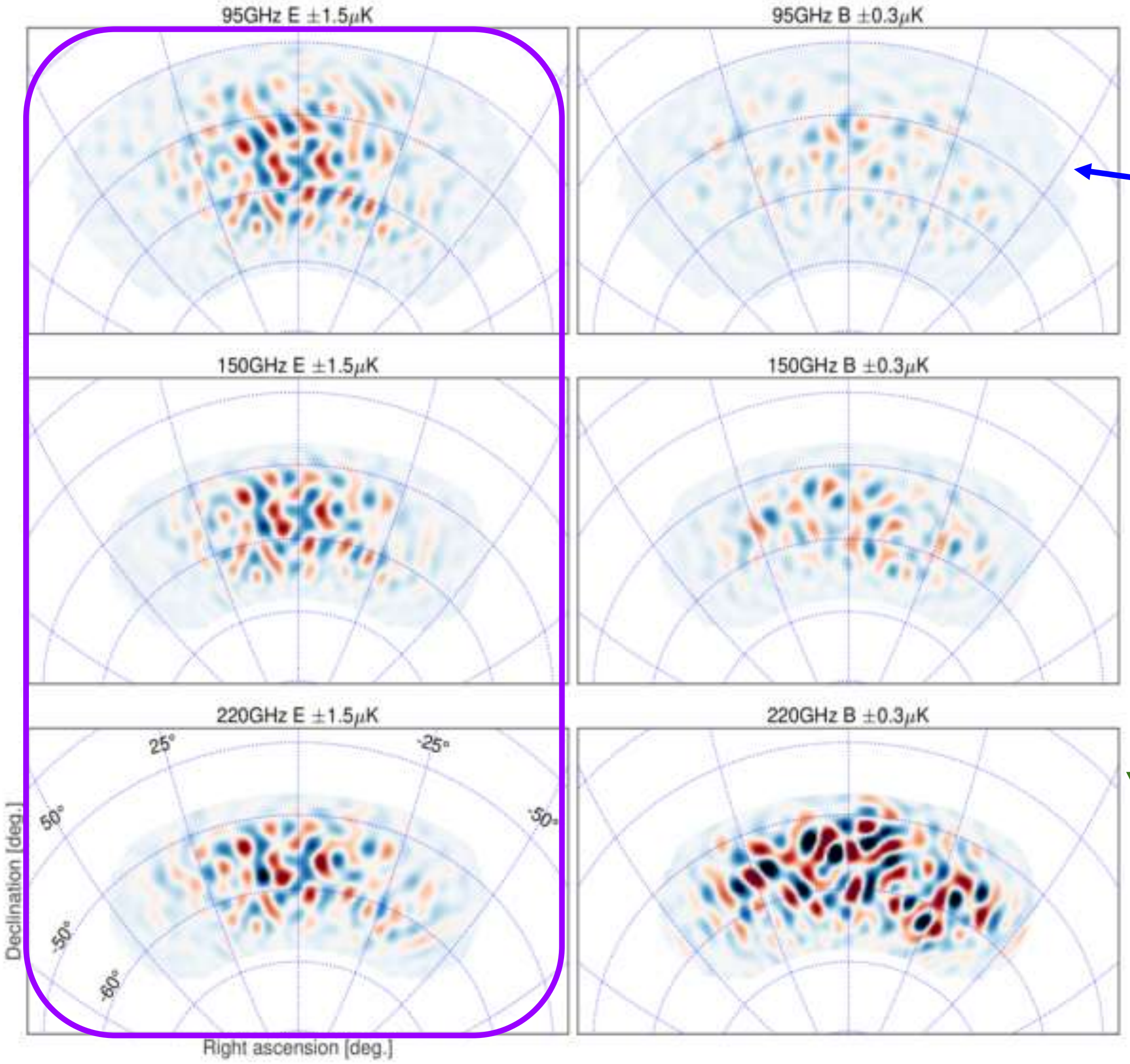
~2500 sensors



~2500 sensors

Deepest maps of CMB polarization to date

E maps are bright and correlated: robust detection of LCDM E-modes

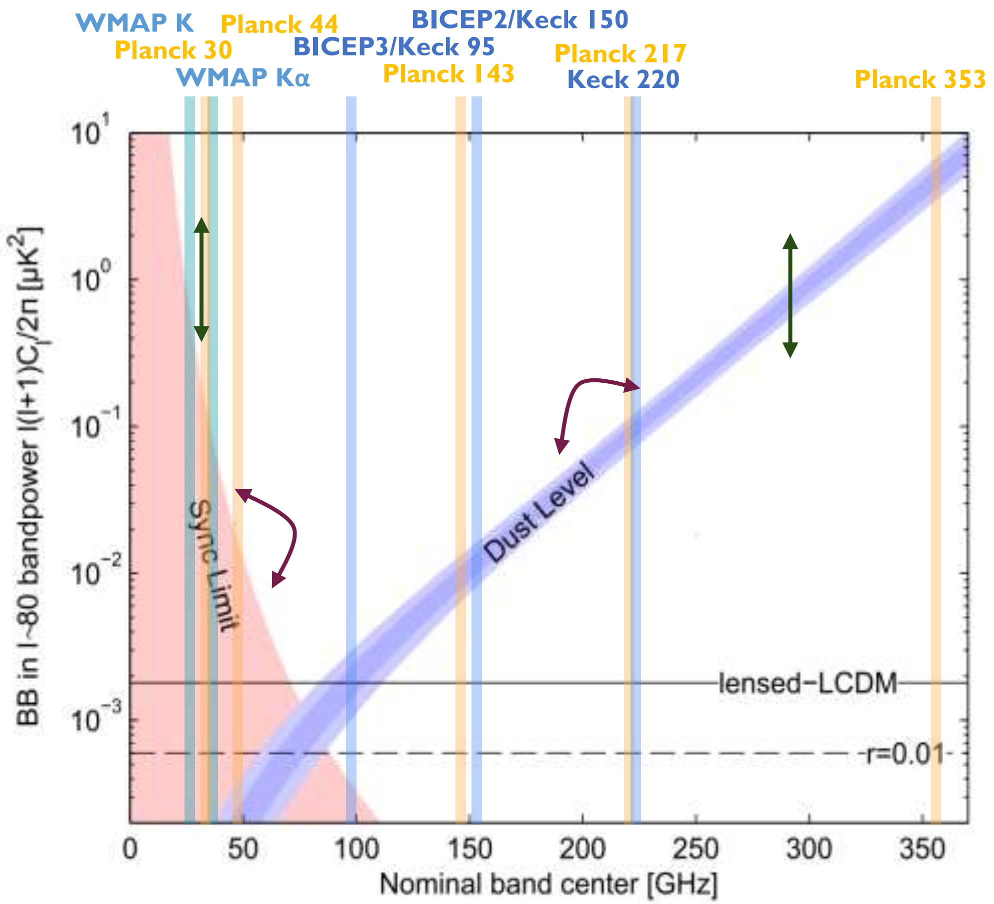


95GHz maps are larger due to larger B3 FOV

B maps are increasing in brightness: detection of polarized galactic dust

Multicomponent Likelihood Analysis

data model = r + ΛCDM + dust + synchrotron



dust	sync	
A_{dust}	A_{sync}	amplitudes @ l=80
β_{dust}	β_{sync}	frequency spectral indices
α_{dust}	α_{sync}	spatial spectral indices

ε — dust/sync spatial correlation

BK18 produces the tightest constraints on inflation to date:

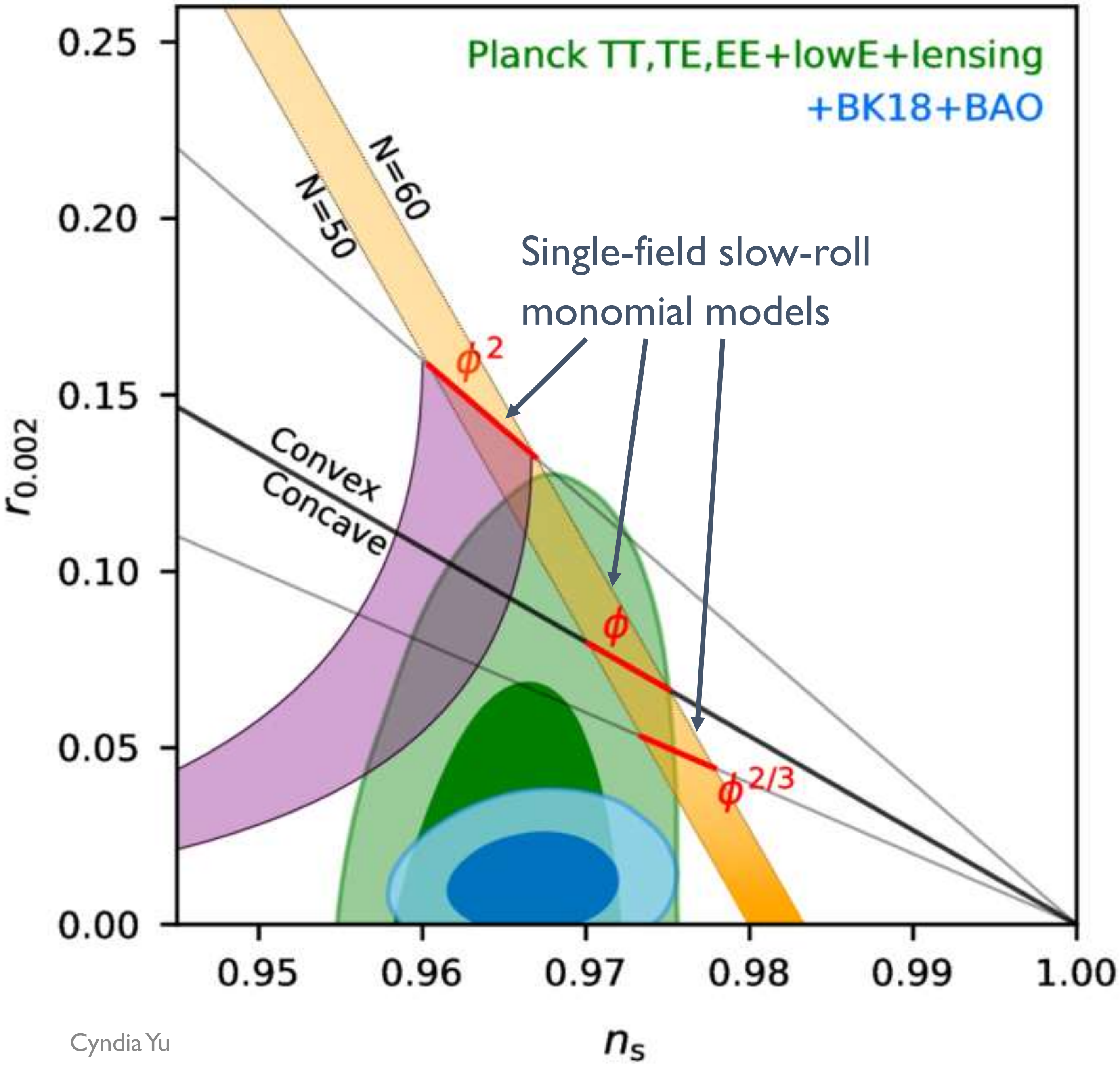
PHYSICAL REVIEW LETTERS **127,** 151301 (2021)

Editors' Suggestion | Featured in Physics

Improved Constraints on Primordial Gravitational Waves using *Planck*, WMAP, and BICEP/*Keck* Observations through the 2018 Observing Season

P. A. R. Ade,[1] Z. Ahmed,[2] M. Amiri,[3] D. Barkats,[4] R. Basu Thakur,[5] C. A. Bischoff,[6] D. Beck,[2,7] J. J. Bock,[5,8] H. Boenish,[4] E. Bullock,[9] V. Buza,[10] J. R. Cheshire IV,[9] J. Connors,[4] J. Cornelison,[4] M. Crumrine,[11] A. Cukierman,[7,2] E. V. Denison,[12] M. Dierickx,[4] L. Duband,[13] M. Eiben,[4] S. Fatigoni,[3] J. P. Filippini,[14,15] S. Fliescher,[11] N. Goeckner-Wald,[7] D. C. Goldfinger,[4] J. Grayson,[7] P. Grimes,[4] G. Hall,[11] G. Halal,[7] M. Halpern,[3] E. Hand,[6] S. Harrison,[4] S. Henderson,[2] S. R. Hildebrandt,[5,8] G. C. Hilton,[12] J. Hubmayr,[12] H. Hui,[5] K. D. Irwin,[7,2,12] J. Kang,[7,5] K. S. Karkare,[4,10] E. Karpel,[7] S. Kefeli,[5] S. A. Kernasovskiy,[7] J. M. Kovac,[4,16] C. L. Kuo,[7,2] K. Lau,[11] E. M. Leitch,[10] A. Lennox,[14] K. G. Megerian,[8] L. Minutolo,[5] L. Moncelsi,[5] Y. Nakato,[7] T. Namikawa,[17] H. T. Nguyen,[8] R. O'Brient,[5,8] R. W. Ogburn IV,[7,2] S. Palladino,[6] T. Prouve,[13] C. Pryke,[11,9,*] B. Racine,[4,18] C. D. Reintsema,[12] S. Richter,[4] A. Schillaci,[5] R. Schwarz,[11] B. L. Schmitt,[4] C. D. Sheehy,[19] A. Soliman,[5] T. St. Germaine,[4,16] B. Steinbach,[5] R. V. Sudiwala,[1] G. P. Teply,[5] K. L. Thompson,[7,2] J. E. Tolan,[7] C. Tucker,[1] A. D. Turner,[8] C. Umiltà,[6,14] C. Vergès,[4] A. G. Vieregg,[20,10] A. Wandui,[5] A. C. Weber,[8] D. V. Wiebe,[3] J. Willmert,[11] C. L. Wong,[4,16] W. L. K. Wu,[2] H. Yang,[7] K. W. Yoon,[7,2] E. Young,[7,2] C. Yu,[7] L. Zeng,[4] C. Zhang,[5] and S. Zhang[5]

The likelihood analysis yields the constraint $r_{0.05} < 0.036$ at 95% confidence. Running maximum likelihood search on simulations we obtain unbiased results and find that $\sigma(r) = 0.009$. These are the strongest constraints to date on primordial gravitational waves.

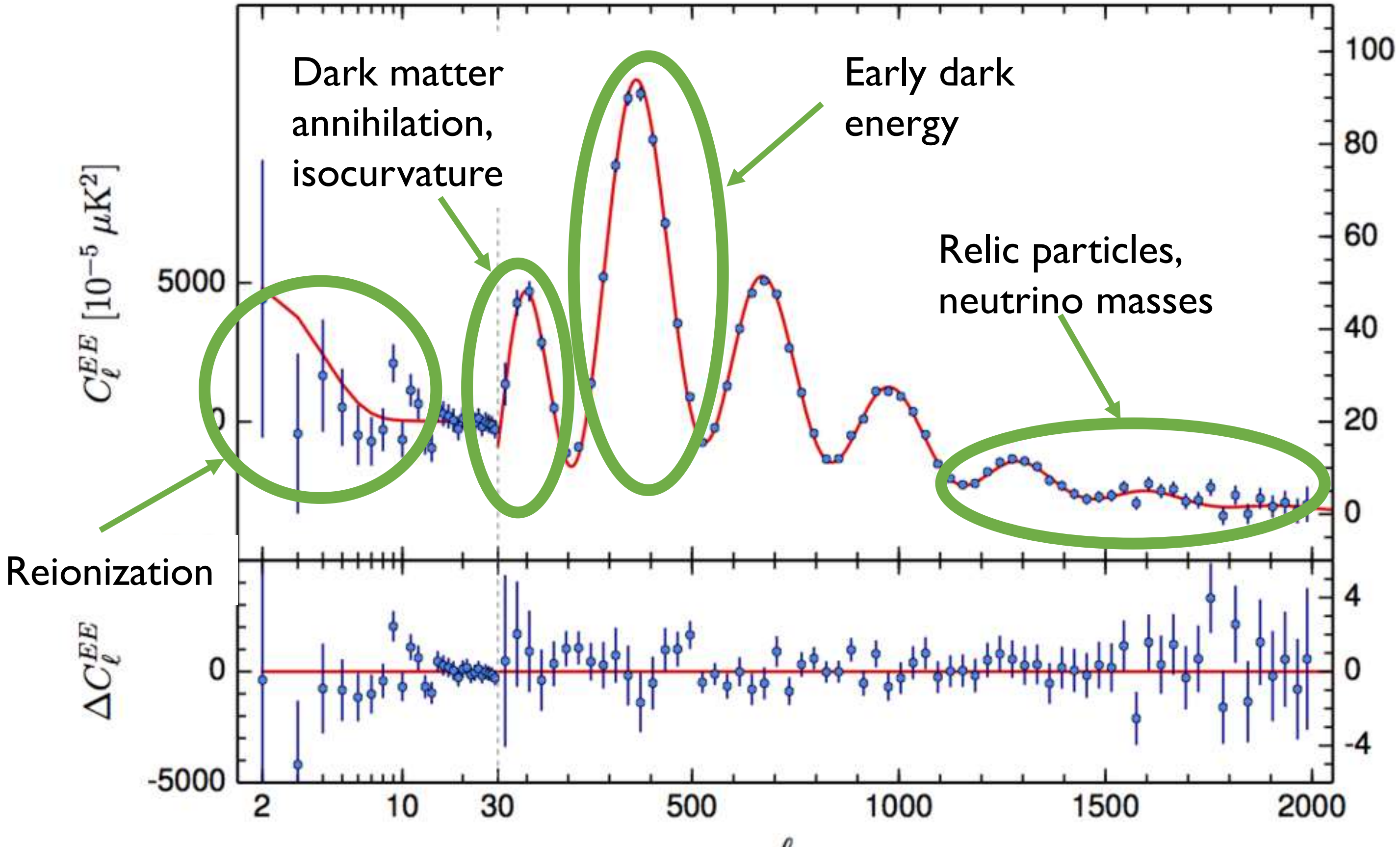


BK18 constraints on inflationary models

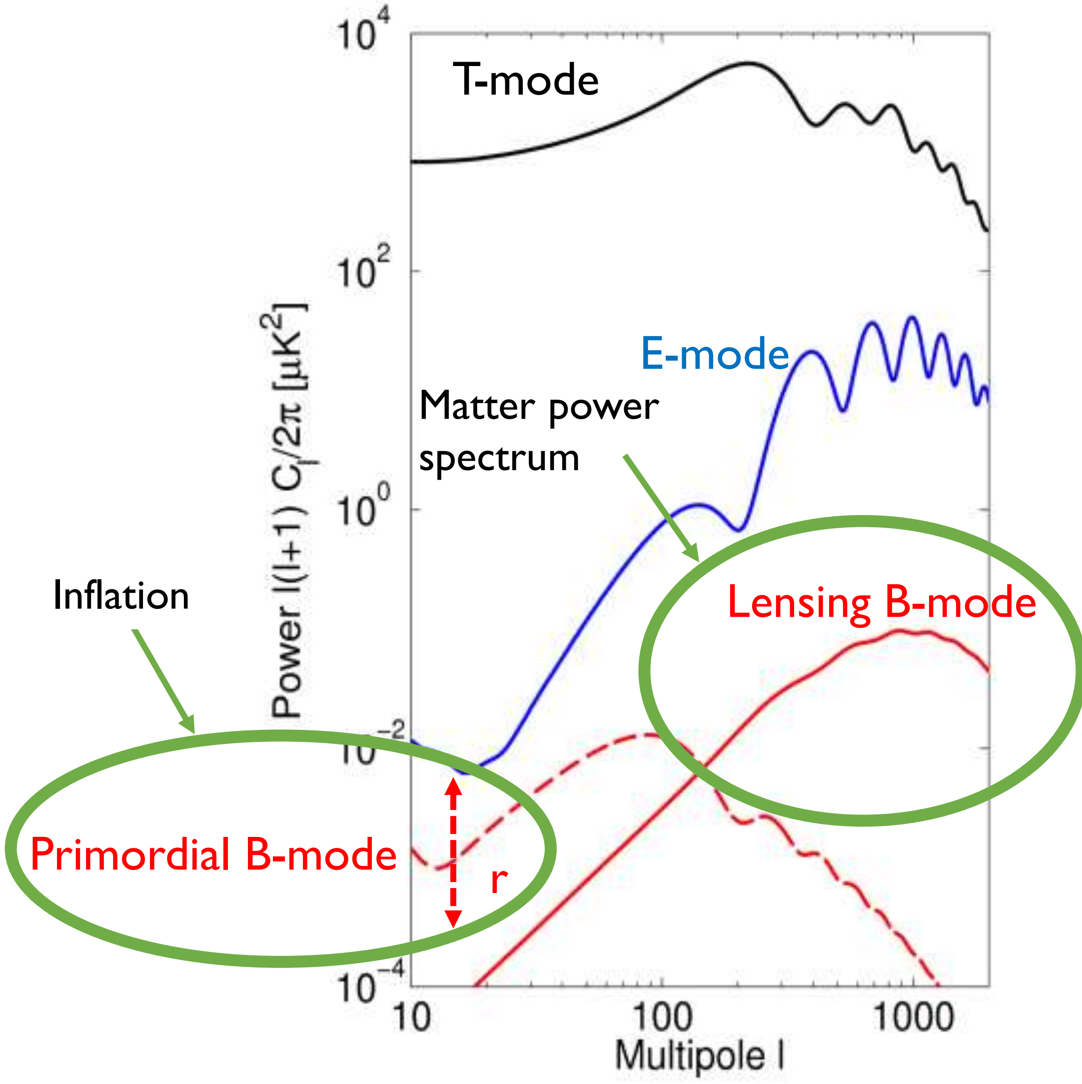
Beyond *r*

More cosmology with large-scale CMB polarization

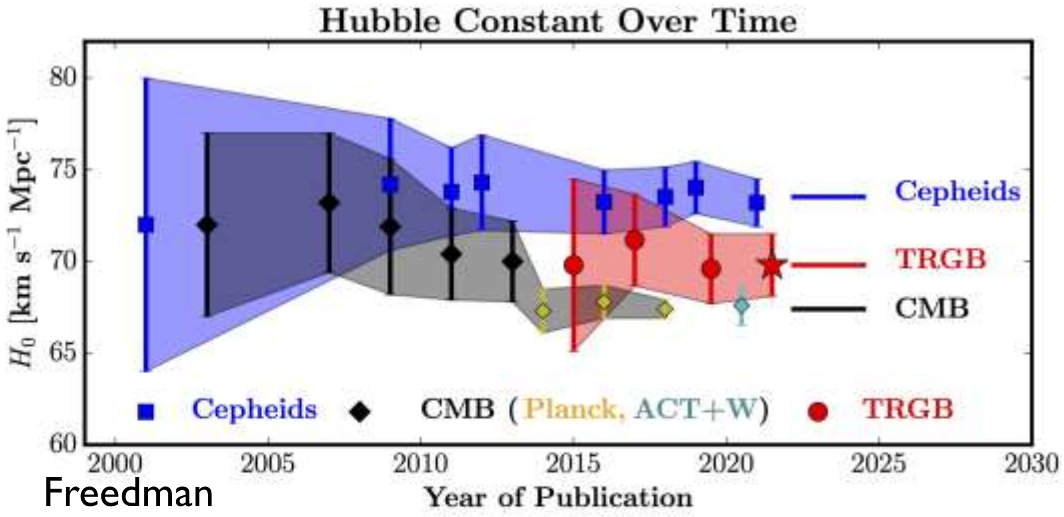
Cosmology in CMB Polarization



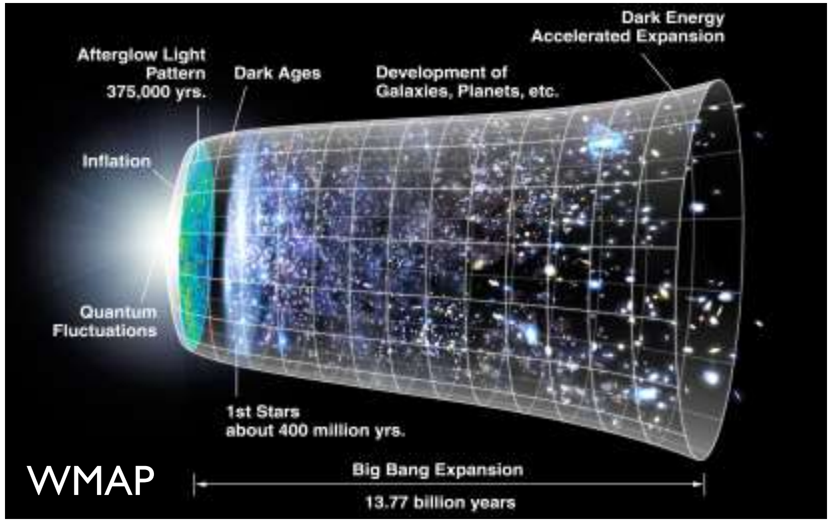
Planck 2018



Early Dark Energy and H0



Freedman



WMAP

PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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Atacama Cosmology Telescope: Constraints on prerecombination early dark energy

J. Colin Hill et al.

Phys. Rev. D **105**, 123536 – Published 30 June 2022

Article References No Citing Articles PDF HTML Export Citation

ABSTRACT

The early dark energy (EDE) scenario aims to increase the value of the Hubble constant (H_0) inferred from cosmic microwave background (CMB) data over that found in the standard cosmological model (ΛCDM), via the introduction of a new form of energy density in the early Universe. The EDE component briefly accelerates cosmic expansion just prior to recombination, which reduces the physical size of the sound horizon imprinted in the CMB. Previous work has found that nonzero EDE is not preferred by *Planck* CMB power spectrum data alone, which yield a 95% confidence level (C.L.) upper limit $f_{EDE} < 0.087$ on the maximal fractional contribution of the EDE field to the cosmic energy budget. In this paper, we fit the EDE model to CMB data from the Atacama Cosmology Telescope (ACT) data release 4. We find that a combination of ACT, large-scale *Planck* TT (similar to *WMAP*), *Planck* CMB lensing, and BAO data prefers the existence of EDE at $> 99.7\%$ C.L.: $f_{EDE} = 0.091^{+0.020}_{-0.036}$, with $H_0 = 70.9^{+1.0}_{-2.0}$ km/s/Mpc (both 68% C.L.). From a model-selection standpoint, we find that EDE is favored over ΛCDM by these data at roughly 3σ significance. [illegible] analysis of the full *Planck* and ACT data yields no evidence for EDE, as previously found for *Planck* alone. We show [illegible] across a wide range of multipoles in TE and EE, indicating that a powerful test of this scenario is anticipated with near-future data from ACT and other ground-based experiments.

Issue

Vol. 105, Iss. 12 — 15 June 2022

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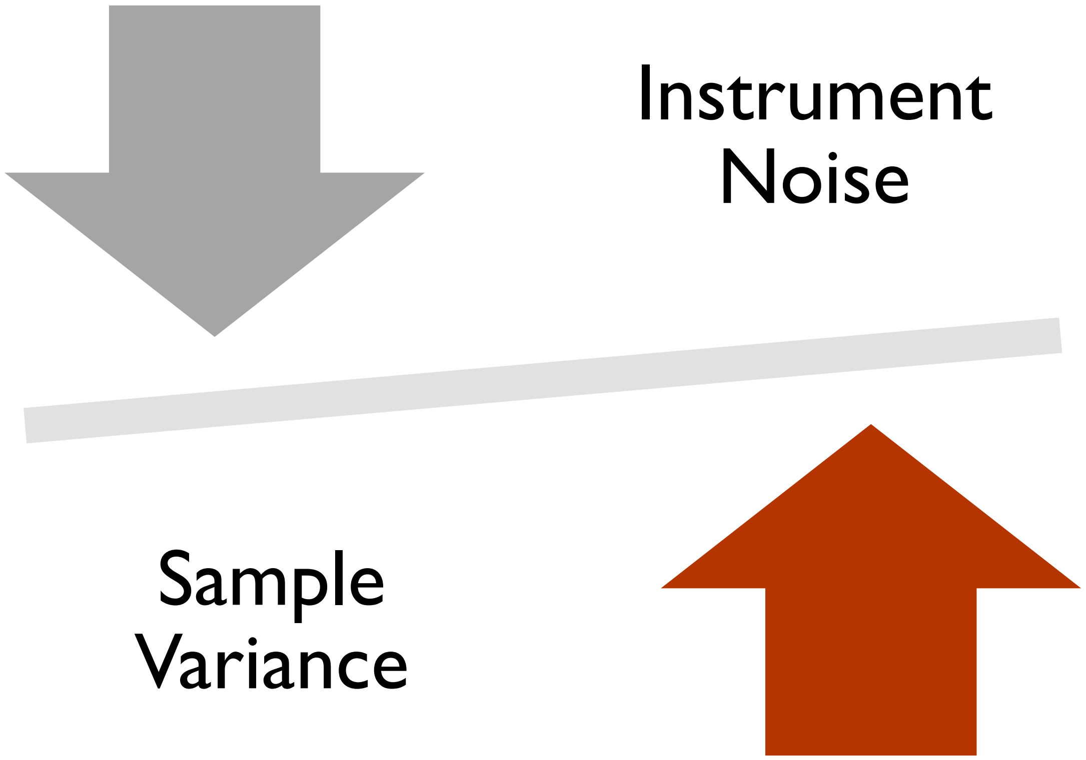
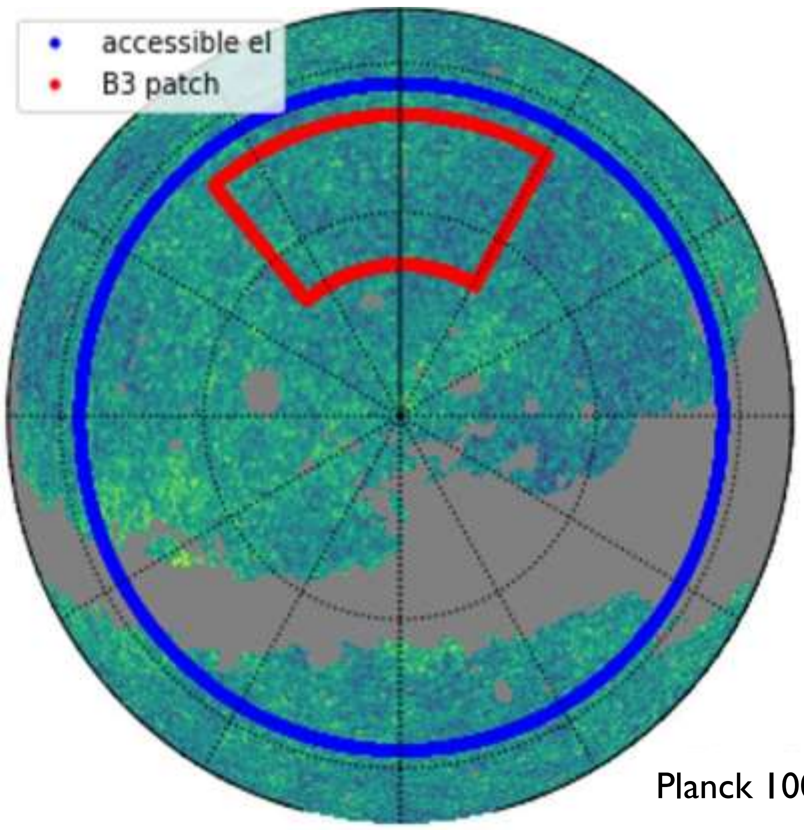
find that EDE is favored over ΛCDM by these data at roughly 3σ significance

What's in an error bar?



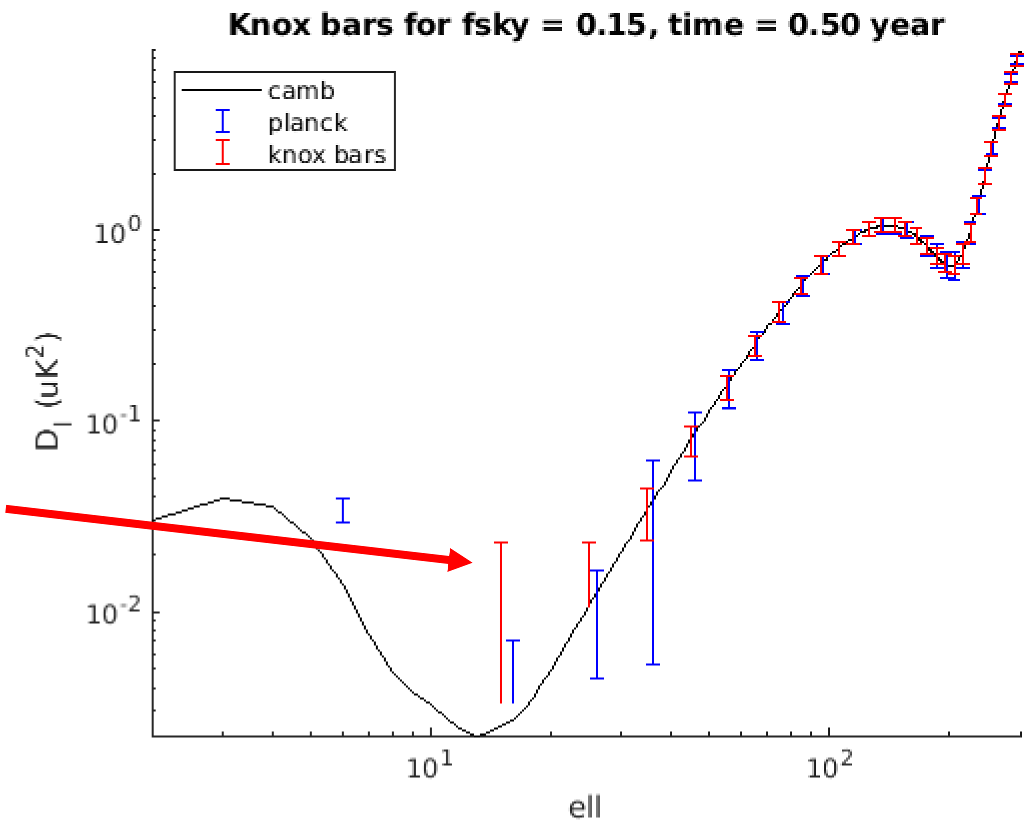


Planck 100GHz

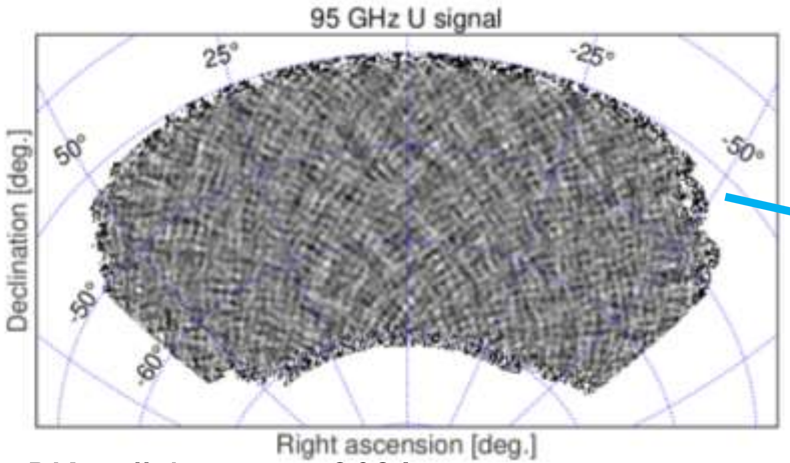
BK18 patch: f_{sky} = 3%
Available from Pole: f_{sky} ~16%

BICEP3 can quickly improve on *Planck* errors

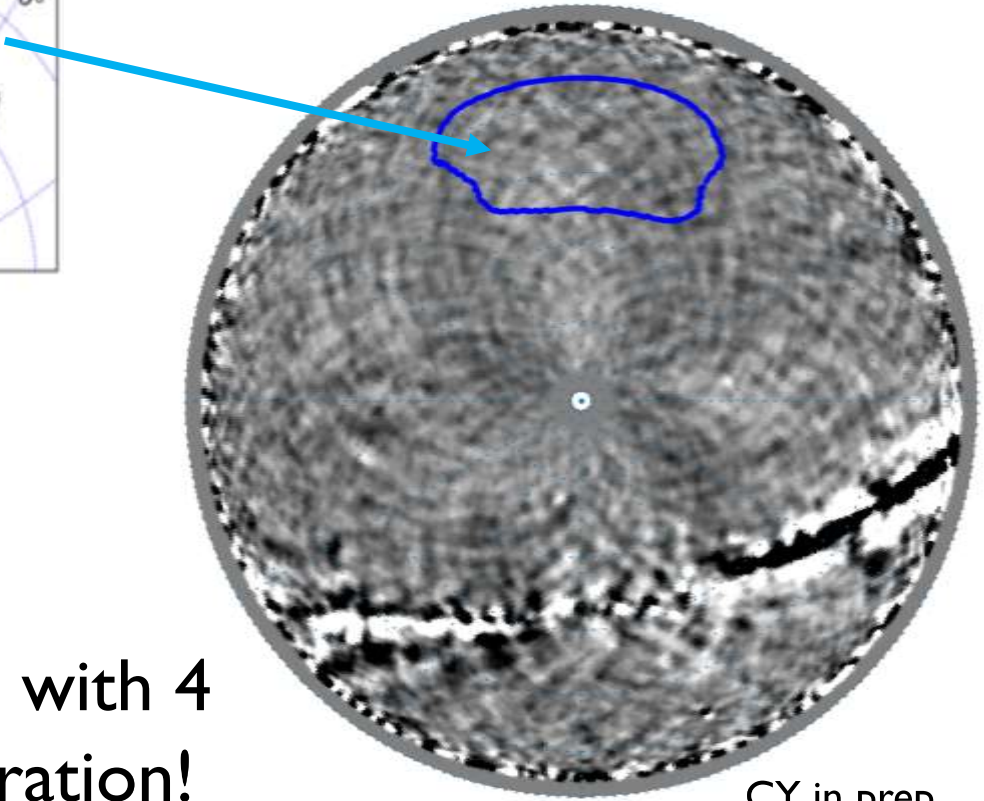
- Scaling from achieved BICEP3 performance (frequency map only, no foregrounds)
- Scaled integration time accounts for usual observing efficiency hits
  - "1 year" = March - October
- Low-ell modes traditionally heavily filtered for B-mode science, but (in principle) recoverable



E-modes observed at high signal-to-noise!



BK collaboration 2021



CY in prep.

Over 8000 sq deg < 20μK-arcmin with 4 months of (mostly summer) integration!

Error bar estimation

- Signal is small deviations from LCDM: proper error bar estimation is critical!
- Recall error bars come from **sample variance + instrument noise**

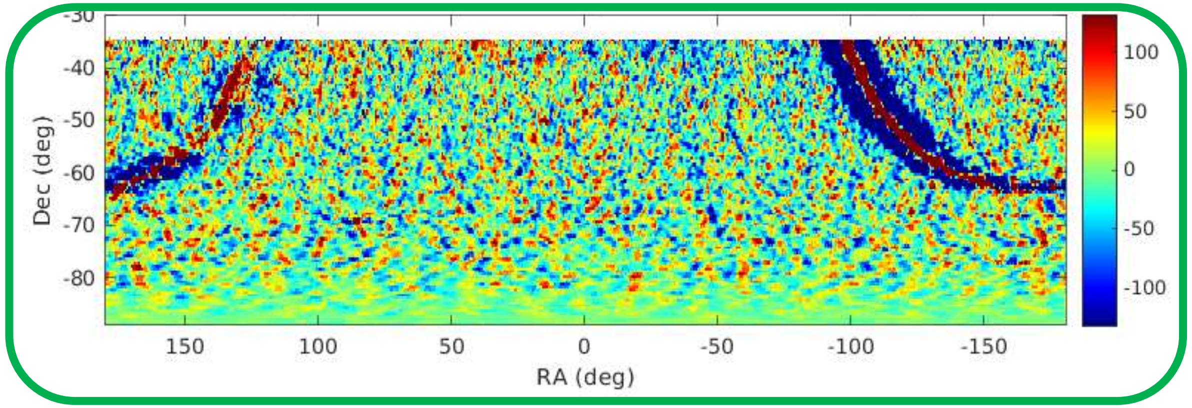
Sample Variance
Signal-only sims
+
Instrument model

Instrument Noise
Signflip noise sims
+
Incorporate covariances

Check maps for systematics via jackknives

Moon up

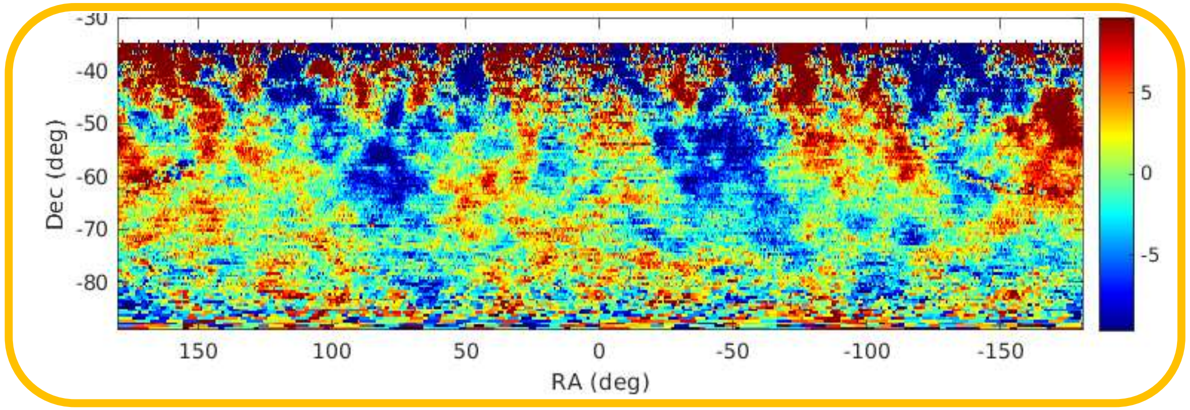
Moon down



Half dataset map

Half dataset map

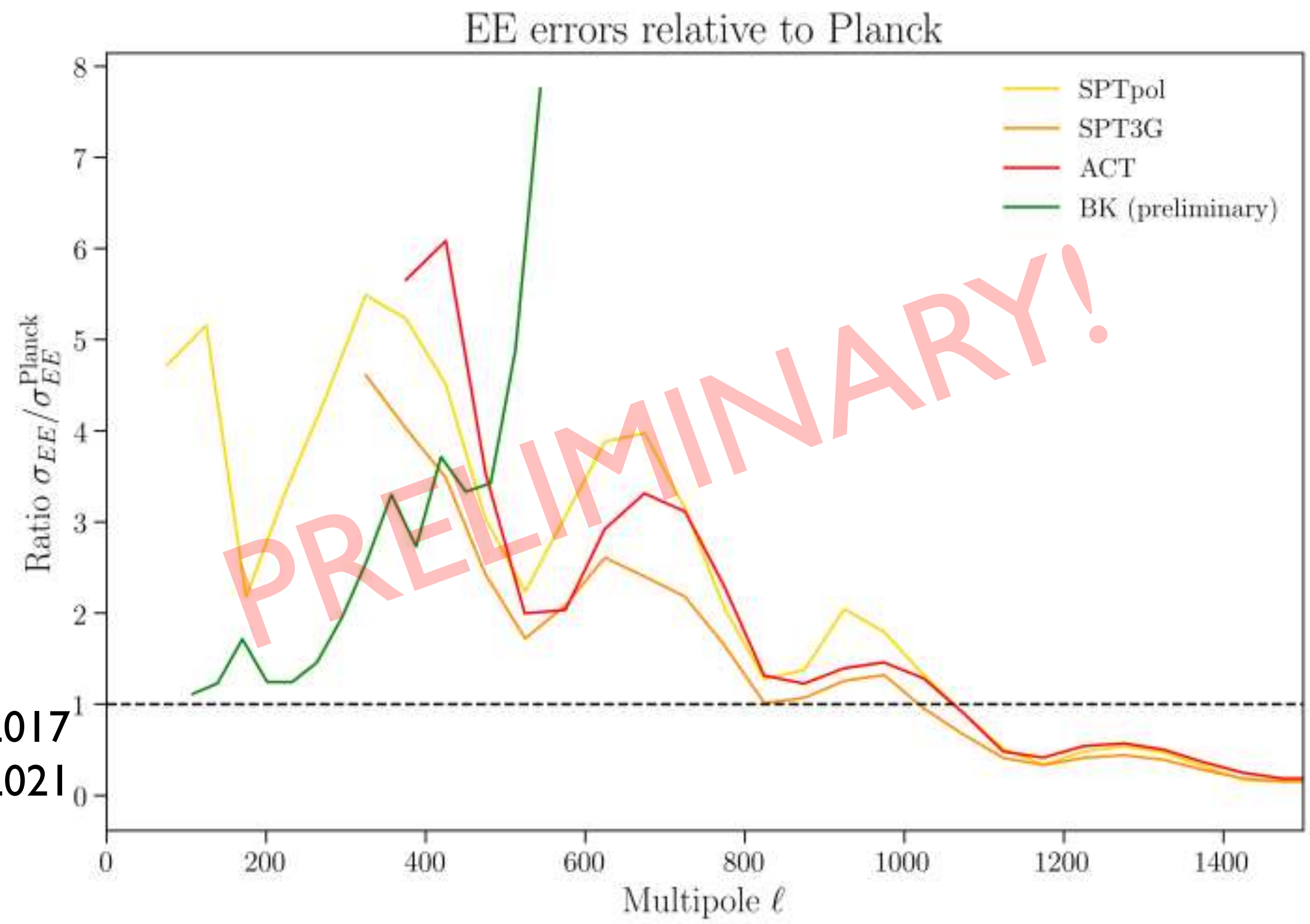
Difference map



Compare power spectrum to simulations, examine ensemble of tests for outliers and bias.

Must pass jackknives before proceeding with cosmology analysis!

Preliminary instrumental sensitivity



SPTpol: Henning et al. 2017
SPT3G: Dutcher et al. 2021
ACT: Aiola et al. 2021
BK: CY in prep

Looking Forward

The next decade of large-scale CMB polarization experiments

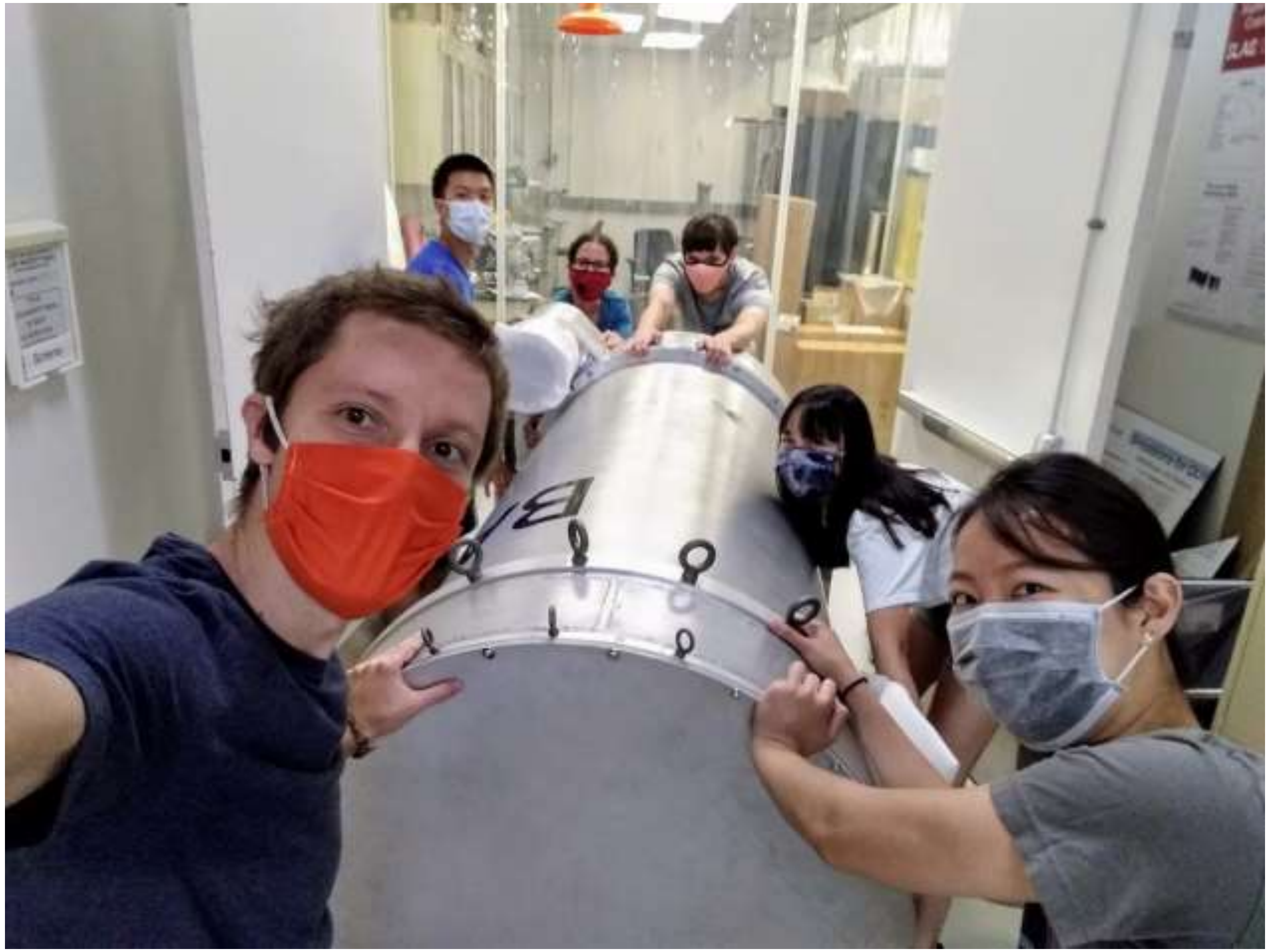
What limits *r*?

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

	σ(r)
Baseline (foregrounds, lensing, noise)	0.009
No foregrounds	0.007
No lensing	0.004
No foregrounds, no lensing	0.002

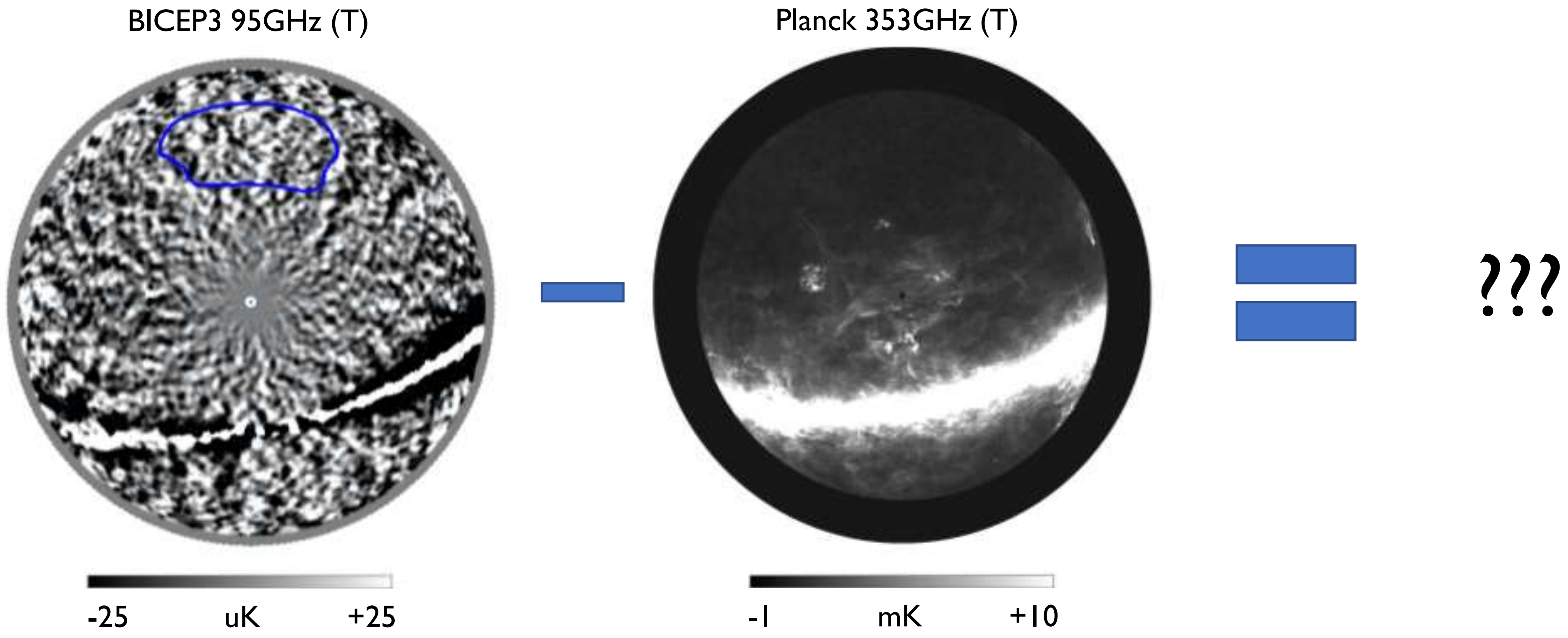
Moving forward: foregrounds

- 4 BICEP3-style receivers
- BA1 installed in 2019, upgraded in 2021
- Observing in 6 bands: 30/40, 95, 150, 220/270
- Confronting foreground models with deeper data



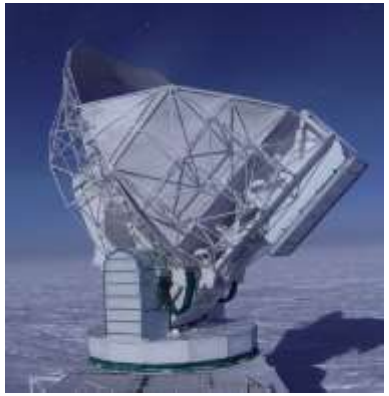
BA4 (220/270GHz) shipping to South Pole in < 1 year!

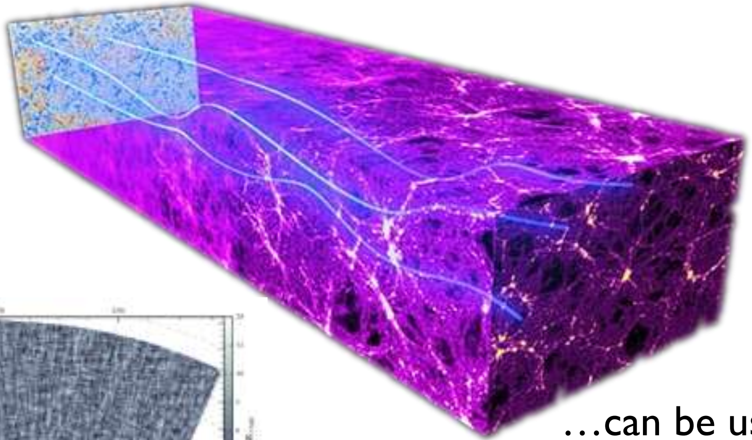
Moving forward: foregrounds

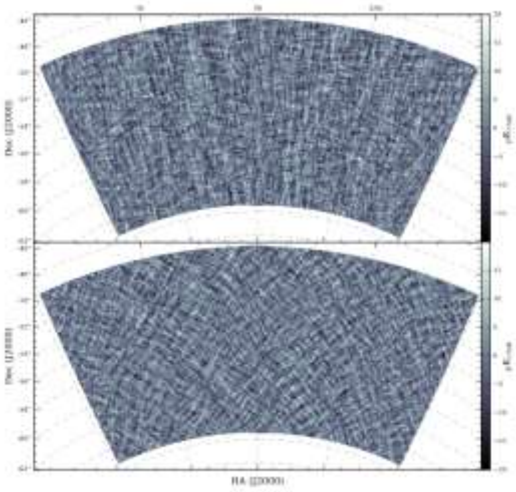


Usual parametric foreground model may be insufficient…but an opportunity for future BA observations!

Moving forward: delensing with SPT-3G

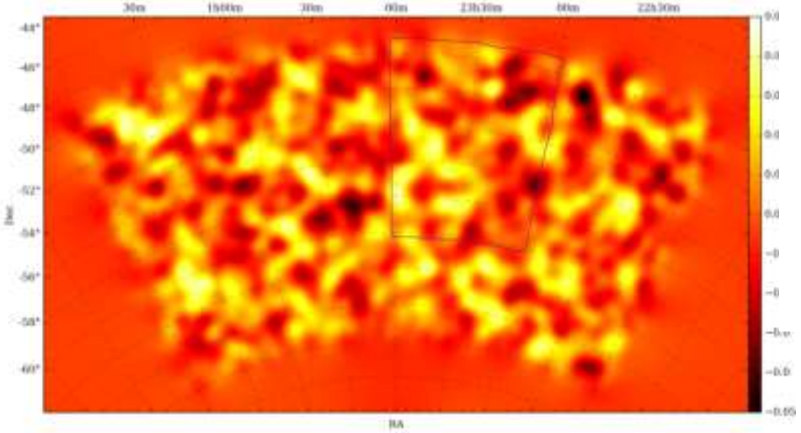


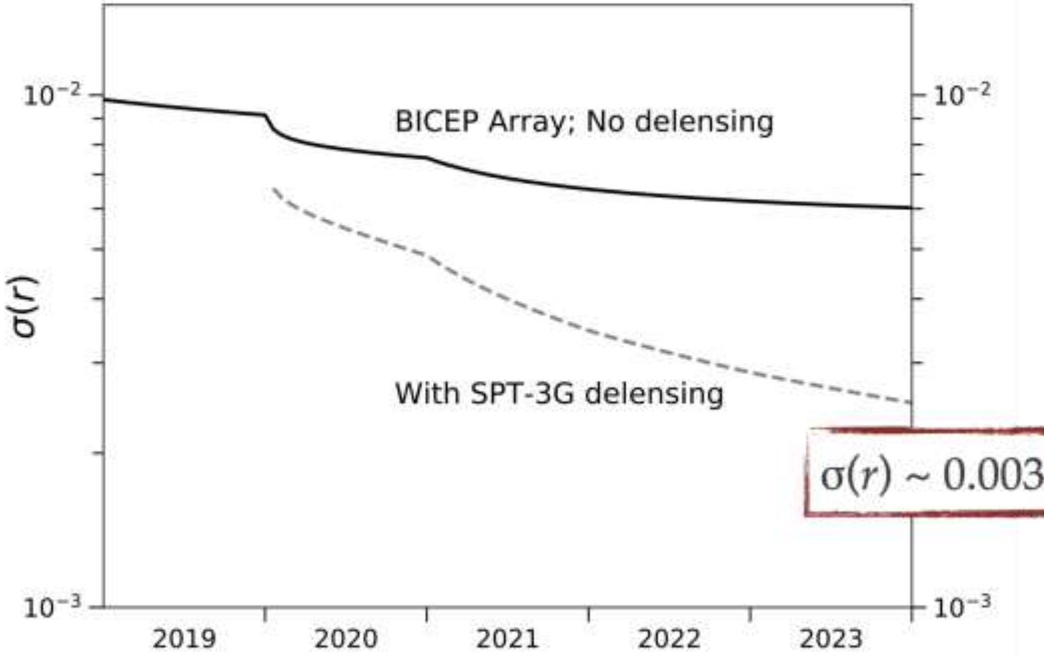




High-resolution maps from a large-aperture instrument…

…can be used to reconstruct the lensing deflection map…

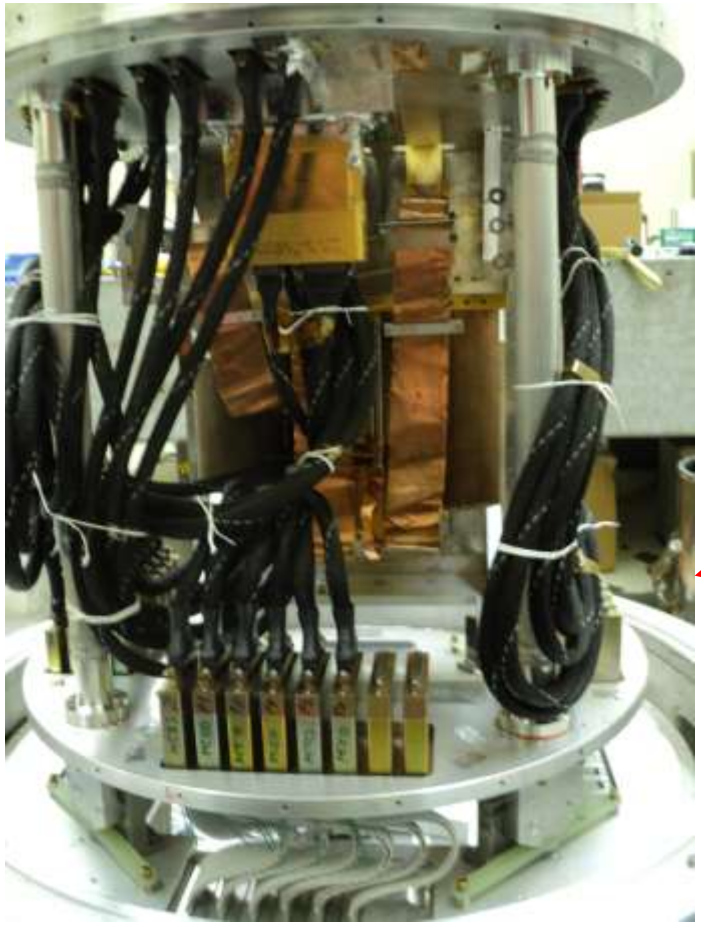




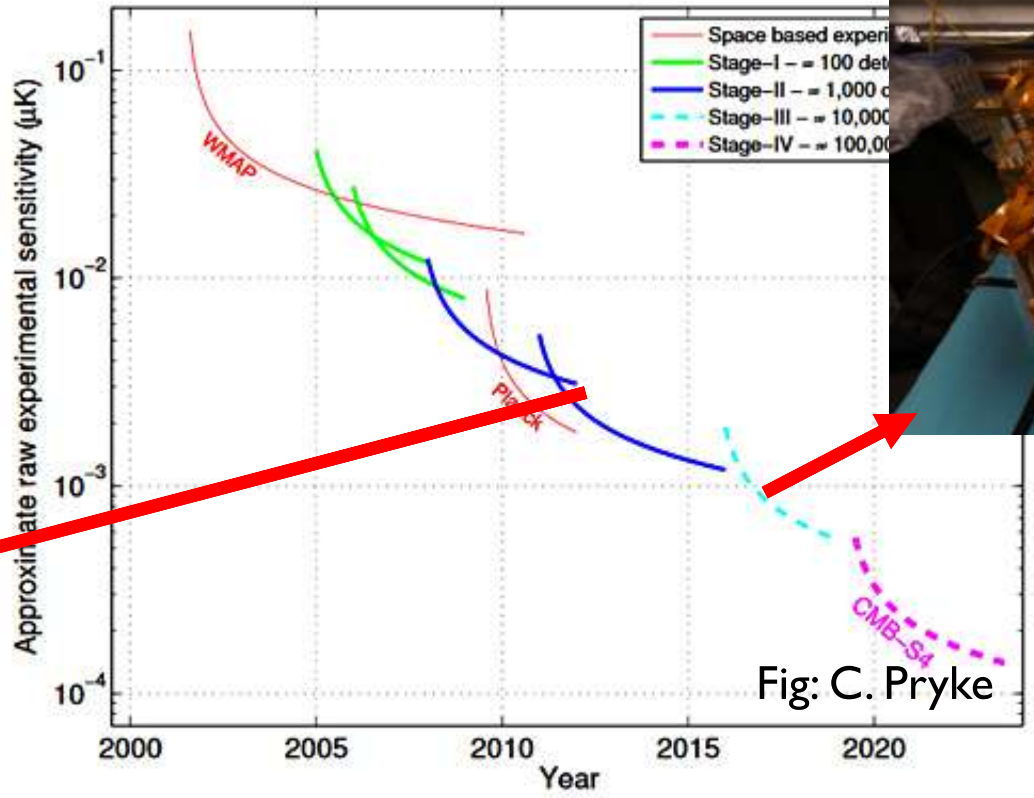
…which can then be used to calculate and remove the lensing signal!

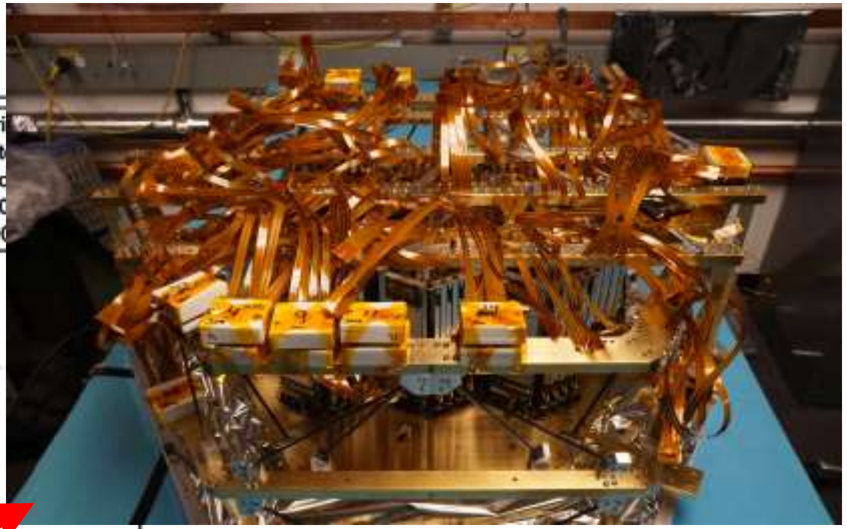
Proof of concept: BK14+SPTpol (arXiv:2011.08163)

Moving forward: noise



BICEP3, ~2500 TESs



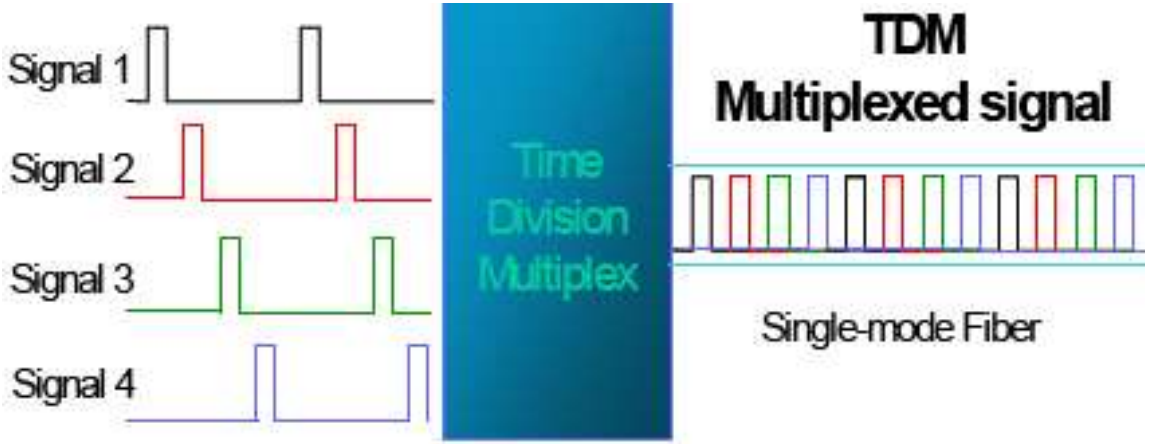


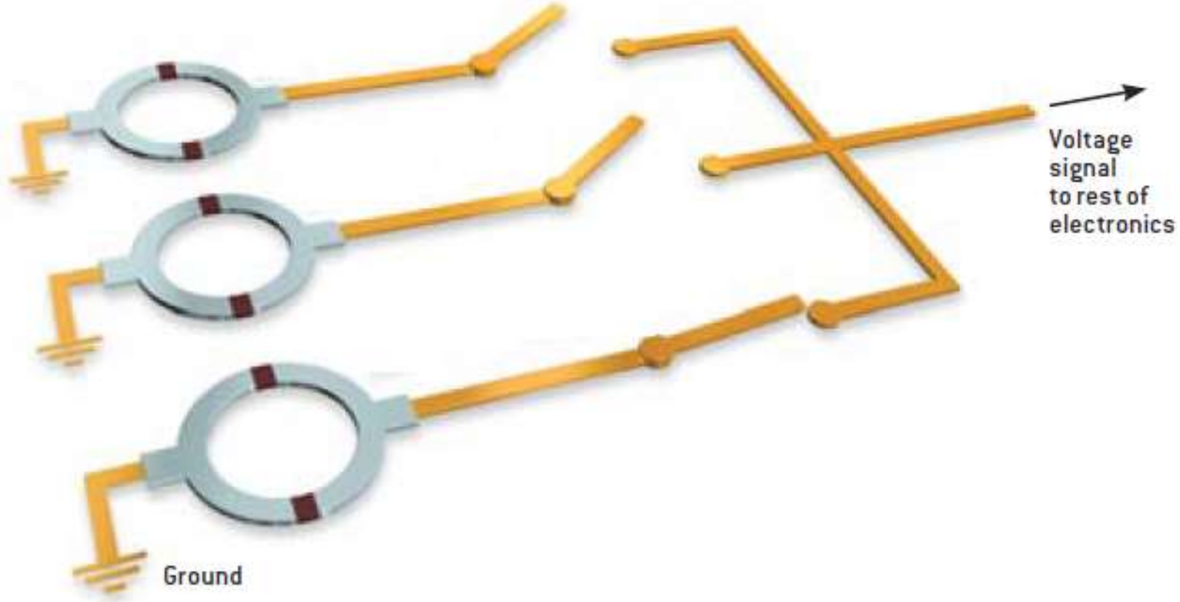
SPT-3G, ~15000 TESs

Multiplexing is a way to reduce:

1. Heat load on the focal plane
2. Integration complexity

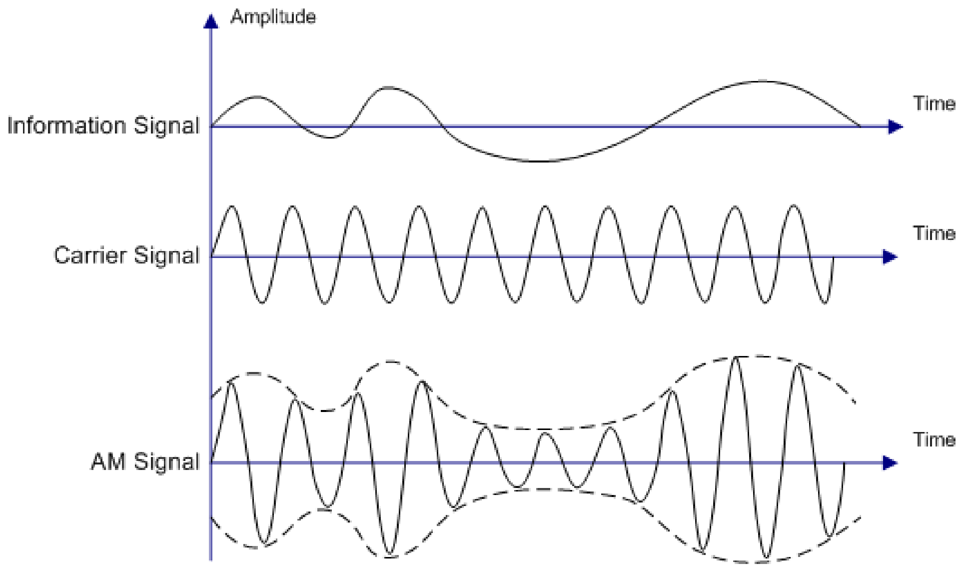
Time Division Multiplexing (TDM)



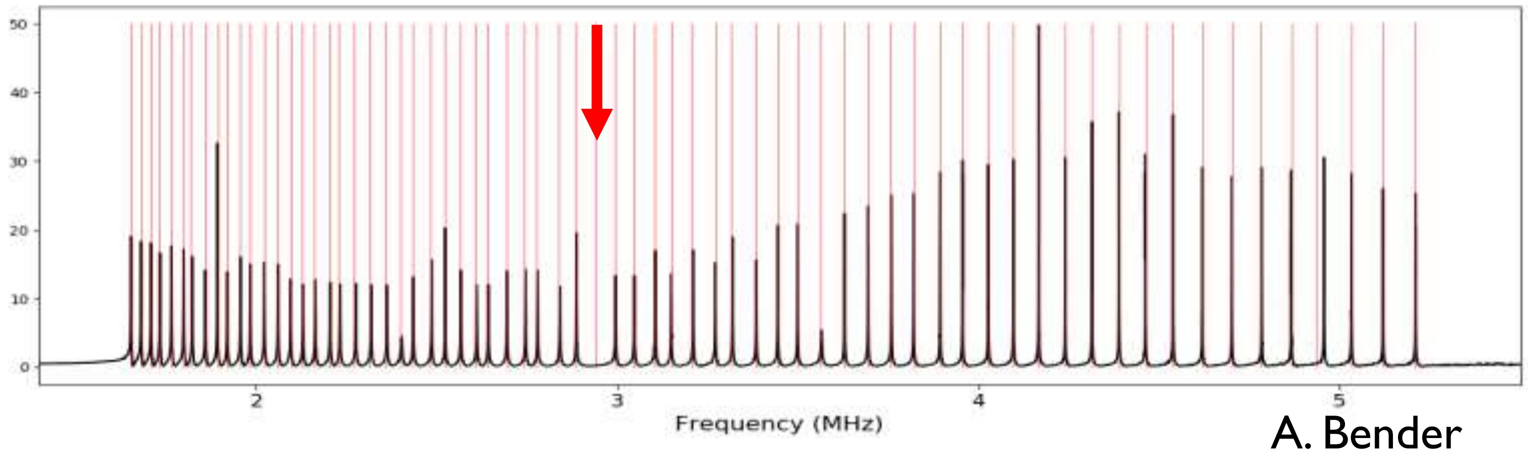


CMB Fielded Instruments	ABS, ACT, BICEP/Keck, SPIDER, CLASS
Achieved MUX Factor	64
Potential MUX Factor	256

Frequency Division Multiplexing (DfMUX)



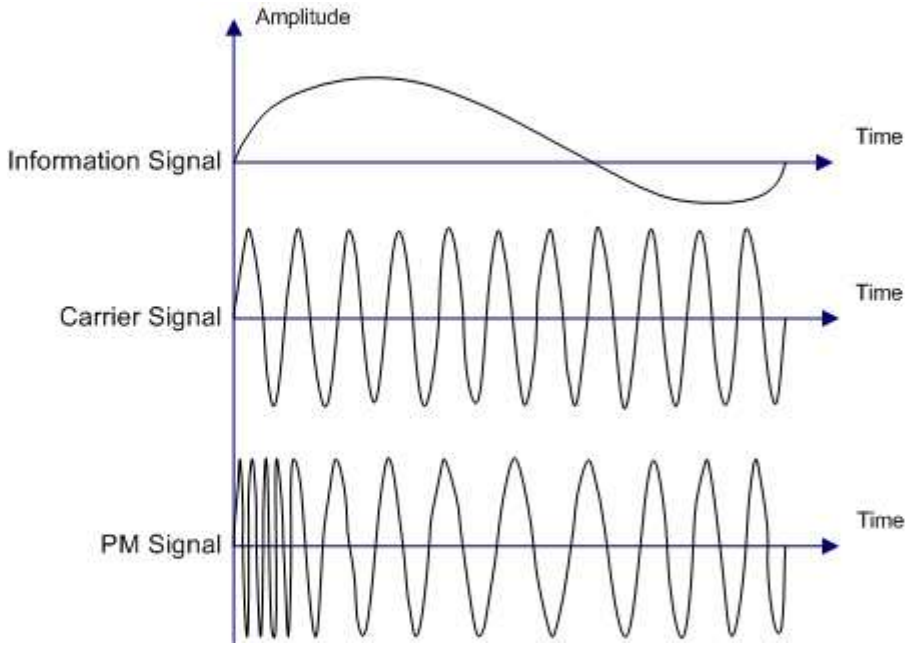
Commonly known as “AM Radio”

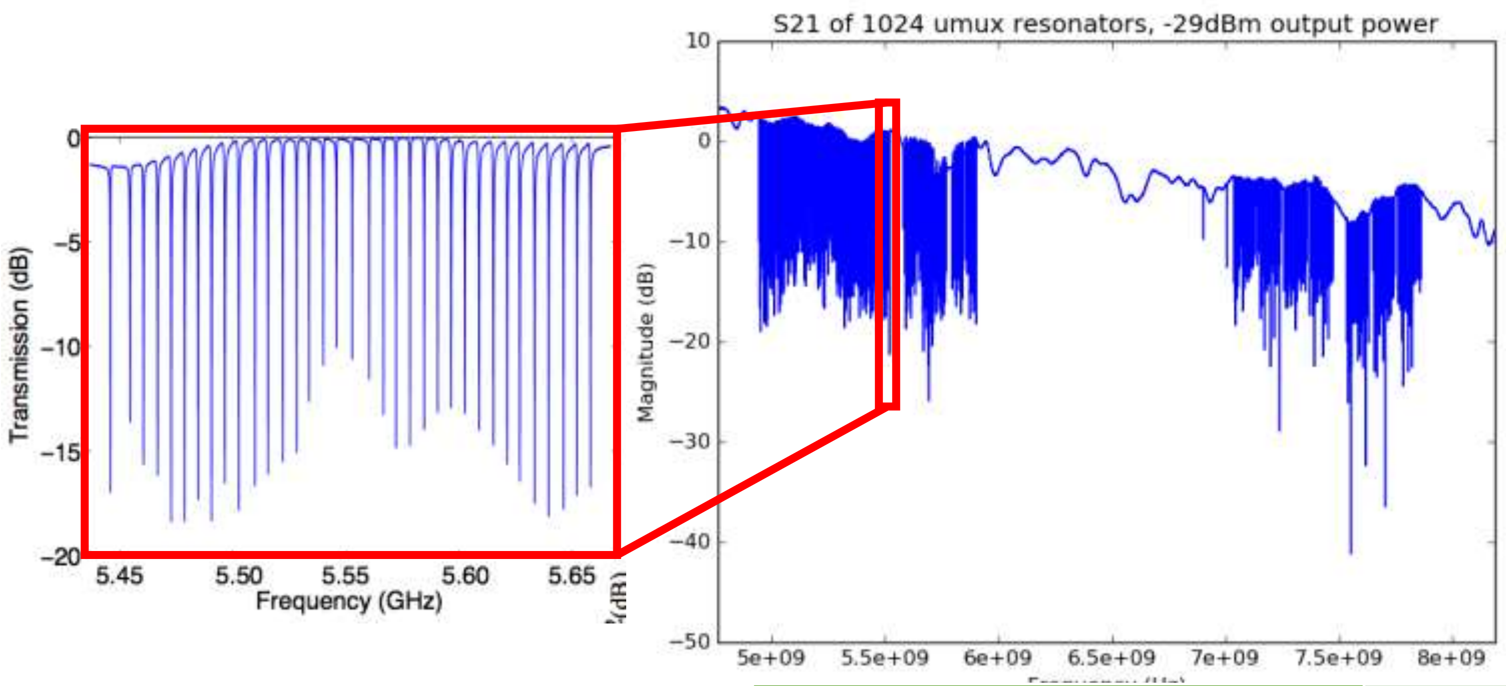


A. Bender

CMB Fielded Instruments	POLARBEAR, SPT, APEX-SZ
Achieved MUX Factor	68
Potential MUX Factor	256

Microwave SQUID Multiplexing (μmux)

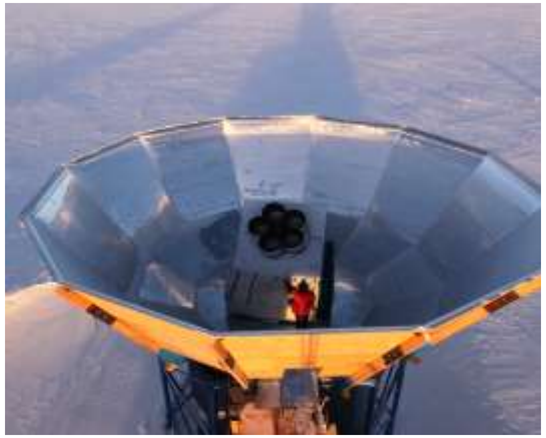


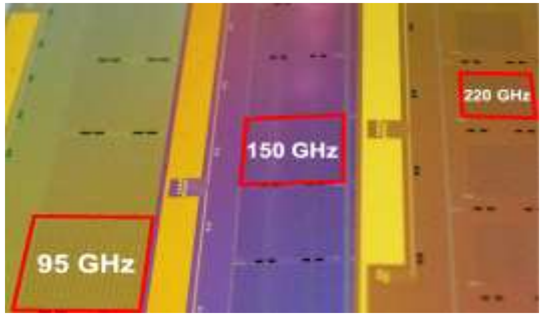


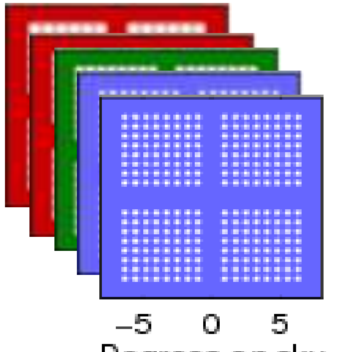
Achieved MUX Factor	910
Potential MUX Factor	2000

- μmux enables > order of magnitude increase in multiplexing factor over existing technologies!
- Leverages recent commercial progress in RF components

First demonstration on Keck Array:

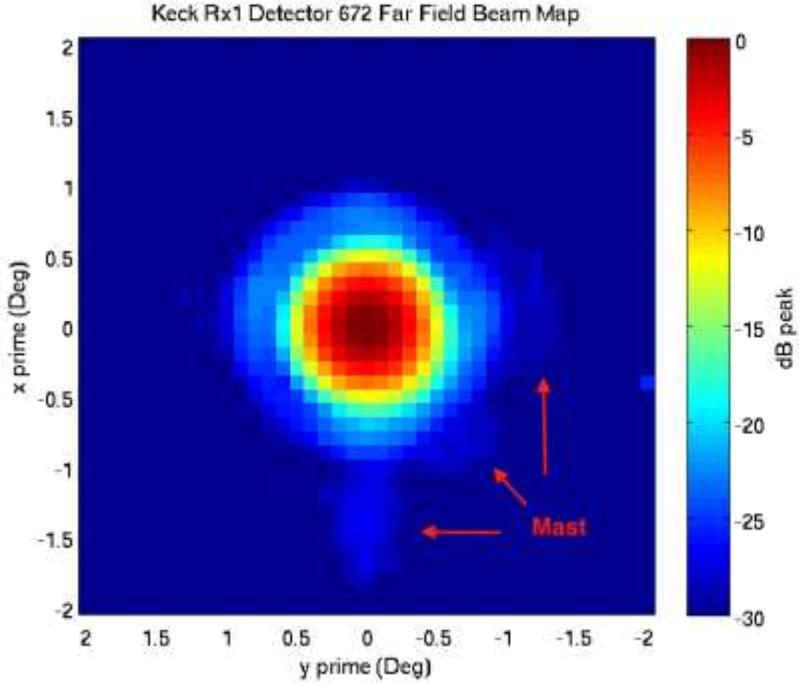




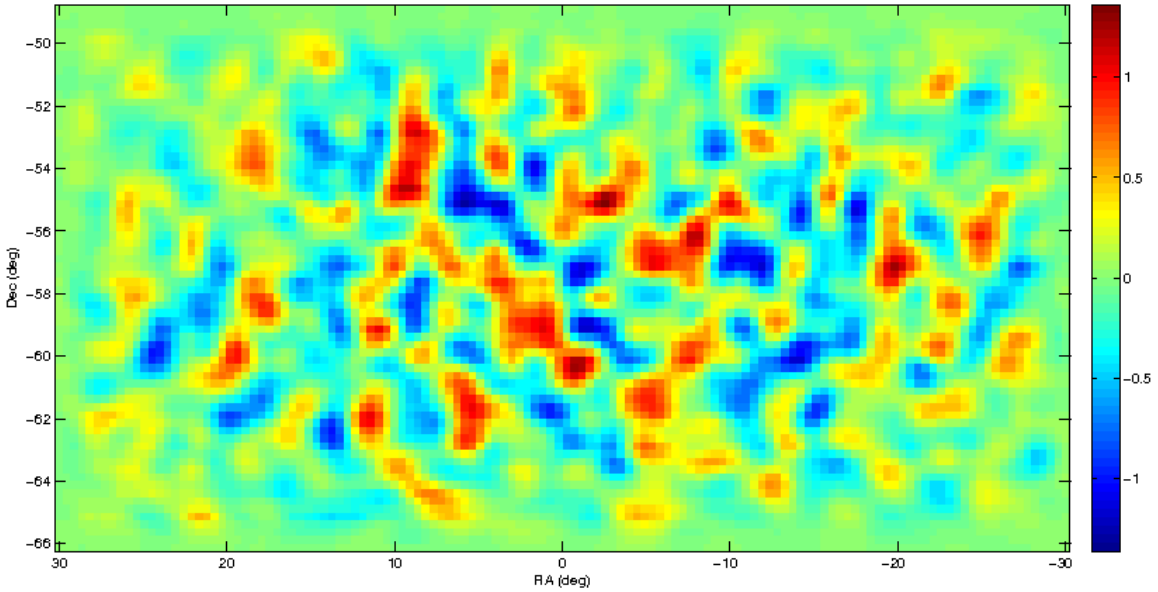


Before: TDM
MUX factor: 33x

After: μmux
MUX factor: ~200x



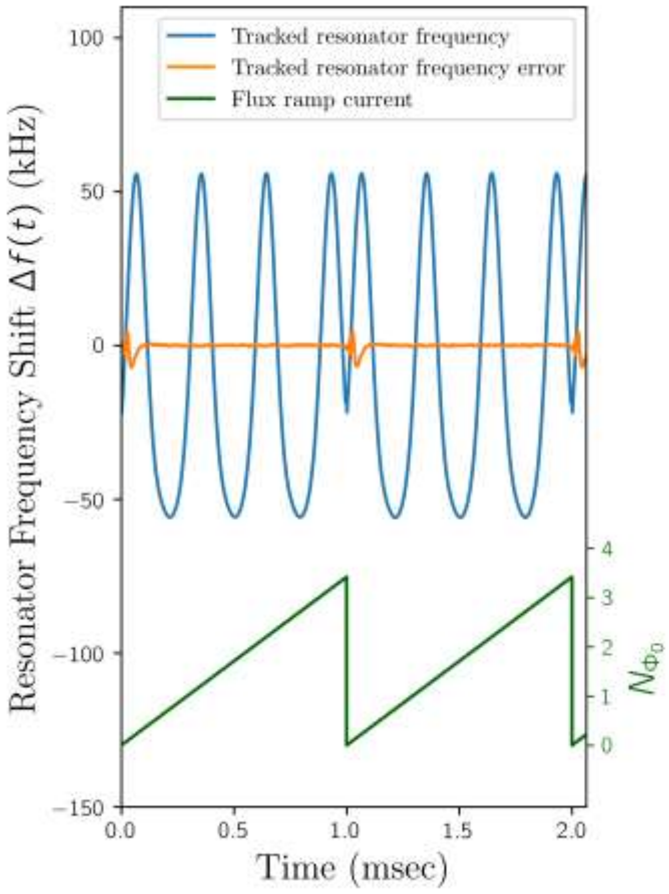
CMB with umux receiver at 150GHz



First demonstration of an end-to-end μmux system for CMB observations!

Cukierman et al. (incl. CY) 2019, JLTP
CY LTD19

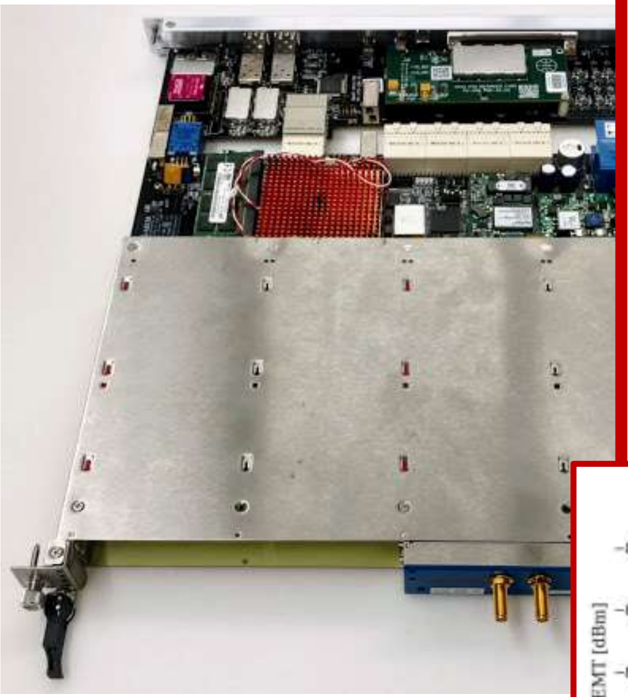
SMuRF tone-tracking electronics

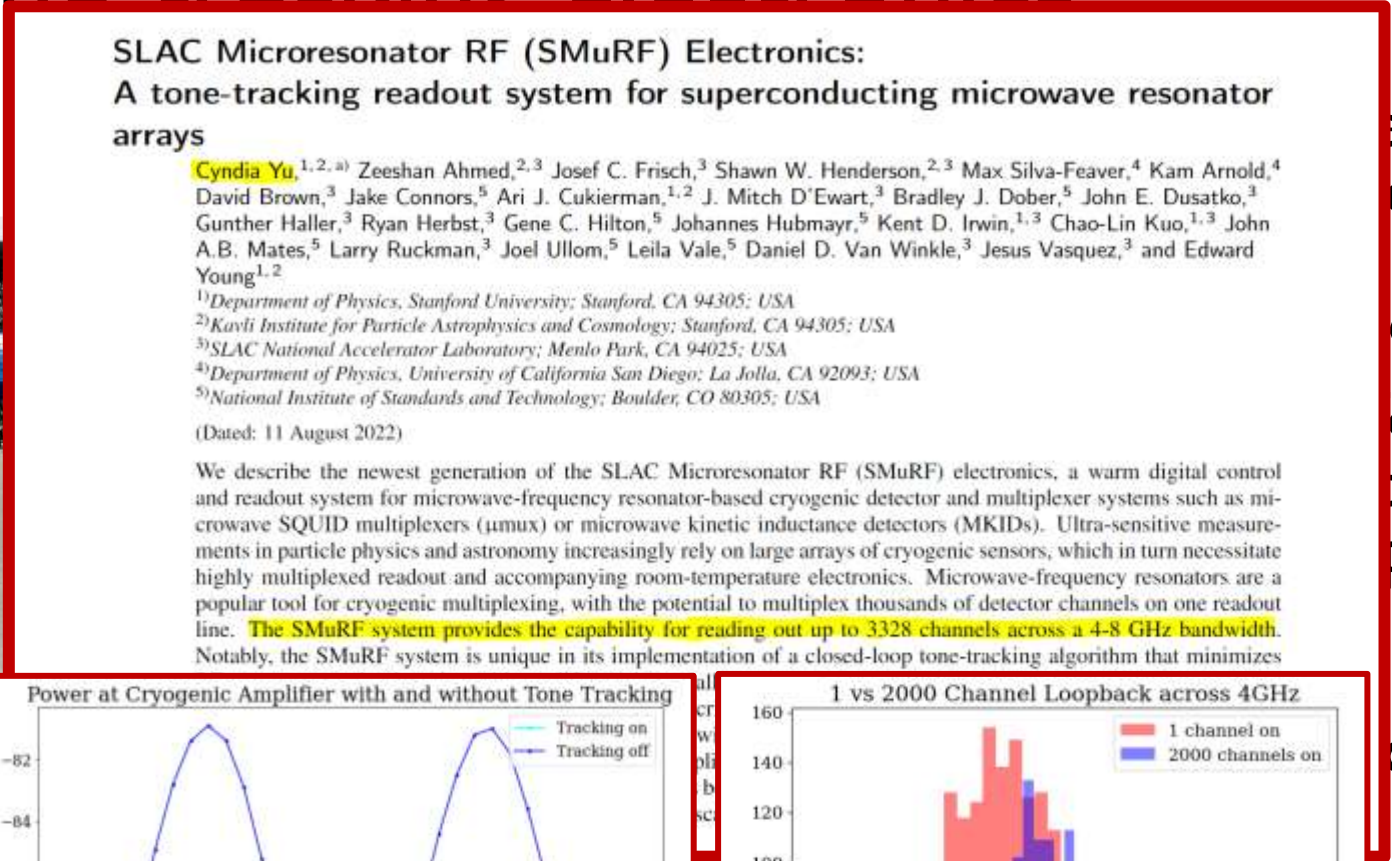


- Readout system for probe tone generation + readback, detector/amplifier biases, DAQ interface
- Probe tones for 1000s of GHz resonators saturate cryogenic amplifiers when off-resonance → implement a closed-loop feedback system to track resonances as they move
- Tone-tracking **enables** umux

Henderson et al. (incl. CY) 2018, Proc. SPIE
CY et al. 2022, Rev. Sci. Inst.

SMuRF tone-tracking electronics





SLAC Microresonator RF (SMuRF) Electronics:
A tone-tracking readout system for superconducting microwave resonator arrays

Cyndia Yu,[1,2,a)] Zeeshan Ahmed,[2,3] Josef C. Frisch,[3] Shawn W. Henderson,[2,3] Max Silva-Feaver,[4] Kam Arnold,[4] David Brown,[3] Jake Connors,[5] Ari J. Cukierman,[1,2] J. Mitch D'Ewart,[3] Bradley J. Dober,[5] John E. Dusatko,[3] Gunther Haller,[3] Ryan Herbst,[3] Gene C. Hilton,[5] Johannes Hubmayr,[5] Kent D. Irwin,[1,3] Chao-Lin Kuo,[1,3] John A.B. Mates,[5] Larry Ruckman,[3] Joel Ullom,[5] Leila Vale,[5] Daniel D. Van Winkle,[3] Jesus Vasquez,[3] and Edward Young[1,2]
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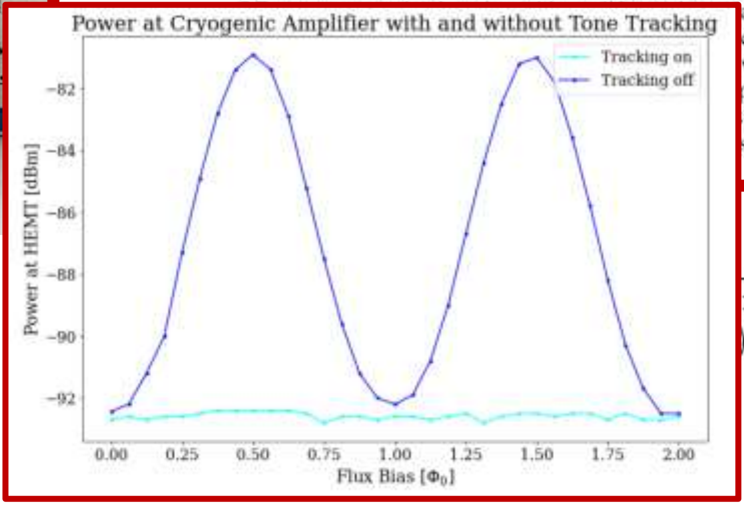
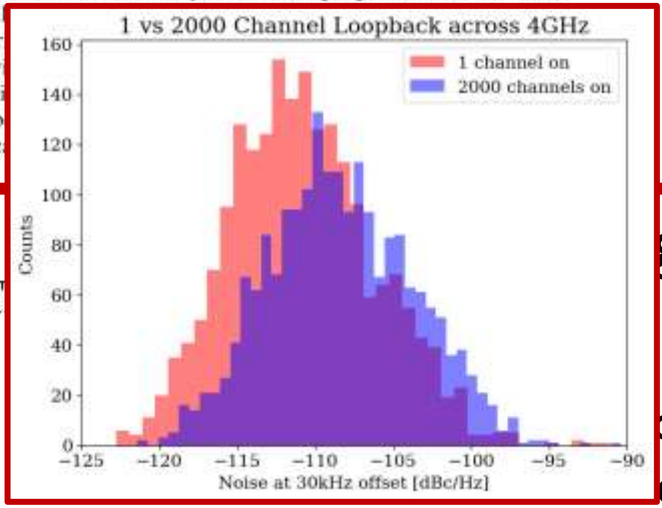
[2)]Kavli Institute for Particle Astrophysics and Cosmology; Stanford, CA 94305; USA
[3)]SLAC National Accelerator Laboratory; Menlo Park, CA 94025; USA
[4)]Department of Physics, University of California San Diego; La Jolla, CA 92093; USA
[5)]National Institute of Standards and Technology; Boulder, CO 80305; USA

(Dated: 11 August 2022)

We describe the newest generation of the SLAC Microresonator RF (SMuRF) electronics, a warm digital control and readout system for microwave-frequency resonator-based cryogenic detector and multiplexer systems such as microwave SQUID multiplexers (µmux) or microwave kinetic inductance detectors (MKIDs). Ultra-sensitive measurements in particle physics and astronomy increasingly rely on large arrays of cryogenic sensors, which in turn necessitate highly multiplexed readout and accompanying room-temperature electronics. Microwave-frequency resonators are a popular tool for cryogenic multiplexing, with the potential to multiplex thousands of detector channels on one readout line. The SMuRF system provides the capability for reading out up to 3328 channels across a 4-8 GHz bandwidth. Notably, the SMuRF system is unique in its implementation of a closed-loop tone-tracking algorithm that minimizes





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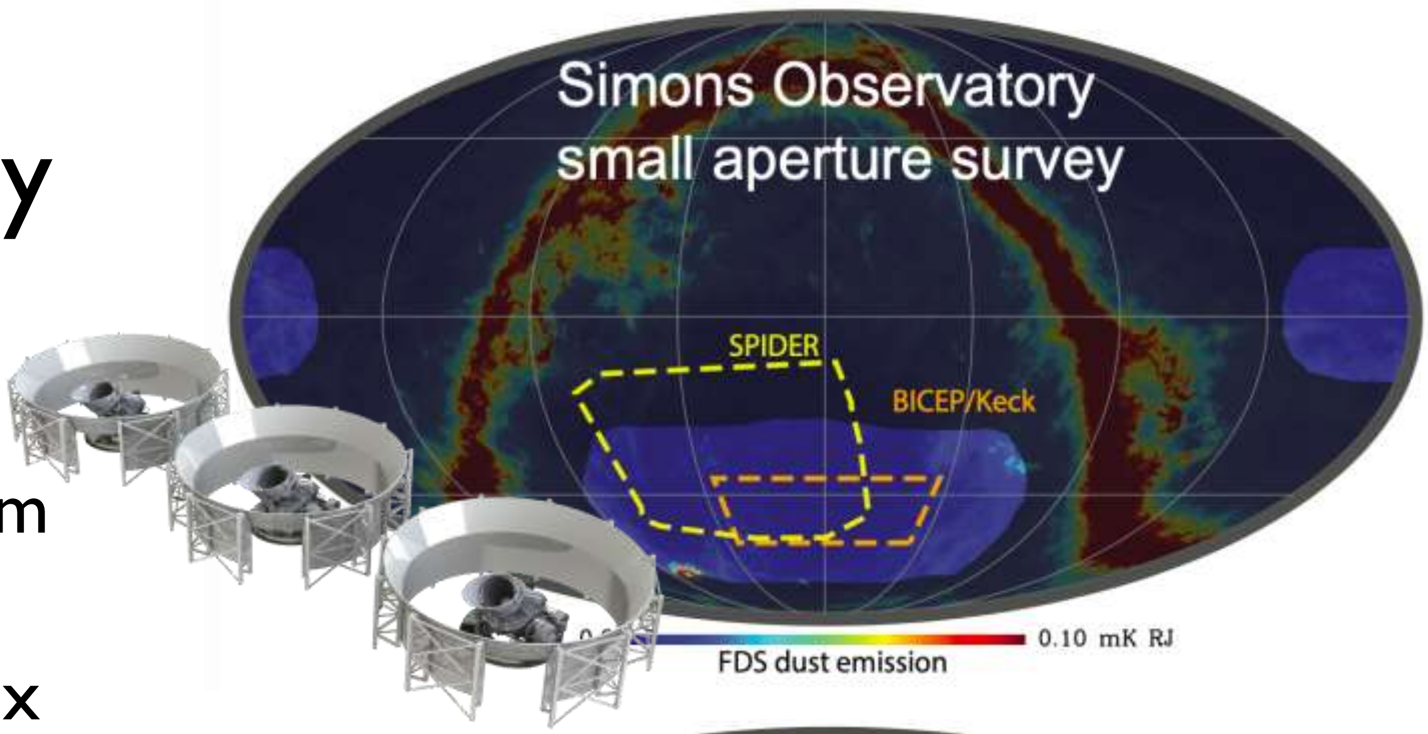
→ implement
feedback
ck resonances

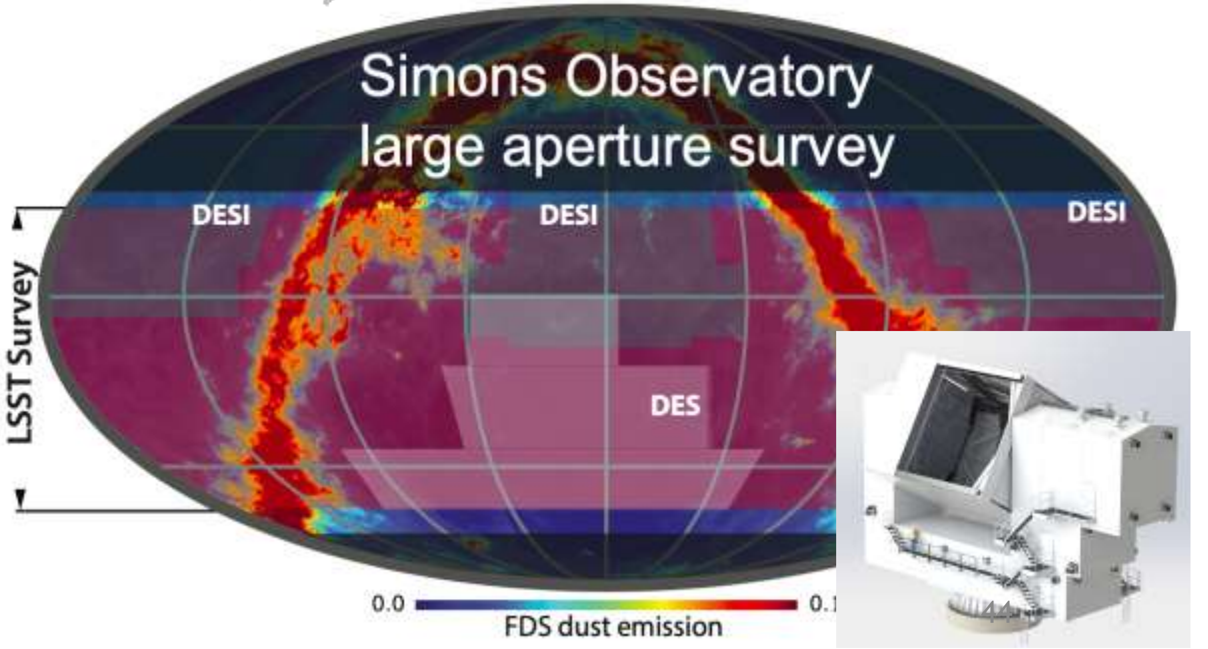
g **enables**

cl. CY) 2018, Proc. SPIE
et al. 2022, Rev. Sci. Inst.

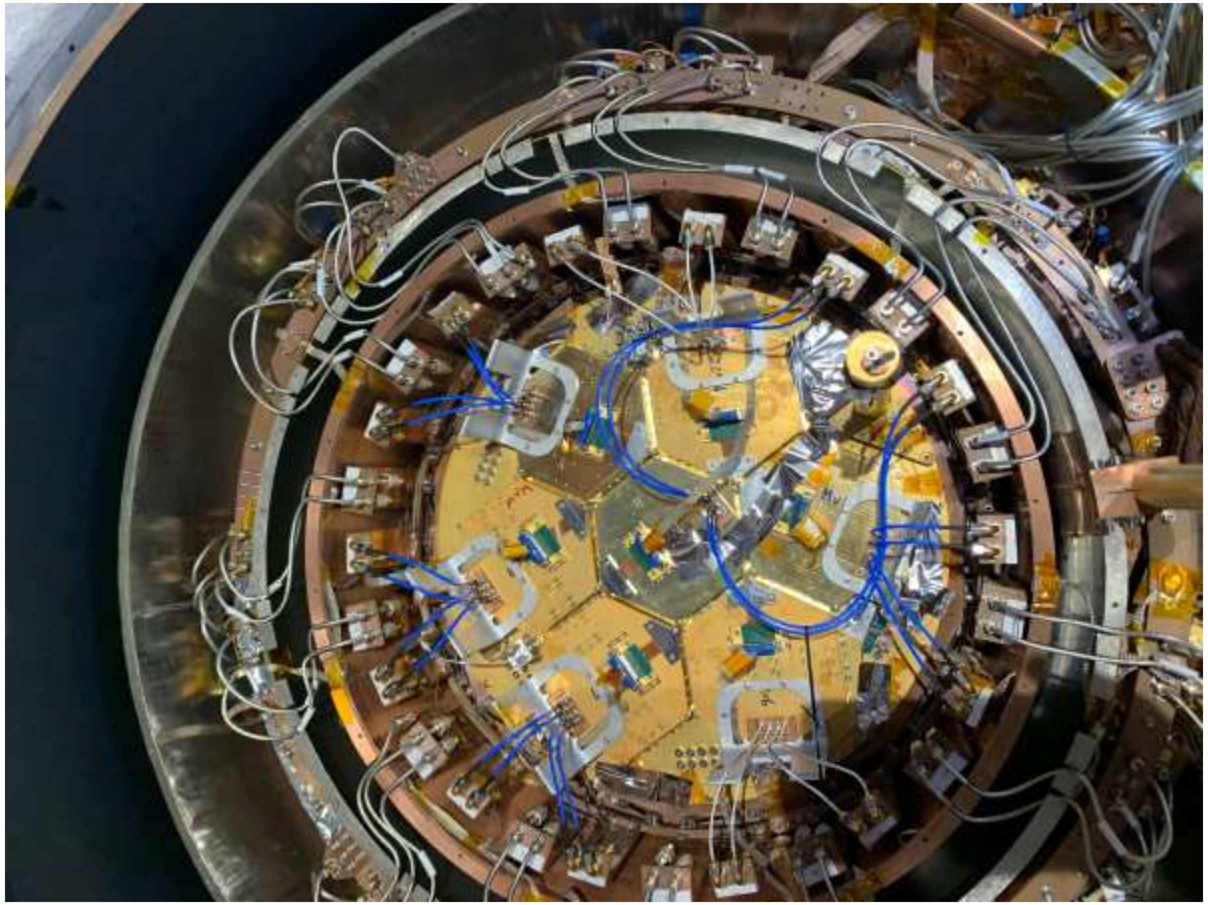
Simons Observatory

- 3 small-aperture and 1 large-aperture polarization-sensitive CMB telescopes observing from Chile
- First science-grade use of μmux for CMB, ~60,000 detectors total
- Broad range of science targets across multipole space
  - Baseline target σ(r)=0.003
- First light mid-2023!





SO SAT1 @ UCSD final cooldown now!



7 wafers = 13k detectors reading out simultaneously with SMuRF + µmux!

CMB-S4: the ultimate ground-based experiment

- 18 BICEP-style small-aperture telescopes observing from 30-300GHz for inflation search
- Large-aperture telescopes in Chile and South Pole for small-scale measurements
- Target: detect or constrain $\sigma(r)$= 0.001
- Observations to begin late 2020s

Conclusions

- BK18 places the tightest constraints to date on primordial gravitational waves from inflation
- We achieve this with compact, small aperture receivers and tightly-controlled systematics
- Beyond inflation there is rich physics in large-scale CMB polarization
- Future instruments will require new breakthroughs in cryogenic detector and readout technology to achieve requisite camera densities
- There is much to look forward to! Stay tuned!

Photo: G. Hall