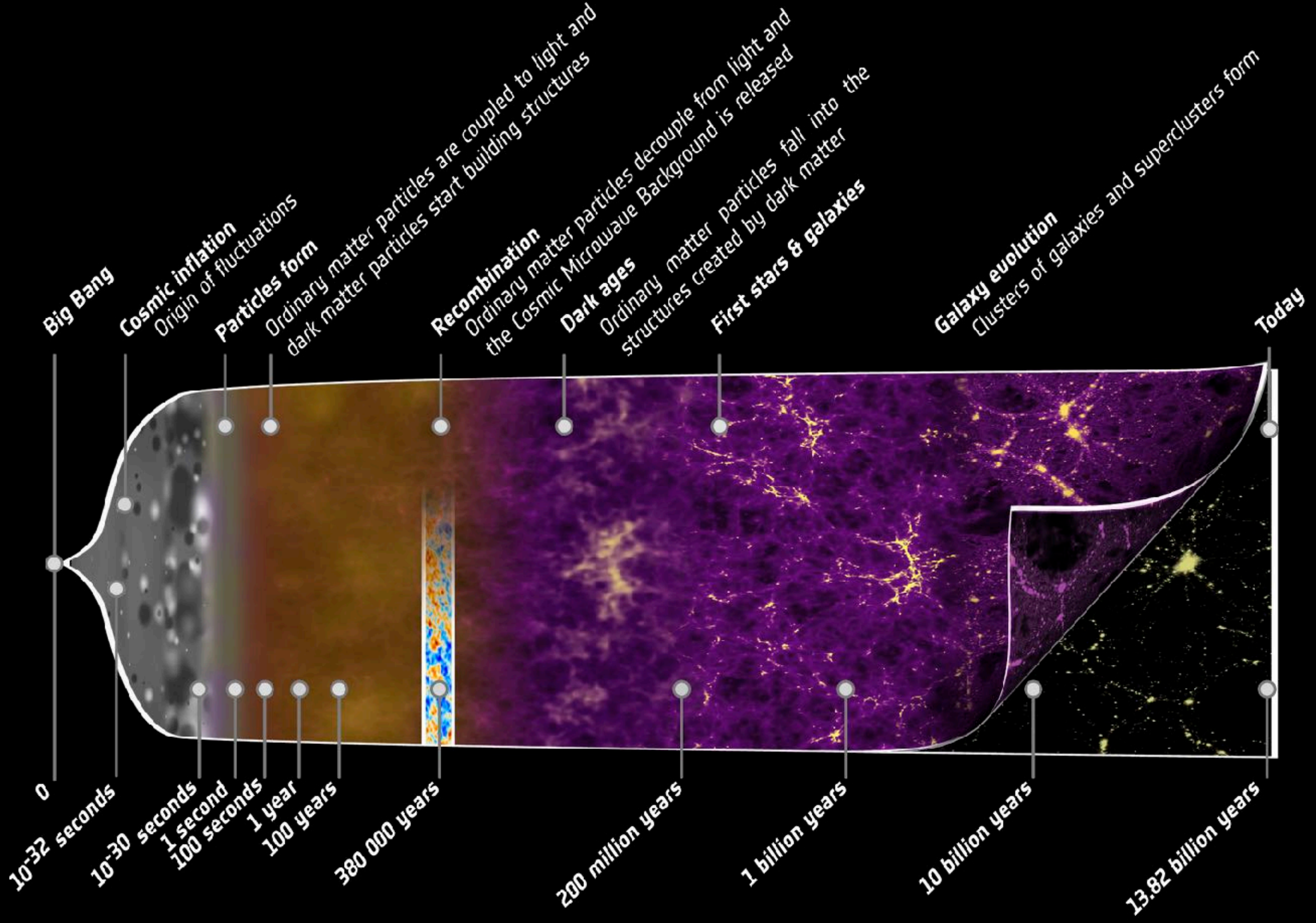
Investigating cosmic origin and evolution with the Cosmic Microwave Background

Zeeshan Ahmed, SLAC/Stanford

PPC 2024, Hyderabad, October 17, 2024

Photo by Keith Vanderlinde

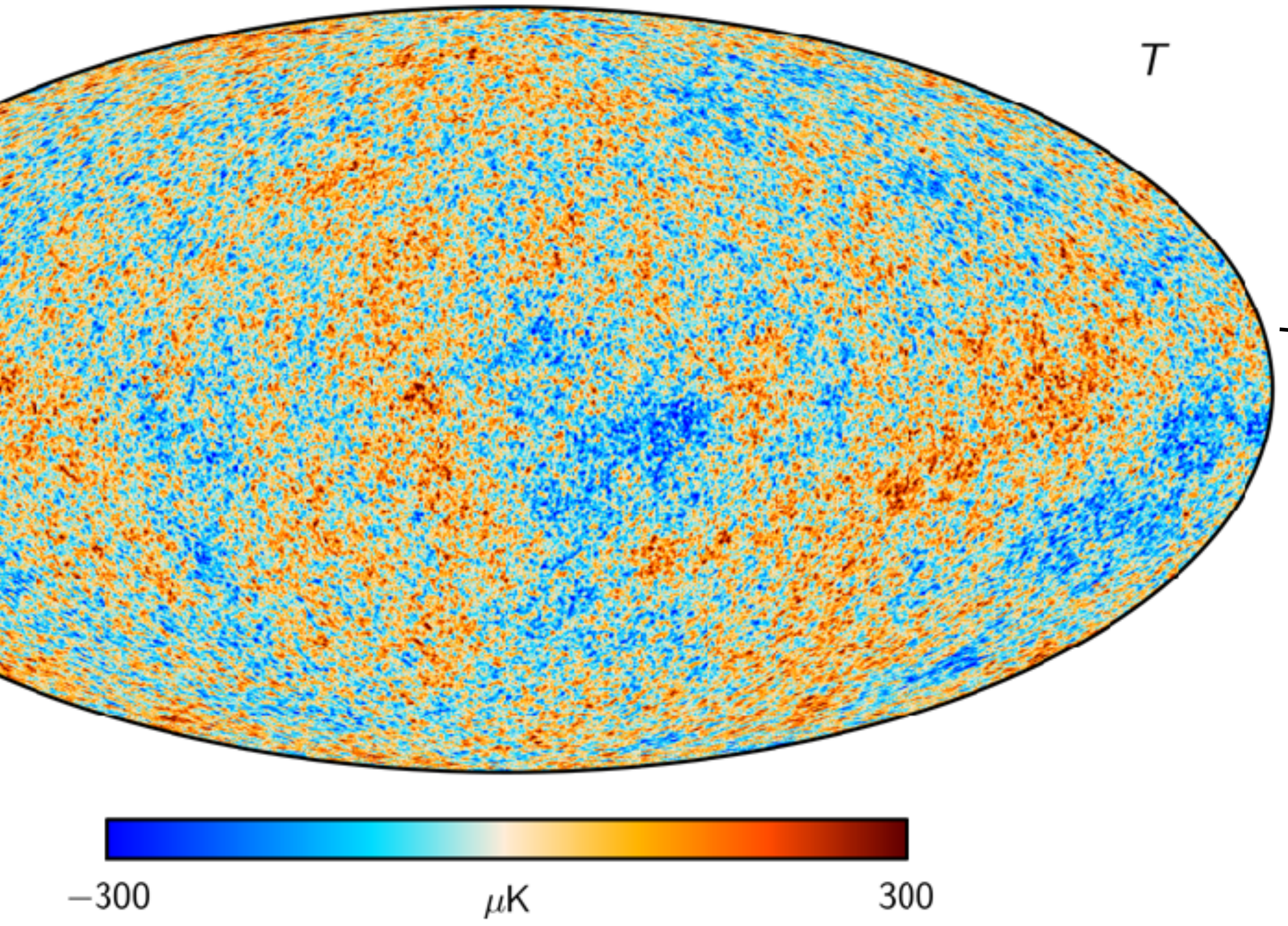


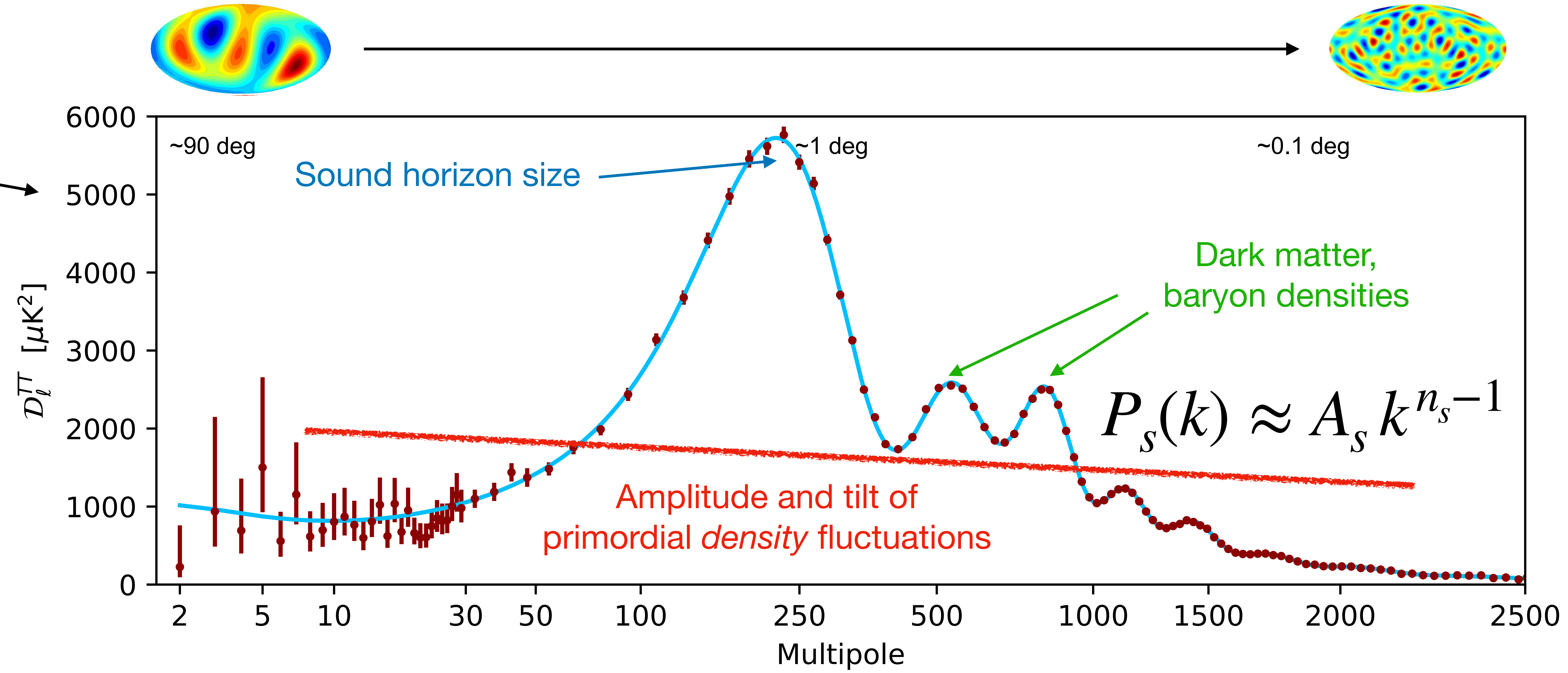
Redshift (z) ~1100 20 6 0.3 0

ESA/Planck

Statistical information from CMB

Suggests primordial seeds of structure





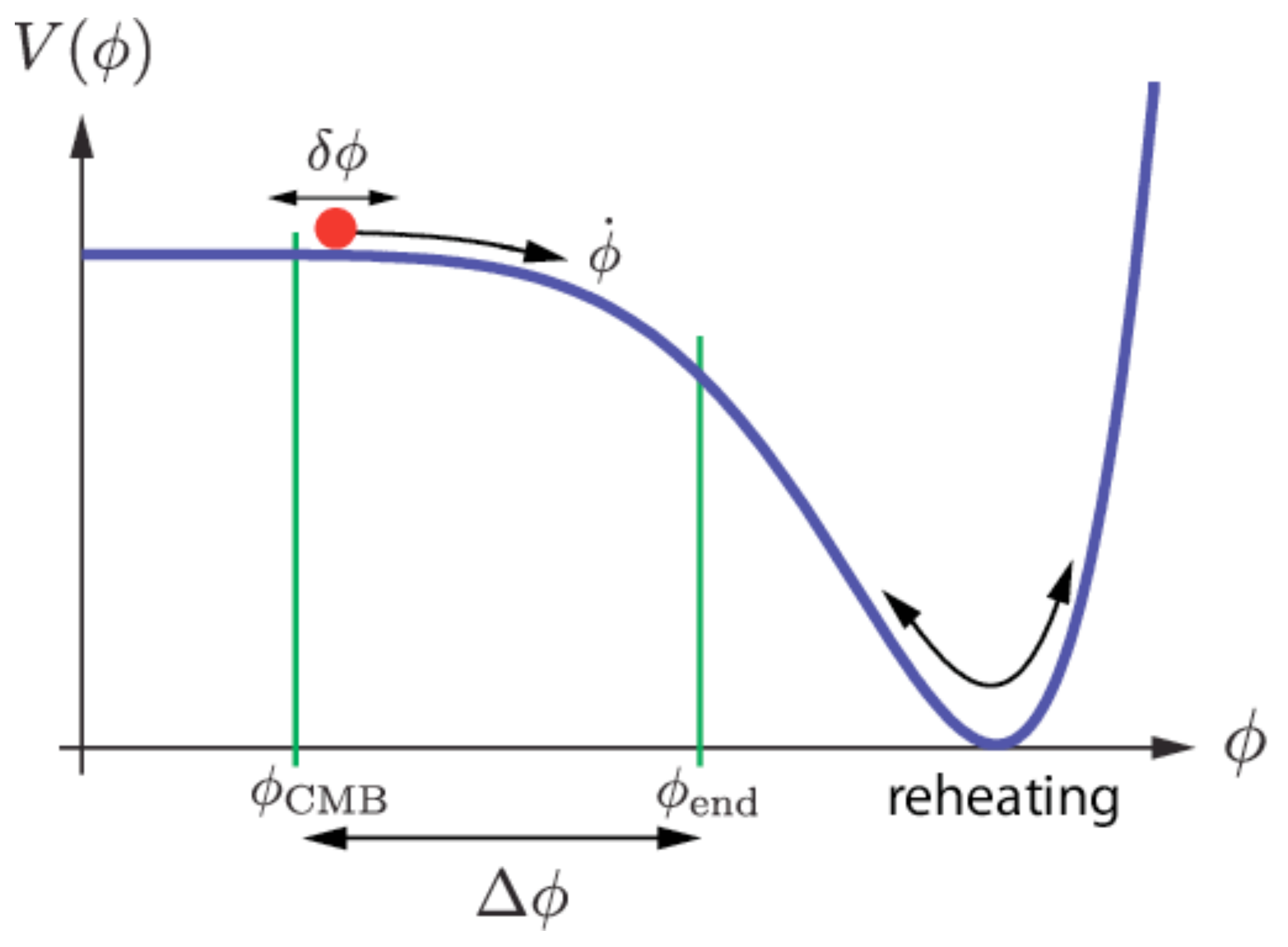
θ_*	Sound horizon (angular size)
$\Omega_c h^2$	Cold Dark Matter density
$\Omega_b h^2$	Baryon density
A_s	Primordial Density Spectrum Amplitude
n_s	Spectral index
τ	Optical depth to reionization

We measure a simple, flat power spectrum for primordial fluctuations. When evolved forward, it matches the matter power spectrum observed today.

Figures from Planck Legacy Release 2018

Inflation seeds primordial structure

Scalar field(s) for exponential expansion



Figures from Baumann/Peiris 2009, Astronomy Today and Planck 2018

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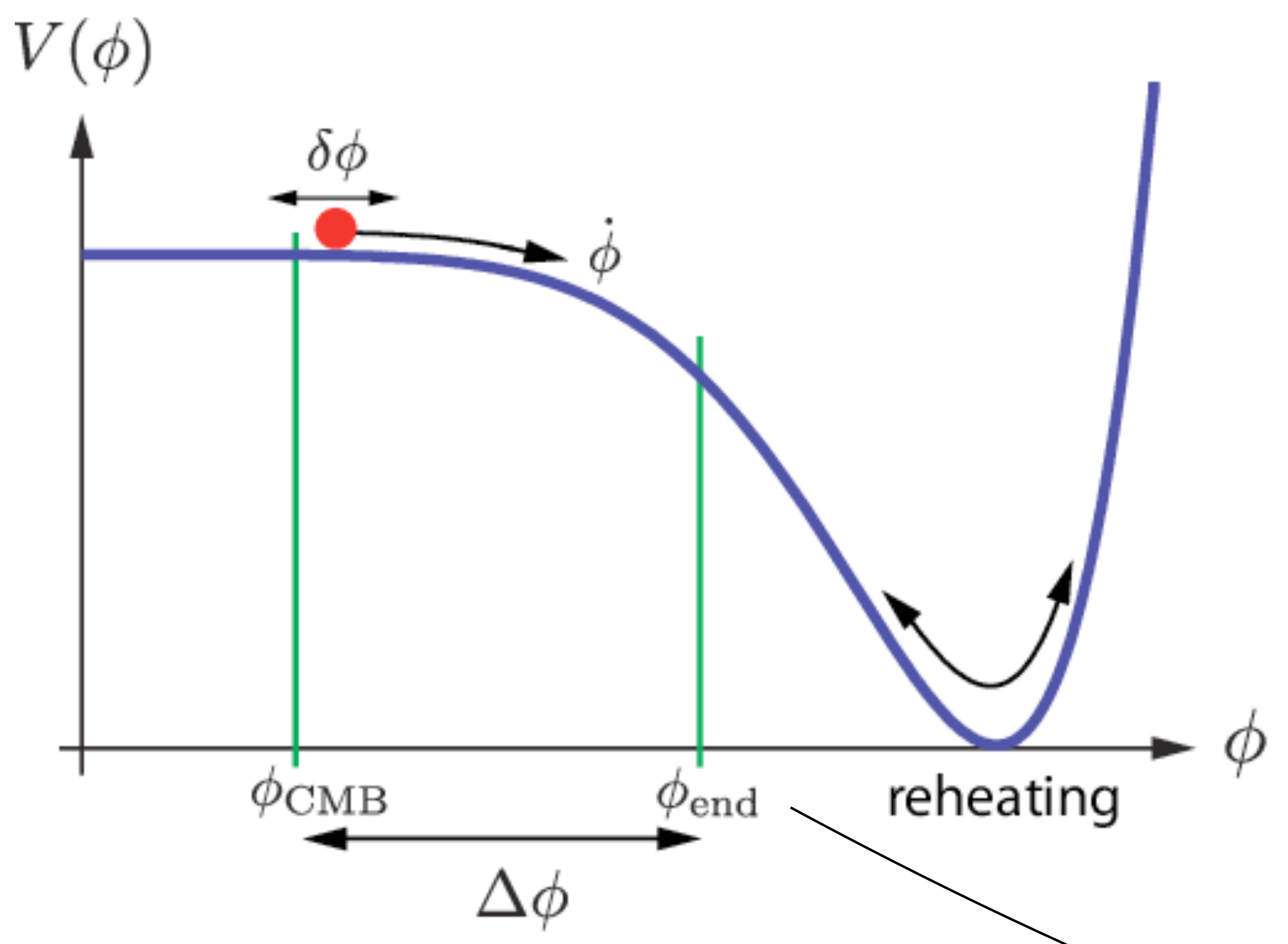
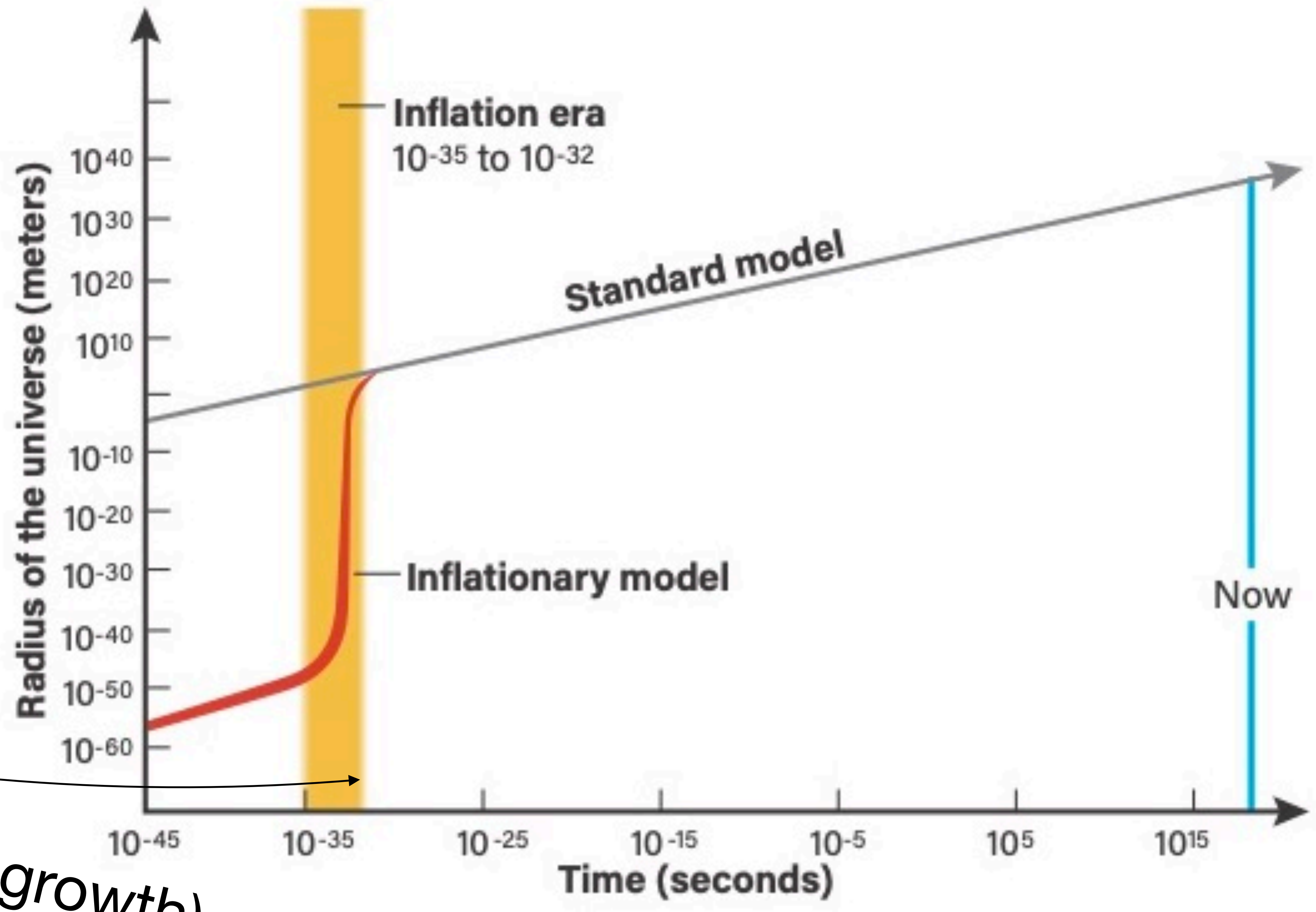




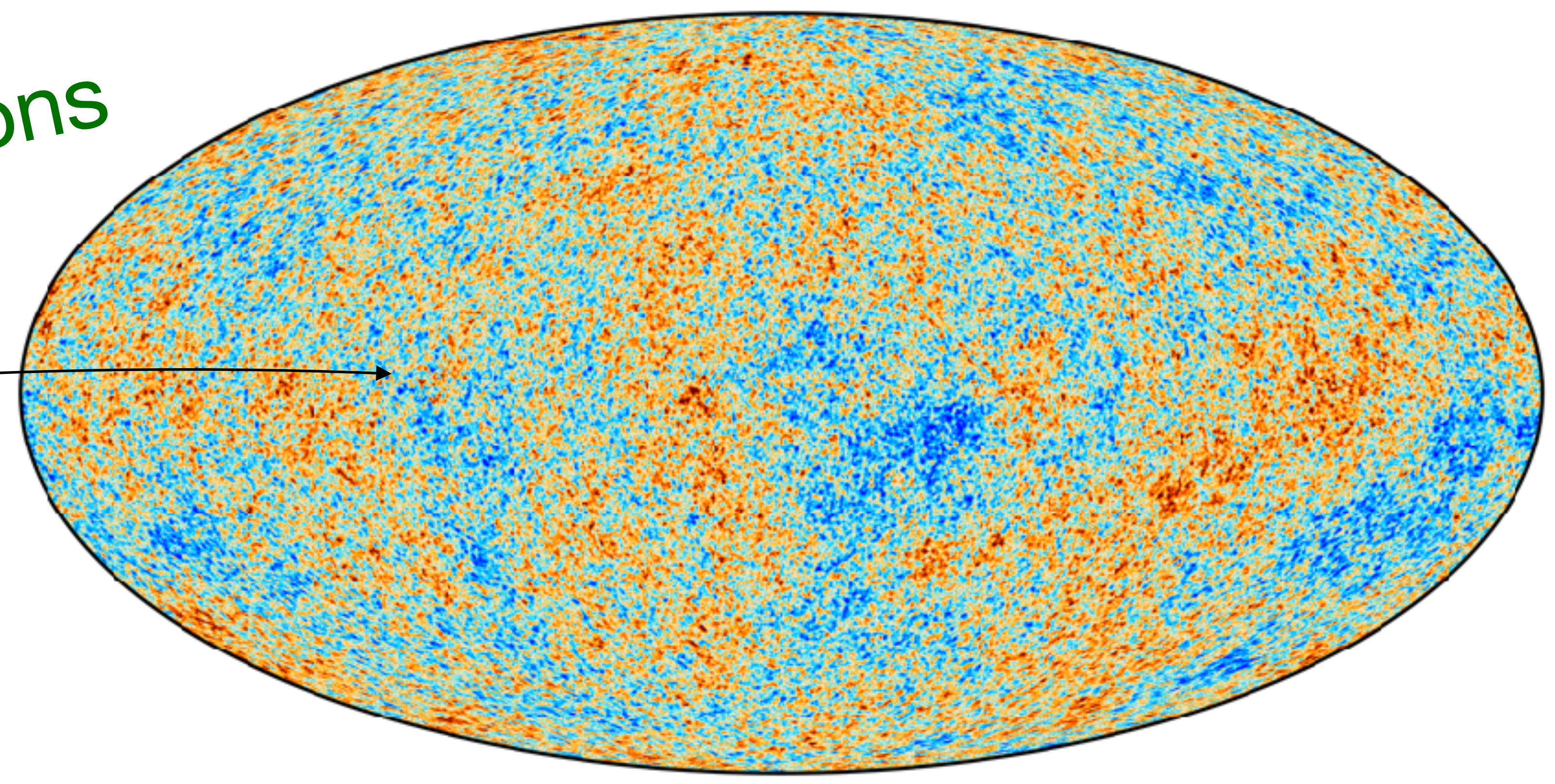
While "ball rolls slowly", $a \propto e^{Ht}$ (exponential growth)

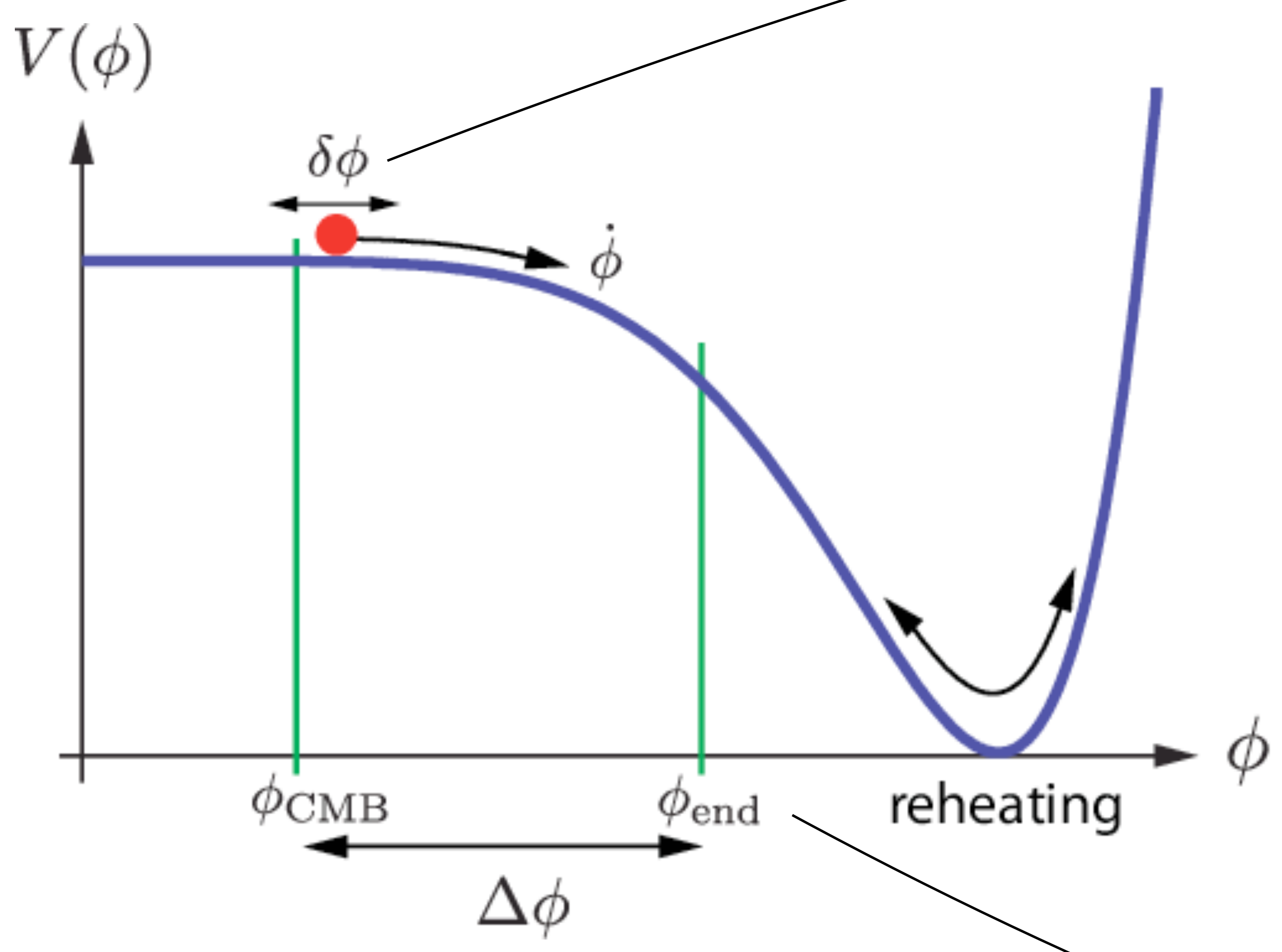
Figures from Baumann/Peiris 2009, Astronomy Today and Planck 2018

Inflation seeds primordial structure

Scalar field(s) for exponential expansion

Quantum fluctuations of ϕ source primordial density fluctuations





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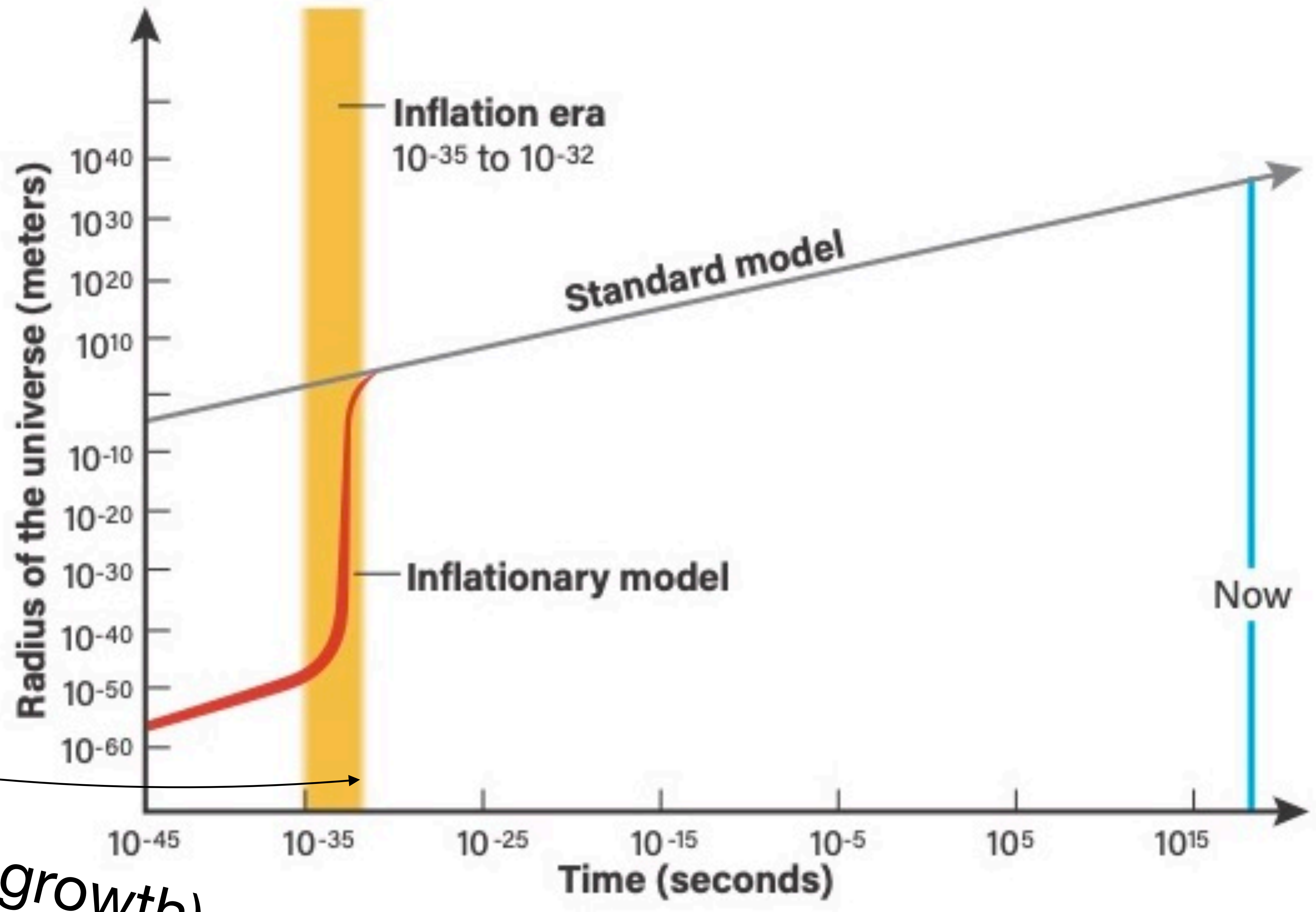
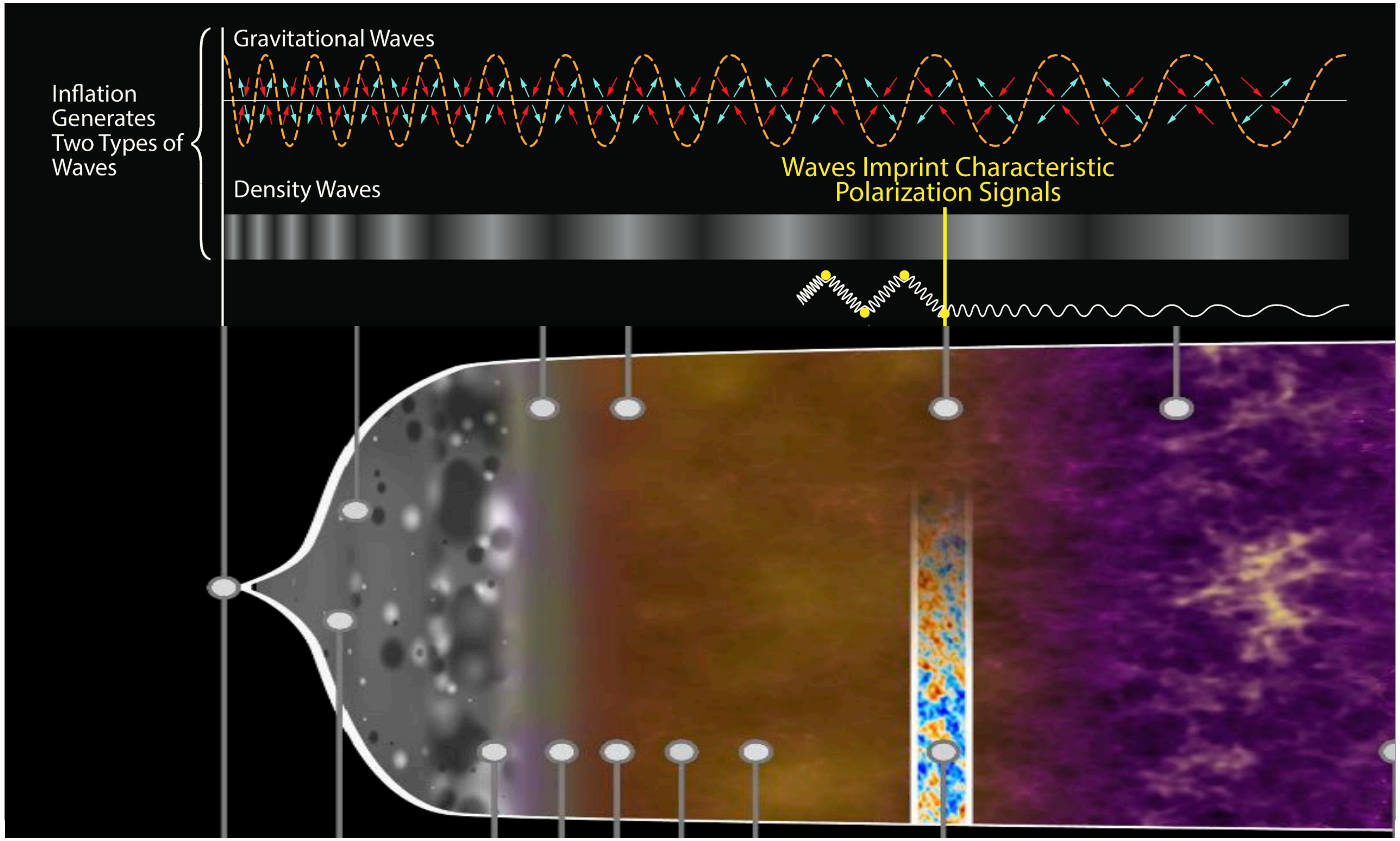


Figures from Baumann/Peiris 2009, Astronomy Today and Planck 2018

Inflation models generically predict primordial gravitational waves (PGWs)



Figures from ESA/Planck and JPL/BICEP

Tensor/GW

$$P_t(k) \approx A_t k^{n_t}$$

$$P_s(k) \approx A_s k^{n_s - 1}$$

Scalar/ density waves

Tensor-to-scalar Ratio

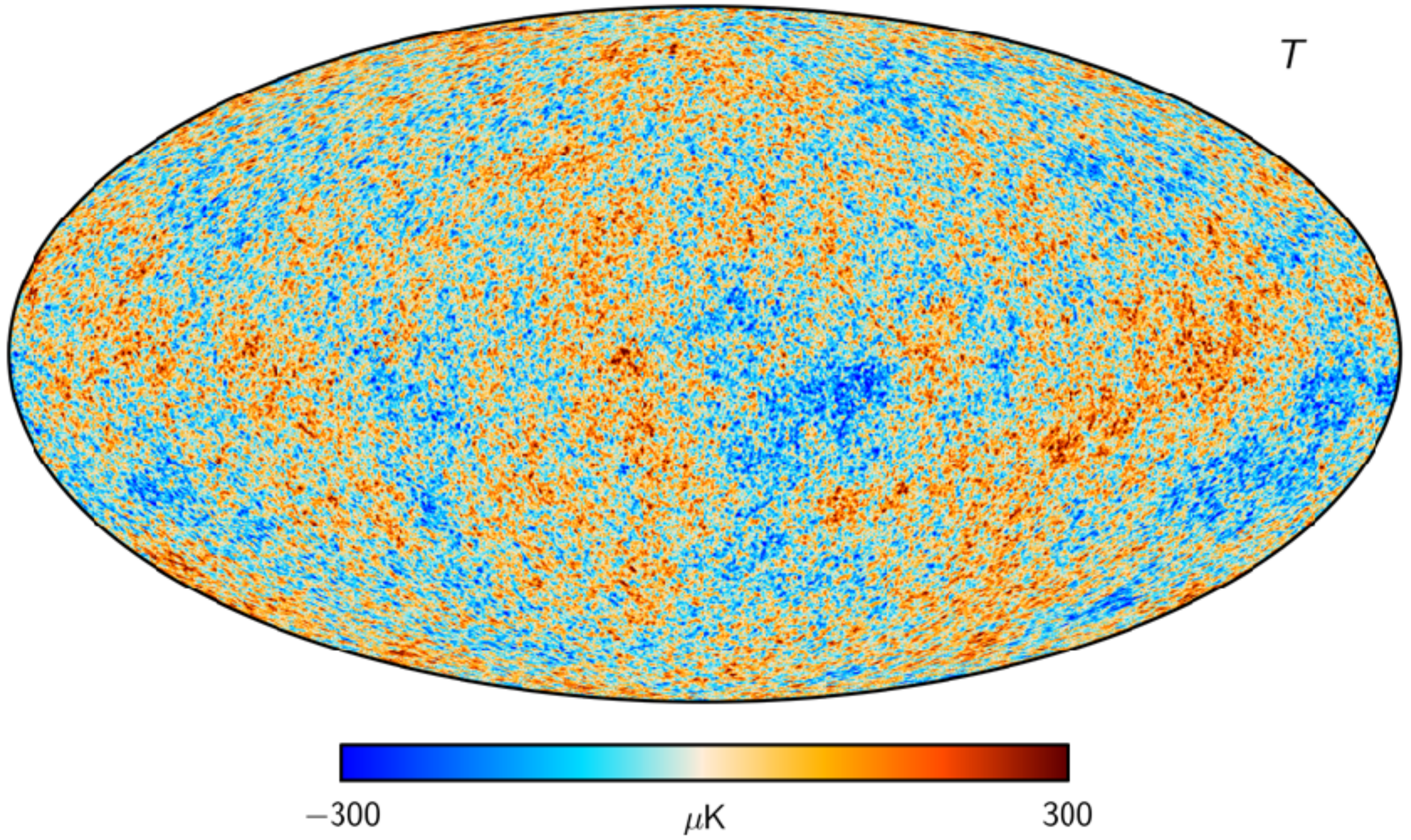
$$r \equiv \frac{A_t}{A_s}$$

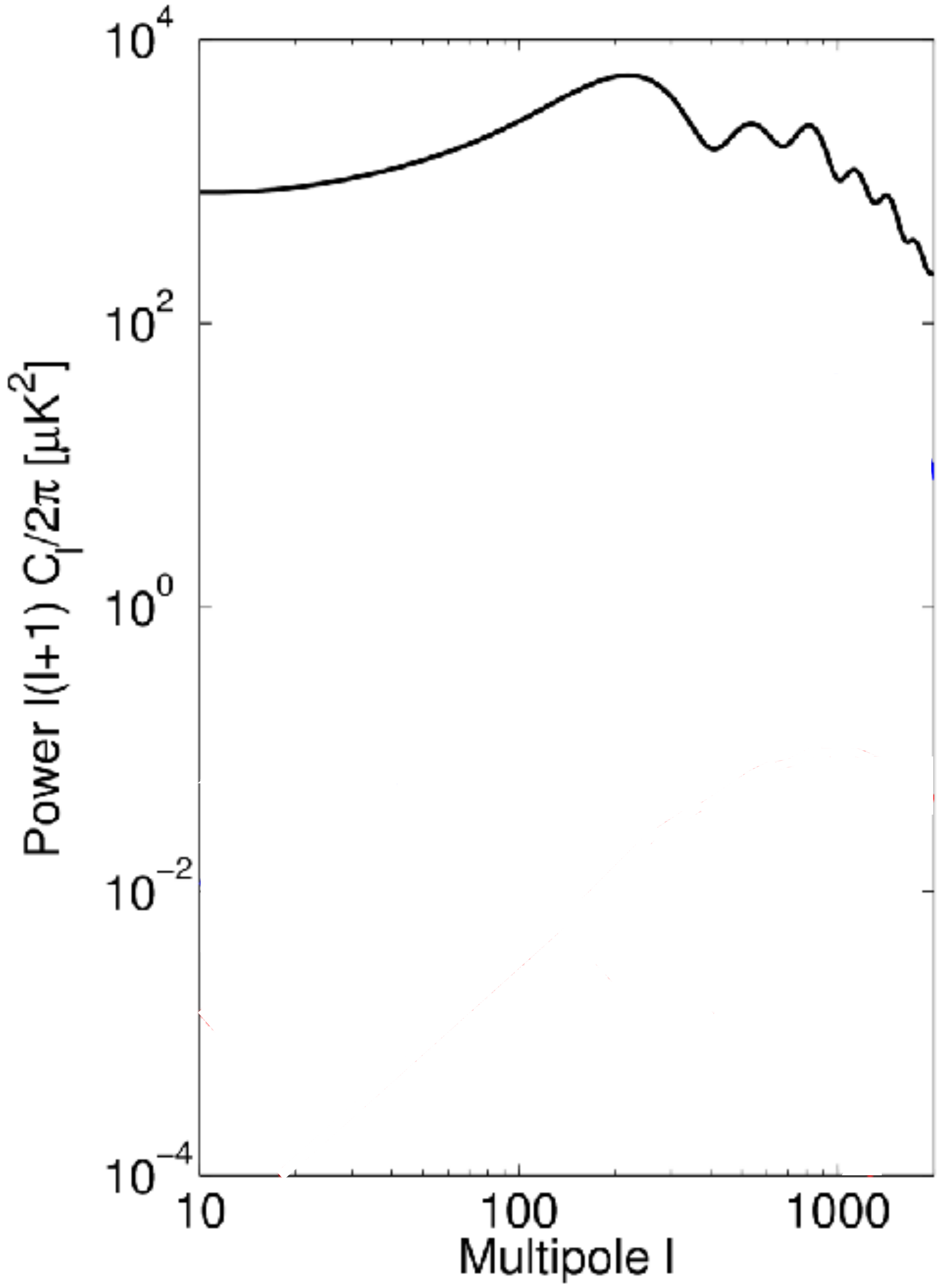
Inflation energy scale

$$V^{1/4} = 1.04 \times 10^{16} \text{GeV} \left(\frac{r}{0.01} \right)^{1/4}$$

Search for inflation by looking for PGWs

Imprinted into polarization of CMB light





Figures from
Planck 2018 and BICEP

Search for inflation by looking for PGWs

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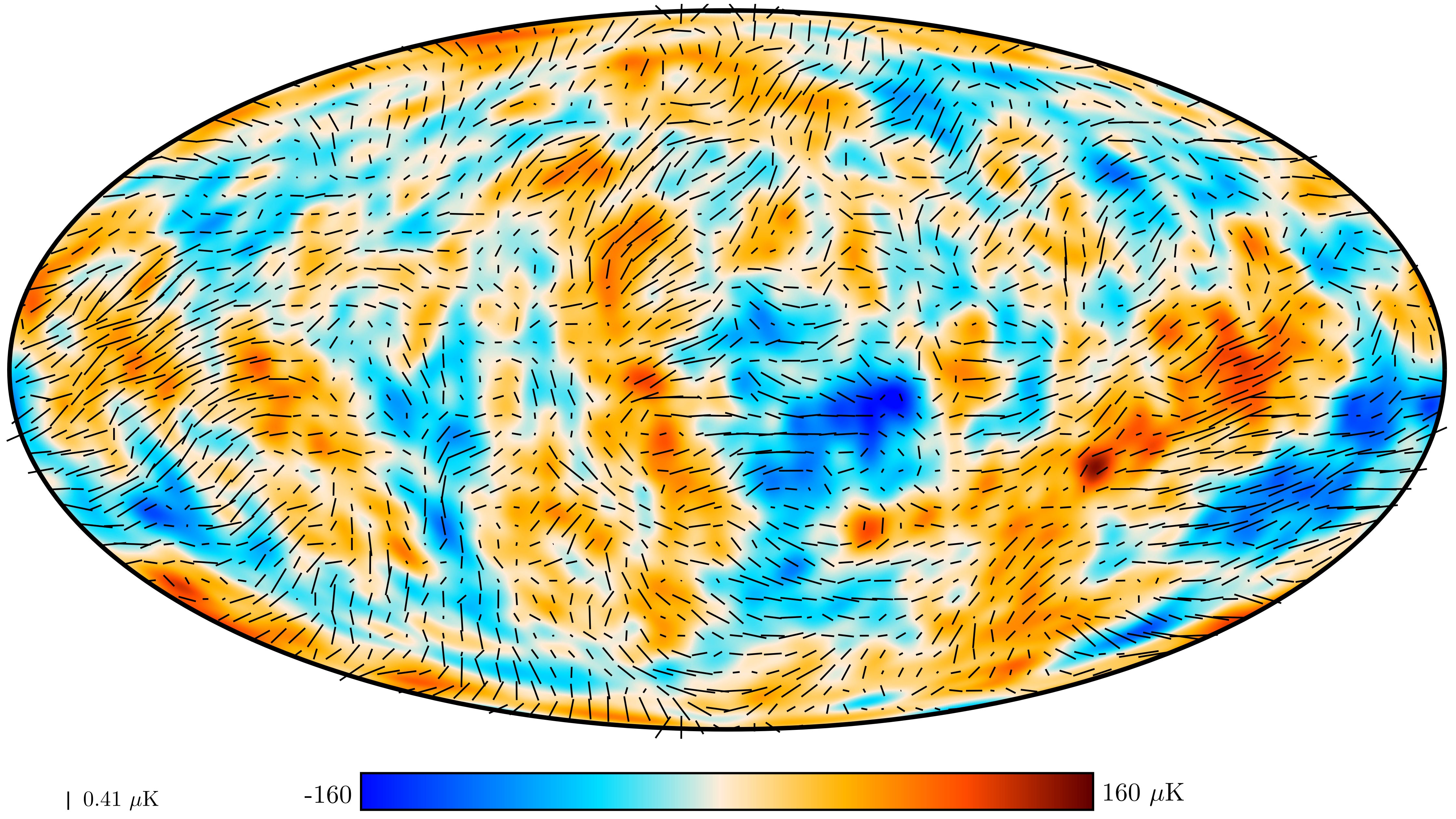

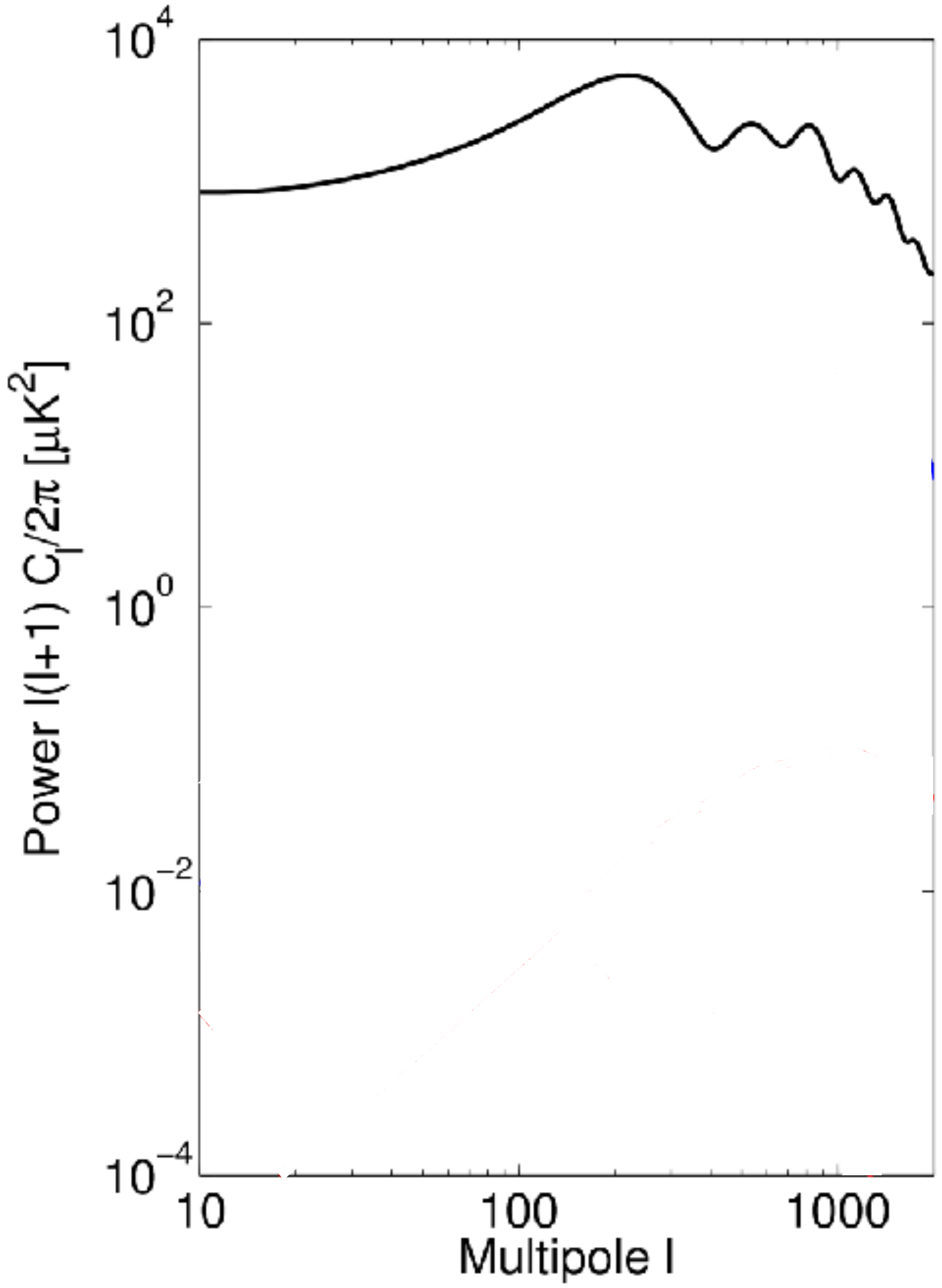

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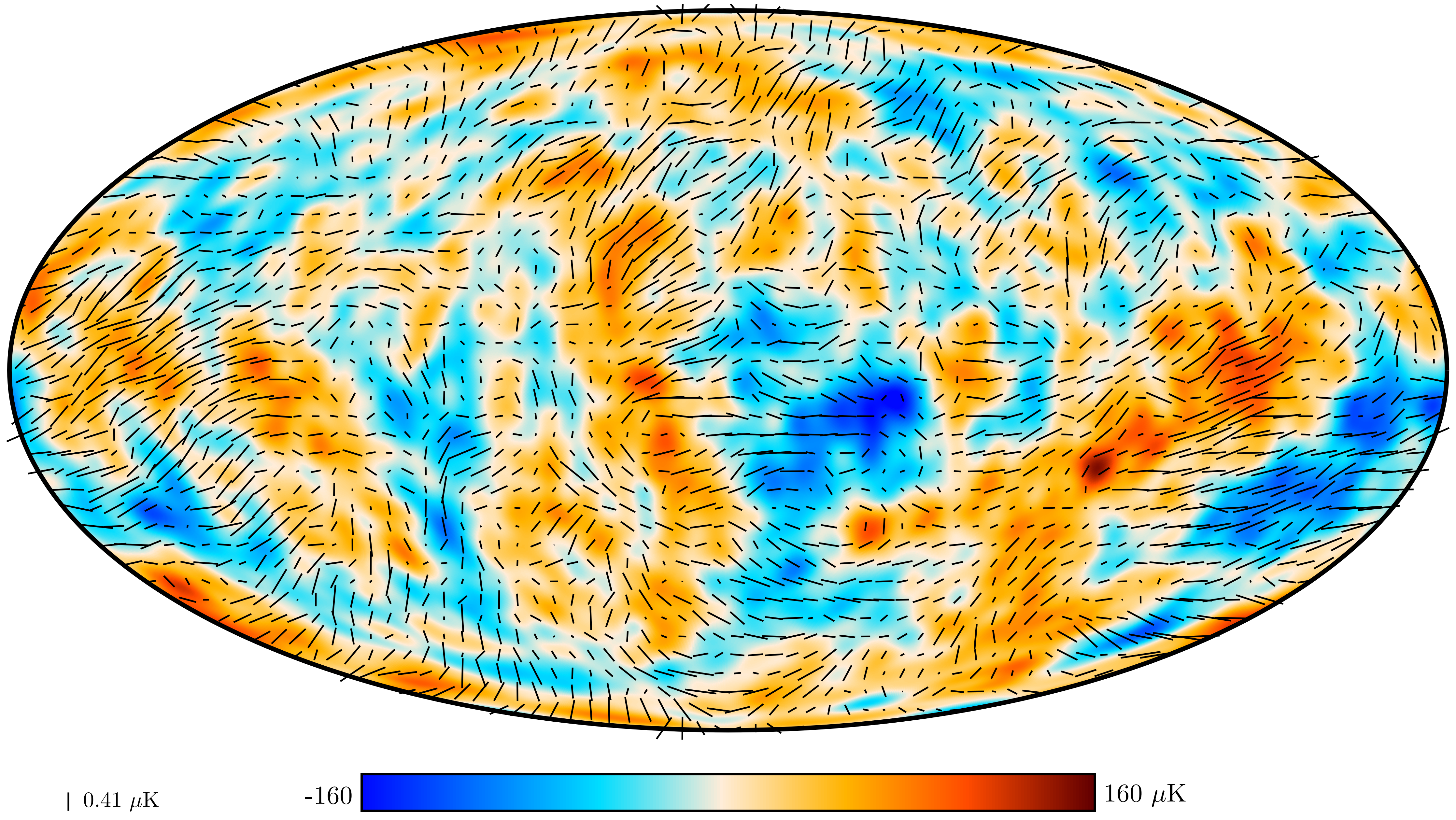

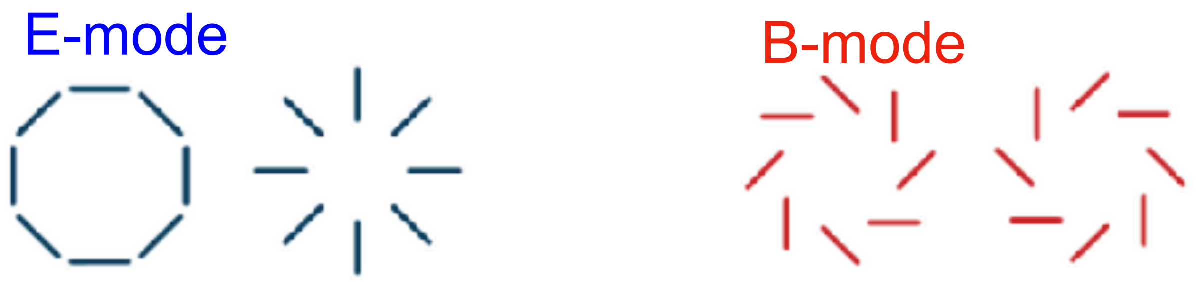

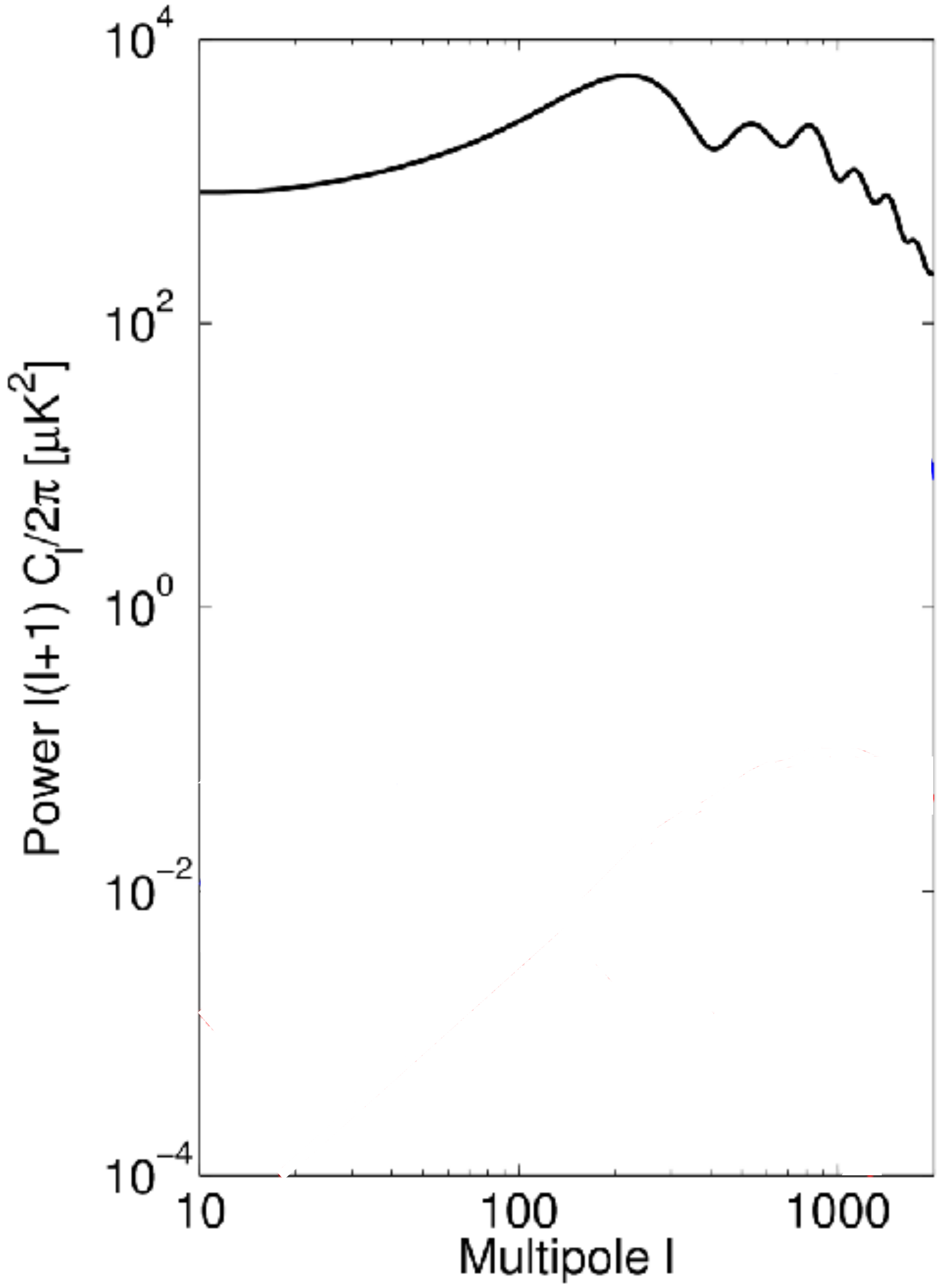

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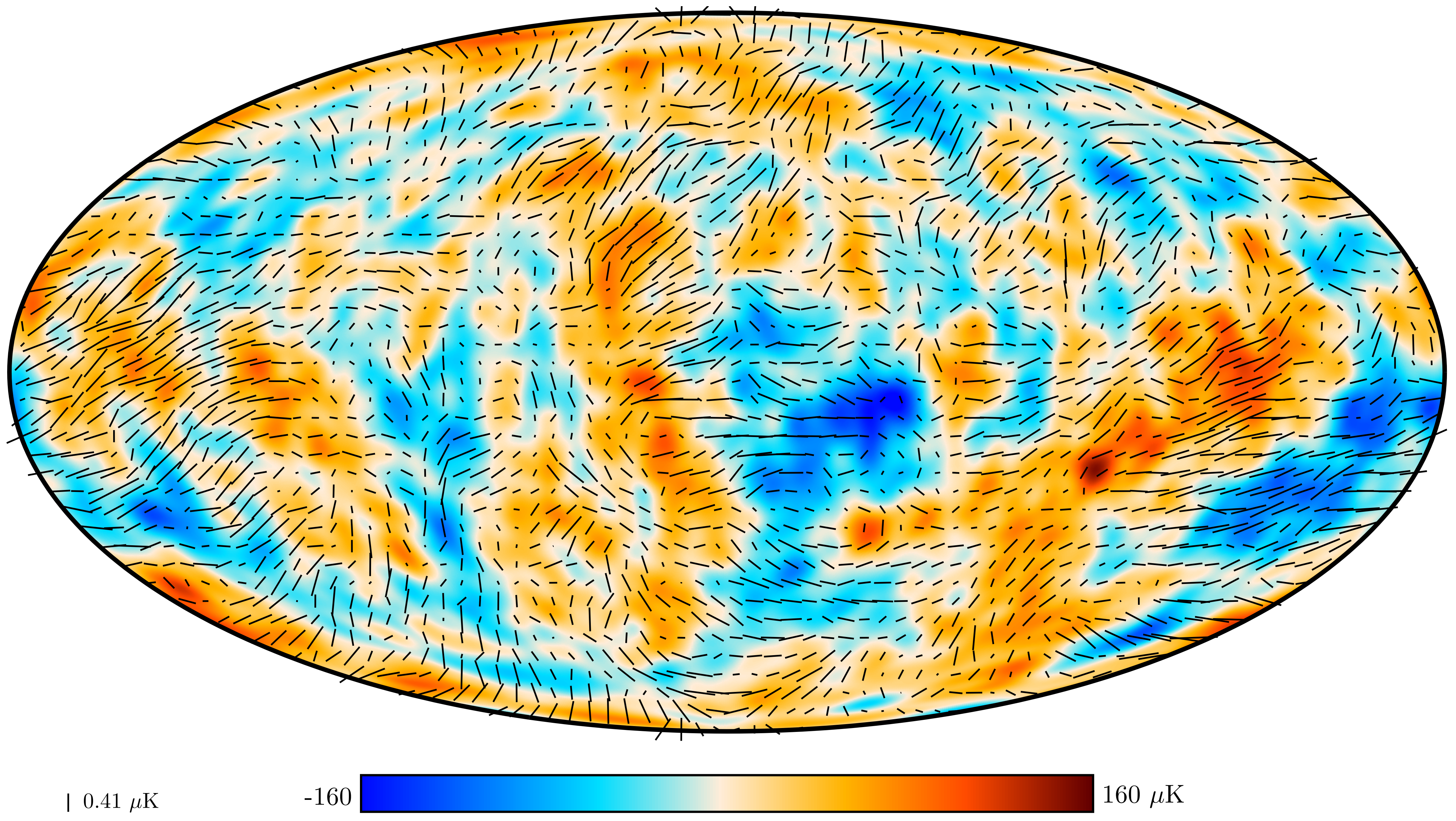
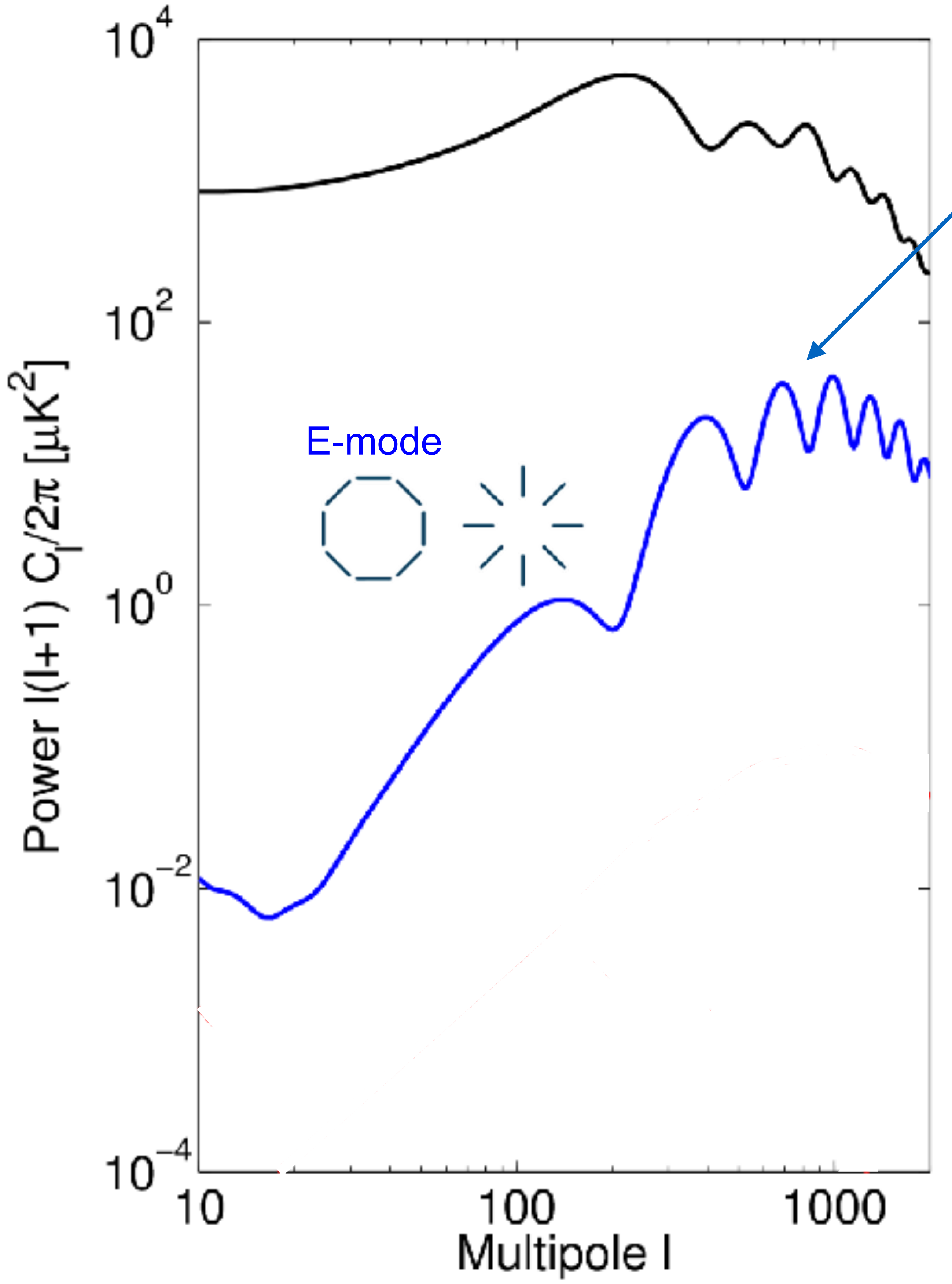


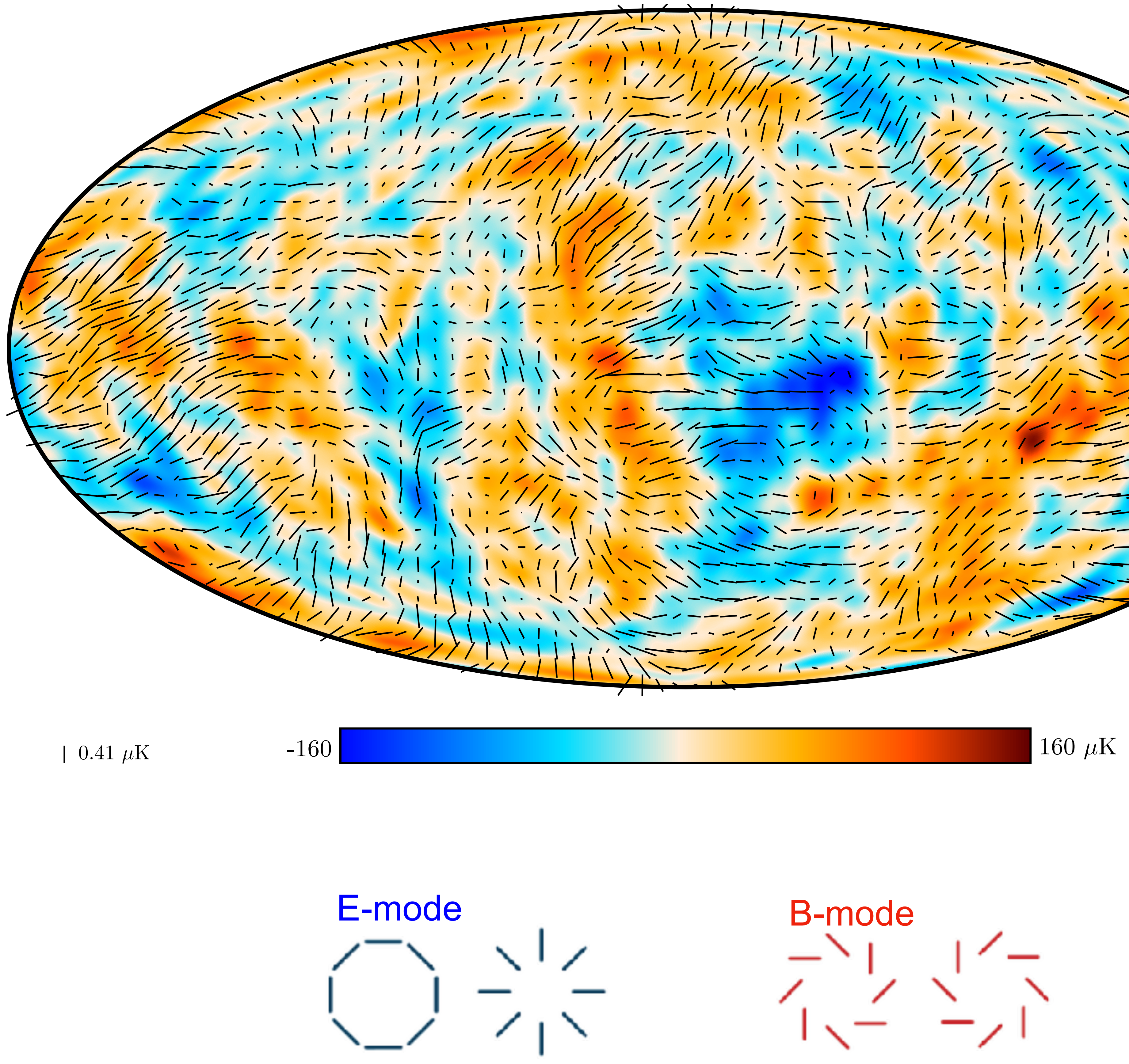


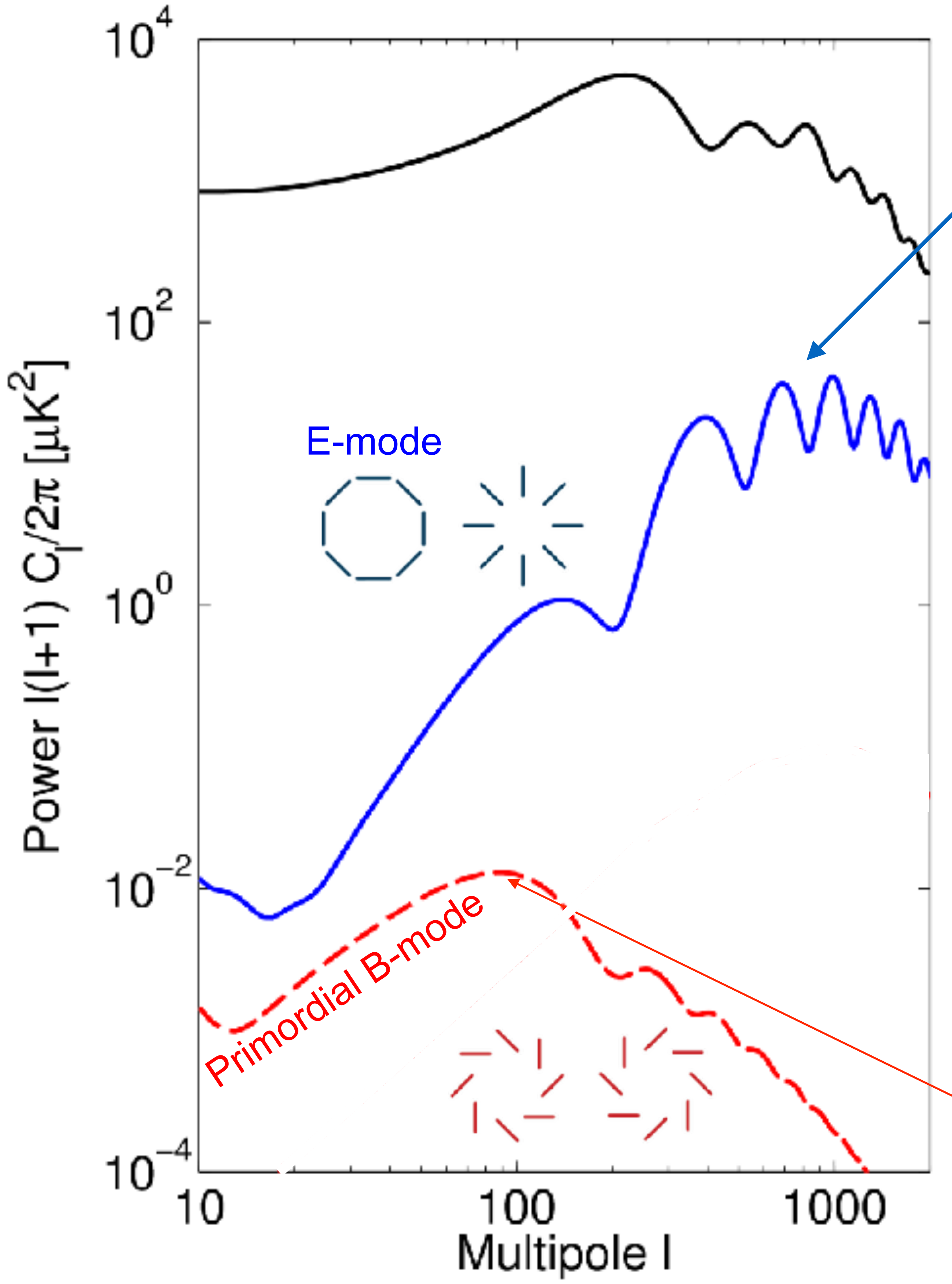
In standard ΛCDM only E-modes are present when CMB released. Help constrain ΛCDM, light relics

Figures from Planck 2018 and BICEP

Search for inflation by looking for PGWs

Imprinted into polarization of CMB light





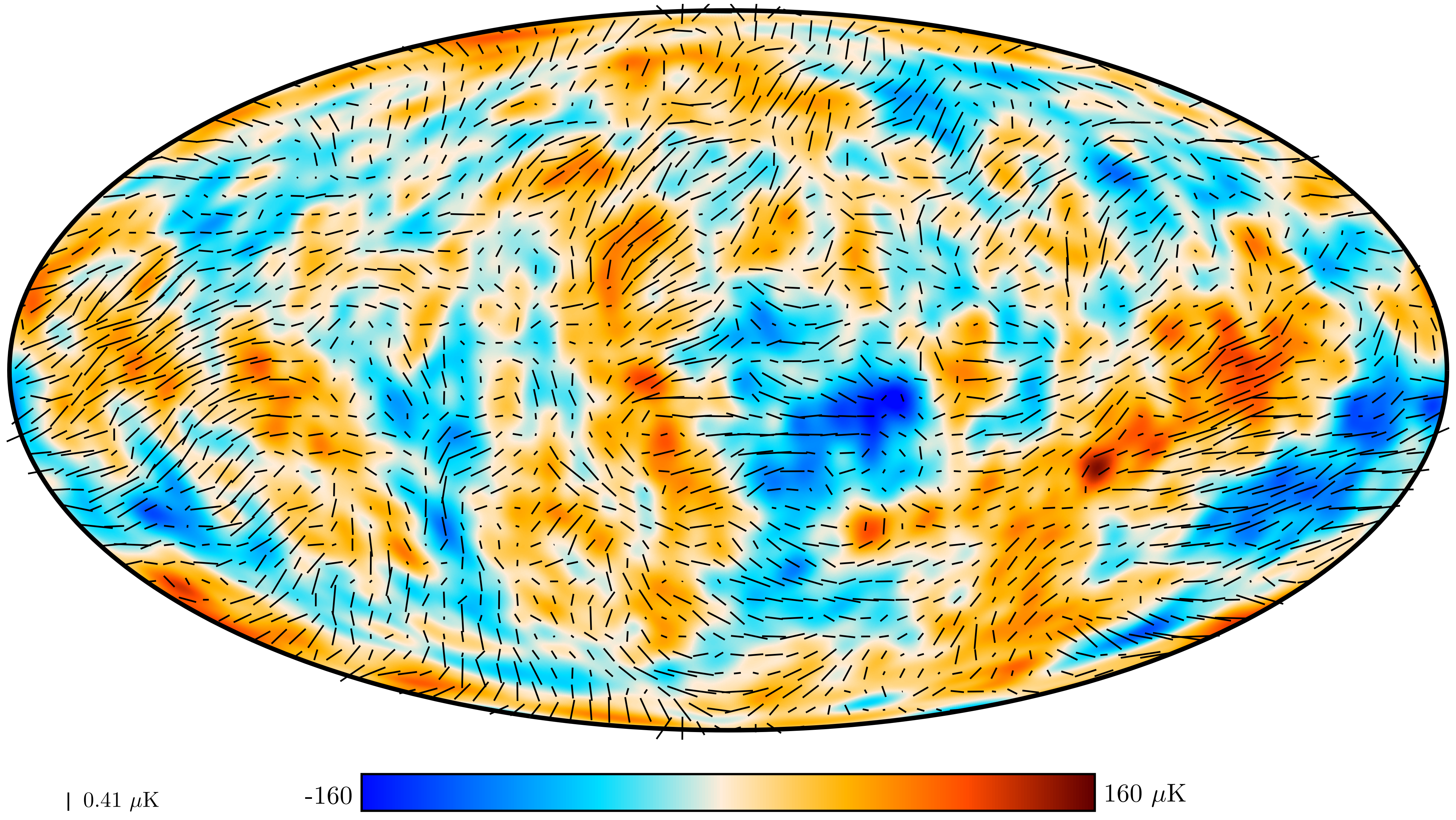
In standard ΛCDM only E-modes are present when CMB released. Help constrain ΛCDM, light relics

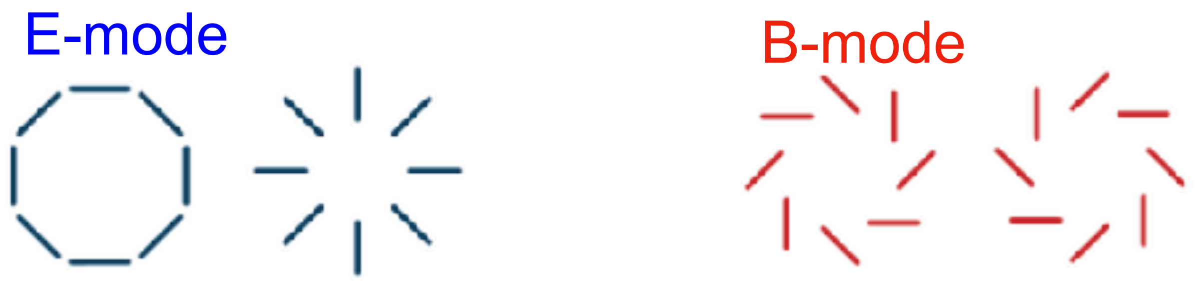
Primordial gravitational waves produce B-modes peaking at degree scales. Amplitude set by r

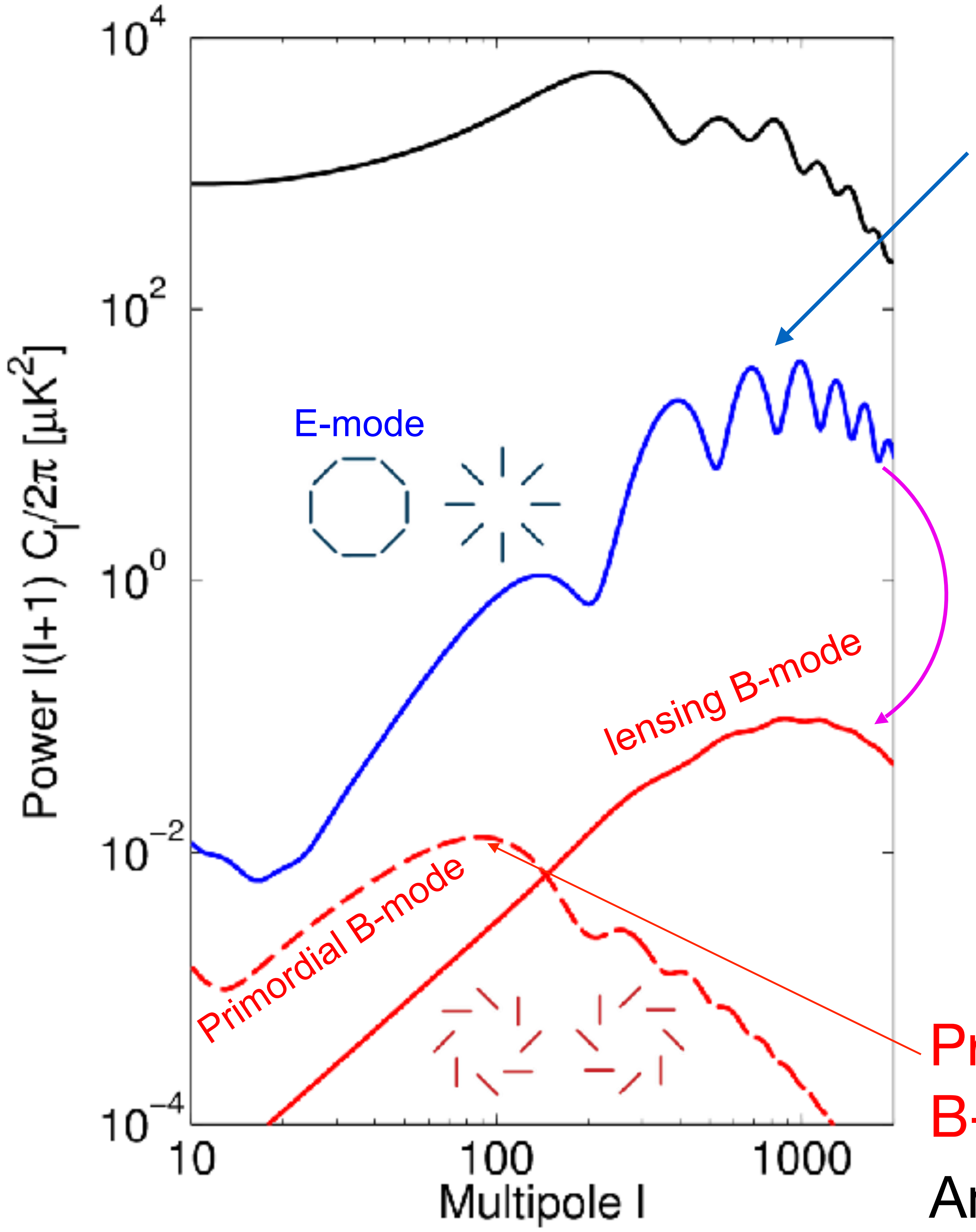
Figures from Planck 2018 and BICEP

Search for inflation by looking for PGWs

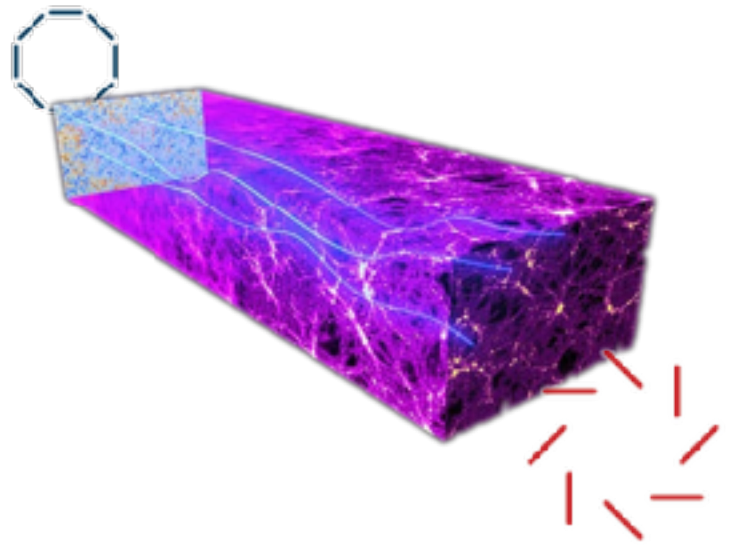
Imprinted into polarization of CMB light







In standard ΛCDM only E-modes are present when CMB released. Help constrain ΛCDM, light relics



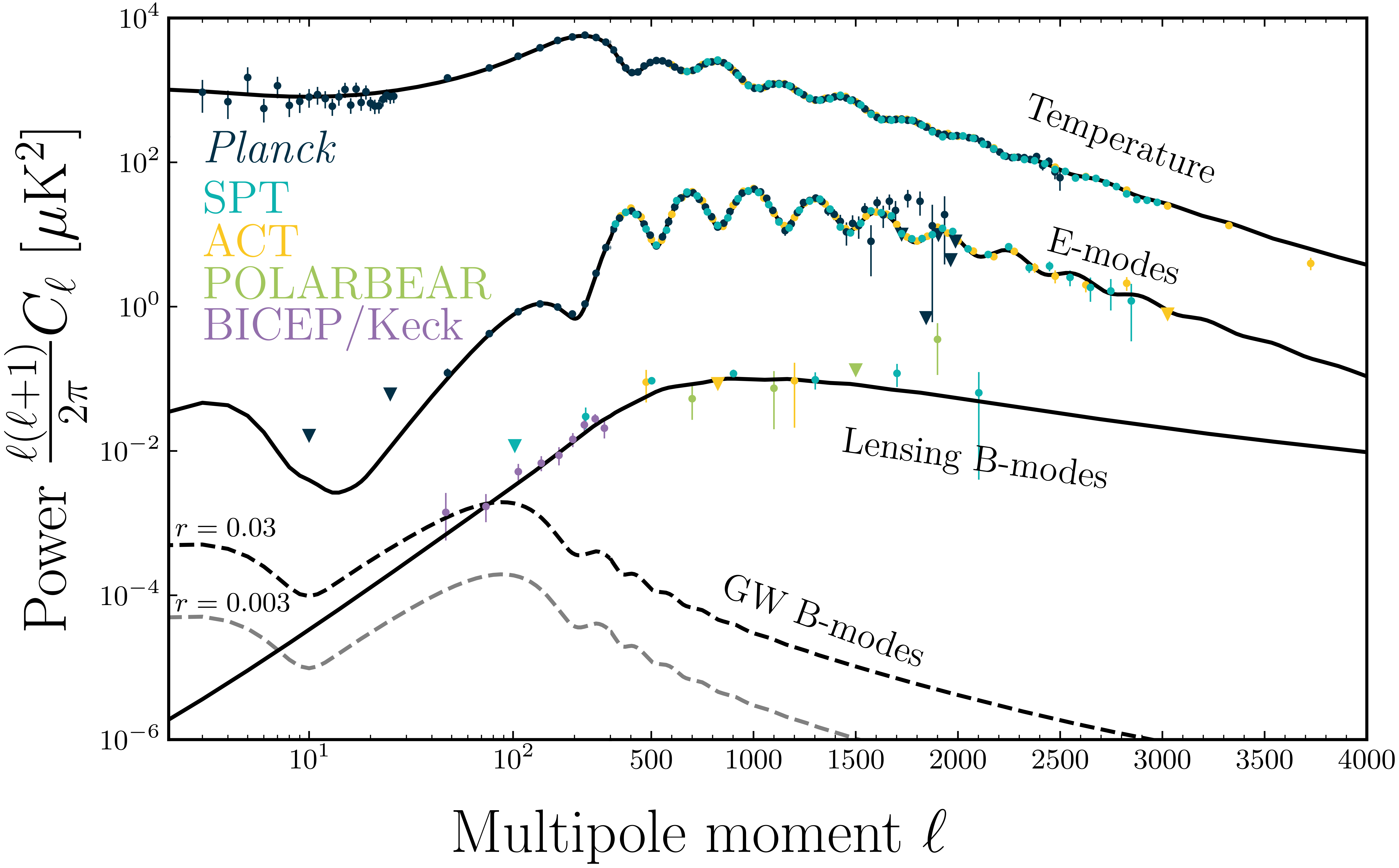
Lensing by intervening structure converts some to B-modes

Primordial gravitational waves produce B-modes peaking at degree scales.

Amplitude set by r

Figures from Planck 2018 and BICEP

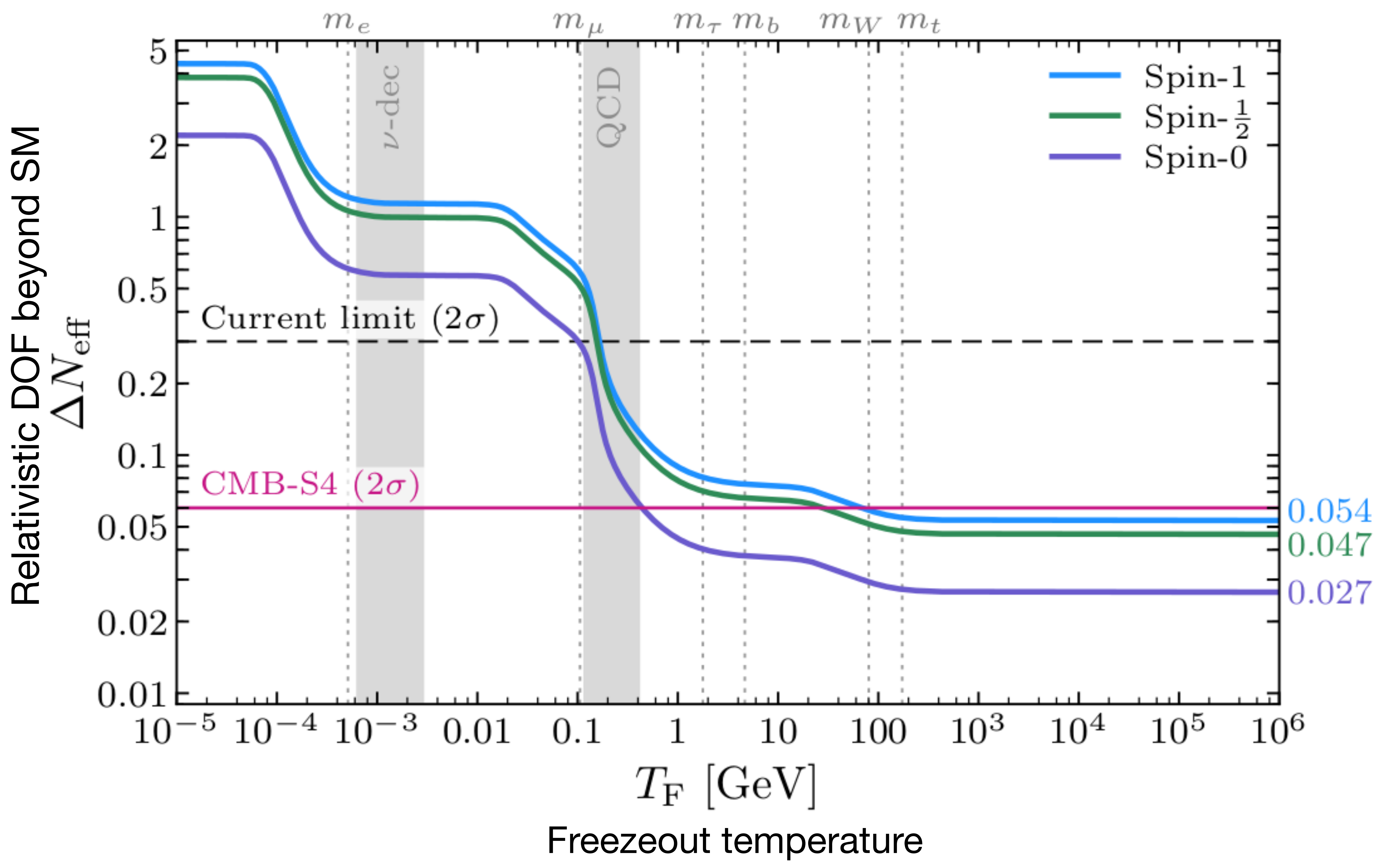
State of CMB measurements and constraints



Plot from Federico Bianchini

Light relics

Relativistic thermal particles in early universe imprint the CMB



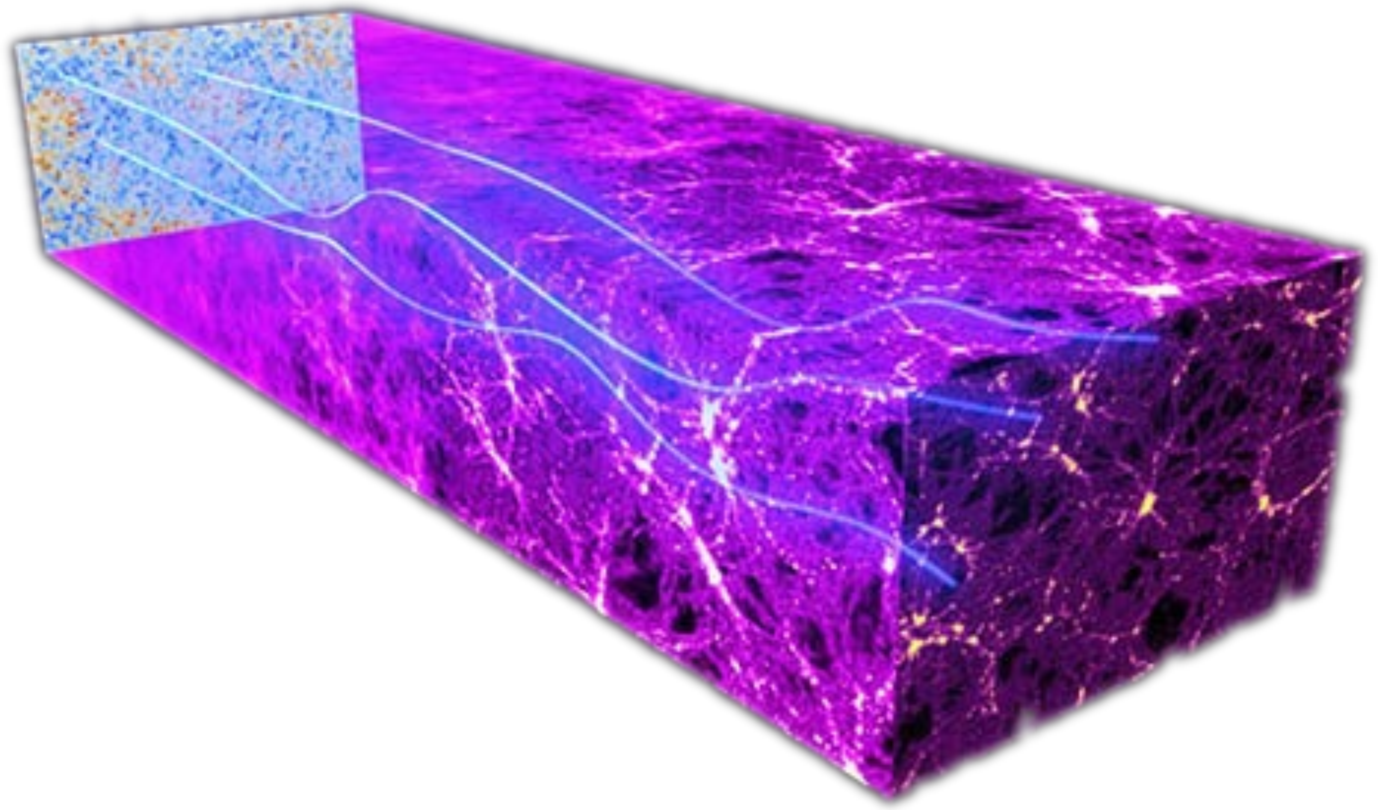
Light particles that were ever in thermal equilibrium with the primordial plasma will affect the mass-energy budget and leave an imprint in the CMB.

This includes many BSM sterile neutrinos, axions, dark radiation.

Plot from CMB-S4 Collaboration

CMB weak lensing

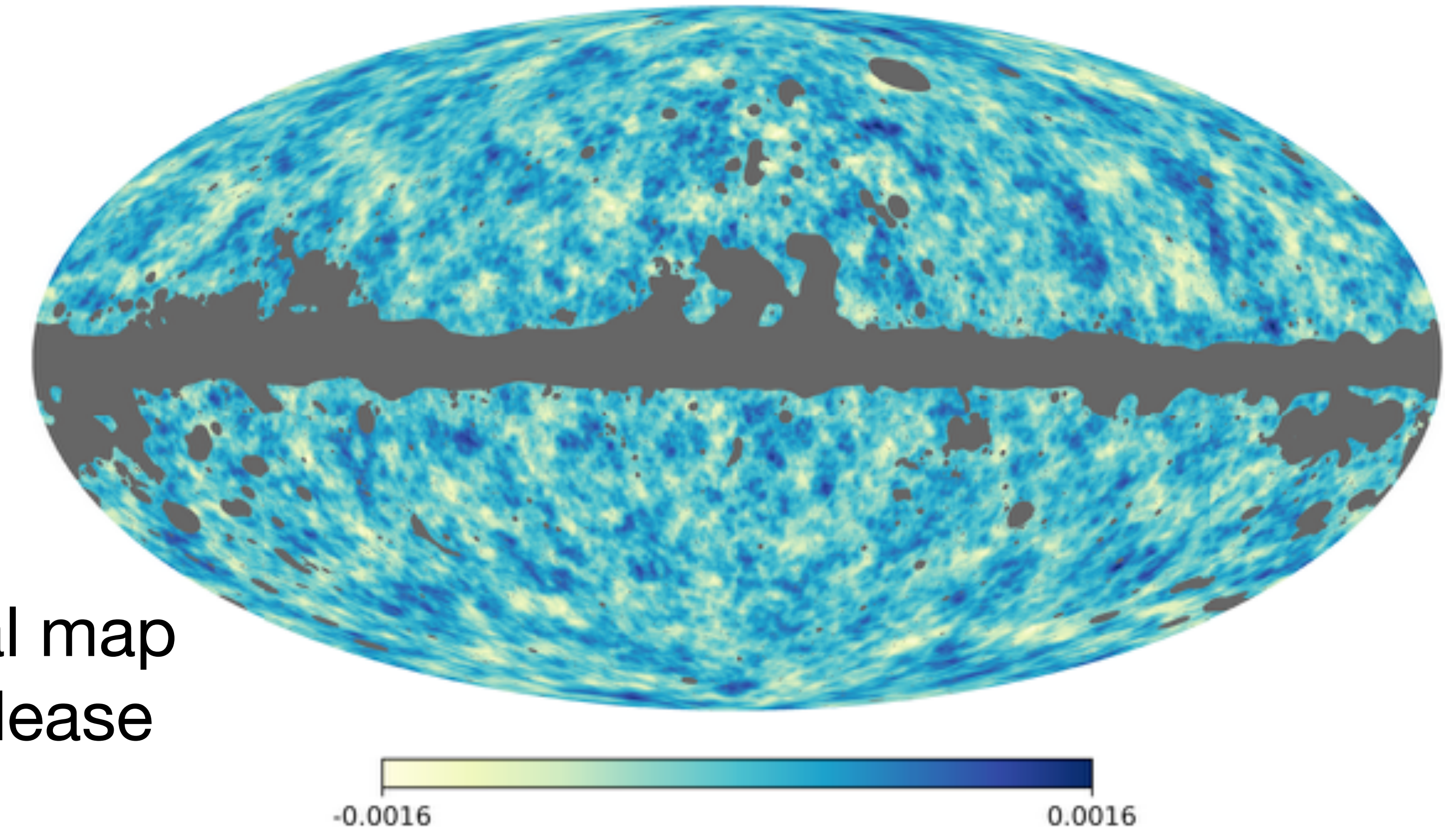
Photons deflected by structure. Can reconstruct deflections



$$T^{\text{lensed}} = T^0(\hat{\boldsymbol{n}} + \nabla\phi)$$

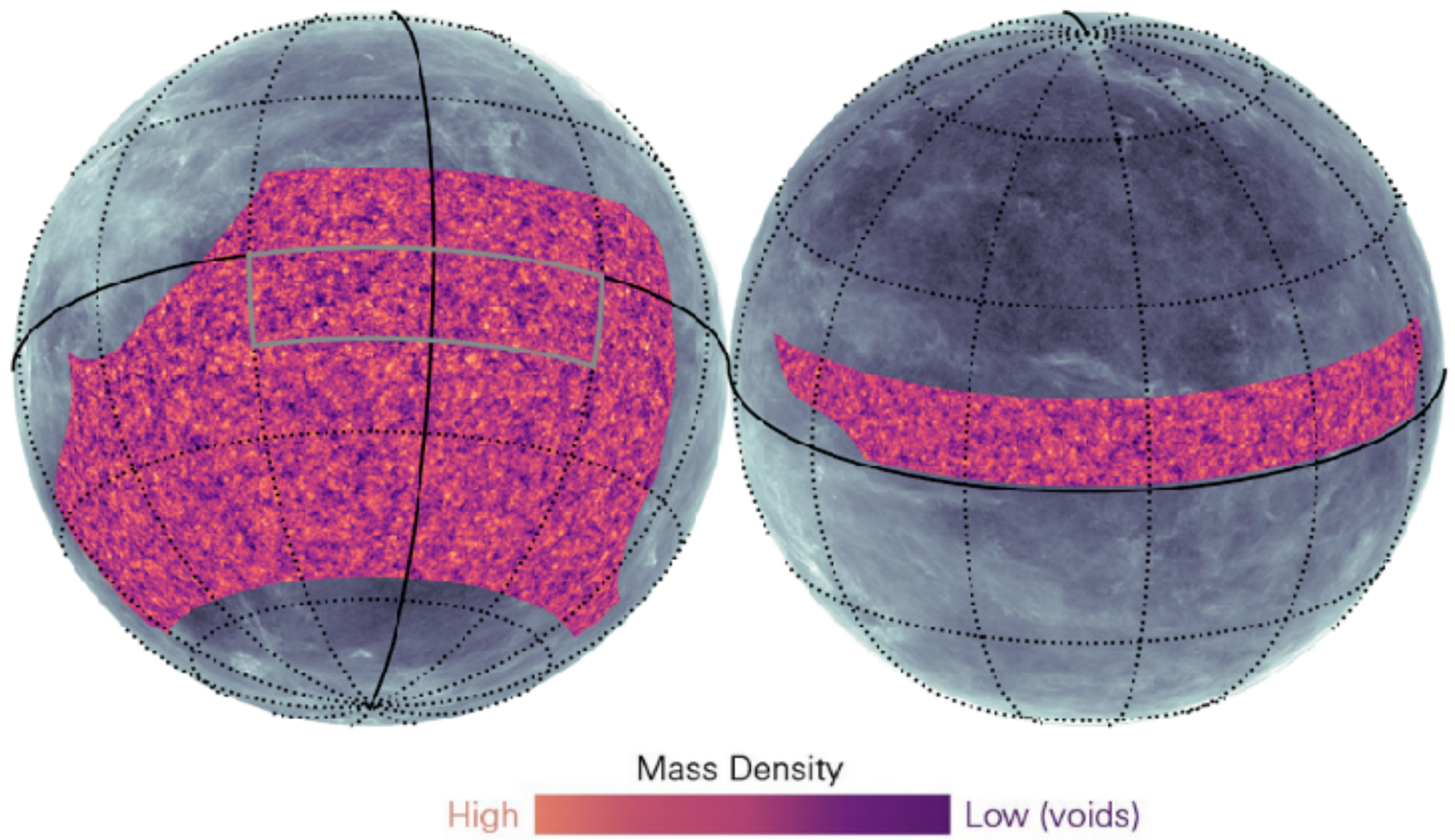
$$\hat{\phi}^{XY}_{\mathbf{L}} = \frac{1}{R^{XY}_L}\int d^2\boldsymbol{\ell} W^{XY}_{\boldsymbol{\ell},\boldsymbol{\ell}-\mathbf{L}} \bar{X}_{\boldsymbol{\ell}} \bar{Y}^*_{\boldsymbol{\ell}-\mathbf{L}}$$

Can reconstruct deflections from T, E and B to get lensing potential



For e.g., lensing potential map Planck 2018 Legacy Release

For e.g., ACT DR6 lensing mass map



Madhavacheril et al. (ACT Collaboration), Arxiv:2304.05203

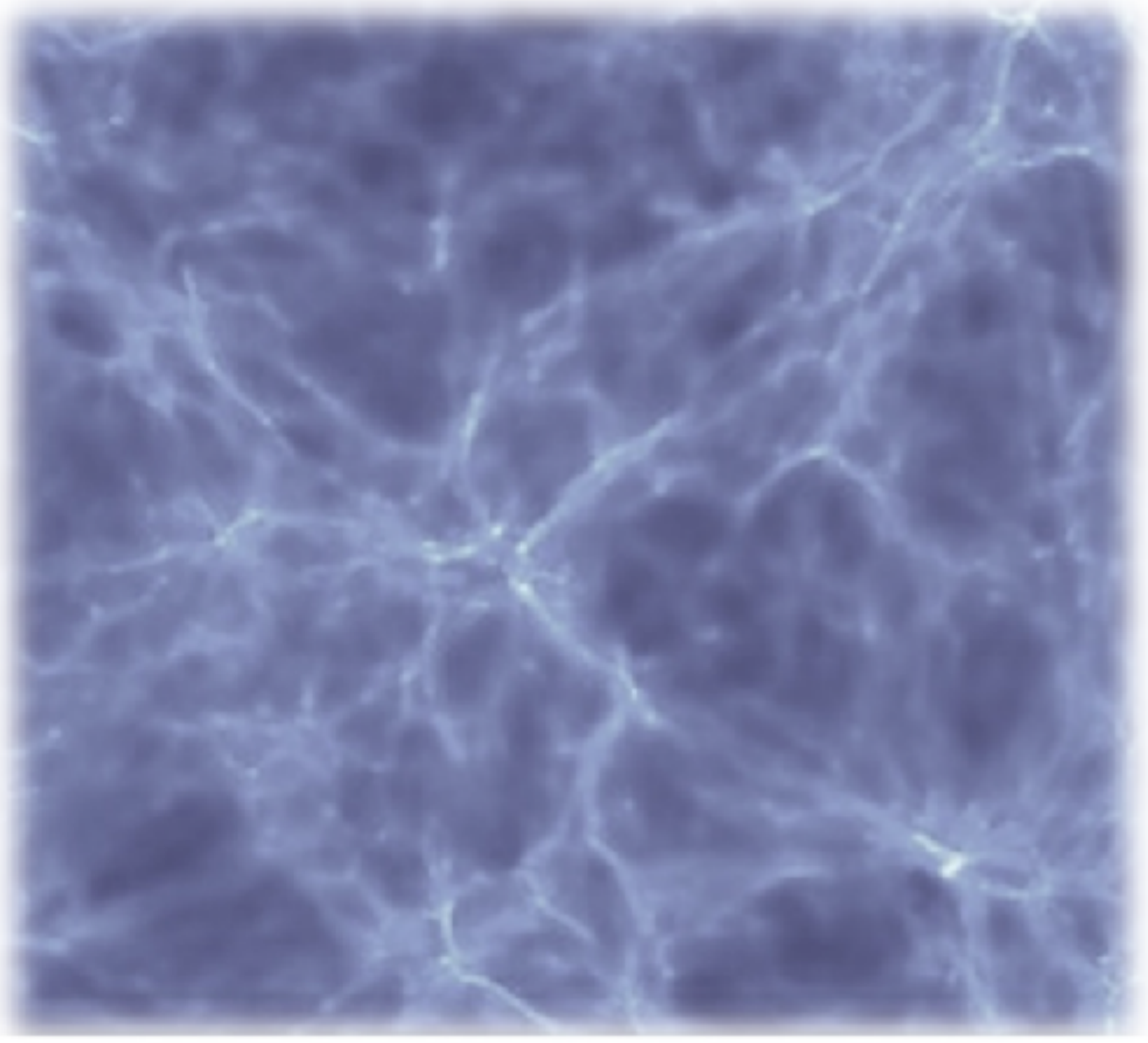
Figures from ESA and Planck Legacy Release 2018


$T(\hat{n})$ $(\pm 350\mu K)$
Plots from Duncan Hanson
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
(no primordial B-modes)
unlensed

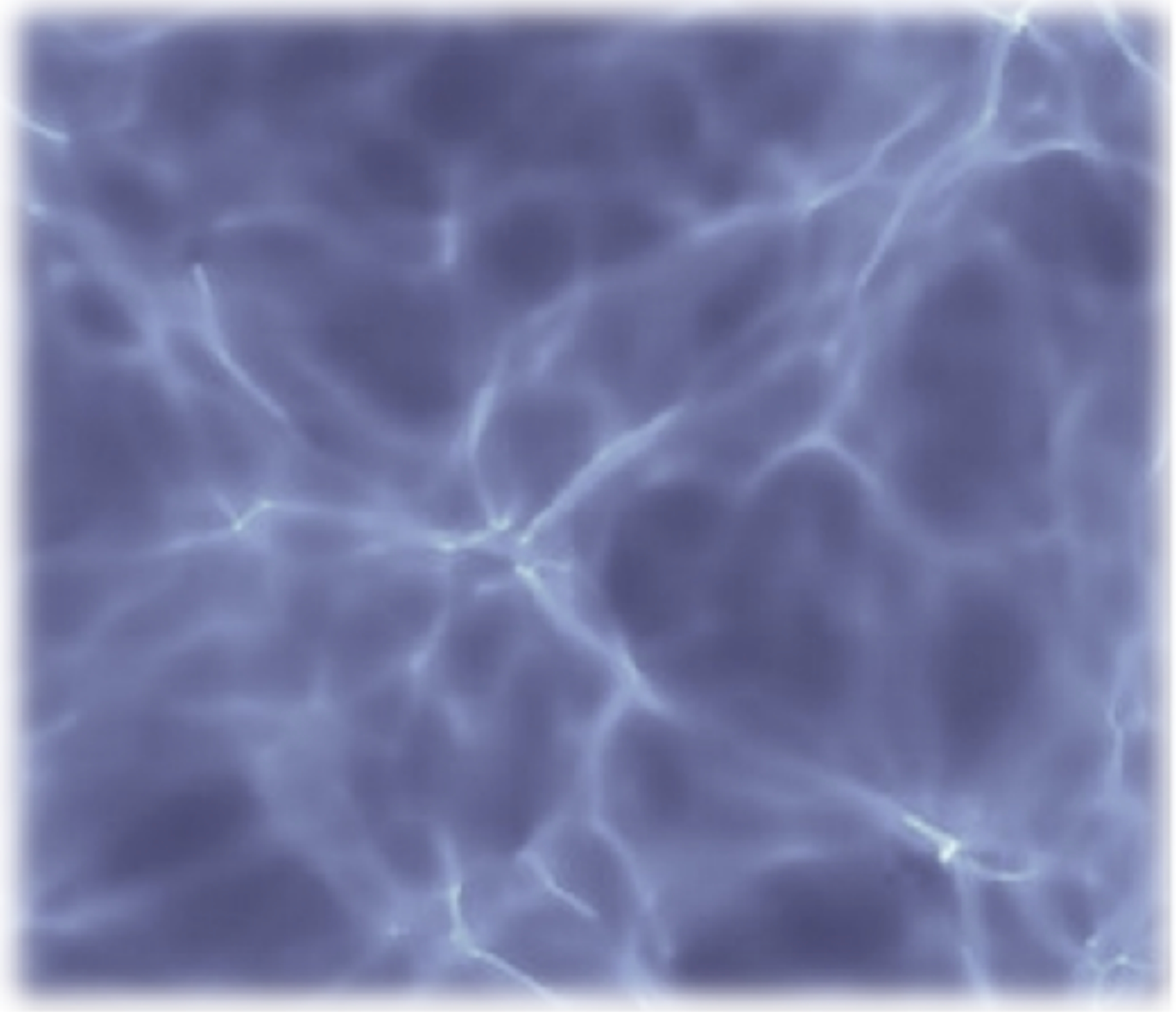

$T(\hat{n})$ $(\pm 350\mu K)$
Plots from Duncan Hanson
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
(no primordial B-modes)
lensed

CMB lensing helps weigh neutrino masses

Neutrinos contribute only **0.5%** of the matter but gravitationally suppress LSS by **4%**

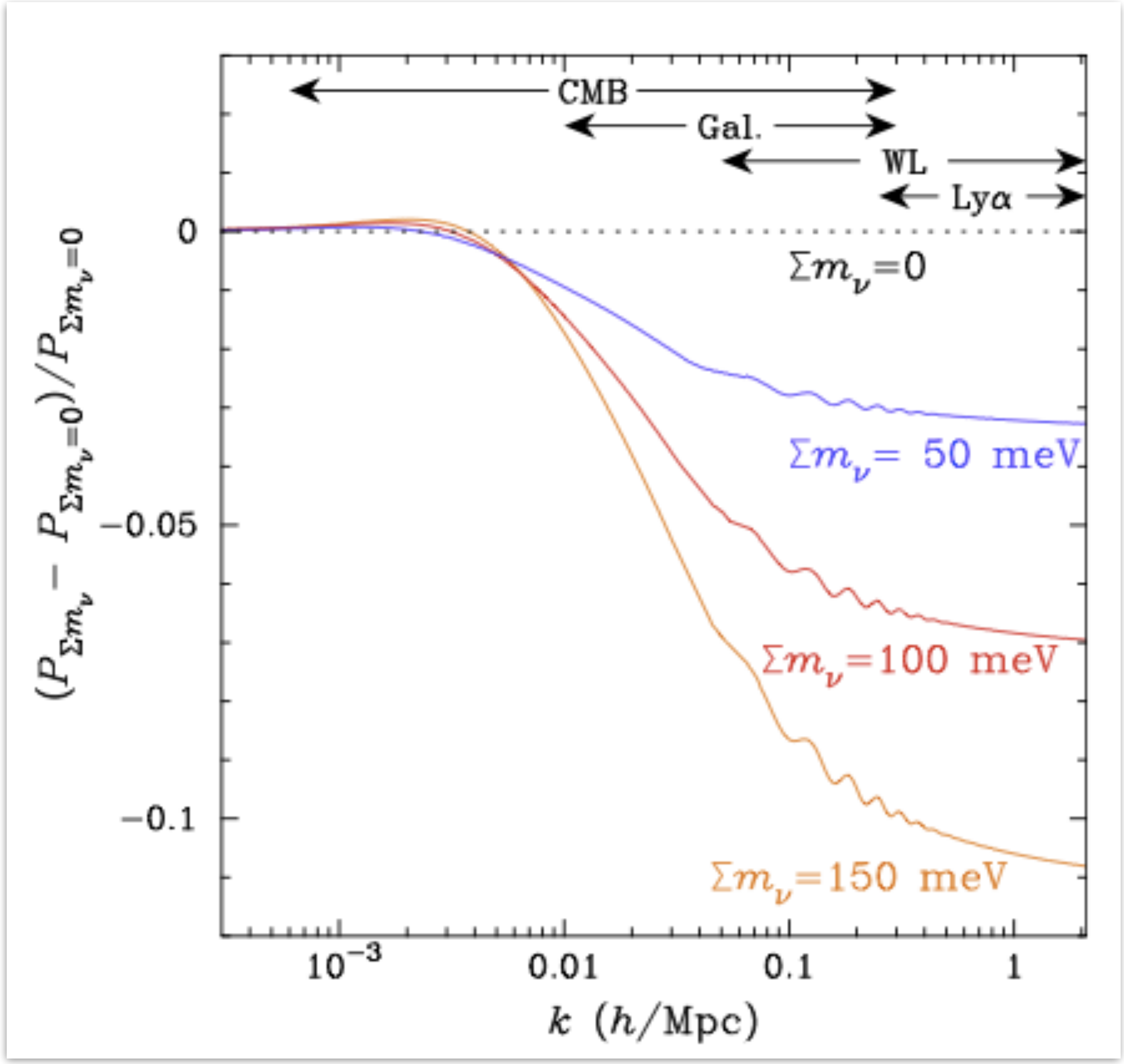


Negligible neutrino mass



Very large neutrino mass

Viel et al, 2013



Abazajian et al, 2015

Slide adapted from Frank Qu

Early Universe v. Late Universe tests of Hubble (H0) and Large-scale structure growth (S8)

"Predicted, indirect H0 or S8"

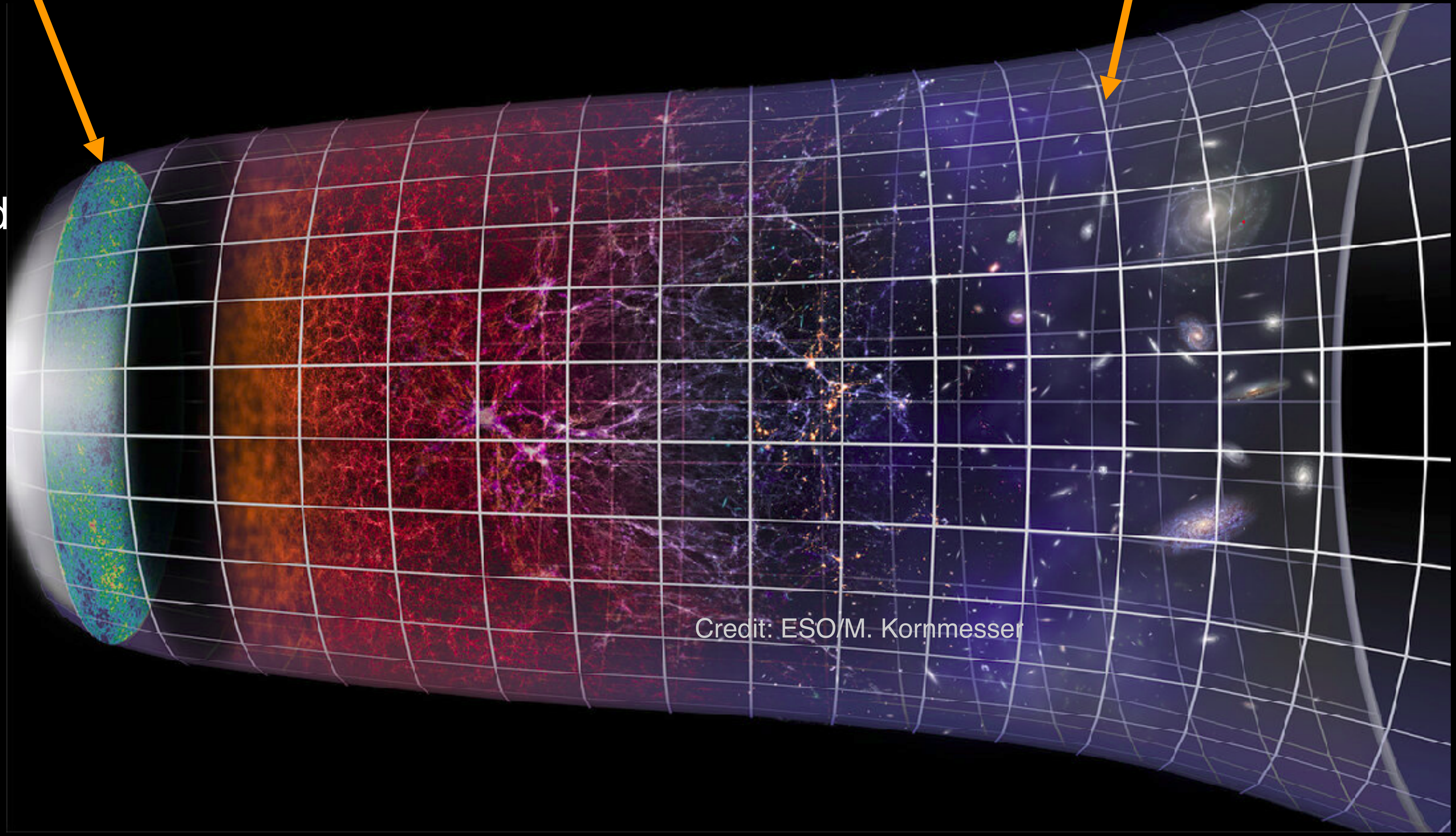
1. Fit LCDM model to CMB at z~1100
2. Predict structure growth to z~1-2

Assumptions:

- Standard GR
- Dominated by Cold Dark Matter
- Constant Dark Energy

"Direct S8"

1. Measure matter amplitude directly with galaxy surveys
2. Compare with prediction



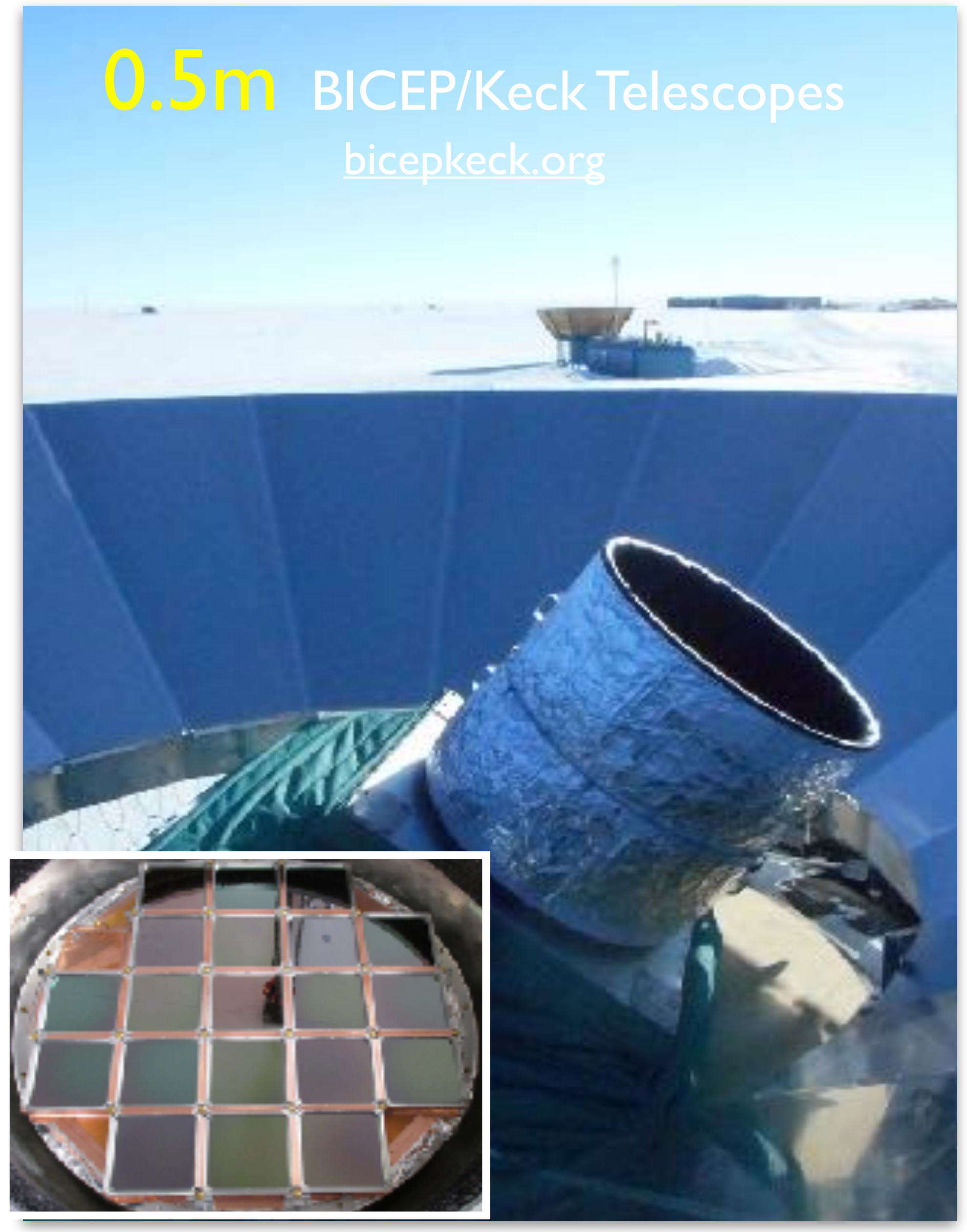
"Direct H0"

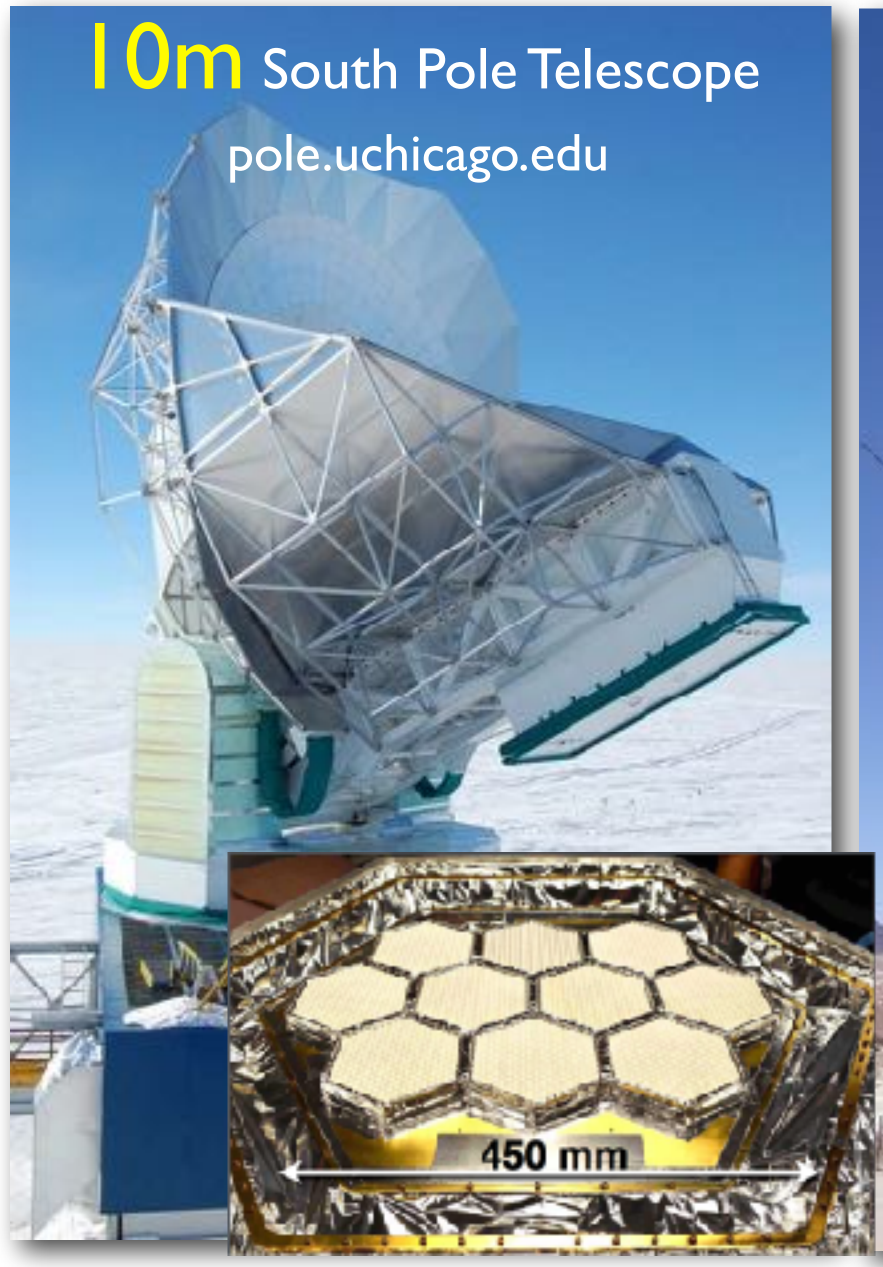
1. Measure H0 via SNIa, variables
2. Compare with prediction

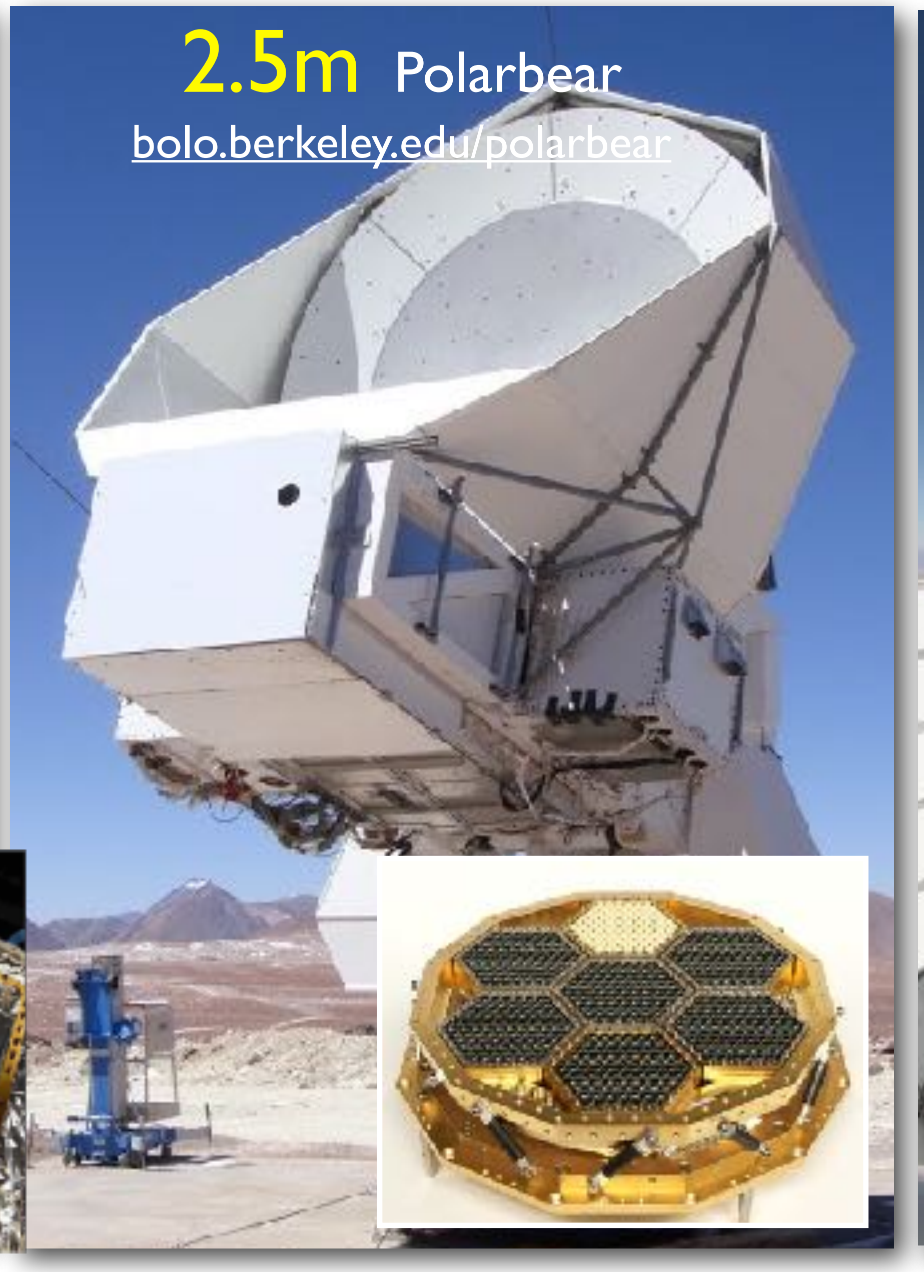
Slide adapted from Frank Qu

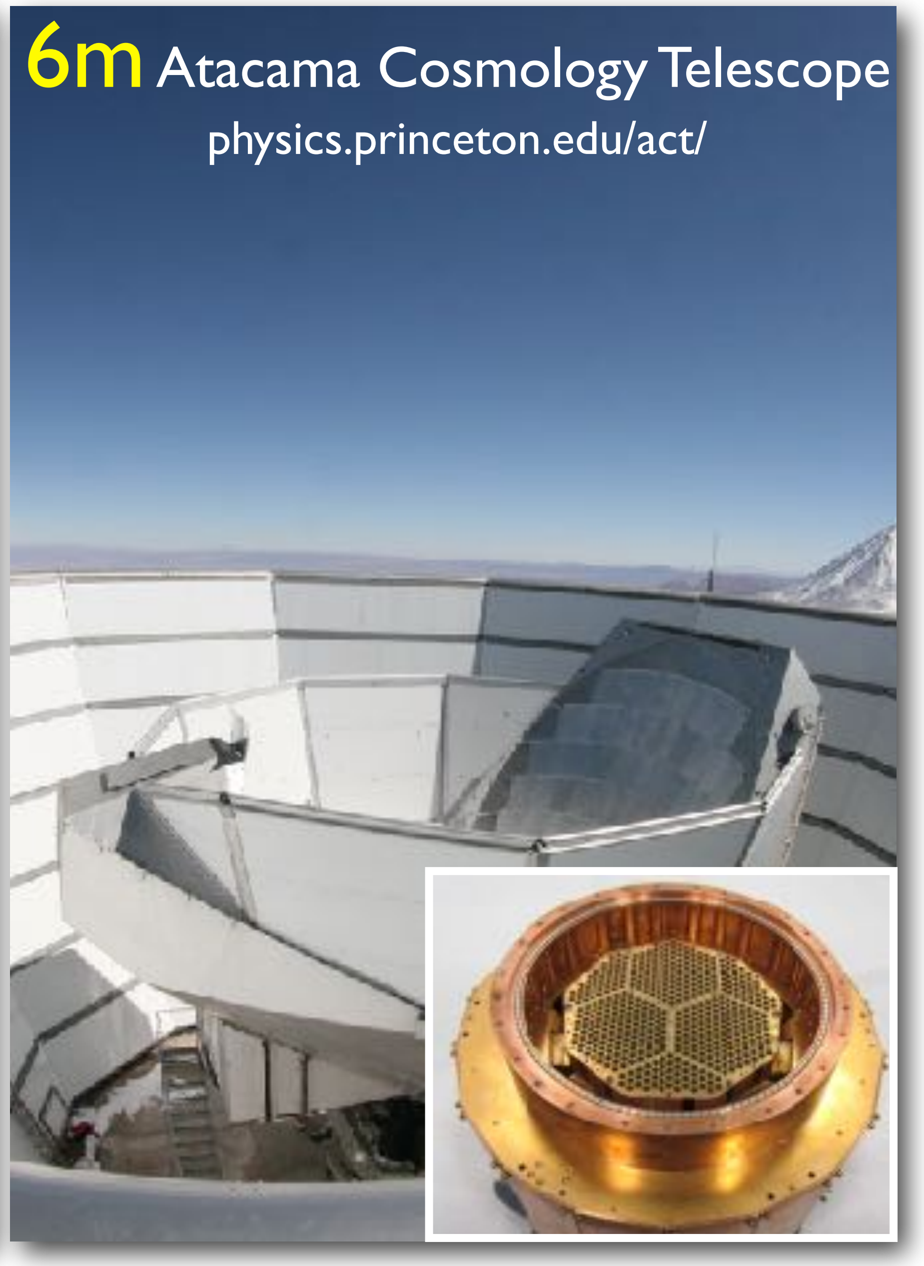
Ground-based CMB experiments

Observe in mm-wave windows from high, dry deserts, using superconducting noise-limited sensors.









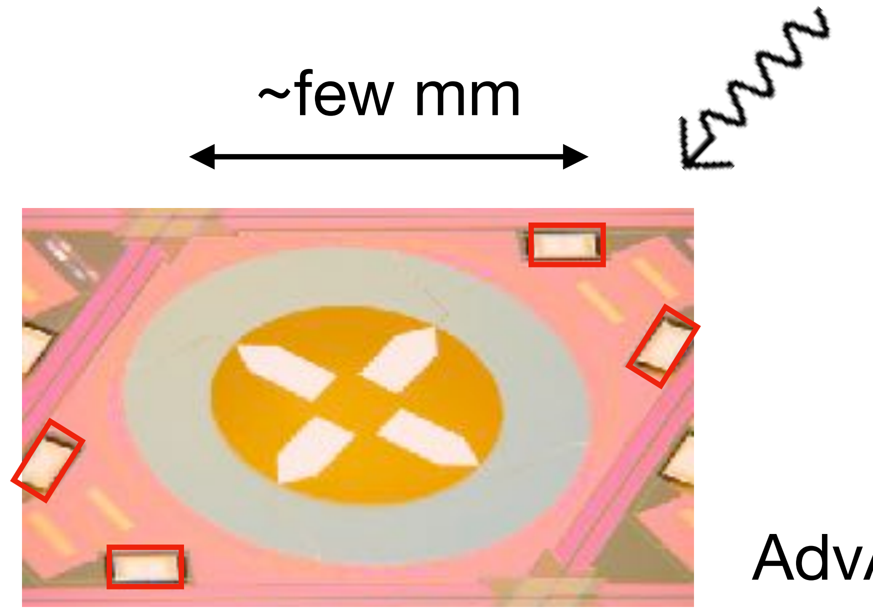
Compact receivers for inflation, high-resolution for cosmology, large-scale structure and its evolution

Superconducting sensors for CMB

Transition-edge sensor (TES) bolometers operated at sub-kelvin temperatures

Superconducting sensors for CMB

Transition-edge sensor (TES) bolometers operated at sub-kelvin temperatures

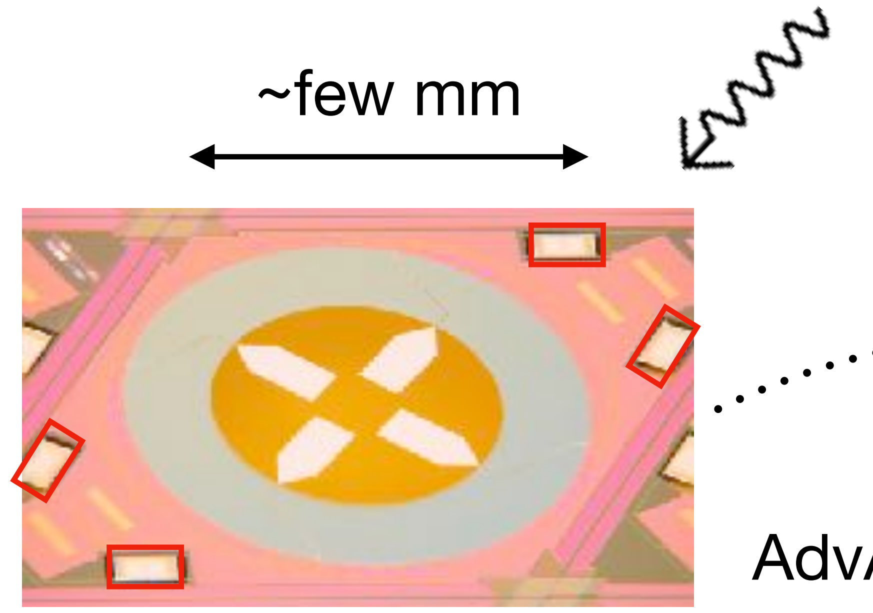


AdvACT

Incoming CMB power deposited on TES bolometer by antenna or feedhorn-coupled orthomode transducer

Superconducting sensors for CMB

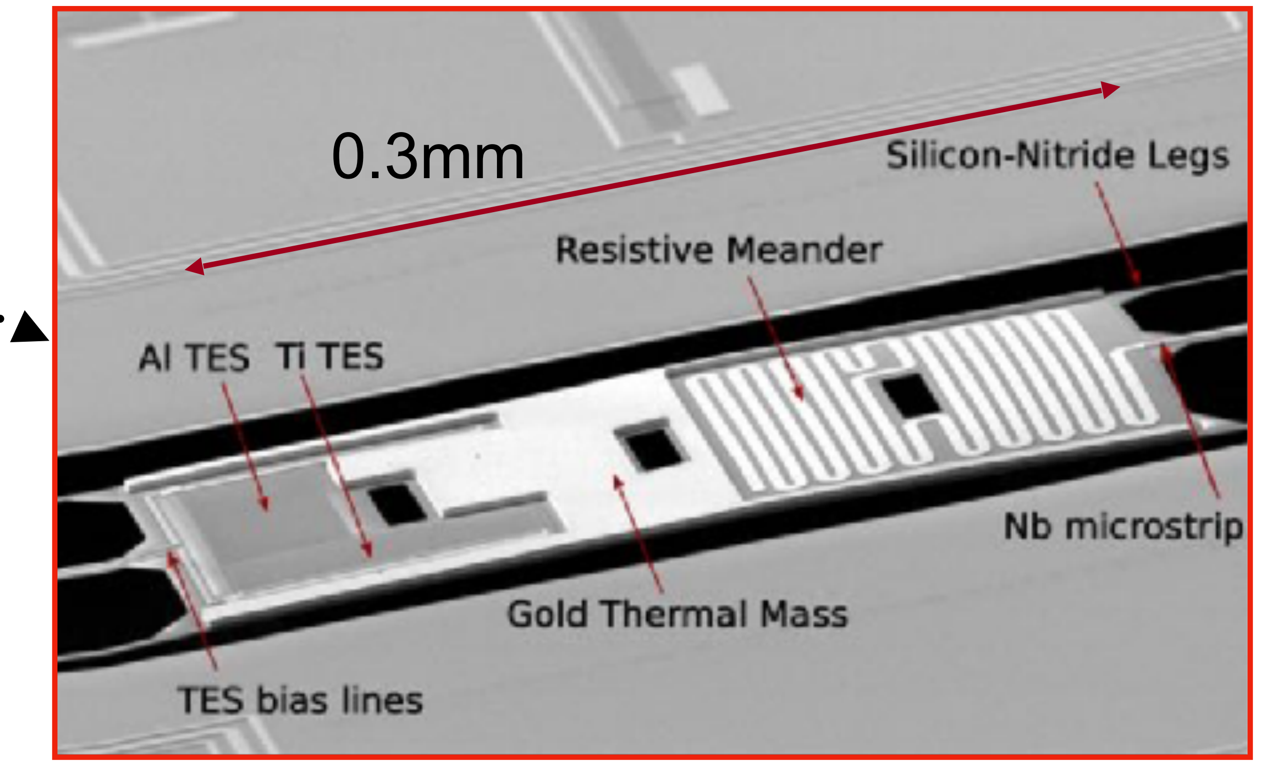
Transition-edge sensor (TES) bolometers operated at sub-kelvin temperatures



AdvACT

Incoming CMB power deposited on TES bolometer by antenna or feedhorn-coupled orthomode transducer

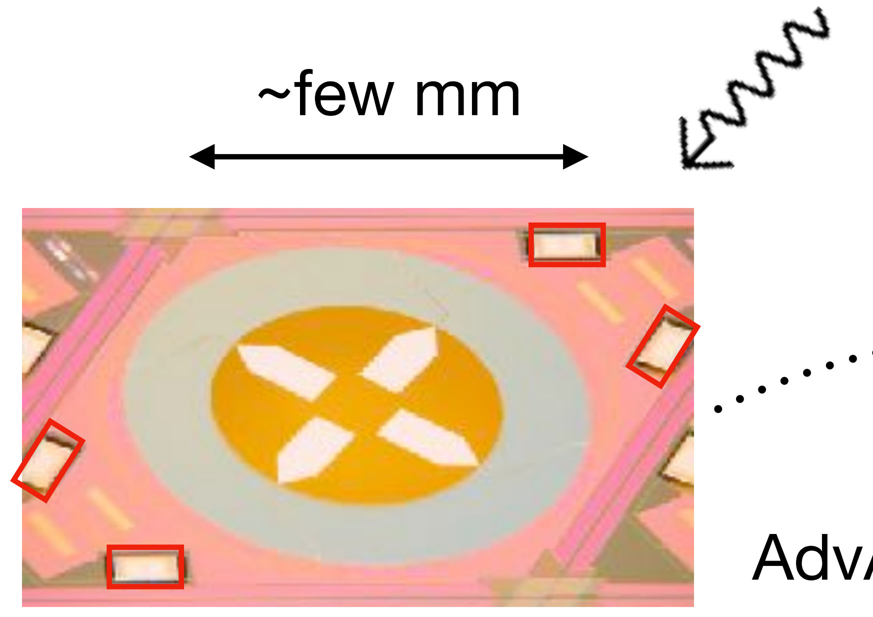
BICEP



TES bolometer measures that power, and converts to a current we measure

Superconducting sensors for CMB

Transition-edge sensor (TES) bolometers operated at sub-kelvin temperatures



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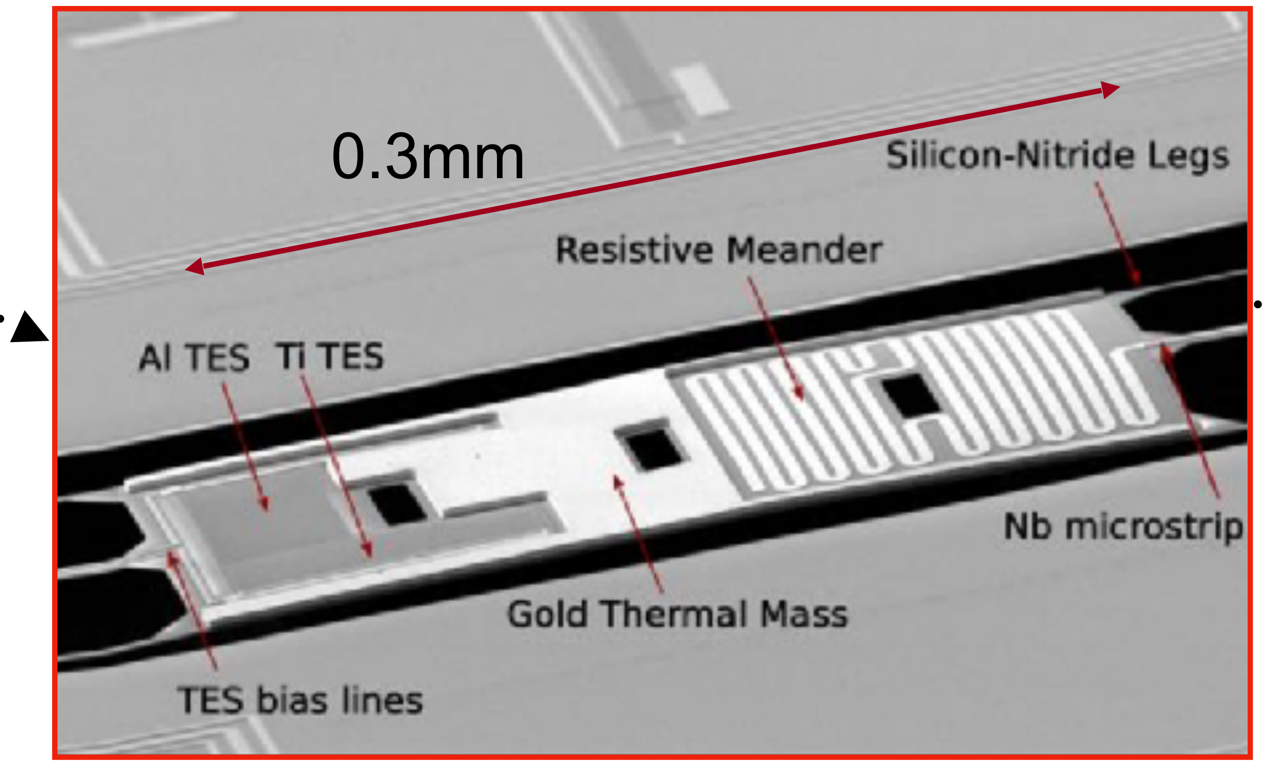

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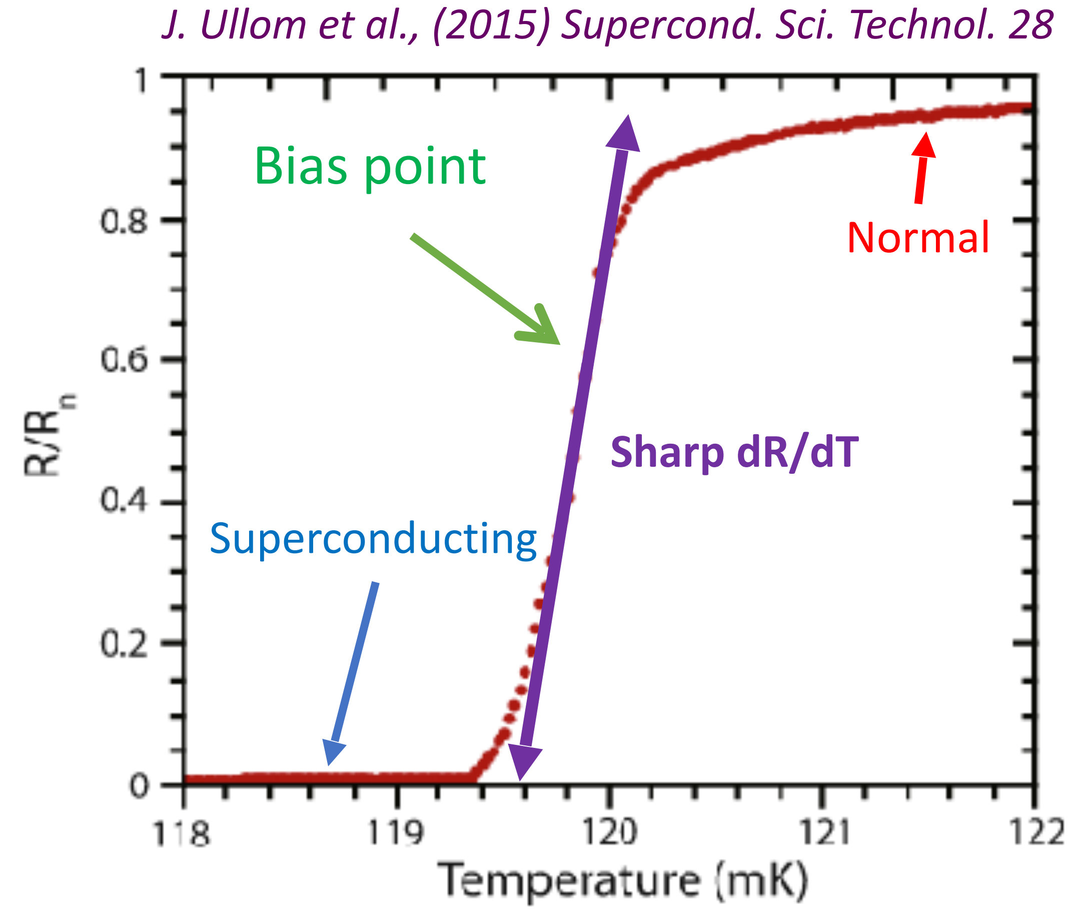


Sensitivity comes from operating on the very sharp superconducting phase transition at ~0.1-0.3K

How we measure r

Deep integration, characterize foregrounds, lensing, systematics

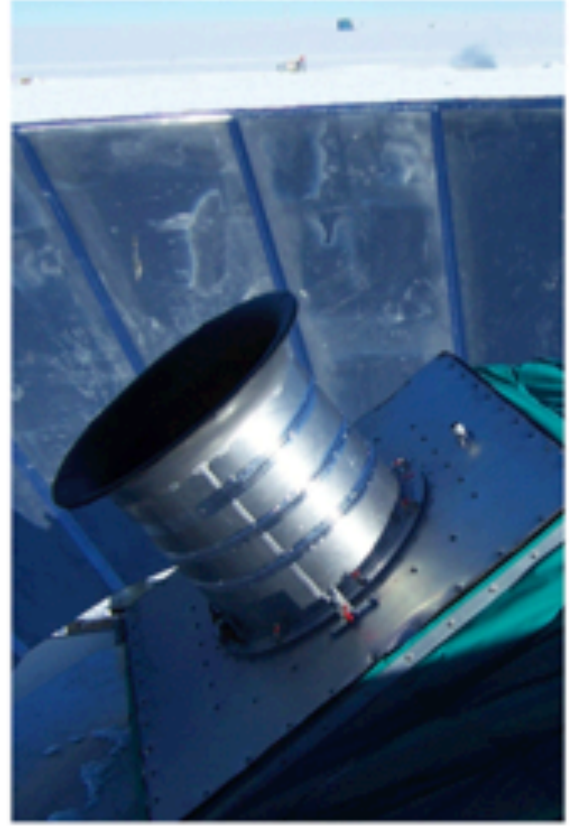
$$N \sim \sqrt{\frac{A}{n_{det} \cdot t}}$$

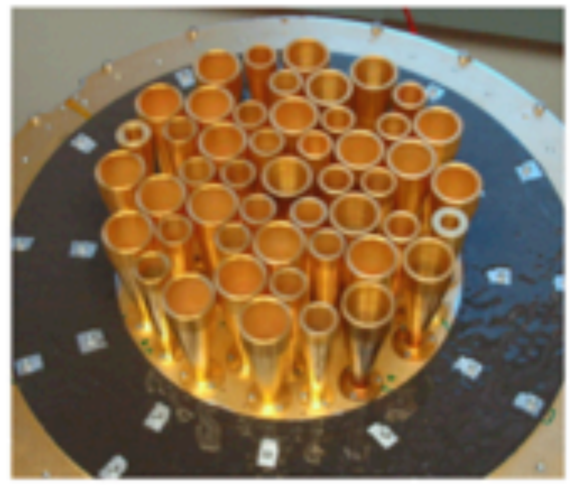
BICEP program 2006-present

Compact CMB cameras with increasing sensitivity to inflation

Generation 1

BICEP1
(2006-2008)
100, 150 GHz

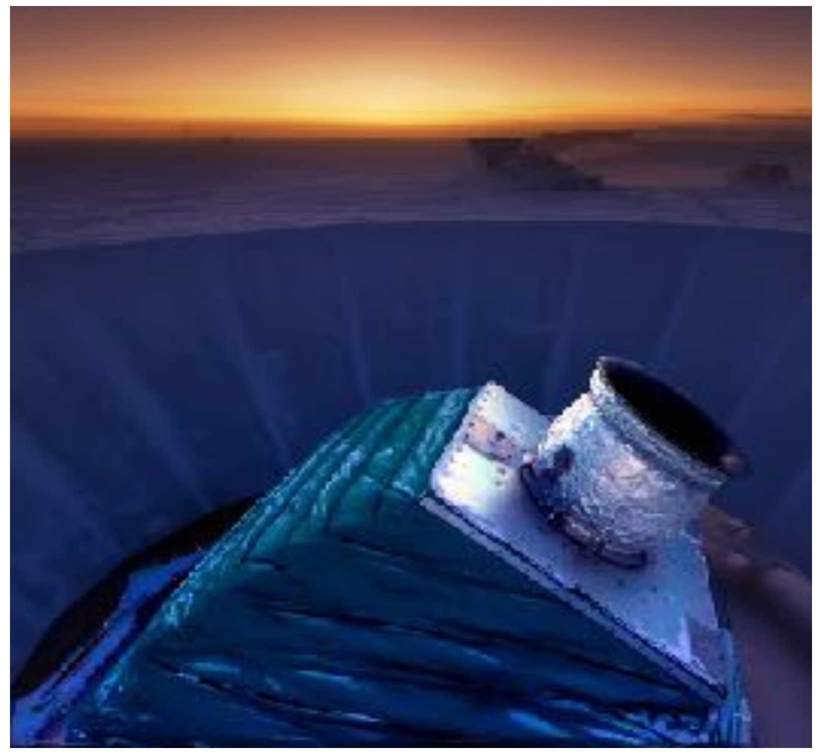


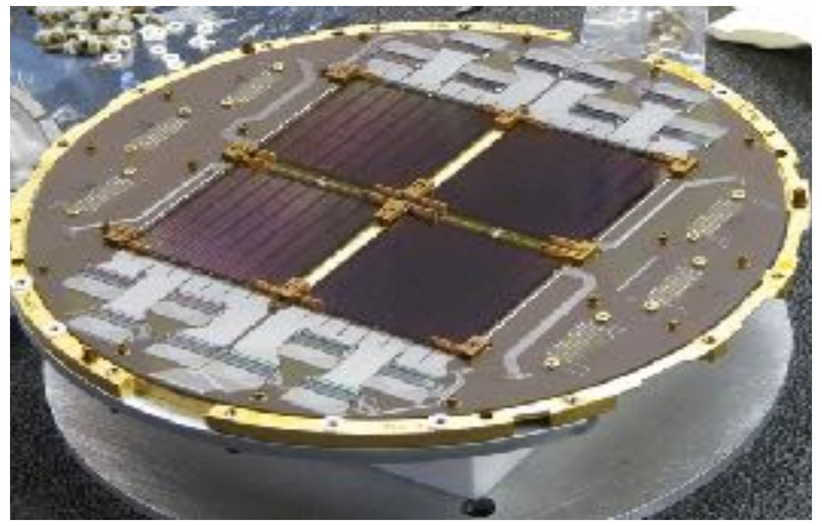


~100 sensors

Generation 2 →

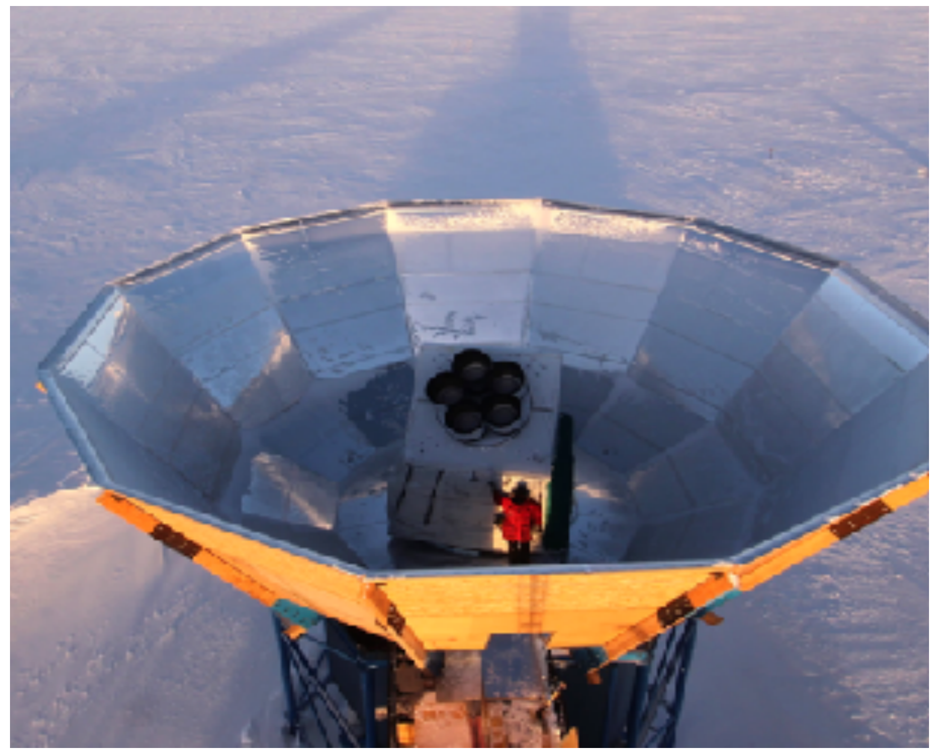
BICEP2
(2010-2012)
150 GHz

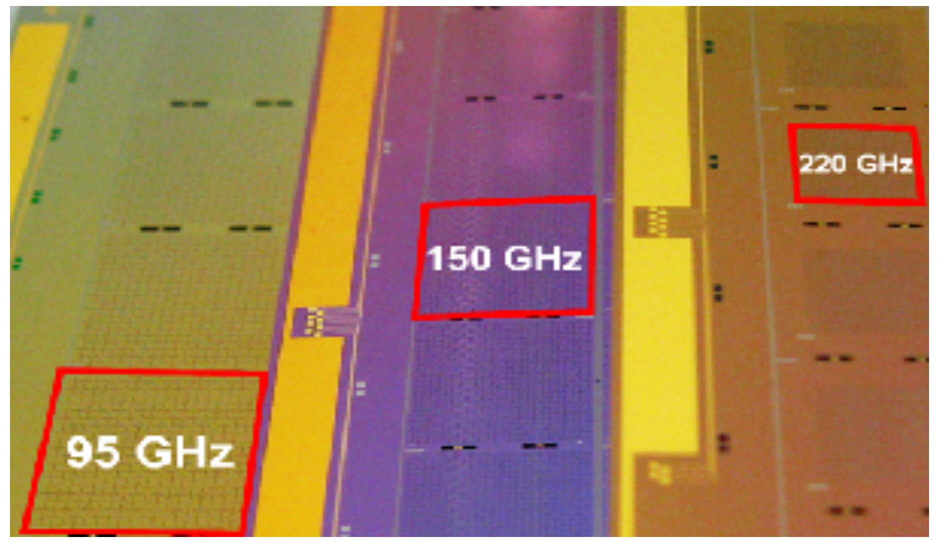




~500 sensors

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

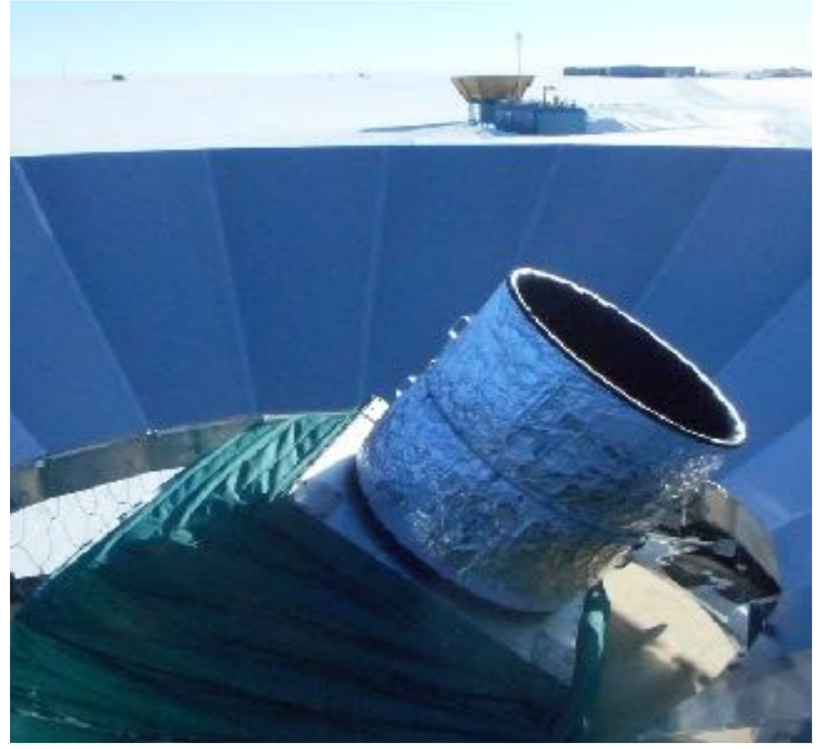


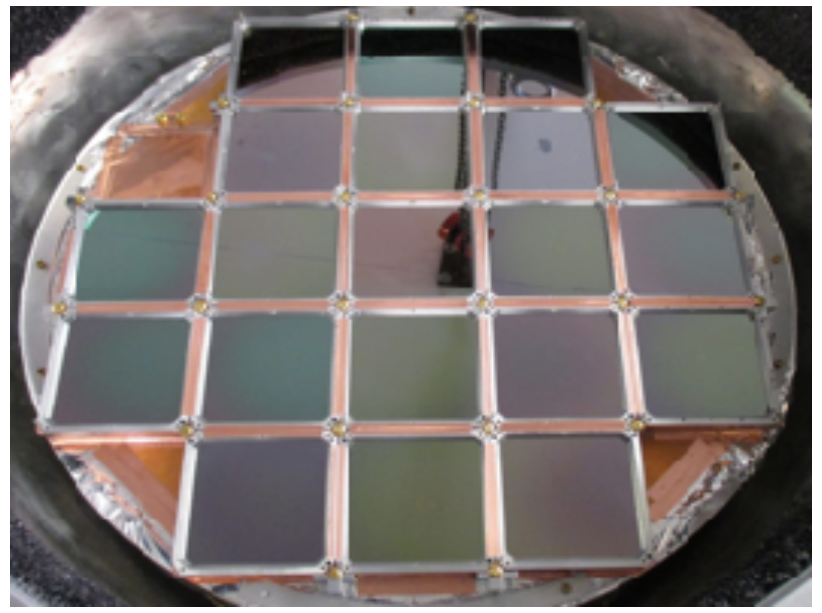


~2500 sensors in five BICEP2-like cameras

Generation 3 →

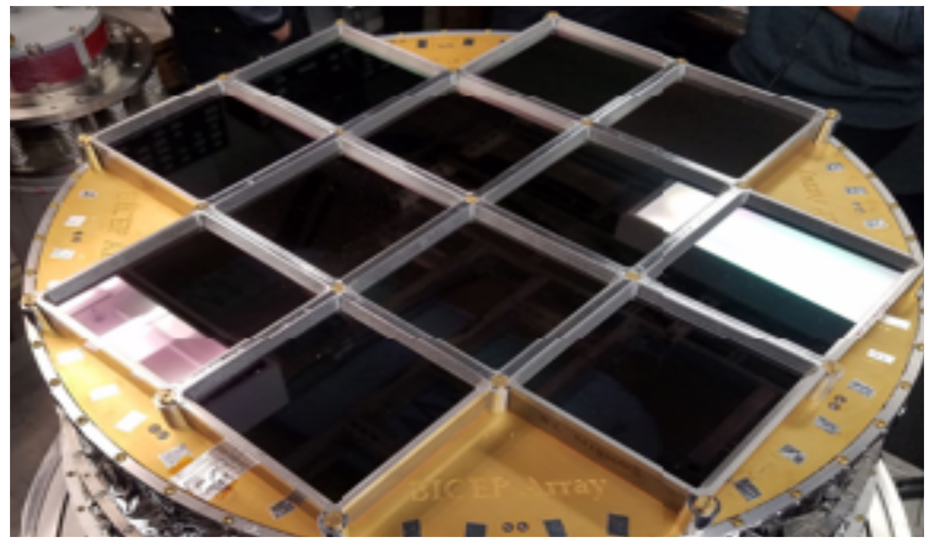
BICEP3
(2015+) $\sigma(r) \sim 0.01$
95 GHz





~2500 sensors

BICEP Array
(2019-2027) $\sigma(r) \sim 0.002$
30, 40, 95, 150, 220, 270 GHz

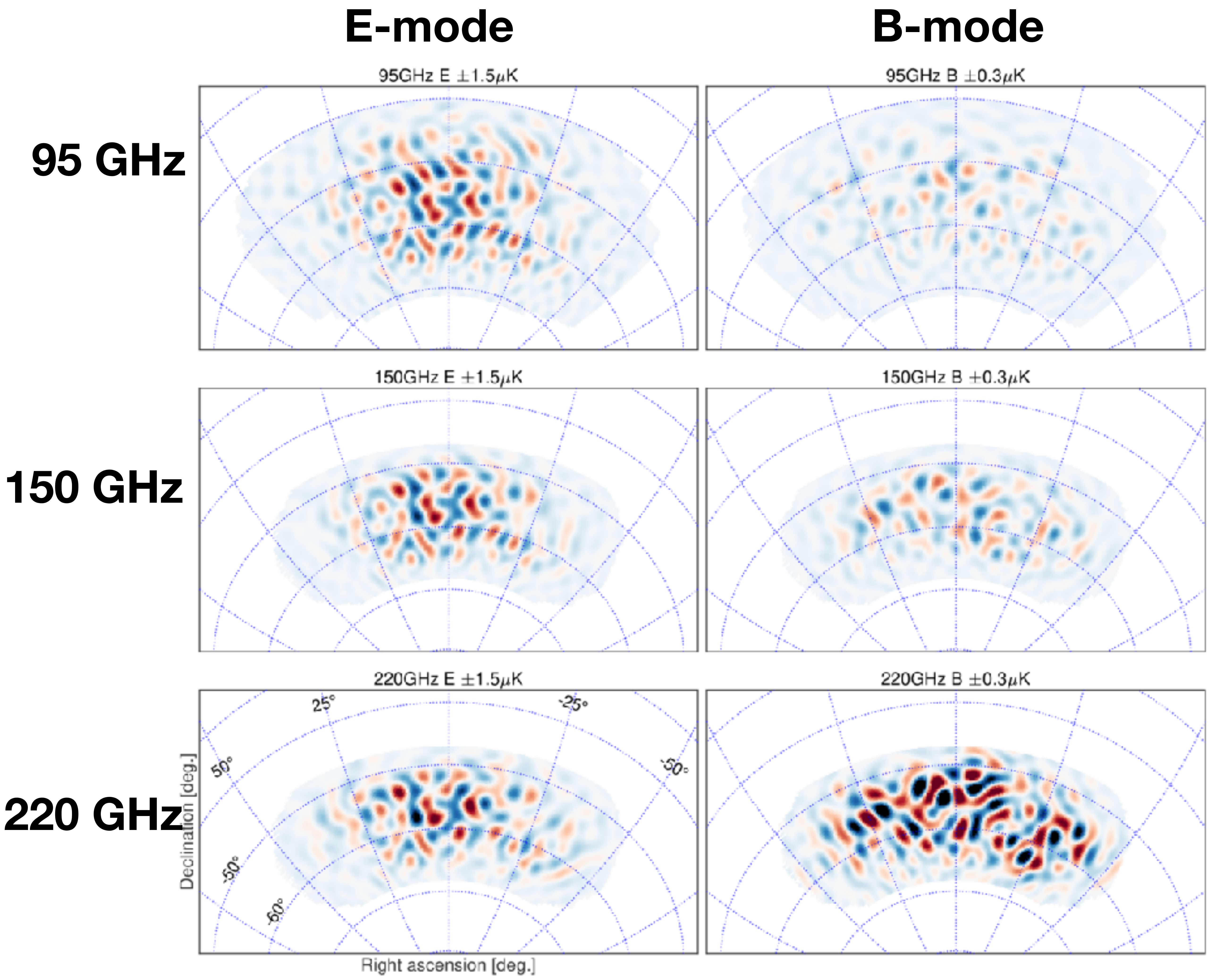


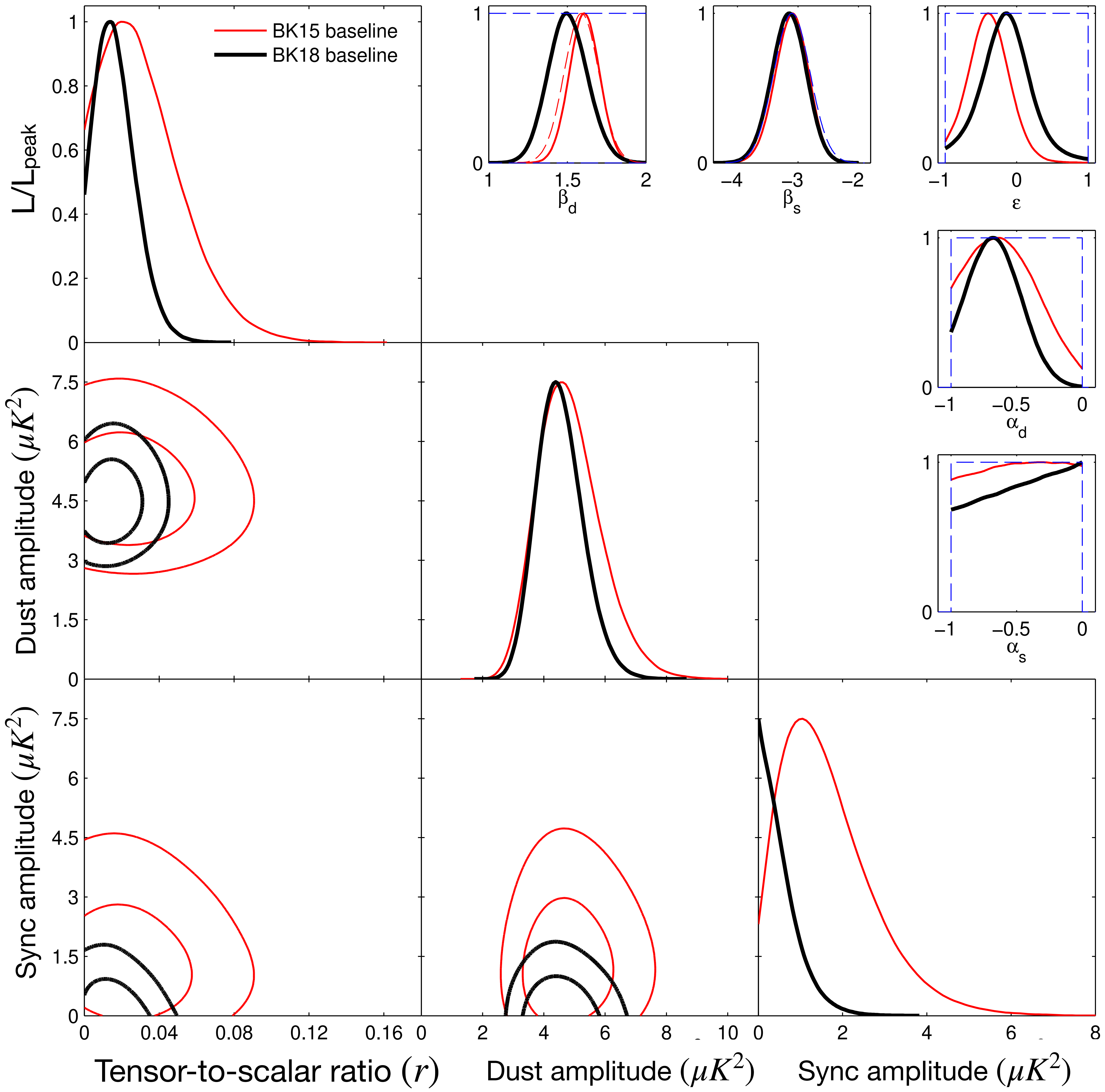
~30k sensors in four BICEP3-like cameras

BICEP/Keck Collaboration, PRL 127, 151301 (2021)

Deepest CMB polarization maps (BK18)

Jointly constrain r, CMB lensing amplitude, dust, synchrotron





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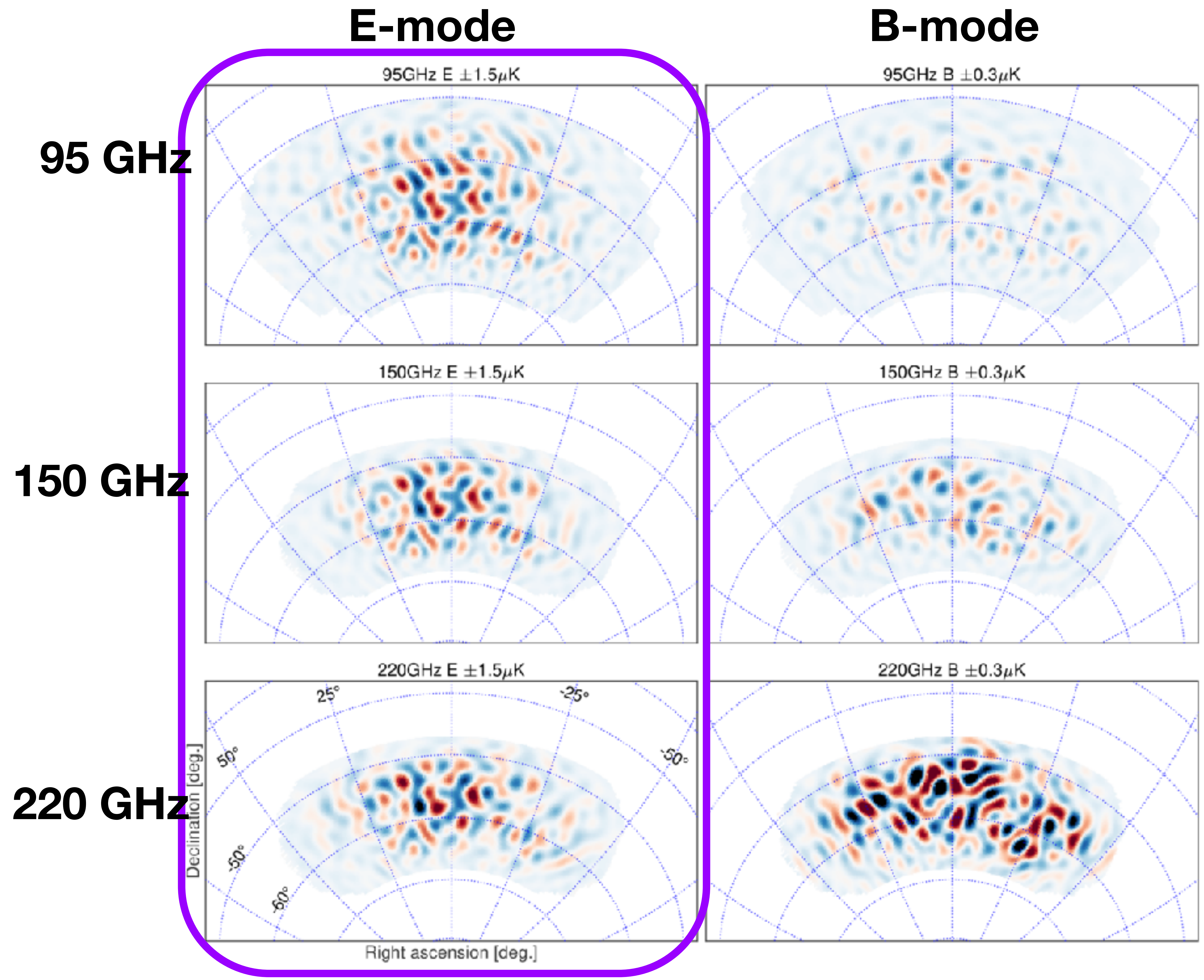
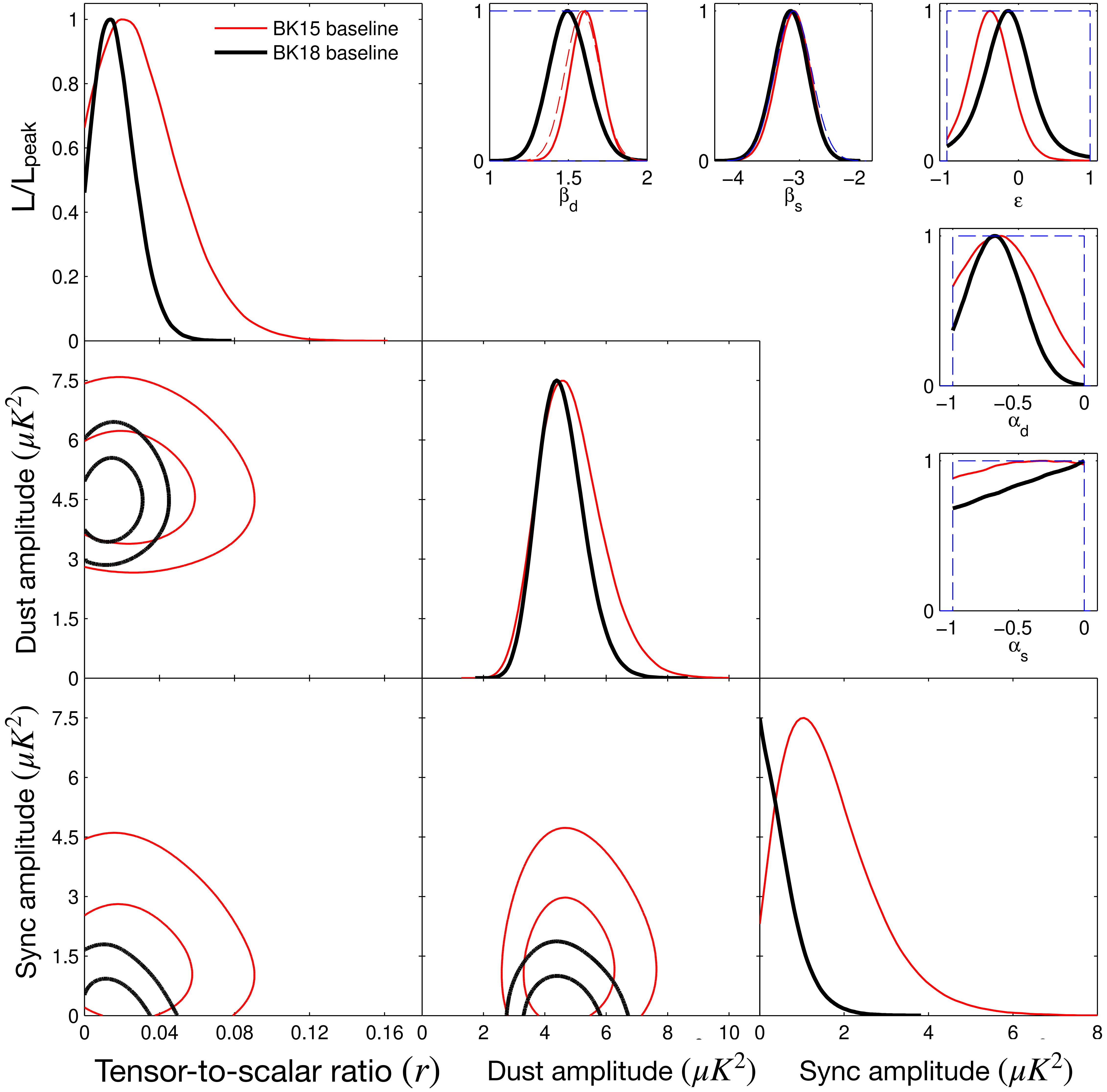
E maps are bright and correlated; robust detection of LCDM E-modes





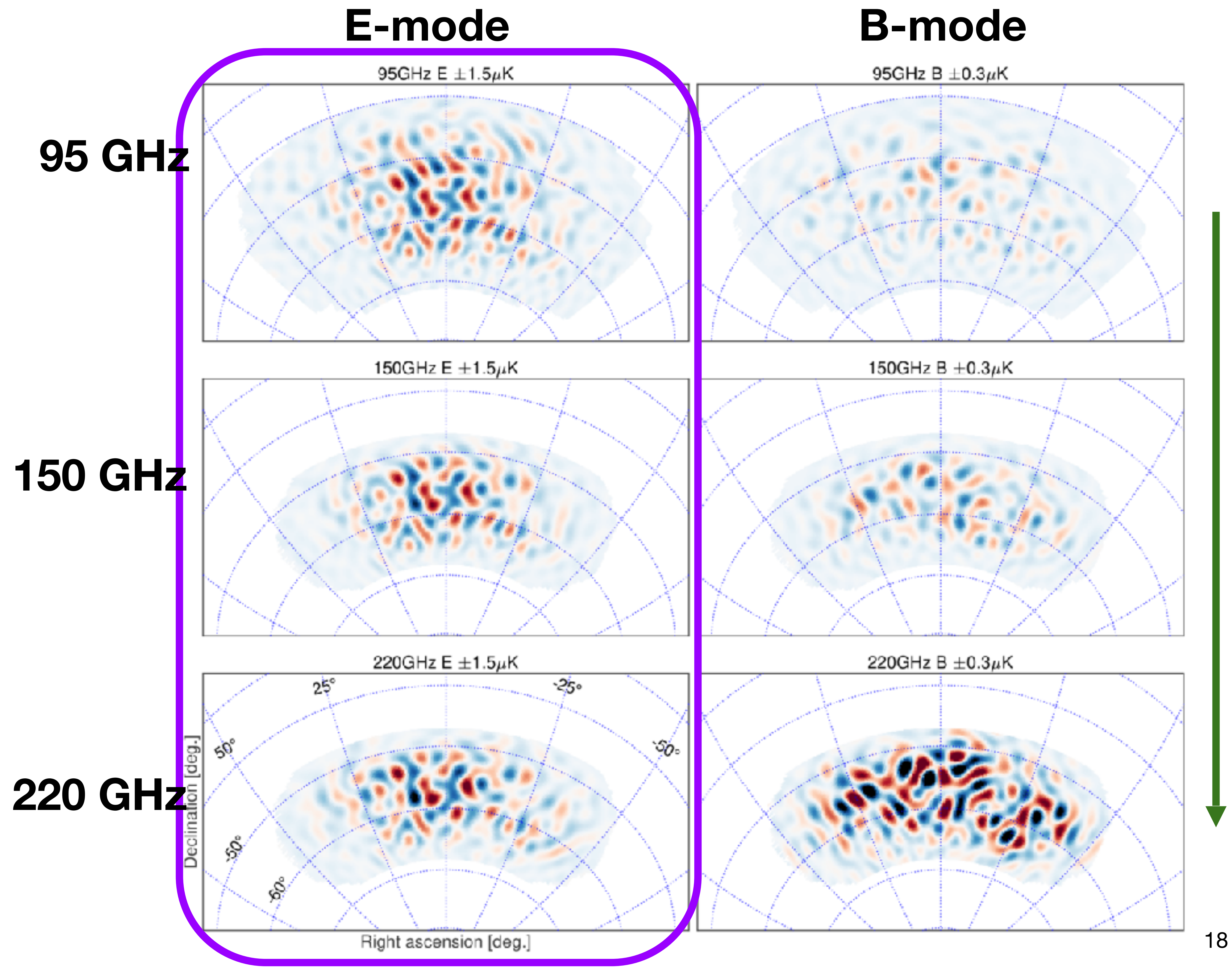
BICEP/Keck Collaboration, PRL 127, 151301 (2021)

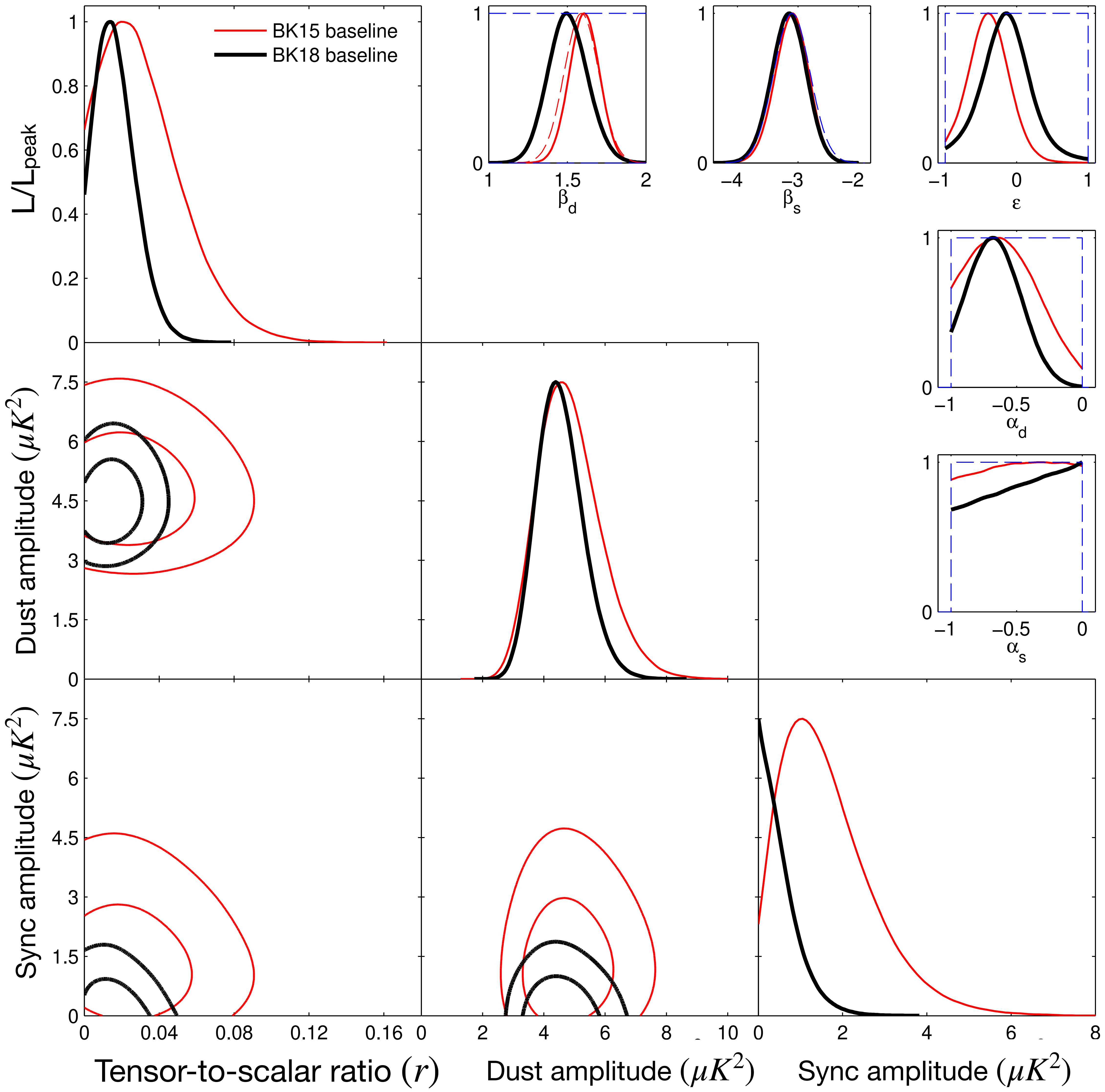
Deepest CMB polarization maps (BK18)

Jointly constrain r, CMB lensing amplitude, dust, synchrotron

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

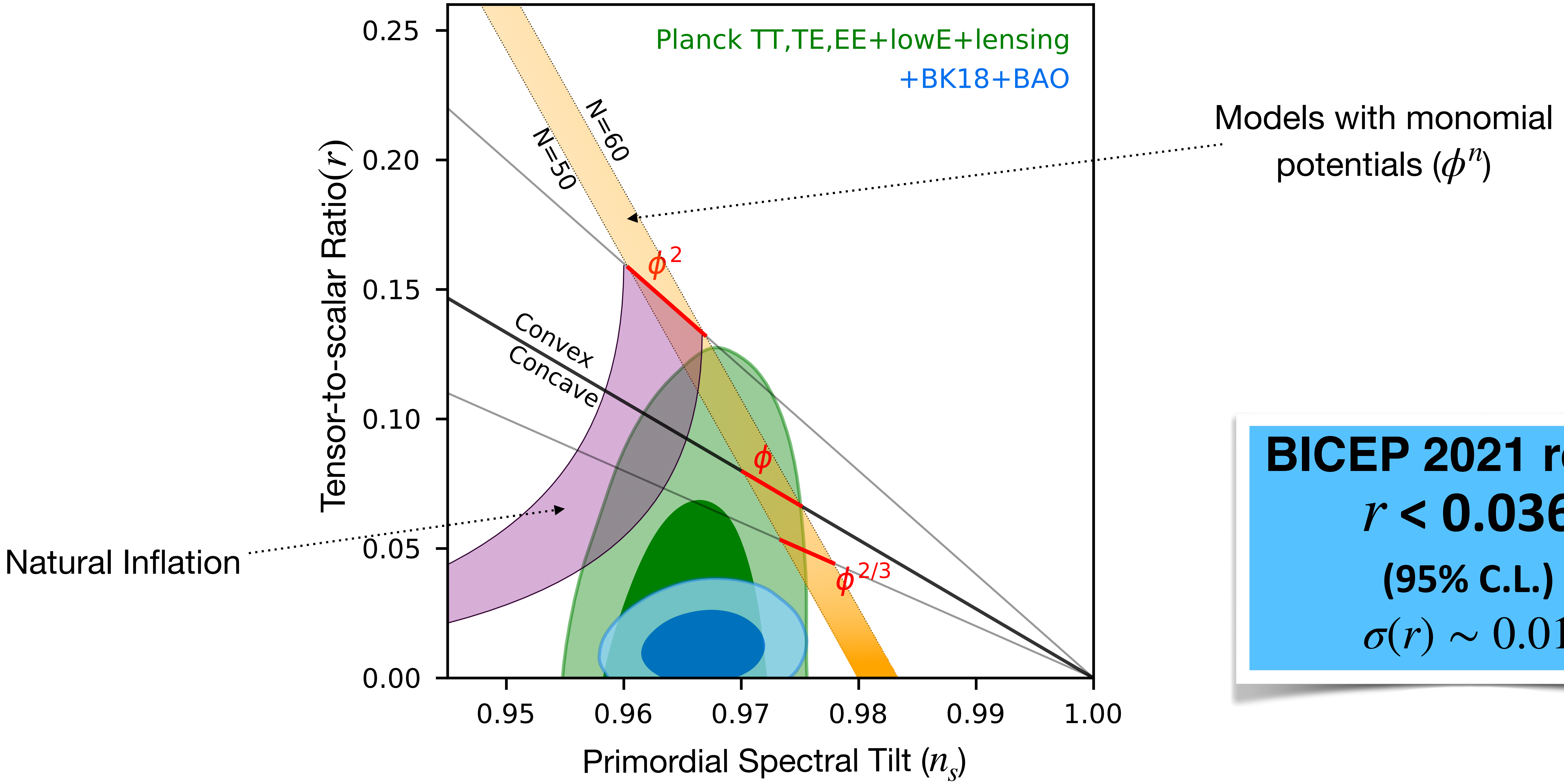
B maps are increasing in brightness; detection of polarized galactic dust





Best constraints on inflation parameters

Single-field slow-roll inflation models with monomial potentials* ruled out



BICEP 2021 result

r **< 0.036**

(95% C.L.)

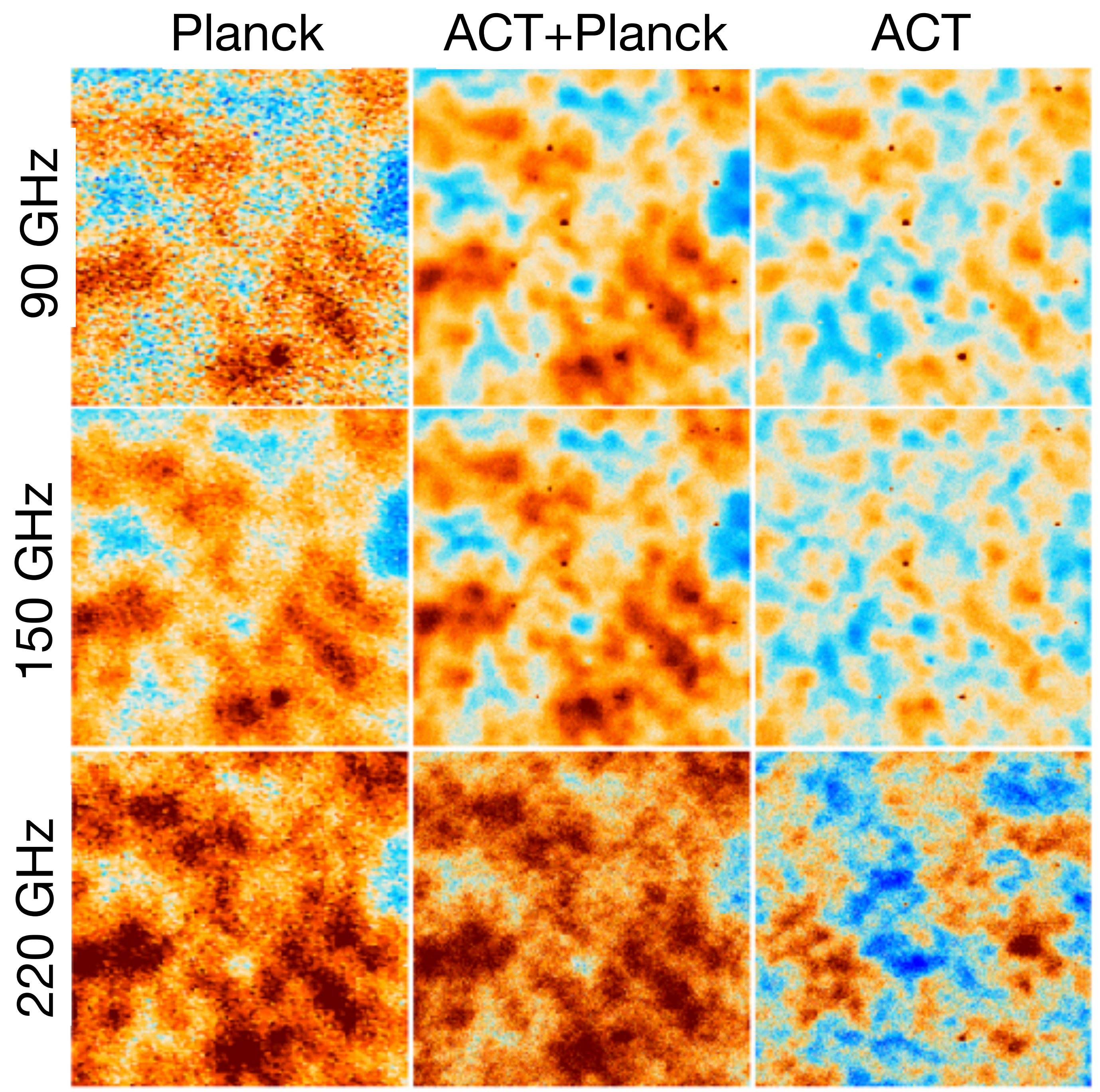
$\sigma(r) \sim 0.01$

*= with canonical kinetic terms

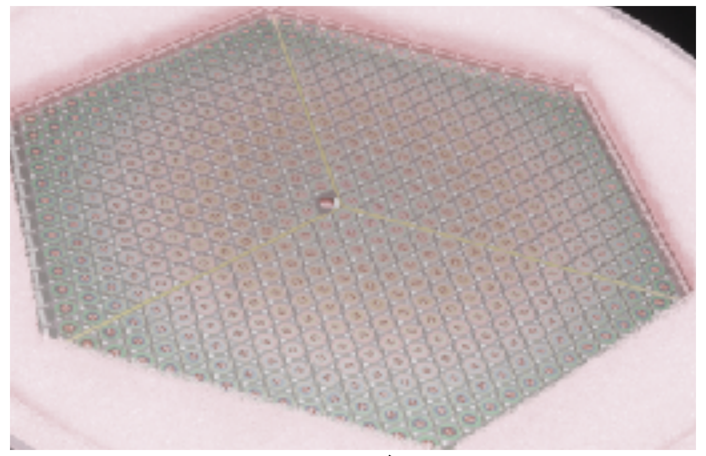
BICEP/Keck Collaboration, PRL 127, 151301 (2021)

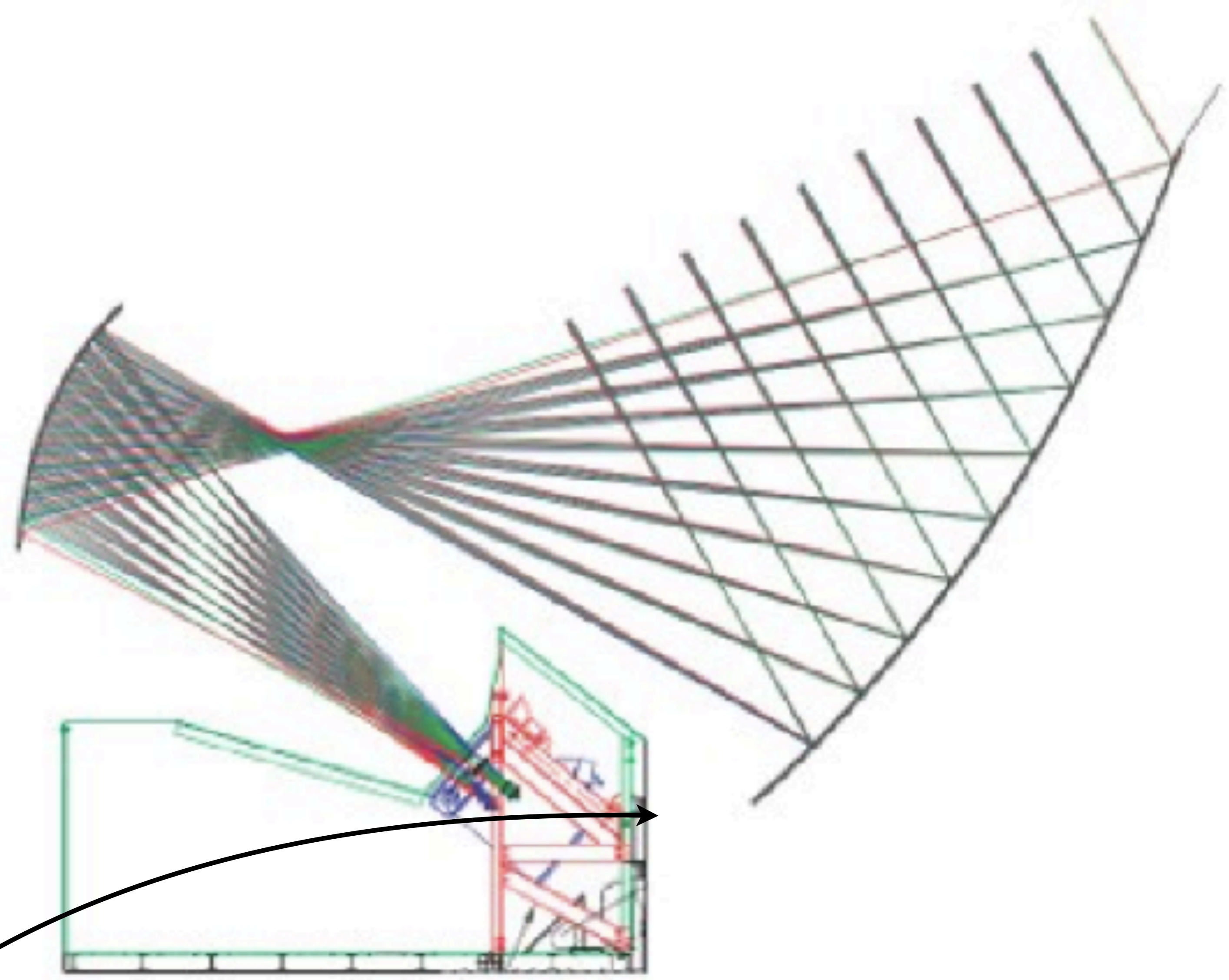
Advanced Atacama Cosmology Telescope (AdvACT)

Wide-area, high-resolution survey ended 2023

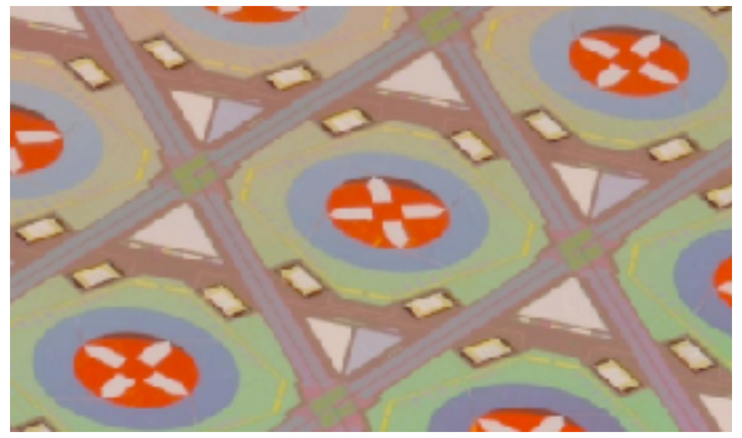


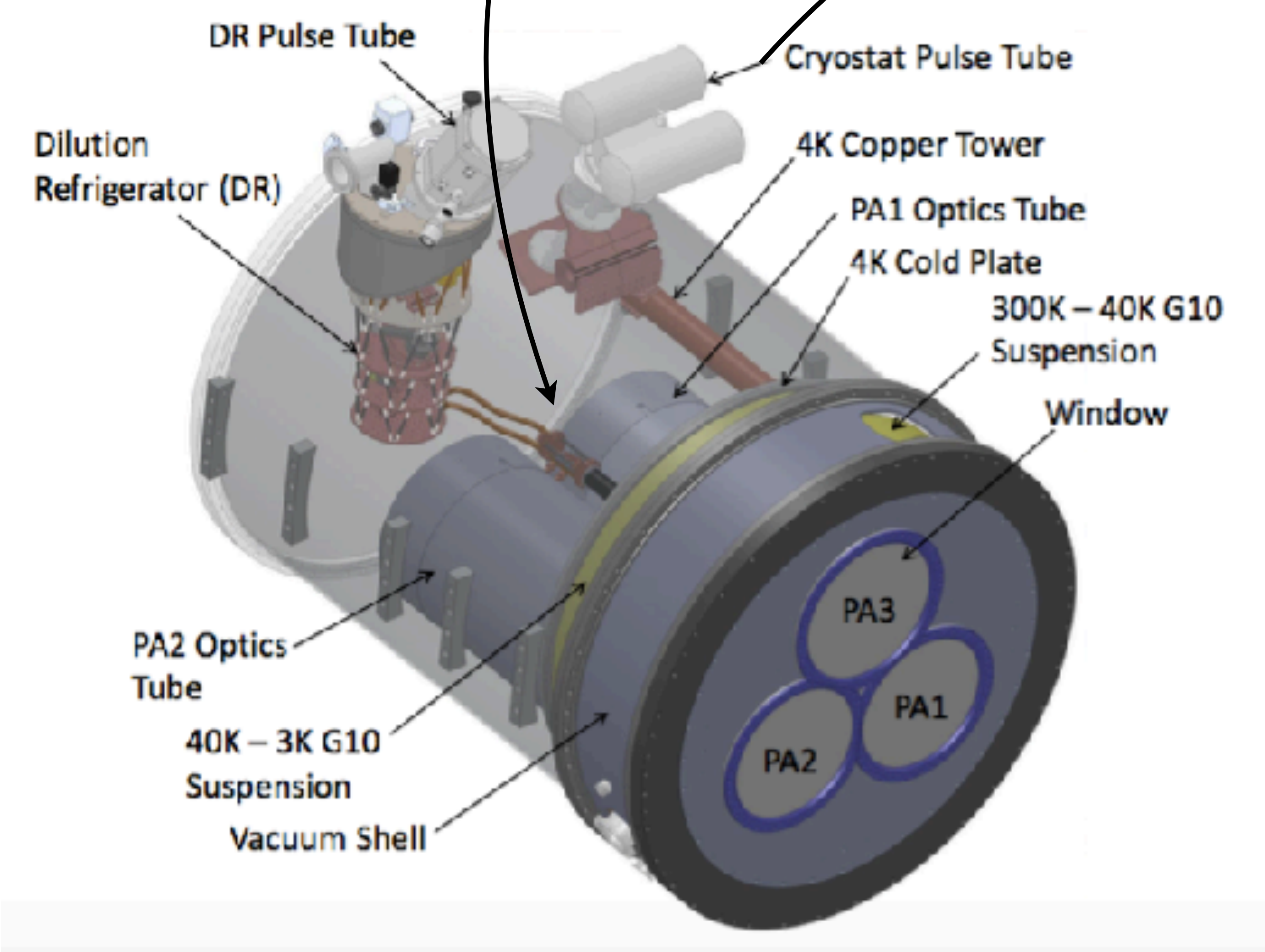
Detector/
Bolometer Arrays

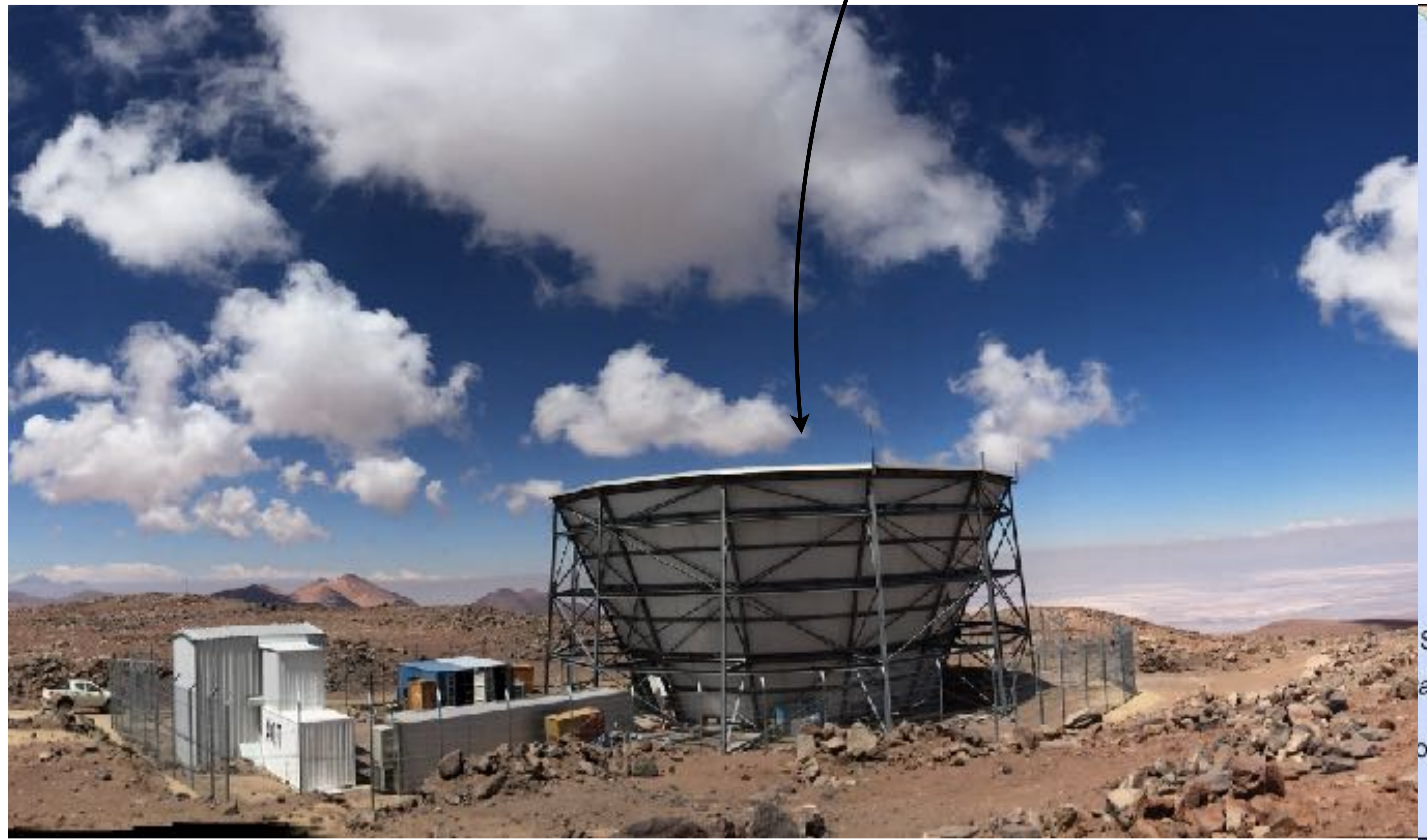




~3000 detectors







Material from Suzanne Staggs

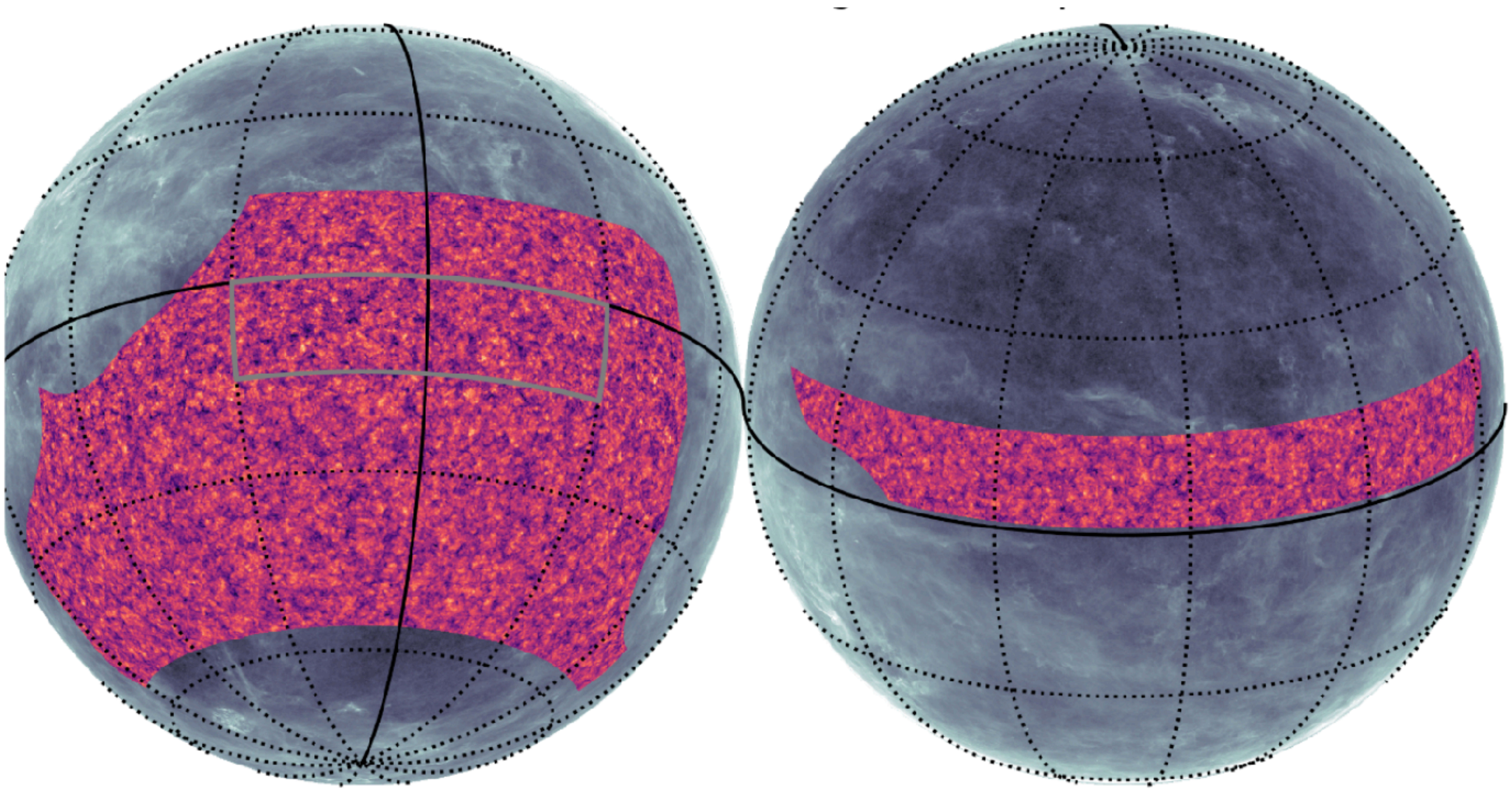
Material from Frank Qu

ACT DR6 high-fidelity lensing maps

Gravitational Lensing Convergence

$\kappa \propto$ mass density

- 2017-2021 Advanced ACT DR6 observations
- Covers 9400 sq deg, ~25% of the sky
- Detection at 43 σ
- 2x SNR per mode compared with *Planck*



Signal-dominated mass map covering a quarter of the sky

Constraining neutrino mass sum

- We combine with CMB anisotropies which predict low-redshift clustering amplitude

- Translate observed low-redshift clustering amplitude to suppression caused by massive neutrinos

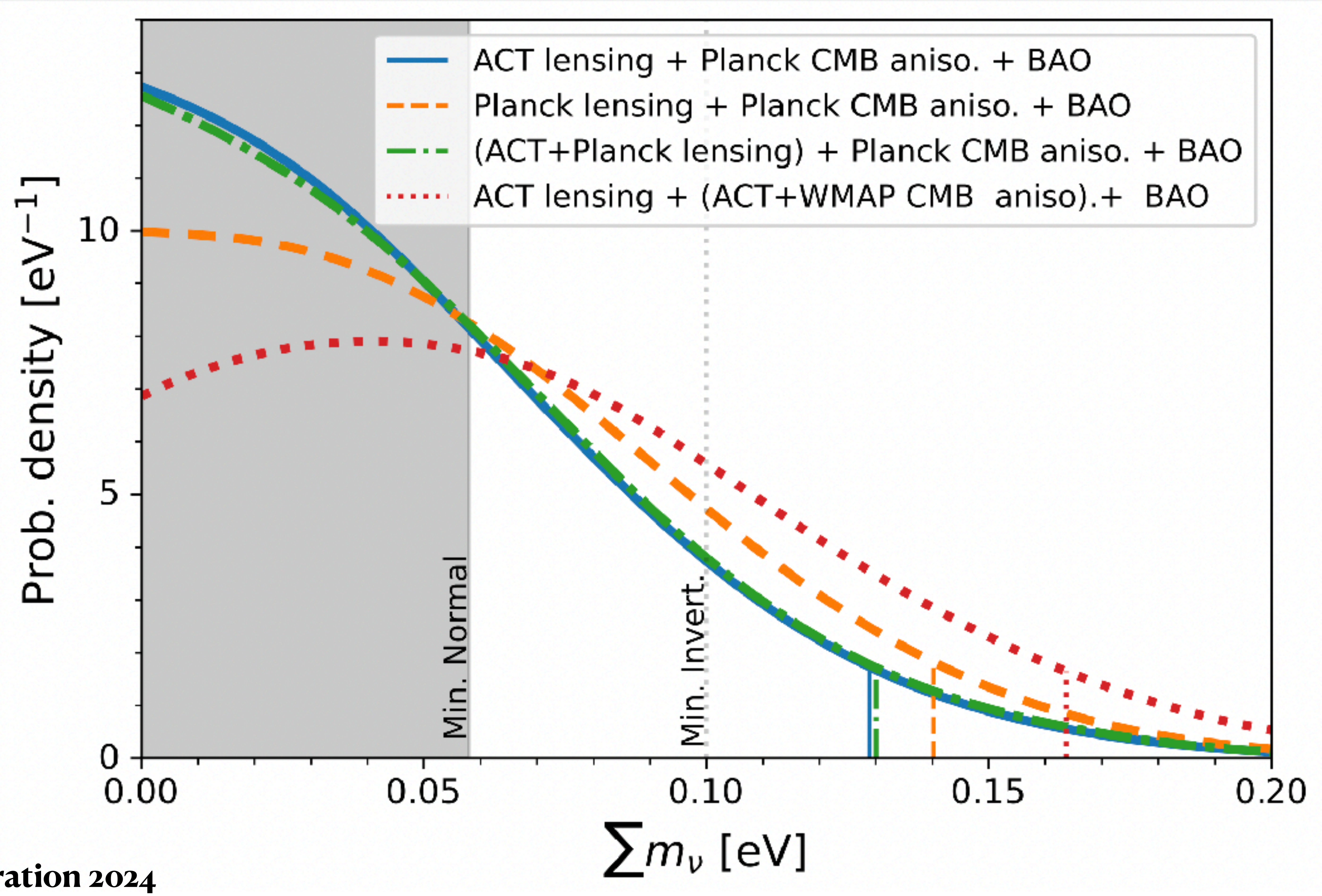
- **m<0.13 eV 95% c.l.** with BOSS BAO

  Compare to:

  (m<0.14 eV; Planck lensing)

  (m<0.16 eV; no lensing, only CMB+BAO)

- **m<0.072 eV with DESI BAO** **DESI Collaboration 2024**



Madhavacheril et al. (ACT Collaboration), Arxiv:2304.05203

See also *Shao et al 2409.02295* and *Farren, Krolewski, Qu, Ferraro et al 2409.02109* for more recent neutrino mass constraints

Slide from Frank Qu

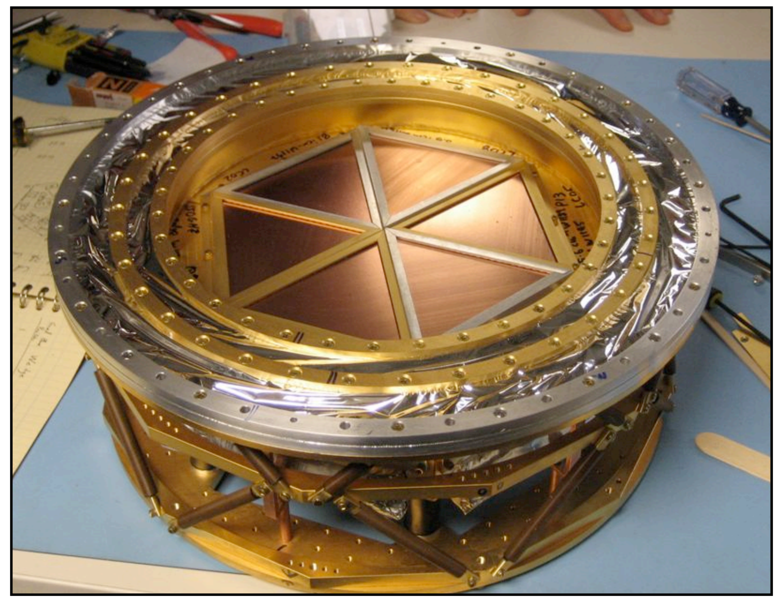
South Pole Telescope

Wide-area, high-resolution survey

2007-11: SPT-SZ

960 detectors

95,150,220 GHz

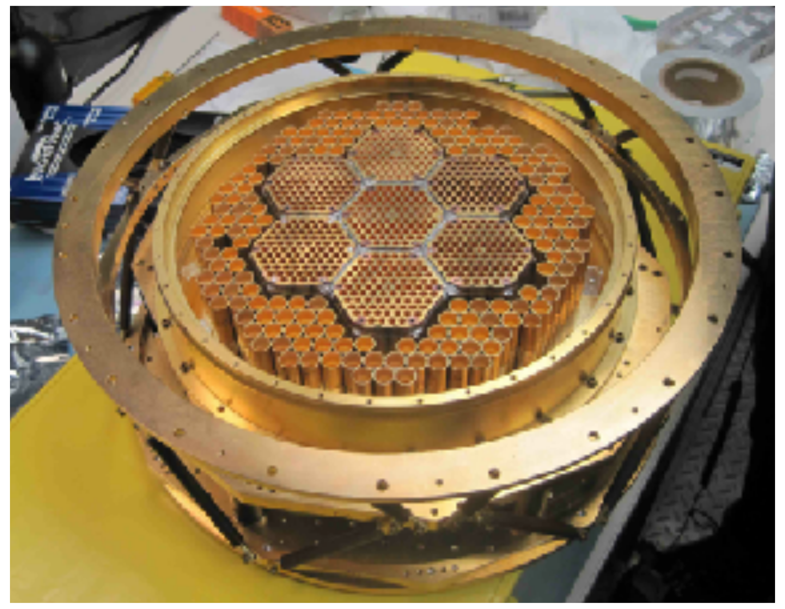


2012-16: SPTpol

1600 detectors

95,150 GHz

+polarization

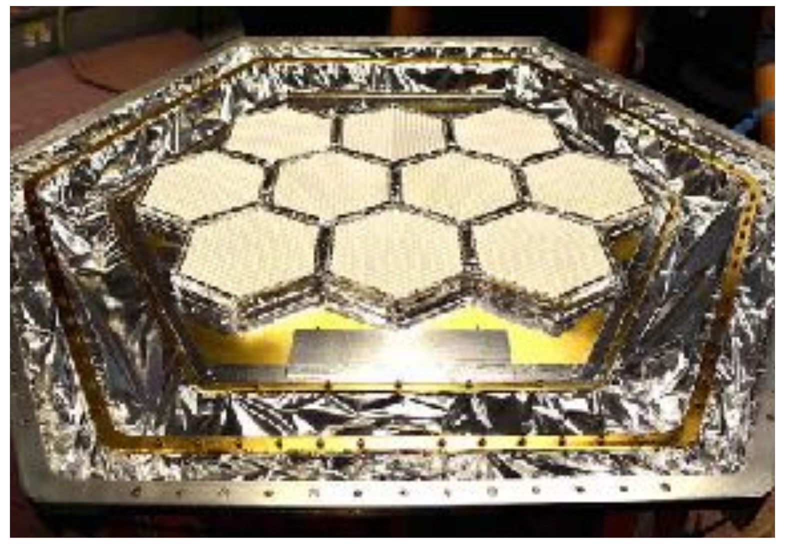


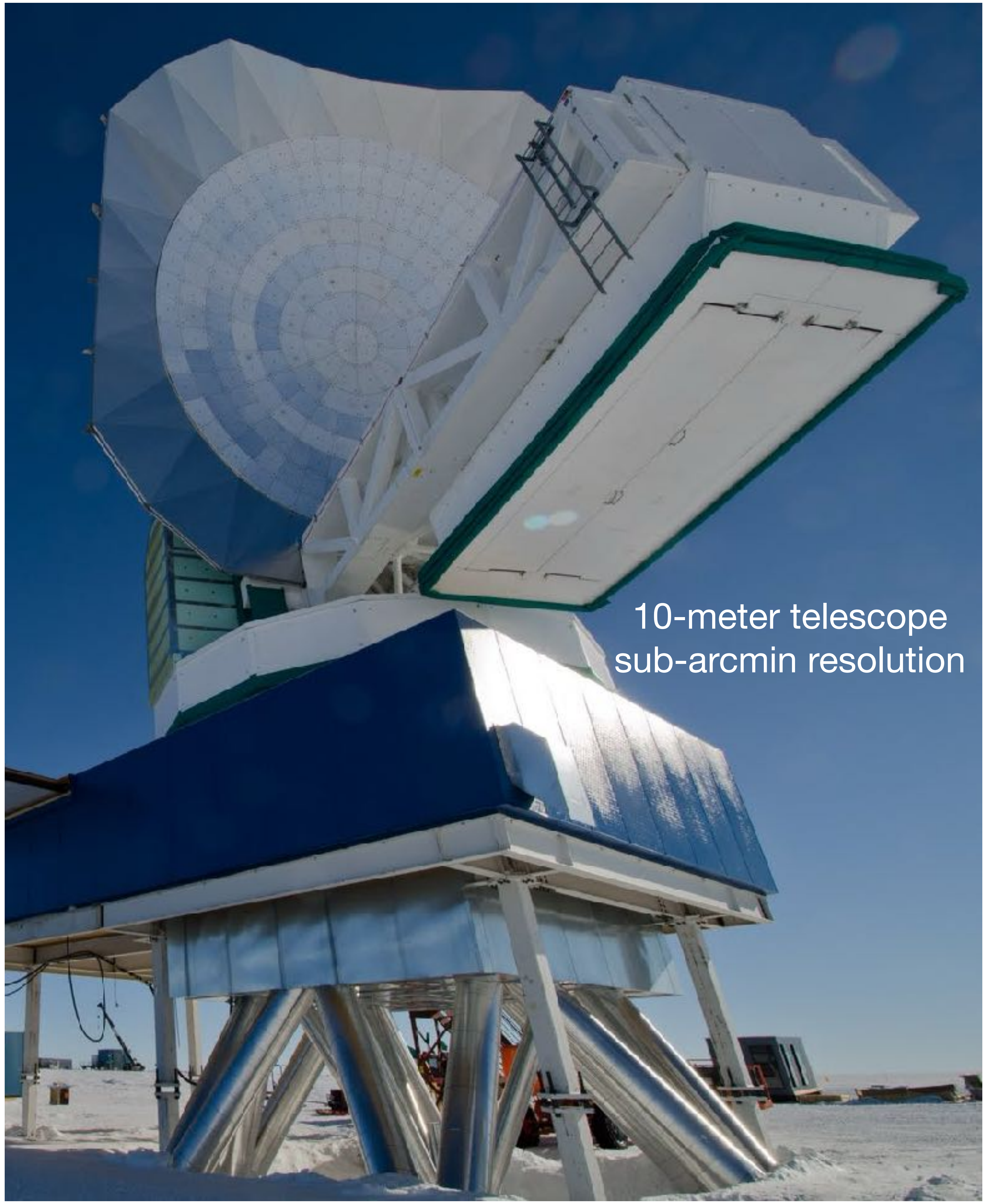
2018-now: SPT-3G

~16,200 detectors

95,150, 220 GHz

+polarization



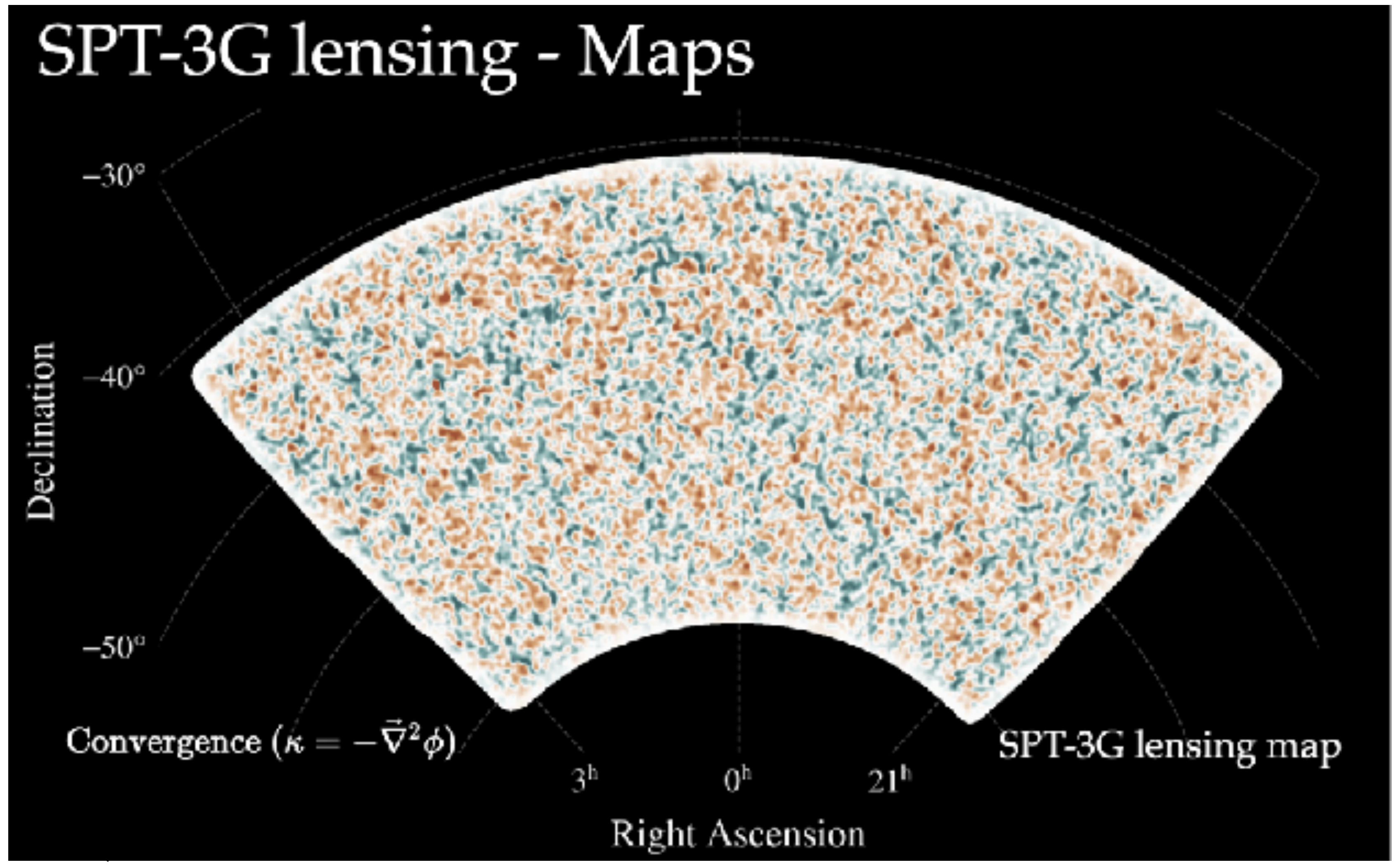


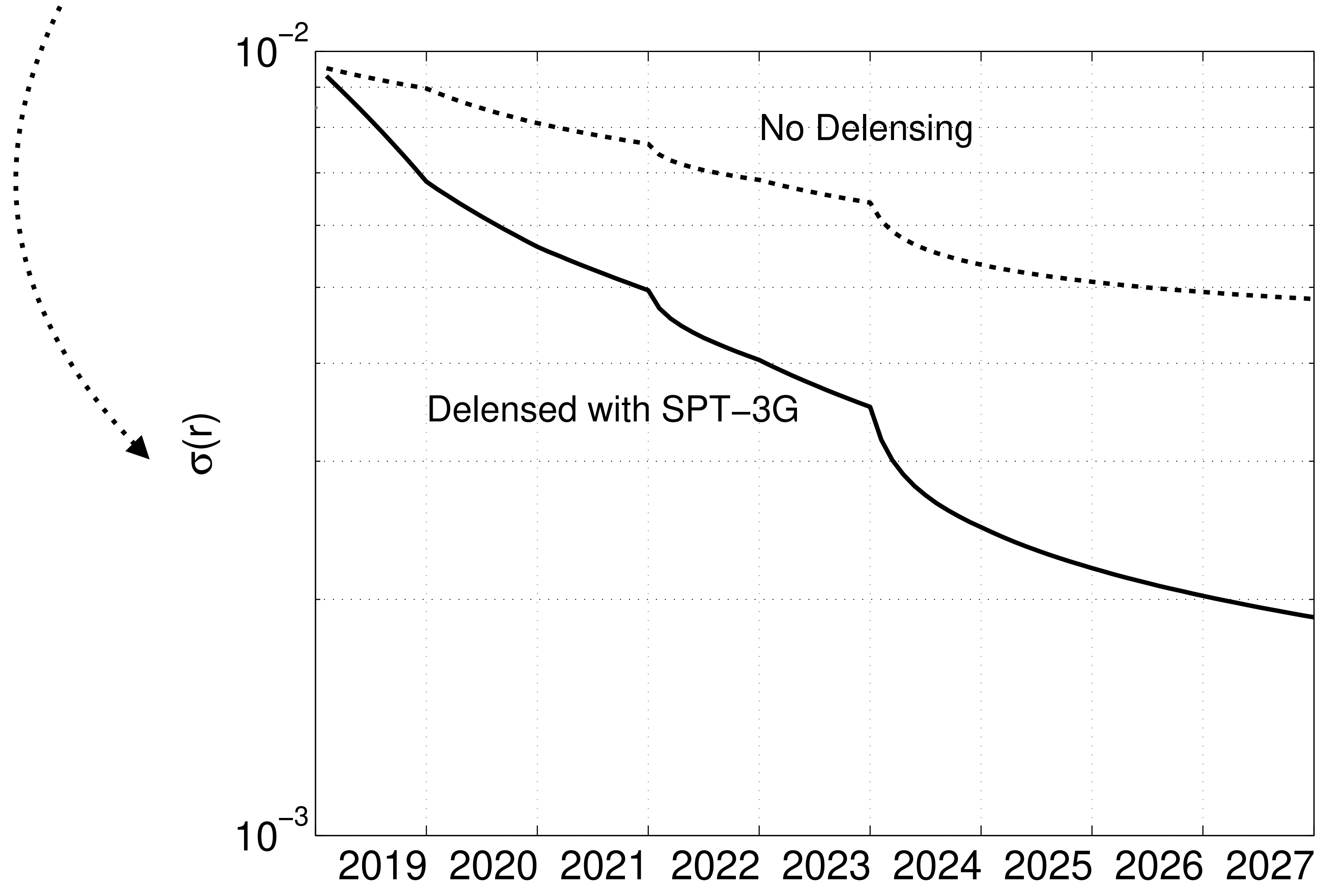
Slide from Federico Bianchini

Material from Yuuki Omori and Federico Bianchini

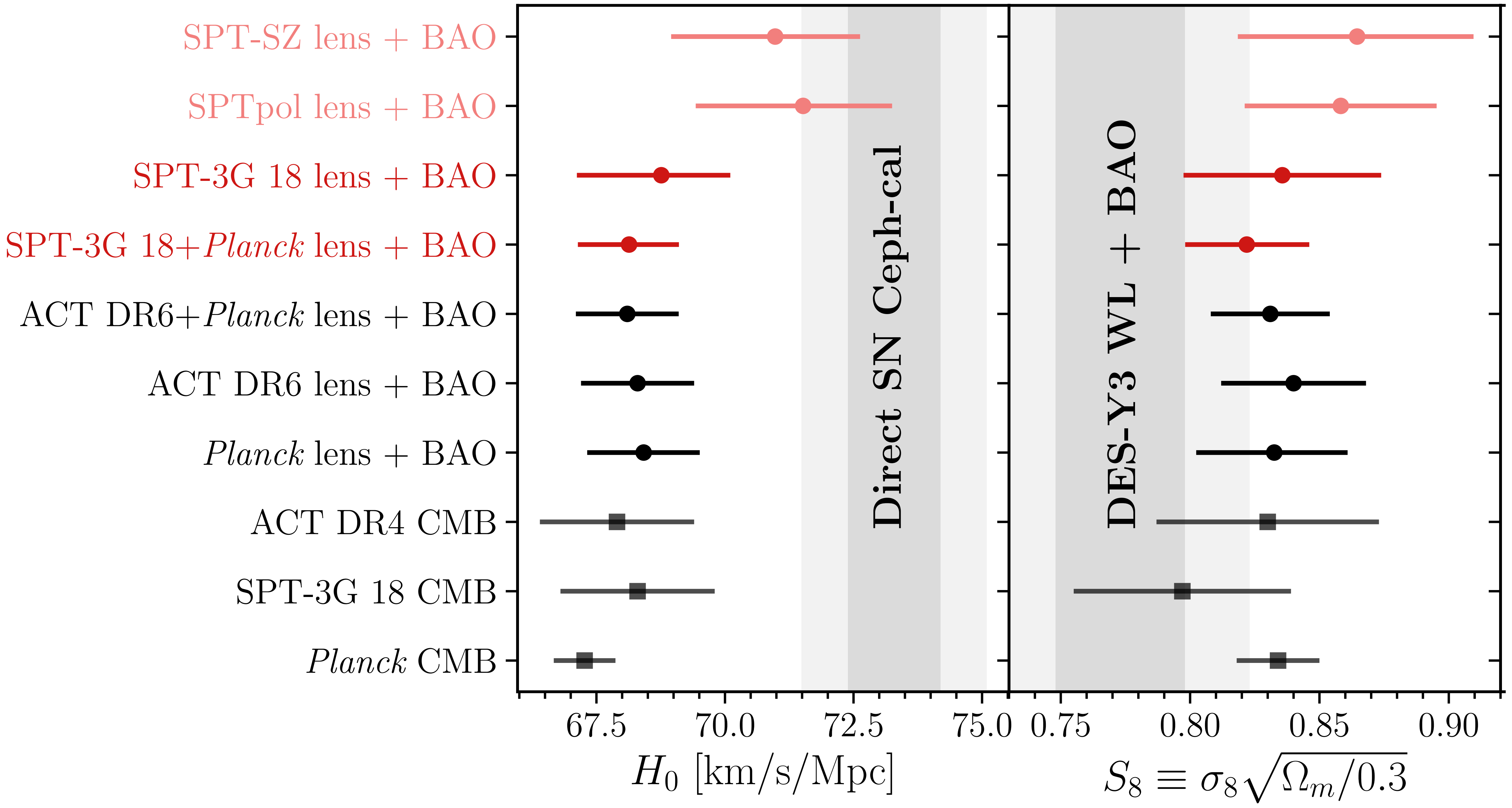
South Pole Telescope

Delensing and cosmology from ~few months of 2018 data





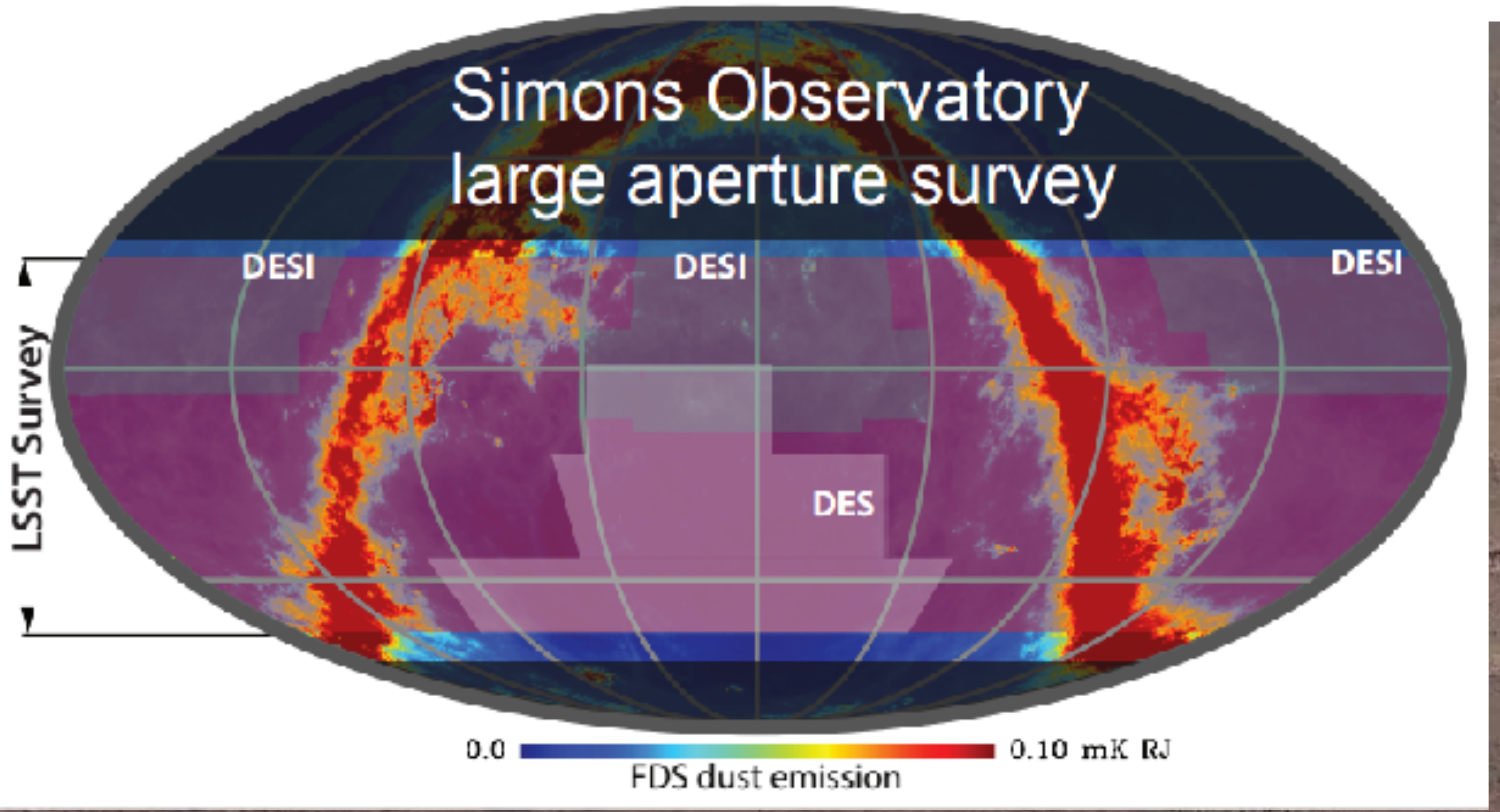
Pan et al (SPT Collaboration) 2308.11608

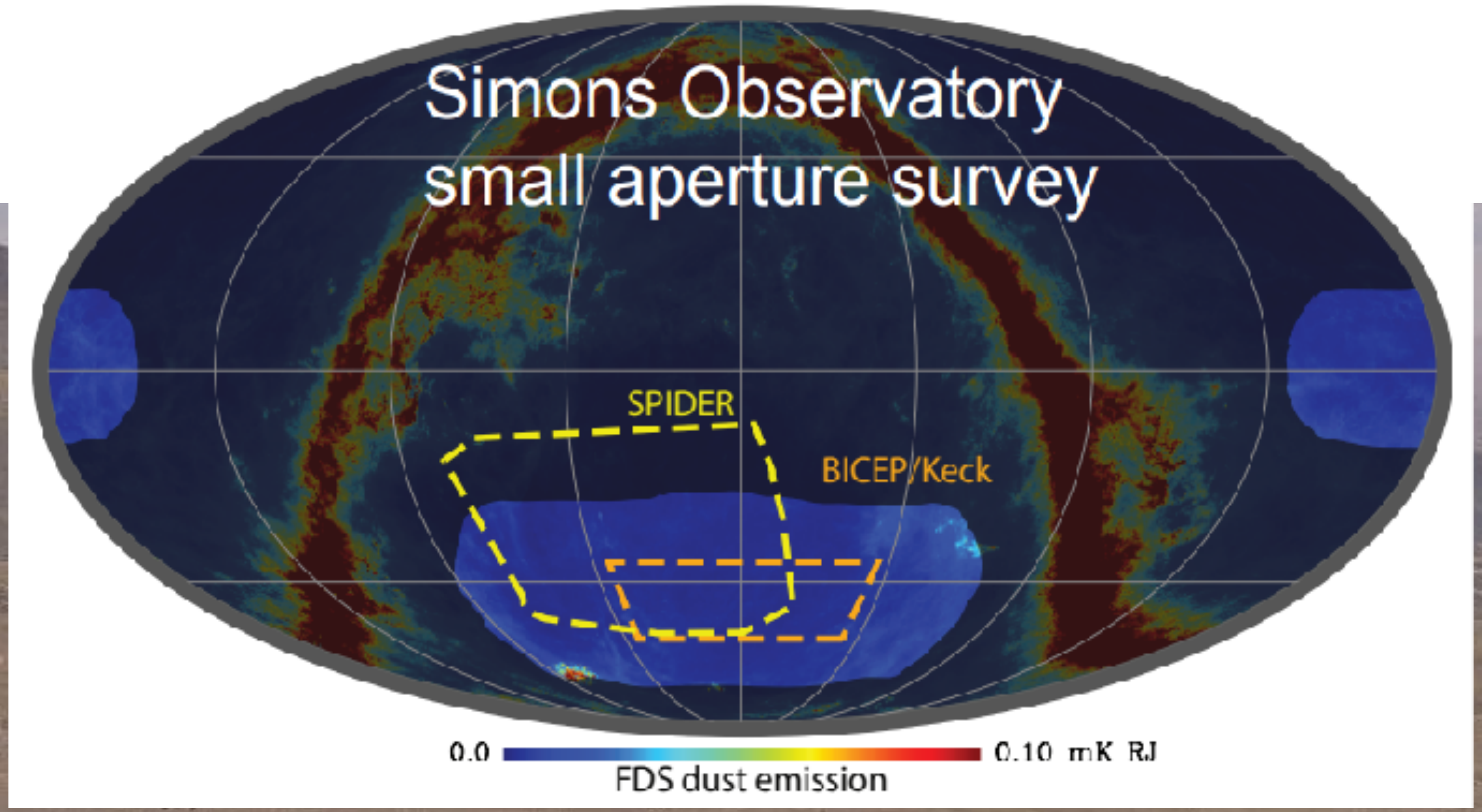


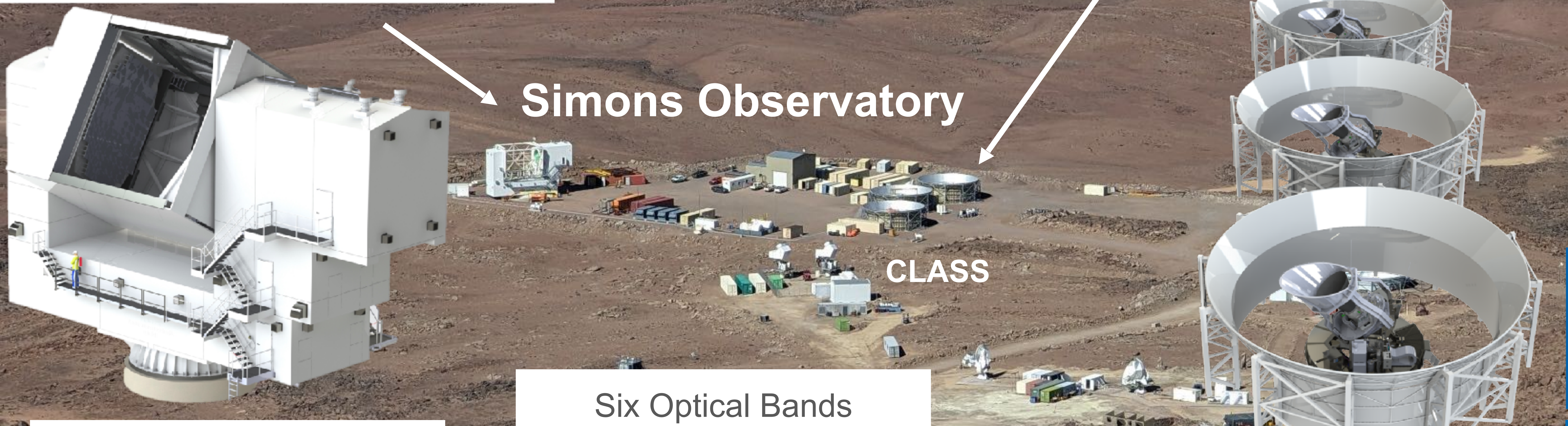
- H_0 and S_8 consistent with the cosmology inferred from Planck primary CMB measurements
- σ(H_0) ~ 1.5 km/s/Mpc when combined with BAO (2% measurement!)
- Good consistency with LCDM (deviations <1σ)

Substantially improved results in ~few weeks

The Simons Observatory (2024+)







6 meter cross-dragone
→ map 50% of sky
30,000 detectors

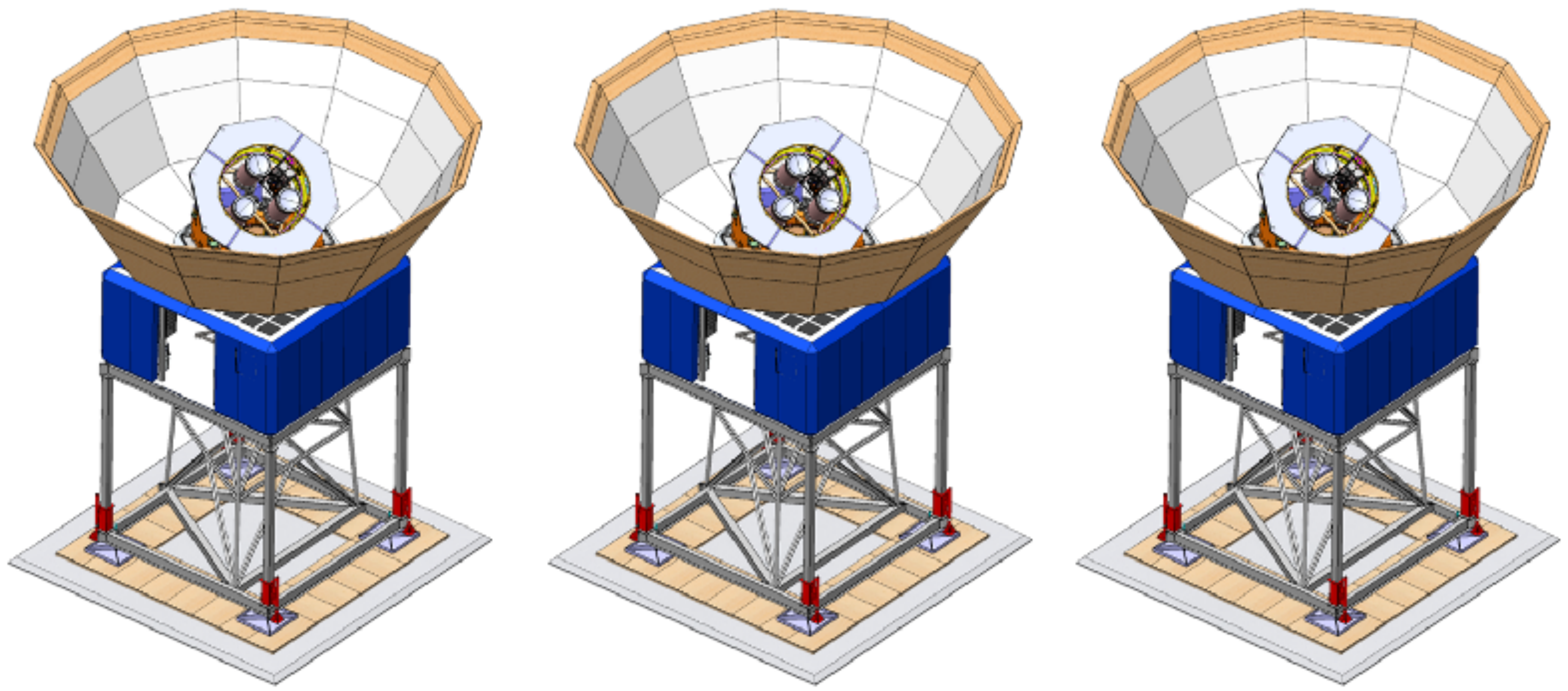
Six Optical Bands
LF: 30/40 GHz
MF:90/150 GHz
UHF: 220/280 GHz

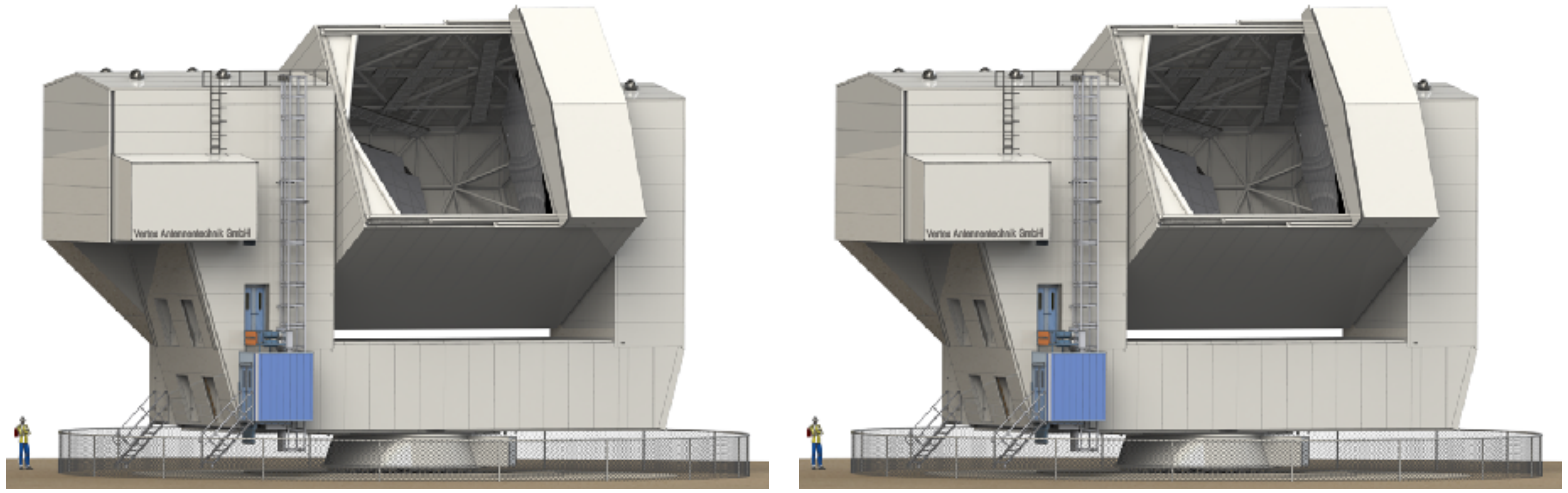
3 SATs → map 15% of sky
0.5 meter apertures
30,000 detectors

CMB S4

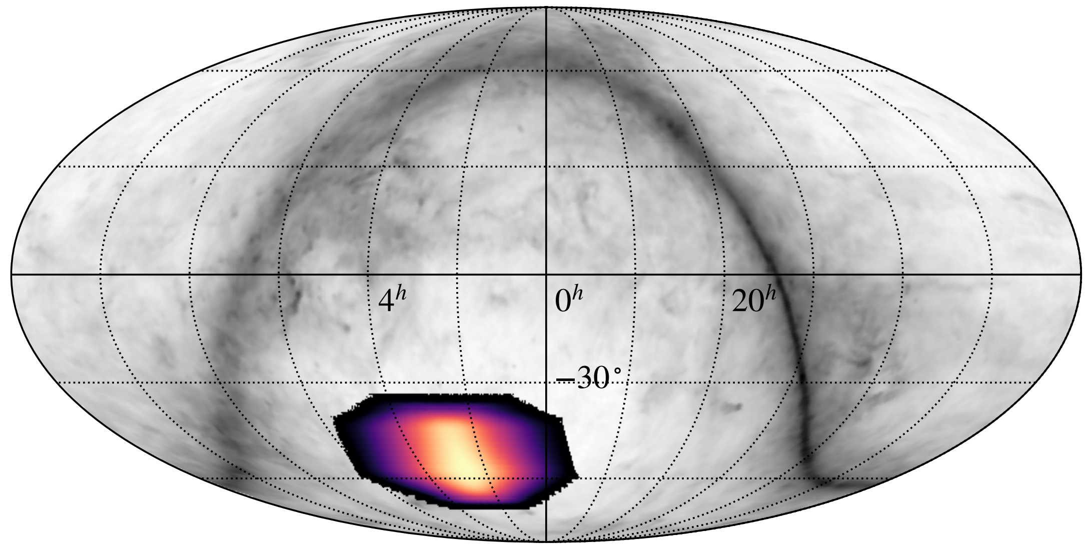
CMB-S4 Collaboration,
arXiv:1610.02743
arXiv:1706.02464
arXiv:1907.04473

The ultimate ground-based CMB survey experiment (2034+)

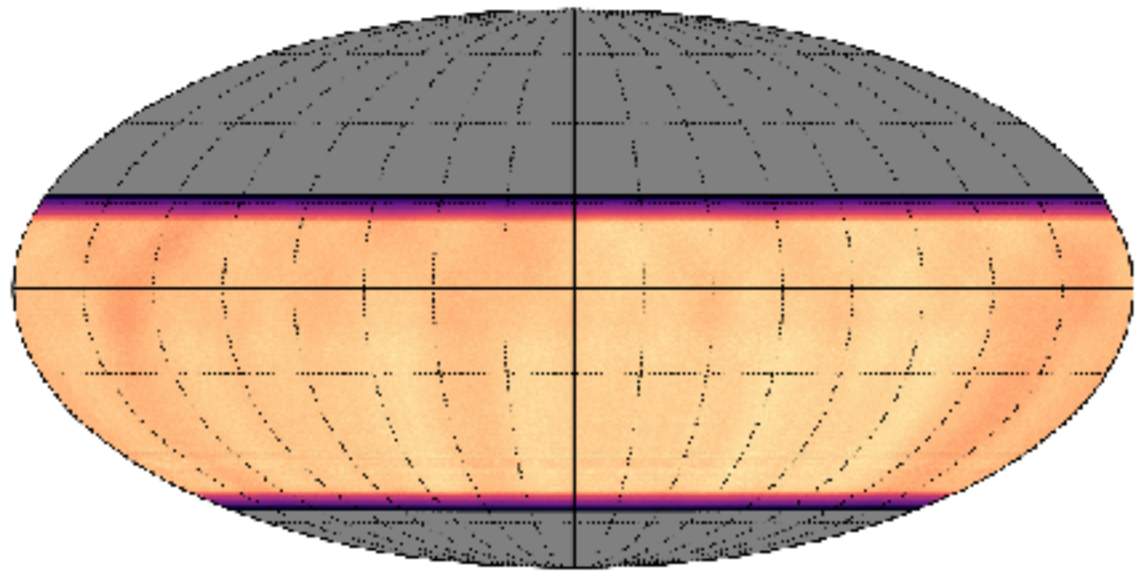




~500,000 detectors



Target **~3% of the cleanest sky** for deep integration with ~10-20x 0.5-m small-aperture telescopes to target inflation



Target **~60% sky**, from the **Atacama**, for wide area survey with ~3-5 high-resolution telescopes to target large-scale structure, particle physics, CMB lensing

Site renderings from CMB-S4 collaboration

The CMB science of the 2020s and 30's

Broad appeal to the HEP and astronomy communities

Light relic search
$\Delta N_{\text{eff}} \leq 0.06\ (2\sigma)$
via T, E spectra

Inflation
$r > 0.003\ (5\sigma)$
via B spectrum

Reionization mapping
via kSZ

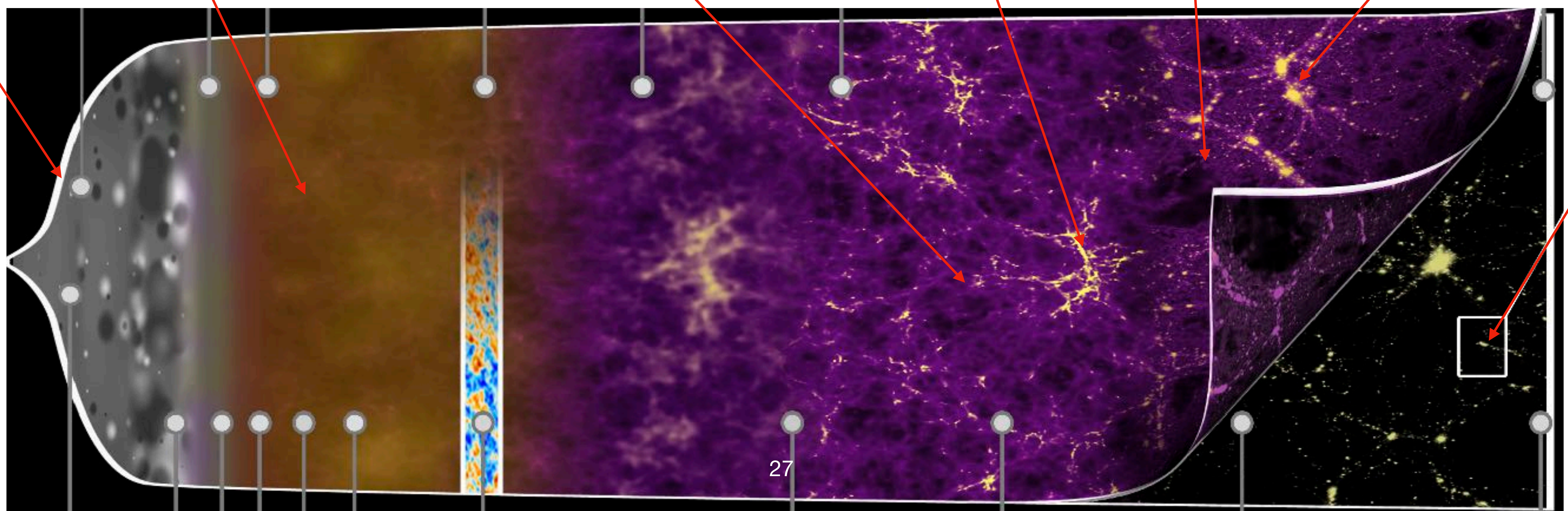
Neutrino masses
$\sigma(\sum m_\nu) \sim 0.025\,\text{eV}$
via tSZ clusters, lensing (+LSST, DESI)

Galaxy evolution and baryonic feedback
via SZ mapping of gas pressure and momentum

Dark Energy, Growth of structure (σ_8)
via kSZ, lensing, and tSZ clusters (~70,000)

Galactic science, Magnetic fields, ISM

mm-wave transient survey GRBs, fast transients, AGN

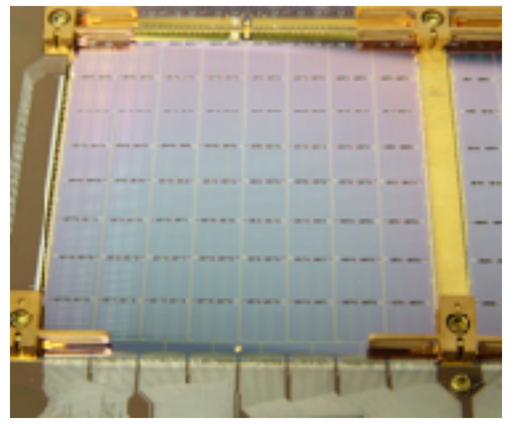


tSZ = thermal SZ
kSZ = kinetic SZ
SZ= Sunyaev Zeldovich effect

Summary

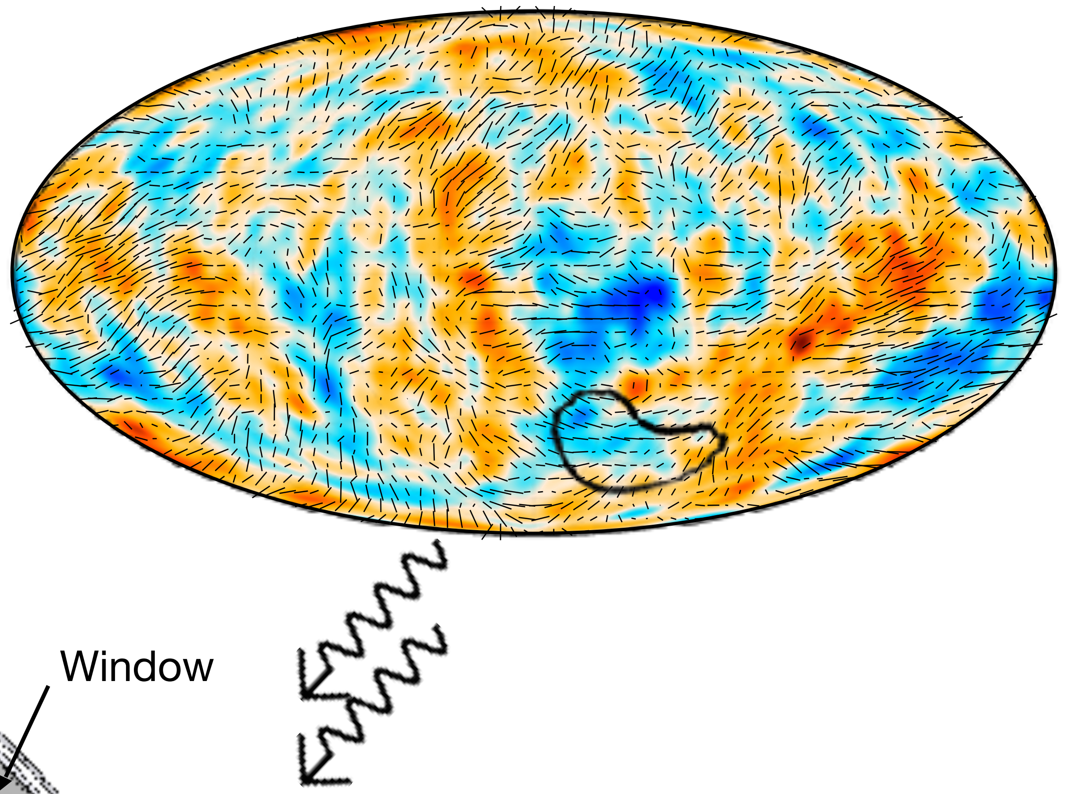
- The Cosmic Microwave Background provides an early universe view of cosmology and particle physics. It also provides a backlight to cosmic structure which probes intermediate redshifts and provides more modes to constrain parameters.
- The tightest constraints on tensor-to-scalar ratio come from BICEP. Parameter space exploration will continue with BICEP and upcoming inflation experiments.
- The CMB contains information about light relics, neutrino mass and cosmological parameters. CMB weak lensing is starting to offer a new probe for many of these measurements. ACT and SPT are producing new parameter constraints with CMB lensing.
- Exciting results to come over the next decade from BICEP, SPT and Simons Observatory.
- Subsequently, CMB-S4 will provide a substantial leap in sensitivity.

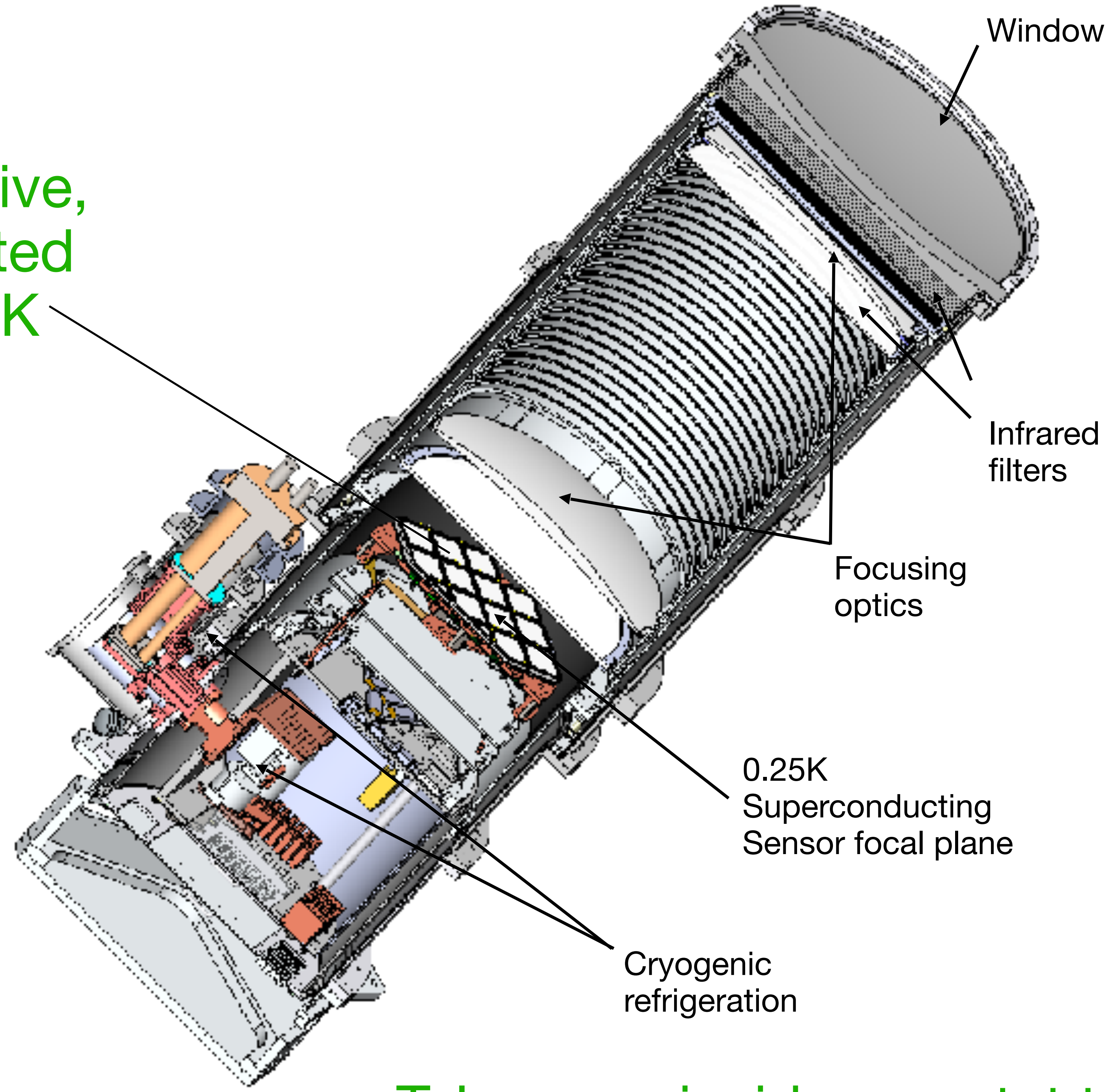
BICEP program designed to maximize sensitivity



Polarization-sensitive, photon-noise-limited sensors at 100mK

Integrate deeply on a small patch of sky





The BICEP3 camera

Telescope inside cryostat to reduce instrument's own thermal noise

~10,000ft, ~0.25mm precipitable water vapor

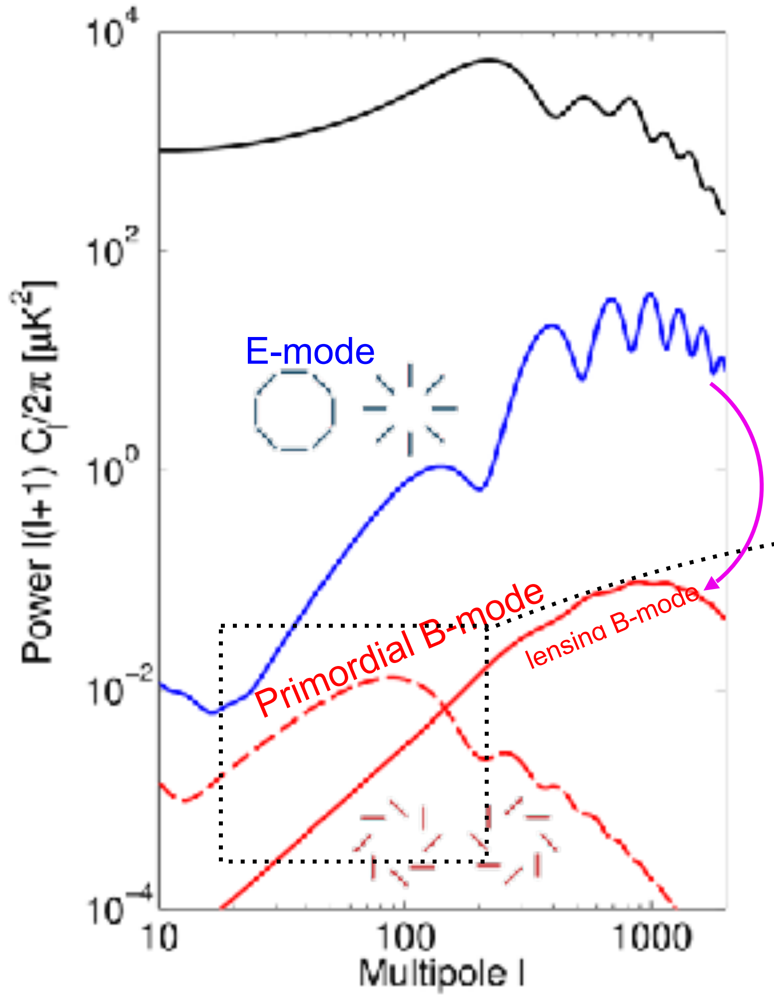
High atmospheric transmission in mm-wave windows

6 months of cold, stable winter sky (no diurnal variation)

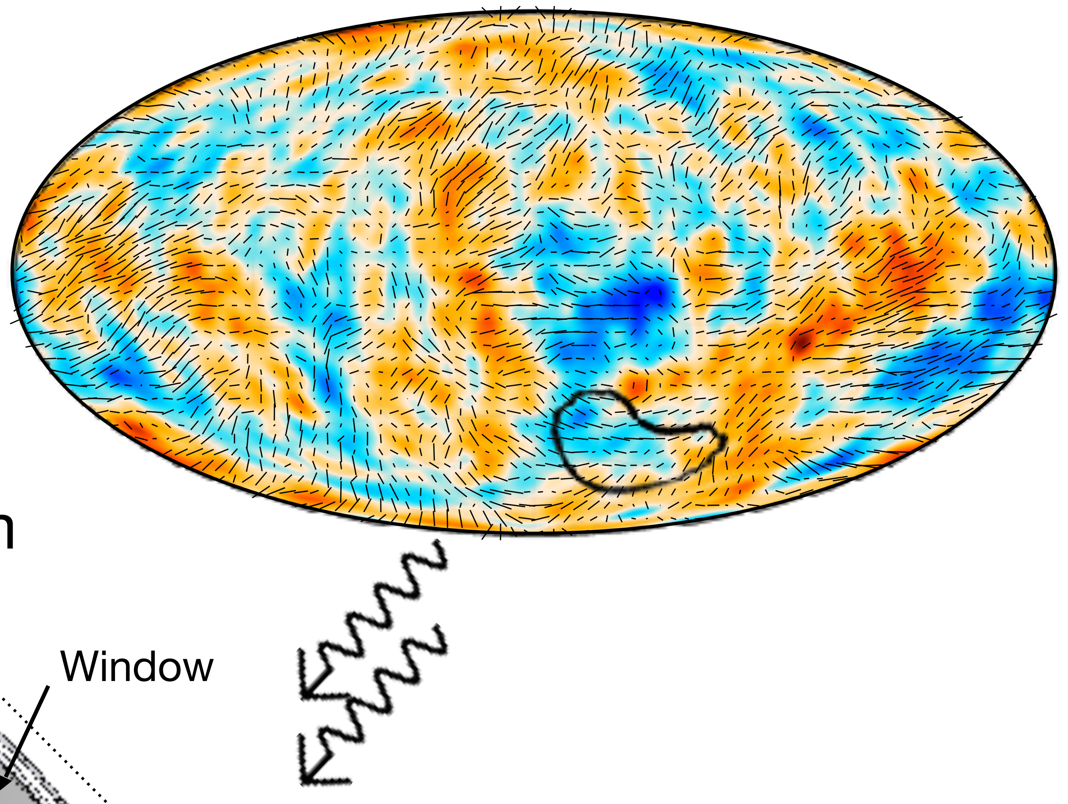
Long periods of uninterrupted integration

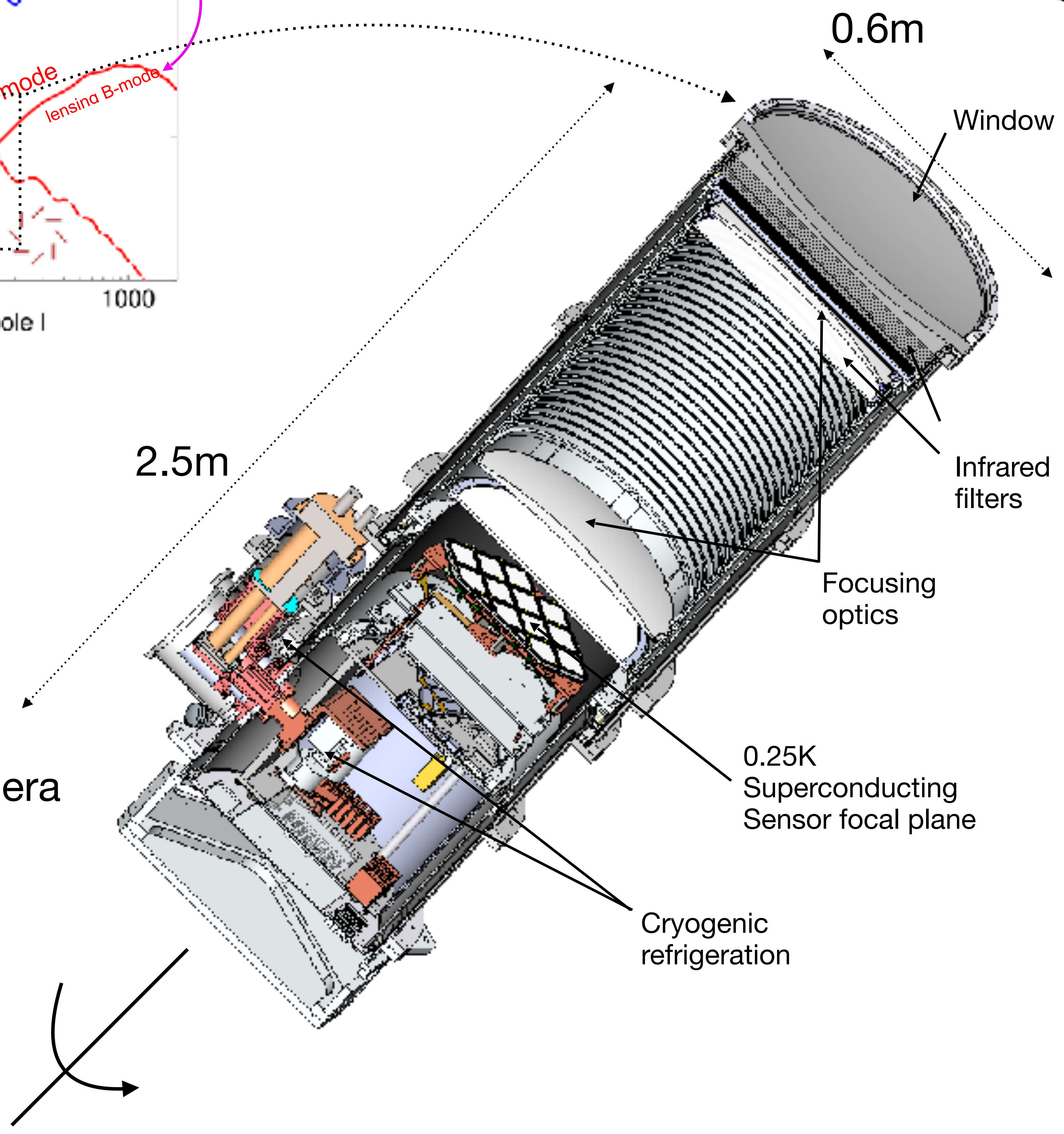
BICEP/Keck Collaboration, ApJ 927 77 (2022)

BICEP program designed to control systematic effects



Only sufficient resolution for degree scale B-modes, so can make compact

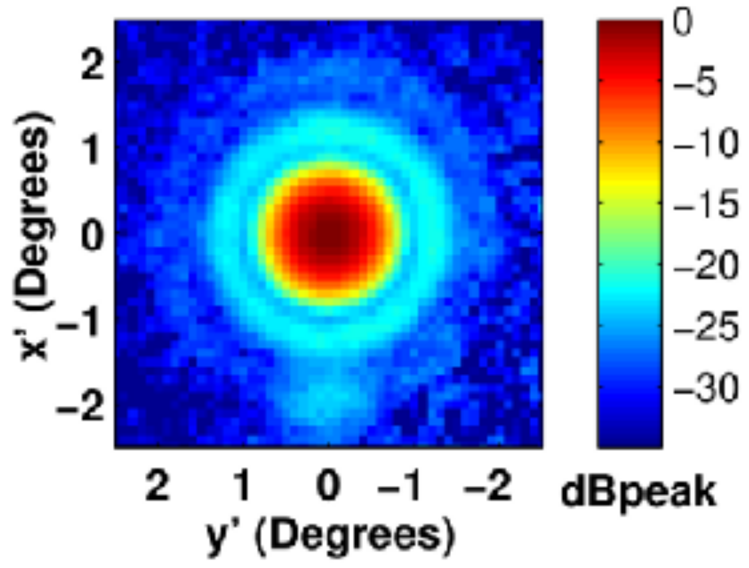


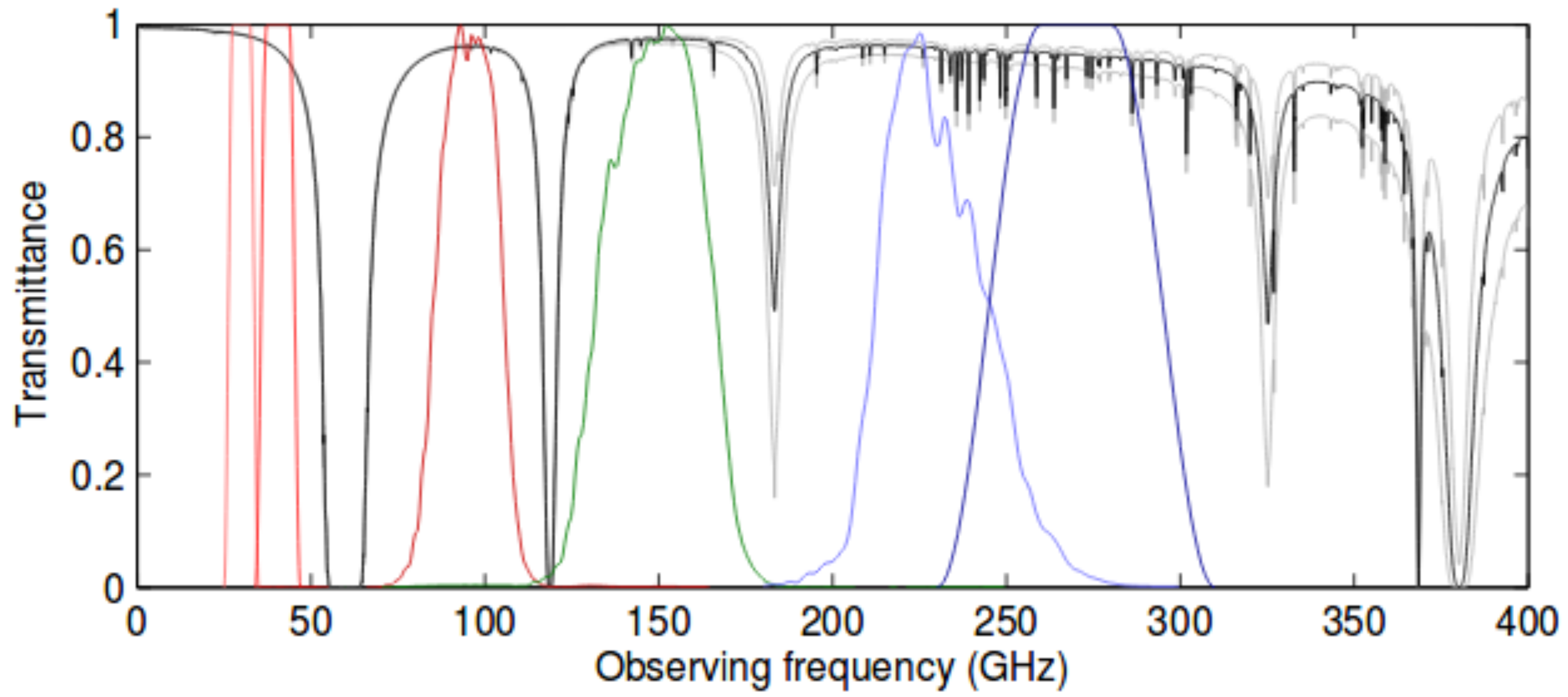


BICEP3 camera

Boresight rotation to average down certain classes of systematics

Extensive characterization of instrument response (point spread function, spectral response etc.)



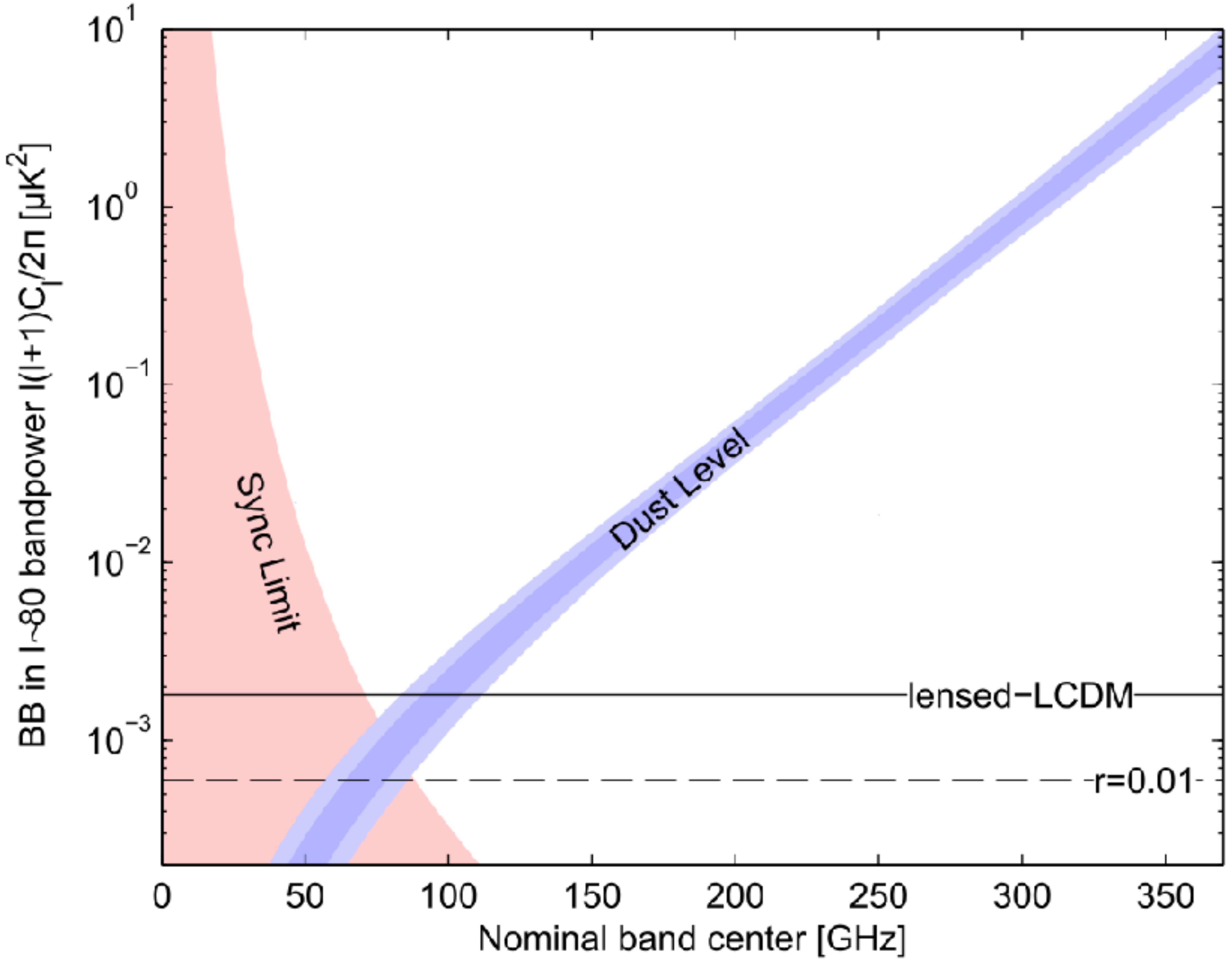


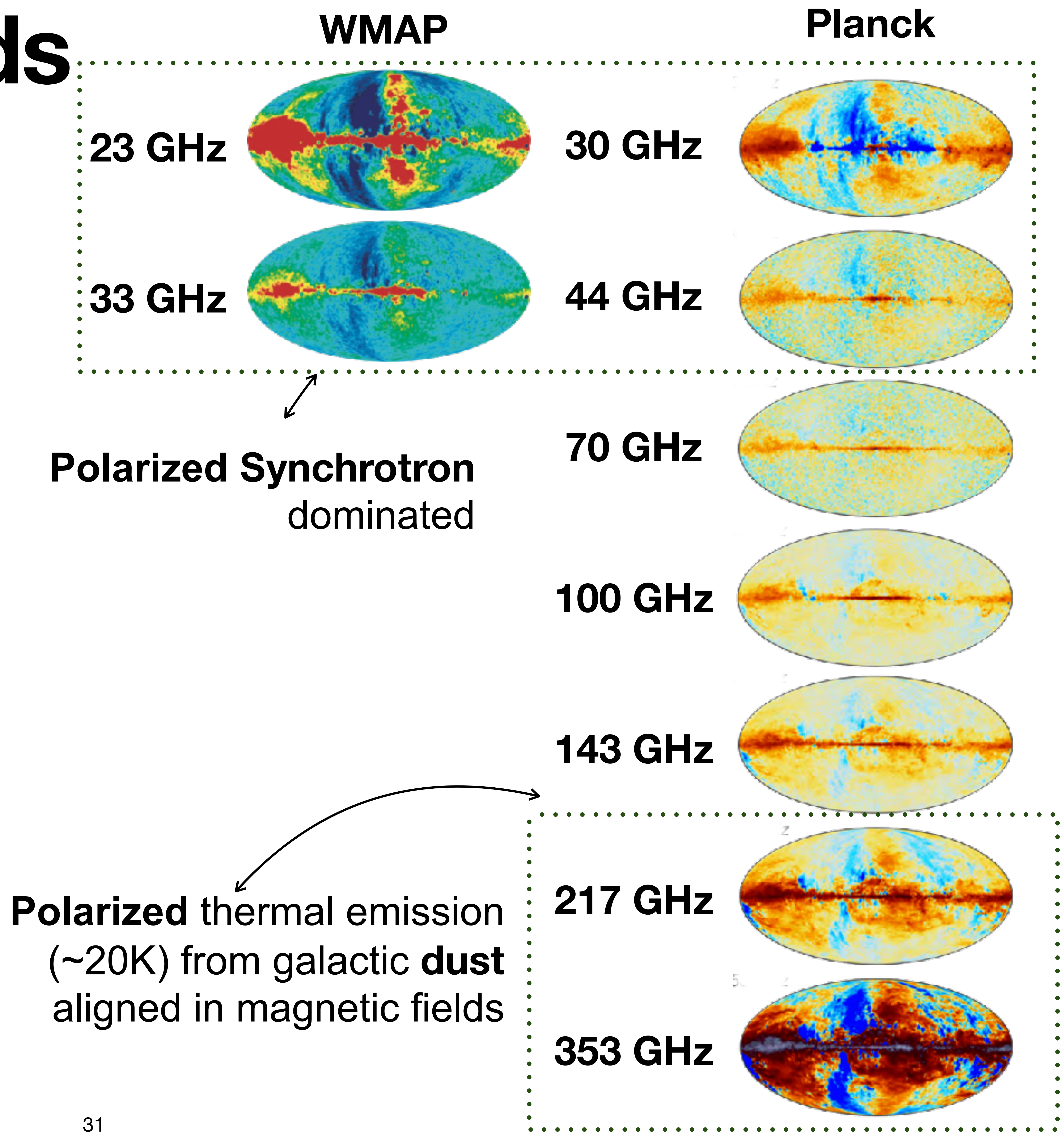
Observe in multiple frequencies (30, 40, 90, 150, 220, 270 GHz) to tease apart CMB from dust and synchrotron foregrounds

BICEP/Keck Collaboration, ApJ 927 77 (2022)

Galactic Foregrounds

Different spectral behavior

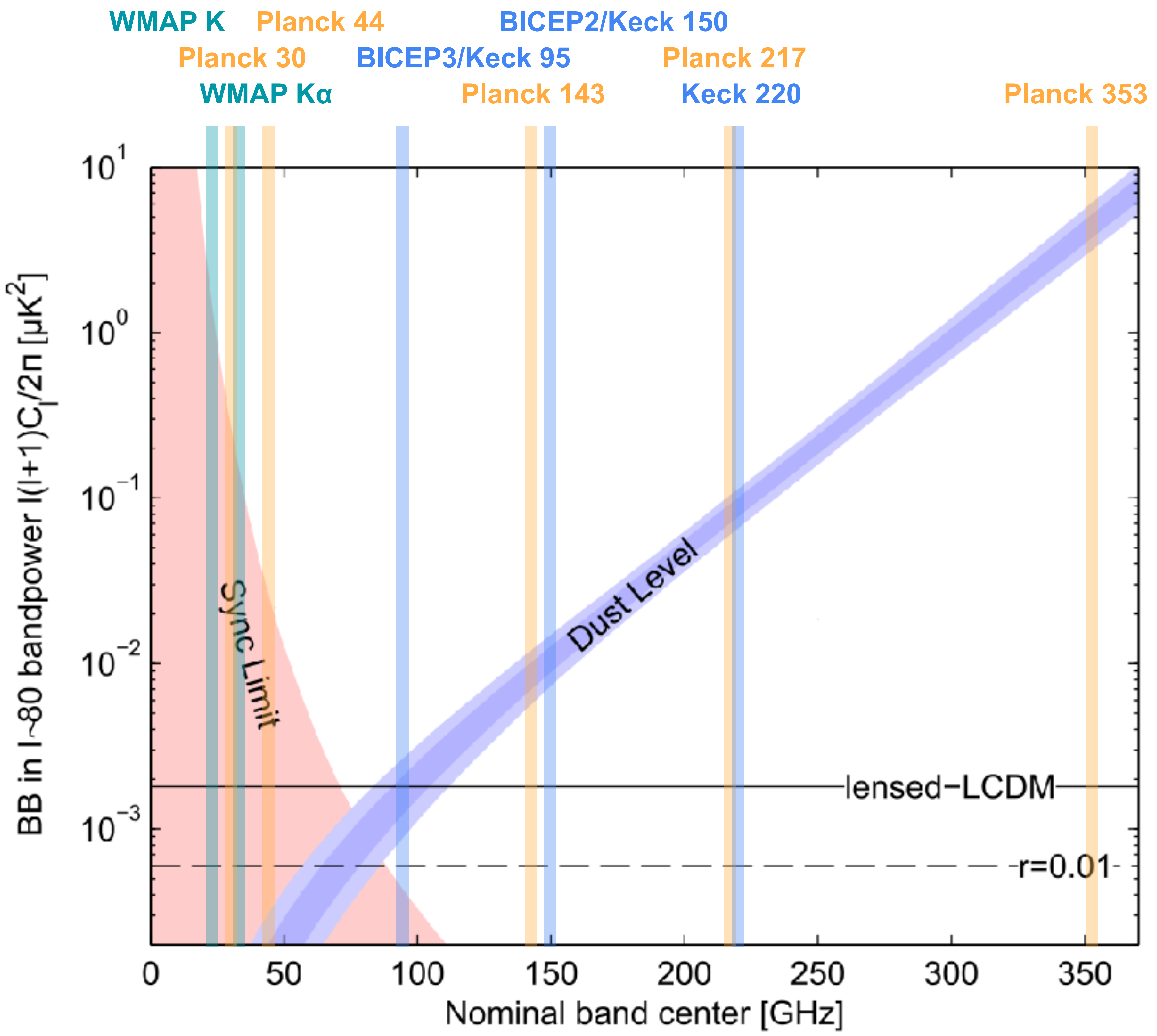


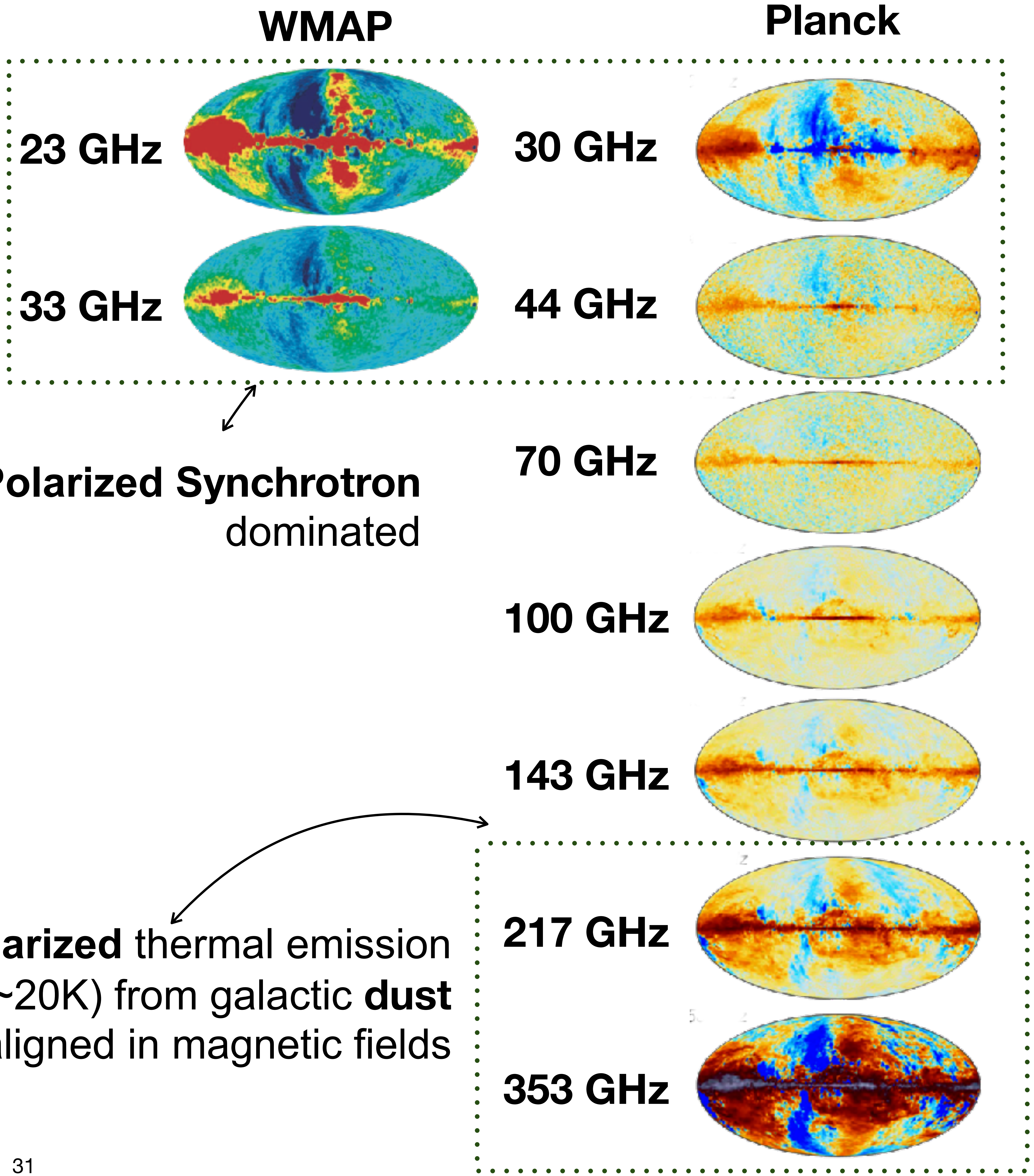


Figures from BICEP, Planck and WMAP

Galactic Foregrounds

Different spectral behavior





Polarized Synchrotron dominated

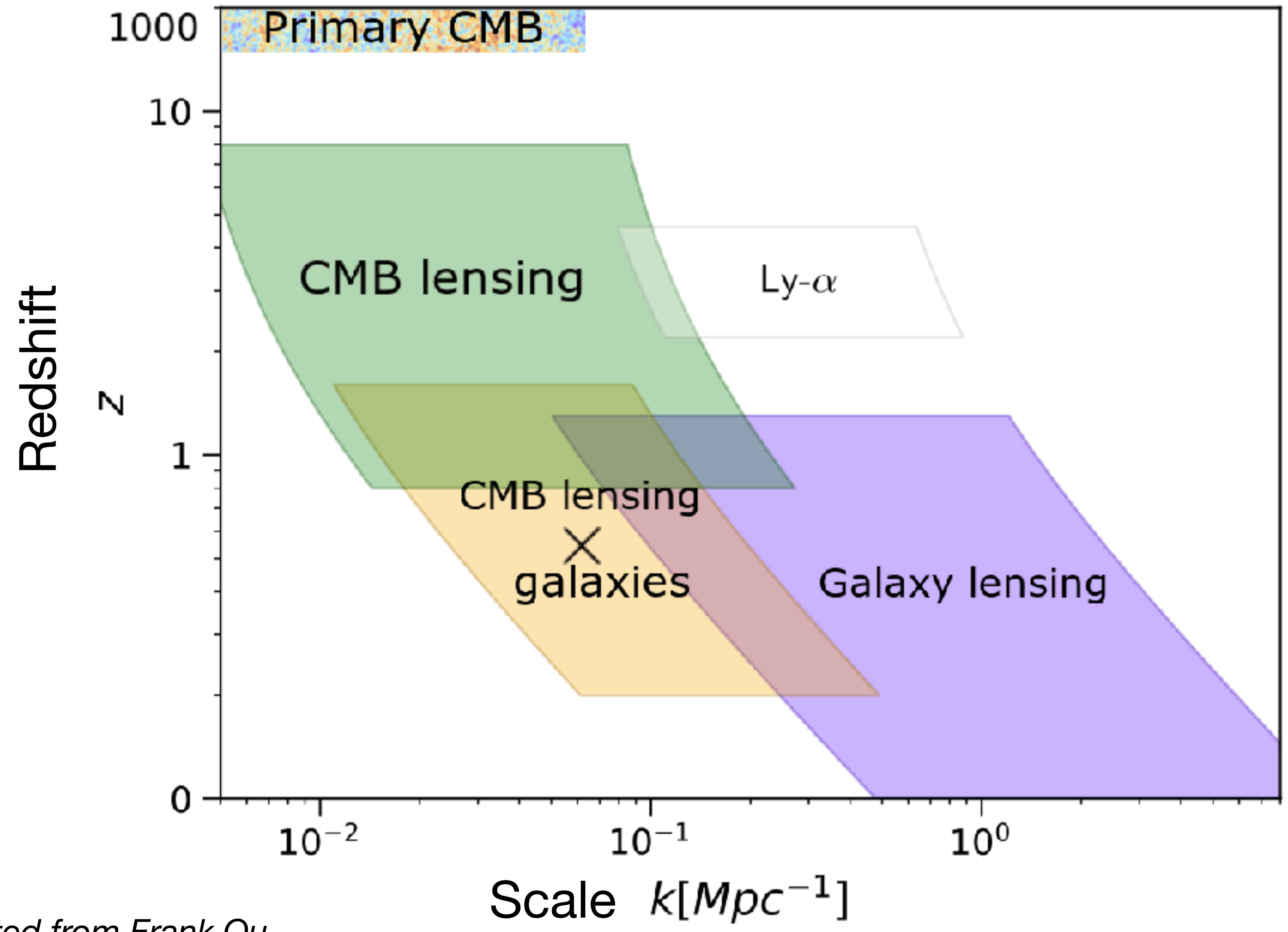
Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields

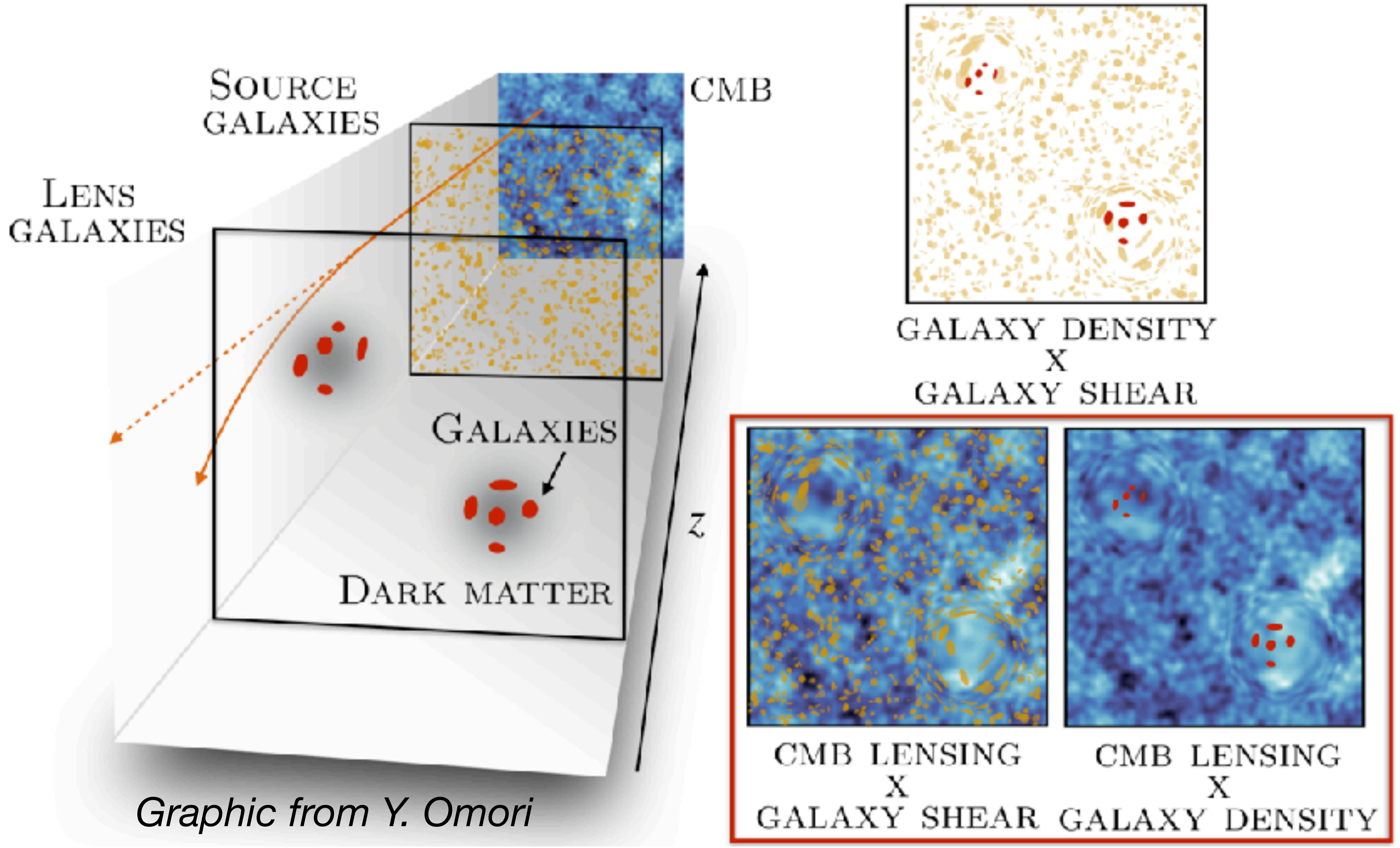
Figures from BICEP, Planck and WMAP

How can CMB lensing help clarify the S8 tension?

Cross correlation of CMB lensing and galaxy lensing probes

Can provide complementary insight into systematics and test redshift or scale dependence of any new physics





Graphic from Y. Omori

Slide adapted from Frank Qu

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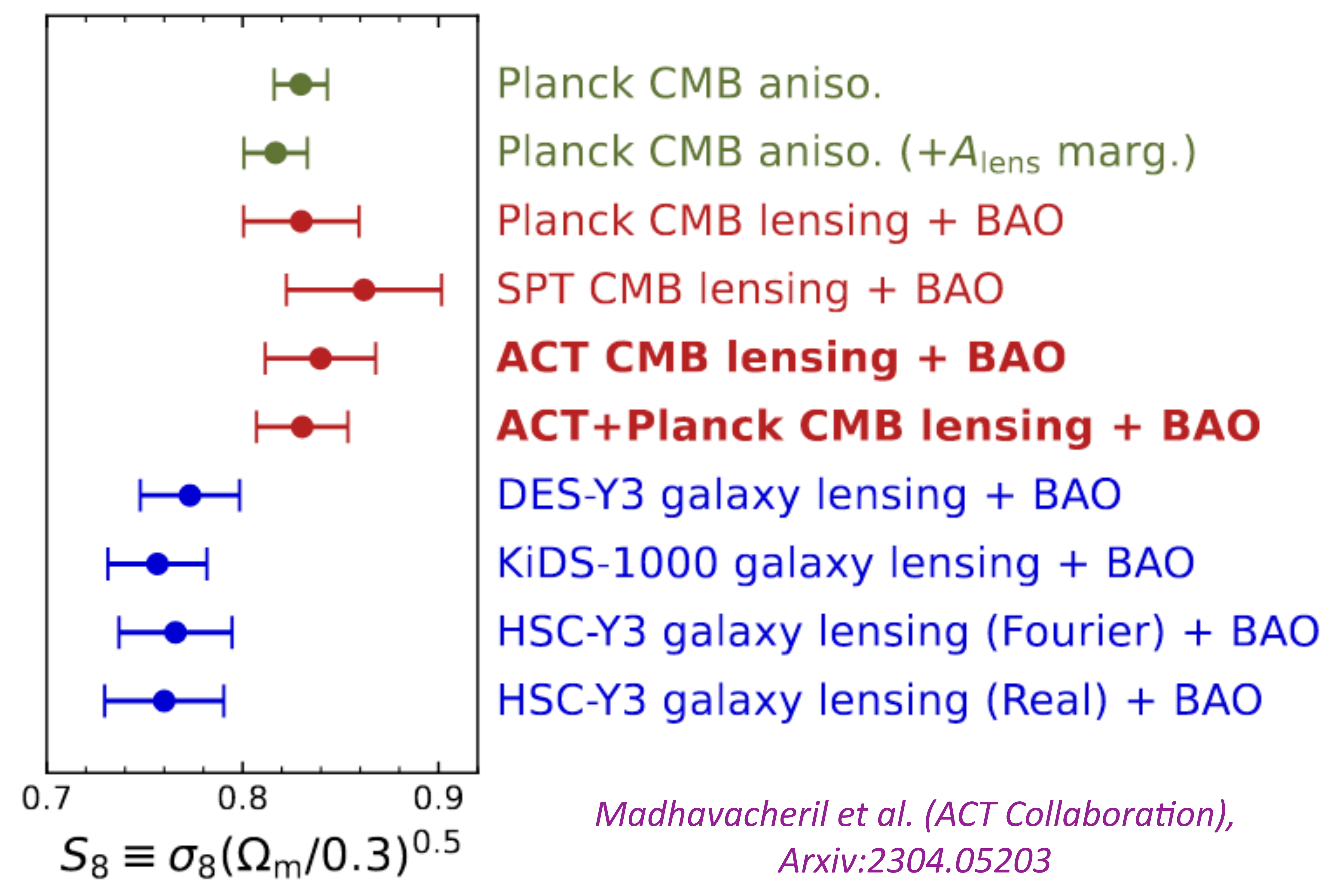
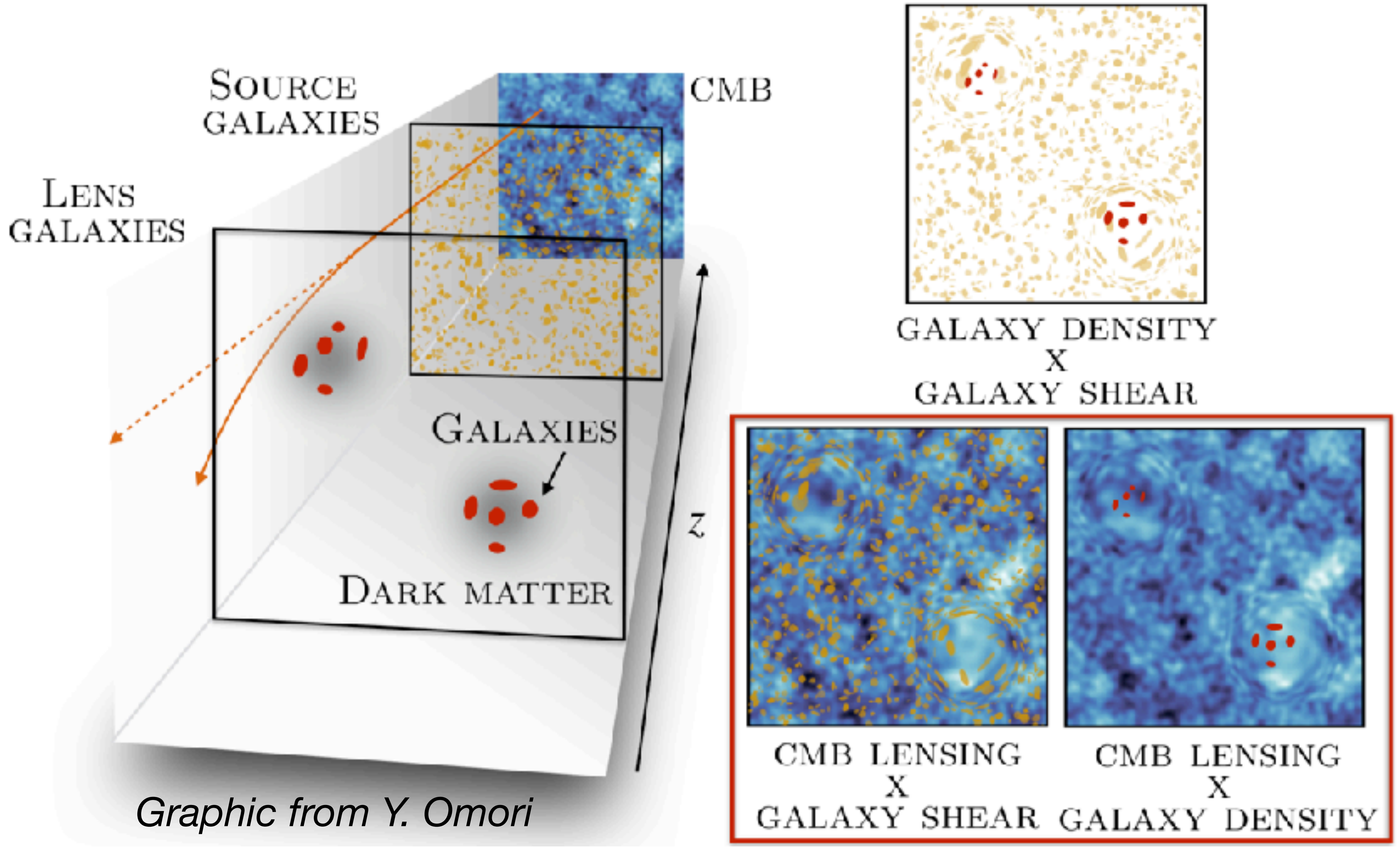


Madhavacheril et al. (ACT Collaboration), Arxiv:2304.05203



Graphic from Y. Omori

Redshift

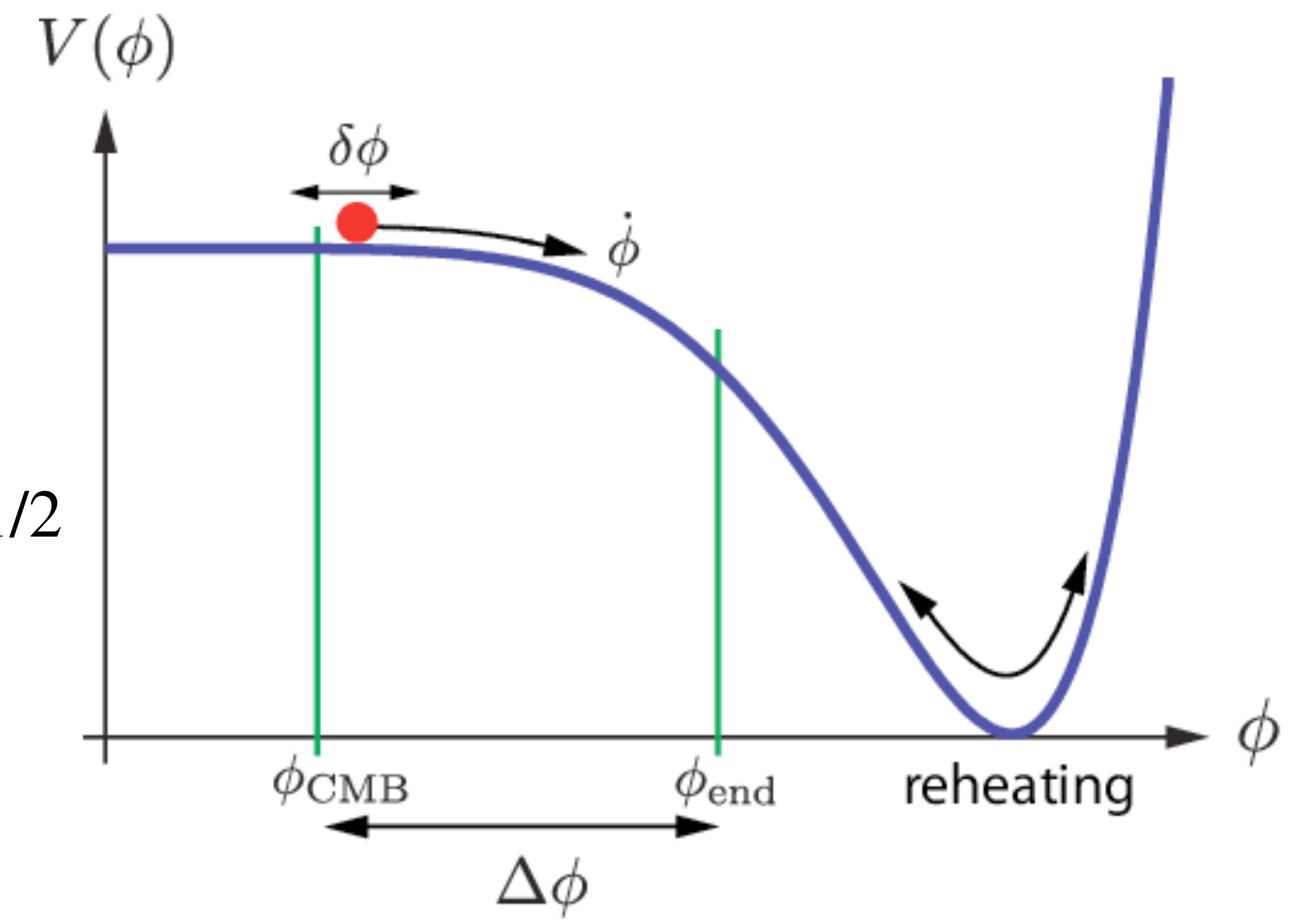
Scale

Slide adapted from Frank Qu

Why look for PGW?

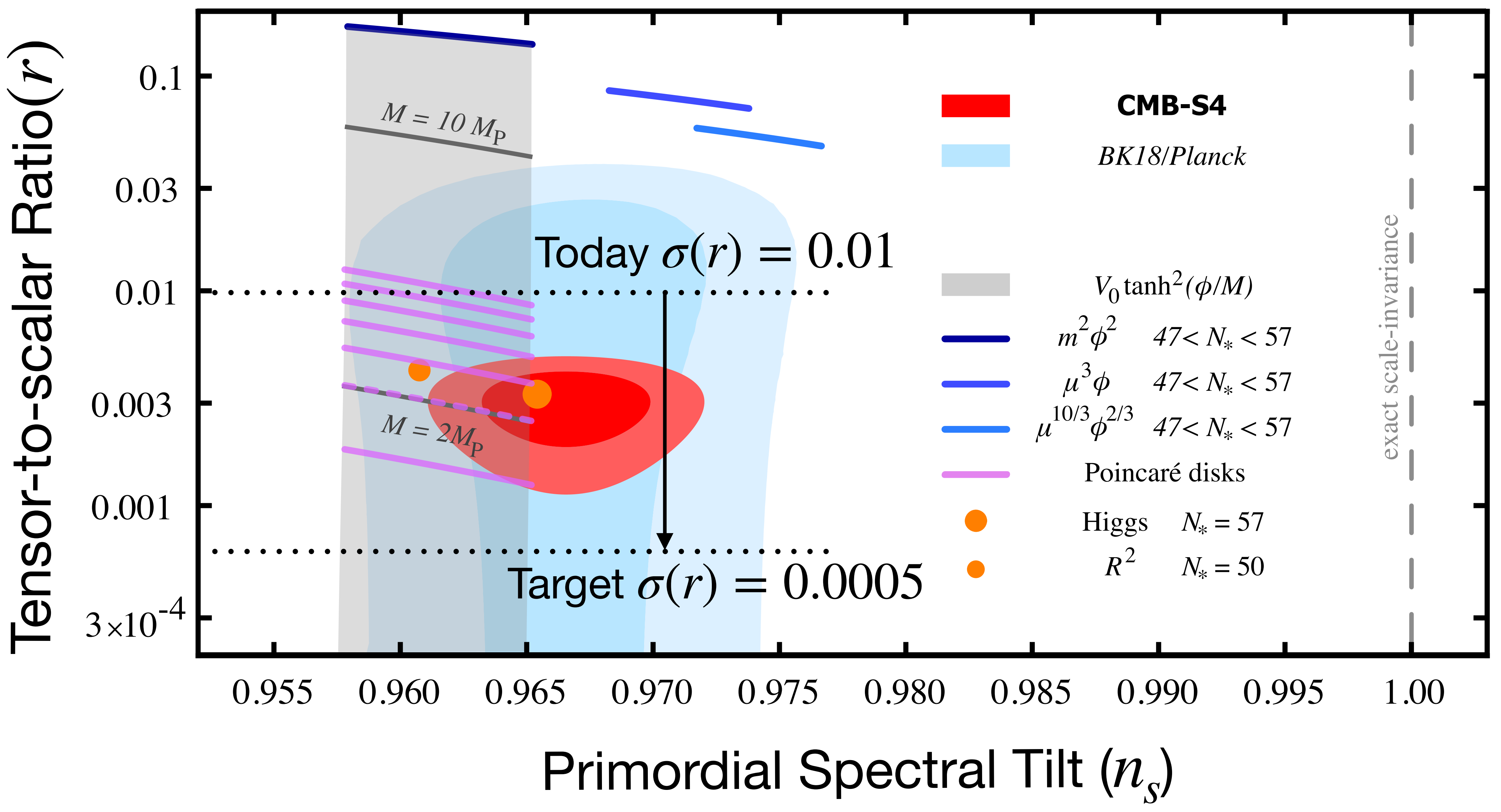
Compelling parameter space explores effective inflaton field range $\Delta\phi$ in units of Planck scale, M_P

$$\frac{\Delta\phi}{M_P} \sim \left(\frac{r}{0.01}\right)^{1/2}$$



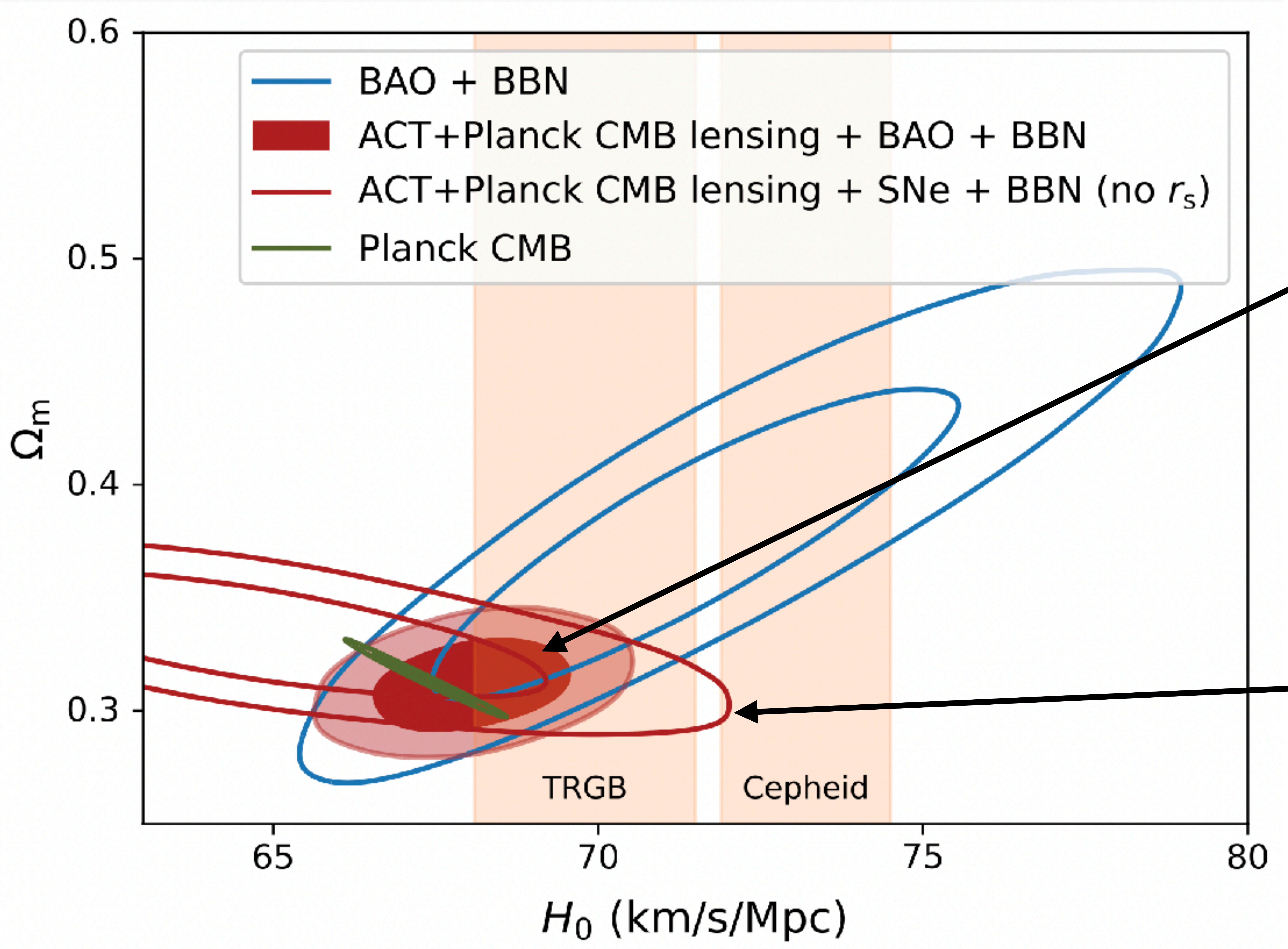
A detection in this regime would provide a significant empirical clue about how quantum gravity works

Need 20x reduction in $\sigma(r)$ to cover this parameter space!



Plot from CMB-S4 Collaboration

Measuring Hubble with lensing



- Hubble constant measurements that depend on the sound horizon (combination with BAO)

$$H_0 = 68.1 \pm 1.0 \quad \mathrm{km}s^{-1}\mathrm{Mpc}^{-1}$$

- **Independent of BAO and sound horizon**, using, as a ruler, the **matter-radiation equality scale** imprinted in the matter distribution

$$H_0 = 64.9 \pm 2.8 \quad \mathrm{km}s^{-1}\mathrm{Mpc}^{-1}$$

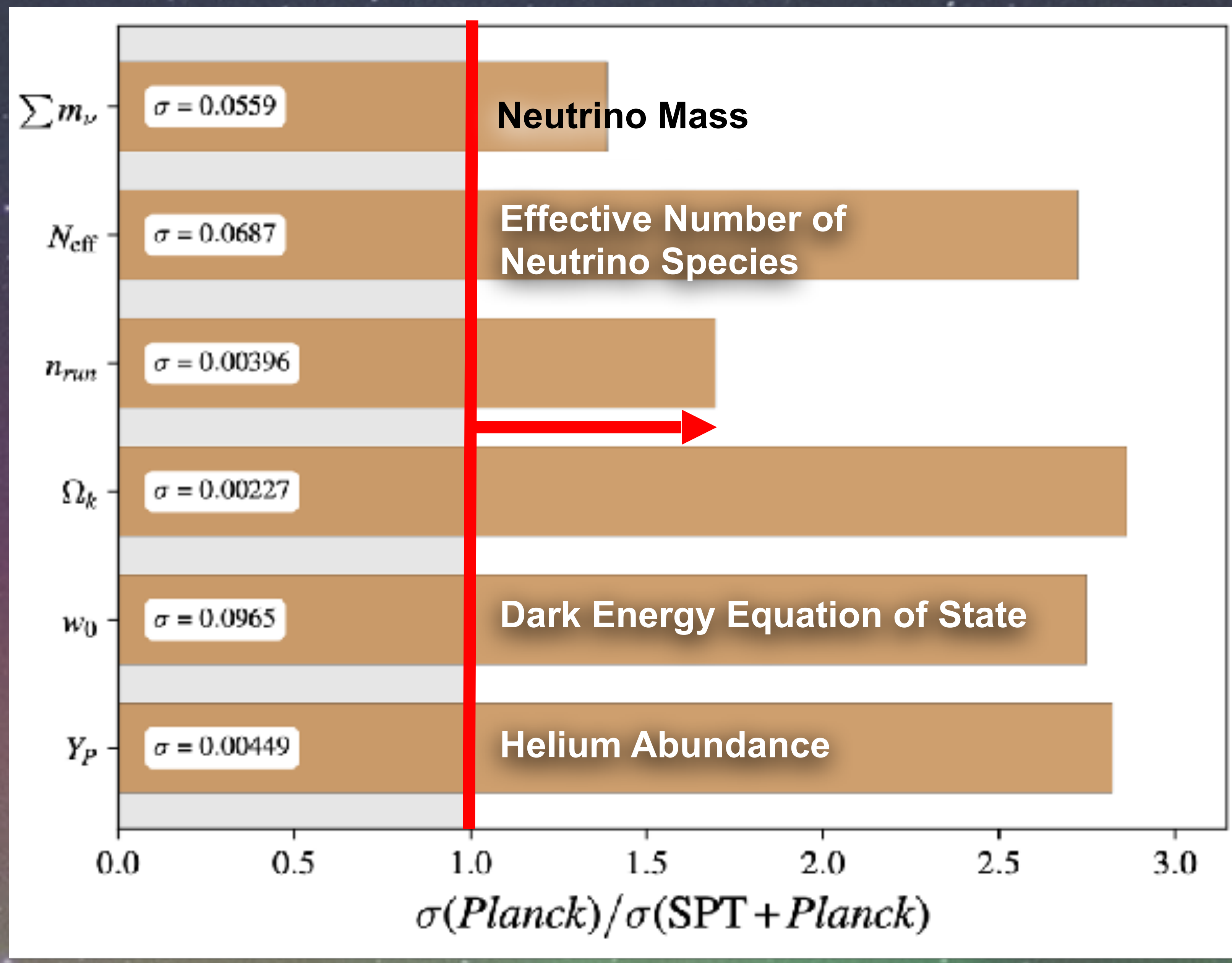
- Both consistent, and both low w.r.t to Cepheids

Slide from Frank Qu

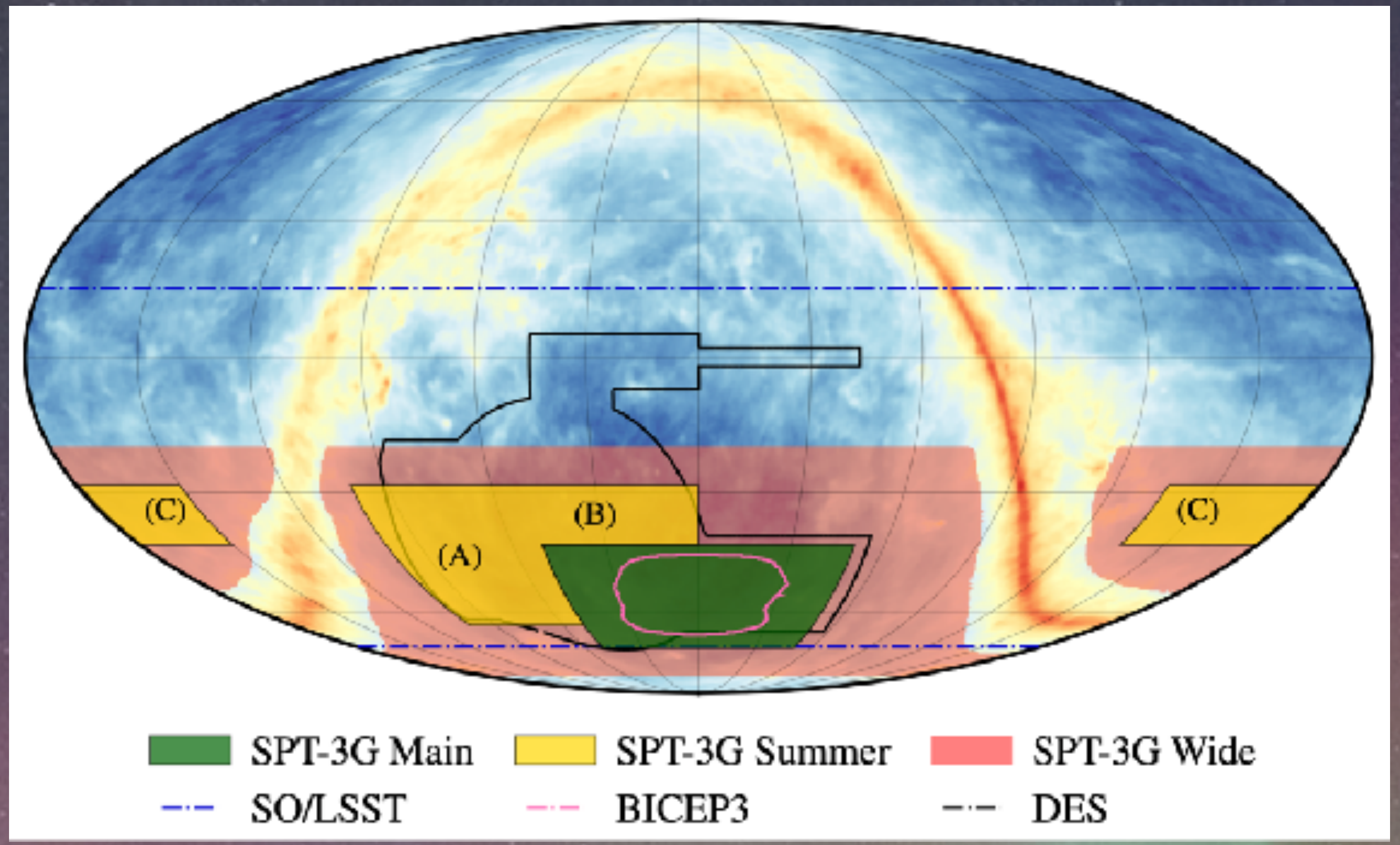
South Pole Telescope (SPT)

[Prabhu et al. (arXiv: 2403.17925)](https://arxiv.org/abs/2403.17925)

SPT-3G will improve CMB constraints on many individual parameters by ~2-3x



SPT-3G 10,000 deg² survey



- **In 2017, SPT-3G survey began** measuring the **cosmic microwave background (CMB).** Data has broad science reach for cosmology, astronomy, & HEP:
  - World-leading constraints on cosmic Inflation with **BICEP** and **South Pole Observatory, SPO**
  - New constraints on **dark matter** and **neutrino** density
  - Discovering the earliest formed **galaxies** and **clusters**, and new classes of **astrophysical transients**.
  - Physics of **Black Holes** and general relativity with **Event Horizon Telescope (EHT)**

Funded By:

NSF · U.S. Antarctic Program · U.S. DEPARTMENT OF ENERGY

Photo credit: Aman Chokshi

https://pole.uchicago.edu/

Slide from Brad Benson

Key Science Goals from the Simons Observatory

	Current[b]	Advanced SO 2024-2033	Using Rubin, DESI, or *Euclid*
Primordial perturbations			
n_s	0.004	0.002	-
$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	3%	0.4%	-
$f_{\rm NL}^{\rm local}$	5	1	✓
Relativistic species			
$N_{\rm eff.}$	0.2	0.045	-
Neutrino mass			
Σm_ν (eV, $\sigma(\tau)=0.01$)	0.1	0.03	✓
Σm_ν (eV, $\sigma(\tau)=0.002$)		0.015	✓
Accelerated expansion			
$\sigma_8(z=1-2)$	7%	1%	✓
Galaxy evolution			
$\eta_{\rm feedback}$	50-100%	2%	✓
$p_{\rm nt}$	50-100%	4%	✓
Reionization			
Δz	1.4	0.3	-
τ	0.007	0.0035	-
Cluster catalog	4000	33,000	✓
AGN catalog	2000	100,000	-
Galactic science			
Molecular cloud B-fields	10s	> 860	-
$\sigma(\beta_{dust})$	0.02	< 0.01	-
Planet 9			
Distance limit for 5 $M_\oplus$		900 AU	✓
Transient detection distance			
Long GRBs, on-axis		420 Mpc	✓
Low-luminosity GRBs		60-190 Mpc	✓
Normal SNe		$\gtrsim 4$ Mpc	✓
TDEs, on-axis		2100 Mpc	✓

- **Threshold Goals** for the Simons Observatory including the Advanced Simons Observatory.
  - Nine years of observations.
- **LAT/LATR:**
  - 20,000 sq.deg.
  - 2.5 μK-arcmin
- **SATs (x3)** (not including planned expansion)
  - 15% of the sky.
  - $\sigma(r) = 0.002$ (0.0012 Goal)

Updated White Paper on Advanced SO goals coming soon!

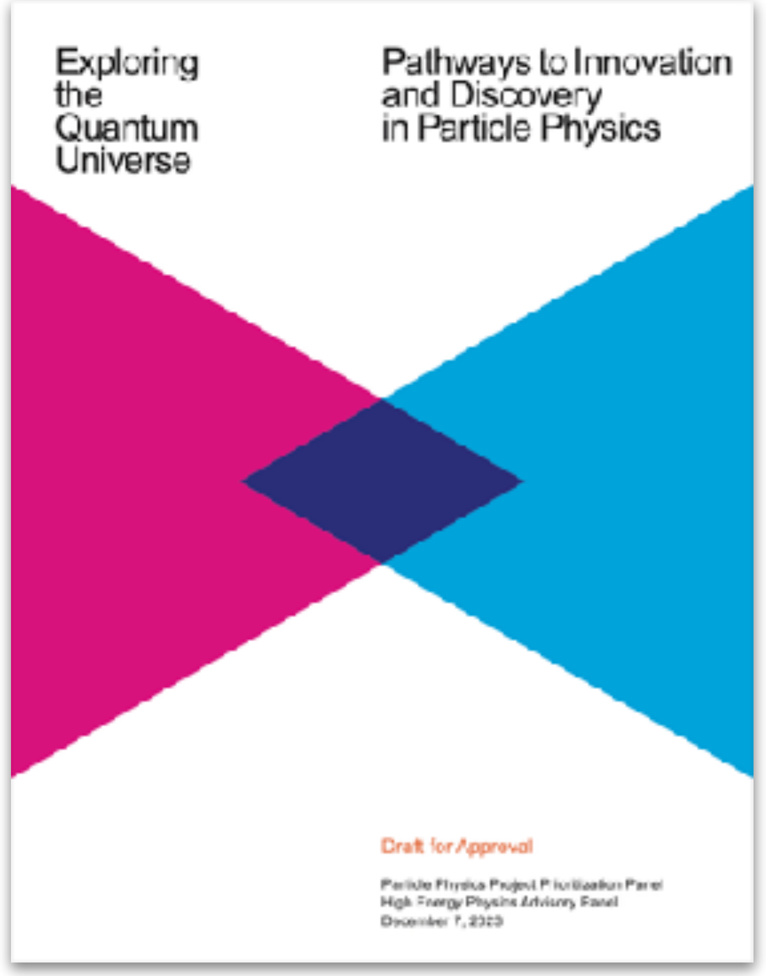
CMB S4

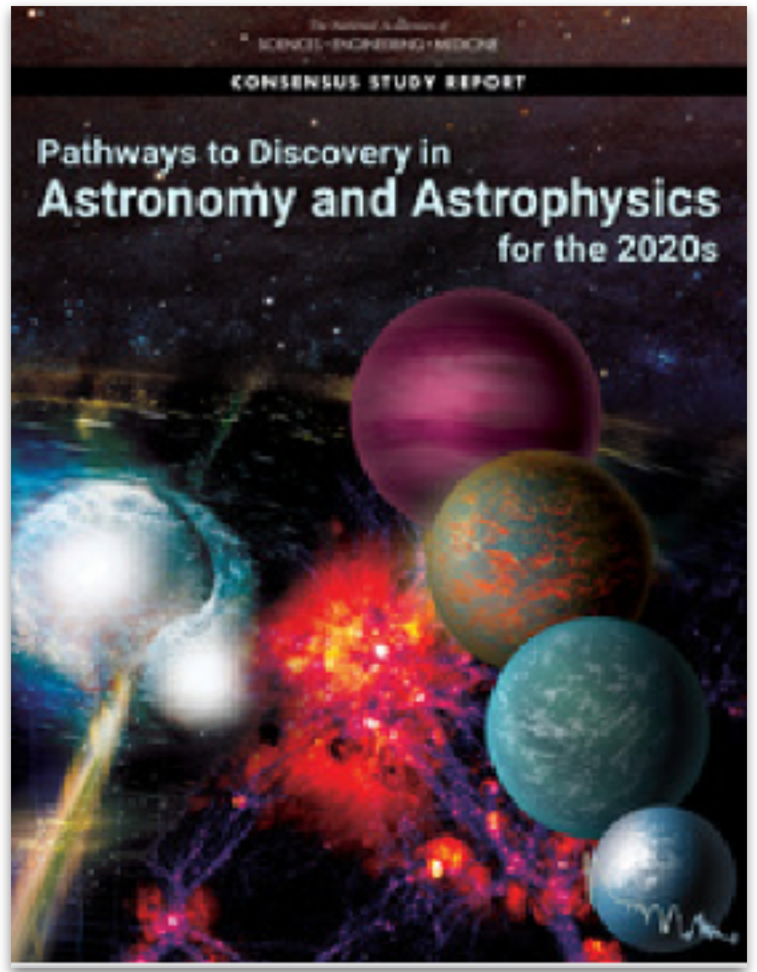
The ultimate ground-based Cosmic Microwave Background survey experiment

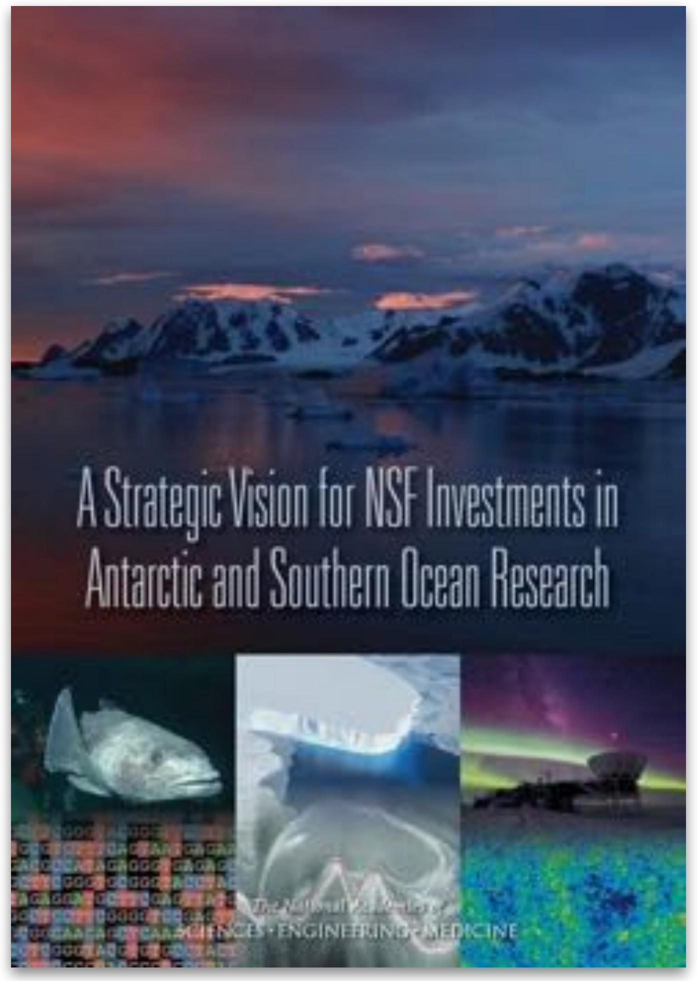
- Designed for transformational advances in our understanding of cosmic acceleration, the dark sector, and discoveries in the mm-wave sky

- Broad participation of US and international CMB and cosmology communities and the High Energy Physics community. *500 members from 119 institutions, 21 countries. 32% Early Career. 30% international*

- Ranked highly by 2023 P5, Astro2020, 2015 NSF Antarctic Strategic Vision



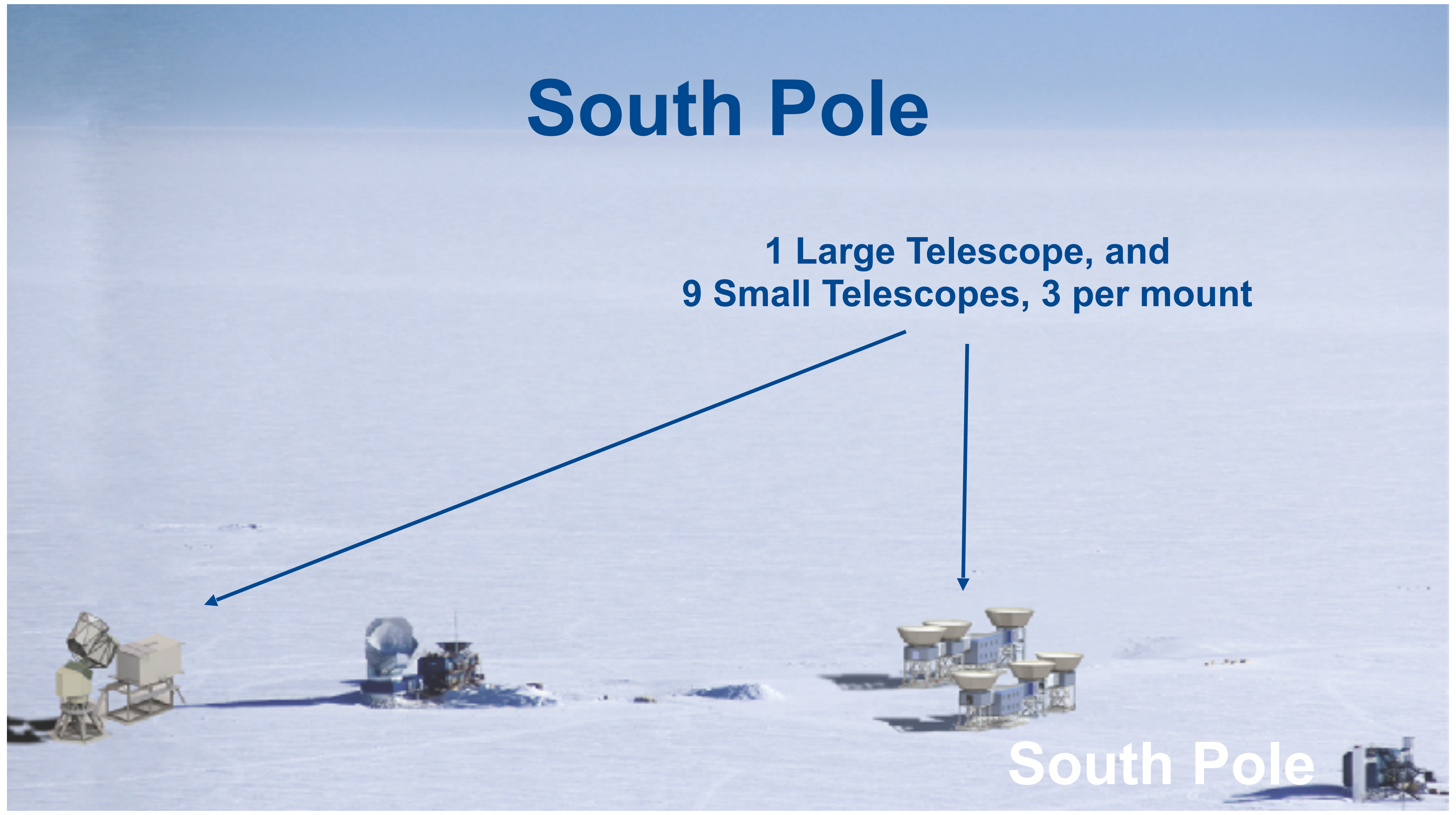


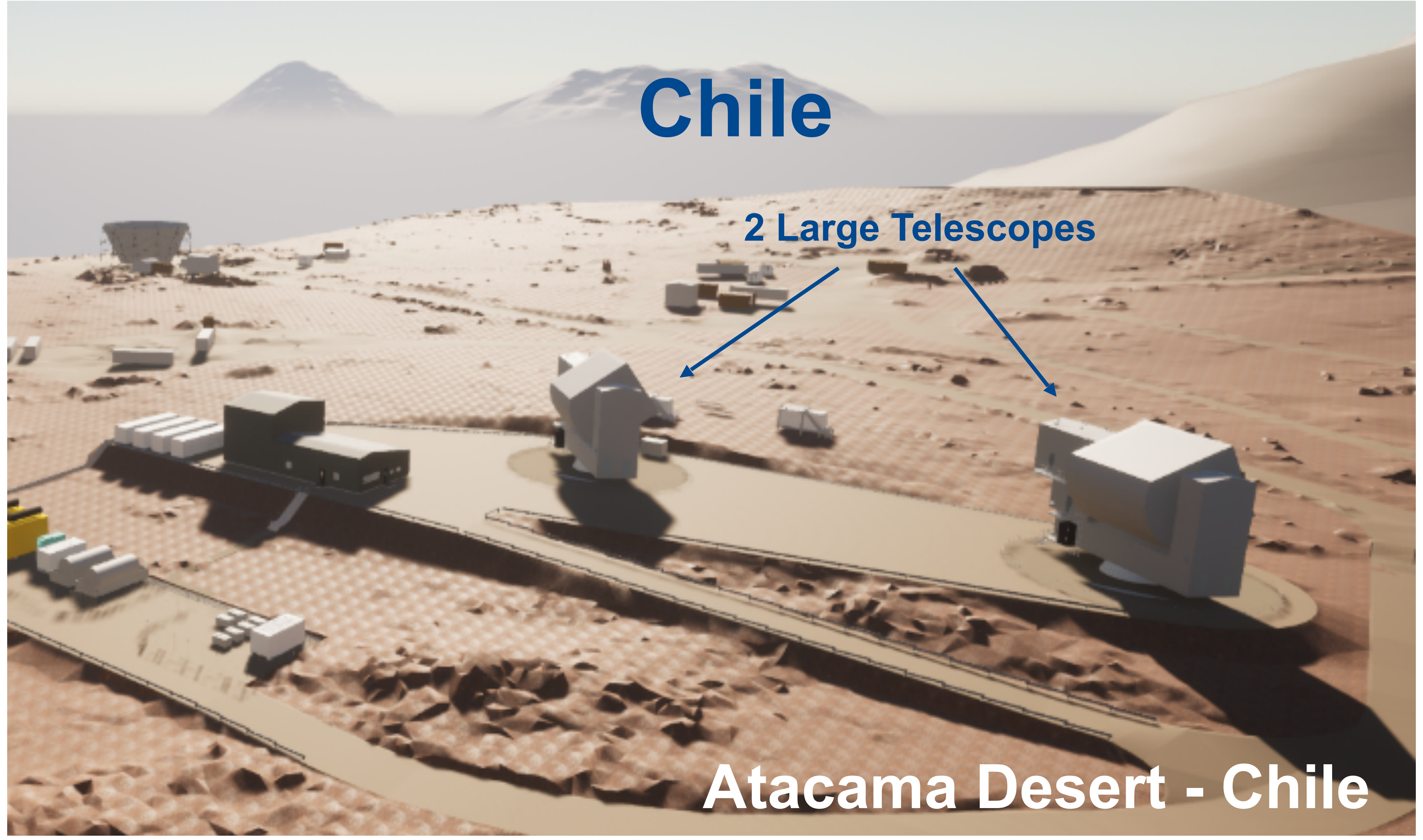


CMB-S4 Collaboration,
arXiv:1610.02743
arXiv:1706.02464
arXiv:1907.04473

CMB S4

The ultimate ground-based CMB survey experiment





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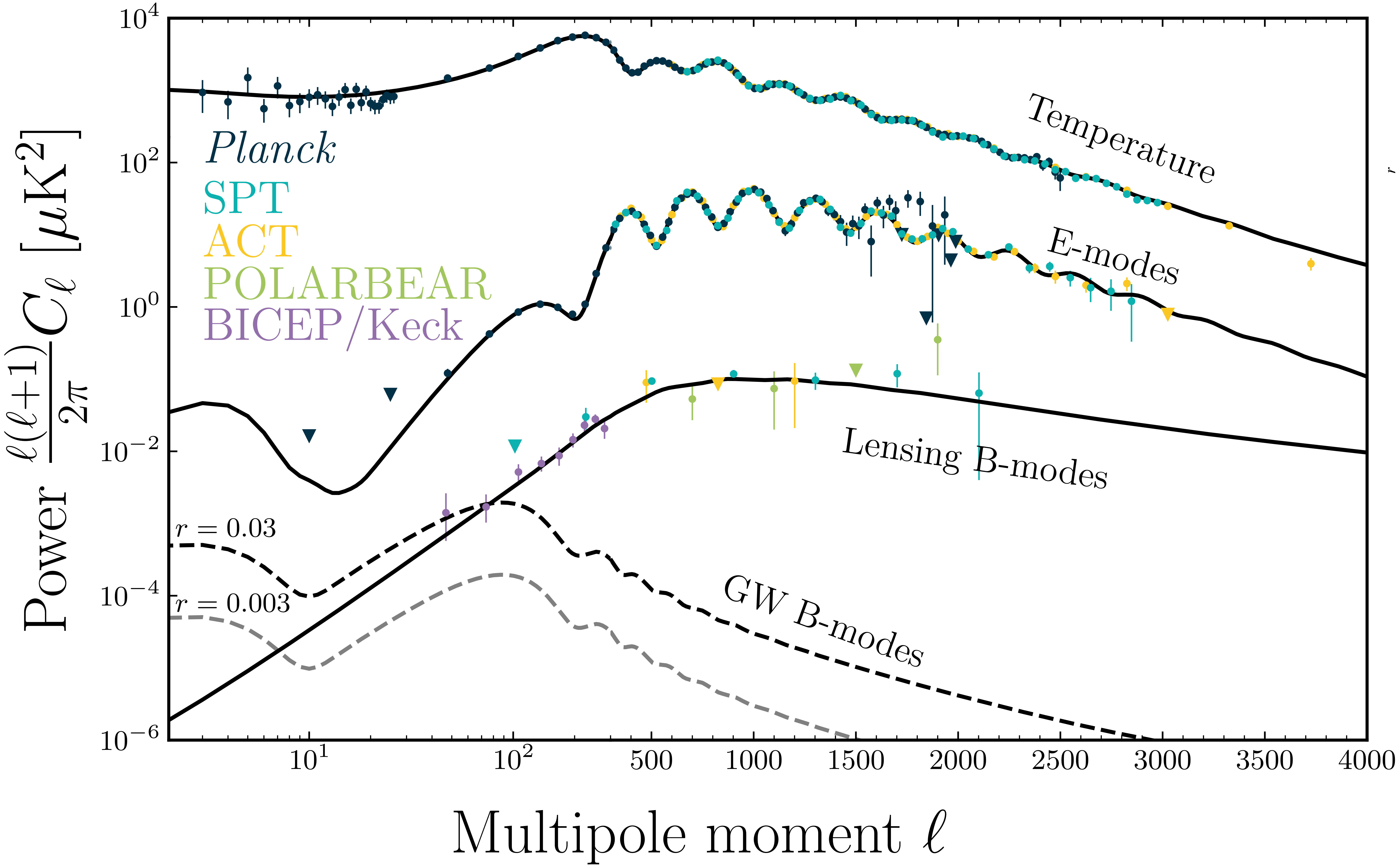
A US DOE-NSF joint project to build **12 CMB telescopes at the South Pole and in Chile** incorporating **~500,000** photon-noise-limited sub-Kelvin, superconducting detectors. **First light in 2033**

Endorsed by 2023 P5, and by Astro2020

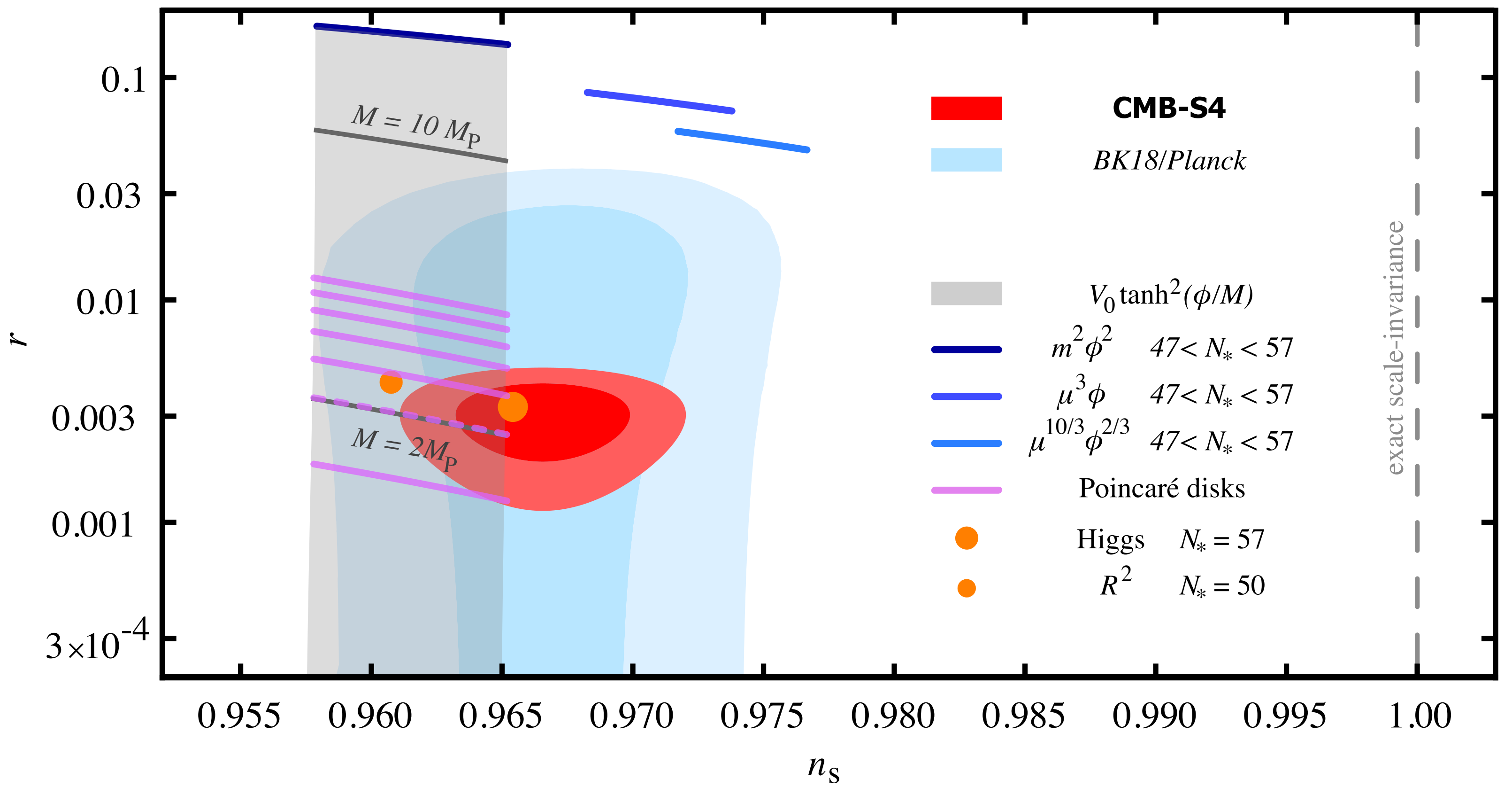
Site renderings from CMB-S4 collaboration

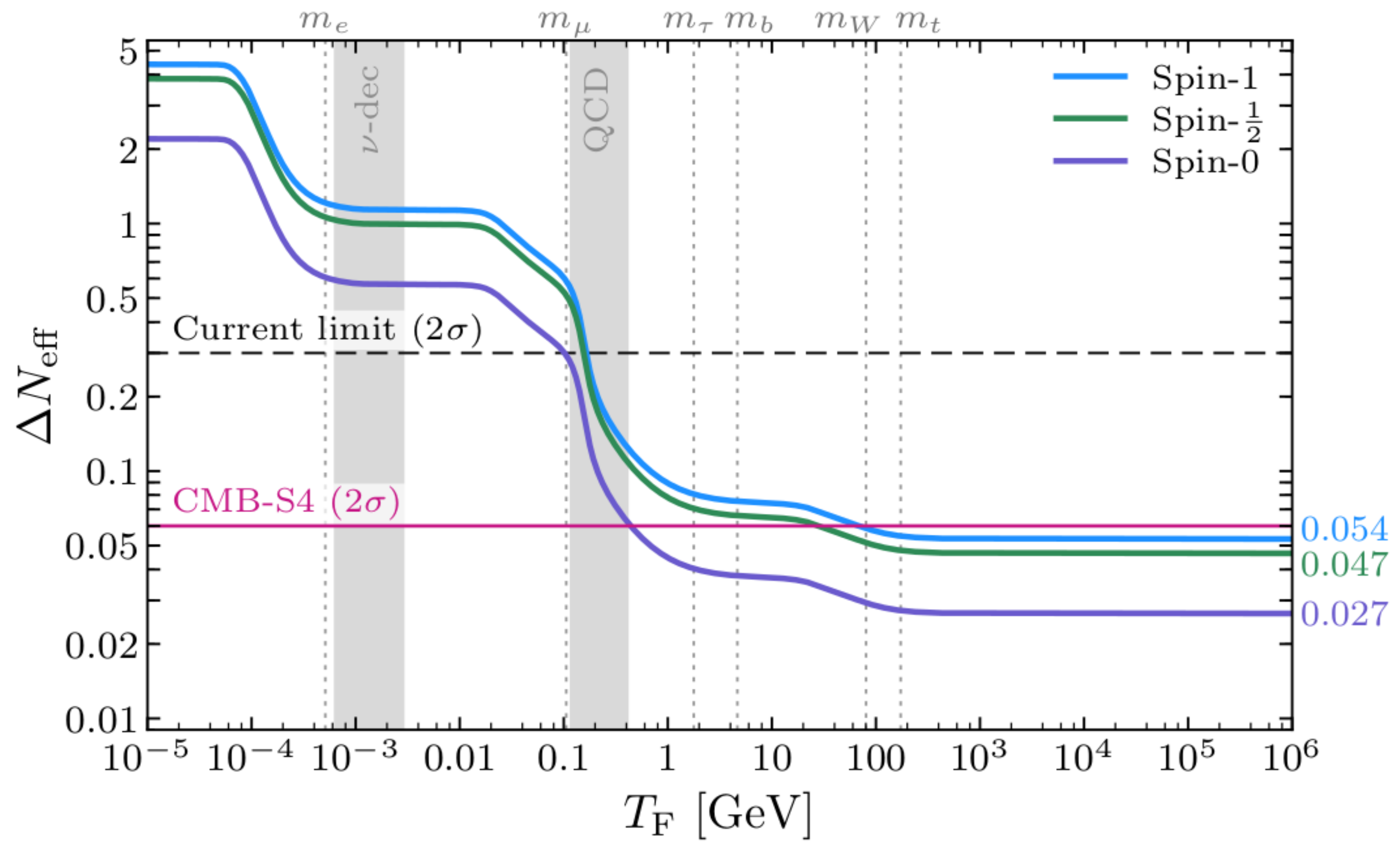
CMB S4

Scientific reach



Tensor-to-Scalar Ratio





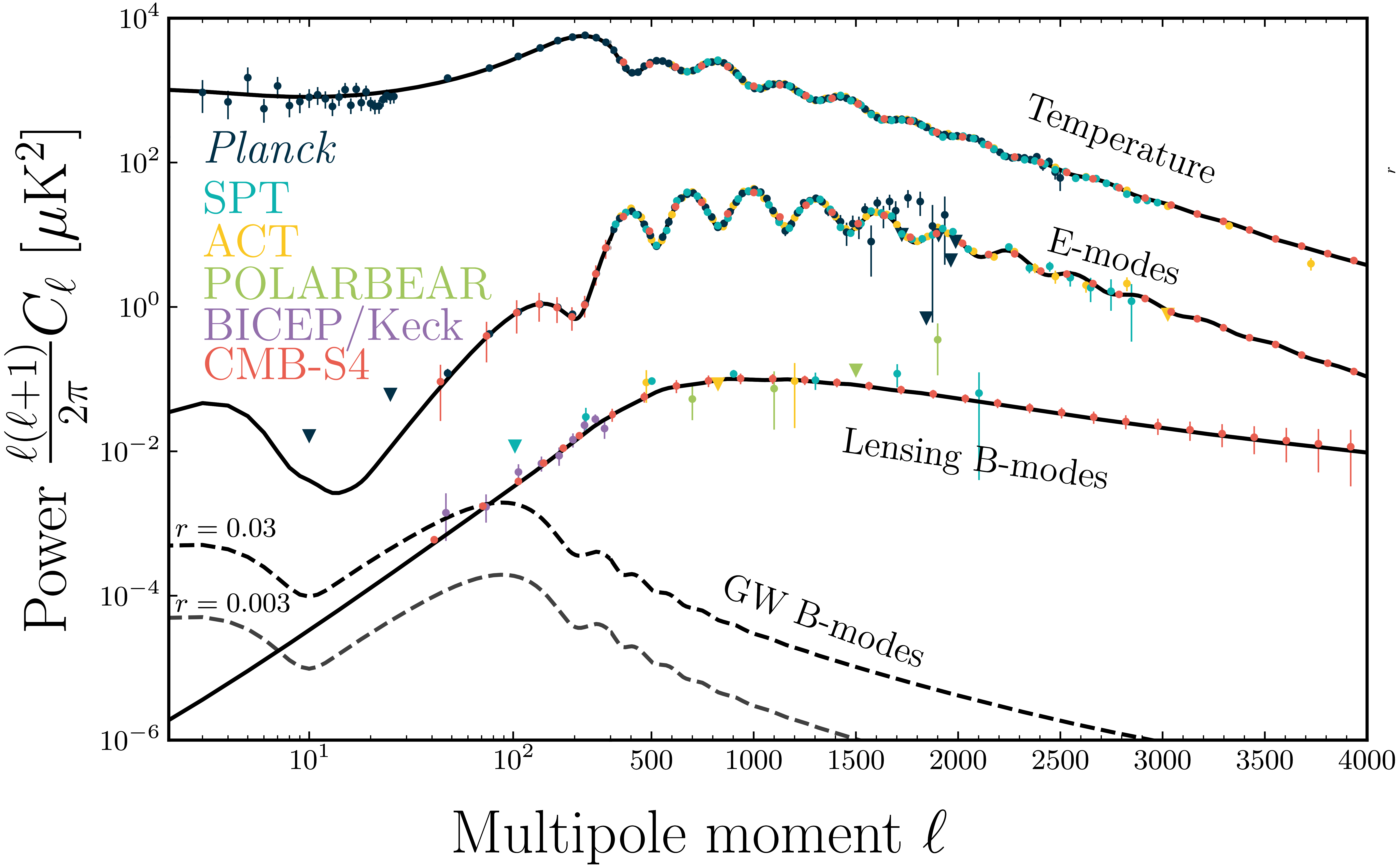
Light Relics

Power spectrum plot from Federico Bianchini

r and N_{eff} plots from CMB-S4 Collaboration

CMB S4

Scientific reach



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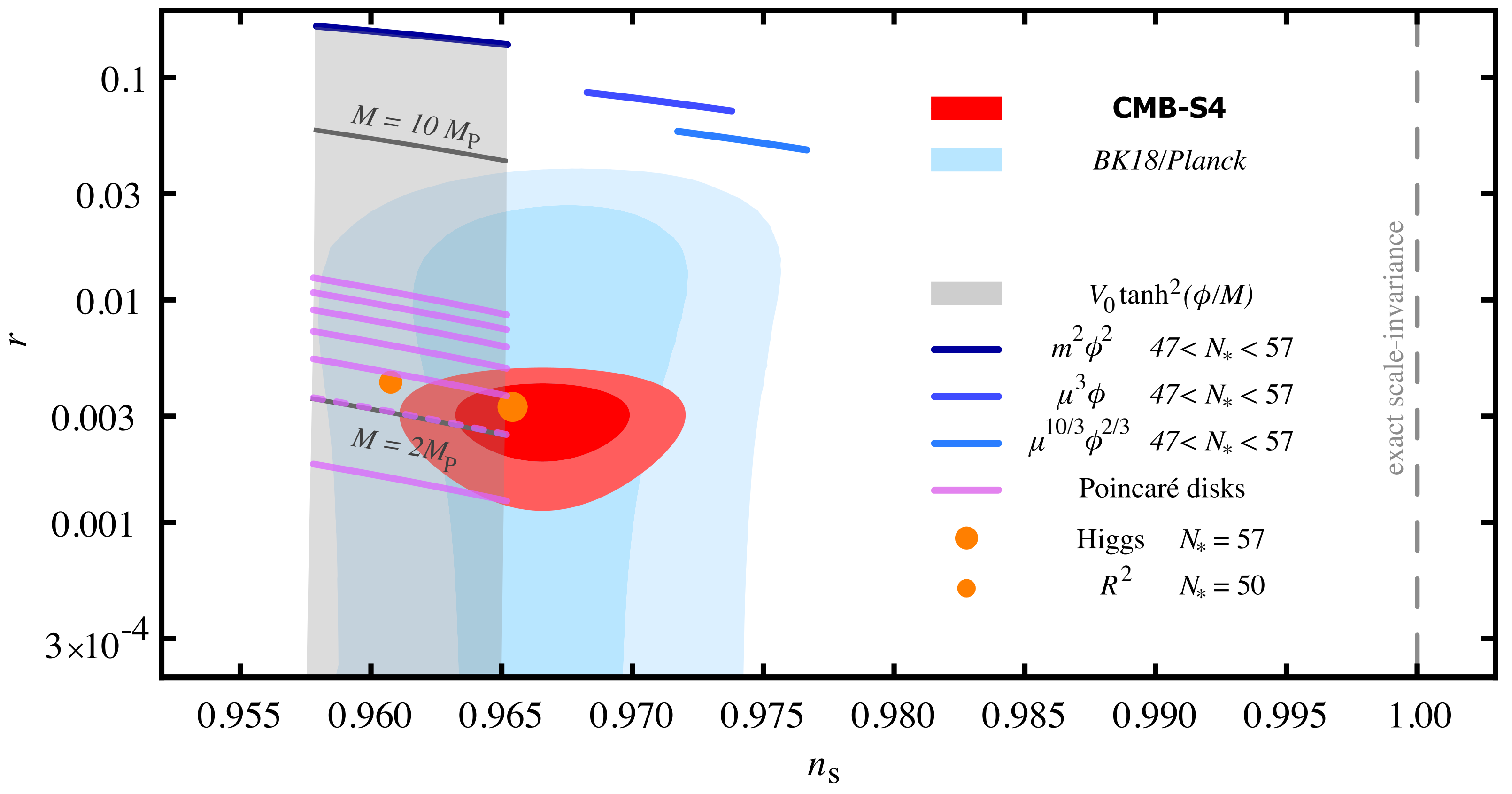

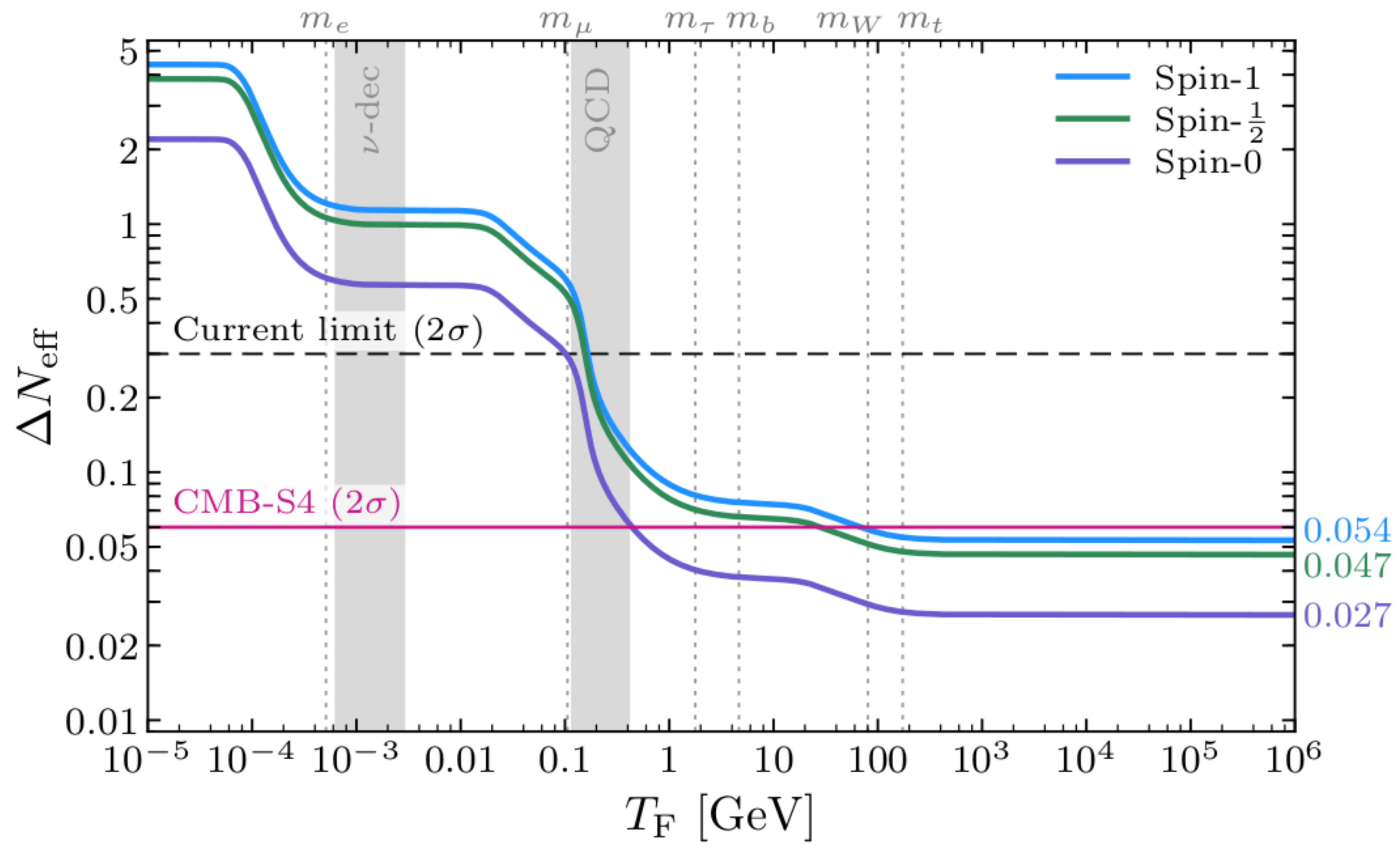

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