Next-Generation CMB: SPT-3G and CMB-S4

Adam Anderson
Fermilab / KICP
13 June 2019
Fermilab Users' Meeting

photo: Joshua Montgomery

CMB and the Cosmic Timeline

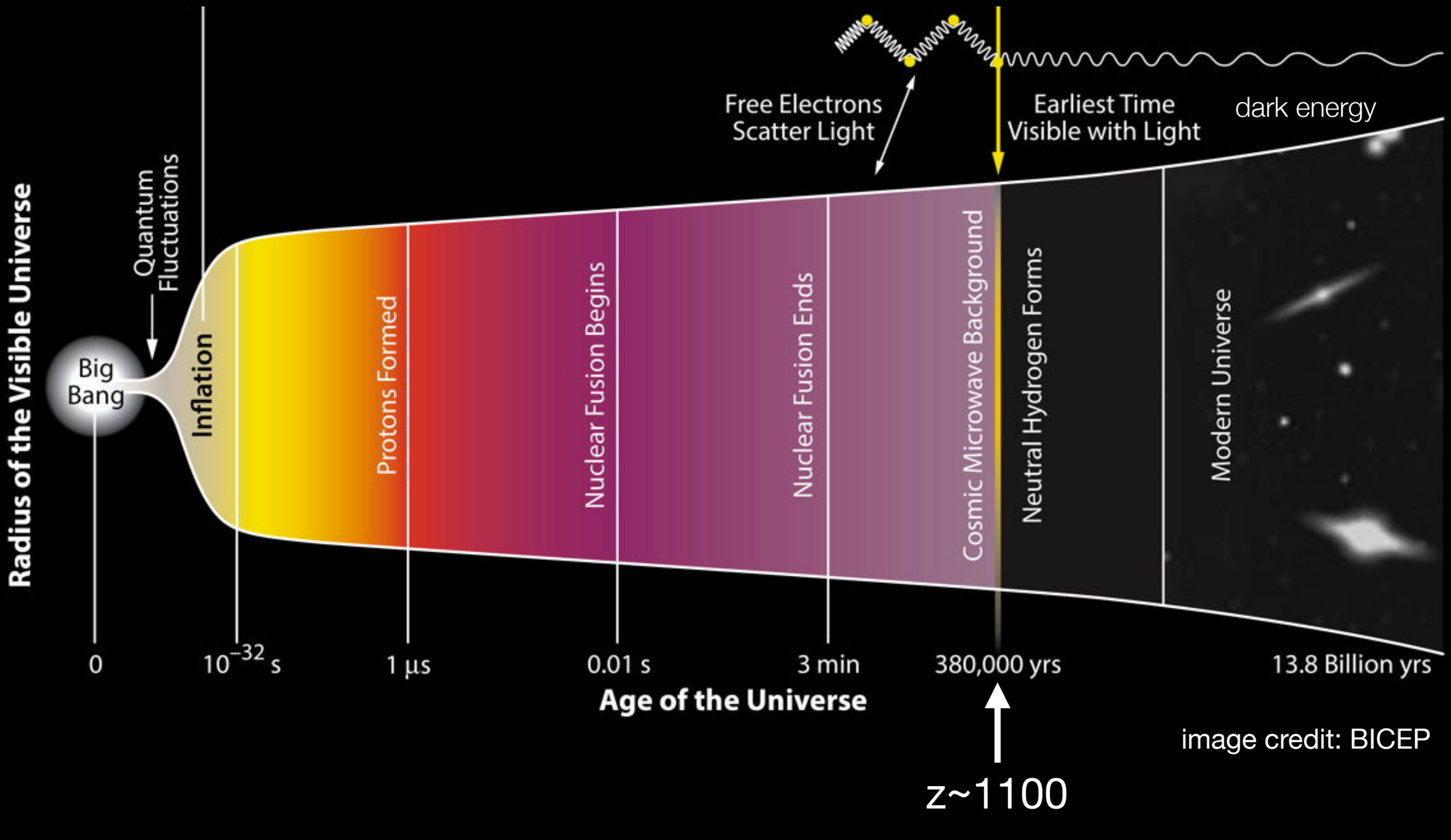


image credit: BICEP

CMB and the Cosmic Timeline

I. Recombination

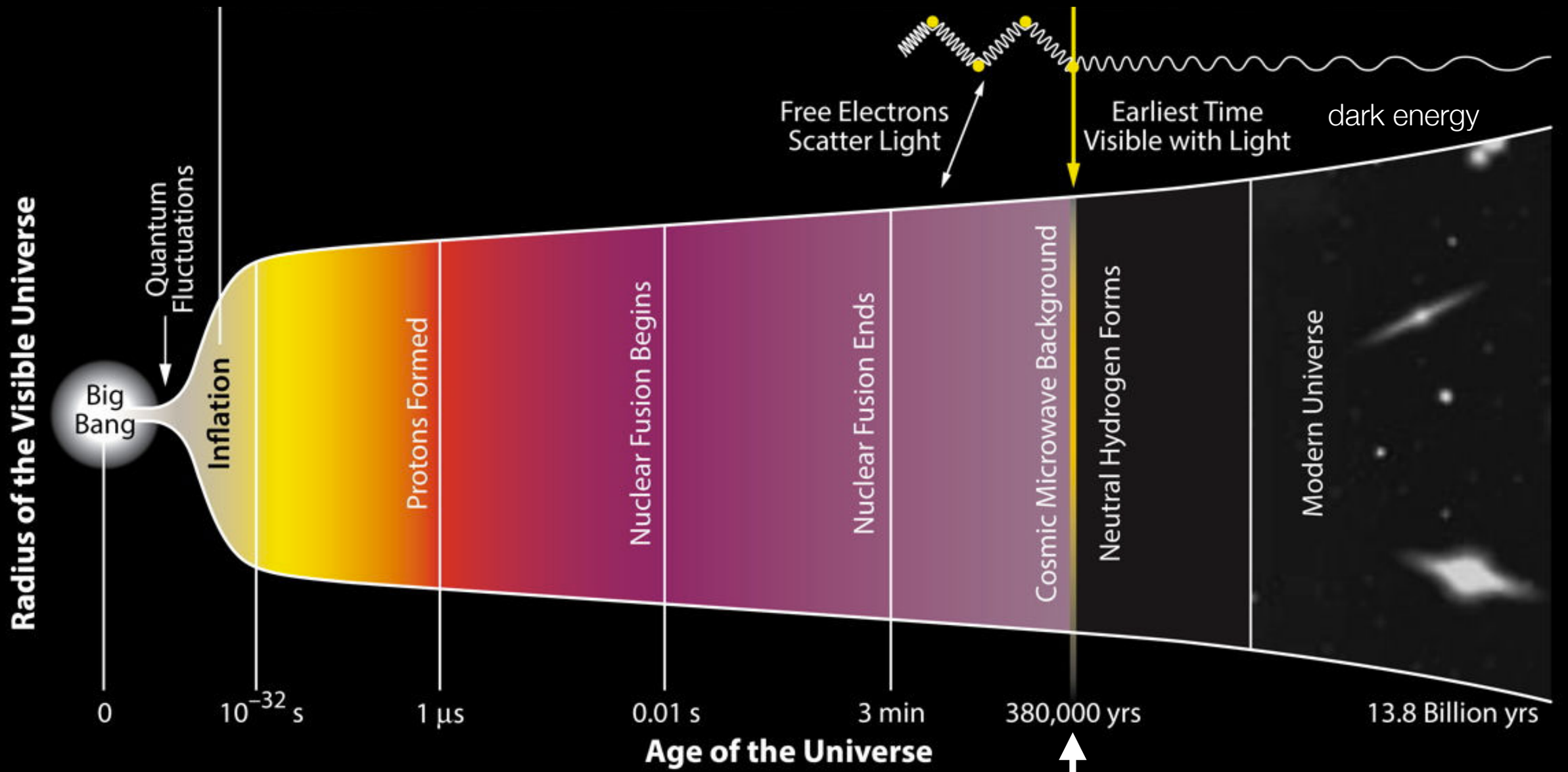
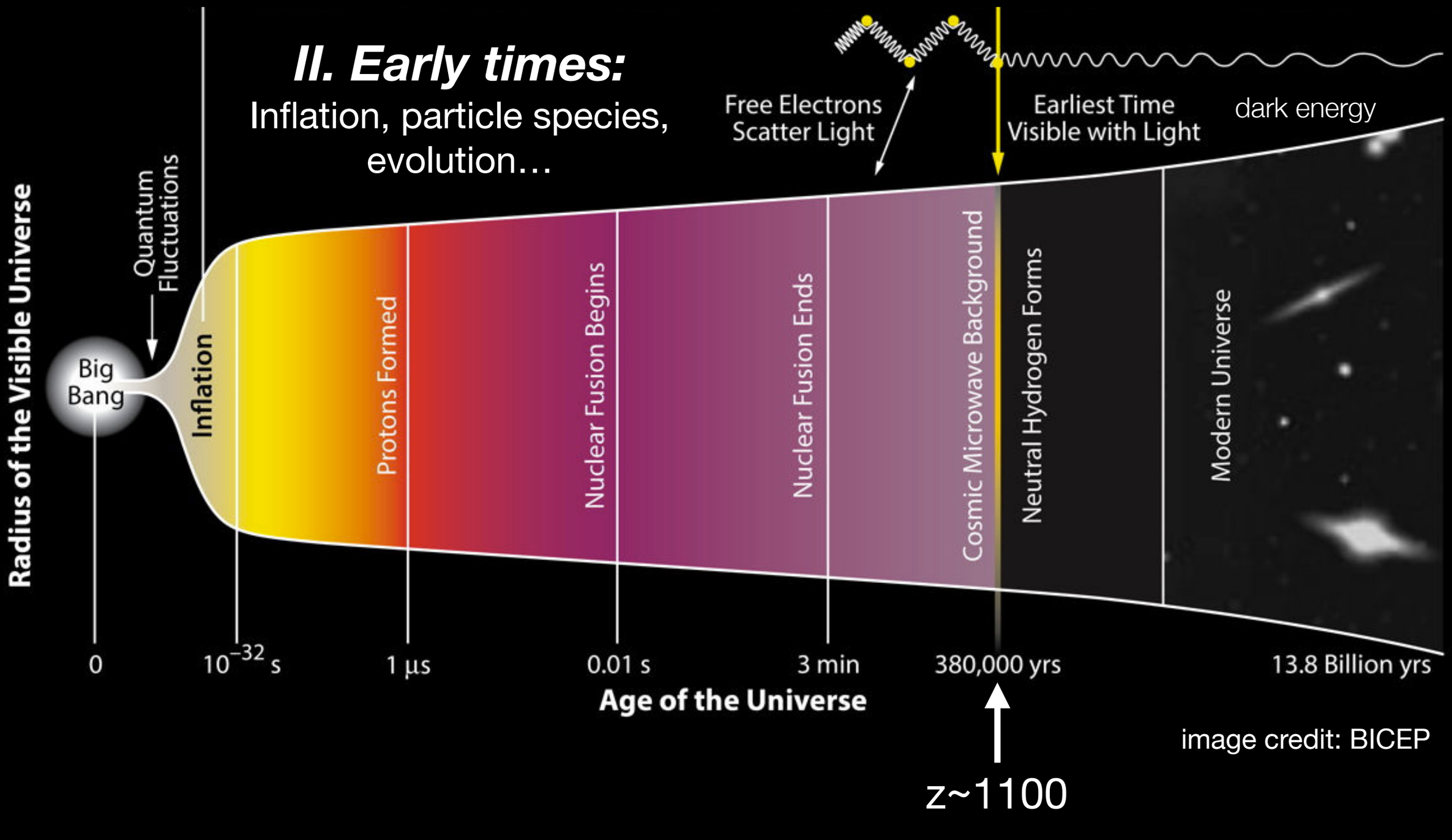


image credit: BICEP

z~1100

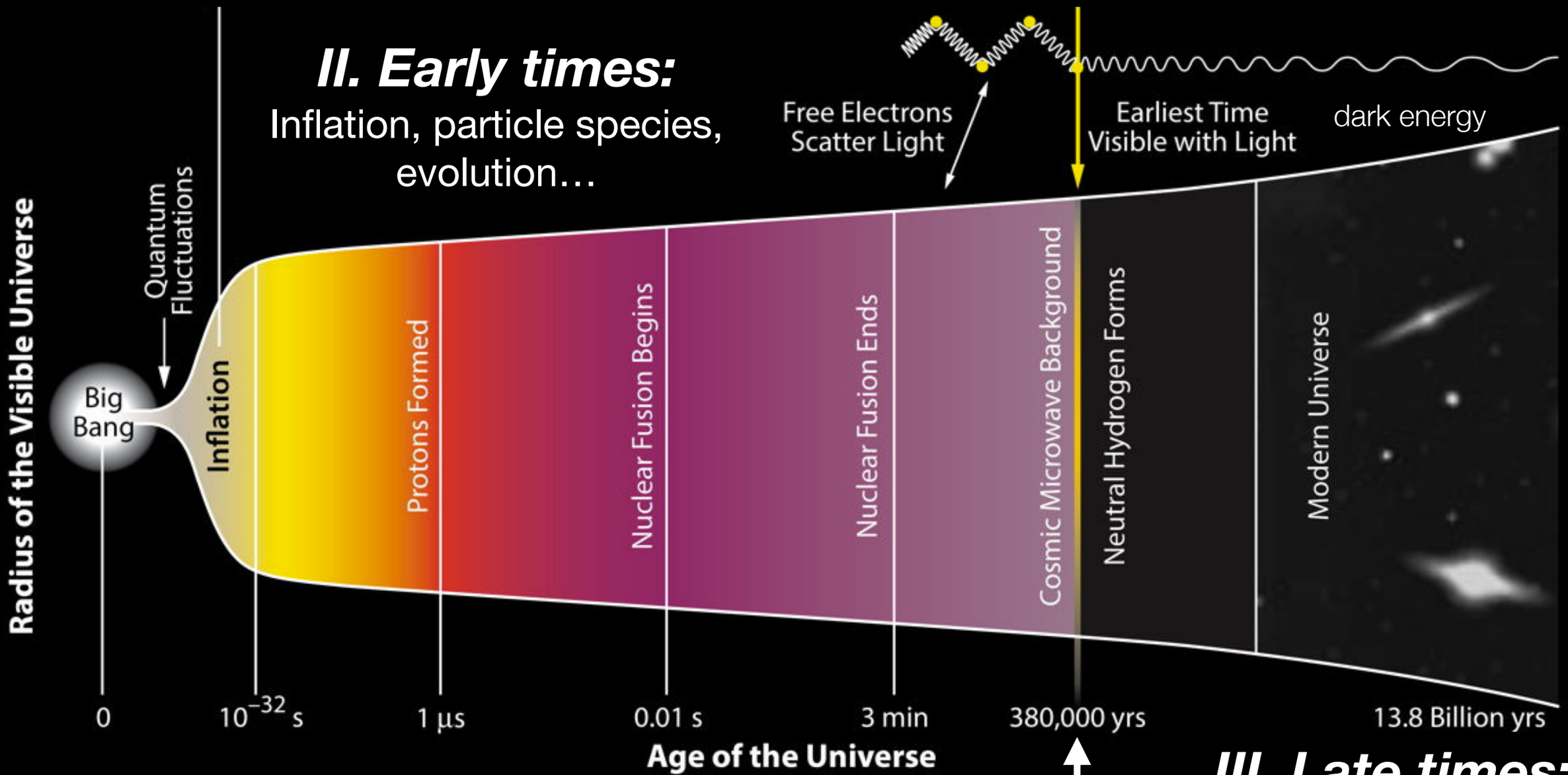
CMB and the Cosmic Timeline



CMB and the Cosmic Timeline

I. Recombination

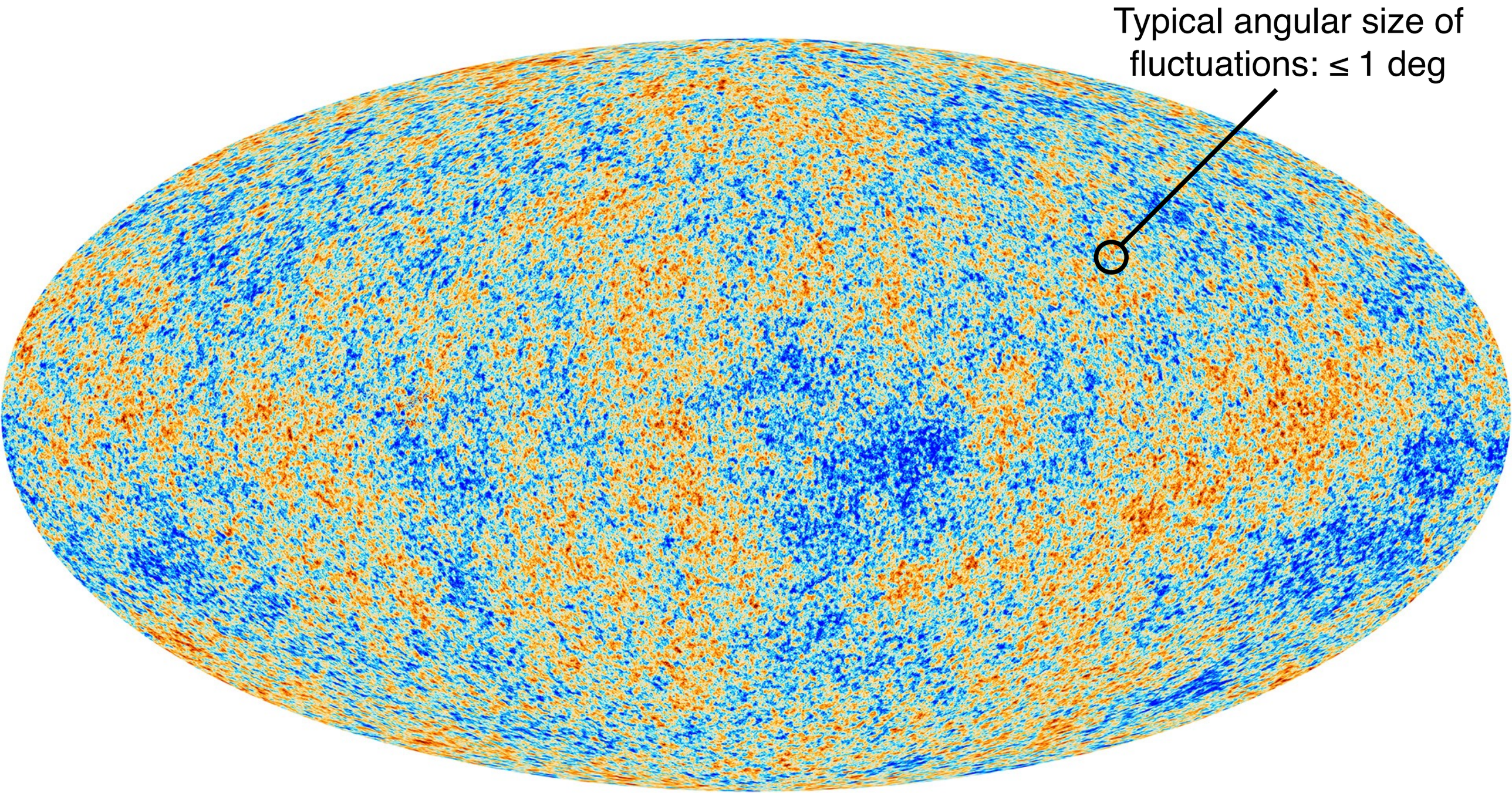
II. Early times:
Inflation, particle species, evolution…



z~1100

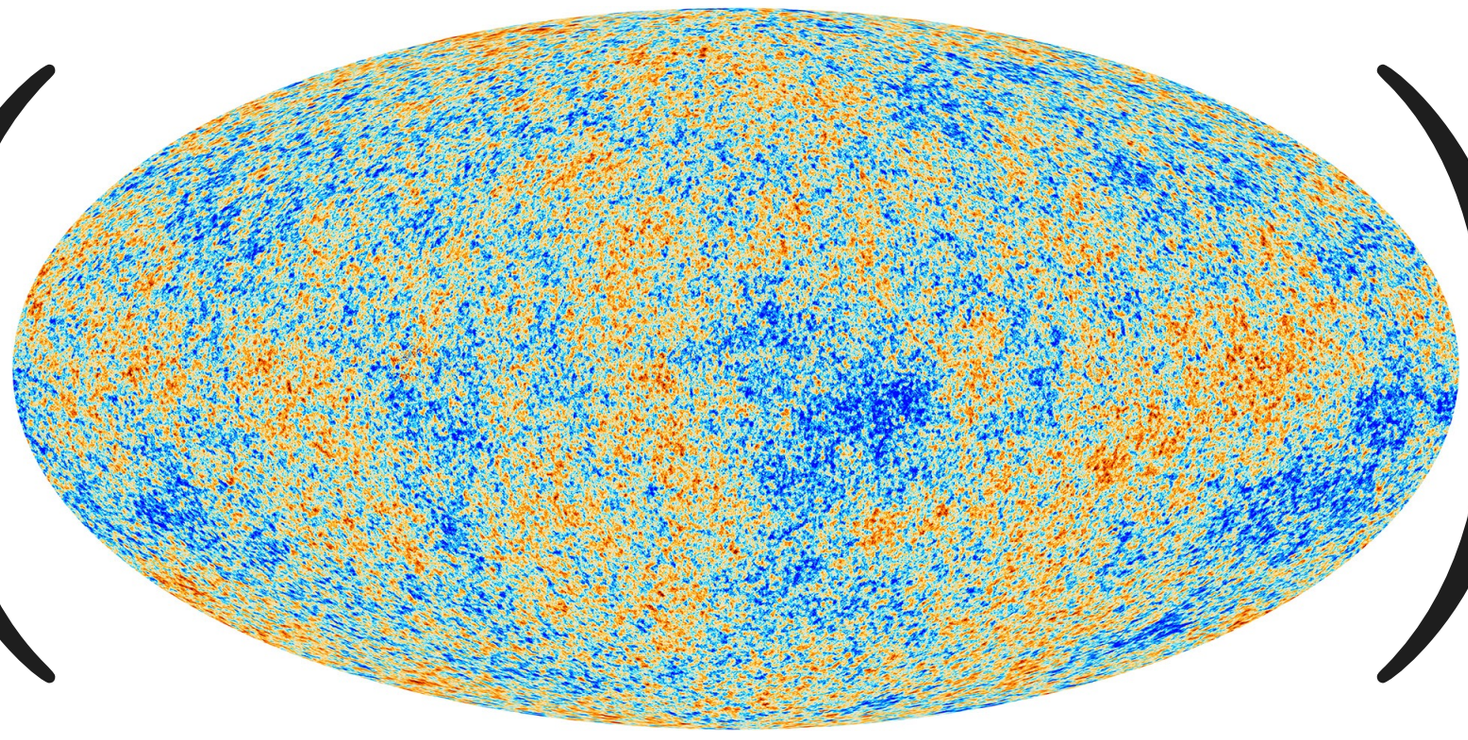
III. Late times:
Gravitational lensing, structure formation…

Planck Temperature Map

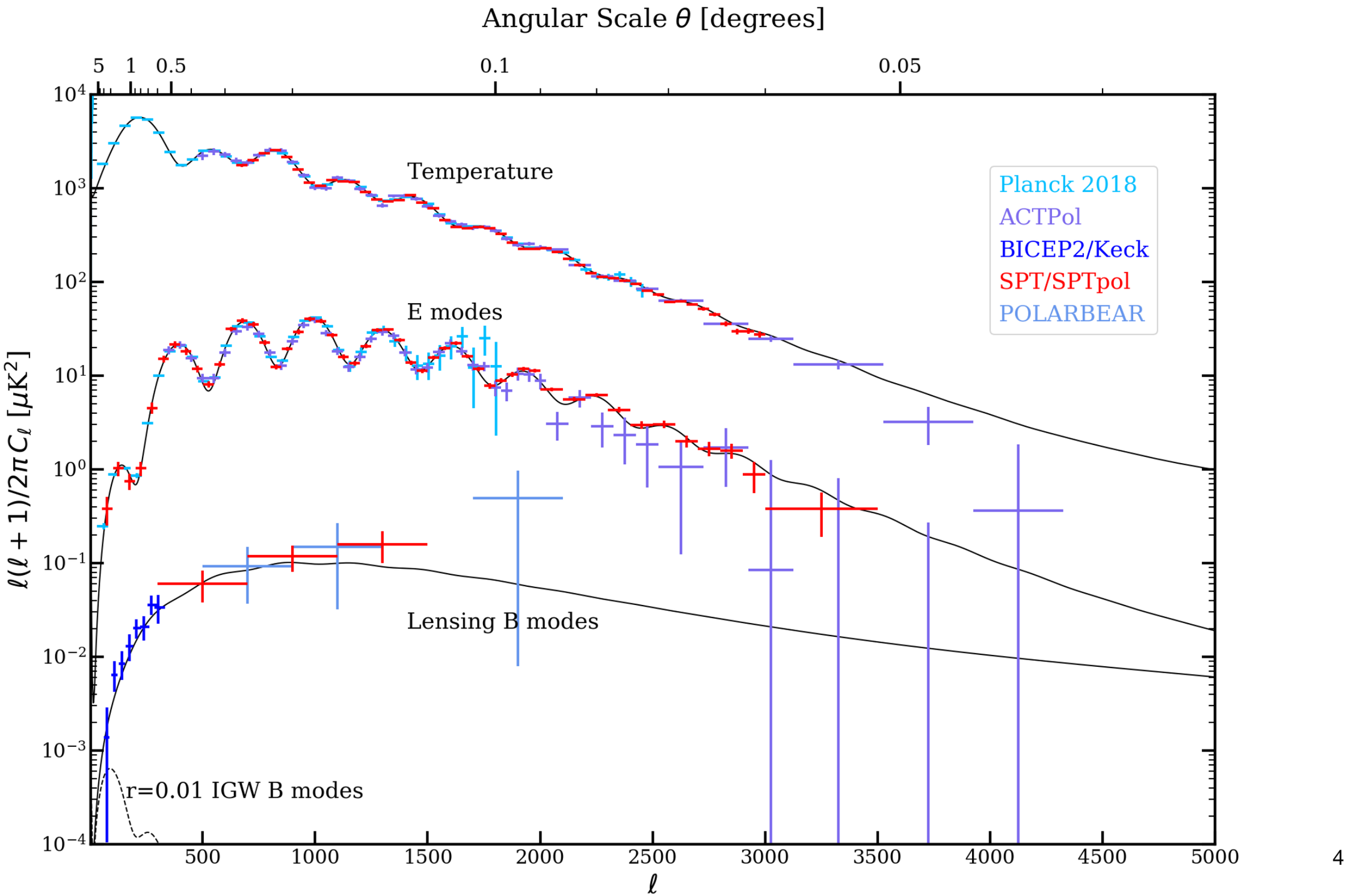


30μK rms fluctuation on a 3K blackbody

Planck Temperature Map

$T($  $)$

Power Spectra



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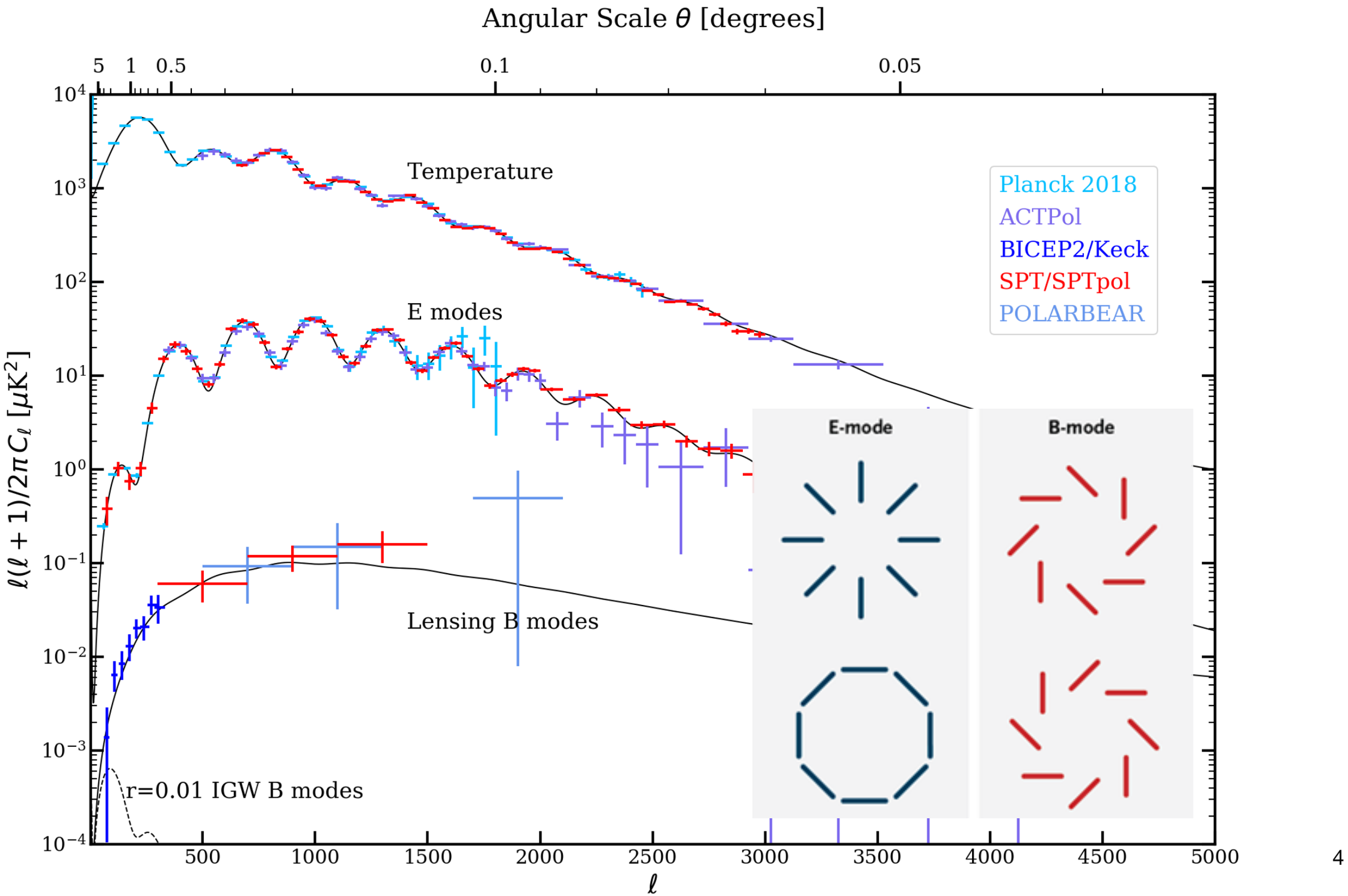

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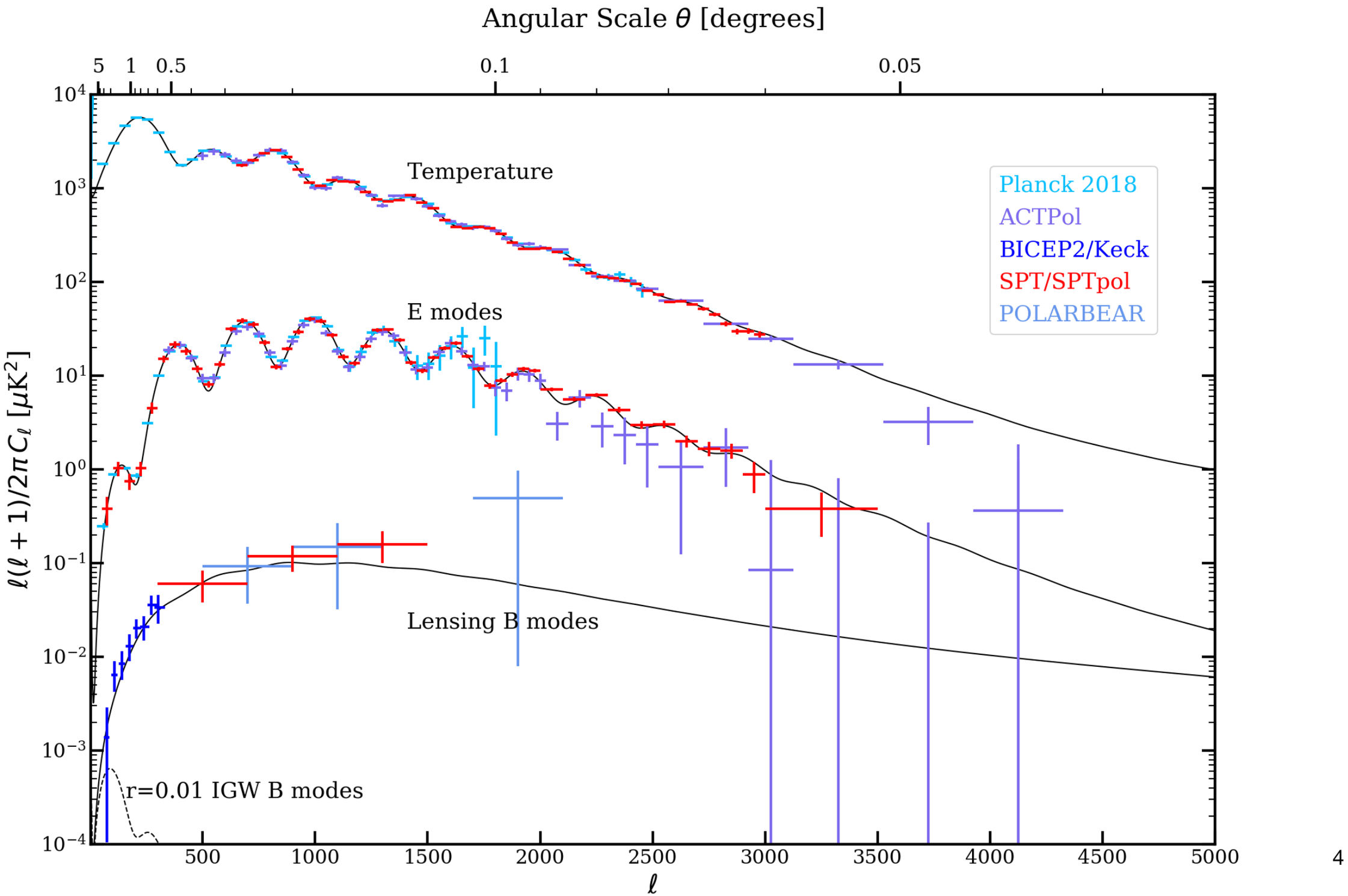

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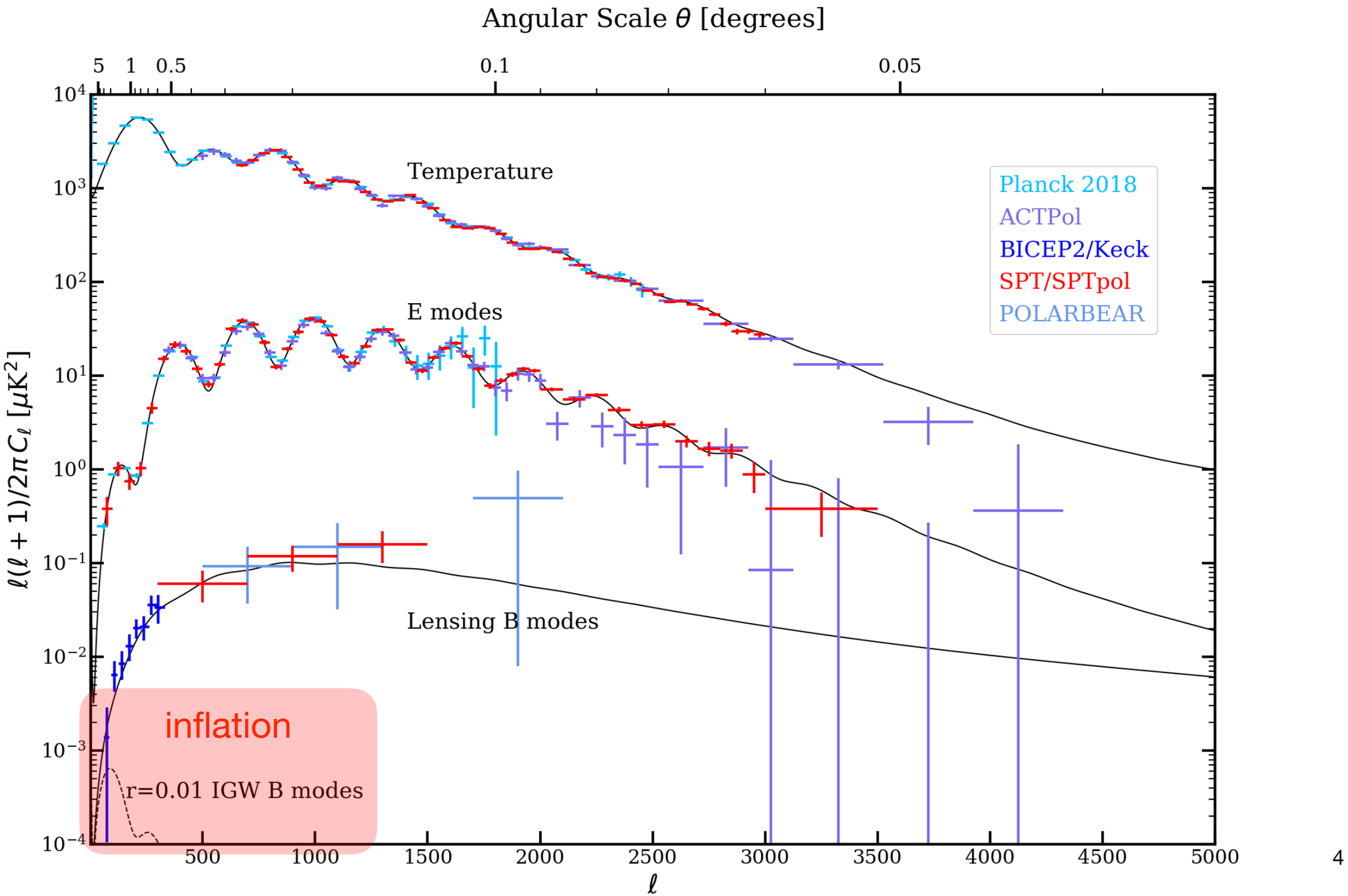

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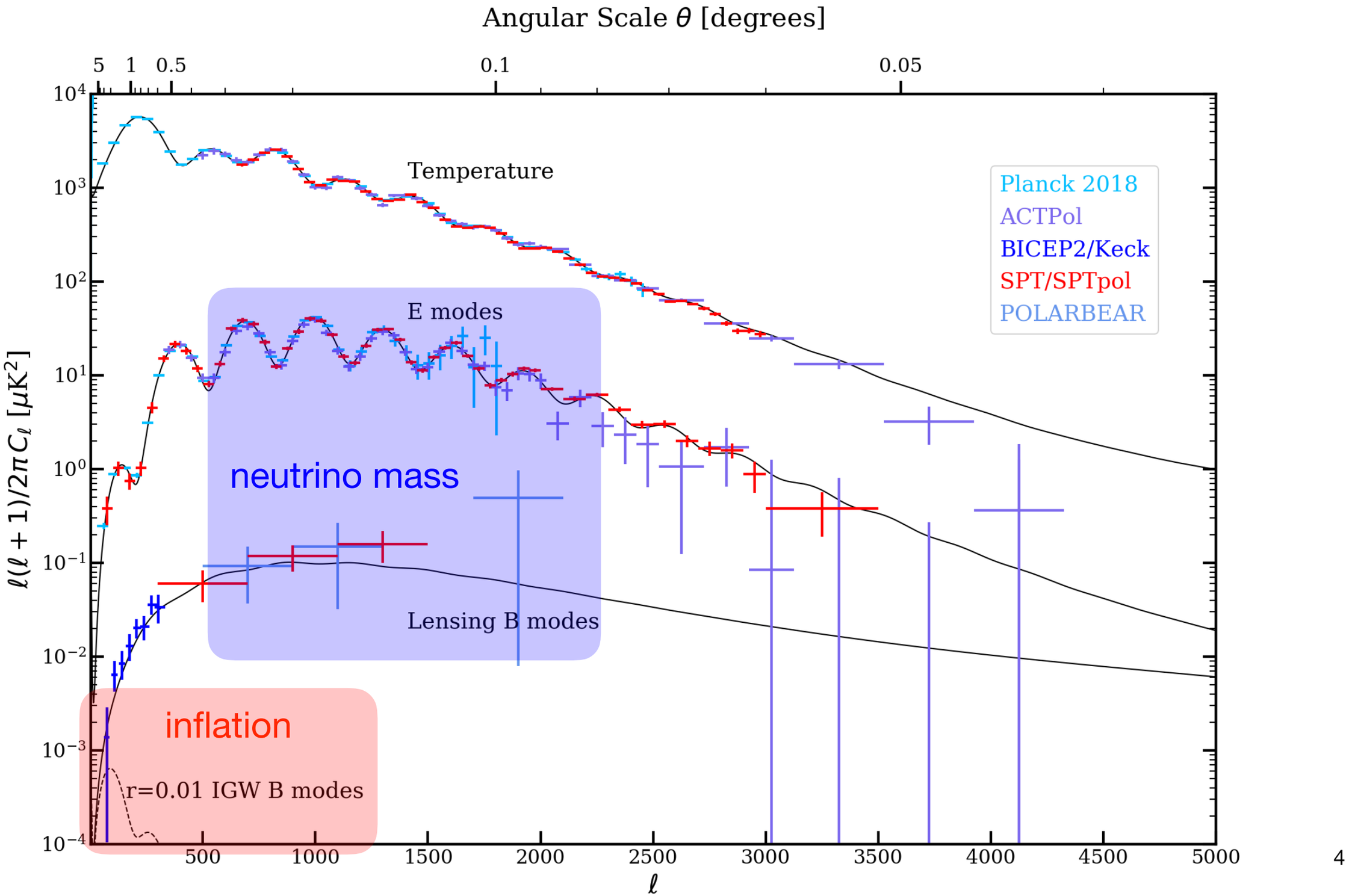

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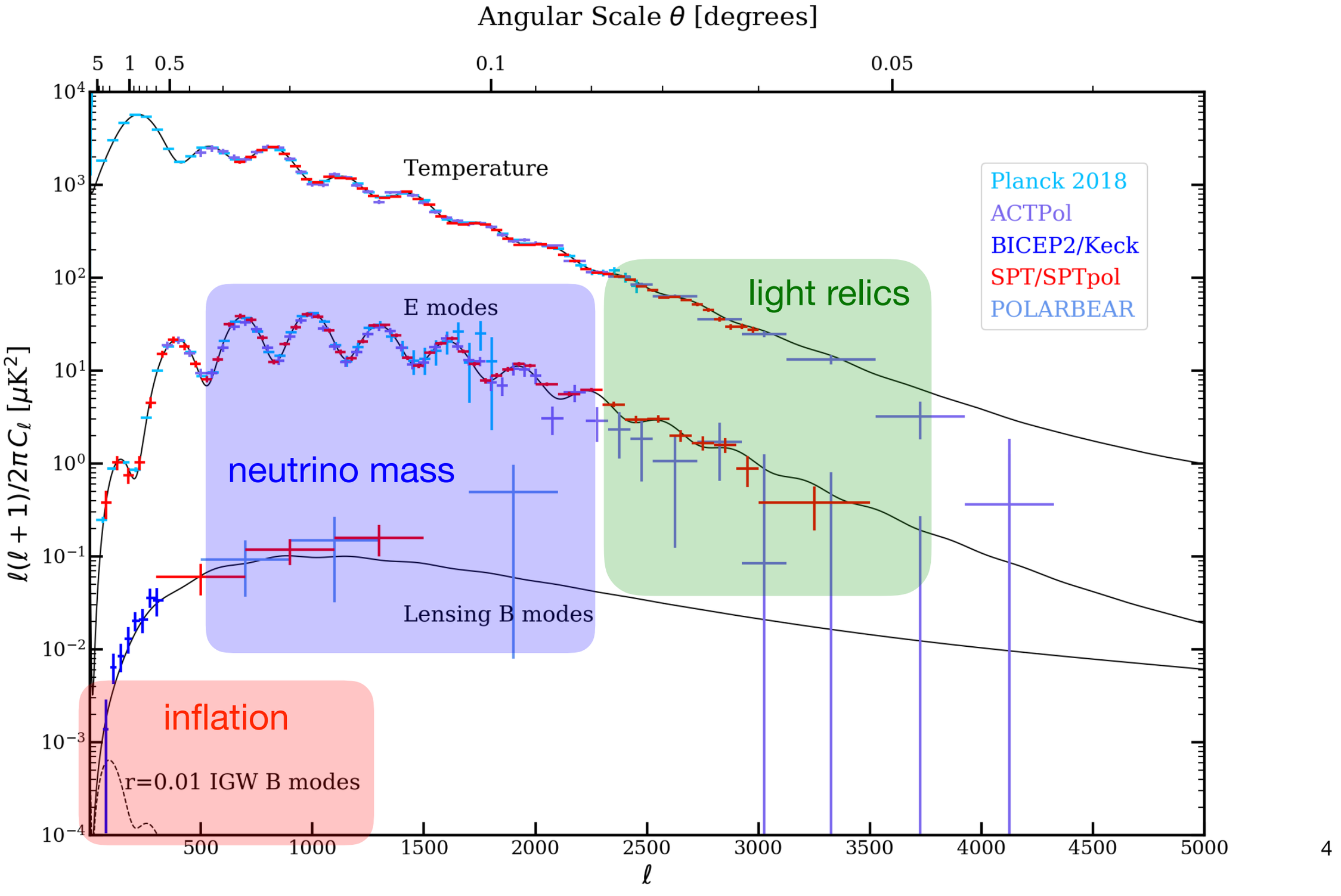
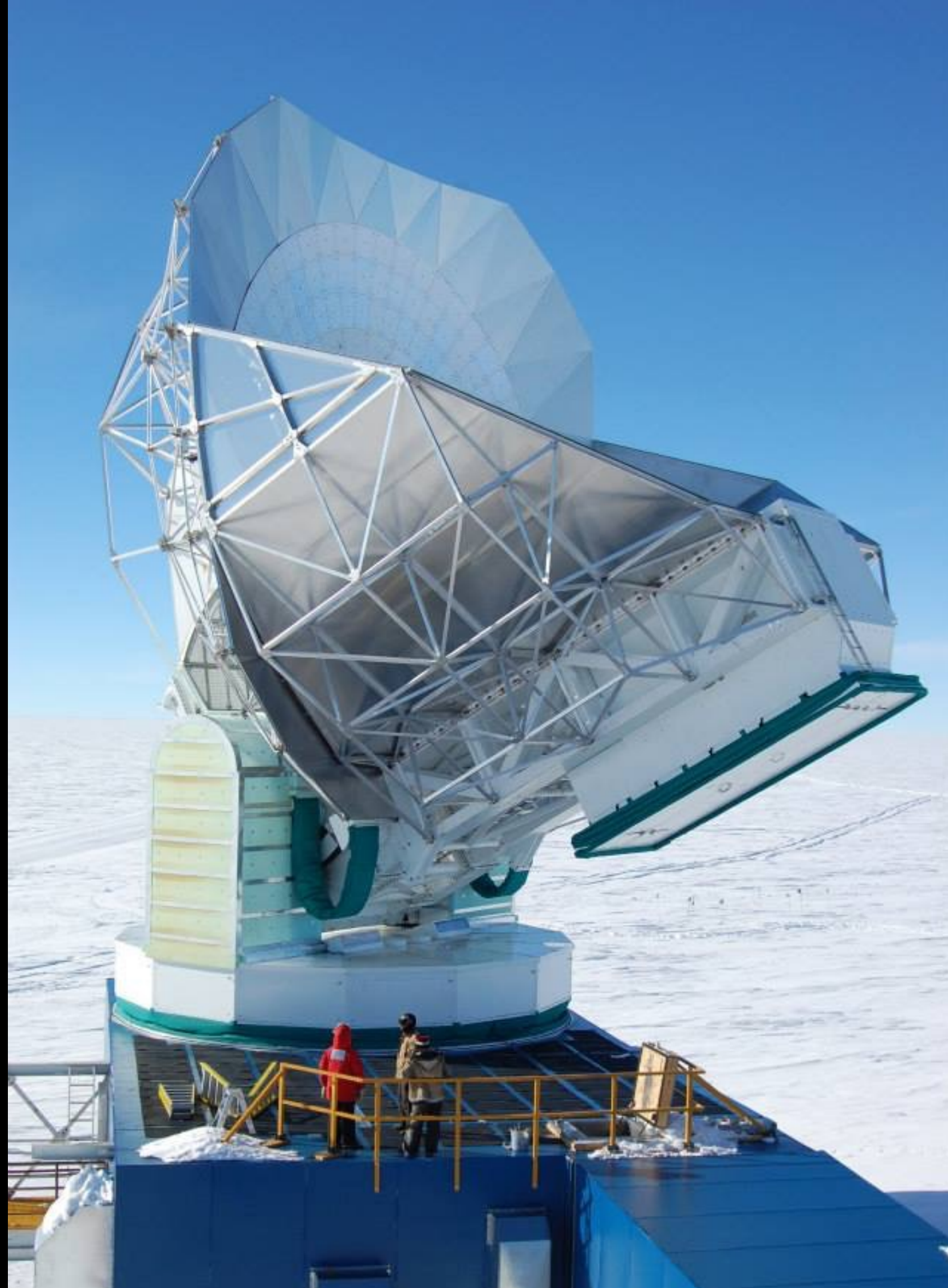


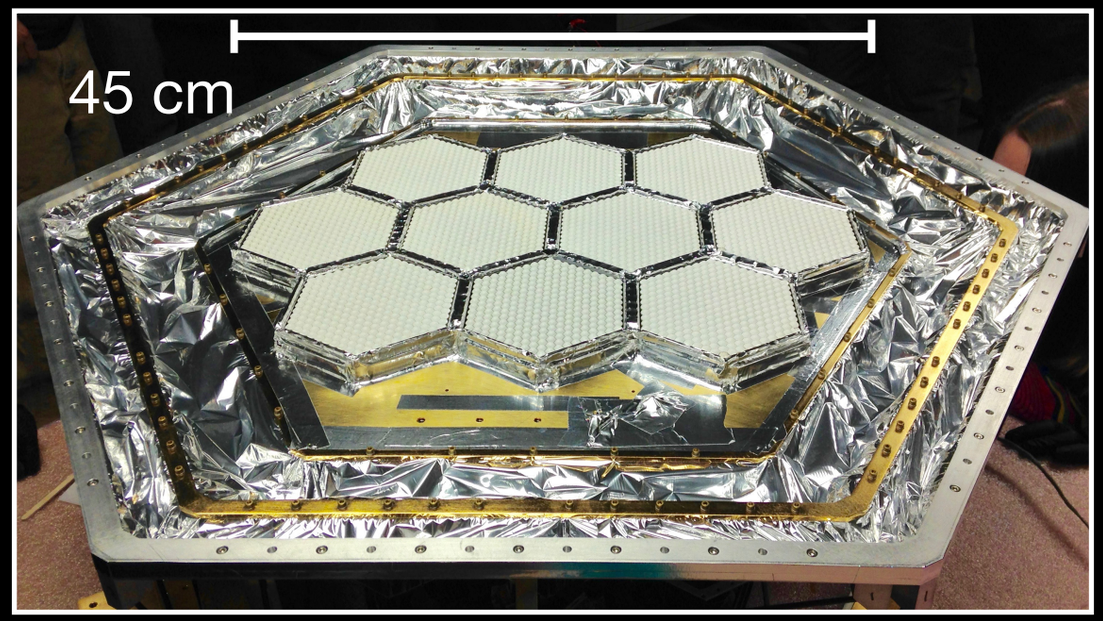
The South Pole Telescope (SPT)

- Unique 10 m primary mirror, largest of its kind
- resolution of ***1.0 to 1.5 arcmin***, highest resolution CMB maps
- South Pole is an excellent site:
  - dry
  - extremely stable atmosphere
  - 24/7 access to the same clean patches of sky (“relentless” observing)



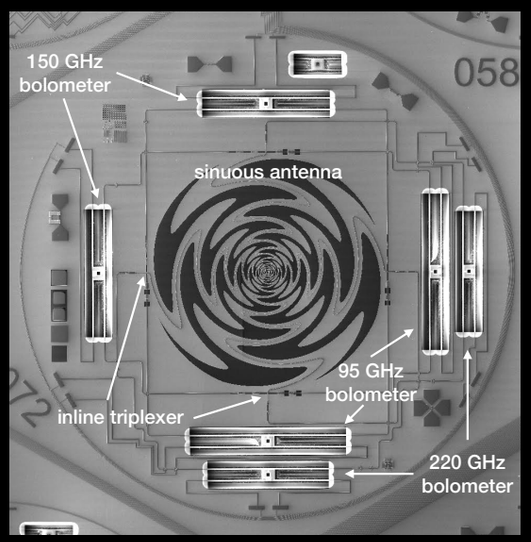
SPT-3G: A New Camera for SPT

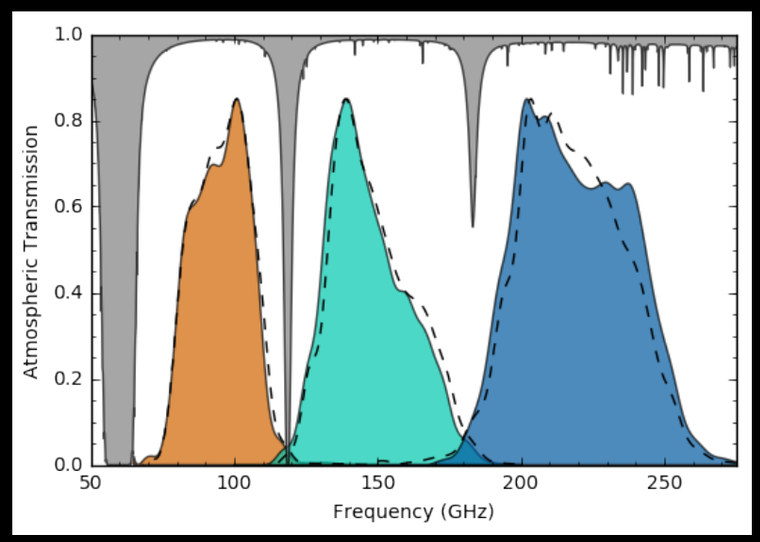
10x more detectors



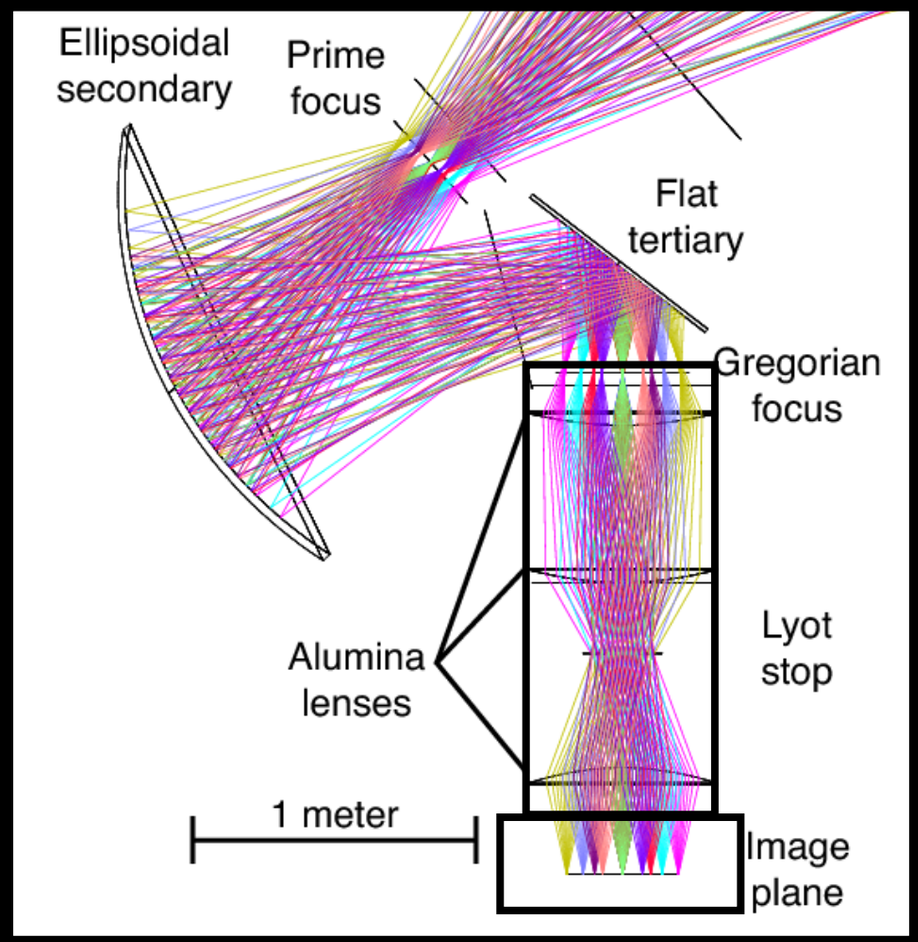
15,000 detectors at 95, 150, 220 GHz w/polarization

3-color pixel architecture





New optics with 2x throughput



SPT-3G Collaboration

Argonne NATIONAL LABORATORY

BERKELEY LAB

NIST

Fermilab

UNIVERSITY OF TORONTO

KICP Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

Berkeley University of California

Case CASE WESTERN RESERVE UNIVERSITY

McGill

Colorado University of Colorado at Boulder

UC DAVIS UNIVERSITY OF CALIFORNIA

THE UNIVERSITY OF CHICAGO

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Harvard-Smithsonian Center for Astrophysics

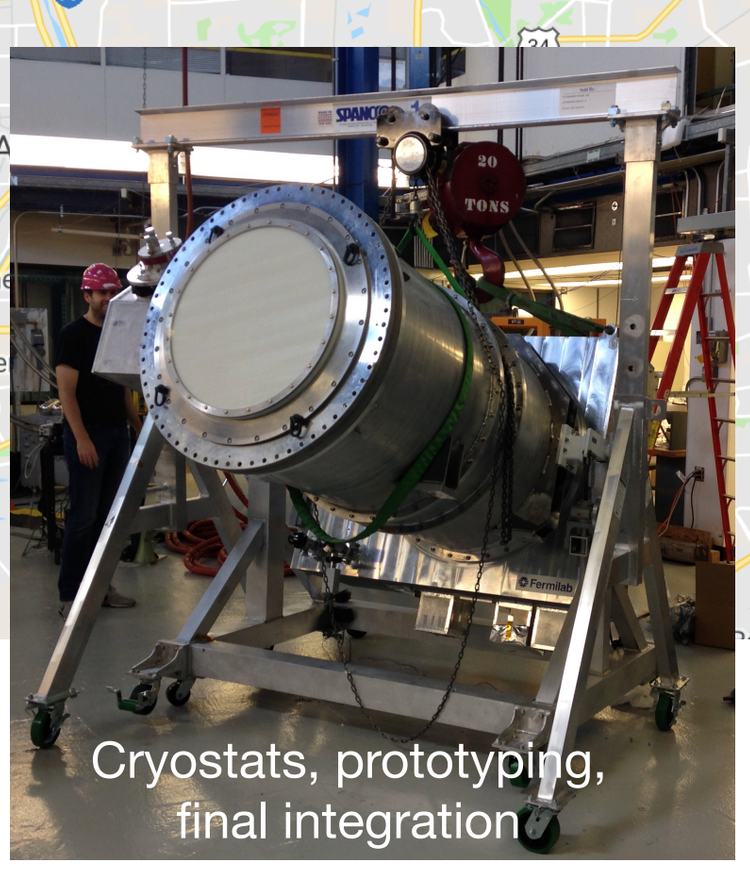
SLAC

NSF

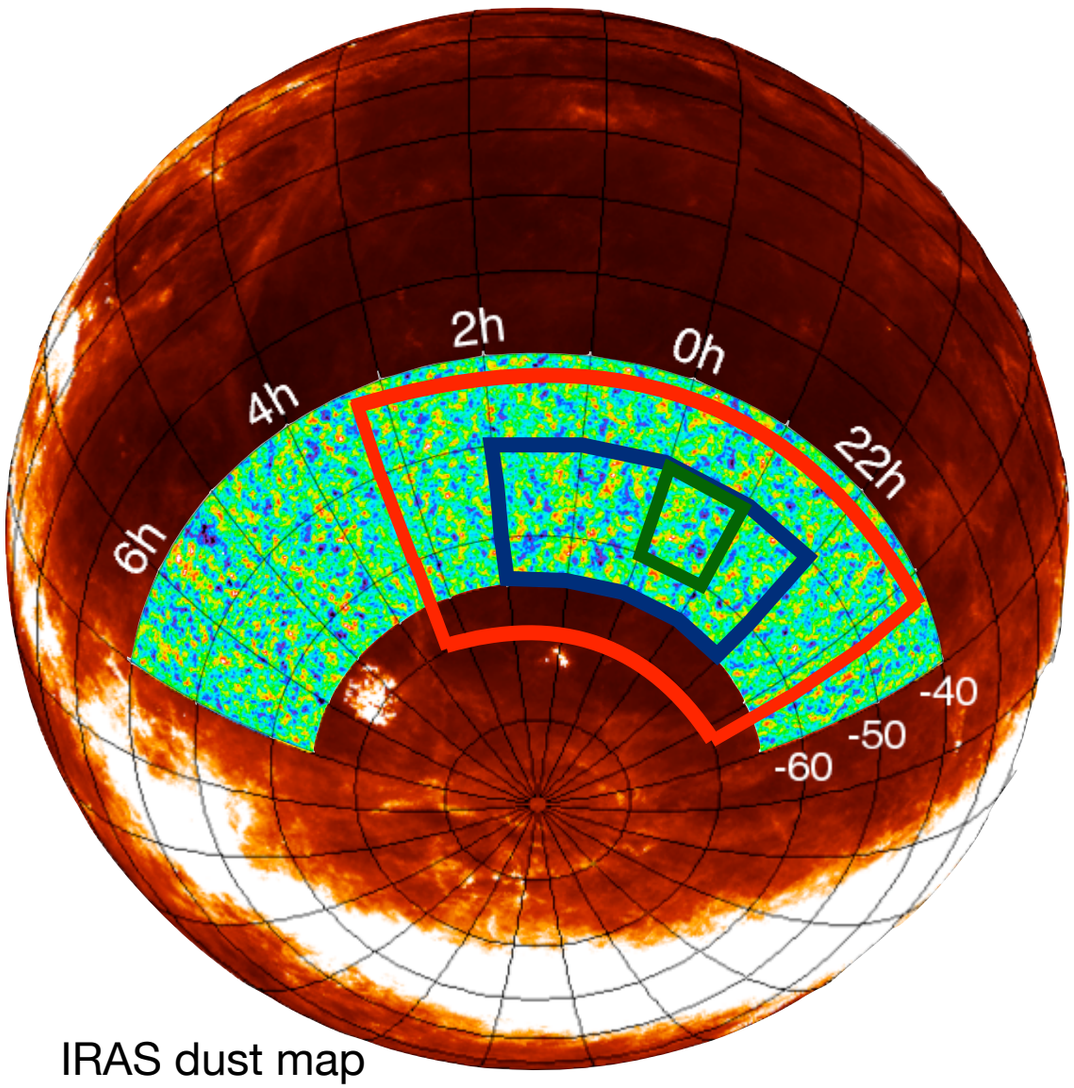
UNITED STATES ANTARCTIC PROGRAM NATIONAL SCIENCE FOUNDATION

U.S. DEPARTMENT OF ENERGY

Made in Chicagoland™



SPT-3G Survey and Sensitivity



IRAS dust map

	Obs. Years	Area (deg2)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPT-SZ	2007-11	2500	40	17	80
SPTpol-Main	2012-16	500	13	5	-
SPTpol-Deep	2012-16	100	10	3.5	-
SPT-3G *projected*	***2018-23***	***1500***	***2.7***	***2.2***	***8.8***

- Started observing 1500d field in March of 2018
- Overlaps with BICEP/Keck patch of sky—good for ***delensing***
- Overlaps with Dark Energy Survey (DES)—good for ***cross-correlation*** analyses

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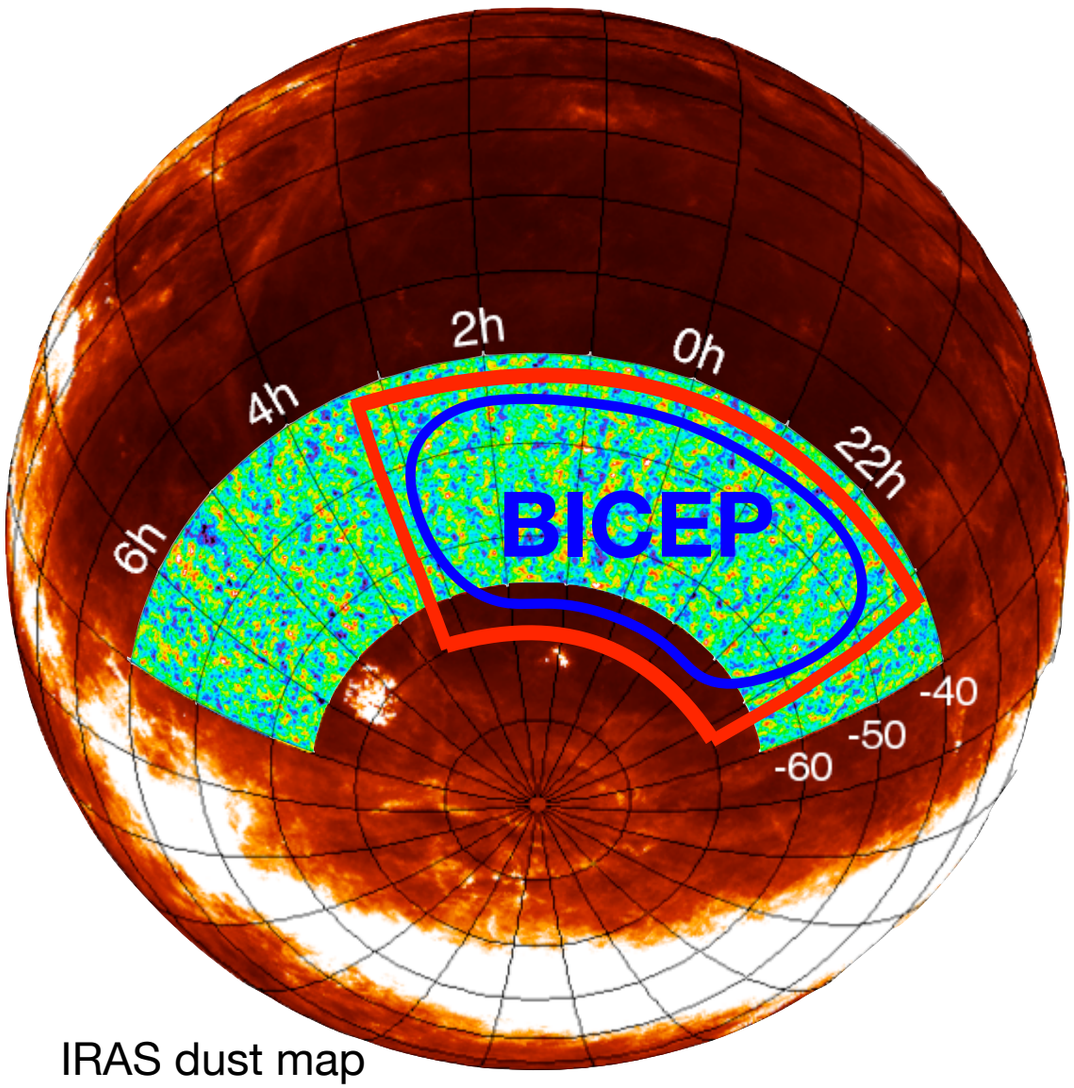

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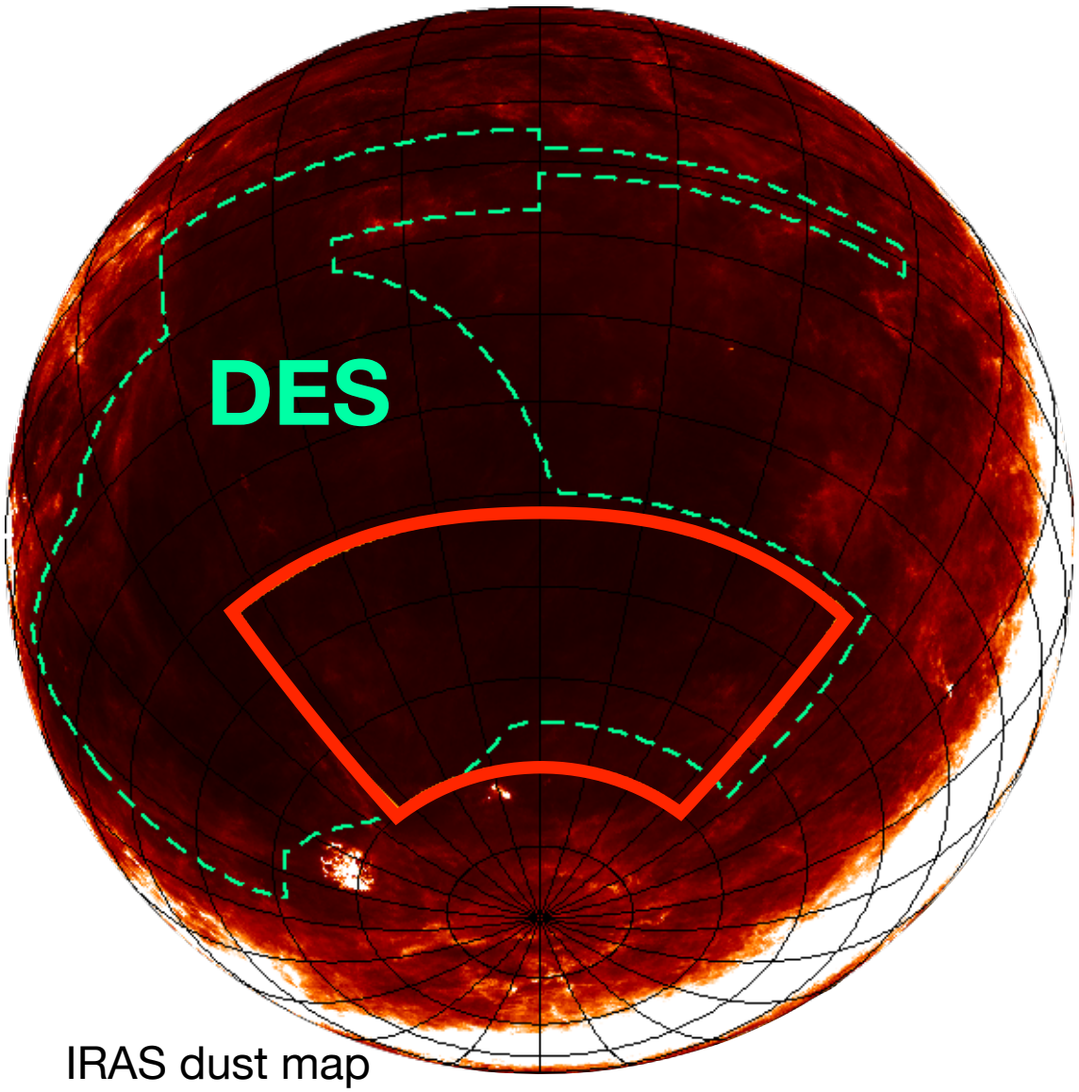

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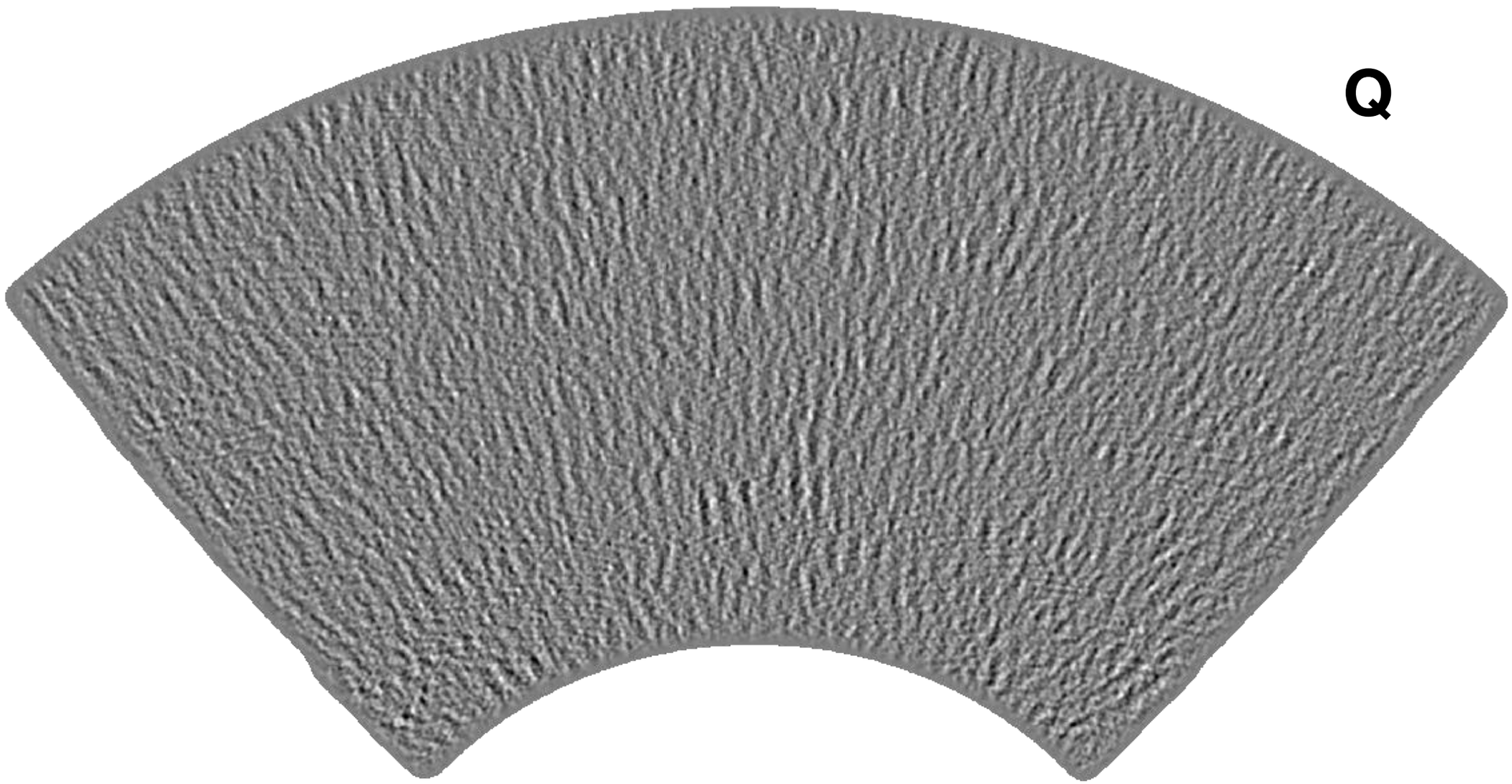
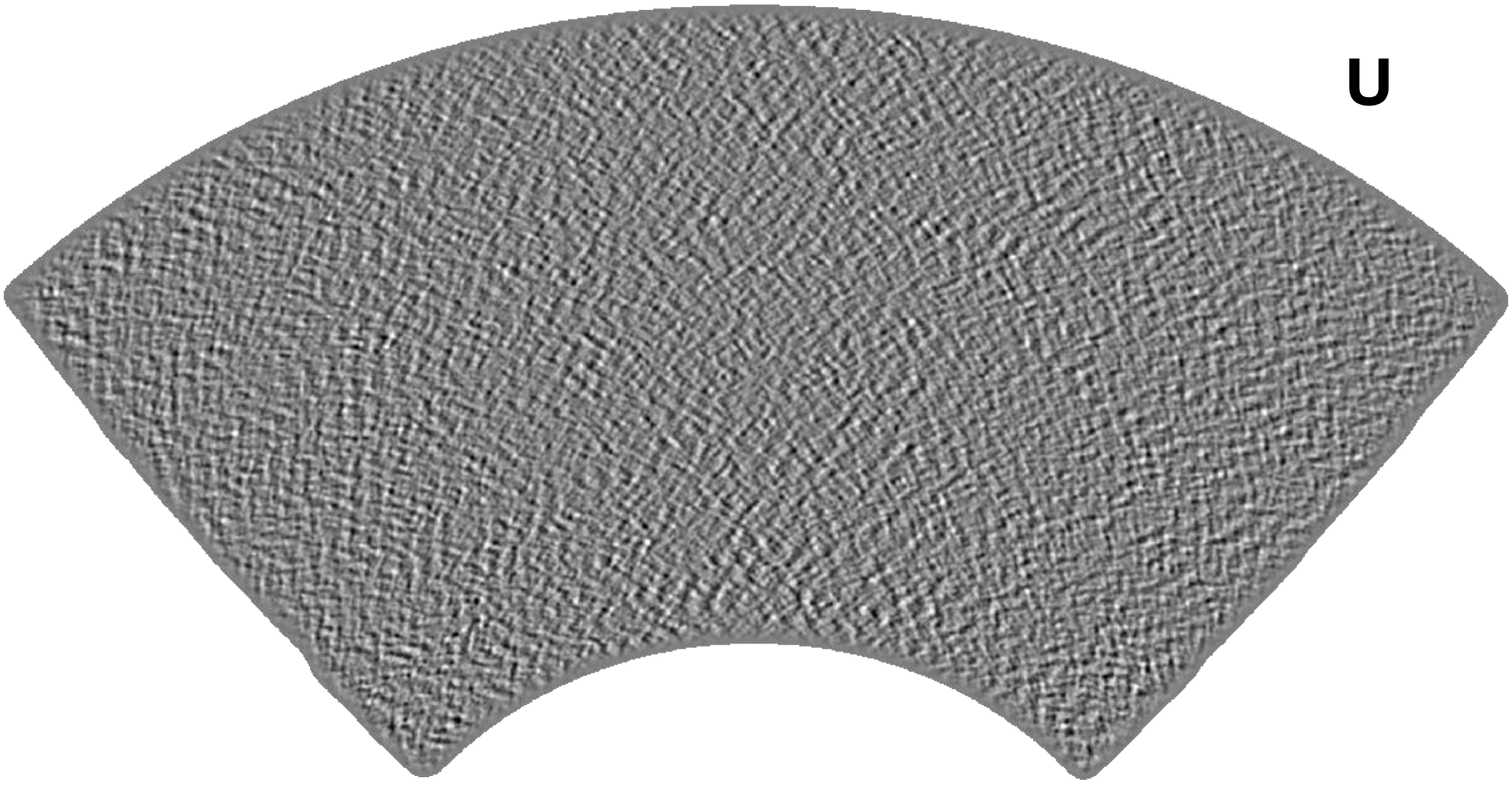
SPT-3G 2018 E Modes



SPT-3G 2018 E Modes



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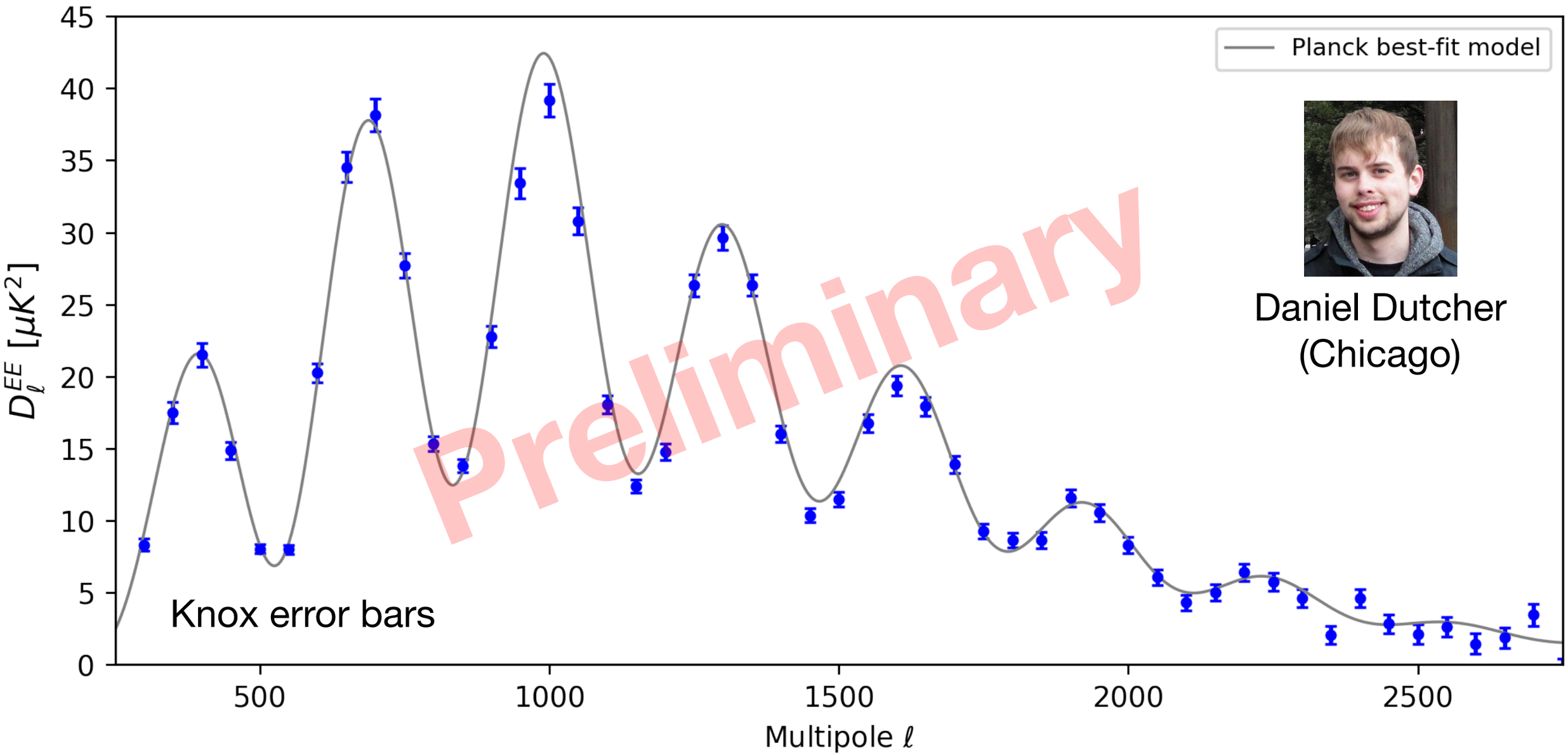


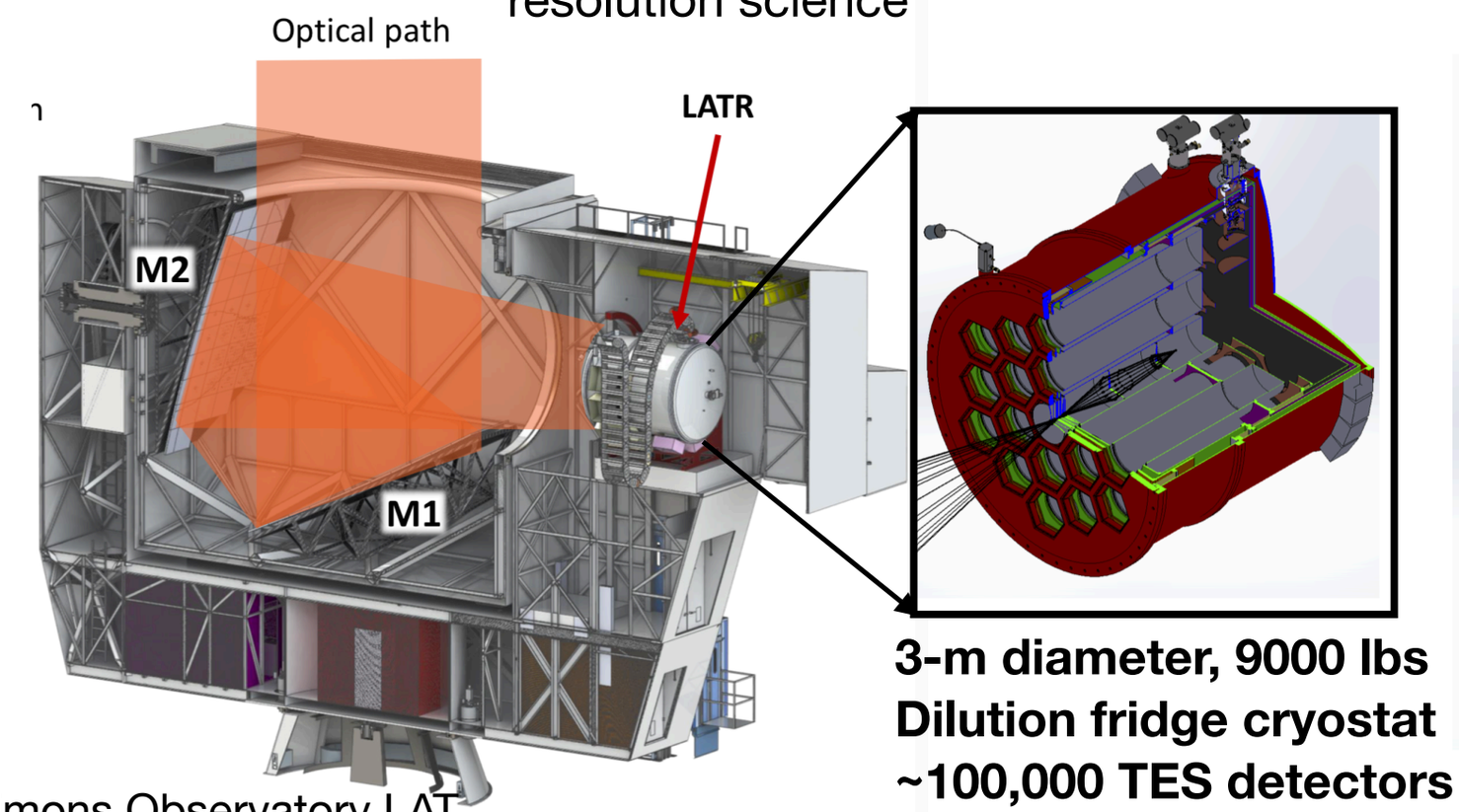
Daniel Dutcher
(Chicago)

- Work in progress! Still needs point source masking, mode-coupling, beam, improved transfer function from simulations, etc.
- ***AND 2019 data so far already deeper than entire 2018 dataset***

The CMB-S4 Concept

- Endorsed by DOE/NSF P5 report, NRC/NSF Antarctic Science report, Concept Definition Taskforce (CDT) report accepted by AAAC panel
- **Concept:**
  - **400,000 detectors** split between 3x 6m-aperture, ~18x 0.5m-aperture telescopes
  - **Two sites:** South Pole + Atacama in Chile
  - **Two surveys:** Inflation survey (3-8% sky) + neutrinos and cross-correlation (40% sky)
  - ***FY 2027***

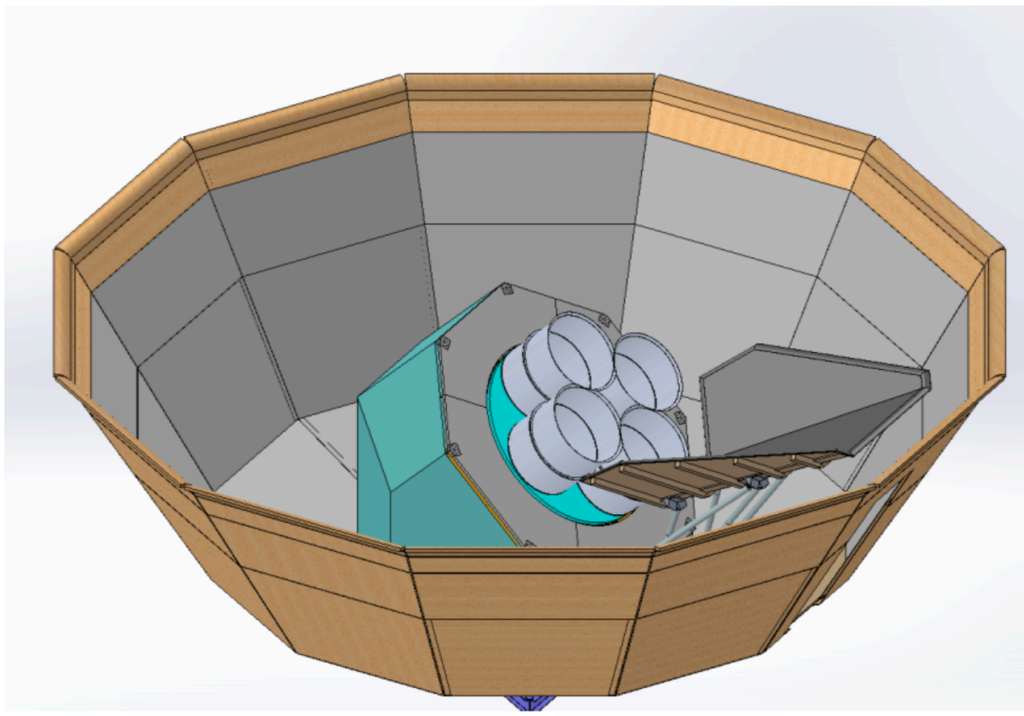
Large aperture: delensing, neutrinos, high-resolution science



Simons Observatory LAT

3-m diameter, 9000 lbs
Dilution fridge cryostat
~100,000 TES detectors

Small aperture: inflationary B modes



BICEP Array

CMB-S4 Science

	Stage 2	Stage 3	Stage 4	Top level goal for S4
Inflation: σ_r	≤ 0.1	≤ 0.01	≤ 0.001	Detect or rule out the most natural class of inflationary models.
	single field slow roll			
Light Relativistic Species: σ_{Neff}	0.14	0.06	0.027	Detect or rule out all light relativistic speicies with spin.
	Minimum ΔN_{eff}			
Neutrino Masses: $\sigma_{\Sigma Mv}$	0.15eV	0.06eV	0.015eV	>3σ detection of neutirno mass, potential to determine the neutrino mass hierarchy.
	lower limit Σm_v			
Dark Energy: FOM	~180	~300-600	~1250	Improve tests of modified gravity and tests for new dynamical fields.

+ much more ancillary science!

CMB-S4 Outlook

- ***Now-2022:*** Design and prototyping of detectors, readout electronics, and optics
    - Viable detector, readout, optics technologies demonstrated by Stage-3 experiments
    - Challenge is to scale to 50x detectors on 20x telescopes!
    - At a scale that can only be coordinated by the DOE labs—tight ongoing collaboration between Fermilab, ANL, LBL, and SLAC
- ***2022-2027:*** Construction, integration, commissioning
- ***2027:*** Start of science operations

Summary

- SPT-3G is deployed and operating at full sensitivity
- 1500 sq deg survey is well underway and will continue for 5 years
- Many exciting analysis opportunities, especially in combination with other surveys
- CMB-S4 is next!

photo: Joshua Montgomery

Experimental Approaches

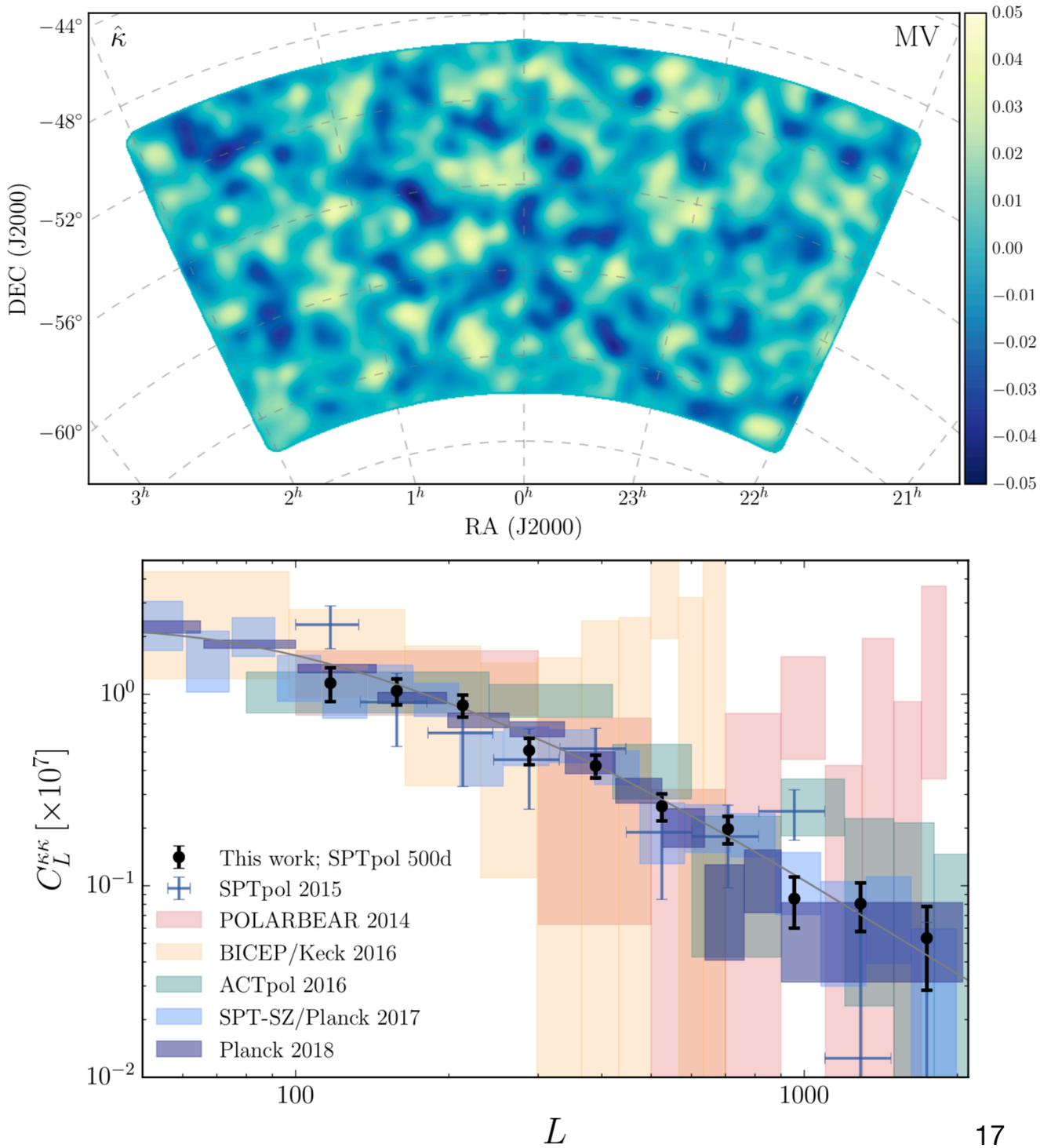
	Large aperture (5 m ~ 10 m)	*Small aperture (~ 0.5 m)*
cost / scalability	expensive	cheap
systematics control	harder	easier
resolution	high (~1 arcmin)	low (~ 30 arcmin)
science targets	neutrino mass, light relics, astrophysics, inflation*	inflation
primary optics	reflecting	refracting

SPTpol 500d Lensing

- Gravitational lensing of CMB photons deflects paths by ~2 arcmin, coherently over degree scales

- Correlates previously uncorrelated Fourier modes

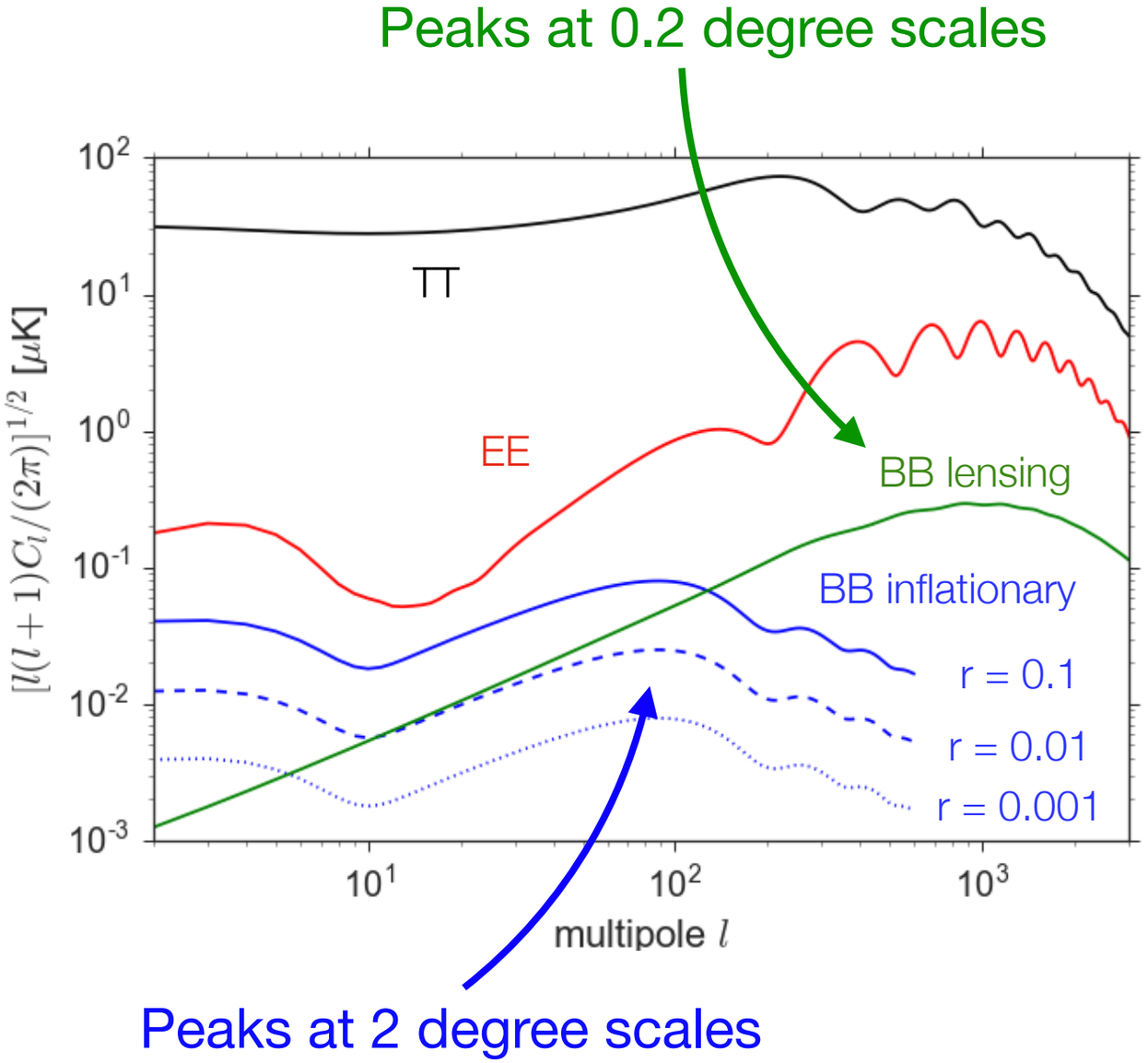
- Reconstruct map of integrated gravitational potential between us and CMB



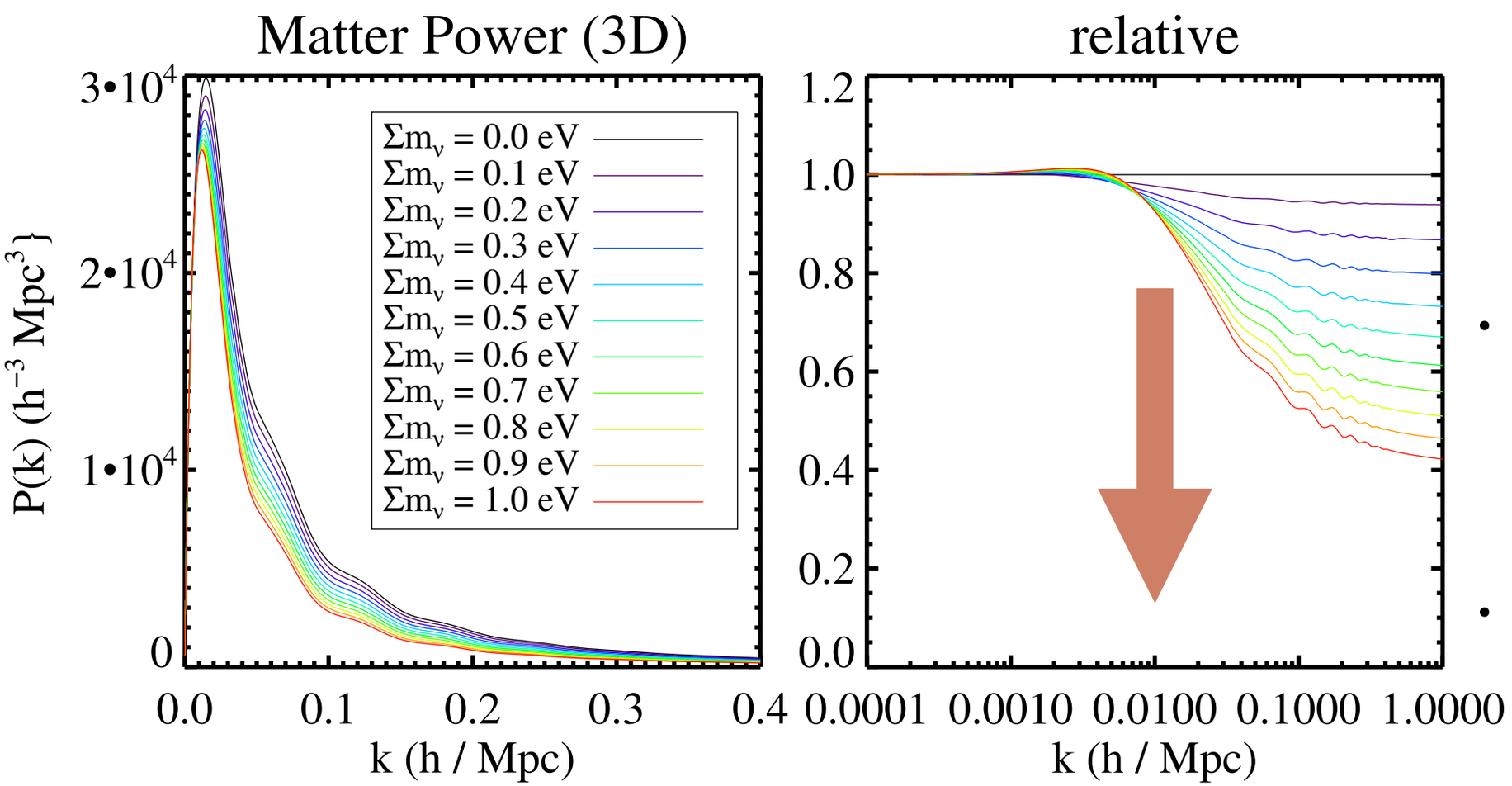
Kimmy Wu (Chicago), et al. (1905.05777)

Primordial B Modes

- Inflation produces a background of gravitational waves that persist through recombination
- "Primordial B modes" are produced ***only*** by these gravitational waves
- Unambiguous evidence for inflation
- Signals peaks on degree scales with amplitude proportional to *r* "tensor-to-scalar" ratio
- "Lensing B modes" produced by gravitational lensing that distorts E modes into B modes



Neutrino Mass: Matter Power Spectrum

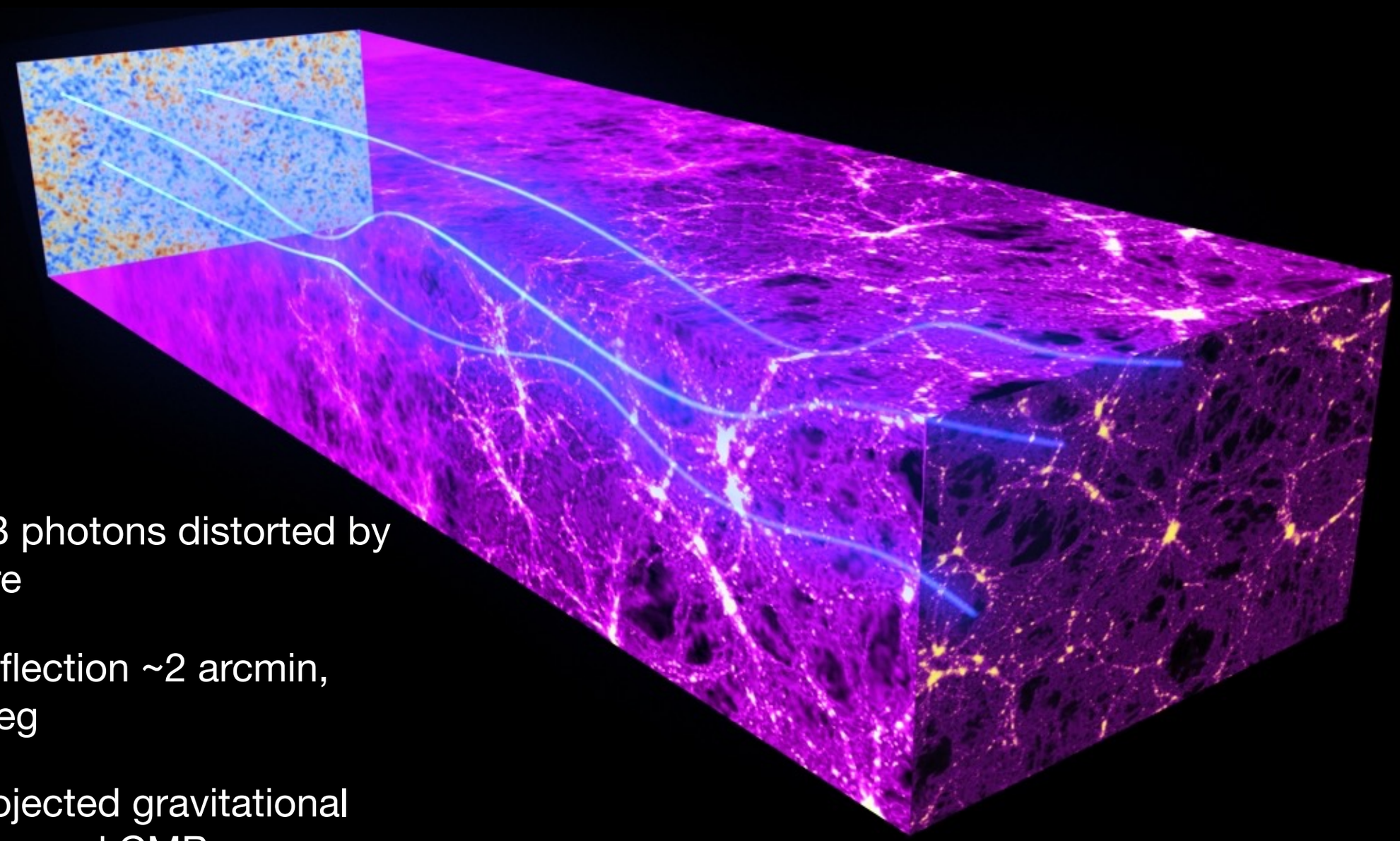


CMB-S4 science book

- ***Sum of neutrino masses affect growth of structure in universe***
- Clustering of matter suppressed at scales < 100 MPc
- ~5% suppression per 0.1eV in total mass
- ***Lower*** limit from oscillations:

oscillations depend on squared mass differences, not absolute mass scale → $\sum m_\nu > 0.06\text{eV}$

Neutrino Mass and Gravitational Lensing

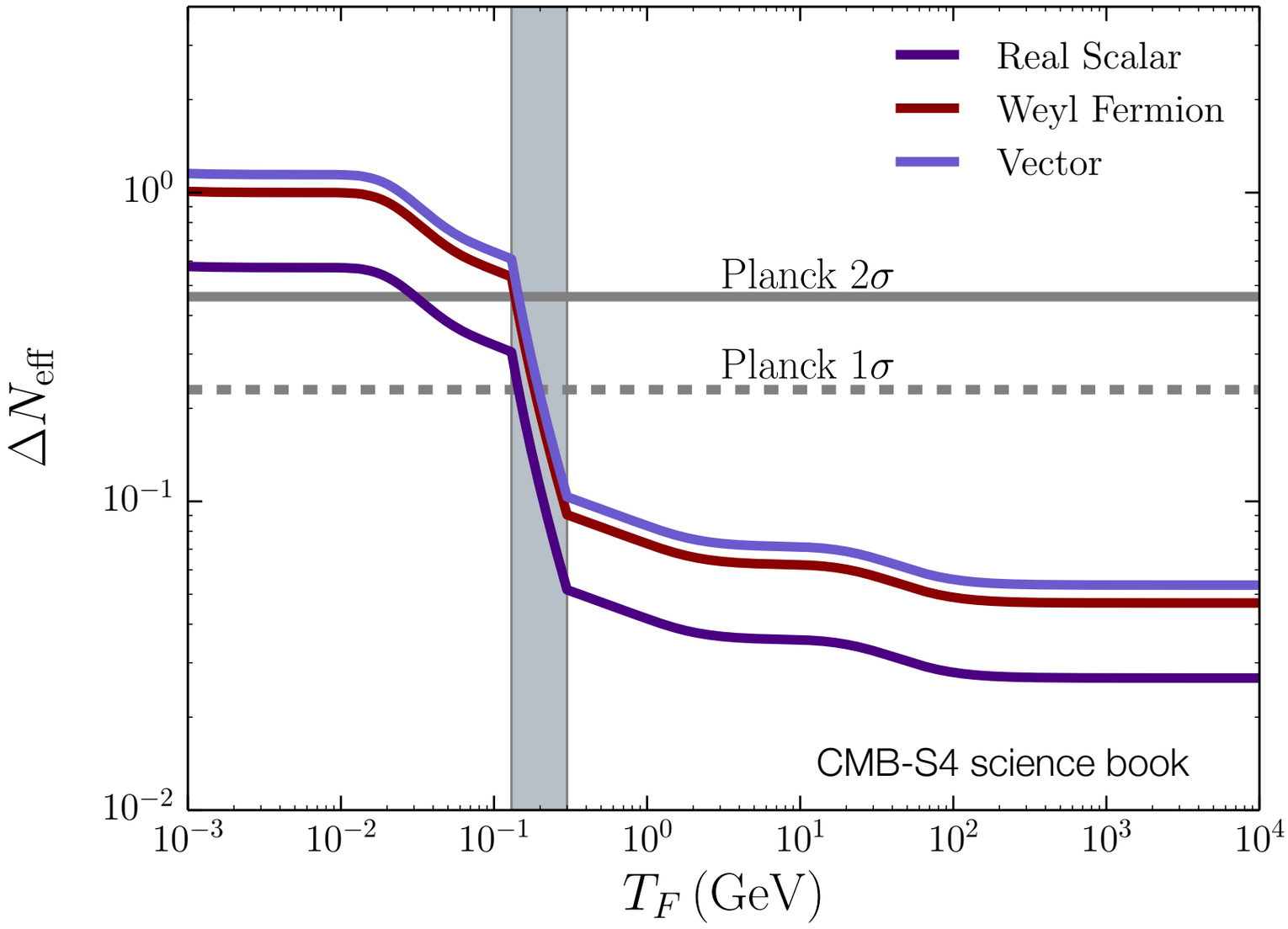


- Trajectories of CMB photons distorted by large-scale structure
- Angular scale of deflection ~2 arcmin, coherent over ~2 deg
- Reconstruct the projected gravitational potential between us and CMB

CMB probes matter power spectrum and neutrino mass

Light Relics: N_{eff}

- ***Any*** light particle in thermal equilibrium contributes to relativistic energy density (~N_{eff})
- Standard model N_{eff} = 3.046
- After decoupling, contribution is diluted relative to neutrinos as Standard Model particles annihilate
- But there is a ***minimum*** contribution corresponding to freeze out above the top quark mass



Planck measurement:

$$N_{\rm eff} = 2.99 \pm 0.17$$