

Overview of Cosmic Microwave Background experiments

Credit: Aman Chokshi



Ground



Christian Reichardt
University of Melbourne

Space



Probing the Cosmic Frontier with CMB

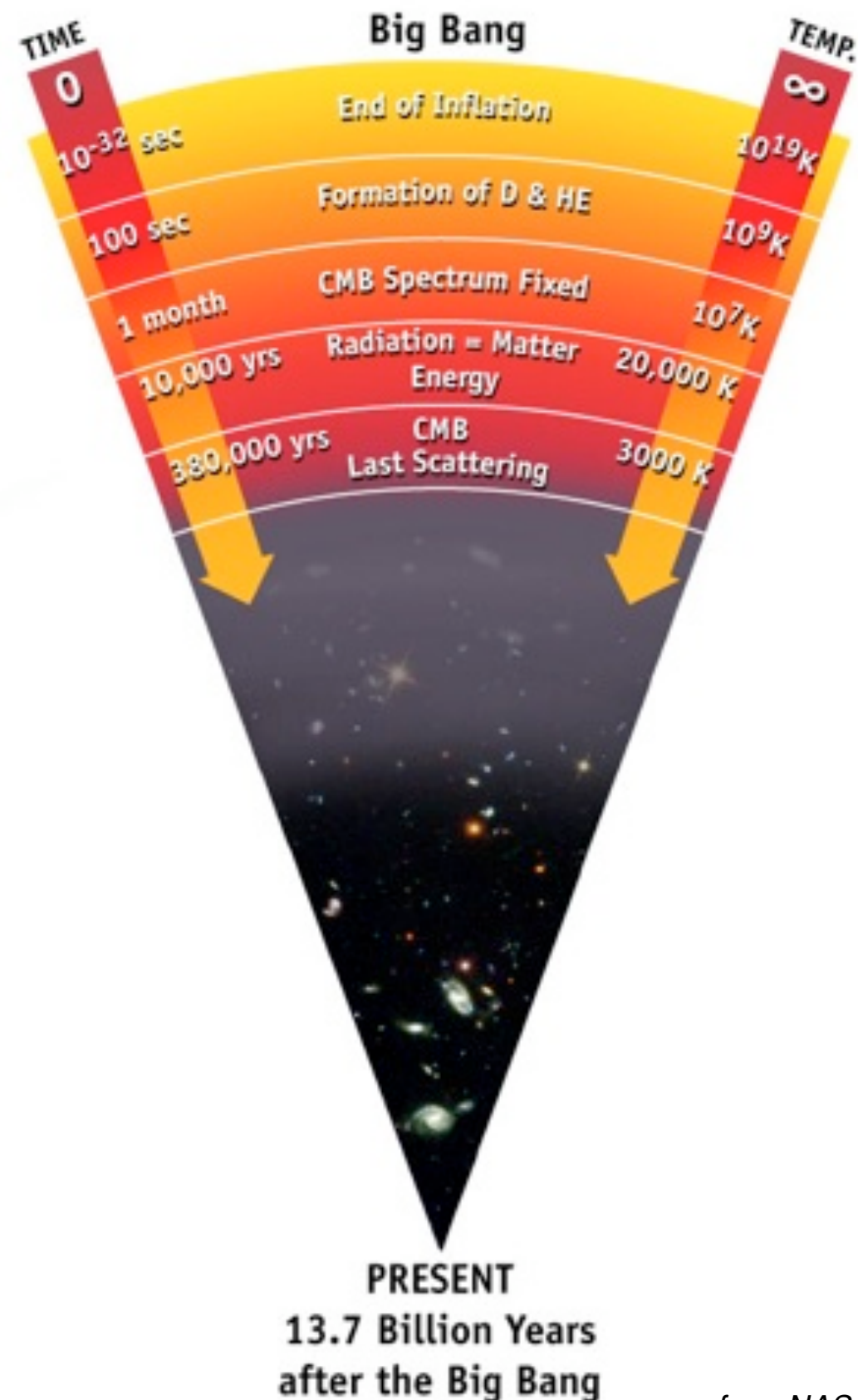
We now have a model that describes the evolution of our Universe from a hot and dense state.

The model has some unusual features

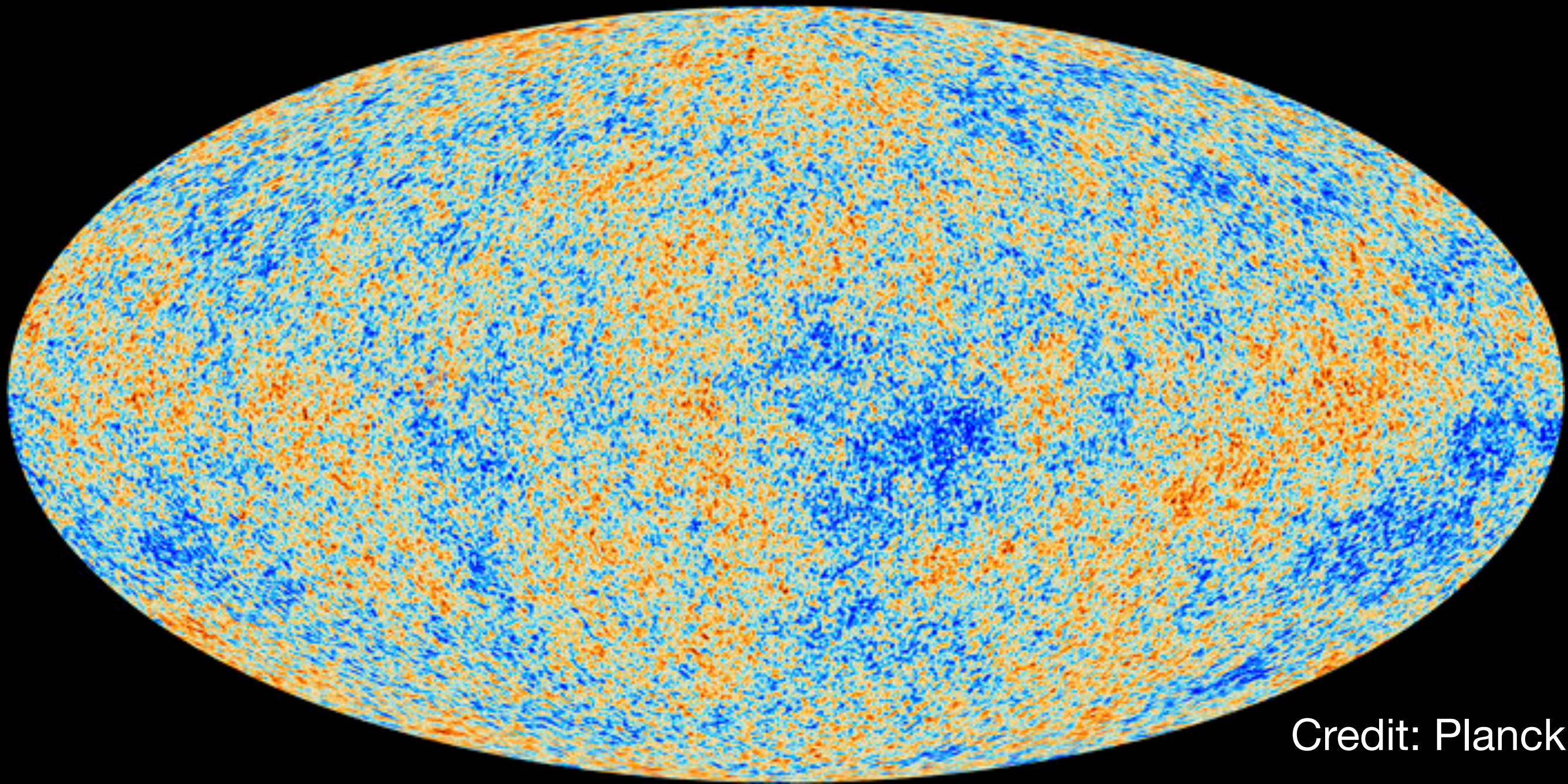
- ***new physics*** -

Dark Matter, Dark Energy, and starts with a period of **Inflation**.

Most of the model has been learned from measurements of the cosmic microwave background (CMB).



The goal: snapshot of the Universe
just after the Big Bang



Credit: Planck

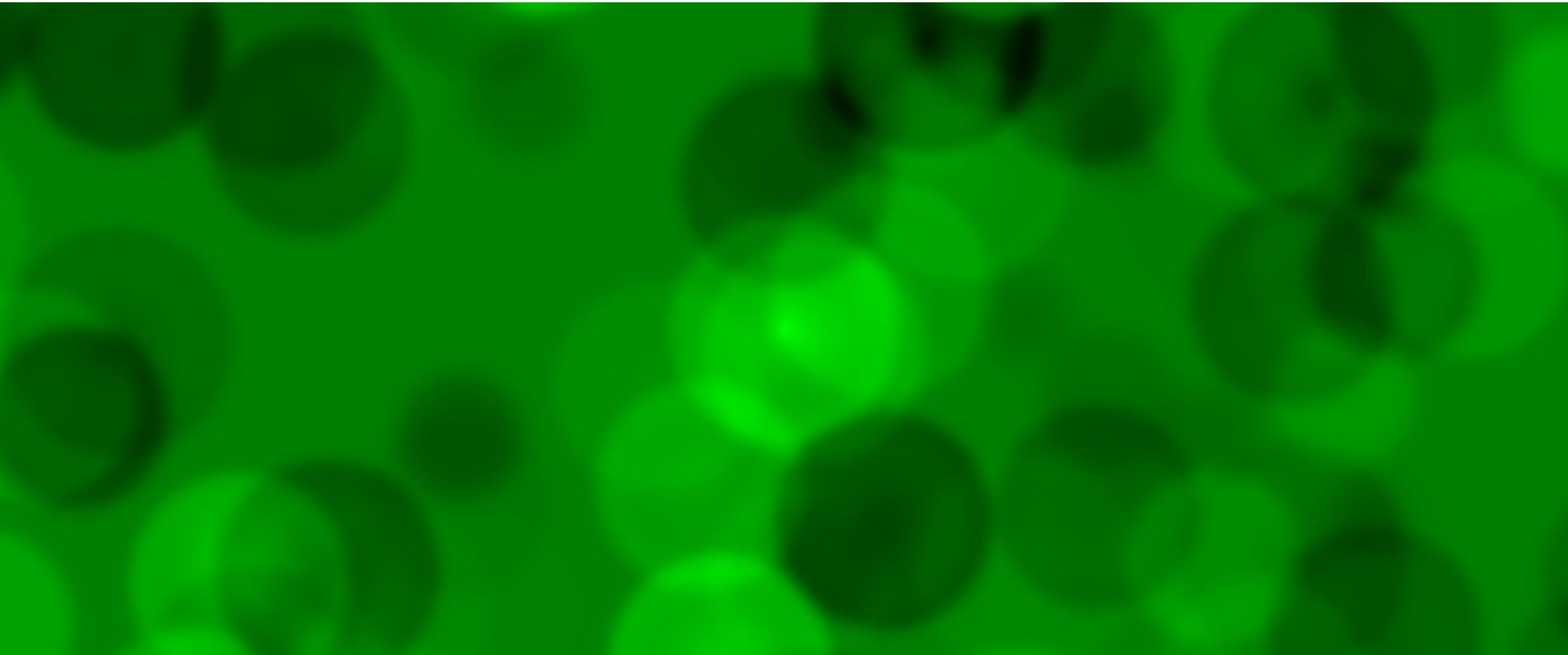
Adding “pebbles”

1



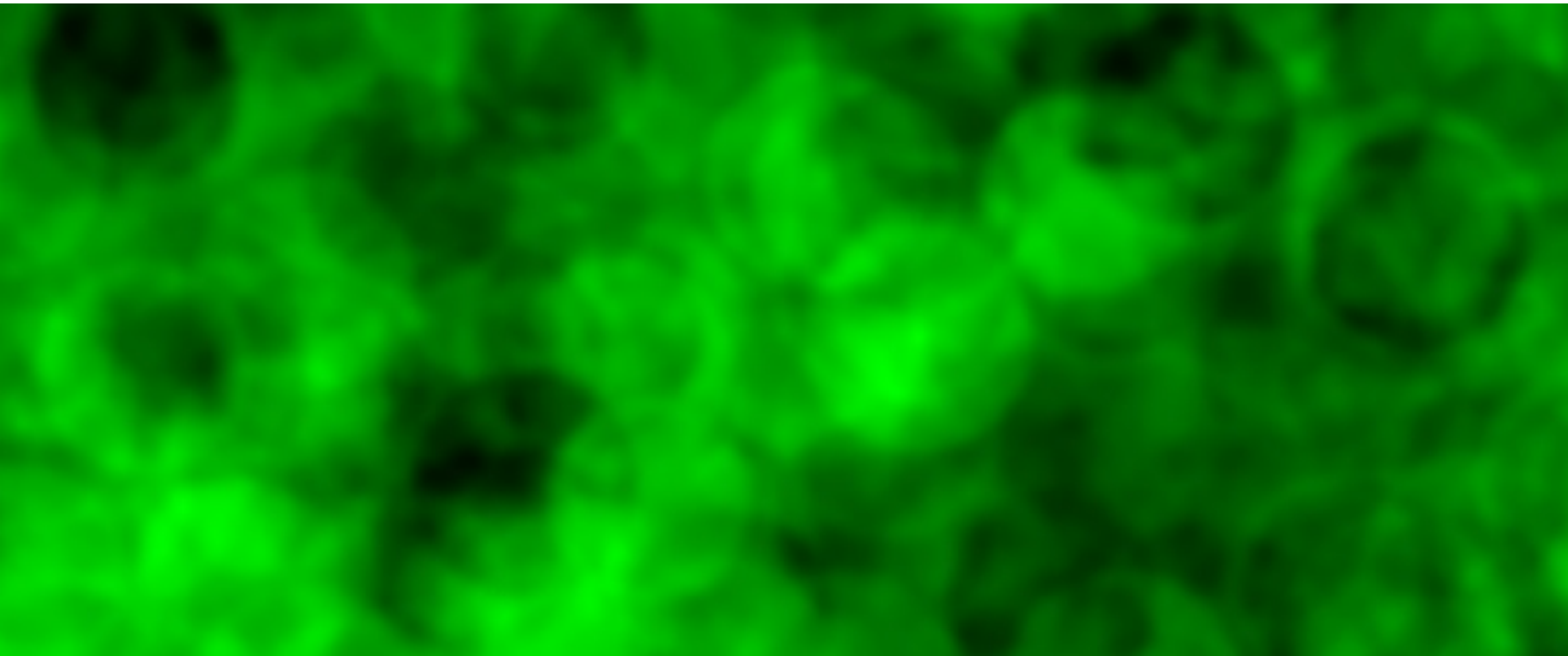
Adding “pebbles”

100



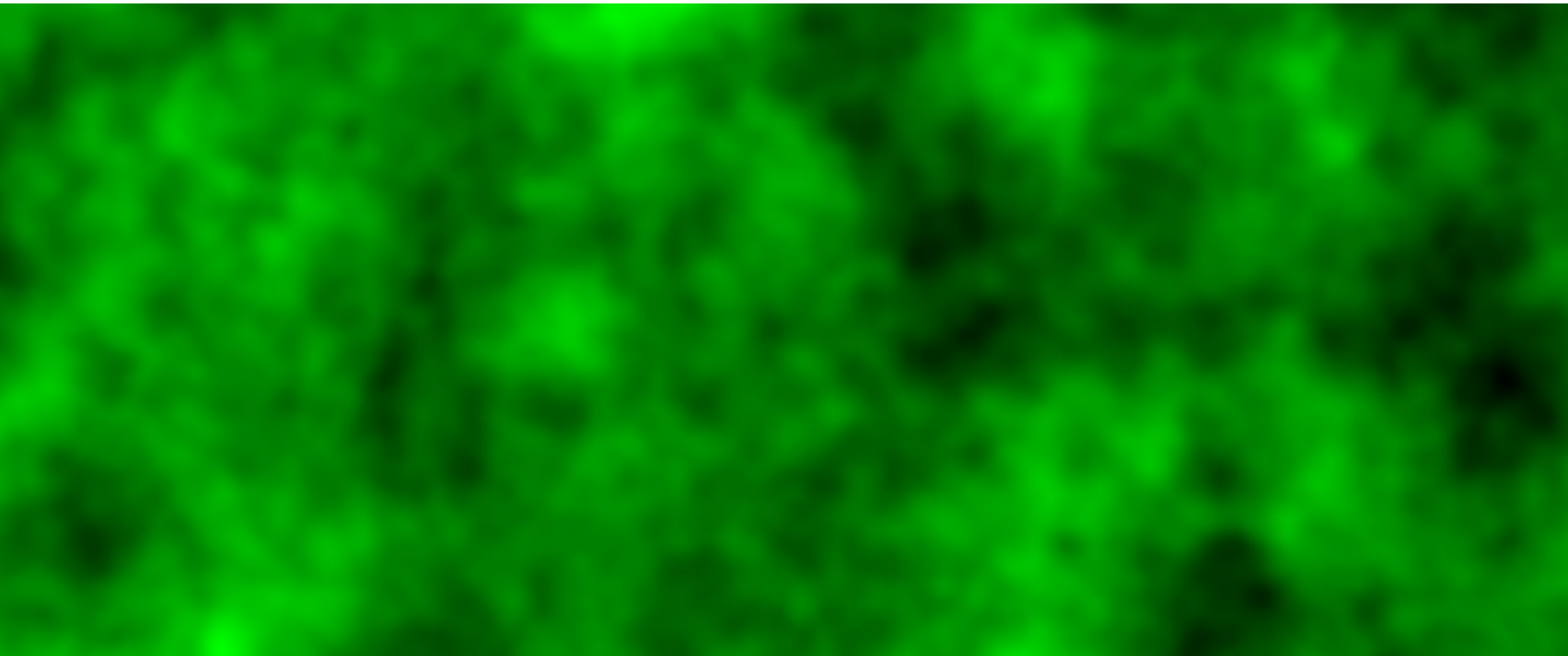
Adding “pebbles”

1000



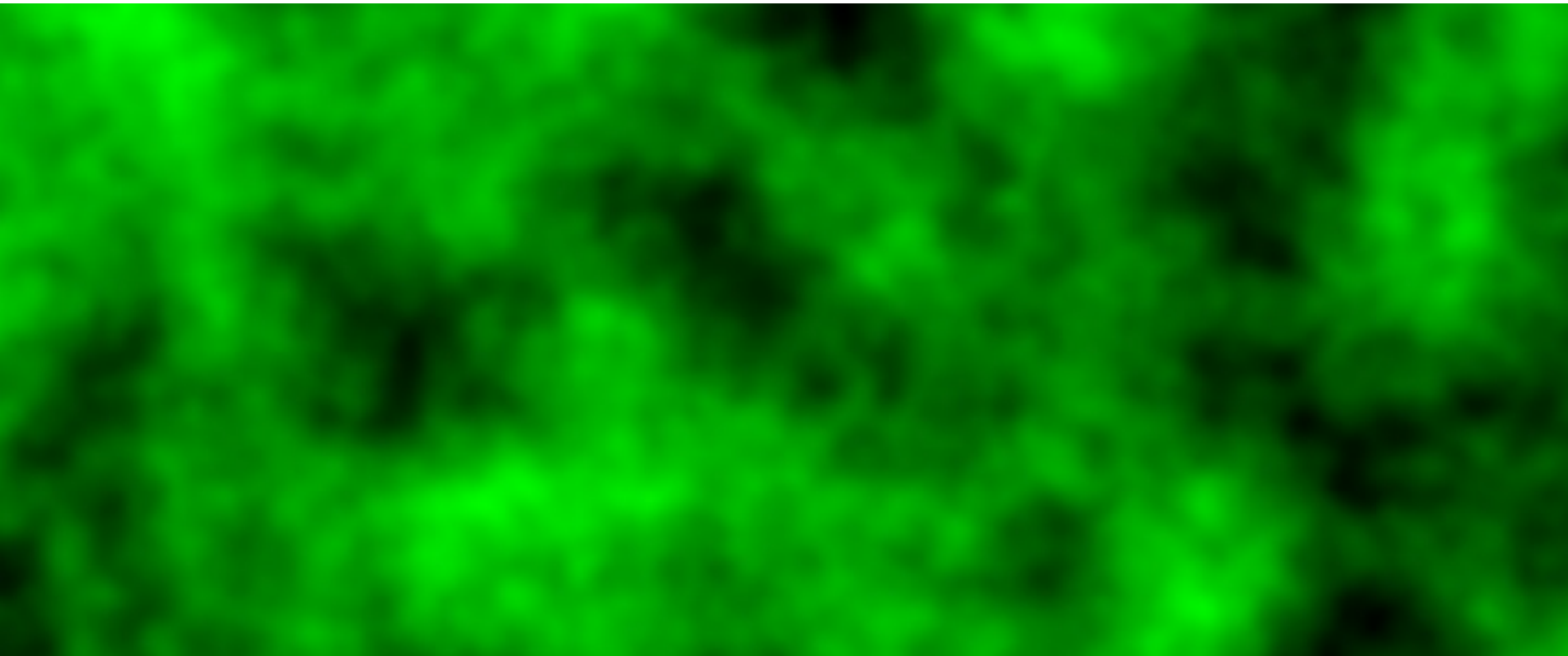
Adding “pebbles”

10,000



Adding “pebbles”

490,000

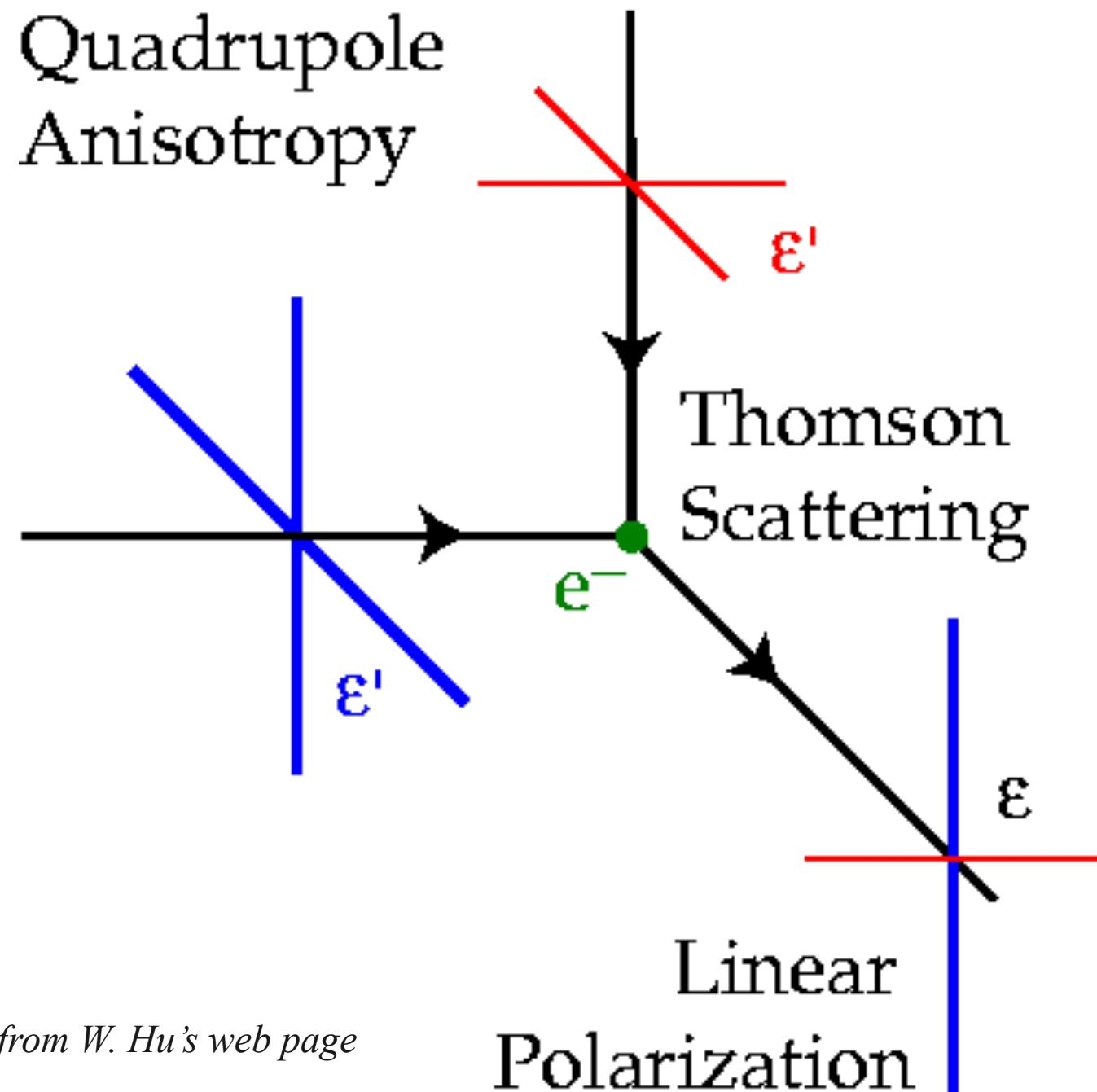


The map of the CMB anisotropy is well-described by acoustic waves around an ensemble of dark matter potentials

Credit: Adam Hincks

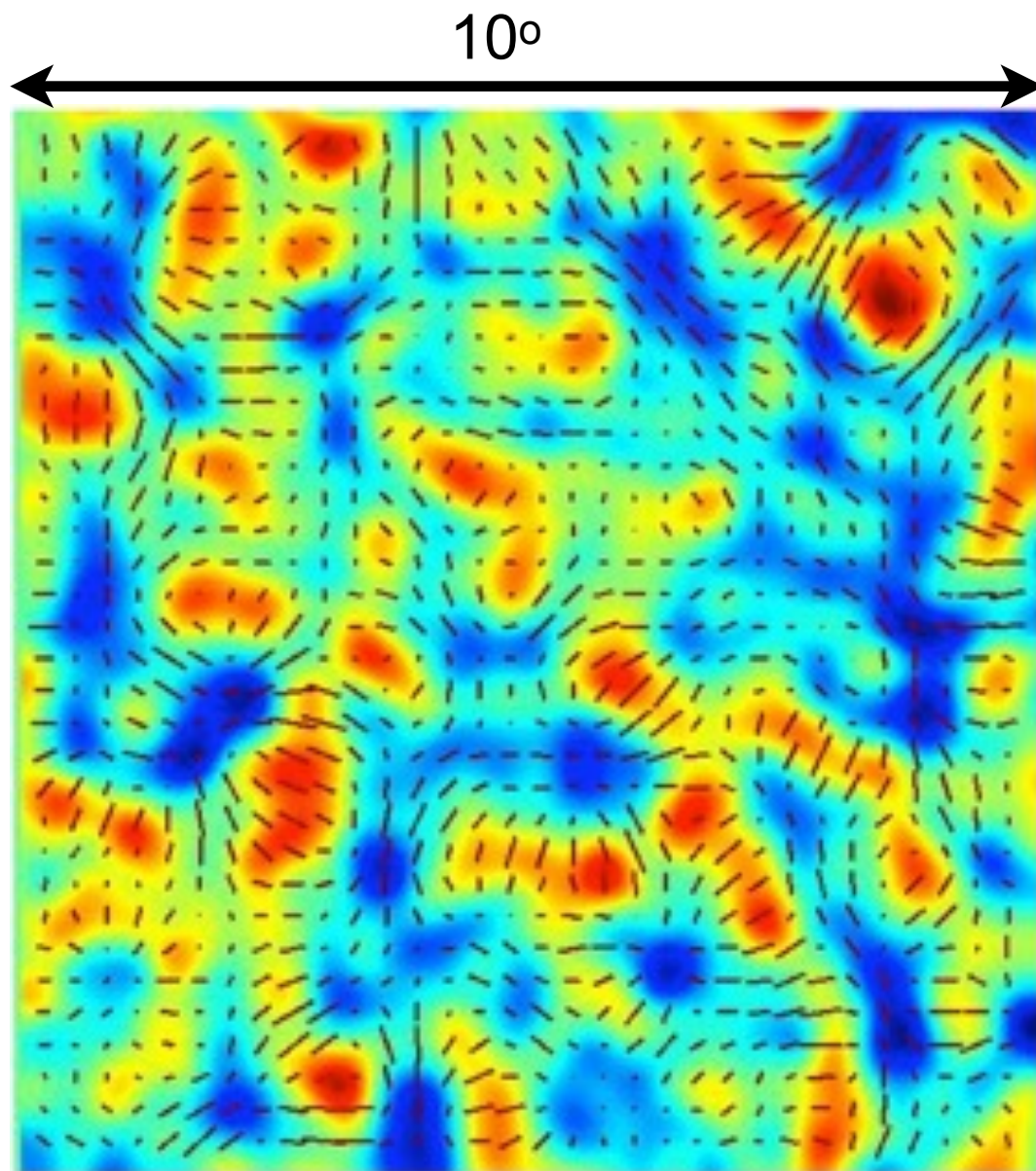
Polarization of the CMB

CMB is polarized by Thomson Scattering



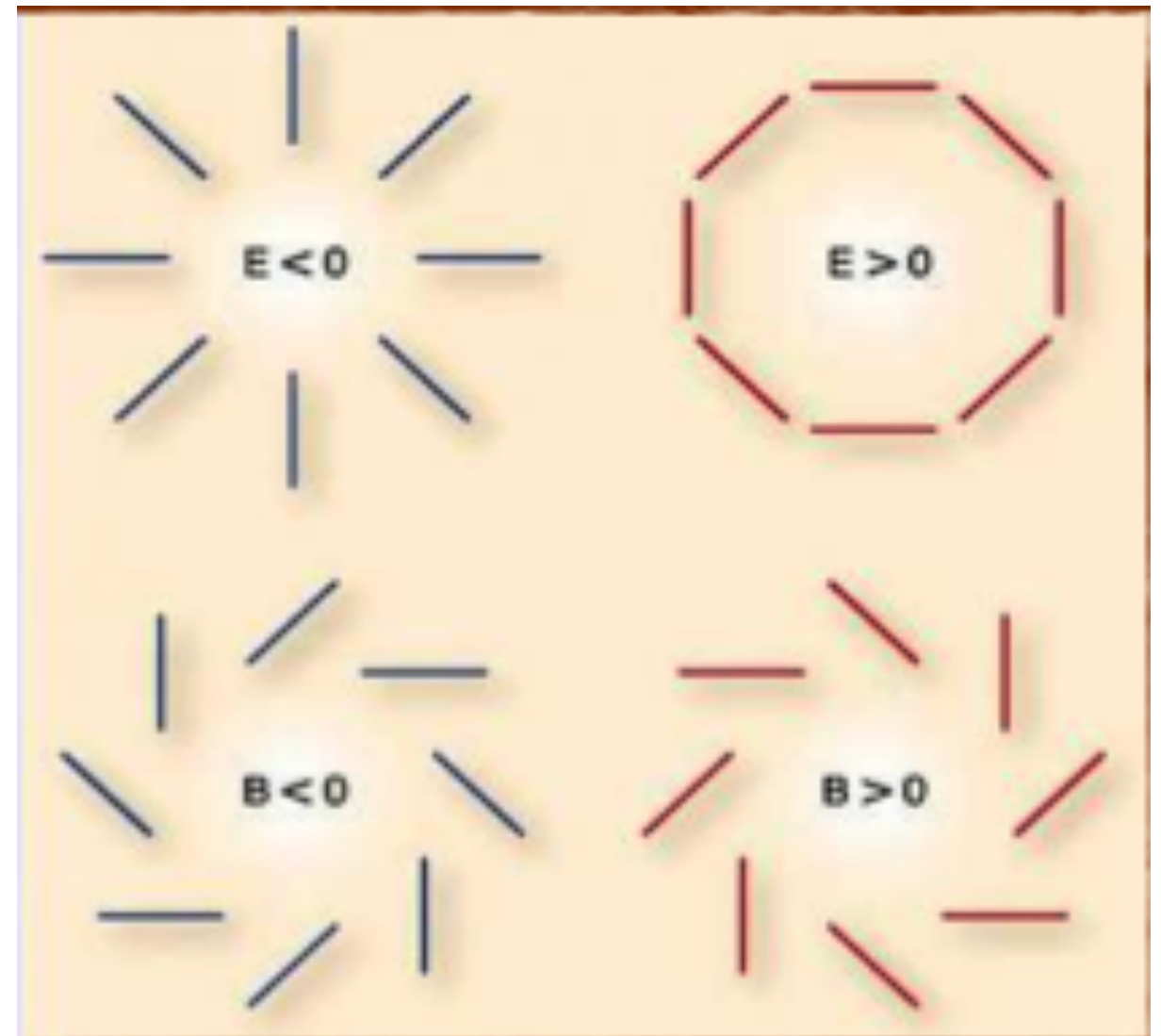
from W. Hu's web page

The CMB is polarised (~10%)

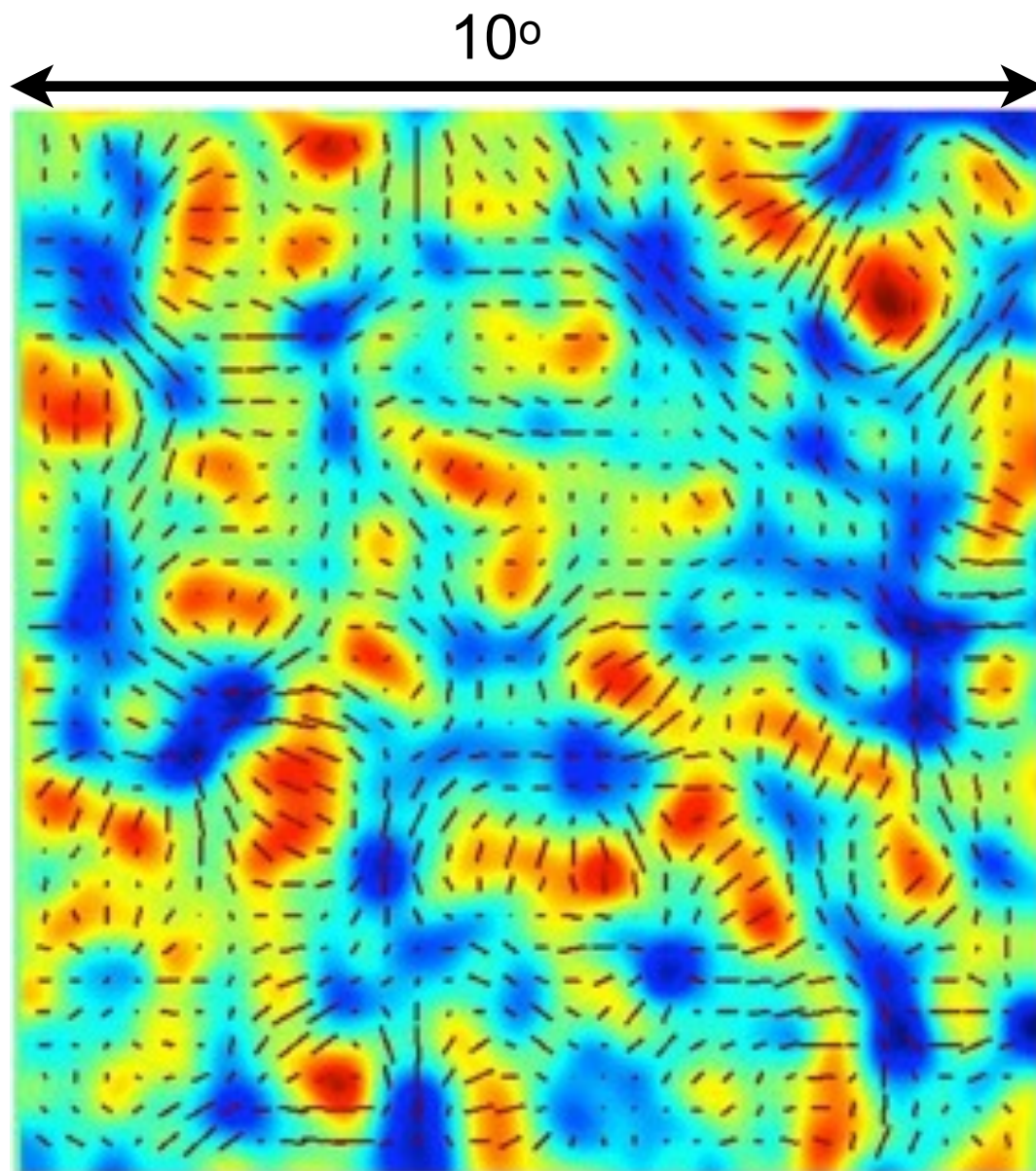


Smith et al 2008

- Any polarisation pattern can be decomposed into “E” (grad) and “B” (curl) modes



The CMB is polarised (~10%)



Smith et al 2008

- Any polarisation pattern can be decomposed into “E” (grad) and “B” (curl) modes

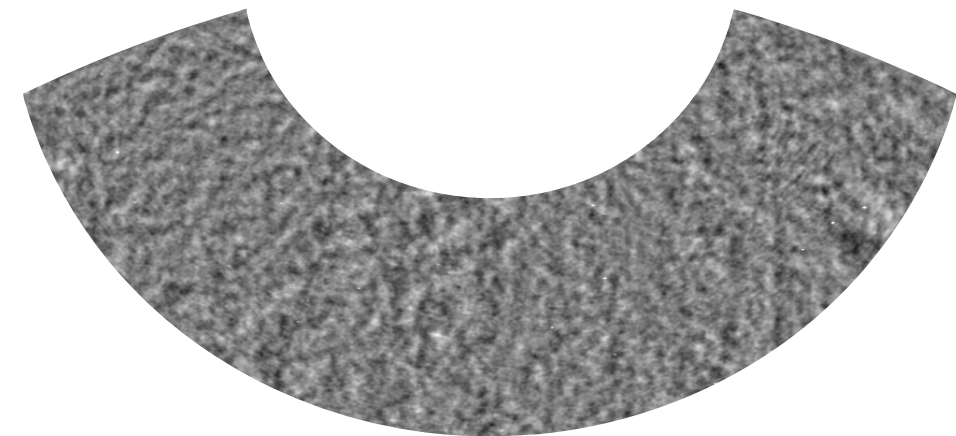
B-modes are a great place (low background) to look for gravitational waves from inflation.

Temperature and E-modes tell us about density fluctuations.

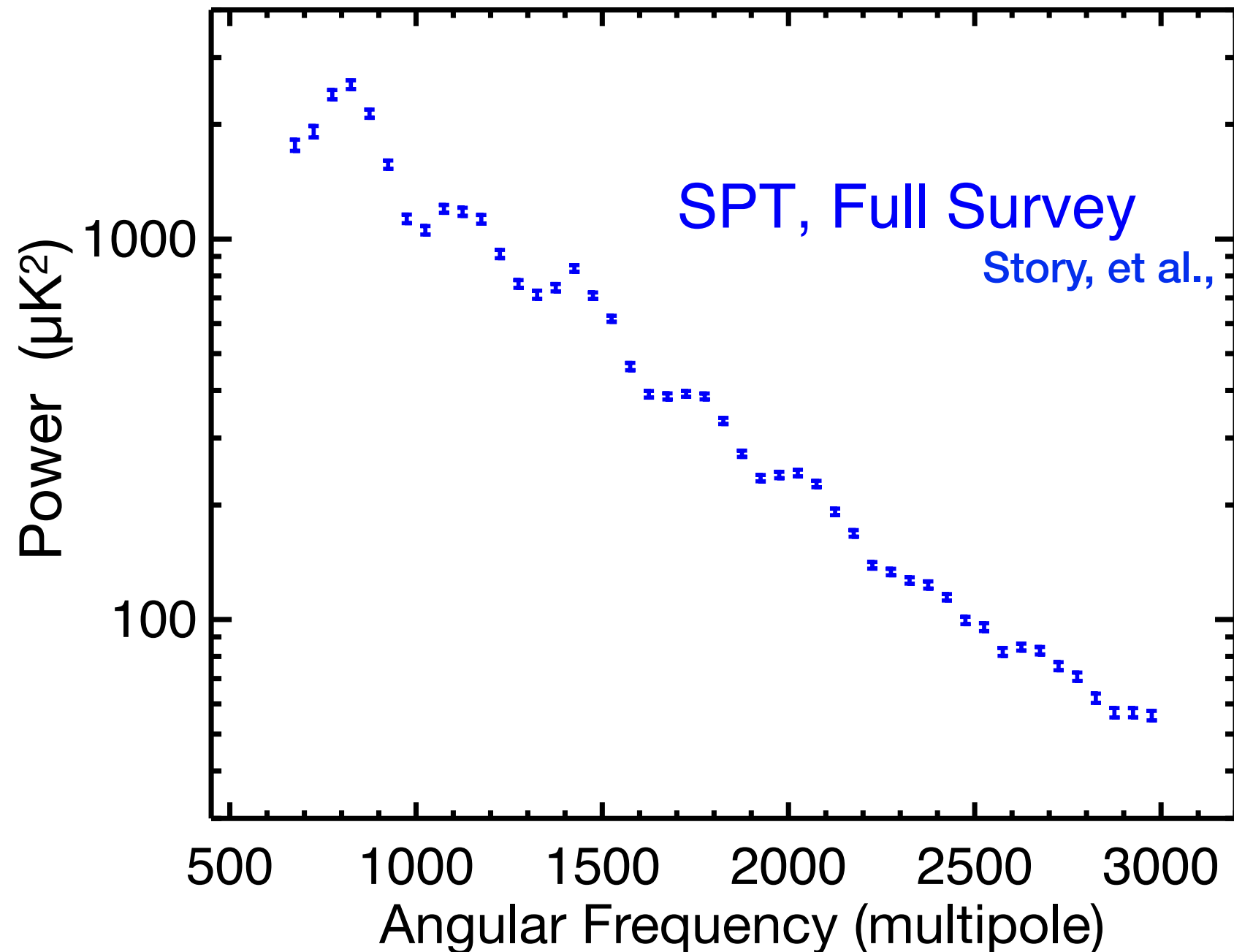
Cosmic Microwave Background (CMB) Power Spectra

Basic idea:

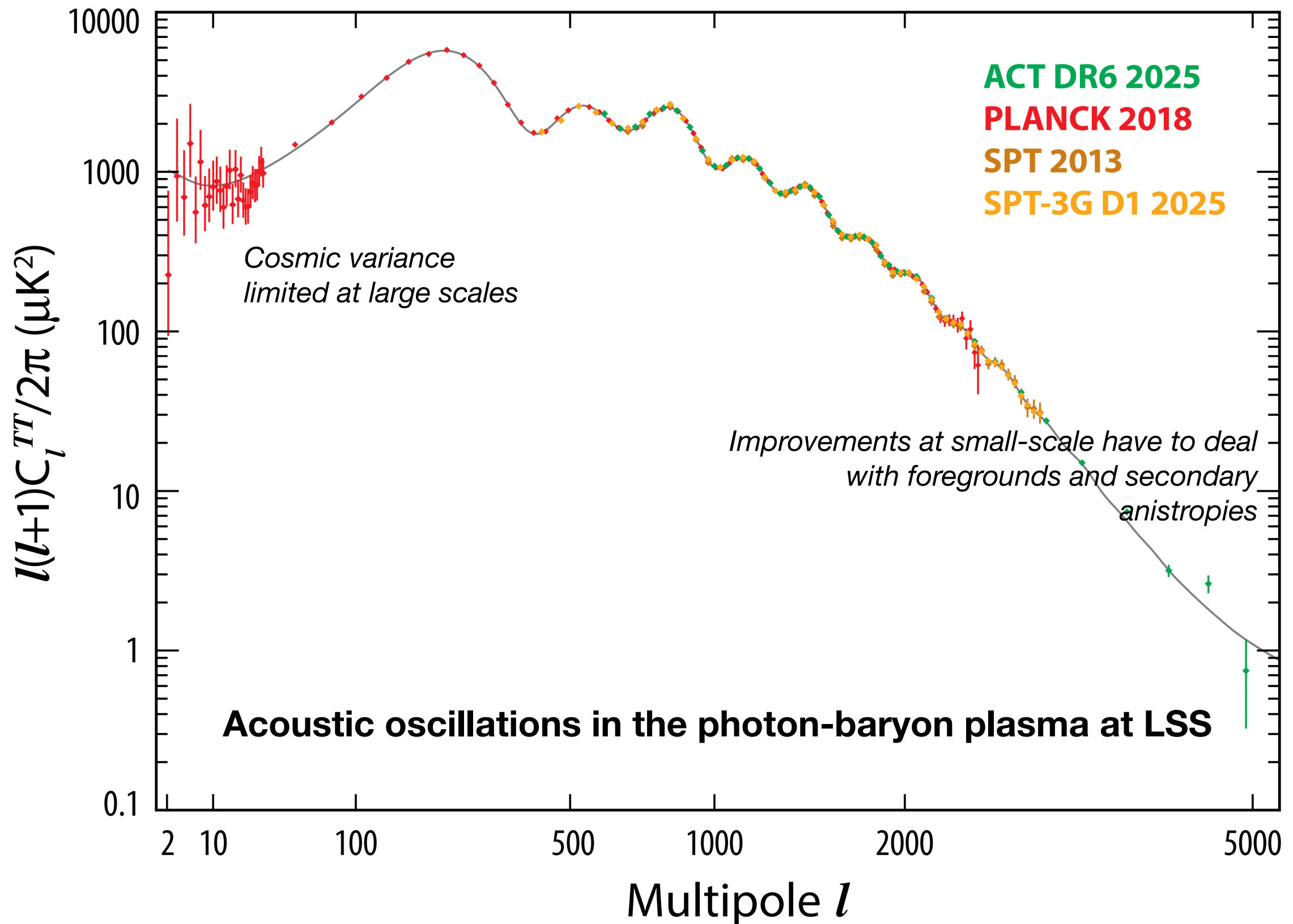
Fourier transform this



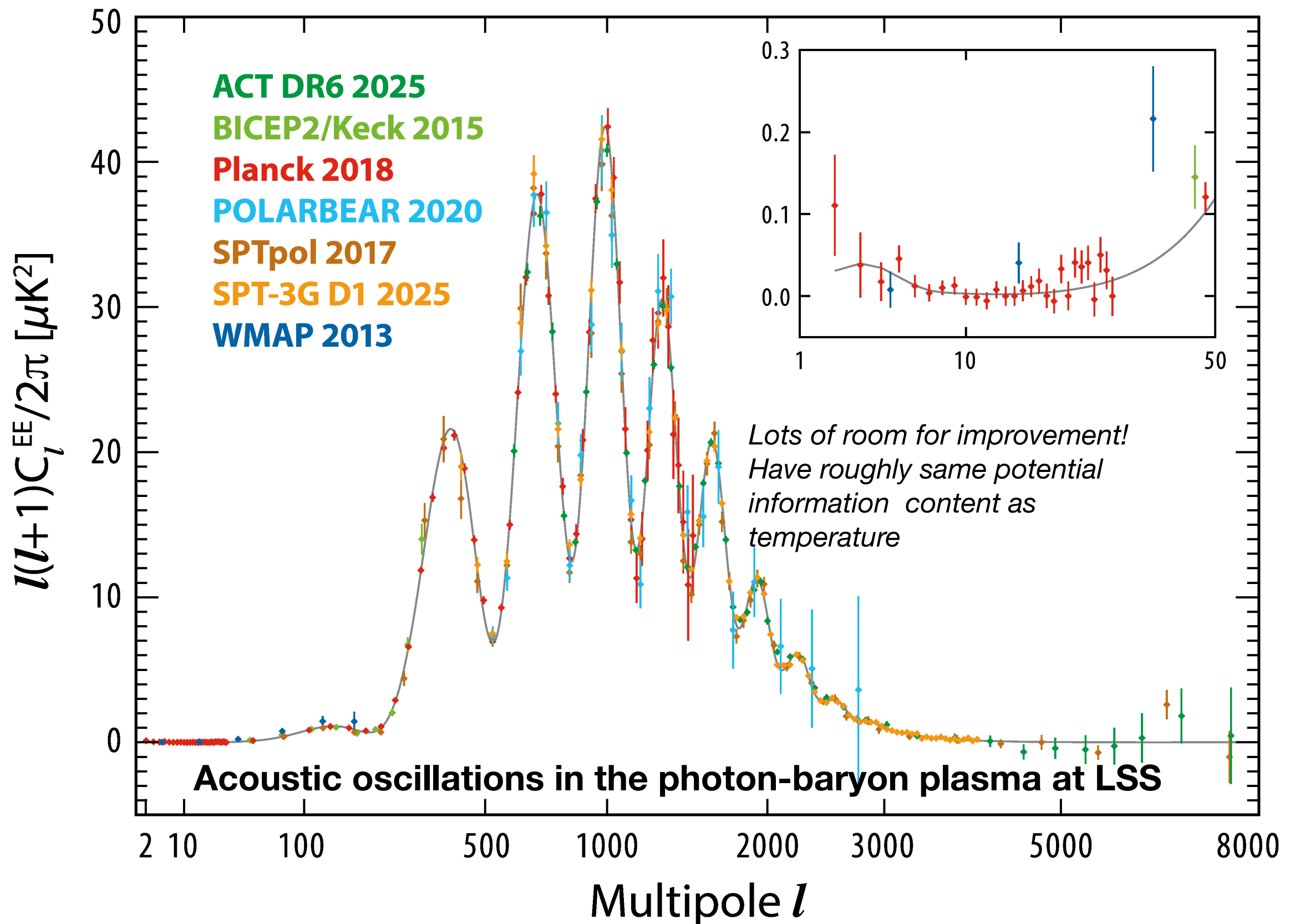
and you get....



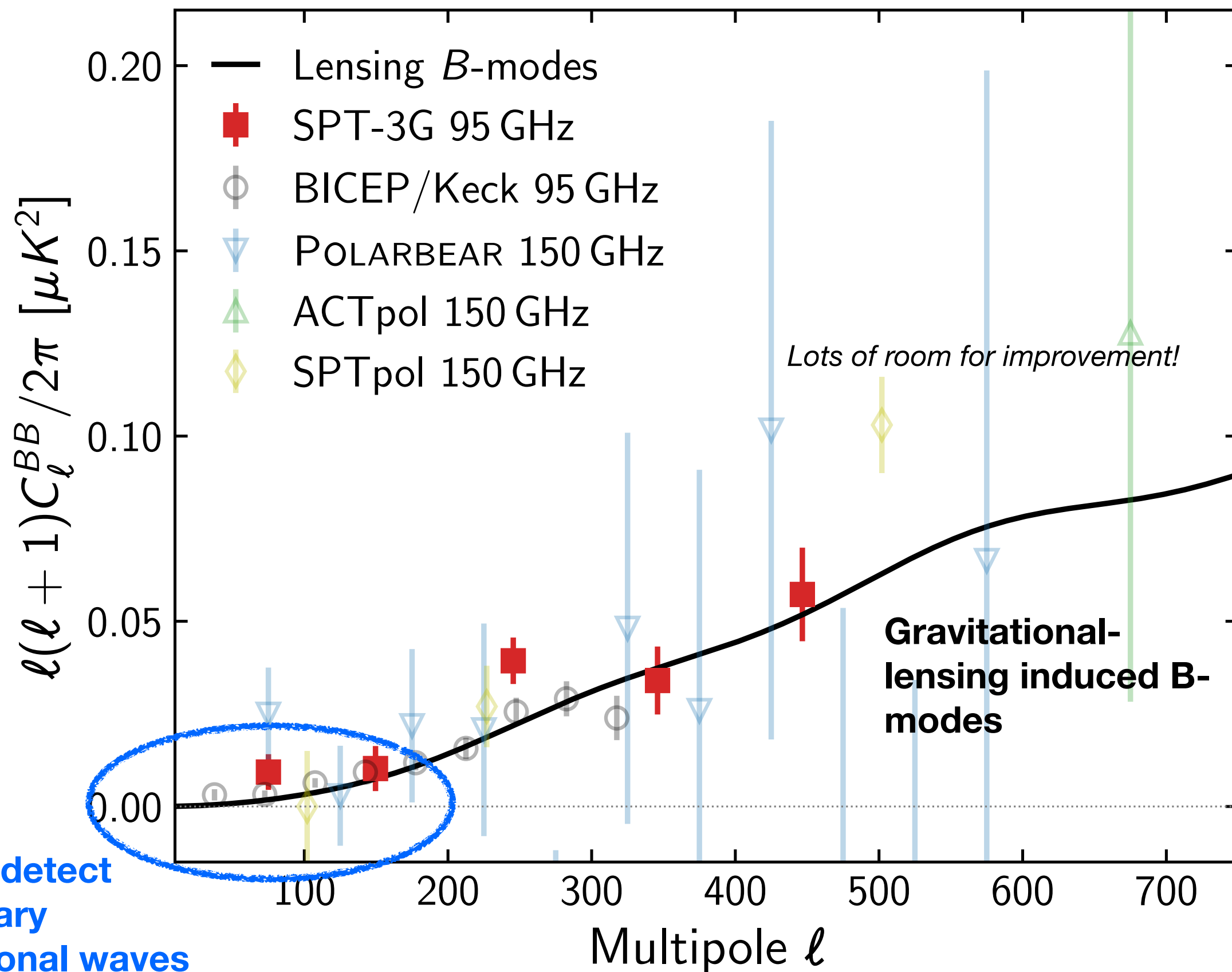
CMB Power Spectra



CMB Power Spectra



CMB Power Spectra



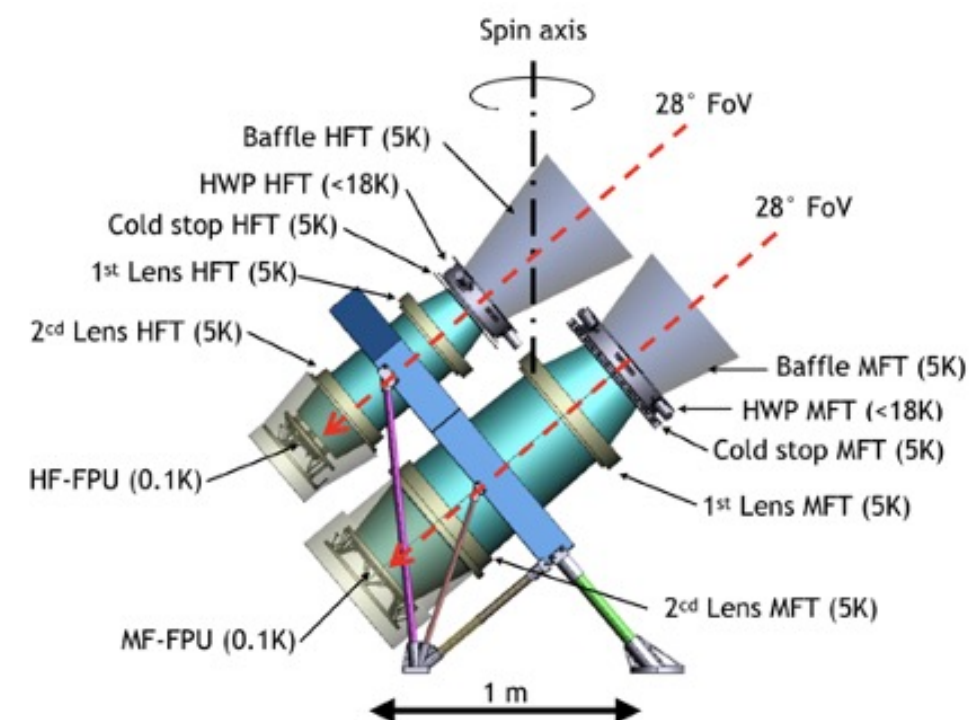
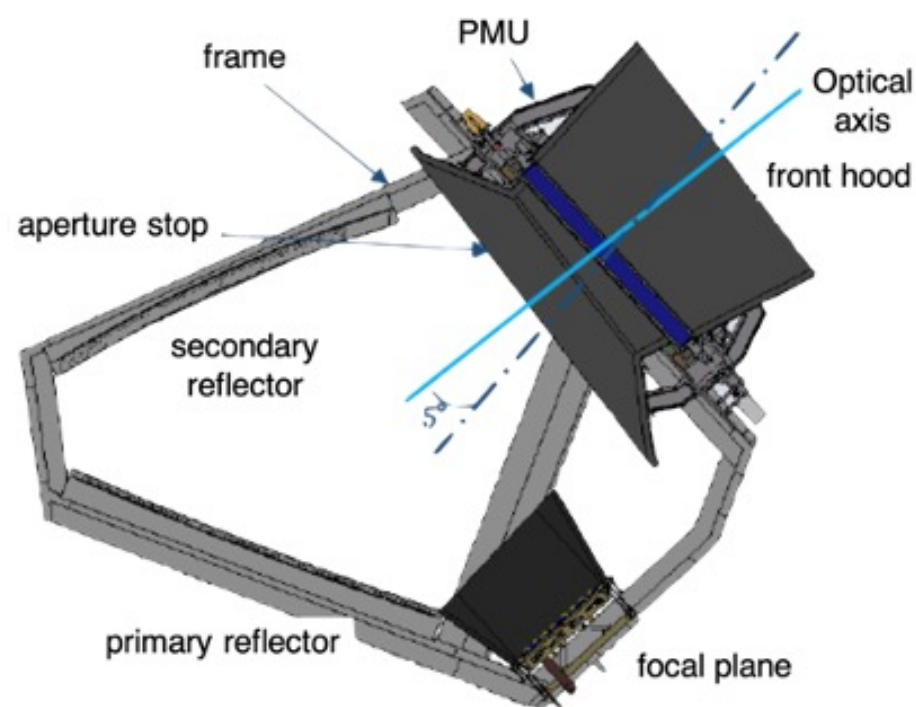
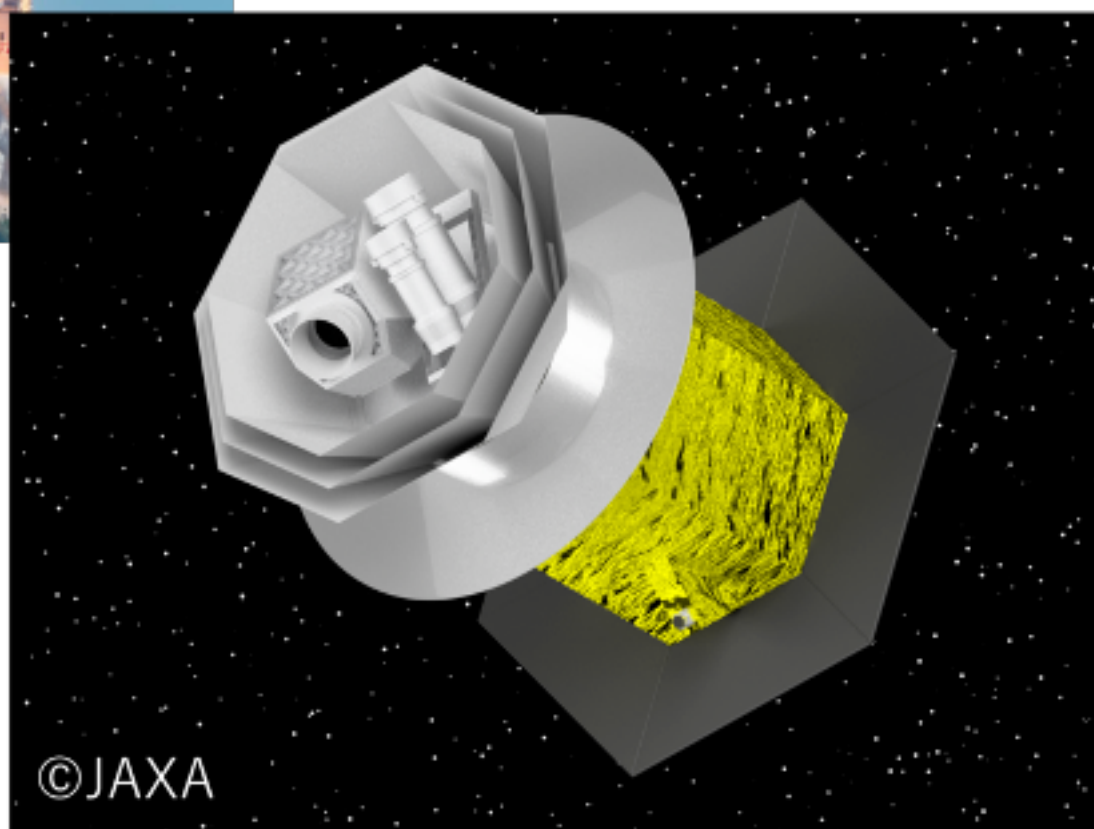
What experiments are coming?



LiteBIRD

launch FY2036 for L2

precise maps of polarisation at
 $\ell \leq 200$ to achieve $\sigma(r) = 0.002$



Changes from Planck to LiteBIRD

- Upgrades:
 - More detectors - 4000 bolometers (HFI had 54); better sensitivity!
 - More frequency bands (12 vs 9); better foreground removal!
 - Polarisation modulation; systematic control!
- Downgrades:
 - 0.5 m aperture (from 1.5m); high resolution not needed for $\ell \leq 200$

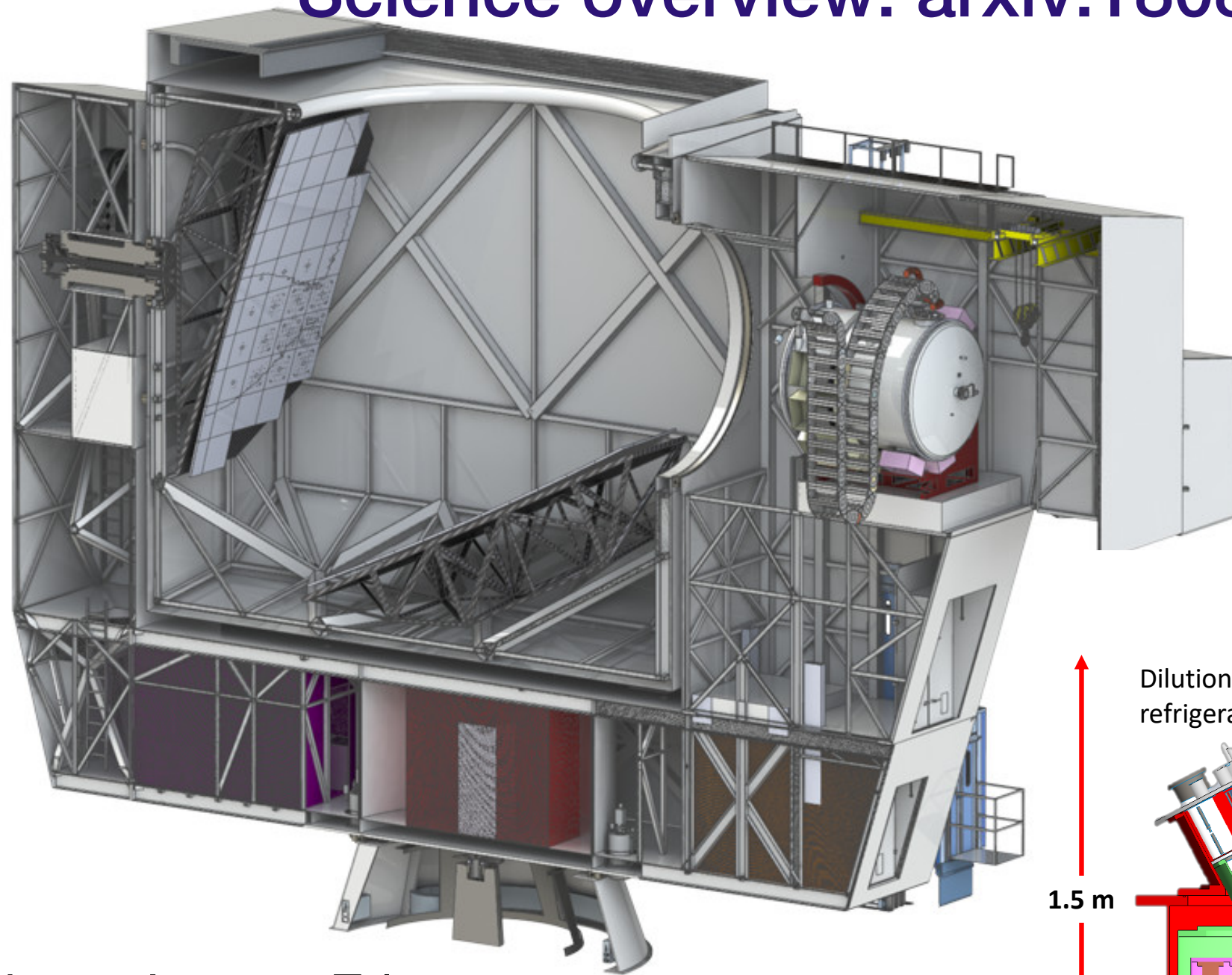
~~CMB-S4~~

- CMB-S4 was being designed with telescopes in Chile and at the South Pole as the ‘ultimate’ ground-based CMB experiment, having done well in US DoE and NSF decadal plans
- 2020-2023: NSF concerns about footprint at Pole
- 2024 NSF closed the Pole to new experiments
- July 2025: **CMB-S4 canned.**

Simons Observatory

Instrument overview: [arxiv:1808.04493](https://arxiv.org/abs/1808.04493)

Science overview: [arxiv:1808.07445](https://arxiv.org/abs/1808.07445)

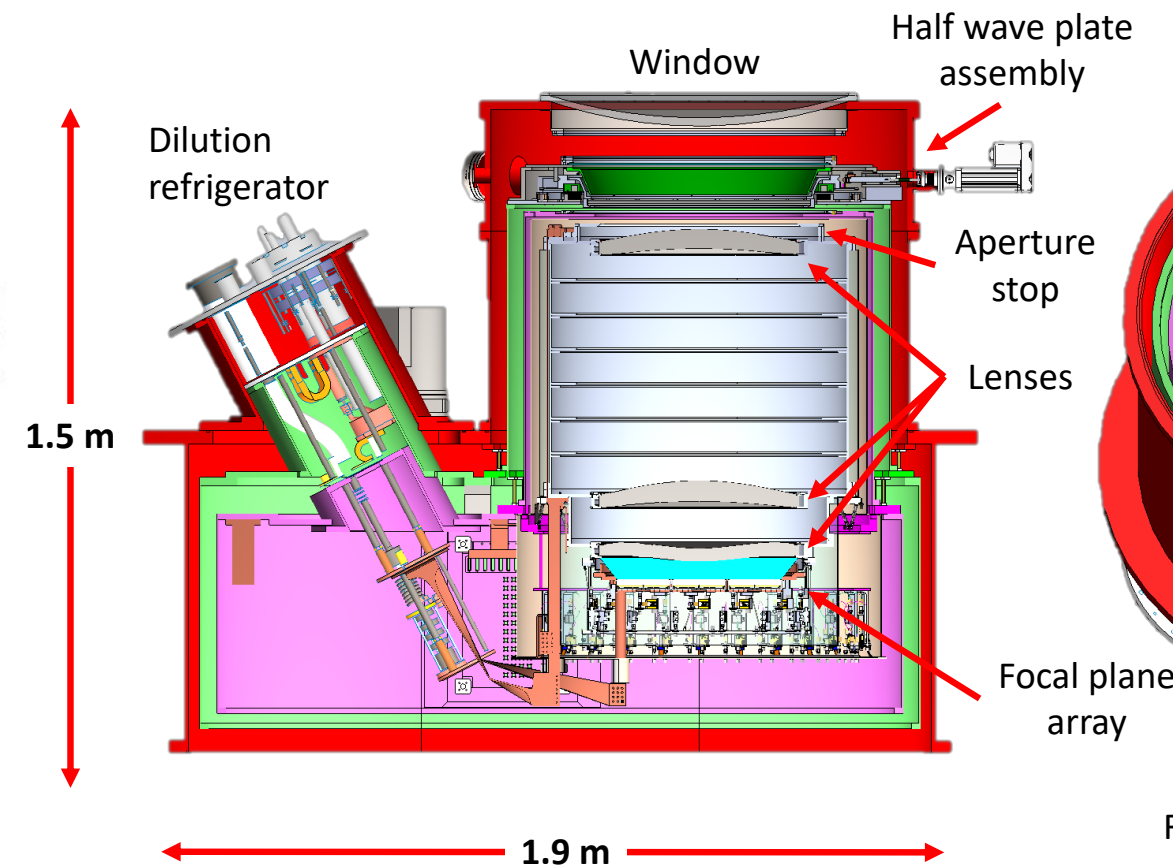


3x Small Aperture Telescopes

Key advs: 1) Cheap way to get sensitivity
2) Improved systematics control

1x Large Aperture Telescope
crossed Dragone design

Key adv: Allows large focal plane (2m!) for lots of detectors



Simons Observatory

Instrument overview: [arxiv:1808.04493](#)

Science overview: [arxiv:1808.07445](#)

First light with first SAT in June 2024

Currently in initial science observations with the original SO configuration

telescopes

way to
sensitivity
matics
control

wave plate
assembly

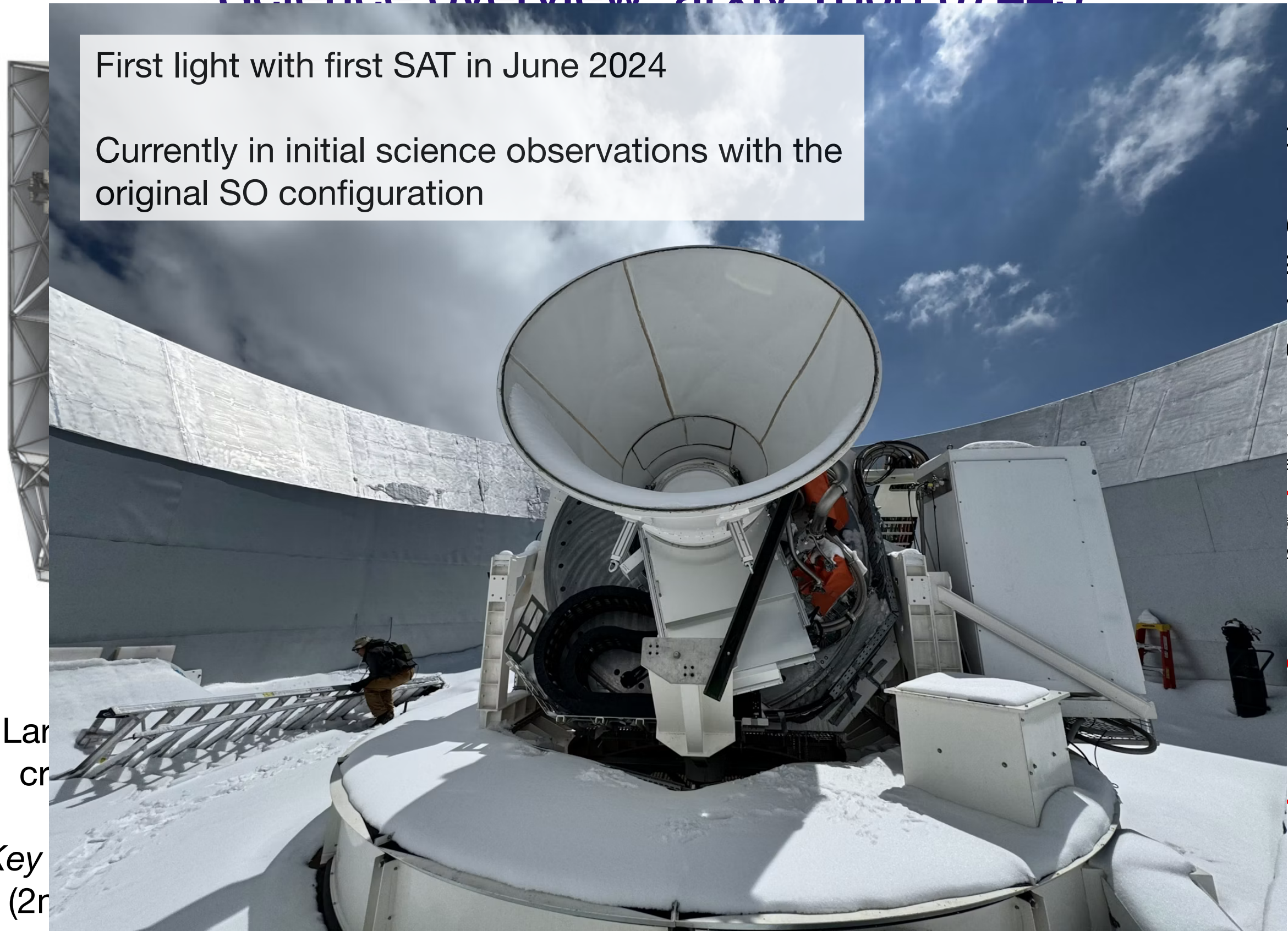
Aperture
stop

Lenses

Focal plane
array

1x Large
cryogenic

Key
plane (2m)



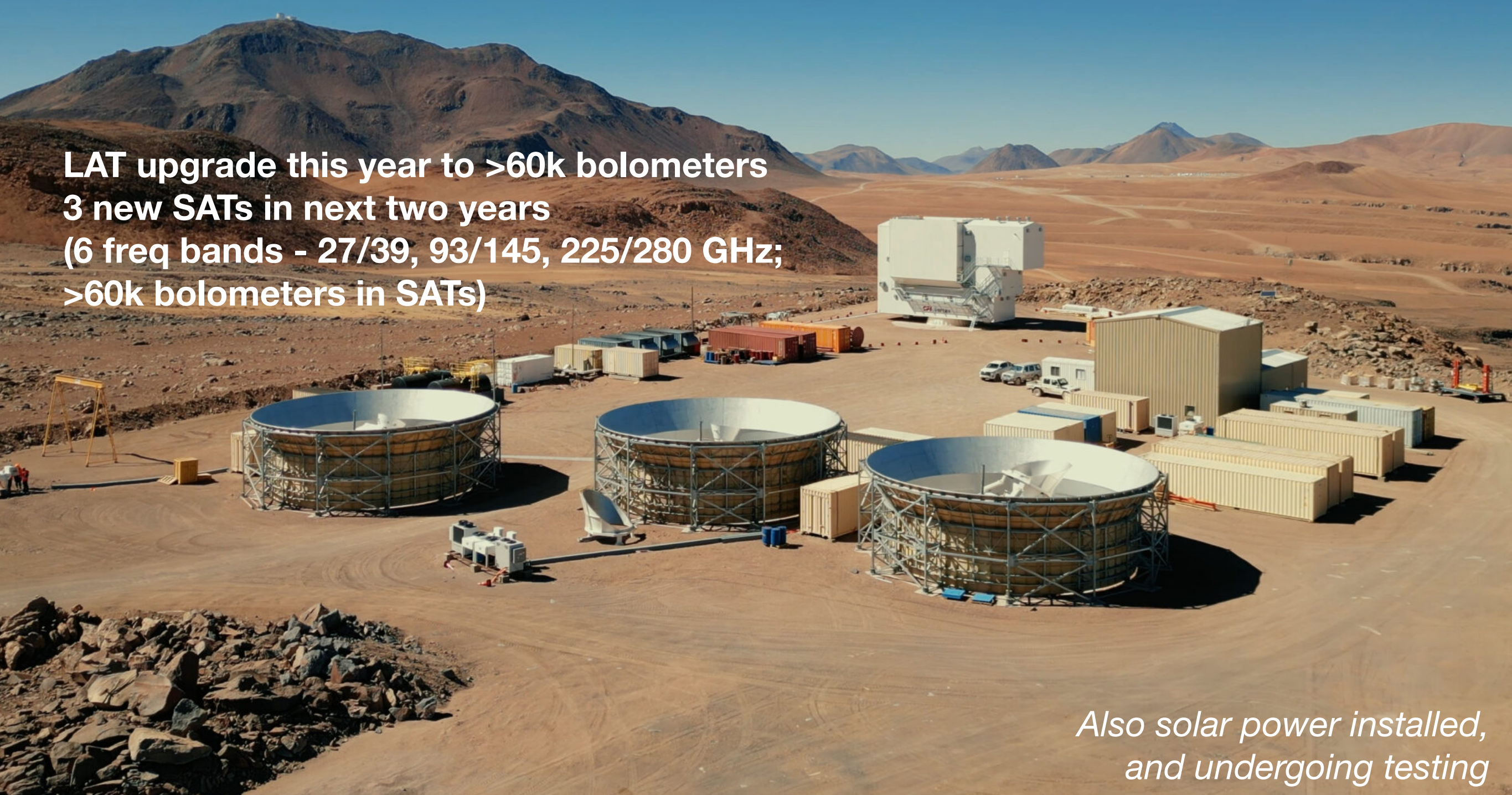
Doubling Simons Observatory

7->13 optics tubes in LAT; arXiv:2503.00636

3->6 SATs; arXiv:2512.15833

5 -> 10 year survey

**LAT upgrade this year to >60k bolometers
3 new SATs in next two years
(6 freq bands - 27/39, 93/145, 225/280 GHz;
>60k bolometers in SATs)**

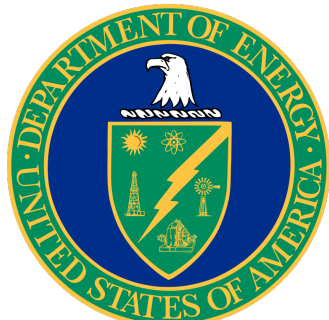
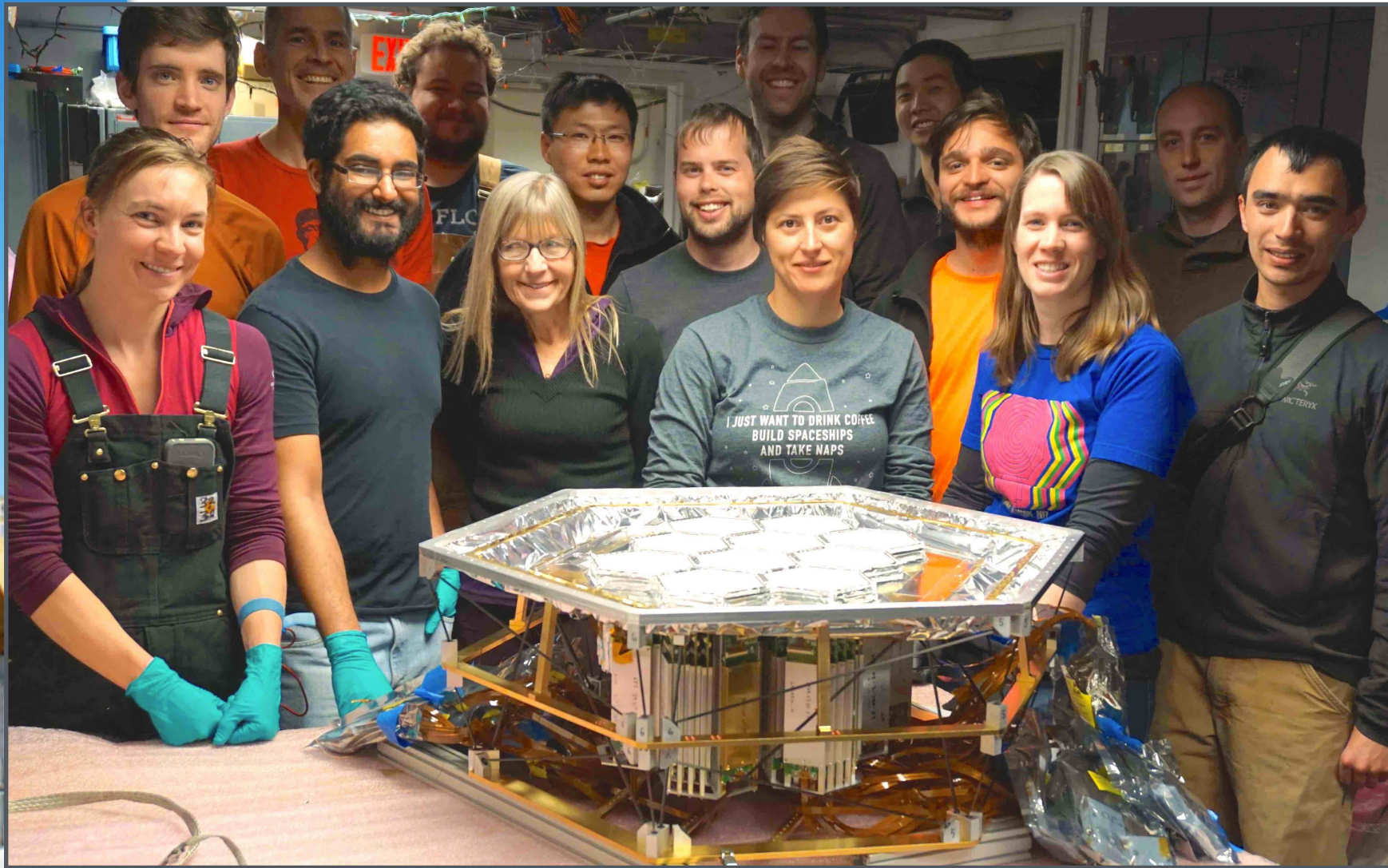
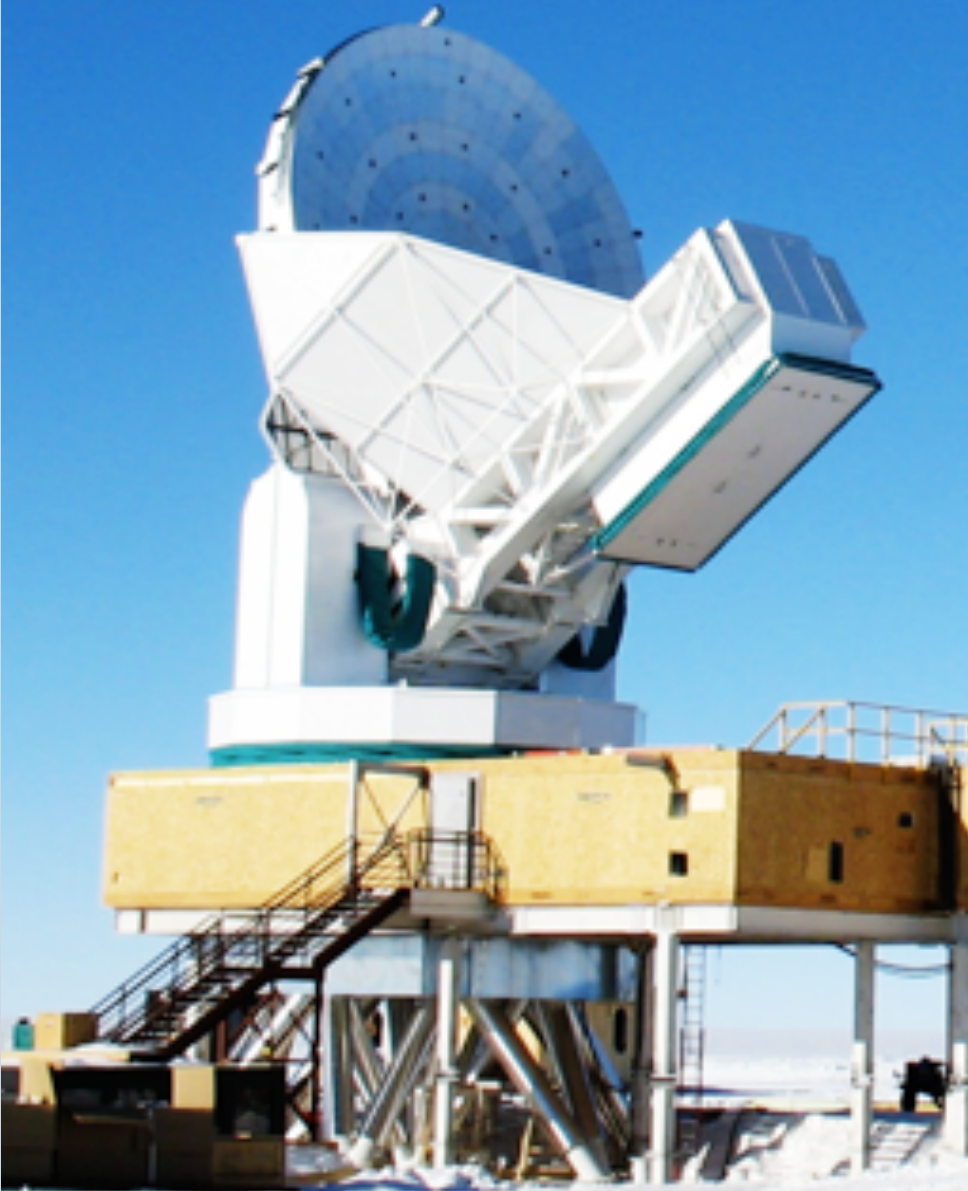


*Also solar power installed,
and undergoing testing*

The South Pole Telescope (SPT)

10 m telescope

SPT-3G - 3rd camera on SPT



- 16,200 bolometers in trichroic pixels
- Currently surveying 10,000 deg² at 95, 150, 220 GHz

The South Pole Telescope (SPT)

10 m telescope

SPT-3G+ - next camera on SPT
x7 mapping speed

Optical Window
(Transparent)

Dilution Refrigerator

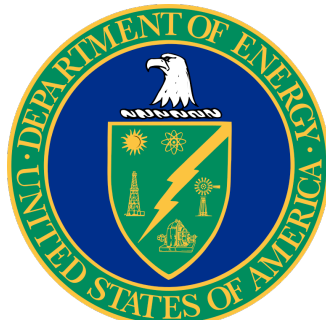
Access
Panels

Housekeeping P

Pulse Tube Cryocoolers

1 meter

- 24k bolometers at 95 & 150 GHz
- Observing from 2029



BICEP Array + BICEP3



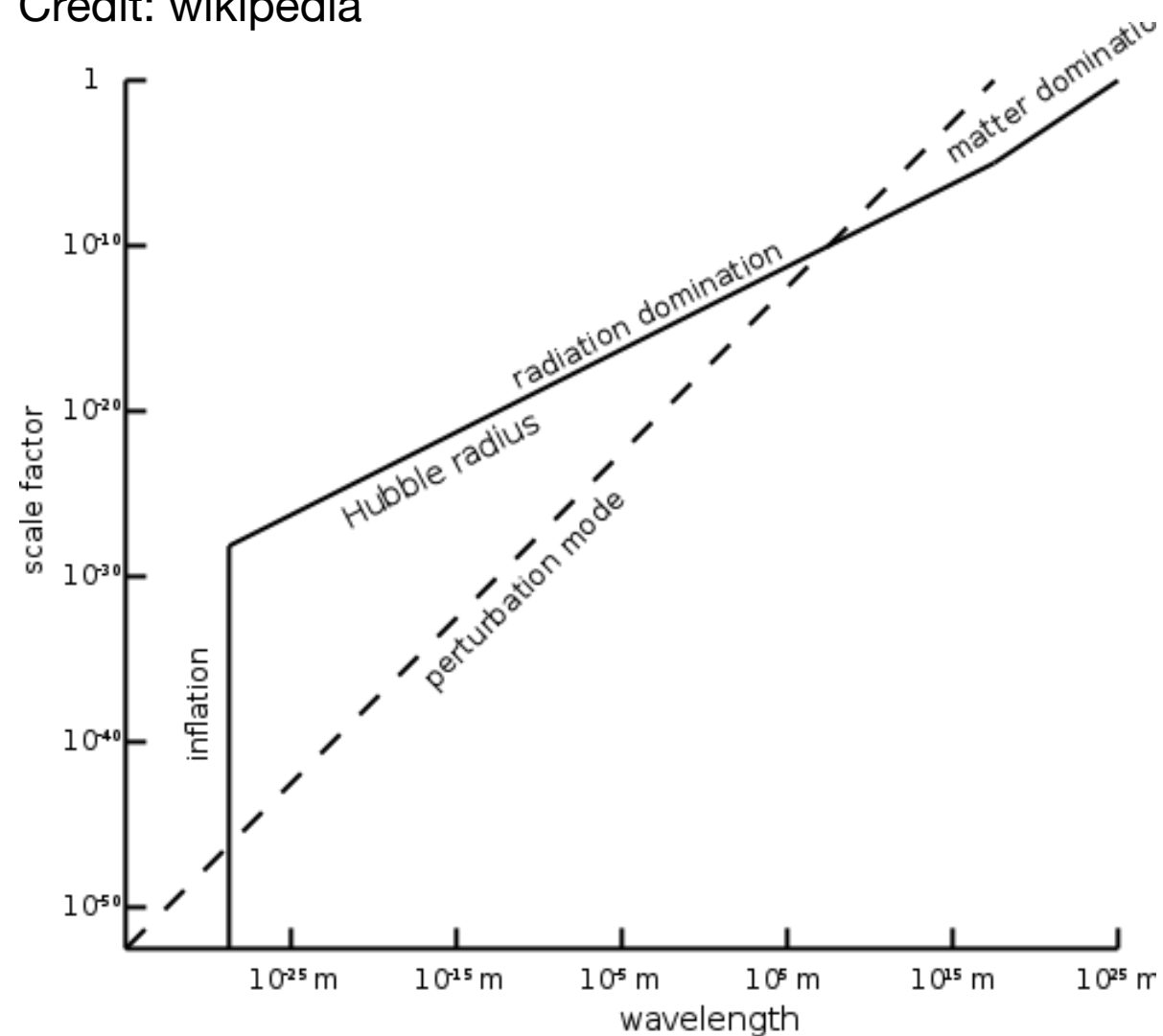
BICEP Array
3 slots observing: 30/40 GHz, 150 GHz,
220/270 GHz,

4th slot coming this summer: 90/150 GHz



BICEP3
95 GHz

More than 30,000 TES bolometers over five frequency bands



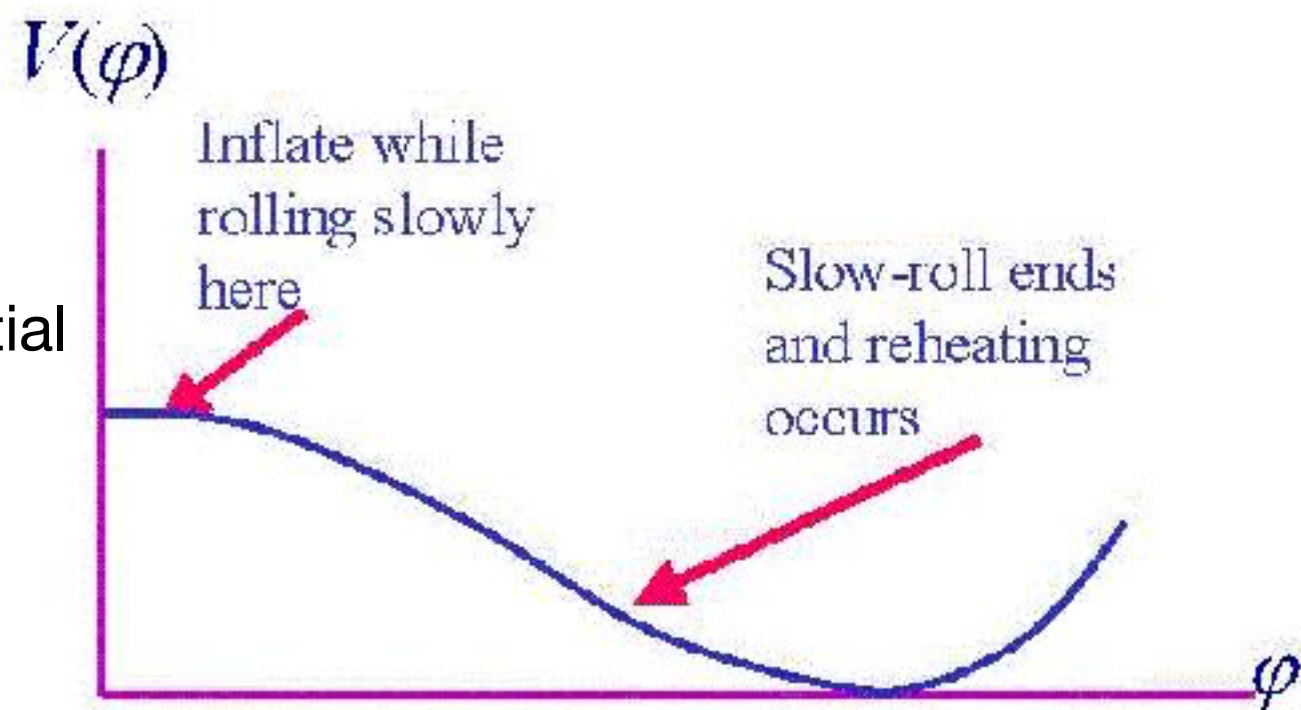
Inflation

Period of accelerating expansion in the early Universe during which the observable Universe shrinks

Favored model - Slow-roll inflation:

Universe's density is dominated by the potential of a scalar field with 'flattish' potential

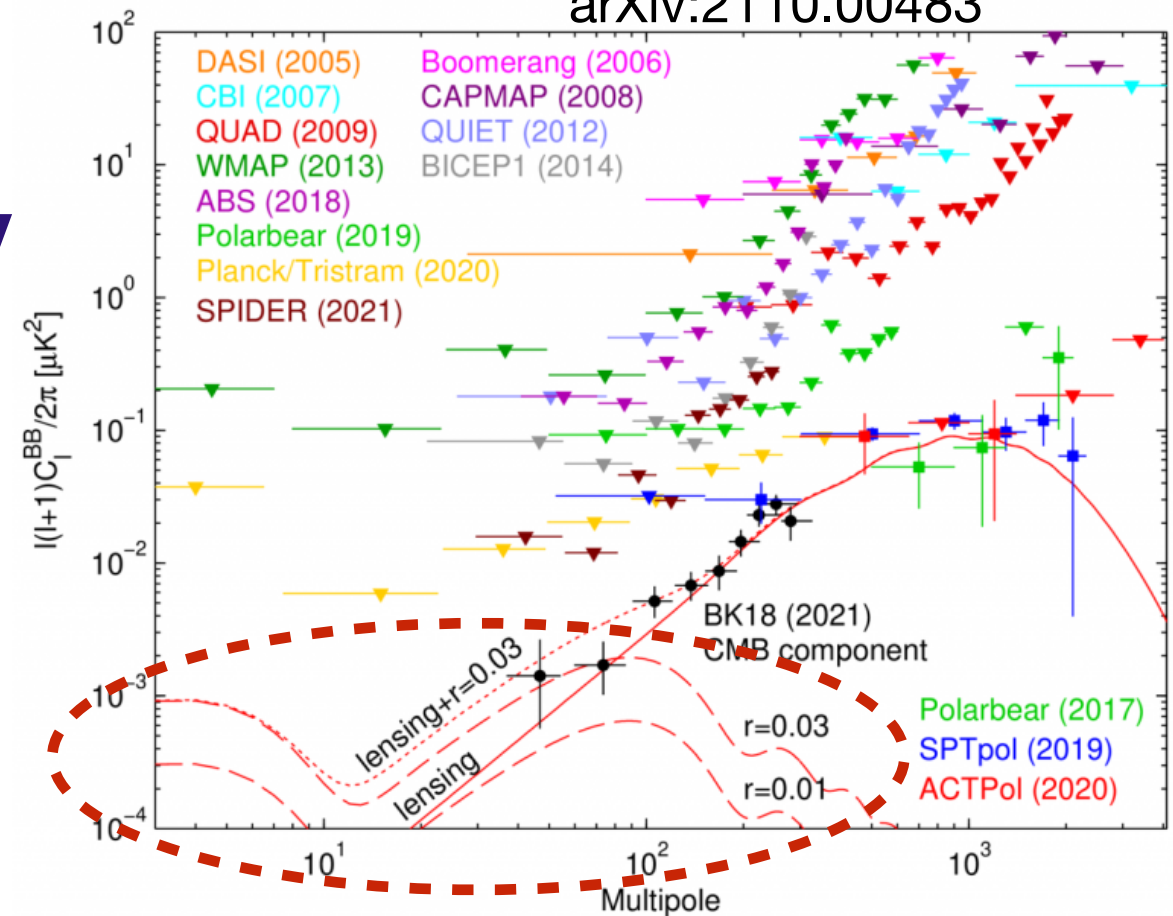
- ☒ Flat universe
- ☒ No relics
- ☒ Nearly scale invariant primordial scalar spectrum (even on super-horizon scales)
- ☒ Adiabatic and Gaussian fluctuations (single field case)
- ☐ Gravitational waves



Credit: Albrecht

Chasing inflationary gravitational waves

“smoking gun of inflation”



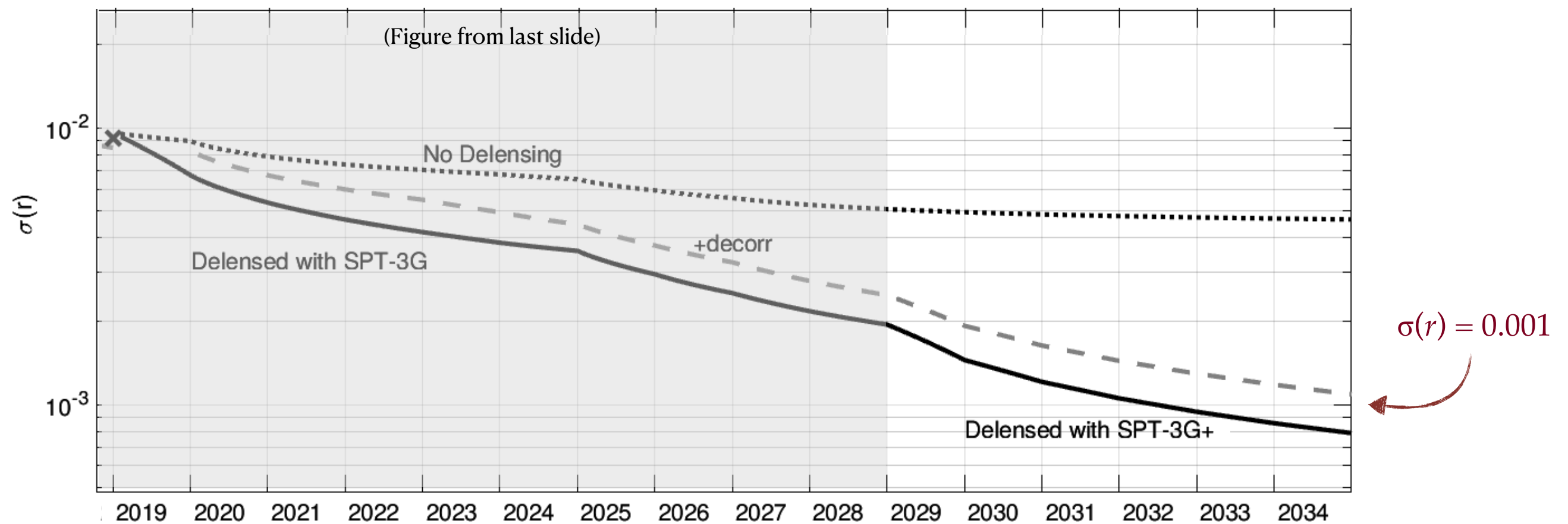
The power in G. Waves often described by “ r ” = tensor-to-scalar ratio. Larger r increases power at super-horizon scales.

Current 95% CL upper limit is $r < 0.036$ (BICEP/Keck + Planck+WMAP)

Goal: $r < 0.001$ ($\sigma(r)=0.0005$)

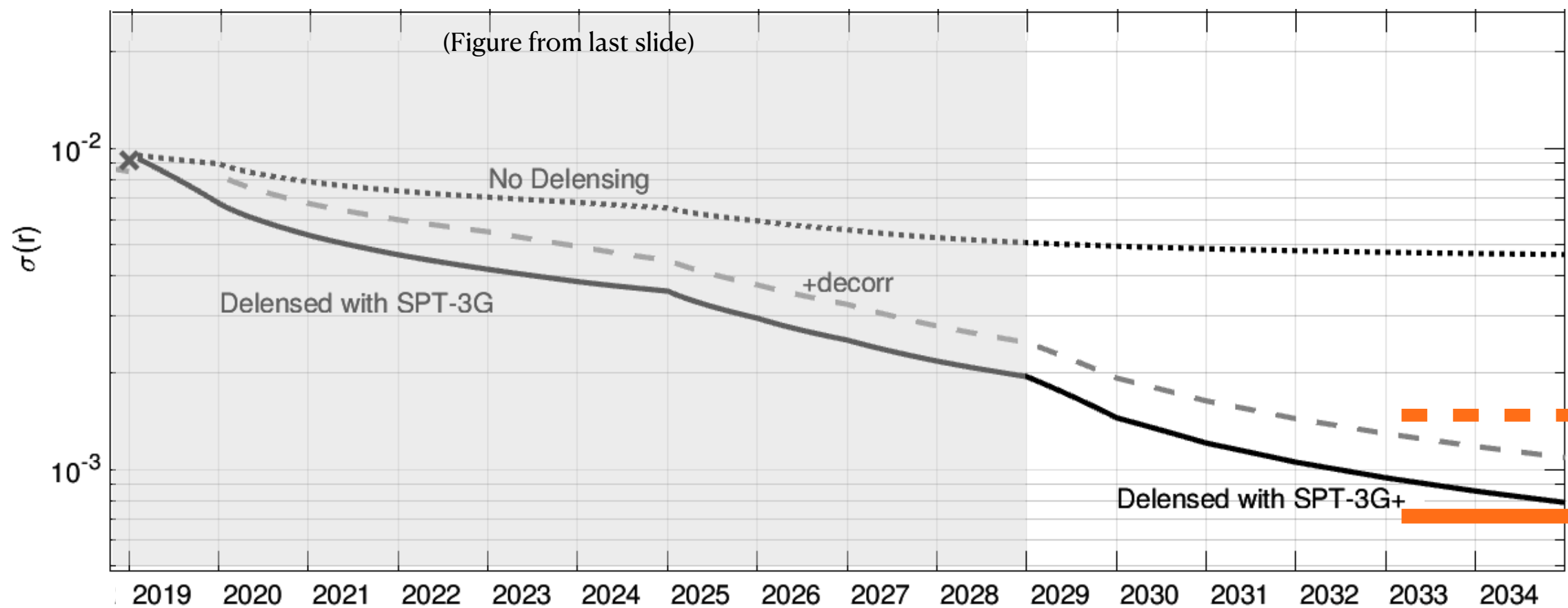
How do we get the next factor of ~60?

Chasing gravitational waves



1 LAT + 5 SATs at South Pole

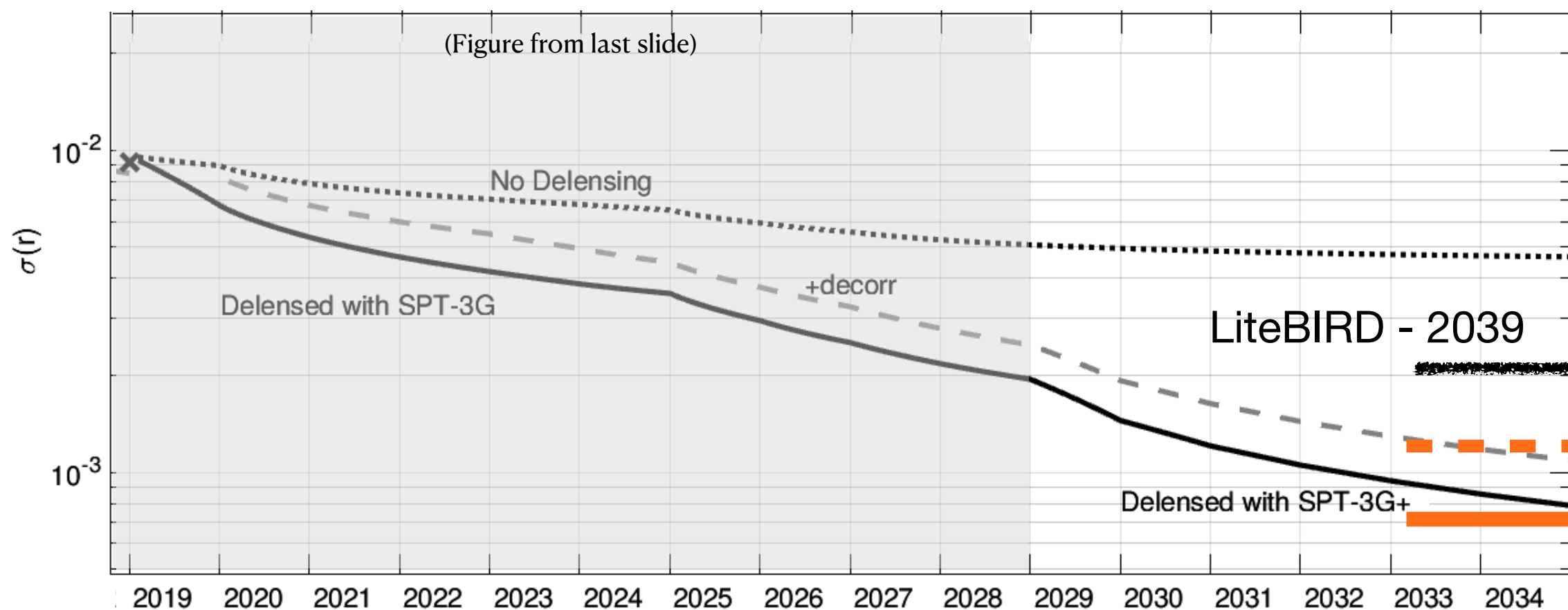
Chasing gravitational waves



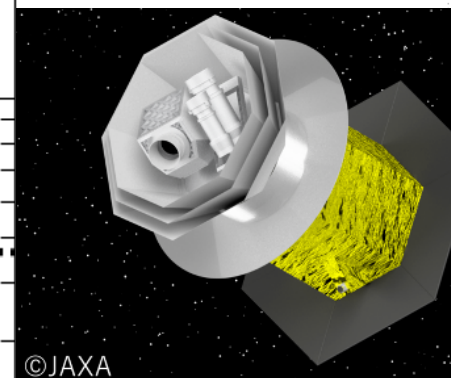
Simons
Observatory - 2035
arXiv:2512.15833

1 LAT + 6 SATs in Chile

Chasing gravitational waves



arXiv:2607.25285

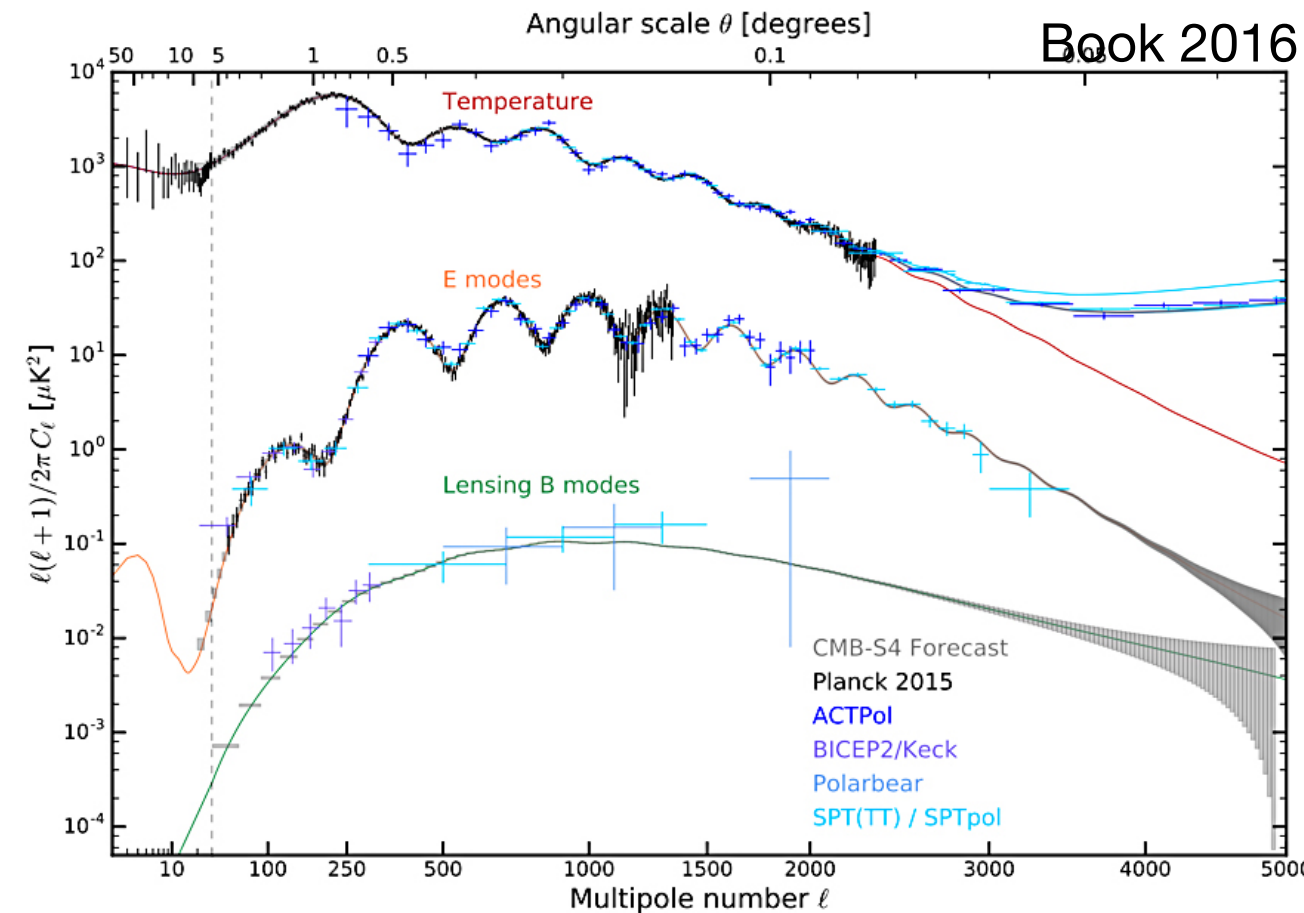


Simons
Observatory - 2035
arXiv:2512.15833

Several options to get to $\sigma(r) \sim 0.001$ in late 2030s
Foregrounds remain uncertain...
(Nothing that meets CMB-S4 target planned yet)

Studying the early universe

Use N_{eff} as a benchmark

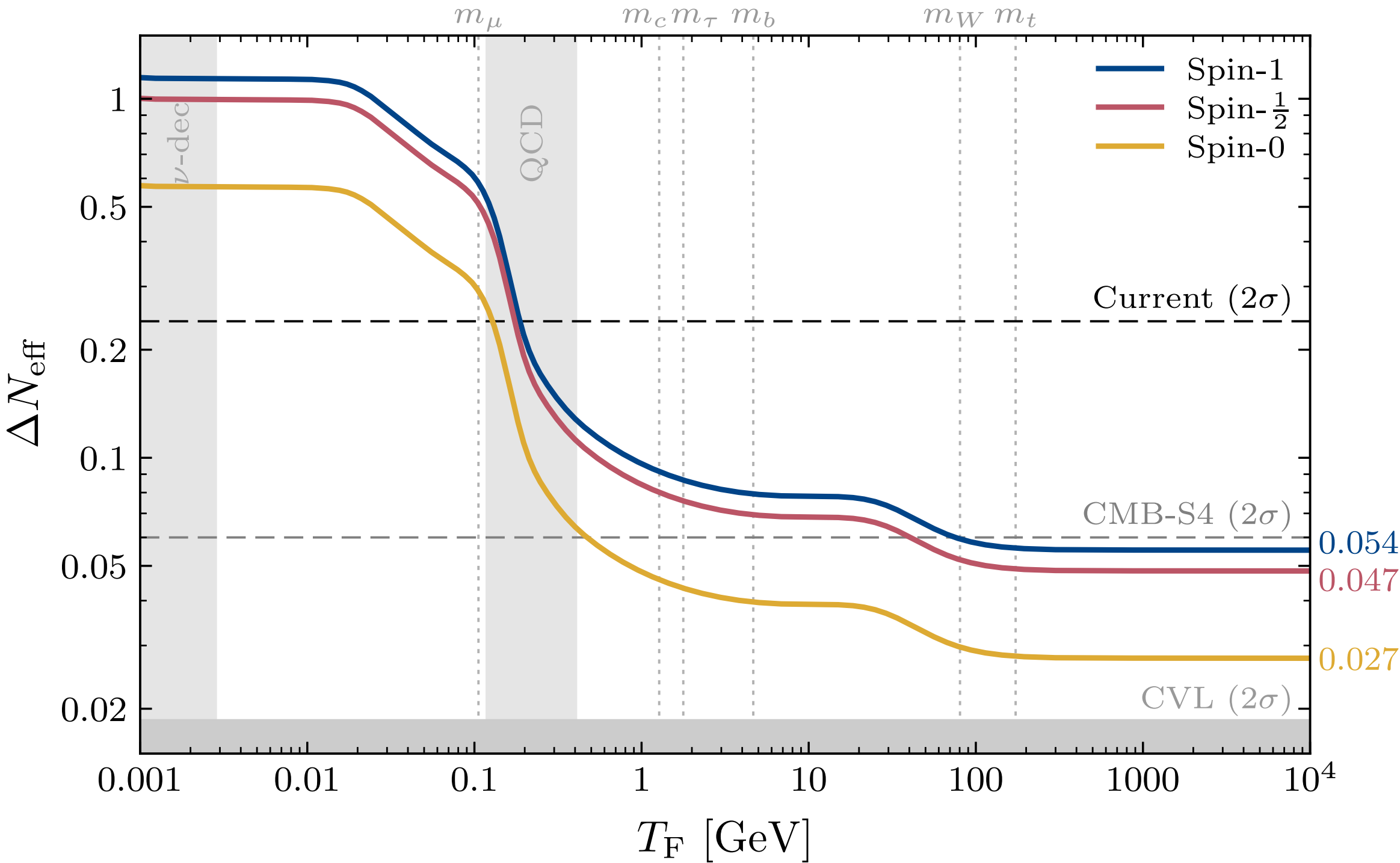


CMB anisotropies provide a first snapshot of the early universe, and underpin many tests of Λ CDM

- Relativistic energy density (N_{eff})
- early dark energy
- decaying/interacting dark matter
- birefringence
- others...

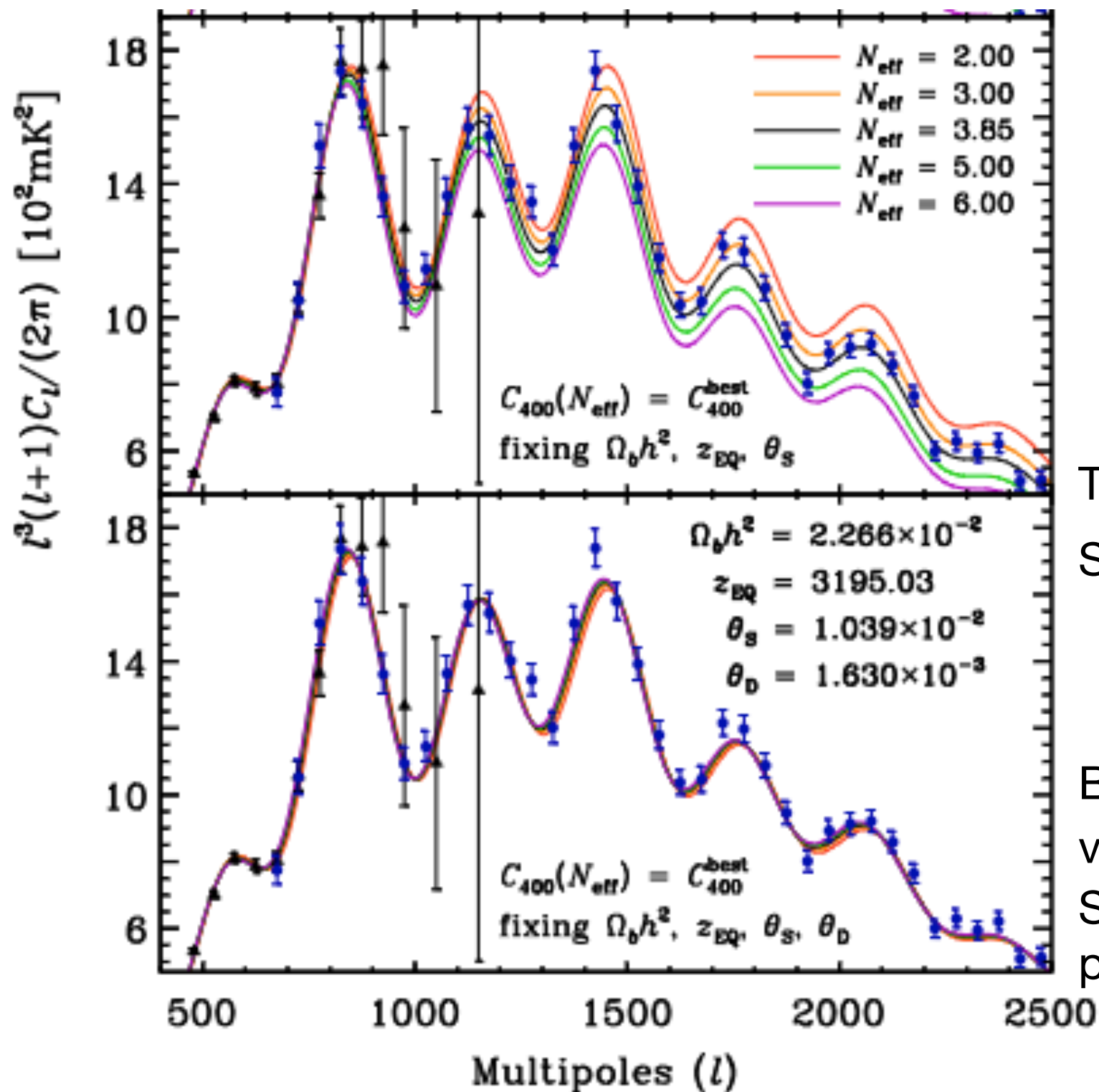
Upcoming measurements from the large telescopes will improve tests of cosmological models

Light relics



What do new species do to the CMB?

Hou et al - arXiv:1104.2333



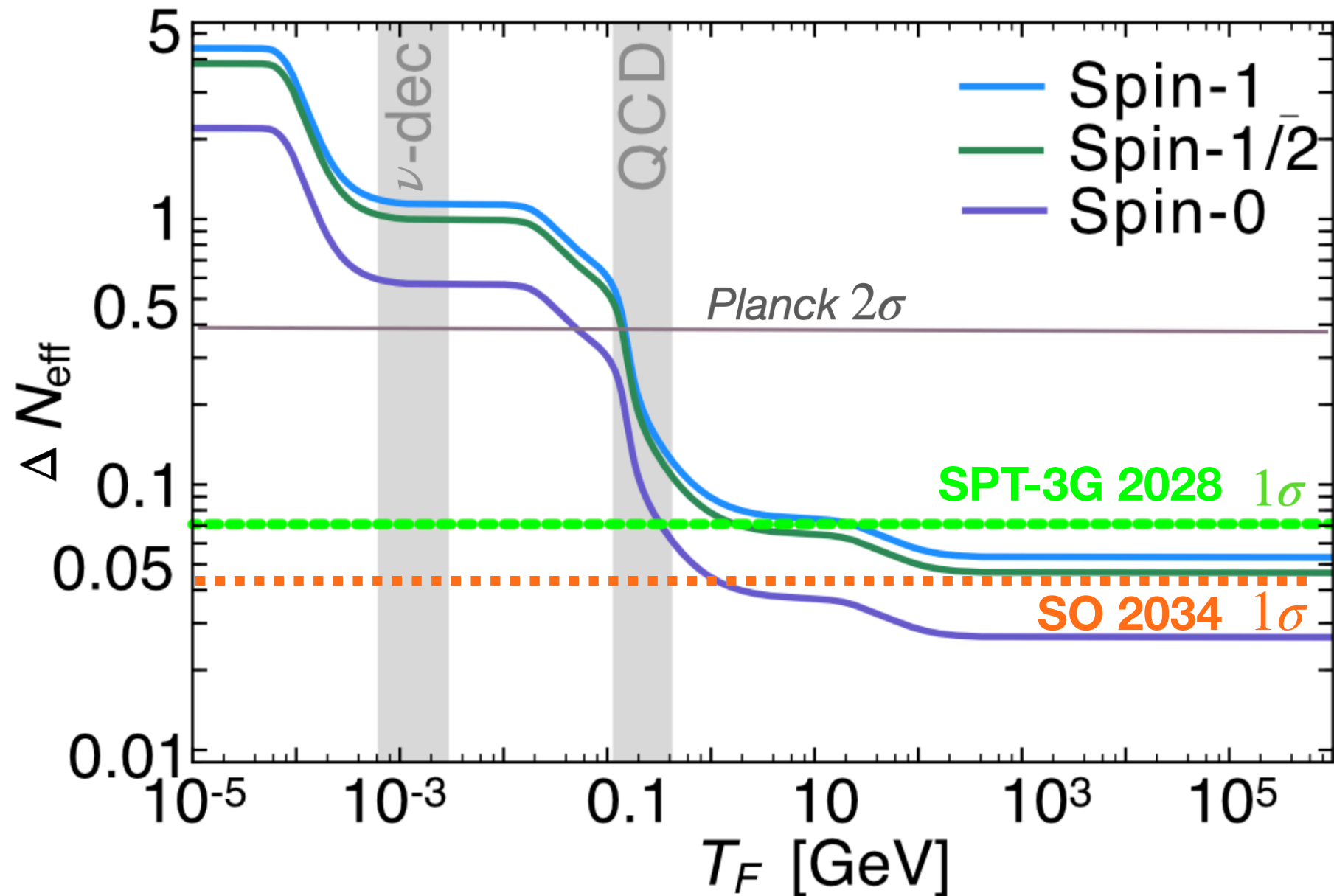
- Biggest effect is on damping scale
- Smaller effect on peak locations due to c instead of $c/\sqrt{3}$ speed.

Top: Hold fixed $\rho_b, \theta_s, z_{\text{EQ}}$
See effect on damping θ_d

Bottom: Also fix damping scale by varying Y_{He}
See phase shifts between acoustic peaks

Forecasts for N_{eff}

- Planck: $\sigma(N_{\text{eff}}) = 0.2$; Planck+SPT+ACT: $\sigma(N_{\text{eff}}) = 0.12$ arXiv:1903.04763
arXiv:2506.20707
- Data through **2028** from **SPT-3G**: $\sigma(N_{\text{eff}}) = 0.069$ arXiv:2403.17925
- Data through **2034** from **Simons Observatory**:
 $\sigma(N_{\text{eff}}) = 0.045$ arXiv:2503.00636



Also $\sum m_\nu$

$\sigma = 56 \text{ meV}$
(2028)
 $= 15\text{-}30 \text{ meV}$
(2034)

depending on
knowledge of τ

Conclusions

- Next decade: 30-fold improvement in searches for inflationary gravitational waves
 - More detectors
 - Careful treatment of galactic foregrounds
 - Removing grav lensing noise
- Significant improvements to other cosmological tests - eg 3-fold on effective number of light relics

