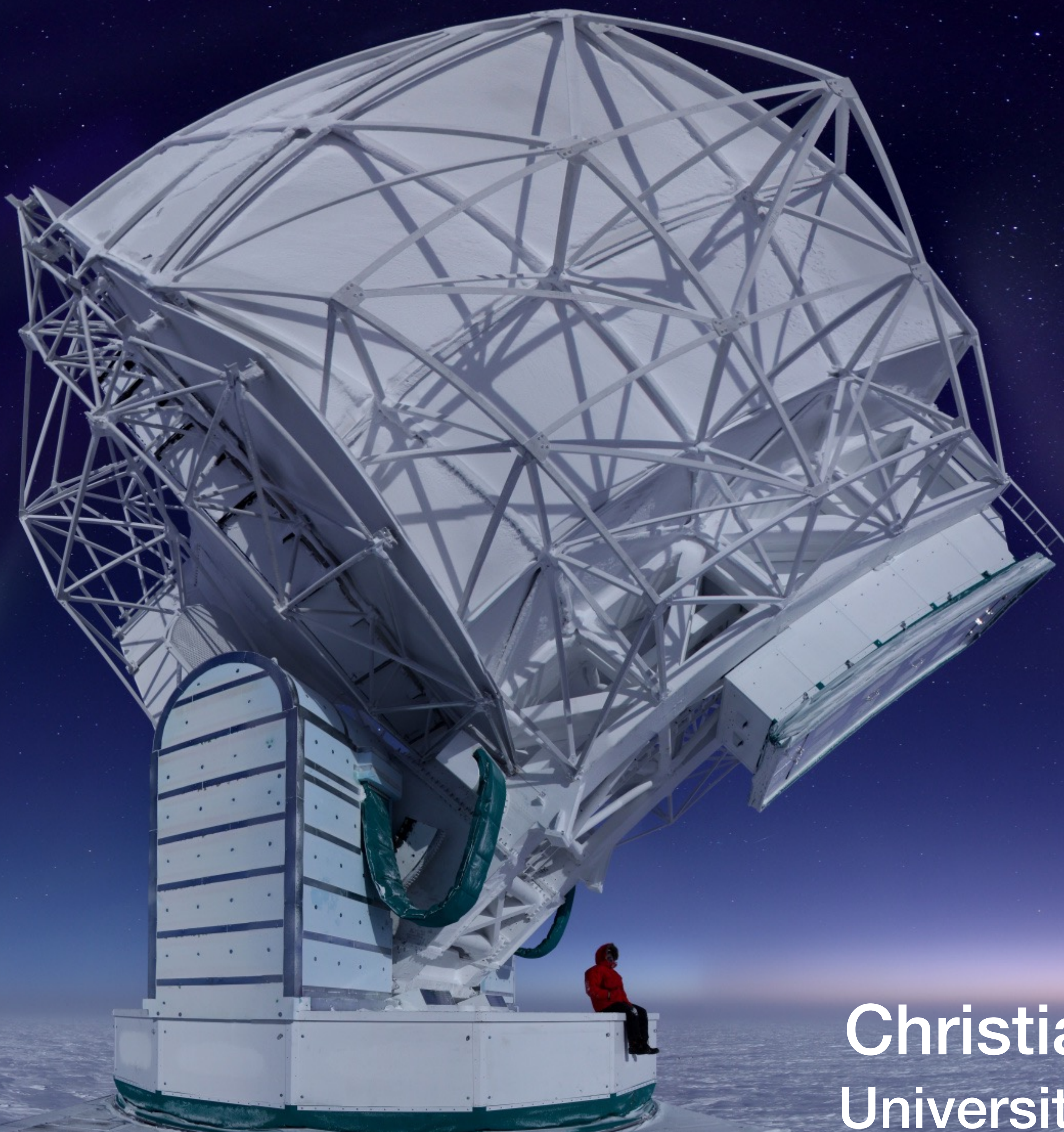
Recent Cosmic Microwave Background Results



Christian Reichardt
University of Melbourne

Probing the Cosmic Frontier with CMB

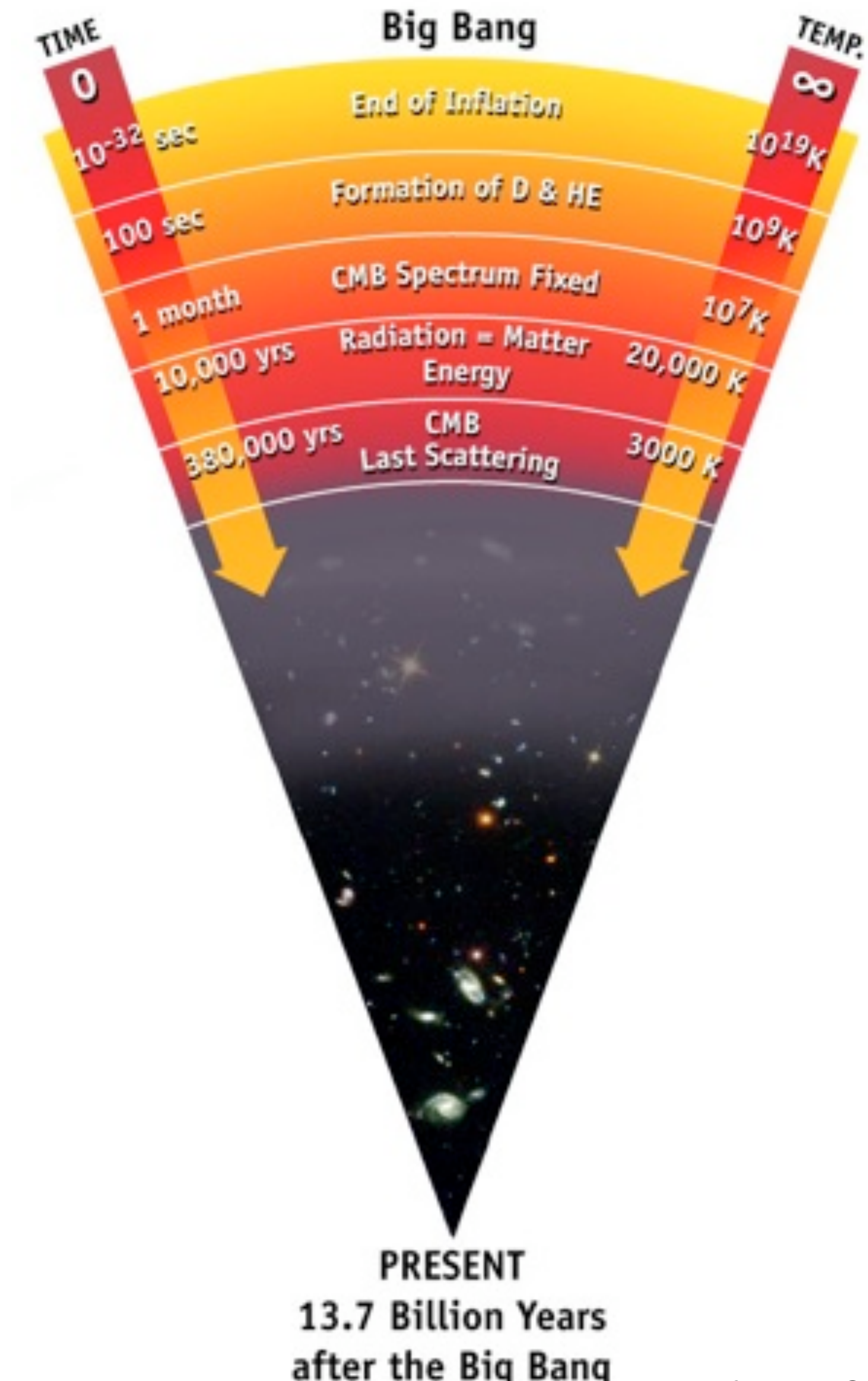
We now have a model that describes the evolution of our Universe from a hot and dense state.

The model has some unusual features

- new physics -

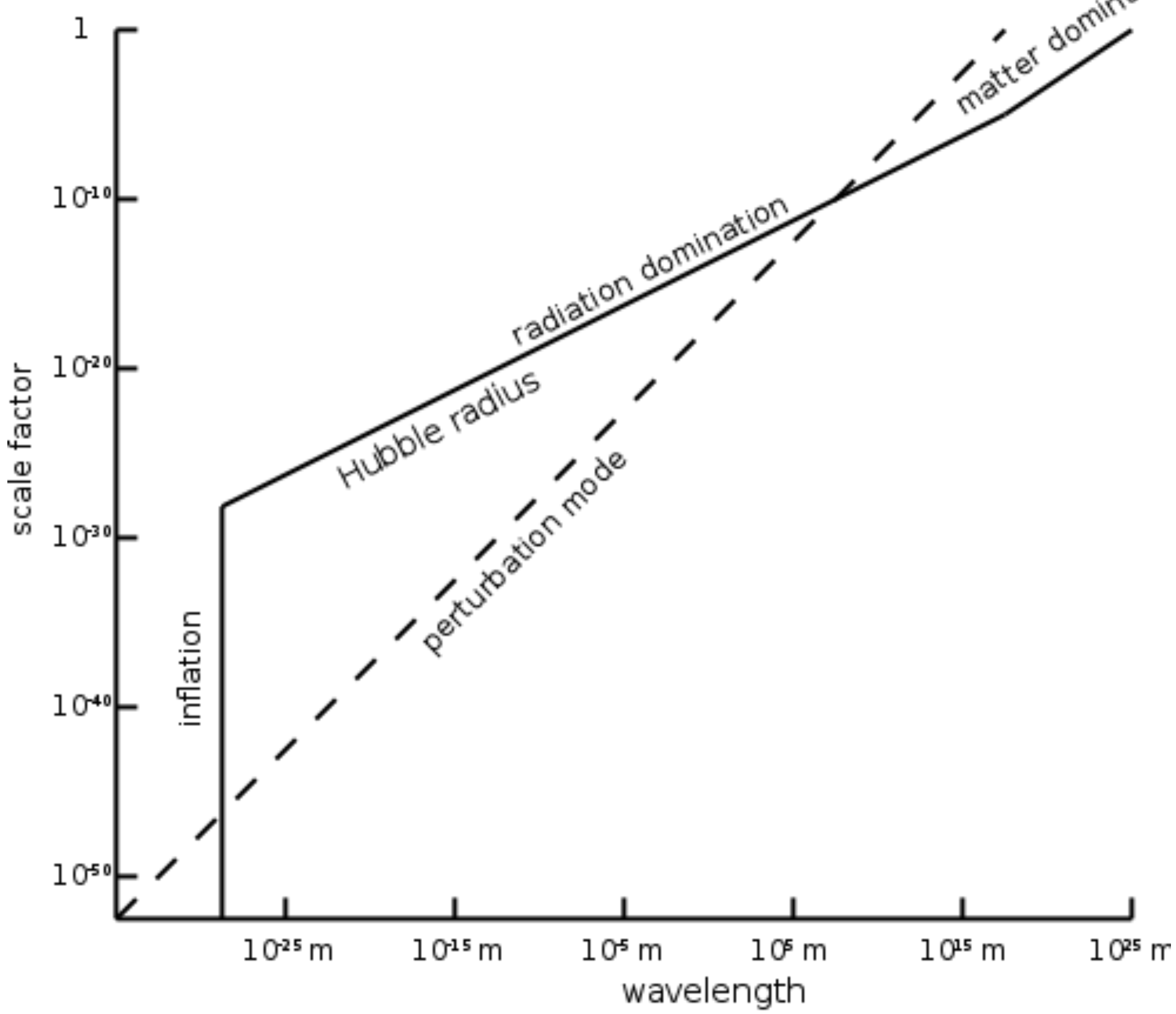
Dark Matter, Dark Energy, and starts with a period of **Inflation**.

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



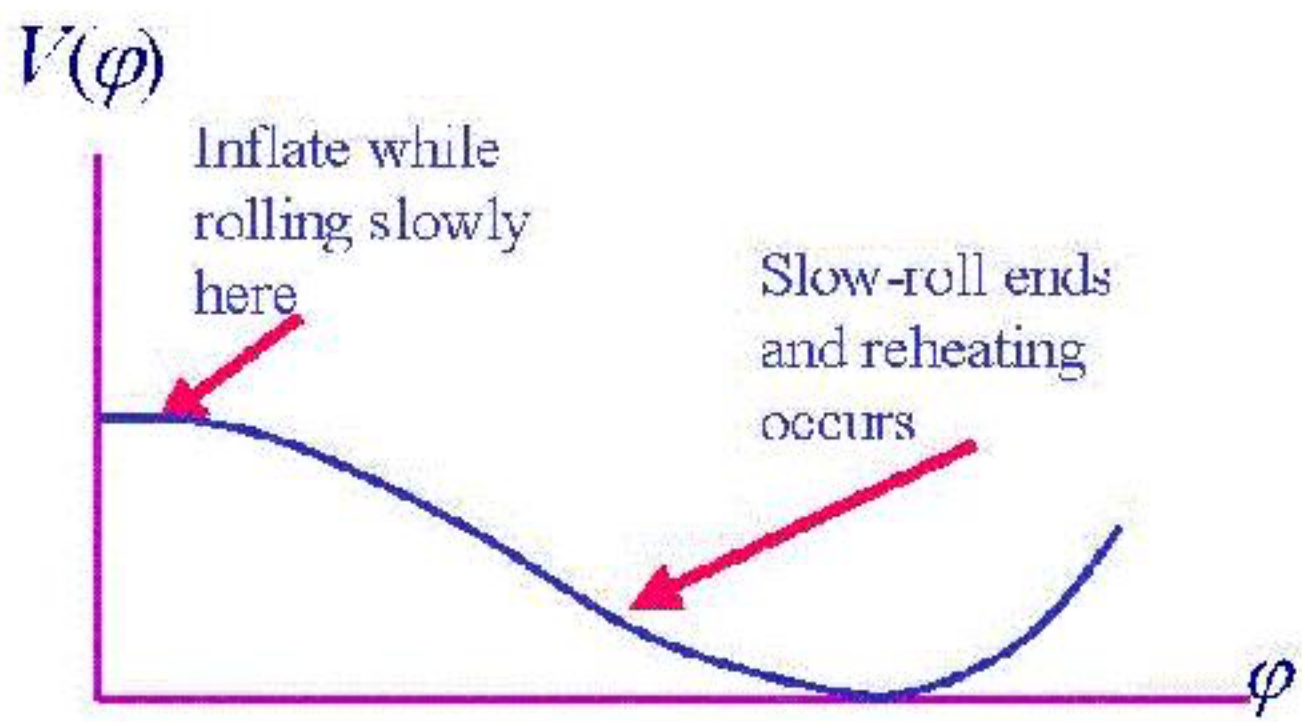
from NASA/WMAP Team

Credit: wikipedia



Inflation

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

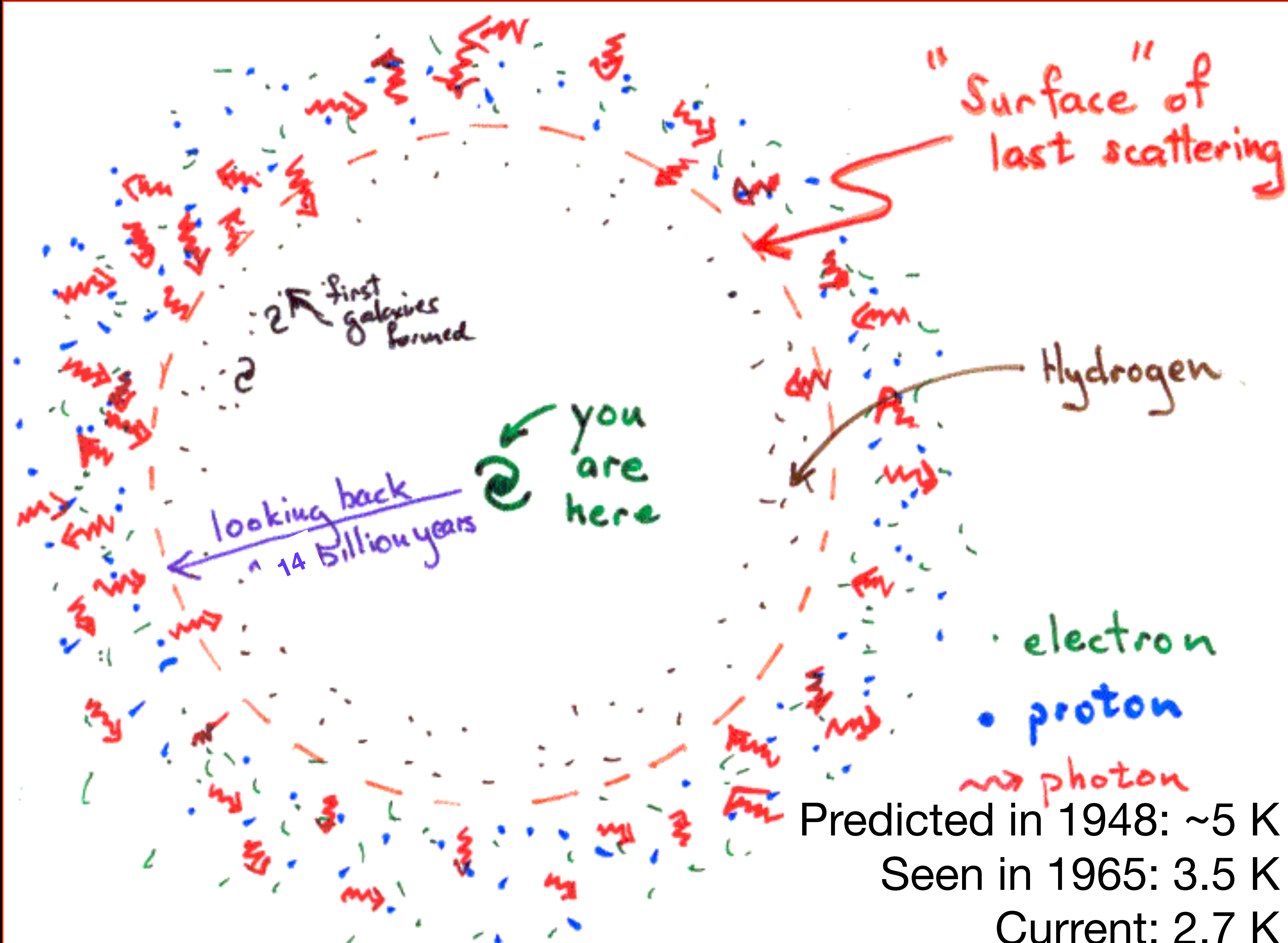


Credit: Albrecht

Favored model - Slow-roll inflation:
Universe's density is dominated by the potential of a scalar field with 'flattish' potential

Open question: Can you use the Higgs for this scalar field? (see last talk)

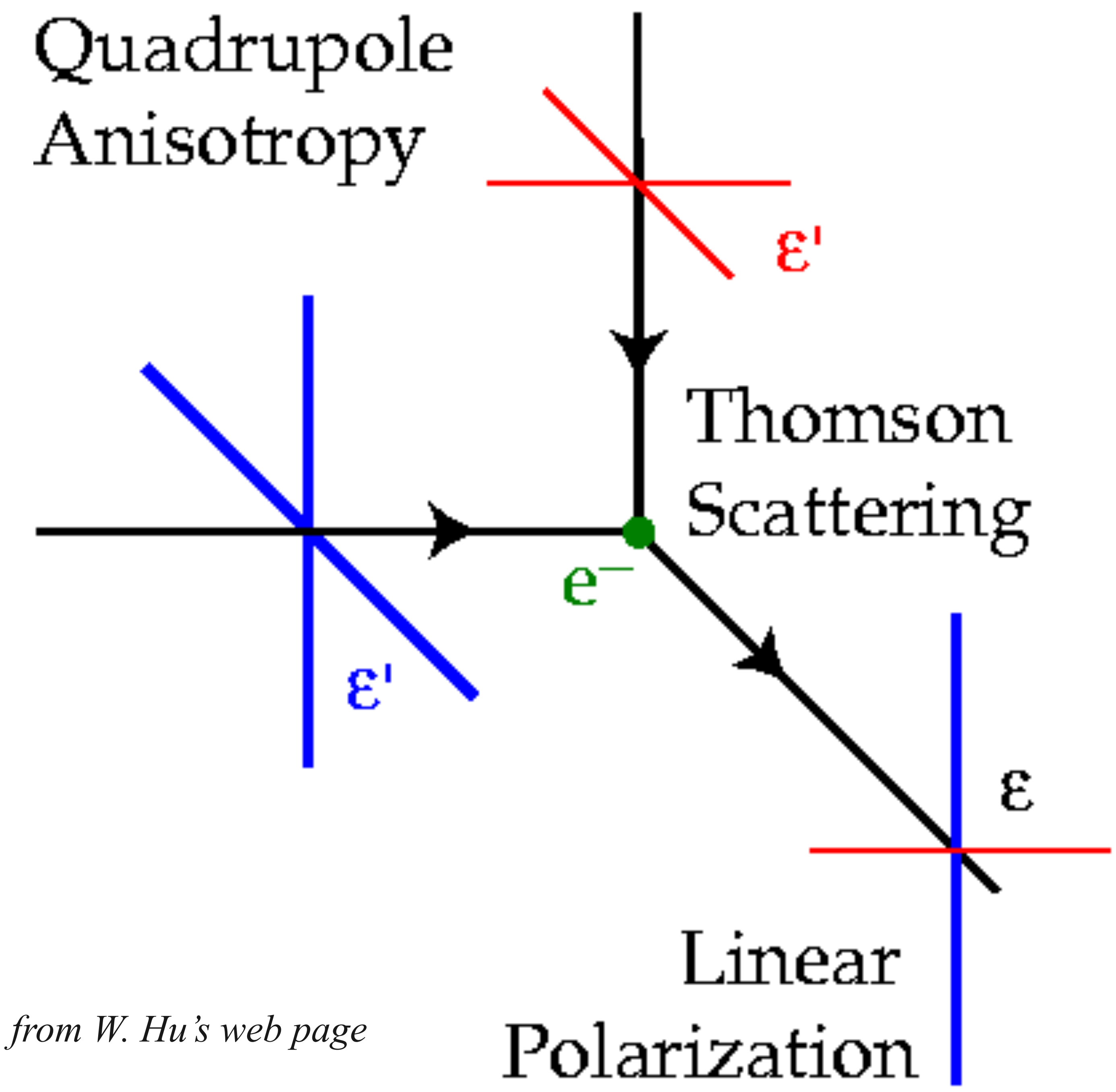
Cosmic Microwave Background



Predicted in 1948: ~5 K
Seen in 1965: 3.5 K
Current: 2.7 K

Polarization of the CMB

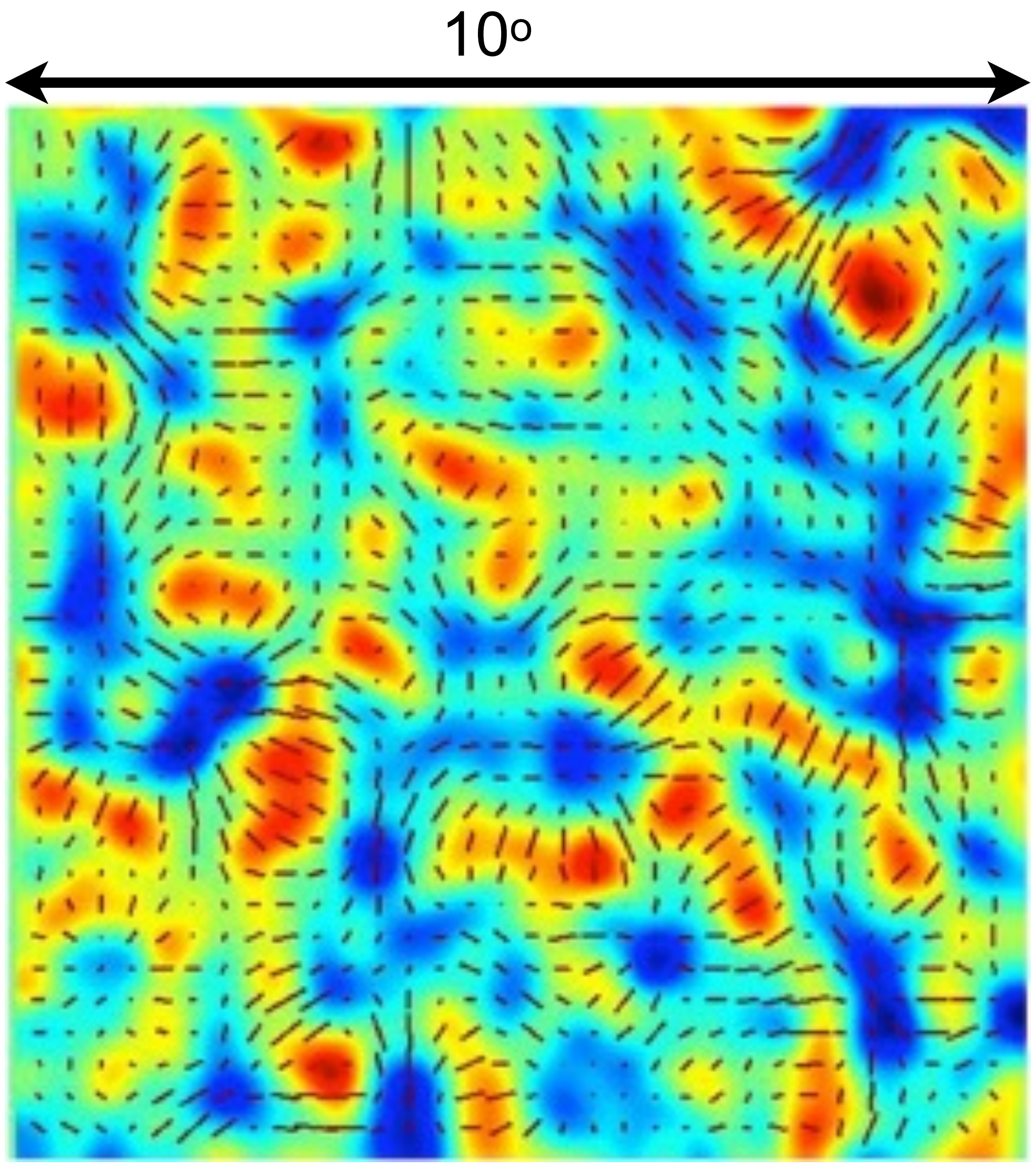
CMB is polarized by Thomson Scattering



from W. Hu's web page

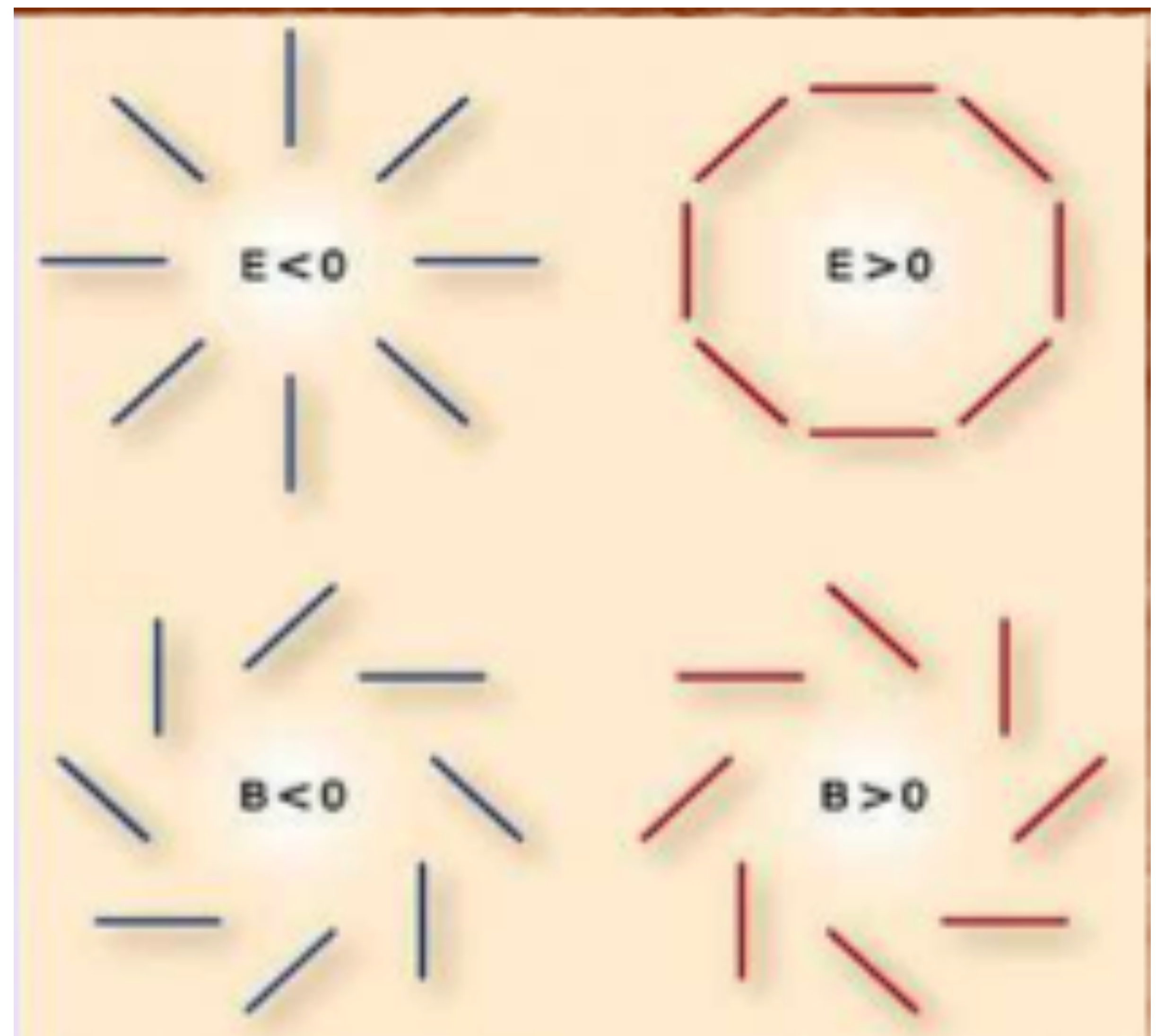
Credit: Talex

The CMB is polarised (~10%)



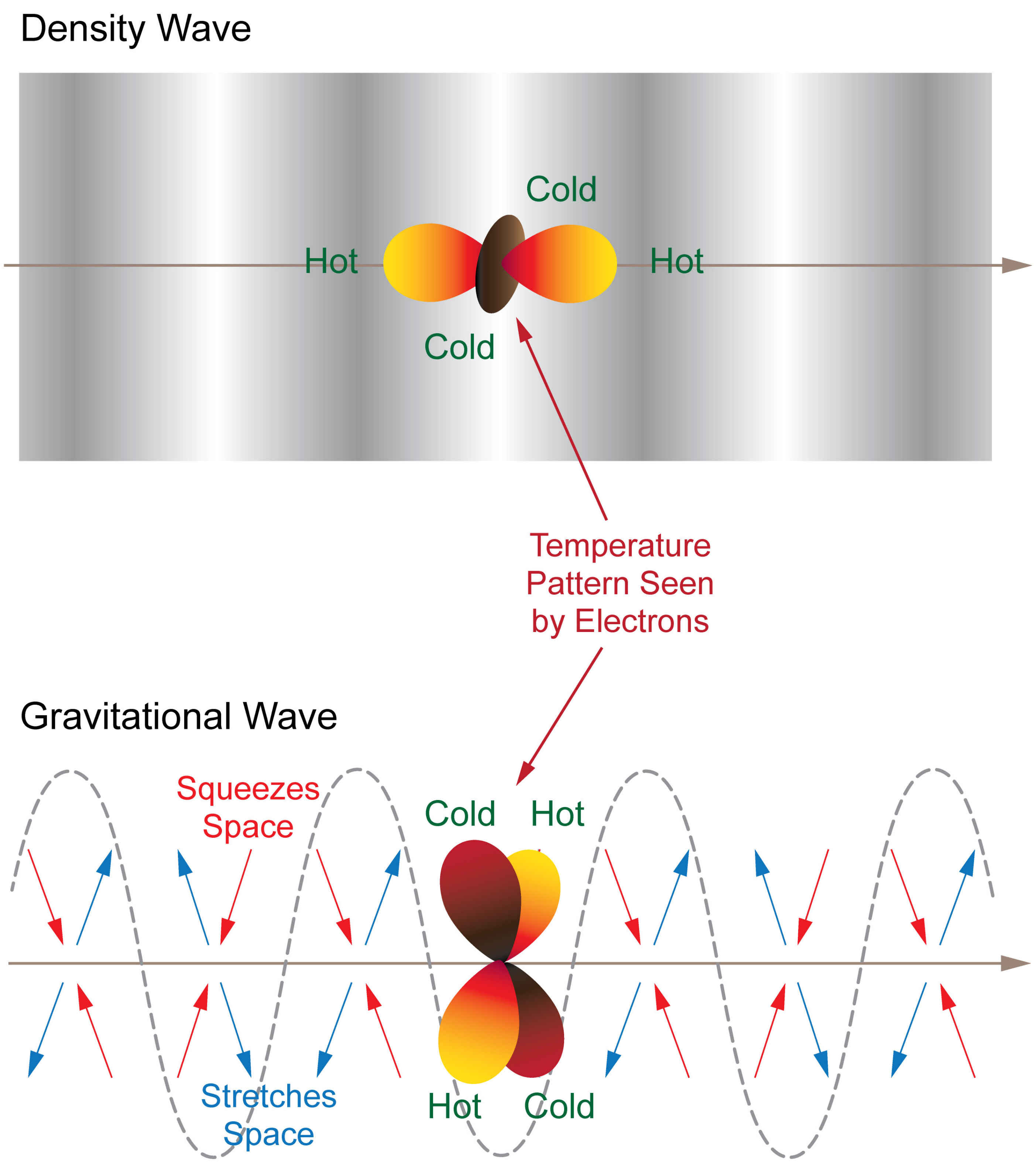
Smith et al 2008

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

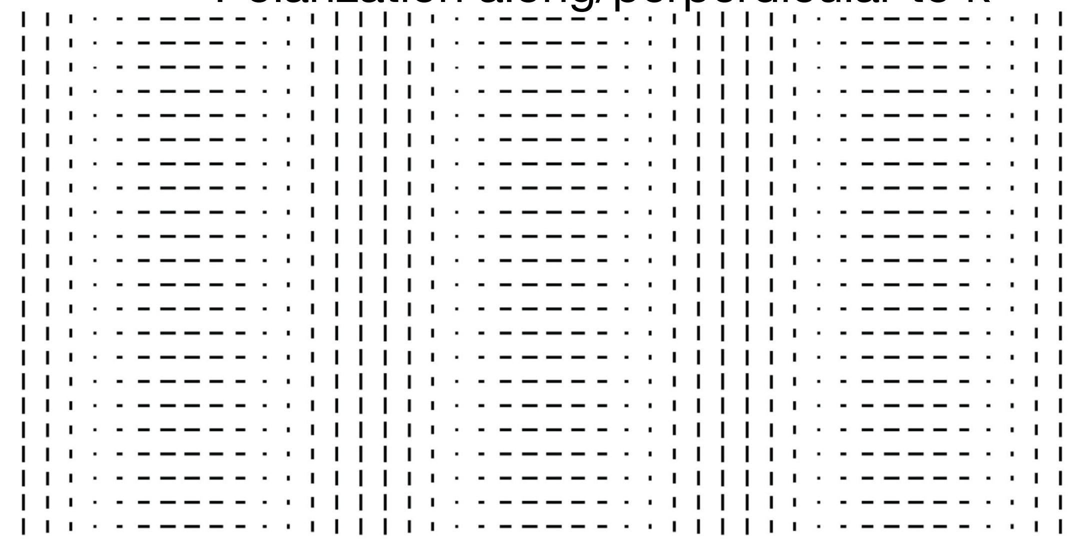


Why use E&B?

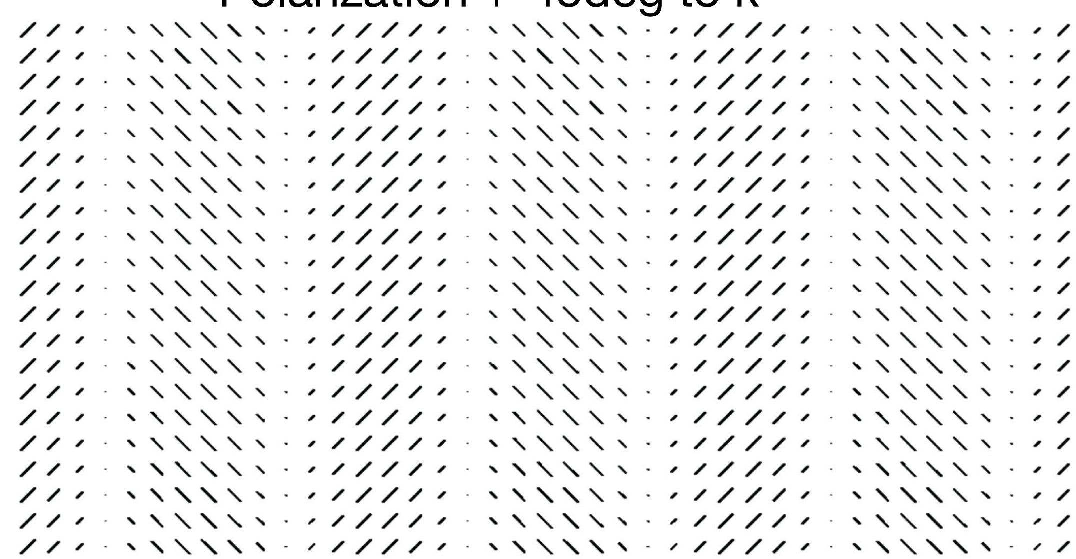
look at what produces each



E-Mode Polarization Pattern
Polarization along/perperdicular to k



B-Mode Polarization Pattern
Polarization +-45deg to k



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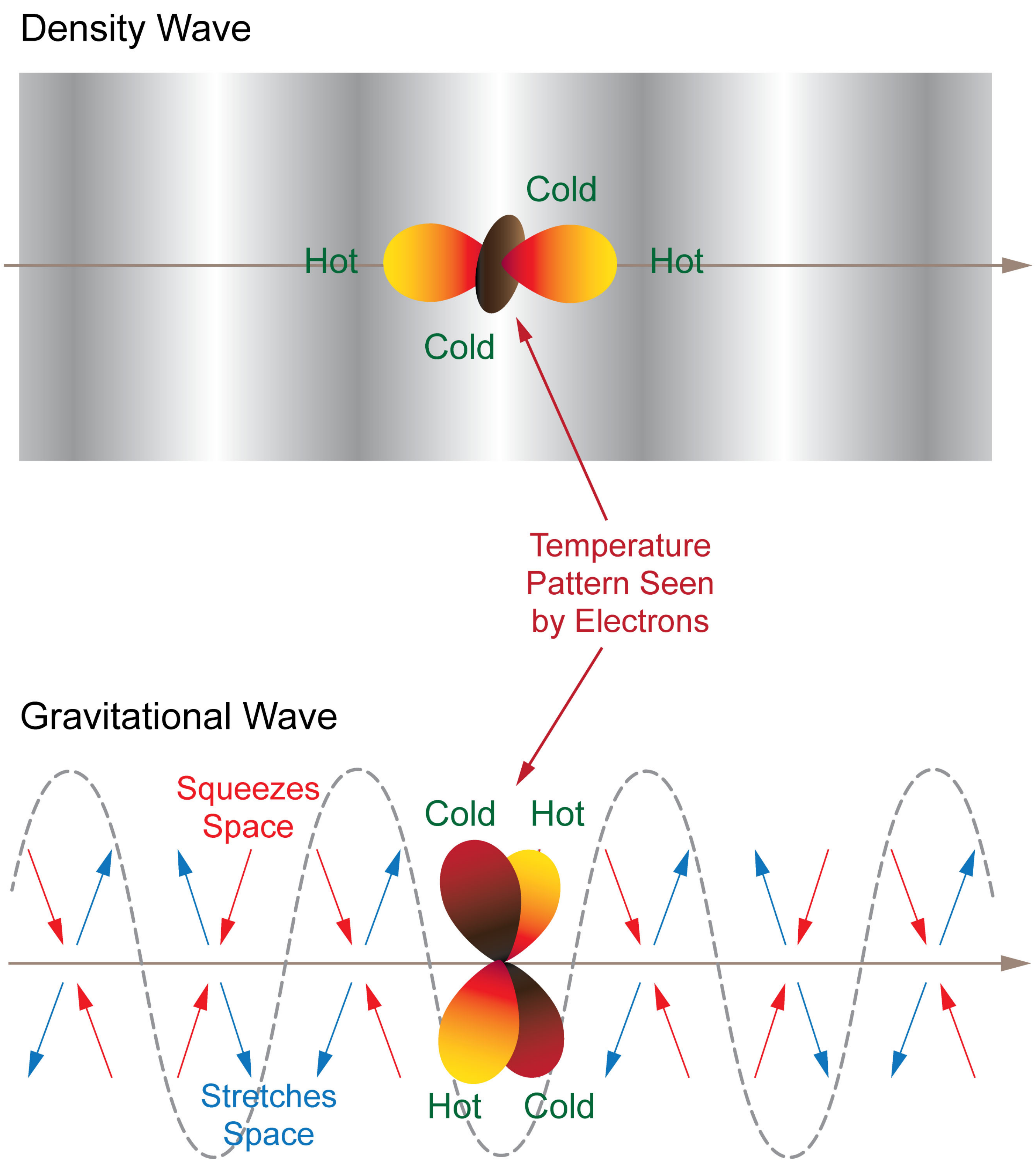

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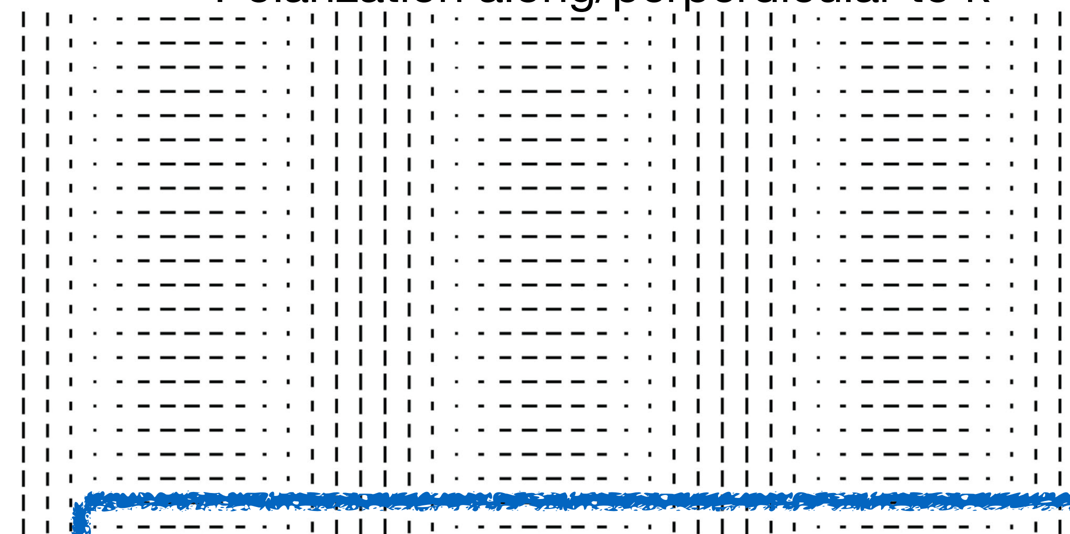
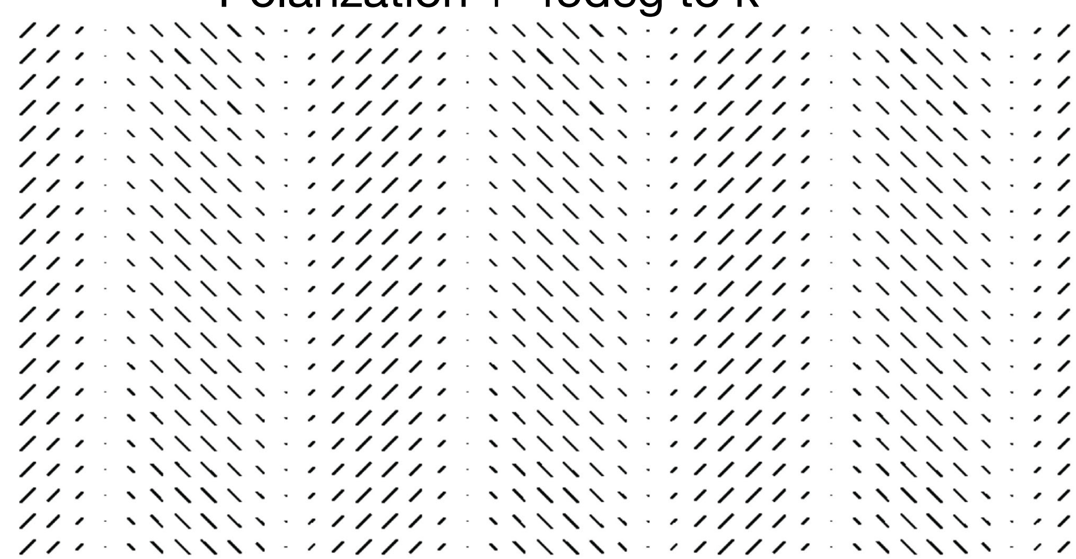


Density fluctuations at LSS do not produce “B” modes;

Gravitational waves do!

B-Mode Polarization Pattern
Polarization +-45deg to k



Why use E&B?

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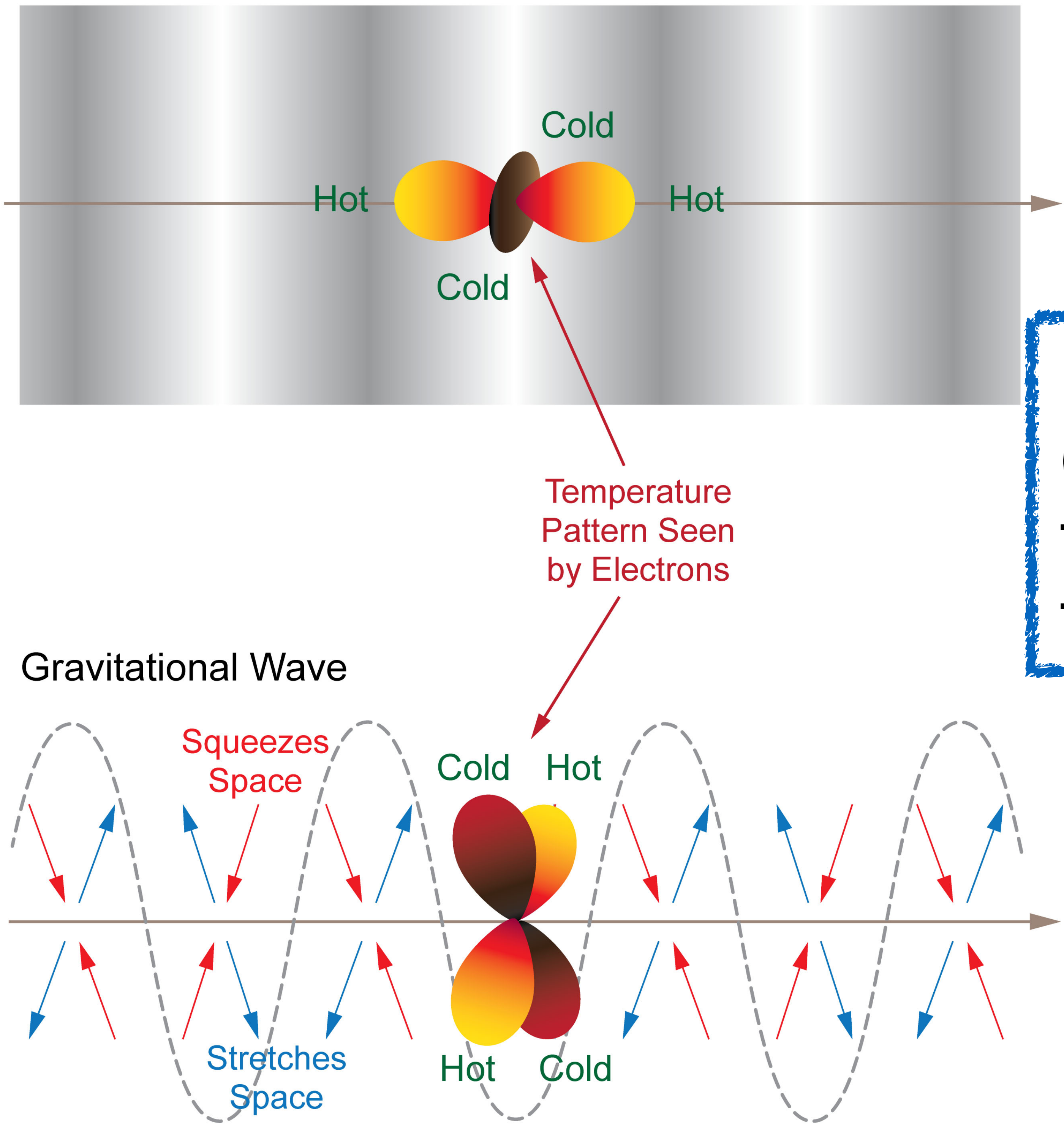
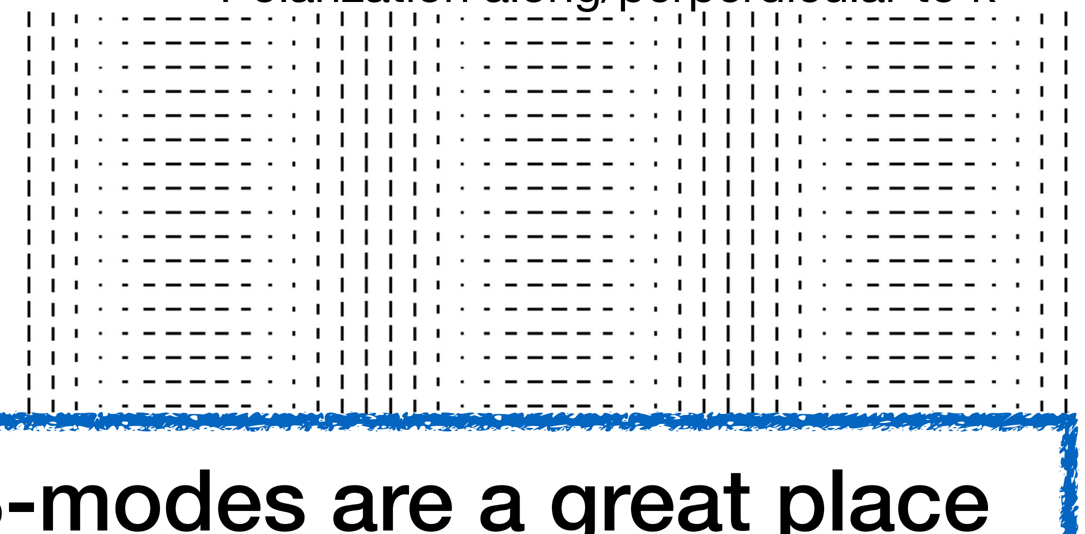
Density Wave



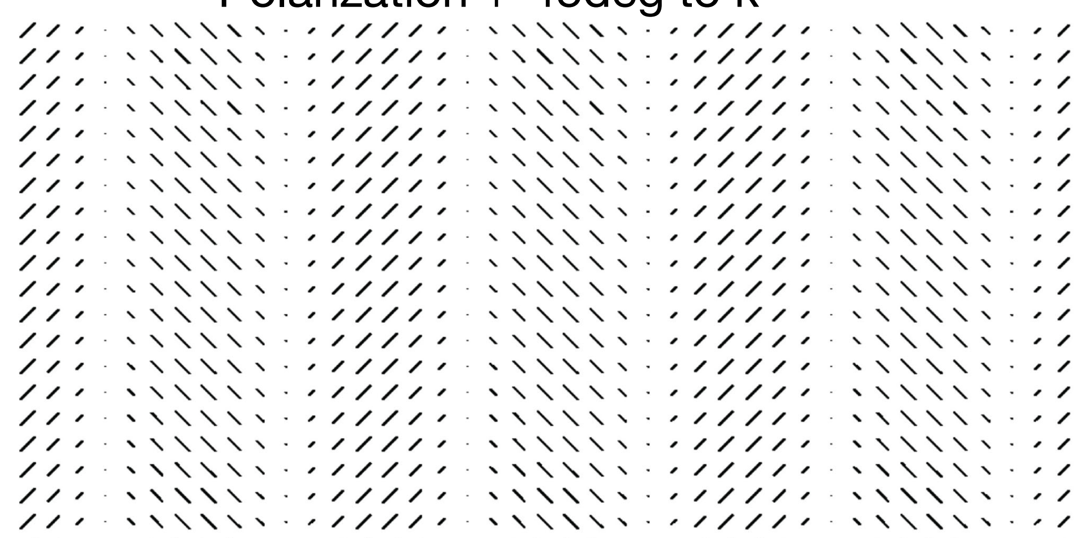
Gravitational Wave

E-Mode Polarization Pattern
Polarization along/perperdicular to k



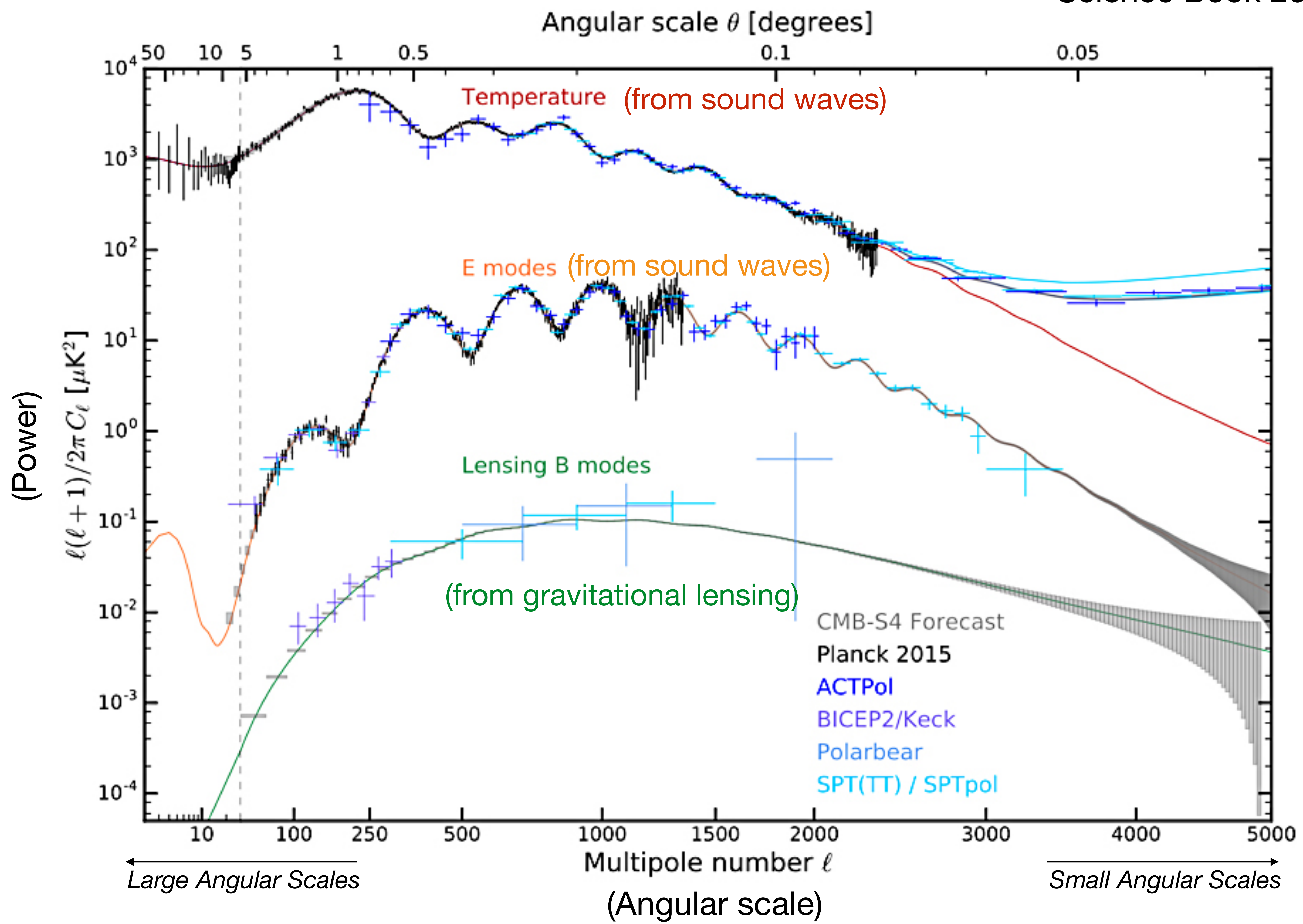
B-modes are a great place (low background) to look for gravitational waves from inflation

Polarization +-45deg to k



Measurements of CMB Power spectra

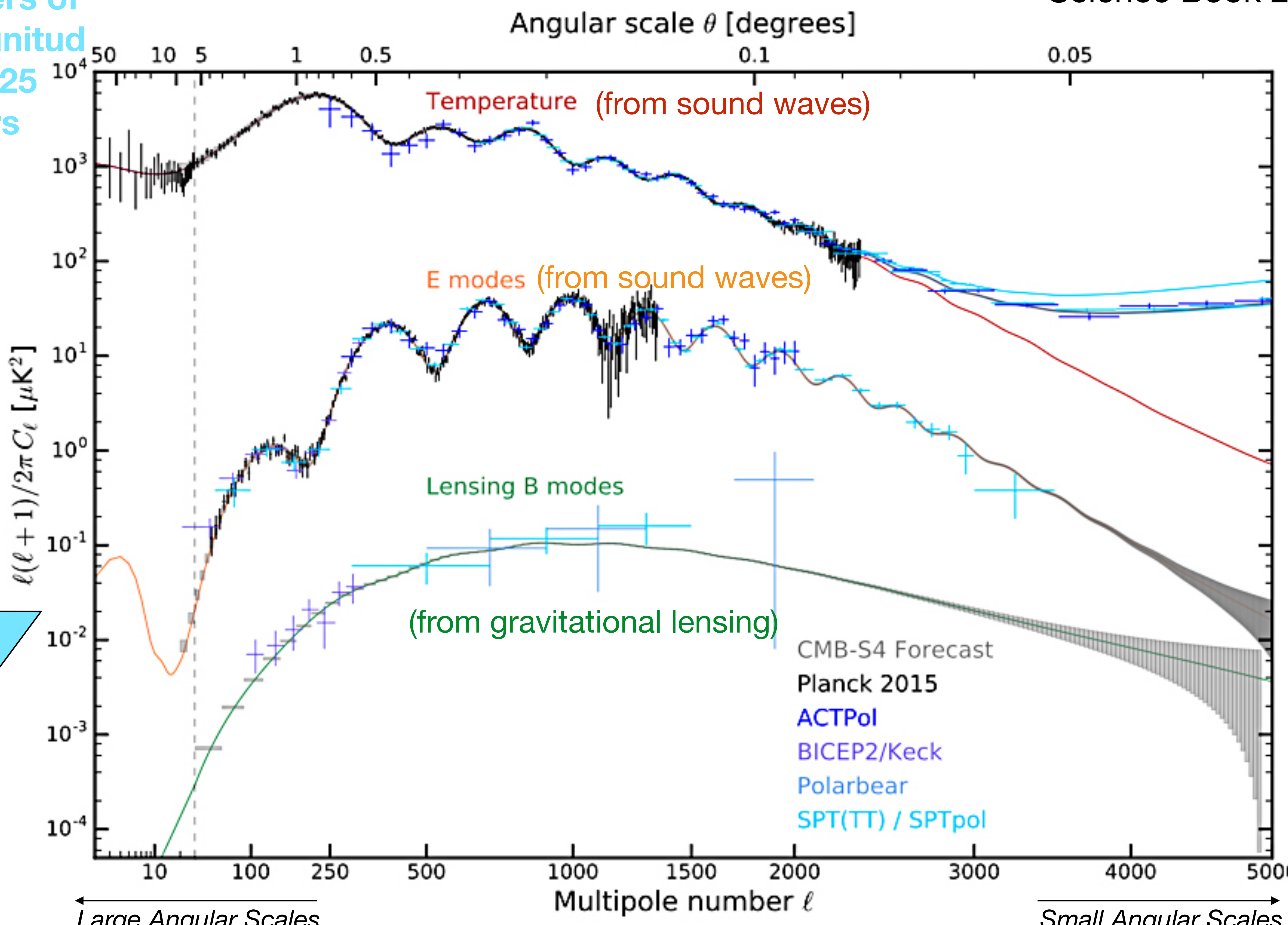
from CMB-S4
Science Book 2016



Measurements of CMB Power spectra

from CMB-S4 Science Book 2016

Six orders of magnitude in 25 years



(Angular scale)

Measurements of CMB Power spectra

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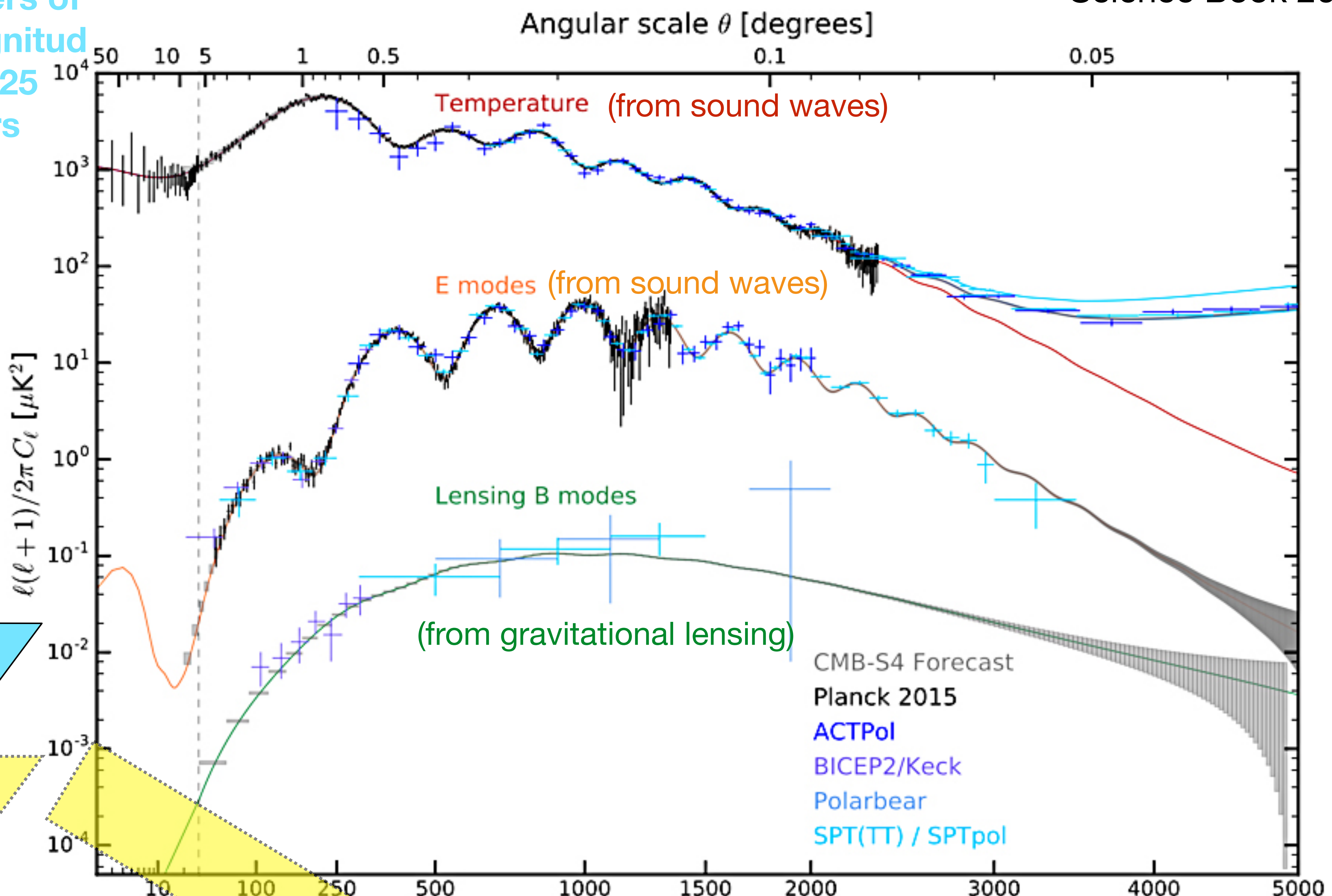


Goal:
Inflationary B-modes

(Angular scale)

Small Angular Scales

Chasing inflationary gravitational waves

"smoking gun of inflation"

The power in G. Waves is described by "r" = tensor-to-scalar ratio

Current 95% CL upper limit is $r < 0.06$ (BICEP/Keck + Planck)

Goal: $r < 0.002$ ($\sigma(r)=0.001$)

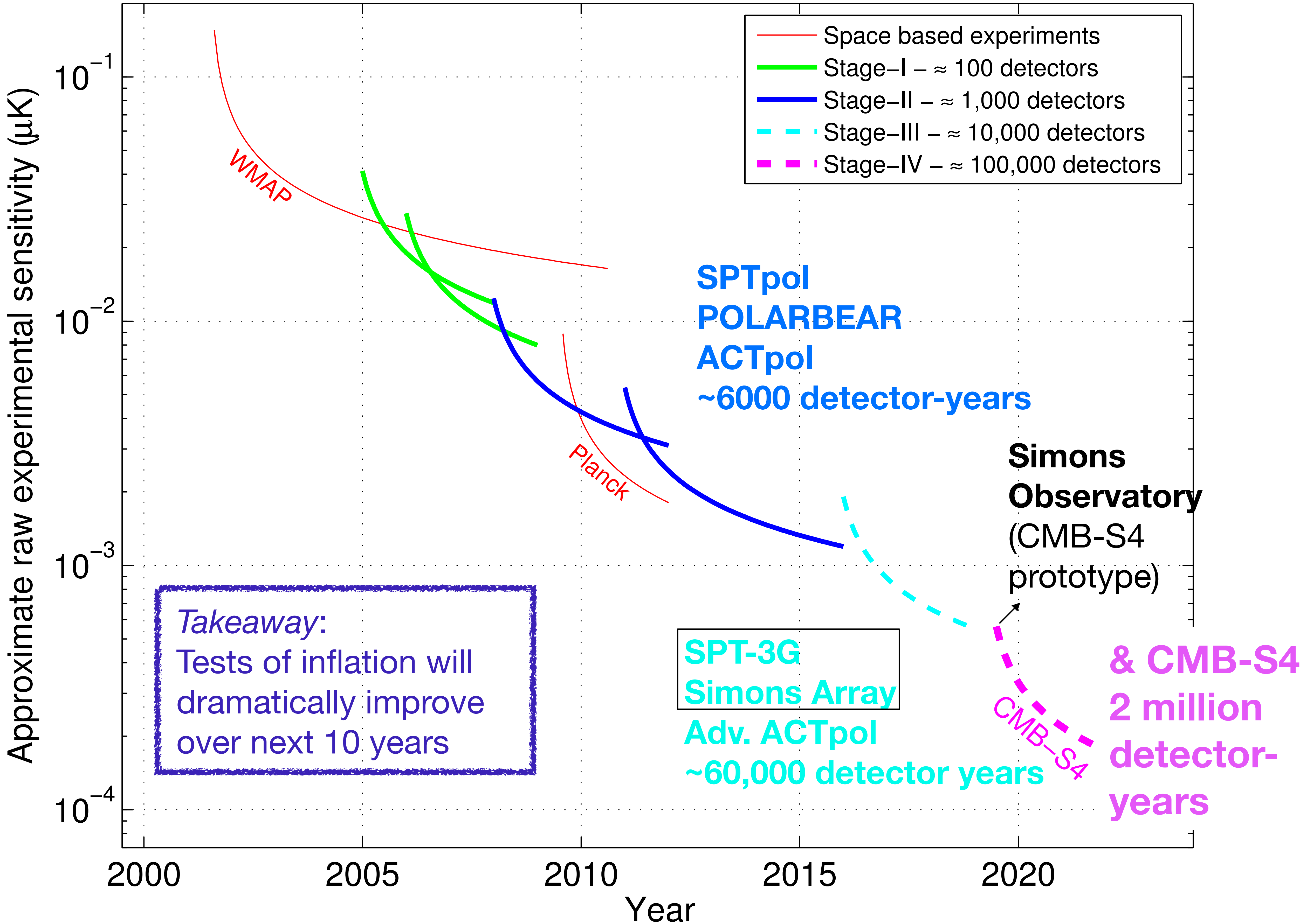
How do we get the next factor of ~30?

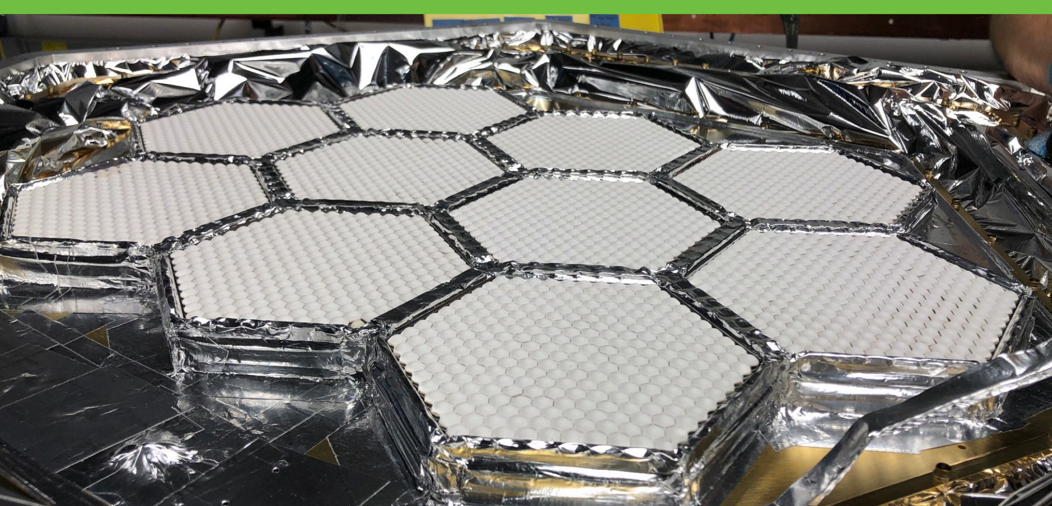
Basic Ingredients

- More detectors
  - Detectors have reached noise floor of photon statistics
- Both large and small angular scales
  - Large scales for IGW signal; small scales to remove lensing power
- Wide frequency coverage
  - Separating CMB and the Milky Way

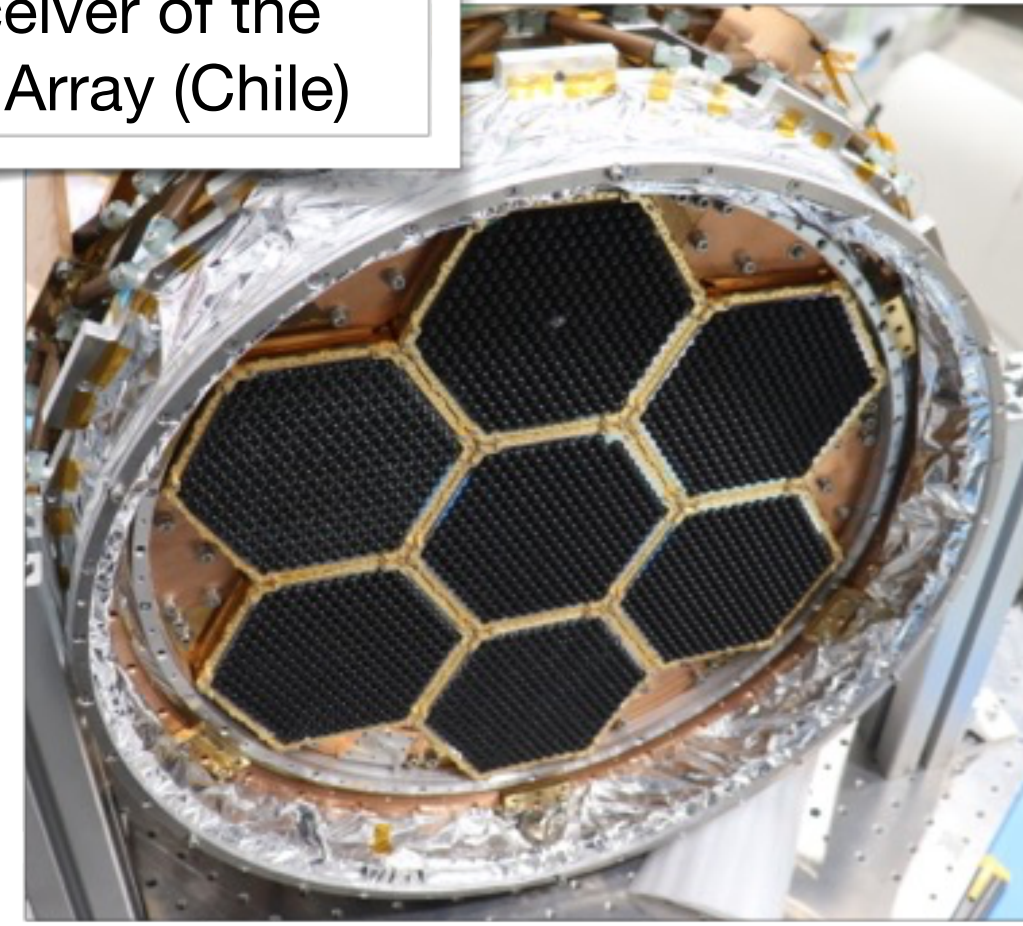
Contribution to
Snowmass
2013

CMB's "Moore's Law"





Putting New wafers on the South Pole Telescope



First receiver of the Simons Array (Chile)

Instrument work on right now!

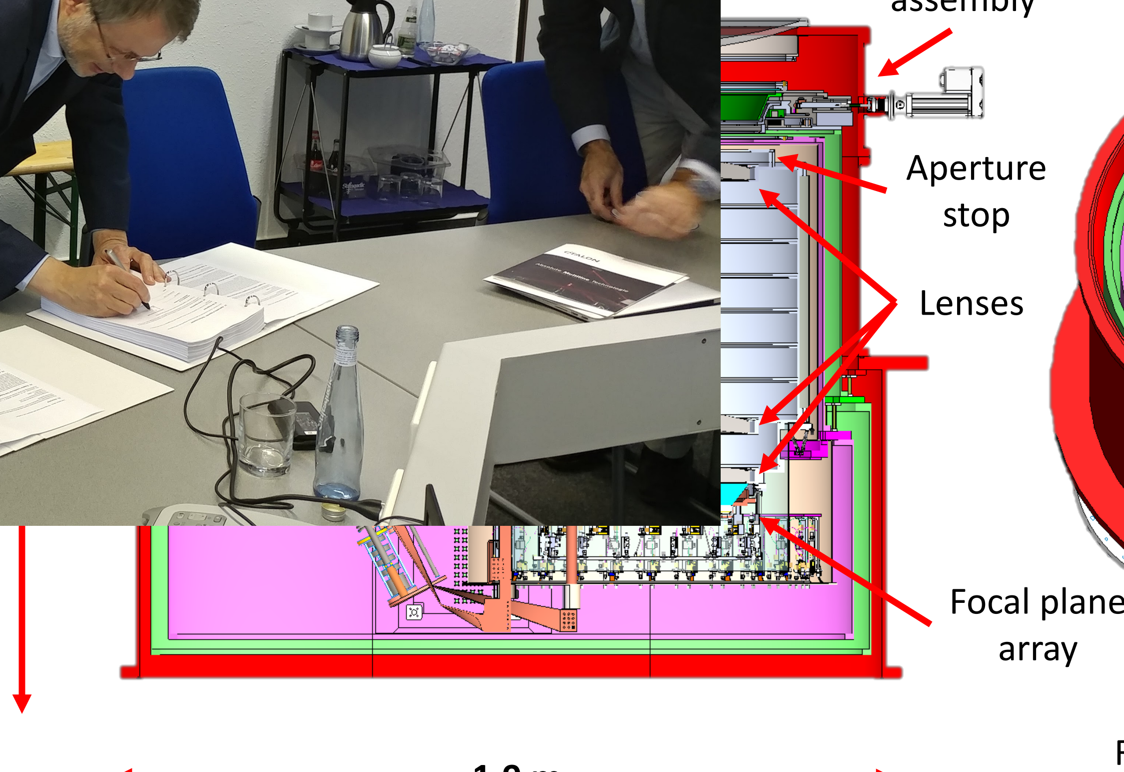
Simons Observatory

Instrument overview: arxiv:1808.04493
Science overview: arxiv:1808.07445

3x Small Aperture Telescopes

Key advs: 1) Cheap way to
et sensitivity
systematics
control

No pretty hardware pictures yet, but telescope contract is signed



1x Large Aperture
crossed Dragone design

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

Simons Observatory

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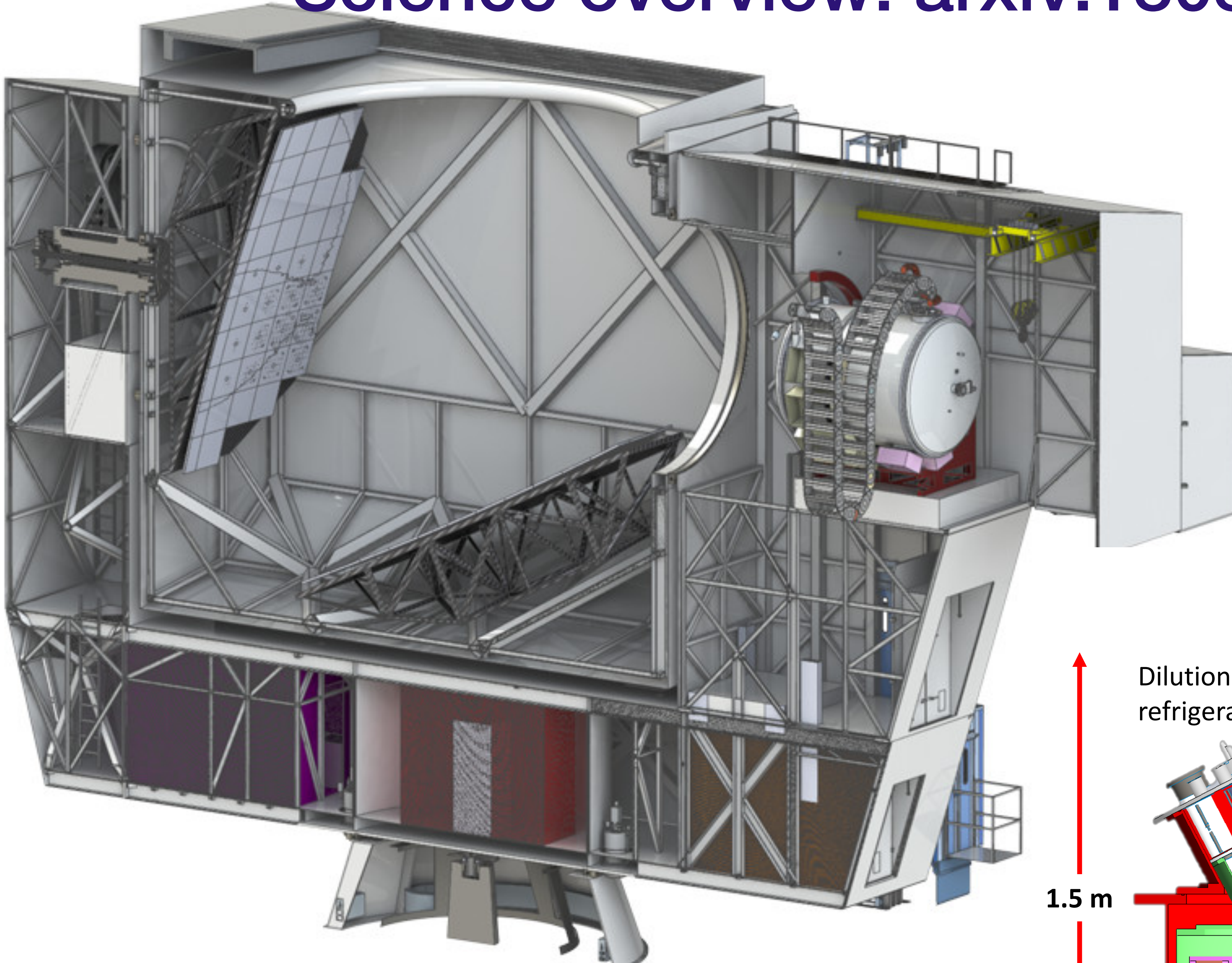
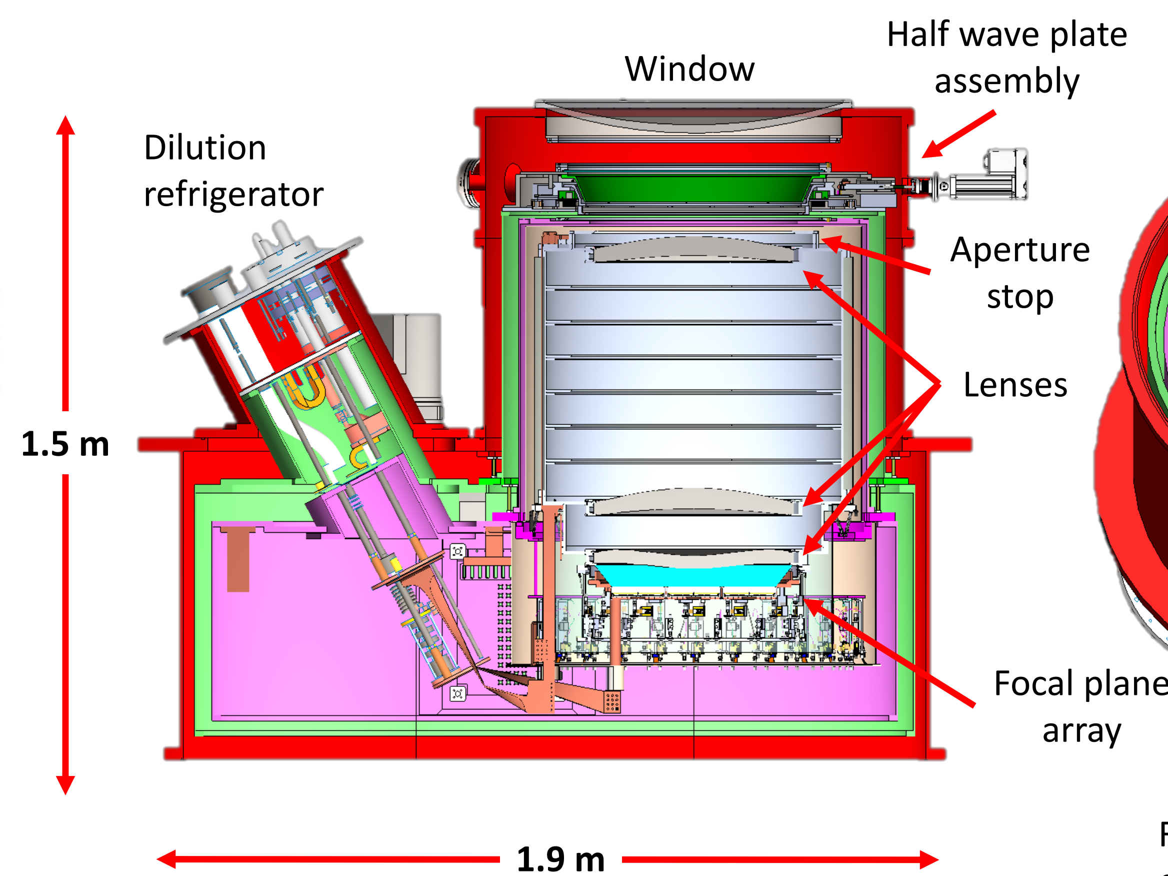


3x Small Aperture Telescopes

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



1x Large Aperture Telescope
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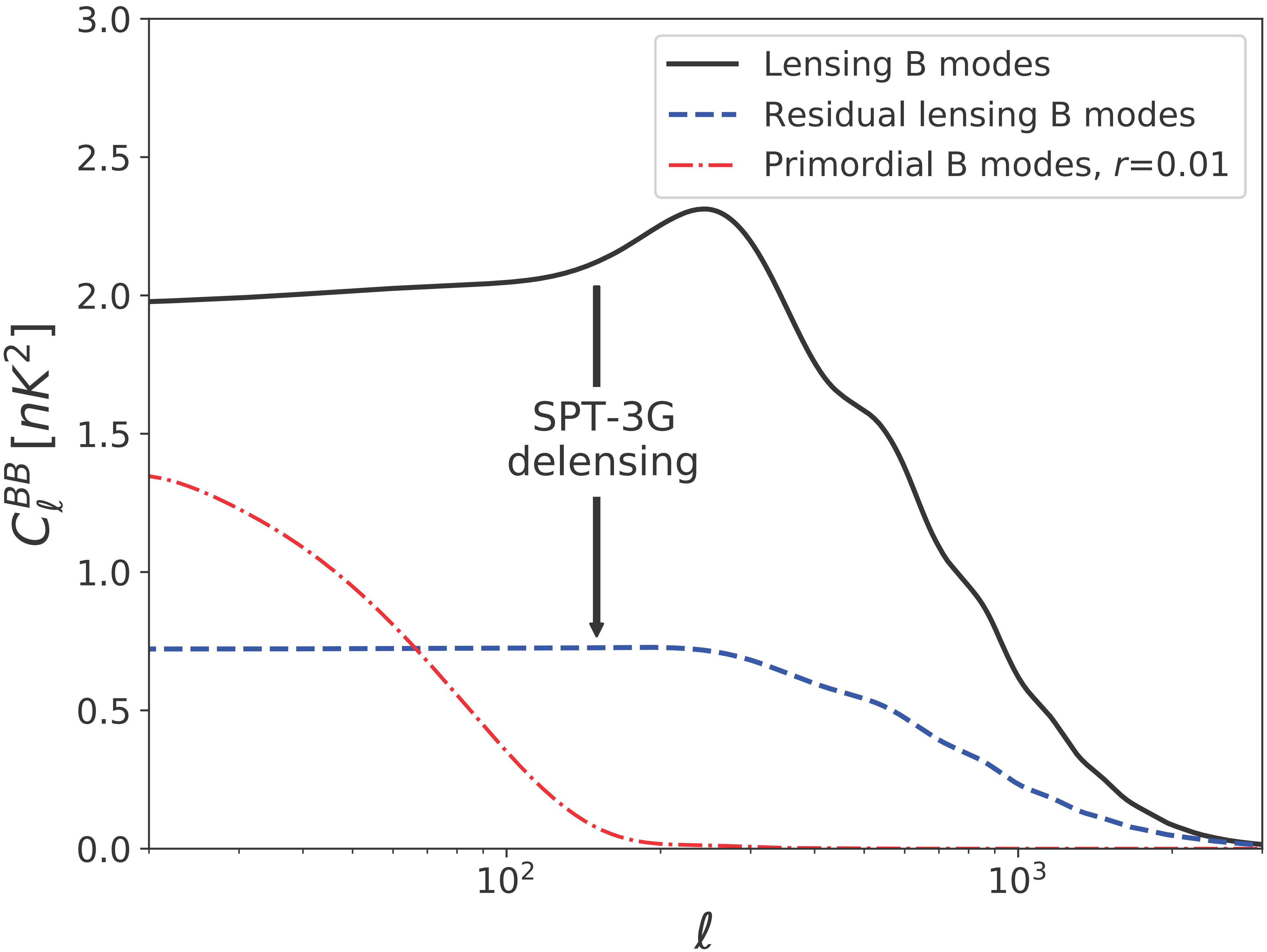
Key adv: Allows large focal plane (2m!) for lots of detectors

Importance of Delensing

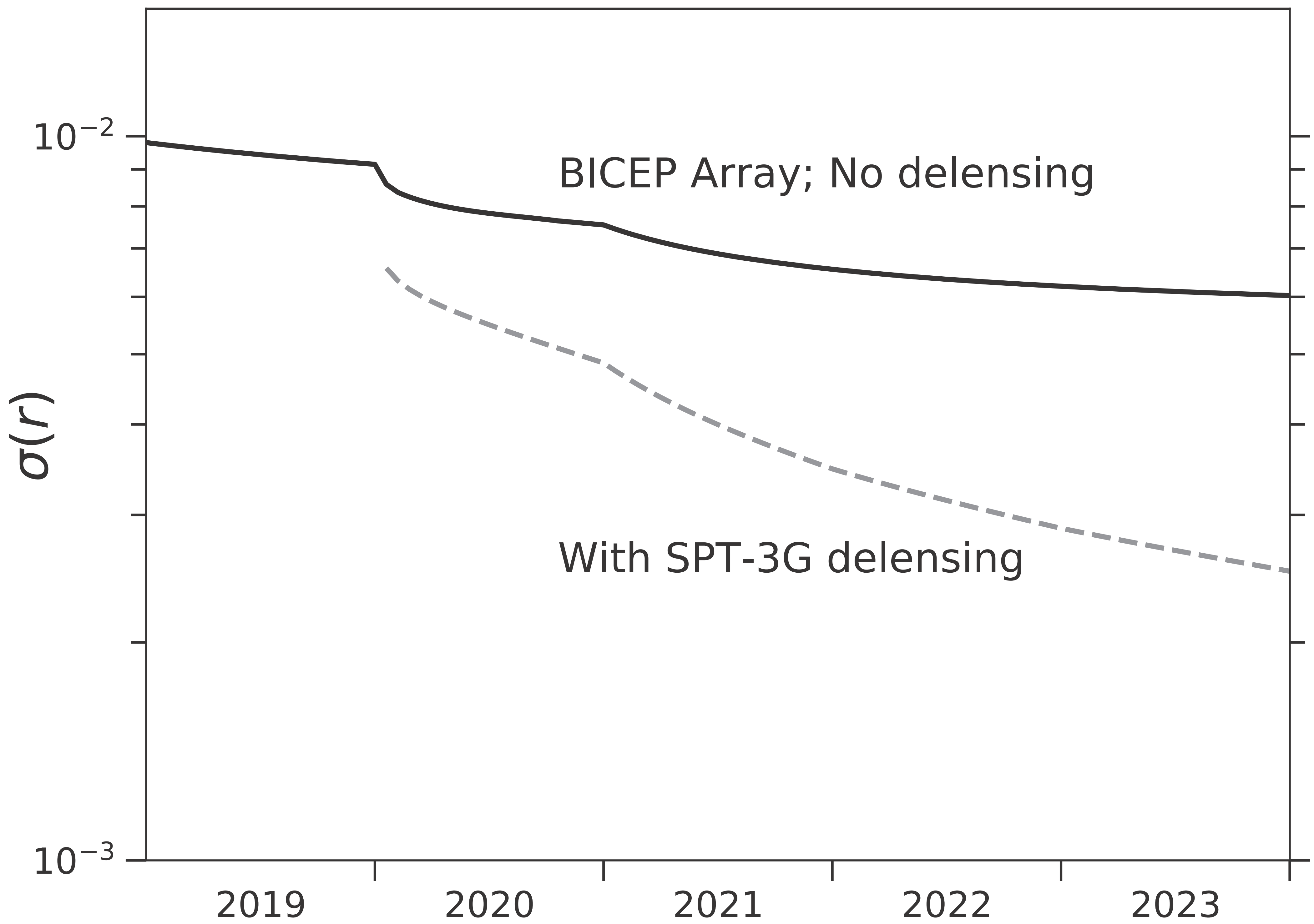
Manzotti et al. ApJ 2017: 24% delensing on the SPTpol 100d field



SPT-3G will remove 2/3s of lensing BB power

New era: delensing crucial to IGW searches

Credit: BICEP Array collaboration

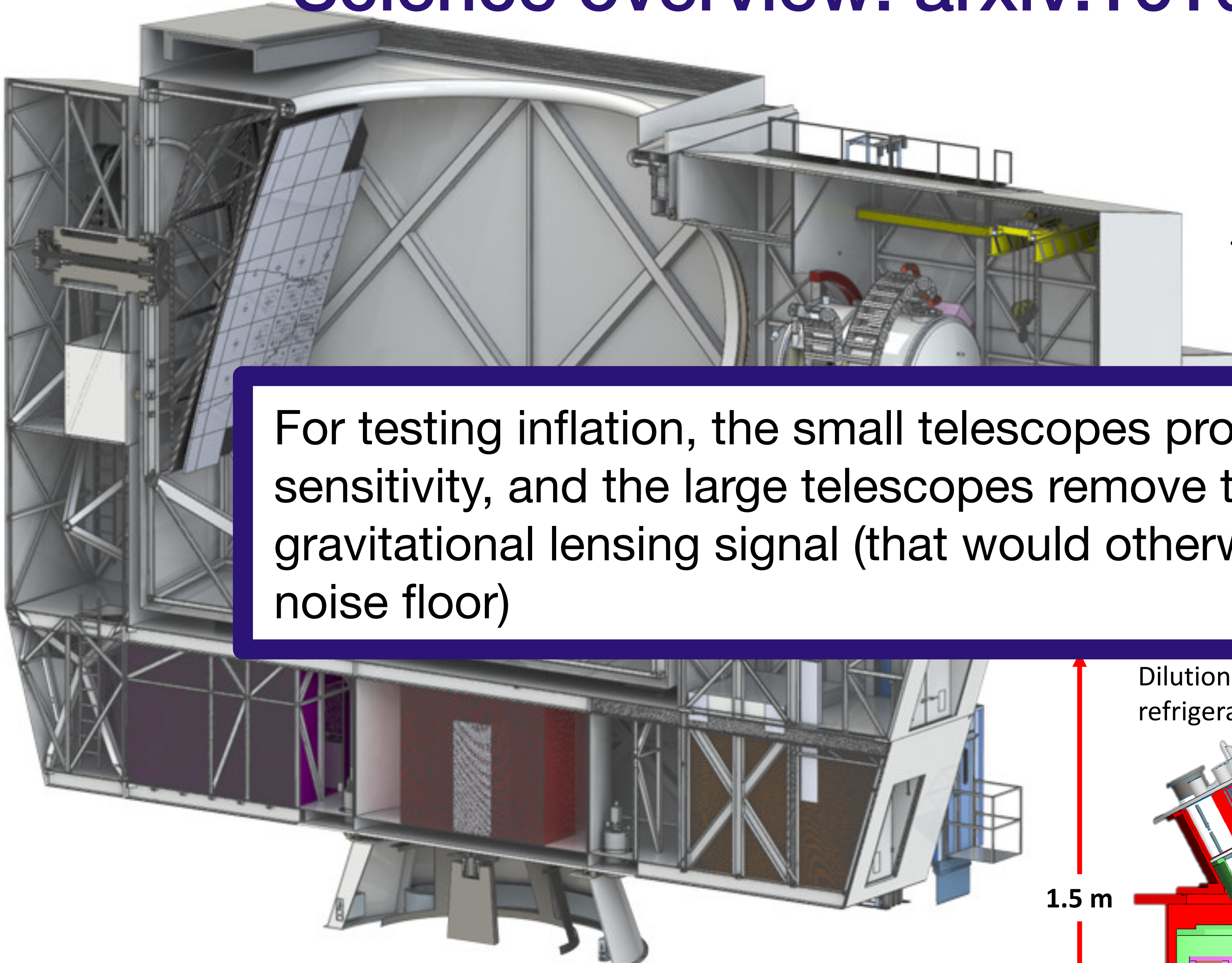


SPT-3G will remove 2/3s of lensing BB power

also, CMB-S4 *(still in flux)*

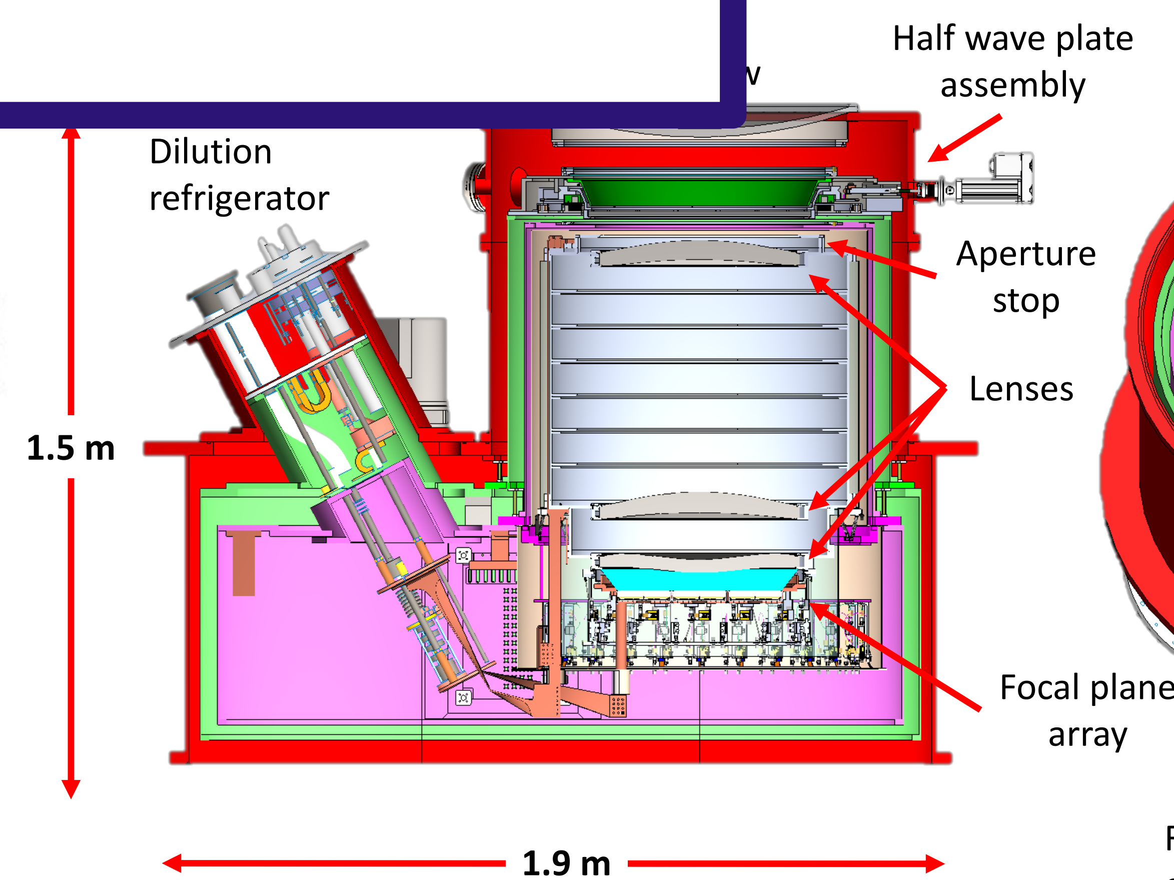
More details coming soon

Technology overview: arxiv:1706.02464
Science overview: arxiv:1610.02743



Current plan:
18x Small Aperture Telescopes

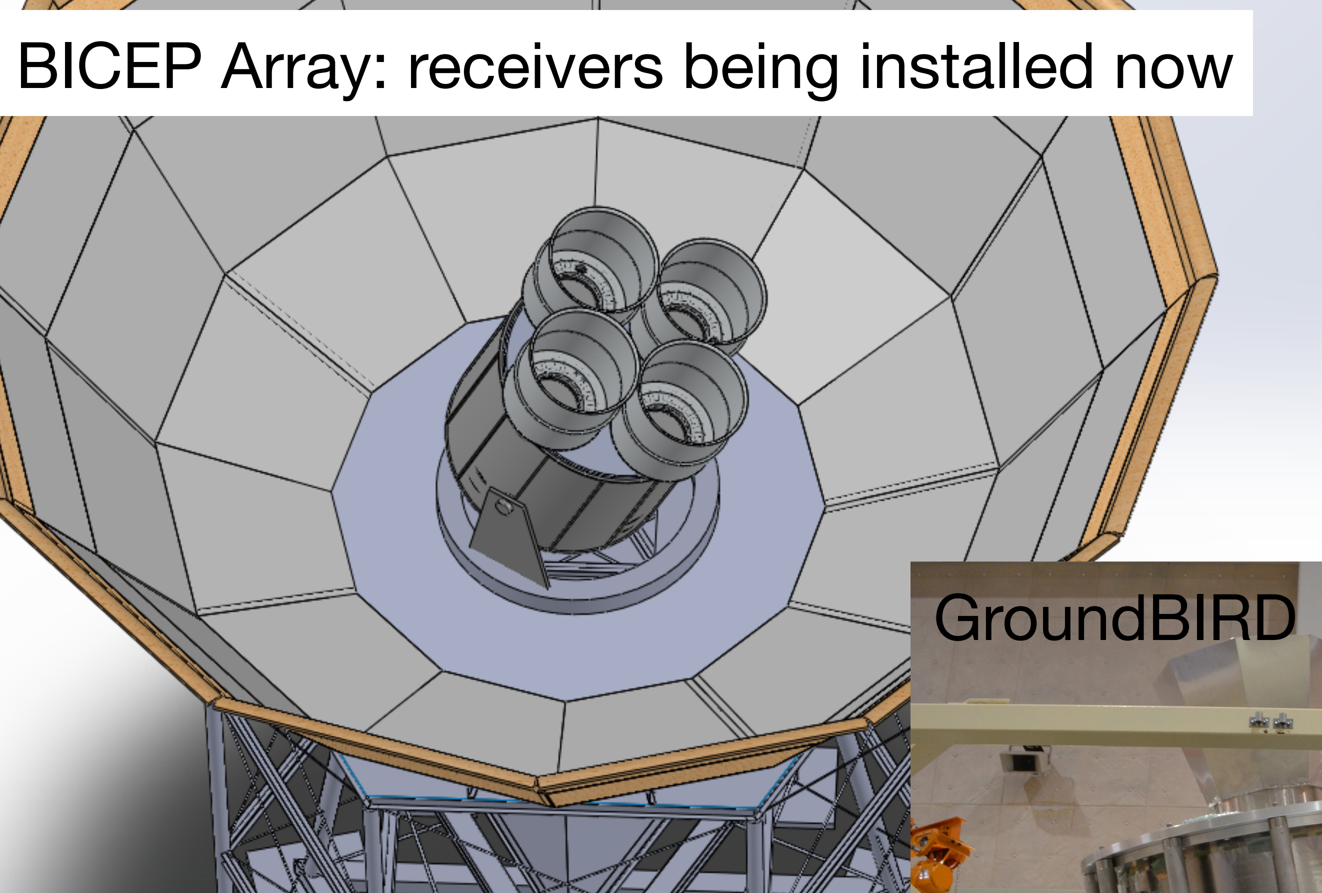
For testing inflation, the small telescopes provide the raw sensitivity, and the large telescopes remove the gravitational lensing signal (that would otherwise act as a noise floor)

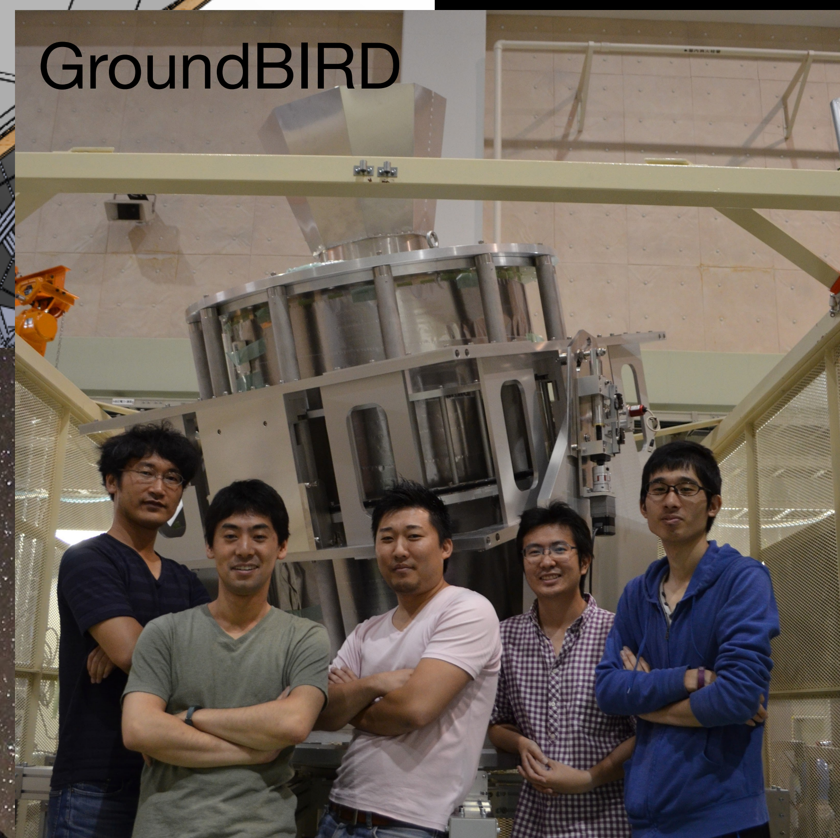


Current plan:
2x Large Aperture Telescope
~6m crossed Dragone

And many others

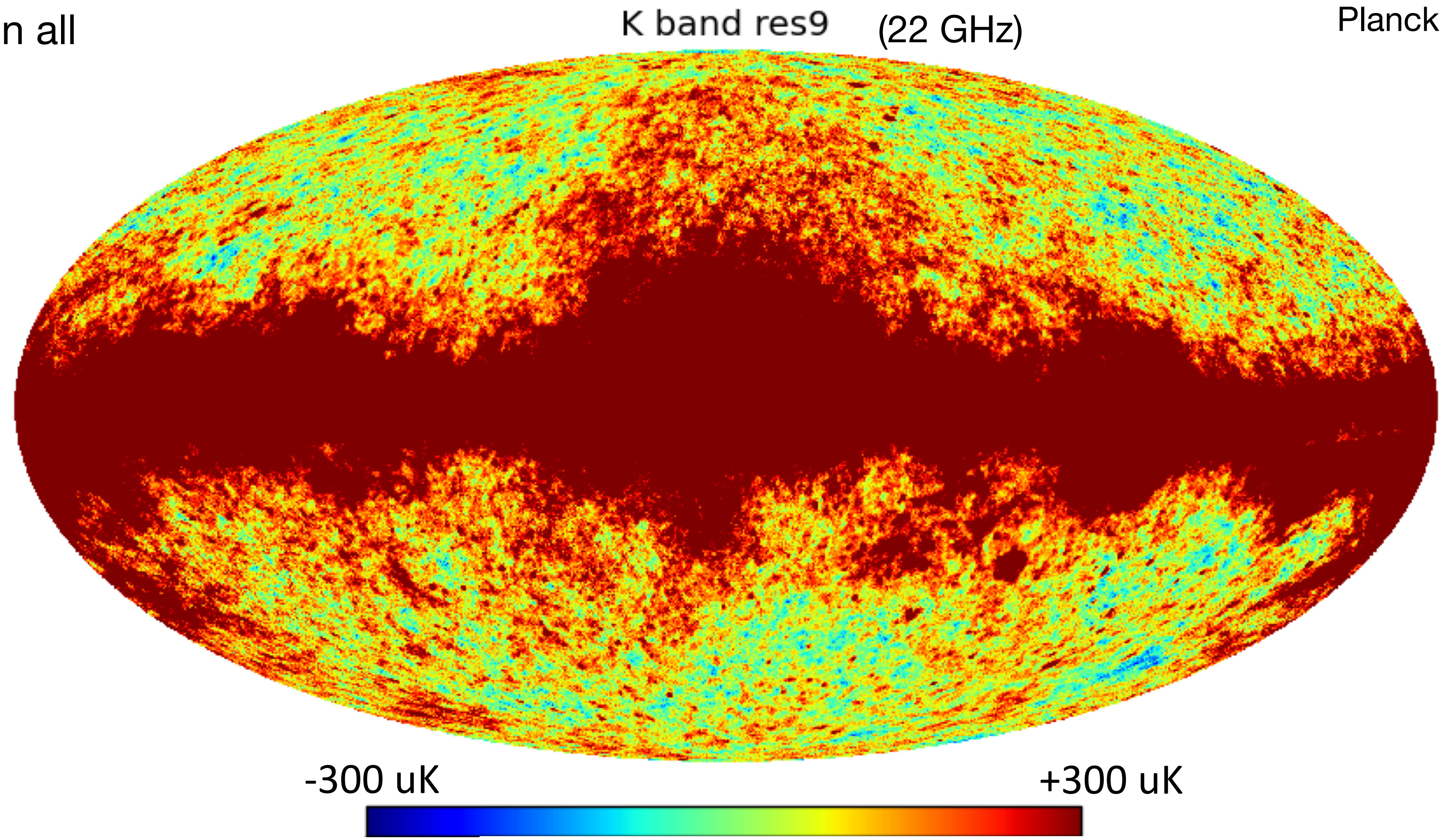
such as

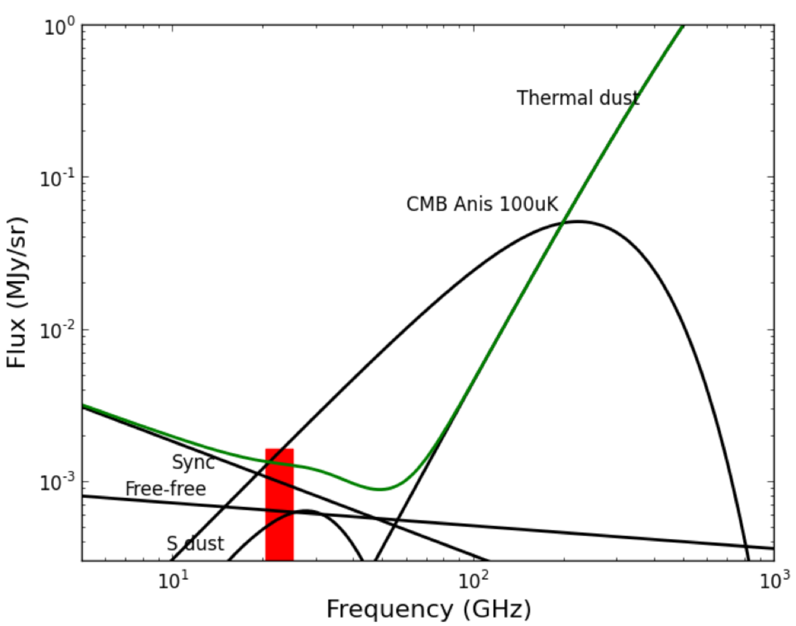




Note: CMB looks the same in all plots

Credit: S. Ferrara & Planck



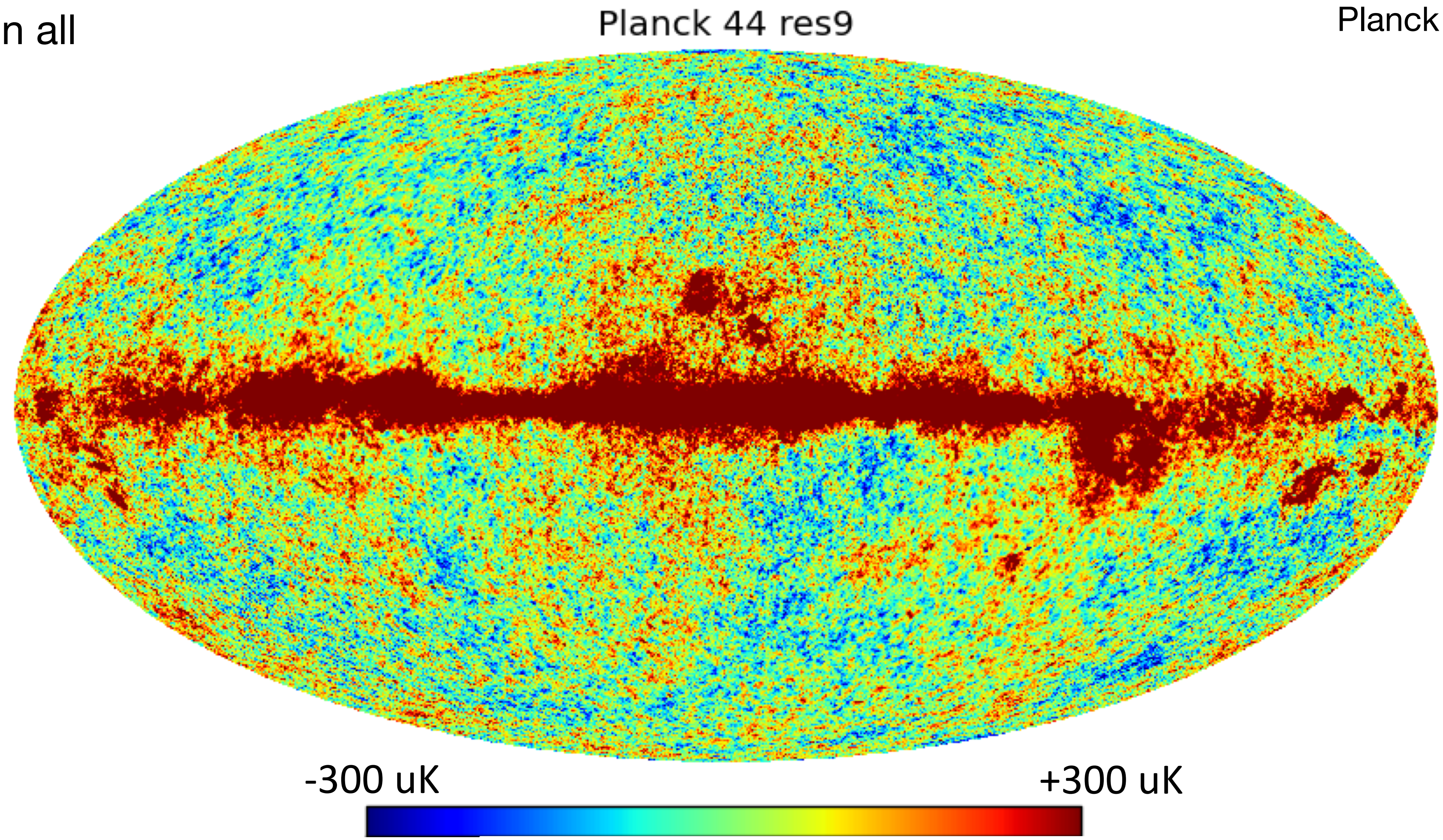


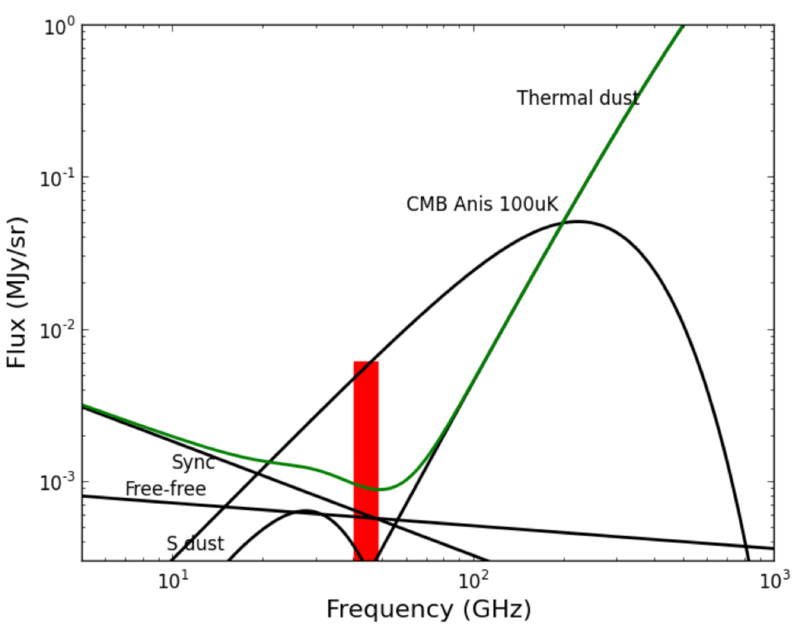
Separating the CMB and Milky Way:
A trip from low to high frequencies

Multiple frequency bands can distinguish CMB from the dust and synchrotron emission of the Milky Way

Note: CMB looks the same in all plots

Credit: S. Ferrara & Planck





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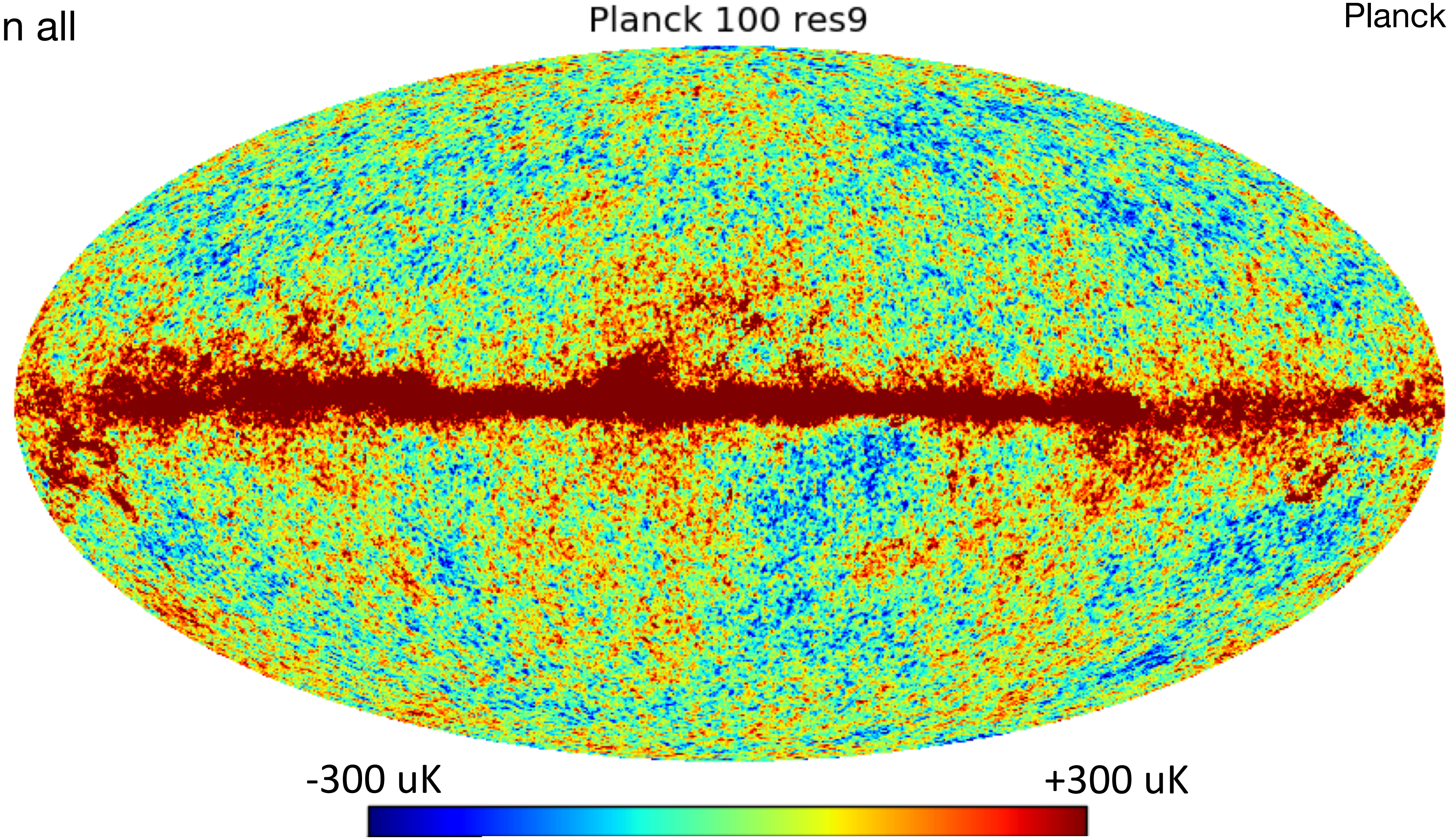

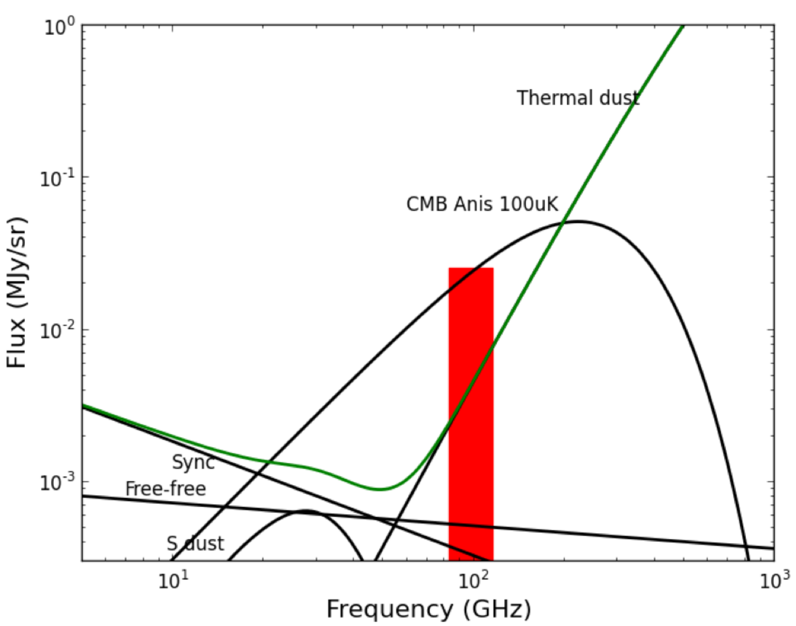

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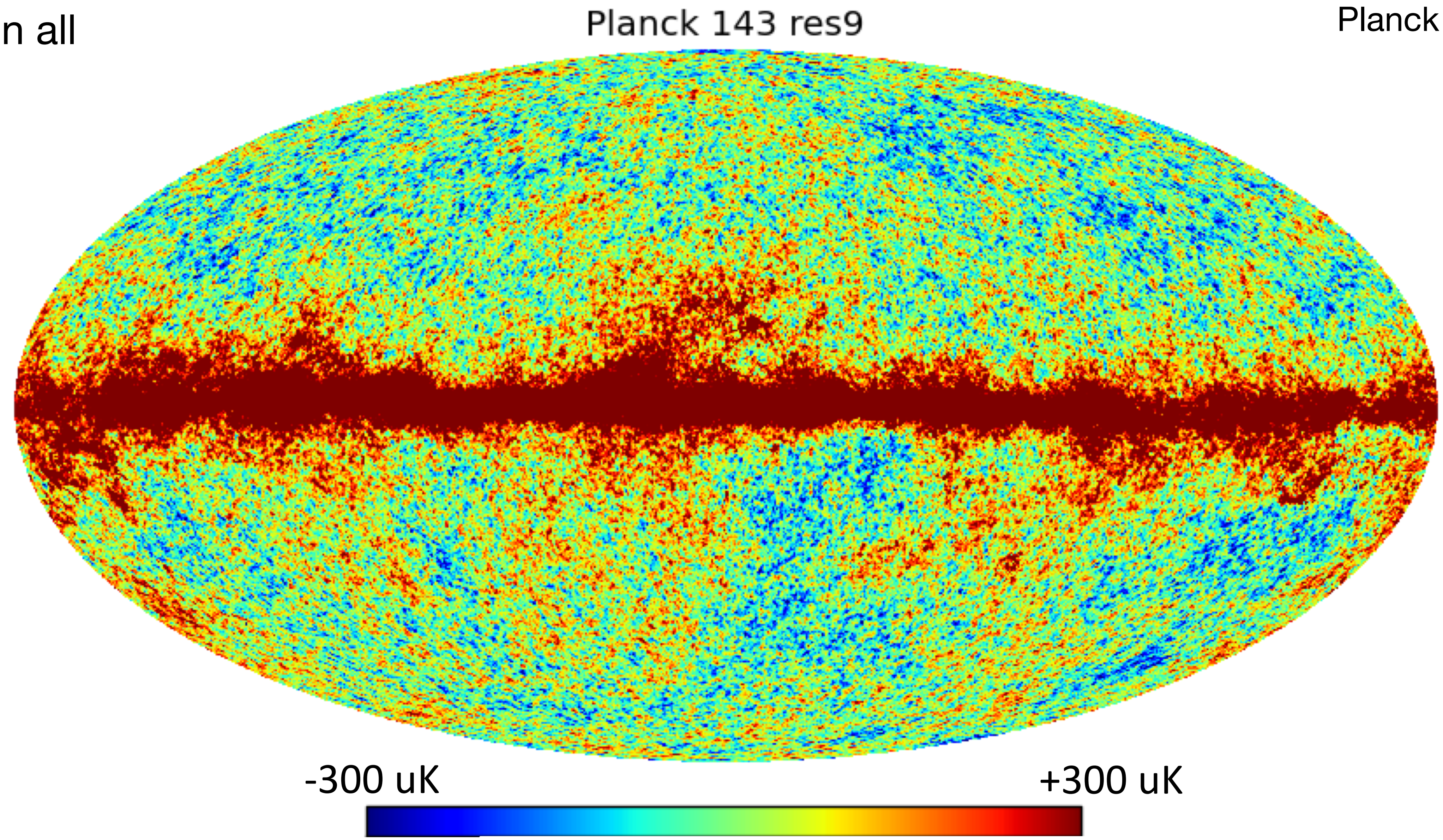

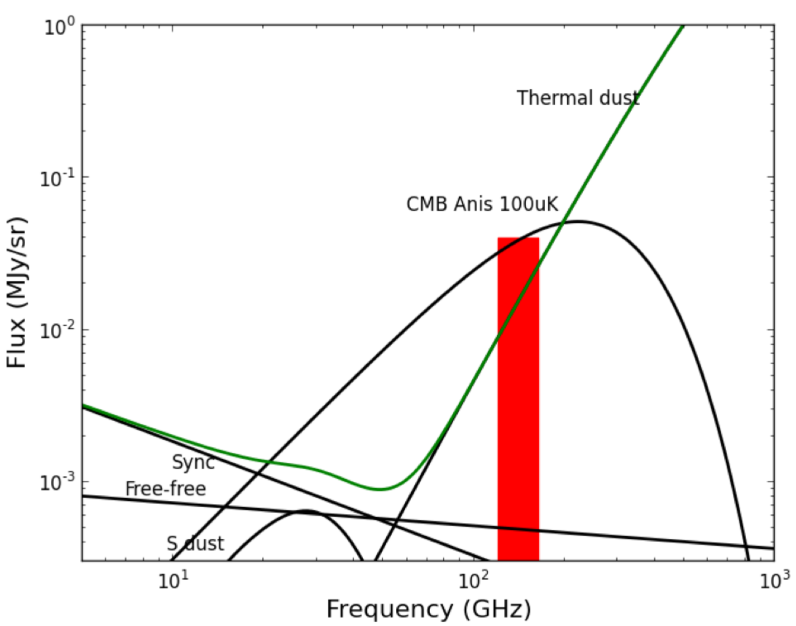

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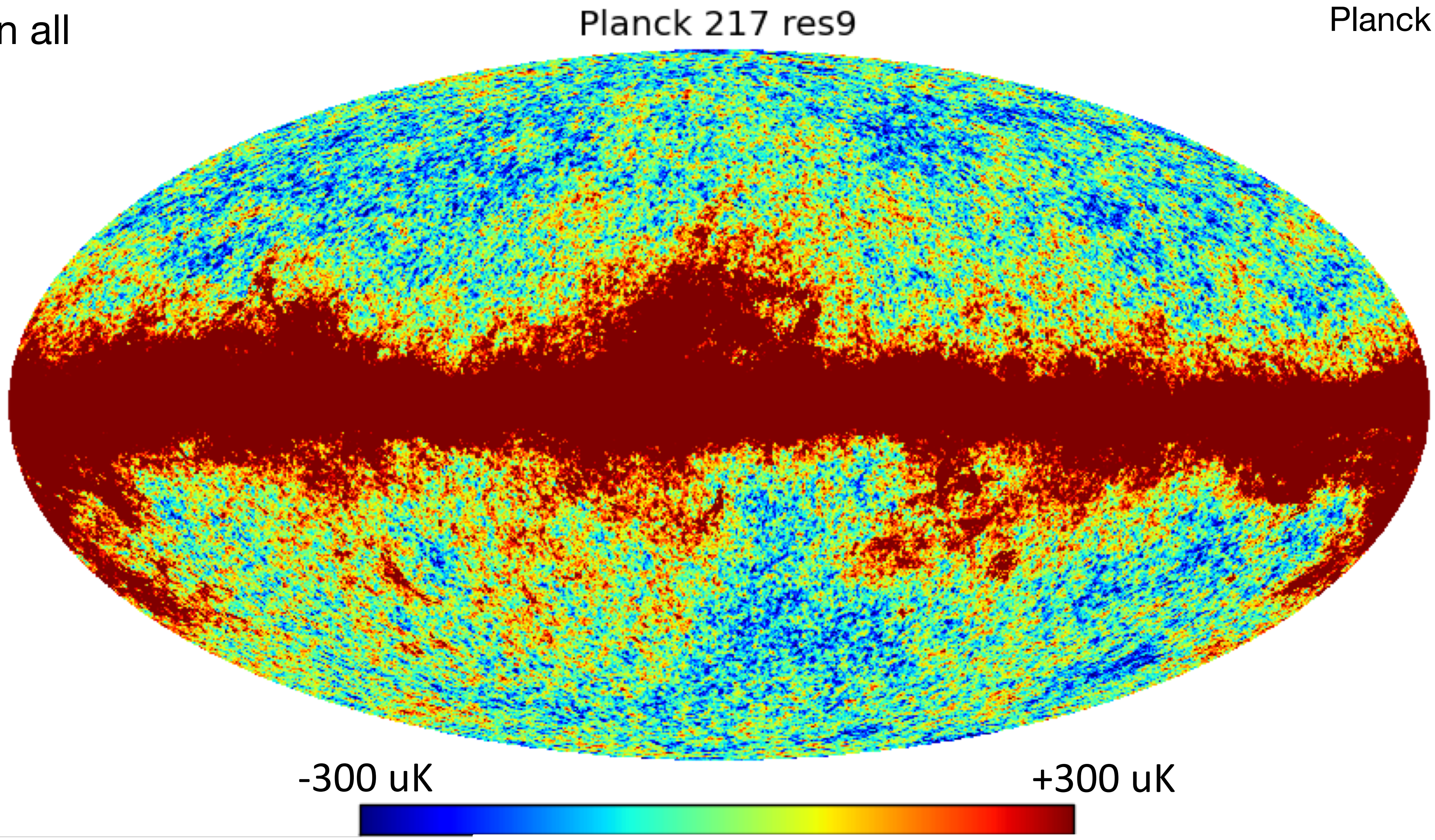

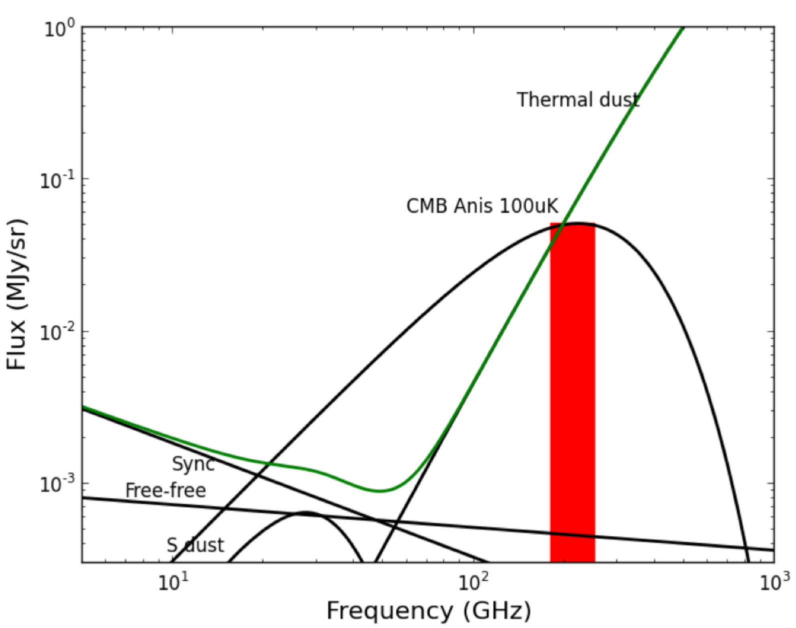

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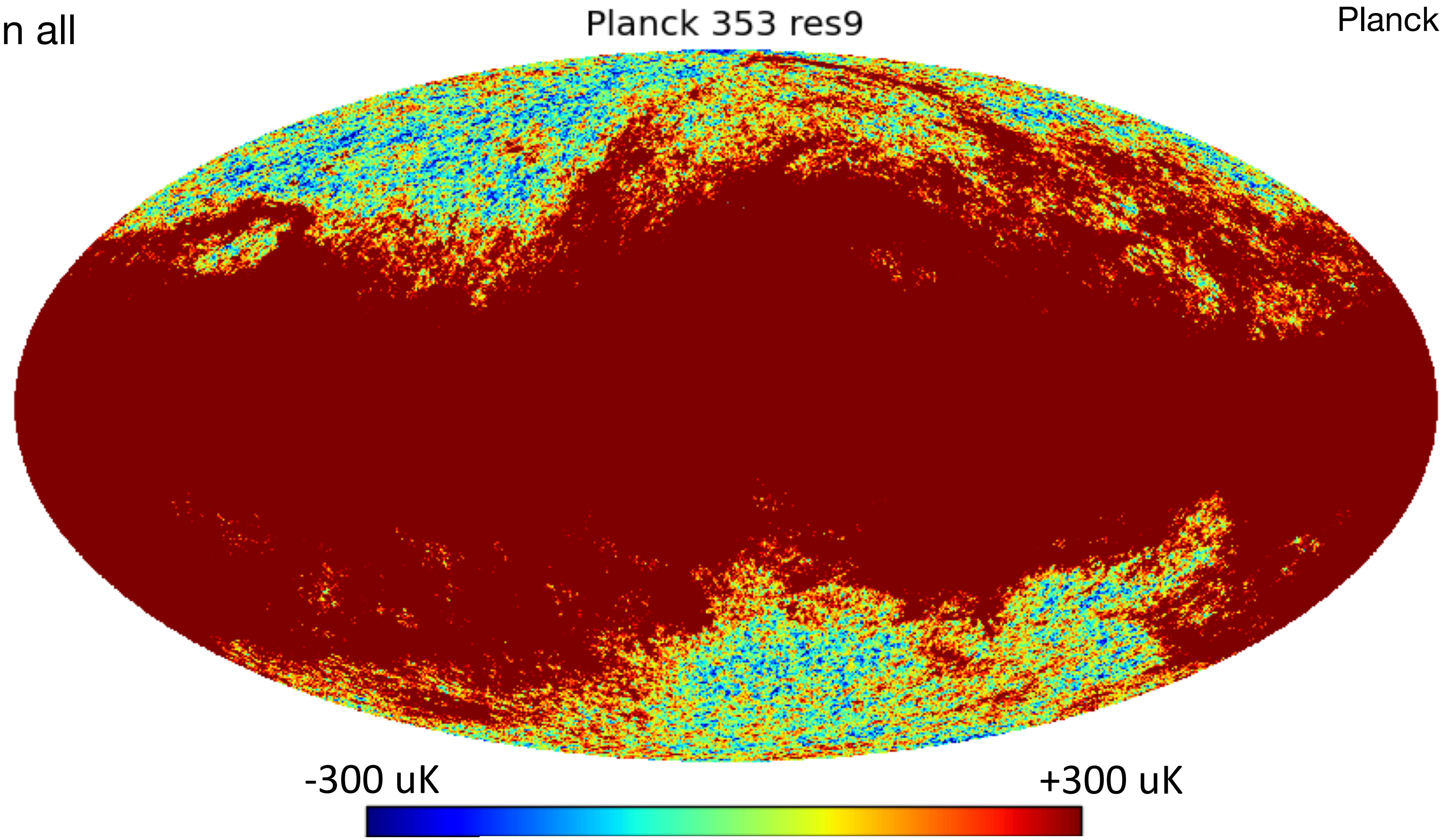
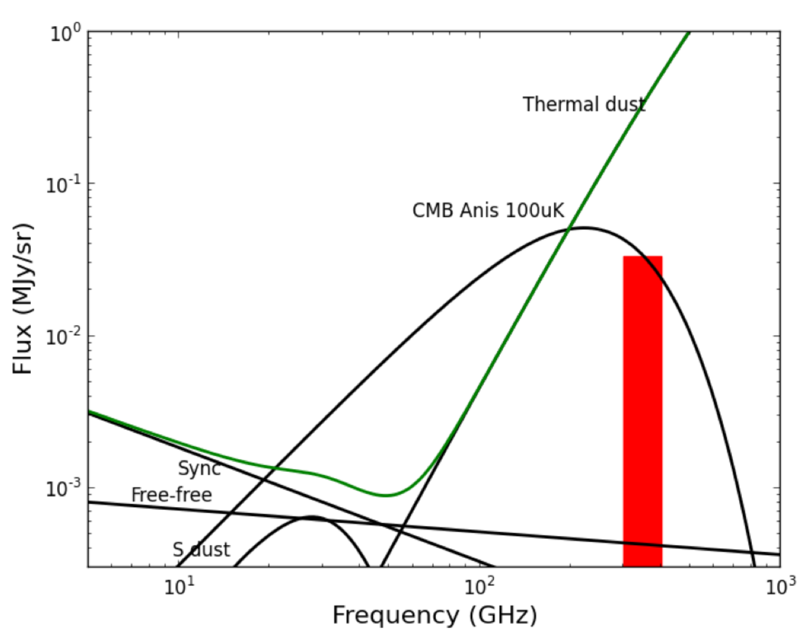




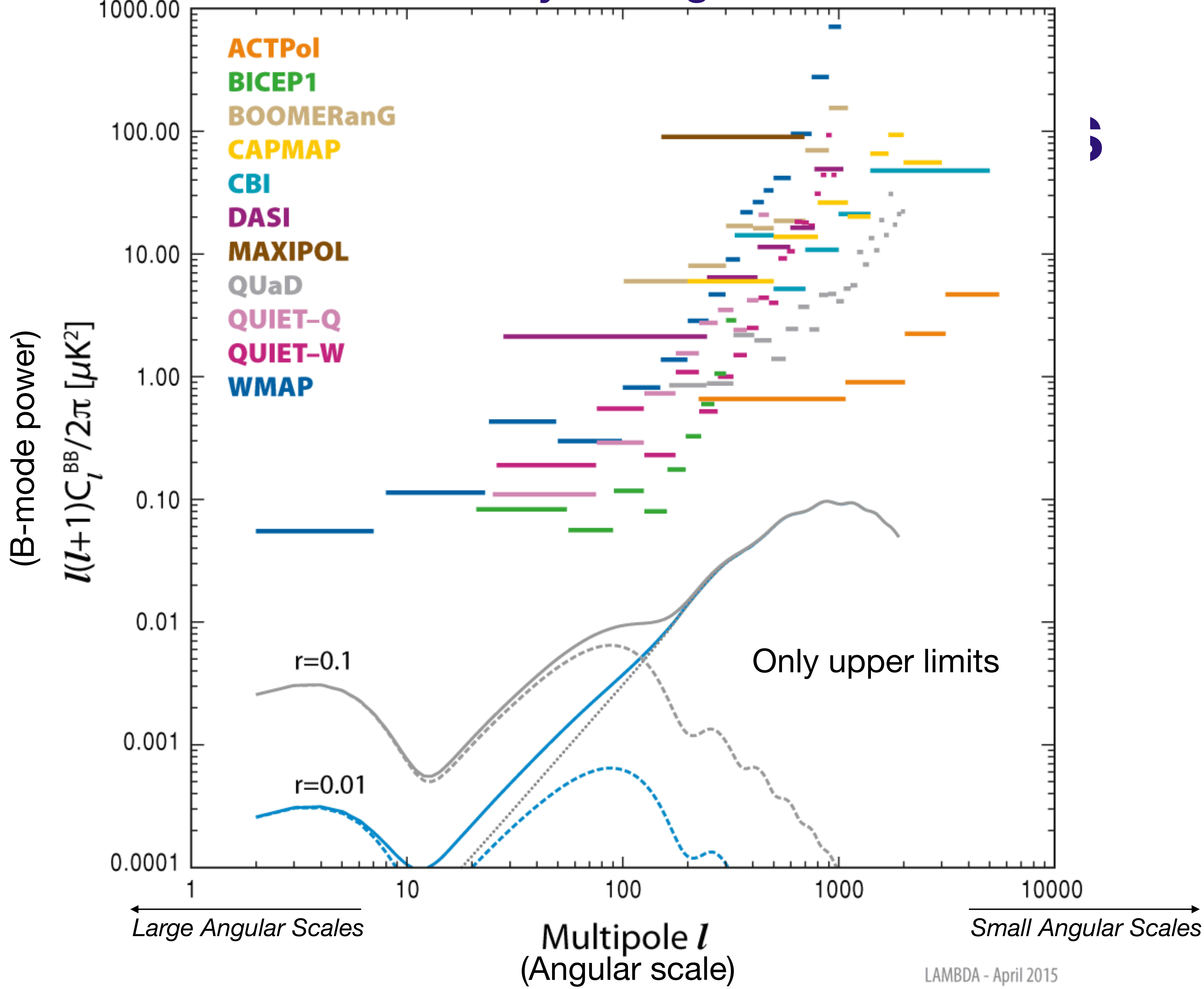
Separating the CMB and Milky Way:

A trip from low to high frequencies

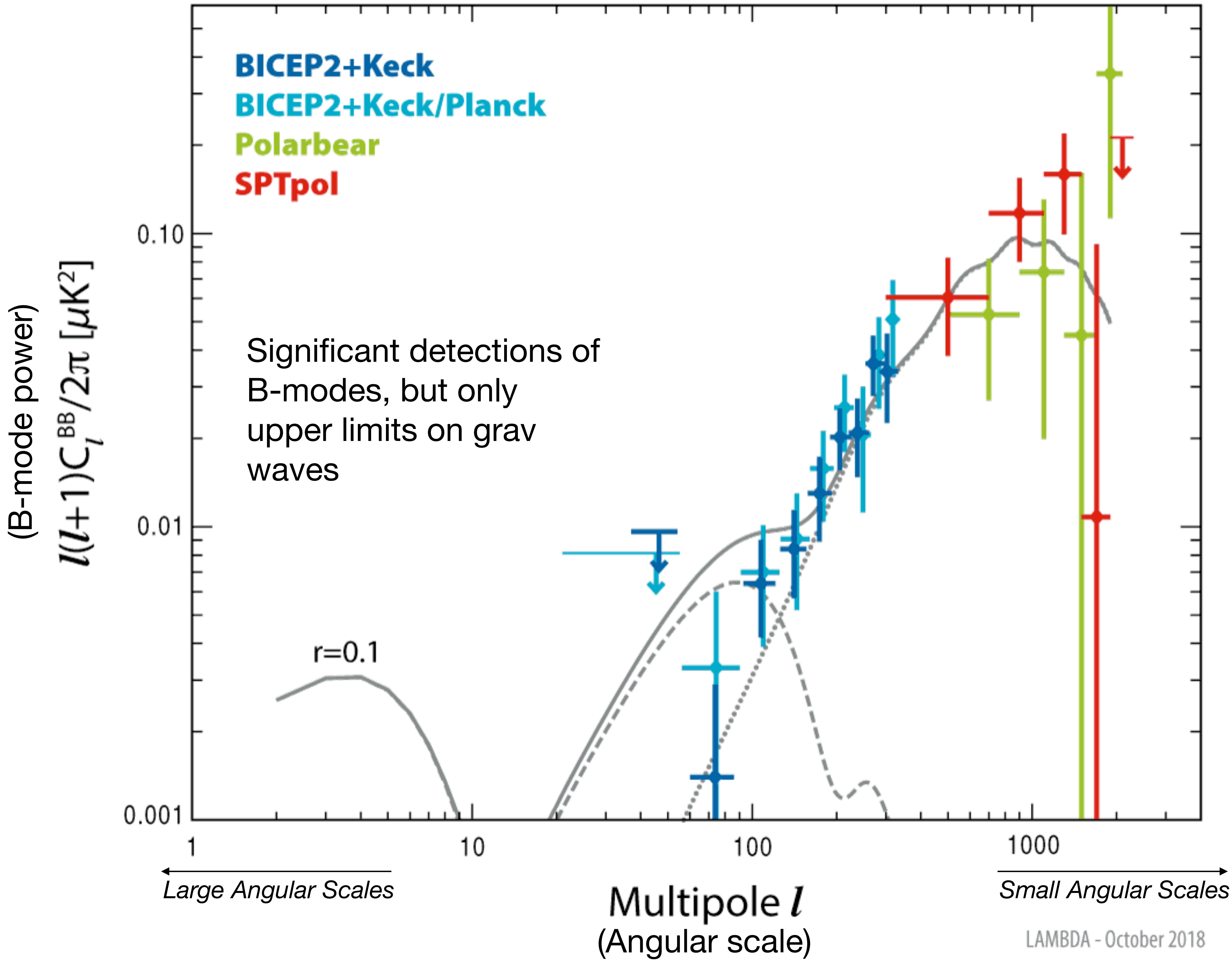
Takeaway: Foreground cleaning will be crucial. Even at the best frequency, far away from the plane of the Milky Way, galactic signals are much larger than r=0.001

Current state of play

Three years ago

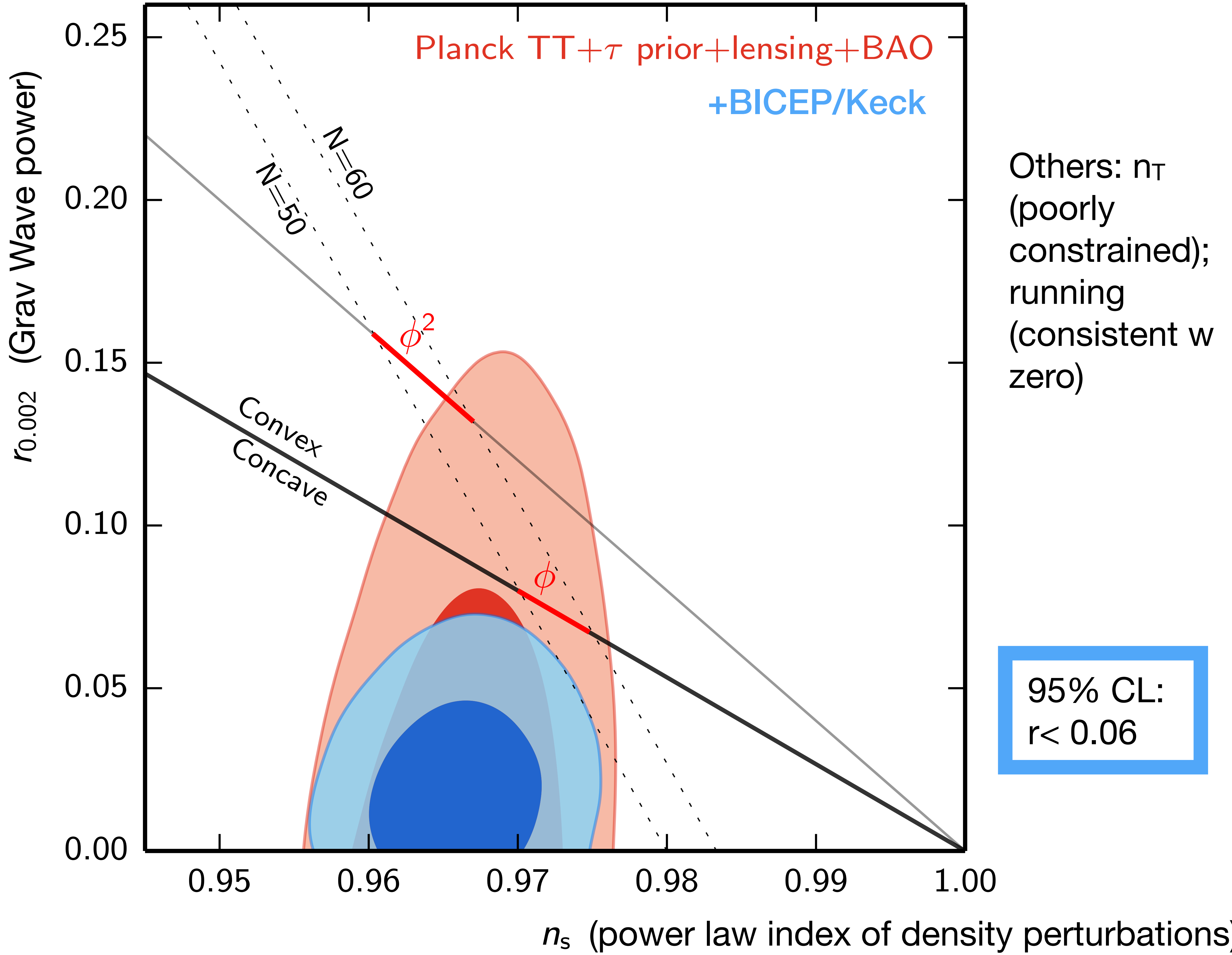


Today



BICEP2+Keck
BICEP2+Keck/Planck
Polarbear
SPTpol
Significant detections of B-modes, but only upper limits on grav waves
r=0.1
0.10
0.01
0.001
1
10
100
1000
(B-mode power)
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
Large Angular Scales
Small Angular Scales
Multipole l
(Angular scale)
LAMBDA - October 2018

Observational constraints on Inflation Parameters

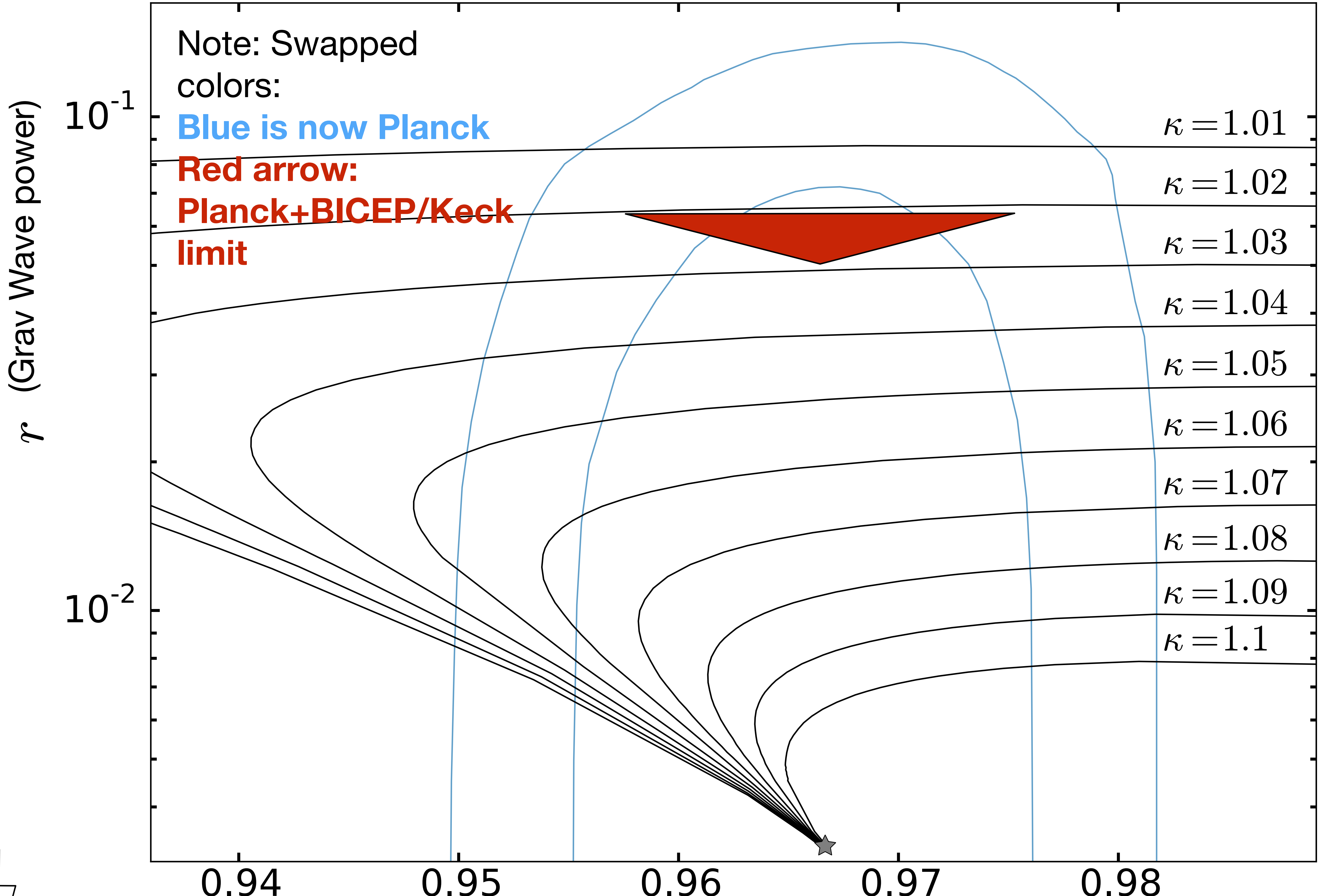


Others: n_T (poorly constrained); running (consistent w zero)

95% CL: r< 0.06

Credit: Rubio 2018

Applied to Higgs Inflation



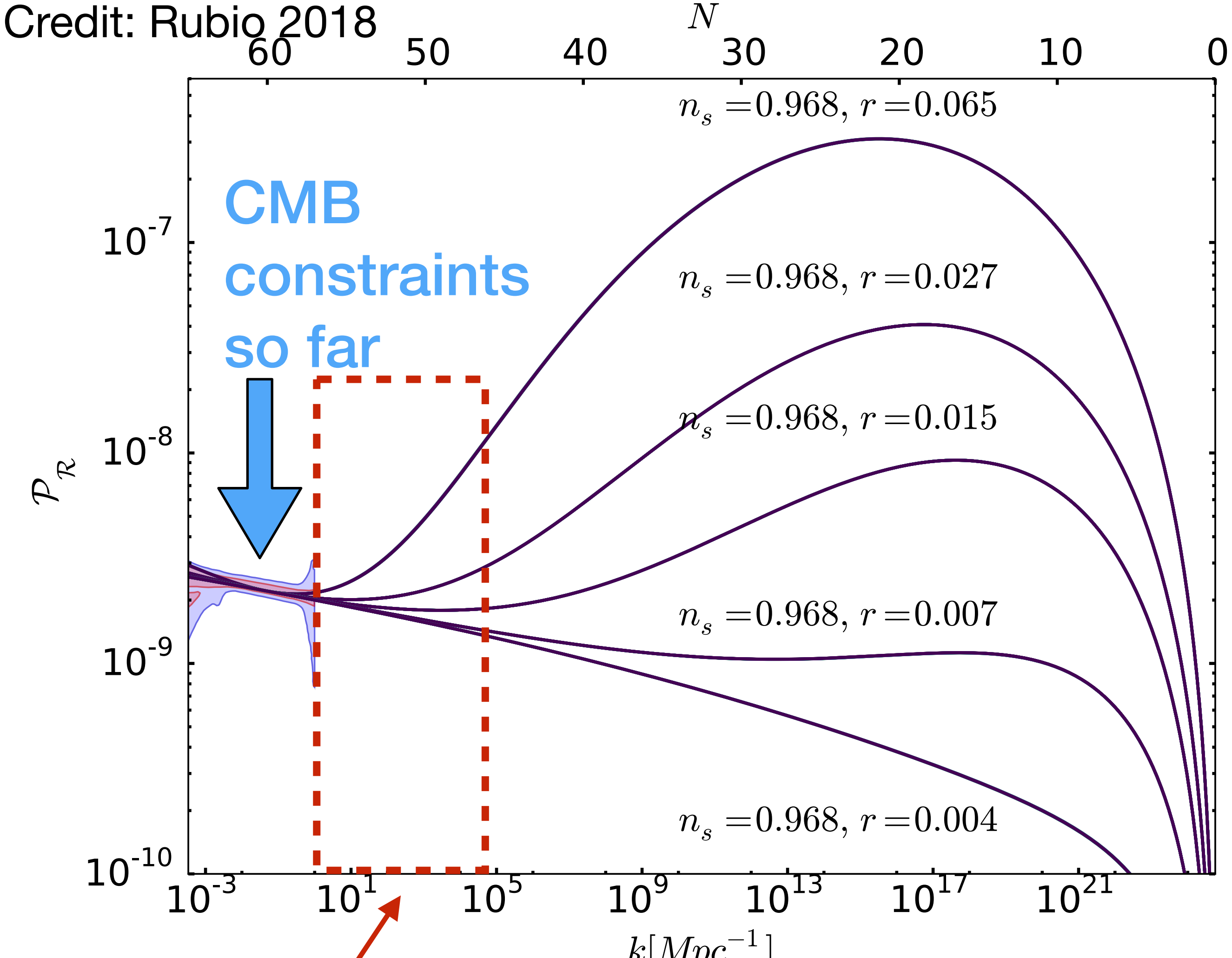
NB: Will reach down here in next 5-10 years

Conclusions

- Next decade: 30-fold improvement in searches for inflationary gravitational waves
  - More detectors
  - Careful treatment of galactic foregrounds
  - Removing grav lensing noise

- Also other science: neutrinos, dark energy, dark matter, …

Credit: Rubio 2018



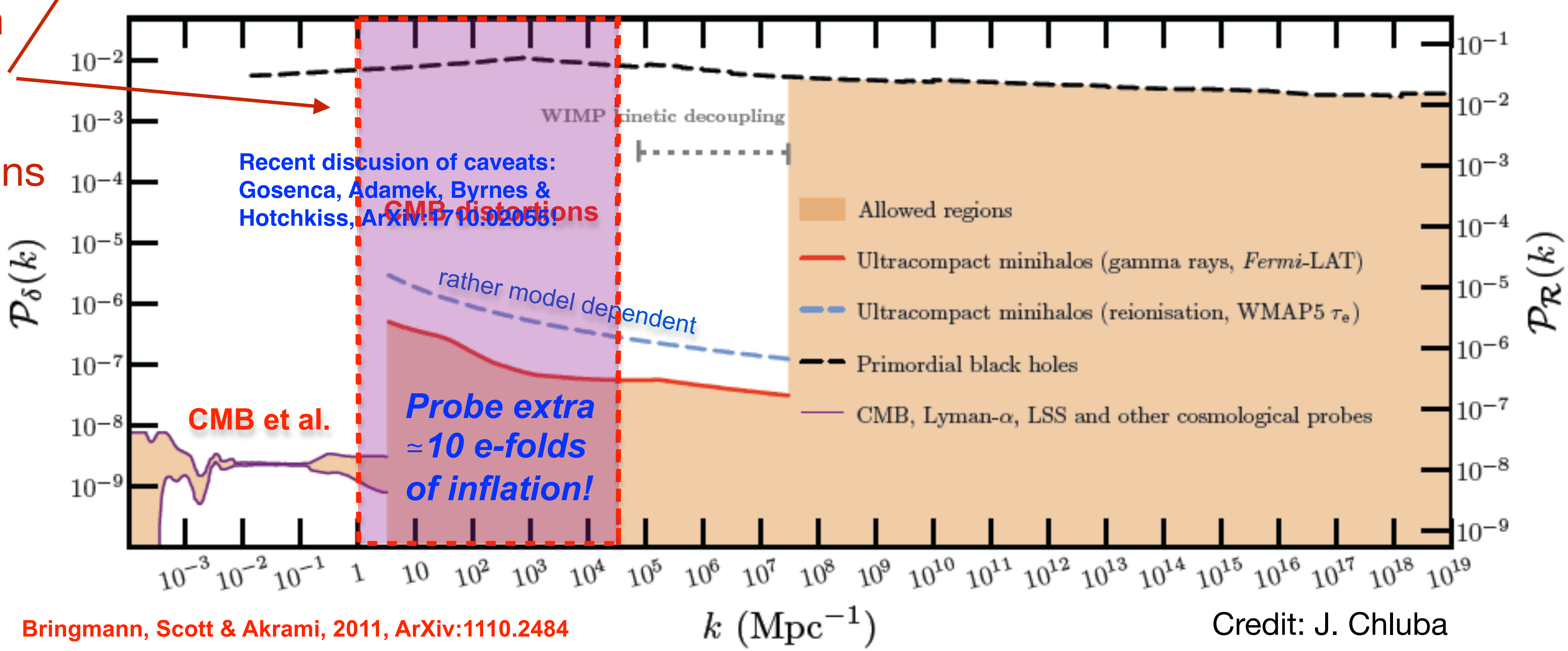
Beyond r/n_s

Higgs inflation produces more complex power spectra

- **CMB Spectral distortions can probe smaller scales**

- **Need a satellite: LiteBIRD; PIXIE**

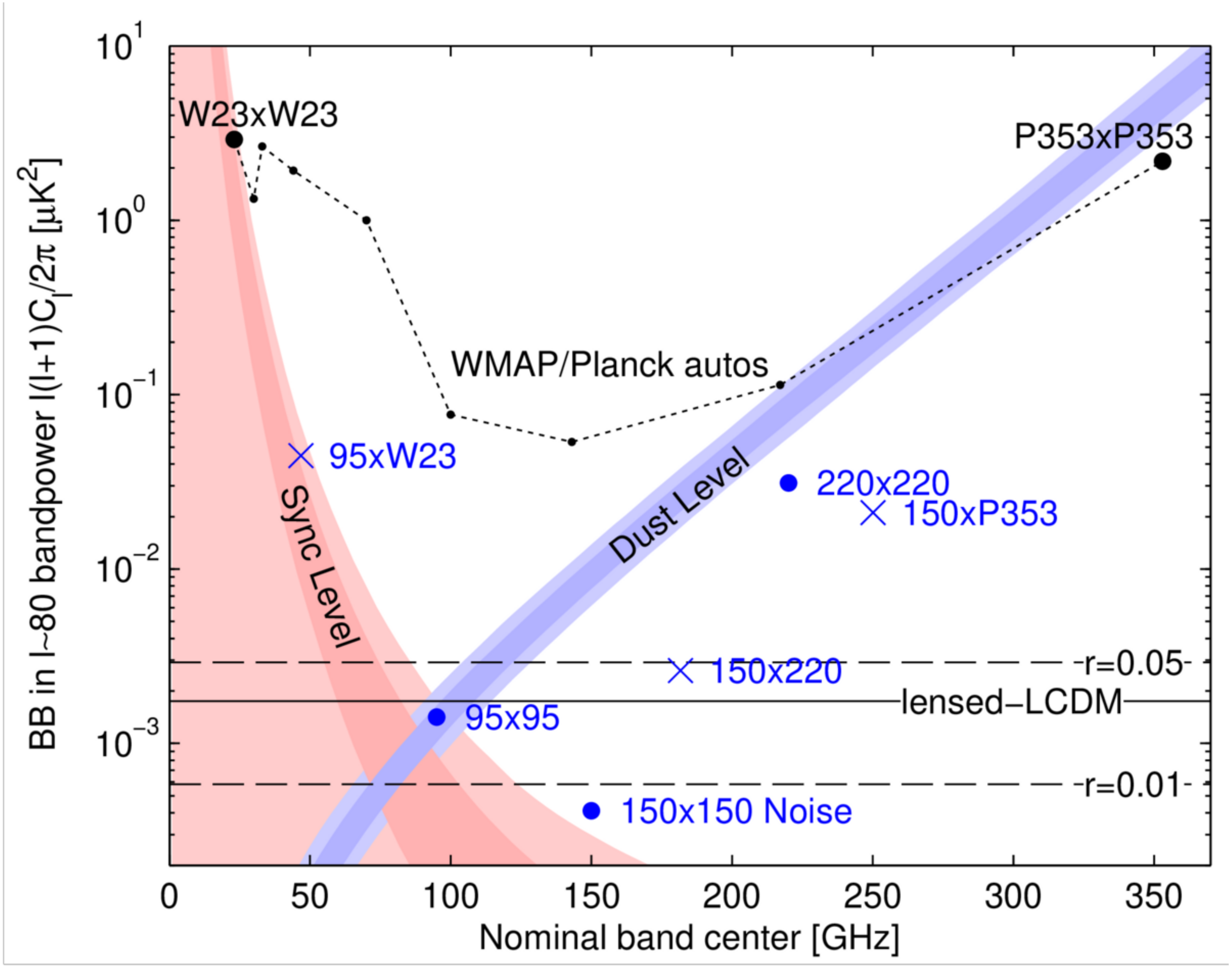
Addition from spectral distortions



Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

Credit: J. Chluba

Credit: The Keck Array
and BICEP2
Collaborations, 2018



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