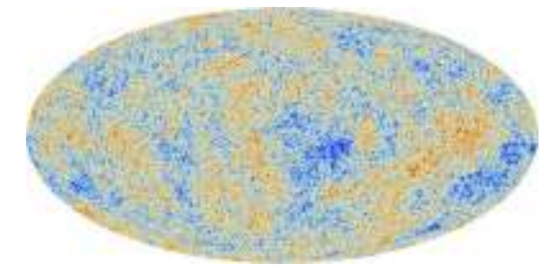
News from BICEP/Keck Array CMB telescopes

Zeeshan Ahmed
KIPAC, SLAC National Accelerator Laboratory

Pi Day, 2016
Southern Methodist University

Outline



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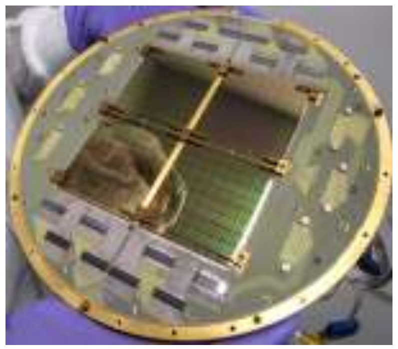

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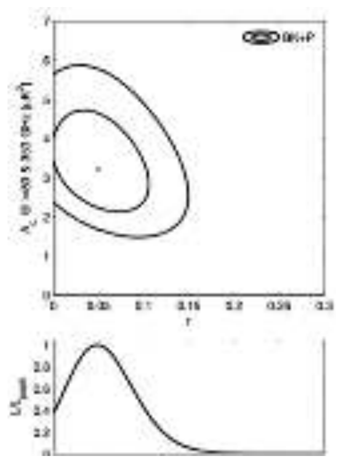
Detectors, Receivers, Site, Observing



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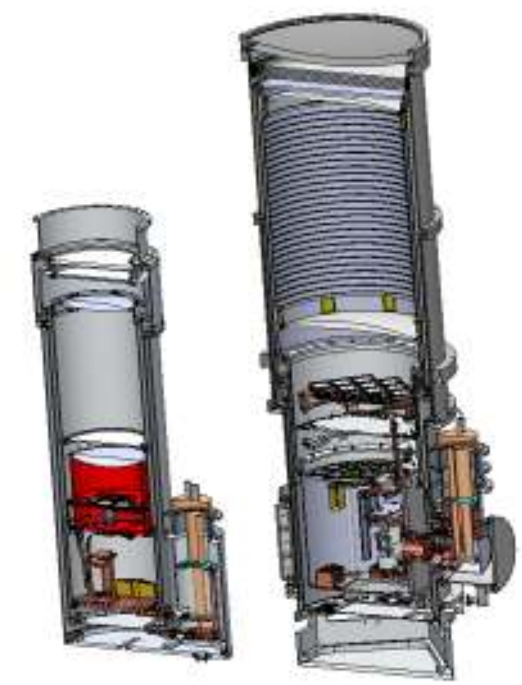

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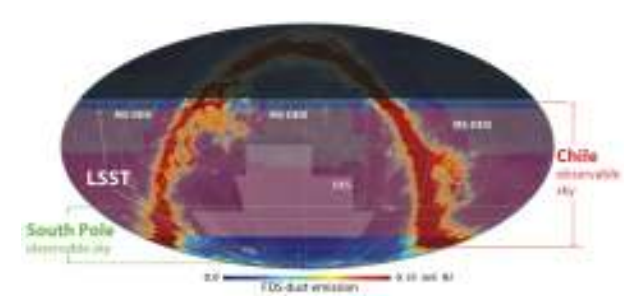
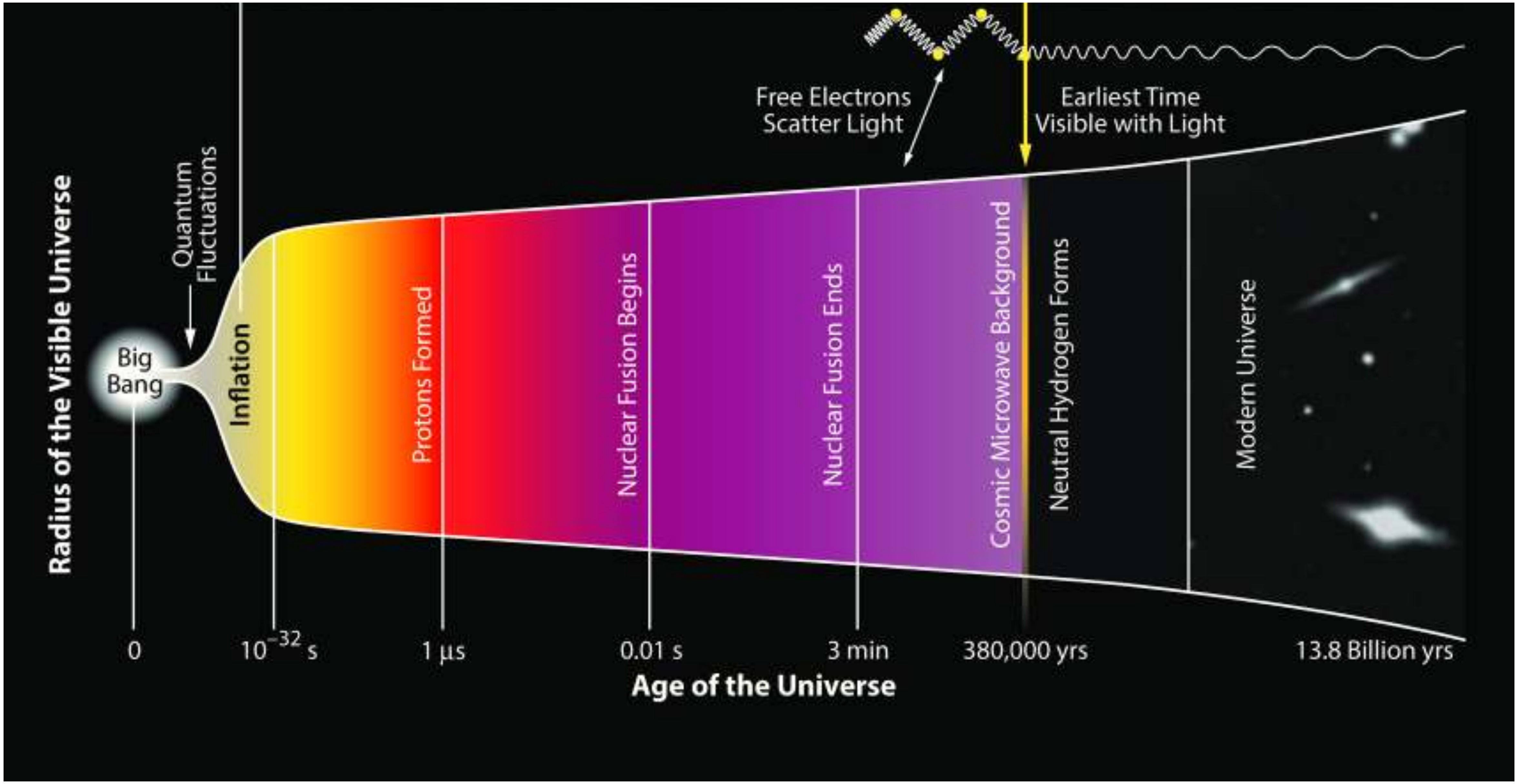


The Story of the Universe



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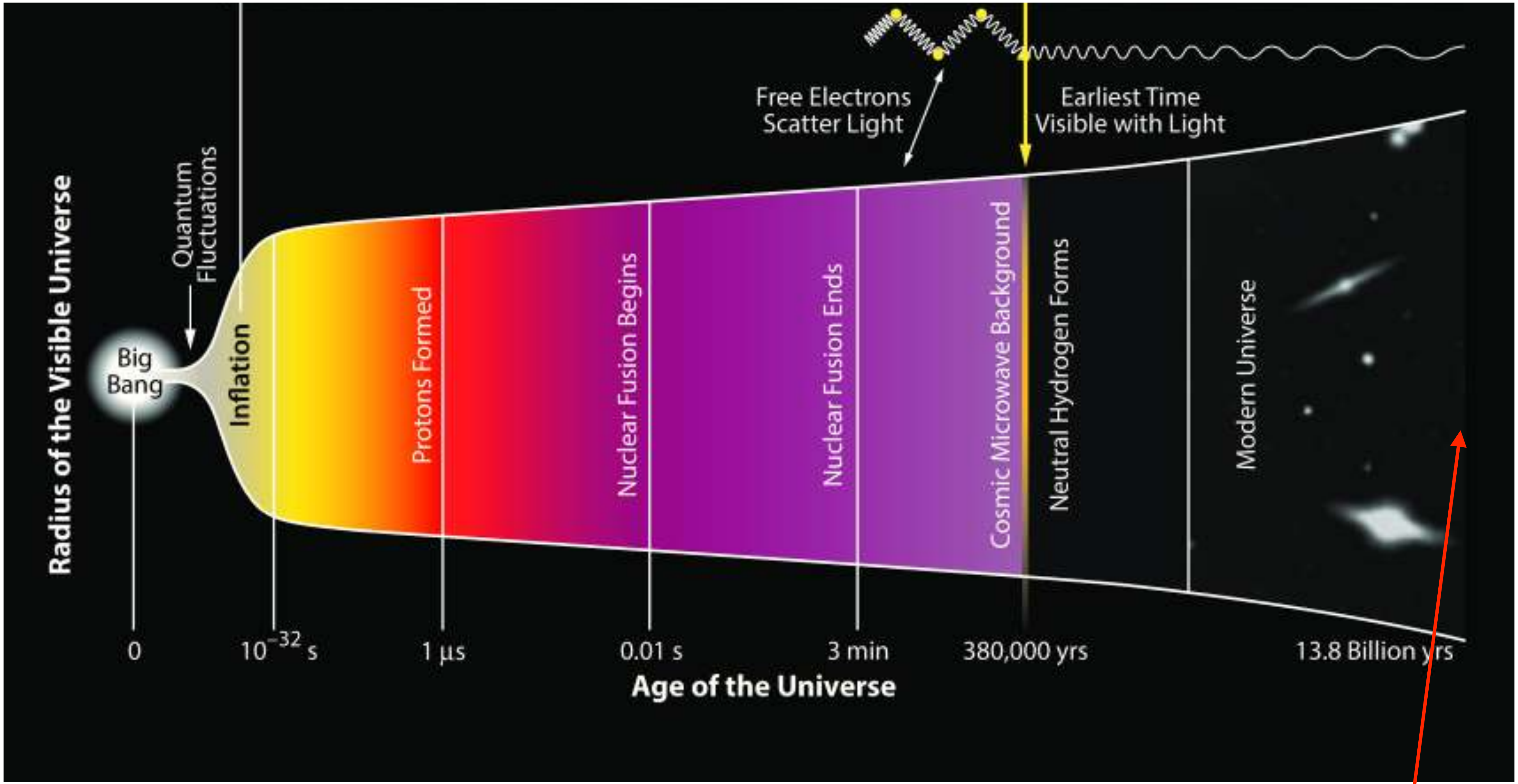

We are here. Universe appears to be expanding!

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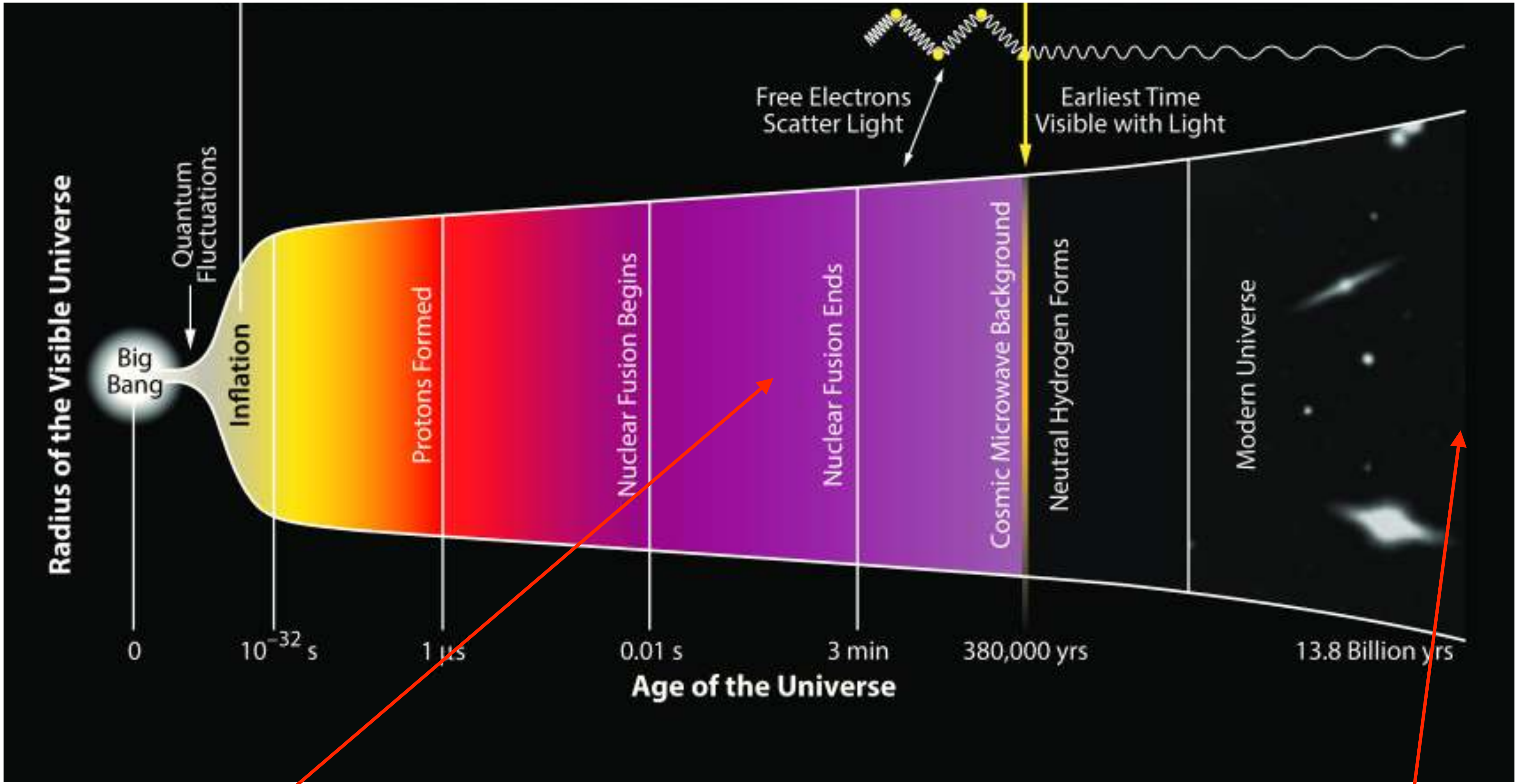

Light element abundances suggest hot, dense conditions very early on

We are here. Universe appears to be expanding!

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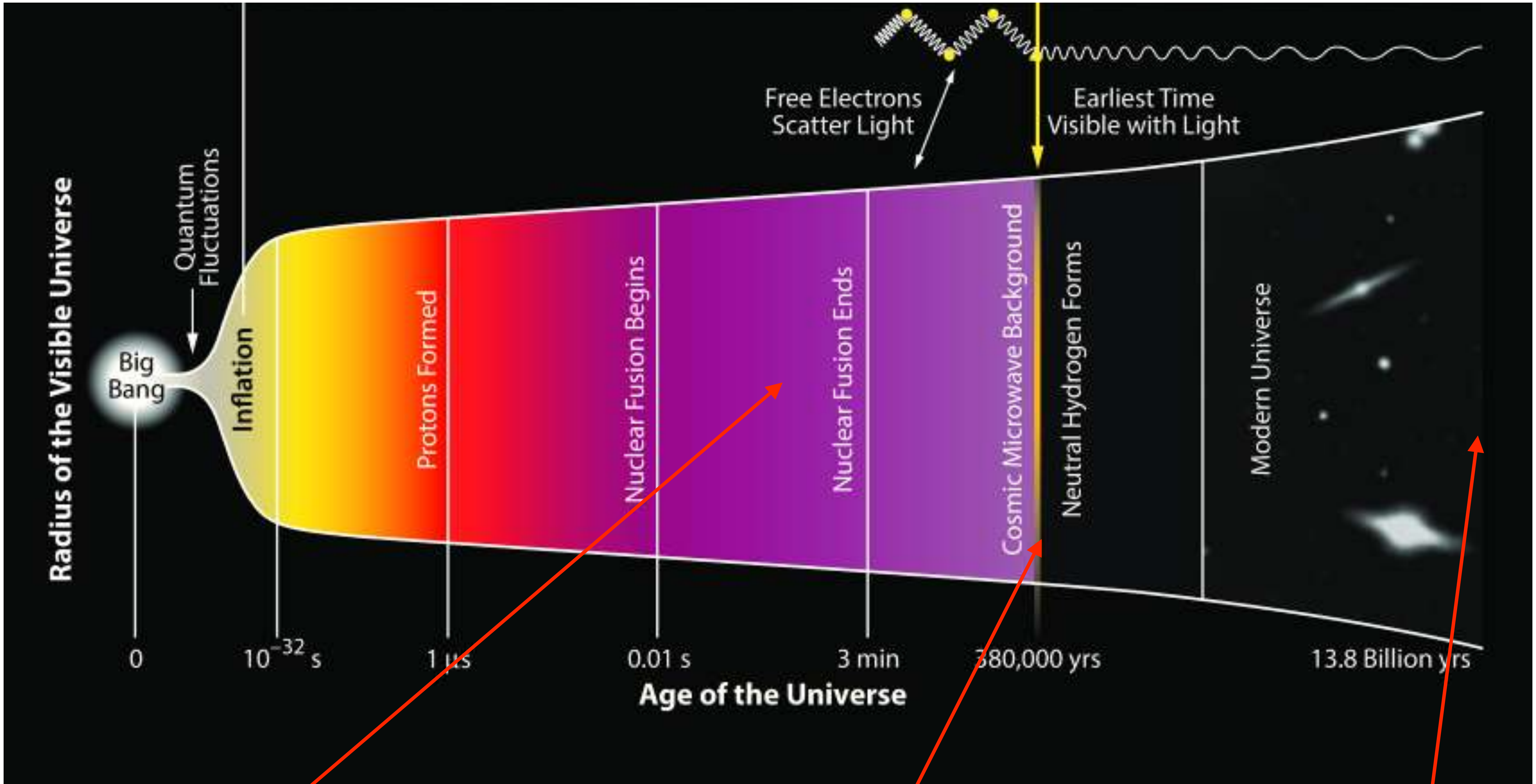


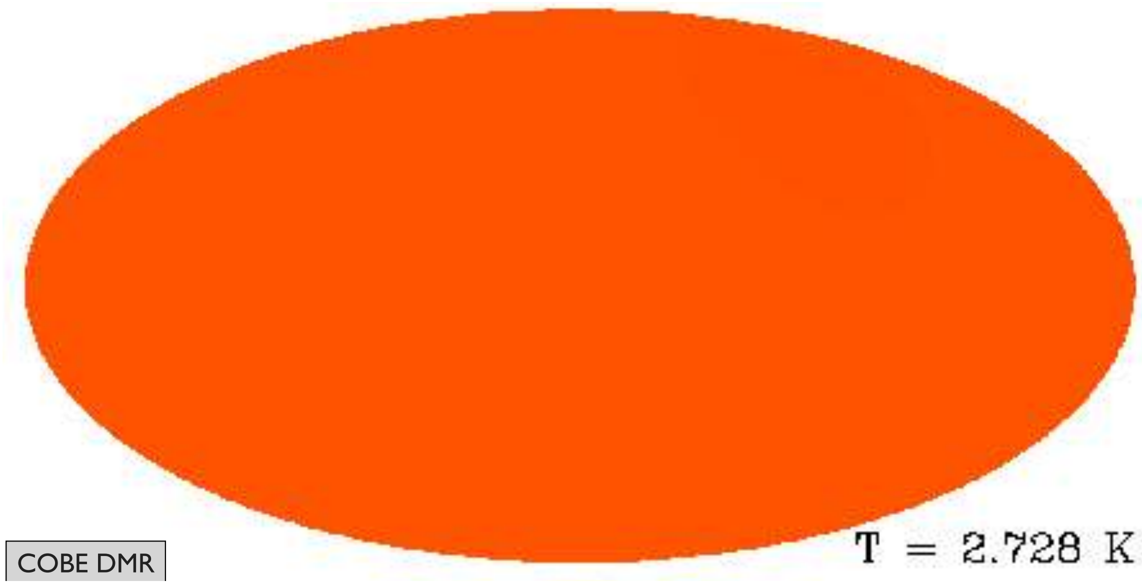
Light element abundances suggest hot, dense conditions very early on

Oldest direct light comes from here; blackbody relic of a small, hot, dense Universe

We are here. Universe appears to be expanding!

Cosmic Microwave Background (CMB)

2.7K blackbody, homogenous, isotropic..



COBE DMR

Cosmic Microwave Background (CMB)

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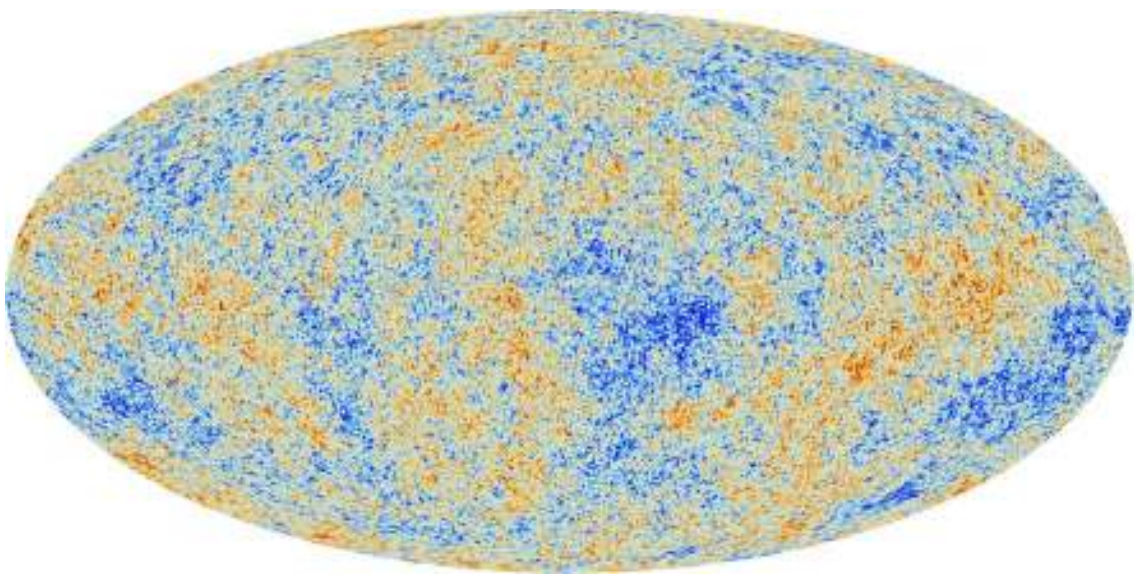
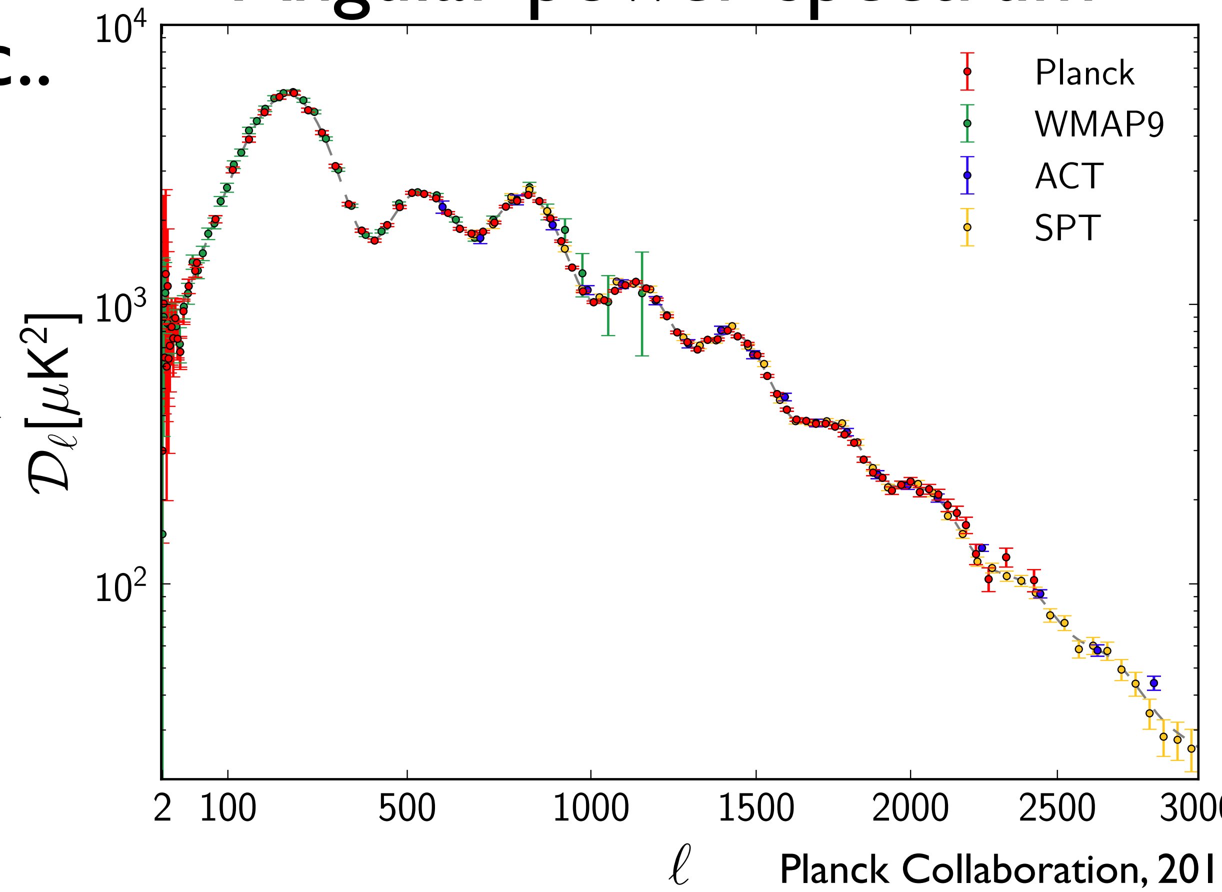
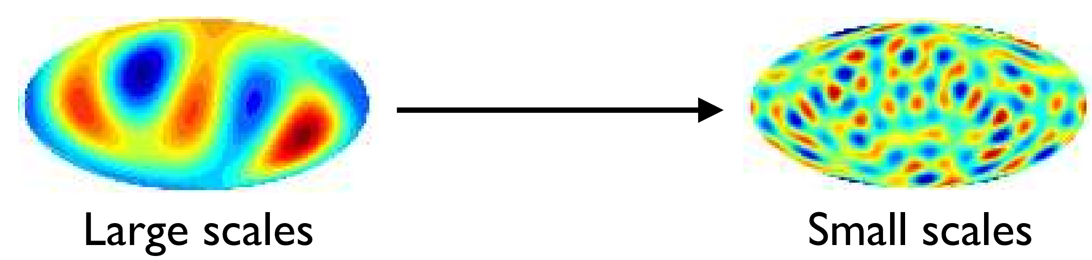


.. anisotropies only at ~10^{-5}

Angular power spectrum



Planck Collaboration, 2013



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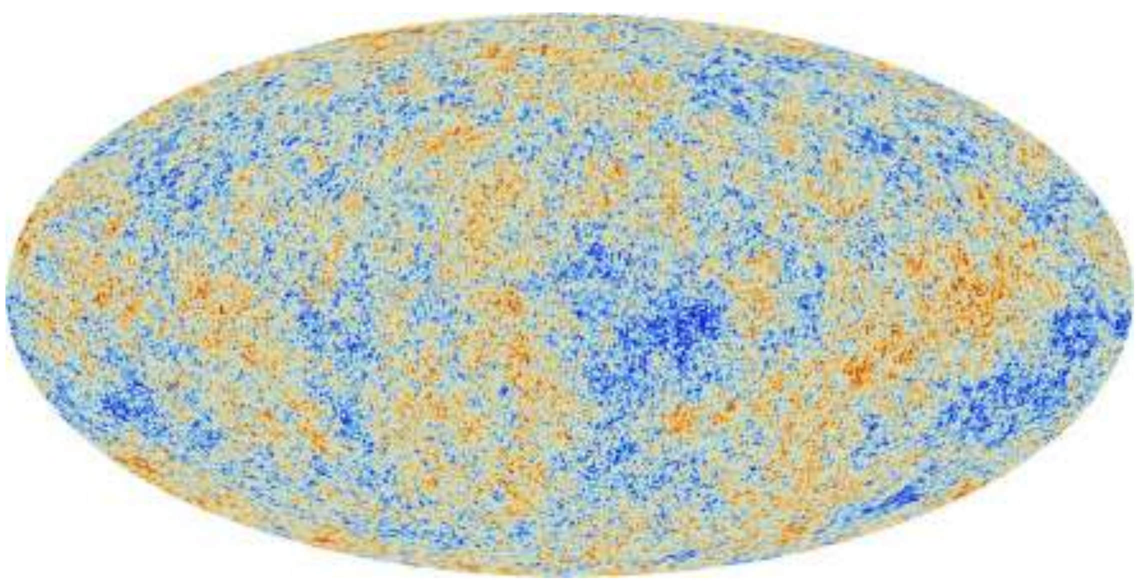

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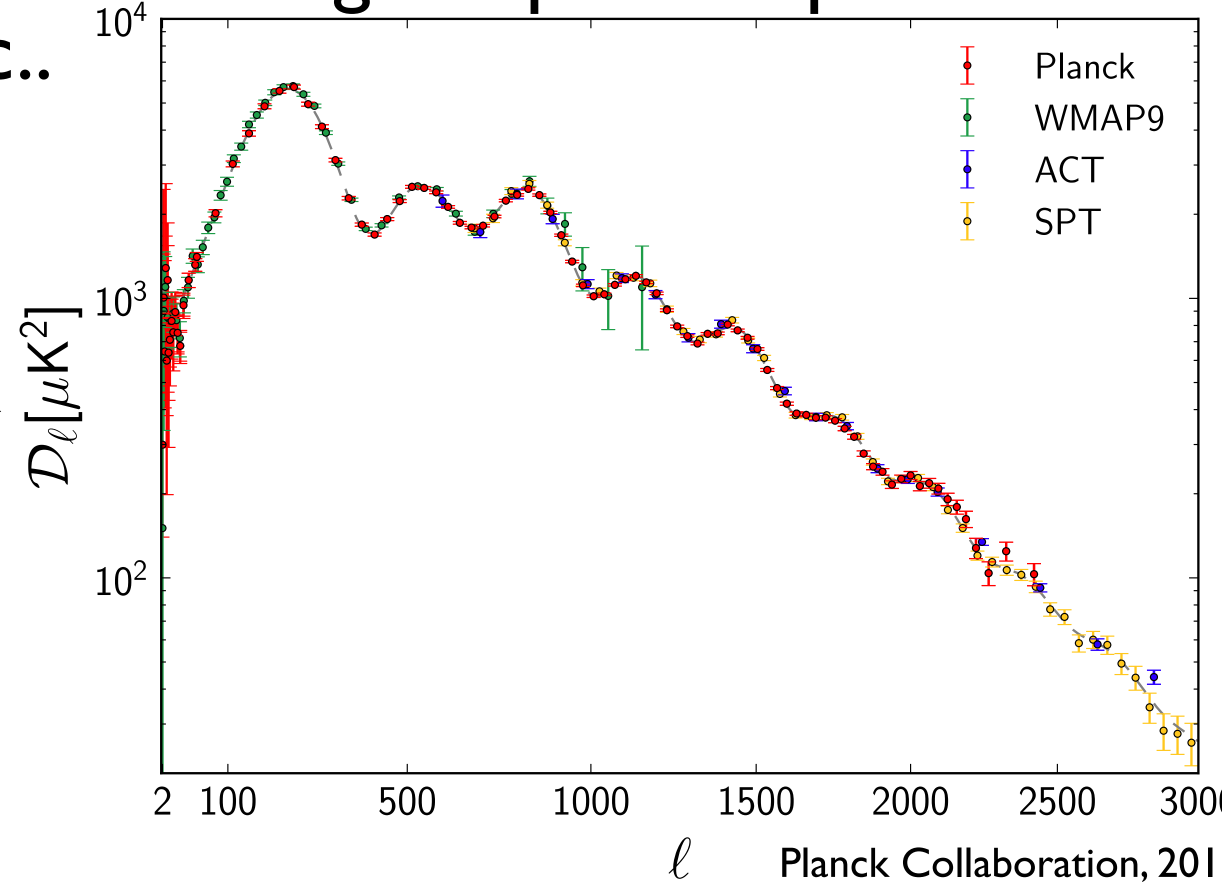

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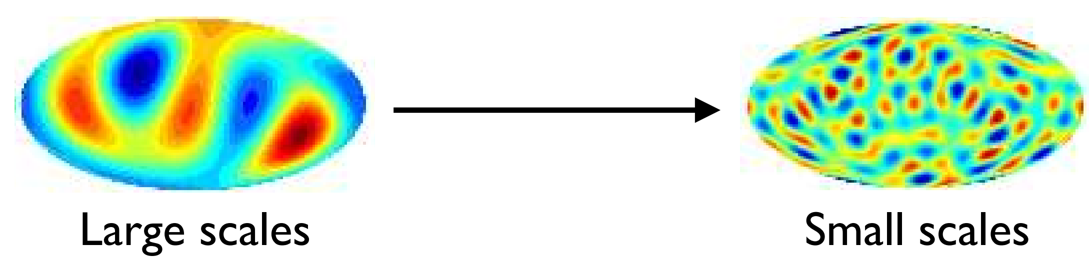
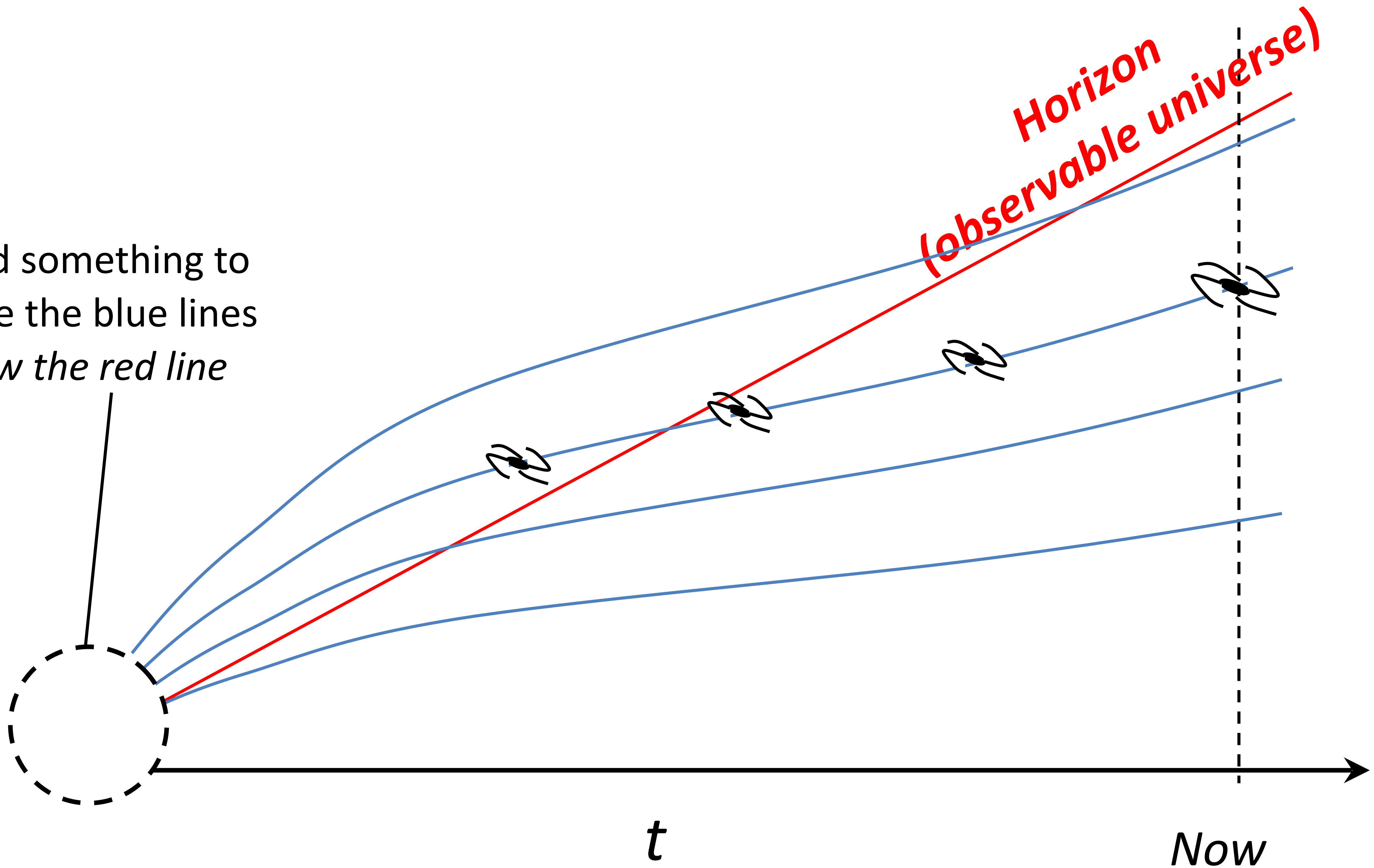


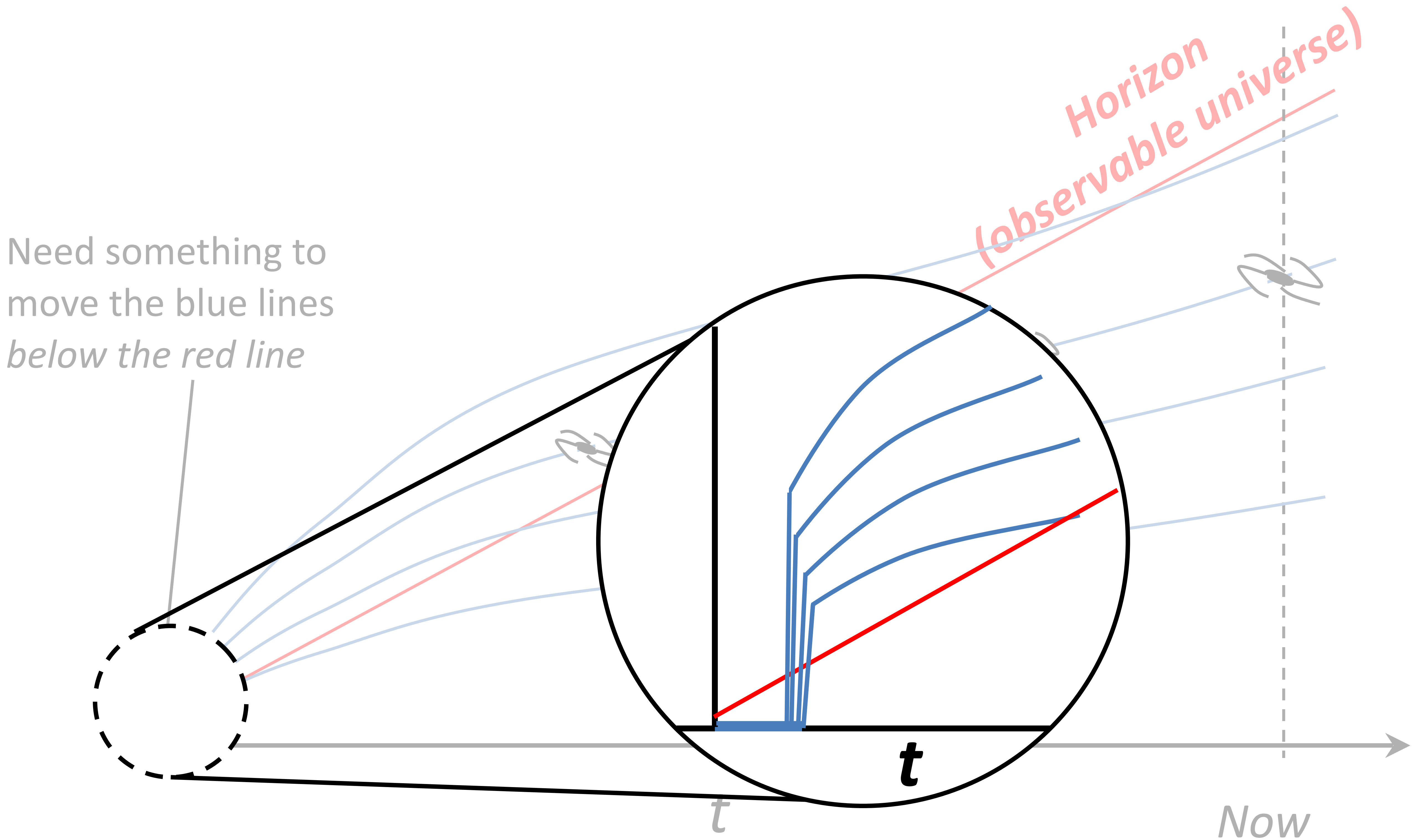
- CMB, SN, BAO, clusters = LCDM
- How so homogenous? < degree scales should be causally disconnected!
- What seeds structure and T anisotropies?

Look at horizon problem heuristically..

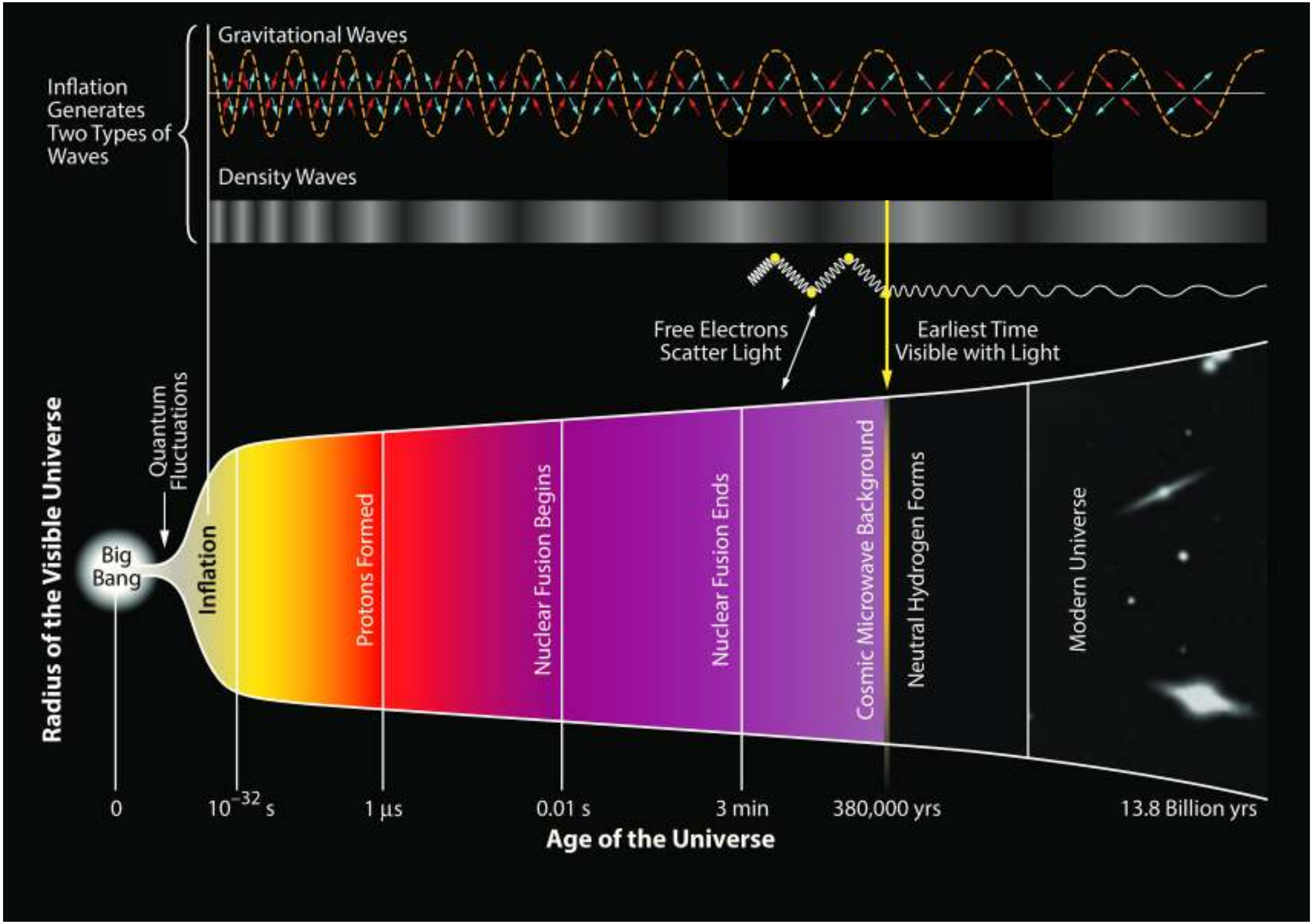
Need something to move the blue lines *below the red line*



Inflation: The Real Big Bang



Inflation generates scalar and tensor perturbations



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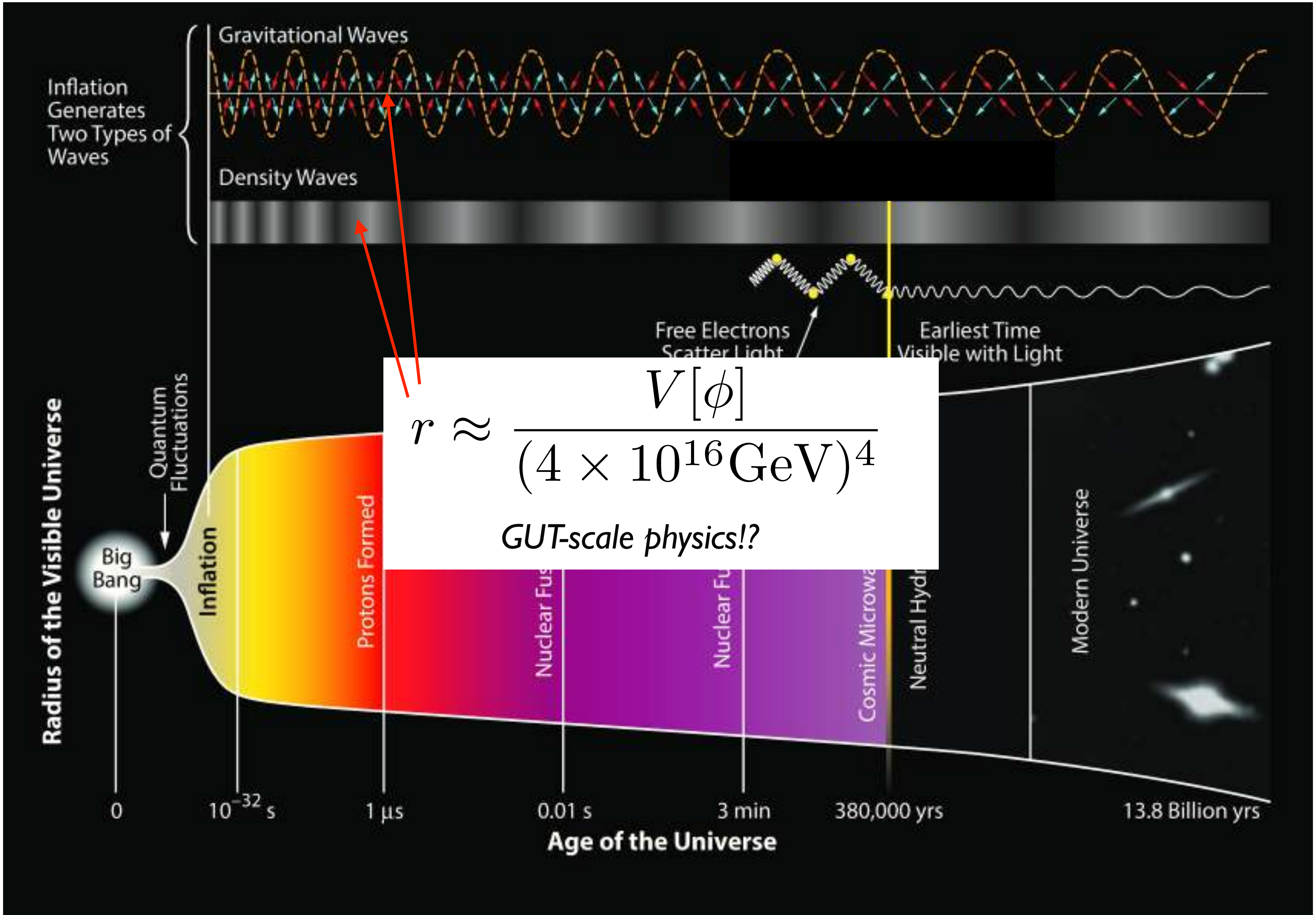
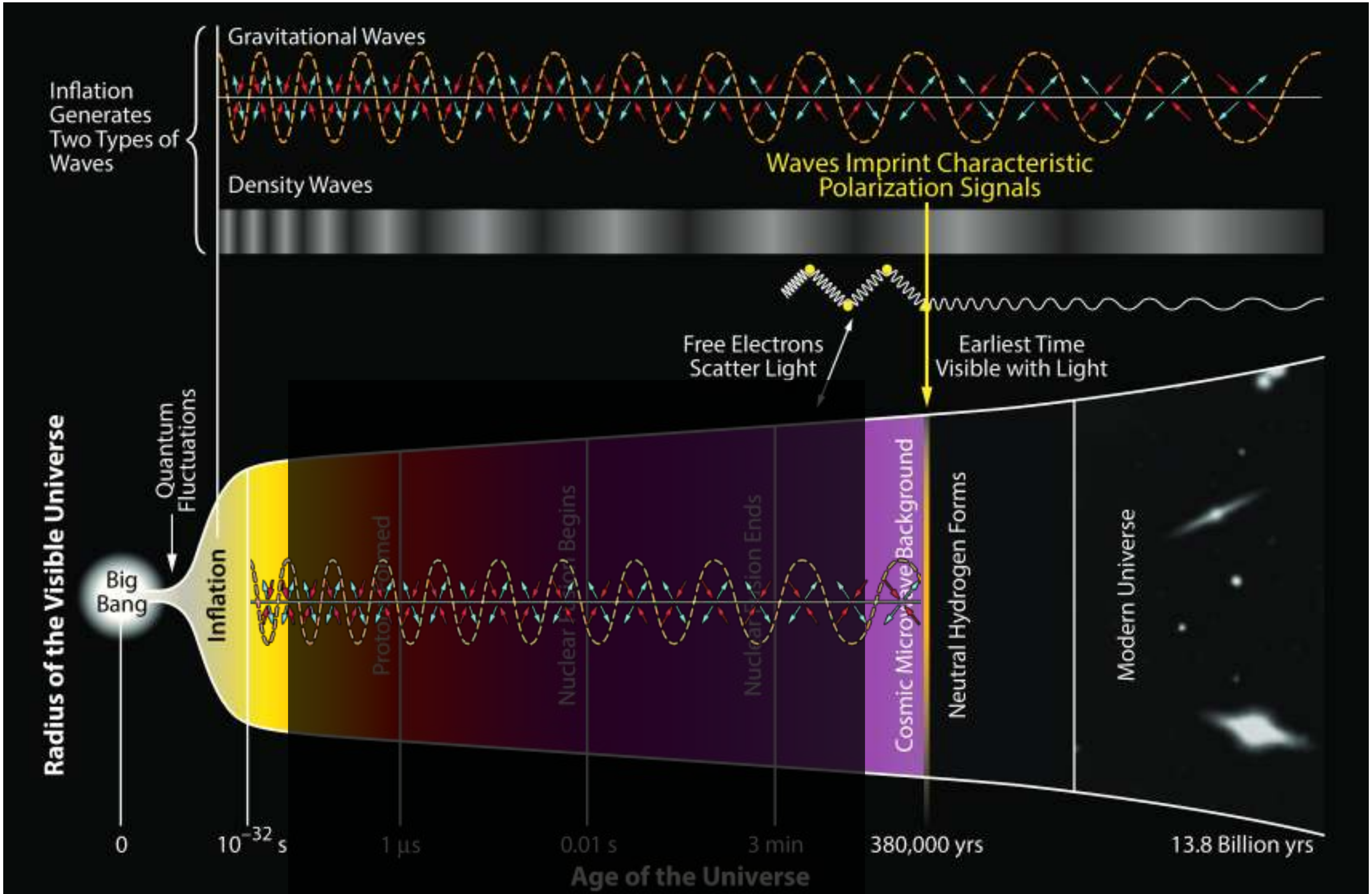


$$r \approx \frac{V[\phi]}{(4 \times 10^{16}\mathrm{GeV})^4}$$

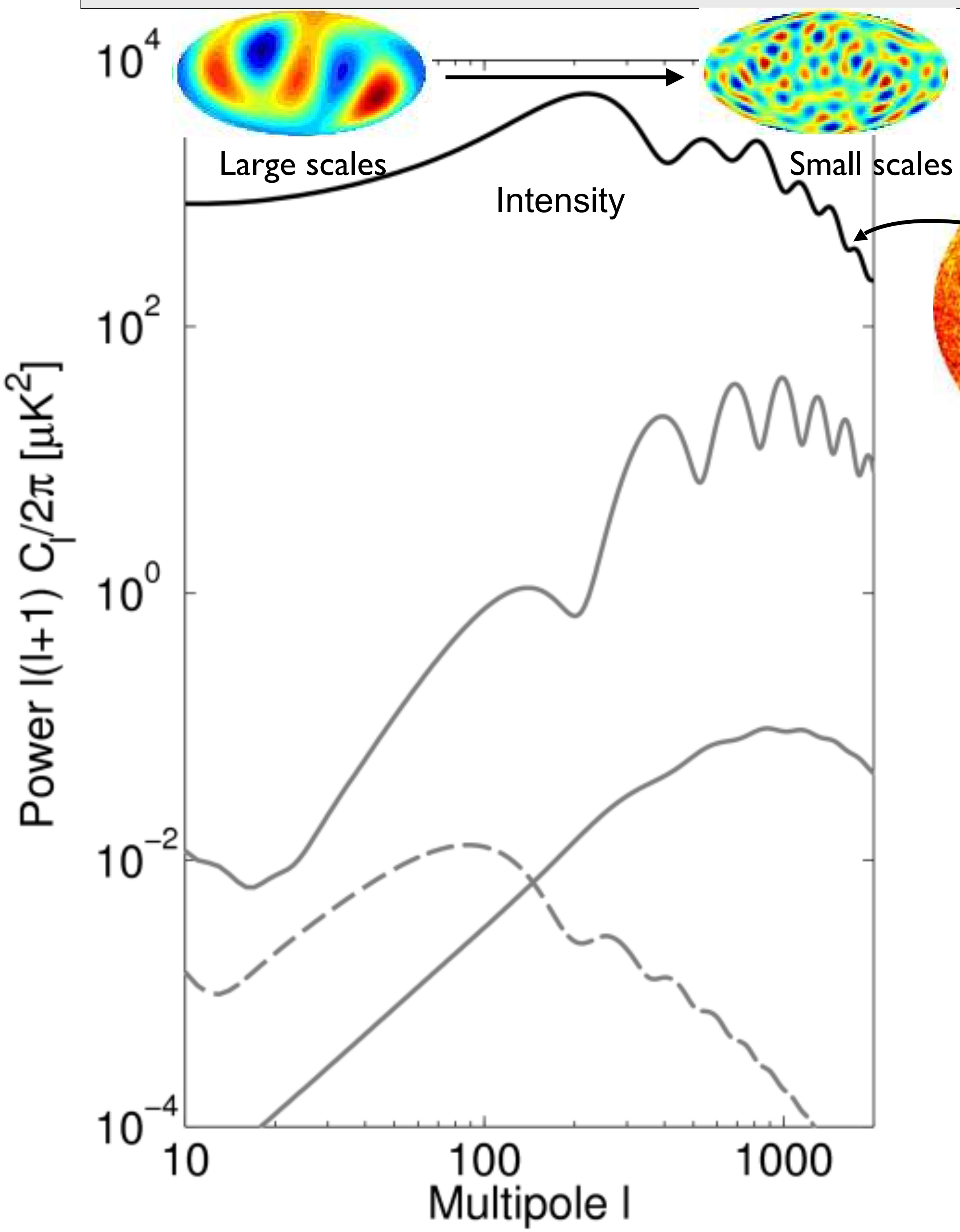
GUT-scale physics!?

GWB imprints CMB

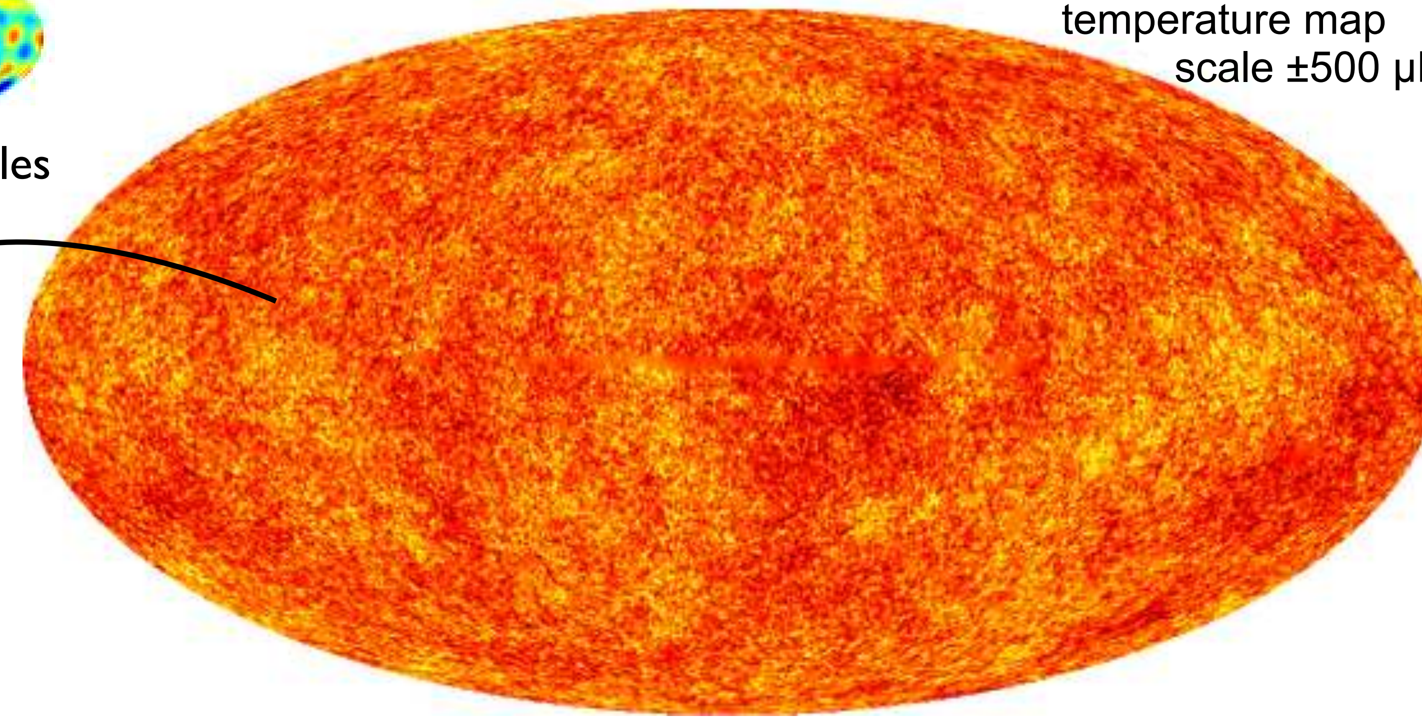


r=ratio of tensor to scalar perturbation amplitude

Understanding CMB Polarization angular power



Planck's all sky CMB temperature map scale ±500 μK



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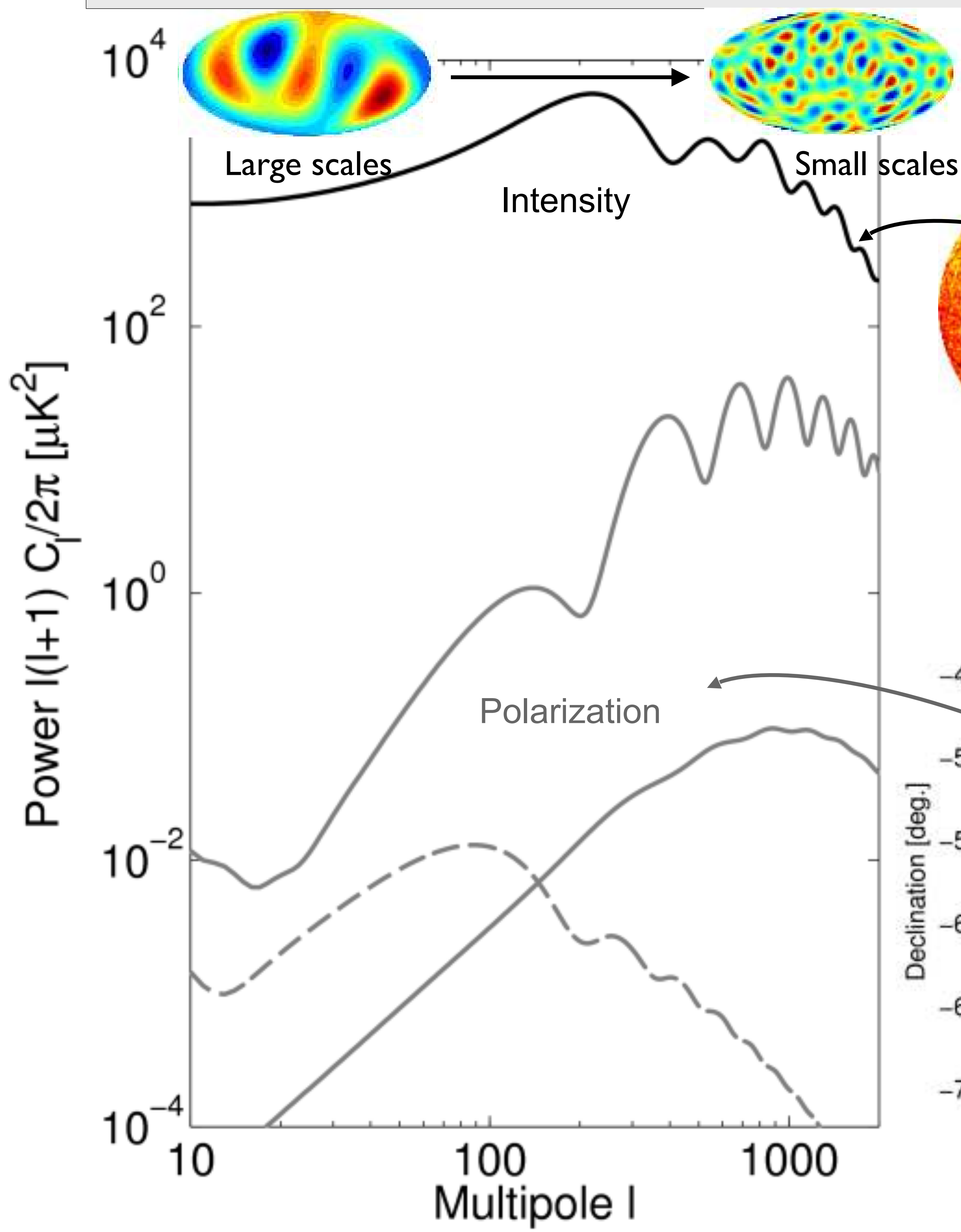

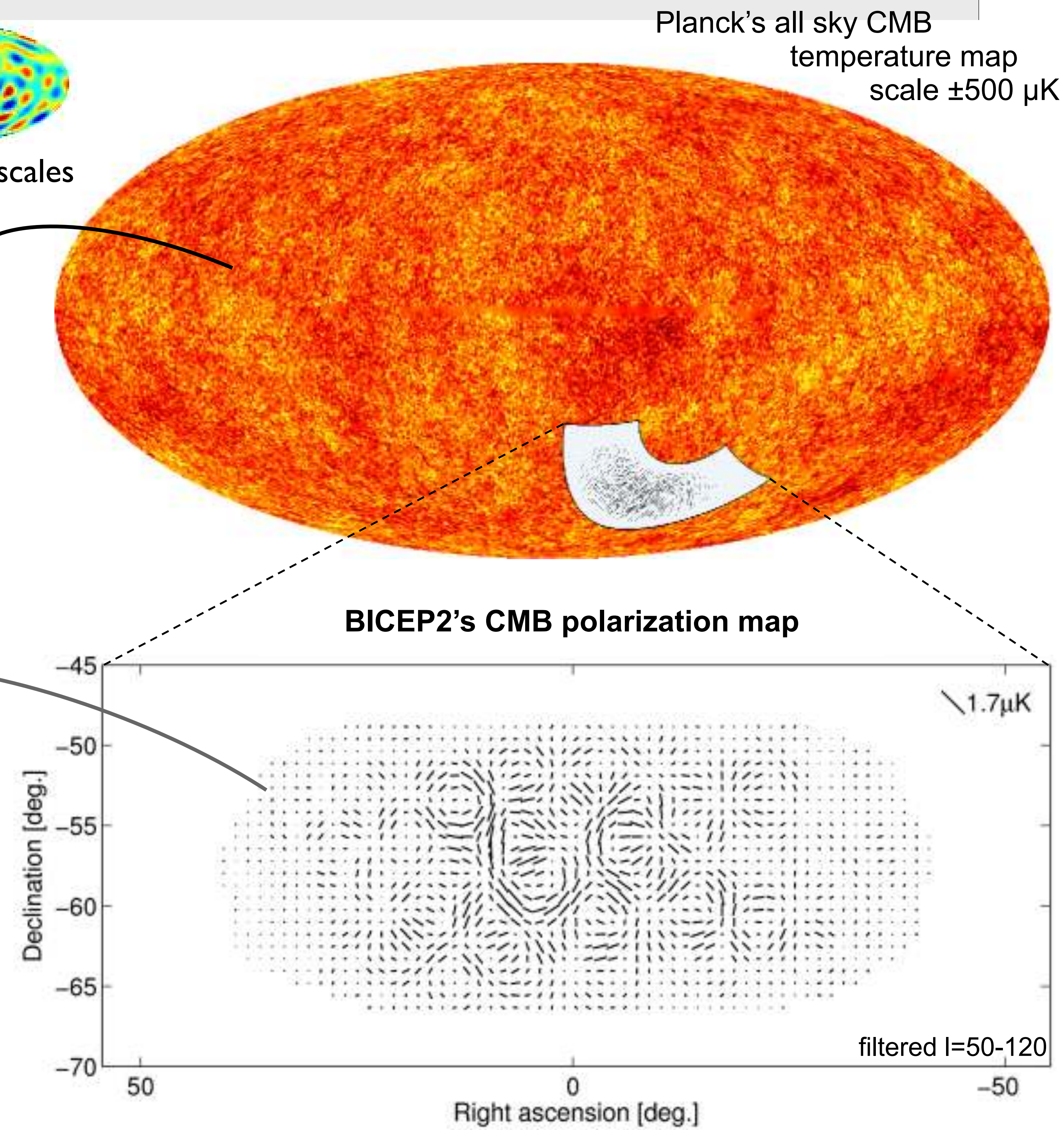

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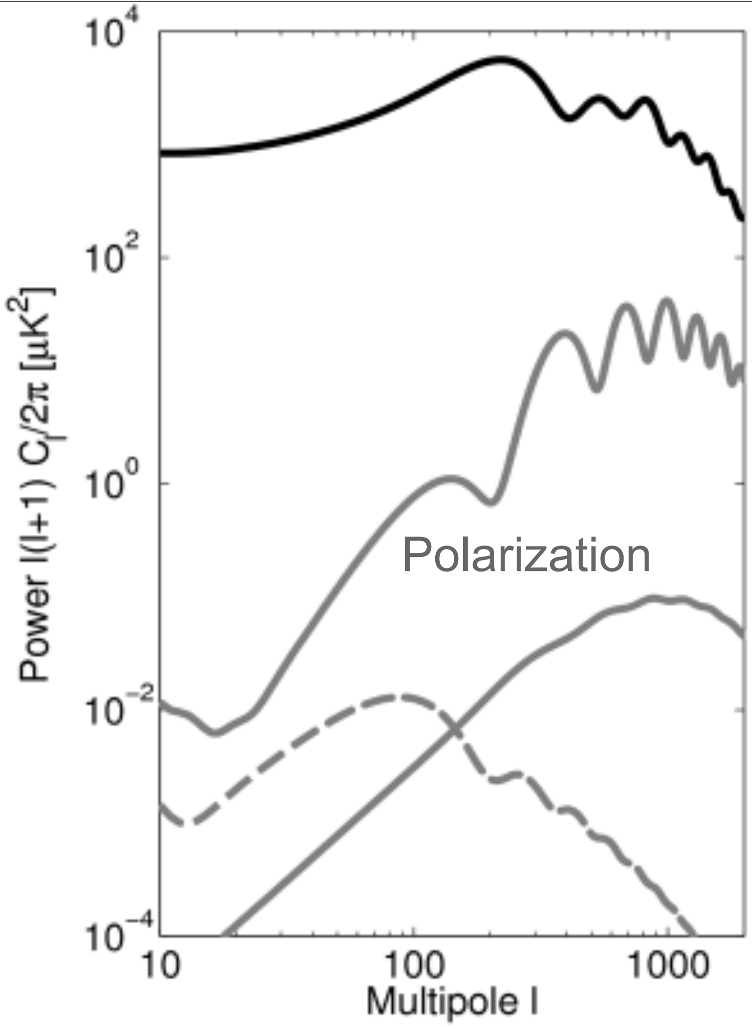

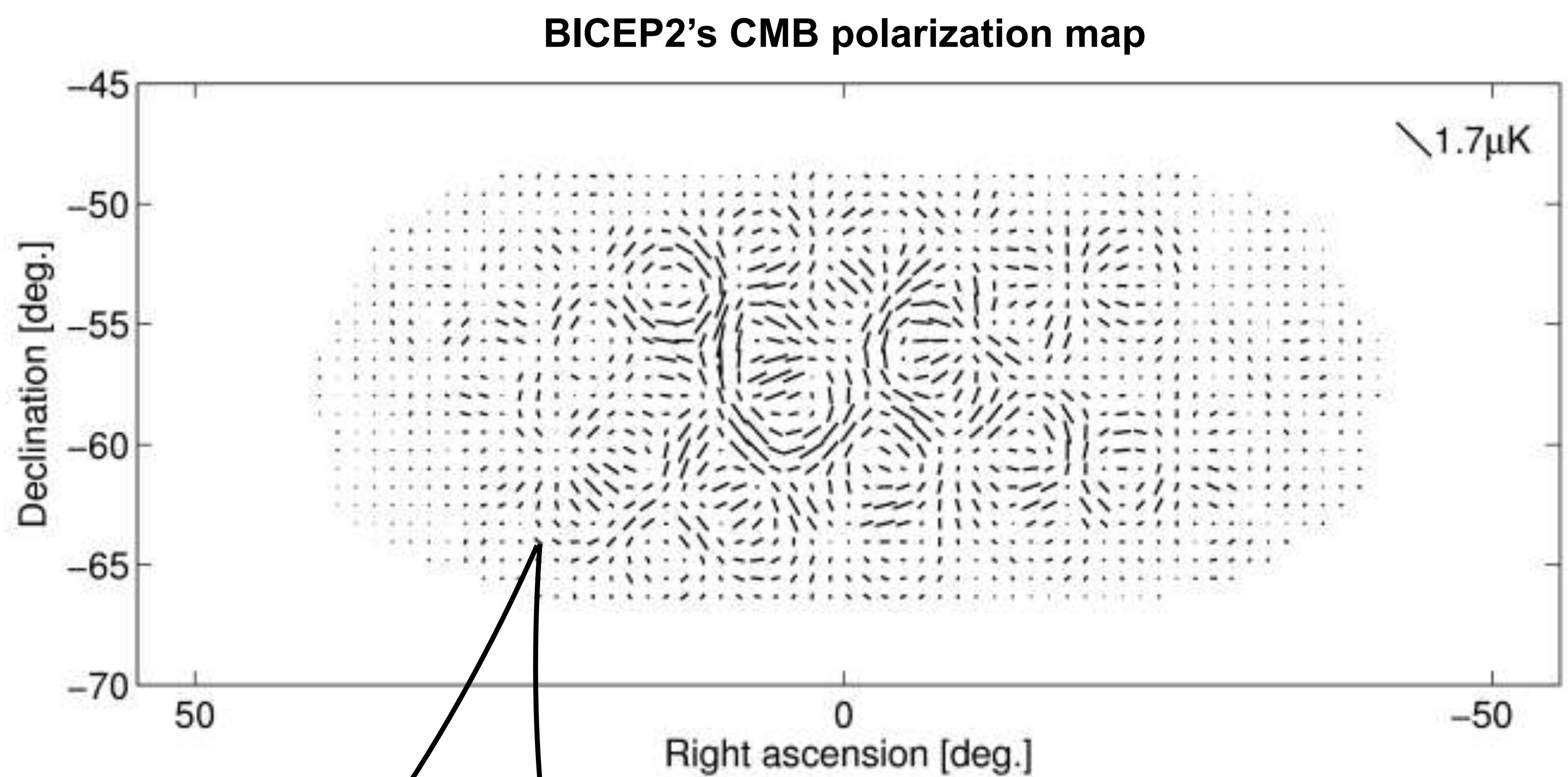

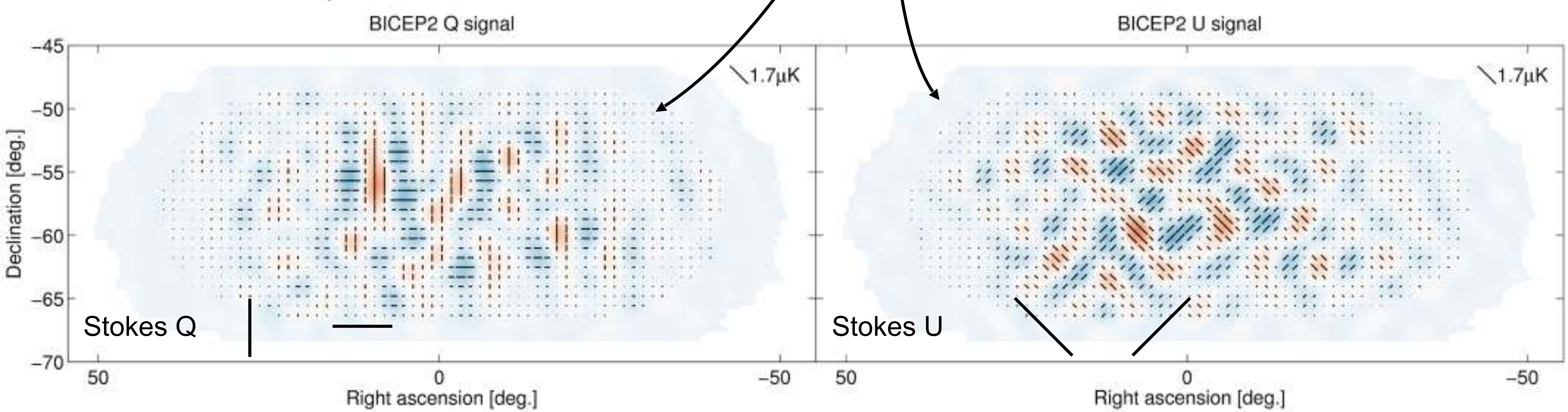

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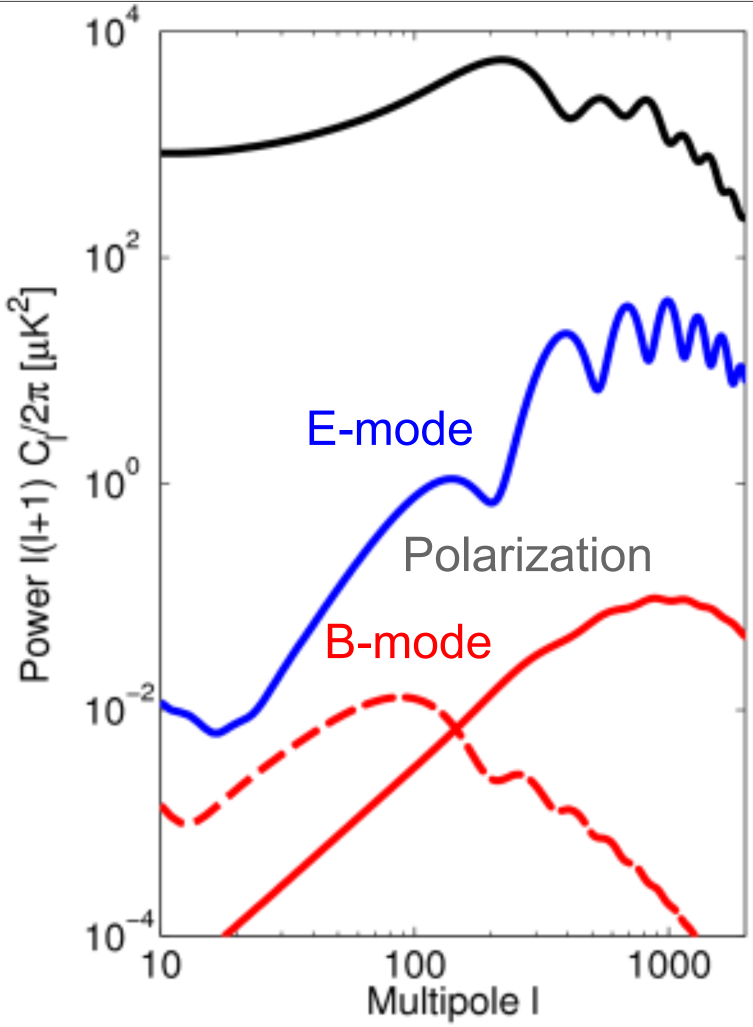
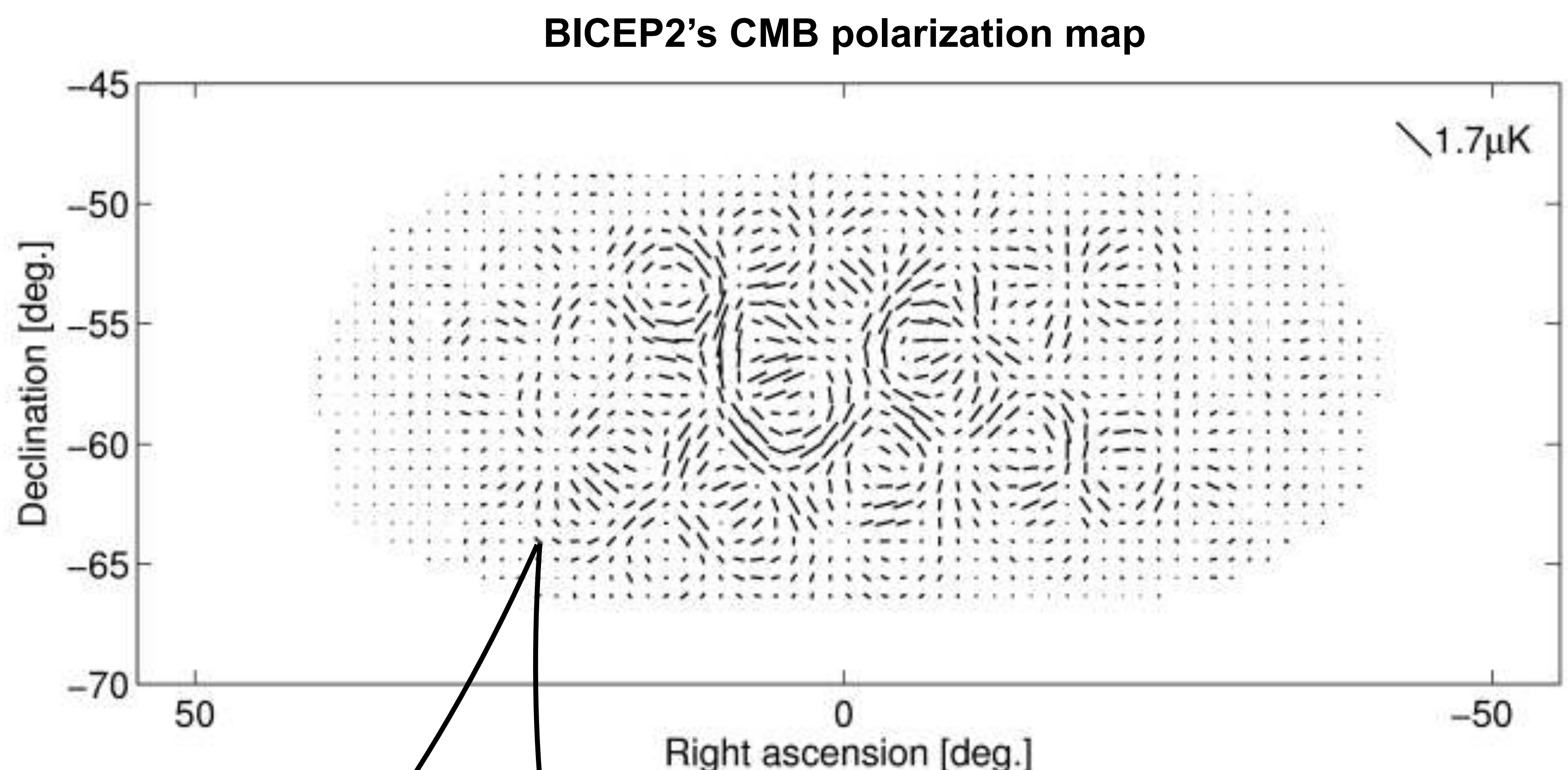
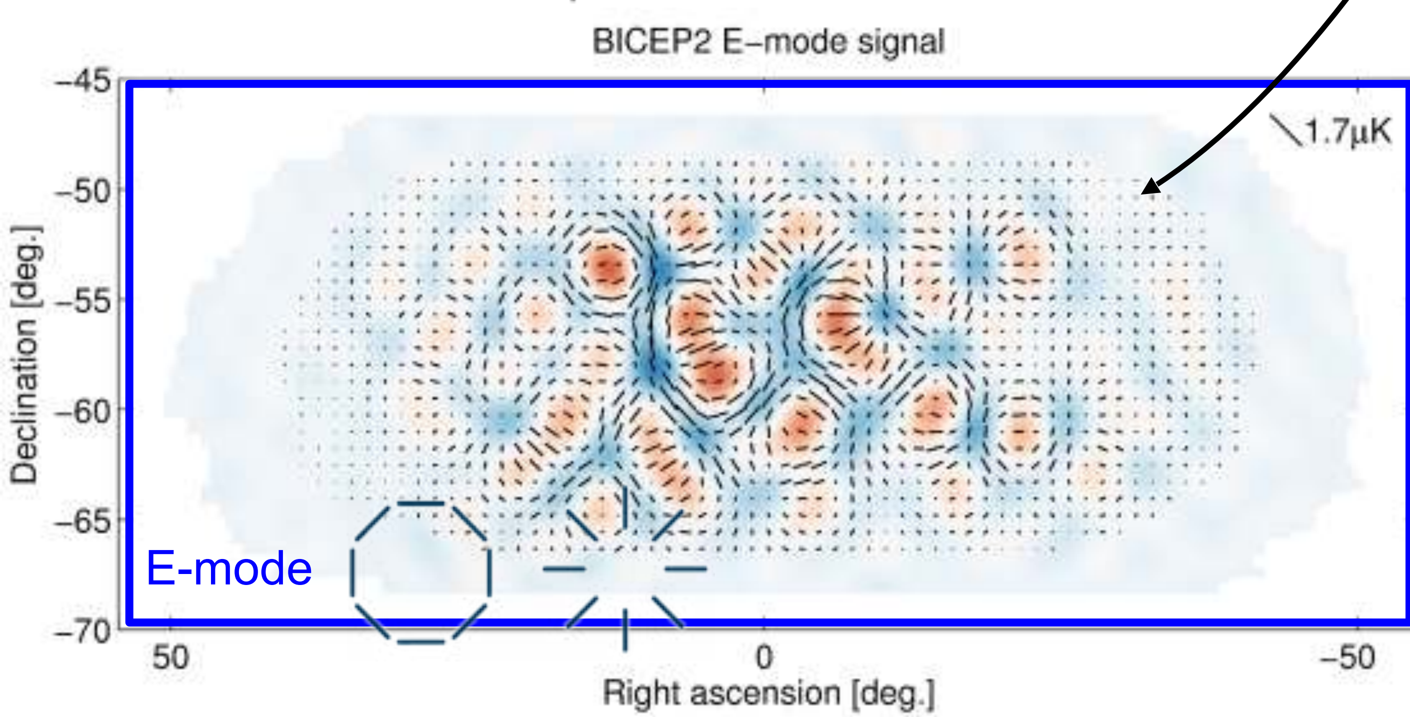
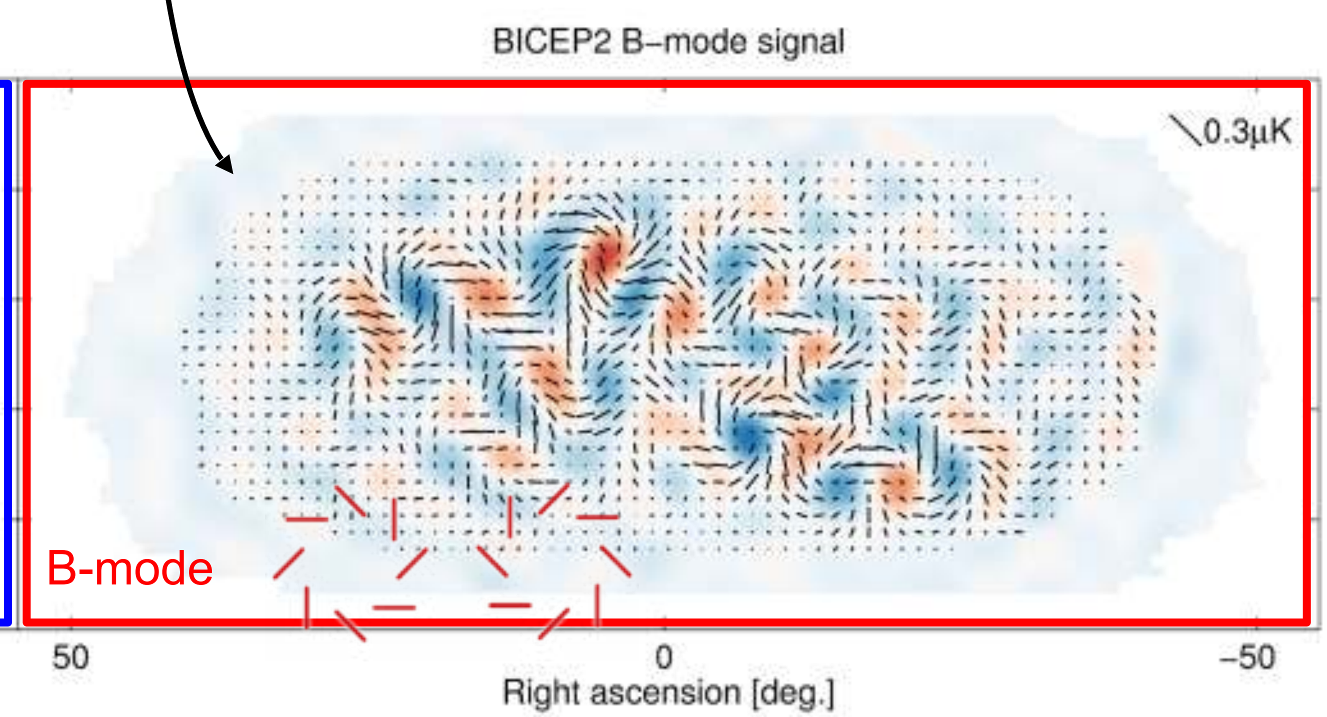




...clever choice for cosmology: E&B-modes





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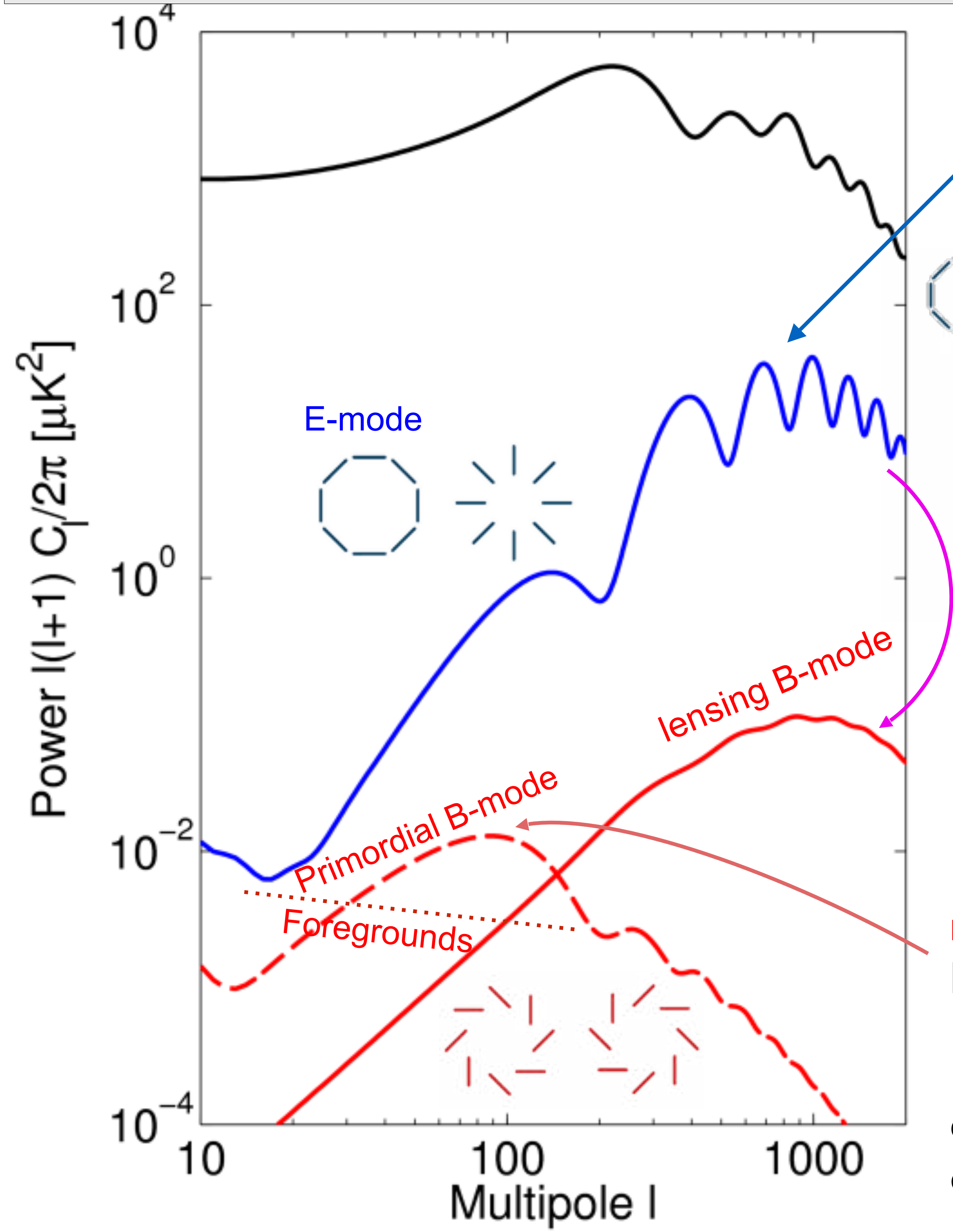
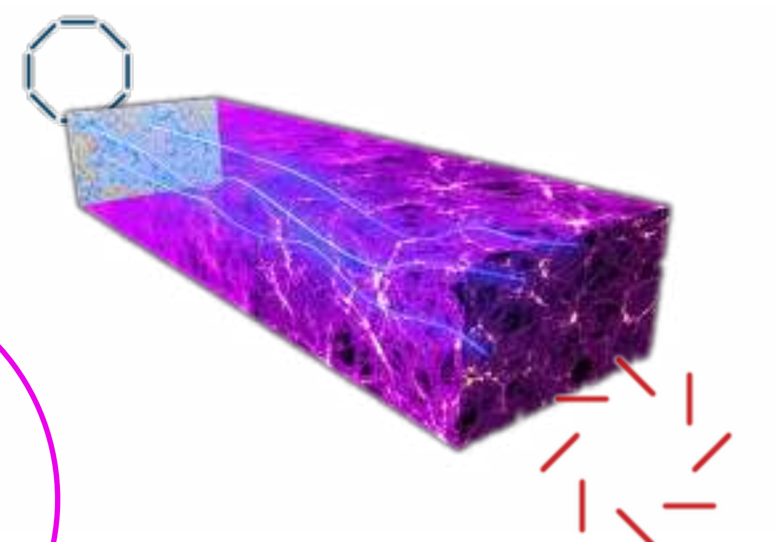


In standard ΛCDM only E-modes are present at last scattering



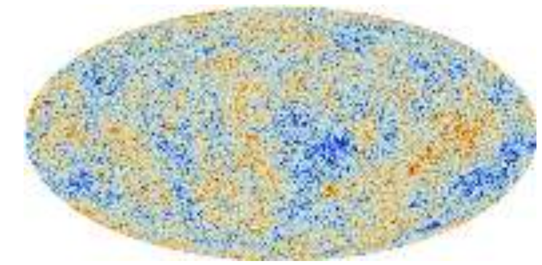
Lensing by intervening structure converts some to B-modes

Enables reconstruction of a map of all matter between us and recombination.

Inflationary gravity waves produce B-modes peaking at l≈100 : degree scales. Measure tensor-to-scalar ratio, *r*

Foregrounds also generate polarized emission. Can be teased apart from different spectral dependence cf CMB

Outline



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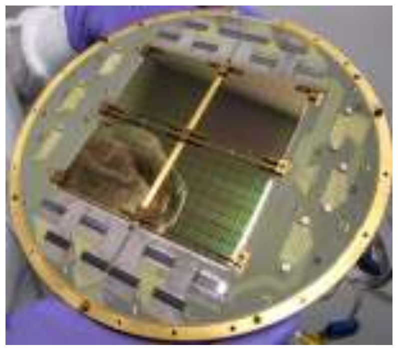

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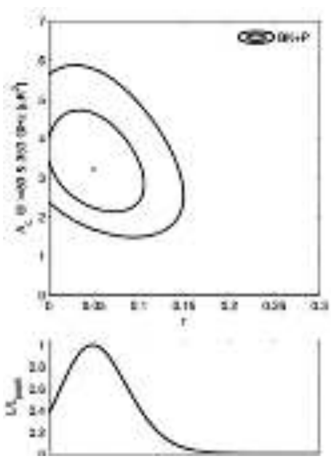

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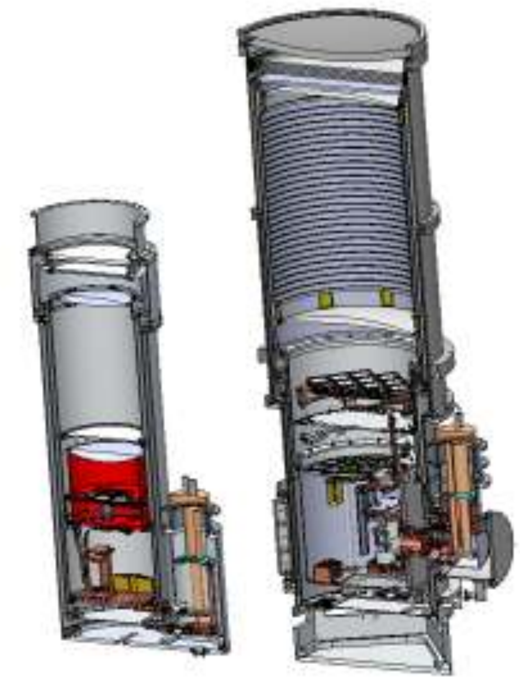

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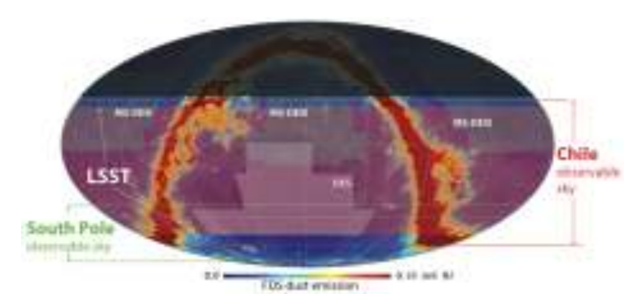
5. The future — adapting and scaling BICEP3 surveys

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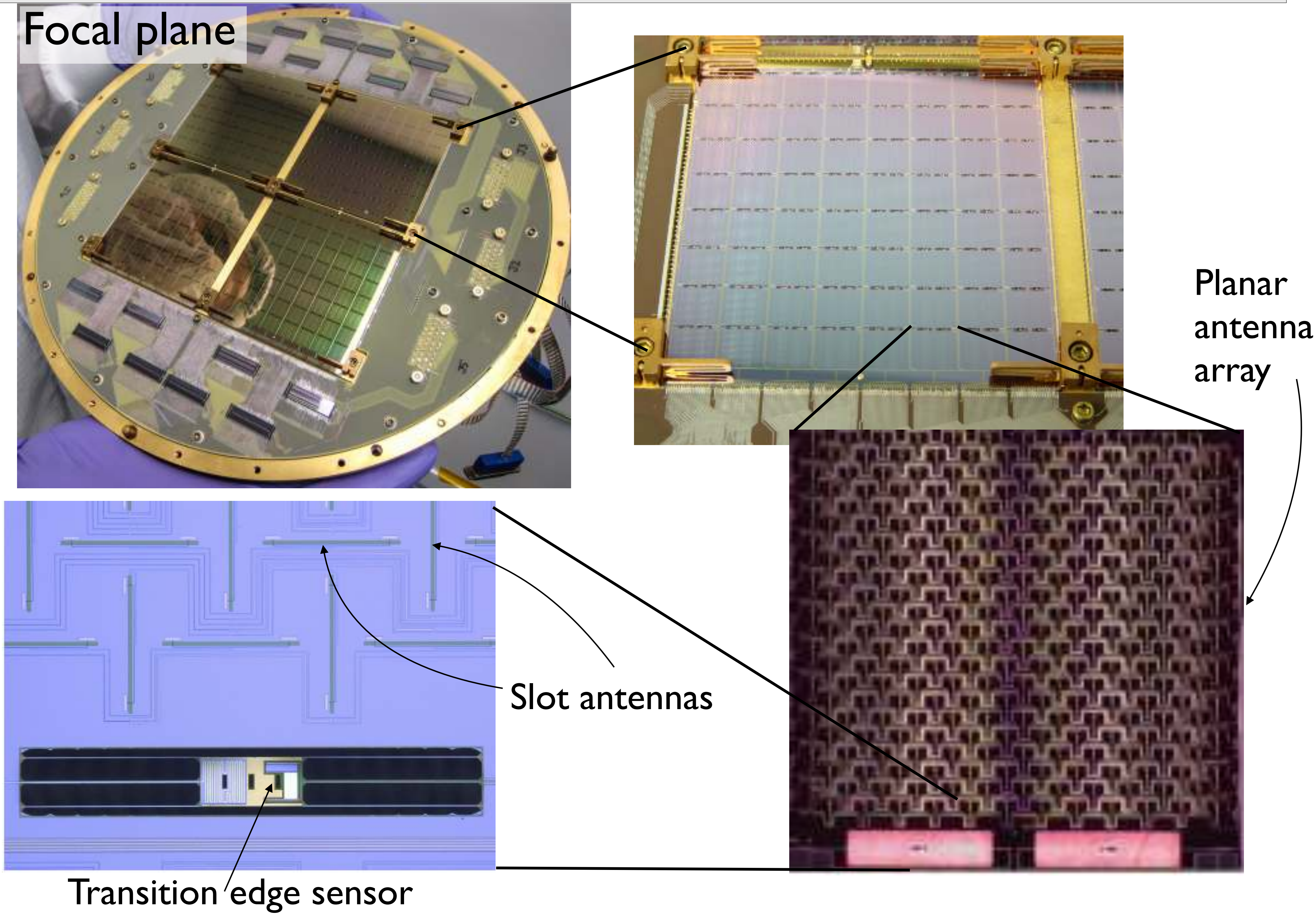
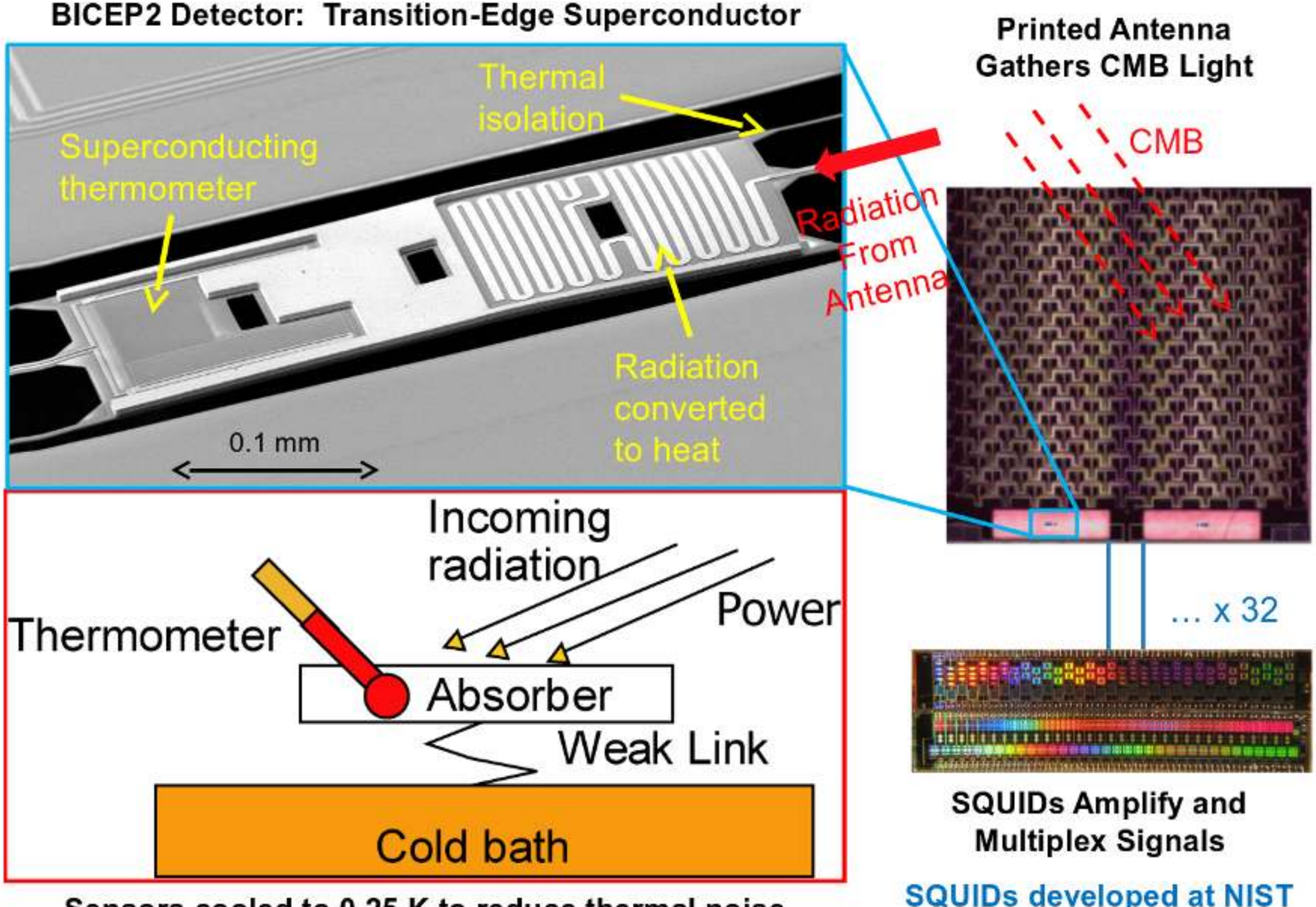
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
cea
UCSD
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

Mass-produced superconducting detectors



Detecting CMB Radiation

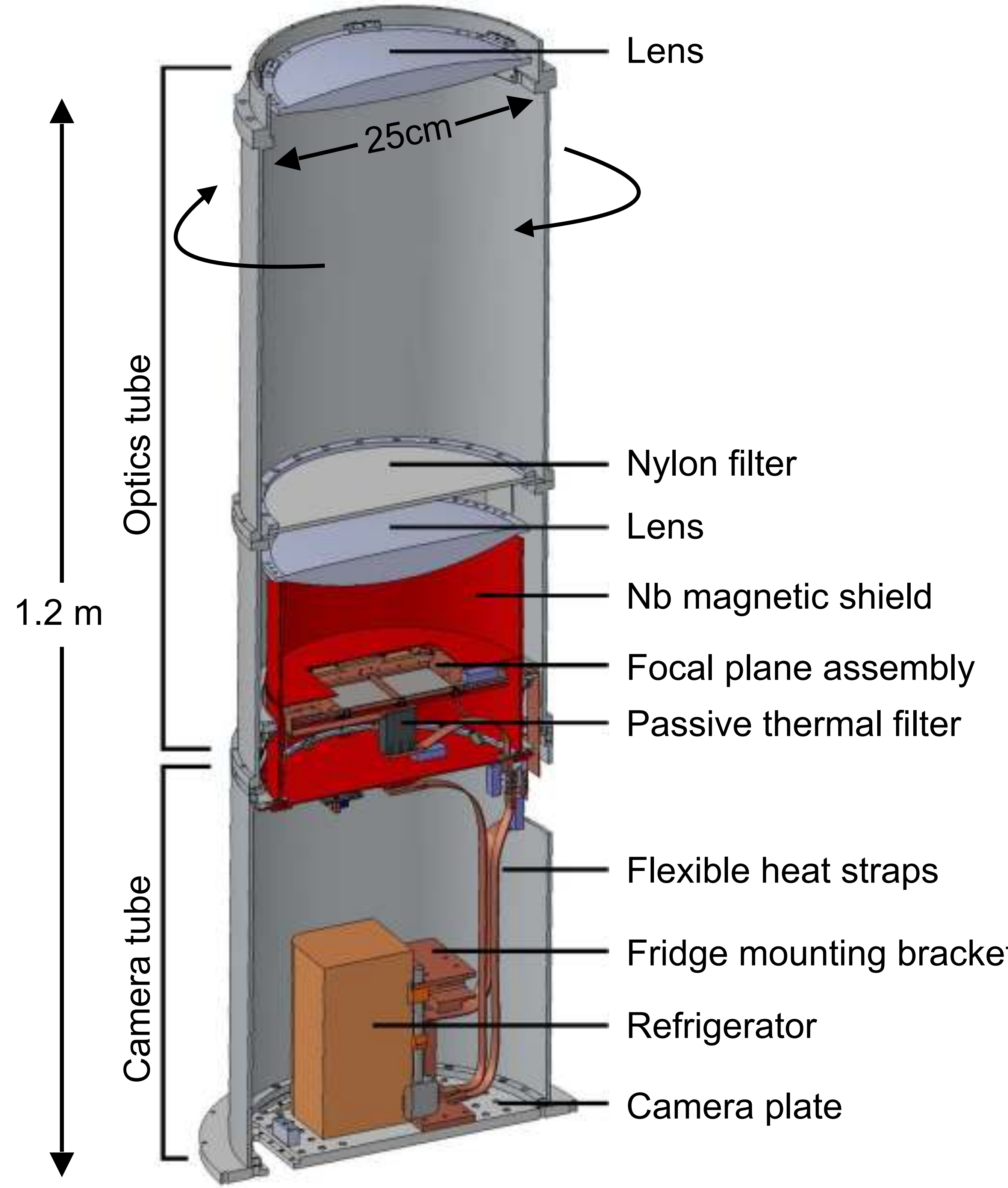
BICEP2 Detector: Transition-Edge Superconductor



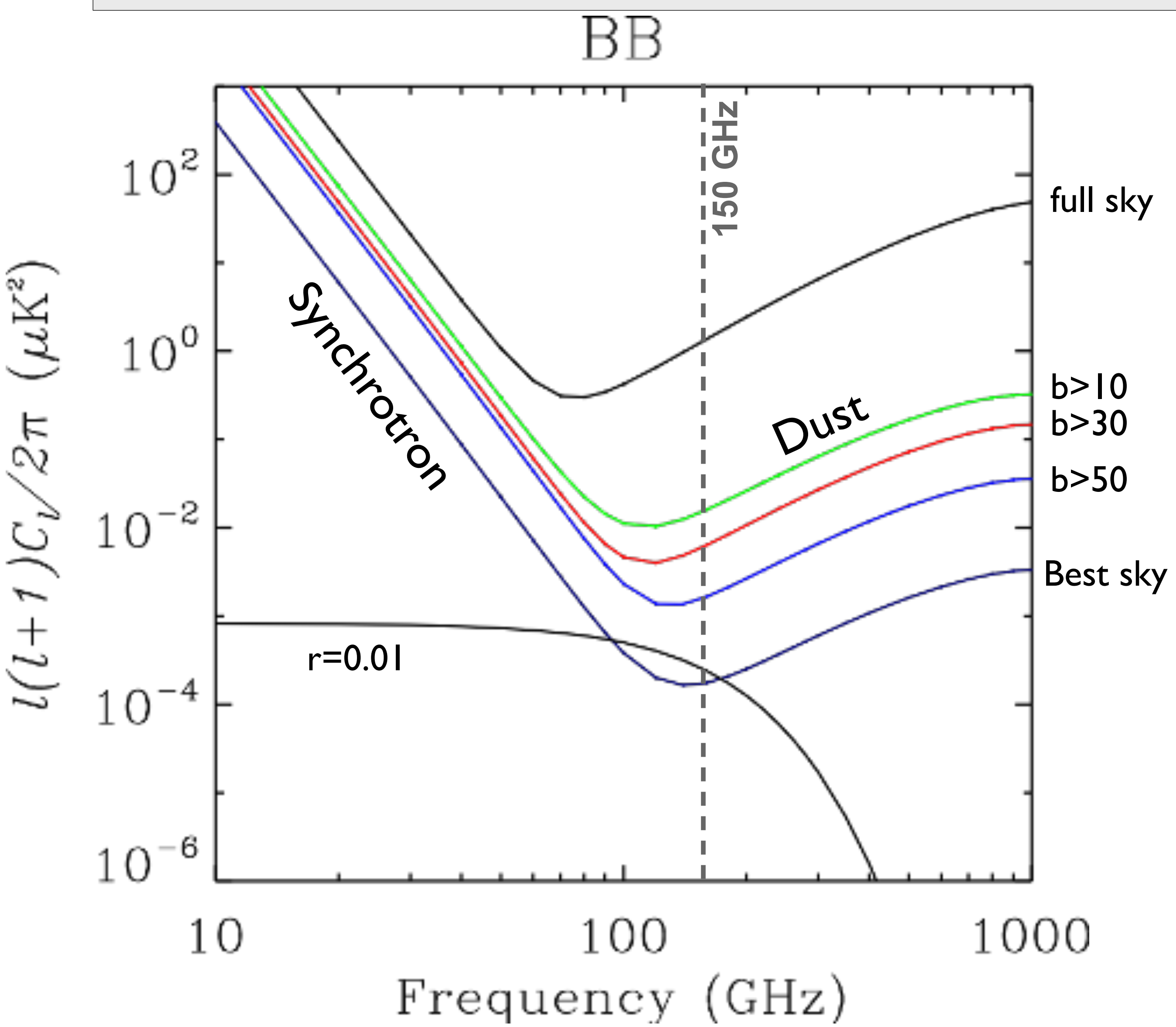
Sensors cooled to 0.25 K to reduce thermal noise

Compact receiver + Cold Optical Design

- Telescope as compact as possible while still having the angular resolution to observe degree-scale features.
- On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.
- Optical elements are cooled to ~4K to reduce internal loading
- A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.

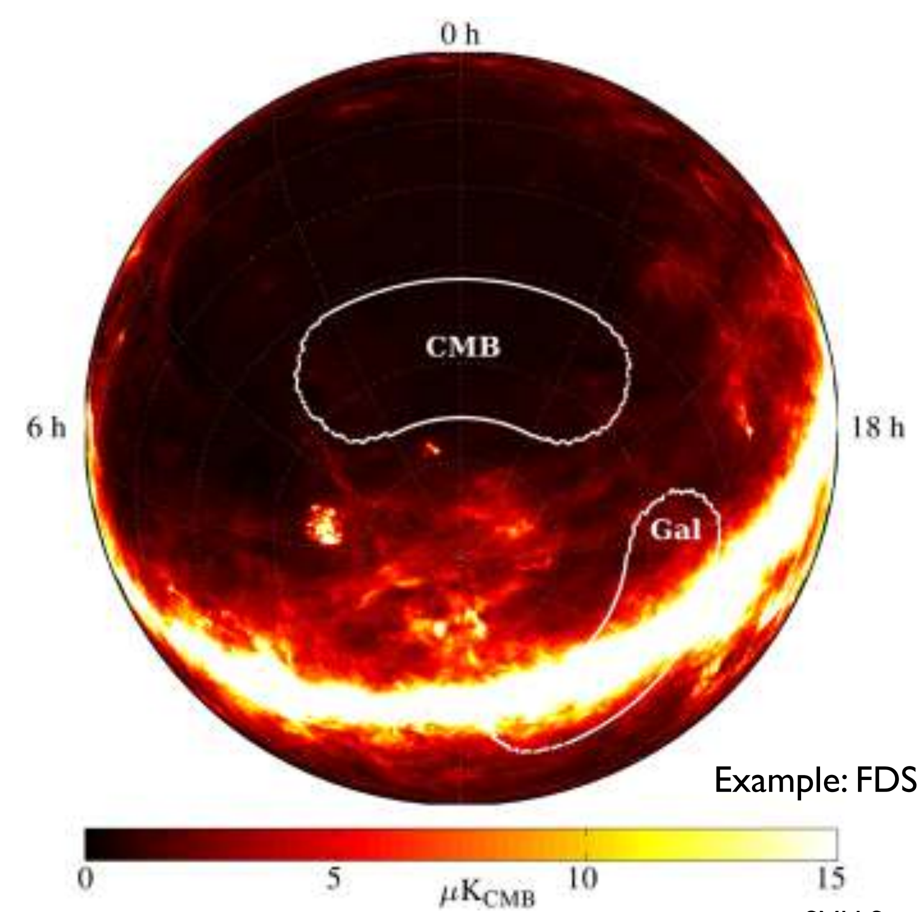


Observational Strategy & Foregrounds



From Dunkley et al arxiv/0811.3915

- Target 1% of the sky for deep integration
- Which 1%?
  - Pre-Planck, only models for dust
  - Pick cleanest patch **predicted** to be lowest foregrounds (dust+sync)
- Try to search in the frequency minimum for contamination



Example: FDS dust model

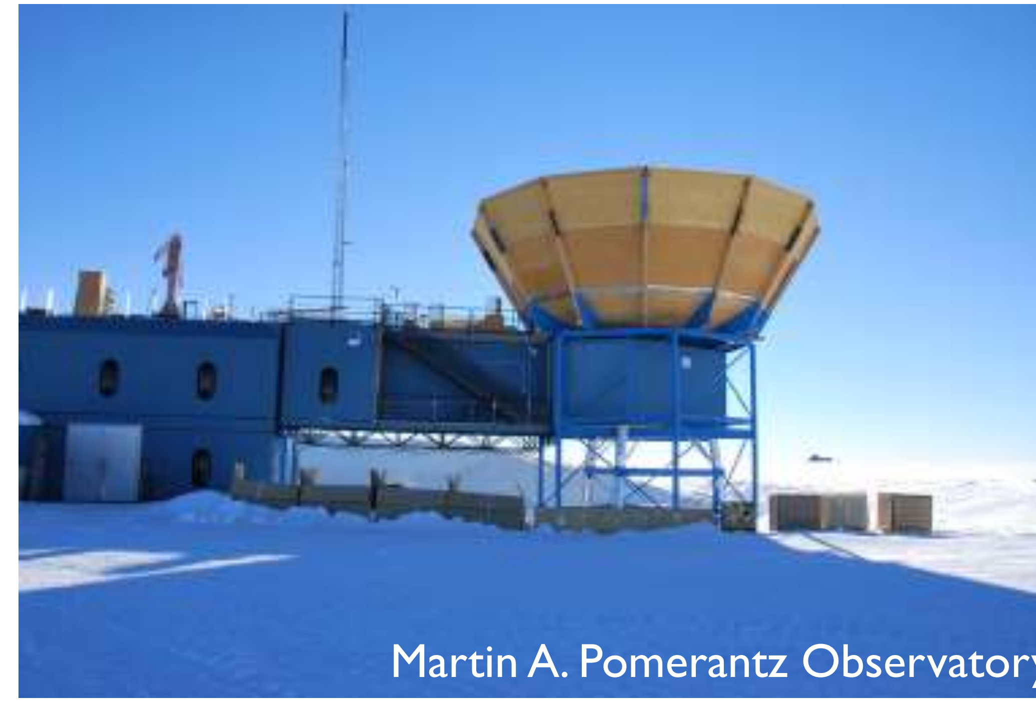
Situated at a high, dry desert

South Pole Research Station, Antarctica

~10,000ft, ~0.25mm PWV

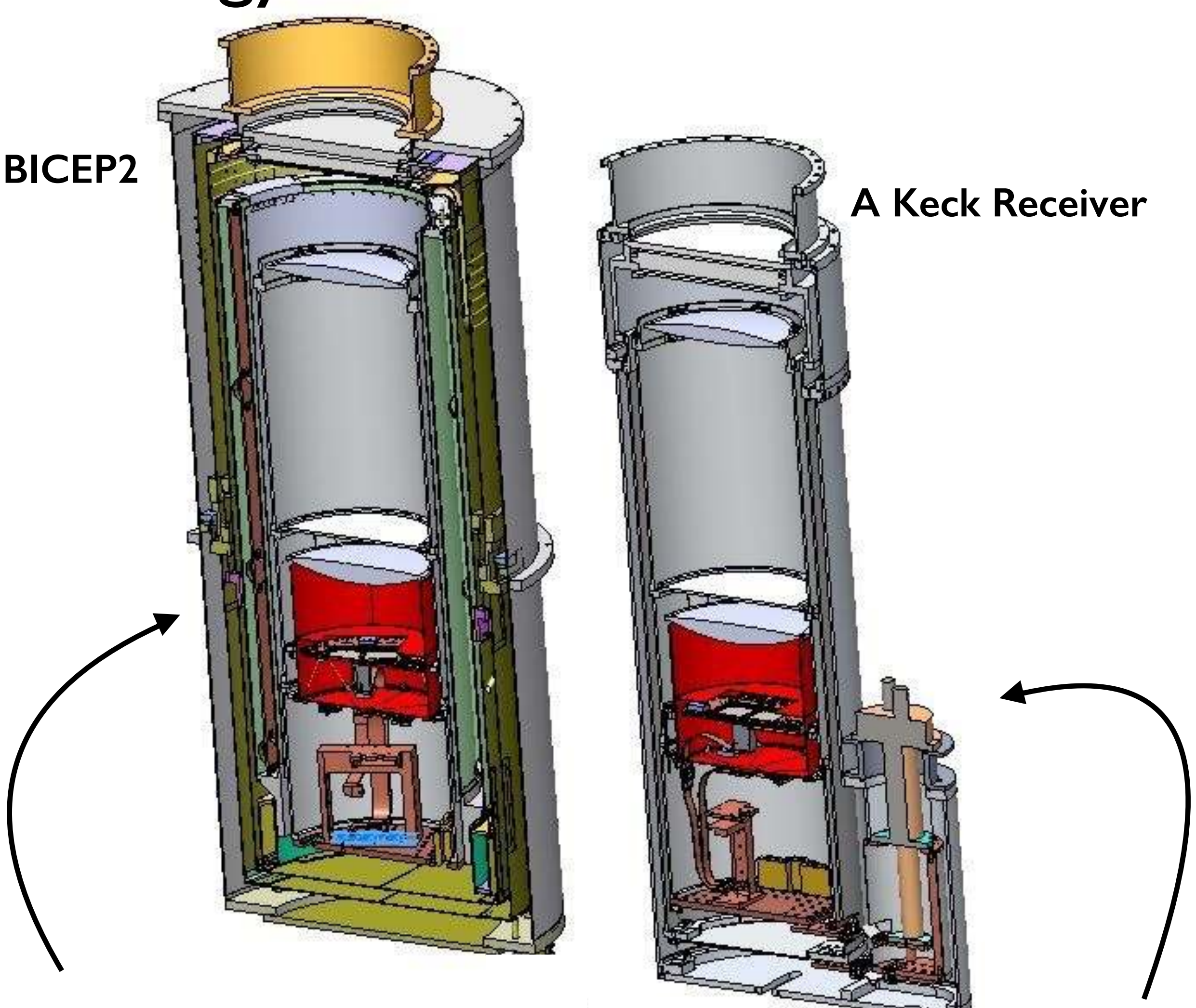
6 months of cold, stable winter sky with uninterrupted integration

BICEP2 design replicated into the Keck Array



Multiply BICEP2 x5

- 5 receivers in single mount
- Pulse-tube cooler operation to avoid liquid cryogens
- Same site, receiver insert, observation strategy etc.



Keck receiver vacuum shell simplified compared to B2 for cryogen-free operation

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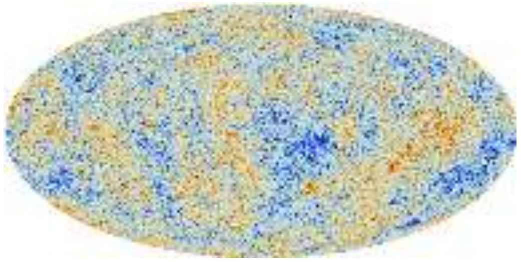

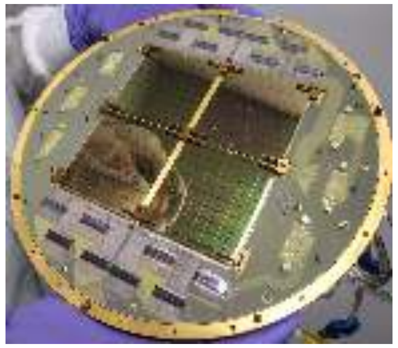

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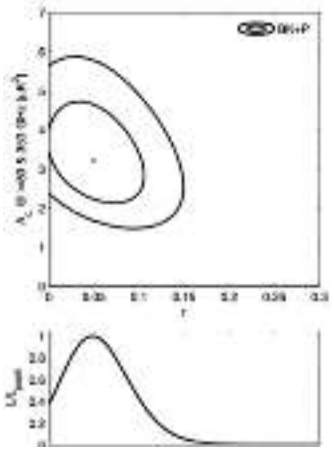

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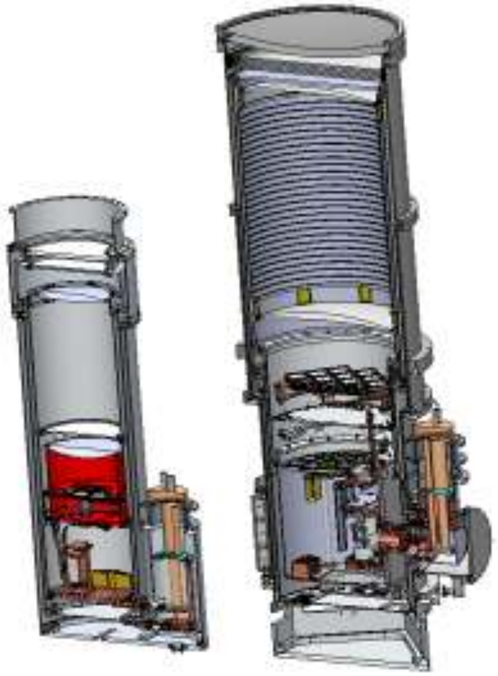

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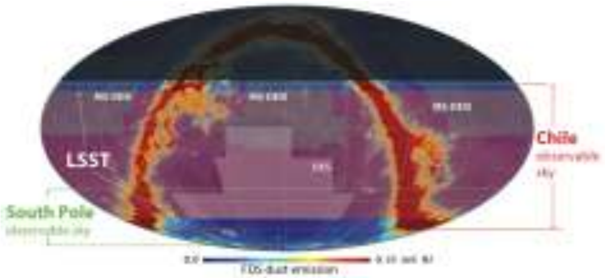
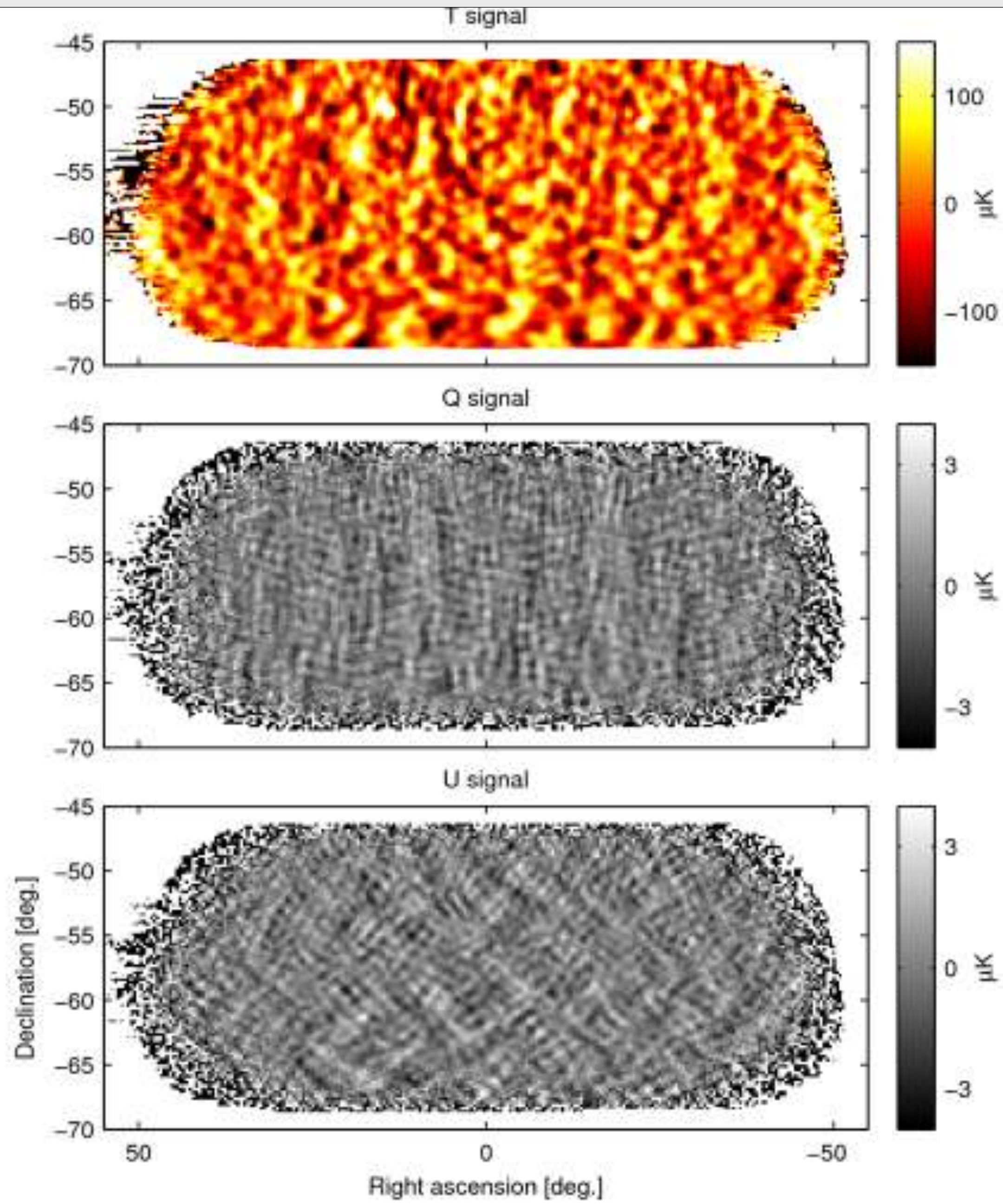
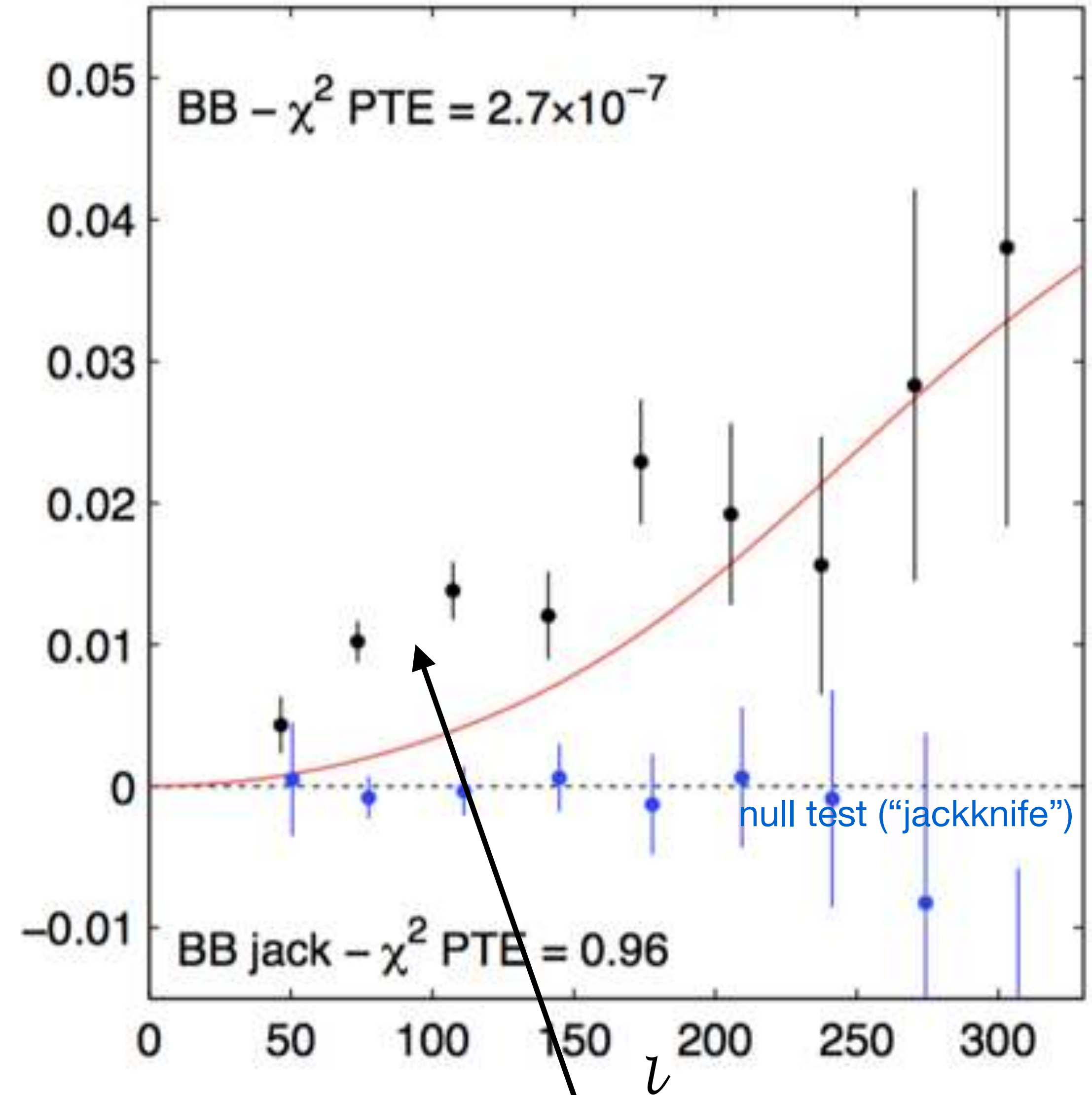


BICEP2+Keck through 2013 (150 GHz)





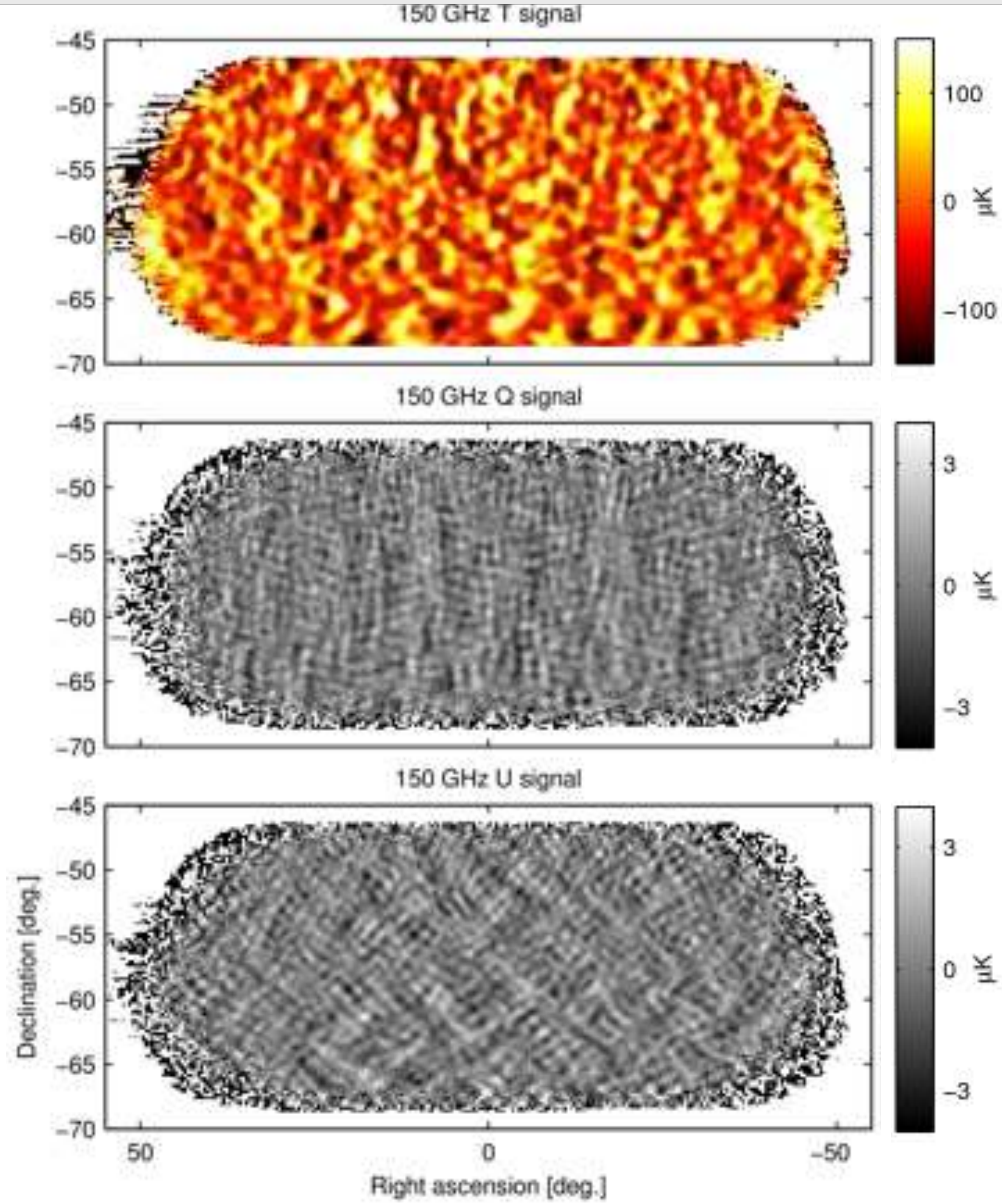
Observation at 150 GHz focused on ~**400 deg²** patch = 1% of the sky

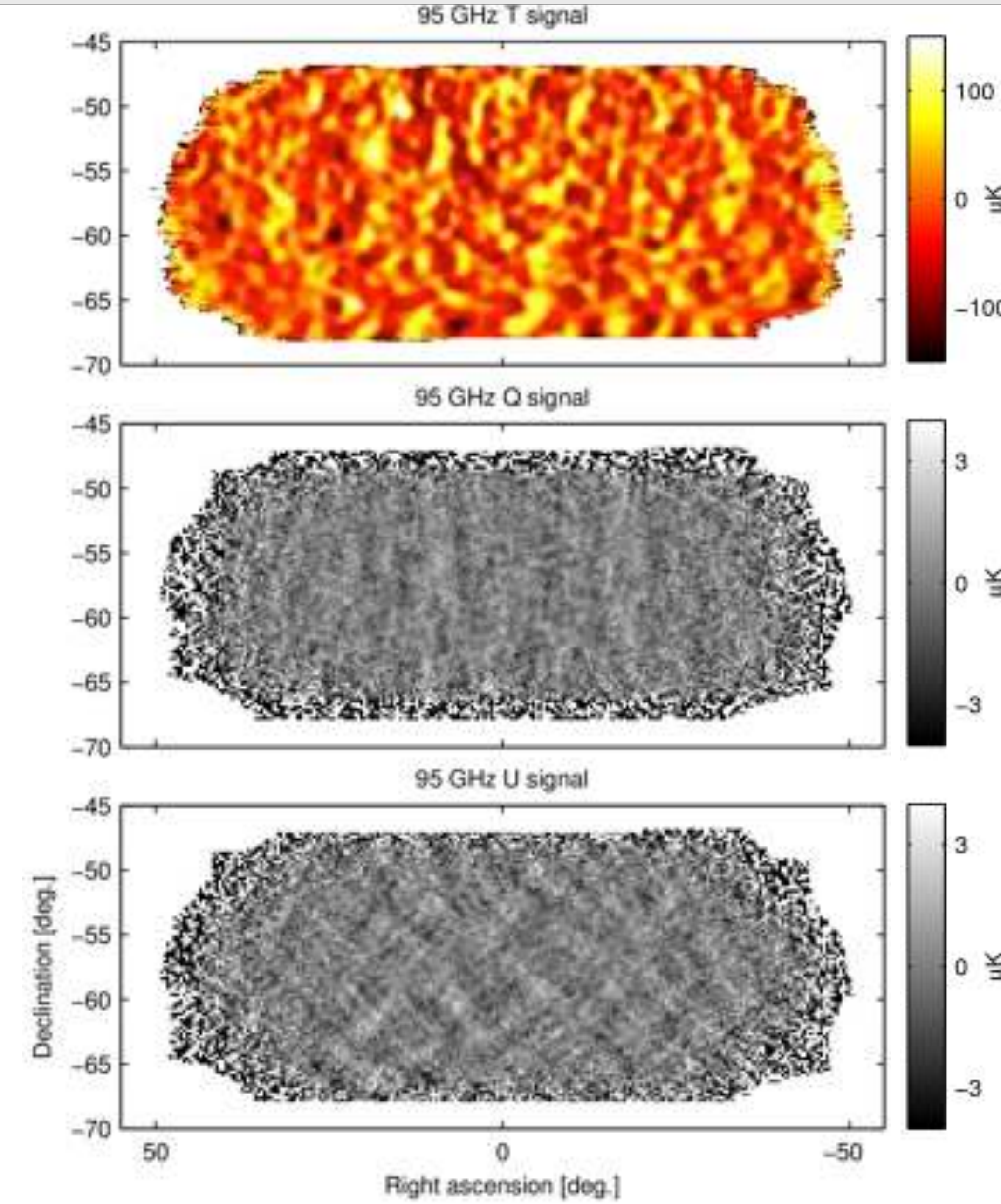
BB power spectrum shows excess over lensed ΛCDM at degree scales. **Joint analysis w/ Planck, shows significant fraction dust**

BICEP2 + Keck thru 2013 → Final map depth: 3.4 μK arcmin / 57 nK deg

(RMS noise in sq-deg pixels)

BICEP2+Keck through 2014 (150 + 95 GHz)





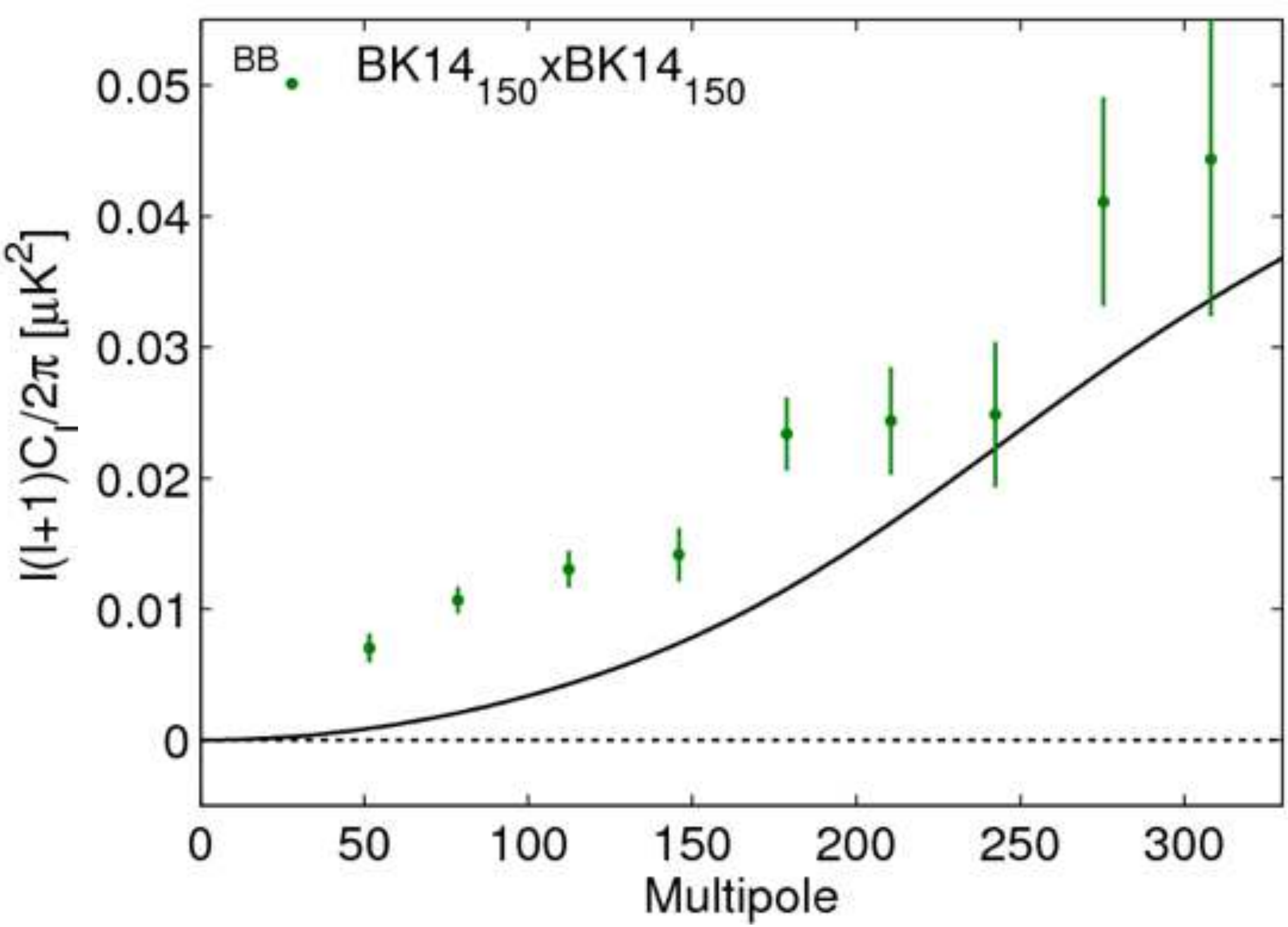
Observation at **150 GHz** focused on ~400 deg^2 patch = 1% of the sky

BICEP2 + Keck thru 2014 → Final map depth: 3.0 μK arcmin / 50 nK deg
(RMS noise in sq-deg pixels)

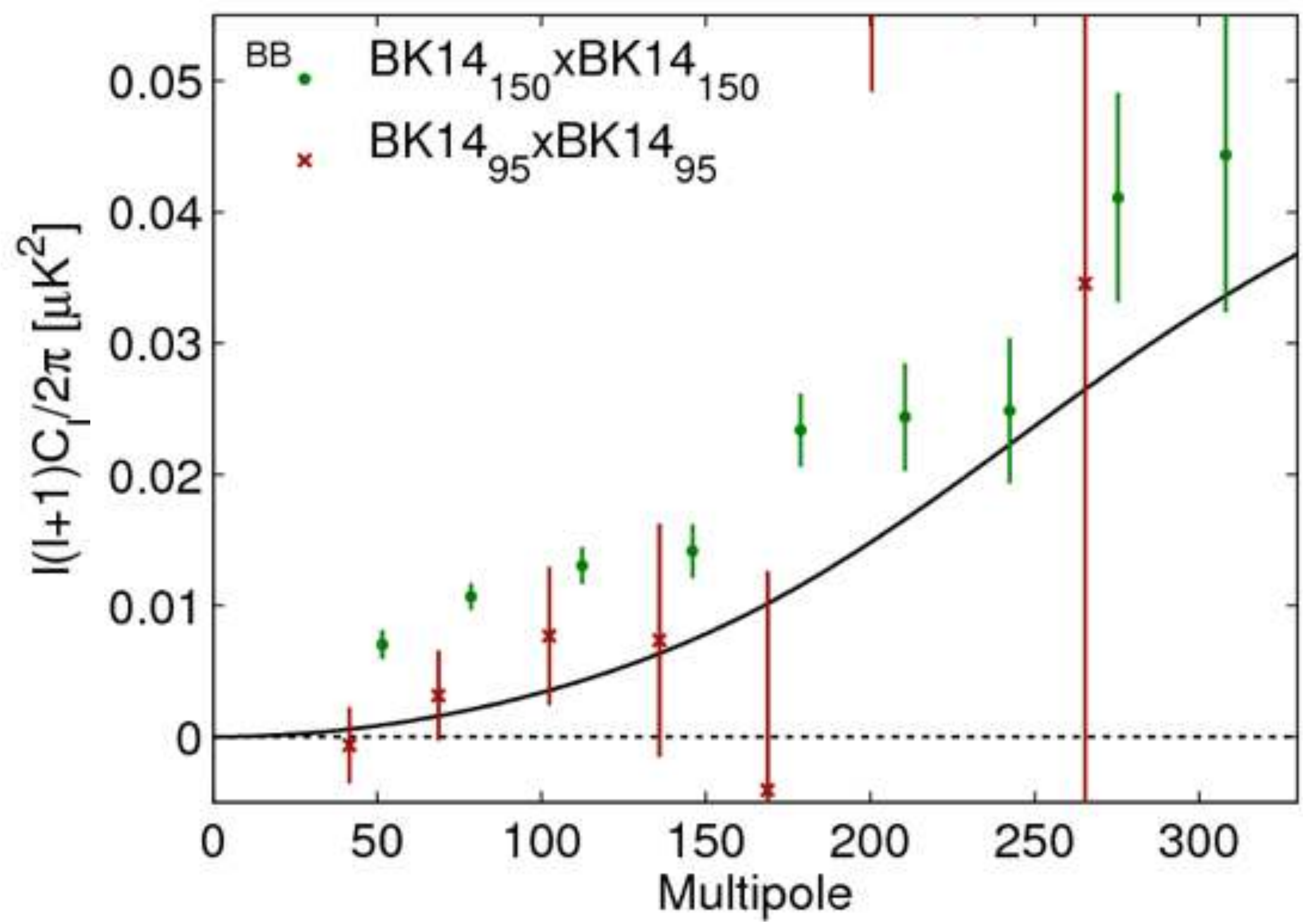
Observation at **95 GHz** focused on ~400 deg^2 patch = 1% of the sky

Keck 2014 → Final map depth: 7.6 μK arcmin / 127 nK deg
(RMS noise in sq-deg pixels)

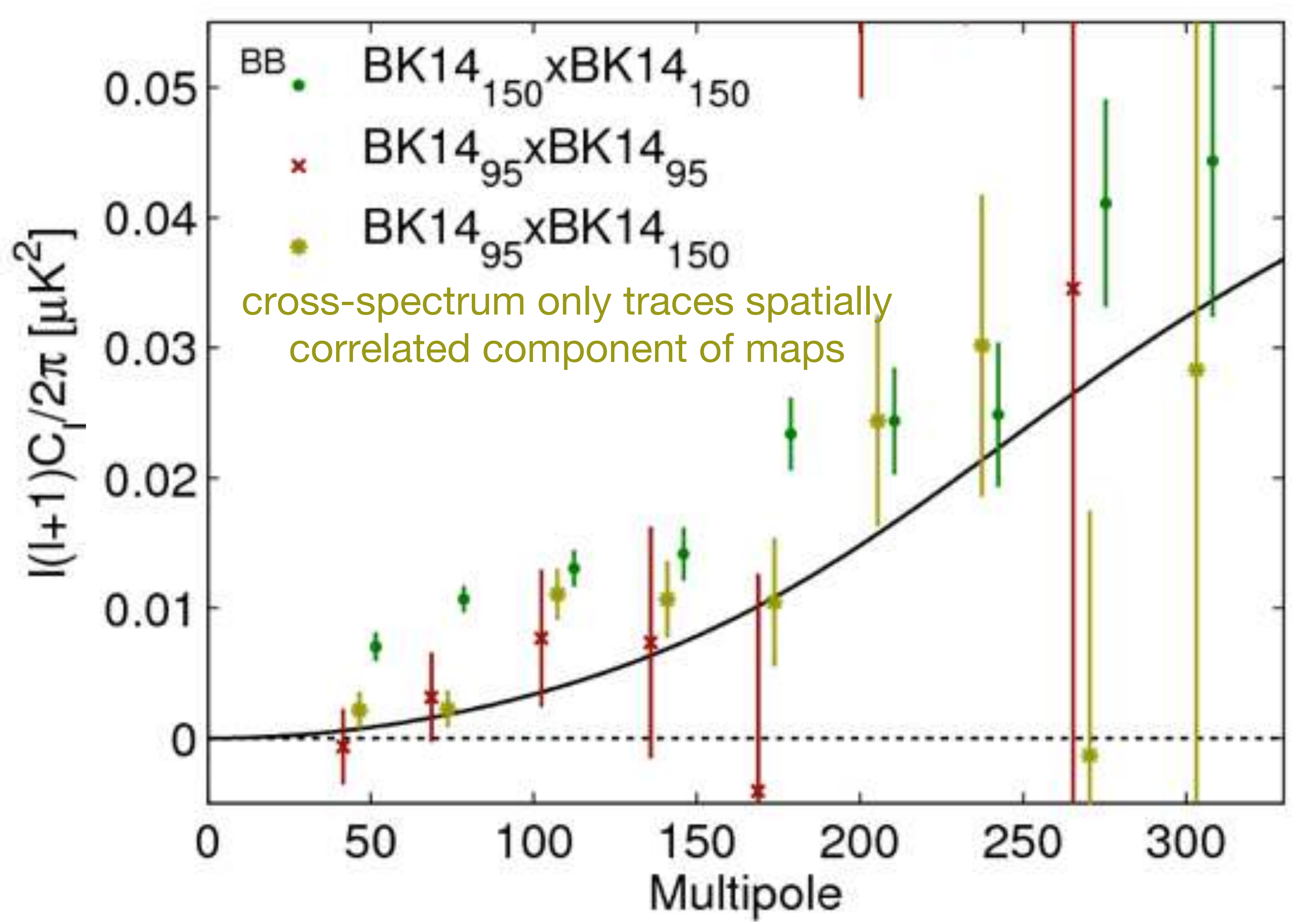
BICEP2+Keck through 2014 150 GHz Auto-spectrum



Add 95 GHz Auto-spectrum..

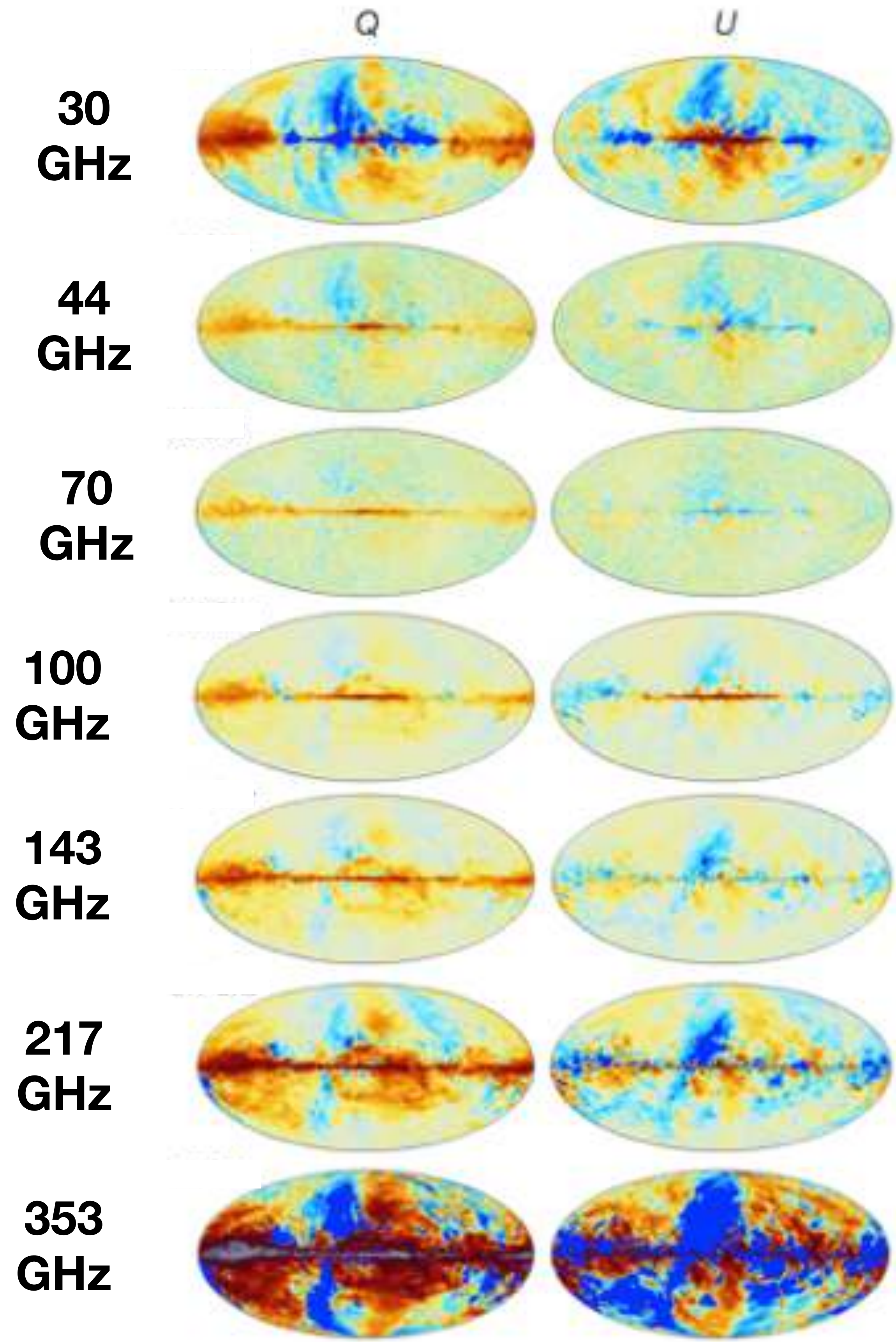


Finally, add 95 x 150 GHz..



Add Planck, WMAP bands..

Planck then provided polarized maps at 7 frequencies
(two more from WMAP at low frequencies already existed)



Add Planck, WMAP bands..

Polarized galactic **synchrotron** dominates at low frequencies

30 GHz

44 GHz

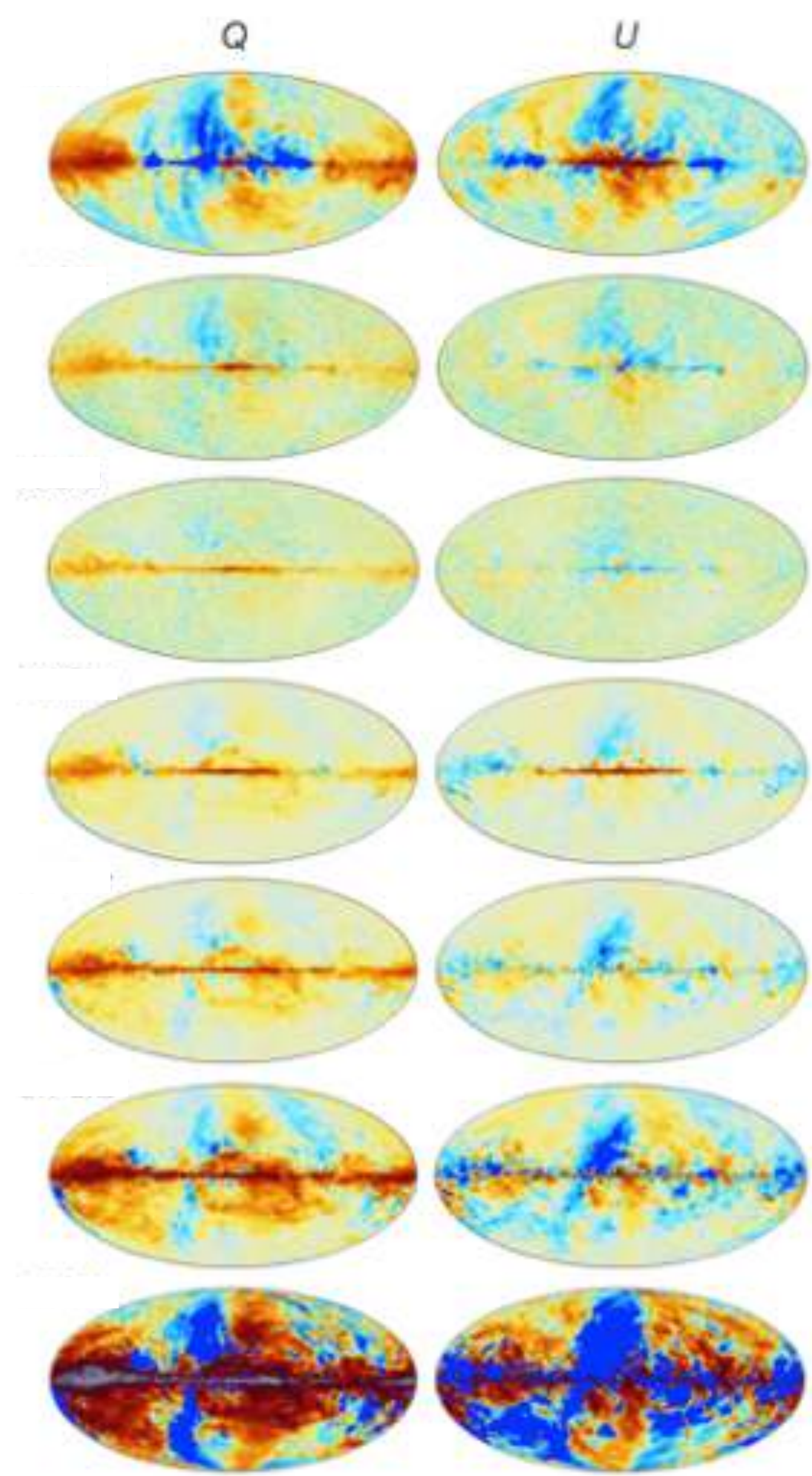
70 GHz

100 GHz

143 GHz

217 GHz

353 GHz



Planck then provided polarized maps at 7 frequencies
(two more from WMAP at low frequencies already existed)

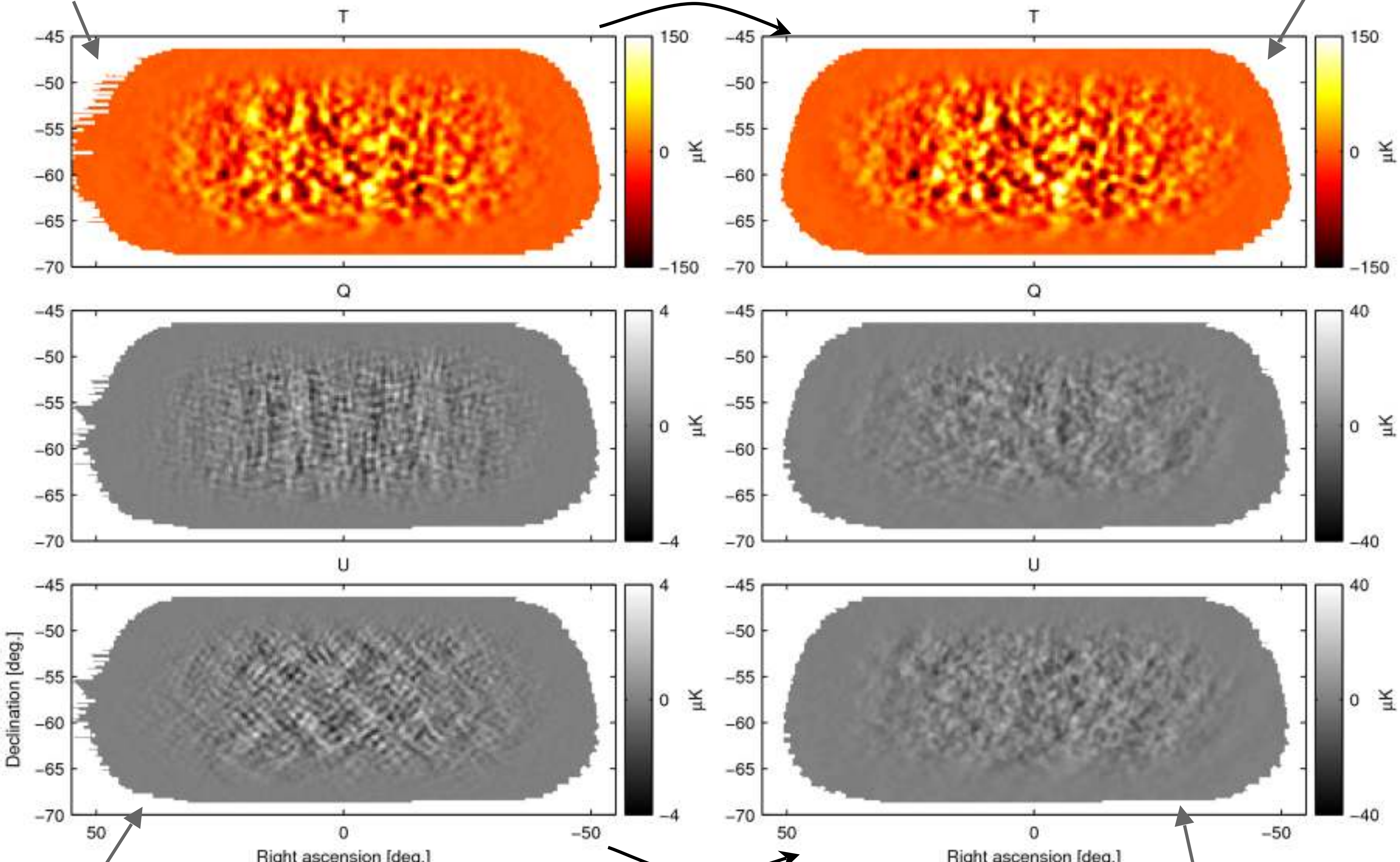
Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates
at high frequencies

Compare BK 150 GHz (left) with Planck 353 GHz (right)

Dominated by LCDM T

T maps same color stretch

Dominated by LCDM T

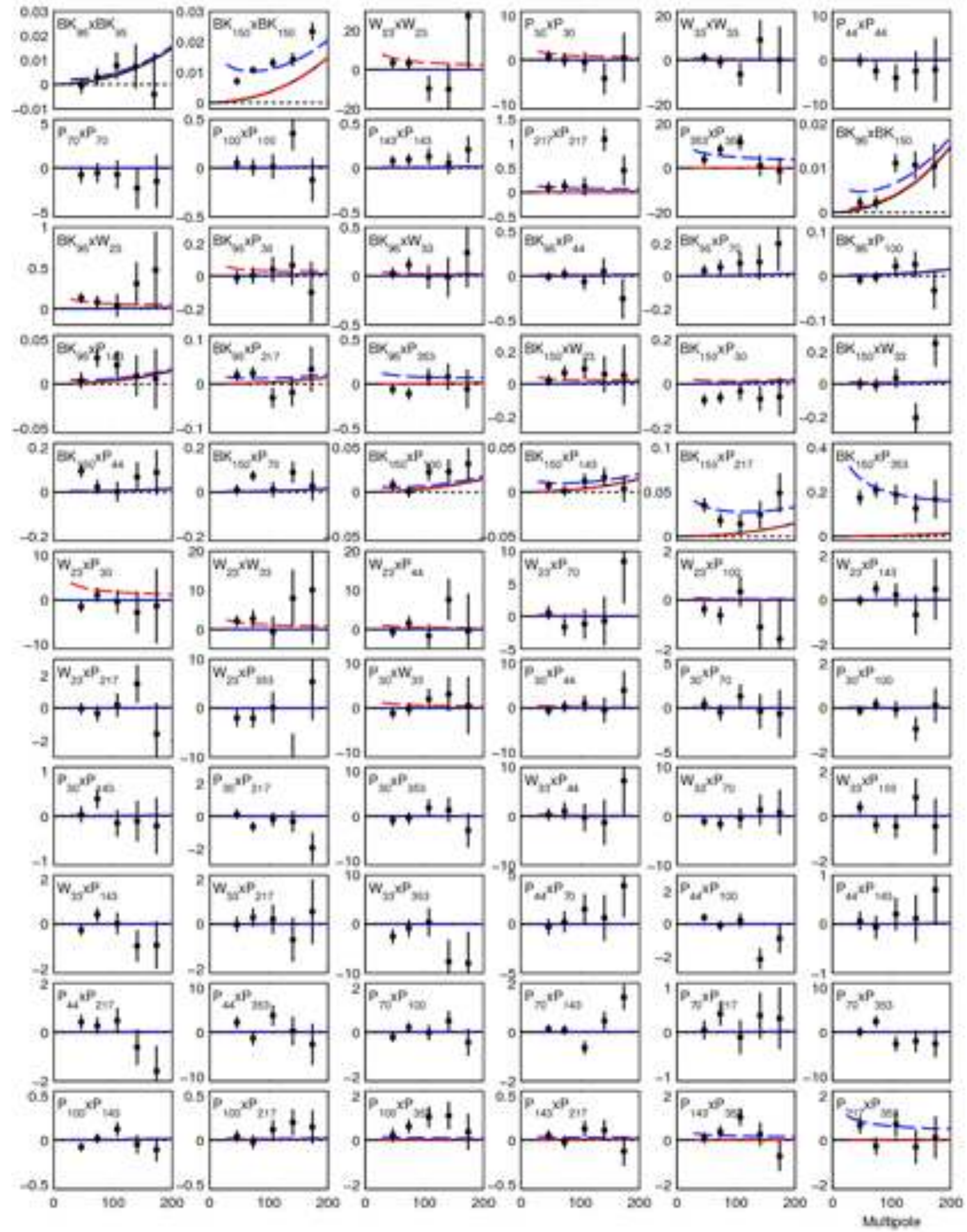


Dominated by LCDM E-modes

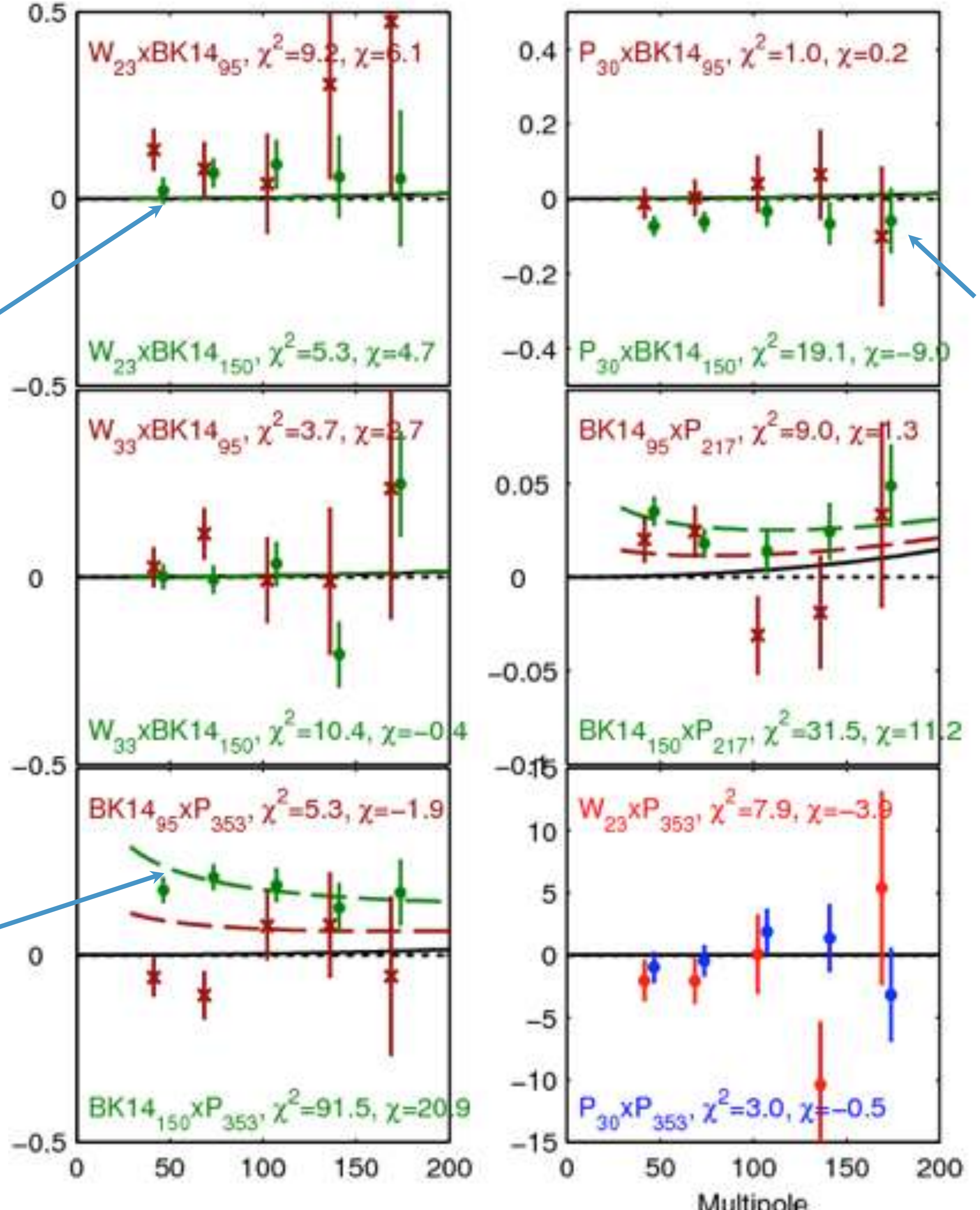
Q/U maps x10 color stretch

Dominated by noise & dust

Take all possible auto- and cross- spectra! (66 of them)



A sample of interesting spectra



23x150 shows hint of synchrotron…

but 30x150 doesn't want it

Strong detection of dust in 150x353

No evidence for dust/sync correlation in 23x353 etc.

Multi-component multi-spectral likelihood analysis

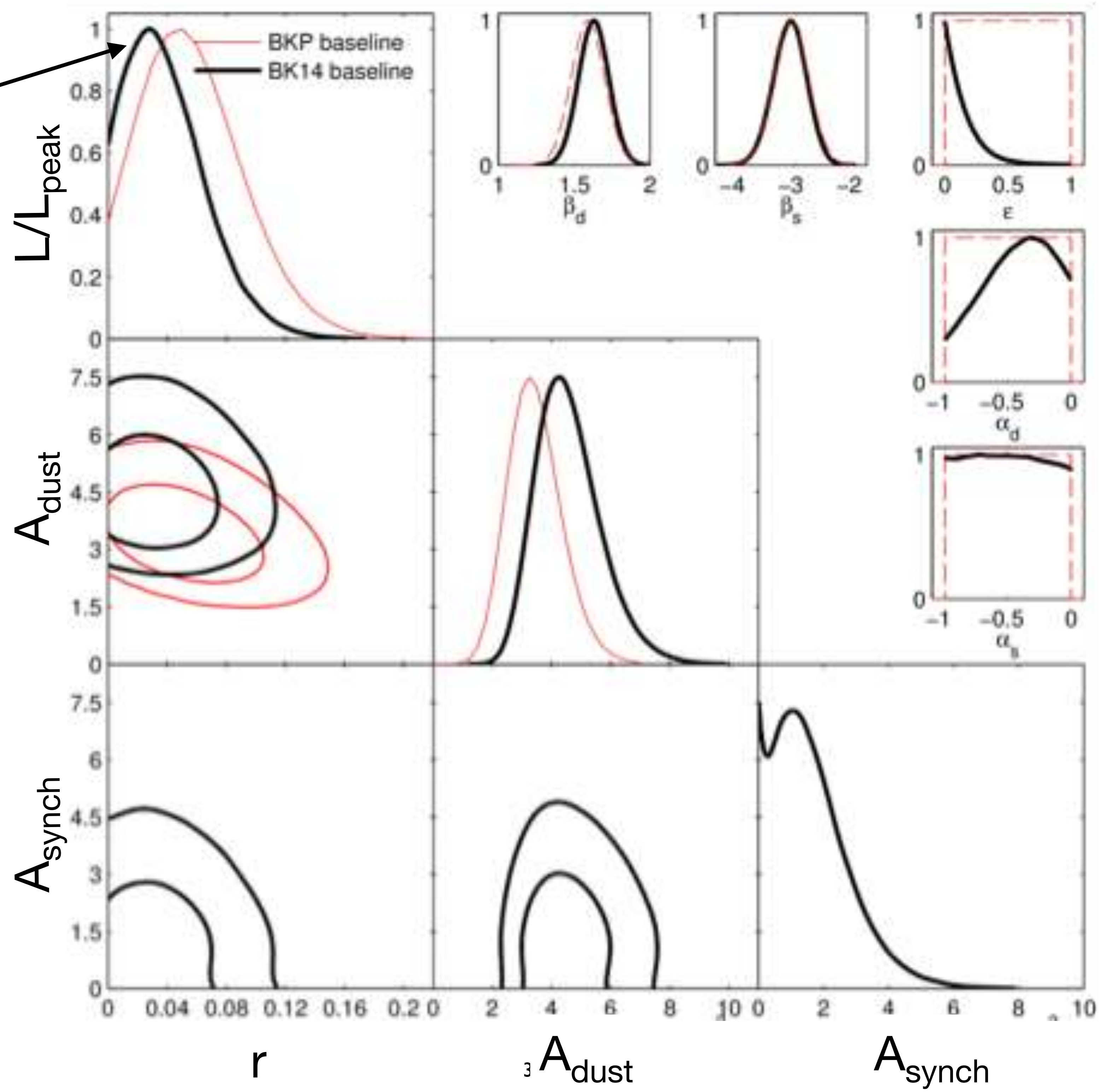
r<0.09
(95% CL)

dust vs. r
degeneracy lifted

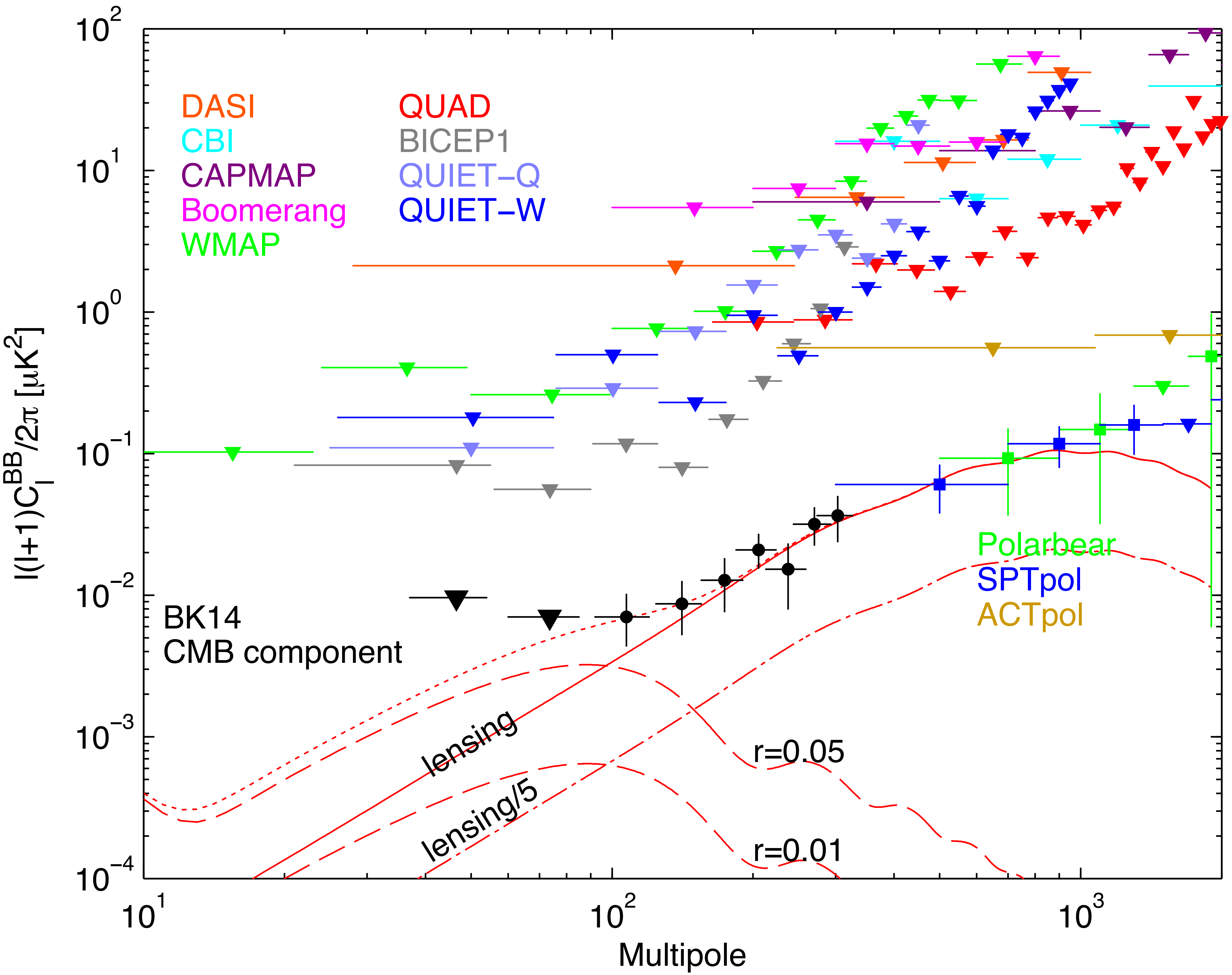
Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

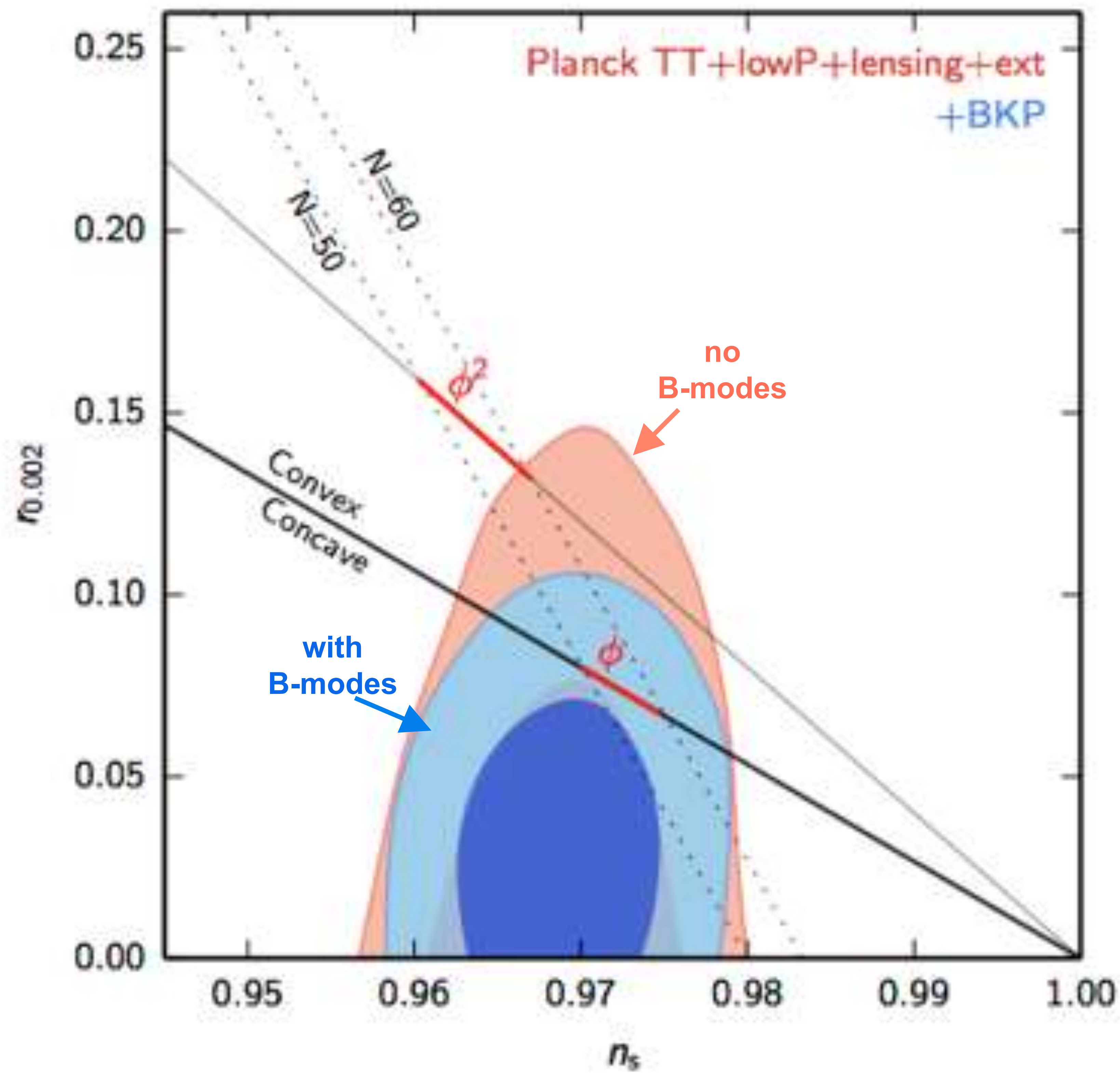
Marginalize over generous ranges in spatial spectral indices



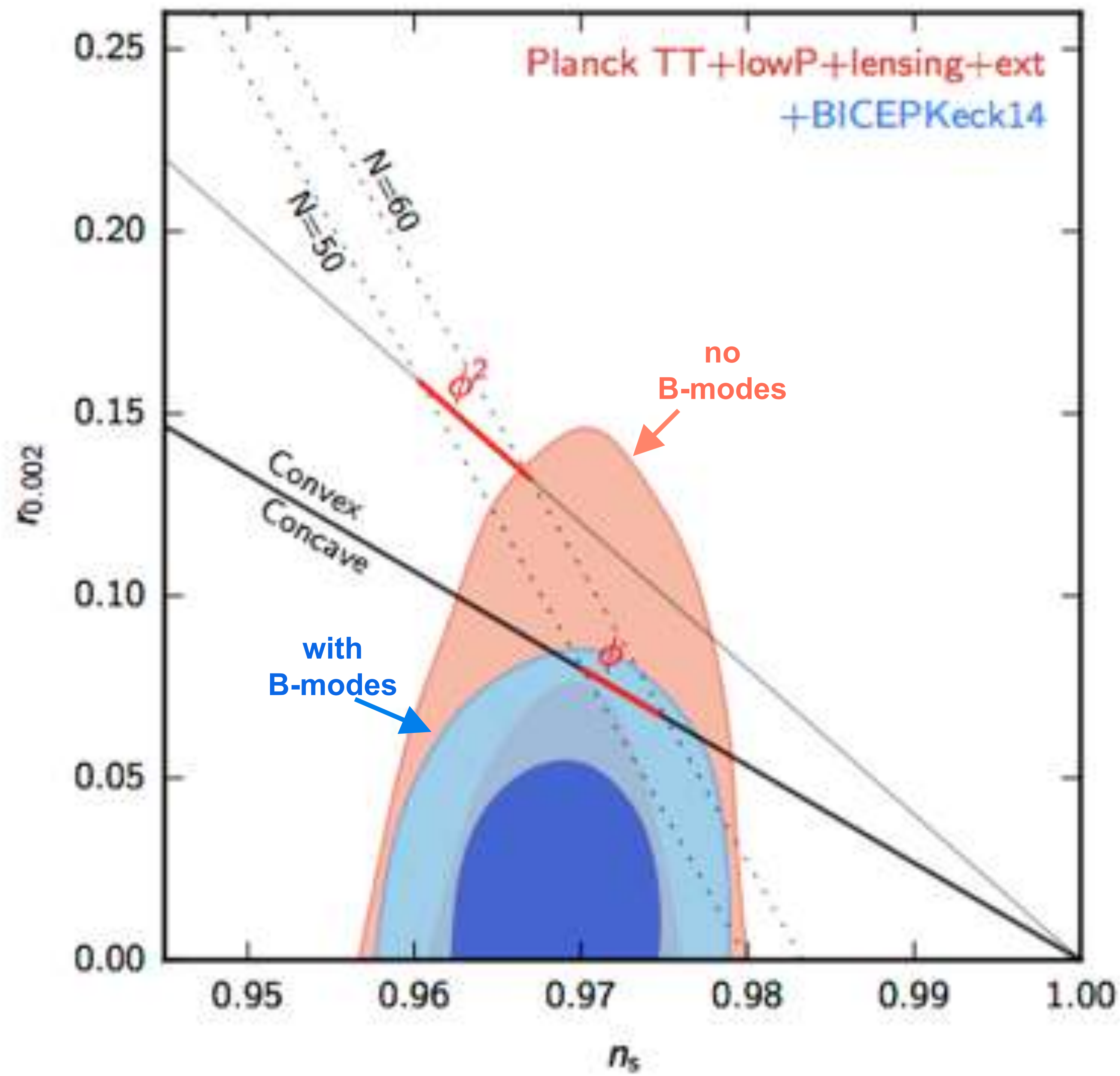
State of the field (BB power spectrum)



Inflation parameter space

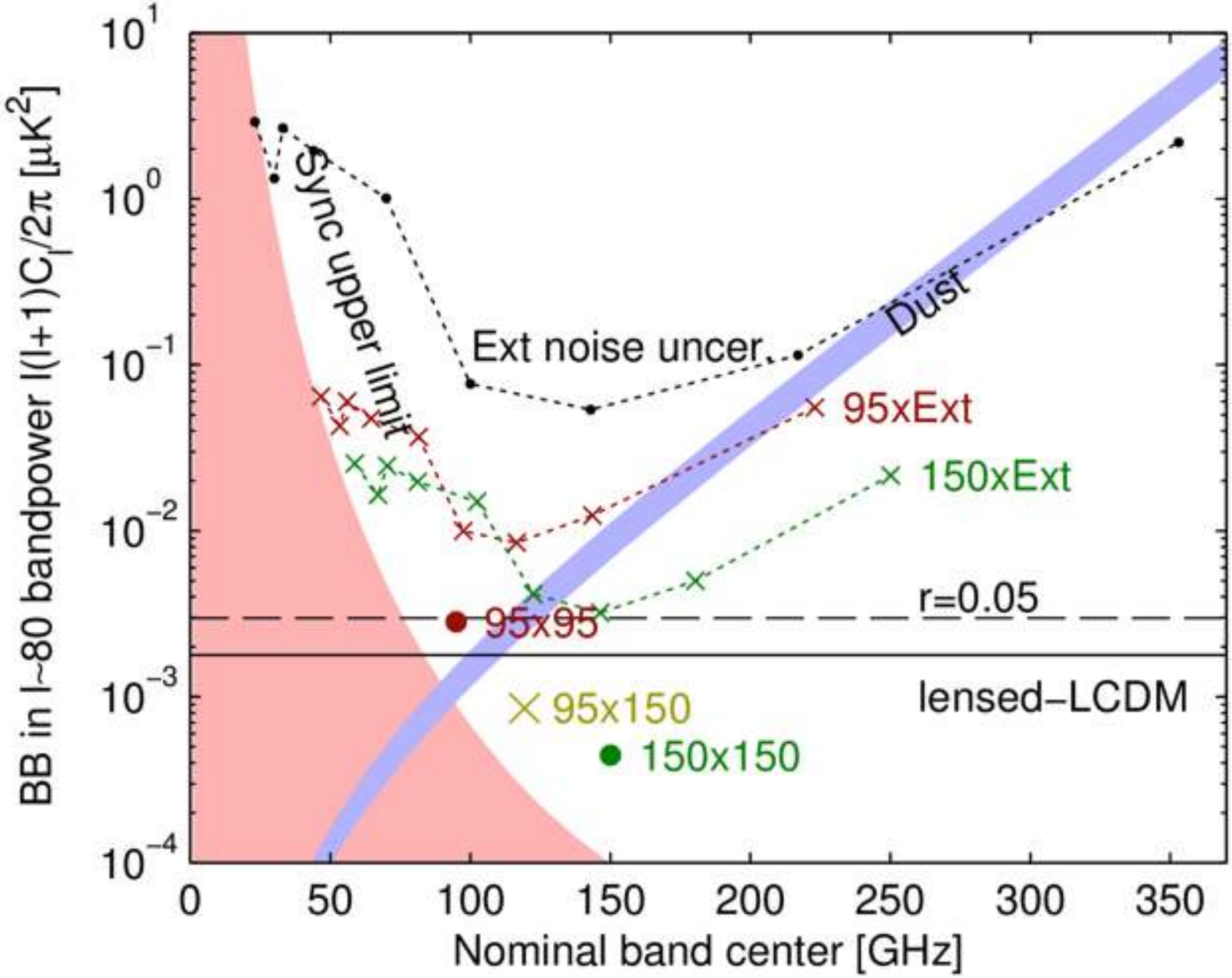


Inflation parameter space



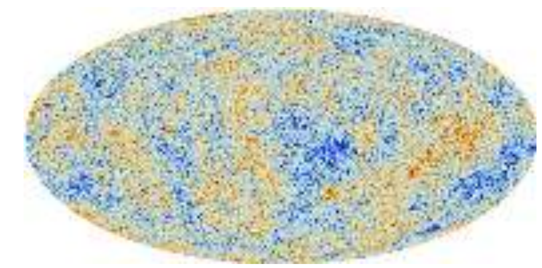
$r_{.05} < 0.07$

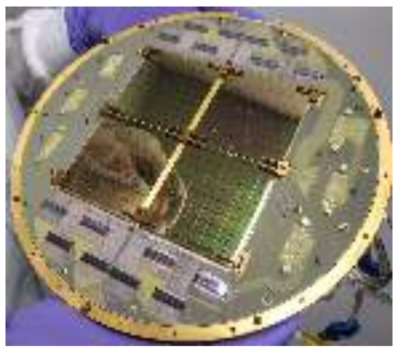
Comparison of signal levels and noise uncertainties at ell=80



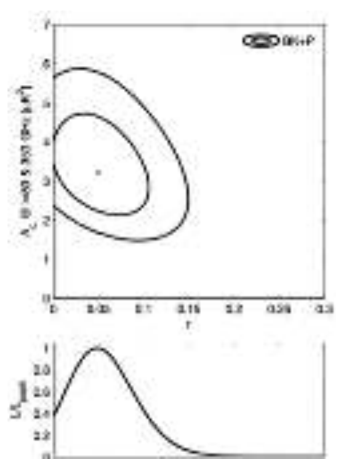
Outline

1. Cosmology — CMB, Inflation, B-modes



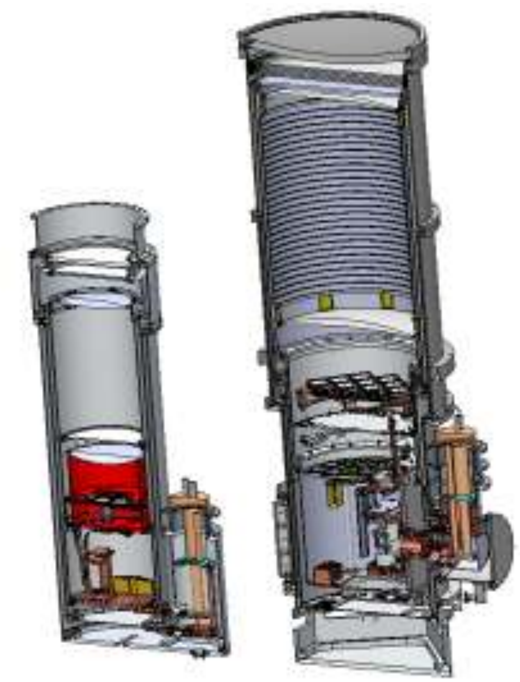


2. The Compact Refractor Strategy — BICEP/Keck
Detectors, Receivers, Site, Observing

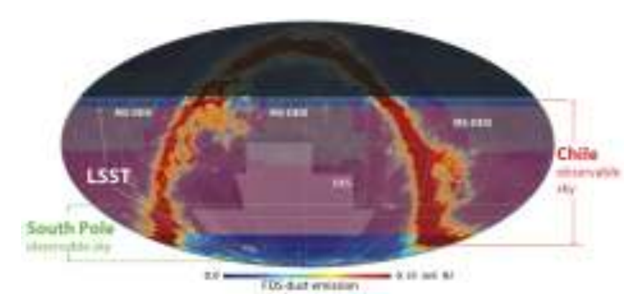


3. Latest BICEP2+Keck+Planck (BKP) results

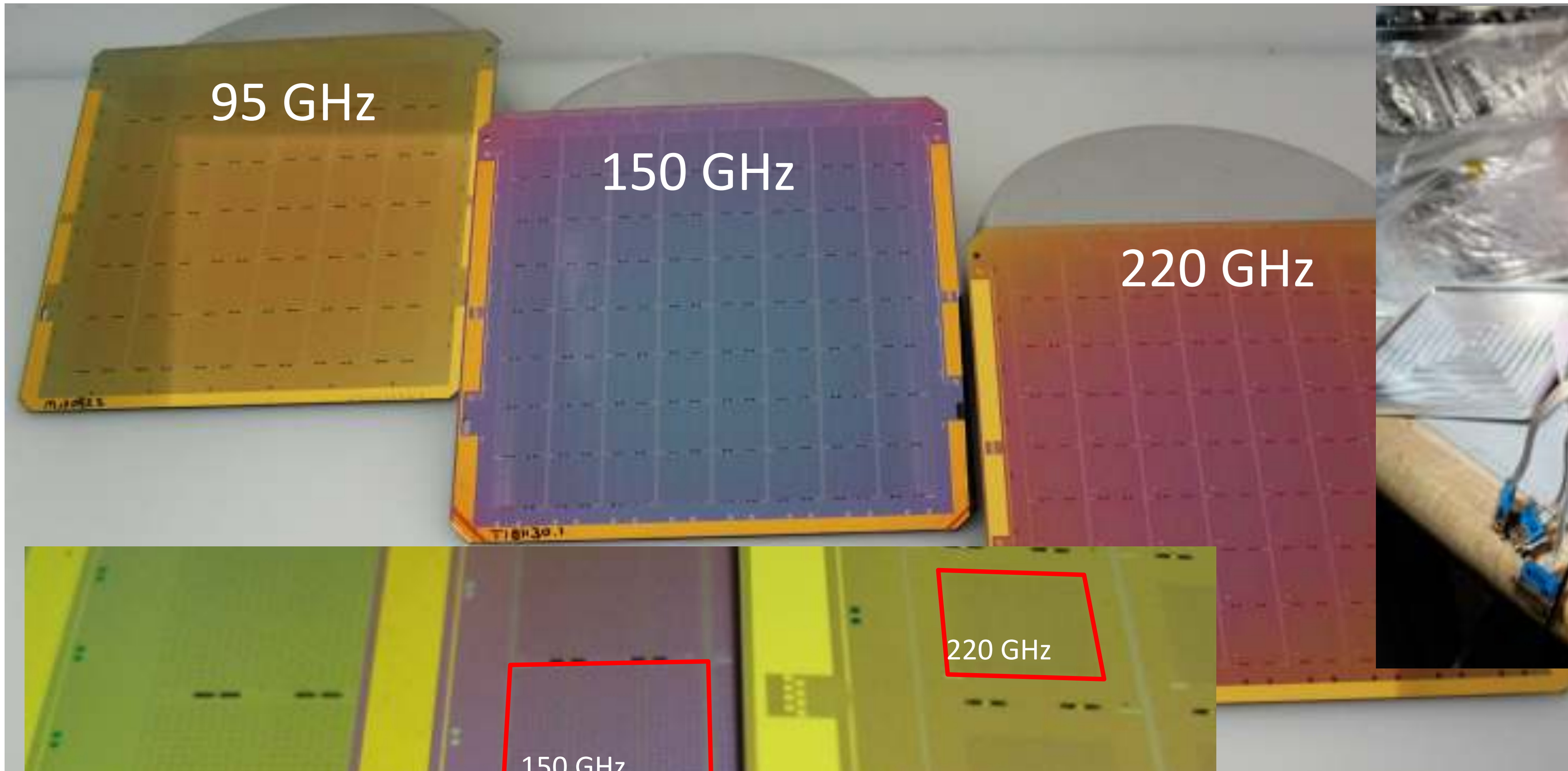
4. Multifrequency program, BICEP3

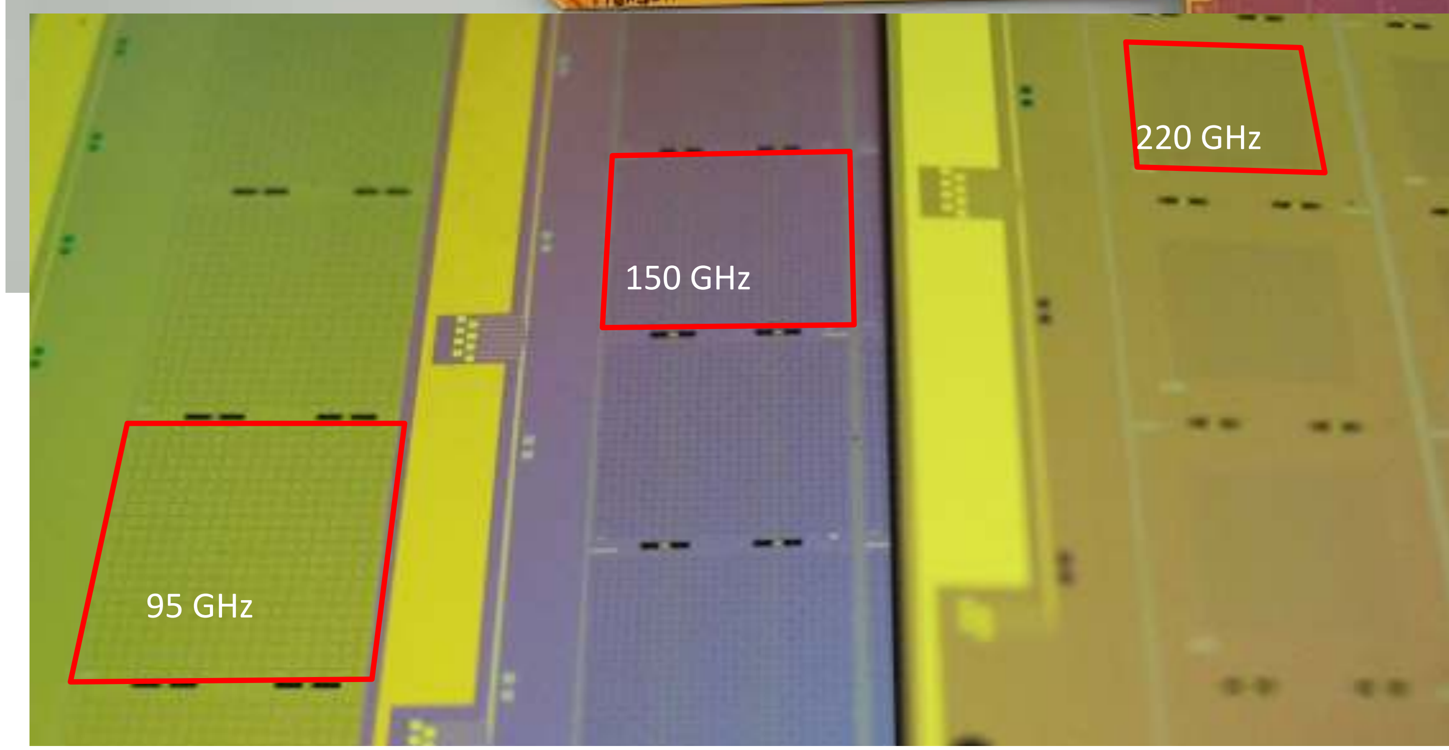


5. The future — adapting and scaling BICEP3 for surveys



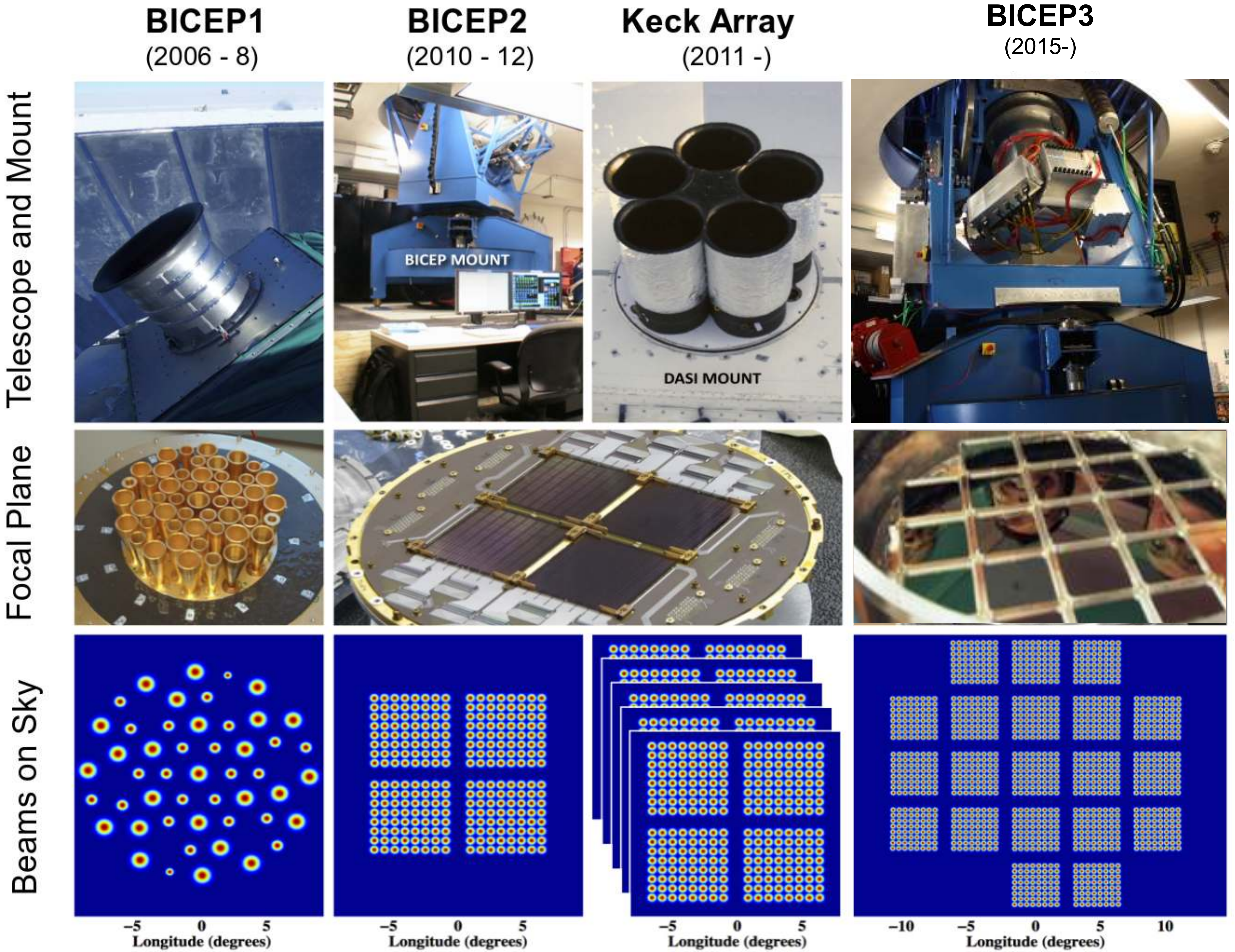
Keck 2014-16 multi-frequency upgrades



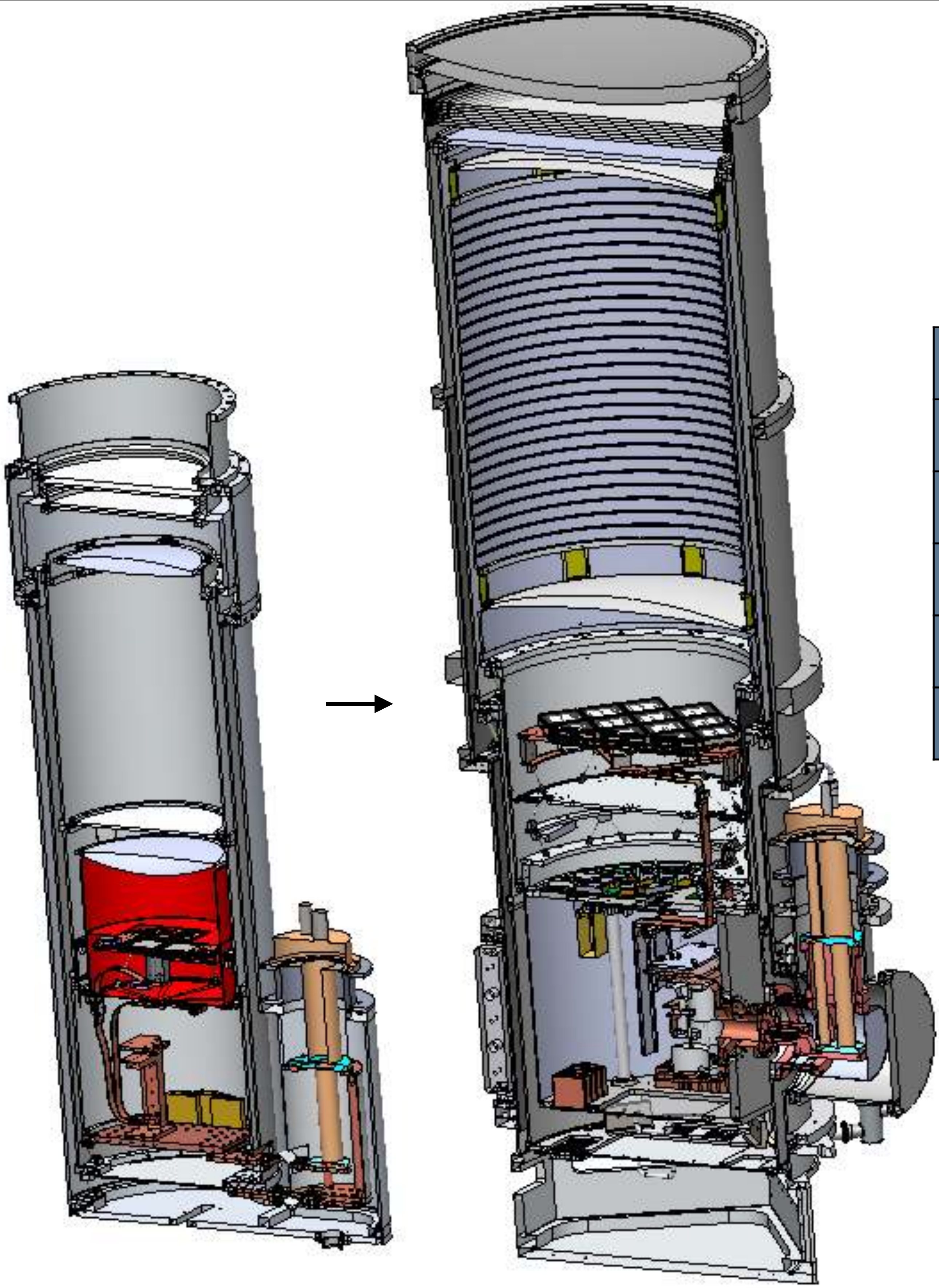


Keck now observing at multiple frequencies

- 2014: 3x150, 2x95
- 2015: 1x150, 2x95, 2x220
- 2016:1x150, 4x220


BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2015-)
Telescope and Mount
Focal Plane
Beams on Sky
BICEP MOUNT
DASI MOUNT
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−10 −5 0 5 10
Longitude (degrees)

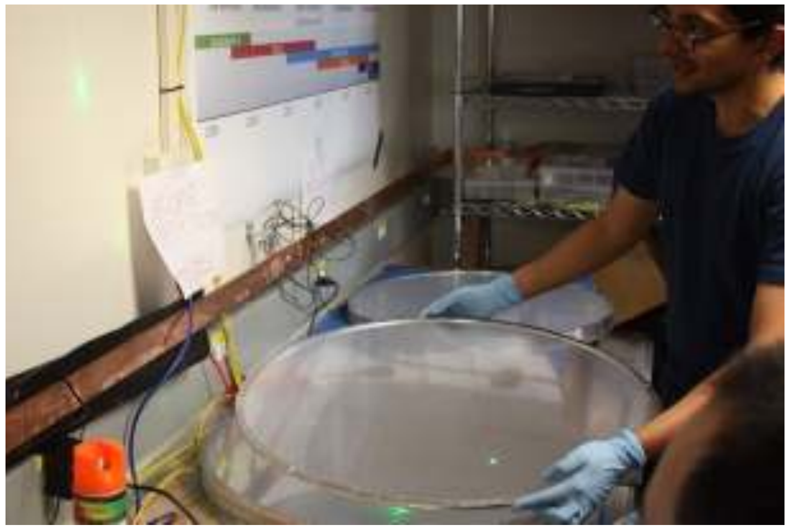
Scale to a super-receiver w/ 10x throughput



	B2/Keck	BICEP3
Aperture	260mm	680mm
Optics	f/2.4	f/1.6
FOV	18 deg	28 deg
Beams	0.7 deg	0.35 deg
Dets	288	2560

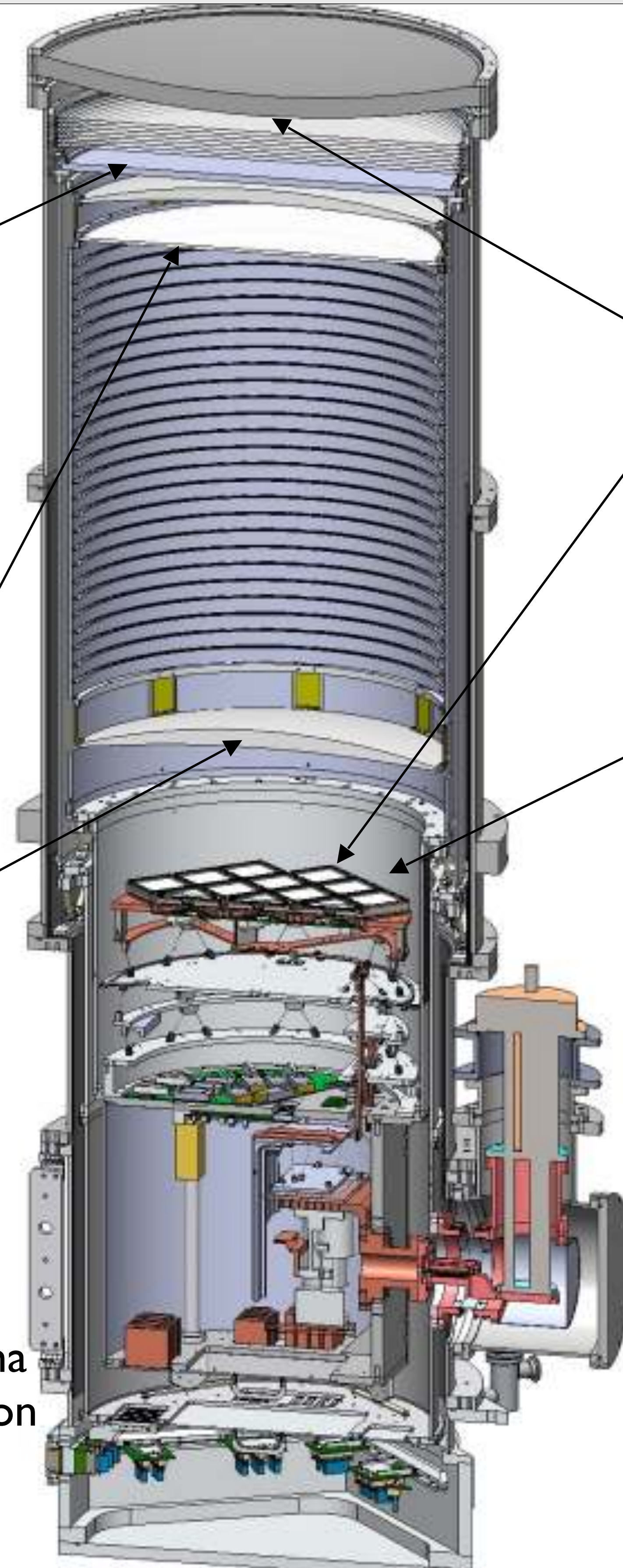
*comparisons at 95 GHz

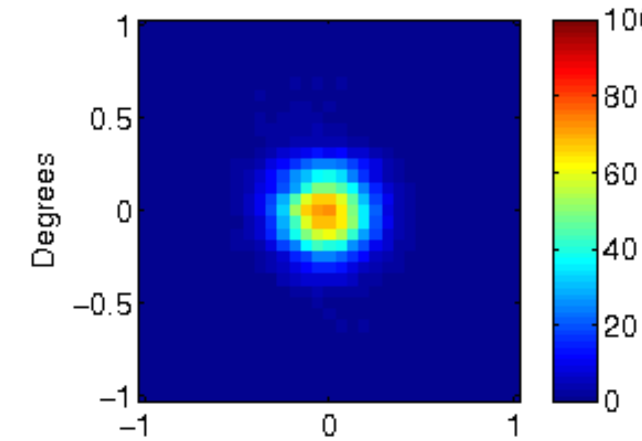
BICEP3 technology



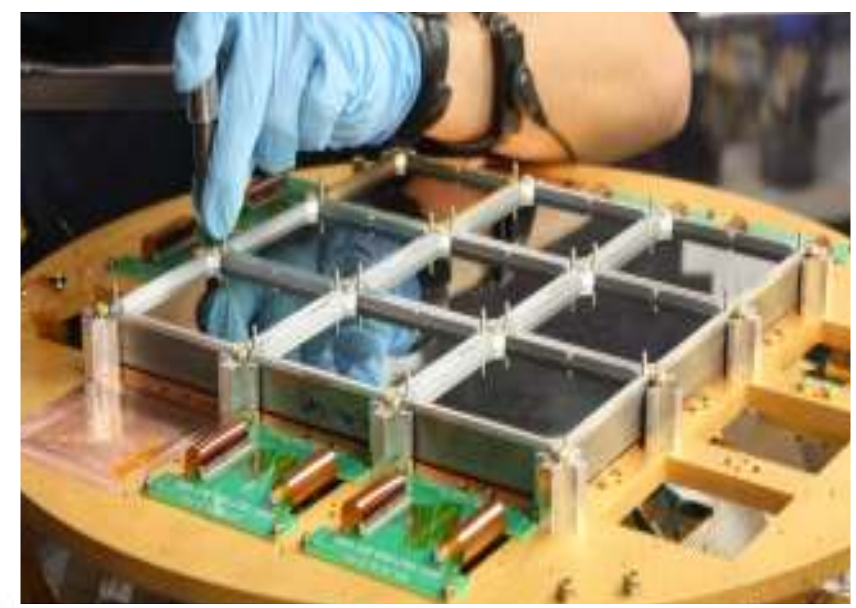
Large area Infrared shaders with ~O(10) micron aluminum features on mylar

Thin, low loss, high thermal conductivity alumina filters and lenses with epoxy-based antireflection coating





680-mm clear aperture window, fast optics (f/1.6), FOV ~28°
95 GHz beam FWHM ~0.35°



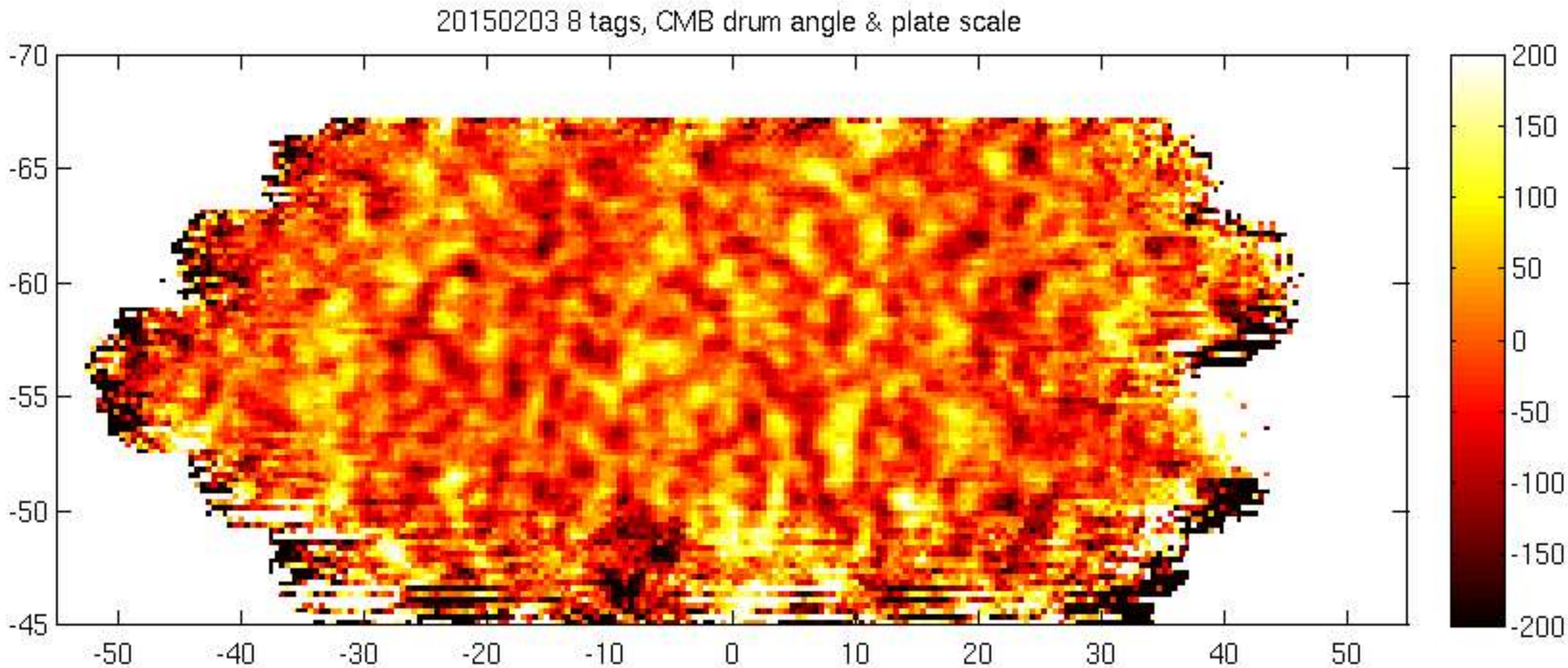
Plug & play detector modules each have 64 dual-pol 95 GHz camera pixels and contain cold multiplexing electronics. Contain all of Keck in one receiver!

December 2014: BICEP3 assembly at South Pole

January 2015: Installed in BICEP mount

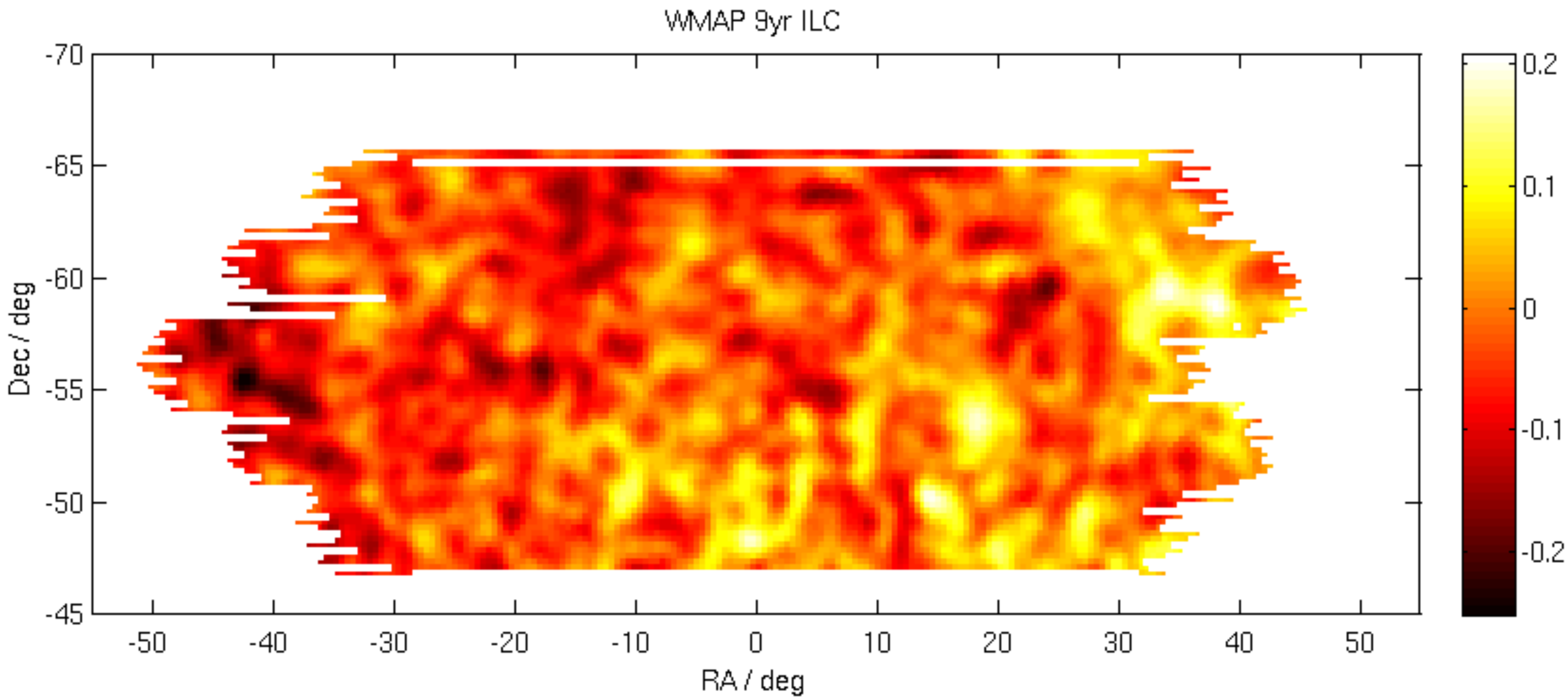
Replaces BICEP2 in Dark Sector Lab at South Pole

First light: See CMB T anisotropies in 6 hours!



BICEP3 first six hours of test CMB scans,
no filtering, approximate noise weighting and calibration

First light: Compare with WMAP 9 yr



WMAP 9yr T anisotropies as seen in BICEP field

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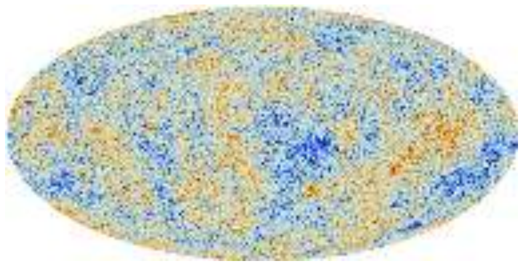

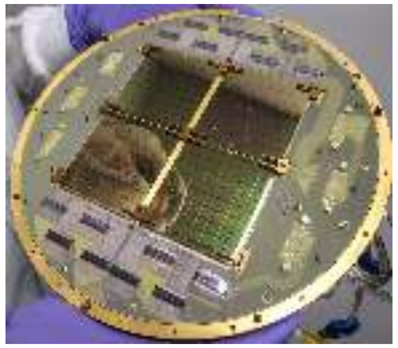

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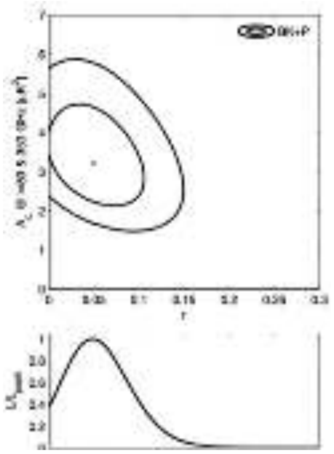

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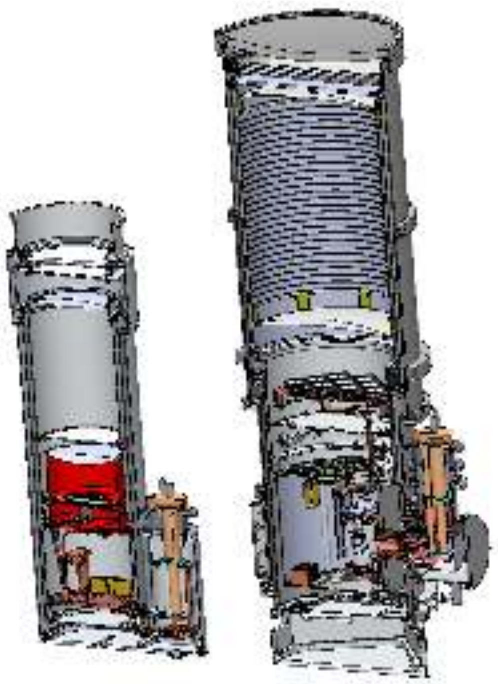

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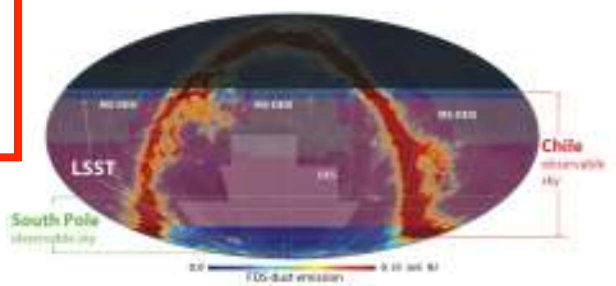
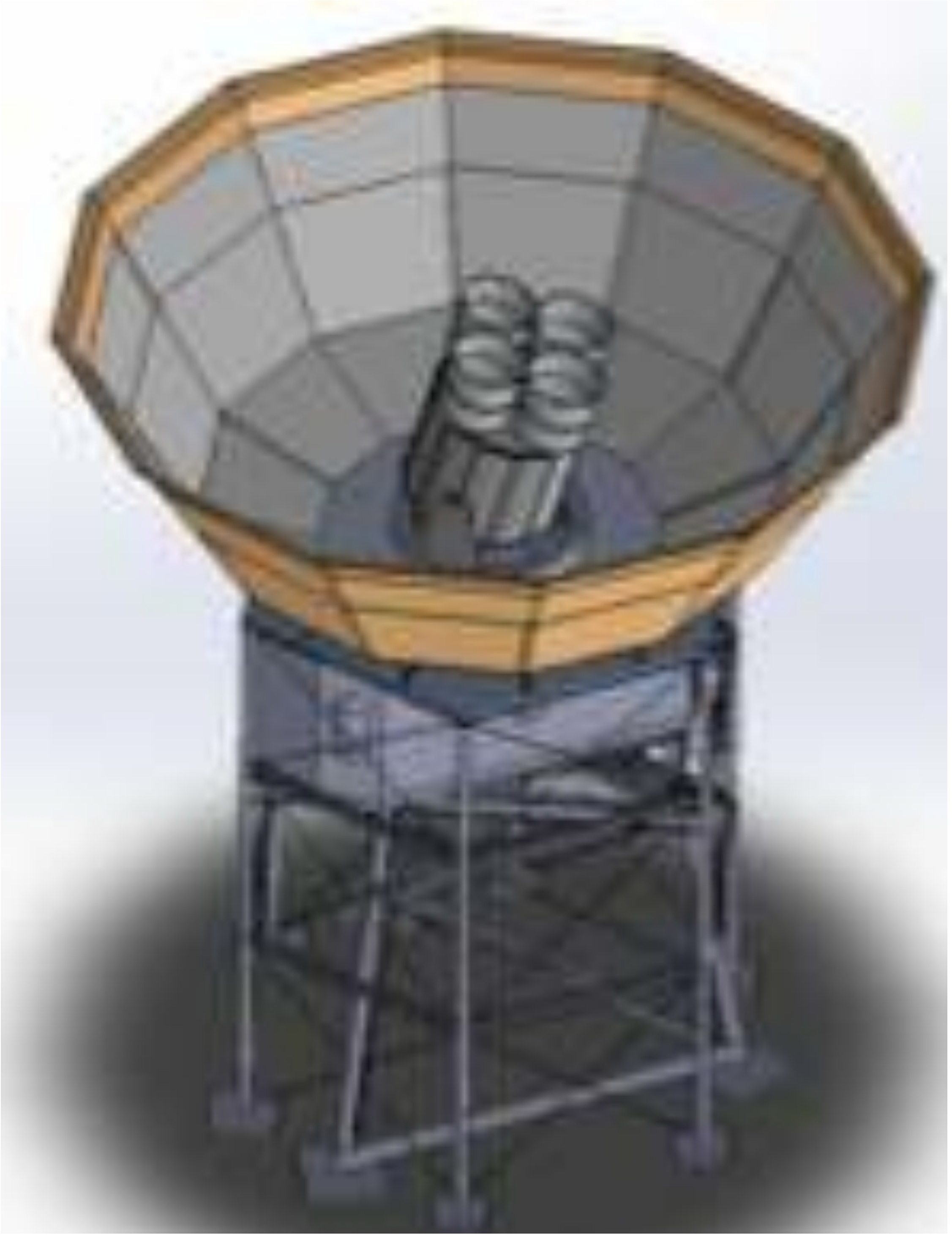


BICEP Array (2018-22)

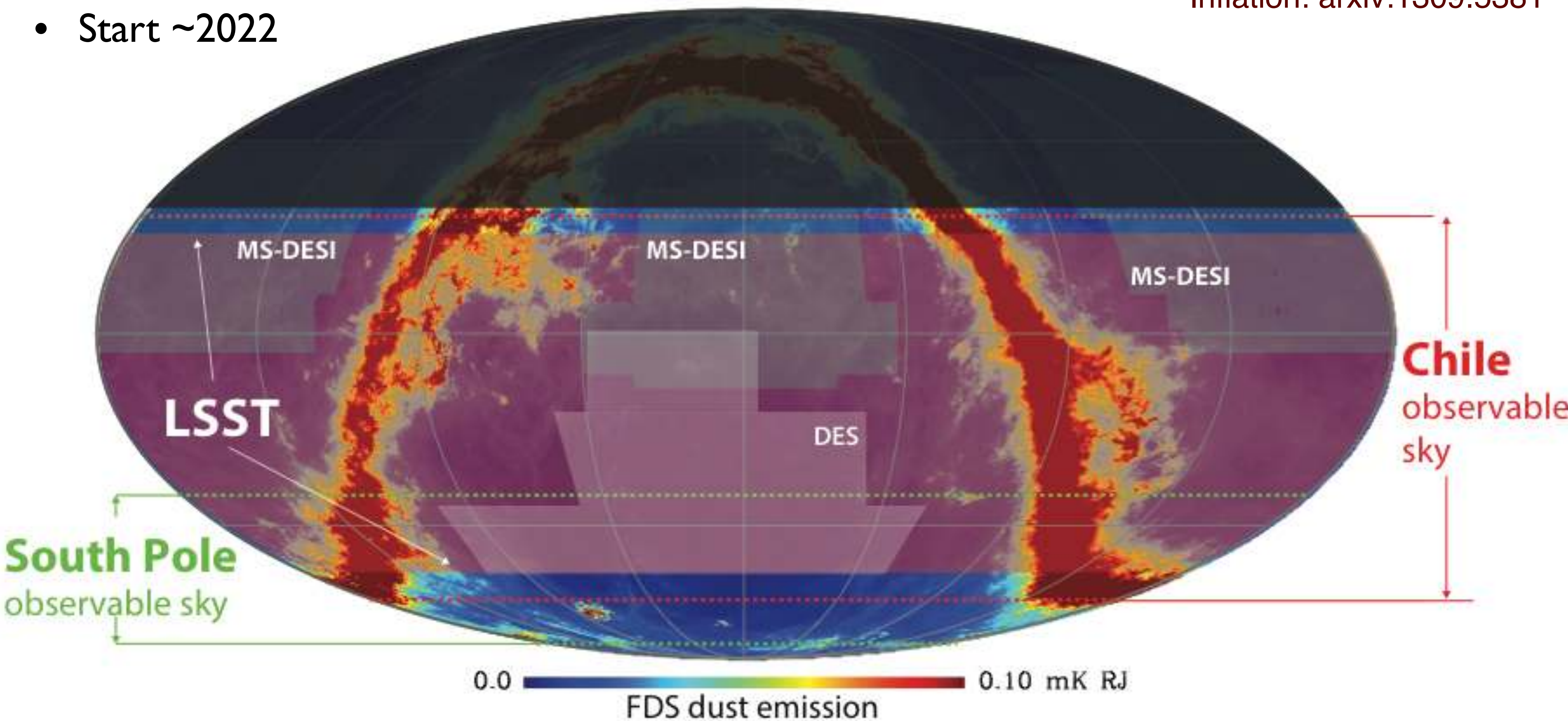
- Replace BICEP2-style receivers in Keck with BICEP3-style receivers
- ~20,000 detectors
- Multifrequency bands (eg. 35, 95, 150, 220, 250, 270 GHz)
- $\boldsymbol{\sigma}$(r) ~ 0.005 for standard foreground scaling and removal, no delensing.



'CMB-S4' Stage 4 CMB experiment

- 200,000 - 500,000 detectors on multiple platforms
- 40 - 240 GHz
- Target noise of ~1 μK-arcmin depth over half the sky
- < 3 arcmin resolution
- Start ~2022

CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381



Conclusions

- CMB polarization is a powerful probe of inflation
- BICEP2+Keck sees excess power over ΛCDM at degree scales
- Combining with Planck, WMAP bands, see dust at high significance, no synchrotron.
- $r<0.09$ (95% CL) from polarization. Better for first time than CMB T limit. Combined $r<0.07$ (95% CL).
- Keck 95 GHz, 220 GHz in the field and taking data
- BICEP3 is a leap forward in scalability of compact degree-scale receivers for deeper CMB polarimetry. In the field and taking data
- BICEP3's technology enables next generation experiments, paving way for ground-based large sky survey

Thanks for your attention!