Updates from the BICEP/Keck Array Collaboration

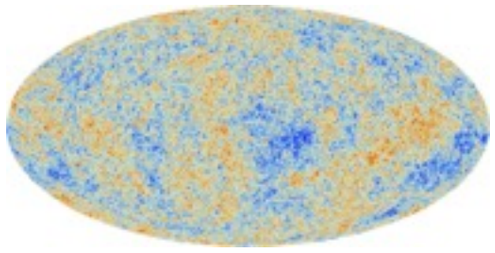
Zeeshan Ahmed
KIPAC, Stanford University

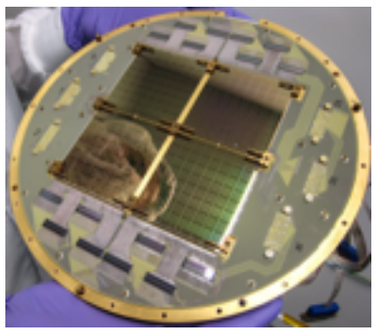
June 8, 2015

String Pheno 2015, IFT UAM-CSIC

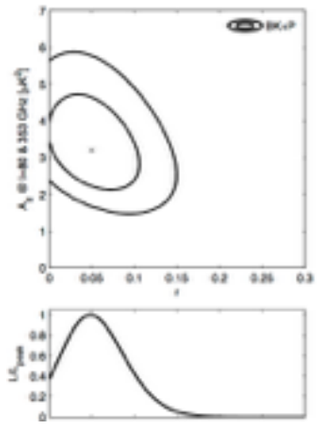
Outline

1. Cosmology — CMB, Inflation, B-modes

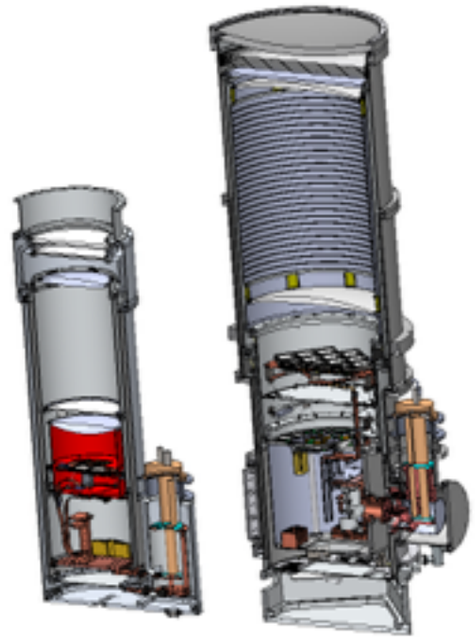




2. The Compact Refractor Strategy — BICEP/Keck
Detectors, Receivers, Site, Observing

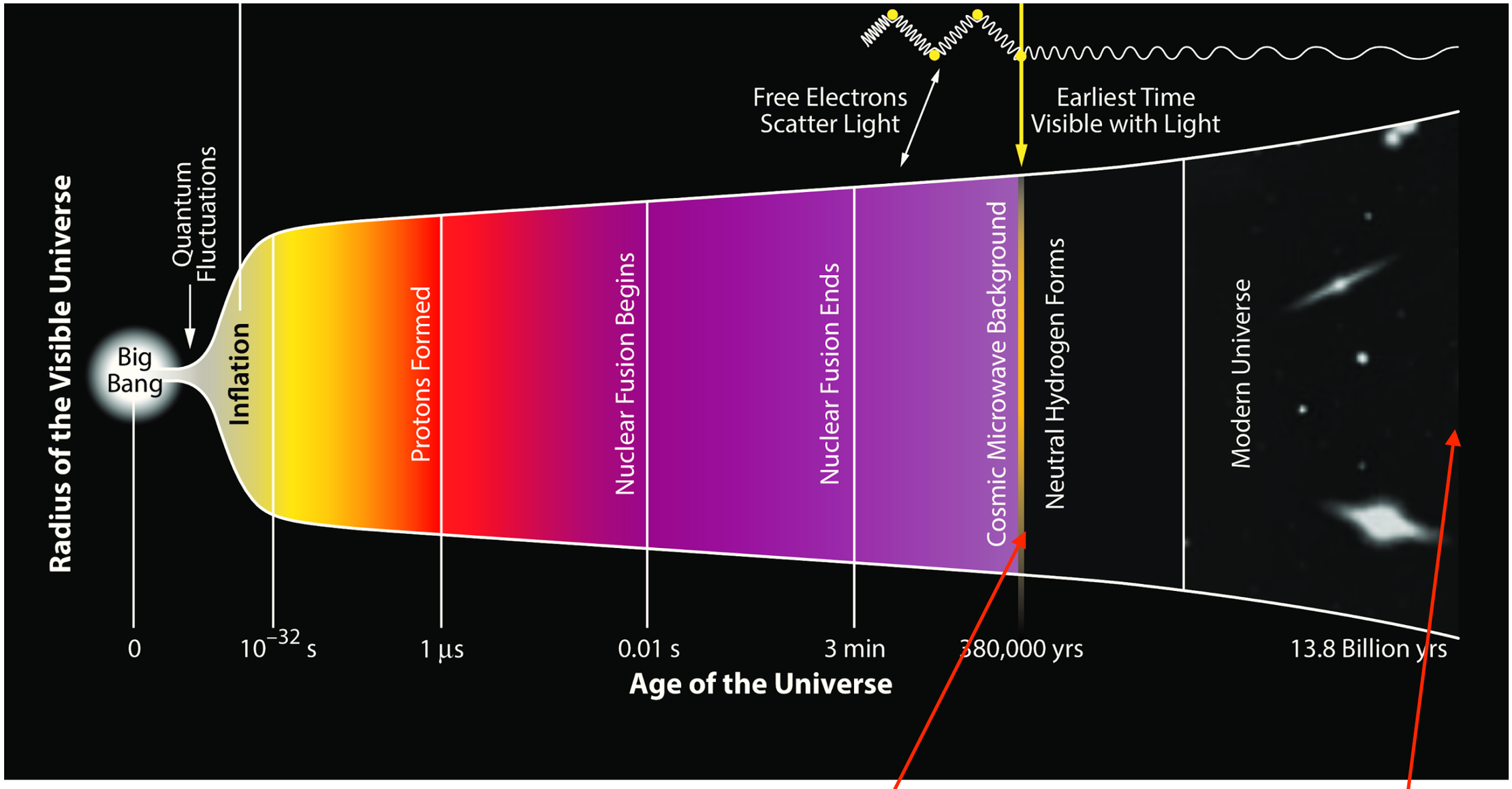


3. BICEP2+Keck+Planck (BKP) results



4. What's under way and coming up next?
multi-frequency Keck, BICEP3

CMB in the story of the Universe

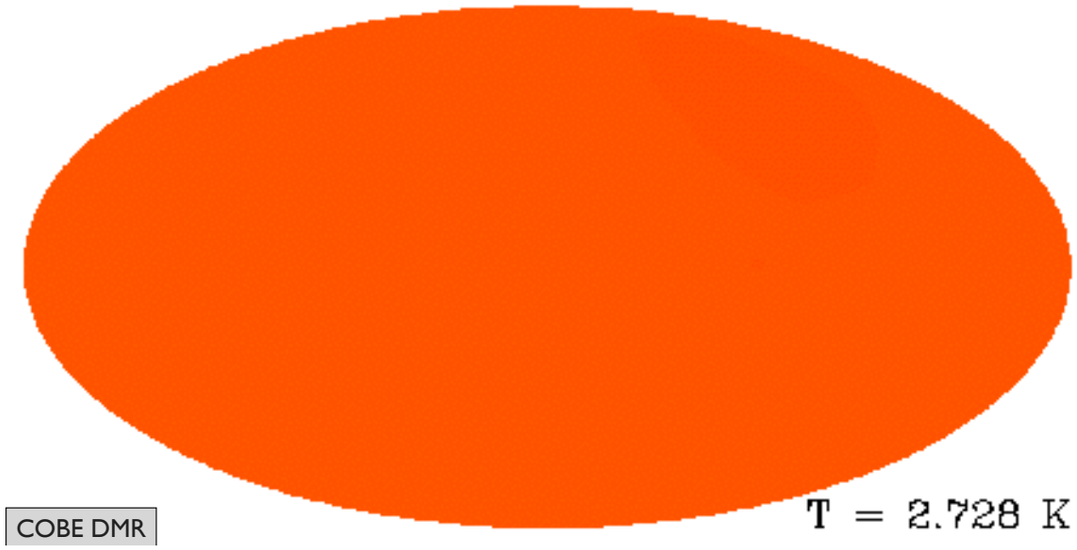


Oldest direct light comes from here; blackbody relic of a small, hot, dense Universe

We are here. Universe appears to be expanding!

Cosmic Microwave Background (CMB)

2.7K blackbody, homogenous, isotropic..



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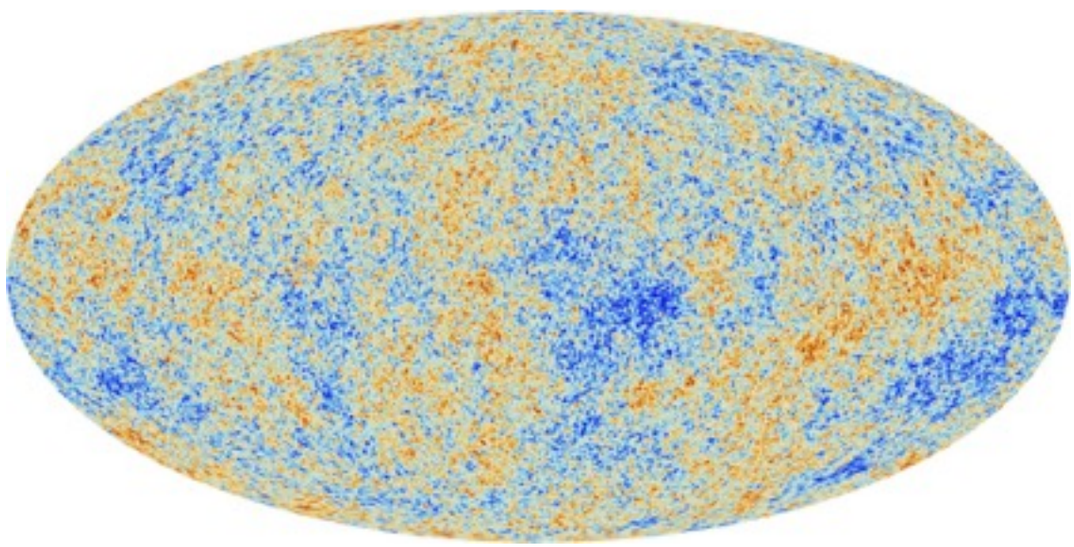
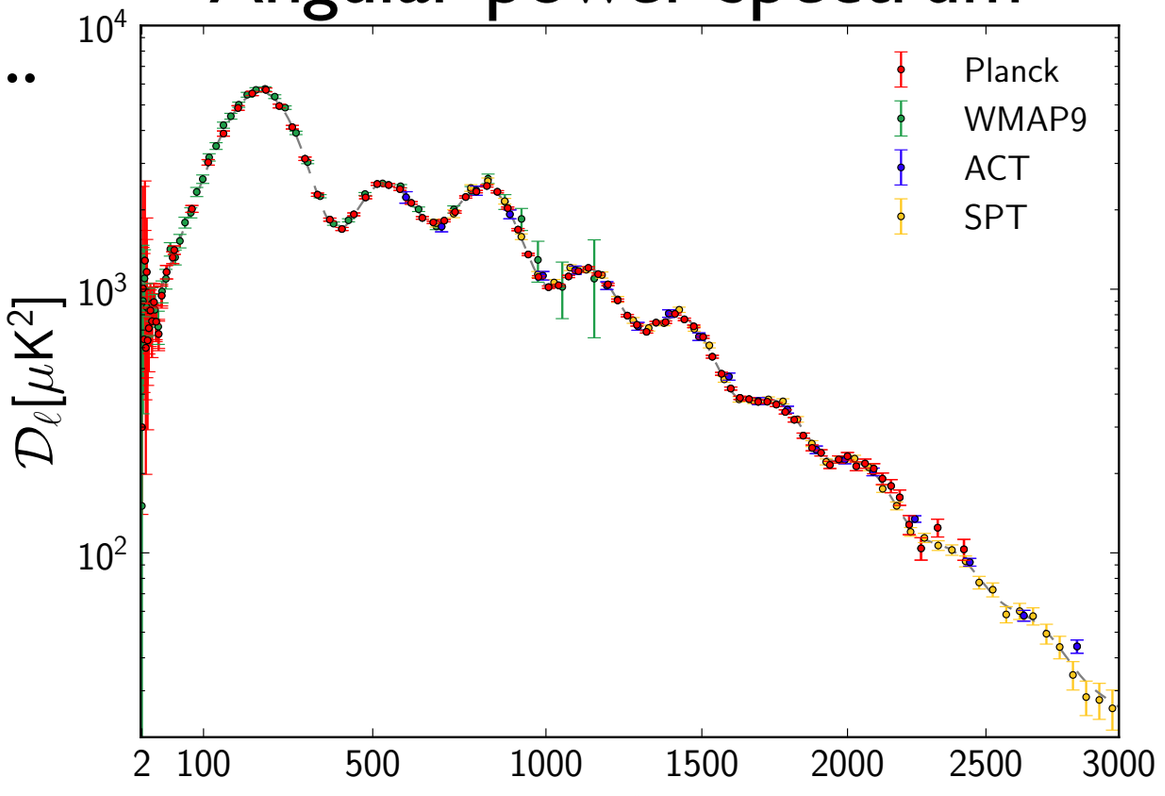
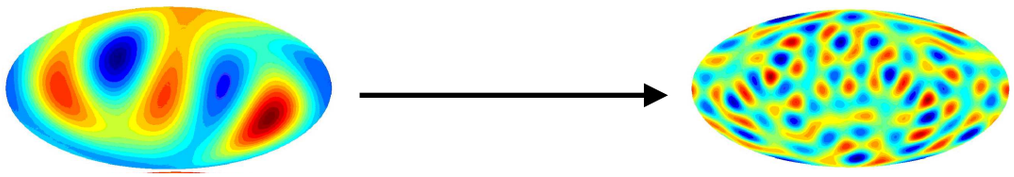


.. anisotropies only at ~10^{-5}

Angular power spectrum



Planck Collaboration, 2013



Large scales

Small scales

Cosmic Microwave Background (CMB)

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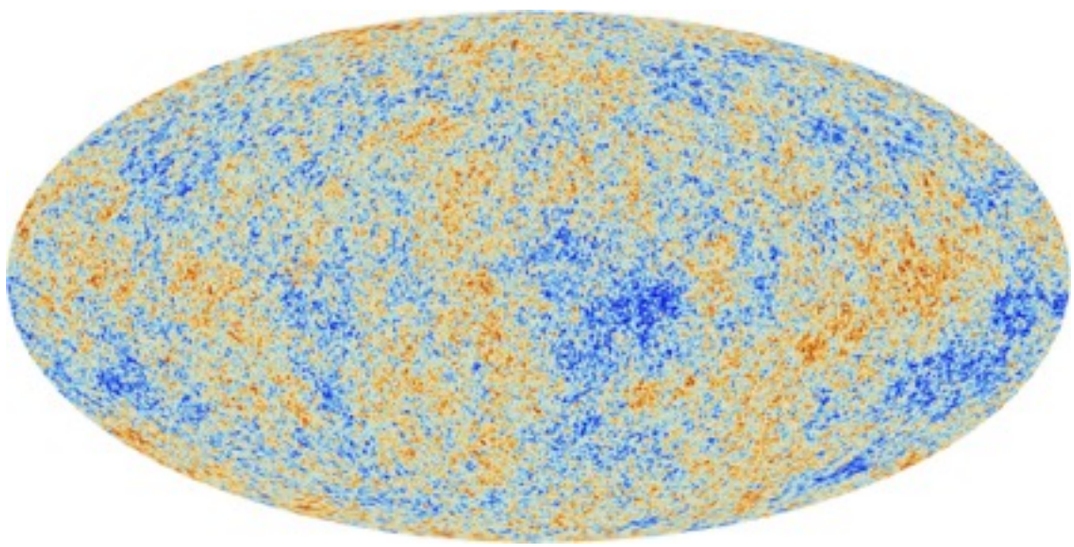

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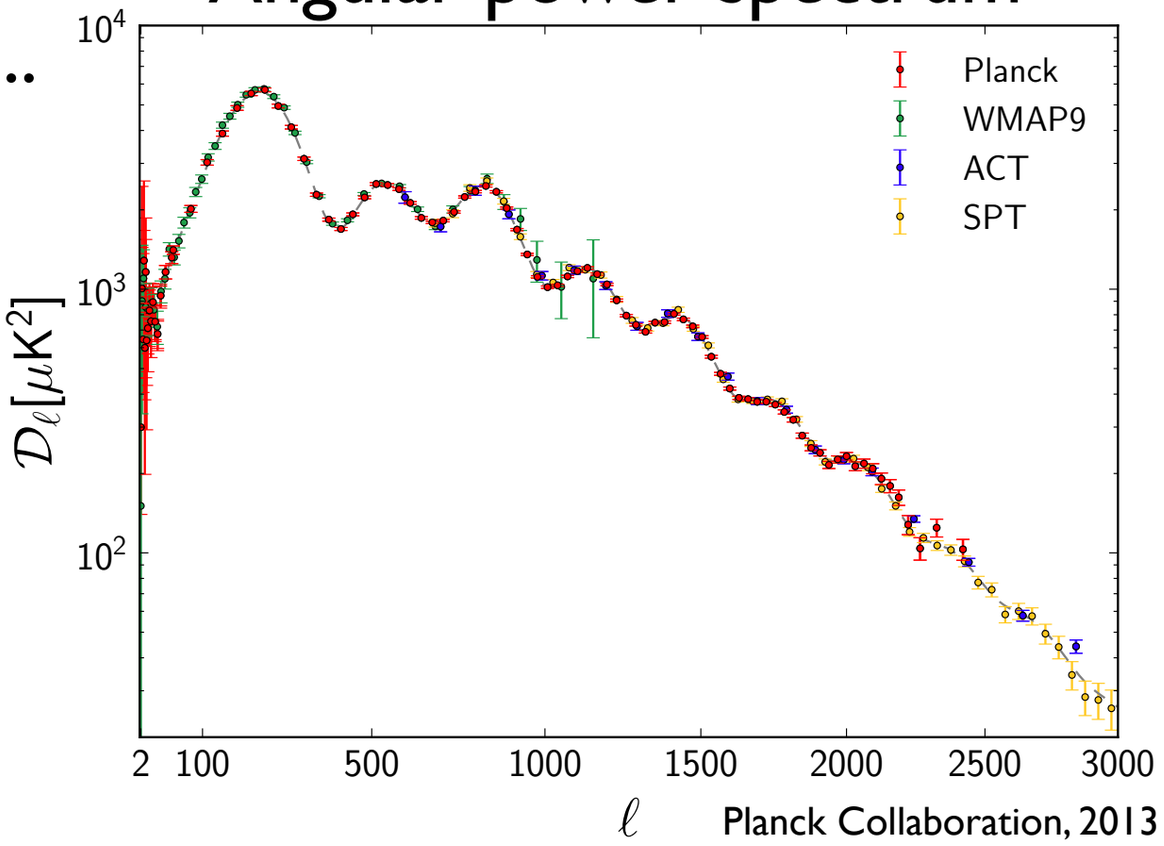
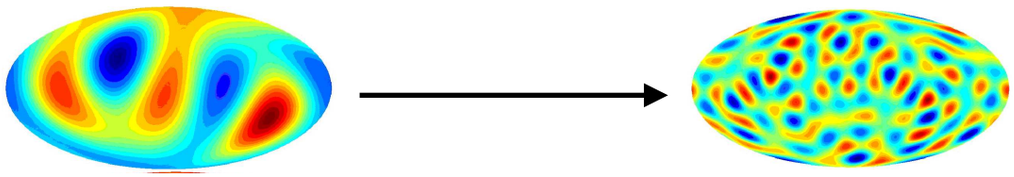


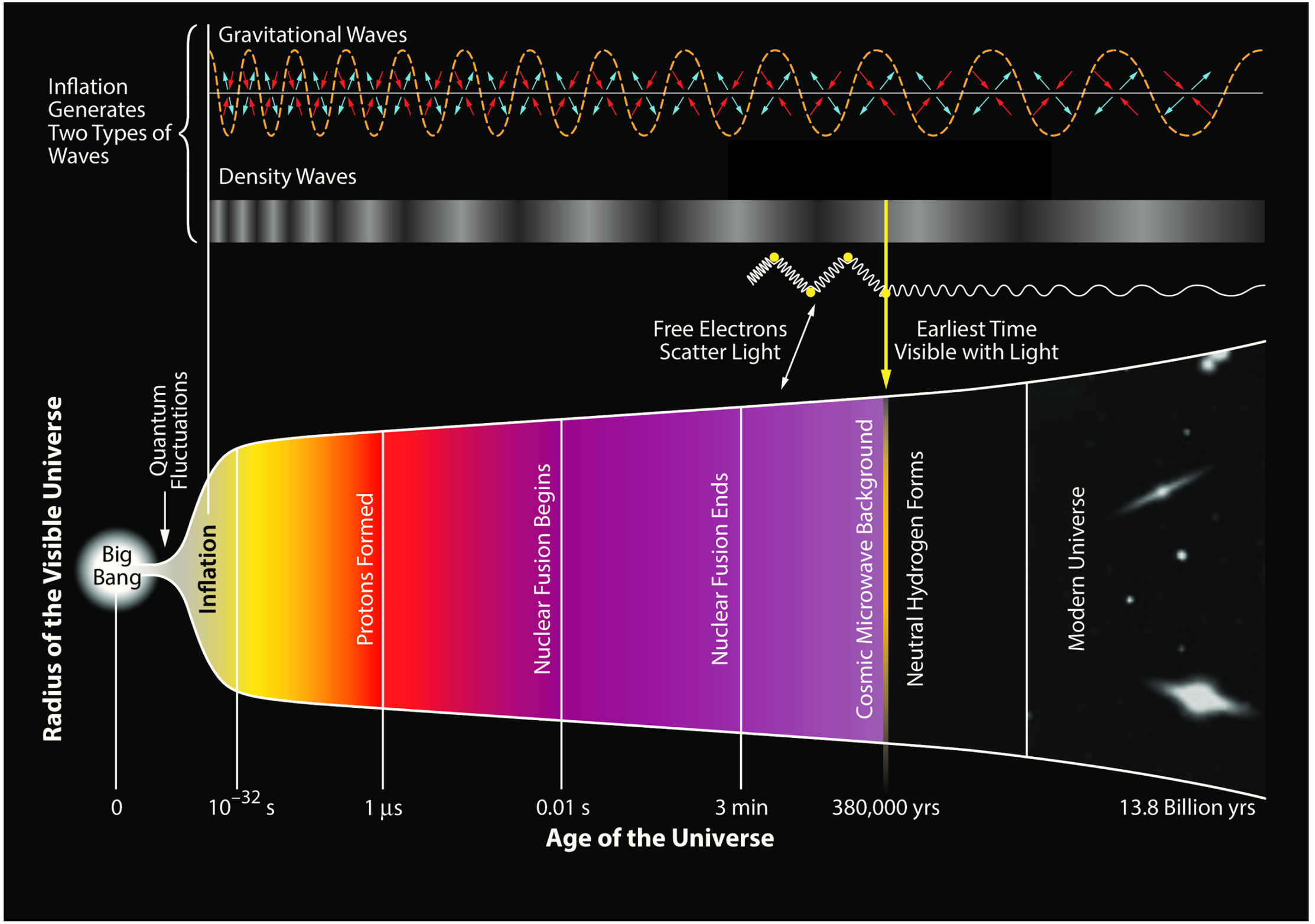


Large scales

Small scales

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

Inflation generates scalar and tensor perturbations



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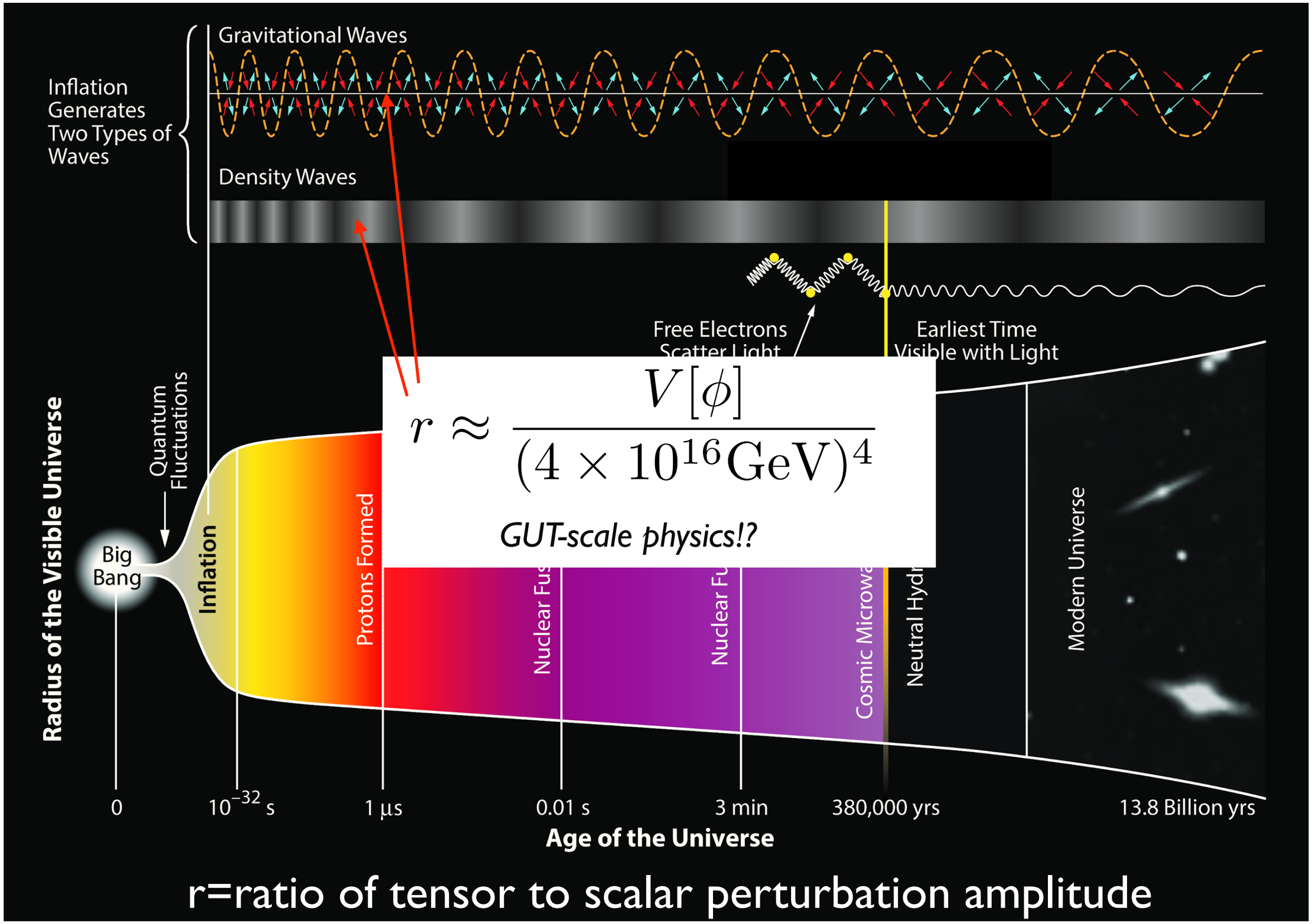
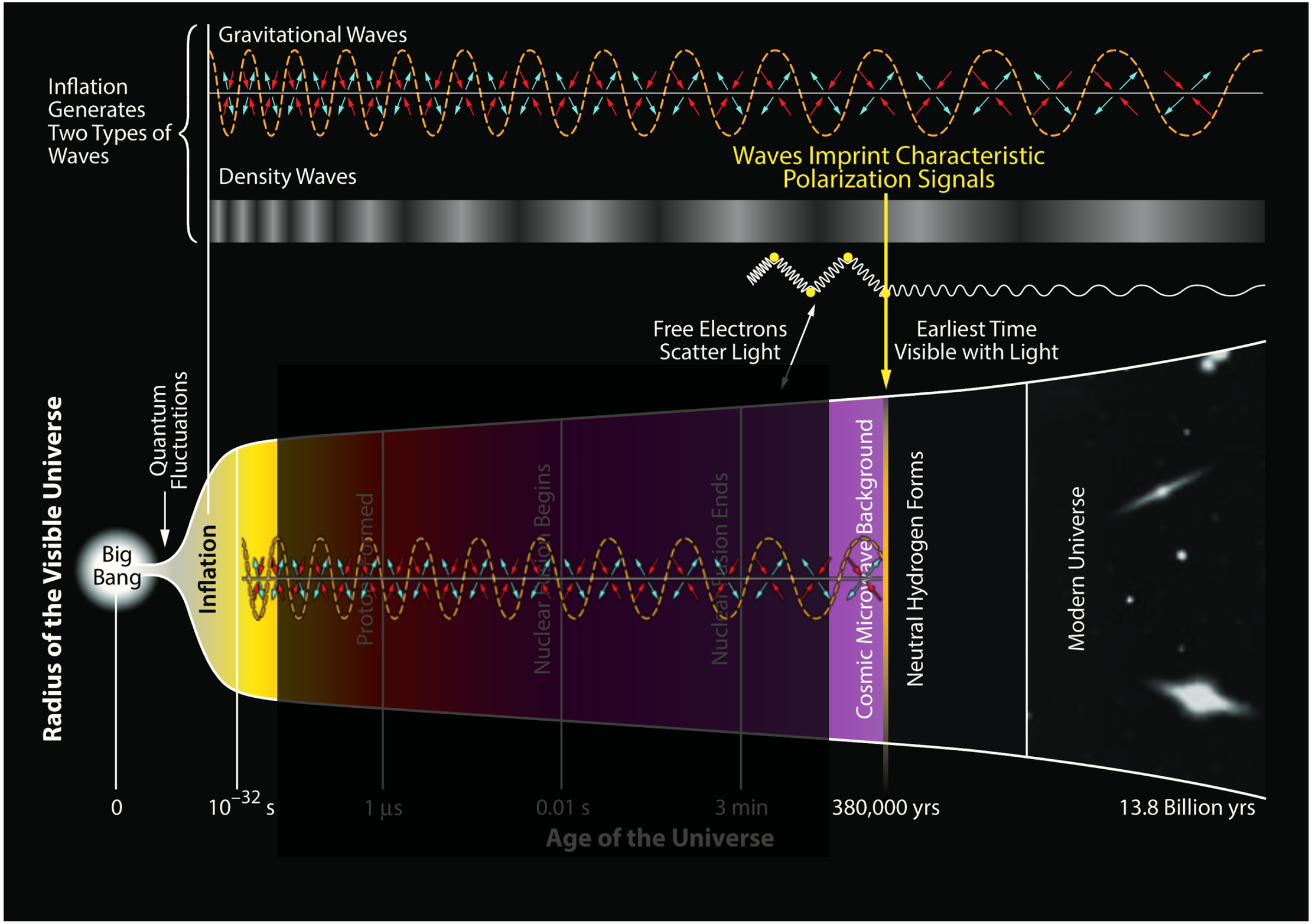
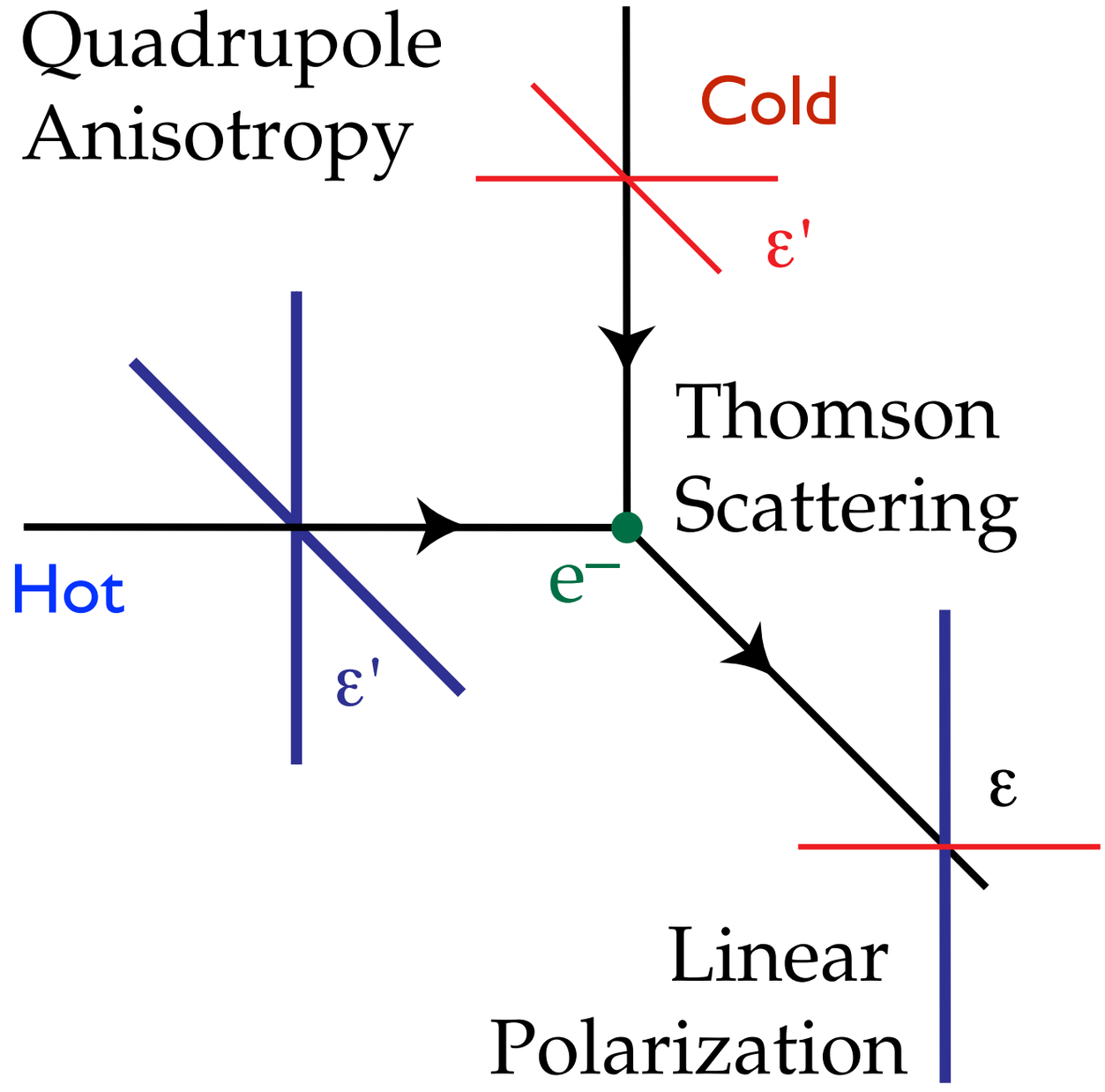


r=ratio of tensor to scalar perturbation amplitude

GWB imprints CMB

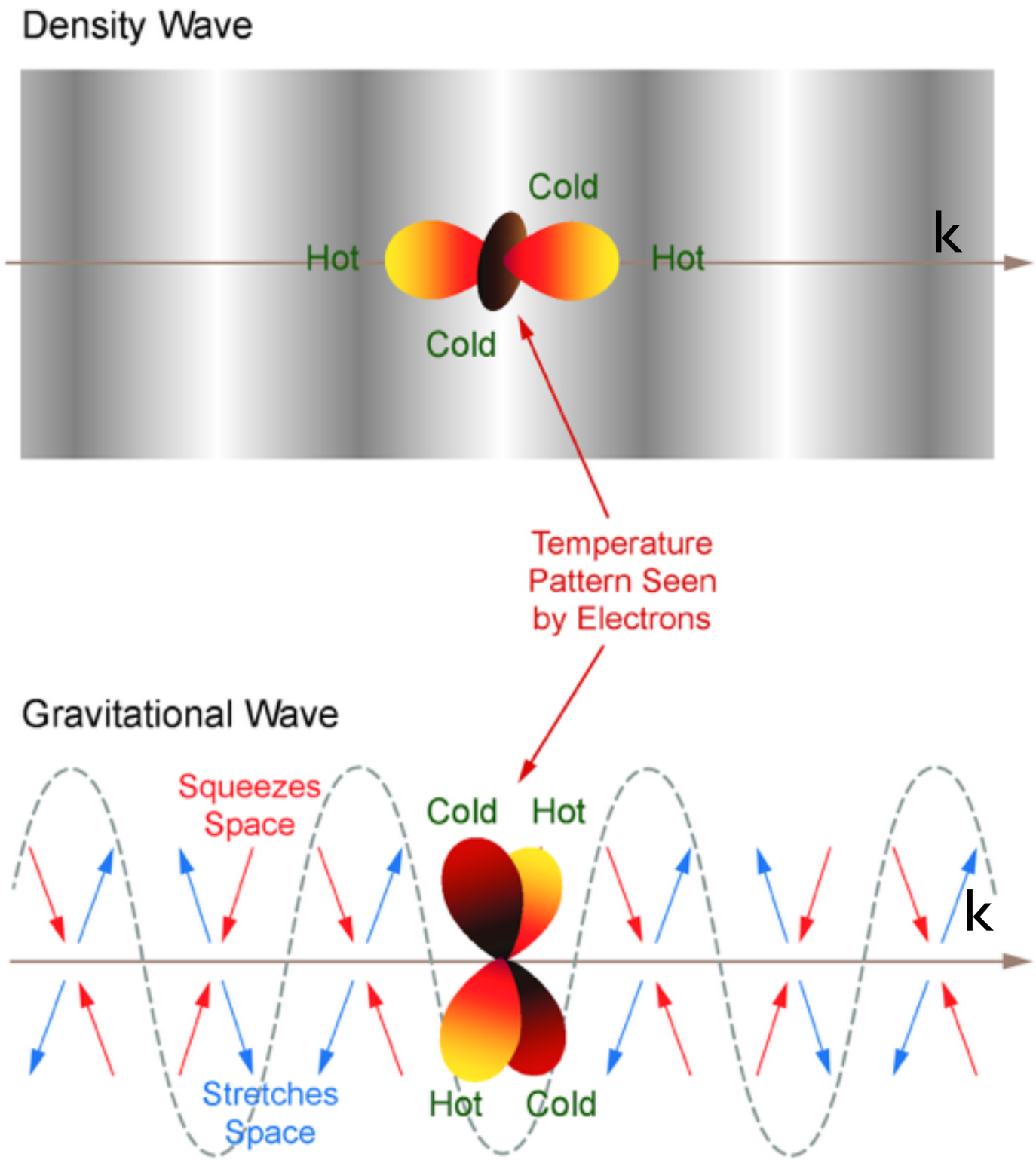


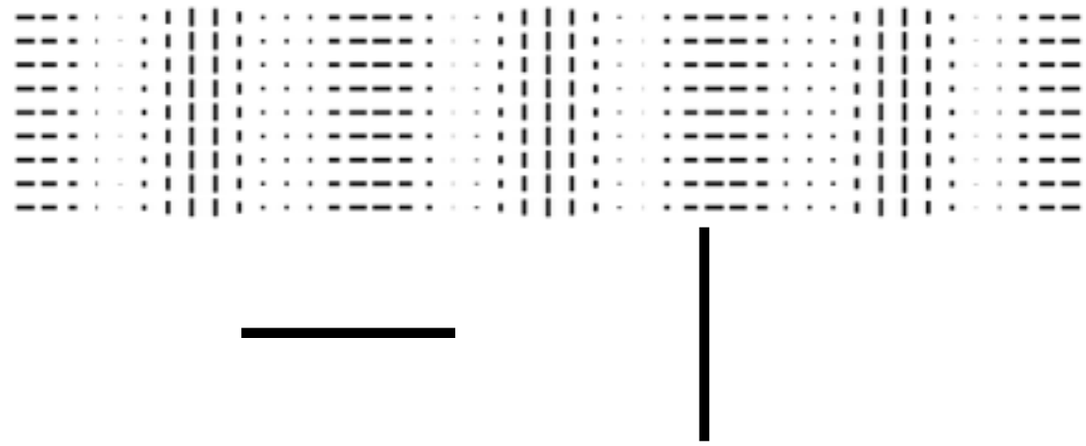
Thomson scattering off electrons polarizes CMB

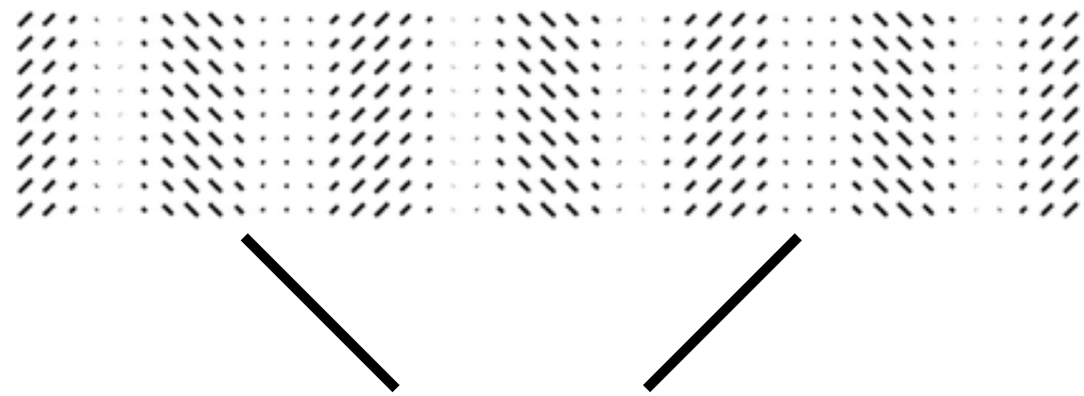


Hu & White 1997

Perturbations are seen as quadrupolar T anisotropies!

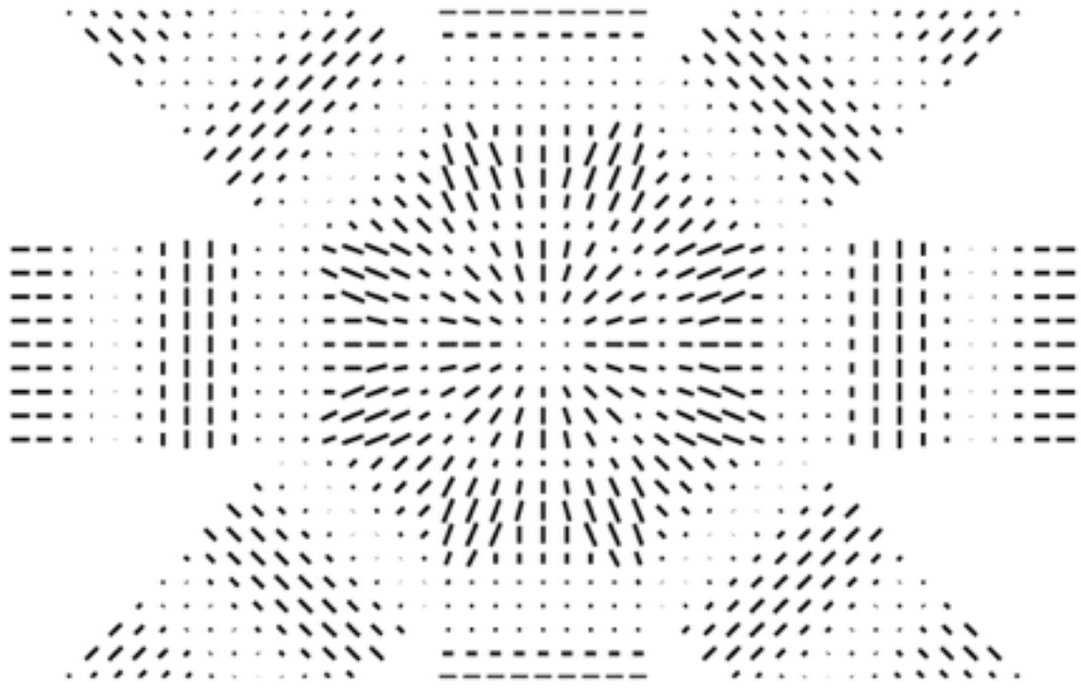




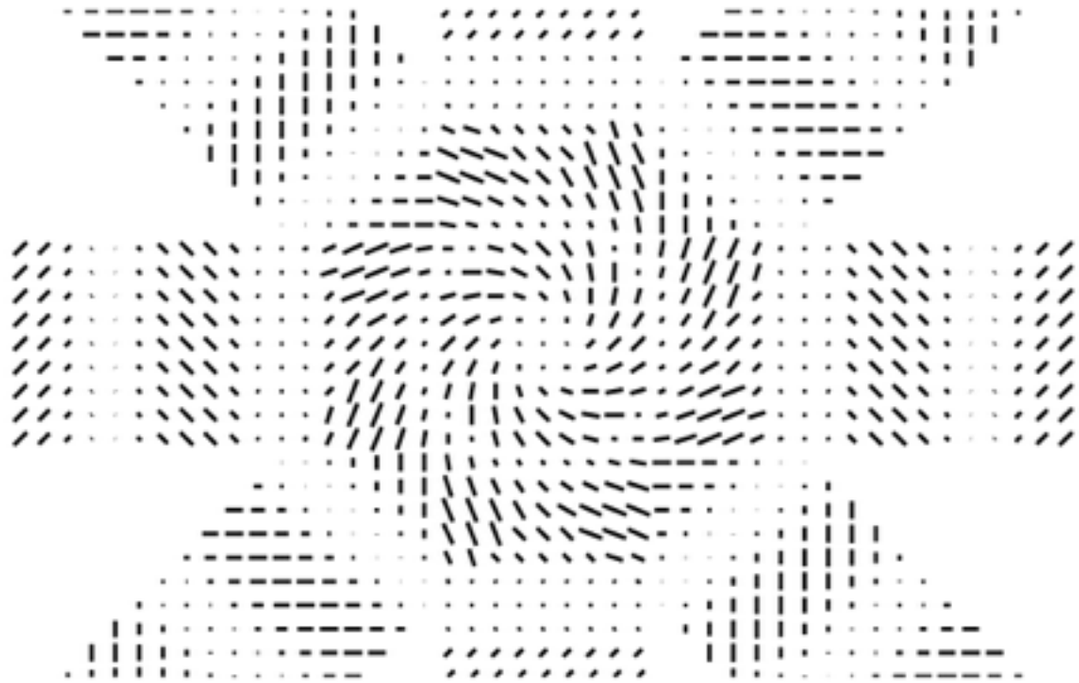


CMB Polarization

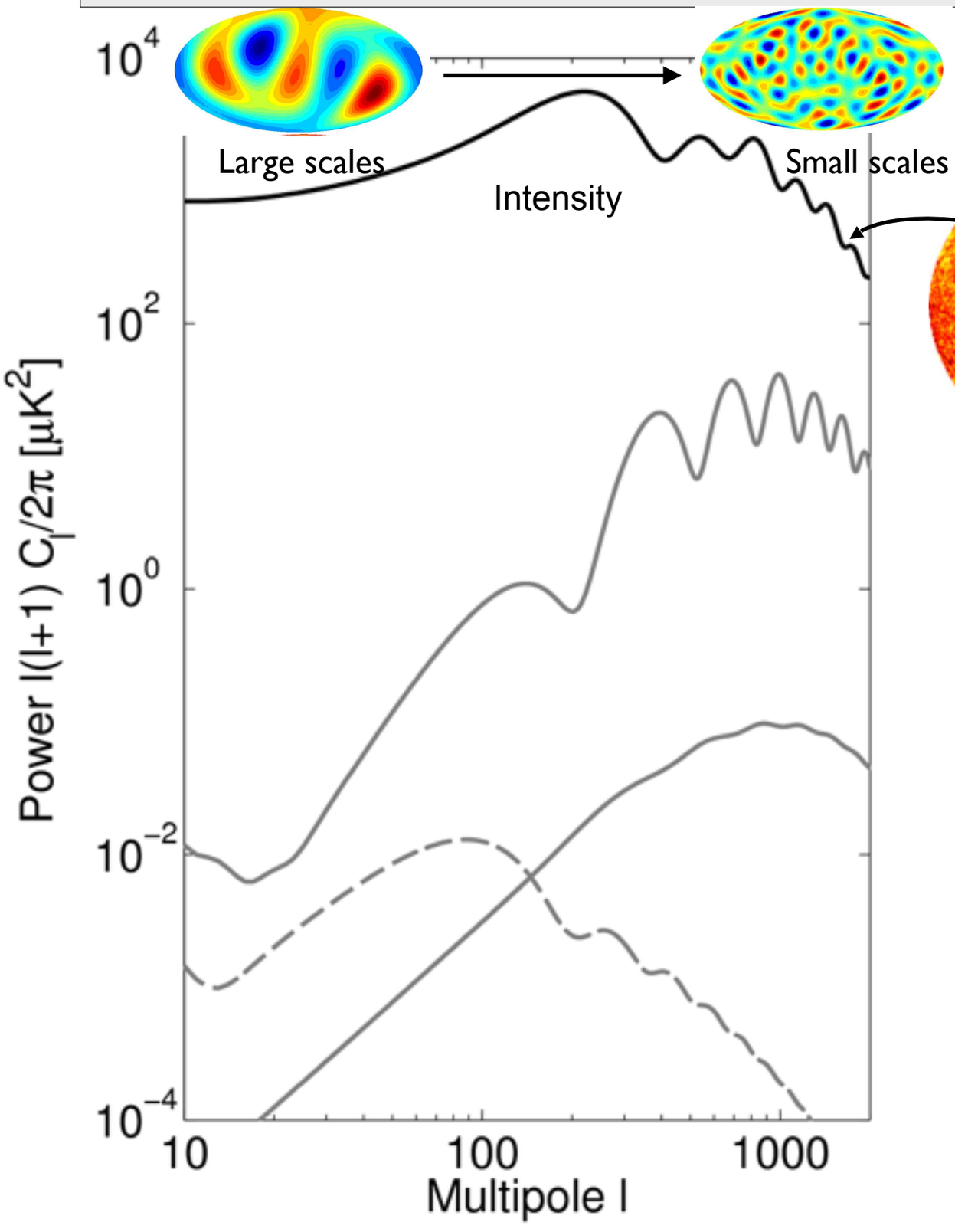
E-Mode Polarization



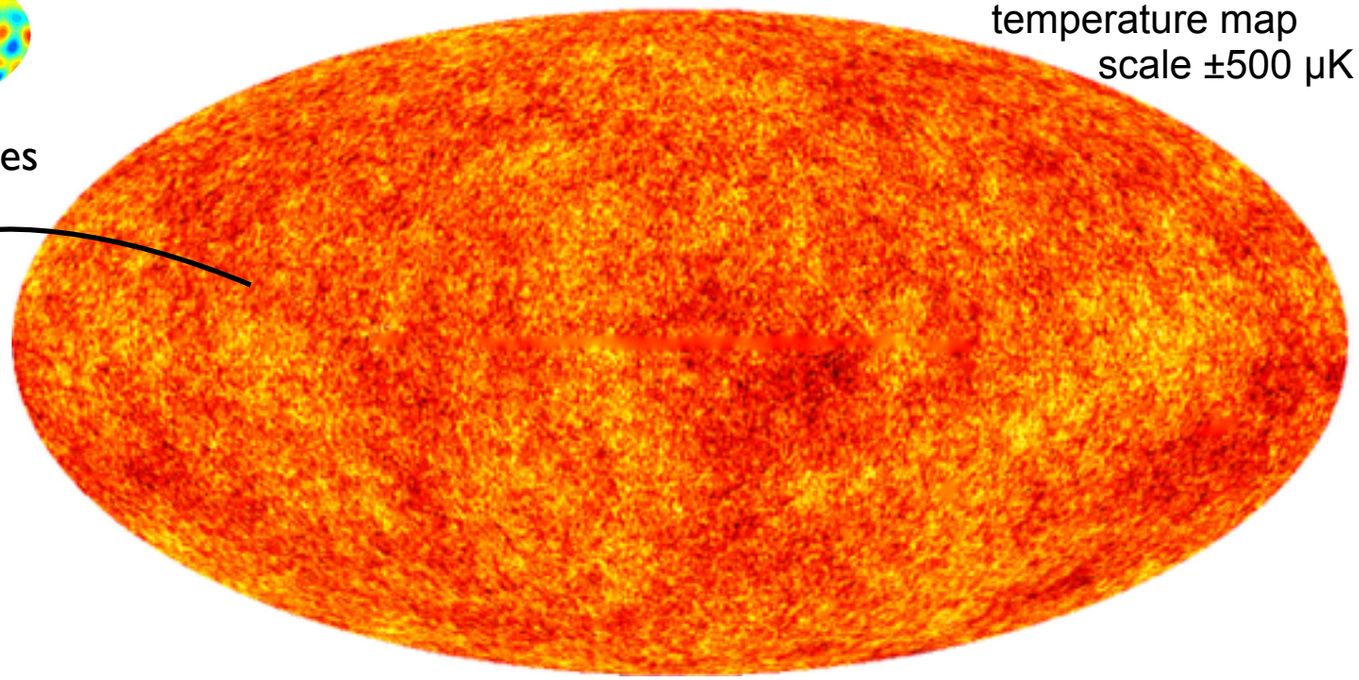
B-Mode Polarization



Understanding CMB Polarization angular power



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



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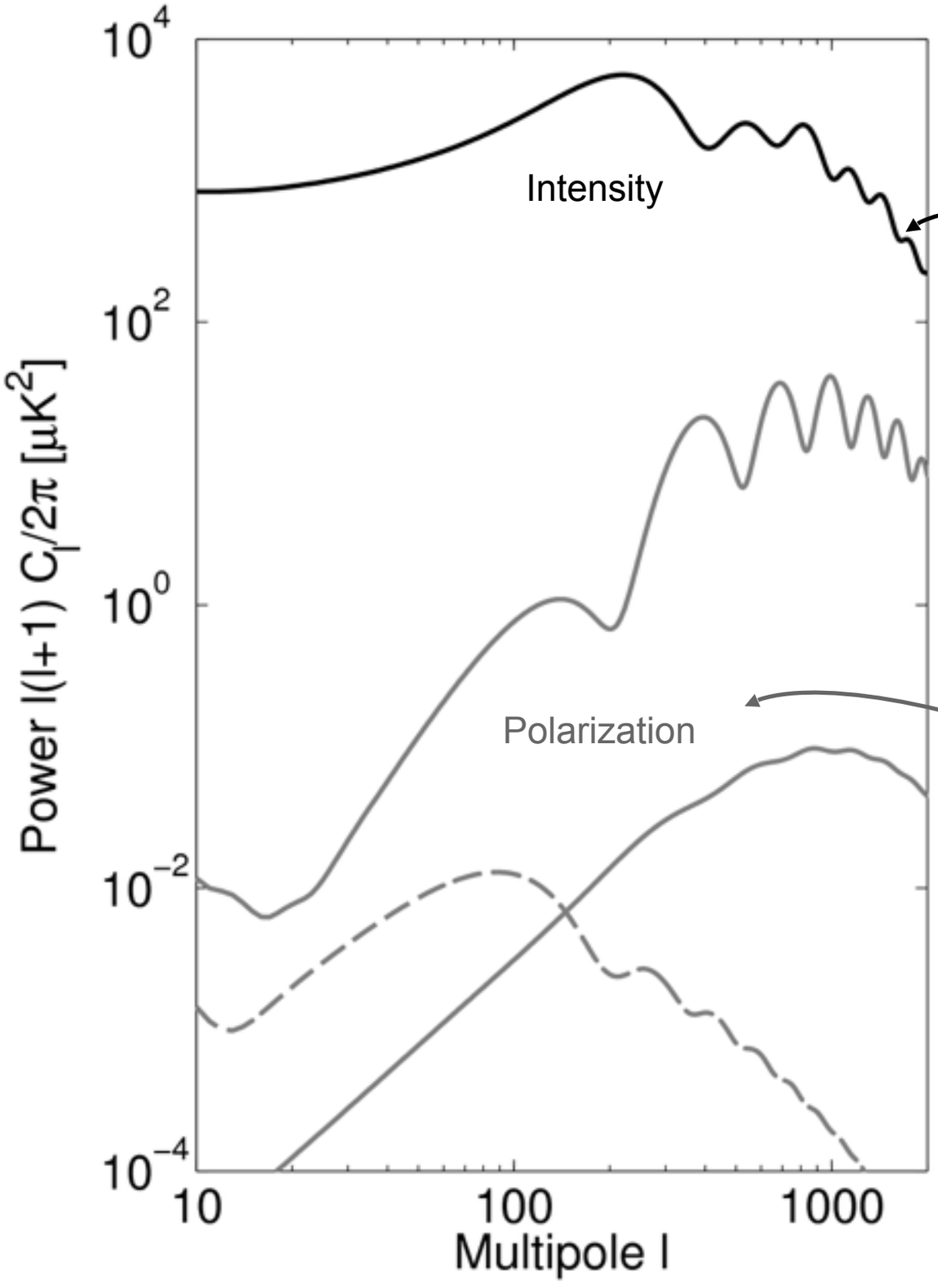

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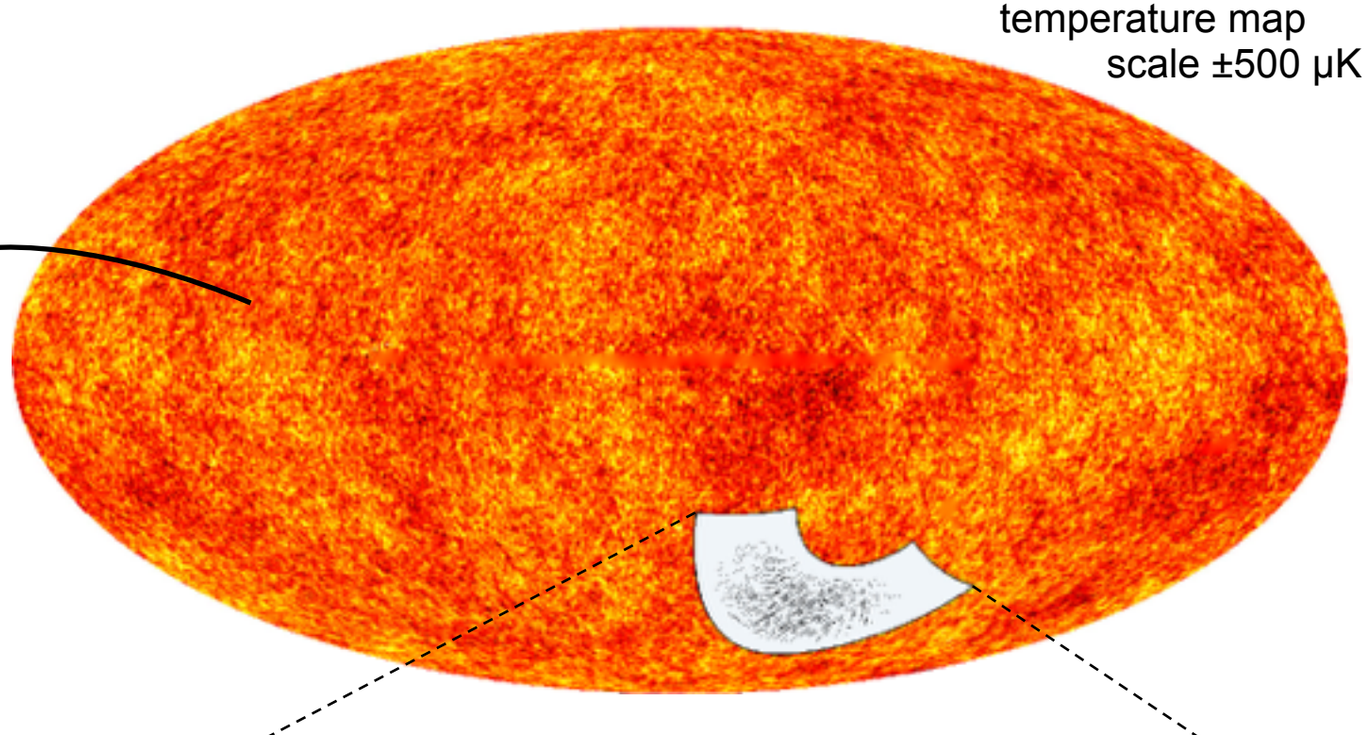
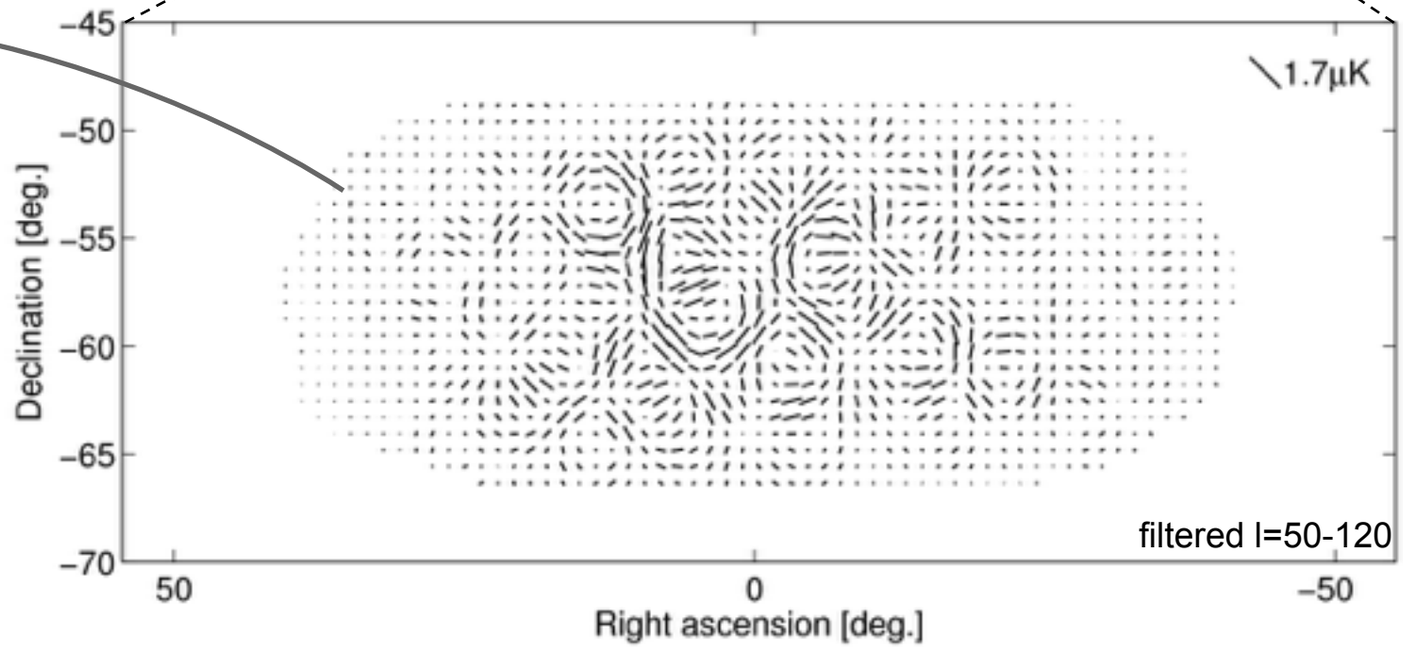


BICEP2's CMB polarization map



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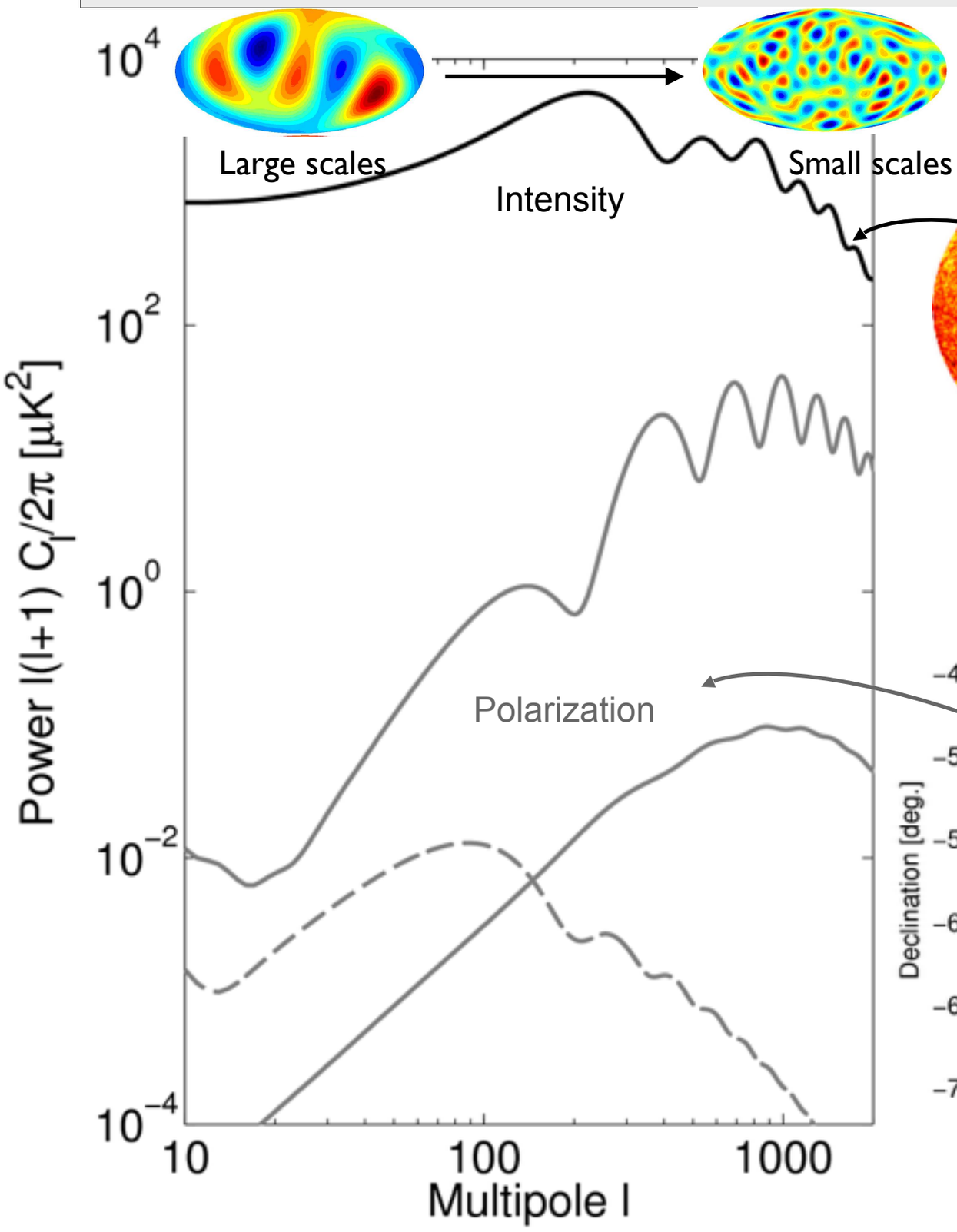

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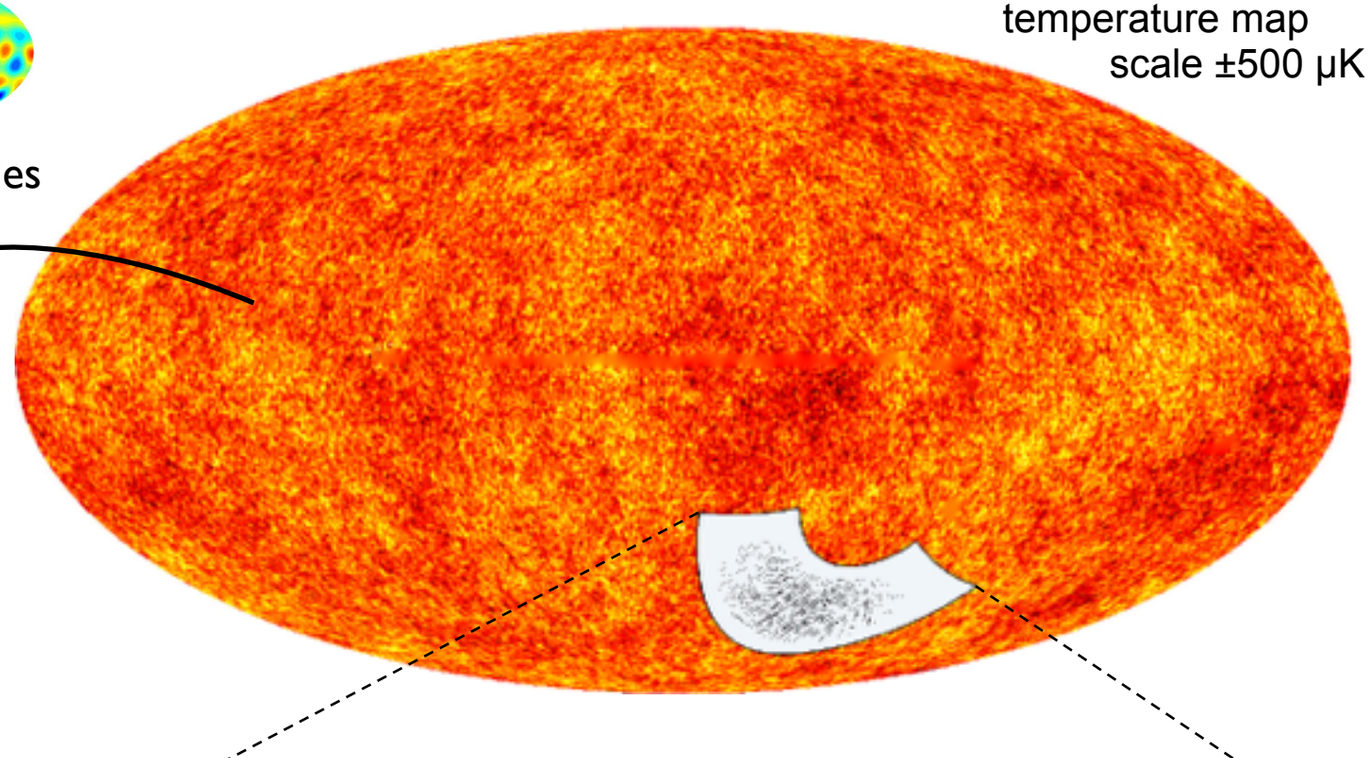

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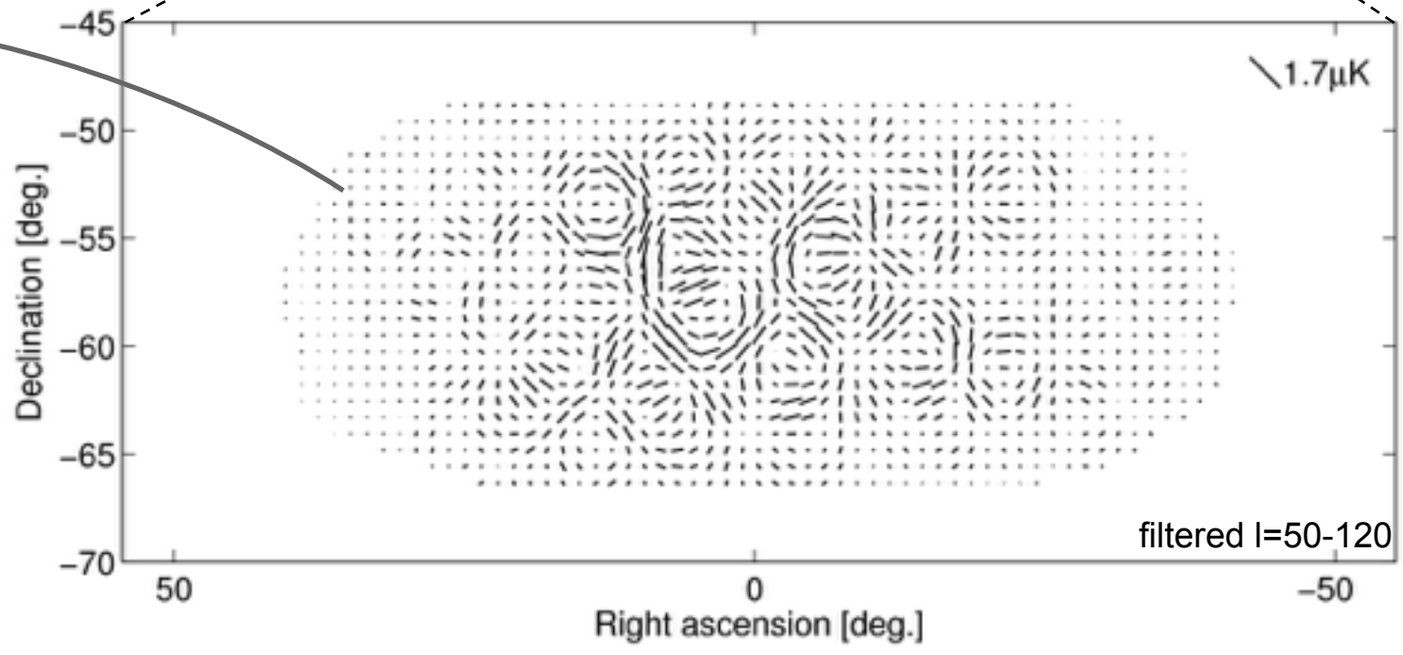

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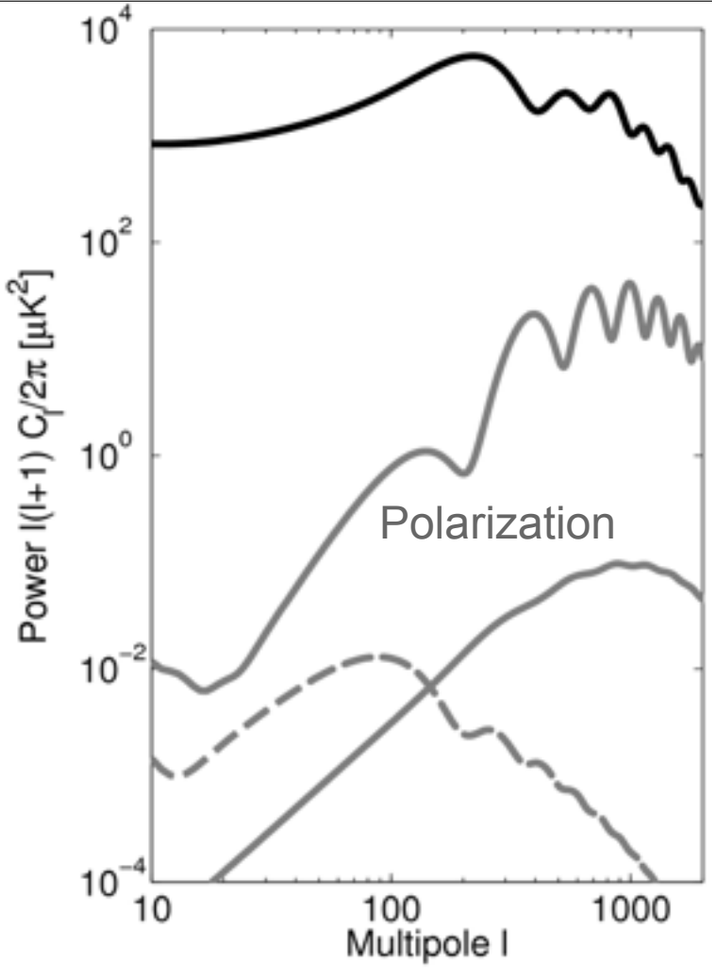

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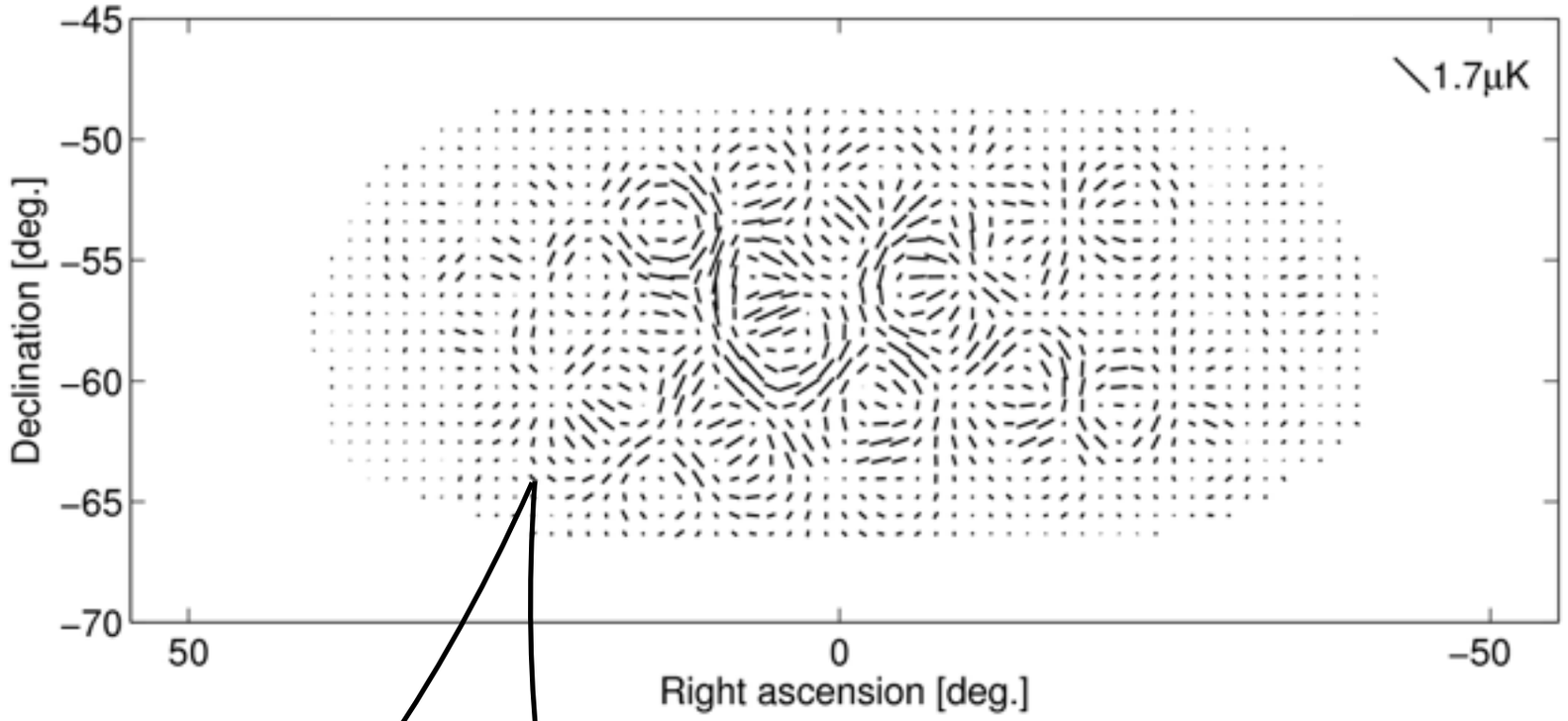

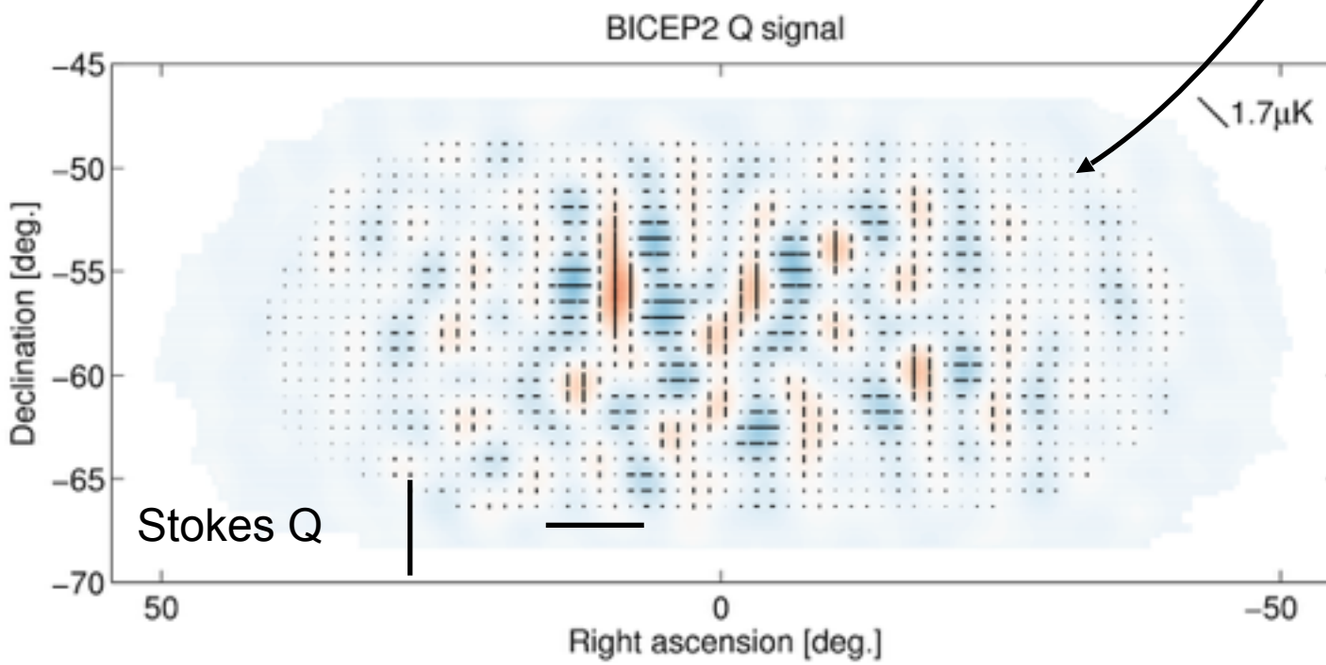

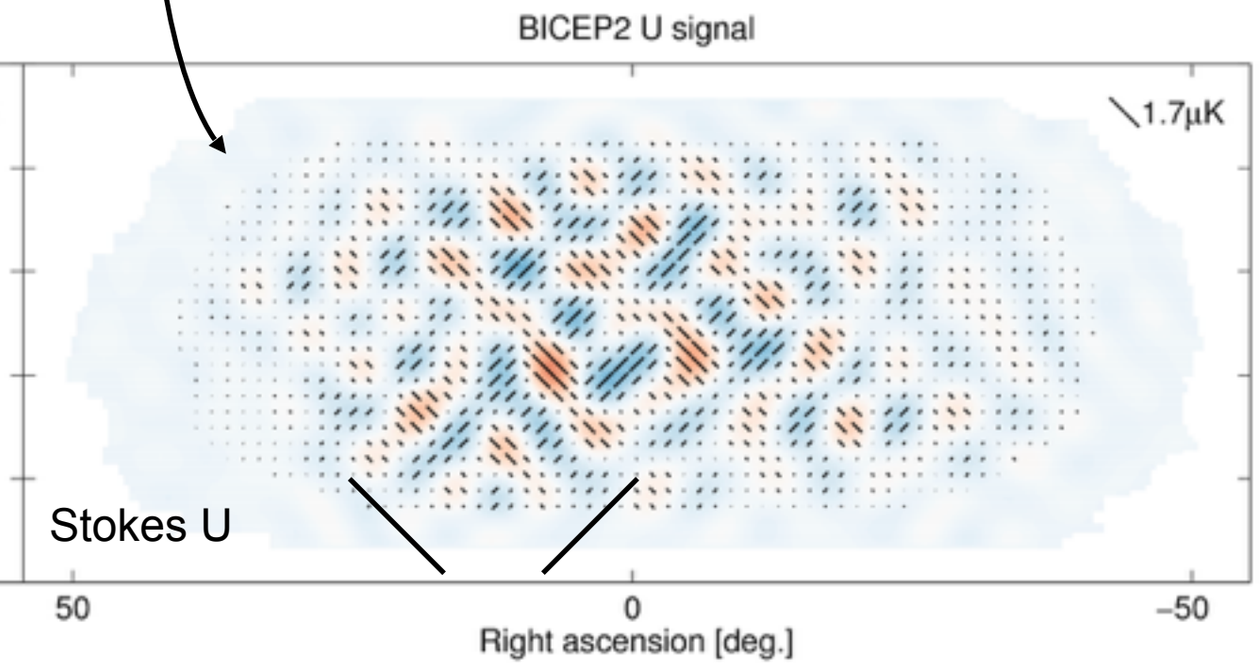

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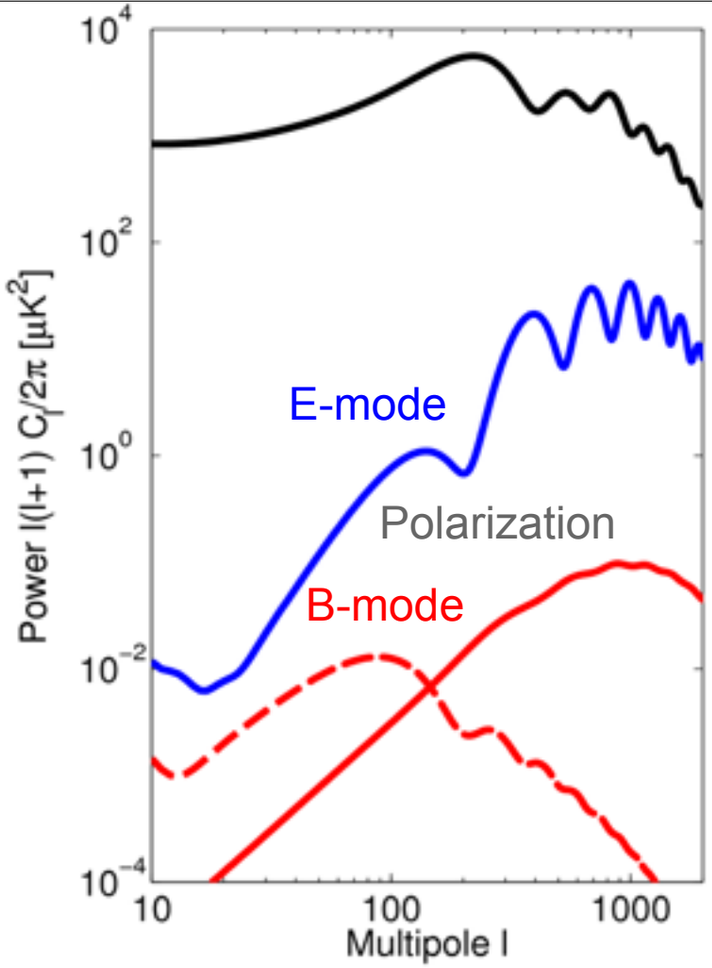

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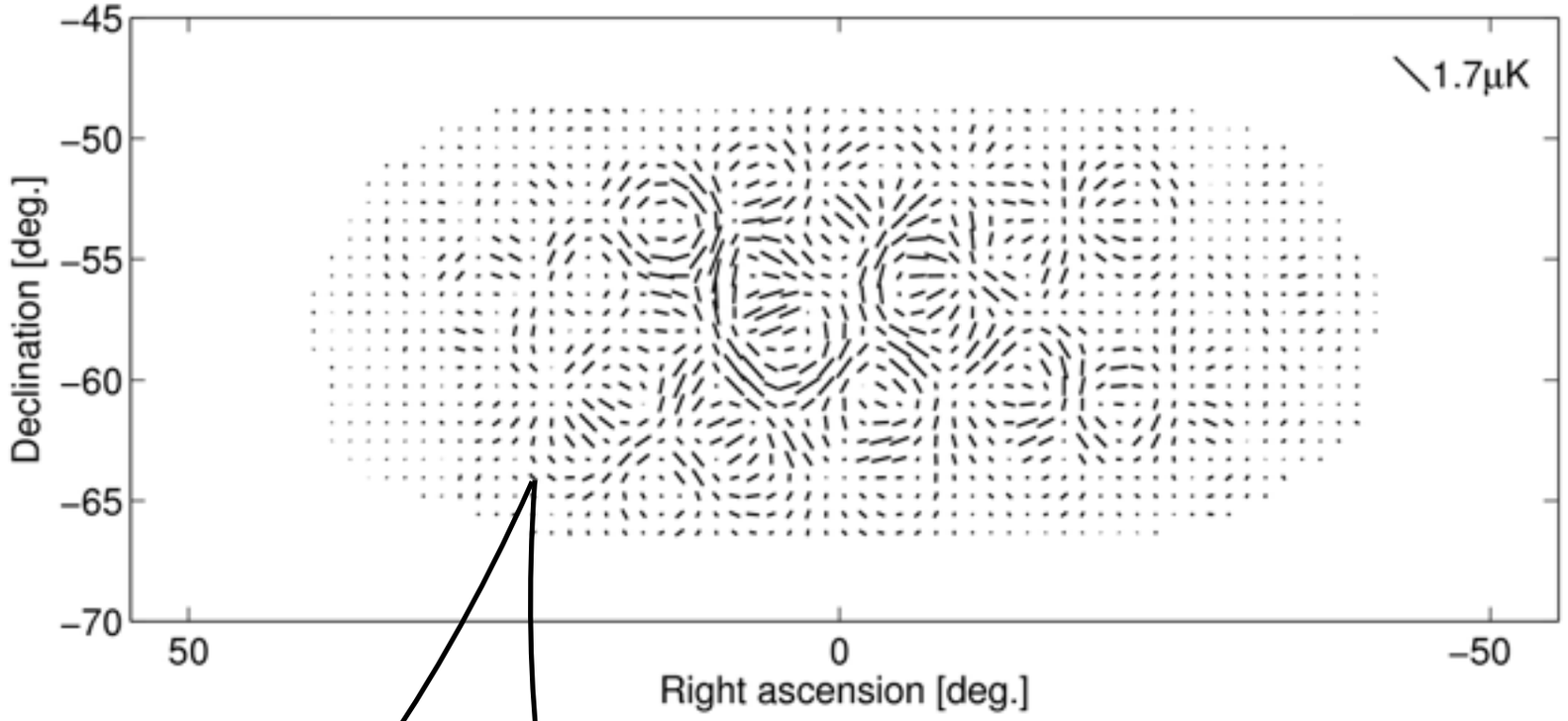
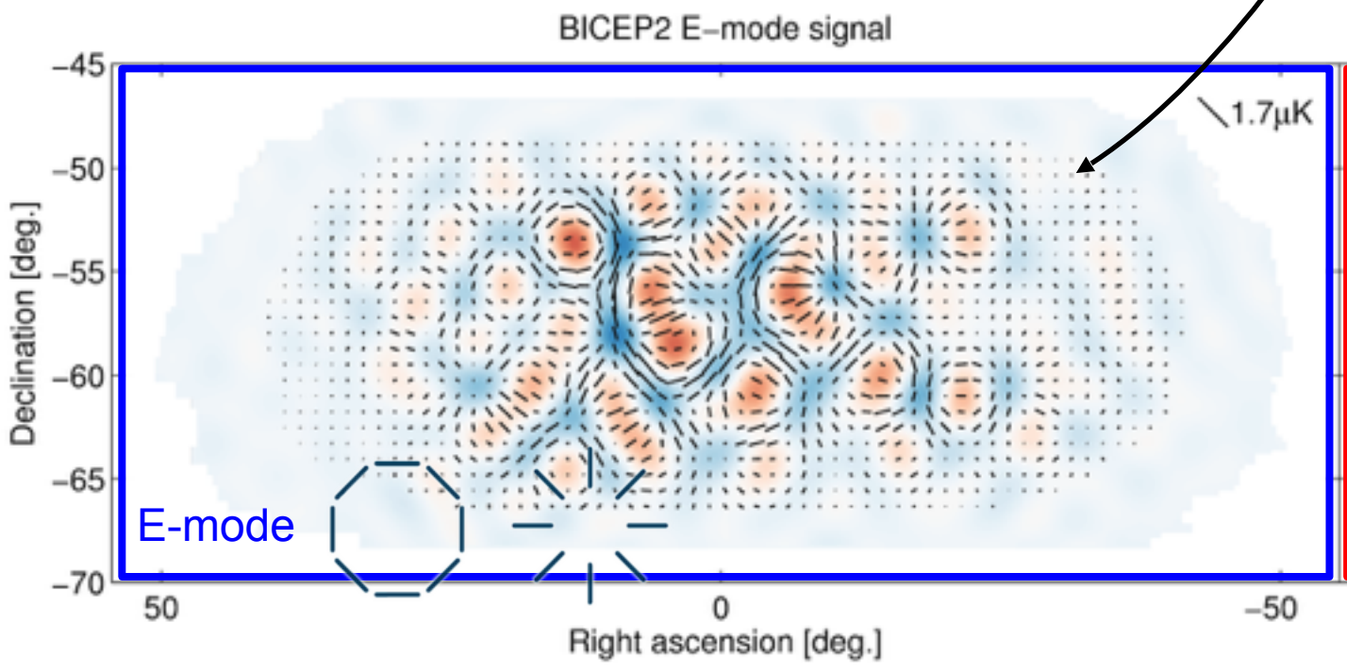
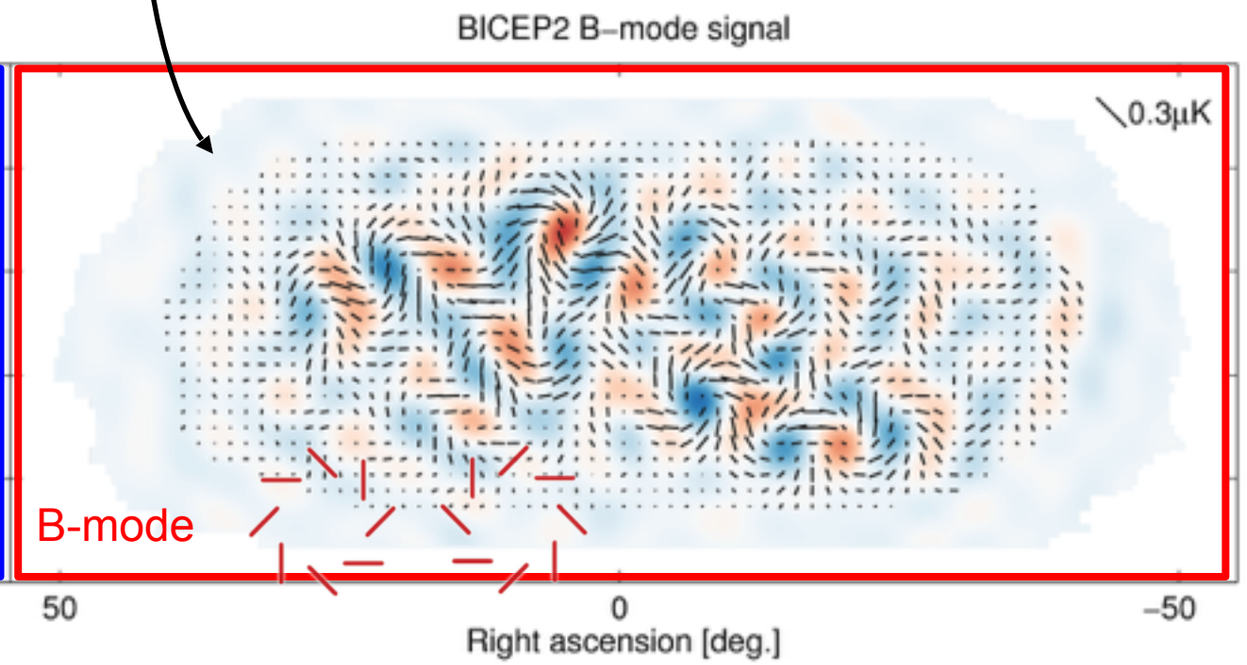


...clever choice for cosmology: E&B-modes





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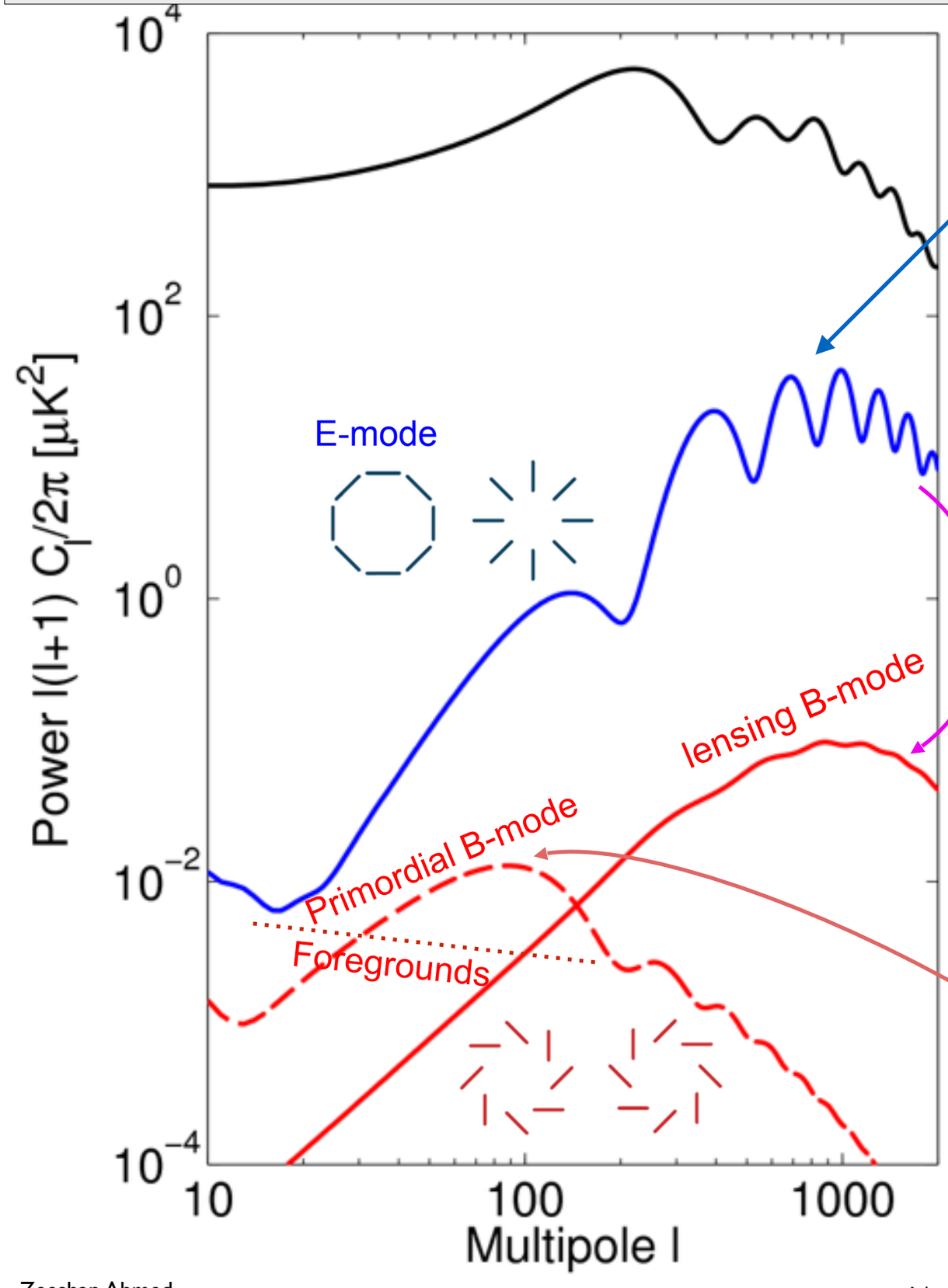
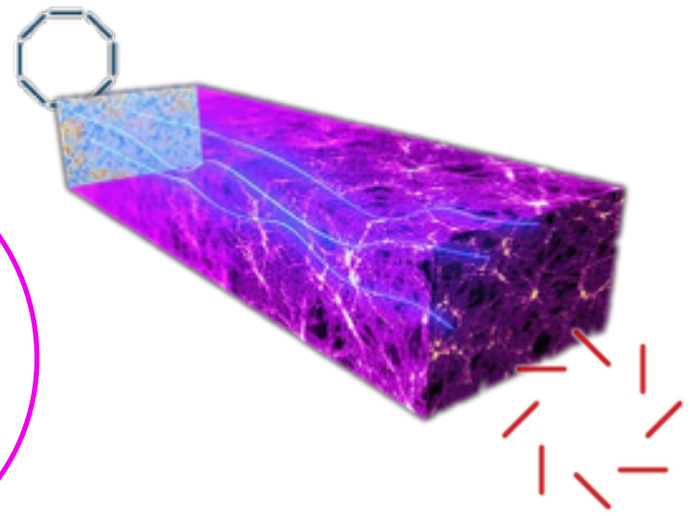


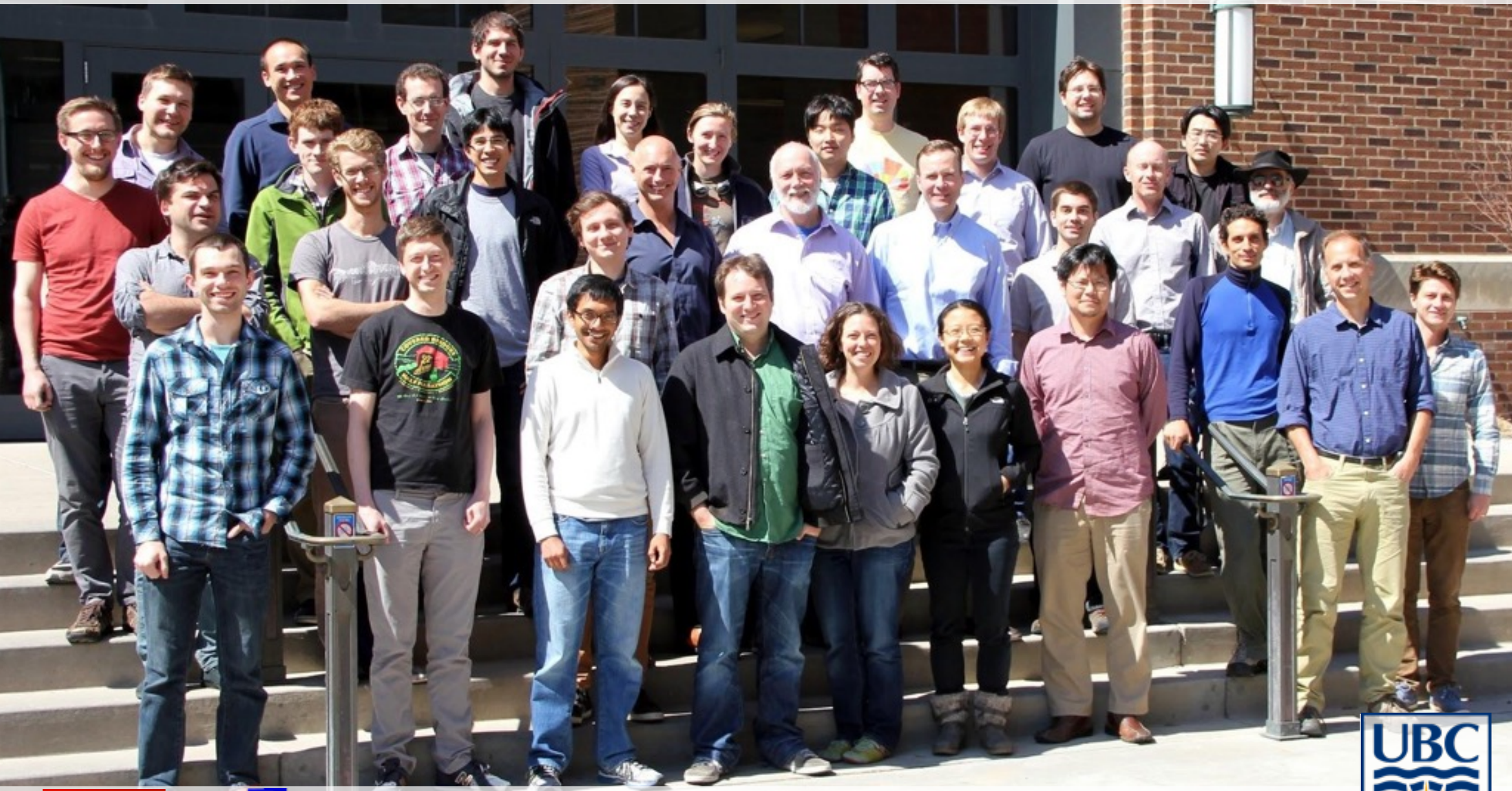
In standard ΛCDM only E-modes are present at last scattering



Lensing by intervening structure converts some to B-modes

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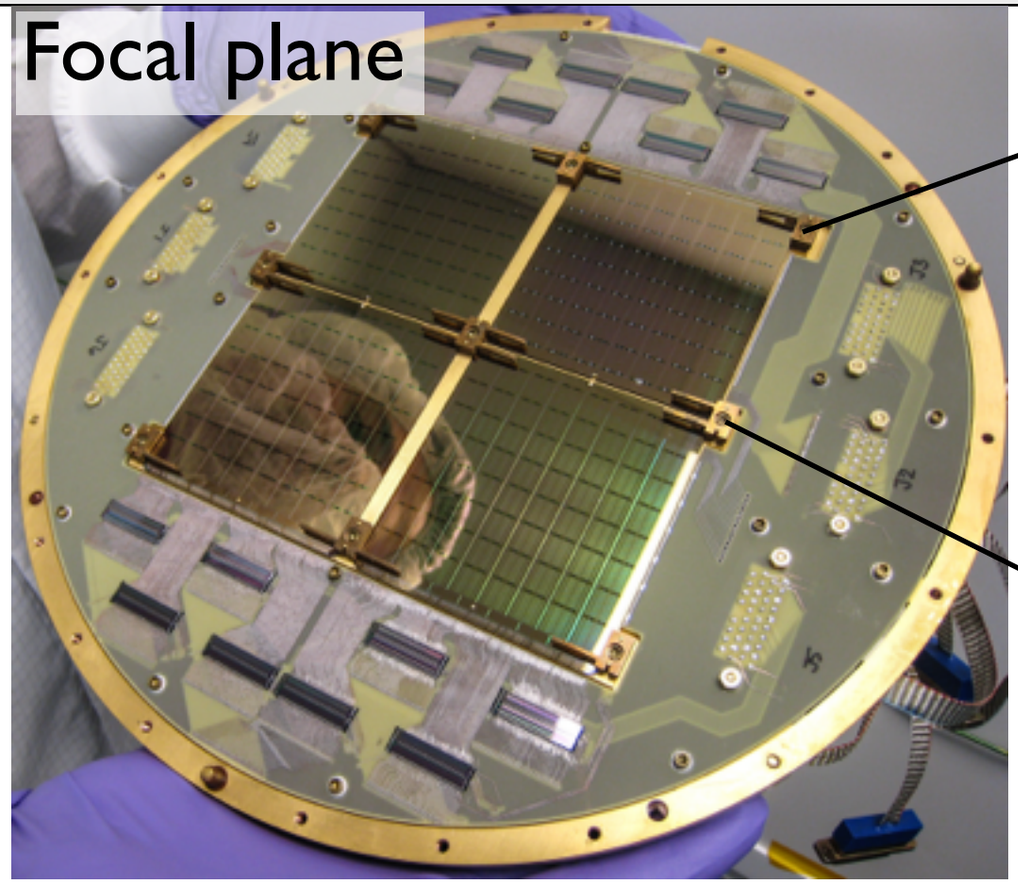
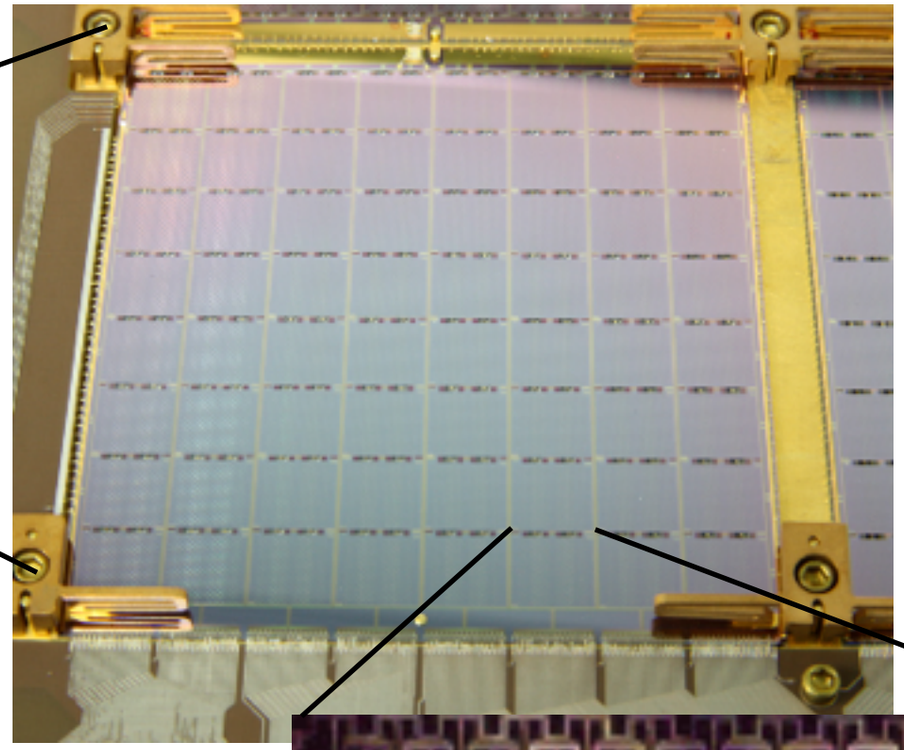
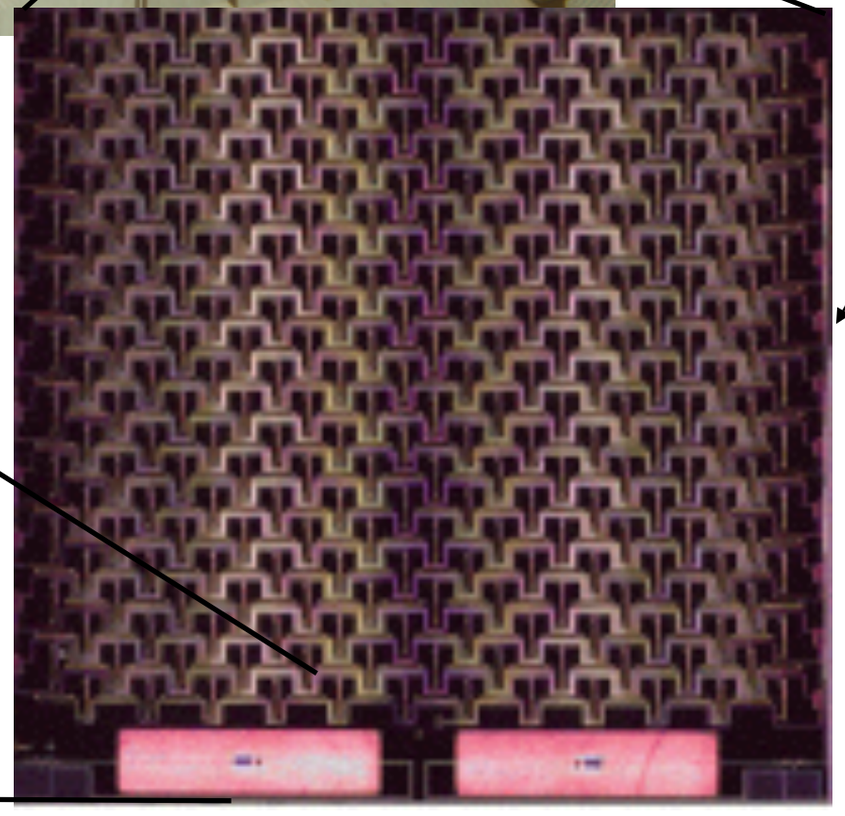
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
cea
UCSD
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

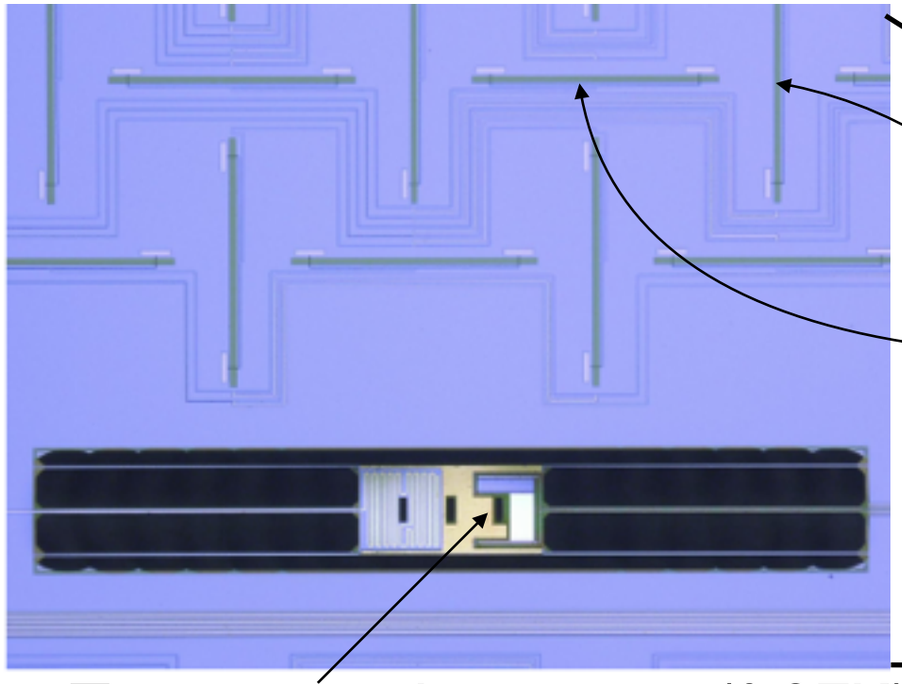
Mass-produced superconducting detectors







Planar antenna array

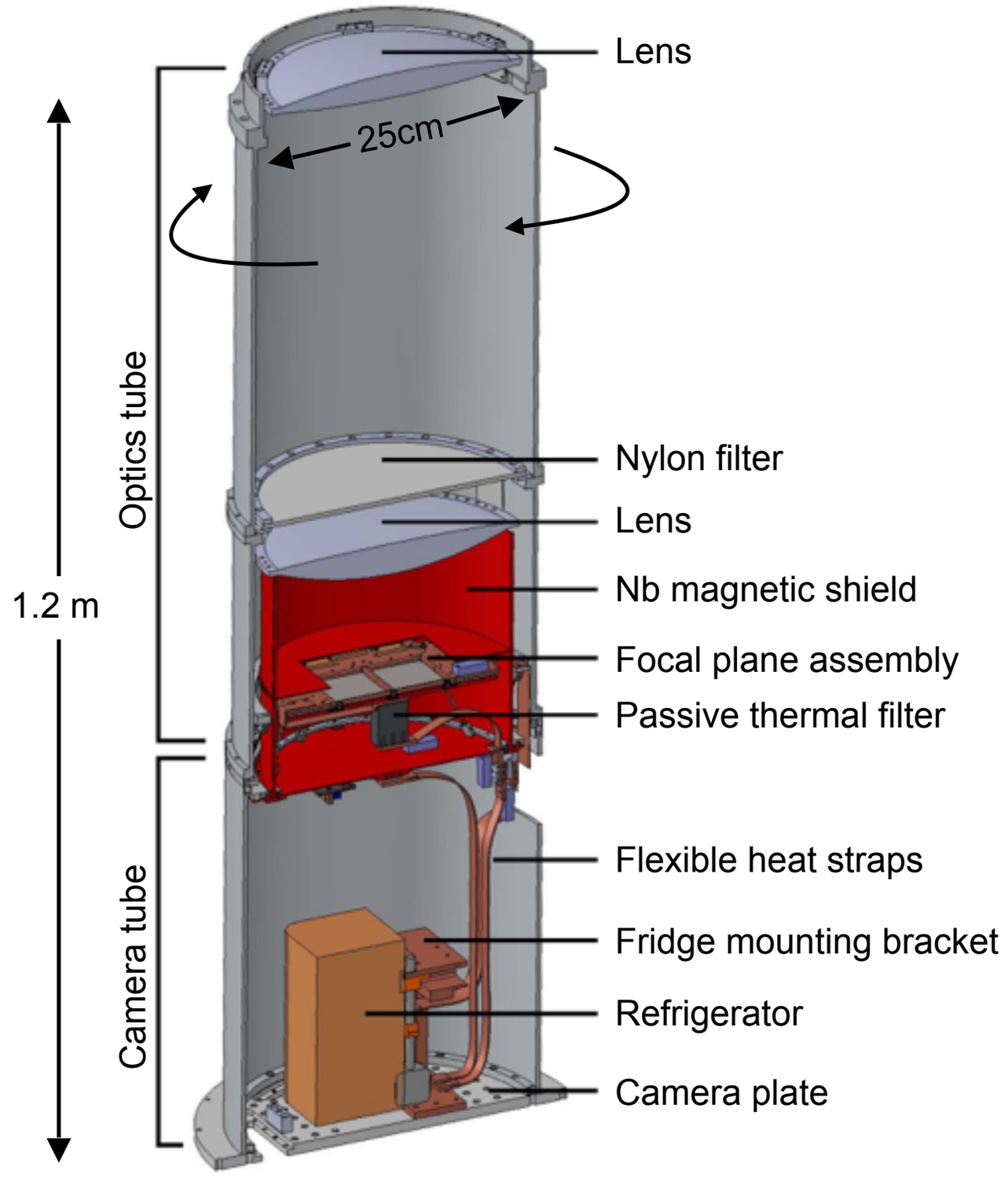


Slot antennas

Transition edge sensor (0.27K)

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.



Situated at a high, dry desert

BICEP2/3

Keck Array

South Pole Research Station, Antarctica

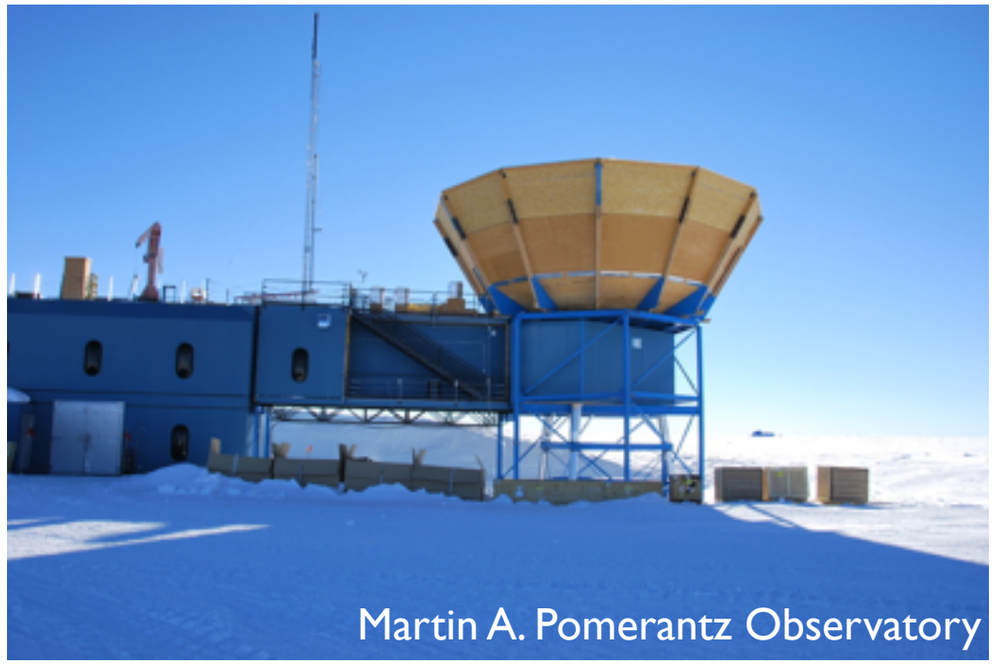
~10,000ft, ~0.25mm PWV

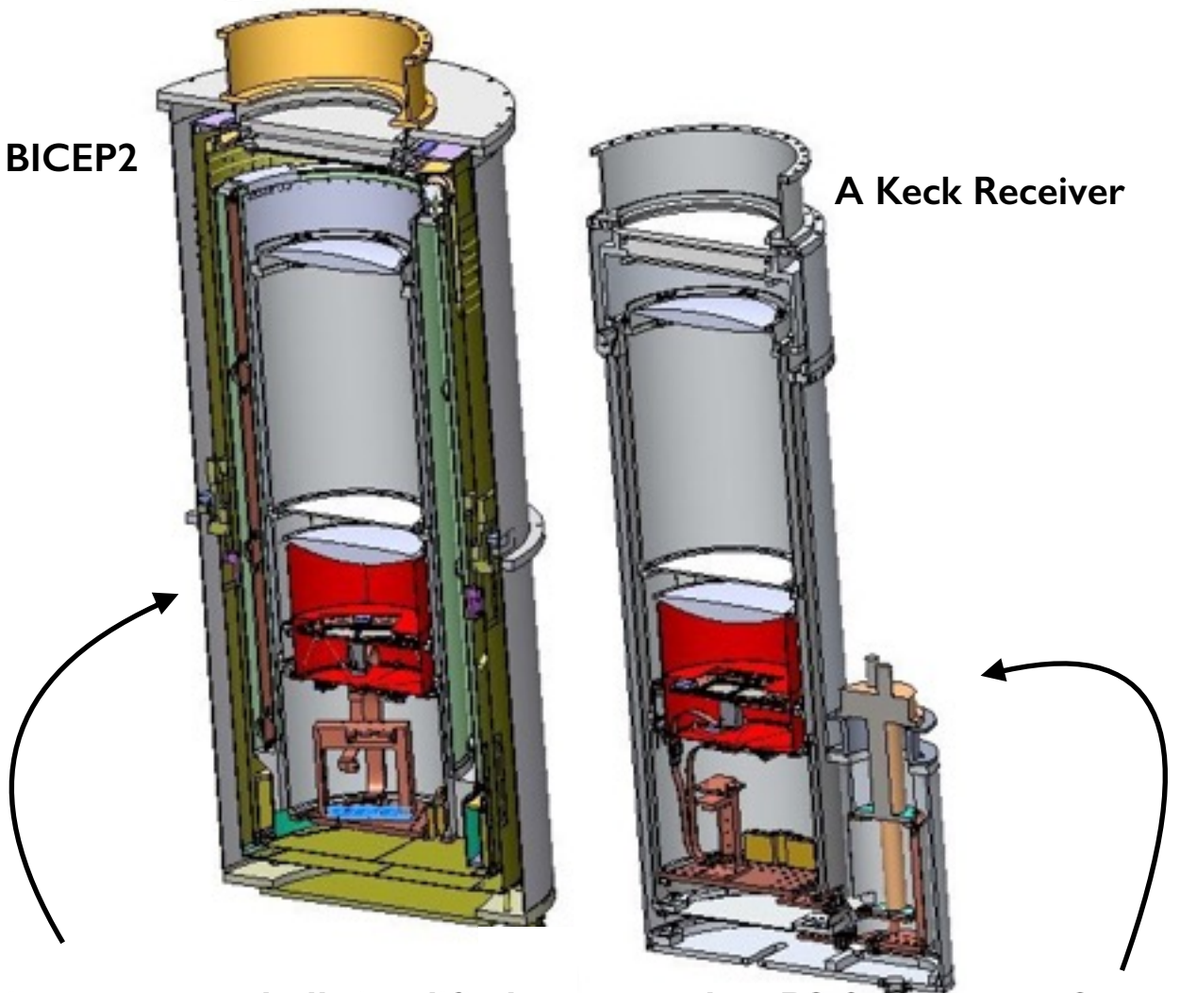
6 months of cold, stable winter sky with uninterrupted integration

BICEP2 design replicated into the Keck Array

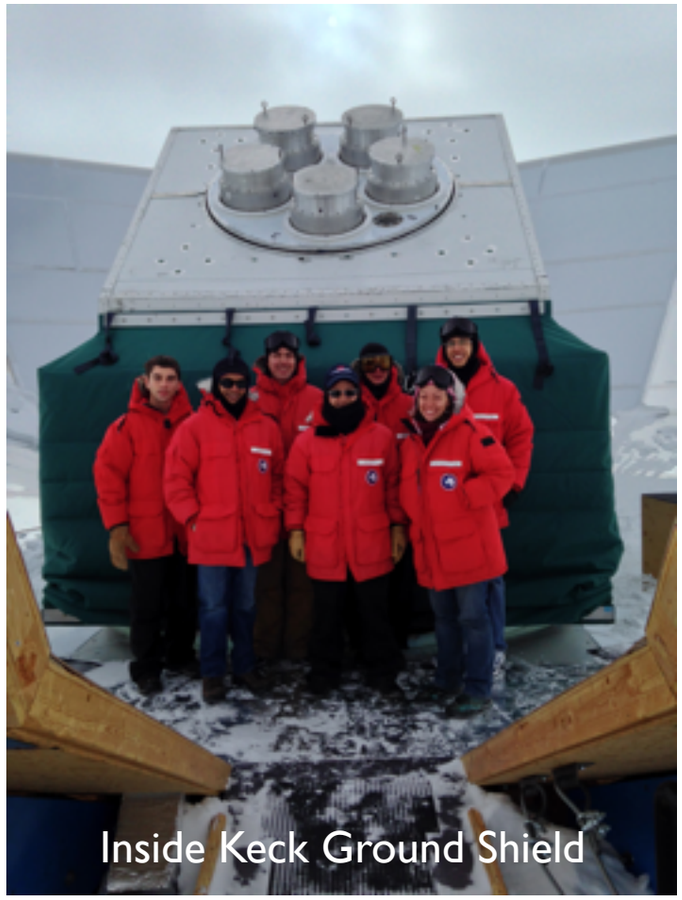
Multiply BICEP2 x5

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

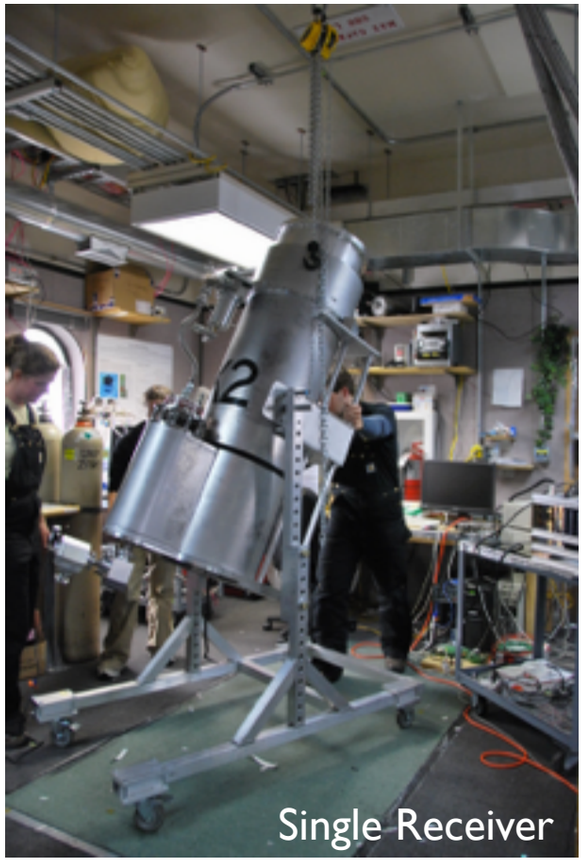


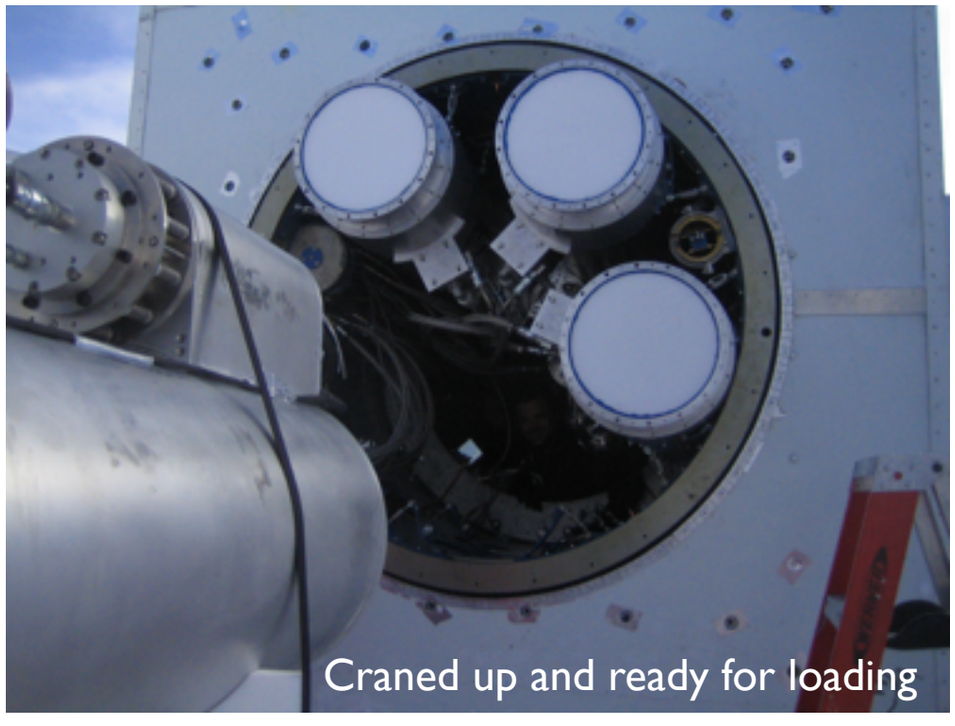


Keck receiver vacuum shell simplified compared to B2 for cryogen-free operation

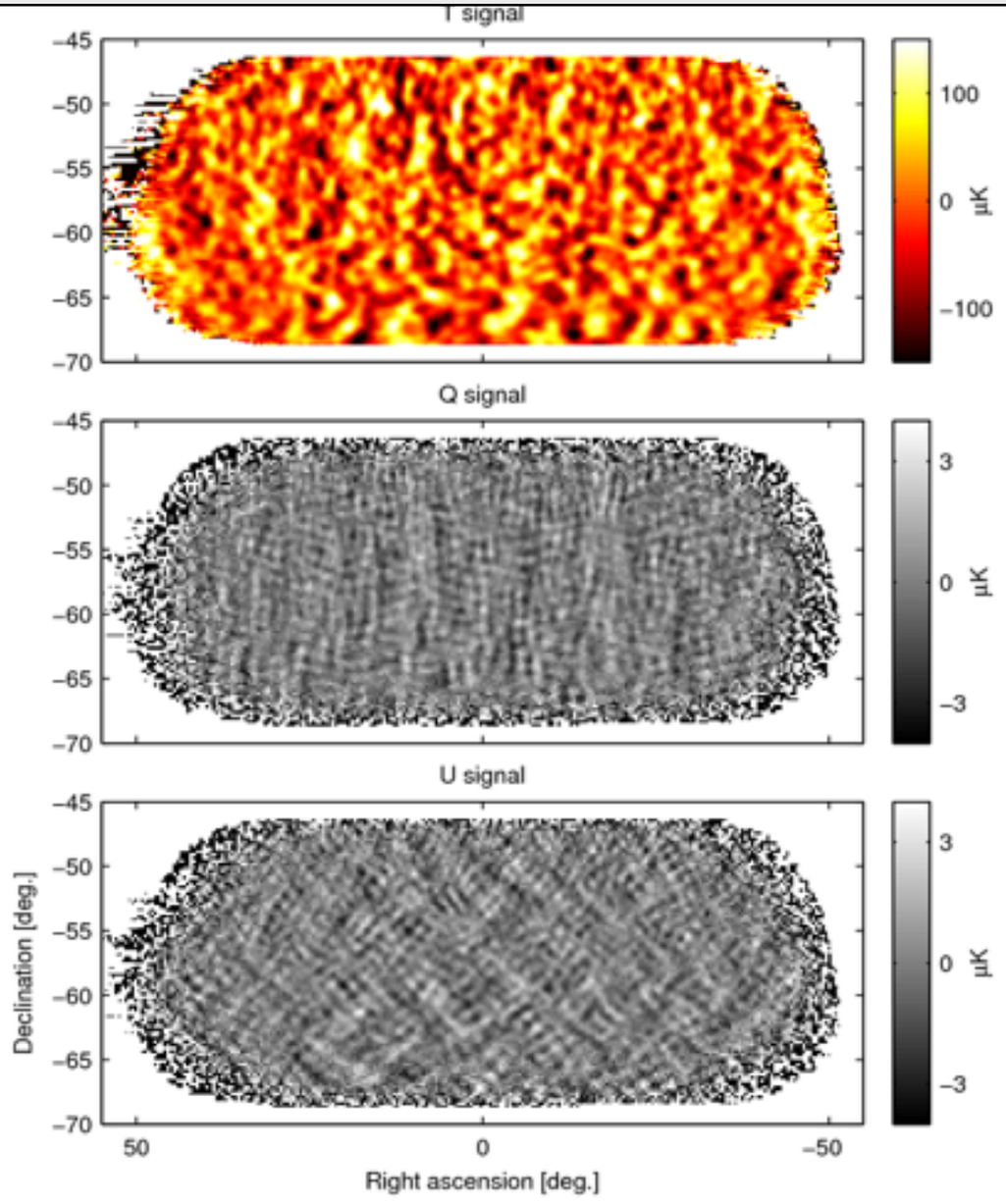


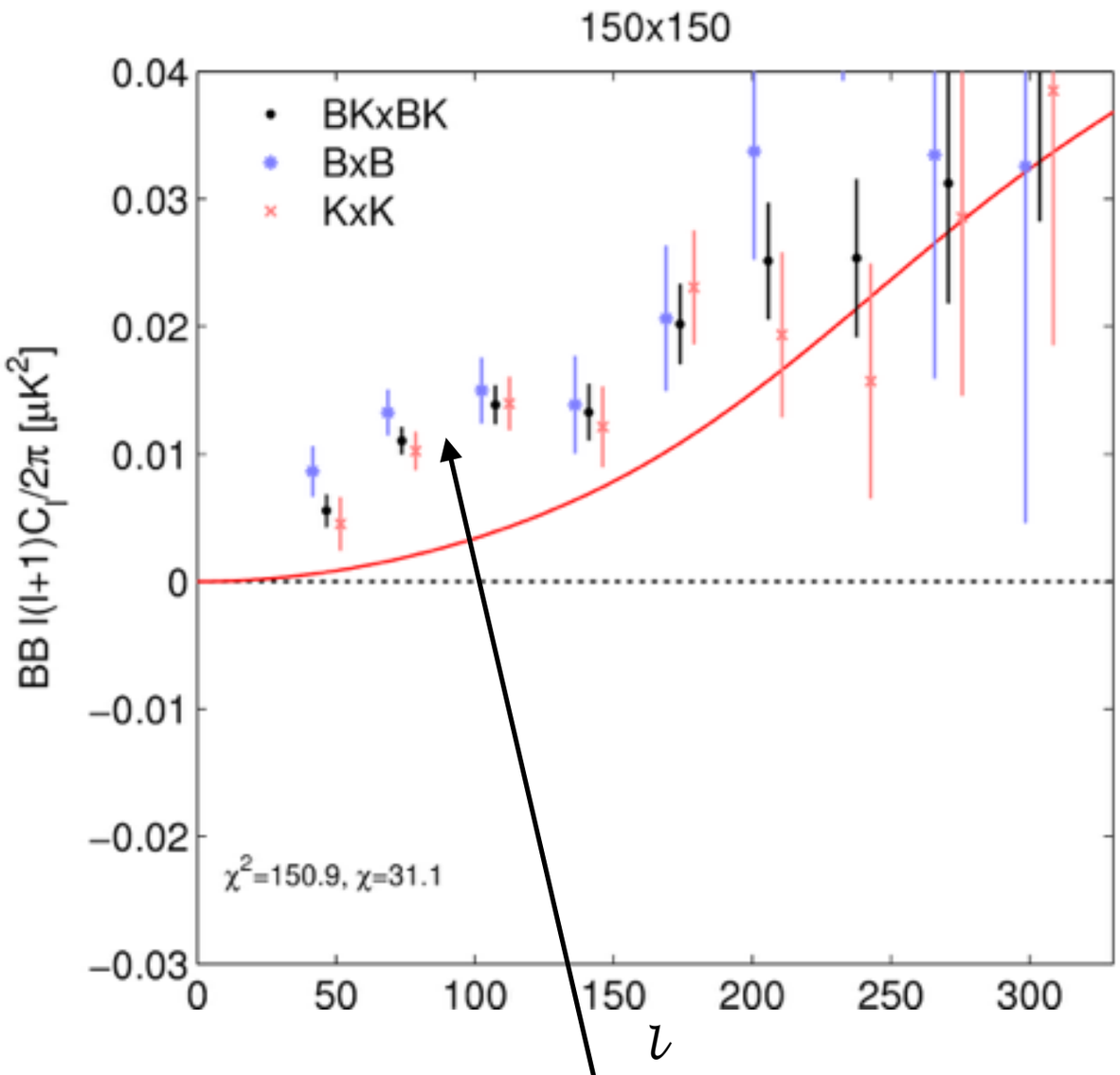
Keck = Array of BICEP2-like receivers





BICEP2+Keck through 2013 (150 GHz)





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

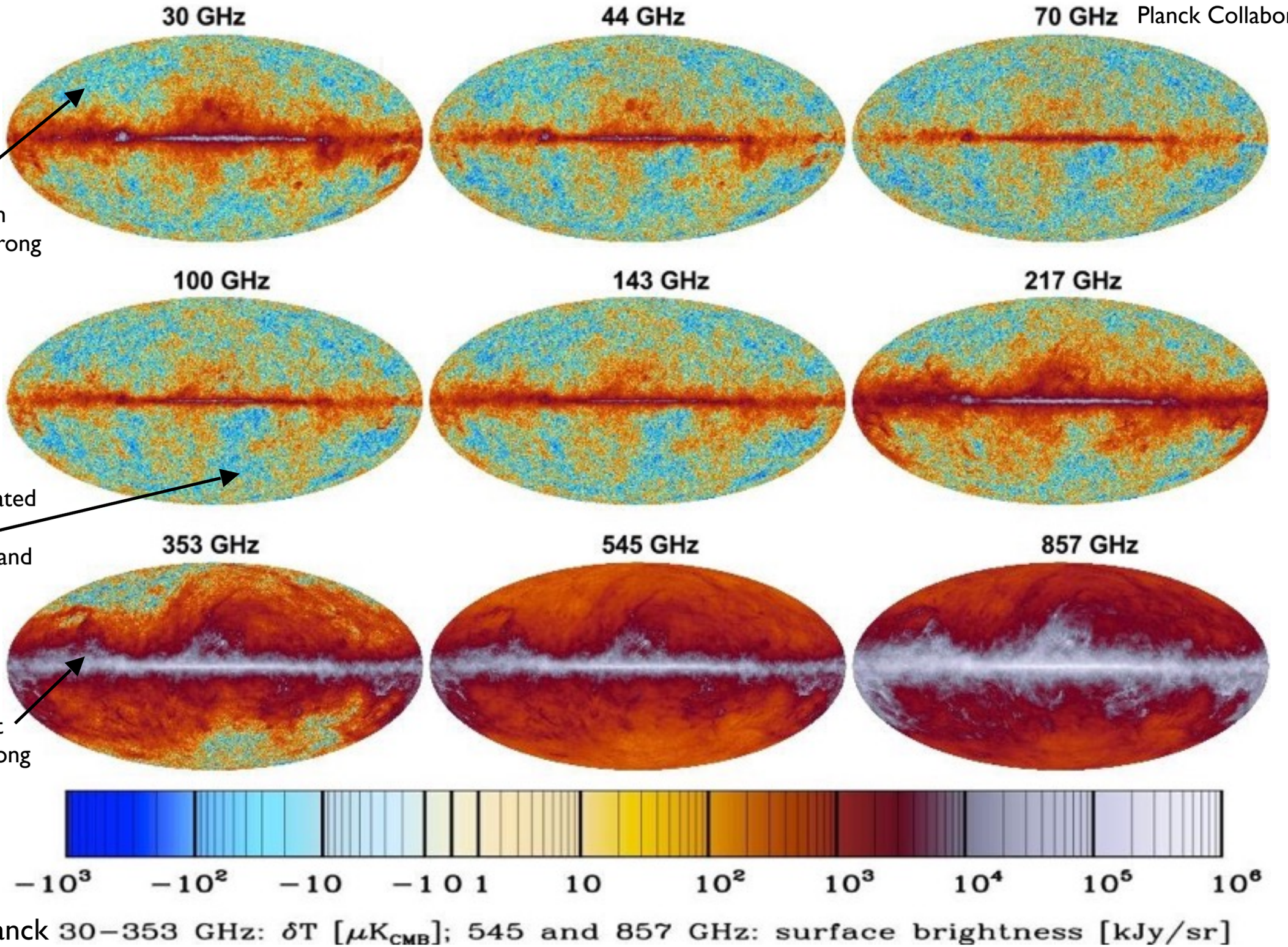
BICEP2 + Keck thru 2013 → Final map depth: 3.4 μK arcmin / 57 nK deg

(RMS noise in sq-deg pixels)

BB power spectrum shows excess over lensed ΛCDM at degree scales.

To investigate this, we do a joint analysis w/ Planck, which has frequency bands w/ sensitivity to dust

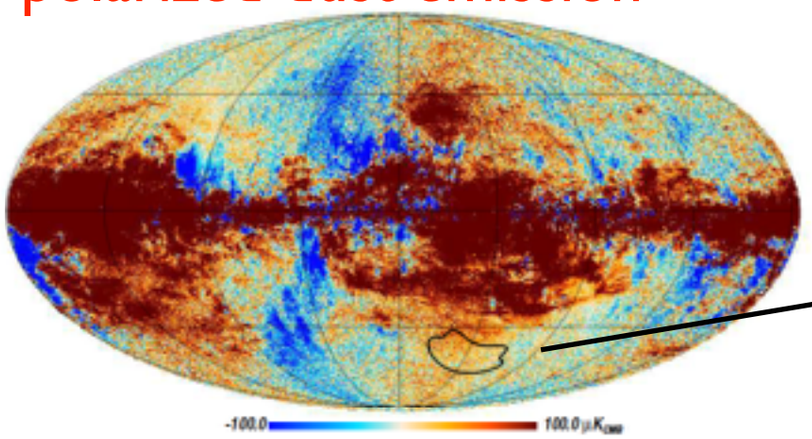
Spectral dependence of CMB & contaminants



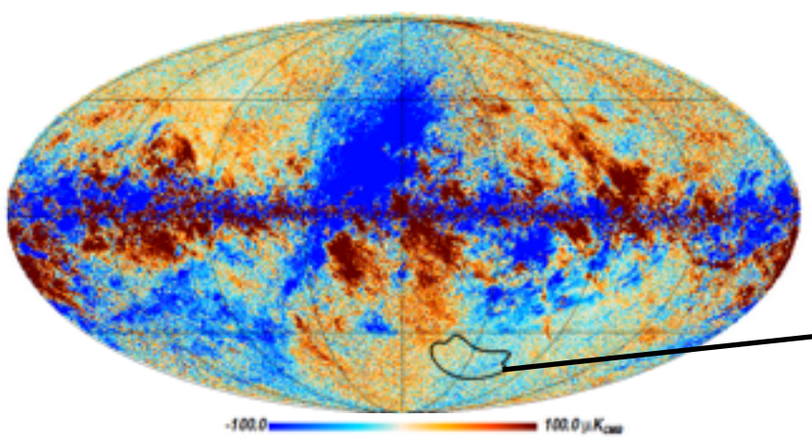
Planck 353 GHz

- Planck is the third generation space mission to observe the CMB: observes the full sky in multiple frequency bands.
- Full sky measurement, but in any given sky patch much less deep than BICEP2+Keck
- 353 GHz band is very sensitive to polarized dust emission

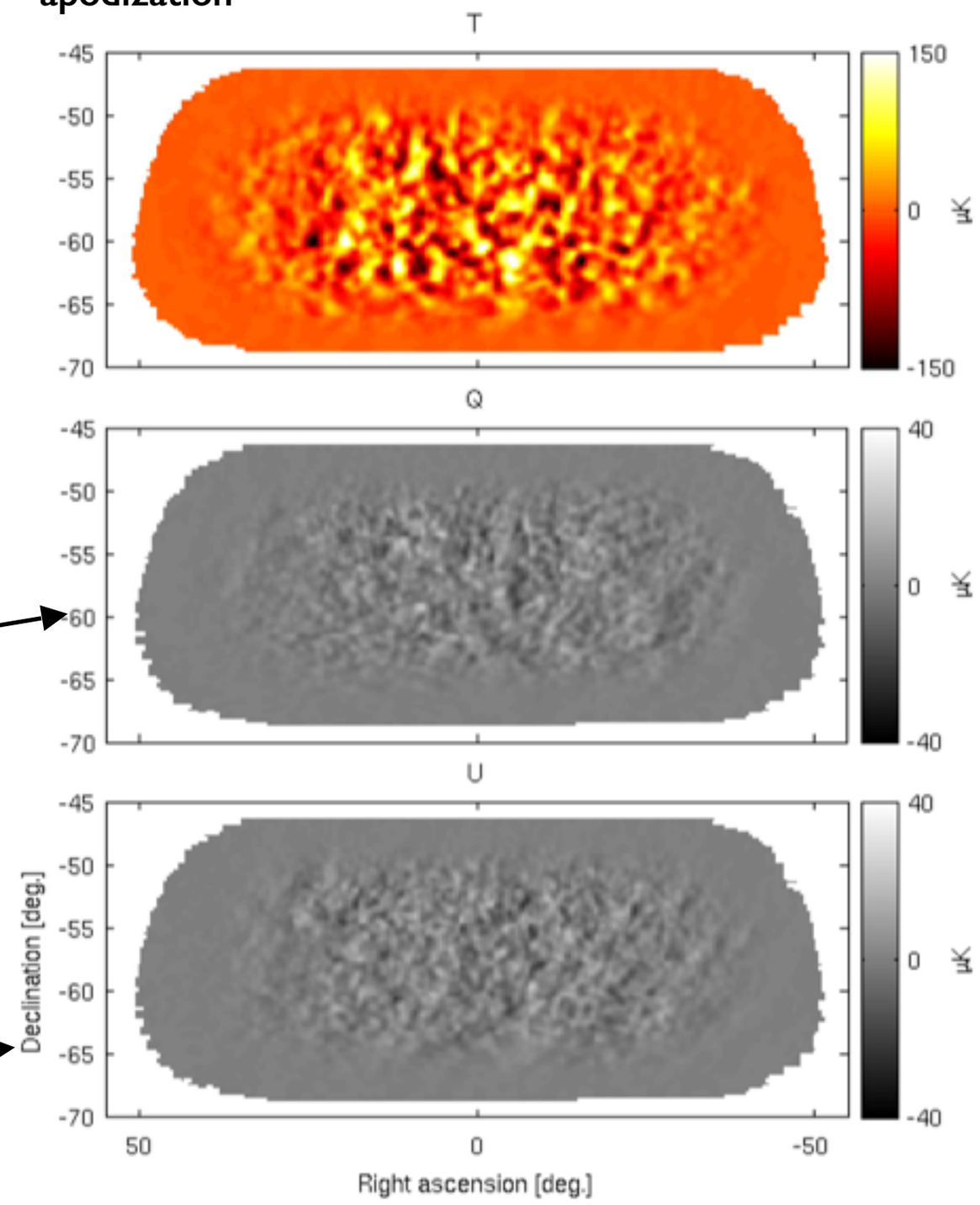
Q



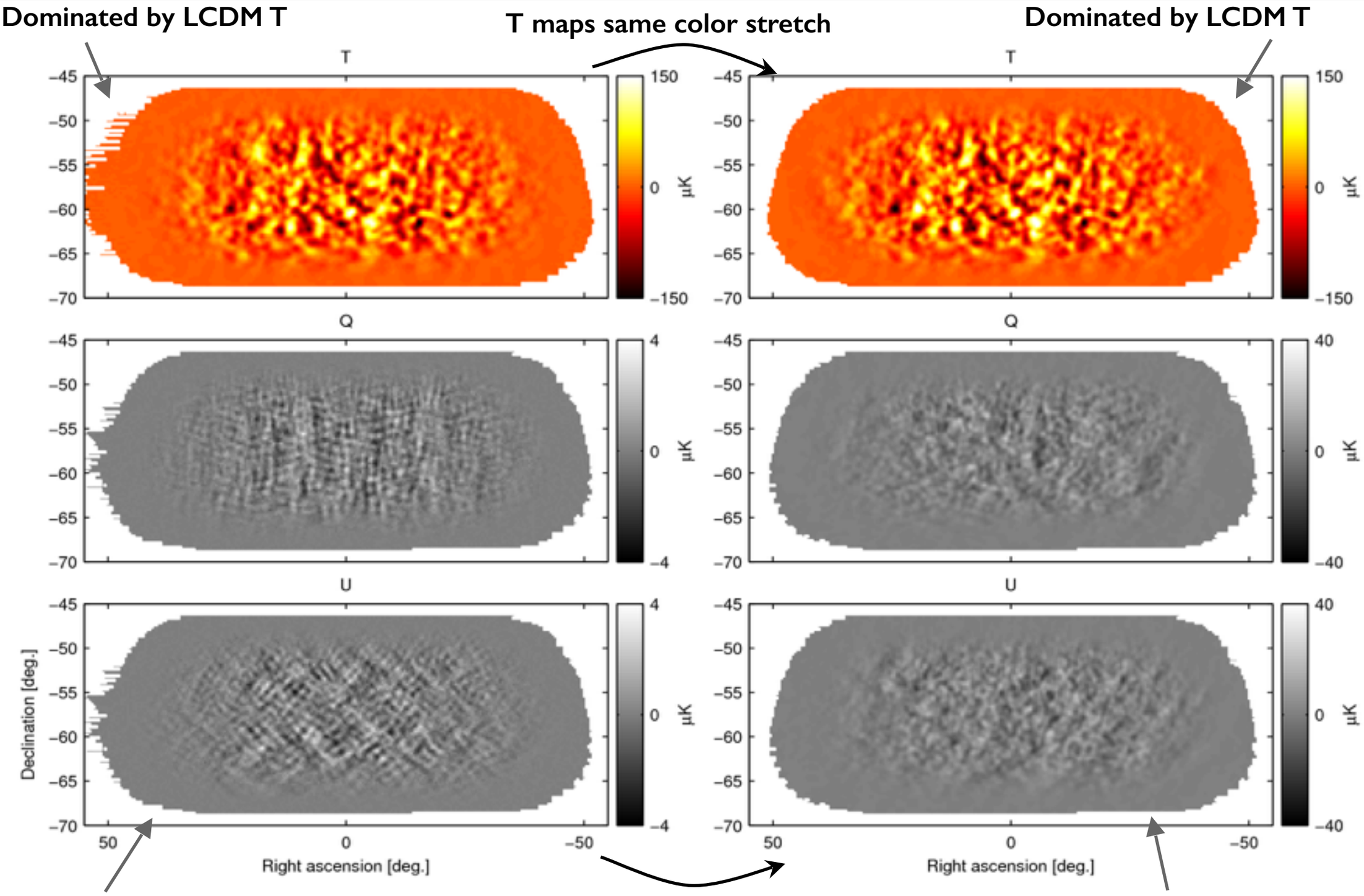
U



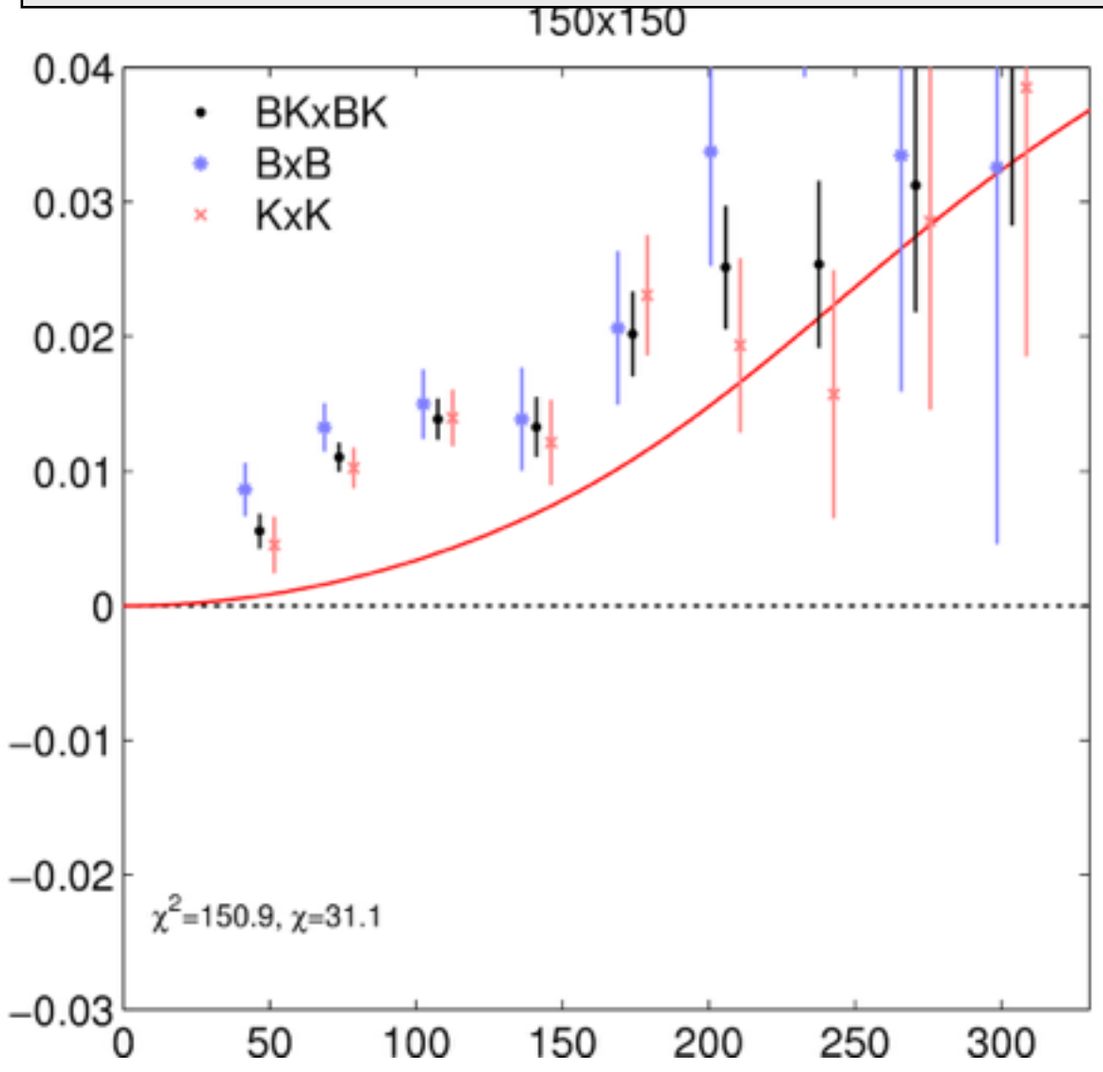
Planck 353GHz maps in BICEP2+Keck sky region with full simulation of observation and filtering applied plus apodization

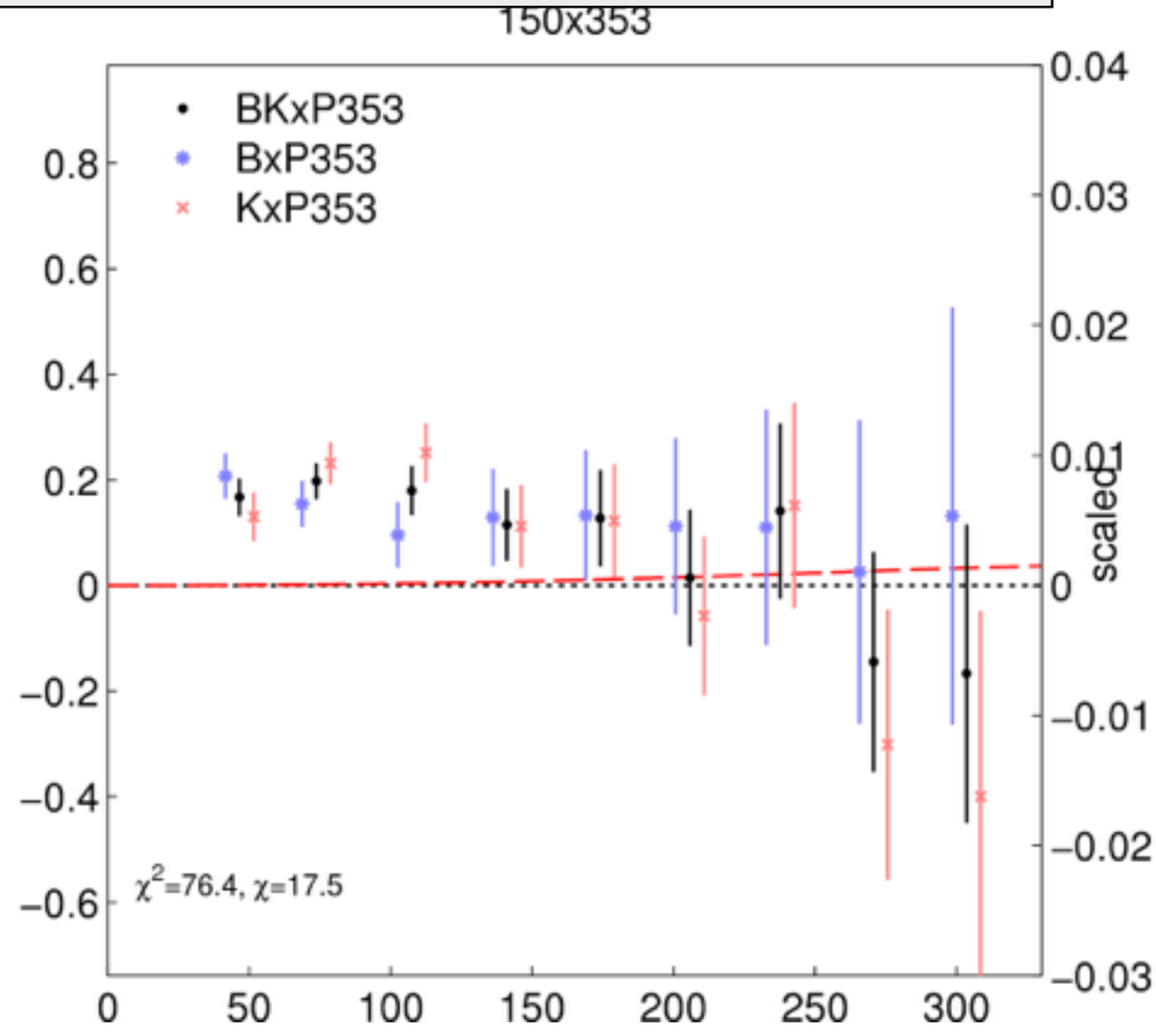


Compare BK 150 GHz (left) with Planck 353 GHz (right)



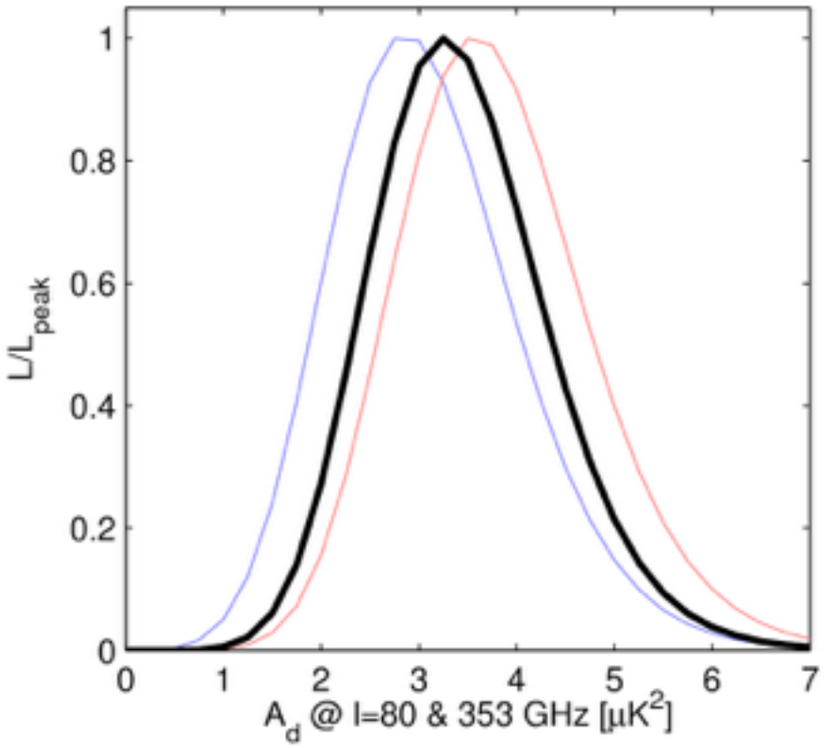
BB Spectra

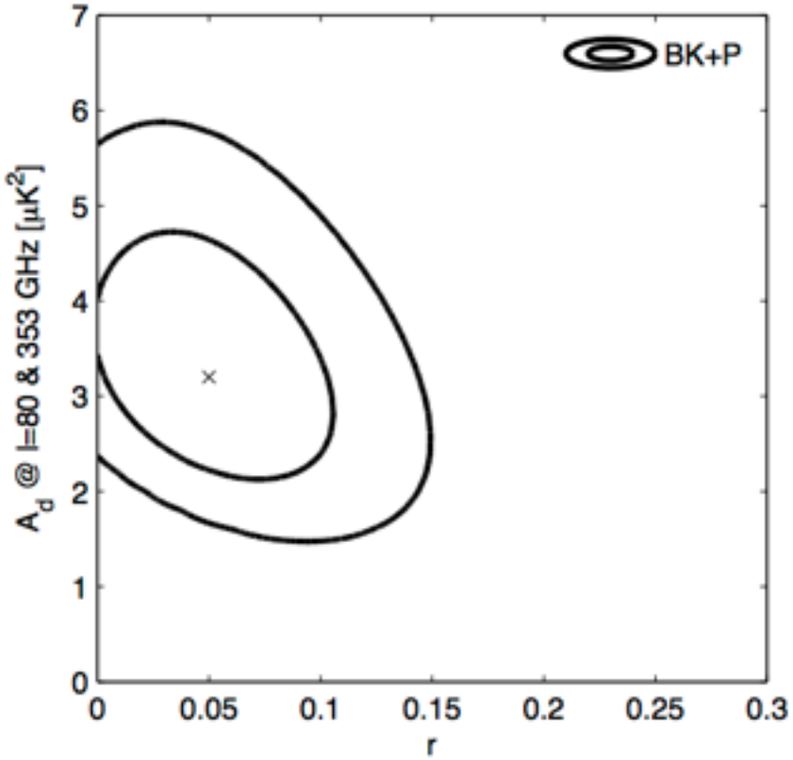


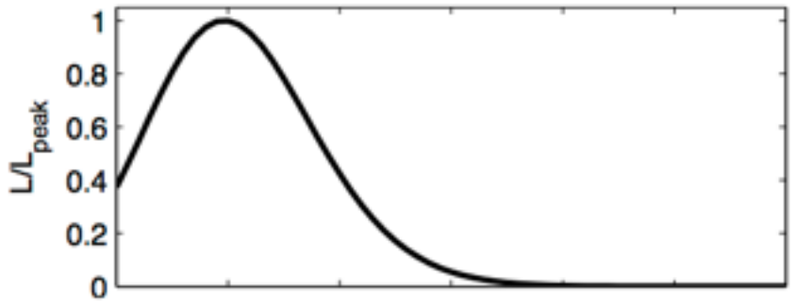


- Correlation of 150 GHz and 353 GHz B-modes is detected with high signal-to-noise.
- Scaling the cross-frequency spectrum by the expected brightness ratio (x25) of dust (right y-axis) indicates that dust contribution is comparable in magnitude to BICEP2+Keck excess over ΛCDM.

Multi-component multi-spectral likelihood analysis

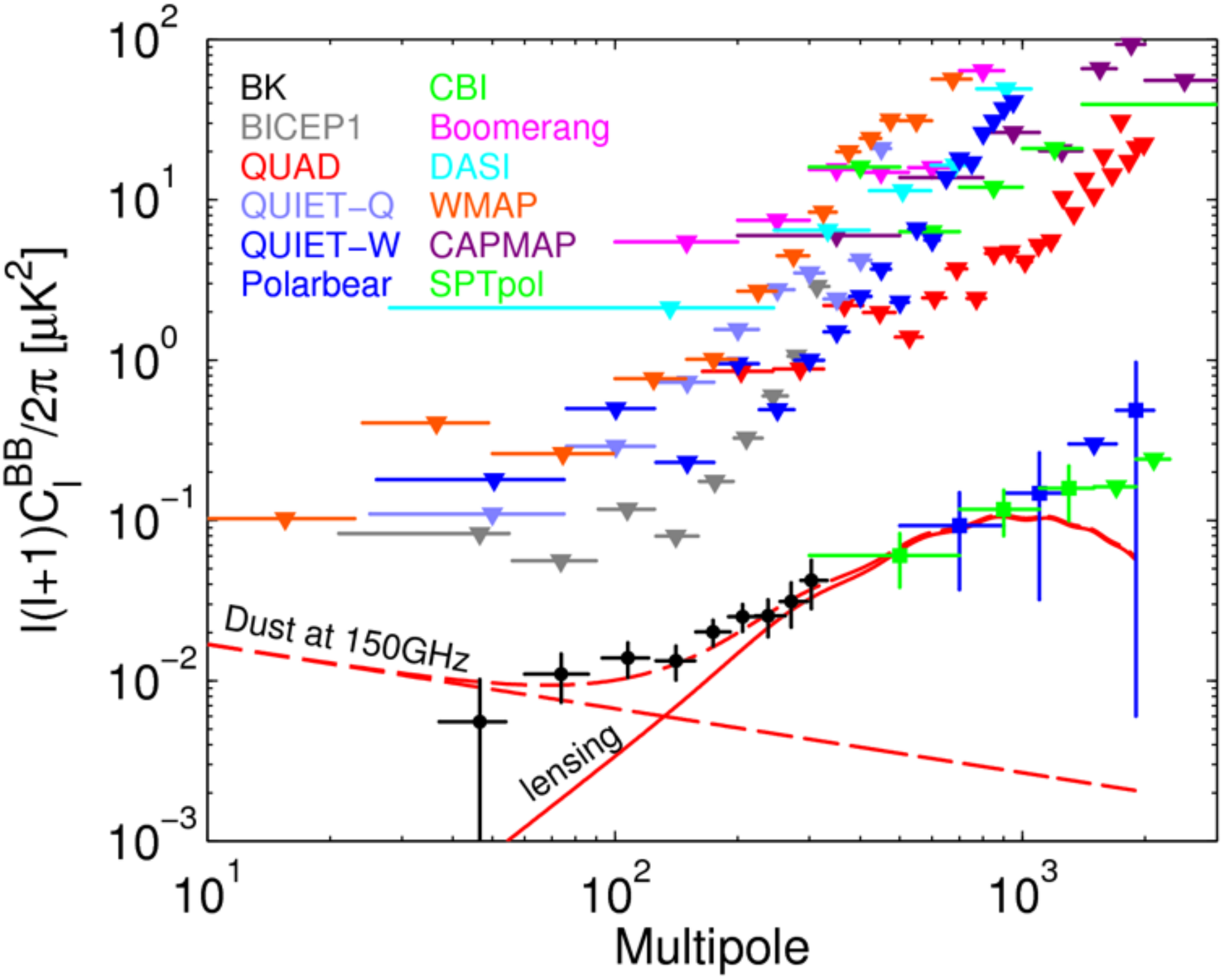




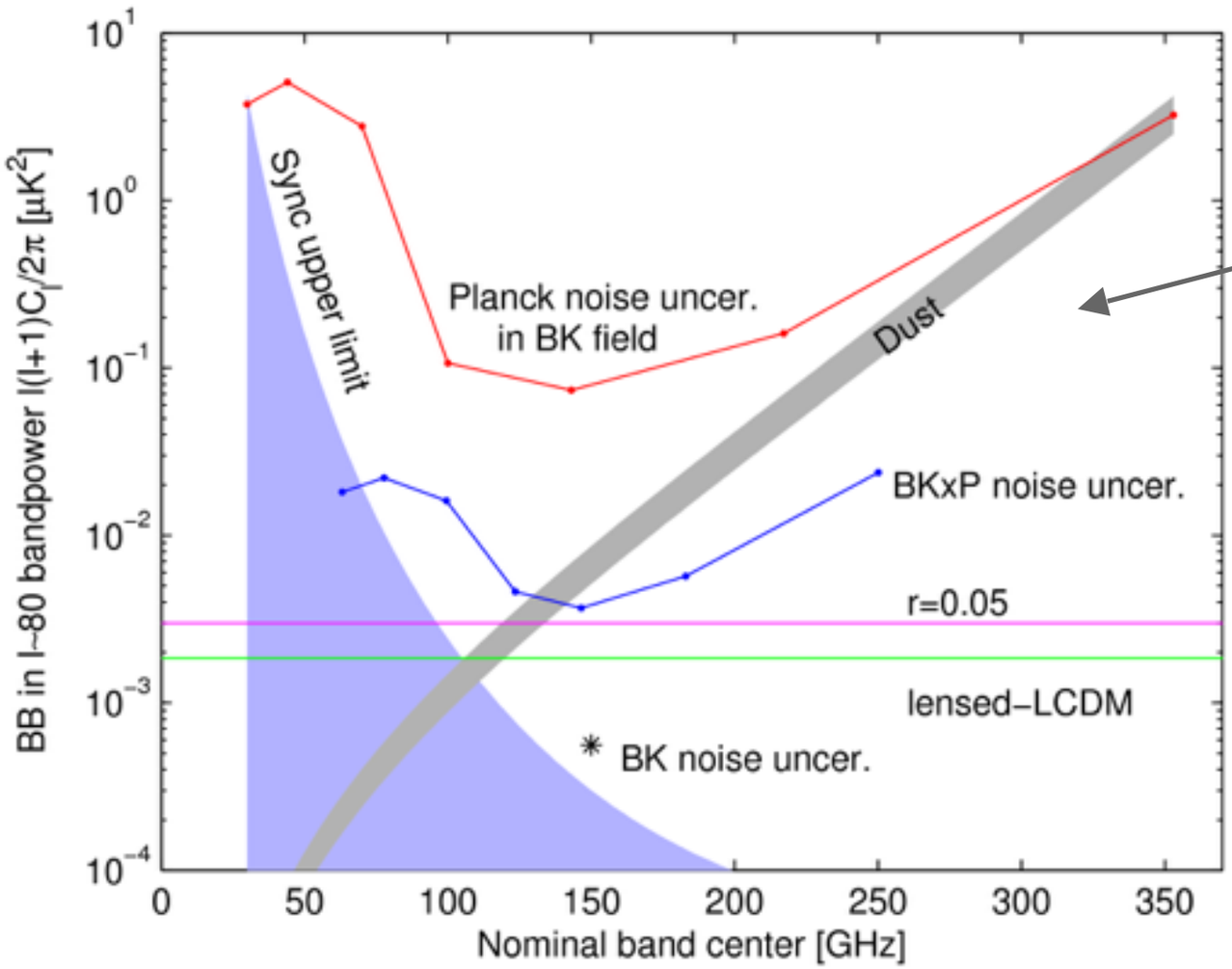


- Use single- and cross-frequency spectra between BK 150 GHz and Planck 217 & 353 GHz channels.
- Vary *r* and amplitude of dust, A_d
- Dust is detected with 5.1 σ significance
- *r* likelihood peaks at 0.05 but constraint consistent with zero; r < 0.12 (95% CL)

State of the field (BB power spectrum)



Comparison of signal levels and noise uncertainties



Noise uncertainty and signal levels in single ell=80 bandpower

- The BICEP2+Keck noise is lower than the Planck noise in observed patch
- The noise in the cross spectra is the geometric mean providing high sensitivity to dust for 150x353. Thus a tight constraint can be set on dust amplitude.
- **Noise in P353 is the limiting factor and to make further progress; better data at frequencies other than 150 GHz is required**

Moving ahead in the short term..

Starting to see foreground!

- Foreground dust significant component at 150 GHz
- Not sufficient Planck S/N to pick out '*r*' if buried in there

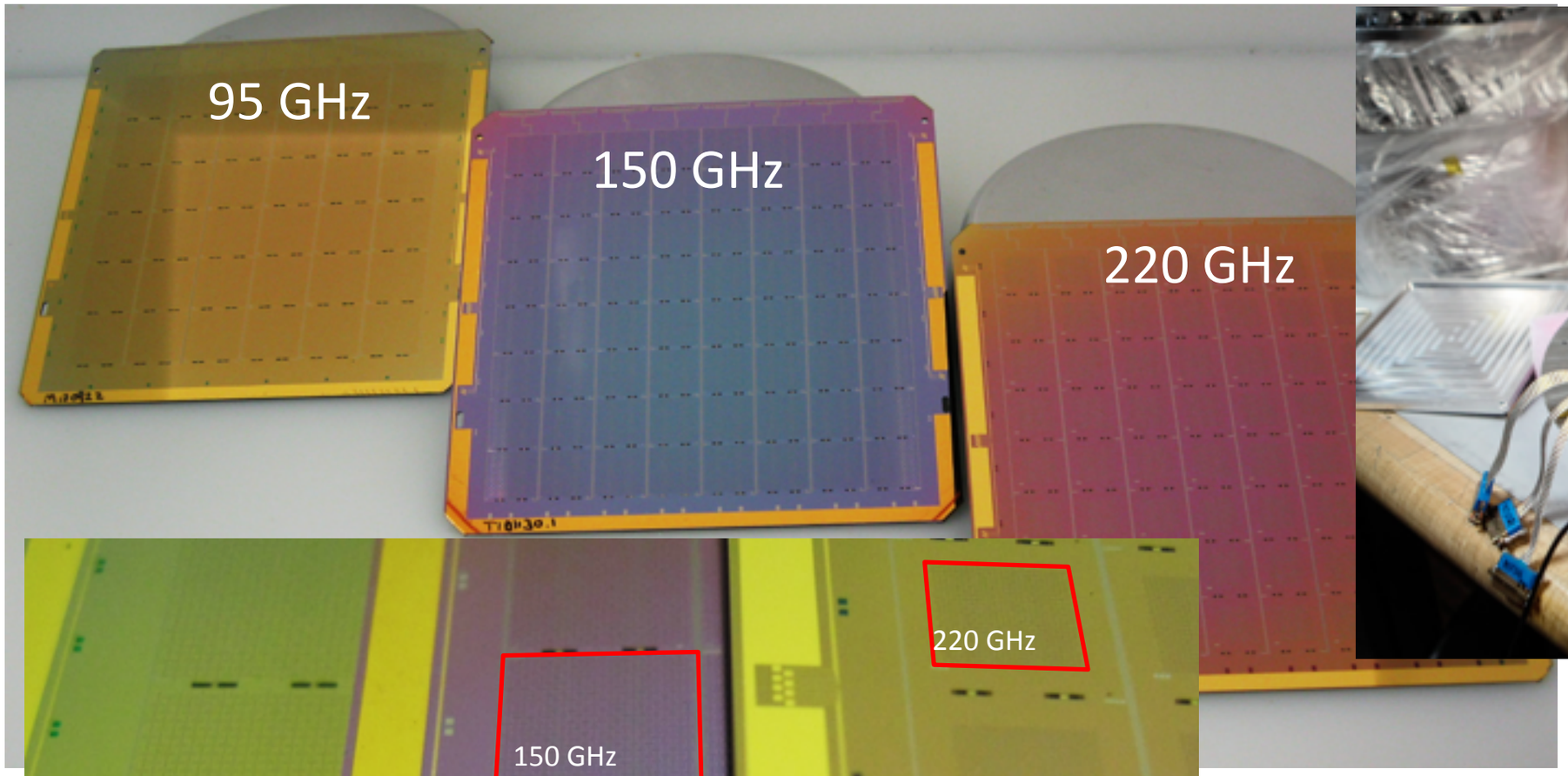
What to do next?

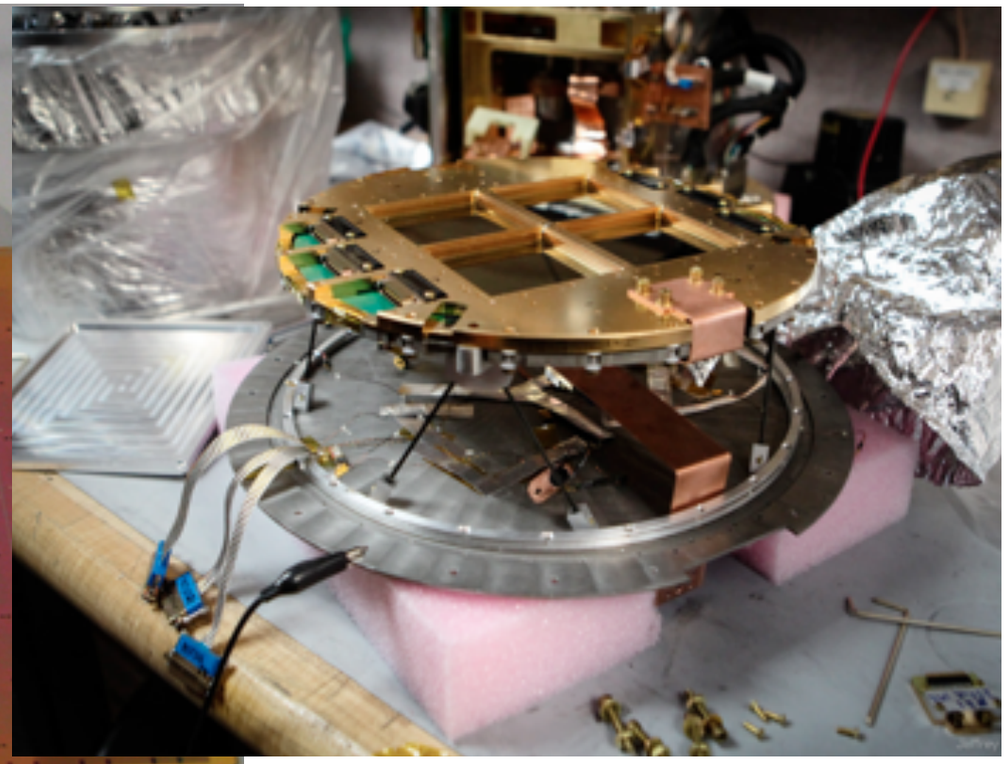
- Increase frequency coverage — acquire more map depth at 95 GHz, 220 GHz.
- If necessary, continue to integrate deeper

How to do it?

- Compact receiver, targeted observation strategy successful — retain these elements
- Scaling to 5+ B2/Keck-style receivers becomes logistically challenging

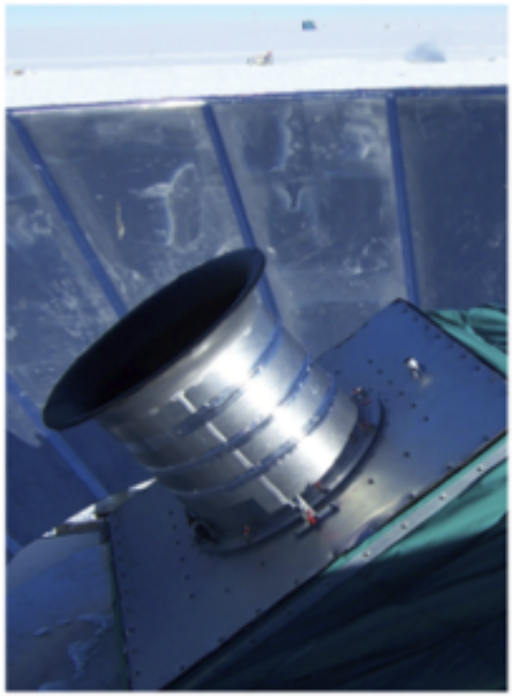
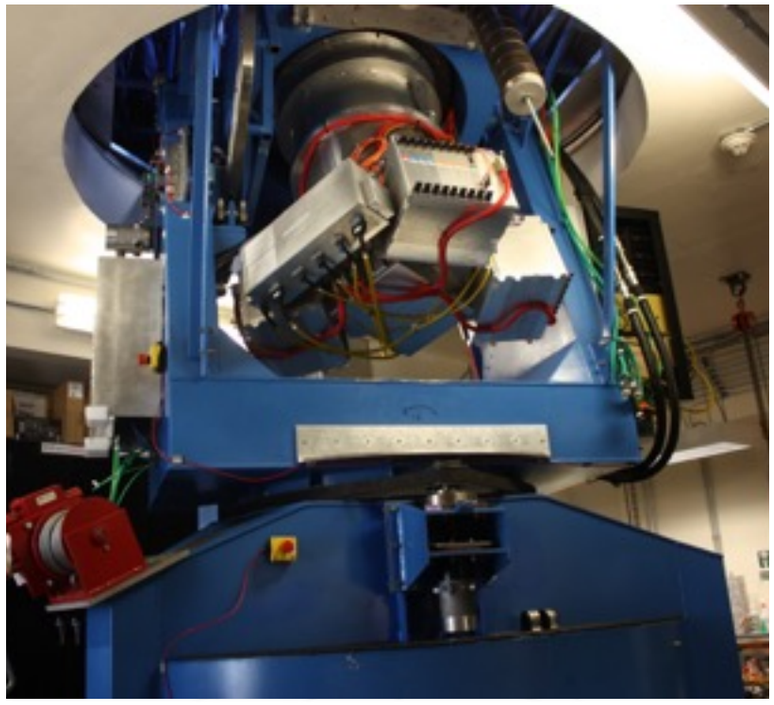
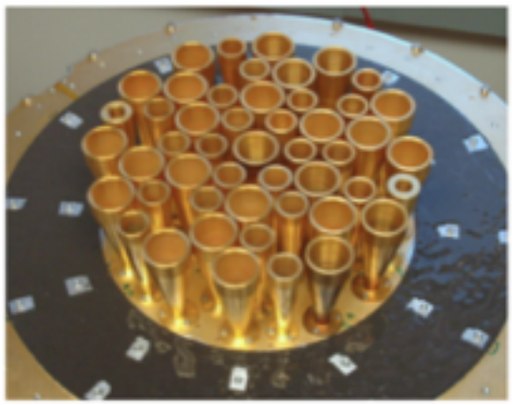
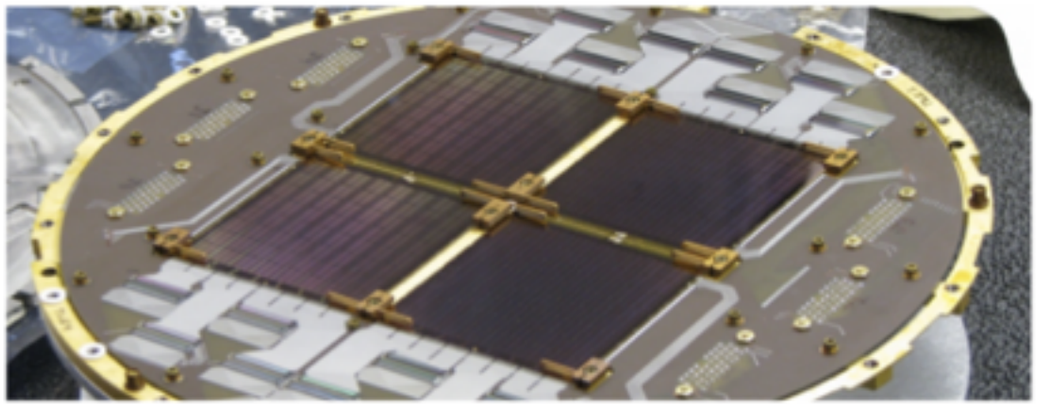
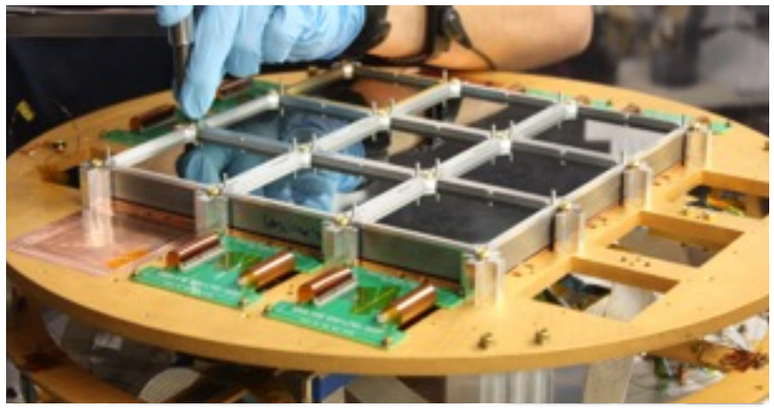
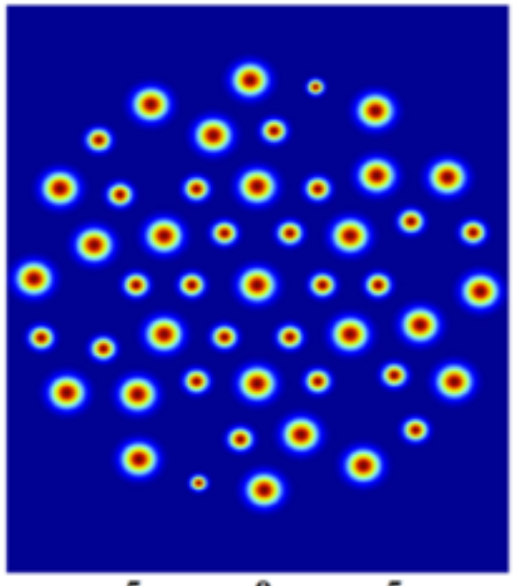
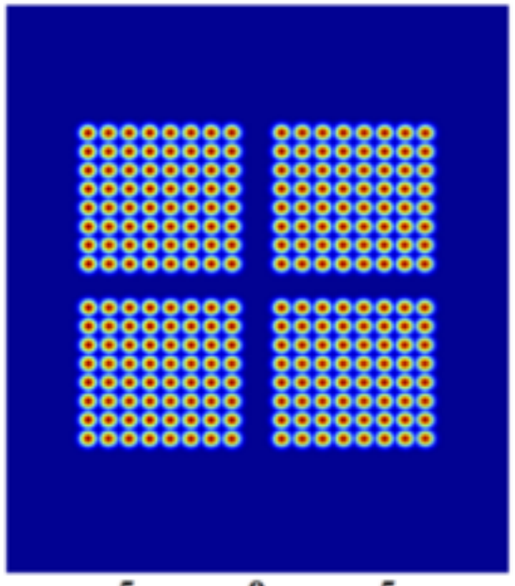
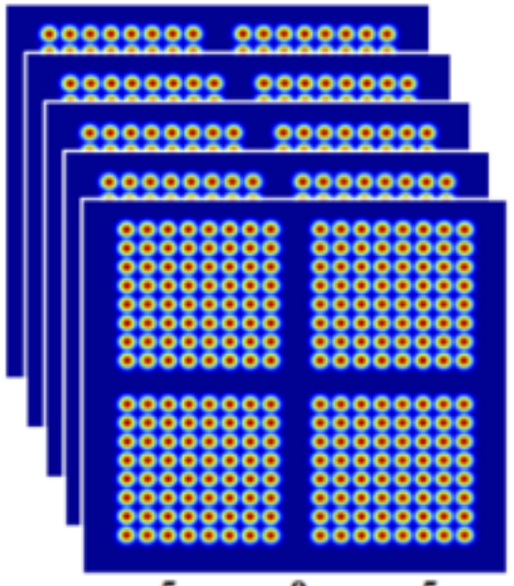
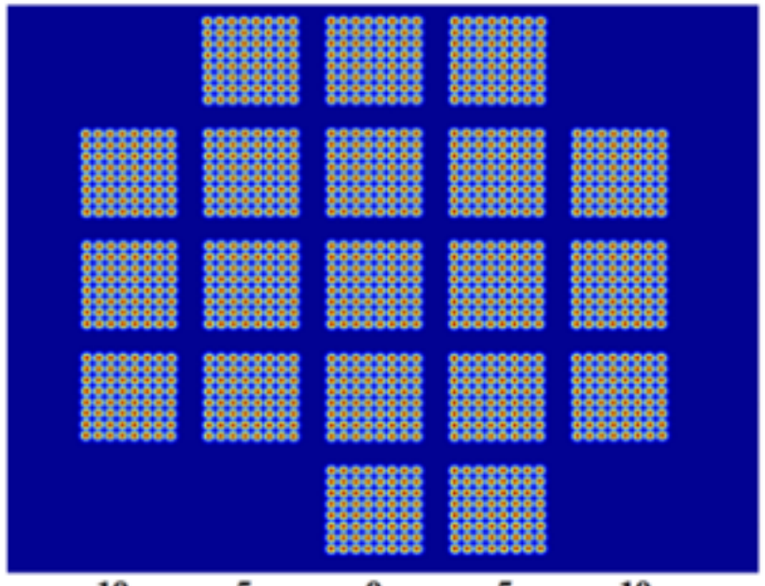
Keck 2014, 2015 multi-frequency upgrades



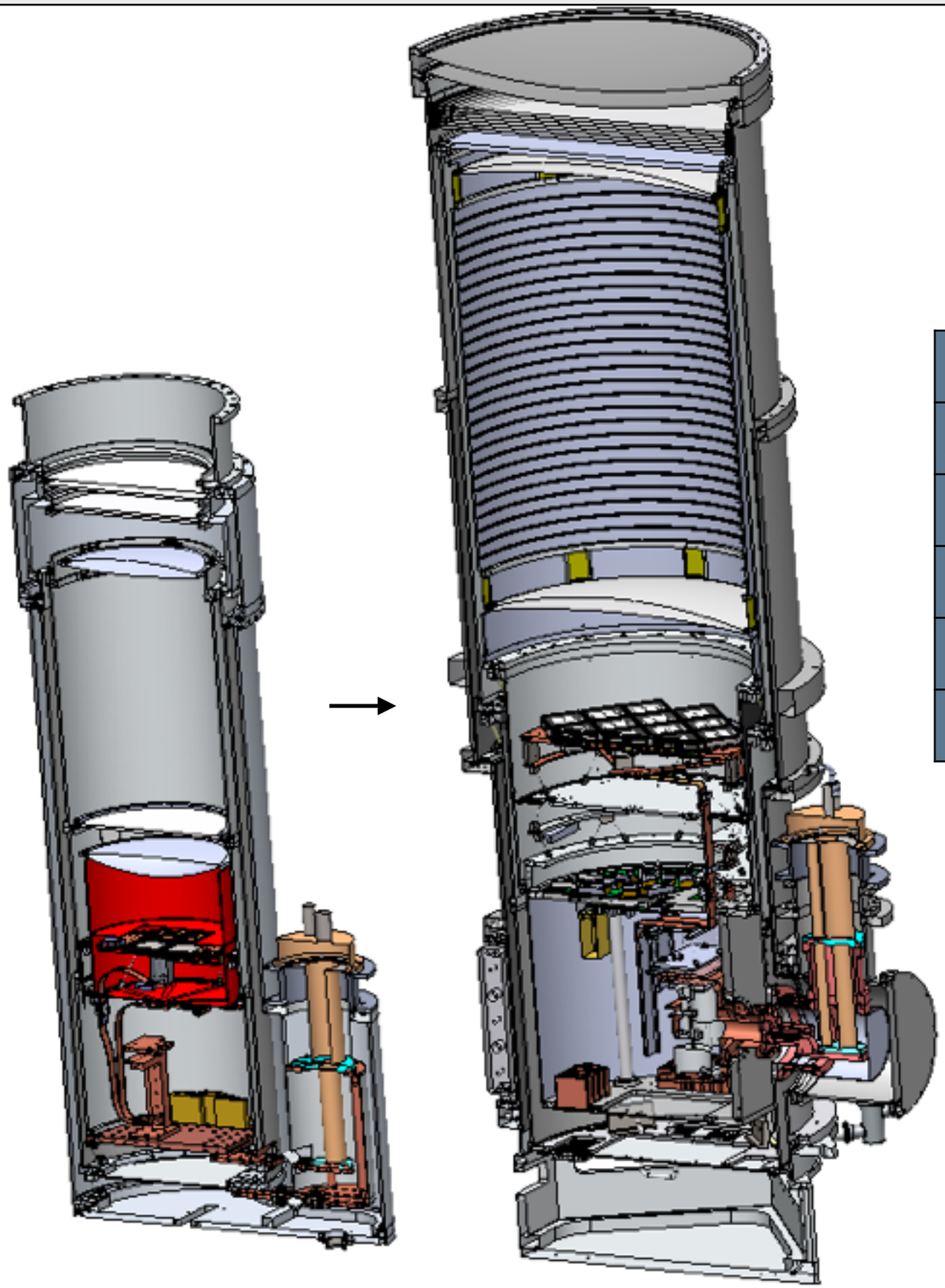


Keck now observing at multiple frequencies

- Changed 2 focal planes to 95 GHz in 2014
- Changed 2 focal planes to 220 GHz in 2015

	BICEP1 (2006 - 8)	BICEP2 (2010 - 12)	Keck Array (2011 -)	BICEP3 (2015-)
Telescope and Mount				
Focal Plane				
Beams on Sky				

Scale to a super-receiver with 10x throughput

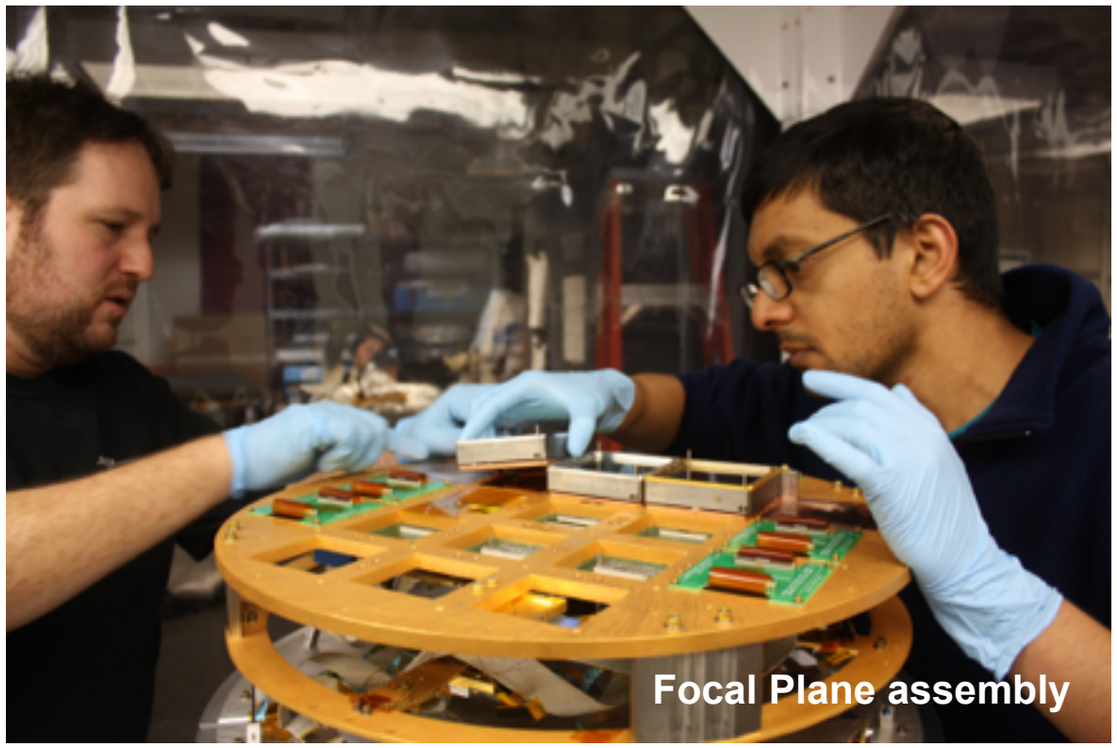


	B2/Keck	BICEP3
Aperture	260mm	680mm
Optics	f/2.4	f/1.6
FOV	18 deg	28 deg
Beams	0.7 deg	0.35 deg
Dets	288	2560

*comparisons at 95 GHz

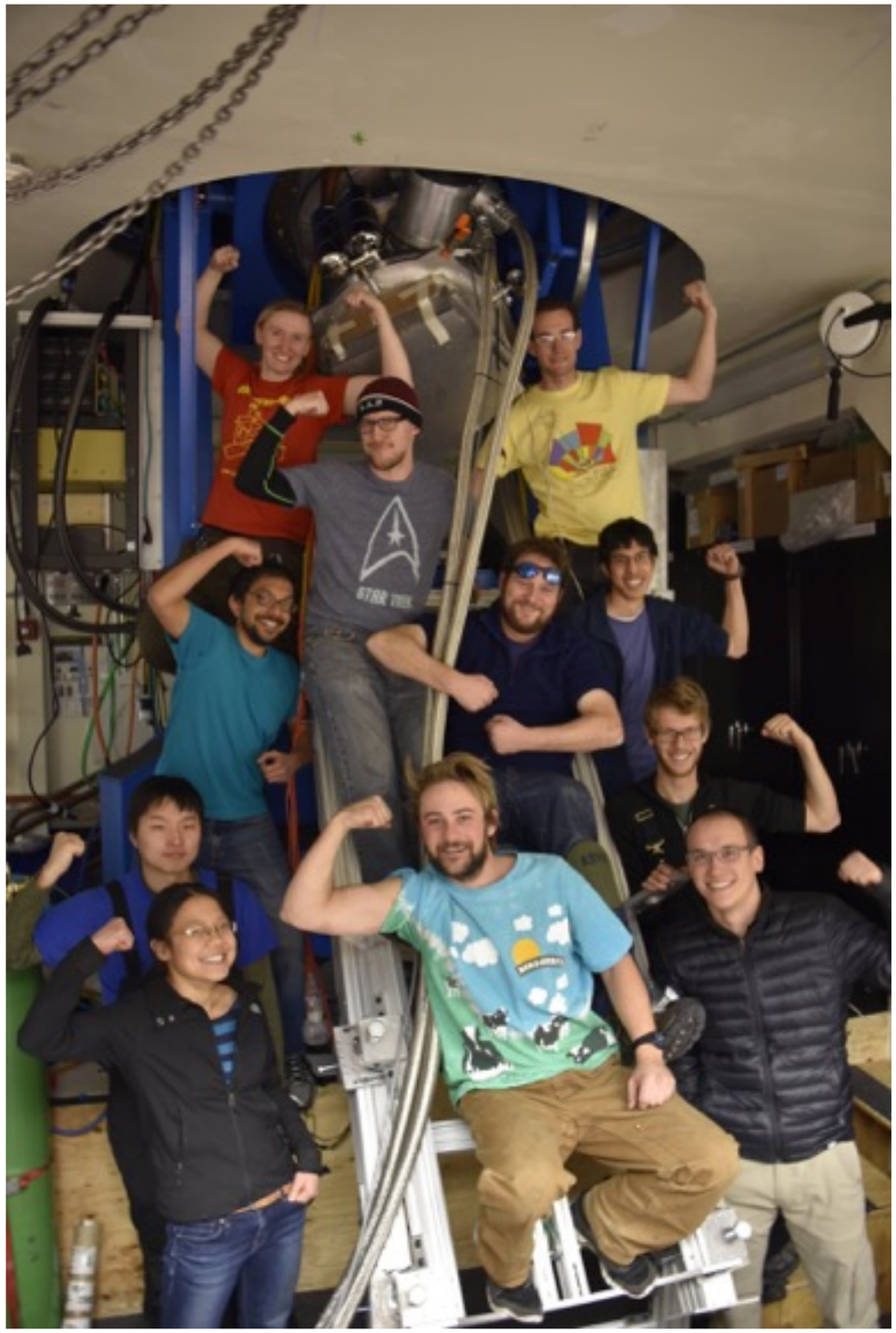
December 2015: BICEP3 assembly at South Pole


Optics tube installation


Focal Plane assembly

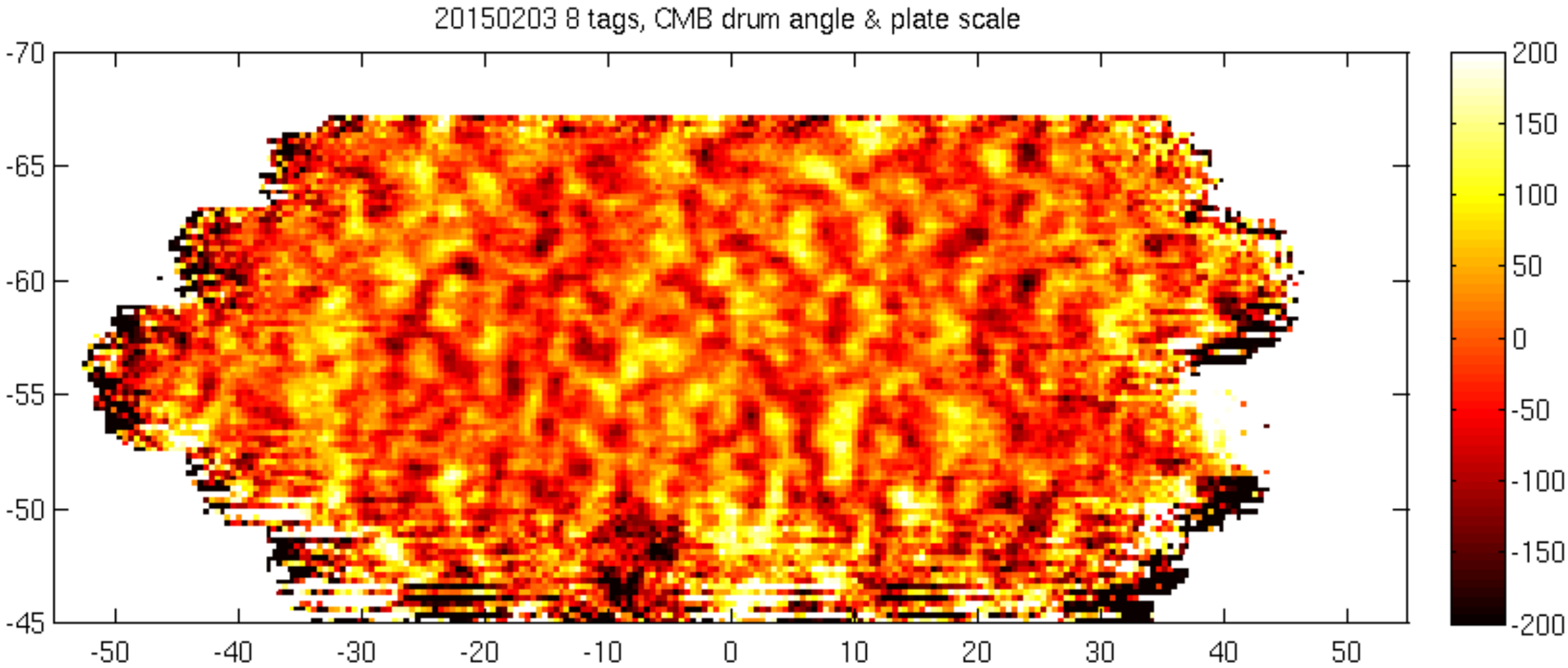

Cryogenics close up

January 2015: Installed in BICEP mount



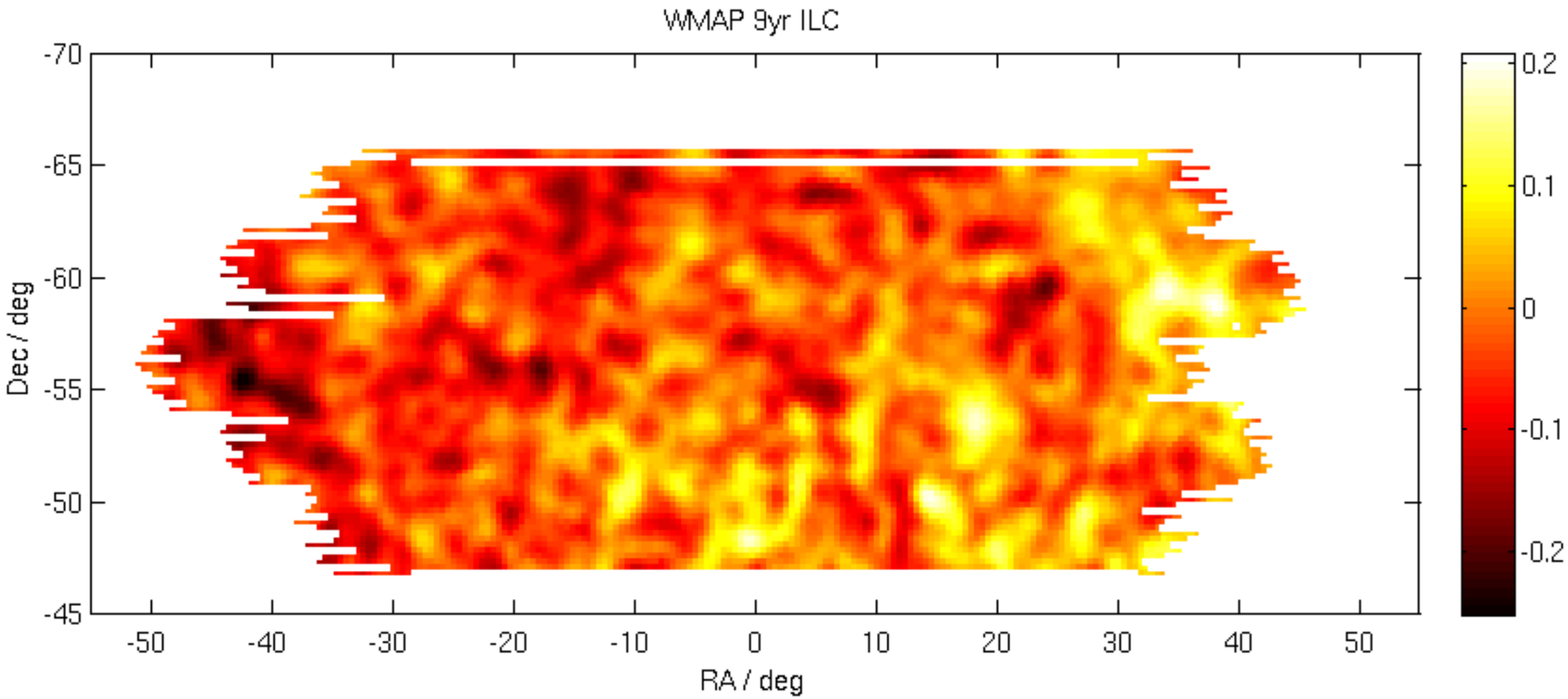
Replaces BICEP2 in Dark Sector Lab at South Pole

First light: See CMB T anisotropies in 6 hours!



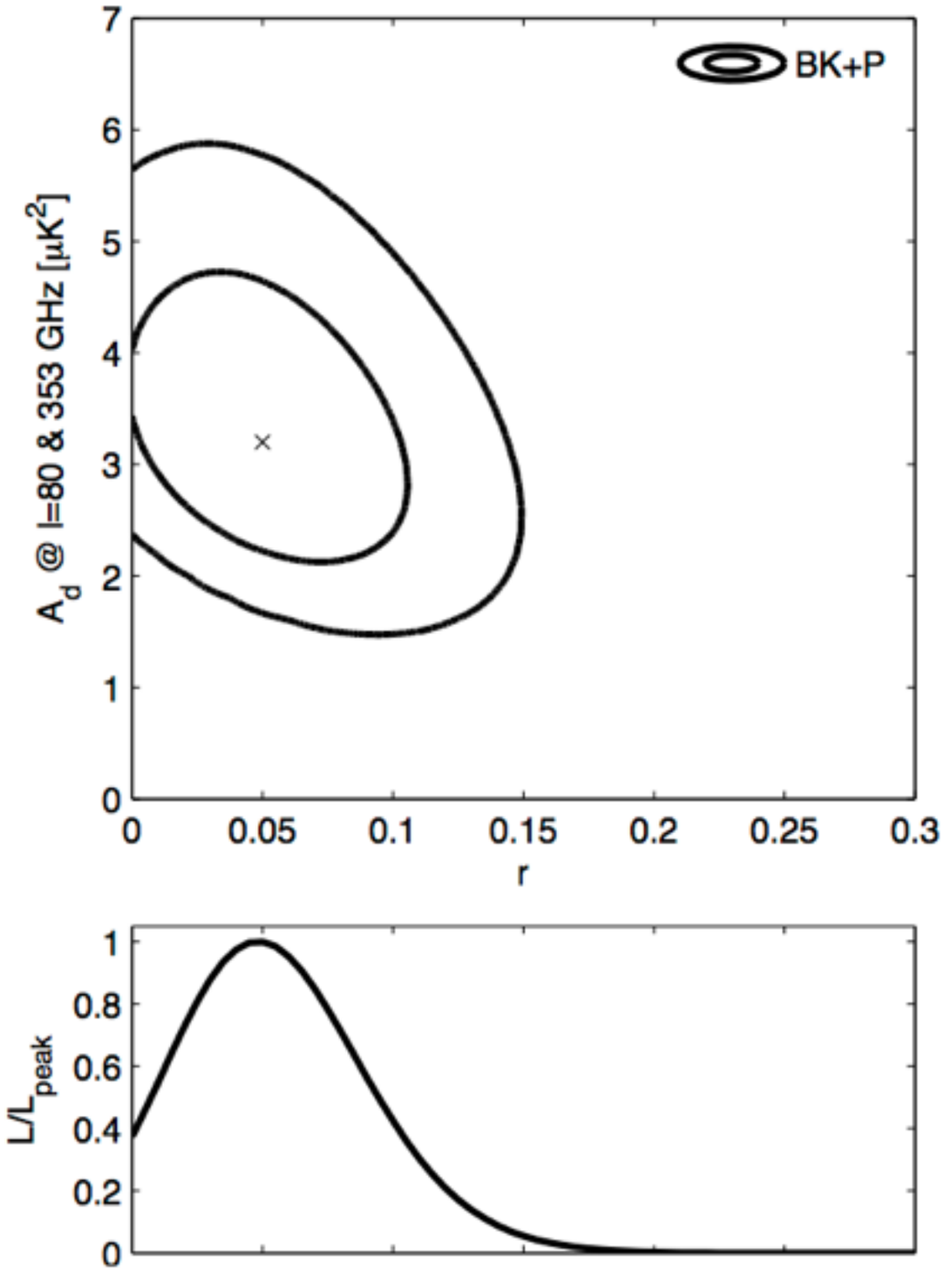
BICEP3 first six hours of test CMB scans,
no filtering, approximate noise weighting and calibration

First light: Compare with WMAP 9 yr



WMAP 9yr T anisotropies as seen in BICEP field

Recall likelihood from BKP



Data Included:

- BK150 GHz (through 2013)
- Planck 217 and 353 GHz

Likelihood results from a basic lensed-ΛCDM+r +dust model, fitting the 5 lowest bandpowers of the BB auto- and cross-spectra taken between maps at the above frequencies.

The Maximum likelihood on the grid has:

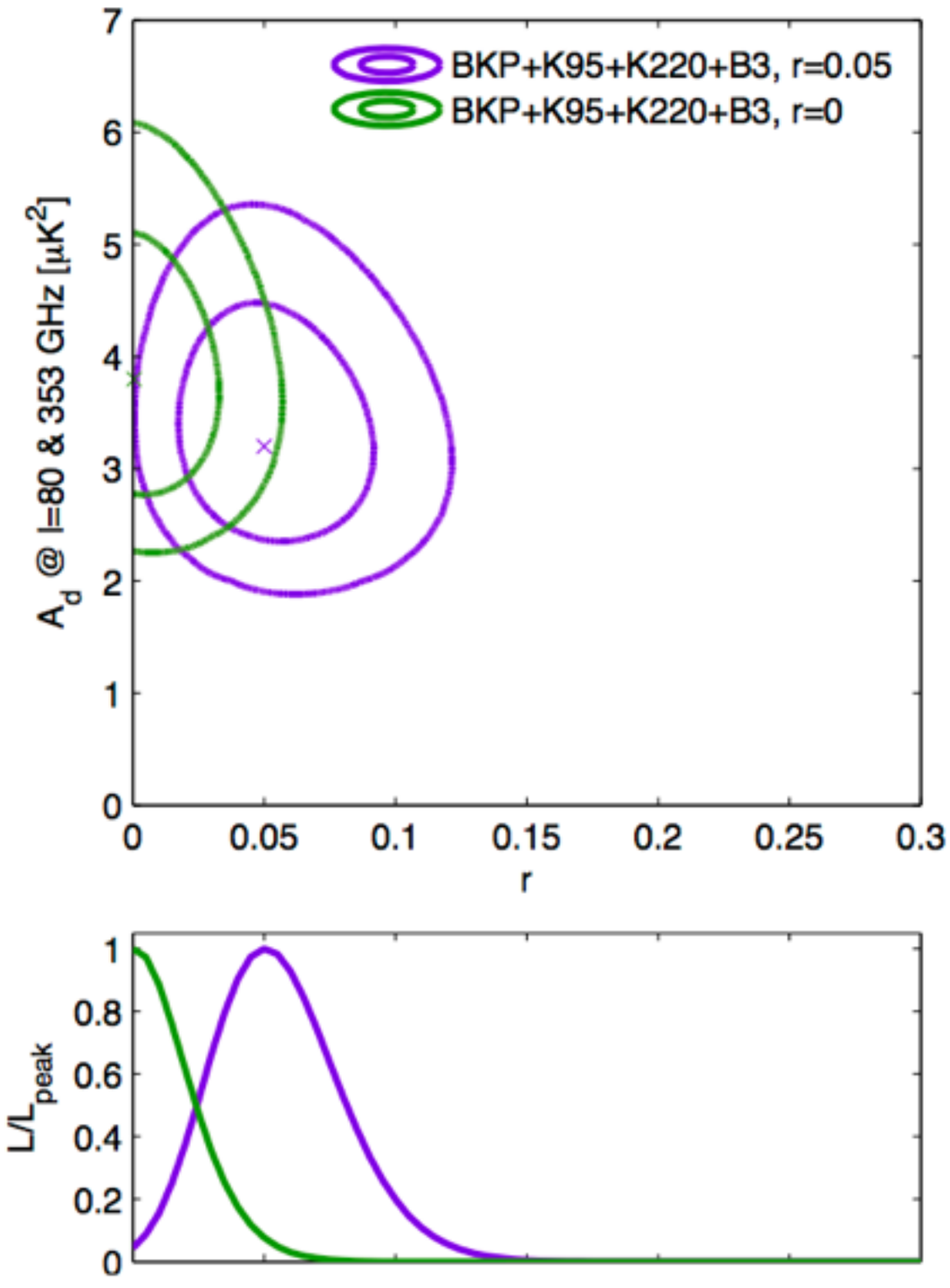
$r = 0.05, A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

For dust SED use modified blackbody model and marginalize over range $\beta_d = 1.59 \pm 0.11$

We assume no synchrotron contribution here.

Foregrounds only PTE = 8.0%

Likelihood forecast for BKP through 2015



Data Included:

- BK150 GHz (through 2013)
- Planck 30 - 353 GHz
- BK 95 GHz, 220 GHz (through 2015)

Contours are projected likelihood contours centered on different expectation values:

$r = 0.05, A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

$r = 0, \quad A_d = 3.8\ \mu K^2_{CMB}$

Both cases here assume synchrotron contribution, β_s=-3.3 and A_{sync} = 3e-4 μK^2_{CMB} (current BKP 95% upper limit).

Foregrounds only PTE = 0.6%

— or —

r < 0.041 (95%)

Conclusions

- BICEP2+Keck sees excess power over ΛCDM at degree scales
- Joint analysis with Planck finds dust at high significance
- Progress requires multi-frequency observation beyond Planck sensitivity
- Keck 95 GHz, 220 GHz in the field and taking data
- BICEP3 provides 10x scaling for faster CMB polarimetry

Thanks for your attention!