Listening for the Echoes of Inflation with BICEP2

BICEP2 I: Ade et al., PRL 112, 241101 (2014)

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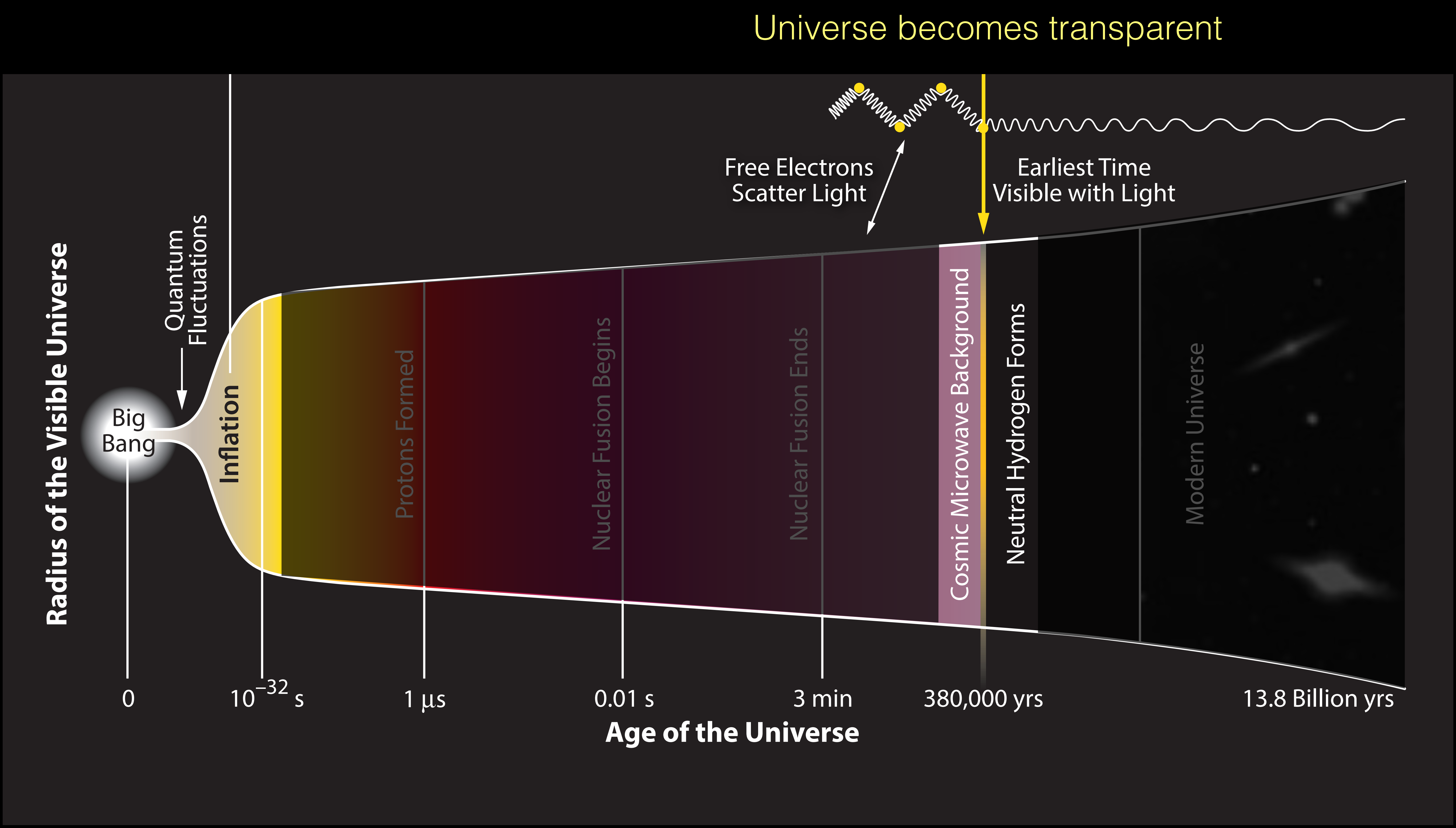
for the BICEP2 collaboration

A History of Creation

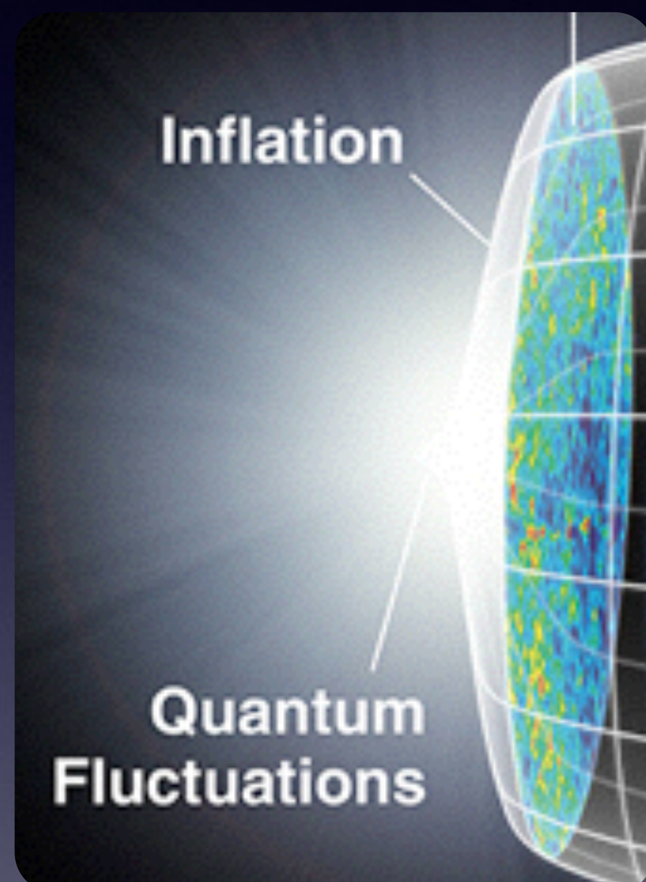


Inflation

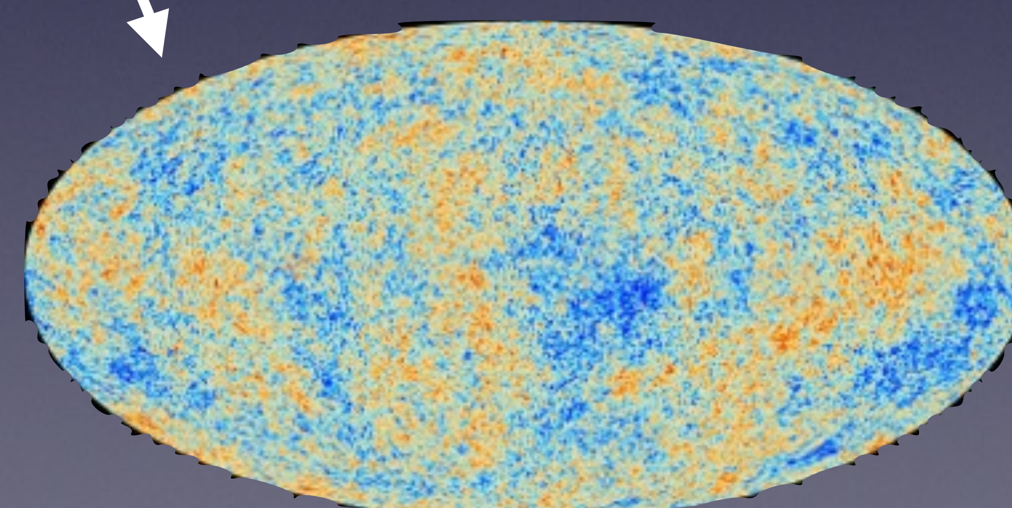
Quantum fluctuations…

"**inflaton**"

… imprinted onto cosmic scales

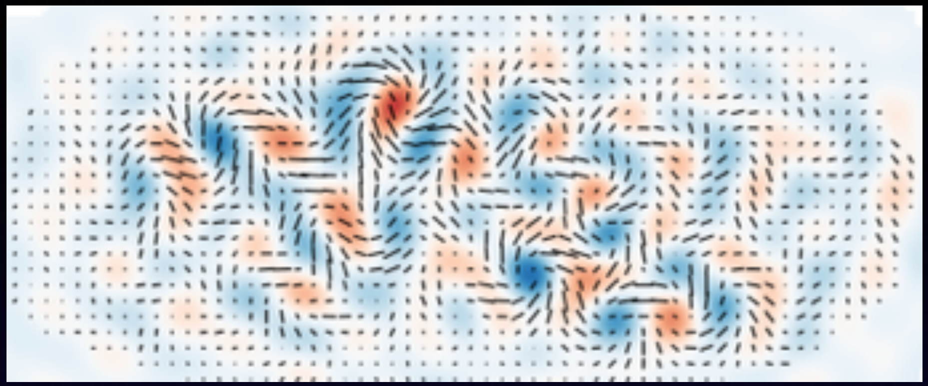


- ✓ Homogeneity
- ✓ Isotropy
- ✓ Nearly-flat geometry ($\Omega \sim 1$)
- ✓ Super-horizon fluctuations
- ✓ Nearly-scale invariant density perturbations ($n_s \sim 1$)



Density perturbations

Primordial Perturbations



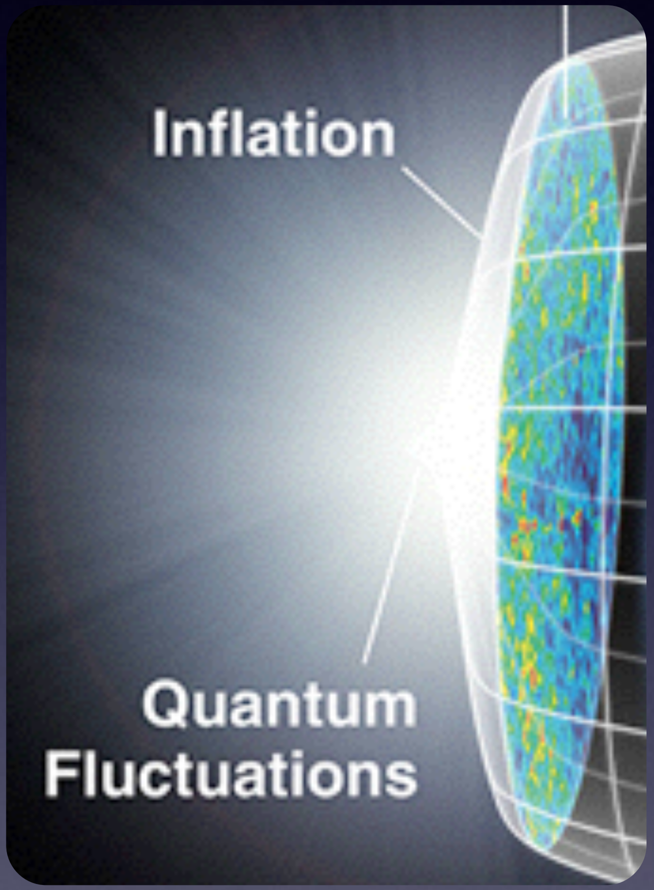
Primordial gravitational waves

Quantum fluctuations…

“**inflaton**”

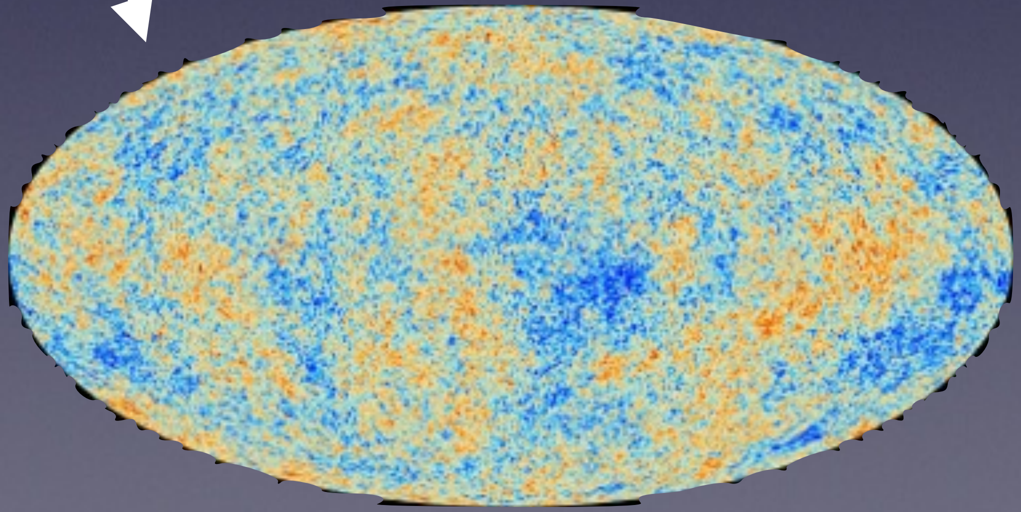
metric tensor

… imprinted onto cosmic scales



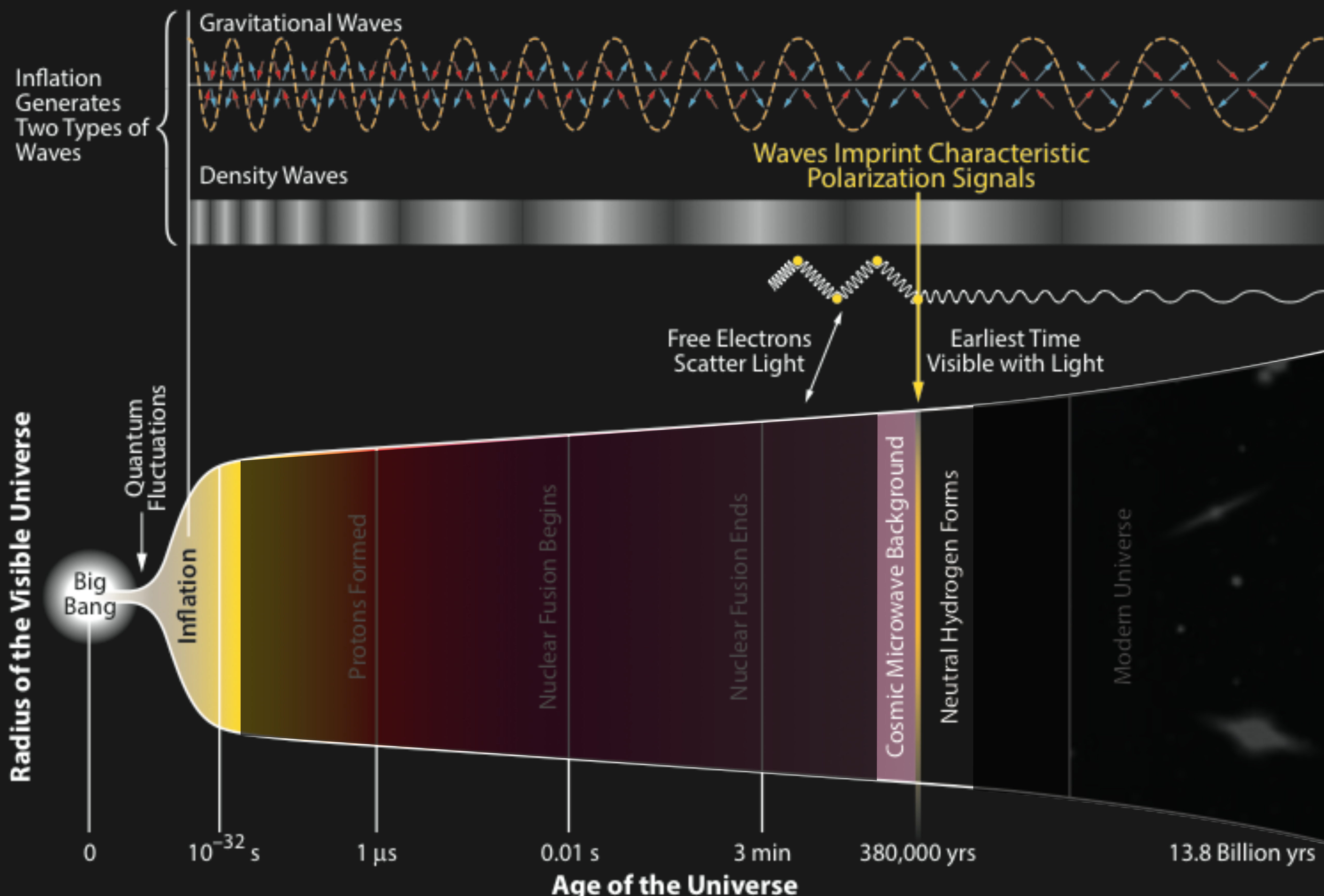
$$r \approx \frac{V[\phi]}{(4 \times 10^{16}\mathrm{GeV})^4}$$

GUT-scale physics!?

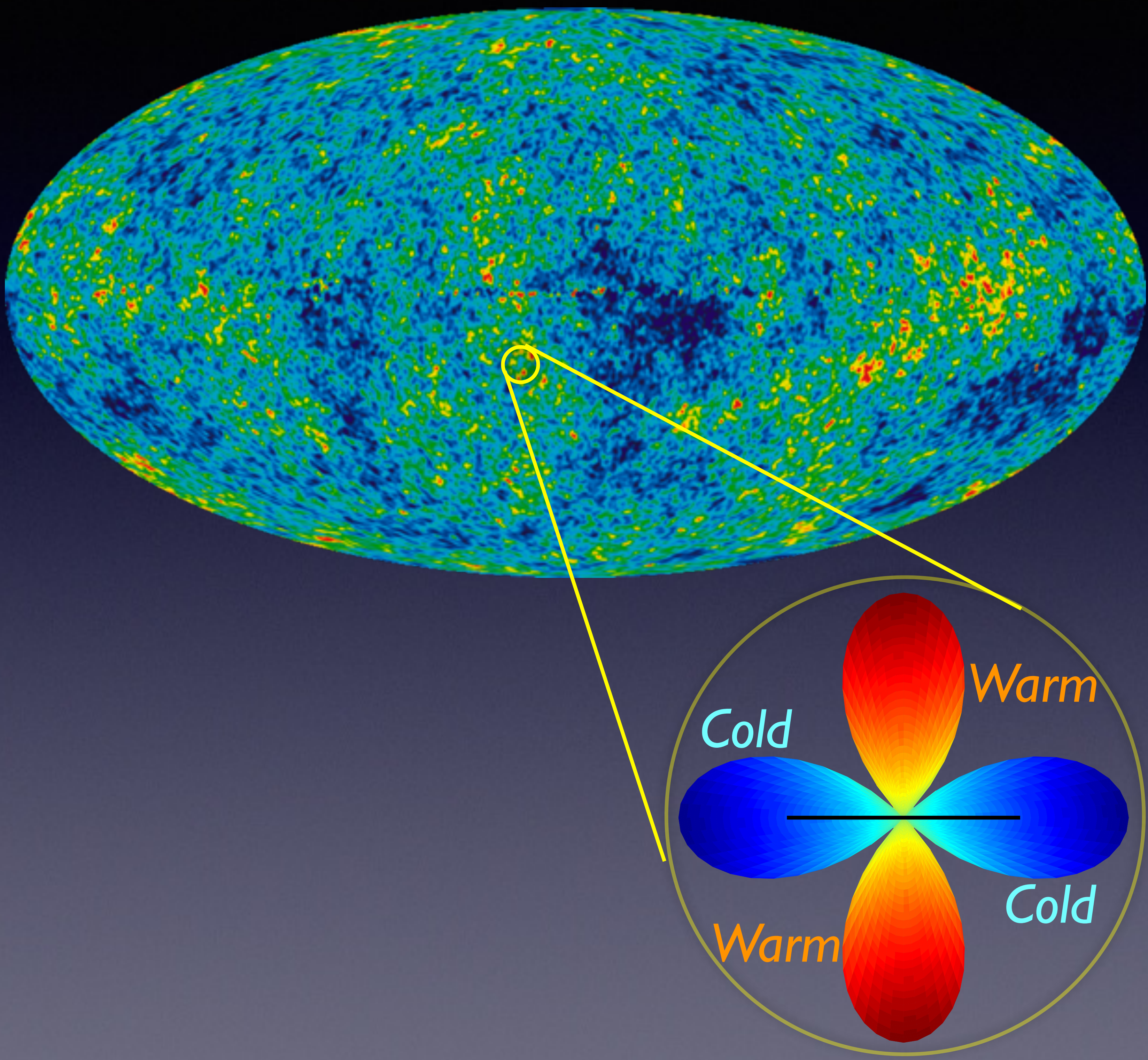


Density perturbations

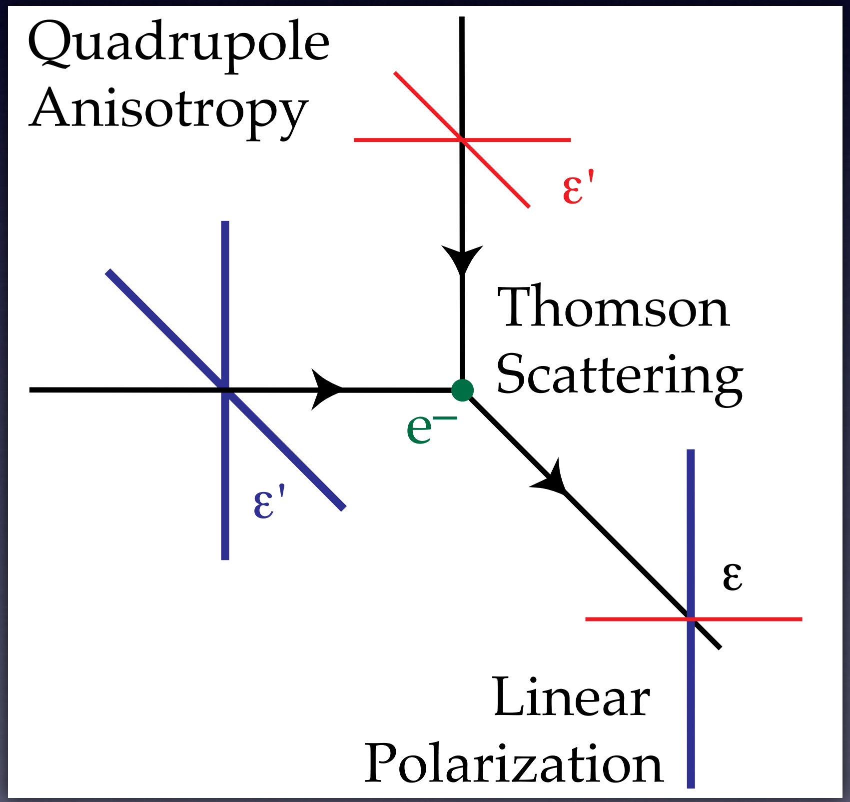
History of the Universe



CMB Polarization

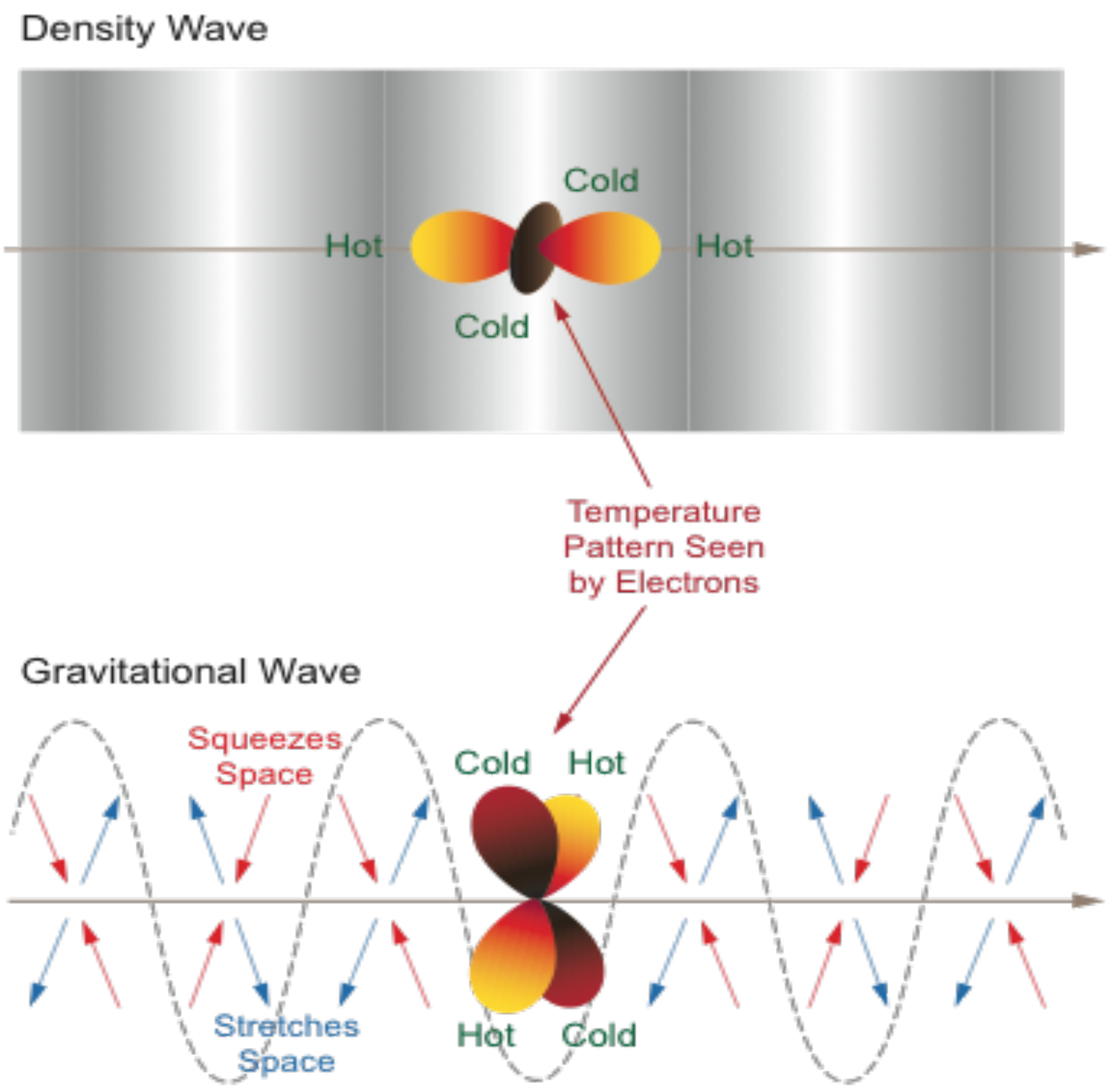


From Thomson scattering wherever there is ionized gas and quadrupole anisotropy



Wayne Hu

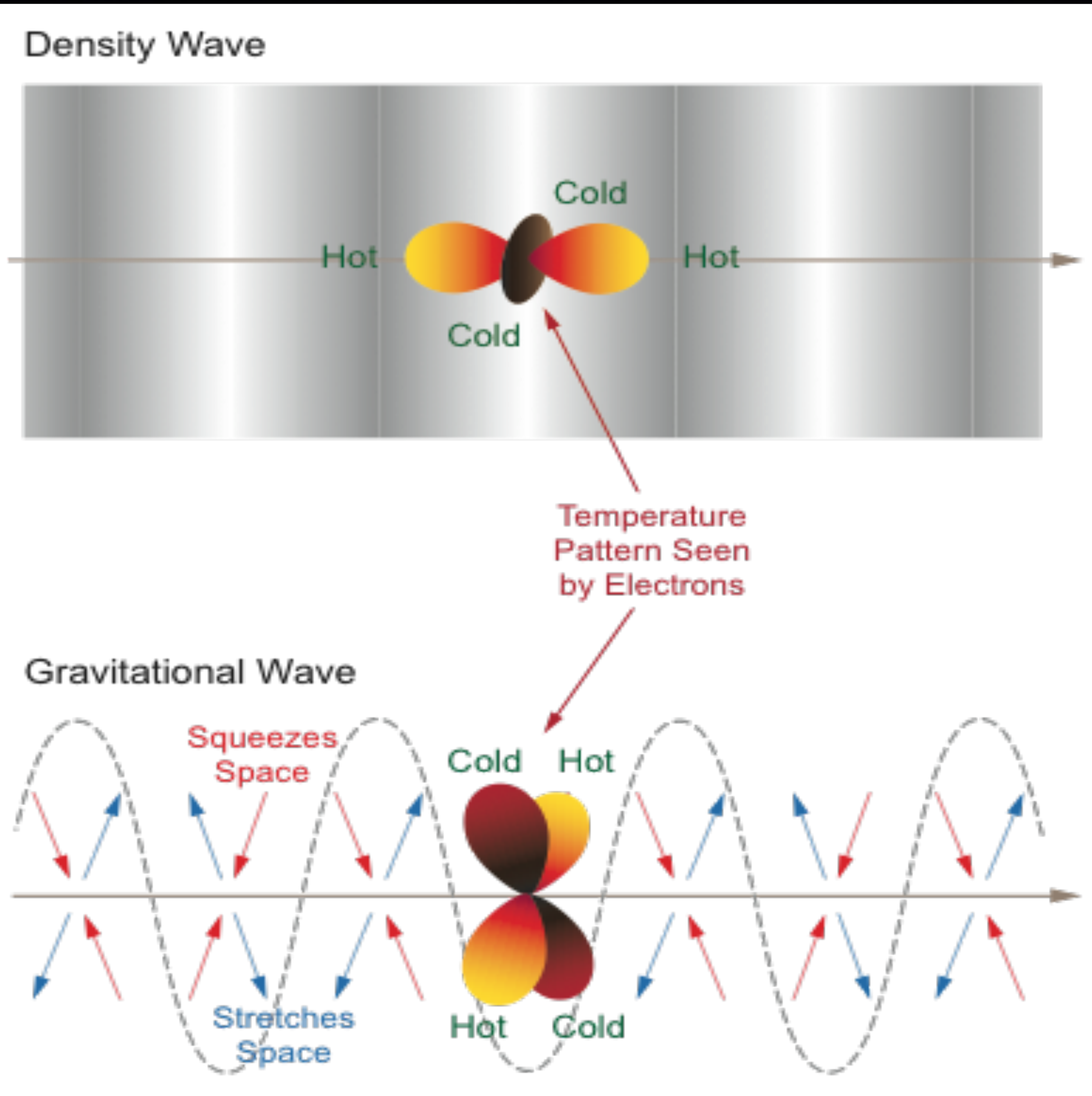
Patterns of Polarization

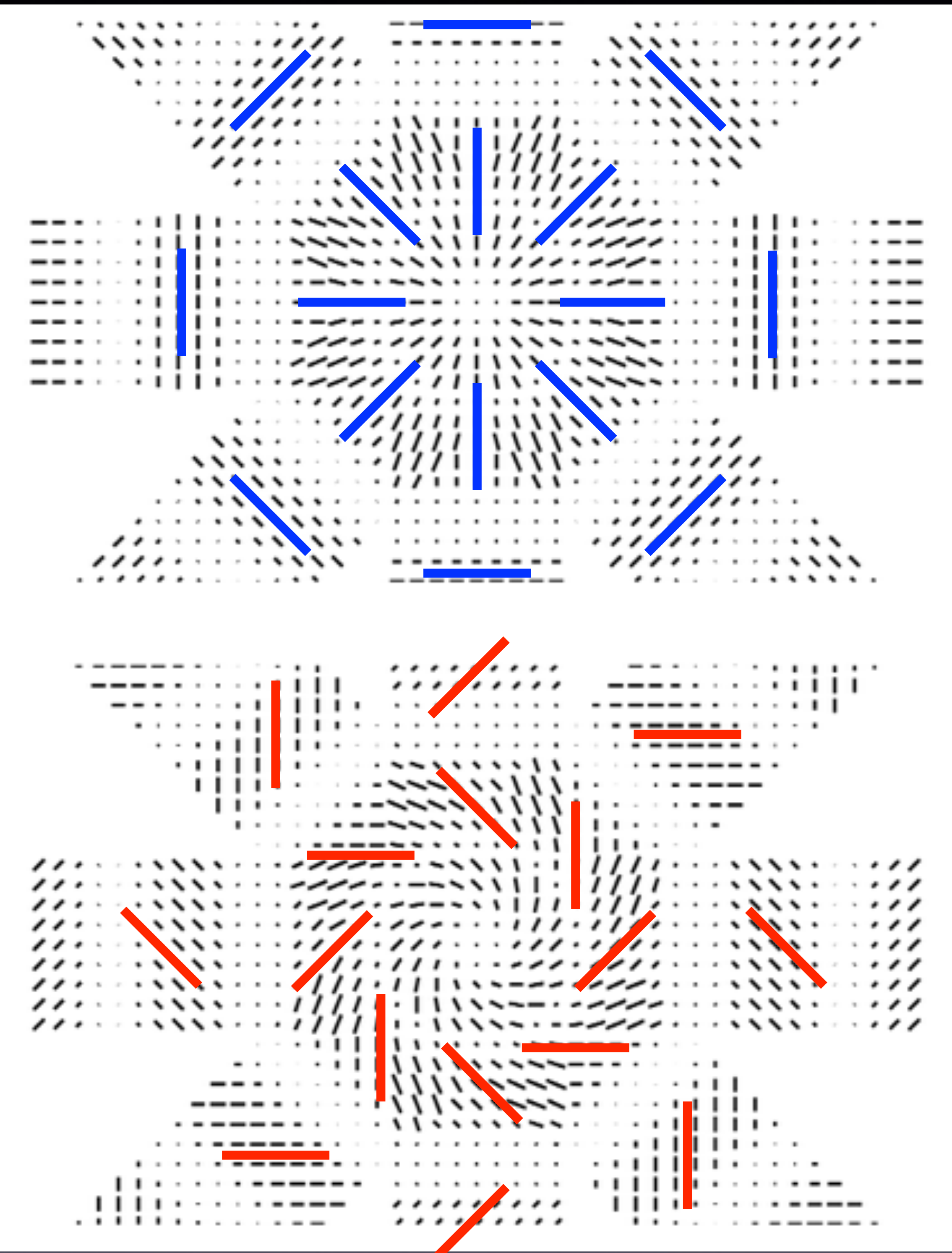


E-mode Polarization

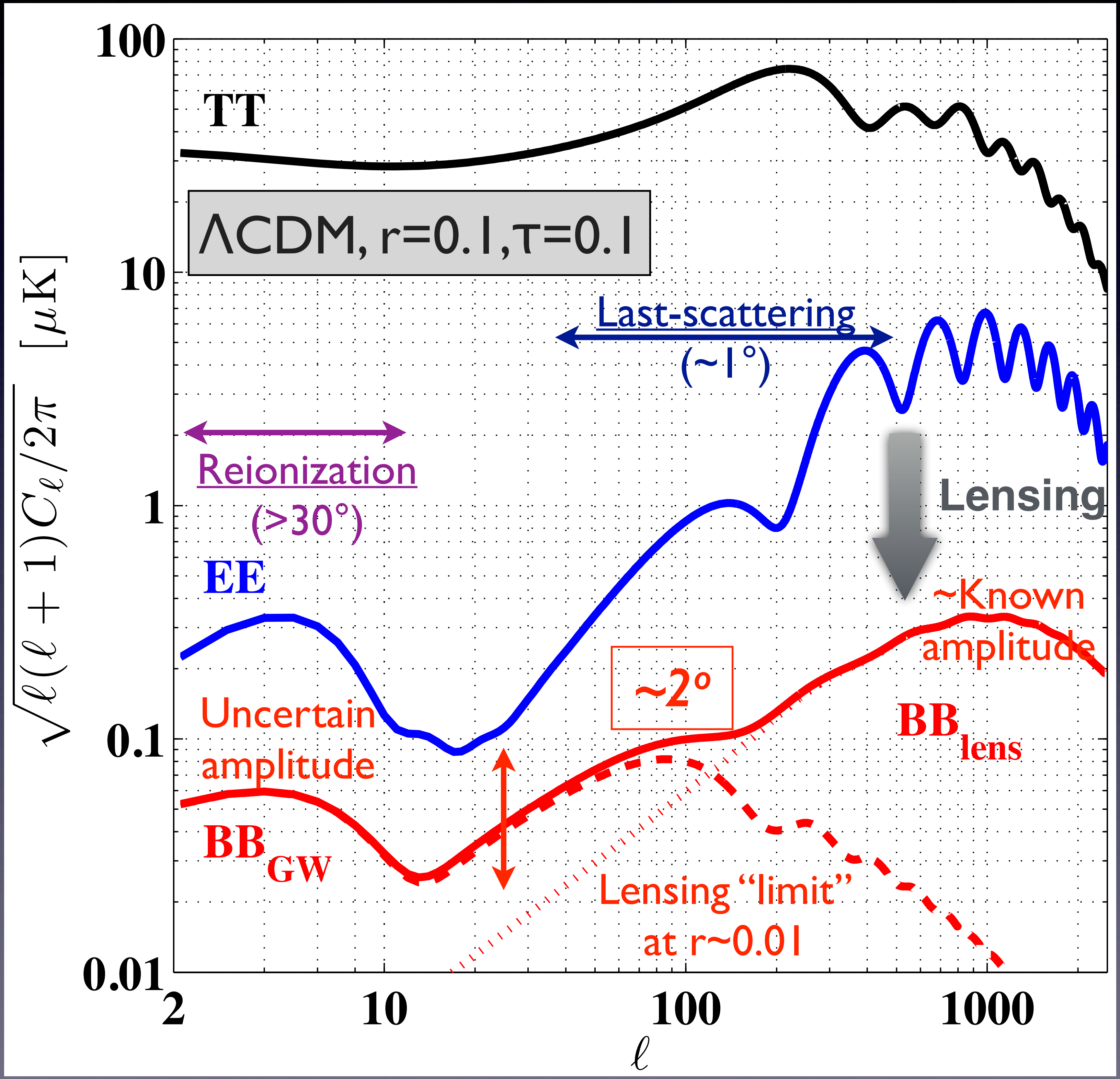
B-mode Polarization

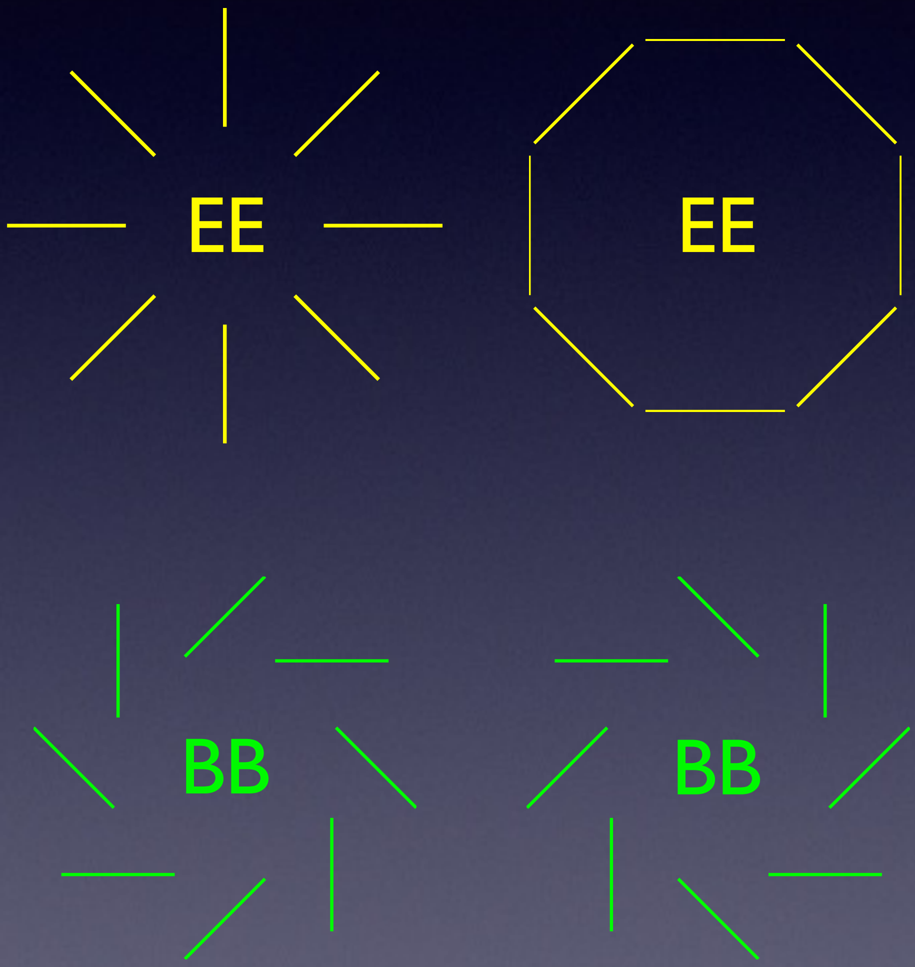
Patterns of Polarization





The Lay of the Land





The Challenge

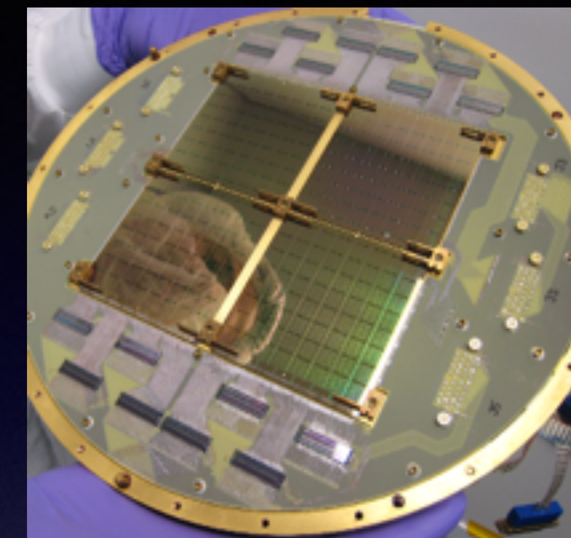
Extremely faint signal demands a map that is...

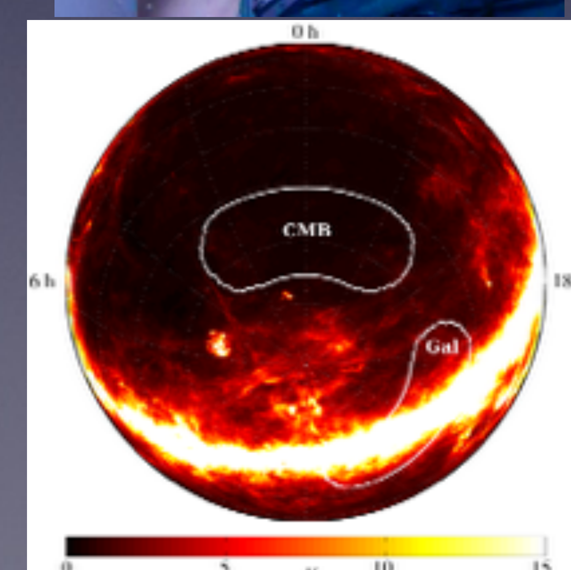
- **Precise**
  Detectors approach photon noise limit
  Many detectors (*multiplexing*)

- **Accurate**
  Rigid control of polarized systematics

- **Uncontaminated**
  Avoidance (or subtraction) of polarized foregrounds

- *Not necessarily high angular resolution!*

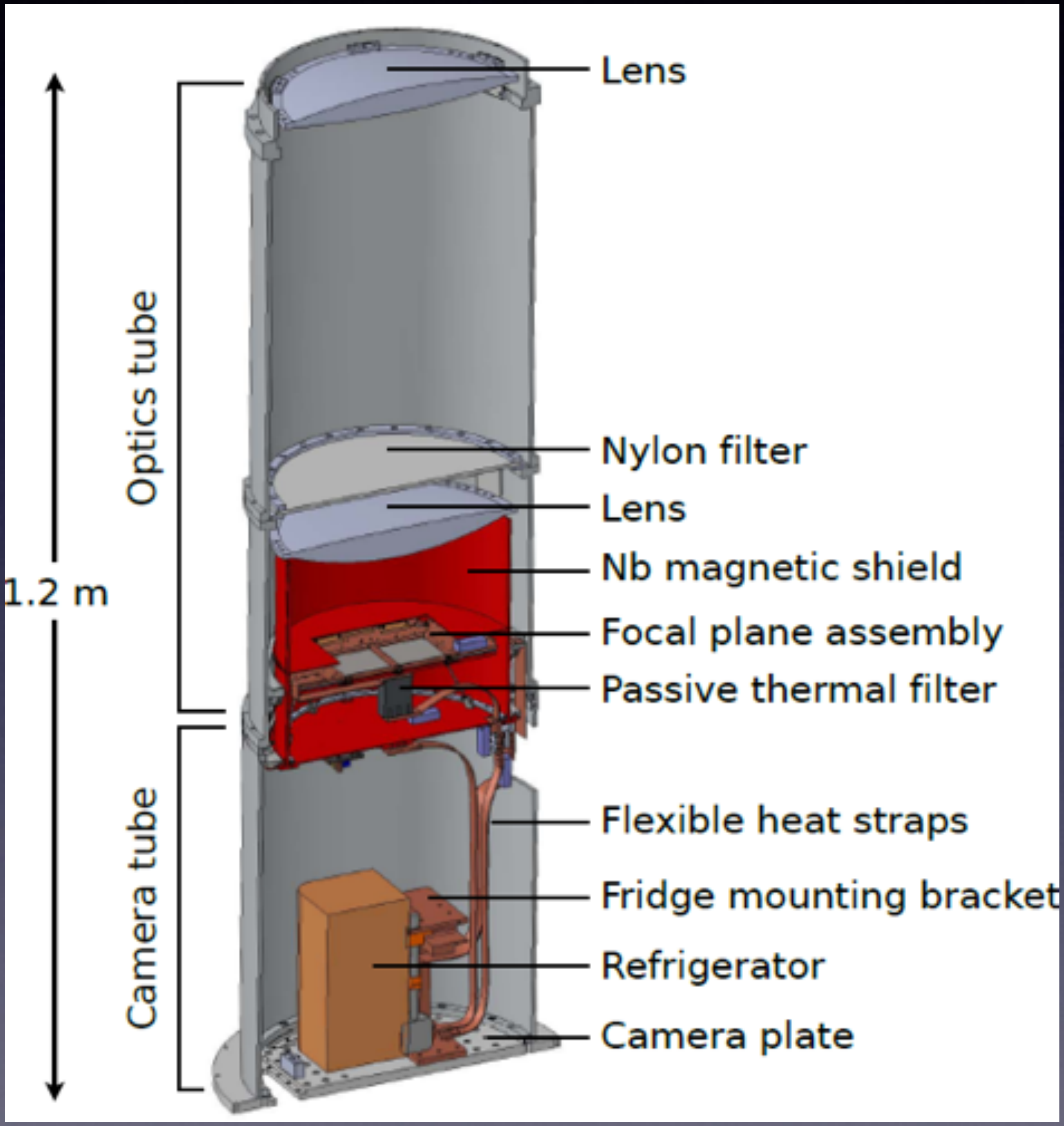




Inflation Investigators

A Targeted Strategy

- **Minimum aperture** (~26 cm) to resolve degree scales
- Systematic control
  - Cold (4.2K), on-axis optics
  - Bore sight rotation
- Foreground avoidance
  - Clean sky: ~400 sq. deg.
  - 150 GHz: low atmospheric and foreground emission
- Deep mapping
  - 3 years: 87 nK-deg!



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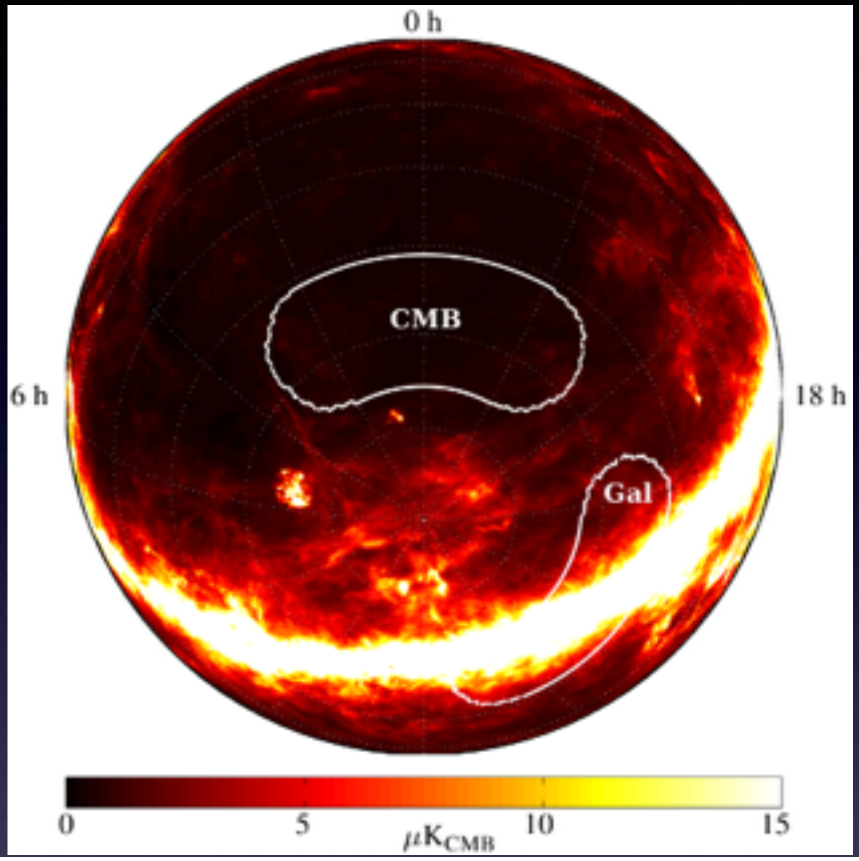
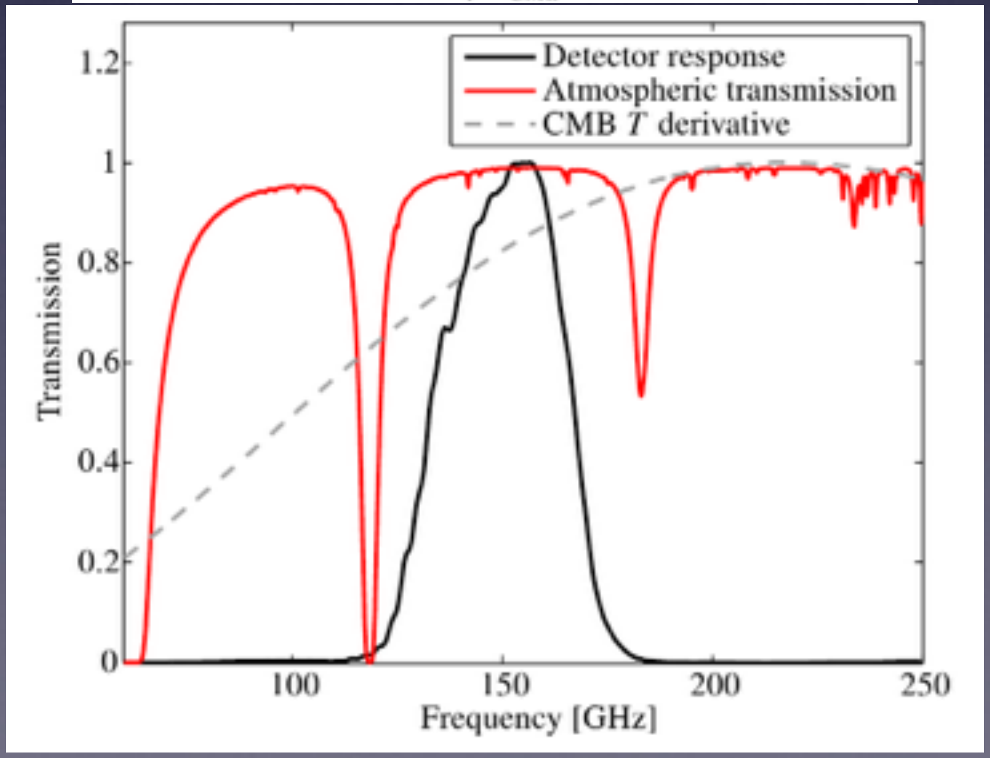
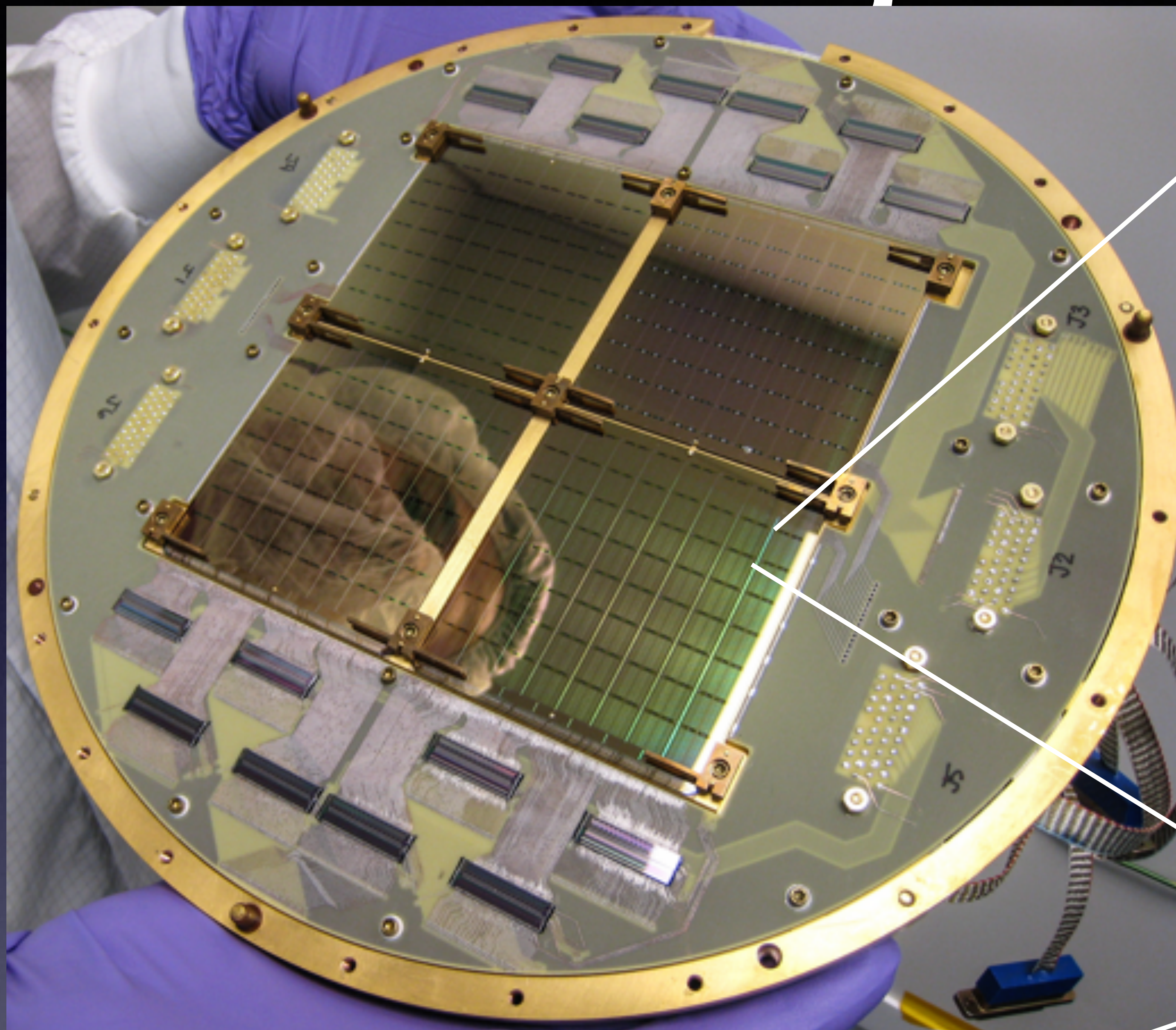
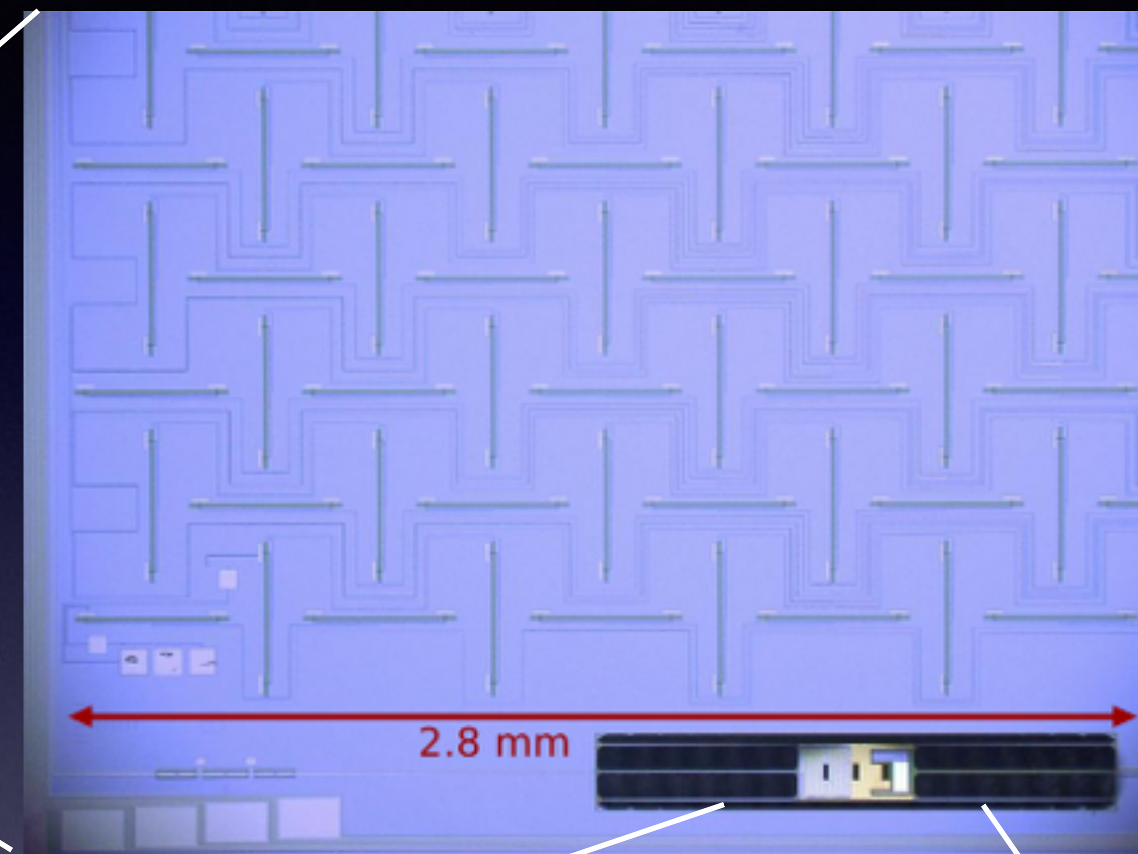
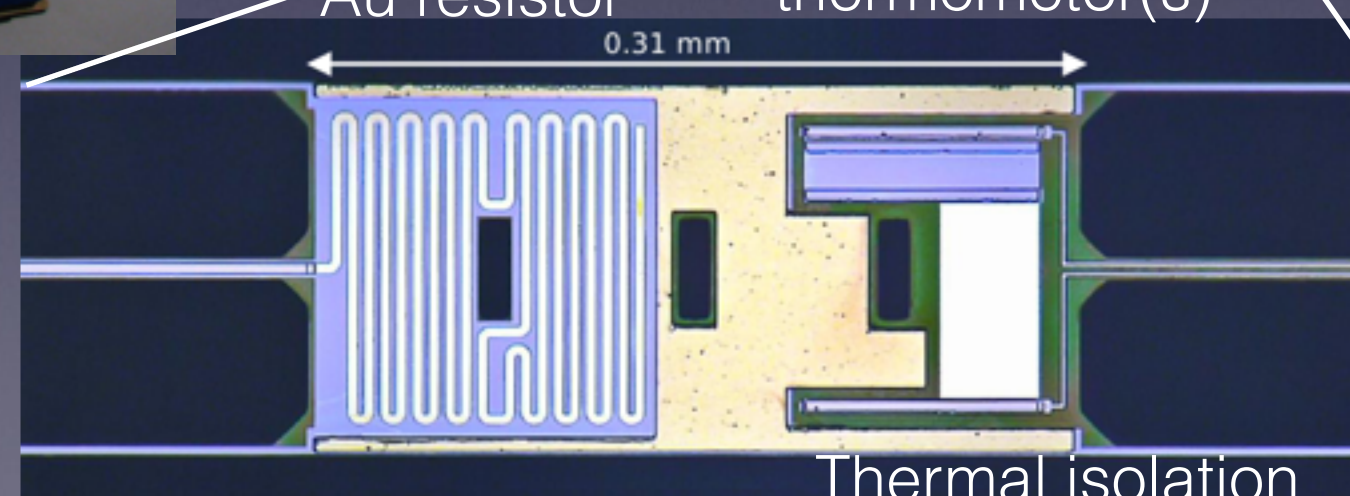




Caltech/JPL Detectors



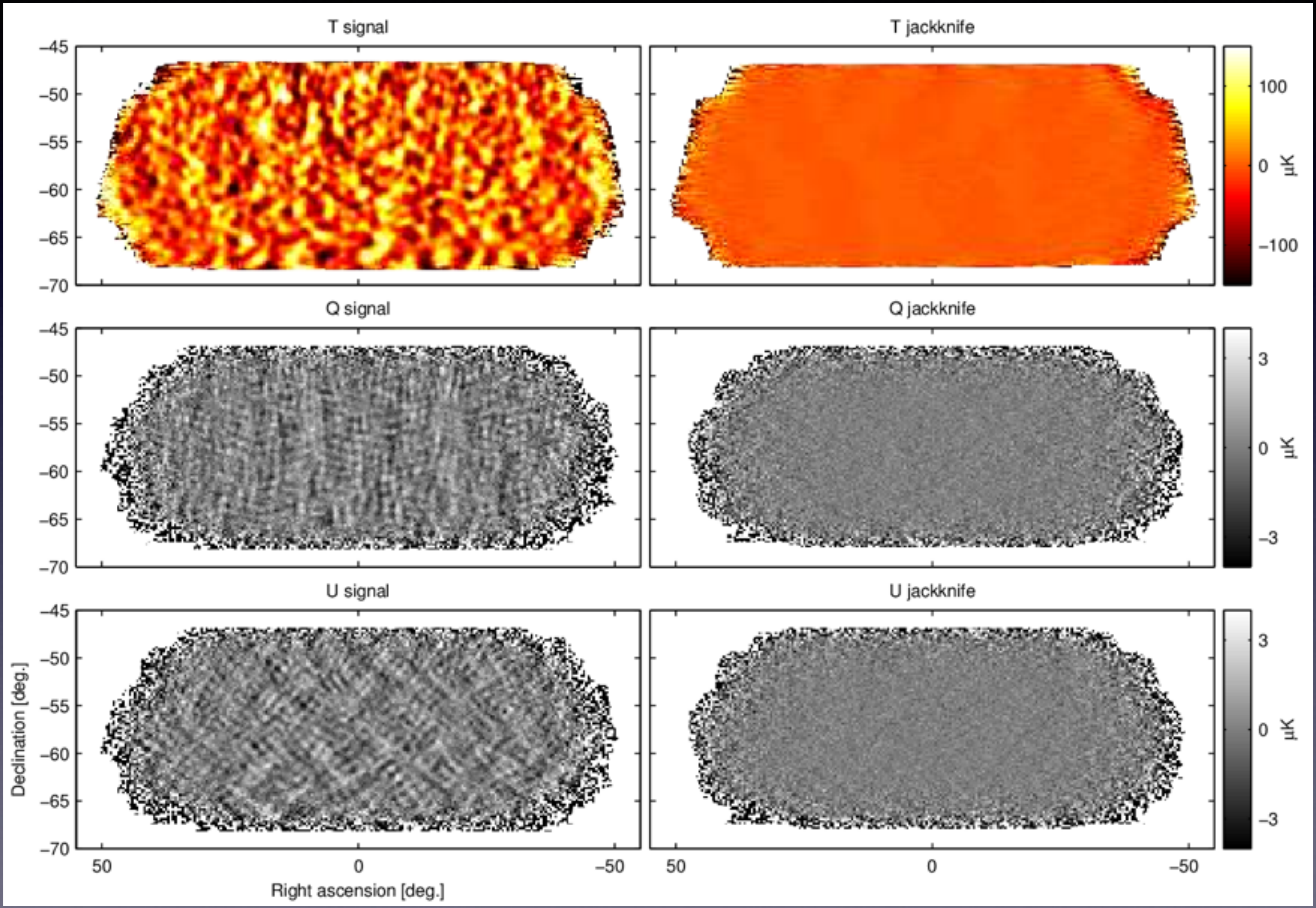




The View from the Bottom of the World

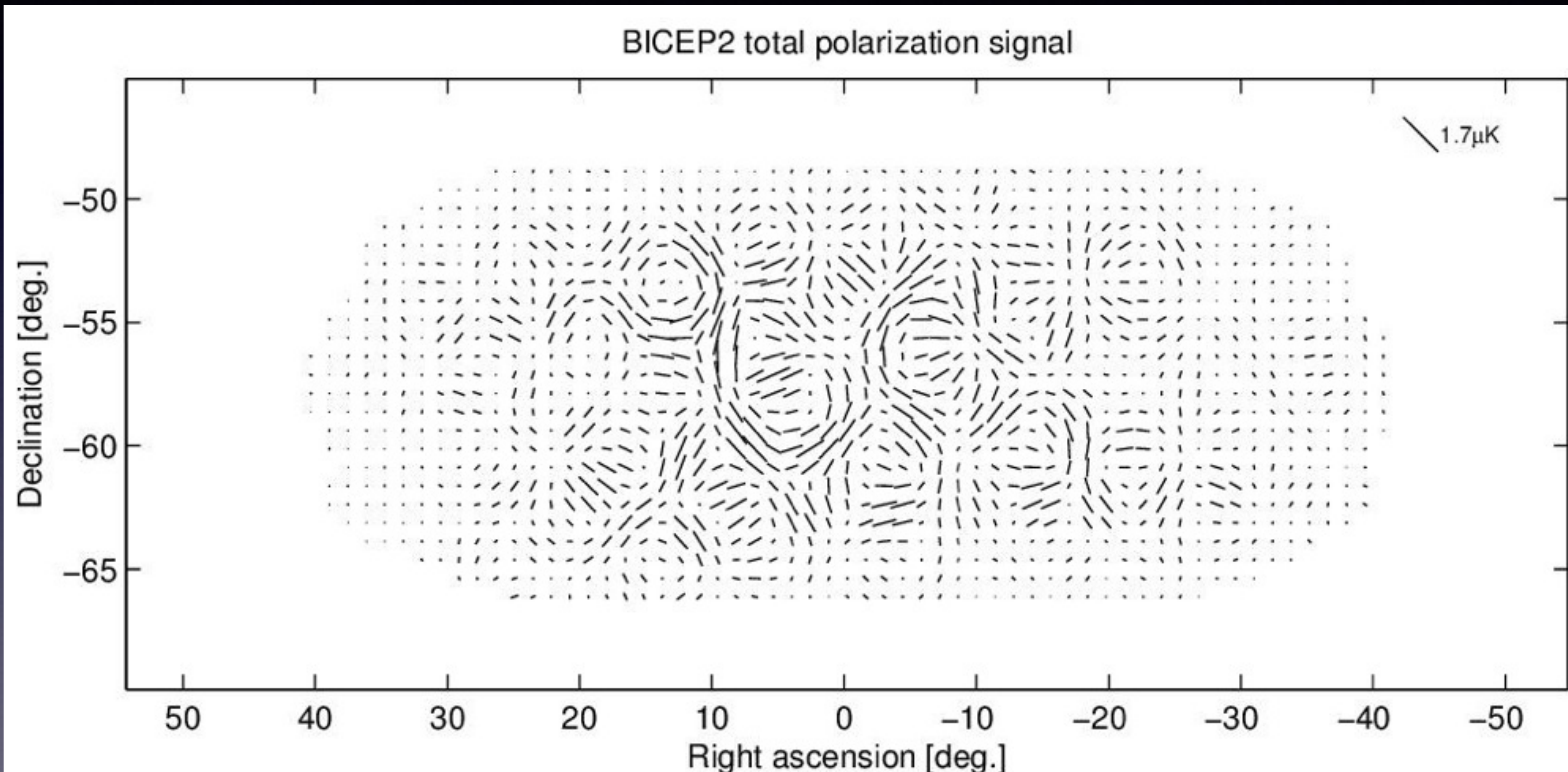
photo: Keith Vanderlinde

BICEP2 T and Stokes Q/U Maps

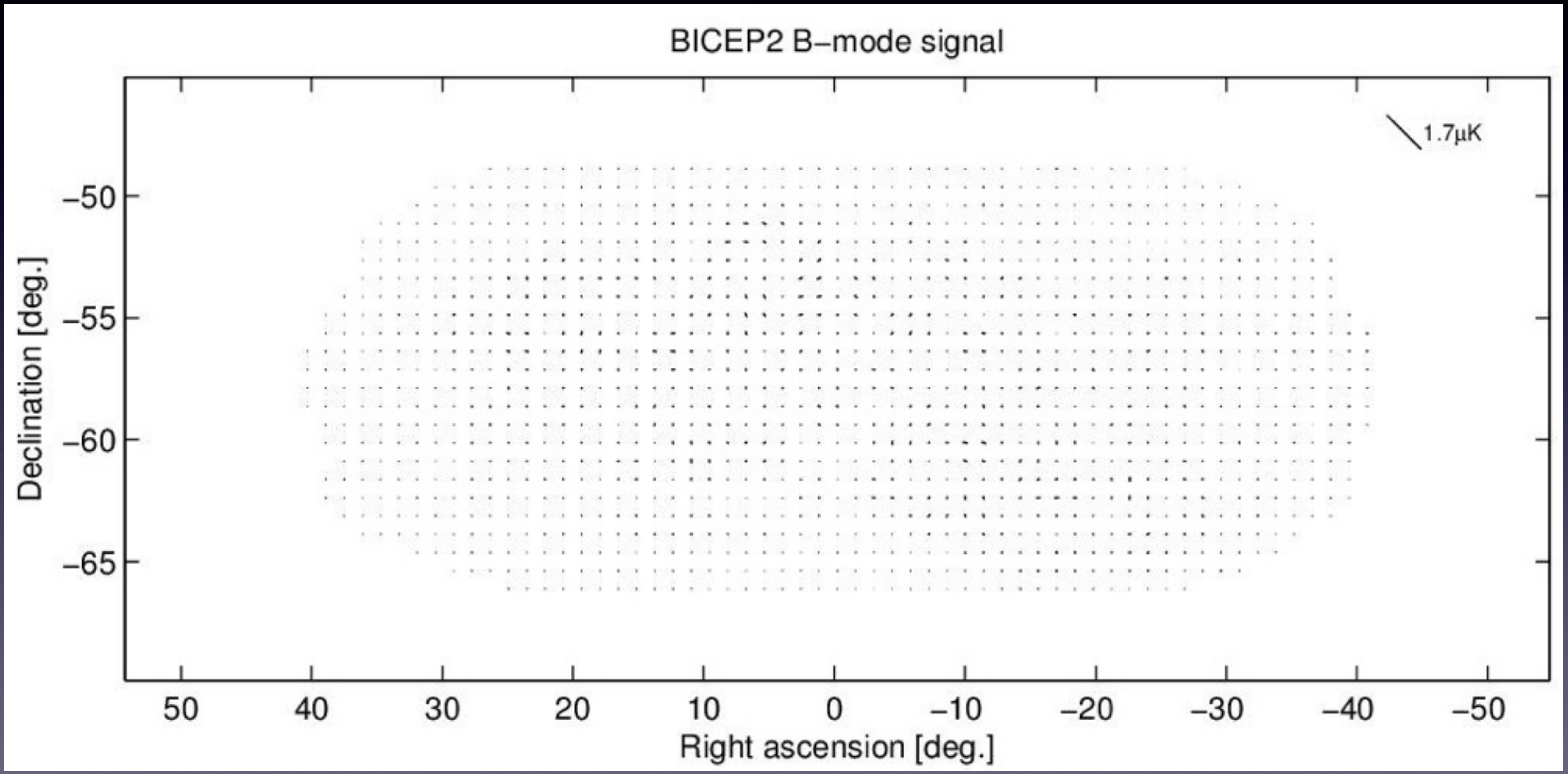


Sum maps Difference maps

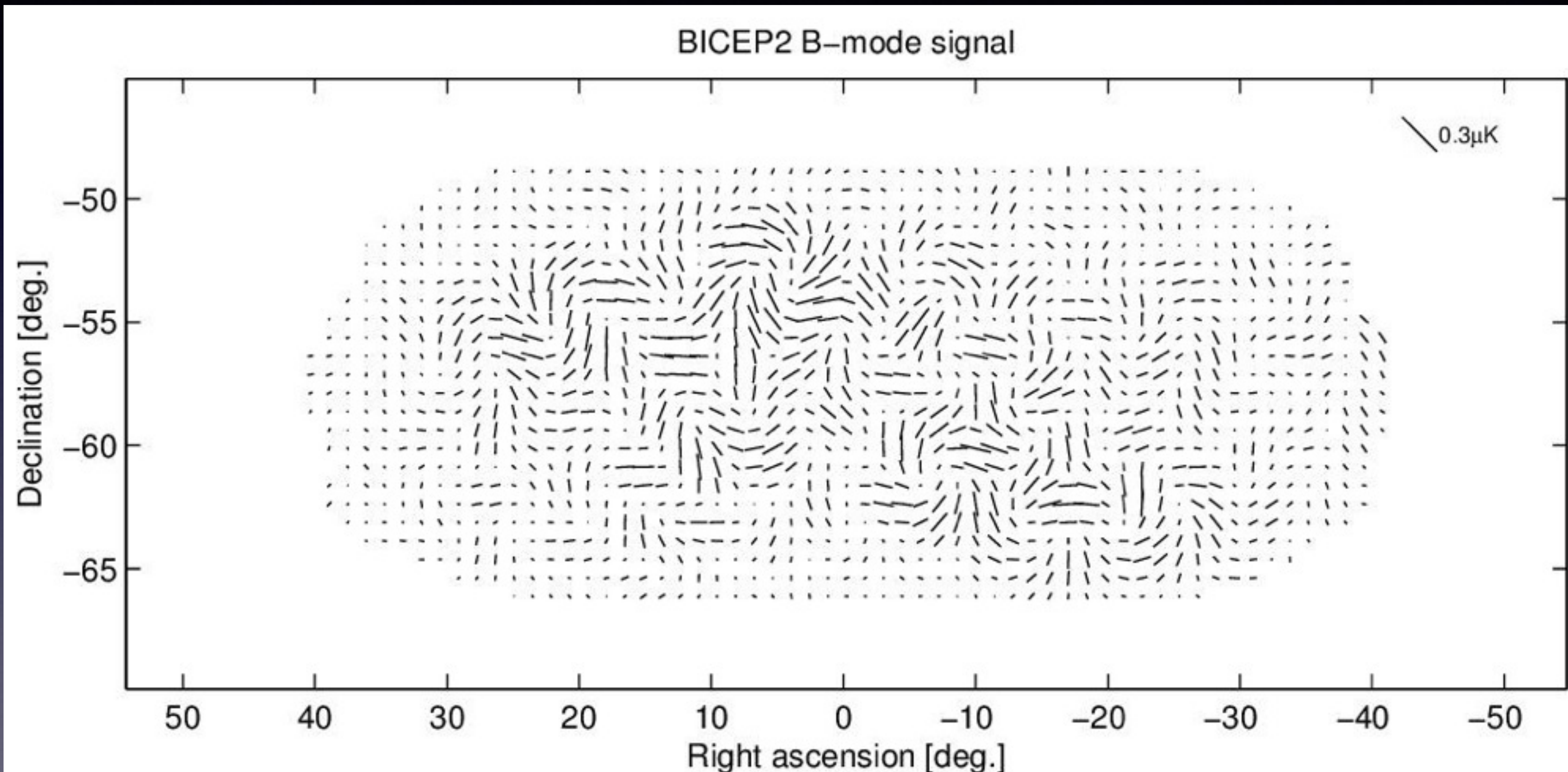
Total Polarization



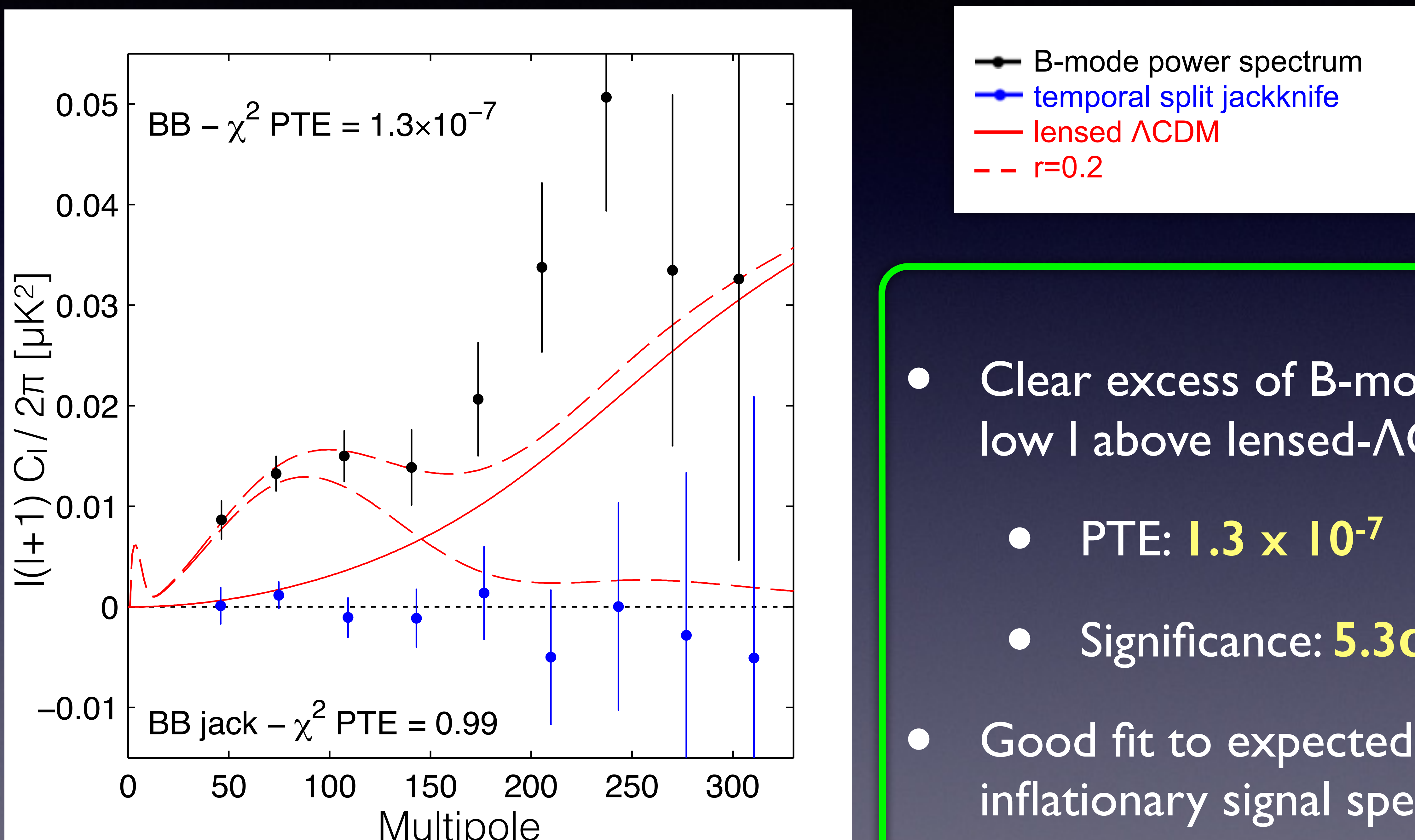
B-mode Signal



B-mode Signal



BICEP2 B-mode Power Spectrum



- Clear excess of B-modes at low l above lensed-ΛCDM
  - PTE: **1.3×10^{-7}**
  - Significance: **5.3σ**
- Good fit to expected inflationary signal spectrum

What could this be?

- **Instrumental systematics?**
- Galactic foregrounds?
- Cosmology?

Jackknife tests

TABLE 1

JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.046	0.030	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.725	0.890
Tag Split jackknife				
EE	0.541	0.377	0.916	0.938
BB	0.902	0.992	0.449	0.585
EB	0.477	0.689	0.856	0.615
Tile jackknife				
EE	0.004	0.010	0.000	0.002
BB	0.794	0.752	0.565	0.331
EB	0.172	0.419	0.962	0.790
Phase jackknife				
EE	0.673	0.409	0.126	0.339
BB	0.591	0.739	0.842	0.944
EB	0.529	0.577	0.840	0.659
Mux Col jackknife				
EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
EB	0.866	0.968	0.876	0.697
Alt Deck jackknife				
EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.381	0.086
EB	0.150	0.060	0.170	0.291
Mux Row jackknife				
EE	0.052	0.178	0.653	0.739
BB	0.345	0.361	0.032	0.008
EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.088	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.850	0.838
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.79[illegible]

Splits by boresight rotation

Amplifies differential pointing in comparison to fully added data. Check of deprojection.

Splits by time

Checks for contamination on long ("Tag Split") and short ("Scan Dir") timescales. Short timescales probe detector transfer functions.

Splits by channel selection

Checks for contamination in channel subgroups, divided by focal plane location, tile location, and readout electronics grouping

Splits by possible external contamination

Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

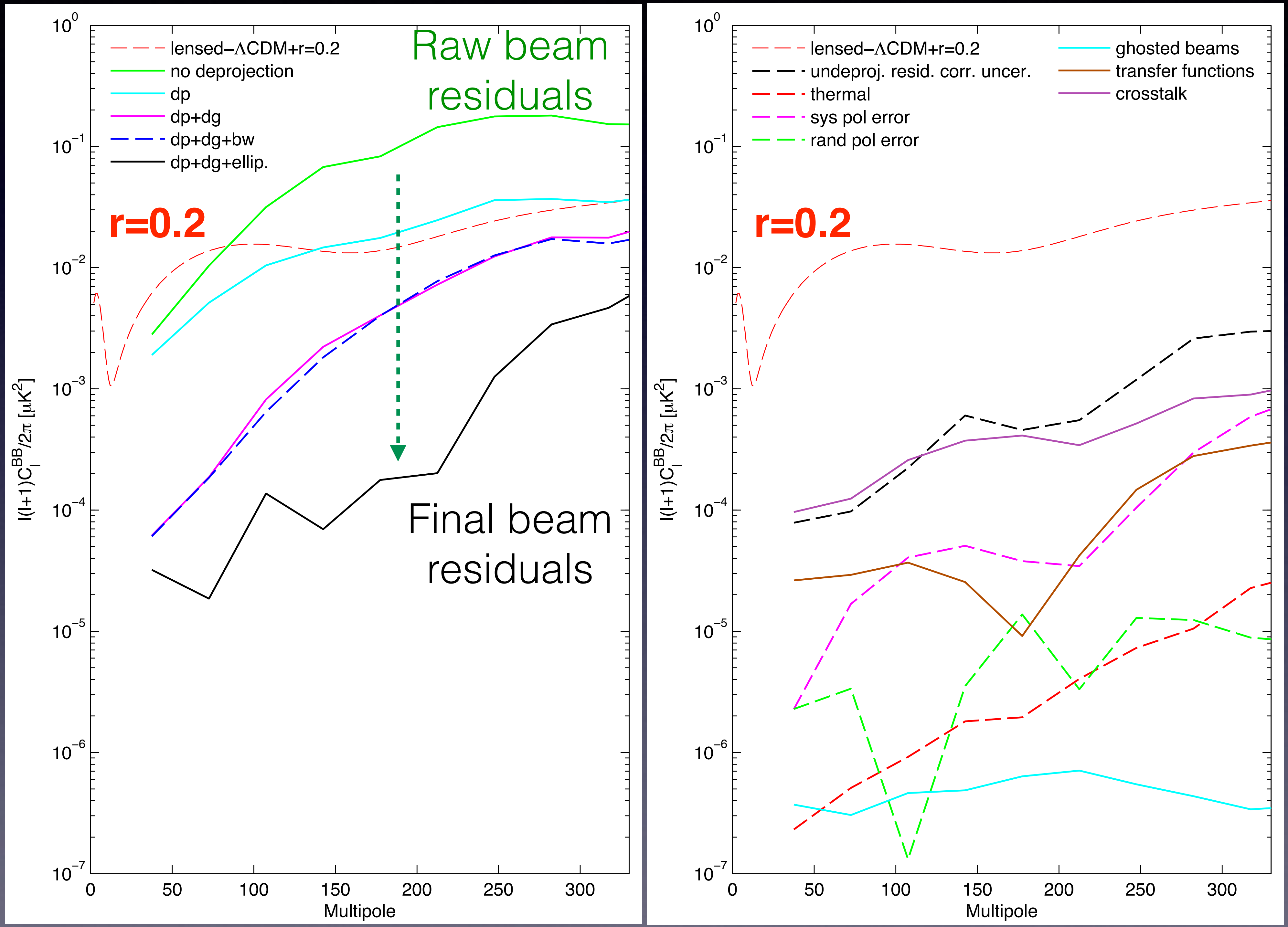
Splits to check intrinsic detector properties

Checks for contamination from detectors with best/worst differential pointing. "Tile/dk" divides the data by the orientation of the detector on the sky.

Systematic Errors

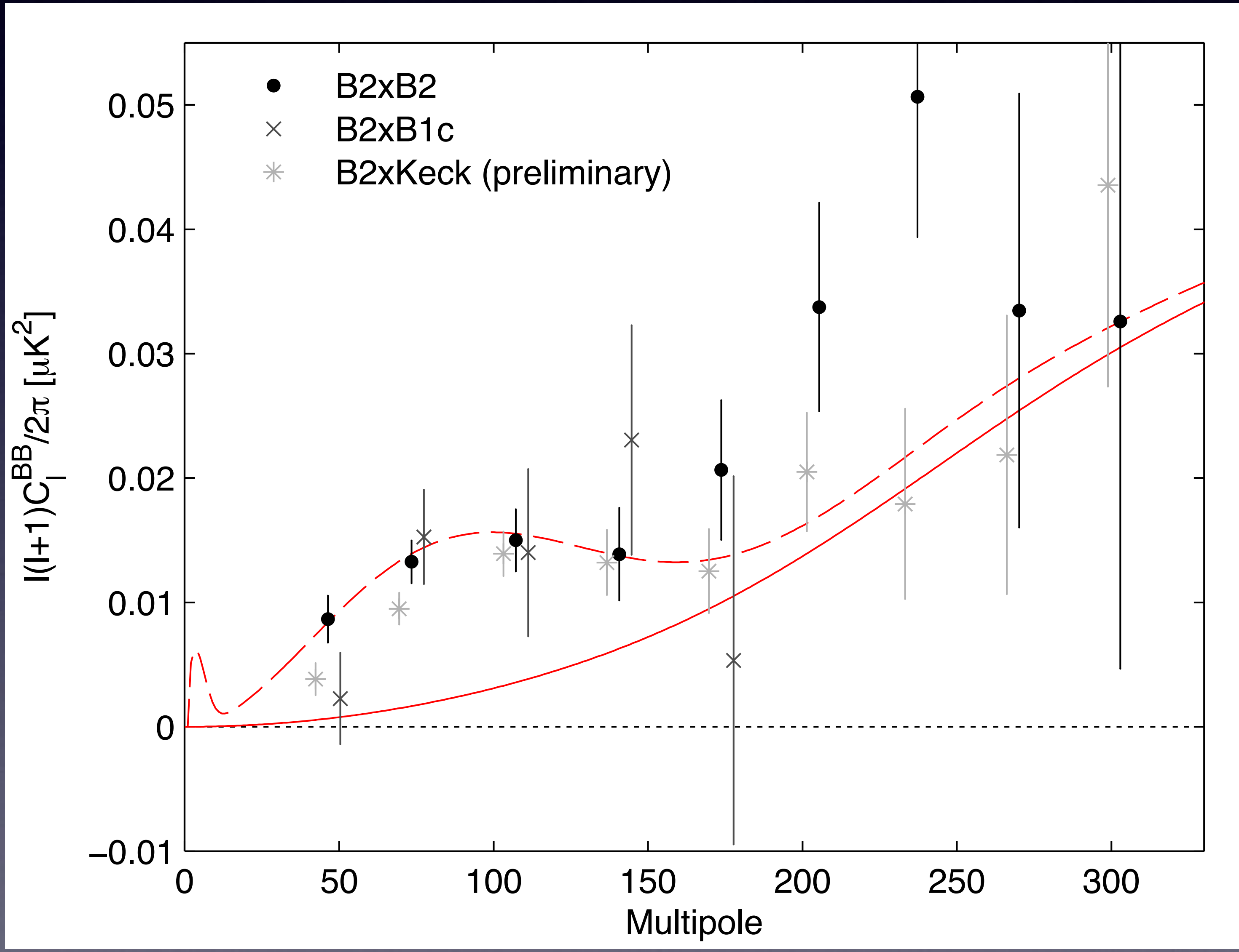
Simulate effect of **measured** beam and instrument imperfections.

We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics



Cross Spectra

- **3.5σ** detection of BB in cross with color-combined BICEP1 (r_{max}=0.19)
- Excess power also evident in cross with 2 years of **Keck Array** data (*150 GHz*, *preliminary*)!

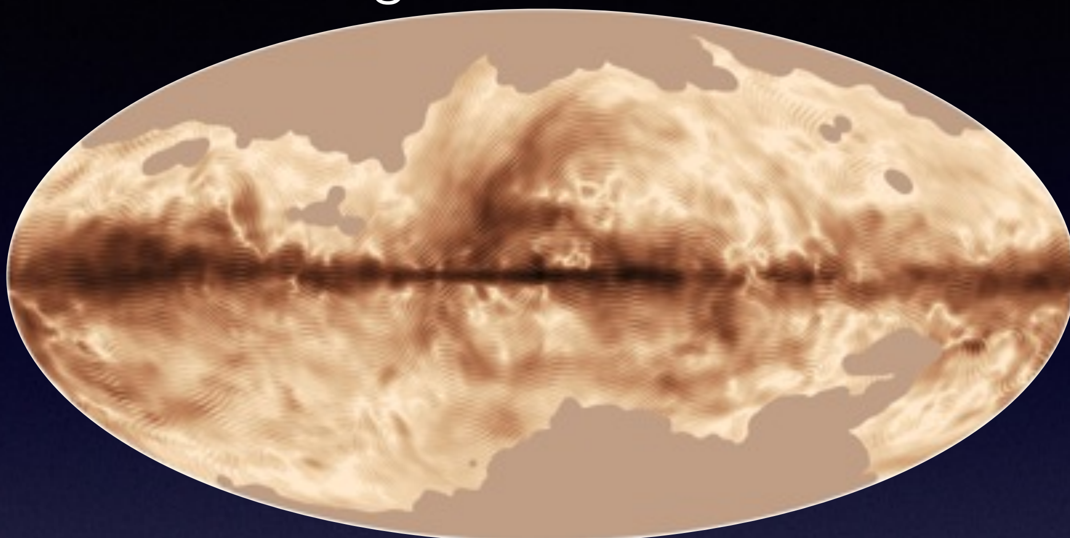


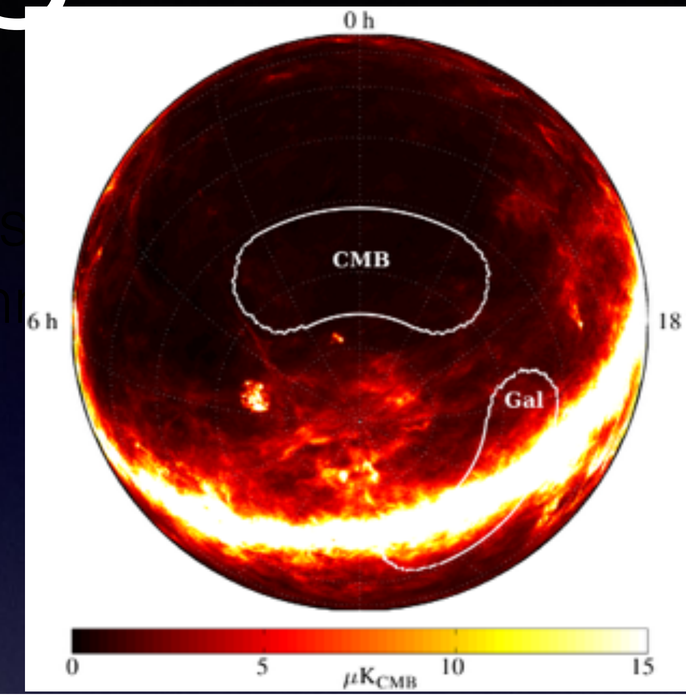
What could this be?

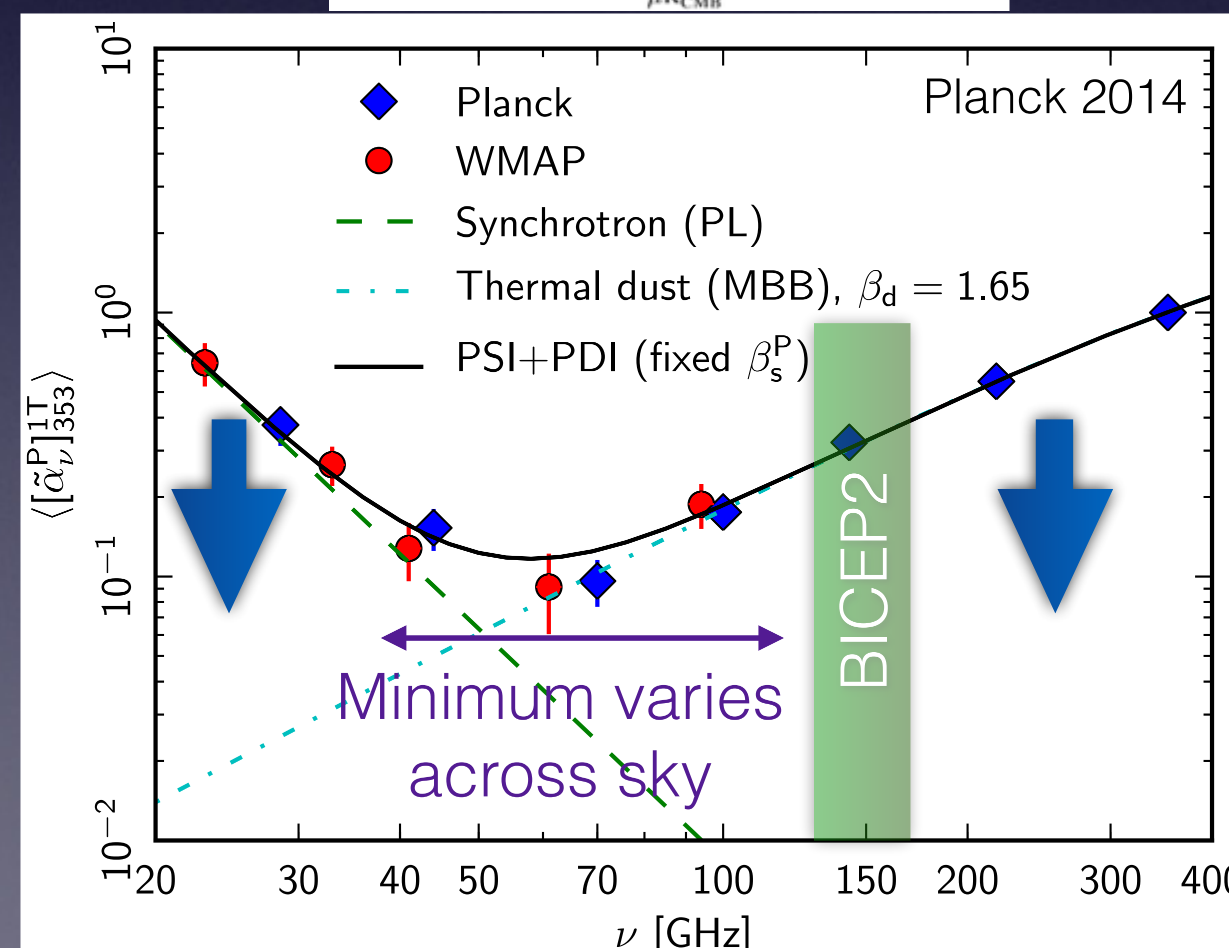
- Instrumental systematics?
- **Galactic foregrounds?**
- Cosmology?

Polarized Foregrounds

Planck 2014 magnetic field



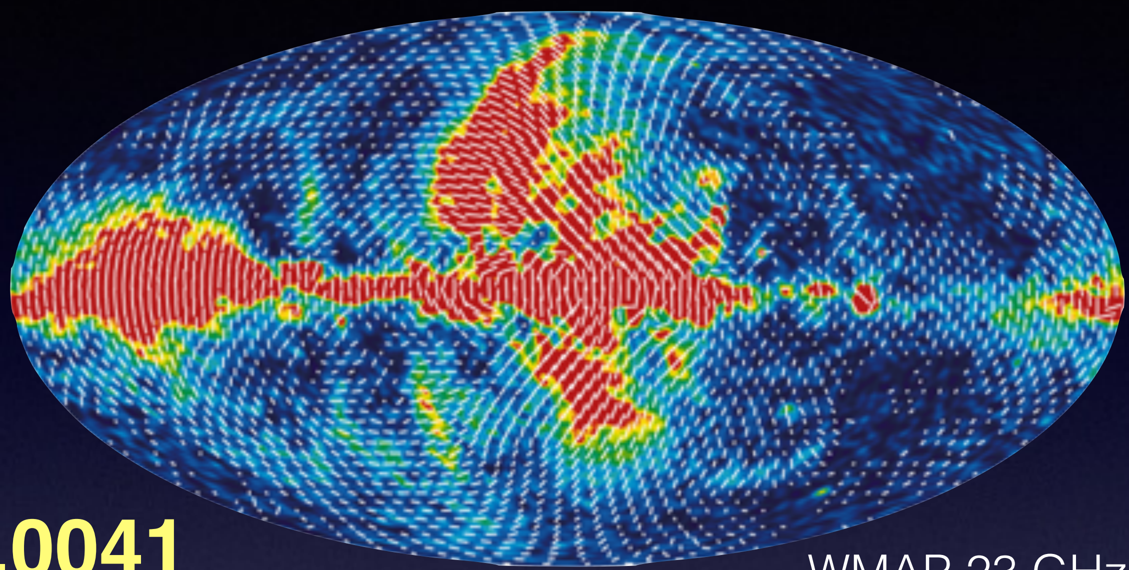




- Galactic emission can be polarized by galactic magnetic fields!
- BICEP2 observes where galactic emission is dim
- BICEP2 observes at one "color": 150 GHz

Polarized Foregrounds

Any polarized astrophysical emission between last scattering and us!



WMAP 23 GHz

- **Synchrotron** "Red":~ ν^{-3}

  No correlation with WMAP-K

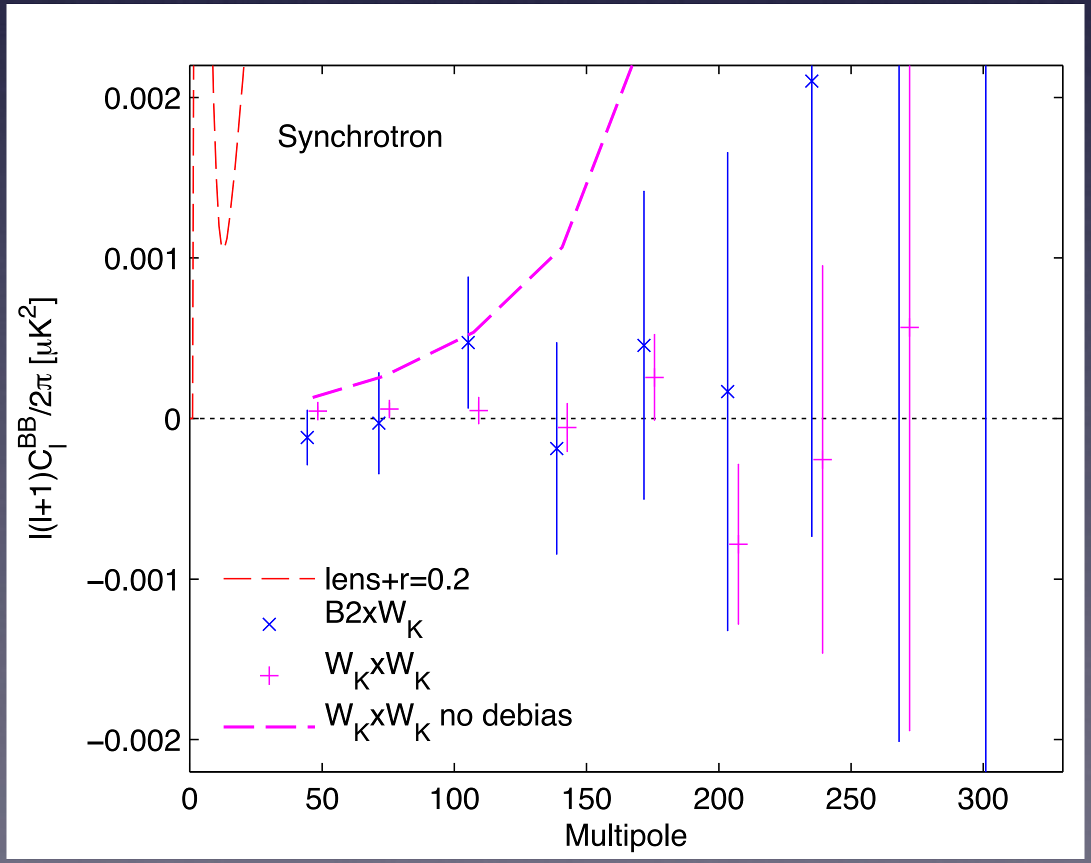
  β = -3.3 : $\mathbf{r_{sync}=0.0008 \pm 0.0041}$

- **Dust** "Blue": ~ $\nu^{+1.75}$

  Brighter than existing models

  Lack of cross-correlation

  Angular spectrum consistent with GW signal



- **Point sources**

  No cross-correlation with source catalogs

  (Planck, ATCA)

Polarized Foregrounds

Any polarized astrophysical emission between last scattering and us!

- **Synchrotron** "Red": $\sim \nu^{-3}$
  No correlation with WMAP-K

- **Dust** "Blue": $\sim \nu^{+1.75}$
  Brighter than existing models
  Lack of cross-correlation
  Angular spectrum consistent with GW signal

- **Point sources**
  No cross-correlation with source catalogs
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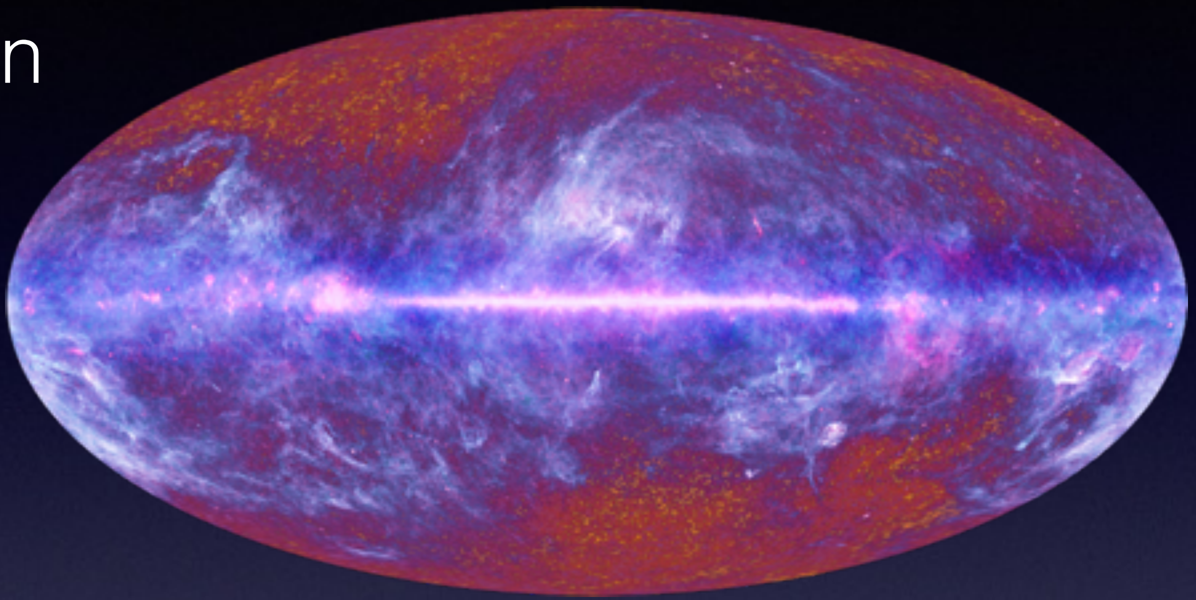
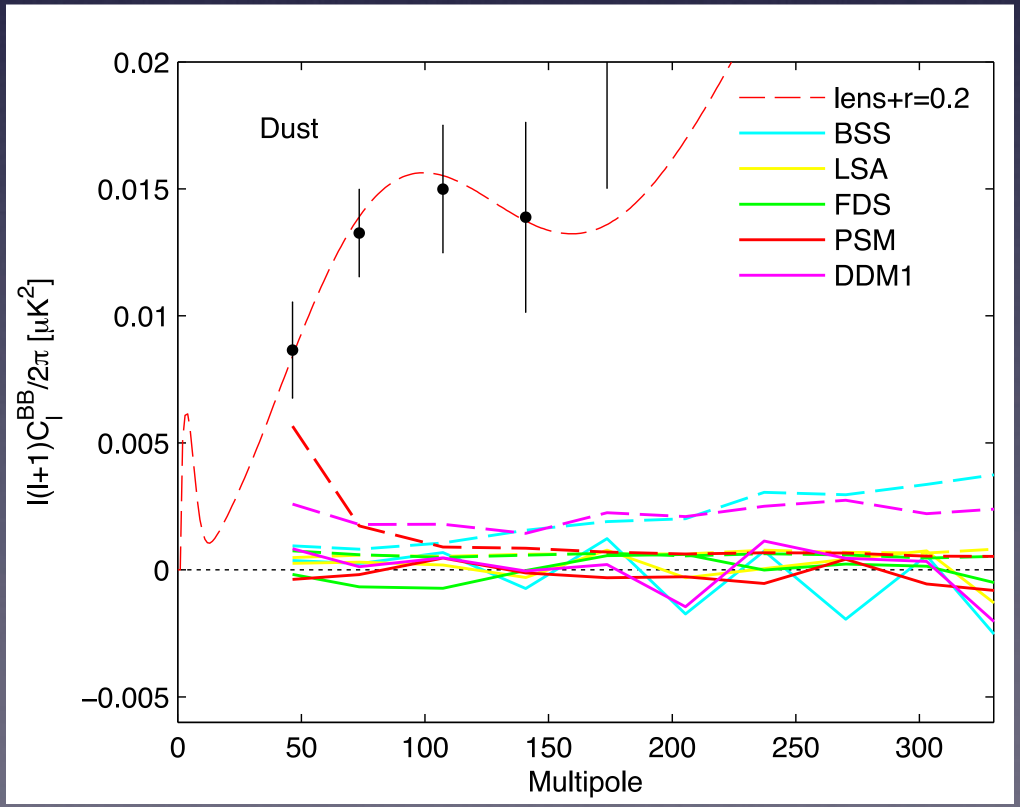
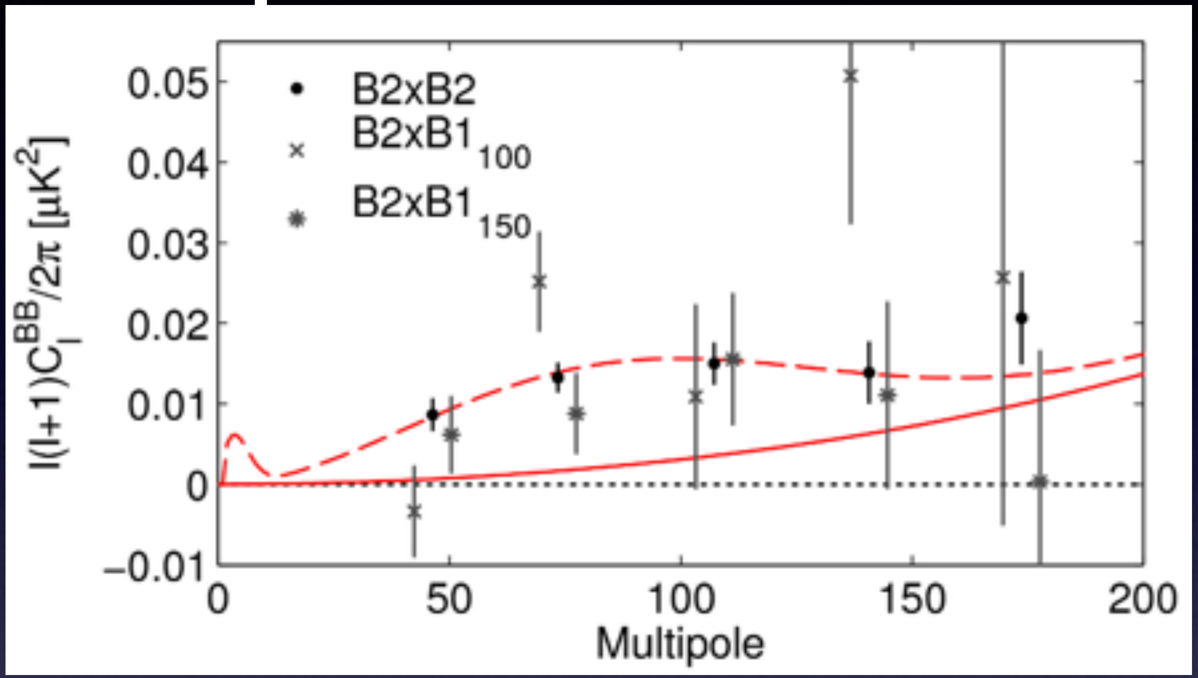
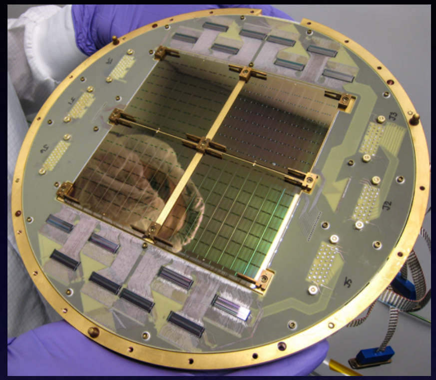




Spectral Index Constraint

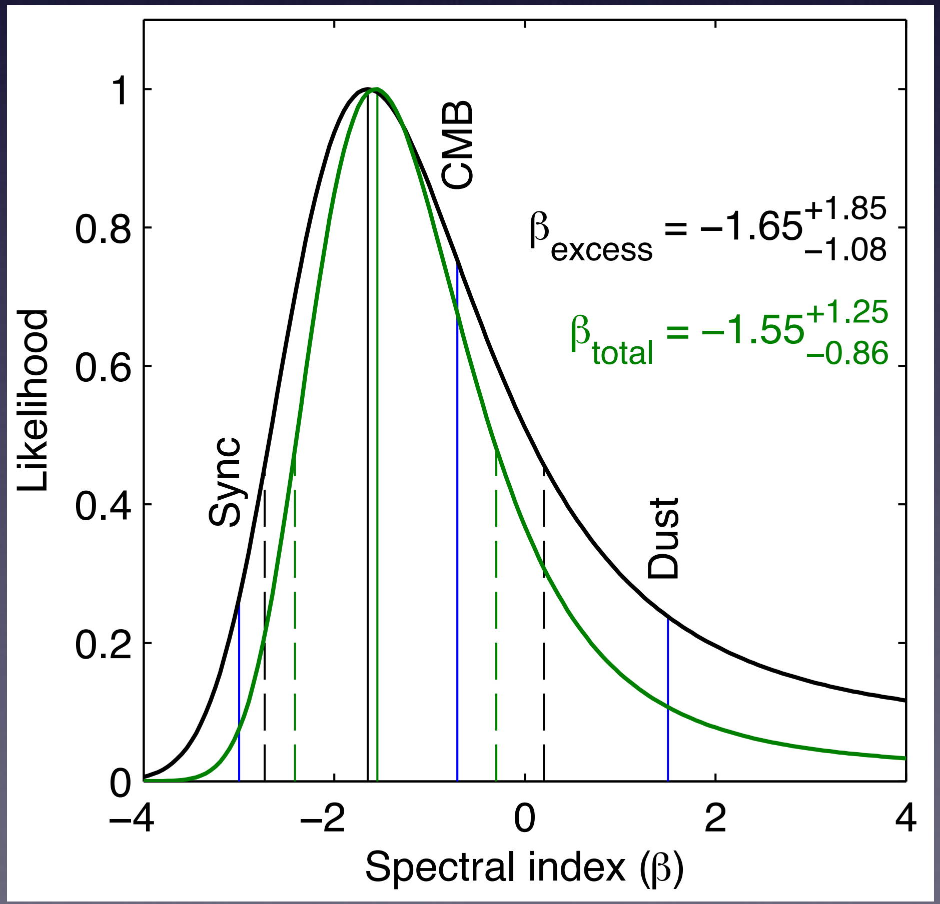




BICEP2: Phased antenna array,TESs,150 GHz

BICEP1: Feedhorns,NTDs, 150 and 100 GHz

- Constrain BB signal color with $B2_{150}xB1_{100}$
  - If **dust**, expect little correlation
  - If **synchrotron**, expect bright correlation

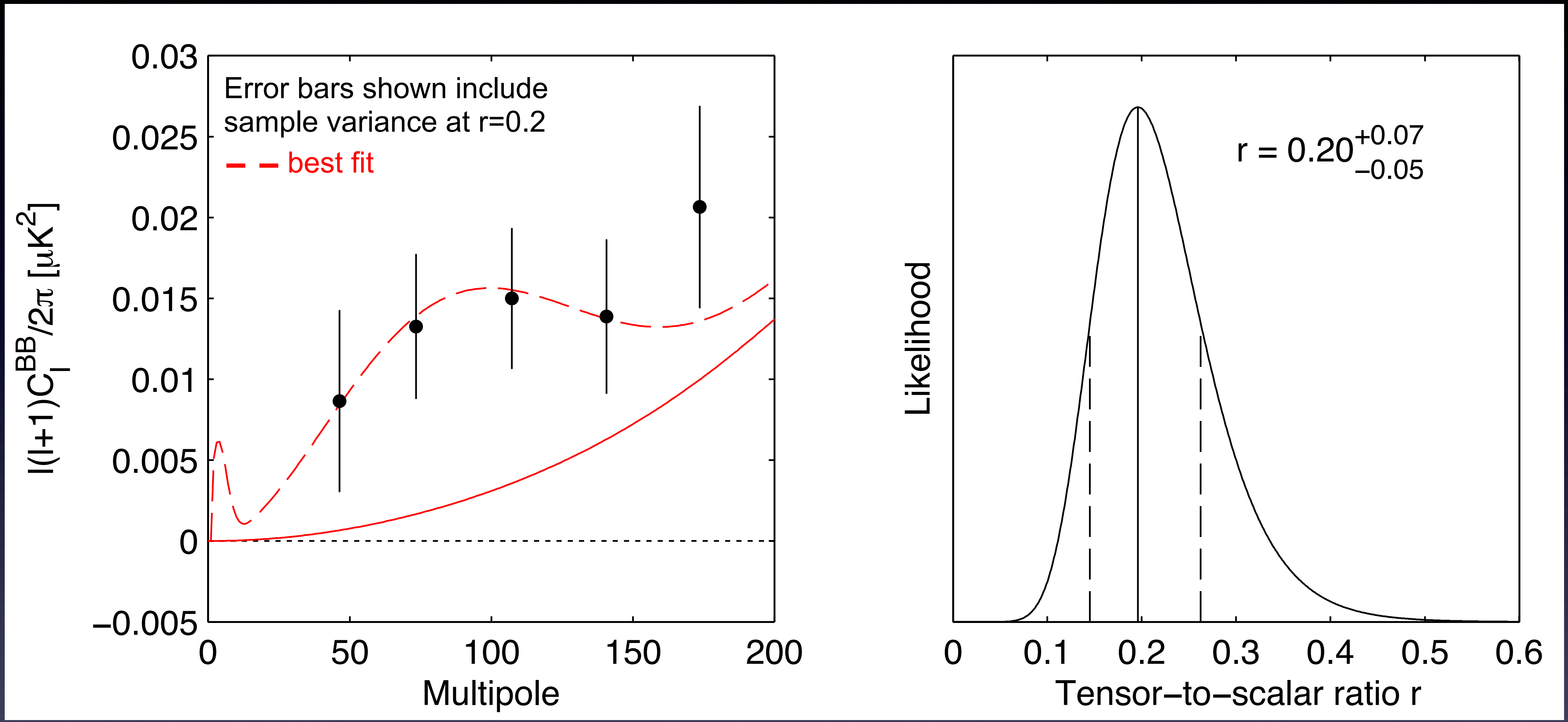


Antenna temperature frequency power law

What could this be?

- Instrumental systematics?
- Galactic foregrounds?
- **Cosmology**

Constraint on Tensor/Scalar Ratio

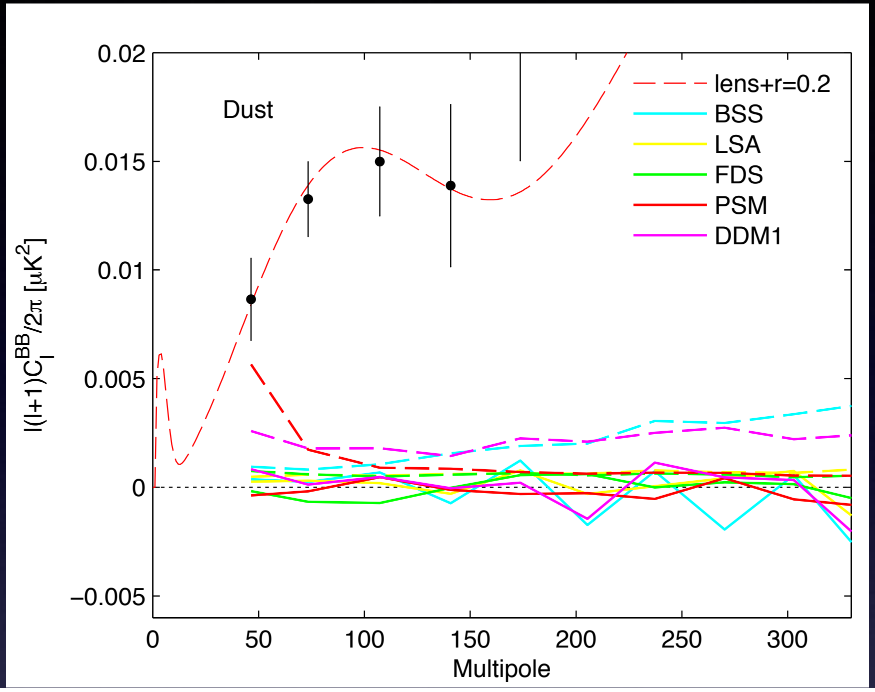


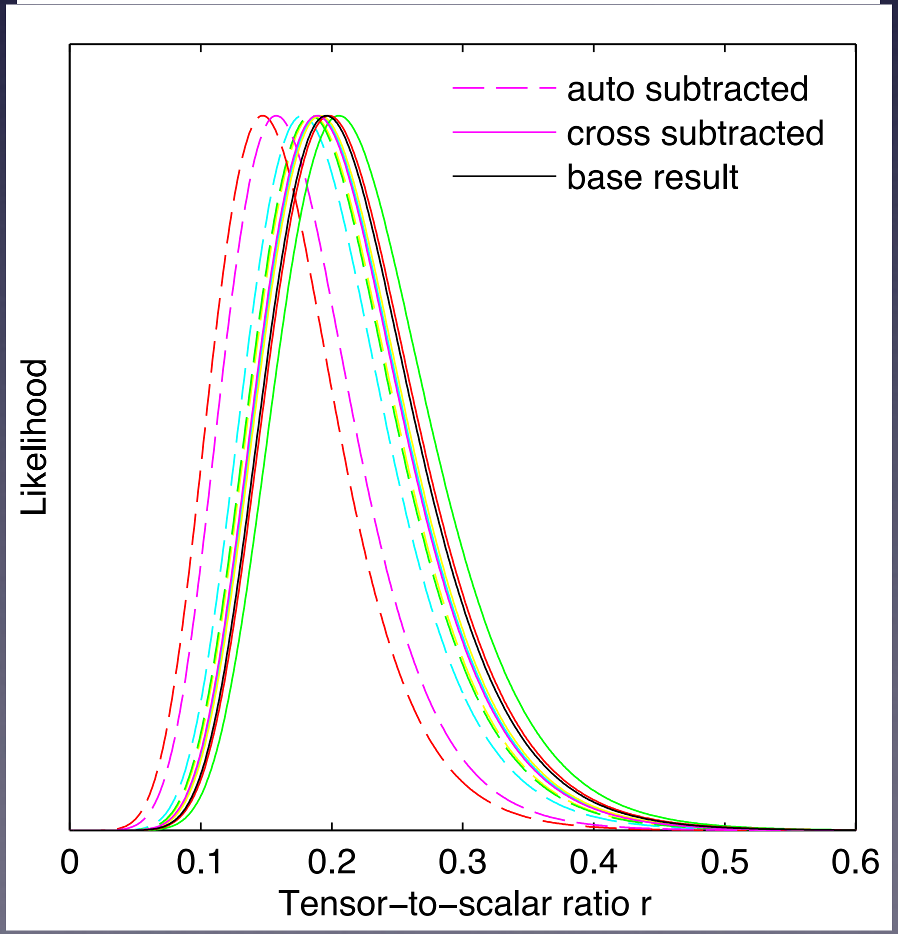
- Best-fit **r=0.20** (PTE of fit 0.9)
  Consistent with large-field, GUT-scale inflation

- r=0 disfavored at **7.0σ** (PTE 3.3 x 10^{-12}) (*no FG)*

- Sample variance dominated -> *Need more sky!*

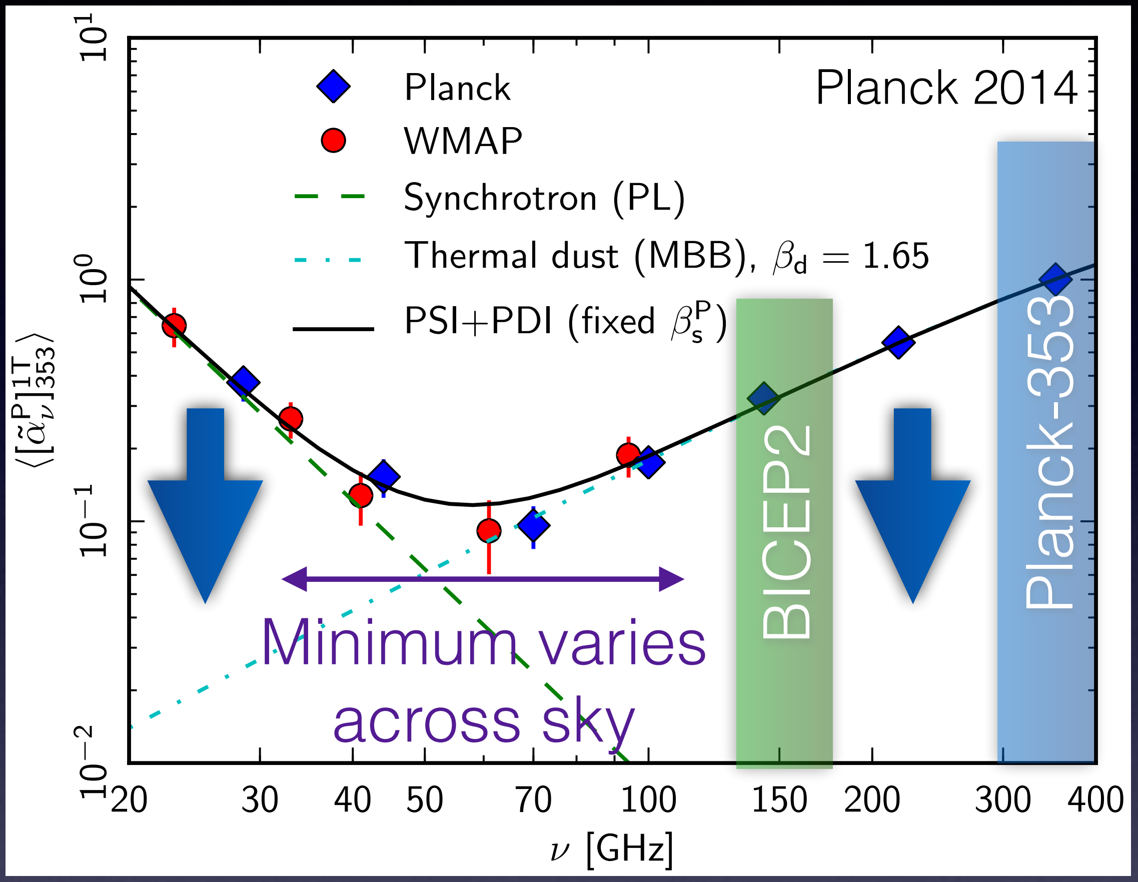
Effect of Foregrounds

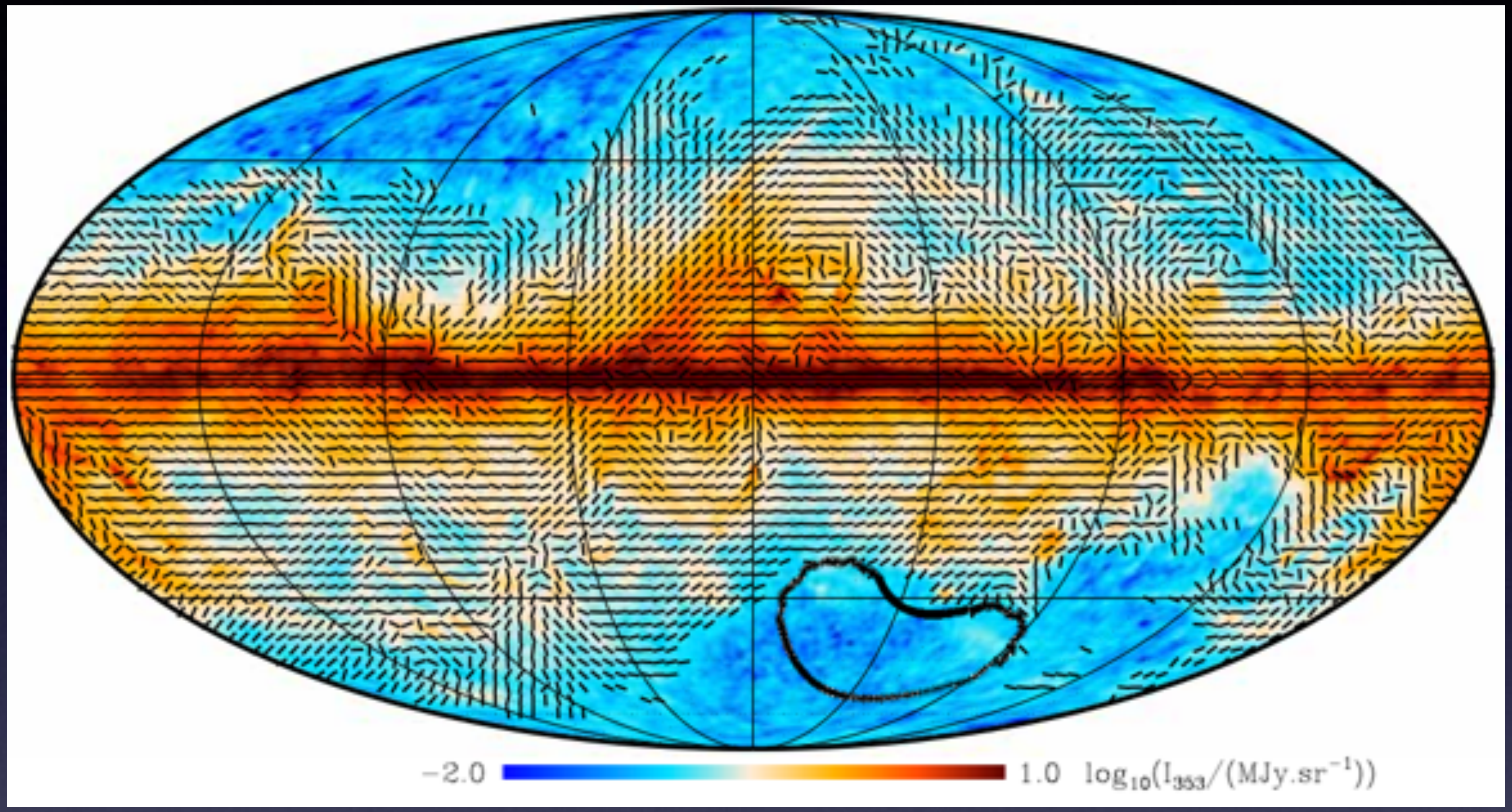




- Foregrounds could contribute small amount of observed BB
- Total power spectrum does not look like foreground expectations
- Dust contributes most in the first band power. Deweighting this bin would give less deviation from our base result

Dust-up



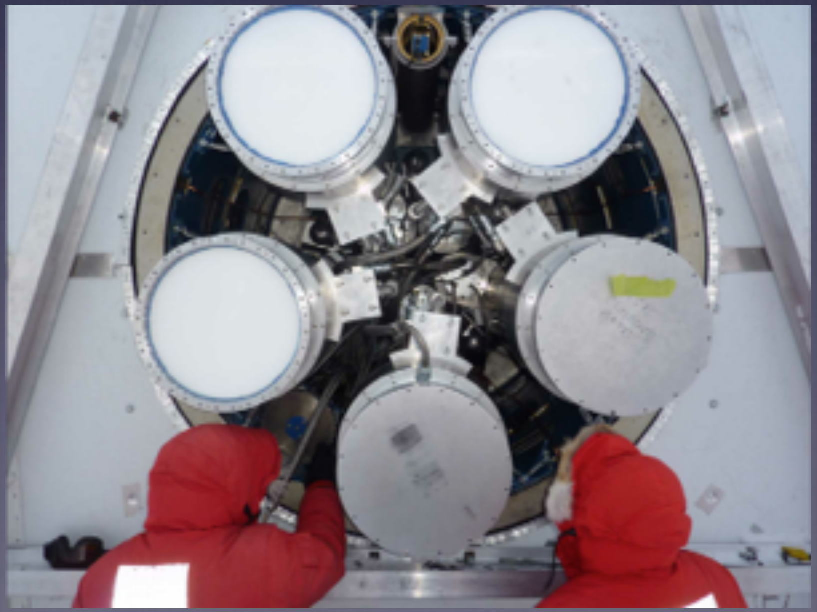


- Planck maps polarized dust up to 353 GHz
- Data for BICEP2 region has not been released *(challenging!)*
- More data in coming months: Planck, Keck 100 GHz, others …
- **Planck-BICEP2 joint analysis is in progress!**

What next?

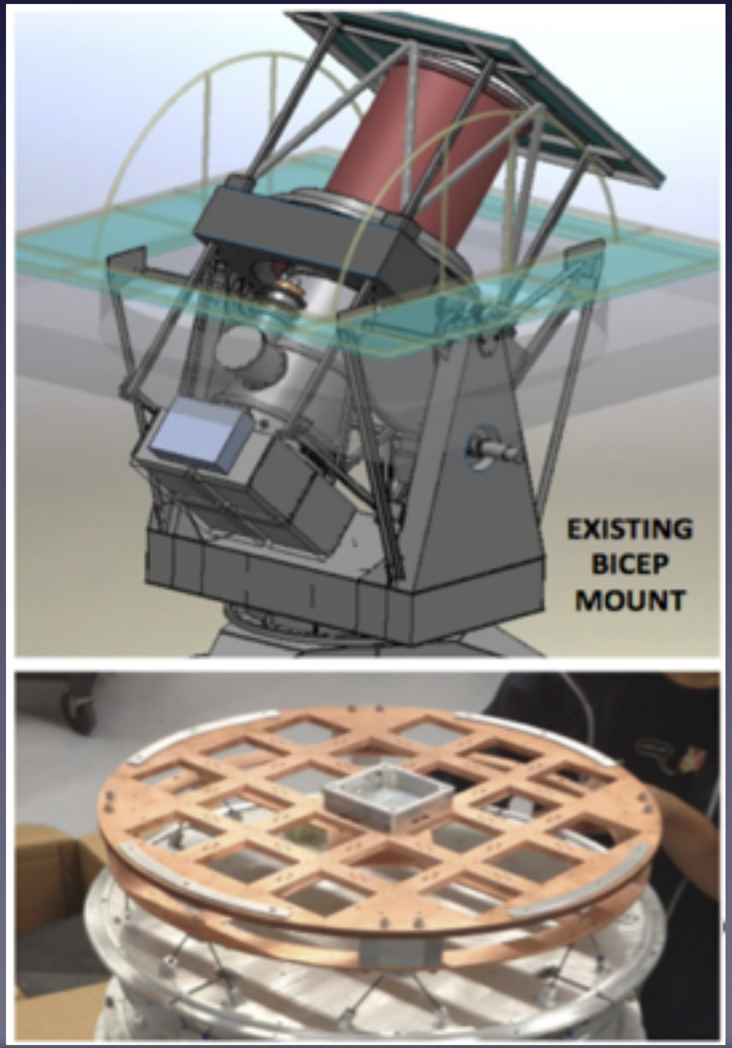
Keck Array

- South Pole, 2011 - 2016
- 2011: **1536** TESs @150 GHz
- 2012-13: **2560** @150 GHz
- 2014 upgrade:
  - **1536** @ 150 GHz
  - **576** @ 100 GHz



BICEP3

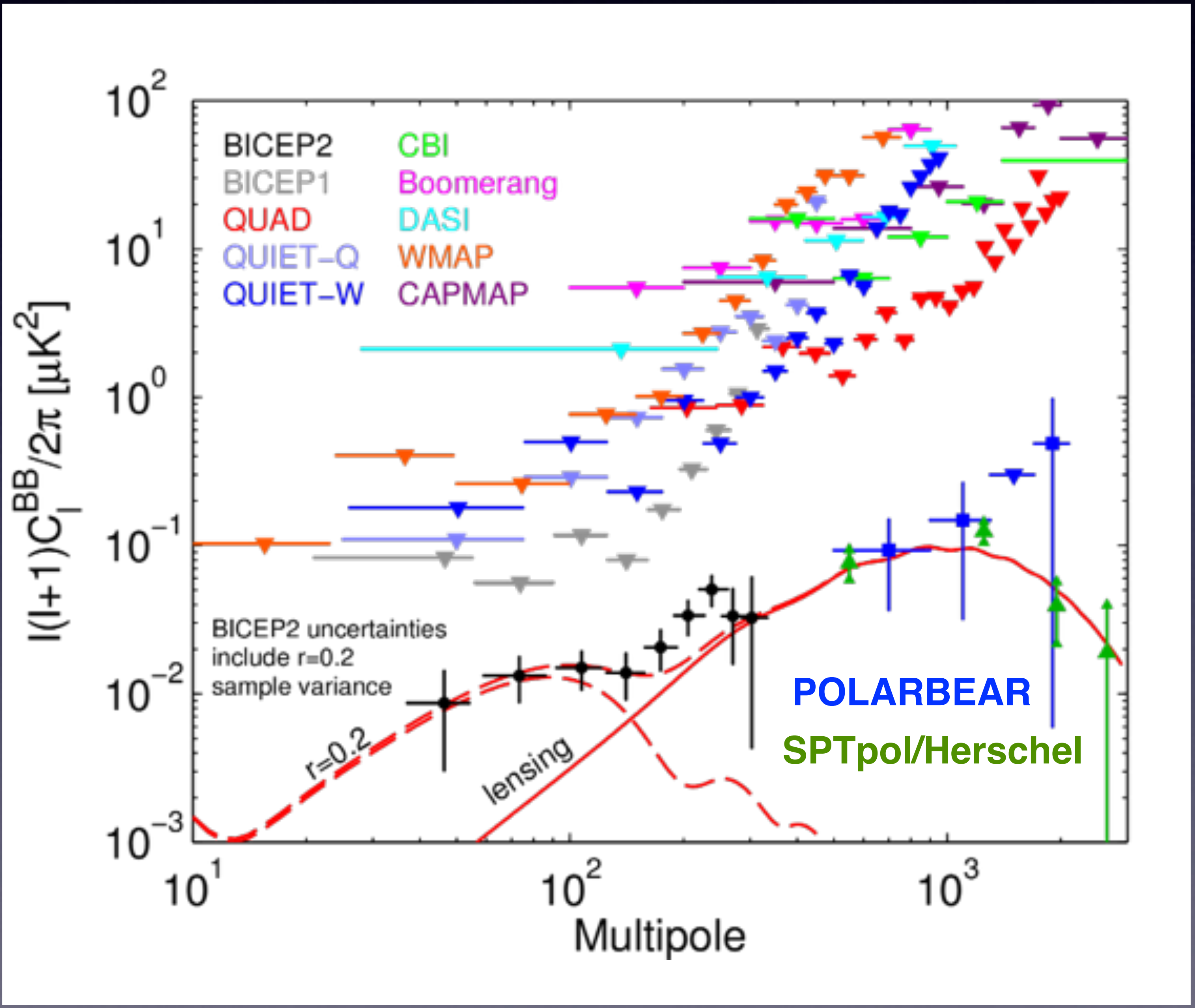
- South Pole, 2015-16
- **2560** TESs @ 100 GHz



Spider

- Long-duration balloon 2014
- Large (~10%) sky coverage
- Half-wave plate
- **2400** TESs
  - 1536 @ 150 GHz
  - 864 @ 100 GHz

Conclusions



- BICEP2 observes **5.3σ excess** above lensed-ΛCDM; r=0 disfavored at **7σ** before foreground subtraction
- Consistent with expectations for primordial gravitational waves from GUT-scale inflation
- Extensive studies disfavor systematic error or synchrotron radiation as origin
- Data from Planck will update dust models; **Planck-BICEP2 joint analysis** in progress to understand signal origin
- The era of B-mode cosmology has begun!