Listening for the Echoes of Inflation with BICEP2 and Beyond

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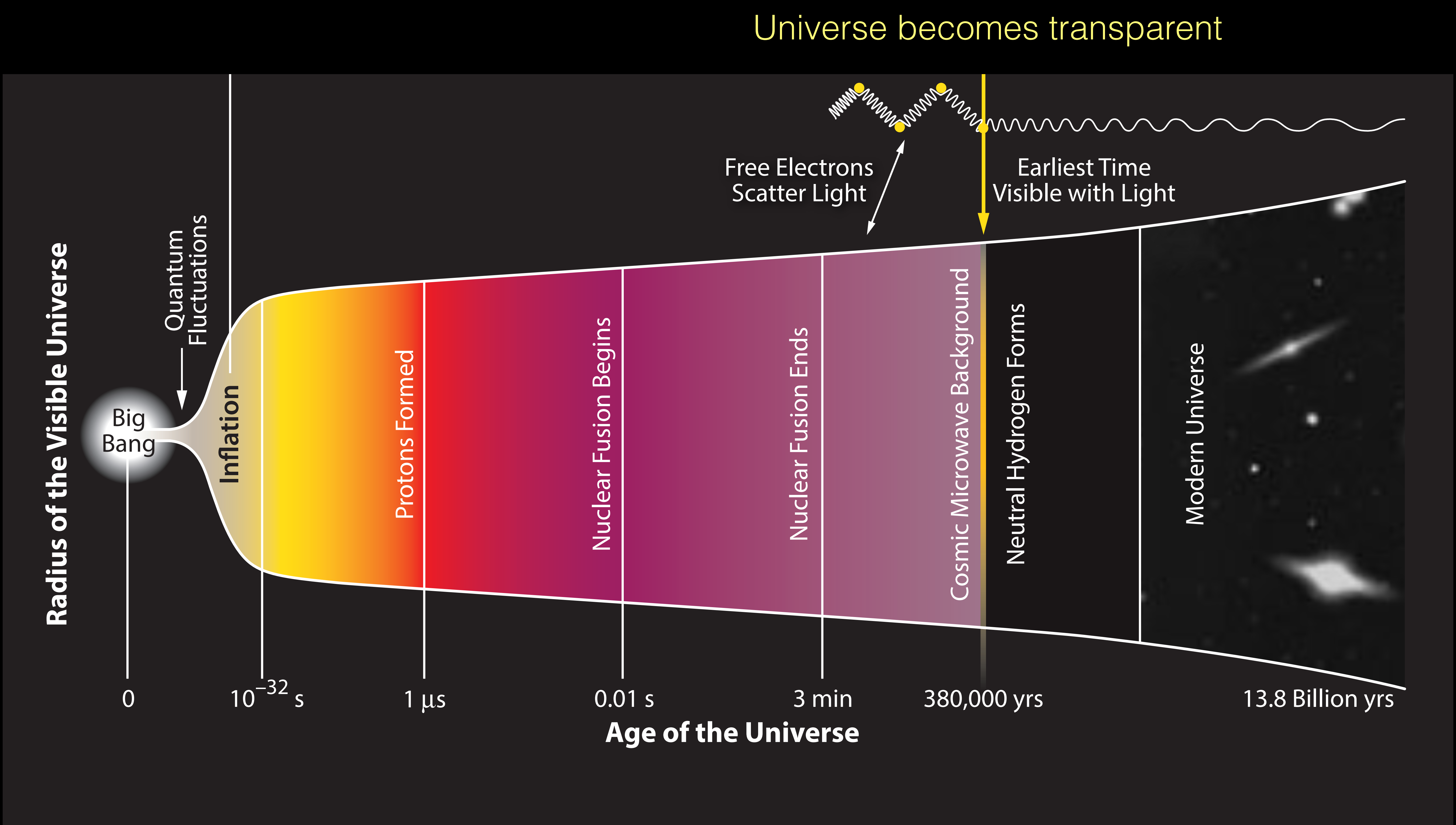
Outline

- The Echoes of Inflation
- The BICEP2 Instrument
- Results and Interpretation
- The Future

A History of Creation

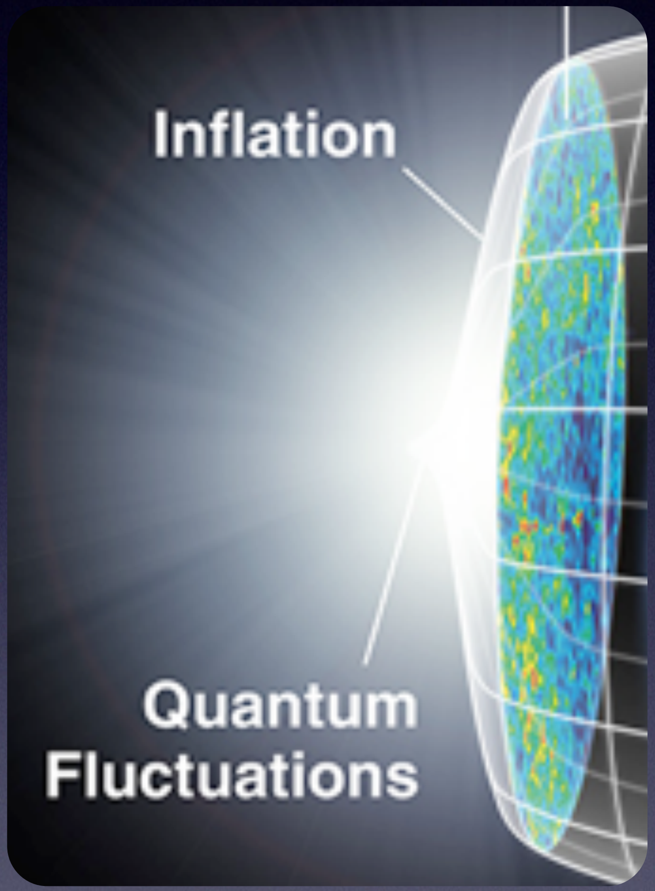


Inflation

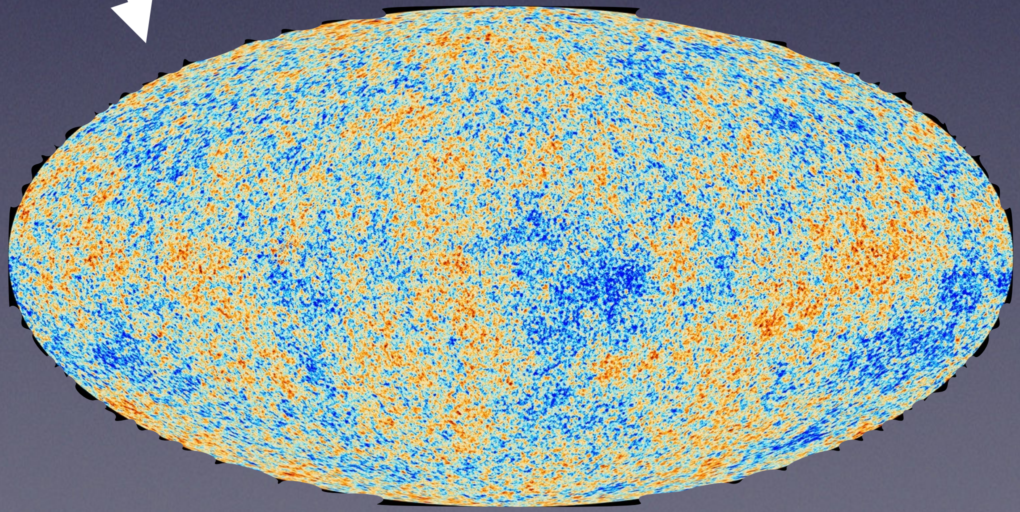
Quantum fluctuations…

"**inflaton**"

… imprinted onto cosmic scales



- ✓ Homogeneity
- ✓ Isotropy
- ✓ Nearly-flat geometry (Ω~1)
- ✓ Super-horizon fluctuations
- ✓ Nearly-scale invariant density perturbations (n_s~1)



Density perturbations

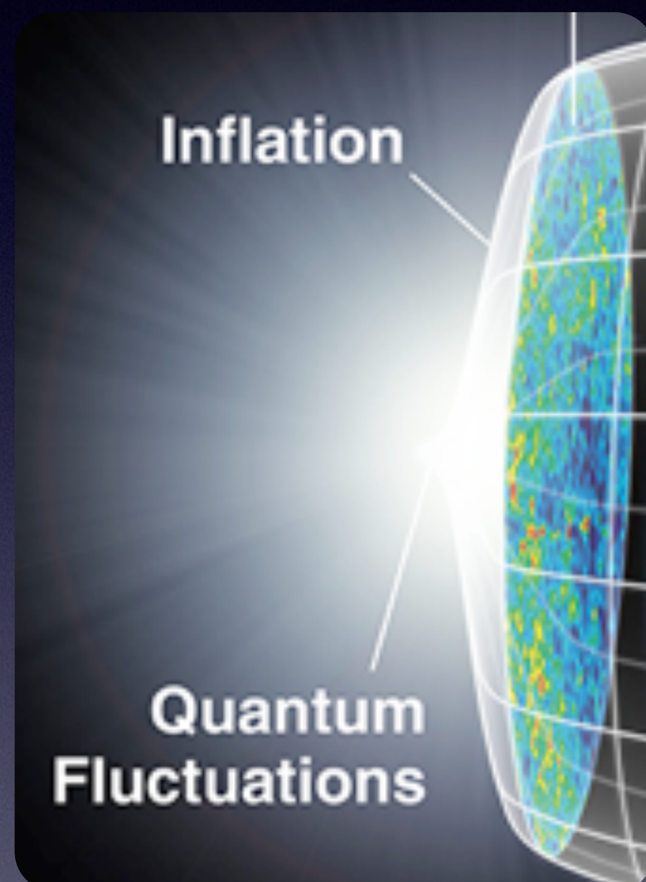
Primordial Perturbations

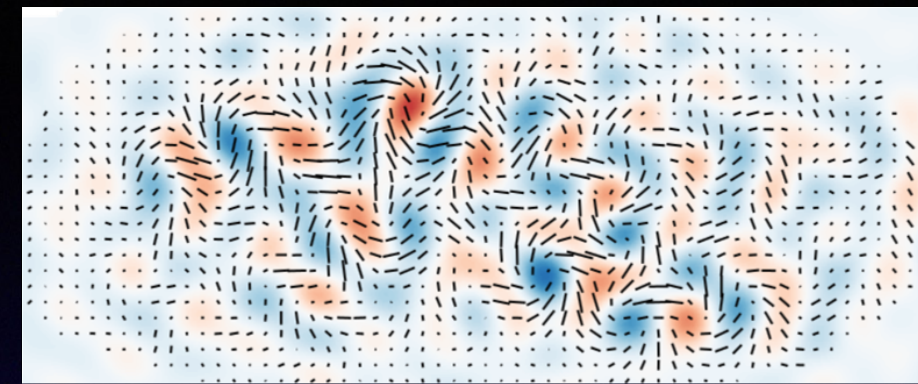
Quantum fluctuations…

“**inflaton**”

metric tensor

… imprinted onto cosmic scales

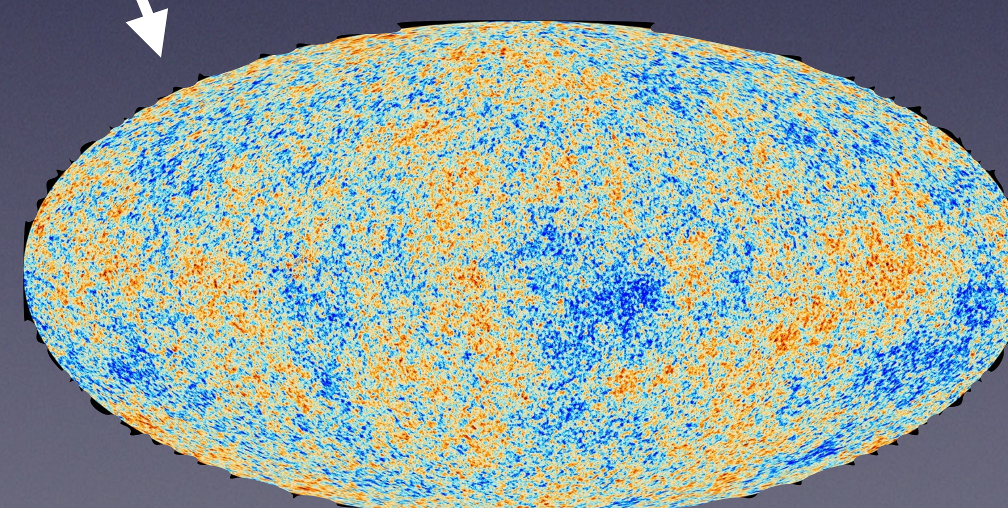




Primordial gravitational waves

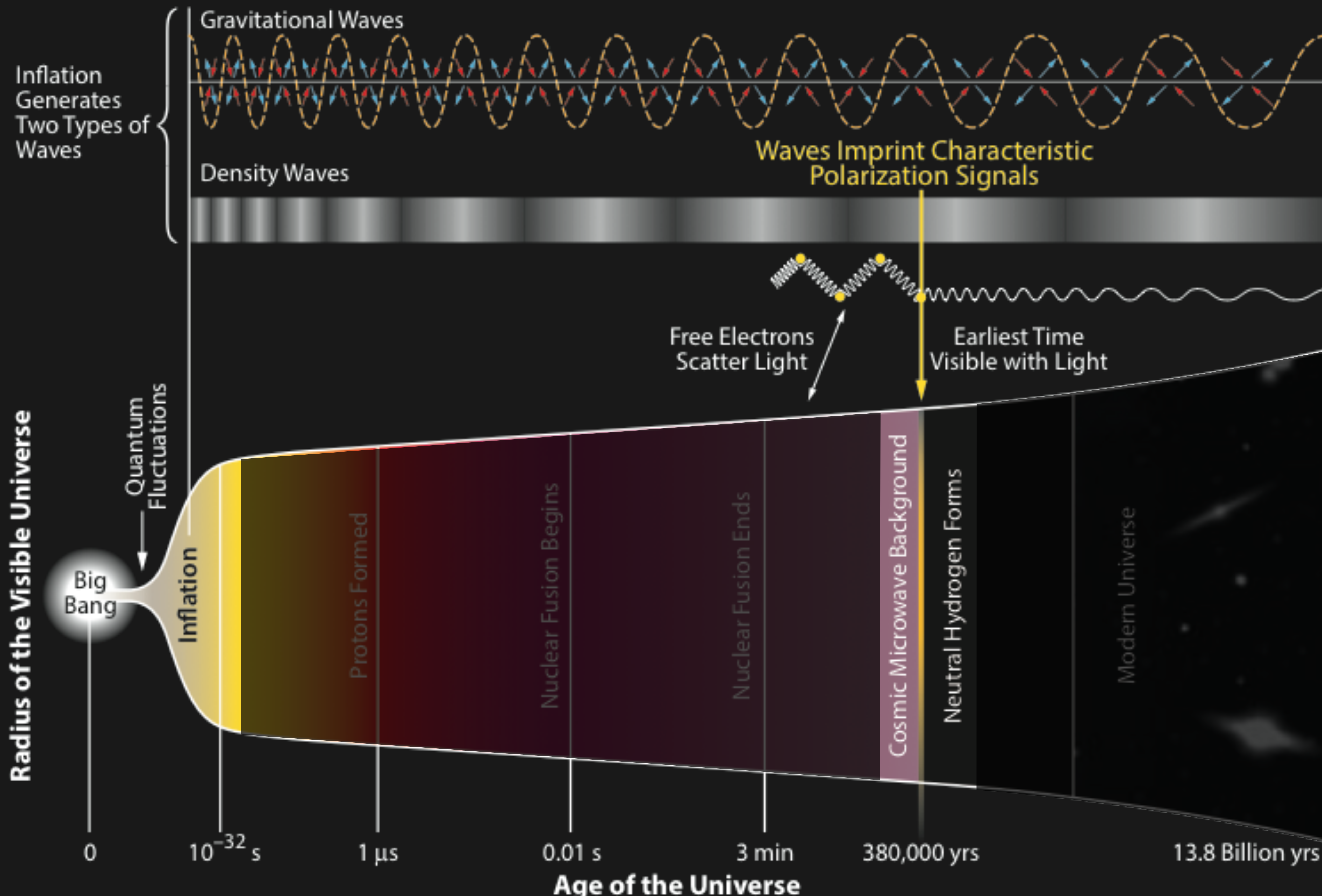
$$r \approx \frac{V[\phi]}{(4 \times 10^{16}\mathrm{GeV})^4}$$

GUT-scale physics!?



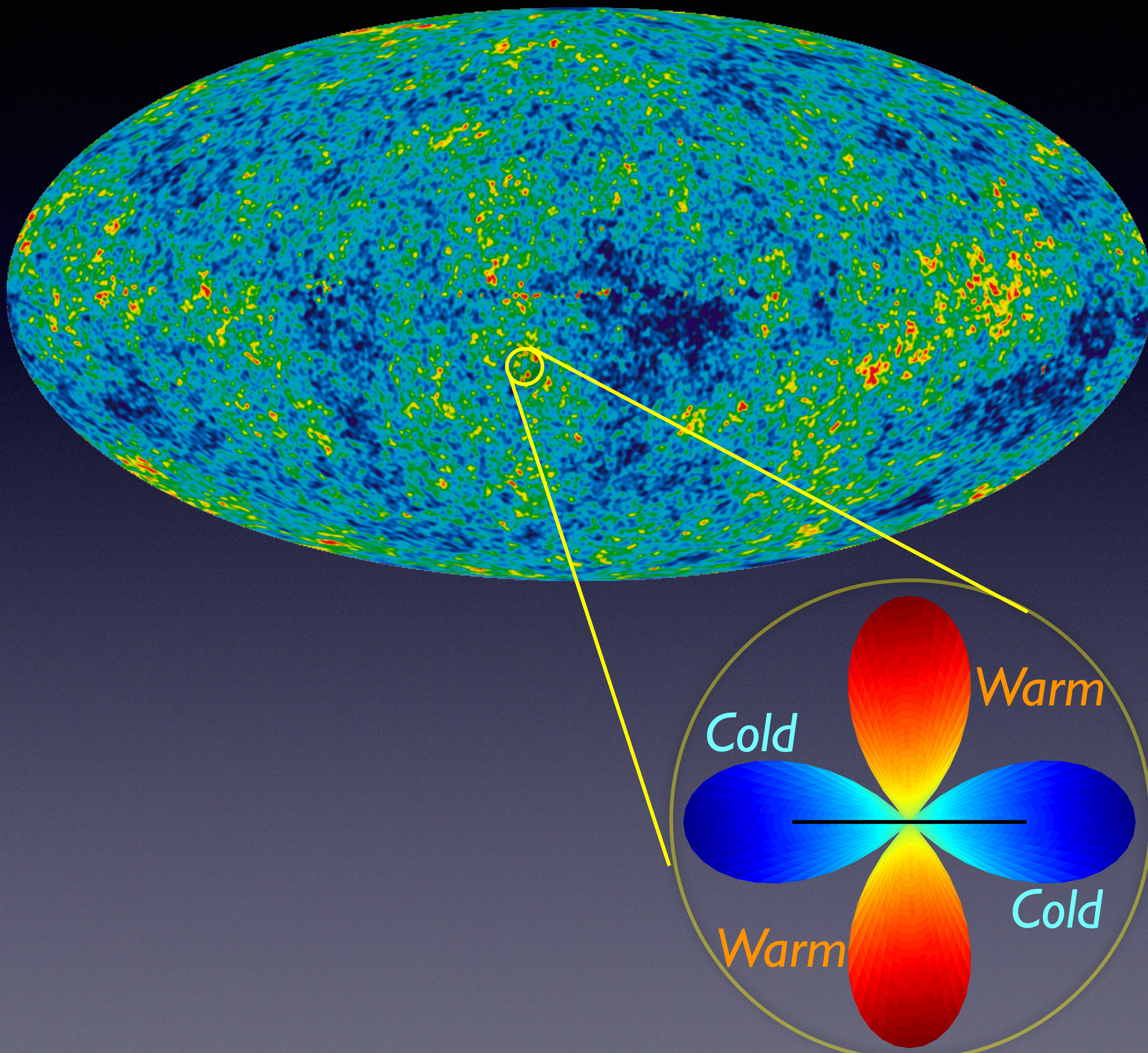
Density perturbations

History of the Universe

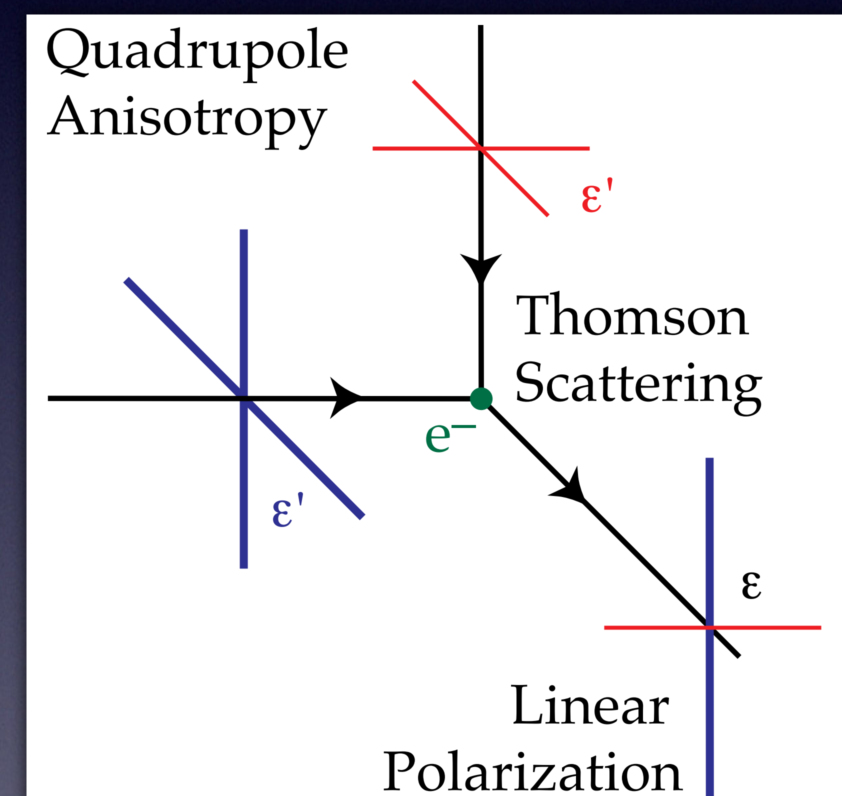


J. Filippini - Rencontres de Blois 2014

CMB Polarization

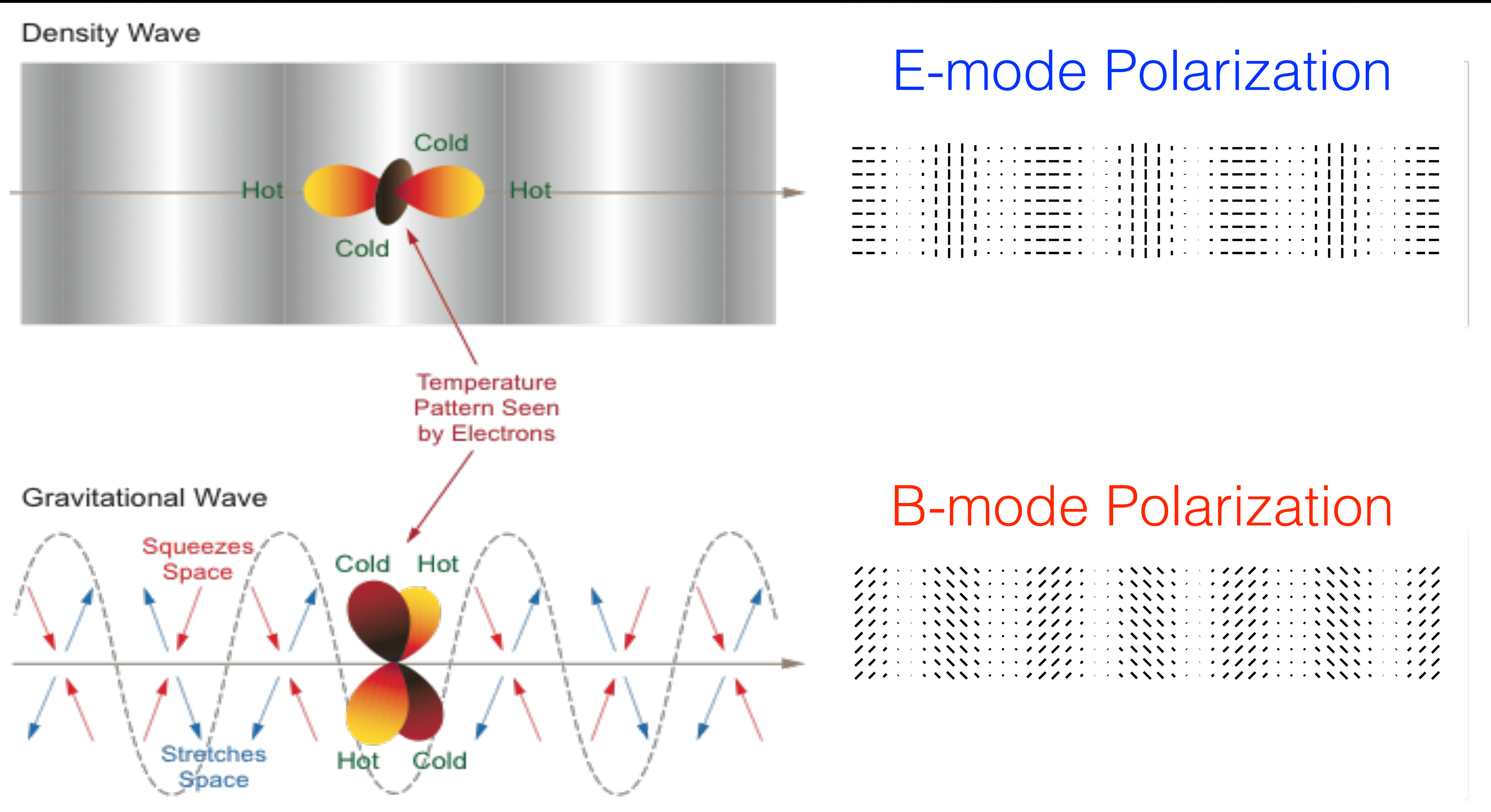


From Thomson scattering wherever there is ionized gas and quadrupole anisotropy



Wayne Hu

Patterns of Polarization



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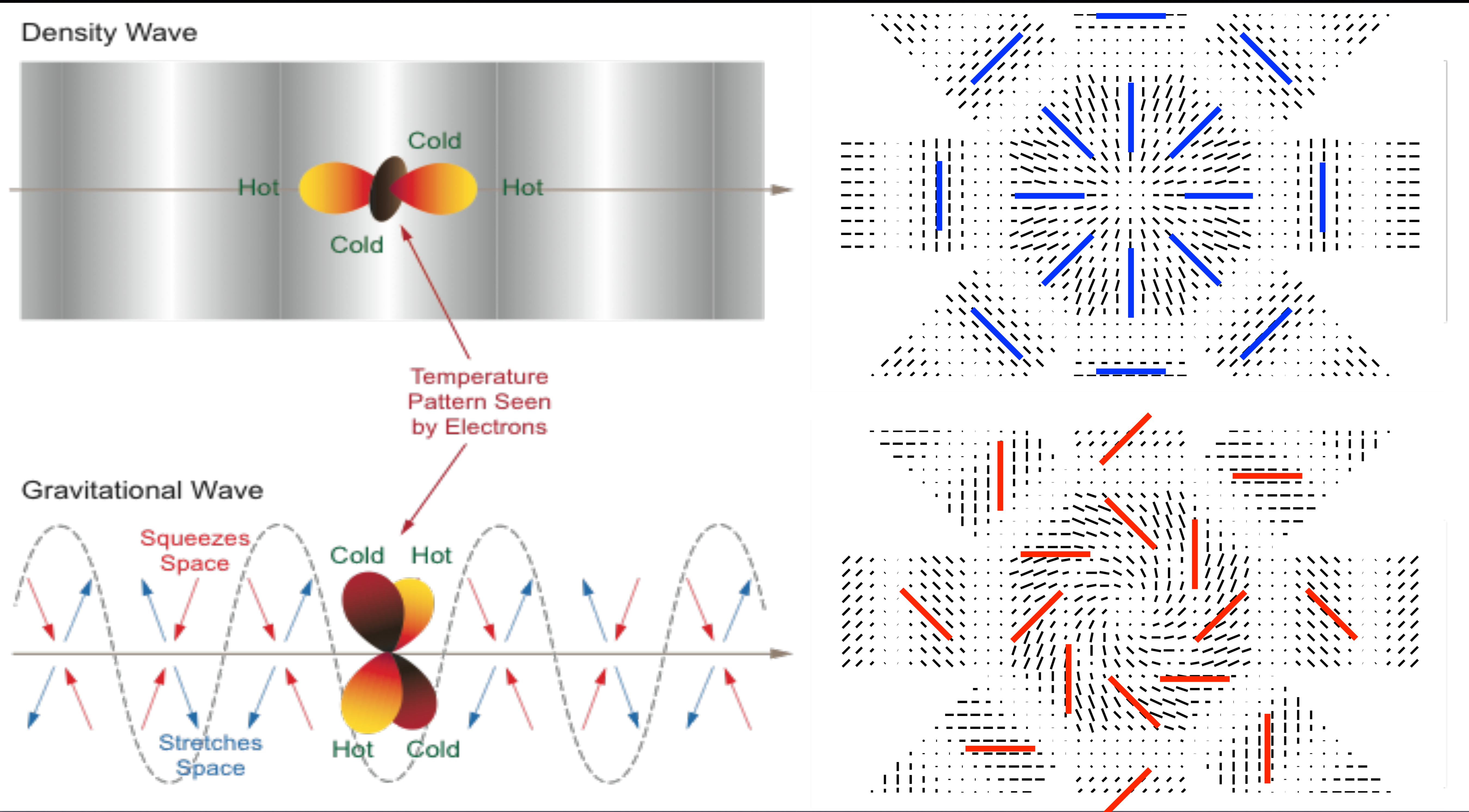
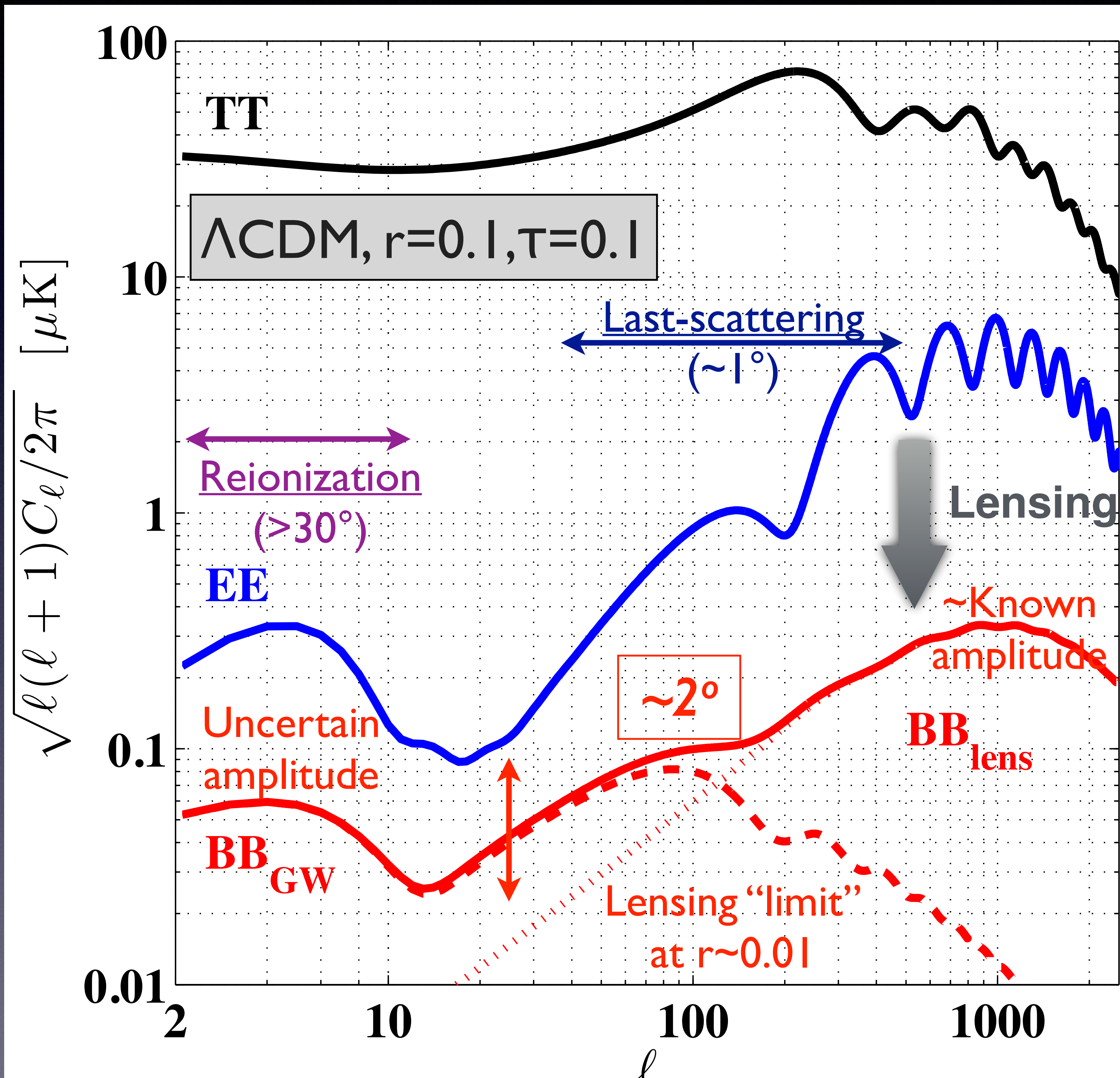
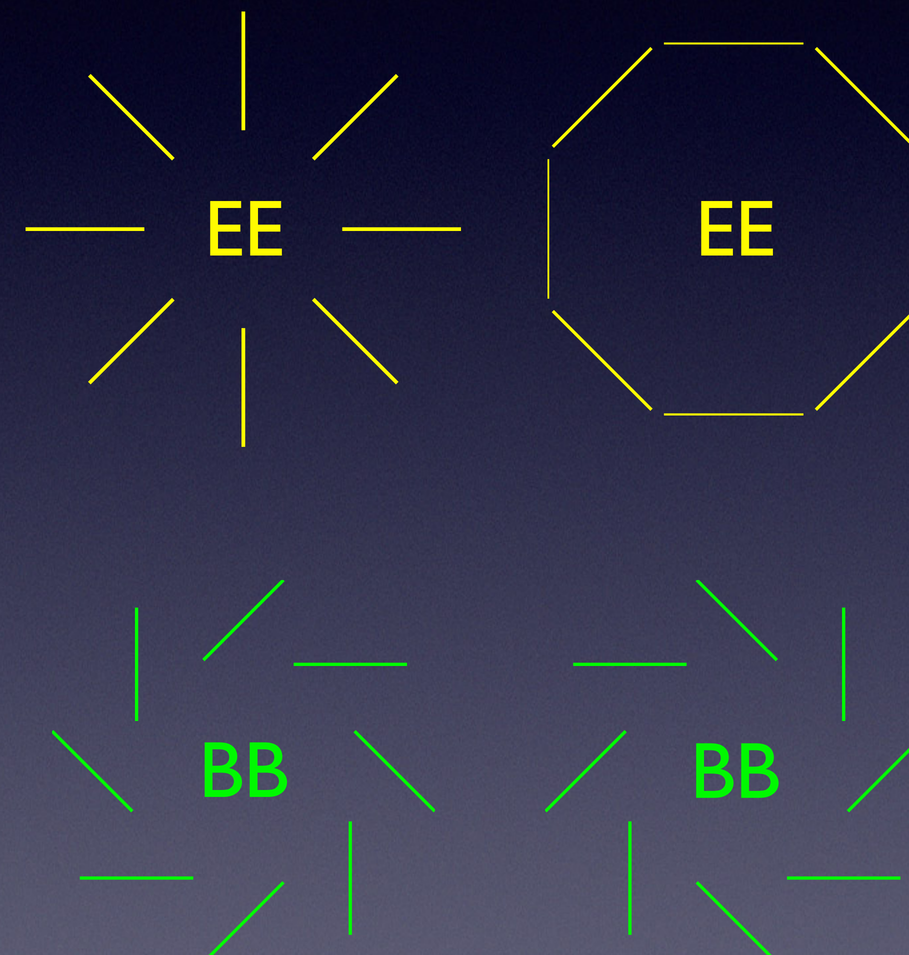


The Lay of the Land





The Challenge

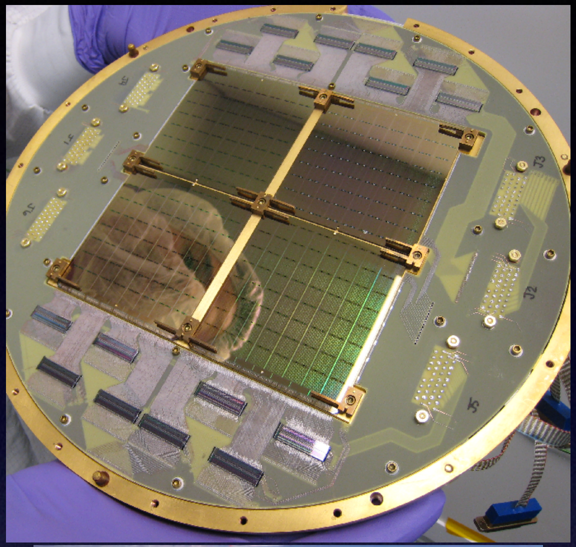
Extremely faint signal demands a map that is...

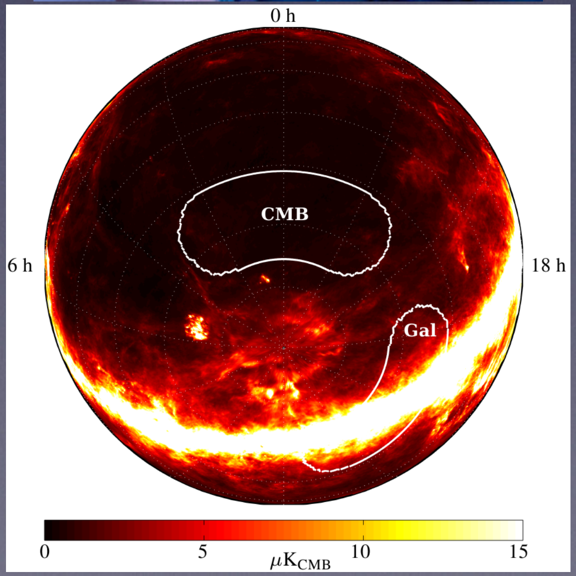
- **Precise**
  Detectors approach photon noise limit
  Many detectors (*multiplexing*)

- **Accurate**
  Rigid control of polarized systematics

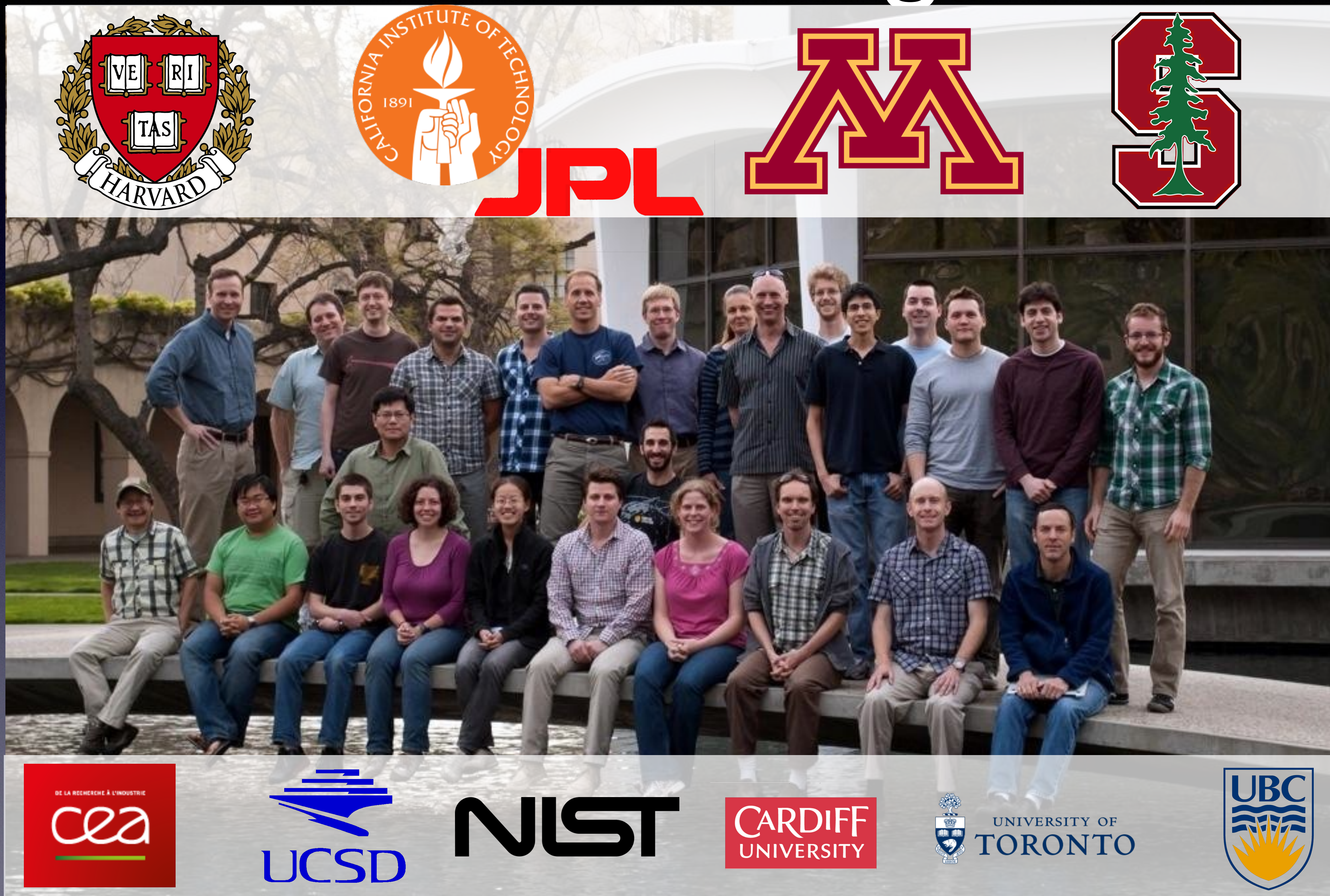
- **Uncontaminated**
  Avoidance (or subtraction) of polarized foregrounds

- *Not necessarily high angular resolution!*



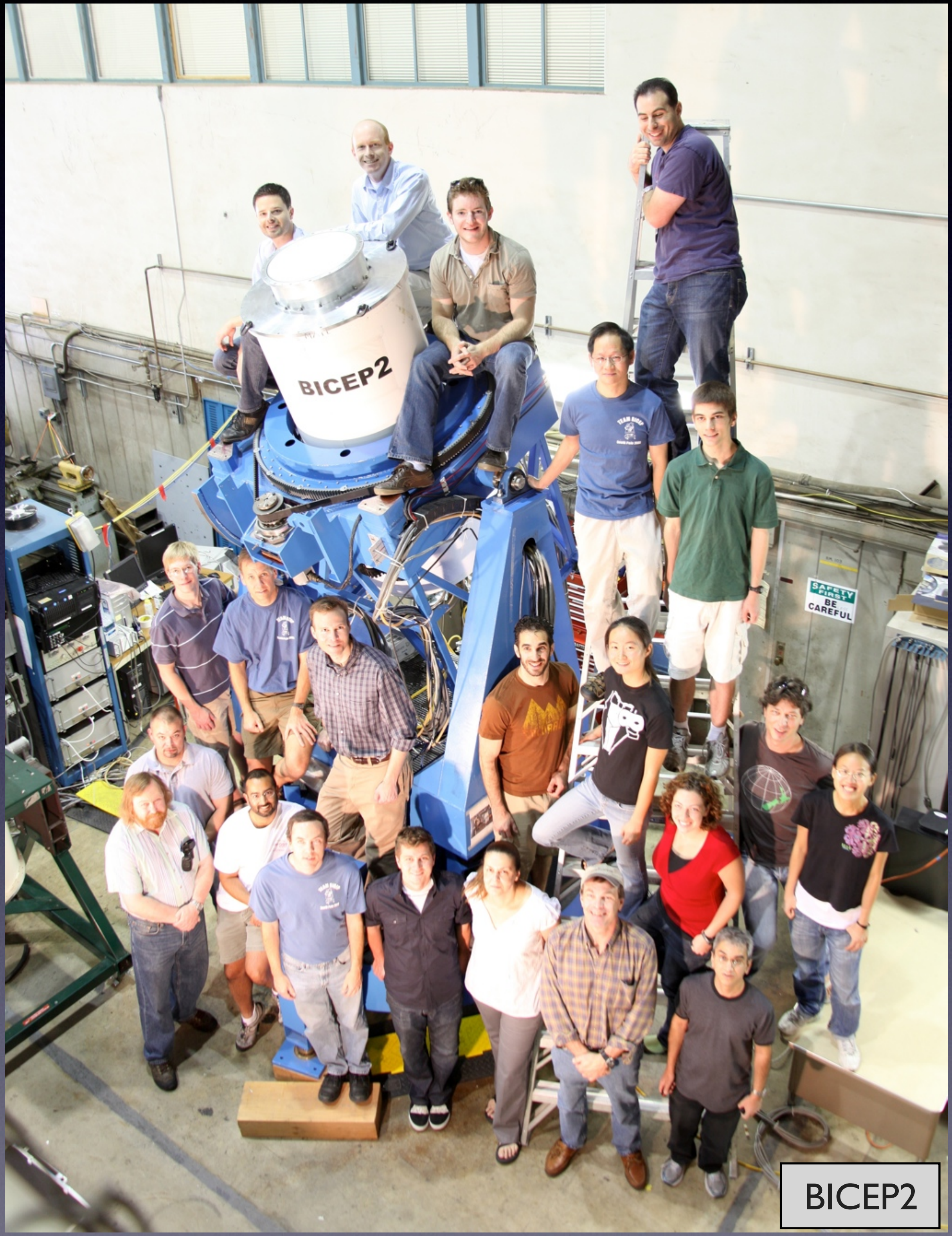


Inflation Investigators



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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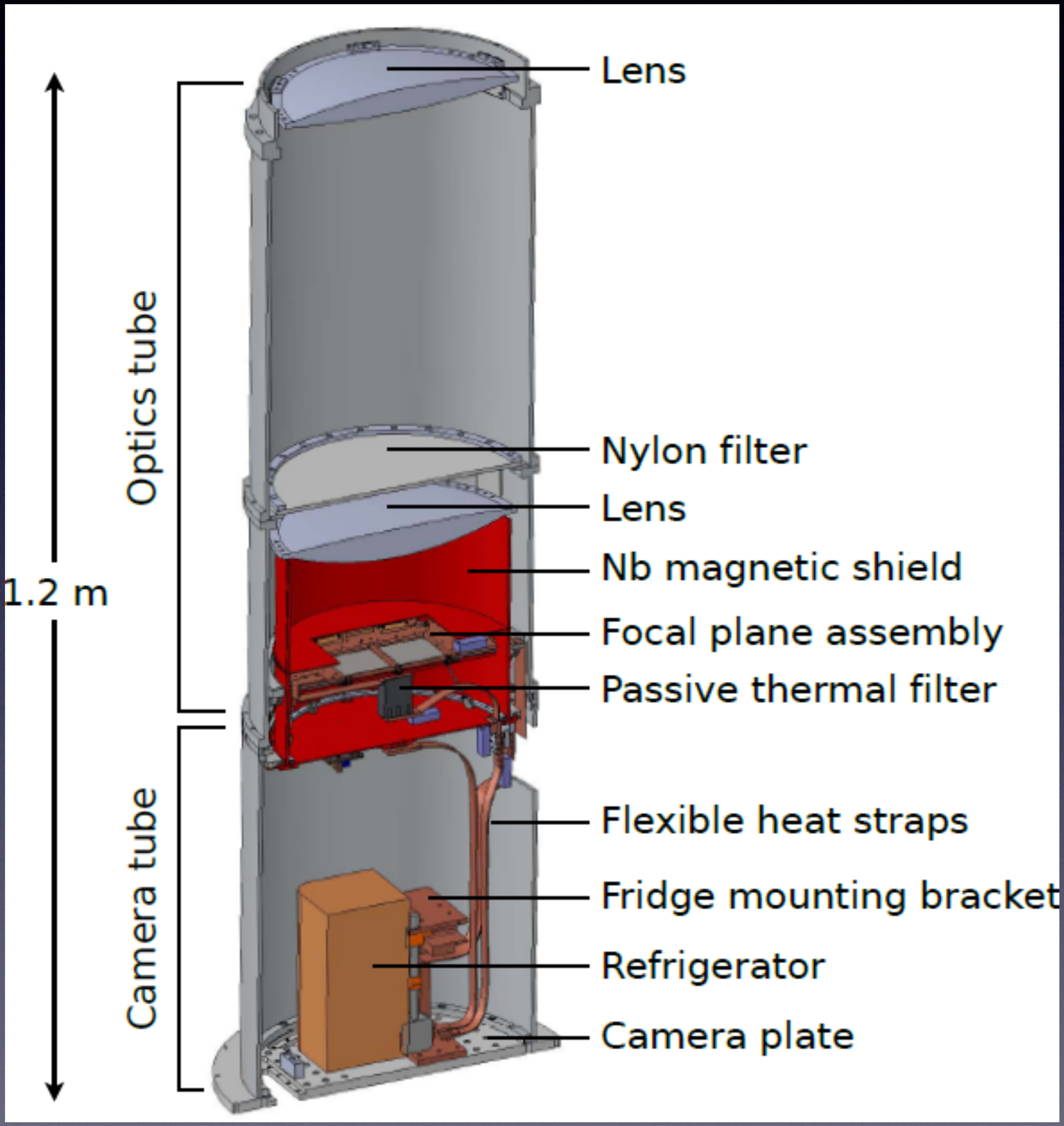

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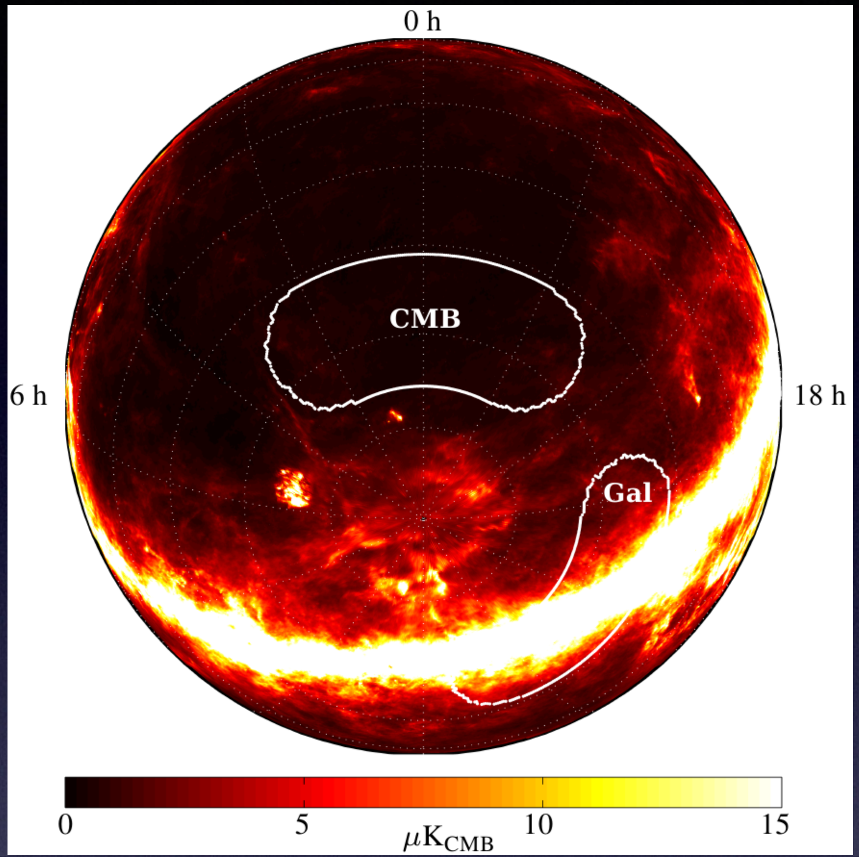
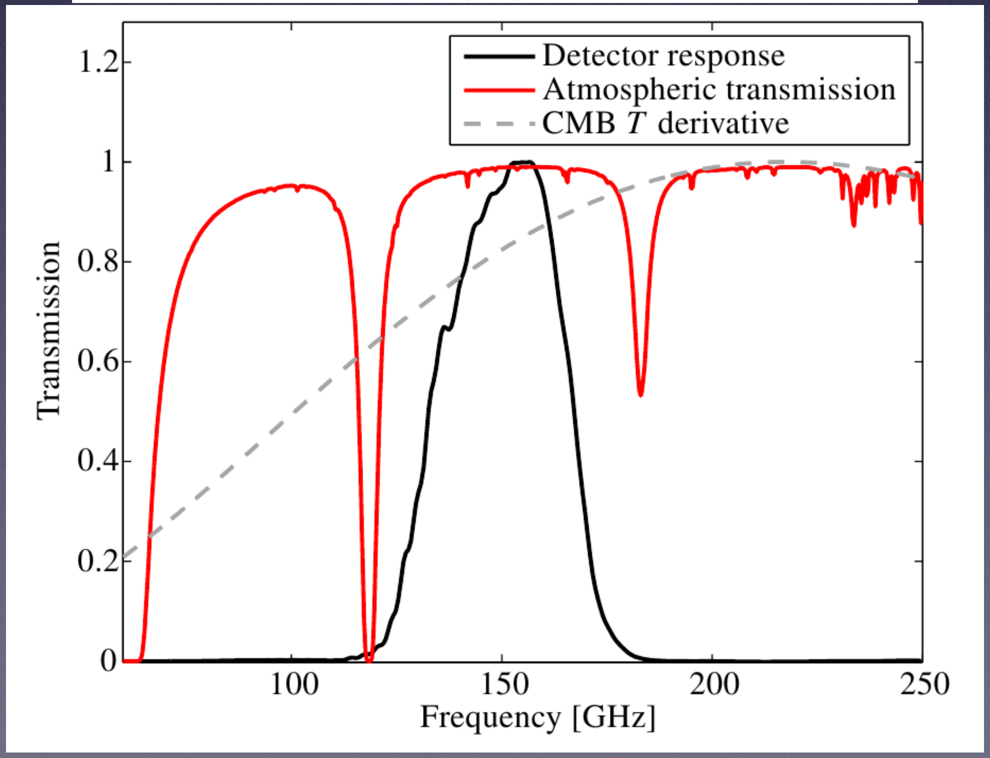
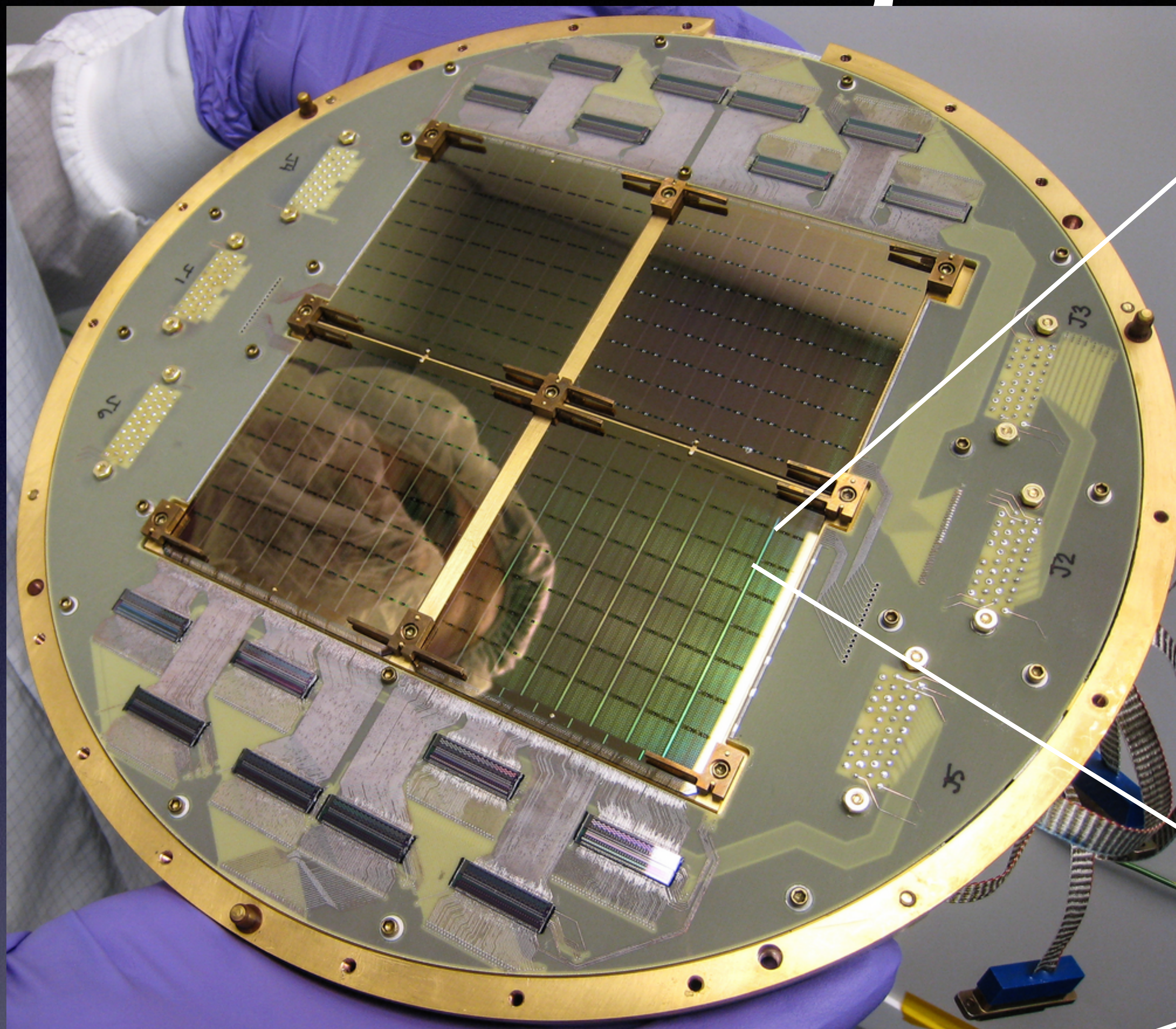
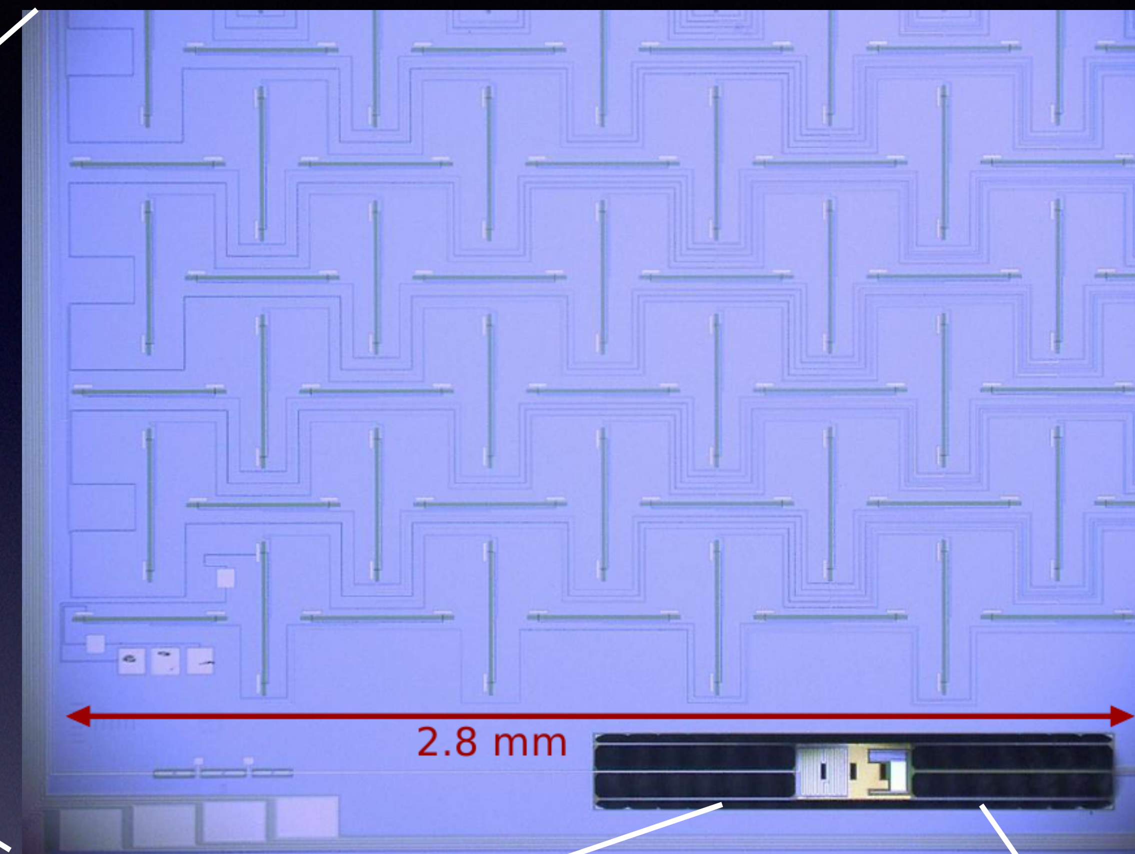
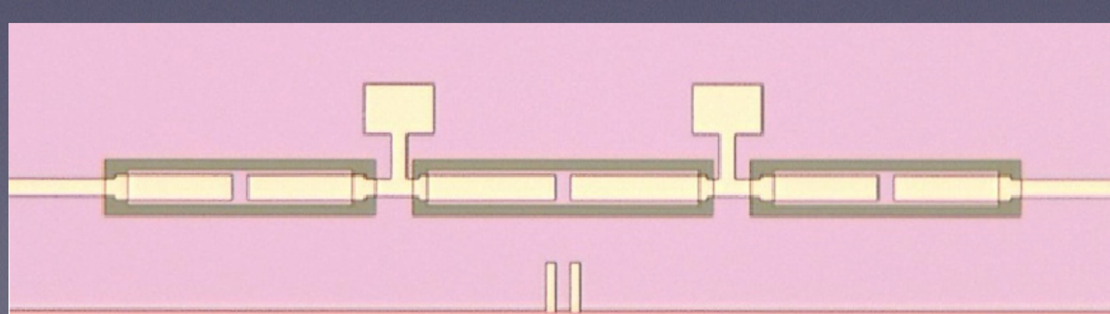


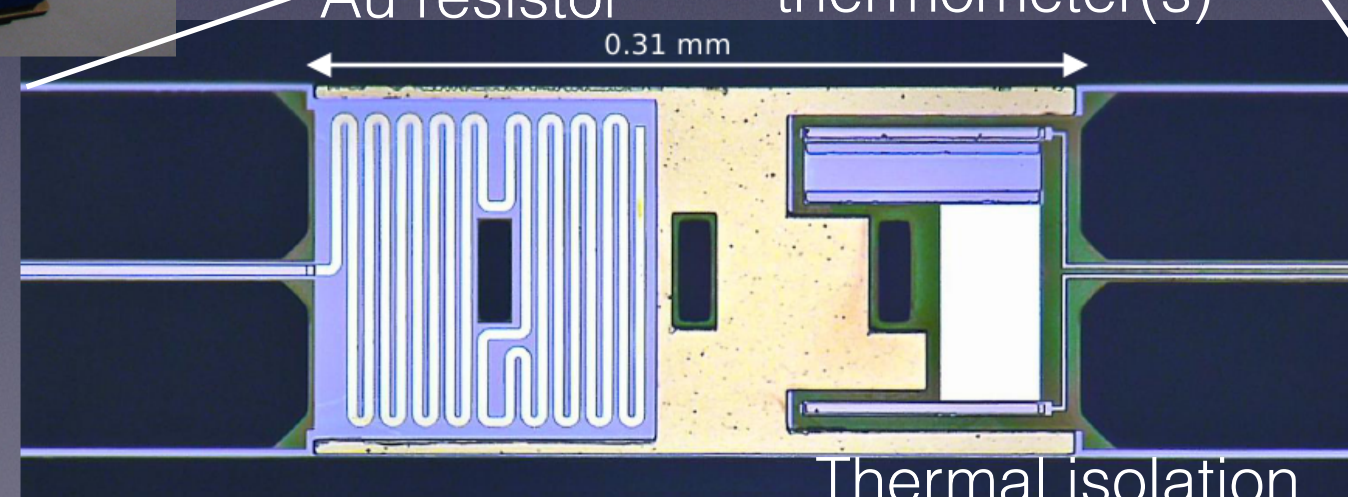


Caltech/JPL Detectors









The View from the Bottom of the World

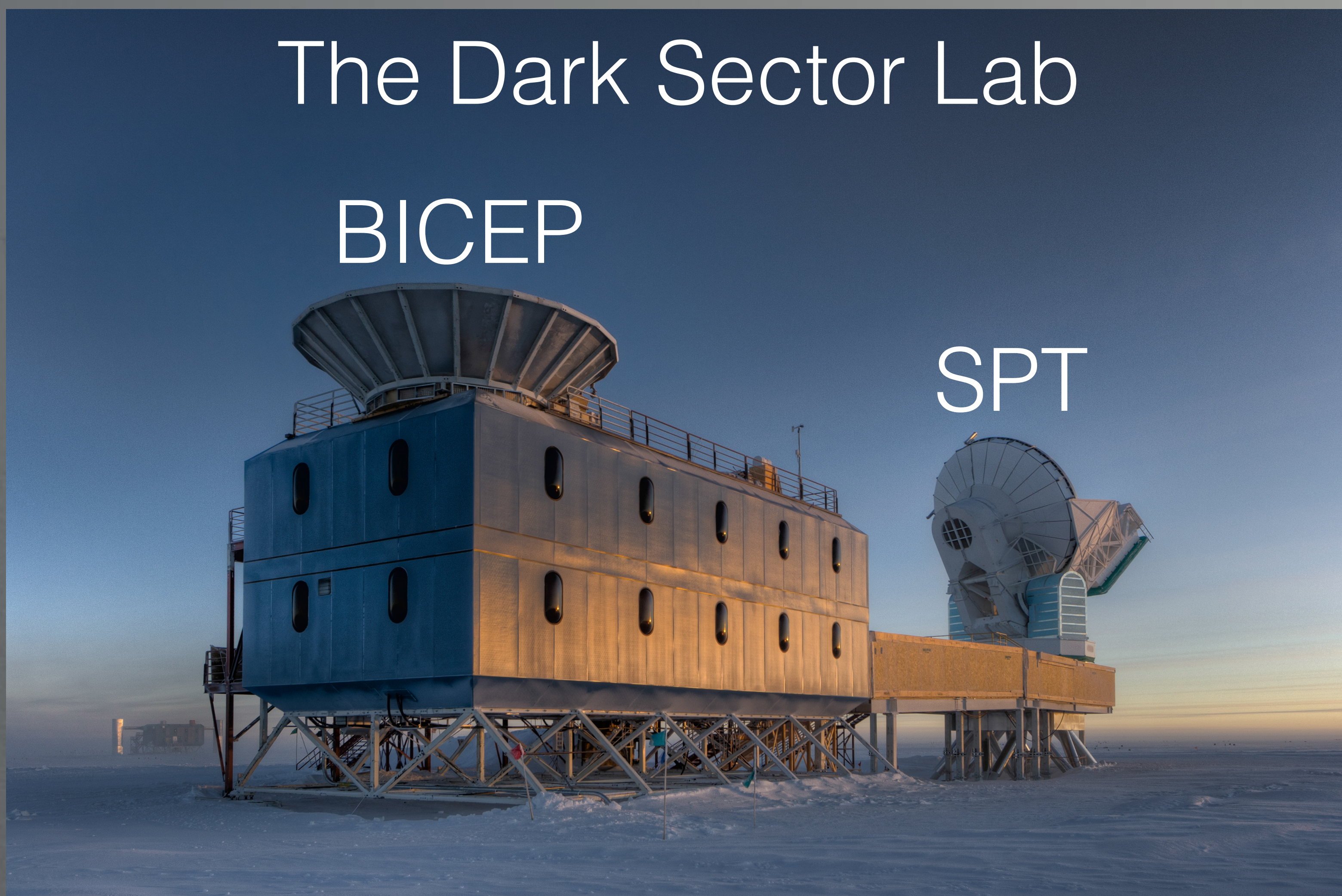
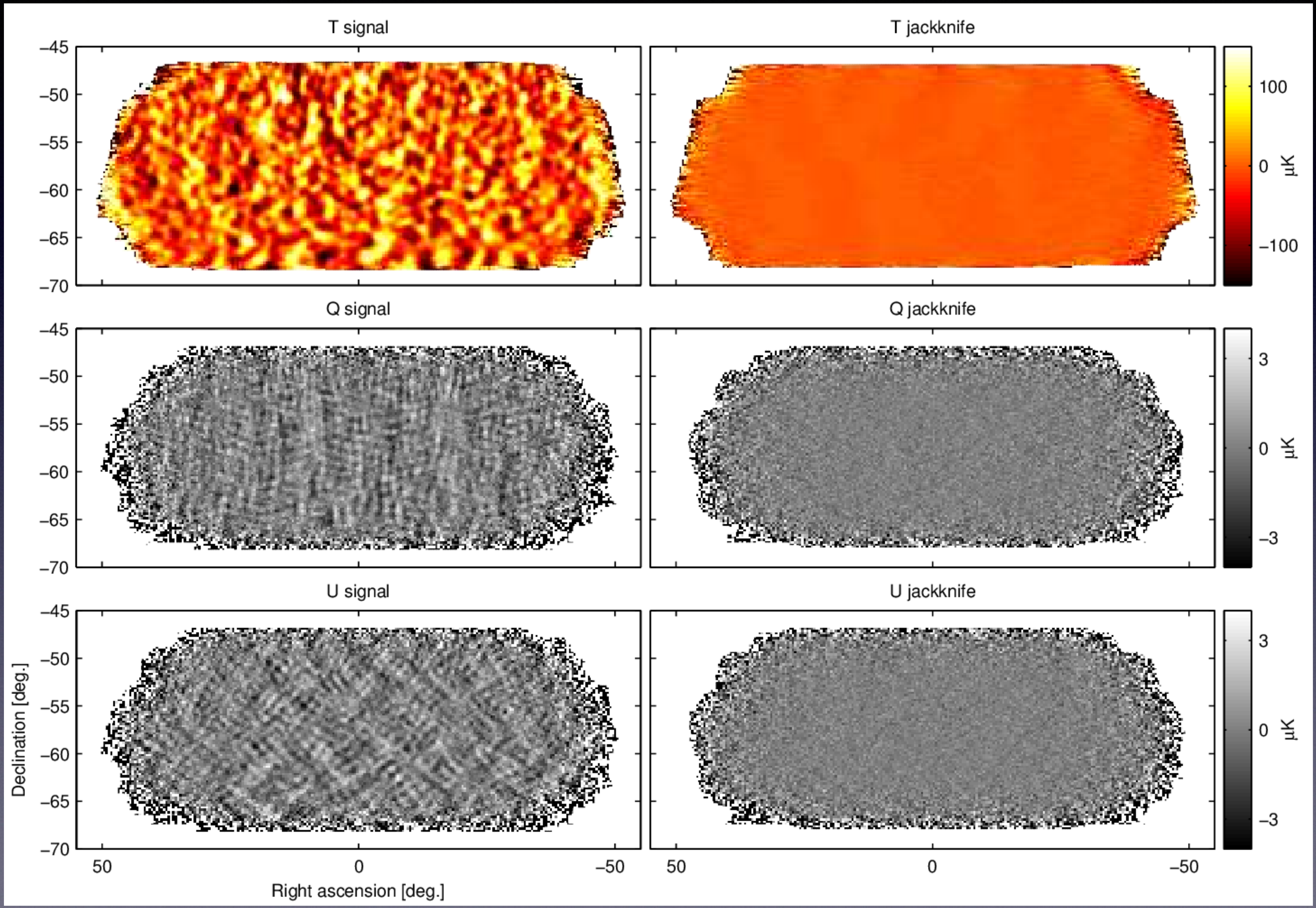



photo: Keith Vanderlinde

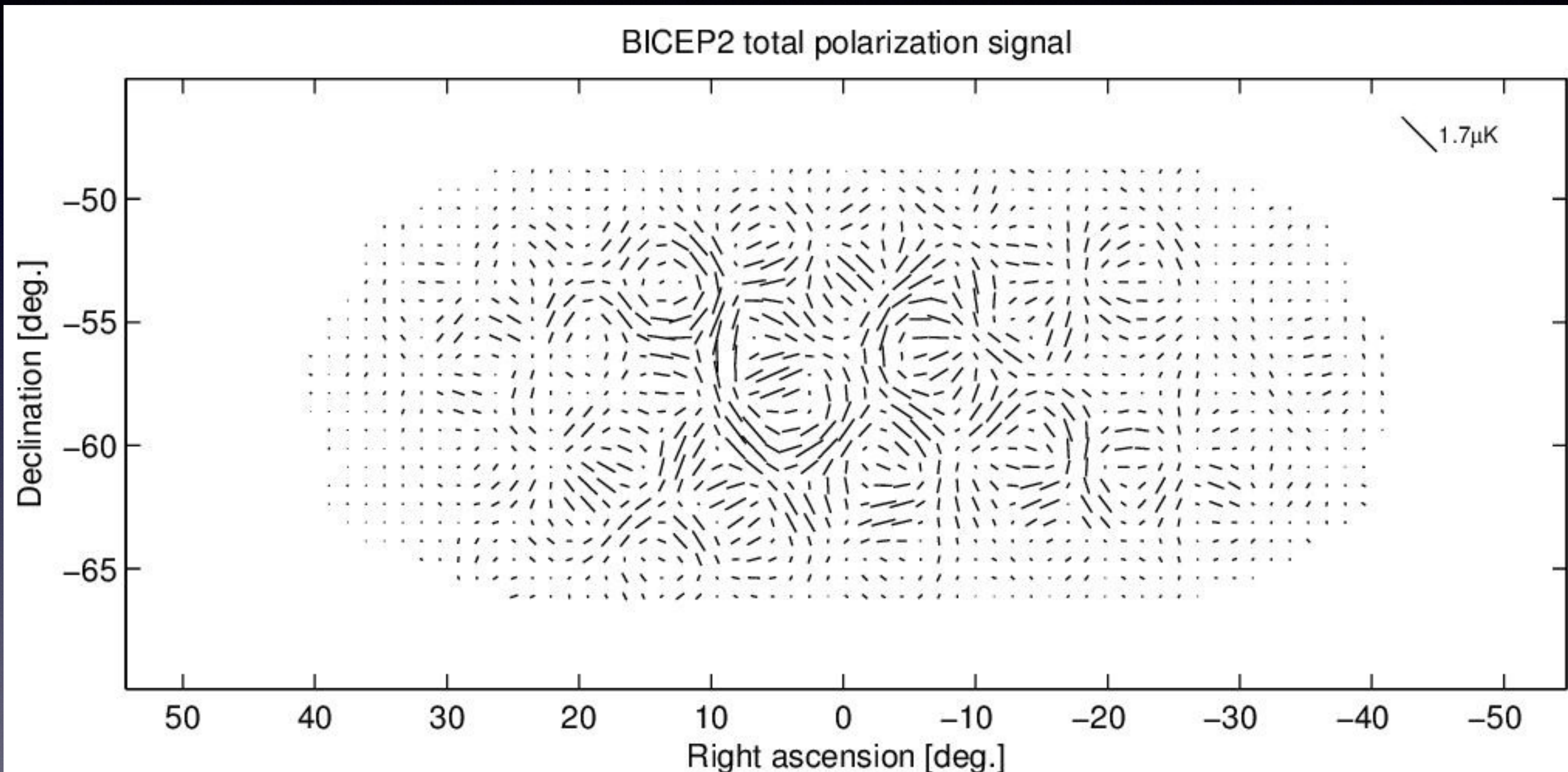
BICEP2 T and Stokes Q/U Maps



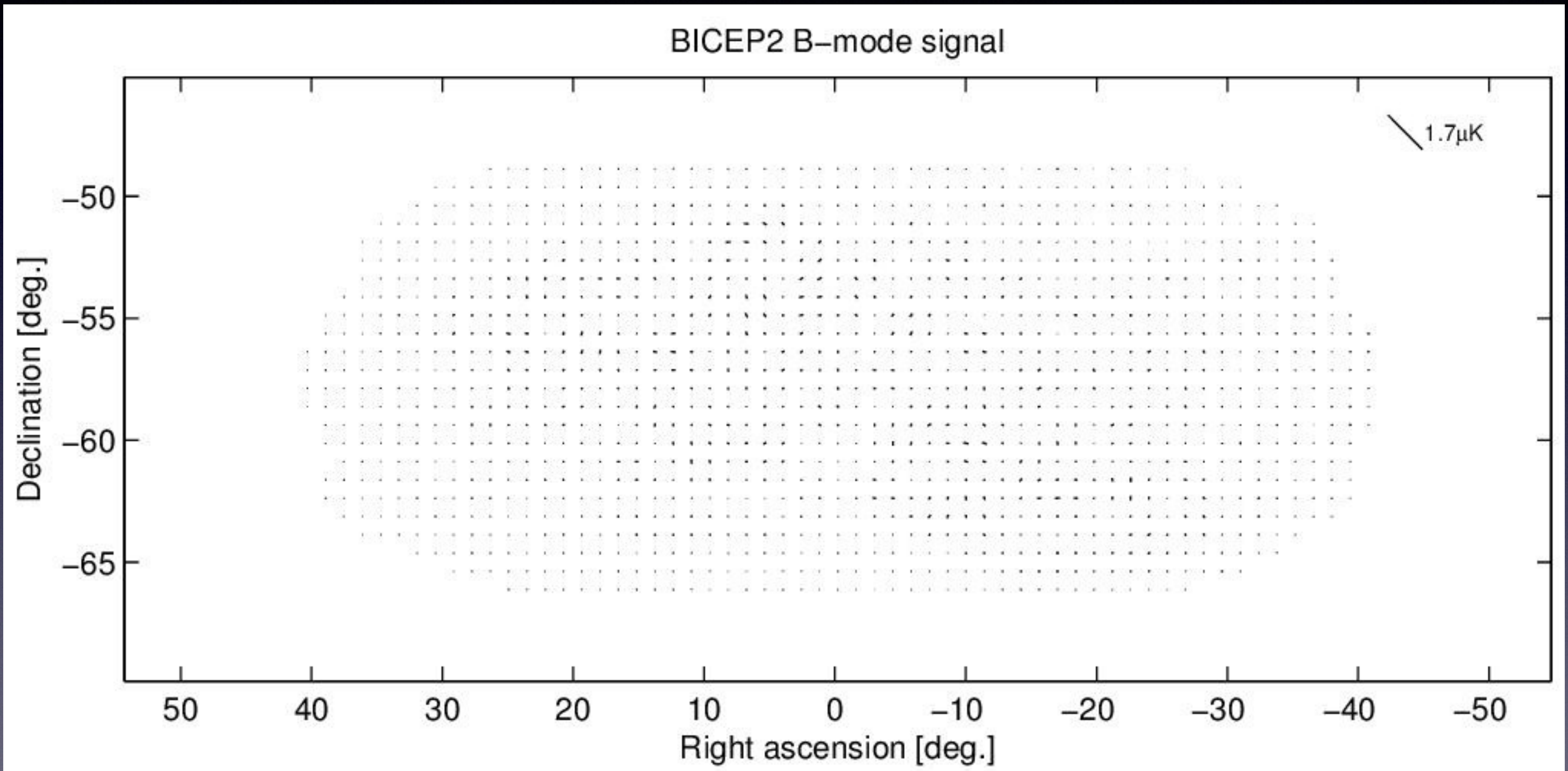
Sum maps

Difference maps

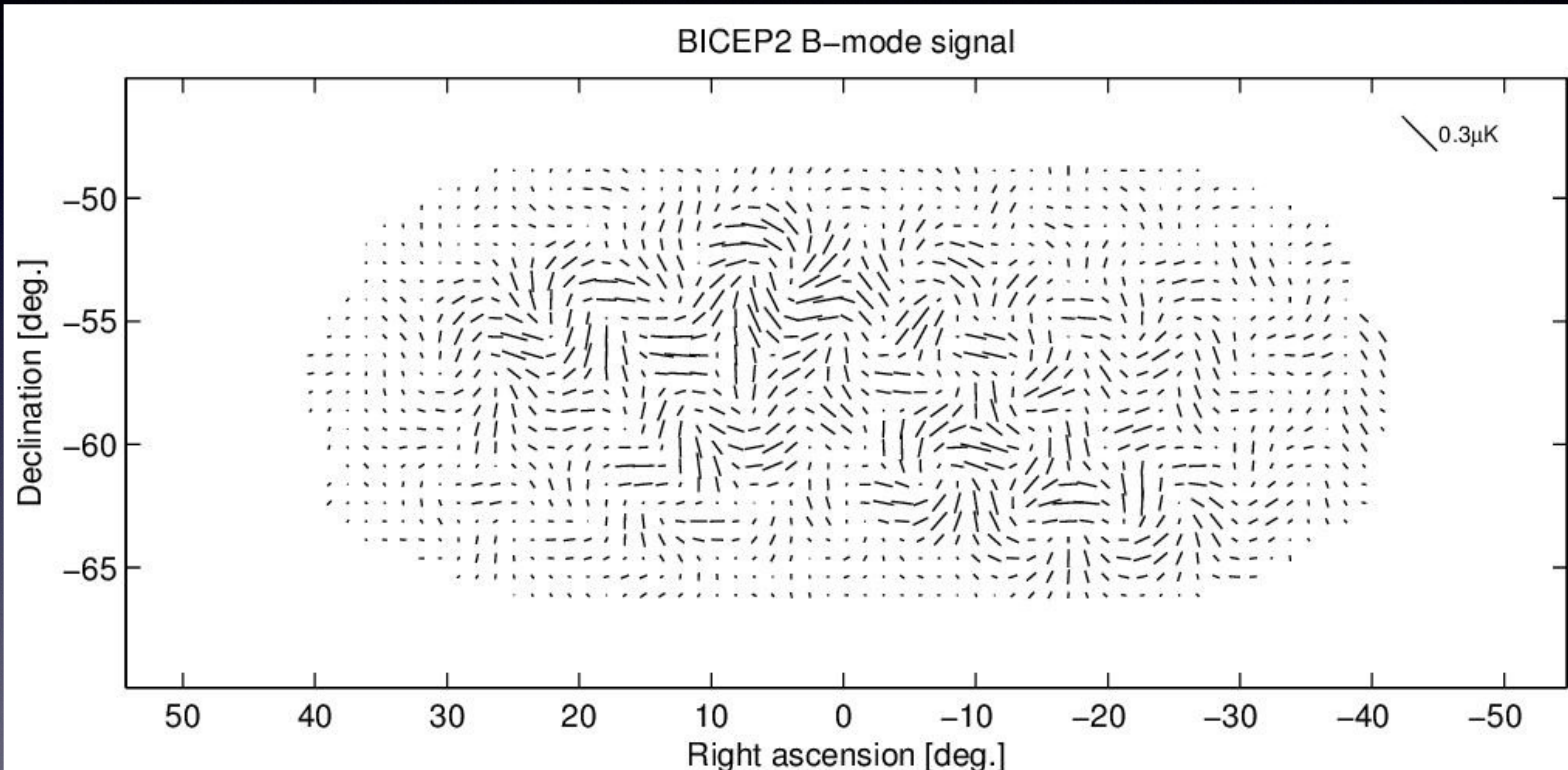
Total Polarization



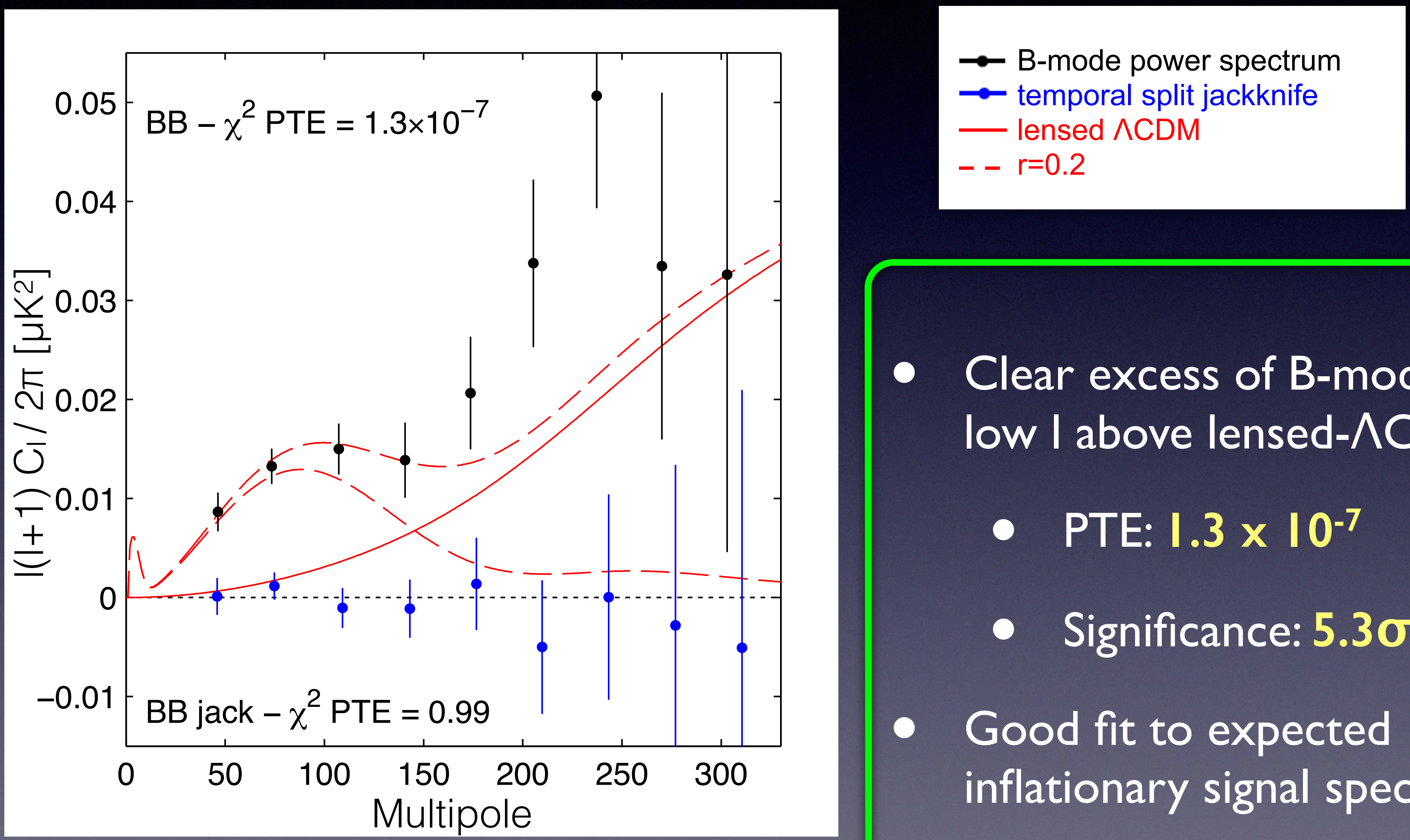
B-mode Signal



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

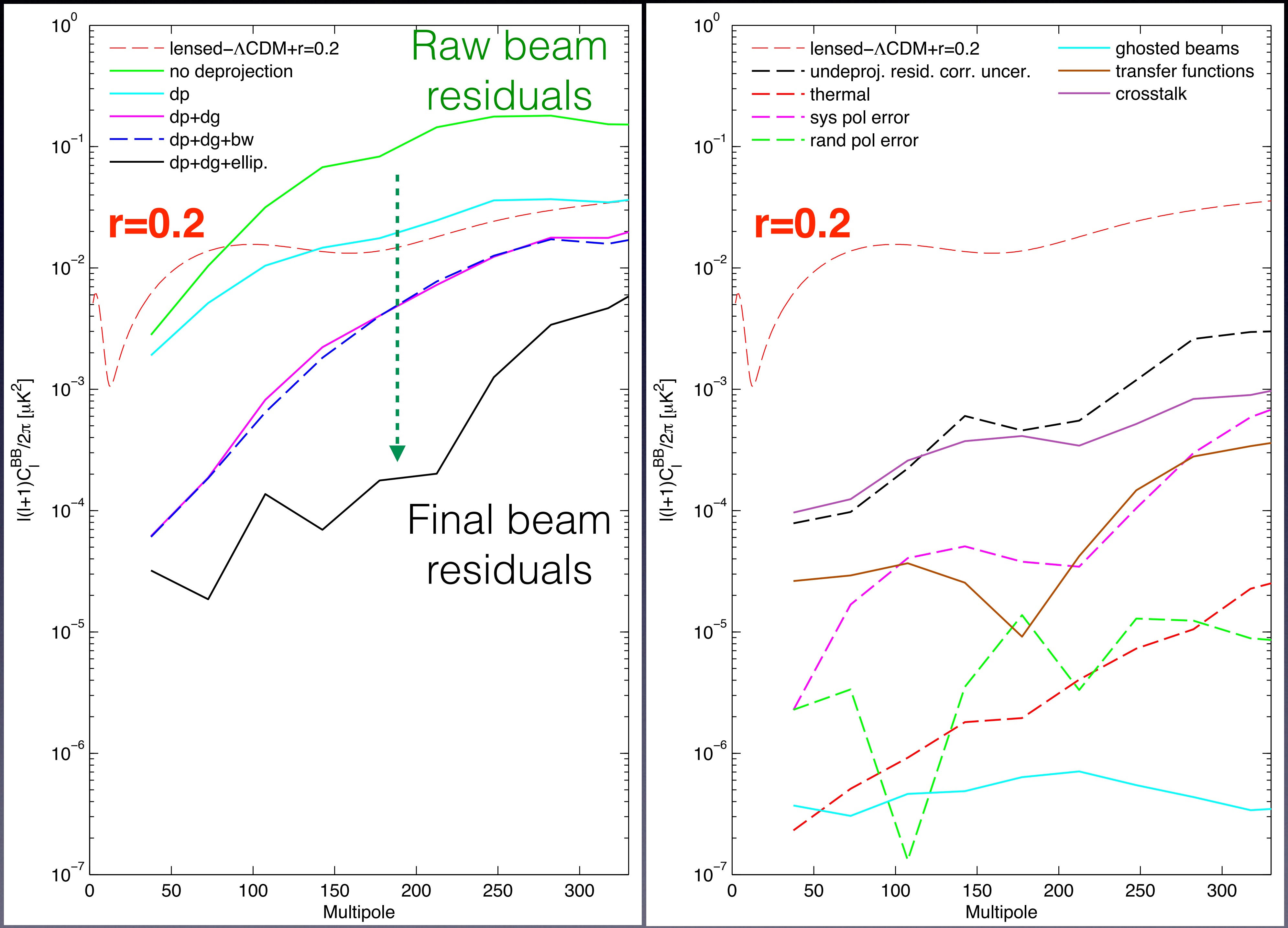
What could this be?

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

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



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	0.790

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

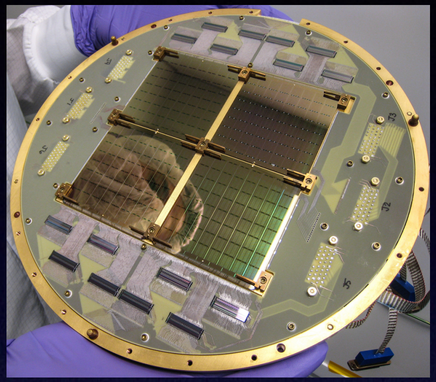
Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

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.

Cross Correlations

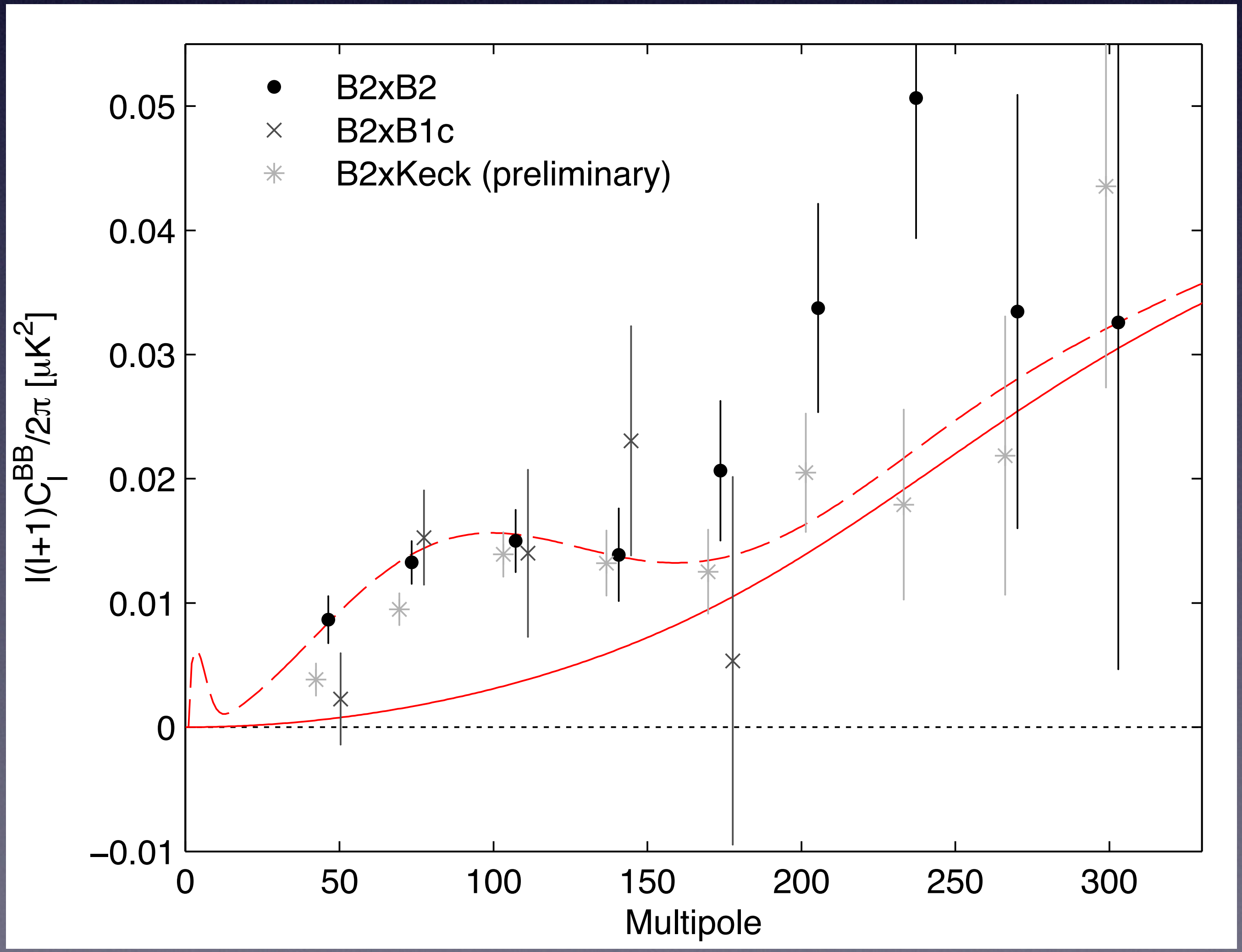
BICEP1: Feedhorns,NTDs, 150 and 100 GHz



BICEP2: Phased antenna array,TESs,150 GHz

Keck Array: Phased antenna array,TESs,150 GHz

- **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*)!



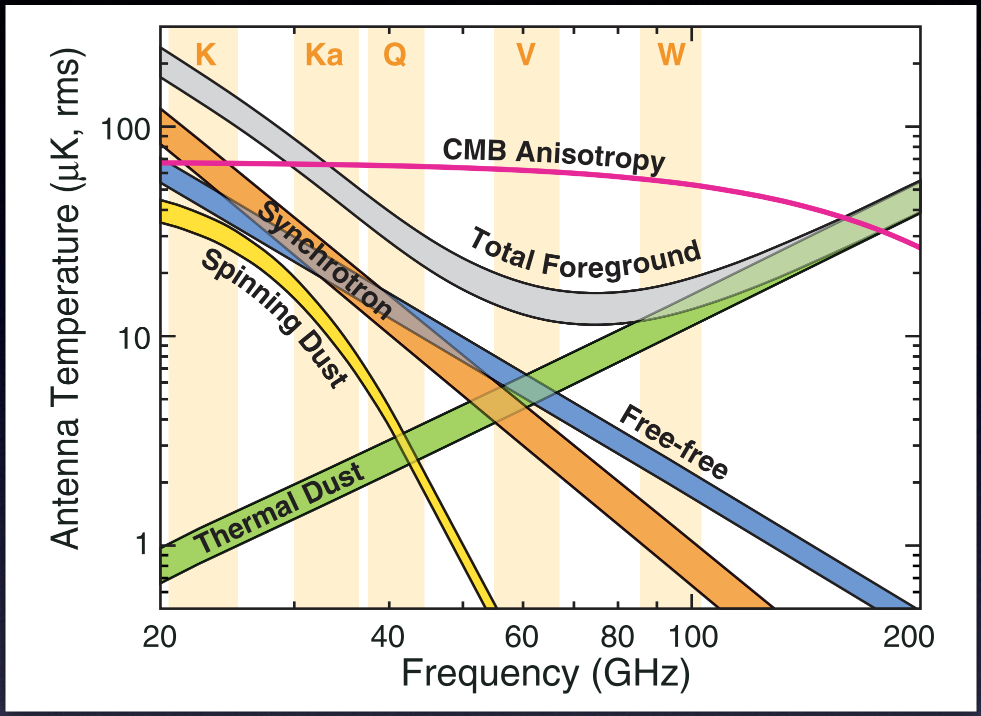
What could this be?

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

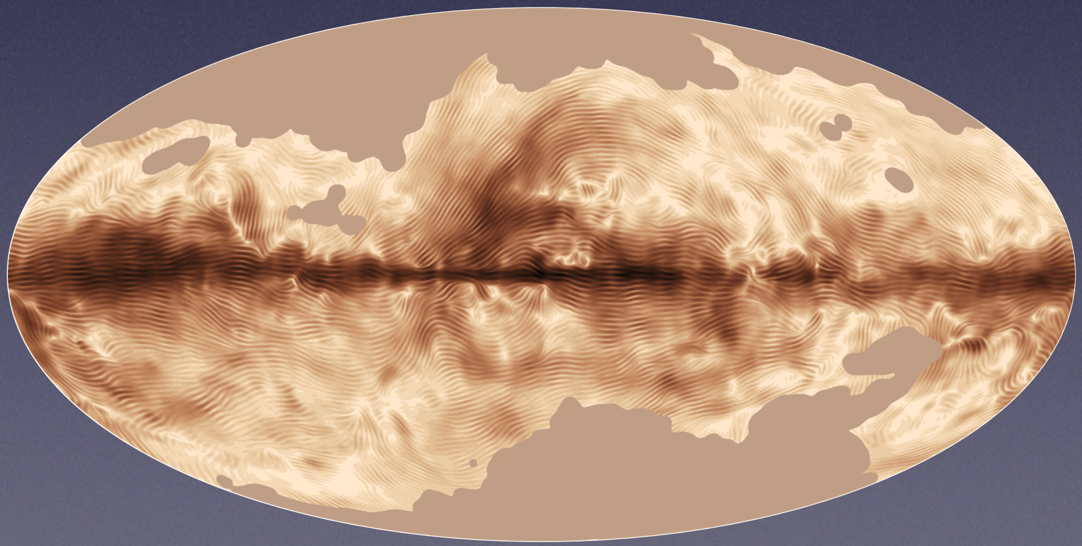
Polarized Foregrounds

Any polarized astrophysical emission between last scattering and us!

- **Synchrotron** "Red":~ ν^{-3}
- **Dust** "Blue": ~ $\nu^{+1.75}$
- **Point sources**



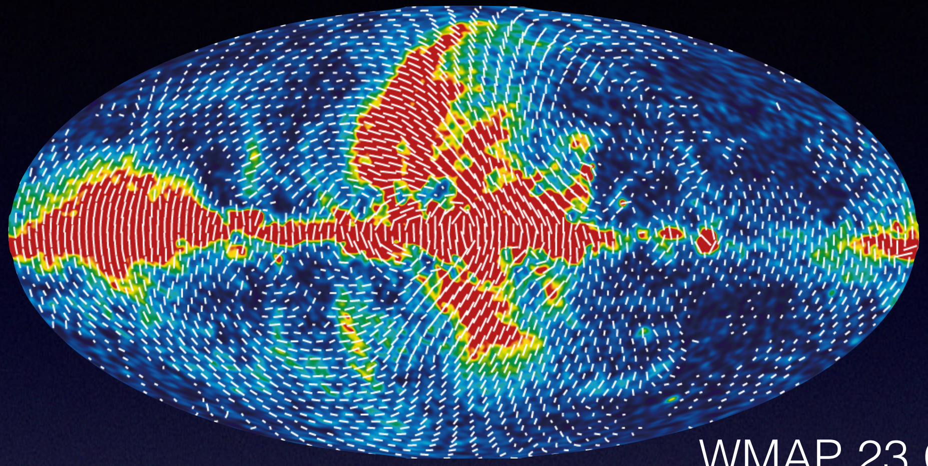
WMAP *unpolarized*



Planck 2014 magnetic field

Polarized Foregrounds

Any polarized astrophysical emission between last scattering and us!

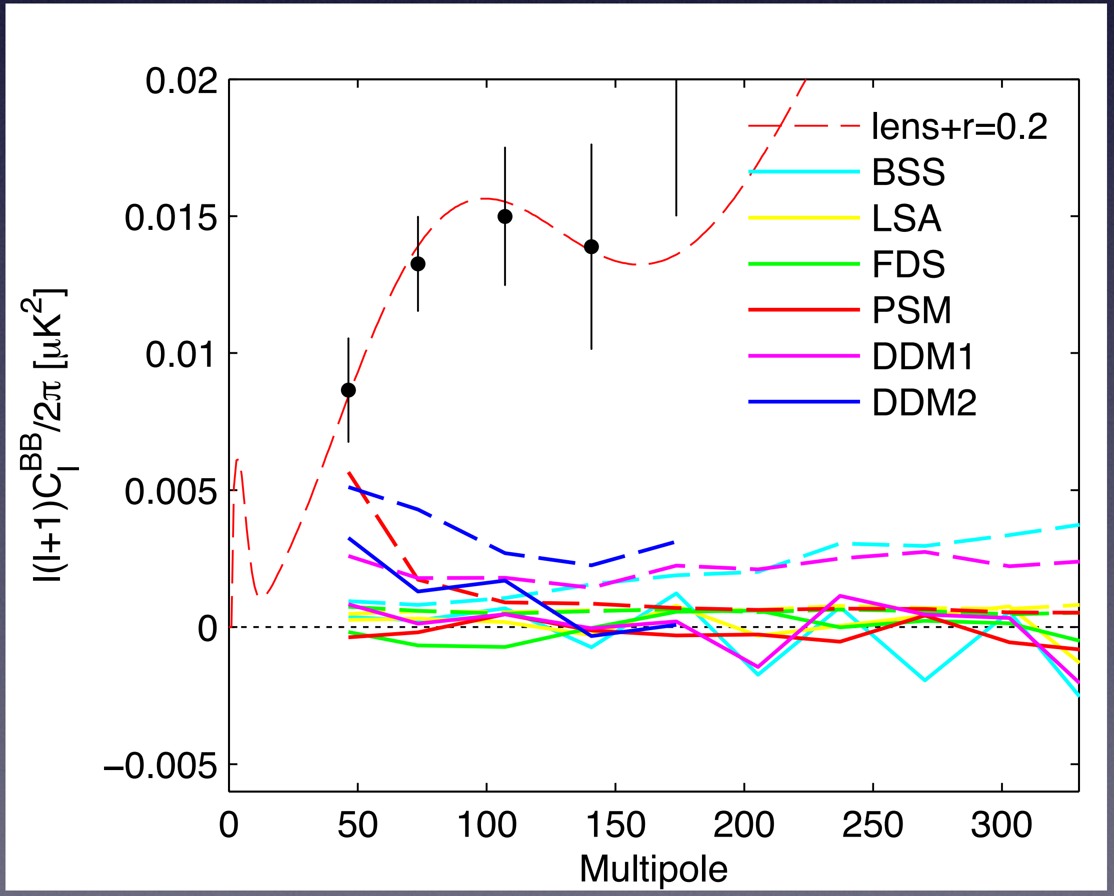


WMAP 23 GHz

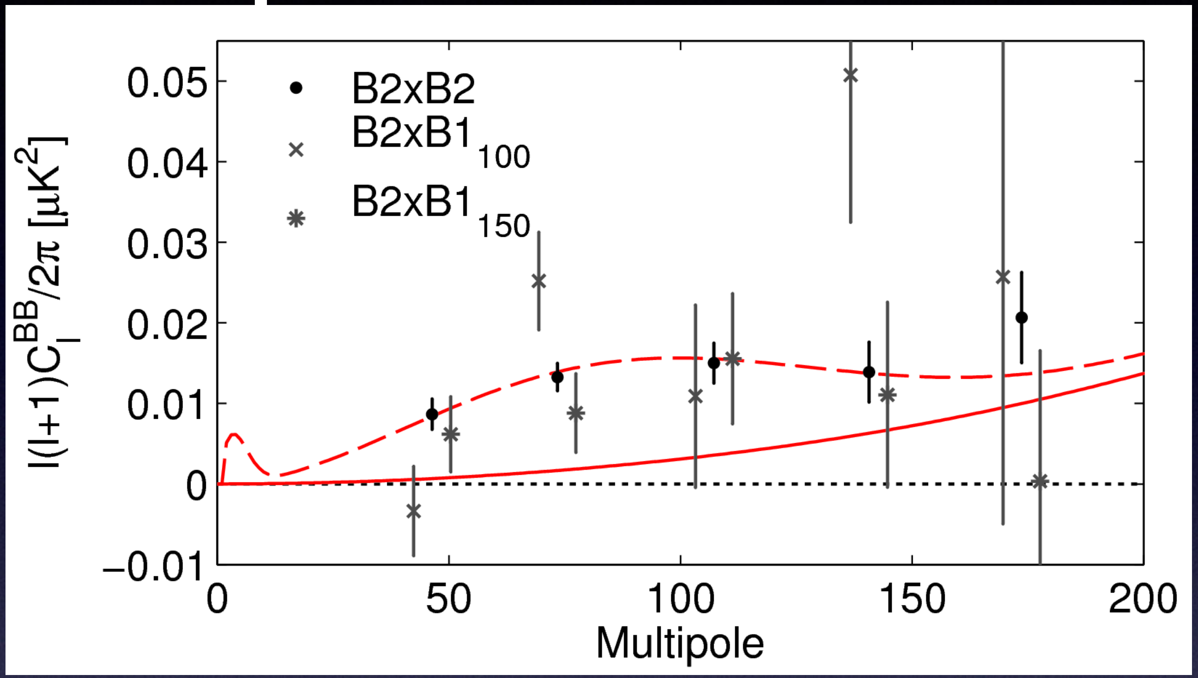
- **Synchrotron** "Red": ~ ν^{-3}
  No correlation with WMAP-K

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

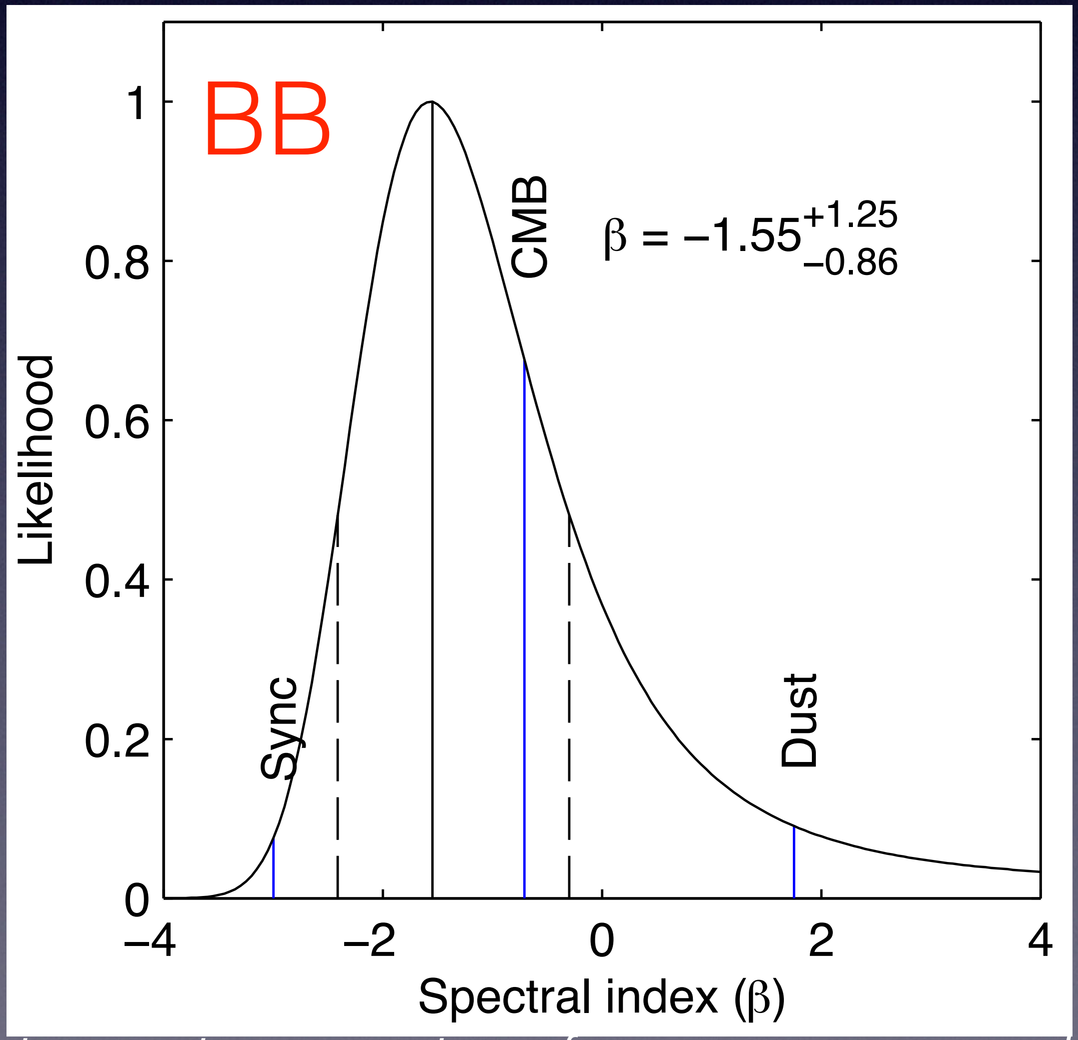
- **Point sources**
  No cross-correlation with source catalogs
  (Planck, ATCA)



Spectral Index Constraint



- **Consistent with CMB**, disfavor benchmark dust and sync models at **2.2**/**2.3σ**



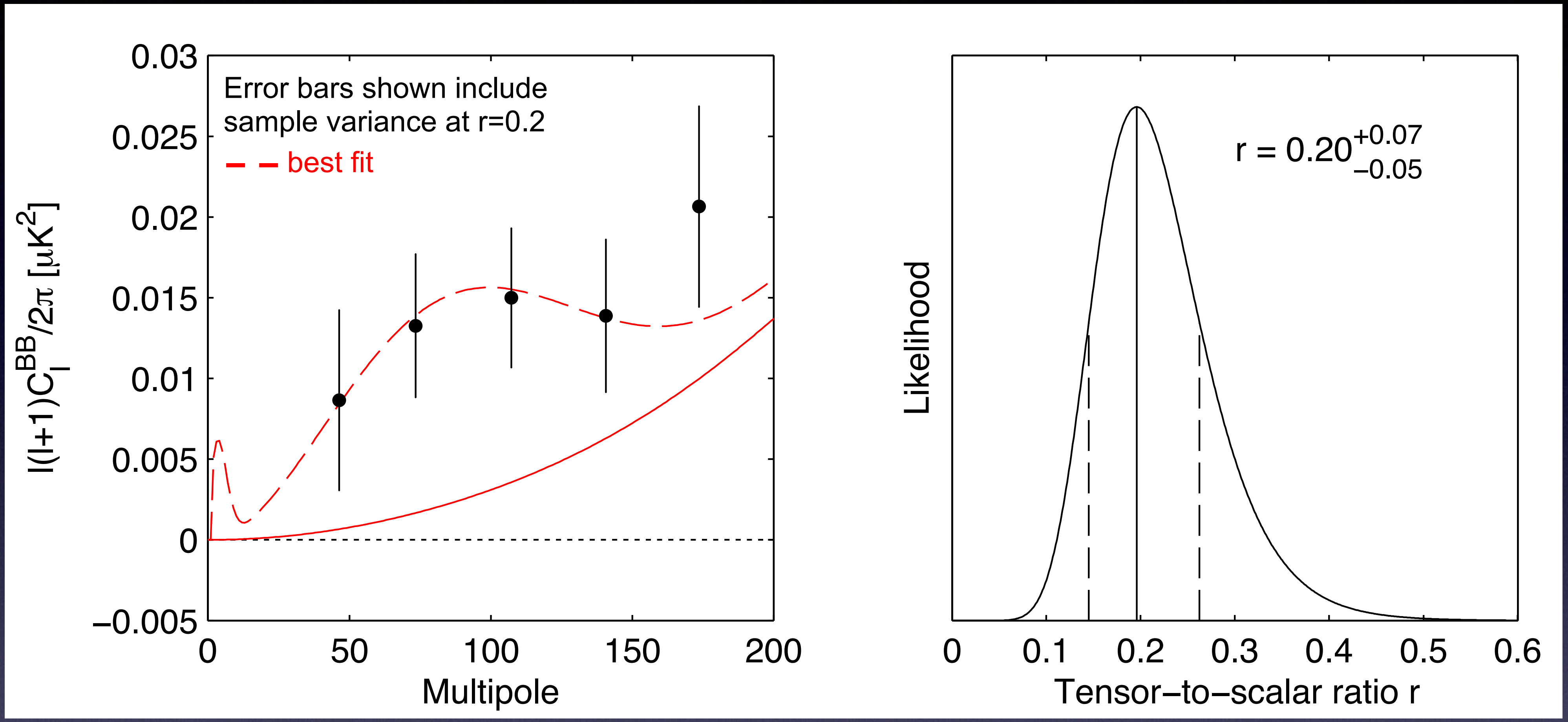
Antenna temperature frequency power law

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

What could this be?

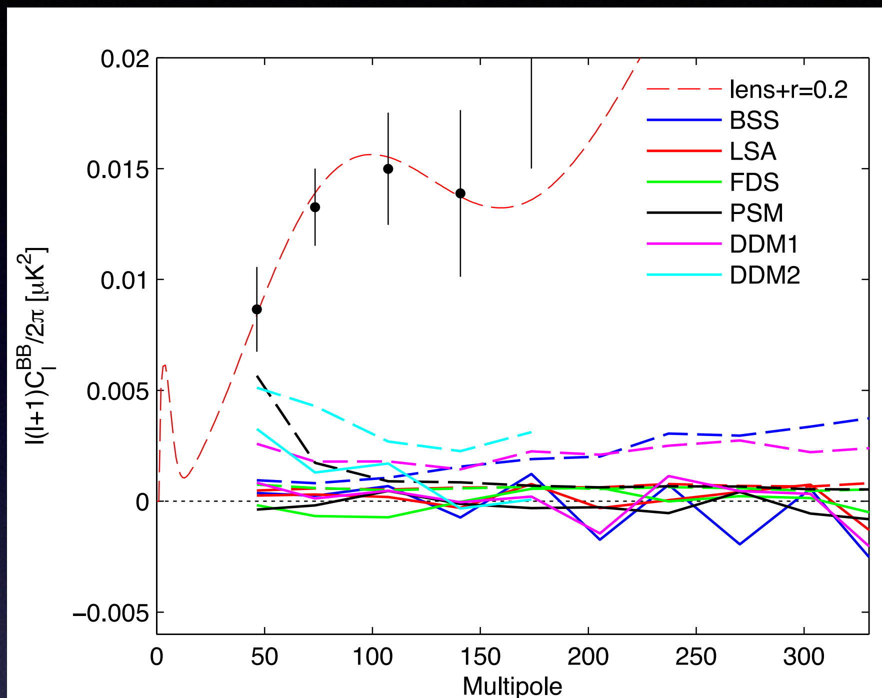
- Instrumental systematics?
- Galactic foregrounds?
- **Cosmology**

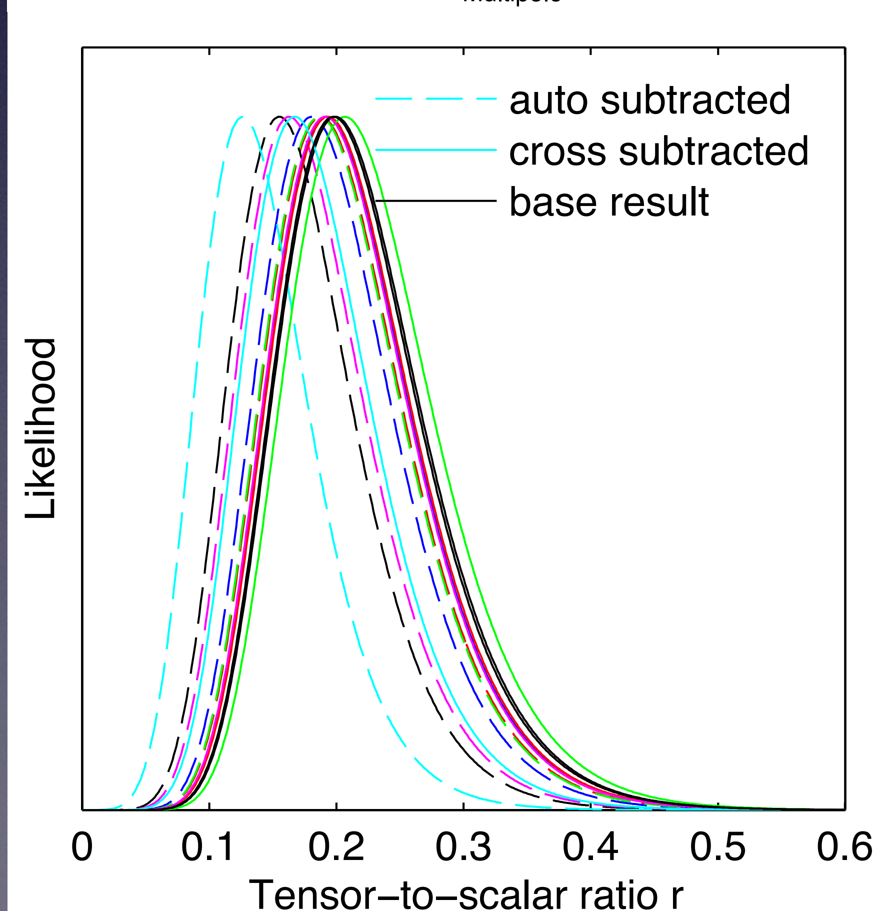
Constraint on Tensor/Scalar Ratio



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

Effect of Foregrounds



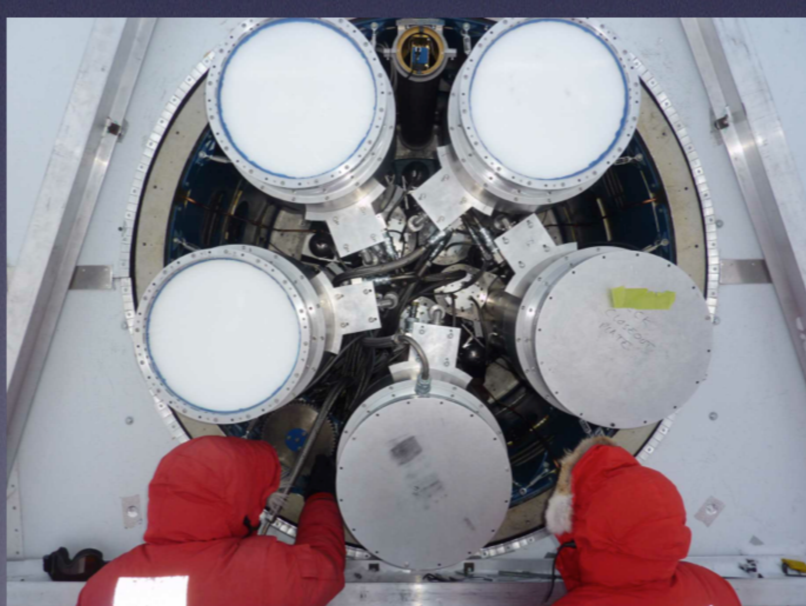


- Foregrounds could contribute small amount of observed BB
- Total power spectrum does not look like foreground expectations
- Subtracting DDM2 cross gives $r_{sub} = 0.16^{+0.06}_{-0.05}$
- … still disfavors r=0 at **5.9σ**
- Dust contributes most in the first band power. Deweighting this bin would give less deviation from our base result

What next?

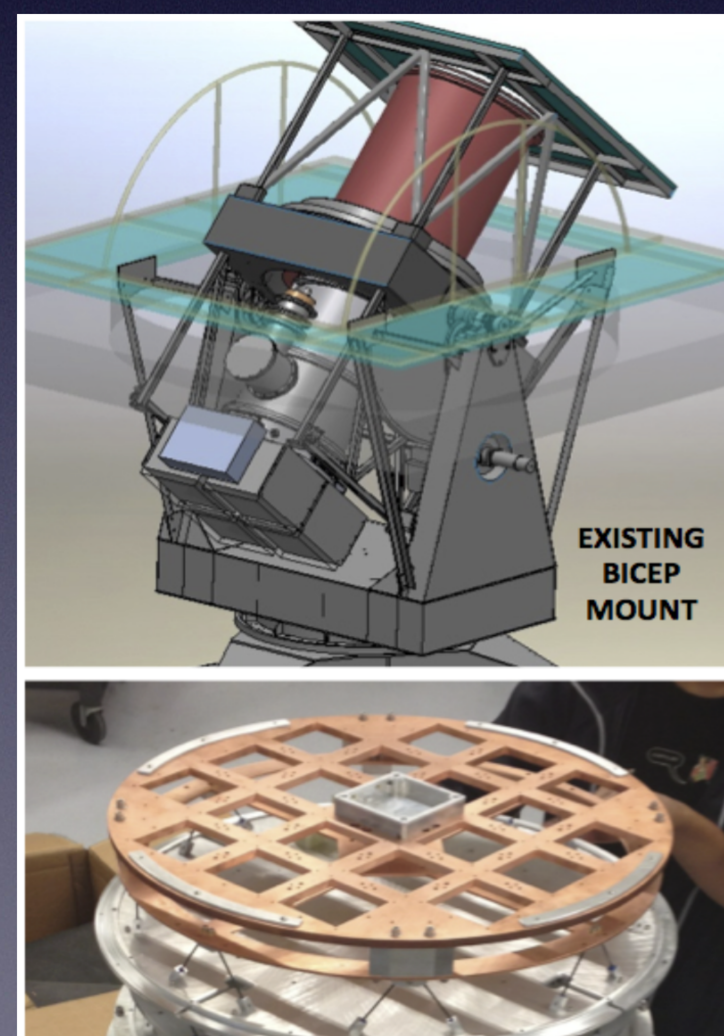
KECK ARRAY

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



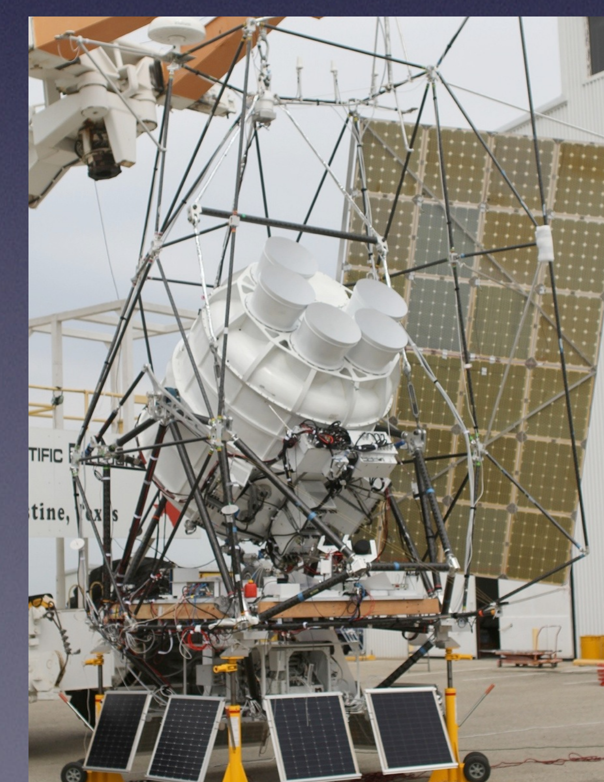
BICEP3

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

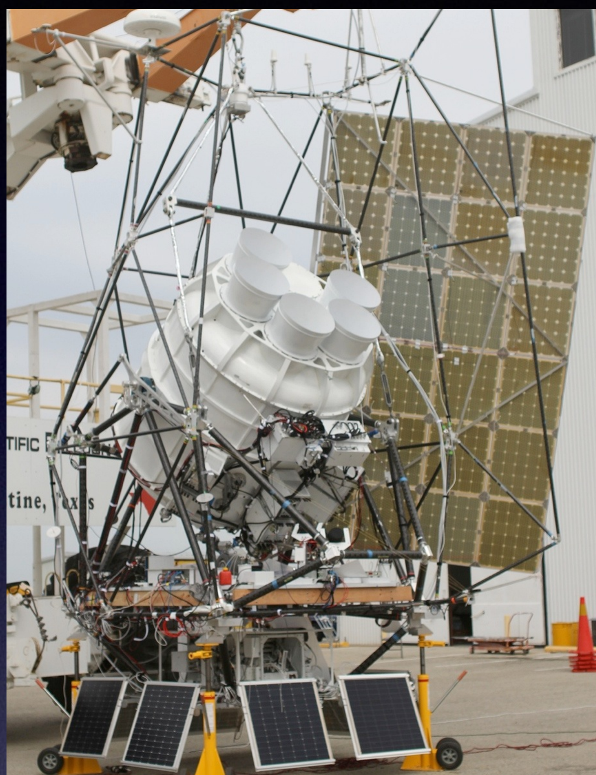


SPIDER

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

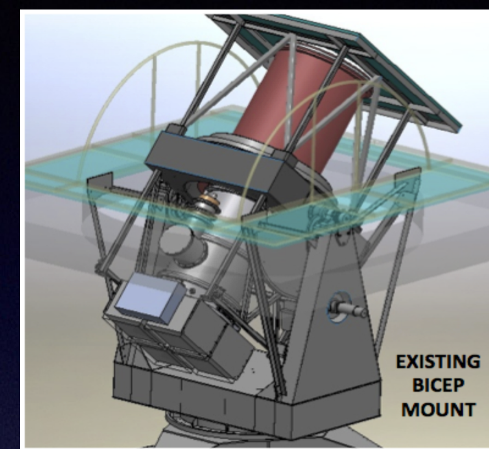


A Rich Field



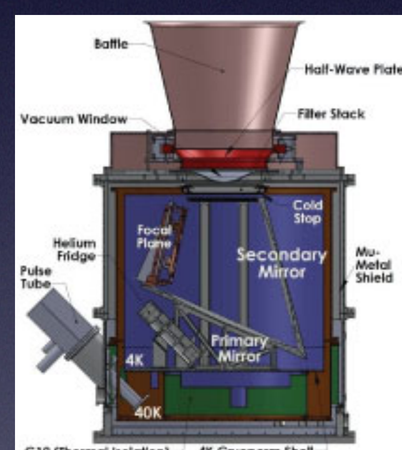
SPIDER

Keck Array

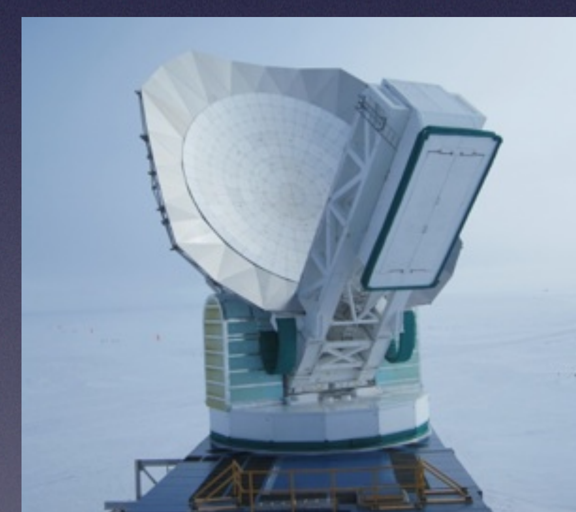


BICEP3

EBEX

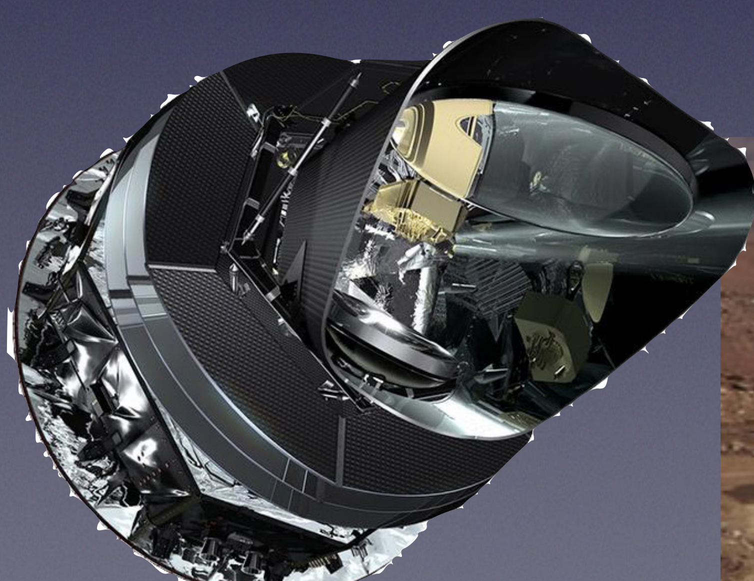


ABS



SPTpol

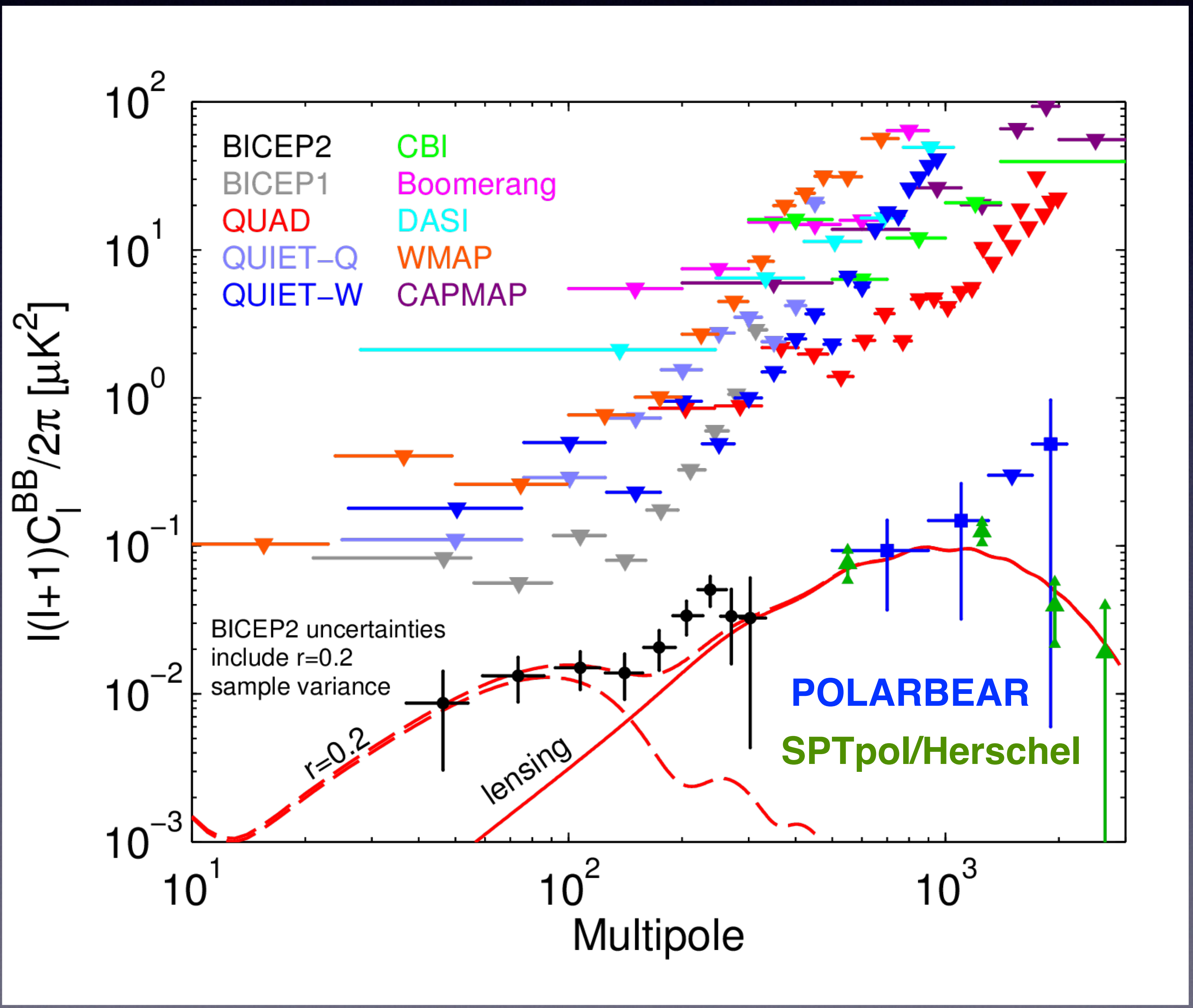
POLARBEAR



Planck

ACTpol

Conclusions



- BICEP2 observes **5.3σ excess** above lensed-ΛCDM; r=0 disfavored at **7σ** (no foreground subtraction)
    - Extensive studies disfavor systematic error as origin
    - Foregrounds do not appear to constitute the bulk of the signal
- Consistent with expectations for primordial gravitational waves from GUT-scale inflation
- The era of B-mode cosmology has begun!