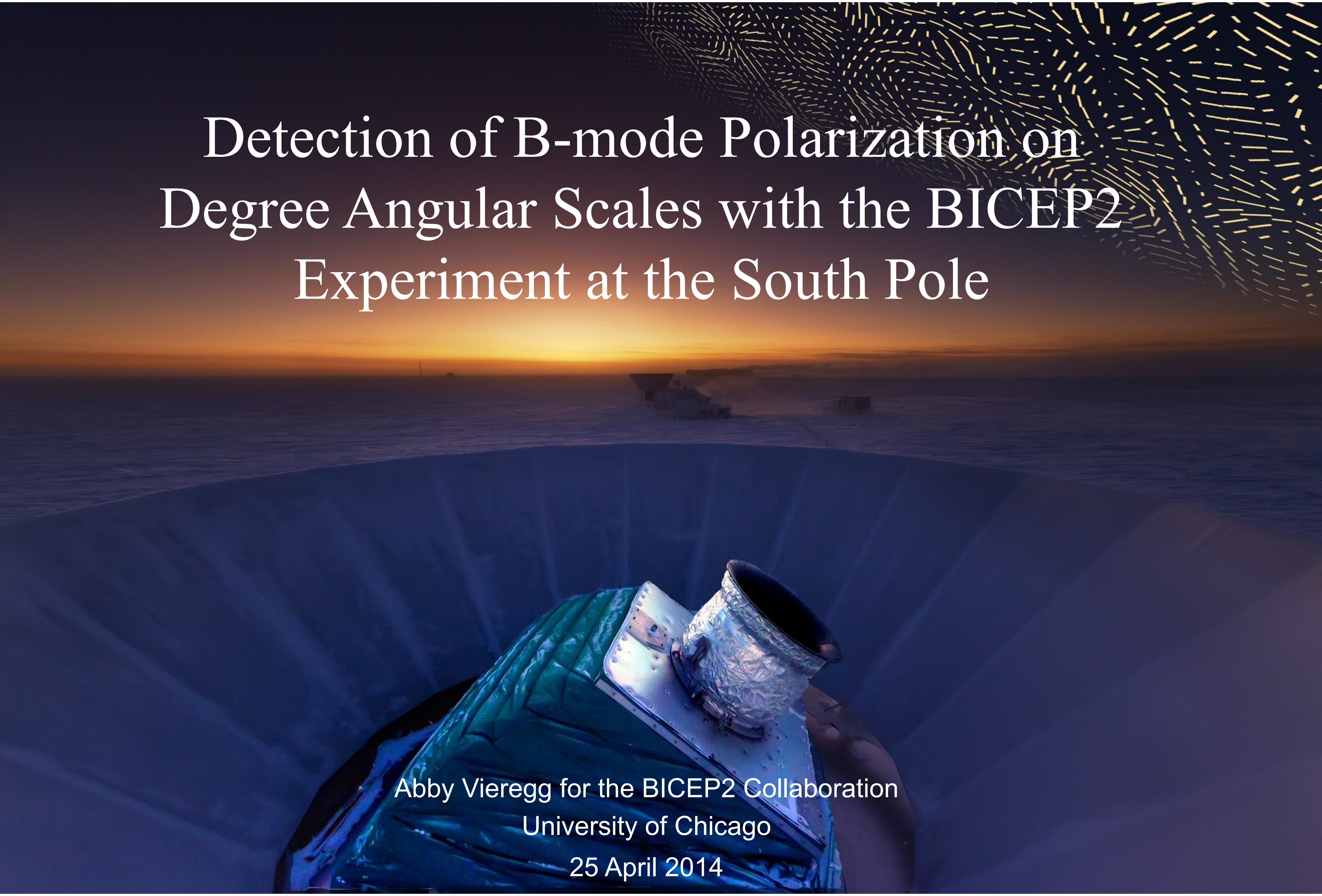
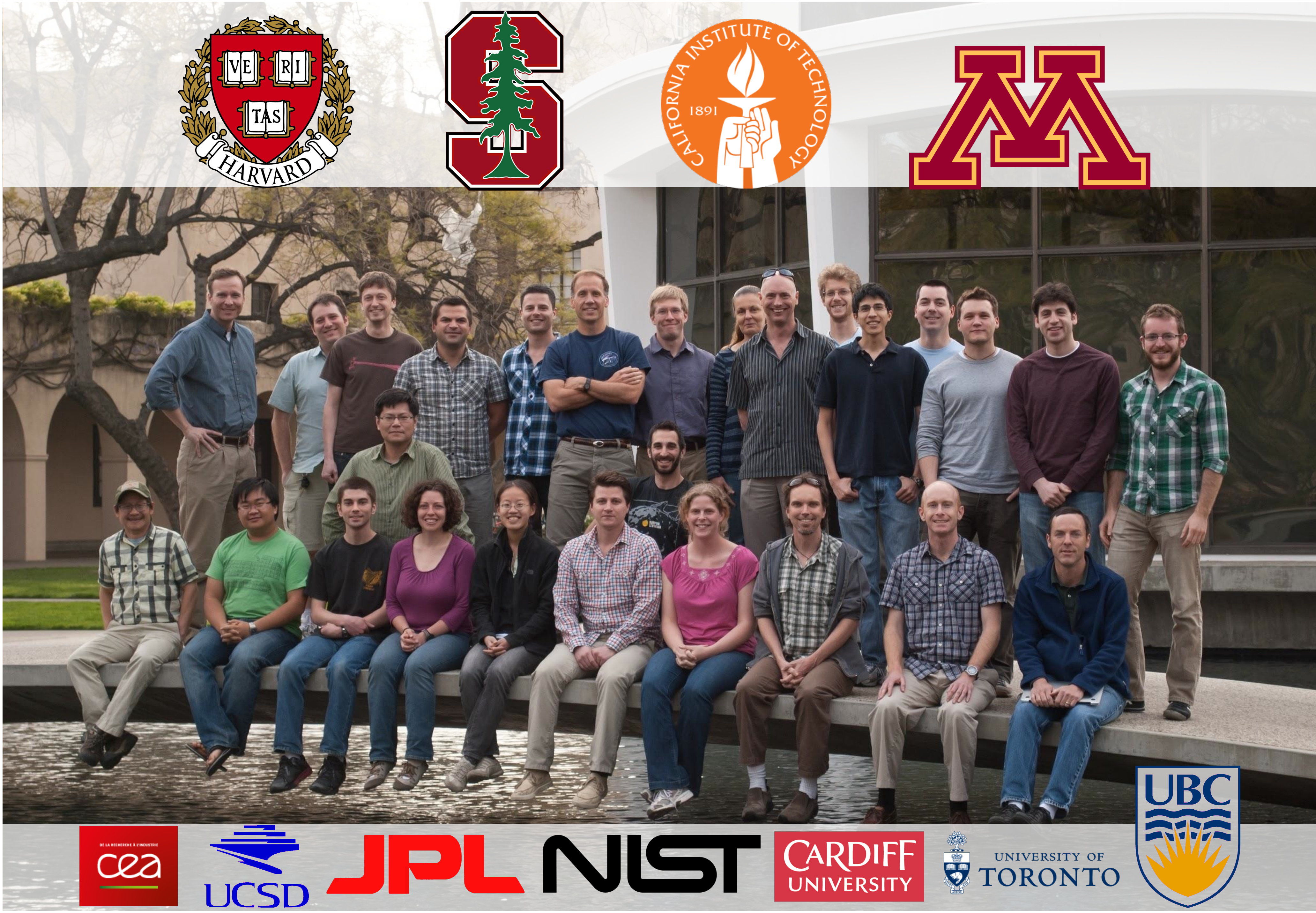
Detection of B-mode Polarization on Degree Angular Scales with the BICEP2 Experiment at the South Pole



Abby Vieregg for the BICEP2 Collaboration
University of Chicago
25 April 2014


VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
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UCSD
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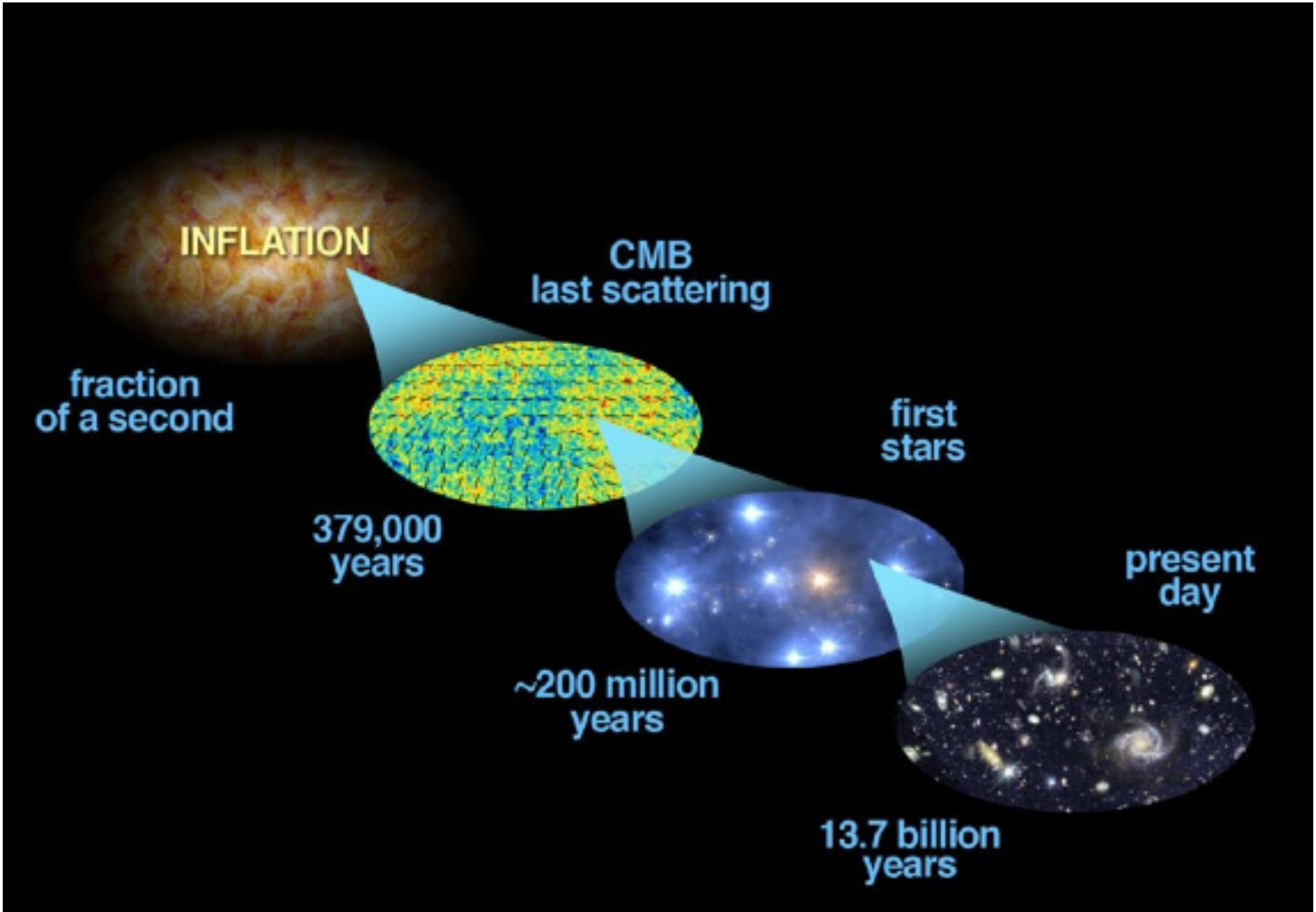
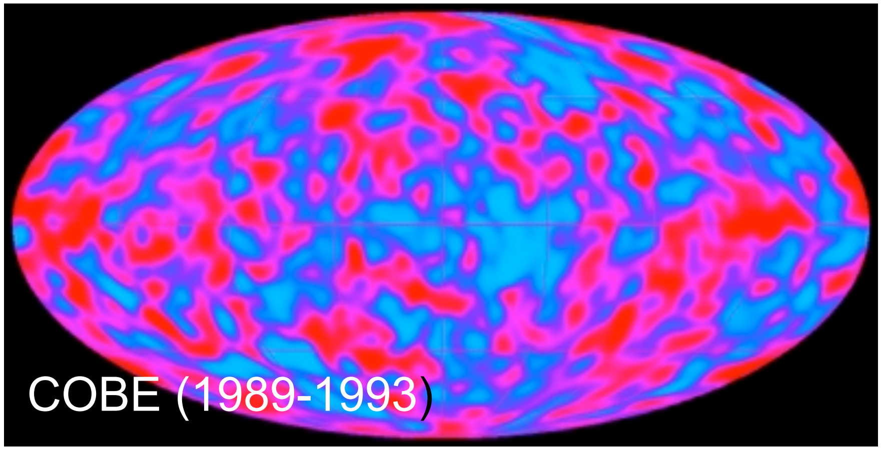
NIST
CARDIFF
UNIVERSITY
UNIVERSITY OF
TORONTO
UBC

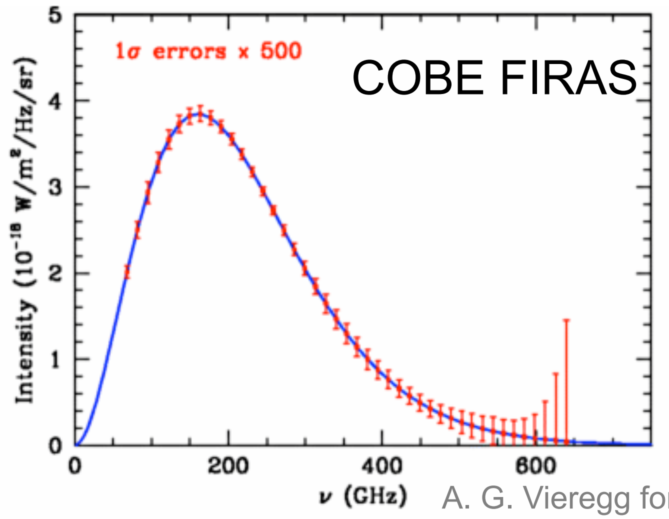


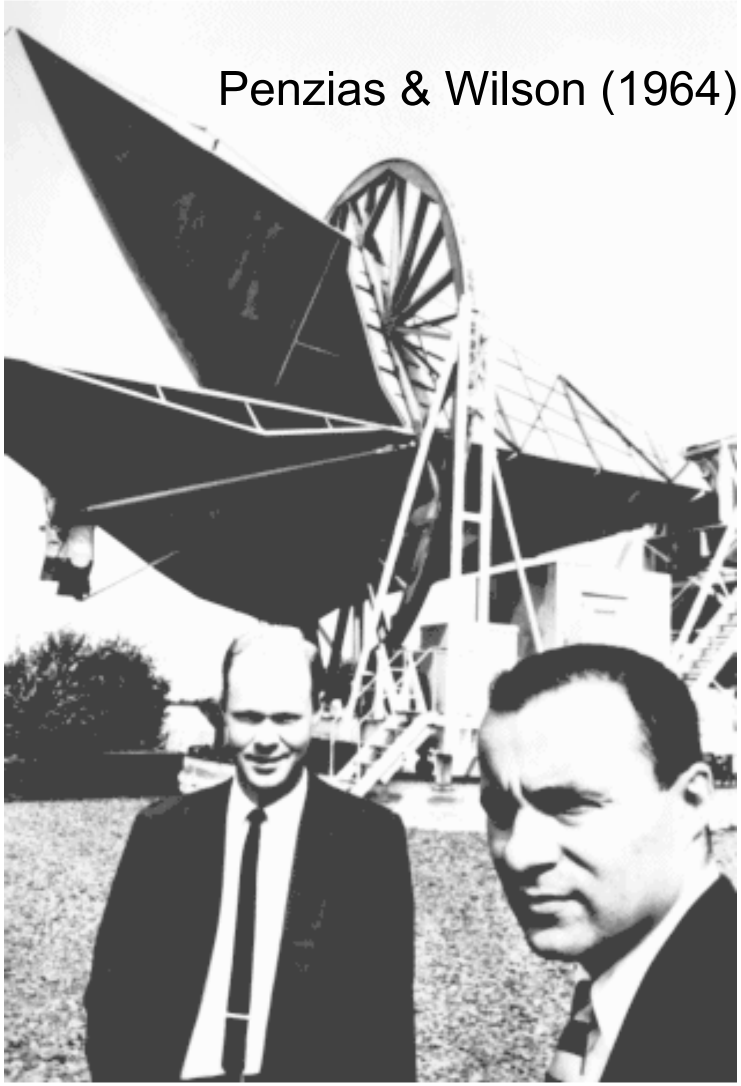
NASA/WMAP Team

Early CMB Observations

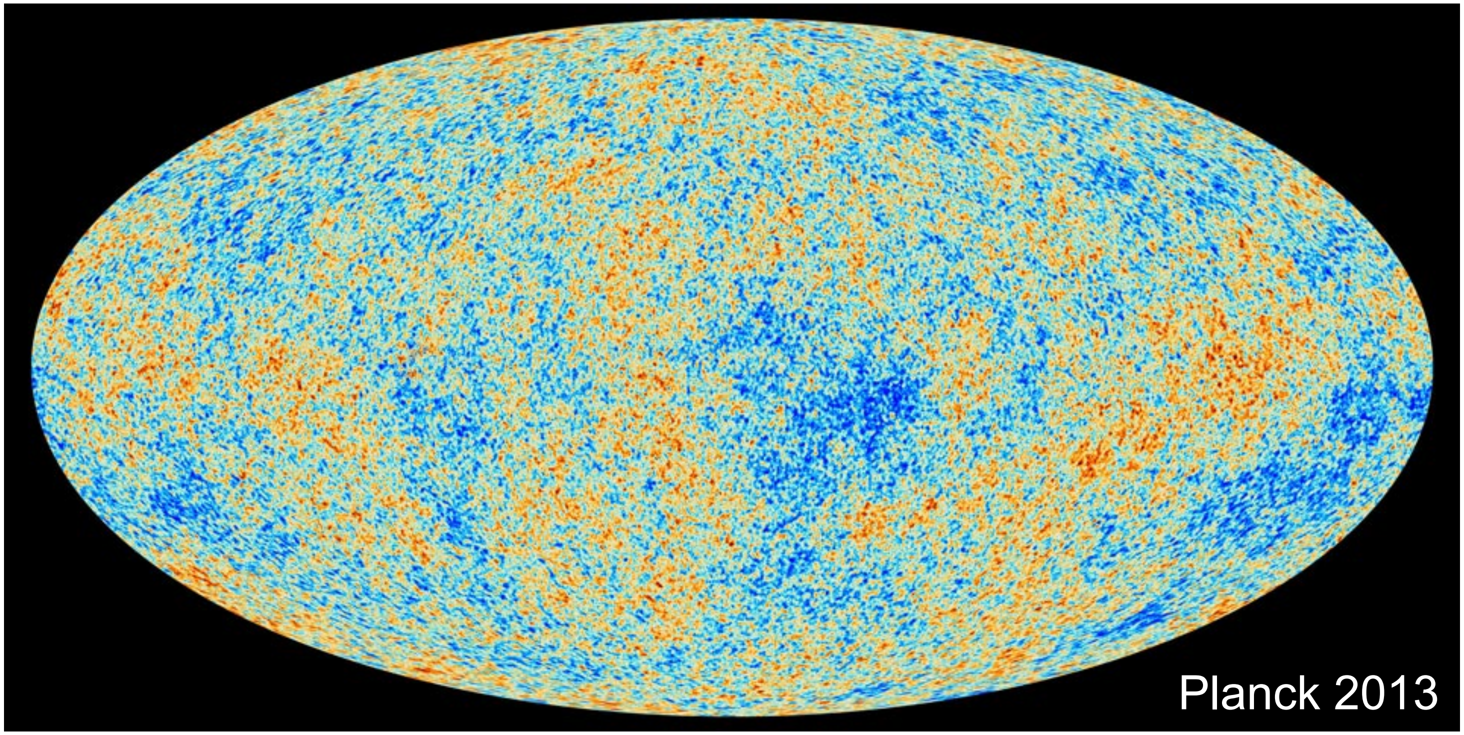
- Discovery of 2.7K background → 1978 Nobel Prize
- Observation of Anisotropy & Blackbody spectrum → 2006 Nobel Prize







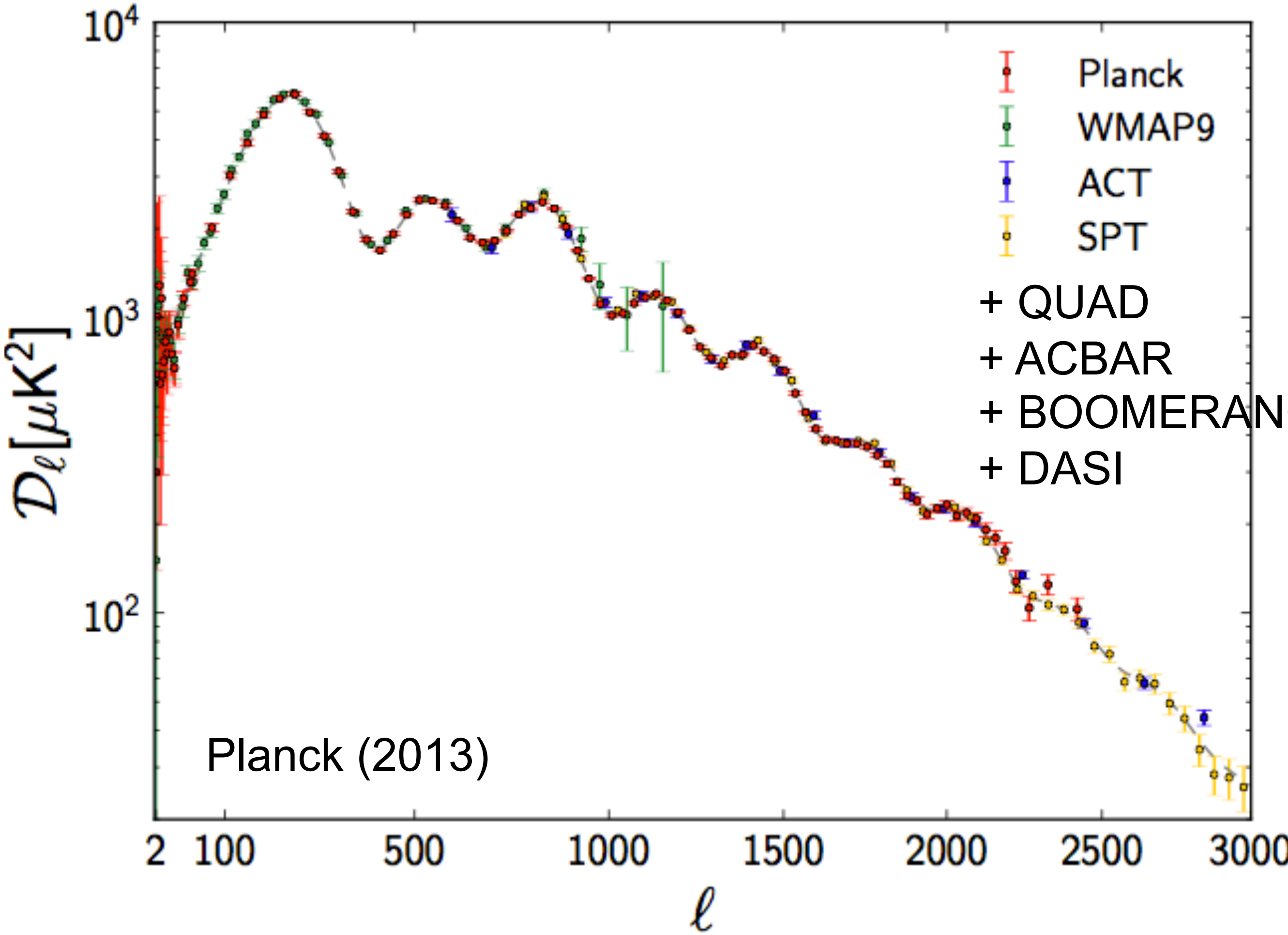
Our Universe As Told By Its Oldest Light



- Universe Initial Conditions – Seeds of Structure
- Age of the Universe – 13.8 Gyr
- Geometry of the Universe - Flat
- Baryon (5%) / Dark Matter (27%) / Dark Energy (68%) Composition – Λ_{CDM}
- Plus much more

CMB Temperature Spectrum

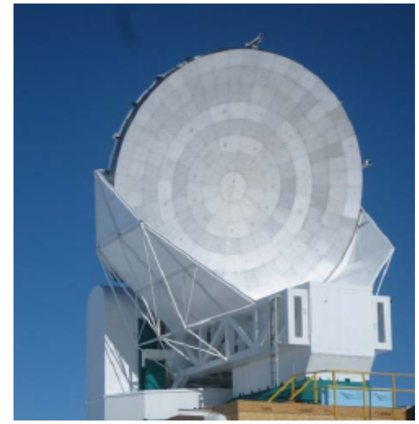
Fourier transform of the CMB temperature map

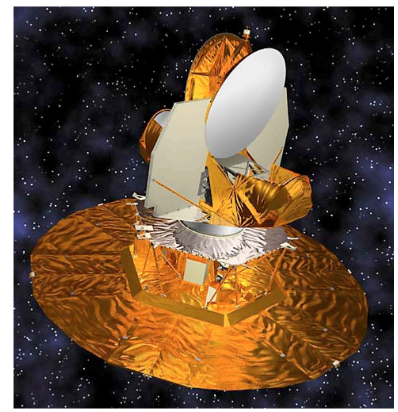


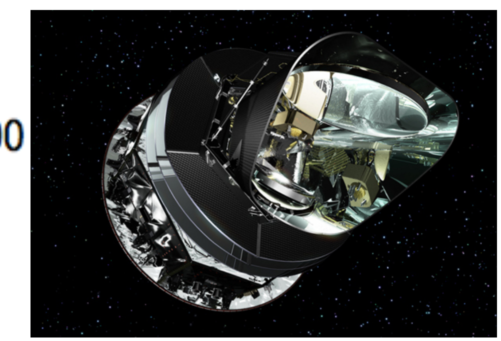
+ QUAD
+ ACBAR
+ BOOMERANG
+ DASI

(Amplitude of Fourier Mode)

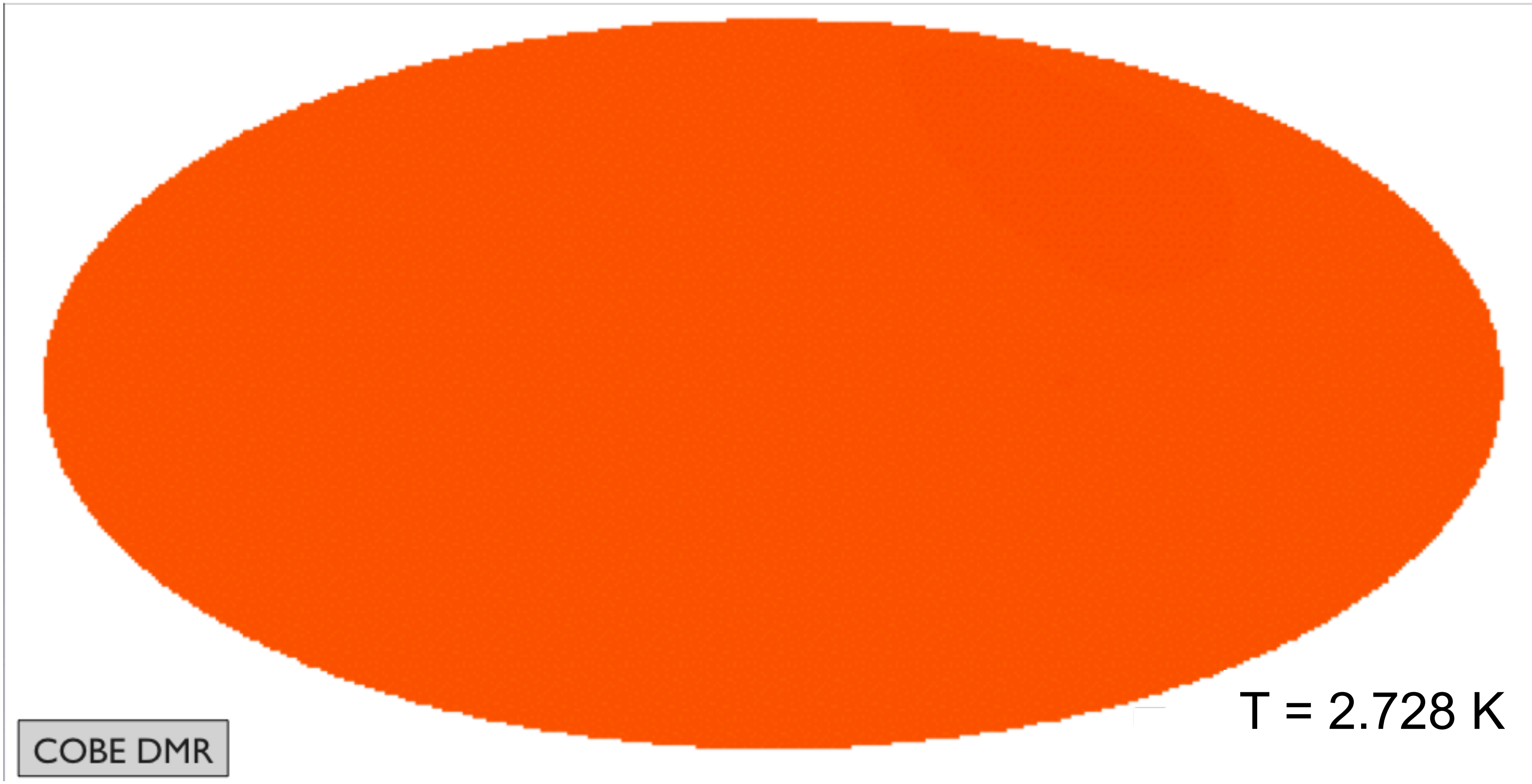
(Angular Scale)





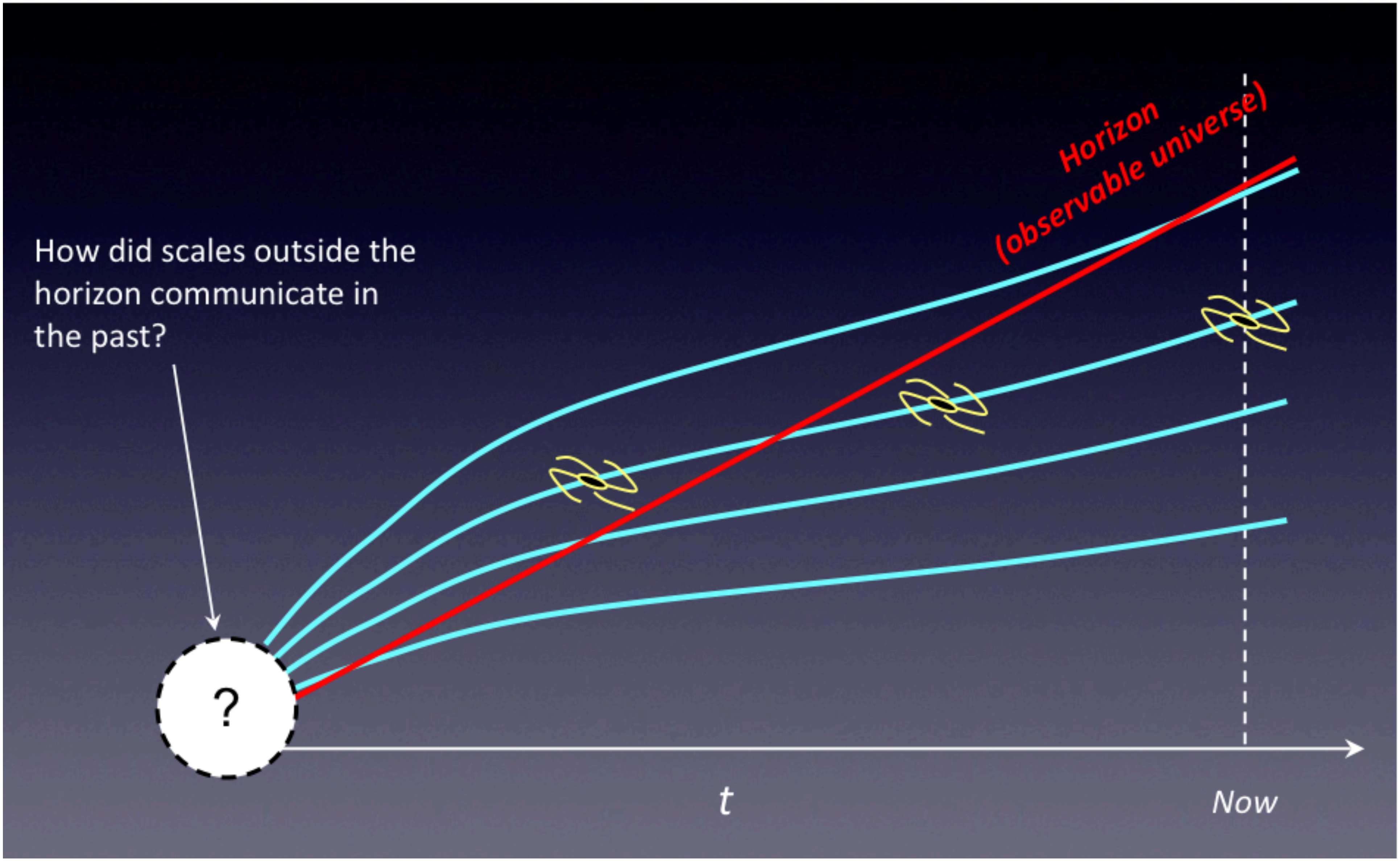


The Horizon "Problem"

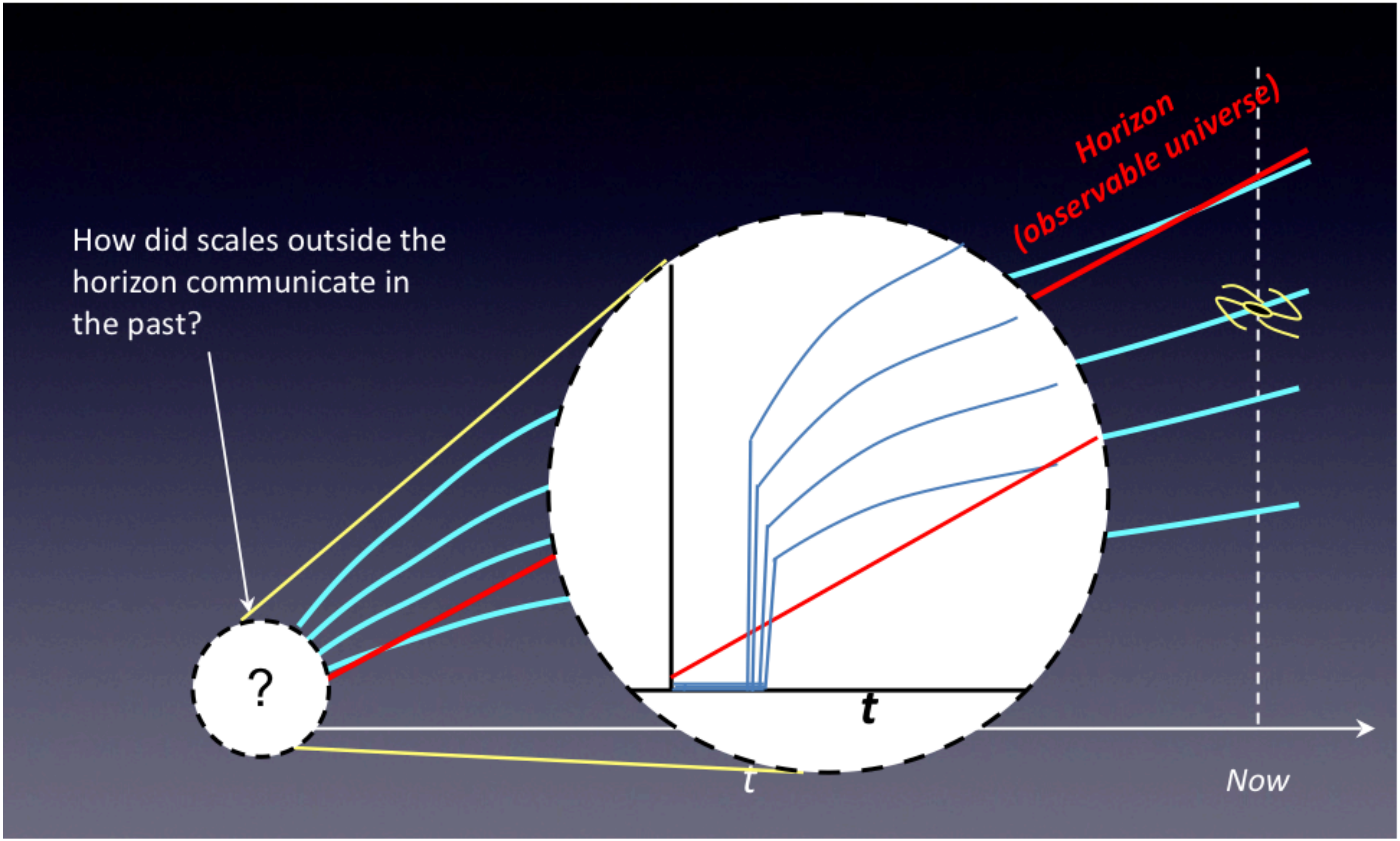


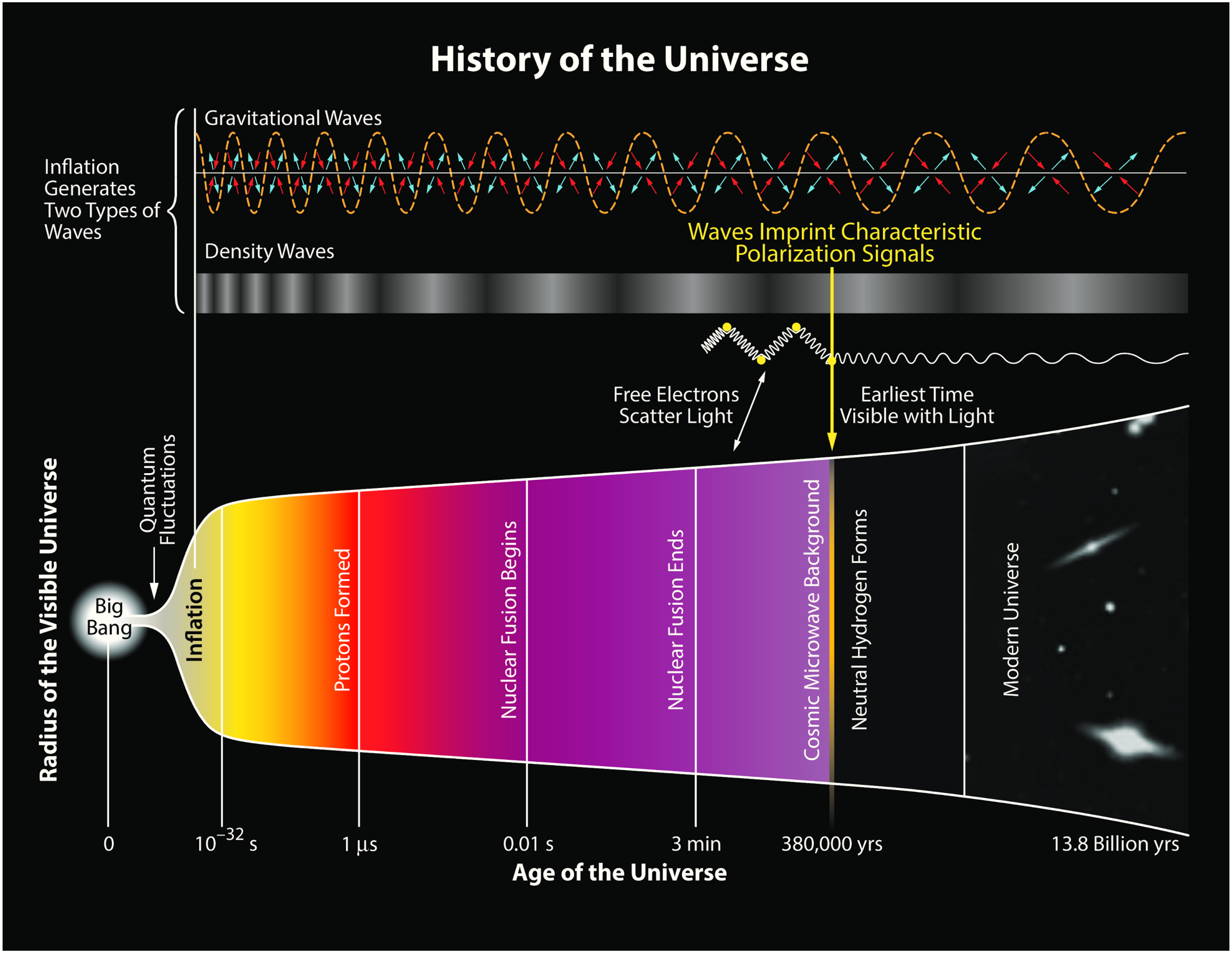
Homogeneous, isotropic, spatially flat, ….

The Horizon "Problem"

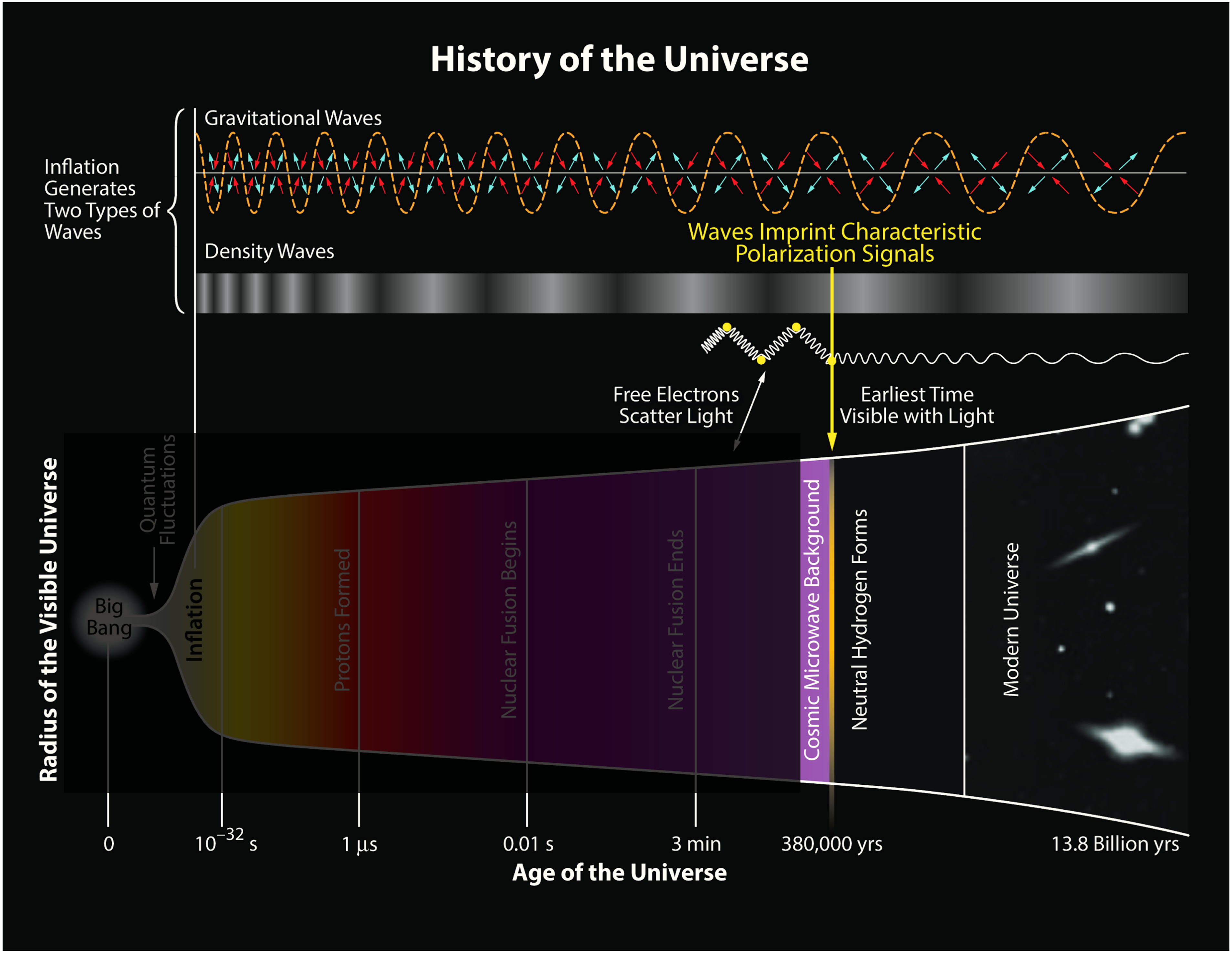


Inflation: The Real Big Bang





History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe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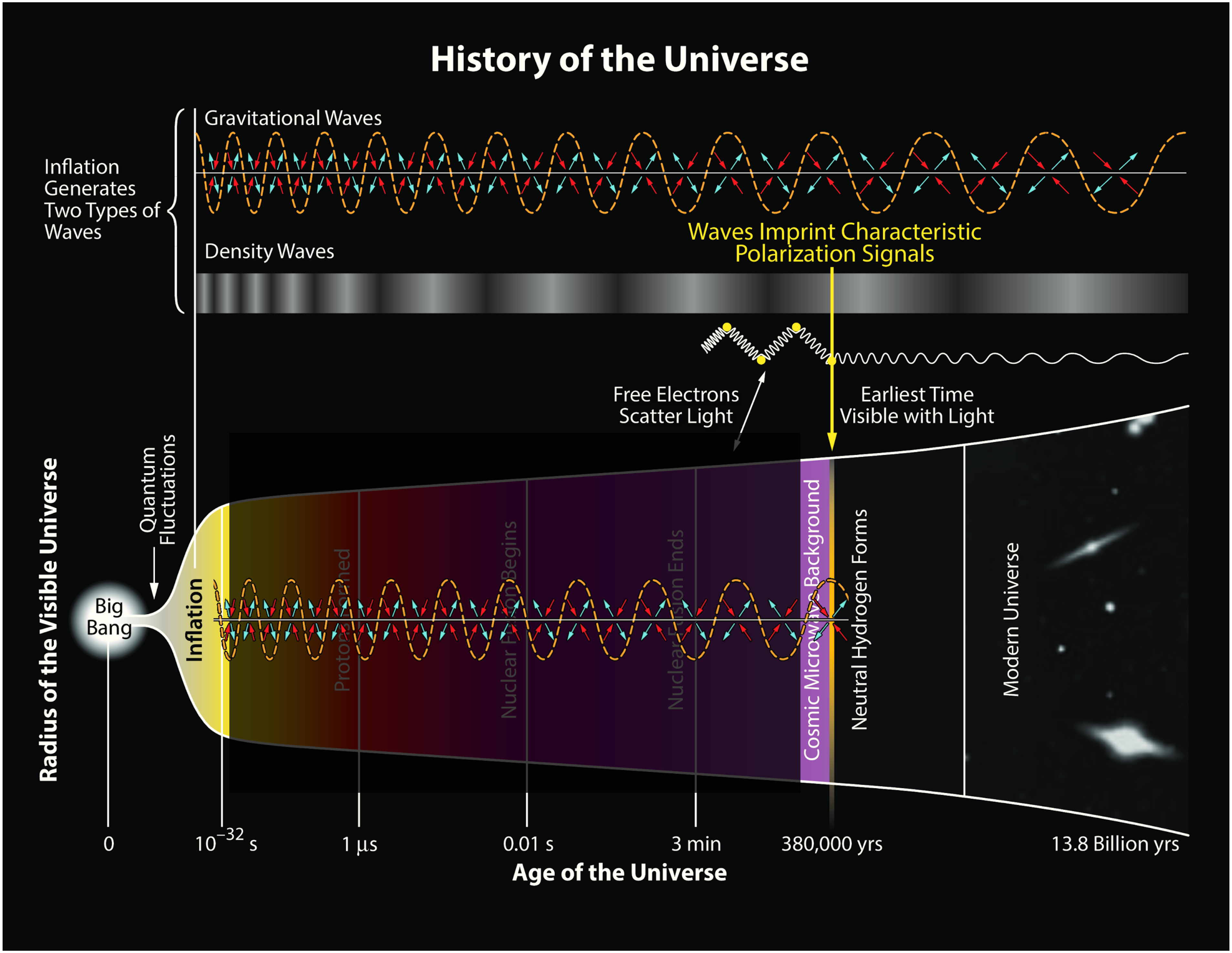

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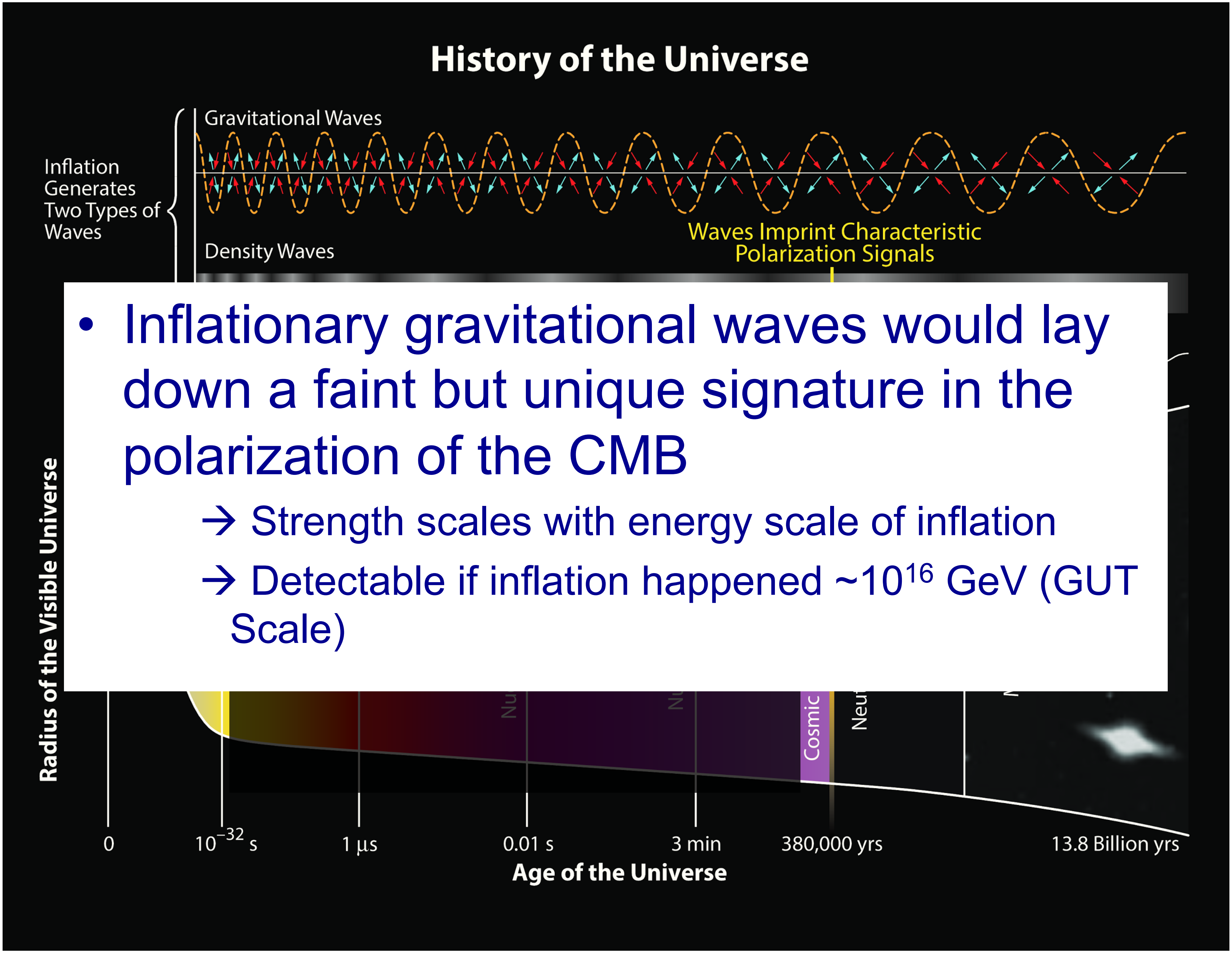
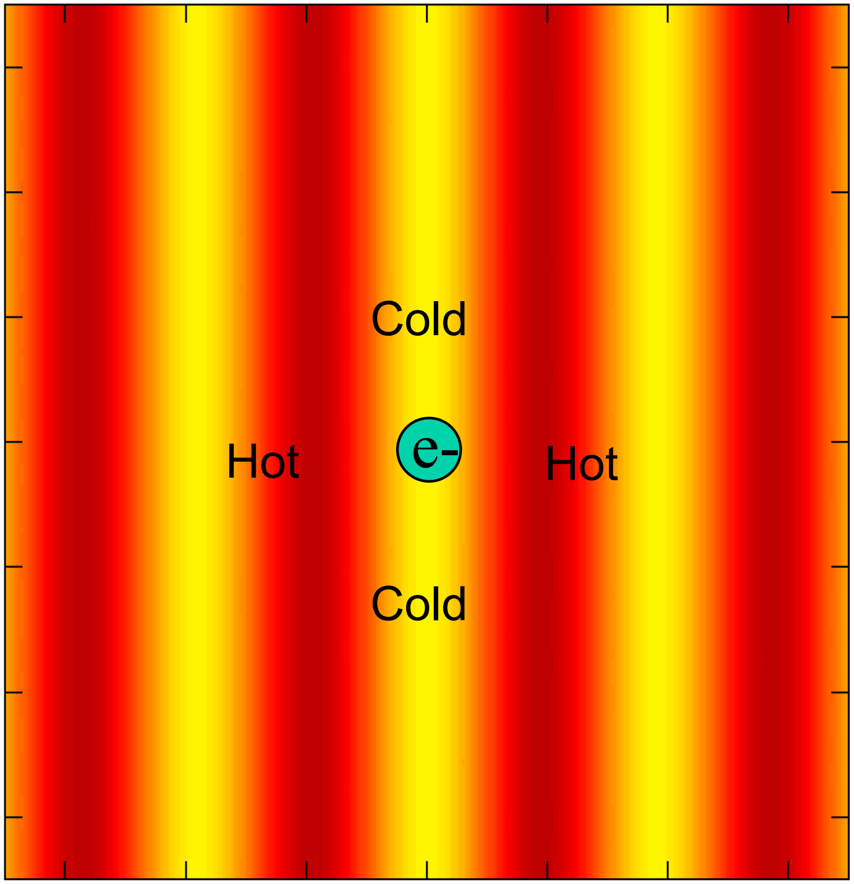


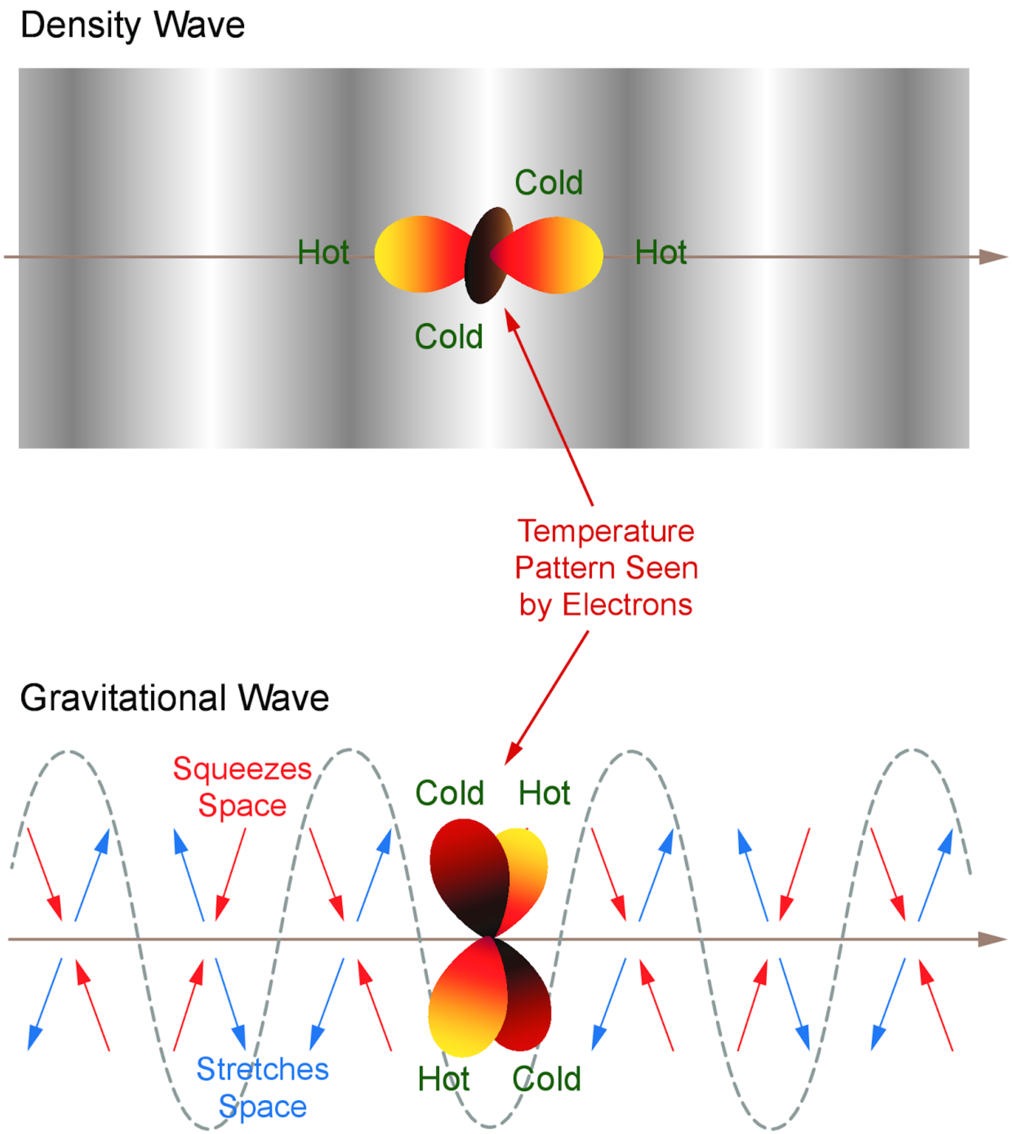
- Inflationary gravitational waves would lay down a faint but unique signature in the polarization of the CMB
  - → Strength scales with energy scale of inflation
  - → Detectable if inflation happened ~10^{16} GeV (GUT Scale)

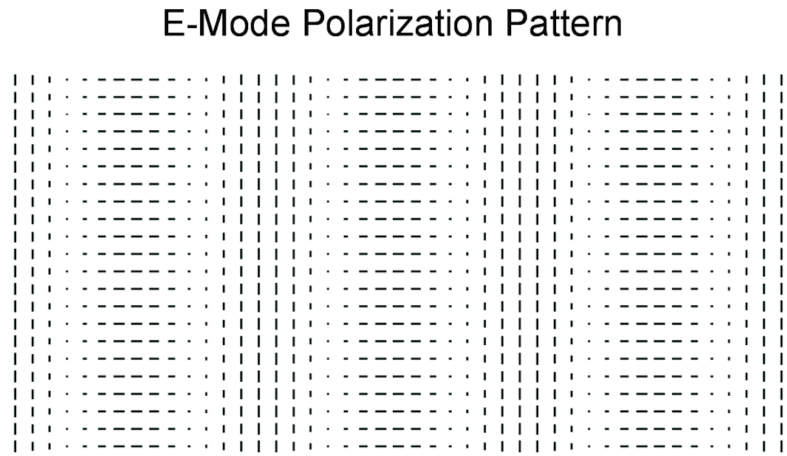
Why is the CMB Polarized?

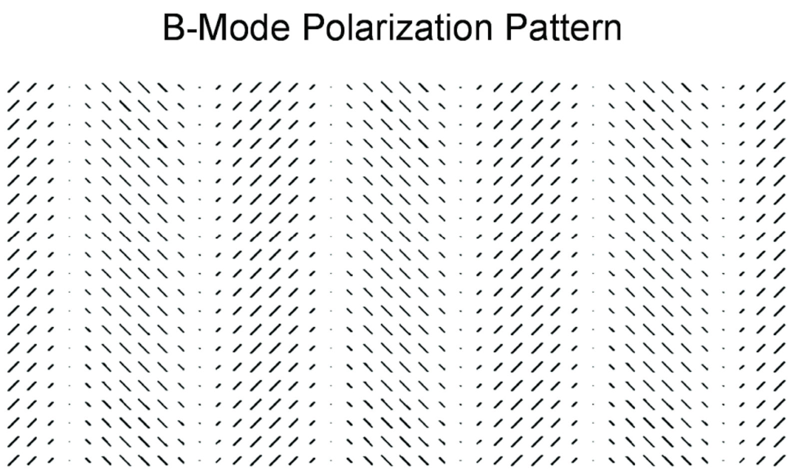
- Thomson scattering cross section depends on polarization
- Quadrupole anisotropy (as seen by electron) @ last scattering → net linear polarization



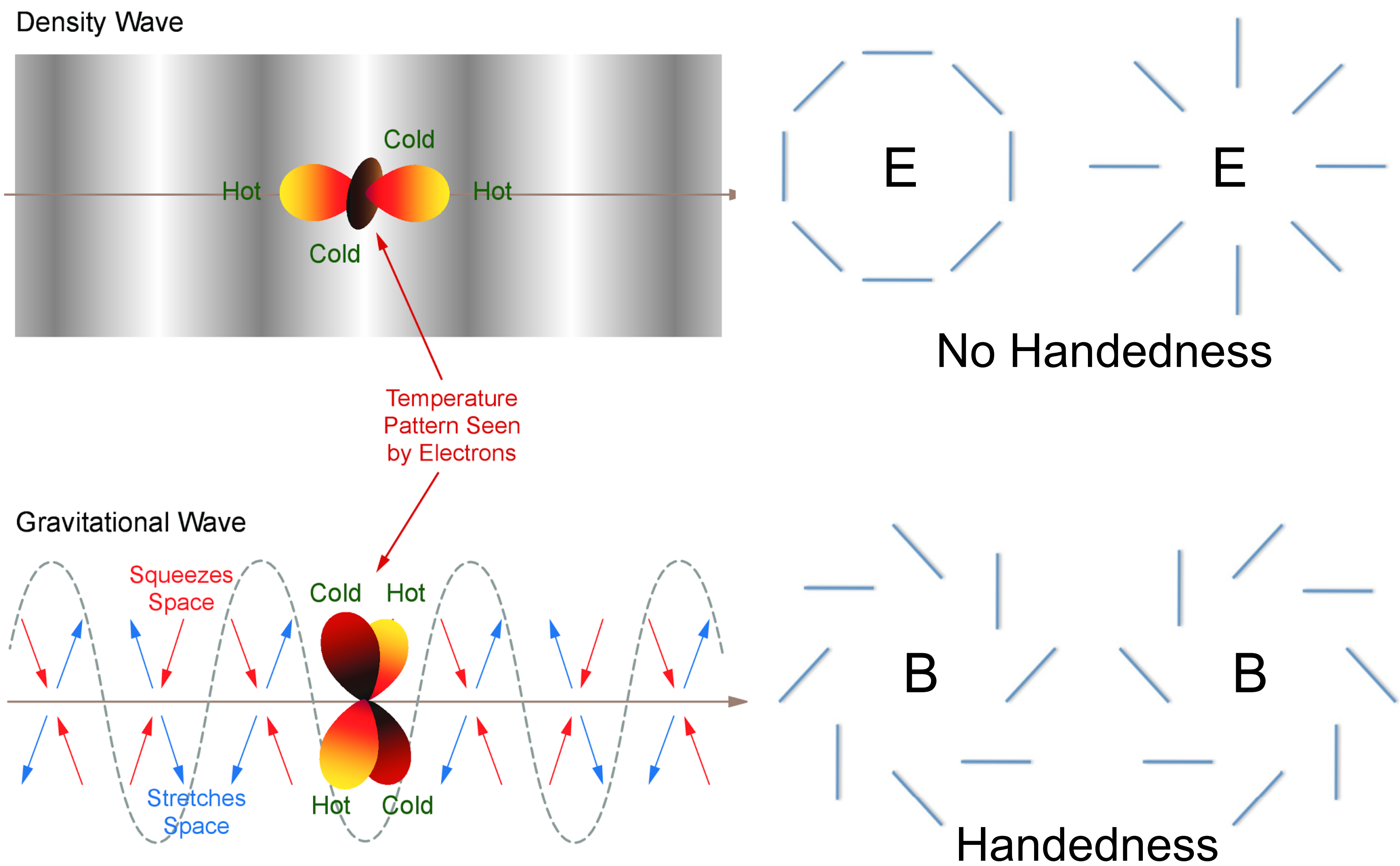
E-Modes & B-Modes



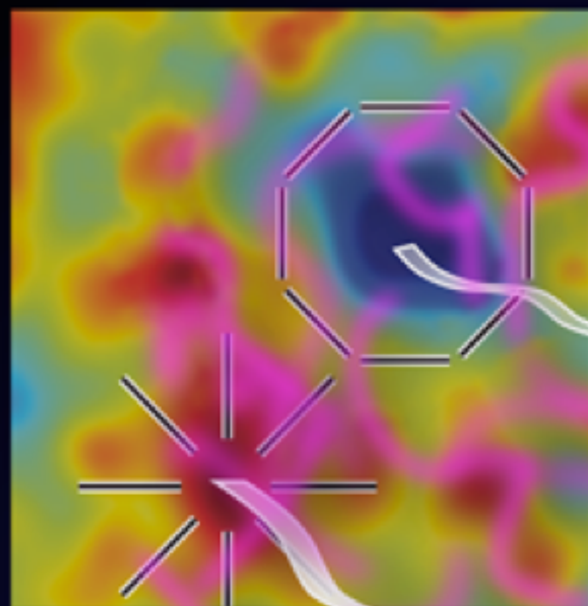


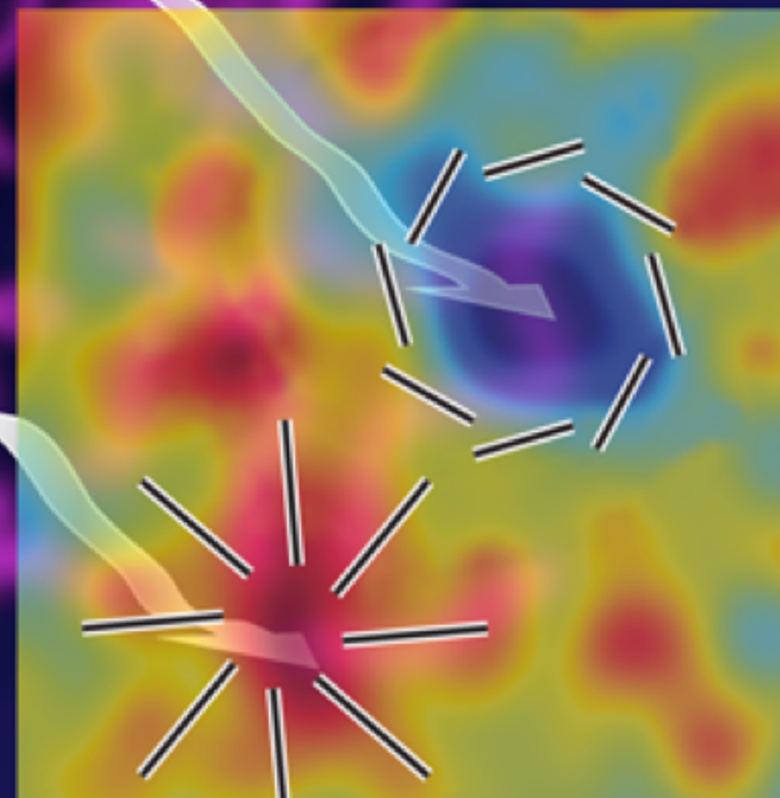


E-Modes & B-Modes



Gravitational Lensing: Converting E to B





- Gravitational lensing deflects CMB photon trajectory
- Twists E-modes to have some component of B-modes
- Lensing B-modes detected by SPT and PolarBEAR in 2013

$$\hat{n} \rightarrow \hat{n} + \nabla\phi(\hat{n})$$

Features of the CMB Spectrum

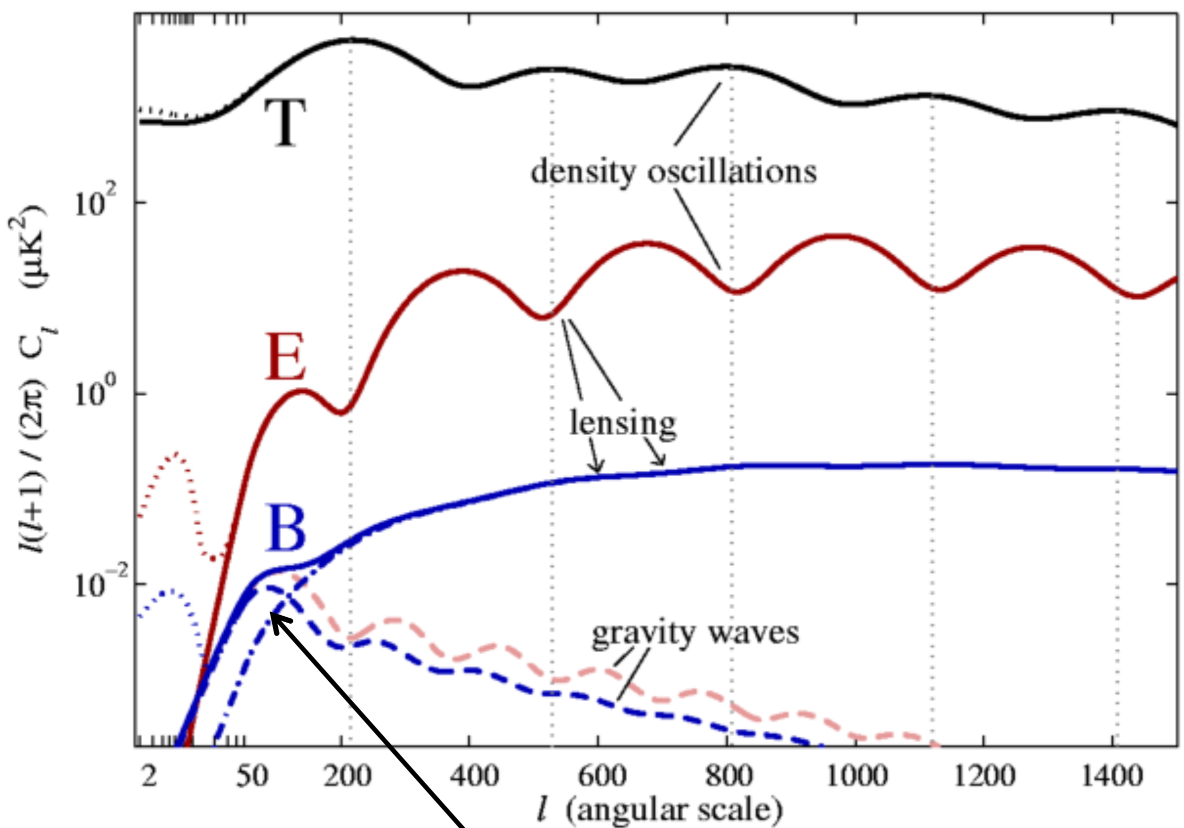
Temperature spectrum traces density evolution of acoustic oscillations in early universe.

E-polarization spectrum (first measured by DASI, Kovac et al. 2002) :

- 10^2 lower
- correlated with T but out of phase

B-polarization spectrum:

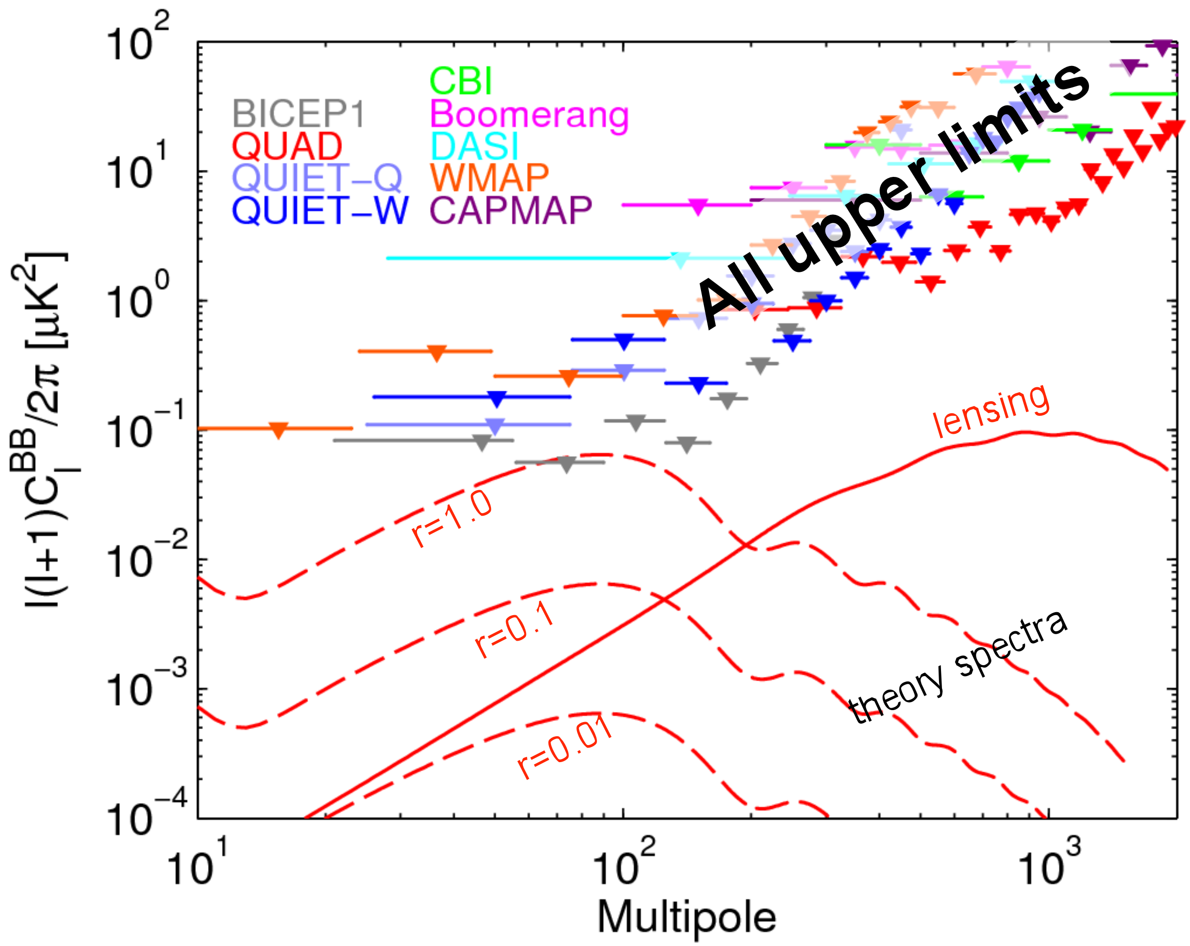
- 10^2 - 10^3 lower still!
- gravitational waves: large angular scale
- lensing: small angular scale



B-modes are a teeny signal! Hard to detect!

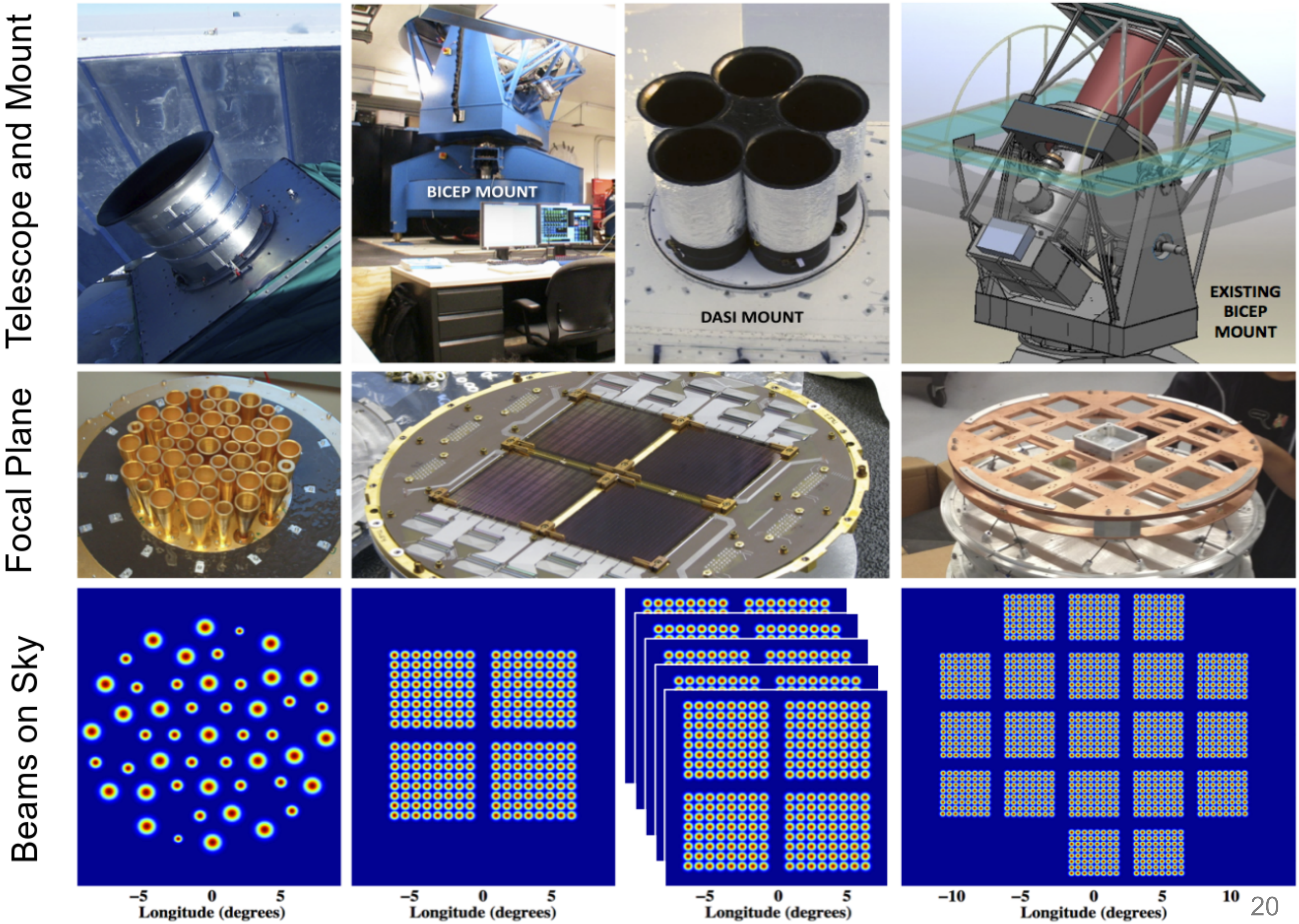
reasonable GUT-scale inflation models

The Hunt for B-modes



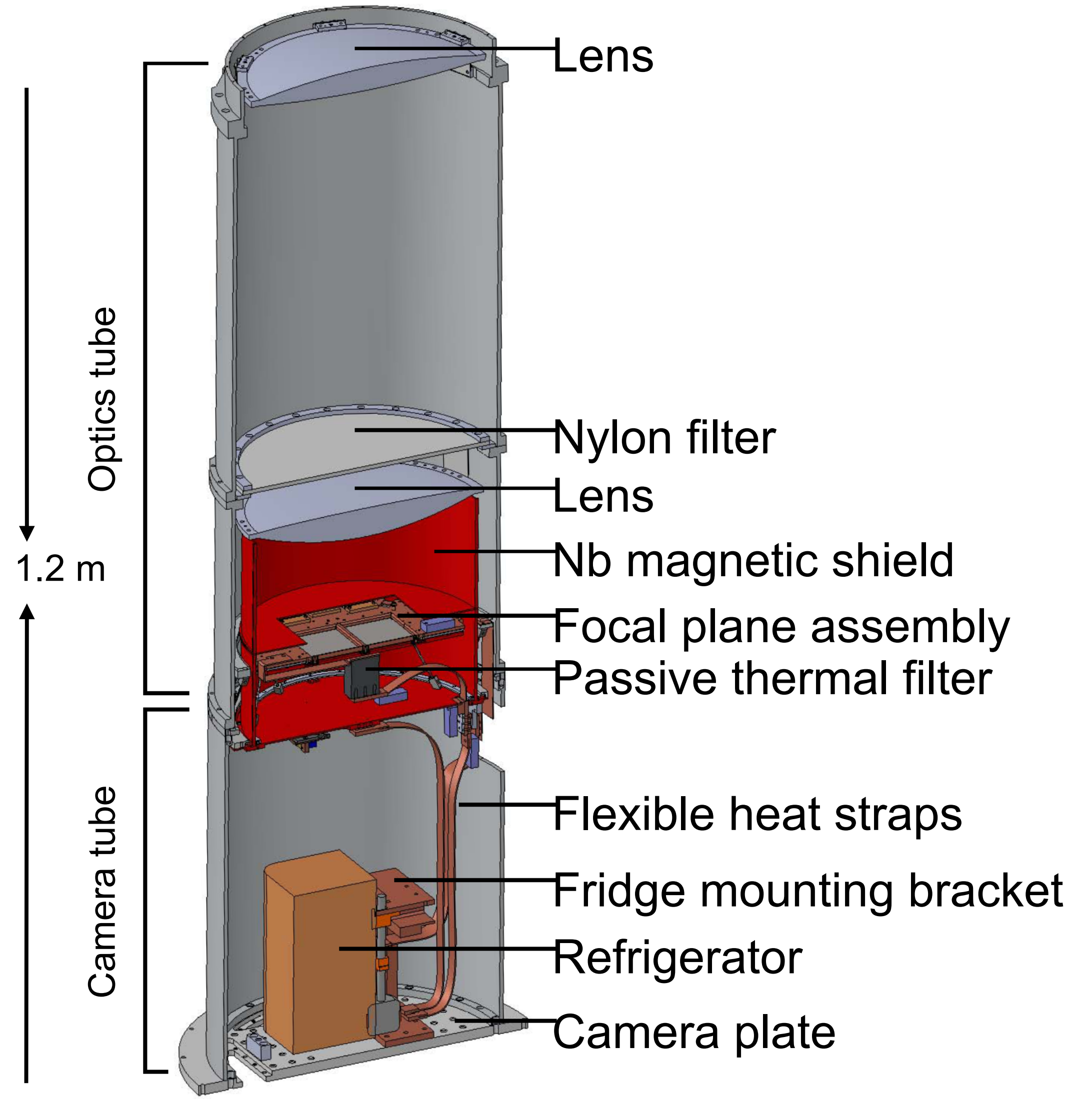
- Characterize the strength of the inflationary signal by the tensor-to-scalar ratio, **r**
- Up to now: upper limits from searches for B-modes
  - Best limit on **r** from BICEP1: **r < 0.7 (95% CL)**
- At high multipoles, lensing B-mode signal dominant

BICEP1	BICEP2	Keck Array	BICEP3
(2006 - 8)	(2010 - 12)	(2011 -)	(2014 -)

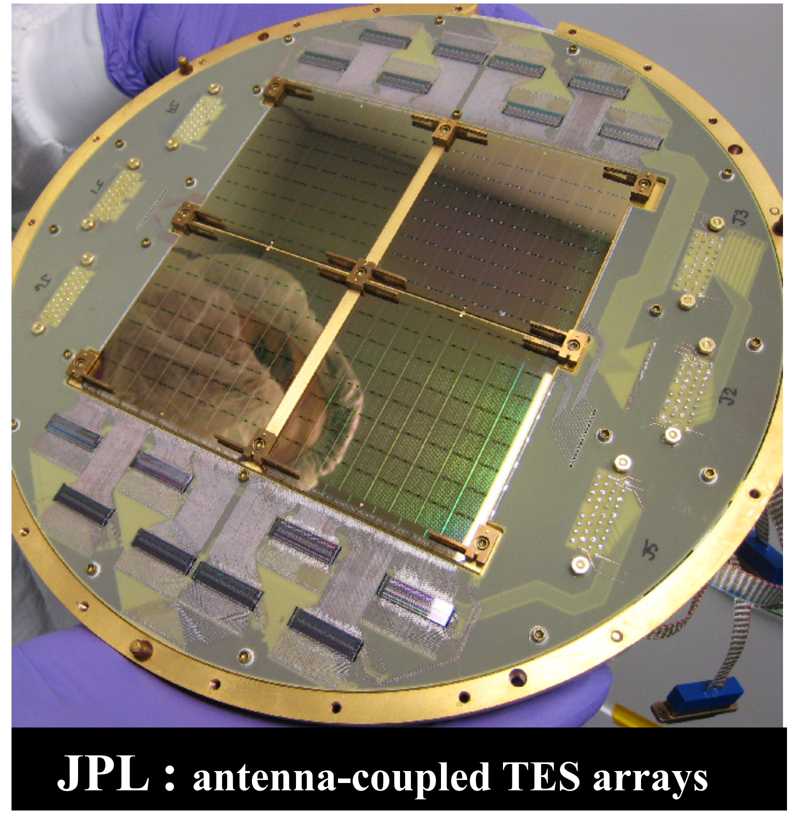


The BICEP2 Telescope

- Cold (4K), on-axis, refractive optics
- 12” aperture → 0.5 degree beams
- Compact telescope for tight systematics control and ability to rotate around optical axis
- Detectors cooled to 250 mK using a helium sorption refrigerator

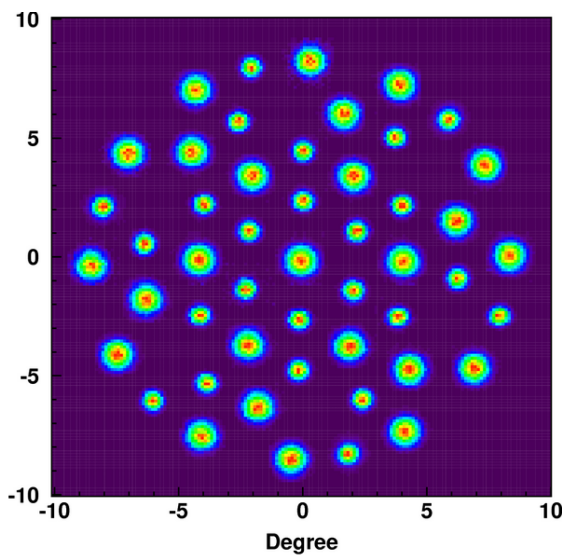


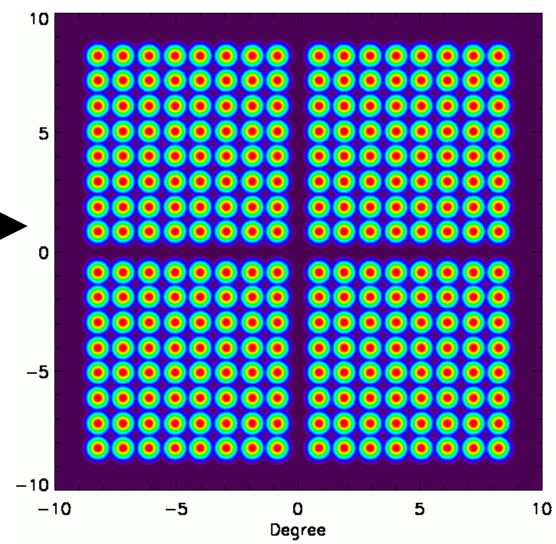
BICEP2: 10-fold increase in mapping speed:



BICEP1

48
150 GHz
detectors

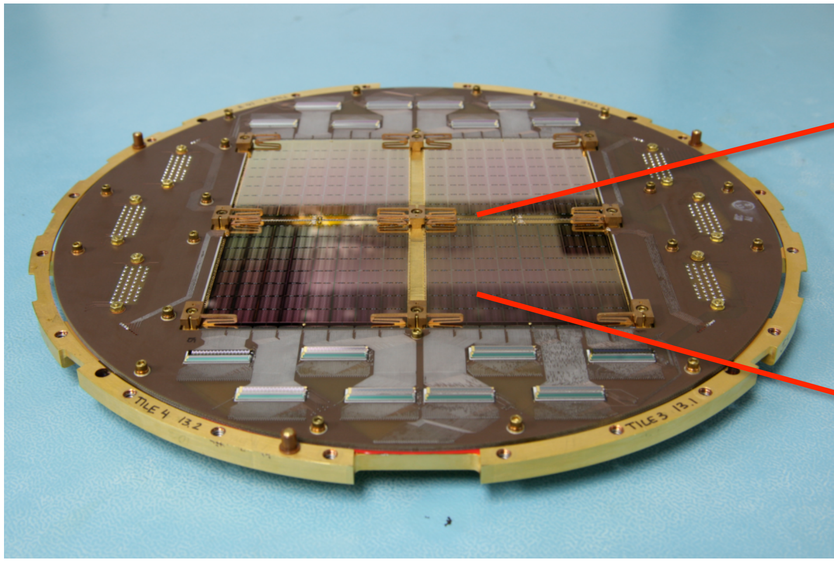


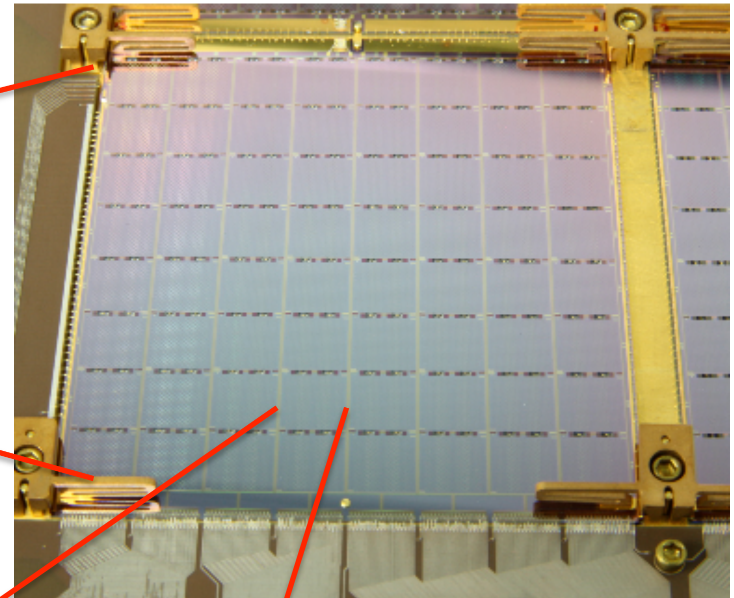


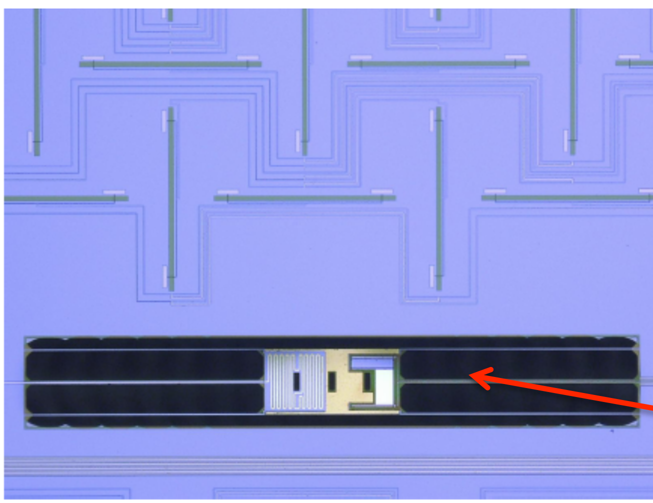
BICEP2

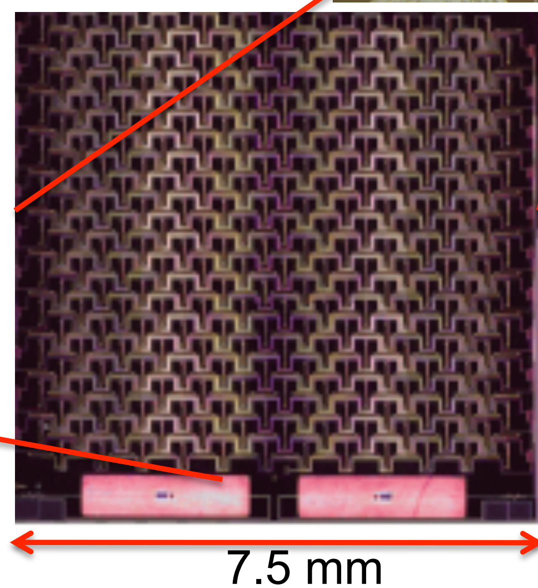
512
150 GHz
detectors

Anatomy of A BICEP2/Keck Focal Plane





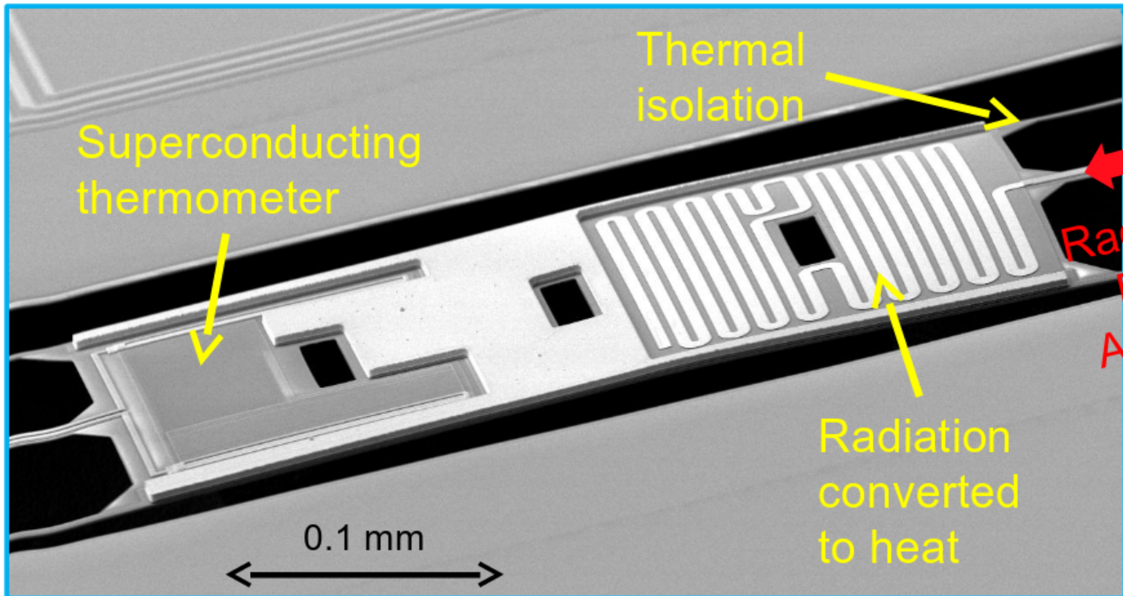


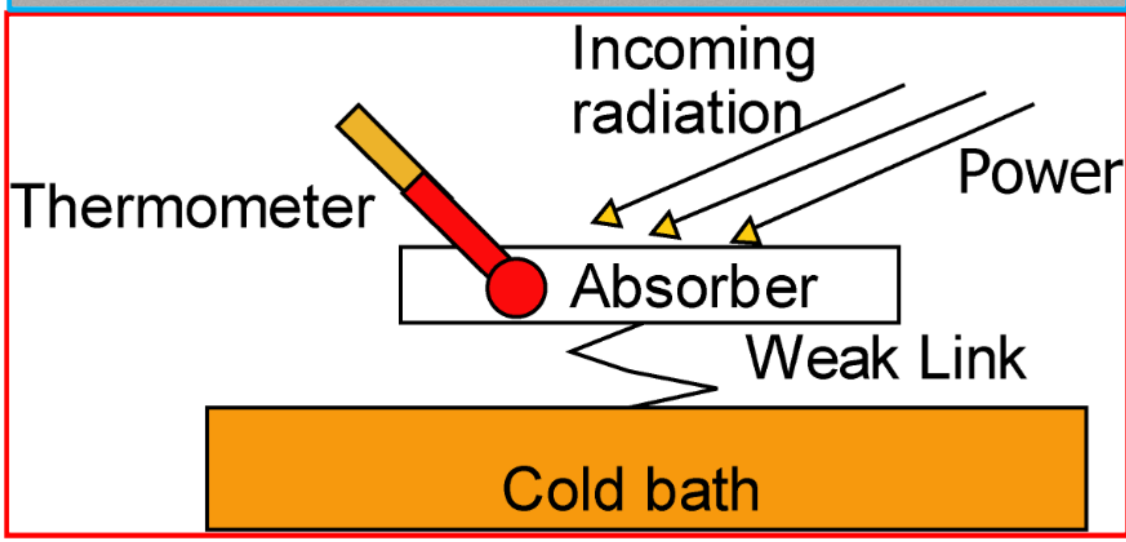


- 256 pixels per focal plane
- Slot antenna array per polarization per pixel
- Ti Transition Edge Sensor (TES) Bolometers

Detecting CMB Radiation

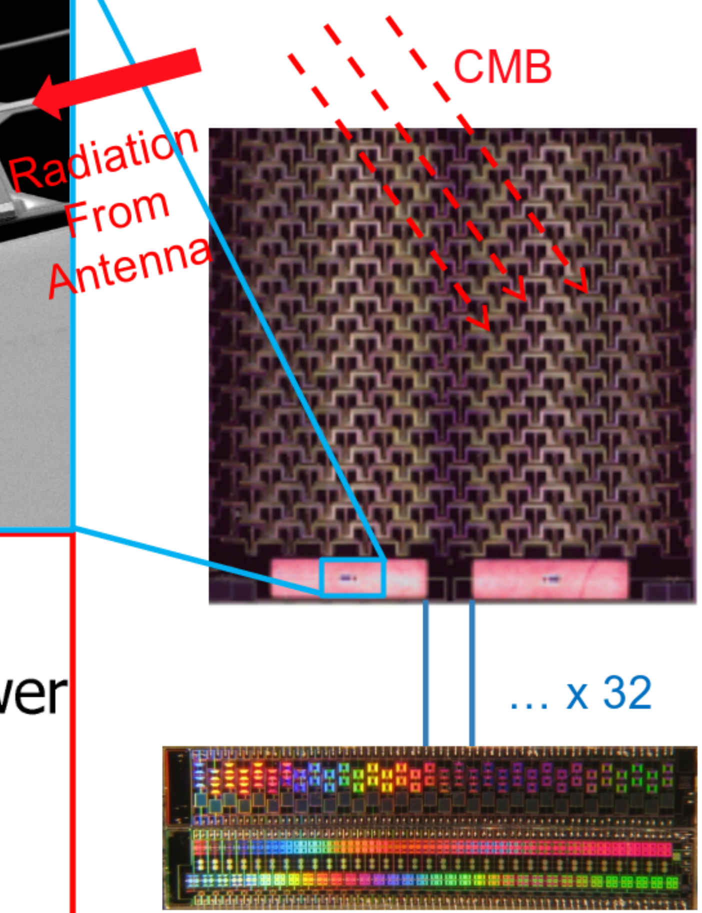
BICEP2 Detector: Transition-Edge Superconductor





Sensors cooled to 0.25 K to reduce thermal noise

Printed Antenna Gathers CMB Light

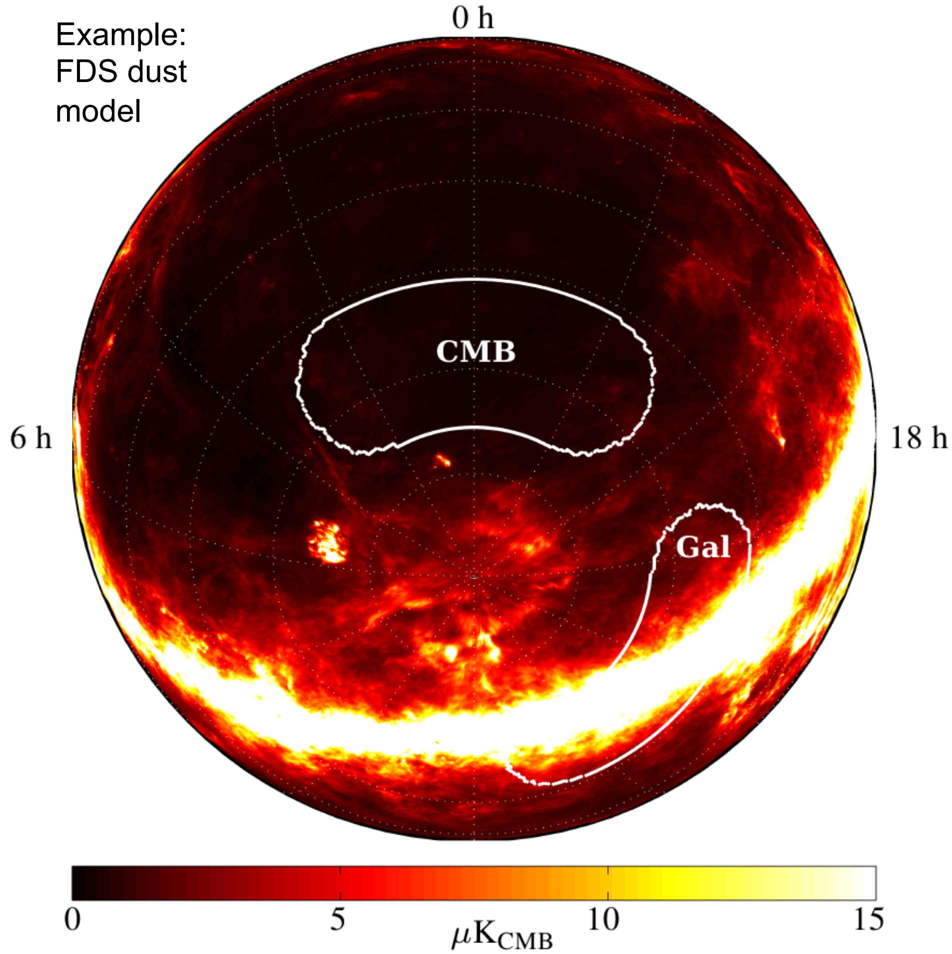


SQUIDs Amplify and Multiplex Signals

SQUIDs developed at NIST

Observational Strategy

Example:
FDS dust
model



Target the "Southern Hole" – an exceptionally clean region of the sky

Observe @ 150 GHz until you see B-modes

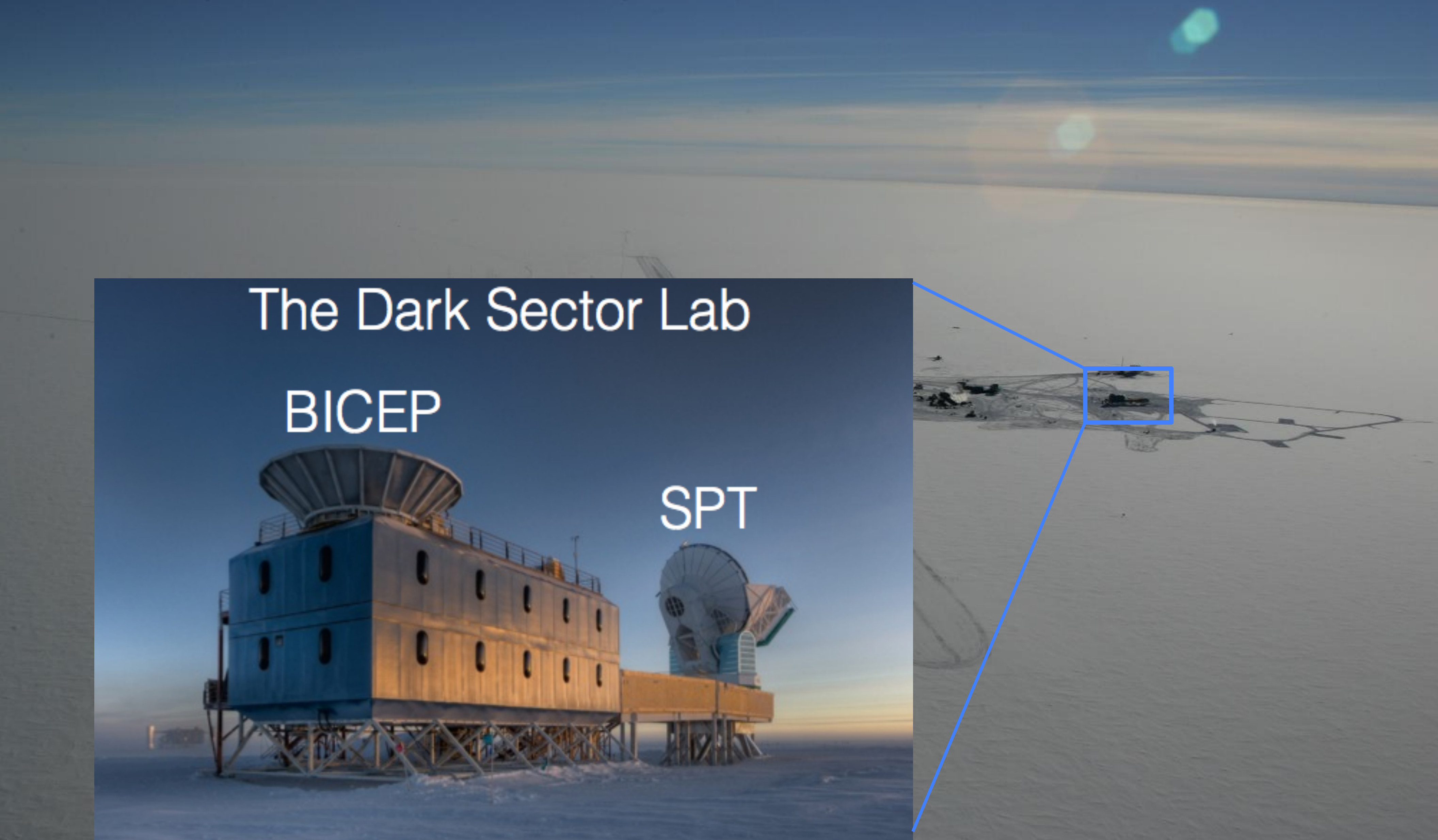
- → Near peak of CMB spectrum
- → Dust + synchrotron predicted to be at a minimum

Expected foreground contamination of the B-mode power: r ≤ ~0.01

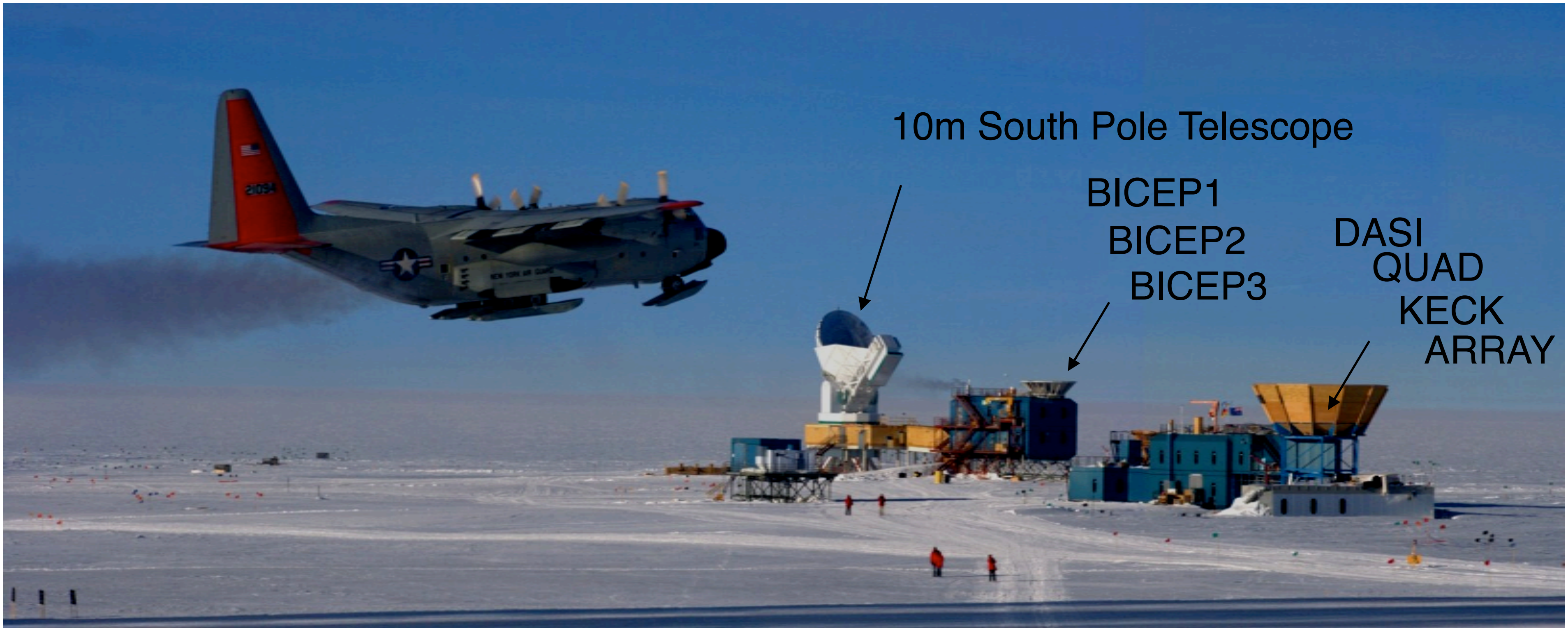
Experimental Strategy

→ Small aperture telescope
→ Target the 2 degree peak of the B-mode
→ Integrate continuously from South Pole

Experimental Strategy



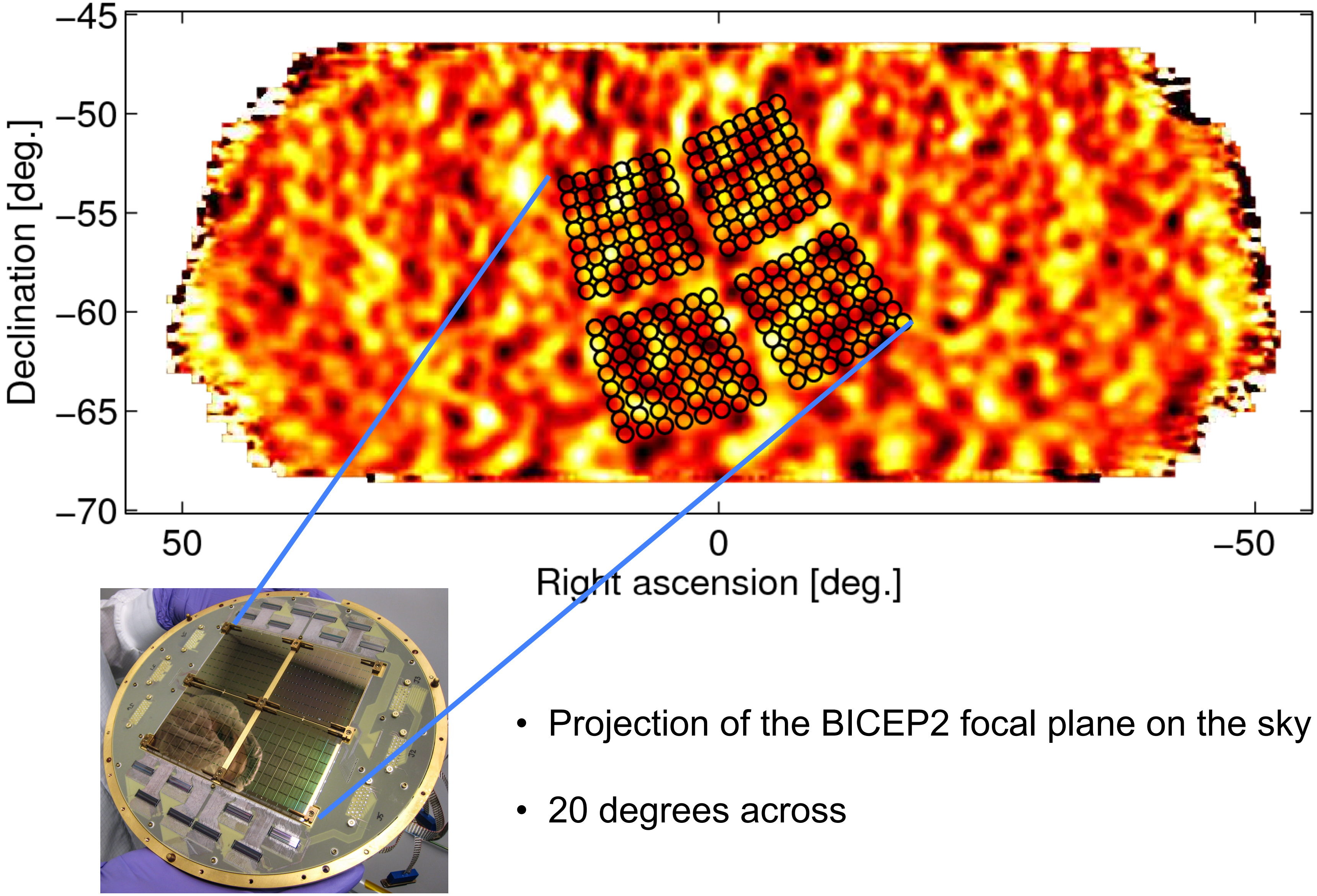
The South Pole Site



- Extremely stable, dry atmosphere
- Pressure altitude: 10,500 ft
- One night and one day per year
- High Observing Efficiency
  - “Southern Hole” visible 24/7
- Power, 200 GB/day, cryo facility, 3 square meals, and Tuesday Pub Trivia.


photo: Keith Vanderlinde

BICEP2 on the Sky

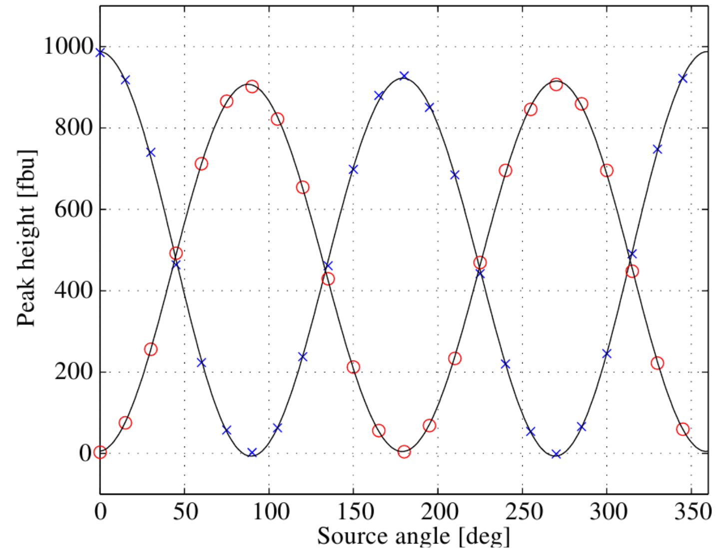


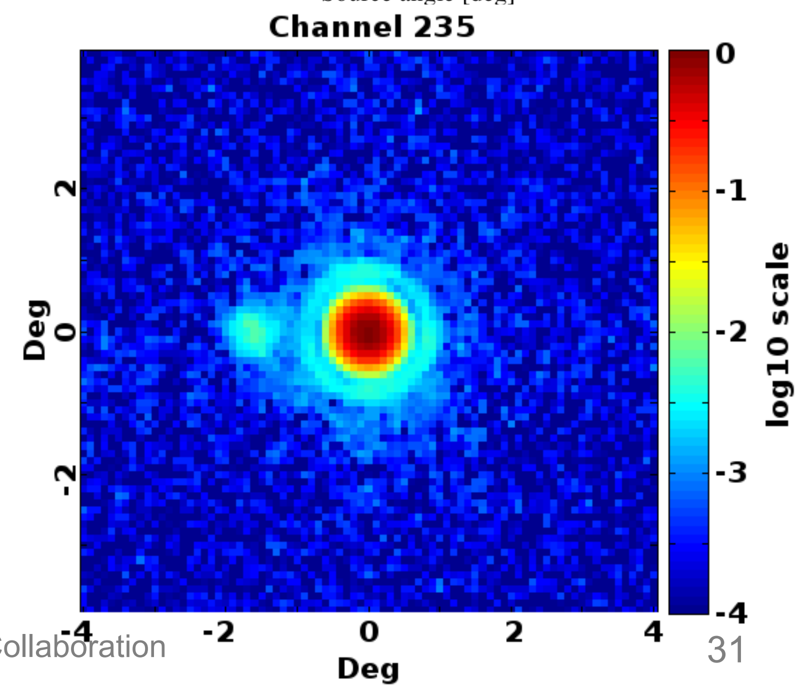
- Projection of the BICEP2 focal plane on the sky
- 20 degrees across

In-Situ Calibration Measurements

Far field beam mapping

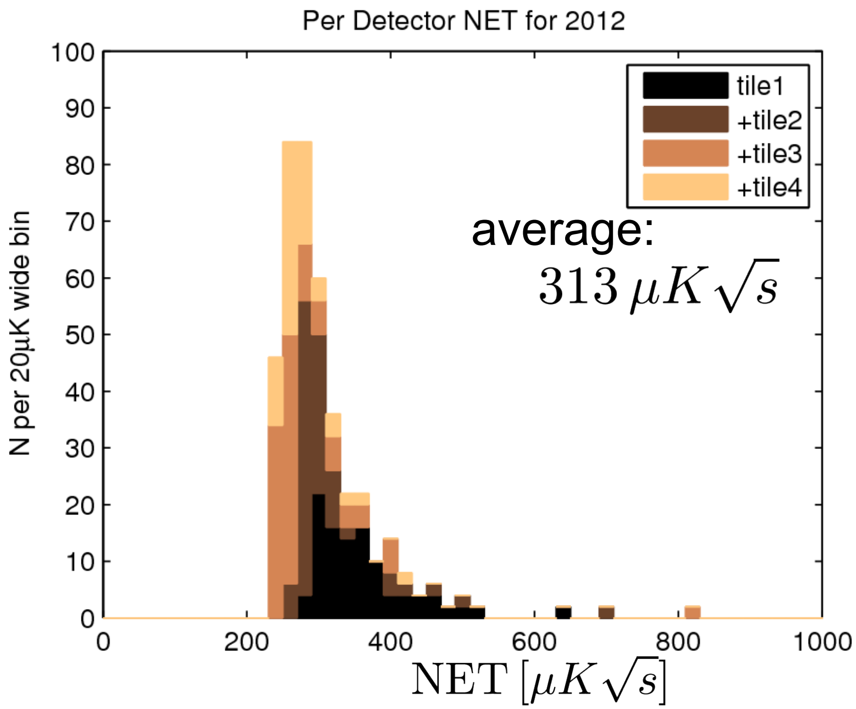
Detector Polarization Calibration





High fidelity beam maps of individual detectors

BICEP2 Sensitivity



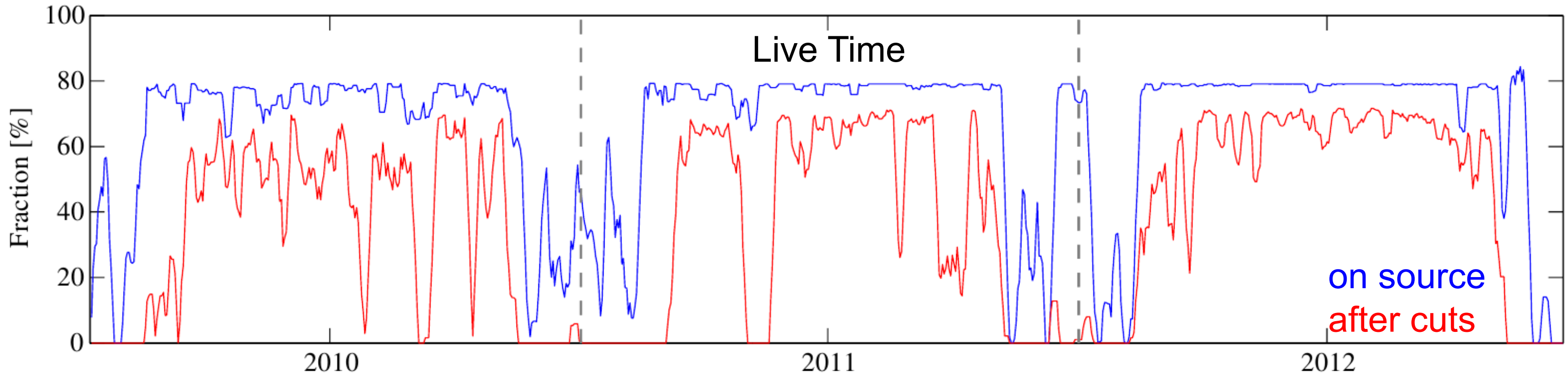
Per-detector noise equivalent temperature (NET): $313\,\mu K\sqrt{s}$

Our recipe for high sensitivity:

- High optical efficiency (40% end-to-end)
- Cold optics
- Low loading/photon noise
- Low thermal conductance/phonon noise
- High detector count

Total Sensitivity for full BICEP2 instrument: $15.8\,\mu K\sqrt{s}$

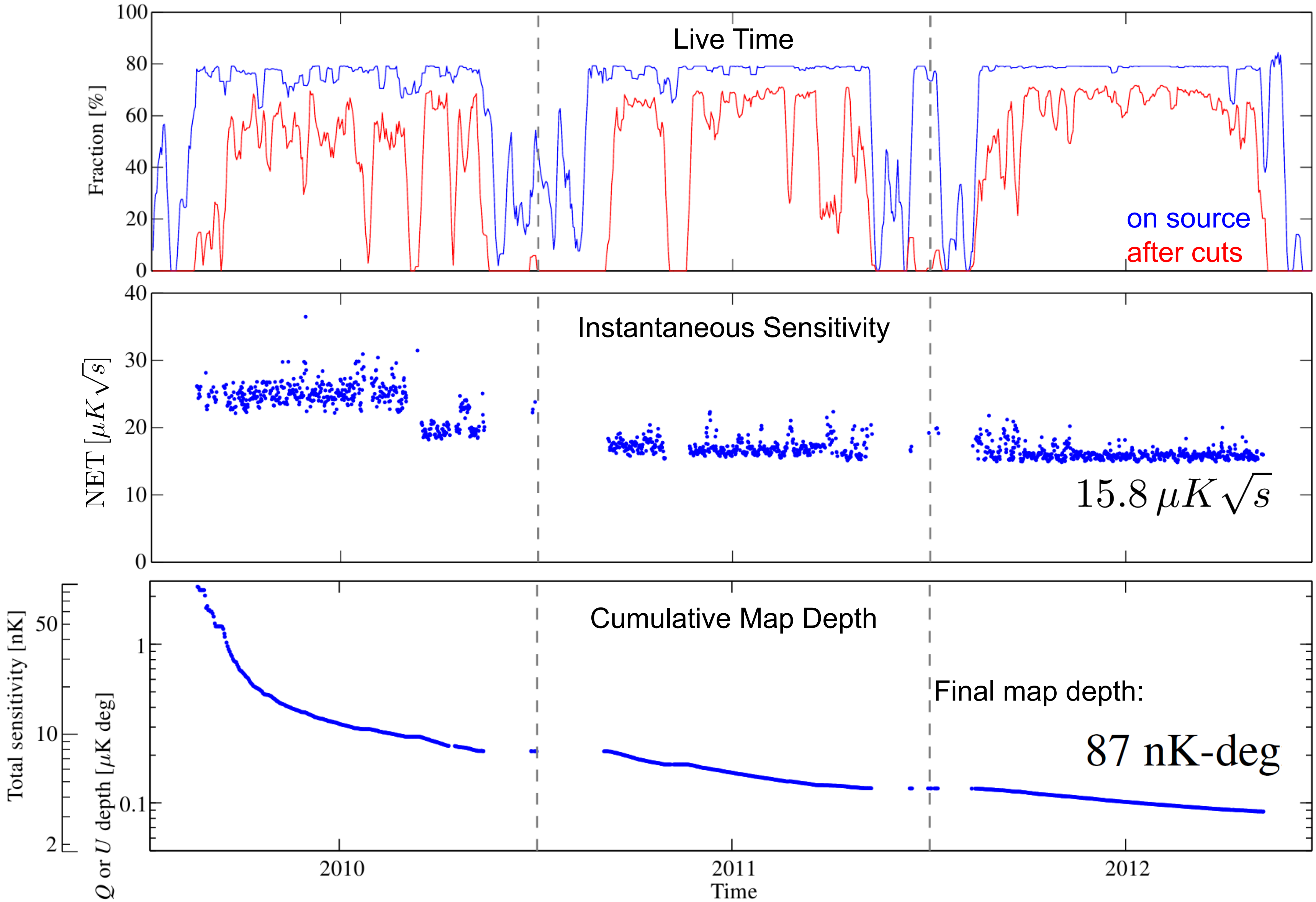
Data Quality Cuts



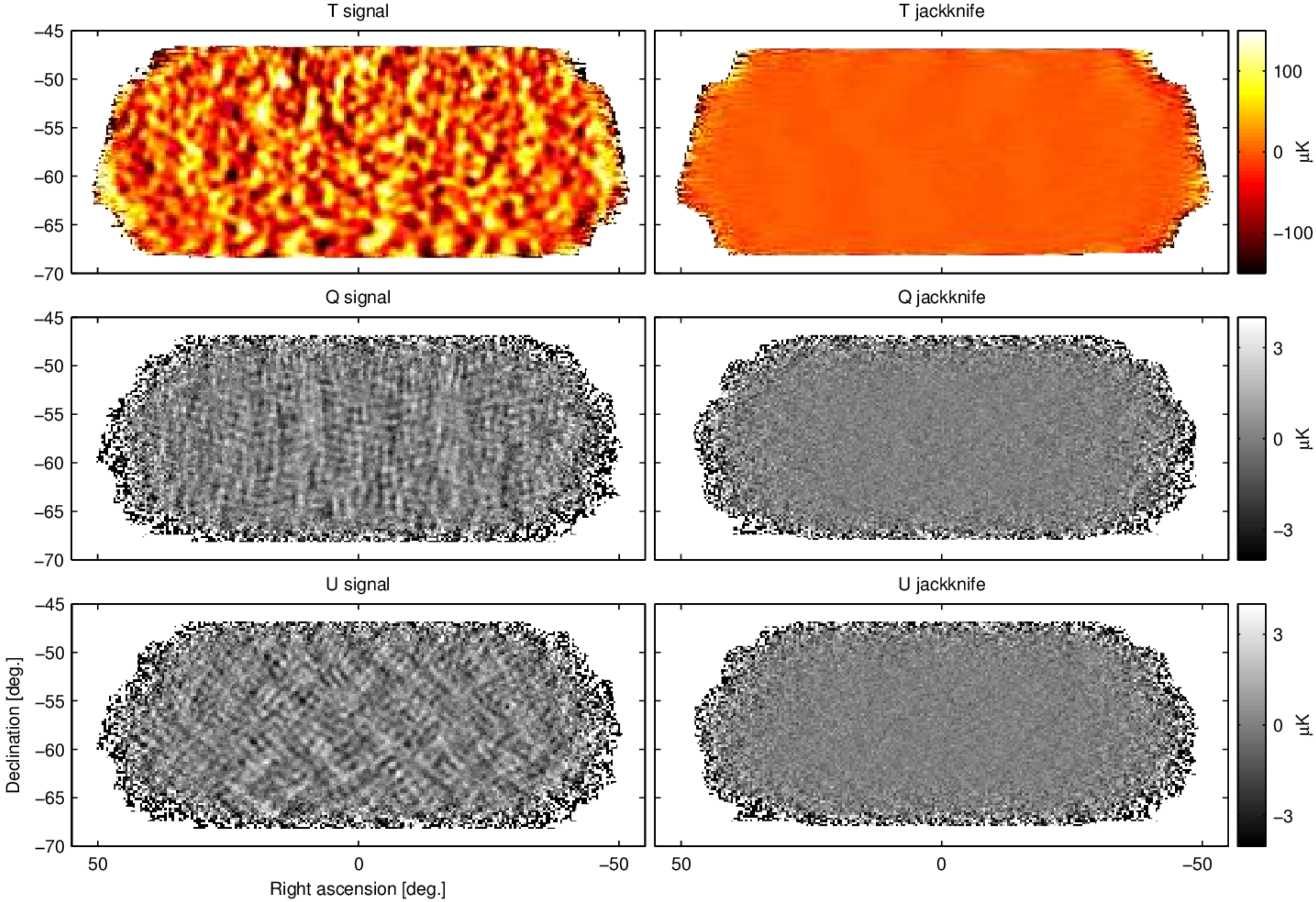
Cut parameter	Total time [10^6 s]	Integration [10^9 det · s]	Fraction cut [%]
Before cuts	36.5	14.8	–
Channel cuts	36.5	13.2	10.9
Synchronization	35.3	12.7	3.1
Deglitching	33.6	10.7	13.8
Per-scan noise	33.6	10.7	$< 0.01\%$
Passing channels	33.3	10.7	0.22
Manual cut	33.0	10.6	0.43
Elevation nod	31.0	9.2	9.5
Fractional resistance	31.0	9.2	0.16
Skewness	31.0	9.1	0.41
Time stream variance	30.9	9.0	0.52
Correlated noise	30.9	9.0	$< 0.01\%$
Noise stationarity	30.7	8.9	0.64
FPU temperature	30.6	8.9	0.20
Passing data	27.6	8.6	1.7

- Ensure that data used in map making is from periods of well-behaved data
- Most cuts identify bad weather and overlap
- BICEP2 data very well behaved
  → 63% passes

BICEP2 3-year Data Set

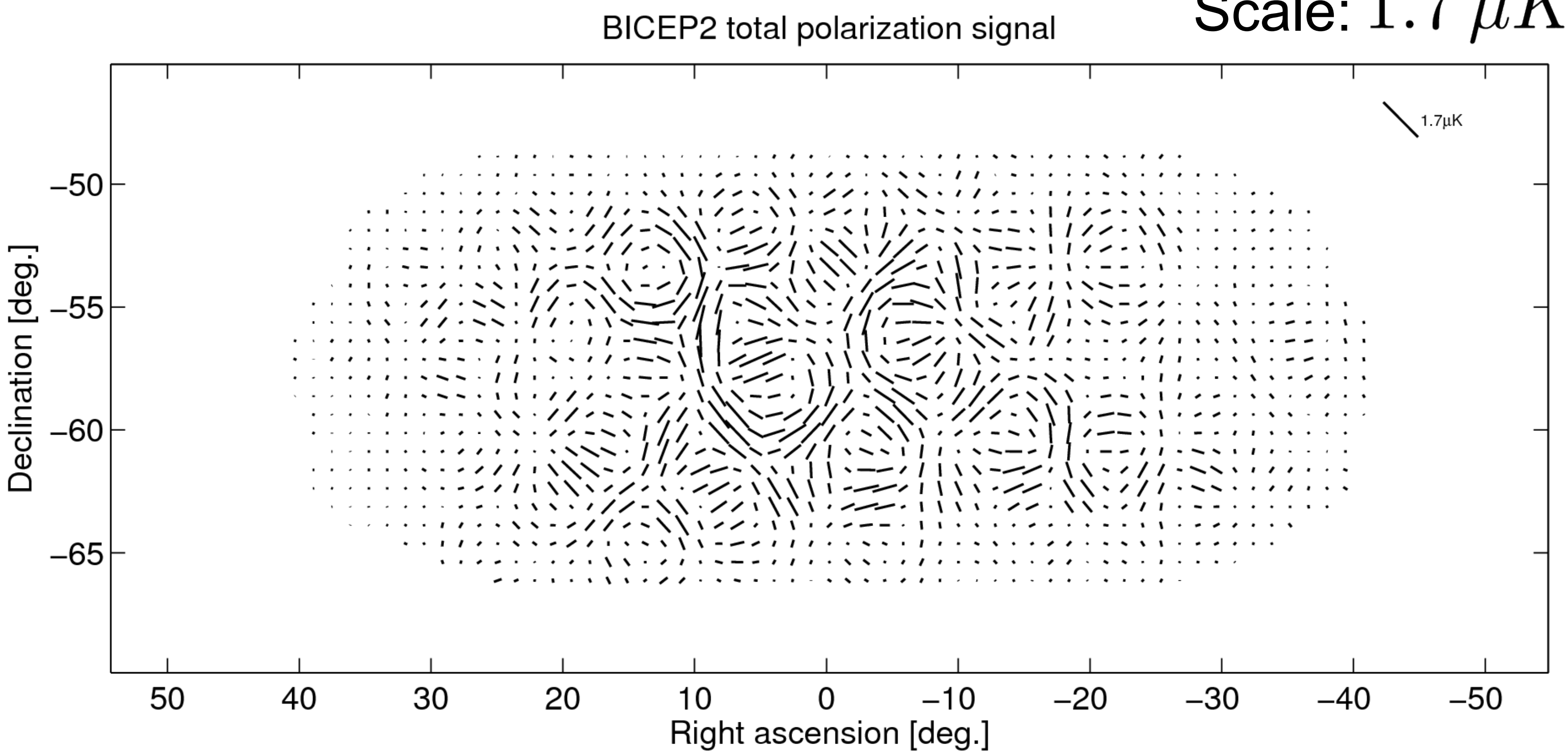


BICEP2 T and Stokes Q/U Maps



Total Polarization

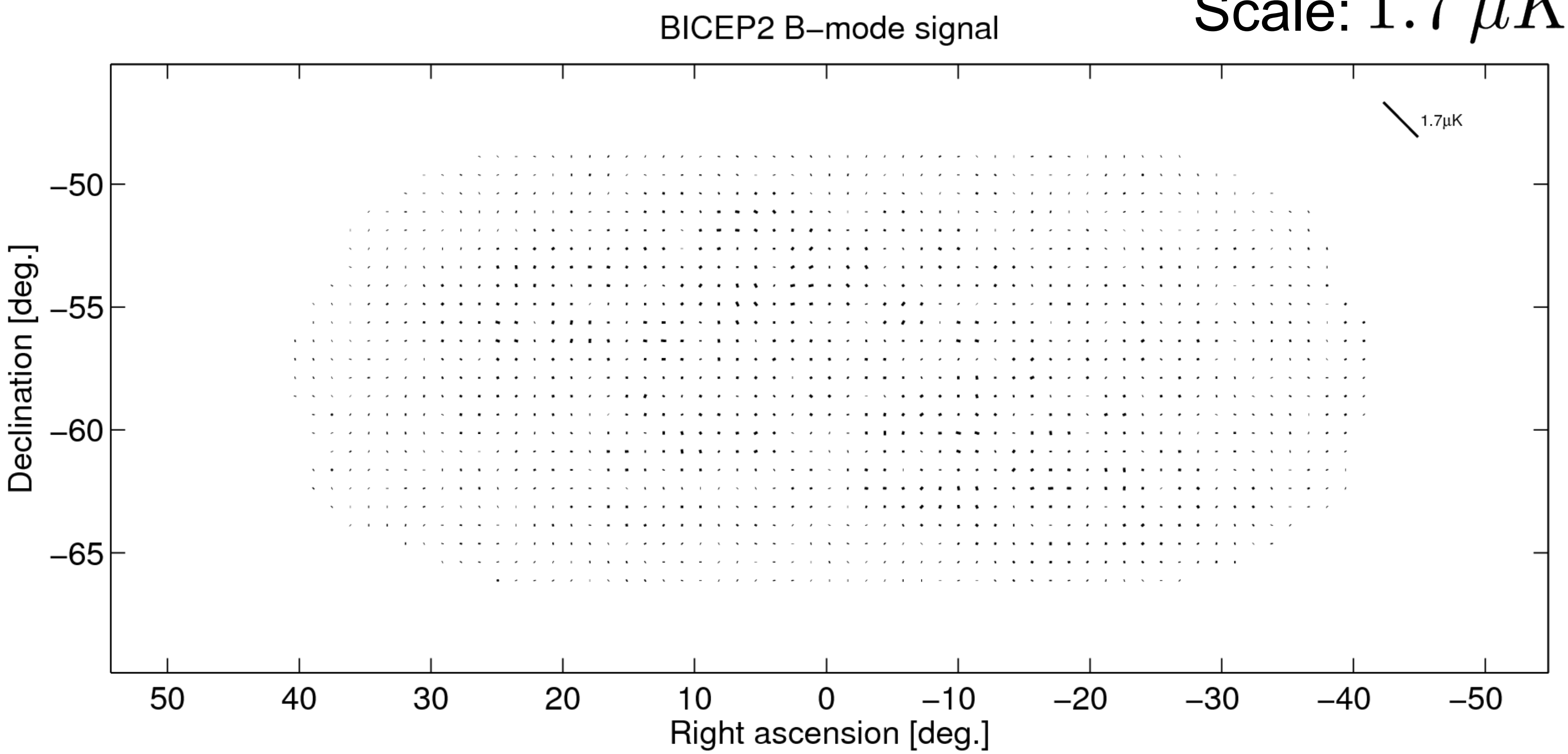
Scale: $1.7\ \mu K$



B-modes of **r** = 0.1 contribute ~1/10 of the total polarization amplitude at ℓ=100

B-mode Contribution

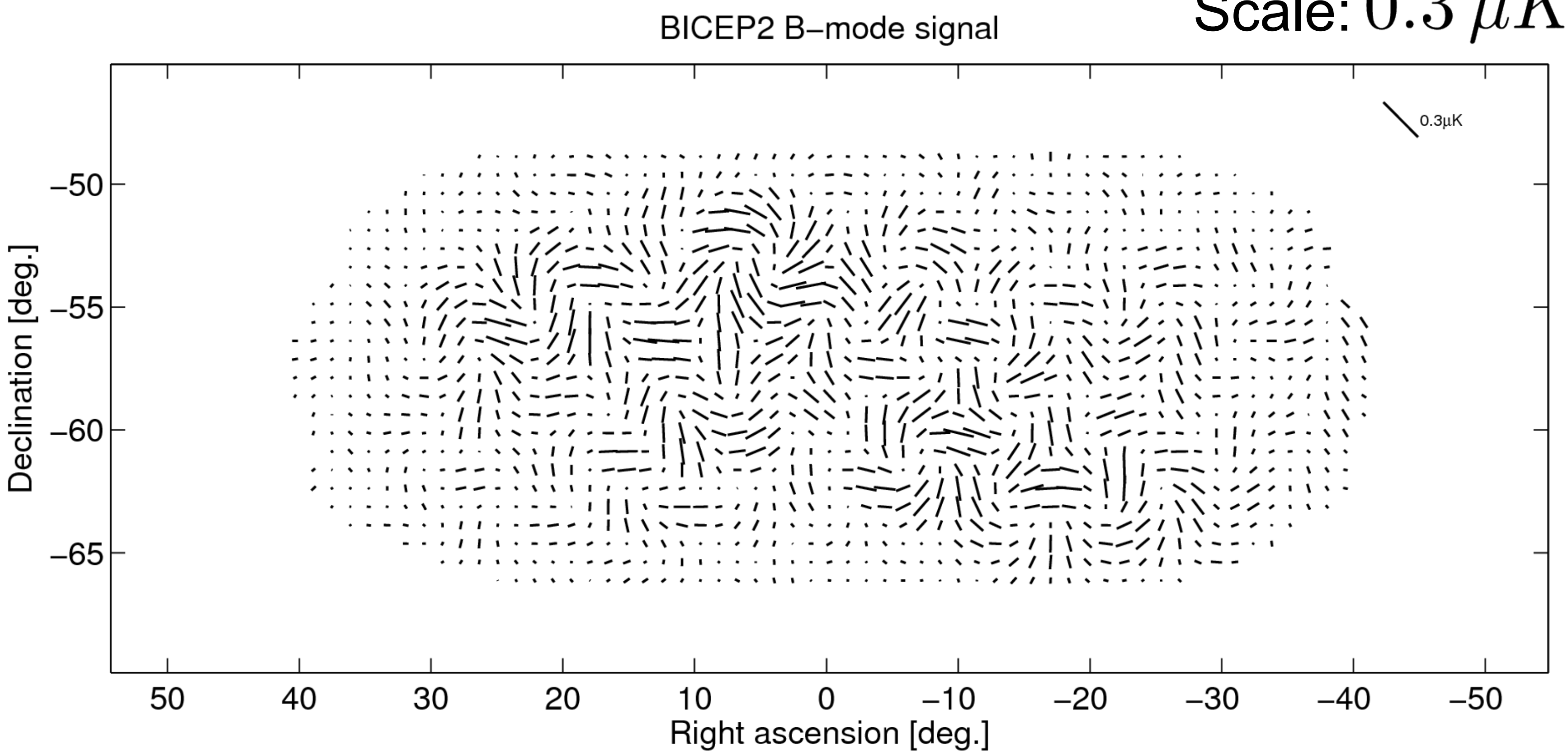
Scale: $1.7\ \mu K$



B-modes of **r** = 0.1 contribute ~1/10 of the total polarization amplitude at ℓ=100

B-mode Contribution

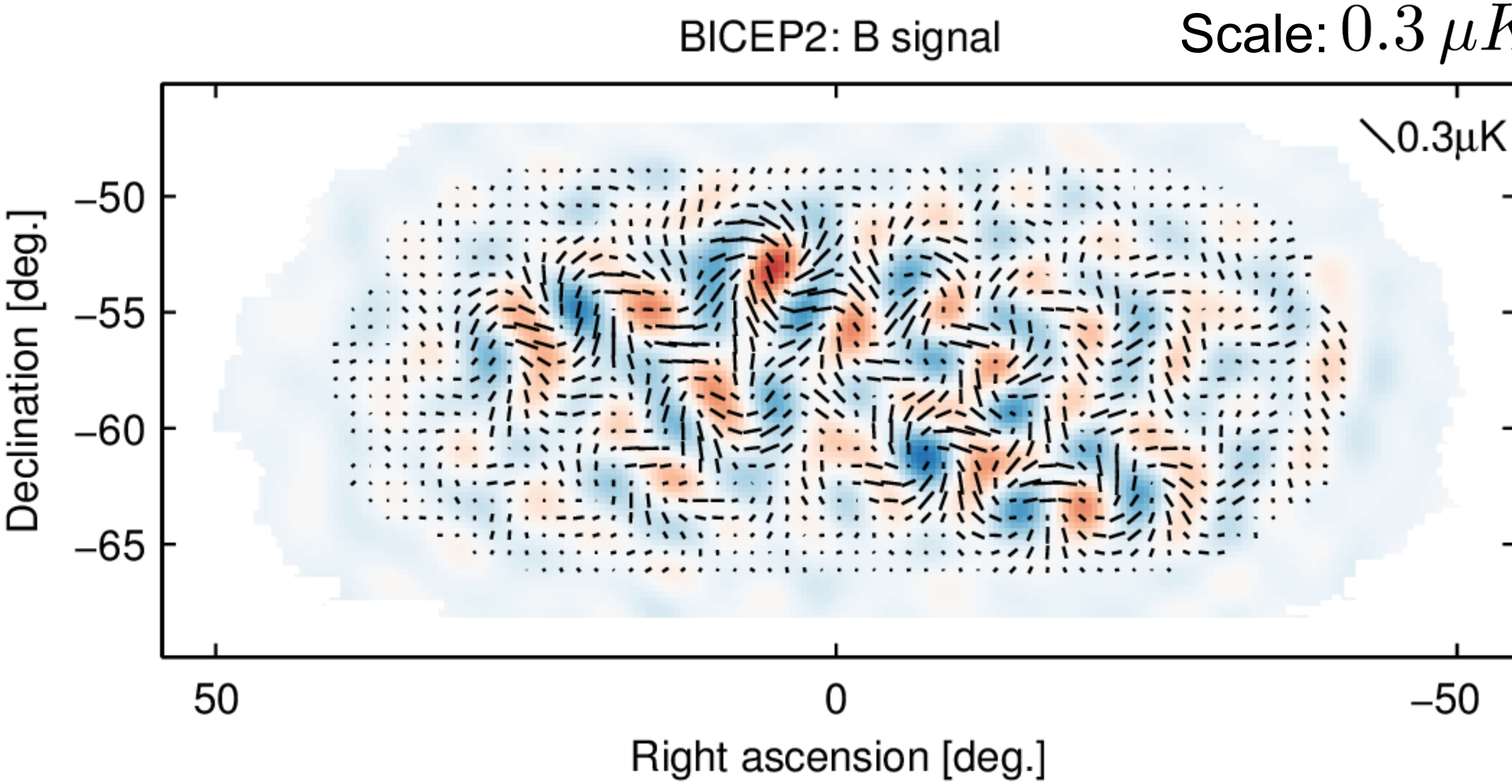
Scale: $0.3\ \mu K$



B-modes of **r** = 0.1 contribute ~1/10 of the total polarization amplitude at ℓ=100

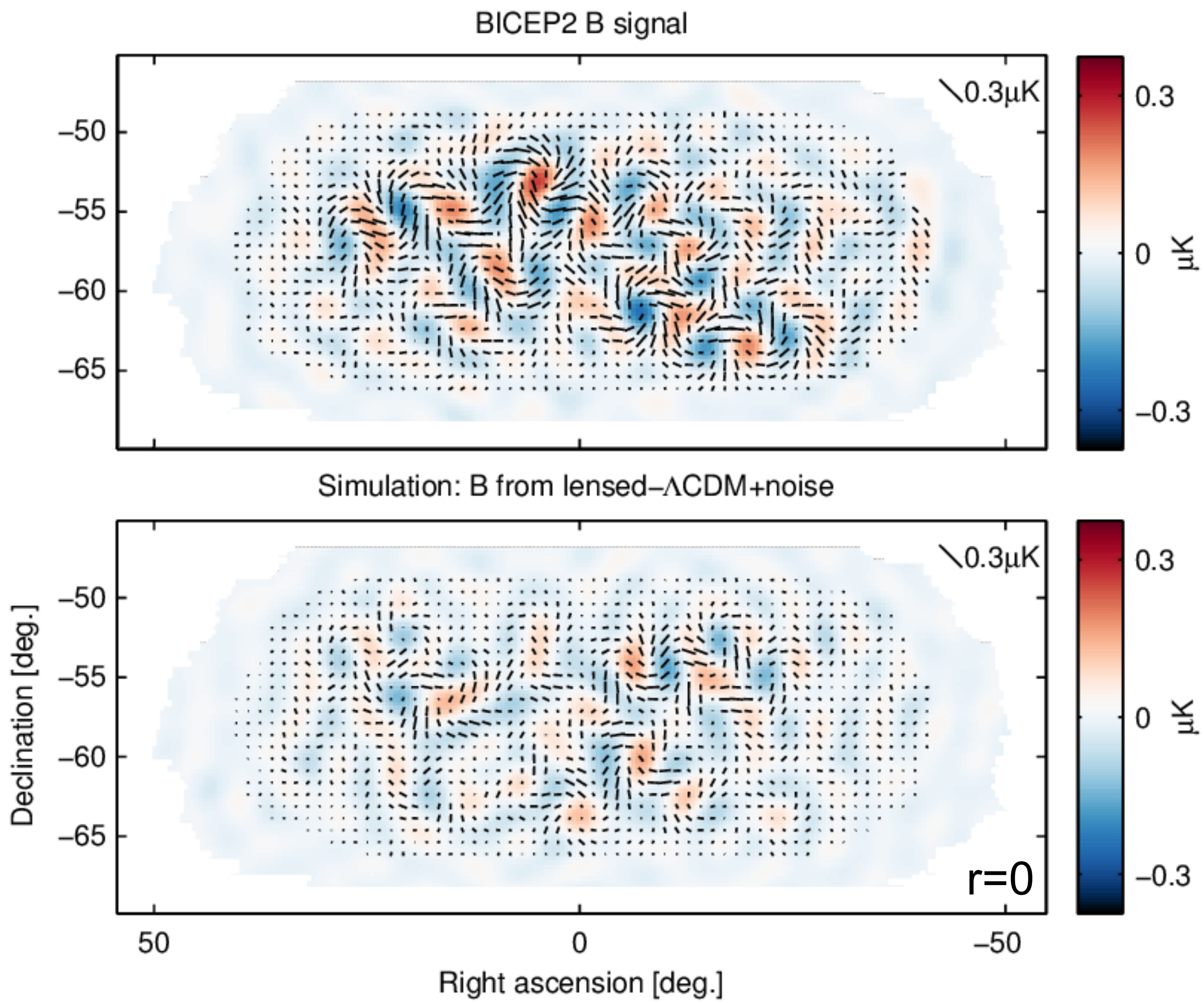
B-mode Contribution

Scale: $0.3\ \mu K$



B-modes of **r** = 0.1 contribute ~1/10 of the total polarization amplitude at ℓ=100

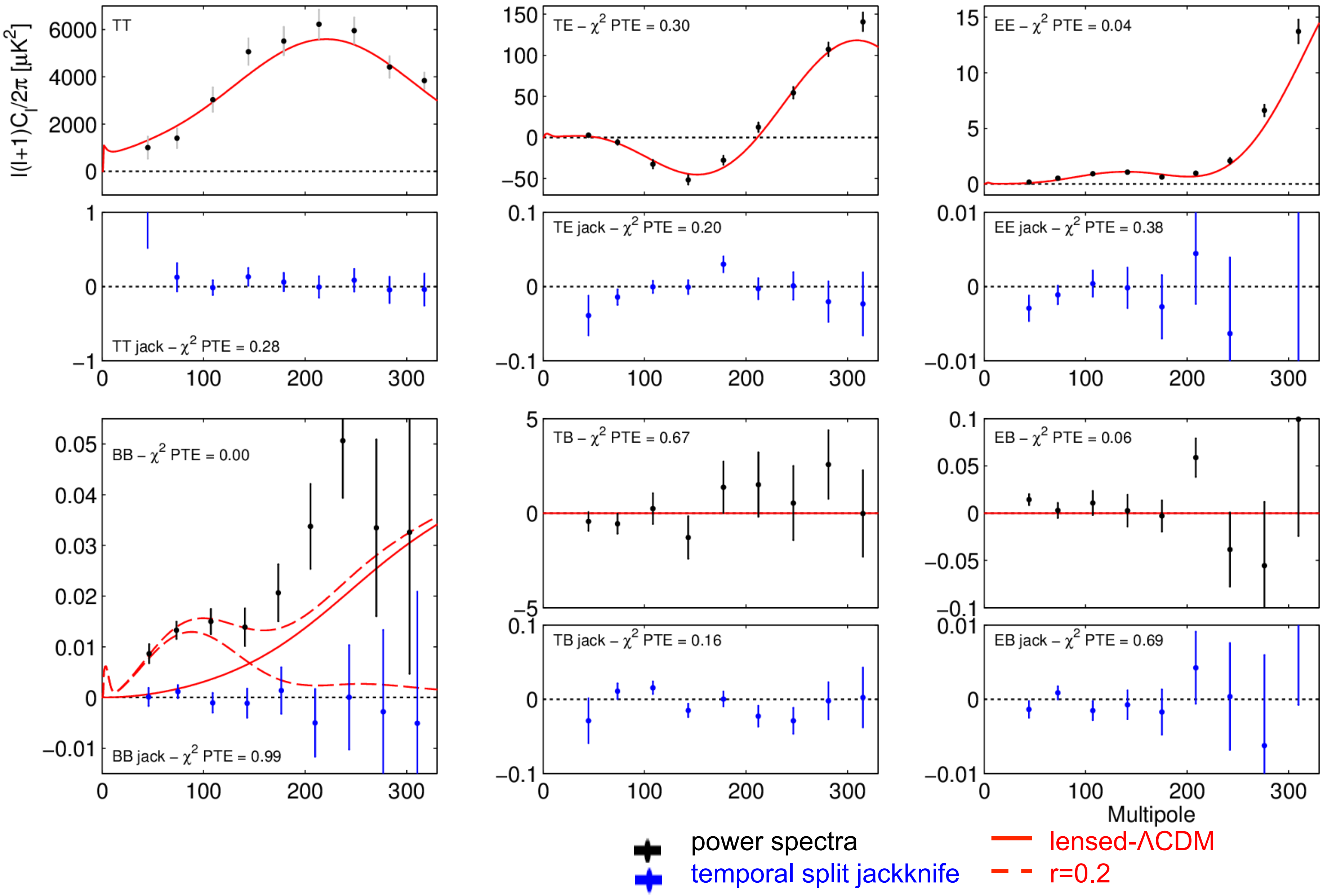
B-mode Map vs. Simulation



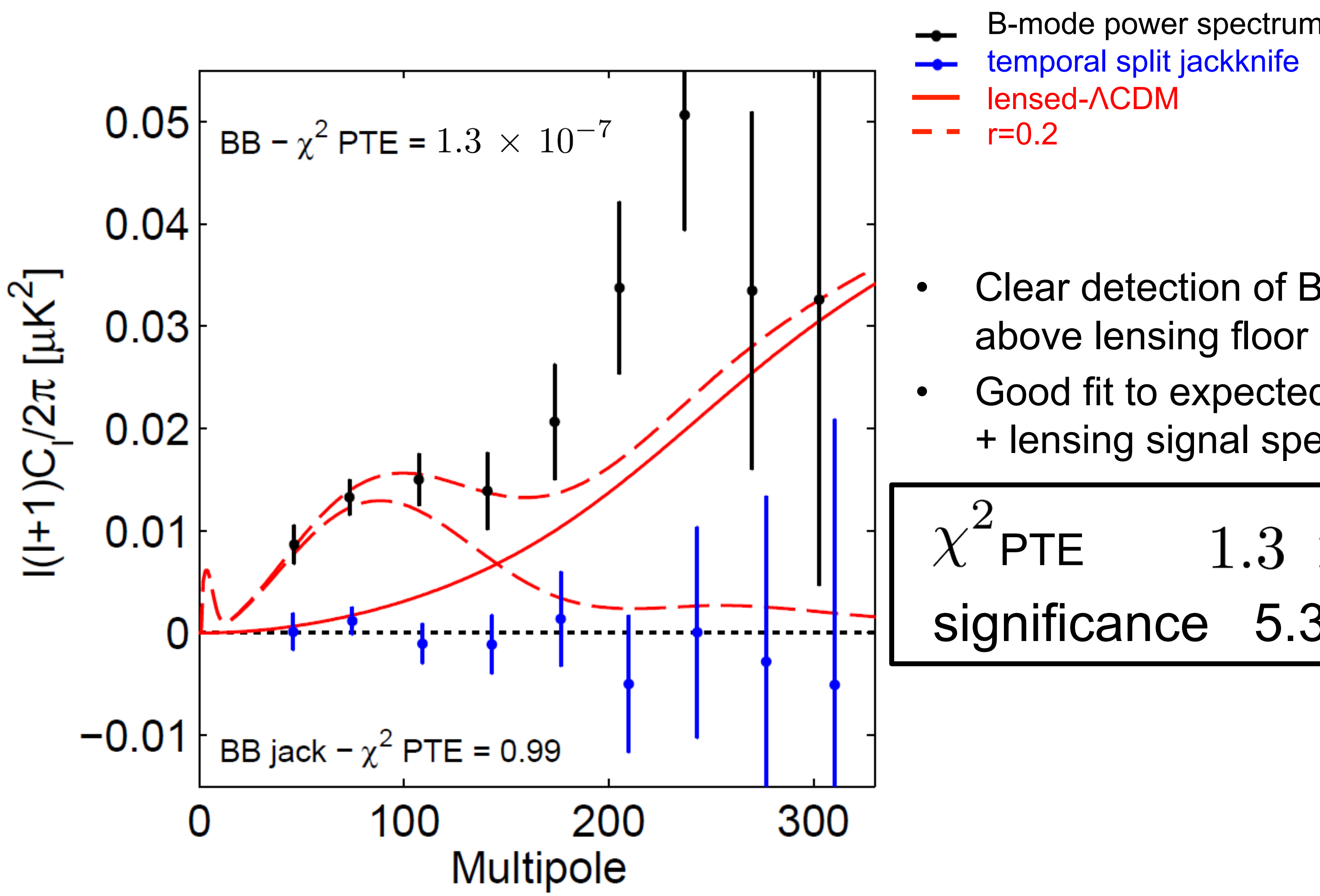
Simulation pipeline: compare real data to 500 lensed-Λ_{CDM} +noise simulations each at various levels or **r**, including all filtering.

From simulations, derive bias and uncertainties in our measurements

Temperature and Polarization Spectra



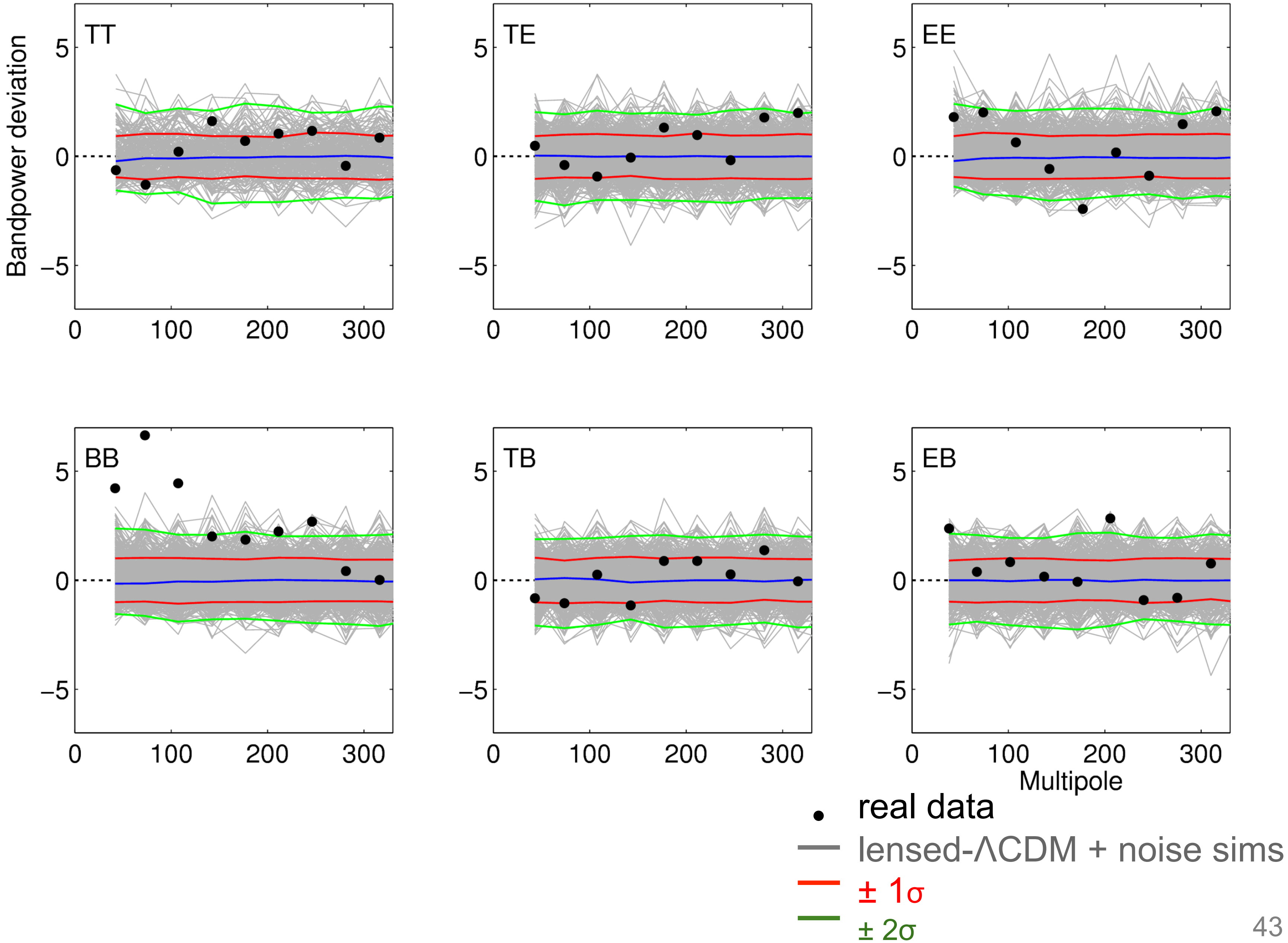
BICEP2 B-mode Power Spectrum



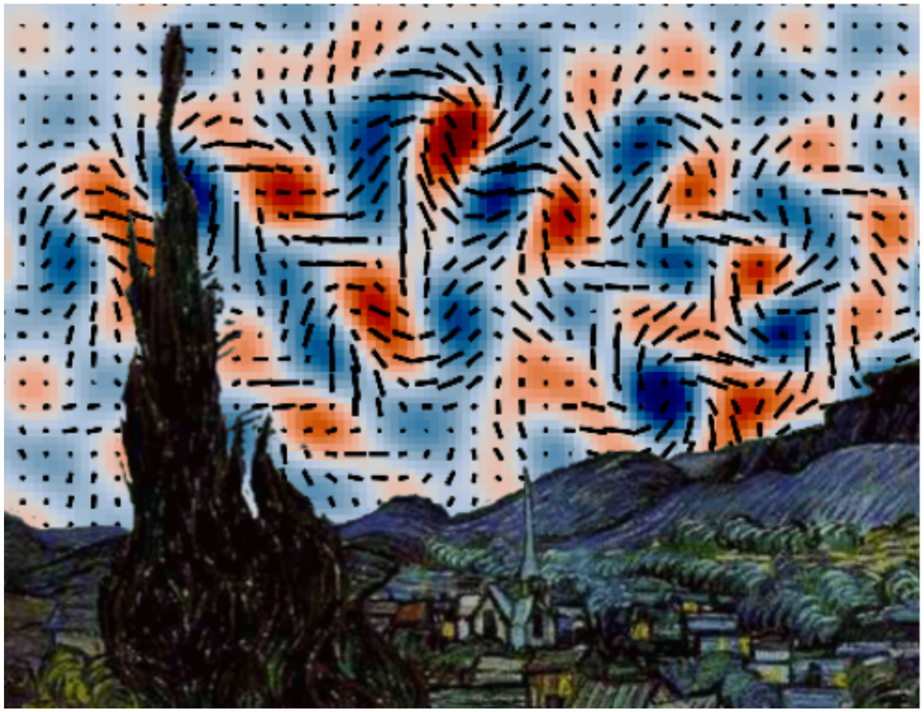
- Clear detection of B-modes above lensing floor
- Good fit to expected inflationary + lensing signal spectrum

χ^2 PTE	1.3×10^{-7}
significance	5.3σ

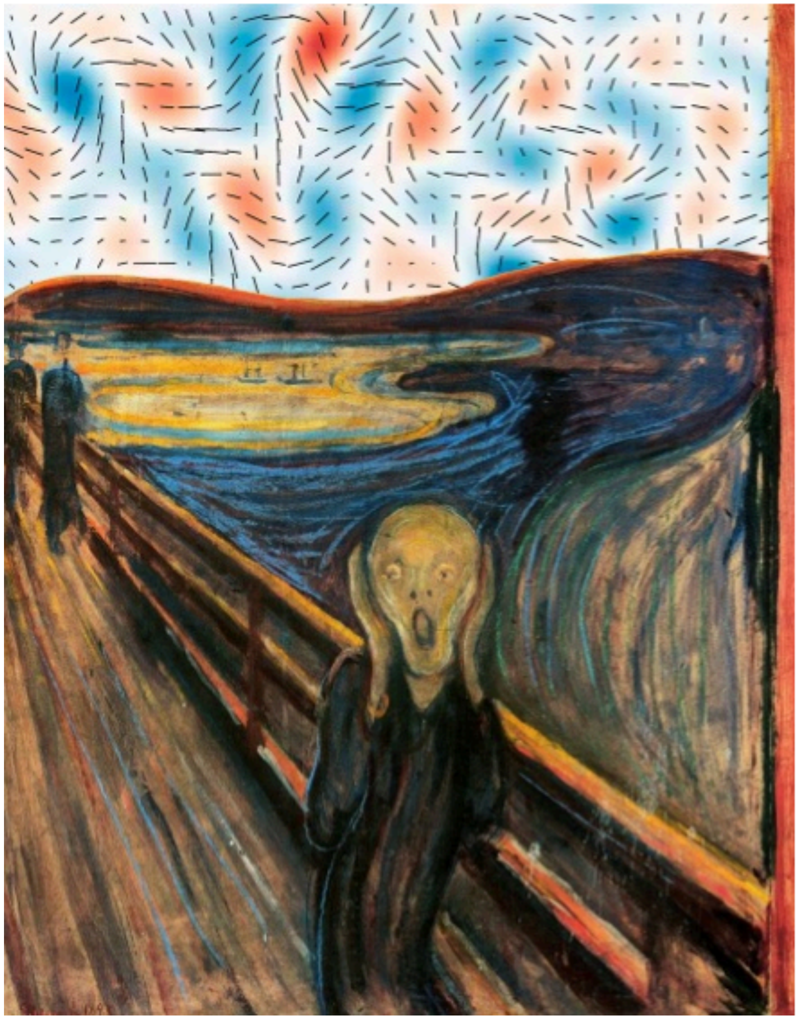
Bandpower Deviations



First Impressions



Van Gogh/Halpern



Munch/Bischoff

What Could This Be?

- Instrumental Systematics?
- Galactic Foregrounds?
- Cosmology?

What Could This Be?

- Instrumental Systematics?
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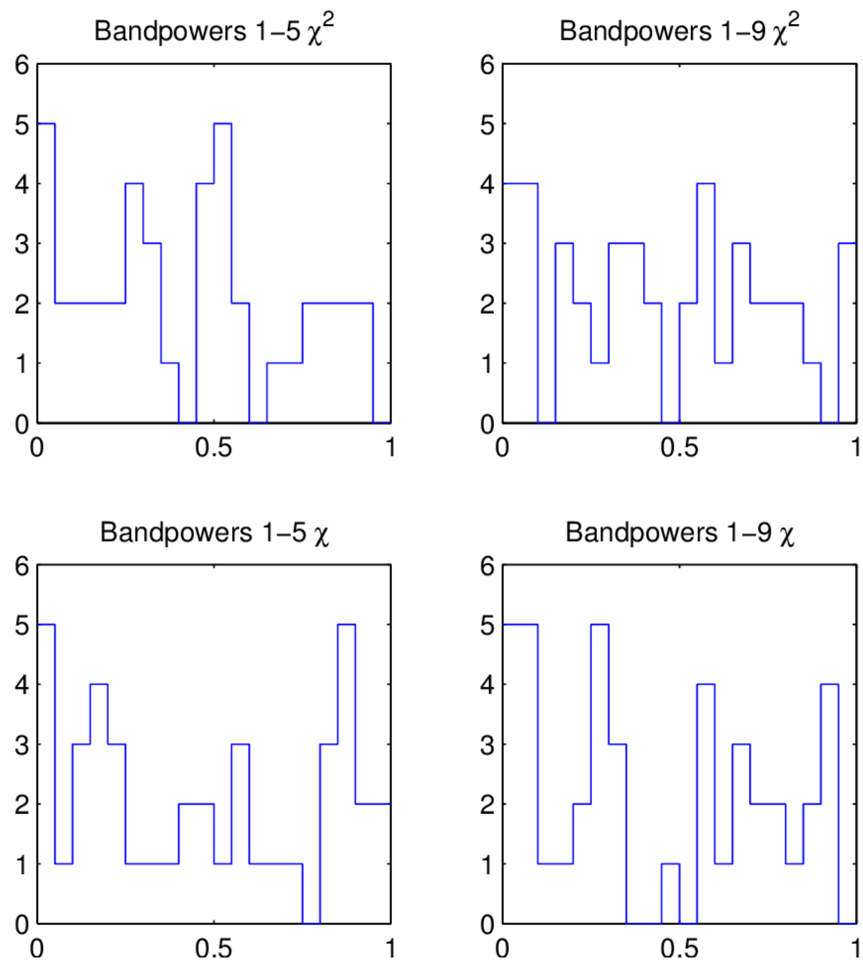
Check Systematics: Jackknifes

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

14 jackknife tests applied to 3 spectra, 4 statistics

All 4 statistics defined from the jackknife tests result in uniform probability to exceed (PTE) distributions:



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Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
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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				
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BB	0.255	0.086	0.421	0.036
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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 the 4 boresight rotations

Amplifies differential pointing in comparison to fully added data.

Check Systematics: Jackknifes

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
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EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
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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
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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
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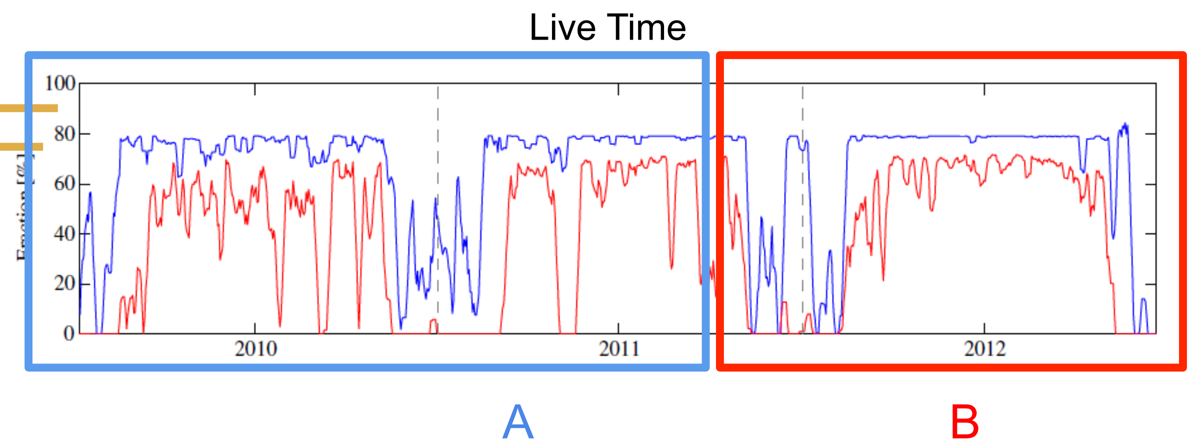
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

Splits by time



Checks for contamination on long and short timescales. Short timescales probe detector transfer functions.

Check Systematics: Jackknifes

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				
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BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
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EE	0.483	0.762	0.978	0.938
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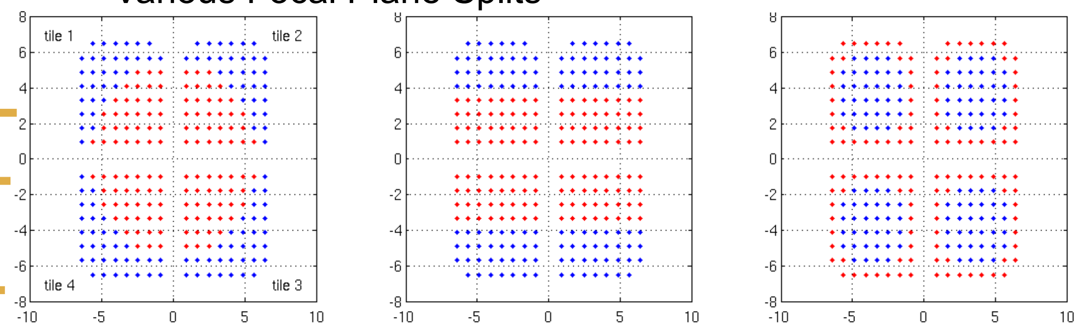
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

Splits by channel selection

Various Focal Plane Splits



Checks for contamination in channel subgroups
- → focal plane location
- → tile location
- → readout electronics grouping

Check Systematics: Jackknifes

TABLE 1
JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

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Alt Deck jackknife				
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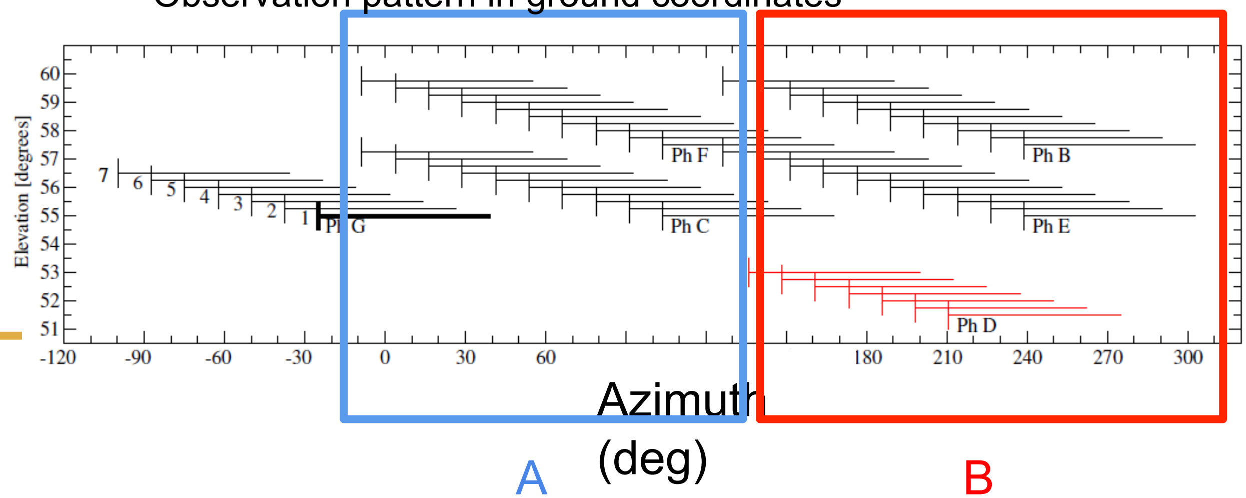
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

Splits by possible external contamination

Observation pattern in ground coordinates



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

Check Systematics: Jackknifes

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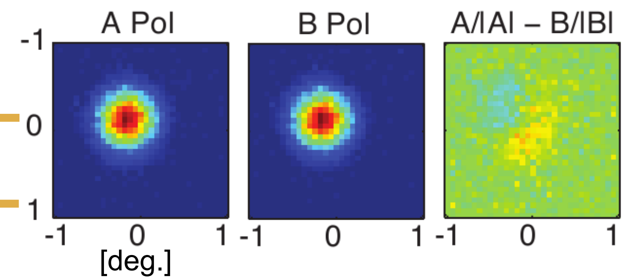
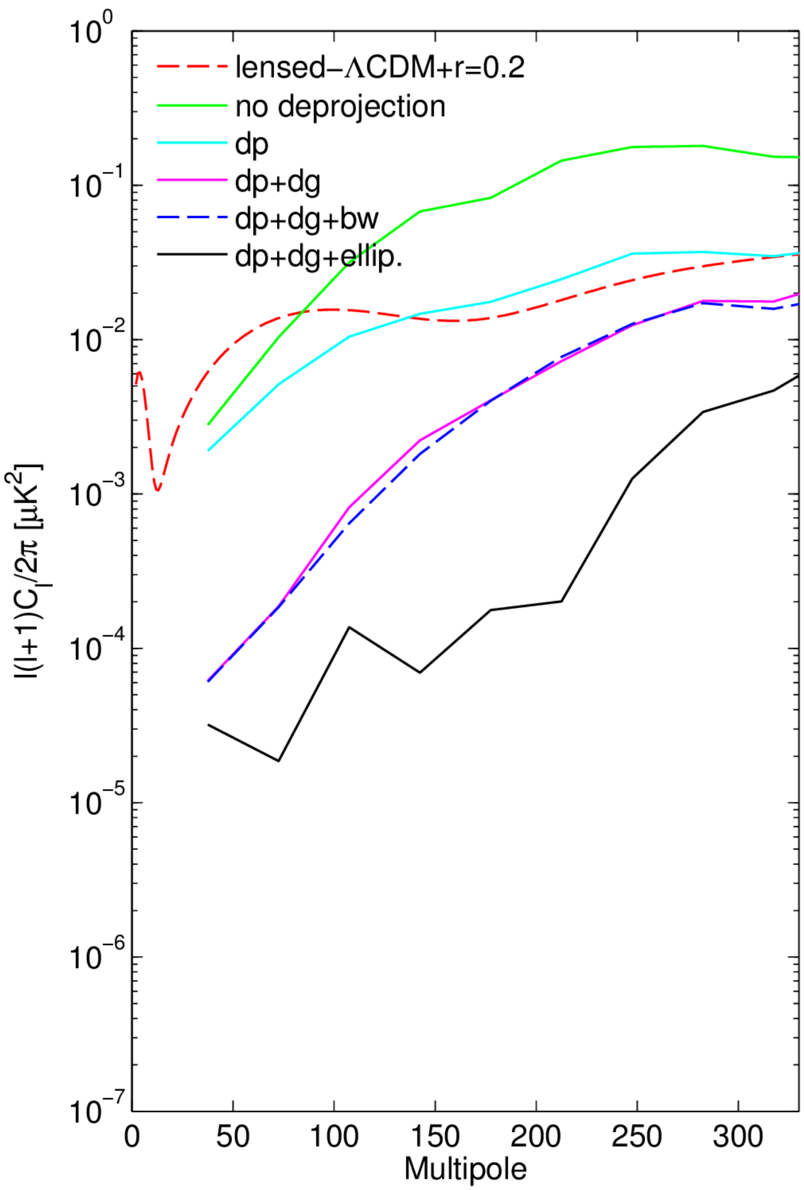
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

Splits to check intrinsic detector properties

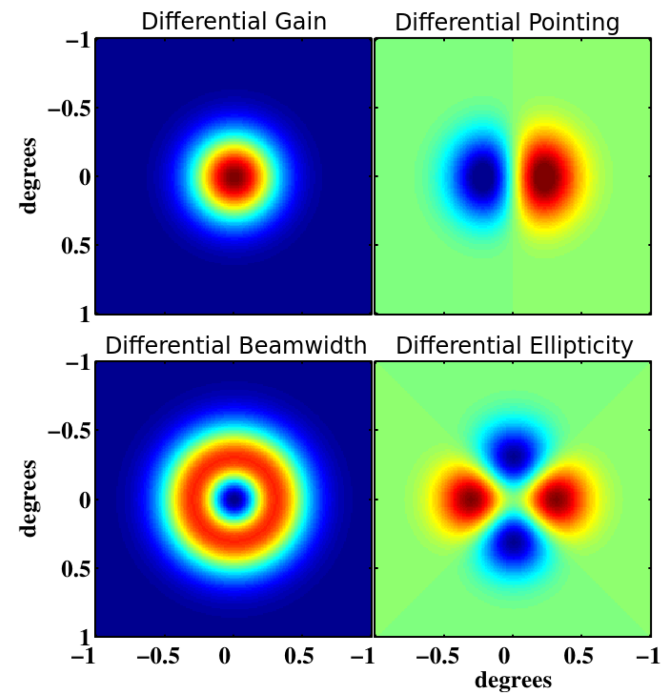


Checks for contamination from detectors with best/worst differential pointing. "Tile/dk" divides the data by the orientation of the detector on the sky.

Systematics Removal: Deprojection



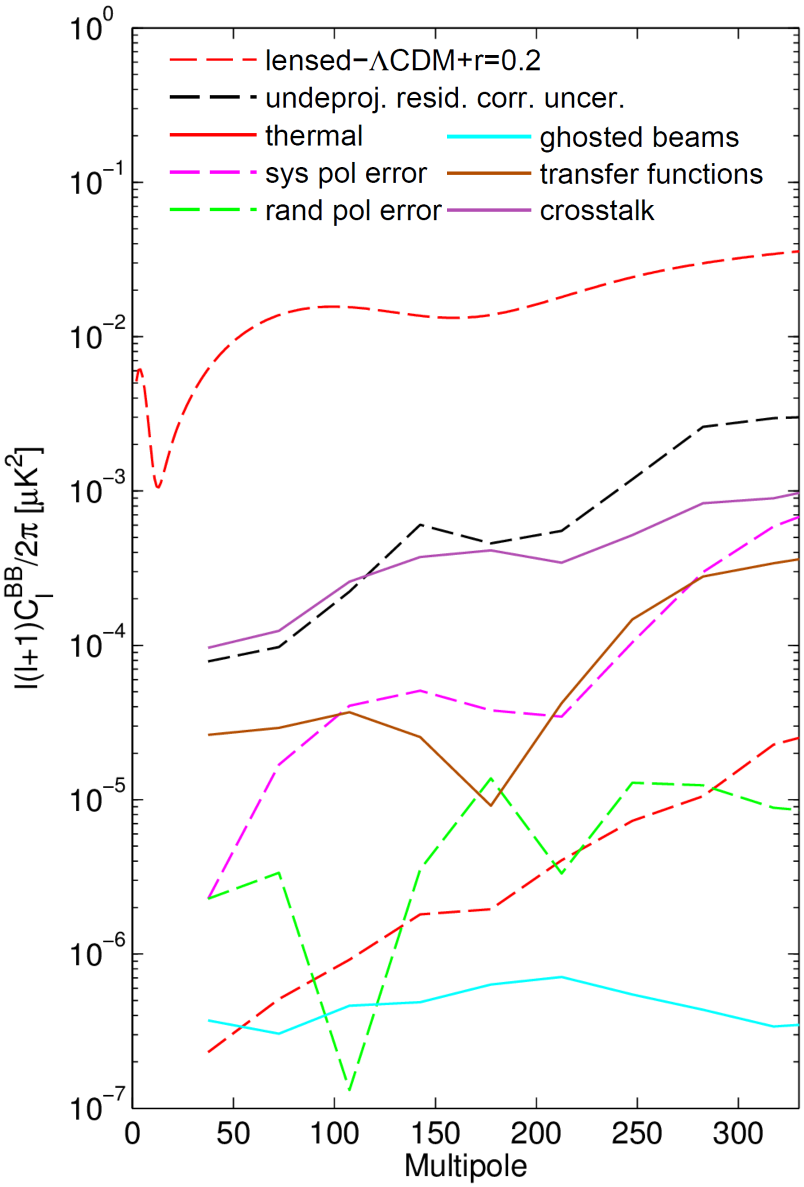
False polarization from beam differences is deterministic, given temperature map (WMAP/Planck)



Deproject differential gain and pointing, subtract differential ellipticity

→ Residuals are small

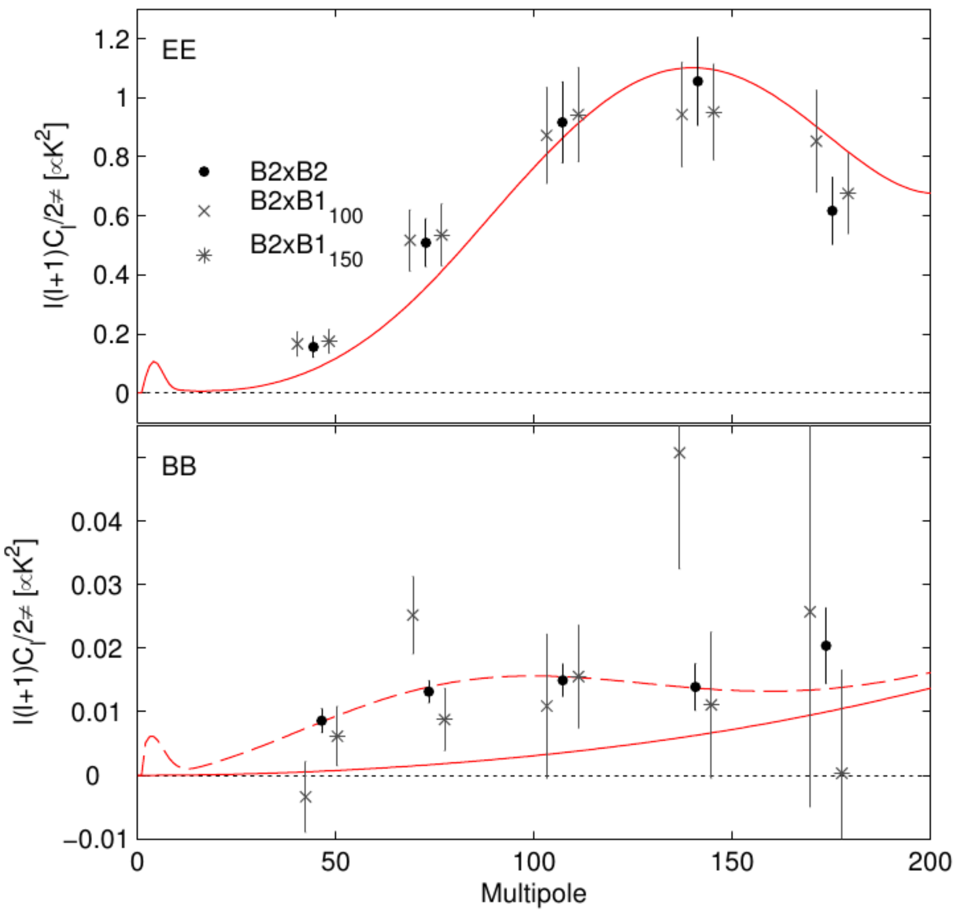
Systematics beyond Beam imperfections

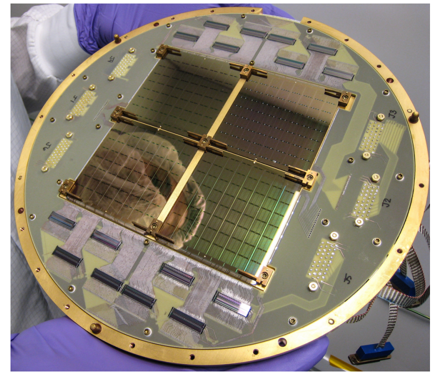


Many other systematics studied with simulations based on measured imperfections

No significant residuals for any!

Cross Correlation with BICEP1





BICEP2: Phased antenna array and TES readout 150 GHz

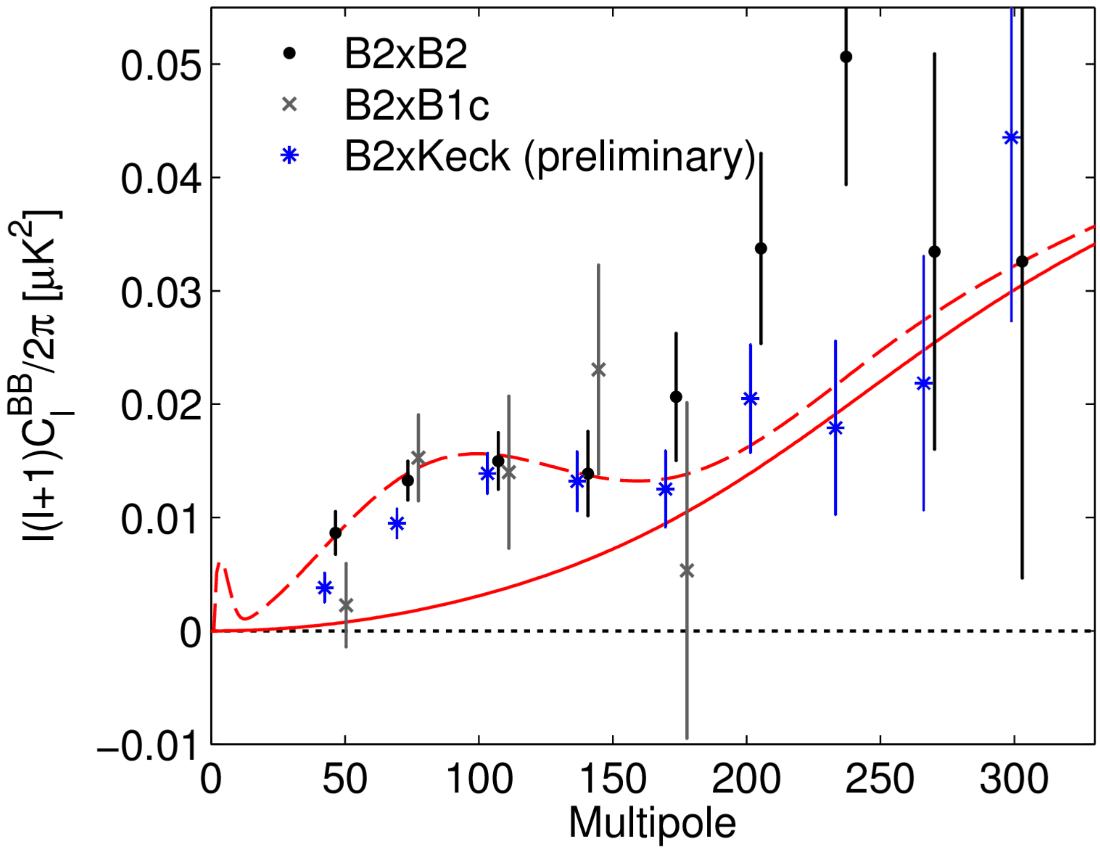
BICEP1: Feedhorns and NTD readout 150 and 100 GHz

BICEP1 is less sensitive, but **different technology** and **multiple colors** on the **same sky**.

Cross-correlations with both colors are **consistent** with the B2 auto spectrum

Cross with B2 x $B1_{100}$ detects BB power at **3σ**

Additional Cross Spectra



3.5σ detection of BB in cross with color-combined BICEP1

Excess power also evident in cross with 2 years of Keck Array data (150 GHz)

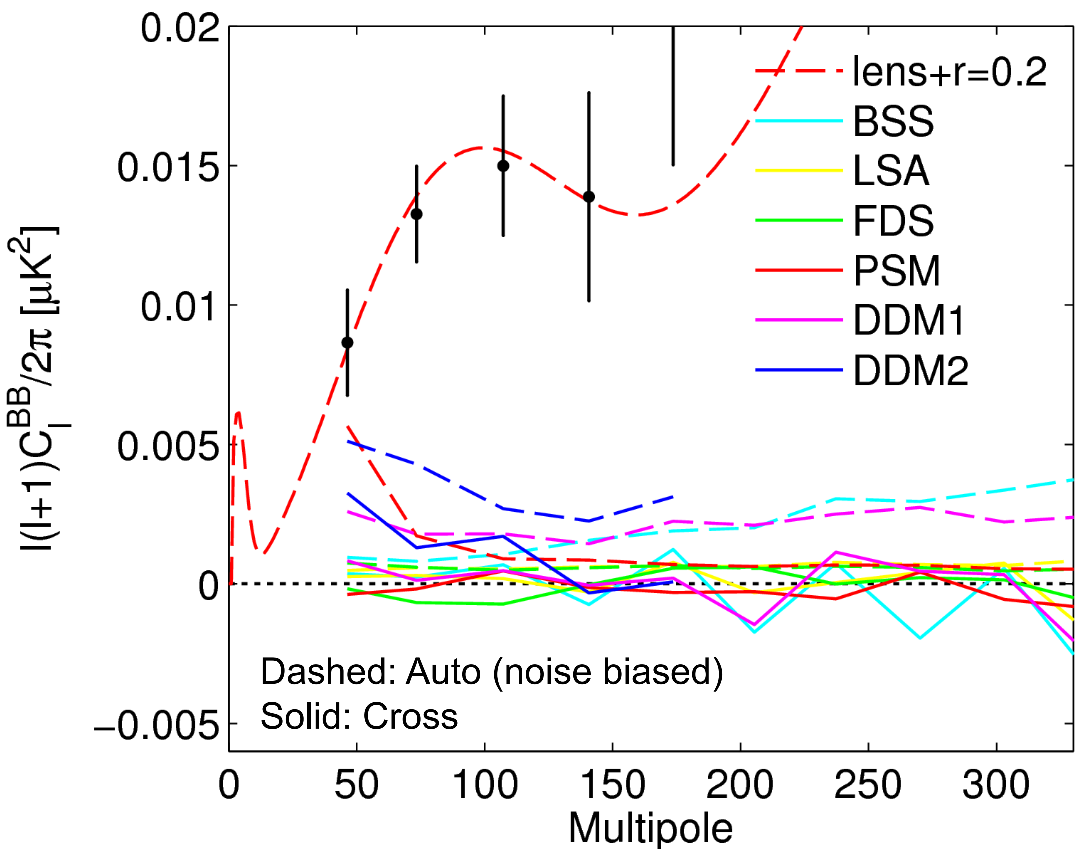
What Could This Be?

- Instrumental Systematics?
- Galactic Foregrounds?
- Cosmology?

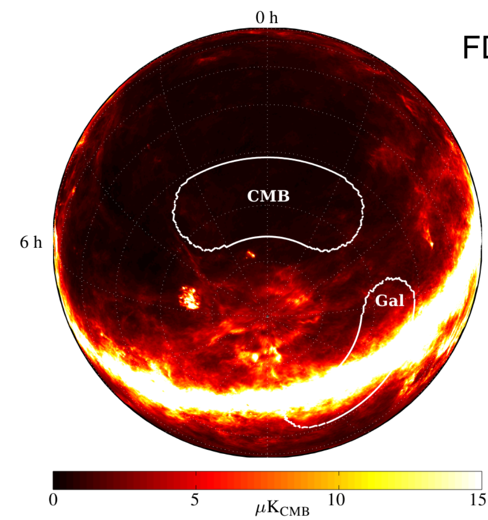
Polarized Foregrounds

- Any polarized astrophysical emission between the surface of last scattering and us
- Dust "Blue" ~ $\nu^{+1.75}$
  - Needs careful thought
- Synchrotron "Red" ~ ν^{-3}
  - WMAP, Planck Sky Model: upper limit $r<0.003$. Negligible.
- Polarized sources (all possibilities but localized in space)
  - Planck source catalogs, ATCA. Negligible.

Polarized Dust Foreground Projections



FDS Model



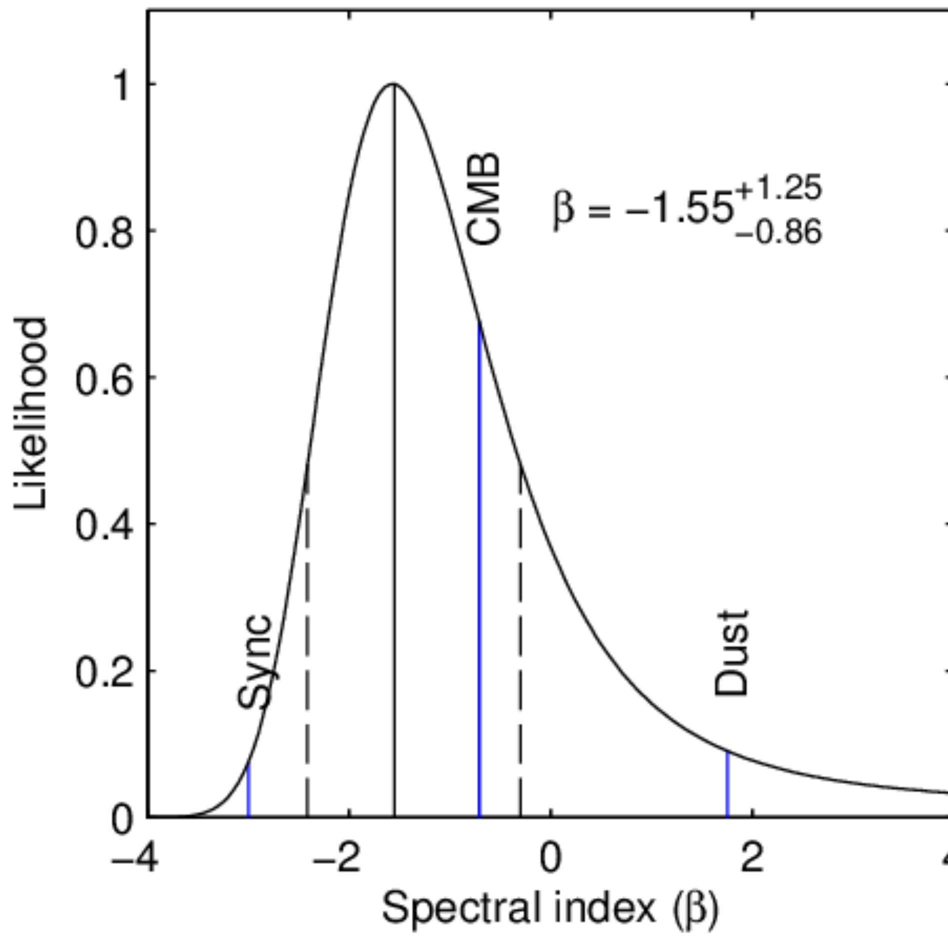
The BICEP2 region is chosen to have extremely low foreground emission.

Various models of polarized dust emission to estimate foregrounds

→ All well below signal level

Spectral Index of the B-mode Signal

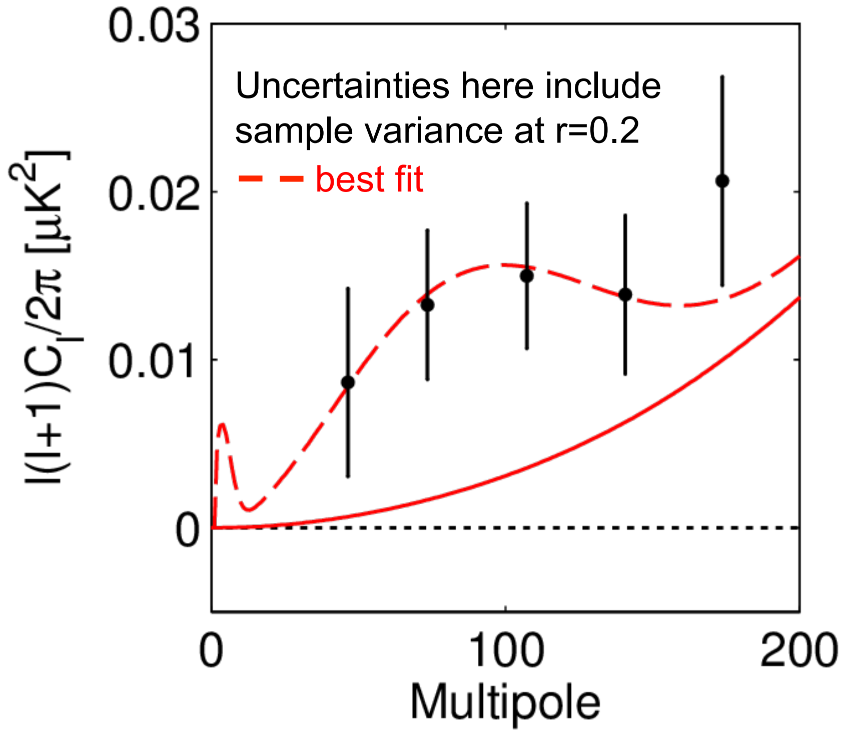
- Constrain BB signal color with $B2_{150}xB1_{100}$
  - If **pure dust**, expect little correlaiton
  - If **pure synchrotron**, expect bright correlation
  - Find consistent with CMB
- Disfavor benchmark dust and synchrotron models at **2.2**/**2.3σ**

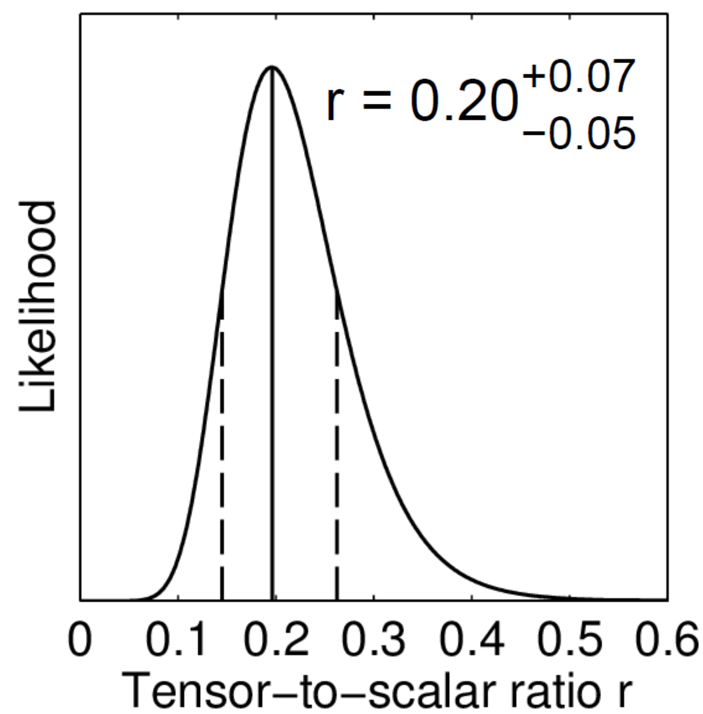


What Could This Be?

- Instrumental Systematics?
- Galactic Foregrounds?
- Cosmology?

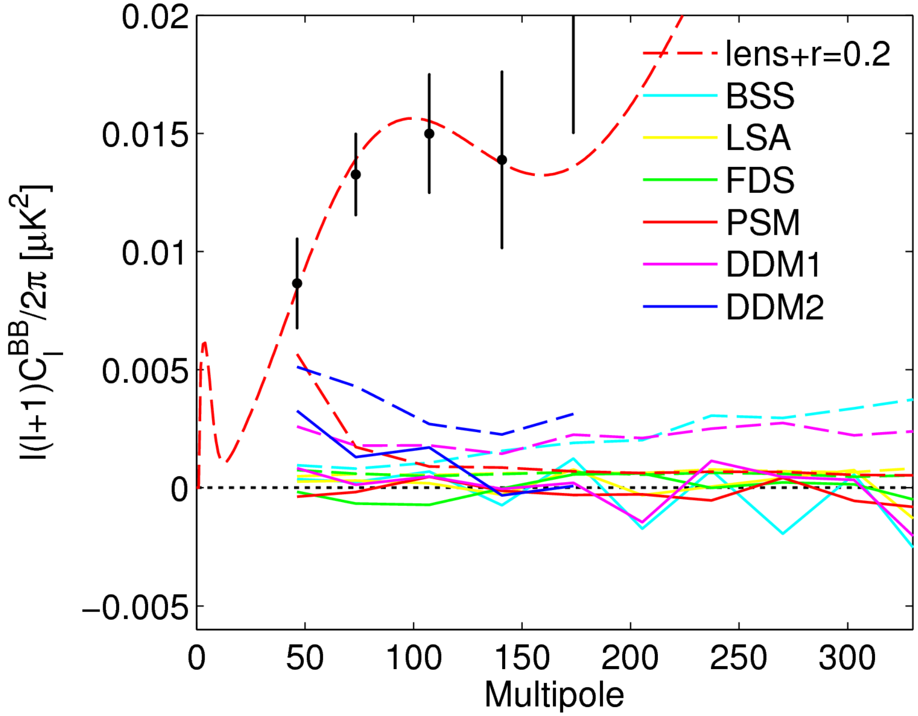
Constraint on Tensor-to-scalar Ratio r

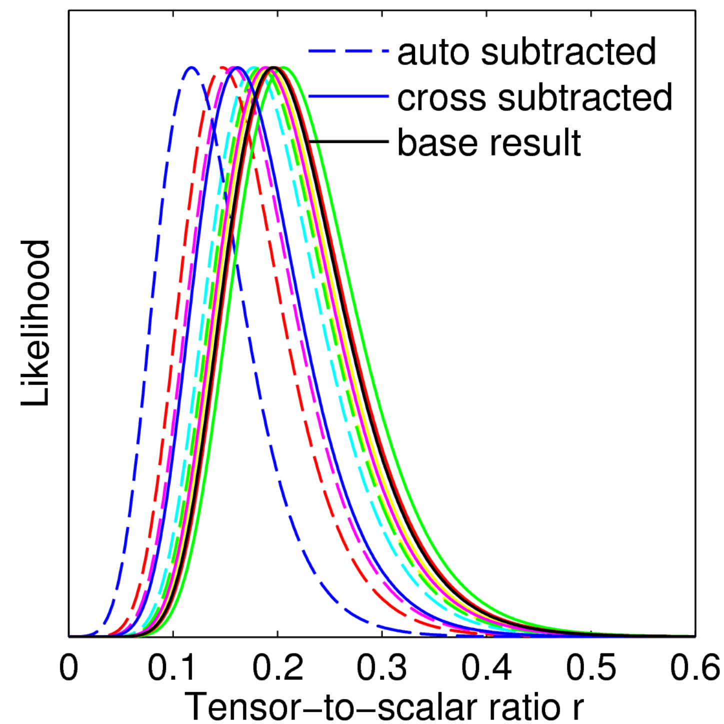




- Best fit **r = 0.20** (PTE of fit 0.9)
  - Consistent with large-field, GUT-scale inflation
- r = 0 is disfavored at **7.0σ**
- Sample variance dominated → need more sky!

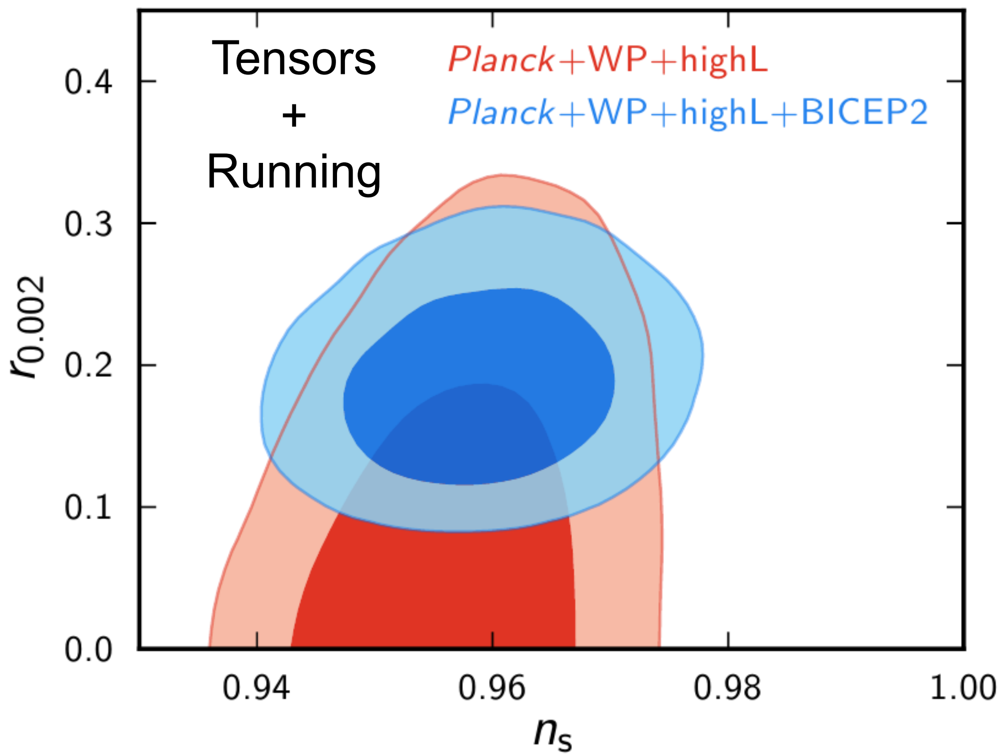
Effect of Foregrounds





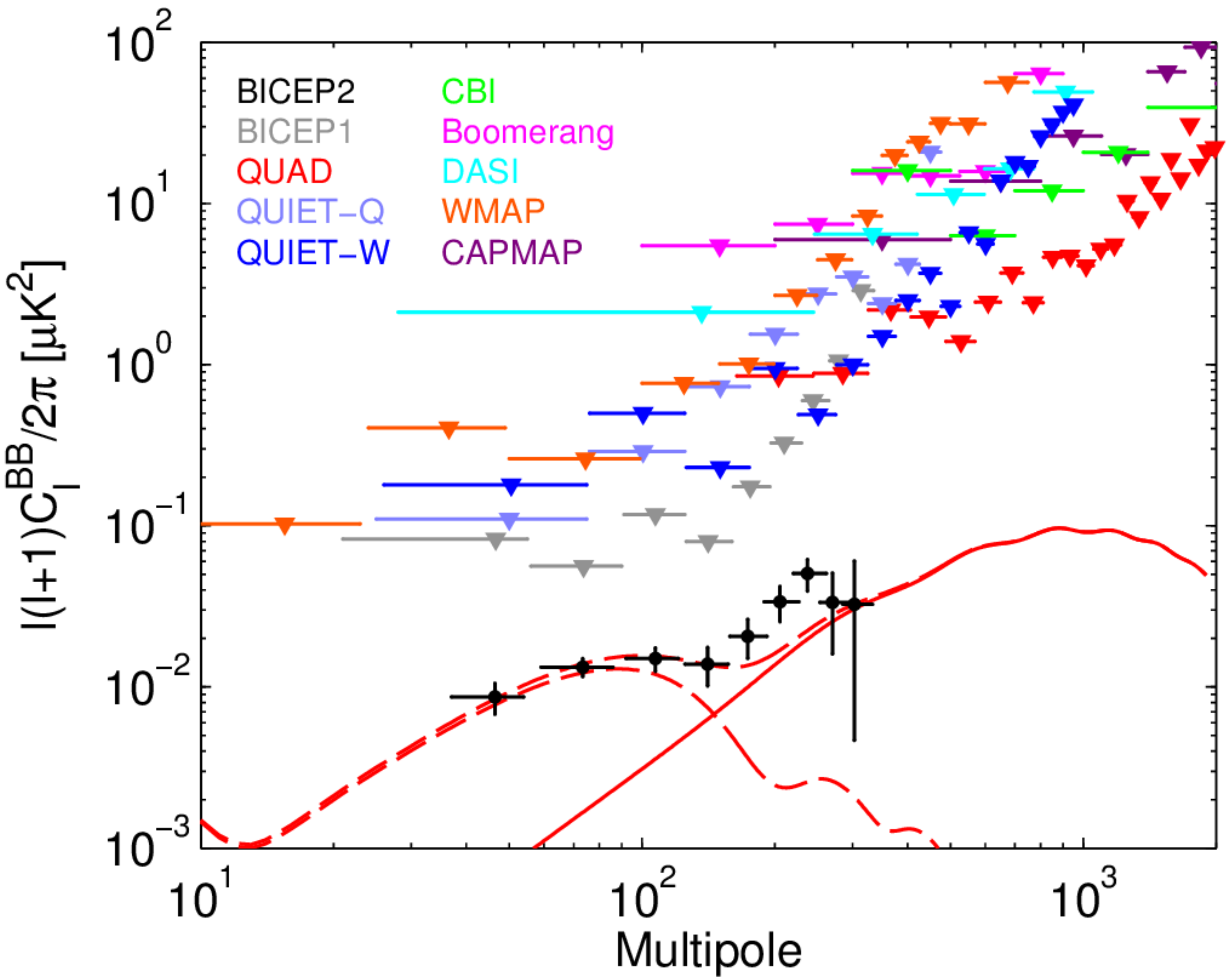
- Foregrounds could contribute a small amount of observed BB
- Total power spectrum does not look like foreground expectations
- Subtracting DDM2 gives $r = 0.16^{+0.06}_{-0.05}$
- Still disfavors r = 0 at **5.9σ**

Parameter Constraints



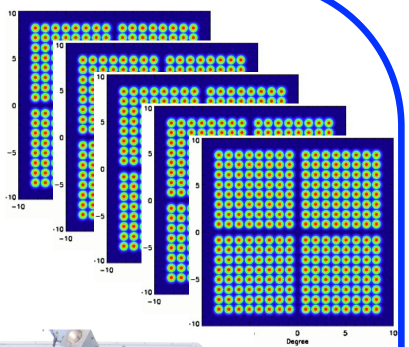
- Some tension with SPT/Planck, etc.
  - Indirect measurement from temperature: r<0.11
- Could be relieved with running, foregrounds, etc.
- Specific resolution remains to be seen

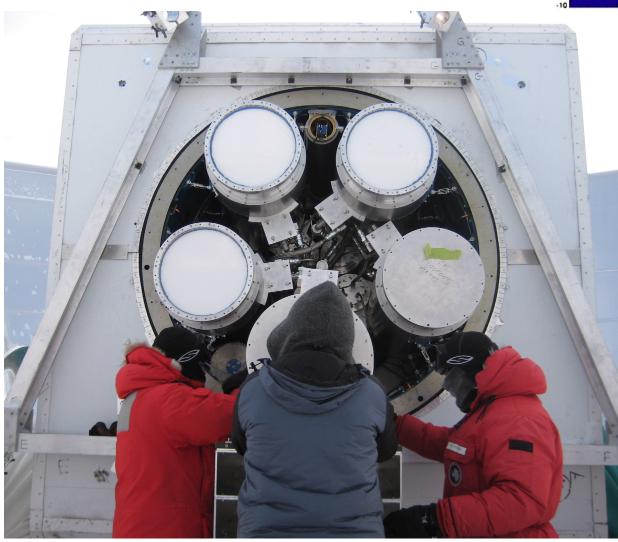
BICEP2 Results



What comes next for us?

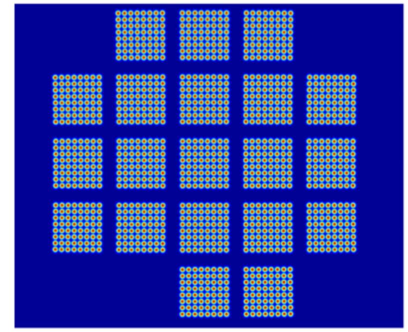
Keck Array
3 x deployed Jan 2011
2 x deployed Jan 2012
5 Years of Observation

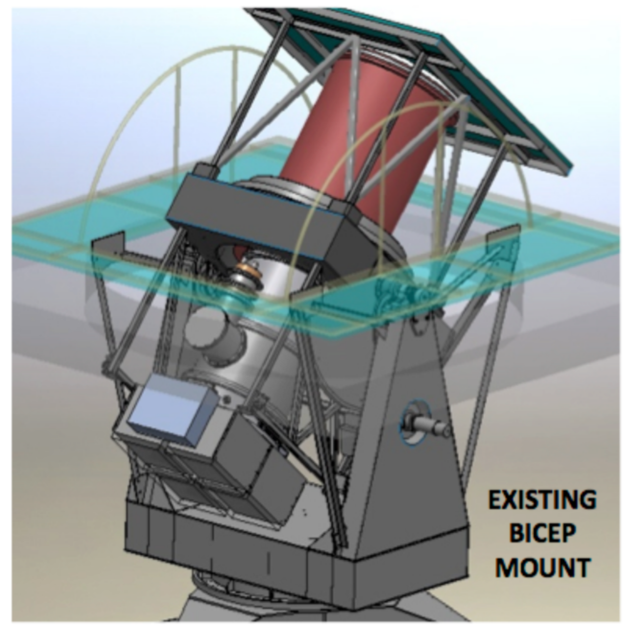




5 x 512 @ 150 GHz (2012-2013)
Upgraded 2014: 2 x 512 @ 100 GHz

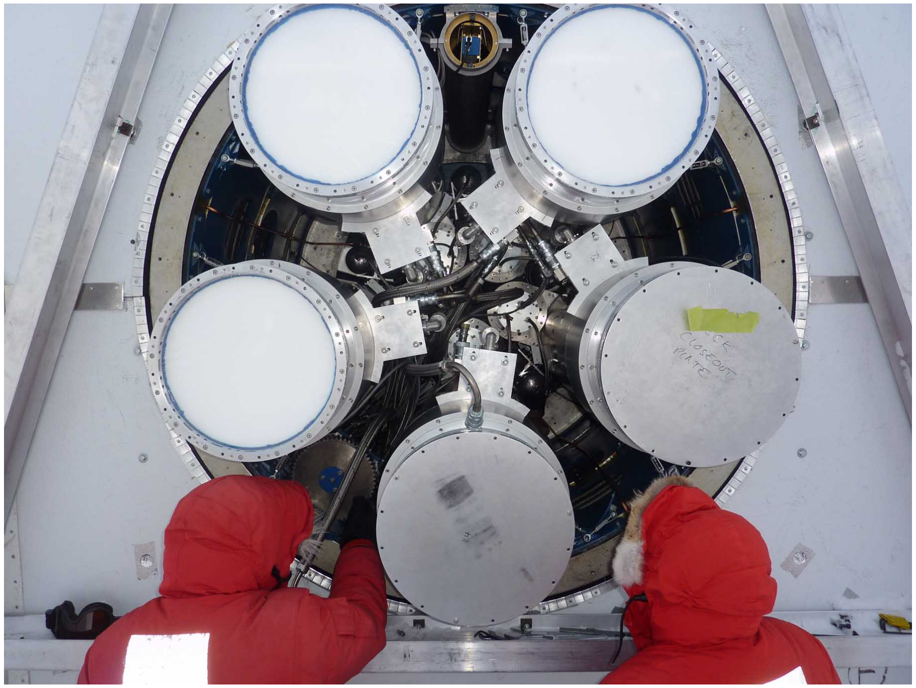
BICEP3
Will Deploy in 2014



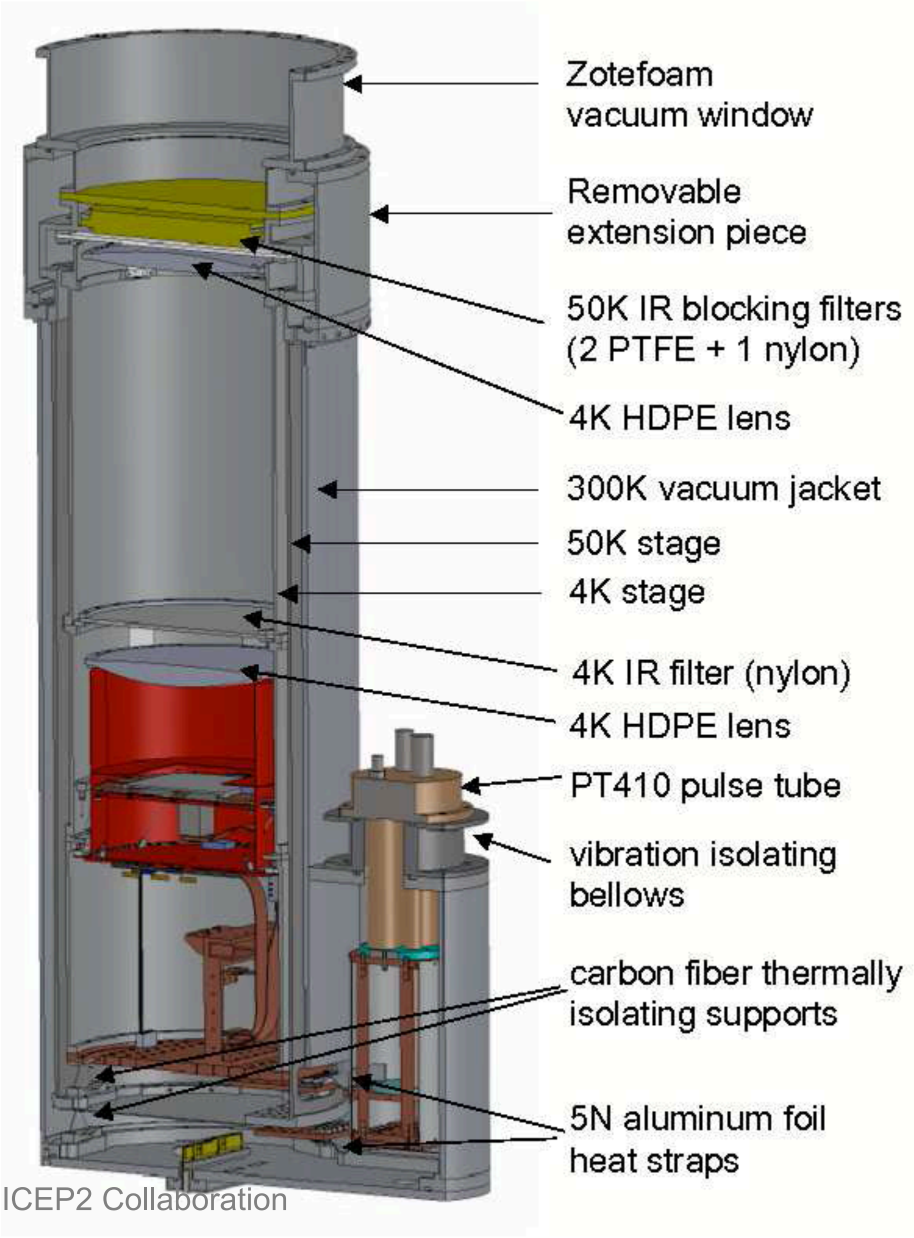


2056 @ 100 GHz

The Keck Array (2011 -)



- 5x BICEP2
- New: pulse tube coolers
- 2012-13: 5 @ 150 GHz




Winter Overs:
Robert Schwarz
and Steffen Richter

Achieved BICEP/Keck Array Program

	Sensitivity ($uK \sqrt{s}$)
BICEP 1	54
BICEP 2	17
Keck Array 2011	20
Keck Array 2012	11
Keck Array 2013	9.5

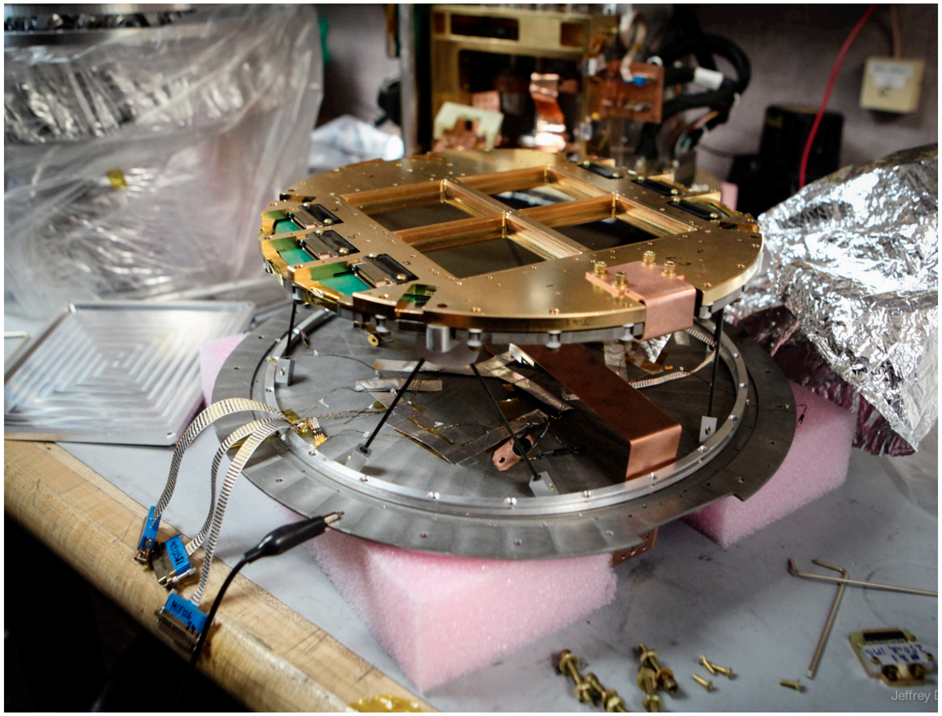
3 receivers only in 2011

All 5 receivers deployed

5 receivers, 2 more focal planes with improved sensitivity

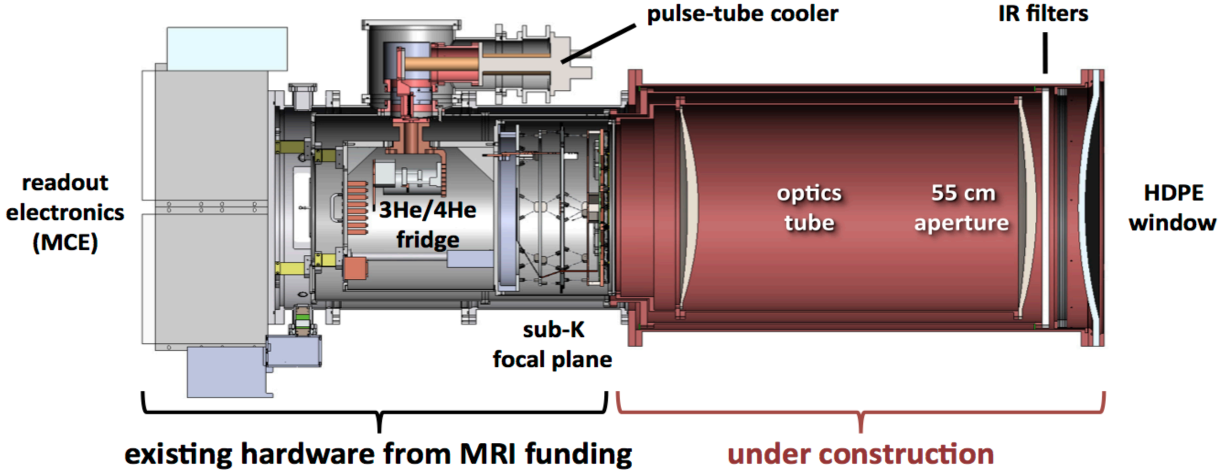
New in 2014: Keck Array Upgraded to 100 GHz

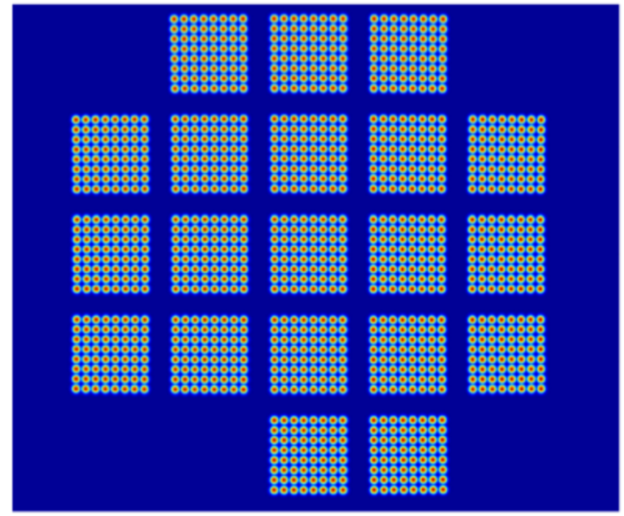
- 2 Receivers now at 100 GHz
- Frequency coverage: important for immediate feedback on color



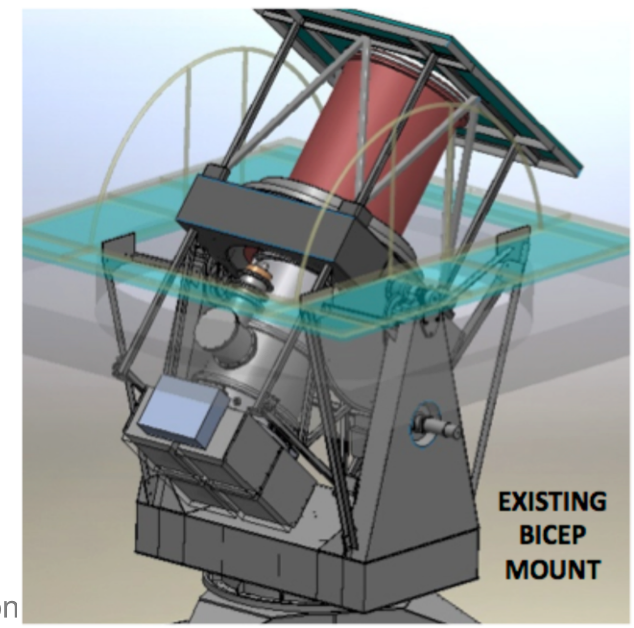
BICEP3 (2015 -)

Will deploy in December 2014: 2056 Detectors @ 100 GHz



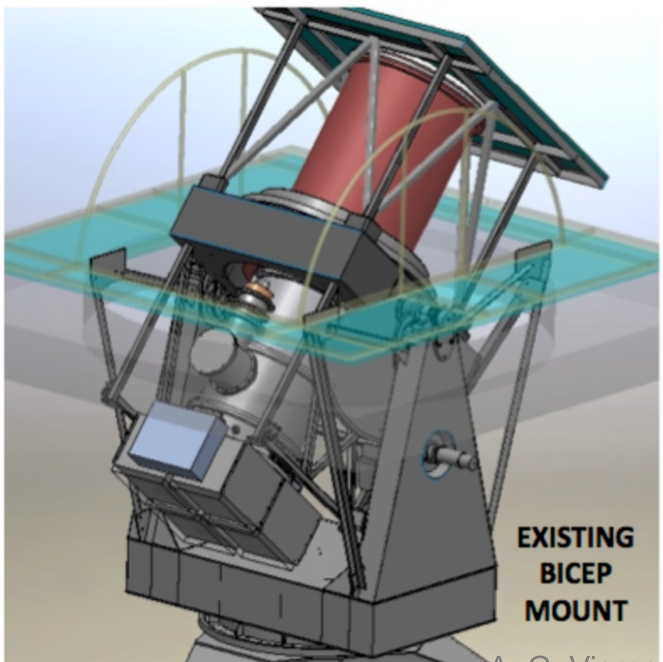


- Larger aperture, faster optics → 10x BICEP2's optical throughput
- Doubles the program's survey speed
- Important for foreground separation



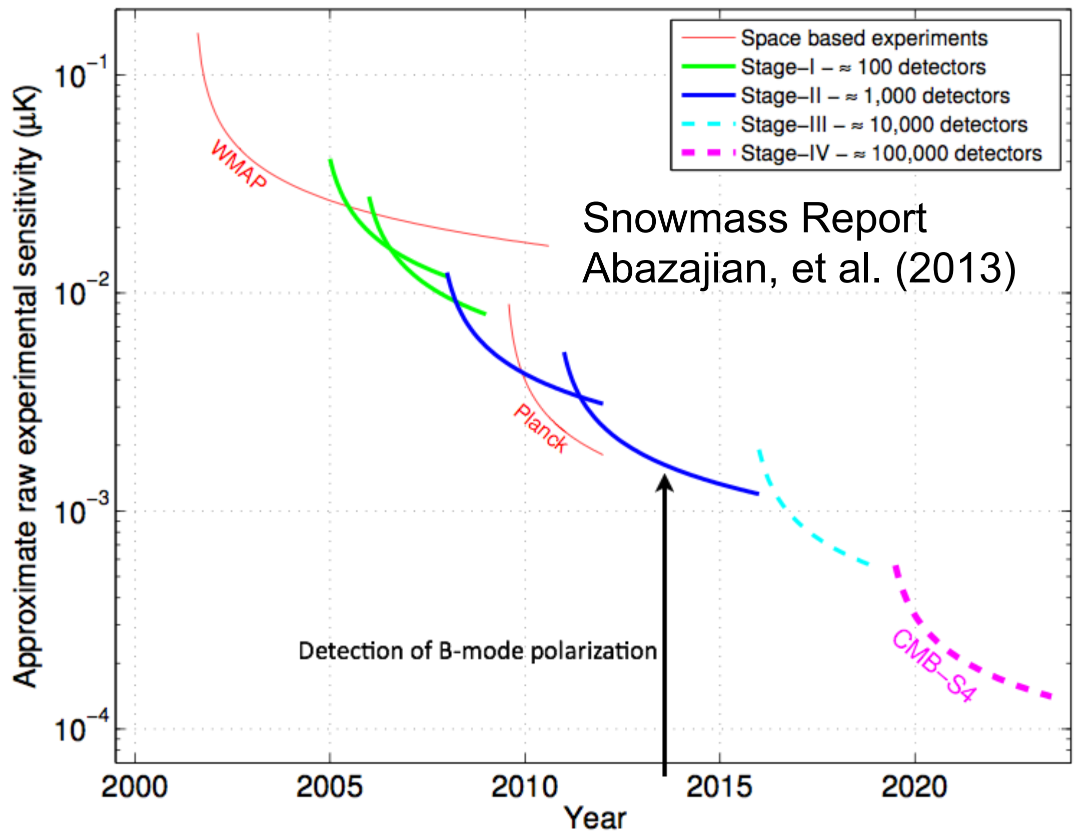
BICEP3 Status

- Detectors in production at Caltech
- Successful cryogenic run at Stanford (December 2013)
- → Harvard for beam mapping and integration Spring 2014
- → South Pole October 2014



A Foundation for Something Bigger

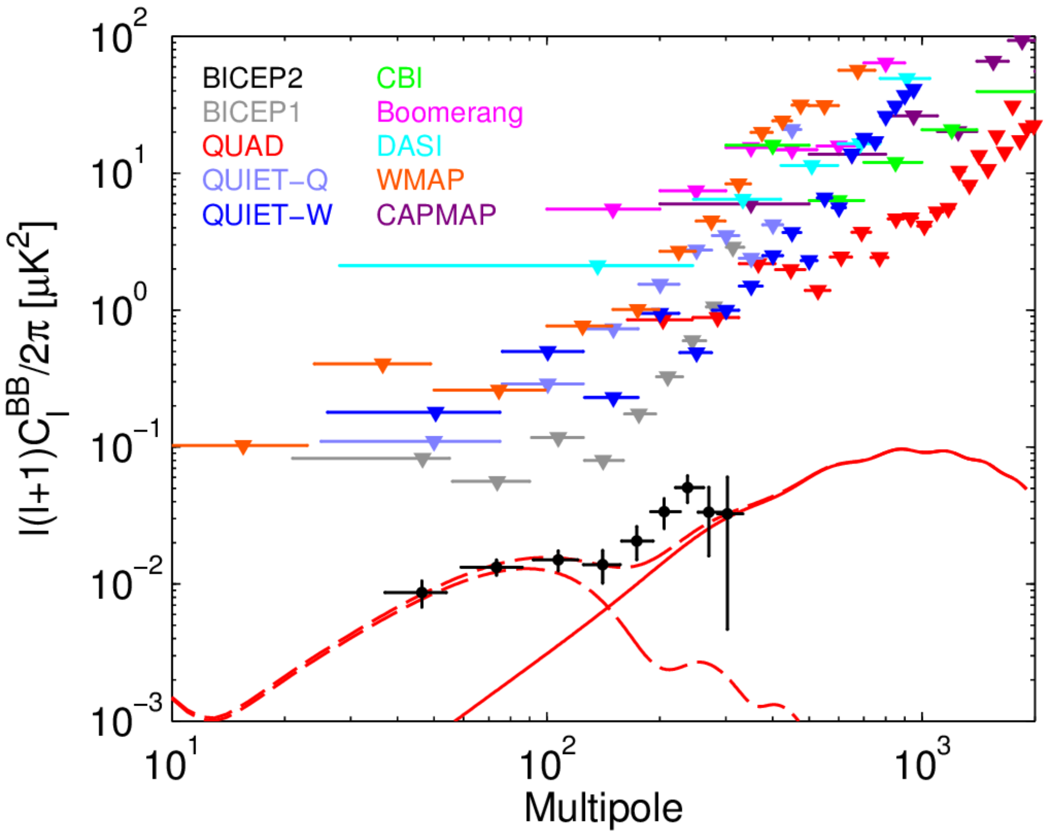
- What next on inflationary science?
  - Beat down sample variance on r, multiple frequencies, measure n_T
- CMB Stage-IV ground based experiment
  - Inflation
  - Physics at the GUT scale
  - Neutrino masses
  - Large scale structure
- A combination of large and small angular scales
- 100,000's of detectors in multiple platforms



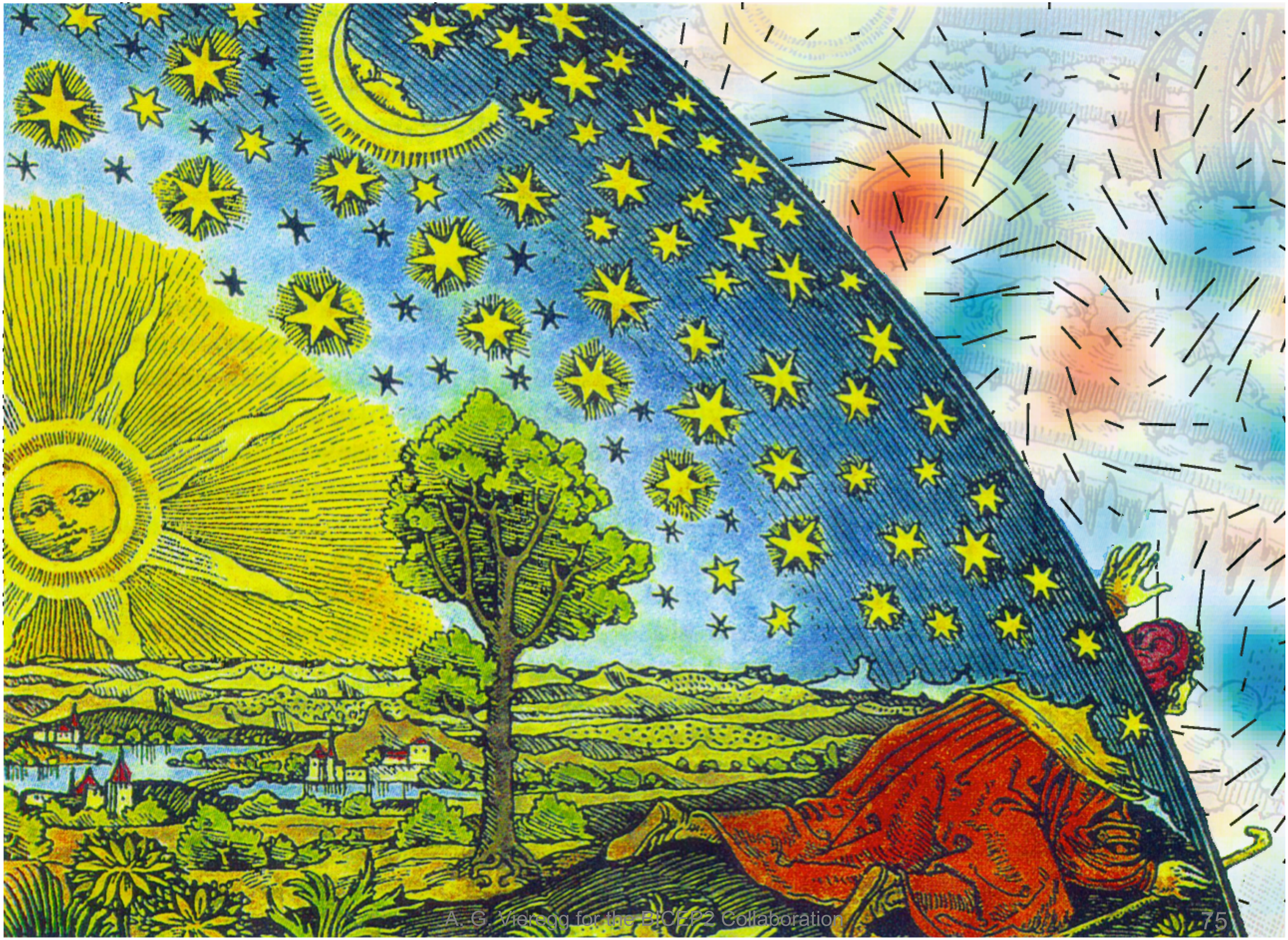
Snowmass Report
Abazajian, et al. (2013)

Conclusions

- 5.3σ excess above lensed Λ_{CDM}; 7.0σ preference for nonzero r
- Significant contributions from foregrounds and systematics disfavored
- Consistent with expectations from primordial gravitational waves from GUT-scale inflation
- We await confirmation from Planck, SPTPol, etc.
- The future of CMB science is as bright as ever



$r = 0.20^{+0.07}_{-0.05}$



BICEP2 / Keck Array