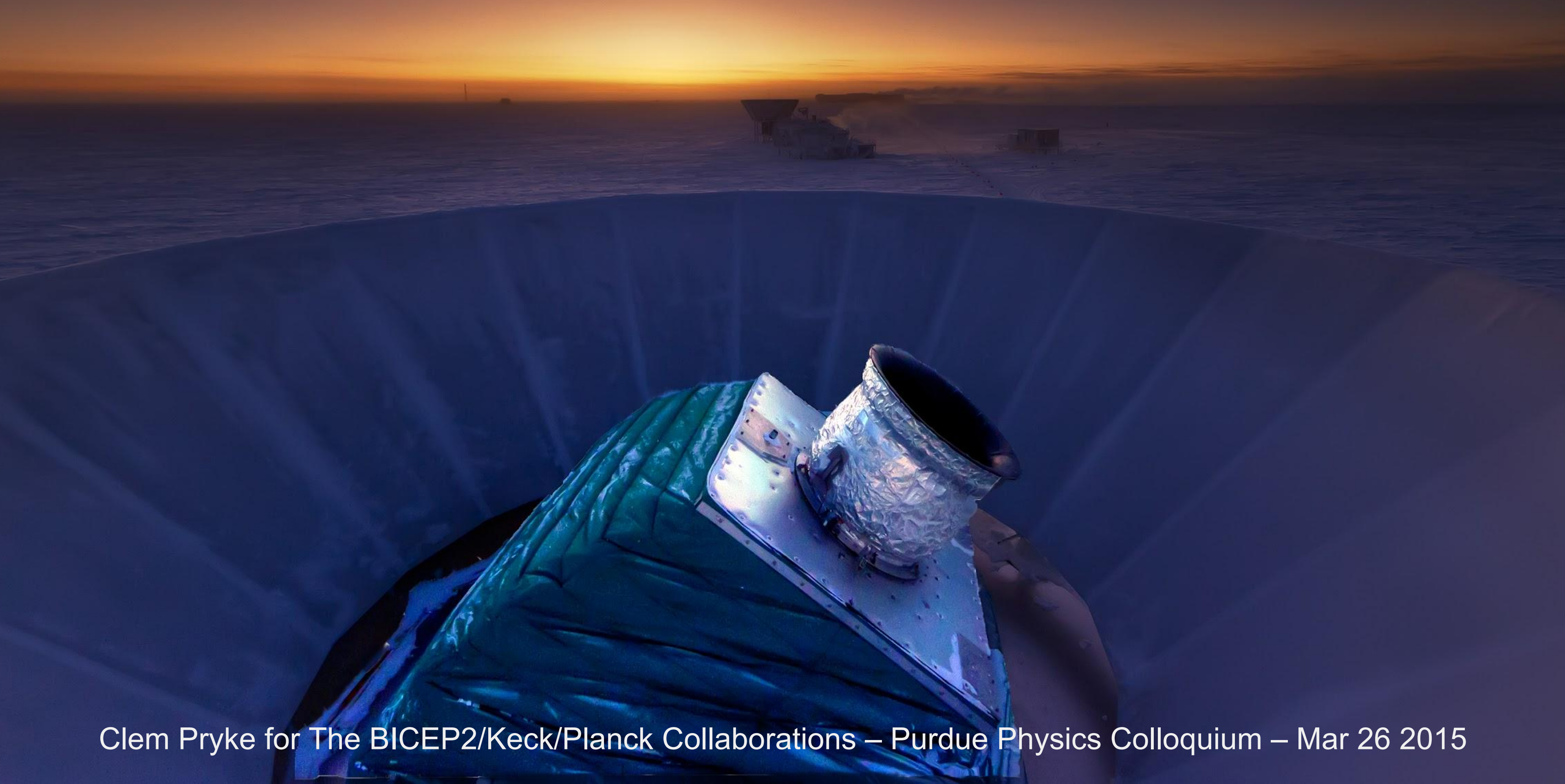
Detection of B-mode Polarization at 150 GHz and Degree Angular Scales by BICEP2 and Keck Array



Clem Pryke for The BICEP2/Keck/Planck Collaborations – Purdue Physics Colloquium – Mar 26 2015

Modern cosmology in a nutshell:

Edwin Hubble

1) The universe is expanding.

(Hubble, 1920s)

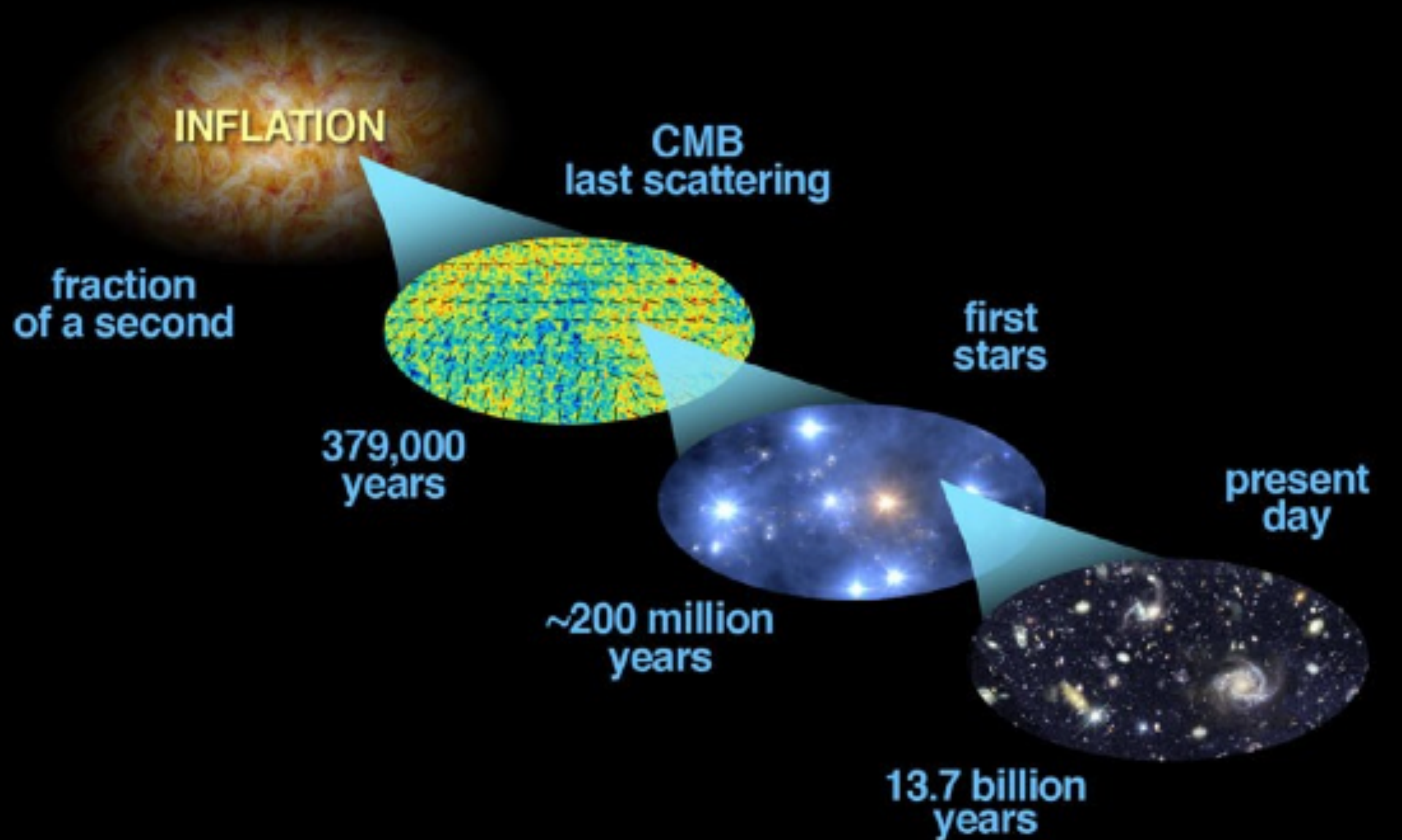
2) It was once hot and dense, like the inside of the Sun.

(Alpher, Gamow, Herman, 1940s)

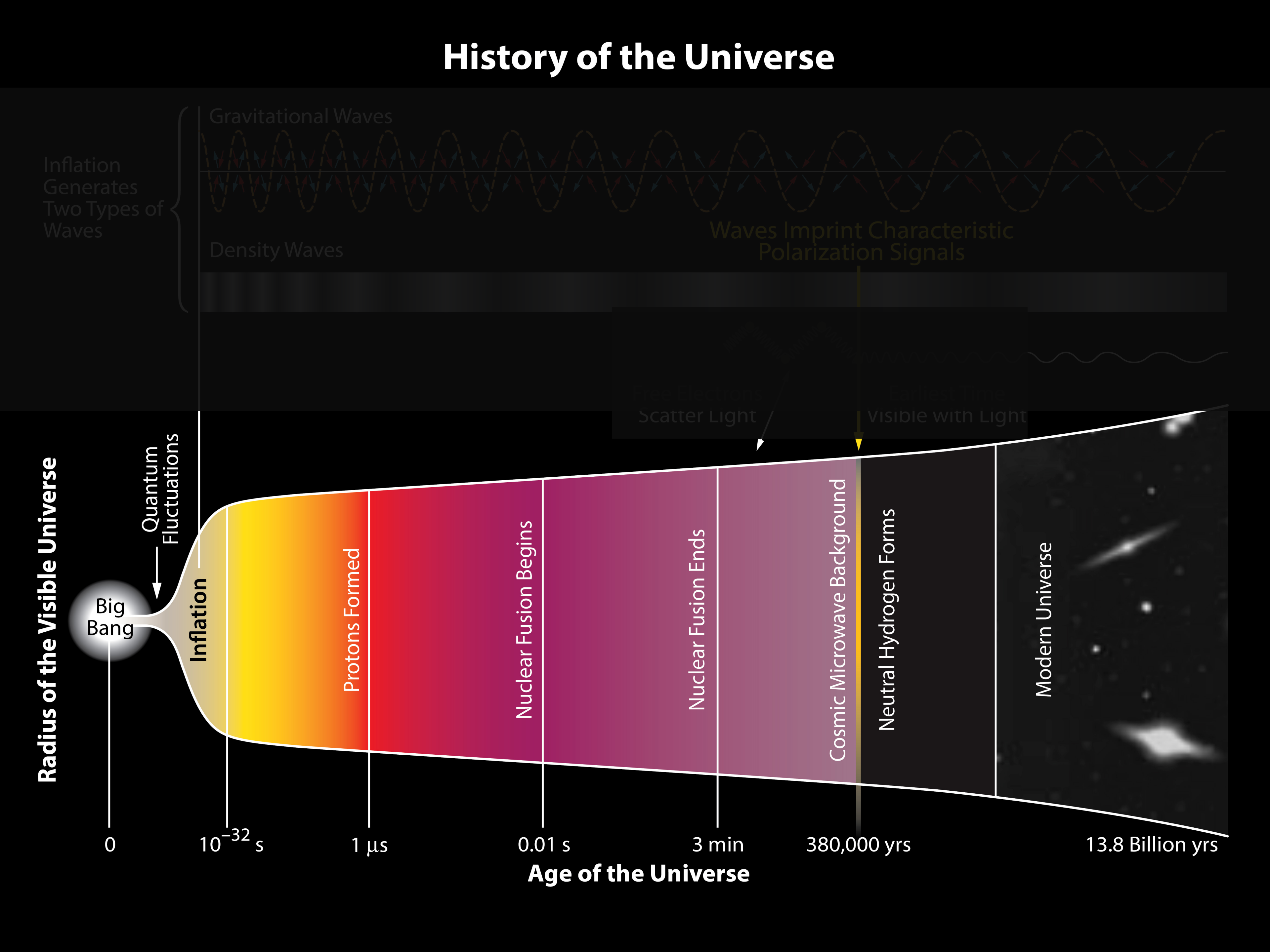
Bob Wilson & Arno Penzias
1978 Nobel Prize

3) You can still see the glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

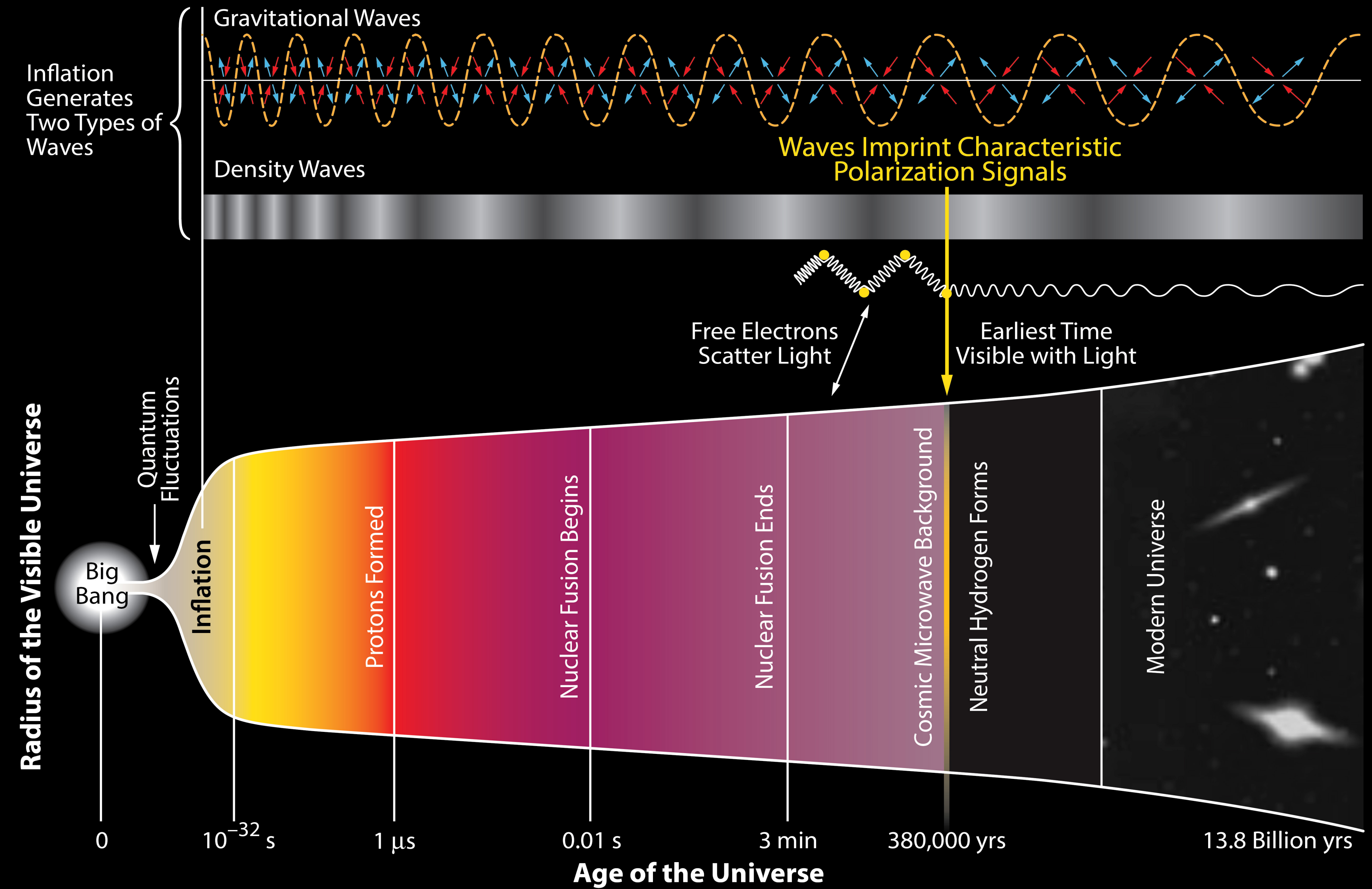
⇒ acceptance of the "HOT BIG BANG"



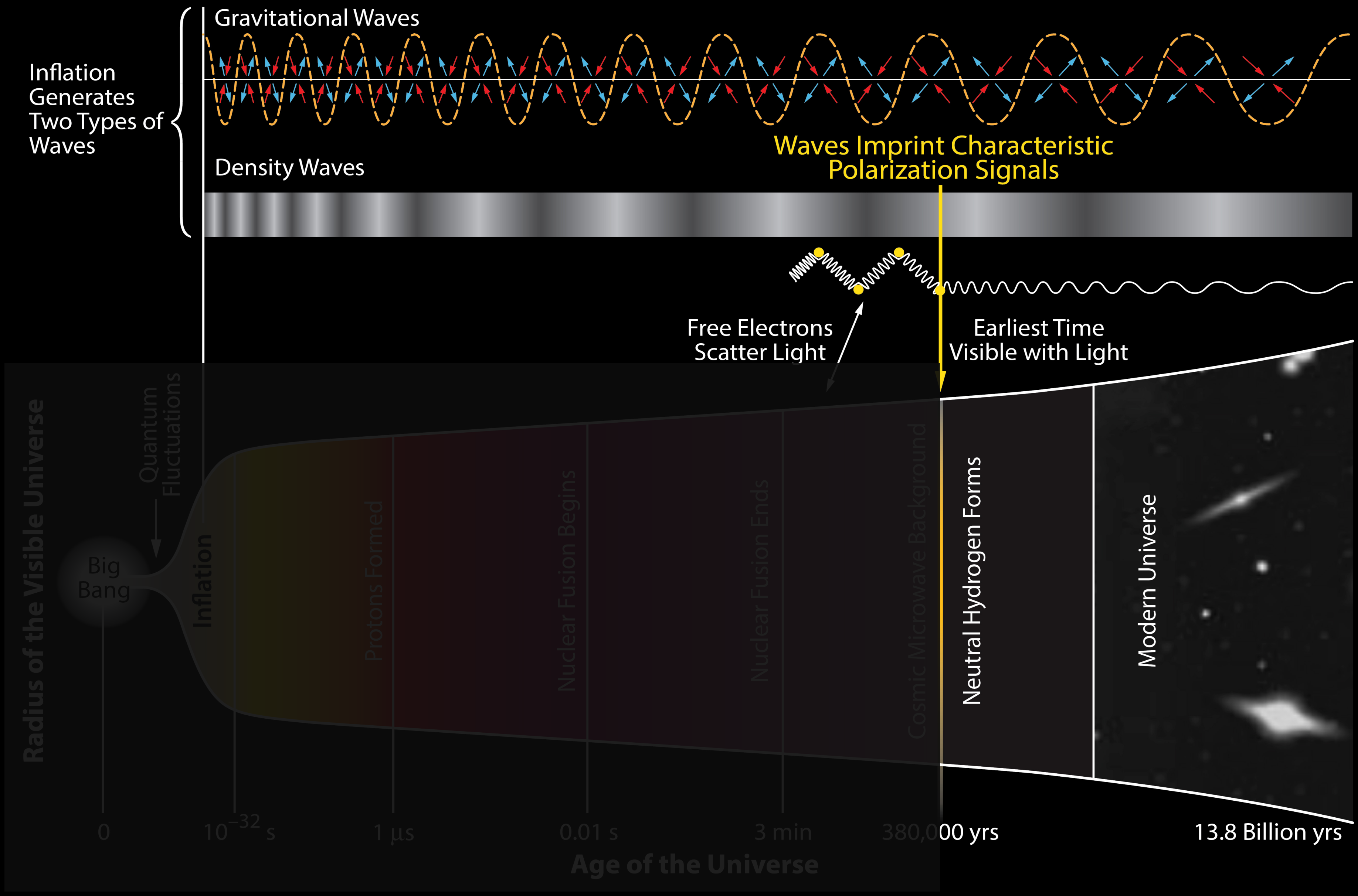
INFLATION
CMB
last scattering
fraction
of a second
first
stars
379,000
years
present
day
~200 million
years
13.7 billion
years


History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Scatter Light
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

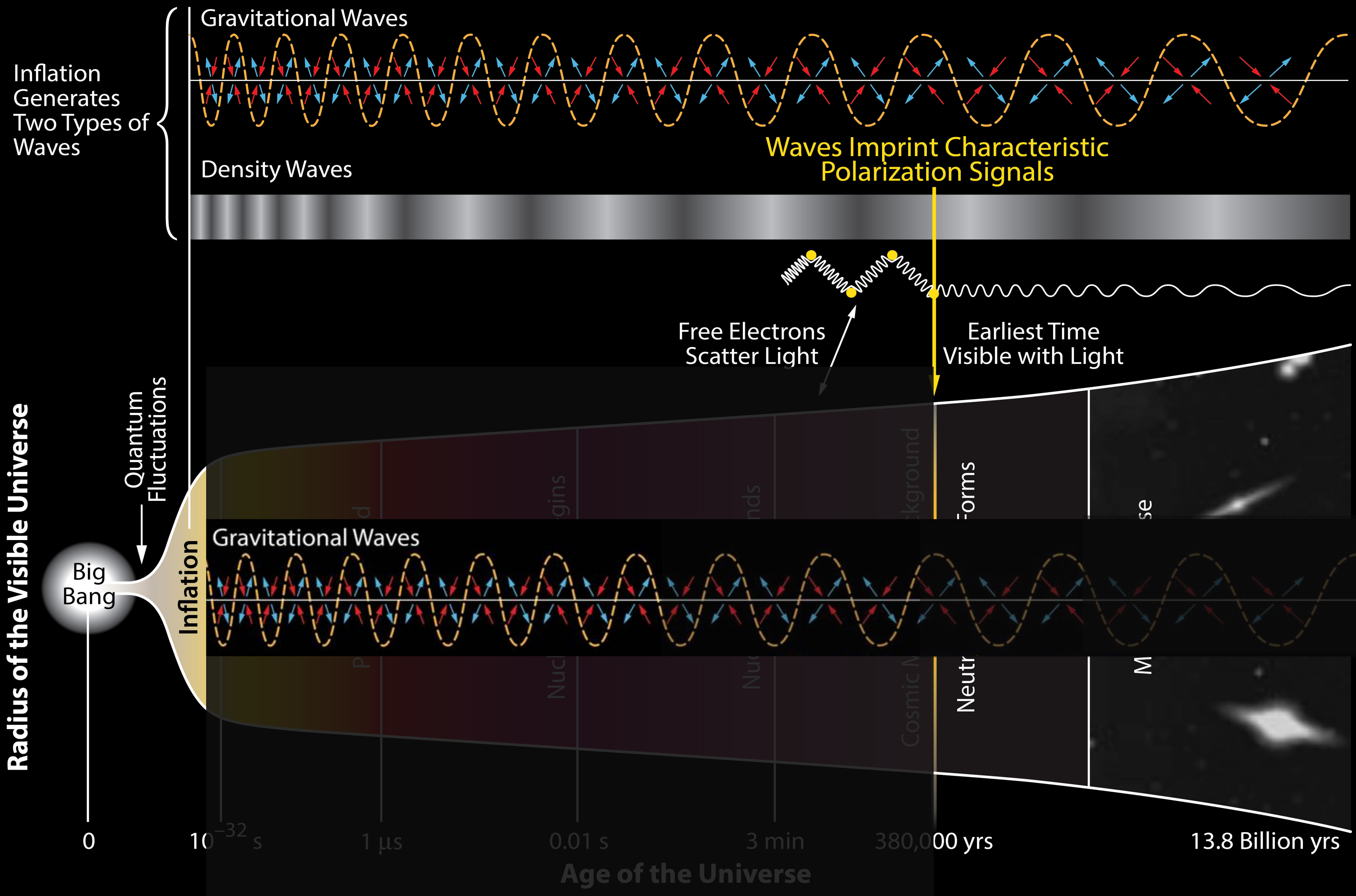
History of the Universe



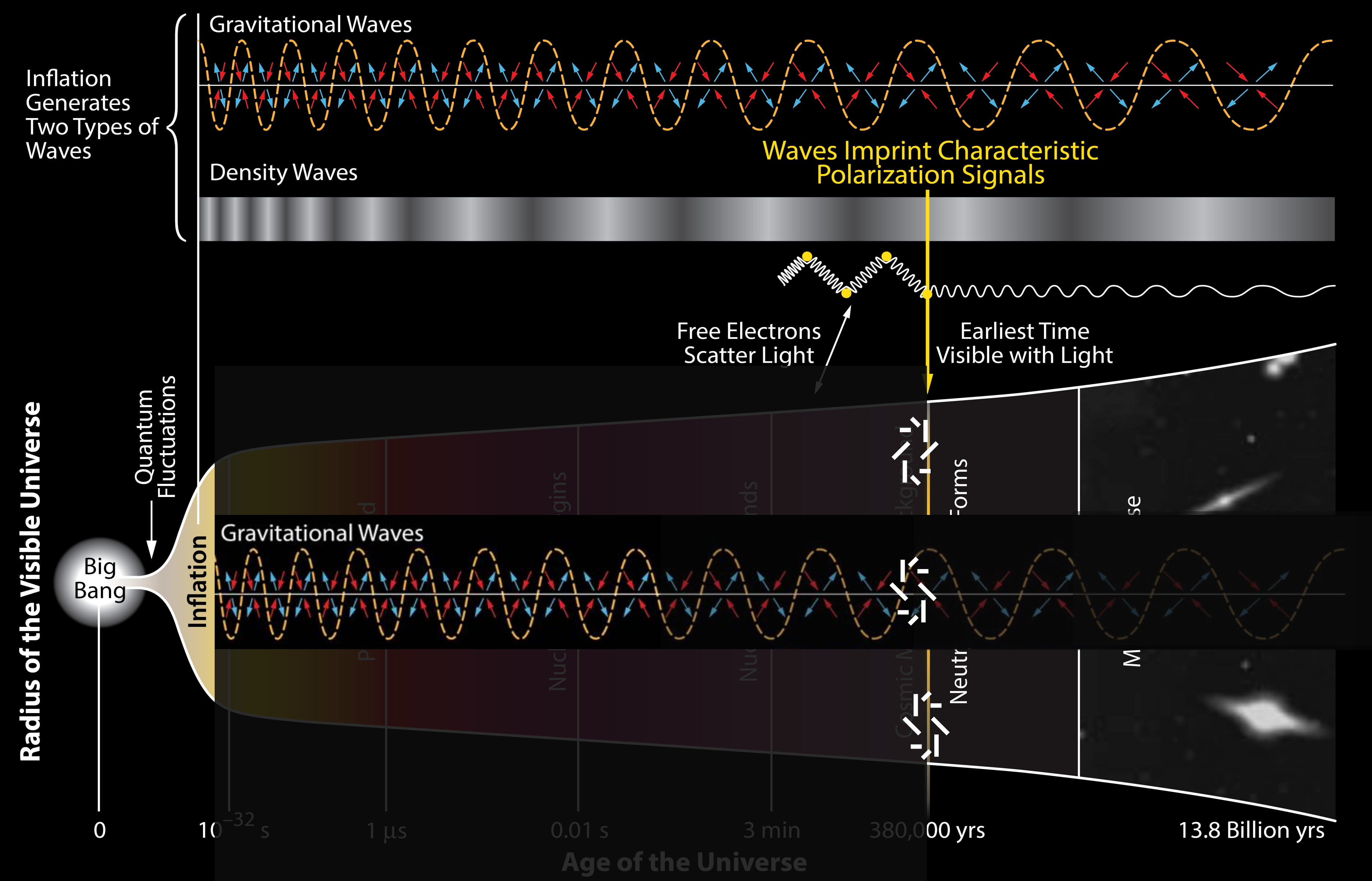
History of the Universe



History of the Universe



History of the Universe



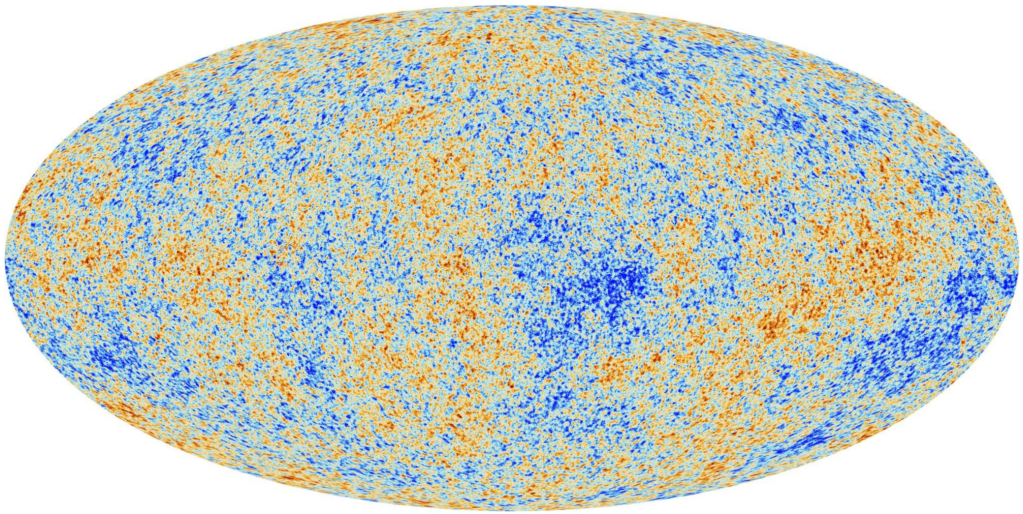
CMB Temperature Measurements / Inflation

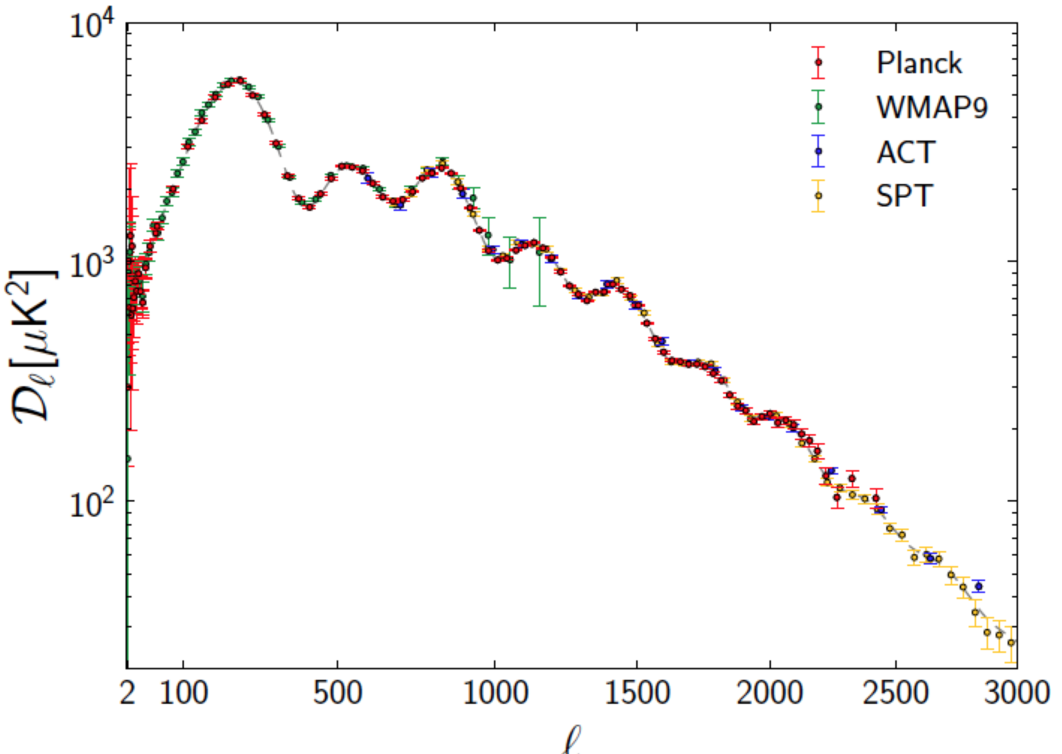
CMB temperature anisotropy now measured over full range of angular scales.

Consistent with ΛCDM paradigm(?) and constrains its parameters to sub percent accuracy.

Inflation “invented” in 1980s to explain facts about the Universe which were known or suspected.

Makes additional prediction of a background of gravitational waves (aka tensor modes) – which will imprint a specific CMB polarization pattern…
→ so-called “smoking gun”
→ amplitude tells us the energy scale at which inflation ocurred





Why Inflation?

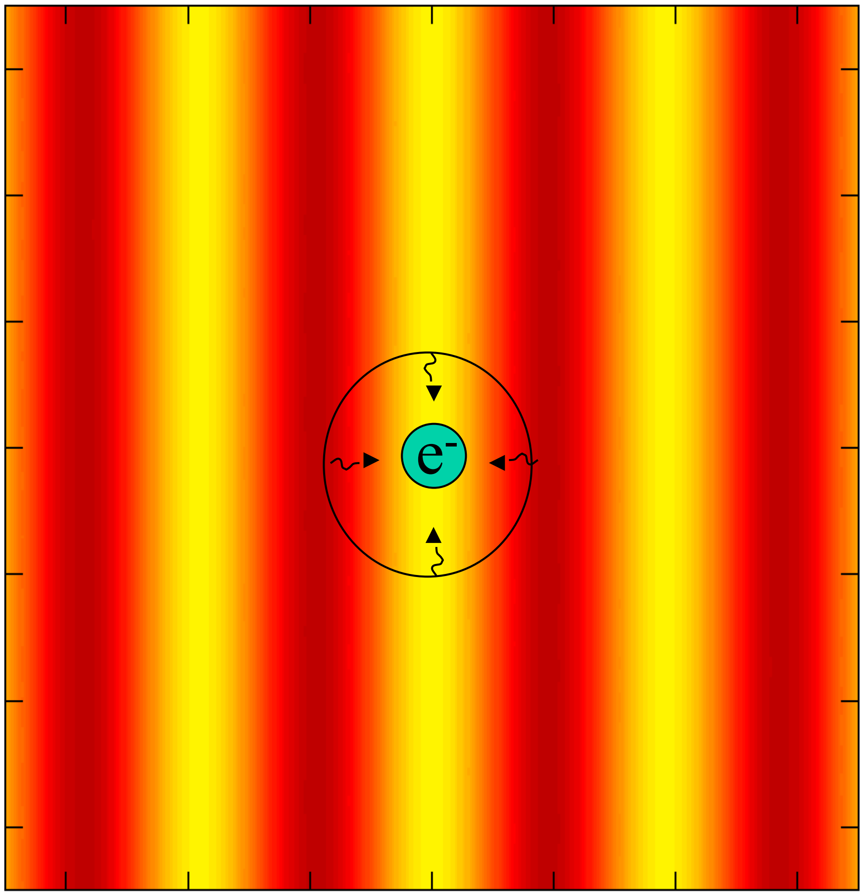
Solves the horizon problem: Why is the CMB nearly uniform? How do apparently causally disconnected regions of space get set to the same temperature? → A volume much larger than our entire observable universe today was once a caussally connected sub atomic spec.

Solves the flatness problem: Why is the net spatial curvature close to zero? → Any initial spatial curvature is diluted away to undetectabilty by the hyper expansion.

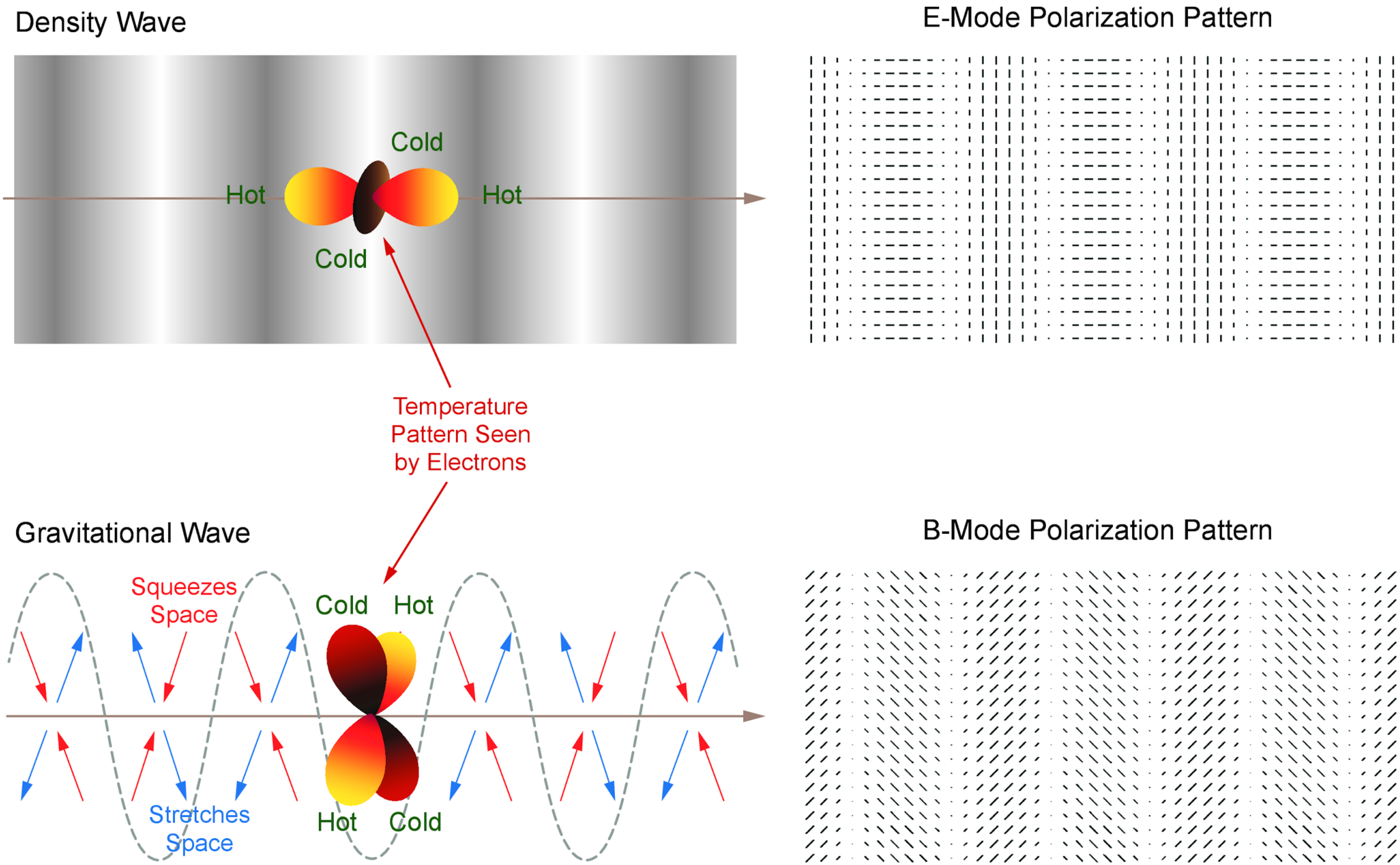
Explains the initial perturbation spectrum: Why was it close to flat power law? → Equal amount of perturbations are injected at each step in the exponential expansion.

Solves the monopole problem: Why do we not observe magnetic monopoles in the Universe today? → Monopoles are diluted away to undetectability.

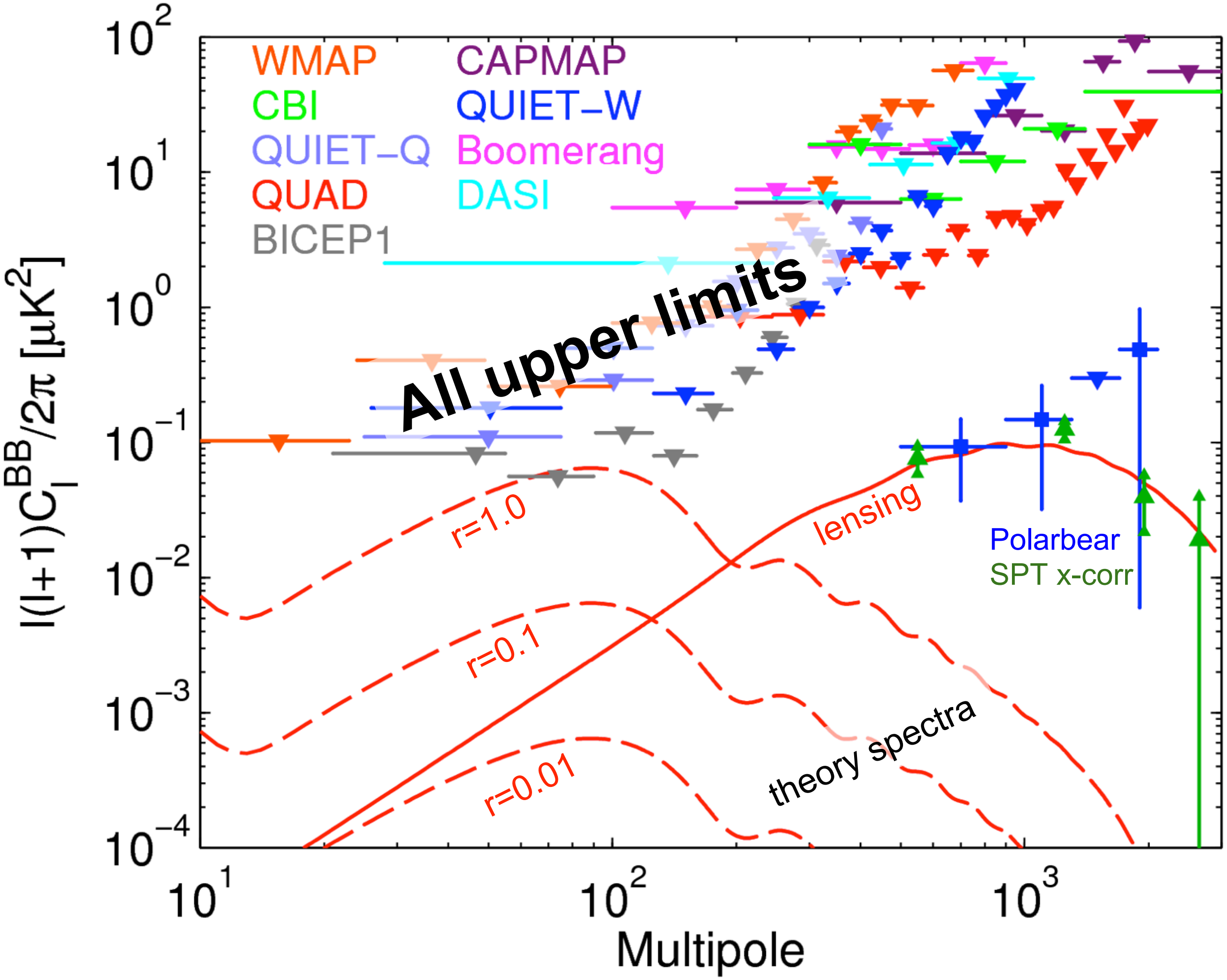
CMB polarization: arises at last scattering from local radiation quadrupole



CMB polarization



The State of B-mode Measurements last March



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

Before BICEP2: only upper limits from searches for Inflationary B-modes

BICEP1 limits translated to:

r < 0.7 (95% CL)

At high multipoles lensing B-mode dominant.

SPT x-corr: lower limits on lensing B-mode from cross correlation using the CIB

Clem Pryke for The Bicep2 Collaboration

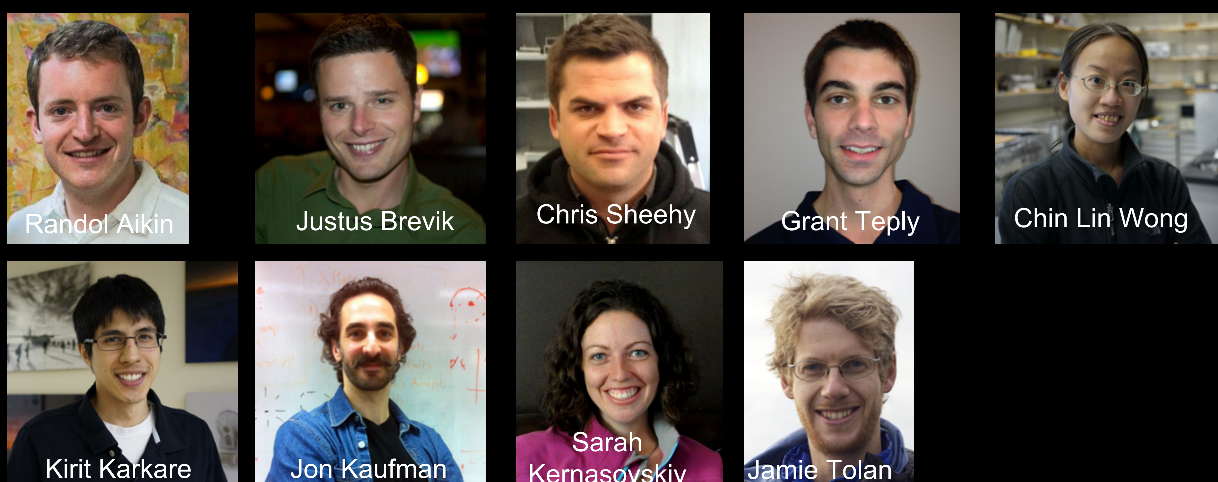
VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

UCSD
JPL
NIST
CARDIFF UNIVERSITY
cea
UNIVERSITY OF TORONTO
UBC

The BICEP2/Keck Postdocs

The BICEP2/Keck Graduate Students



Winterovers

BICEP2

2010

2011

2012

2013

2014

2015

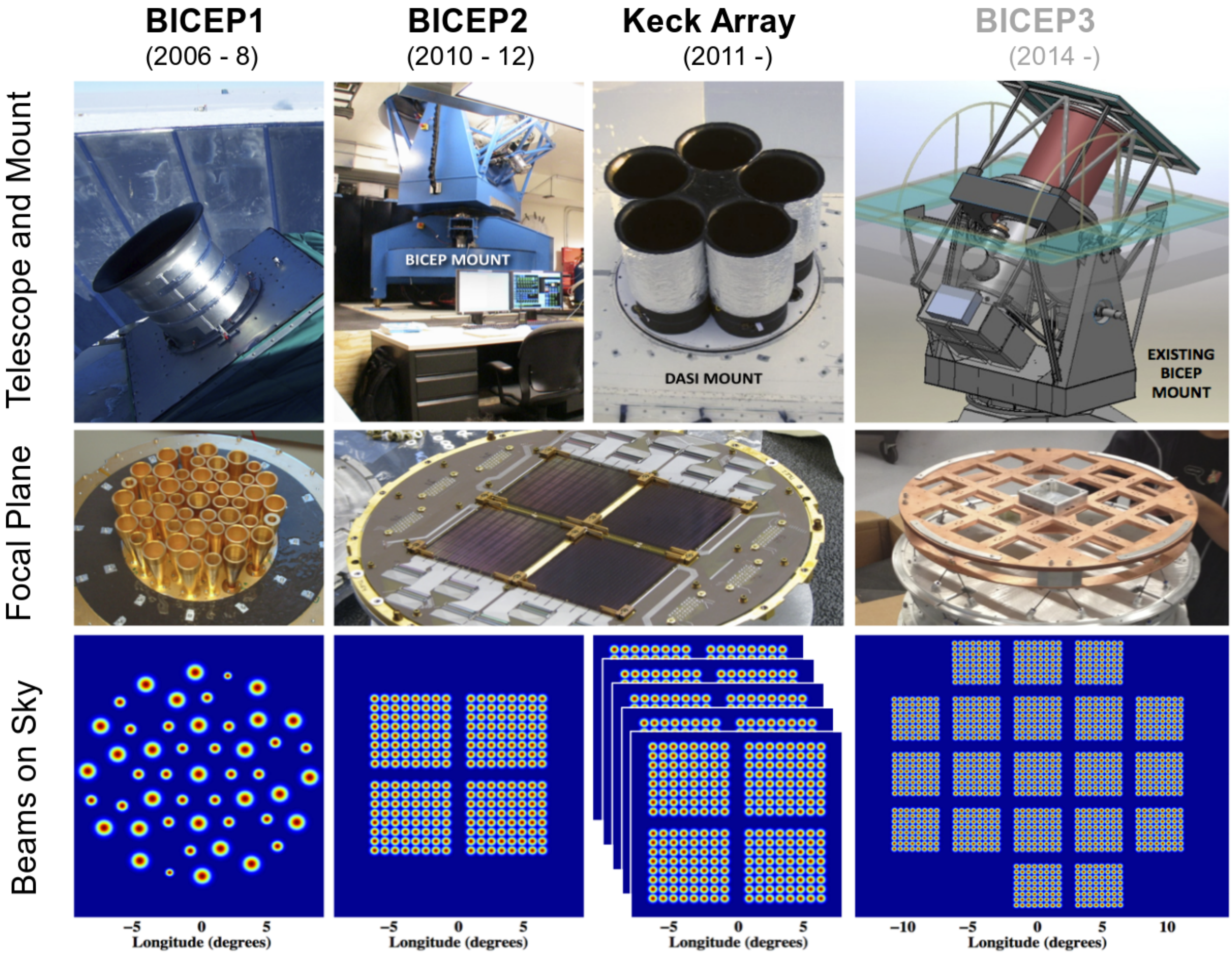
Keck

South Pole CMB telescopes

NSF's South Pole Station:
A popular place with CMB Experimentalists!

Super dry atmosphere and 24h coverage of low foreground sky.

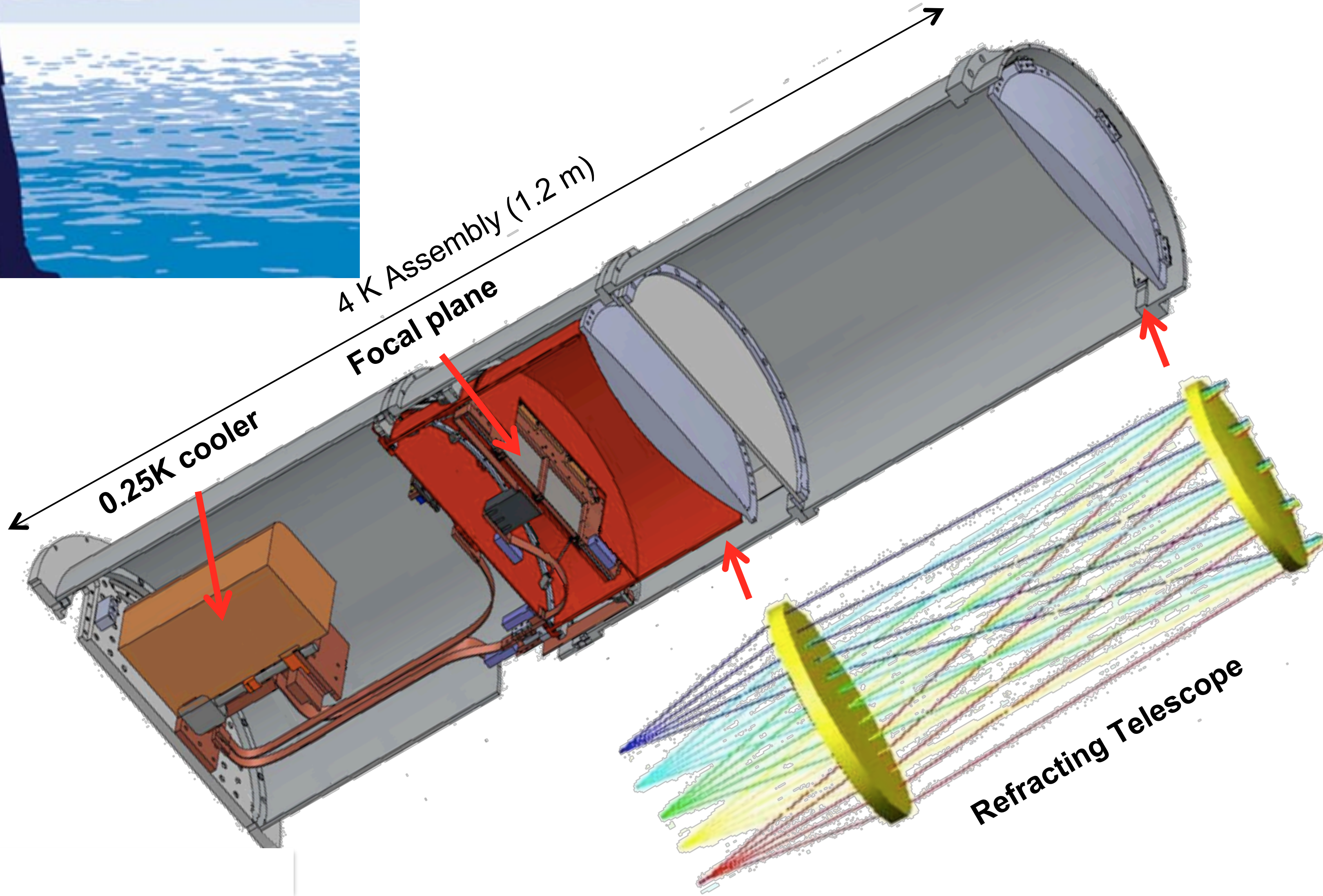
Also power, LHe, LN_2, 200 GB/day, 3 square meals, and bingo night...



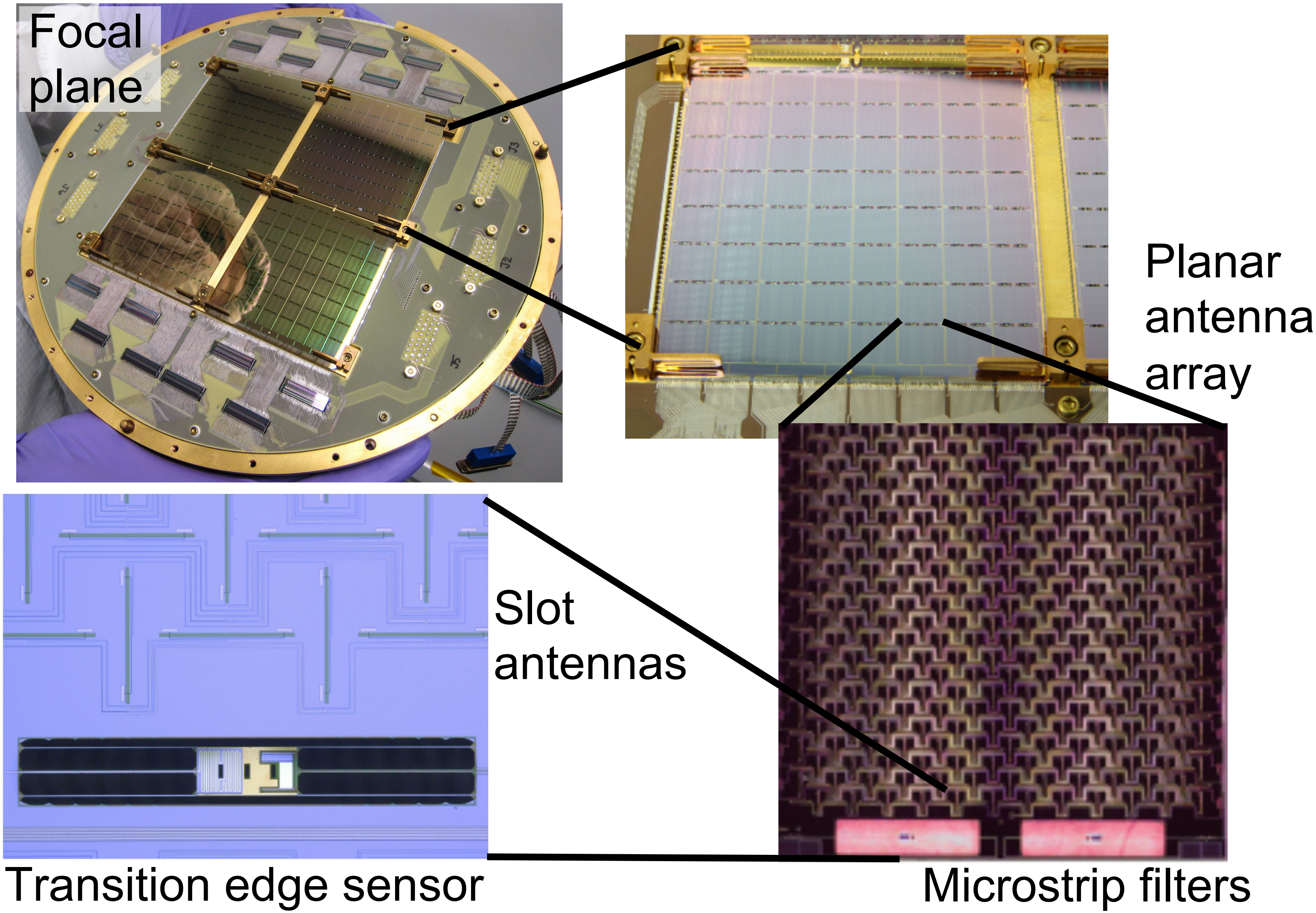
BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2014 -)
Telescope and Mount
BICEP MOUNT
DASI MOUNT
EXISTING BICEP MOUNT
Focal Plane
Beams on Sky
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−10 −5 0 5 10
Longitude (degrees)

BICEP2/Keck Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor

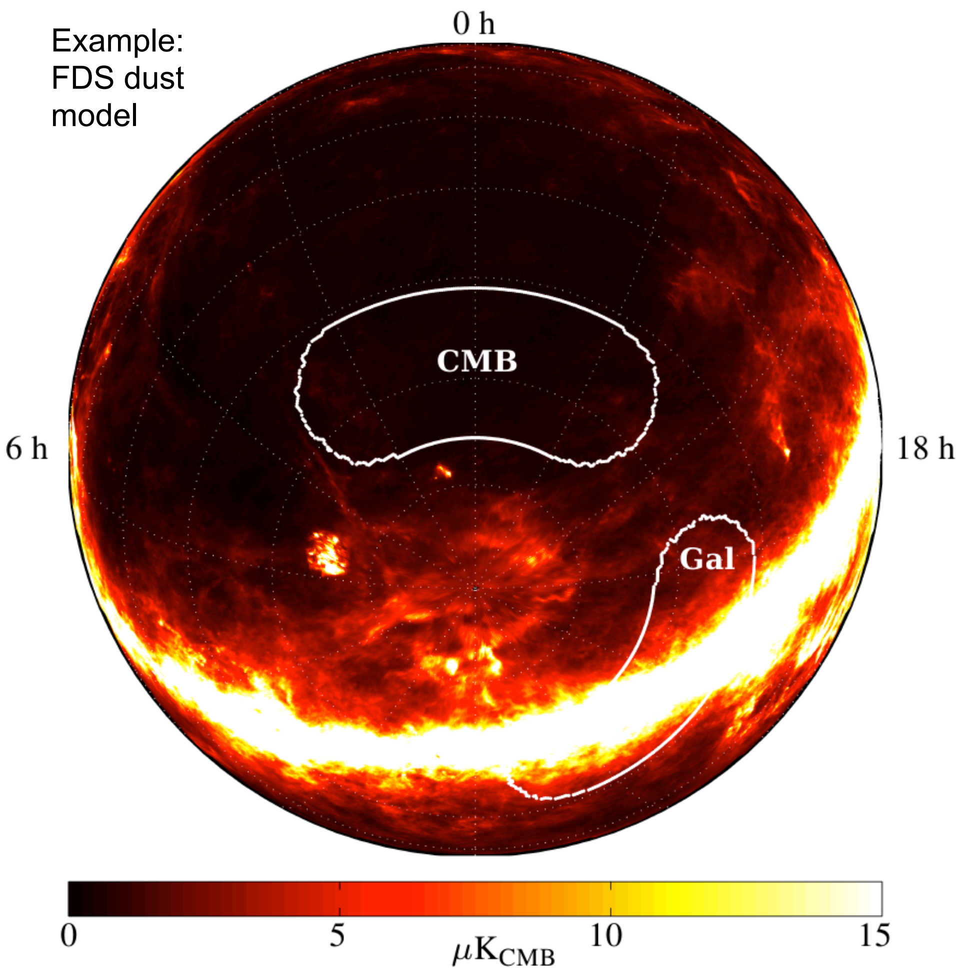


Mass-produced superconducting detectors



Observational Strategy

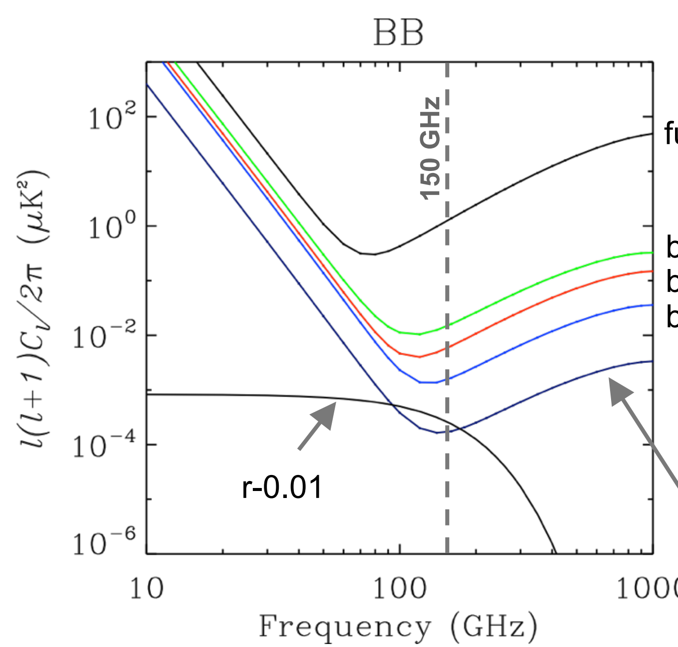
Example:
FDS dust
model



Go deep in a region of sky where galactic foregrounds are low

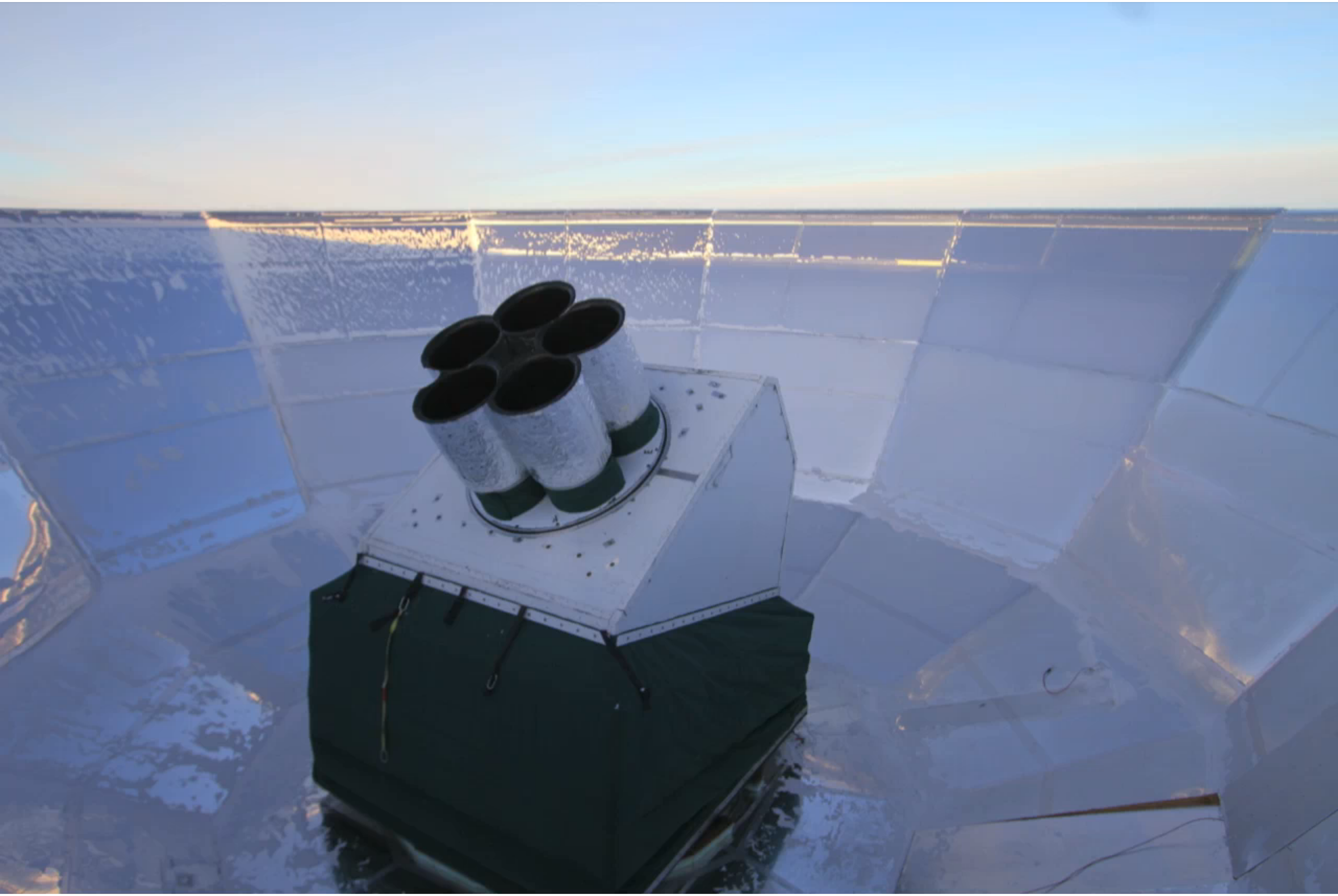
Observe at frequencies where the CMB is brightest with respect to:
Synchrotron emission (from high energy electrons) - falls with increasing freq
Thermal dust emission – rises with increasing freq

Foreground contamination of the B-mode power in clean regions previously projected to be equivalent to r ≤ ~0.01.



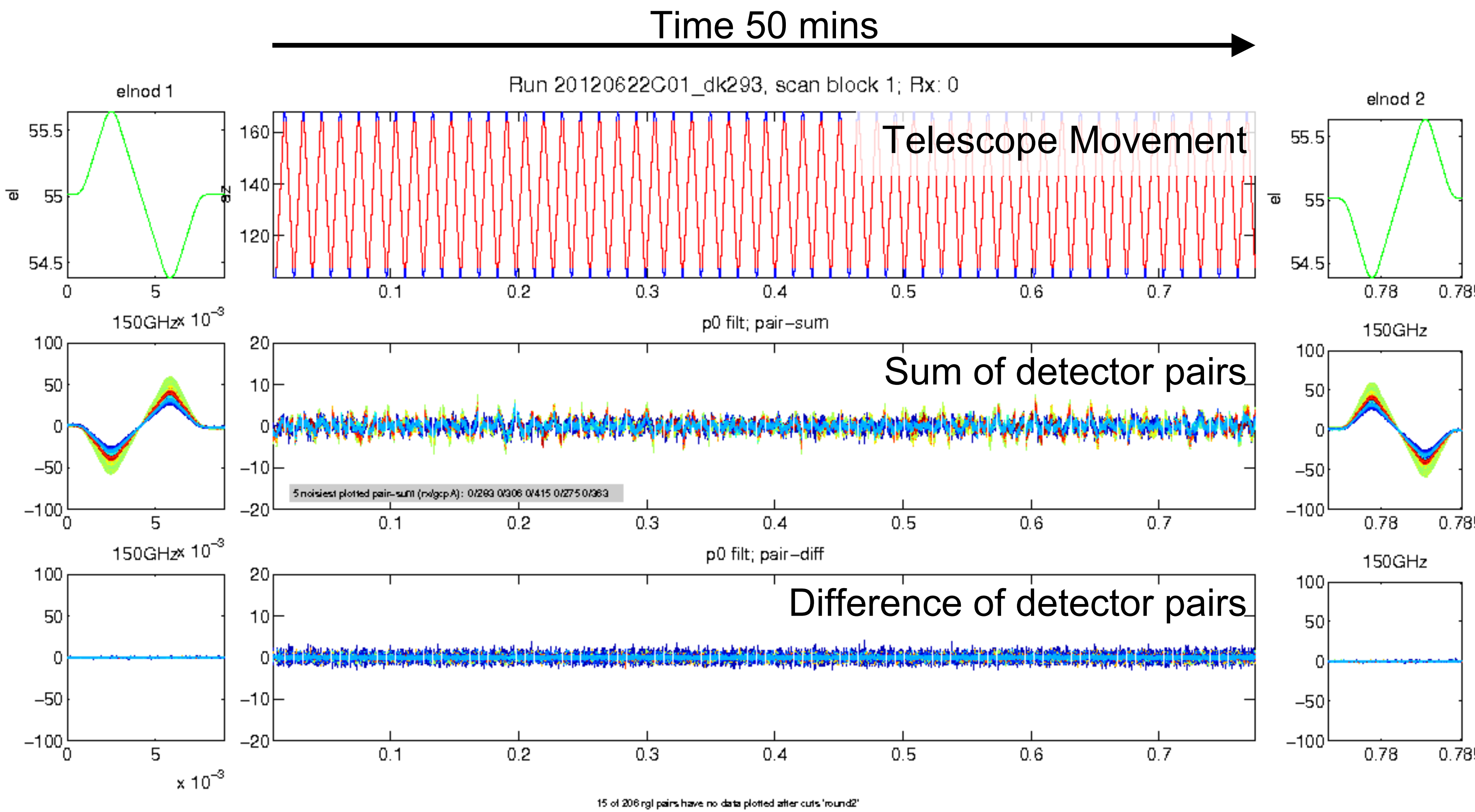
Clem Pryke for The Bicep2 Collaboration

From Dunkley et al arxiv/0811.3915



Clem Pryke for The Bicep2 Collaboration

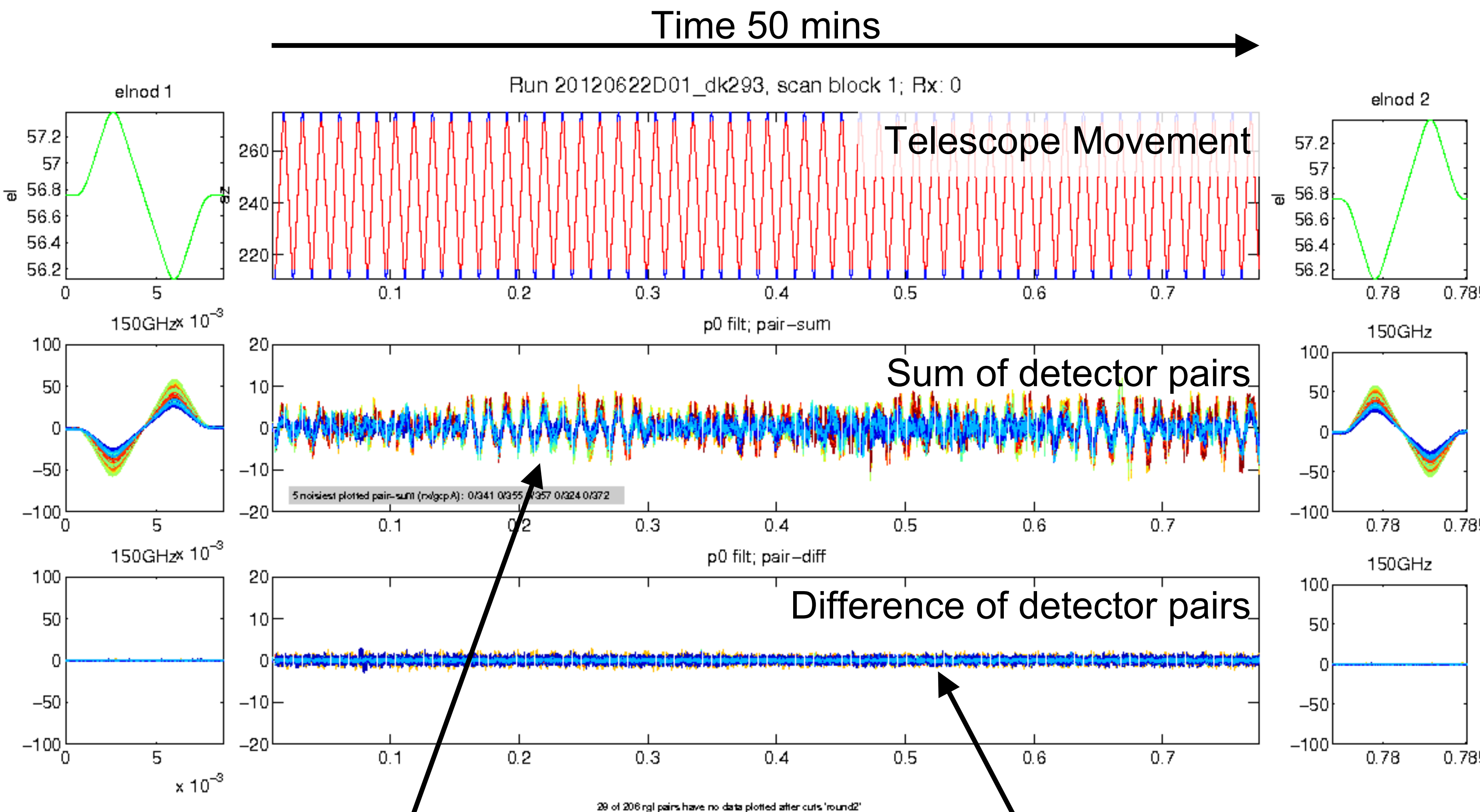
Raw Data - Perfect Weather



➢ Cover the whole field in 60 such scansets then start over at new boresight rotation

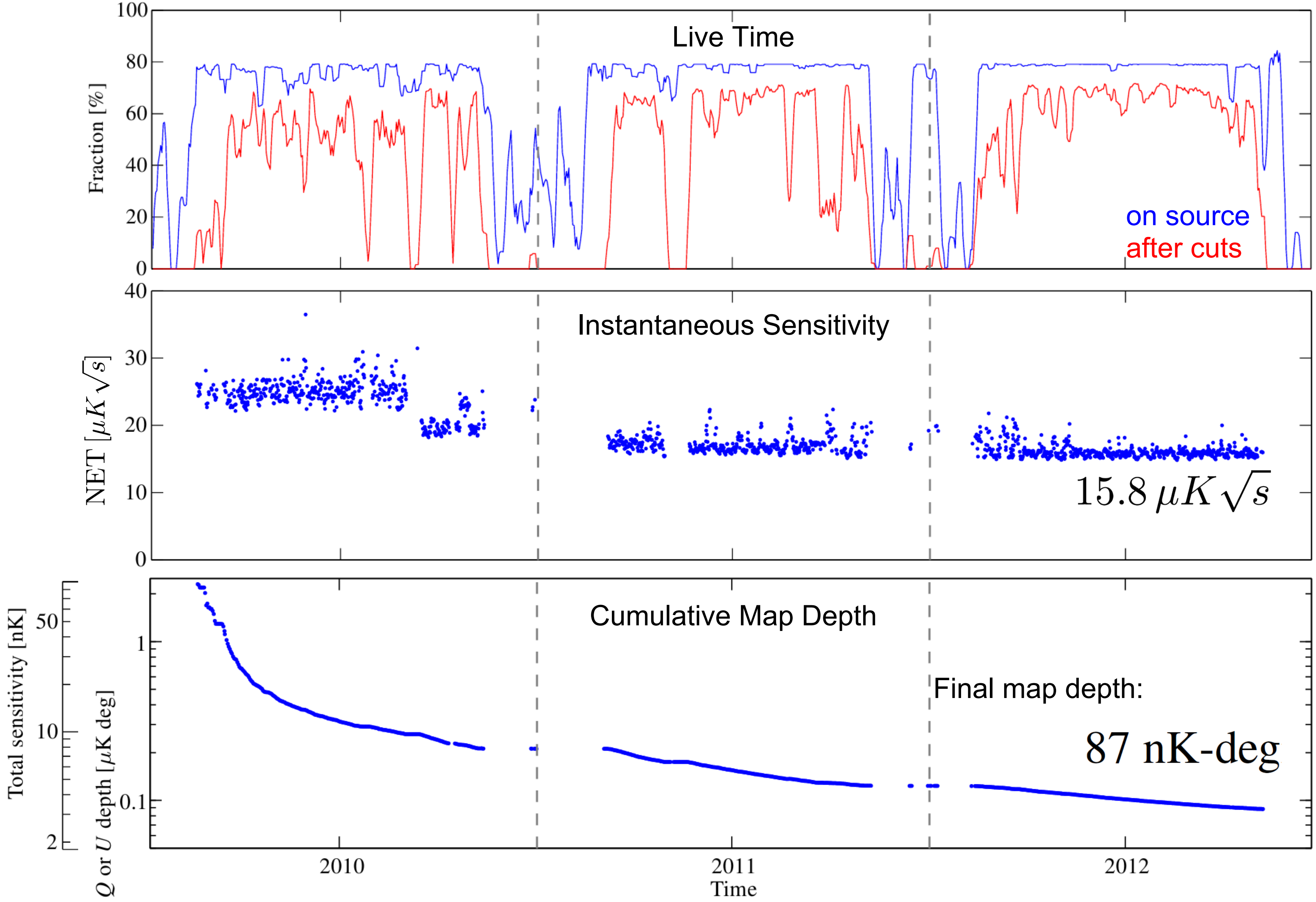
➢ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather

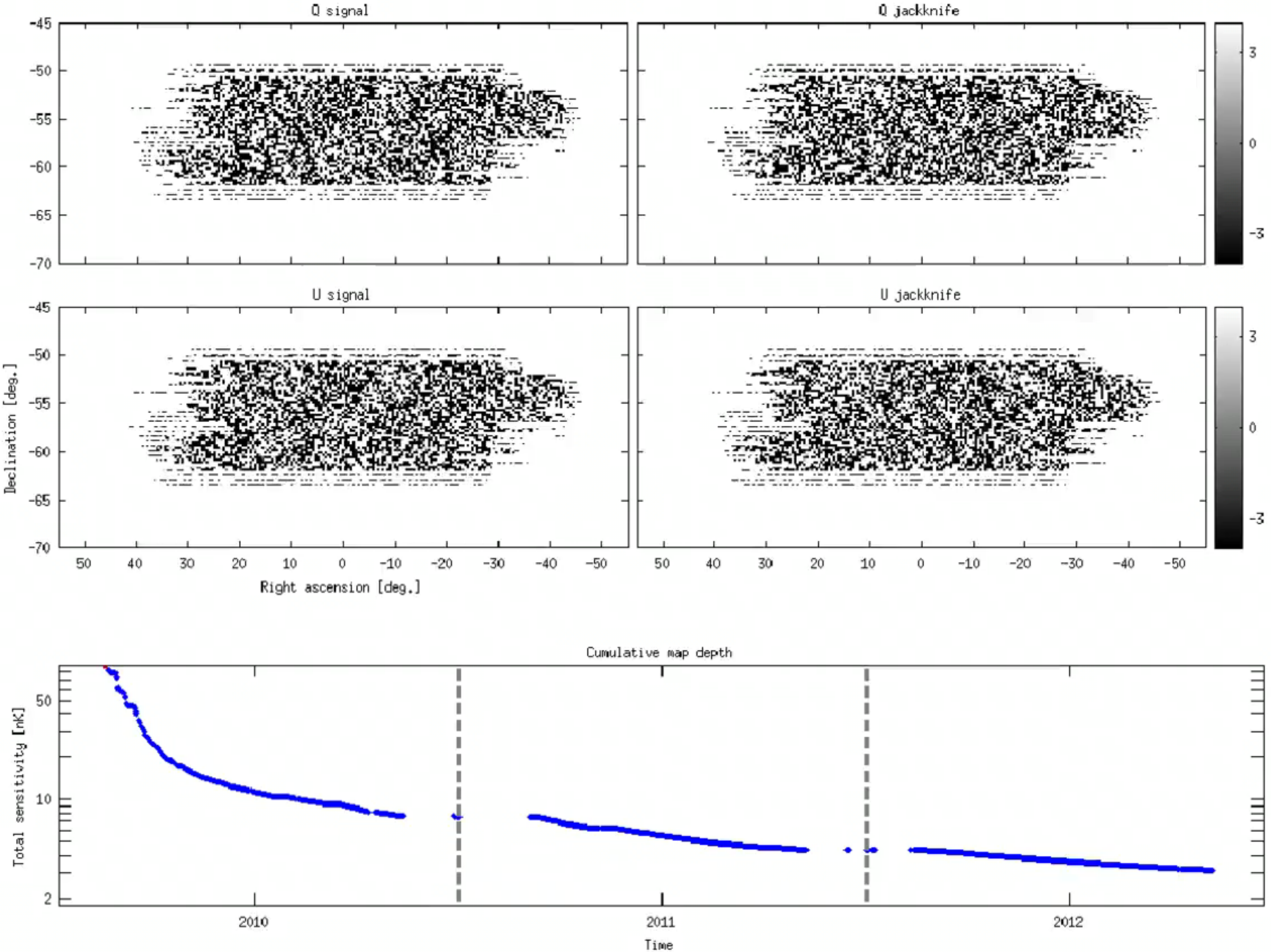


- ➢ Scanning over lumpy atmosphere → “clouds”
- ➢ Pair difference still clean → atmosphere is unpolarized

BICEP2 3-year Data Set

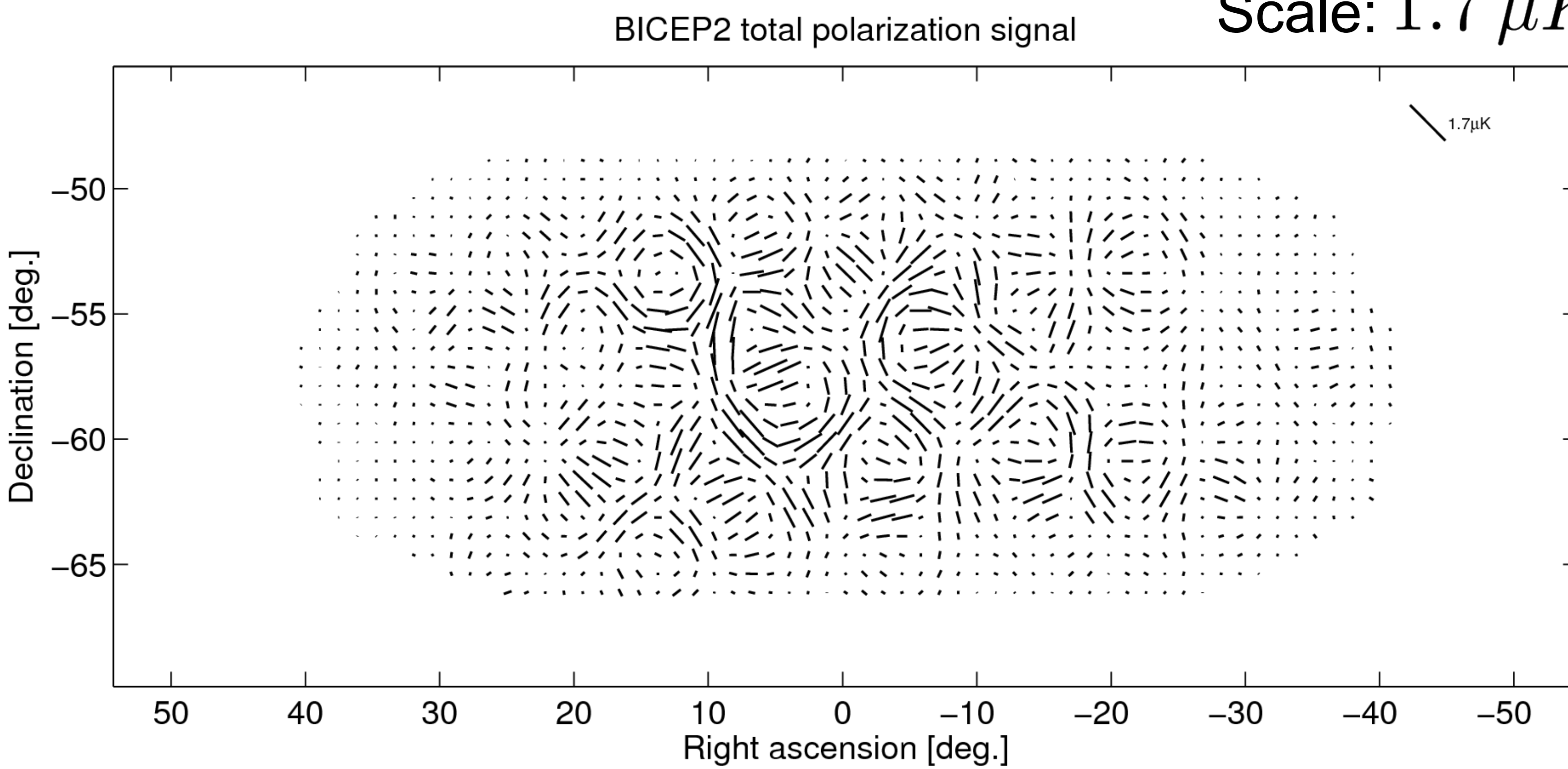


Clem Pryke for The Bicep2 Collaboration


Q signal
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
mK
Cumulative map depth
Total sensitivity [nK]
Time
2010
2011
2012

Total Polarization

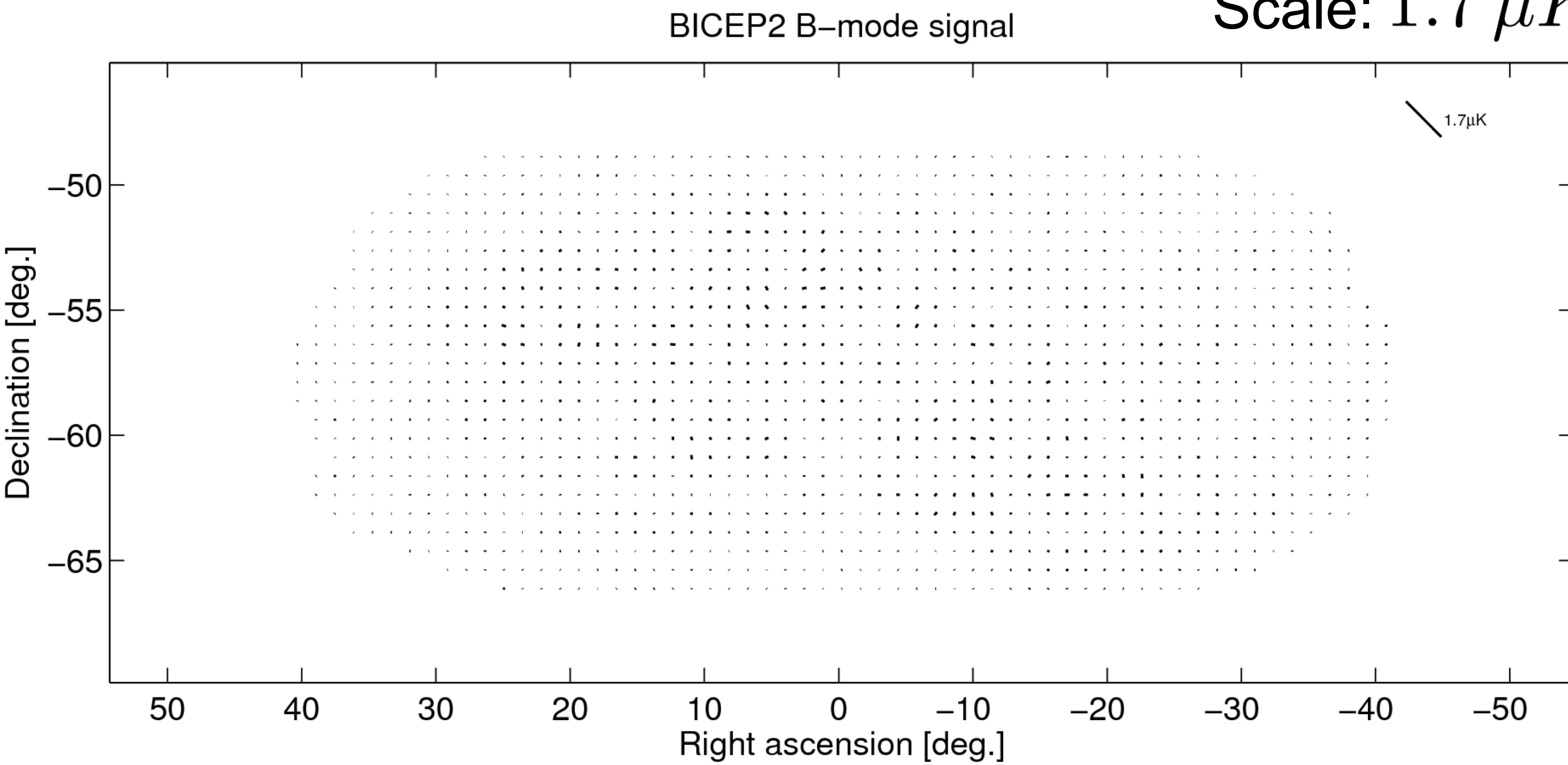
Scale: $1.7\,\mu K$



E-mode dominated pattern – no obvious curl component

B-mode Contribution

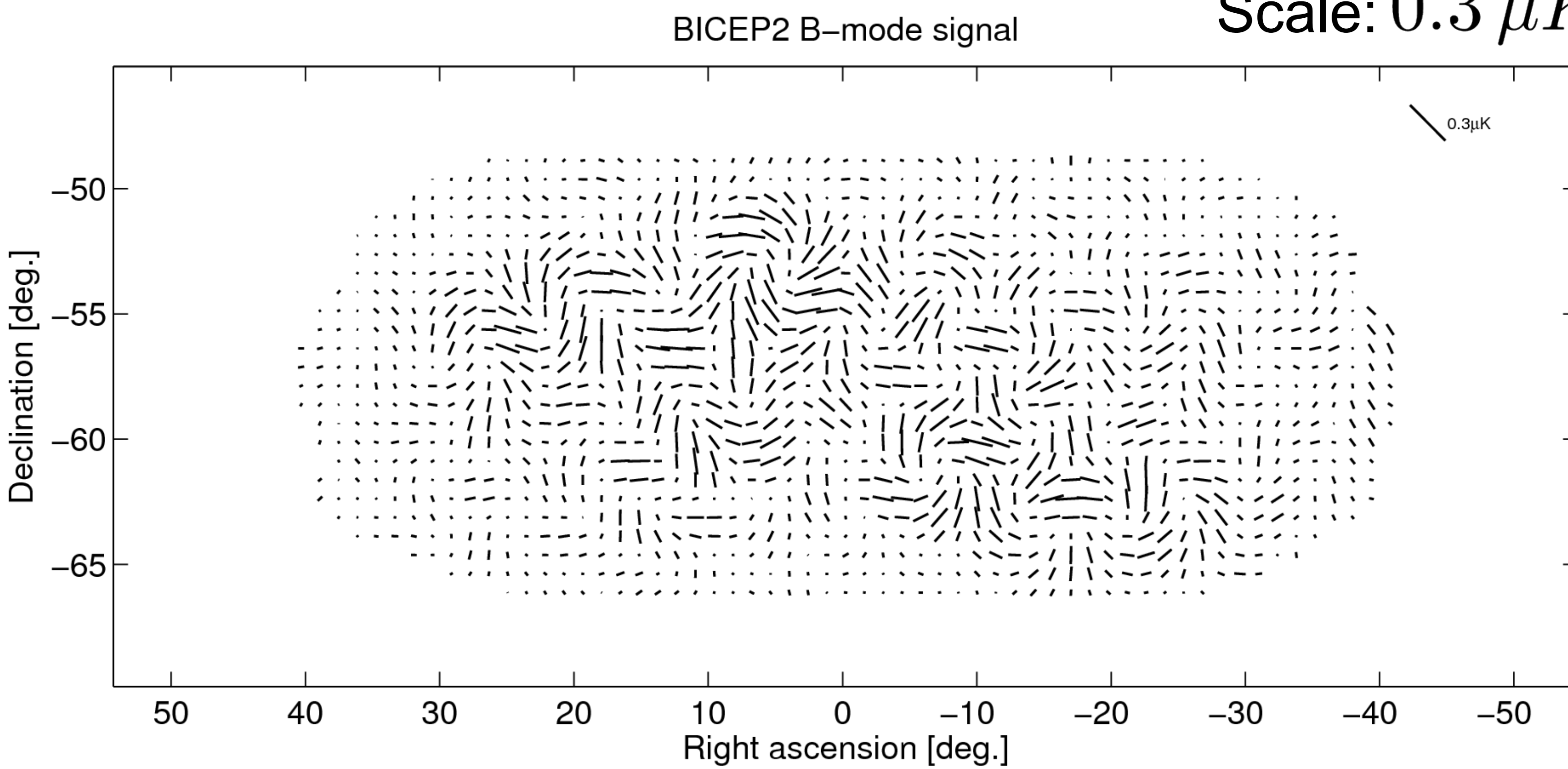
Scale: $1.7\,\mu K$



Apply purification operation to Q/U maps which leaves only B-modes (given all timestream filterings etc.)

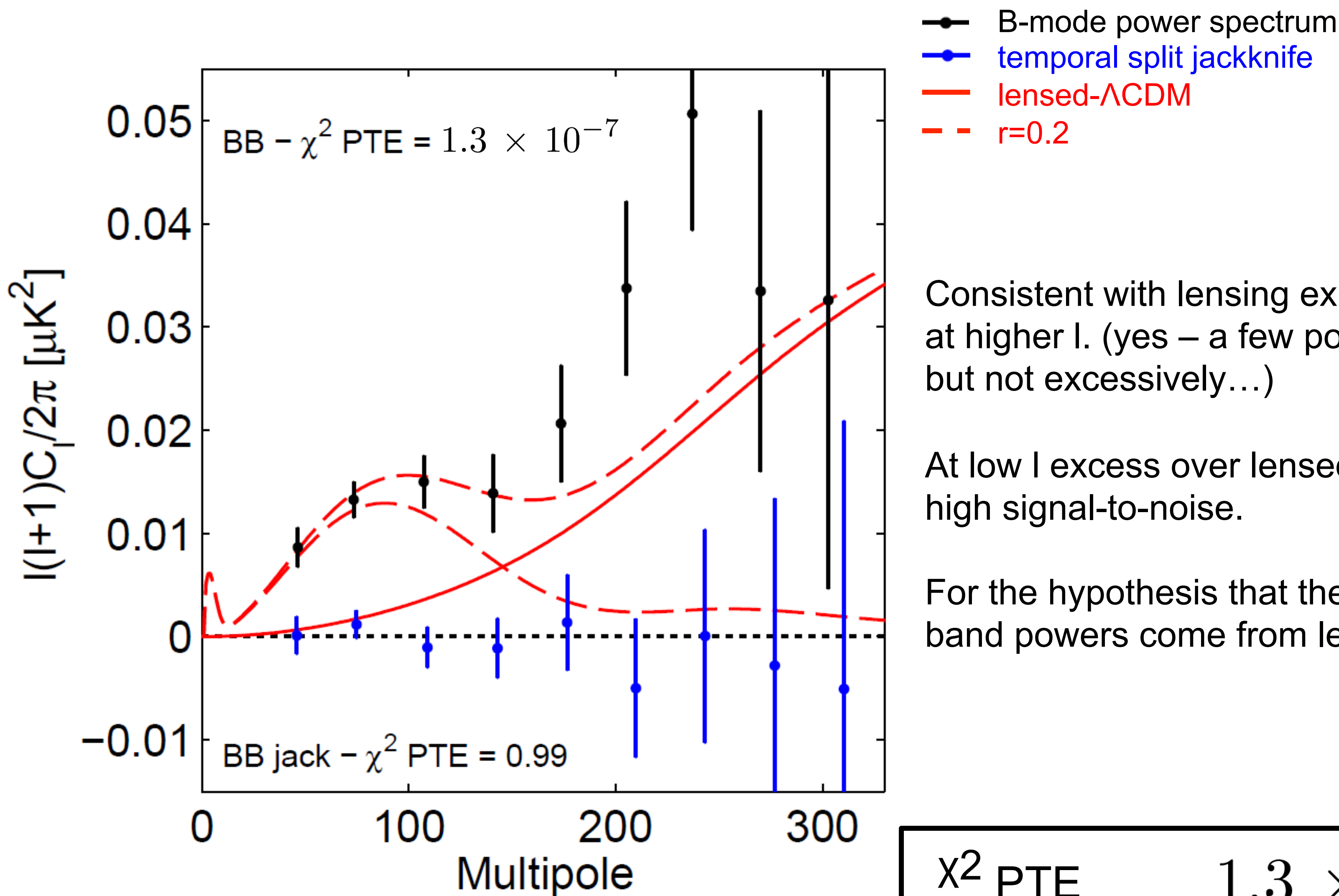
B-mode Contribution

Scale: $0.3\,\mu K$



Stretch scale by factor 6 – see "swirly" B-mode

BICEP2 B-mode Power Spectrum



Consistent with lensing expectation at higher l. (yes – a few points are high but not excessively…)

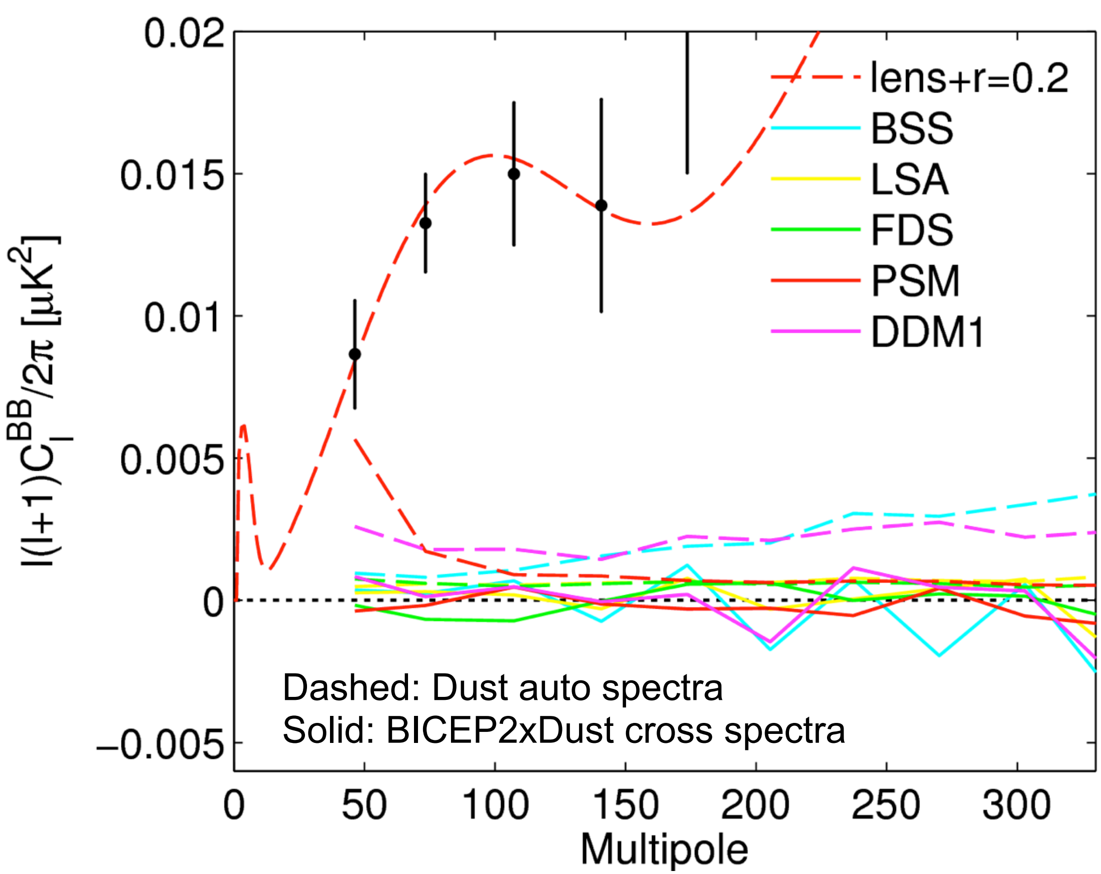
At low l excess over lensed-ΛCDM with high signal-to-noise.

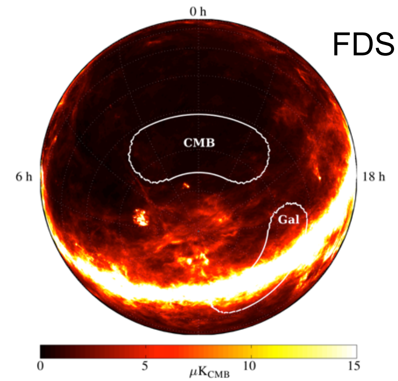
For the hypothesis that the measured band powers come from lensed-ΛCDM:

χ^2 PTE	1.3×10^{-7}
significance	$5.3\,\sigma$

Clem Pryke for The Bicep2 Collaboration

Pre-Planck Polarized Dust Foreground Projections





FDS Model

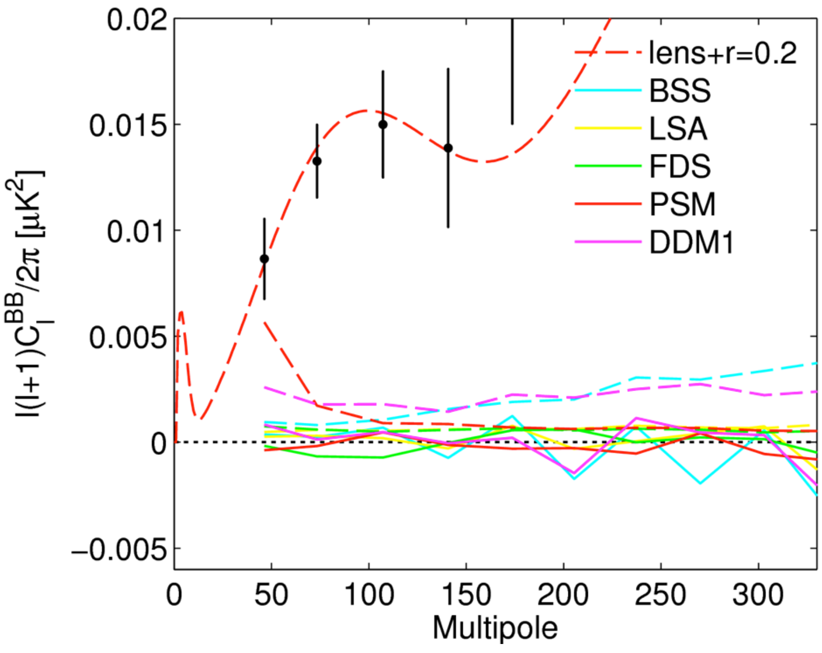
The BICEP2 region was chosen on the basis of extremely low *unpolarized* dust power.

Used various models of polarized dust emission to estimate dust power.

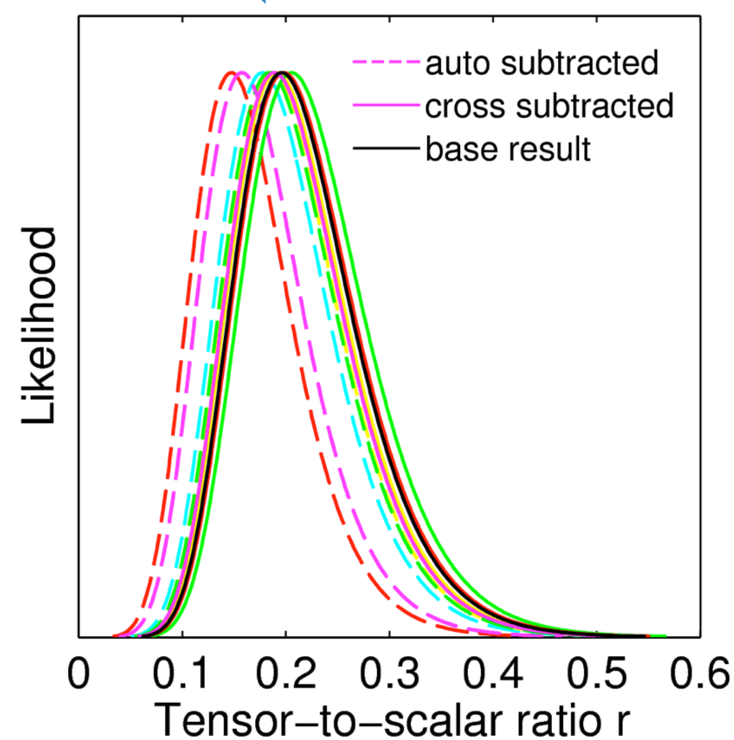
Result: All auto spectra were well below observed signal level. (and cross spectra consistent with zero.)

But considerable uncertainty in these models...

Fitting with Dust Projections Subtracted…



Adjust likelihood curve by subtracting the dust projection auto and cross spectra from our bandpowers:

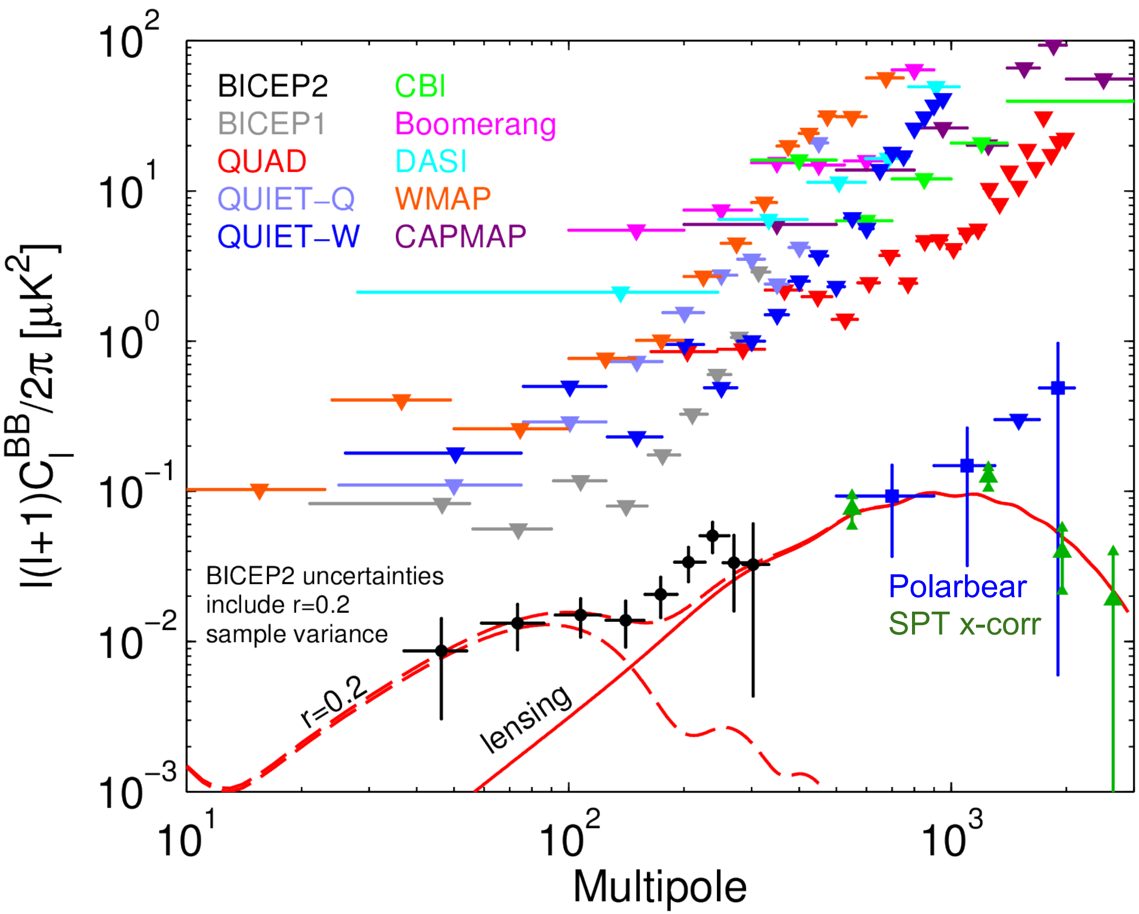


Probability that each of these models reflected reality was hard to assess.

DDM1 used all publicly available information from Planck. Polarization fraction here assumed p = 5%. p ~ 13% would explain the full excess under this model.

Conclusions circa March 17th 2014

BICEP2 data and upper limits from other experiments:



Most sensitive polarization maps ever made!

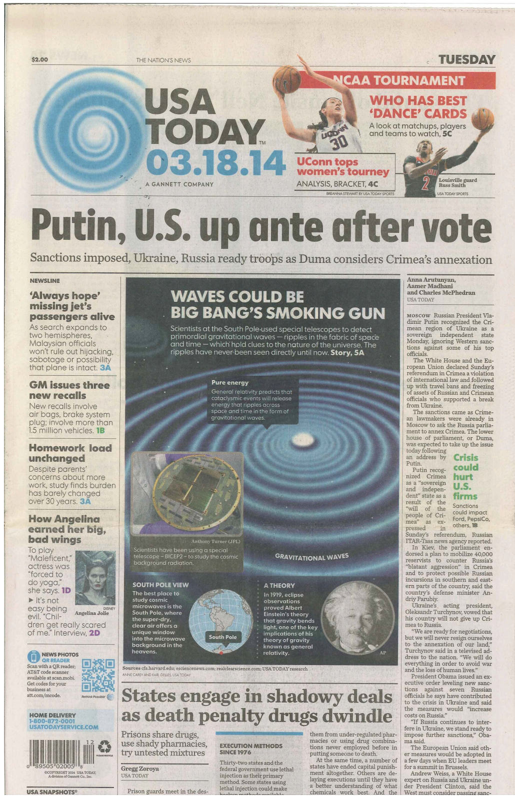
Power spectra perfectly consistent with lensed-ΛCDM except:
5.2σ excess in the B-mode spectrum at low multipoles!

Extensive studies and jackknife tests strongly argued against systematics as the origin

Data fit well to LCDM+r=0.2 expectation

Foregrounds did not appear to be a large fraction of the signal…

Storm of Media Attention

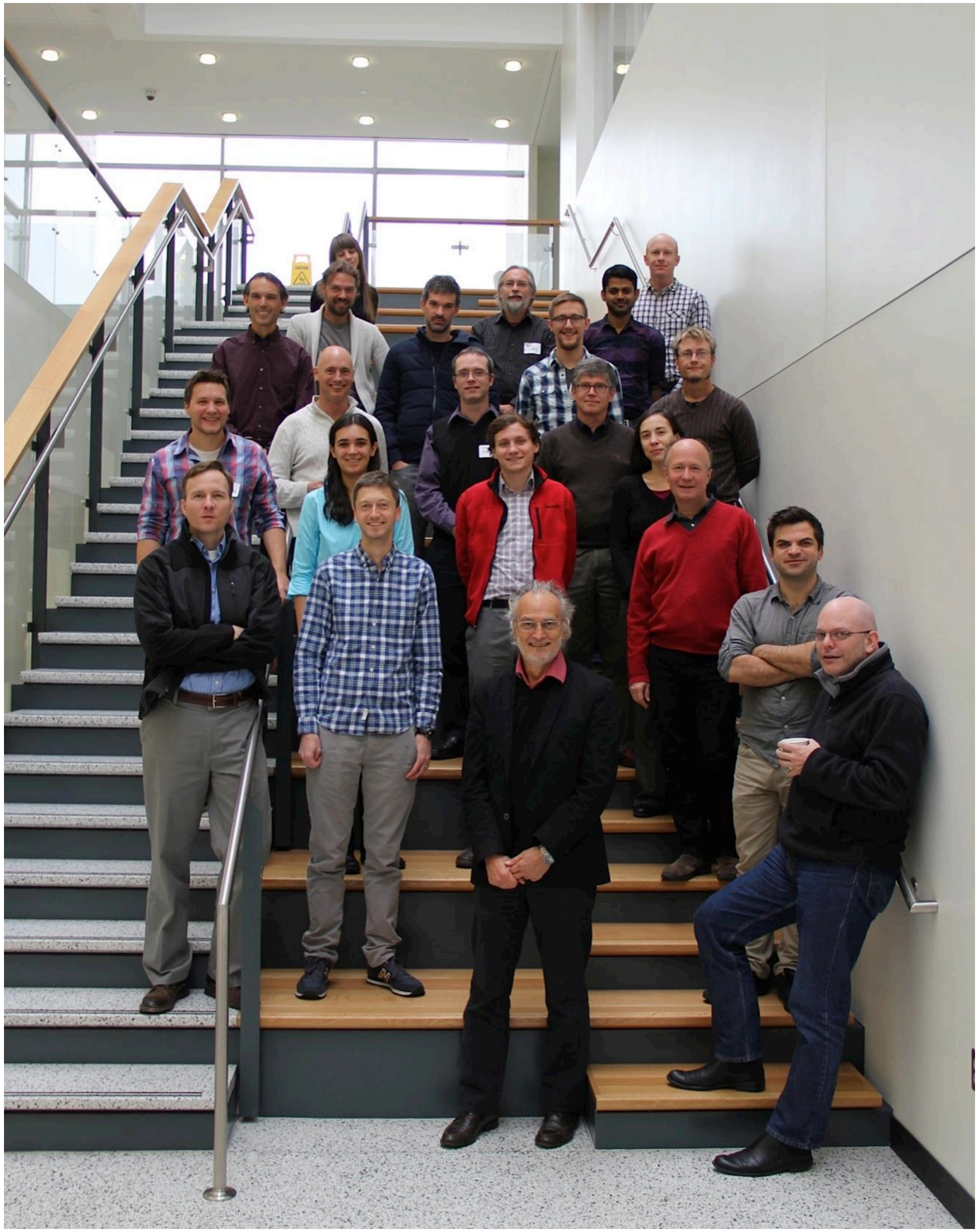


Actually not a lot of fun…

Developments last year

- Intense media and science community interest…
- Many early instrumental queries – faded away – everybody now seems to trust our measurements.
- Concerns about synchrotron – also faded away.
- But persistent concerns about dust…
  - Mostly based on online pdf's of Planck talks
- In September we finally got some solid information from Planck about the actual level of polarized dust emission in the BICEP2 field (arxiv:1409.5738). Much higher than any of the projections…

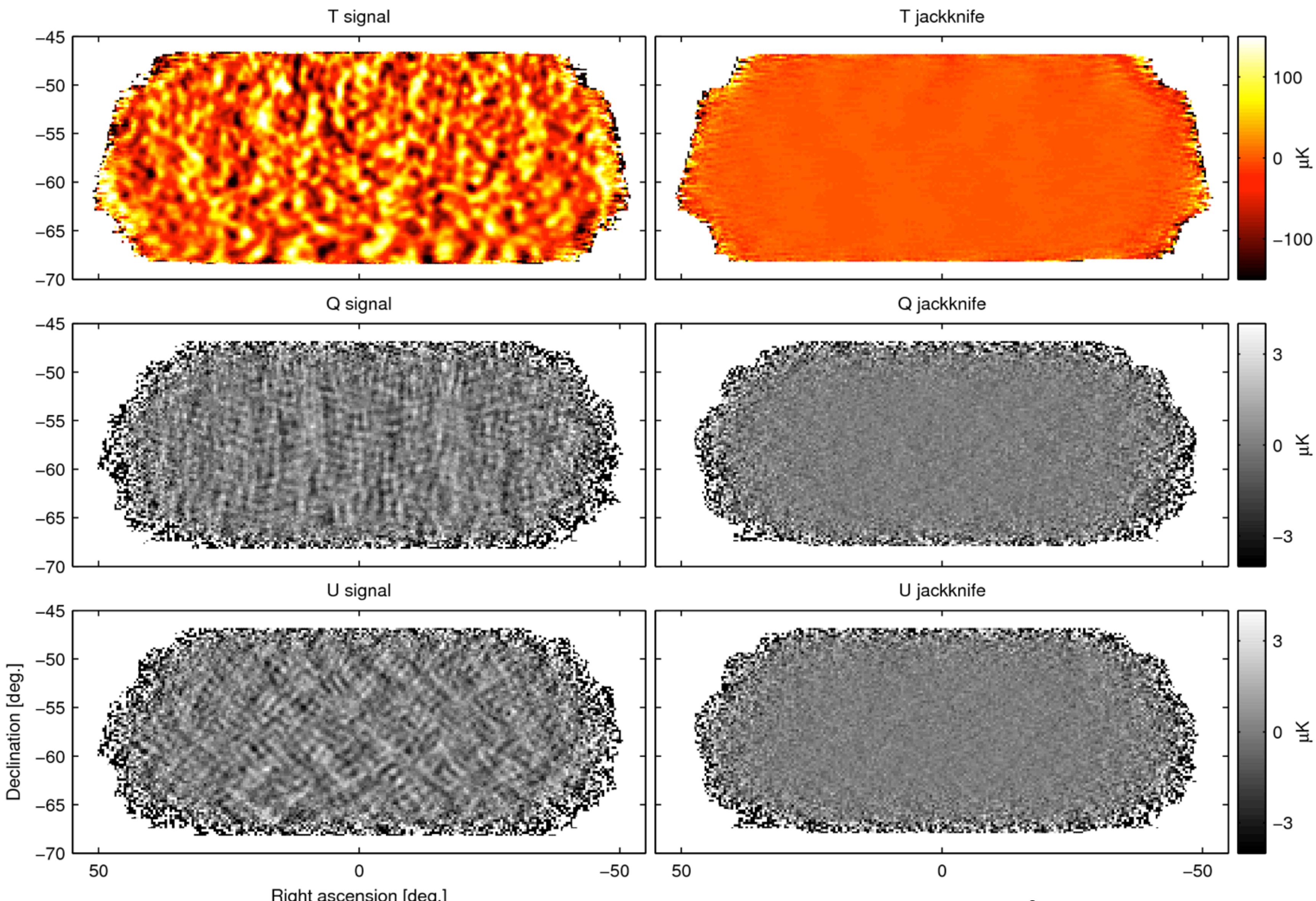
Results from Joint analysis of BICEP2/Keck and Planck data



- In summer 2014 BICEP2/ Keck and Planck collaborations signed MOU to do a joint analysis of their data
- Data exchanged in late July
- Today reporting on results of this analysis as presented in paper arxiv:1502.00612 (now published by PRL)

BICEP2/Keck/Planck meeting at University of Minnesota 5 Nov 2014

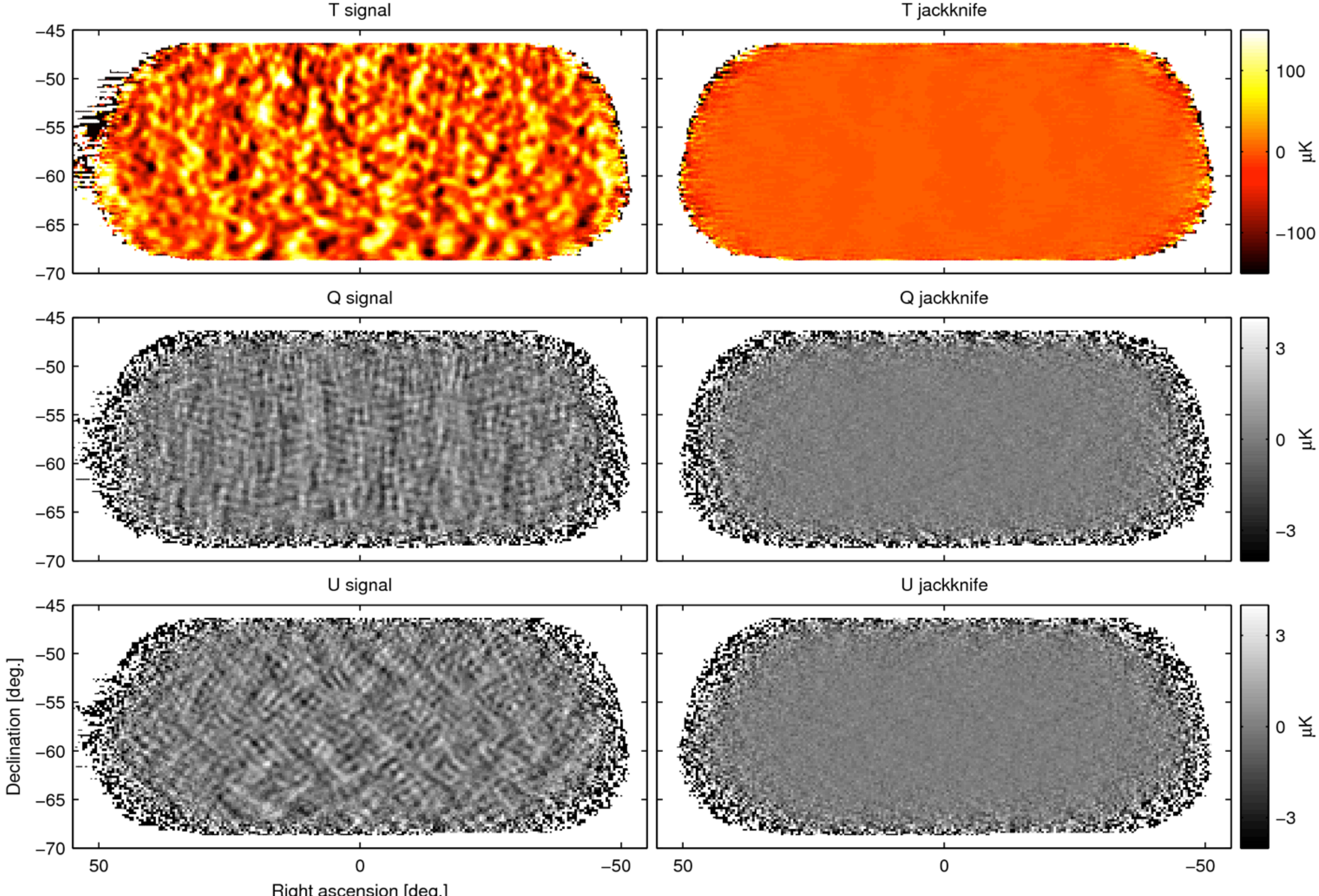
B2 150 GHz T/Q/U maps of small sky patch



87 nK deg (5.2 μK arcmin) over 380 deg^2 area - as used in BICEP2 paper

Bicep2, Keck Array and Planck Collaboration

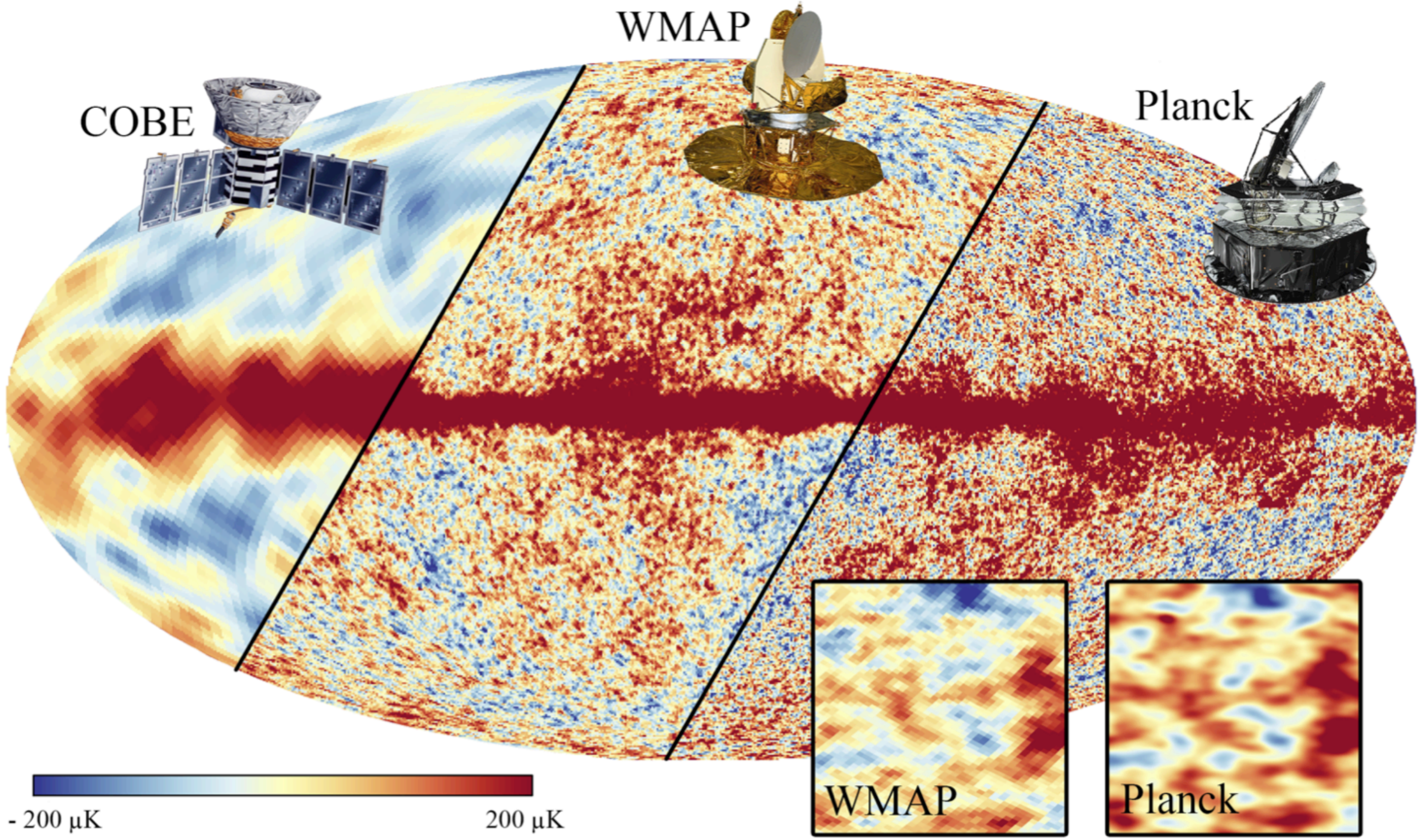
B2+Keck 150 GHz T/Q/U maps of small sky patch



57 nK deg (3.4 µK arcmin) when adding 2012/13 Keck data - by far the deepest maps ever made - but apodized and filtered...

Bicep2, Keck Array and Planck Collaboration

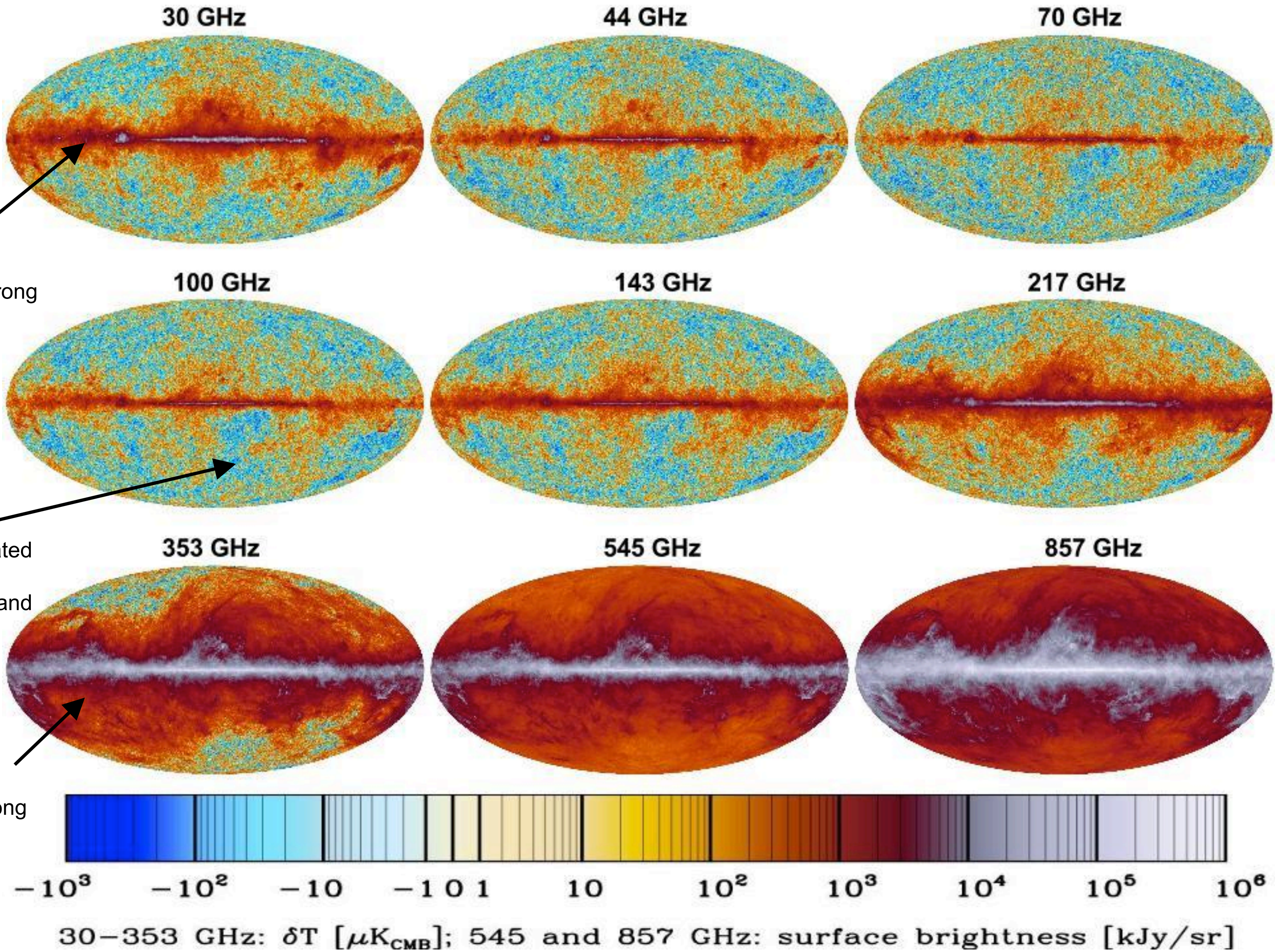
Planck



graphic: J. Gudmundsson

- Planck is the third space mission to observe the CMB: An ESA-led mission
  Launched 14 May 2009, mission completed Oct 2013
- Full sky maps produced in seven polarization-sensitive bands centered at 30,44,70,(100,143,217),353 GHz (to be) released in 2015. Also intensity maps at 545 and 857 GHz.

Planck full sky maps at 9 frequencies



Galactic synchrotron emission strong at low frequencies

CMB most uncontaminated at mid frequencies and high latitude

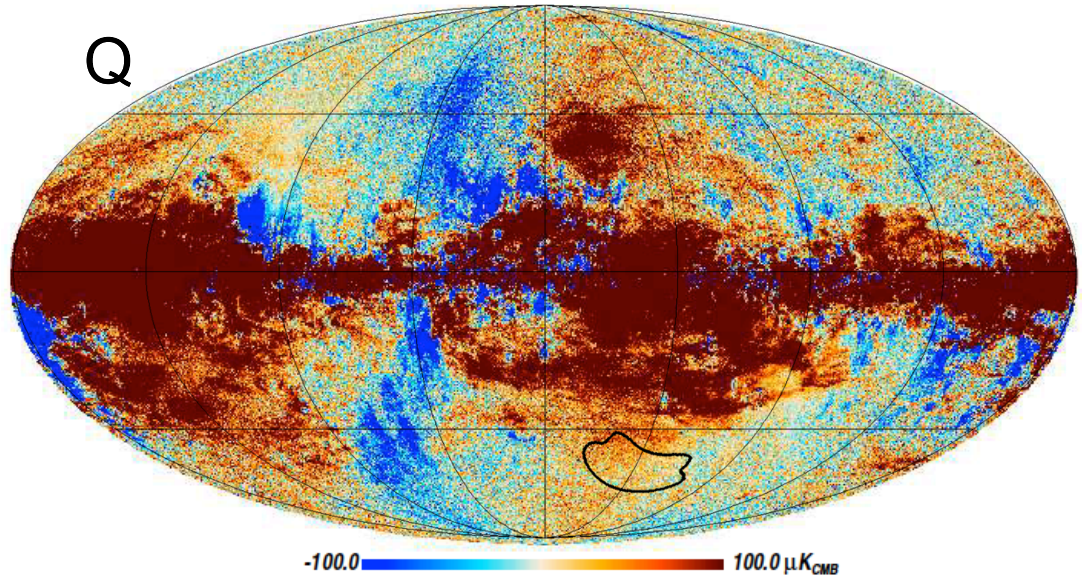
Galactic dust emission strong at high frequencies

Full sky coverage and 9 frequencies - but not as deep as BICEP2/Keck in any given region of the sky

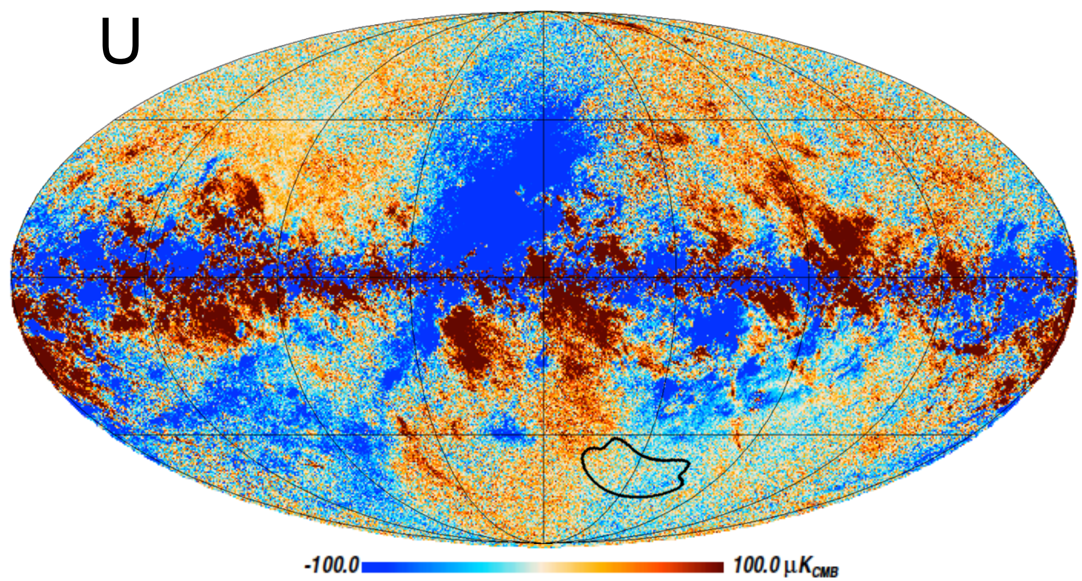
Planck 353 GHz full sky maps in polarization

- 353 GHz polarized maps are dominated by Galactic dust emission

Q

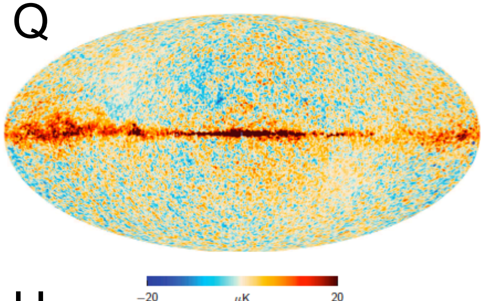


U

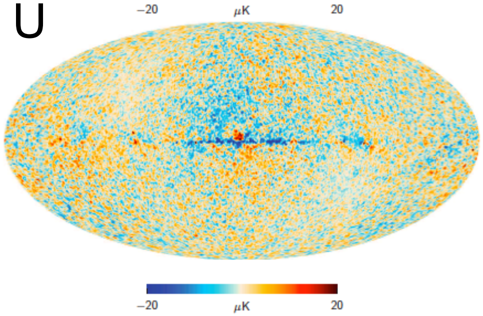


For comparison, Planck 70 GHz is close to the minimum of Galactic foreground emission

Q



U

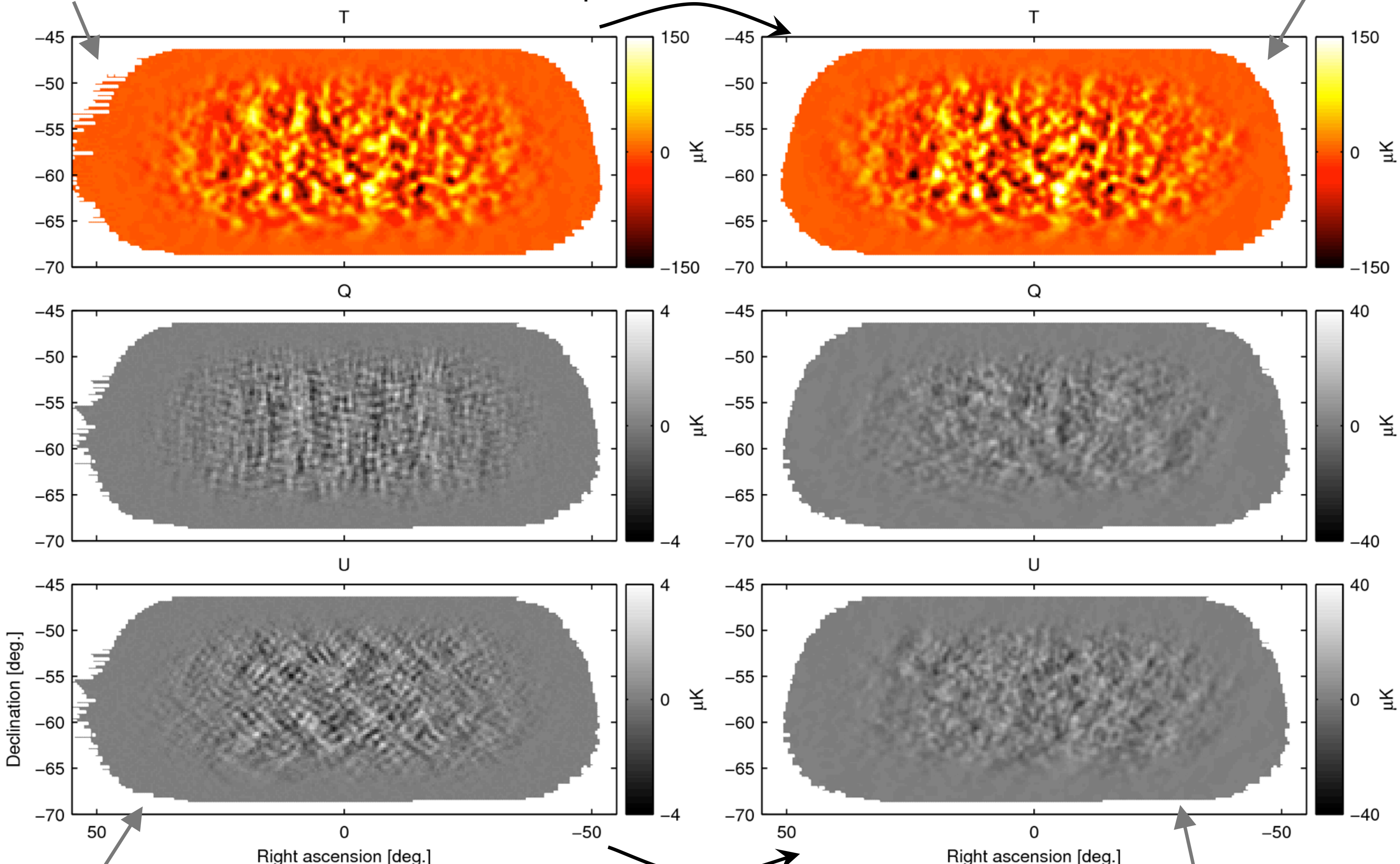


Compare BK 150 GHz (left) with Planck 353 GHz (right)

Dominated by LCDM T

T maps same color stretch

Dominated by LCDM T



Dominated by LCDM E-modes

Q/U maps x10 color stretch

Dominated by noise&dust

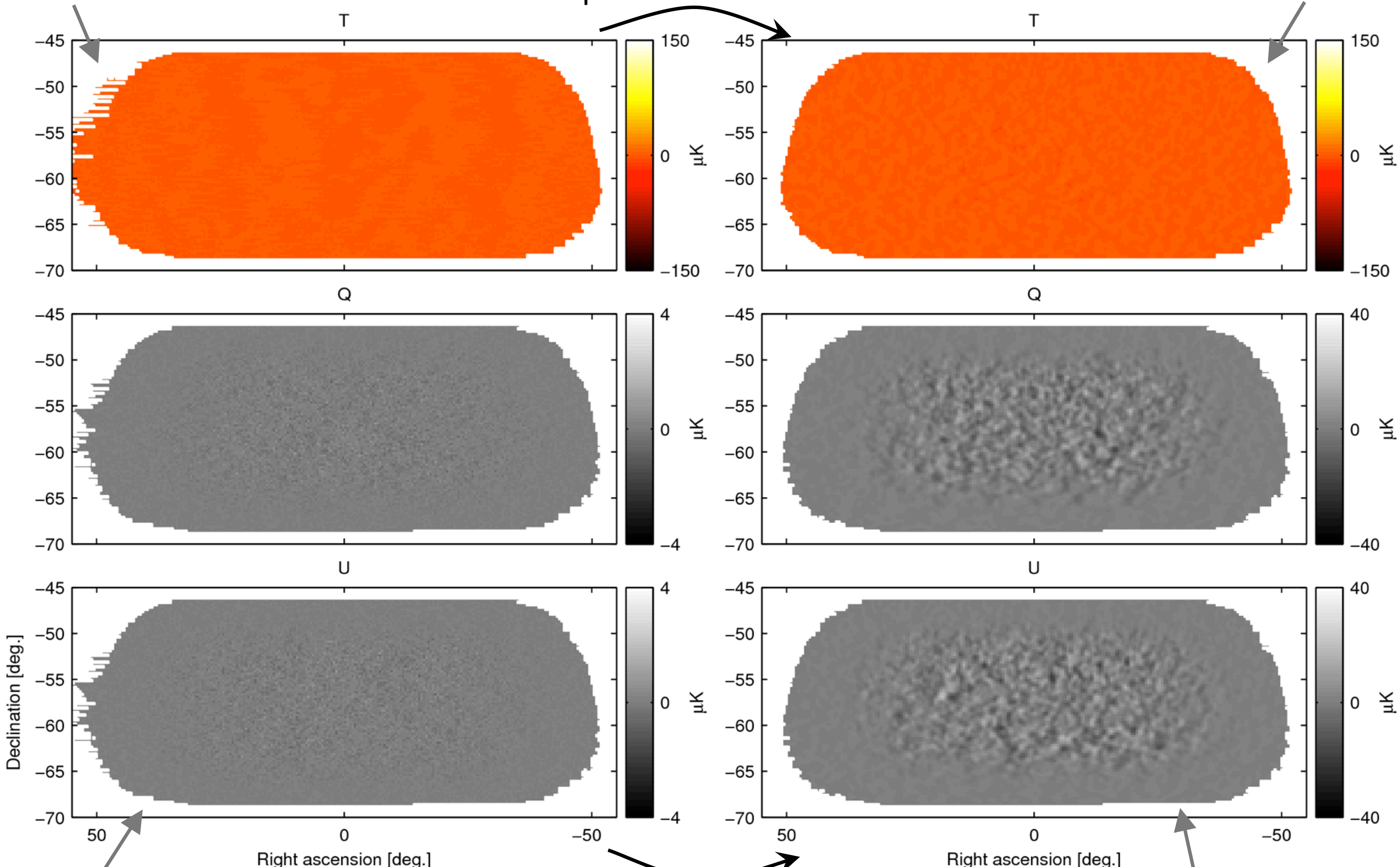
The Real Data

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

Noise small compared to signal

T maps same color stretch

Noise small compared to signal



Noise small compared to signal

Q/U maps x10 color stretch

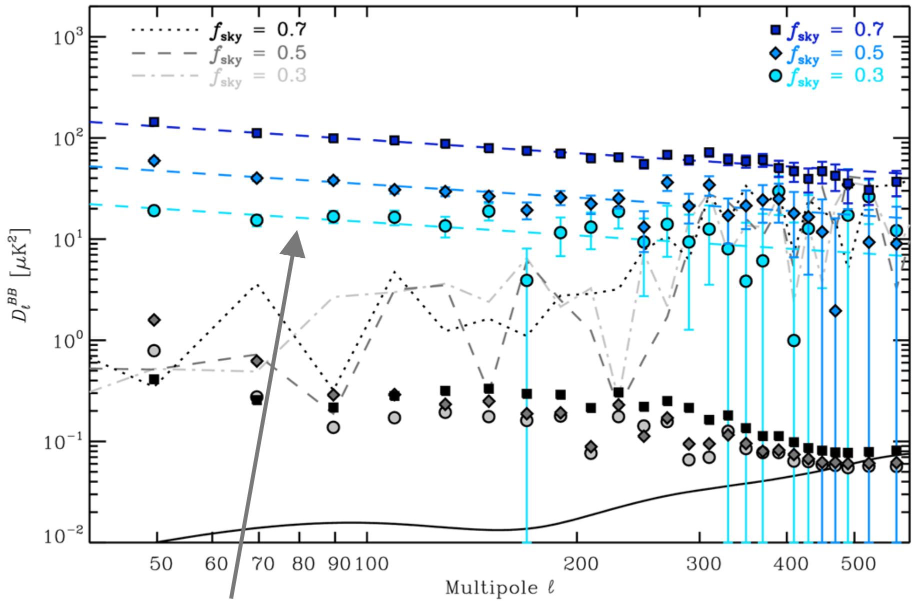
Noise comparable to dust signal

A Noise Simulation

What are the expectations for dust?

- In the BK patch Planck's signal-to-noise on dust is limited even at 353GHz.
- However a series of Planck papers have investigated the spatial and frequency spectra of dust over the intermediate and high latitude sky:

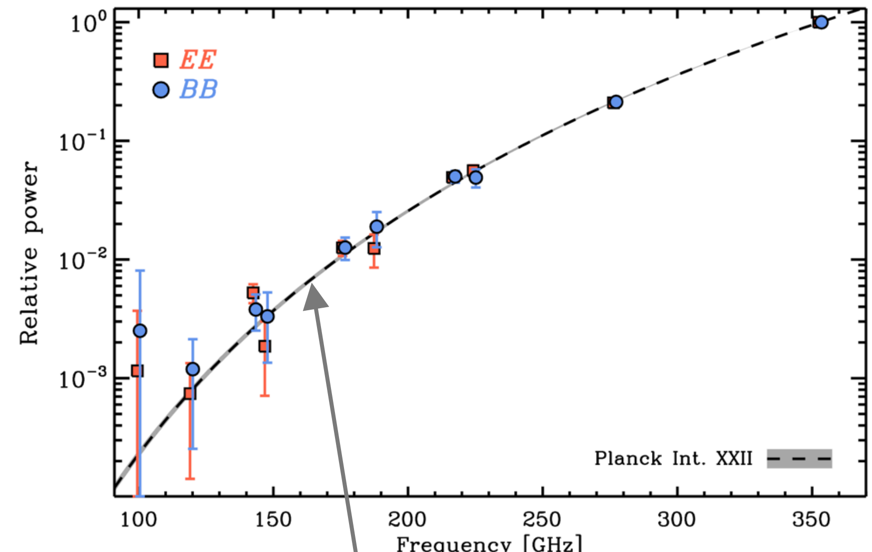
Fig 2 of arxiv:1409.5738



Dust BB spatial power spectra follow $\ell^{-0.42}$ power law when averaging over large sky regions

- No evidence of deviation from this behavior for small sky patches although s/n low

Fig 6 of arxiv:1409.5738

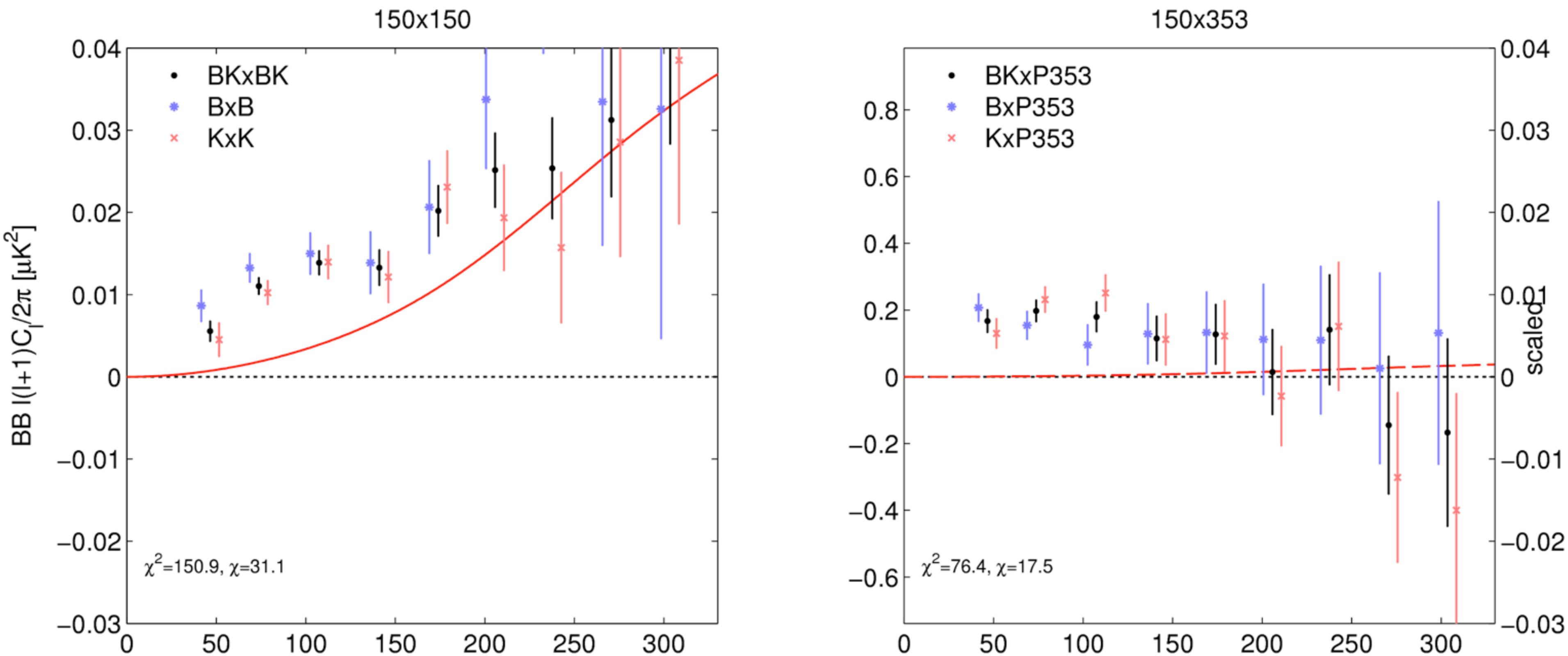


Spectral energy distribution of polarized dust emission follows modified blackbody model with T=19.6K and β_d=1.59

- Seems to be remarkably uniform over the high latitude sky

→ Good news for component separation

Zoom in on BB



- ➢ 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 LCDM.
  - ○ Shape looks consistent with $\ell^{-0.42}$ power law expectation

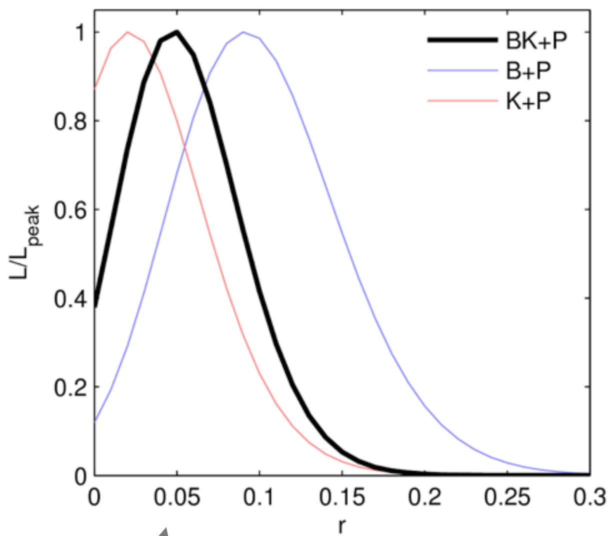
Multi-component multi-spectral likelihood analysis

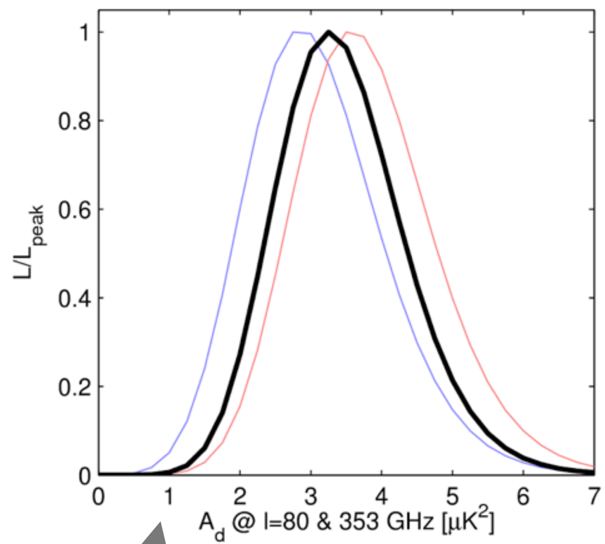
- Define “fiducial analysis” to use single- and cross-frequency spectra between BK 150 GHz and Planck 217&353 GHz channels
  - (Detail: for Planck single-frequency use detector set split cross spectrum)

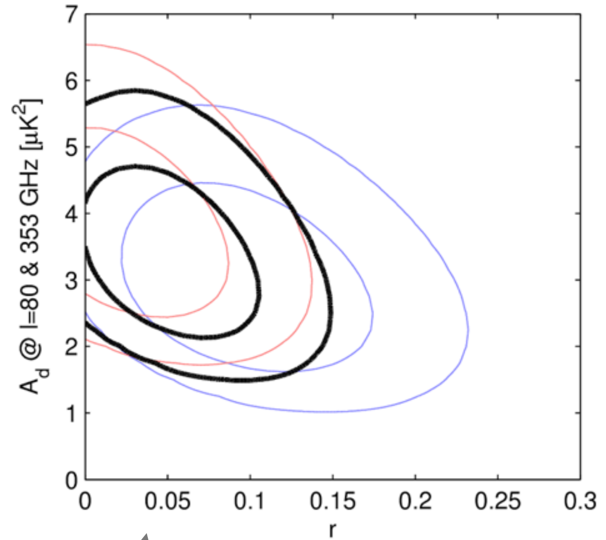
- As addition to basic LCDM lensing signal include gravity wave signal (with amp r) and dust signal with amplitude A_d (specified at ℓ =80 and 353 GHz)
  - For dust SED use modified blackbody model and marginalize over range β_d=1.59±0.11

- Use 5 lowest BB bandpowers only (20<ℓ <200)

Multi-component multi-spectral likelihood analysis





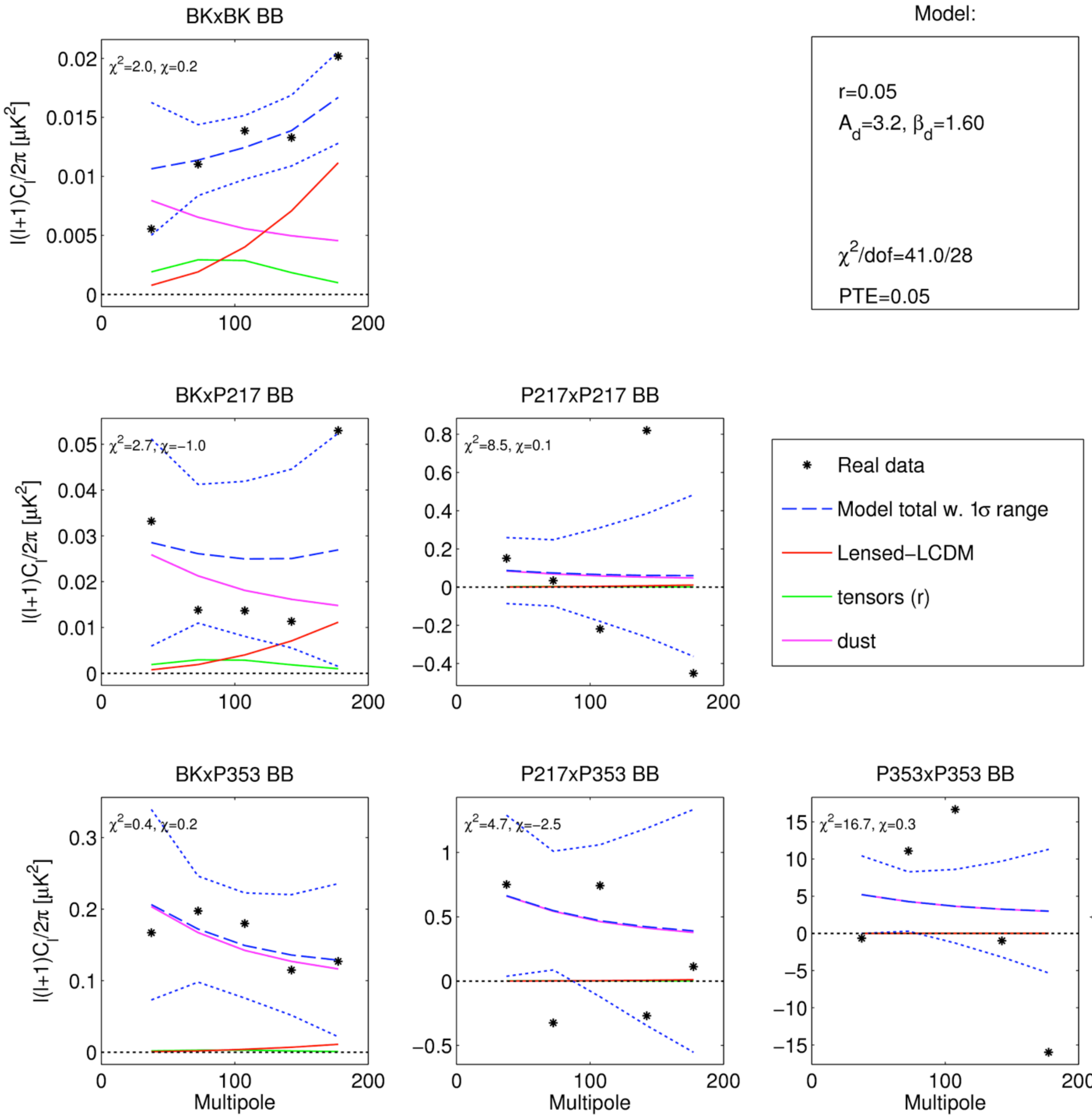


r constraint consistent with zero (For BK+P L_0/L_{peak} ratio is 0.4 which happens 8% of the time in a dust only model.)

Dust is detected with 5.1 σ significance

As expected dust and *r* are partially degenerate - reducing dust means more of the 150x150 signal needs to be *r*

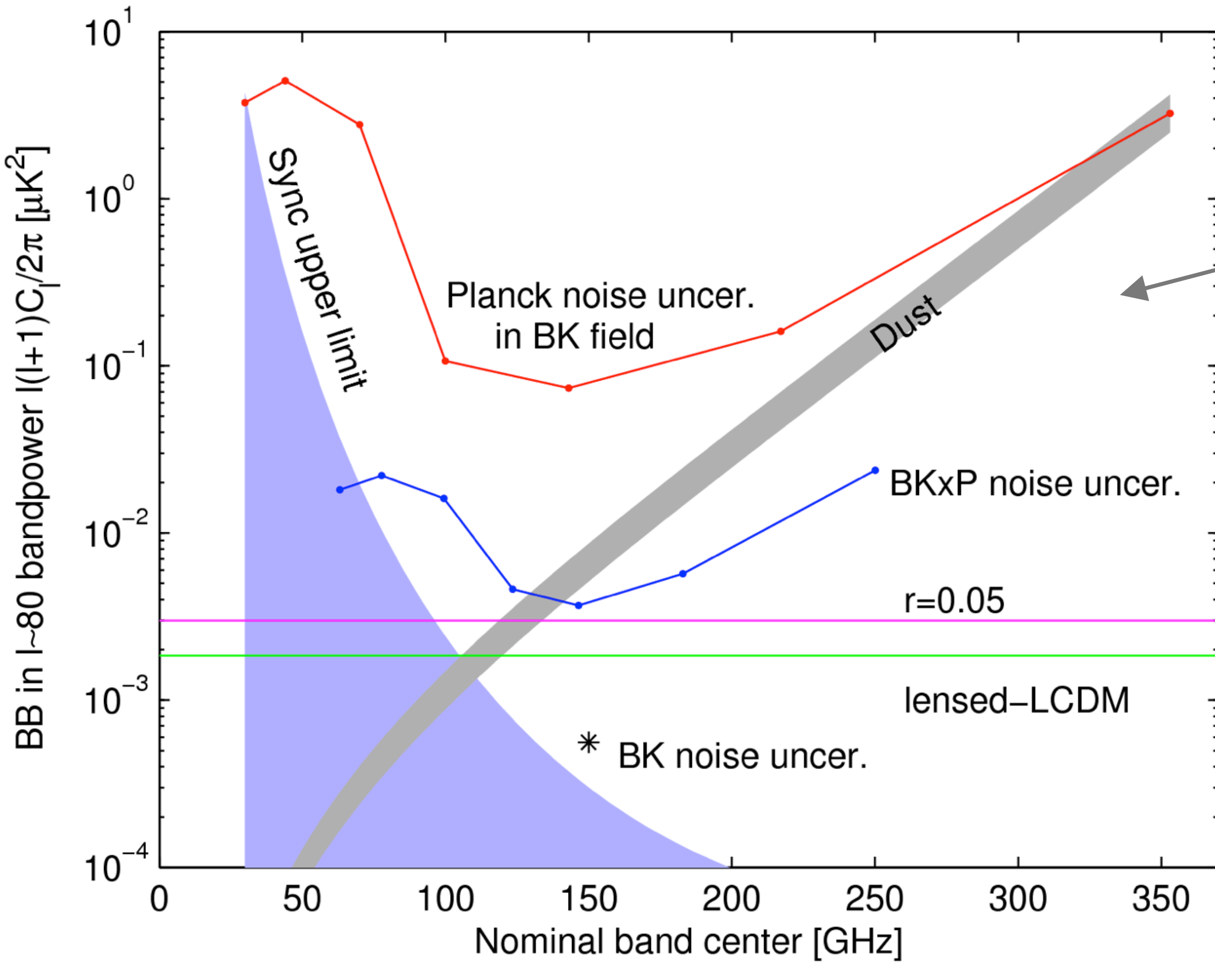
Best fit model



- ➢ The maximum likelihood model has acceptable χ^2 (with the biggest contribution coming from P353xP353.)
- ➢ The BKxBK and BKxP353 spectra are both very well fit by the model.

These plots show data as "naked points" versus center value and spread of best fit model to emphasize that uncertainty varies with the model (due to sample variance)

Comparison of signal and noise levels



Noise and signal levels in single ell=80 bandpower

- The BICEP2/Keck noise is much lower than the Planck noise in the small sky patch observed
- However dust is much brighter at 353 GHz and Planck detects it
- The noise in the cross spectra is the geometric mean and a fairly tight constraint on dust amplitude is set

Current Conclusions

- Last March BICEP2 reported detection of B-mode polarization in the CMB at 150GHz well in excess of the standard model expectation
  - This signal is confirmed by new data from the successor experiment Keck Array

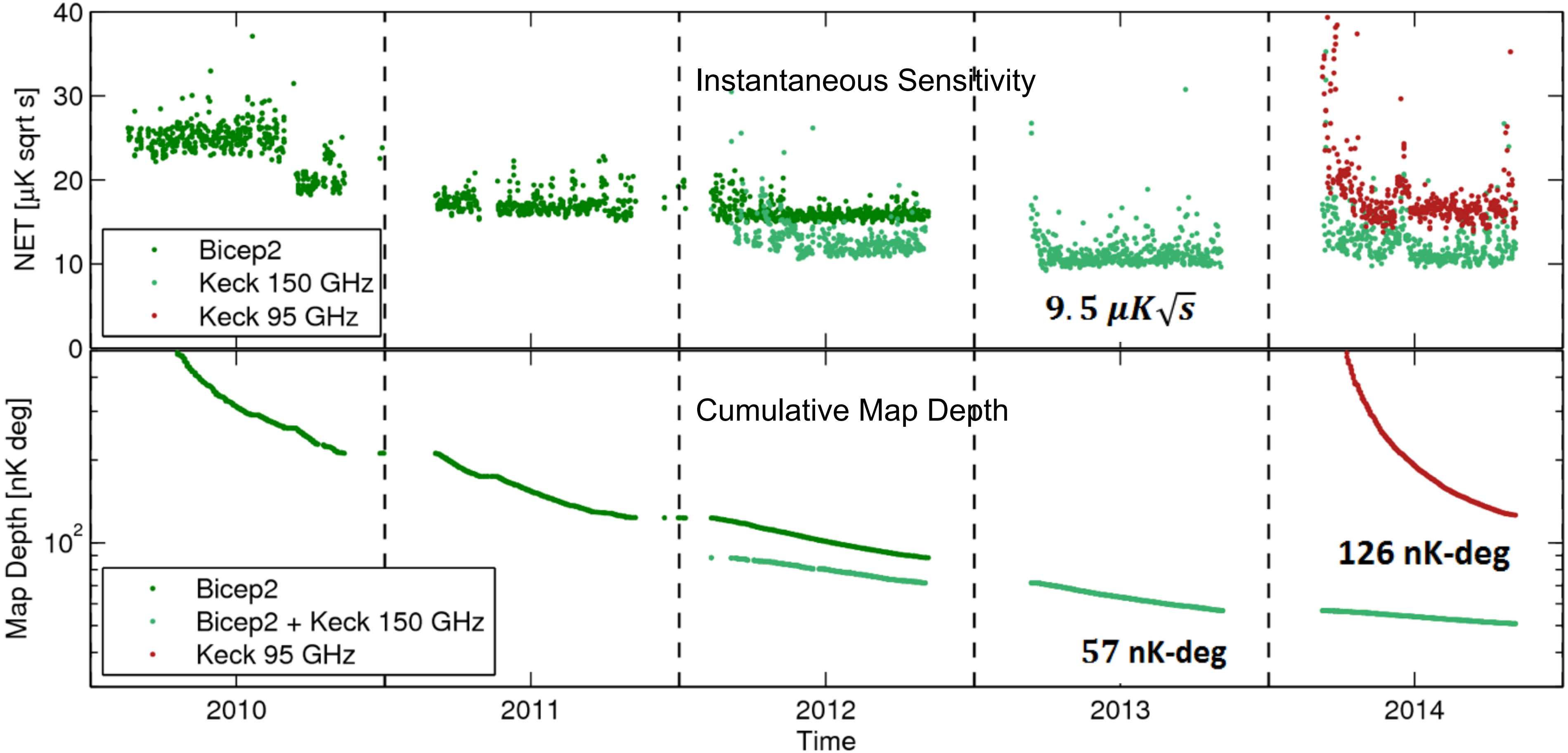
- Last summer Planck released new information on the polarized emission from galactic dust which showed this might be due to dust emission.

- We have now done a joint analysis with Planck - The fundamental conclusion is that dust is detected at high significance, and $r < 0.12$ at 95% confidence.
  - Multi-component likelihood gives $\sigma(r) \sim 0.035$ -- This is a very direct constraint on tensors!
  - No significant evidence for $r > 0$. Currently $r = 0$ and $r = 0.1$ are at equal likelihood.
  - There may yet be a gravitational wave signal, but if there is it must be considerably smaller than the full signal.

- Additionally, lensing B-modes are detected at 7.0 σ significance

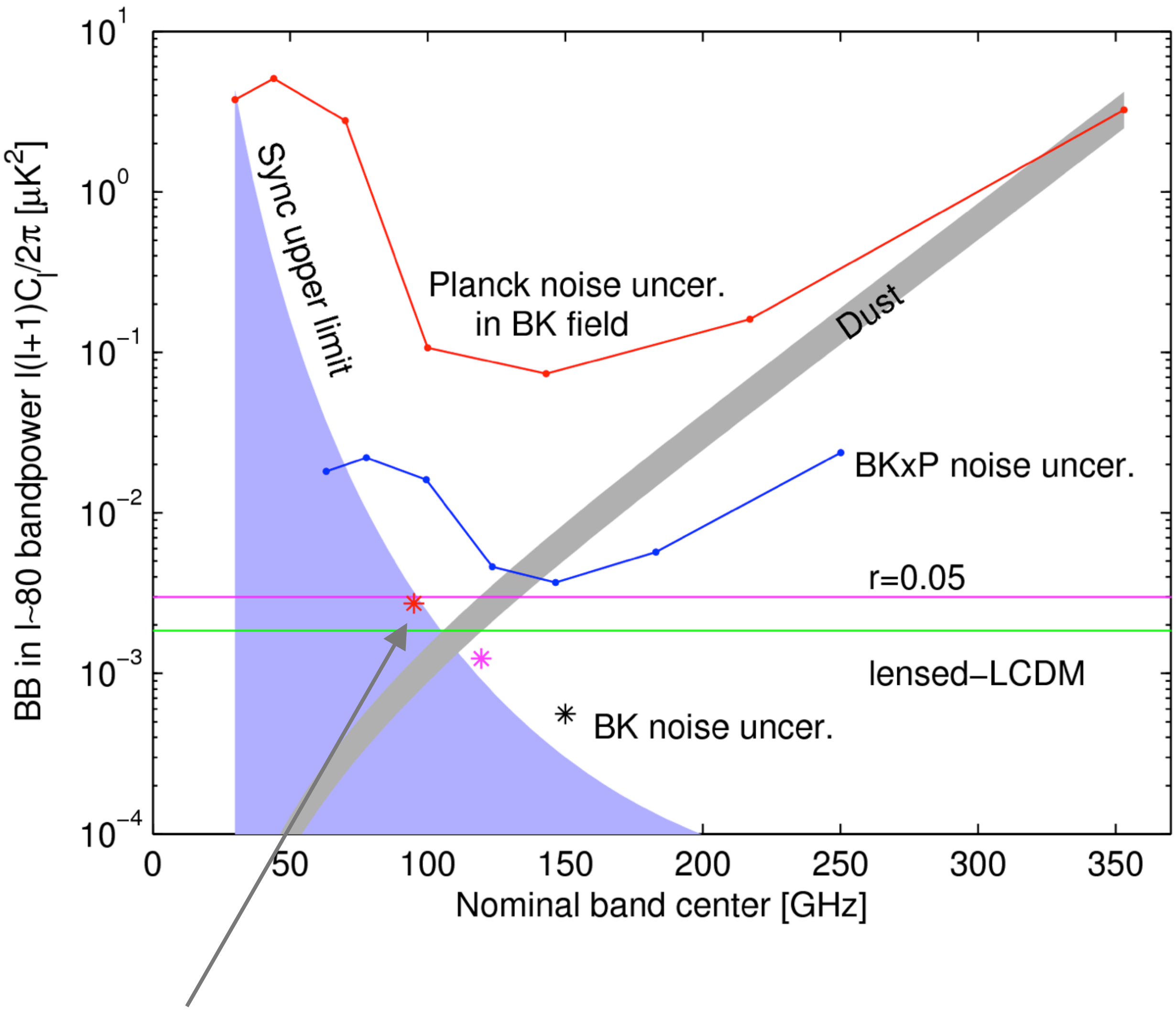
- Noise in P353 is the current limiting factor and to make further progress better data at frequencies other than 150 GHz is required

Results Coming soon - Keck 2014 95 GHz

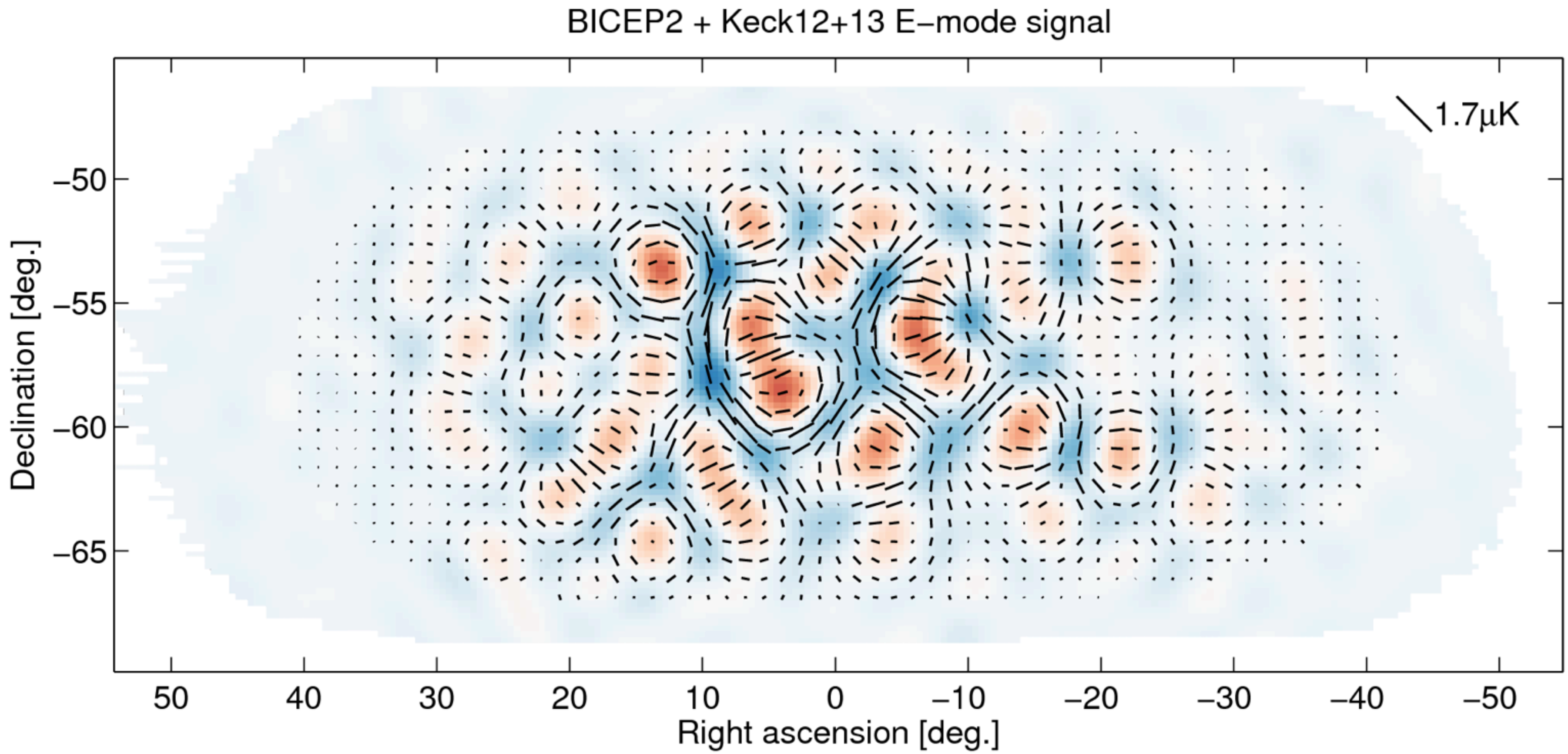


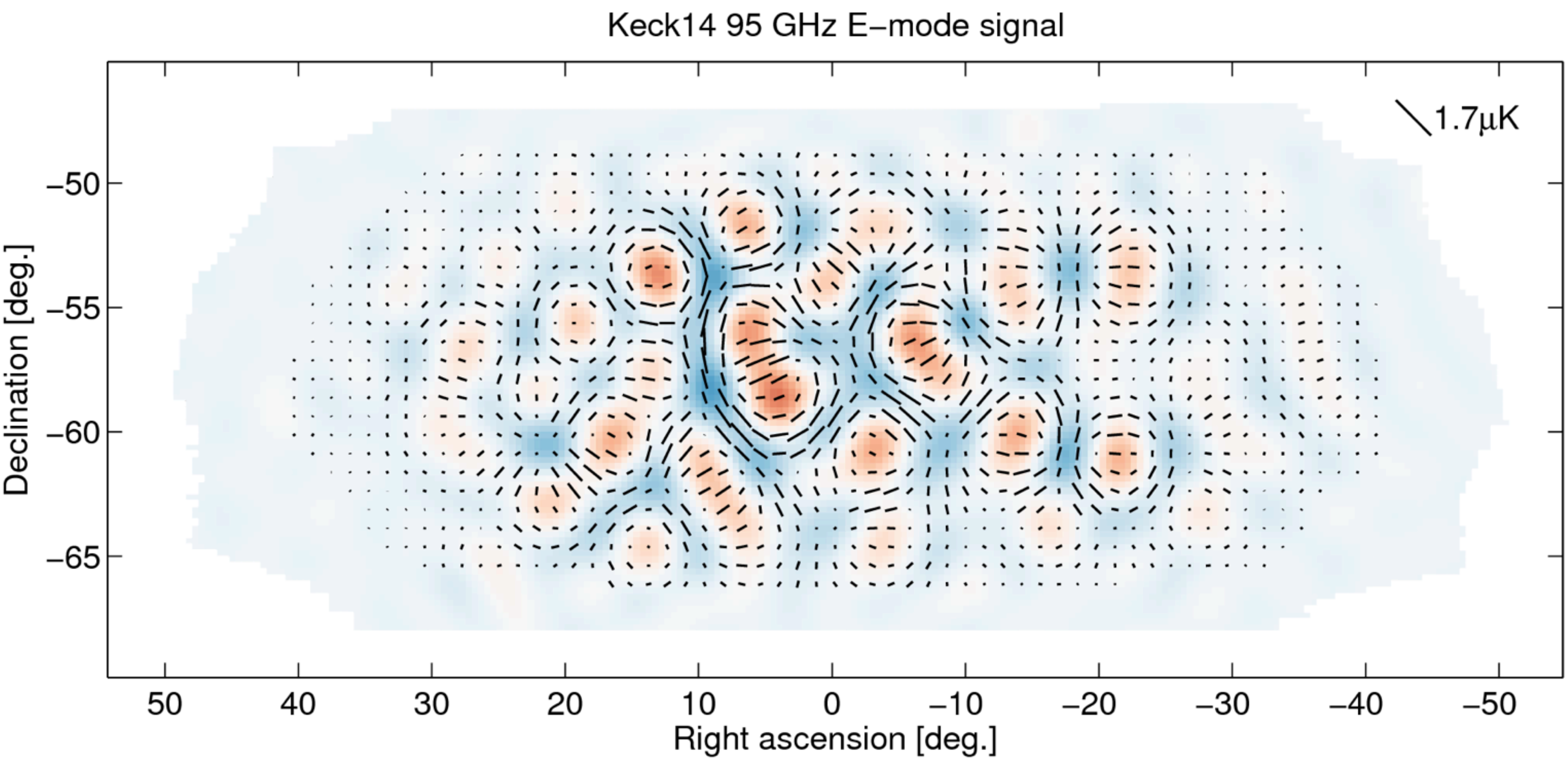
For 2014 season two of the Keck array receivers switched out for 95 GHz

Comparison of signal and noise levels



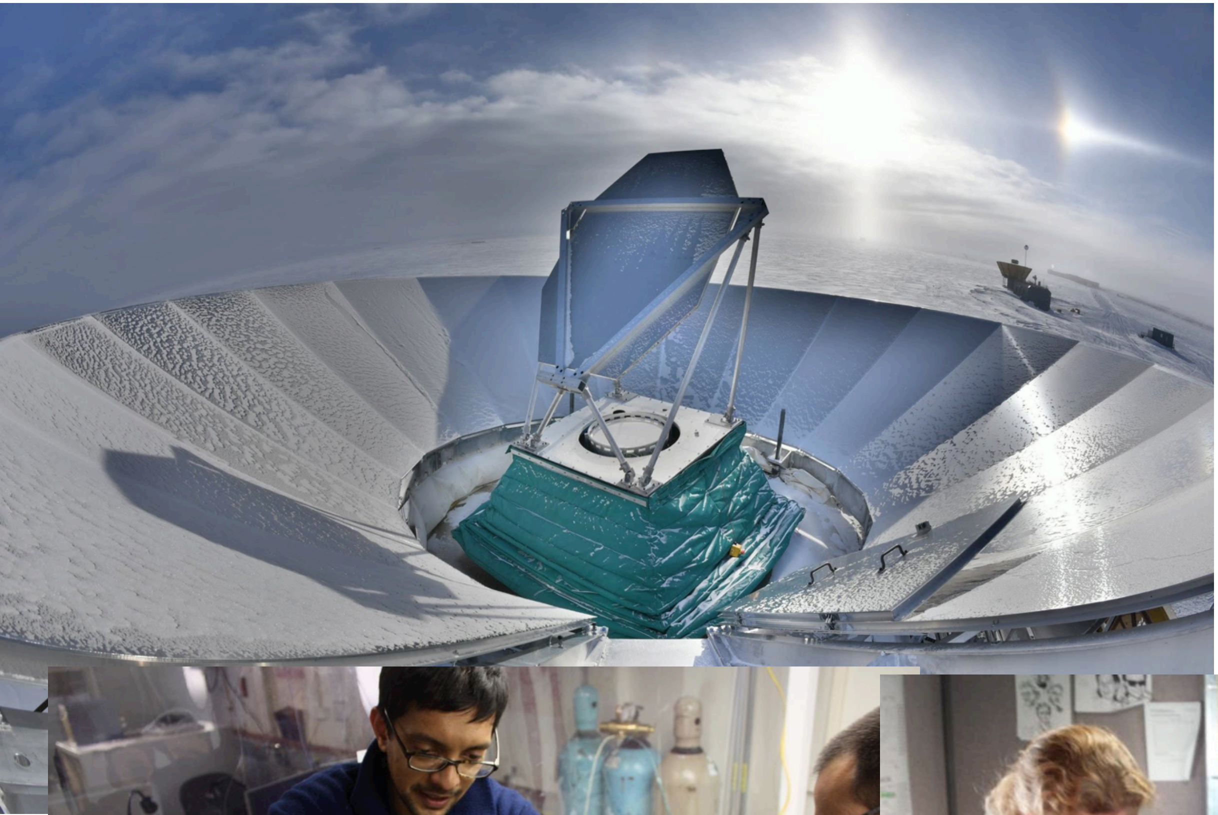
Keck 2014 95 GHz achieved noise level


BICEP2 + Keck12+13 E−mode signal
1.7μK
Declination [deg.]
−50
−55
−60
−65
Right ascension [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50



Reduction in amplitude with respect to 150 GHz due to increased beam size (which is uncorrected in these map plots)

New for 2015 - Keck220 and BICEP3



- BICEP3 receiver installed on old BICEP mount - all 95 GHz "super receiver"
- Two more Keck receivers switched out for 220 GHz
- Watch for more soon…