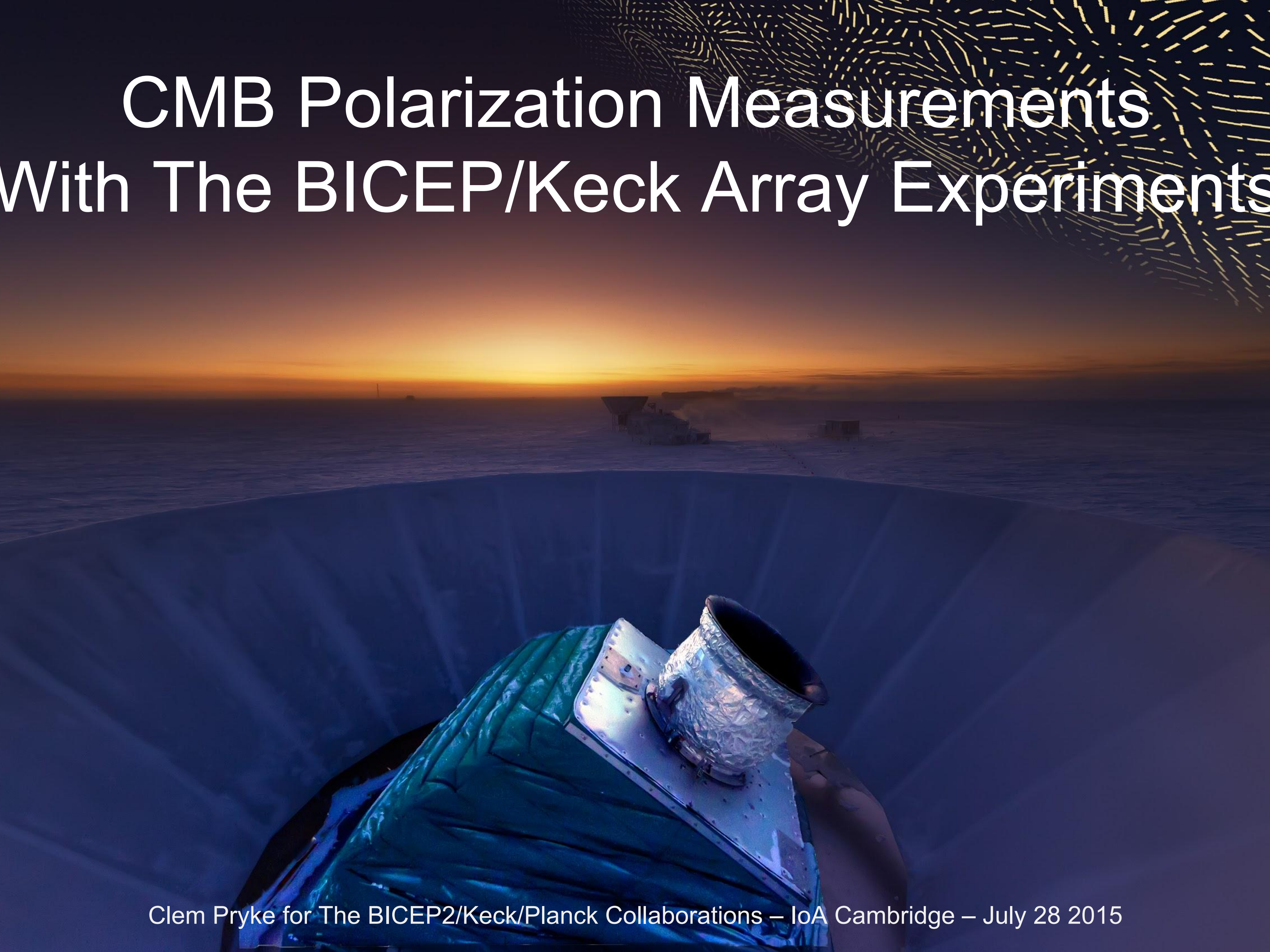
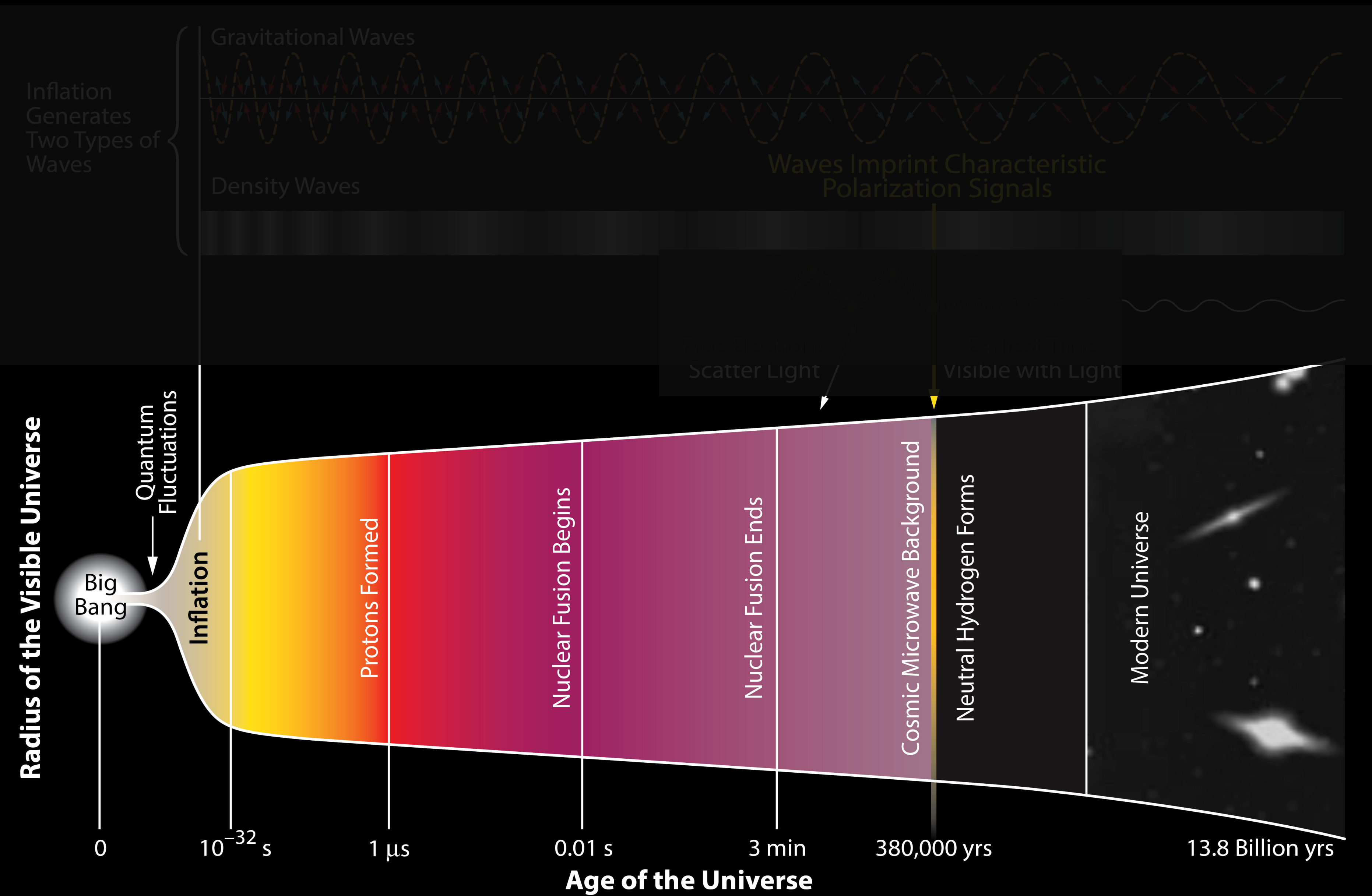
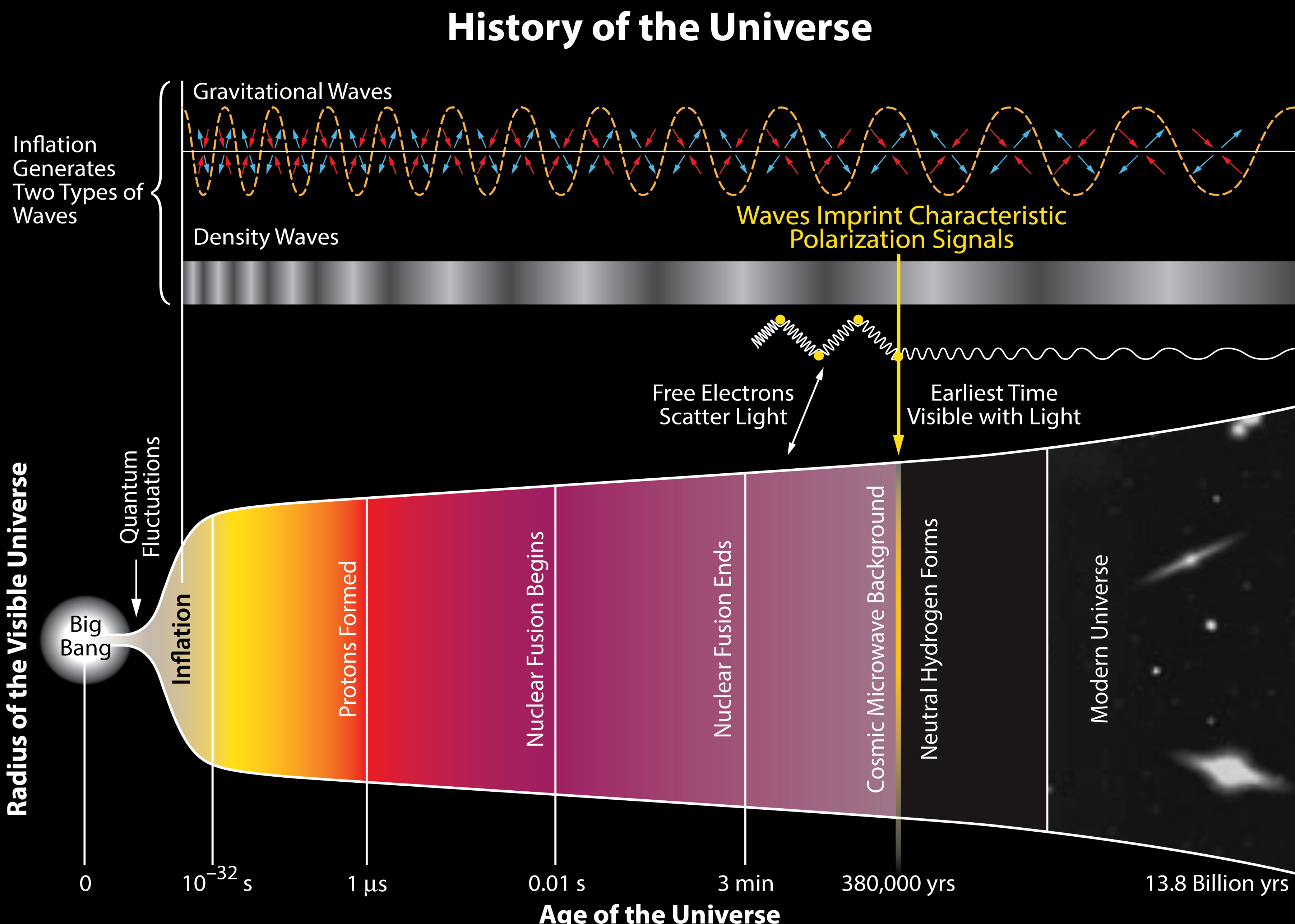
CMB Polarization Measurements With The BICEP/Keck Array Experiments



Clem Pryke for The BICEP2/Keck/Planck Collaborations – IoA Cambridge – July 28 2015

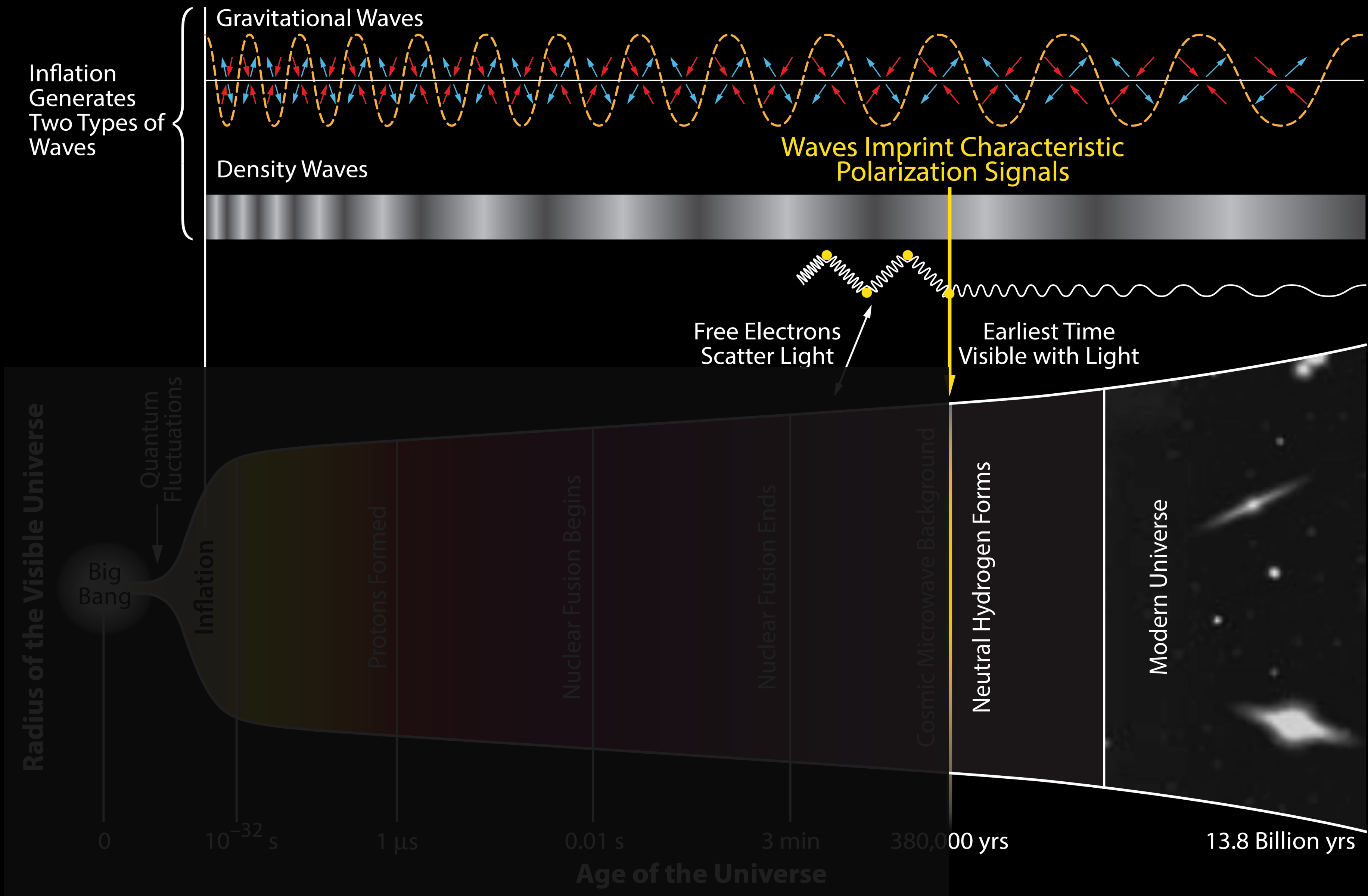
History of the Universe



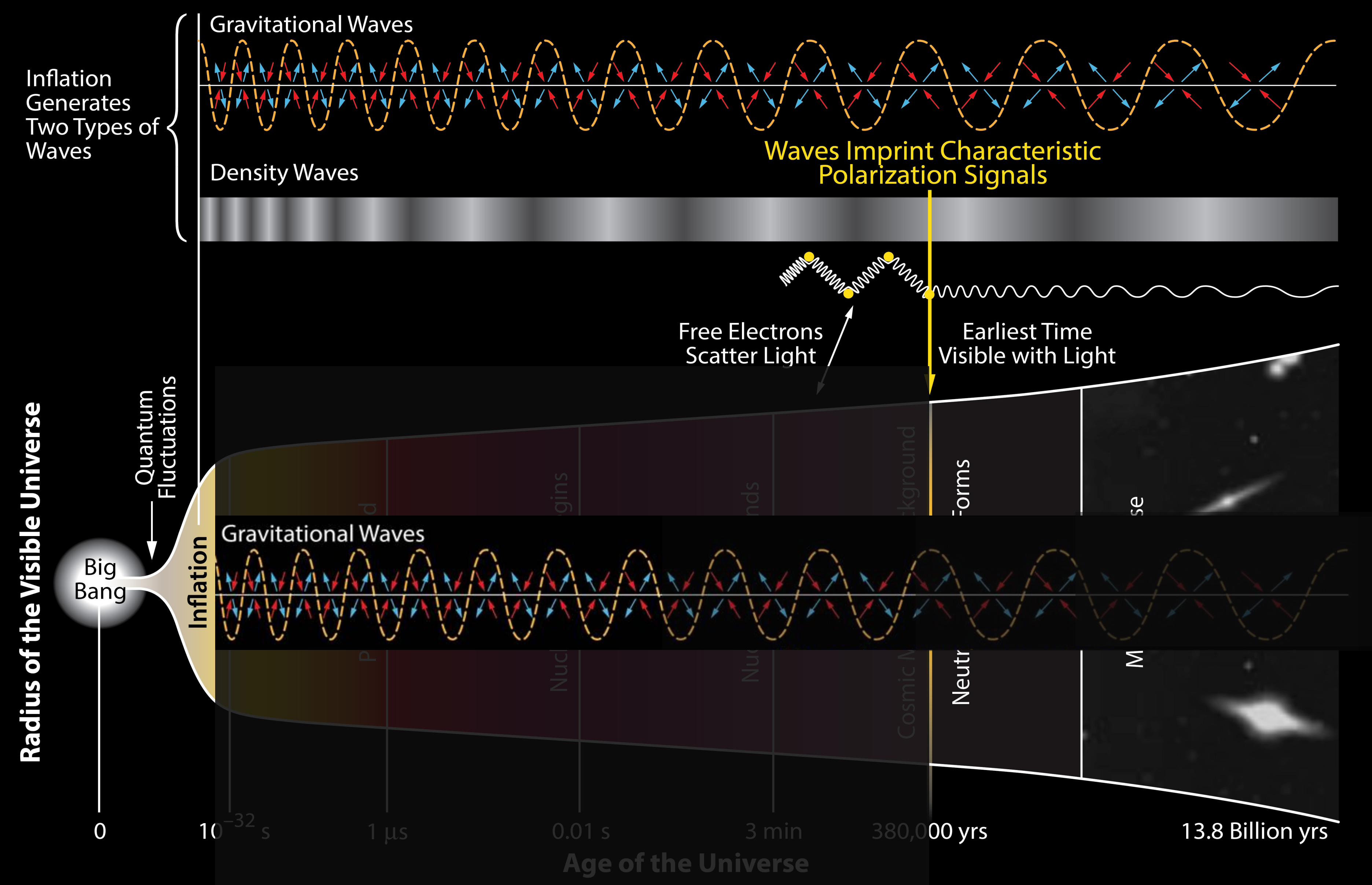


History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear 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

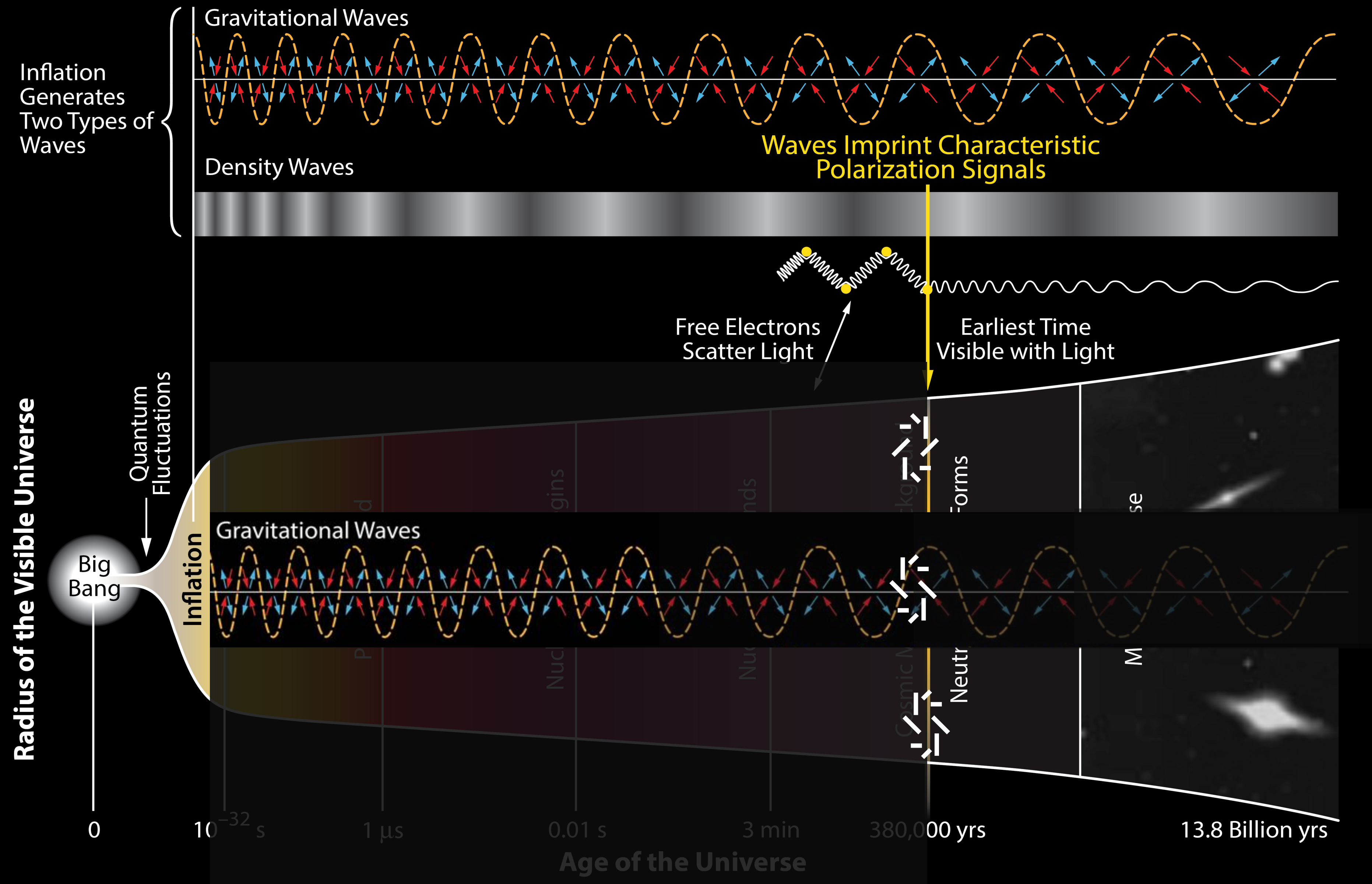
History of the Universe



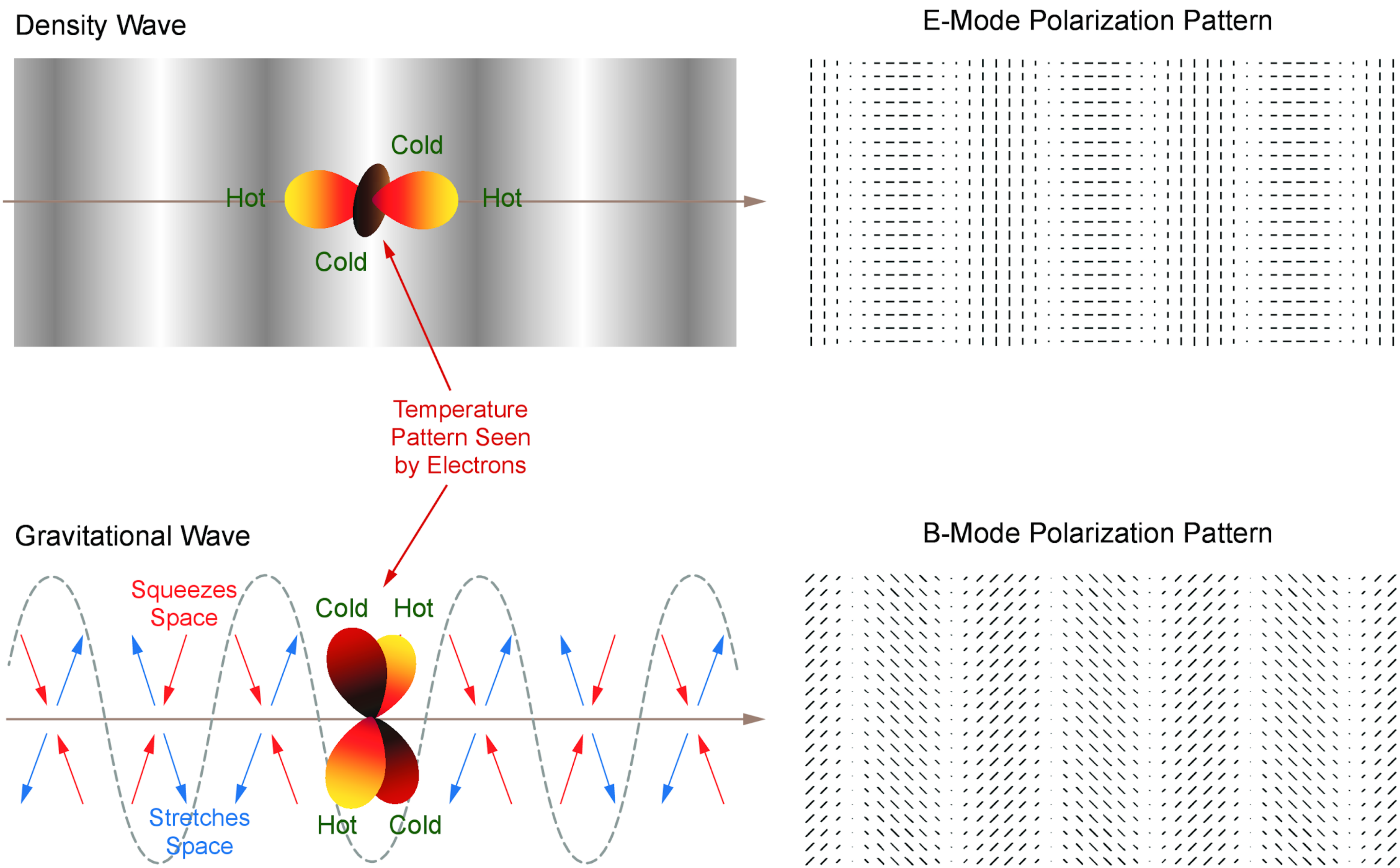
History of the Universe



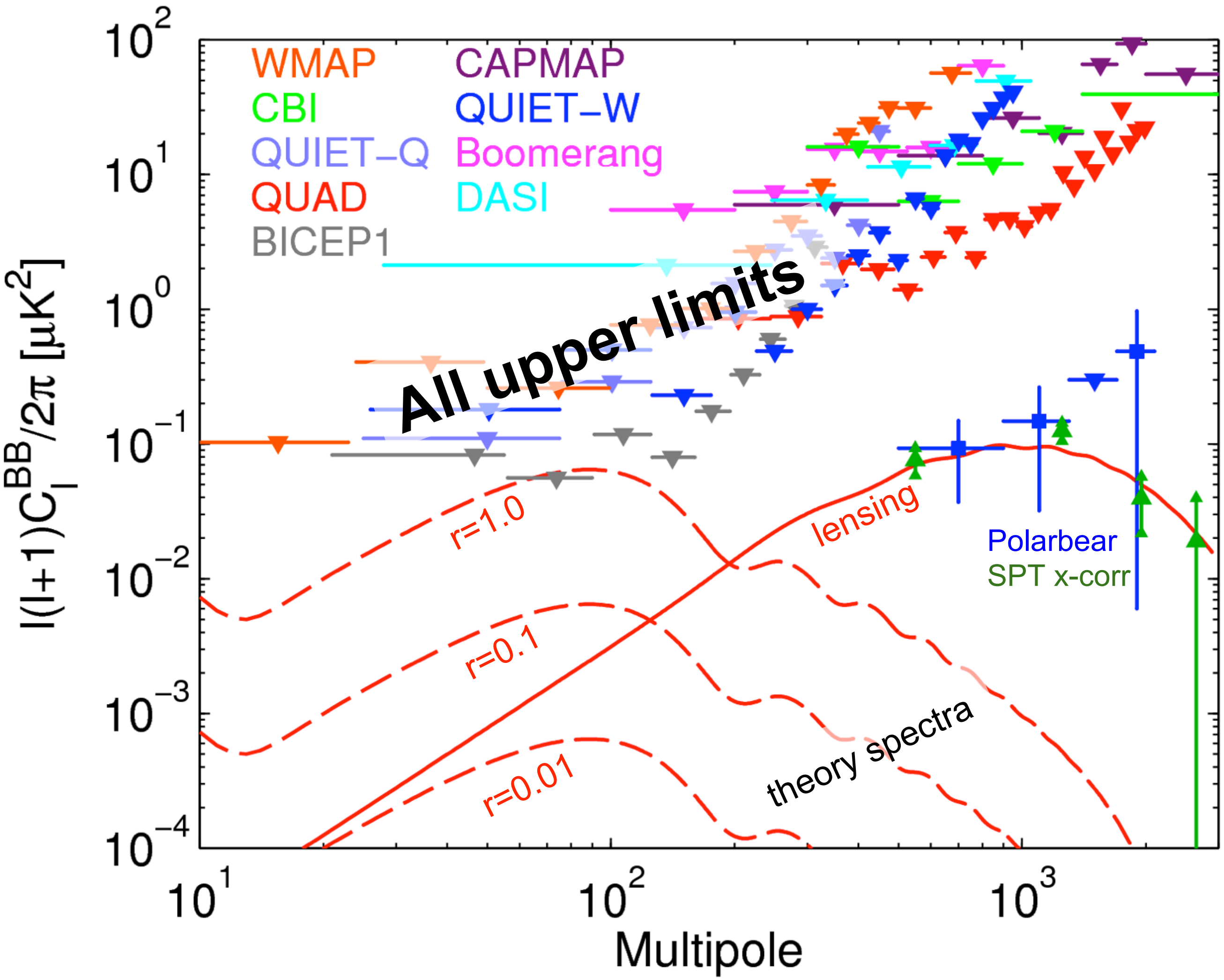
History of the Universe



CMB polarization



The State of B-mode Measurements in March 2014



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.

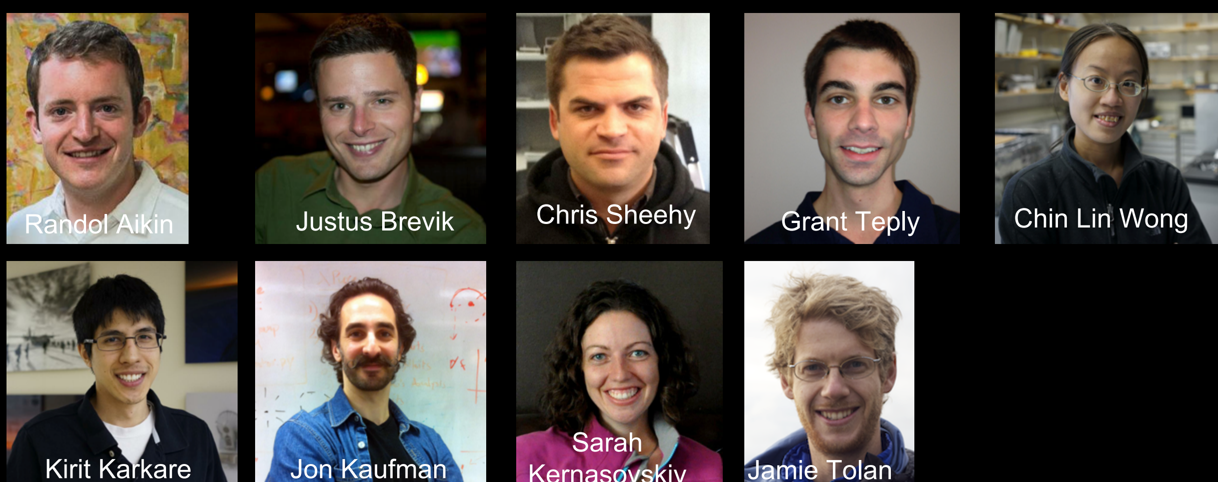
SPT x-corr: lower limits on lensing B-mode from cross correlation using the CIB

Clem Pryke for The Bicep2 Collaboration


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

The BICEP2/Keck Postdocs

The BICEP2/Keck Graduate Students



Winterovers

BICEP2

2010

2011

2012

Keck

2013

2014

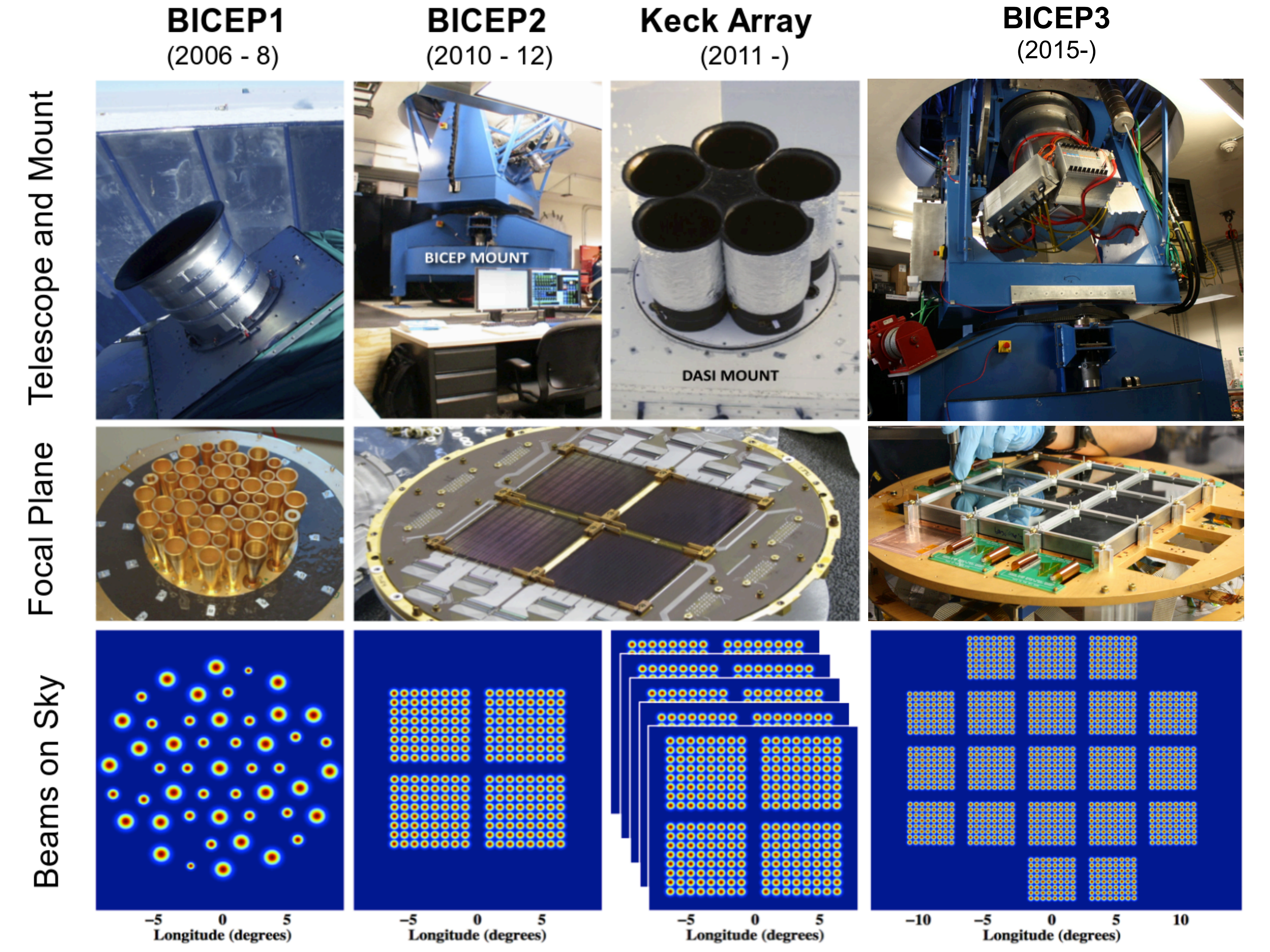
2015

South Pole CMB telescopes

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

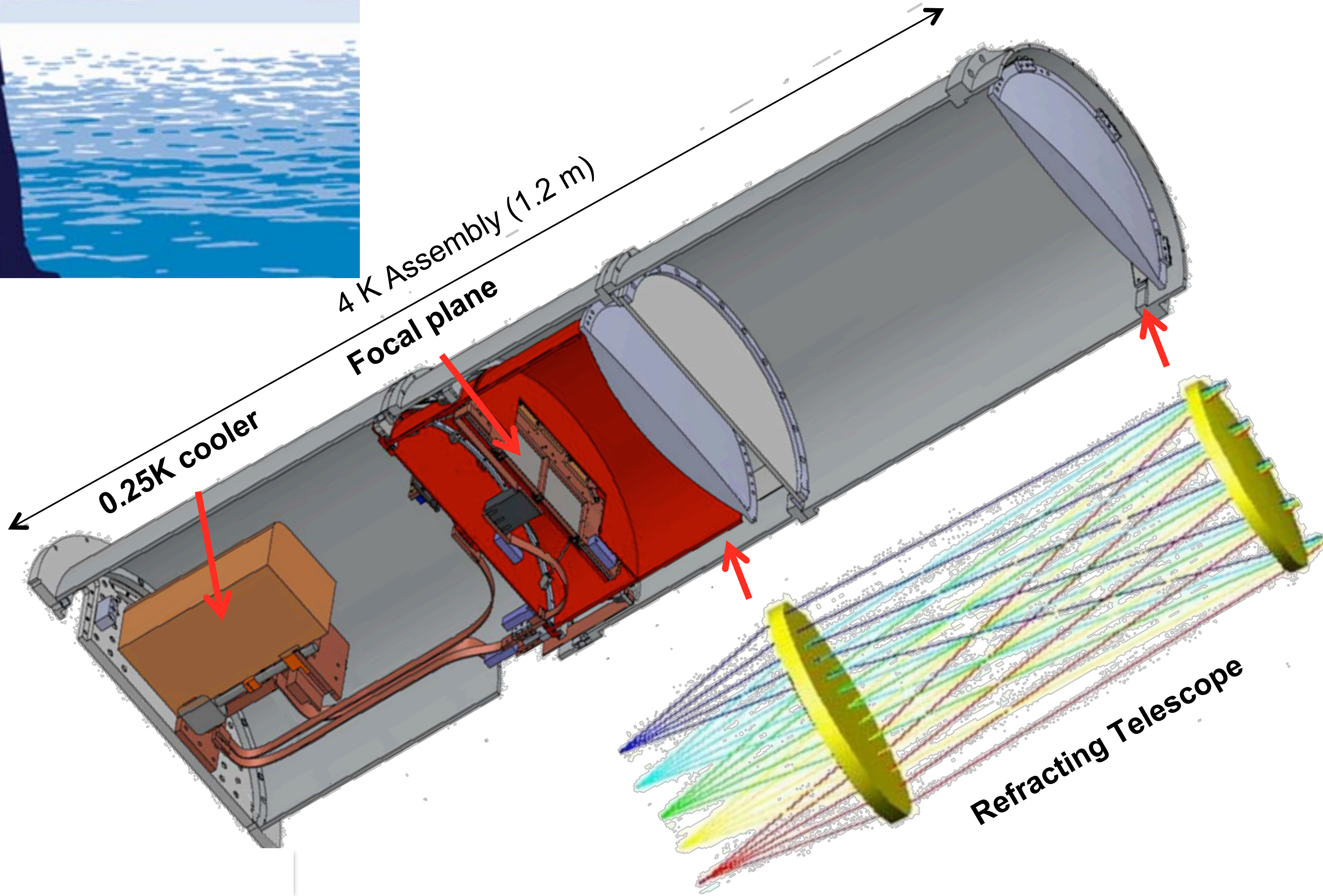
Super dry atmosphere and 24h coverage of low foreground sky.

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


BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2015-)
Telescope and Mount
BICEP MOUNT
DASI 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)

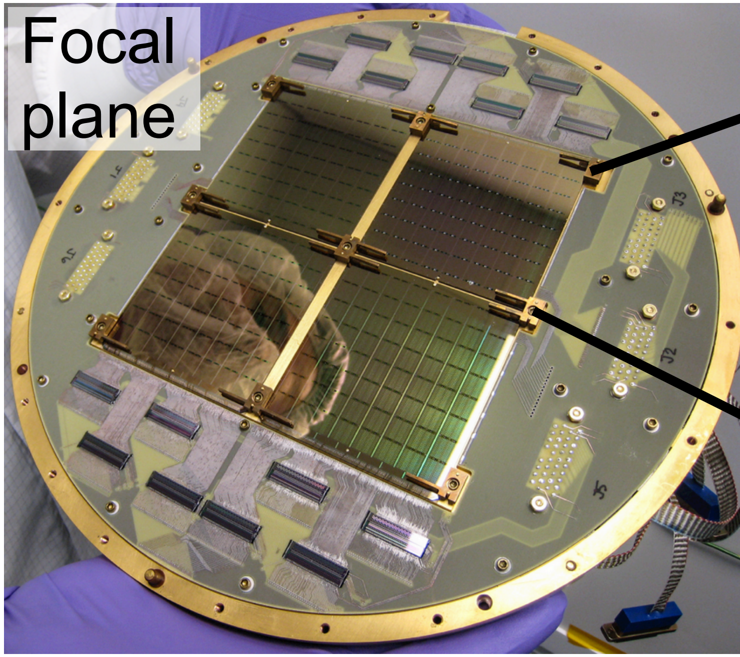
BICEP2/Keck Experimental Concept

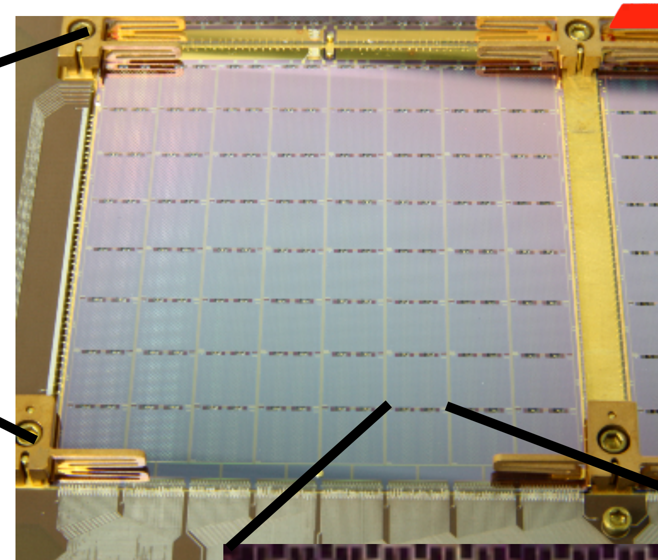
- Small aperture
- Wide field of view
- Cold refractor



Mass-produced Superconducting Detectors

JPL

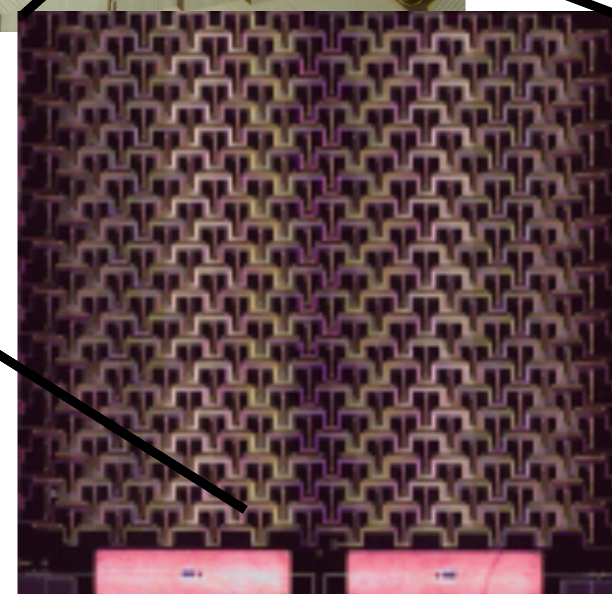




Planar antenna array

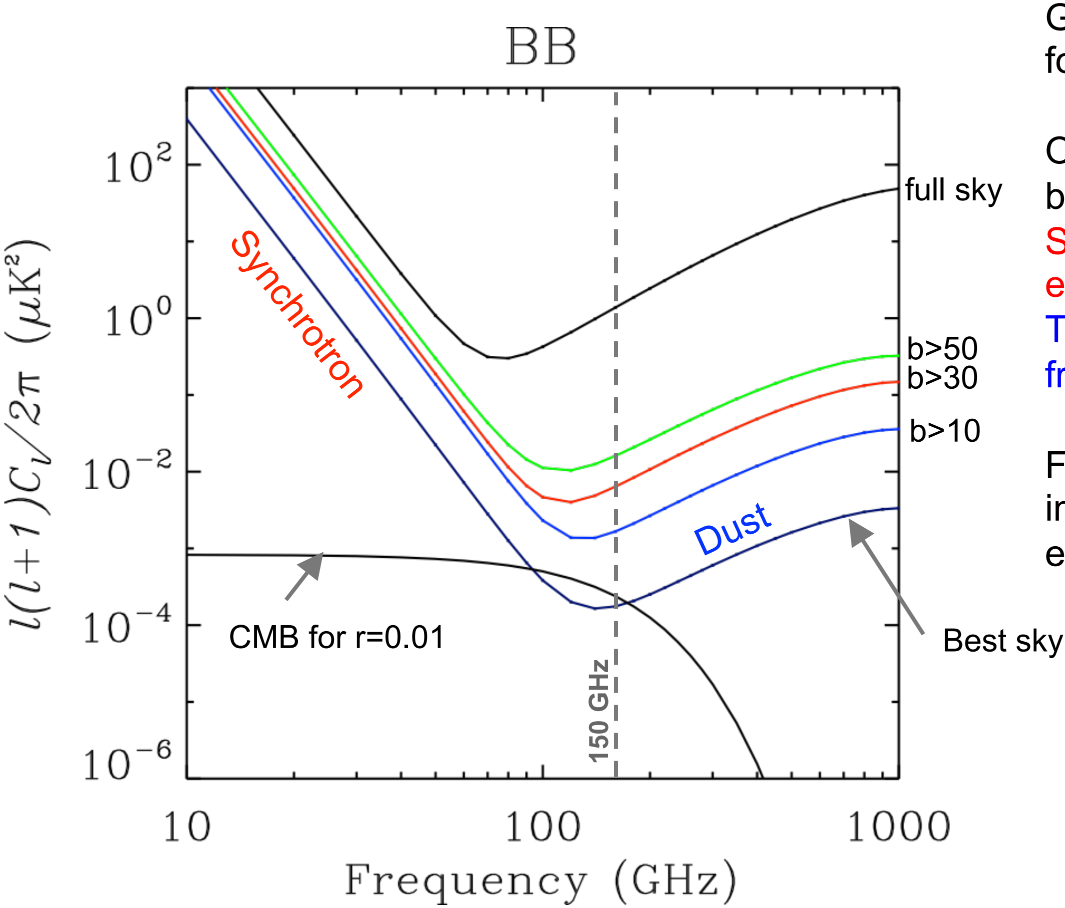
Slot antennas

Transition edge sensor



Microstrip filters

BICEP Observational Strategy



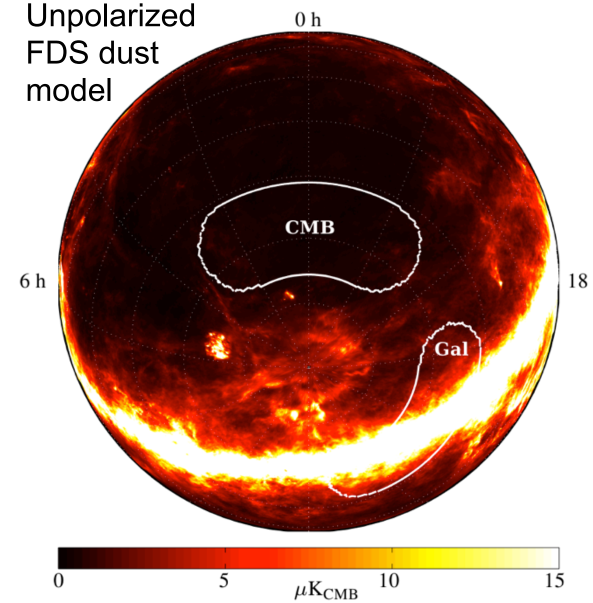
From Dunkley et al arxiv/0811.3915

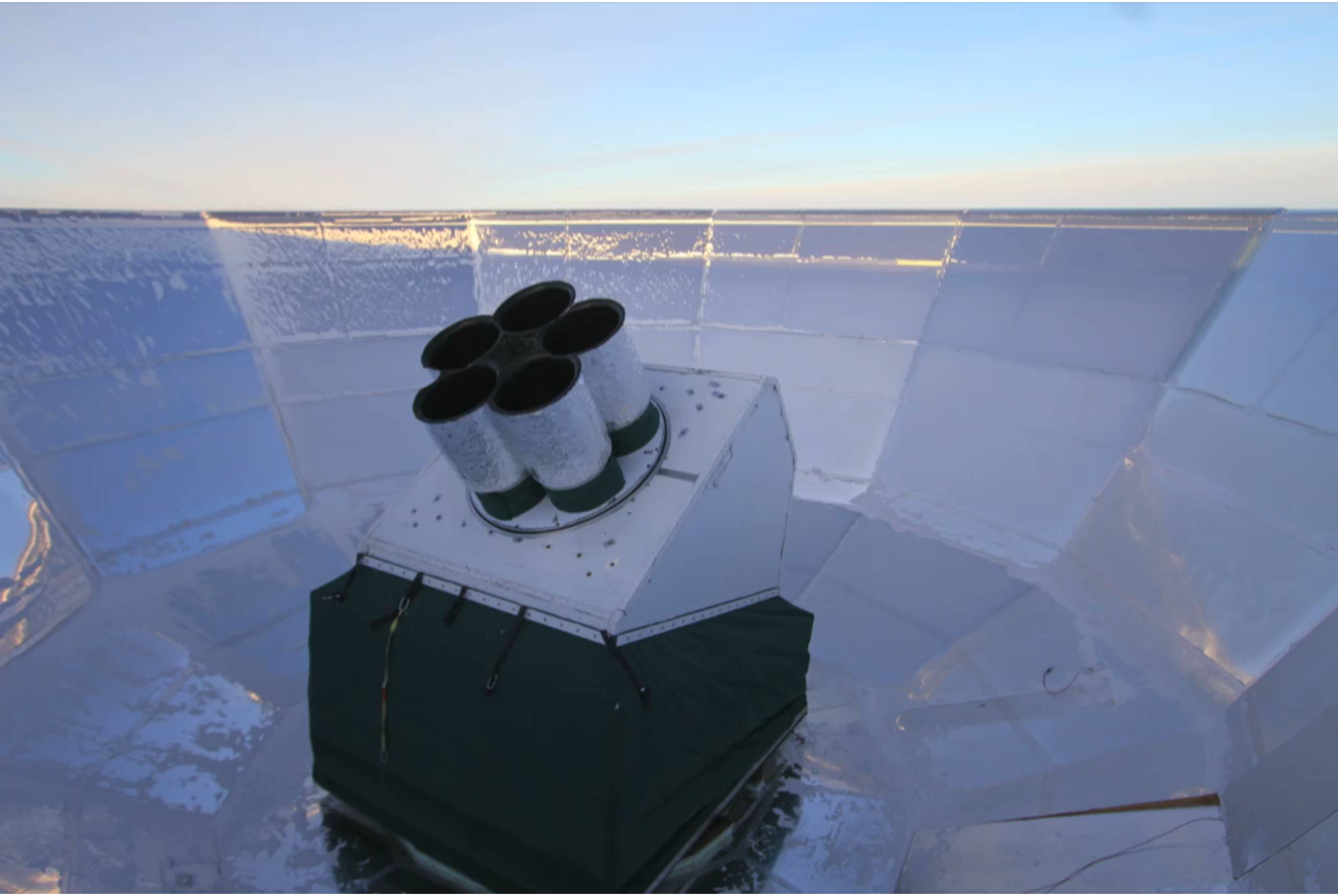
Go deep in a region of sky where galactic foregrounds are low

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.

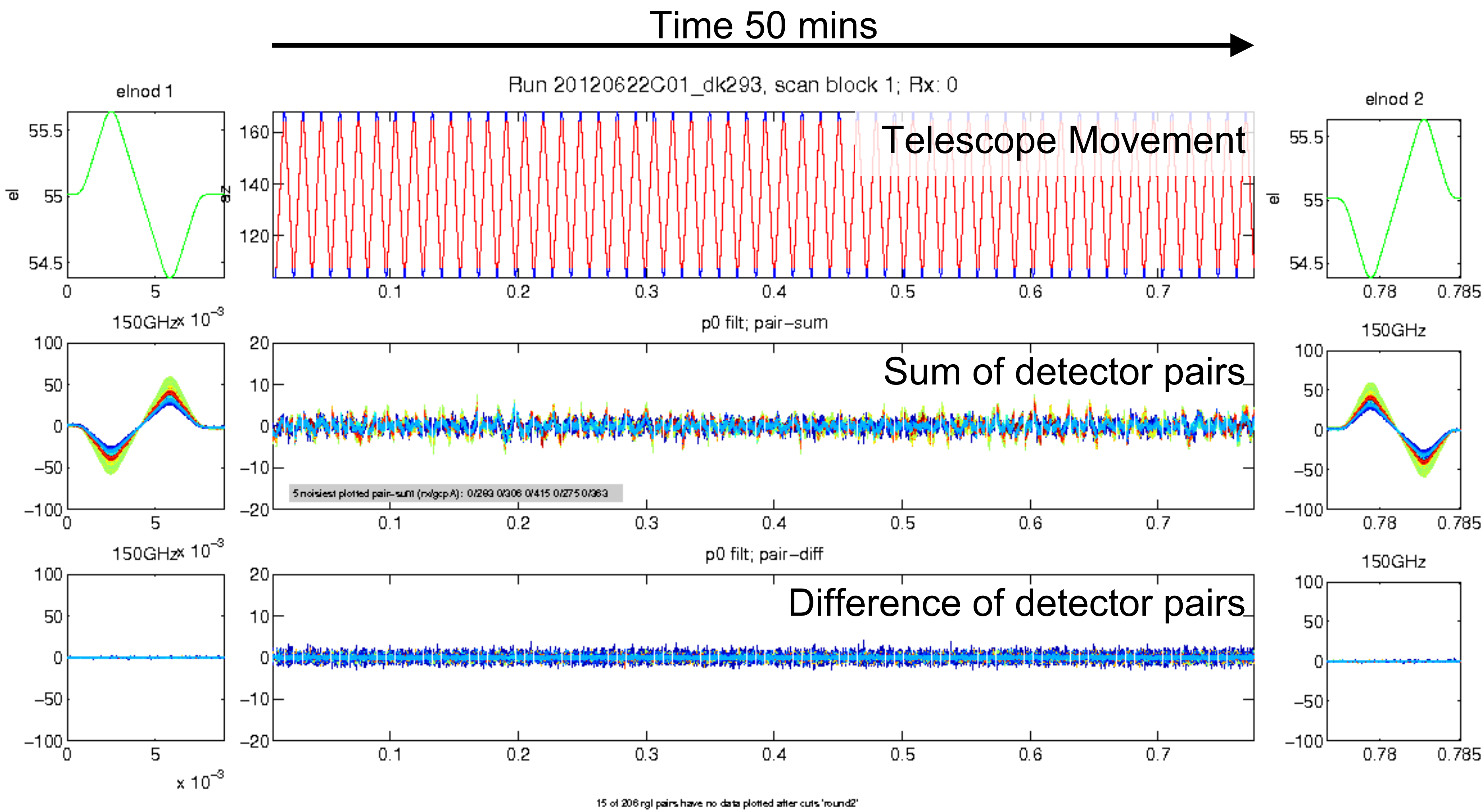
Unpolarized FDS dust model





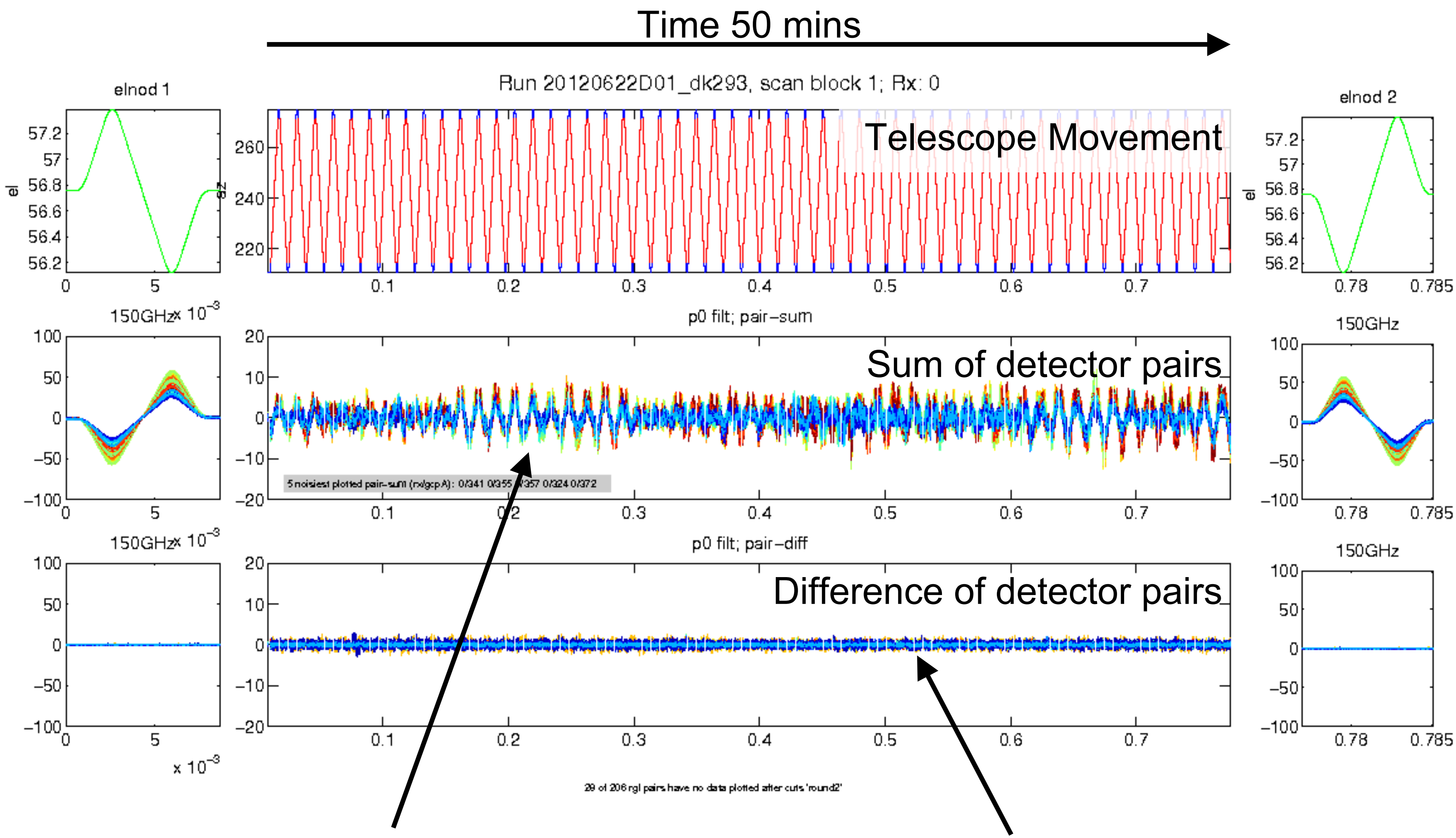
Clem Pryke for The Bicep2 Collaboration

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

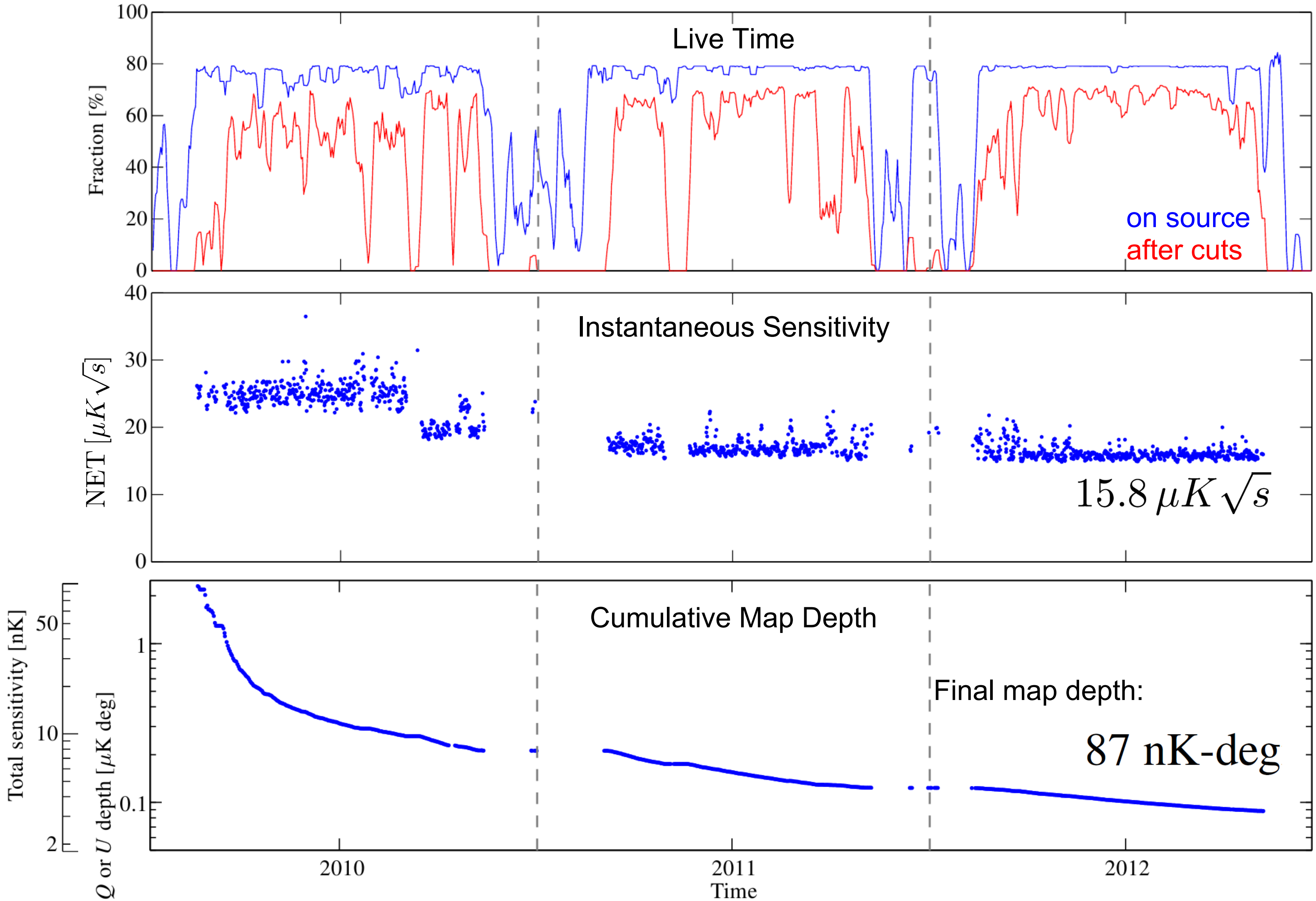
Raw Data - Worse Weather



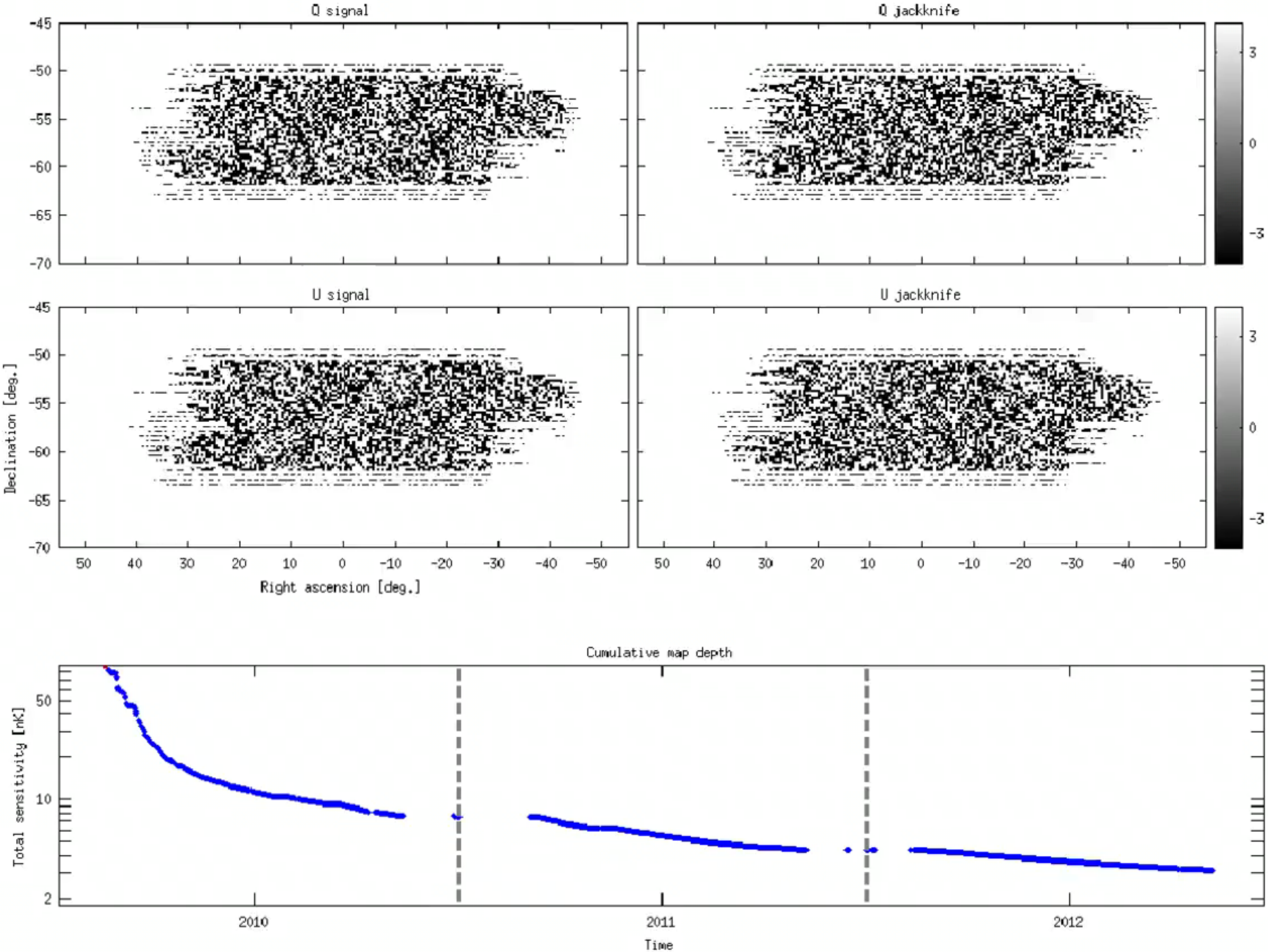
- ➢ Scanning over lumpy atmosphere → "clouds"
- ➢ Pair difference still clean → atmosphere is unpolarized

Clem Pryke for The Bicep2 Collaboration

BICEP2 3-year Data Set



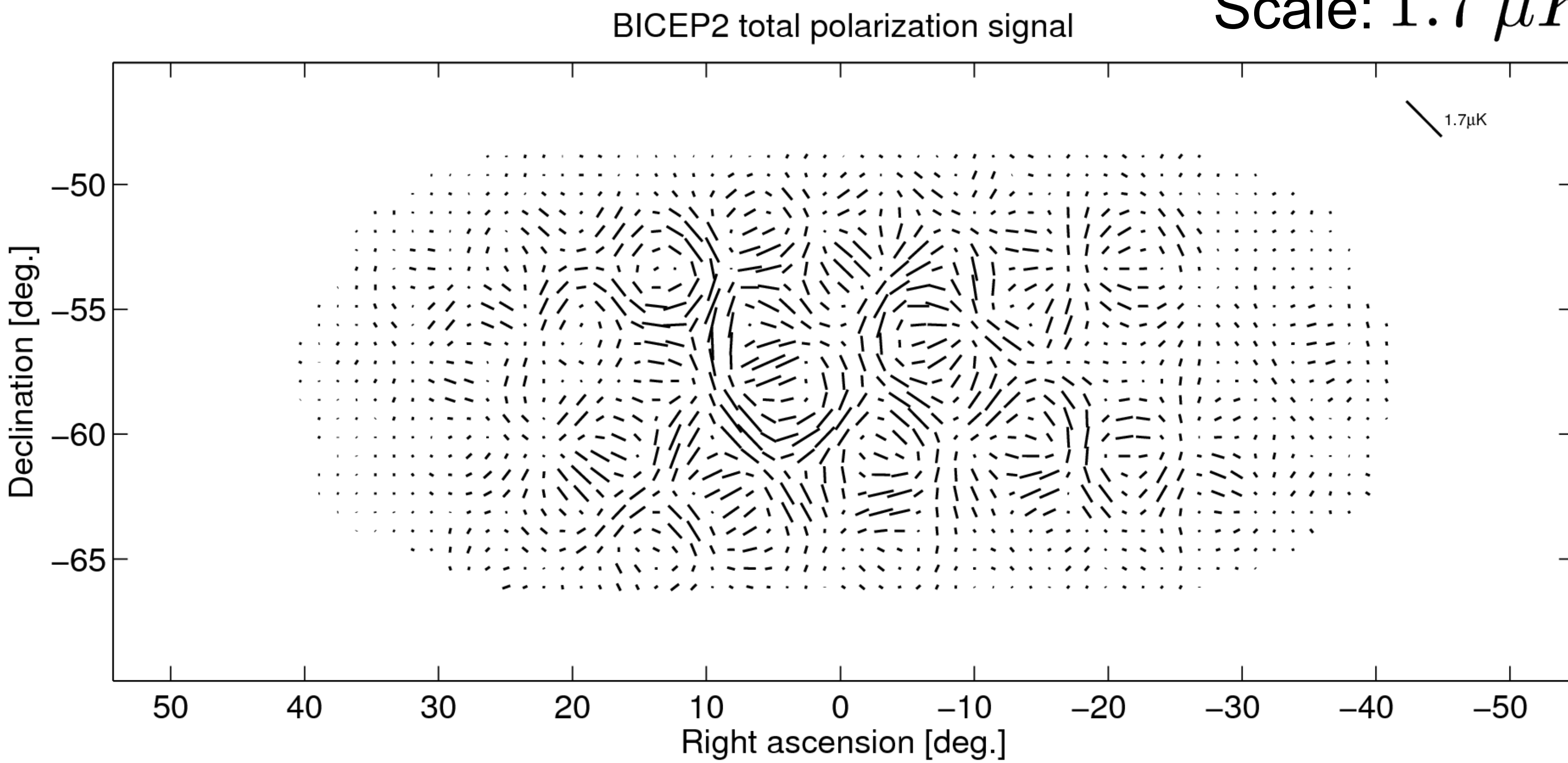
Clem Pryke for The Bicep2 Collaboration



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

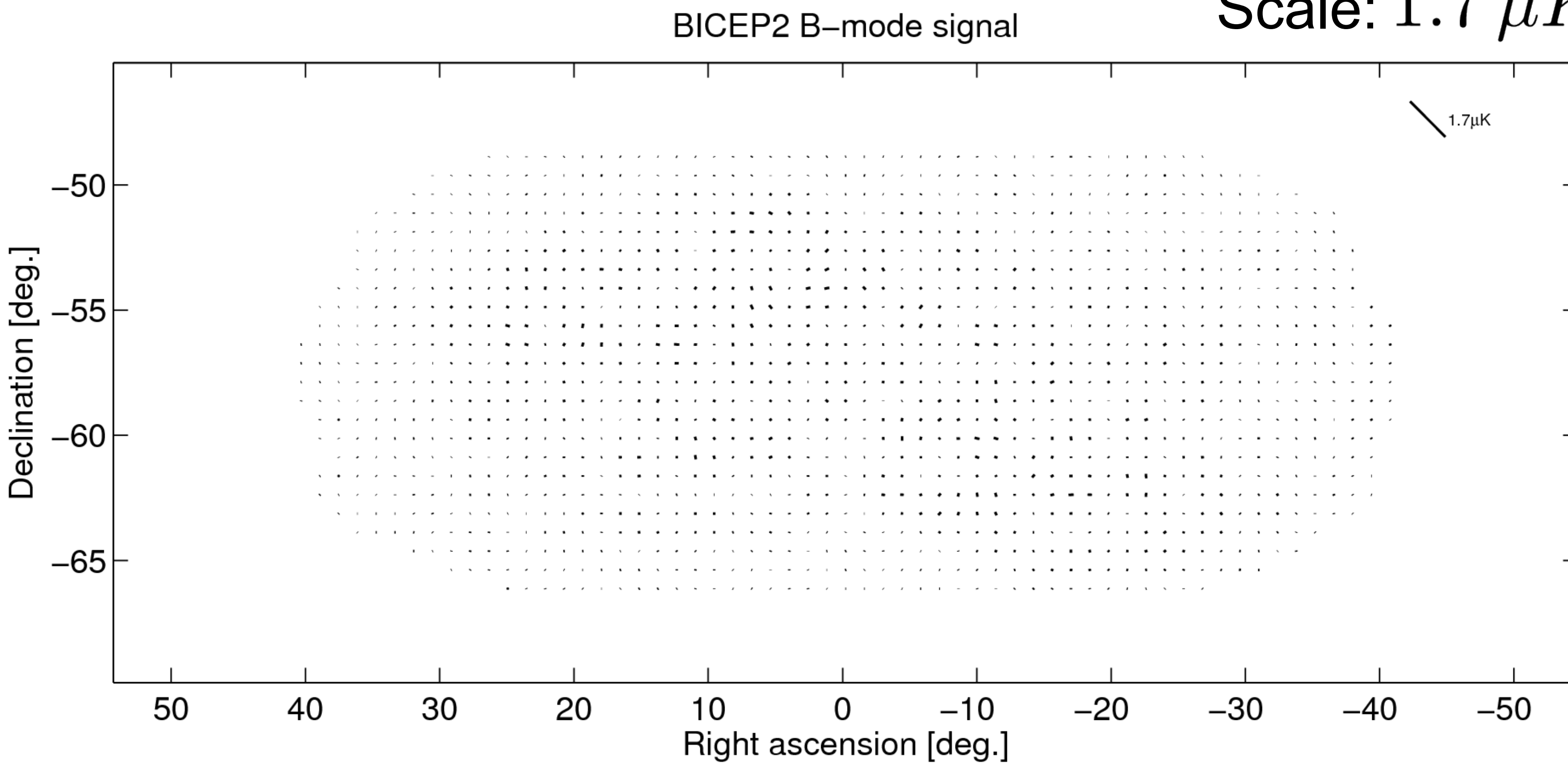
Scale: $1.7\,\mu K$



E-mode dominated pattern – no obvious curl component

B-mode Contribution

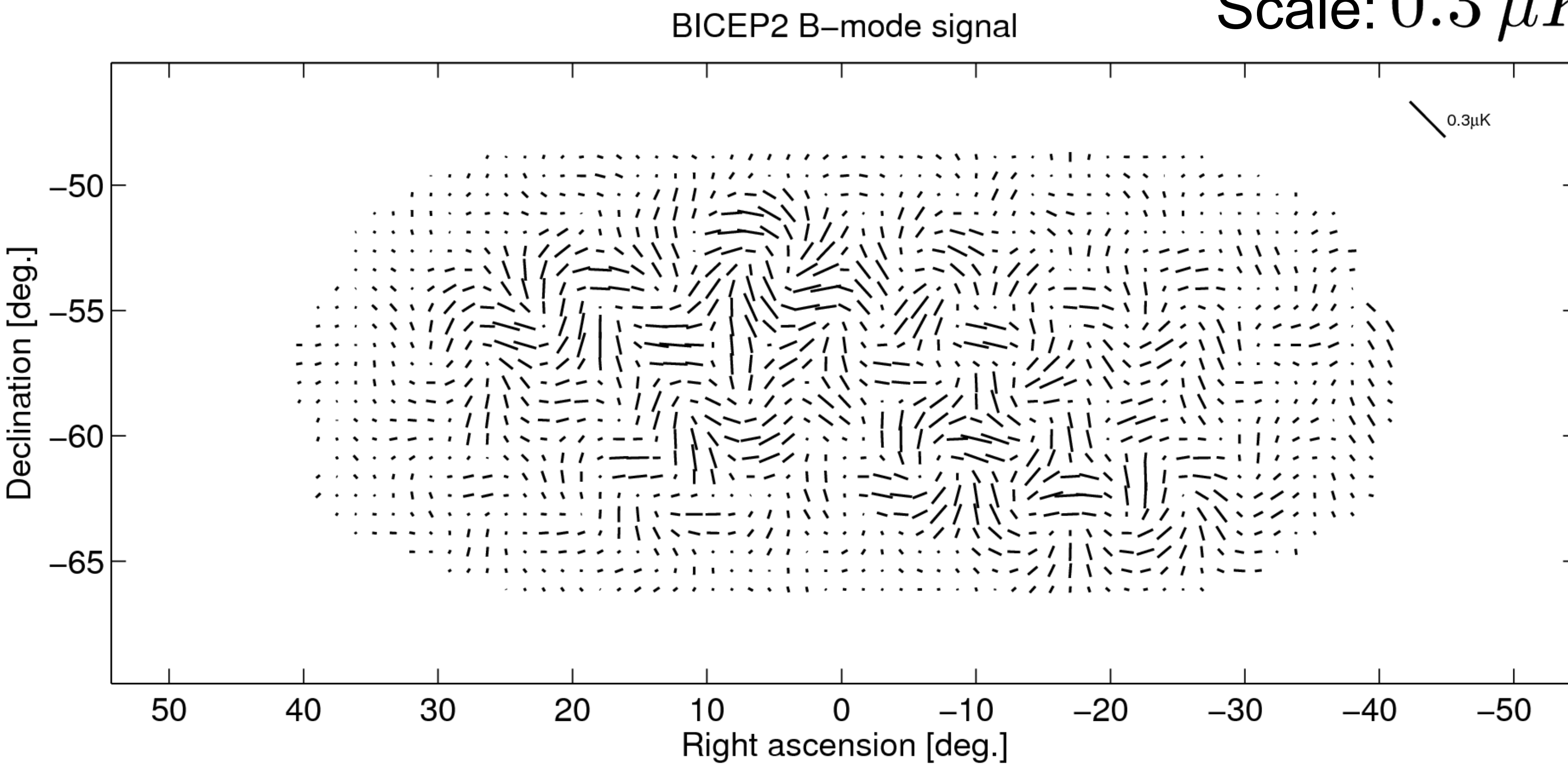
Scale: $1.7\,\mu K$



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

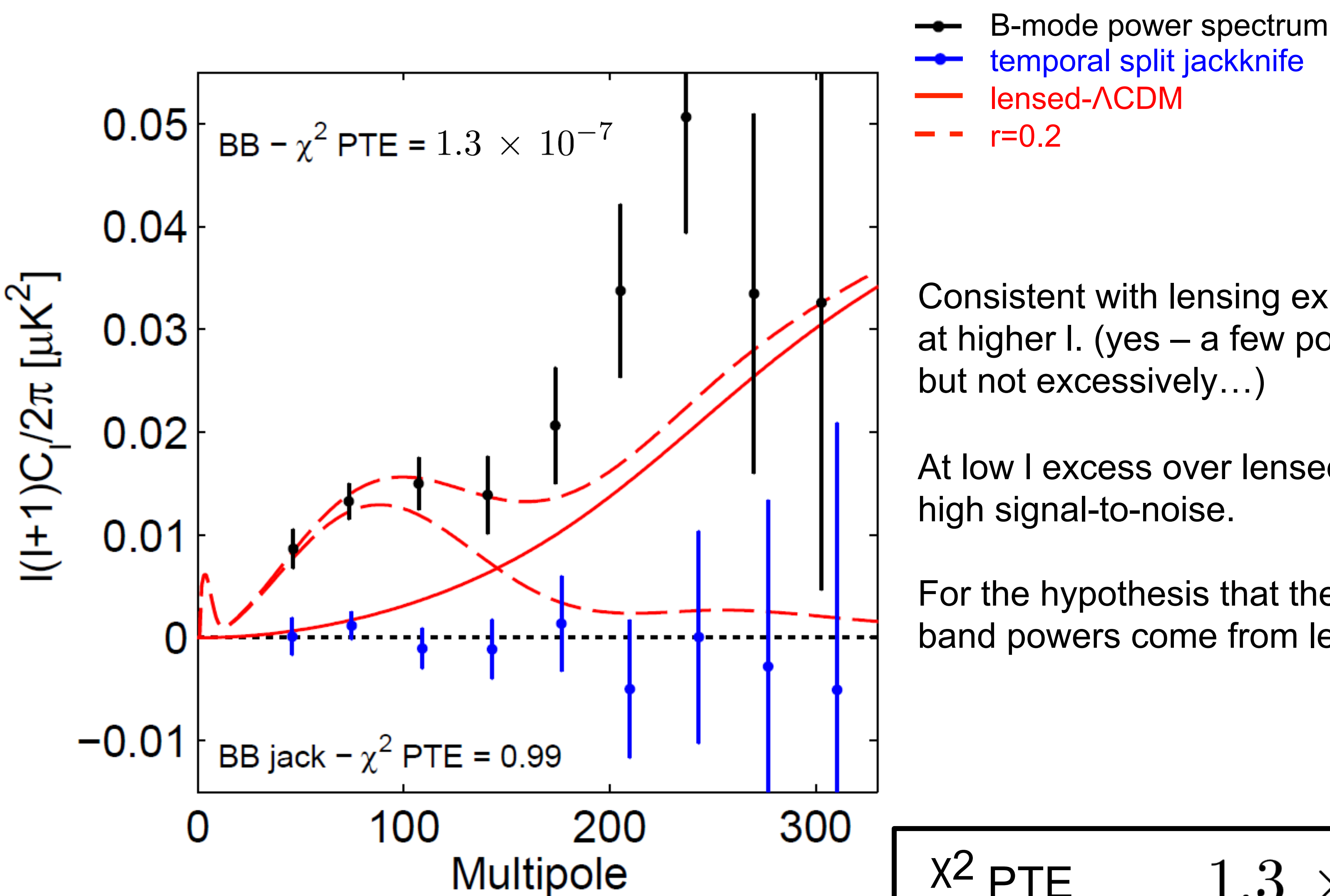
B-mode Contribution

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…)

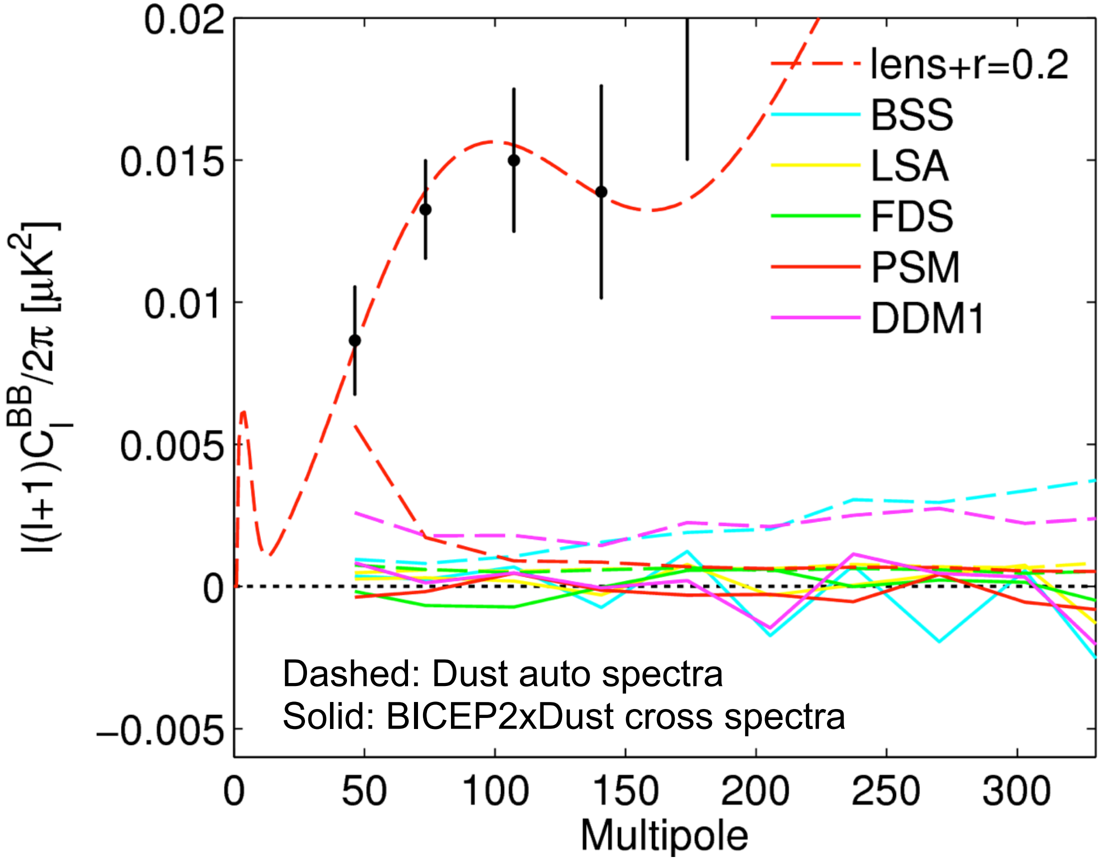
At low l excess over lensed-ΛCDM with high signal-to-noise.

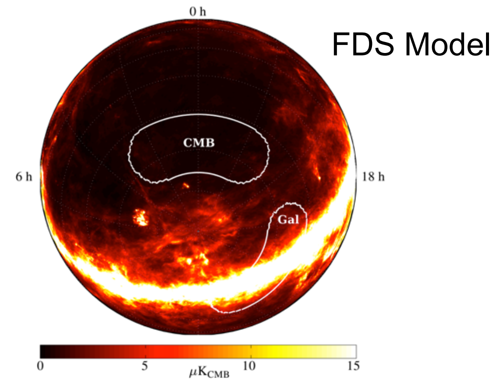
For the hypothesis that the measured band powers come from lensed-ΛCDM:

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

Clem Pryke for The Bicep2 Collaboration

Pre-Planck Polarized Dust Foreground Projections





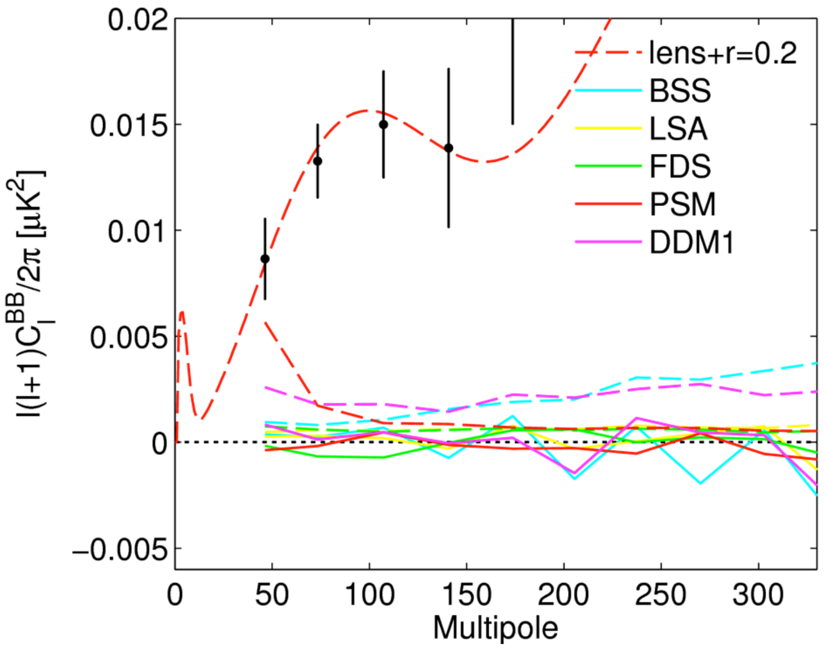
The BICEP2 region was chosen on the basis of extremely low *unpolarized* dust power.

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

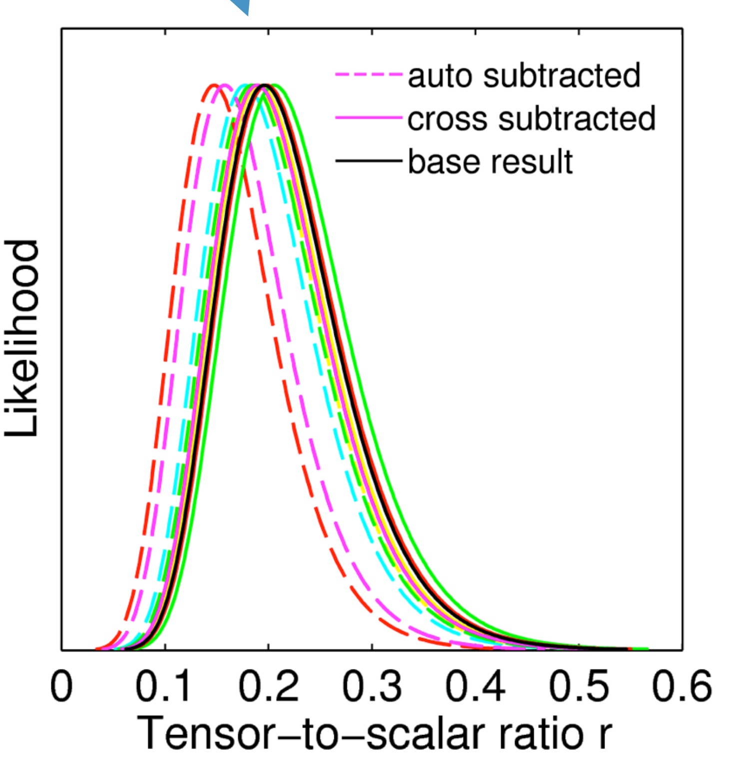
Result: All auto spectra were well below observed signal level. (and cross spectra consistent with zero.)

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:

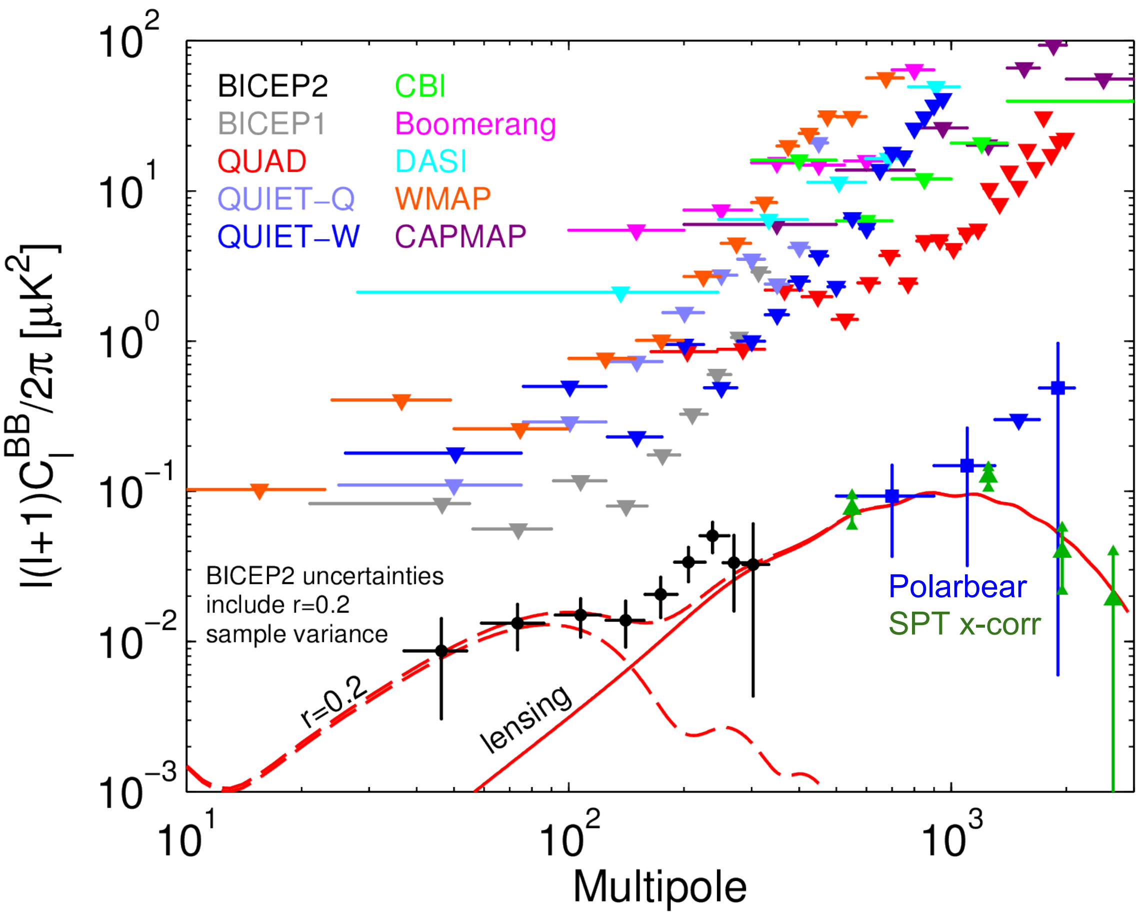


Probability that each of these models reflected reality was hard to assess.

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!

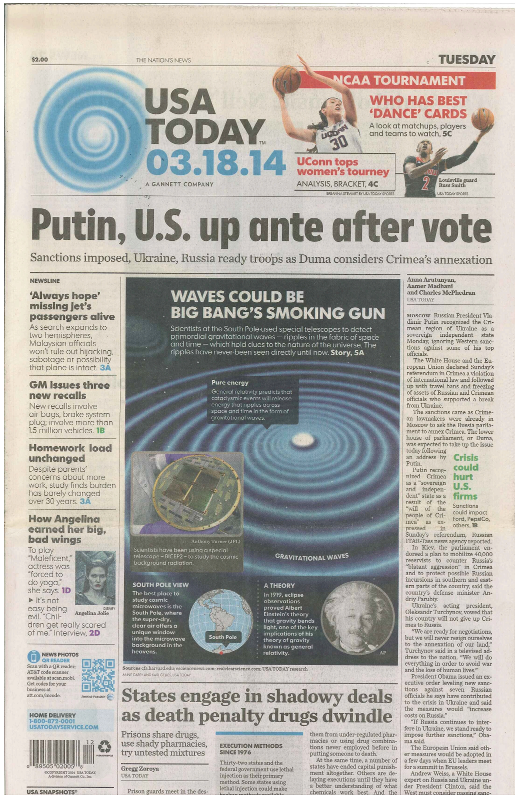
Power spectra perfectly consistent with lensed-ΛCDM except:
5.2σ excess in the B-mode spectrum at low multipoles!

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

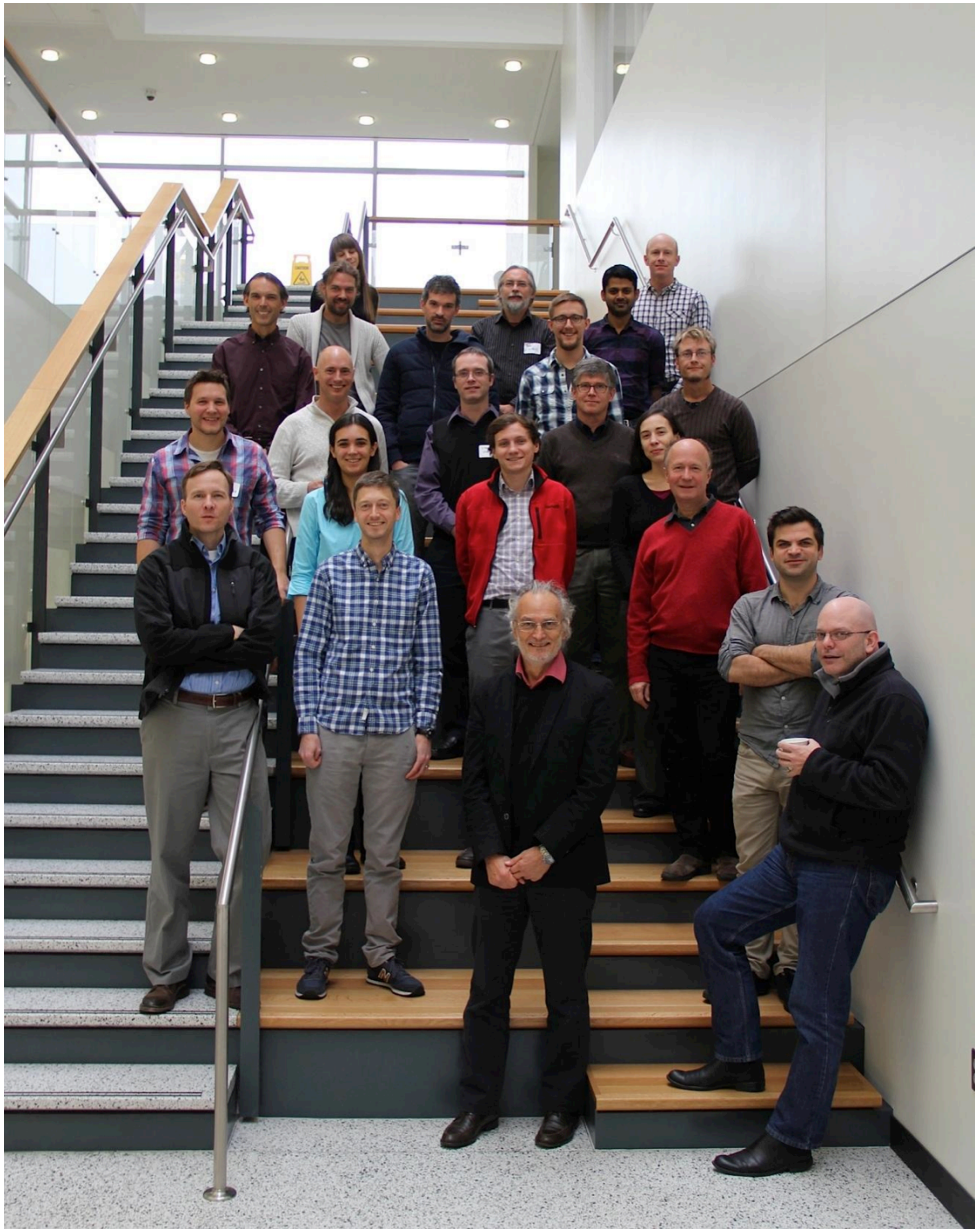


Actually not a lot of fun…

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…

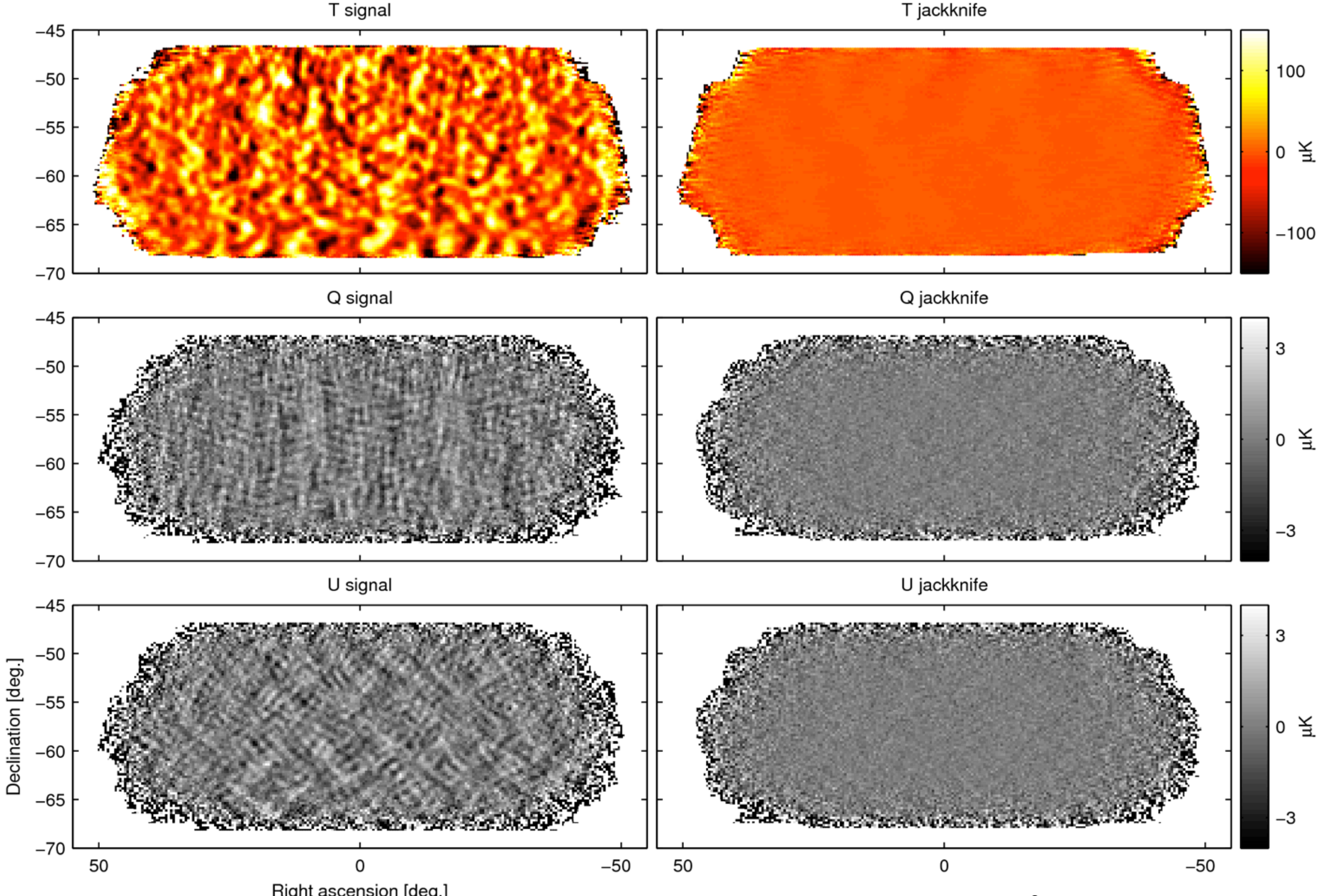
Joint analysis of BICEP2/Keck and Planck data



- In summer 2014 BICEP2/ Keck and Planck collaborations signed MOU to do a joint analysis of their data
- Data exchanged in late July
- Results reported in paper arxiv:1502.00612 (and published in PRL)

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

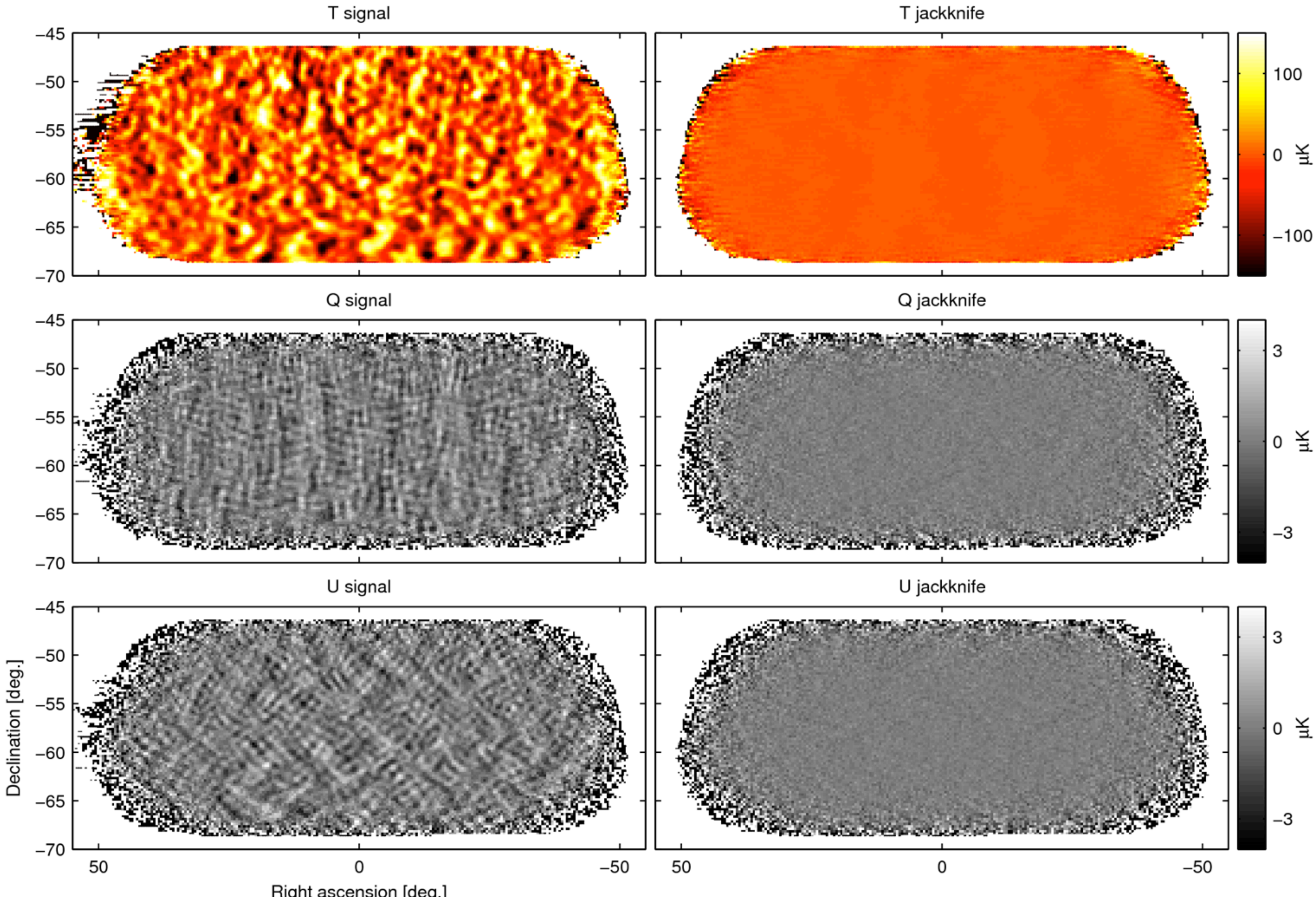
B2 150 GHz T/Q/U maps of small sky patch



87 nK deg (5.2 μK arcmin) over 380 deg² area - as used in BICEP2 paper

Bicep2, Keck Array and Planck Collaboration

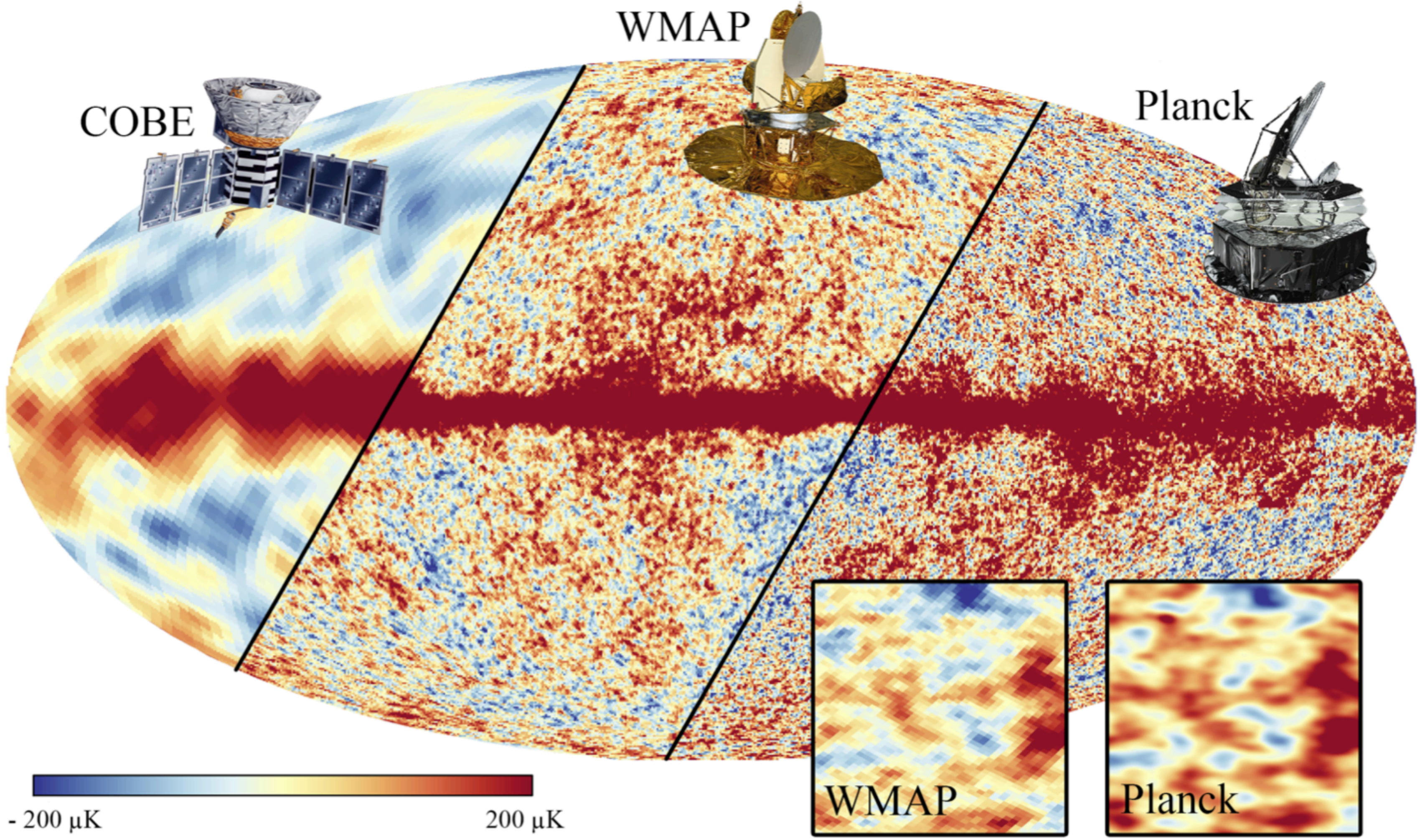
B2+Keck 150 GHz T/Q/U maps of small sky patch



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

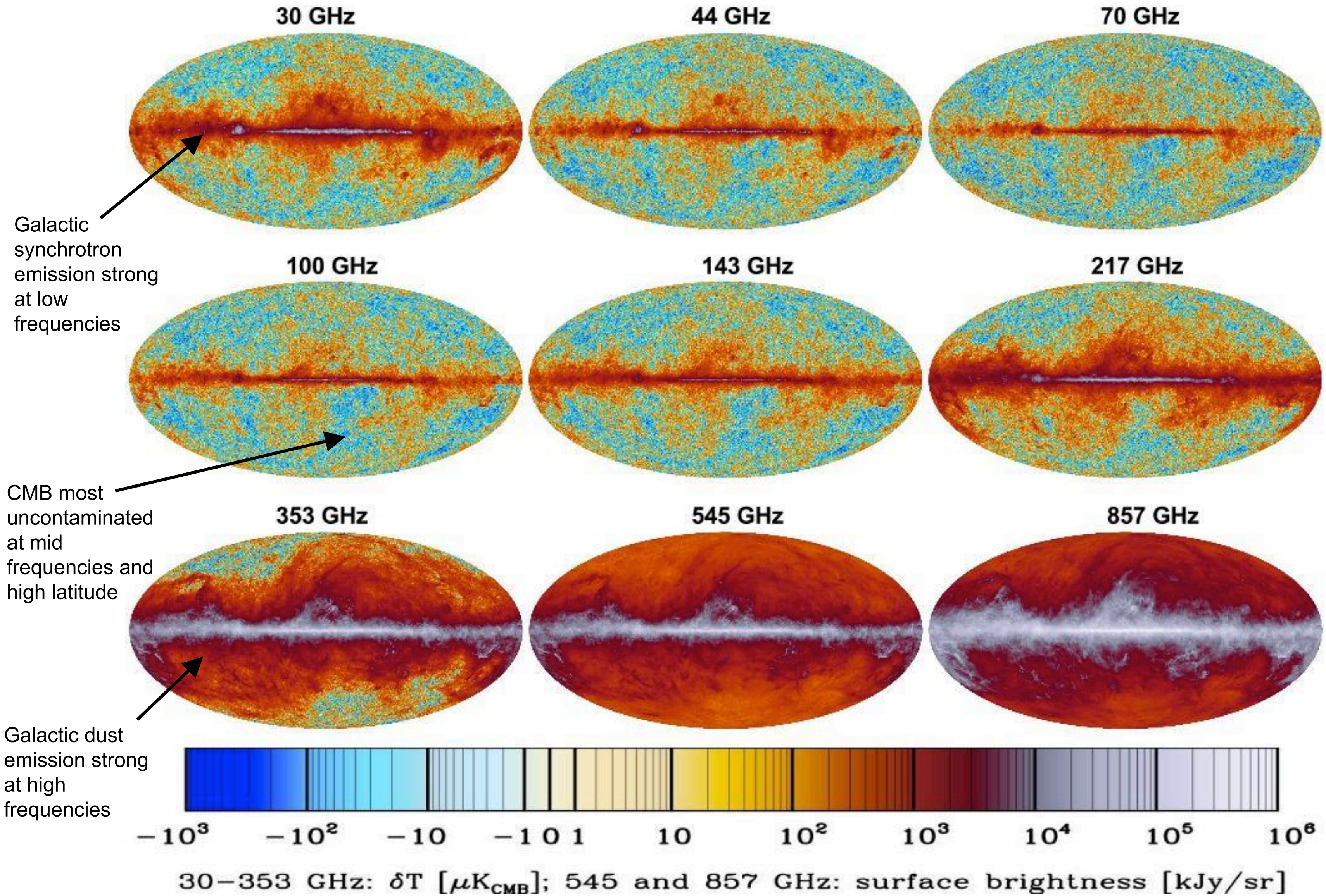
Planck



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



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

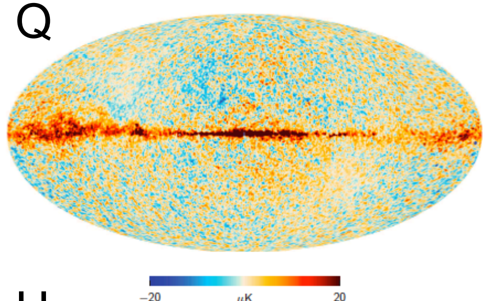
Bicep2, Keck Array and Planck Collaboration

Planck 353 GHz full sky maps in polarization

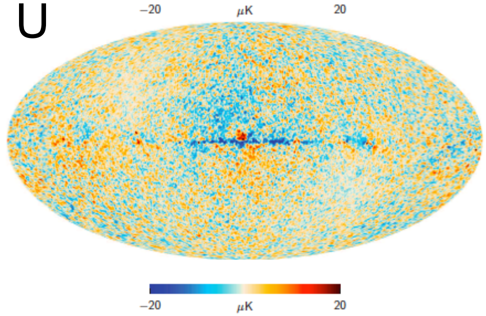
- 353 GHz polarized maps are dominated by Galactic dust emission

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

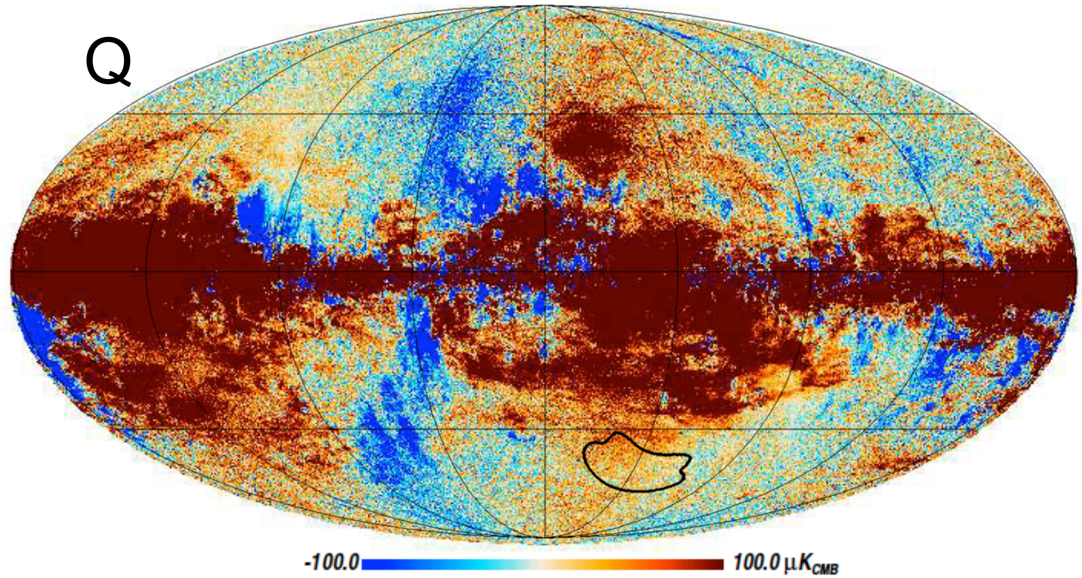
Q



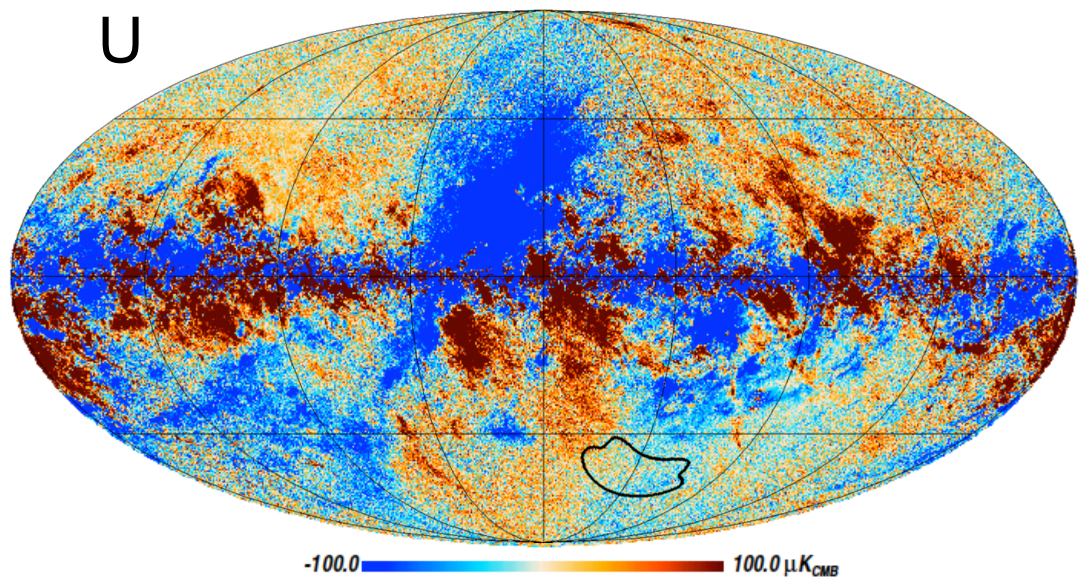
U



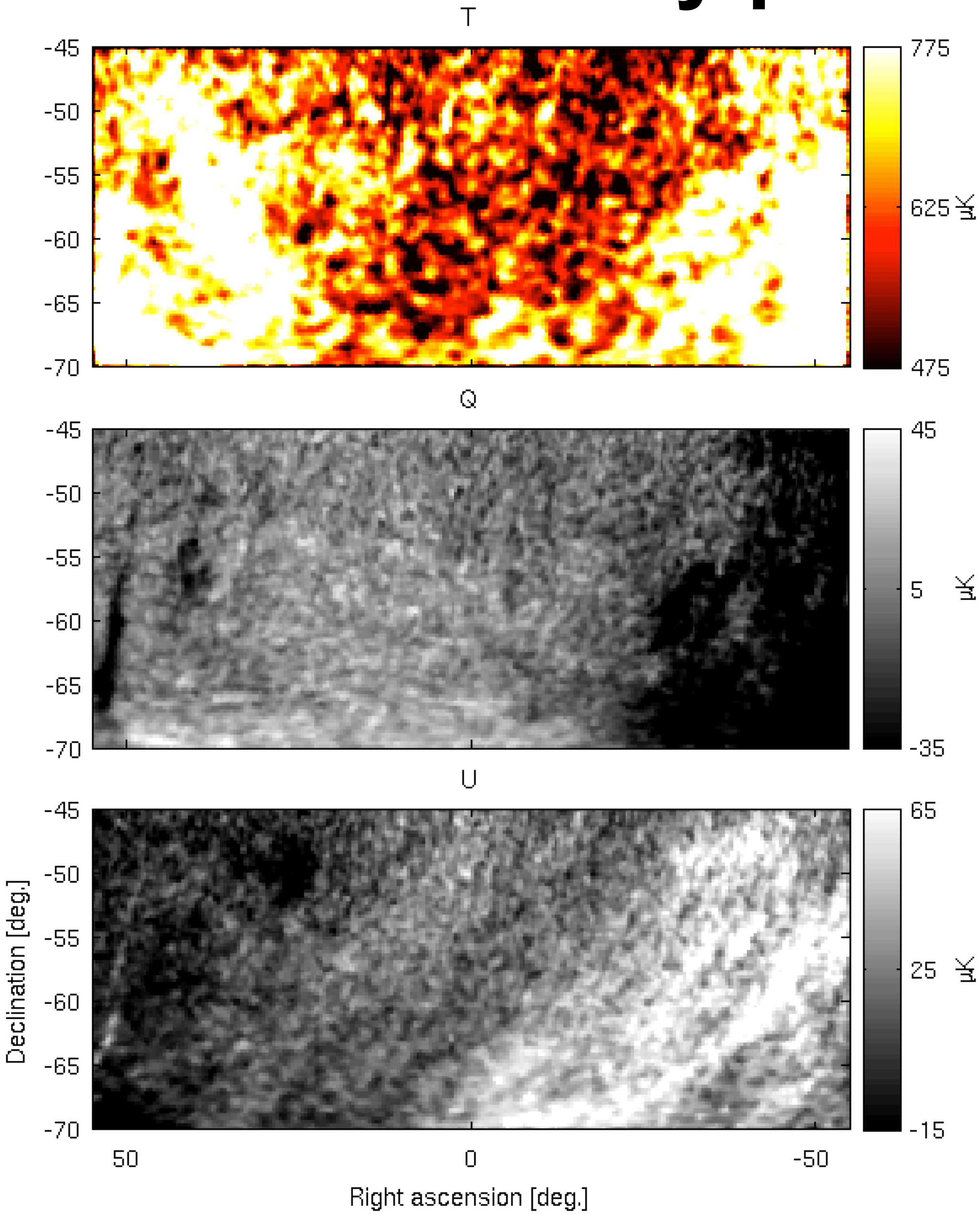
Q



U



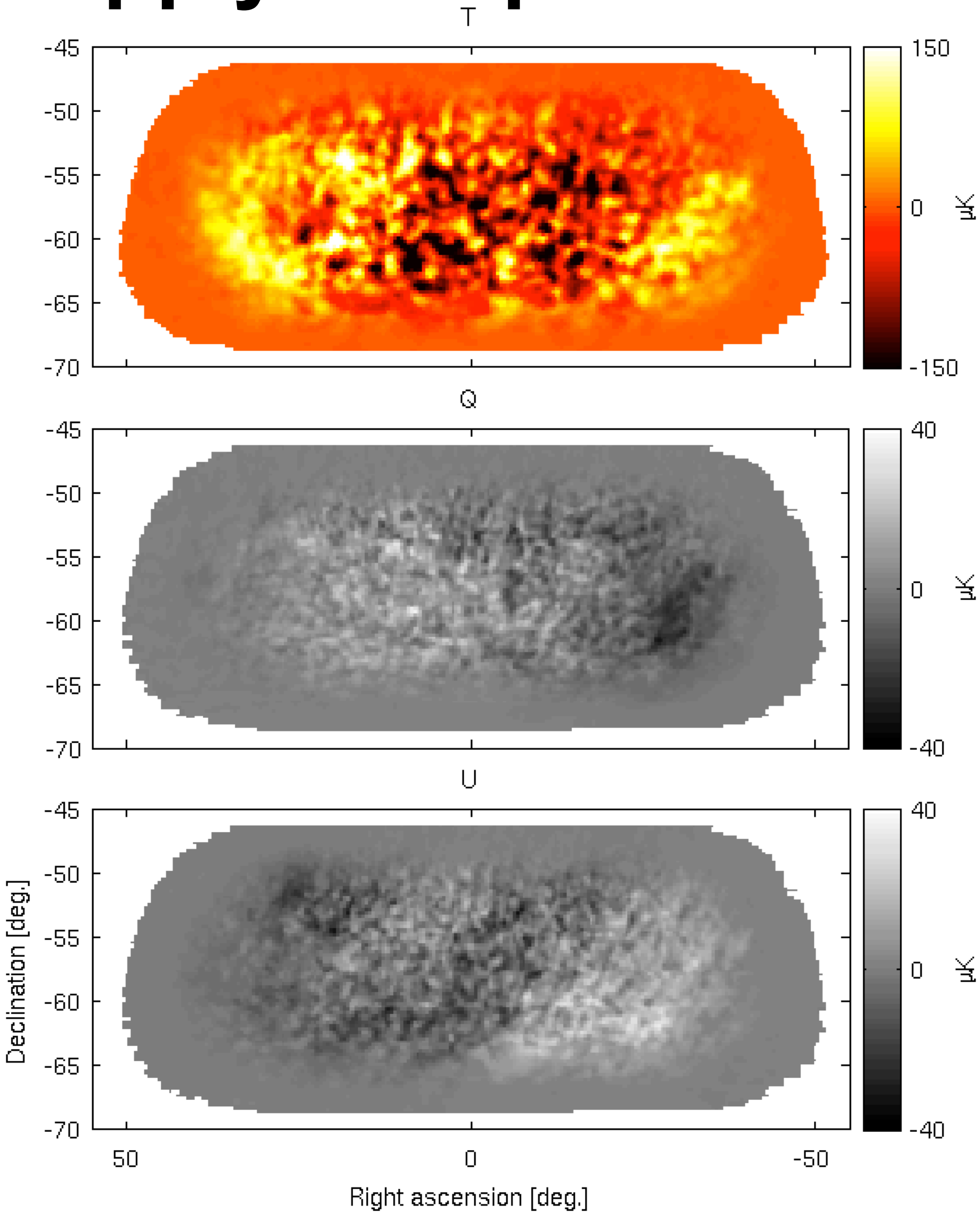
Zoom in on BK sky patch...



Planck 353GHz maps in BICEP2/Keck sky region

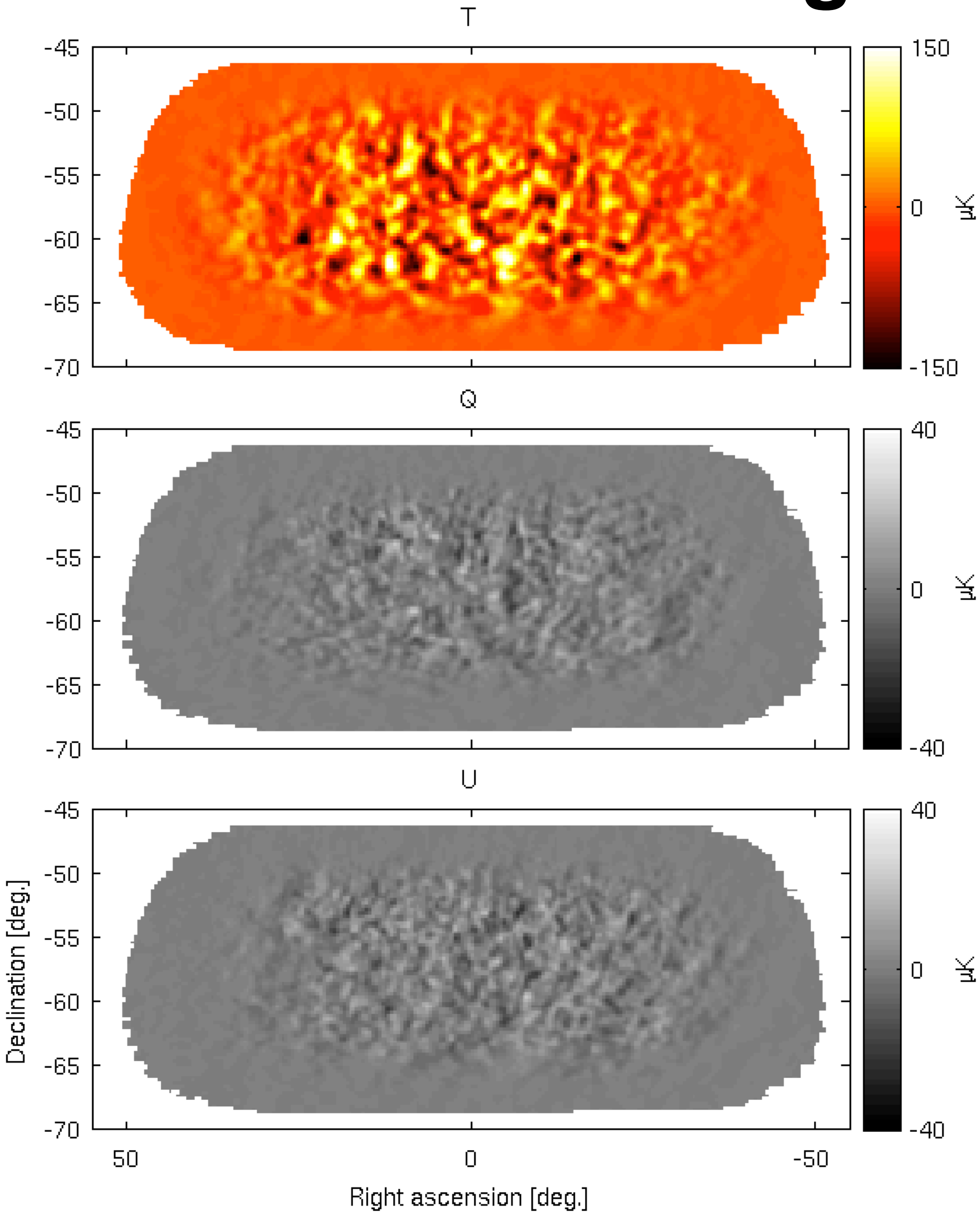
(re-smoothed to BICEP2/Keck beam size)

...apply BK apodization...



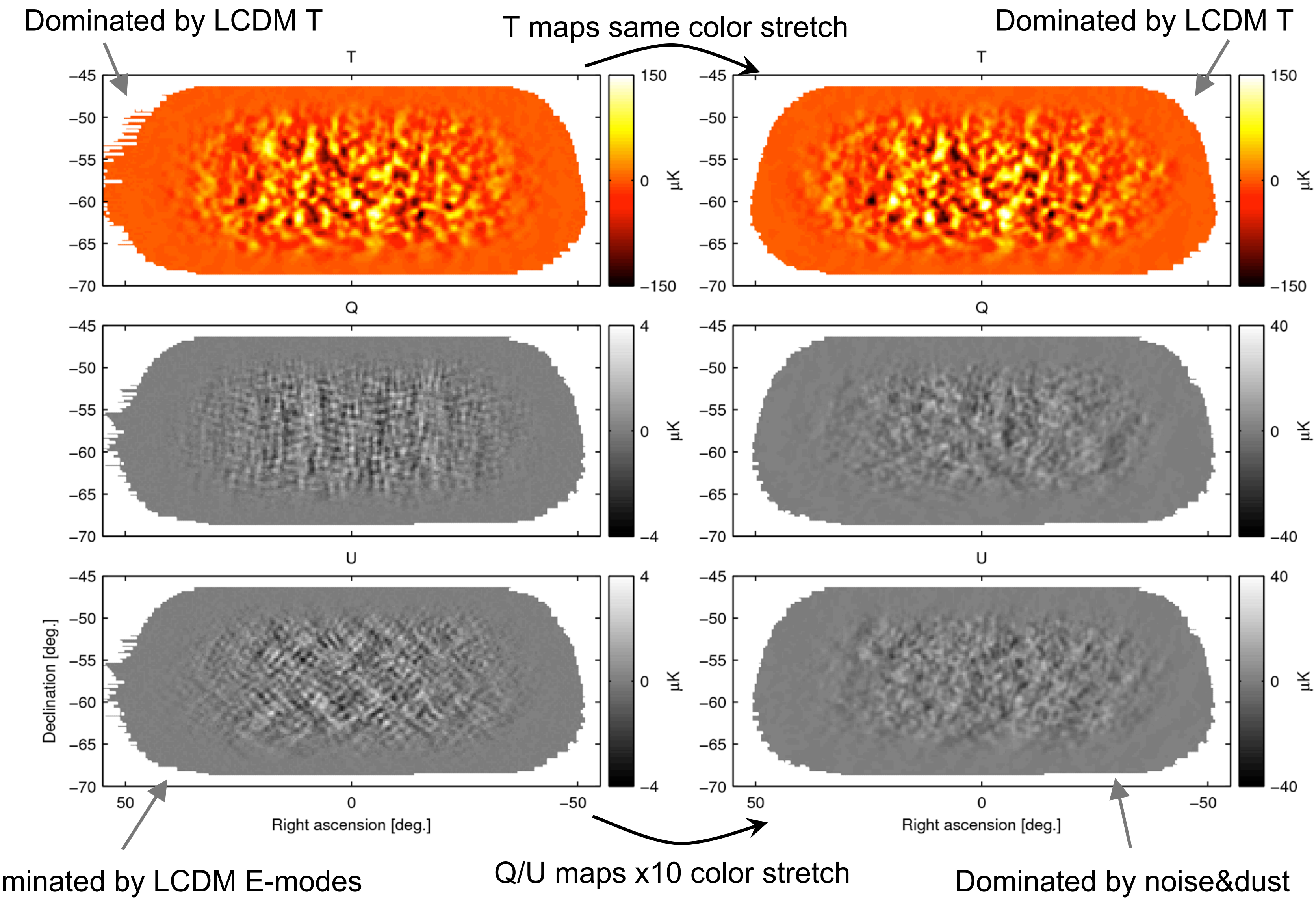
Planck 353GHz maps in BICEP2/Keck sky region with mean subtracted and apodization mask applied

...and BK filtering



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

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



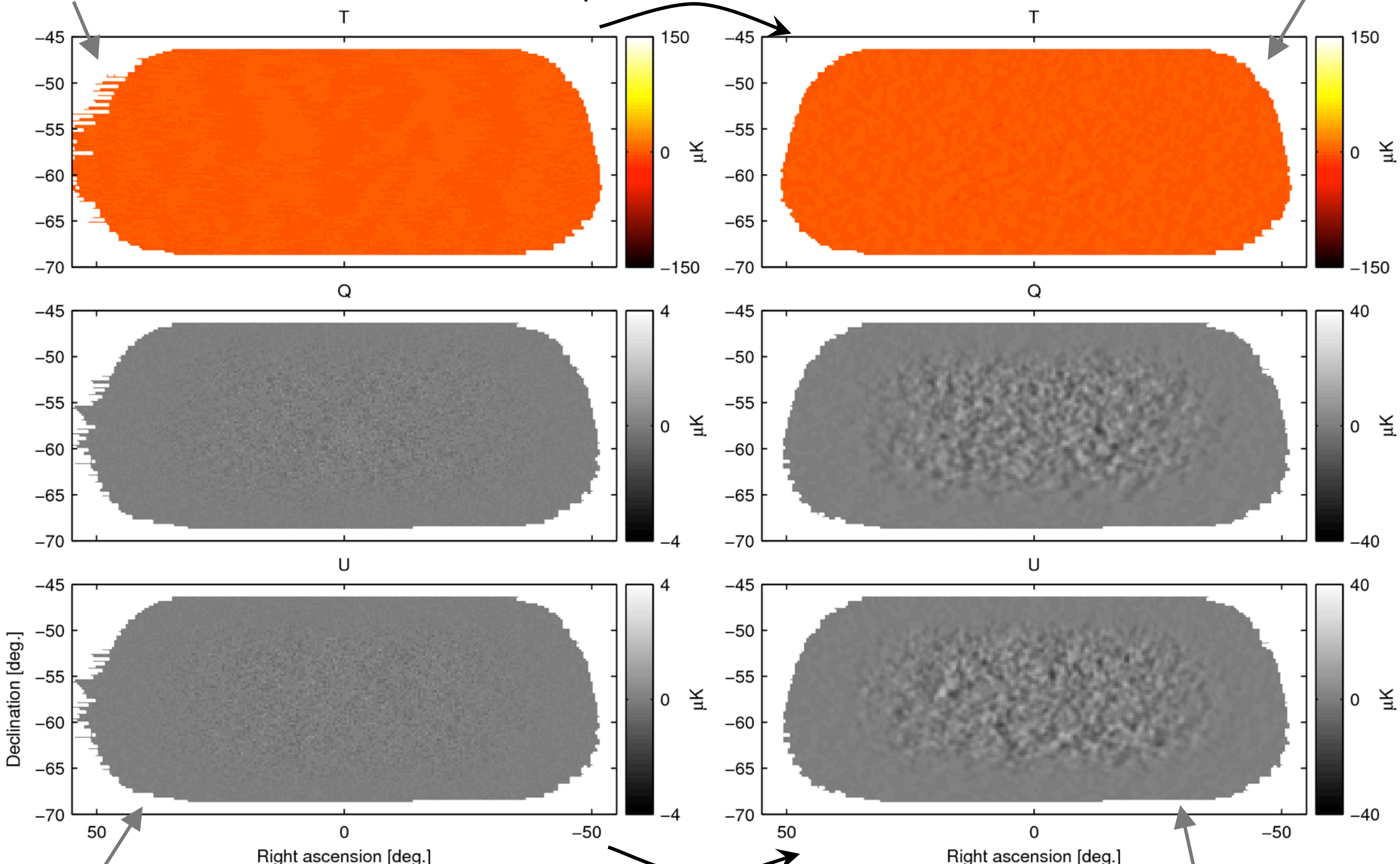
The Real Data

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



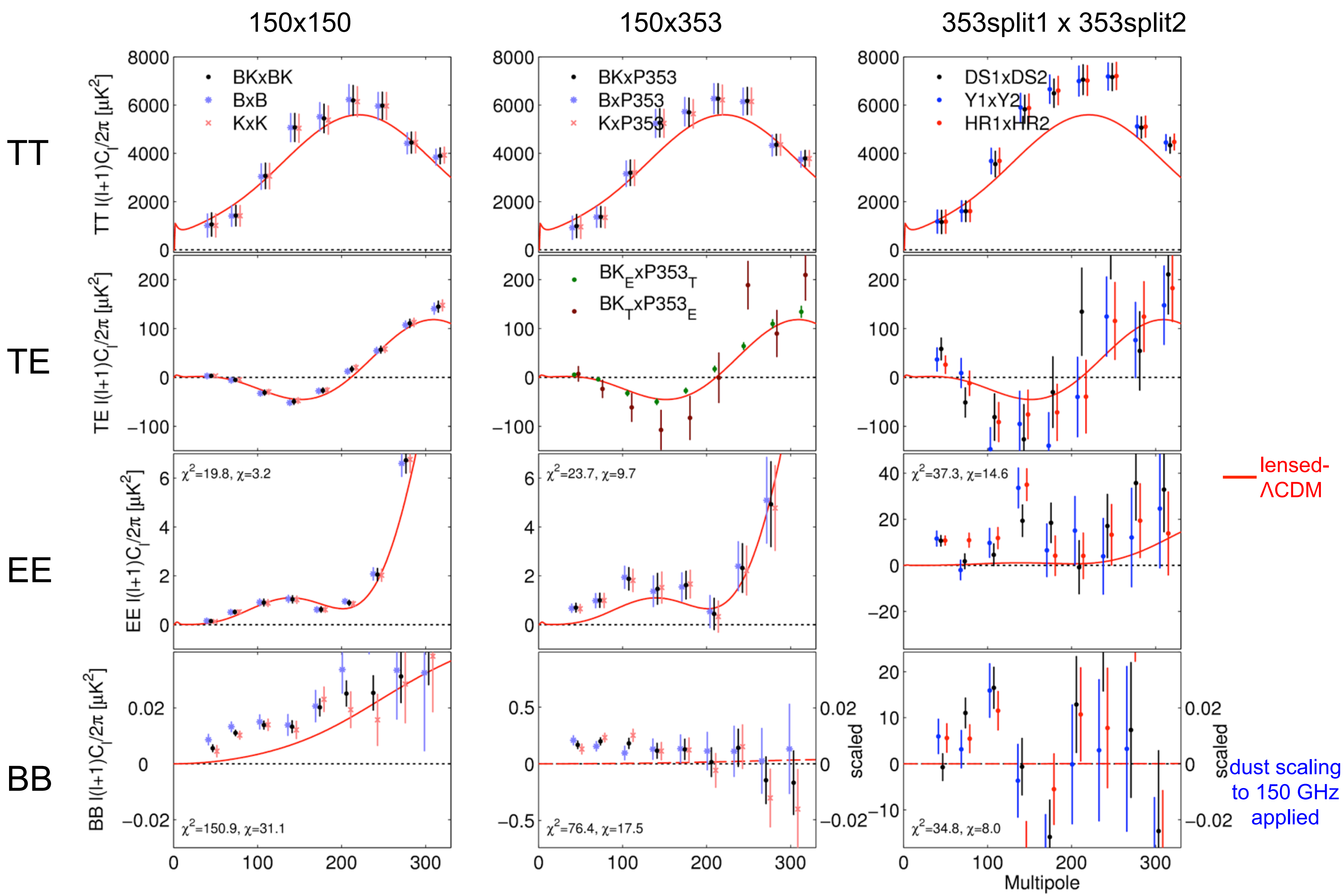
Noise small compared to signal

Q/U maps x10 color stretch

Noise comparable to dust signal

A Noise Simulation

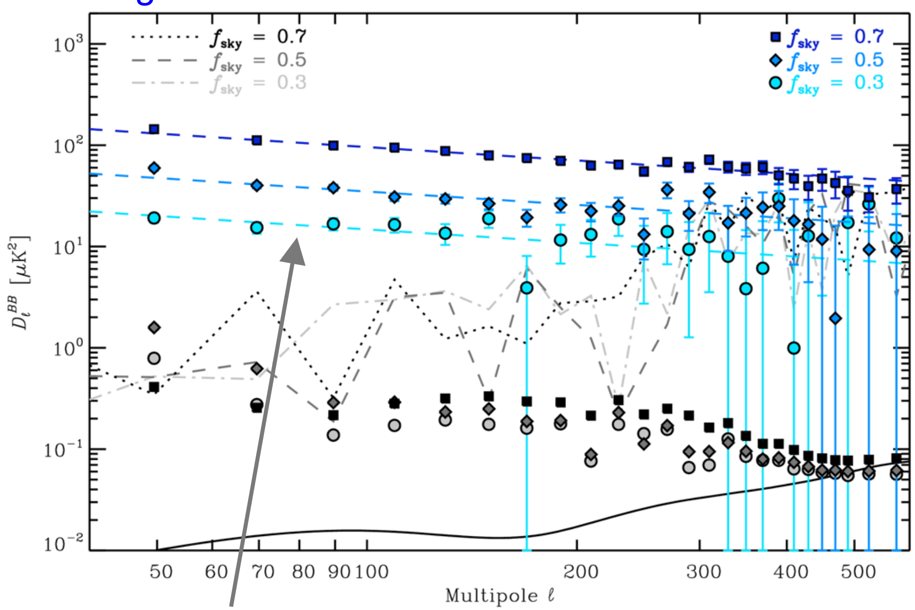
Single- and Cross-Frequency Spectra



What are the expectations for dust in BICEP/Keck sky patch?

- 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:

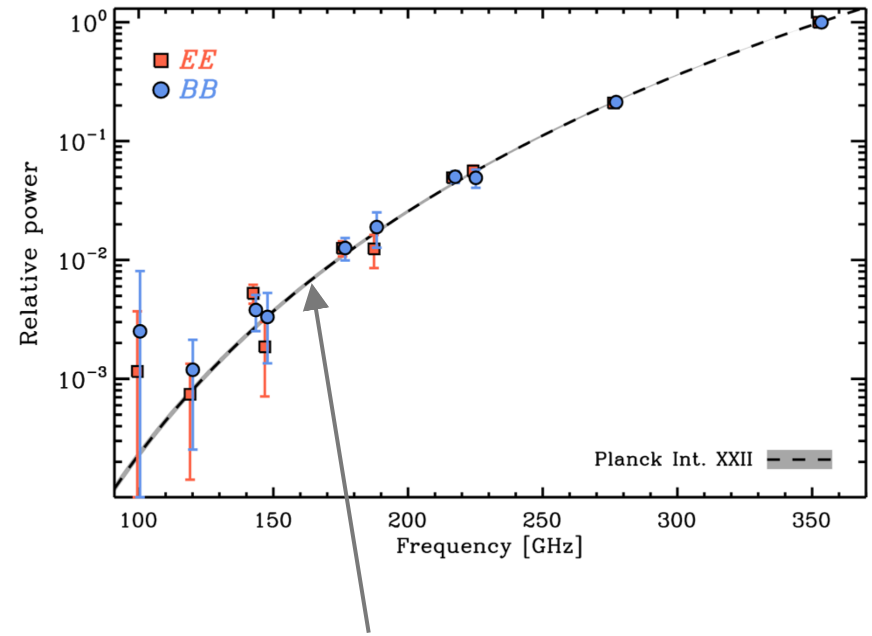
Fig 2 of arxiv:1409.5738



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

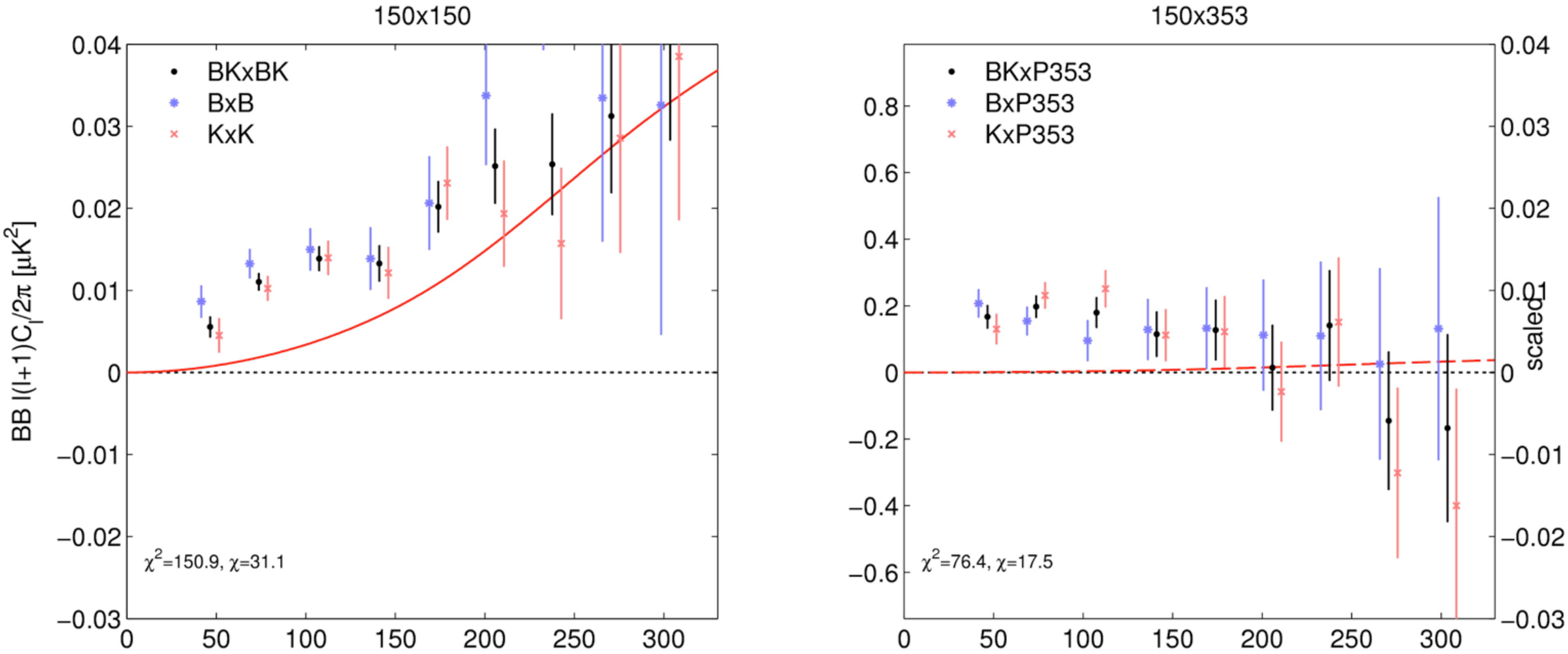


Spectral energy distribution of polarized dust emission follows modified blackbody model with T=19.6K and β_d=1.59

- Seems to be remarkably uniform over the high latitude sky

→ Good news for component separation

Zoom in on BB

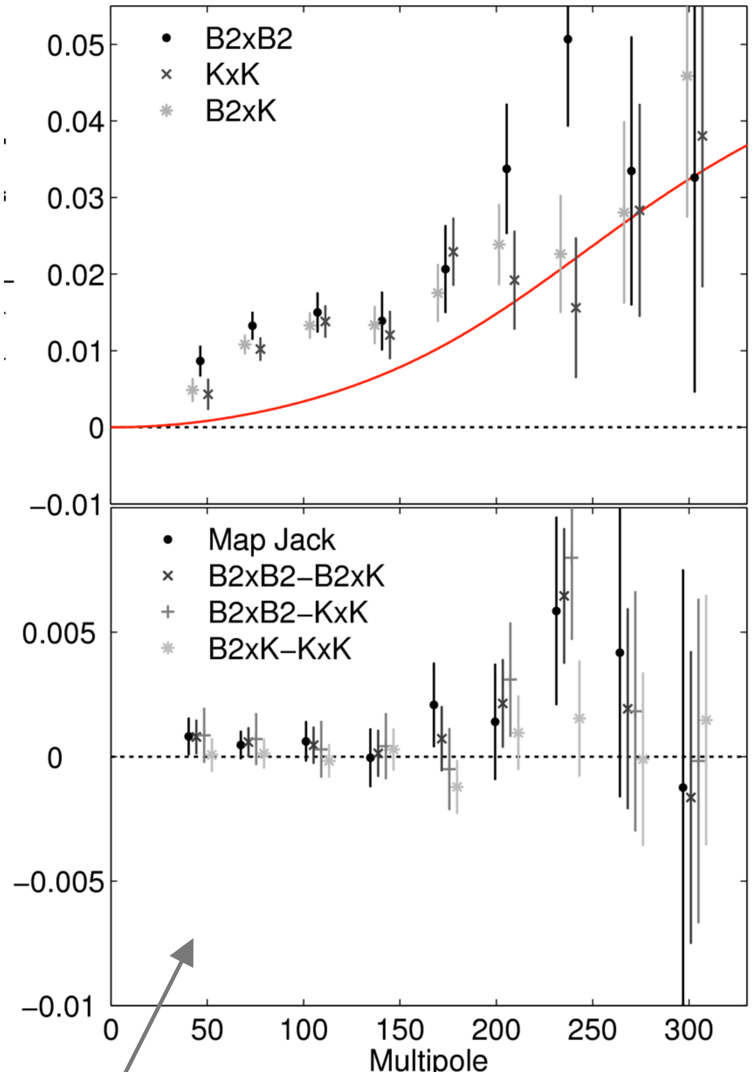


➢ Correlation of 150 GHz and 353 GHz B-modes is detected with high signal-to-noise.

➢ 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

Is it OK for the B2 and Keck spectra to differ as much as they do?



Correct way to ask this question is to compare the differences of the real spectra to the pairwise-differences of sims which share common input skies with power level comparable to the real data

- The bottom line answer is that simulations show: Yes, the spectra are compatible - see papers for details

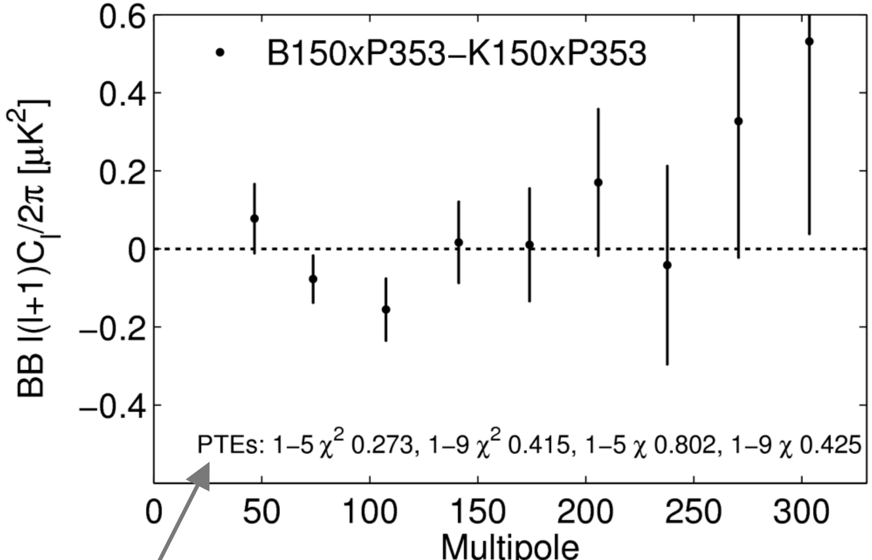
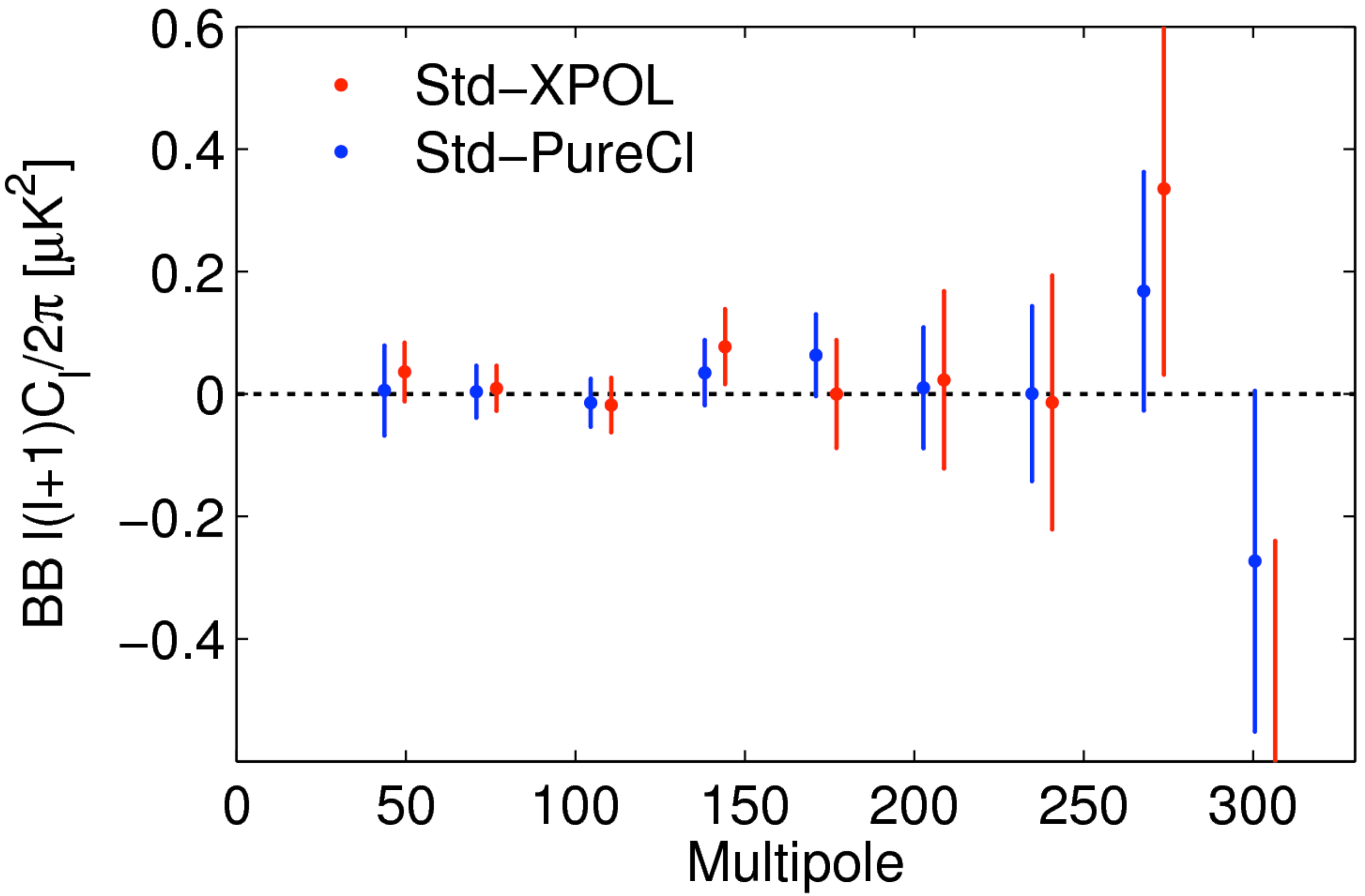


Fig 8 of Keck paper
(Note these tests are not independent)

Fig 4 of BKP paper

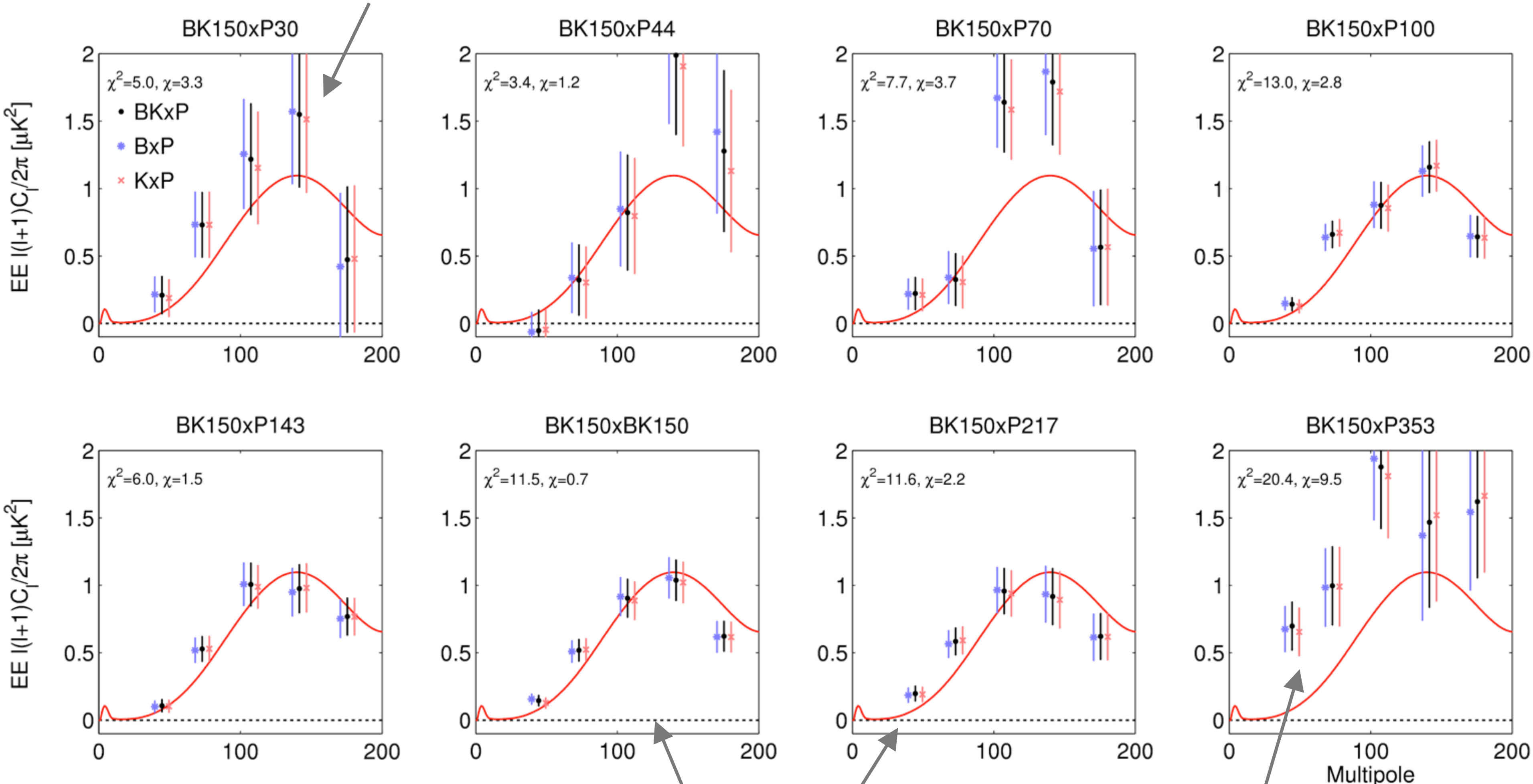
Check the power spectrum estimation



Comparing BKxP353 BB bandpower as computed with BICEP/Keck pipeline to those computed using Planck tools. Errorbars from pairwise differences of simulations which share common input skies. Spectra are compatible.

Look at cross spectra with other Planck frequencies - EE

Maybe evidence for excess due to sync. here? Actually turns out not really...



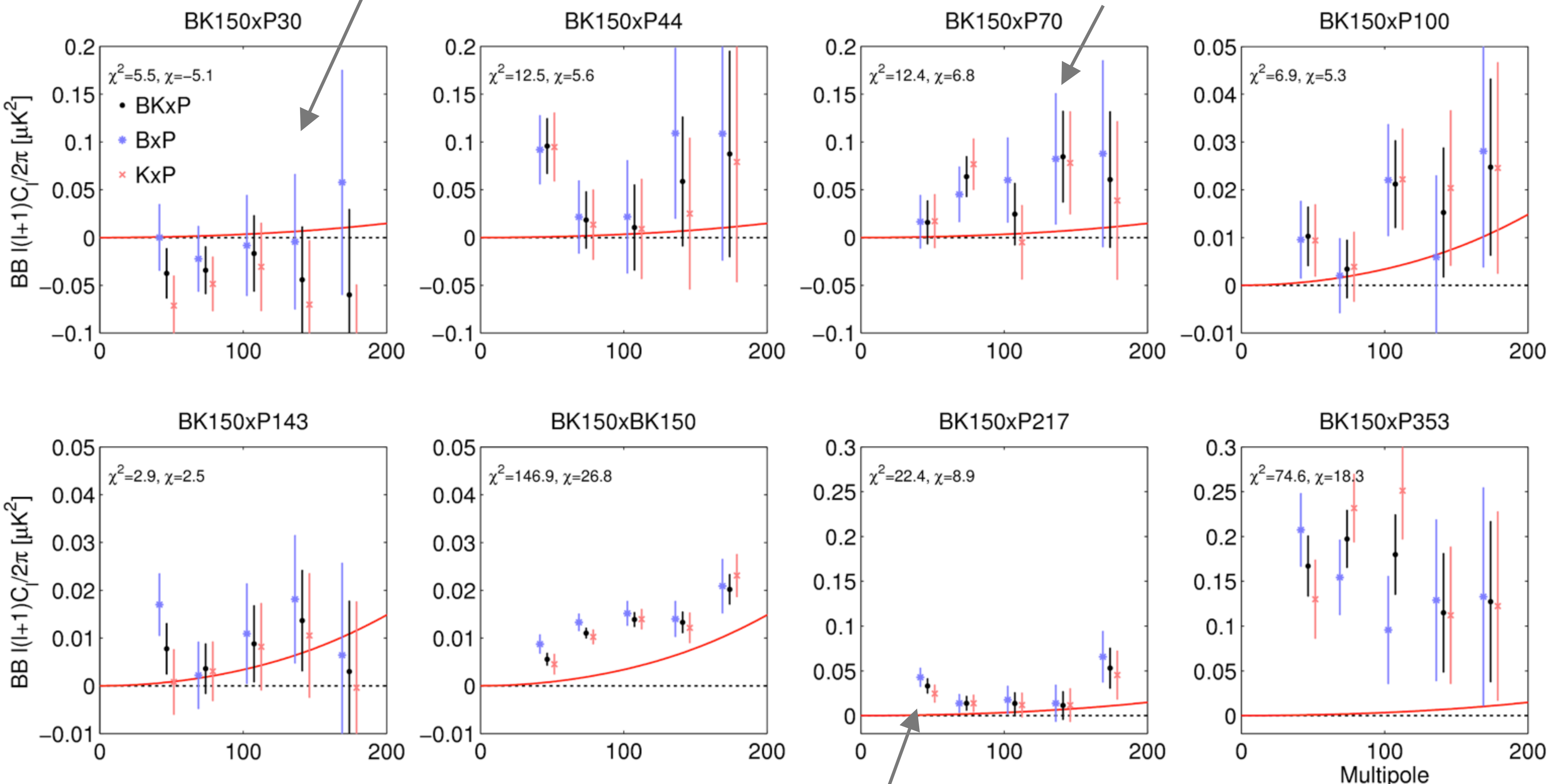
These two basically look the same - suggesting dust contribution in BK150xBK150 EE is small fraction

Clear evidence for excess due to dust here (already saw this)

Look at cross spectra with other Planck frequencies - BB

No evidence for sync. here

Curious apparent correlation between 150 and 70 GHz - presumably chance



Some additional evidence for excess due to dust

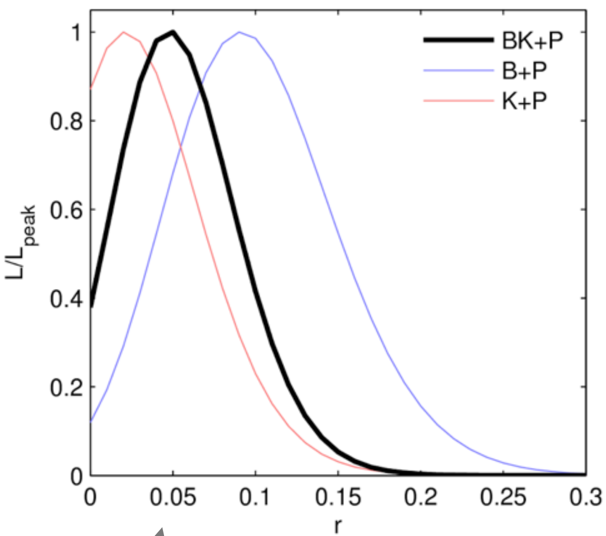
Multi-component multi-spectral likelihood analysis

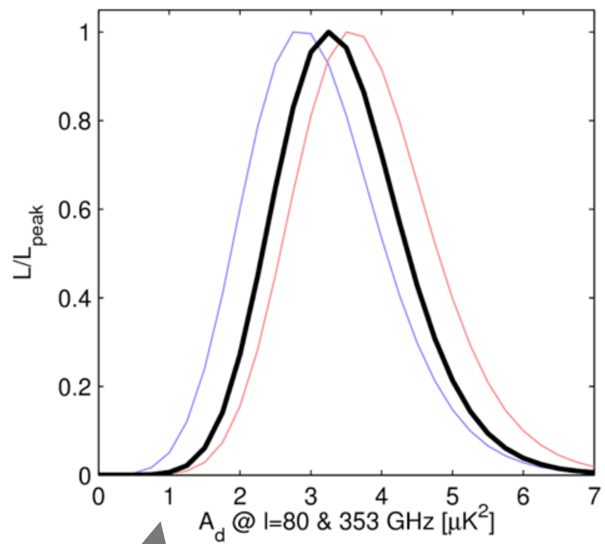
- Define “fiducial analysis” to use single- and cross-frequency spectra between BK 150 GHz and Planck 217&353 GHz channels
  - (Detail: for Planck single-frequency use detector set split cross spectrum)

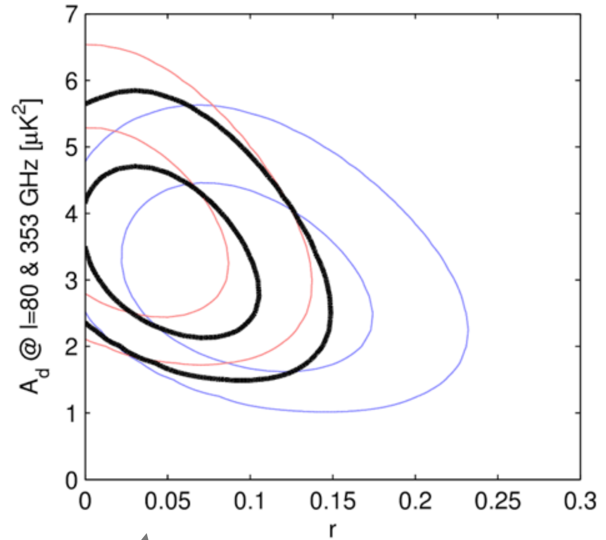
- As addition to basic LCDM lensing signal include gravity wave signal (with amp r) and dust signal with amplitude A_d (specified at ℓ =80 and 353 GHz)
  - For dust SED use modified blackbody model and marginalize over range β_d=1.59±0.11

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

Multi-component multi-spectral likelihood analysis





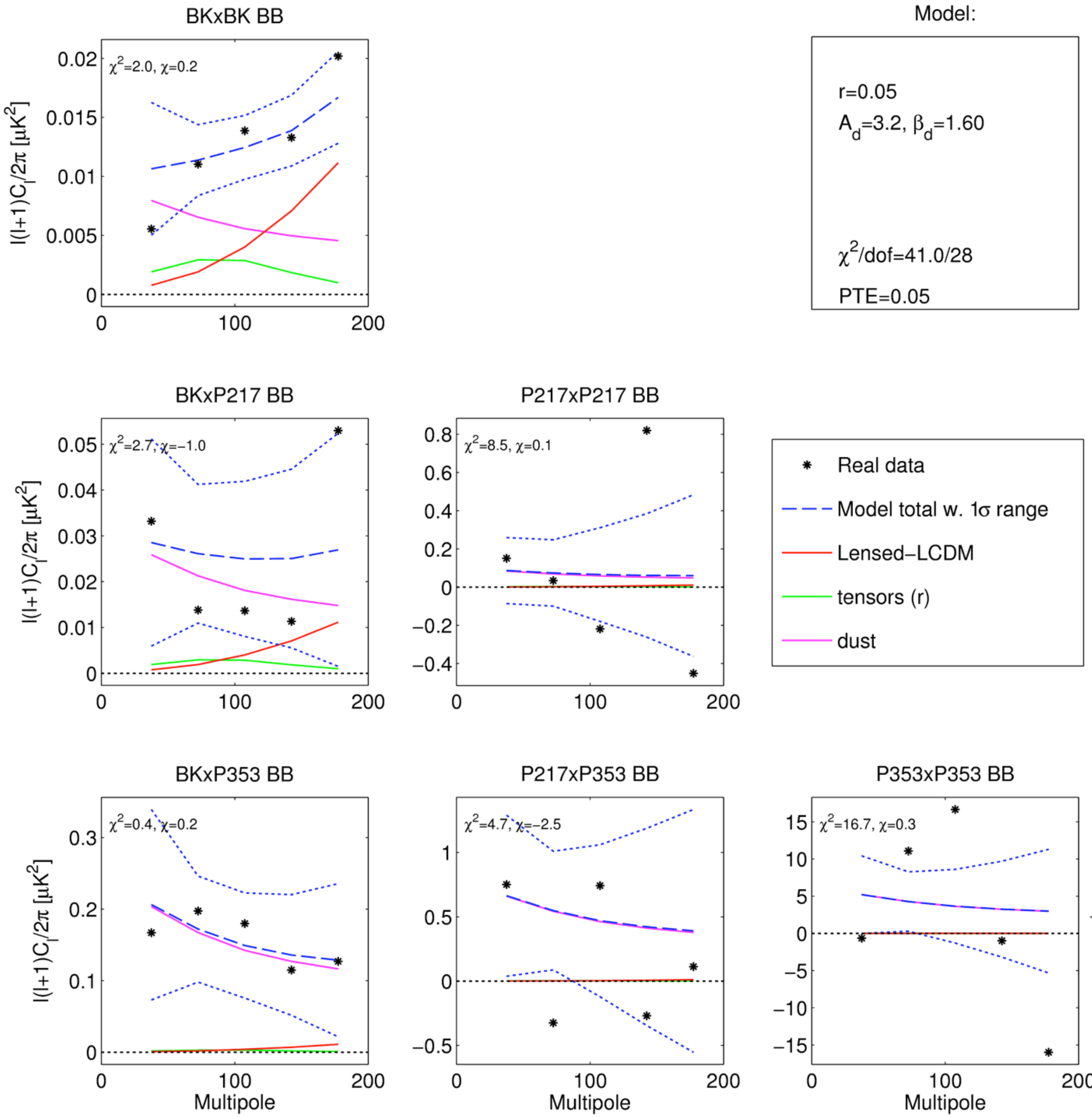


r constraint consistent with zero (For BK+P L_0/L_{peak} ratio is 0.4 which happens 8% of the time in a dust only model.)

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*

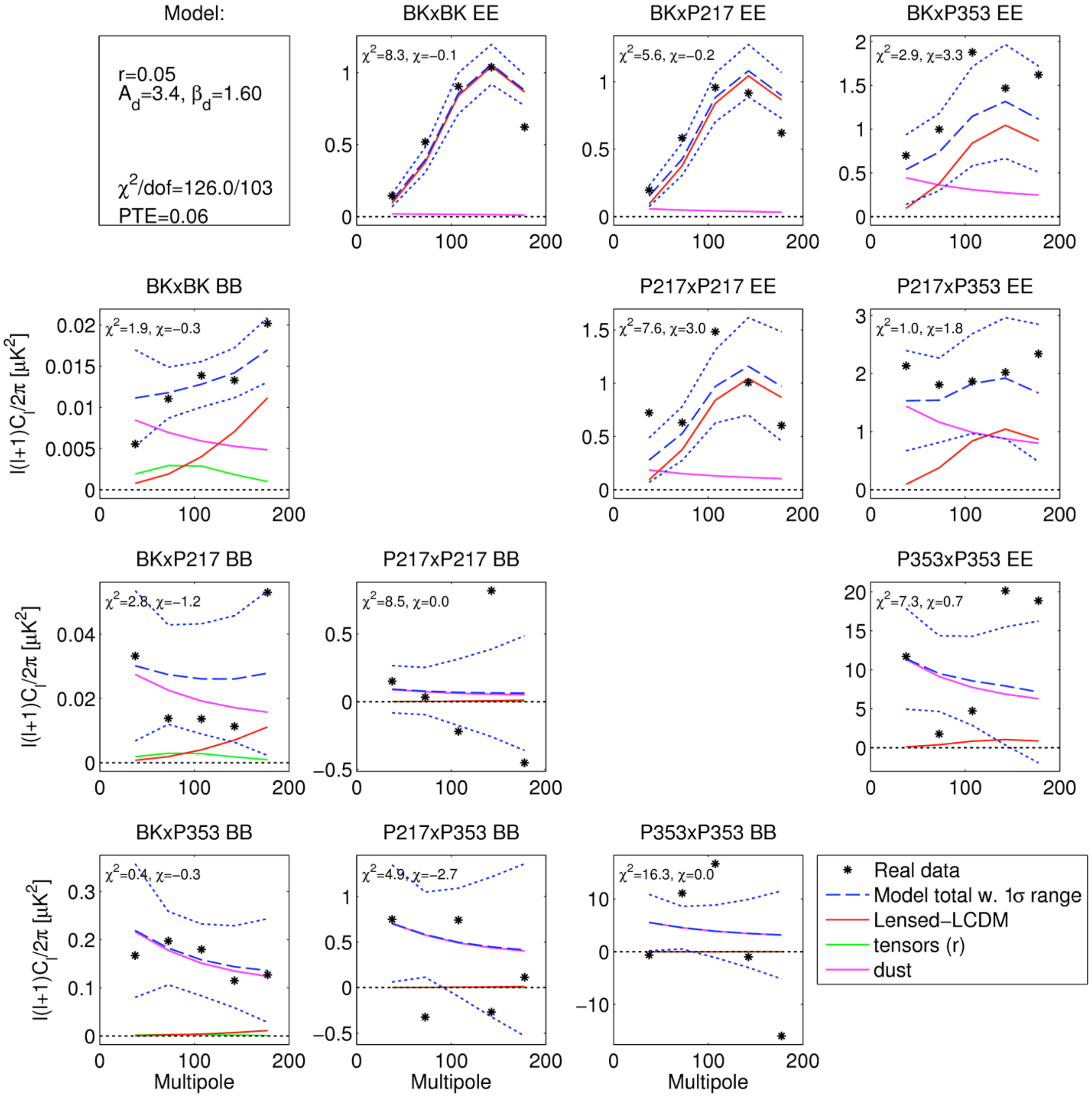
Best fit multi-frequency model



- 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.

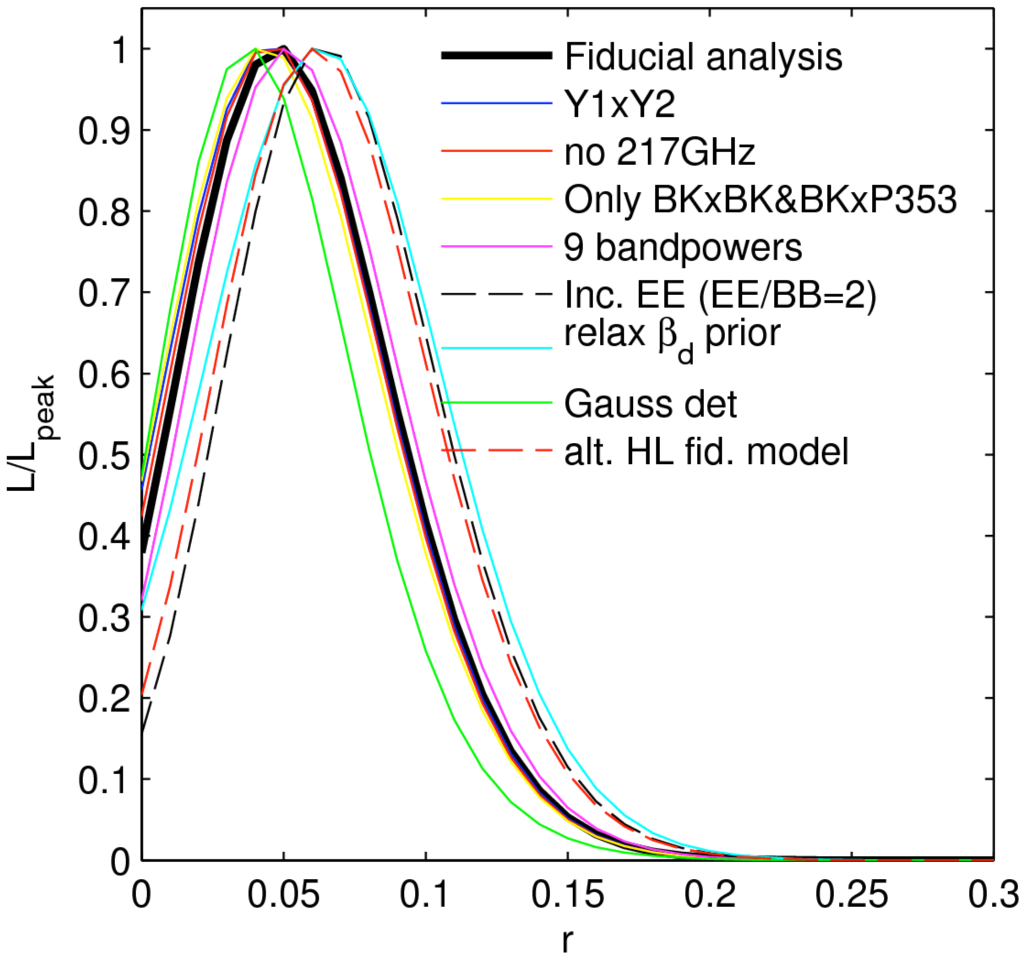
These plots show data as "naked points" versus center value and spread of best fit model to emphasize that uncertainty varies with the model (due to sample variance)

Best fit model including EE spectra



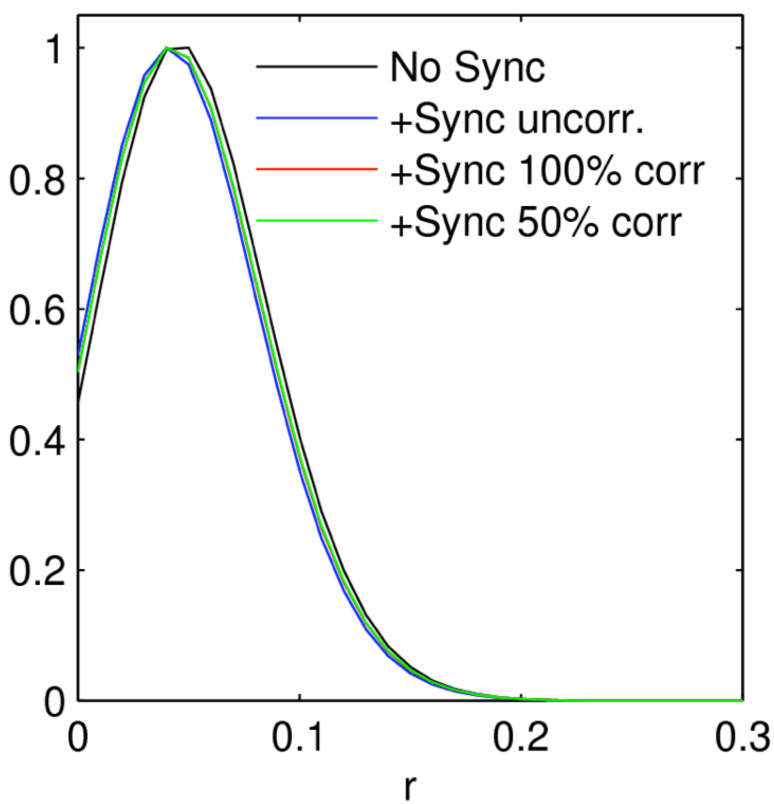
- Adding EE spectra to the fit while assuming dust EE/BB=2 hardly changes the maximum likelihood model, and the global χ^2 remains acceptable.
- Note that the dust contribution to BKxBK EE under this model is fractionally very small.

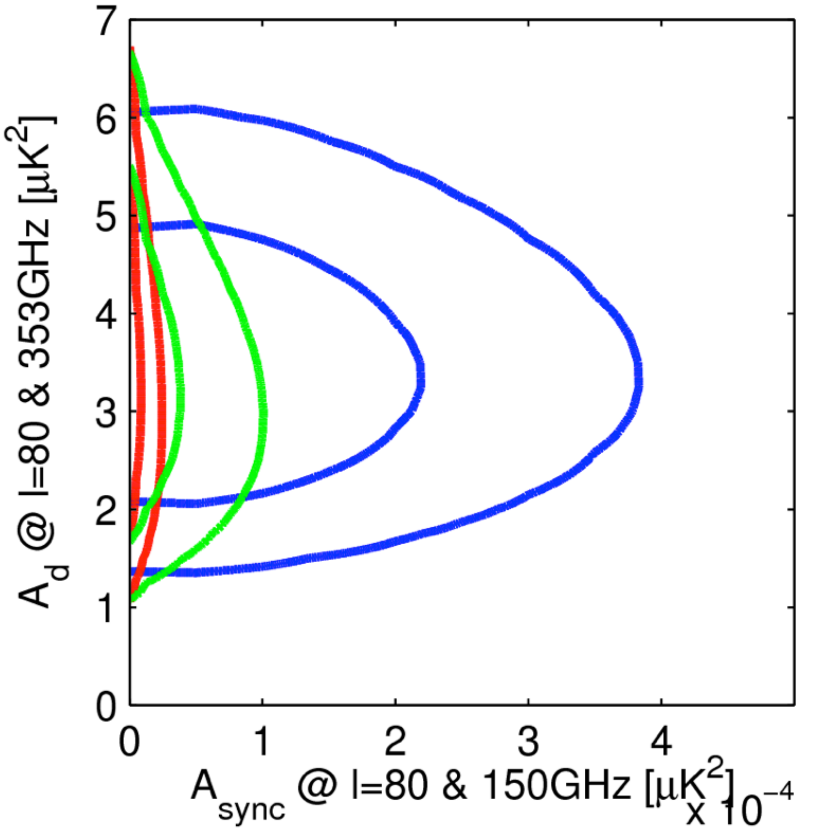
Variations on fiducial analysis



- We consider a range of variations on the fiducial analysis
- Most make little difference - see paper for details
- Excluding 353x353 makes little difference - this spectrum has little statistical weight
- The data “wants” a steeper dust SED - relaxing the β_d prior it pulls to the top end of the range and hence more of the 150x150 signal is interpreted as *r*. However β_d appears to be pretty well known so this should not be over interpreted.

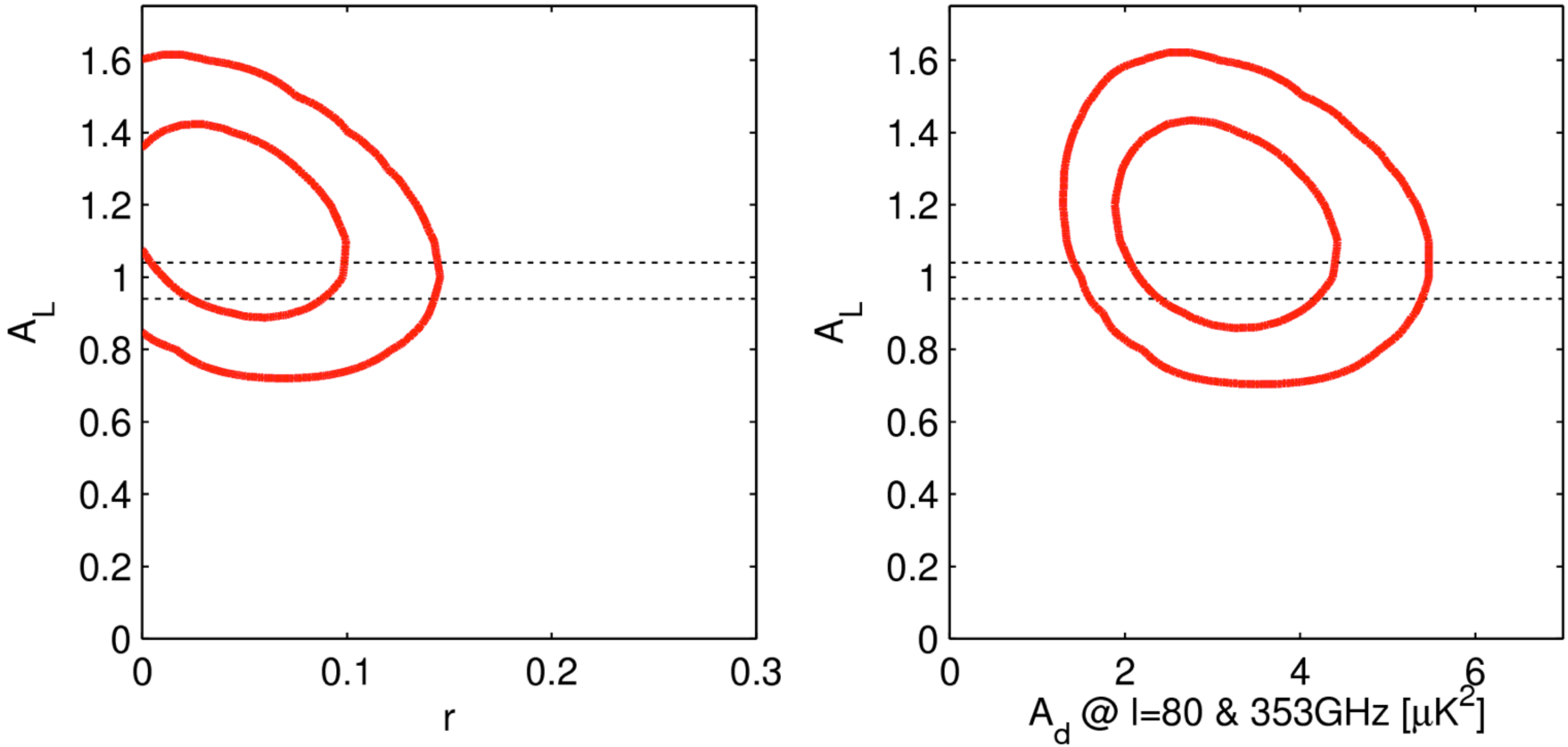
Adding synchrotron to the model





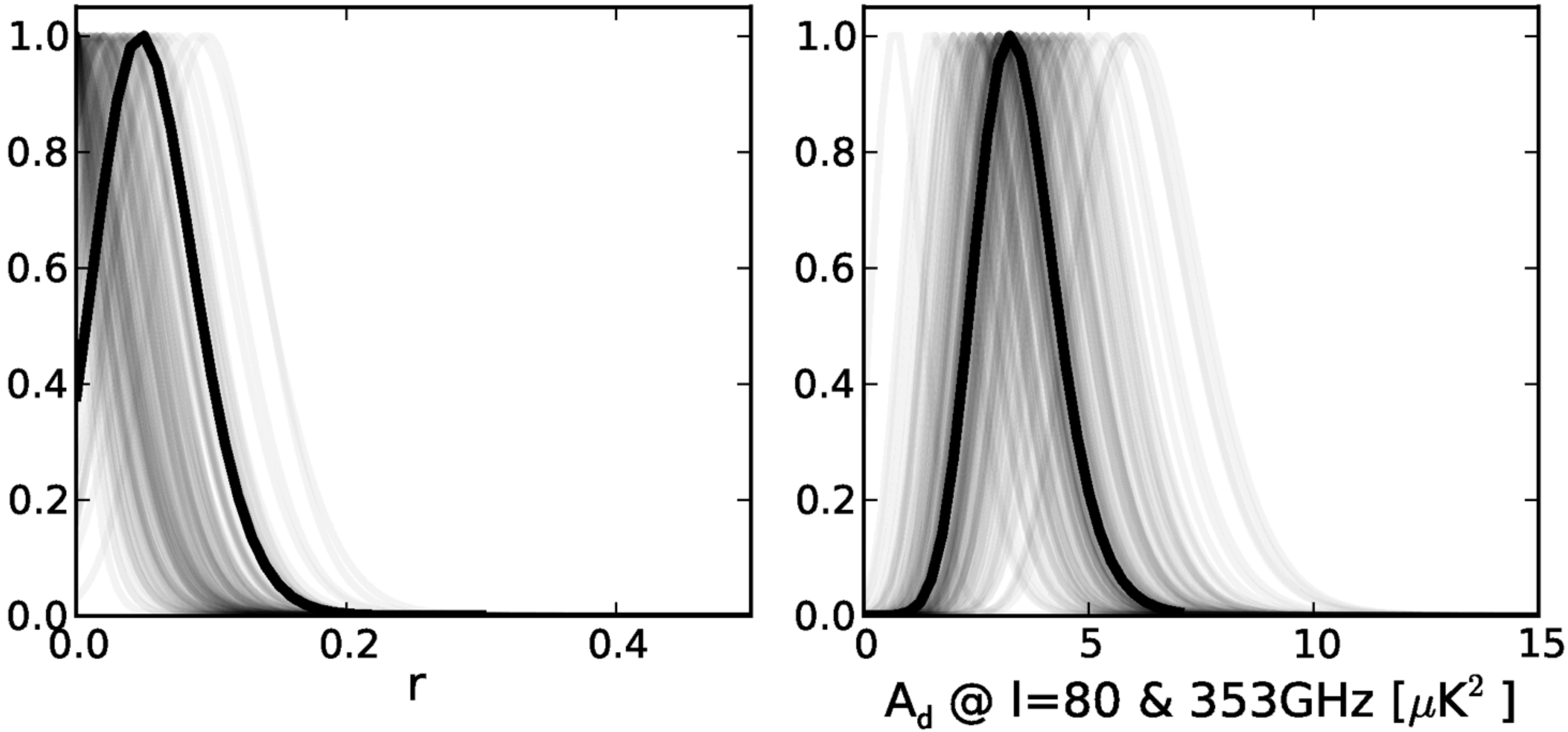
- We try adding synchrotron to the model while also adding all of the frequency channels of Planck
- We assume a spectral index for sync taken from WMAP's spectral index map in our sky region
  - The results for *r* and A_d hardly change while synchrotron is tightly limited
  - If one assumes that the dust and sync sky patterns are correlated this limit gets *tighter*.

Constraints on lensing B-modes



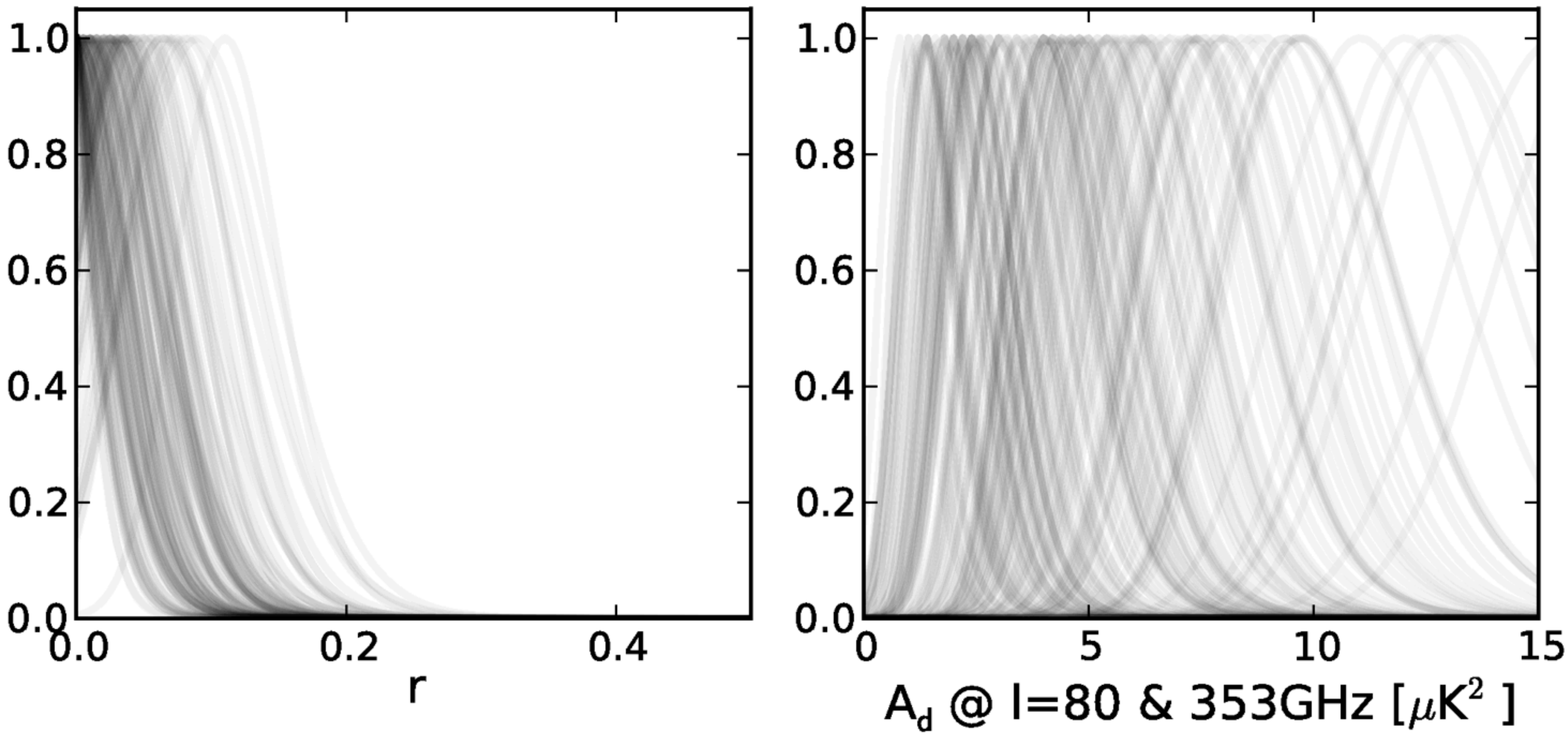
- ➢ We next allow the amplitude of the lensing signal to vary while also extending the ℓ range up to 330
- ➢ We find that the lensing and dust components can be cleanly separated
  - ○ And detect lensing at 7.0 σ significance

Likelihood validation



- We validate the likelihood machinery using simulations of a dust only model with mean A_d set a little higher than the value preferred by the real data.
- As expected 50% of the *r* constraints peak at zero with 8% having a zero/peak likelihood ratio less than that of the real data

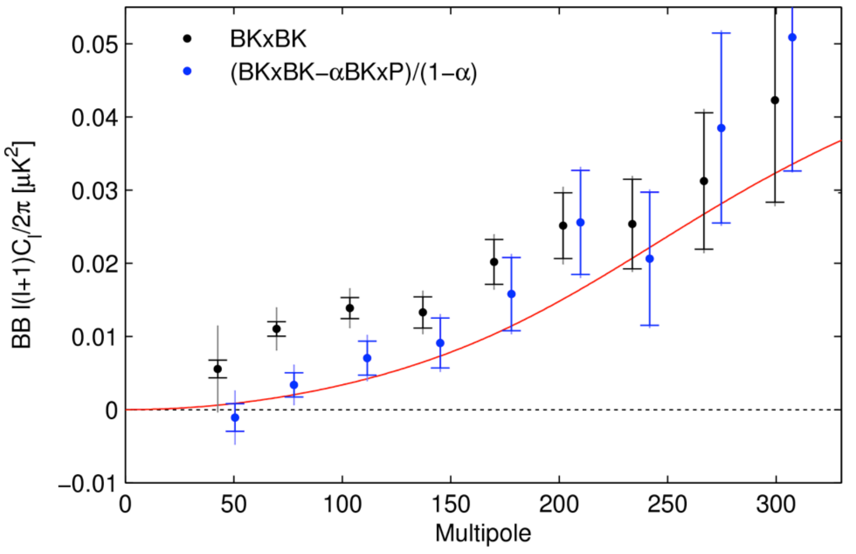
Likelihood validation II

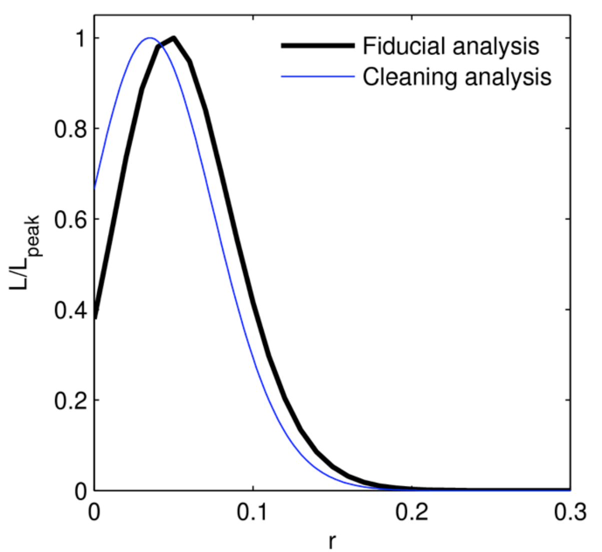


- ➢ We also run sims using dust sky patterns drawn from the old version of the Planck Sky Model
  - ○ These sky patterns are not necessarily Gaussian random fields and have a wide range of brightnesses (as seen at right)

- ➢ However 50% of the *r* constraints still peak at zero (and curves broaden in brighter dust regions)

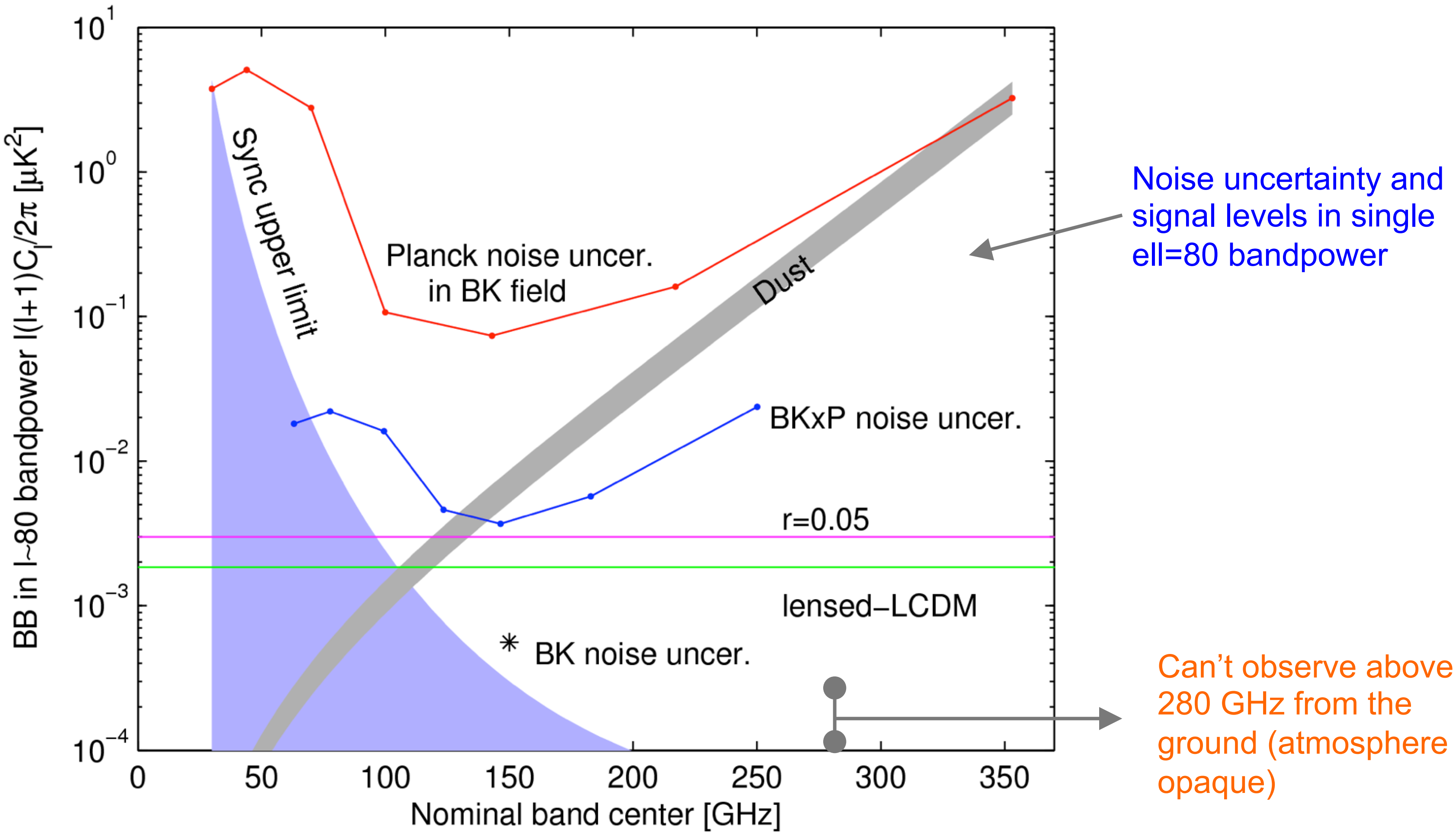
Spectral subtraction analysis





- We also try a simple analysis subtracting the scaled 150x353 spectrum from the 150x150
  - (This approximates a map based cleaning)
- The resulting *r* constraint is similar (although a little less powerful)

Comparison of signal and noise levels



- 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

- In March 2014 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 additional data from the successor experiment Keck Array

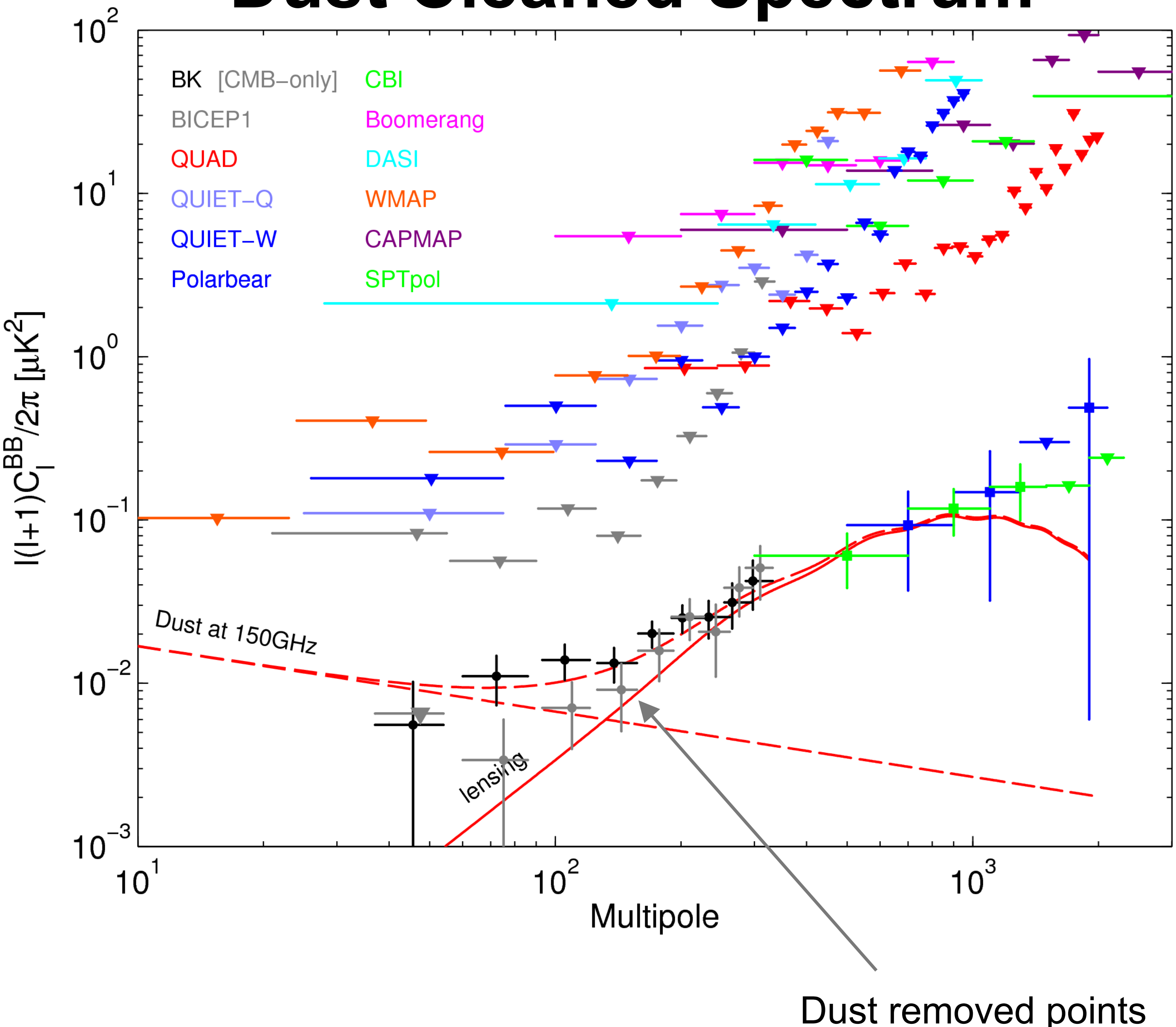
- Last summer Planck released new information on the polarized emission from galactic dust which showed this might be due to dust emission.

- We have 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 less than about half of the full signal.

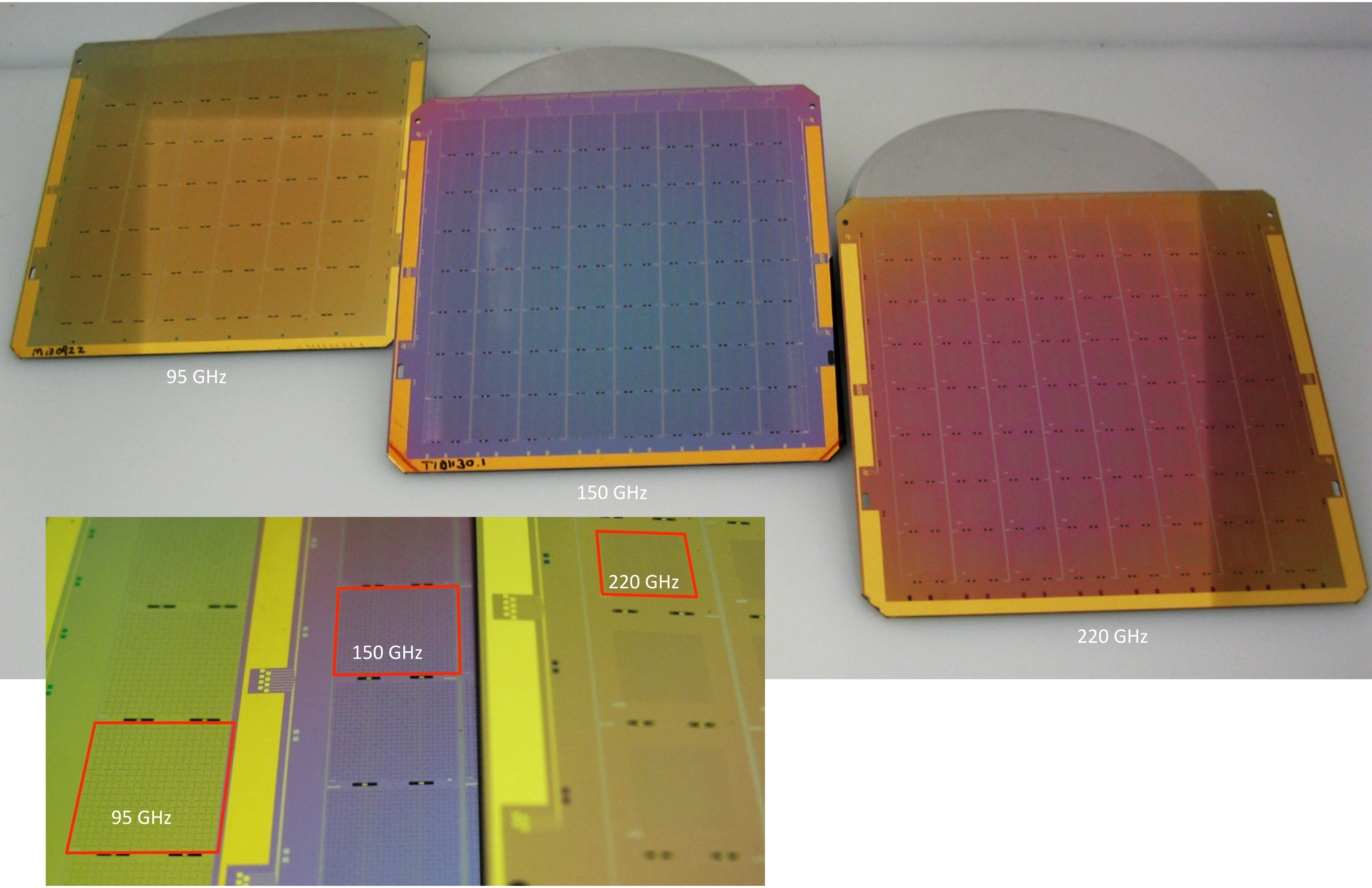
- Additionally, lensing B-modes are detected at 7.0 σ significance

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

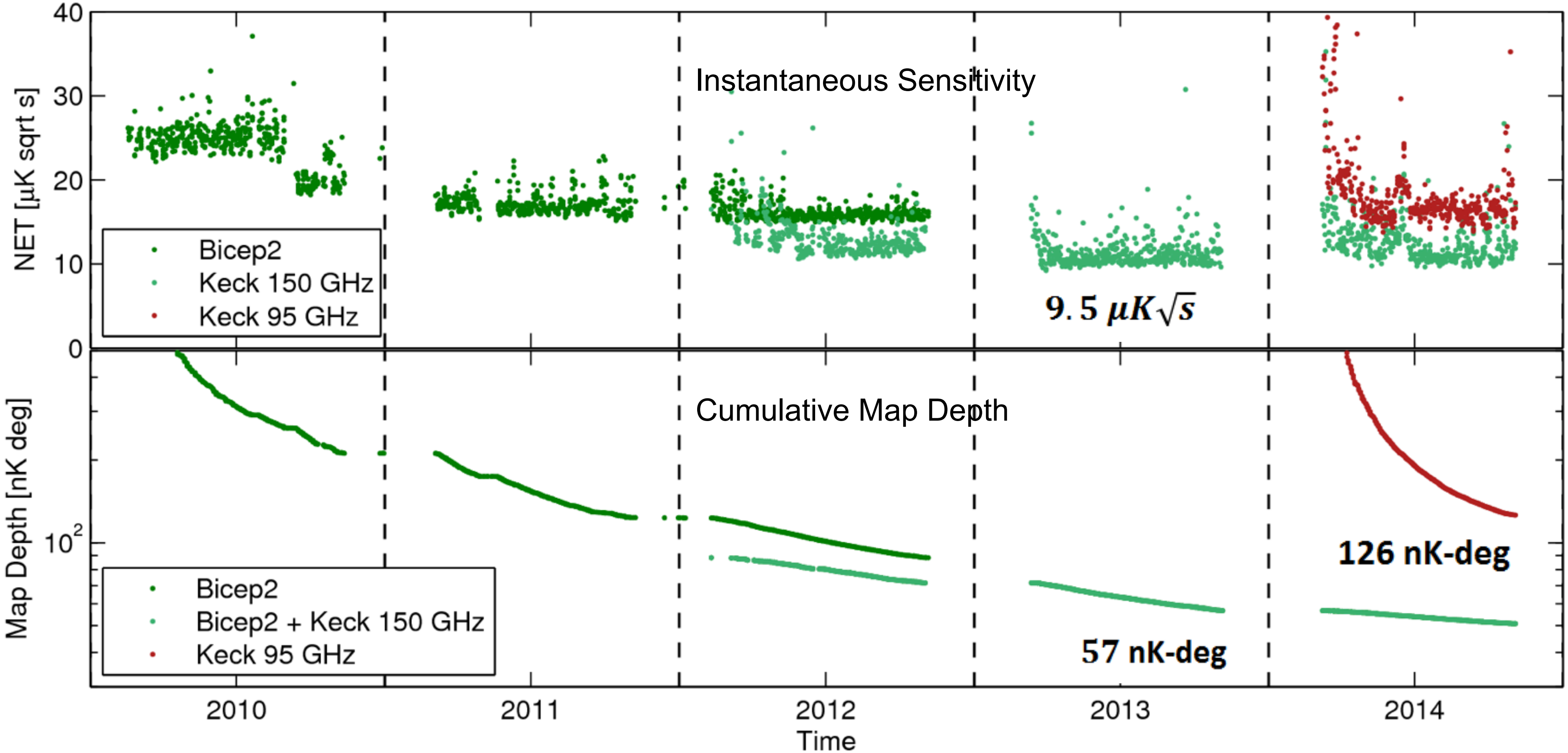
Dust Cleaned Spectrum



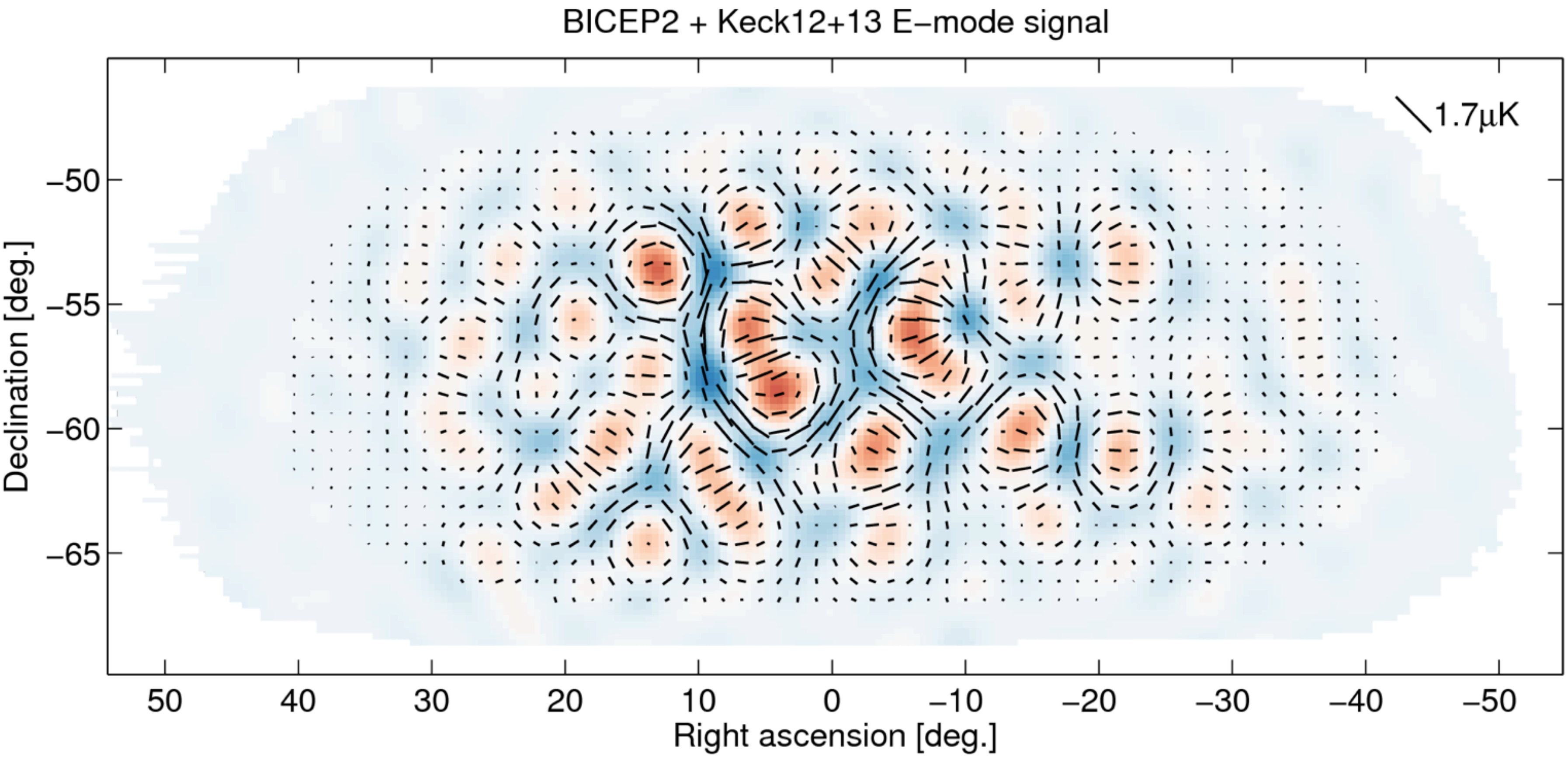
Detectors Designed to Scale in Frequency

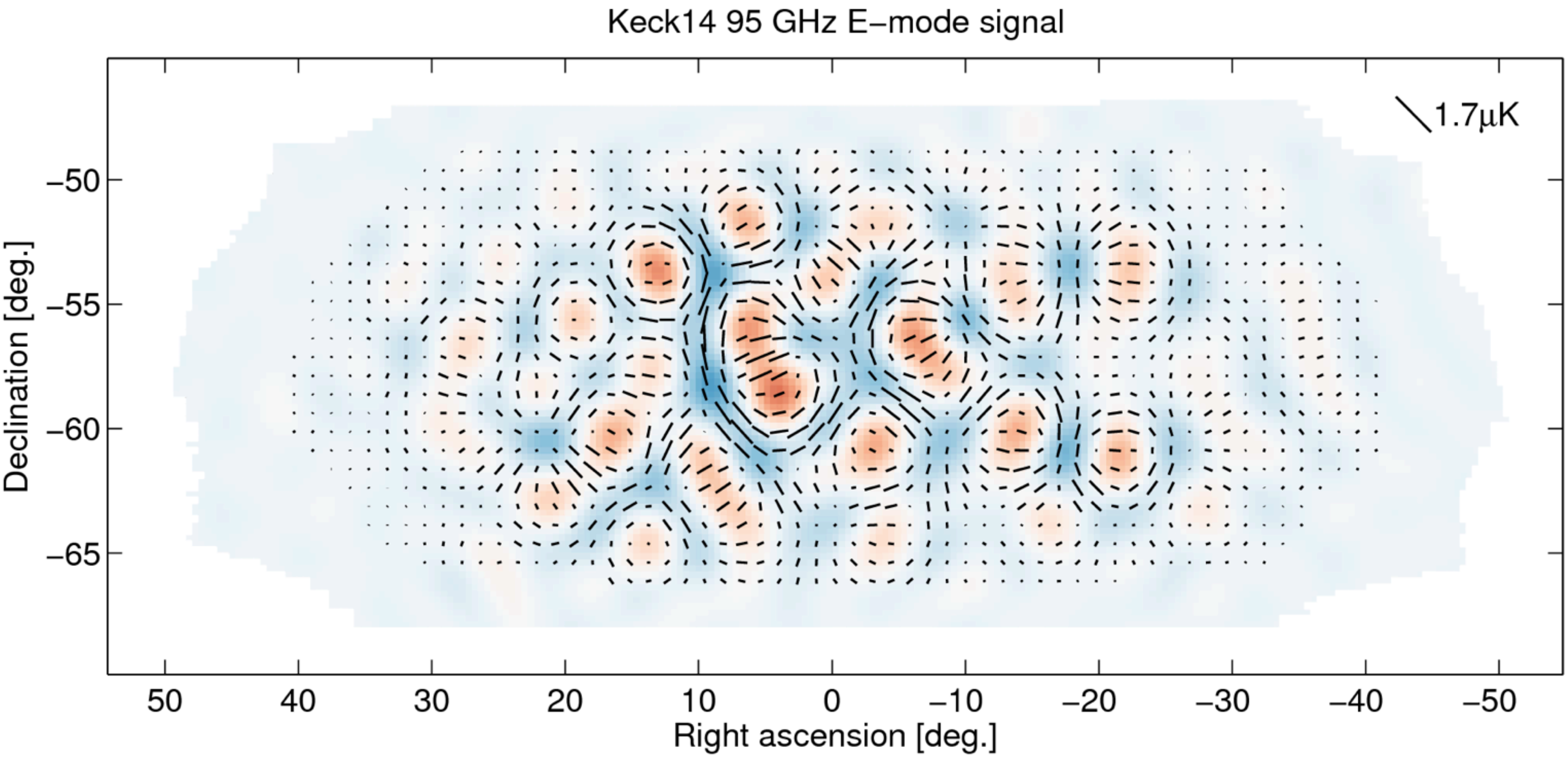


In 2014 Keck added 95 GHz sensitivity



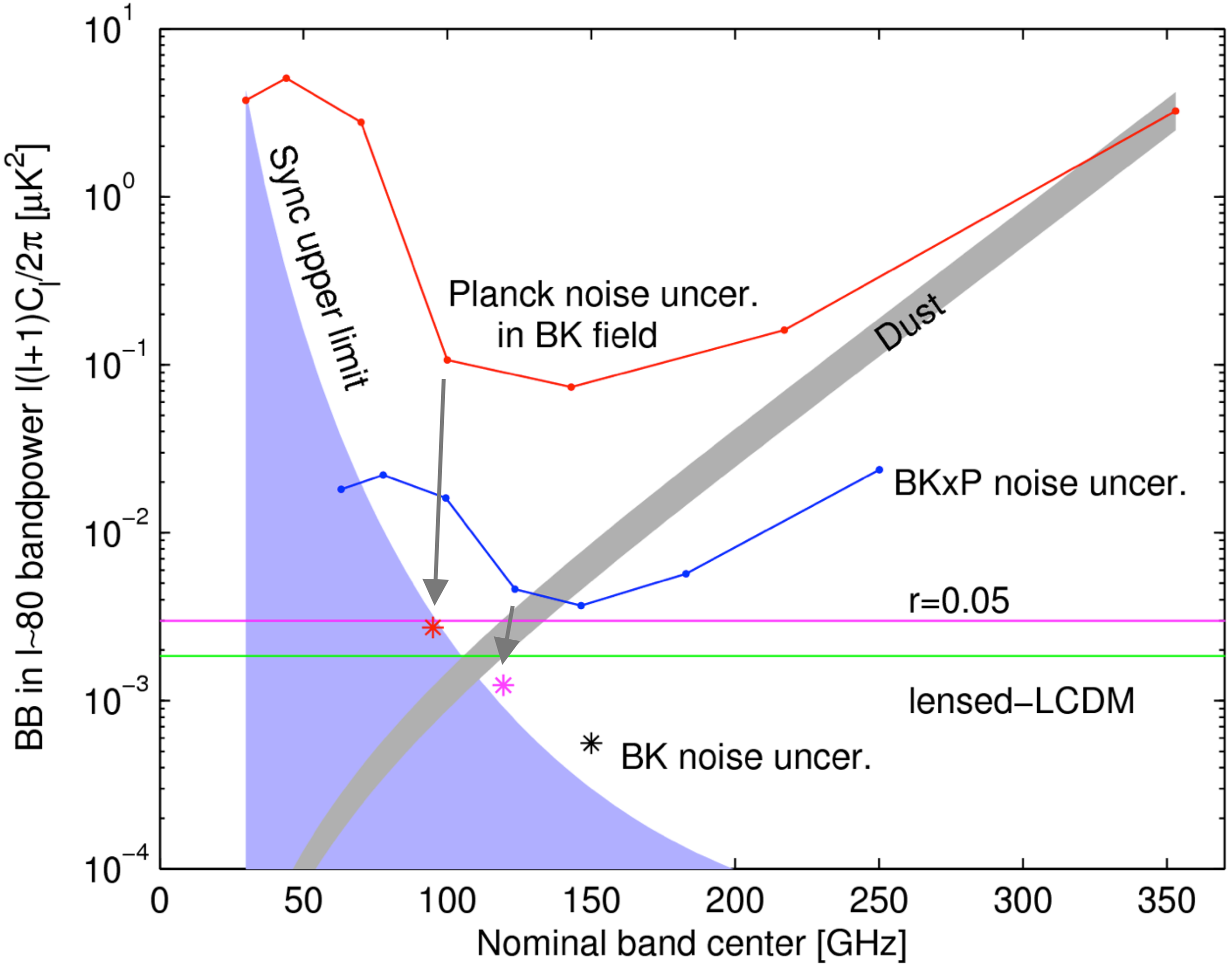
For 2014 season two of the Keck array receivers switched out for 95 GHz


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)

Keck 95 GHz already better than Planck 100 GHz



Keck 2014 95 GHz achieved noise level improves by large factor vs Planck 100 GHz

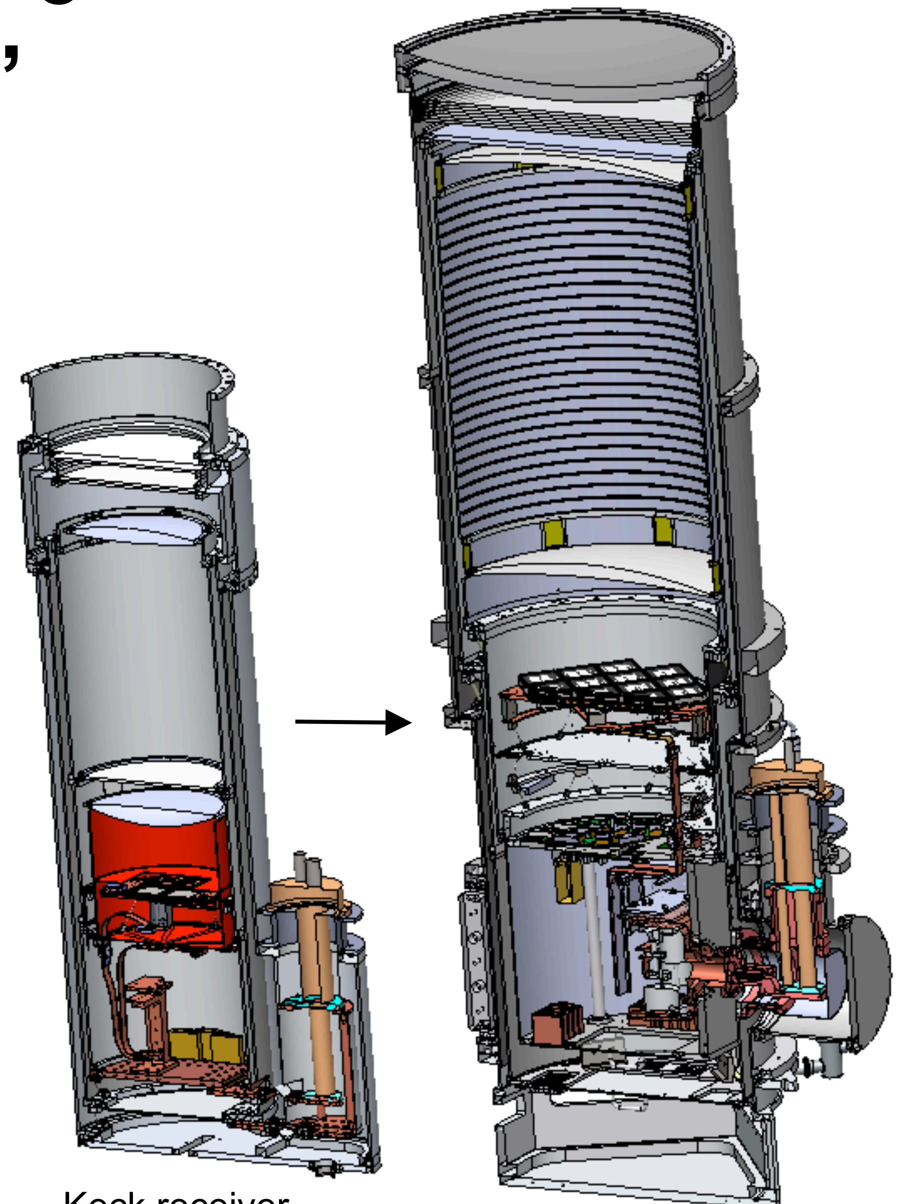
New in 2015 BICEP3
"Super Receiver"

All 95 GHz

2560 detectors in modular focal plane (45% populated in 2015)

Large-aperture optics and infrared filtering

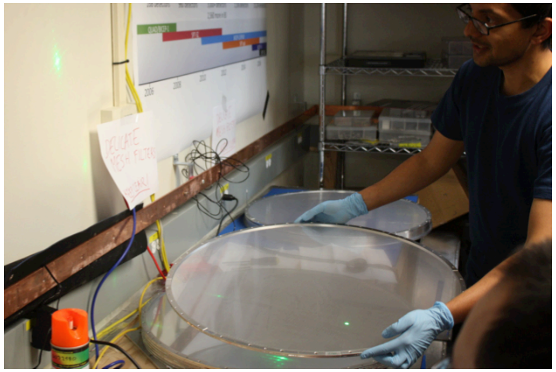
> 10x optical throughput of single BICEP2/Keck receiver



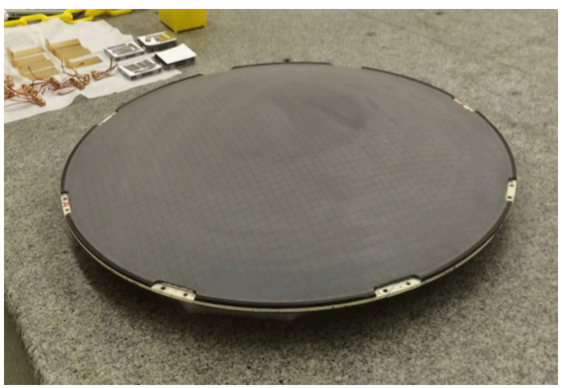
Keck receiver

BICEP3

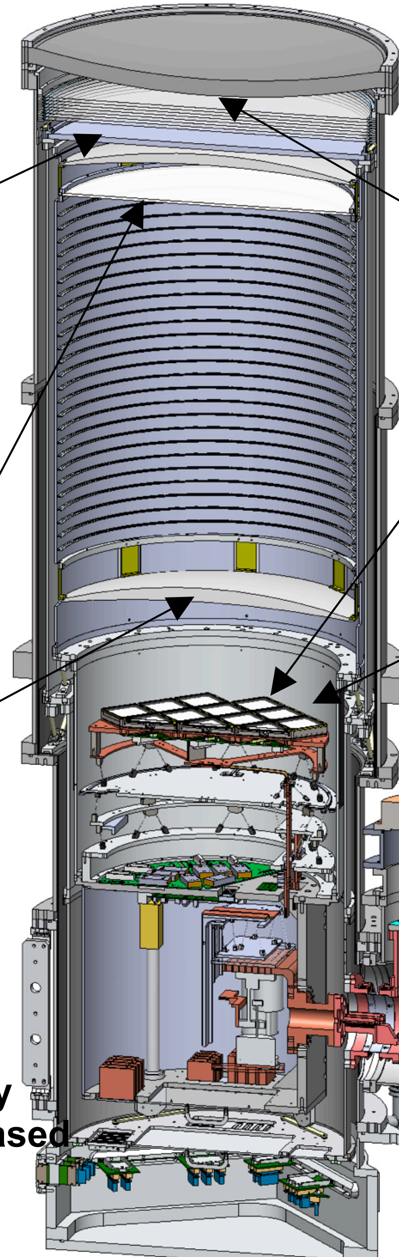
BICEP3 technology

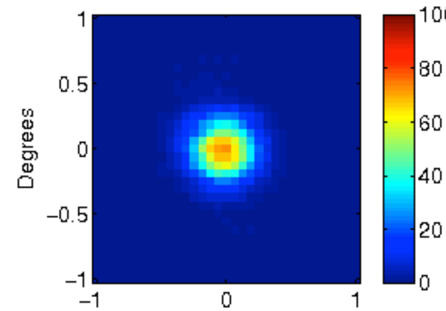


Large area Infrared shaders with ~O(10) micron aluminum features on mylar

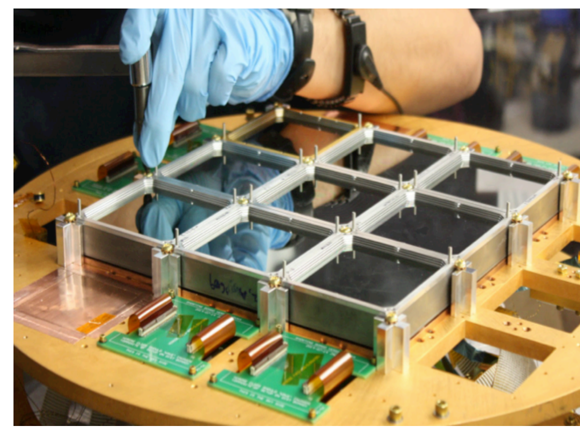


Thin, low loss, high thermal conductivity alumina filters and lenses with epoxy-based antireflection coating

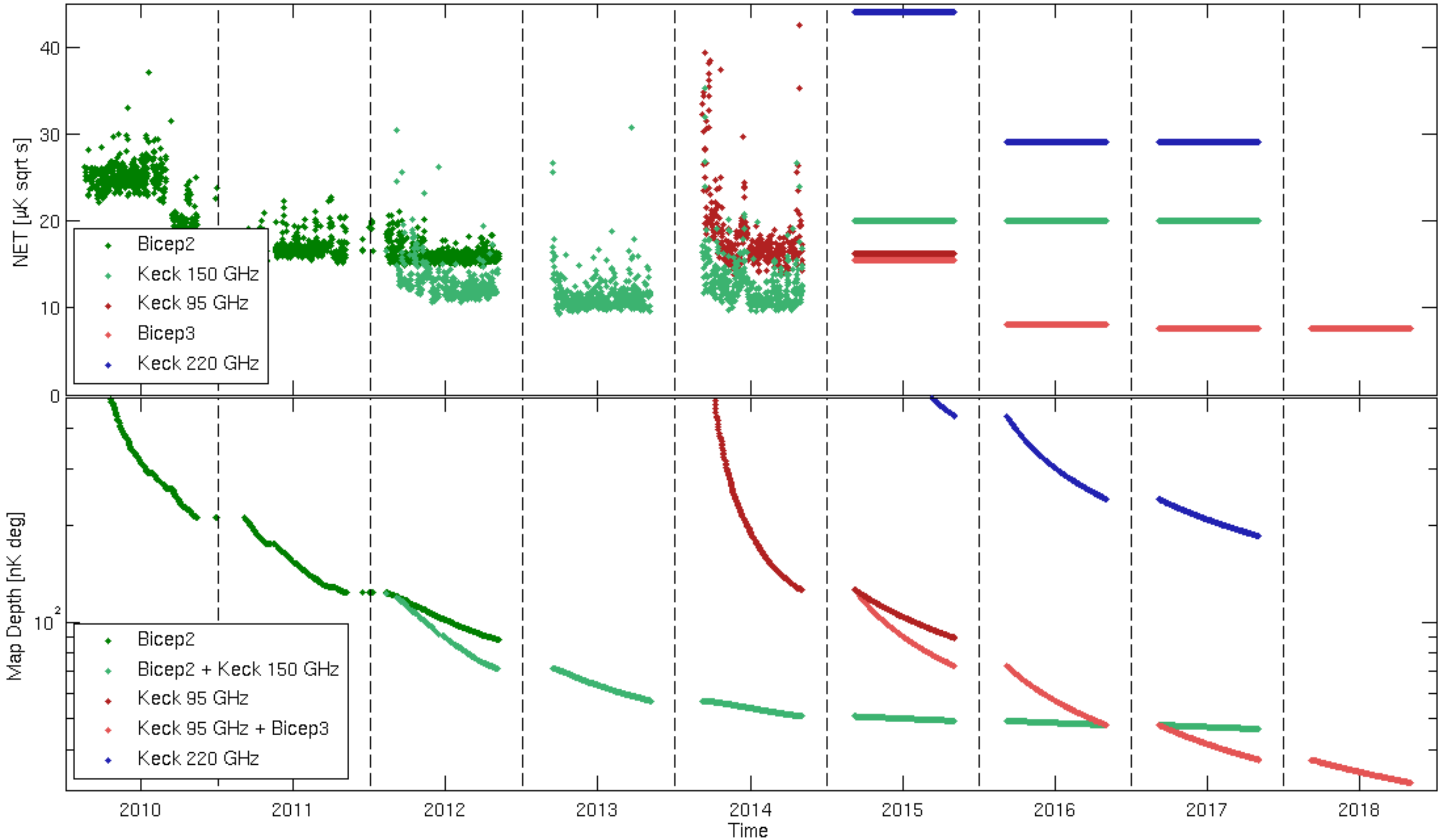




680-mm clear aperture window, fast optics (f/1.6), FOV ~28°
95 GHz beam FWHM ~0.35°



Plug & play detector modules each have 64 dual-pol 95 GHz camera pixels and contain cold multiplexing electronics.



The BICEP2/Keck/BICEP2 program is on-going – now with 3 frequency bands: 95/150/220 GHz

BICEP/Keck have delivered the highest sensitivity to date

	Q,U Map rms noise N [nK-deg] (uK-arcmin)	Survey effective area A [deg^2]	**Total** Q+U **Survey Weight** $W=2A/N^2$ [uK^{-2}]
Bicep2 150 GHz	87 (5.2)	380	**101,000**
Bicep2 + Keck12/13 150 GHz	57 (3.4)	400	**248,000**
Keck14 95 GHz	126 (7.6)	375	**47,000**
Planck 143 GHz (for reference)	1170 (70.2)	41,000	**60,000**

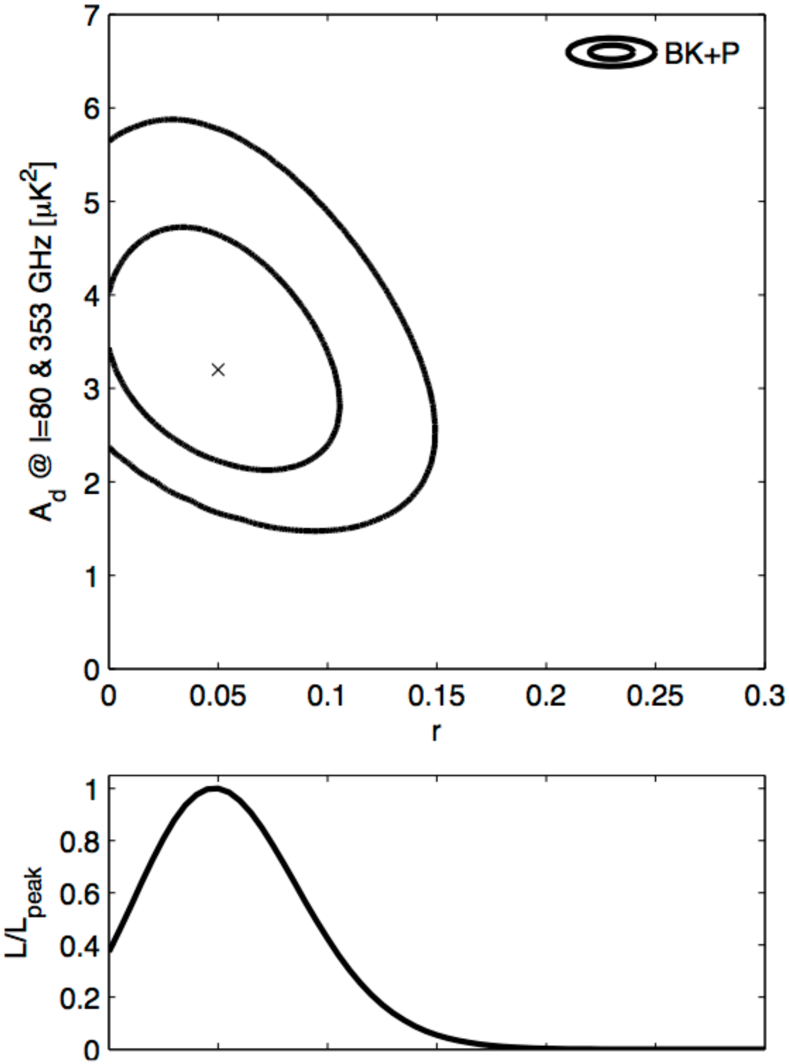
← BICEP2 paper 3/2014

← Keck paper 2/2015

← Paper coming soon!

↑ A quantity which is linear in number of detectors and integration time – i.e. difficulty of achieving – other experiments have yet to publish numbers which get close to BK (highest so far is SPTpol 100d at 11,000)

Tightening of constraints when adding additional data



Data Included:

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

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

The Maximum likelihood on the grid has:
$r = 0.05$, $A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

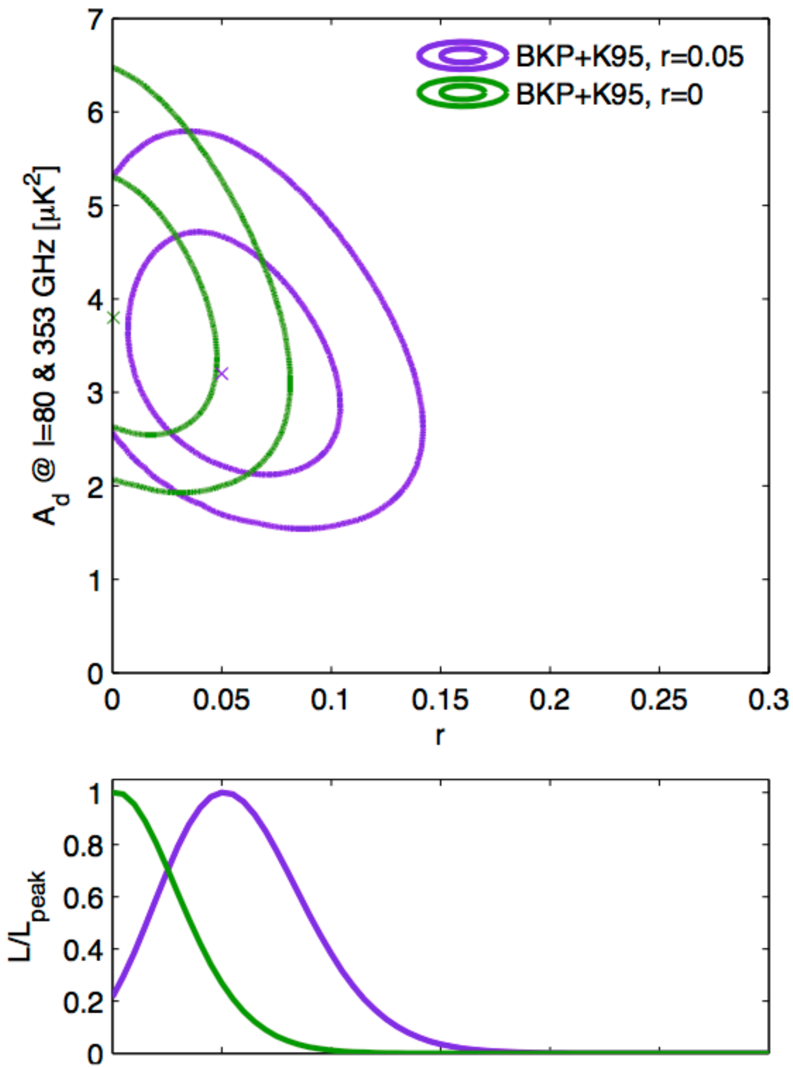
For dust SED use modified blackbody model and marginalize over range β_d=1.59±0.11

We assume no synchrotron contribution here.

Foregrounds only PTE = 8.0%

Now

Tightening of constraints when adding additional data



Data Included:

- BK150 (2013)
- Planck, 30 - 353 GHz
- Keck (2014), 95 GHz

Contours are projected likelihood contours centered on different expectation values:

r = 0.05, A_d = 3.3 μK^2_{CMB} (BKP ML point)

r = 0, A_d = 3.8 μK^2_{CMB}

Of course we can't predict how the actual data will shift.

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

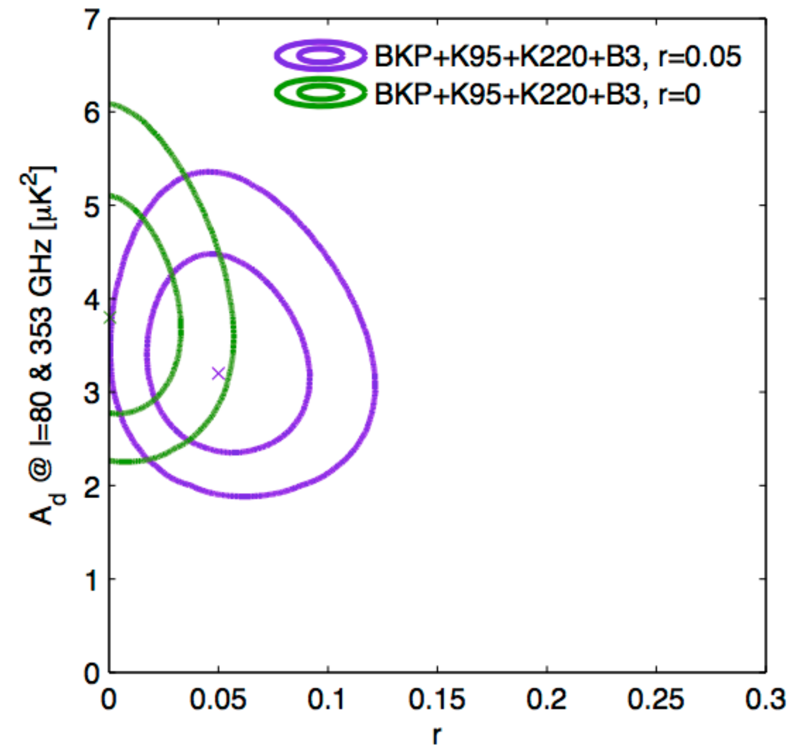
r < 0.060 (95%) [0.062 if β_s=-3.0]

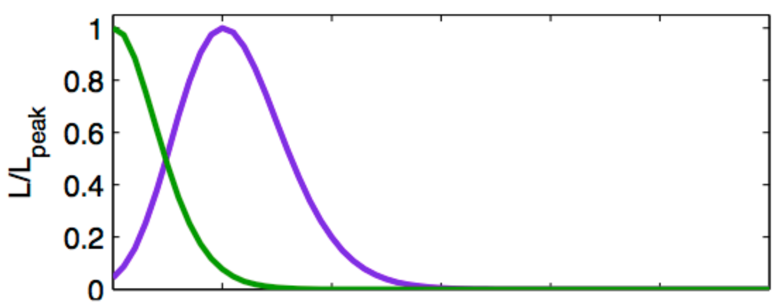
— or —

Foregrounds only PTE = 4.0% [4.3% if β_s=-3.0]

1 month from now

Tightening of constraints when adding additional data





Data Included:

- BK150 (2013)
- Planck, 30 - 353 GHz
- Keck (2014 + 2015), 95 GHz
- Keck (2015), 220 GHz
- BICEP3 (2015), 95 GHz

Contours are projected likelihood contours centered on different expectation values:

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

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

Of course we can't predict how the actual data will shift.

Both cases here assume synchrotron contribution, $\beta_s=-3.3$ and $A_{sync} = 3e\text{-}4\ \mu K^2_{CMB}$ (current BKP 95% upper limit).

$r < 0.041$ (95%) [0.043 if $\beta_s=-3.0$]

— or —

Foregrounds only PTE = 0.6% [0.9% if $\beta_s=-3.0$]

This time next year

Trying to reproduce PIPXXX small patch analysis

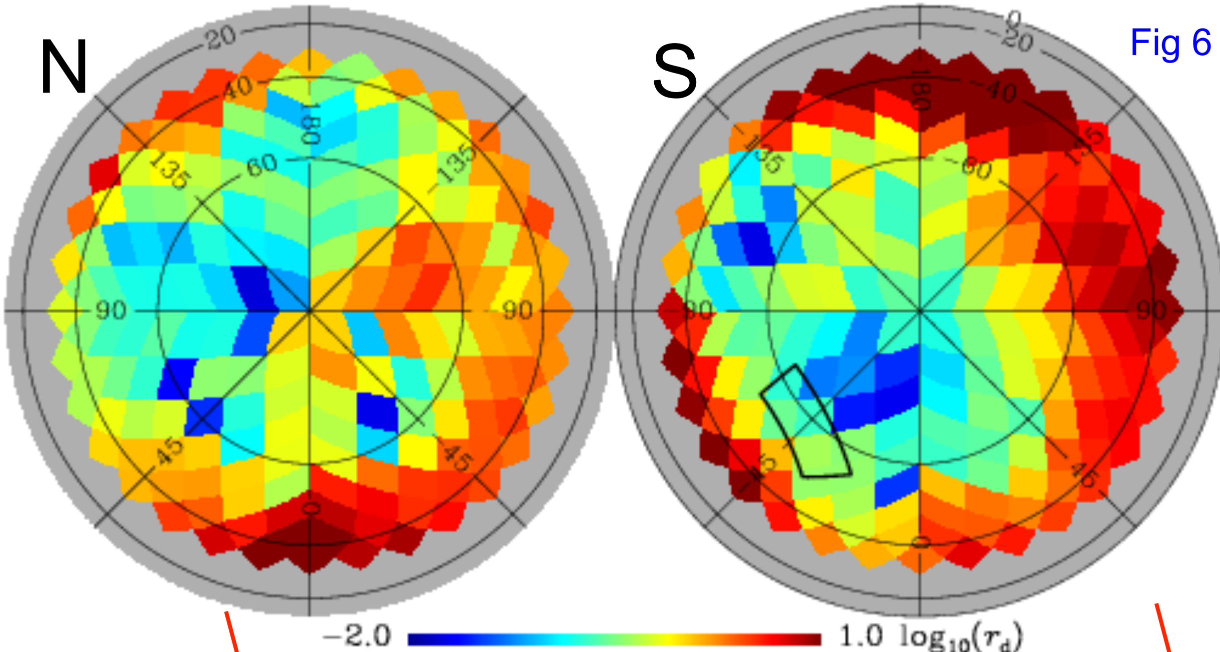
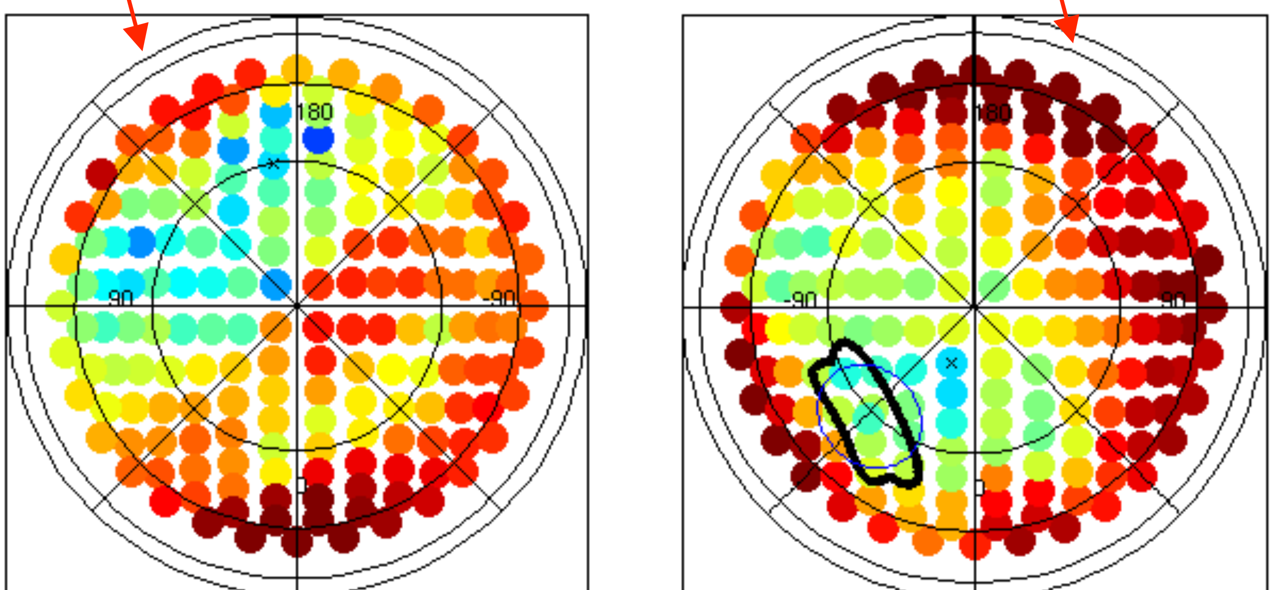


Fig 6 of arxiv:1409.5738

This figure has been doing heavy rotation and appears to show that BK sky region is not the best



Nominally identical reanalysis fails to reproduce this plot in detail