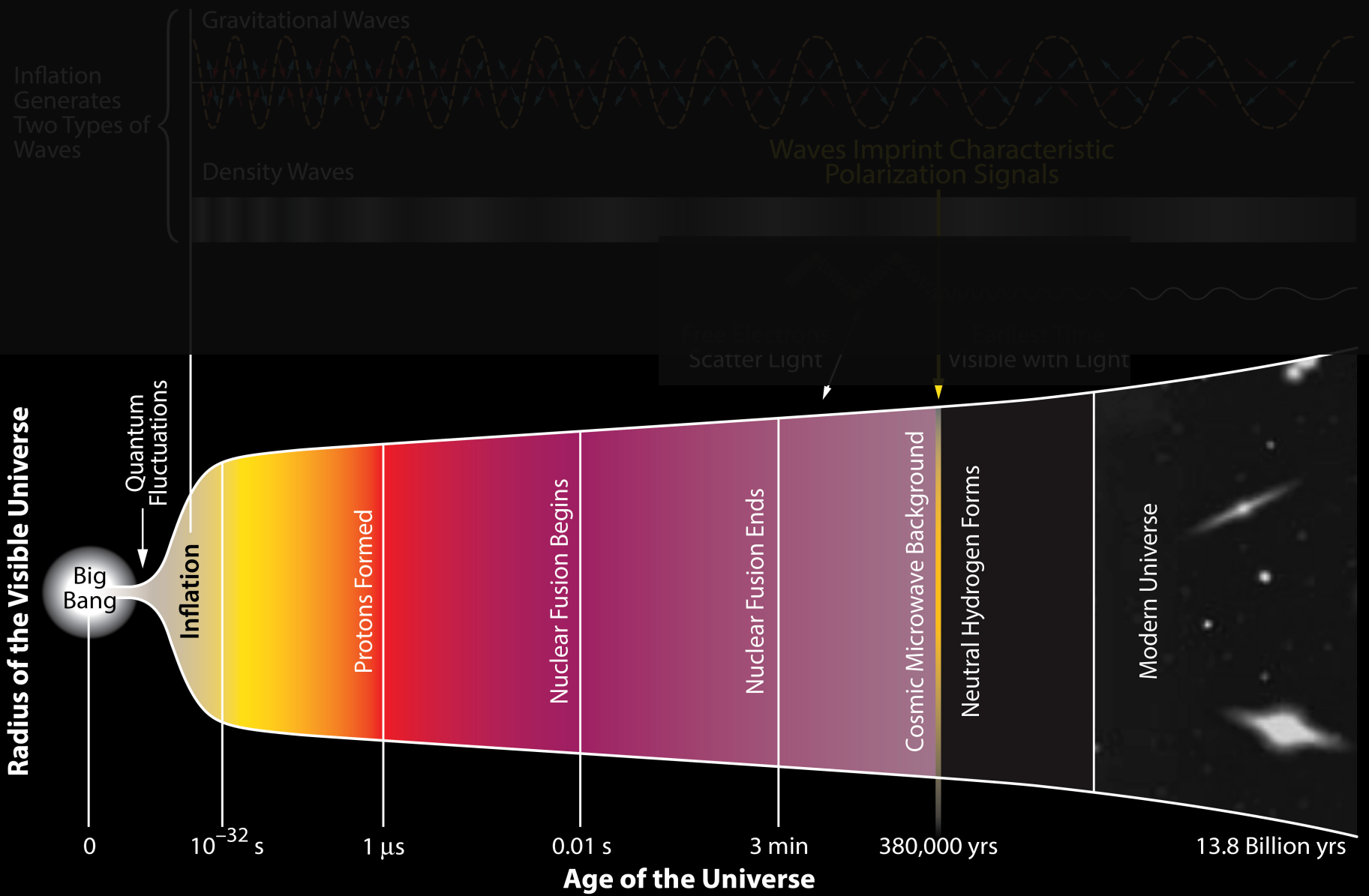
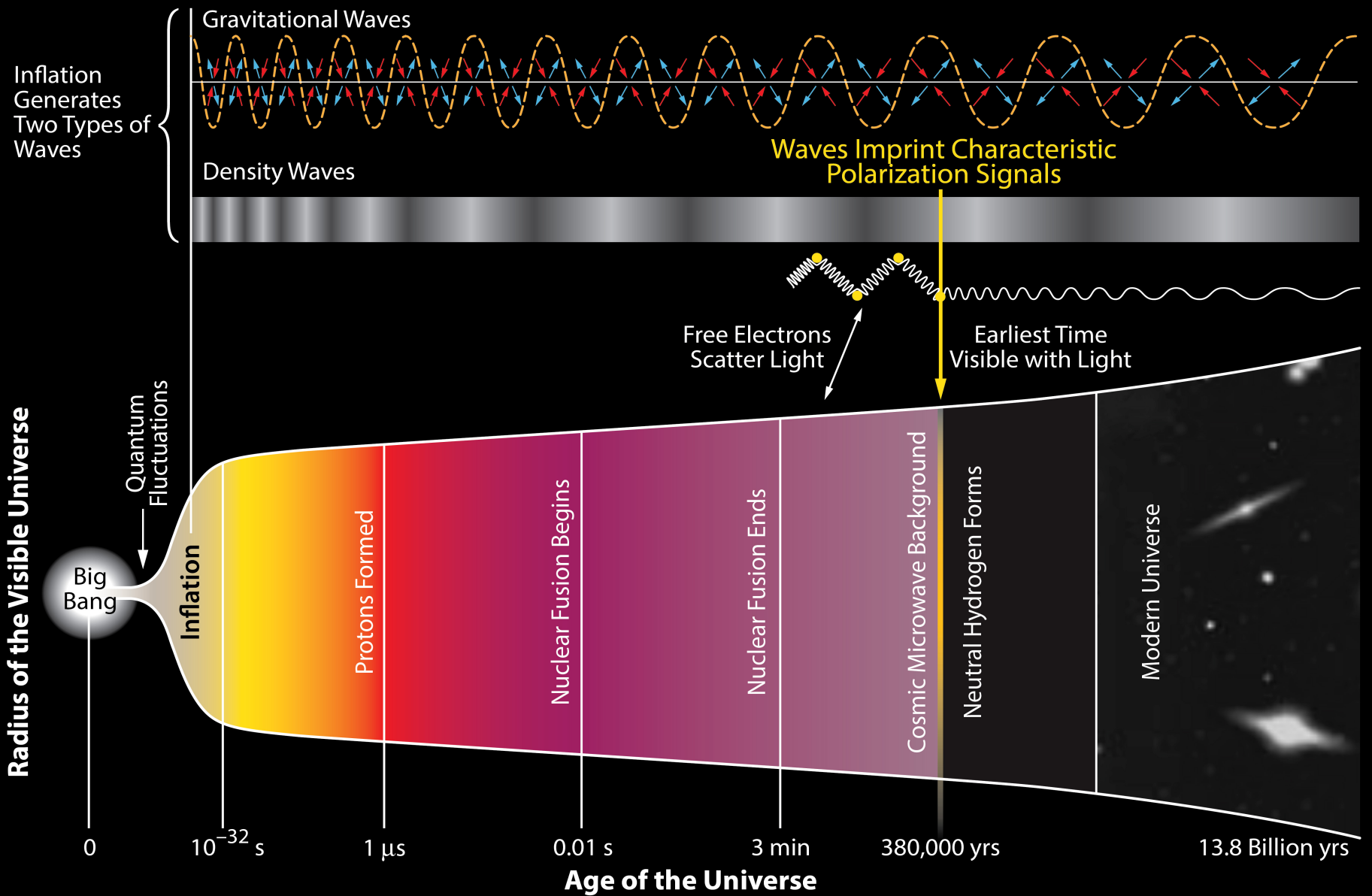


CMB Polarization Measurements With The BICEP/Keck Array Experiments

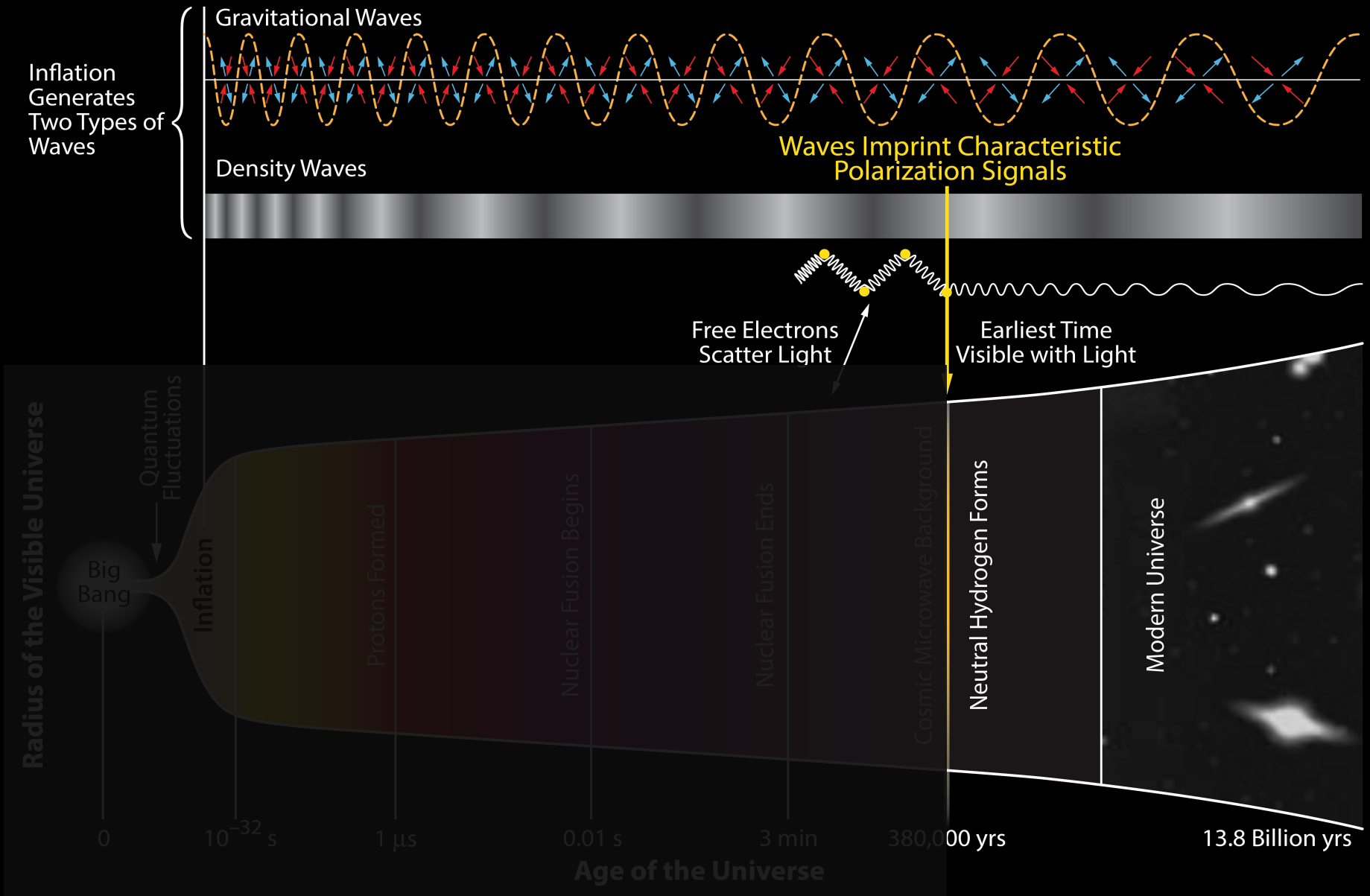
History of the Universe



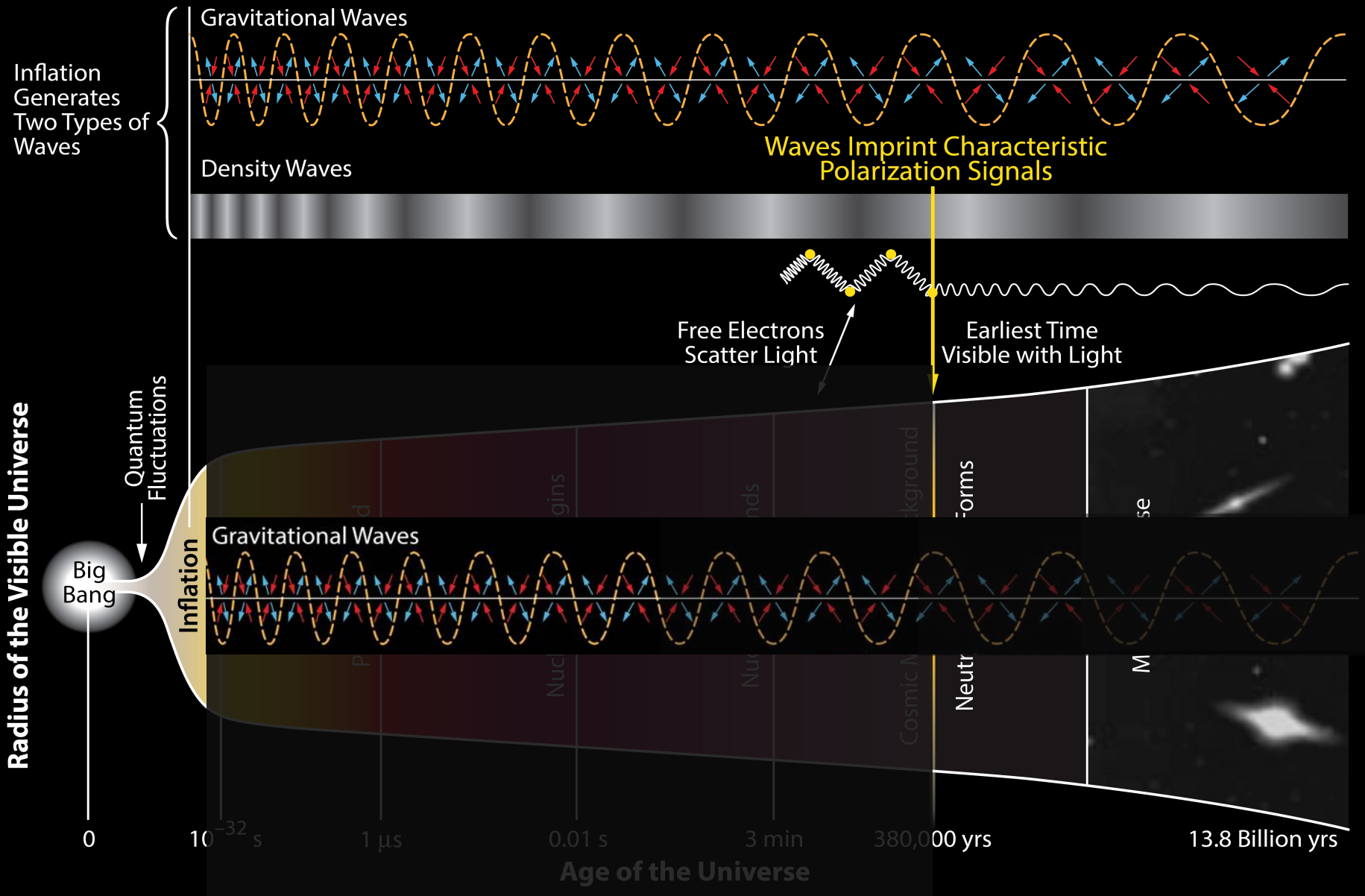
History of the Universe



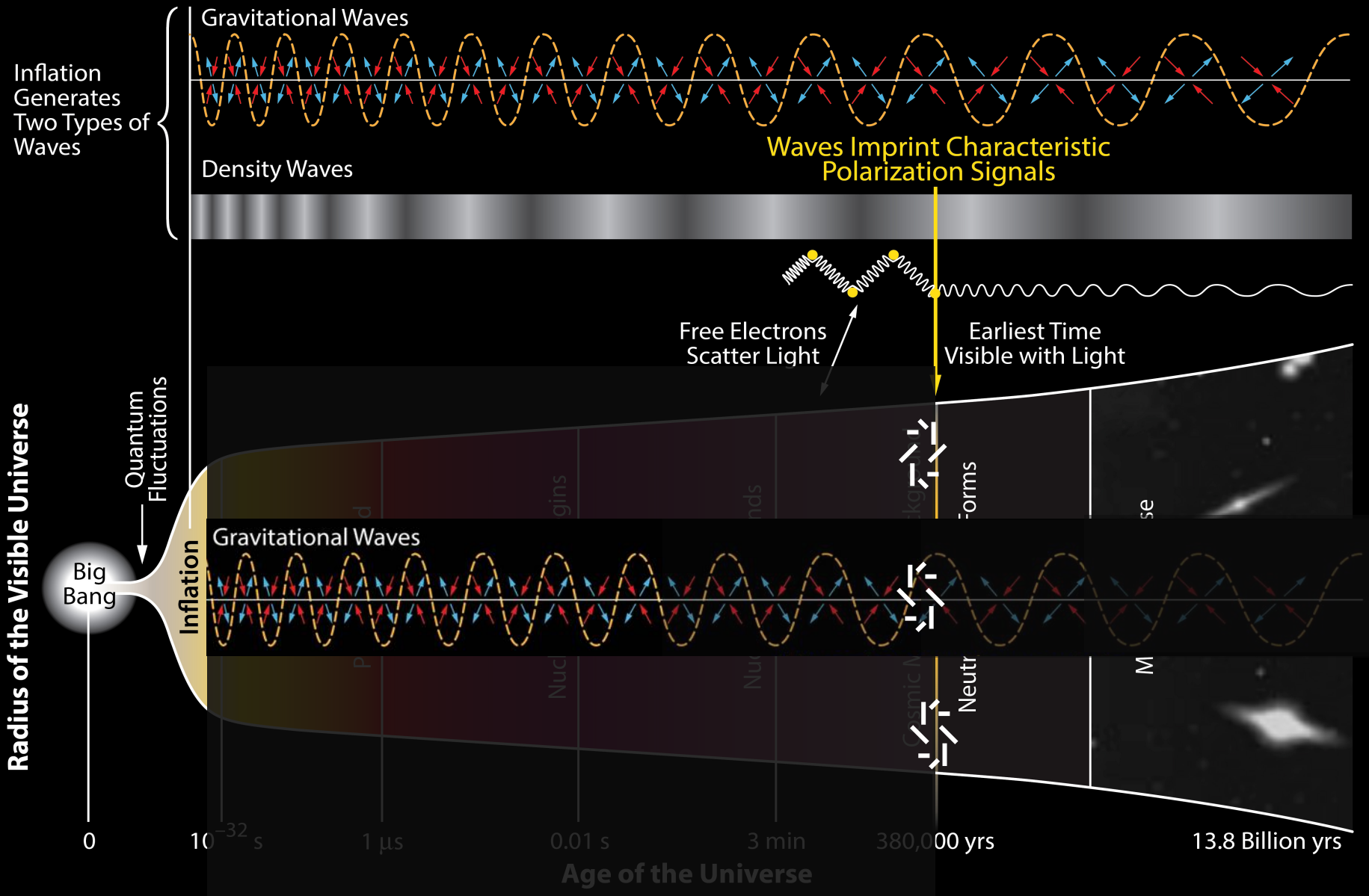
History of the Universe



History of the Universe

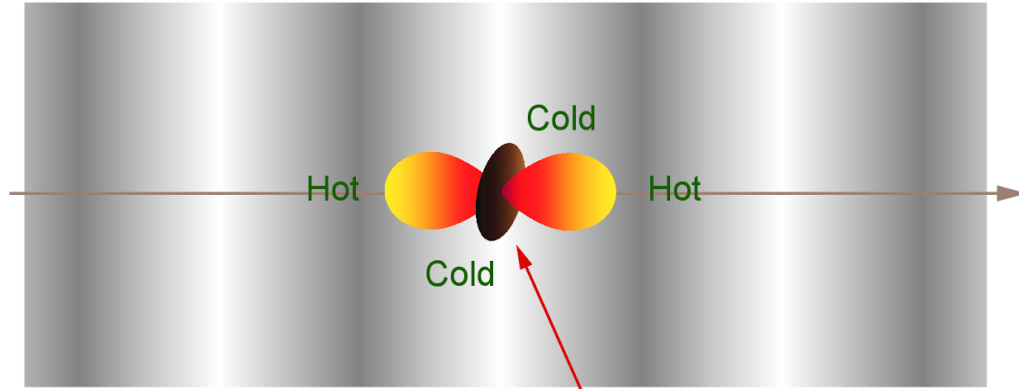


History of the Universe

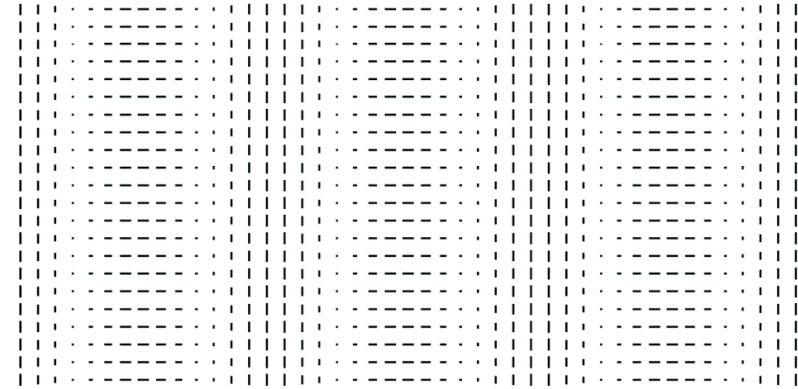


CMB polarization

Density Wave

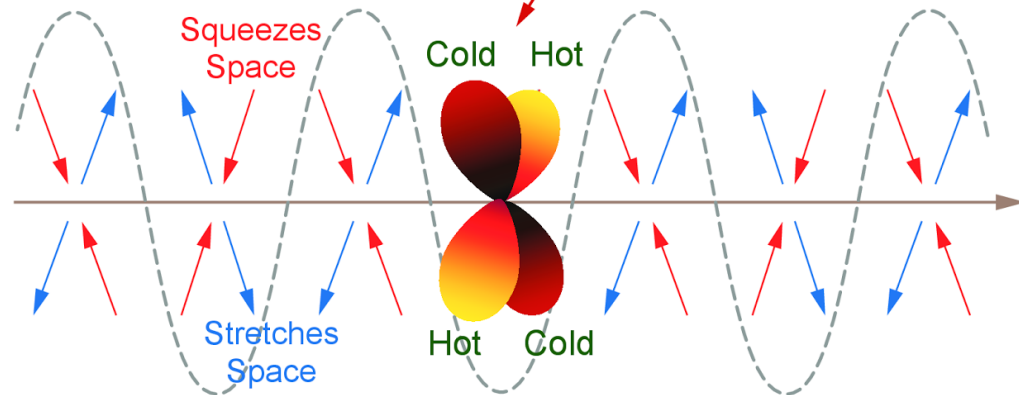


E-Mode Polarization Pattern

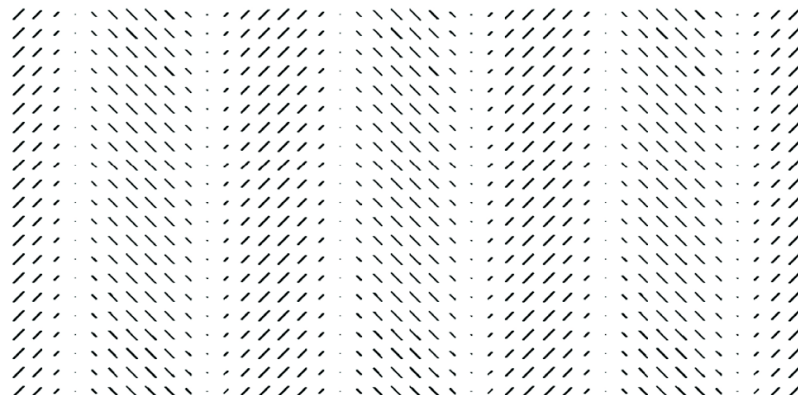


Temperature Pattern Seen by Electrons

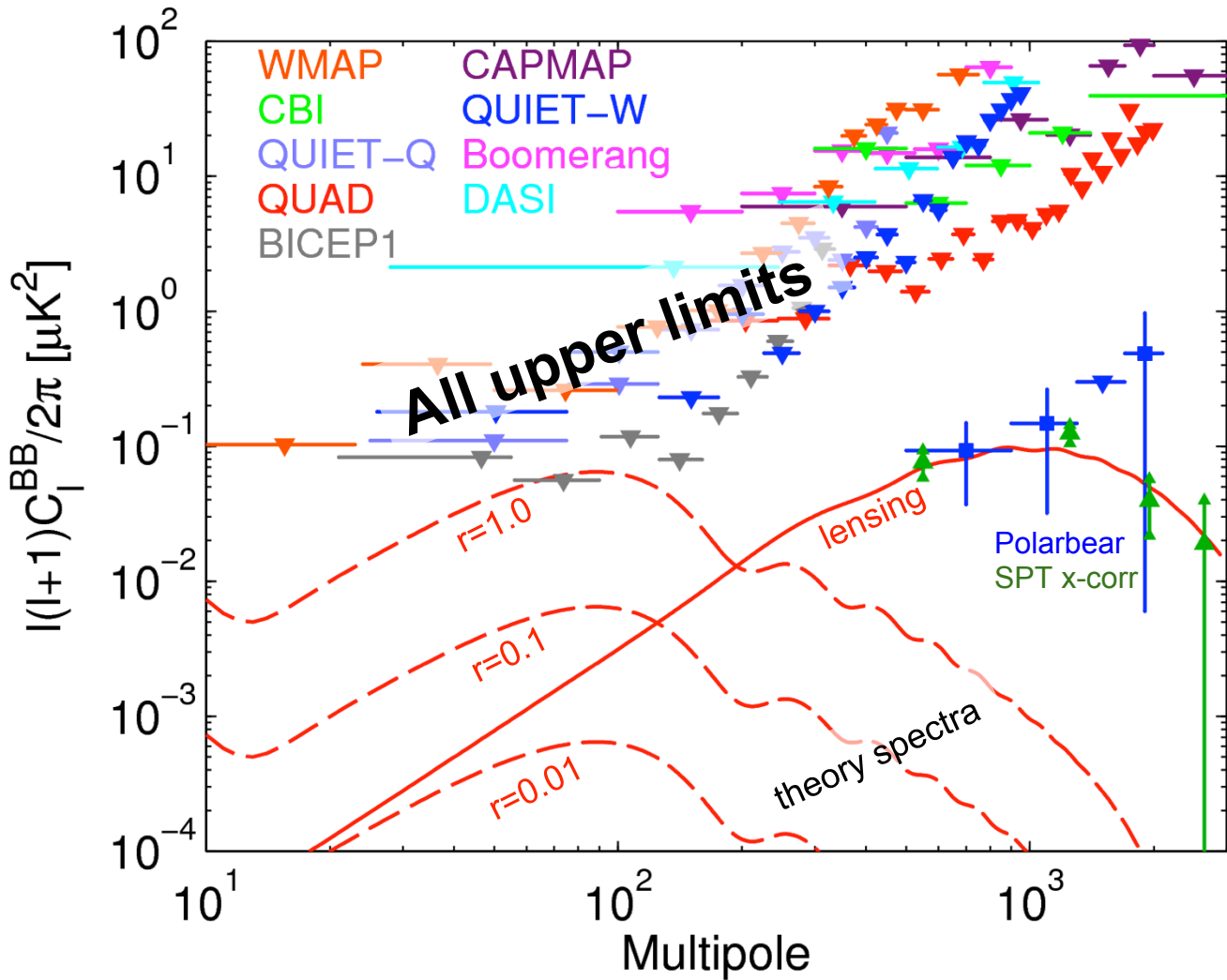
Gravitational Wave



B-Mode Polarization Pattern



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.

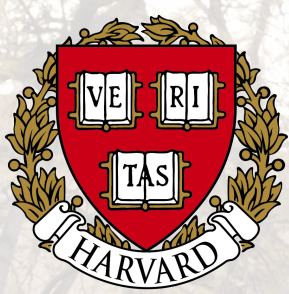
Before BICEP2: only upper limits from searches for Inflationary B-modes

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



The BICEP2/Keck Postdocs



Colin Bischoff



Jeff Filippini



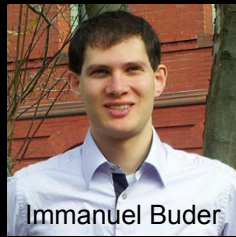
Martin Lueker



Walt Ogburn



Abigail Vieregg



Immanuel Buder



Stefan Fliescher



Roger O'Brient



Angiola Orlando



Zak Staniszewski



Steffen Richter



Steffen Richter



Steffen Richter

2010

2011

2012

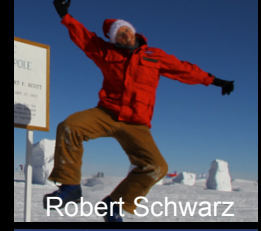
2013

2014

2015

Winterovers BICEP2

Keck



Robert Schwarz



Robert Schwarz



Robert Schwarz



Robert Schwarz

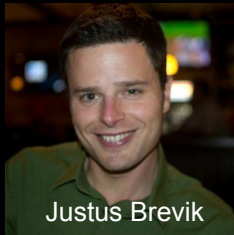


Robert Schwarz

The BICEP2/Keck Graduate Students



Randol Aikin



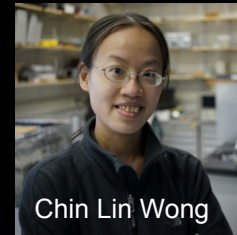
Justus Brevik



Chris Sheehy



Grant Teply



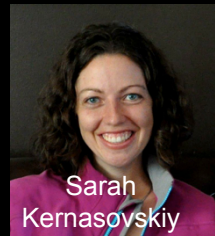
Chin Lin Wong



Kirit Karkare



Jon Kaufman



Sarah
Kernasovskiy



Jamie Tolan

2015

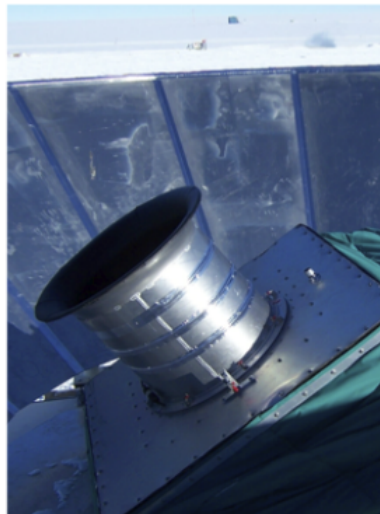
South Pole CMB telescopes



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

**Super dry atmosphere and 24h coverage of low foreground sky.
Also power, LHe, LN₂, 200 GB/day, 3 square meals, and bingo night...**

BICEP1
(2006 - 8)



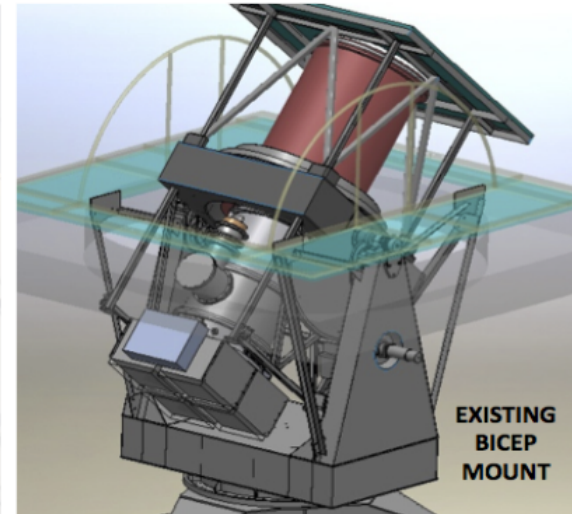
BICEP2
(2010 - 12)



Keck Array
(2011 -)

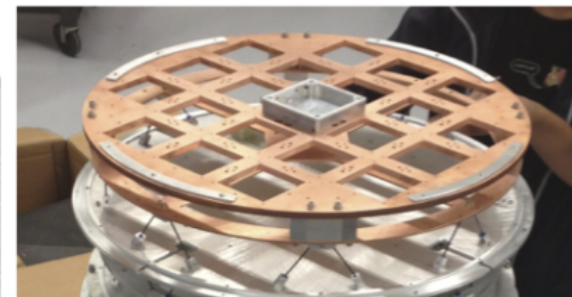
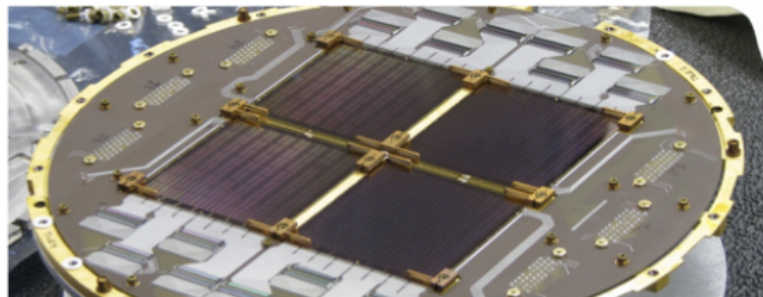
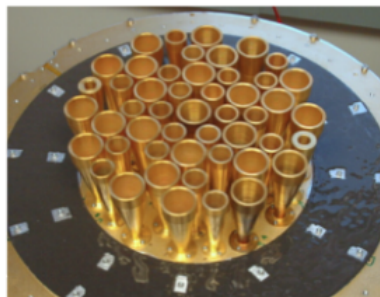


BICEP3
(2014 -)

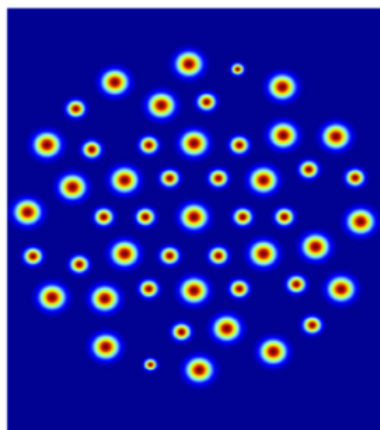


Telescope and Mount

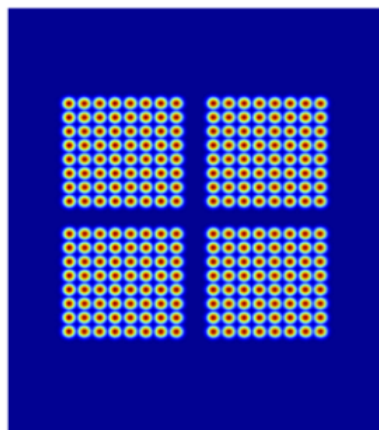
Focal Plane



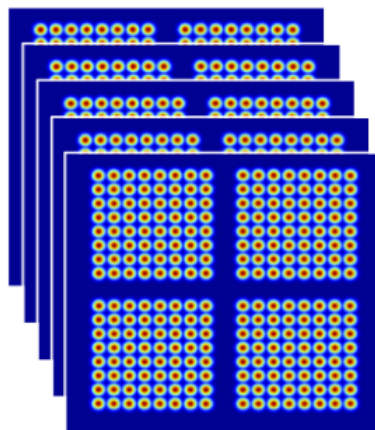
Beams on Sky



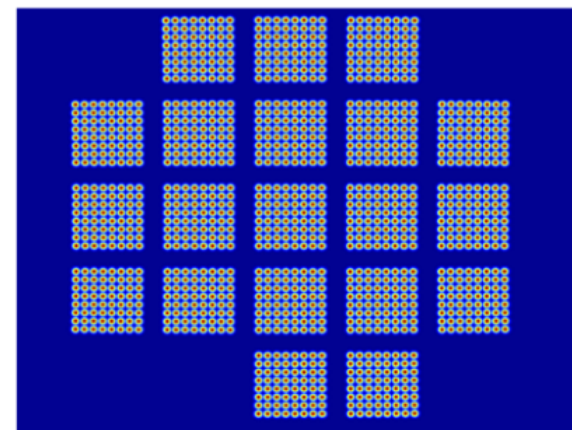
-5 0 5
Longitude (degrees)



-5 0 5
Longitude (degrees)



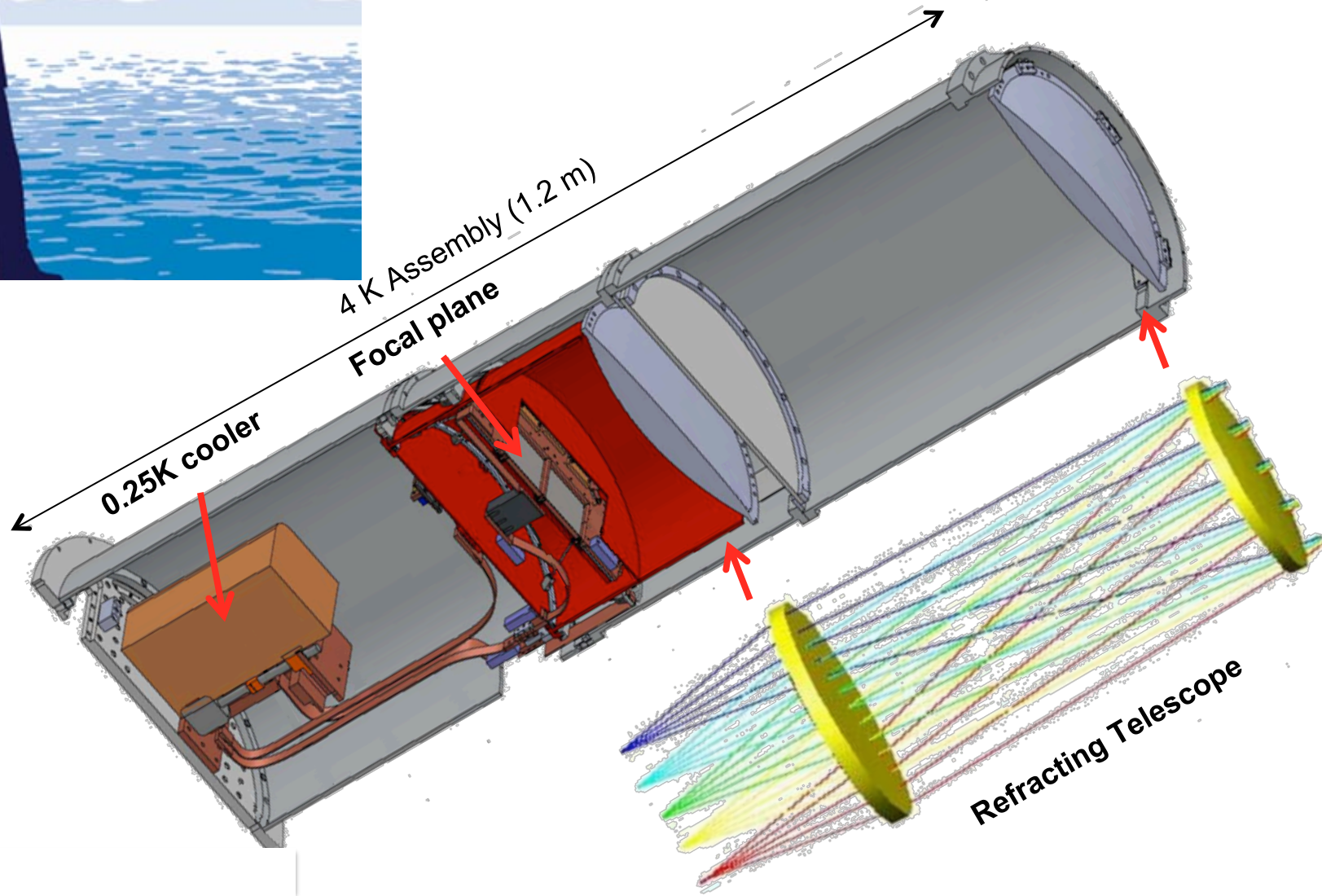
-5 0 5
Longitude (degrees)



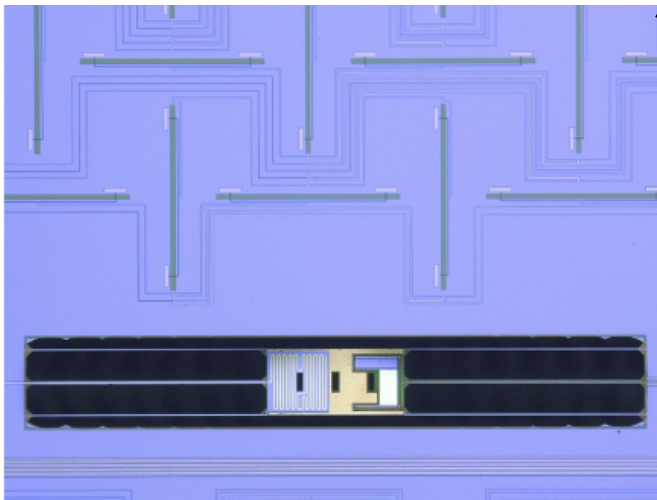
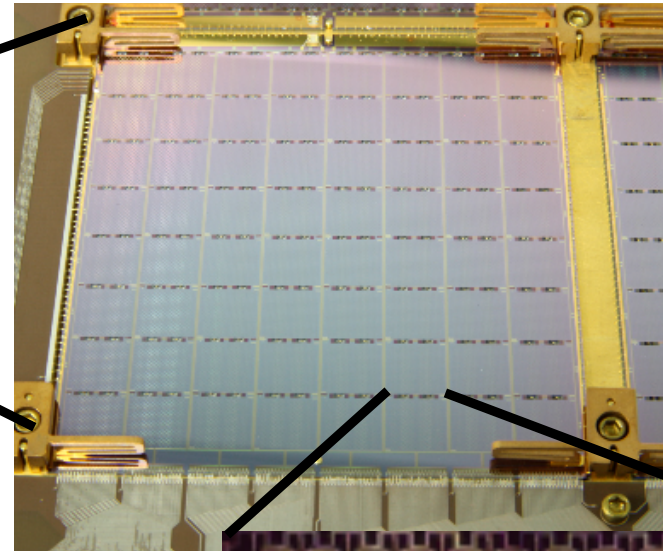
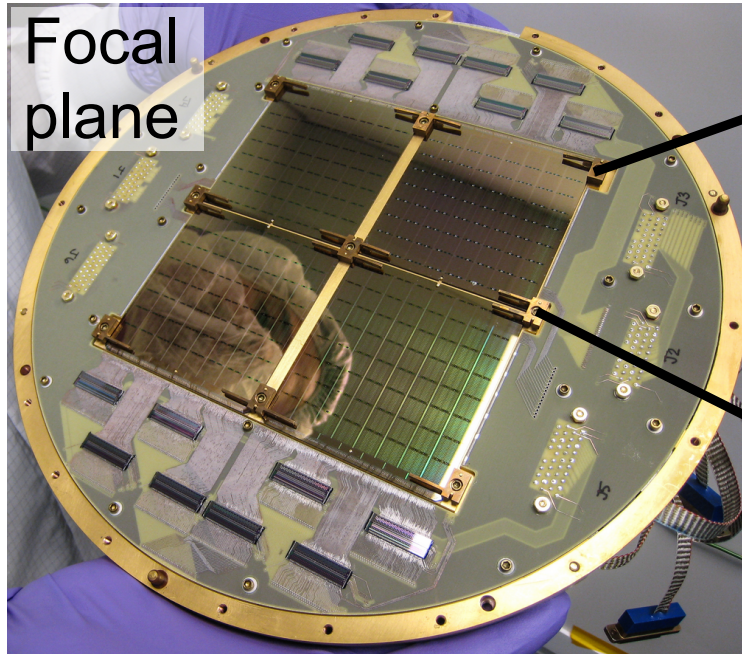
-10 -5 0 5 10
Longitude (degrees)

BICEP2/Keck Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor



Mass-produced superconducting detectors



Transition edge sensor

Slot antennas



Microstrip filters

BICEP Observational Strategy

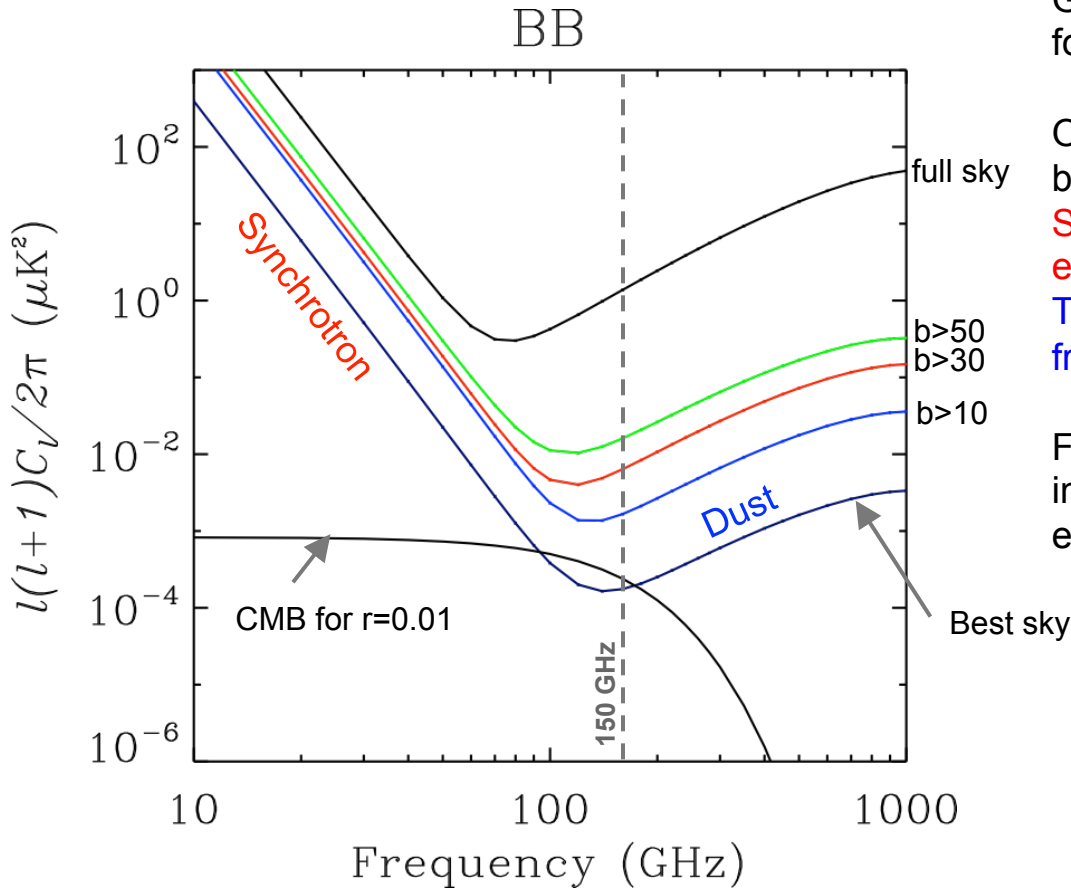
Go deep in a region of sky where galactic foregrounds are low

Observe at frequencies where the CMB is brightest with respect to:

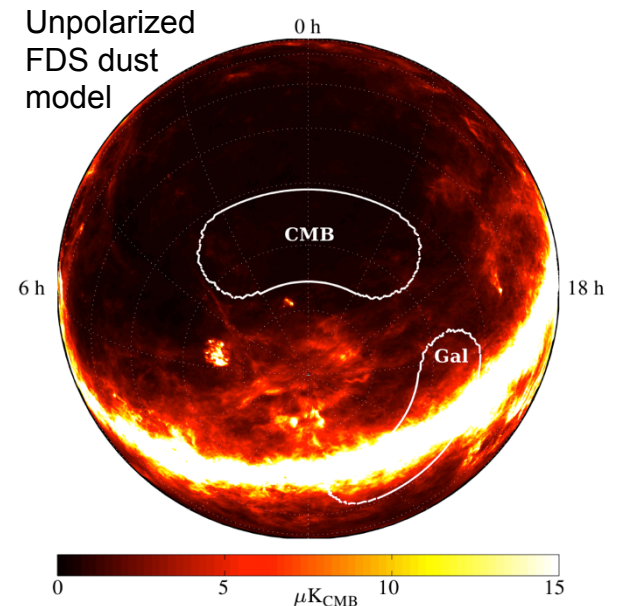
Synchrotron emission (from high energy electrons) - falls with increasing freq

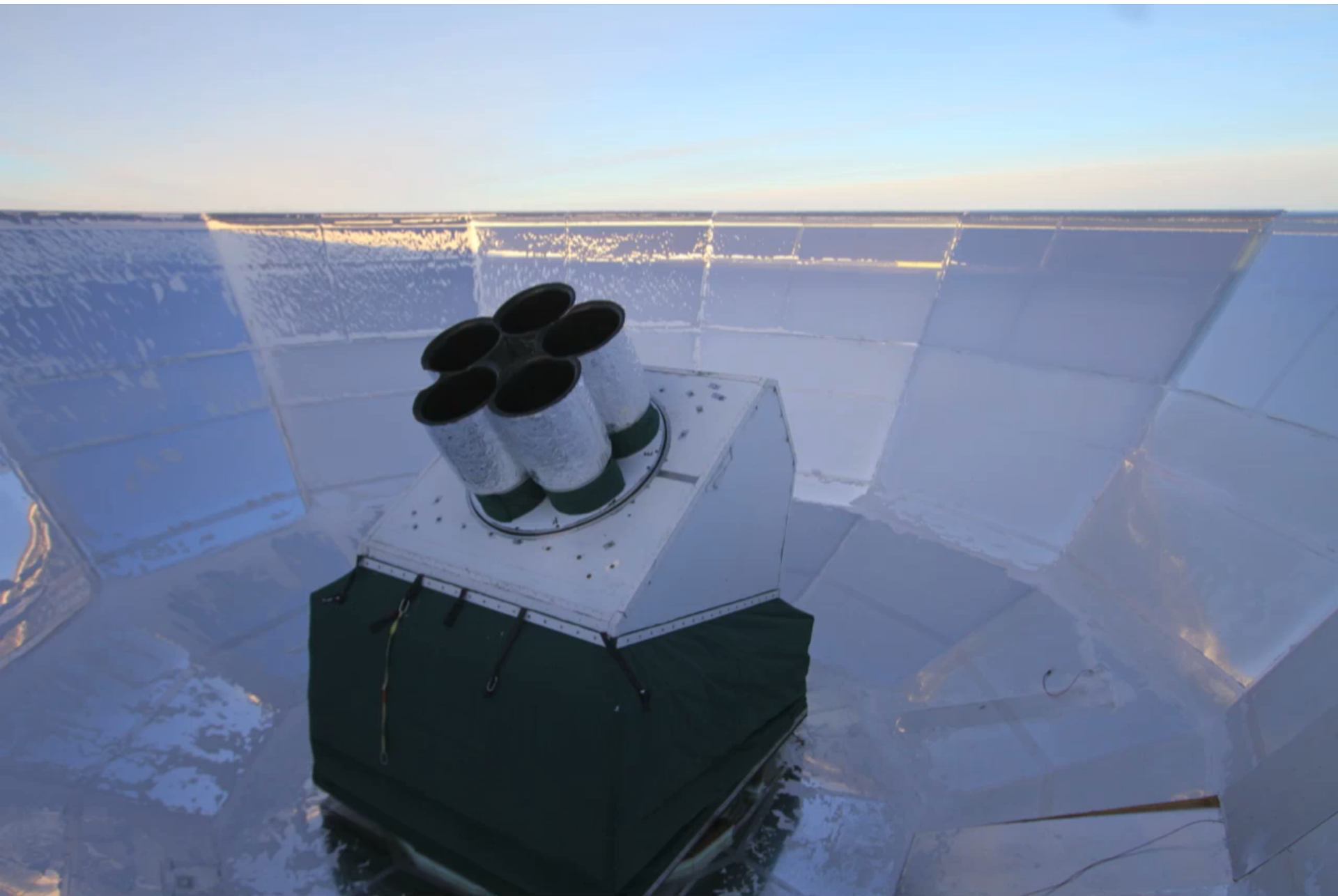
Thermal dust emission – rises with increasing freq

Foreground contamination of the B-mode power in clean regions previously projected to be equivalent to $r \leq \sim 0.01$.



From Dunkley et al arxiv/0811.3915

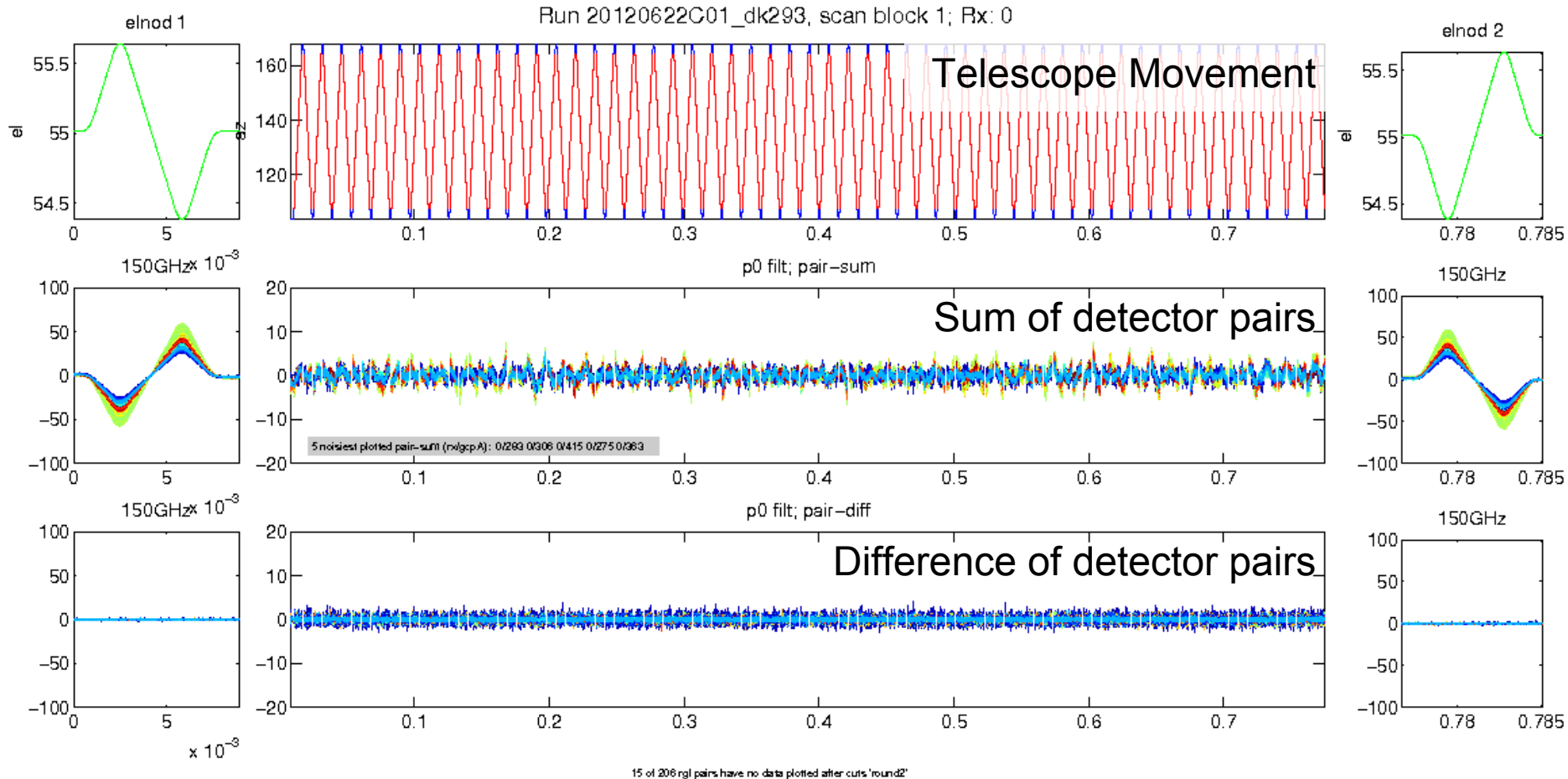




Clem Pryke for The Bicep2 Collaboration

Raw Data - Perfect Weather

Time 50 mins

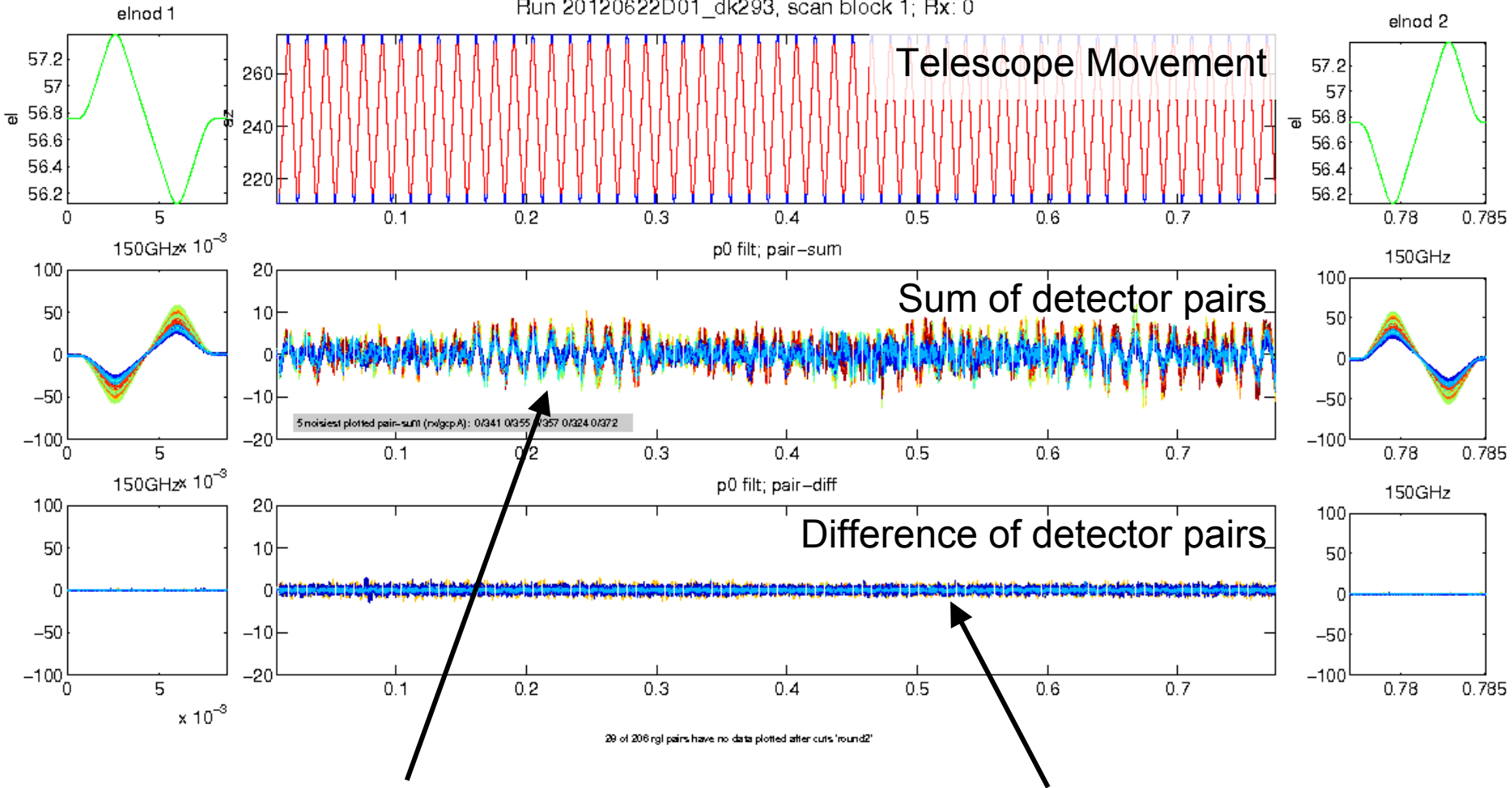


➤ Cover the whole field in 60 such scansets then start over at new boresight rotation

➤ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather

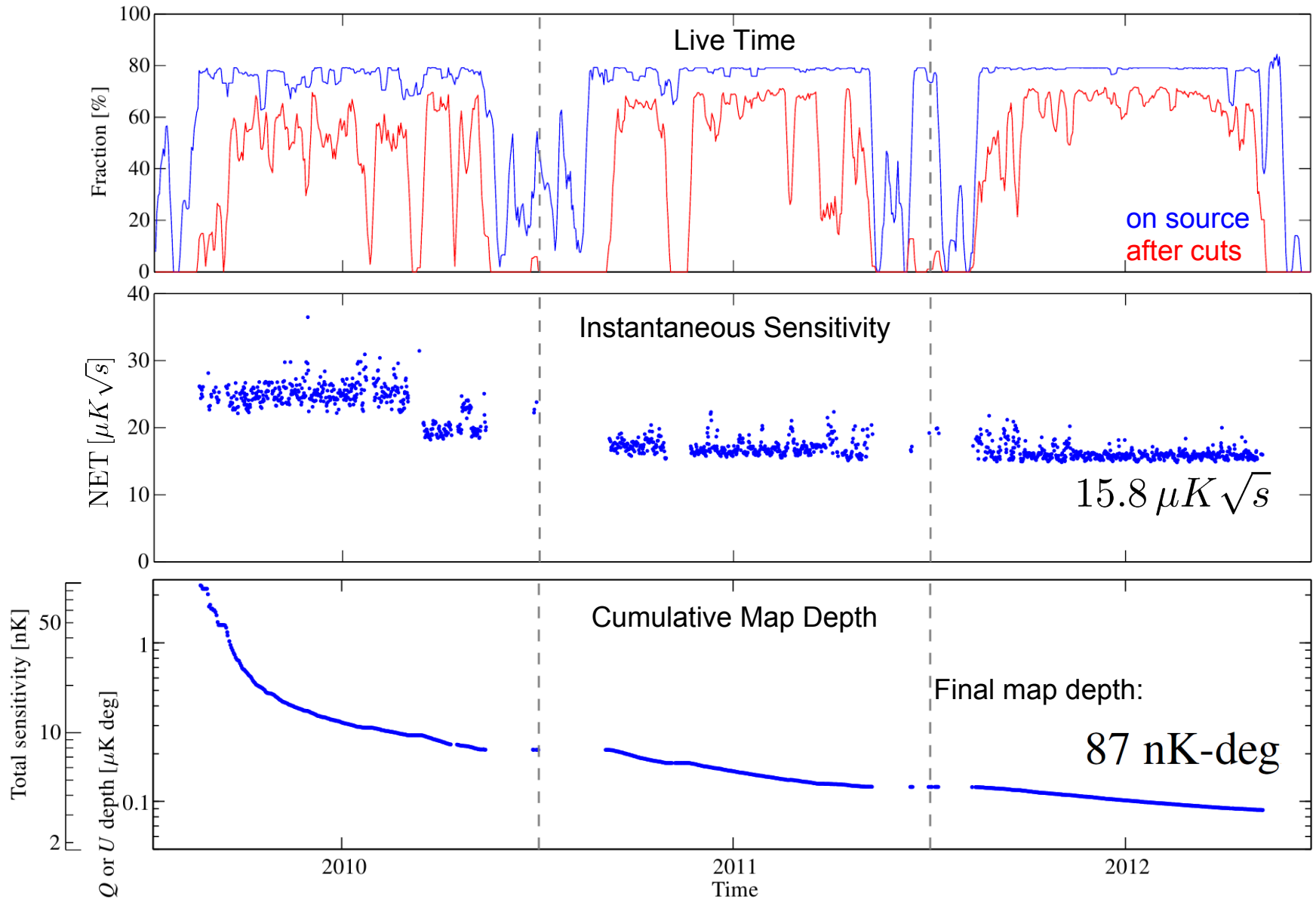
Time 50 mins

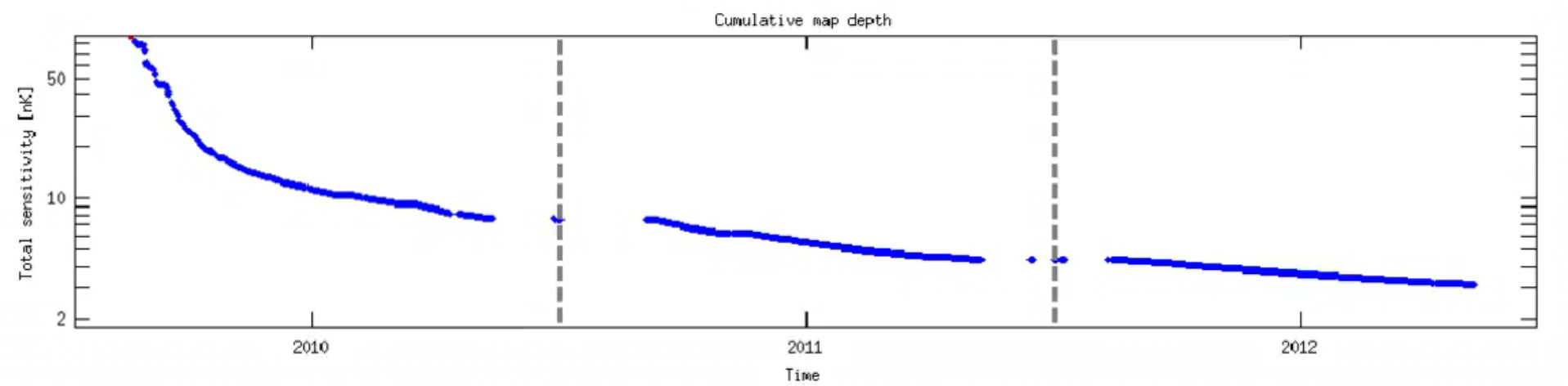
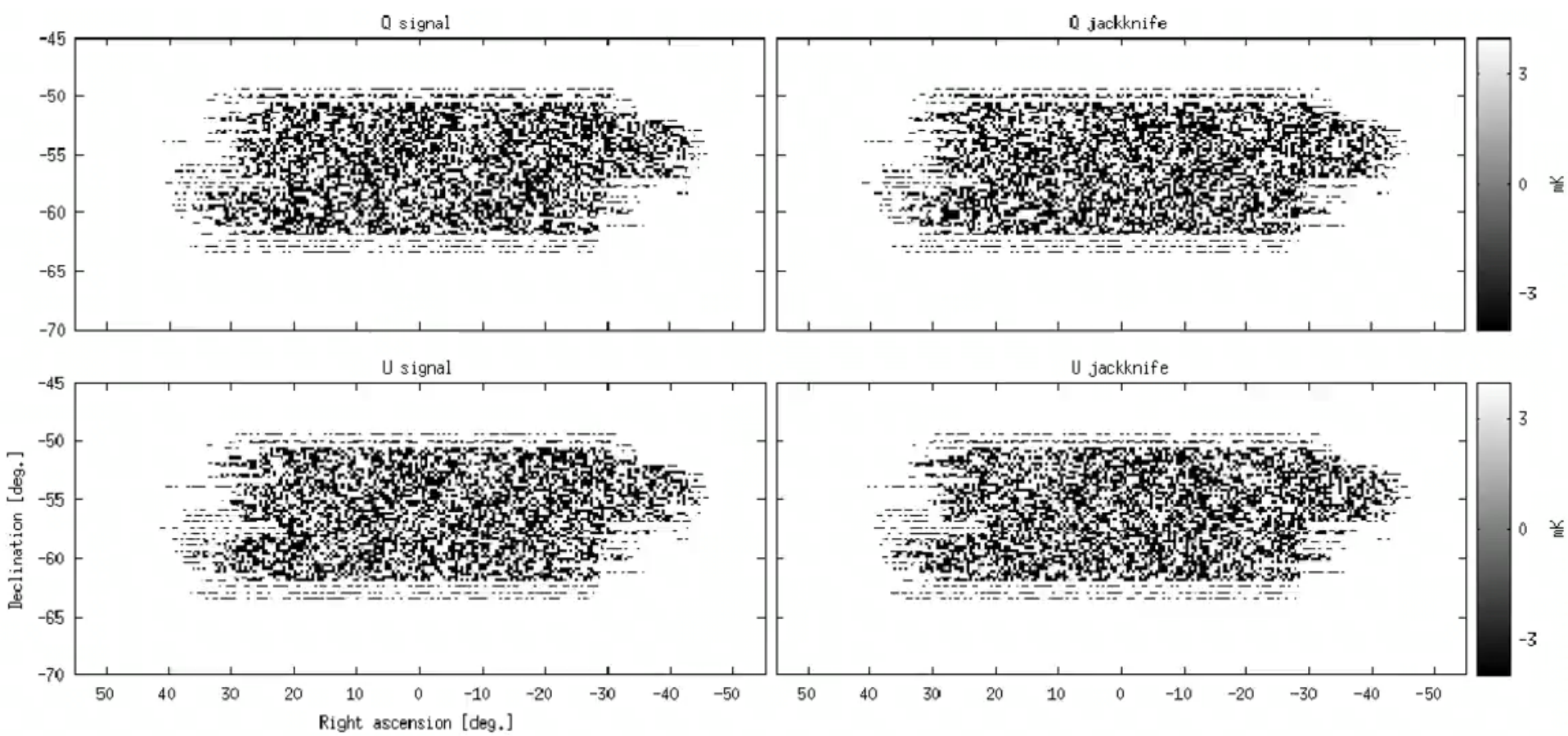


➤ Scanning over lumpy atmosphere
→ “clouds”

➤ Pair difference still clean
→ atmosphere is unpolarized

BICEP2 3-year Data Set

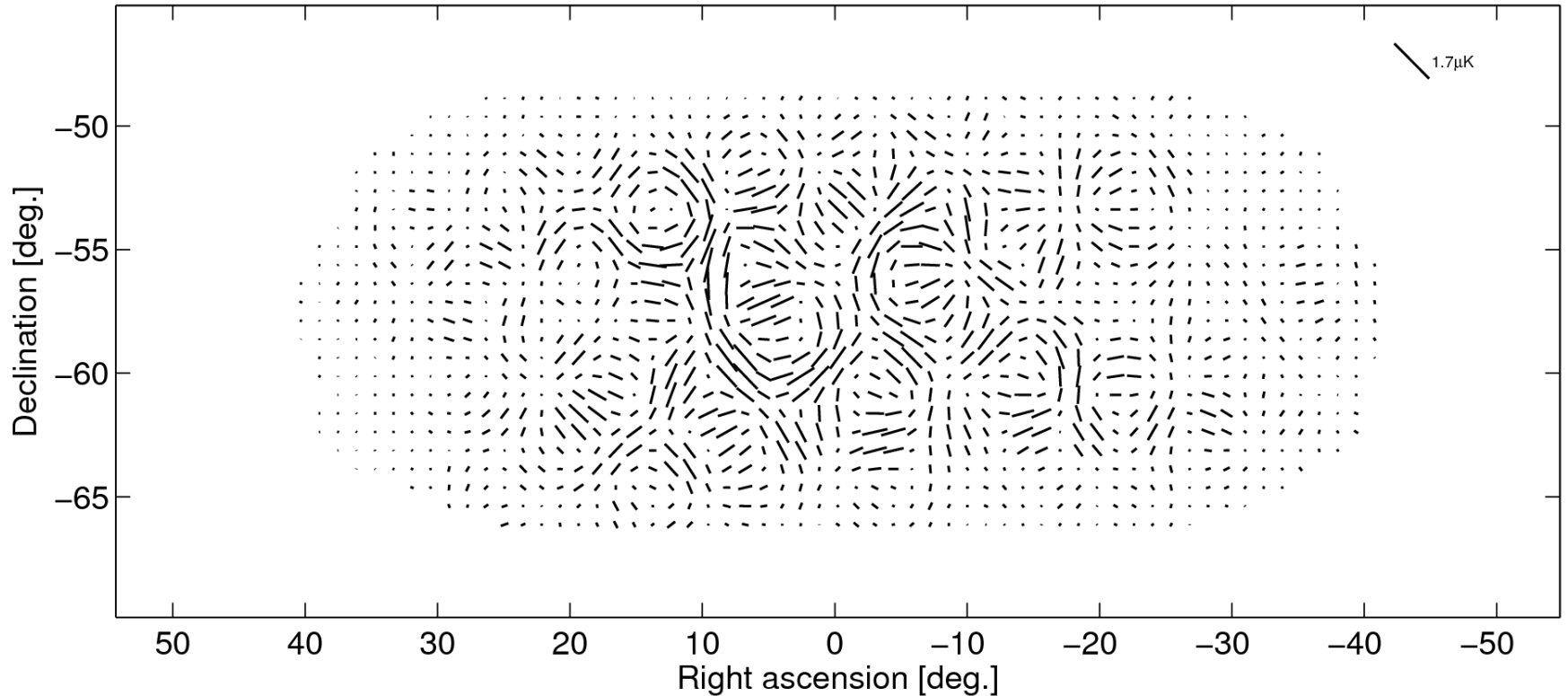




Total Polarization

BICEP2 total polarization signal

Scale: $1.7 \mu K$

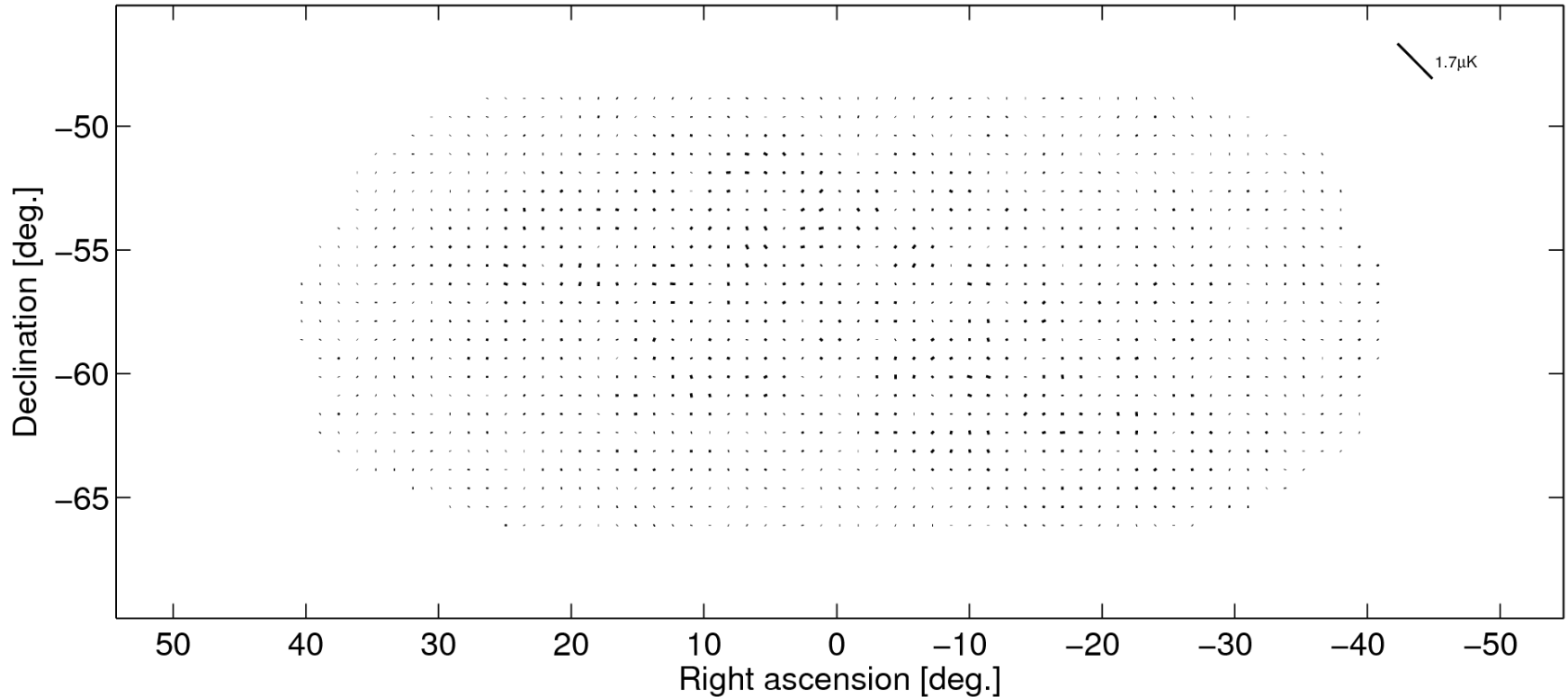


E-mode dominated pattern – no obvious curl component

B-mode Contribution

BICEP2 B-mode signal

Scale: $1.7 \mu K$

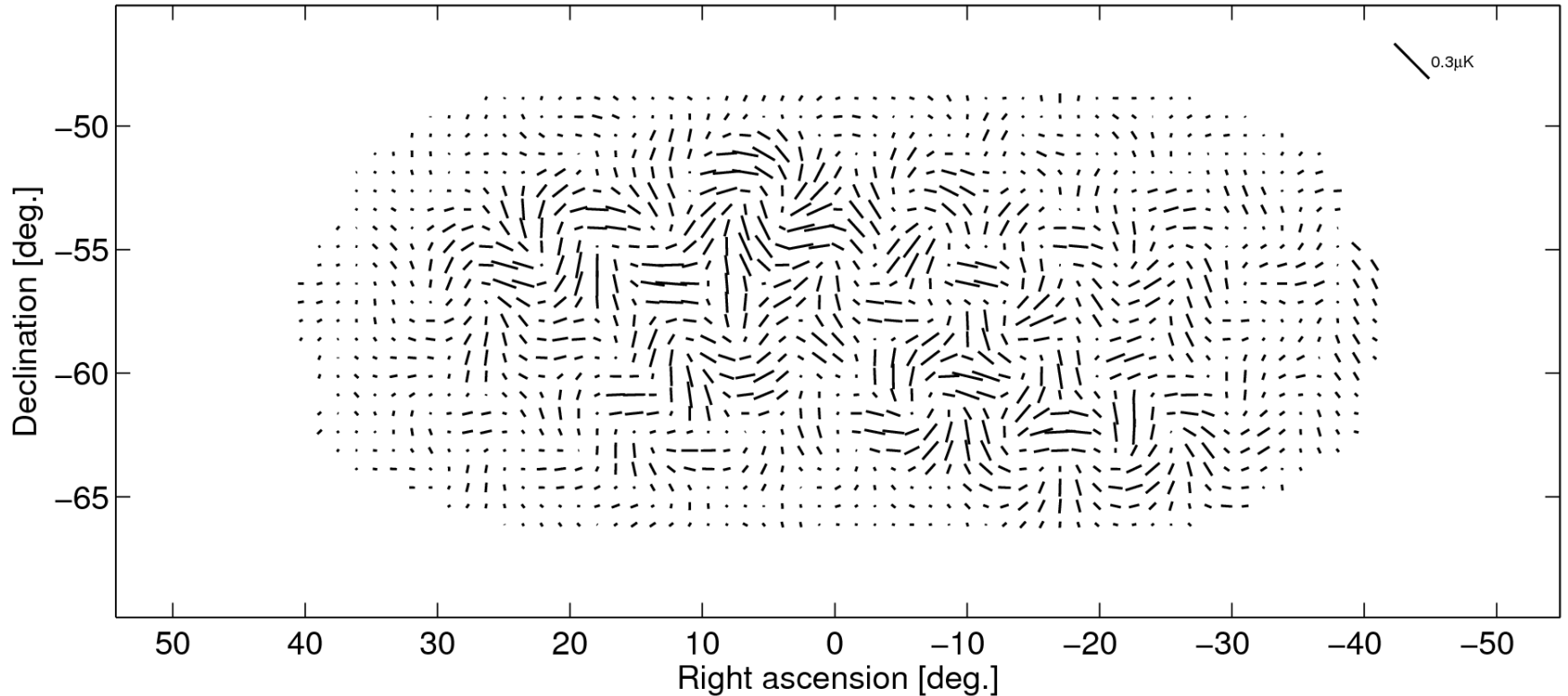


Apply purification operation to Q/U maps which leaves only B-modes (given all timestream filterings etc.)

B-mode Contribution

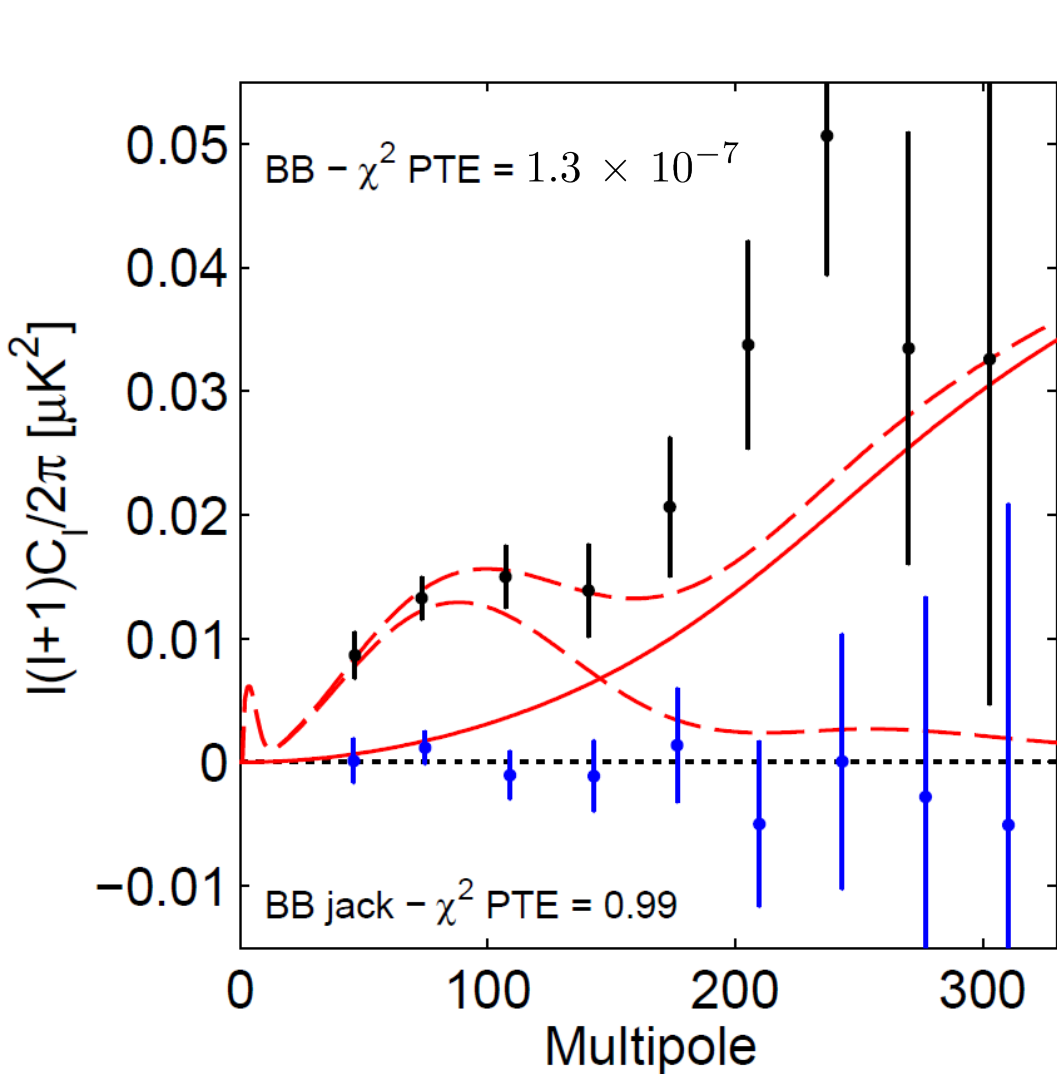
BICEP2 B-mode signal

Scale: $0.3 \mu K$



Stretch scale by factor 6 – see “swirly” B-mode

BICEP2 B-mode Power Spectrum



- B-mode power spectrum
- temporal split jackknife
- lensed- Λ CDM
- - - $r=0.2$

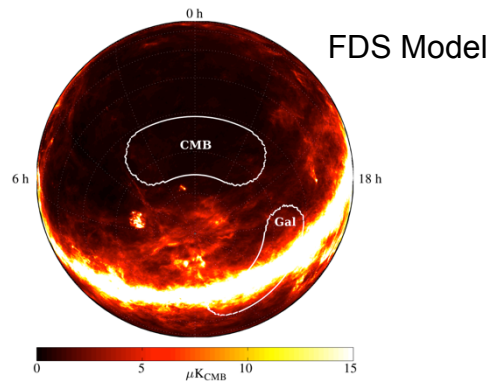
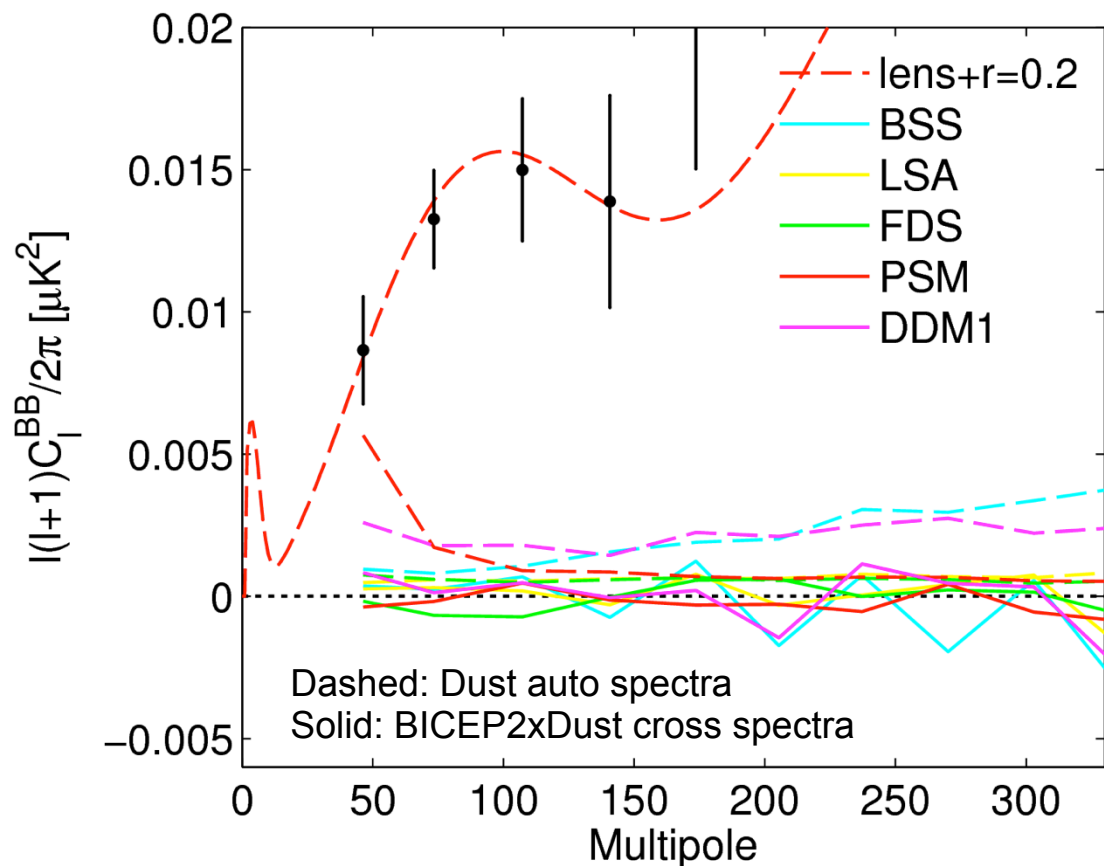
Consistent with lensing expectation at higher l . (yes – a few points are high but not excessively...)

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

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

χ^2 PTE	1.3×10^{-7}
significance	5.3σ

Pre-Planck Polarized Dust Foreground Projections



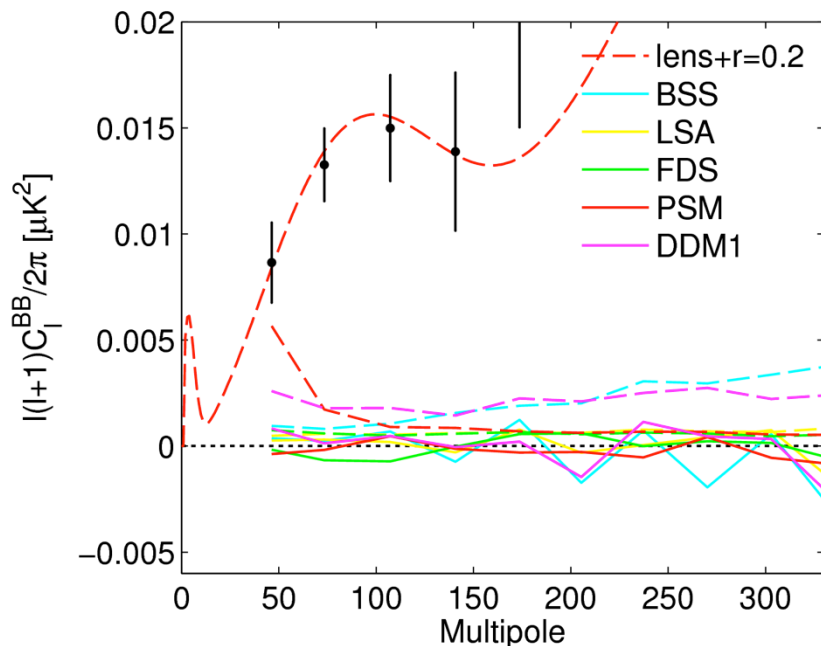
The BICEP2 region was chosen on the basis of extremely low *unpolarized* dust power.

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

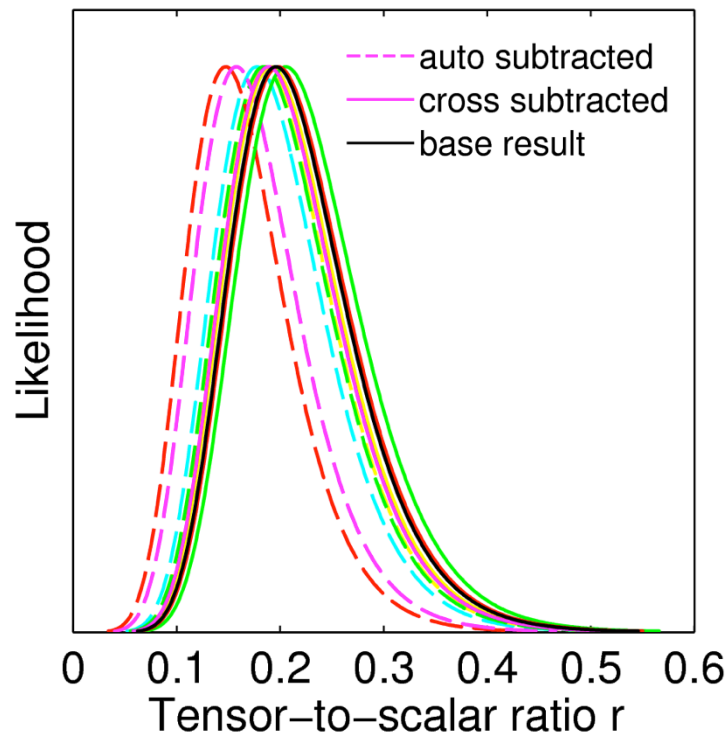
Result: All auto spectra were well below observed signal level. (and cross spectra consistent with zero.)

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:

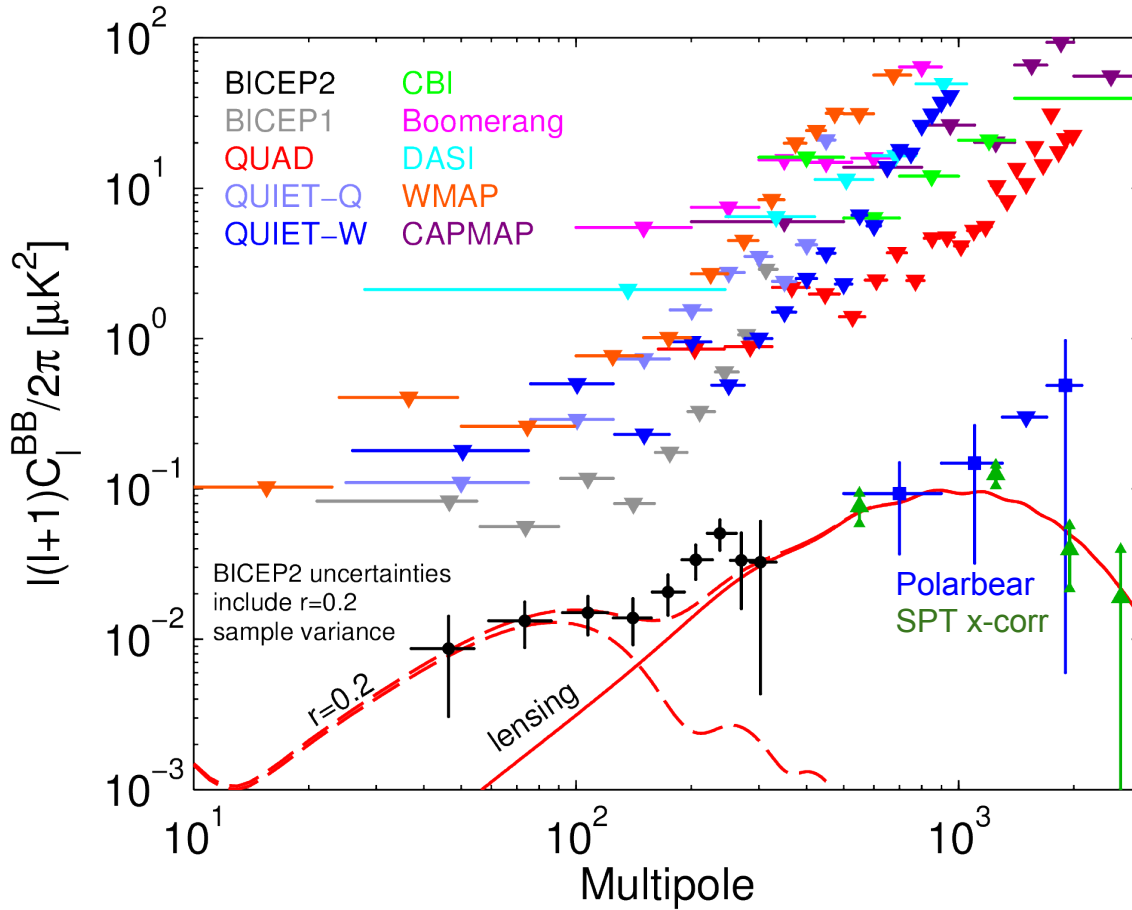


Probability that each of these models reflected reality was hard to assess.

DDM1 used all publicly available information from Planck. Polarization fraction here assumed $p = 5\%$. $p \sim 13\%$ 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- Λ CDM except:
5.2 σ 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

9:30 THE NETHERLANDS

TUESDAY

USA TODAY
A GANNETT COMPANY

NCAA TOURNAMENT
WHO HAS BEST "DANCE CARDS"
A look at matchups, player stats and teams to watch, 5C

UConn tops women's tourney
ANALYSIS, BRACKET, 4C

USA TODAY NEWS APP
Download our free app to get breaking news and more.

Putin, U.S. up ante after vote

Sanctions imposed, Ukraine, Russia ready troops as Duma considers Crimea's annexation

'Always hope' missing jet's passengers alive

As search expands to find Malaysia Airlines flight MH370, officials say they want to rule out possibility that plane is intact. **3A**

GM issues three new recalls

New recalls include oil logs, cruise system plug, involve more than 15 million vehicles. **1B**

Homework load unchanged

Despite parents' concerns about more work, study finds burden has barely changed over 20 years. **3A**

How Angela earned her big, bad wings

From 2010 to 2013, she flew 100,000 miles, but now she's flying solo. **2B**

WAVES COULD BE BIG BANG'S SMOKING GUN

Scientists of the South Pole-based special telescope to detect primordial gravitational waves — ripples in the fabric of space and time — which hold clues to the nature of the universe. The ripples have never been seen directly until now. **5A**

GM issues three new recalls

New recalls include oil logs, cruise system plug, involve more than 15 million vehicles. **1B**

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WAVES COULD BE BIG BANG'S SMOKING GUN

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The New York Times

Vol. CLXXIII — No. 56,644 — TUESDAY, MARCH 18, 2014



SEVERAL CHINESE relatives of those on the missing Malaysian plane watched news from Malaysia in Beijing. Page A8.

Lost Jet's Path Seen as Altered

By PATRICK L. WALSH and PHILIP A. SHARPE
KUALA LUMPUR, Malaysia — The flight path of the missing Malaysian Airlines plane was altered, according to a new report. The report says that the plane's path was altered after it was hit by a missile, and that the plane's path was altered after it was hit by a missile.

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBY
WASHINGTON — The first evidence that the universe was once a hot, dense ball of fire is being revealed by a new study. The study says that the universe was once a hot, dense ball of fire.

EU and US take action

More severe measures prepared

Sanctions hit Russian top brass

Putin lays out Crimea demands

Beice 2's 'ripples' add muscle to Big Bang

Prisoners in shadowy deals as death penalty drugs dwindle

States engage in shadowy deals as death penalty drugs dwindle

Prisoners in shadowy deals as death penalty drugs dwindle

States engage in shadowy deals as death penalty drugs dwindle

Prisoners in shadowy deals as death penalty drugs dwindle

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Prisoners in shadowy deals as death penalty drugs dwindle

PUTIN RECOGNIZES CRIMEA SECESSION, DEFYING THE WEST

Decree Increases Fears of Annexation by Russia, Despite More Sanctions

BY STEVE LEE AND PETER BAKER
Moscow and Chechnya, Russia — Vladimir Putin signed a decree on Monday that formally recognizes Crimea's secession from Ukraine. The move, which was widely expected, was a clear signal that Russia was prepared to annex the peninsula. The decree also authorized the transfer of Crimea's assets to the Russian government.

Mr. Putin said that he hoped that the move would lead to a peaceful resolution of the conflict. He also said that he hoped that the move would lead to a peaceful resolution of the conflict.

The move was widely expected, and it was a clear signal that Russia was prepared to annex the peninsula.

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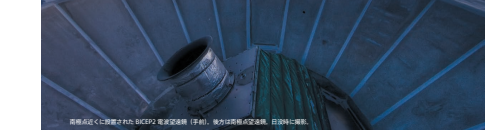
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Gravitational waves were detected by the LIGO observatory in 2015. The image shows the detector's mirrors and lasers.

宇宙急速膨張の証拠、検出される

Telescope captures view of gravitational waves

By CNN 2014年3月18日 09時 04分 507 (2014-03-18)

宇宙が急速に膨張していることを示す証拠として、重力波の検出が報告された。重力波は、時空の歪みを伝える波であり、宇宙の急速な膨張を示している。

重力波は、時空の歪みを伝える波であり、宇宙の急速な膨張を示している。重力波の検出は、宇宙の急速な膨張を示している。

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PHYSICAL REVIEW LETTERS

Articles published week ending 20 JUNE 2014

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PHYSICAL REVIEW LETTERS

Volume 112, Number 24

Financial services advertisement featuring a man in a suit and a cityscape. The advertisement includes a video player and various icons.

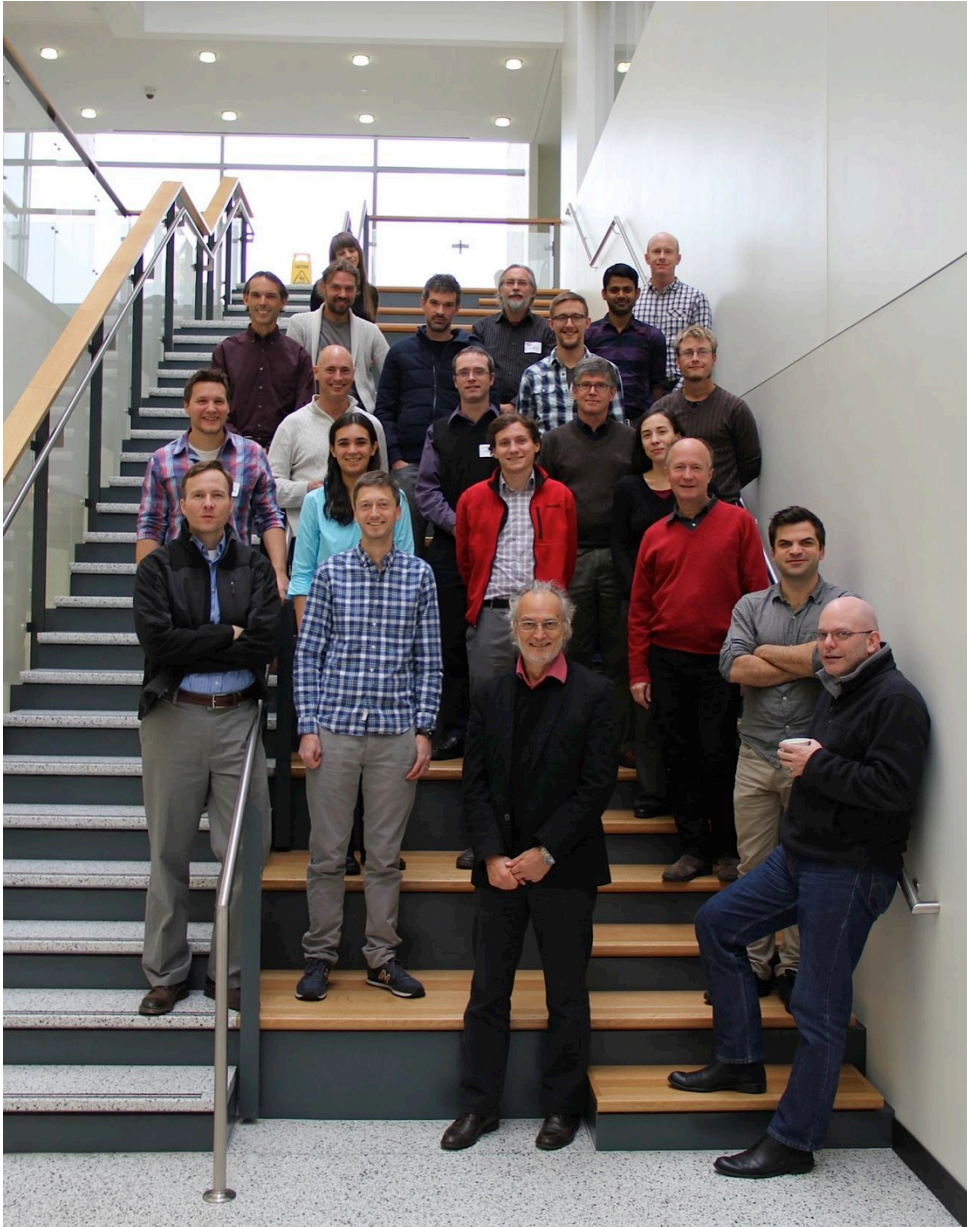
The Financial Times newspaper advertisement. The cover features the headline 'The Apple alumni Steve Jobs' acolytes are taking over the world, Page 8' and 'EU and US take action More severe measures prepared Putin lays out Crimea demands Sanctions hit Russian top brass'.

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...

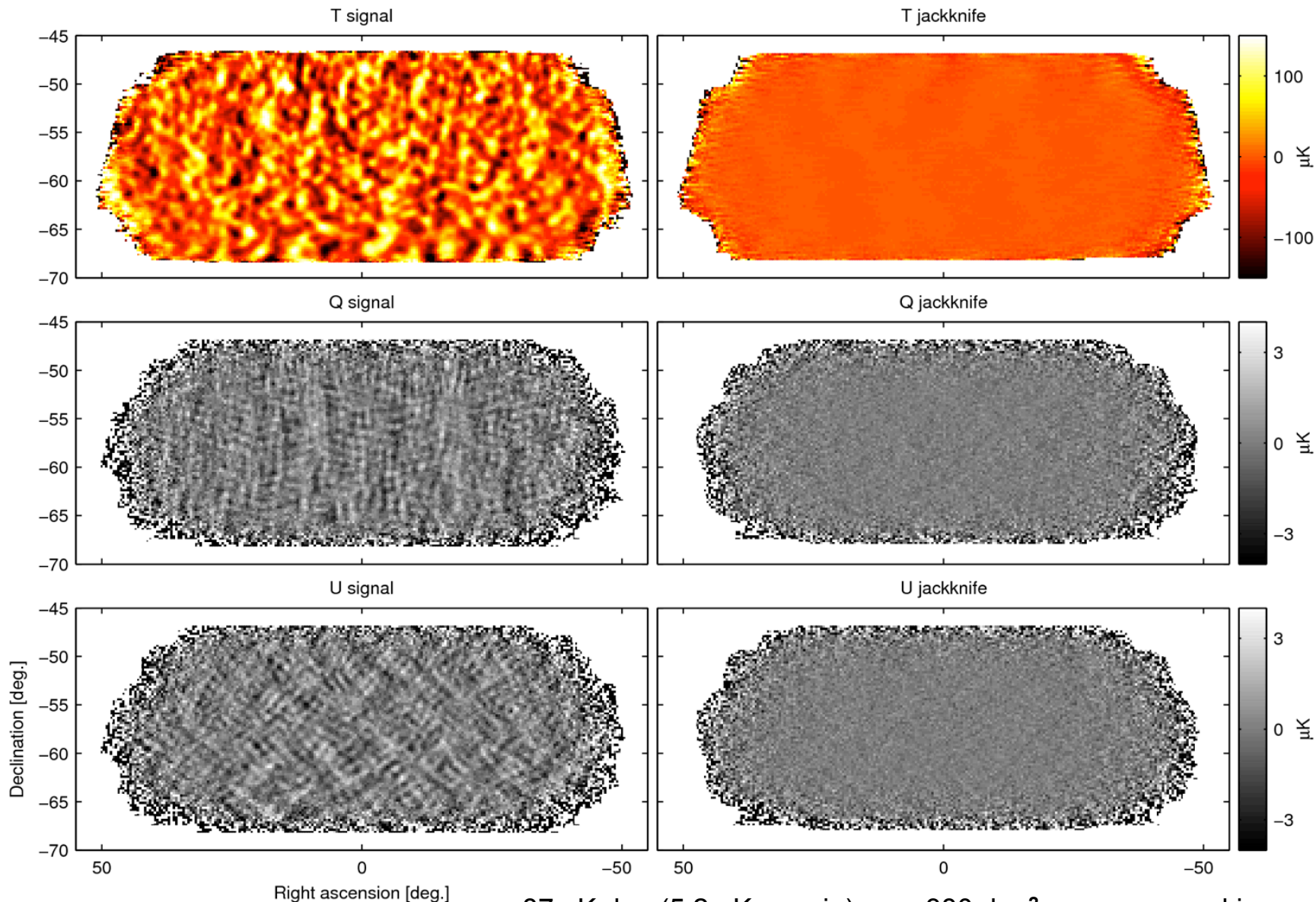
Joint analysis of BICEP2/Keck and Planck data



- 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](https://arxiv.org/abs/1502.00612) (and published in PRL)

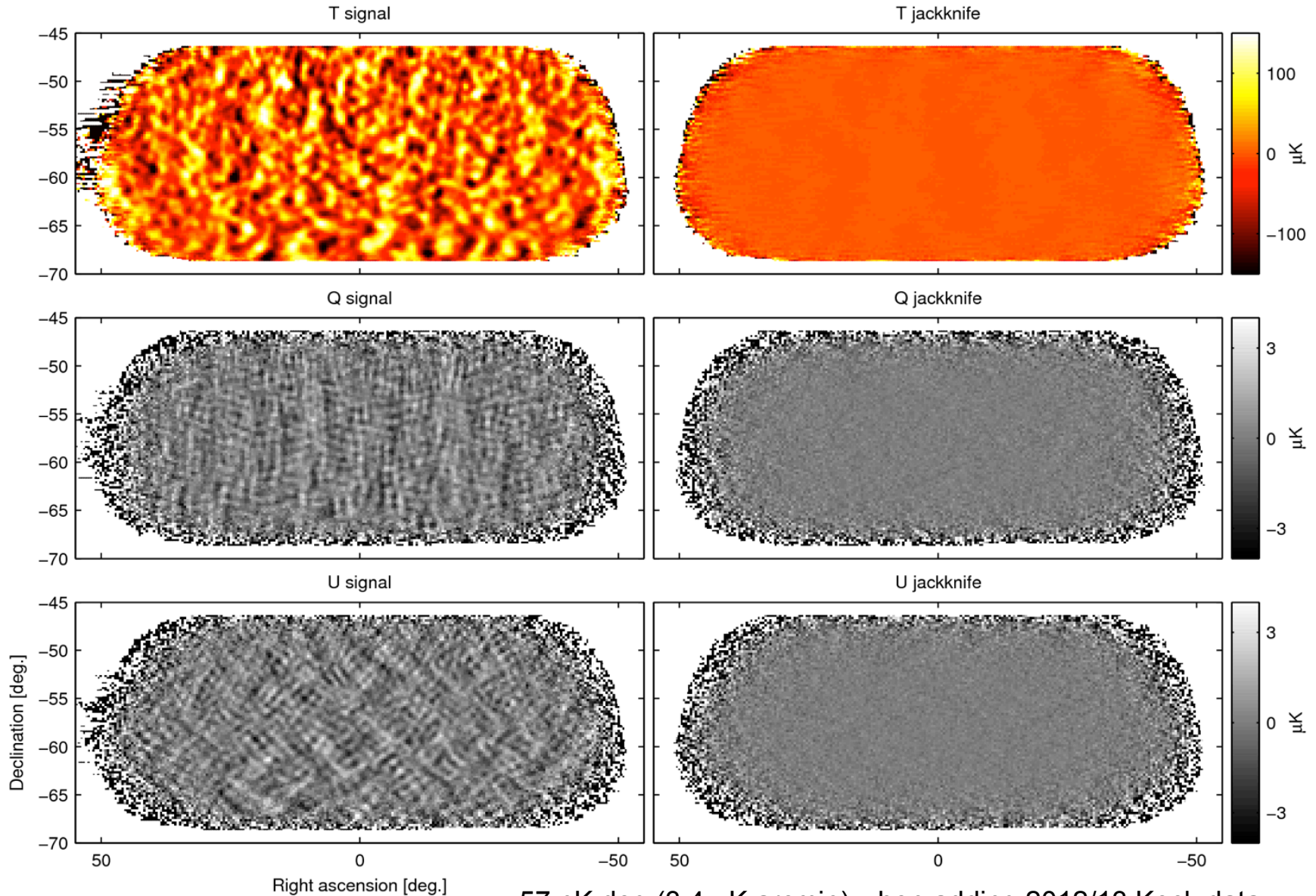
← BICEP2/Keck/Planck meeting at University of Minnesota 5 Nov 2014

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



87 nK deg ($5.2 \mu\text{K arcmin}$) over 380 deg^2 area - as used in BICEP2 paper

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



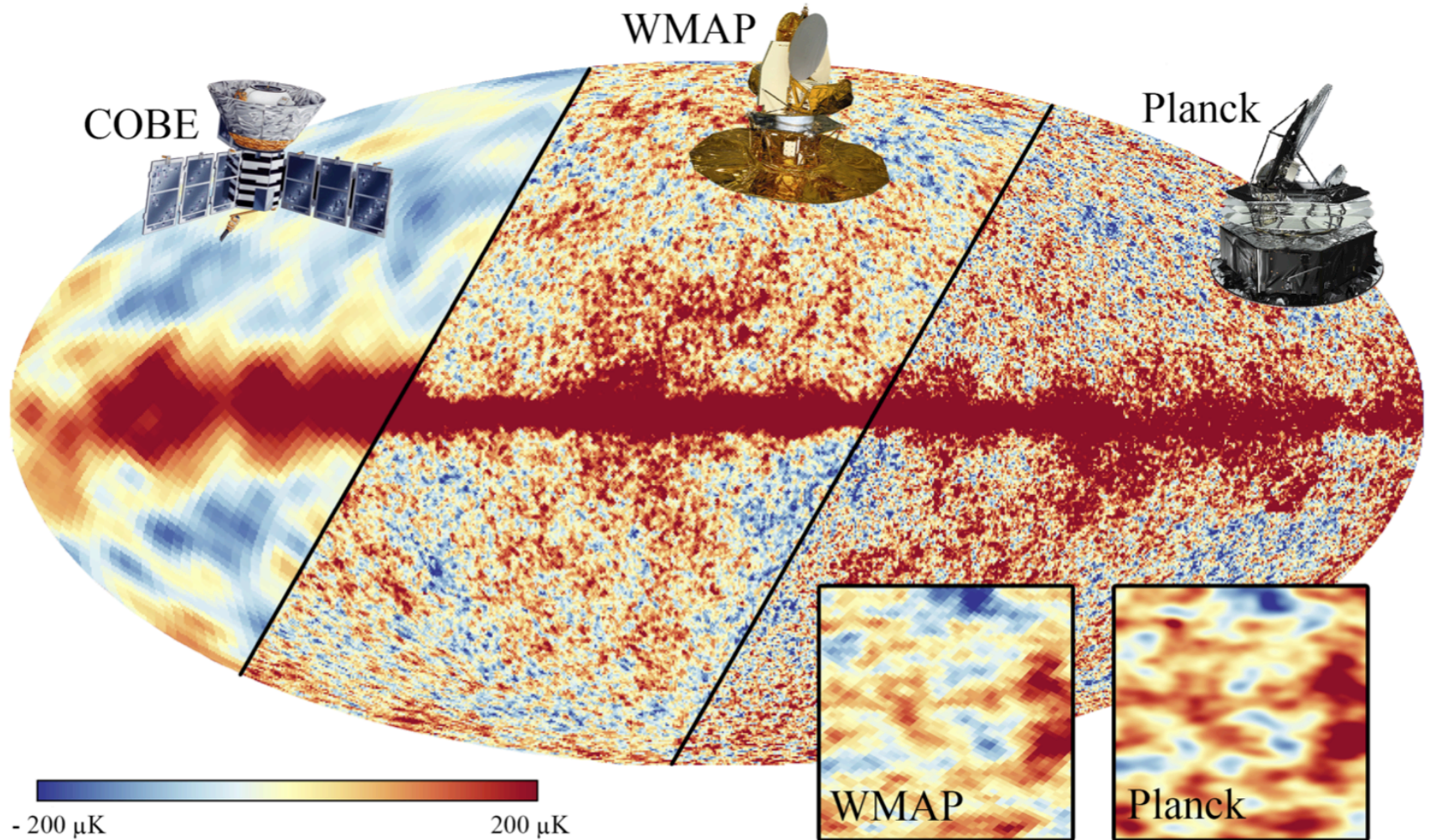
57 nK deg (3.4 μK arcmin) when adding 2012/13 Keck data - by far the deepest maps ever made - but apodized and filtered...

Planck

WMAP

Planck

COBE



- 200 μ K

200 μ K

WMAP

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

30 GHz

44 GHz

70 GHz

100 GHz

143 GHz

217 GHz

353 GHz

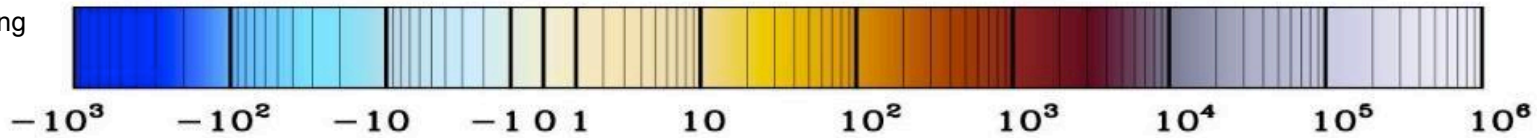
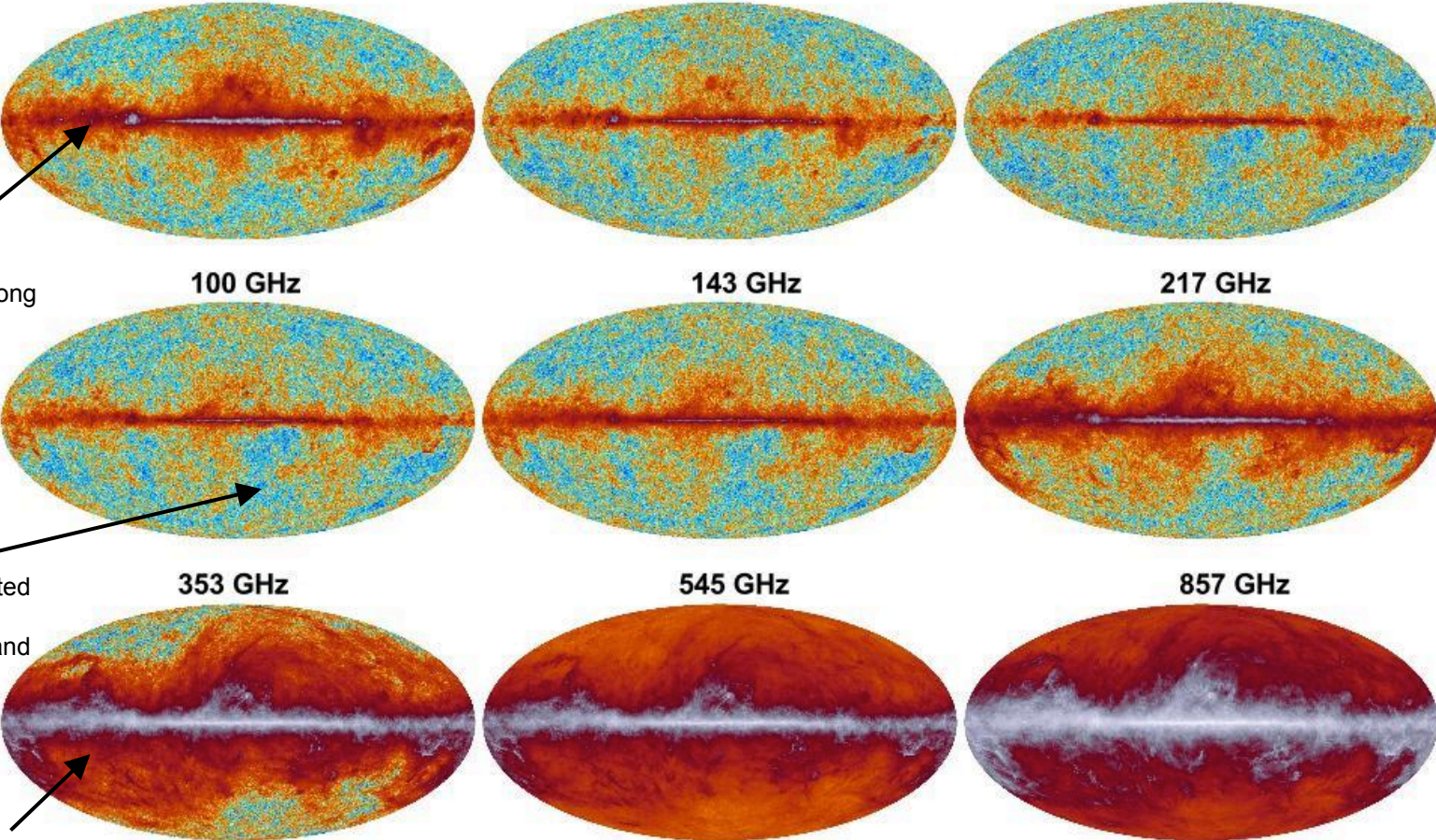
545 GHz

857 GHz

Galactic
synchrotron
emission strong
at low
frequencies

CMB most
uncontaminated
at mid
frequencies and
high latitude

Galactic dust
emission strong
at high
frequencies



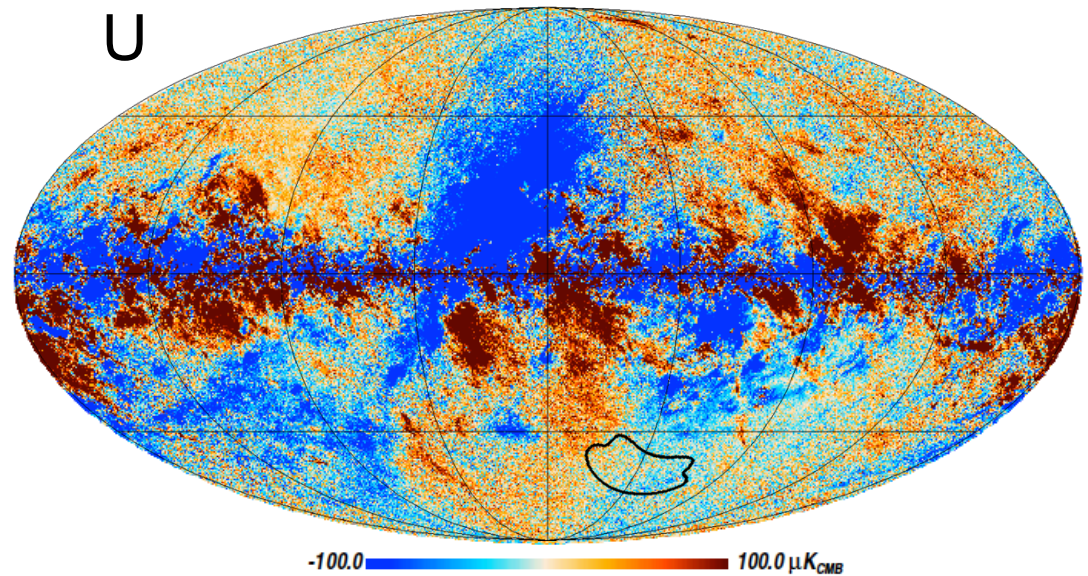
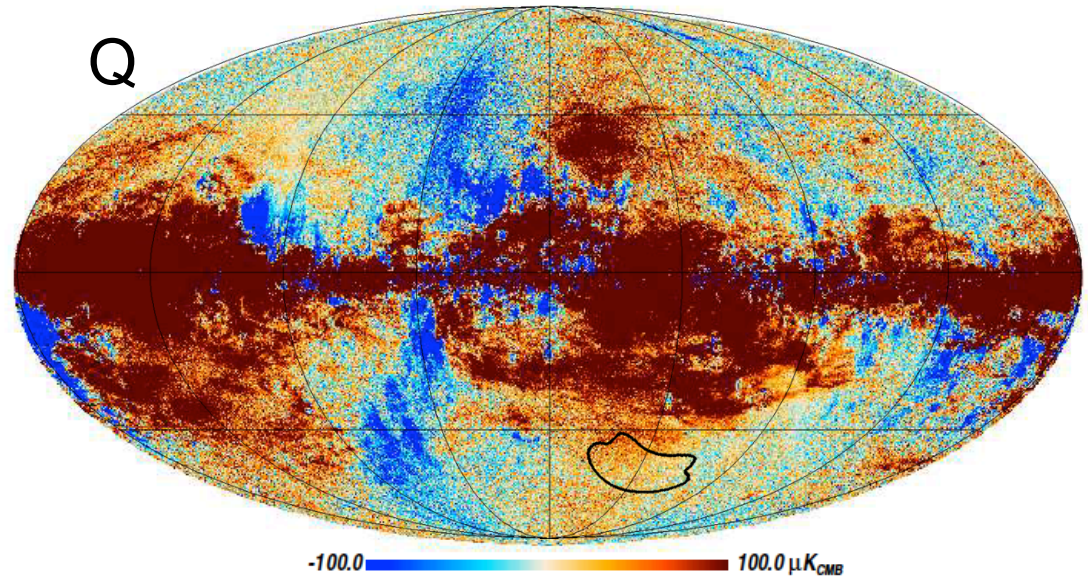
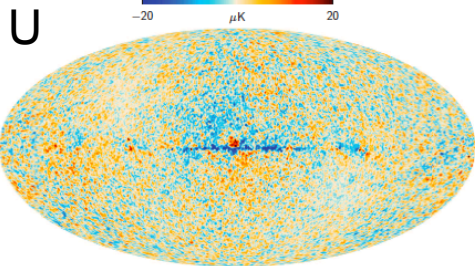
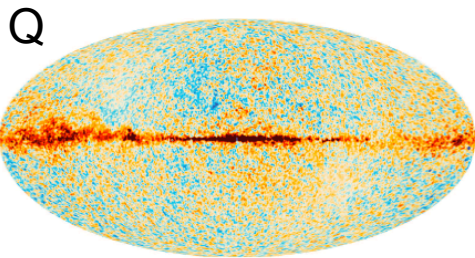
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

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

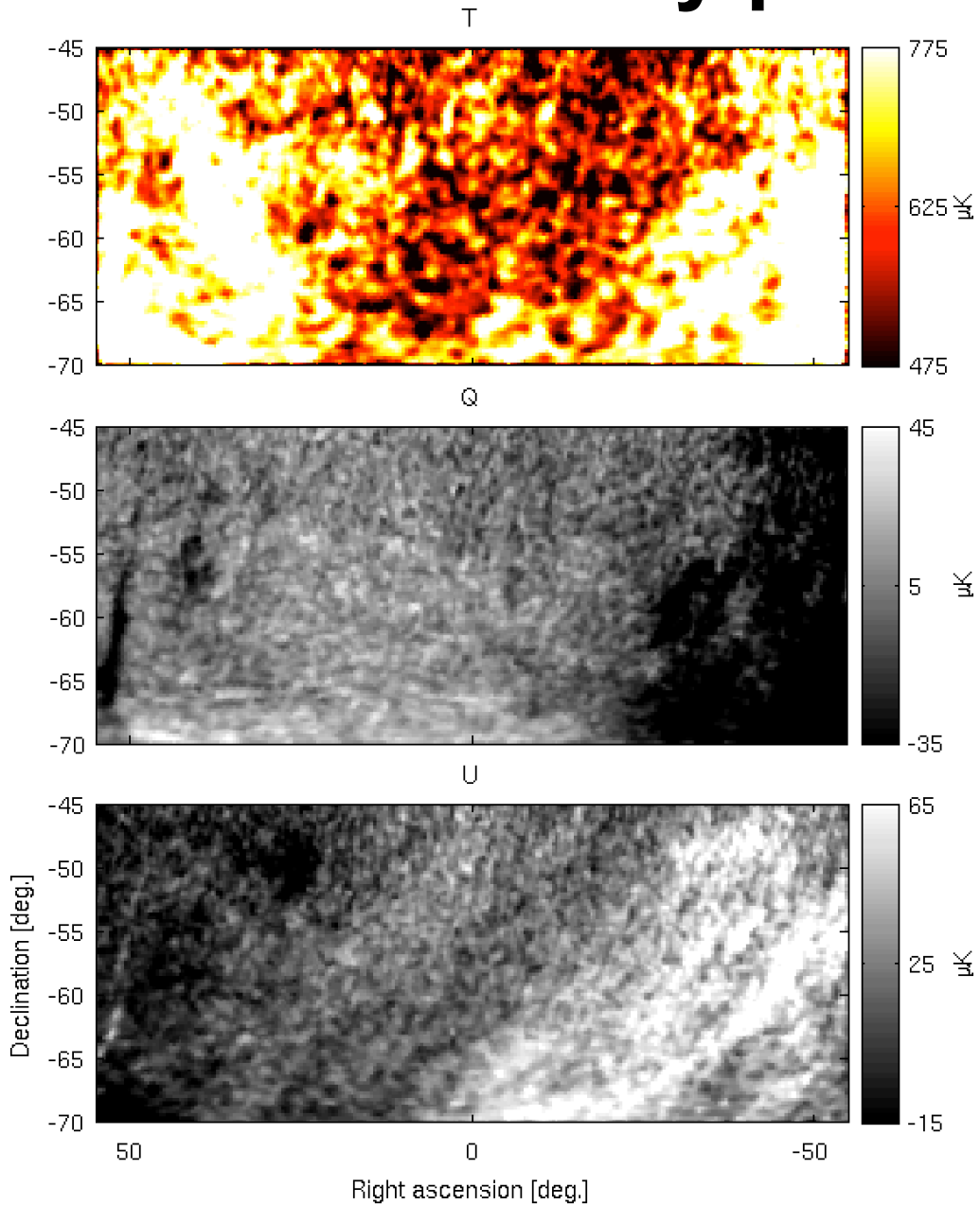
Planck 353 GHz full sky maps in polarization

- 353 GHz polarized maps are dominated by Galactic dust emission

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



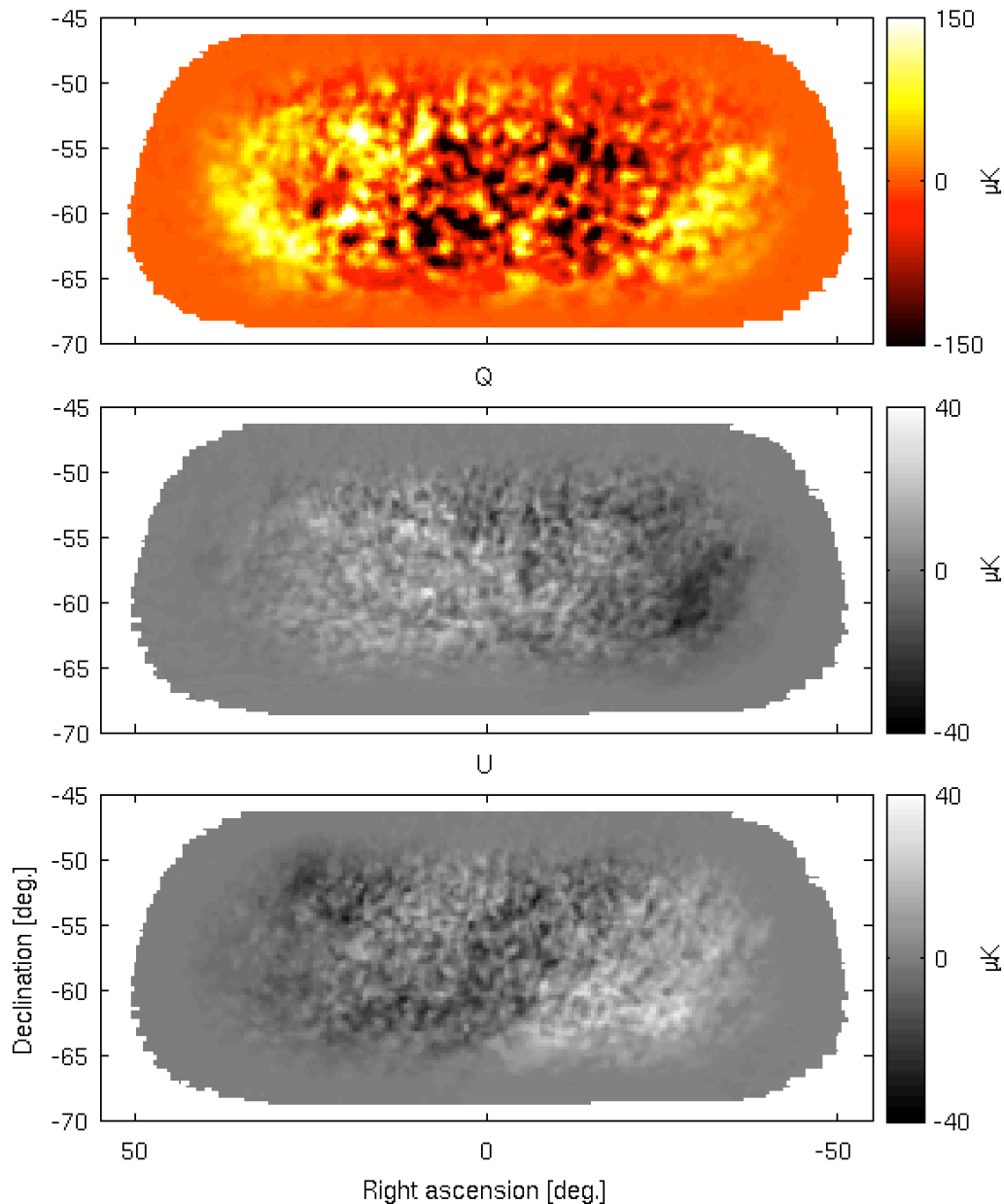
Zoom in on BK sky patch...



Planck 353GHz maps
in BICEP2/Keck sky
region

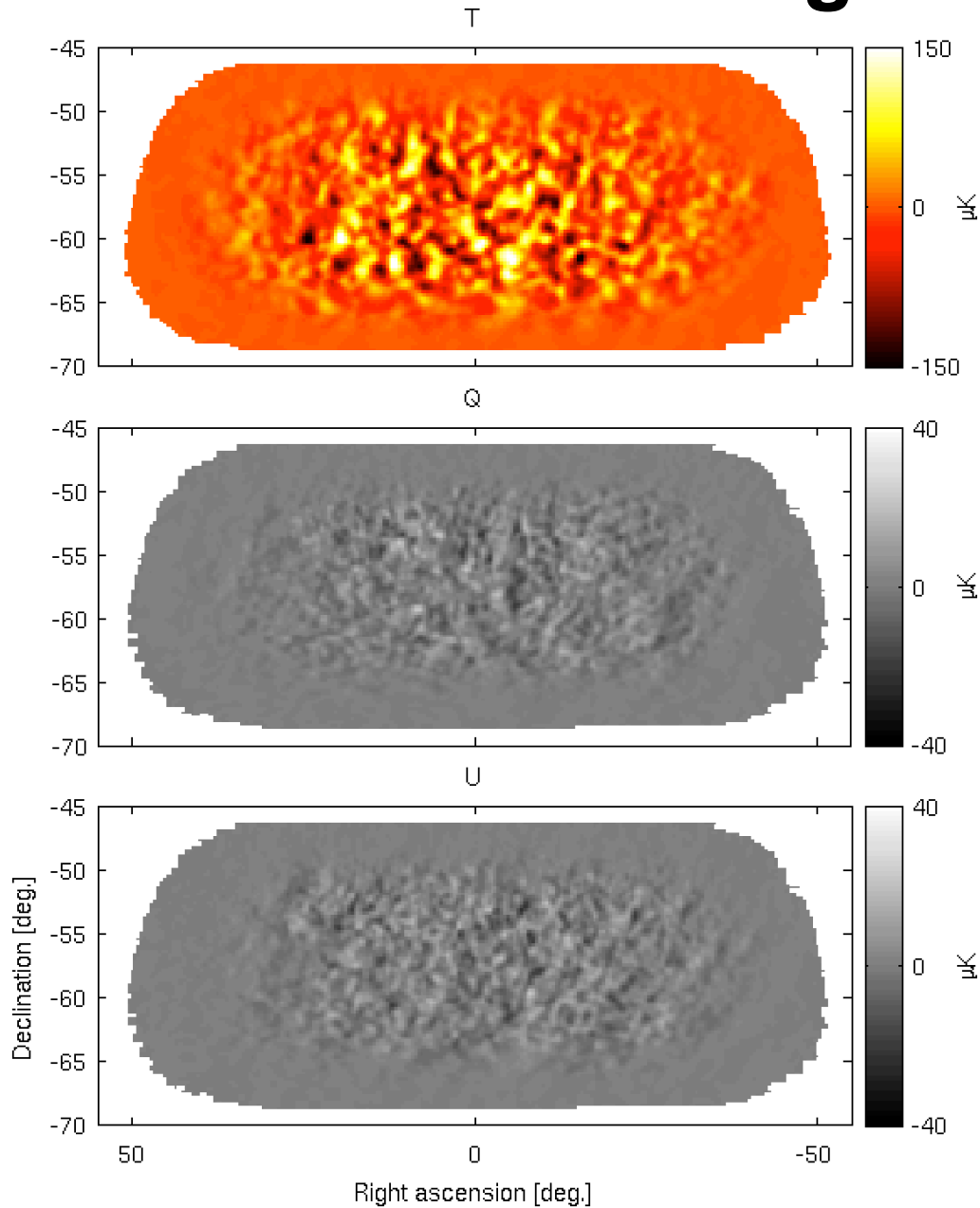
(re-smoothed to
BICEP2/Keck beam
size)

...apply BK apodization...



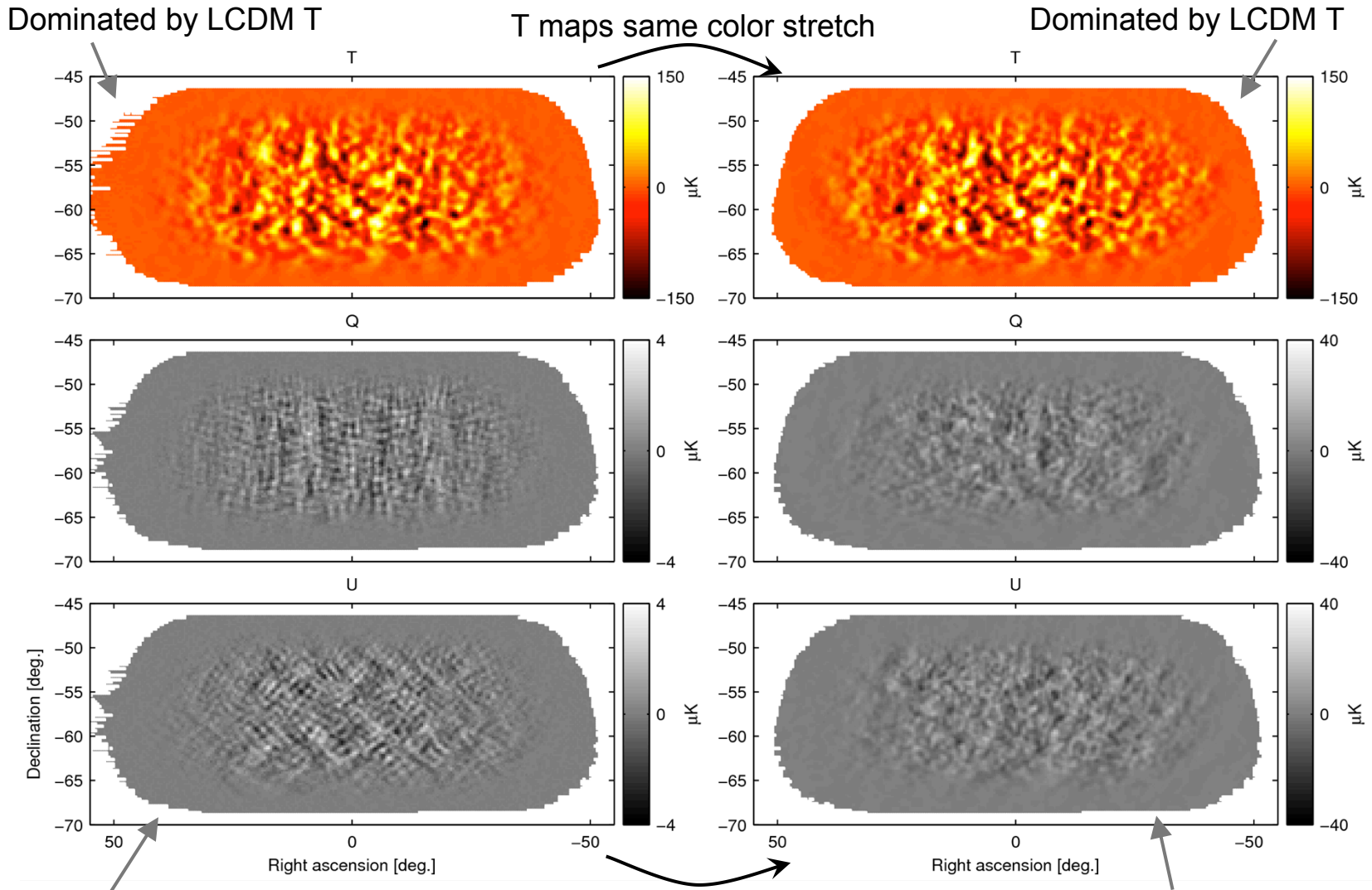
Planck 353GHz maps
in BICEP2/Keck sky
region with mean
subtracted and
apodization mask
applied

...and BK filtering



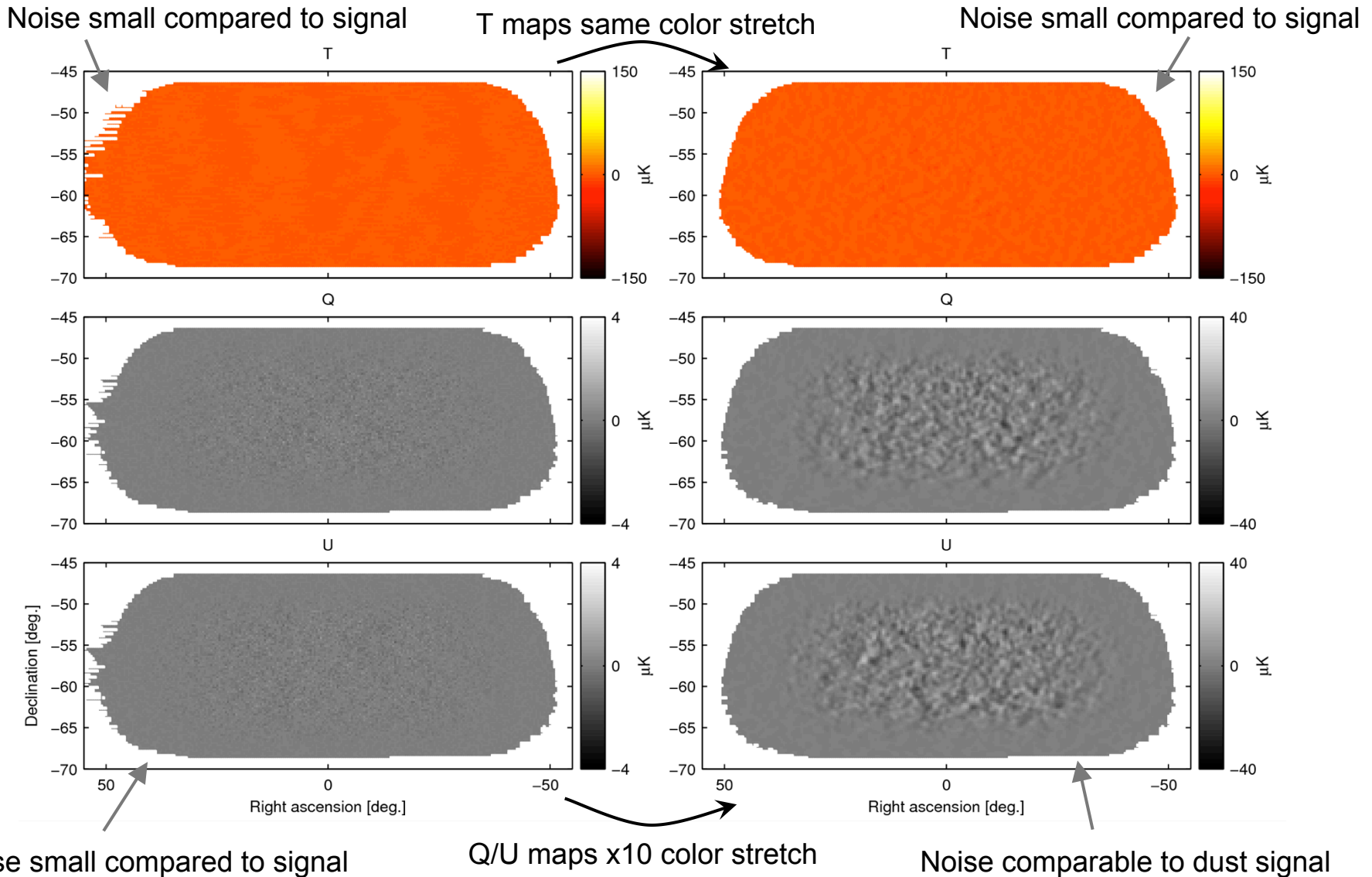
Planck 353GHz maps in BICEP2/Keck sky region with full simulation of observation and filtering applied plus apodization

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



The Real Data

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

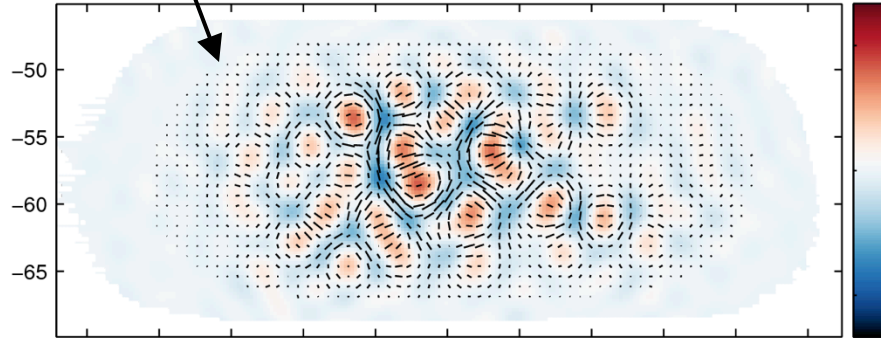


A Noise Simulation

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

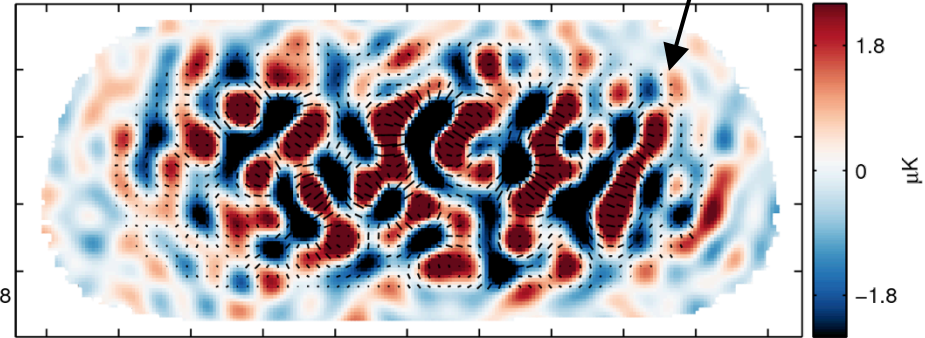
Dominated by LCDM E-modes

BK E

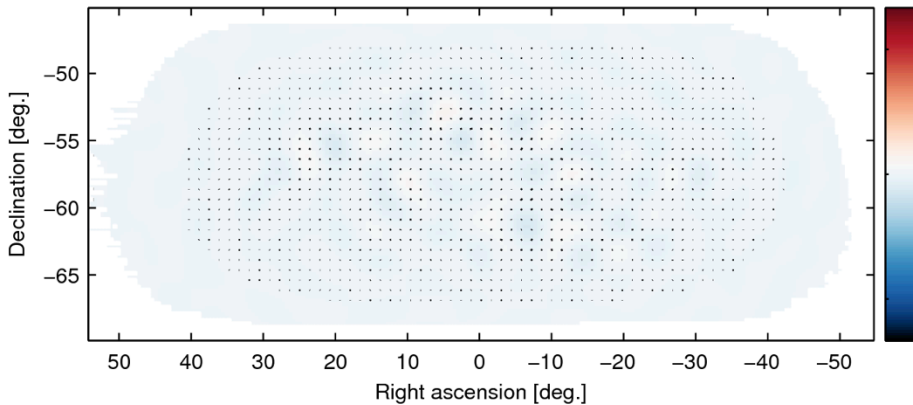


Dominated by noise & dust

P353 E

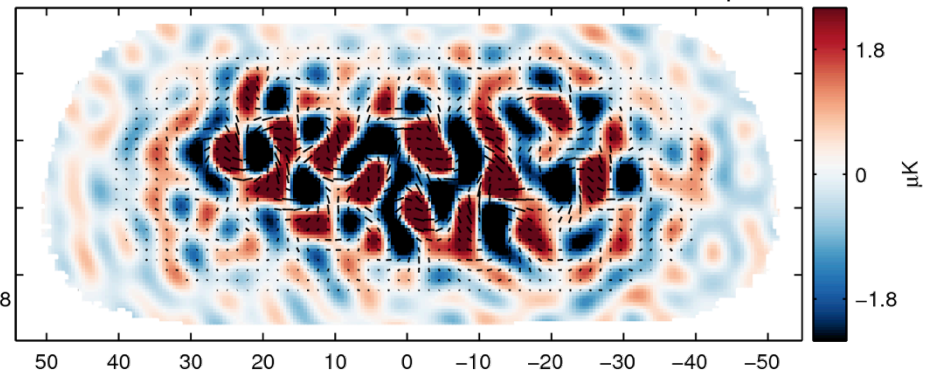


BK B



P353 B

Full Planck map



E-modes and B-modes filtered to range $l=50-120$

all maps shown with the same color stretch

The Real Data

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

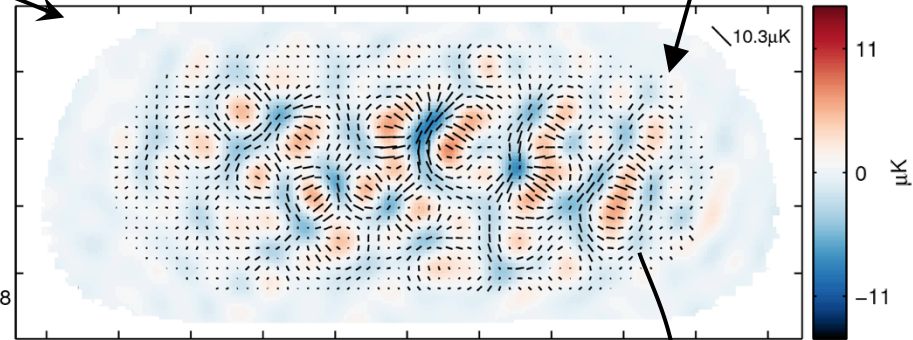
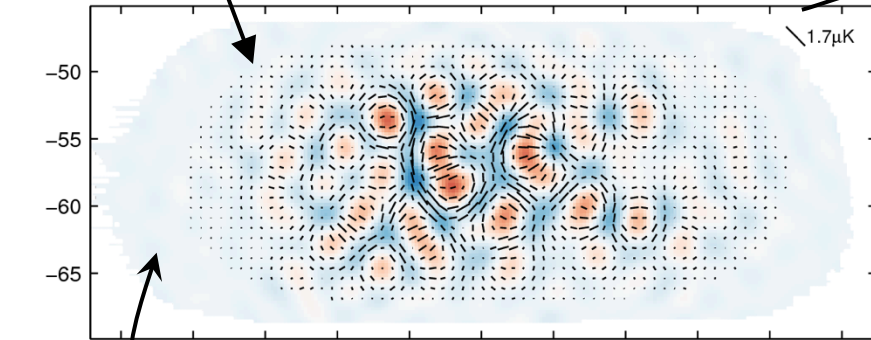
Dominated by LCDM E-modes

BK E

x 6

Dominated by noise & dust

P353 E

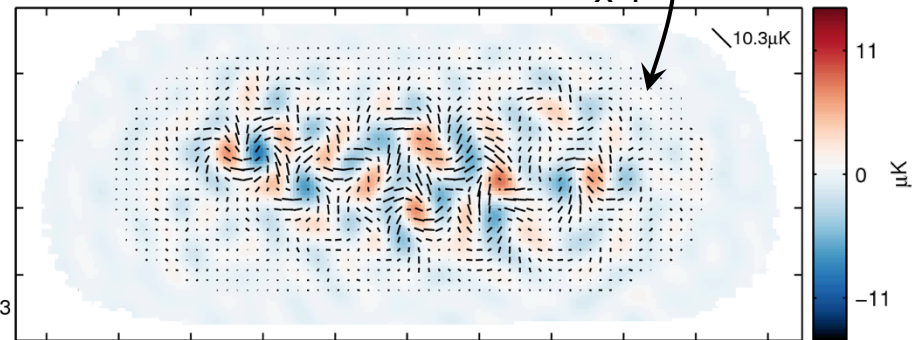
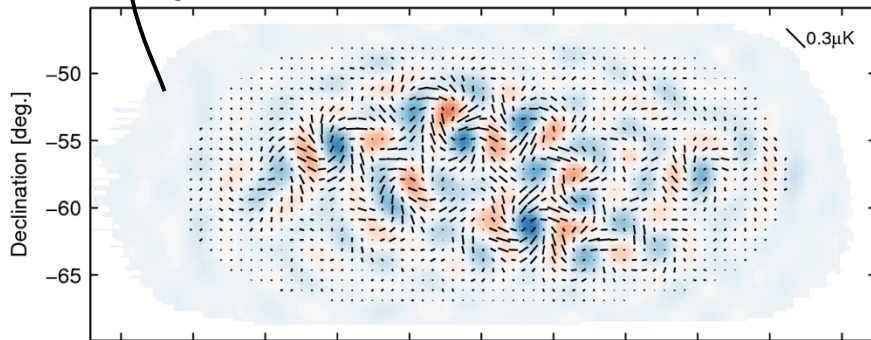


x 6

BK B

P353 B

x 1

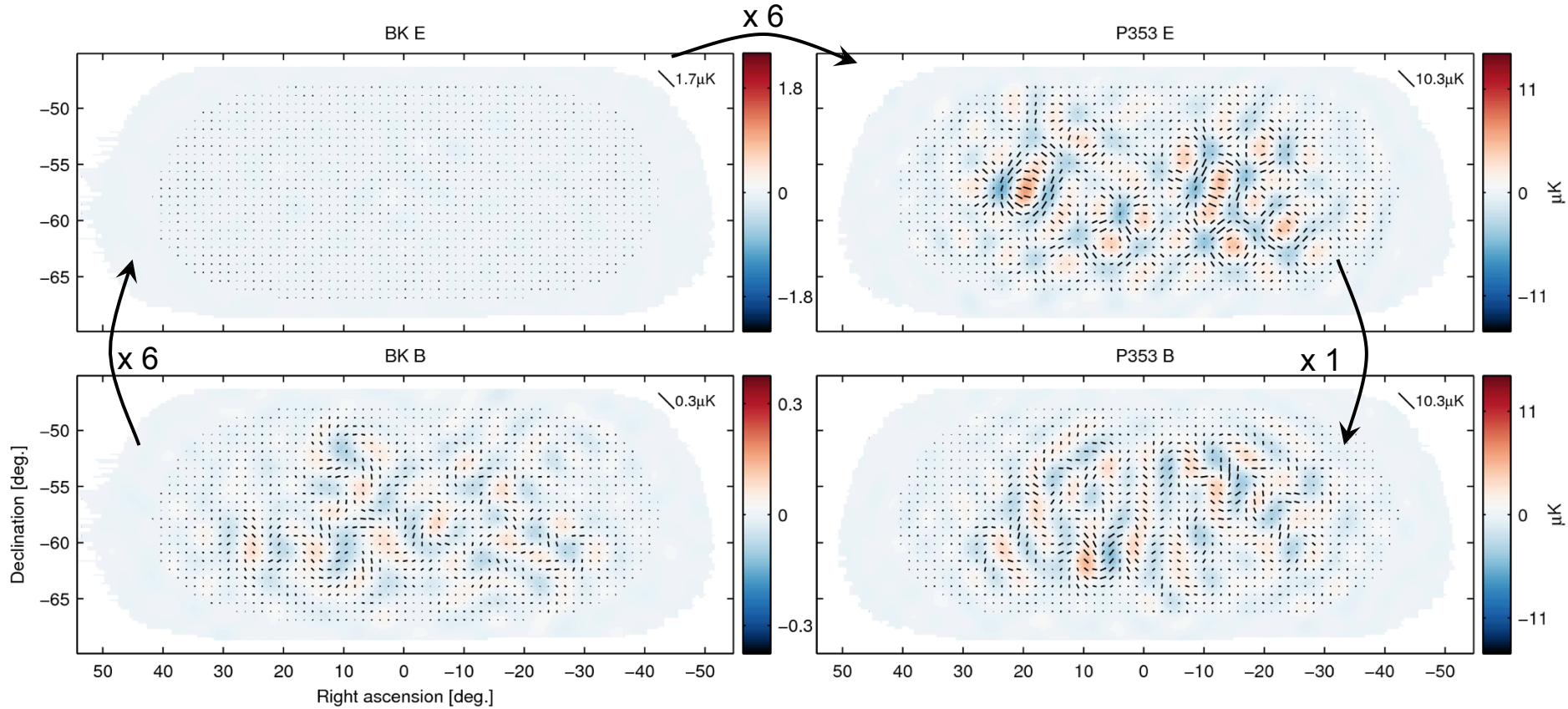


E-modes and B-modes filtered to range $l=50-120$

color stretch adjusted between maps
by factor indicated

The Real Data

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

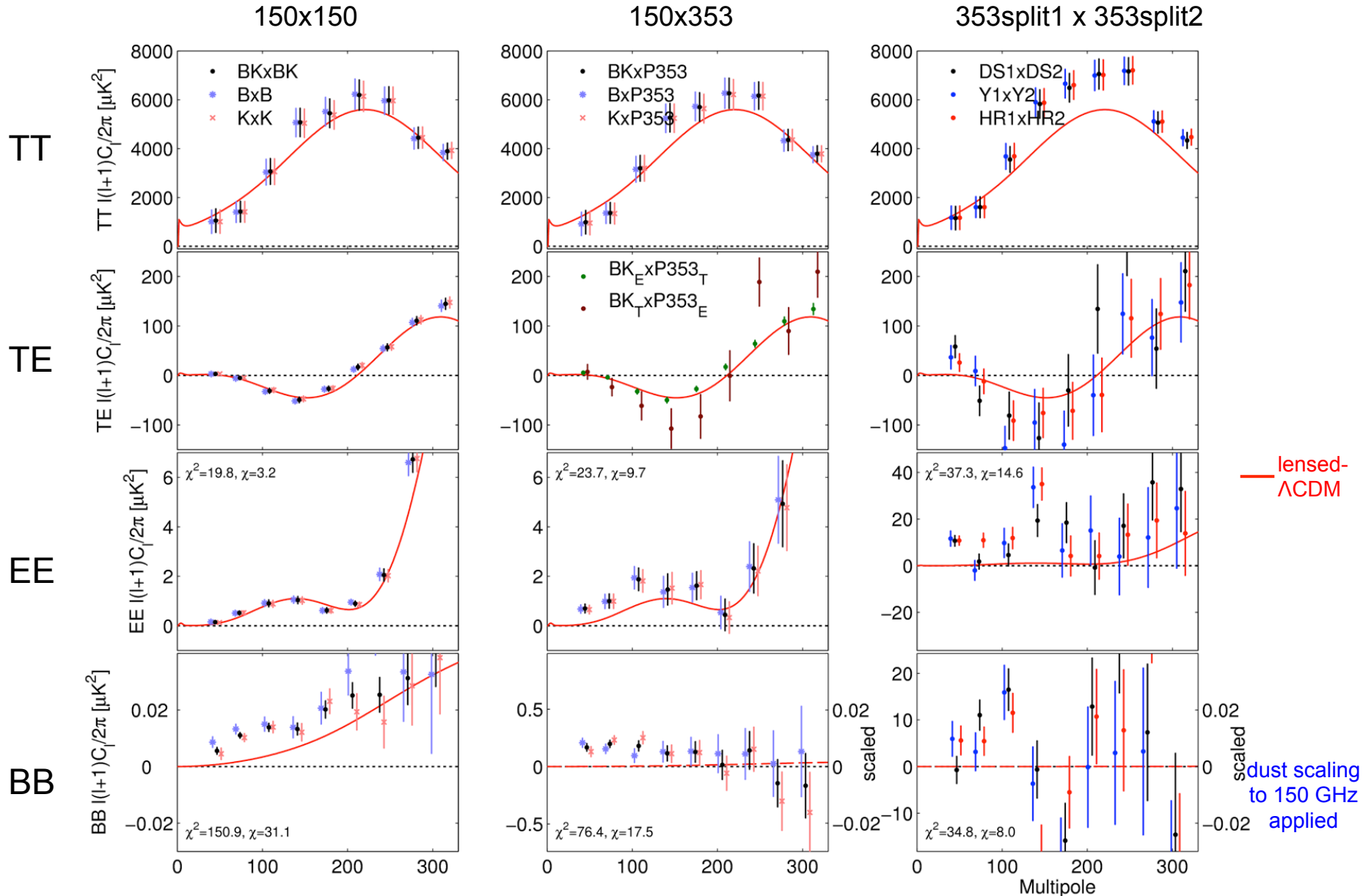


E-modes and B-modes filtered to range $l=50-120$

color stretch adjusted between maps
by factor indicated

A Noise Simulation

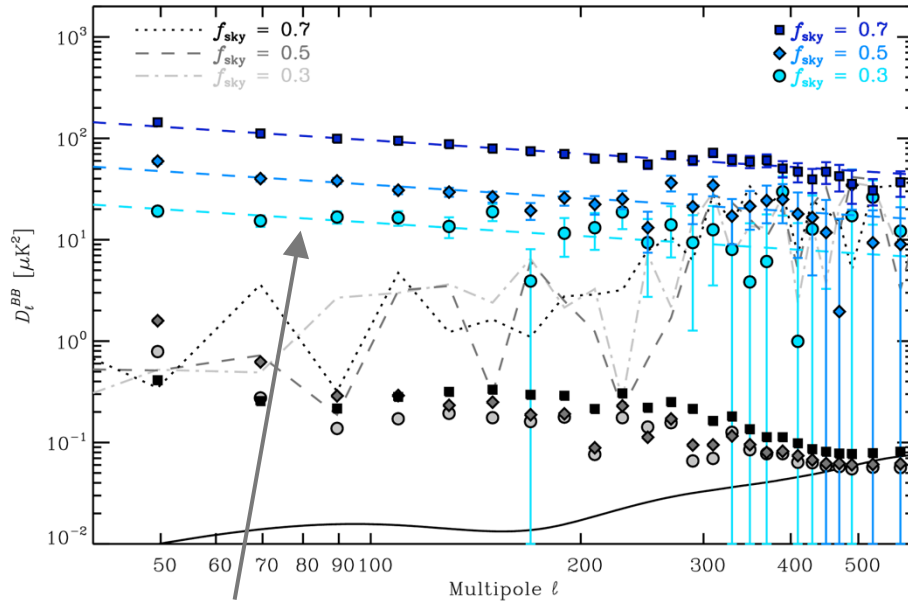
Single- and Cross-Frequency Spectra



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:

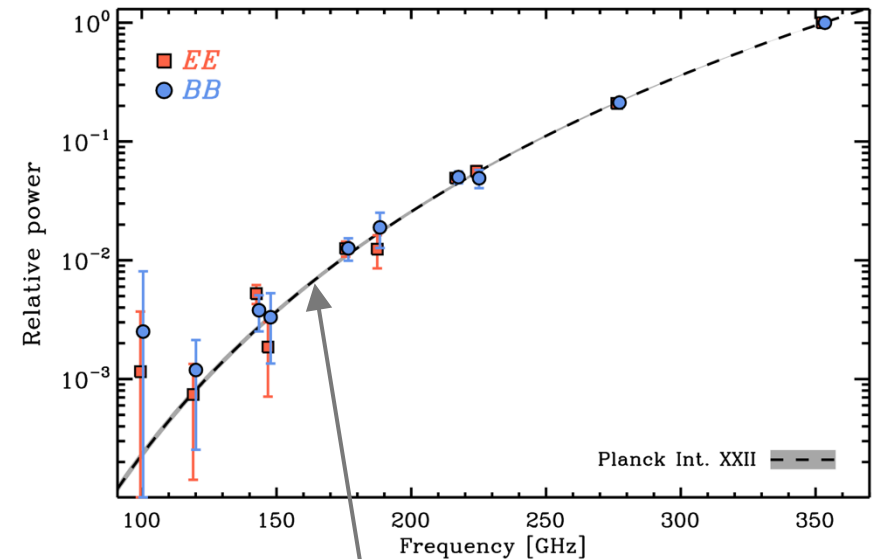
Fig 2 of arxiv:1409.5738



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

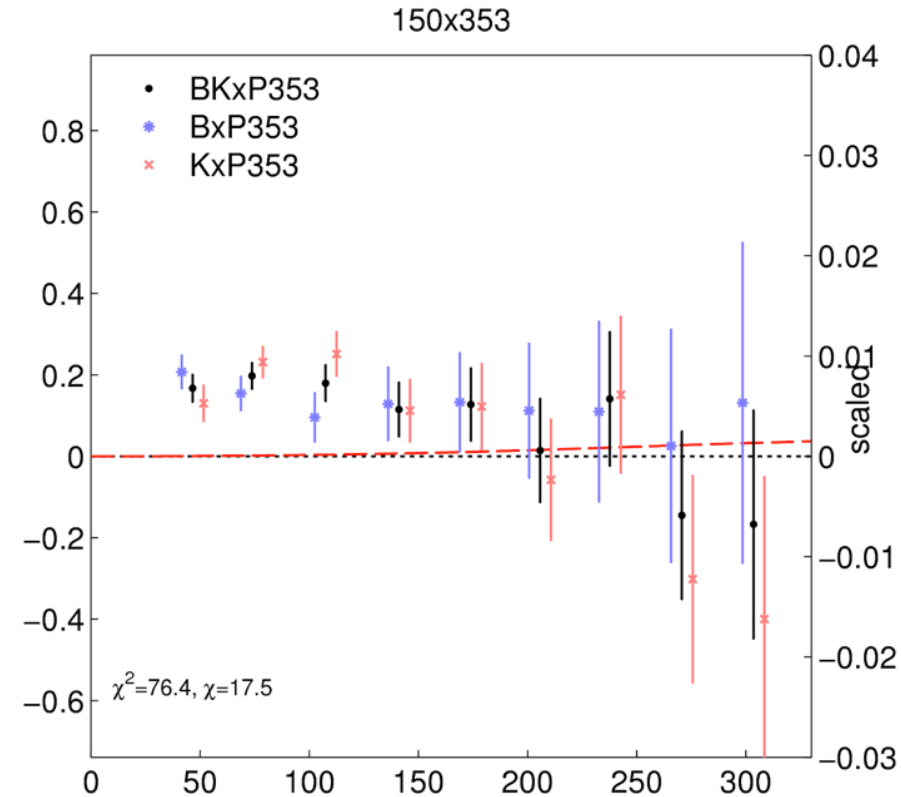
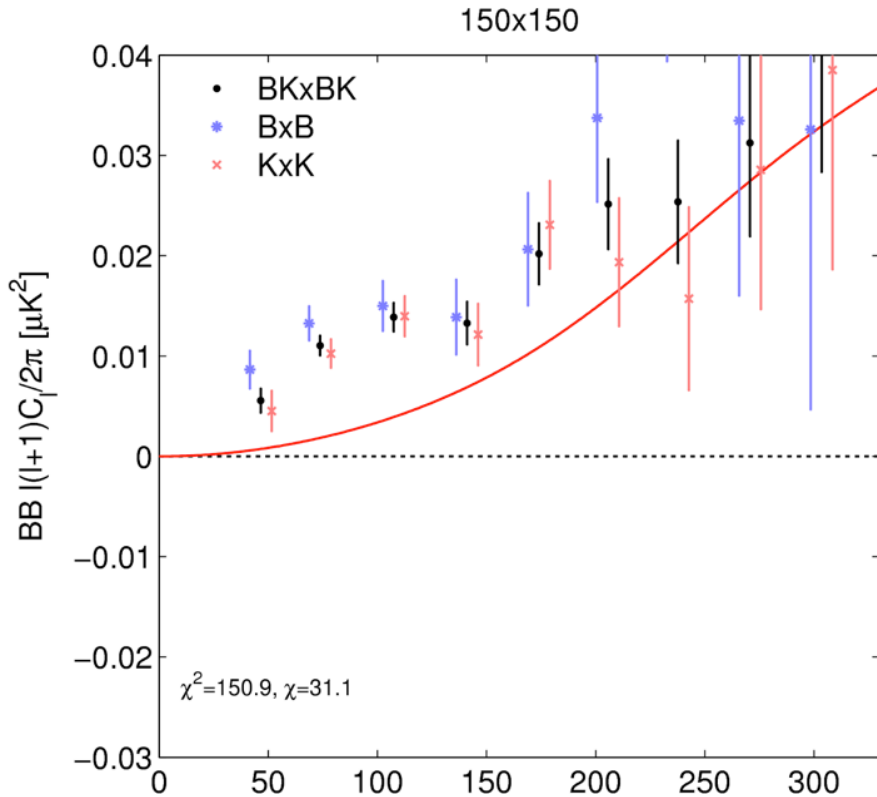


Spectral energy distribution of polarized dust emission follows modified blackbody model with $T=19.6\text{K}$ and $\beta_d=1.59$

- 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?

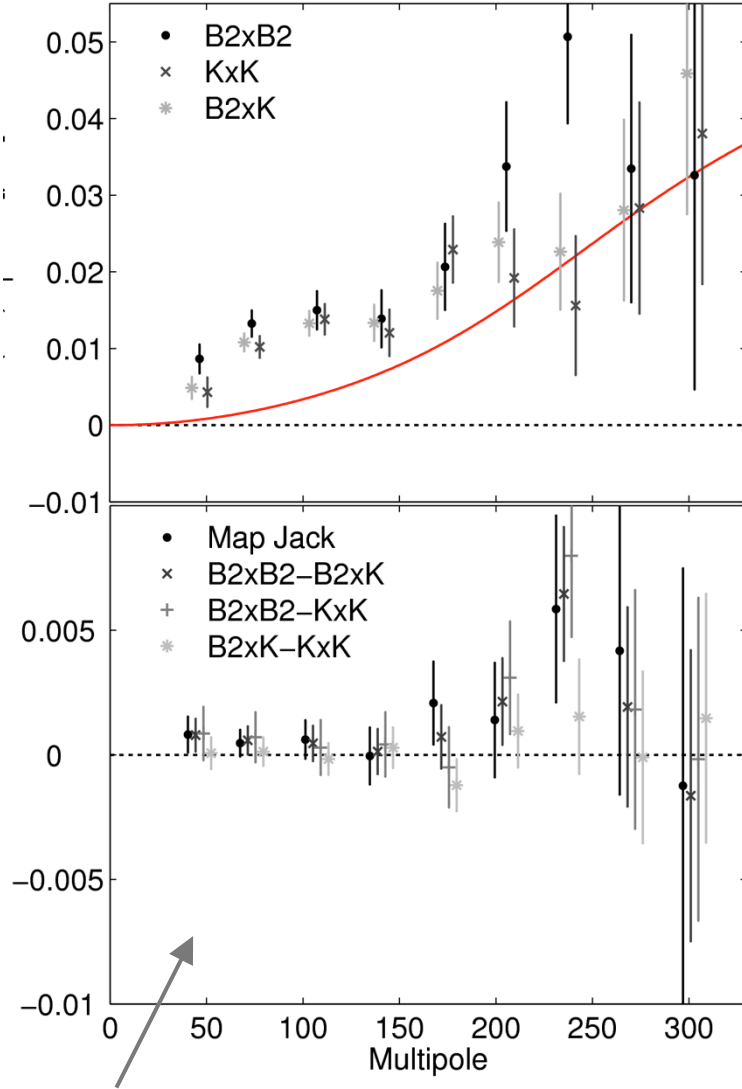


Fig 8 of Keck paper
(Note these tests are not independent)

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

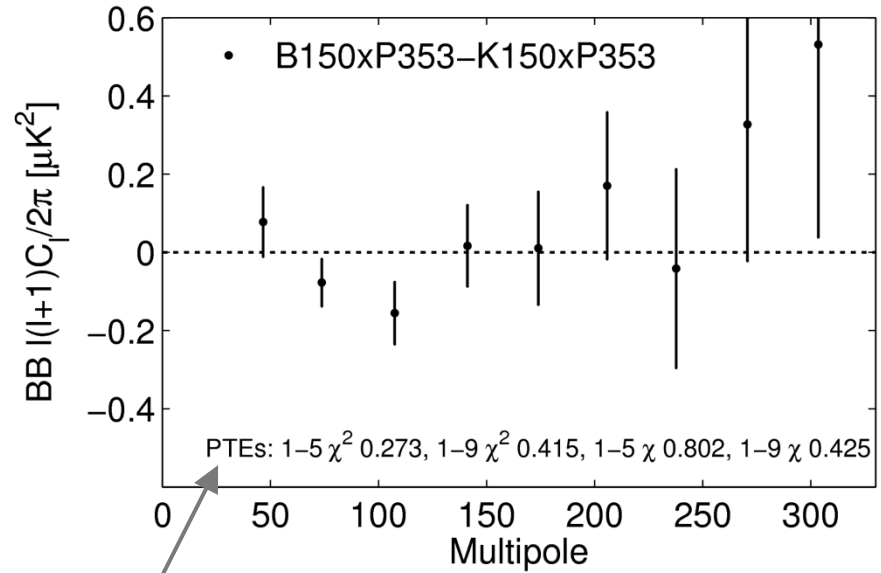
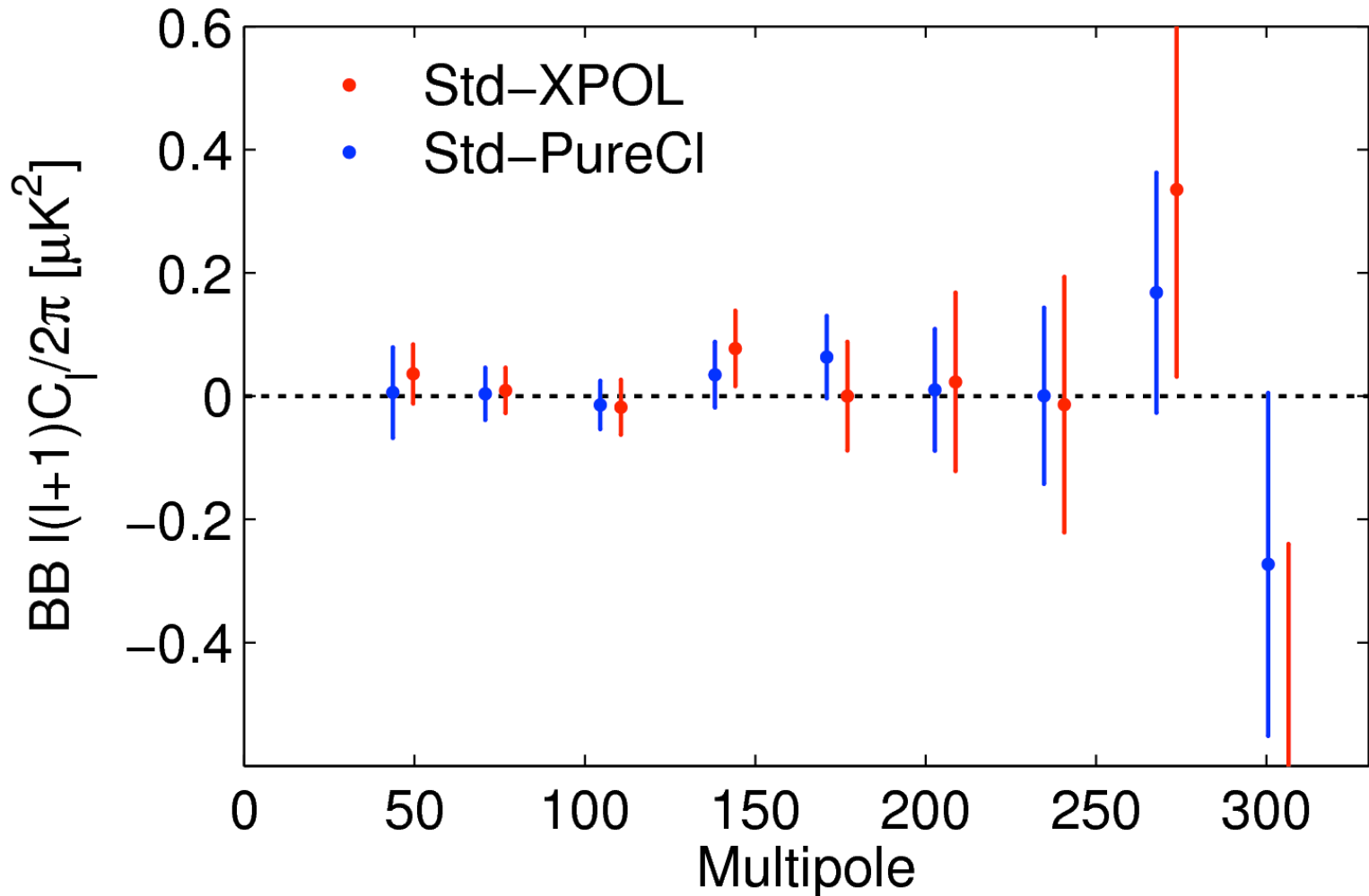


Fig 4 of BKP paper

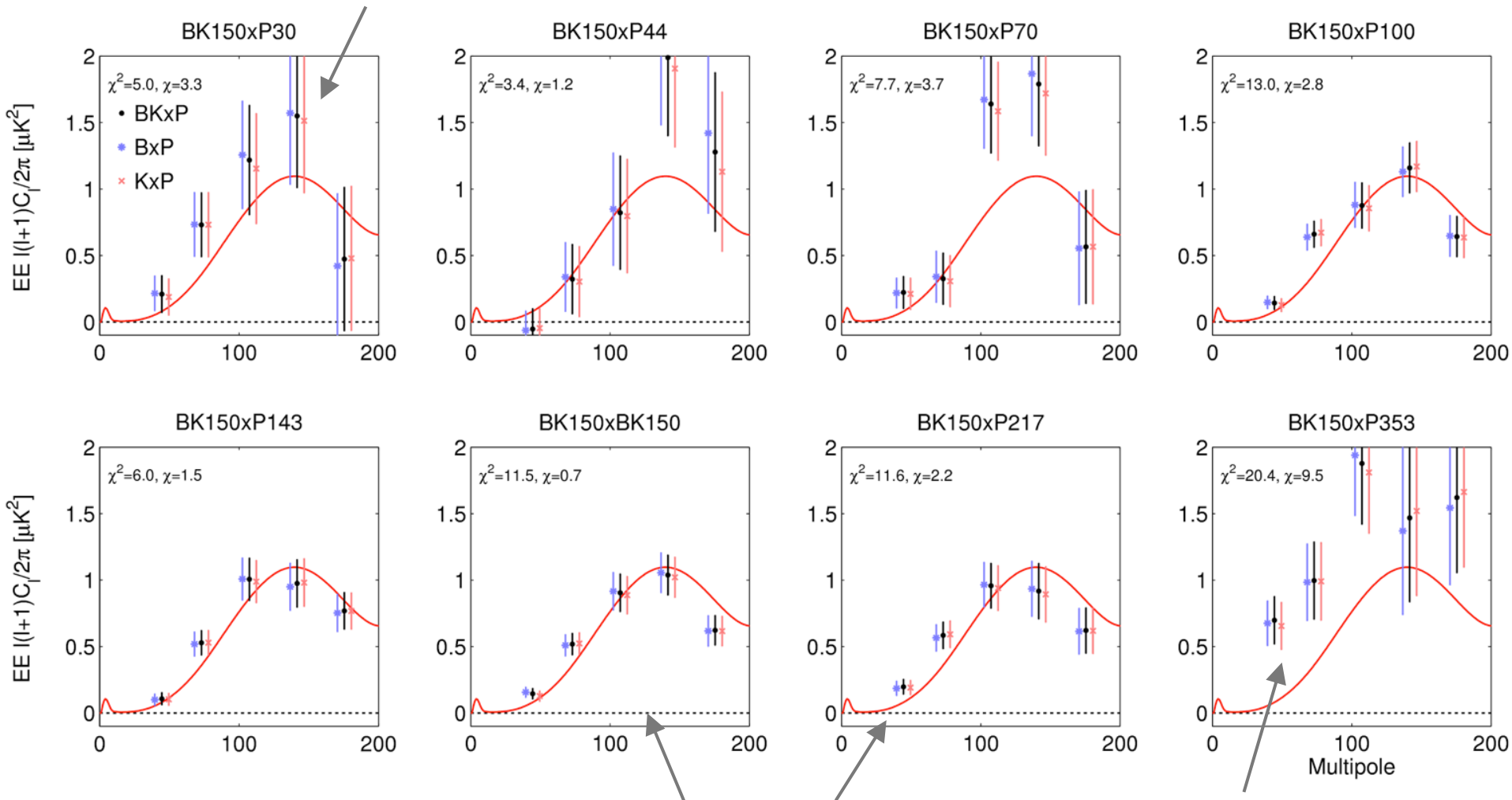
Check the power spectrum estimation



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...



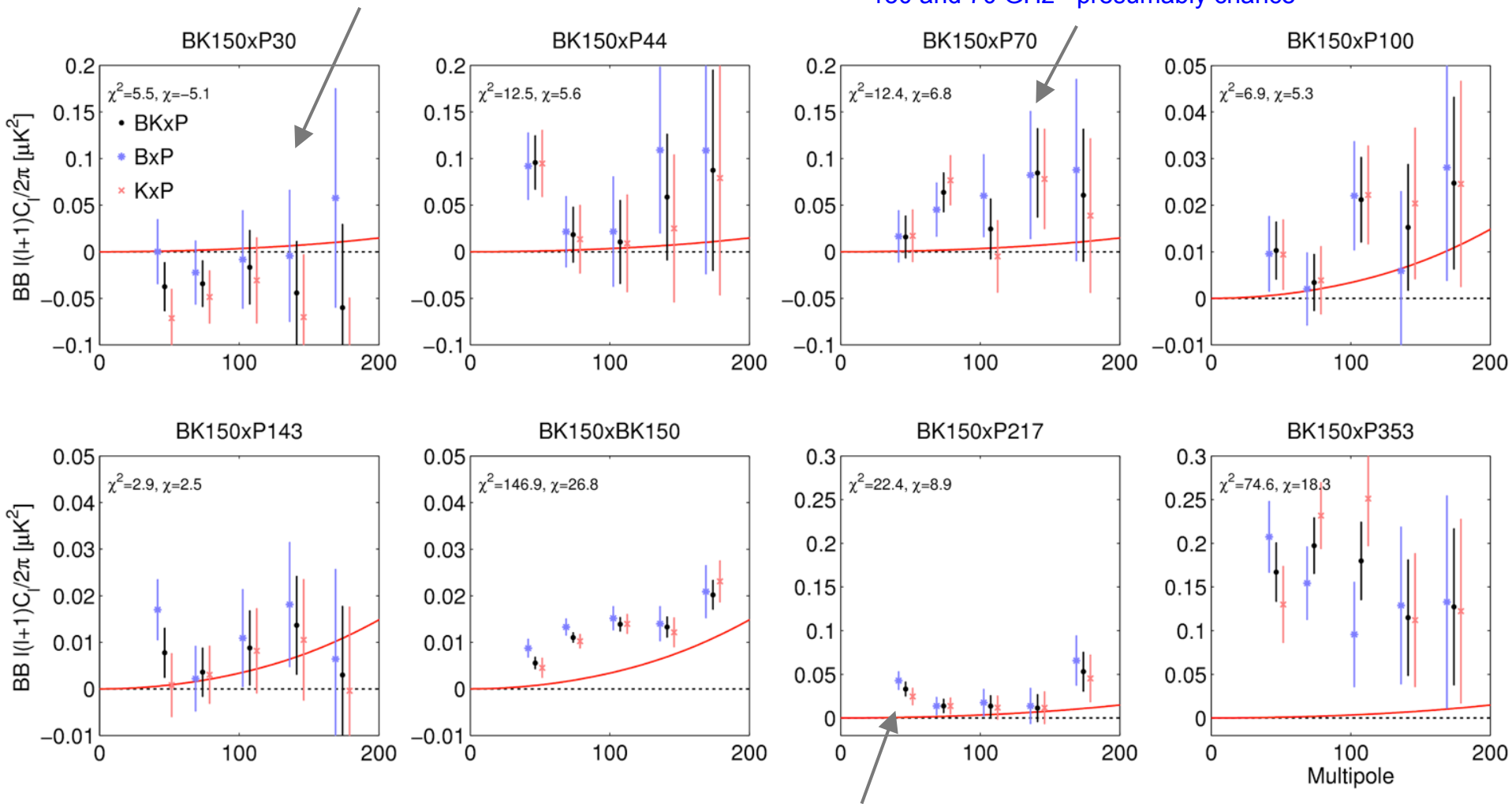
These two basically look the same - suggesting dust contribution in BK150xBK150 EE is small fraction

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

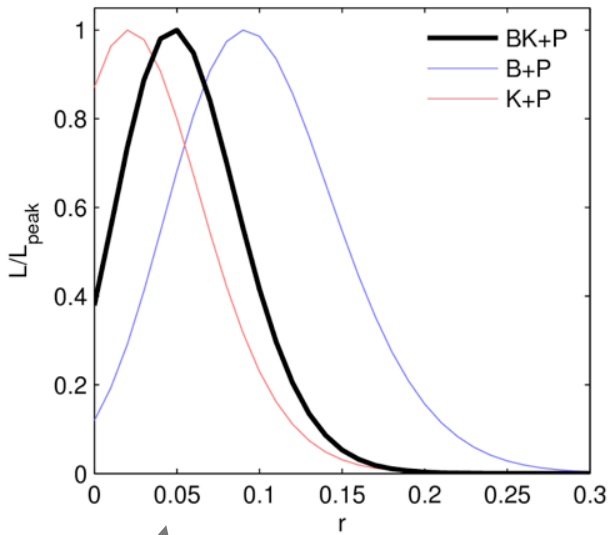


Some additional evidence for excess due to dust

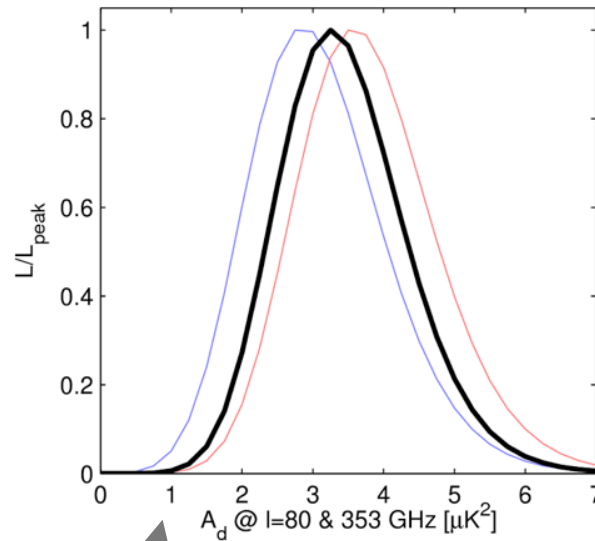
Multi-component multi-spectral likelihood analysis

- 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 $\ell = 80$ and 353 GHz)
 - For dust SED use modified blackbody model and marginalize over range $\beta_d = 1.59 \pm 0.11$
- Use 5 lowest BB bandpowers only ($20 < \ell < 200$)

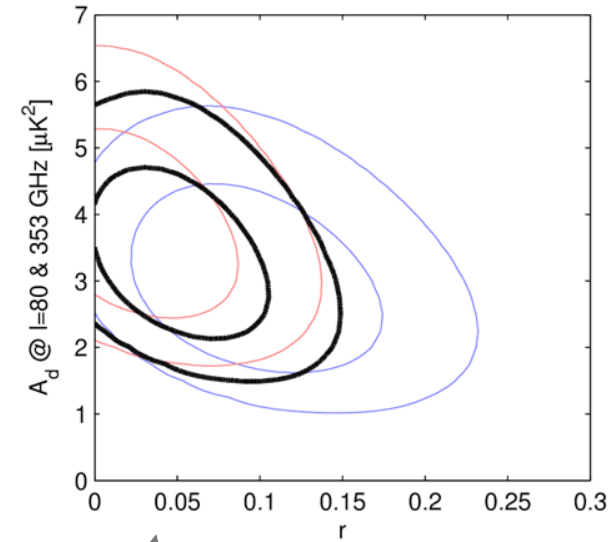
Multi-component multi-spectral likelihood analysis



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.)

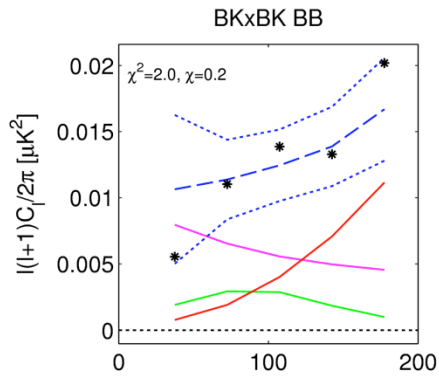


Dust is detected with 5.1σ significance

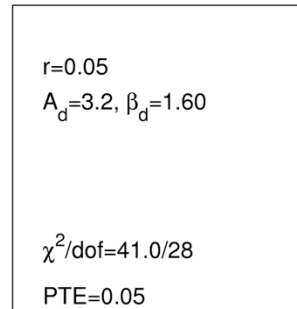


As expected dust and r are partially degenerate - reducing dust means more of the 150x150 signal needs to be r

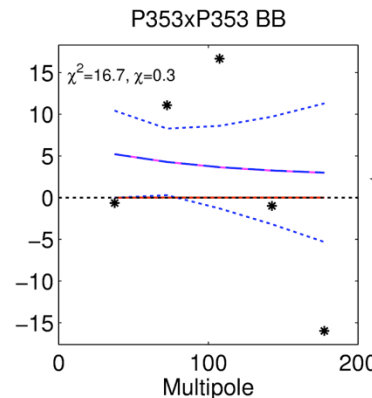
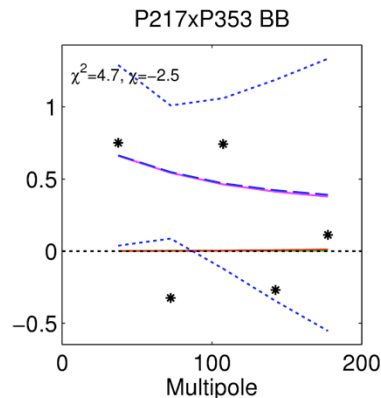
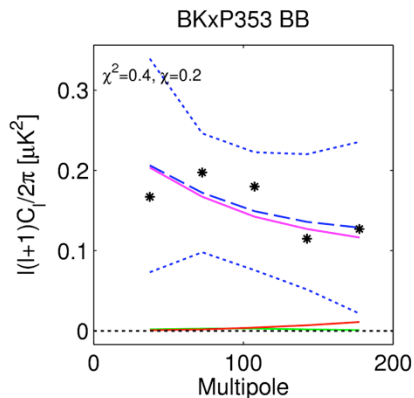
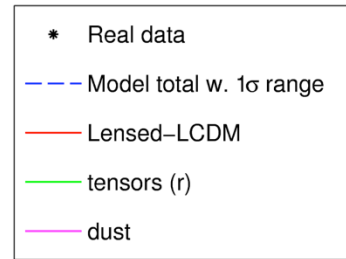
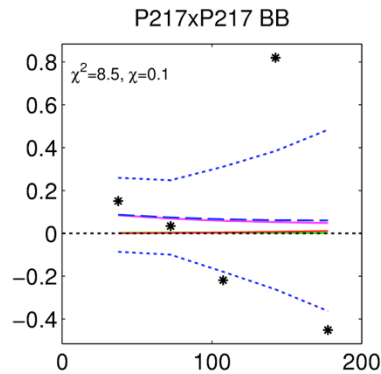
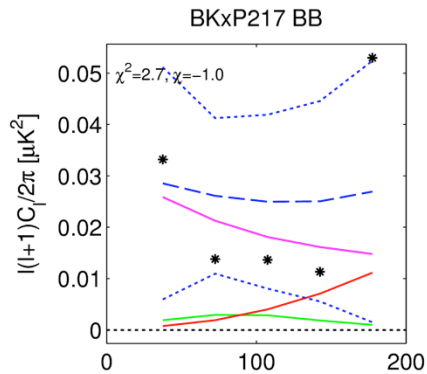
Best fit multi-frequency model



Model:



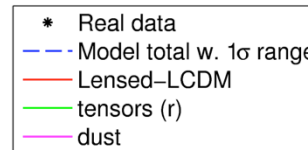
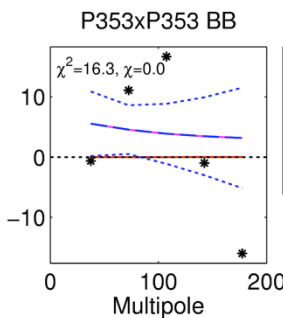
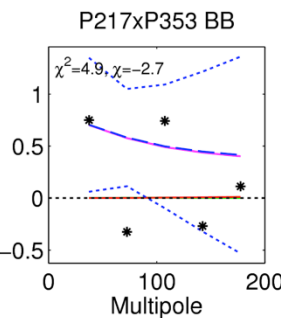
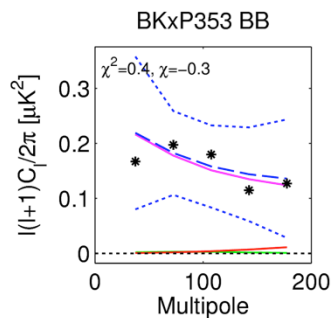
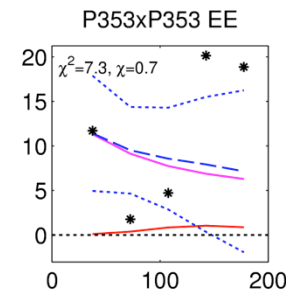
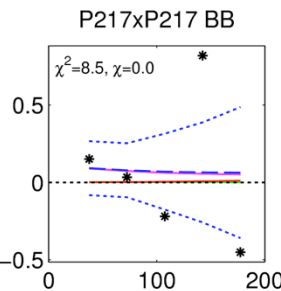
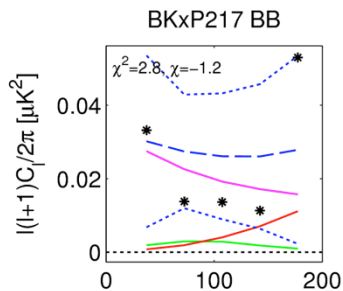
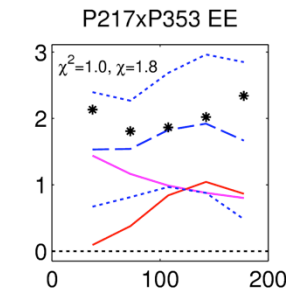
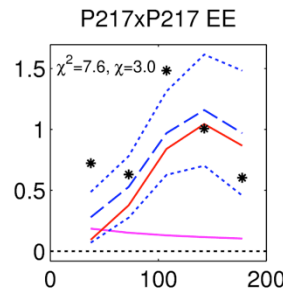
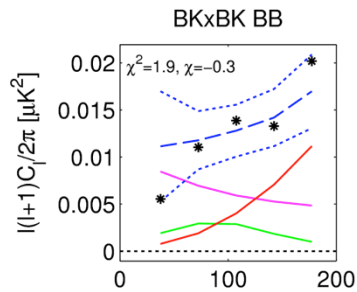
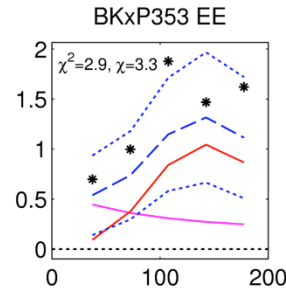
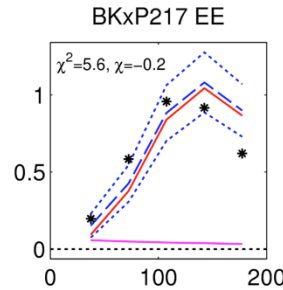
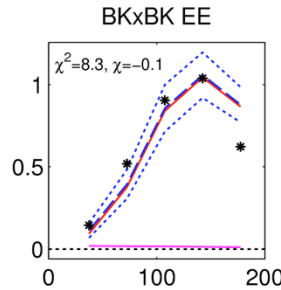
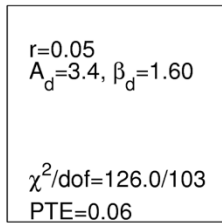
- The maximum likelihood model has acceptable χ^2 (with the biggest contribution coming from P353xP353.)
- The BKxBK and BKxP353 spectra are both very well fit by the model.



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

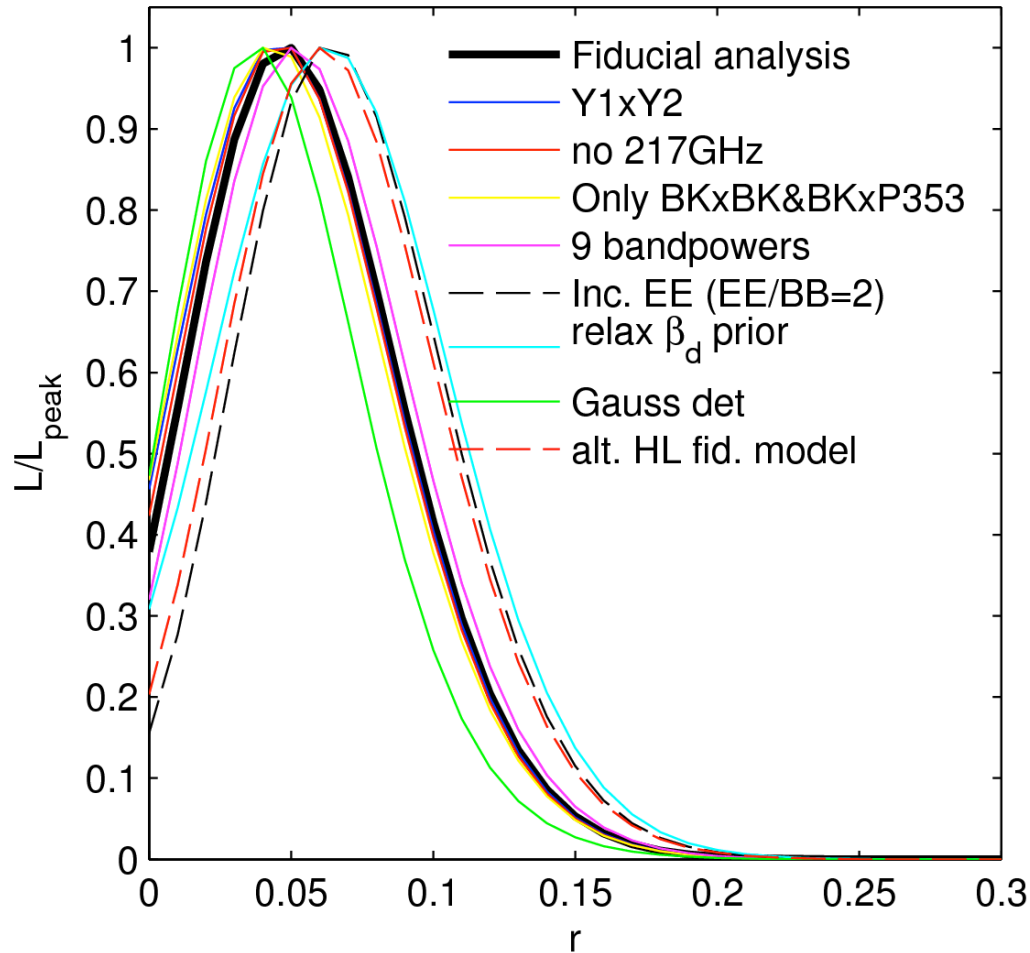
Model:



➤ 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.

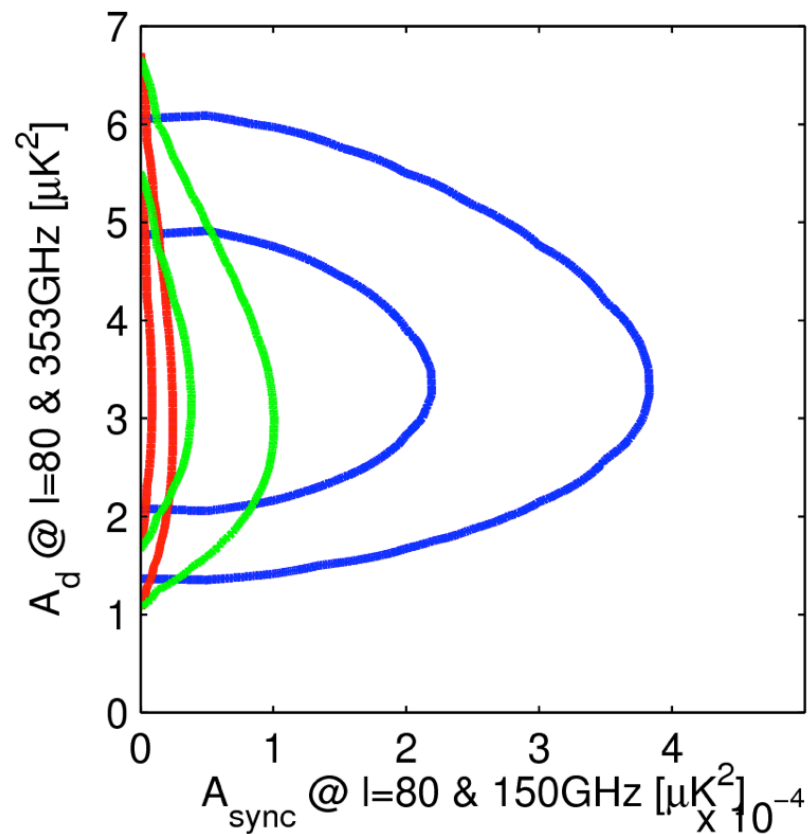
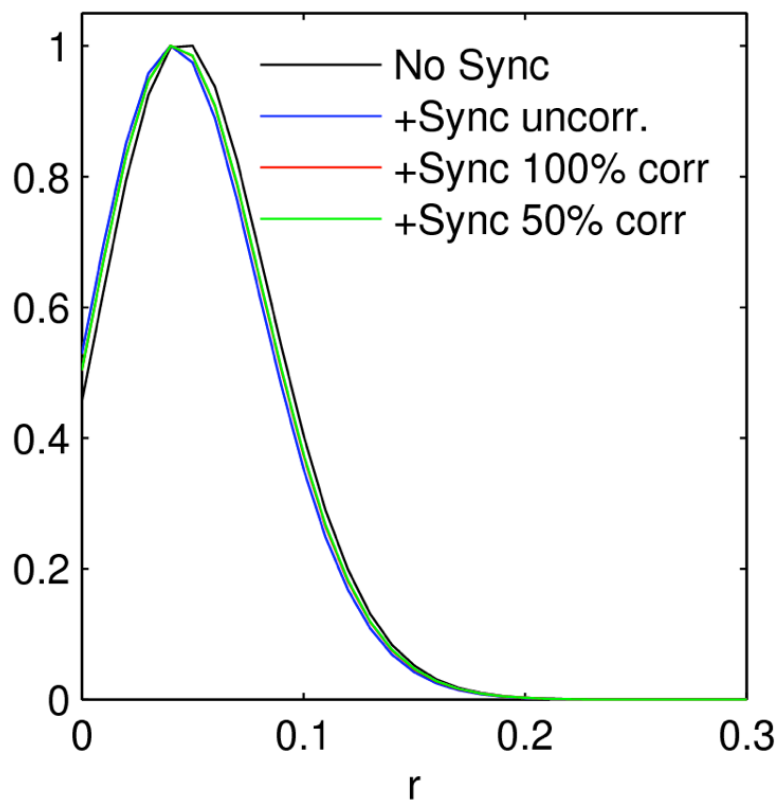
➤ Note that the dust contribution to BKxBK EE under this model is fractionally very small.

Variations on fiducial analysis



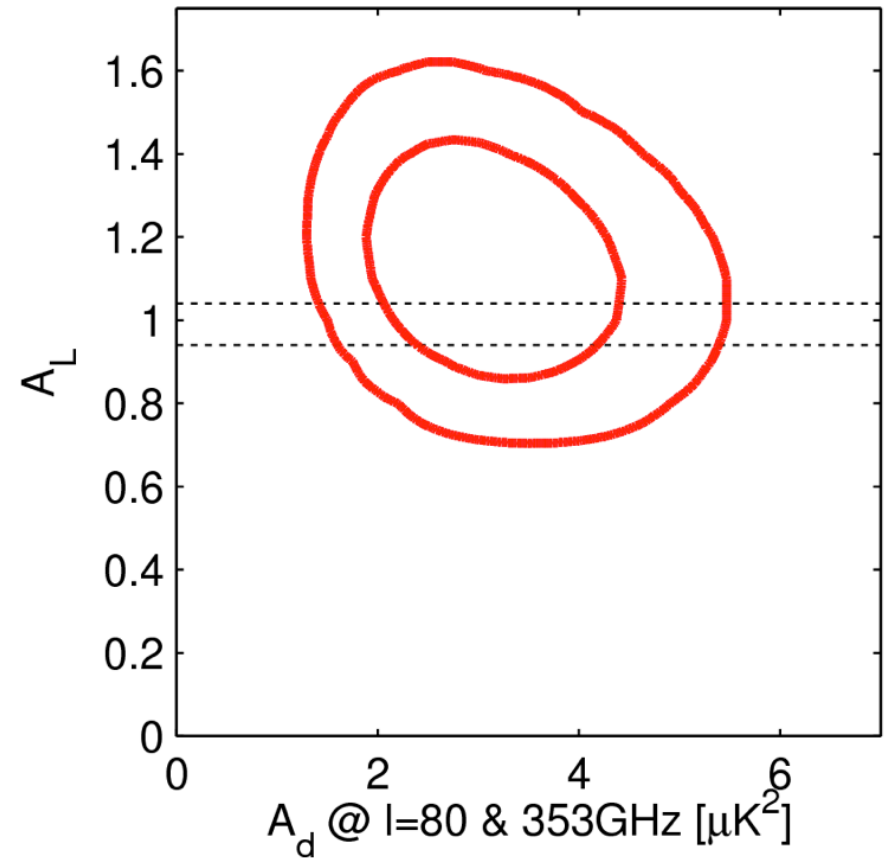
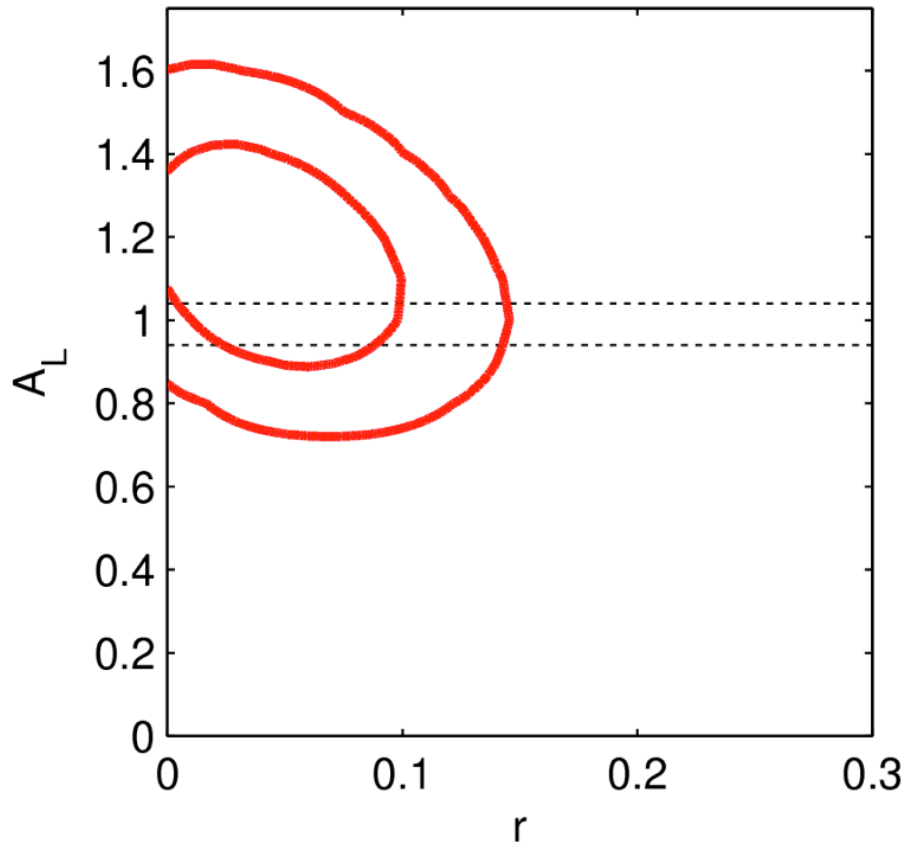
- We consider a range of variations on the fiducial analysis
- Most make little difference - see paper for details
- Excluding 353x353 makes little difference - this spectrum has little statistical weight
- The data “wants” a steeper dust SED - relaxing the β_d prior it pulls to the top end of the range 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



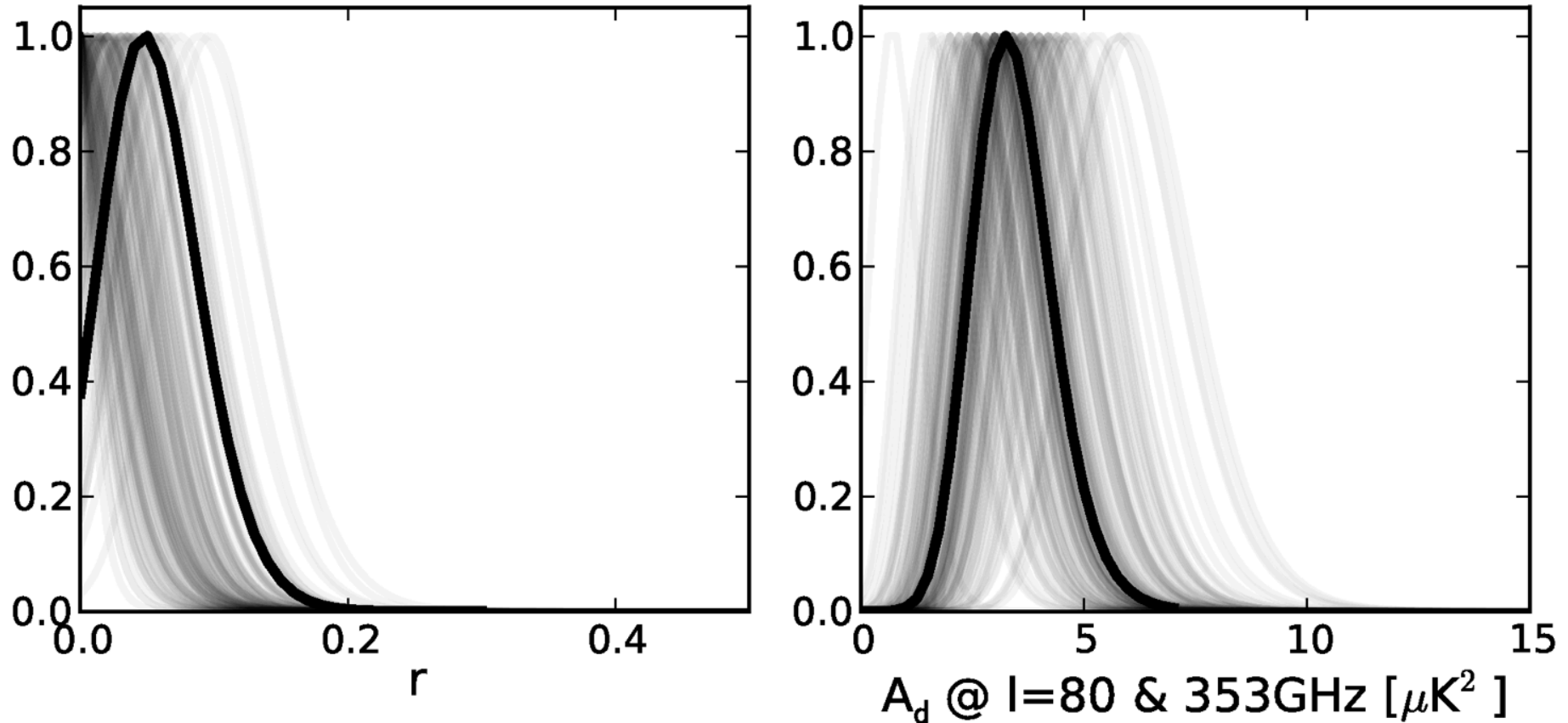
- We try adding synchrotron to the model while also adding all of the frequency channels of Planck
- We assume a spectral index for sync taken from WMAP's spectral index map in our sky region
 - The results for r and A_d hardly change while synchrotron is tightly limited
 - If one assumes that the dust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

Constraints on lensing B-modes



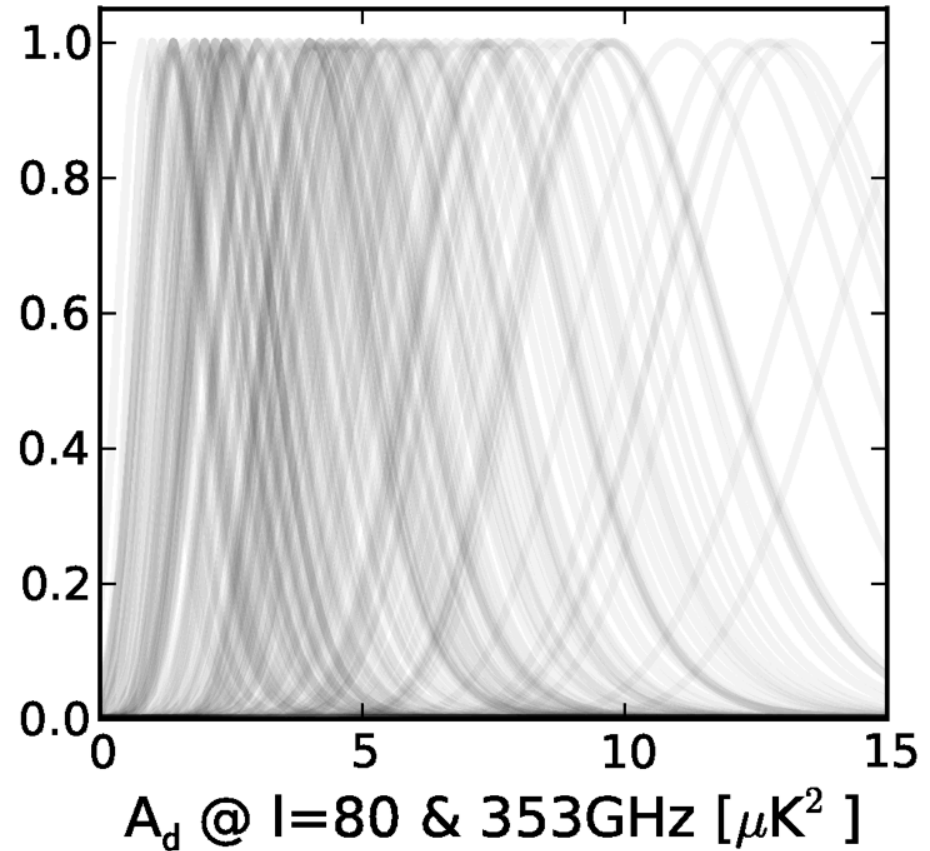
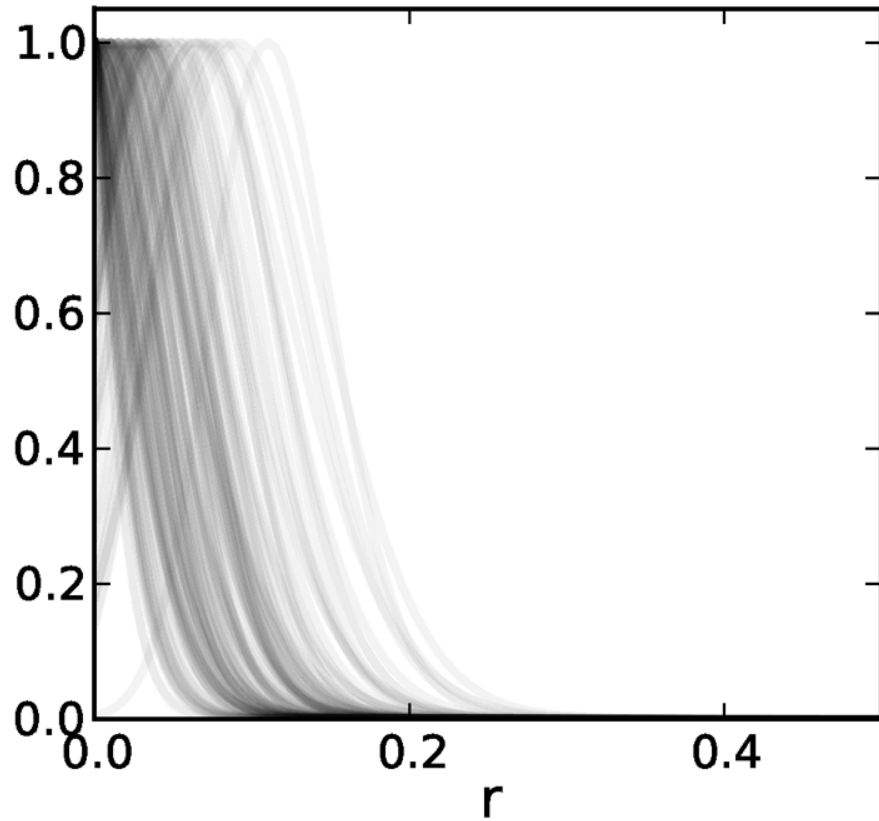
- We next allow the amplitude of the lensing signal to vary while also extending the ℓ range up to 330
- We find that the lensing and dust components can be cleanly separated
 - And detect lensing at 7.0σ significance

Likelihood validation



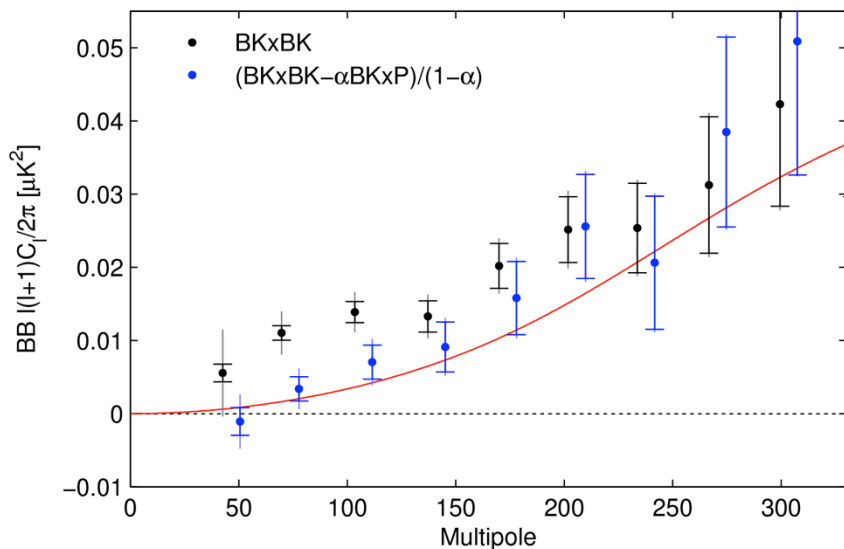
- We validate the likelihood machinery using simulations of a dust only model with mean A_d set a little higher than the value preferred by the real data.
- As expected 50% of the r constraints peak at zero with 8% having a zero/peak likelihood ratio less than that of the real data

Likelihood validation II

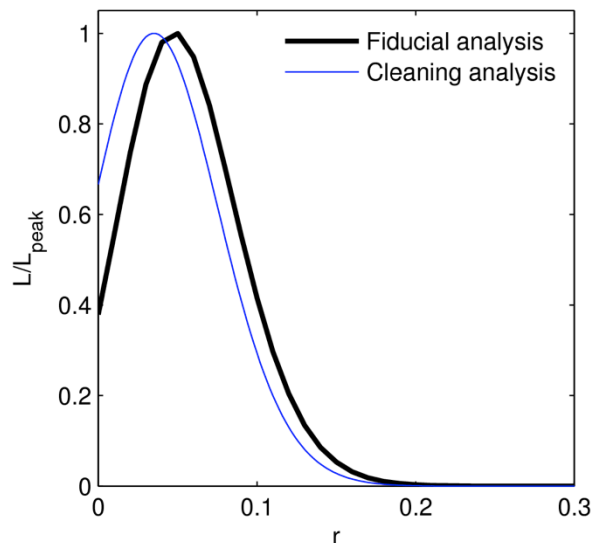


- We also run sims using dust sky patterns drawn from the old version of the Planck Sky Model
 - These sky patterns are not necessarily Gaussian random fields and have a wide range of brightnesses (as seen at right)
- However 50% of the r constraints still peak at zero (and curves broaden in brighter dust regions)

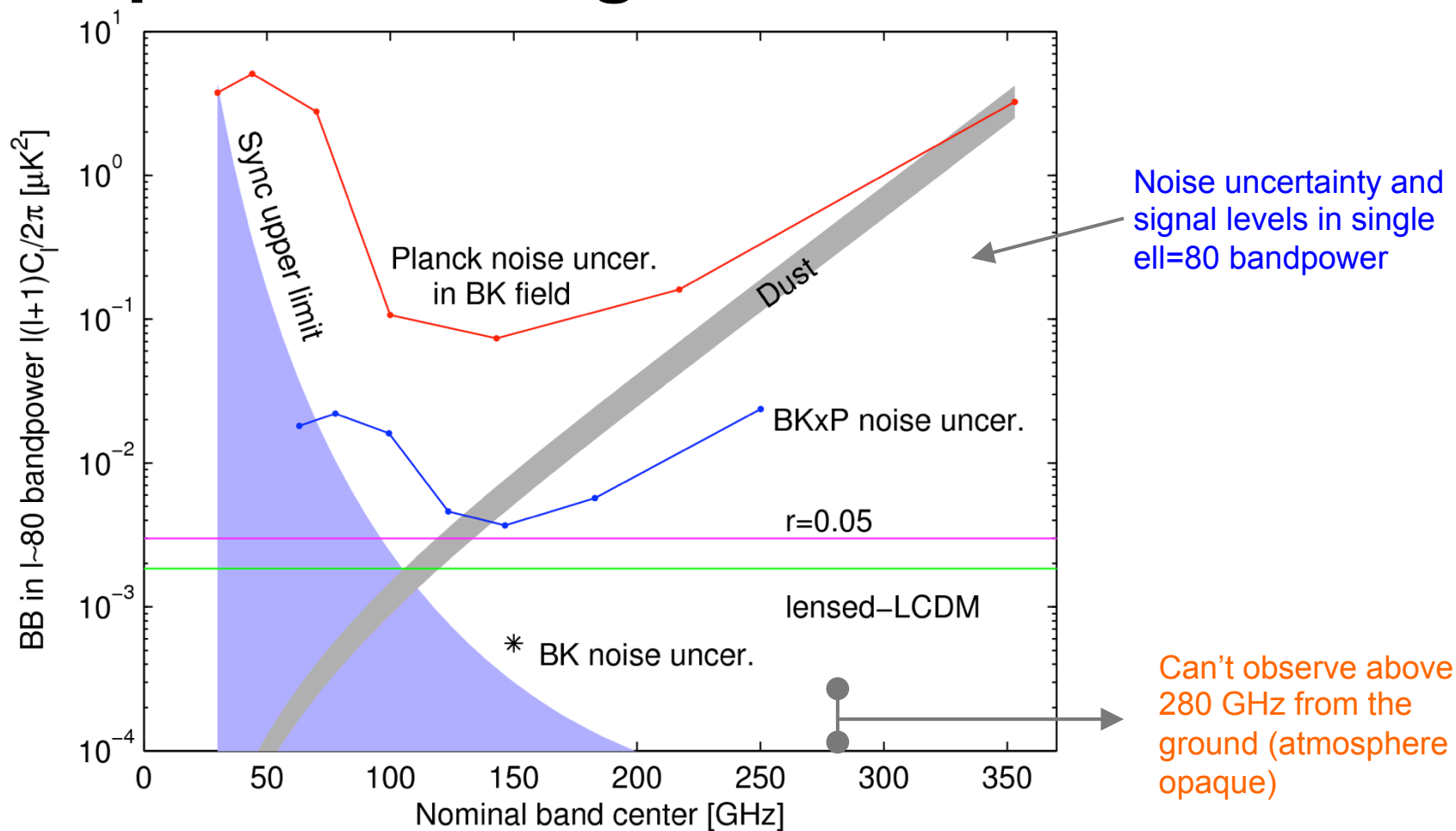
Spectral subtraction analysis



- 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

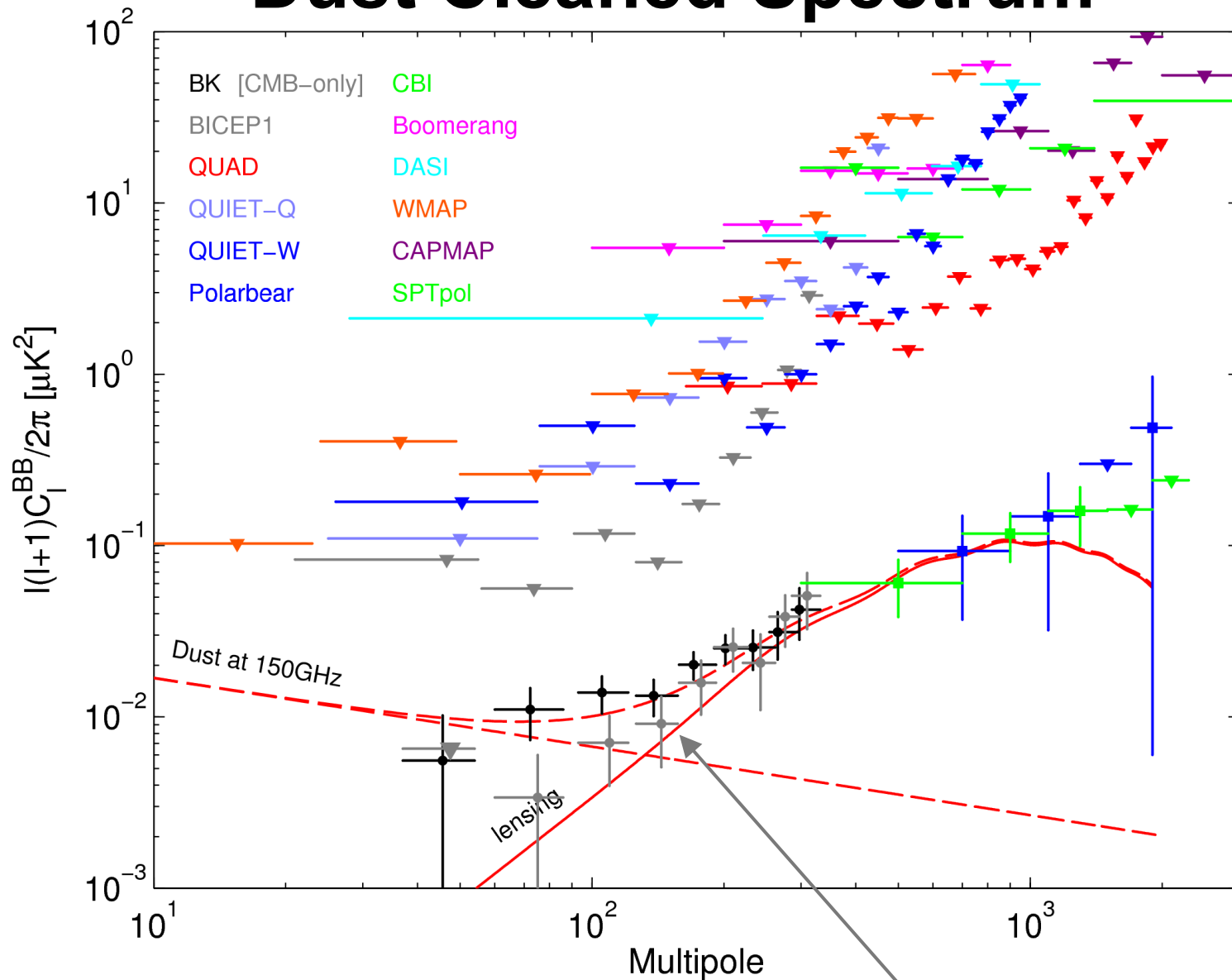


- The BICEP2/Keck noise is much lower than the Planck noise in the small sky patch observed
- However dust is much brighter at 353 GHz and Planck detects it
- The noise in the cross spectra is the geometric mean and a fairly tight constraint on dust amplitude is set

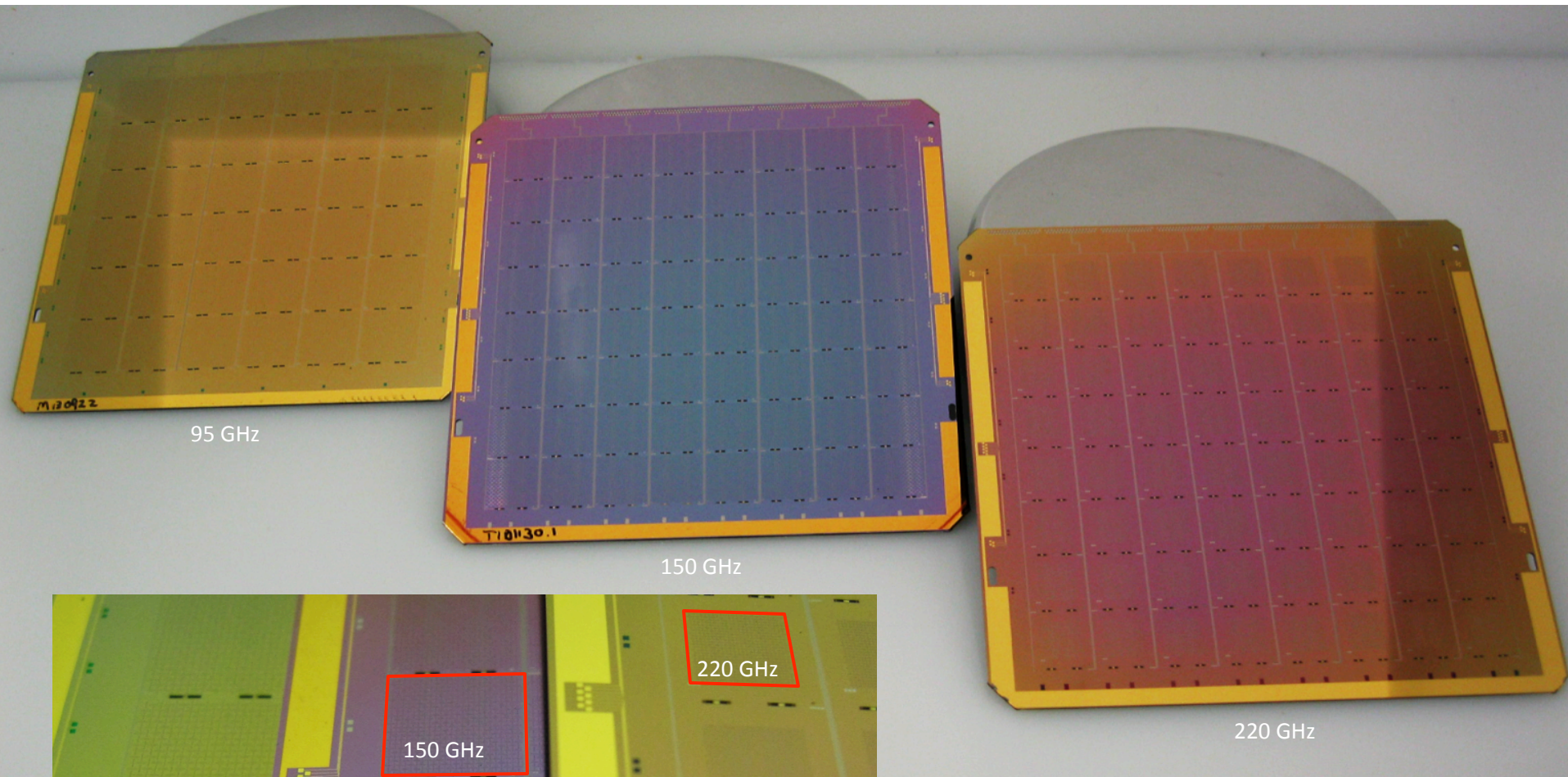
Current Conclusions

- 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 7.0σ 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



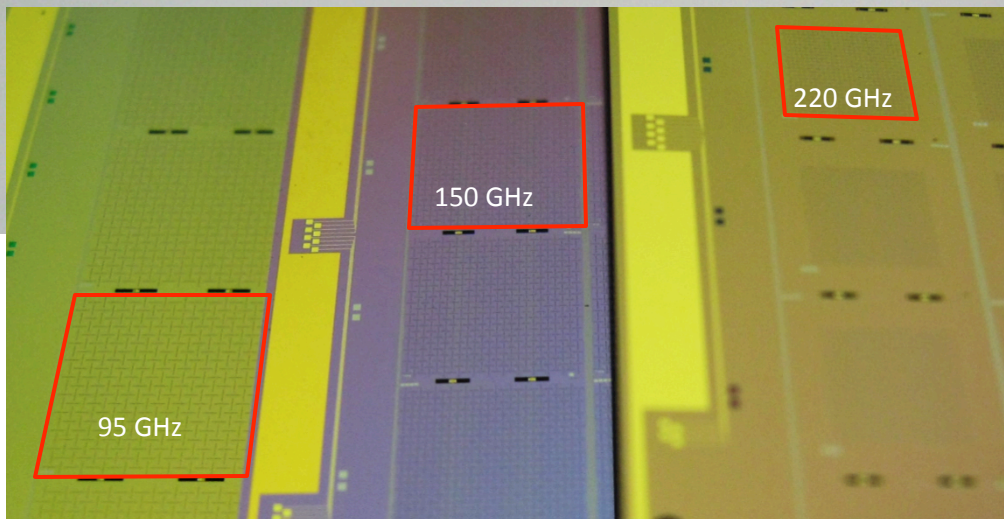
Detectors Designed to Scale in Frequency



95 GHz

150 GHz

220 GHz

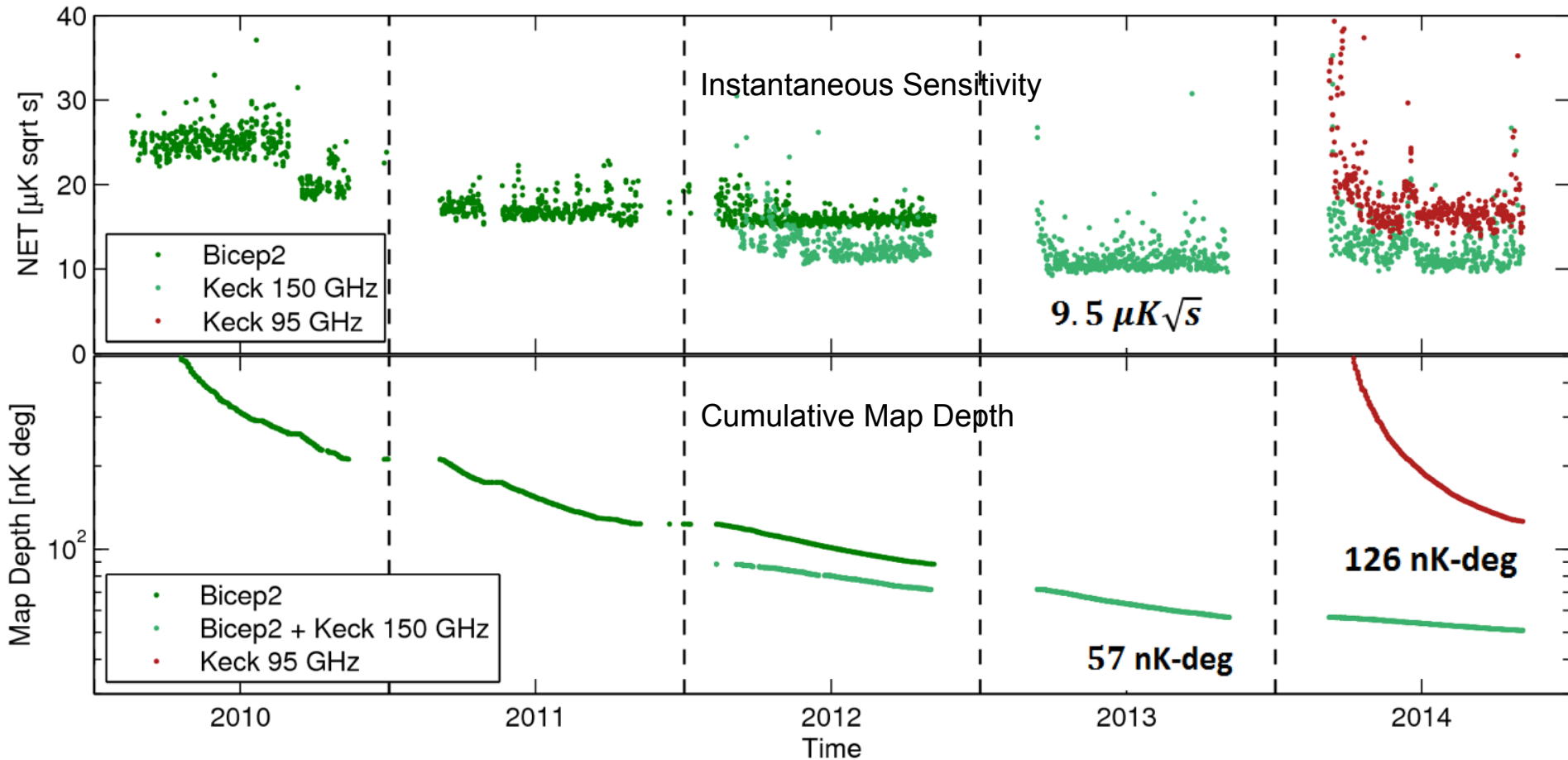


95 GHz

150 GHz

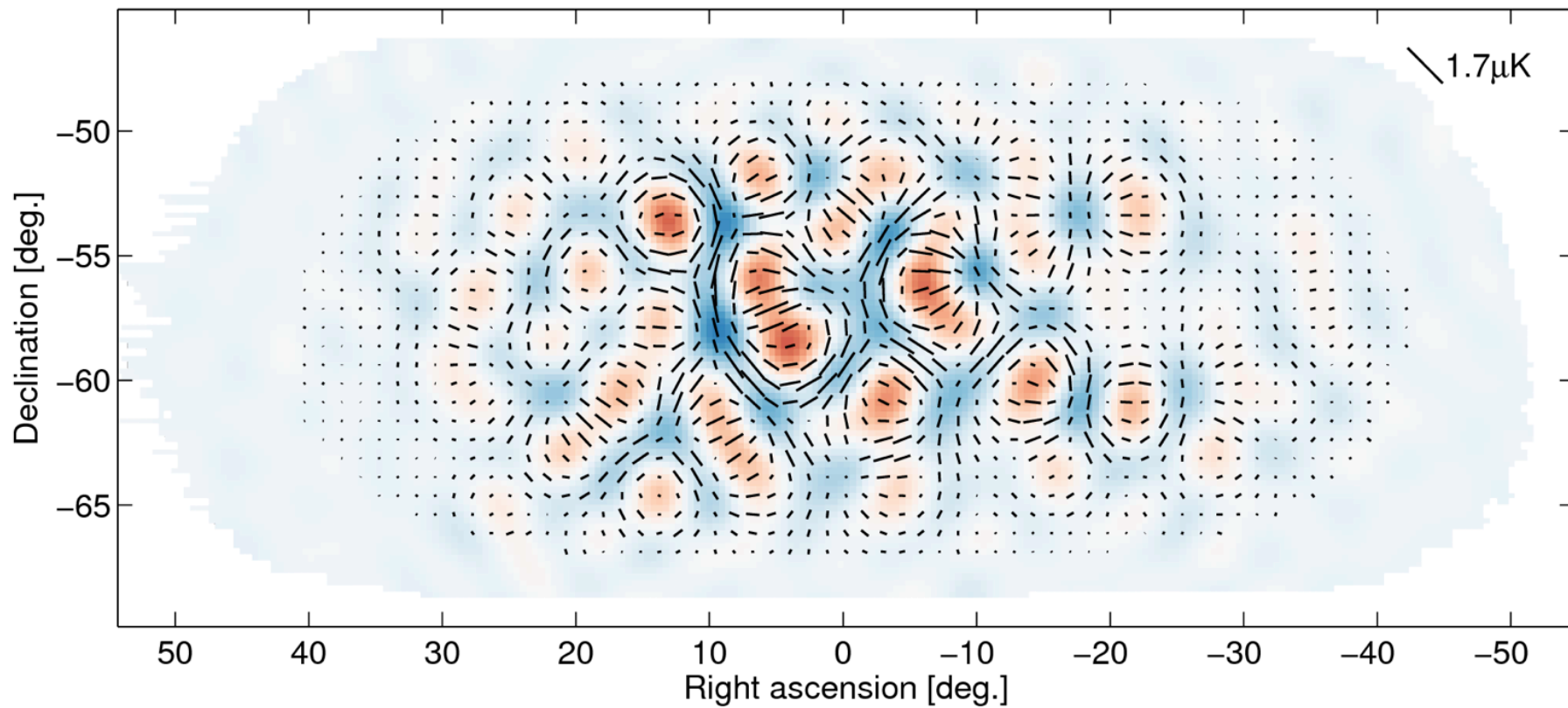
220 GHz

In 2014 Keck added 95 GHz sensitivity

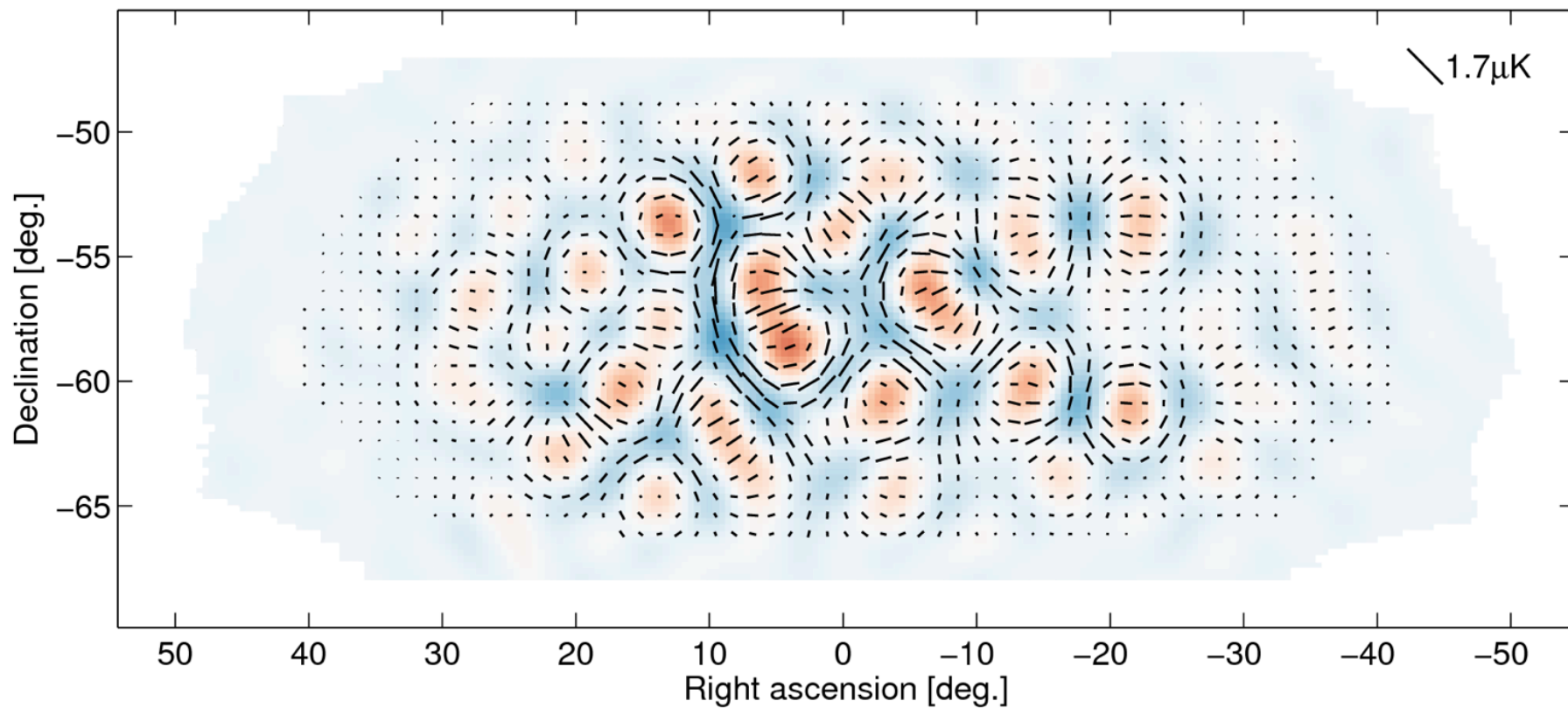


For 2014 season two of the Keck array receivers switched out for 95 GHz

BICEP2 + Keck12+13 E-mode signal

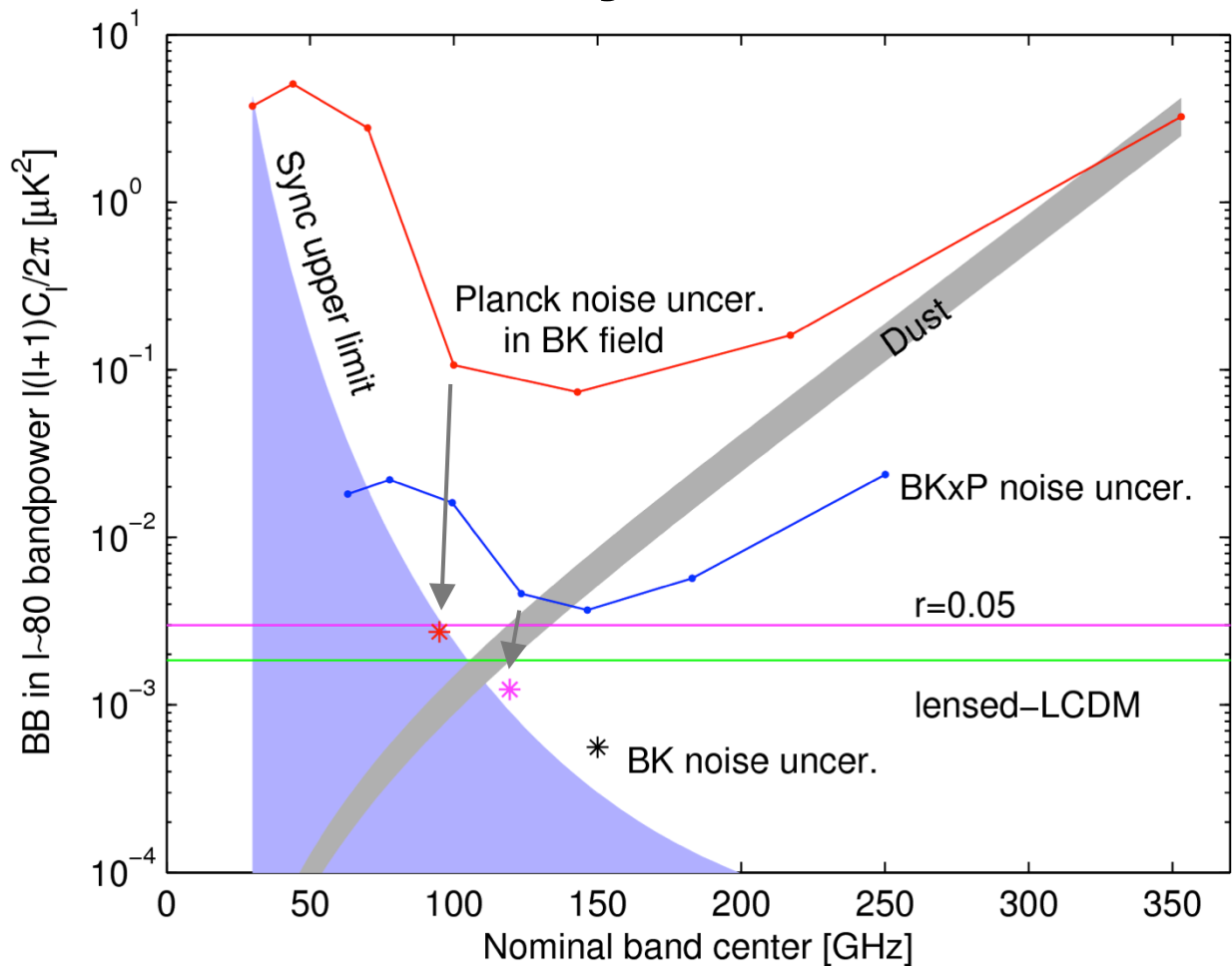


Keck14 95 GHz E-mode signal



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

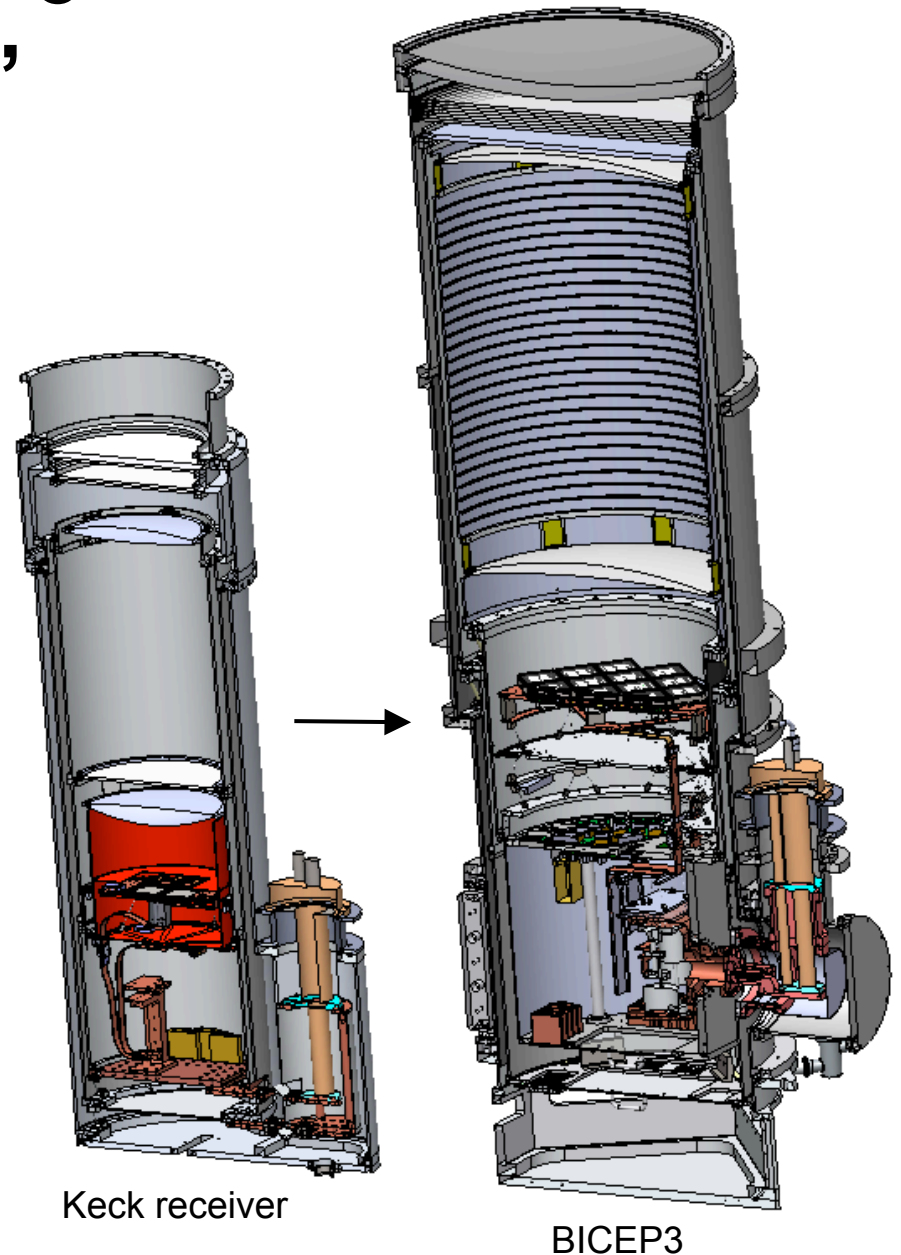
New in 2015 BICEP3 “Super Receiver”

All 95 GHz

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

Large-aperture optics and infrared filtering

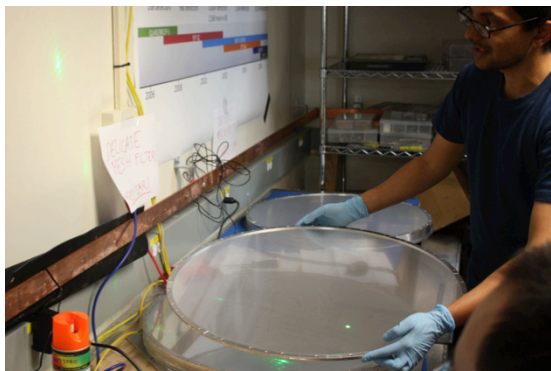
> 10x optical throughput of single BICEP2/Keck receiver



Keck receiver

BICEP3

BICEP3 technology

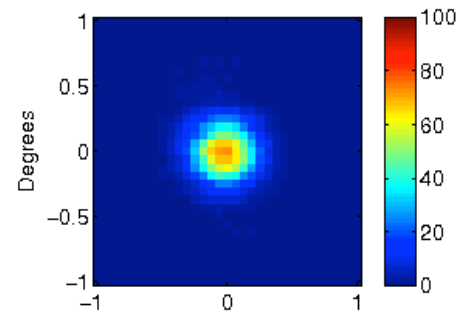
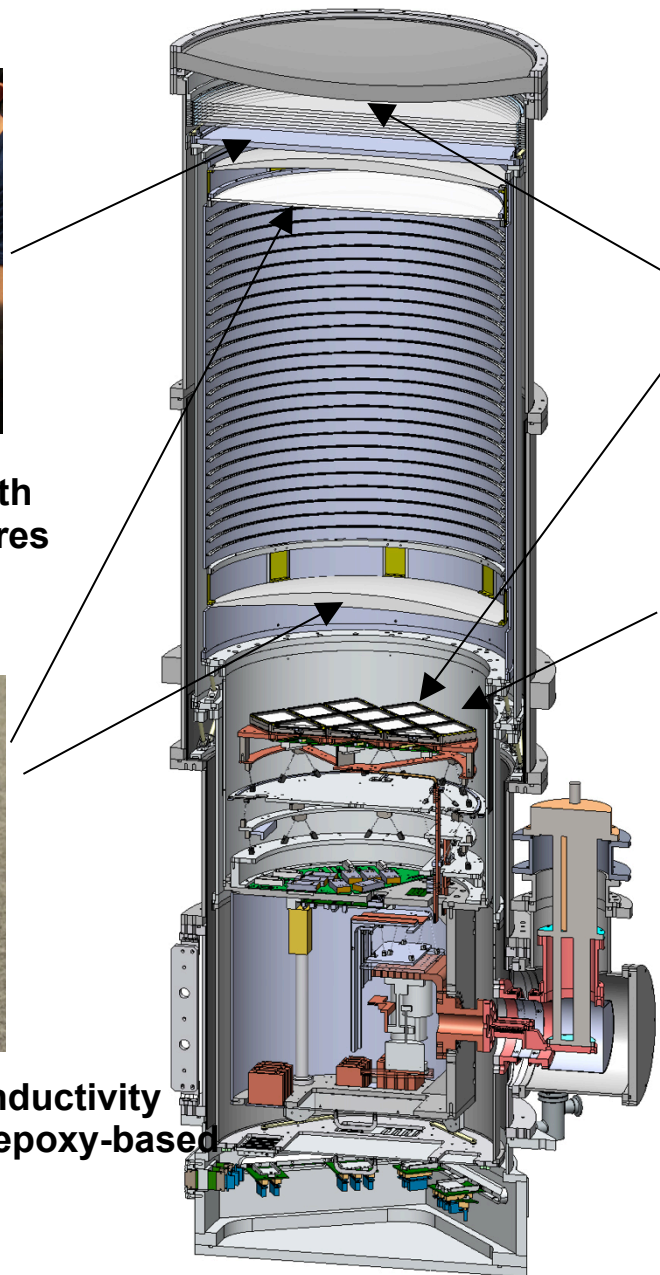


Large area Infrared shaders with $\sim O(10)$ micron aluminum features on mylar

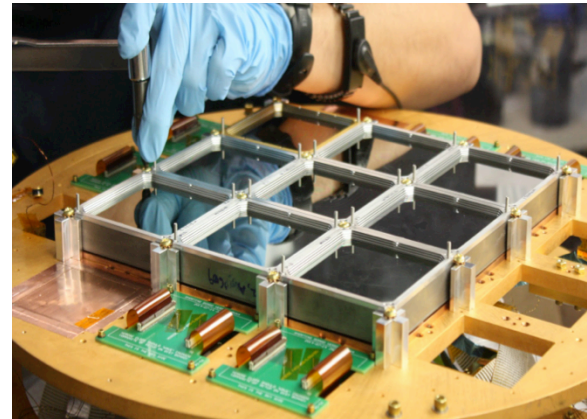


Thin, low loss, high thermal conductivity alumina filters and lenses with epoxy-based antireflection coating

Clem Pryke for The Bicep2 Collaborati



680-mm clear aperture window, fast optics (f/1.6), FOV $\sim 28^\circ$
95 GHz beam FWHM $\sim 0.35^\circ$



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

In 2015 BICEP3 (95GHz) plus Keck 220GHz

