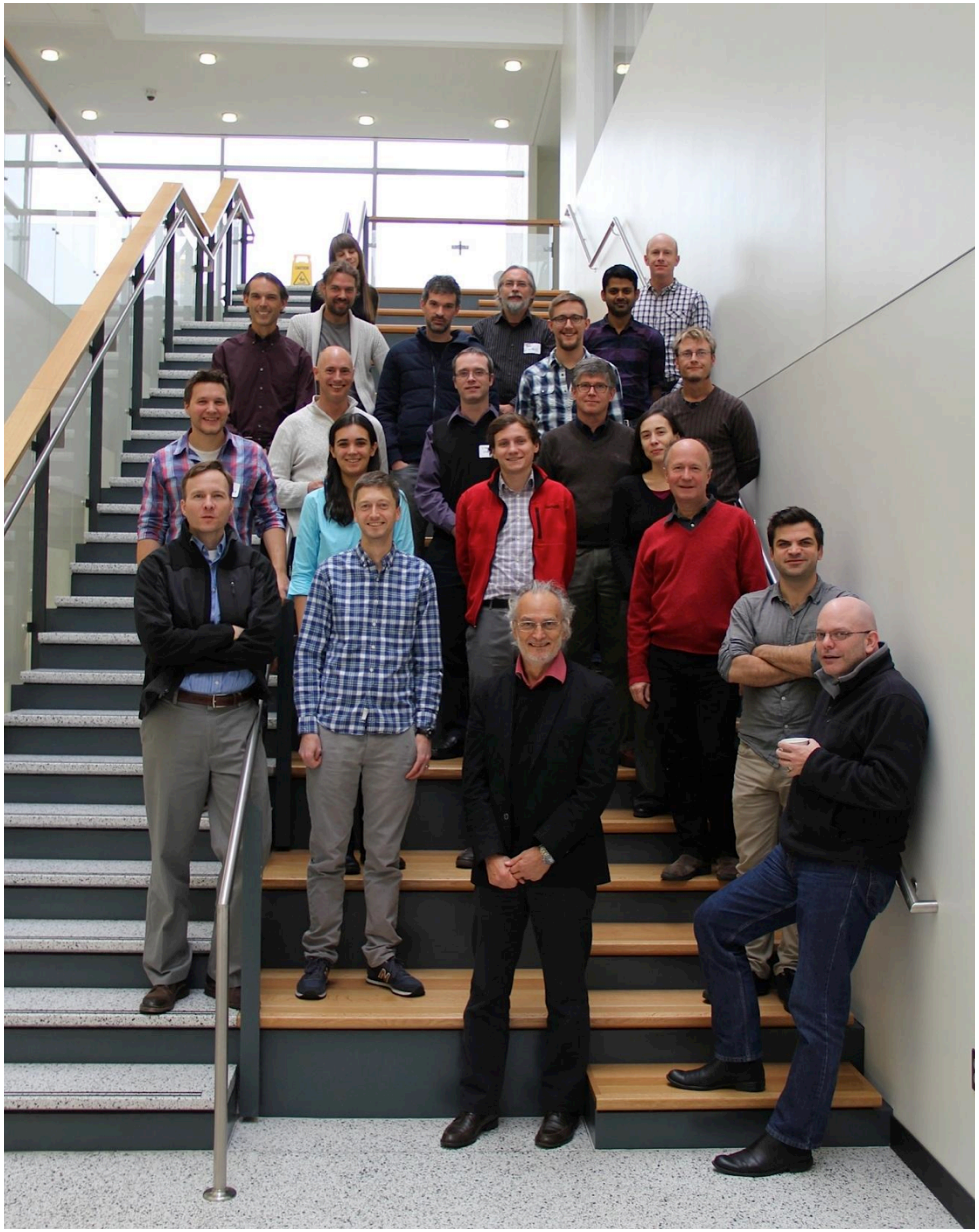
Results from Joint analysis of BICEP2/Keck and Planck data

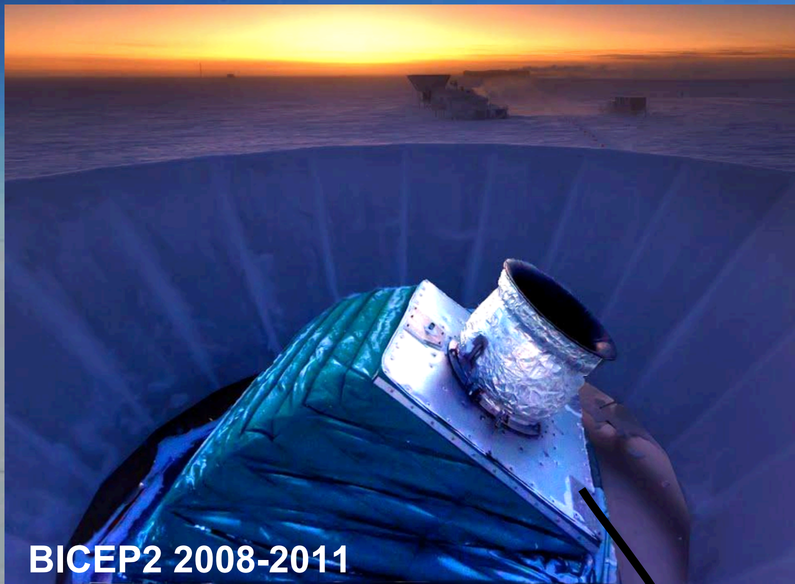


Clem Pryke
UMN Cosmo Seminar
Feb 16 2015

- In summer 2014 BICEP2/Keck and Planck collaborations made 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 (and provisionally accepted by PRL)

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

BICEP2 and Keck Array



BICEP2 2008-2011

x5

Keck Array 2011-present

Relentless observation of the CMB polarization from NSF’s station at the geographic South Pole

Dry, stable atmosphere, high altitude + 24h coverage of the Southern Sky

Compact cold refractive optics optimized for the angular scales of the inflationary signal

Superconducting phased antenna arrays

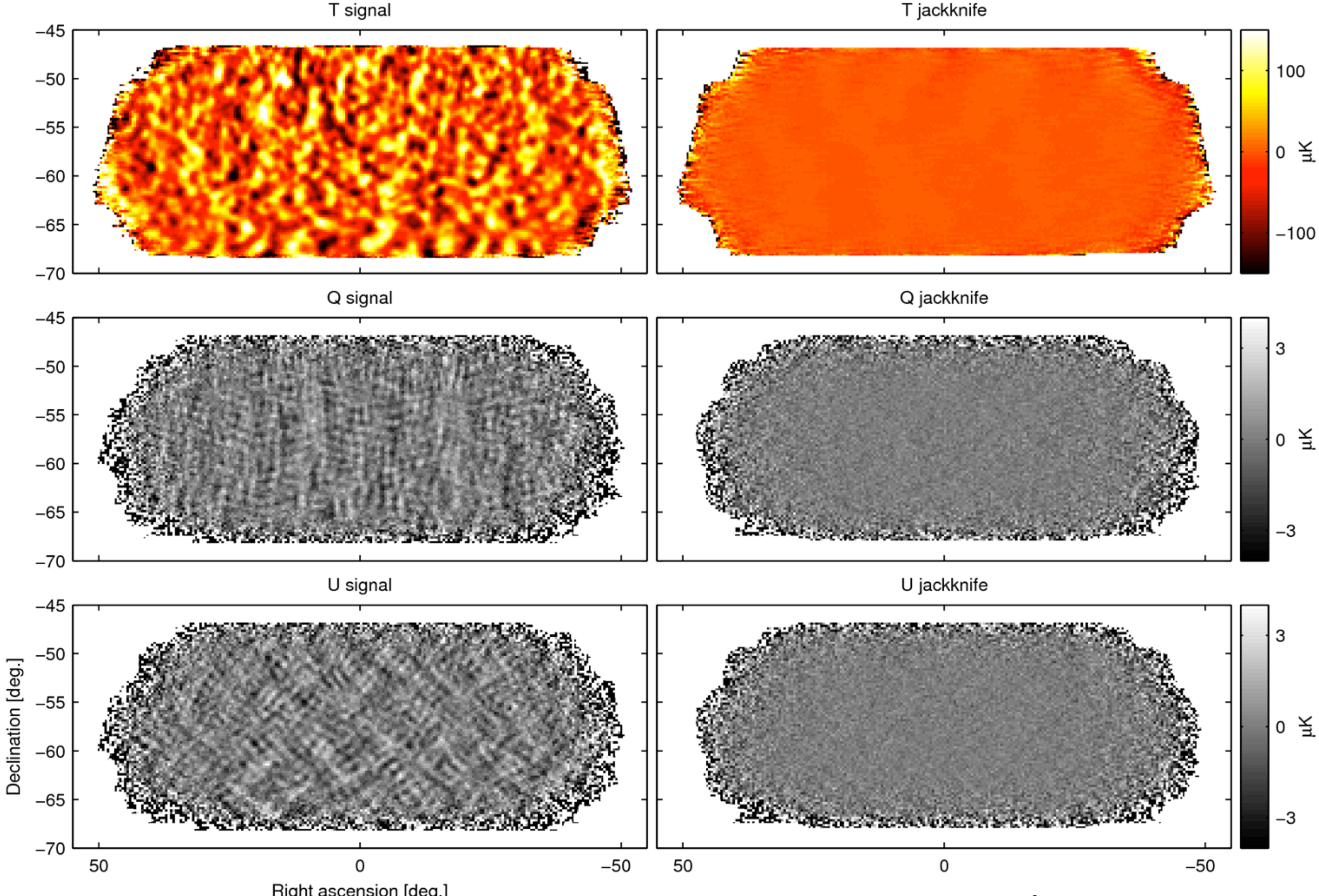
Observation at 150 GHz (Keck 2014 also at 95 GHz)
Focus on ~**400 deg^2** patch = 1% of the sky

3yrs of BICEP2 + Keck 2012/13

→ **Final map depth: 3.4 μK arcmin / 57 nk deg** (RMS noise in sq-d

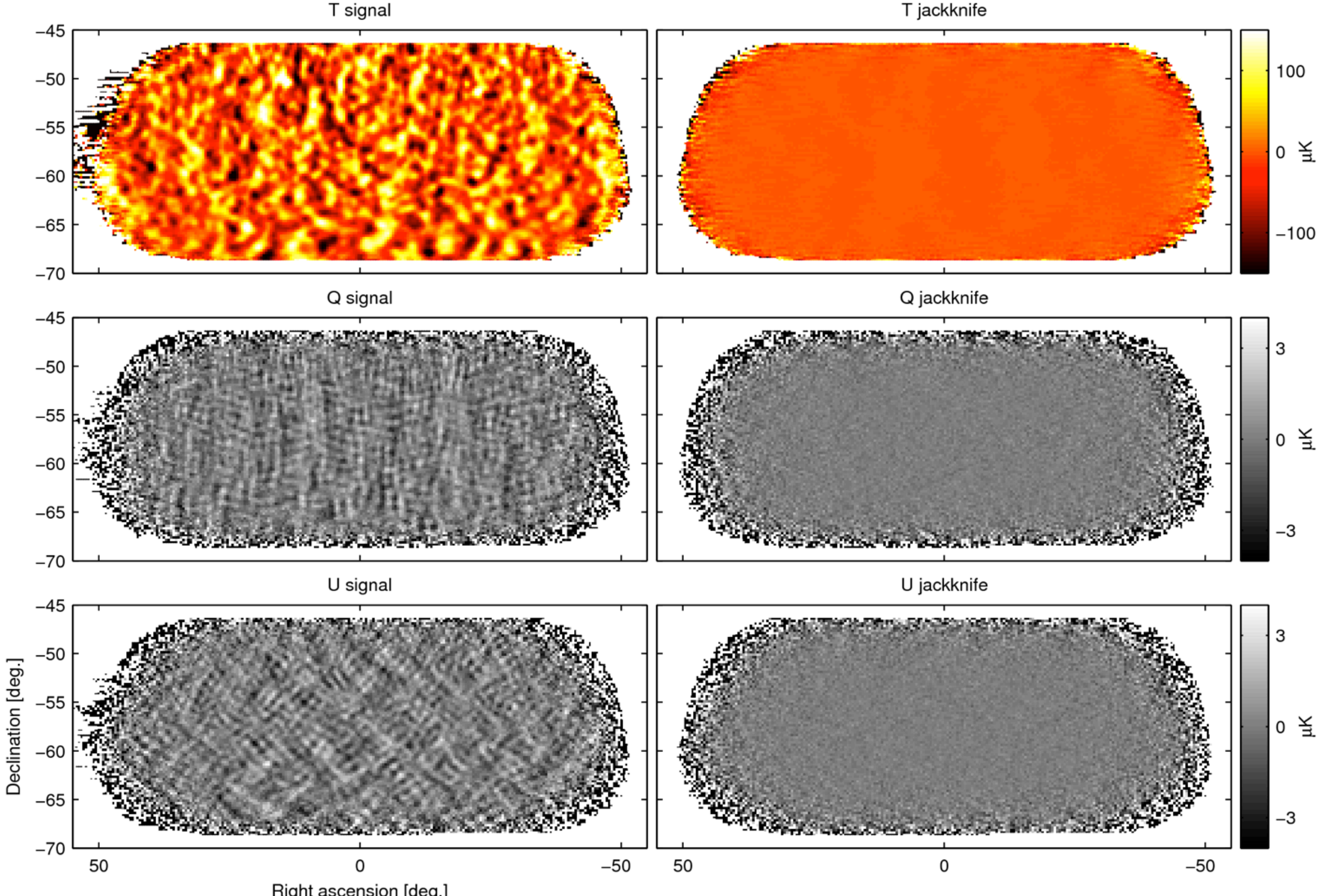
Deepest map of the CMB polarization ever made!

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 arxiv:1403.3985

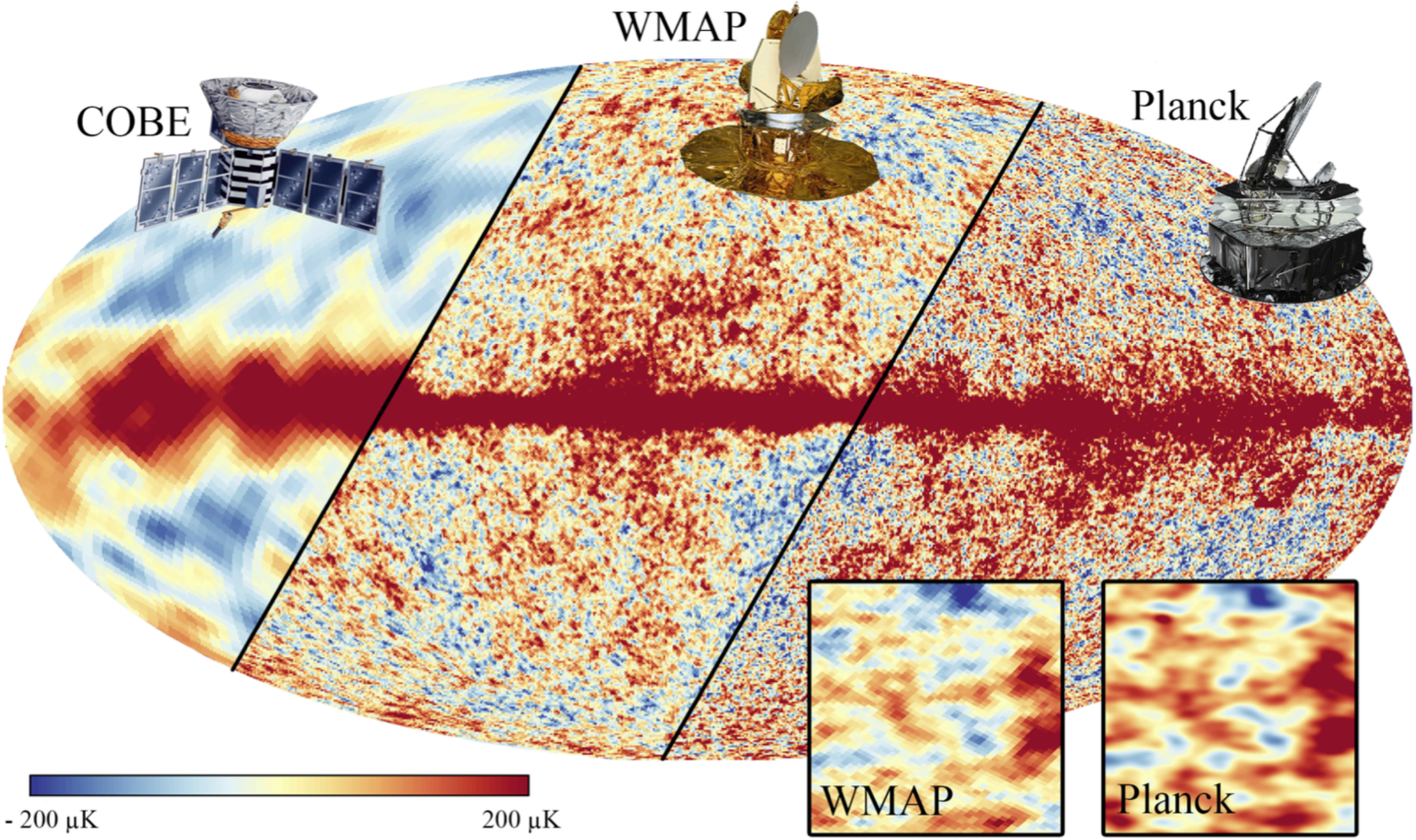
B2+Keck 150 GHz T/Q/U maps of small sky patch



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

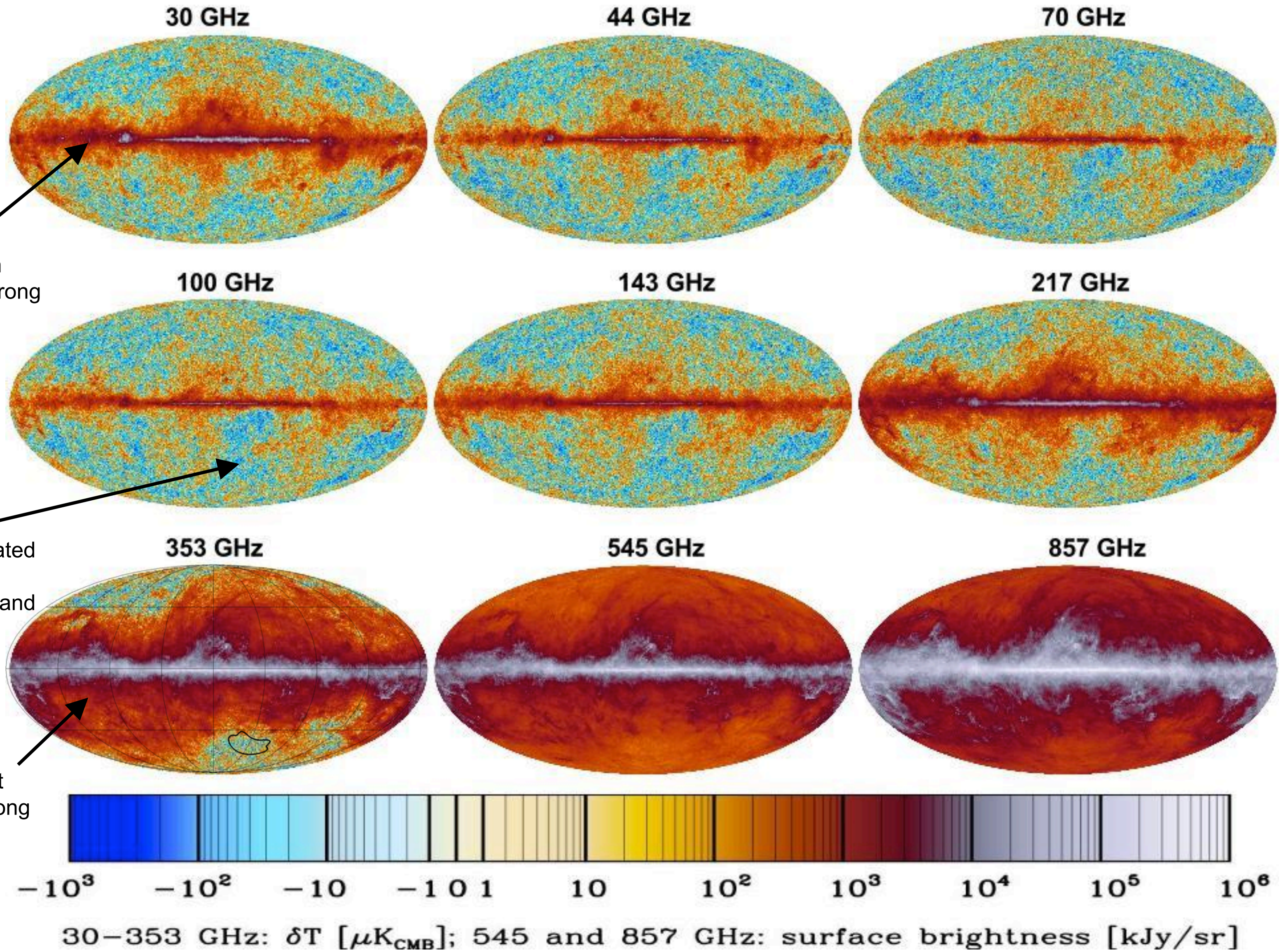
Planck



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

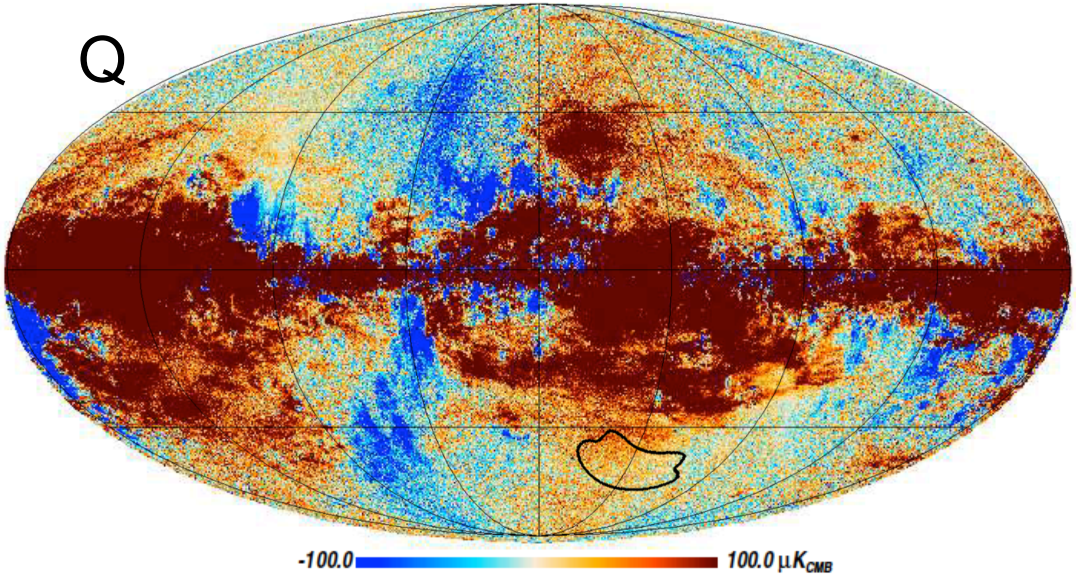
Galactic dust emission strong at high frequencies

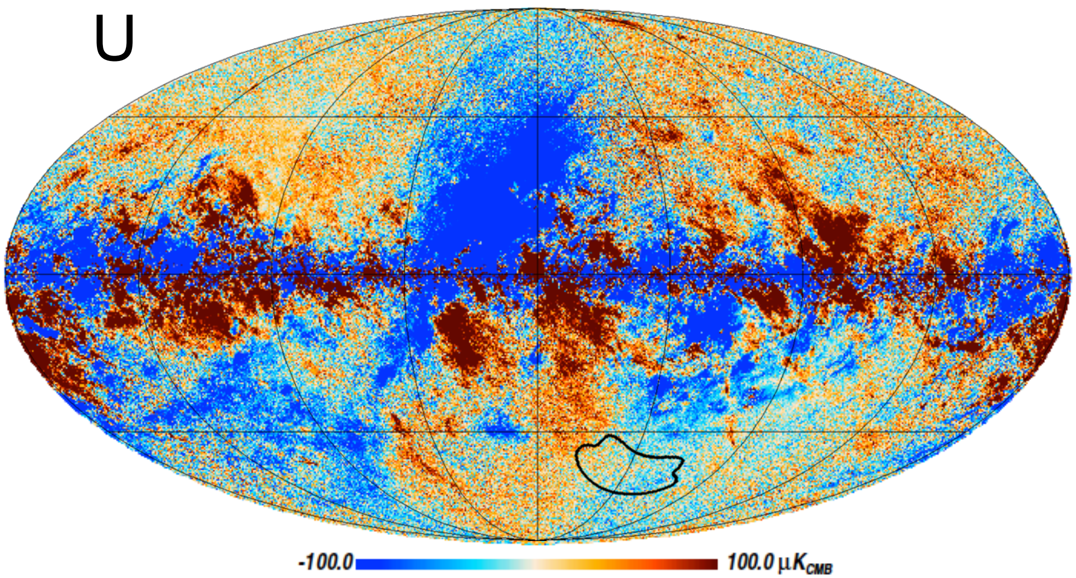
Full sky coverage and 9 frequencies - but not as deep as BICEP2/Keck in any given region of the sky

Bicep2, Keck Array and Planck Collaboration

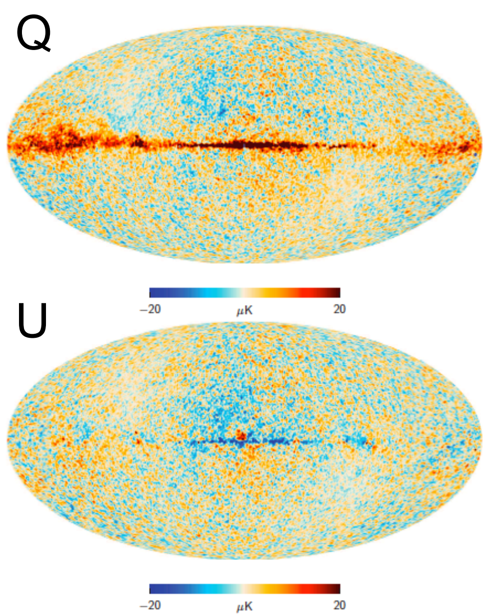
Planck 353 GHz full sky maps in polarization

- 353 GHz polarized maps are dominated by Galactic dust emission



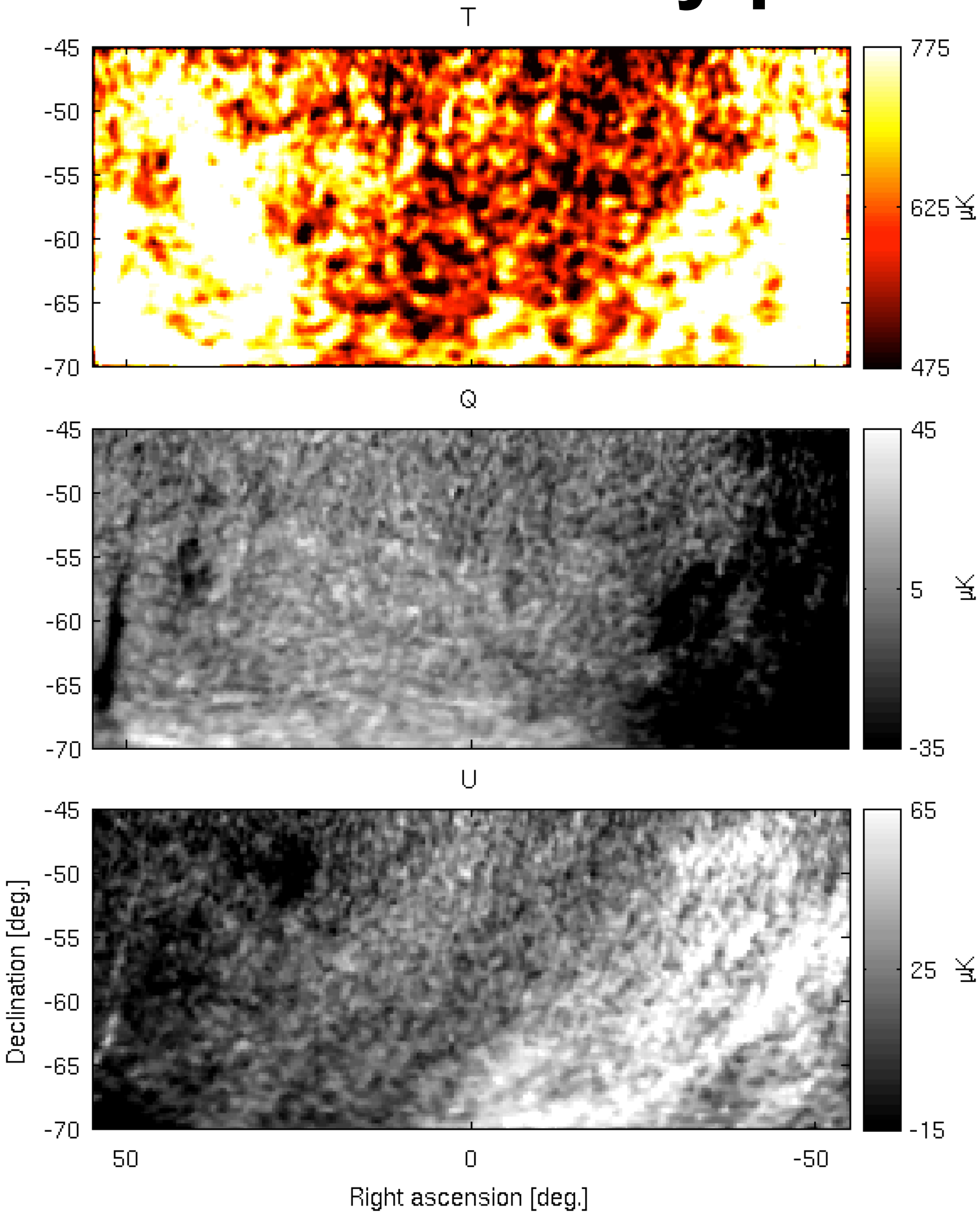


For comparison, Planck 70 GHz is close to the minimum of Galactic foreground emission



Bicep2, Keck Array and Planck Collaboration

Zoom in on BK sky patch...

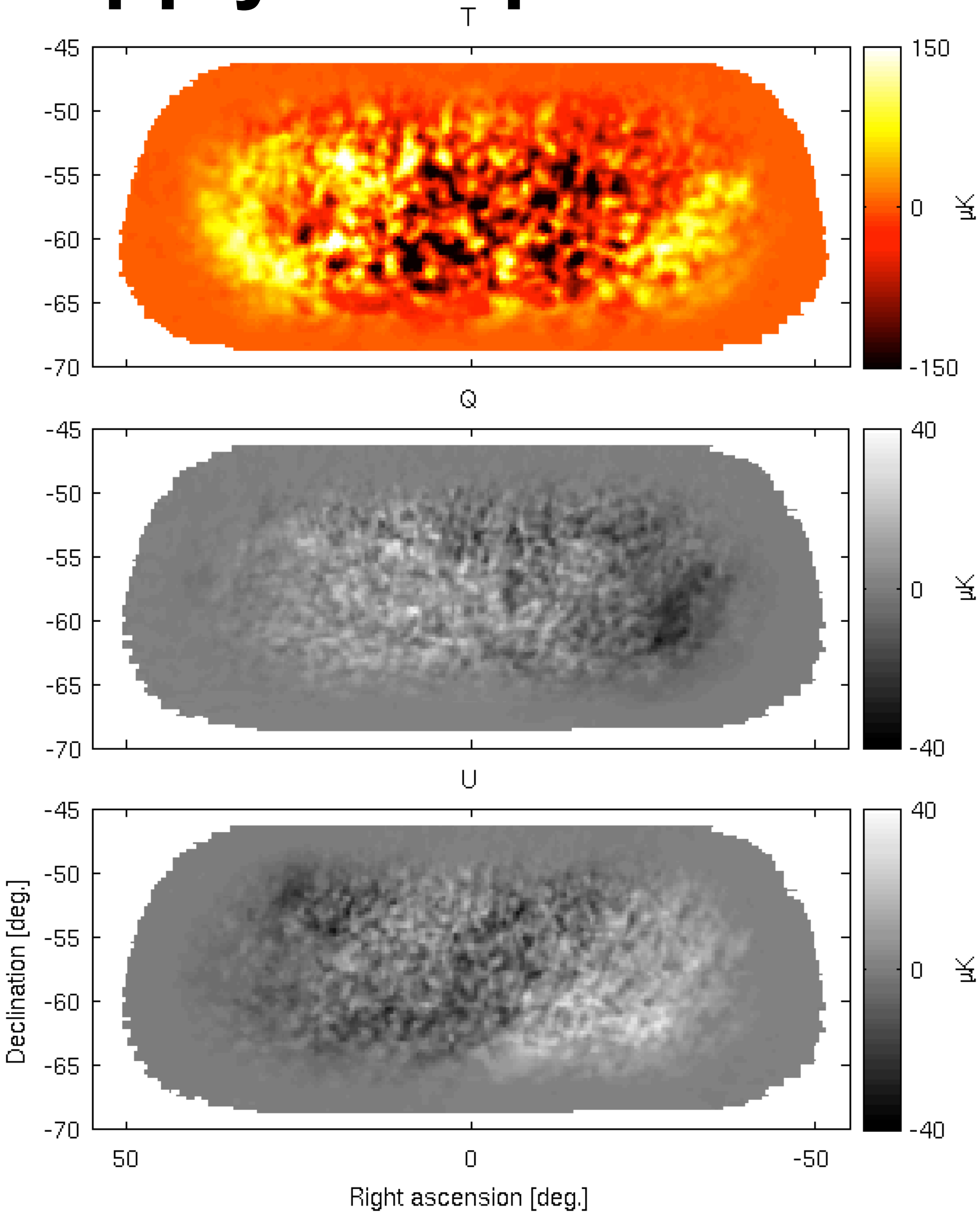


Planck 353GHz maps in BICEP2/Keck sky region

(re-smoothed to BICEP2/Keck beam size)

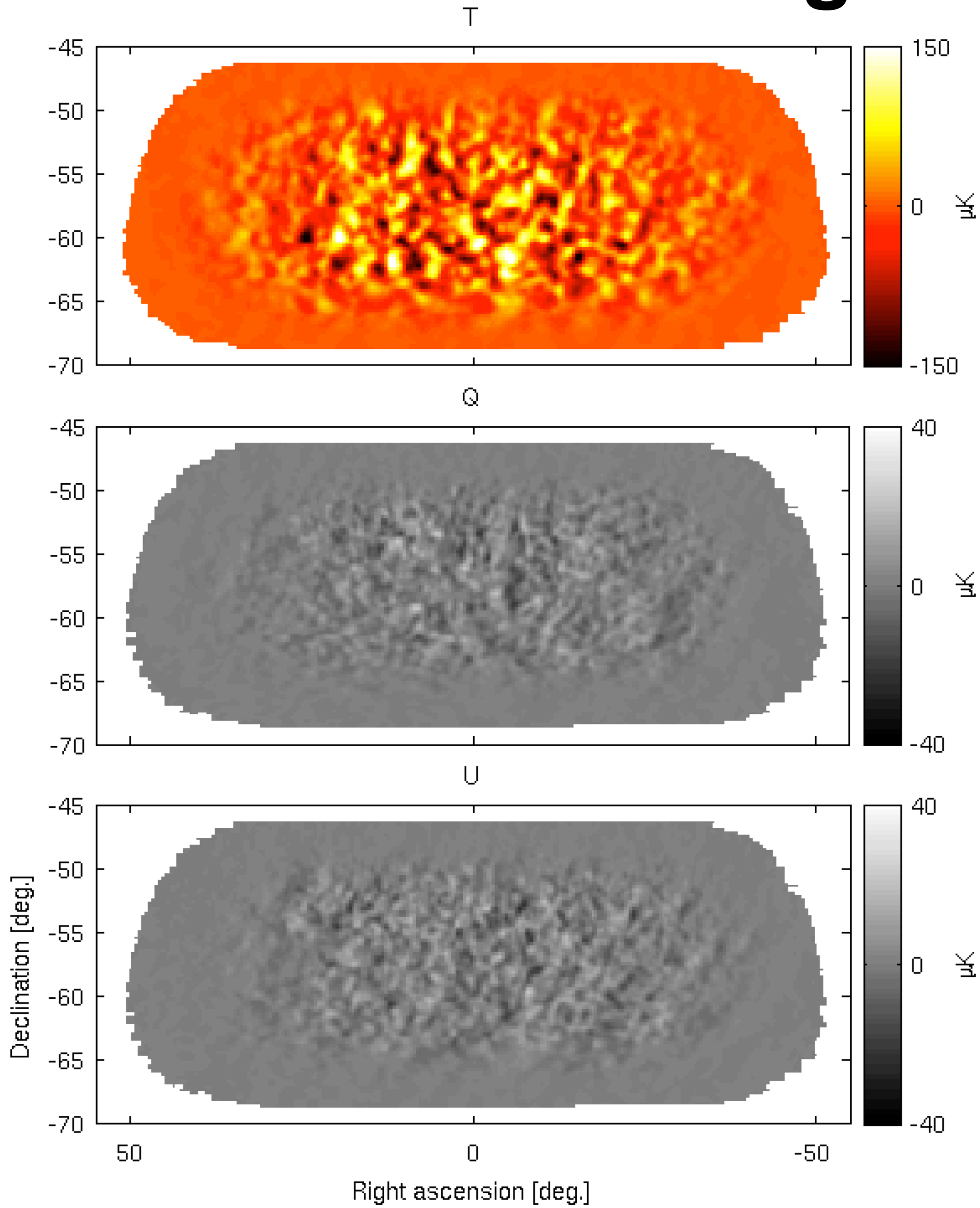
Bicep2, Keck Array and Planck Collaboration

...apply BK apodization...



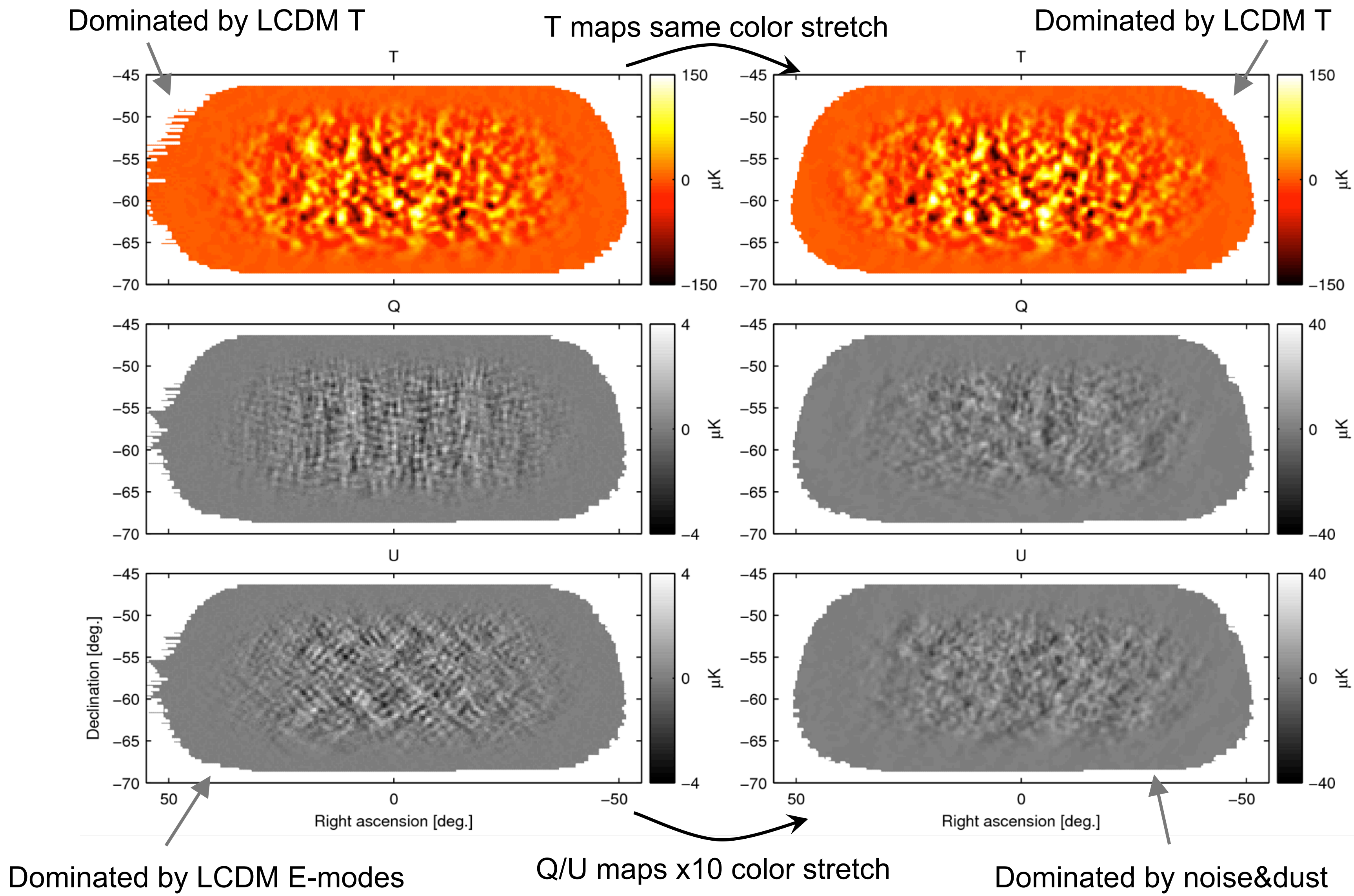
Planck 353GHz maps in BICEP2/Keck sky region with mean subtracted and apodization mask applied

...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

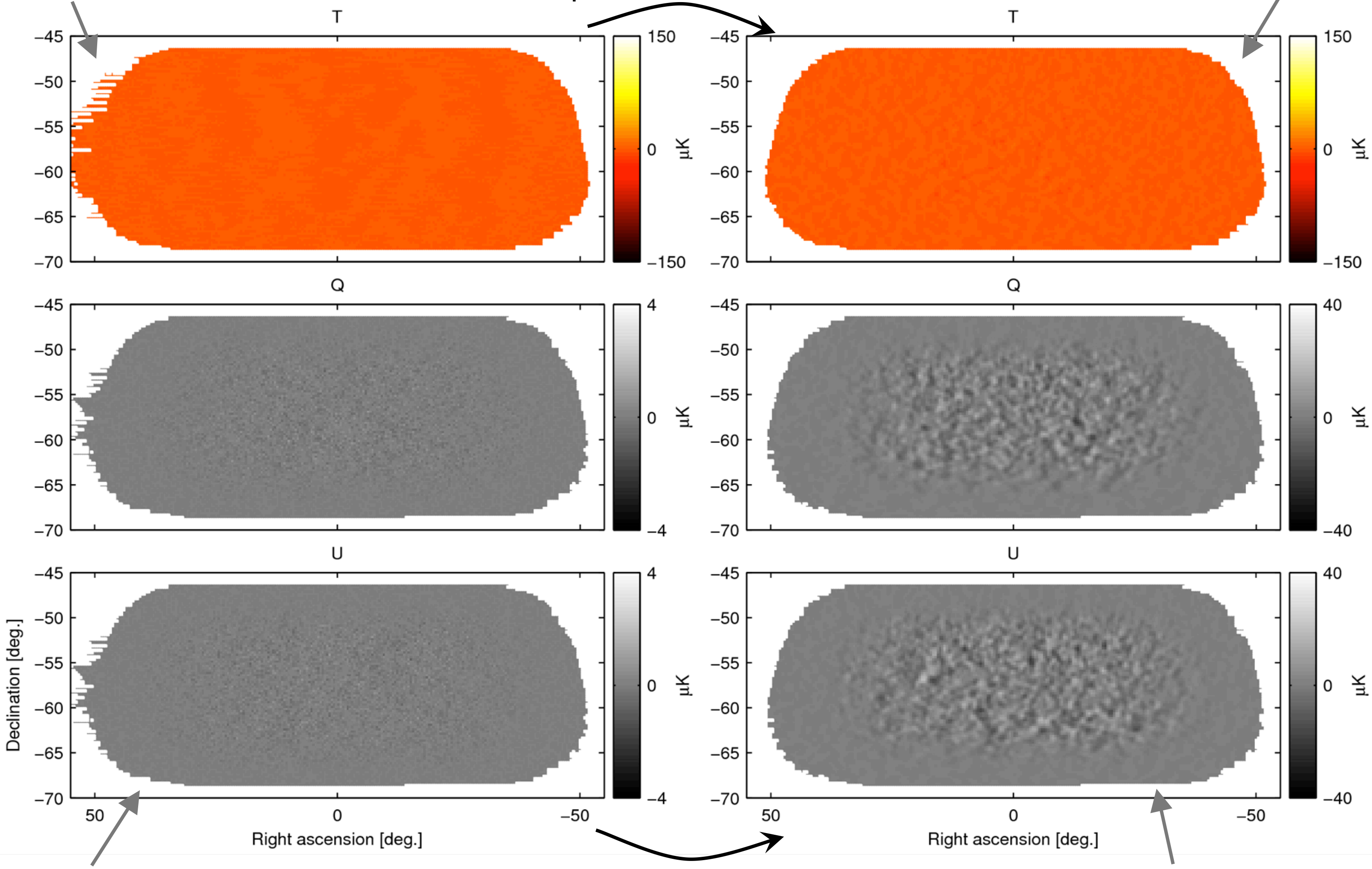
Bicep2, Keck Array and Planck Collaboration

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

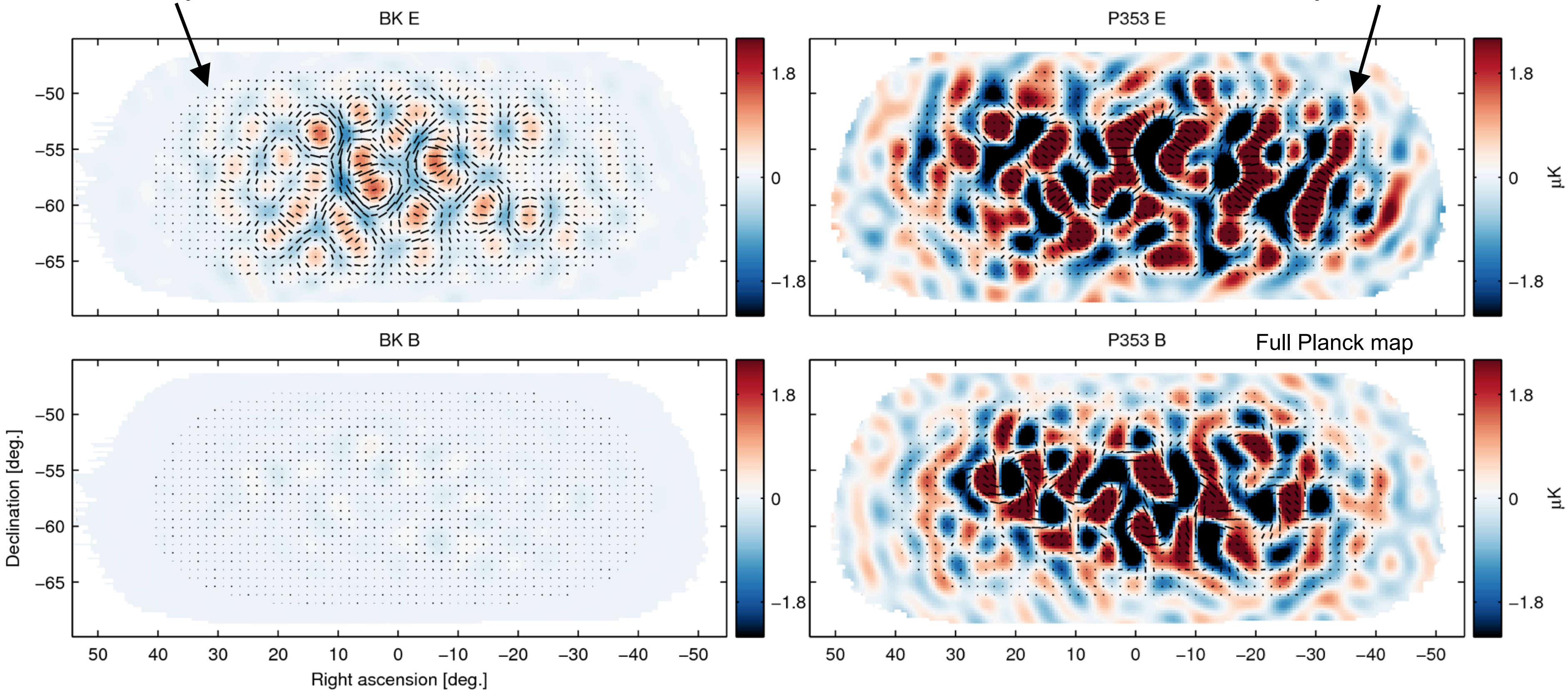
A Noise Simulation

Bicep2, Keck Array and Planck Collaboration

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

Dominated by LCDM E-modes

Dominated by noise & dust



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

all maps shown with the same color stretch

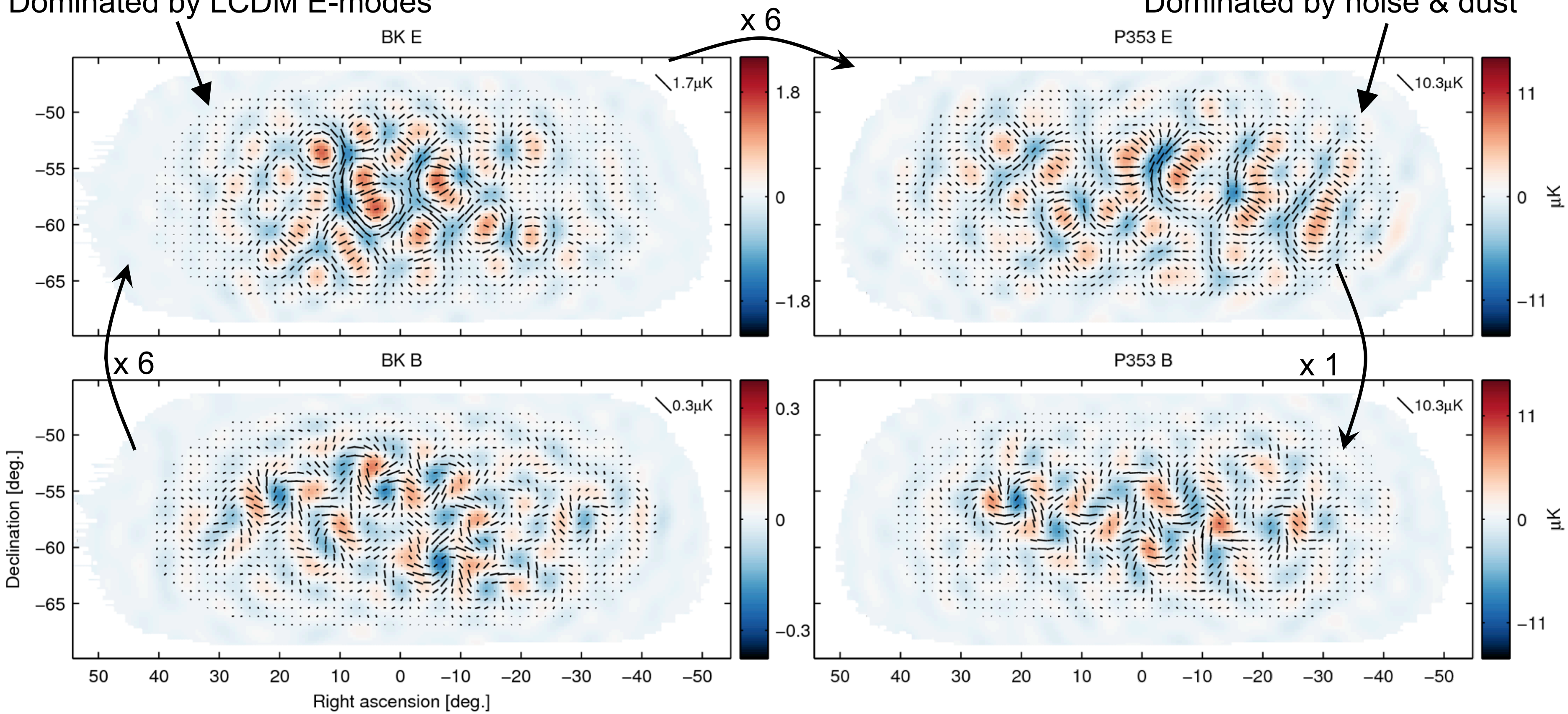
The Real Data

Bicep2, Keck Array and Planck Collaboration

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

Dominated by LCDM E-modes

Dominated by noise & dust



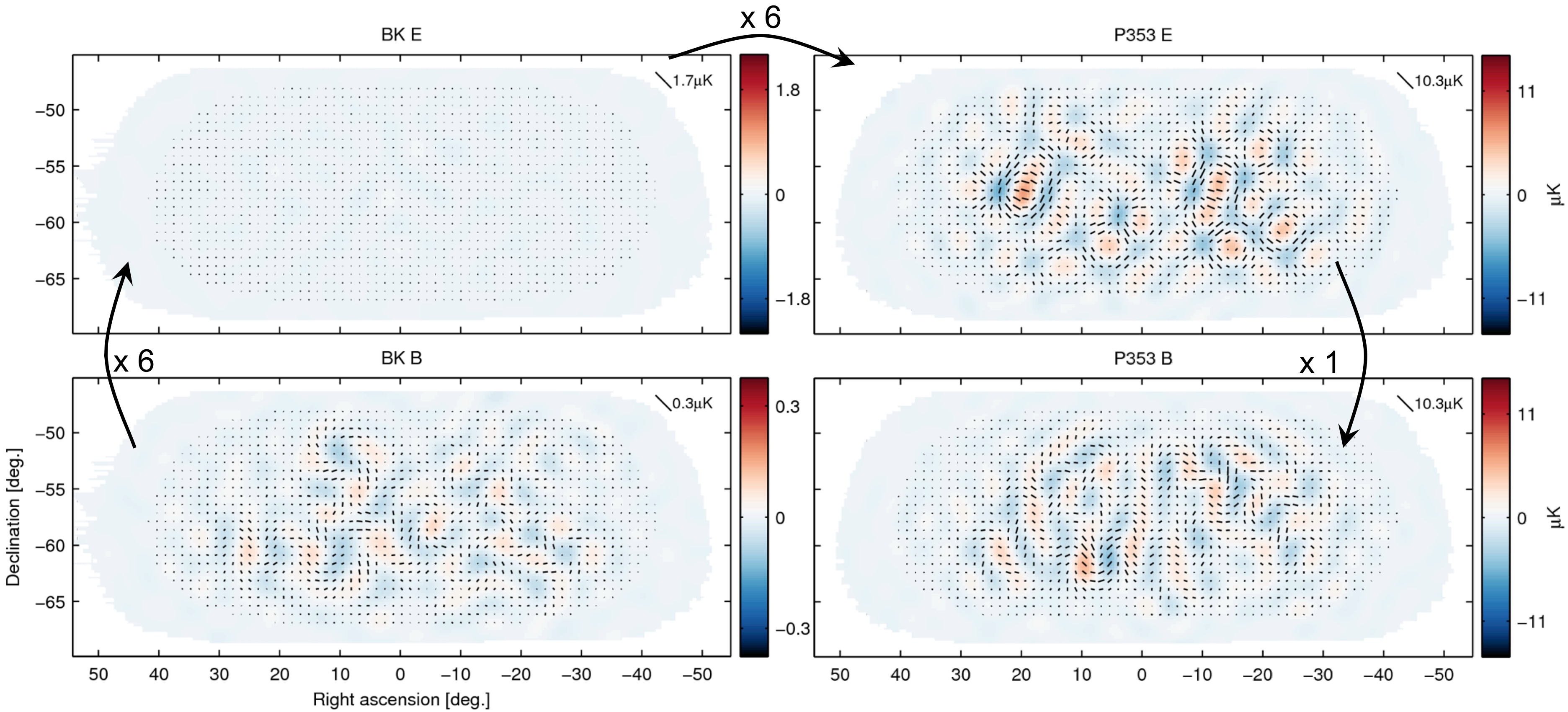
E-modes and B-modes filtered to range l=50-120

color stretch adjusted between maps by factor indicated

The Real Data

Bicep2, Keck Array and Planck Collaboration

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



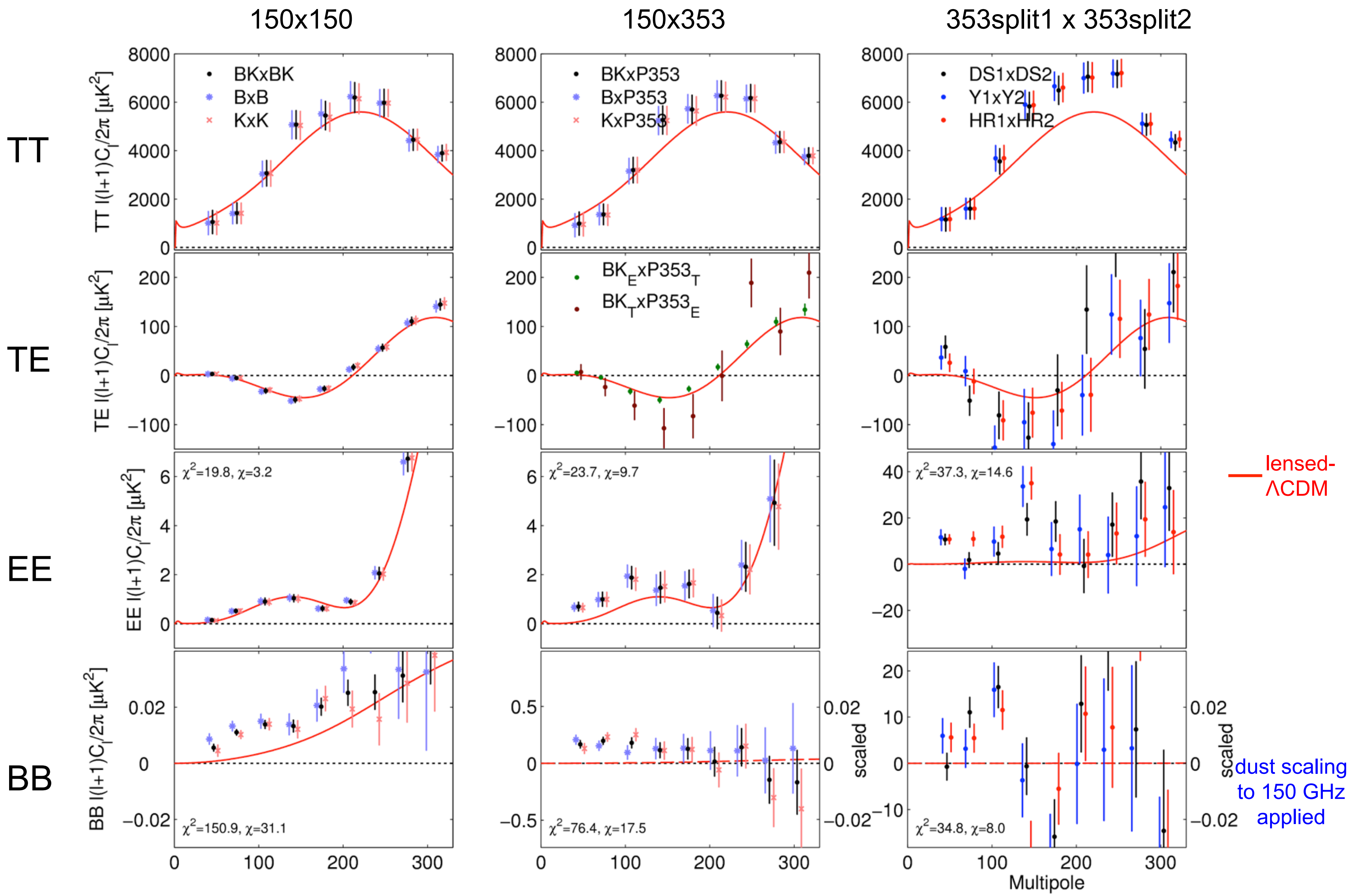
E-modes and B-modes filtered to range l=50-120

color stretch adjusted between maps
by factor indicated

A Noise Simulation

Bicep2, Keck Array and Planck Collaboration

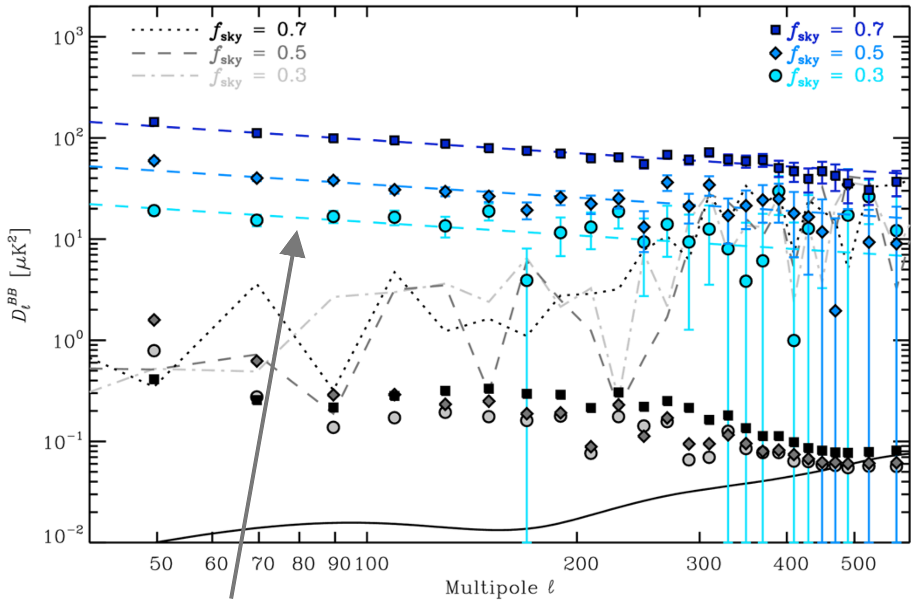
Single- and Cross-Frequency Spectra



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:

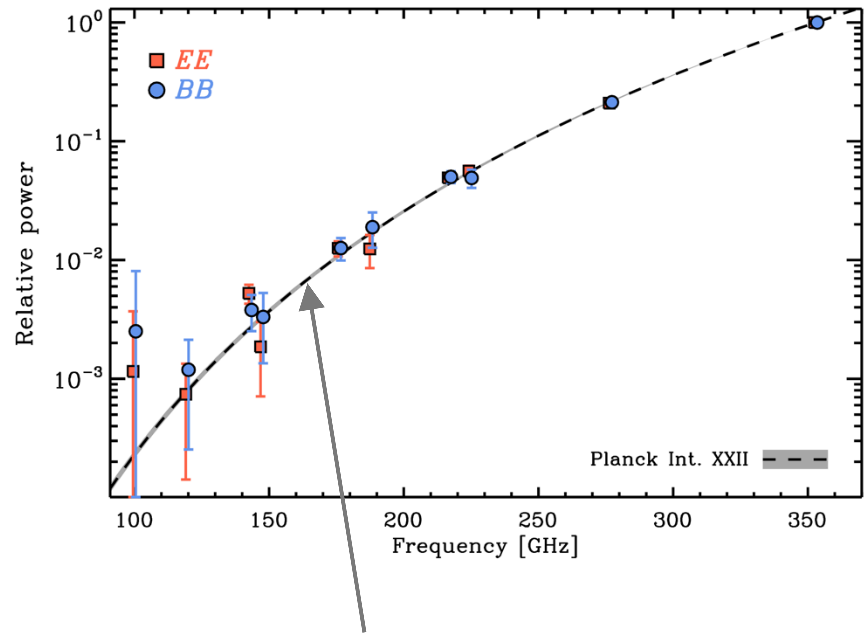
Fig 2 of arxiv:1409.5738



Dust EE/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
- EE/BB=2 on average and no evidence for deviation from this for

Fig 6 of arxiv:1409.5738

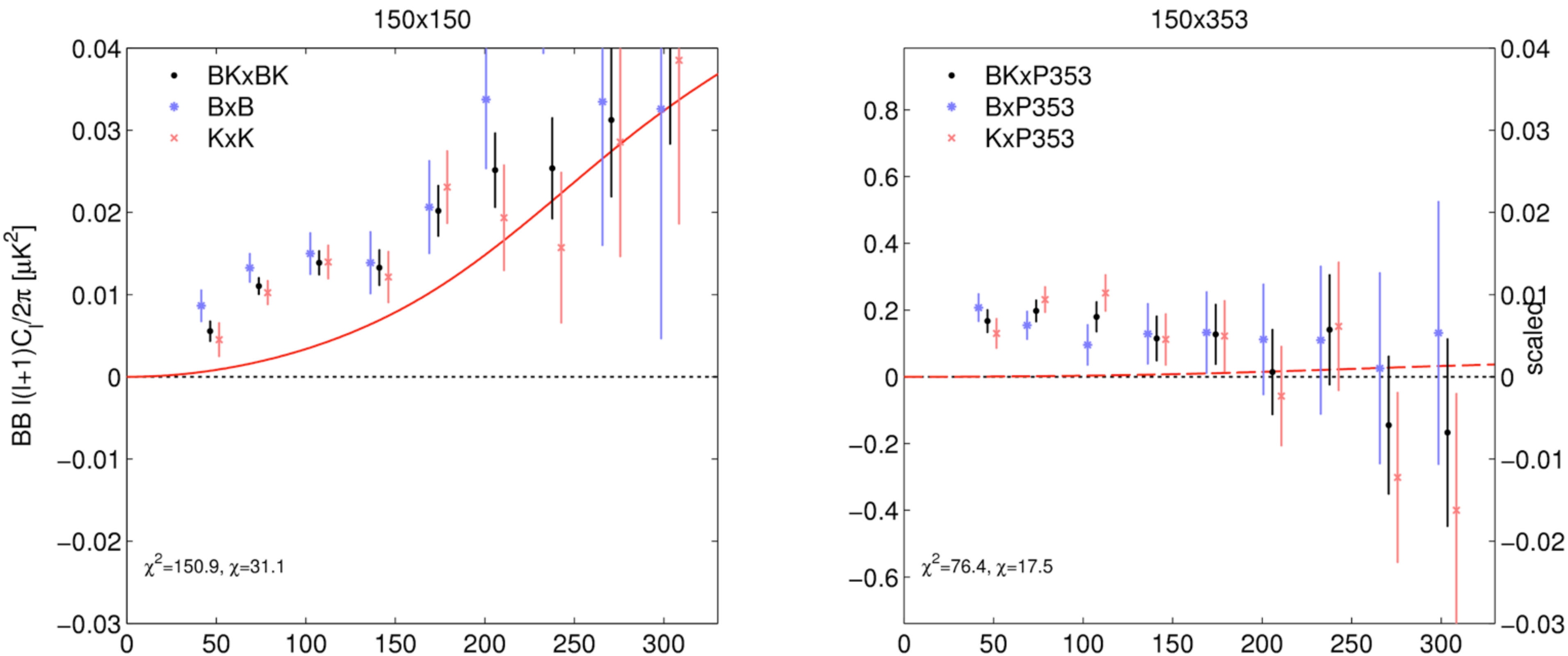


Spectral energy distribution of polarized dust emission follows modified blackbody model with T=19.6K and β_d=1.59

- 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?

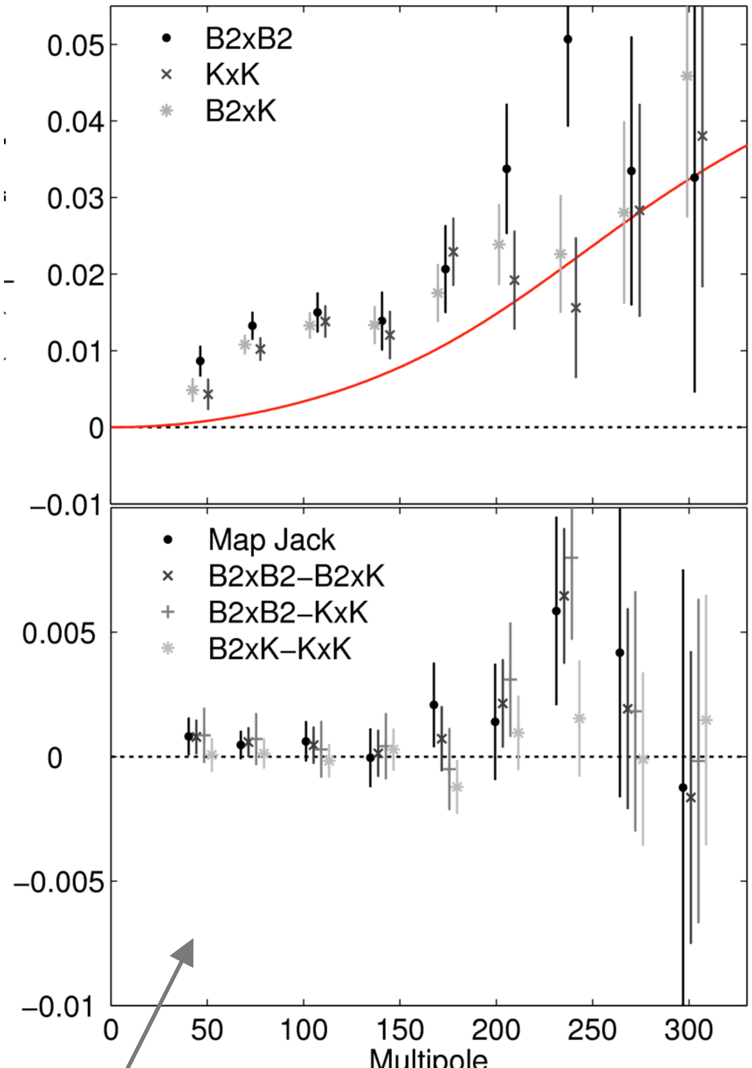


Fig 8 of Keck paper
(Note these tests are not independent)

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

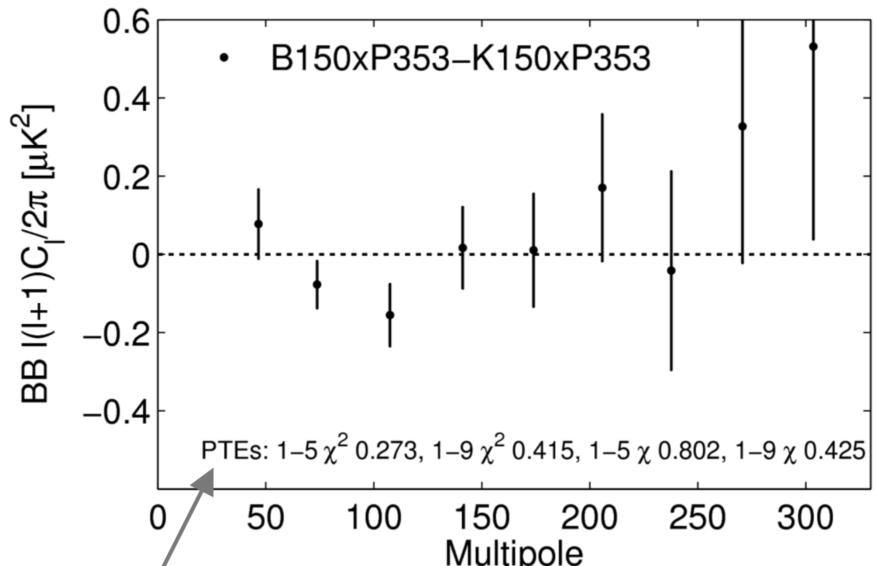
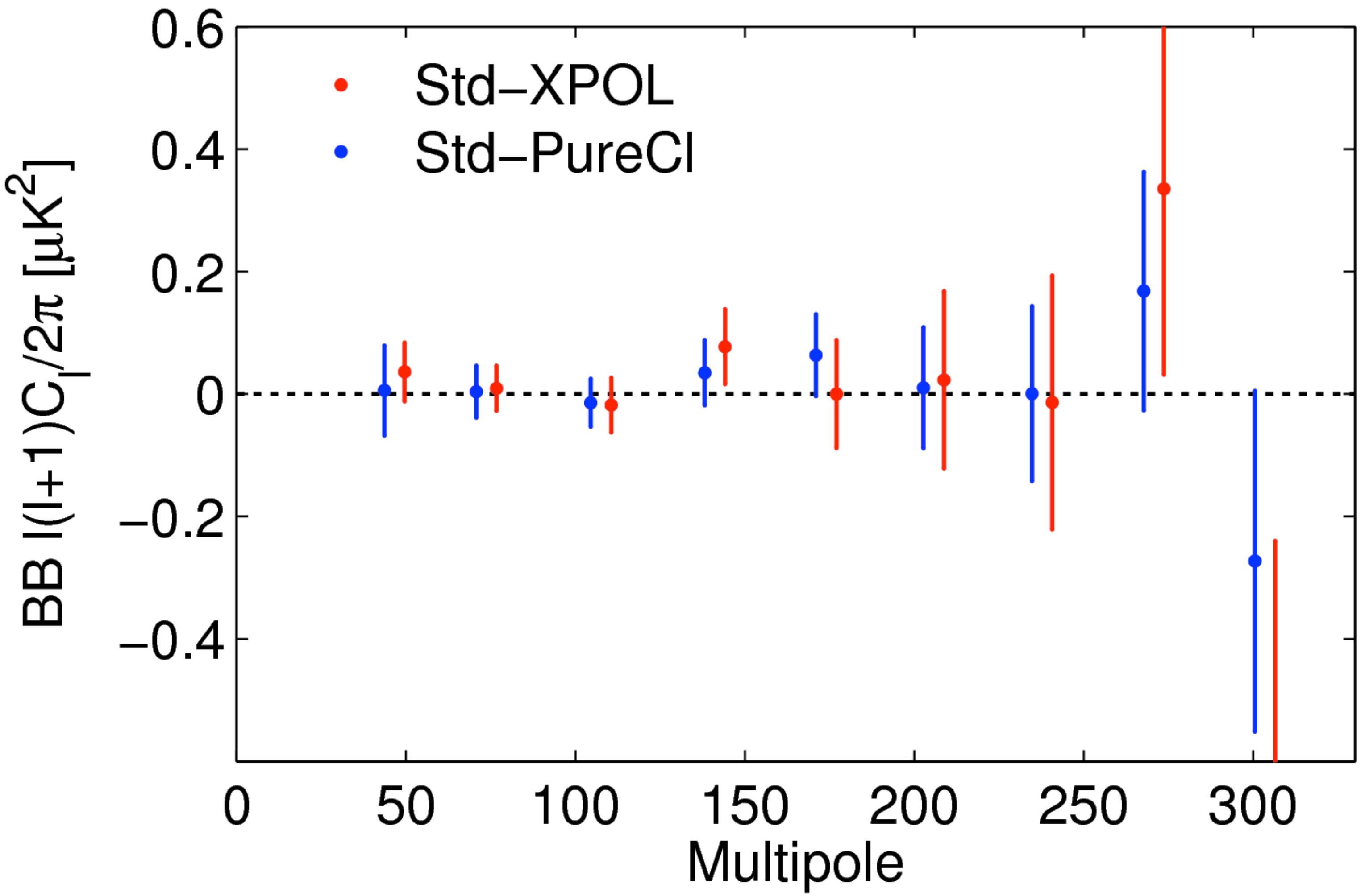


Fig 4 of BKP paper

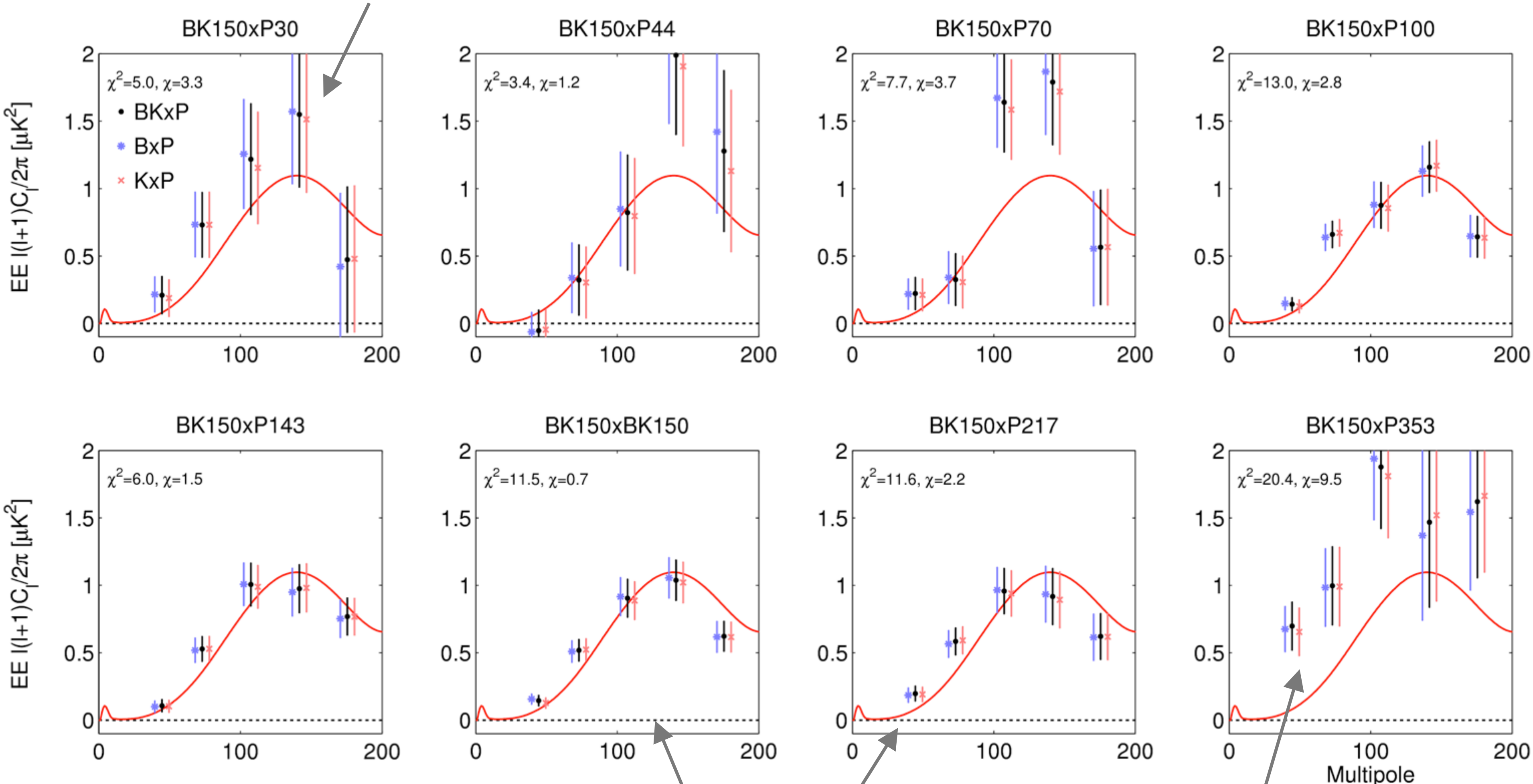
Check the power spectrum estimation



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...

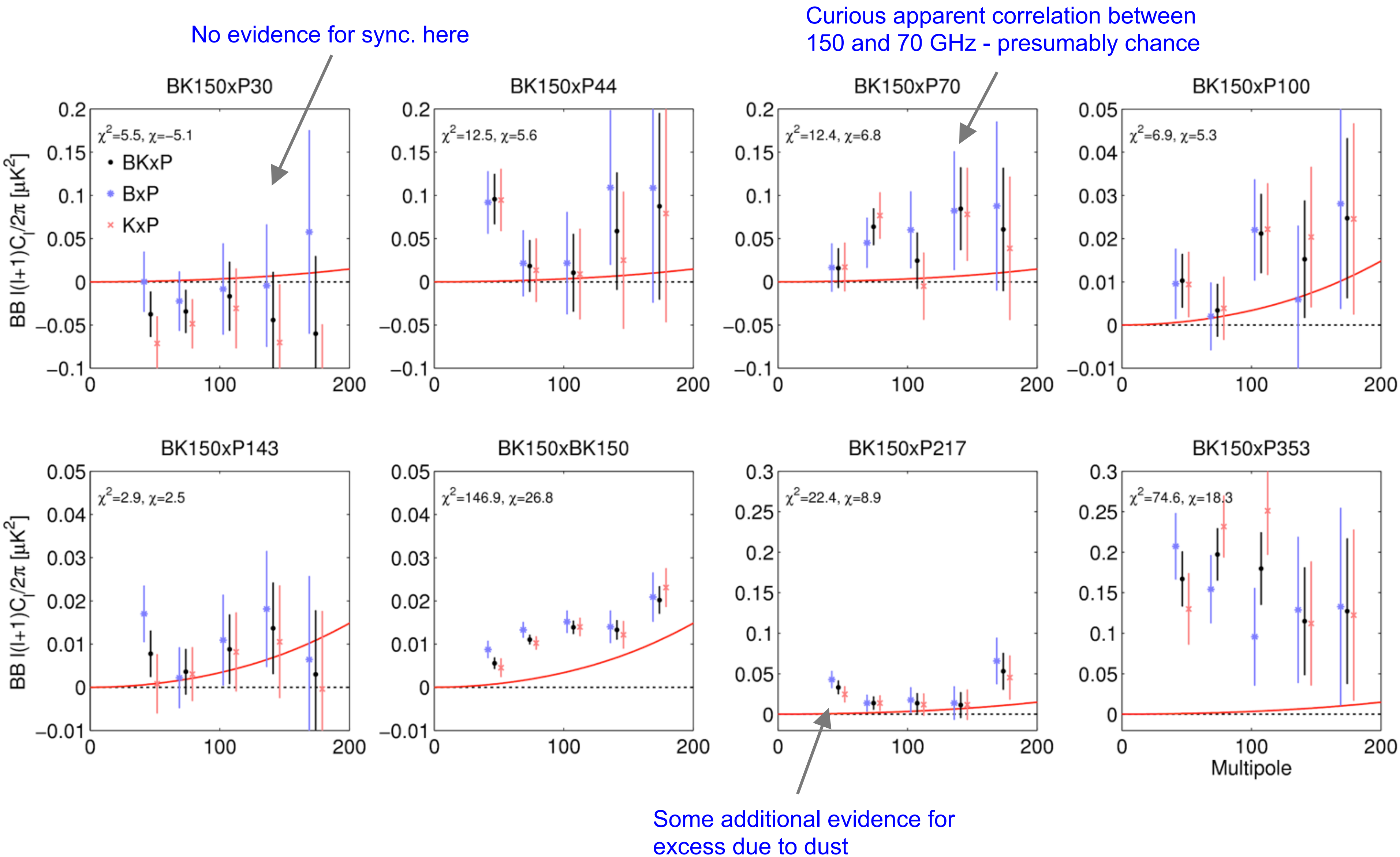


These two basically look the same - suggesting dust contribution in BK150xBK150 EE is small fraction

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

Bicep2, Keck Array and Planck Collaboration

Look at cross spectra with other Planck frequencies - BB



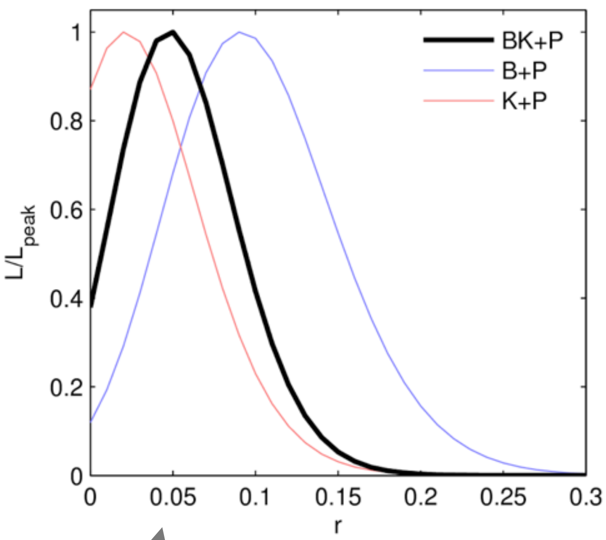
Multi-component multi-spectral likelihood analysis

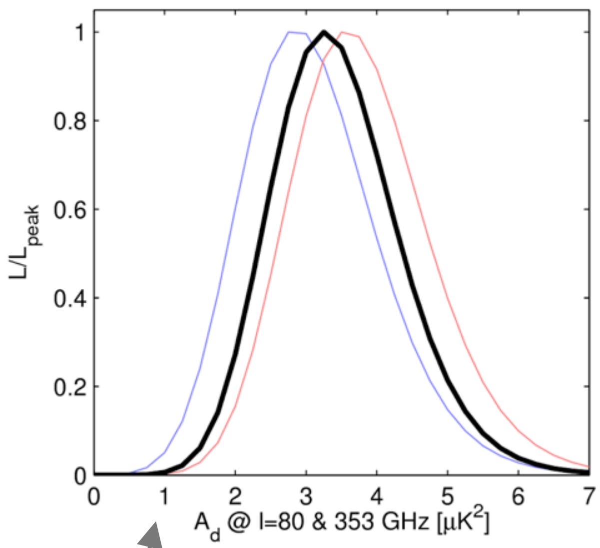
- Define "fiducial analysis" to use single- and cross-frequency spectra between BK 150 GHz and Planck 217&353 GHz channels
  - (Detail: for Planck single-frequency use detector set split cross spectrum)

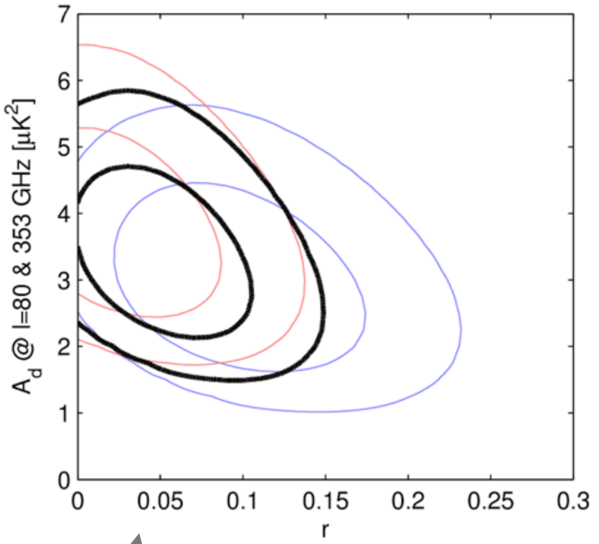
- As addition to basic LCDM lensing signal include gravity wave signal (with amp r) and dust signal with amplitude A_d (specified at ℓ =80 and 353 GHz)
  - For dust SED use modified blackbody model and marginalize over range β_d=1.59±0.11

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

Multi-component multi-spectral likelihood analysis





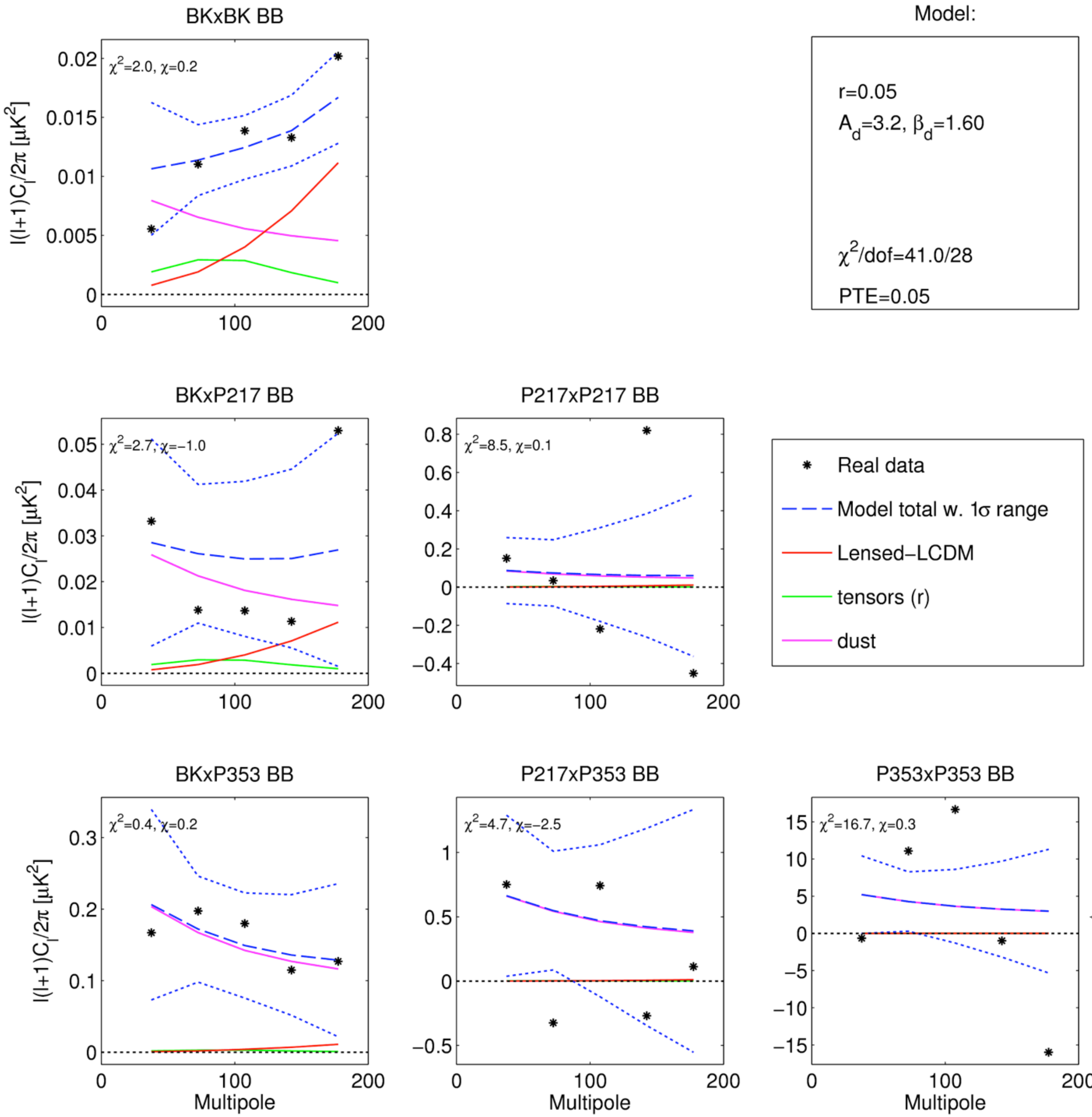


r constraint consistent with zero (For BK+P L_0/L_{peak} ratio is 0.4 which happens 8% of the time in a dust only model.)

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*

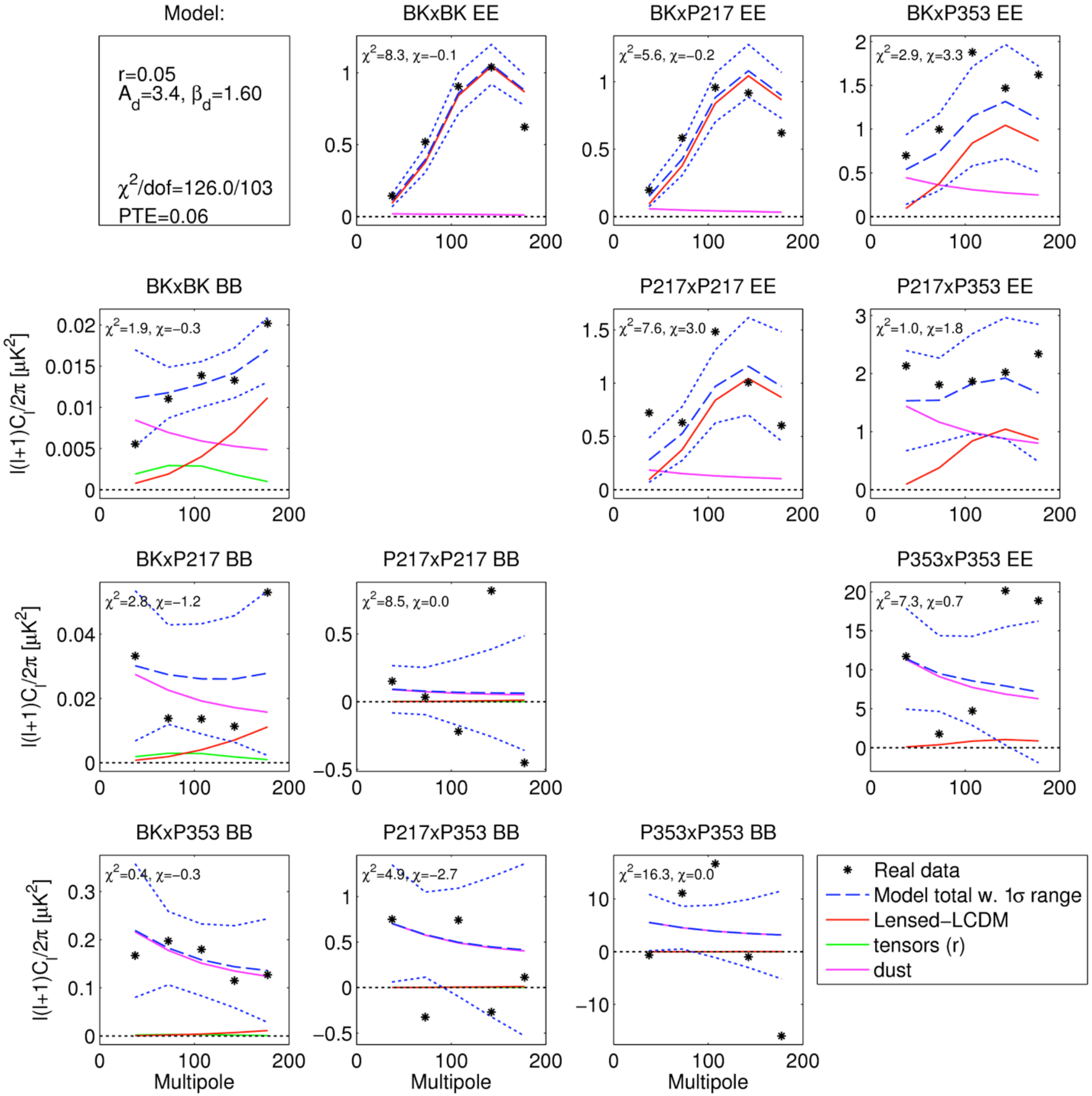
Best fit model



- ➢ 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)

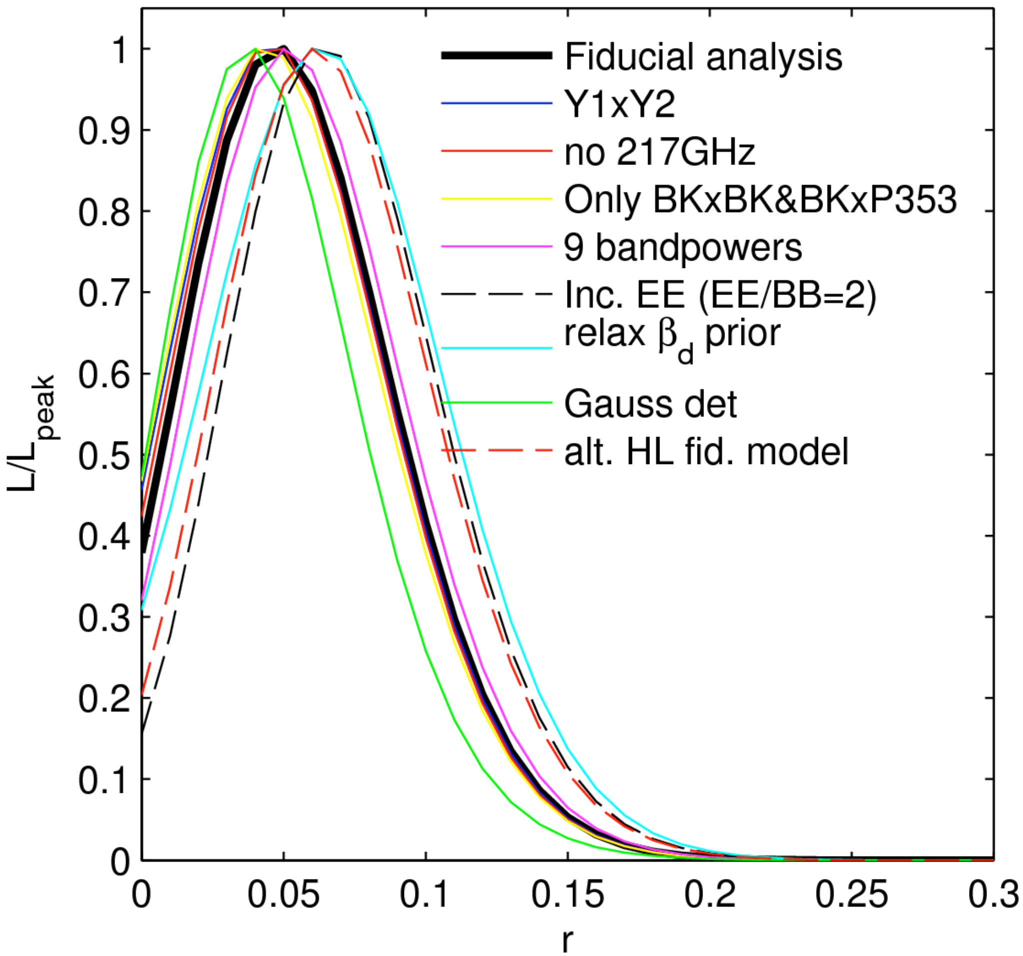
Best fit model including EE spectra



- 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.

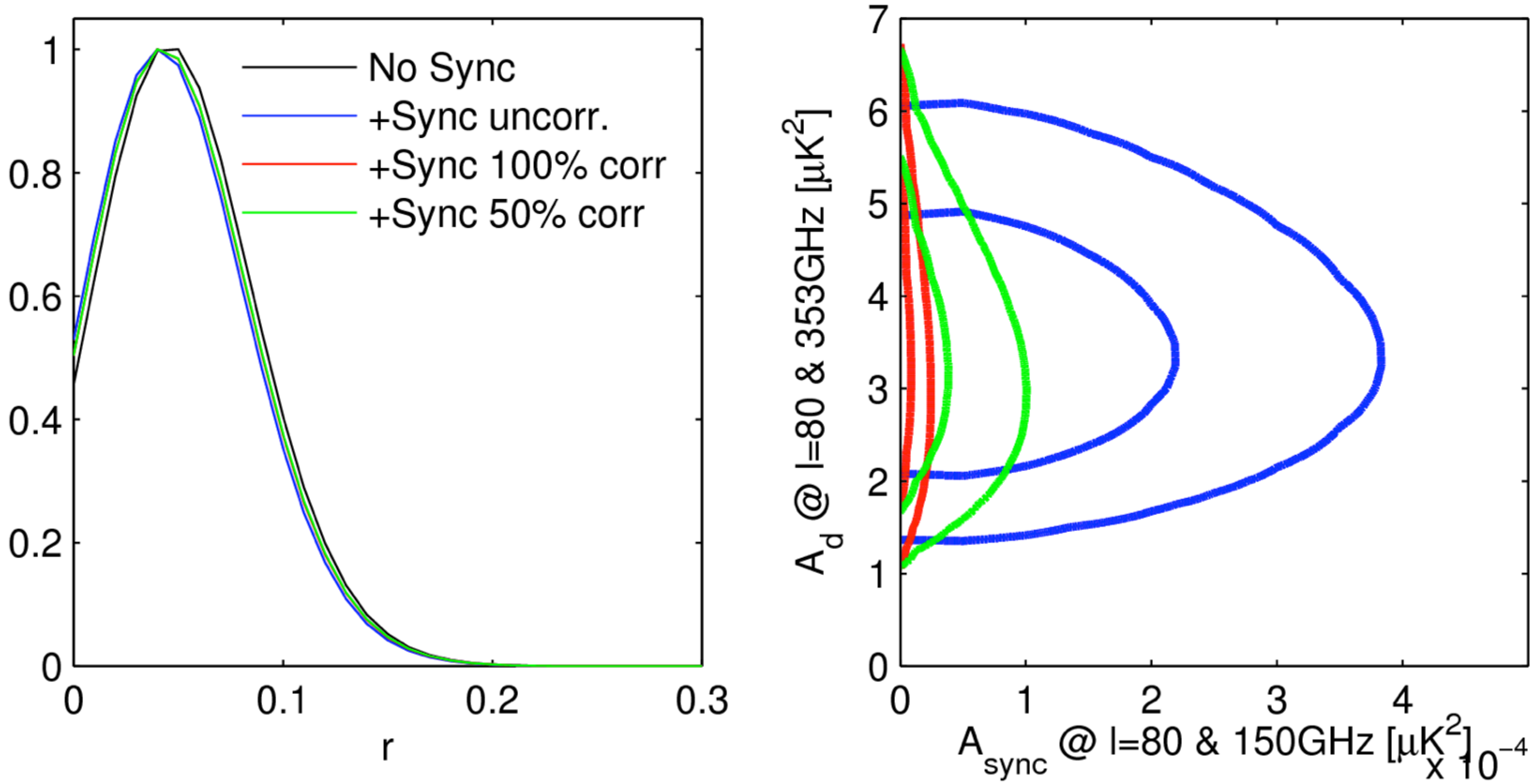
Bicep2, Keck Array and Planck Collaboration

Variations on fiducial analysis



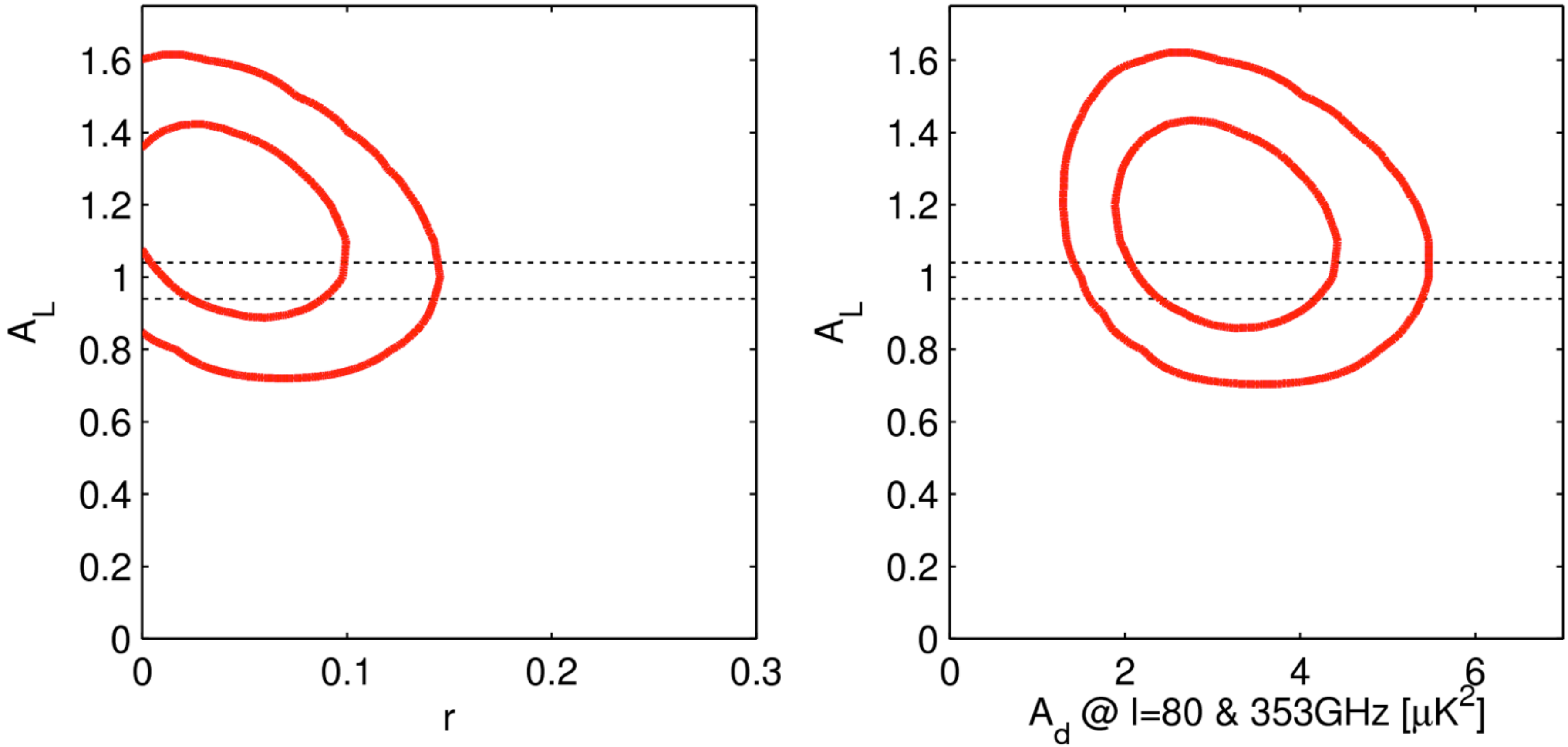
- ➢ We consider a range of variations on the fiducial analysis
- ➢ Most make little difference - see paper for details
- ➢ Excluding 353x353 makes little difference - this spectrum has little statistical weight
- ➢ The data "wants" a steeper dust SED - relaxing the β_d prior it pulls to the top end of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



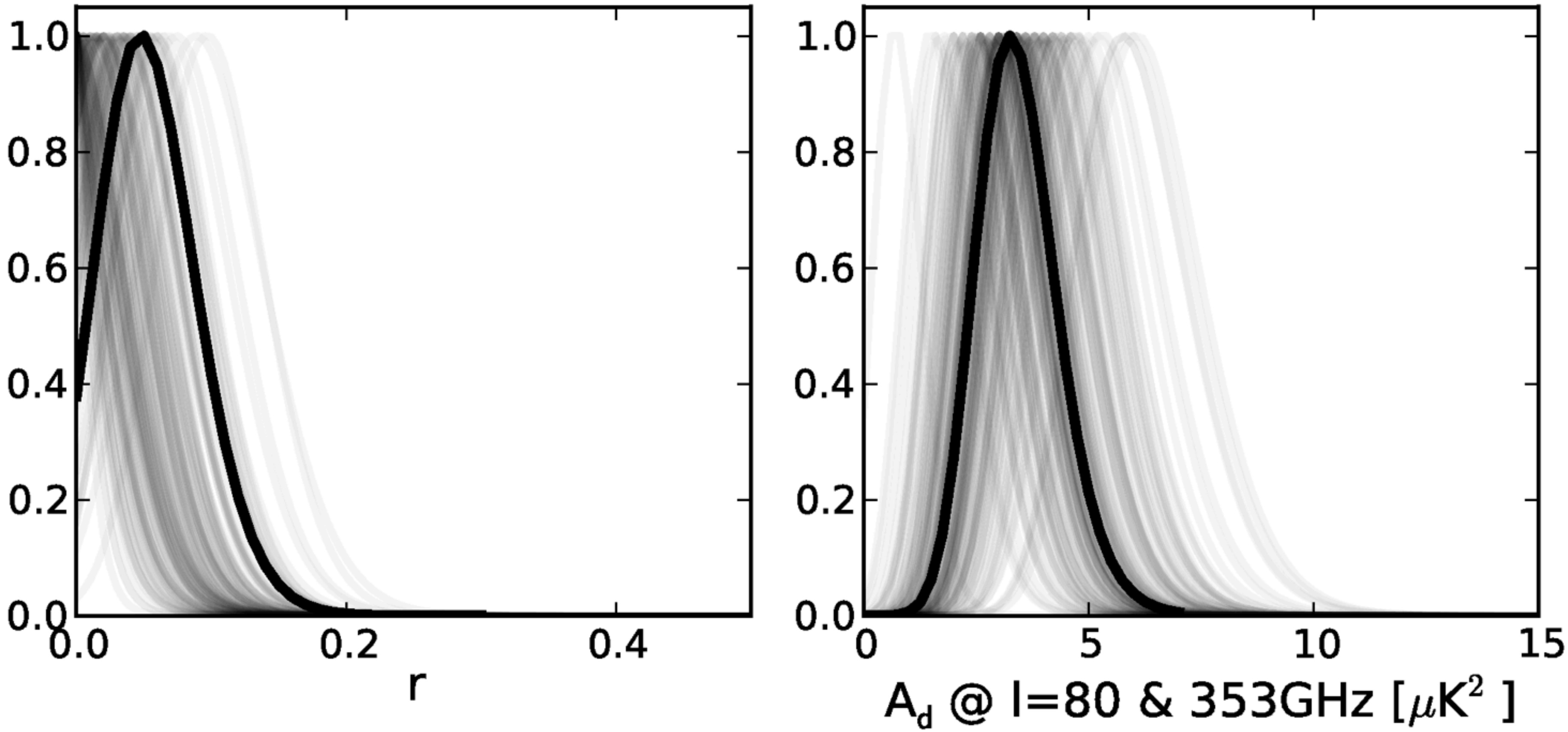
- ➢ We try adding synchrotron to the model while also adding all of the frequency channels of Planck
- ➢ We assume a spectral index for sync taken from WMAP's spectral index map in our sky region
  - ○ The results for *r* and A_d hardly change while synchrotron is tightly limited
  - ○ If one assumes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

Constraints on lensing B-modes



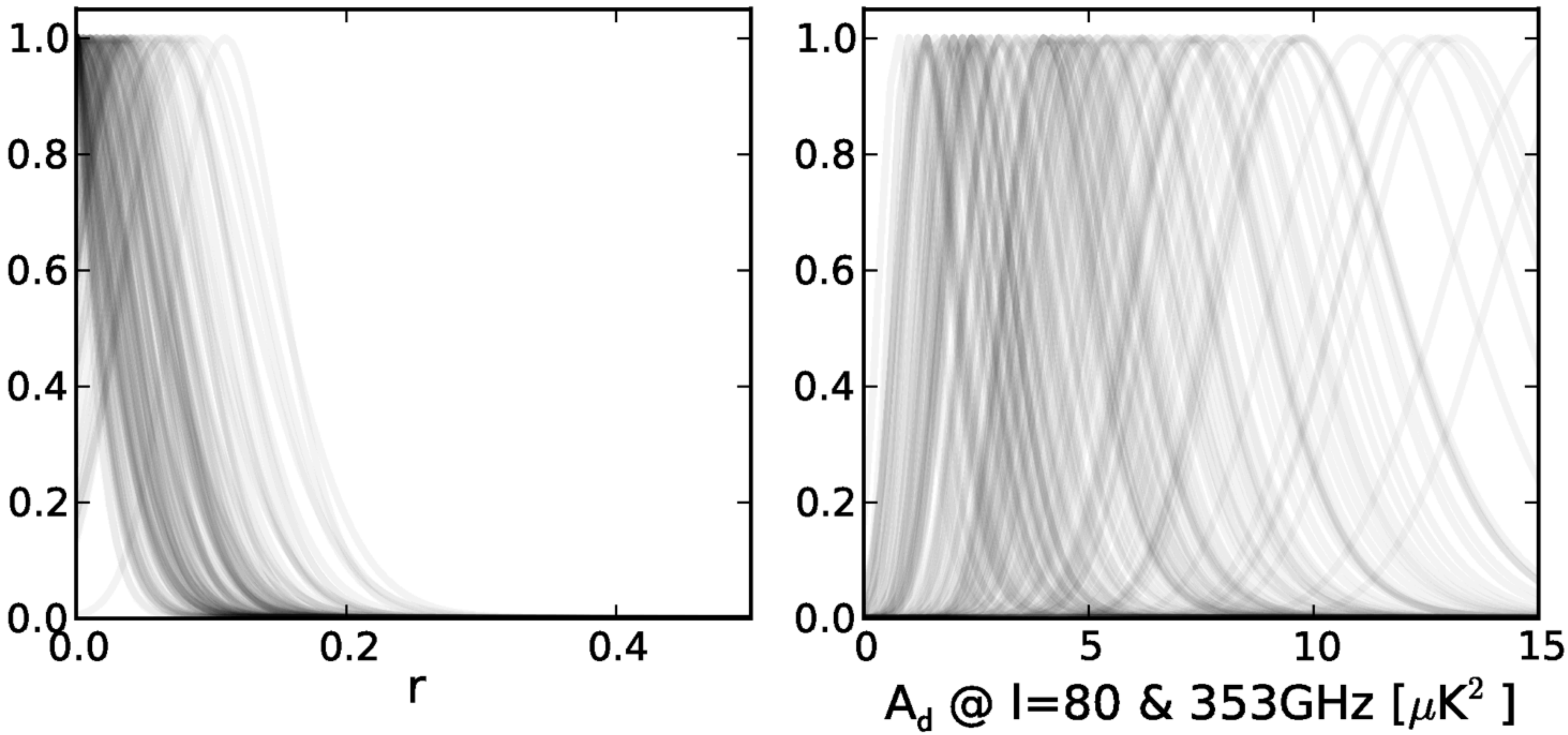
- ➢ We next allow the amplitude of the lensing signal to vary while also extending the ℓ range up to 330
- ➢ We find that the lensing and dust components can be cleanly separated
  - And detect lensing at 7.0 σ significance

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 of the real data

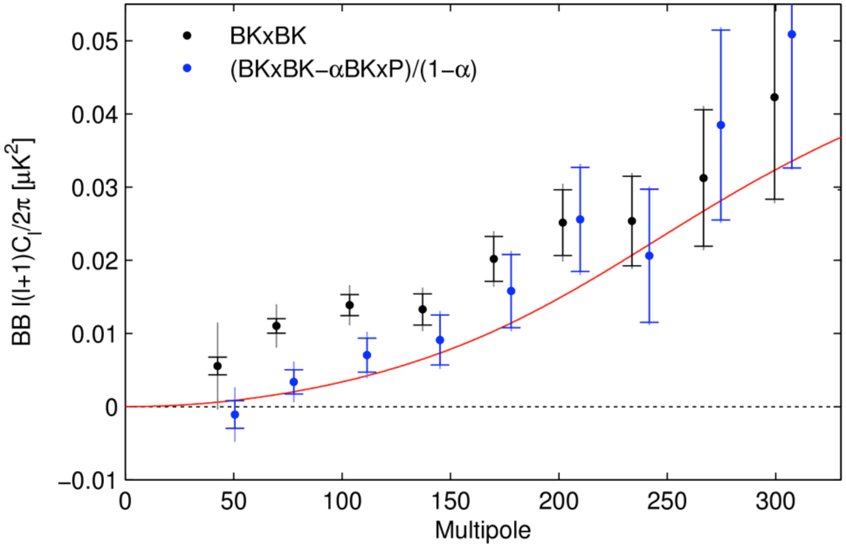
Likelihood validation II



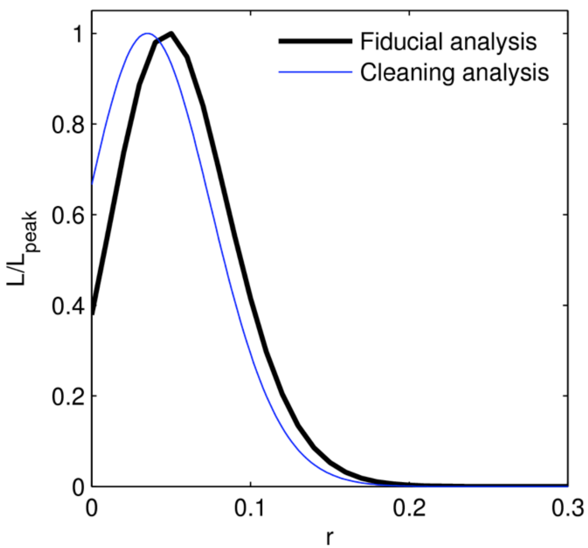
- ➢ We also run sims using dust sky patterns drawn from the old version of the Planck Sky Model
  - ○ These sky patterns are not necessarily Gaussian random fields and have a wide range of brightnesses (as seen at right)

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

Spectral subtraction analysis

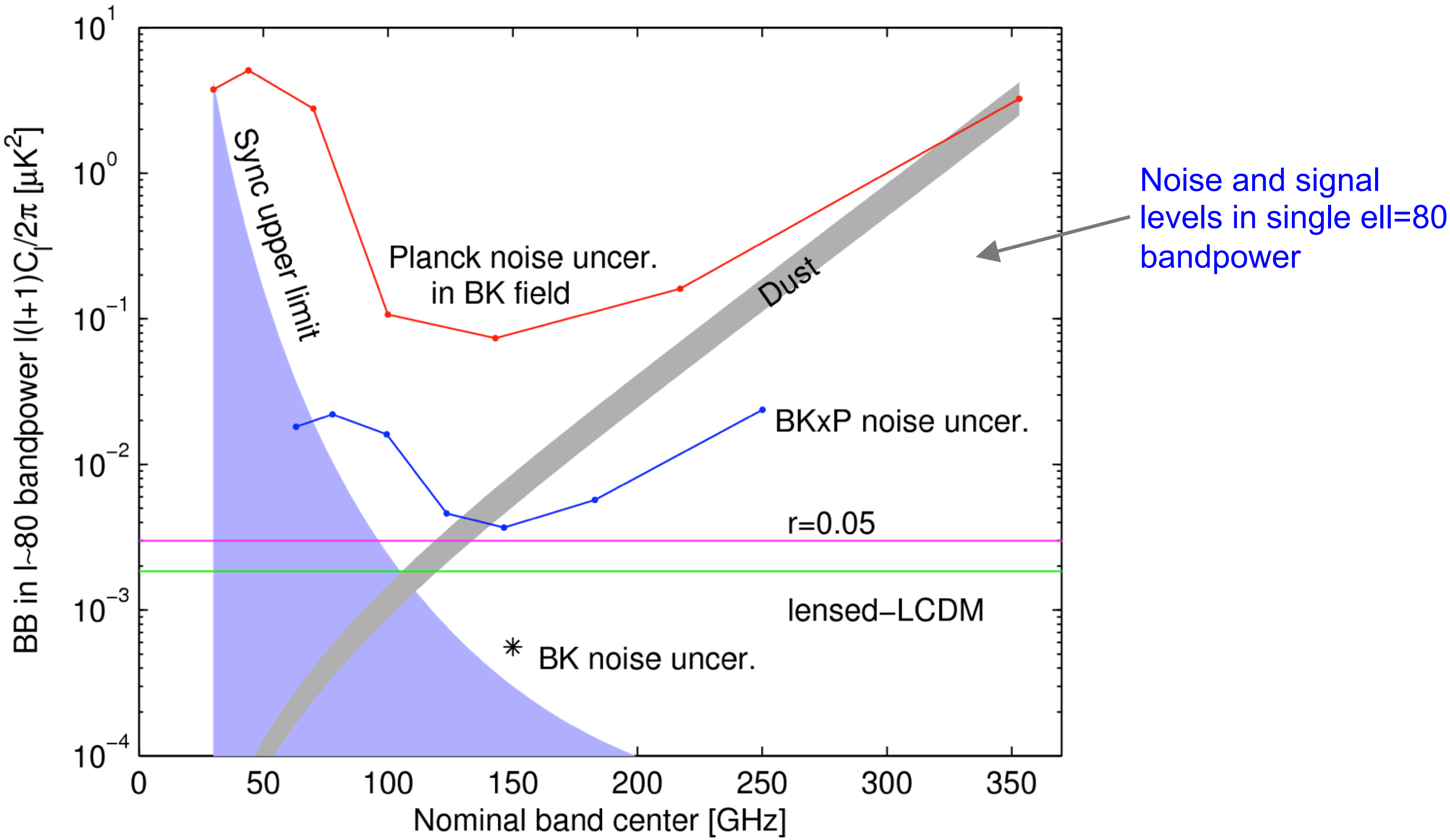


- ➢ We also try a simple analysis subtracting the scaled 150x353 spectrum from the 150x150
  - ○ (This approximates a map based cleaning)
- ➢ The resulting *r* constraint is similar (although a little less powerful)



Bicep2, Keck Array and Planck Collaboration

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 so Planck detects it
- The noise in the cross spectra is the geometric mean and a fairly tight constraint on dust amplitude is set
- Noise in P353 is the limiting factor and to make further progress better data at frequencies other than 150 GHz is required

Current Conclusions

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

- Planck released new information on the polarized emission from galactic dust in a series of papers last year. Planck Intermediate Paper XXX (arxiv:1409.5738) found that the level of dust power in a field centered on the BICEP2/Keck region (but somewhat larger than it) is of the same magnitude as the reported excess, but noted that, “the present uncertainties are large," and that a joint analysis was required.
  - Here we have conducted this joint analysis taking cross spectra between the BICEP2/Keck maps and those from Planck.

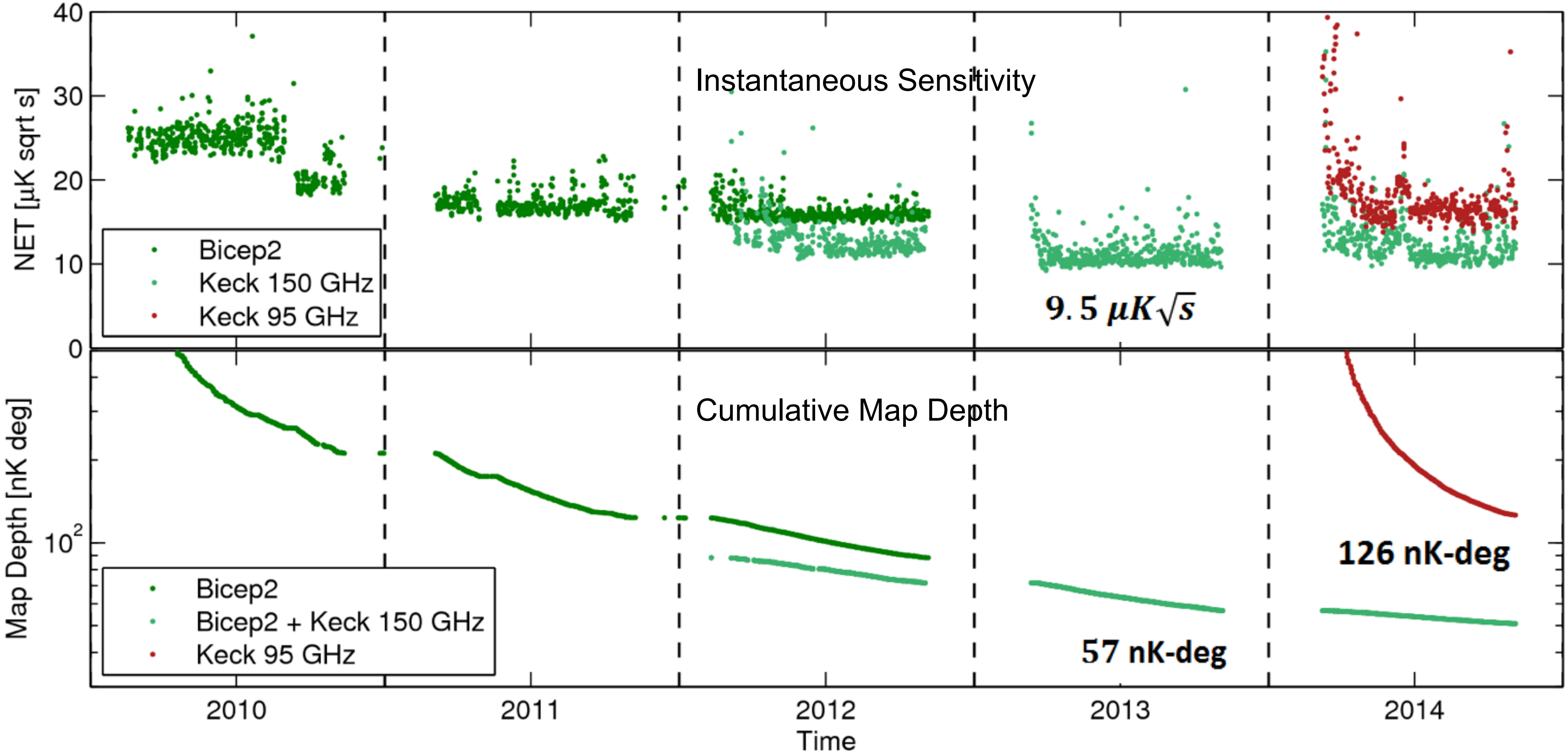
- The fundamental conclusion is that dust is detected at high significance, and $r < 0.12$ at 95% confidence.
  - Multi-component likelihood gives $\sigma(r) \sim 0.035$ -- This is a very direct constraint on tensors!
  - No significant evidence for $r > 0$. Currently $r = 0$ and $r = 0.1$ are at equal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

- We have checked the stability of the analysis under variations of the data selection and other details.
  - Most variations make little difference. There is some difference in the results depending on whether BICEP2 or Keck data is used but this is shown to be within noise fluctuation.

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

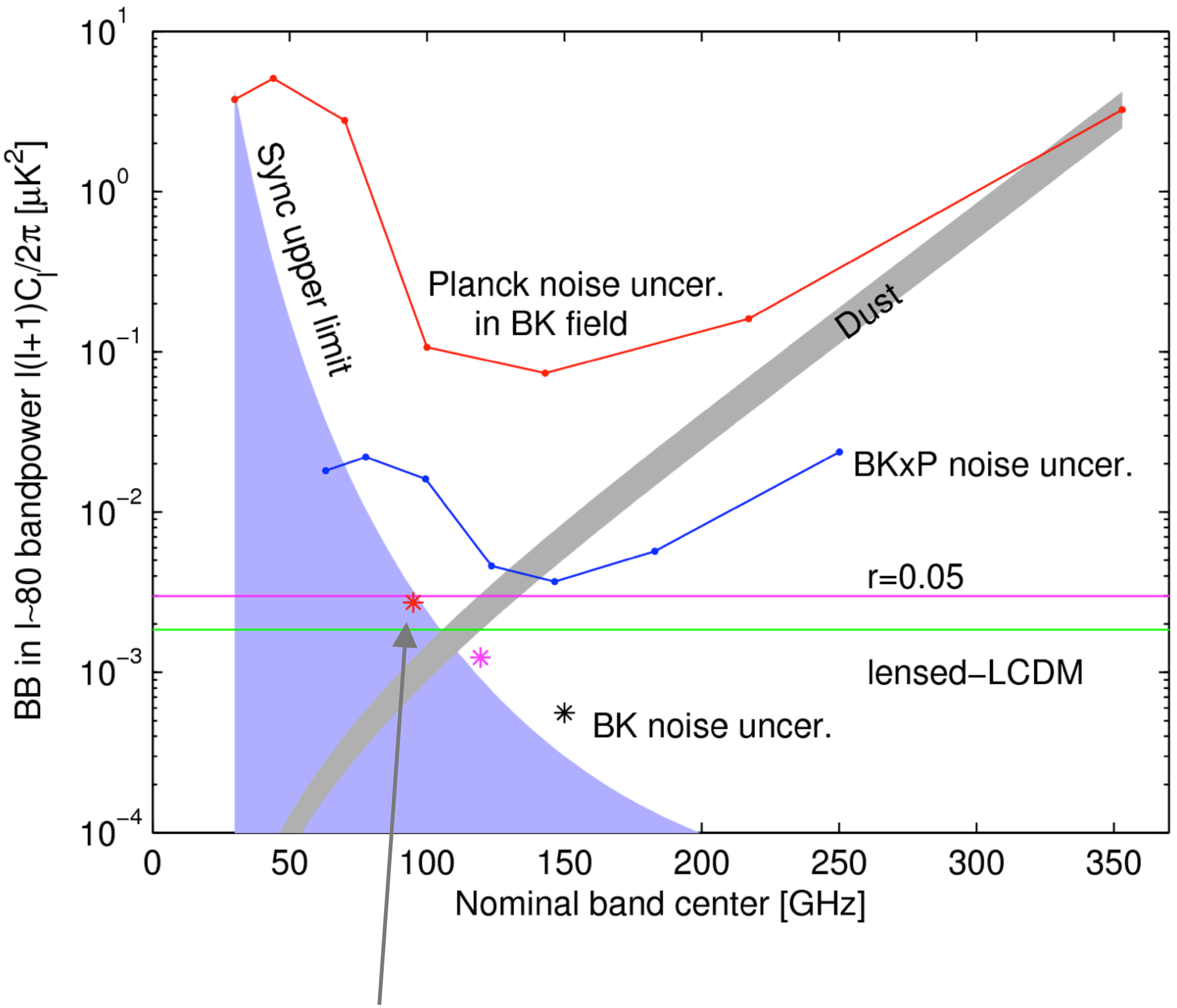
- Further data from Keck Array and BICEP3 at 95 GHz is coming and limits on *r* will tighten in the near future. Planck also have updated analyses coming.

Coming soon - Keck 2014 95 GHz



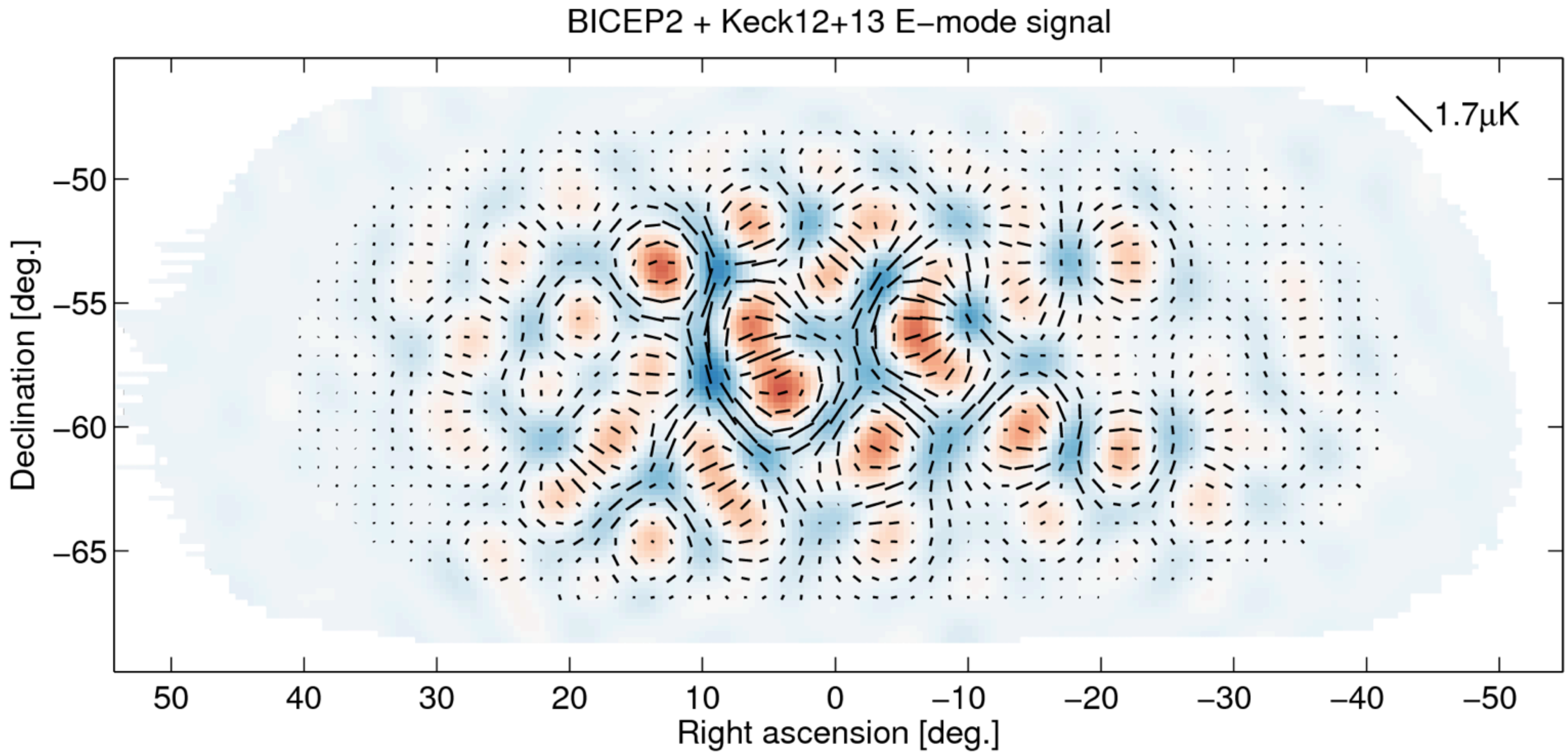
For 2014 season two of the Keck array receivers switched out for 95 GHz

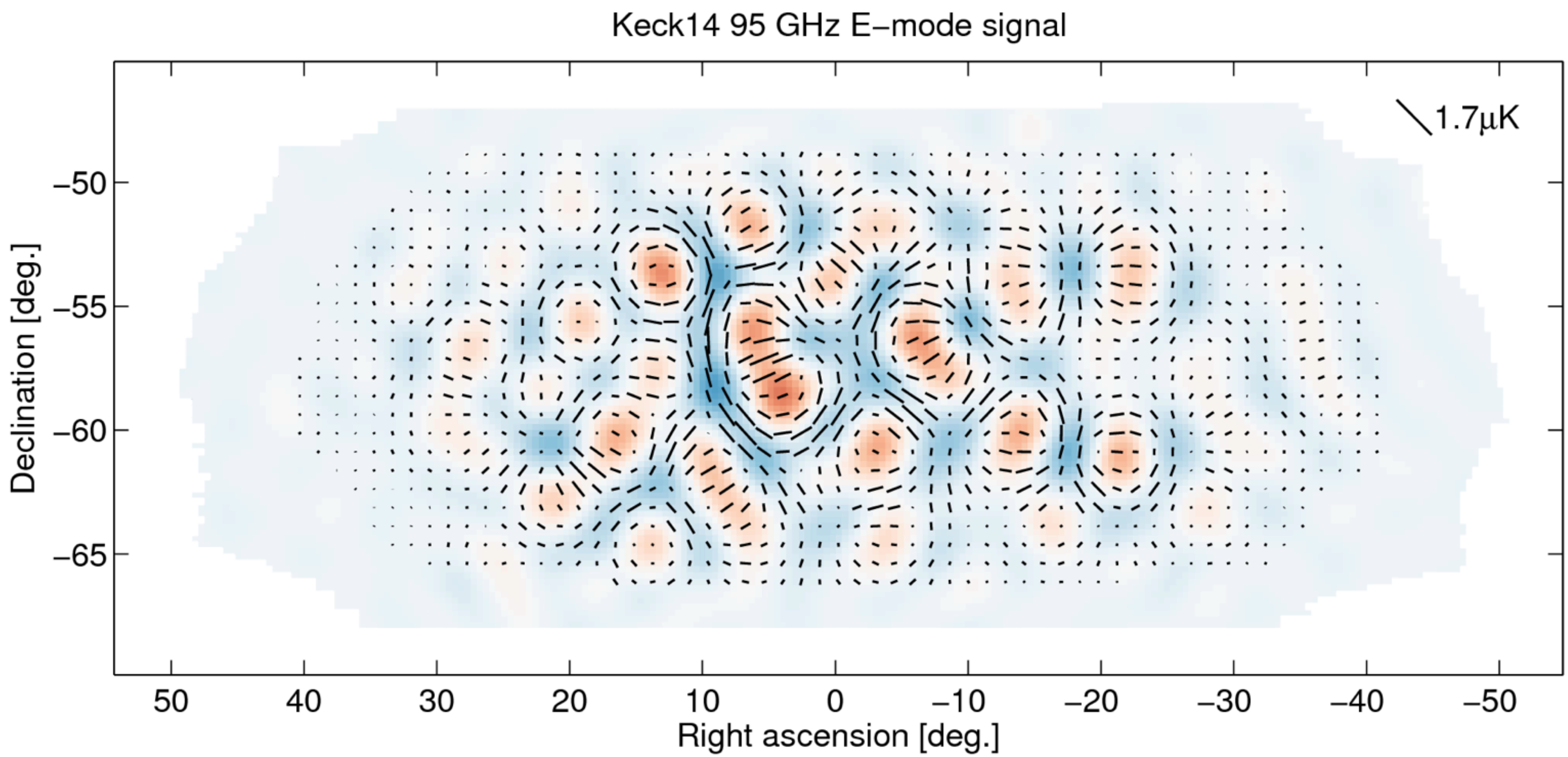
Comparison of signal and noise levels



Keck 2014 95 GHz achieved noise level

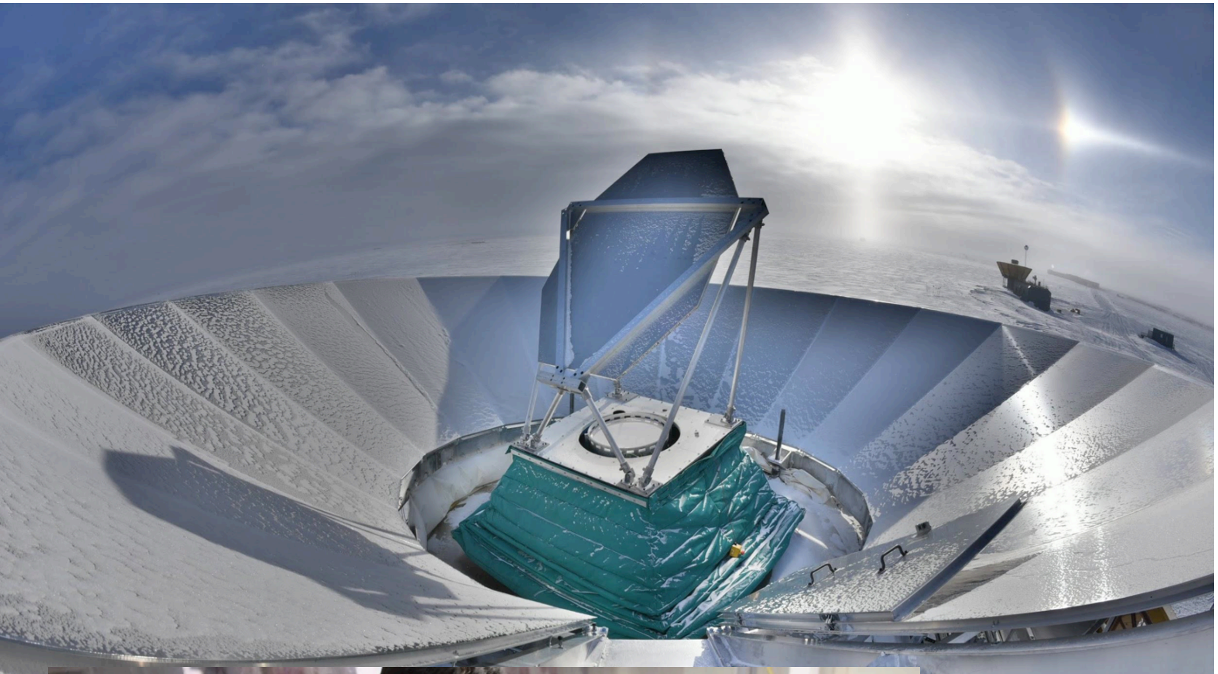
Bicep2, Keck Array and Planck Collaboration


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



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