Bicep2/Keck - Planck joint analysis: Galactic foreground removal in a degree-scale B-mode search

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JPL/Caltech
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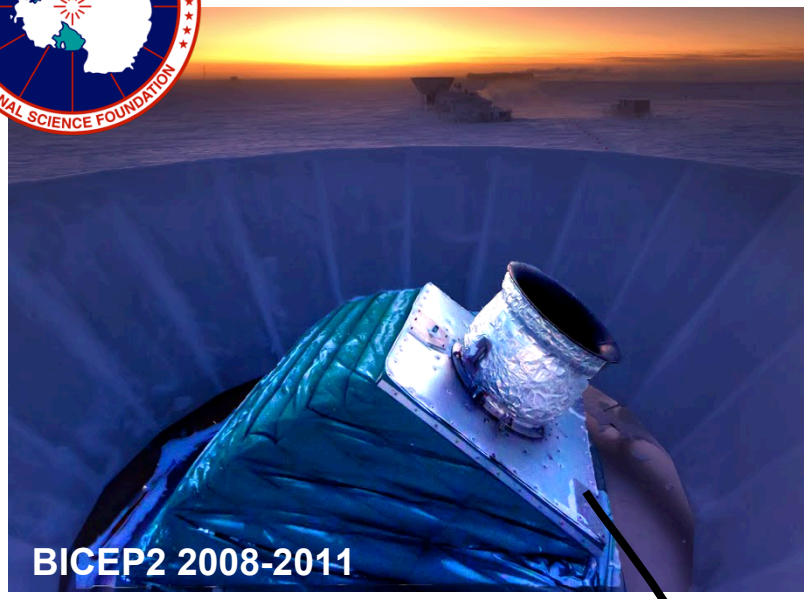
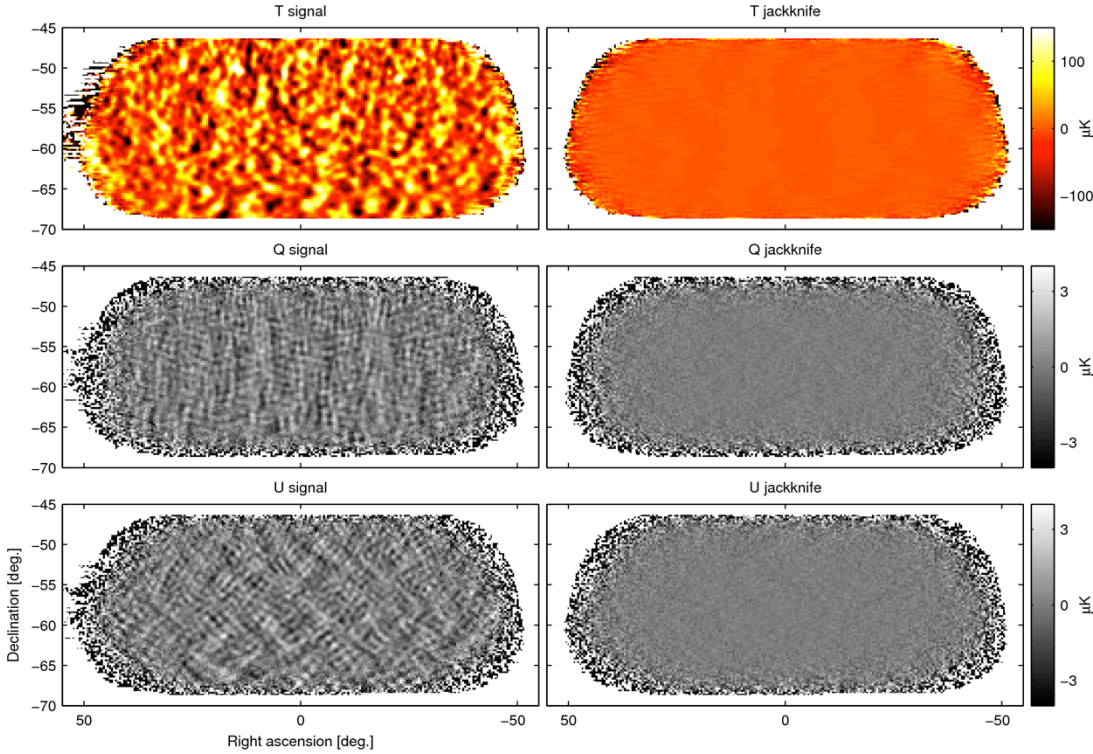
BICEP2 and Keck Array



Keck Array 2011-...

x5



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-deg pixels)

Deepest map of the CMB polarization ever made!

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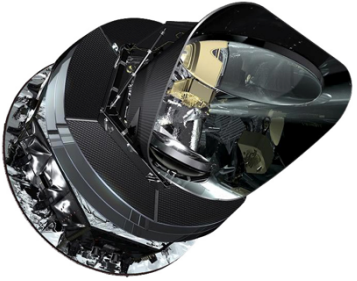
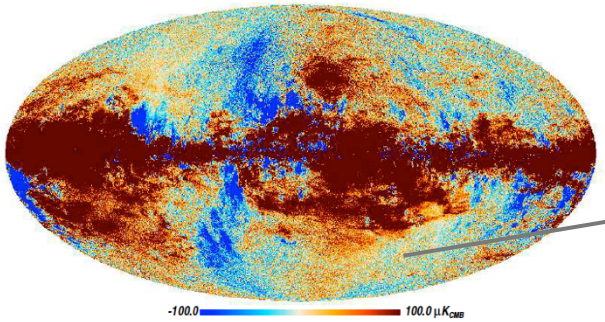


Planck 353 GHz

- Planck is the third generation space mission to observe the CMB: observes the full sky at 9 bands in intensity; 7 in linear polarization
- Full sky measurement, but in any given sky patch much less deep than BICEP2-Keck
- 353 GHz band is very sensitive to polarized dust emission

Q



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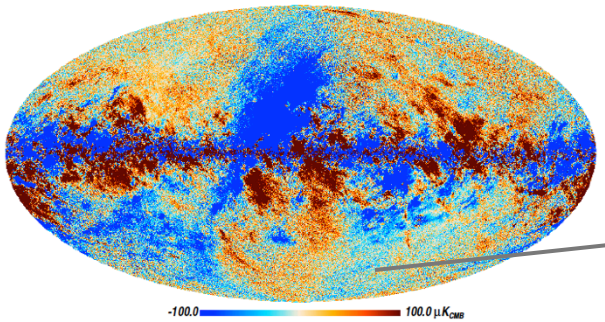
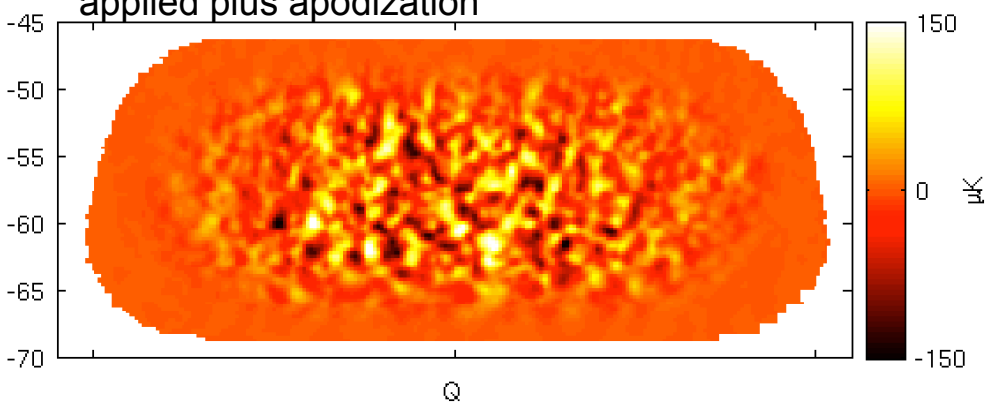
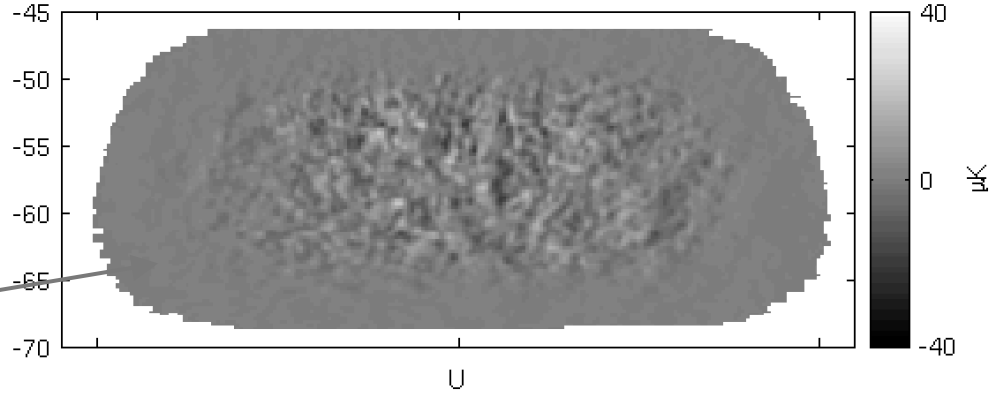
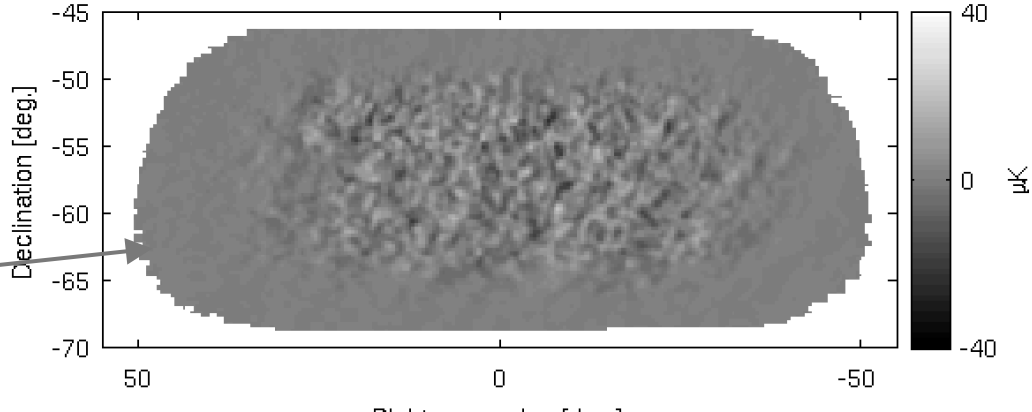


Planck 353GHz maps in BICEP2/Keck sky region with full simulation of observation and filtering applied plus apodization







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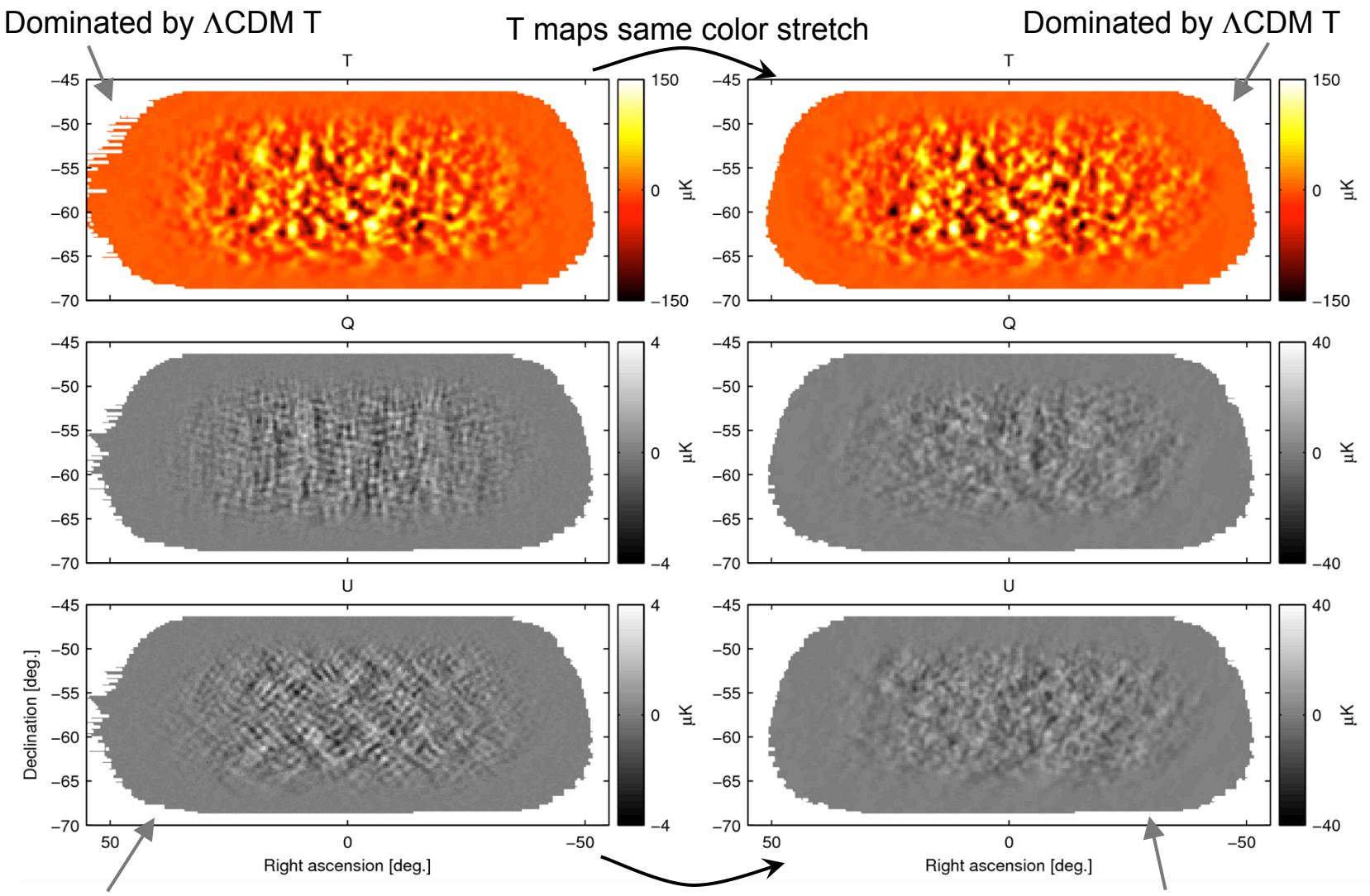
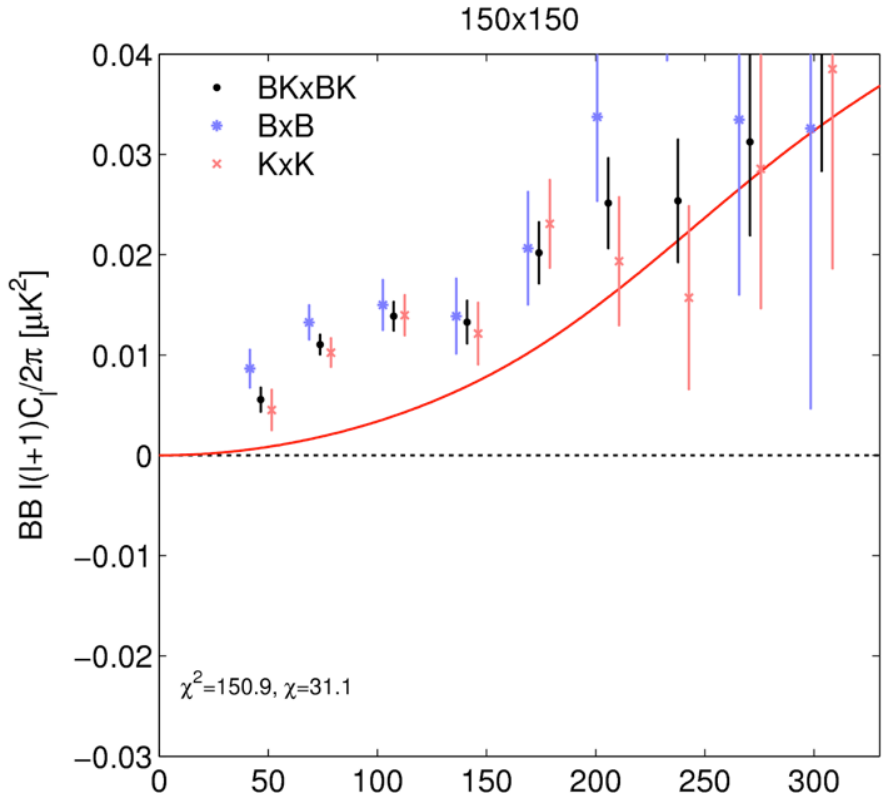
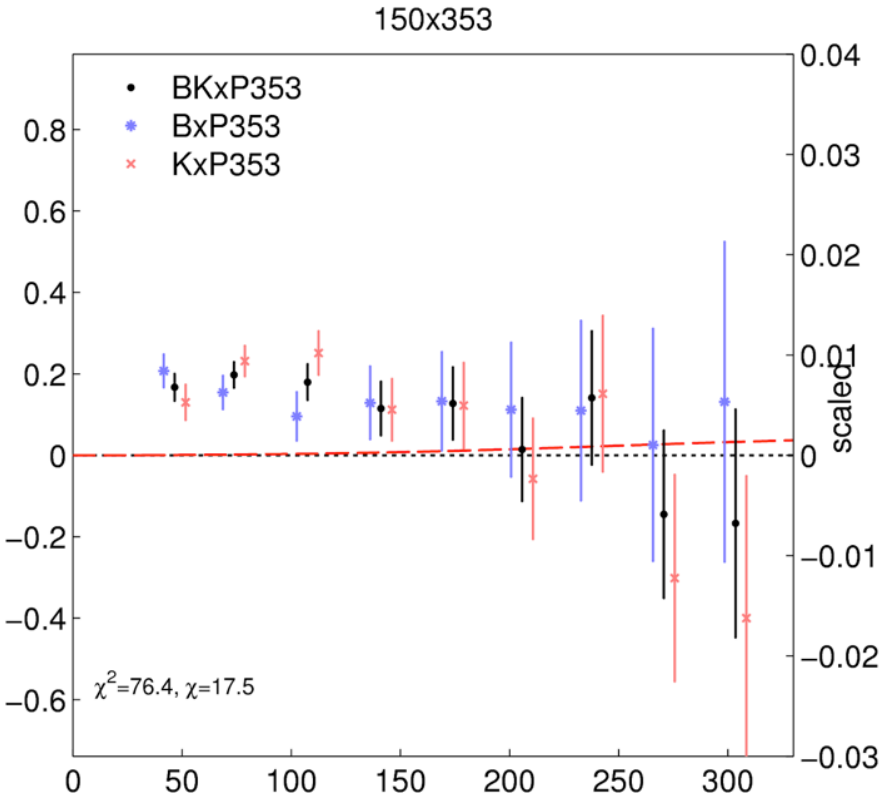
Compare BK 150 GHz (left) with Planck 353 GHz (right)



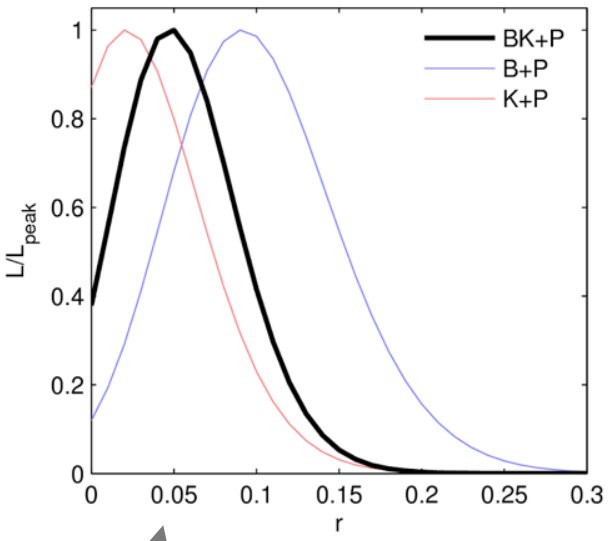
BB Spectra

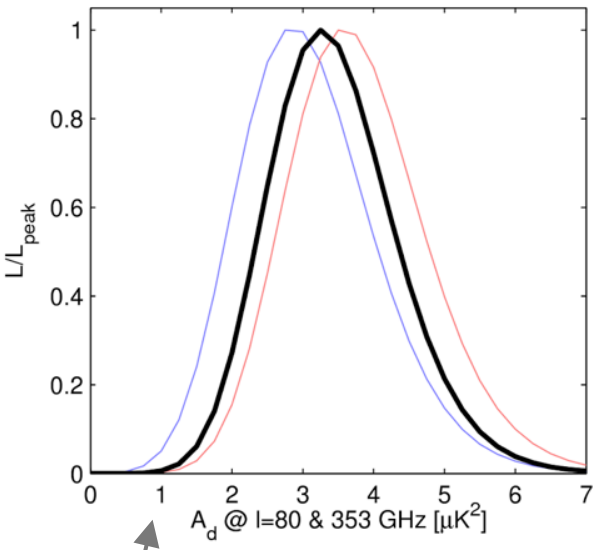


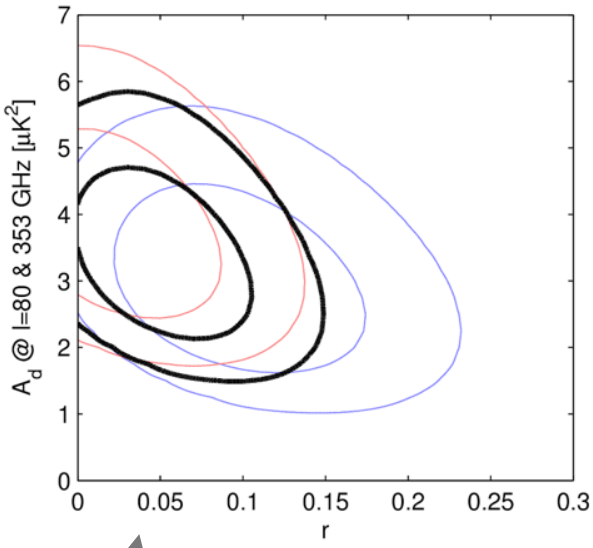


- Correlation of 150 GHz and 353 GHz B-modes detected with high signal-to-noise ratio.
- Scaling the cross-frequency spectrum by the expected brightness ratio (x25) of dust (right y-axis) indicates that dust contribution is comparable in magnitude to BICEP2/Keck excess over LCDM.
  - Shape looks consistent with $\ell^{-0.42}$ power law expectation

Multi-component multi-spectral likelihood analysis







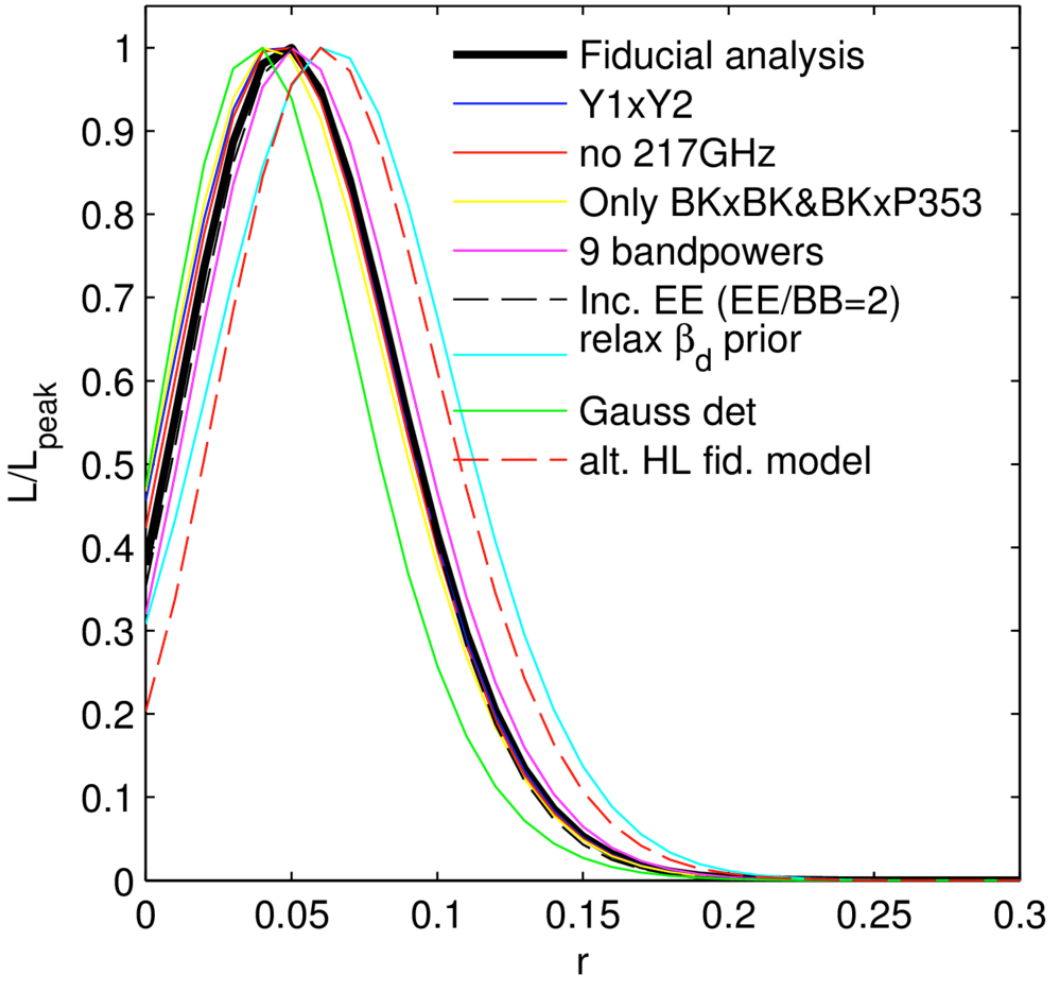
r constraint consistent with zero (For BK+P L_0/L_{peak} ratio is 0.4 which happens 8% of the time in a dust only model.)

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*

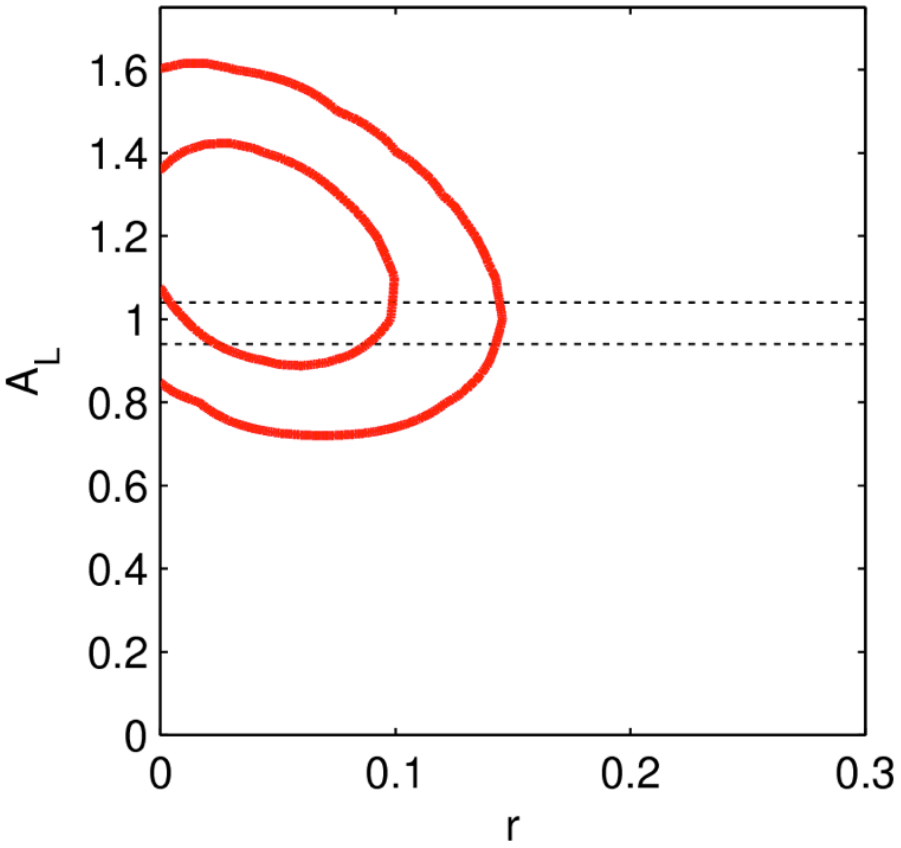
- use single- and cross-frequency spectra between BK 150 GHz and Planck 217 & 353 GHz channels
- As addition to basic LCDM lensing signal include gravity wave signal (with amp *r*) and dust signal with
- amplitude A_d (specified at ℓ =80 and 353 GHz)
  - For dust SED use modified blackbody model and marginalize over range β_d=1.59±0.11
- Use 5 lowest BB bandpowers only (20<ℓ <200)

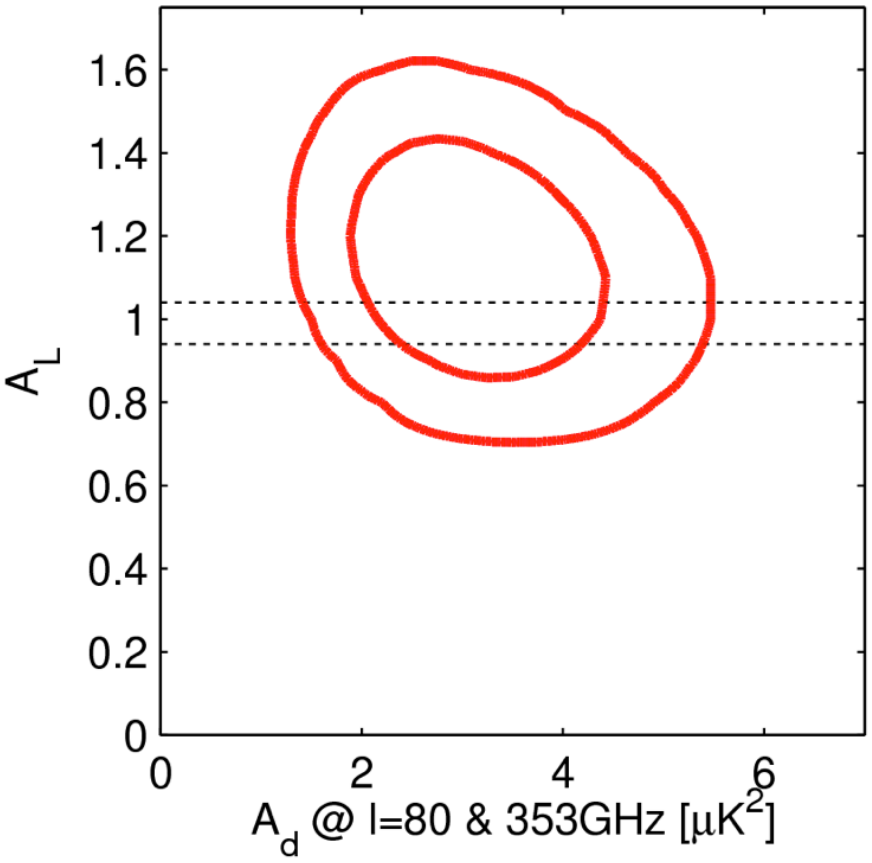
Variations on fiducial analysis



- 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.

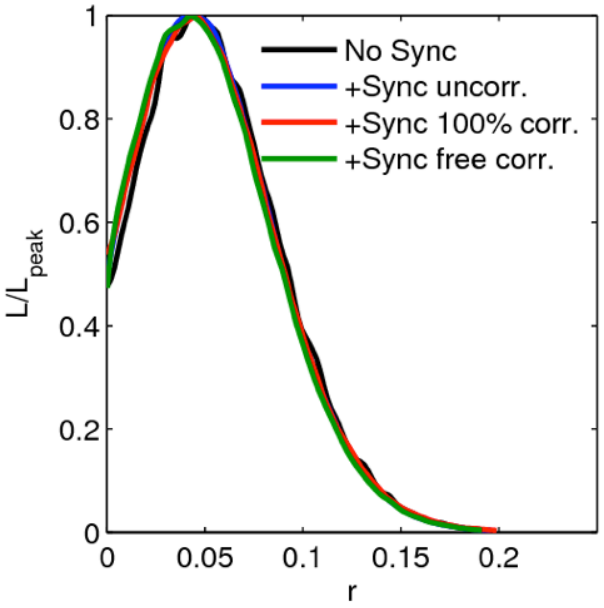
Constraints on lensing B-modes

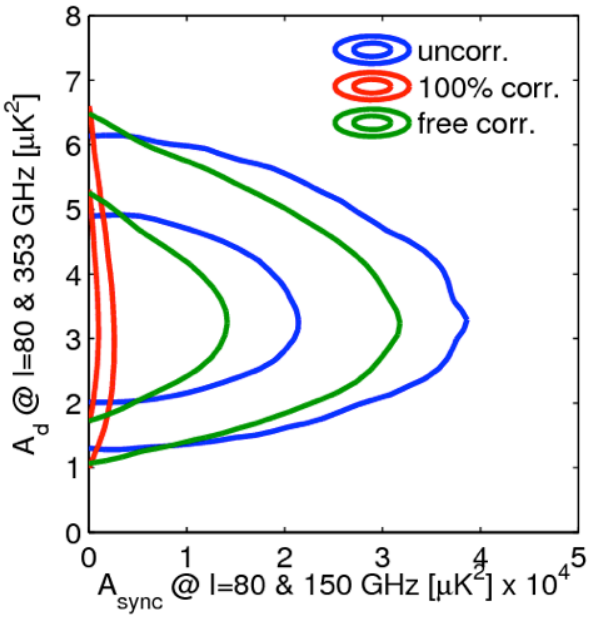


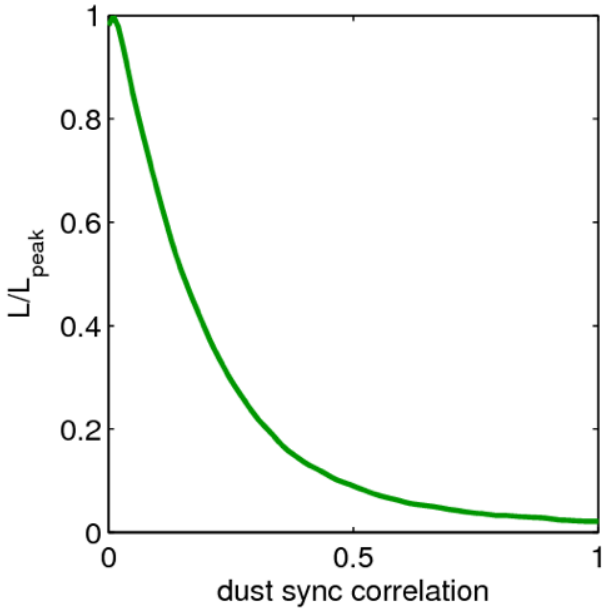


- We next allow the amplitude of the lensing signal to vary while also extending the ℓ range up to 330
- We find that the lensing and dust components can be cleanly separated
  - And detect lensing at 7.0 σ significance

Adding synchrotron to the model

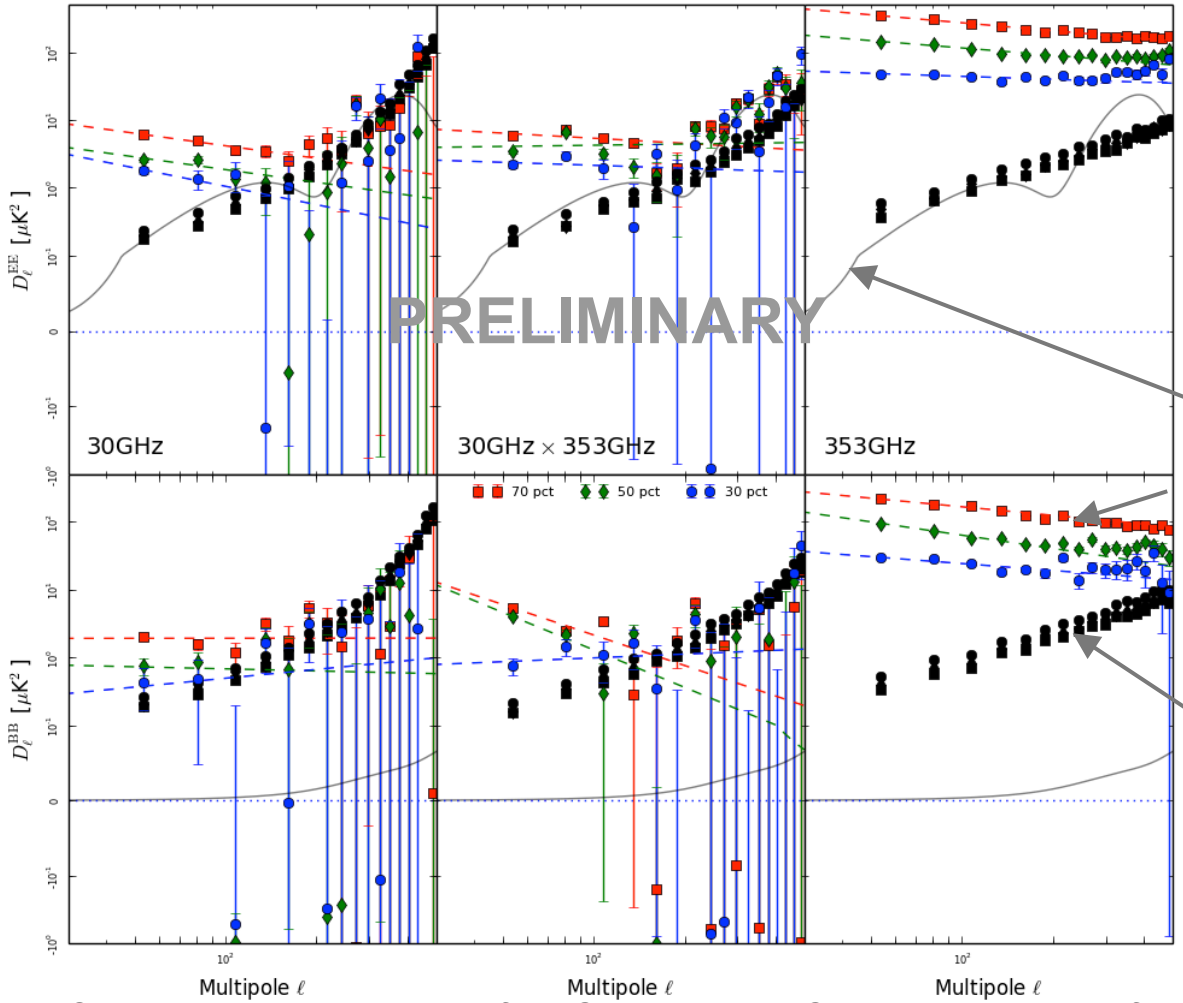




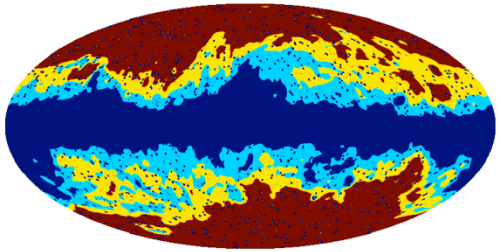


- We try adding synchrotron to the model while also adding all of the frequency channels of Planck
- We assume a spectral index for sync taken from WMAP's spectral index map in our sky region (-3.3)
  - The results for *r* and A_d hardly change while synchrotron is limited to <3% of the observed 150 GHz power
  - Assume dust and sync sky patterns are correlated, limit gets *tighter*.
    - correlation increases the expected power in auto and cross spectra (e.g. P030xP353)

What does Planck say about sync/dust correlation?



Masks



ΛCDM

signal for f_{sky} 30%, 50%, 70%

noise level

- Simple cross correlation of 30 GHz and 353 GHz over large sky fractions
- Used 857GHz intensity selected masks, as well as PCCS2 30 and 353 source masks
- Excess power above ΛCDM seen at 353 GHz and 30 GHz
  - 353 GHz results published in Planck Intermediate Paper XXX (see **J. Aumont talk** next)
- Significant cross correlation between 30 and 353 GHz seen at degree scales

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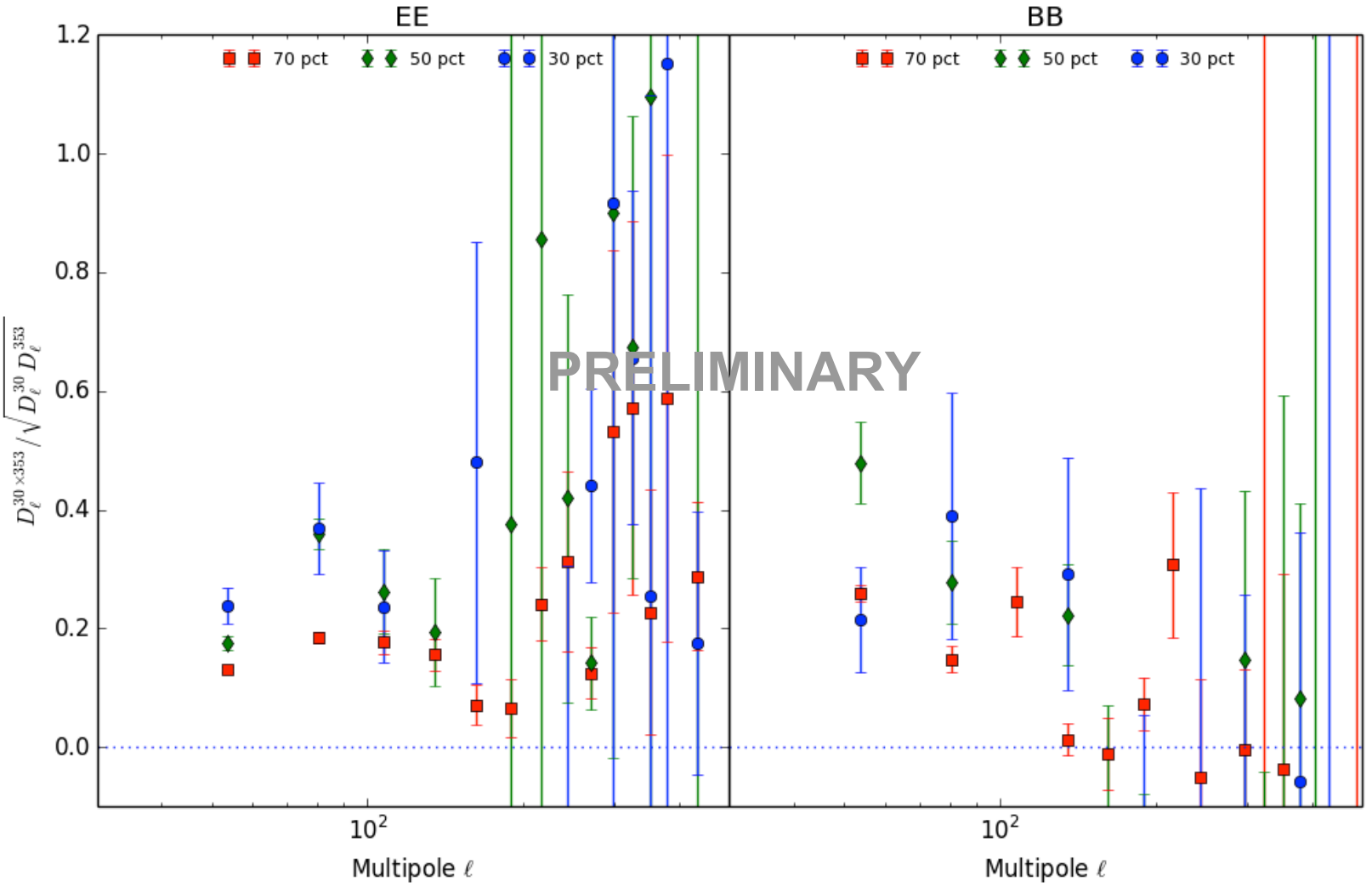
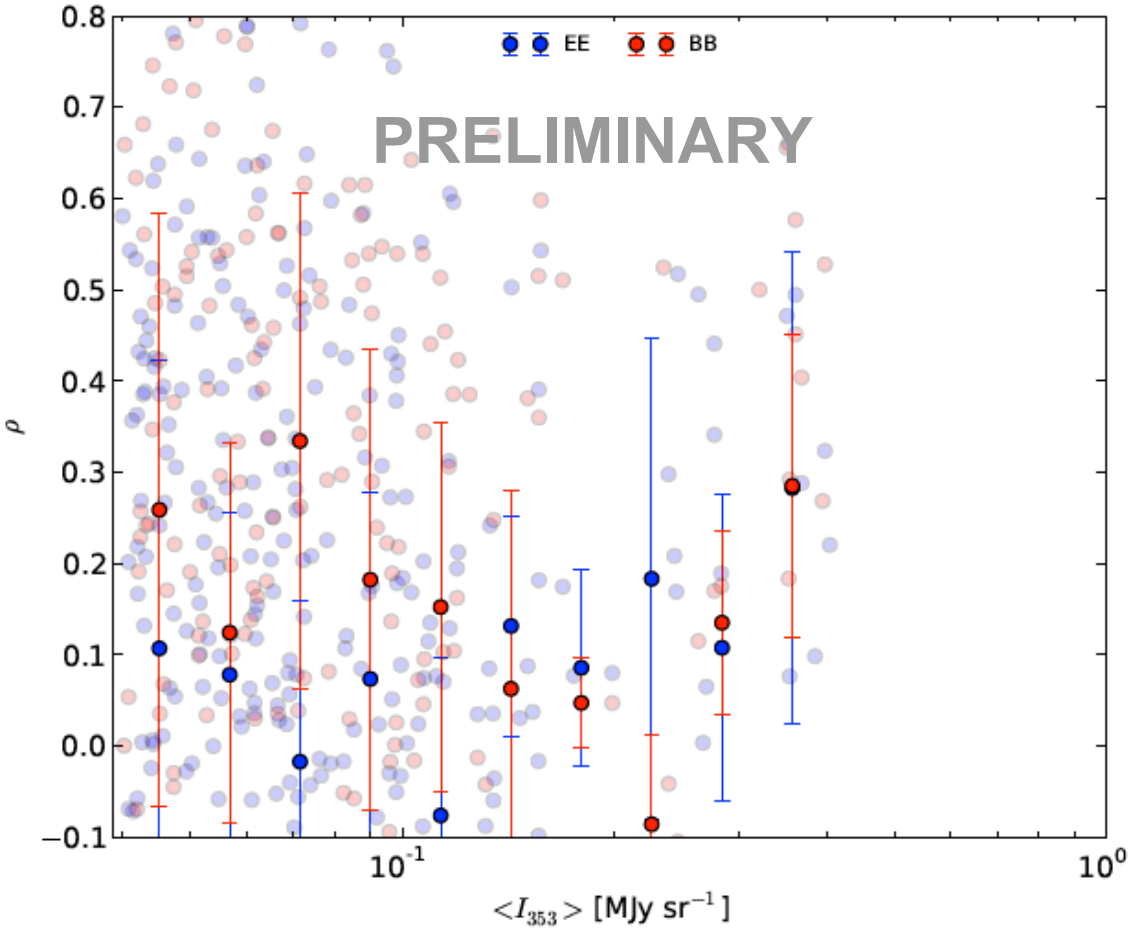
Correlation coefficient



- On degree scales see correlation around 15-40%
- Comparable levels of correlation in E and B modes

Small patches (suborbital survey size)



- Also compute correlation on 400 sq degree patches centered on nside=8 (a la PIP-XXX)
- S/N ratio is low on 30 GHz and 30x353 cross spectrum; bin as a function of local dust contrast

Conclusions

- A joint analysis of Planck data with BICEP2/Keck data at 150 GHz carried out

- Dust is detected in BICEP2/Keck 150 GHz maps 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.

- Lensing B-modes are directly detected at 7.0 σ significance

- Preliminarily analysis shows that correlation between synchrotron and dust on degree scales is significant. On average across the sky, expect 15-40% correlation.