Toward an Understanding of Foregrounds in the BICEP2 Region

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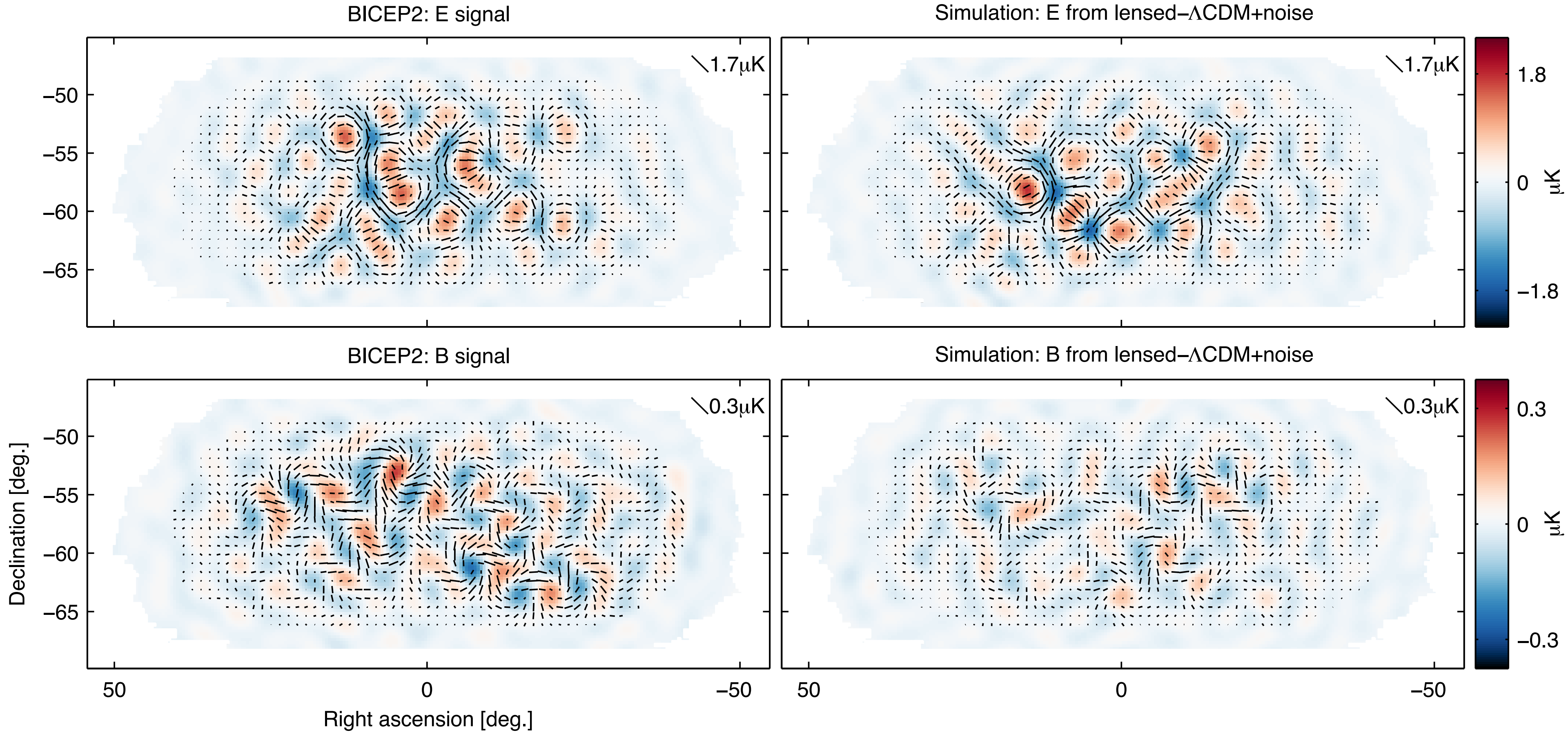
w/ Colin Hill and David Spergel

Status and Future of Inflationary Theory, KICP, August 22, 2014

A map of B-modes



Noise level: 87 nK deg - the deepest map at 150 GHz of this patch of sky

(Planck noise level: few μK deg)

B-mode Power Spectrum

If the signal is cosmological, inflation is our best candidate to explain it.

In this case the detection would imply that we have seen quantum fluctuations in the spacetime metric, and

- $H(t_*) \approx 10^{14} GeV$ or $V^{1/4} \approx 2 \times 10^{16} GeV$
- The field range is roughly Planckian (Lyth, Turner)

Implications

Theory

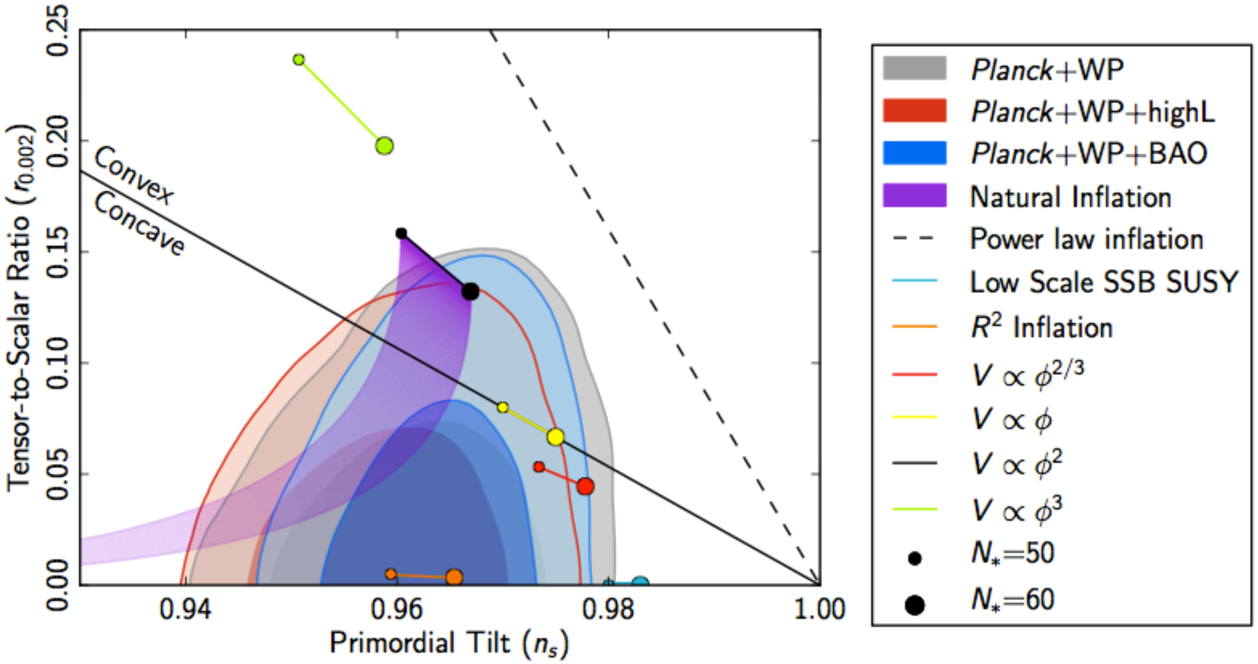
- Our theories make meaningful predictions at these high energies.
- We should think harder about
  - large field models, moduli, gravitino problem, ...
- The graviton mass is below $3 \times 10^{-28}\, eV$
- ...

Experiment

- If the signal is this large a per cent-ish measurement of r is achievable!
- Even the inflationary consistency condition may become testable.

Implications

Theory - Part II



- The value of the tensor-to-scalar ratio and the tilt are extremely valuable to distinguish between different models of the early universe, but one has to understand the contribution from foregrounds to measure them

Origin of B-modes

Is it in the sky?

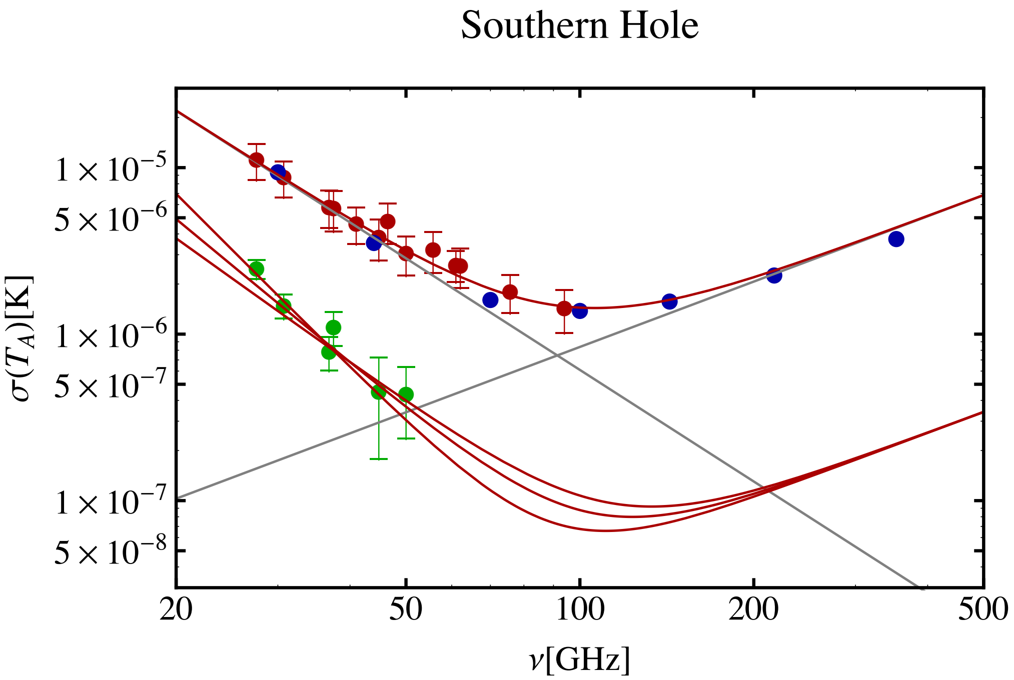
- The measurement is extremely challenging.
- It requires exquisit control over differential gain, differential pointing, beams,...
- These and many more systematics are briefly discussed in the BICEP2 paper, and will be discussed in the systematics paper (see also PhD thesis by Chris Sheehy)

One should wait for the promised systematics paper, but in my opinion what has been shown suggests there are degree-scale B-modes in the sky.

Origin of B-modes

Is it cosmological?

- One needs to understand polarized foregrounds
- WMAP can help with synchrotron



measurement in the BICEP patch, but on larger angular scales than BICEP's

Origin of B-modes

Is it cosmological?

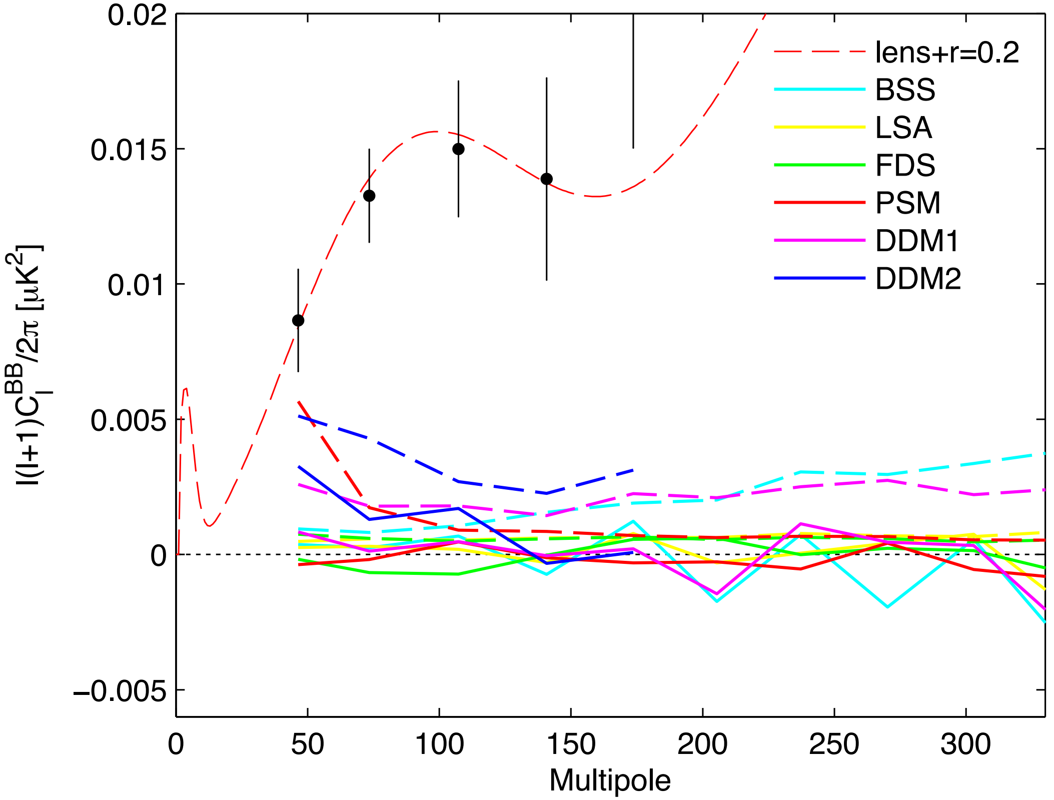
- One needs to understand polarized foregrounds
- WMAP can help with synchrotron
- Planck would help with both synchrotron and dust, but its polarization data is not yet public

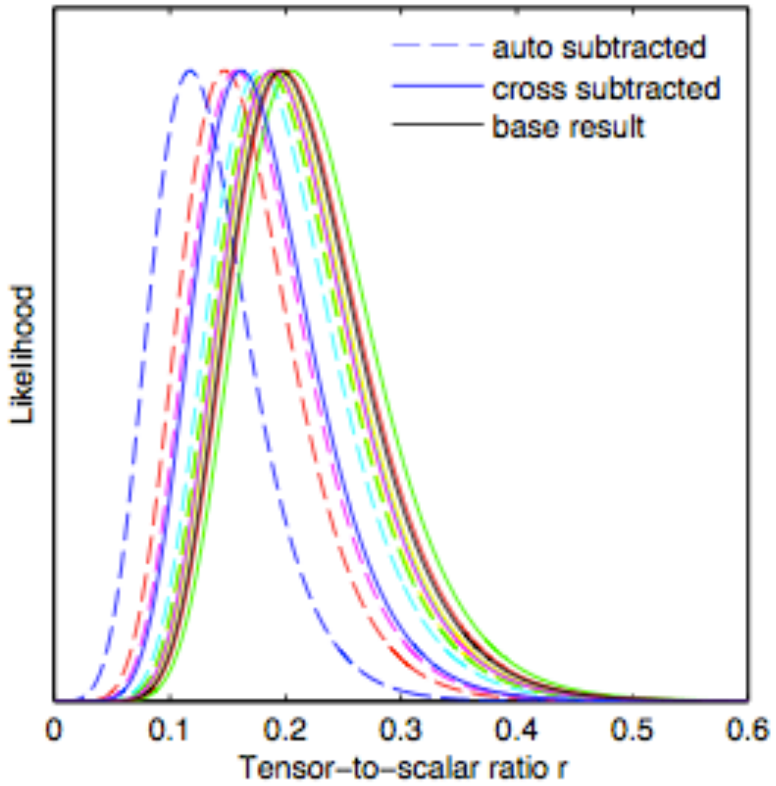
Even under conservative assumptions synchrotron radiation cannot make up the entire signal.

To make progress on dust, one has to be creative (or wait)

Effect of foregrounds

Foreground models initially presented by BICEP



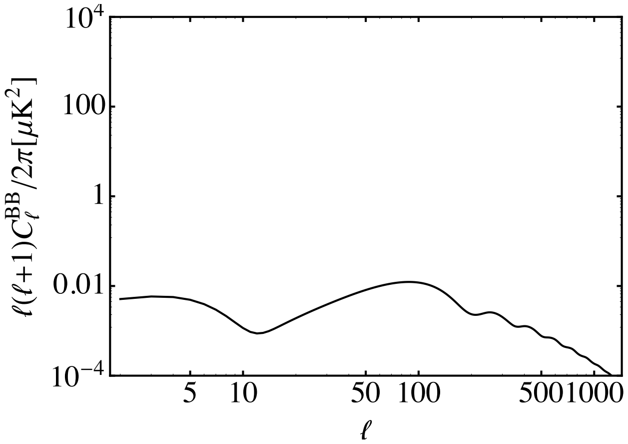


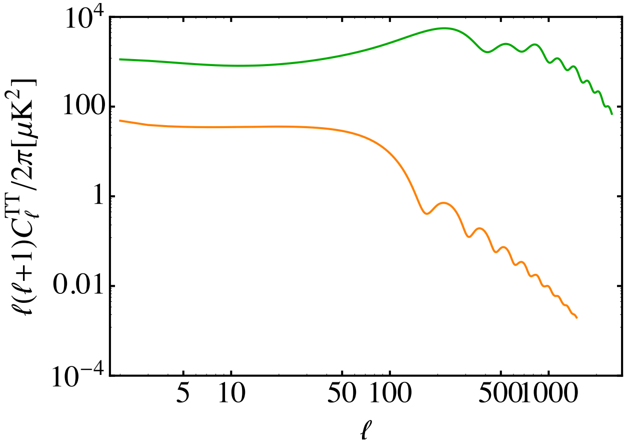
Effect of foregrounds

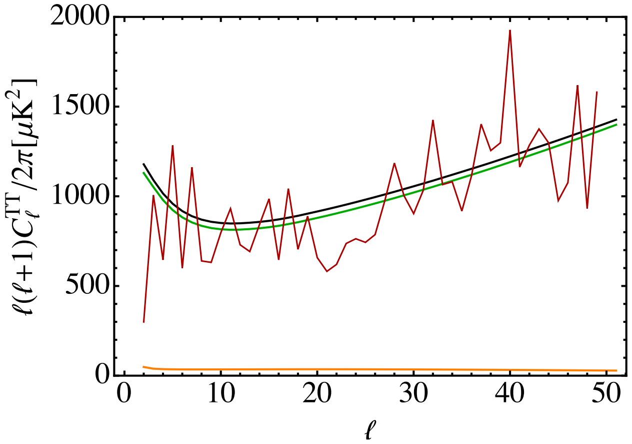
Effect of foregrounds on tensor-to-scalar ratio

r	unsubtracted	DDM2 cross	DDM2 auto
BICEP2	$0.2^{+0.07}_{-0.05}$	$0.16^{+0.06}_{-0.05}$	$0.12^{+0.05}_{-0.04}$
BICEP2×Keck	$0.13^{+0.04}_{-0.03}$	$0.10^{+0.04}_{-0.03}$	$0.06^{+0.04}_{-0.03}$

Not negligible, especially if one wants do discuss potential tensions with Planck.

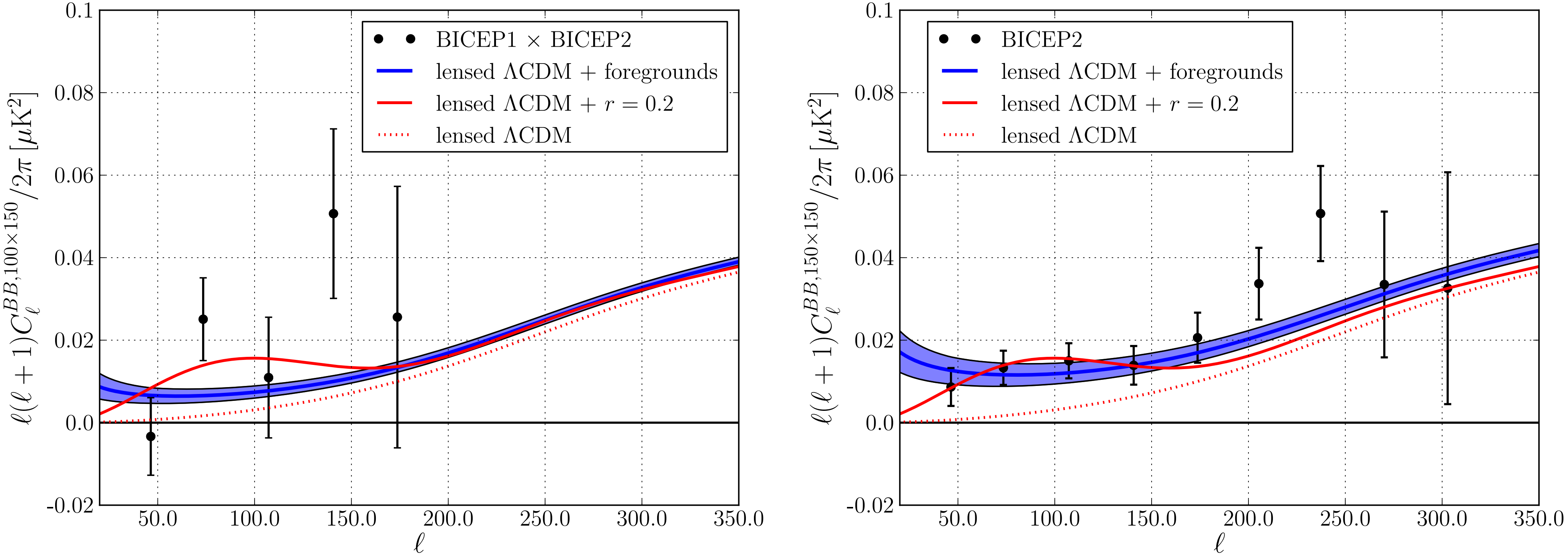






Testing the Null Hypothesis

Could the observed excess be consistent with lensing of E-mode, synchrotron, and dust?

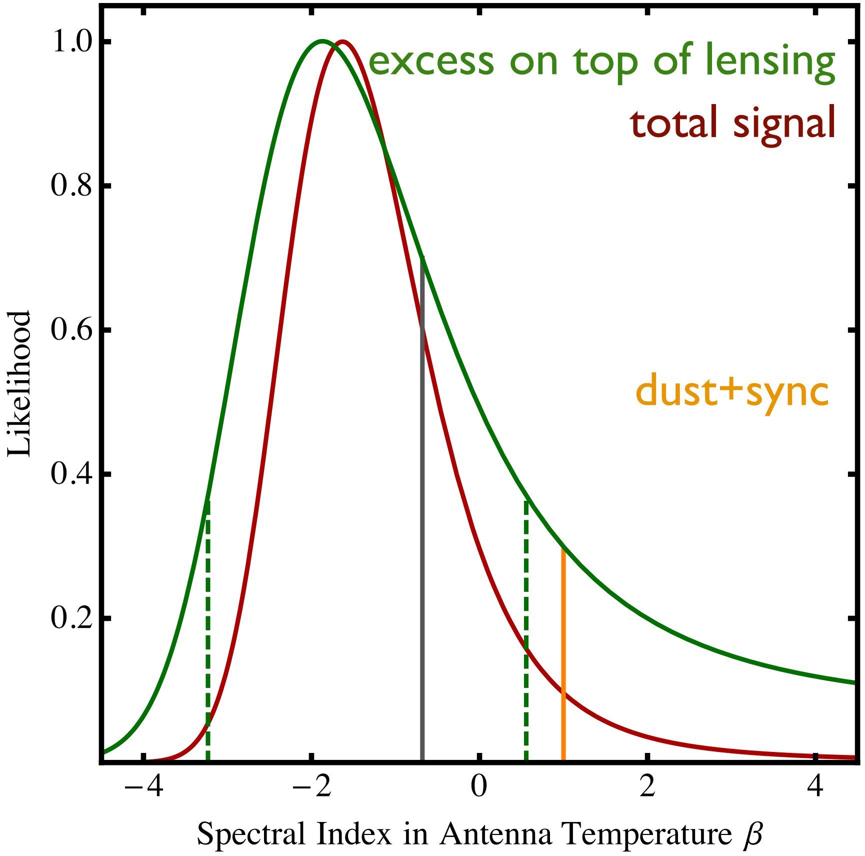


- Requires $\ell(\ell+1)C_\ell^{BB}/2\pi = 0.01\,\mu\mathrm{K}^2$ at $\ell = 46$ from dust
- Can we constrain the dust amplitude well enough from Planck data to rule it out?

Testing the Null Hypothesis

- Eventually observations at multiple frequencies will distinguish CMB from null hypothesis

- Currently, a joint fit to BICEP1xBICEP2 100x150 and BICEP2150 GHz data weakly favors the gravitational wave hypothesis ($1.3 - 1.7\,\sigma$), but does not convincingly rule out foregrounds as source of the excess.



(fiducial Gaussian approximation for covariance matrix)

CIB corrected foreground models

Models for polarized foreground need three ingredients, typically

- Intensity map
- Polarization fraction
- Polarization angles

$$Q(\hat{n}) = p(\hat{n}) I(\hat{n}) \cos(\psi(\hat{n}))$$

$$U(\hat{n}) = p(\hat{n}) I(\hat{n}) \sin(\psi(\hat{n}))$$

CIB corrected foreground models

DDM-P1

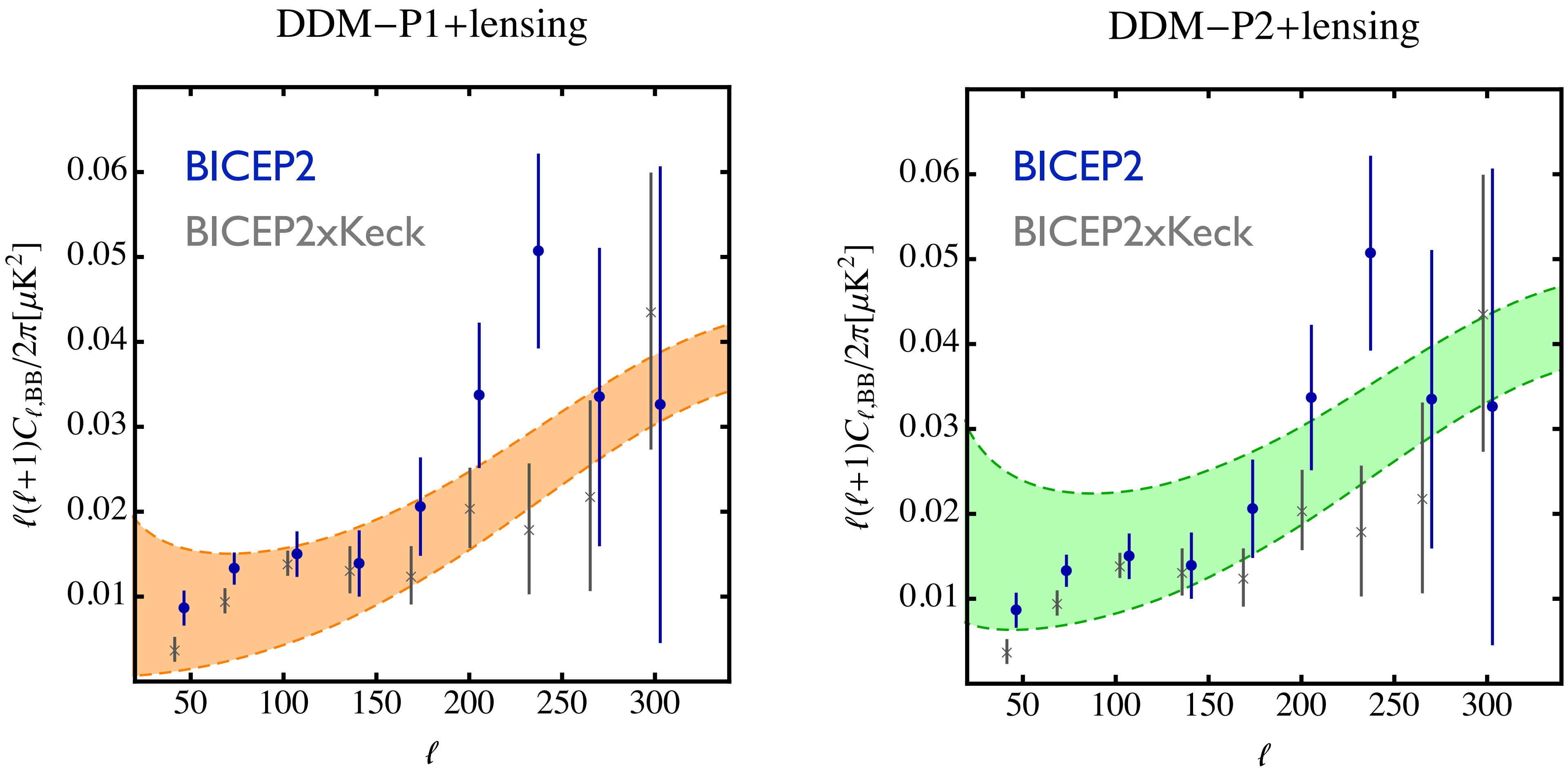
- Intensity from Planck dust model (v1.20)
- Average polarization fraction p
  (from Bernard polarization fraction map or Planck 353 GHz maps, corrected for CIB)
- Polarization angles from starlight data, PSM, or Planck 353 GHz maps

DDM-P2

- Intensity from Planck dust model (v1.20)
- Polarization fraction $p(\hat{n})$
  (from Bernard polarization fraction map or Planck 353 GHz maps, corrected for CIB)
- Polarization angles from starlight data, PSM, or Planck 353 GHz maps

CIB corrected foreground models

Foregrounds plus lensing contribution



bands reflect uncertainties in polarization fraction and angles and uncertainty in frequency rescaling.

CIB corrected foreground models

Remarks

- DDM-P1 ignores fluctuations in polarization fraction which causes it to under-predict the foregrounds
- DDM-P1 overpredicts foregrounds on small scales because dust model contains CIB fluctuations
- This is true of all models relying on average polarization fractions (and one might argue they should not be used at all)
- DDM-P2 should over-predict the foregrounds from dust because of noise bias and noise in polarization fraction map (but ignores synchrotron)

CIB corrected foreground models

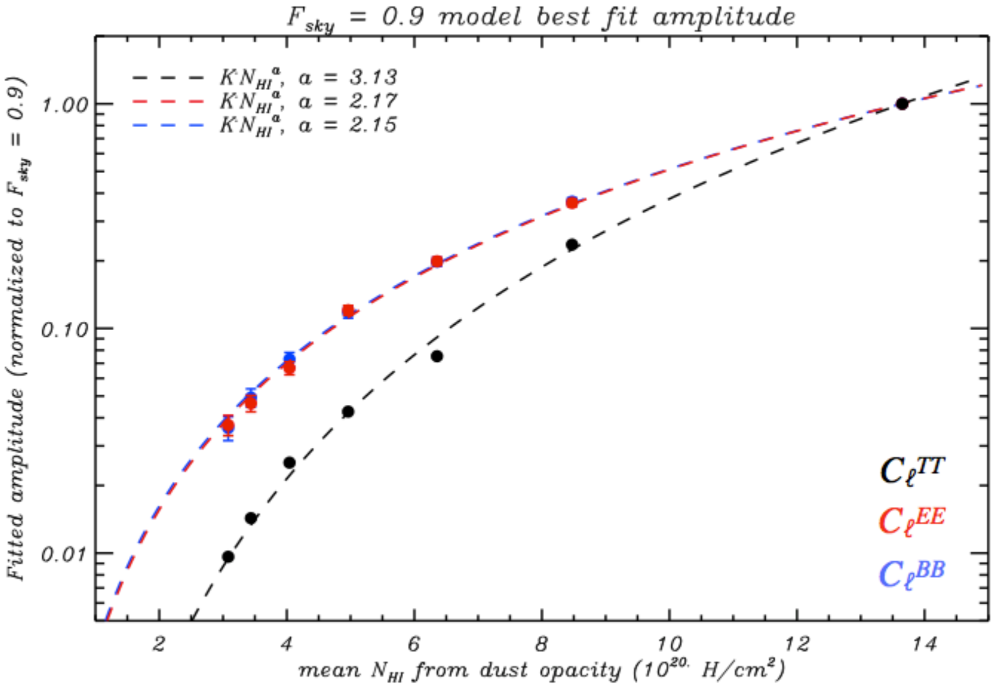
Can we find other estimates?

- HI traces the dust and its column density can be used to predict polarized emission (see ESLAB presentation by J. Aumont)
- If we think they are reliable, we can attempt to measure BB directly from the digitization of Boulanger's Planck 353 GHz maps

Estimate from HI column density

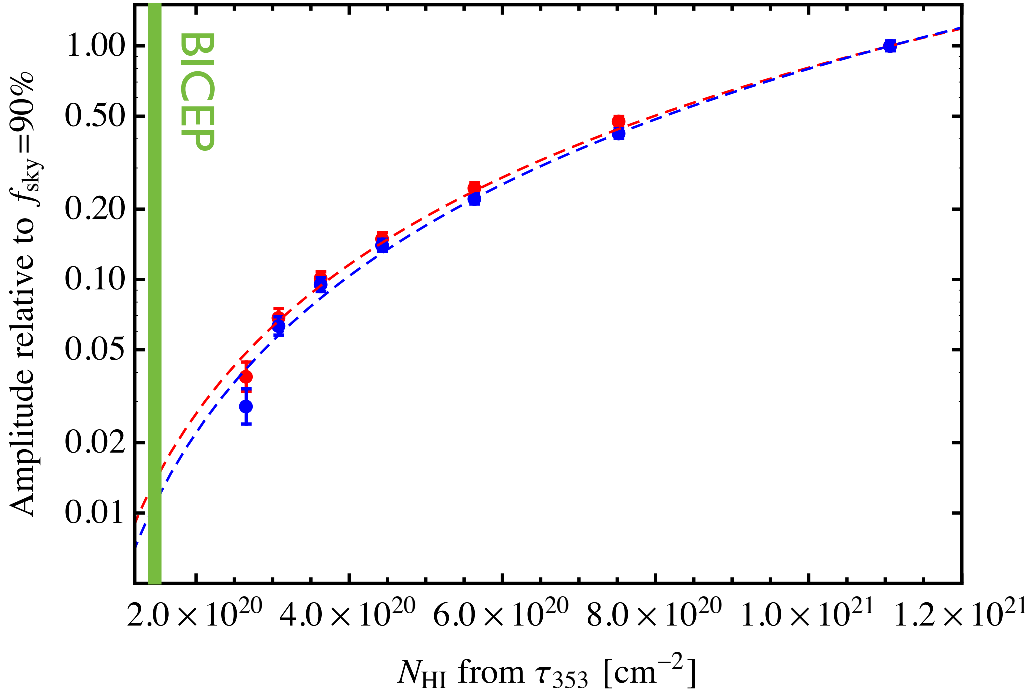
Correlation with HI column density

Aumont ESLAB presentation



differences in column density due to change in Planck dust model 1.10 vs 1.20

Preliminary Q and U maps



corrected for instrumental noise and effects of digitization

Estimate from HI column density

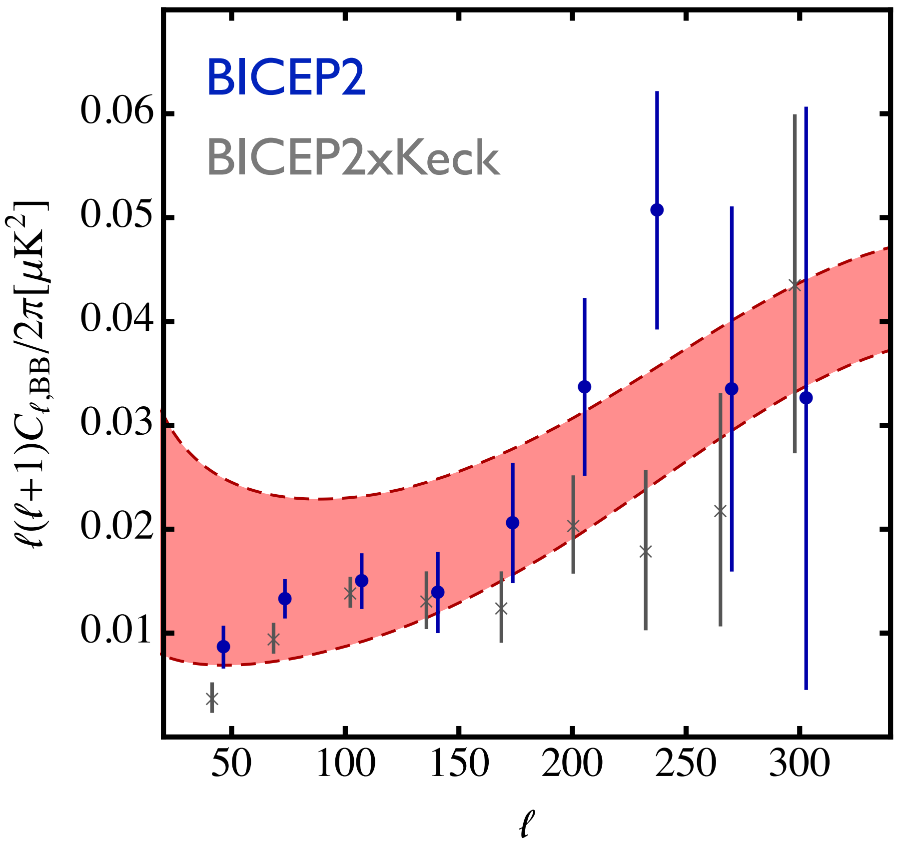
This tells us how to extrapolate to low column density at 353 GHz

How do we extrapolate in frequency?

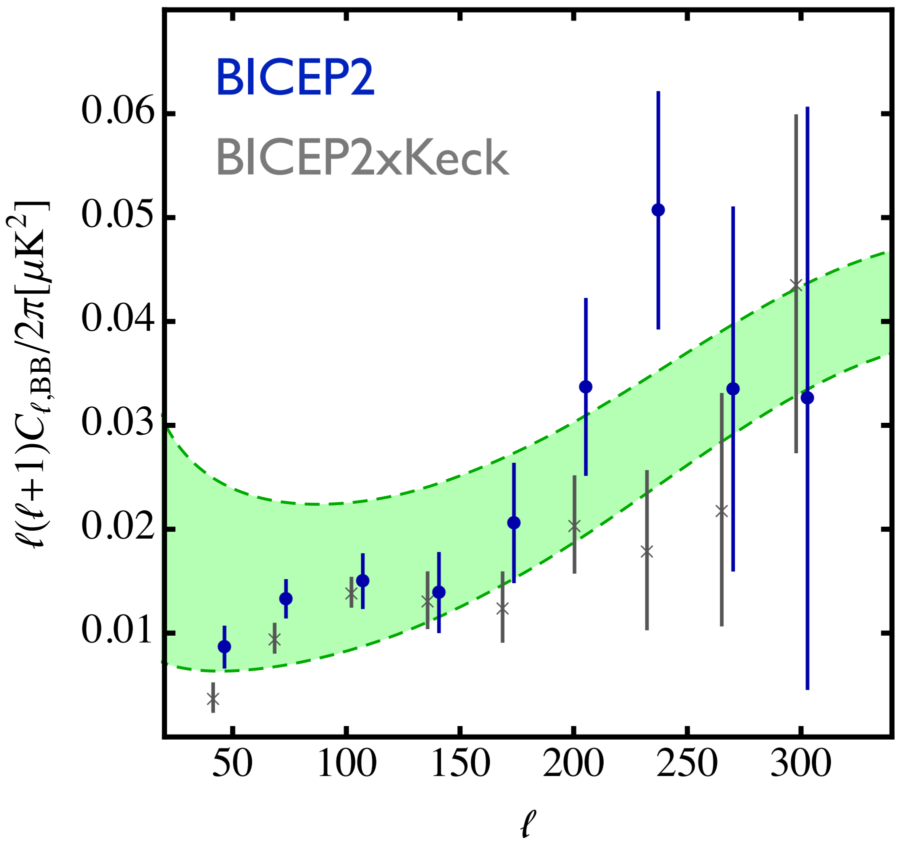
- Using a modified black body assuming the same parameters in the patch as given in the recent Planck papers
- Measuring the coefficient for cleaning the 143 GHz map with CMB-free 353 GHz map in the patch assuming the same frequency dependence as in intensity
- or using additional results from Aumont directly for BB

Estimate from HI column density

Good agreement



N_{HI}−lensing



DDM−P2+lensing

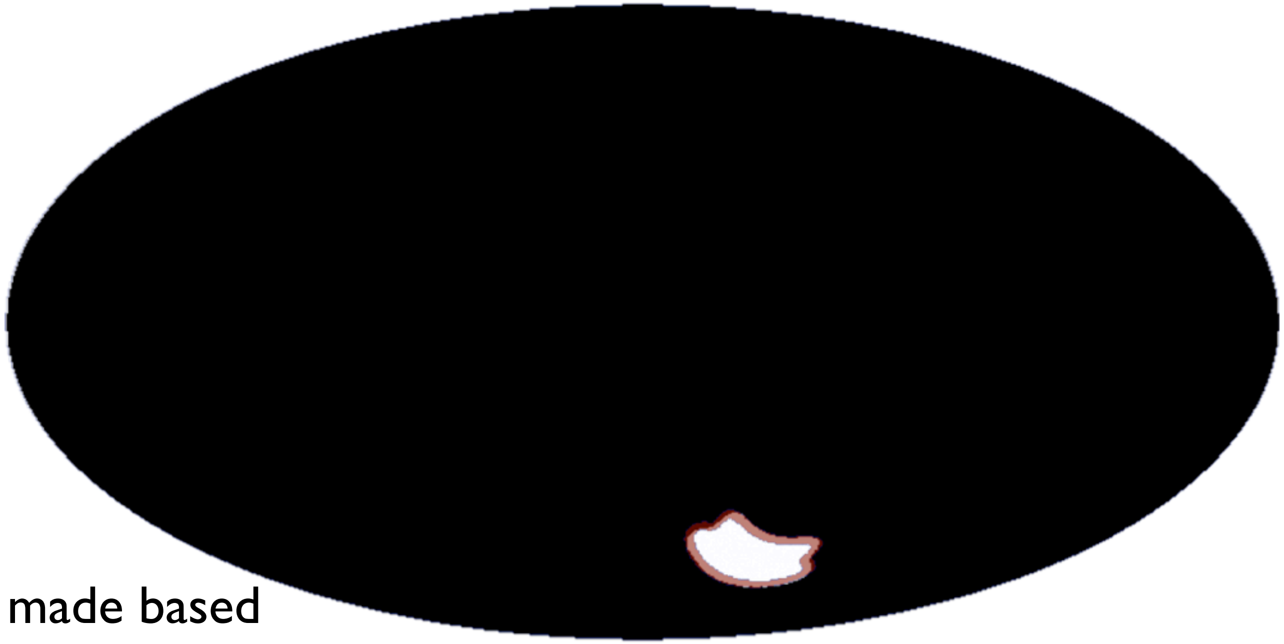
Estimate from HI column density

Points to take away from this analysis

- DDM-P2 models and an estimate based on HI column density agree well
- Foregrounds may be OK if the lower end of the estimates is correct, but the uncertainty is large
- The preliminary maps produce reasonable results on sky fractions studied by Aumont suggesting that one can attempt a direct measurement

Measurement from Q/U maps

- Estimator based on PolSpice, apodization and range of correlation function based on simulations.
- Weighting based on BICEP hit count (made by eye).



reverse engineered mask made based on description of scan strategy before outline was released

released BICEP outline

Measurement from Q/U maps

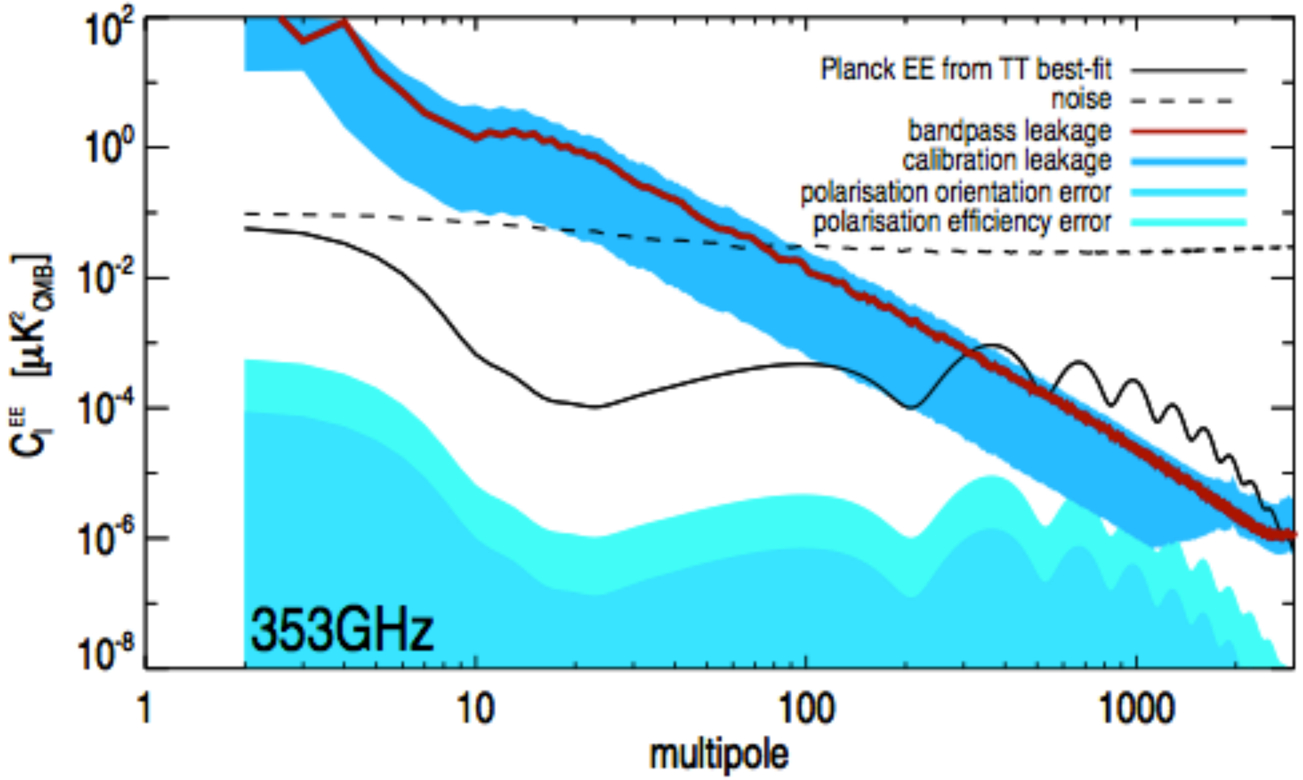
Effect of HEALPix → gif → pdf → gif → HEALPix

- simulate CMB temperature and polarization
- map2gif
- Keynote
- export to pdf
- convert figure back to gif
- convert back to fits map
- measure spectrum with same estimator as for simulations

Measurement from Q/U maps

- Direct measurement from the preliminary Q and U maps agrees well with DDM-P2 models and the estimates based on H1 column density

Could it all be bandpass or calibration leakage?

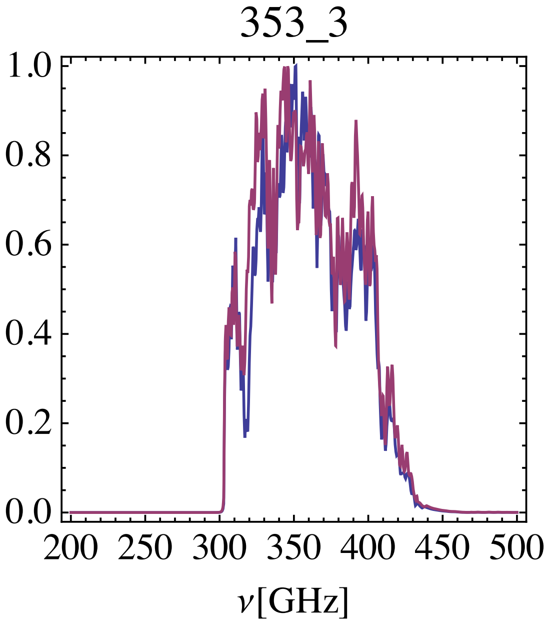


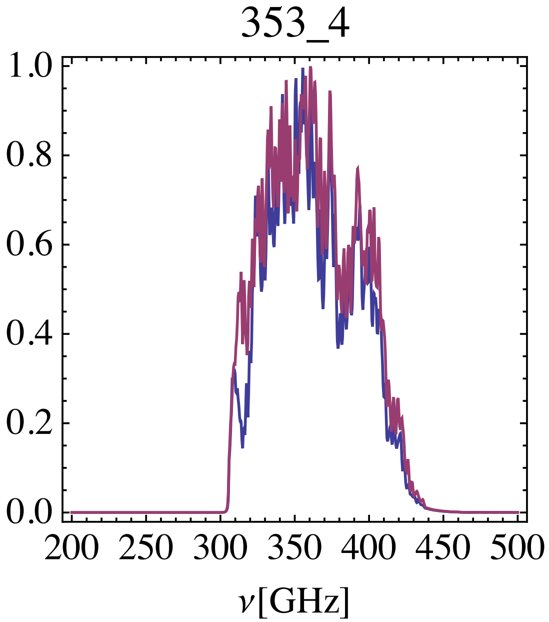
Measurement from Q/U maps

bandpass leakage

$< 0.25\%$
for detector pairs 3-5

$\sim 3.5\%$
for detector pairs 6


353_3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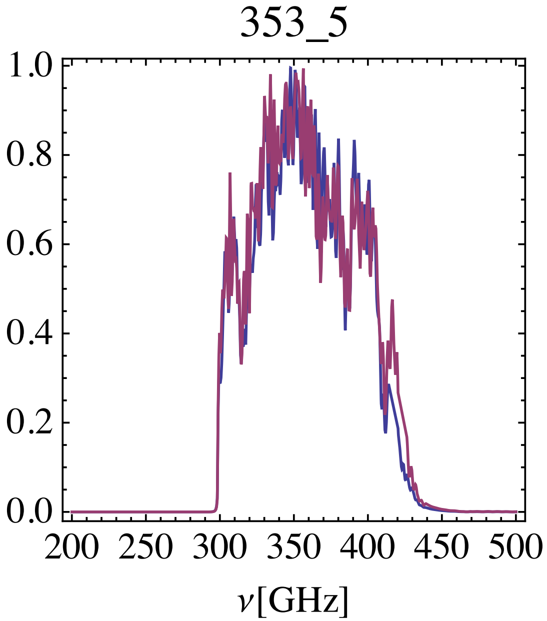
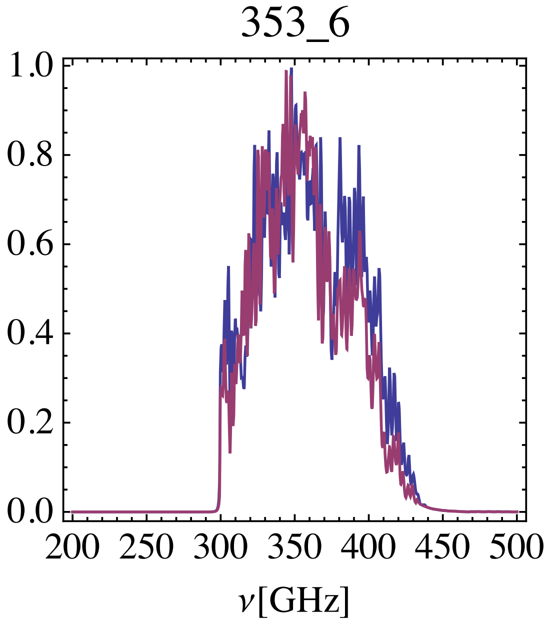
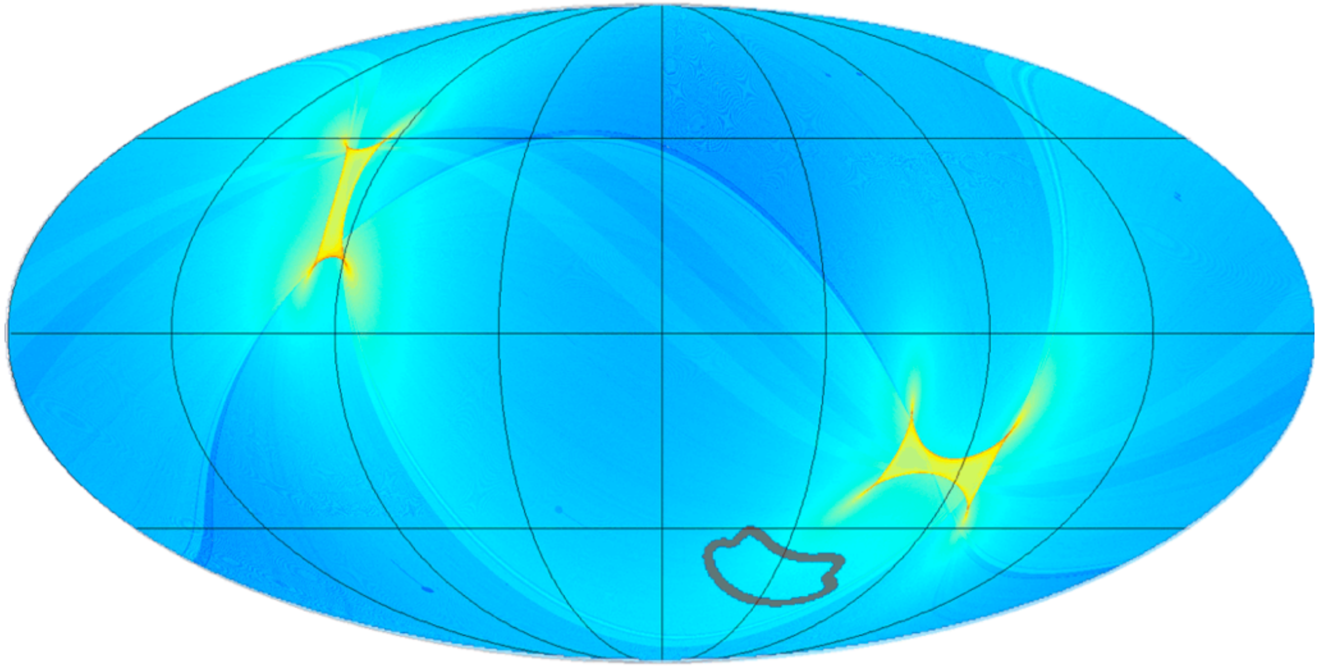

353_5


353_6

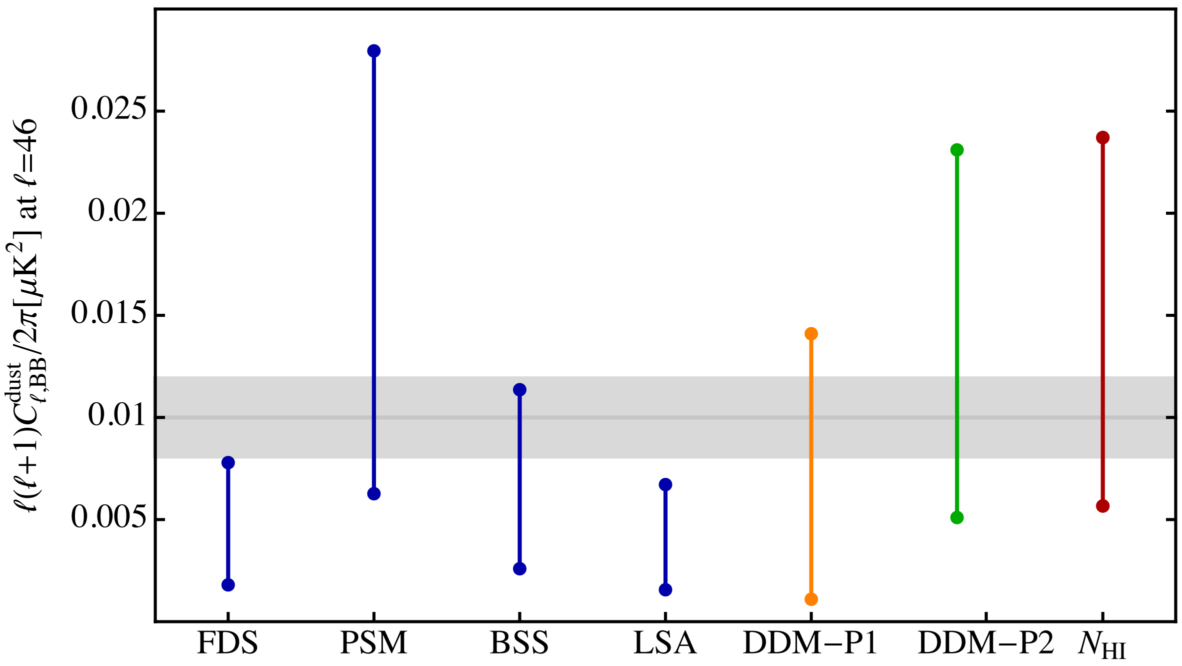
Measurement from Q/U maps

- Bandpass and calibration leakage should not be a problem even for the preliminary Q and U maps, essentially because of the low dust intensity, and can certainly be controlled by Planck

- To what extent noise is a problem remains to be seen, but Planck's noise is lower than average in the BICEP2 region of the sky



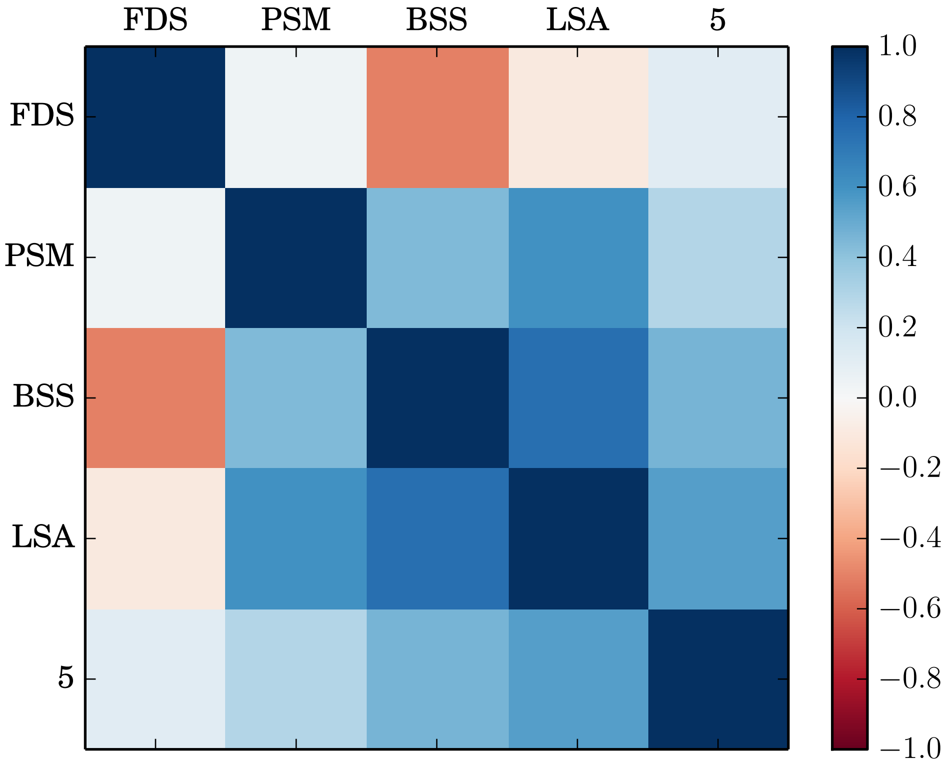
Summary of Foreground Estimates



- For the FDS and LSA models, foregrounds are not expected to be the entire signal
- For all other models, foregrounds may be OK if the lower end of the estimates is correct, but the uncertainty is large

Cross-Spectra of Data with Models

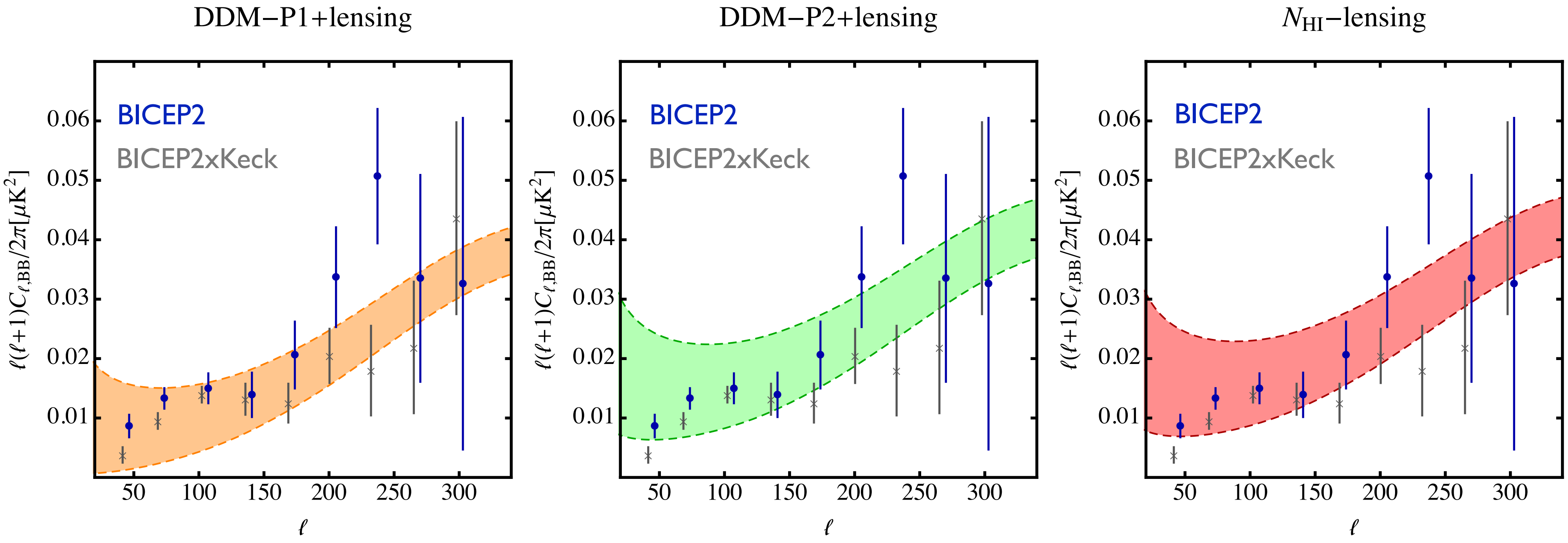
- None of the models capture the foregrounds in the BICEP2 region of the sky well on the relevant scales.
- As a consequence, the cross-spectra between the models and the data underestimate the true foreground contribution.



correlation matrix at $\ell = 46$

Conclusions

- BICEP has provided us with the deepest maps of any patch of the sky at 150 GHz and has detected degree scale B-modes
- According to all estimates, foregrounds may be small enough to allow a primordial signal, but the uncertainty on foregrounds is large and measurements at other frequencies are important for a definitive measurement



Conclusions

- 100 GHz Keck Array data will be available soon (1-2 months?)
- Three frequency BICEP3/Keck Array data (coming 2015?), should be able to characterize foregrounds
- Planck will soon release its polarization data which will be extremely valuable for our understanding of foregrounds because of its frequency coverage
- If the tensor to scalar ratio is 0.1 or larger, Planck may also be able to confirm the measurement directly
- Planck and BICEP will collaborate so that we should soon know whether there is a primordial tensor contribution hiding in the excess B-mode power on degree angular scales observed by BICEP2

Thank you