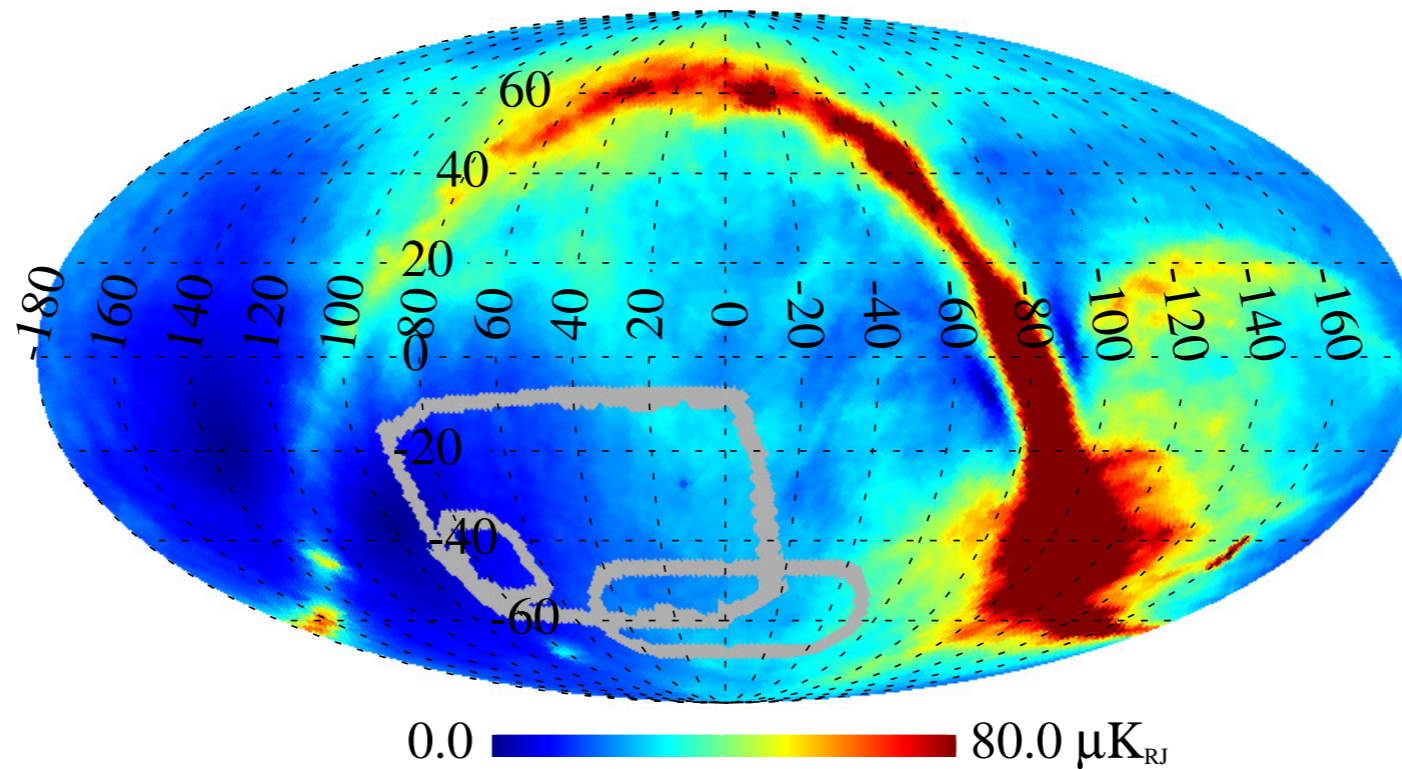


# Primordial B-modes: Foreground modelling and constraints

Carlo Contaldi  
Imperial College London

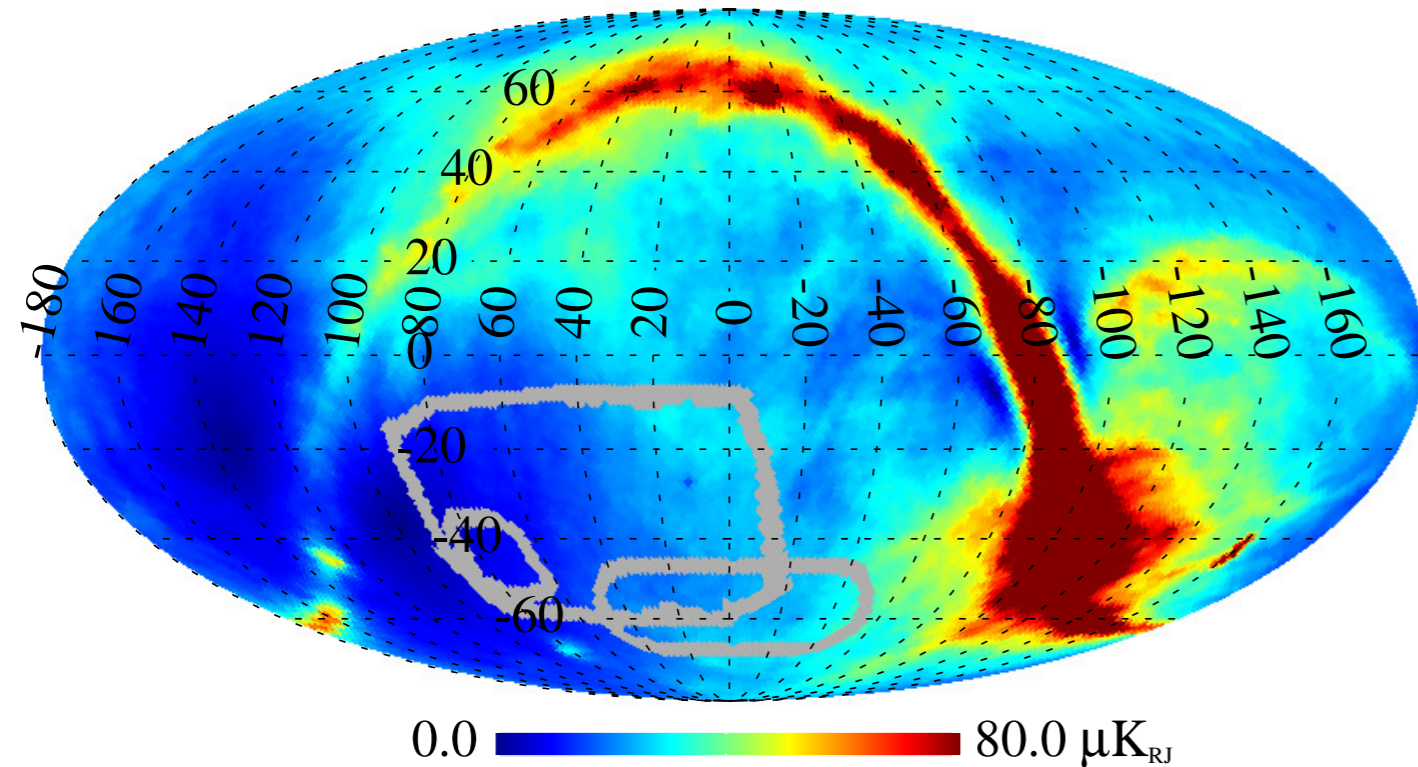
Model Polarisation Amplitude



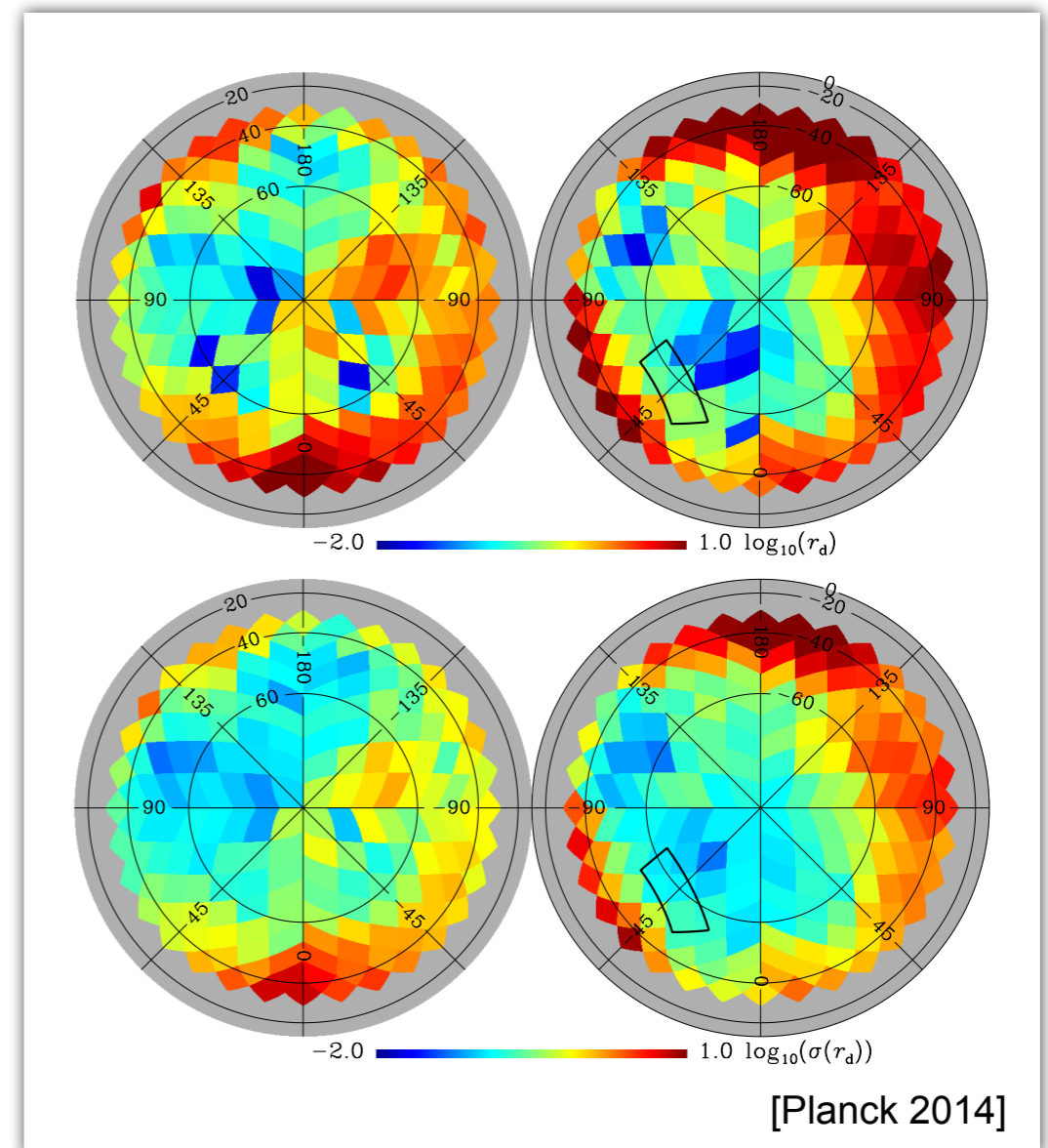
# Dust!

- Polarized foregrounds are here, there is no escape - anywhere in the sky...
- Modelling Polarized Foregrounds.
- Pre-BICEP2 — Planck 2014 — Planck 2015.

Model Polarisation Amplitude



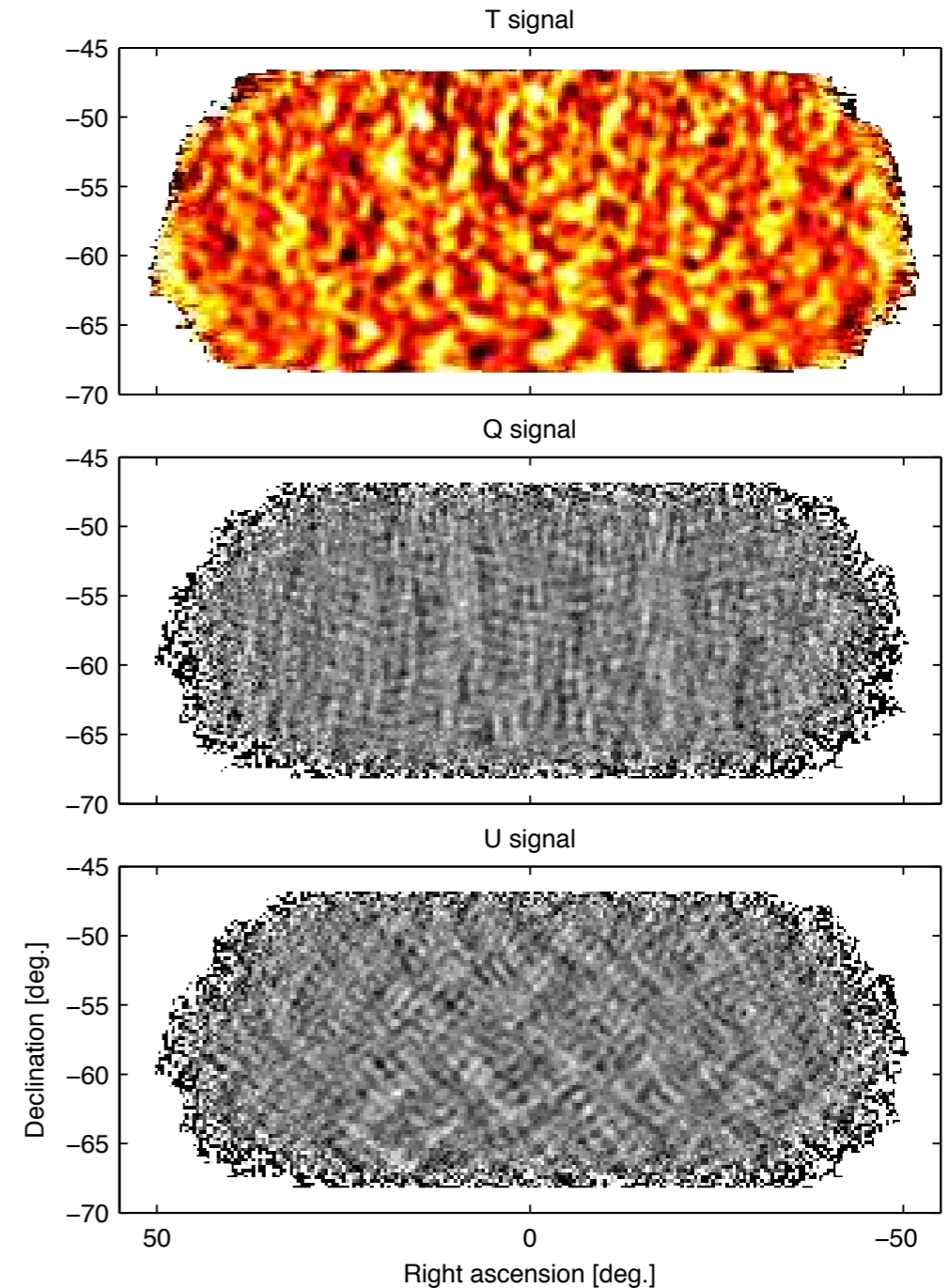
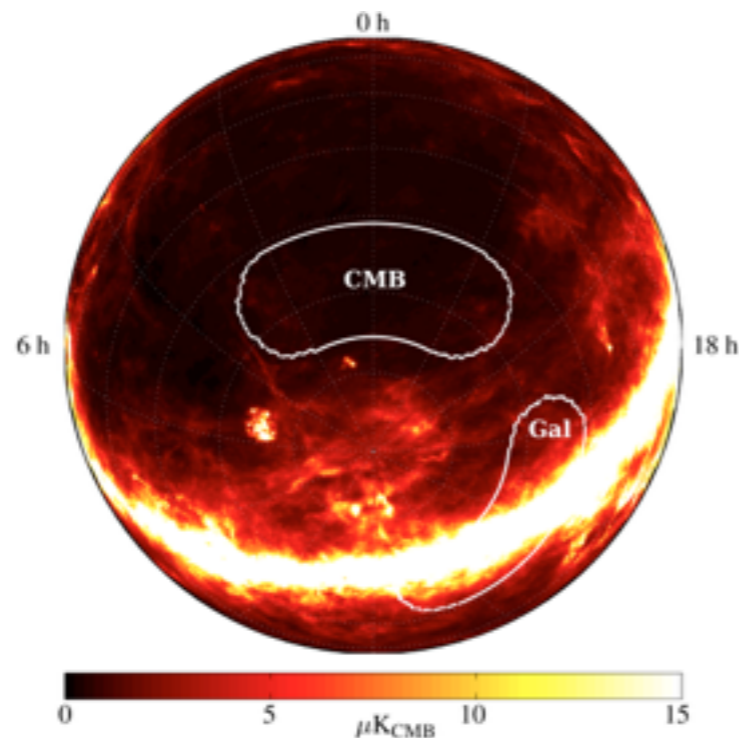
[Clark, Contaldi, MacTavish 2013]



[Planck 2014]

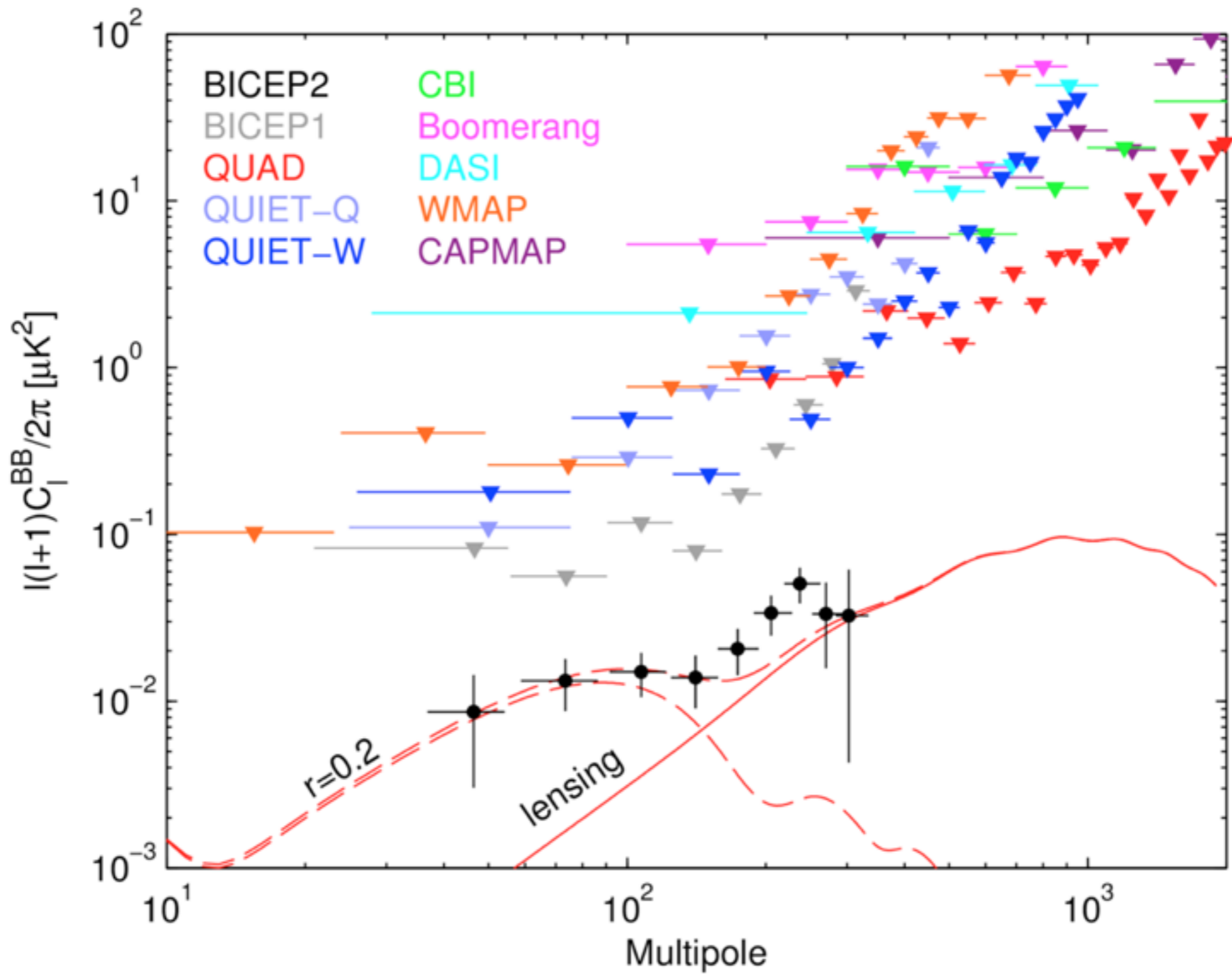
# BICEP2 Foregrounds

- Apr 2014; BICEP2 announces detection of large scale  $l \sim 80$  primordial B-modes with  $r=0.2$ .
- Measurements at single frequency (150 GHz).
- Observations targeted what was thought to be a very “clean” window in polarized foreground emission.



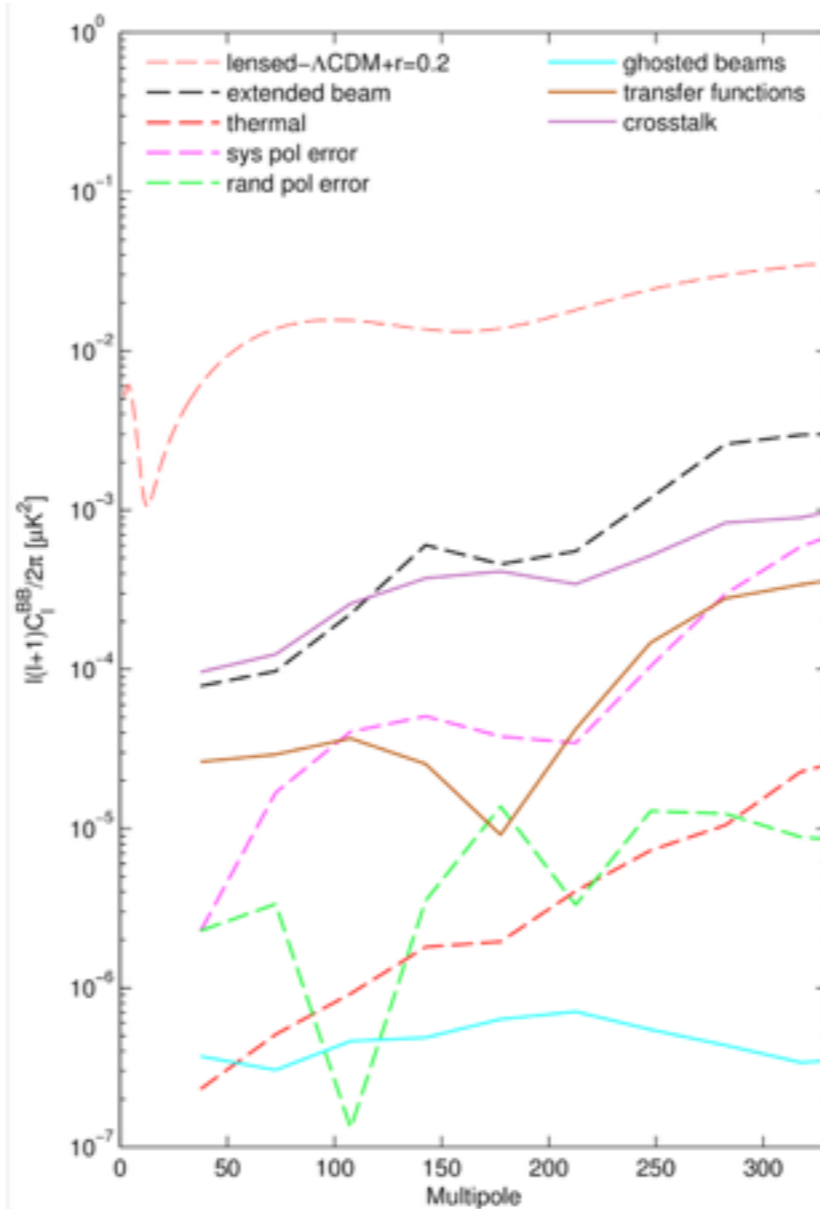
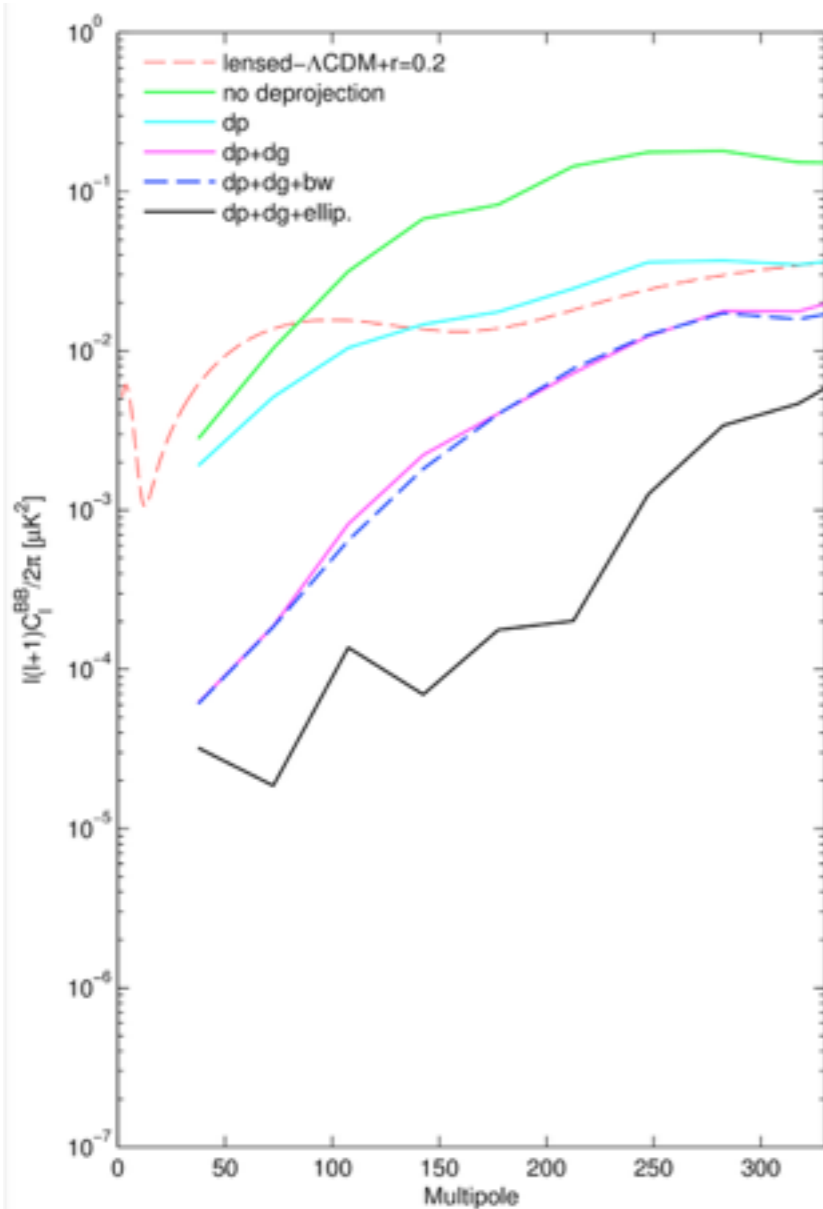
[BICEP2]

# BICEP2 measurement



# BICEP2

- Impressive confirmation that systematics for directly imaged refracting telescopes BICEP/KECK/Spider are under control.
- **Systematic effects can be overcome** to achieve the sensitivity to measure  $r \ll 0.1$  from primordial signal on large scales.



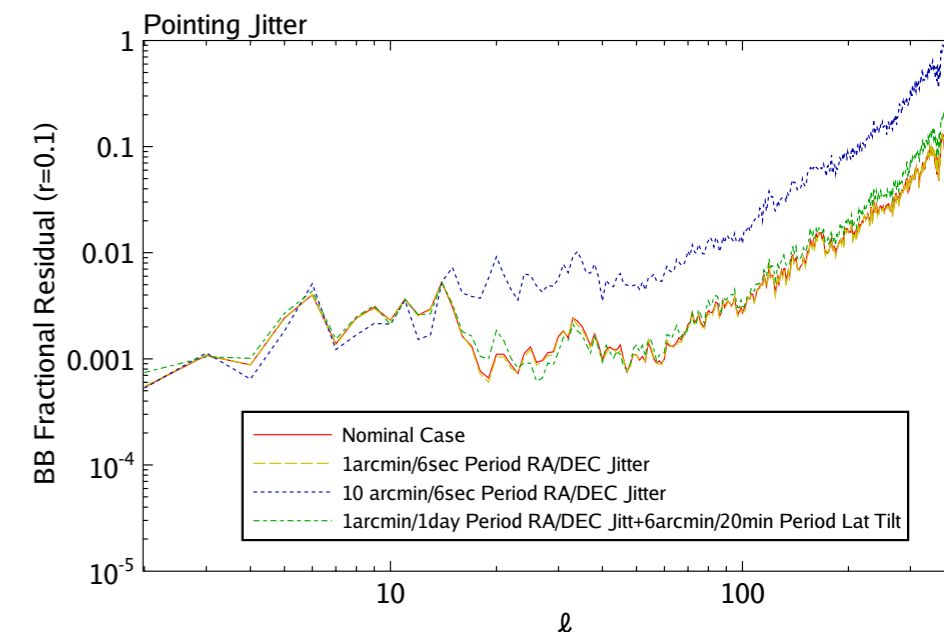
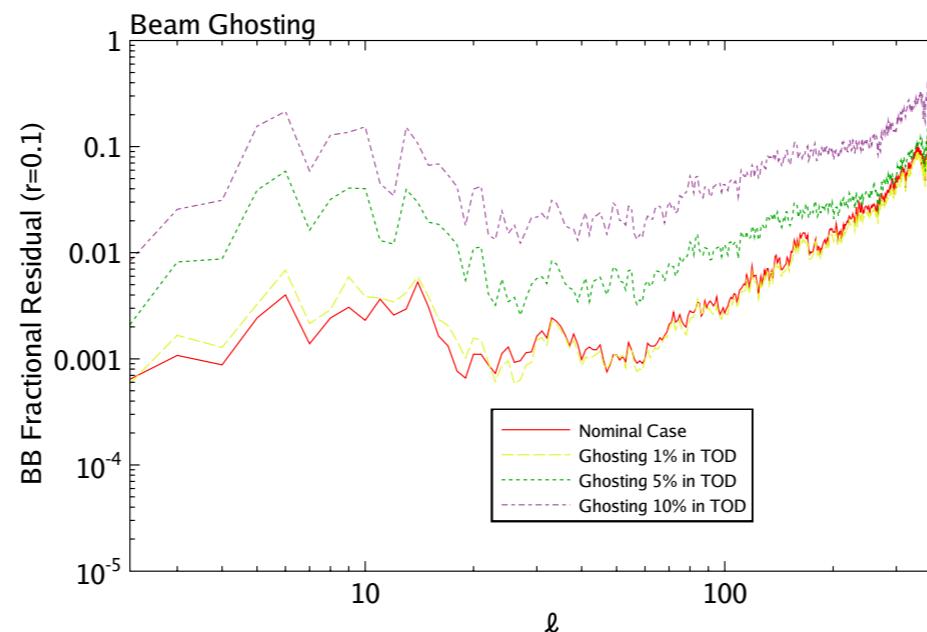
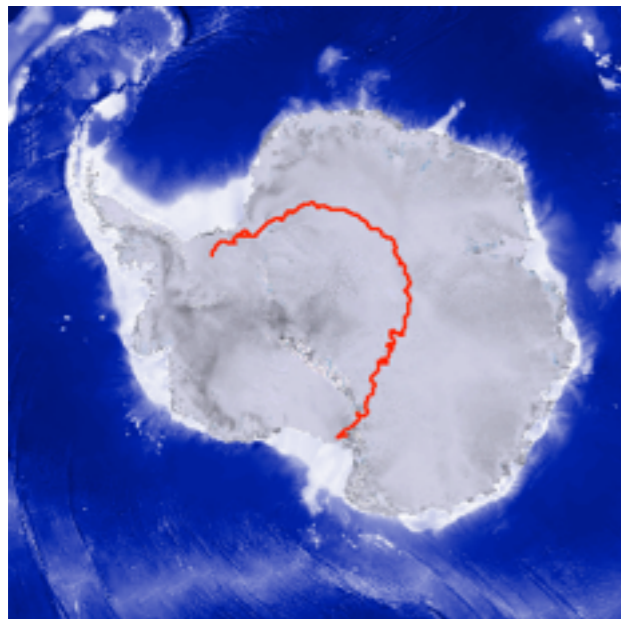
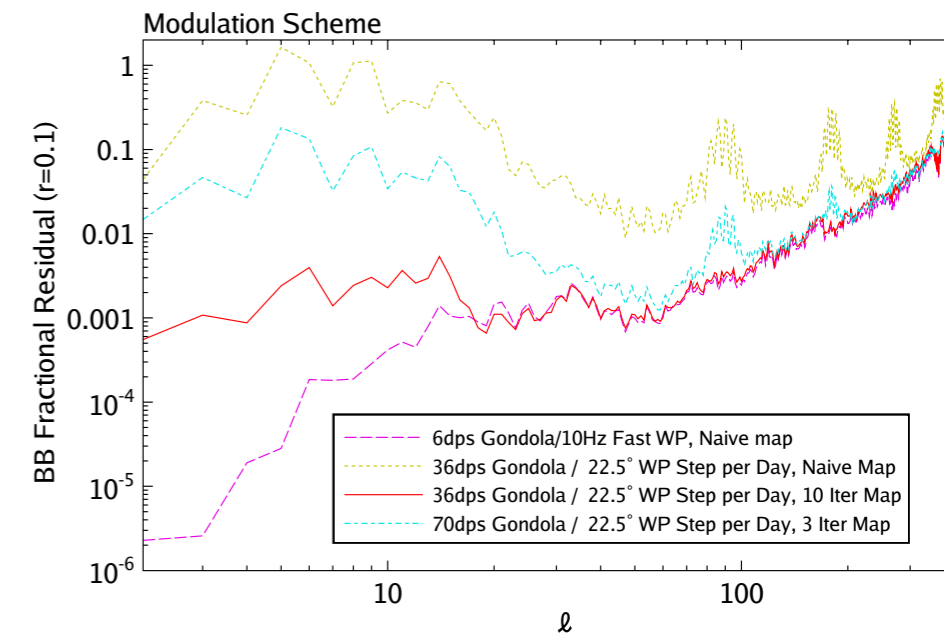
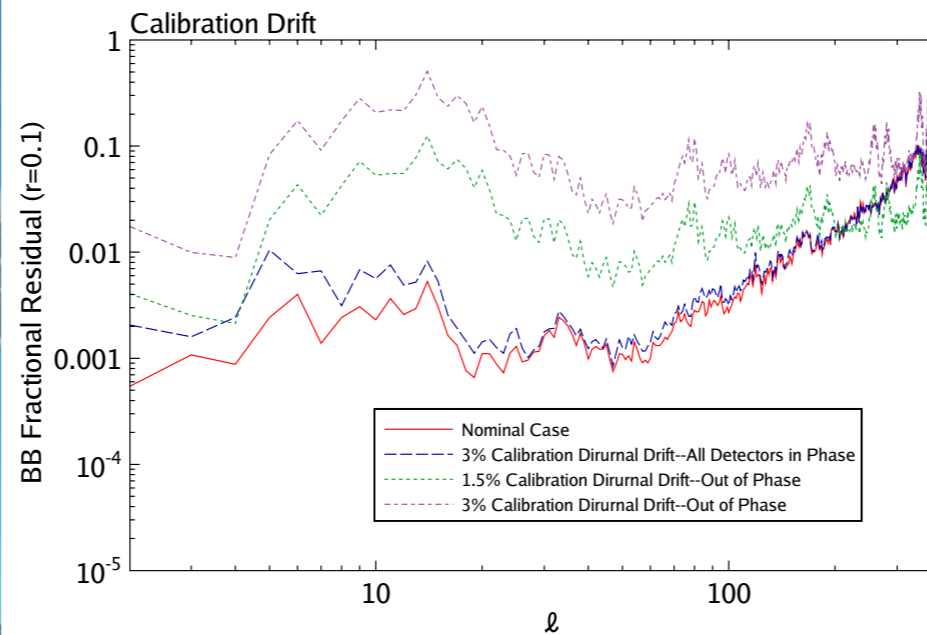
Foregrounds are the limiting factor.

[BICEP2]

# Spider = 6 x BICEP - 30km atm

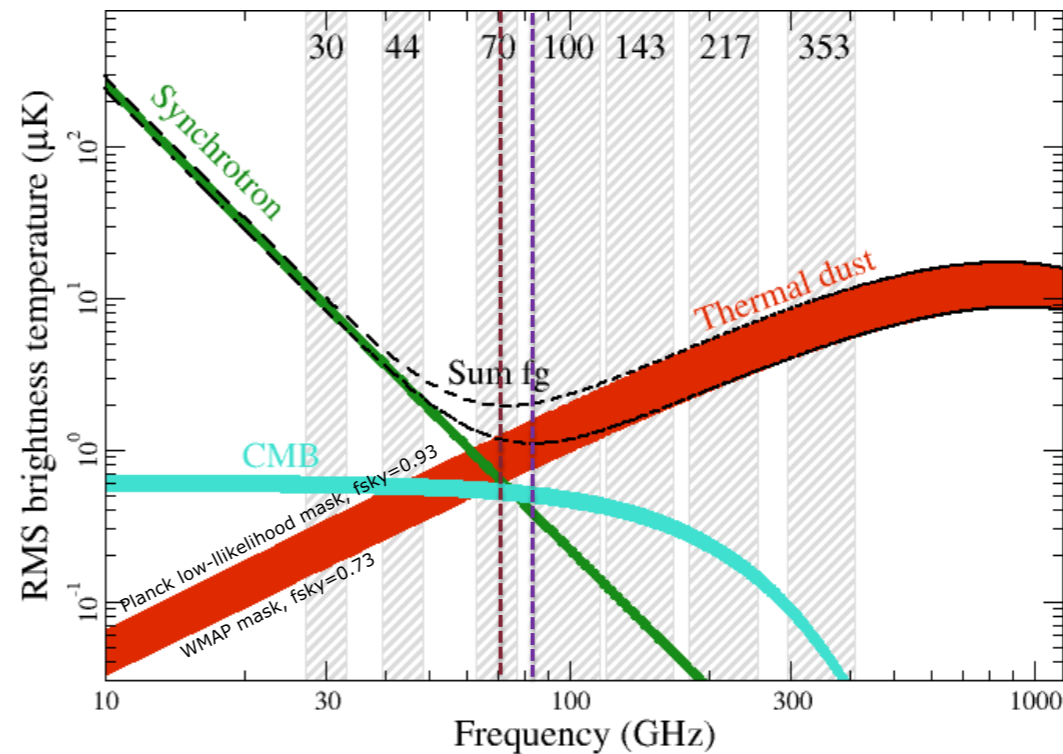
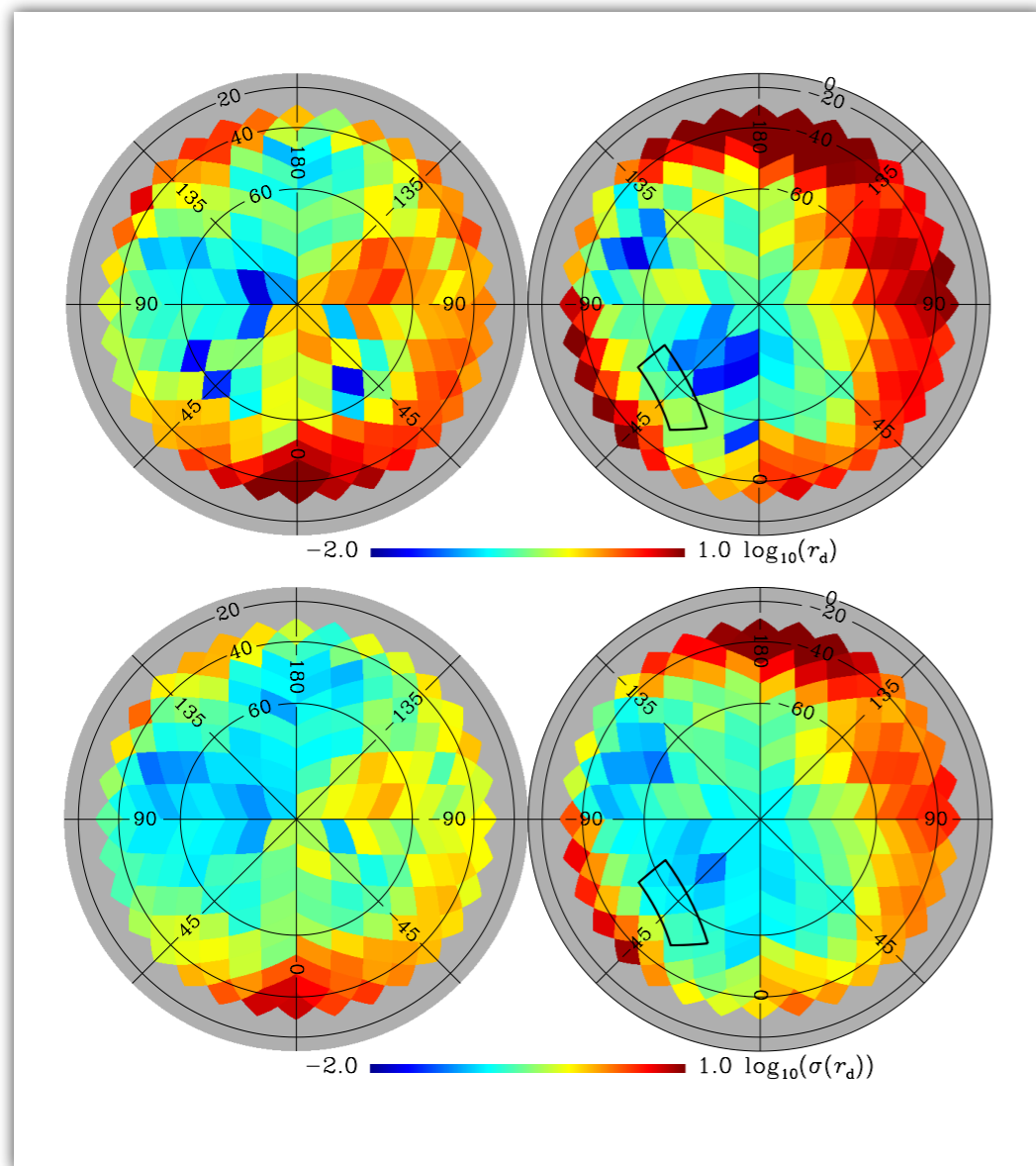


- Similar telescopes to BICEP2/KECK.
- 8% of sky from 34 kms up.
- 3x90 GHz + 3x150 GHz (~2200 detectors)



# BICEP2

- On average, dust contamination expected to be same order of magnitude as B-mode signal.
- Polarization fraction varies significantly over the sky as shown by WMAP (synch) and PLANCK 353 GHz (dust) pol maps.
- Pol fraction correlated in non-trivial way to total intensity - “clean spot” in intensity not a guarantee of “clean spot” in polarization.



Polarization foreground minimum between **70 and 85 GHz** for sky fractions between 73 and 93% at **40 arcmin** resolution



Preliminary

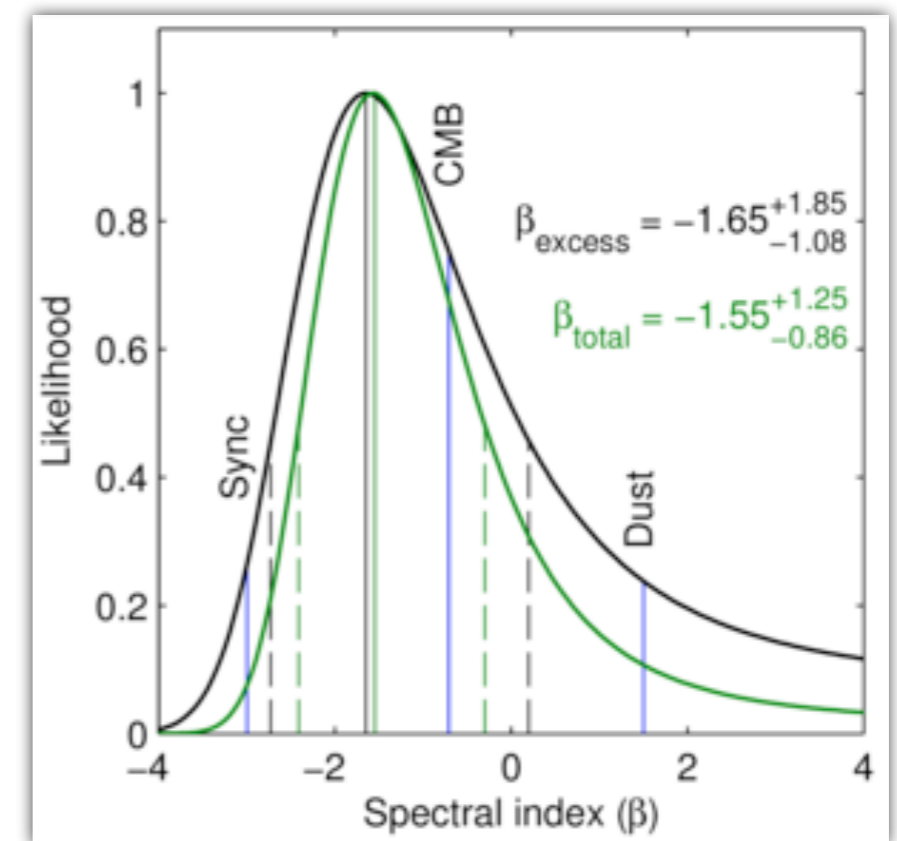
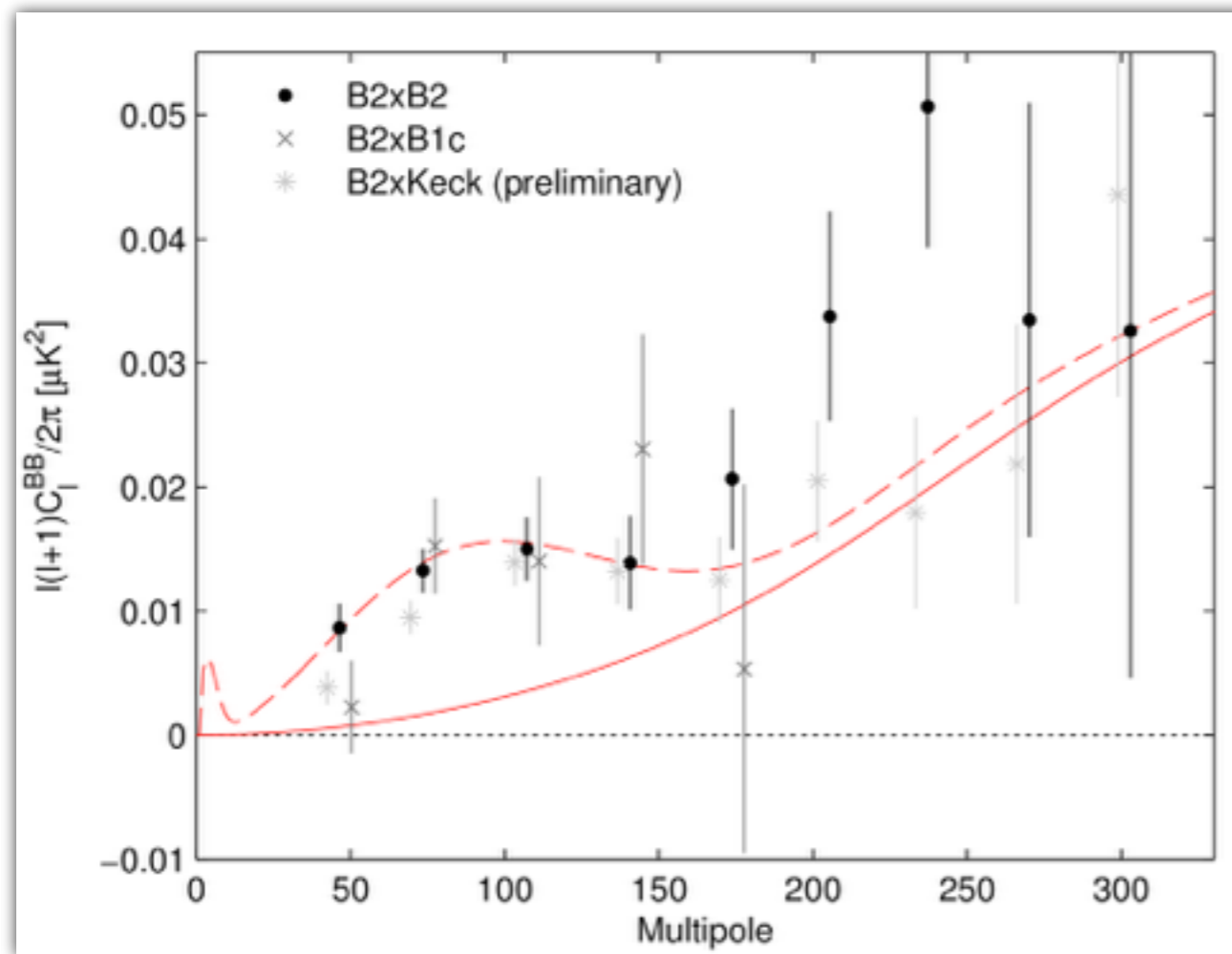


[I. Wehus, Planck 2014, Ferrara talk]

[Planck 353 GHz -> 150 GHz, 2014]

# BICEP2 Foreground Analysis

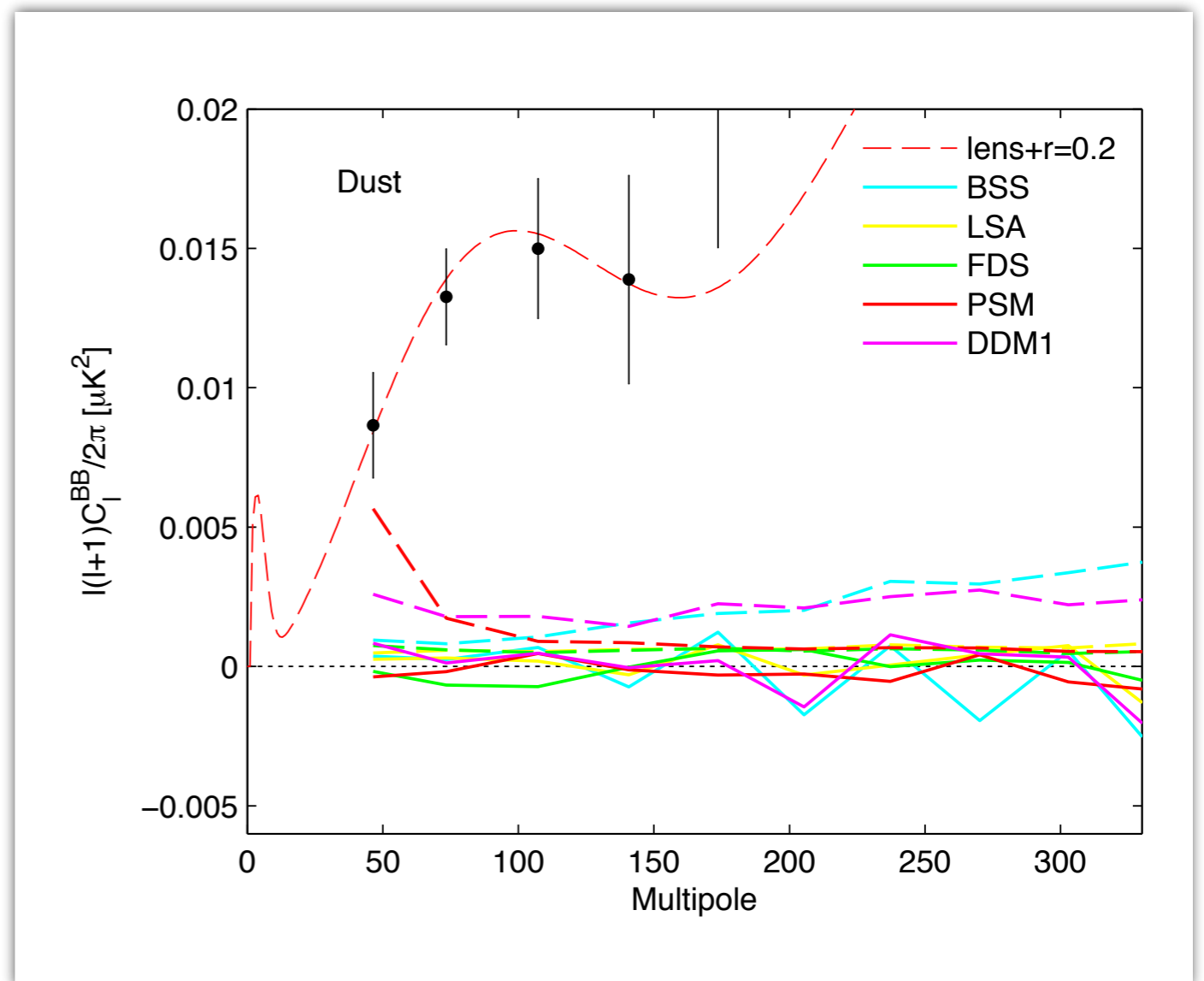
- Relied on various methods;
  1. Cross-correlation with separate data set (BICEP1 100 GHz) and spectral dependence.
  2. Cross-correlation with structure in foreground templates derived from polarized sky models and comparison with template power.





# Template comparison method

- Planck Sky Model (PSM) [e.g. Delabrouille et al 2013]
- Data Driven Models [Planck dust 2013], with uniform 5% pol fraction & Planck talk maps.
- FGPol “LSA” and “BSS” templates [O’Dea et al. 2009, O’Dea et al 2011, Clark et al 2013]

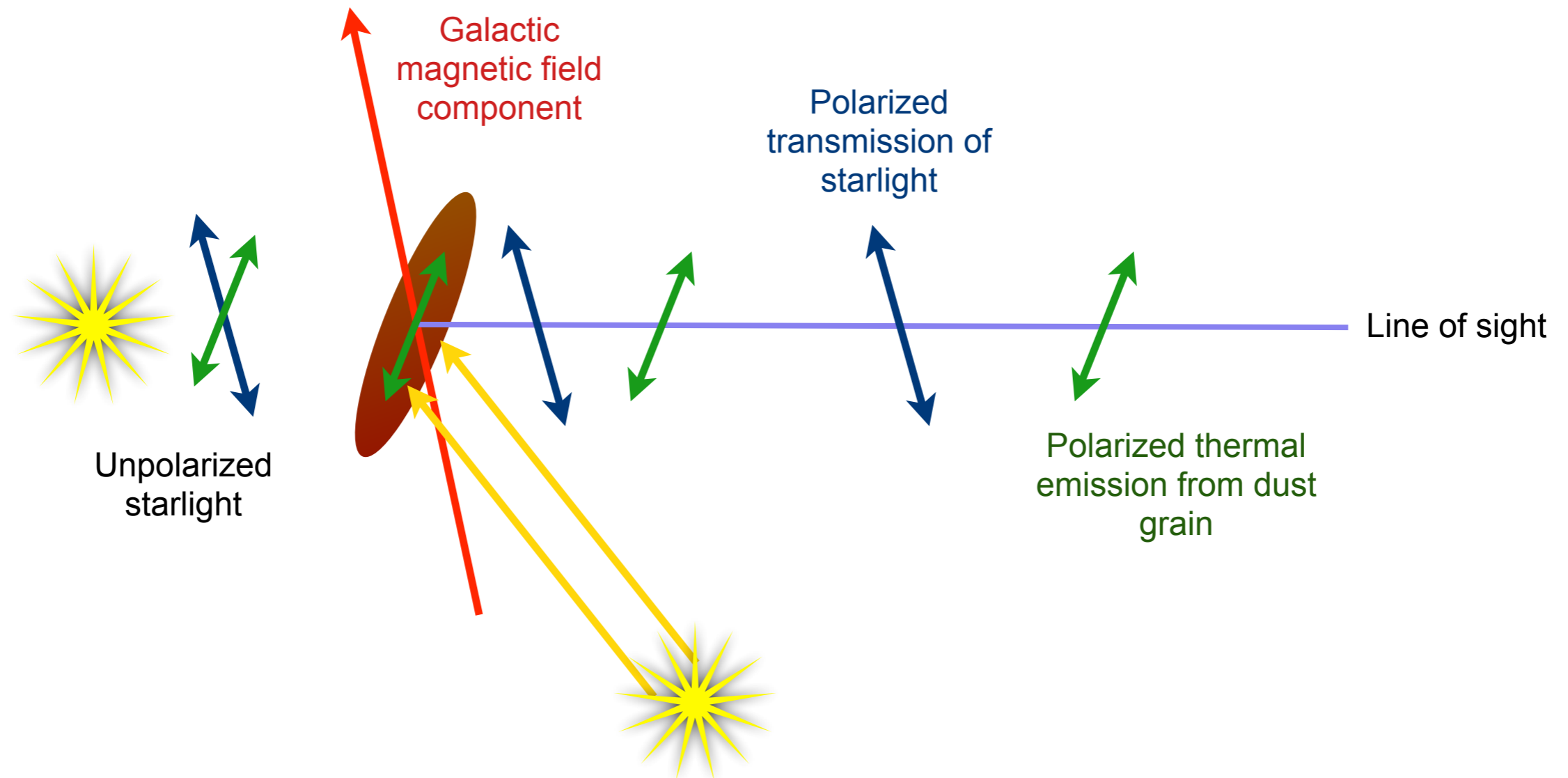


# Modelling the polarized foreground

- Up until Planck 2014 intermediate papers not much known about dust polarization. Dust polarization at lower frequencies still unclear - Planck 2015.
- Model polarization - motivation; forecasting of coverage/sensitivity/component separation errors for future experiments.
- e.g. Planck Sky Model, FGPOL.
- FGPOL aim (2009); Create a polarized sky model for use in forecasting and tailoring analysis methods for Spider experiment.
- How much dust (synchrotron) contamination would experiments such as BICEP/BICEP2 and Spider et al. see?
- Originated as part of thesis work of Daniel O'Dea + development by Caroline Clark, Carrie MacTavish, & CC.

# Dust grain alignment - polarization

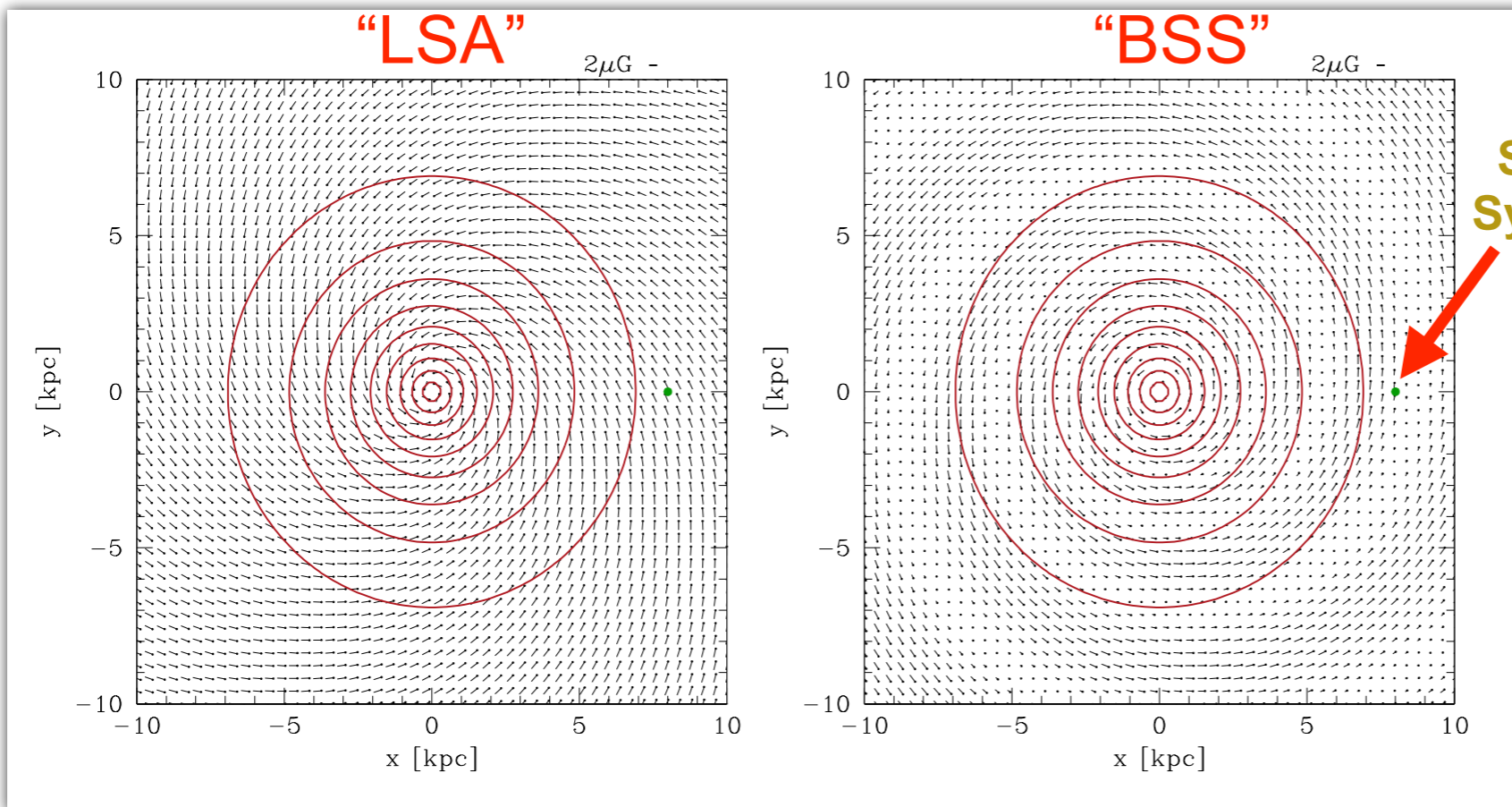
- Morphology and level of polarization of dust (and synchrotron) are determined by;
  - magnetic field of the galaxy
  - distribution of dust (cosmic ray electrons)



# Uncertain physics

- Uncertainties in modelling alignment include efficiency, shape dependence, relation to magnitude of magnetic field etc, etc.
- Assume perfect alignment and degree of polarization is proportional to square of  $|B|$ .
- Use simple models for structure of Galactic magnetic field and distribution of emitters - dust density (cosmic-ray electrons).
- Spectral dependence, maybe not such a problem as first thought.

# Large-Scale Galactic Magnetic Field

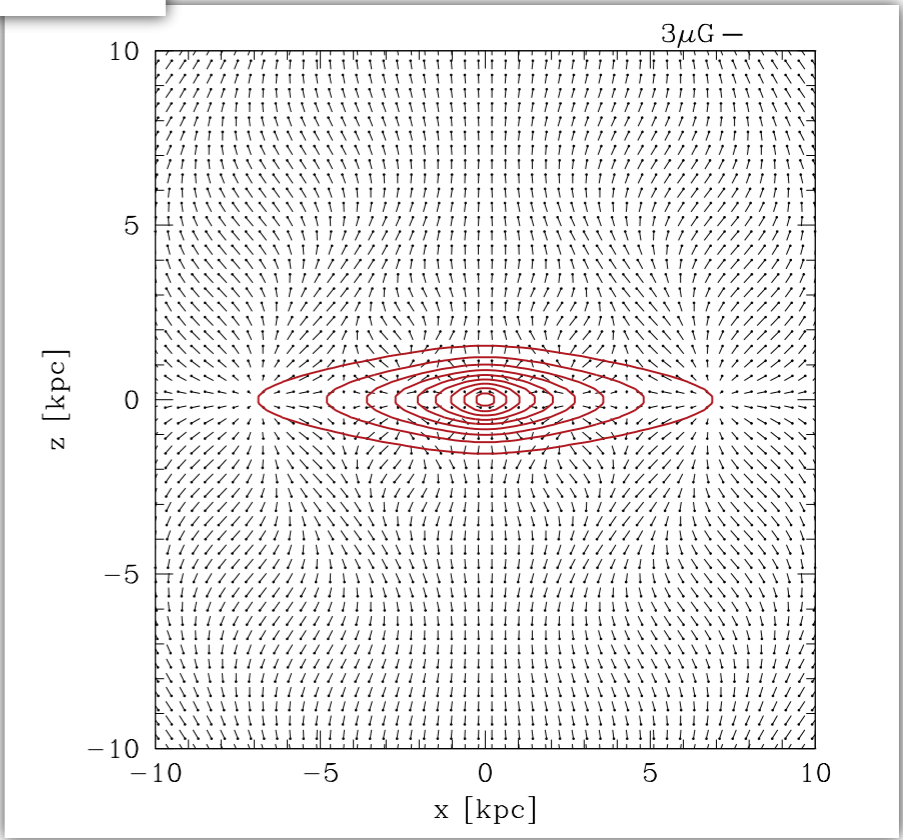


## Scales

$$\begin{aligned}
 B_0 &\sim 3 \mu\text{G} \\
 \rho_W &= 8 \text{ kpc} \\
 z_0 &= 1 \text{ kpc} \\
 r_E &= 8 \text{ kpc}
 \end{aligned}$$

- Assume a simple model for large scale magnetic field - motivated by polarized starlight observations.
- e.g. Logarithmic Spiral Arm (LSA)

$$\begin{aligned}
 B_\rho &= -B_0 \sin \left( \psi_0 + \psi_1 \ln \frac{\rho}{\rho_W} \right) \cos \chi, \\
 B_\Phi &= -B_0 \cos \left( \psi_0 + \psi_1 \ln \frac{\rho}{\rho_W} \right) \cos \chi, \\
 B_z &= B_0 \sin \chi
 \end{aligned}$$



# Dust distribution

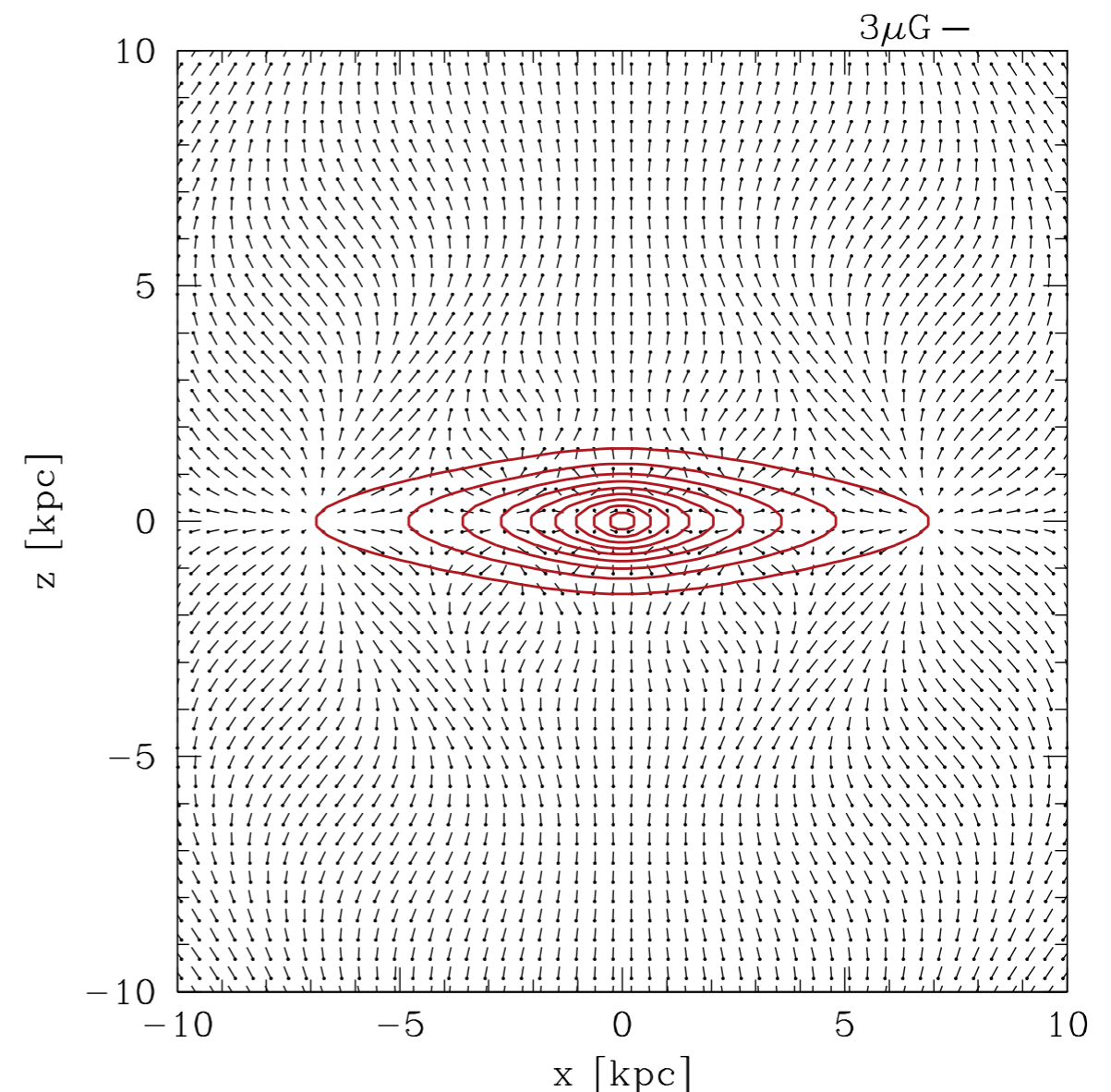
- Dust (cosmic-ray electron) distribution determine the distribution of polarized emission along line of sight.
- Very simple model of dust distribution is used.

$$n_d = n_0 \exp\left(-\frac{\rho}{\rho_d}\right) \operatorname{sech}^2\left(\frac{z}{z_d}\right).$$

*Scales*

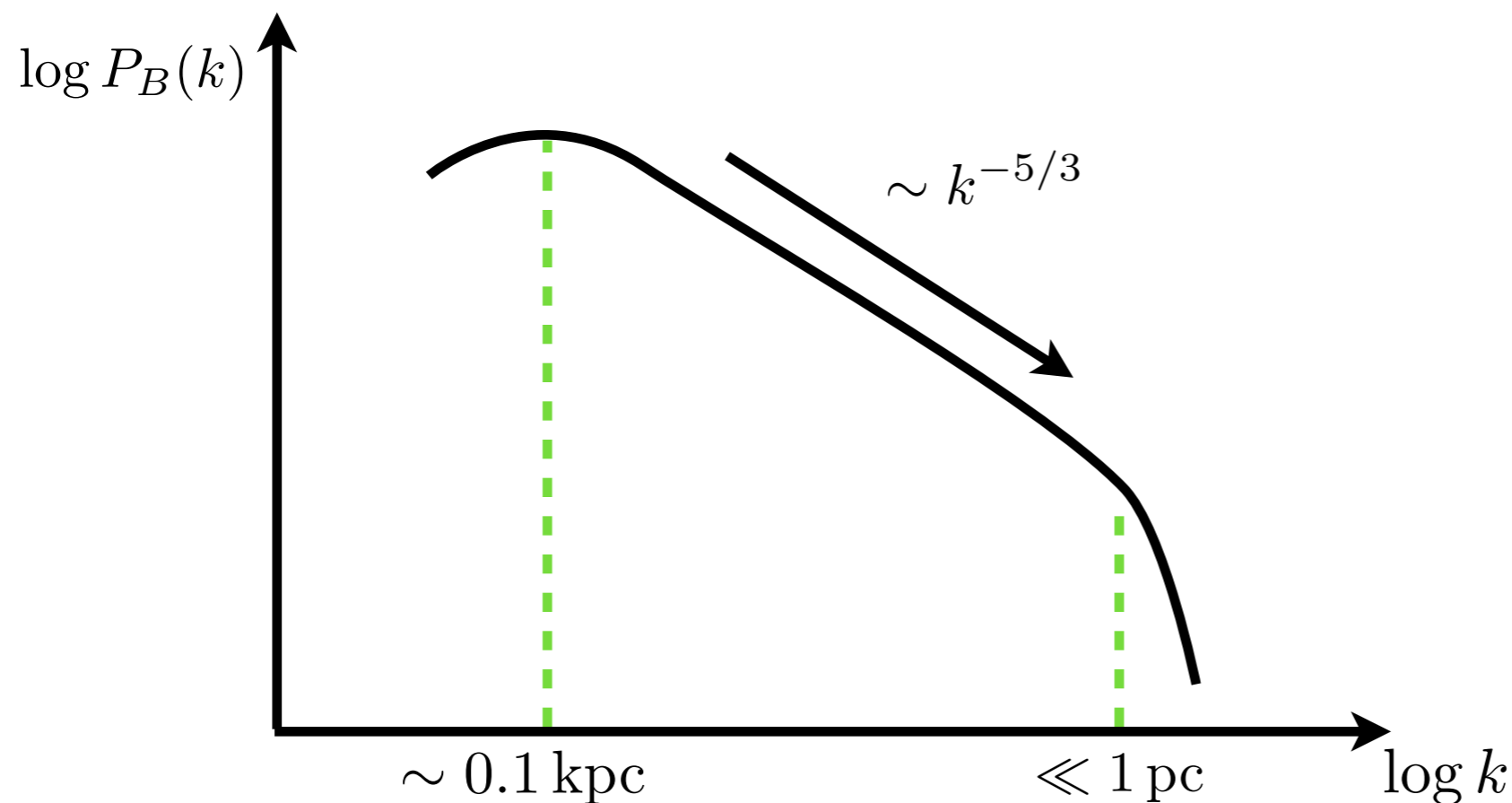
$$\rho_d = 3 \text{ kpc}$$

$$z_d = 200 \text{ pc}$$



# Small-scale Galactic Magnetic Field

- On small scales observations indicate that the field is turbulent.
- Spectrum appears to be Kolmogorov below  $\sim 0.1$  kpc scales.
- Turbulence tends to de-polarize along the line of sight and injects random noise in final polarization amplitude and intensity.



## Scales

$$B_{\text{rms}} = 2 \mu\text{G}$$

$$r_{\text{inj}} \sim 0.1 \text{ kpc}$$

$$r_{\text{dis}} \sim 1 \text{ pc}$$

# Line-of-sight-integration

- A map of Stokes parameters can be calculated by integrating contributions to polarized emission along each line of sight in Healpix map.

$$I_{\text{model}}(\theta, \phi) = \epsilon(\nu) \int_0^{r_{\text{max}}} n_d(\vec{r}) dr ,$$

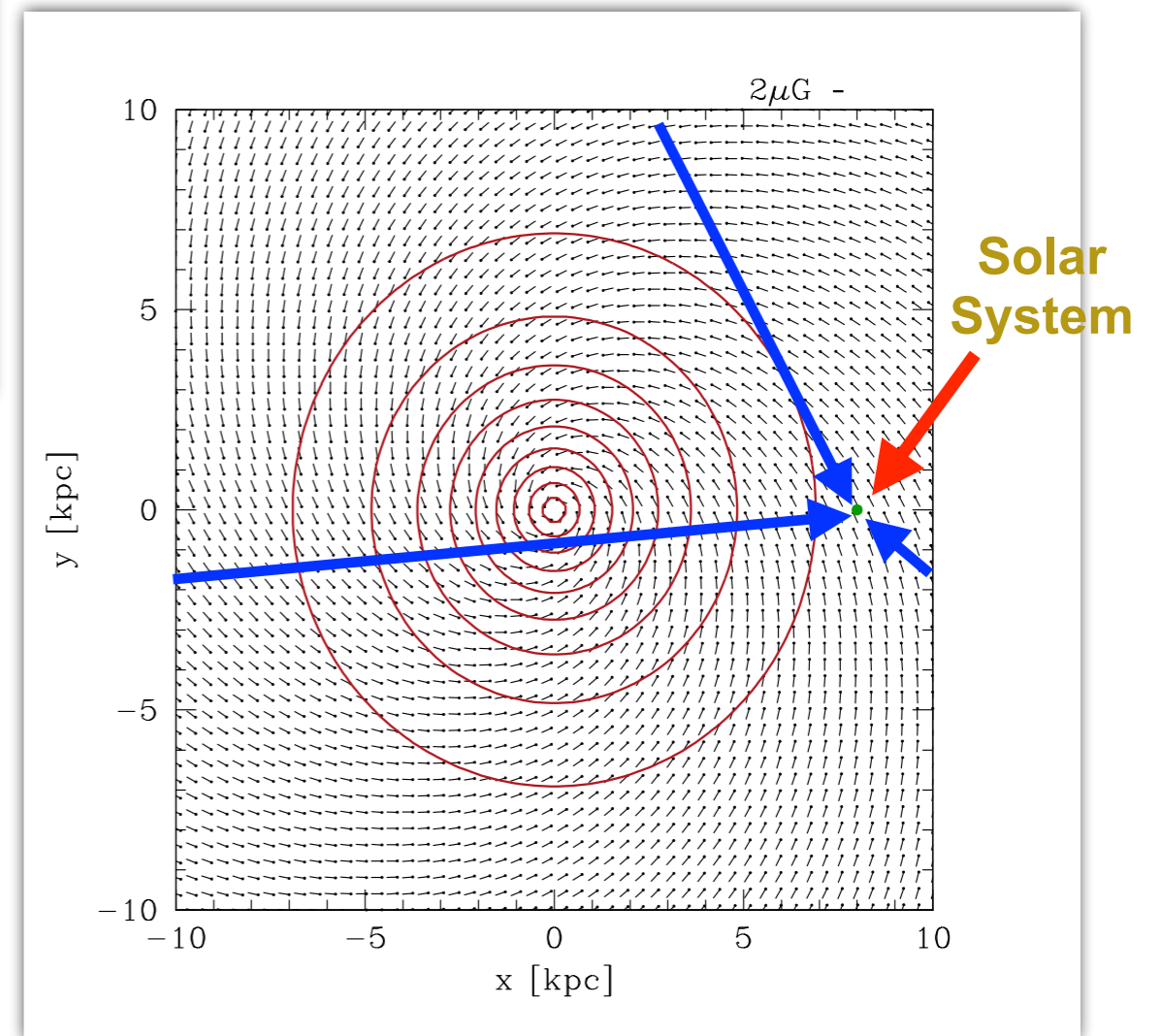
$$Q_{\text{model}}(\theta, \phi) = \epsilon(\nu) \int_0^{r_{\text{max}}} n_d(\vec{r}) p_0 [B_\phi(\vec{r})^2 - B_\theta(\vec{r})^2] dr ,$$

$$U_{\text{model}}(\theta, \phi) = \epsilon(\nu) \int_0^{r_{\text{max}}} n_d(\vec{r}) p_0 [2B_\phi(\vec{r})B_\theta(\vec{r})] dr$$

**Only keep polarization amplitude and angle information**

$$P(\theta, \phi) = \frac{(Q_{\text{model}}^2 + U_{\text{model}}^2)^{\frac{1}{2}}}{I_{\text{model}}} ,$$

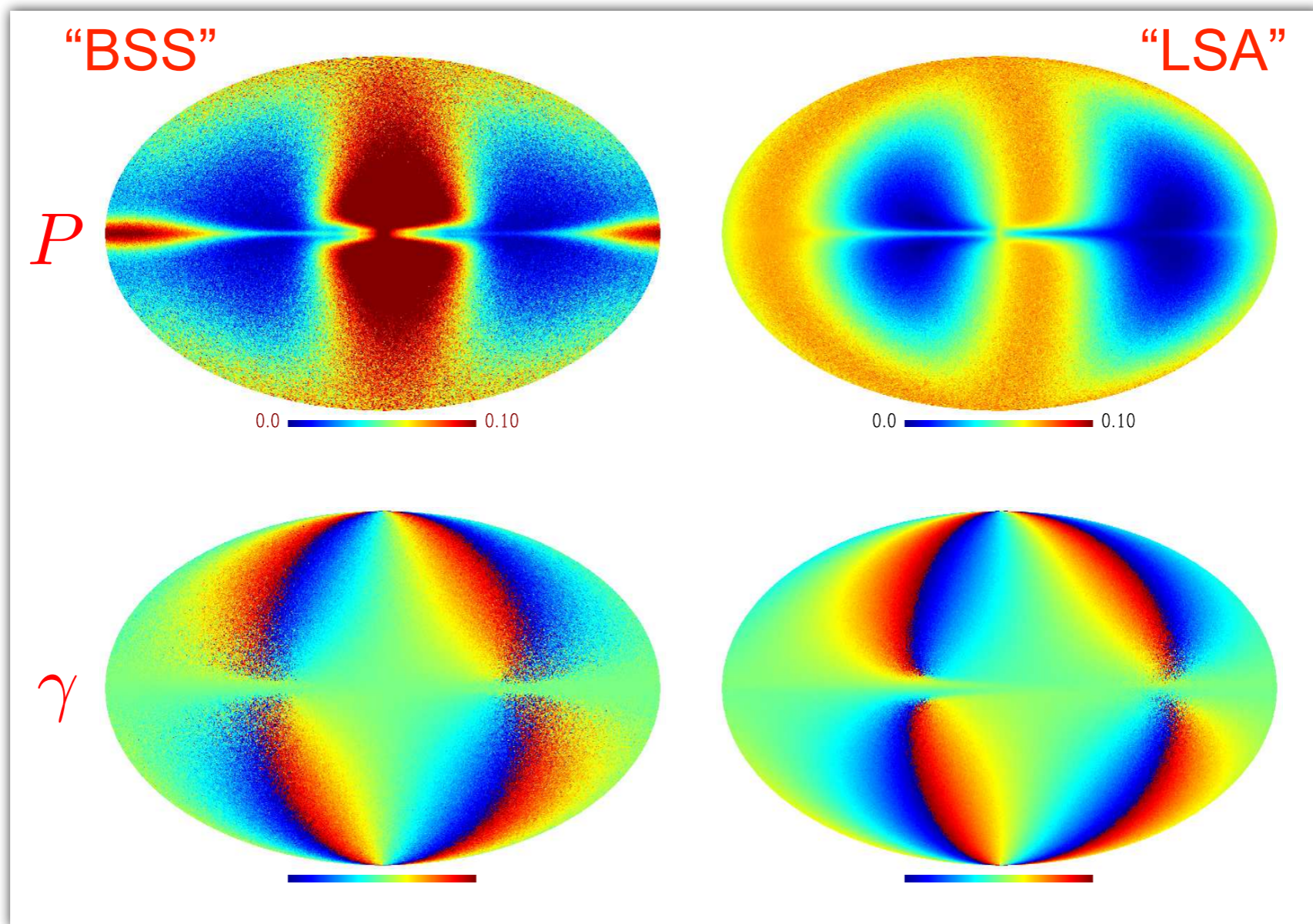
$$\gamma(\theta, \phi) = \frac{1}{2} \arctan \left( \frac{U_{\text{model}}}{Q_{\text{model}}} \right)$$





# Model polarization information

- Information that is *actually* utilised is polarization fraction (amplitude) and angle.
- Coherent structure on very large scales.

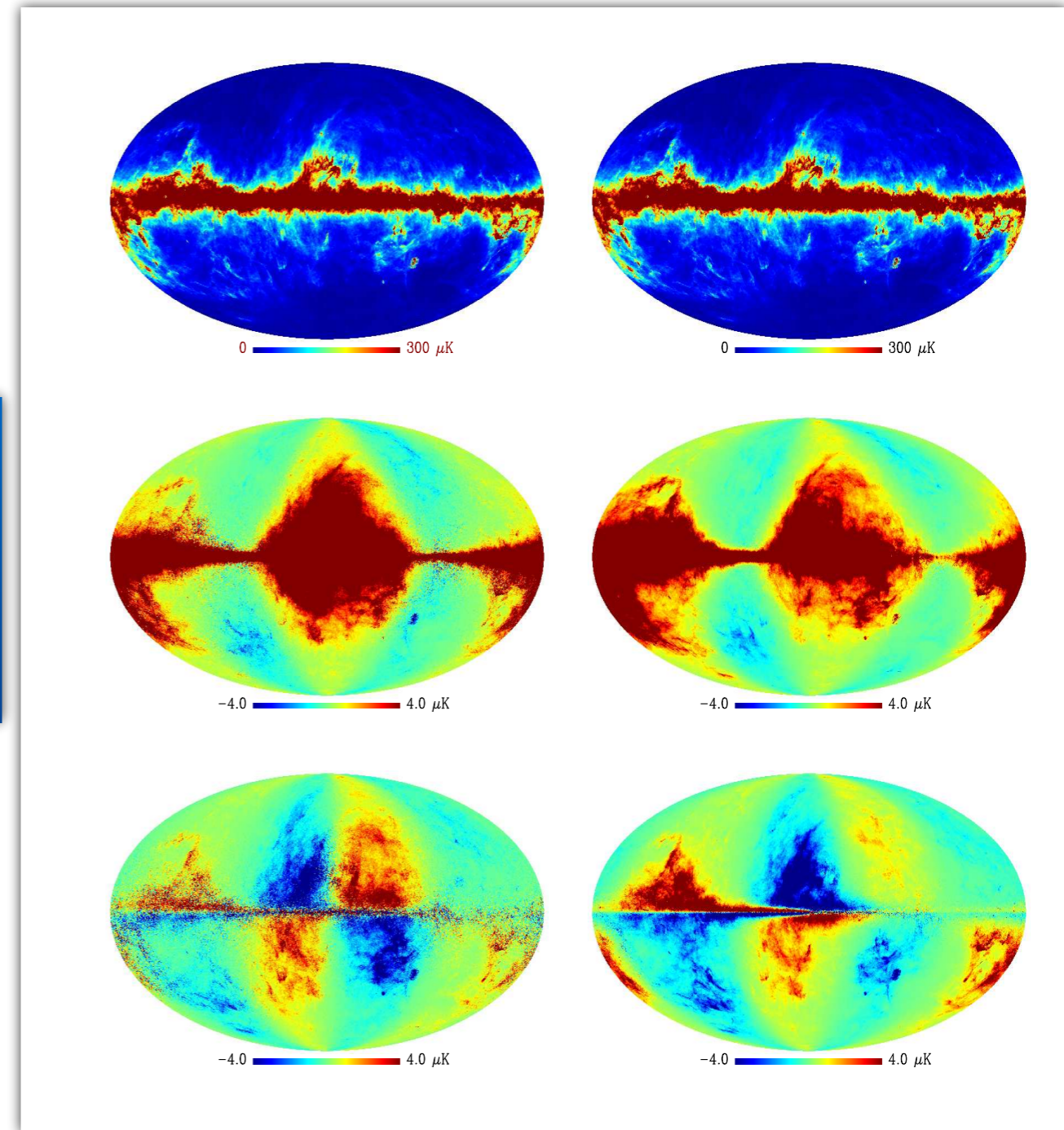


# Construction of Templates

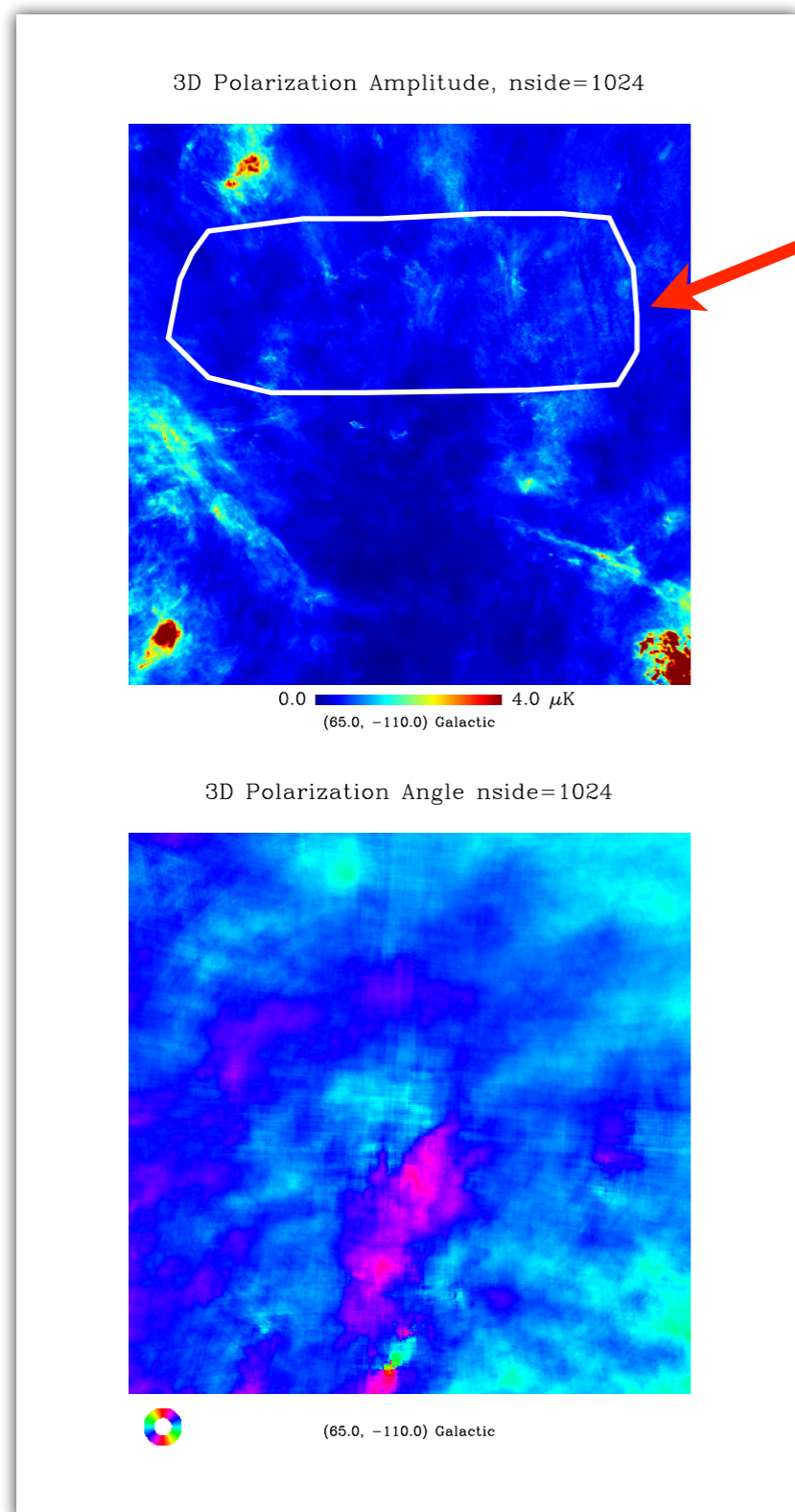
- Multiply polarization fraction template by total intensity template (e.g. FDS, IRAS/DIRBE model).
- Introduces detailed (*projected*) galactic structure.

$$I_{\text{dust}}^{\nu}(\theta, \phi) = I_{\text{fds}}^{\nu}(\theta, \phi),$$
$$Q_{\text{dust}}^{\nu}(\theta, \phi) = I_{\text{fds}}^{\nu}(\theta, \phi) P(\theta, \phi) \cos(2\gamma(\theta, \phi)),$$
$$U_{\text{dust}}^{\nu}(\theta, \phi) = I_{\text{fds}}^{\nu}(\theta, \phi) P(\theta, \phi) \sin(2\gamma(\theta, \phi))$$

- Assumes polarization = pol fraction x projected intensity.
- Total intensity is a projected, integrated emission measure.
- Polarization is sensitive to details of 3D structures - this is missed by method - *on certain scales*.



# The “southern patch”

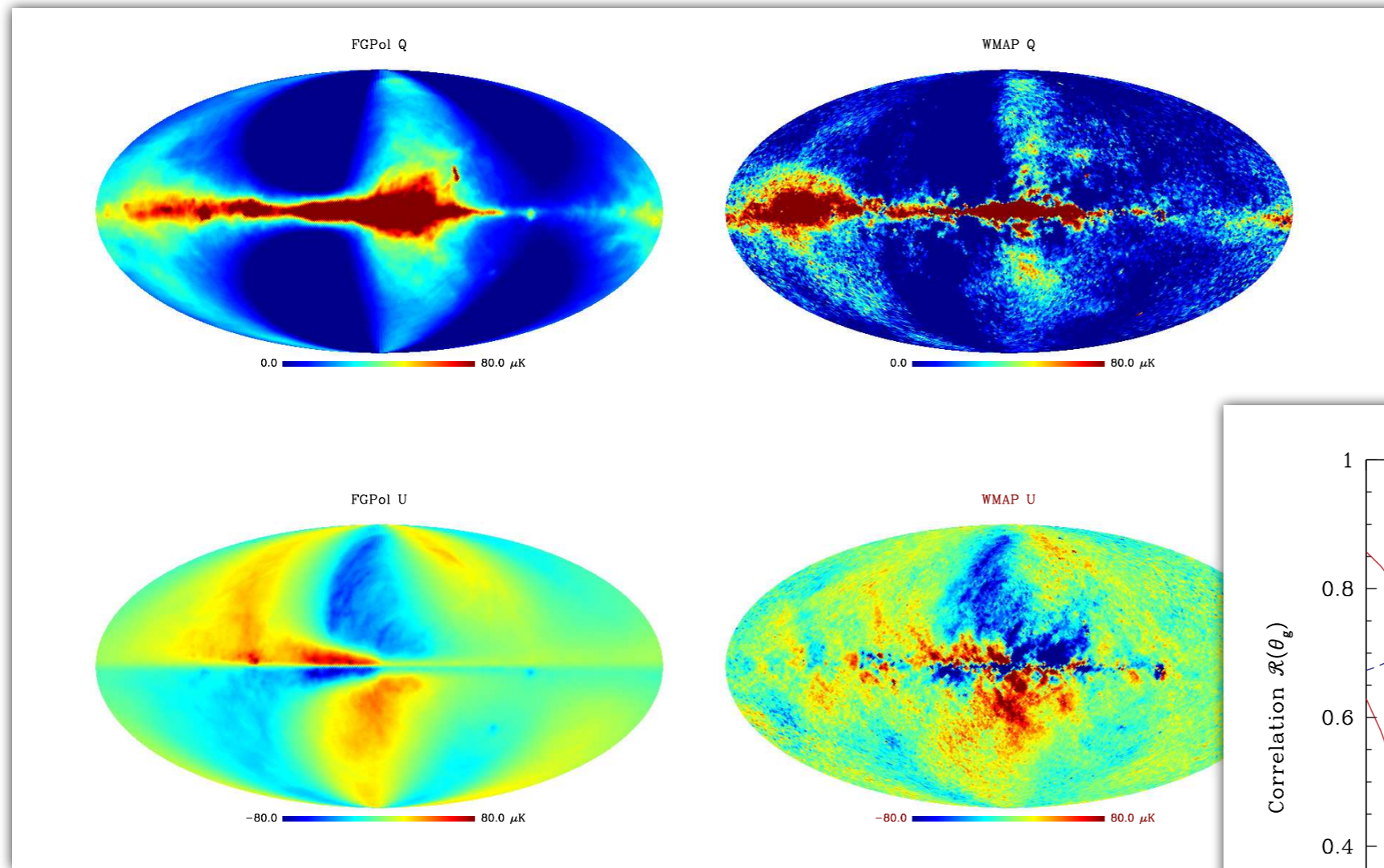


Approximate BICEP2 coverage

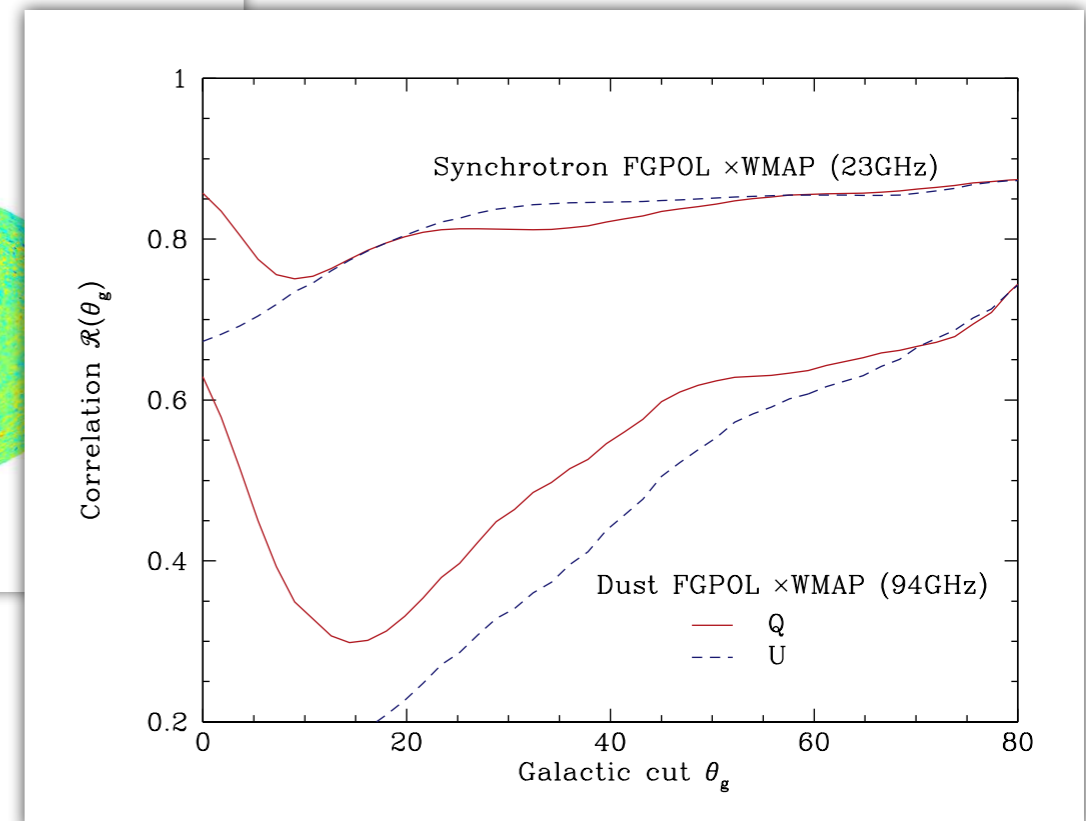
- Small patches; high resolution line of sight integration.
- Full 3D turbulence realisation - proper correlation of small scale component.
- BSS and LSA templates used in BICEP2 analysis.

# Synchrotron vs WMAP

- Method reproduces WMAP 23 GHz (synchrotron) maps very well on large scales.

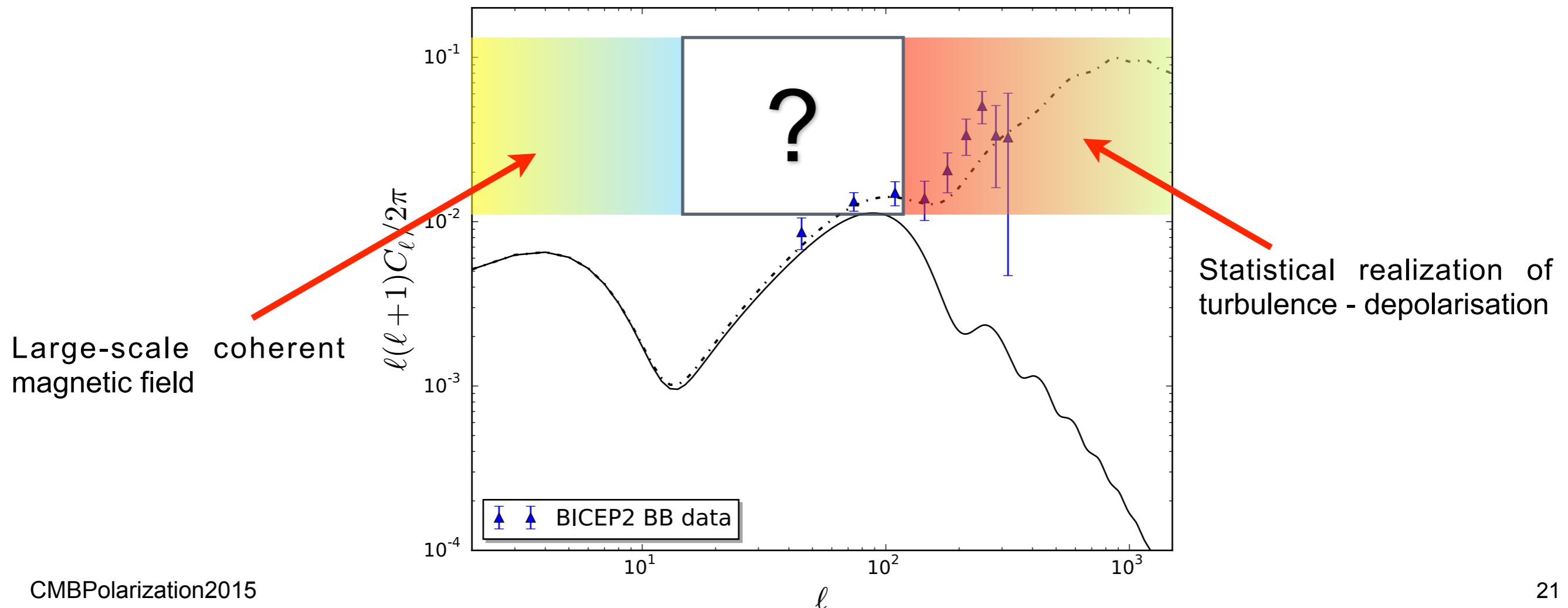


[Clark, CC, MacTavish, Jan 2013]

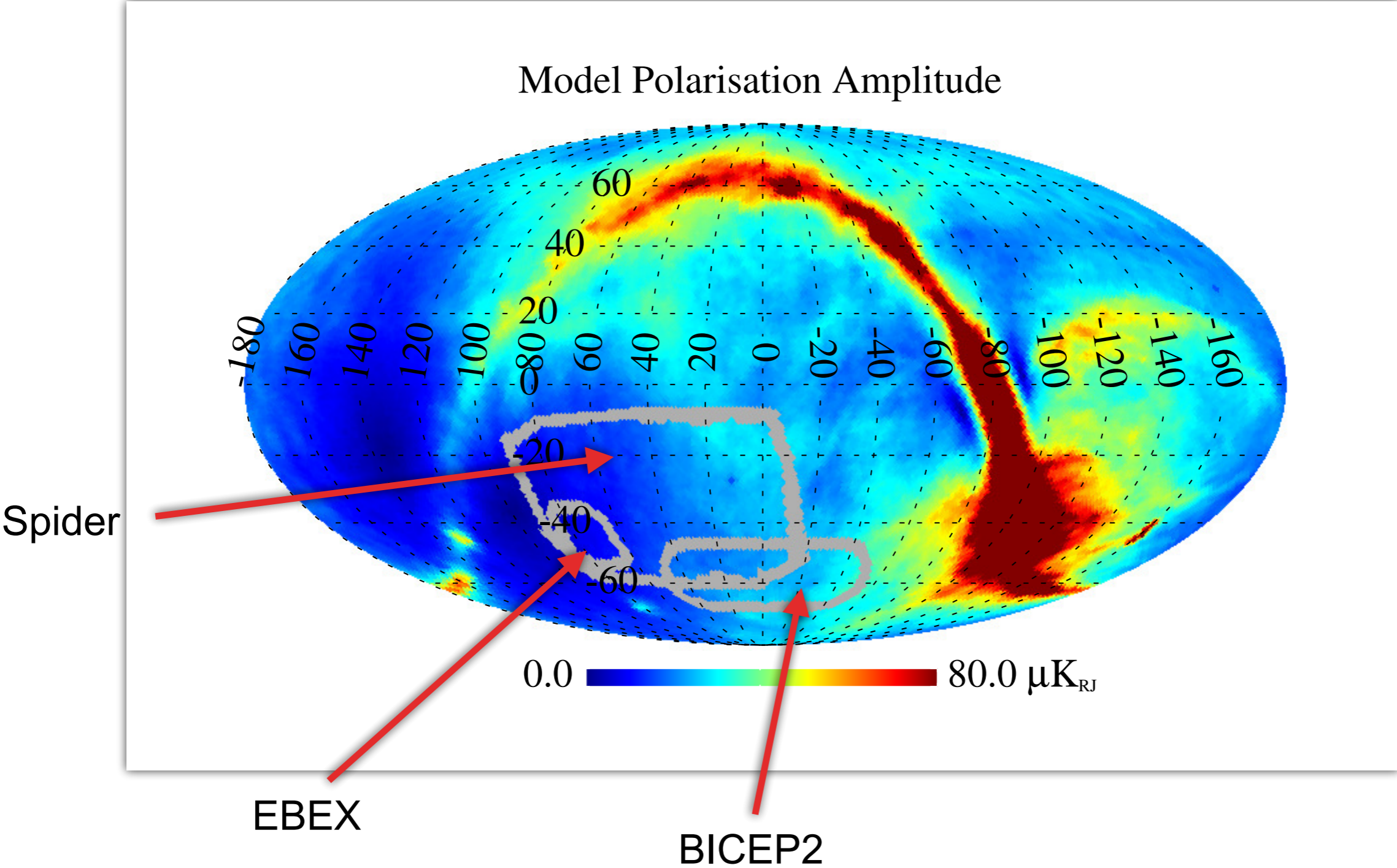


# Model vs Statistical Realization

- Care must be taken when using templates to constrain level of foreground in real data.
- Templates are only fiducial models of the sky on largest scales.
- Intermediate scales have much information missing as models do not include many galactic features (clouds, spiral arms density, supernovae rings, correlation between etc.)

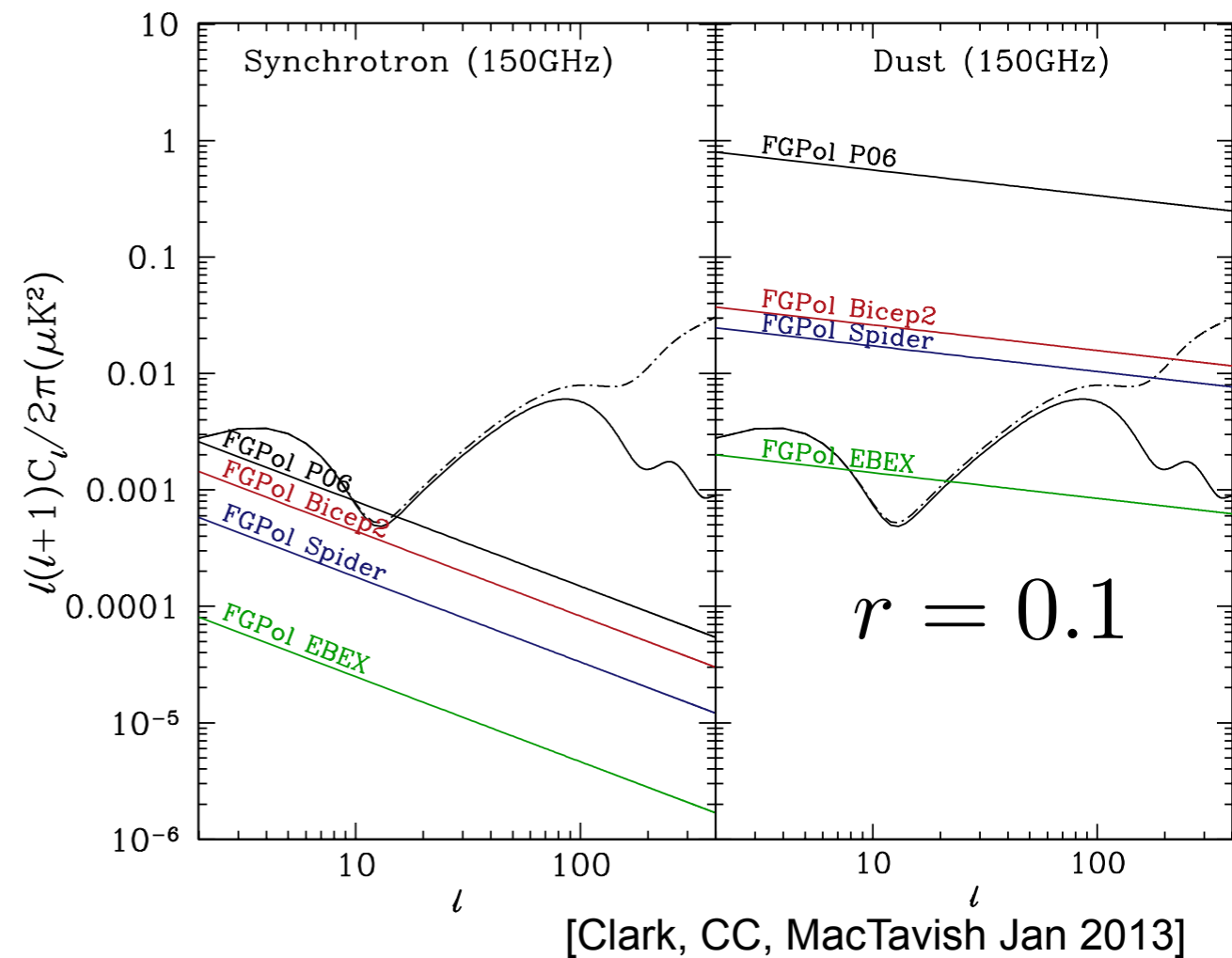
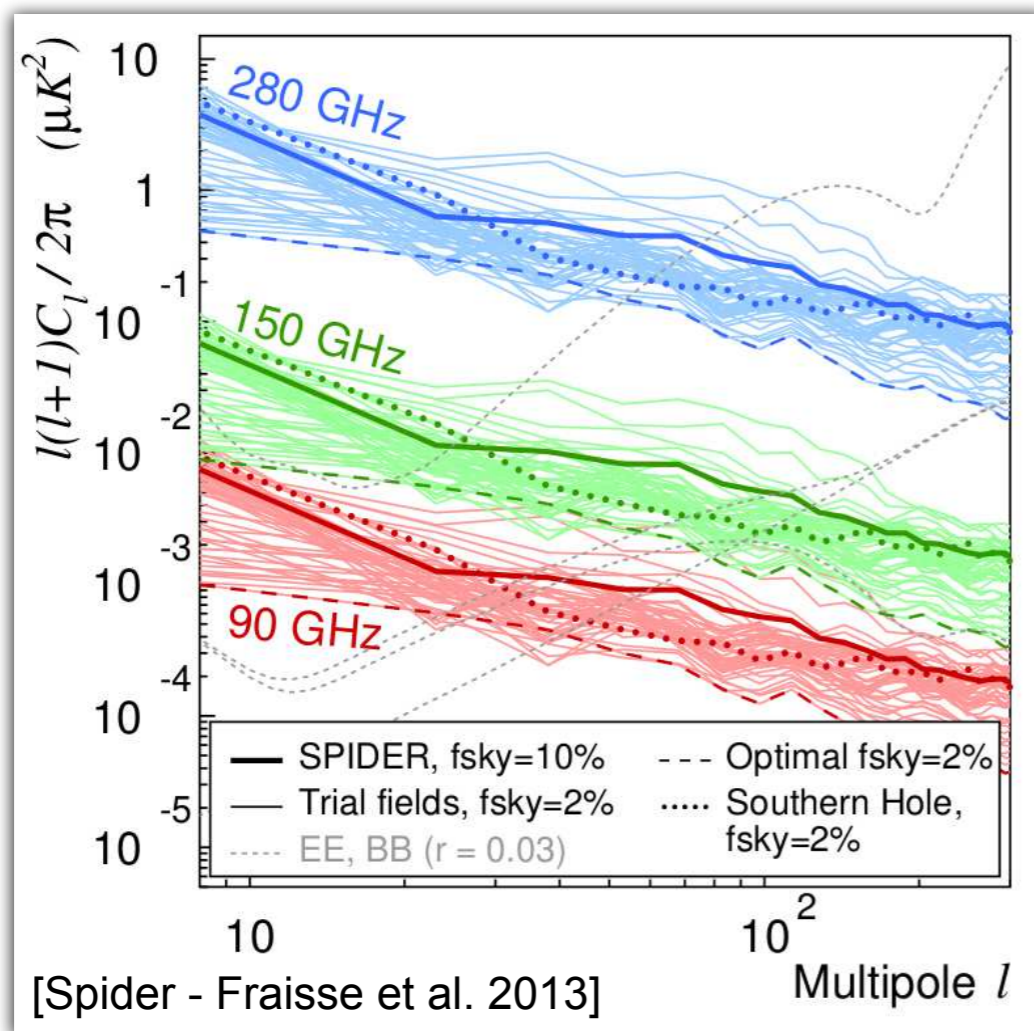


# “Southern patch” Measurements (Forecasts)



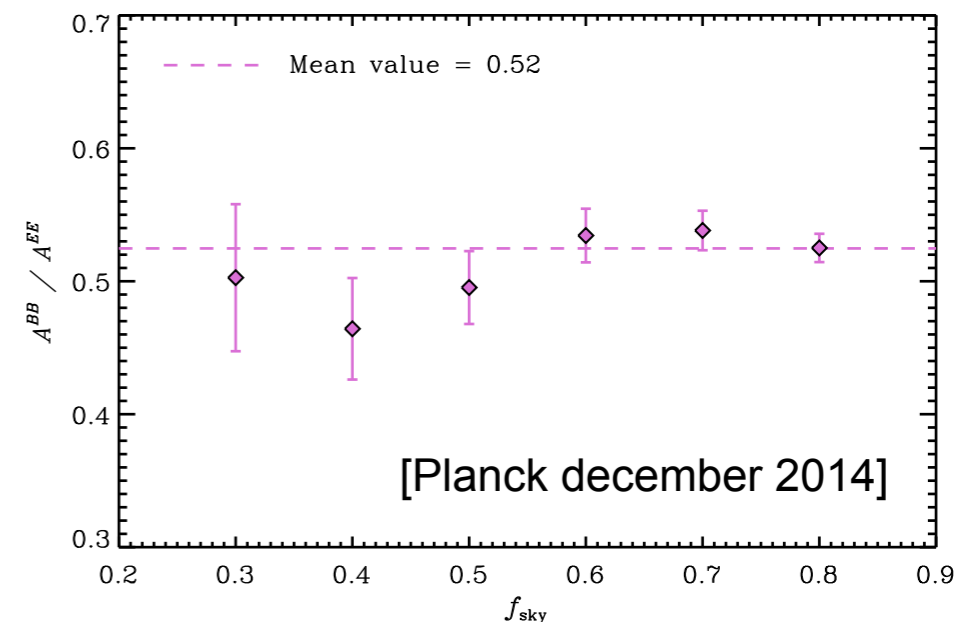
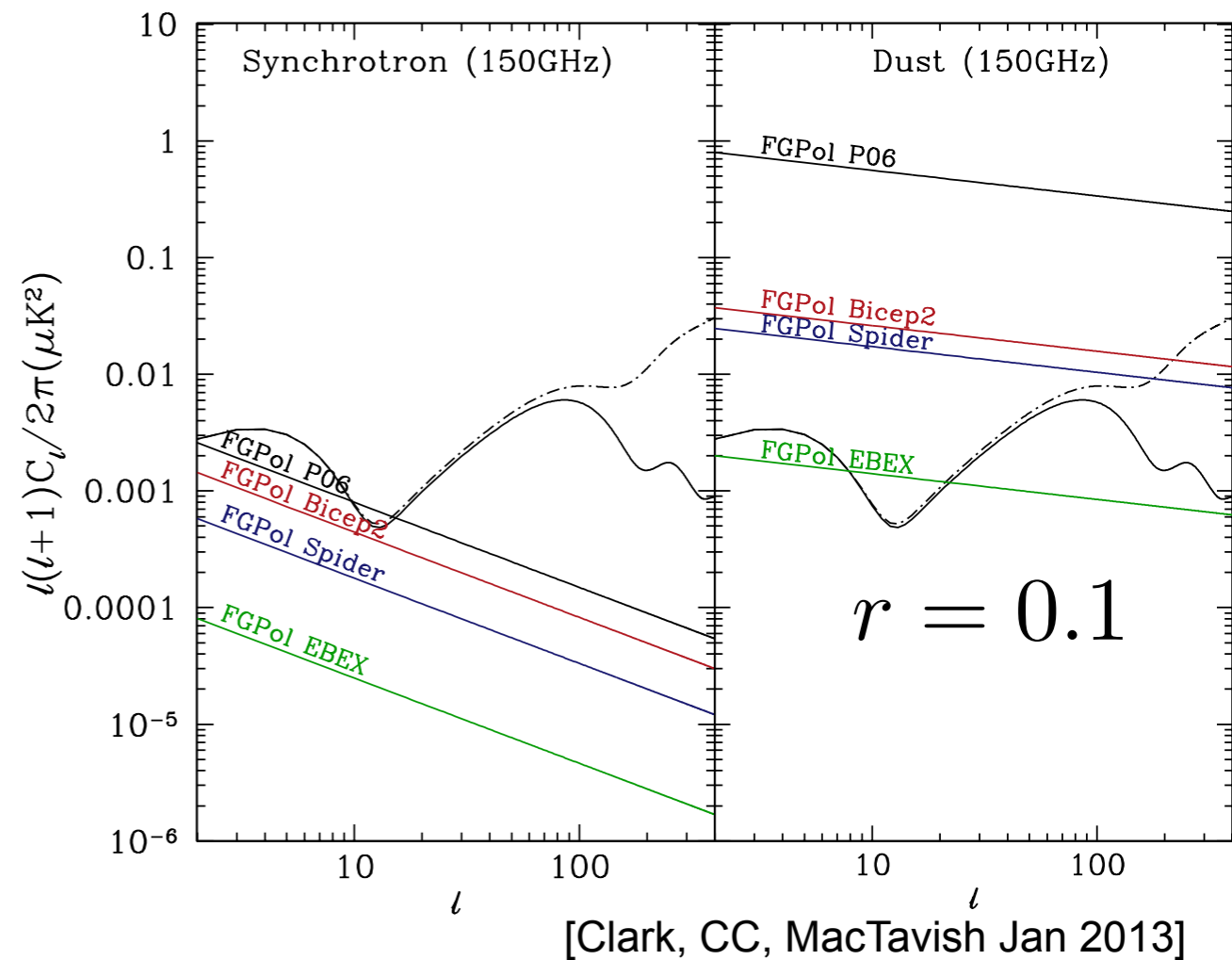
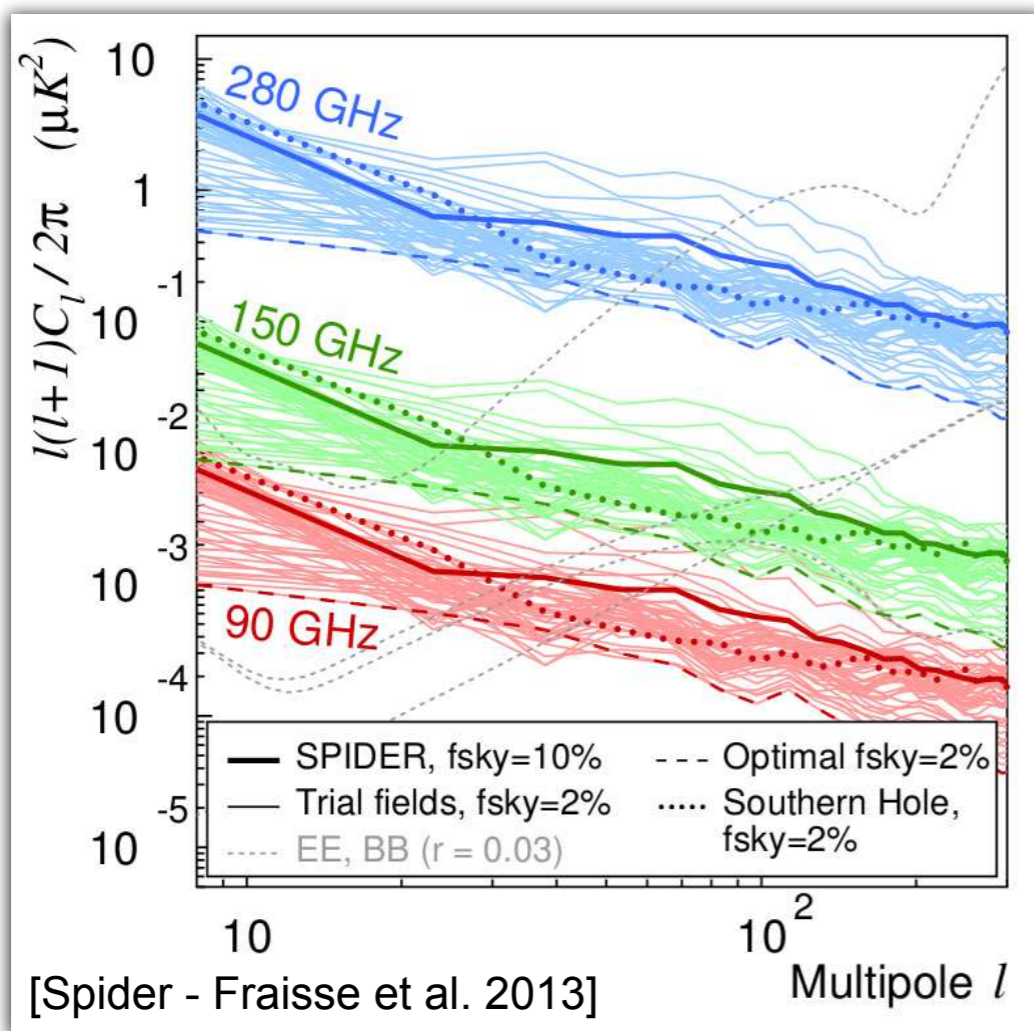
# Polarization Amplitude (pre-2014 predictions)

- Pre-BICEP2 prediction for synchrotron and dust BB signal.
- Planck 353 GHz extrapolation a little lower.
- B-mode tends to be 1/2 as large as E-mode in dust?



# Polarization Amplitude (pre-2014 predictions)

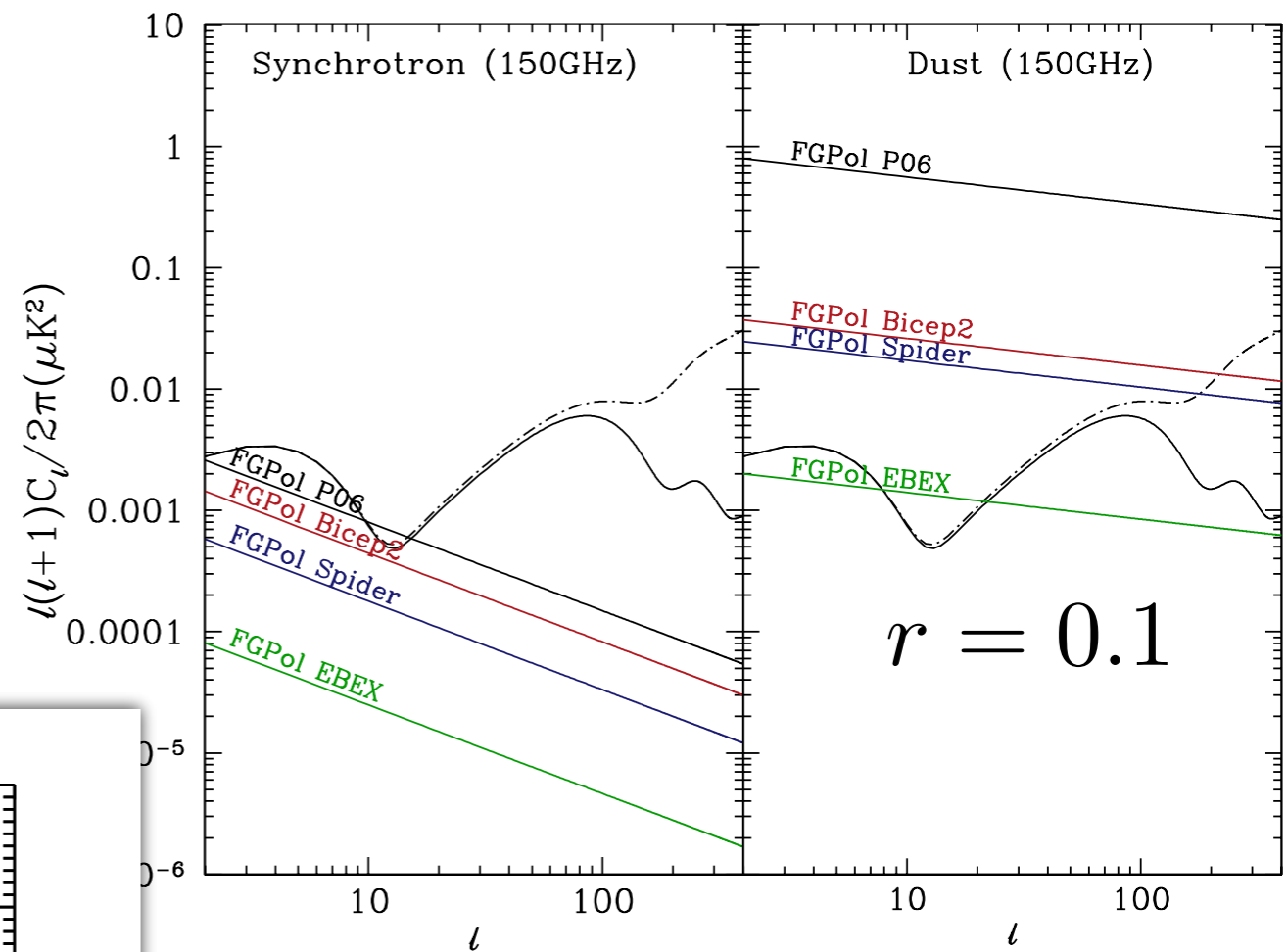
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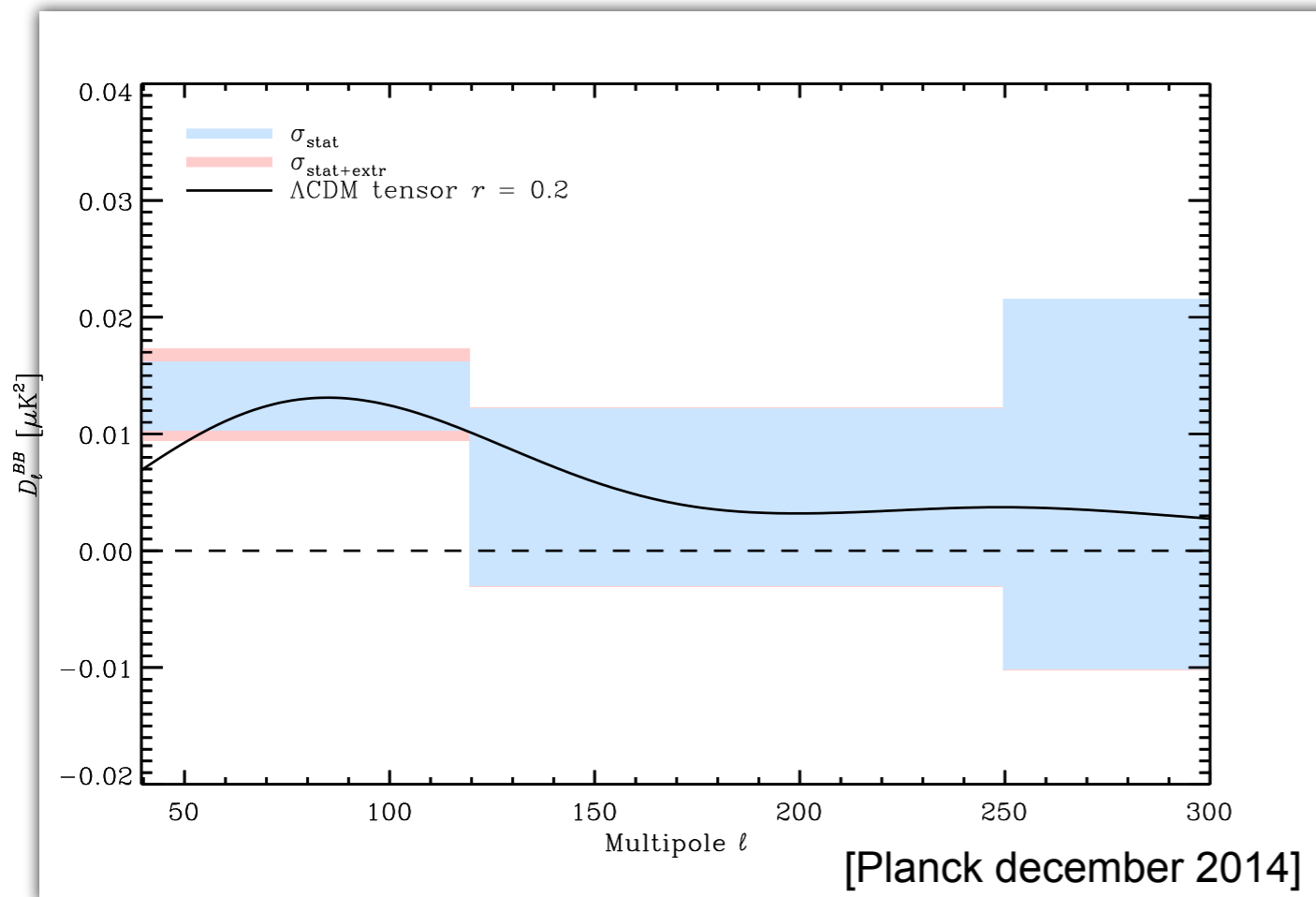


# Polarization Amplitude (pre-2014 predictions)

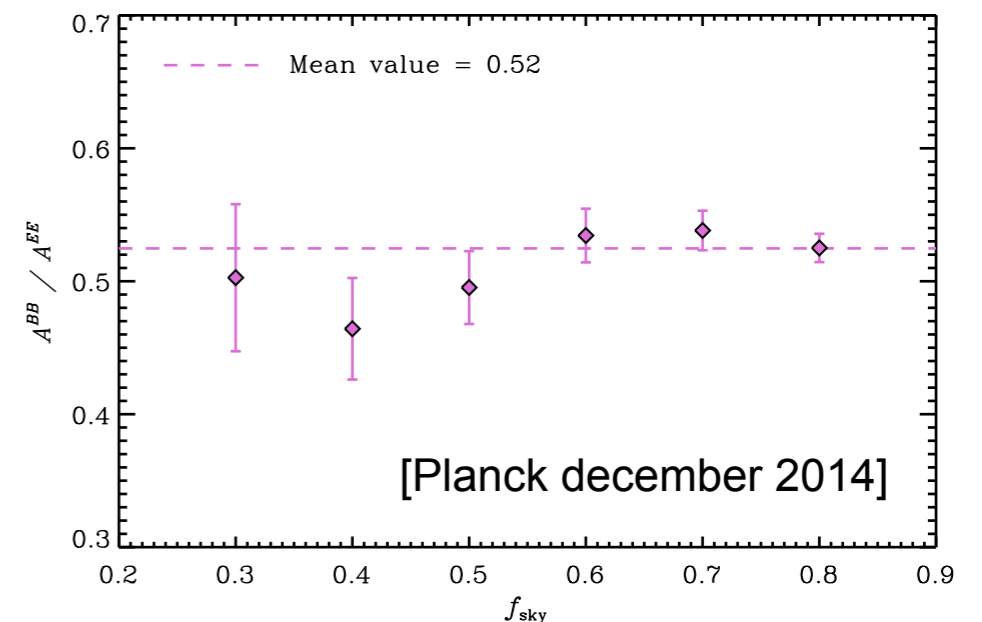
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[Clark, CC, MacTavish Jan 2013]

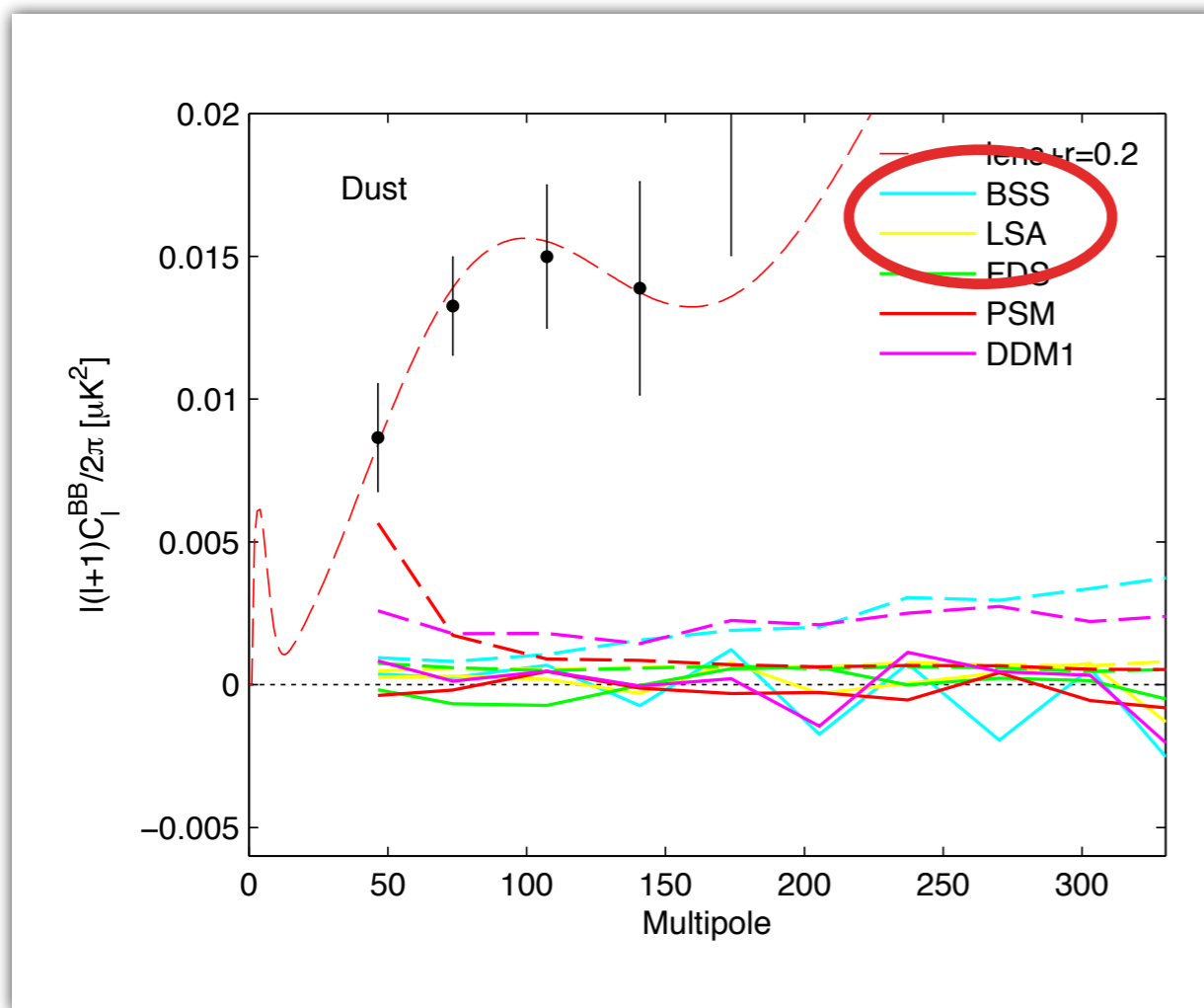


[Planck december 2014]

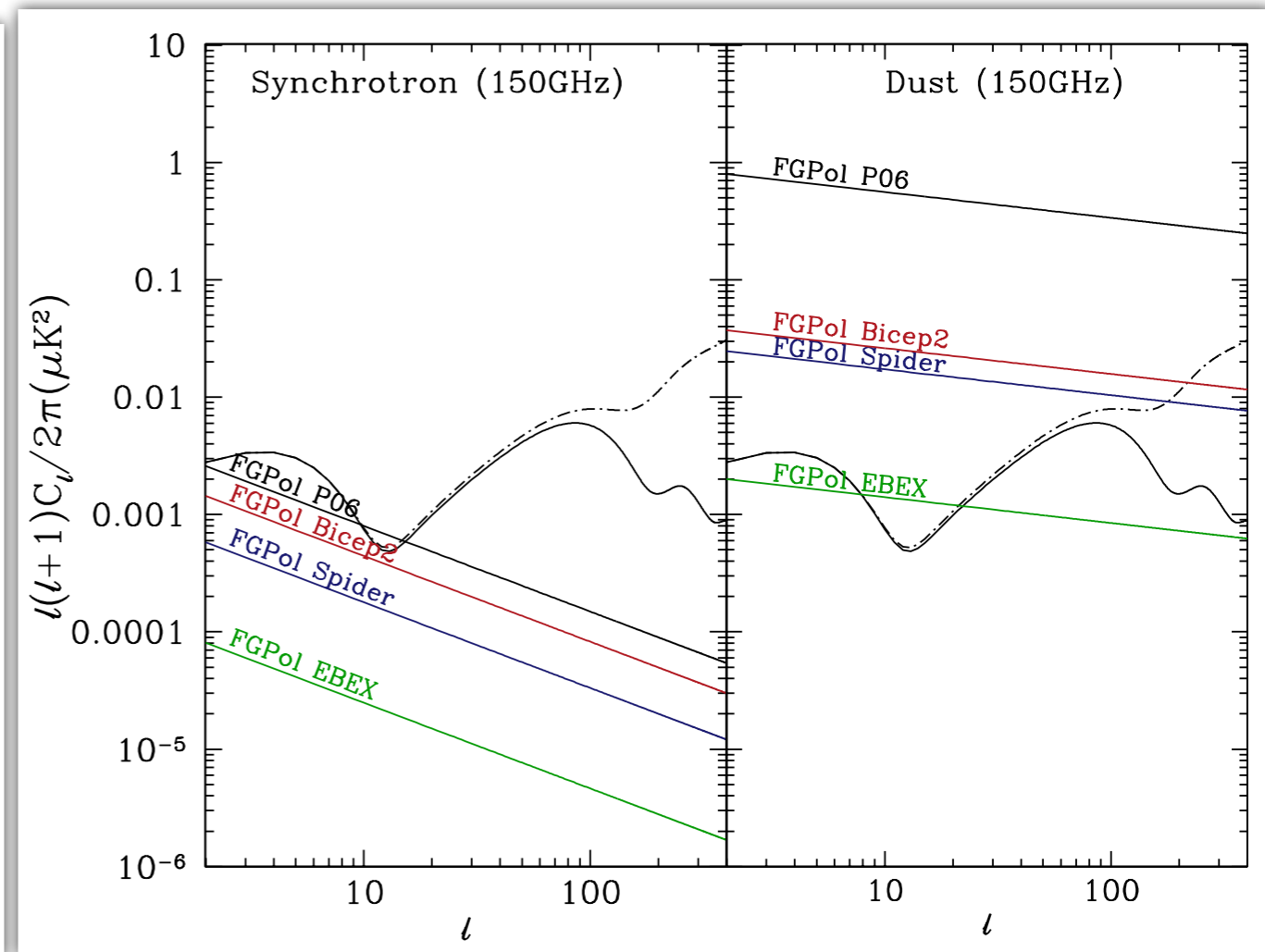


[Planck december 2014]

- Discrepancy between BICEP2 analysis of foregrounds and pre-2014 forecasts?
- Both plots use LSA and BSS FGPol templates.



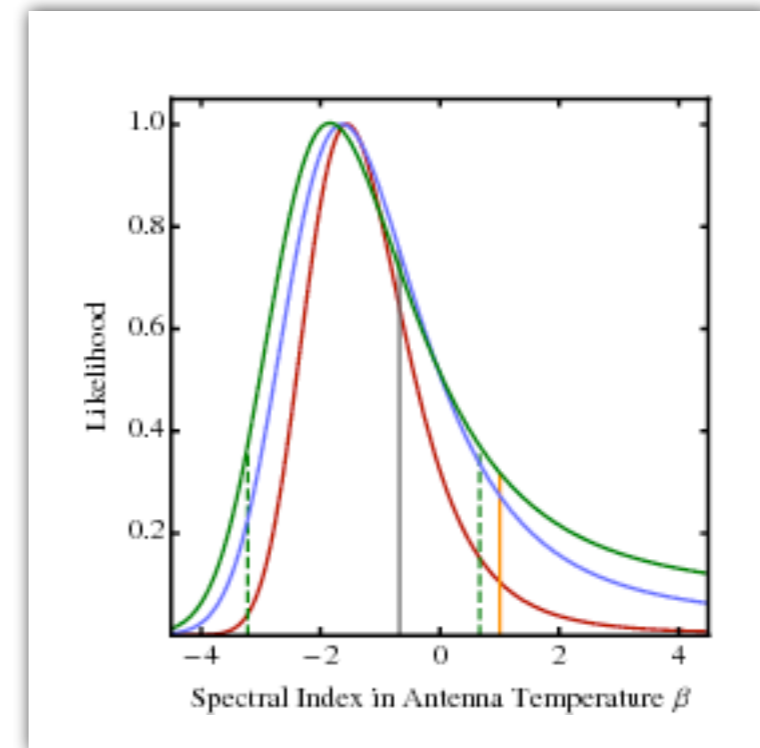
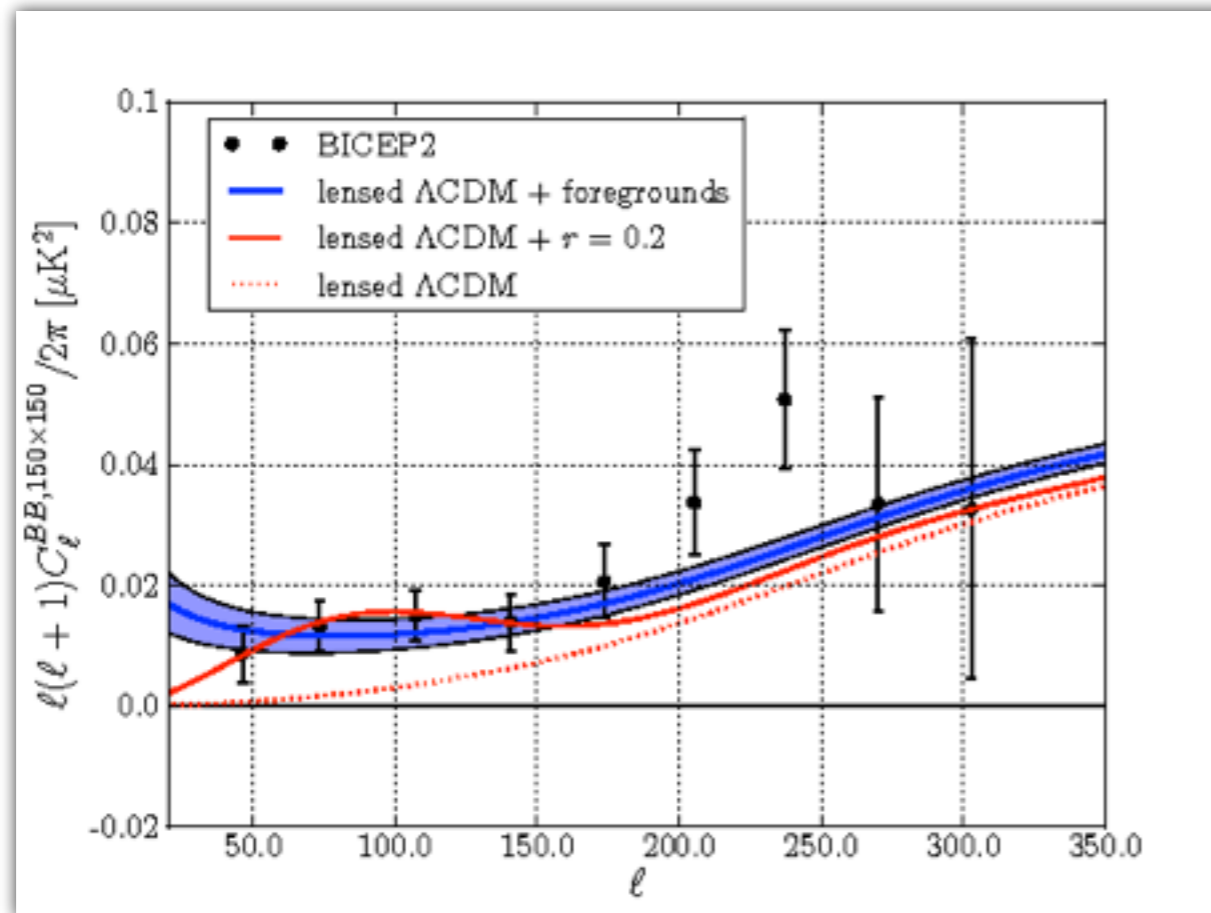
[BICEP2 Apr 2014]



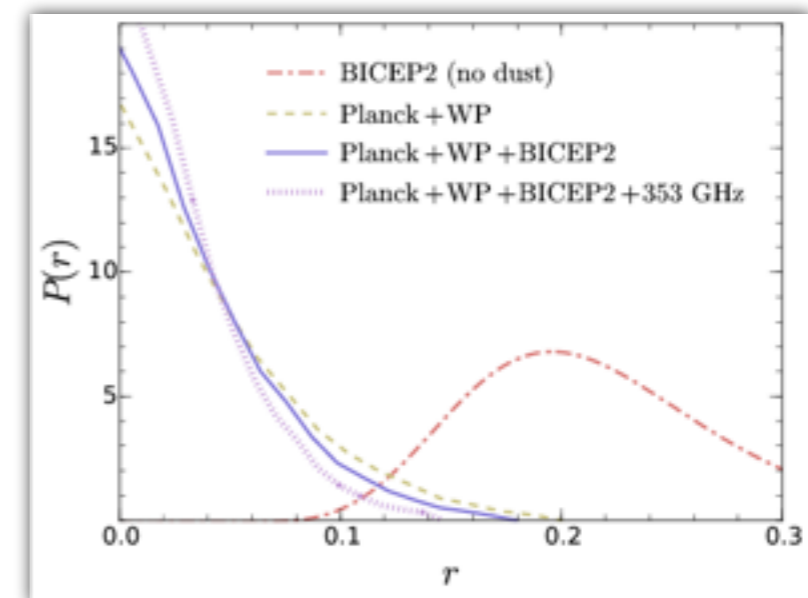
[Clark, CC, MacTavish, Jan 2013]

# Post-Bicep2 Foreground Discussion

- Flauger et al : argued foreground contribution much higher and spectral dependence gave much weaker evidence if lensing included.

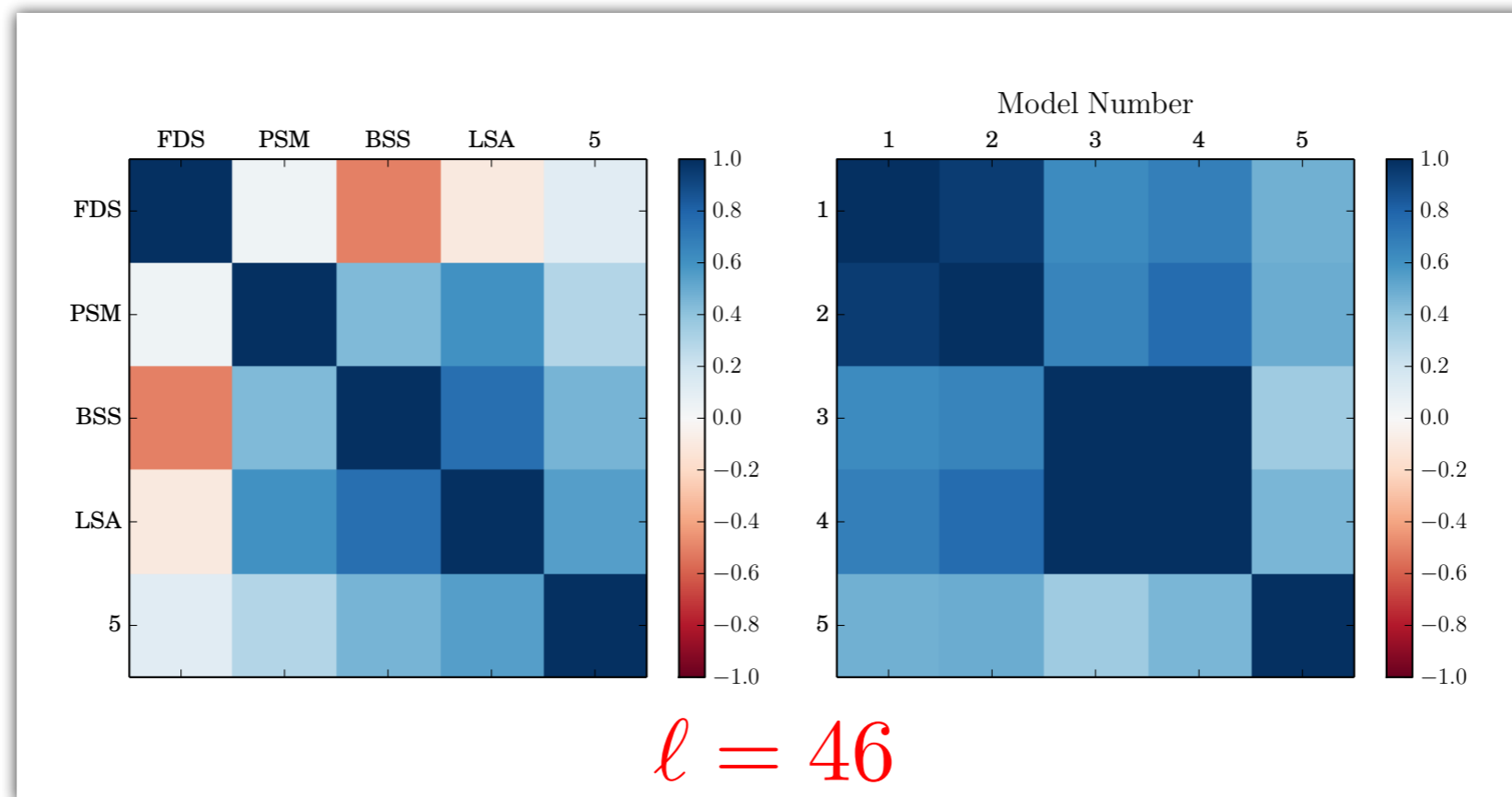


- Mortonson and Seljak: Planck 353 GHz pol indicates dust is major contribution



# Flauger et al. Analysis

- Compared templates with a large range of new “data driven models”.
- Lots of variation between templates.
- Less variation between new “data driven models”.



# Conclusions

- Template polarization maps are (were!) a useful tool for forecasting/analysis.
- Polarization emission models are very basic and make many assumptions but reproduce the qualitative features in dust and synchrotron polarized emission on large scales.
- Templates are only statistical realisations beyond largest coherence scales of Galactic magnetic field.
- Planck 2015 - will provide detailed templates for comparison with sub-orbital maps + multi-frequency, sub-orbital measurements *will* enable limits to be pushed to  $r < 0.1$ .
- Now that polarization measurements exist we can turn problem over and learn much about the 3D structure of the Galaxy - Planck 2014/2015.