Has BICEP2 proved cosmic inflation?

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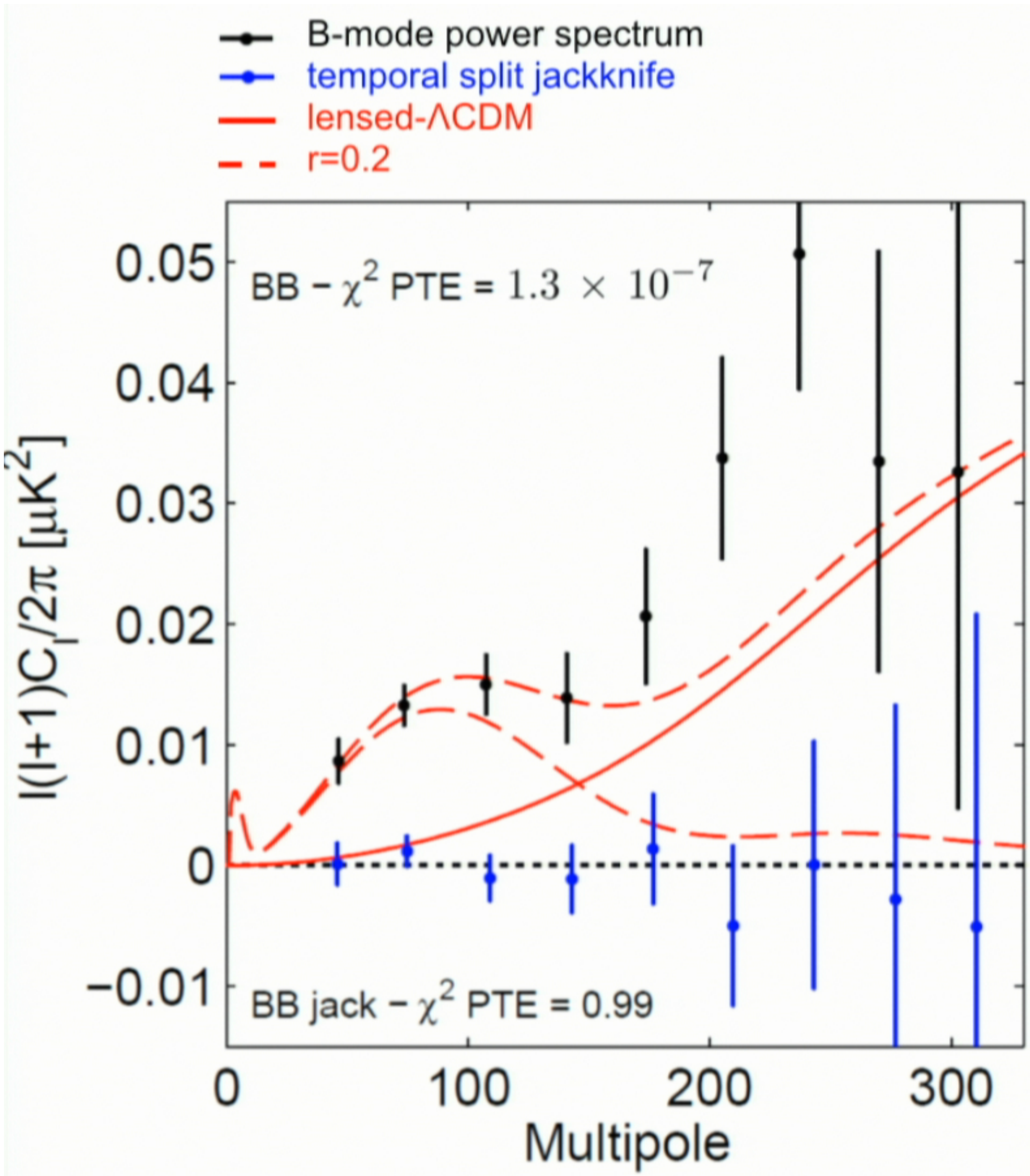
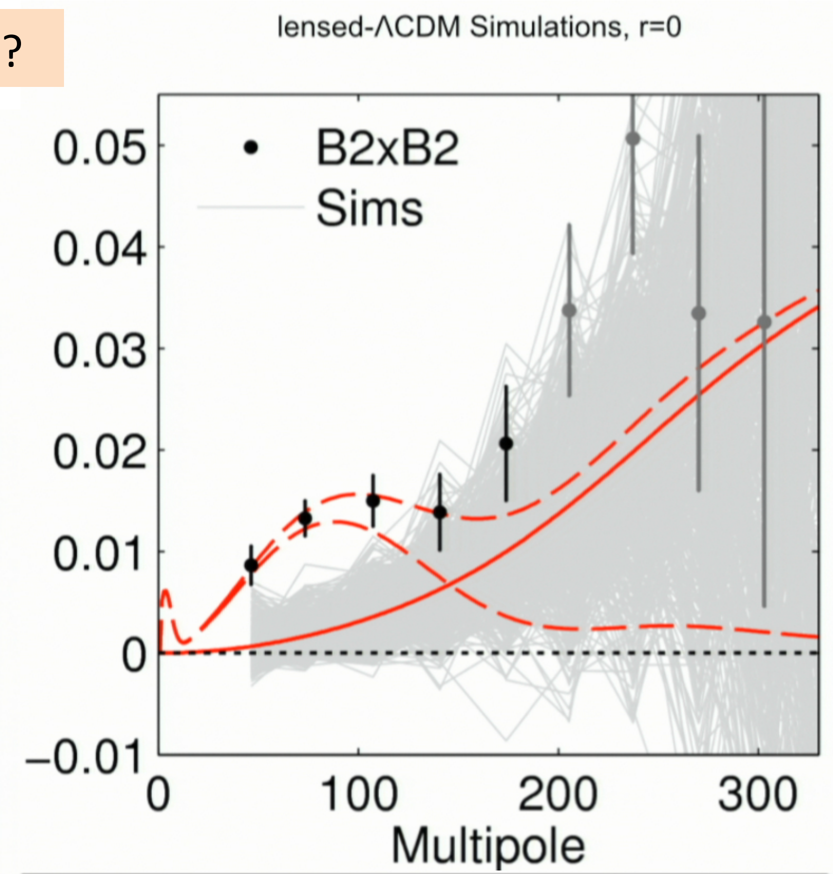
Based on: arXiv:1404.1899 with Liu Hao (NBI Copenhagen) & Philipp Mertsch (KIPAC Stanford)
+ JCAP **06**:041,2013 [arXiv:1304.1078] with Philipp Mertsch + Sarkar, MNRAS **199**:97,1982

What is the significance of the B-mode detection?



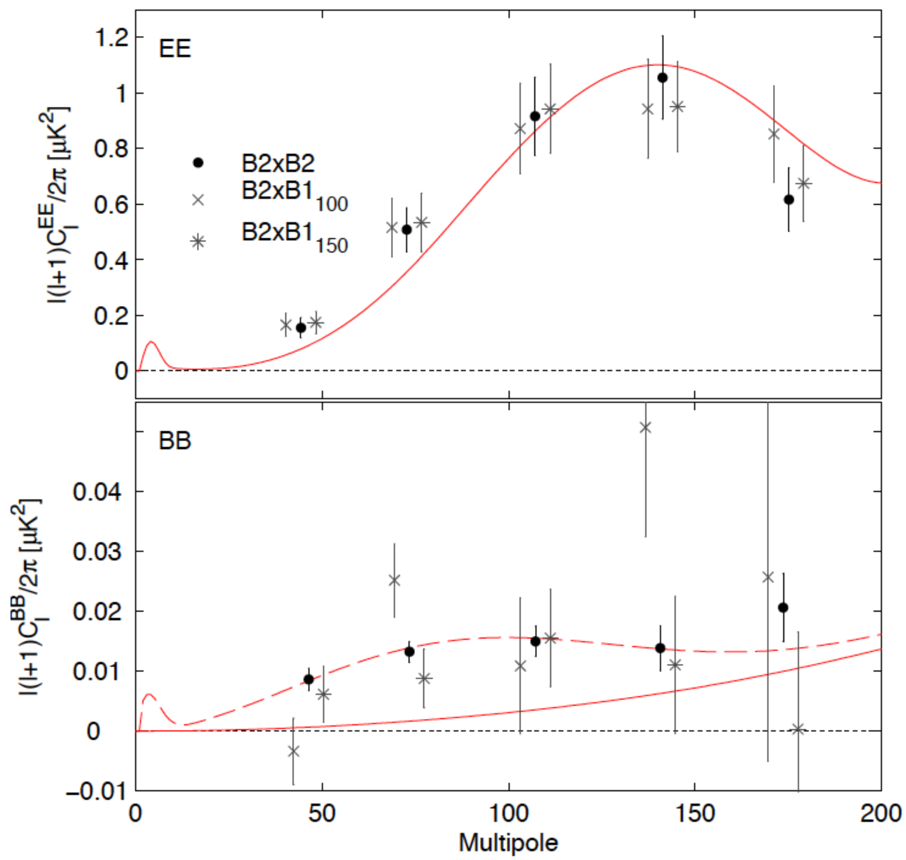


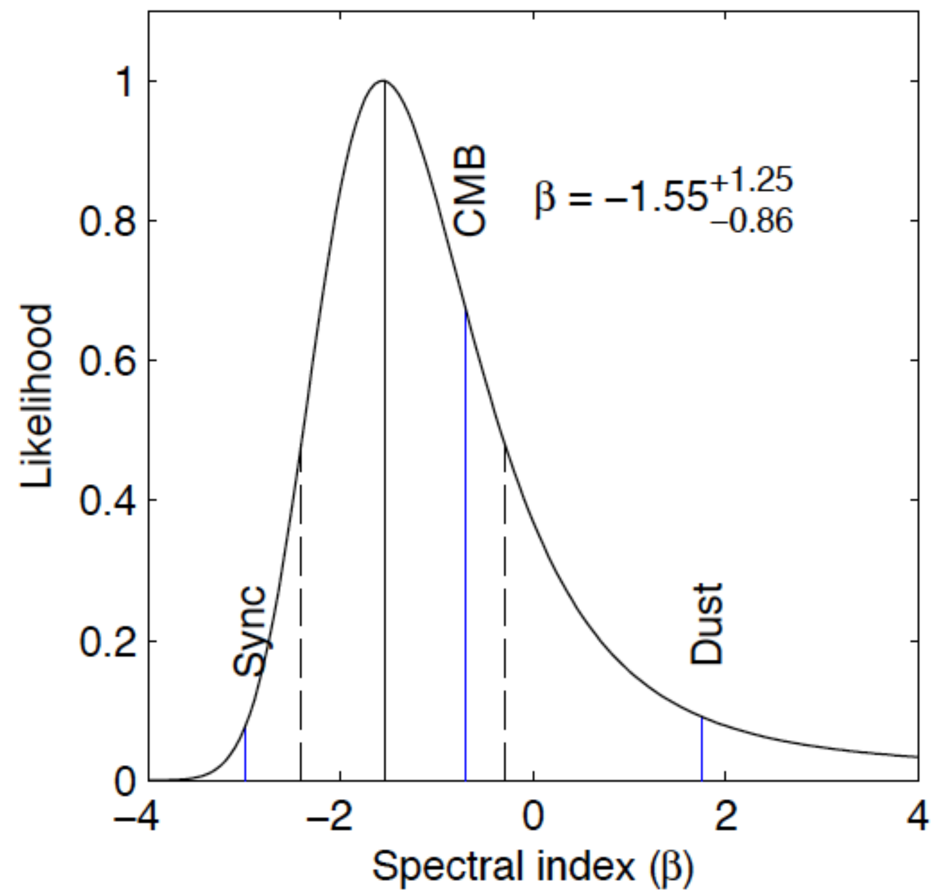
χ^2 PTE	1.3×10^{-7}
significance	$5.2\,\sigma$

[arXiv:1403.3985]

This is just the chance probability of the observed B-mode signal to arise as a fluctuation of the lensed E-mode signal … it does *not* mean a '>5σ detection'!

"We can use the BICEP2 auto and BICEP2xBICEP1$_{100}$ spectra to constrain the frequency dependence of the nominal signal, If the signal at 150 GHz were due to synchrotron we would expect the frequency cross spectrum to be much larger in amplitude than the BICEP2 auto spectrum. Conversely if the 150 GHz power were due to polarized dust emission we would not expect to see a significant correlation with the 100 GHz sky pattern." [arXiv:1403.3985]





... so the significance with which the signal is established to be CMB rather than either synchrotron ($\beta \sim -3$) or dust ($\beta \sim +1.75$) emission is *only* 2.3 σ and 2.2 σ, respectively

The most important "foreground" (i.e. astrophysical) sources of emission at CMB frequencies are

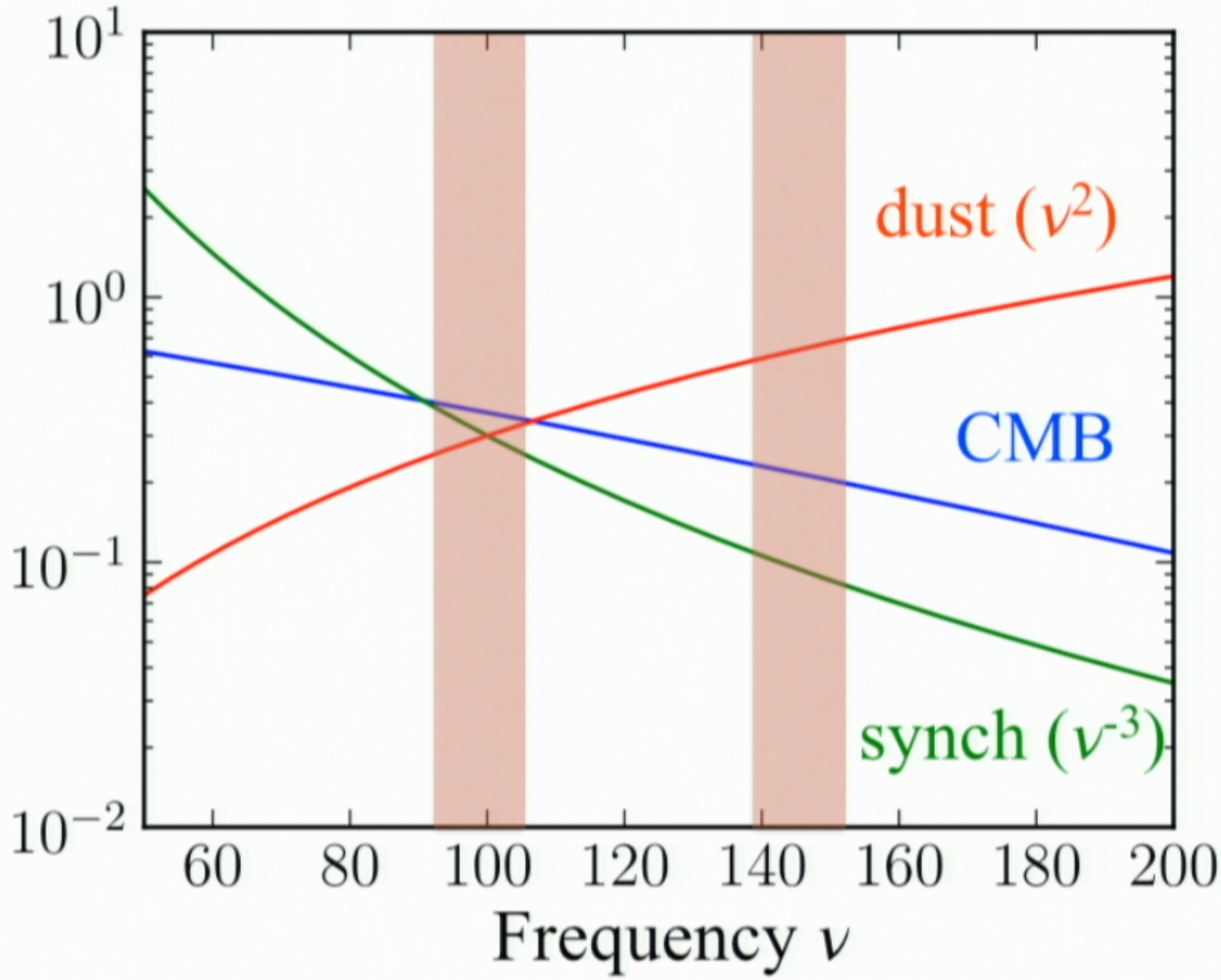
Synchrotron radiation from high-energy electrons accelerating in the magnetic field of our galaxy (polarized perpendicular to magnetic field)

Thermal dust emission, weakly polarized perpendicular to B due to tendency for shortest axis of dust grains to line up with magnetic field

BICEP2 observes in a small (~1%) patch of sky chosen to minimize these foregrounds

Courtesy of Kendrick Smith

Foregrounds/CMB can be separated by making observations at multiple frequencies



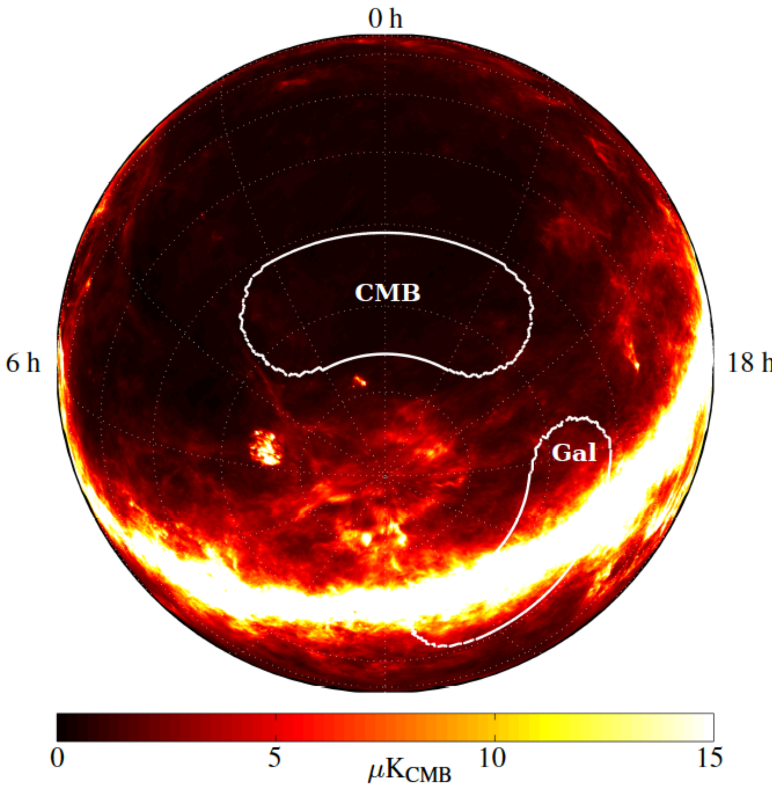
BICEP1
100+150 GHz

BICEP2
150 GHz only

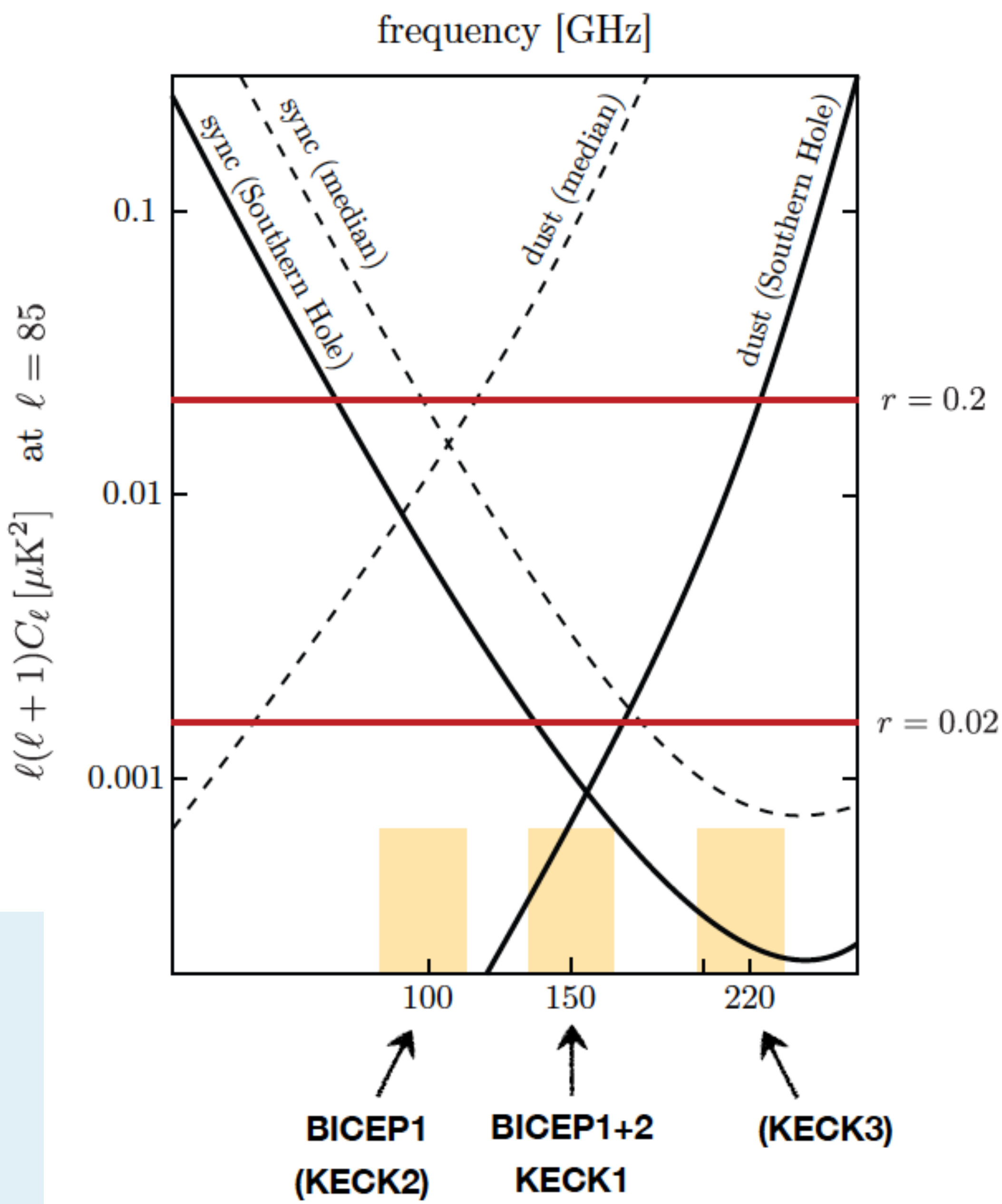
WMAP
23-94 GHz

Planck
30-353 GHz
(polarization)

Courtesy of Kendrick Smith

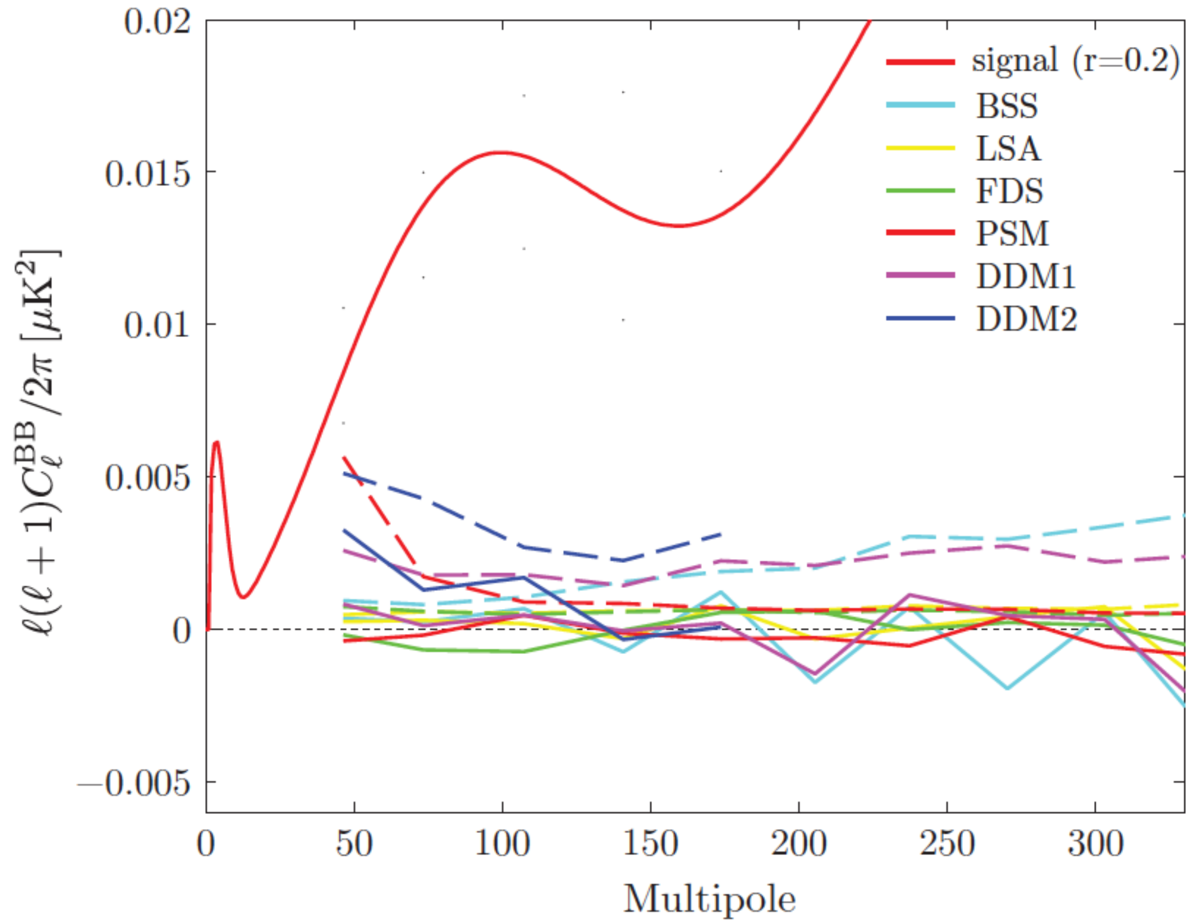


[arXiv:1403.3985]



"The BICEP 2 field is centered on Galactic coordinates (l, b) = (316^0, -59^0) and was originally selected on the basis of exceptionally low contrast in the FDS dust maps (Finkbeiner et al. 1999). It must be emphasized that these ultra clean regions are very special – at least an order of magnitude cleaner than the average $b > 50^0$ level."

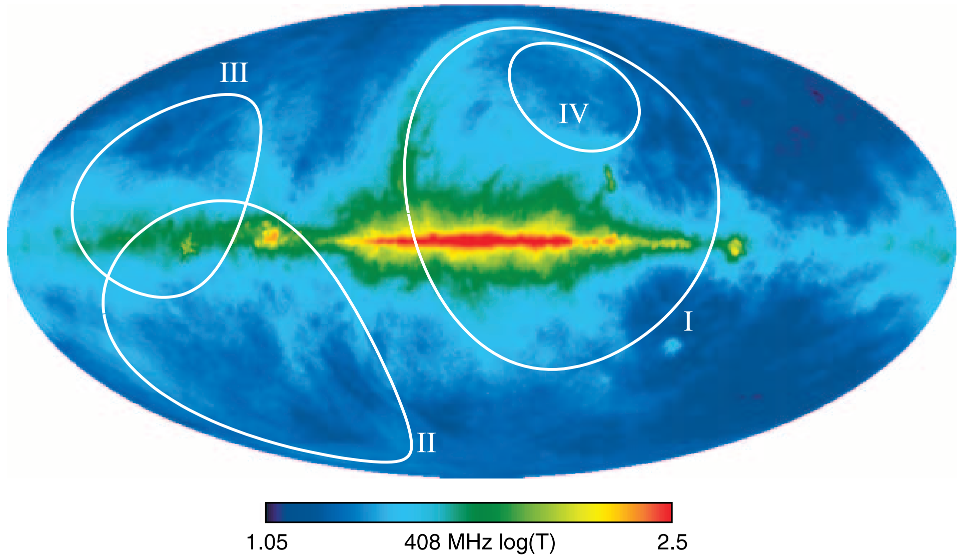
… so a lot depends on whether the 'Southern hole' is indeed as free of foreground as is *assumed*

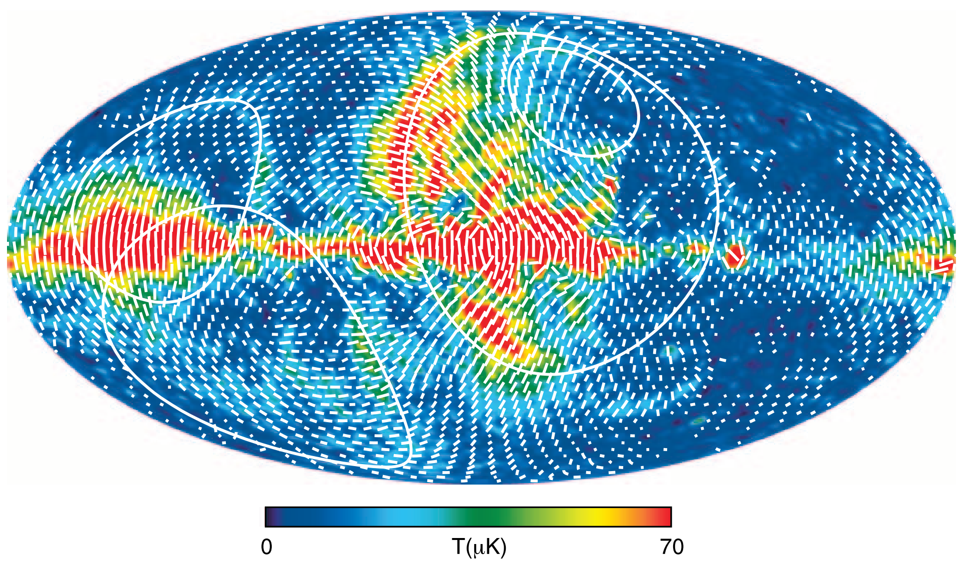


[arXiv:1403.3985]

“Foreground modeling involves extrapolating high signal-to-noise ratio maps taken at lower/higher frequencies to the CMB observation band, and there are inevitably uncertainties … The main uncertainty in foreground modeling is currently the lack of a polarized dust map. (This will be alleviated soon by the next Planck data release.) In the meantime we have investigated a number of existing models and have formulated two new ones. … We can therefore search for a correlation between the models and our signal by taking cross spectra against the BICEP 2 maps. Figure 6 shows the resulting BB auto and cross spectra — note that the autospectra are all well below the level of our observed signal and that the cross spectra are consistent with zero”.

What are the radio loops

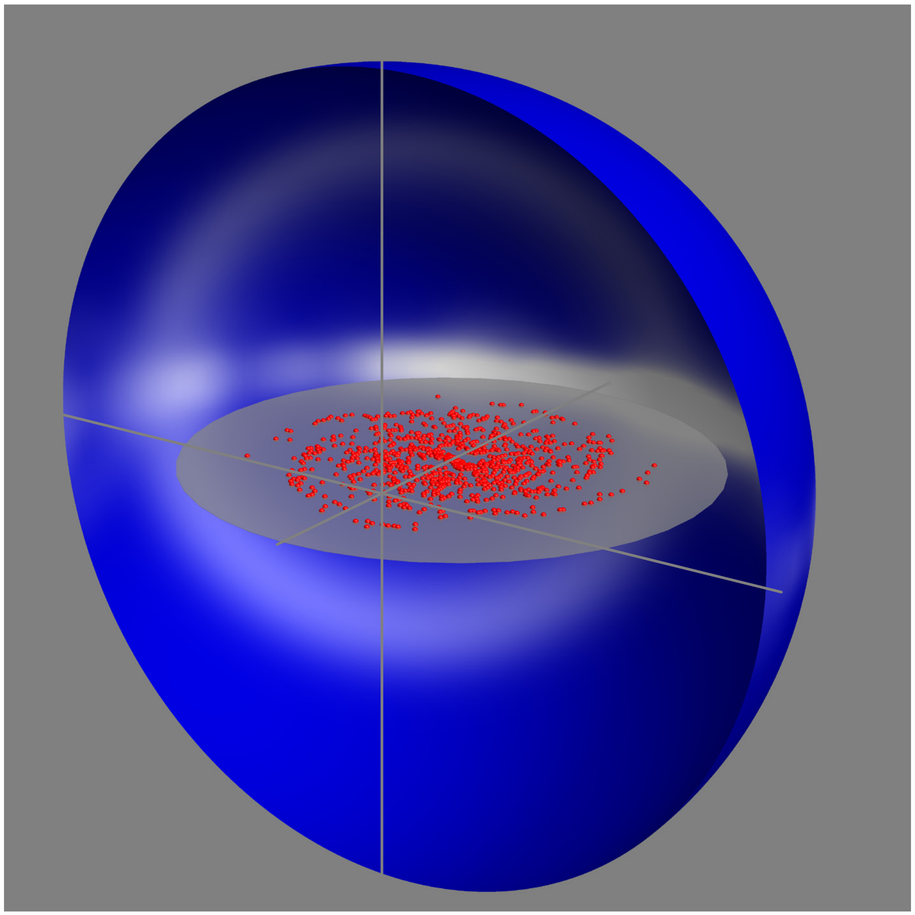


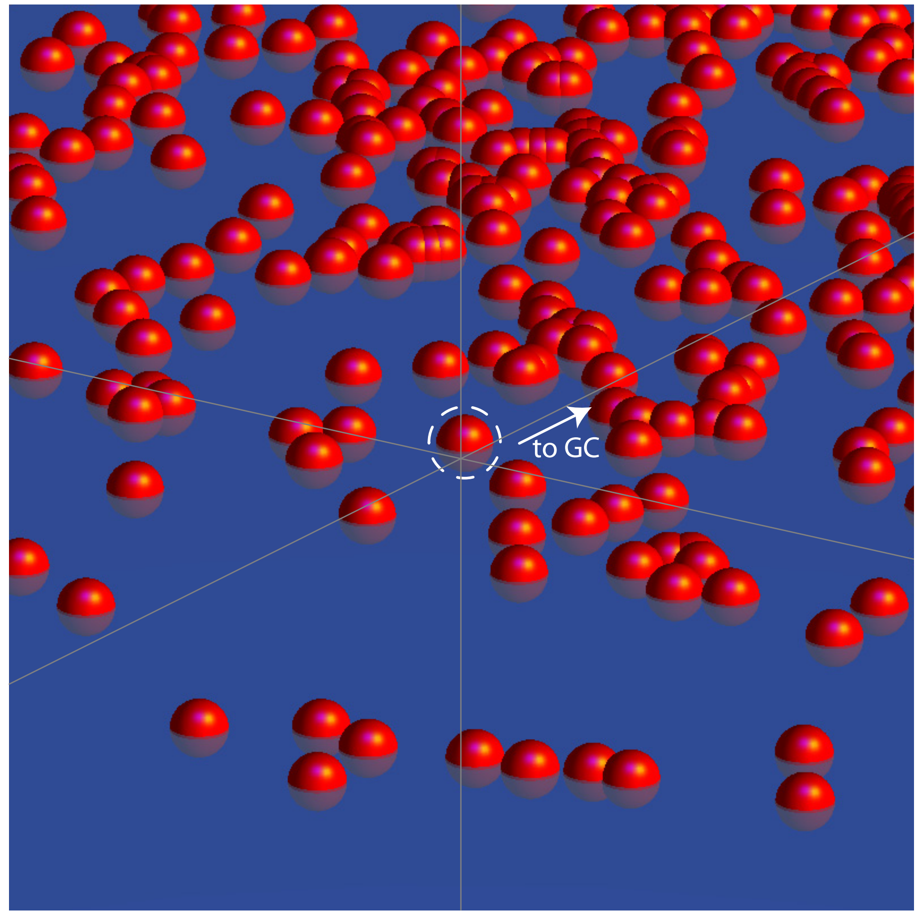


Page *et al.*, ApJS 170 (2007) 335

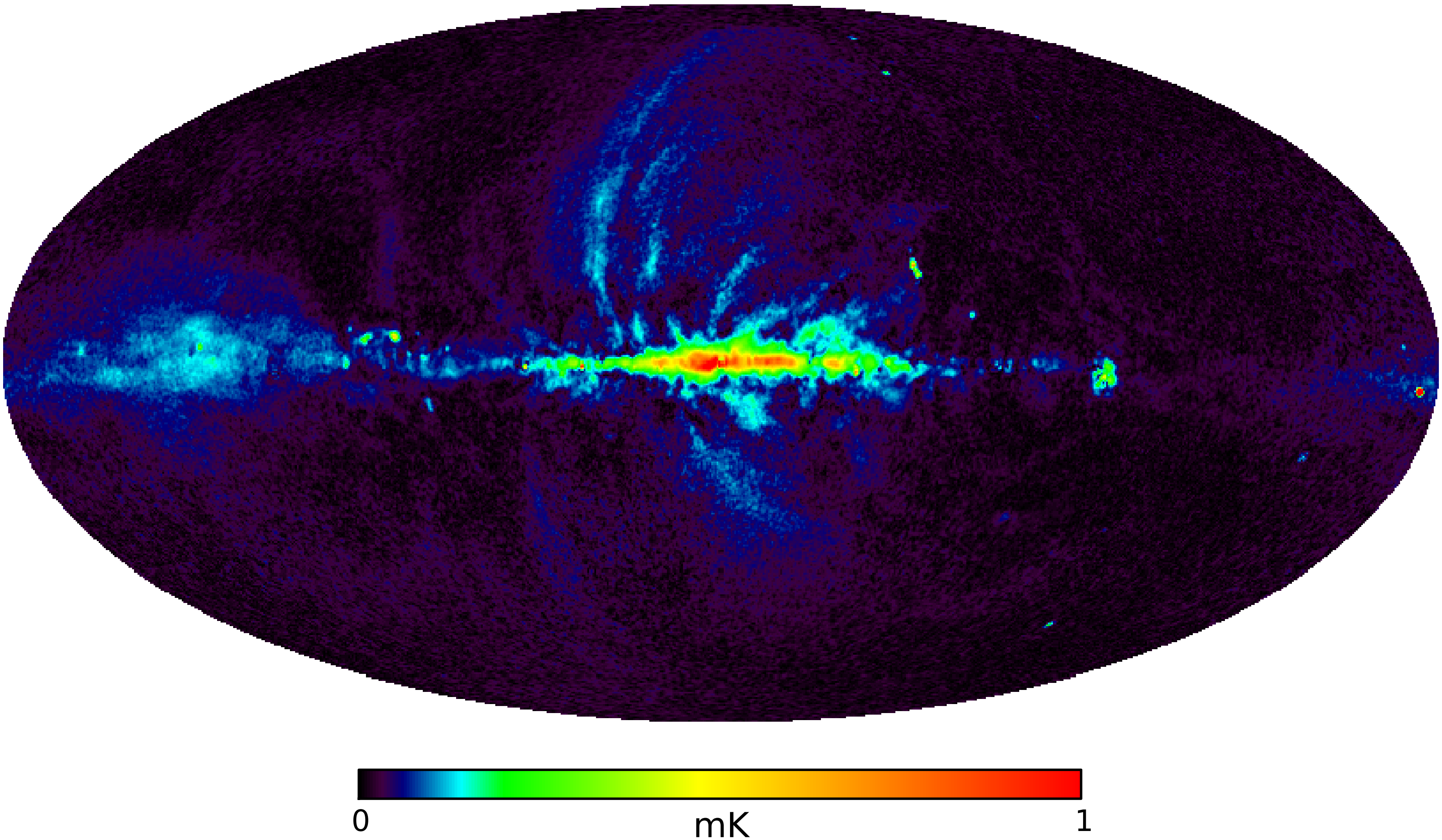
- Probably shells of old SNRs (very nearby)
- Can only see 4-5 of these in radio sky
- However there must be *several thousand loops* in the Galaxy which cannot be resolved against the 'diffuse' galactic radio background – indeed they probably contribute most of the background
(Sarkar, MNRAS **199**:97,1982)

Radio loops





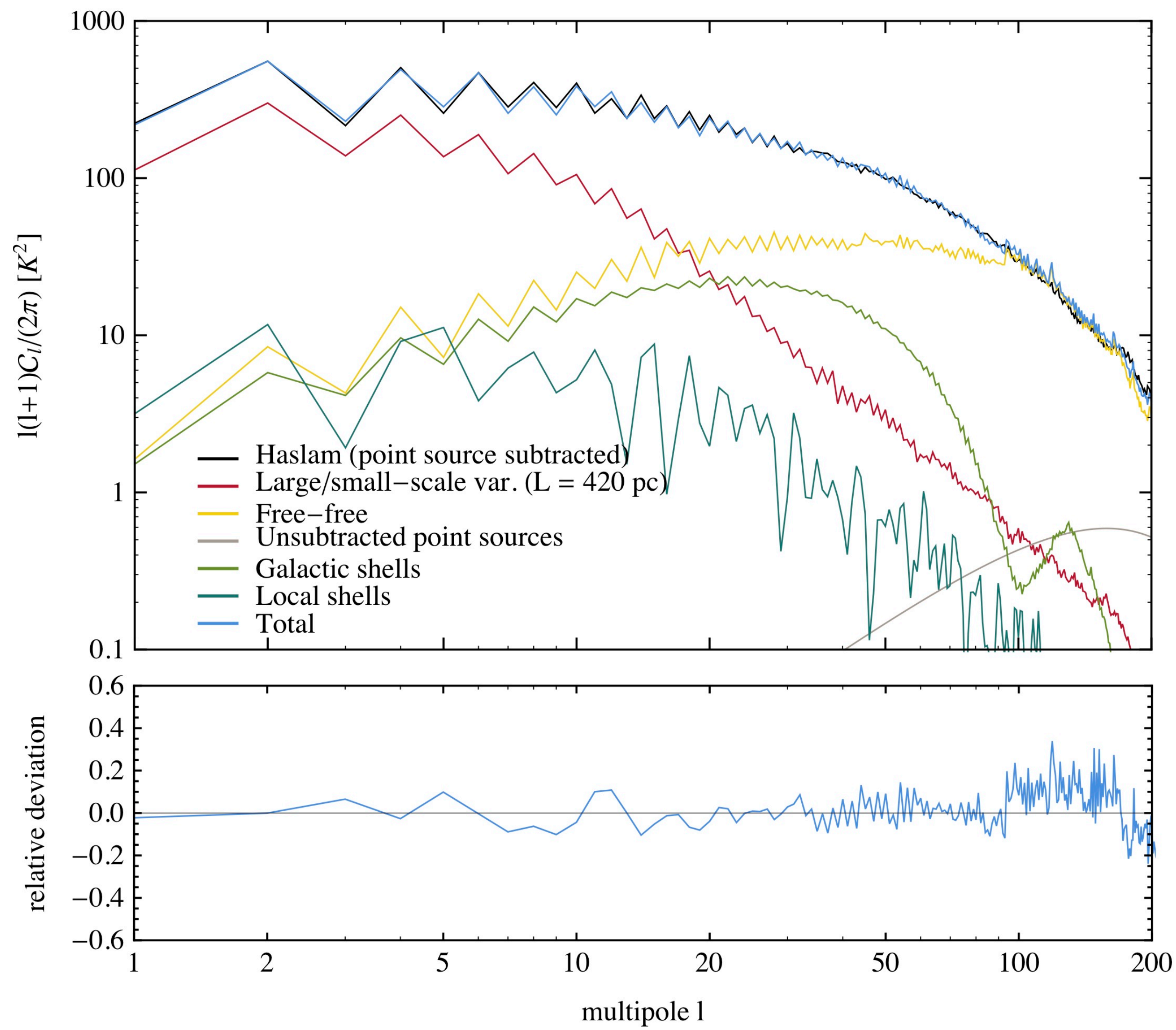
WMAP9 polarisation

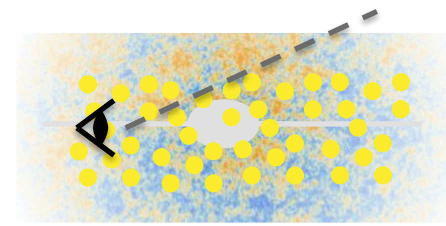


Bennett *al.*, ApJS **208** (2013) 20

To fit the angular power spectrum of the galactic radio background (@ 408 MHz) *requires* a substantial contribution from the radio loops

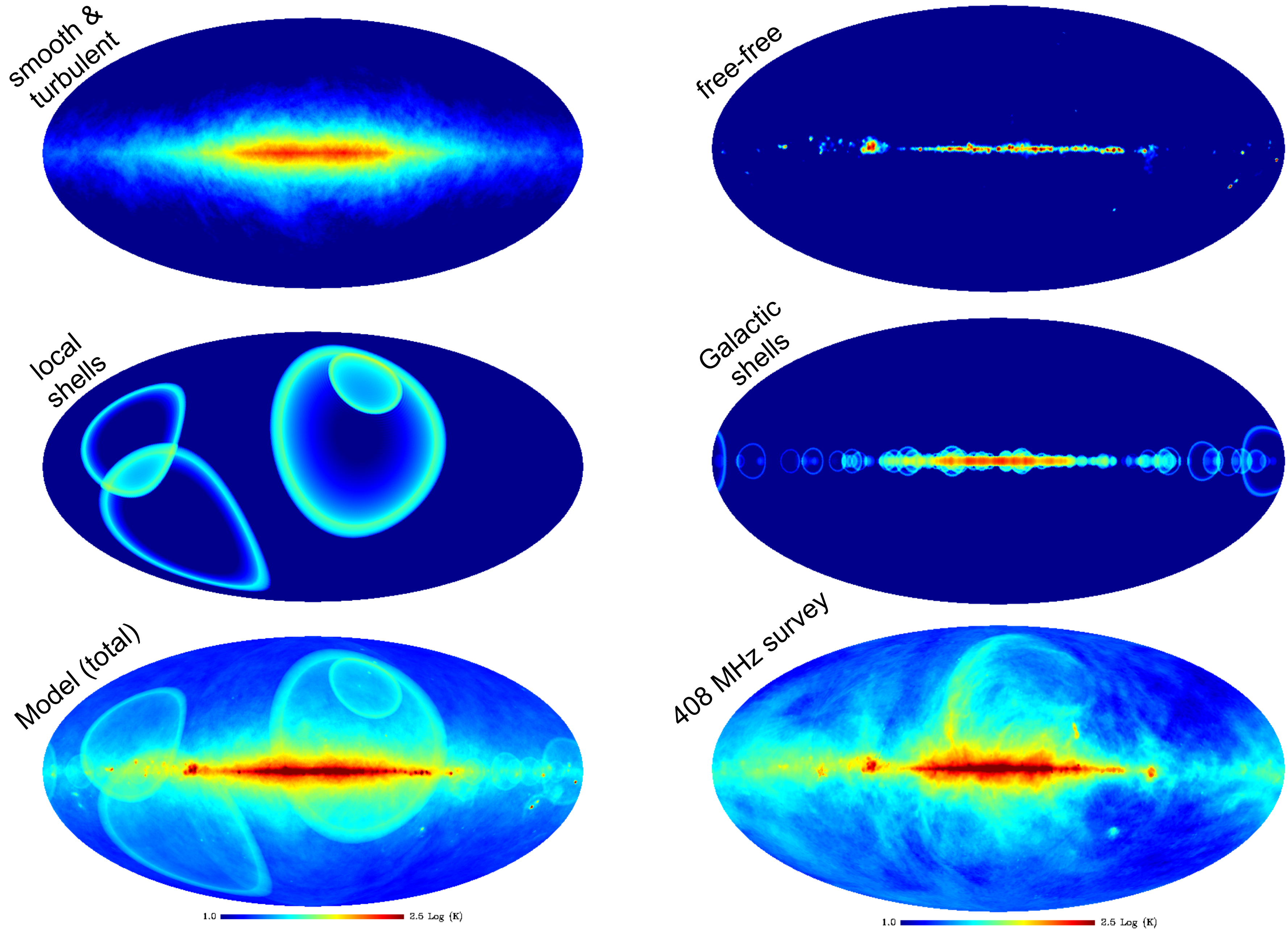
Mertsch & Sarkar, JCAP 06 (2013) 041



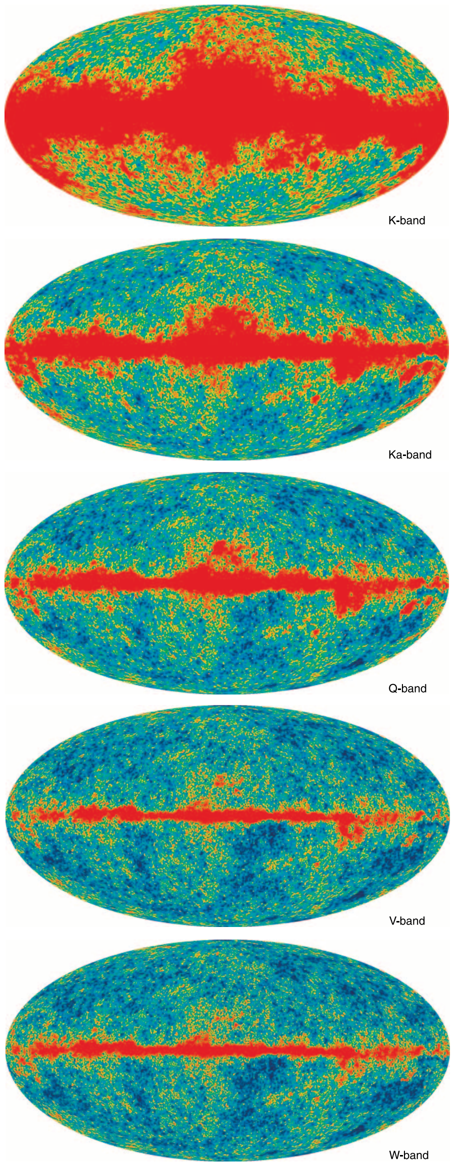


- Several thousand old SNRs present in Galaxy
- We know 4 local shells (Loop I-IV) but others are modeled in MC approach
- They contribute *exactly* in the right multipole range

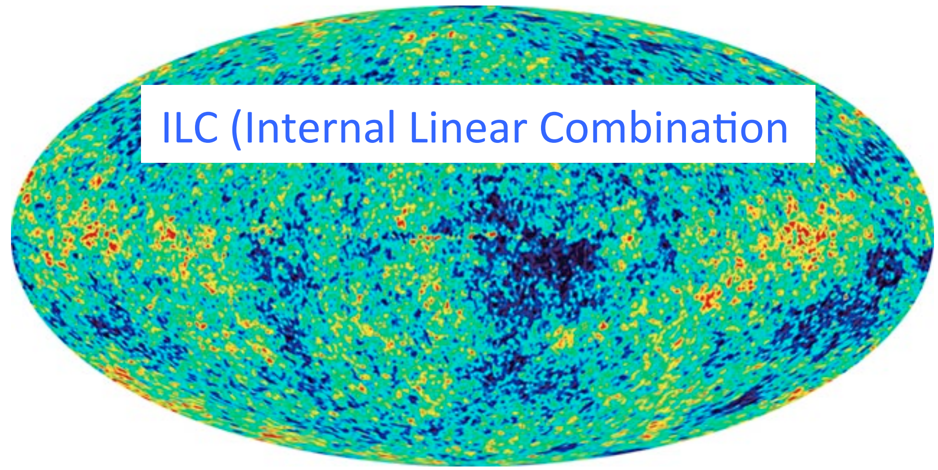
To model the galactic radio background (@ 408 MHz) accurately *requires* a substantial contribution from the radio loops

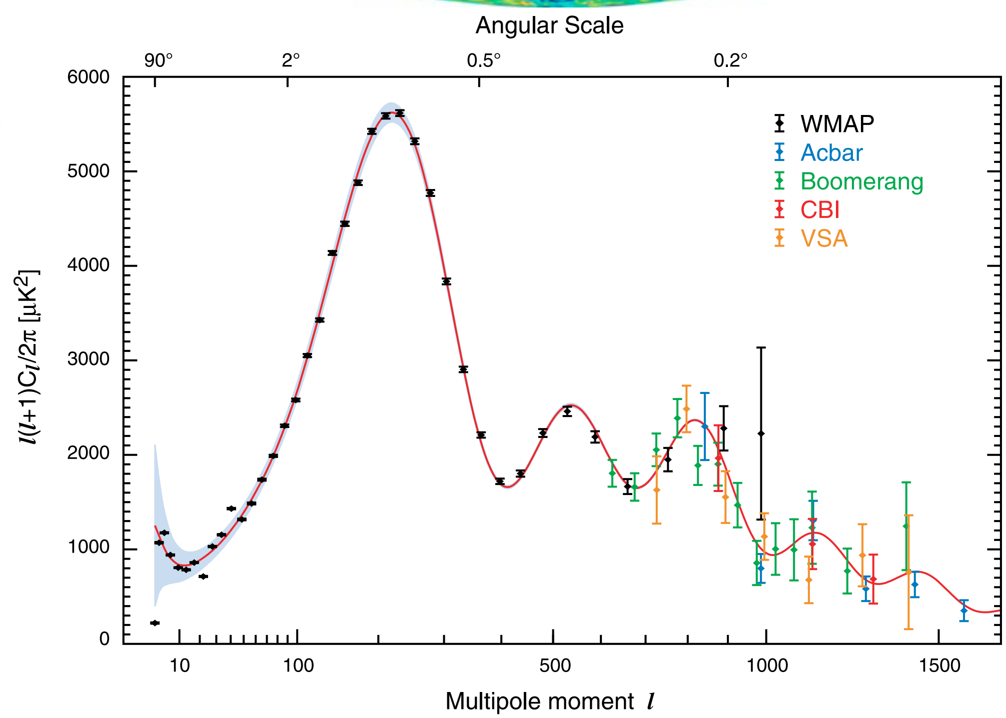


CMB foreground removal

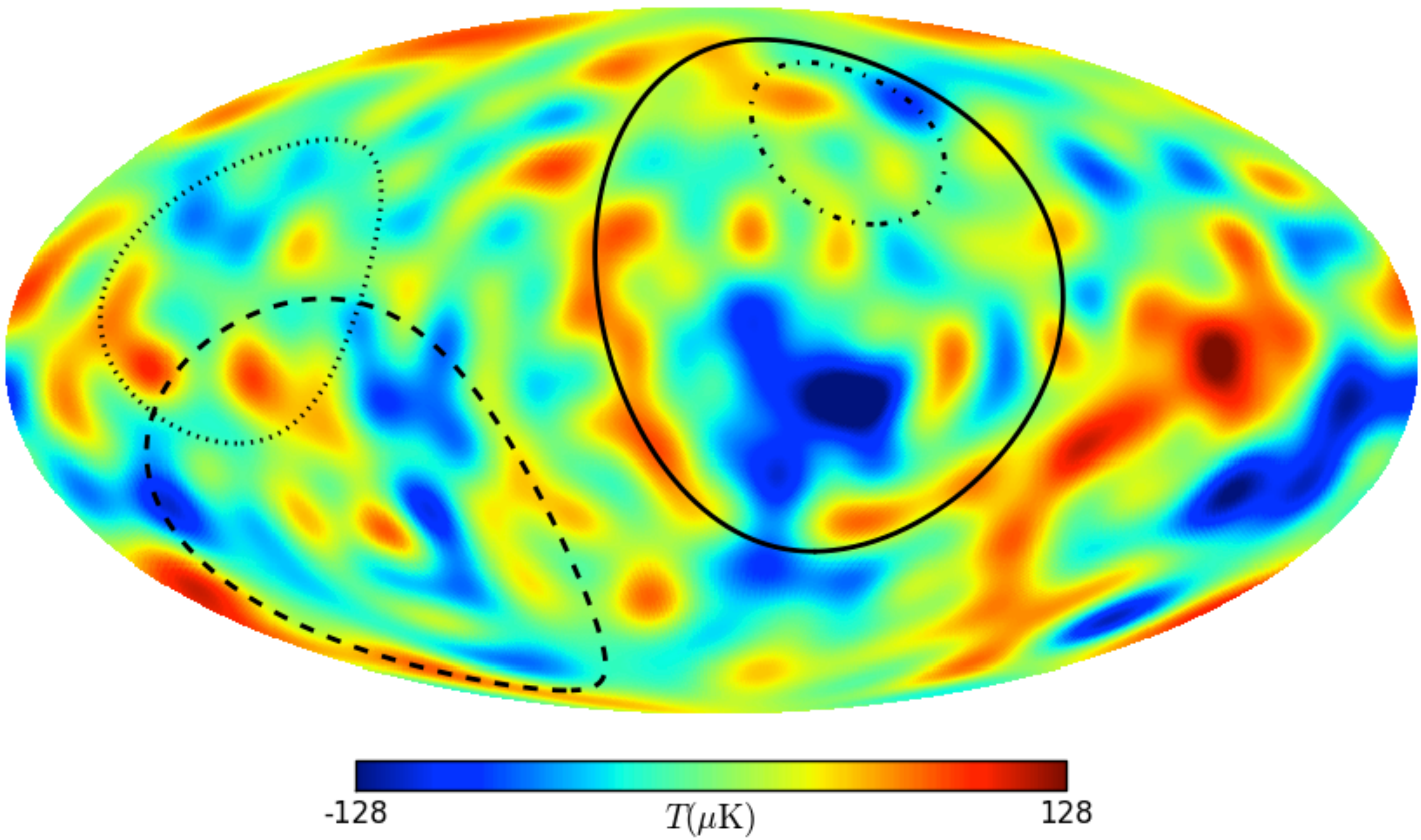


Hinshaw *et al*, ApJS 170 (2007) 288





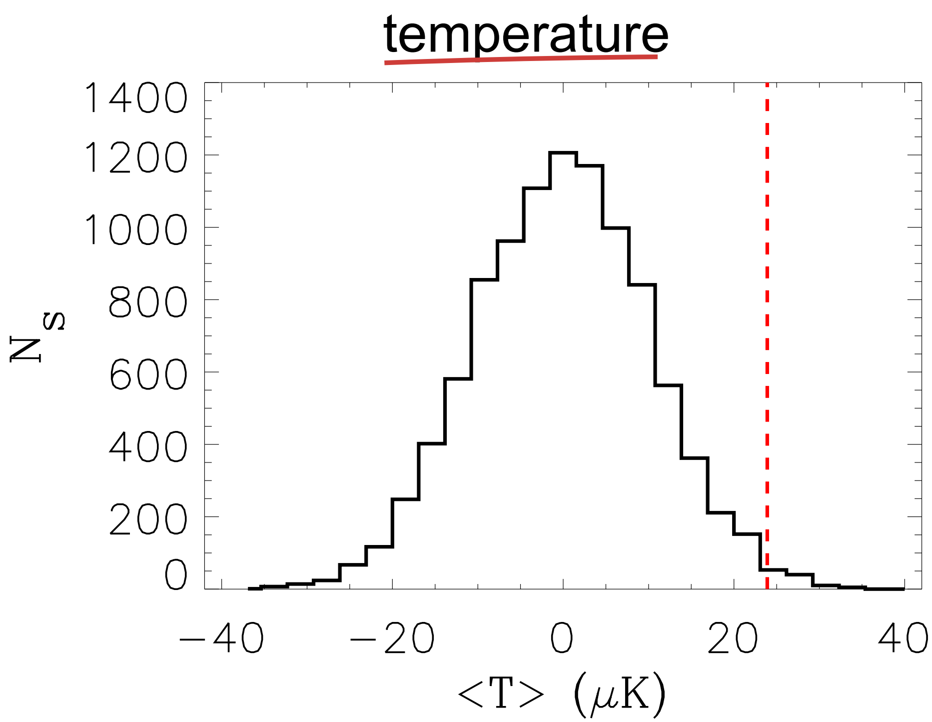
Anomalies in ILC9 ($\ell \leq 20$)
... are the radio loops visible?

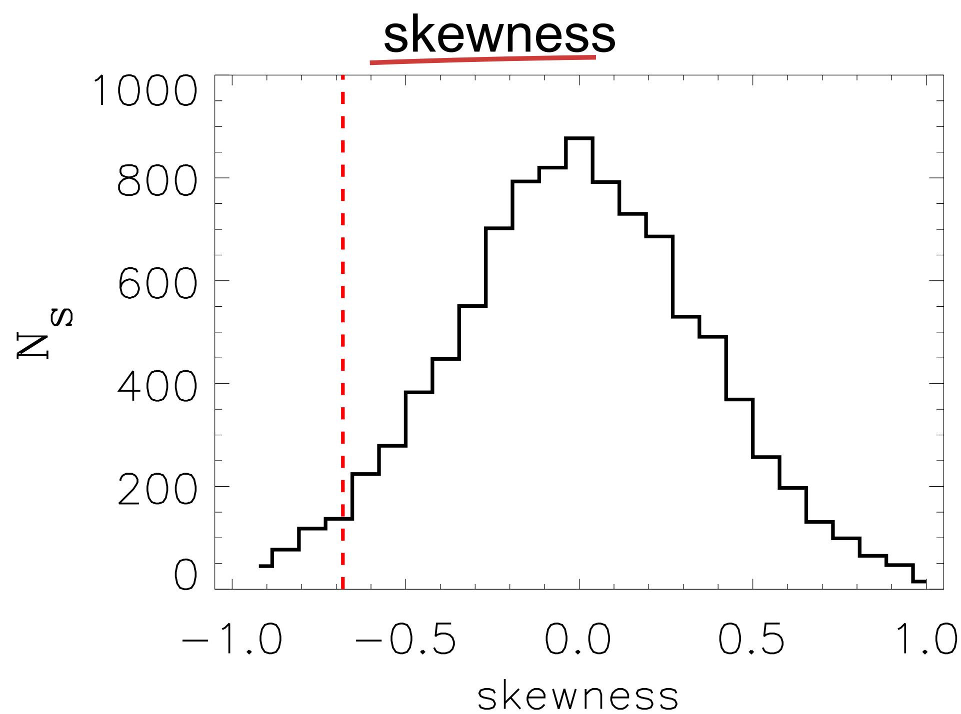


Bennett et *al*, ApJS **208** (2013) 20

Anomalies in ILC9 ($\ell \leq 20$)

There is a 20 μK excess temperature in ring around Loop I



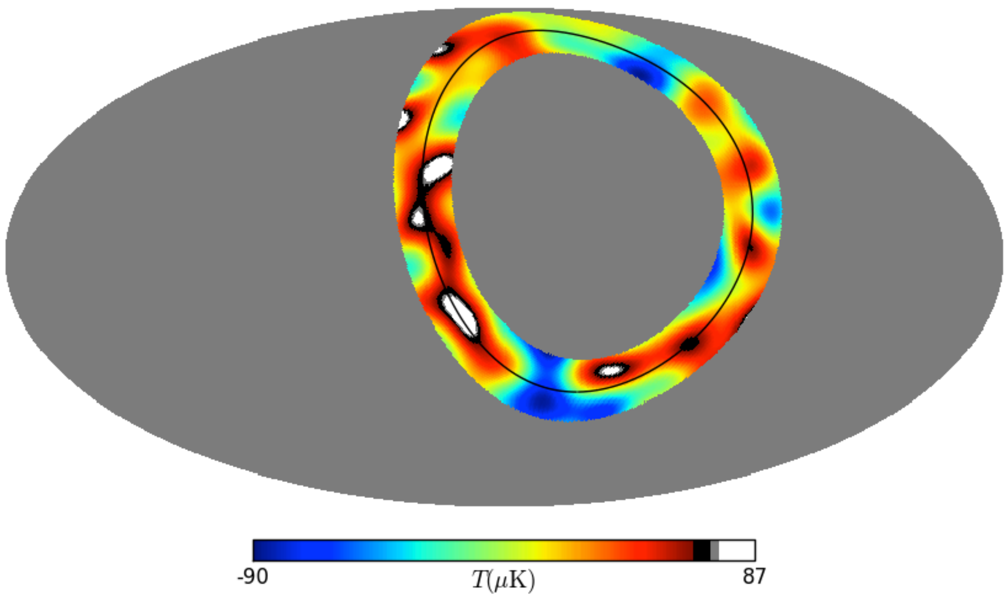


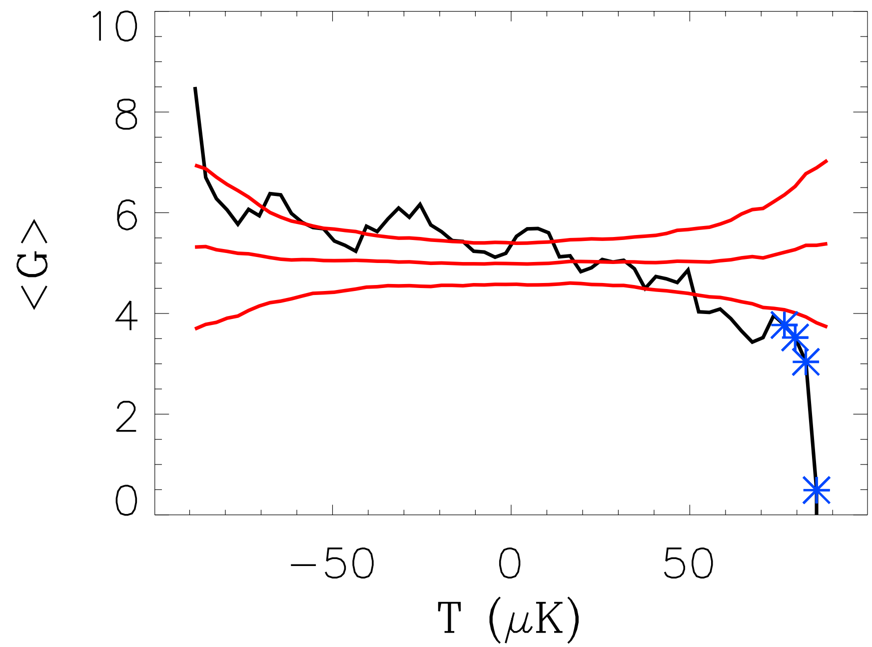
compare with MC ⇒ p-values of $\mathcal{O}(10^{-2})$

Liu, Mertsch & Sarkar, arXiv:1404.1899

Cluster analysis

Naselsky & Novikov, ApJ. **444** (1995) 1

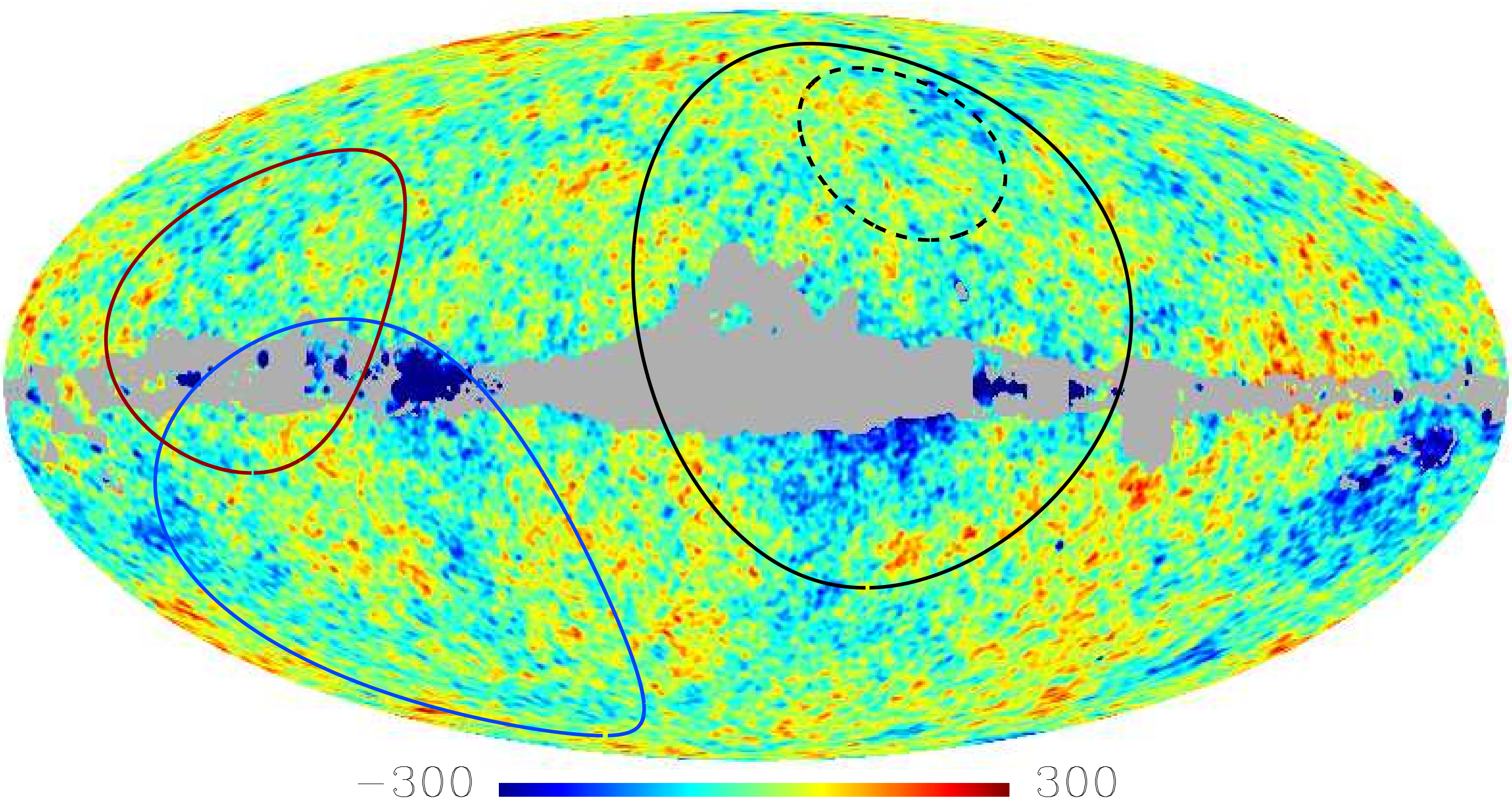




from 100,000 MC runs: probability for *smaller* $\langle G \rangle$ in last four bins $\sim 10^{-4}$

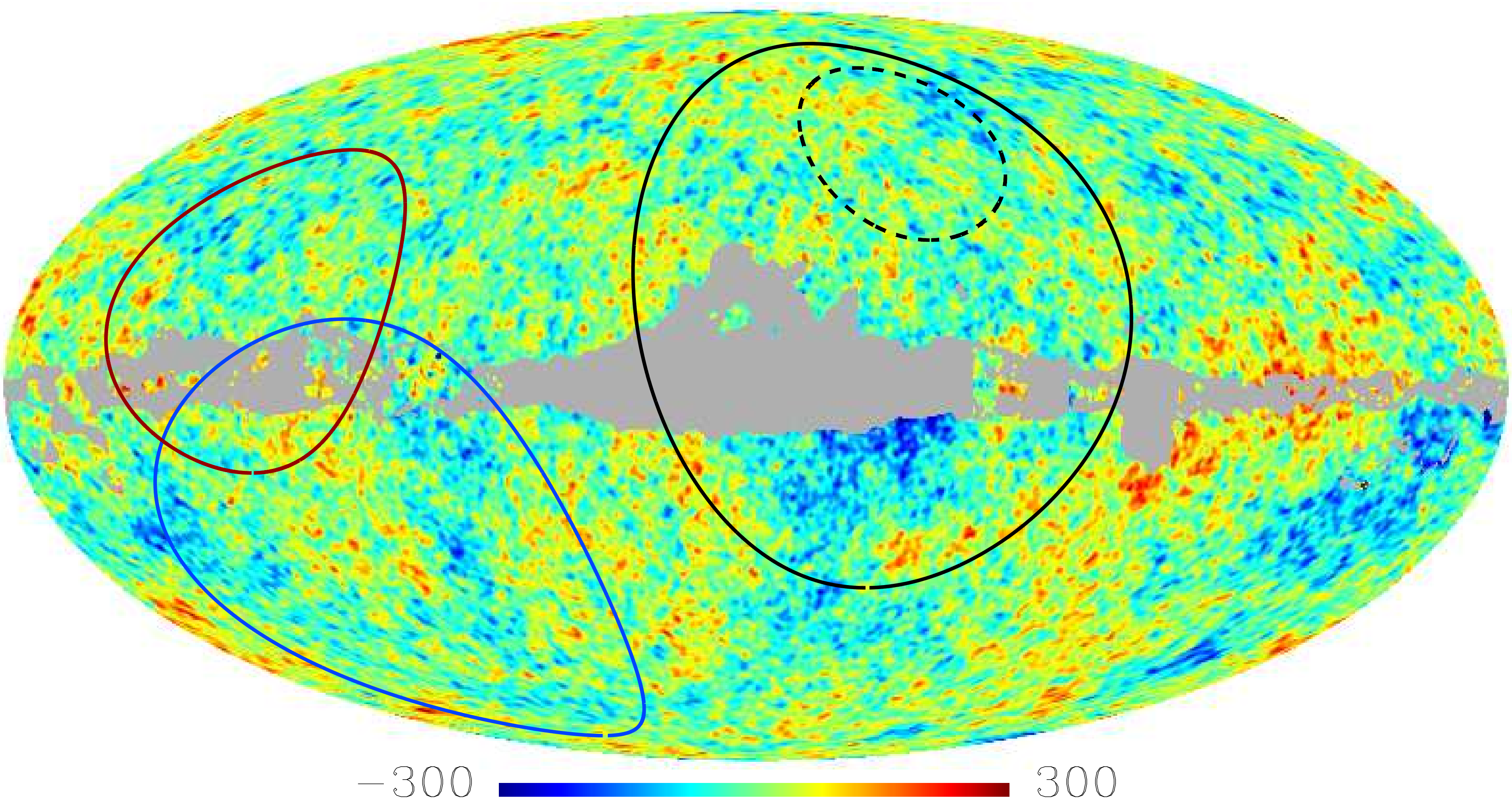
Liu, Mertsch & Sarkar, arXiv:1404.1899

ILC coefficients from Loop I region



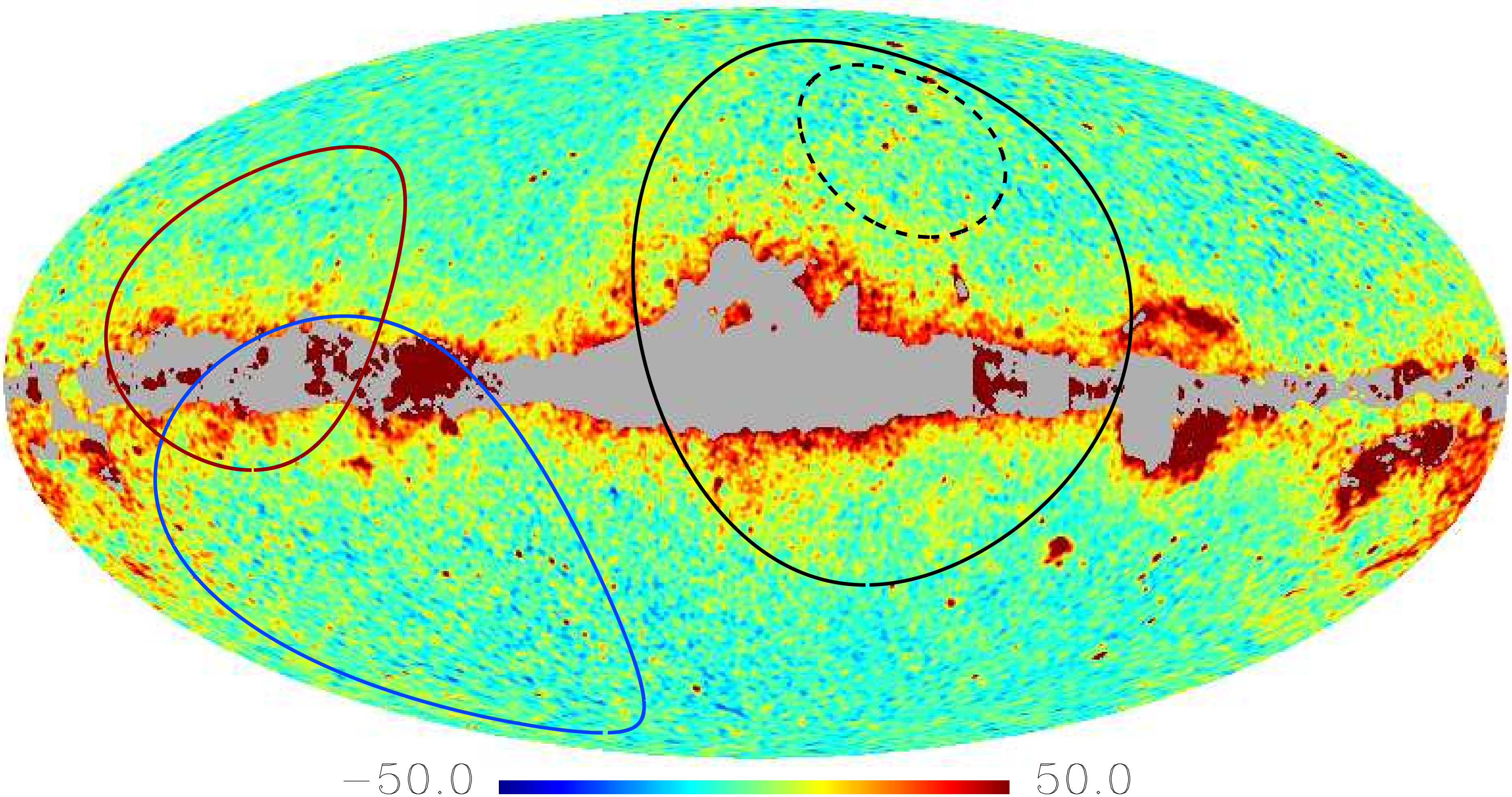
Liu, Mertsch & Sarkar, arXiv:1404.1899

ILC coefficients from rest of sky



Liu, Mertsch & Sarkar, arXiv:1404.1899

Difference $ILC_{rest} - ILC_{Loop\ I}$



The difference indicates the presence of the Loops in the ILC map which has supposedly been cleaned of all foreground emissions (and is used for 'precision cosmology')

What do we know about the anomaly?

- Spatially correlates with Loop I
- *unlikely* to be synchrotron (checked with our synchrotron model)
- frequency dependence:

simple toy model $\xi(\hat{\mathbf{n}}) = \tau(\hat{\mathbf{n}}) T_s \Theta(\nu_{\rm min} \leq \nu_j \leq \nu_{\rm max})$

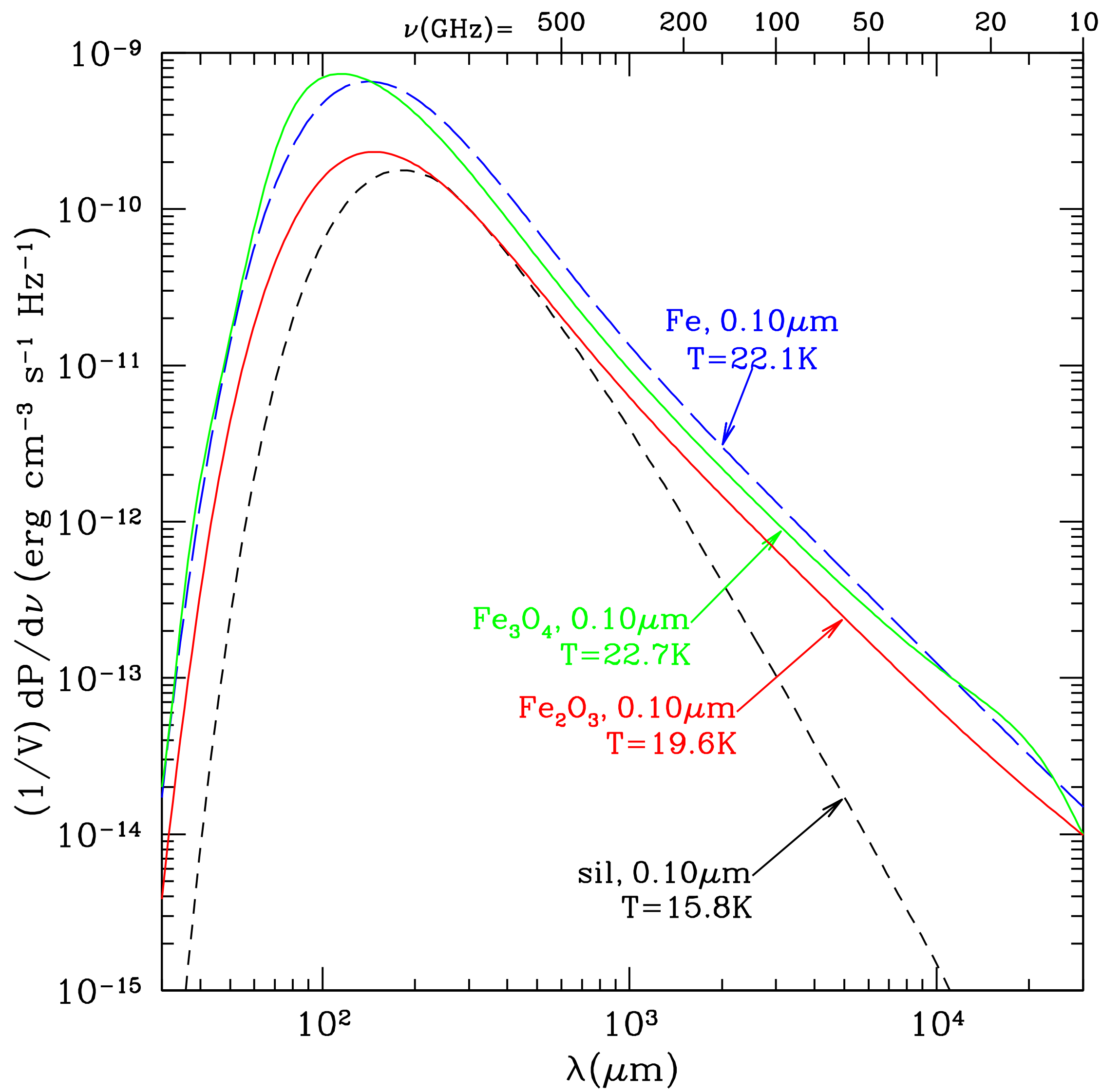
with $\tau(\hat{\mathbf{n}}) \sim 10^{-6}$ and $T_s \sim 20\,\mathrm{K}$

If $\tau(\hat{\mathbf{n}})$ depends only weakly on ν, can estimate frequency dependence from

$$\sum_j W_j \tau(\hat{\mathbf{n}}) T_s \propto \sum_j W_j$$

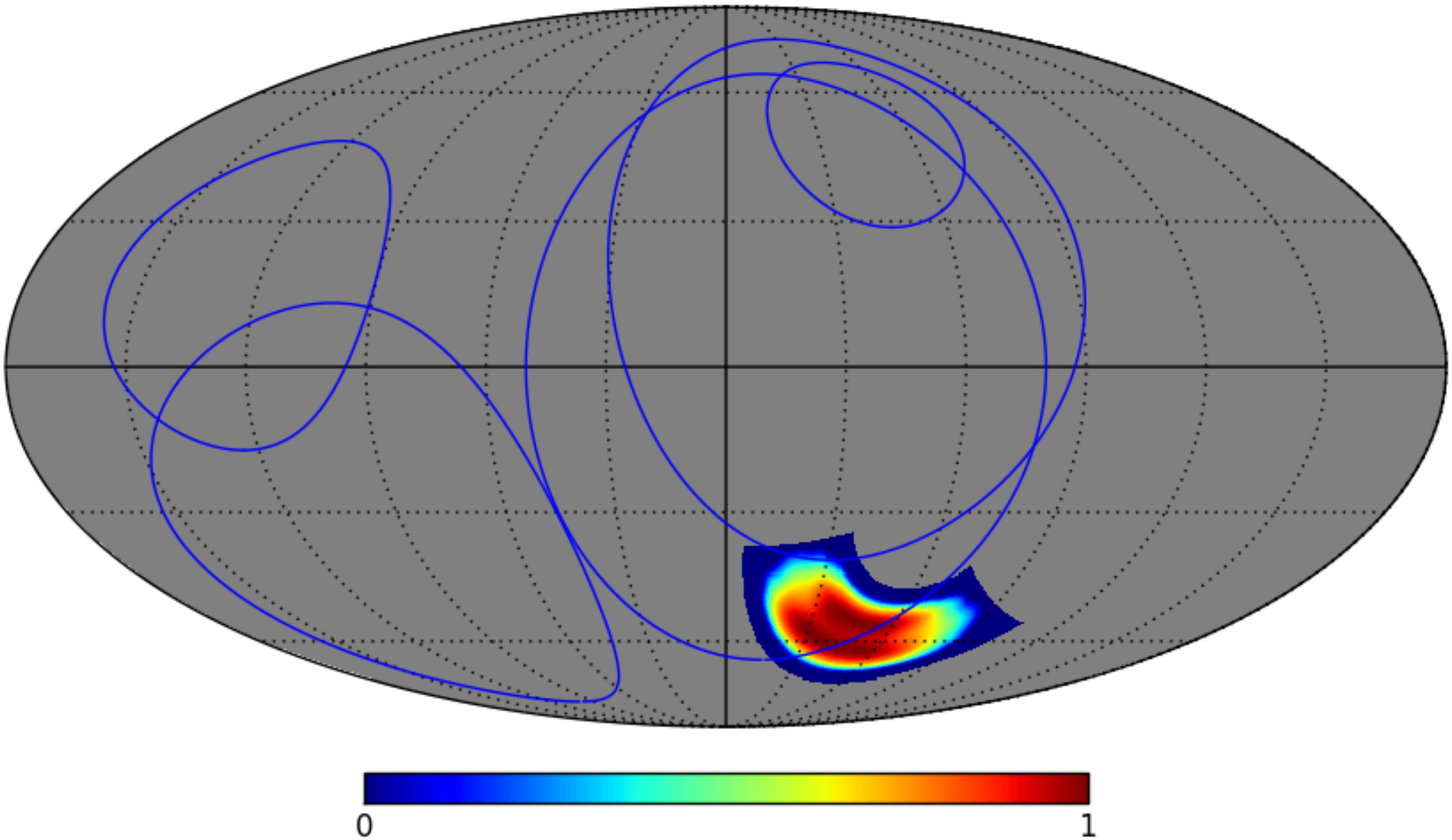
… Can also use polarised V- and W-bands to get handle on dust (?) spectral index

Could it be magnetic dipole radiation from dust?



Draine & Lazarian, ApJ **508** (1998) 157, **512** (1999) 740; Draine & Hensley, ApJ **757** (2012) 103

BICEP2 variance-weight map



Wolleben's 'new Loop' goes right through the region mapped by BICEP2 (of which they say:
"… these ultra clean regions are very special – at least an order of magnitude cleaner than the average $b>50^0$ level")

Conclusions

Inflation has been an important idea at the interface of particle physics and cosmology … and has successfully explained observations of scalar density fluctuations in the CMB

The slow-roll scalar field model for inflation suffers however from our lack of theoretical understanding of how vacuum energy couples to gravity
In fact scalar density fluctuations can be generated by other means, but *tensor* perturbations would be a *direct signature* of vacuum energy dominated inflation

The detection of gravitational waves generated during inflation would therefore be of *enormous* importance (and force us to confront the cosmological constant problem)

The BICEP2 claim to have detected this signal must therefore be subjected to critical scrutiny … they observed a sky patch believed to be (relatively) free of foreground Galactic emissions and showed that the B-mode signal does not correlate with extrapolated known foregrounds

However this sky patch is crossed by a 'radio loop' – remnant of a nearby ancient supernova – which also contains dust … we have shown that these have a spectrum that *evades* the standard foreground cleaning methods so they lurk undetected (until now!) in the maps of the CMB

Forthcoming Planck data will show if this can account for the B-mode signal observed by BICEP2