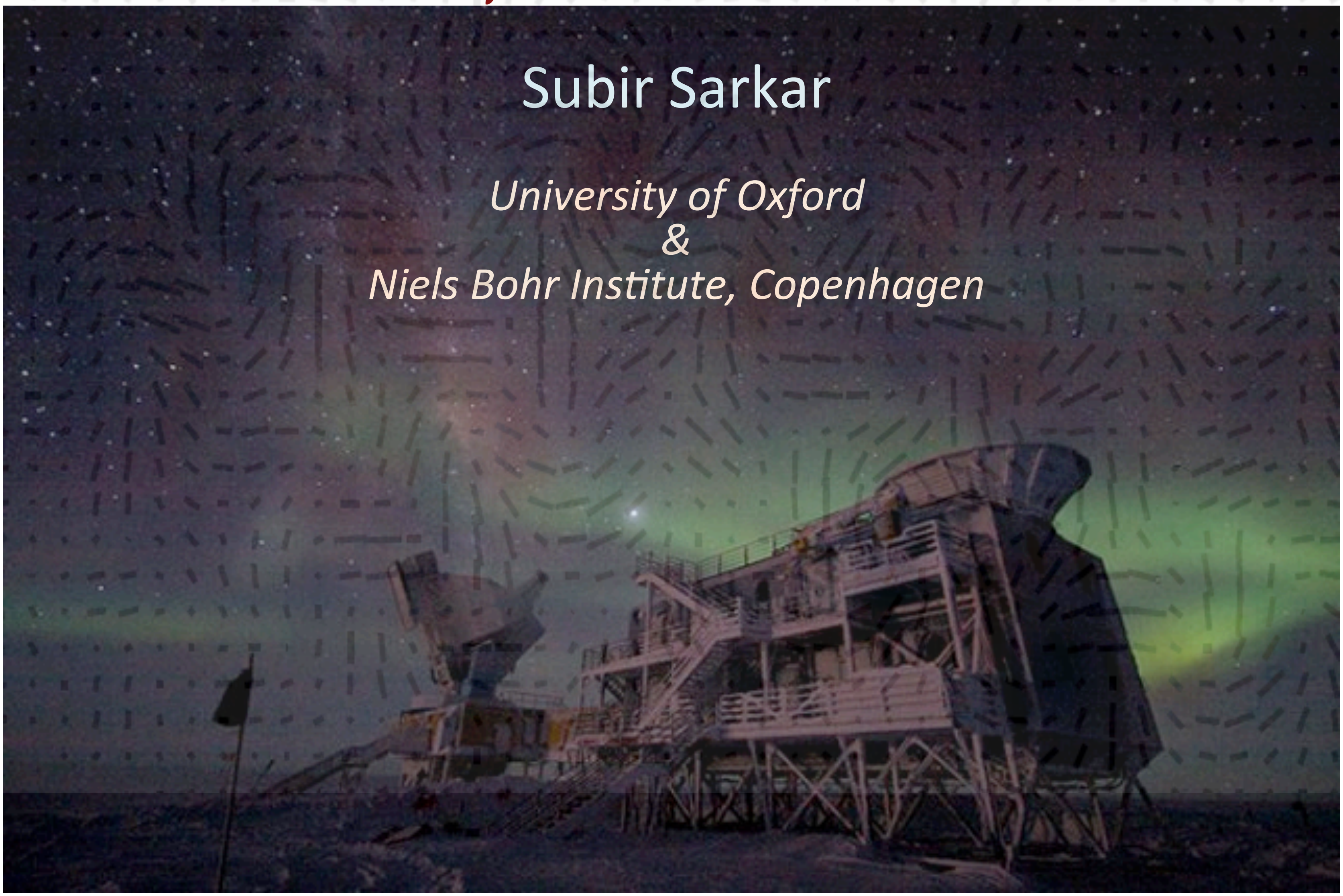
Has BICEP2 proved cosmic inflation?



Subir Sarkar

University of Oxford
&
Niels Bohr Institute, Copenhagen

ApJL 789:L29,2014 [arXiv:1404.1899] with Liu Hao (Copenhagen) & Philipp Mertsch (Stanford)
+ JCAP **06**:041,2013 [arXiv:1304.1078] with Mertsch + Sarkar, MNRAS **199**:97,1982

BICEP2 finds gravitational waves from near the dawn of time

By Andrew Liddle

April 11th 2014

While the discovery of gravitational waves had been widely rumoured in the days leading up to the announcement, including even the size of the measured signal, what took everyone's breath away was the significance of the signal. At 6 to 7-sigma, it exceeds even the gold-standard 5-sigma used at CERN for the Higgs particle detection.

http://blog.oup.com/2014/04/bicep2-finds-gravitational-waves-from-near-the-dawn-of-time/

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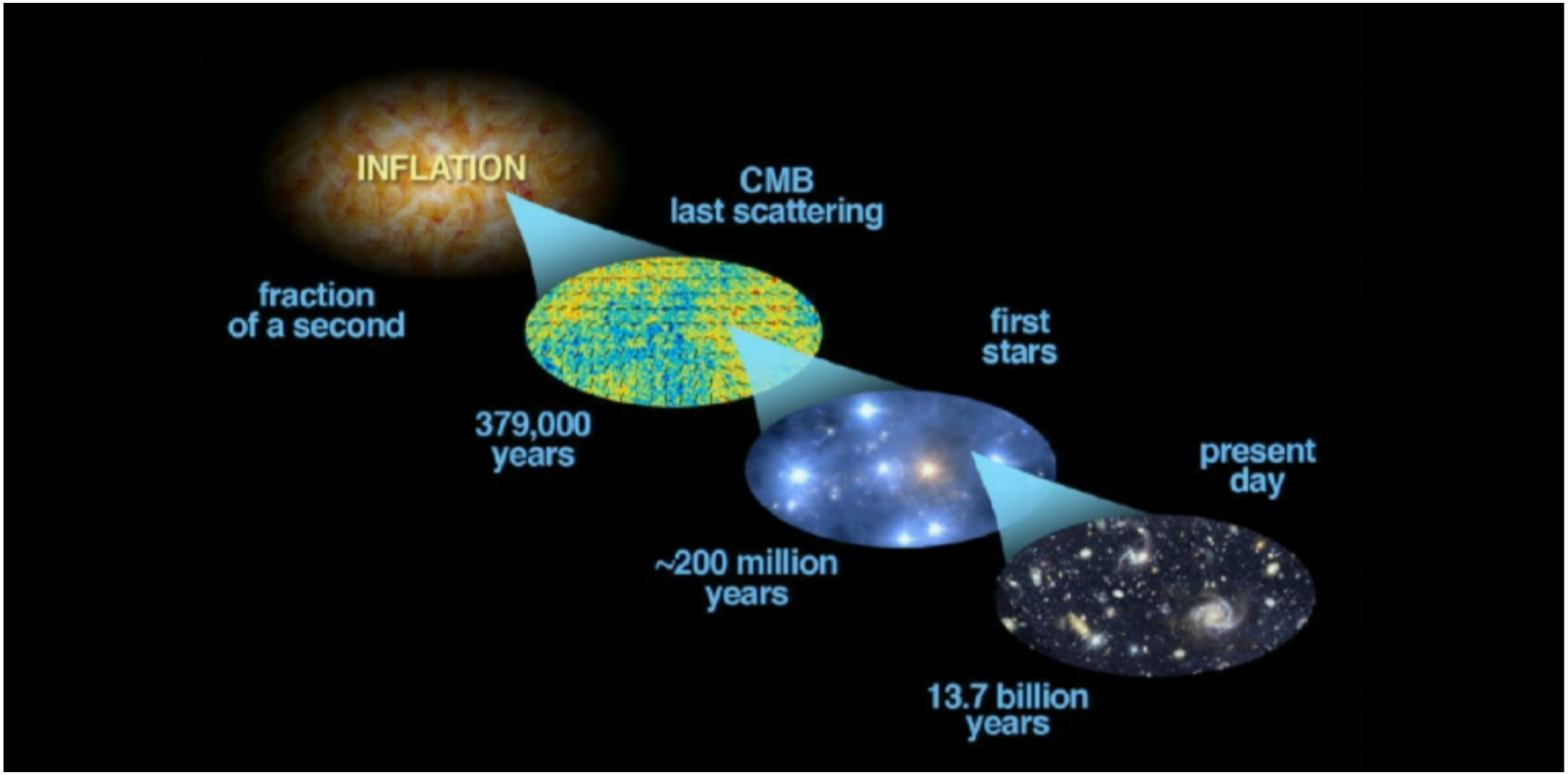
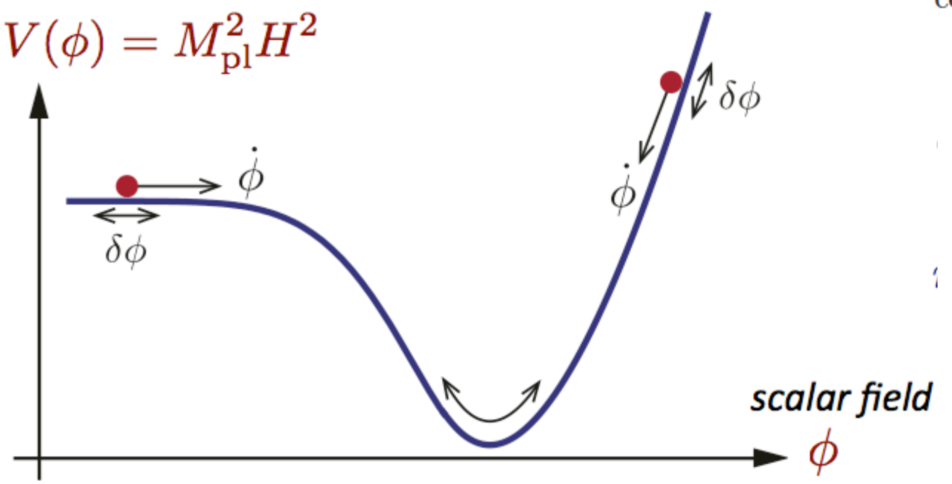
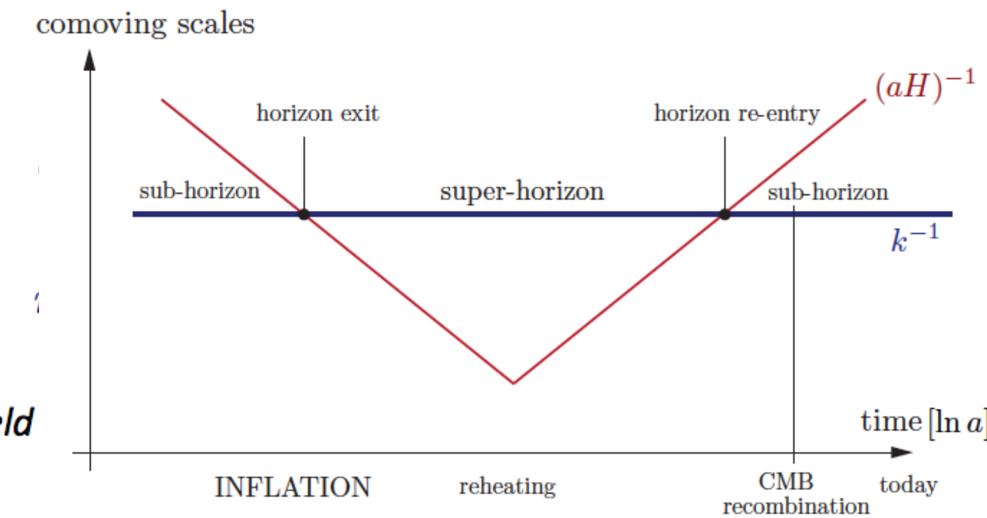
This is indeed very exciting … *if* true



We have a nearly complete picture of the growth of **large-scale structure** through **gravitational instability** in a sea of **dark matter**, starting with **scalar density perturbations** which we have detected imprinted on the **cosmic microwave background** … if these were created by '**inflation**' then seeing the associated **tensor perturbations** would *prove* that inflation actually occurred!

Inflation: If at some early time the universe undergoes a period of exponentially fast expansion due to the energy density being briefly dominated by the **vacuum energy** of a scalar field while it evolves towards the minimum of its potential, it would solve the horizon/flatness problems of the Standard Cosmology and also generate the ~scale-invariant **density fluctuations** necessary for the formation of large-scale structure

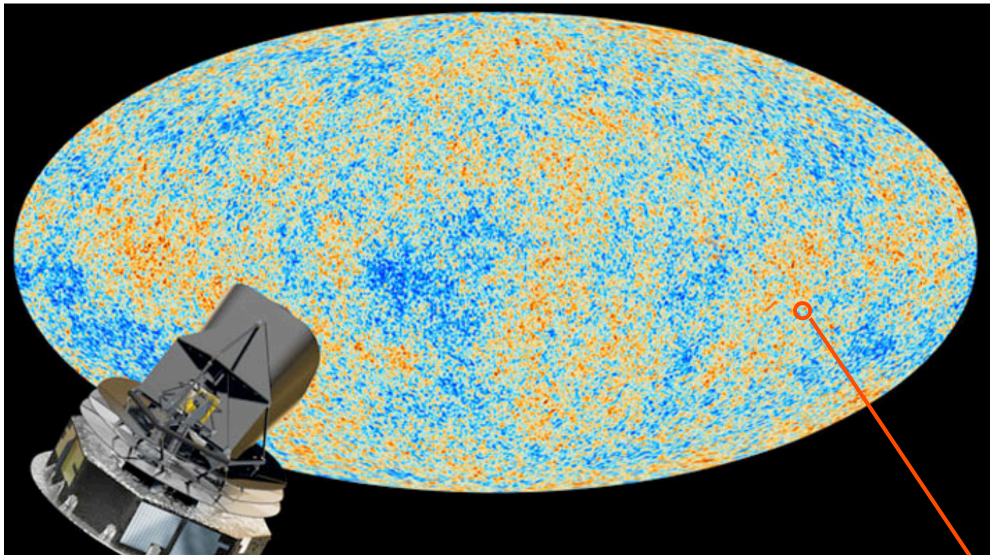




The spectrum of **scalar density perturbations** is $\Delta_s^2 \equiv \left(\frac{H^2}{2\pi\dot{\phi}}\right)^2$, and **gravitational waves** (tensor perturbations) are also generated with spectrum: $\Delta_t^2 \equiv \frac{2}{\pi^2}\frac{H^2}{M_{\rm Pl}^2}$

The ratio of tensor to scalar perturbations is: $r \equiv \frac{\Delta_t^2}{\Delta_s^2} = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot{\phi}}{H}\right)^2$

Having reached its minimum the scalar field oscillates, transferring its energy into radiation, thus 'reheating' the universe and starting off the Standard Cosmology

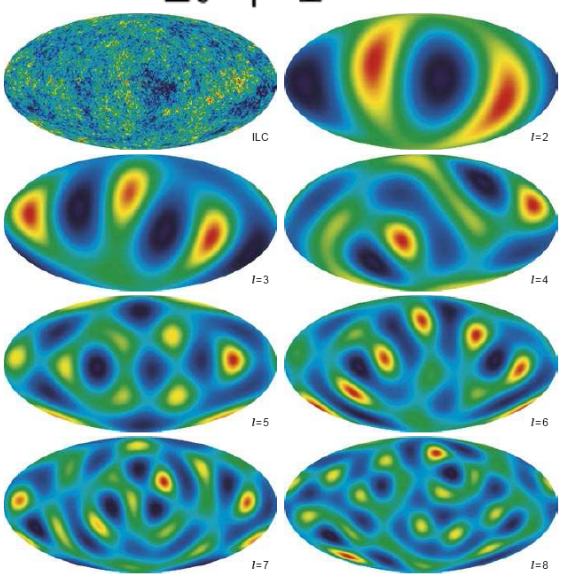


Coherent oscillations in a photon+baryon plasma excited by primordial perturbations on *super*-horizon length scales

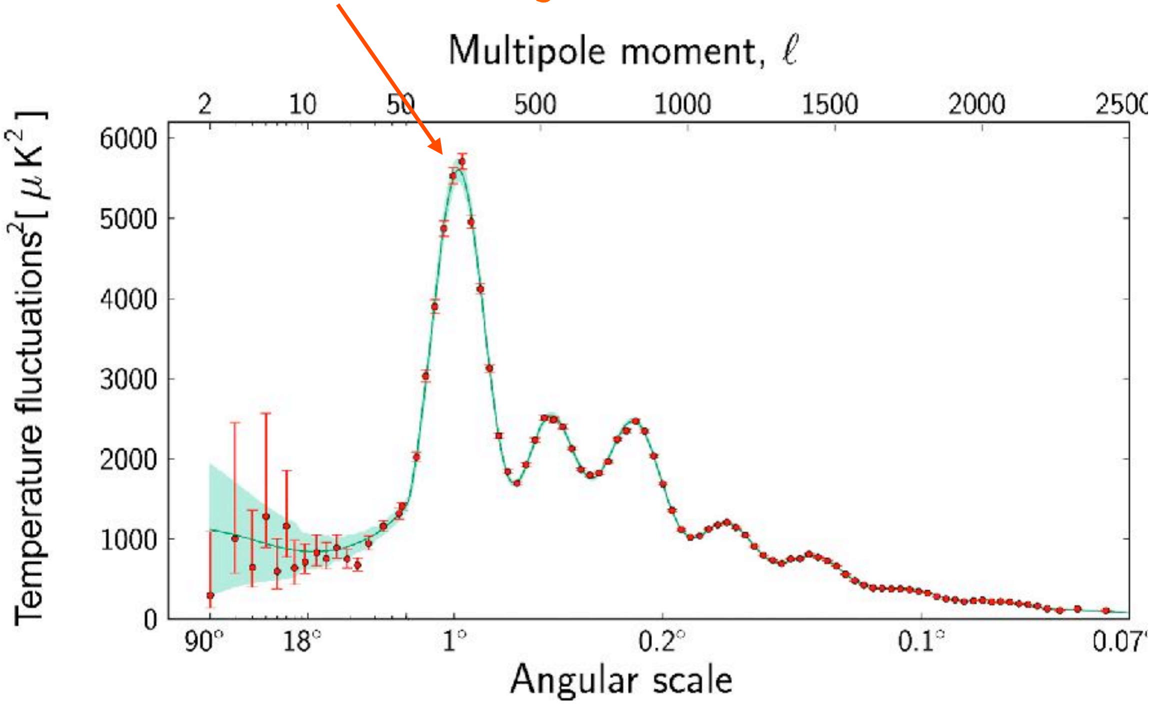
By analysing this pattern we can infer the values of the cosmological parameters *and* test the theory of inflation

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n})$$

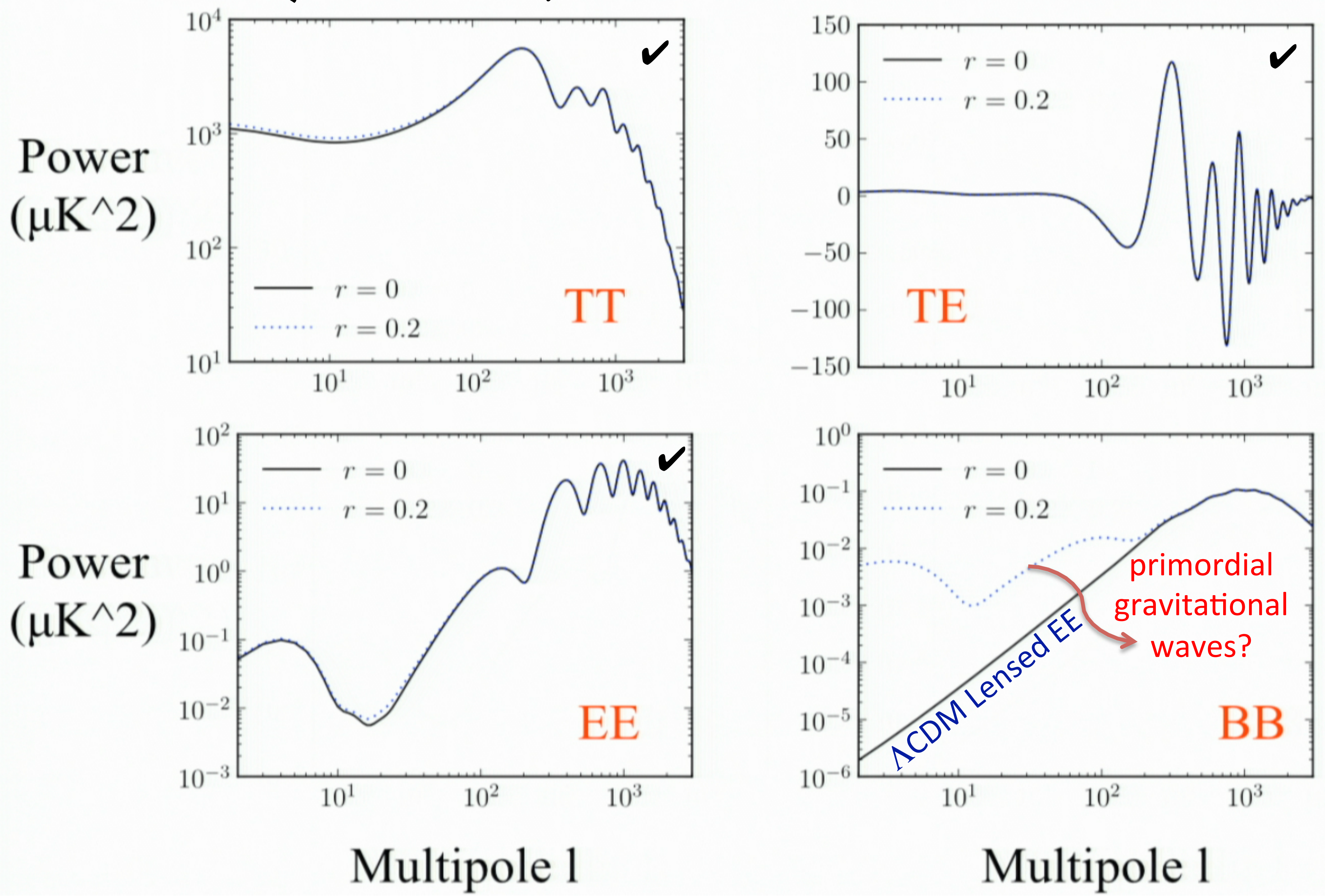
$$C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$



scale of today's universe at (re)combination

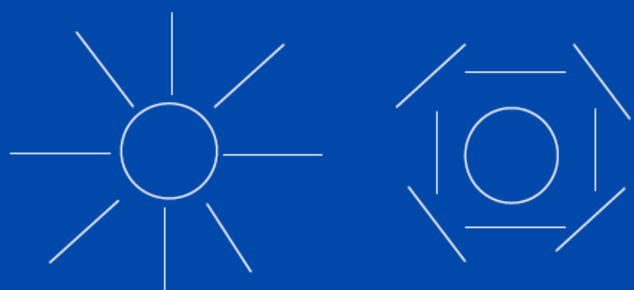


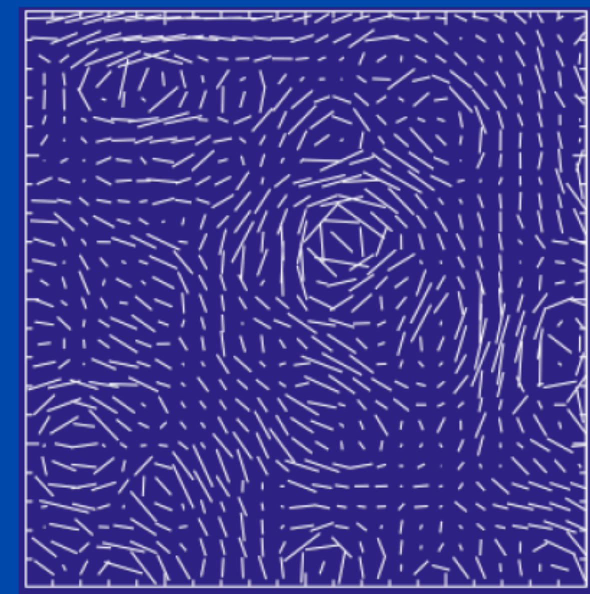
Inflationary predictions for r = 0.2 (adiabatic) CMB fluctuations



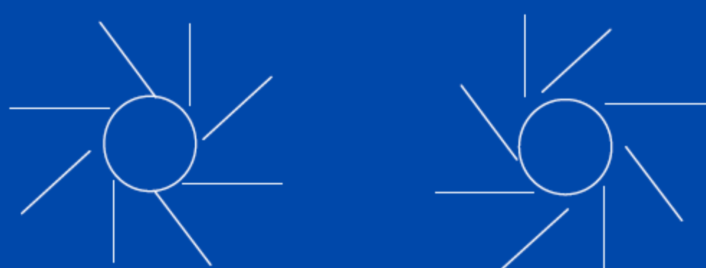
E and B modes polarization (similar to gradient/curl decomposition of vector field)

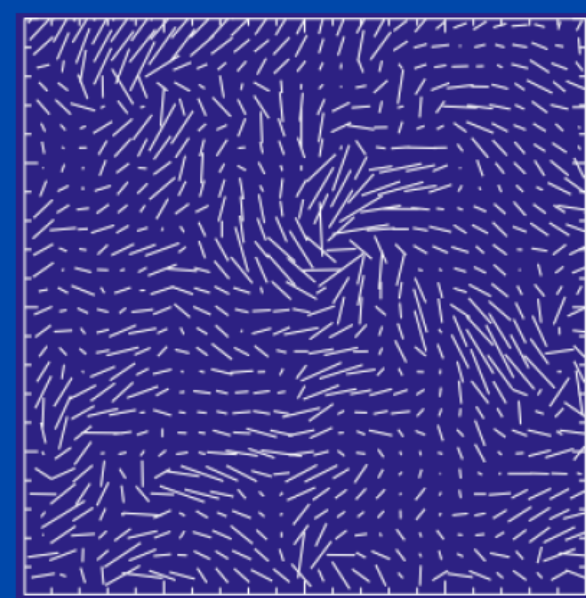
E polarization
from scalar, vector and tensor modes



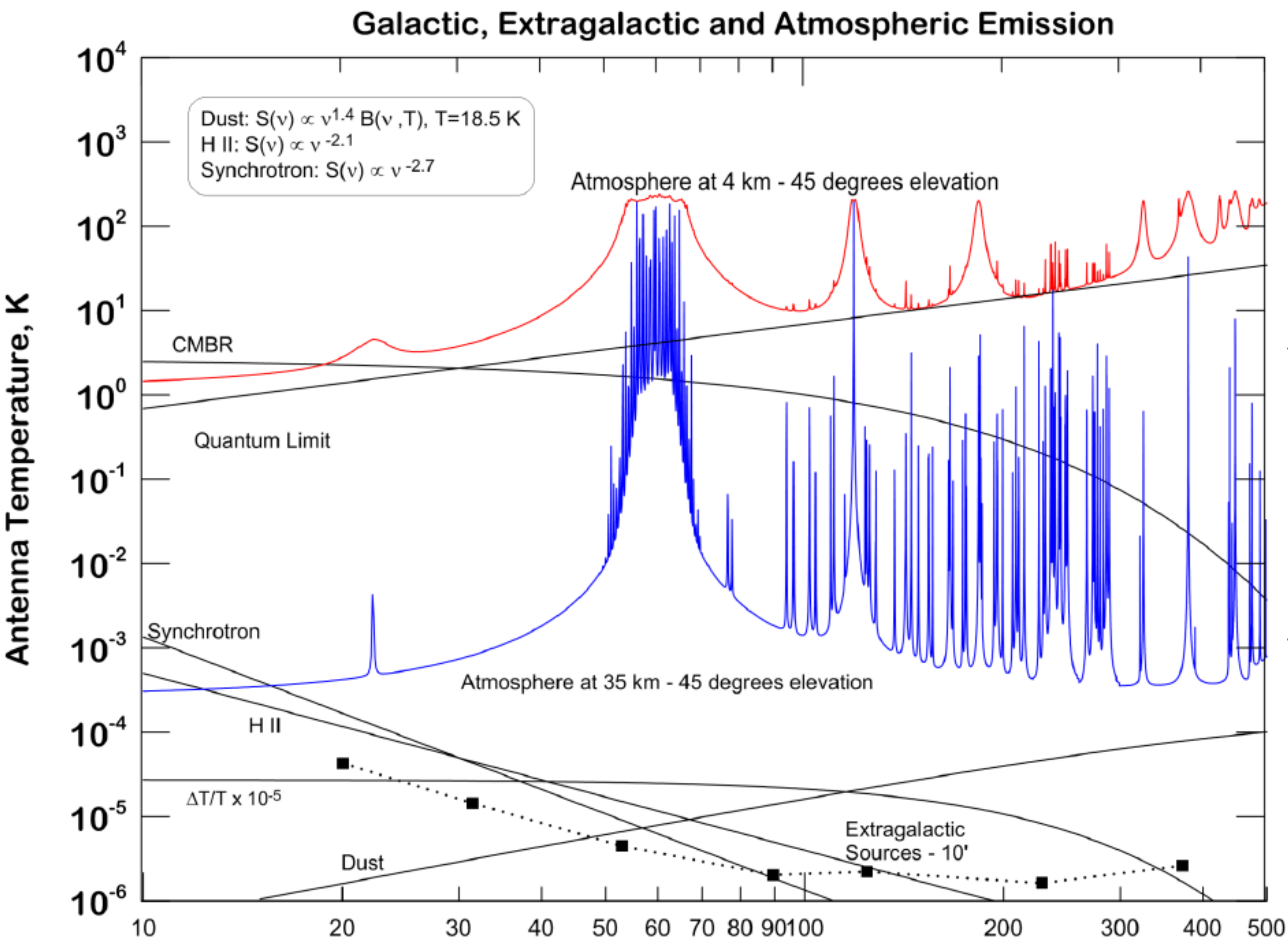


B polarization only from (vector)
tensor modes (*and* gravitational lensing of E polarization)





Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997



(Courtesey: Phil Lubin)

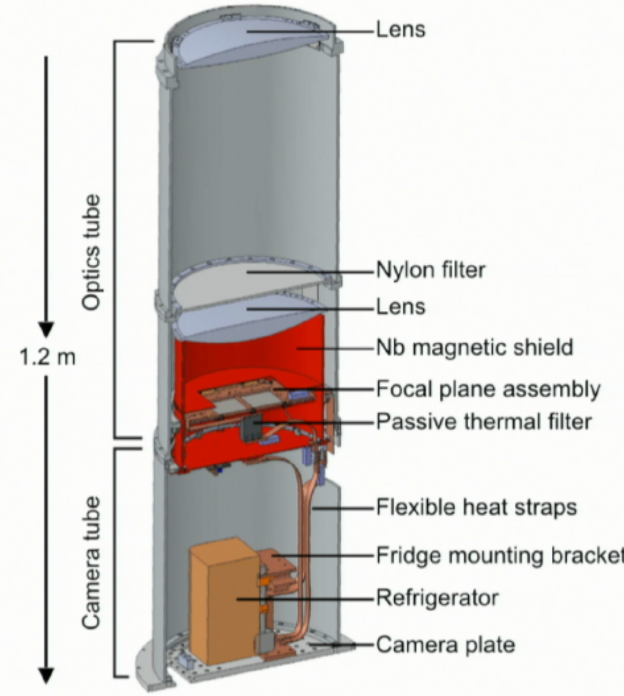
The BICEP2 Telescope

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium cools the optical elements to 4.2 K.

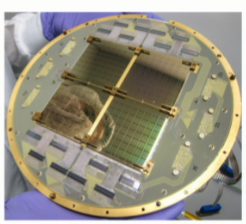
A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.

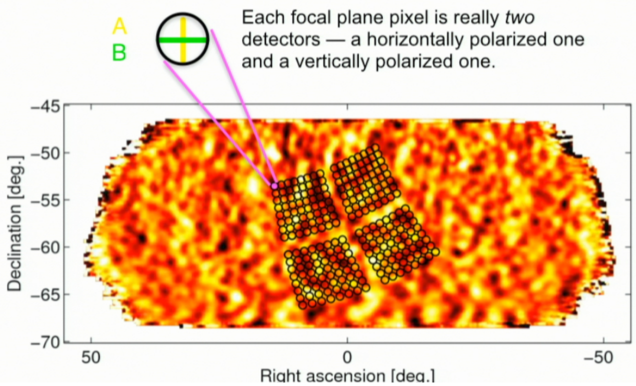


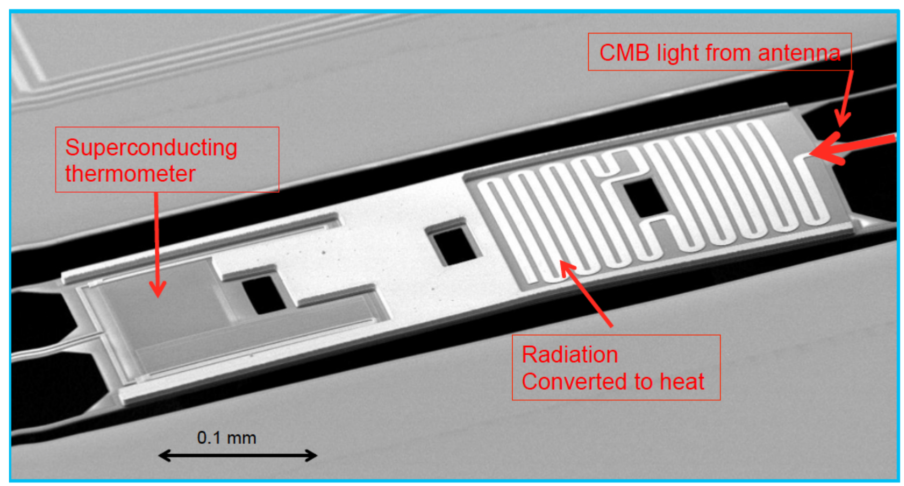
Scan the telescope back and forth on the sky.

Measure CMB T by summing the signal from orthogonally polarized detector pairs.

Measure CMB polarization by differencing the signal.







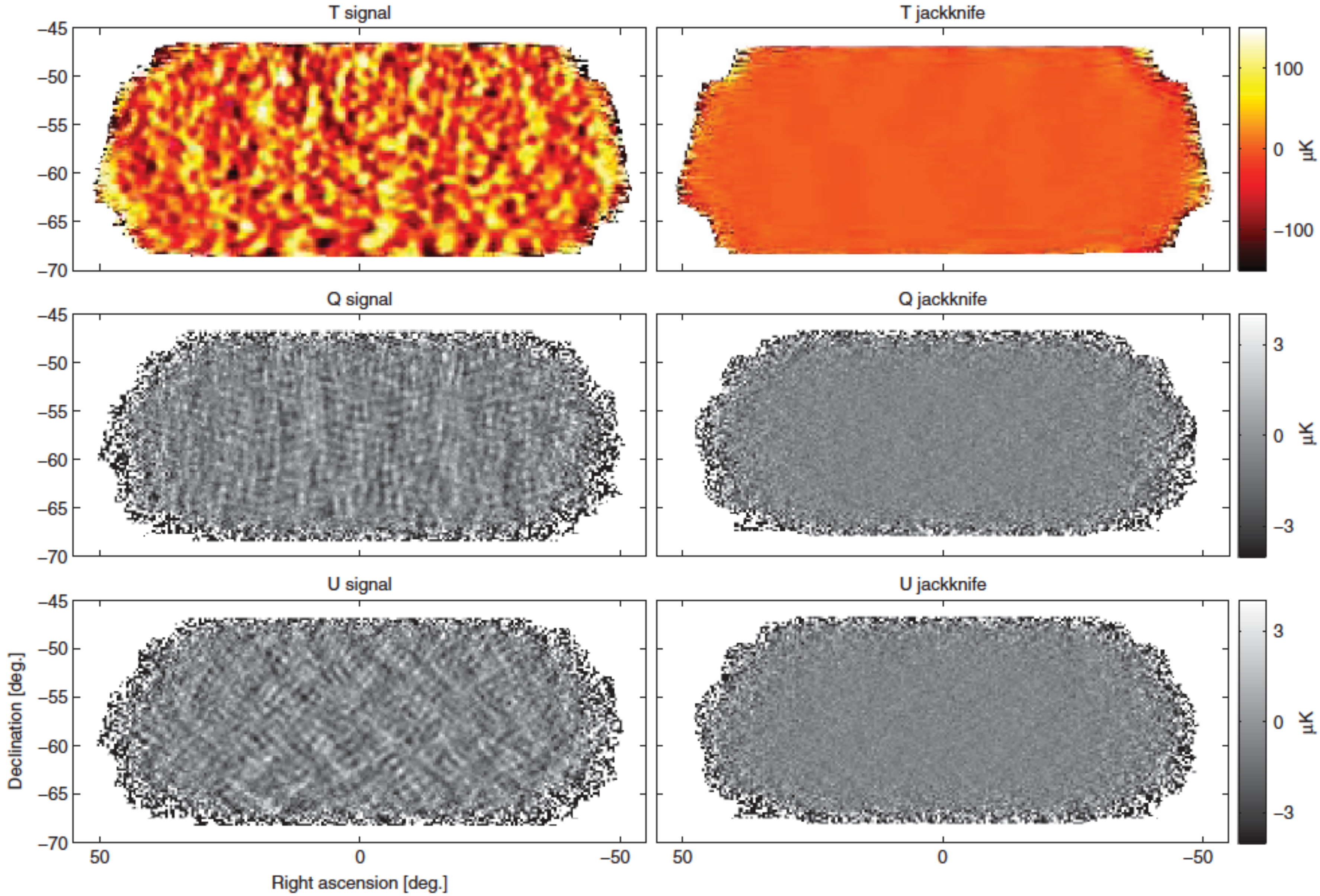


FIG. 1 (color). BICEP2 T, Q, U maps. The left column shows the basic signal maps with 0.25° pixelization as output by the reduction pipeline. The right column shows difference (jackknife) maps made with the first and second halves of the data set. No additional filtering other than that imposed by the instrument beam (FWHM 0.5°) has been done. Note that the structure seen in the Q and U signal maps is as expected for an E-mode dominated sky.

Ade *et al*, PRL 112:241101,2014

BICEP2 claims to have detected the B-mode signal from inflation!

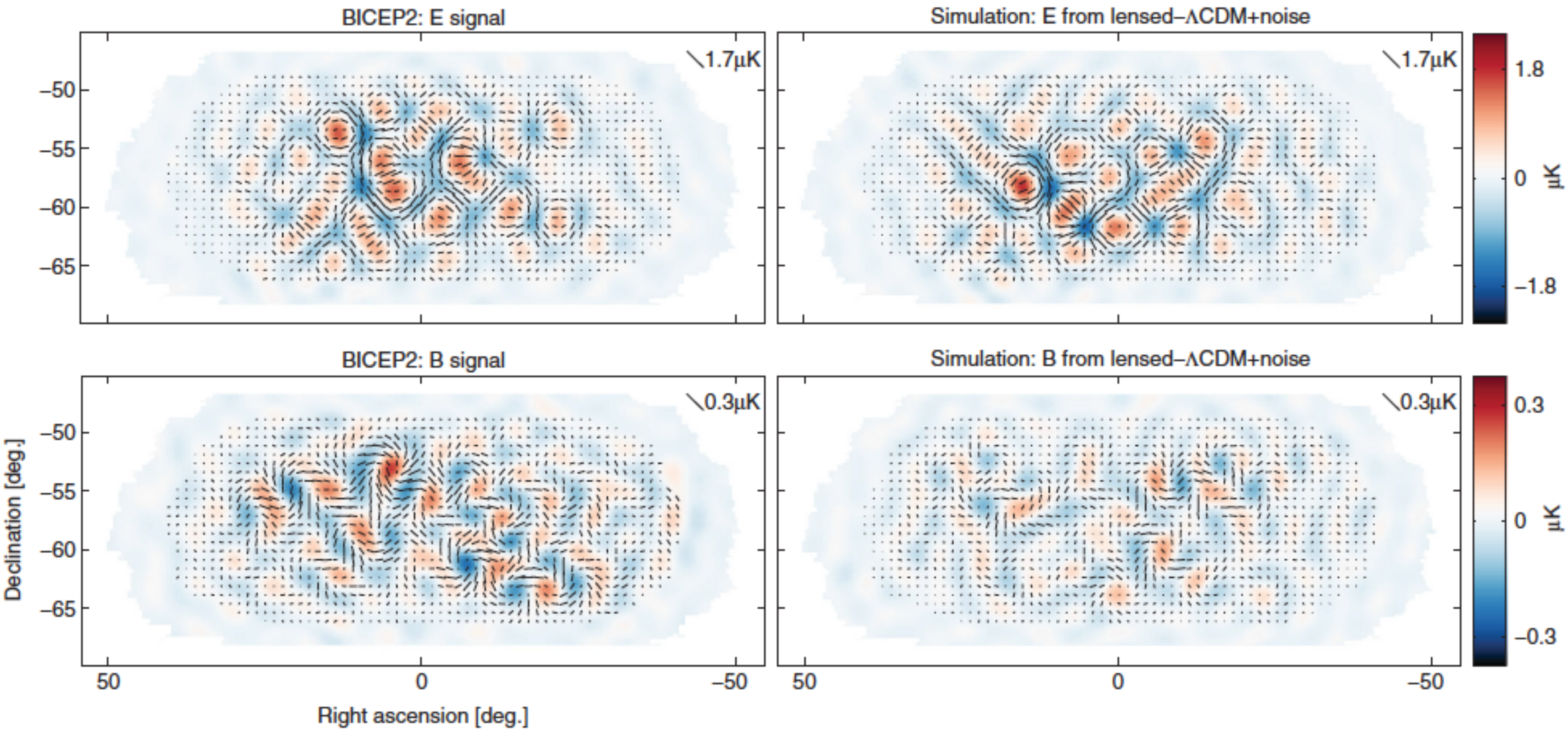
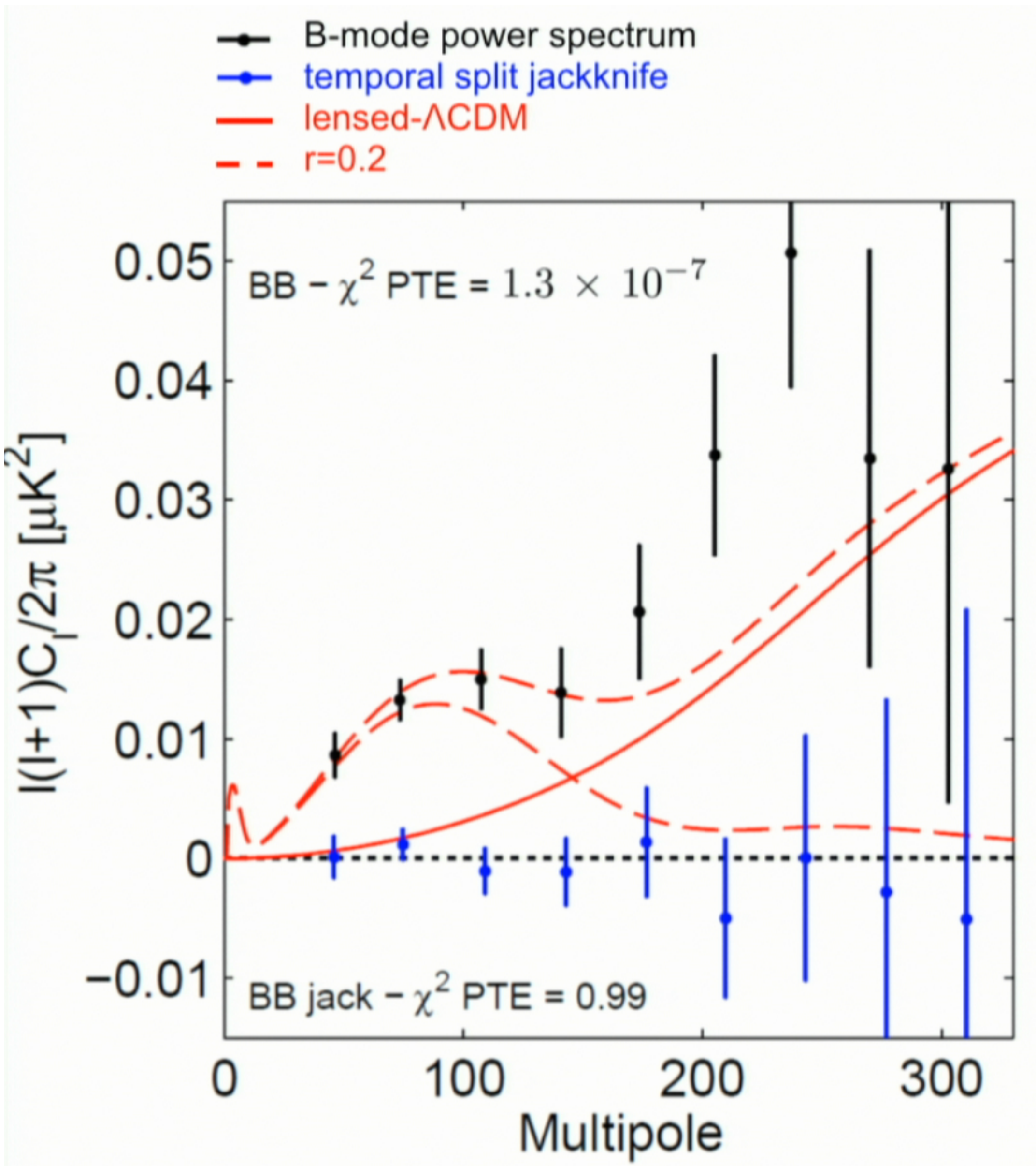


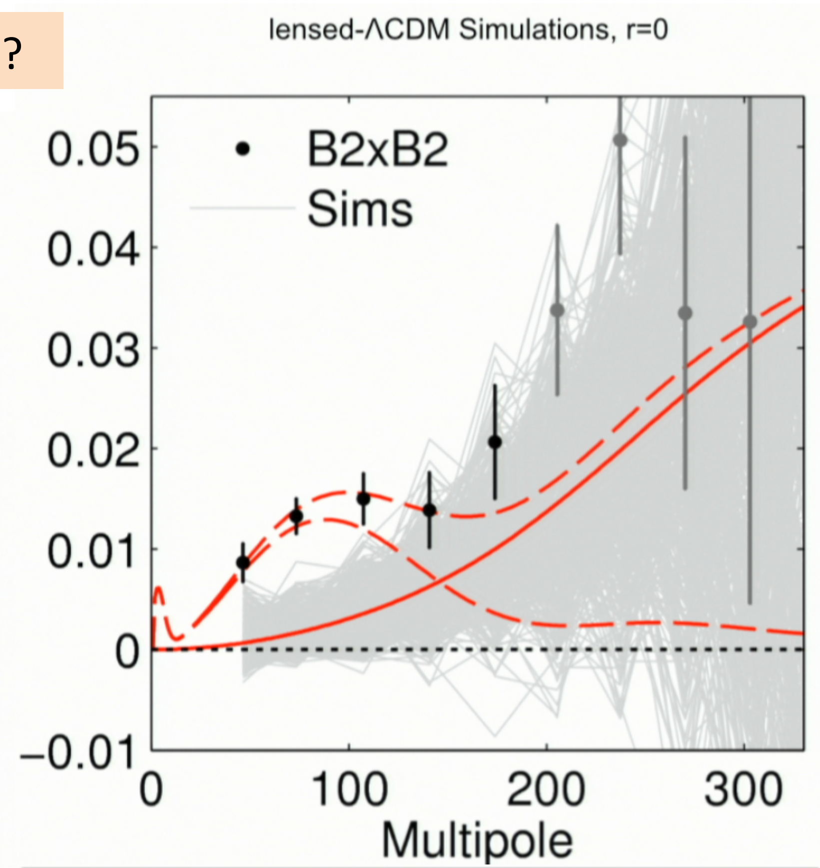
FIG. 3 (color). Left: BICEP2 apodized E-mode and B-mode maps filtered to $50 < \ell < 120$. Right: The equivalent maps for the first of the lensed-ΛCDM + noise simulations. The color scale displays the E-mode scalar and B-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess B mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at $\ell \approx 70$). (Also note that the E-mode and B-mode maps use different color and length scales.)

Ade *et al*, PRL 112:241101,2014

What is the significance of the B-mode detection?



Ade *et al*, PRL 112:241101,2014



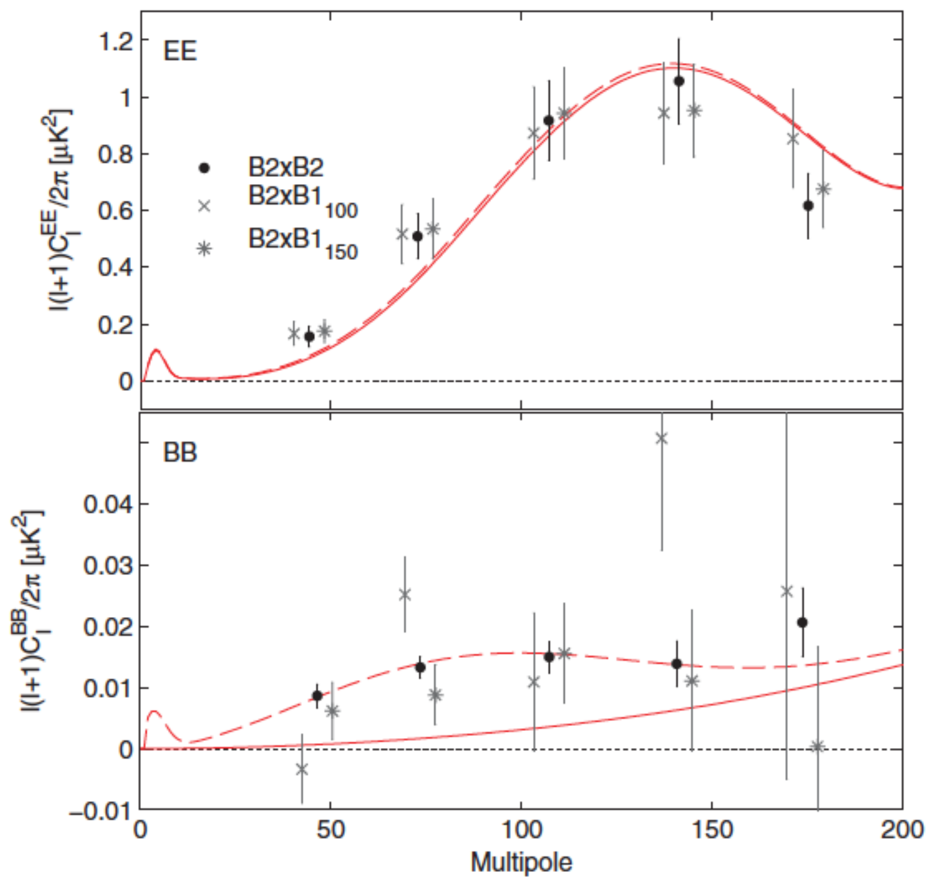
χ^2 PTE 1.3×10^{-7}

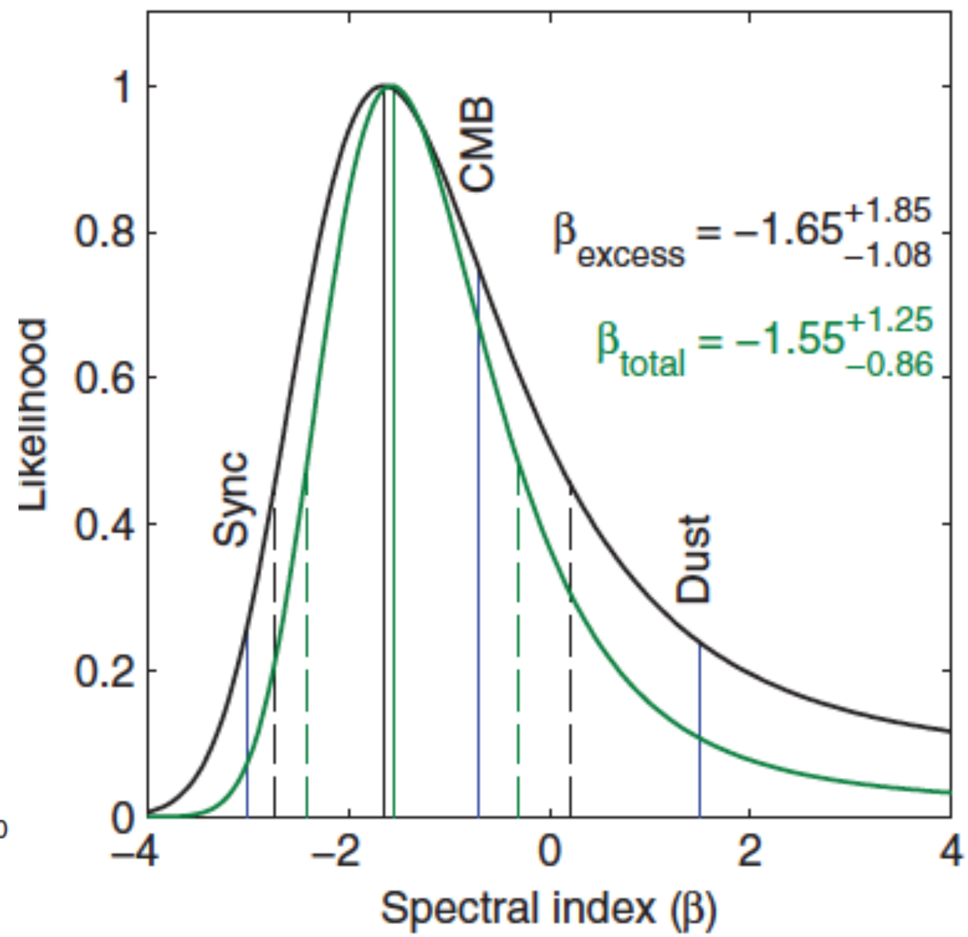
significance $5.2\,\sigma$

This is just the chance probability of the observed B-mode signal to arise as a fluctuation of the lensed E-mode signal …
it is *not* a ‘>5σ detection’ of a CMB signal

"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."

Ade *et al*, PRL 112:241101,2014

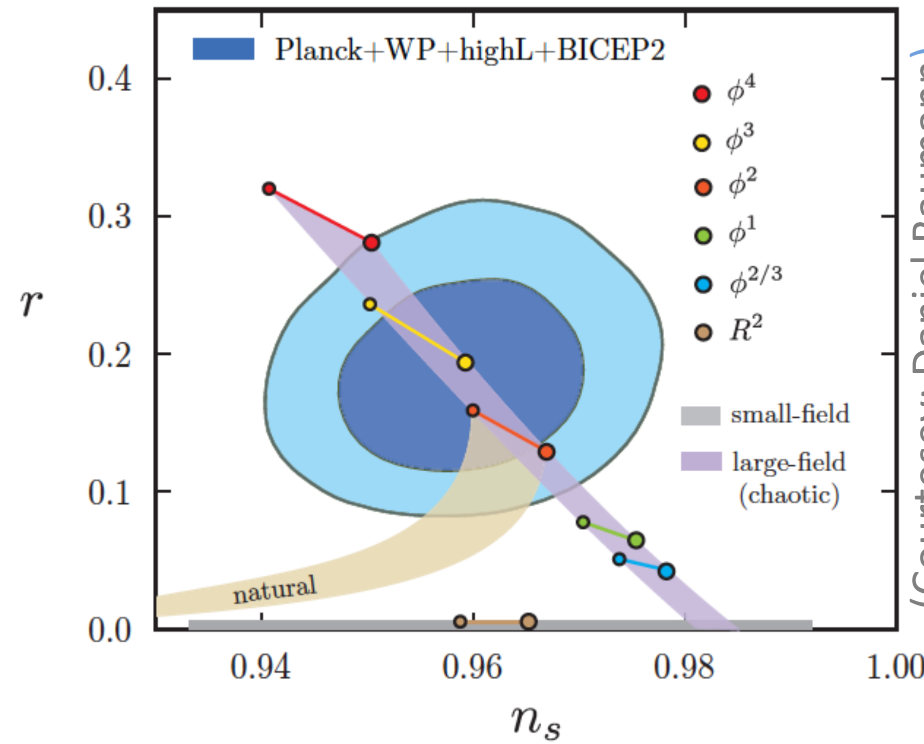




… so the significance with which the observed signal is likely to be **CMB** ($\beta \sim -0.7$) rather than either **synchrotron** ($\beta \sim -3$) or **dust** ($\beta \sim 1.5$) emission is in fact $1.6/1.7\sigma$

If this is all true *then* …

- The energy scale of inflation is: $V^{1/4} \approx 2.1\text{x}10^{16}$ GeV $(r/0.2)^{1/4} \sim M_{GUT}$
- The field excursion was super-Planckian: $\Delta\phi \approx 4\, M_{Pl}\, (r/0.2)^{1/2}$



(Courtesey: Daniel Baumann)

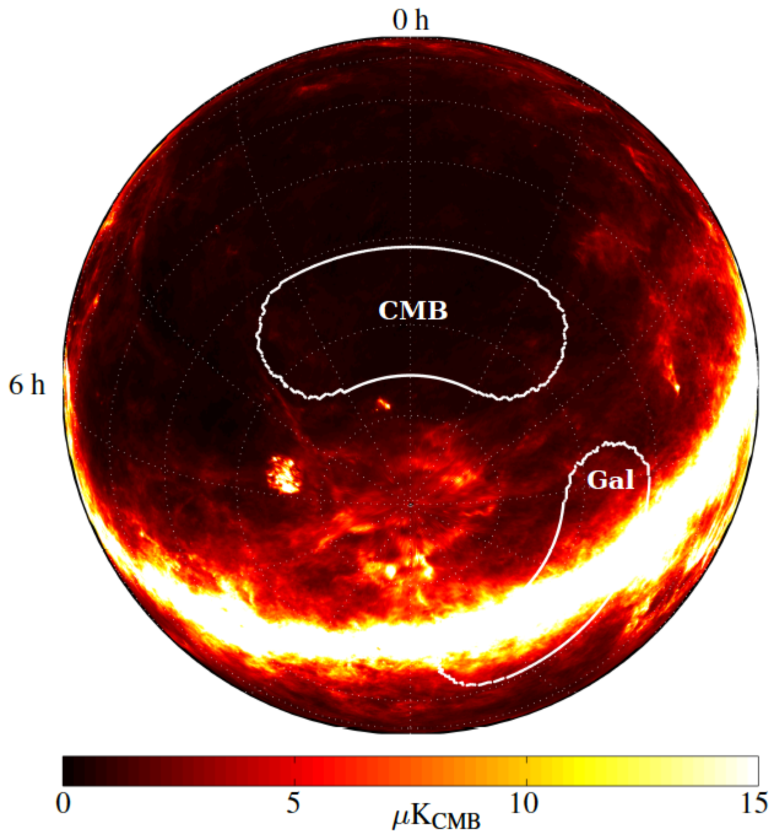
- **The vacuum energy was cancelled to 1 part in 10^{112} after inflation!**

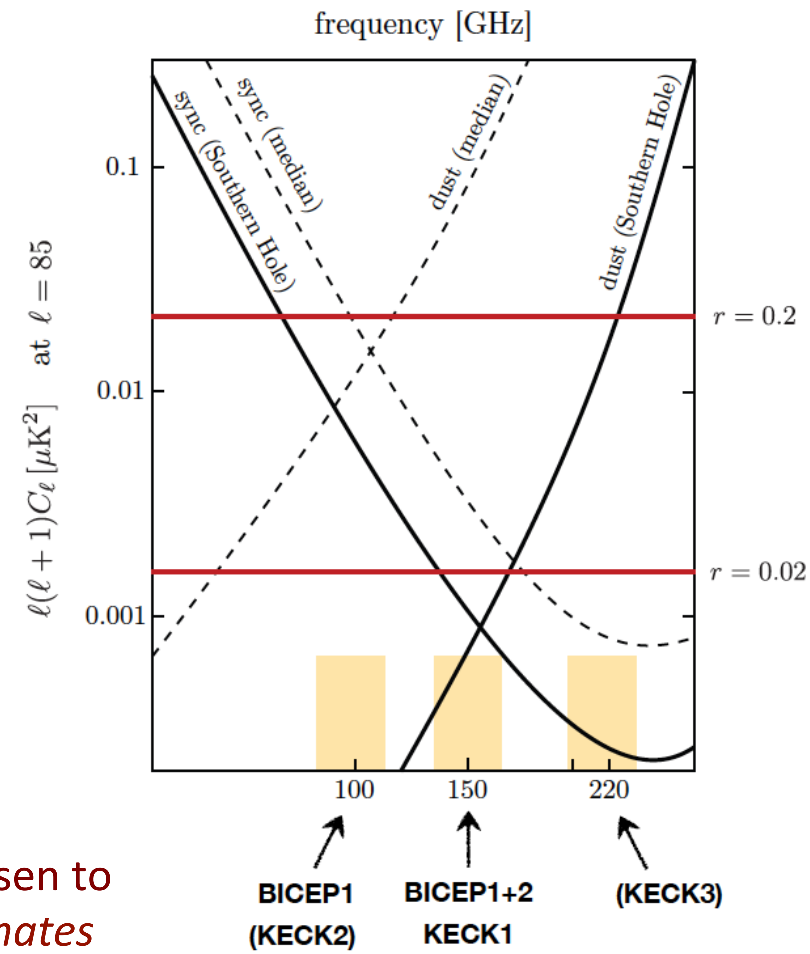
So we ought to be *very* cautious about interpreting the observational result given its momentous implications … e.g. could it just be some astrophysical foreground?

The important astrophysical foregrounds at CMB frequencies are:

- Synchrotron radiation from relativistic cosmic ray electrons gyrating in the Galactic magnetic field (polarised perpendicular to local field direction)

- Thermal emission from interstellar dust (also polarised perpendicular to magnetic field due to tendency of grains to align along the field)

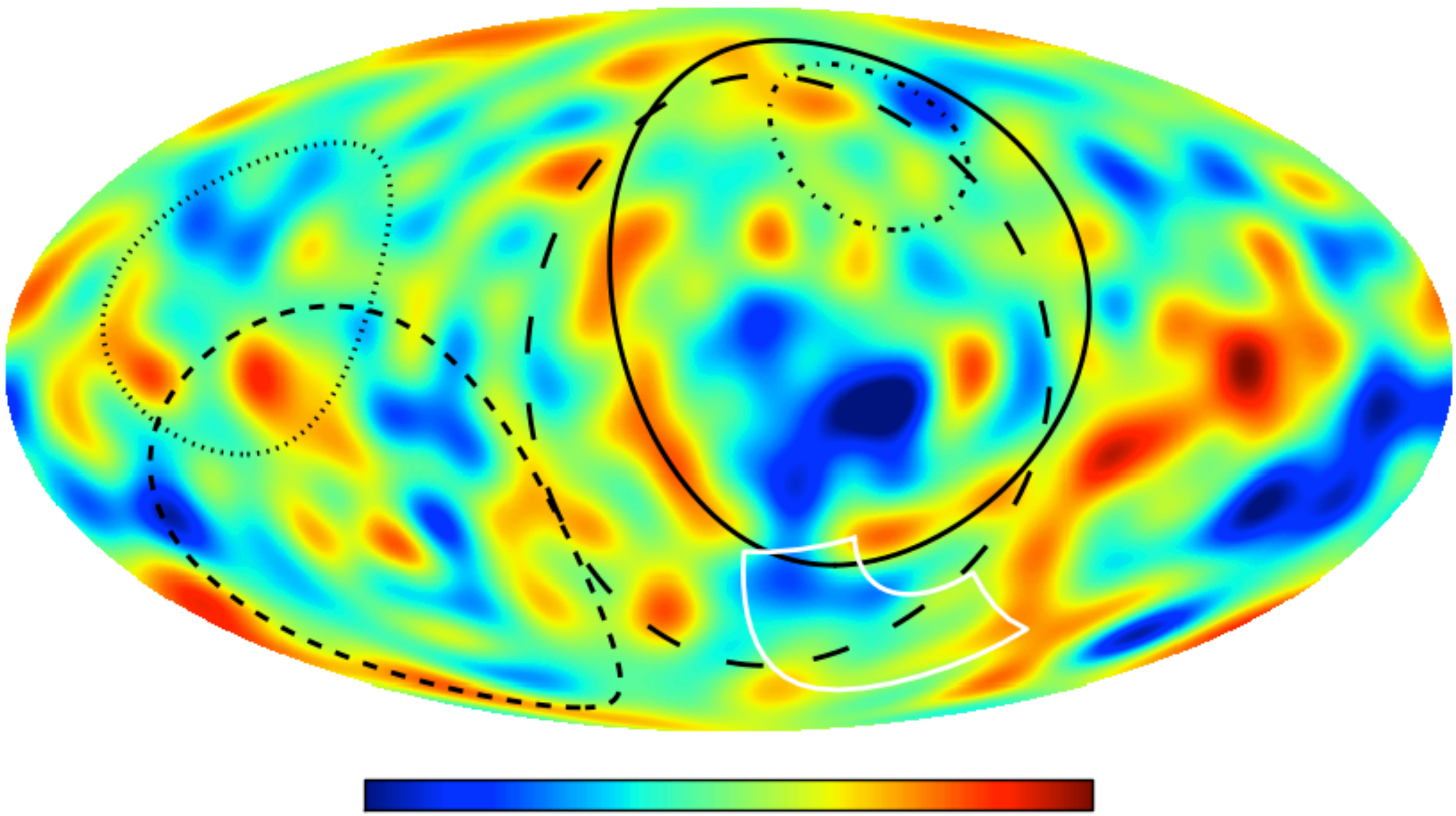




BICEP2 observes a small patch of high-latitude sky chosen to minimise these foregrounds … but the levels are *estimates*

This particular patch of sky was chosen to be observed because:

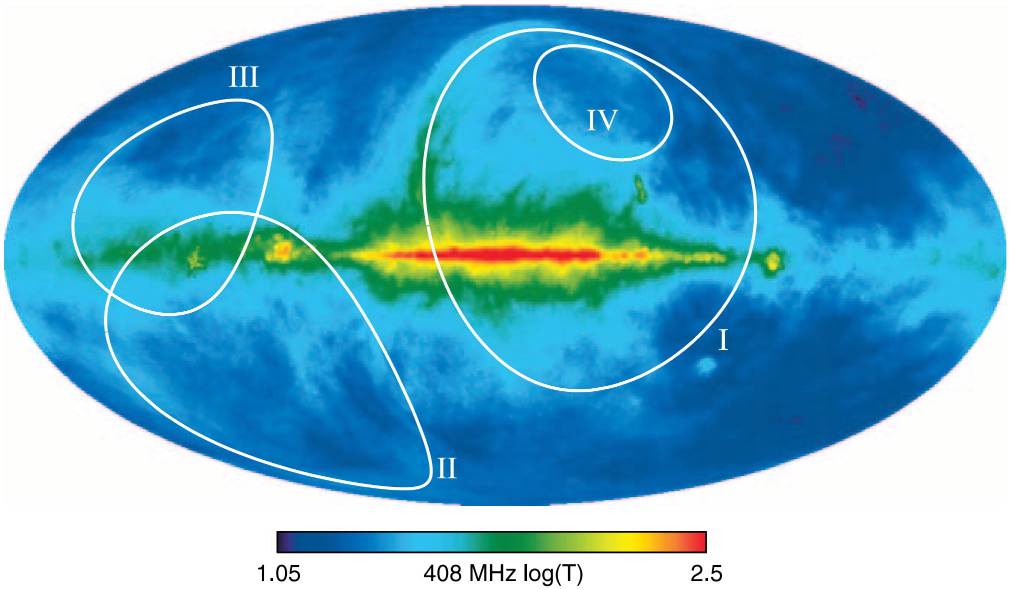
"… such ultra clean regions are very special – at least an order of magnitude cleaner than the average b >50^0 level" Ade *et al*, PRL 112:241101,2014



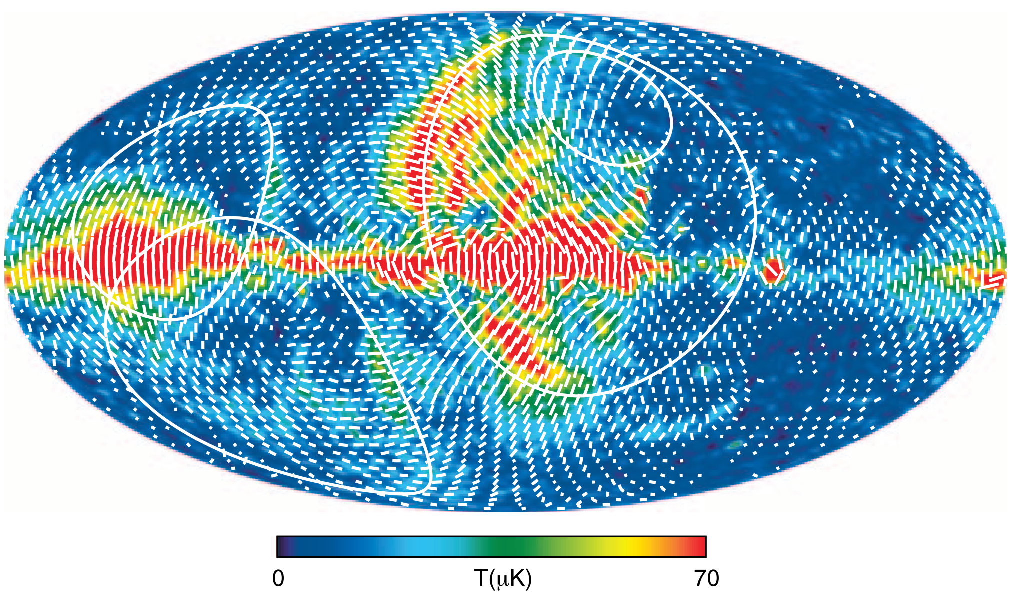
However it is crossed by a 'radio loop'!

What are the ‘radio loops’?

Haslam *et al*, A&AS **47**:1,1982



Page *et al*, ApJS **170**:335,2007



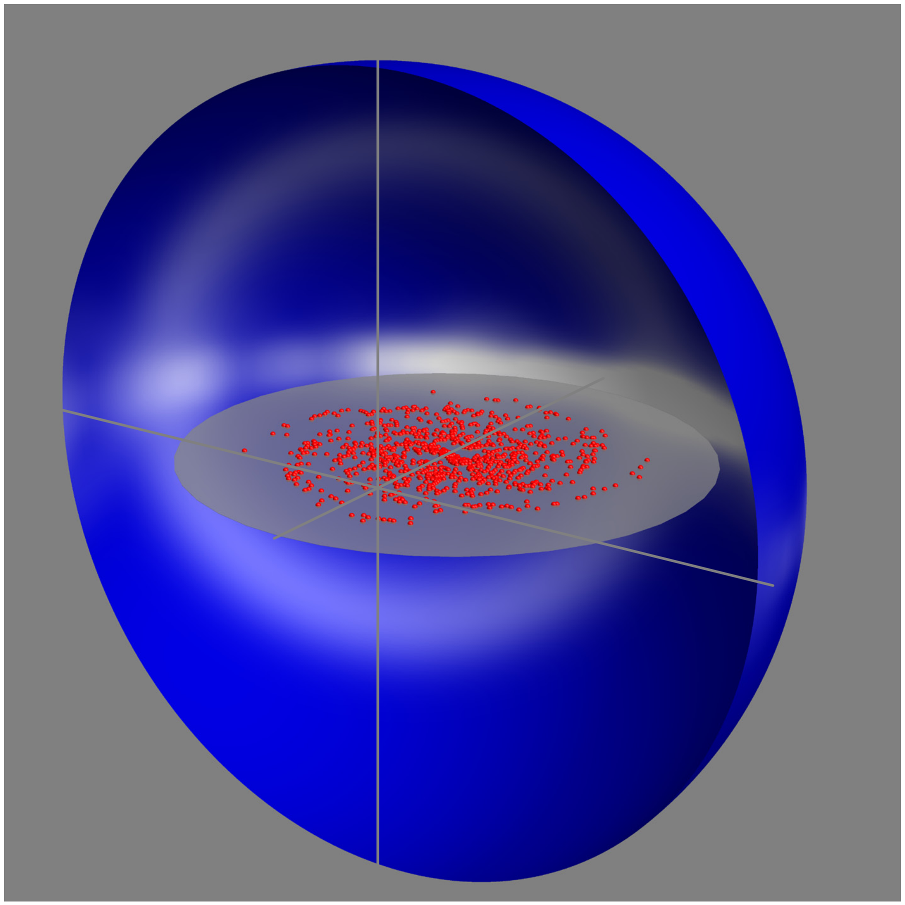
- These are probably shells of very old supernova remnants (*very* nearby)
- Can only see 4 of these in the 408 MHz radio sky

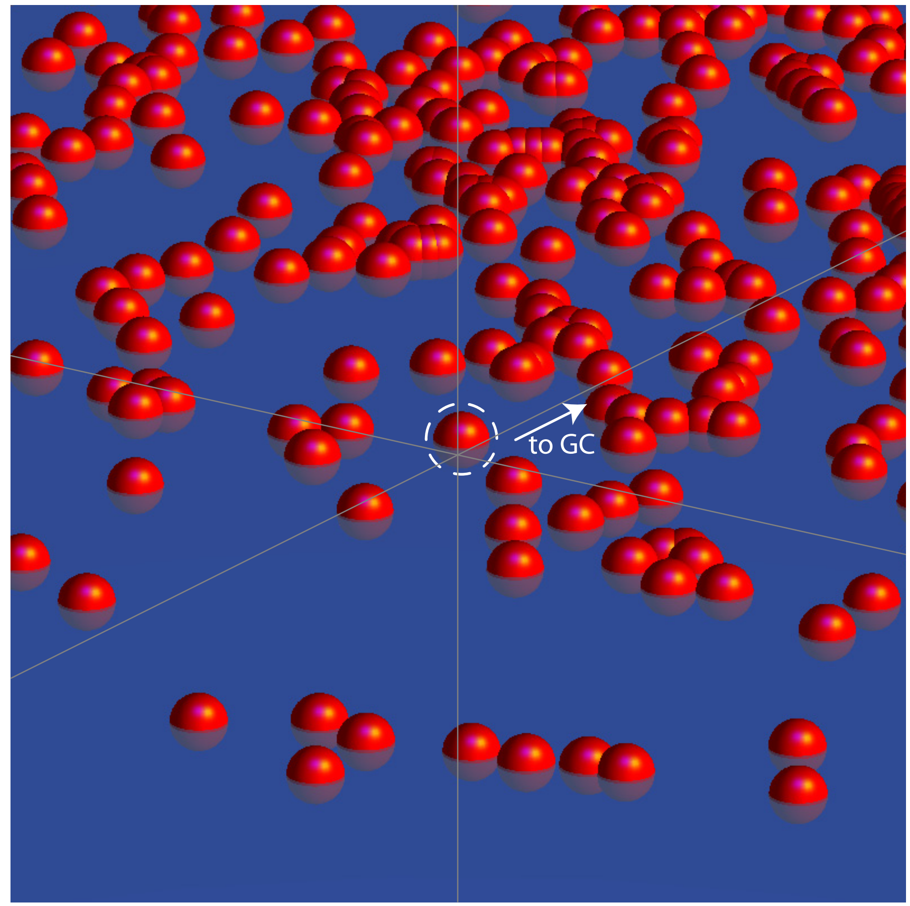
Berkhuijsen *et al*, A&A **14**:252,1971

- However there must be *several thousand* loops in the Galaxy which cannot be resolved against the ‘diffuse’ galactic radio background … indeed they probably make up most of the background

Sarkar, MNRAS **199**:97,1982

Simulating the galactic distribution of old SNRs





With ~3 SN/century, there must be *several thousand* old SNRs in the radiative phase of evolution … their shells will compress the interstellar magnetic field – and the *coupled* cosmic ray electrons – to high values, significantly boosting the synchrotron emissivity

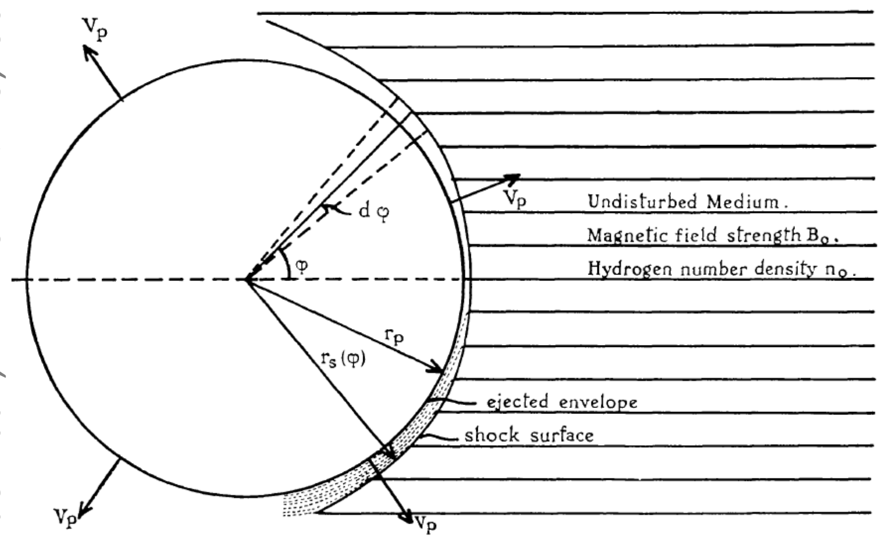
Boosted synchrotron emissivity in old SNRs

If the compression in the shell is by a factor η then a power-law CR electron spectrum $N_i(E_0)\,dE_0 = K_{0i}E_0^{-\gamma_i}\,dE_0$ will be modified to:

$$N_i(E')\,dE' = K_i\left[\frac{1}{2}+\frac{1}{2}\frac{\eta^2}{(\eta-1)(2\eta-1)^{1/2}}\sin^{-1}\left(\frac{\eta-1}{\eta}\right)^{1/2}\right]^{(\gamma_i-1)} E'^{-\gamma_i}\,dE'$$

with: $K_i/K_{0i} = \eta^3/\{3\eta(\eta-1)+1\}$ after pitch-angle scattering behind shock

Van der Laan, MNRAS **124**:125,1962



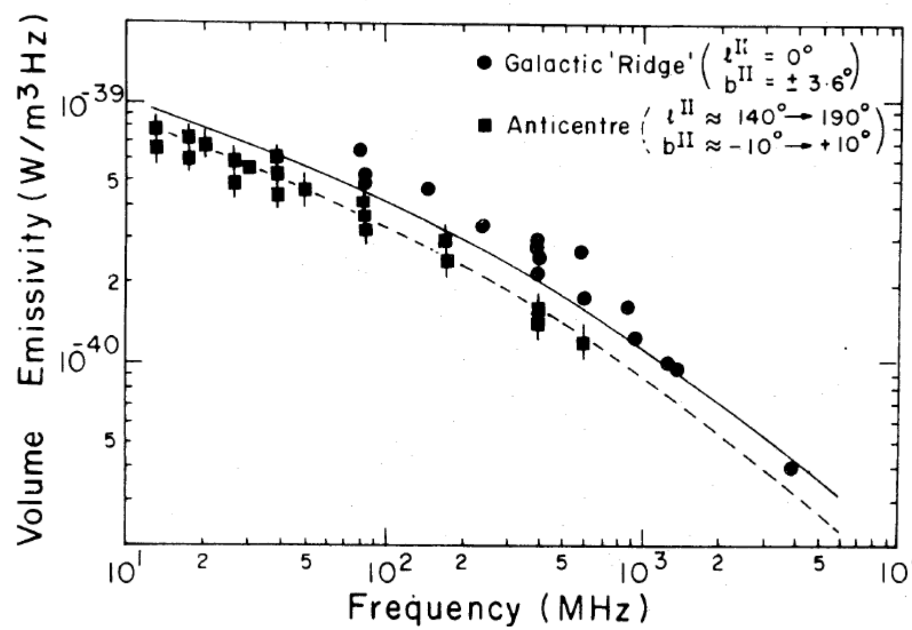


Figure 1. The average interstellar synchrotron emissivity due to old radiative supernova remnants, for a magnetic field of $1\,\mu$G in the hot interstellar medium ($n_0 = 10^{-2}$ cm^{-3}). The dashed and solid lines refer to the cases with and without pitch-angle scattering behind the shocks, respectively. Observational data are from the compilation by Daniel & Stephens (1975).

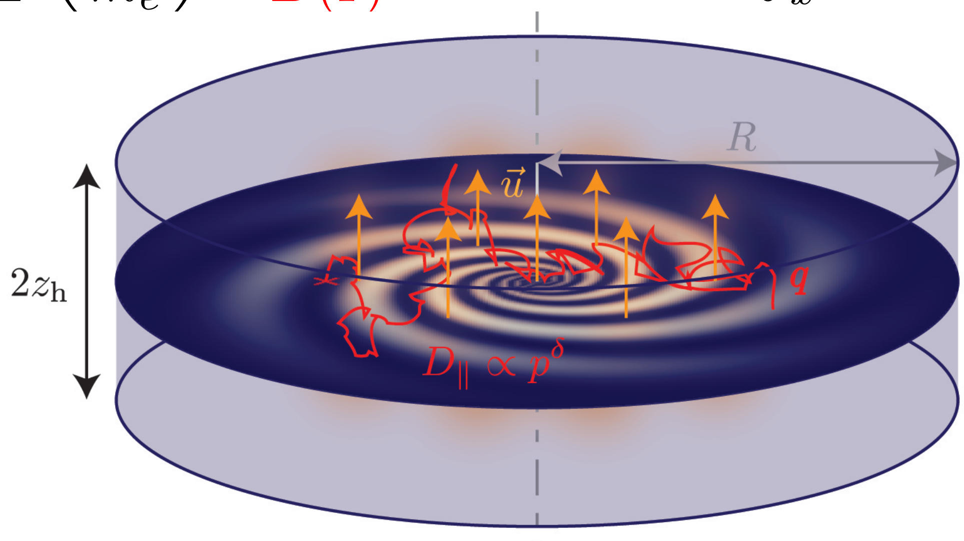
Sarkar, MNRAS **199**:97, 1982

The galactic radio background

Synchrotron radiation by **relativistic cosmic ray electrons** spiralling in the **galactic magnetic field** (regular spiral + turbulent component):

$$P(\mathbf{r};\nu) = \int \mathrm{d}E\, n_e(\mathbf{r};E)\, \frac{\sqrt{3}e^3 B_\perp(\mathbf{r})}{8\pi^2 \varepsilon_0 c\, m_e} F\left(\frac{\nu}{\nu_c}\right)$$

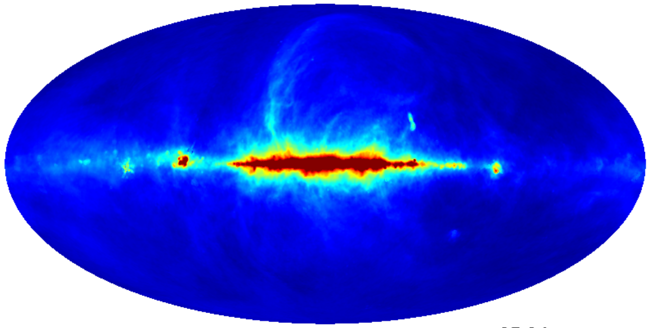
where $\nu_c = \frac{3}{2}\left(\frac{E}{m_e}\right)^2 \frac{B_\perp(\mathbf{r})}{B(\mathbf{r})}$, $F(x) = x\int_x^\infty \mathrm{d}x' K_{5/3}(x')$



Can model using GALPROP code which solves for the diffusion of cosmic rays in the Galaxy (assumed to be a cylindrical slab + extended 'halo')

Angular power spectrum

1. Radio sky:



$$\equiv J(\theta, \phi)$$

2. Spherical harmonics:

$$J(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-l}^{l} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

3. Angular power spectrum:

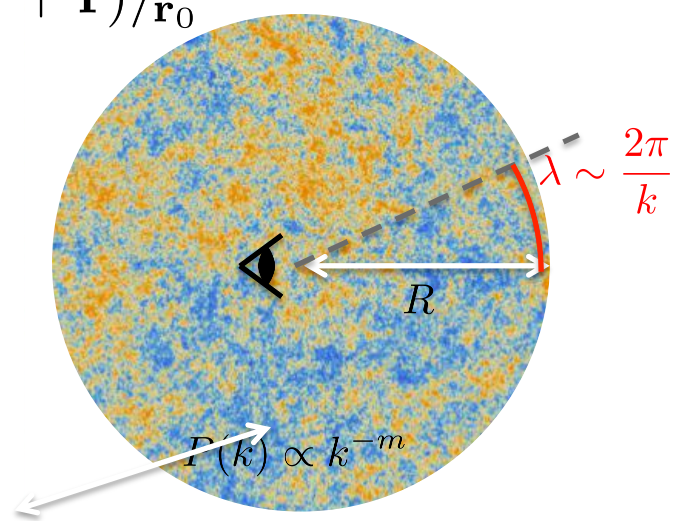
$$C(\ell) \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

Advantages: Information ordered by spatial scale

- Statistically meaningful quantities
- Natural for some applications, e.g. CMB foreground subtraction

Turbulence cascade

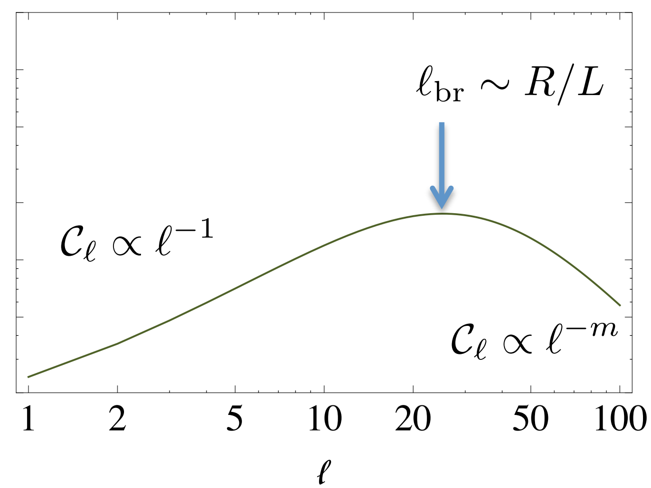
- Plasma perturbations described by MHD modes, e.g. Alfvén waves
- Two-point correlation function: $\langle \mathbf{B}(\mathbf{r}_0)\mathbf{B}(\mathbf{r}_0+\mathbf{r})\rangle_{\mathbf{r}_0}$



- Fourier transform → power spectrum:

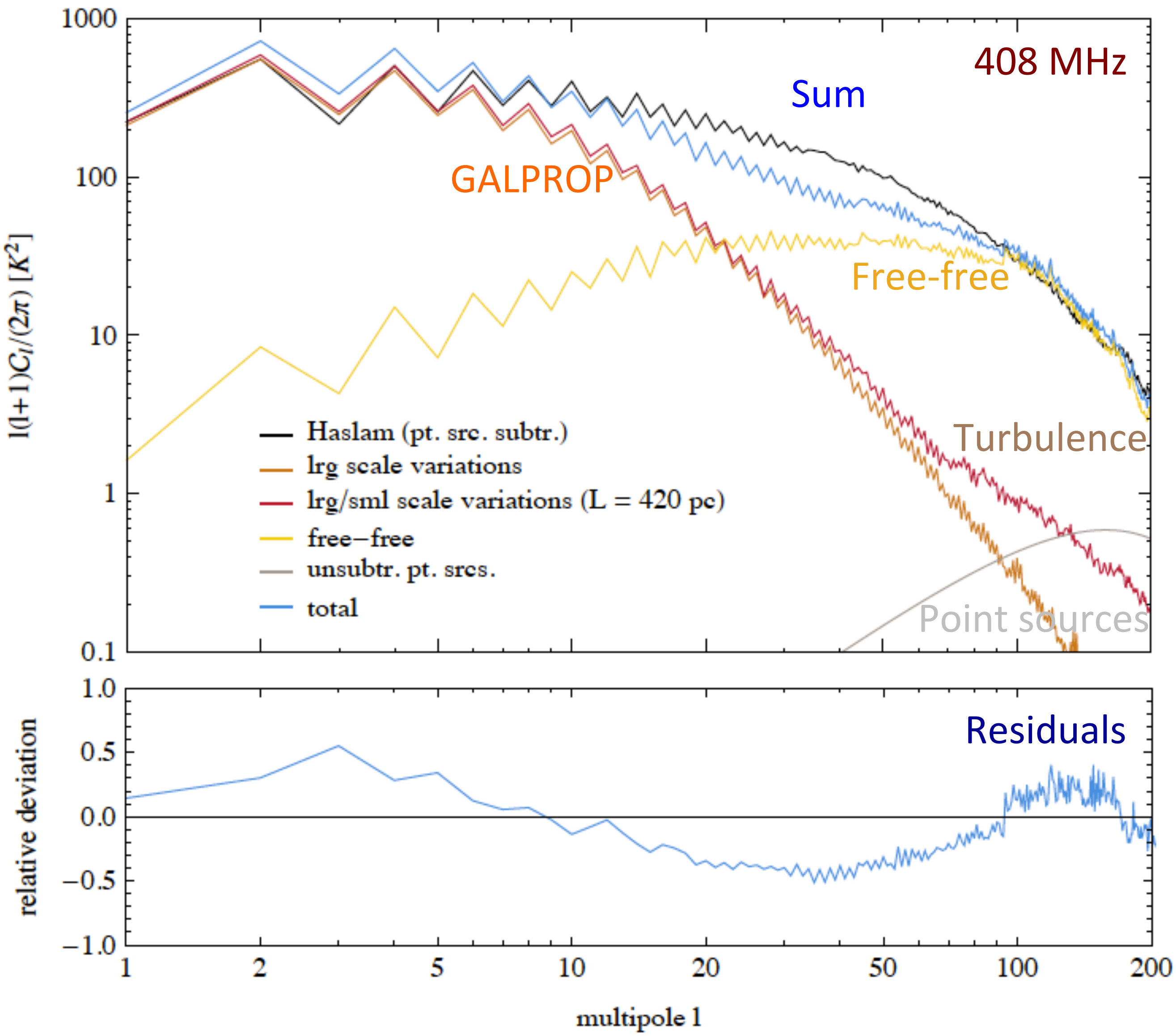
$$P(k) = \int \mathrm{d}\mathbf{r}\, \mathrm{e}^{i\mathbf{k}\cdot\mathbf{r}} \langle \mathbf{B}(\mathbf{r}_0)\mathbf{B}(\mathbf{r}_0+\mathbf{r})\rangle_{\mathbf{r}_0}$$

- Observed in space plasmas with $P(k) \propto k^{-m}$ (Kolmogorov: $m = 11/3$)
- Consider two-point correlations on sphere
- Power-law in wavenumber reflected by power-law in angle θ (or multipole ℓ)



Chepurnov, Astron.Astrophys.Trans. **17**:281,1999

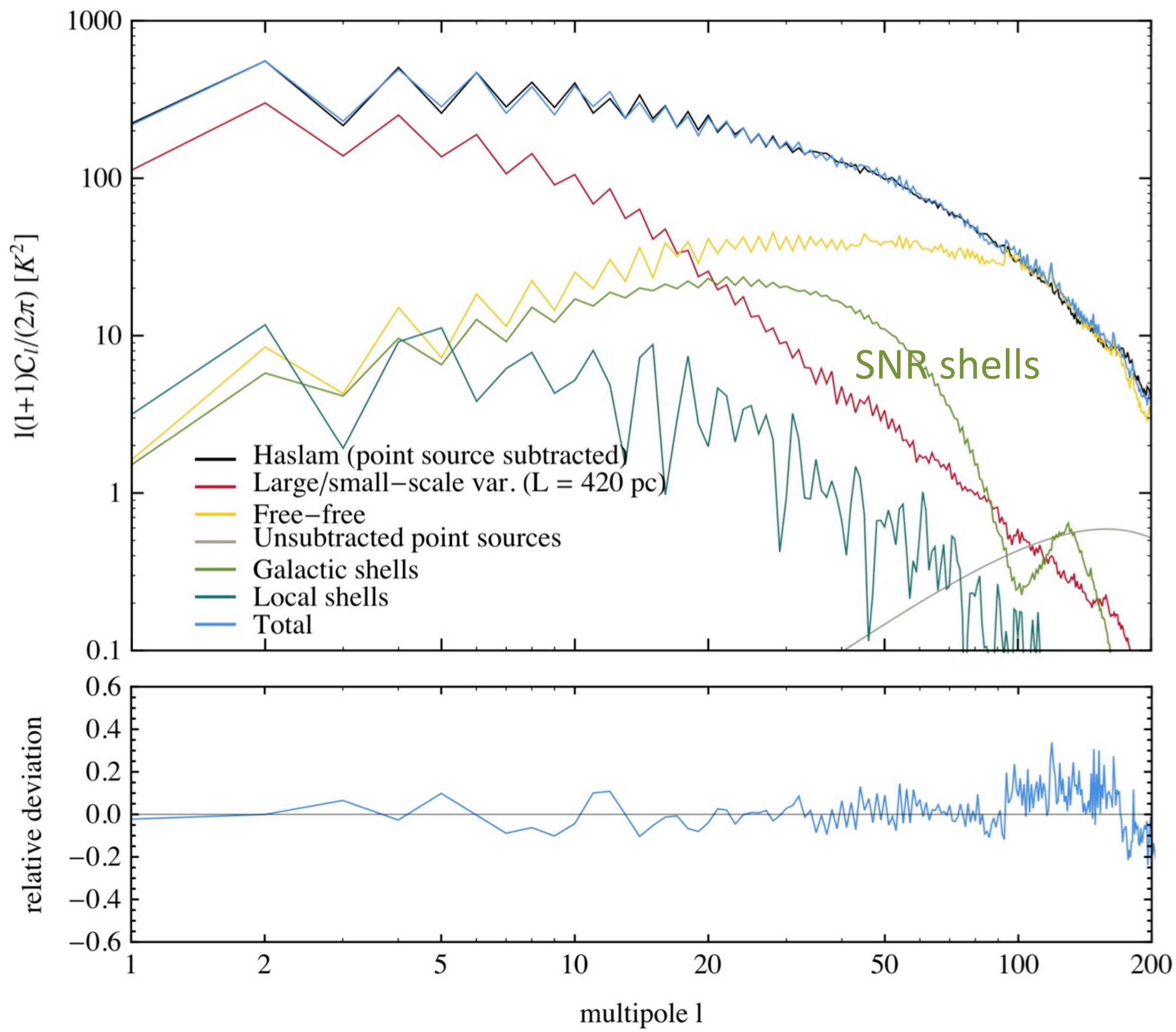
The uniform galaxy model does *not* match the angular power spectrum of the observed radio background

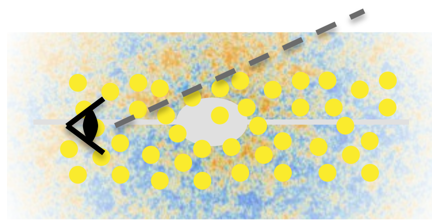


Mertsch & Sarkar, JCAP **06**:041,2013

… but adding a population of old SNRs does!

Mertsch & Sarkar, JCAP **06**:041,2013



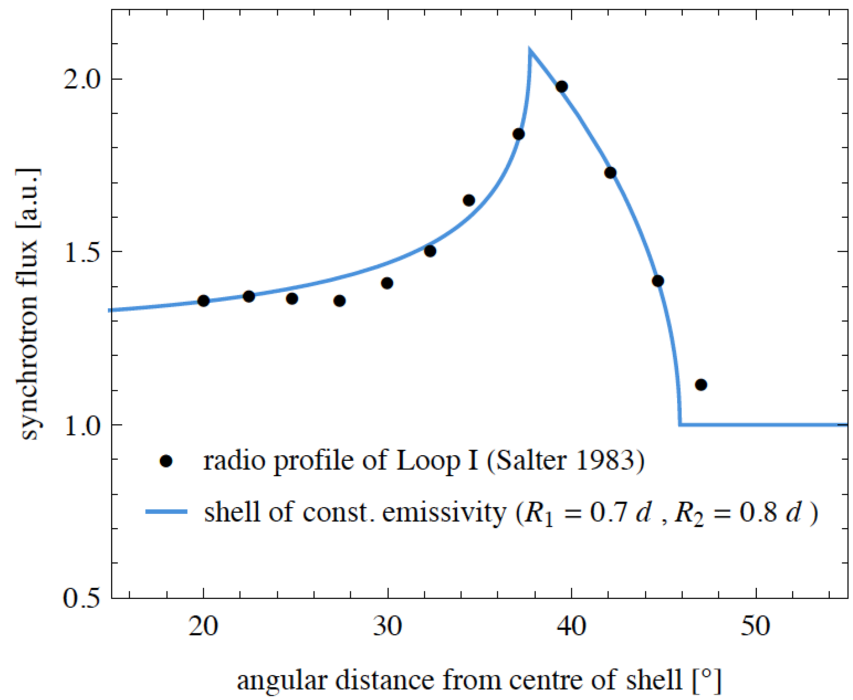


- Several thousand shells of old SNRs in Galaxy
- We know 4 local shells (Loop I-IV) but others are modeled in MC approach
- They contribute in *just* the required multipole range

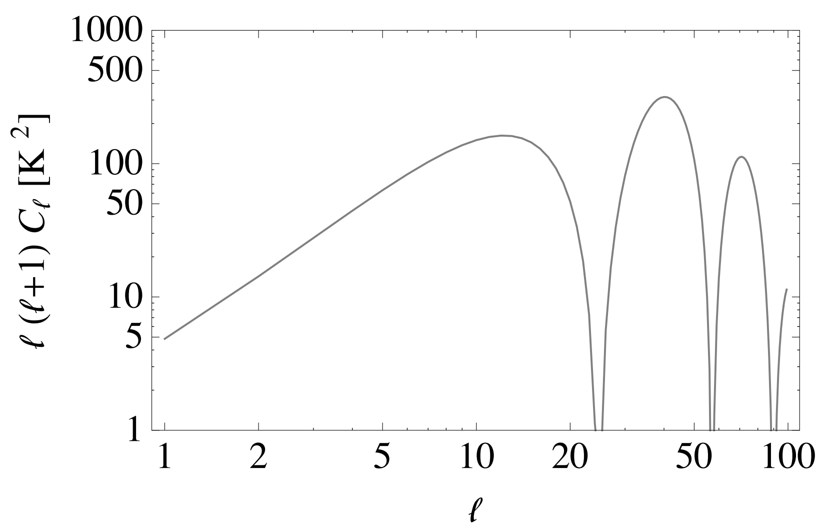
Angular Power Spectrum of a SNR shell

… after projection along line-of-sight, the shell of homogeneous emissivity has angular profile $g(r)$

$$C_l^j = \frac{1}{2l+1} \sum_{m=-l}^{l} \left| a_{lm}^j \right|^2$$
$$= \frac{1}{4\pi} \left(f_j(\nu) \int_{-1}^{1} \mathrm{d}z' P_l(z') g_j(z') \right)$$



Mertsch & Sarkar, JCAP **06**:041,2013



Angular power spectrum for shell i:

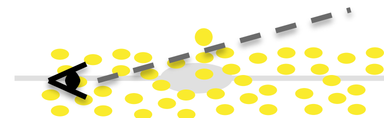
$$C_i(\ell) \propto \left(\mathrm{P}_l \left(\cos \frac{R_i}{d_i} \right) \right)^2$$

… thickness of shell determines cut-off

Modelling an ensemble of shells

Mertsch & Sarkar, JCAP **06**:041,2013

Assumption: flux from one shell factorises into angular part and frequency part: $J_{\text{shell } i}(\nu, \ell, b) = \varepsilon_i(\nu) g_i(\ell, b)$



Frequency part: $\varepsilon_i(\nu)$

Magnetic field gets compressed in SNR shell

Electrons get betatron accelerated

Emissivity increased with respect to ISM

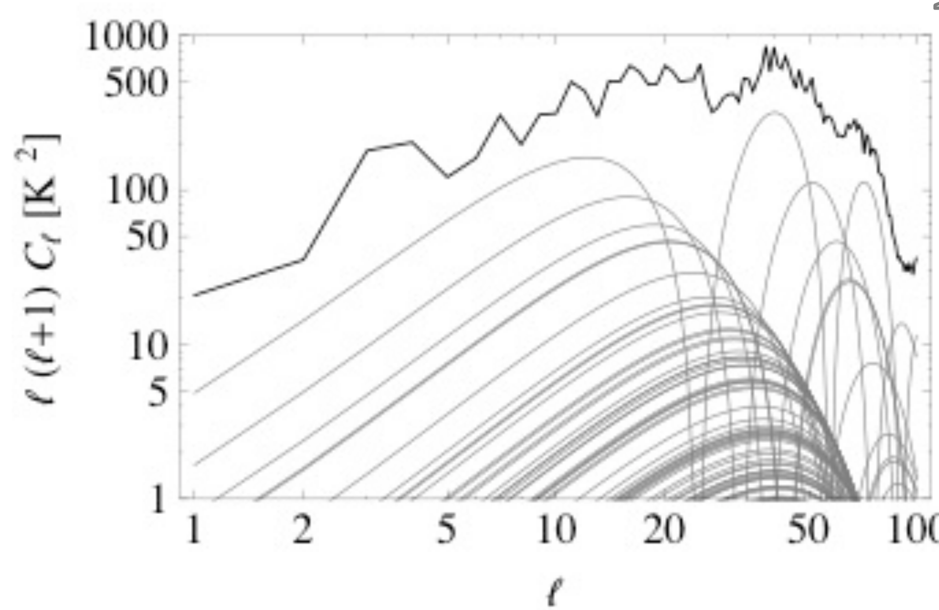
Angular part: $g_i(\cos\psi)$

Assume constant emissivity in shell:

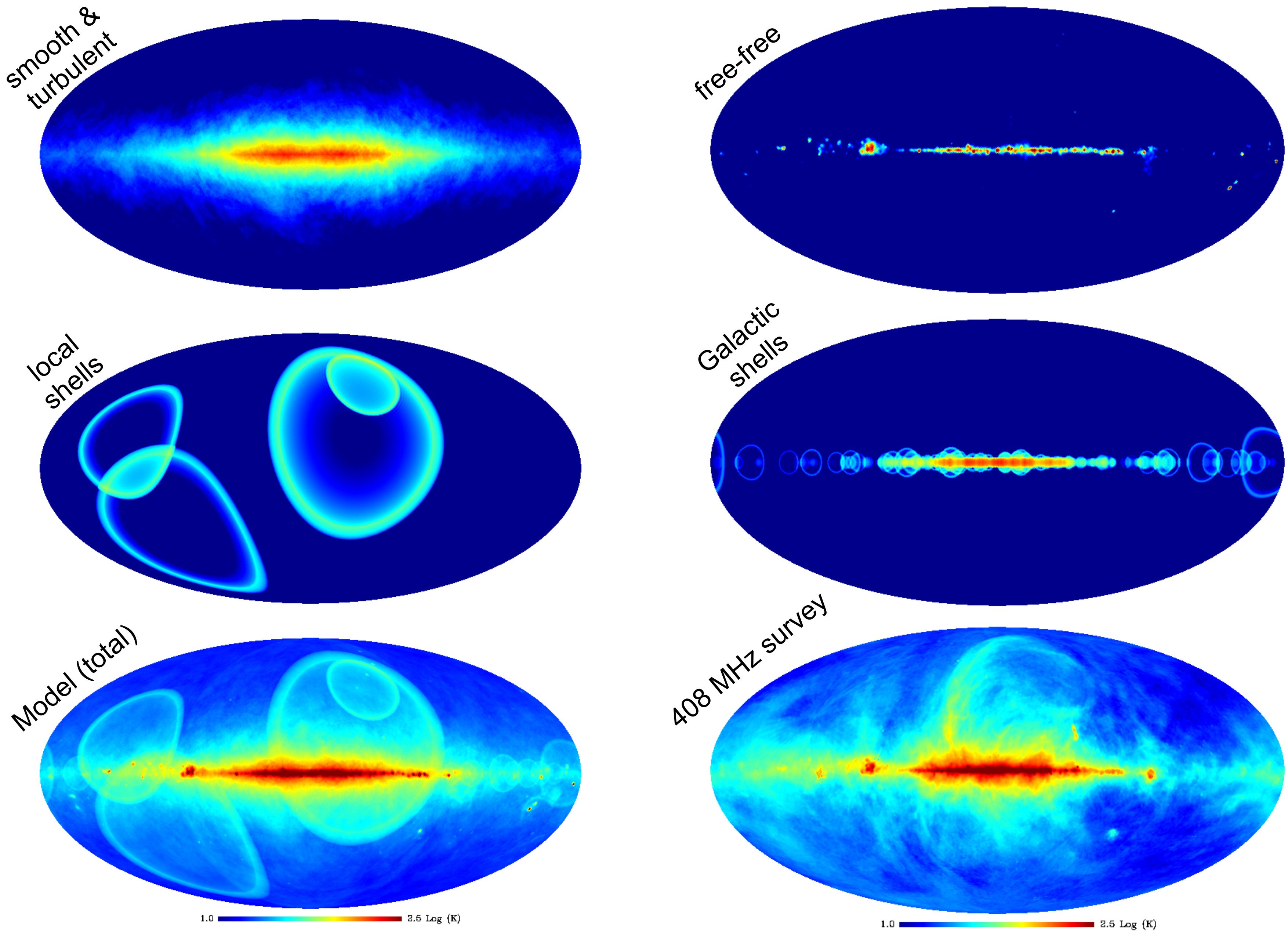
$$a^{i}_{lm}{}' \sim \varepsilon_i(\nu) \int_{-1}^{1} \mathrm{d}z' P_l(z') g_i(z')$$

Add up contribution from all shells:

$$a^{\text{total}}_{lm} = \sum_i a^i_{lm}$$



Our model for the Galactic radio background



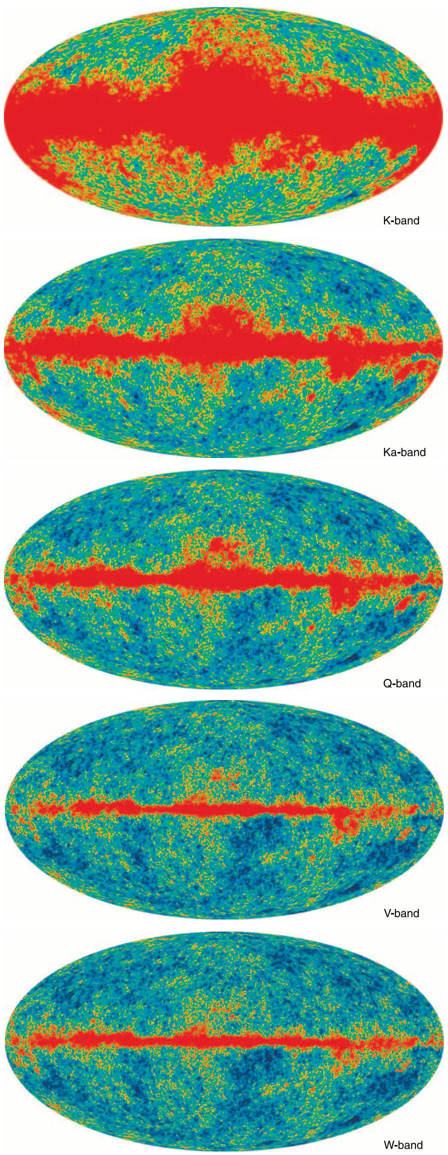
Mertsch & Sarkar, JCAP 06:041,2013

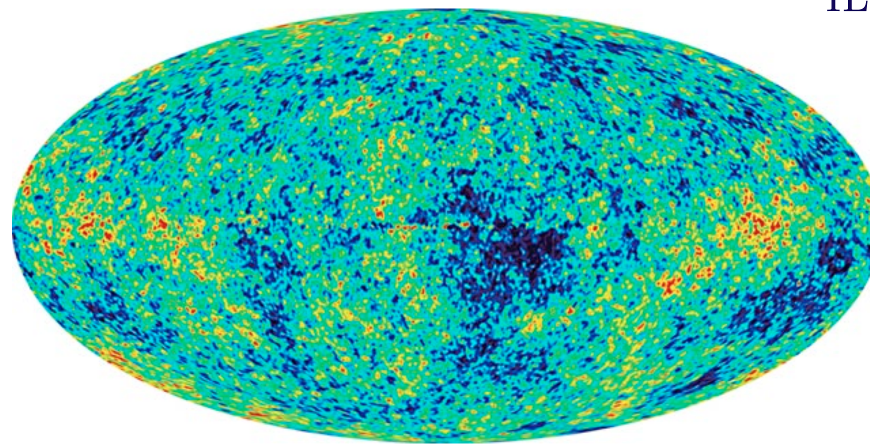
CMB foreground removal: Internal Linear Combination (ILC)

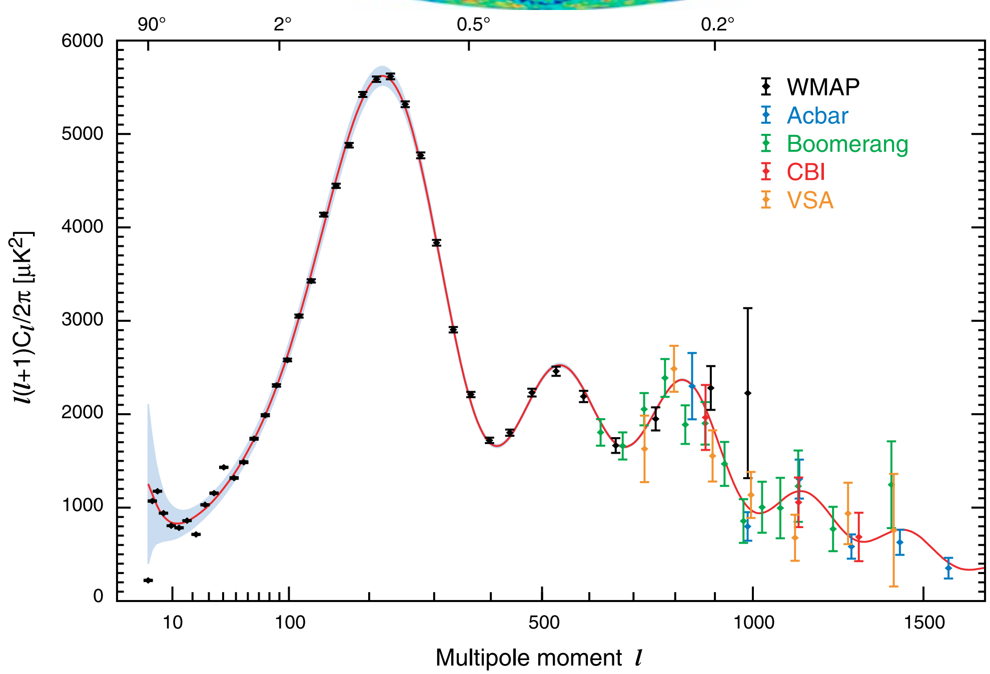
$$T_{\rm ILC} = \sum_i \zeta_i T_i = \sum_i \left(T_{\rm CMB} + S_i T_{\rm foreground}\right)$$

... and minimise the variance $\sigma^2_{\rm ILC}$

Hinshaw *et al*, ApJS 170:288,2007



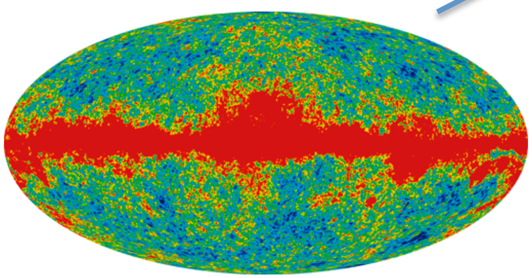




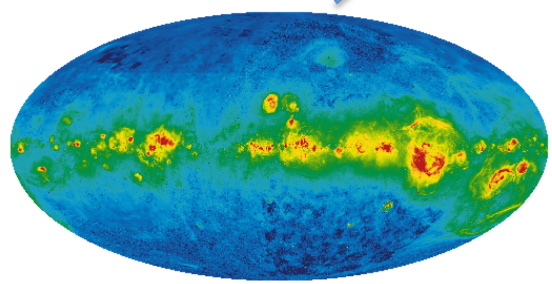
CMB foreground removal: Template subtraction

χ^2 fit to data with foreground model:

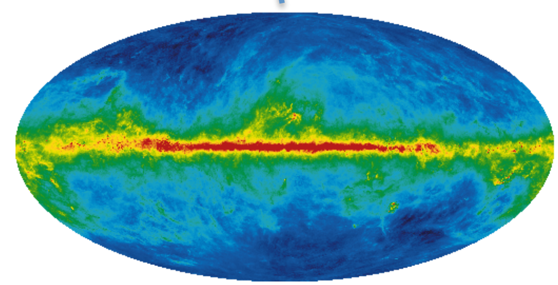
$$M(\nu, p) = b_1(\nu)(T_{\rm K} - T_{\rm Ka}) + b_2(\nu)I_{\rm H\alpha} + b_3(\nu)M_d$$



(K-Ka) difference map:
some combination of
synchrotron + free-free



$\rm H\alpha$ map:
tracer of free-free



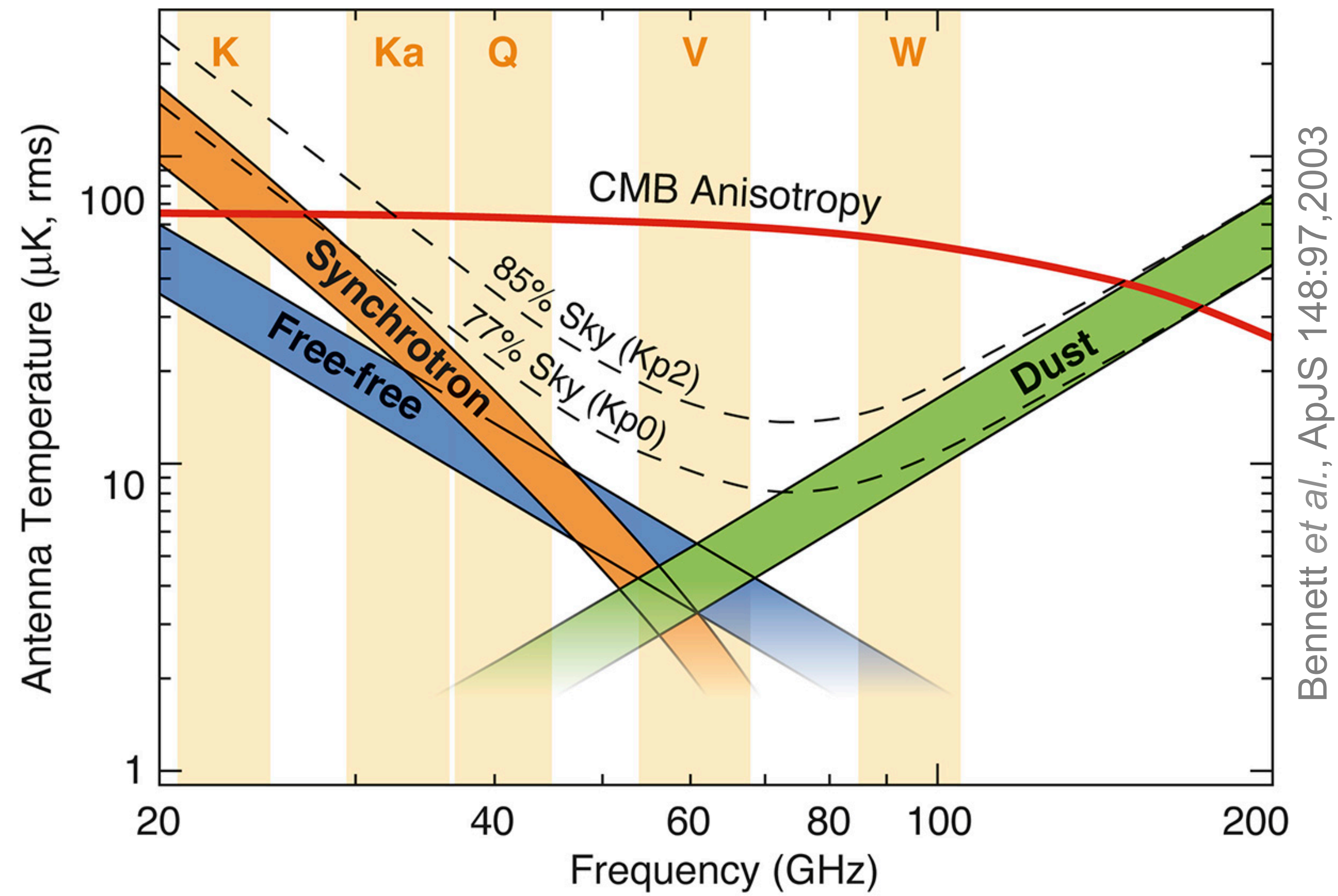
IR map (extrapolated to 94 GHz):
tracer of dust

Hinshaw *et al*, ApJS 170:288,2007

Advantage: Extract spectral information about foregrounds

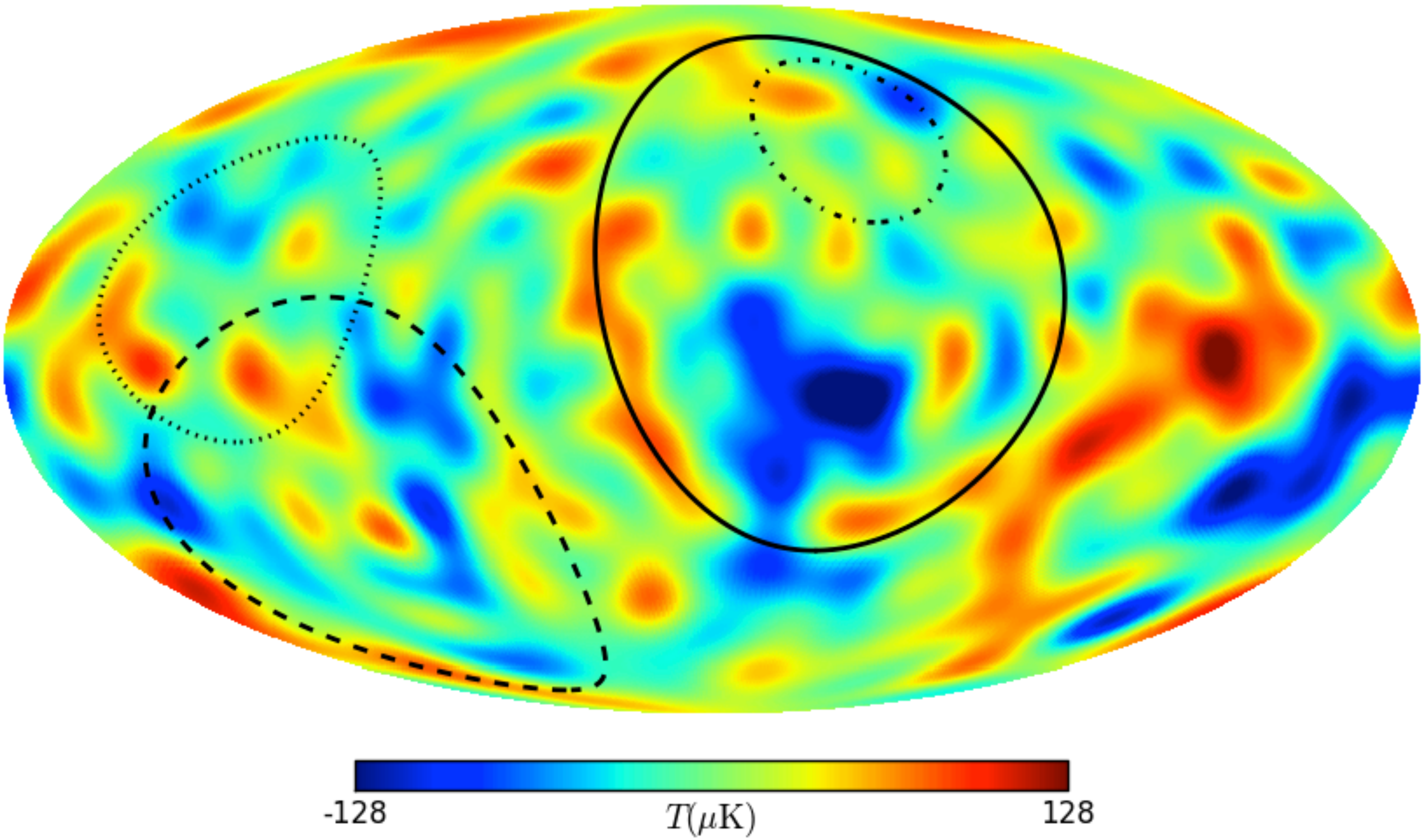
Issue: Direction-dependent spectral indices and/or morphological changes with frequency

Why this is supposed to work …



But this technique might fail *locally* in regions where there is *both* synchrotron and dust emission … e.g. in old supernova remnant shells (nearby – so at high latitude)

Anomalies in WMAP-9 Internal Linear Combination map ($\ell \leq 20$)

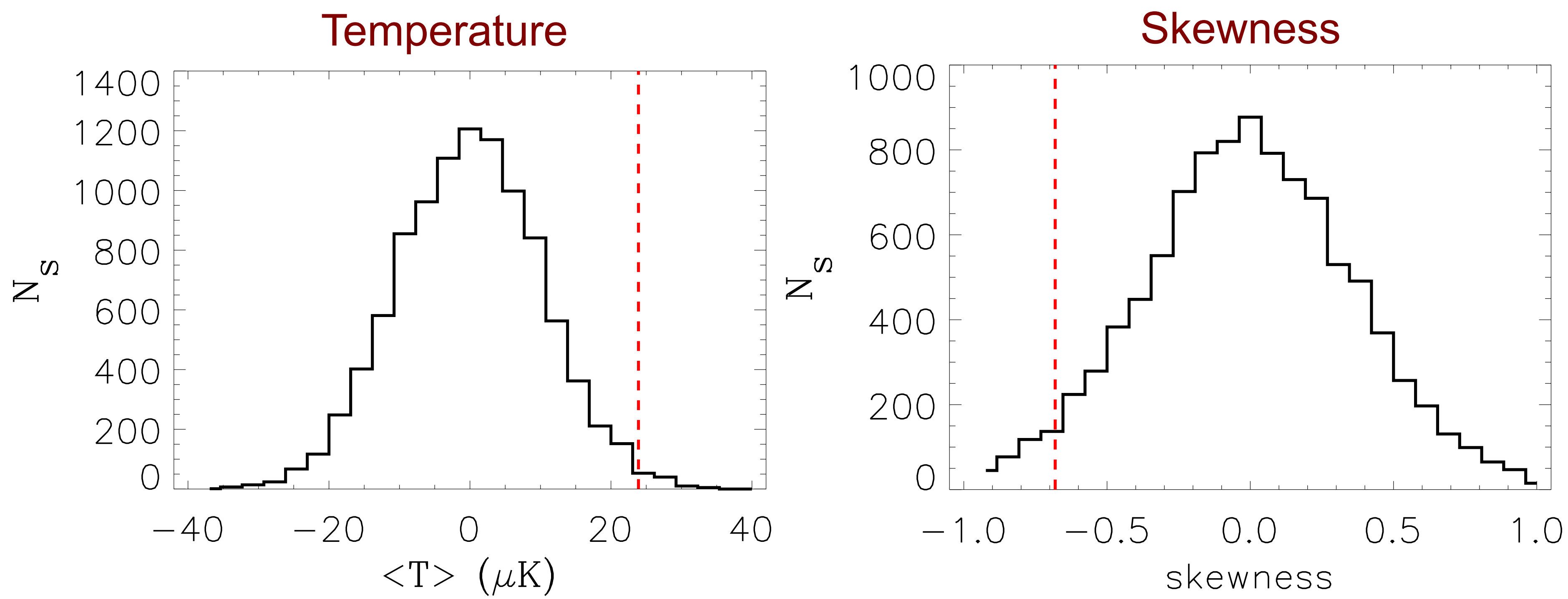


Bennett et *al*, ApJS **208**:20,2013

Are the radio loops visible (even in microwaves)?

Anomalies in WMAP-9 Internal Linear Combination map ($\ell \leq 20$)

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

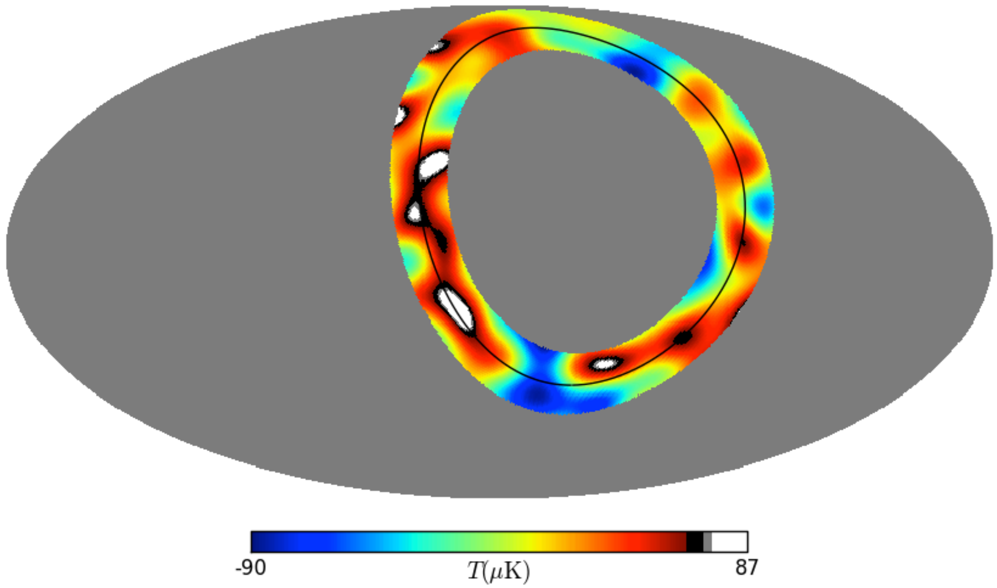


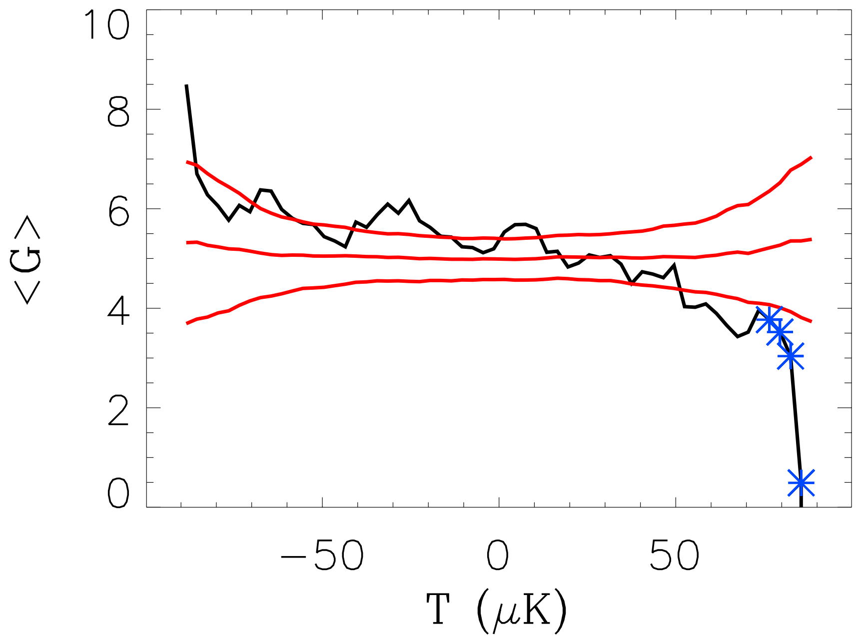
Compare with MC $\Rightarrow$ p-values of $\mathcal{O}(10^{-2})$

Liu, Mertsch & Sarkar, ApJL 789:L29,2014

Anomalies in WMAP-9 Internal Linear Combination map ($\ell \leq 20$)

Cluster analysis (Naselsky & Novikov, ApJ **444**:1,1995): Compute for each pixel the angular distance G from Loop I along great circles crossing both the pixel and the loop center and compare with random realisation of best-fit ΛCDM model

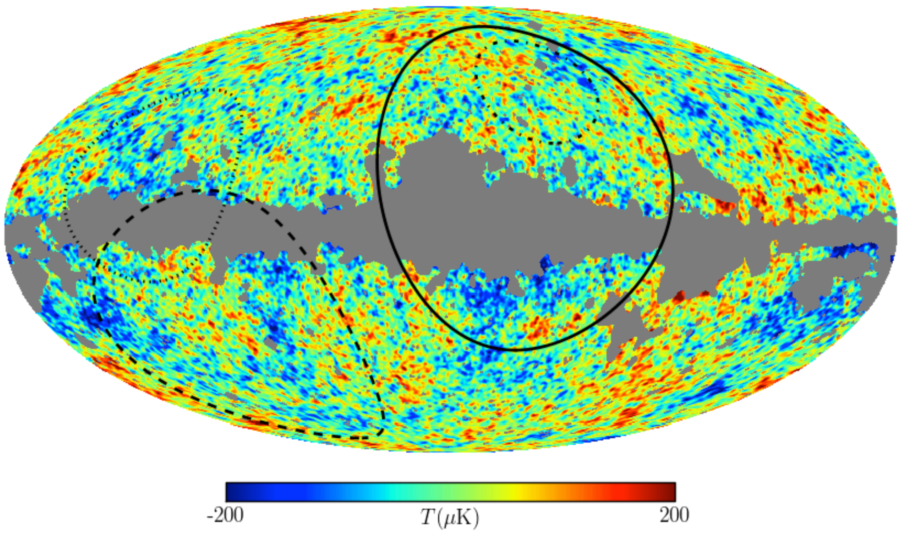




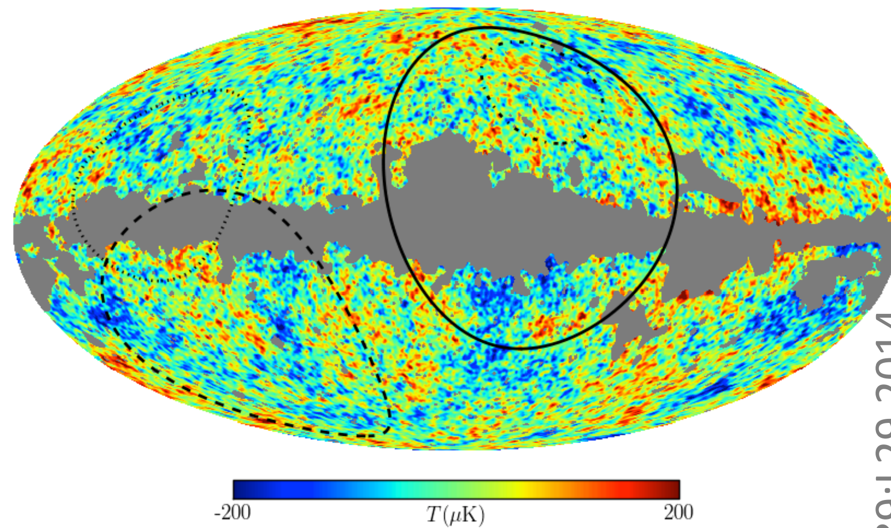
From 100,000 MC runs: probability for *smaller* $\langle G \rangle$ in last 4 bins $\sim 10^{-4}$

Liu, Mertsch & Sarkar, ApJL 789:L29,2014

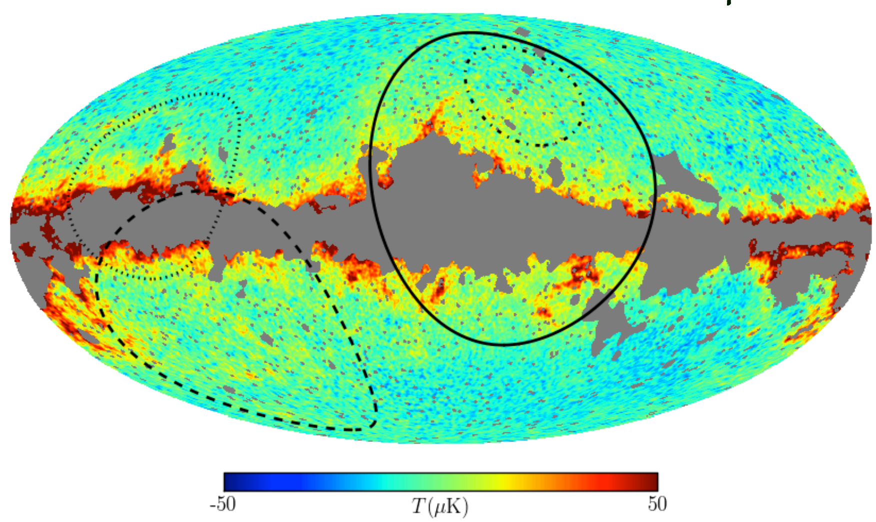
ILC coefficients from Loop I region



ILC coefficients from rest of sky



Difference $\mathrm{ILC}_{\mathrm{rest}} - \mathrm{ILC}_{\mathrm{Loop\ I}}$



Liu, Mertsch & Sarkar, ApJL 789:L29,2014

This demonstrates the presence of the radio loops in the 'internal linear combination' map of the CMB which has supposedly been cleaned of all foreground emissions!

What do we know about the Loop I anomaly?

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

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

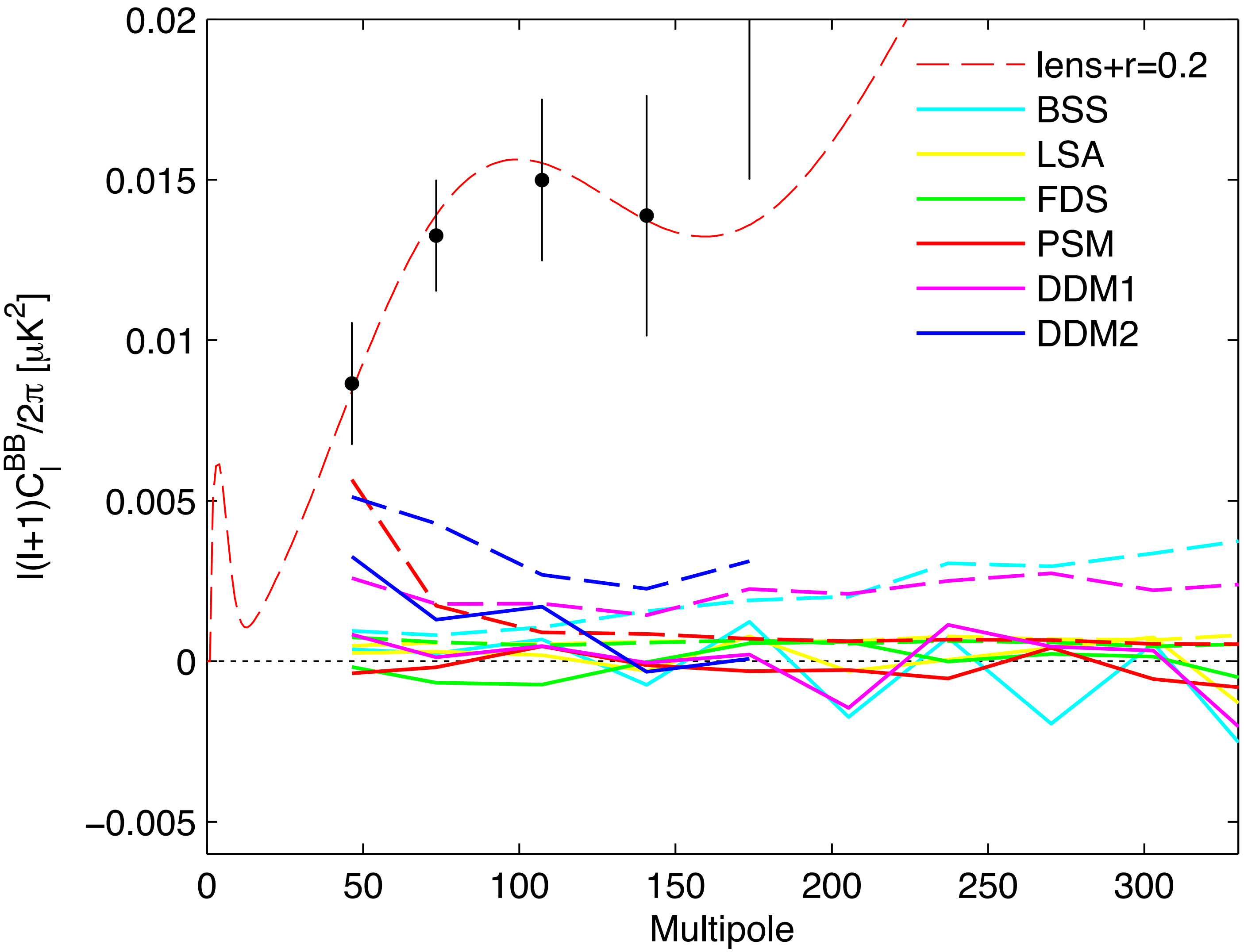
with $\tau(\hat{\mathbf{n}}) \sim 10^{-6}$ and $T_s \sim 20\,\mathrm{K}$

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

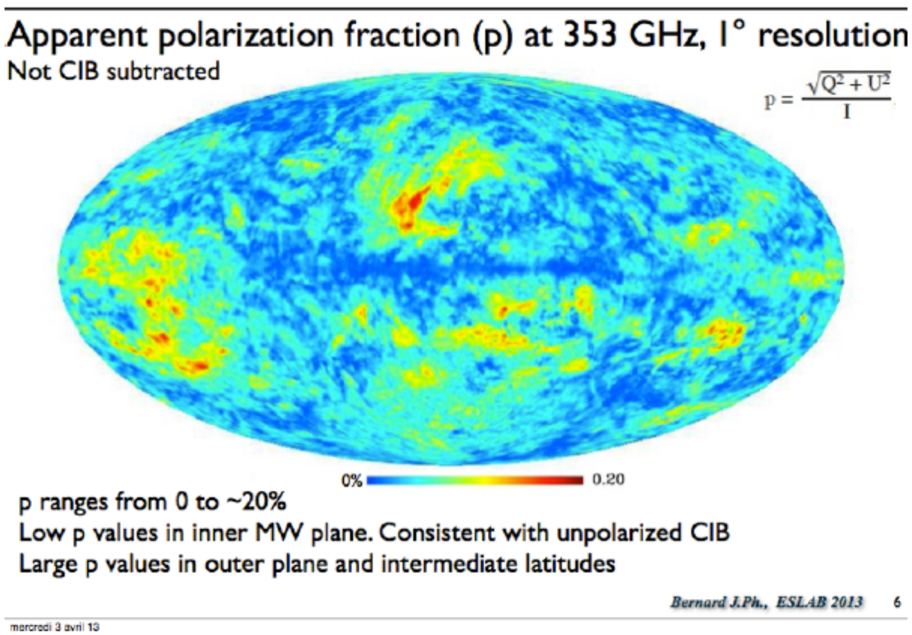
BICEP2 signal is said not to correlate with 'known foregrounds'

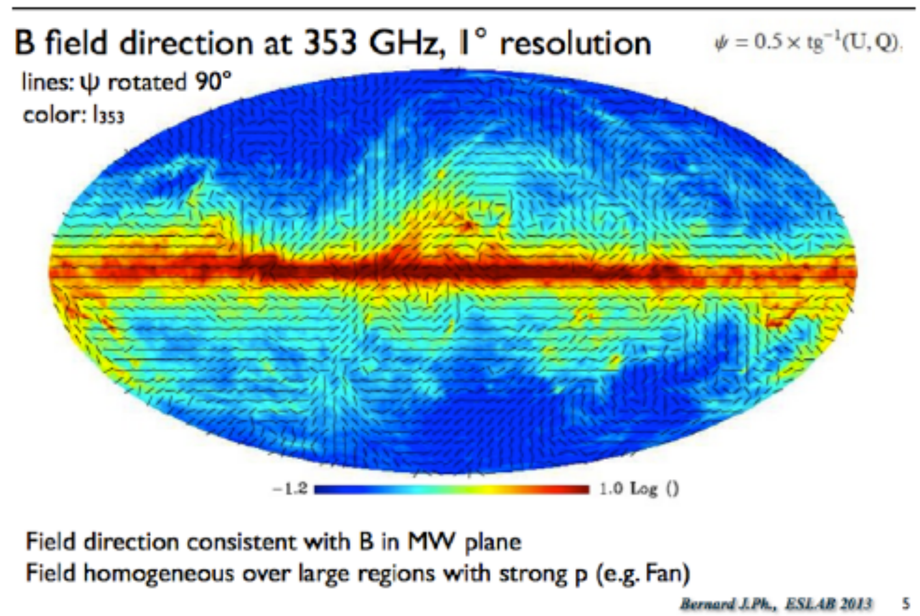


However the new foreground we have identified is *not* included in any of the models…

Synchrotron may well be negligible (relative to $r \sim 0.2$ B-mode signal) at this very high frequency, but is it clear that dust is negligible?

In the WMAP 94 GHz map, the polarisation fraction is a few % but WMAP has *insufficient* sensitivity to provide a template … so ought to wait for the Planck polarisation maps to be published to estimate this





The BICEP2 team decided to use *preliminary* Planck results … but did they take into account that the ‘apparent polarisation fraction’ shown is an *underestimate* since the (unsubtracted) CIB is unpolarised?

A more thorough analysis of foregrounds (consistent results found using three different techniques) can account for the *entire* BICEP2 'signal'!

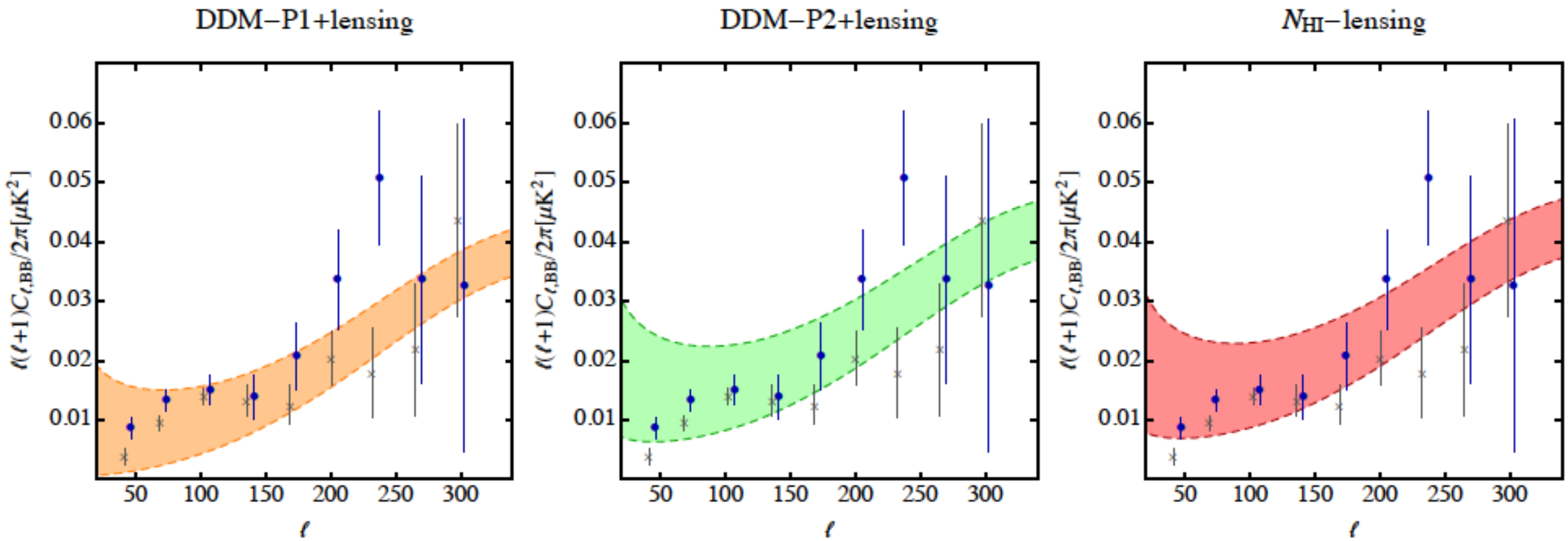
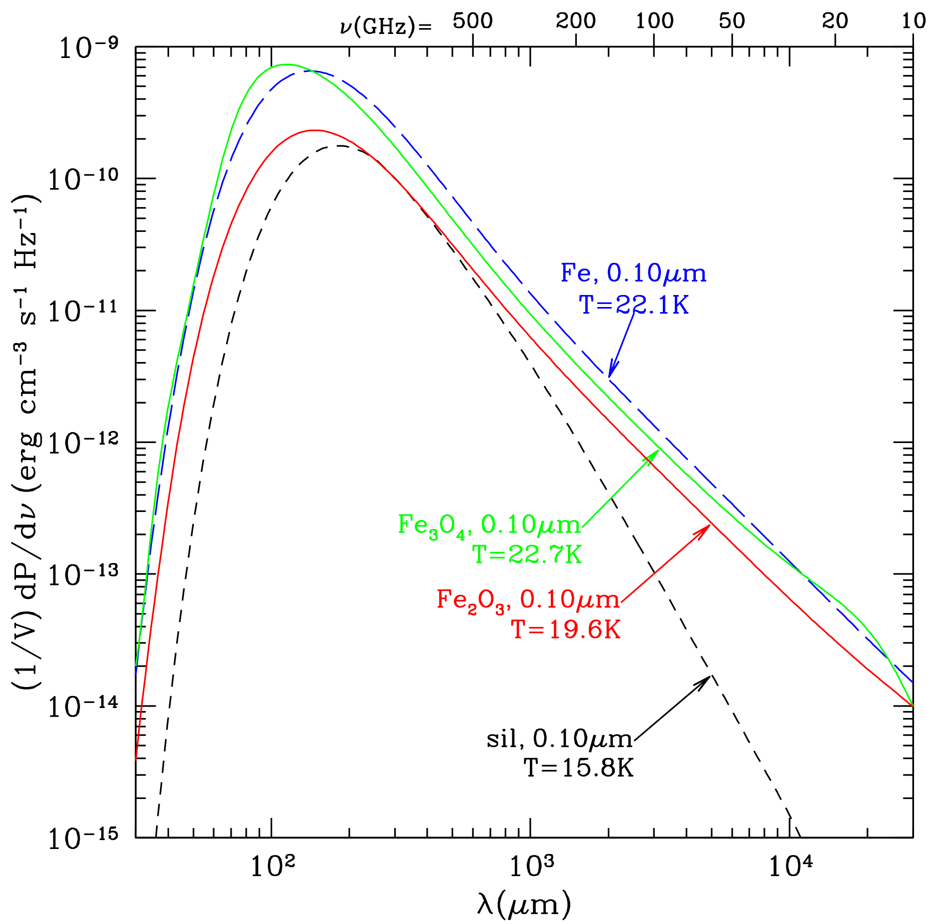


FIG. 4: Comparison of several predictions for the 150 GHz signal versus the reported BICEP2 × BICEP2 and the preliminary BICEP2 × Keck measurements. The predictions are a combination of the dust polarization signal and the predicted lensing signal for standard cosmological parameters. Panel (a) is based on DDM-P1, which assumes that the dust polarization signal is proportional to the dust intensity (extrapolated from 353 GHz) times the mean polarization fraction (based on our CIB-corrected map; see section III). The band represents the 1σ countours derived from a set of 48 DDM-P1 models. Panel (b) shows DDM-P2, with polarization fractions from our CIB-corrected map, and polarization direction based on starlight measurements, the PSM, or [33]. Panel (c) uses the column density of neutral hydrogen in the BICEP2 region inferred from the optical depth at 353 GHz to estimate the dust foreground. In this panel, the band reflects the uncertainty in the extrapolation of the scaling relation to low column densities as well as the uncertainty in the rescaling from 353 GHz to 150 GHz.

(Flauger, Hill & Spergel, arXiv:1405.5857)

But *what* is generating this foreground emission in the 'Southern hole'?

Could it be *magnetic* dipole radiation from dust in the loops (with iron or ferrimagnetic inclusions)?

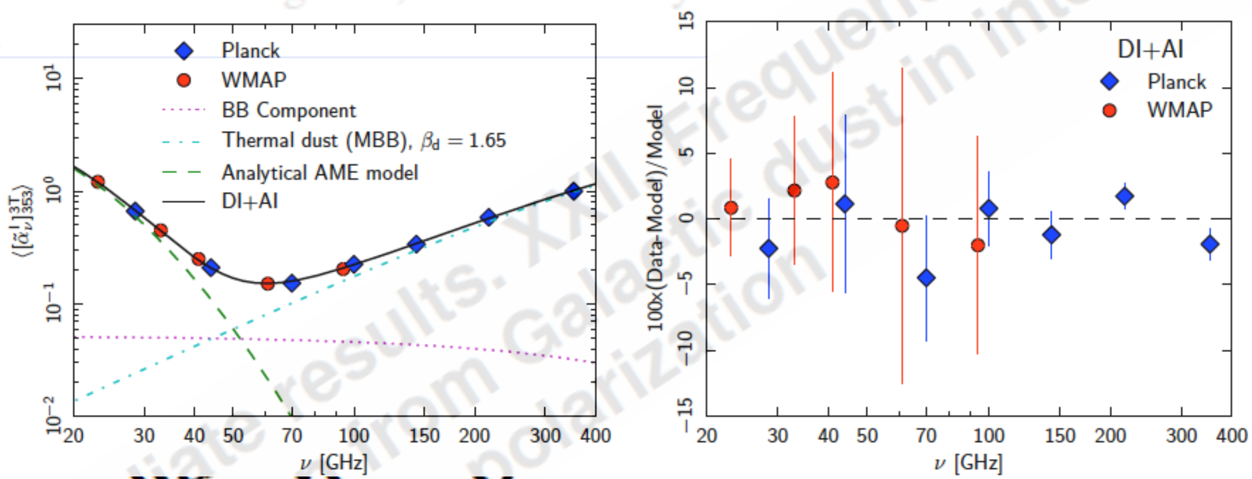


Draine & Lazarian, ApJ **512:740**,1999;
Draine & Hensley, ApJ **757:103**,2012

This has subsequently also ben implicated by *Planck* data from the observed decrease of the polarization fraction of dust emission between 353 & 70 GHz [arXiv:1405.0874]

Planck intermediate results. XXII Frequency dependence of thermal emission from Galactic dust in intensity and polarization

BB component accounts for about (26 ± 4) % of the MBB component at 100 GHz and (47 ± 6) % at 70 GHz, in agreement with what is reported by Planck Collaboration Int. XVII (2014) for the SED at high Galactic latitudes. The ratio between the BB and MBB components at a given frequency is constant at intermediate and high latitudes. The BB component could represent either magnetic dipole emission (MDE) from ferromagnetic particles, or inclusions in interstellar grains, as modelled by Draine & Hensley (2013).



[arXiv:1405.0874]

DE has been introduced by Draine & Hensley (2012) to xplain the flattening of the dust SED at sub-mm wavelengths in the Small Magellanic Cloud (Planck Collaboration XVII 2011). The *Planck* data may indicate that this mechanism contributes to the microwave emission from our own Galaxy. The MDE interpretation is within the plausible range of models presented in Draine & Hensley (2013) for Galactic dust. If this is the correct interpretation, MDE from the Milky Way is detected here with a significance greater than 7σ (for a fixed spectral index of the MBB component).

Conclusions

BICEP2 has detected a ~0.3 μK B-mode signal in a patch of sky believed to be free of foreground Galactic emissions … it was claimed that this does *not* correlate with (extrapolated) 'known foregrounds' so is evidence for gravitational waves from cosmic inflation at the GUT scale

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* standard foreground cleaning methods so they have lurked undetected in (ILC) maps of the CMB

The anomalous radiation has the expected spectrum of magnetic dipole radiation from ferromagnetic dust – a hitherto *unrecognised* foreground

Forthcoming maps of polarized dust emission (e.g. *Planck*) will show if this can indeed account for the B-mode signal observed by BICEP2