Imprint of radio loops on the CMB

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2nd NBIA-APCTP Workshop
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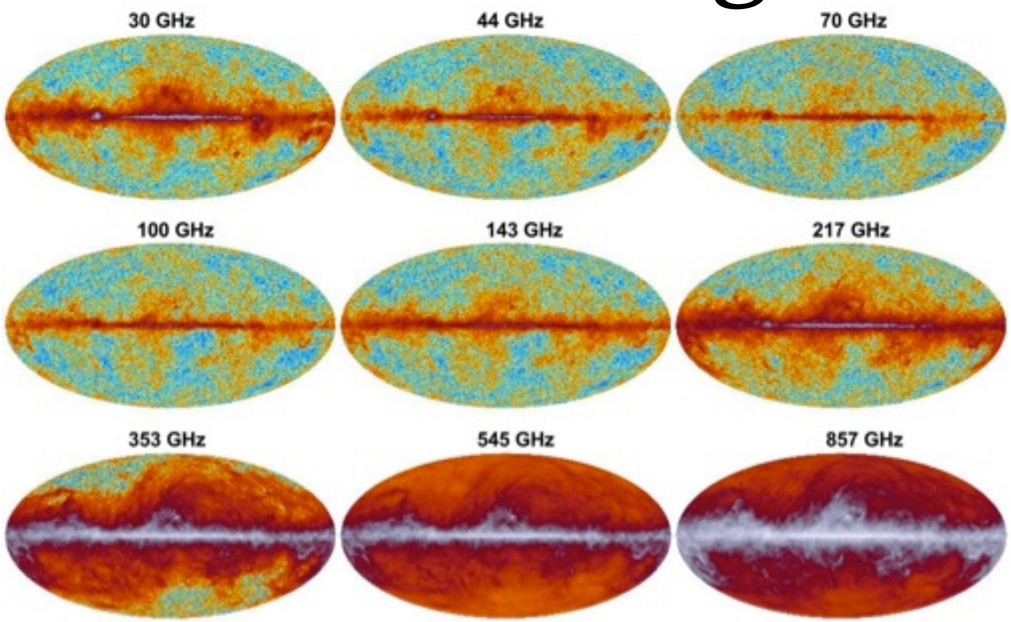
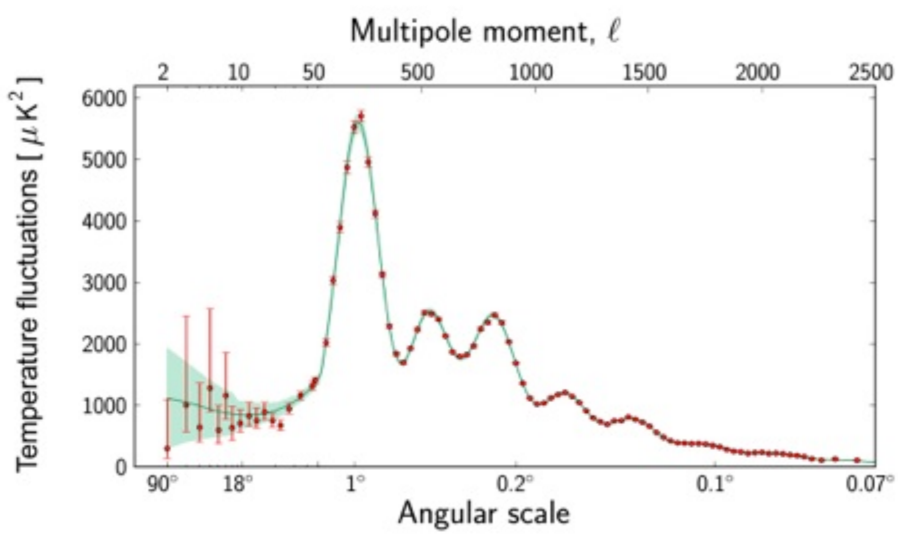
Stanford University

KIPAC

CMB foreground removal



Planck Coll., arXiv:1303.5072



Foreground removal

- mask out strongly contaminated regions:
  Galactic disk & point sources
- look at uncontaminated regions

actively removing foregrounds

1) ILC (Internal Linear Combination):
   exploiting different spectral behaviour
2) template subtraction:
   exploiting different (spatial) distribution

Internal Linear Combination

WMAP maps

$$T_{\mathrm{ILC}}(p) = \sum_i \zeta_i T_i(p) = \sum_i \zeta_i \left[T_c(p) + S_i T_f(p) \right]$$

can be thought of as sum of CMB and foreground map with spectrum

reduce “presence” of foreground in ILC by minimising the ILC variance, but due to CMB-foreground correlation

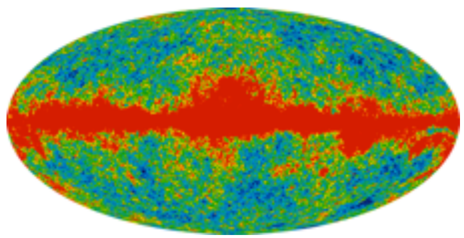
$$\sigma_{\mathrm{ILC}}^2 = \sigma_c^2 - \sigma_{cf}^2 / \sigma_f^2 \ \leq \sigma_c^2$$

advantage: no external maps needed
issue: ILC map somewhat biased

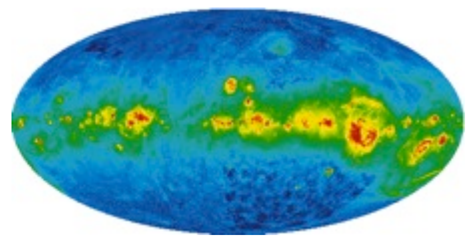
Hinshaw *et al.*, ApJS 170 (2007) 288

Template subtraction

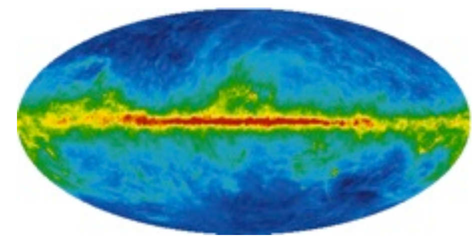
χ^2 fit to data with foreground model: $M(\nu, p) = b_1(\nu)(T_{\mathrm{K}} - T_{\mathrm{Ka}}) + b_2(\nu) I_{\mathrm{H}\alpha} + b_3(\nu) M_d$



(K-Ka) difference map: certain combination of synchrotron and free-free



H α map: tracer of free-free



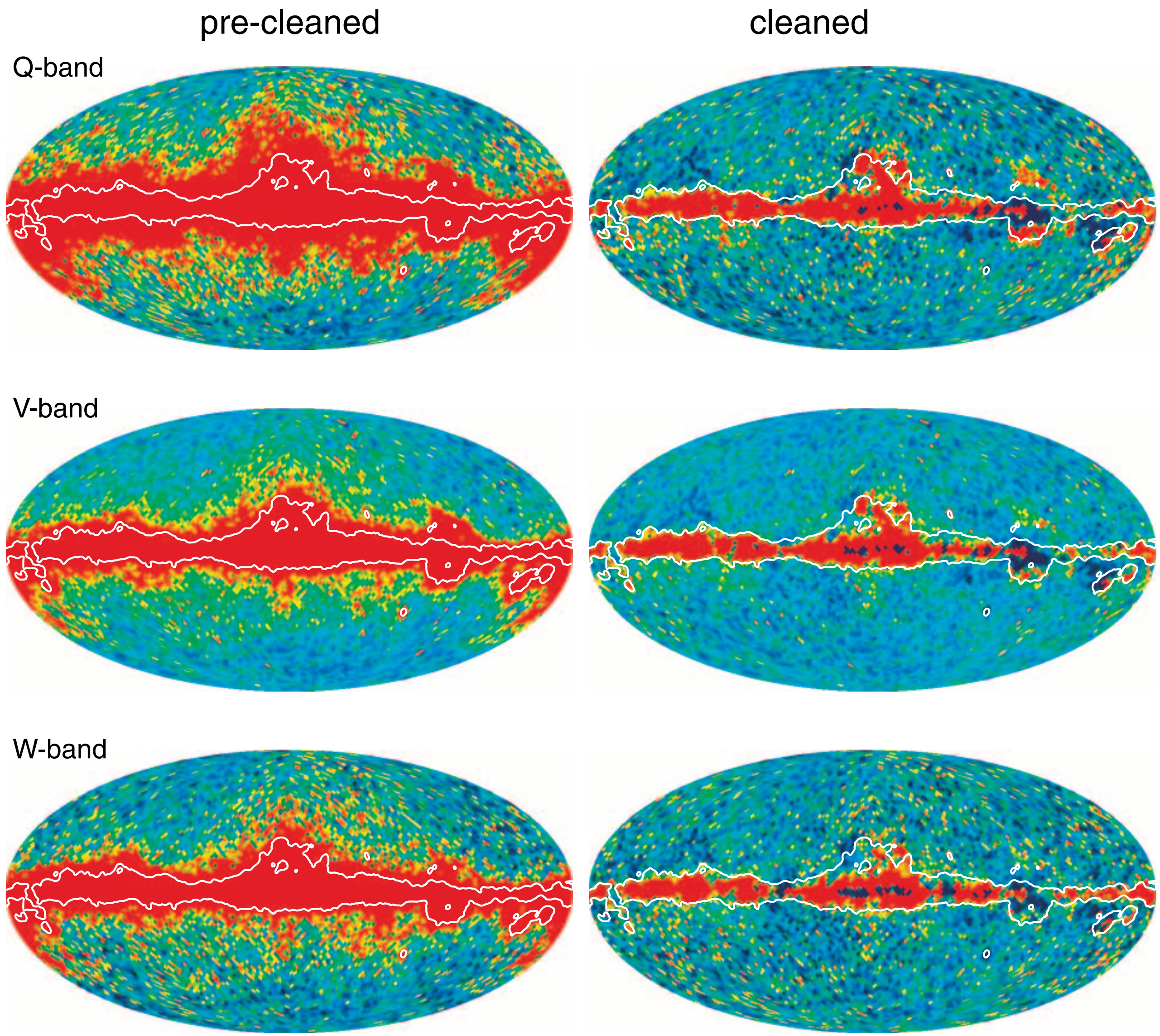
IR map (extrapolated to 94 GHz): tracer of dust

advantage: extract spectral information about foregrounds

issue: direction-dependent spectral indices/morphological changes with frequency

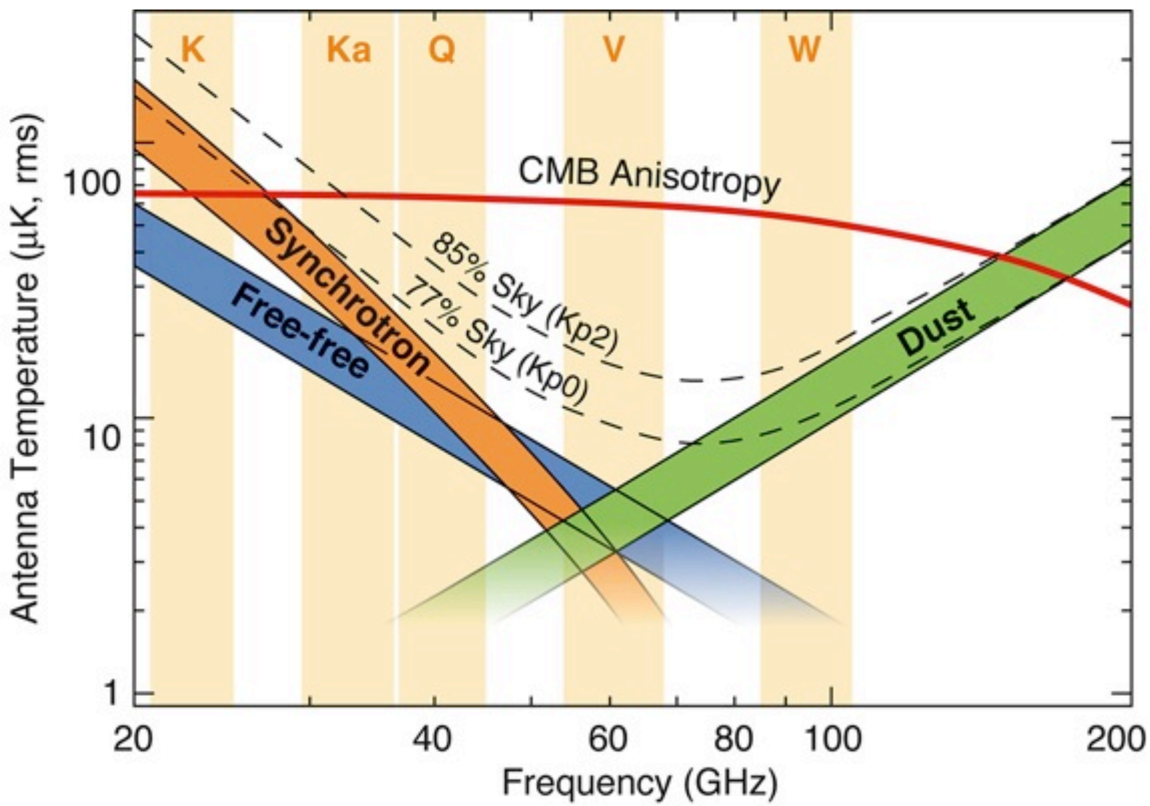
Hinshaw *et al.*, ApJS 170 (2007) 288

Before and after



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

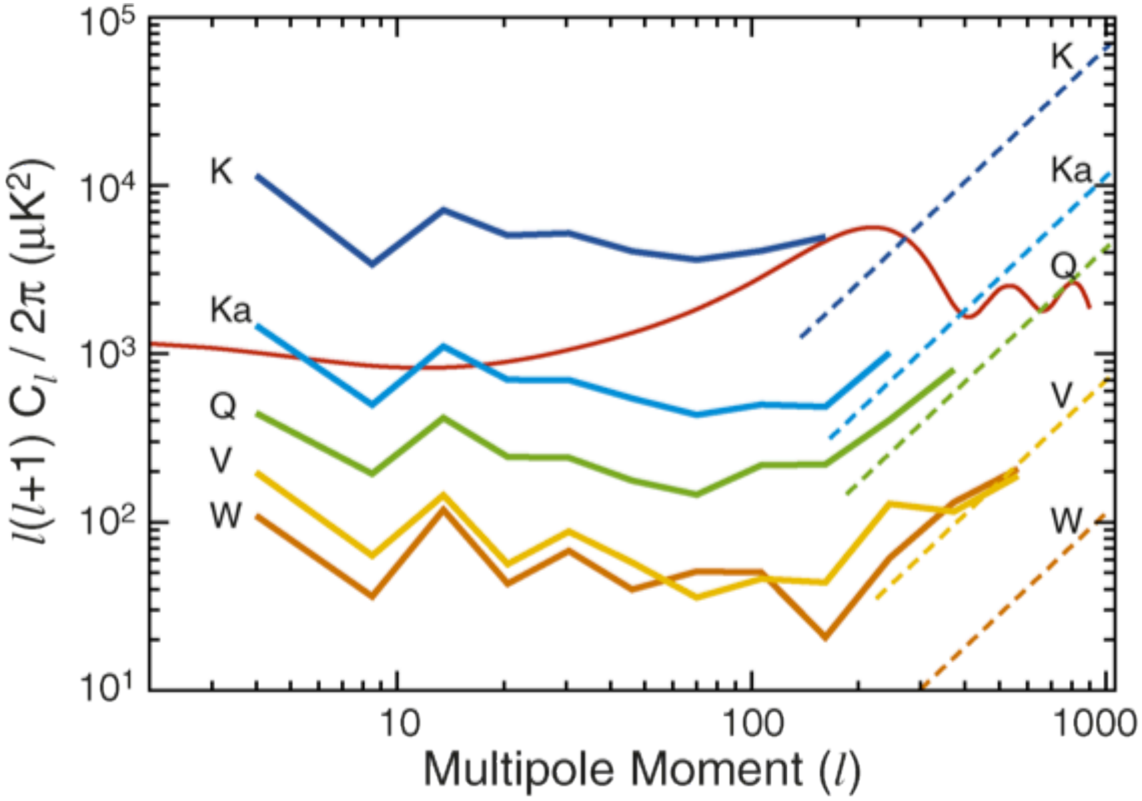
Why this is working…



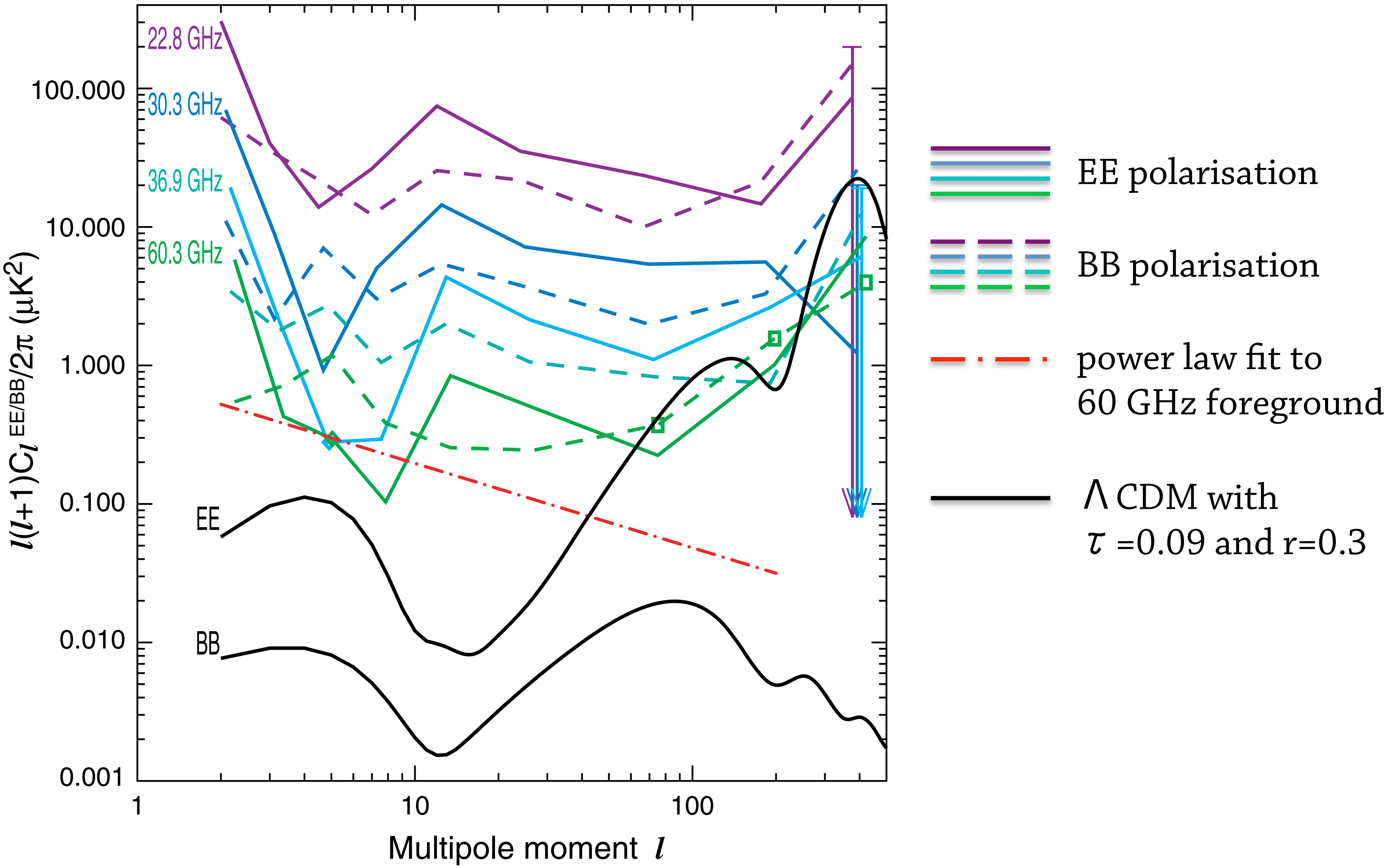
Bennett *et al.*, ApJS 148 (2003) 97

Why this is working…

Bennett *et al.*, ApJS 148 (2003) 97

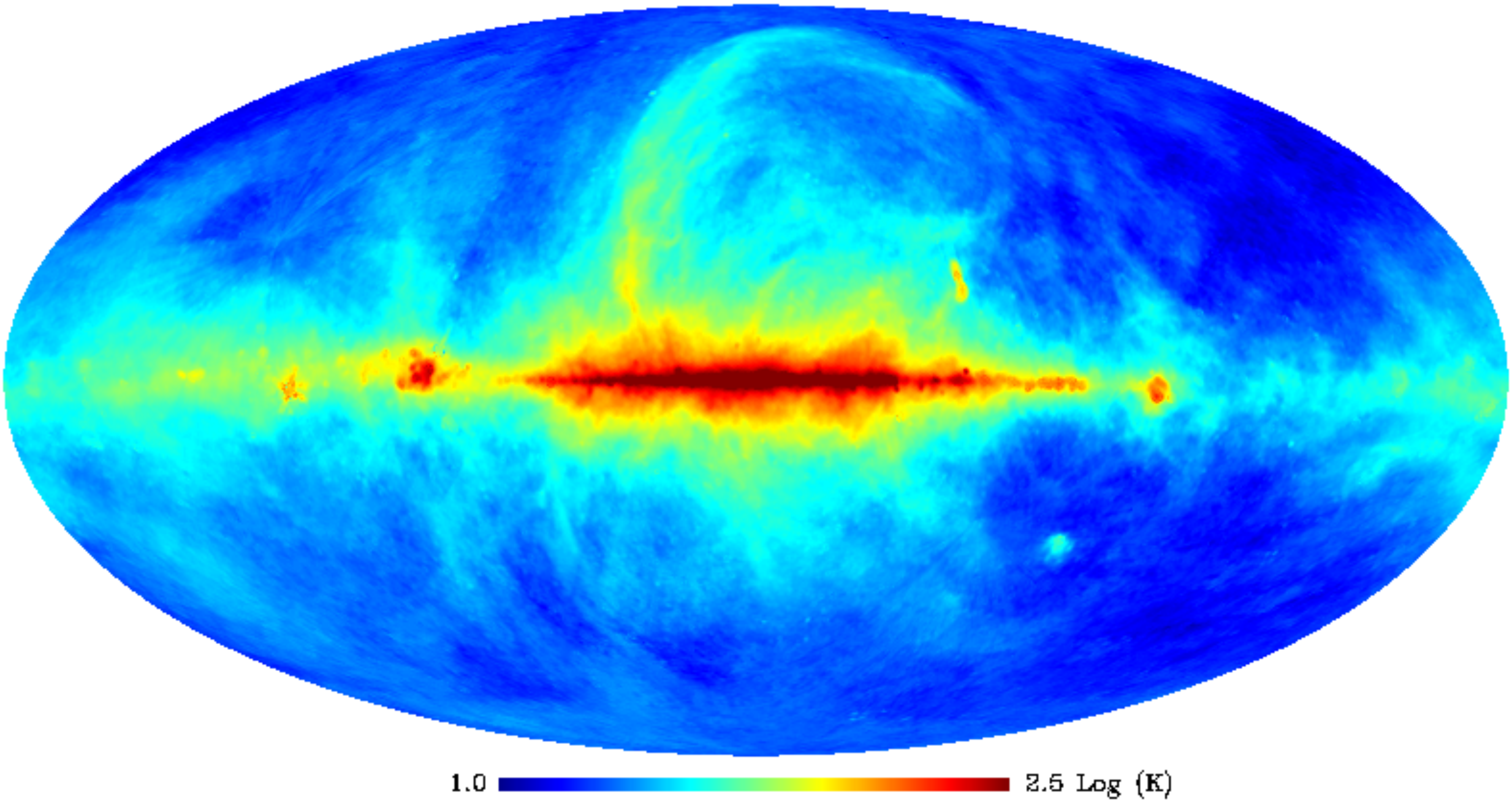


Polarised emission



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

Haslam 408 MHz



Haslam *et al.*, A&AS **47** (1982) 1

The galactic radio background…

… is predominantly synchrotron of CR electrons on the galactic magnetic fields…

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

where $\quad \nu_c = \frac{3}{2}\left(\frac{E}{m_e}\right)^2 \frac{B_\perp(\mathbf{r})}{B(\mathbf{r})}$

and $\quad F(x) = x \int_x^\infty \mathrm{d}x' K_{5/3}(x')$

… and we look at its line-of-sight projections:

$$F(l,b;\nu) = \int \mathrm{d}s\, P(\mathbf{r}_{\mathrm{LOS}}(s,l,b);\nu)$$

Ingredients

CR electrons:

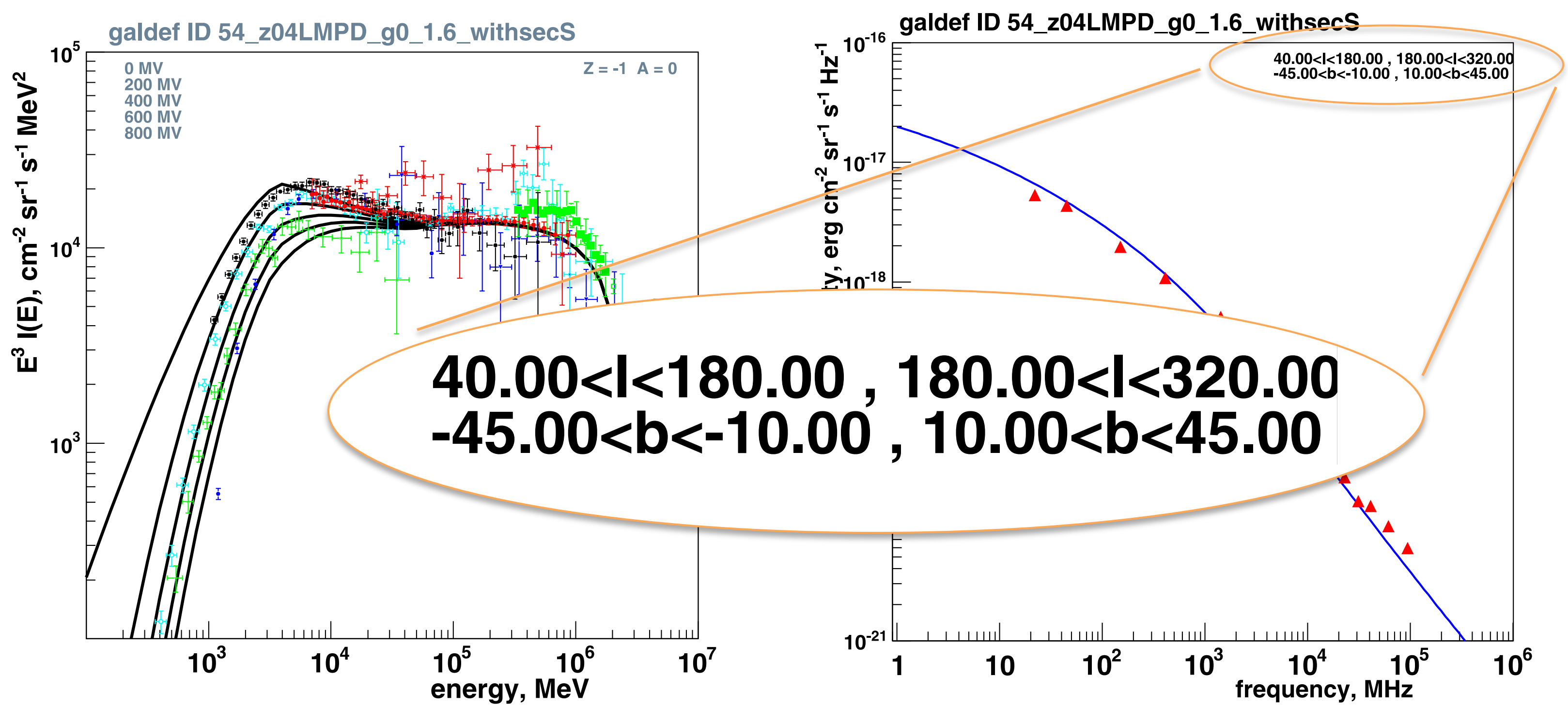
- sources: SNRs! pulsars? PWNe?
  large-scale distribution?!
- conceptual: stochasticity of sources?
- propagation: diffusive! convective?
  reacceleration? energy losses?

Galactic magnetic fields:

- large-scale, ordered component
- small-scale, turbulent component

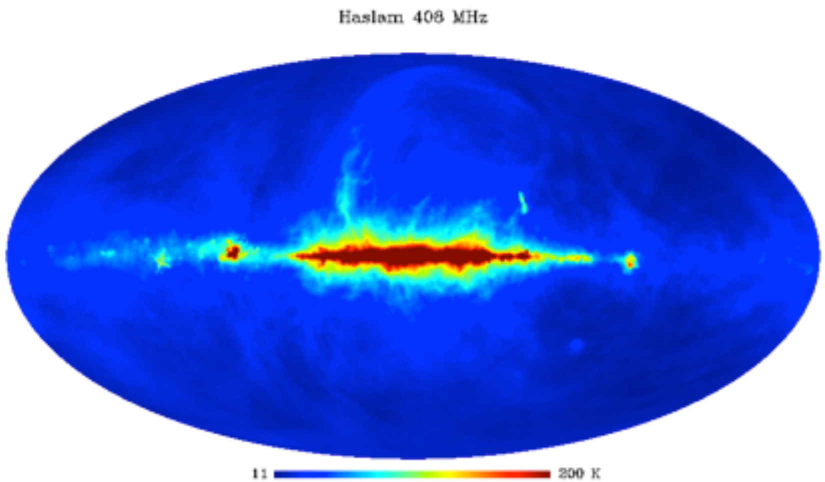
Local e⁻ spectrum and synchrotron

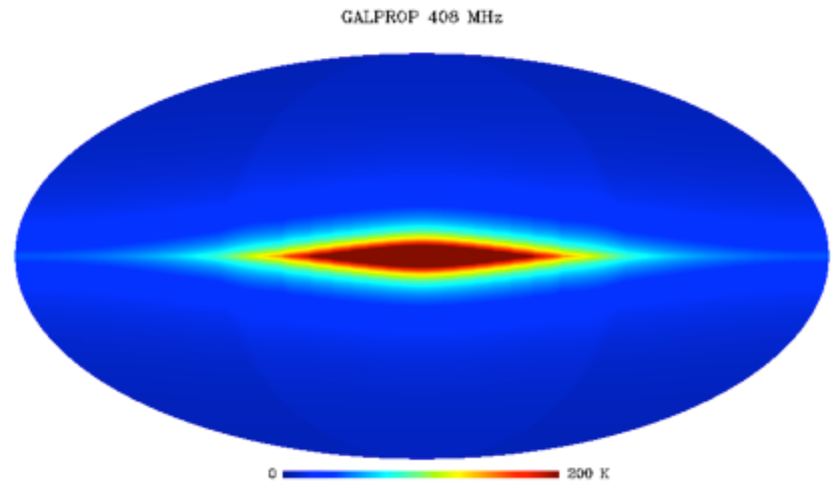
Strong *et al.*, A&A 534 (2011) A54

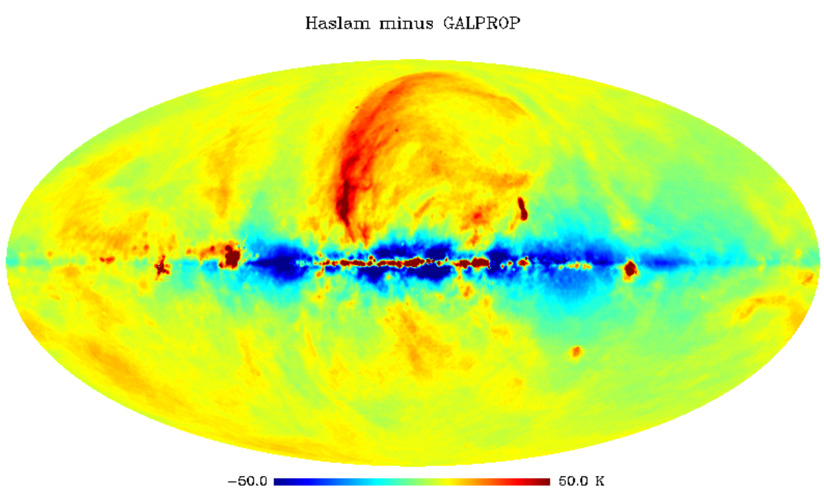


- require break in IS electron spectrum, e.g. at source: $\mathcal{R}^{-1.5} \rightarrow \mathcal{R}^{-2.2}$
- fix local (turbulent) magnetic field: $\sim 8\,\mu\mathrm{G}$
- constrain certain propagation models, e.g. disfavour reacceleration

Haslam vs GALPROP



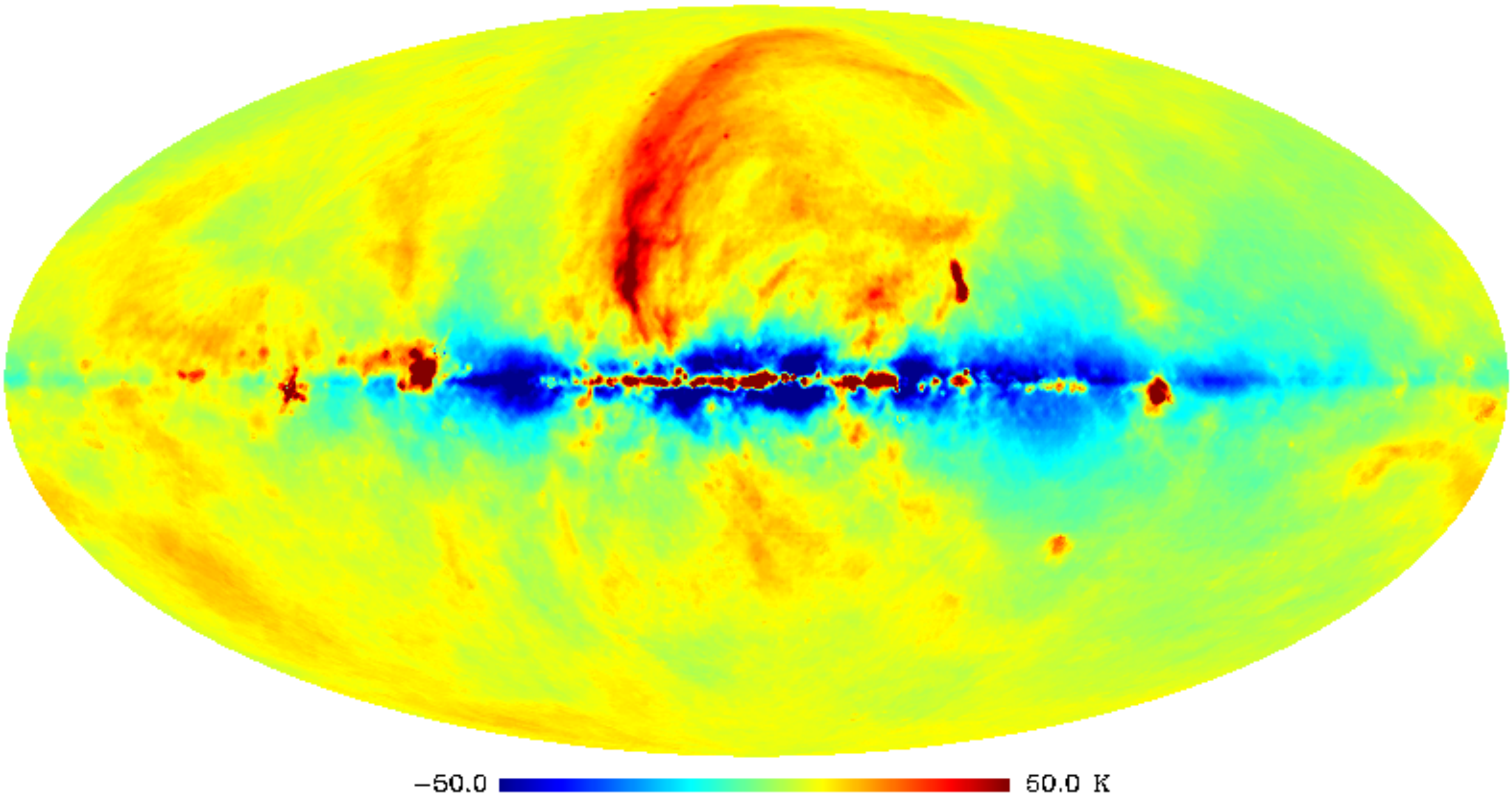




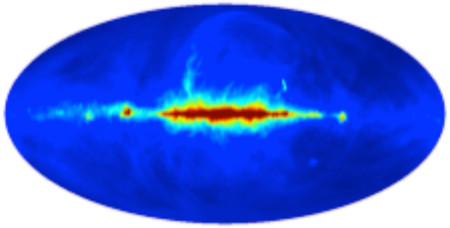
averaging over large parts of the sky…

- assumes factorisation in longitude and latitude
- leads to loss of sensitivity for structures on intermediate scales

Difference: Haslam - GALPROP



Angular power spectrum

1. radio sky:  $\equiv J(\theta, \phi)$

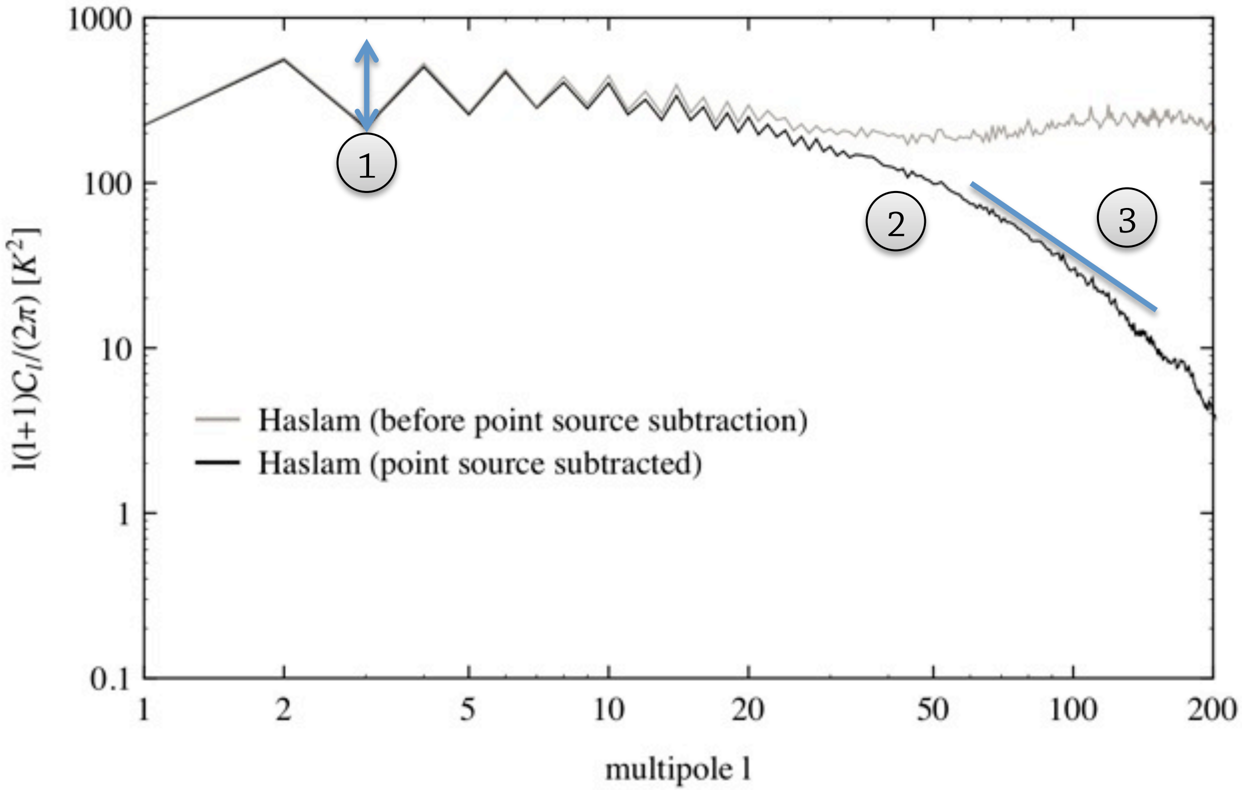
2. spherical harmonics: $$J(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-l}^{l} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

3. angular power spectrum: $$C(\ell) \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

advantages:

- information ordered by scale
- statistically meaningful quantities
- natural for some applications, e.g. CMB foreground subtraction

Haslam APS



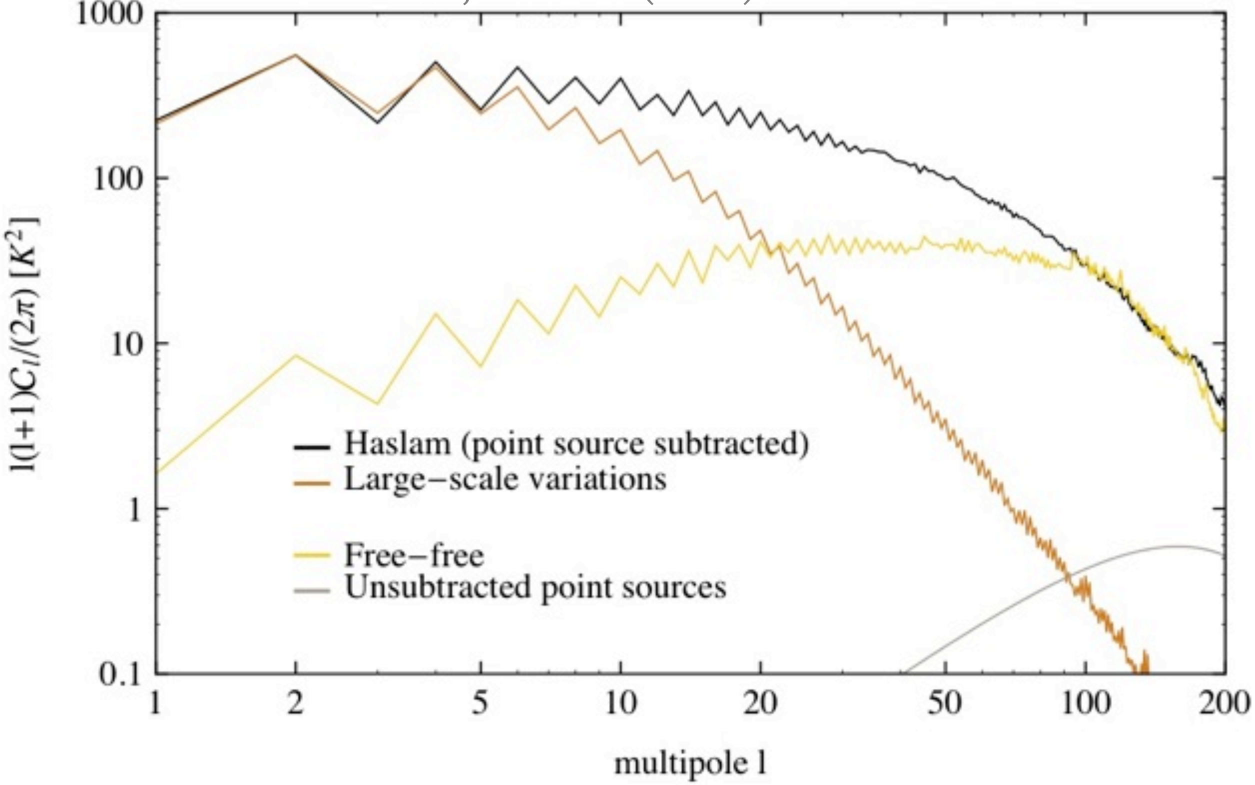
1. even/odd structure reflects symmetries of sky map
2. smoother for higher multipoles
3. power-law

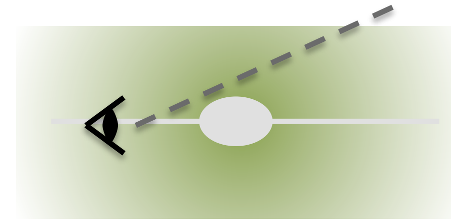
$$C_\ell \propto \ell^{-m}$$

with $m \sim 11/3$
(Kolmogorov turbulence)

Smooth component only…

Mertsch & Sarkar, JCAP 06 (2013) 041





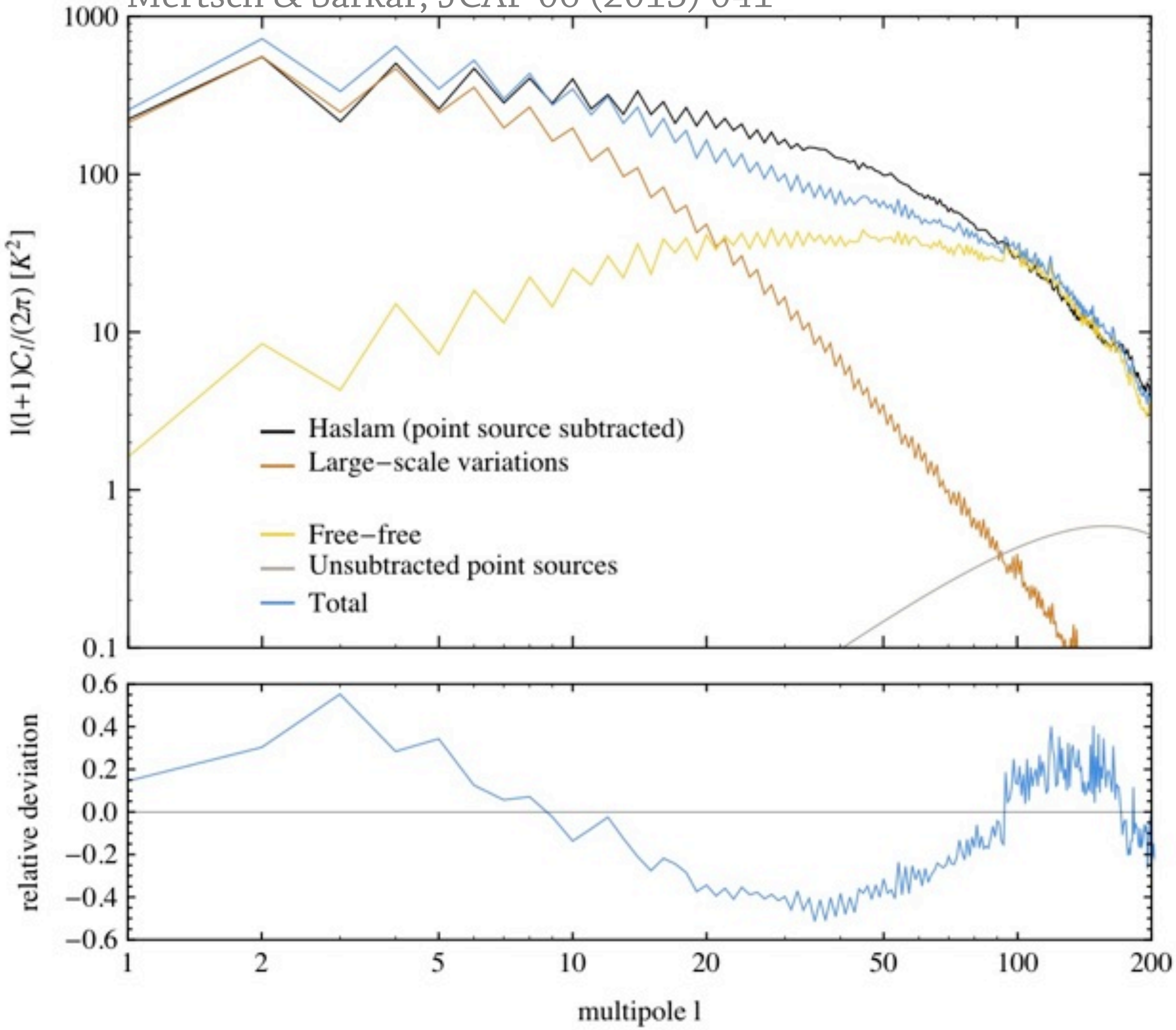
synchrotron:
smooth emissivity (GALPROP)

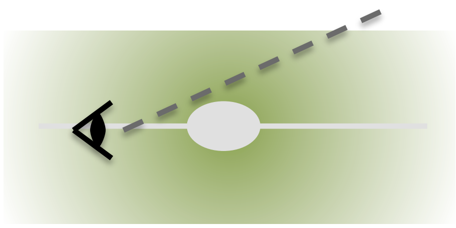
free-free:
WMAP MEM-template

unsubtracted sources:
shot noise

Smooth component only...

Mertsch & Sarkar, JCAP 06 (2013) 041





synchrotron:
smooth emissivity
(GALPROP)

free-free:
WMAP MEM-template

unsubtracted sources:
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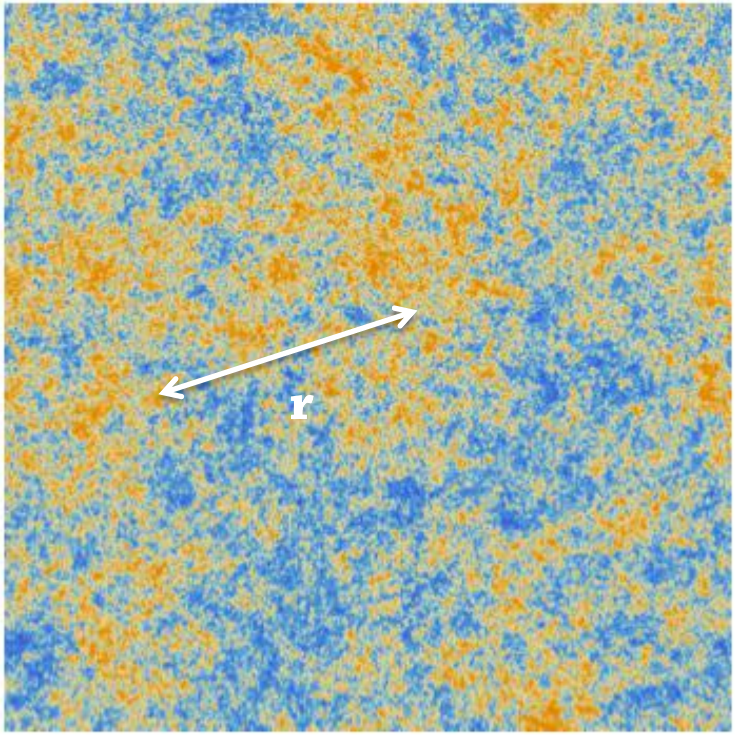
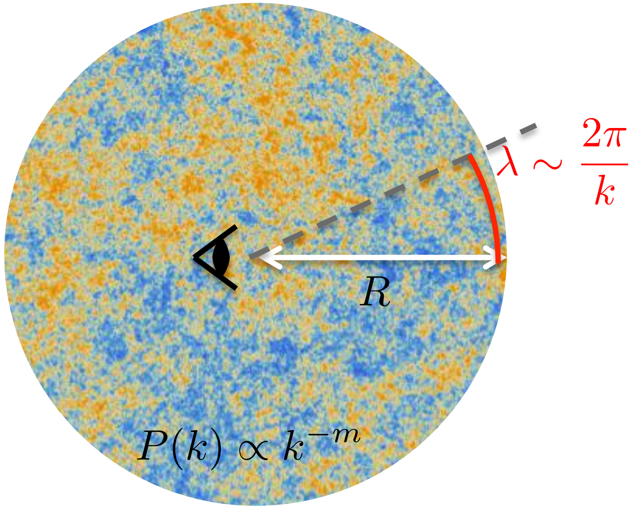
Turbulence cascade

- 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 plasma and simulations
  $$P(k) \propto k^{-m}$$

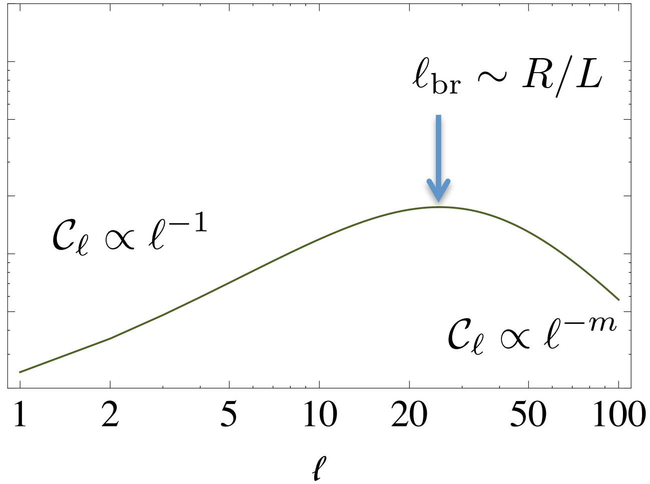
  for $k \in [k_1, k_2]$ with $m \sim 11/3$ (Kolmogorov turbulence)



Turbulence in projection



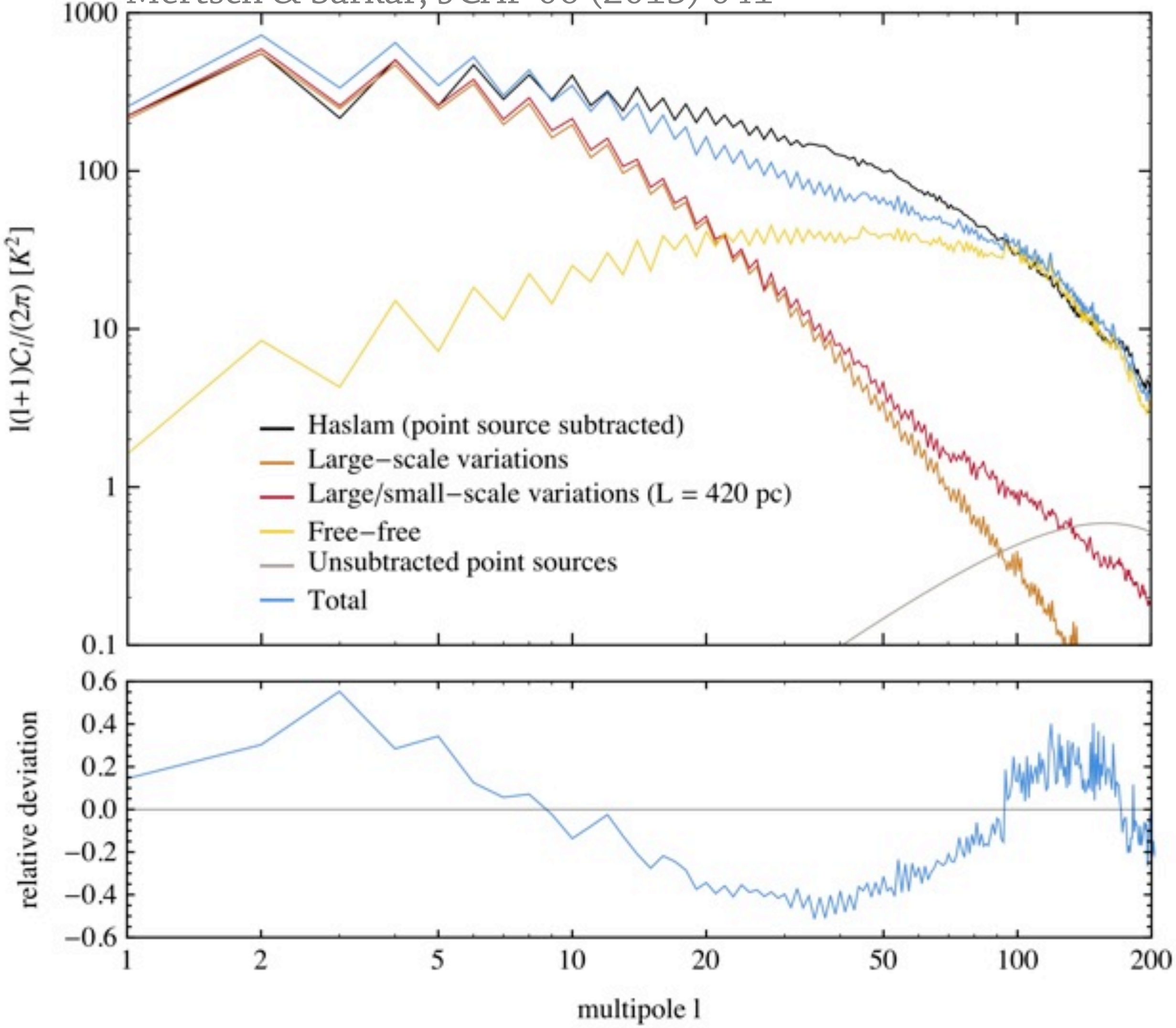
- consider two-point correlations on sphere
- power-law in wavenumber reflected by power-law in angle θ (or multipole ℓ)

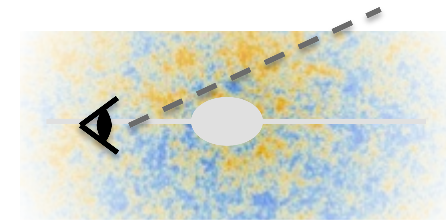


Chepurnov, Astron. Astrophys. Transact. **17** (1999) 281

…including turbulent component

Mertsch & Sarkar, JCAP 06 (2013) 041





synchrotron:
smooth emissivity
and turbulence

free-free:
WMAP MEM-template

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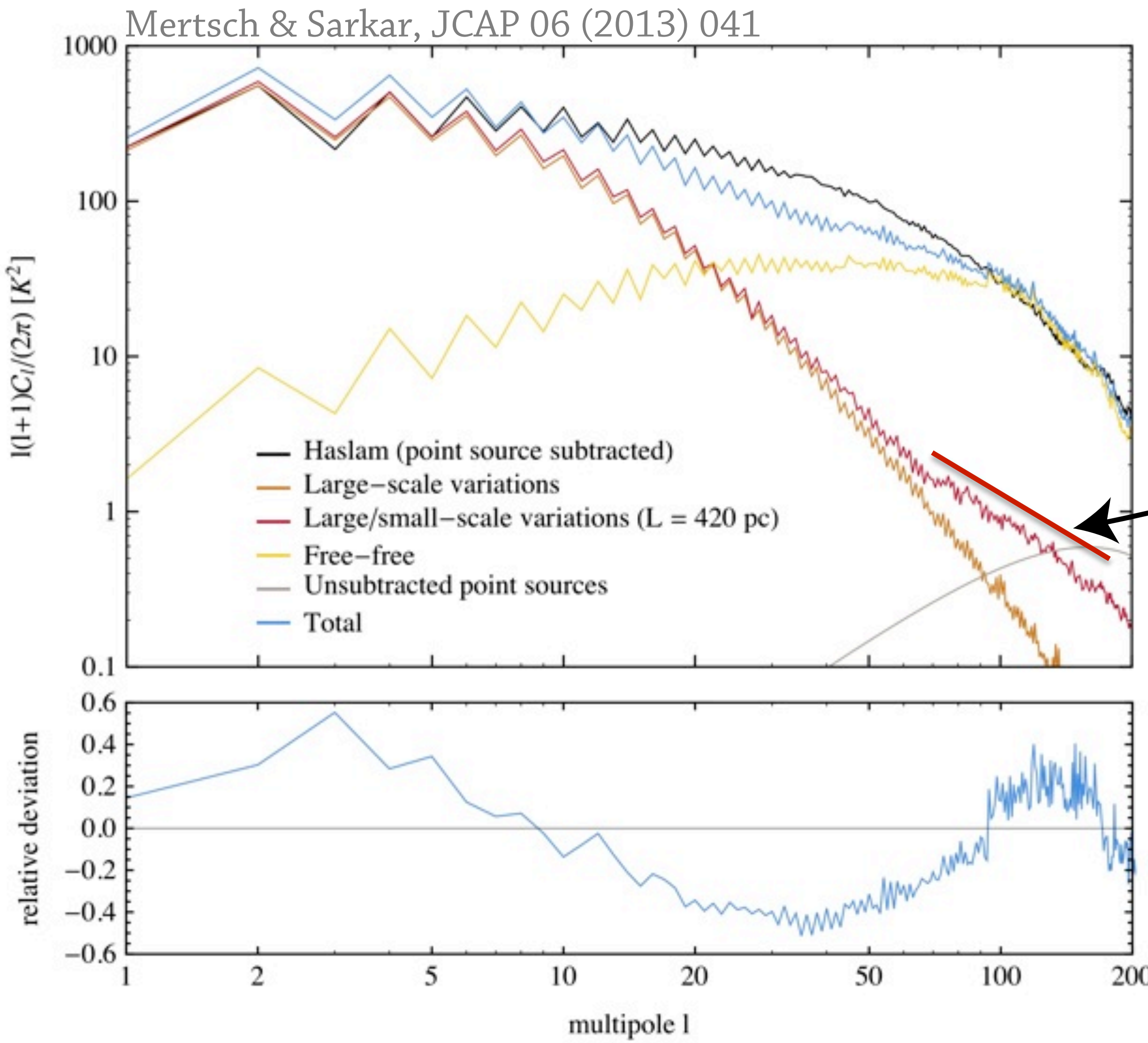
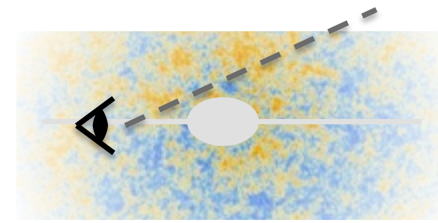
Mertsch & Sarkar, JCAP 06 (2013) 041





power-law in wavenumber

$$P(k) \propto k^{-m}$$

reflected by power-law in angle θ or multipole ℓ :

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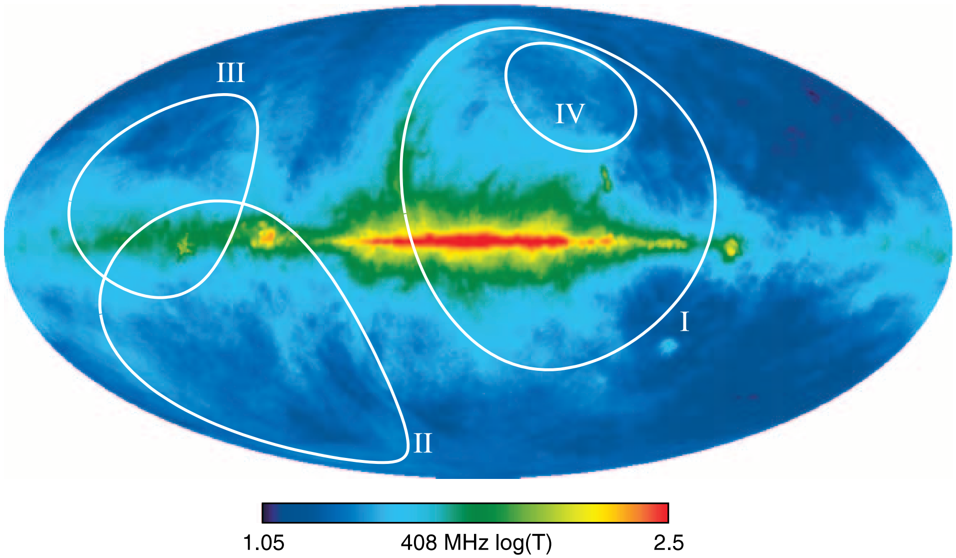
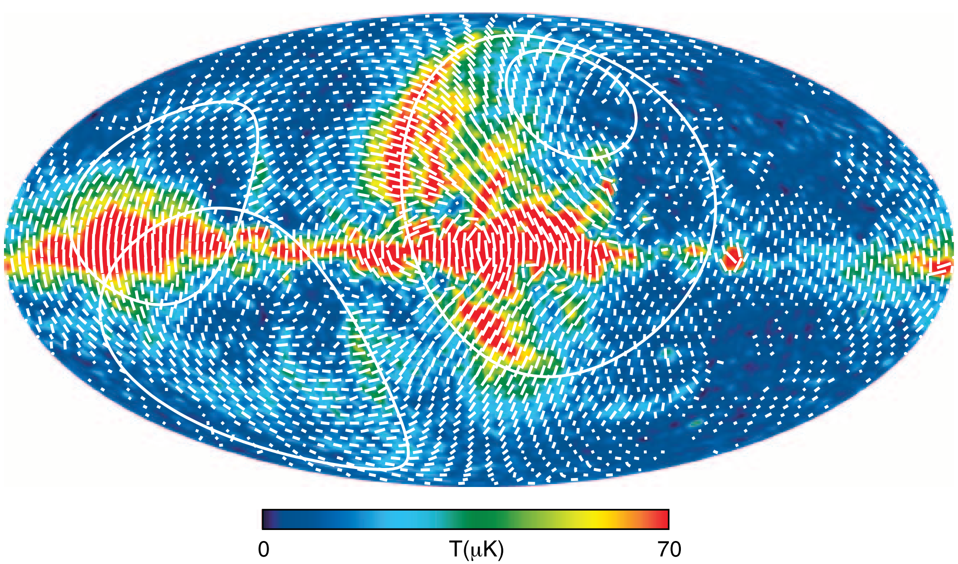
Chepurnov, Astron. Astrophys. Transact. **17** (1999) 281

Radio loops

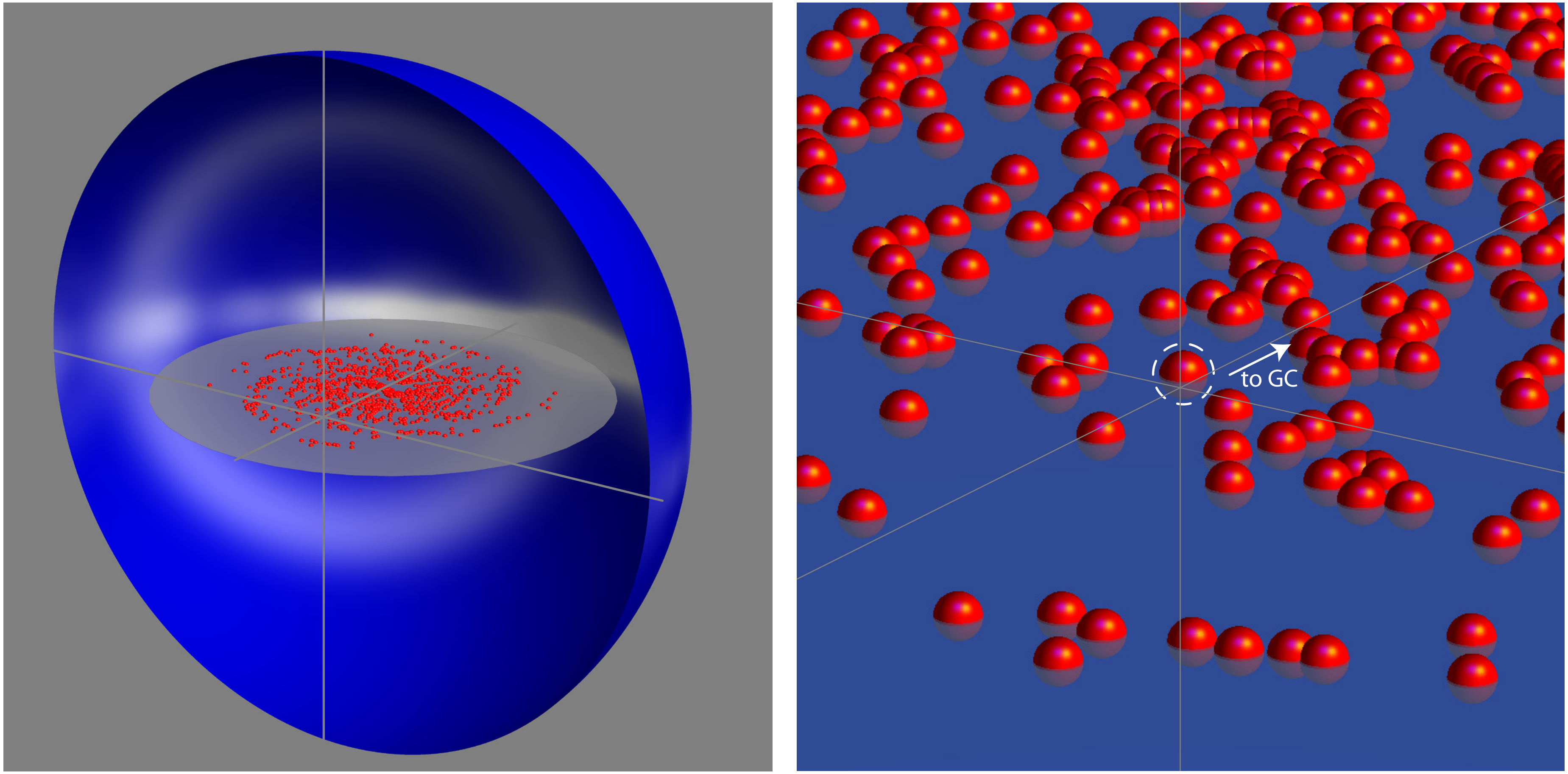




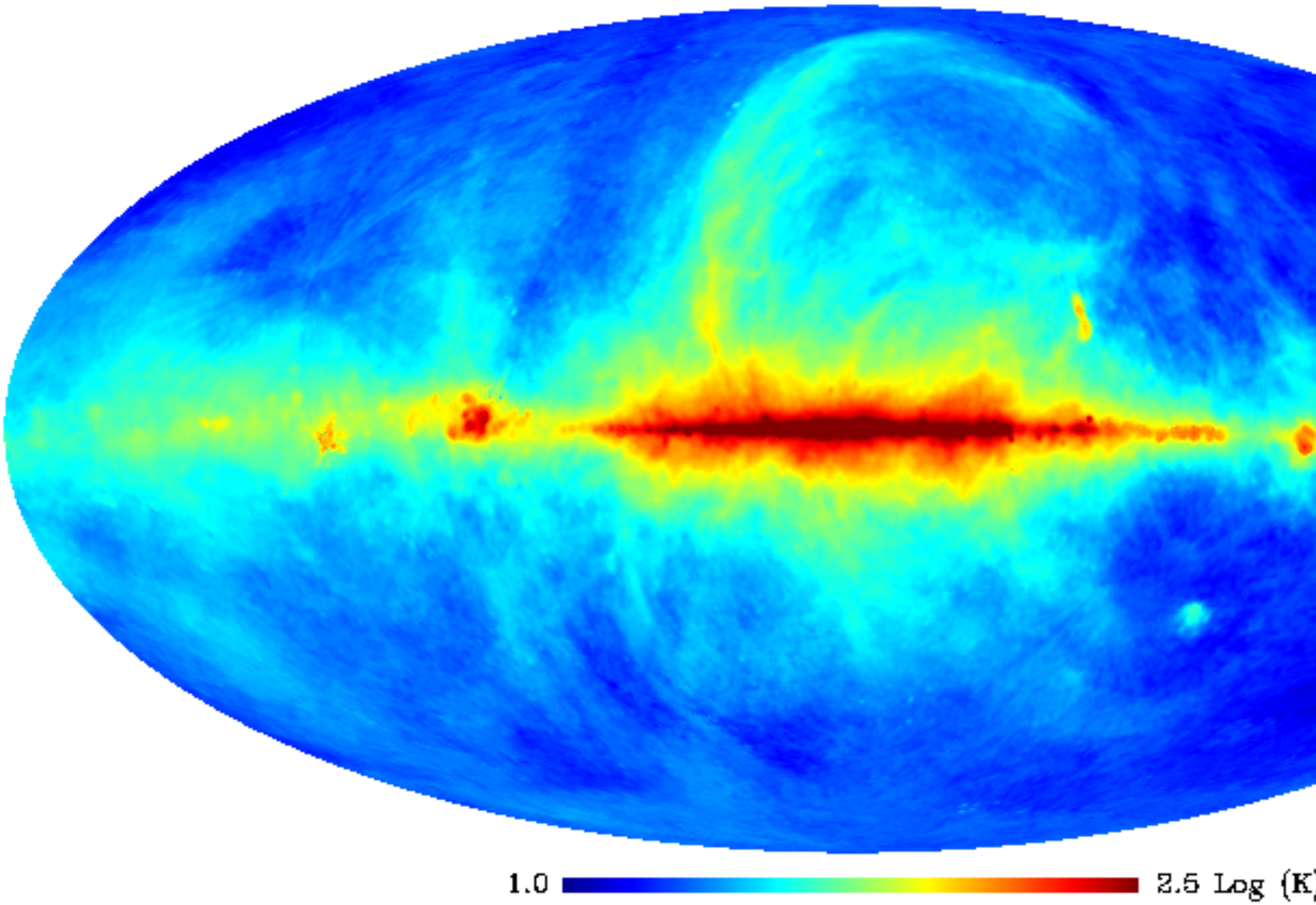
Page *et al.*, ApJS 170 (2007) 335

- probably shells of old SNRs
- can only observe 4 radio loops directly in radio sky
- total Galactic population of up to O(1000) can contribute on *all* scales

Radio loops

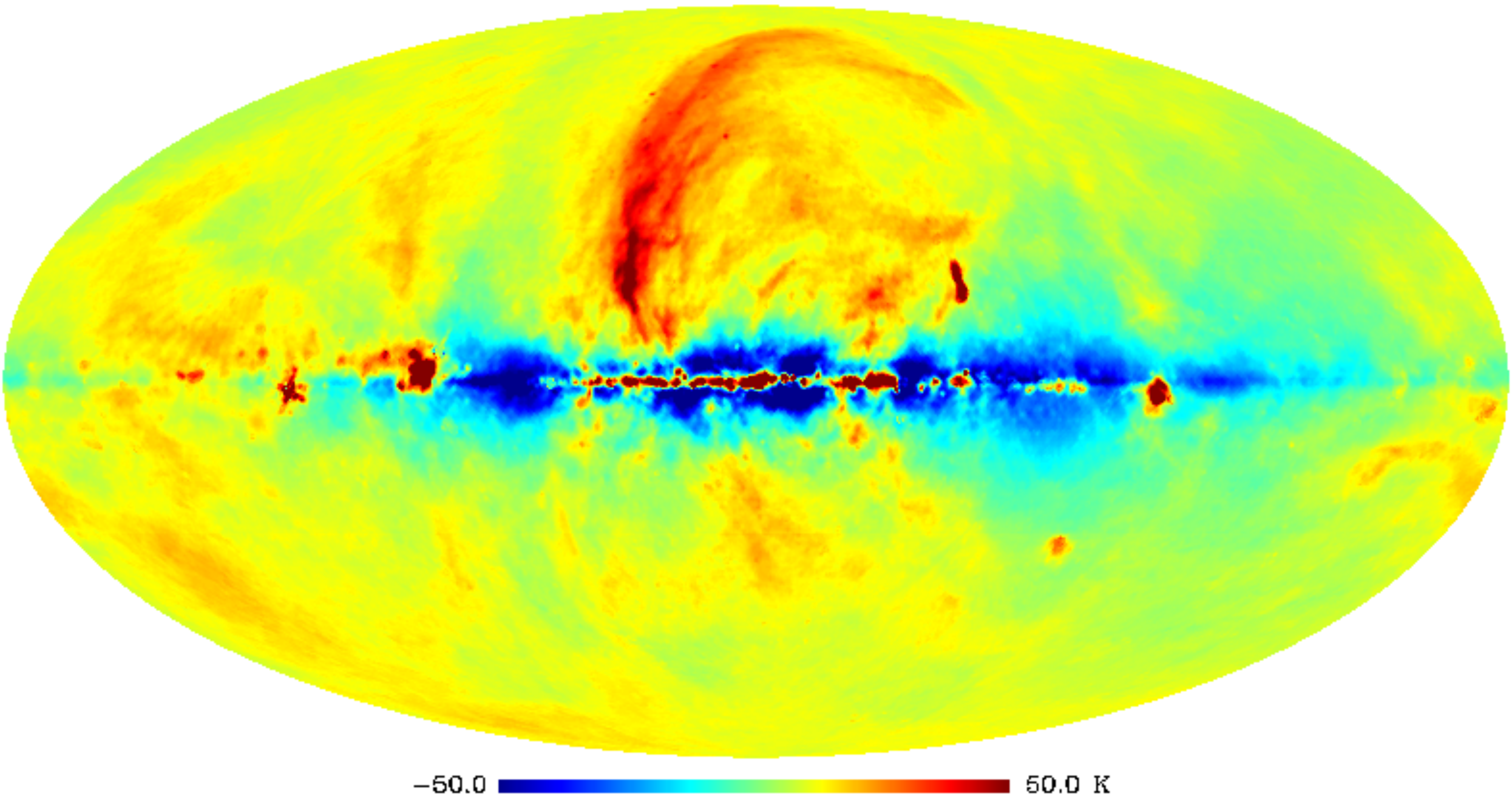


Haslam 408 MHz

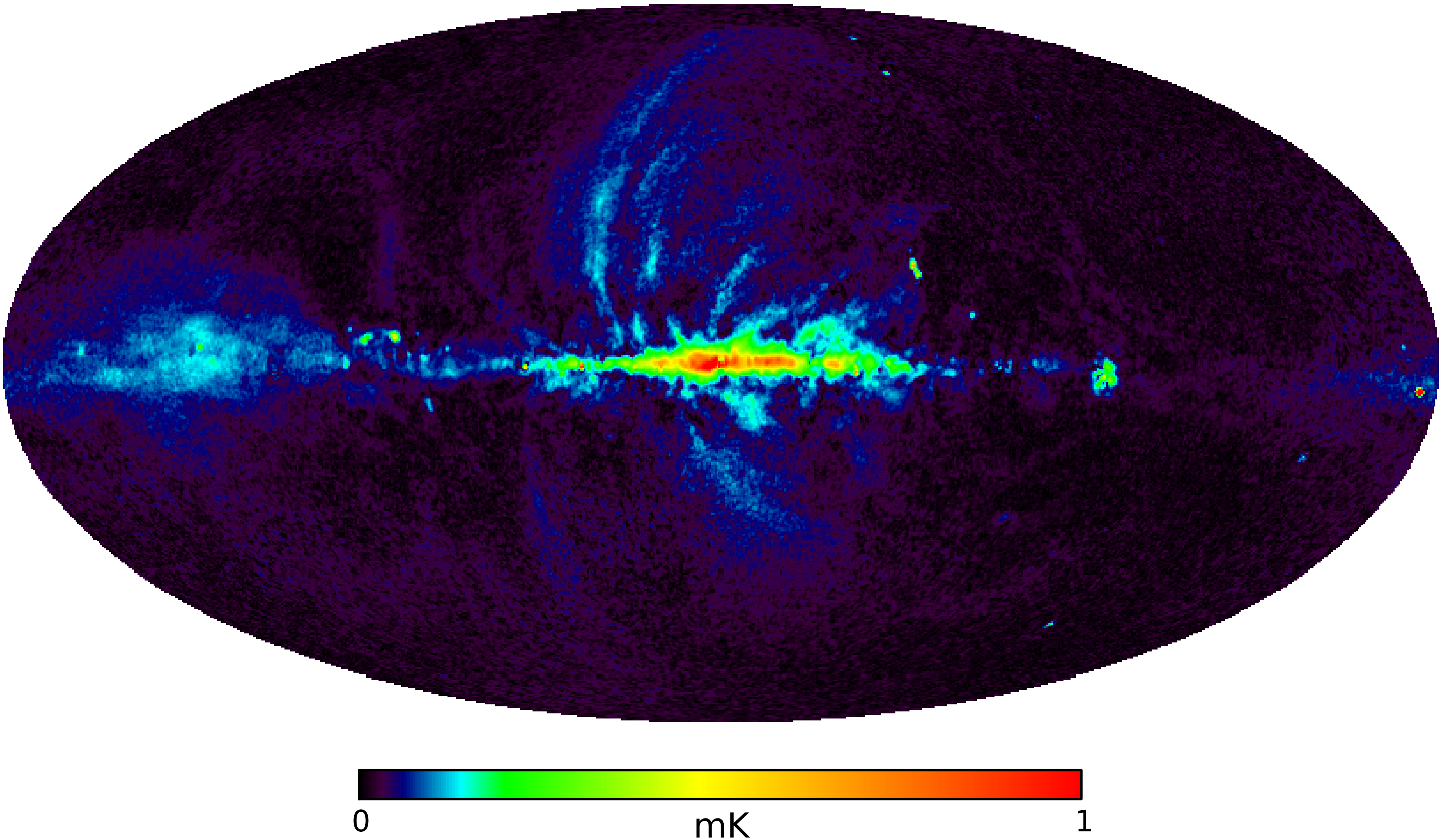


Haslam *et al.*, A&AS **47** (1982) 1

Difference: Haslam - GALPROP

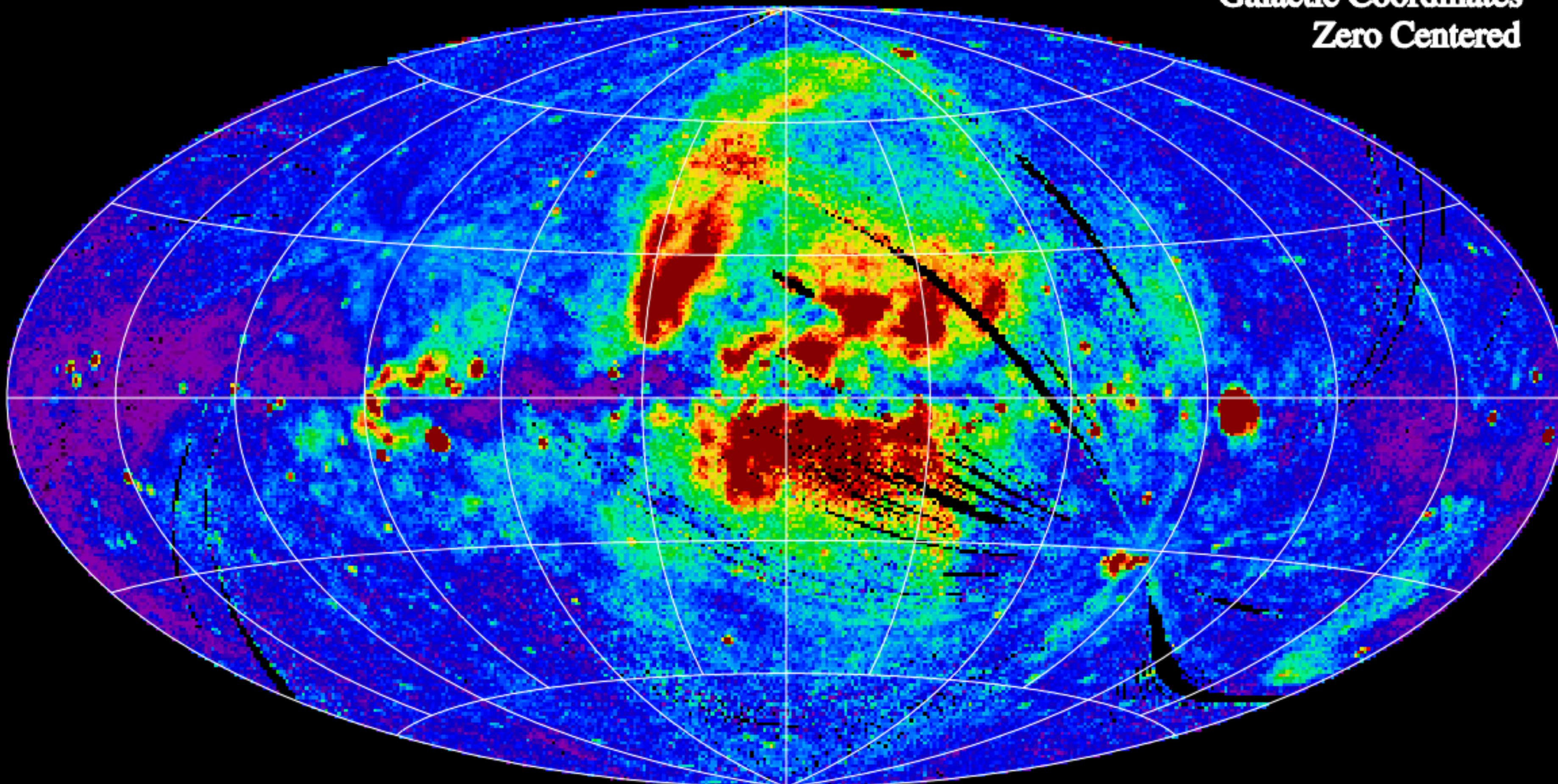


WMAP9 polarisation



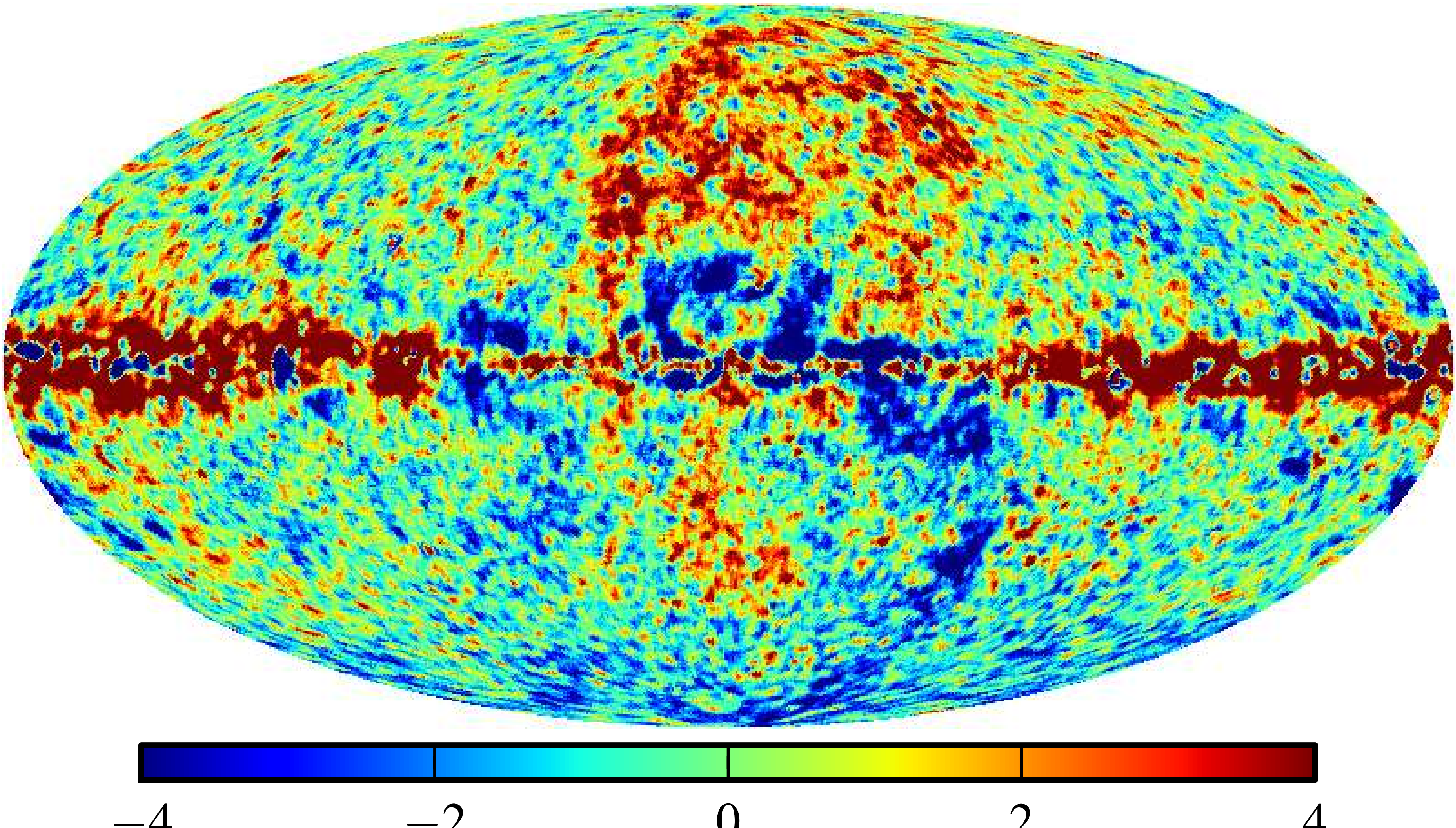
Bennett *al.*, ApJS **208** (2013) 20

ROSAT 0.75 keV



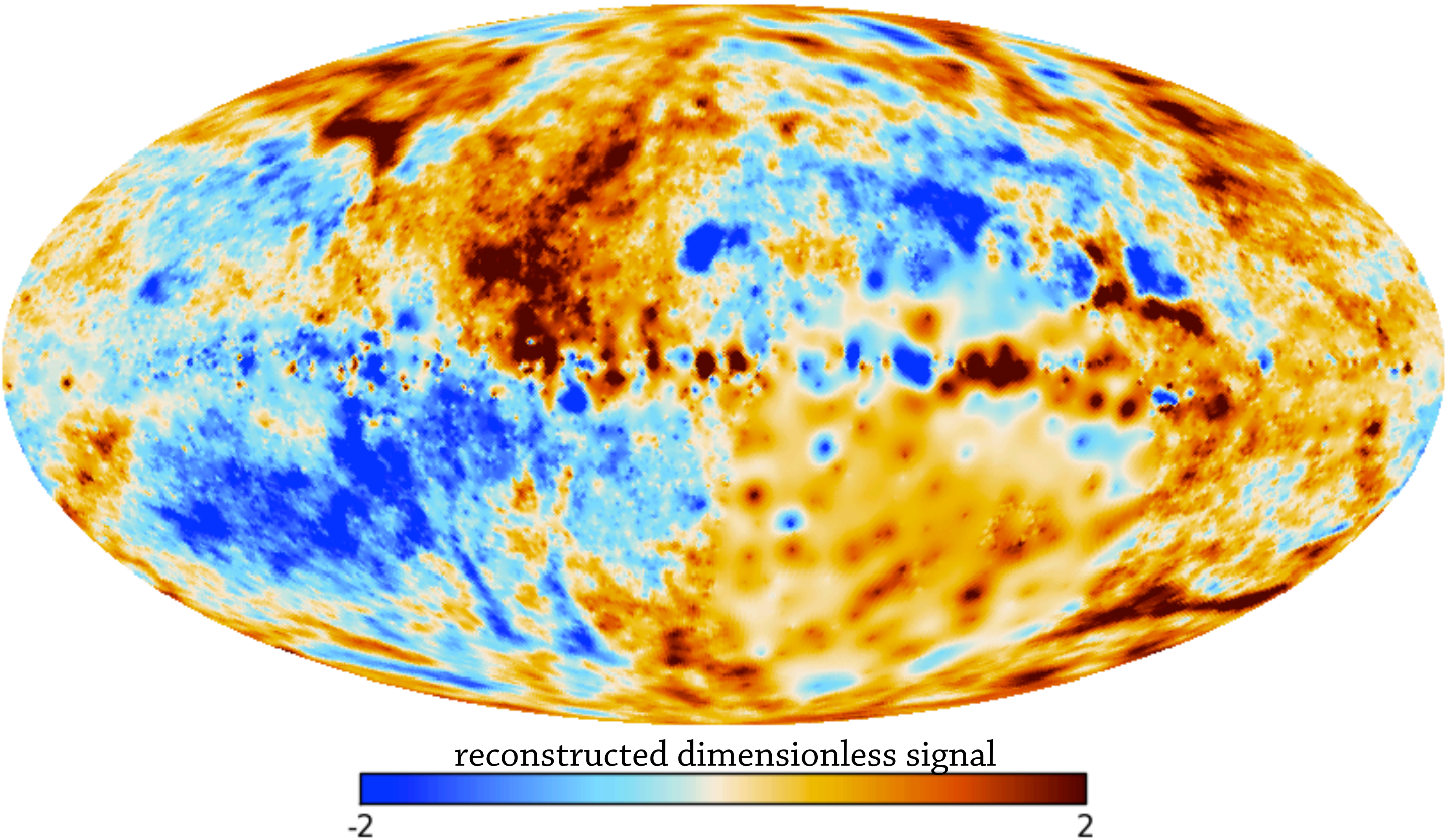
Snowden et al. 1995, ApJ, 454, 643

Difference: Fermi-LAT - GALPROP



Ackermann *et al.*, ApJ **750** (2012) 35

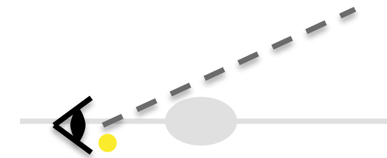
Faraday Rotation



Oppermann *et al.*, A&A **542** (2012) 14

Modelling individual shells

Mertsch & Sarkar, JCAP 06 (2013) 041

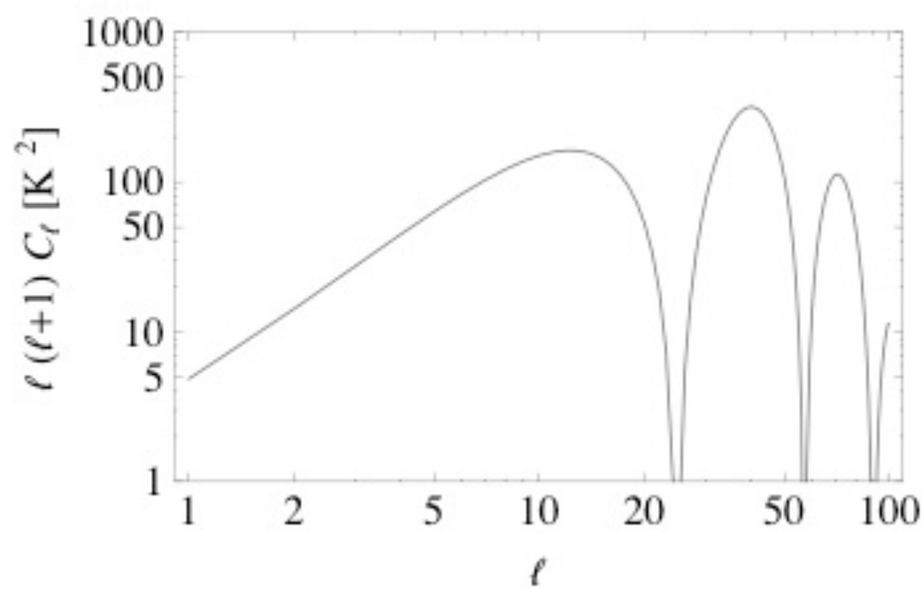


assumption: flux from one shell factorises into angular part and frequency part: $J_{\text{shell } i}(\nu, \ell, b) = \varepsilon_i(\nu) g_i(\ell, b)$

frequency part $\varepsilon_i(\nu)$:
magnetic field gets compressed in SNR shell
electrons get betatron accelerated
emissivity increased with respect to ISM

angular part $g_i(\ell, b)$:
assume constant emissivity in thin shell:

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



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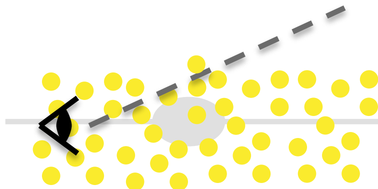

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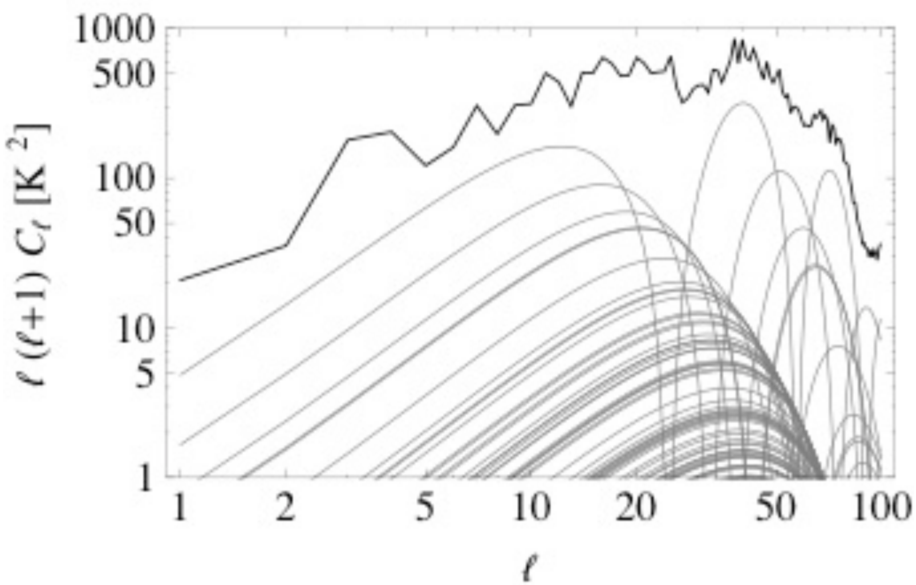
angular part $g_i(\cos\psi)$:
assume constant emissivity in thin shell:

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

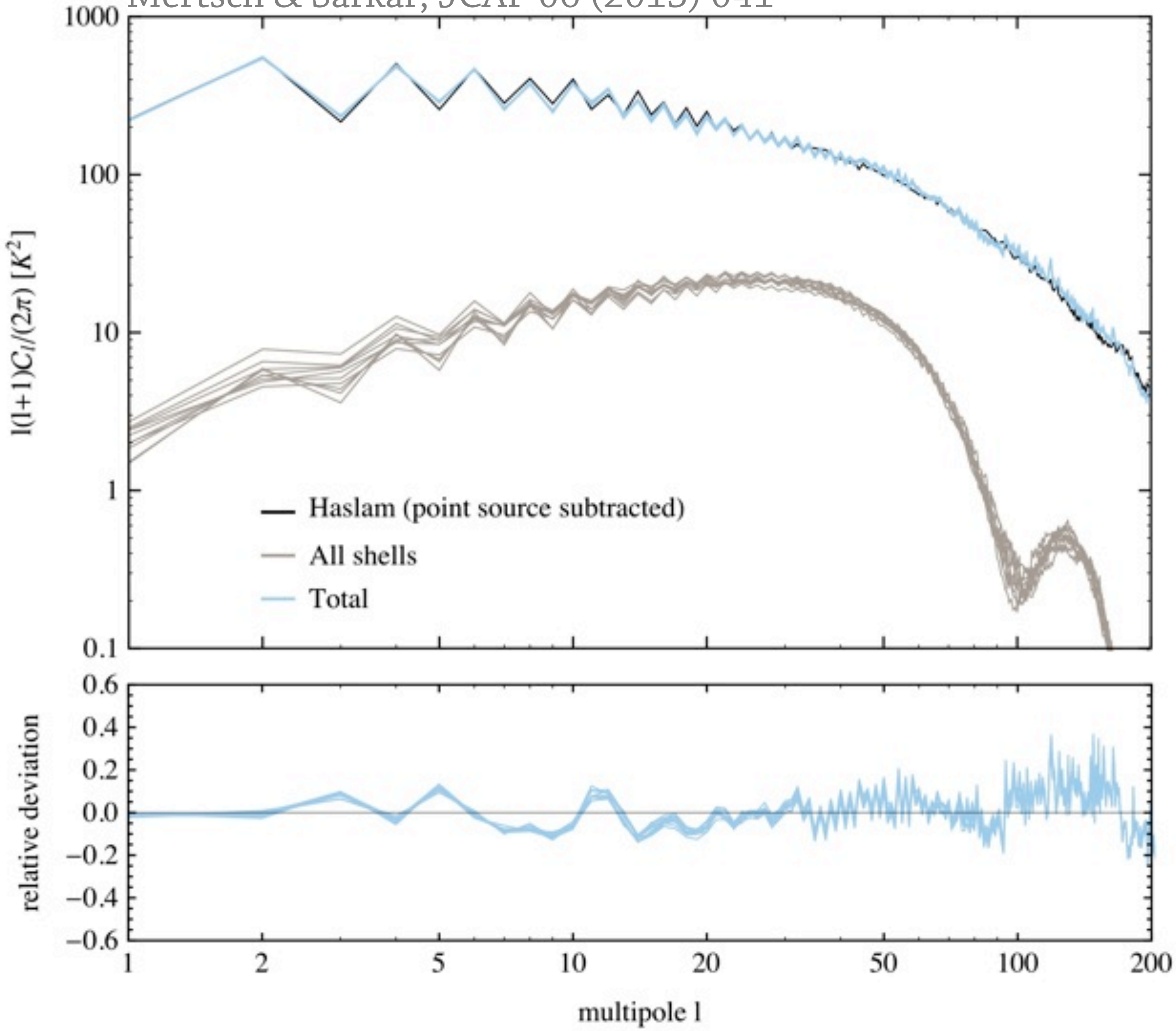
add up contribution from all shells

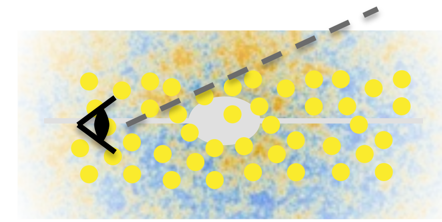
$$a^{\text{total}}_{lm} = \sum_i a^i_{lm}$$



...including ensemble of shells

Mertsch & Sarkar, JCAP 06 (2013) 041





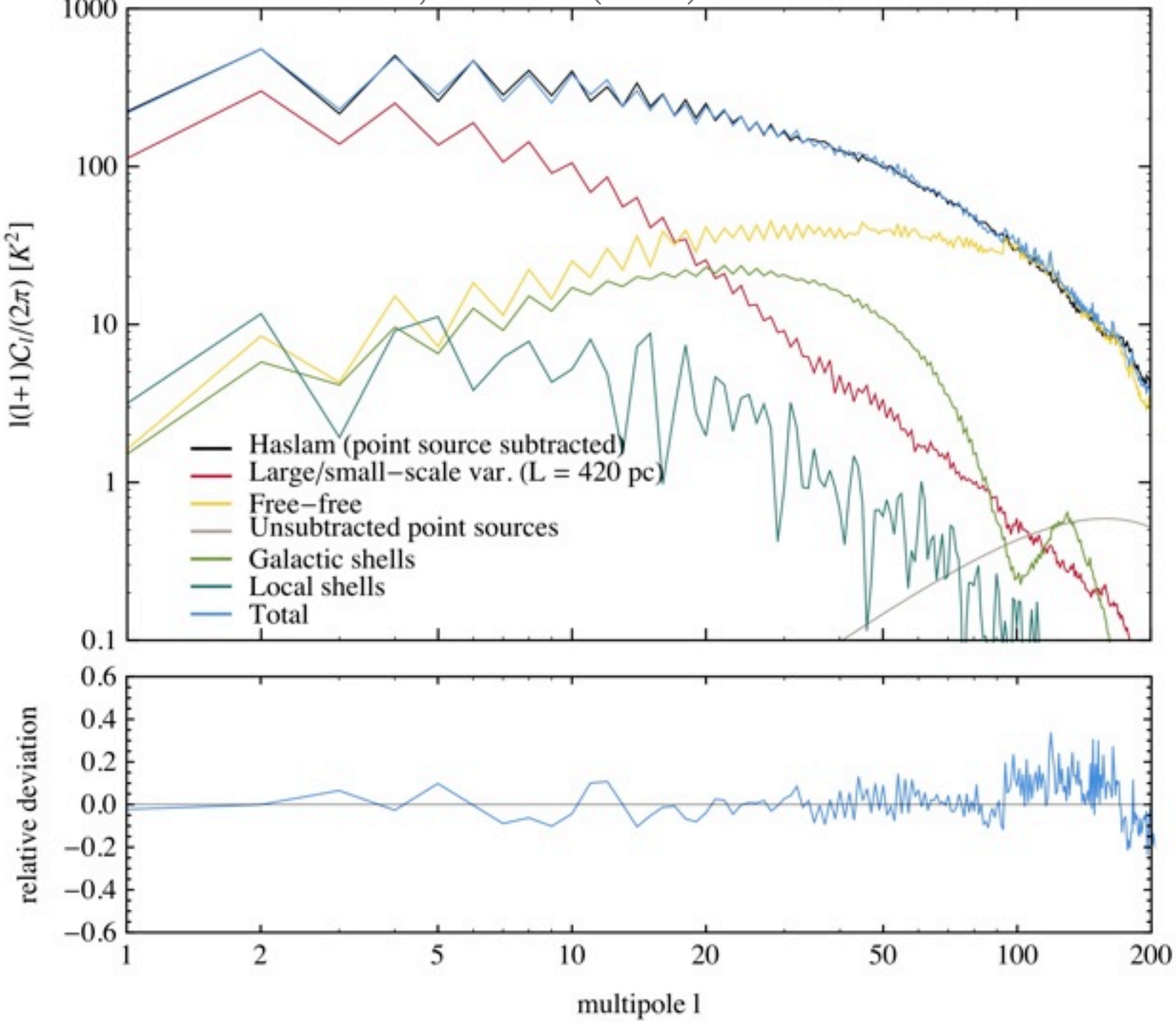
O(1000) shells of old SNRs present in Galaxy

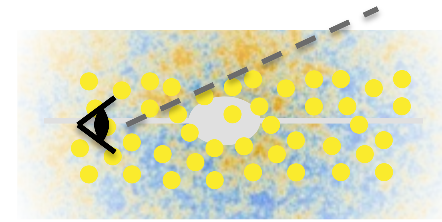
we know 4 local shells (Loop I-IV) but others are modeled in MC approach

they contribute *exactly* in the right multipole

Best fit of local shells and ensemble

Mertsch & Sarkar, JCAP 06 (2013) 041





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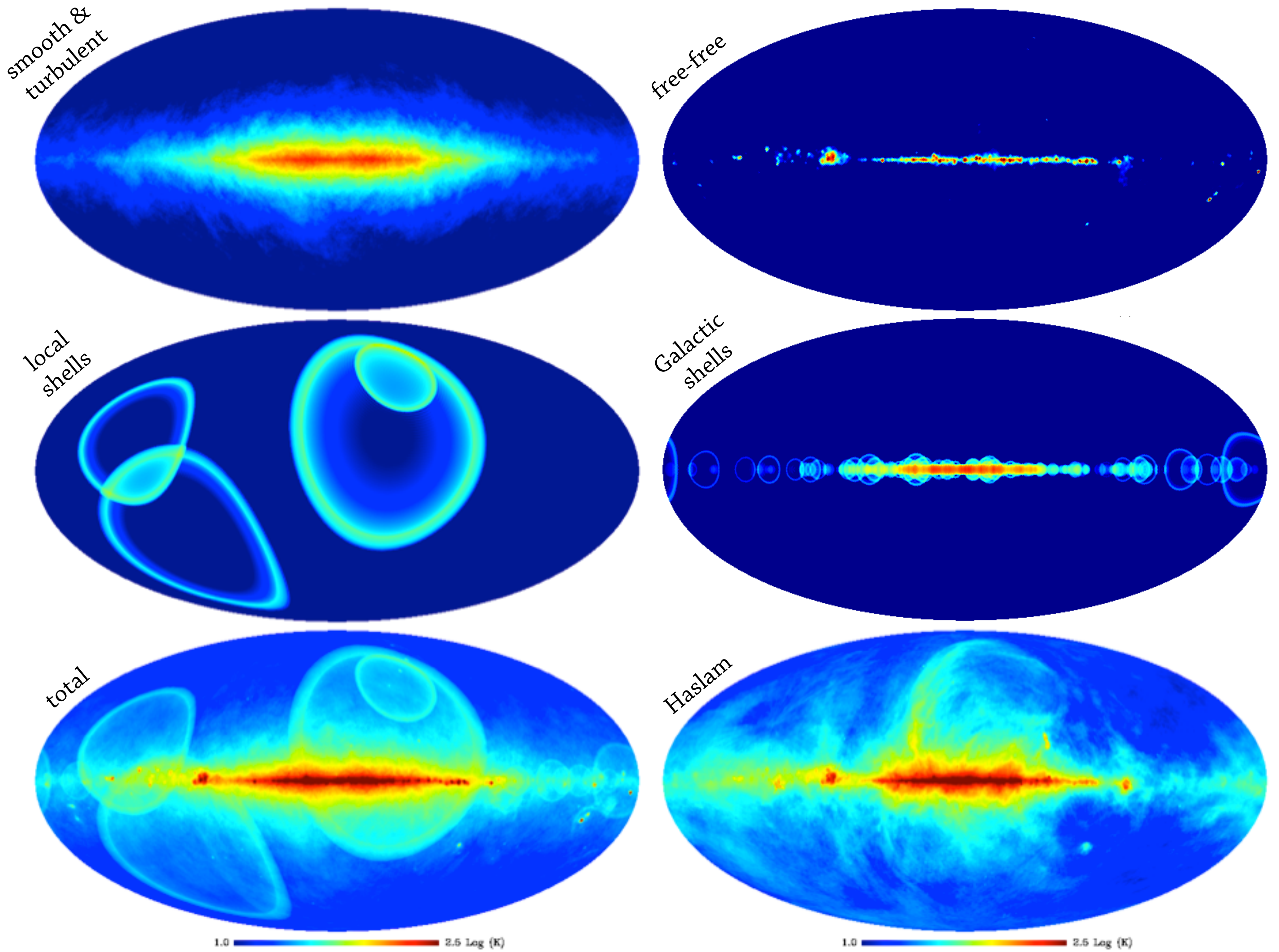
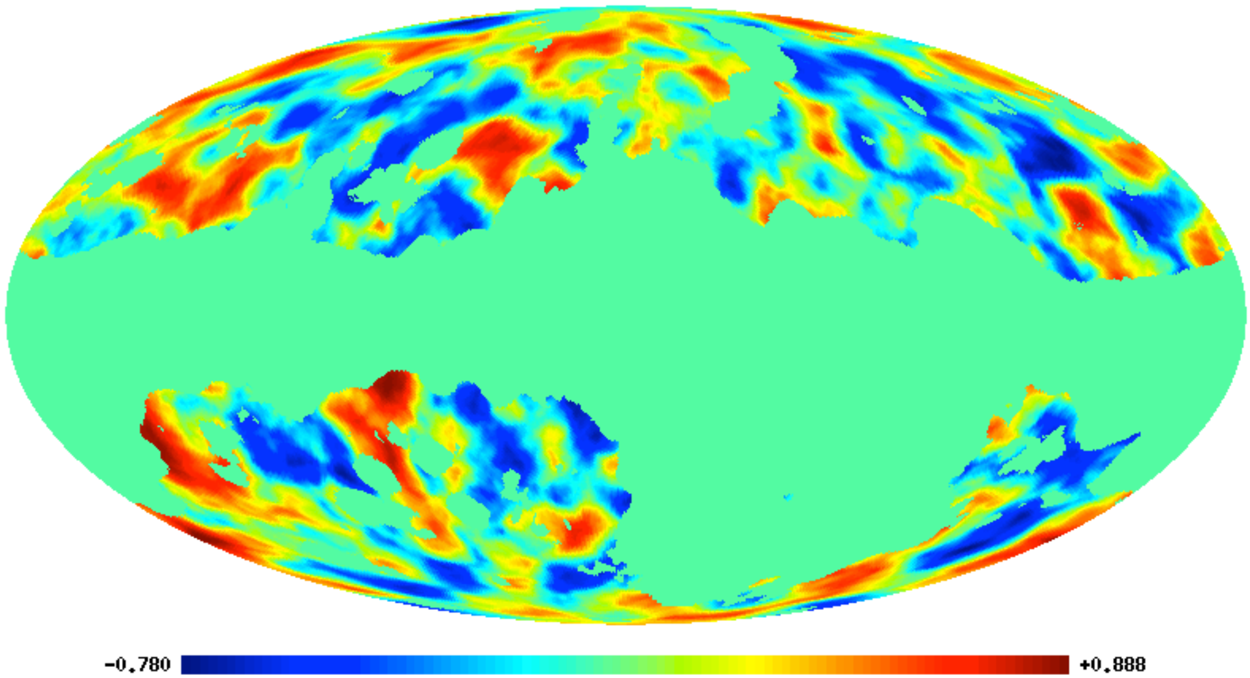

smooth & turbulent
free-free
local shells
Galactic shells
total
Haslam
1.0
2.5 Log (K)
1.0
2.5 Log (K)

CMB contamination at high latitude?

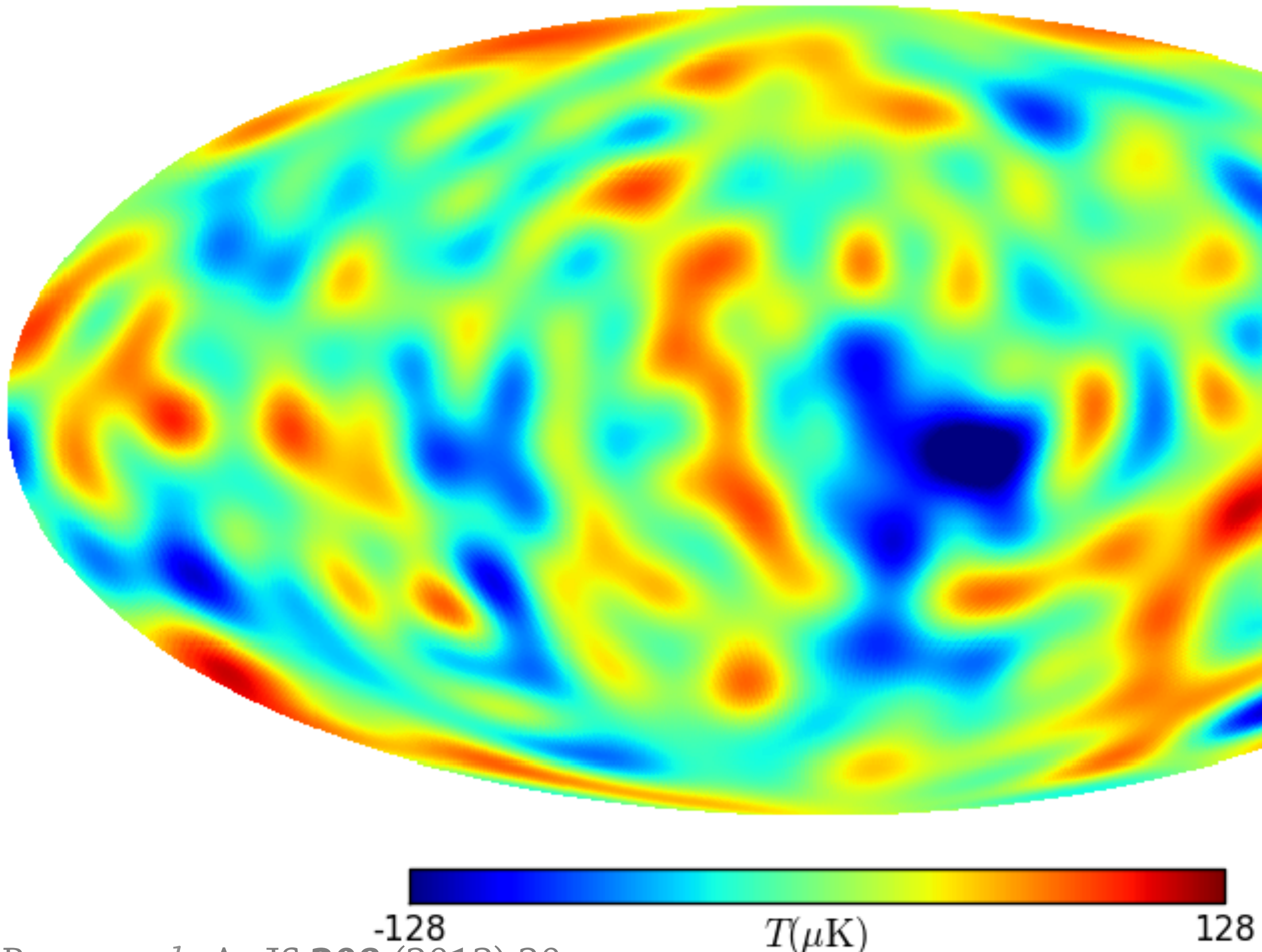


correlation between Faraday depth and WMAP7 ILC

MC simulations: standard deviation of correlation anomalous with p-value $< 5 \times 10^{-4}$

Hansen *et al.*, MNRAS **426** (2012) 57; Dineen & Coles MNRAS **347** (2004) 52

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



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

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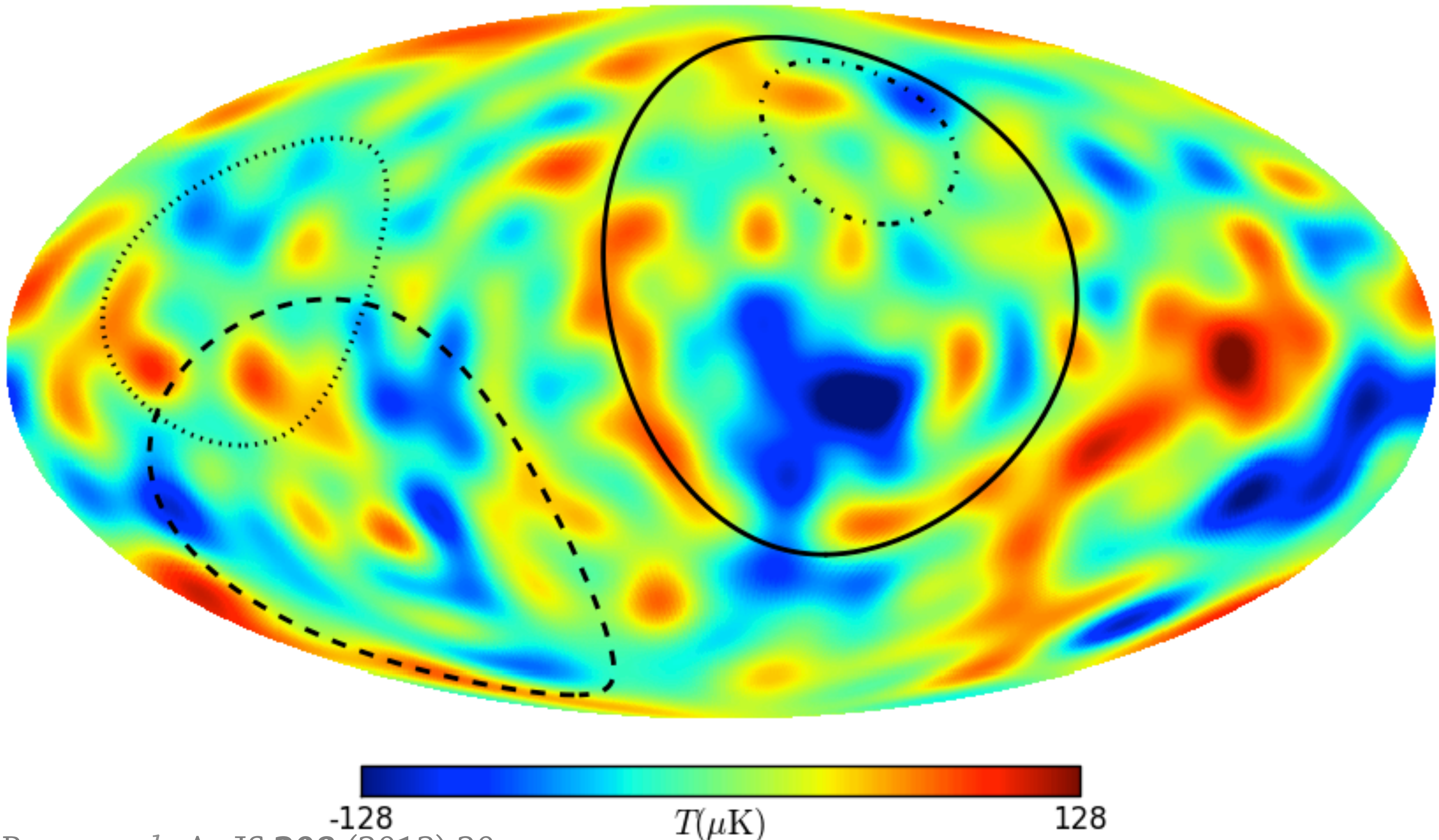

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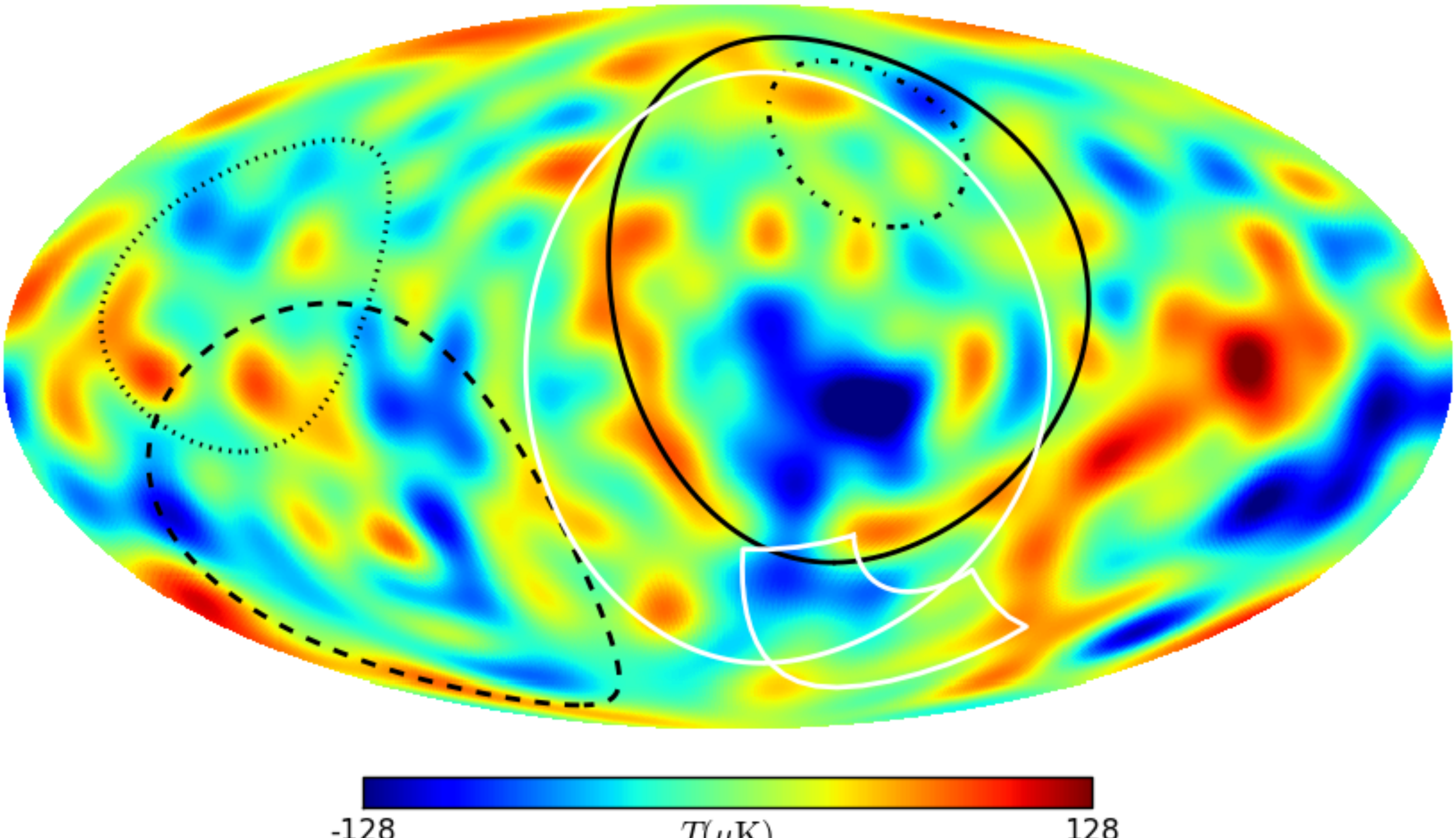
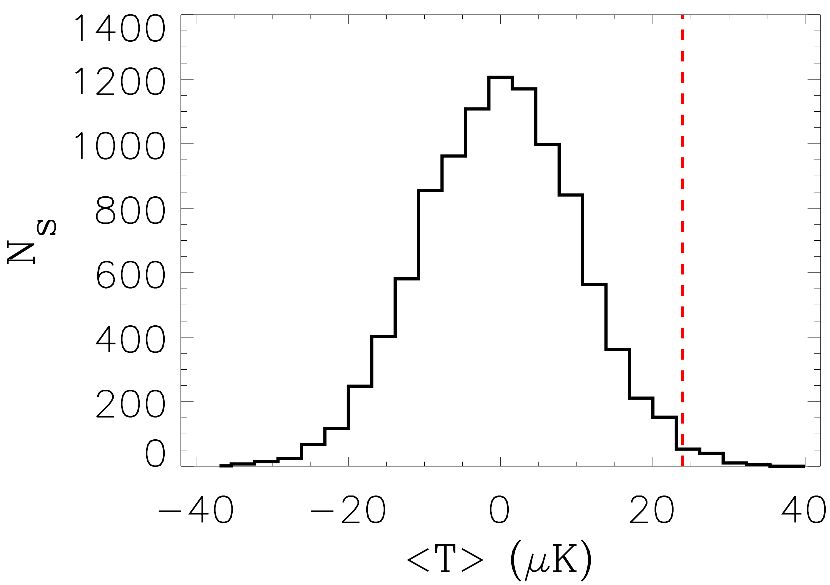


Bennett *al.*, ApJS **208** (2013) 20

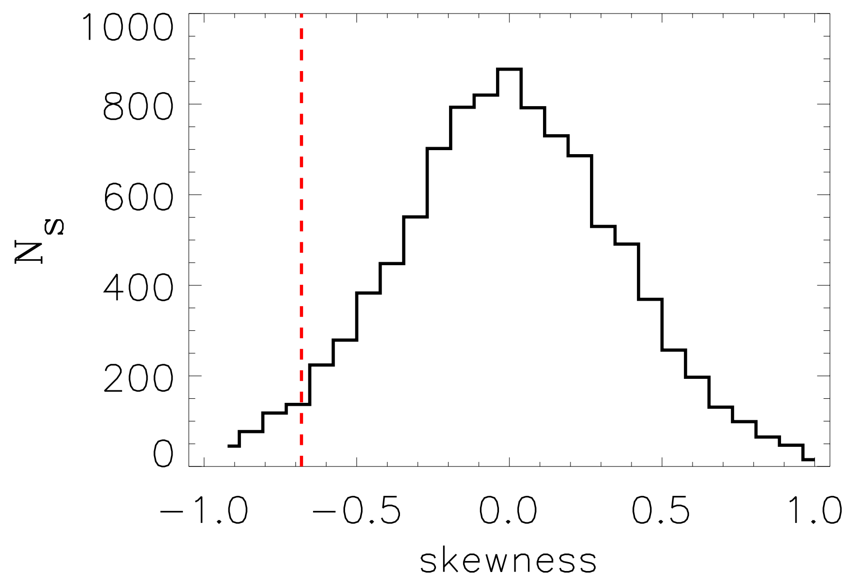
Anomalies in ILC9 ($\ell \lesssim 20$)

in ring around Loop I

temperature



skewness

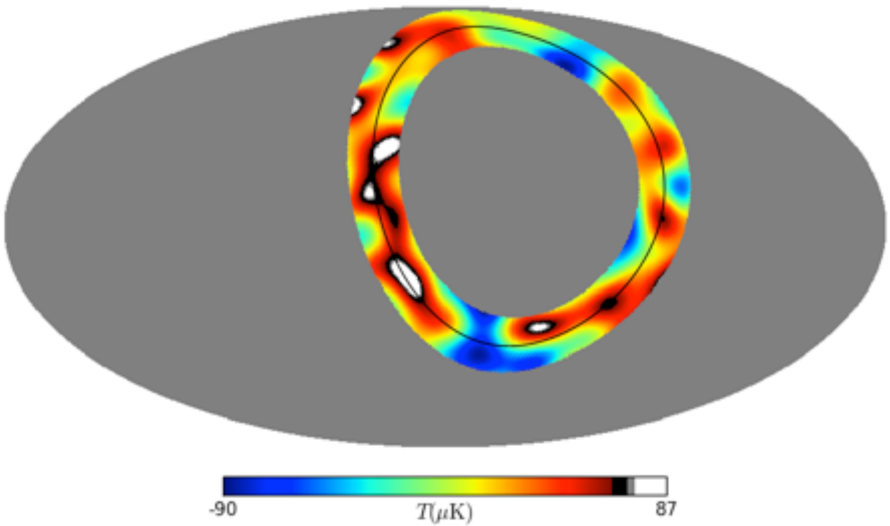


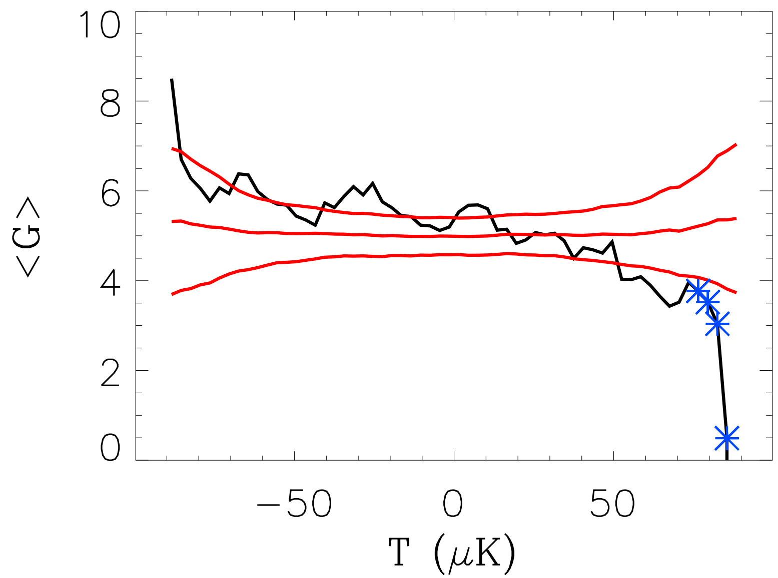
compare with MC ➔ p-values $\mathcal{O}(10^{-2})$

Liu, PM & Sarkar, ApJL **789** (2014) 29

Cluster analysis

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



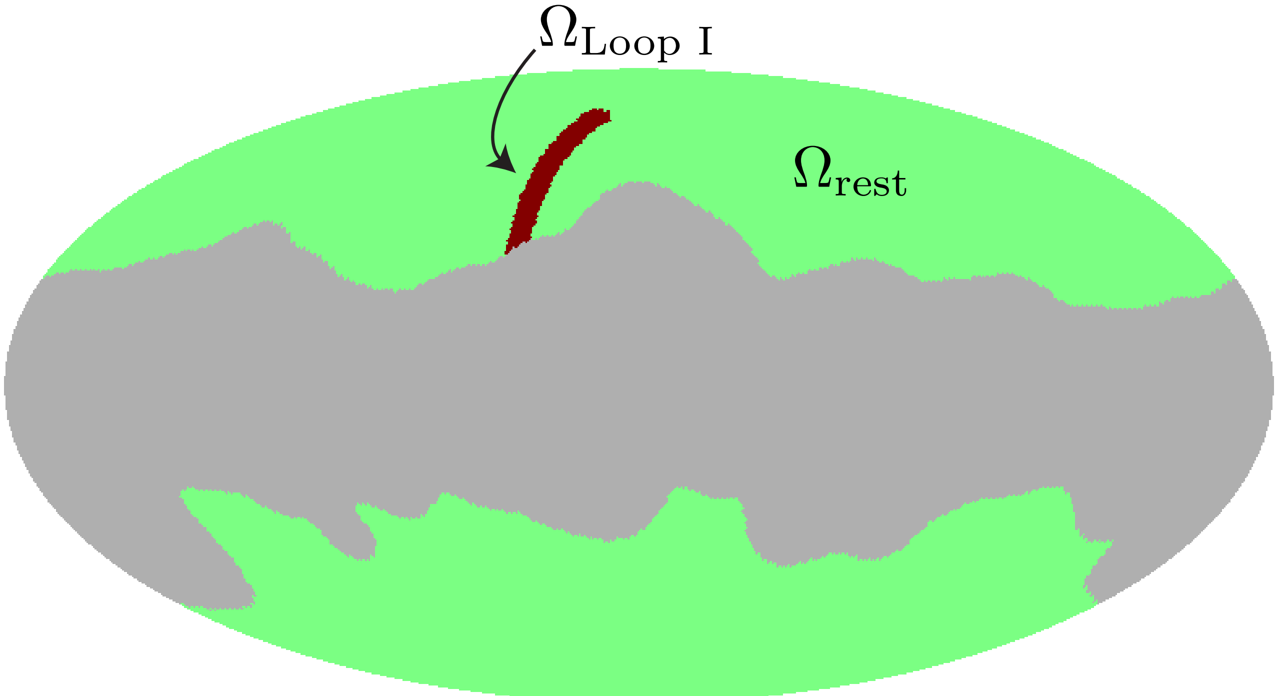


from 100,000 MC runs: probability for smaller $\langle G \rangle$ in last four bins $\sim 10^{-4}$

Liu, PM & Sarkar, ApJL **789** (2014) 29

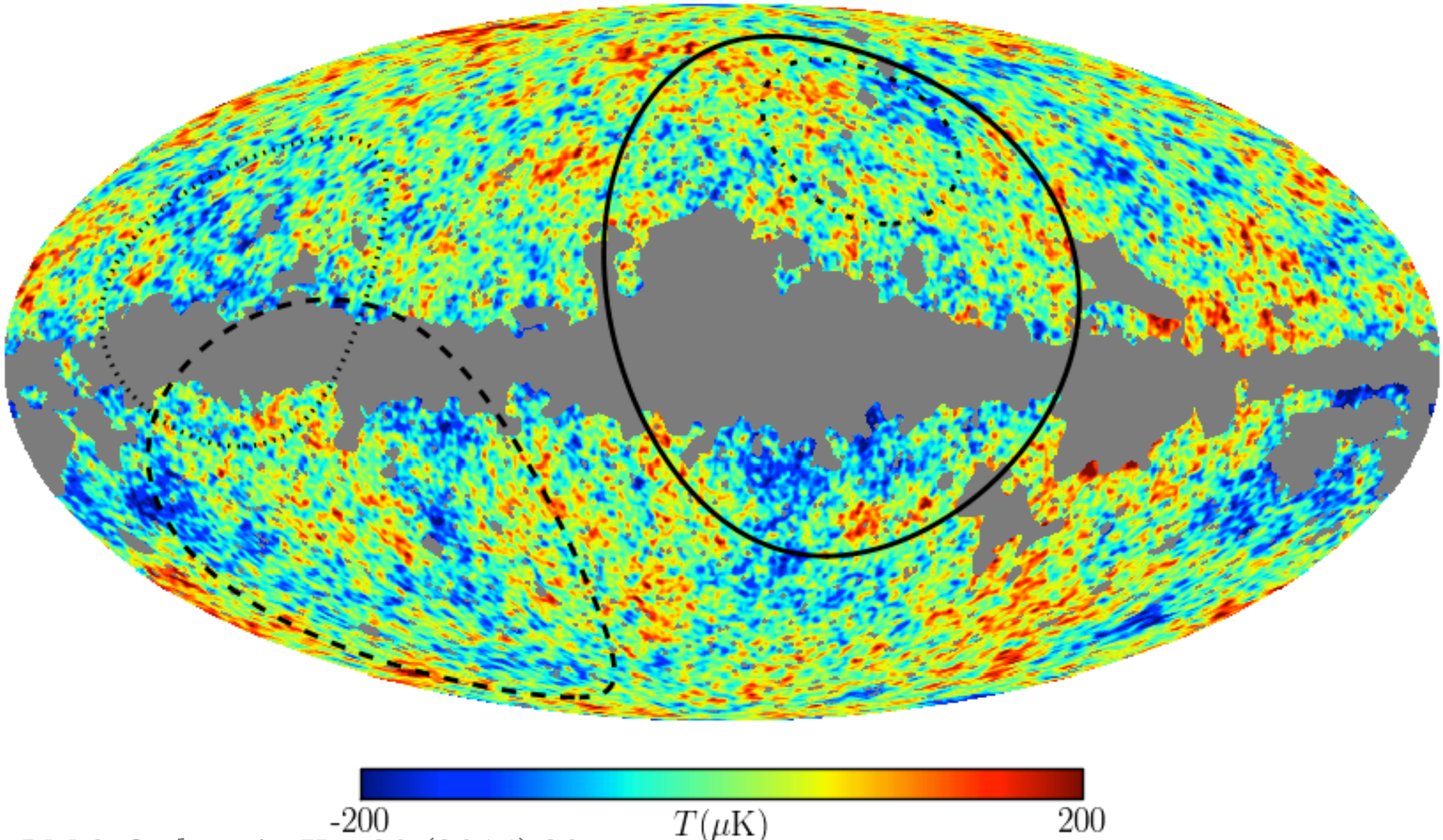
How to evade foreground cleaning:

- ILC coefficients from minimizing variance over whole sky ($\Omega_{\rm rest}$)
- but Loops contribute only locally ($\Omega_{\rm Loop\ I}$)



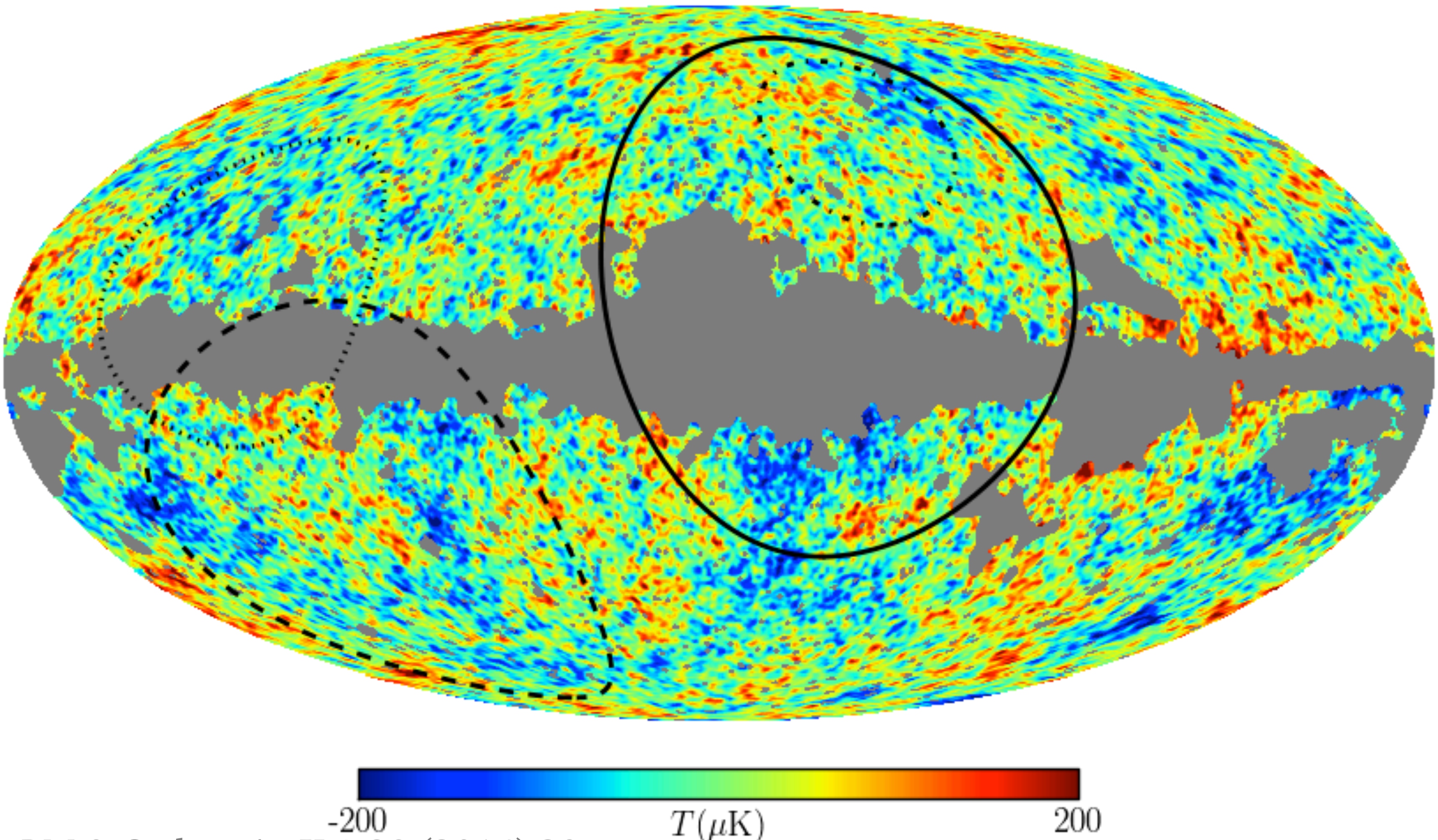
Liu, PM & Sarkar, ApJL **789** (2014) 29

ILC coefficients from Loop I region



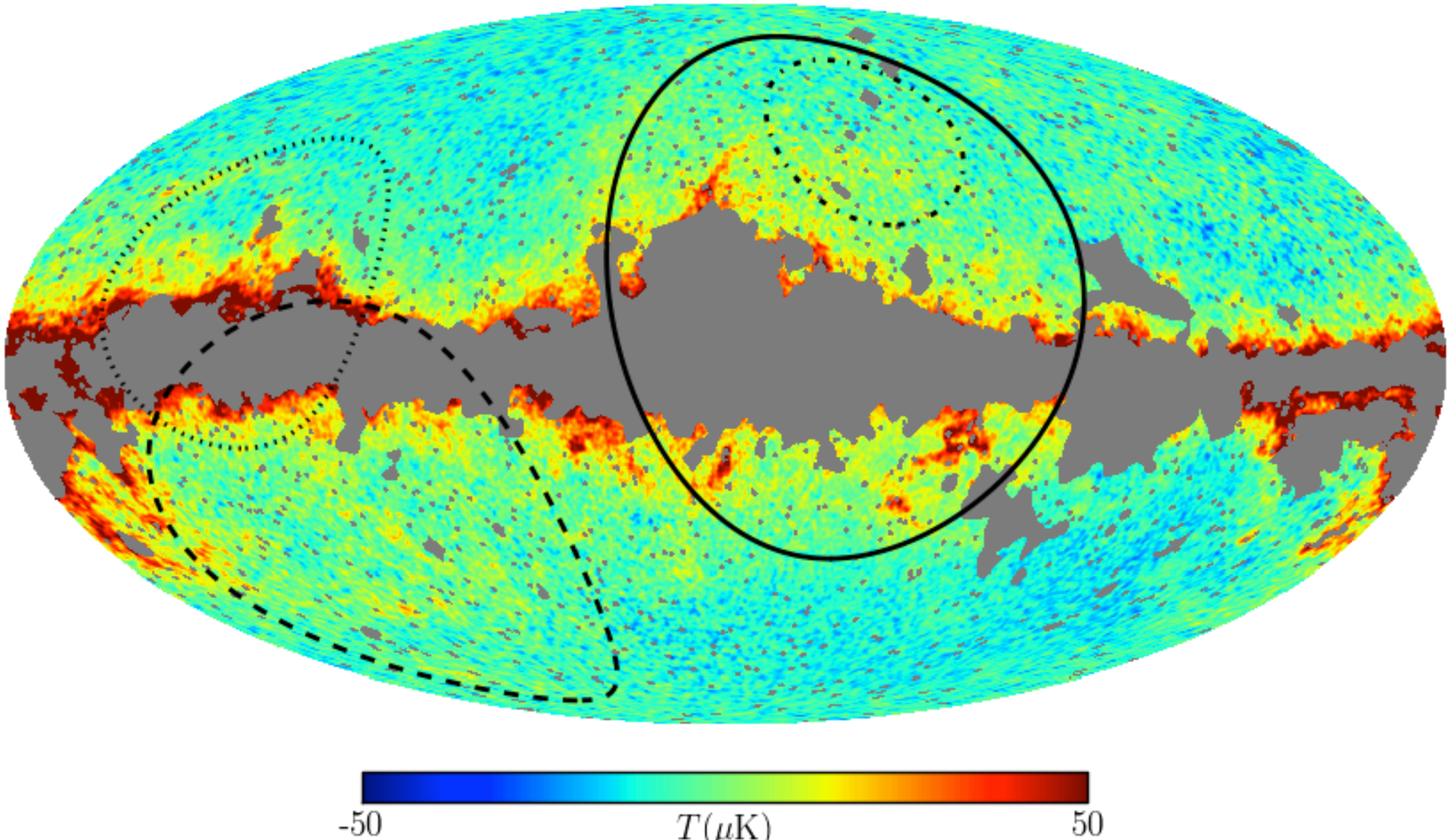
Liu, PM & Sarkar, ApJL **789** (2014) 29

ILC coefficients from rest of sky



Liu, PM & Sarkar, ApJL **789** (2014) 29

difference $\text{ILC}_{\text{rest}} - \text{ILC}_{\text{Loop I}}$



Liu, PM & Sarkar, ApJL **789** (2014) 29

What do we know about anomaly?

- spatially correlates with Loop I
- unlikely synchrotron (checked with our synchrotron model)
- frequency dependence:

which spectral index β gets "zeroed" by ILC method,

i.e. solve $\sum_{j=\mathrm{K}}^{\mathrm{W}} W_j \nu_j^{\beta} = 0$ for β

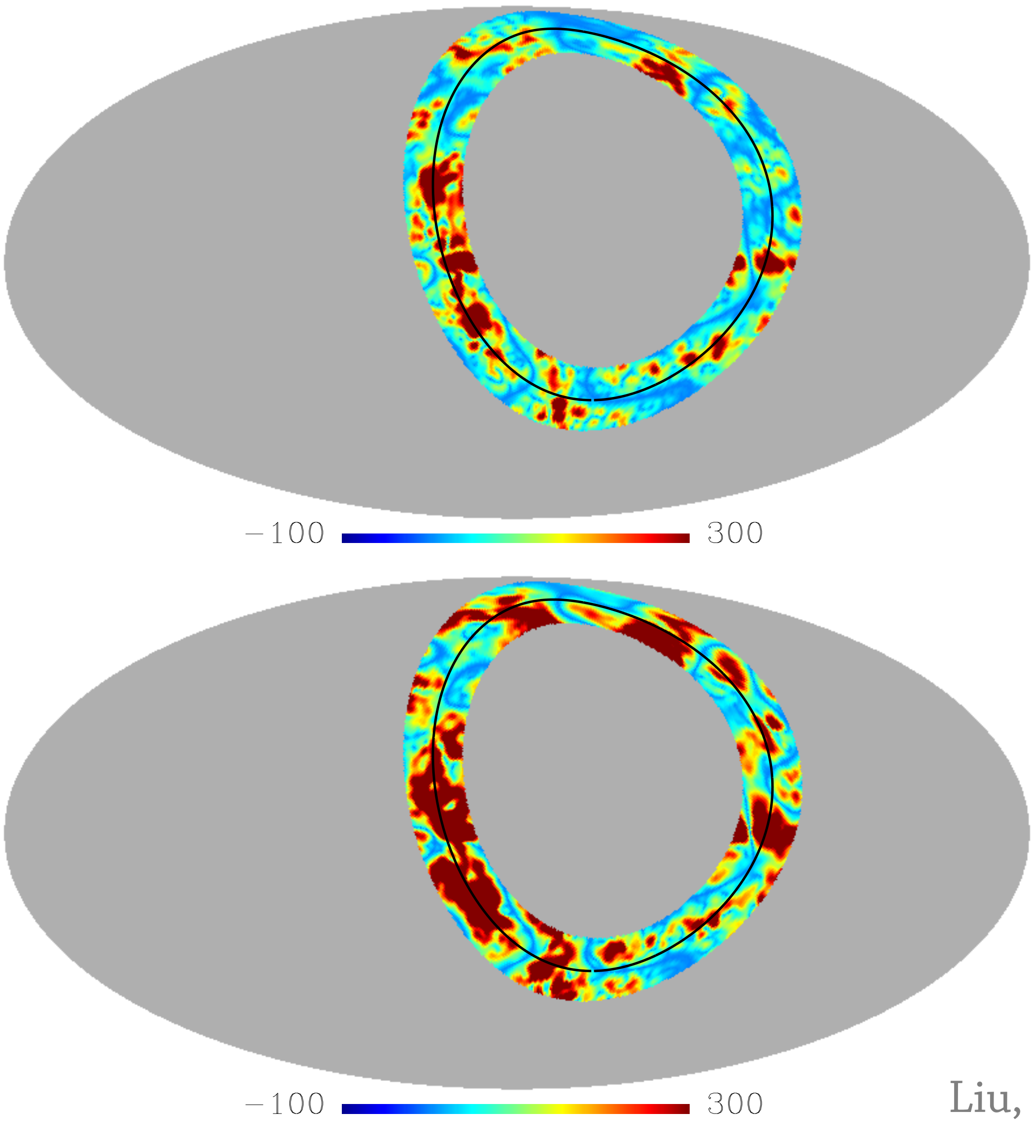
for WMAP9: $\beta \sim -3, -2$ and $1.7 \ldots 1.8$

synch free-free thermal dust

for Loop region: $\beta \sim -3$ and ~ 1.4

Liu, PM & Sarkar, ApJL **789** (2014) 29

Spectral index



- WMAP polarised intensity in
  - W (60 GHz)
  - V (90 GHz)
- correlate with ILC9
- ratio of average intensities in Loop I region: 1.7
- spectral index: ~1.3

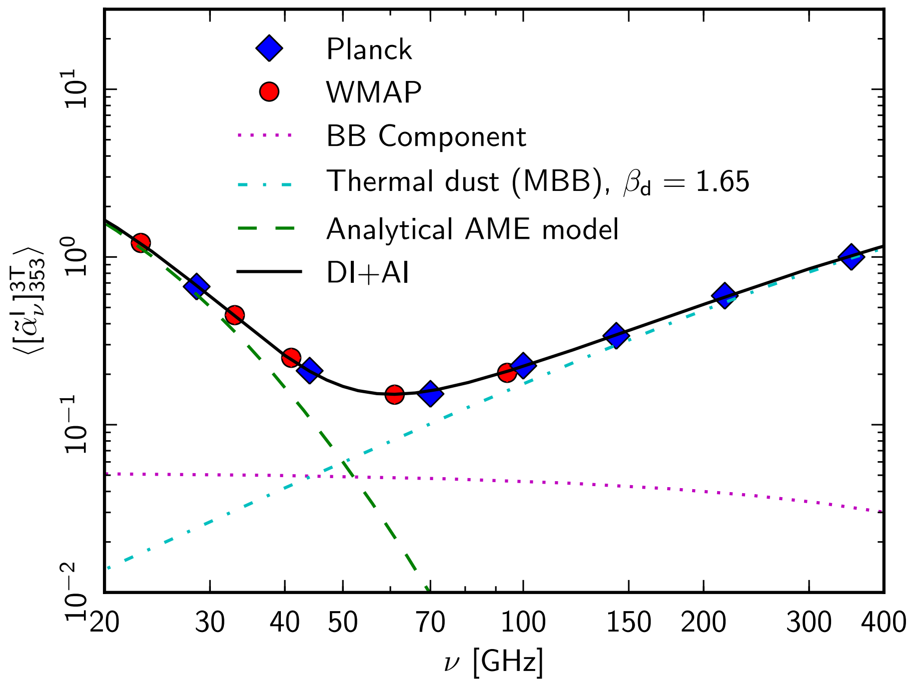
Liu, PM & Sarkar, ApJL **789** (2014) 29


DUST

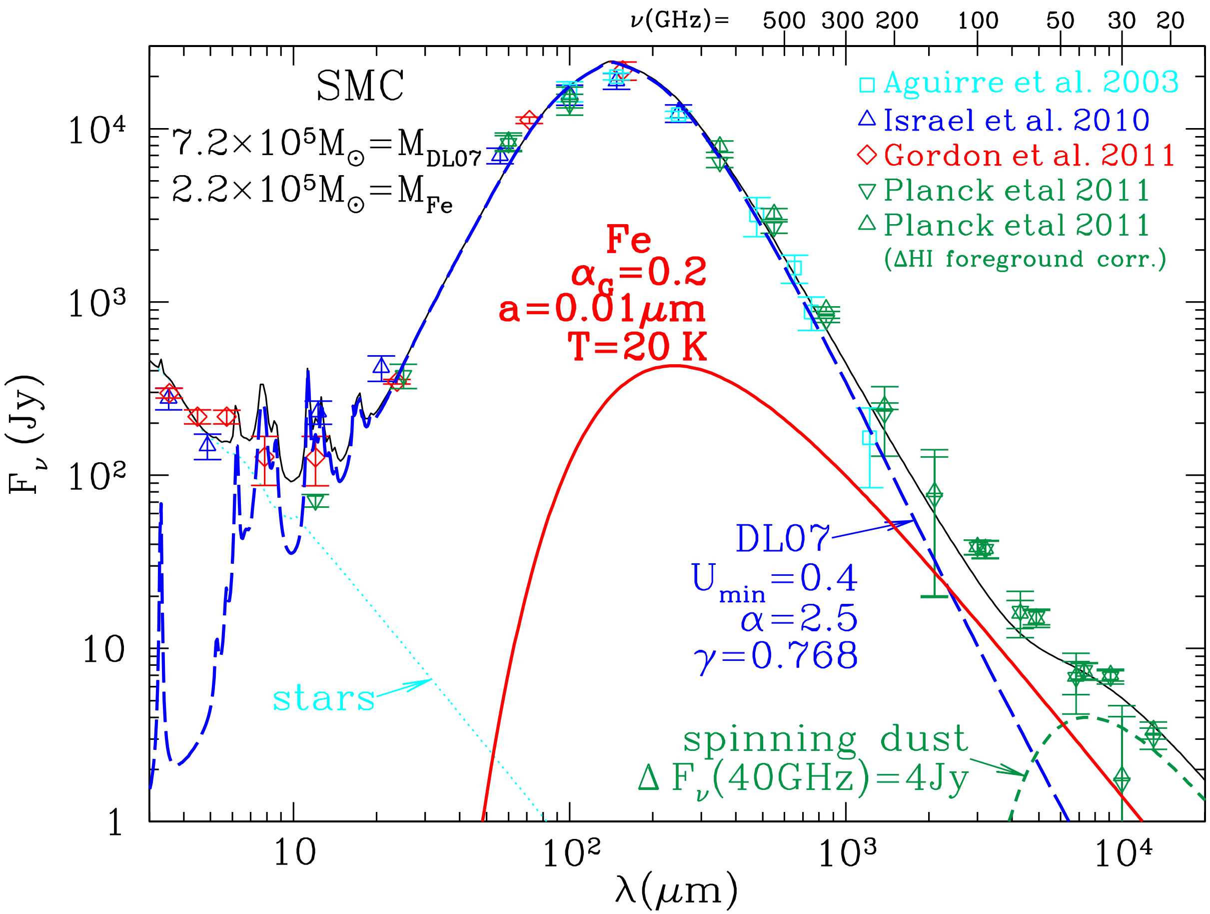
Evidence for magnetised dust I

- correlation $\alpha_{353}(\nu)$ of WMAP and *Planck* frequency maps with dust template (353 GHz) in intensity and polarisation
- model as
  - CMB: achromatic
  - synchrotron: $A_s \nu^{\beta_s}$
  - thermal dust: $A_d \nu^{\beta_d} B(\nu, T_d)$
  - AME: spinning dust
- in intensity: $T_d \simeq 19\,\mathrm{K}$ and $\beta_d \simeq 1.52$ (cf. in FIR, $\beta_d \sim 1.7$)
- possible interpretation: magnetised dust, BB spectrum

→ 7σ evidence for magnetised dust?!



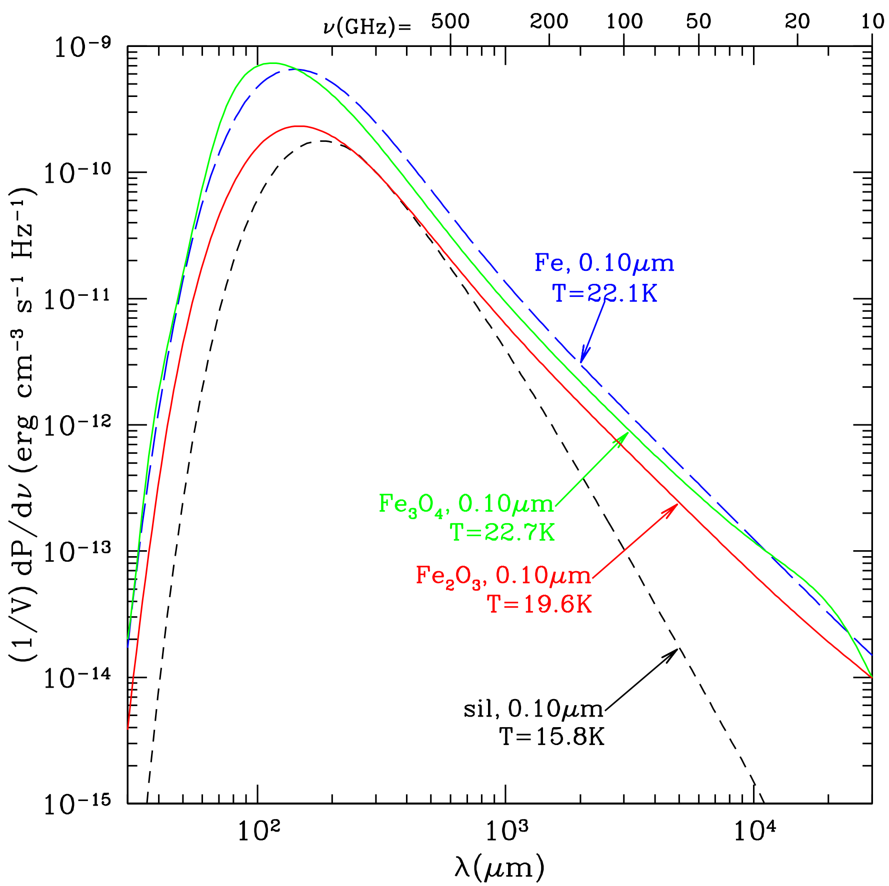
Evidence for magnetised dust II

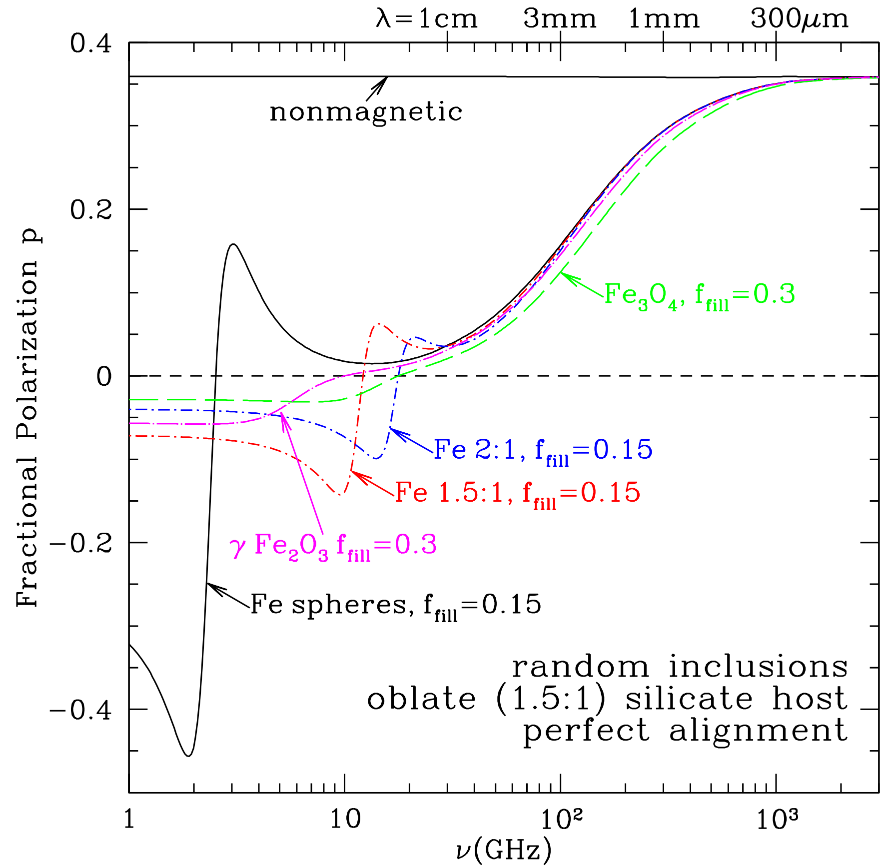


- thermal dust typical $\beta \sim 1.6 \ldots 1.7$
- spinning dust low-ν foreground
- magnetic dust very flat spectra, down to $\beta \sim 0$, depending on compound, grain size, resonances…

Draine & Hensley, ApJ **757** (2012) 103

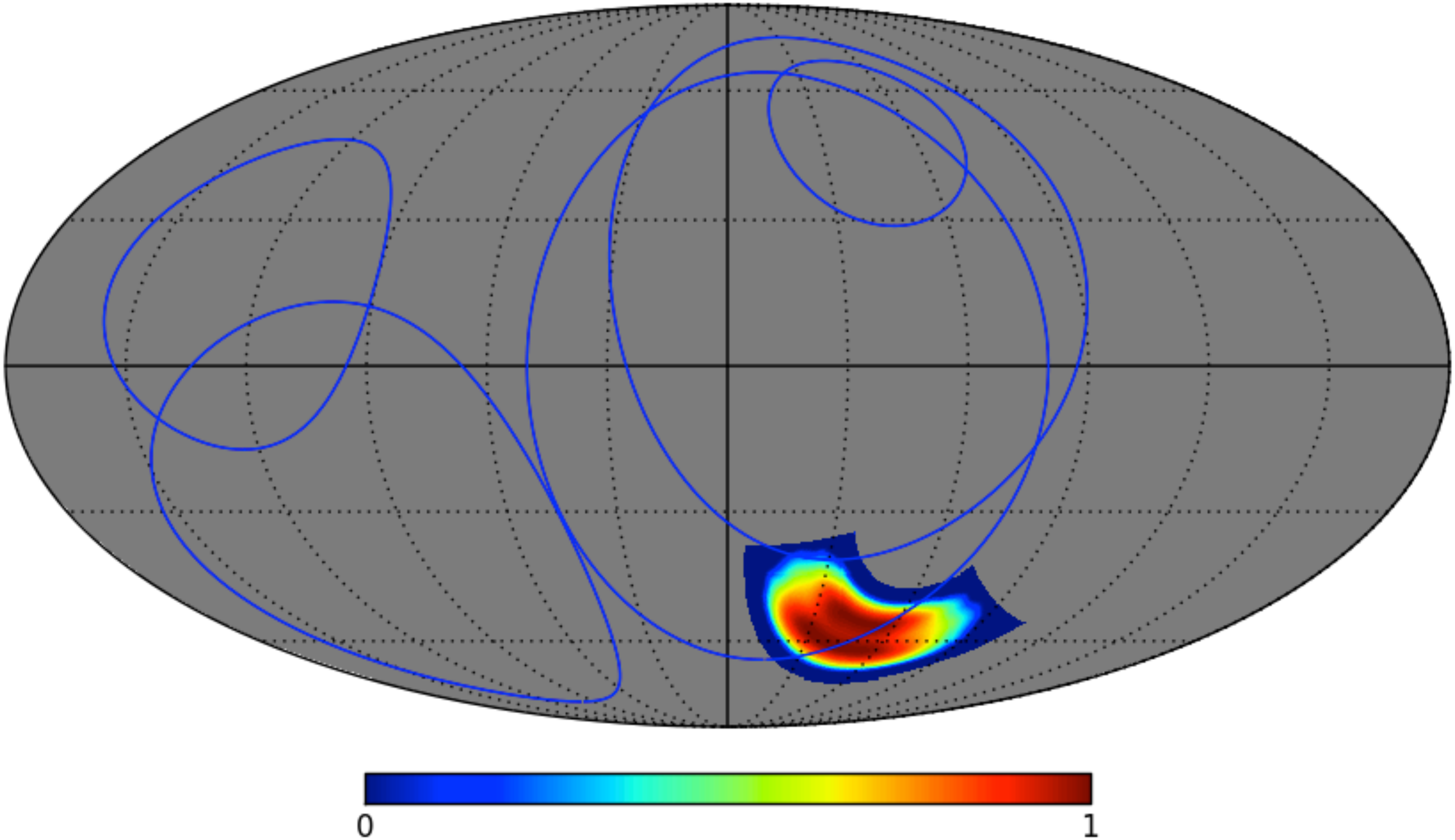
Magnetic dipole radiation



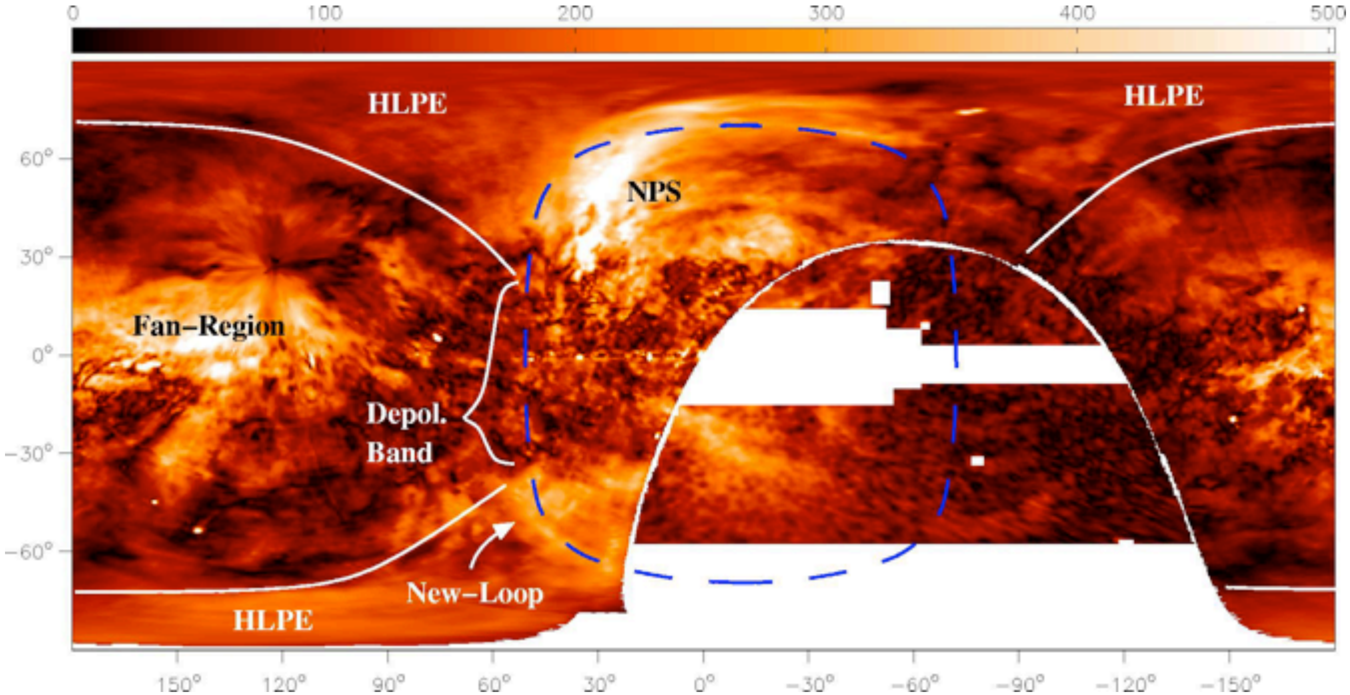


Draine & Lazarian, ApJ **508** (1998) 157, *ibid.*, ApJ **512** (1999) 740
Draine & Hensley, ApJ **765** (2013) 169

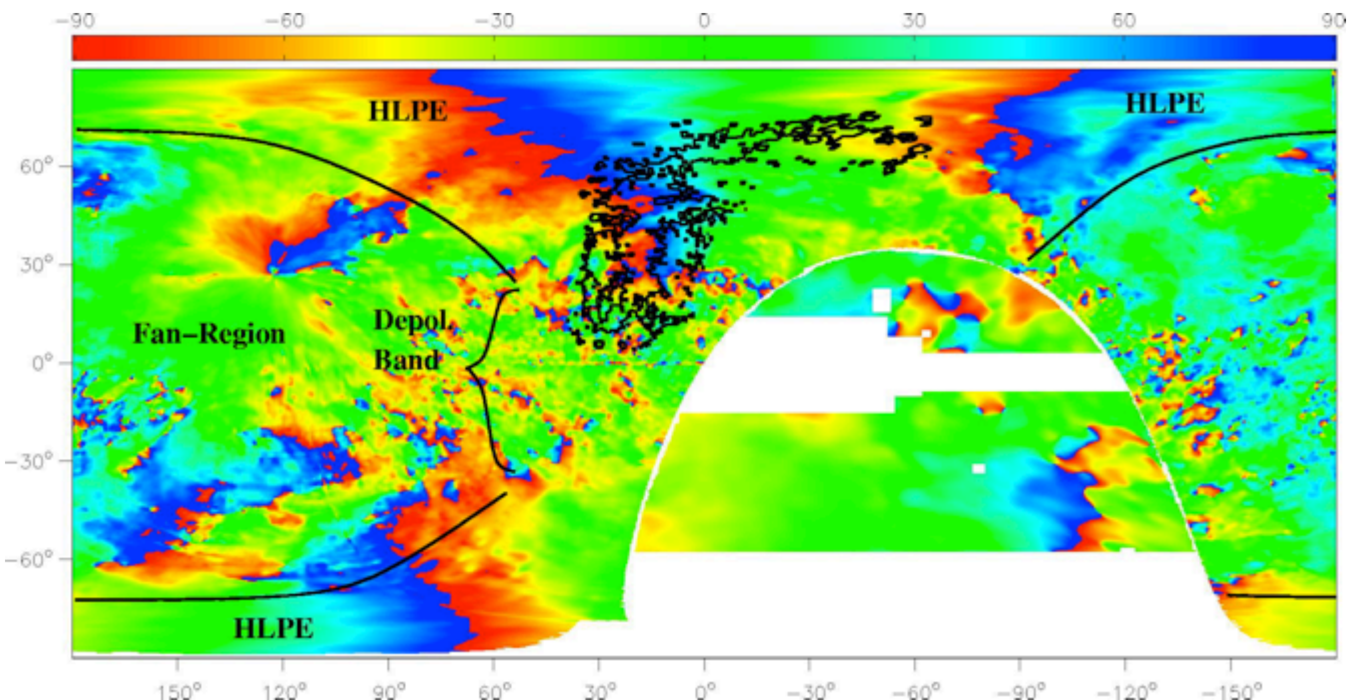
BICEP2 variance-weight map & loops



Wolleben, ApJ **664** (2007) 349

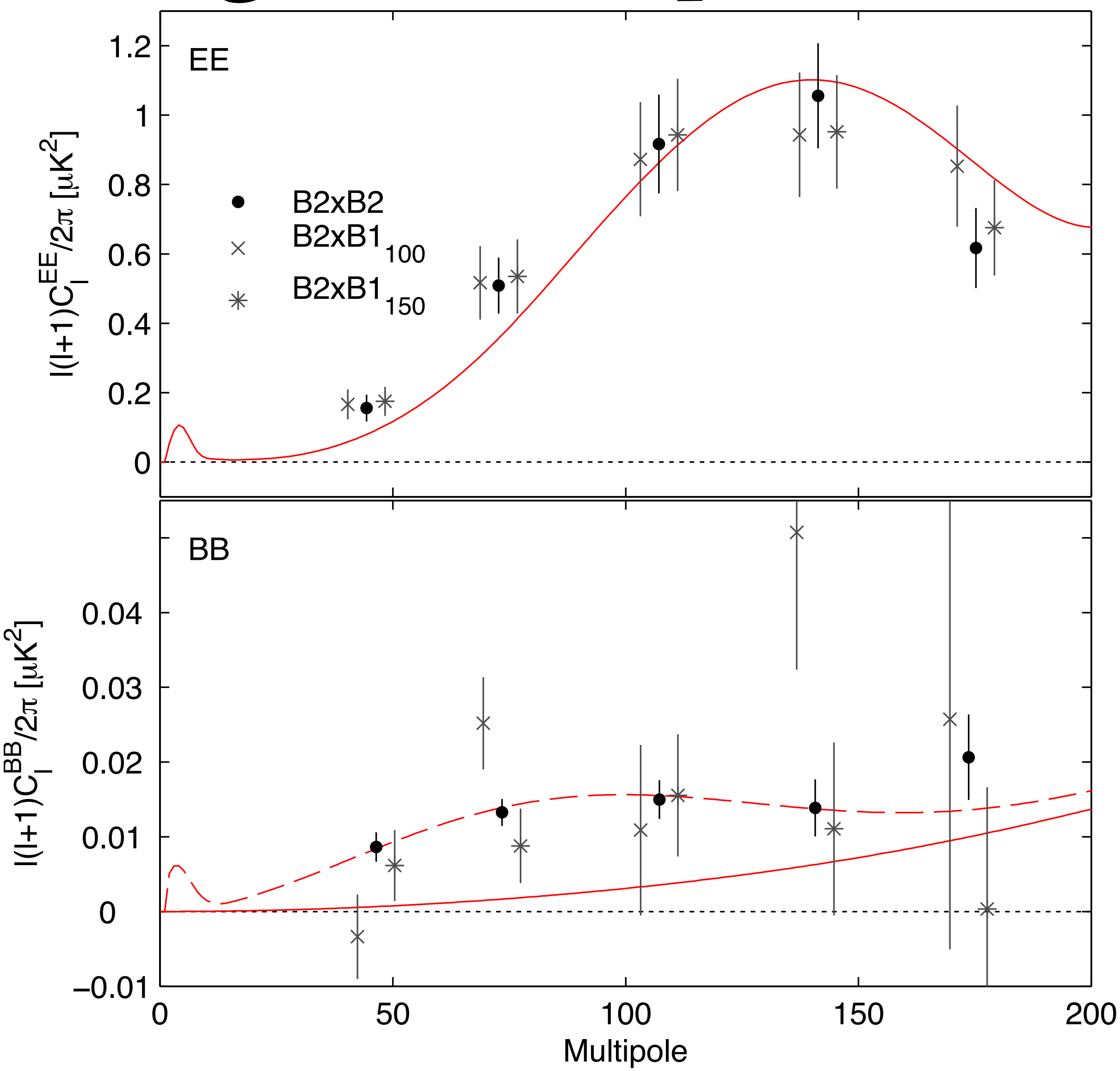


polarisation
(1.4 and 23 GHz)

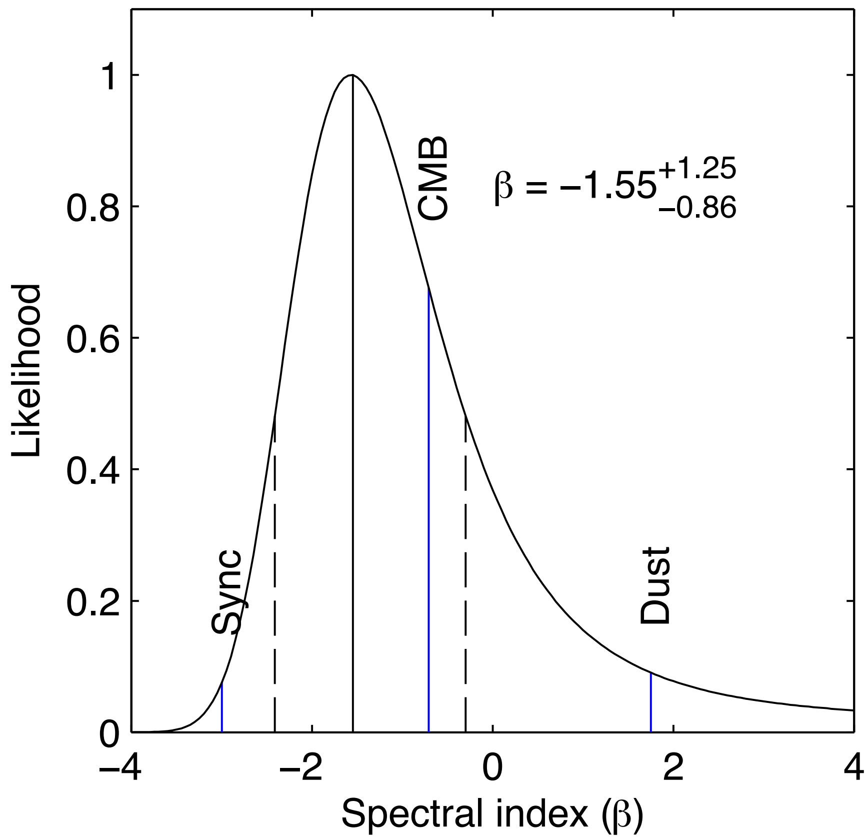


polarisation angle

Foregrounds: spectral index



Foregrounds: spectral index



maximum likelihood fit with 6 parameters:

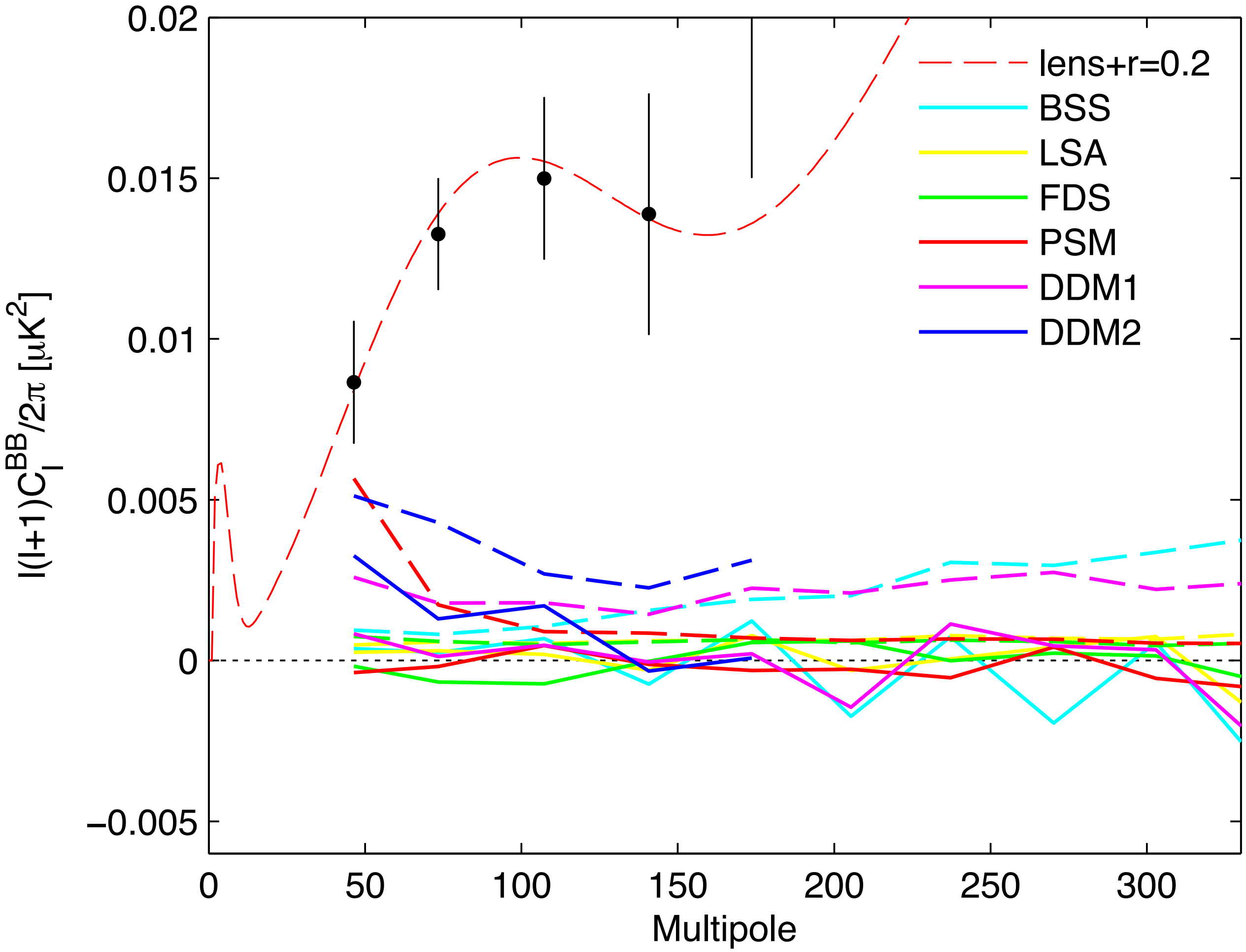
- bandpowers 1-5
- spectral index β

expectations:

- $\beta \sim -3$ for synchrotron
- $\beta \sim 1.75$ for dust
- $\beta \sim -0.7$ for CMB

synchrotron and dust disfavoured at 2.3σ and 2.2σ

Foreground models



Foreground models

FDS
- based on 100 and 240 μm data at few degree resolution
- largely compatible with WMAP 94 GHz morphology, but underestimating dust at GHz by up to 30%
  Gold *et al.*, ApJS **180** (2009) 265
- 5% polarisation fraction and constant angle

BSS
LSA
- based on FDS dust map, modeling different large-scale galactic magnetic field
- 5% polarisation fraction, angle has only large scale structure
  O'Dea *et al.*, MNRAS **419** (2012) 1795

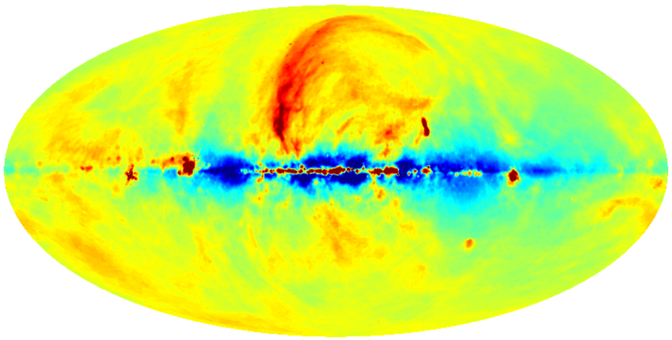
PSM
- similar to O'Dea *et al.*, structure on scales 3-20 degrees from synchrotron maps

based on Planck 353 GHz dust map:

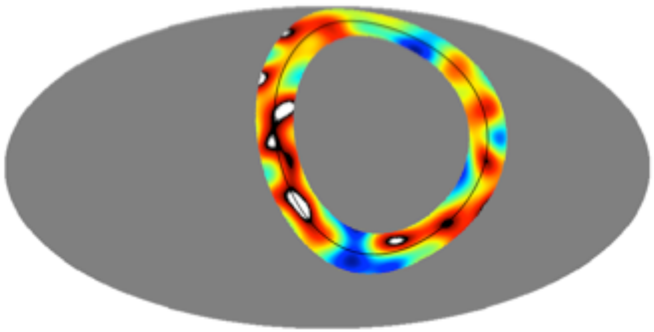
DDM1 – assuming 5% polarisation fraction, angles from PSM

DDM2 – polarisation fraction & angles read off from Planck slides (?)

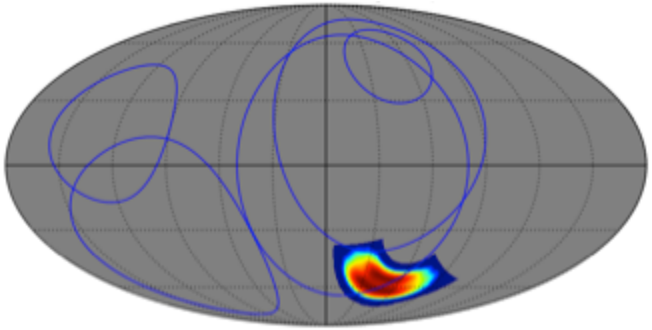
Conlcusion



radioloops
efficiently modelled in angular power spectrum



contamination in CMB maps
anomalous temperature & clustering
➡ magnetised dust?



Wolleben's "New Loop"
potentially high polarisation fraction
potentially low spectral index