47th eslab symposium
2 - 5 april 2013
European Space Agency

Loops & spurs: The angular power spectrum of the Galactic radio background

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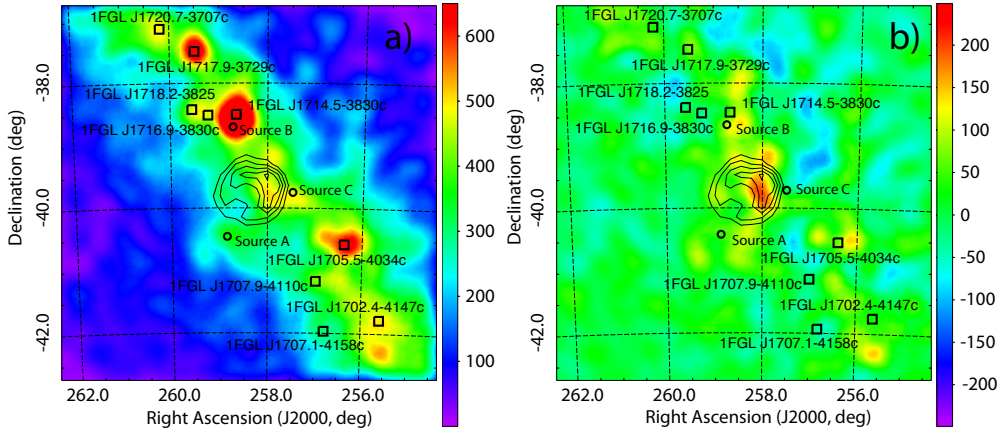
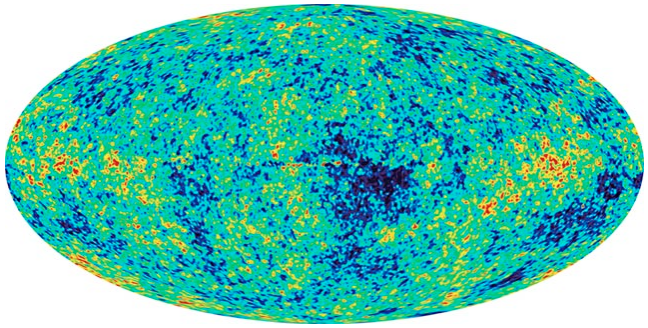
Based on arXiv:1304.1078, with Philipp Mertsch, KIPAC Stanford

Diffuse backgrounds

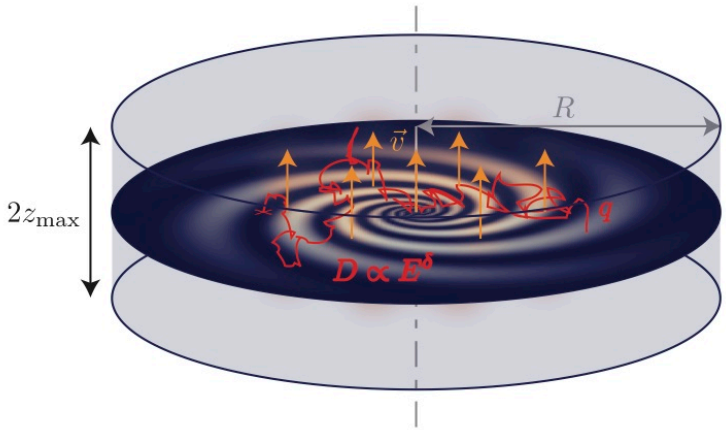
- Background for (point) sources



- Foreground for CMB studies (and searches for DM signals)



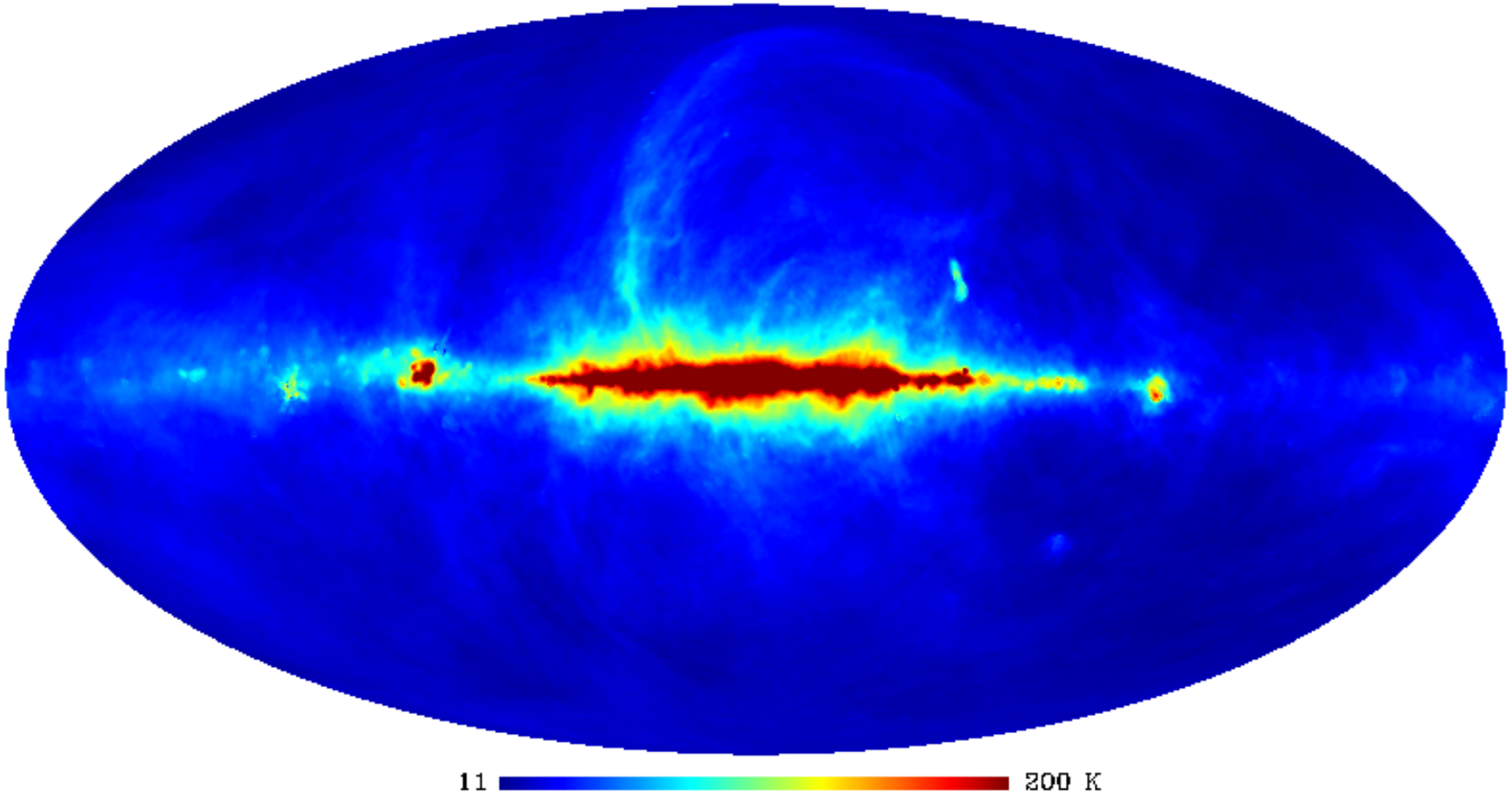
- Information on distribution of CR sources, CR transport, interstellar radiation fields *etc*



The galactic radio background

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

408 MHz



The Galactic radio background…

… is predominantly synchrotron radiation by CR electrons spiralling in the Galactic magnetic field:

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

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

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

… and we observe its line-of-sight projection:

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

Ingredients

CR electrons:

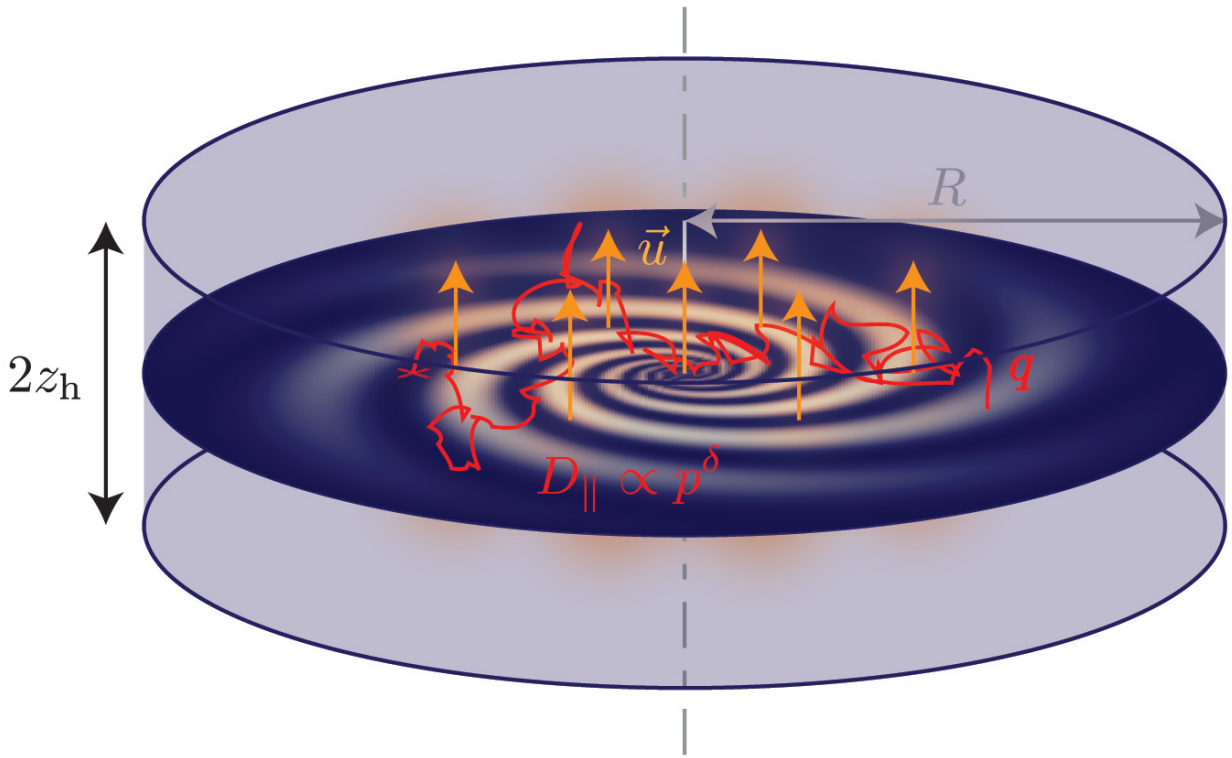
- Sources: SNRs, pulsars? PWNe?
  Large-scale distribution?!
- Distribution: Stochasticity of sources?
- Propagation: Diffusive, Convective?
  Reacceleration? Energy losses?

Galactic magnetic field:

- Large-scale, ordered component
- Small-scale, turbulent component

Propagation of Galactic cosmic rays

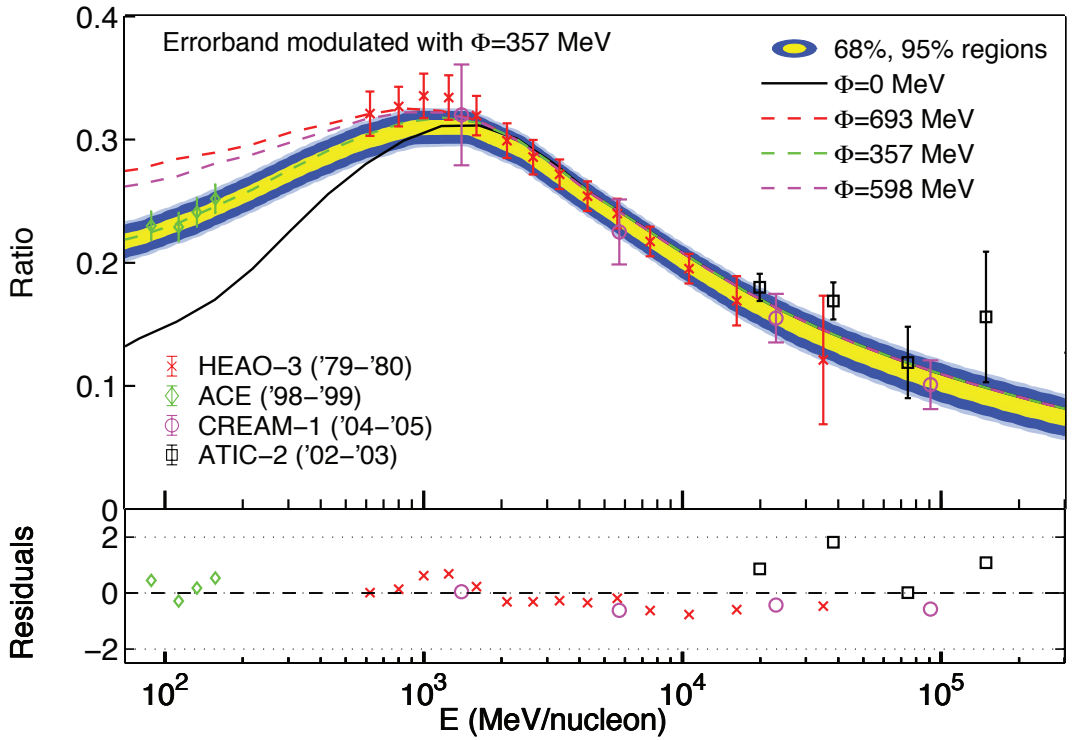
$$\frac{\partial n_i}{\partial t} - \vec{\nabla} \cdot \left(D_{xx} \cdot \vec{\nabla} n_i - \vec{u}\, n_i \right) - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} n_i - \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} n_i - \frac{p}{3} \left(\vec{\nabla} \cdot \vec{u} \right) n_i \right)$$
$$= q + \sum_{i<j} \left(c\, \beta\, n_{\mathrm{gas}}\, \sigma_{j \to i} + \gamma\, \tau_{j \to i}^{-1} \right) n_j - \left(c\, \beta\, n_{\mathrm{gas}}\, \sigma_i + \gamma\, \tau_i^{-1} \right) n_i \,,$$

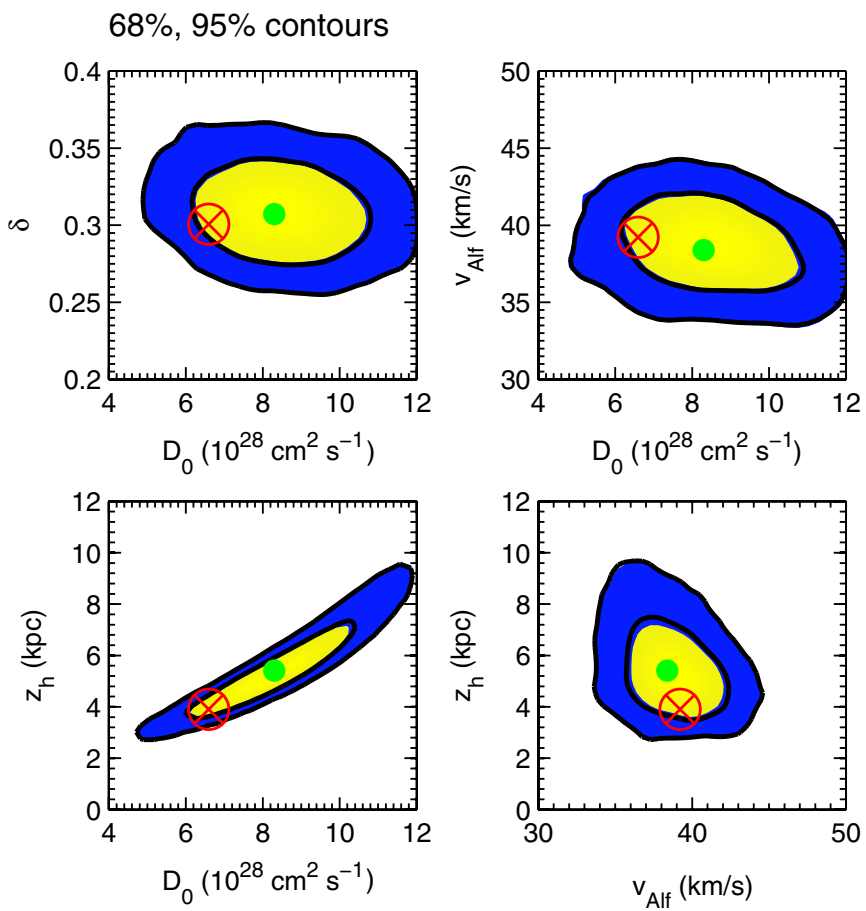


Parameter studies

Transport equation can be solved (semi-) analytically (USINE) or numerically (GALPROP, DRAGON)

Trotta *et al.*, ApJ 729 (2011) 106



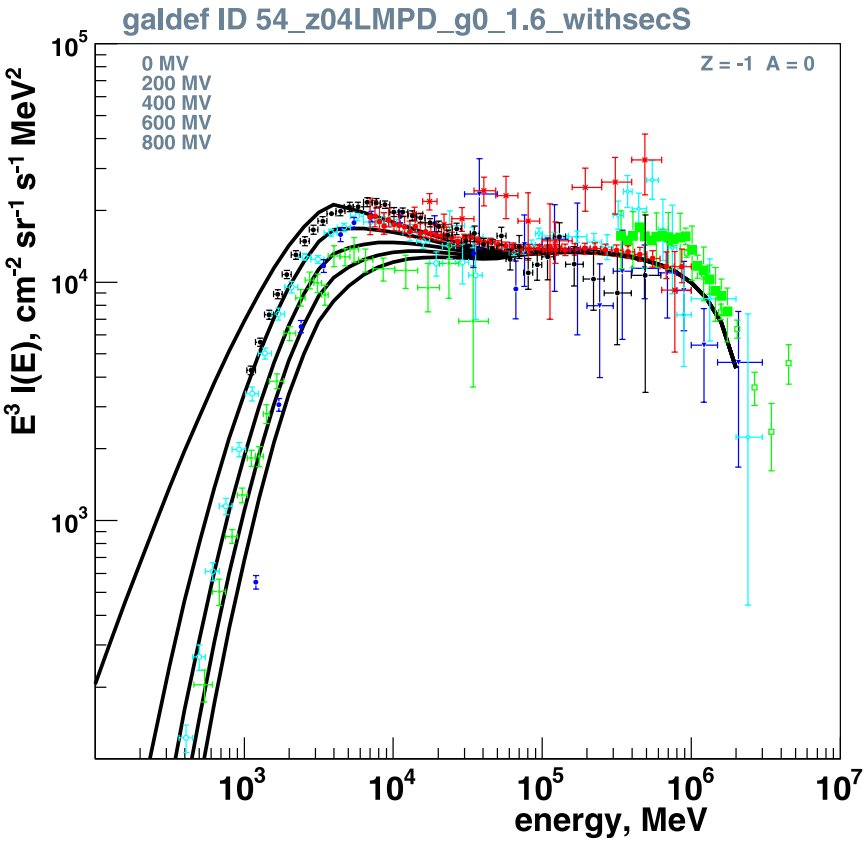


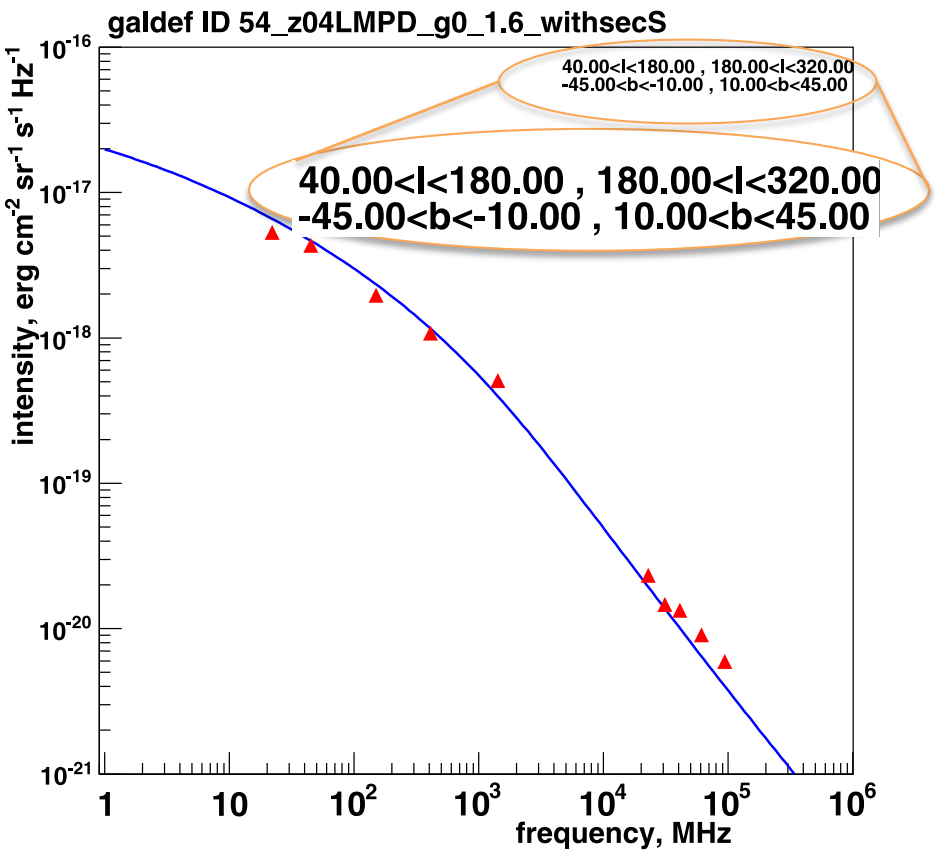
However, secondary-to-primary ratios depend on $D_{||}/z_h$ → degeneracy

(need separate measurement of $D_{||}$ to break this degeneracy)

Local e^- spectrum and synchrotron

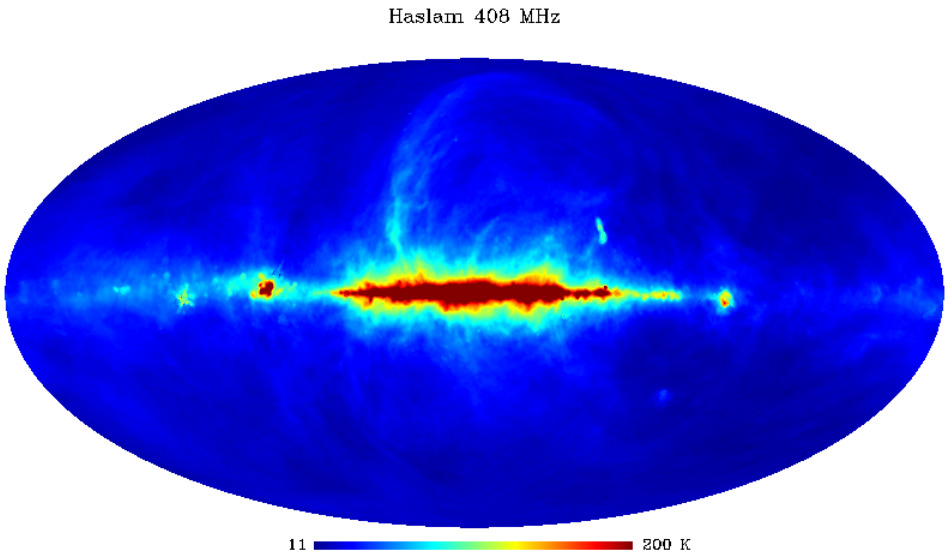
Strong *et al.*, A&A 534 (2011) A54

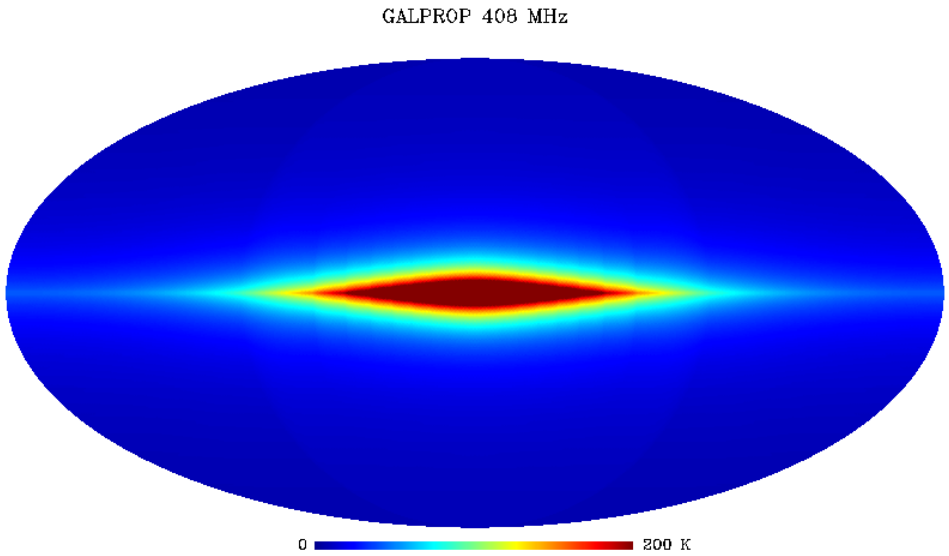


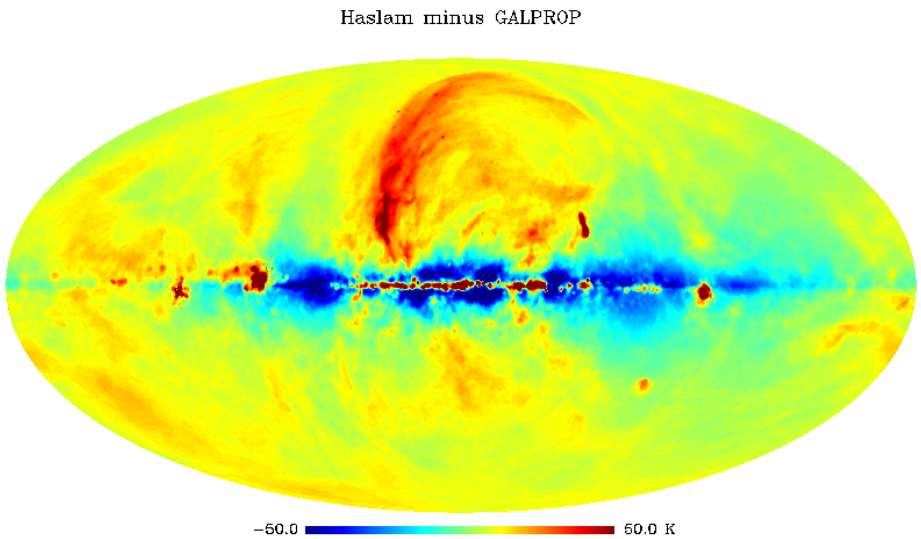


- Require break in IS electron spectrum, e.g. at ~4 GV: $\mathcal{R}^{-1.6} \rightarrow \mathcal{R}^{-2.5}$
- Fix local (turbulent) magnetic field: $\sim 7.5\,\mu G$
- Constrain certain propagation models, e.g. *disfavour* reacceleration

Haslam vs GALPROP





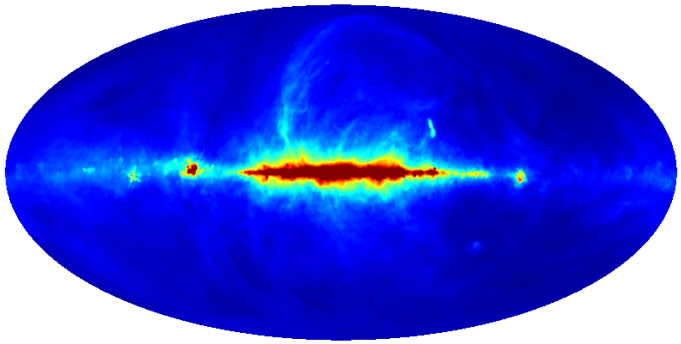


Averaging over large parts of sky…

- Assumes *factorisation* in longitude and latitude
- Leads to *loss of sensitivity* for structures on intermediate scales

Angular power spectrum

1. Radio sky:



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

2. Spherical harmonics:

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

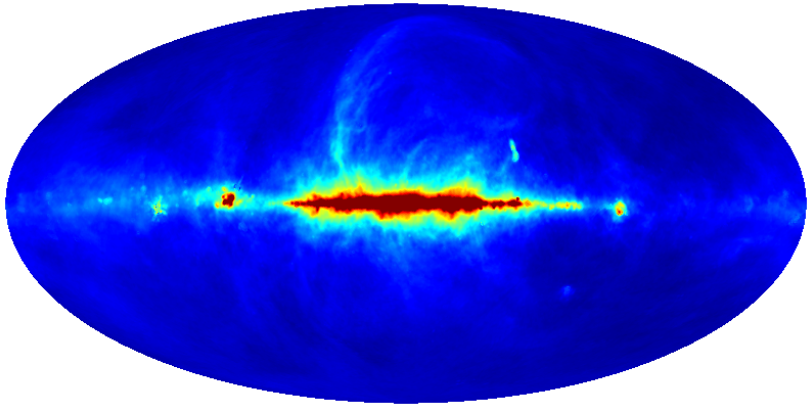
3. Angular power spectrum:

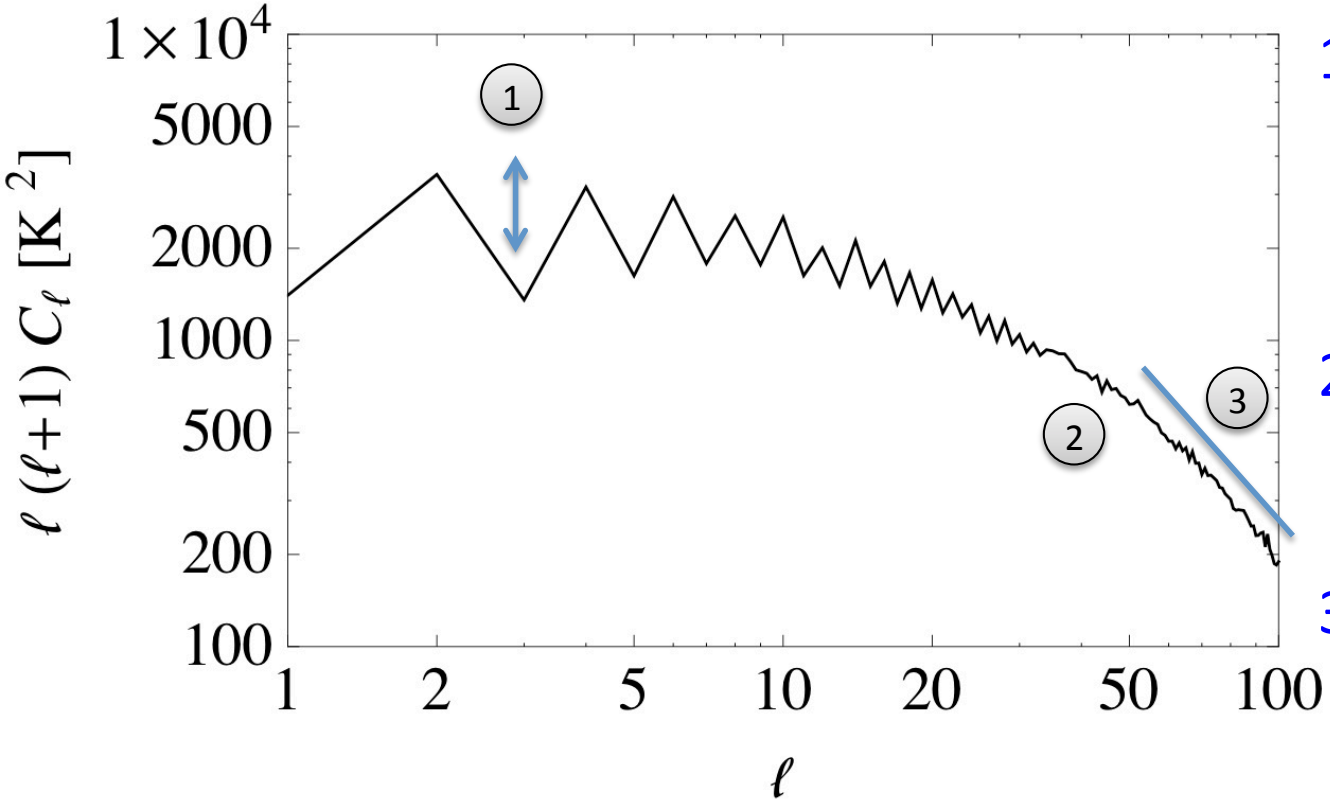
$$C(\ell) \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

<u>Advantages</u>: Information ordered by spatial scale

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

Haslam 408 MHz survey





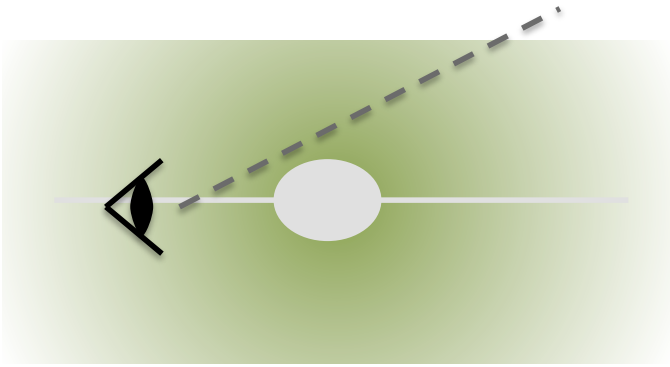
1. Even/odd structure reflects *symmetries* of sky map

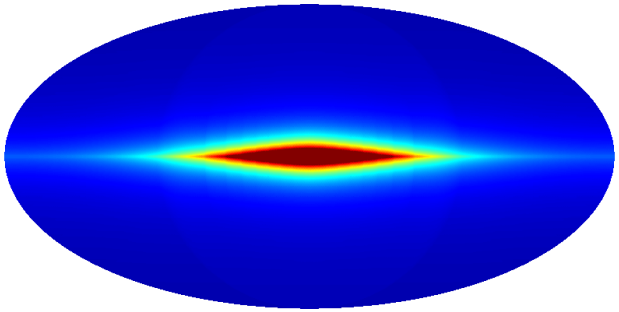
2. Smoother for higher multipoles ℓ

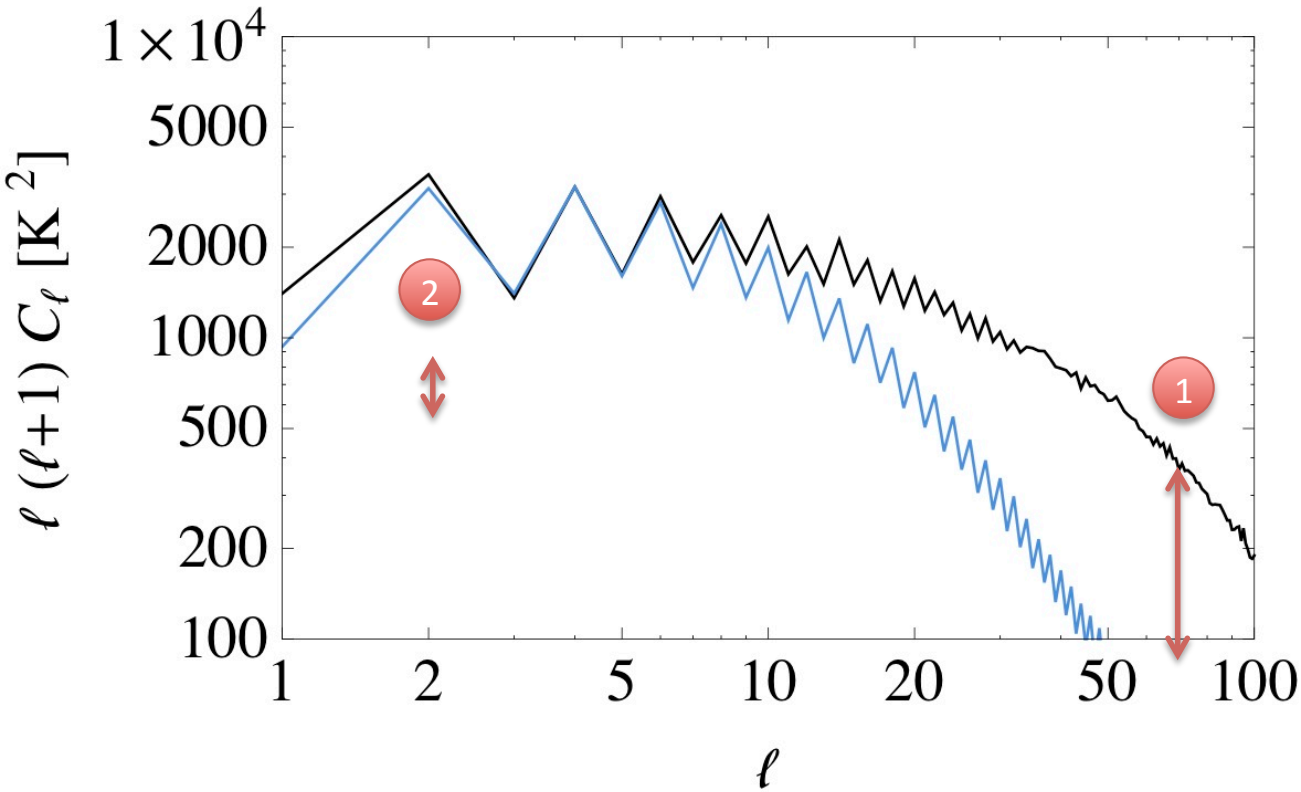
3. Power-law: $C_\ell \propto \ell^{-m}$ with $m \sim 11/3$

(Kolmogorov turbulence)

GALPROP 408 MHz







1. Deficit of power in high multipoles

2. Discrepancies at low l, e.g. dipole

… how about adding in small-scale emission from ISM turbulence?

Turbulence cascade

- Plasma perturbations described by MHD modes, e.g. Alfvén waves

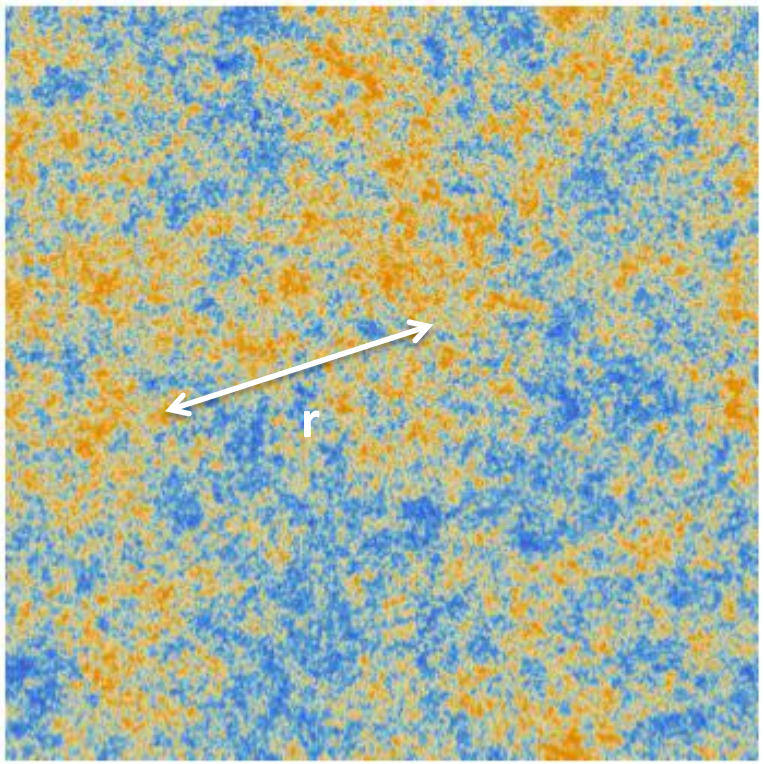
$$\langle \mathbf{B}(\mathbf{r}_0)\mathbf{B}(\mathbf{r}_0+\mathbf{r})\rangle_{\mathbf{r}_0}$$

- Two-point correlation function:

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

- Fourier transform

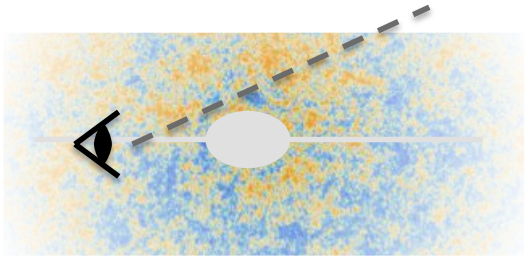
→ power spectrum: $P(k) \propto k^{-m}$

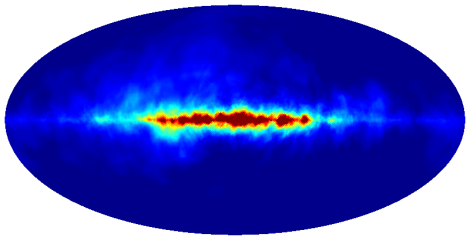


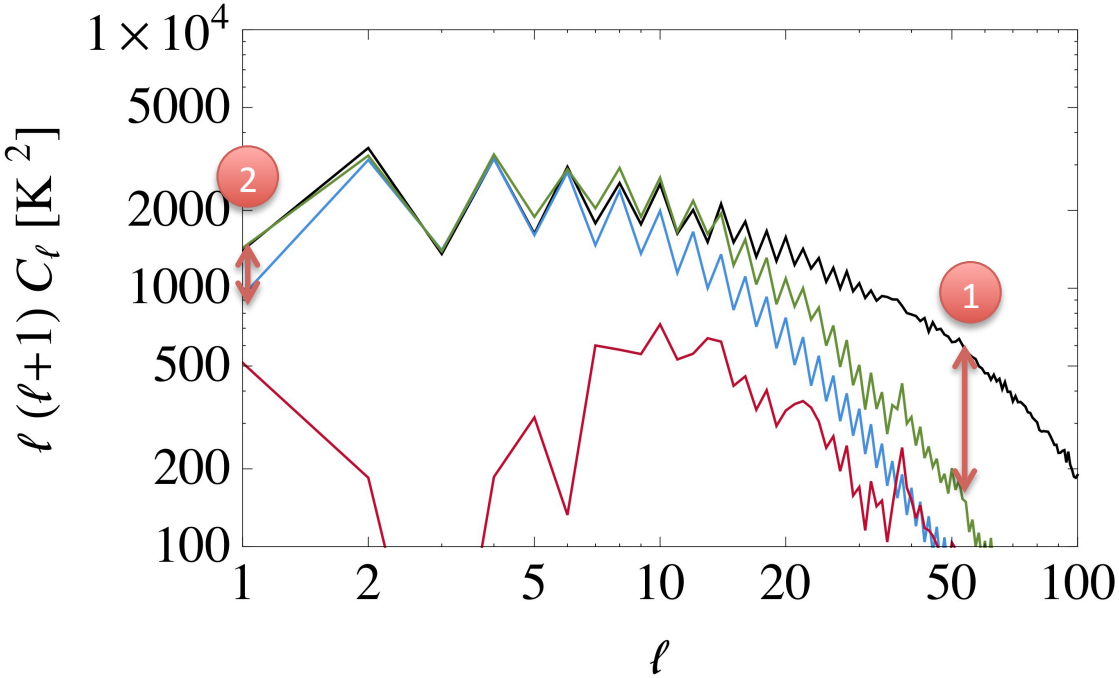
- Observed in space plasma and computer simulations …

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

Turbulence simulation in MC

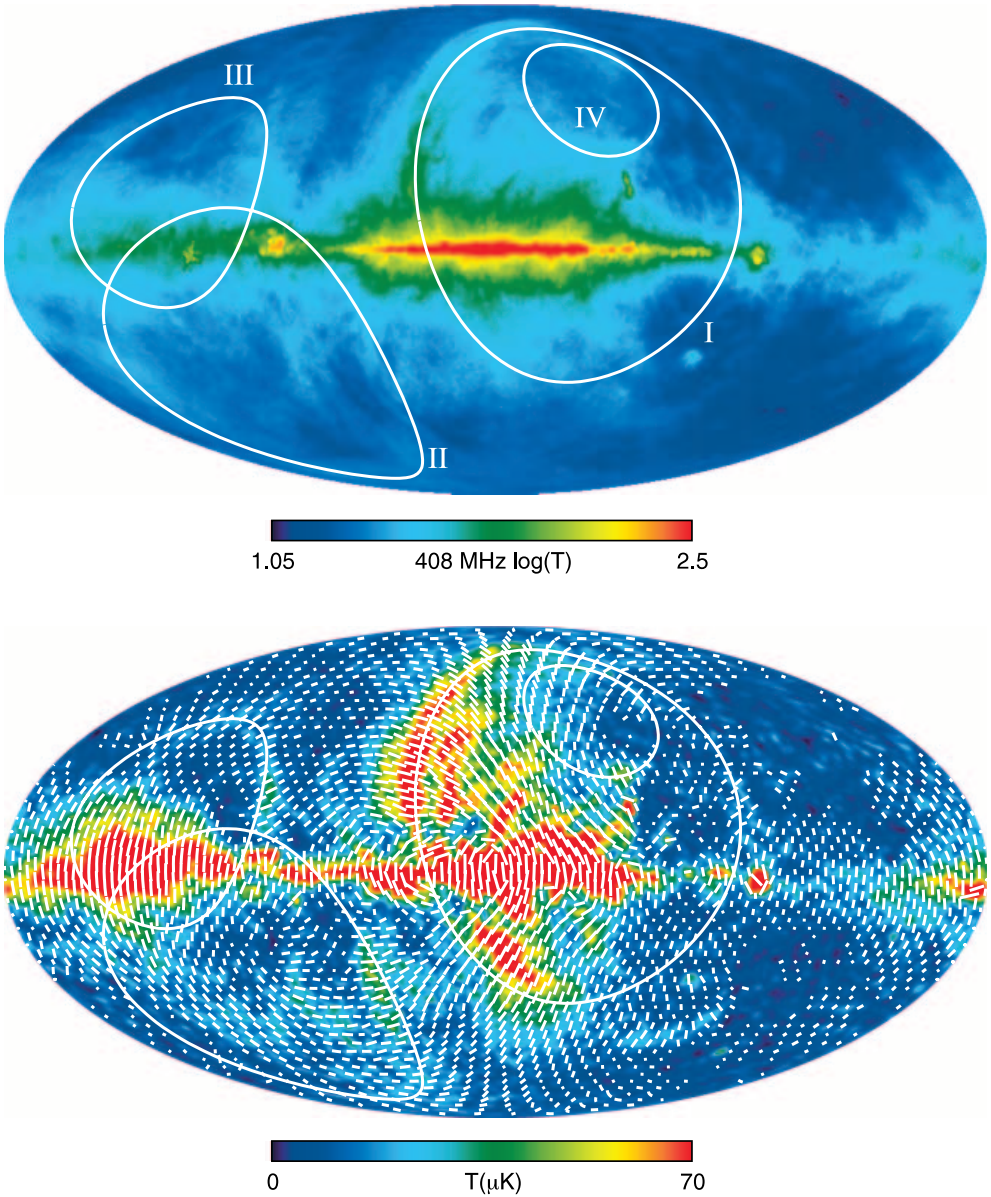






- Still deficit of power at high multipoles
- Discrepancies at low multipoles improved!

Radio loops

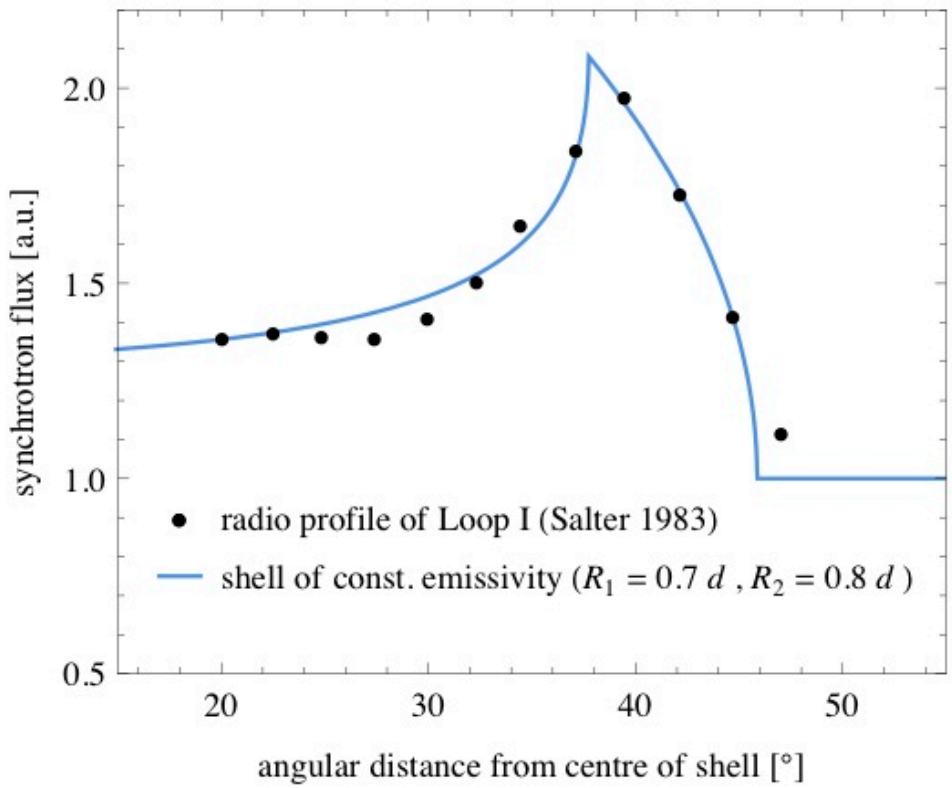


Page *et al.*, ApJS 170 (2007) 335

- ✧ Probably shells of old SNRs
- ✧ Can only observe 4 radio loops directly in radio sky
- ✧ But estimated total Galactic population of up to ~10^4 SNRs can contribute on smaller scales …

Angular Power Spectrum of a shell

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



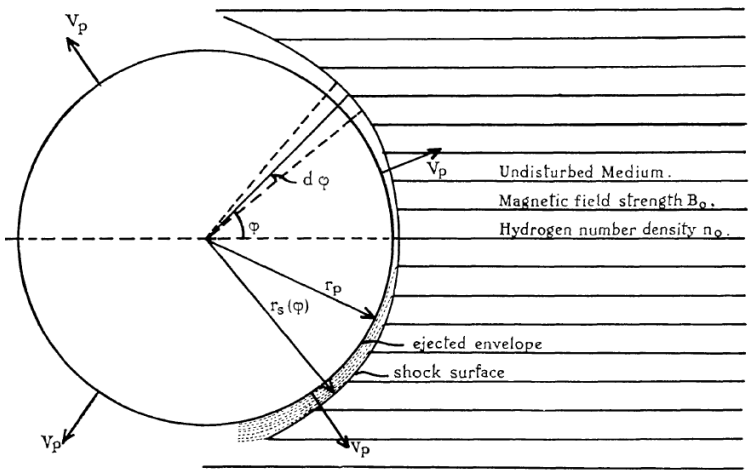
$$C_l^j = \frac{1}{2l+1} \sum_{m=-l}^{l} \left| a_{lm}^j \right|^2 = \frac{1}{4\pi} \left(f_j(\nu) \int_{-1}^{1} \mathrm{d}z' P_l(z') g_j(z') \right)^2$$

Boosted emissivity in old SNRs

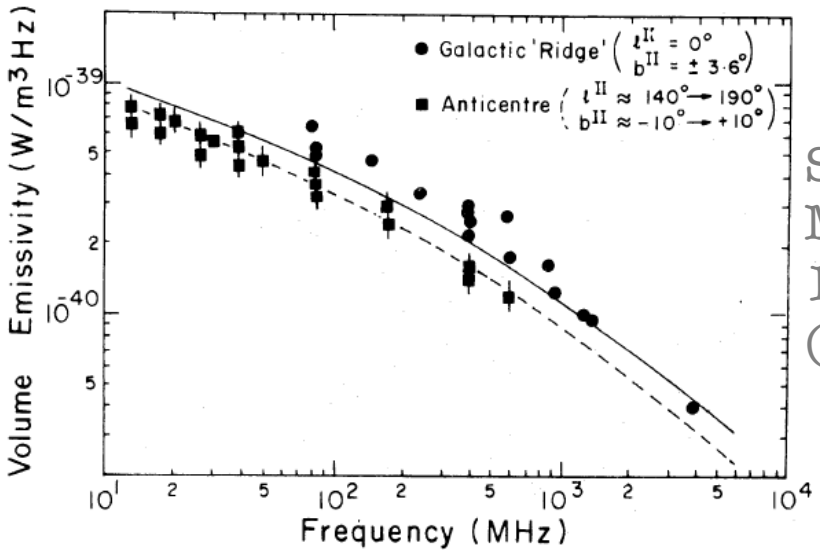
If the compression in the shell is by a factor η then a power-law CR spectrum $N_i(E_0)\,dE_0 = K_{0i}E_0^{-\gamma_i}\,dE_0$ is modified to:

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

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



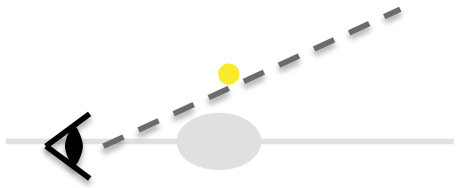
Van der Laan, MNRAS 124 (1962) 125

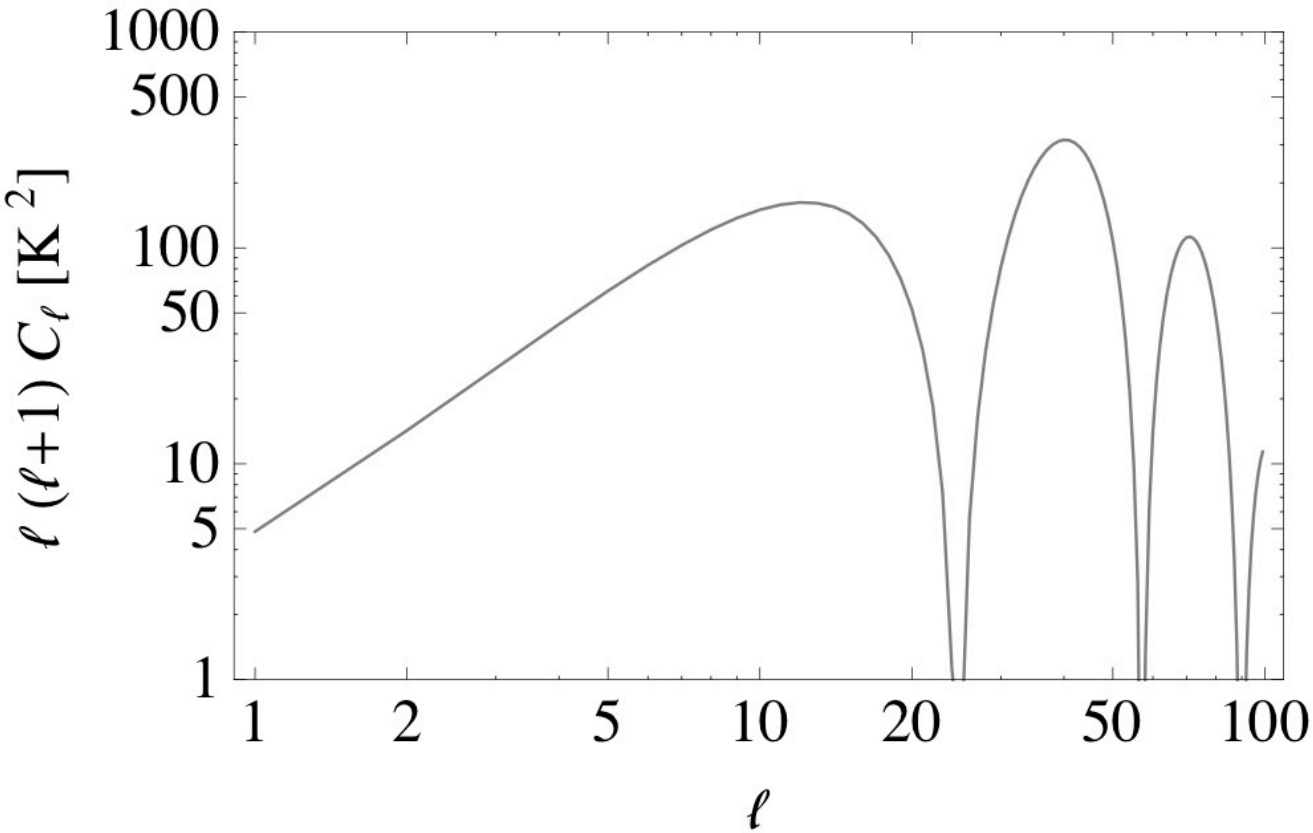


Sarkar, MNRAS 199 (1982) 97

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 ($n_0 = 10^{-2}\,\mathrm{cm}^{-3}$). 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).

Angular Power Spectrum of a shell





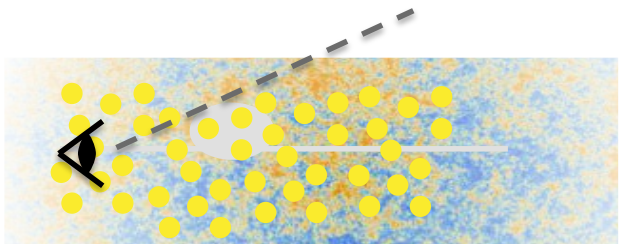
Angular power spectrum for shell i:

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

… thickness of shell determines cut-off

Galactic population of loops

ır power



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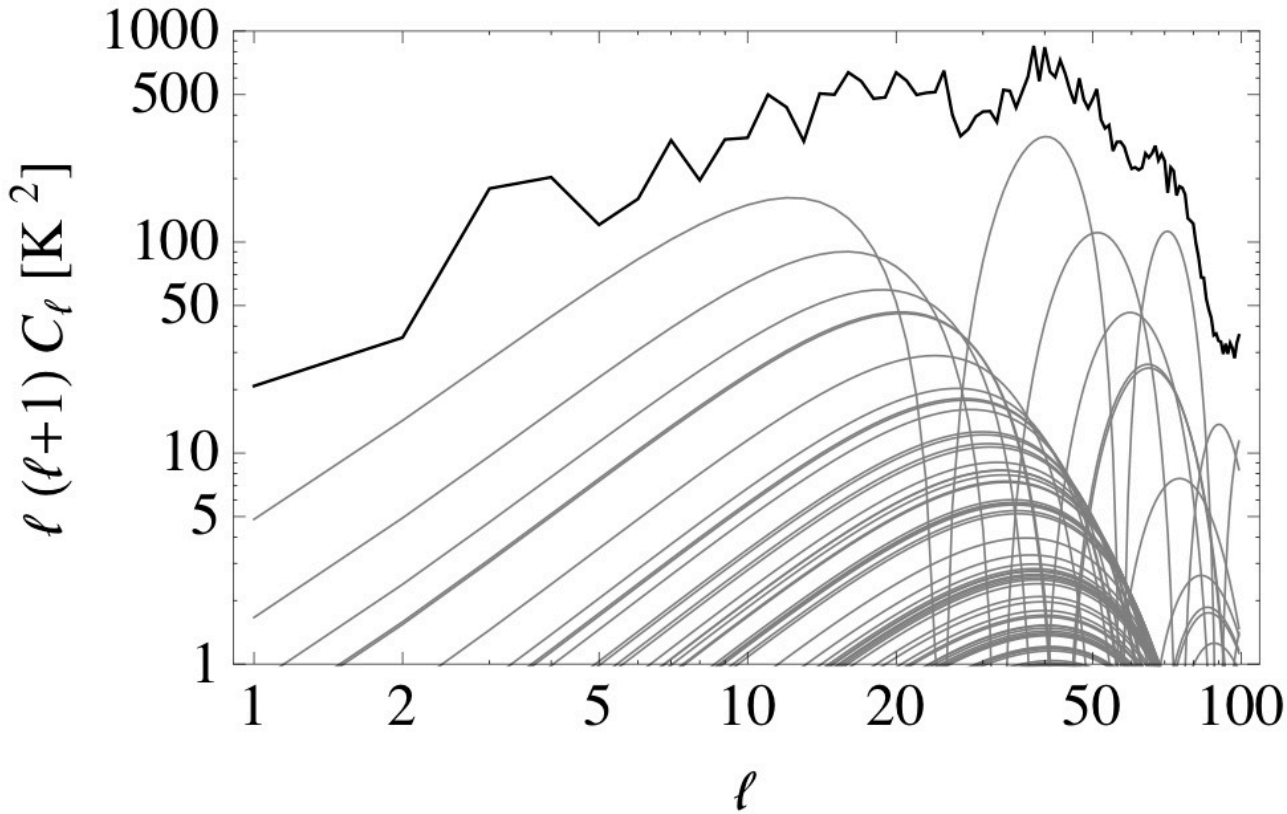

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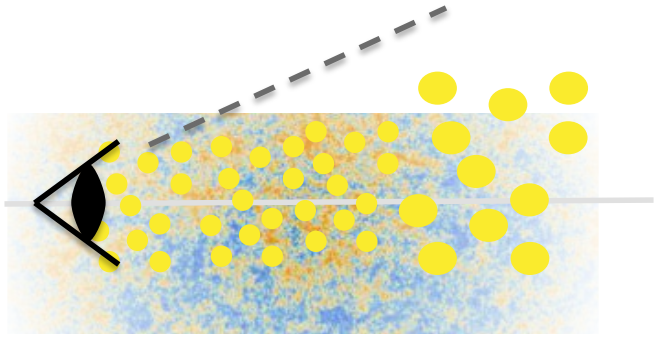

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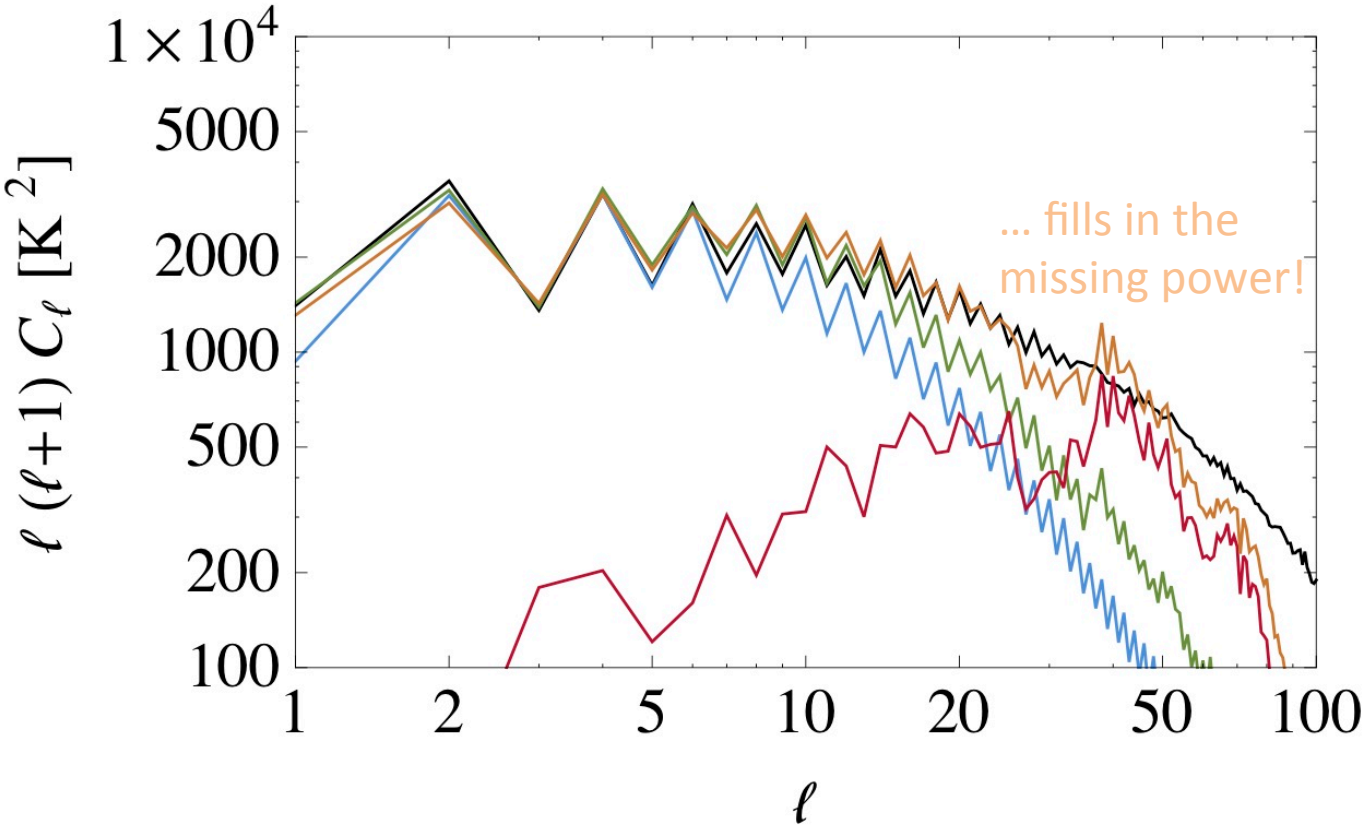

Angular power spectrum for shell i:

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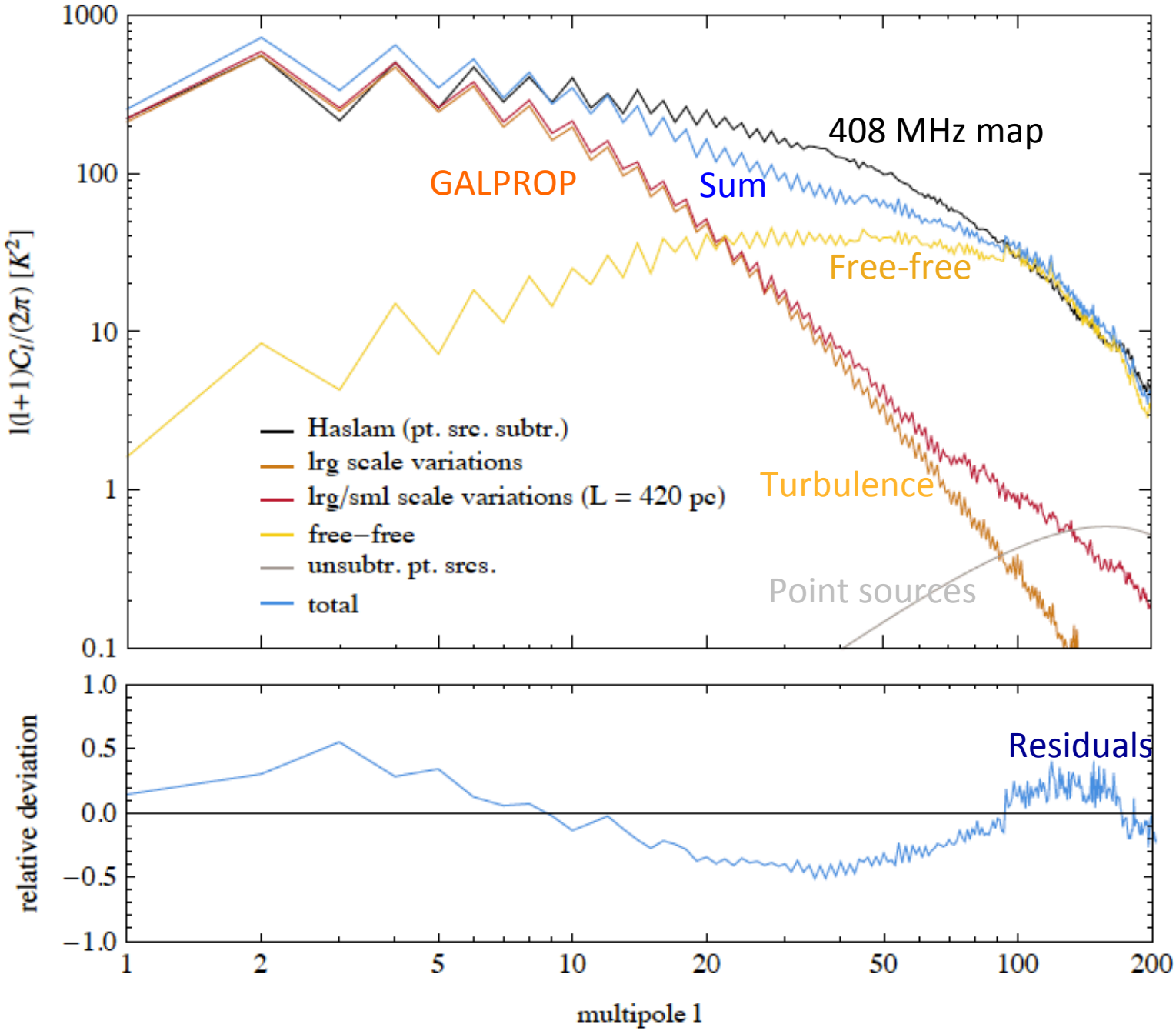
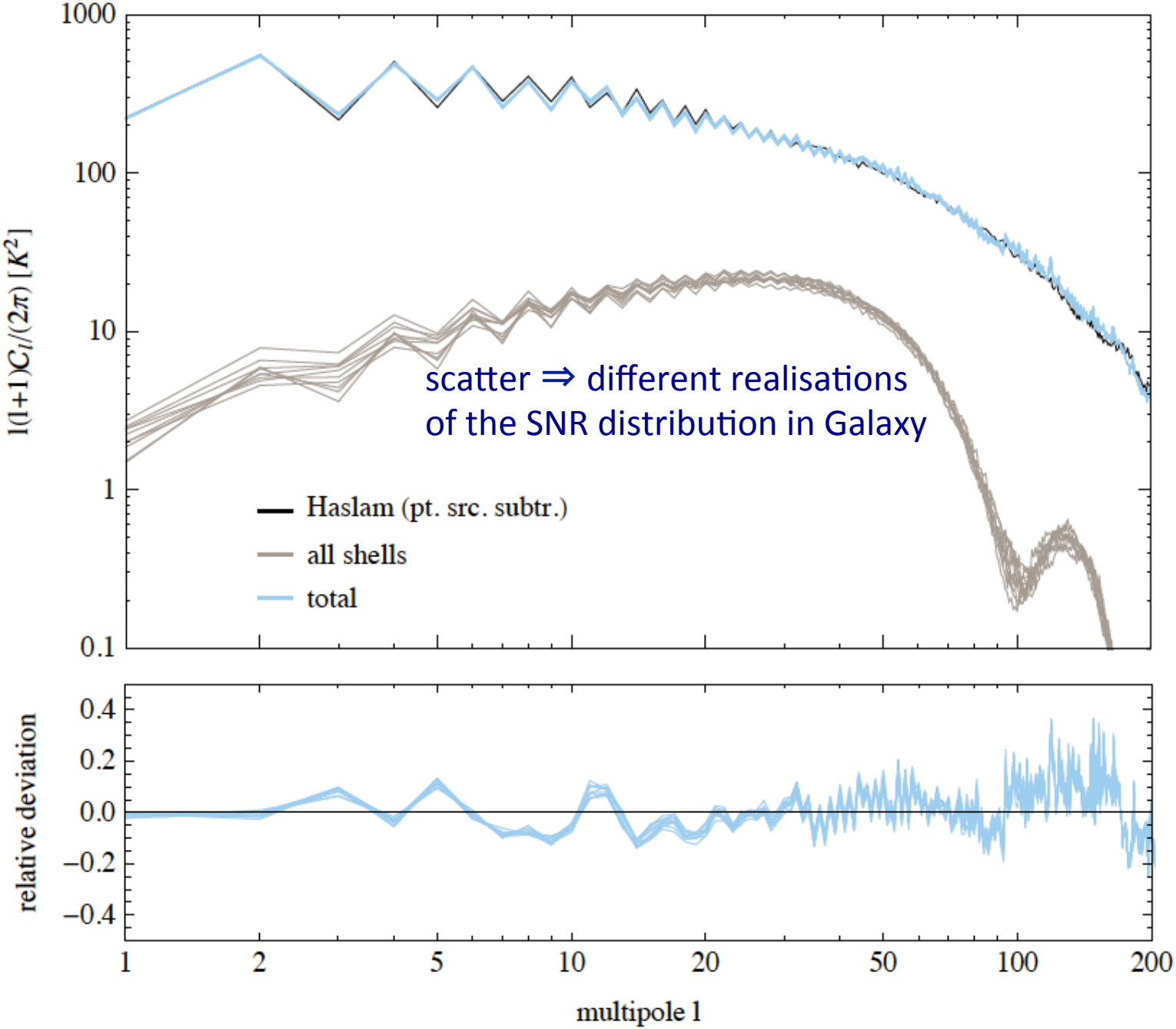
... thickness of shell determines cut-off

The ‘standard’ galaxy model does *not* match the data



… but adding old SNR shells fills in the deficiency nicely!

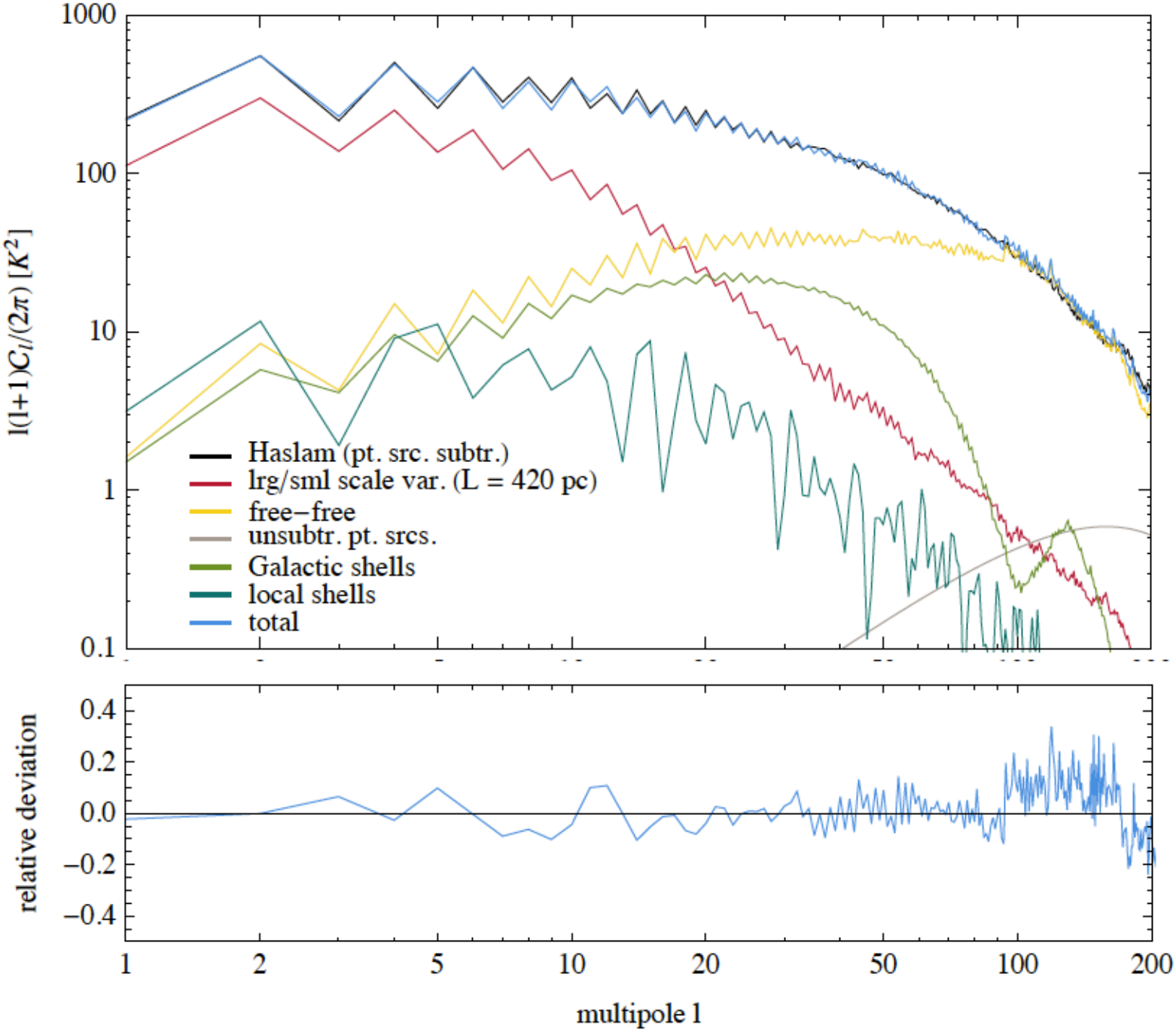


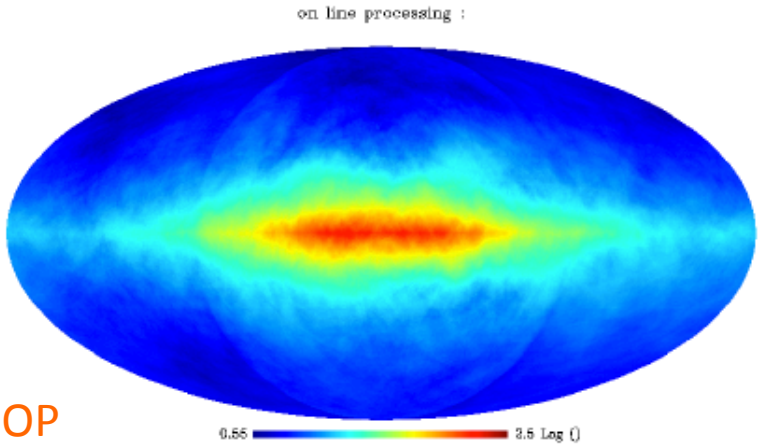
Adopted parameters

Description		Parameter	Value
Spatial diffusion coefficient at 4 GV		D_0	$3.4 \times 10^{28}\,\mathrm{cm^2 s^{-1}}$
Power lax index of the spatial diffusion coefficient		δ	0.5
Half-height of CR propagation volume		z_{max}	4 kpc
Source distribution		*pulsar-like* [40], but held const. for $r > 10\,\mathrm{kpc}$	
Source spectral indices	for $\mathcal{R} \leq \mathcal{R}_1$	Γ_1	1.6
	for $\mathcal{R}_1 < \mathcal{R} \leq \mathcal{R}_2$	Γ_2	2.5
	for $\mathcal{R}_2 < \mathcal{R}$	Γ_3	2.2
Break rigidities		$\mathcal{R}_1$	4 GV
		$\mathcal{R}_2$	50 GV
Magnetic field strength at the Galactic center		B_0	$7.5\,\mu\mathrm{G}$
Scale height in radial direction		ρ	30 kpc, 100 kpc
Scale height in direction perpendicular to Galactic plane		ξ	4 kpc

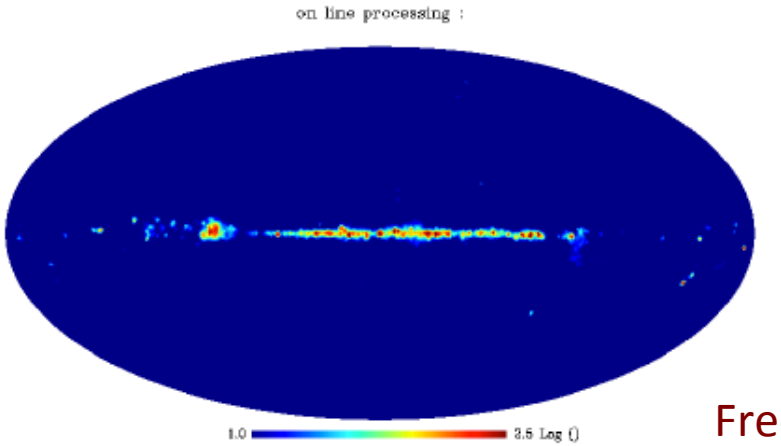
Object	l (centre)	b (centre)	diameter	distance
Loop I	329°	17.5°	116°	240 pc
Loop II	100°	−32.5°	91°	280 pc
Loop III	124°	15.5°	65°	370 pc
Loop IV	315°	48.5°	39.5°	590 pc

… and this is our best fit @ 408 MHz (test at 1.4 GHz?)

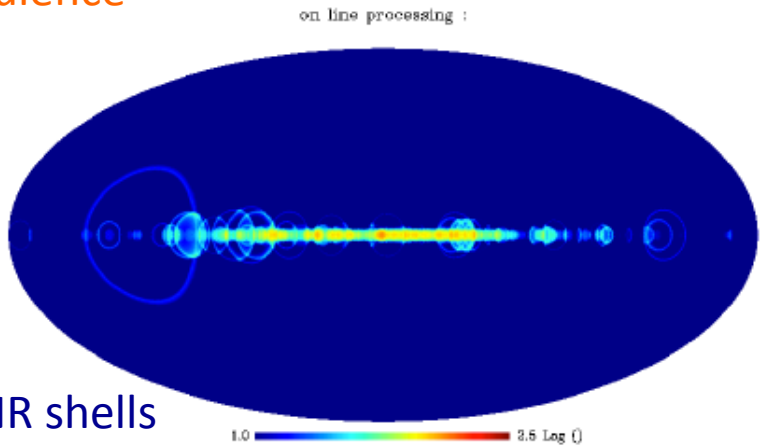




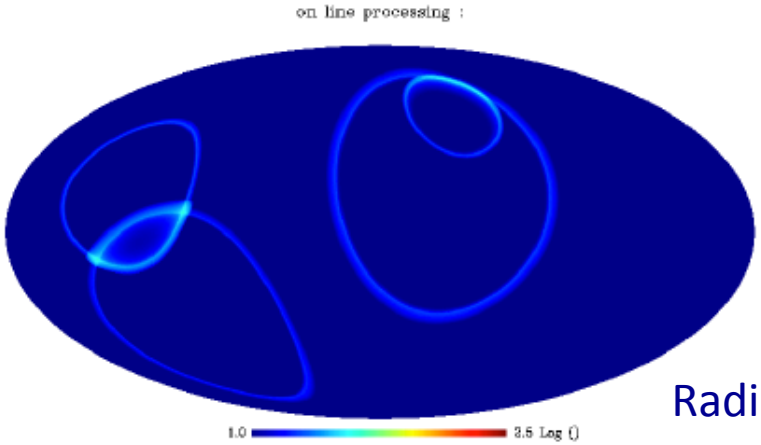
GALPROP
+ turbulence



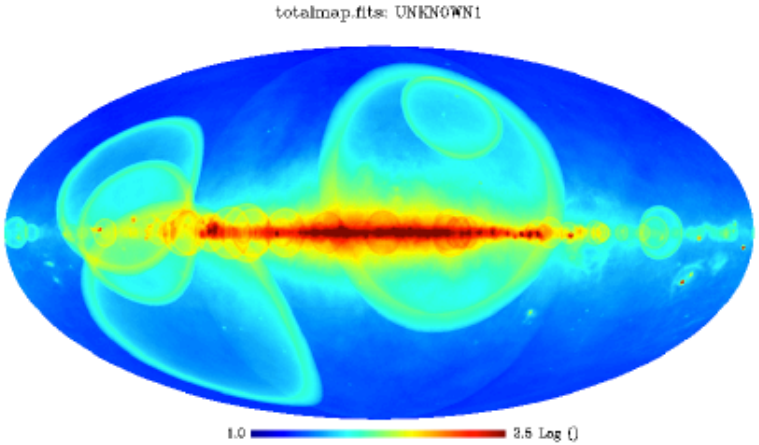
Free-free



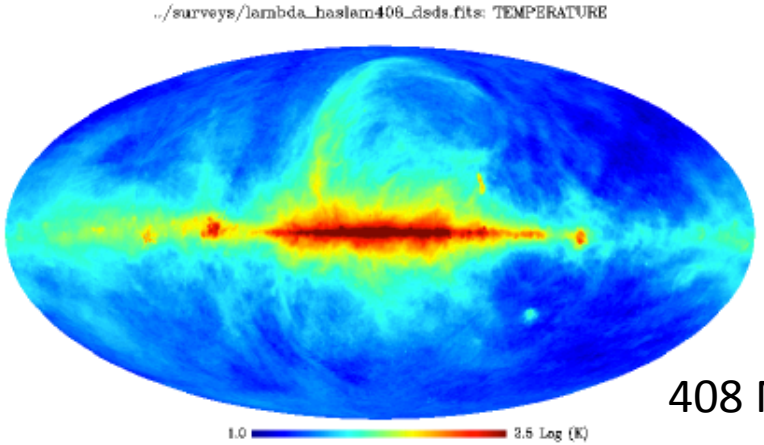
Old SNR shells



Radio loops

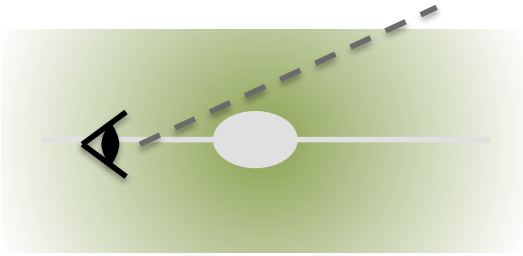


Sum



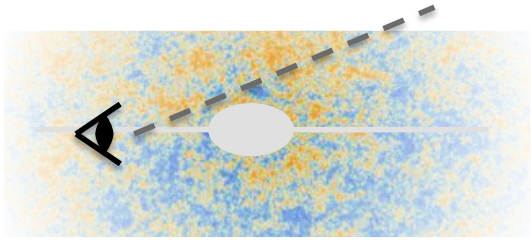
408 MHz map

Summary



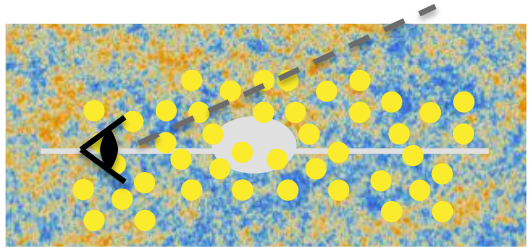
smooth

The 'standard' model of foreground galactic radio emission assumes a *smoothly* varying emissivity … Provides a reasonable match to observed frequency spectrum and latitudinal/longitudinal profiles



Small-scale fluctuations can also be well-modelled by a (Kolgomorov) turbulence cascade in the magnetic field

However in order the match the angular power spectrum of the full-sky radio map (408 MHz) on *intermediate scales* requires adding in ~1000 shells of old supernova remnants (aka `radio loops')



radio loops

Understanding this component will prove crucial for foreground subtraction, *especially for polarised emission* … these contribute at high galactic latitudes so cannot easily be masked