Anisotropies in cosmic rays and in the cosmic microwave background

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Stanford University

KIPAC

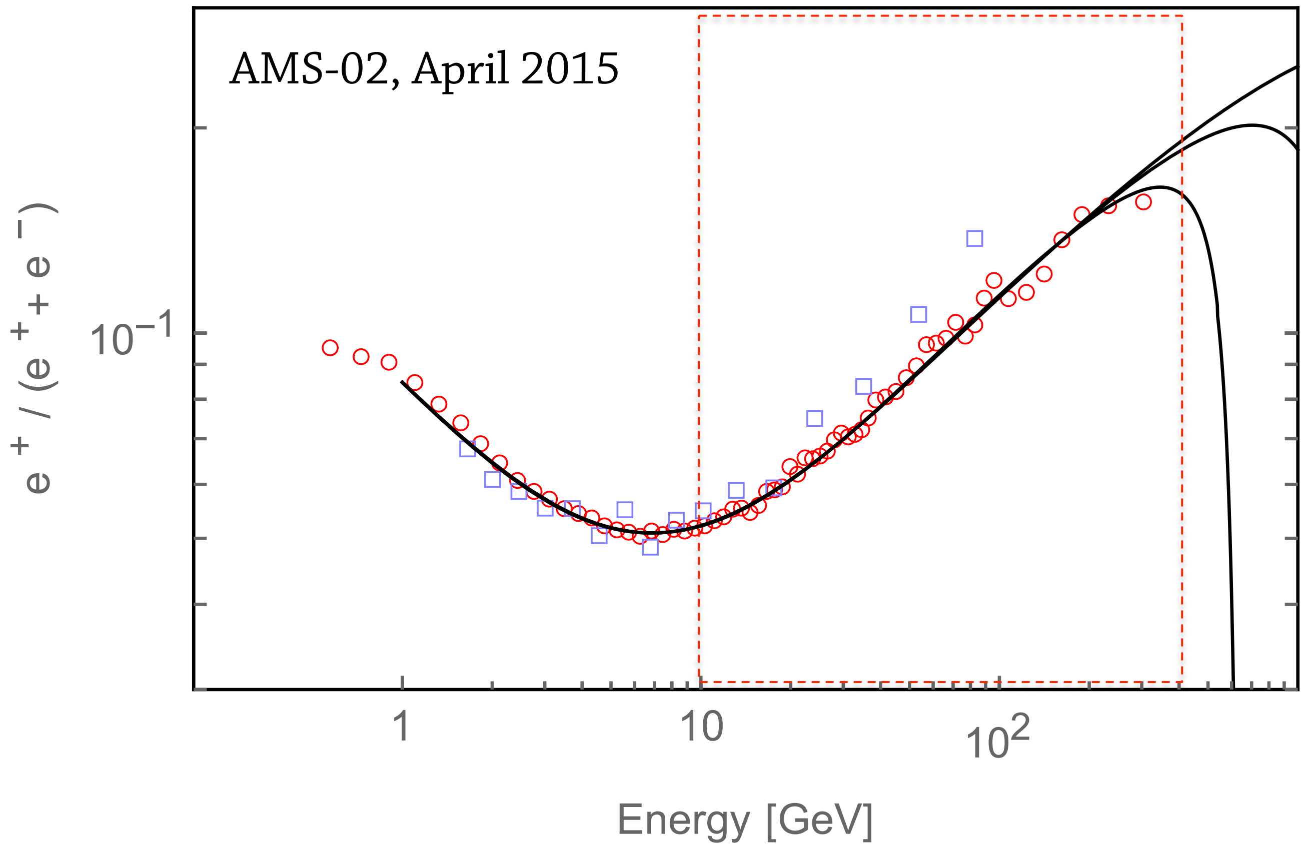
Who I am

Theoretical physicist, working in particle physics, astrophysics & cosmology

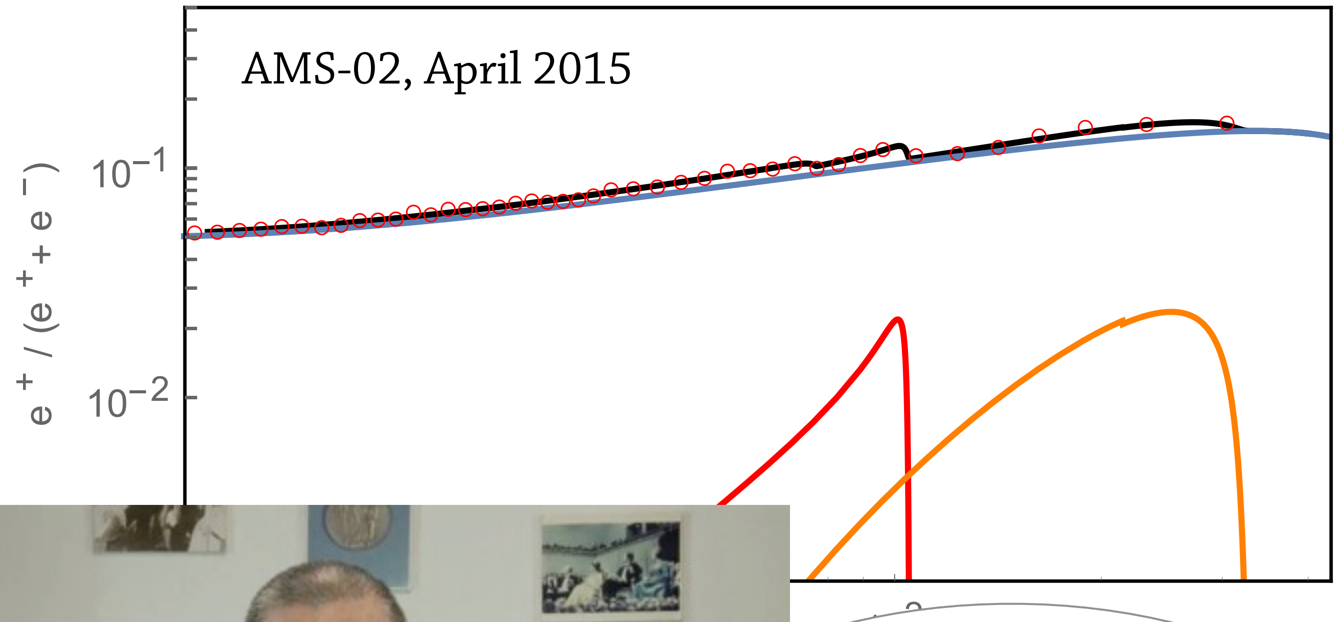
Education and positions

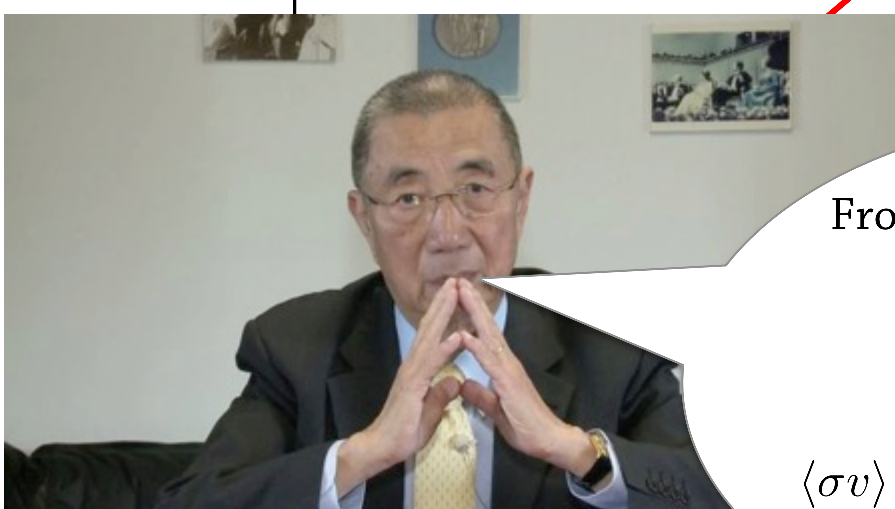
Maîtrise	Université Joseph Fourier GRENOBLE	
Diplom	Julius-Maximilians-UNIVERSITÄT WÜRZBURG	*Cusanuswerk* scholarship (for academic excellence)
PhD, postdoc	UNIVERSITY OF OXFORD	Marie–Curie position and Junior Research Fellowship
Kavli fellow	Stanford University, KIPAC	fellowship from Kavli foundation & NASA grant

Substructure



Subtructure





From $\vec{\delta} = \frac{3D}{c} \frac{\vec{\nabla} n_{\rm CR}}{n_{\rm CR}}$

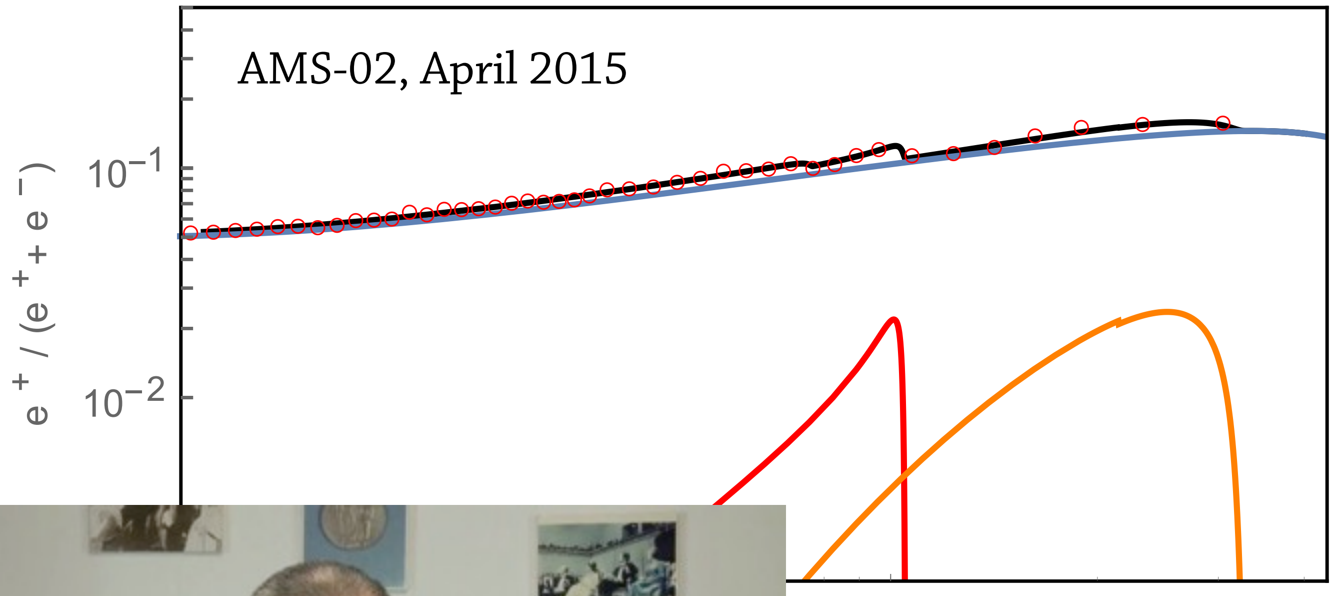
$$(\ell, b) = (-150^\circ, 60^\circ)$$

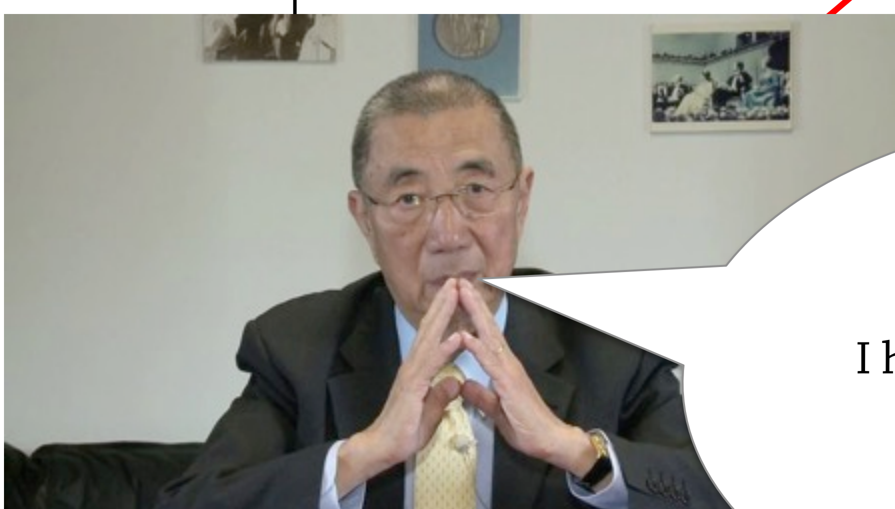
$$d = (3 \pm 1.5)\,\mathrm{kpc}$$

$$\langle \sigma v \rangle = (8 \pm 2) \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

for $L = 10^{7\pm1} M_\odot^2\,\mathrm{pc}^{-3}$

Subtructure





Isotropy

- charged particles interact resonantly with magnetic inhomogeneities

➞ pitch-angle scattering

$$\nu = \left\langle \frac{\Delta\theta^2}{\Delta t} \right\rangle = \frac{\pi}{4} \left(\frac{\delta B^2(k)/8\pi}{B^2/8\pi} \right) \Omega \qquad \text{with} \qquad k \approx \frac{\Omega}{v \cos\theta}$$

- isotropises distribution function

$$f(\vec{r}, \vec{p}, t) \to f_0(\vec{r}, |\vec{p}|, t)$$

- leads to (rigidity-dependent) spatial diffusion

$$\frac{\partial f}{\partial t} + \left(\vec{u} \cdot \vec{\nabla}\right) f - \vec{\nabla} \cdot \left(D_{\|} \vec{\nabla} f\right) = \frac{1}{3} \left(\vec{\nabla} \cdot \vec{u}\right) p \frac{\partial f}{\partial p} \,,$$

with

$$D_{\|} \simeq \frac{v^2}{3\nu} \propto \left(\frac{\delta B^2(k)/8\pi}{B^2/8\pi} \right)^{-1} \frac{1}{\Omega} \propto \mathcal{R}^{\delta} \quad \text{for} \quad \frac{\partial B^2(k)}{\partial k} \propto k^{\delta-2}$$

Secondary-to-primary ratios

- secondaries not from sources but from spallation in ISM, e.g.

$$\mathrm{C} + \mathrm{p}_{\mathrm{ISM}} \text{ or } \mathrm{He}_{\mathrm{ISM}} \rightarrow \mathrm{B} + X$$

- primary produced with spectrum:

$$\mathrm{C} \propto \mathcal{R}^{-\Gamma}$$

- diffusion rigidity dependent:

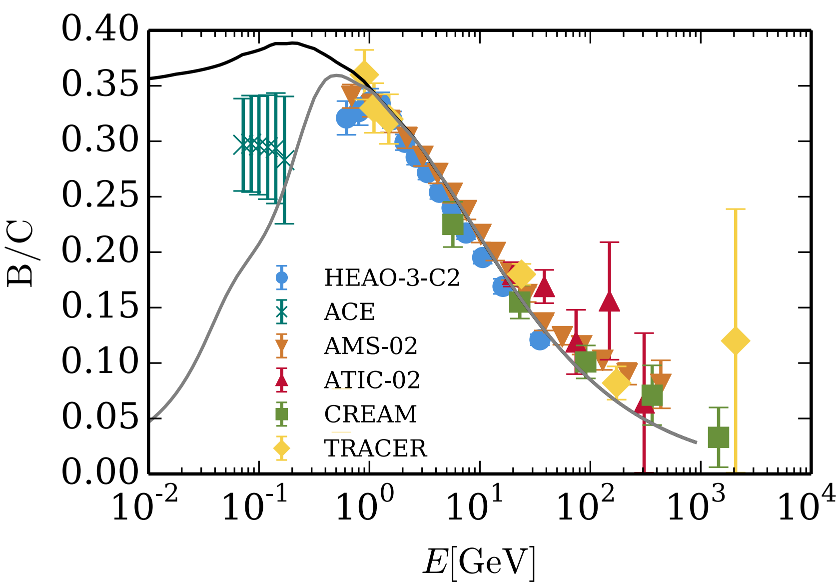
$$D_{\parallel} \propto \mathcal{R}^{\delta}$$

- propagated spectra:

$$\mathrm{C} \propto \mathcal{R}^{-\Gamma-\delta}$$

$$\mathrm{B} \propto \mathcal{R}^{-\Gamma-2\delta}$$

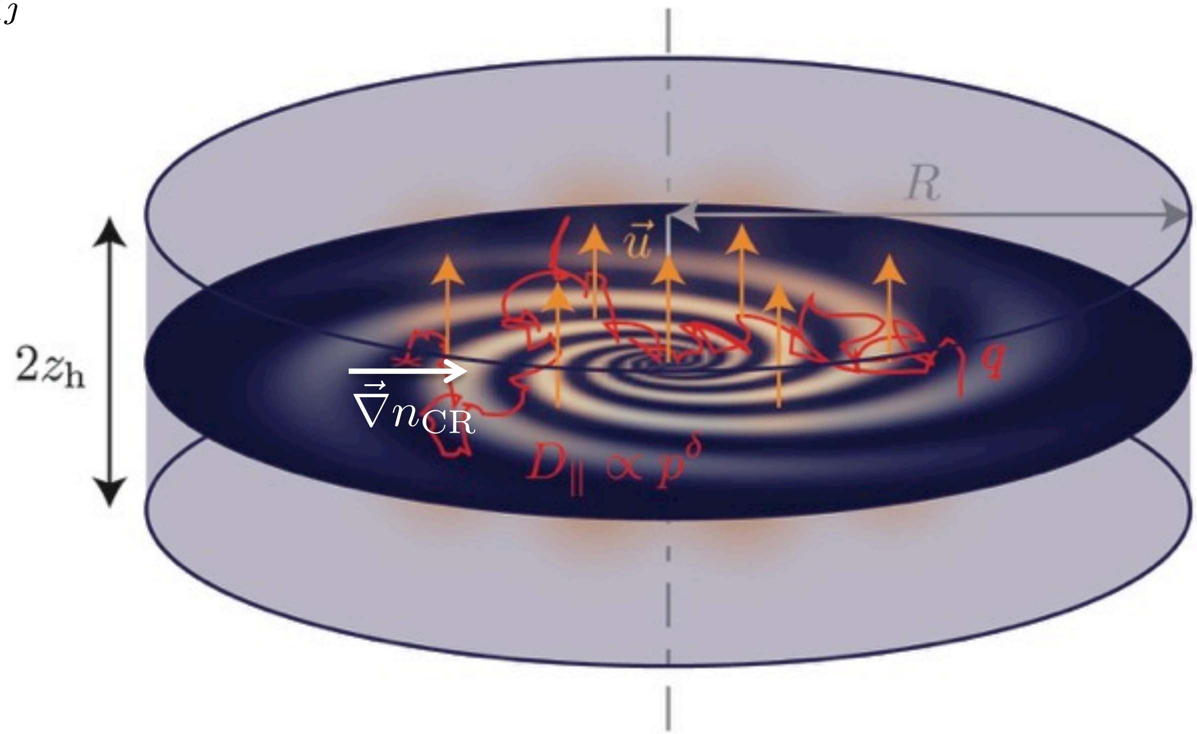
$$\mathrm{B}/\mathrm{C} \propto \mathcal{R}^{-\delta}$$



Why anisotropy? (I)

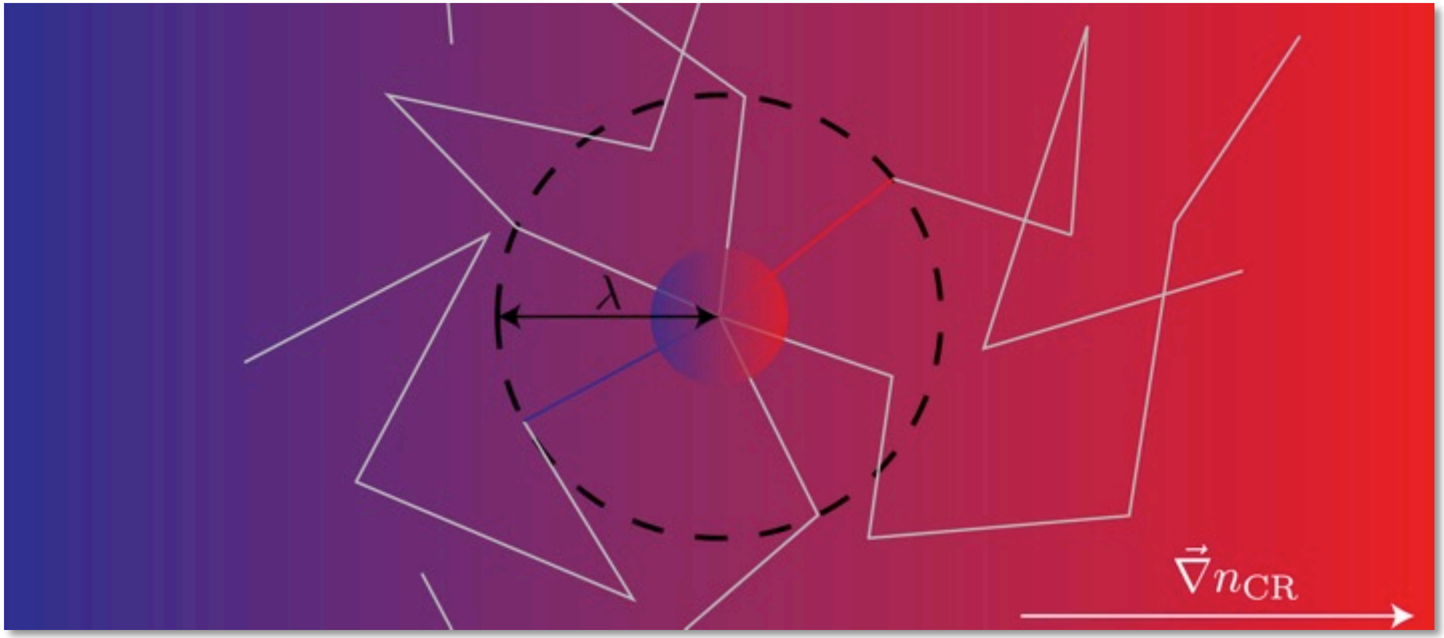
$$\frac{\partial n_i}{\partial t} - \vec{\nabla} \cdot \left(D_{xx} \cdot \vec{\nabla} n_i - \vec{u}\, n_i \right) - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} n_i - \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} n_i - \frac{p}{3} \left(\vec{\nabla} \cdot \vec{u} \right) n_i \right)$$

$$= q + \sum_{i<j} \left(c\, \beta\, n_{\mathrm{gas}}\, \sigma_{j \to i} + \gamma\, \tau^{-1}_{j \to i} \right) n_j - \left(c\, \beta\, n_{\mathrm{gas}}\, \sigma_i + \gamma\, \tau_i^{-1} \right) n_i \,,$$



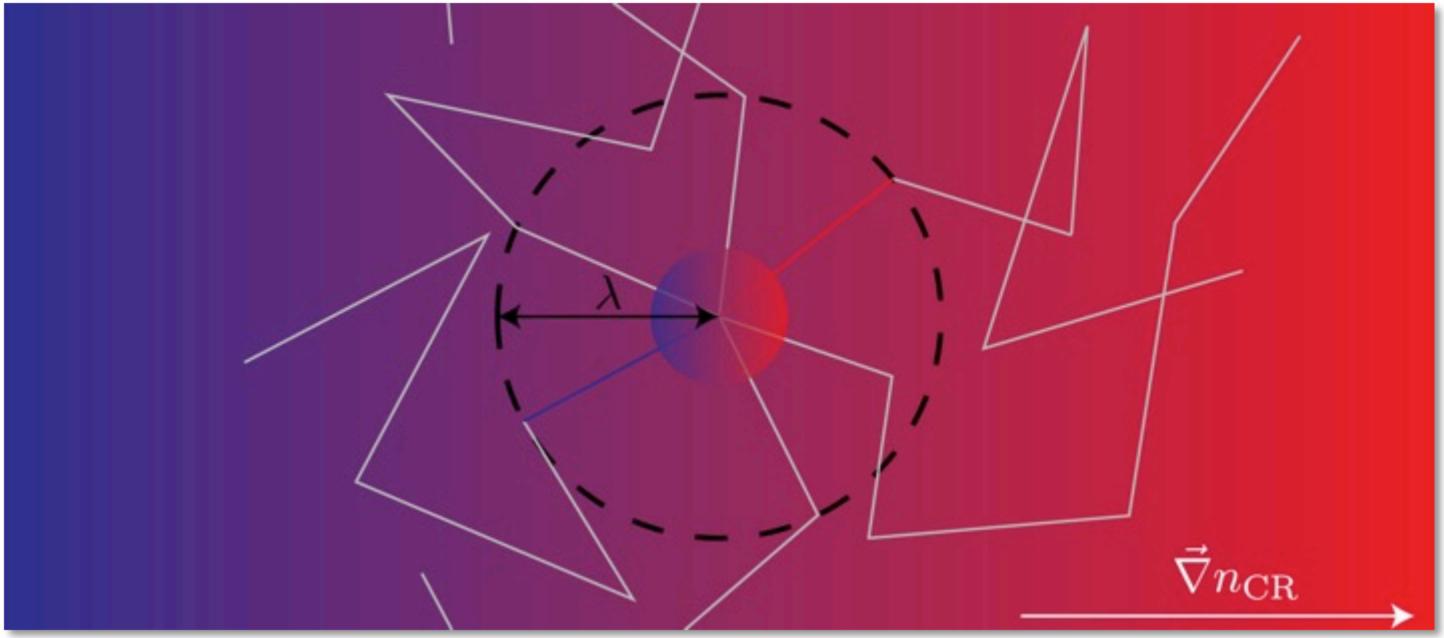
asymmetric source distribution → $\vec{\nabla} n_{\mathrm{CR}}$.

Why anisotropy? (II)



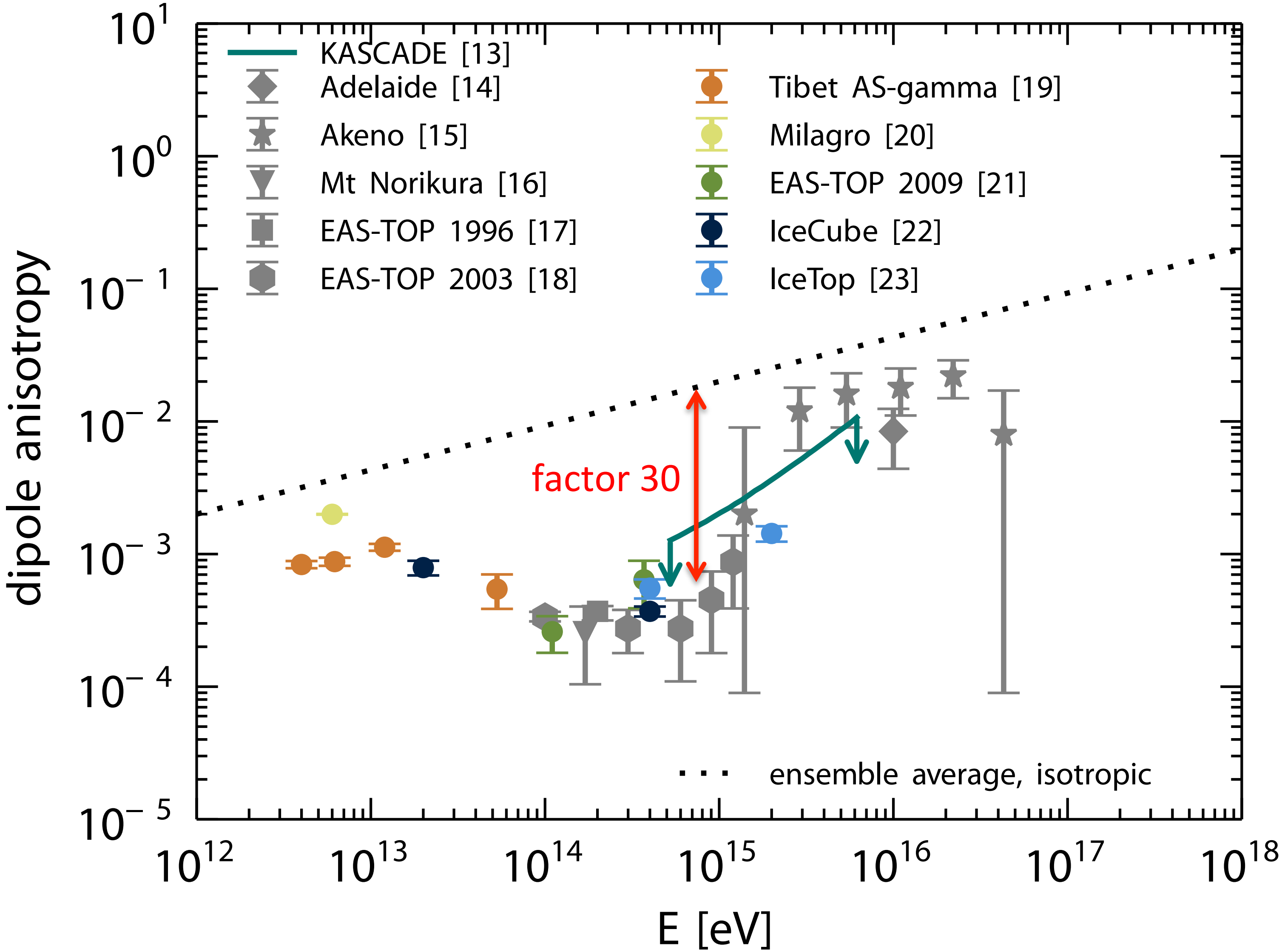
Why anisotropy? (II)

$$|\delta| = \frac{\phi_{\max} - \phi_{\min}}{\phi_{\max} + \phi_{\min}} = \frac{\phi(\vec{r} + \vec{\lambda}) - \phi(\vec{r} - \vec{\lambda})}{\phi(\vec{r} + \vec{\lambda}) + \phi(\vec{r} - \vec{\lambda})} \simeq \frac{2\lambda |\nabla \phi(\vec{r})|}{2\phi(\vec{r})} = \frac{3D}{c} \frac{|\nabla \phi(\vec{r})|}{\phi(\vec{r})}$$

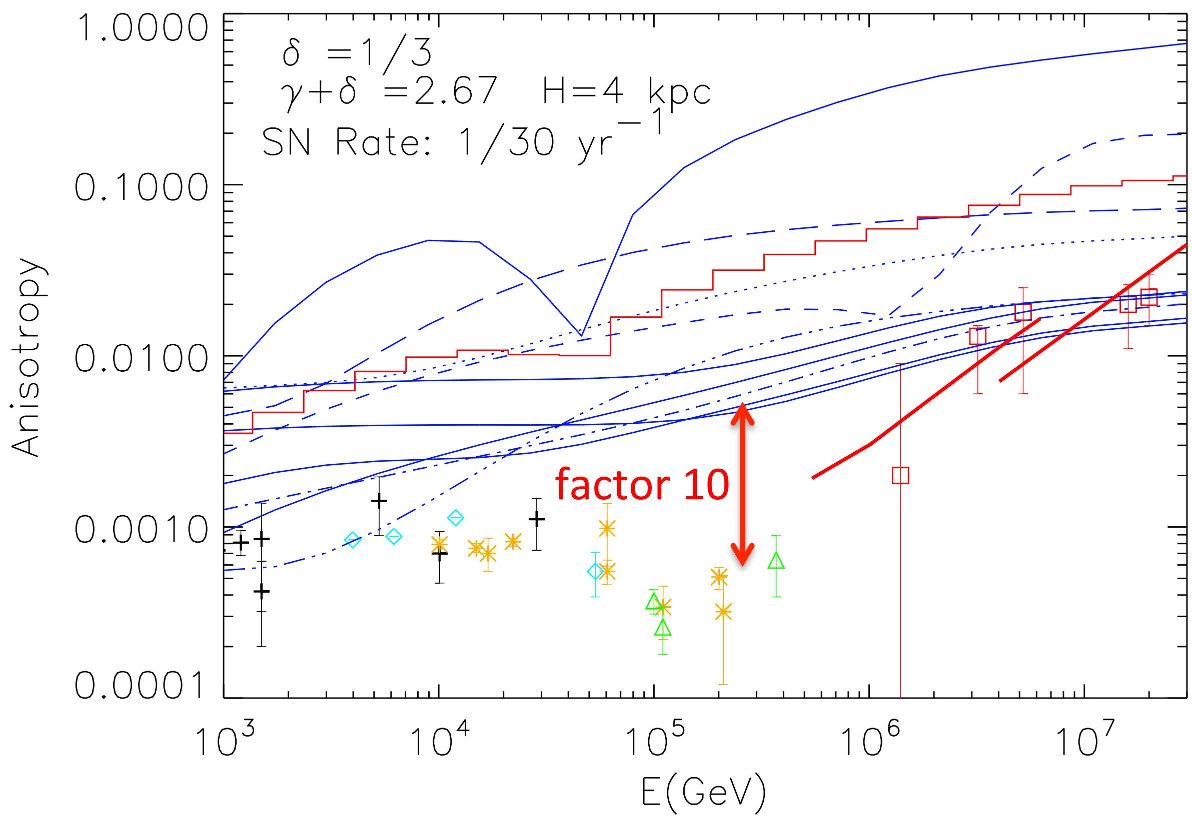


$$\vec{\delta} = \frac{3D}{c} \frac{\vec{\nabla} n_{\mathrm{CR}}}{n_{\mathrm{CR}}}$$

Experimental situation



Source stochasticity



Blasi & Amato, *JCAP* **01** (2012) 011

Measured vs. predicted diffusion coefficient

$$D = D_0(\mathcal{R}/\mathrm{GV})^{\delta}$$

from fitting B/C:

$$\delta = 0.33 \Rightarrow D_0 \simeq 4.0 \times 10^{28}\,\mathrm{cm^2 s^{-1}}$$

$$\delta = 0.55 \Rightarrow D_0 \simeq 2.3 \times 10^{28}\,\mathrm{cm^2 s^{-1}}$$

for $z_{\mathrm{max}} = 4\,\mathrm{kpc}$

from quasi-linear theory:

turbulence spectrum $W(k) \propto k^{-q}$ where $kW(k) \sim \delta B^2(k)$

$$D_{||} \sim r_g \left(\frac{r_g}{L}\right)^{q-1} \left(\frac{\delta B}{B_0}\right)^{-2}$$

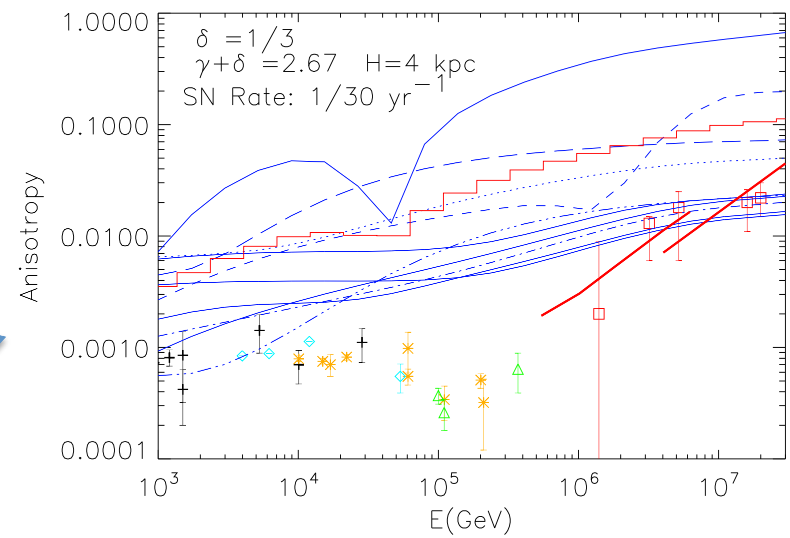
falls short of measured values (for $B_0 = 4\,\mu\mathrm{G}$ and $L = 100\,\mathrm{pc}$)

$$D_{||,0} = 4.3 \times 10^{27}\,\mathrm{cm^2 s^{-1}} \left(\frac{\delta B}{B_0}\right)^{-2} \quad \text{for } 2 - q = \delta = 0.33$$

$$D_{||,0} = 1.6 \times 10^{26}\,\mathrm{cm^2 s^{-1}} \left(\frac{\delta B}{B_0}\right)^{-2} \quad \text{for } 2 - q = \delta = 0.5$$

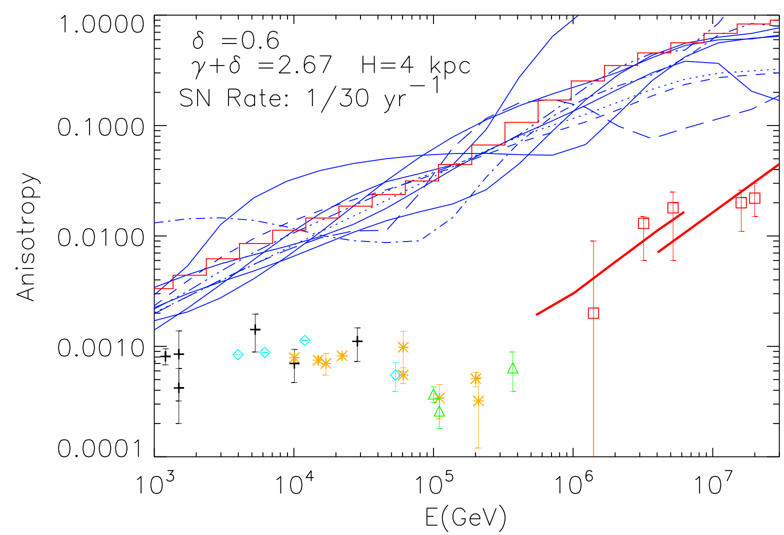
Consequences I

- can be used to constrain spectral index of diffusion coefficient:



- poor agreement for $\delta = 1/3$

- for $\delta = 0.6$, it's even worse



Blasi & Amato, *JCAP* **01** (2012) 011

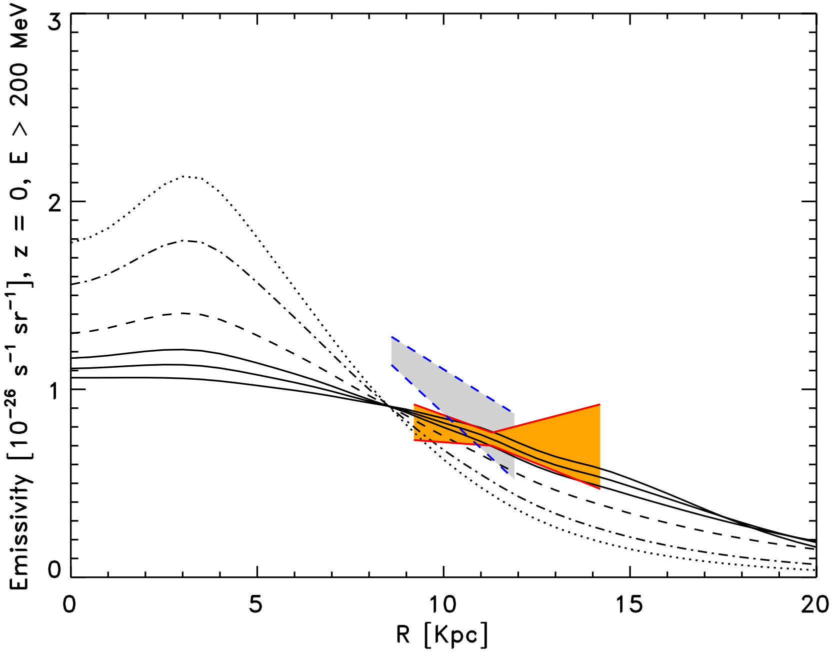
Consequences II

- maybe the predicted global gradient is too large
- also in disagreement with gamma-ray data

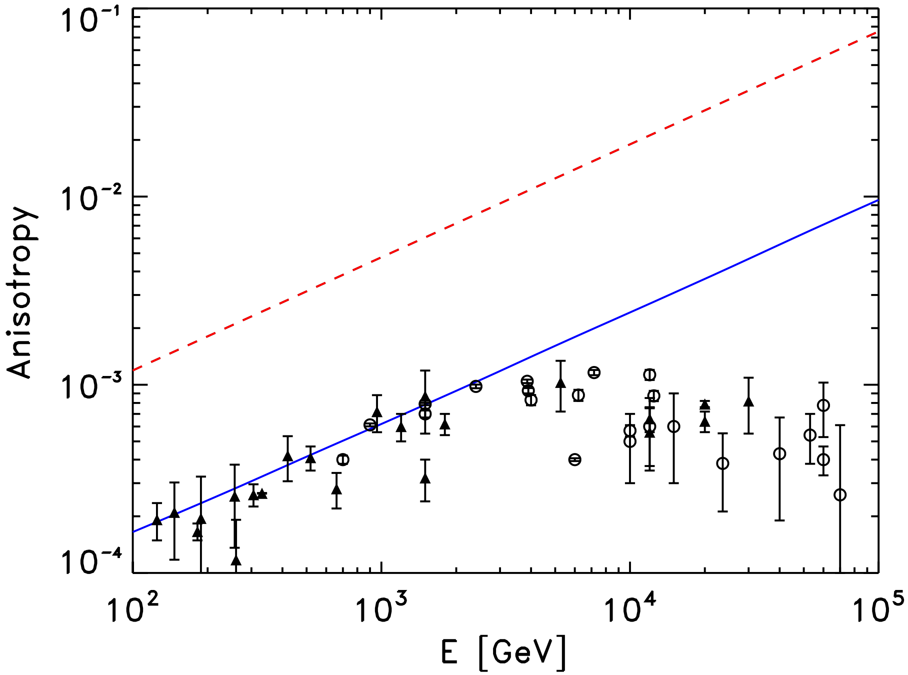
- vary diffusion coefficient with galacto-centric radius
  - $D_{||} \propto \left(\frac{\delta B}{B_0}\right)^{-2}$ but $D_{\perp} \propto \left(\frac{\delta B}{B_0}\right)^{2}$
  - turbulence level follows source density $q(r)$
  - in the inner Galaxy escape is dominated by perpendicular diffusion
  - simulated by $D \propto q(r)^{\tau}$

Evoli *et al.*, *PRL* 108 (2012) 211102

Conclusion II



Evoli *et al.*, *PRL* 108 (2012) 211102



Ensemble averaging

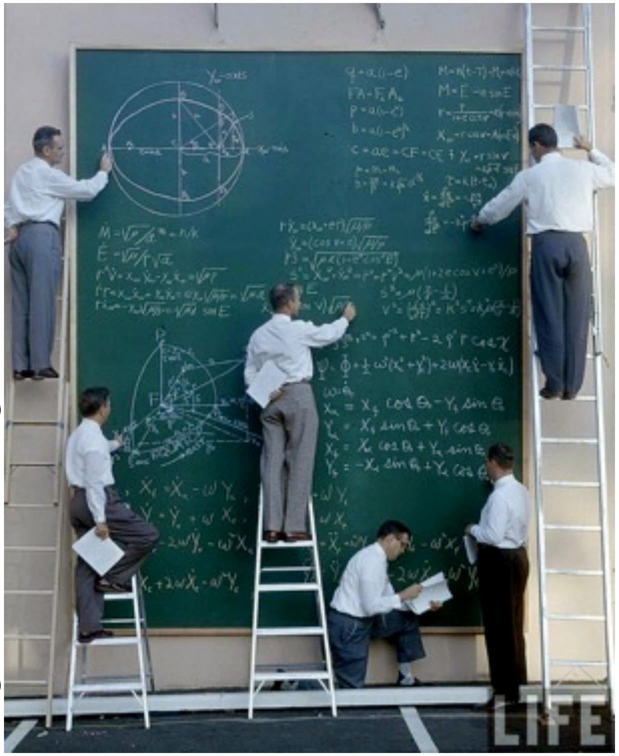


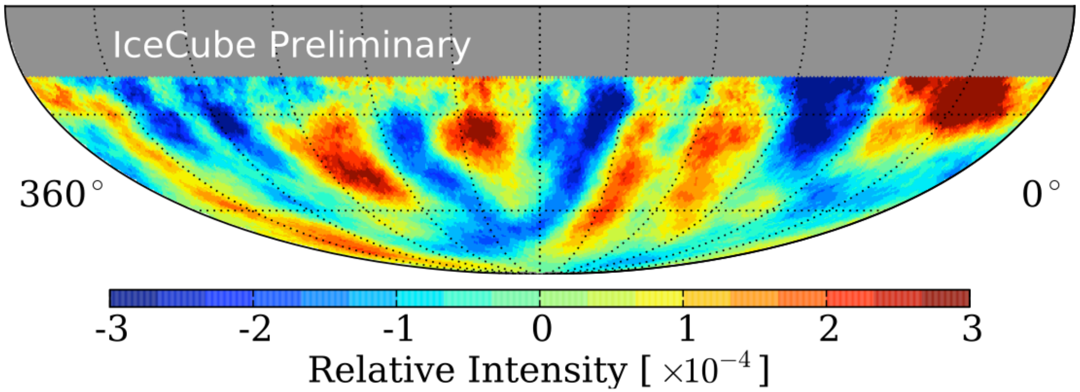
Image credit: LIFE magazine

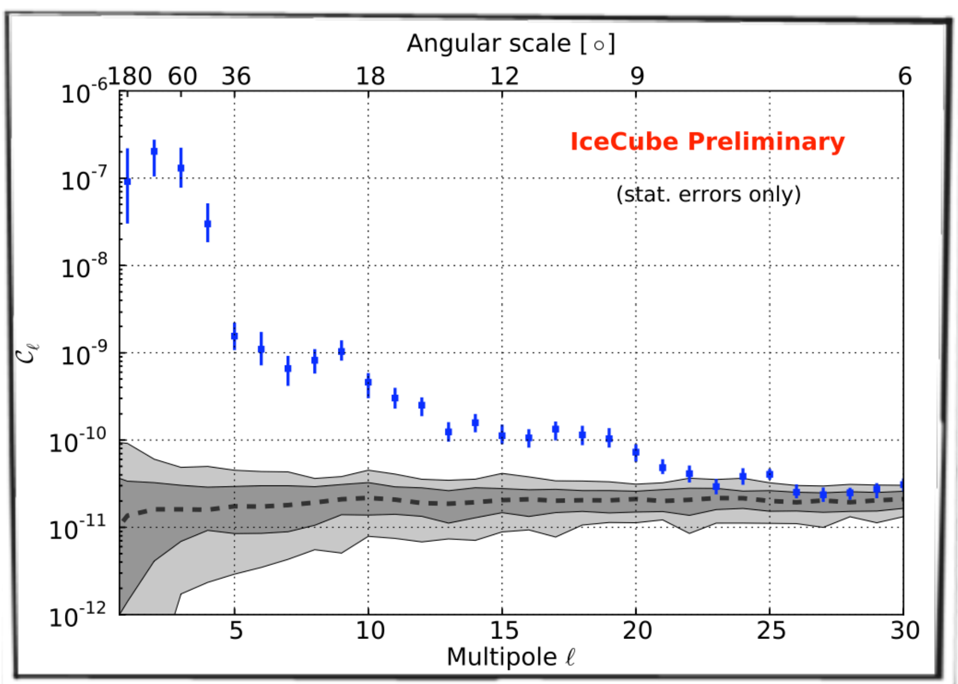
- distribution function $f(\vec{x}, \vec{p}, t)$ develops under influence of $\delta B(\vec{x})$ and $\delta E(\vec{x})$
- we predict only the ensemble average $\langle f(\vec{x}, \vec{p}, t) \rangle$ for ensemble averaged force term
- usually, this is determined from Gaussian random B-field, characterised by $W(k)$

- we live in **one particular realisation** of random magnetic field!

→ deviations from ensemble average

Small scale anisotropies





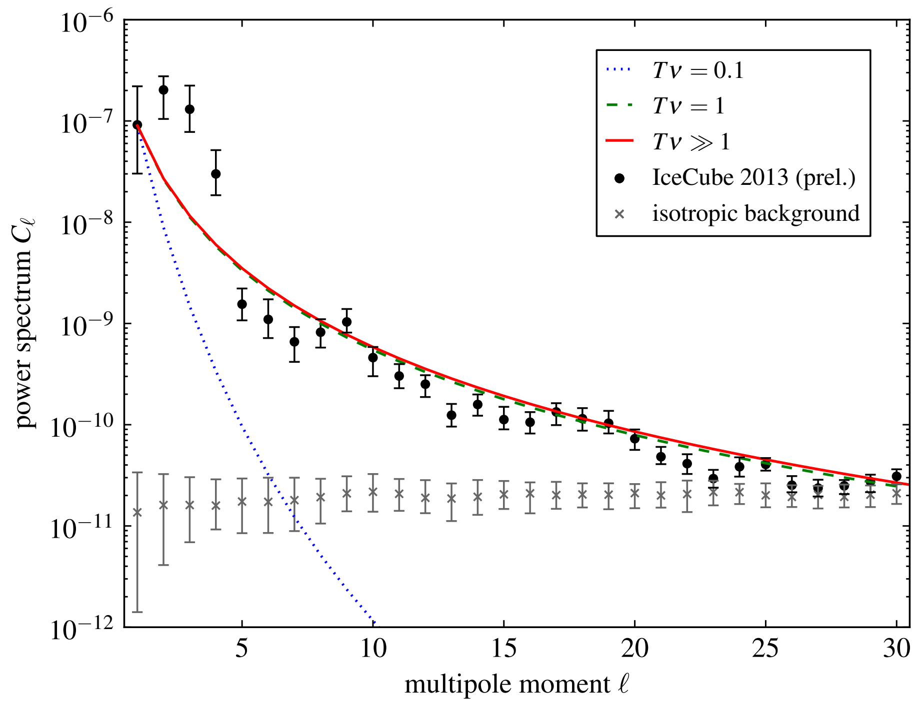
- 5° smoothing
- median energy 20 TeV
- structure below 10°

Santander *et al.*, ICRC 2013
(see also HAWC, arXiv:1408.4805)

Computing the variance

- simplifying assumptions:
  - isotropic turbulence
  - prepare homogeneous, but anisotropic phase-space density
- diffusion as series of random rotations
- can express angular power spectrum in terms of dipole:

$$\lim_{T\to\infty}\frac{\langle C_\ell\rangle(T)}{\langle C_1\rangle(T)} \simeq \frac{18}{(2\ell+1)(\ell+2)(\ell+1)}$$



Ahlers, *PRL* **112** (2014) 021101

Anisotropic diffusion

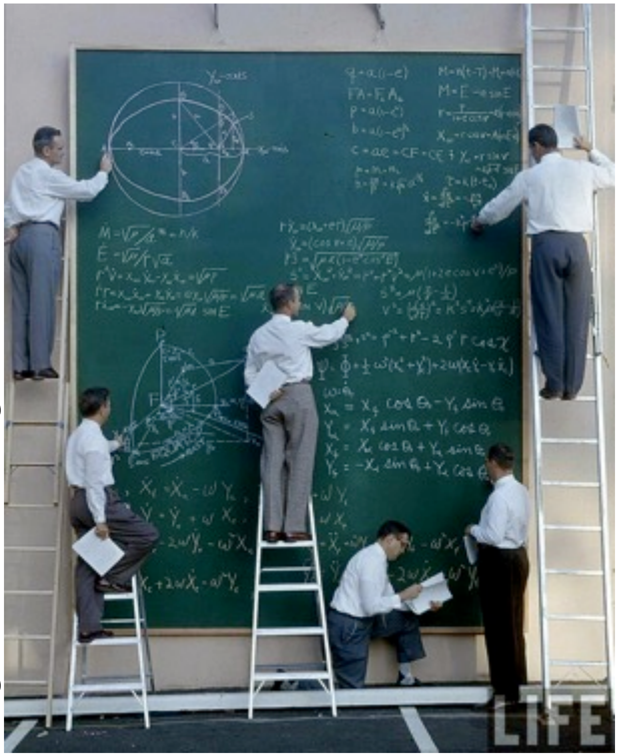
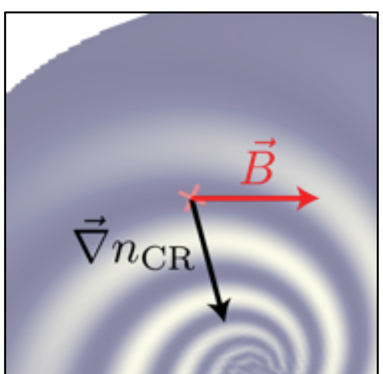


Image credit: LIFE magazine



- decompose distribution function

$$f_0(\vec{x}, p, \mu, t) \equiv F(\vec{x}, p, t) + g(\vec{x}, p, \mu, t)$$

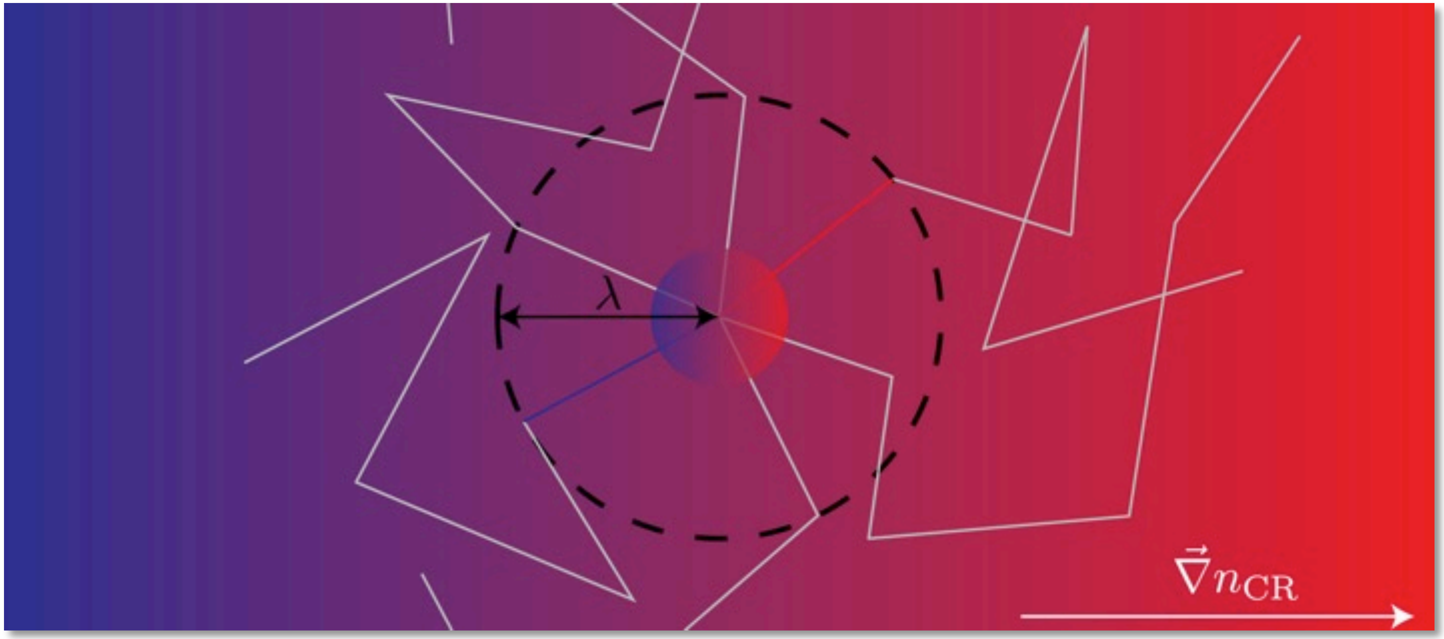
- dipole = first harmonic of anisotropic part

$$|\vec{\delta}| = \frac{3}{2} \frac{\int_{-1}^{1} \mathrm{d}\mu \, g(\mu)}{f_0} = \ldots = -\frac{3}{v} \frac{\partial F / \partial z}{F} D_{\parallel}$$

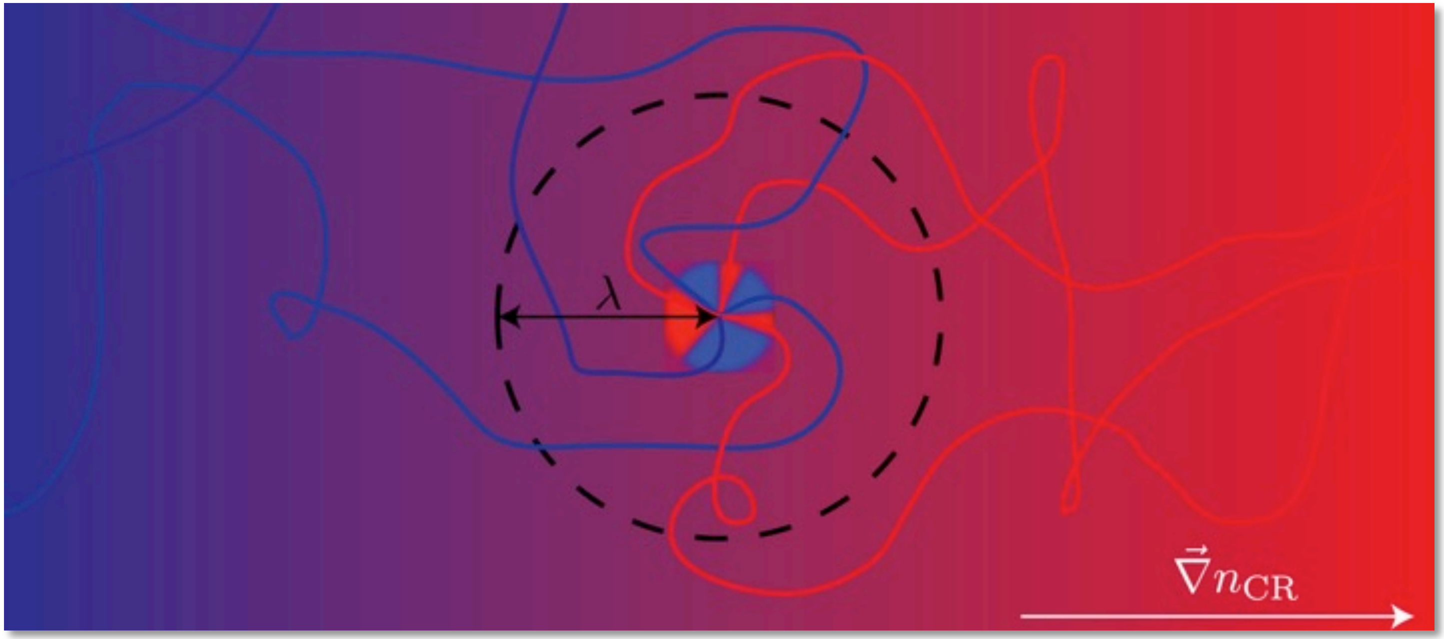
→ amplitude depends on gradient *along* background B-field
→ orientation not in direction of gradient but of background B-field

- can this help decrease the dipole amplitude?

Numerical approach



Numerical approach



1. set up large scale gradient at time $(t_0 - \Delta t)$: $f(\vec{x}, \vec{p}, t_0 - \Delta t) = \ldots$

2. back-track large number of particles $i \in N$ for time Δt:

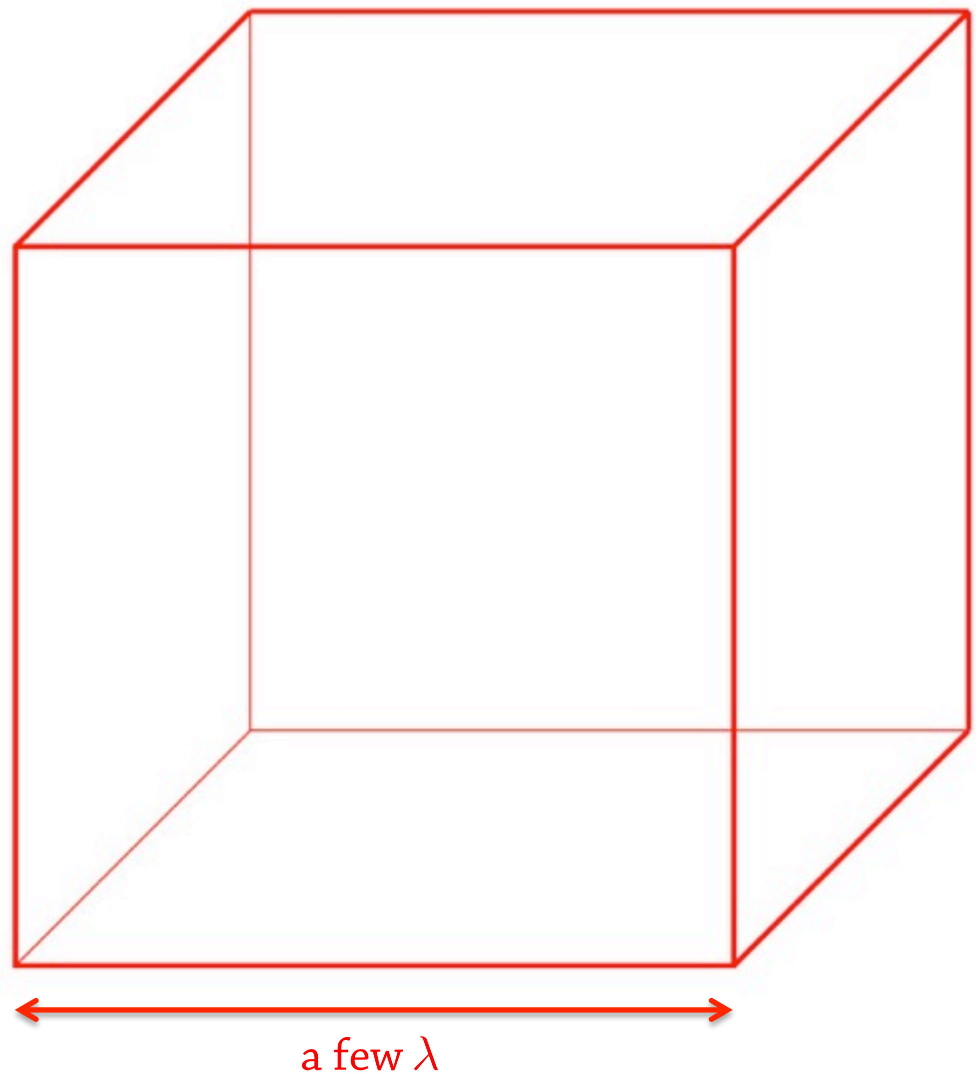
$$\{\vec{x}_i(t_0), \vec{p}_i(t_0)\} \quad \rightarrow \quad \{\vec{x}_i(t_0 - \Delta t), \vec{p}_i(t_0 - \Delta t)\}$$

3. Liouville's theorem:

$$df = 0 \quad \Rightarrow \quad f(\vec{x}_{\rm obs.}, \vec{p}_i(t_0)) = f(\vec{x}_i(t_0 - \Delta t), \vec{p}_i(t_0 - \Delta t))$$

nested grids

Giacinti *et al.*, JCAP **07** (2012) 031



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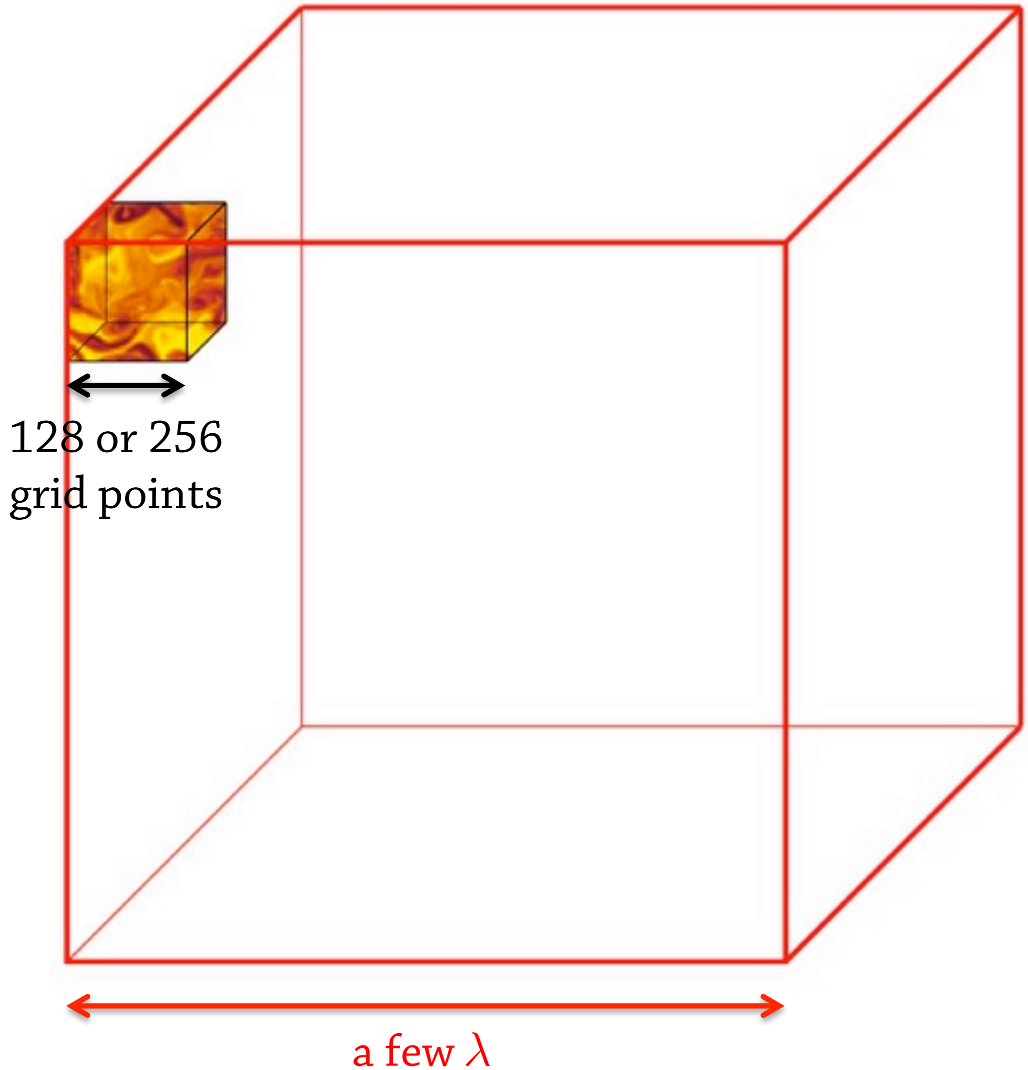
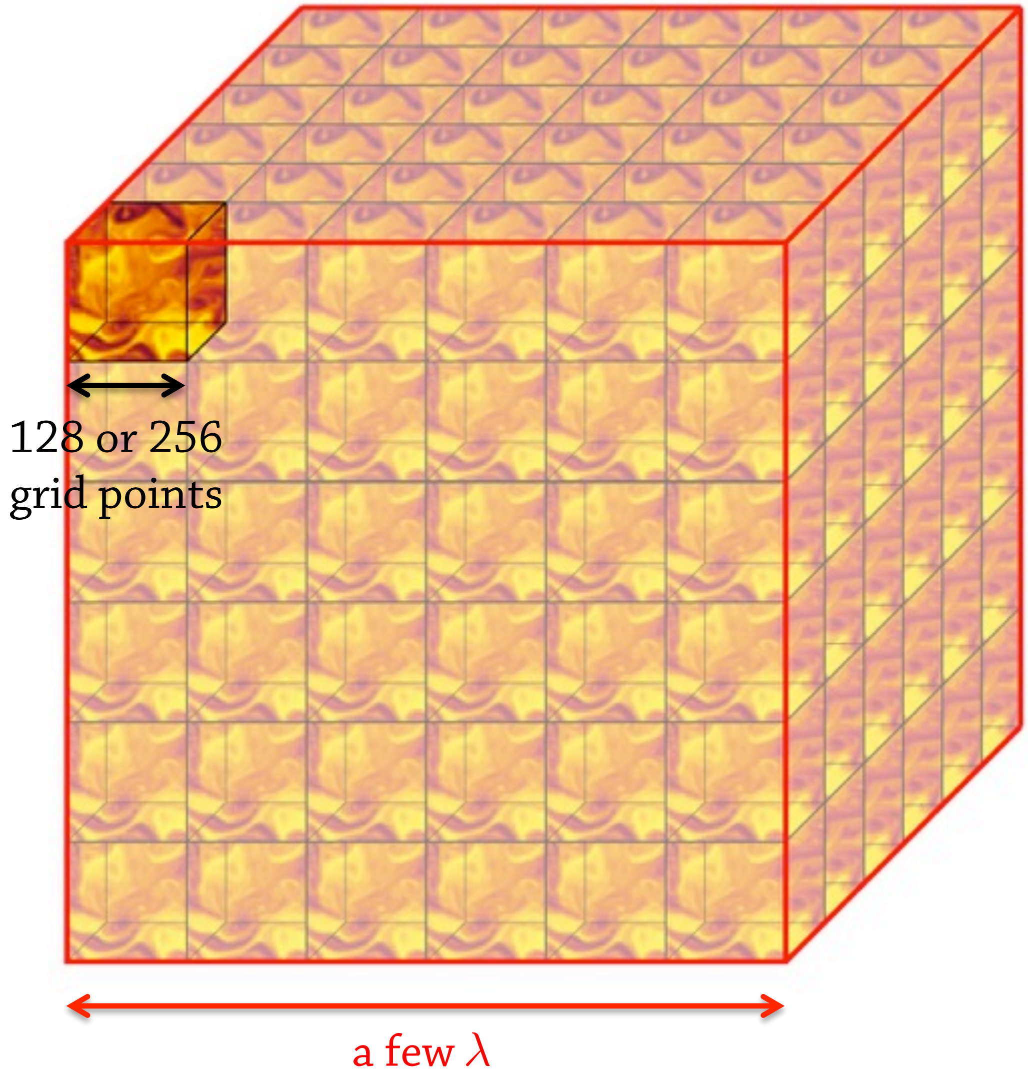


Giacinti *et al.*, JCAP **07** (2012) 031

nested grids



Giacinti *et al.*, JCAP **07** (2012) 031

nested grids

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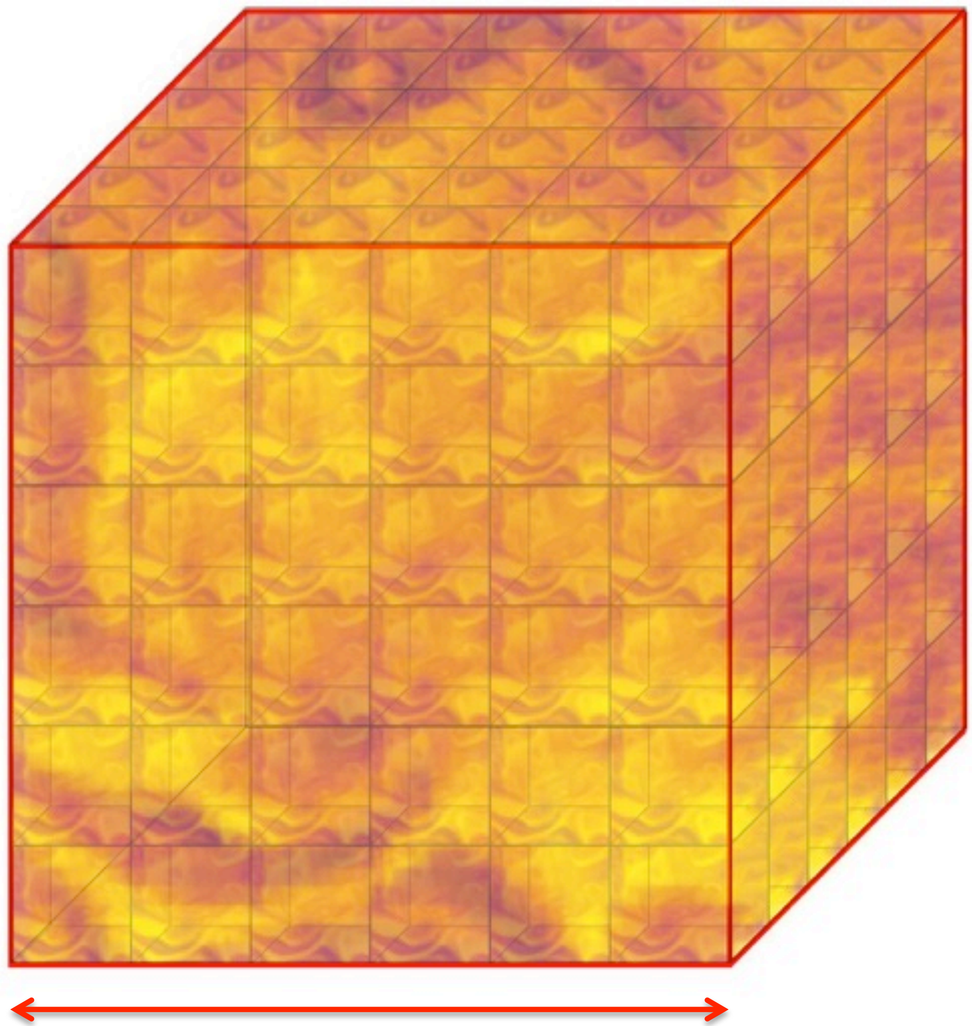
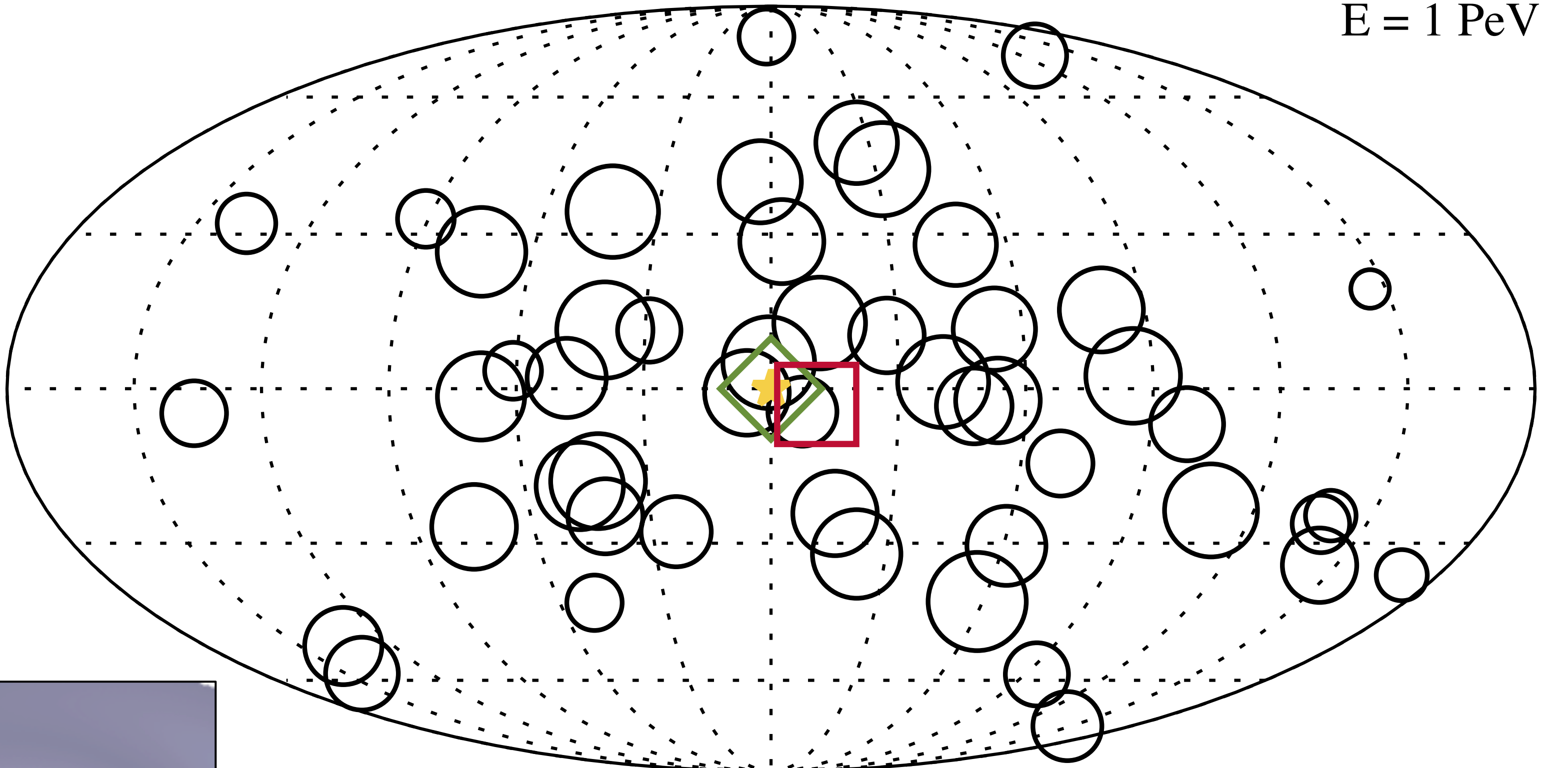
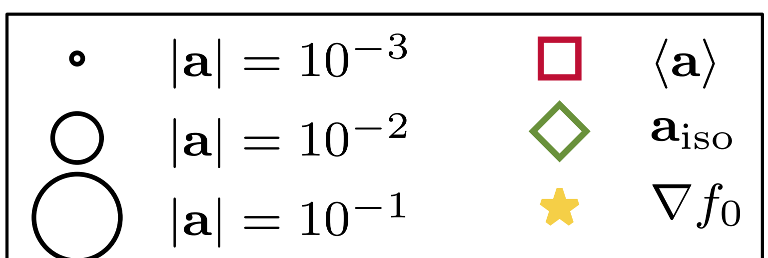


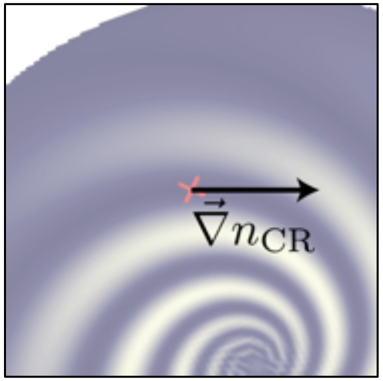
a few λ

- 4 nestings
- 128^3 grids
- $L_{i+1}/L_i \simeq 30 - 40$

w/o background B-field



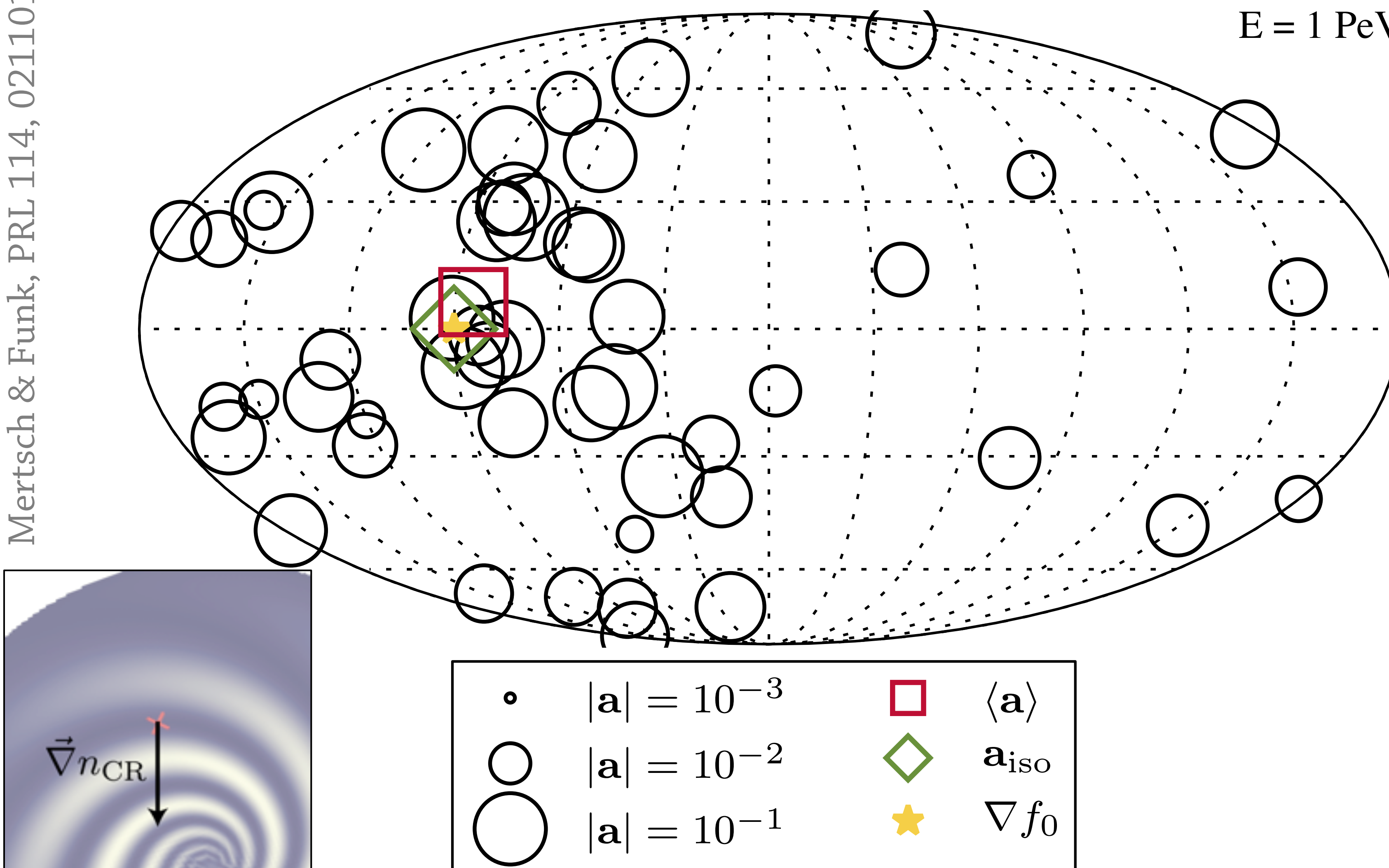




Mertsch & Funk, PRL 114, 021101 (2015)

w/o background B-field

Mertsch & Funk, PRL 114, 021101 (2015)



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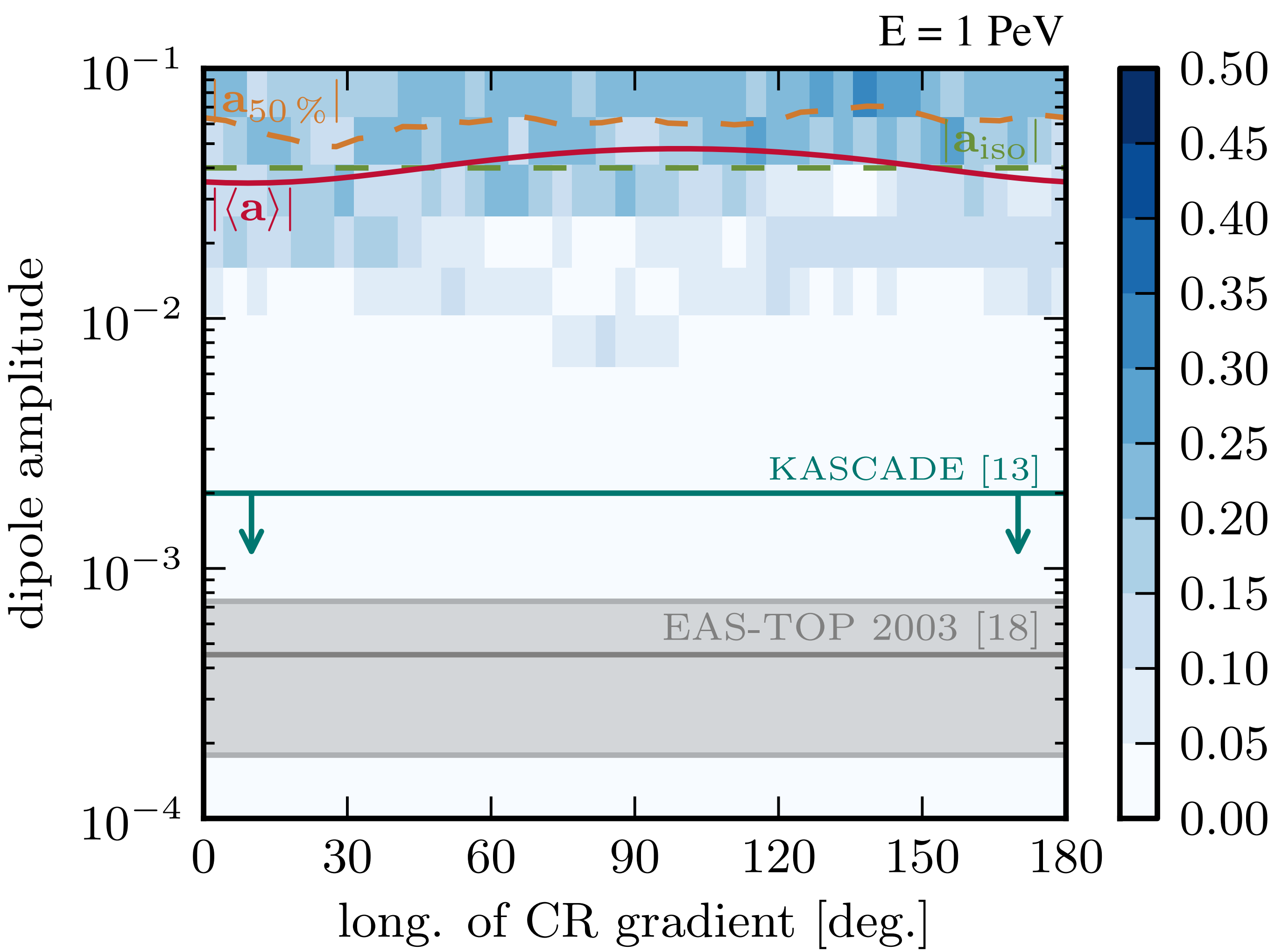
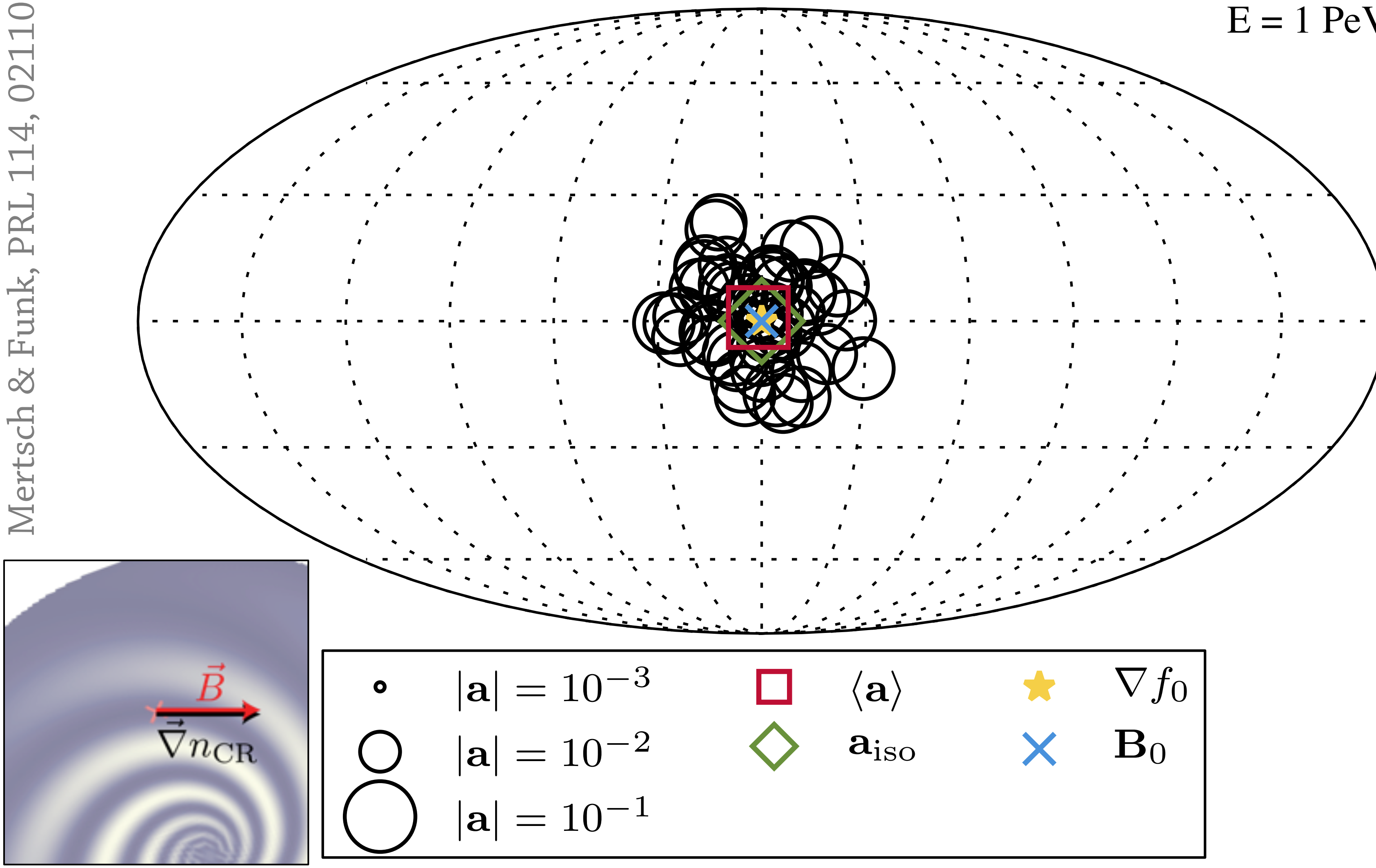


Mertsch & Funk, PRL 114, 021101 (2015)

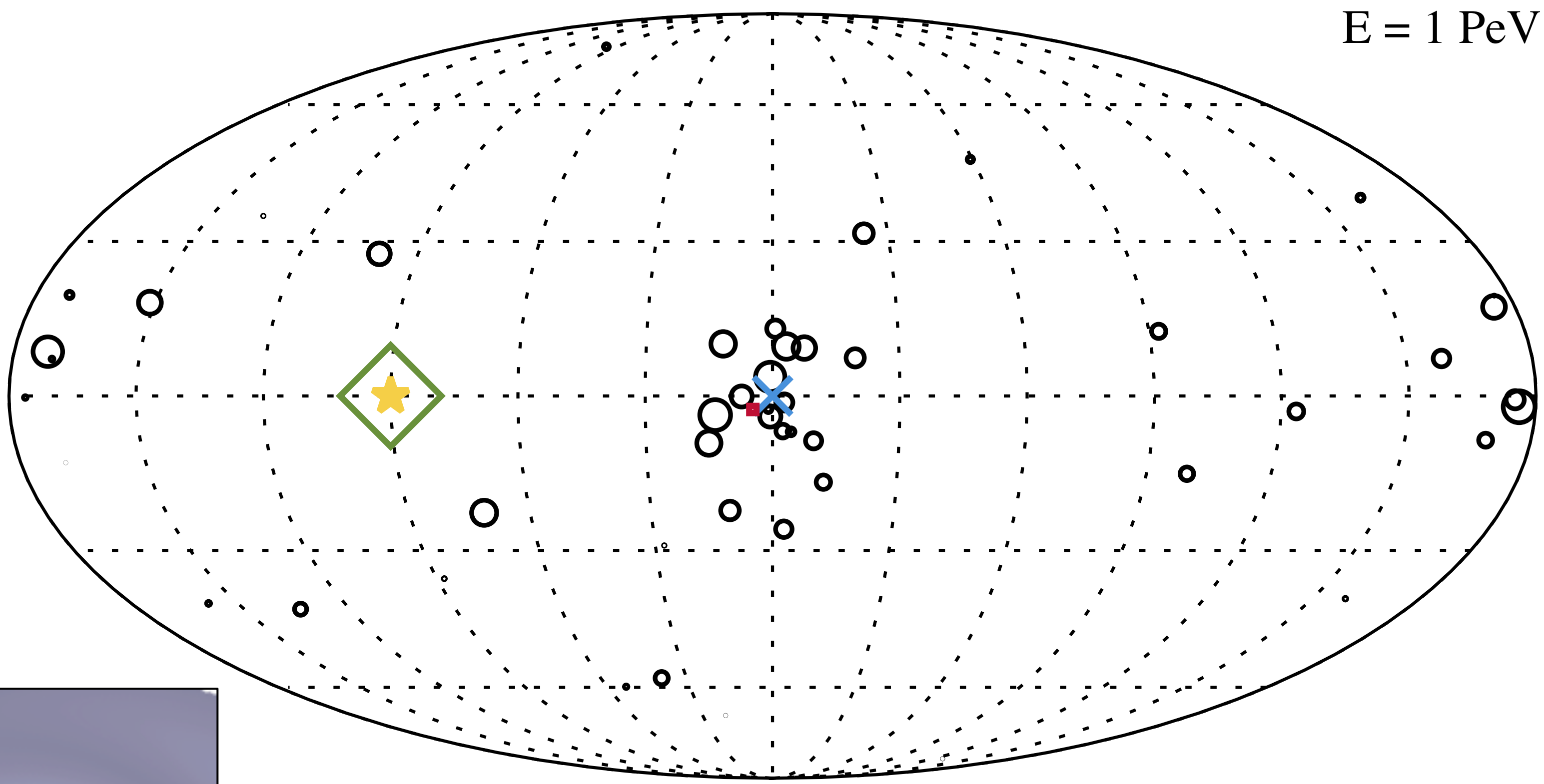
w/ background B-field @ 0°

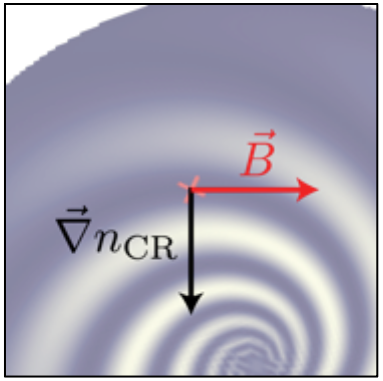
Mertsch & Funk, PRL 114, 021101 (2015)

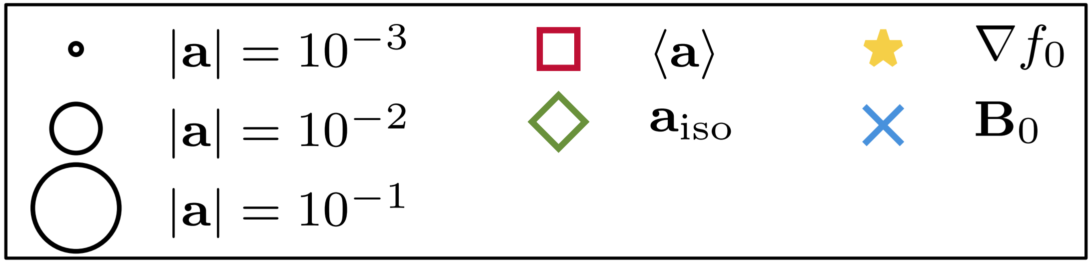


w/ background B-field @ 90°

Mertsch & Funk, PRL 114, 021101 (2015)

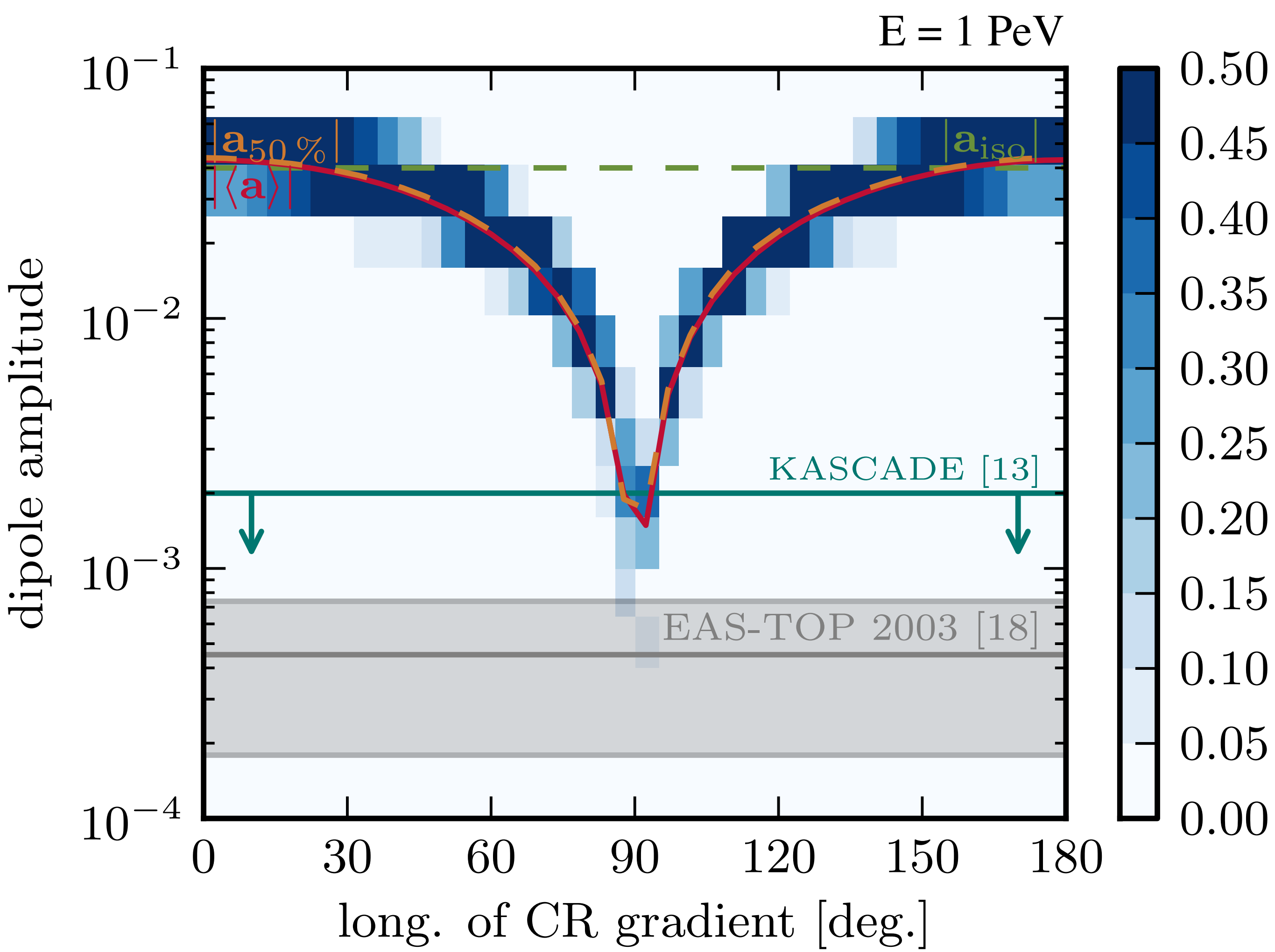






w/ background B-field

Mertsch & Funk, PRL 114, 021101 (2015)



w/ background B-field

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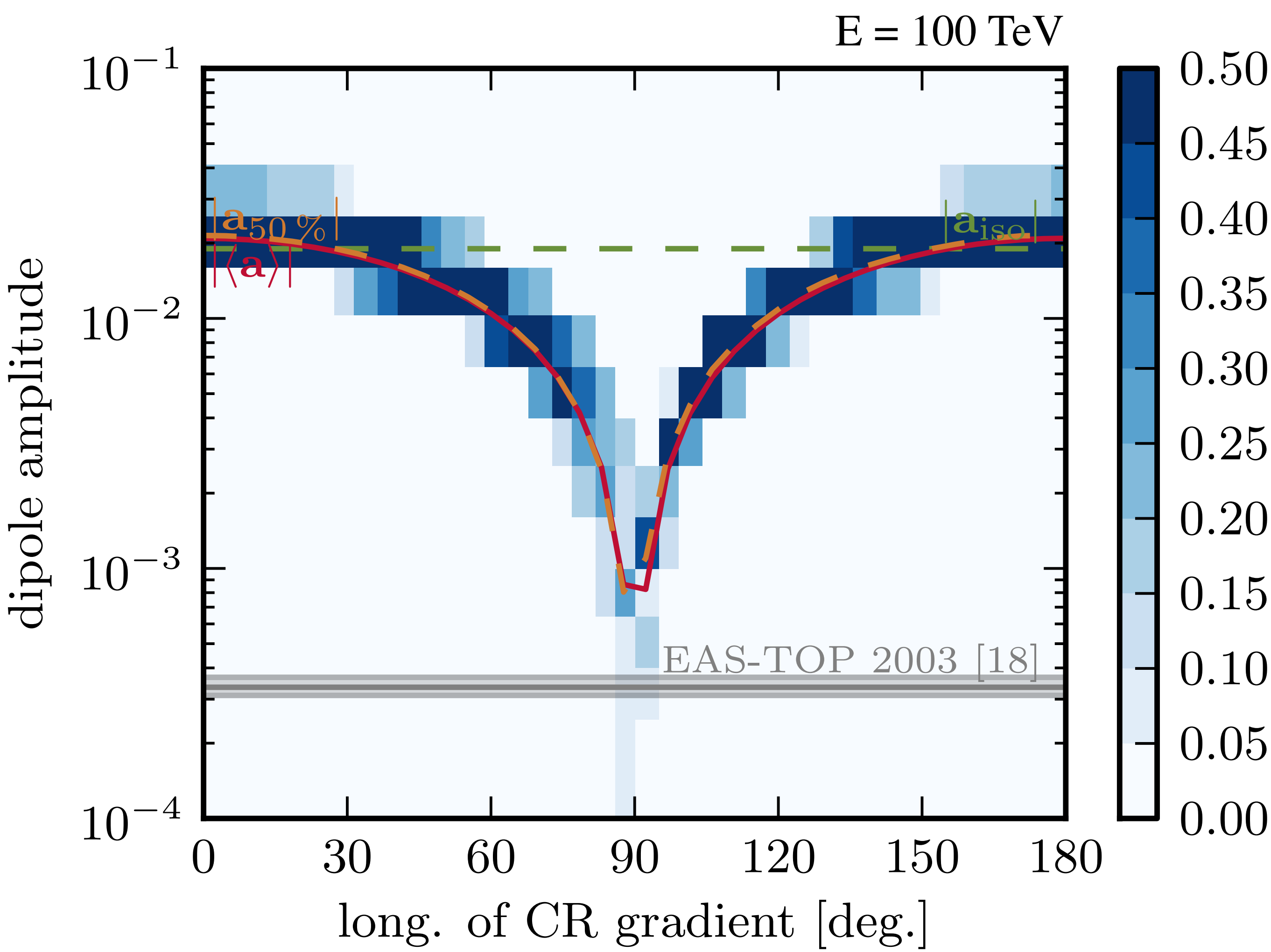
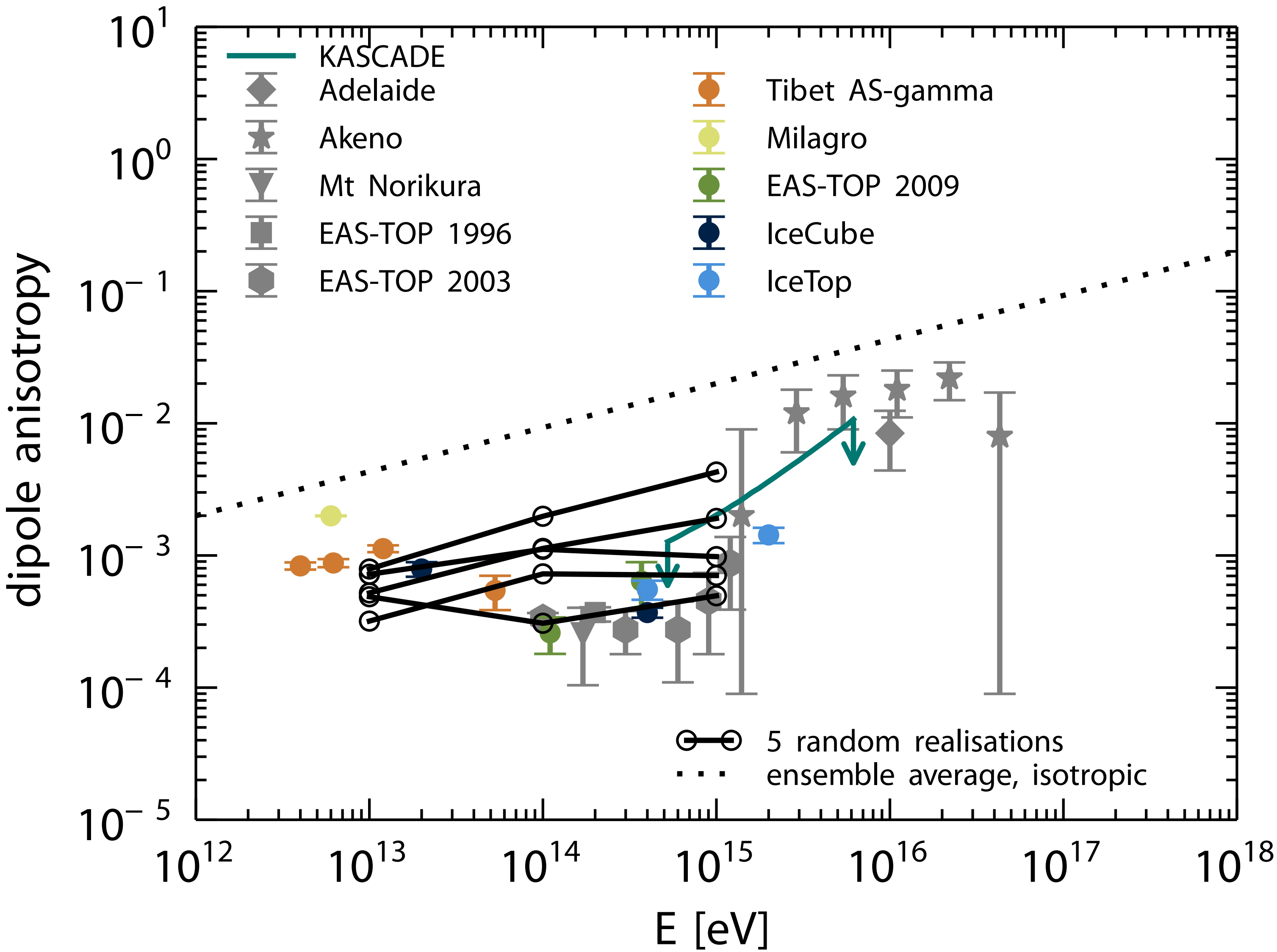


w/ background B-field @ 90°

Mertsch & Funk, PRL 114, 021101 (2015)

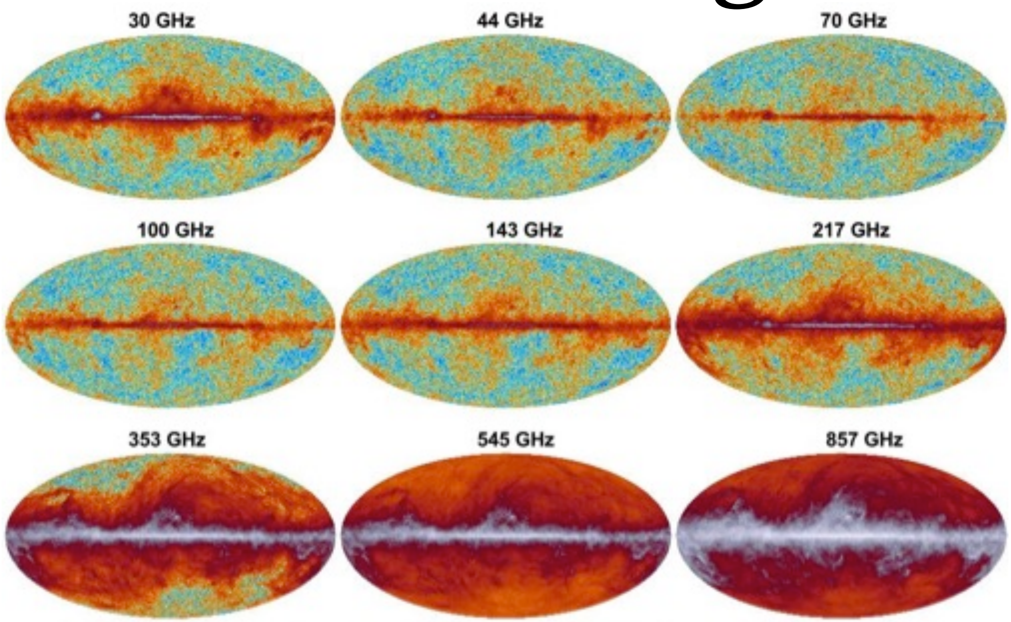


Conclusions

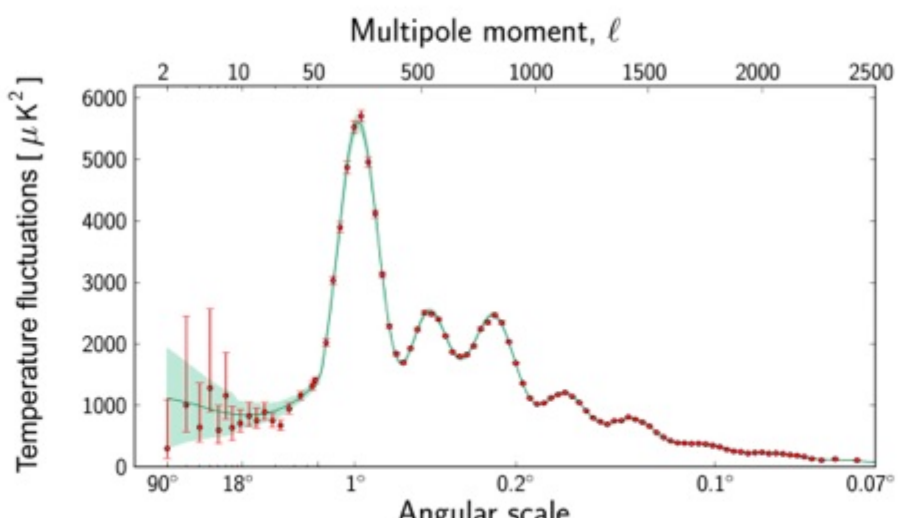
the good: ✔
- can understand small dipole anisotropy: B-field and gradient at 90°
- higher multipoles → higher moments of B-field
- changes in suppression and phase with energy → ongoing work

the bad: ✗
- cannot use dipole direction to find (a) nearby source(s)
  - weak regular field: strong scatter of dipole directions
  - strong regular field: strong scatter when misaligned

CMB foreground removal



Ade *et al.*, arXiv:1303.5072



Internal Linear Combination

WMAP maps

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

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

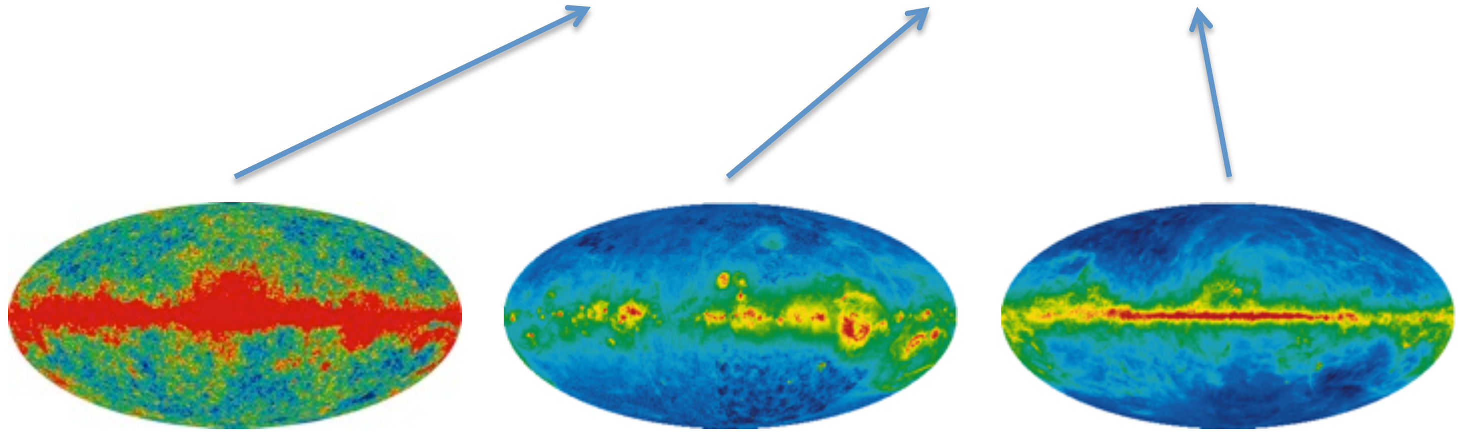
$$\sigma^2_{\rm ILC} = \sigma^2_c - \sigma^2_{cf}/\sigma^2_f \ \leq \sigma^2_c$$

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

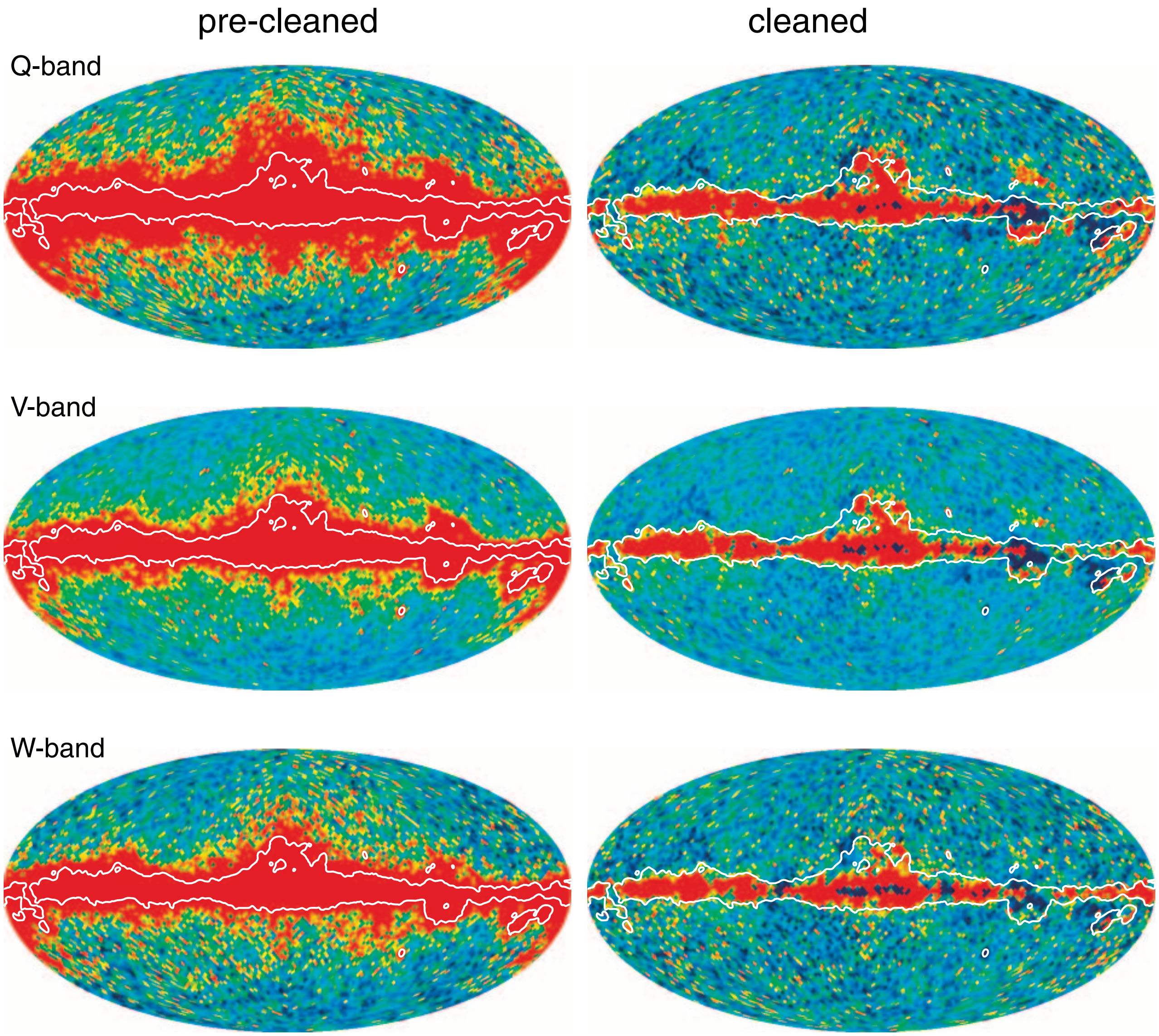
IR map (extrapolated to 94 GHz): tracer of dust

advantage: extract spectral information about foregrounds

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

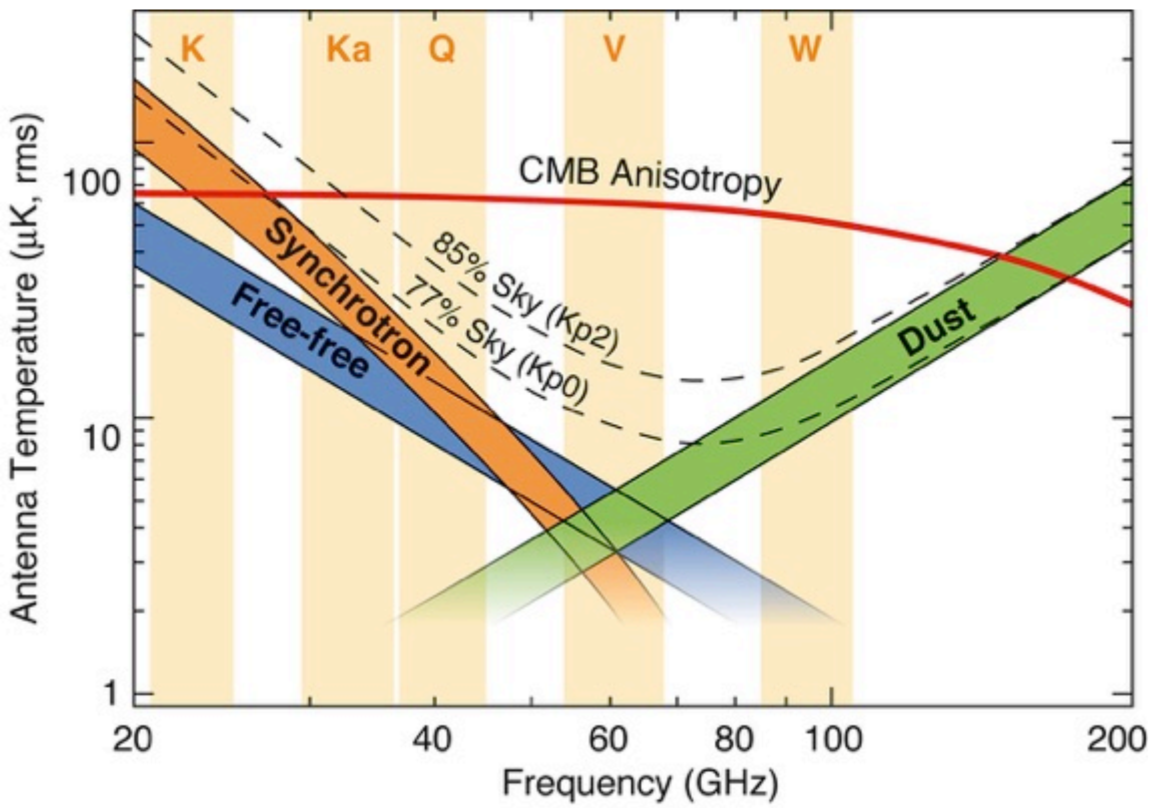
Hinshaw *et al.*, ApJS 170 (2007) 288

Before and after



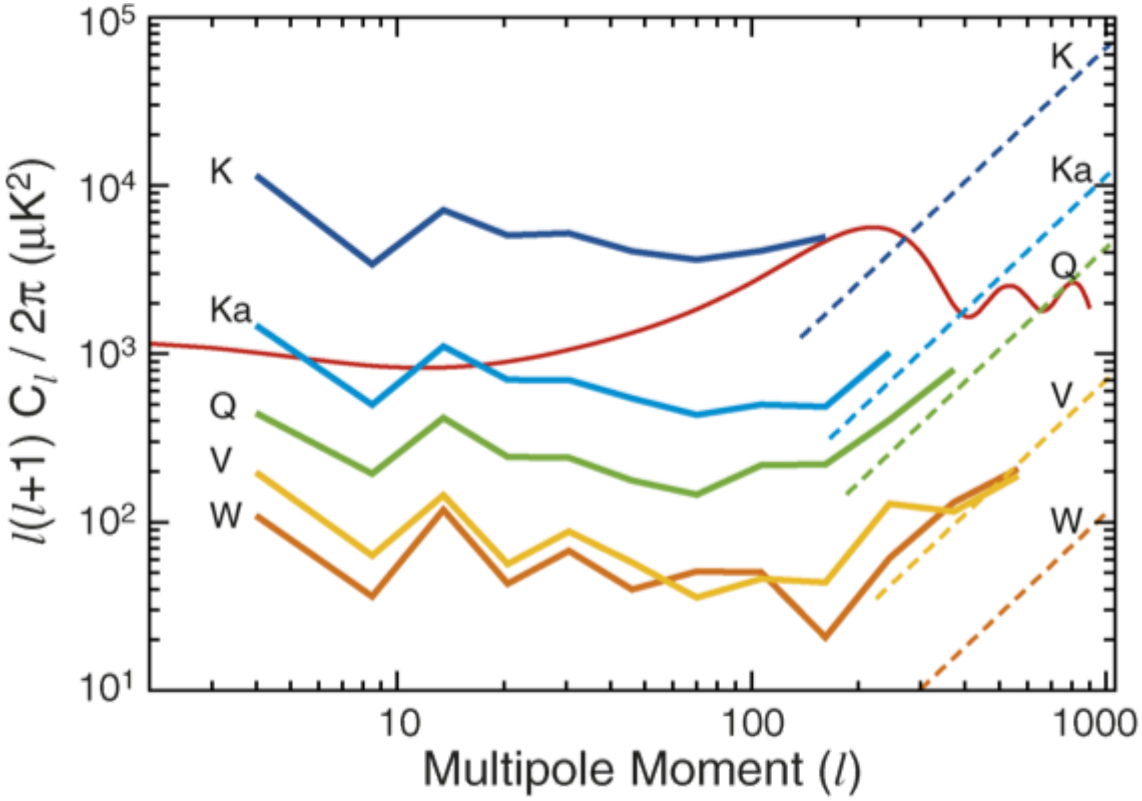
Hinshaw *et al.*, ApJS 170 (2007) 288

Why this is working…



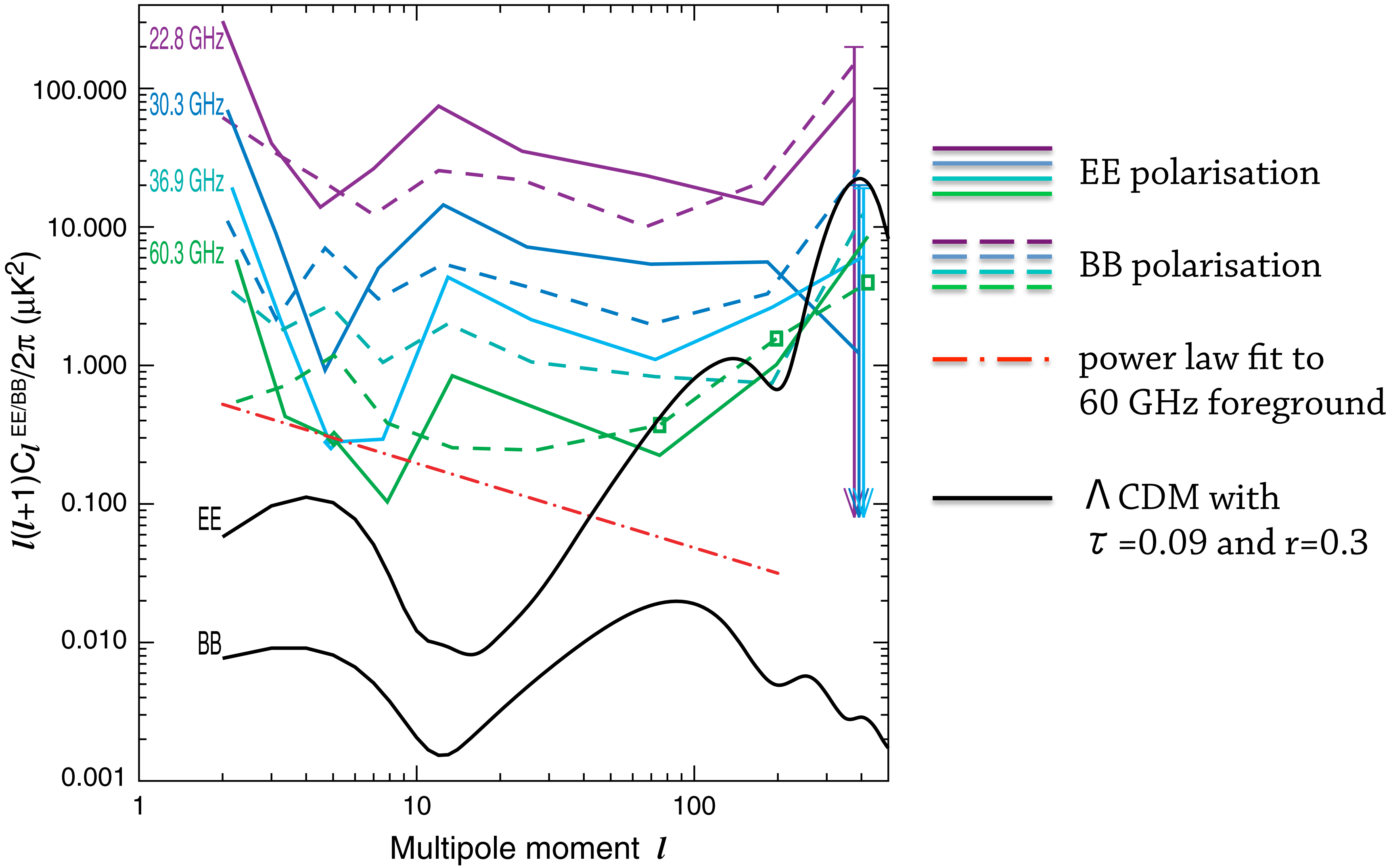
Bennett *et al.*, ApJS 148 (2003) 97

Why this is working…



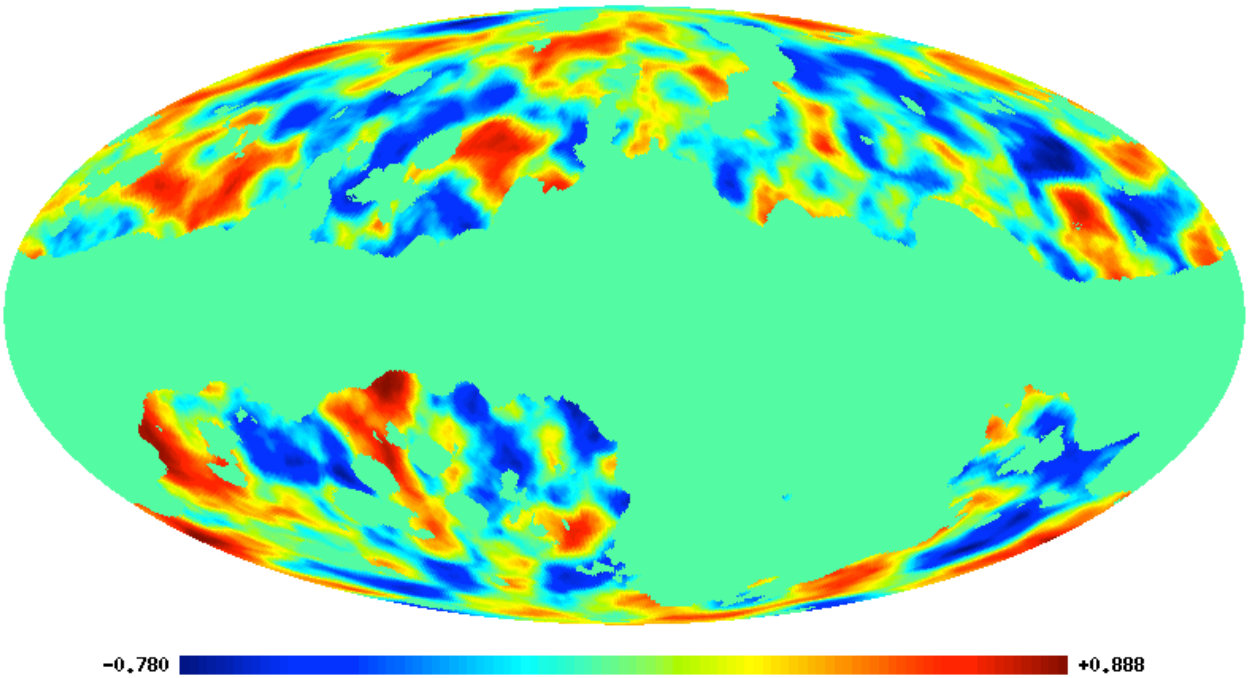
Bennett *et al.*, ApJS 148 (2003) 97

Polarised emission



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

CMB contamination at high latitude?

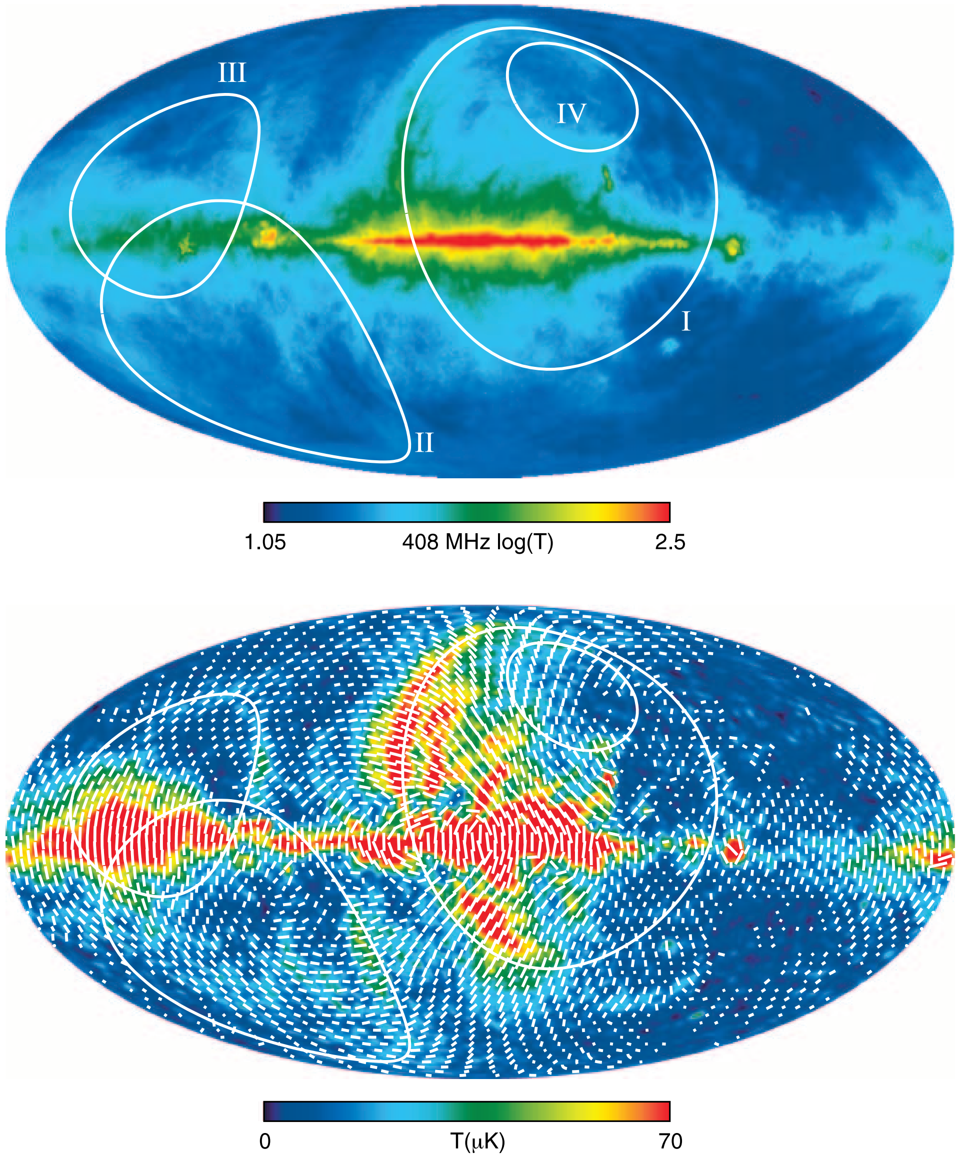


correlation between Faraday depth and WMAP7 ILC

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

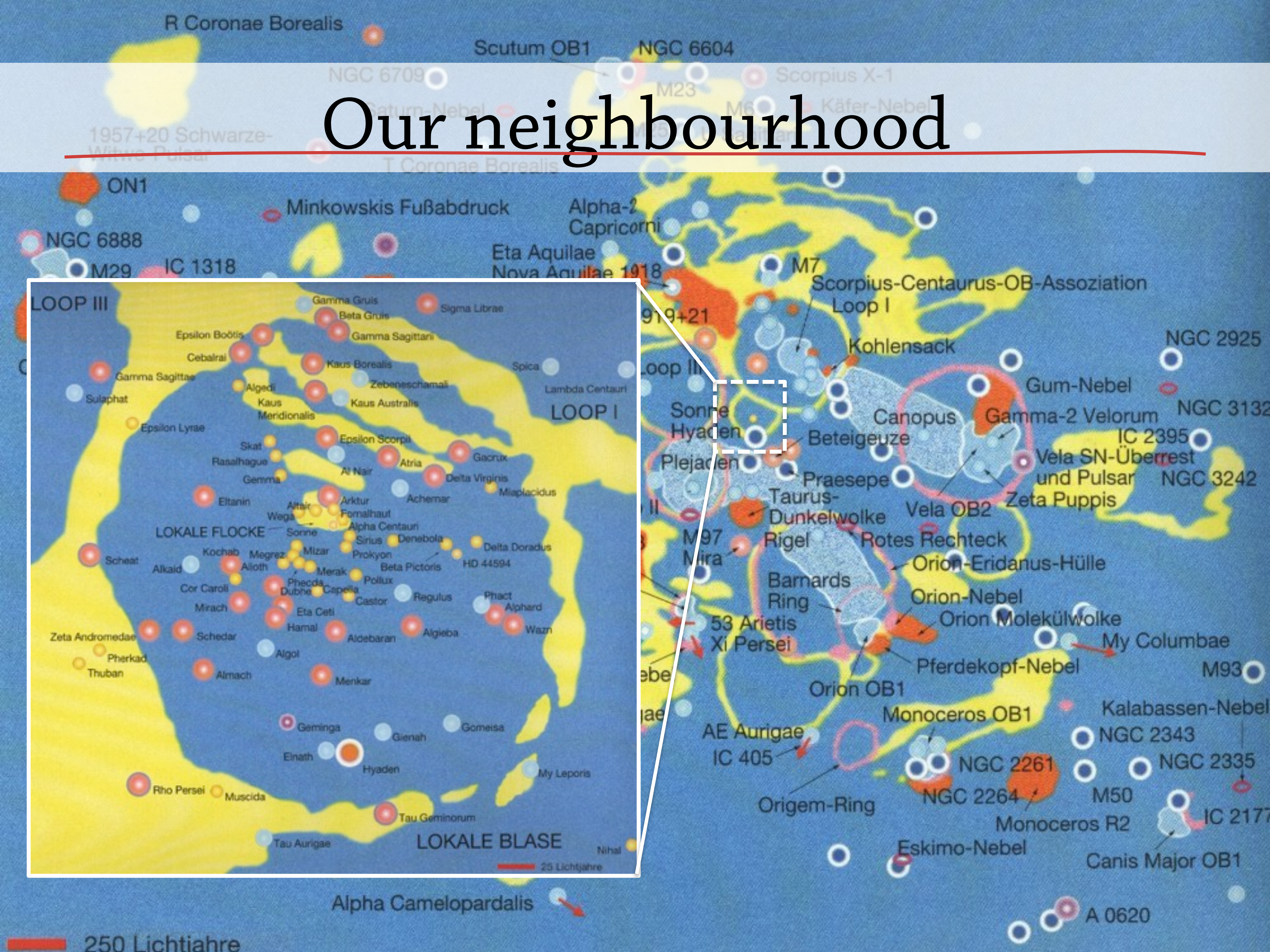
Radio loops



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

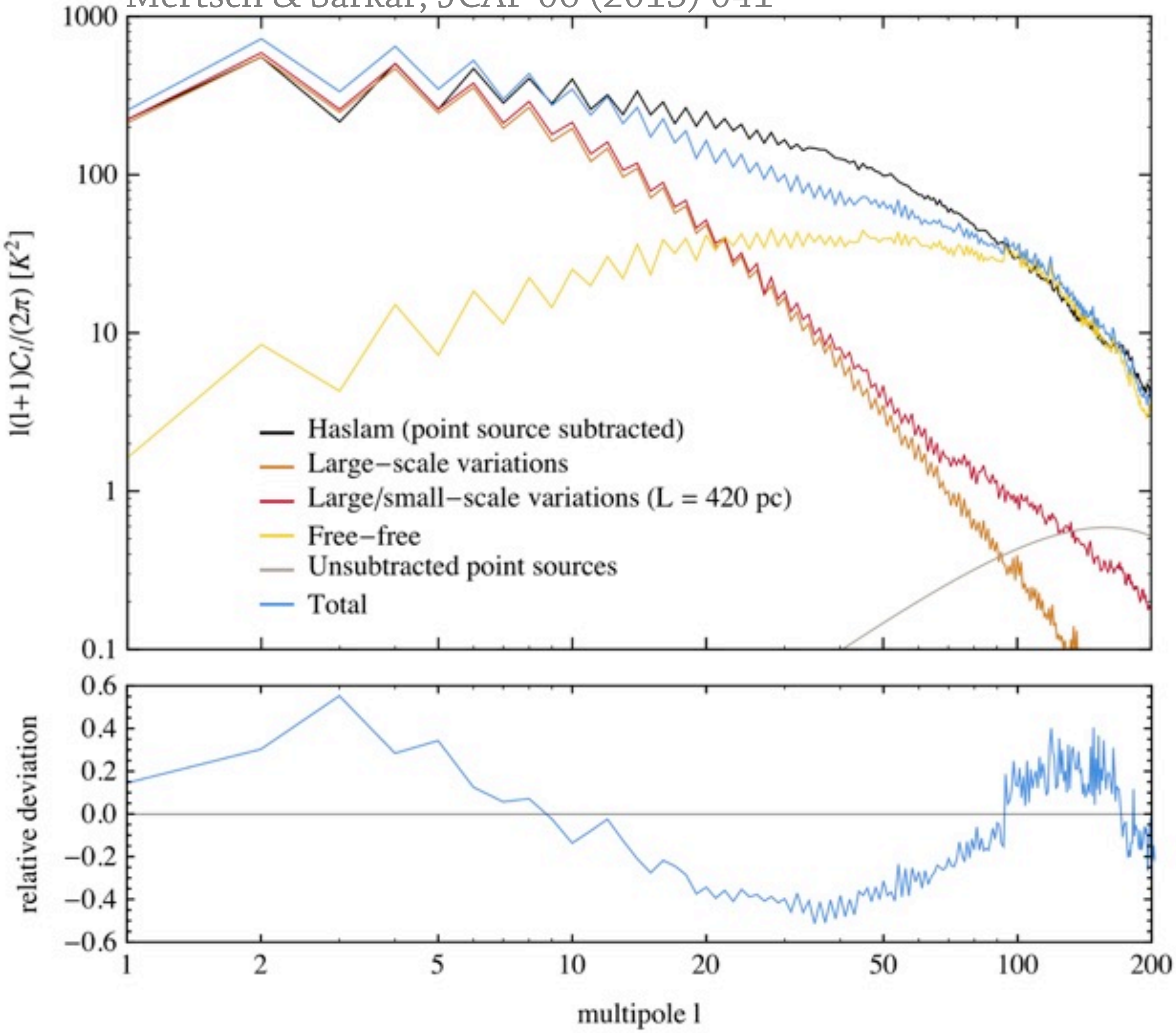
- probably shells of old SNRs
- can only observe 4 (5)radio loops directly in radio maps
- total Galactic population of up to O(1000) can contribute on *all* scales

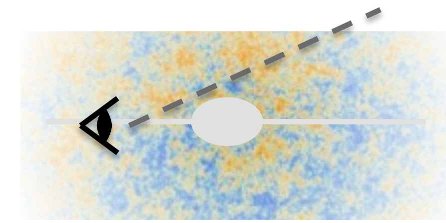
Our neighbourhood



Modelling the APS @ 408 MHz

Mertsch & Sarkar, JCAP 06 (2013) 041





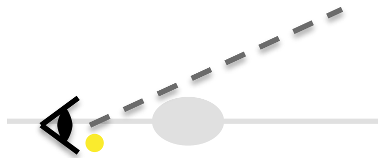
synchrotron:
smooth emissivity
and turbulence

free-free:
WMAP MEM-template

unsubtracted sources:
shot noise

Modelling individual shells

Mertsch & Sarkar, JCAP 06 (2013) 041

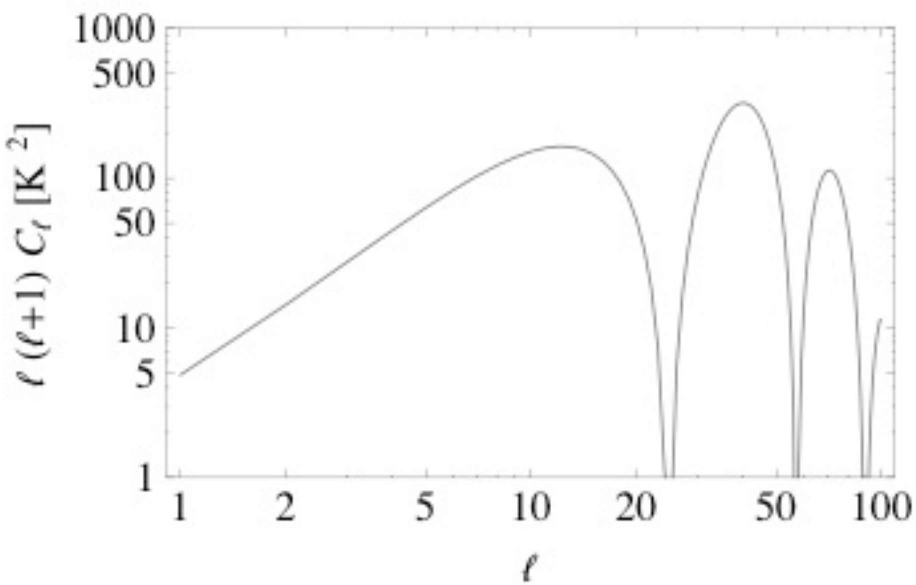


assumption: flux from one shell factorises into angular part and frequency part: $J_{\text{shell }i}(\nu, \ell, b) = \varepsilon_i(\nu) g_i(\ell, b)$

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

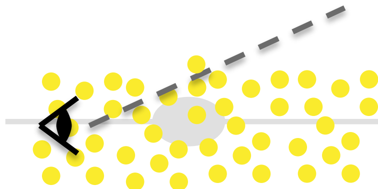
angular part $g_i(\ell, b)$:
assume constant emissivity in thin shell:

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



Modelling individual shells

Mertsch & Sarkar, JCAP 06 (2013) 041



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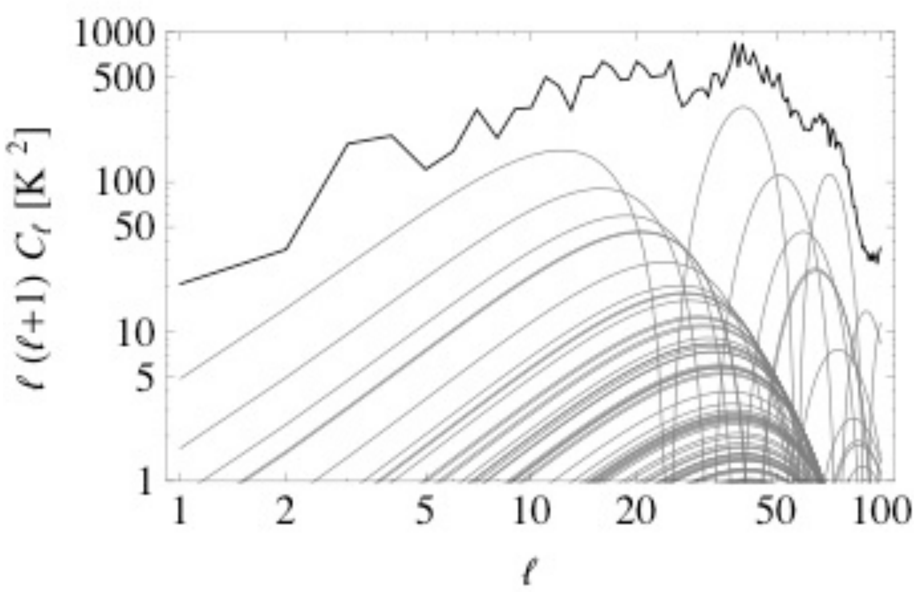
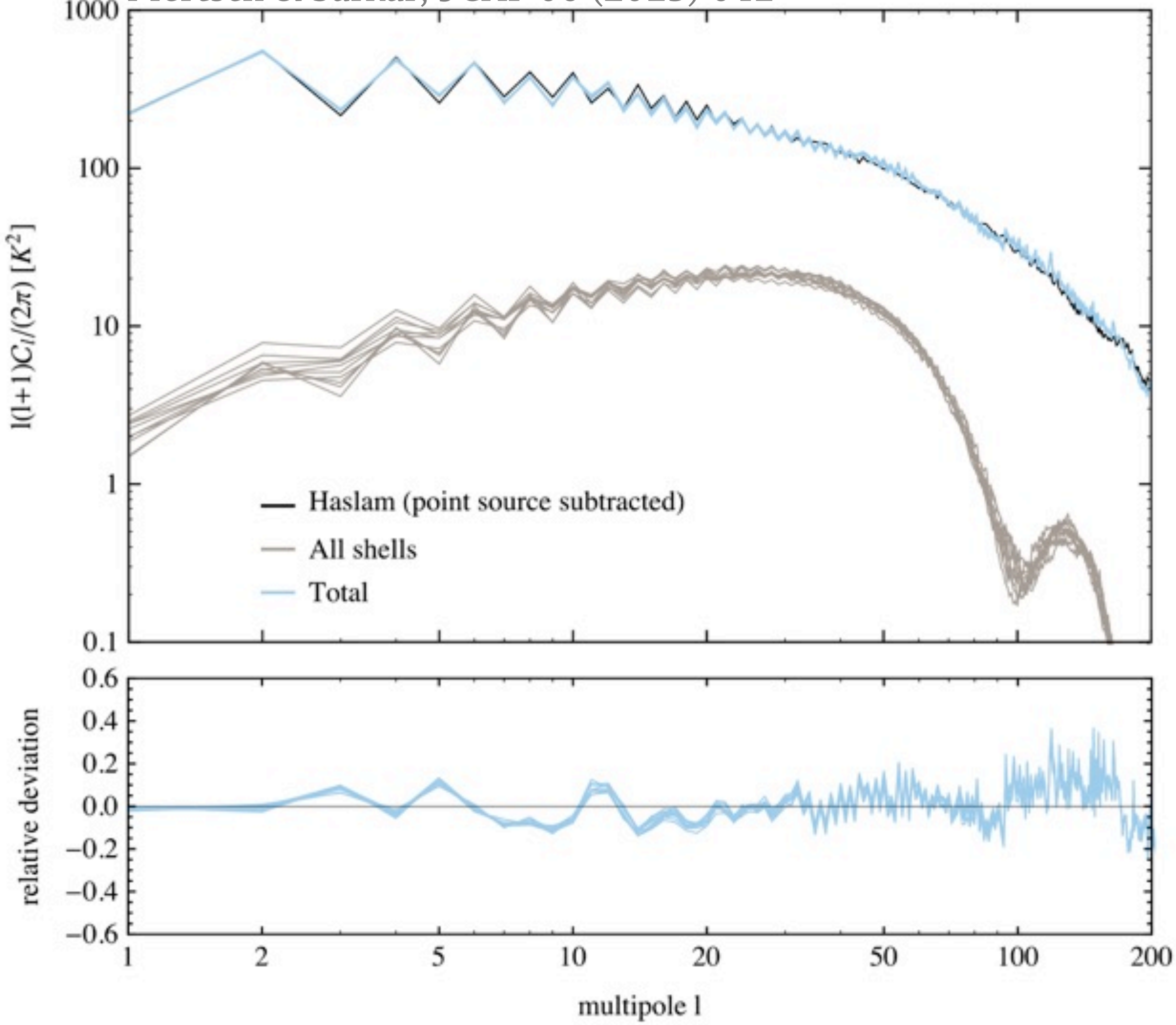


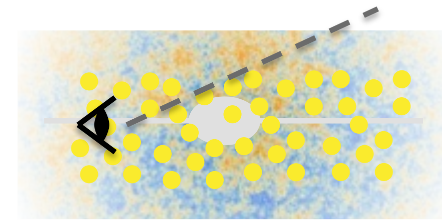
add up contribution from all shells

$$a_{lm}^{\text{total}} = \sum_i a_{lm}^i$$

…including ensemble of shells

Mertsch & Sarkar, JCAP 06 (2013) 041





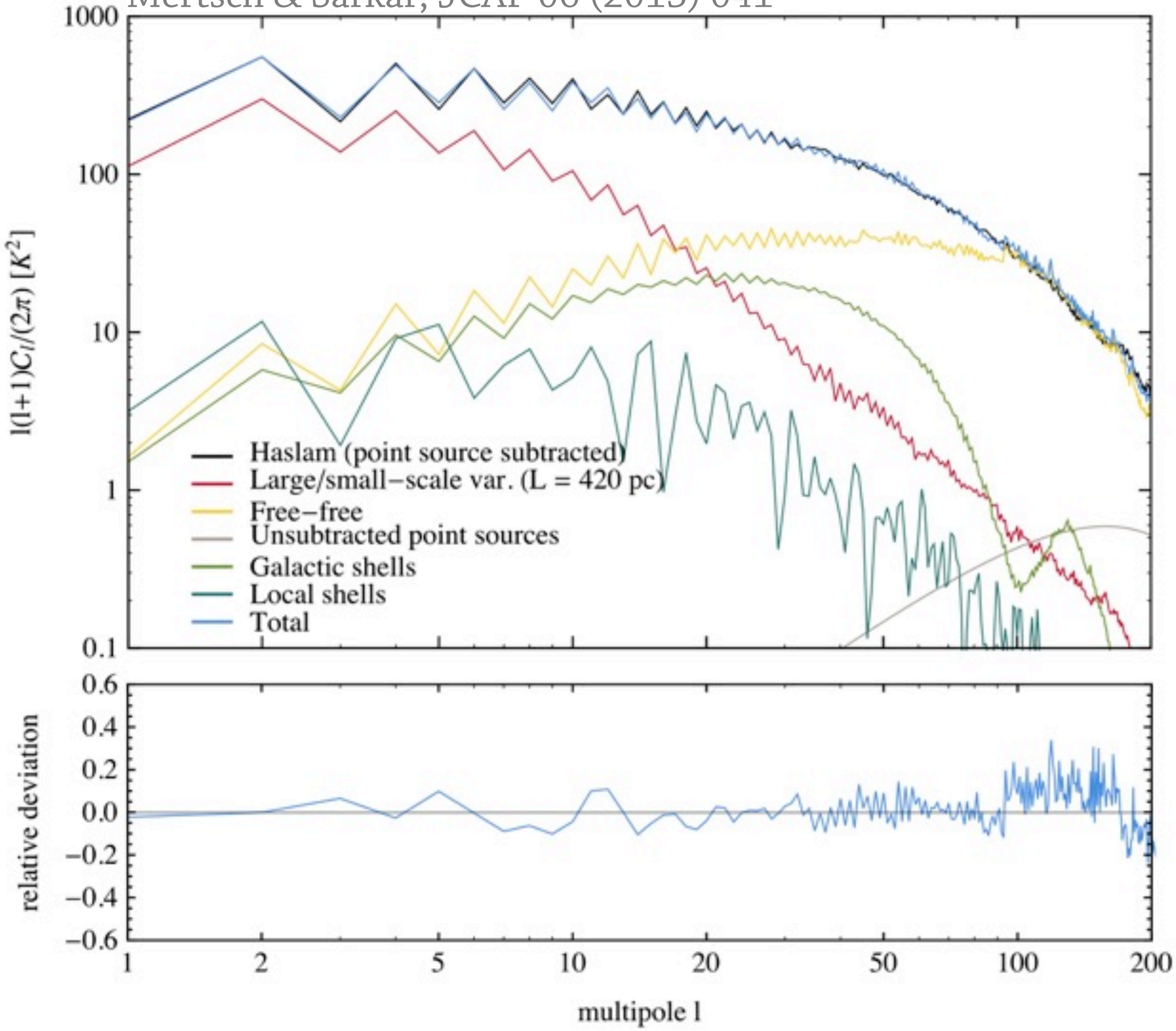
O(1000) shells of old SNRs present in Galaxy

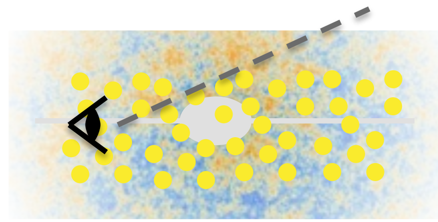
we know 4 local shells (Loop I-IV) but others are modeled in MC approach

they contribute *exactly* in the right multipole

Best fit of local shells and ensemble

Mertsch & Sarkar, JCAP 06 (2013) 041





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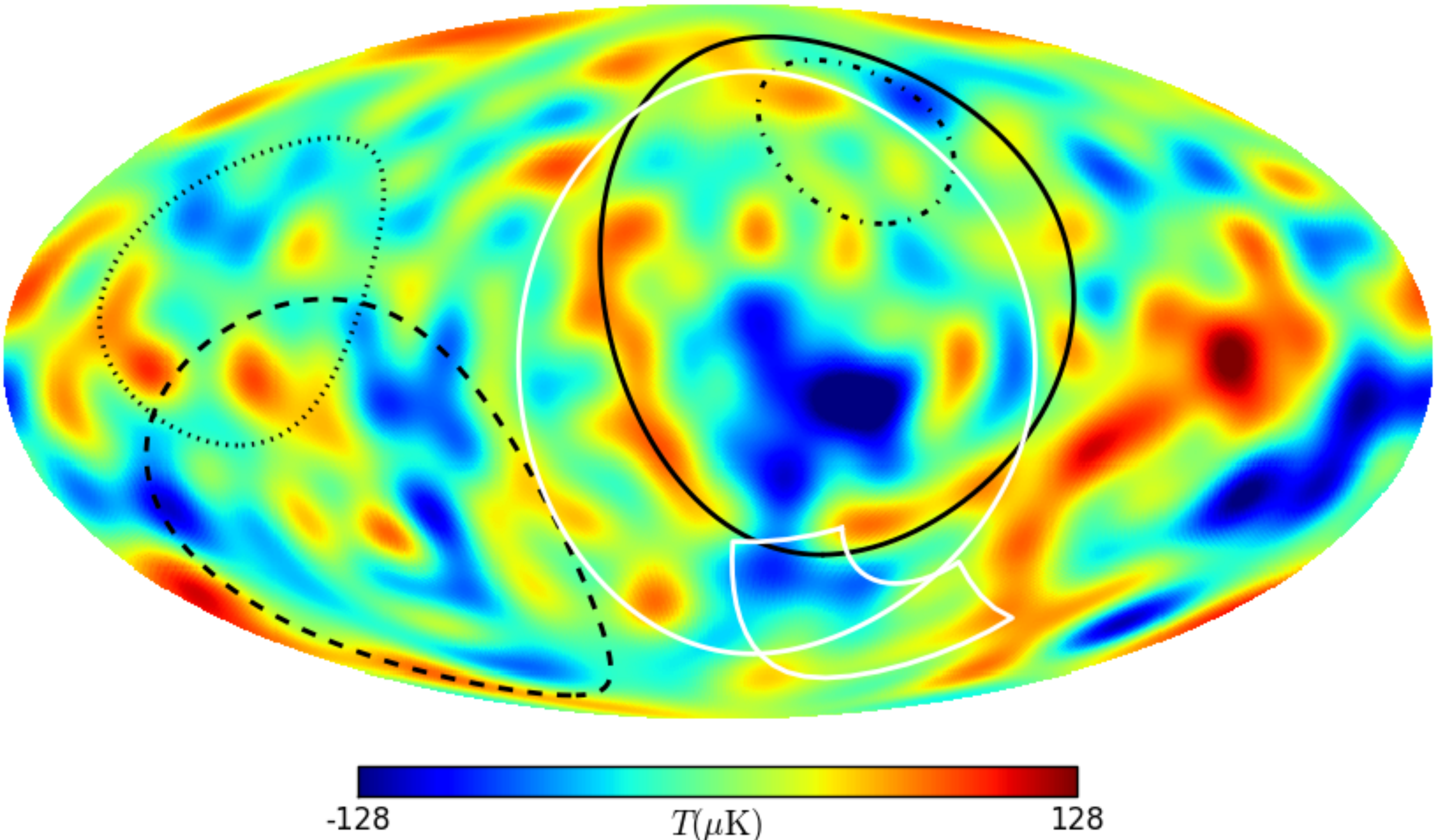
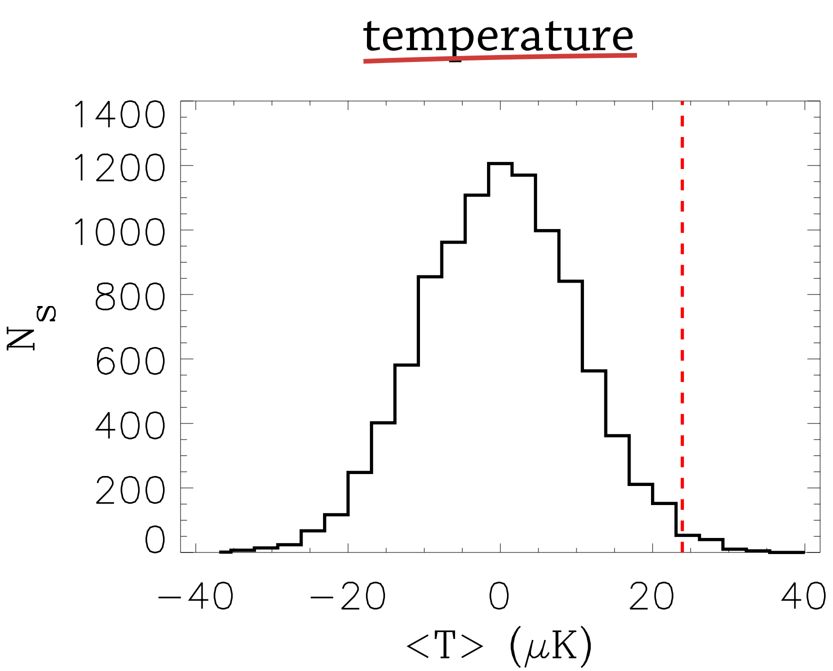
Anomalies in ILC9 ($\ell \leq 20$)

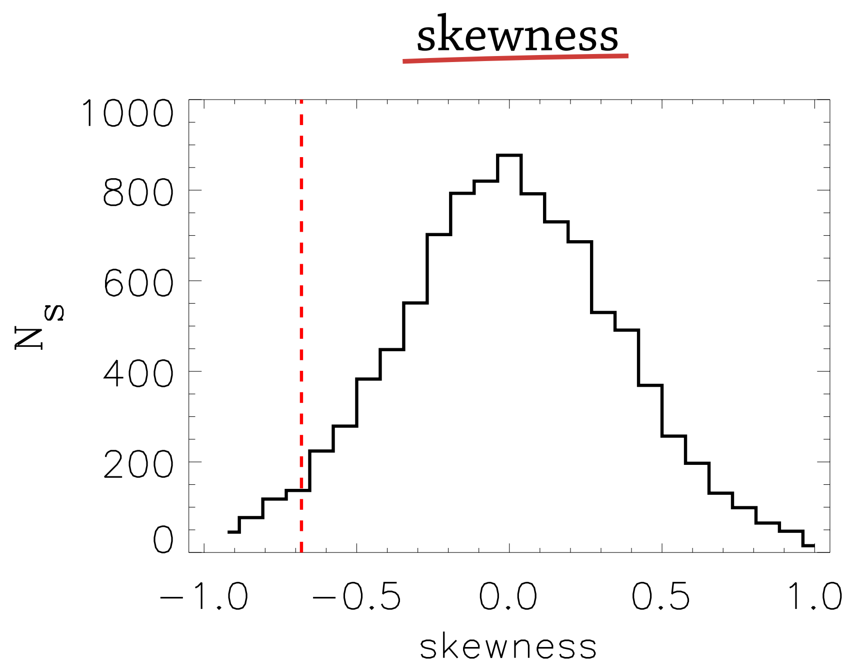


Liu, Mertsch & Sarkar, ApJL **789** (2014) 29

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

in ring around Loop I





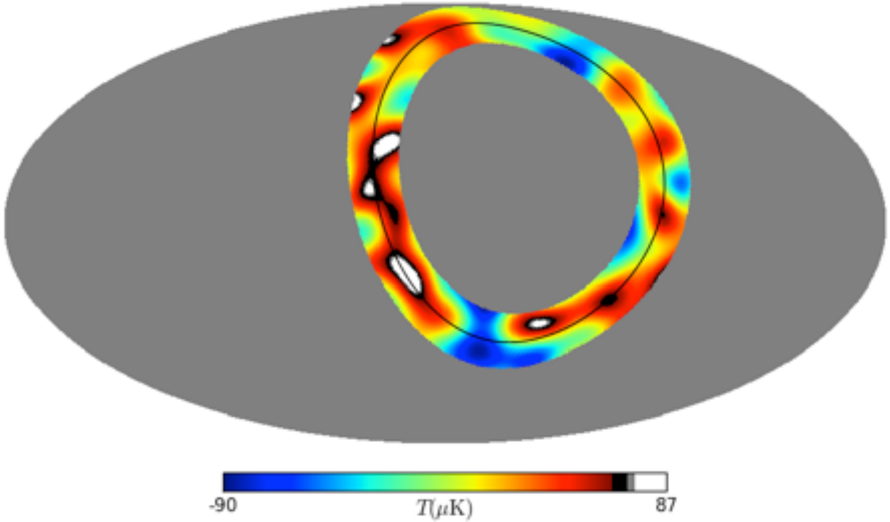
compare with MC ➡ p-values $\mathcal{O}(10^{-2})$

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

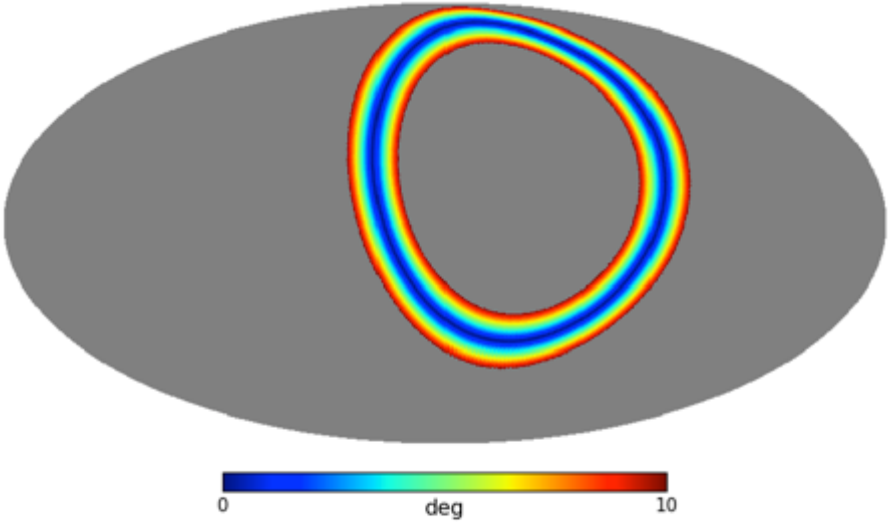
Cluster analysis

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

ILC temperature :



map of distance modulus:



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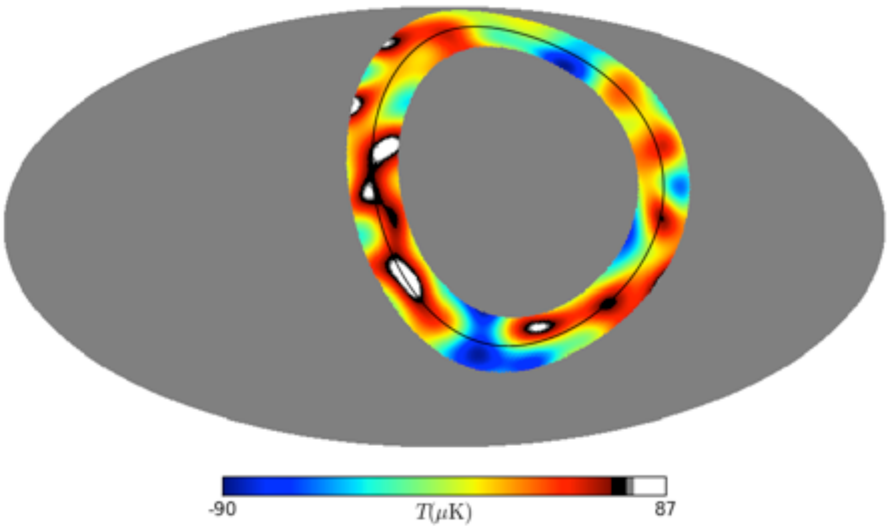

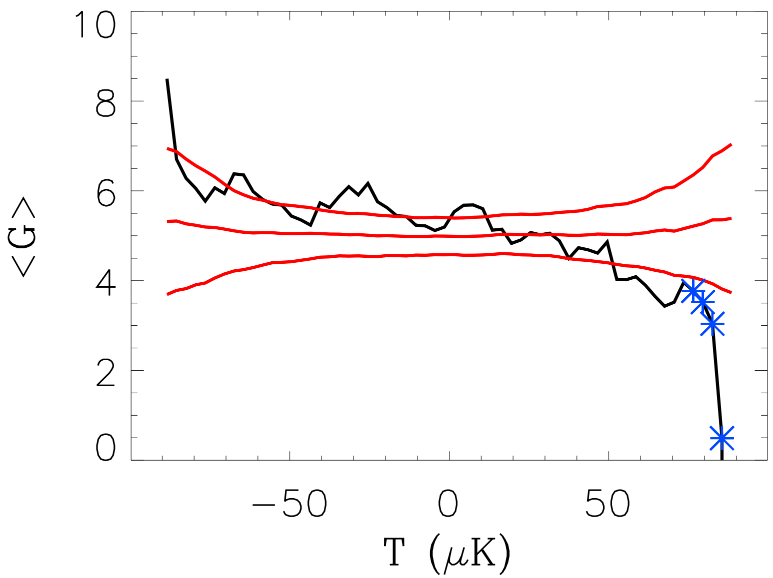

from 100,000 MC runs: probability for smaller $\langle G \rangle$ in last four bins $\sim 10^{-4}$

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

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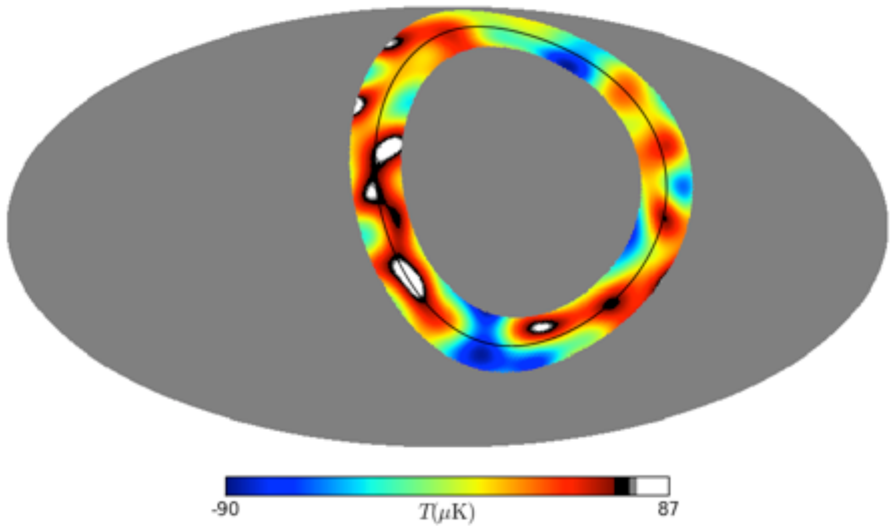
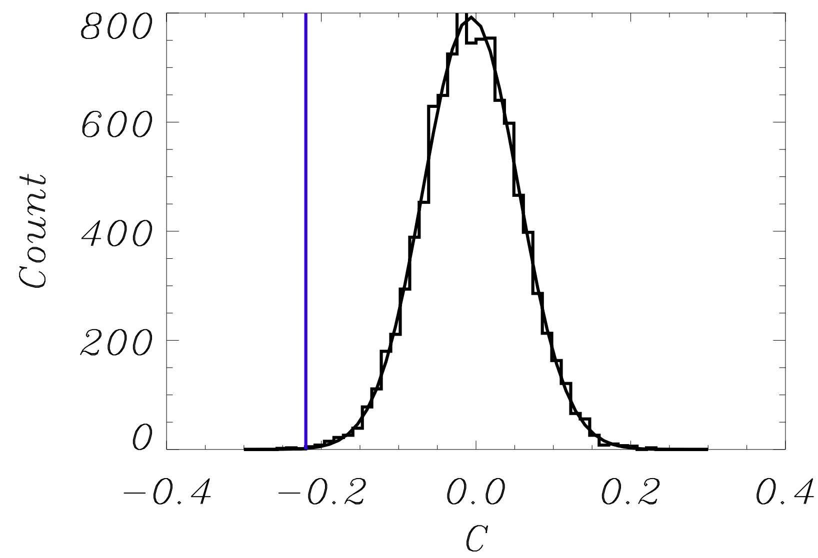
Naselsky & Novikov, ApJ. **444** (1995) 1

$$C = \frac{\sum(G-\bar{G})(T_{\rm ILC}-\bar{T}_{\rm ILC})}{\sqrt{\sum(G-\bar{G})^2(T_{\rm ILC}-\bar{T}_{\rm ILC})^2}}$$





from 100,000 MC runs: probability for smaller C: $\sim 10^{-4}$

Liu, Mertsch & 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

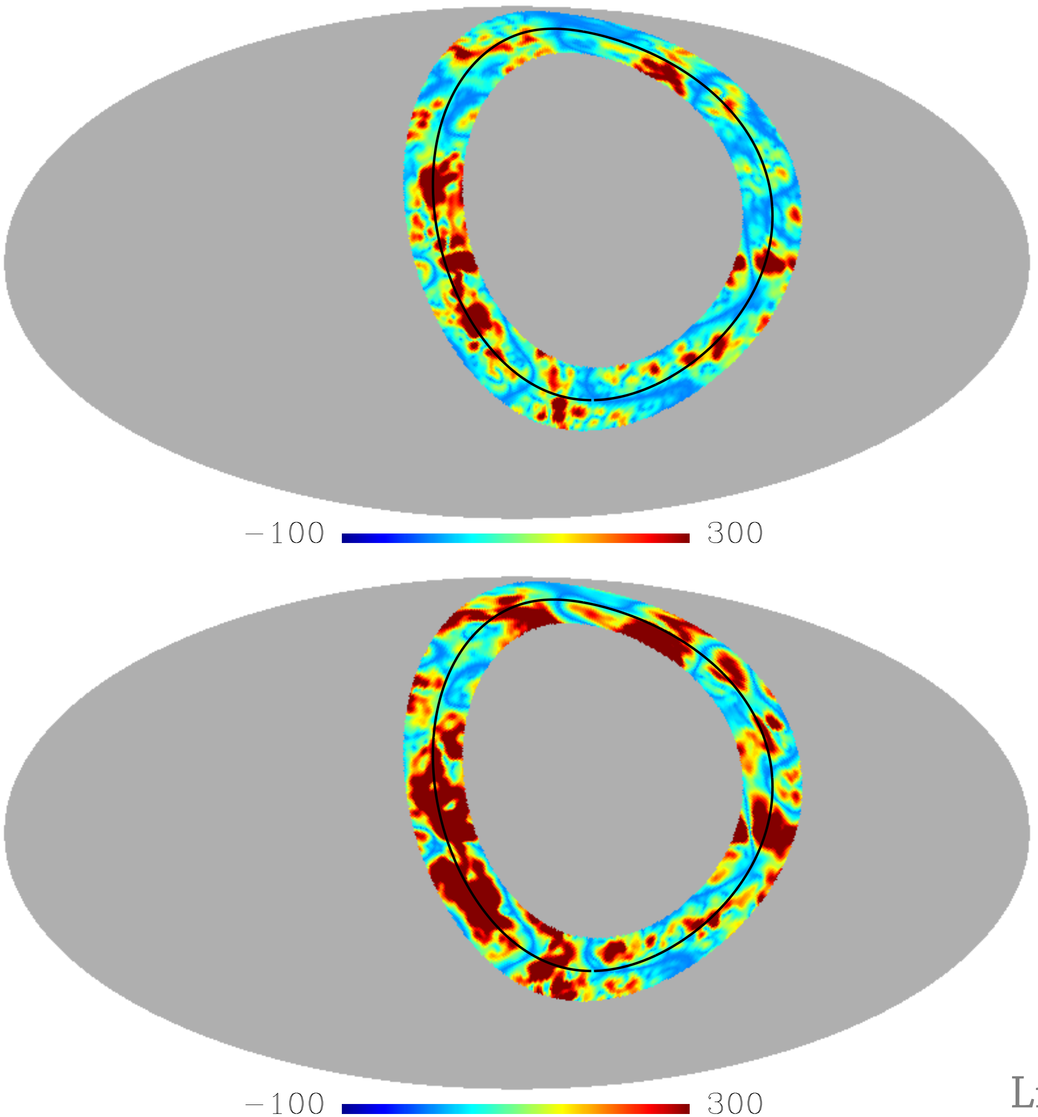
for WMAP9: $\beta \sim -3,\ -2$ and $1.7 \ldots 1.8$

synch free-free thermal dust

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

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

Spectral index



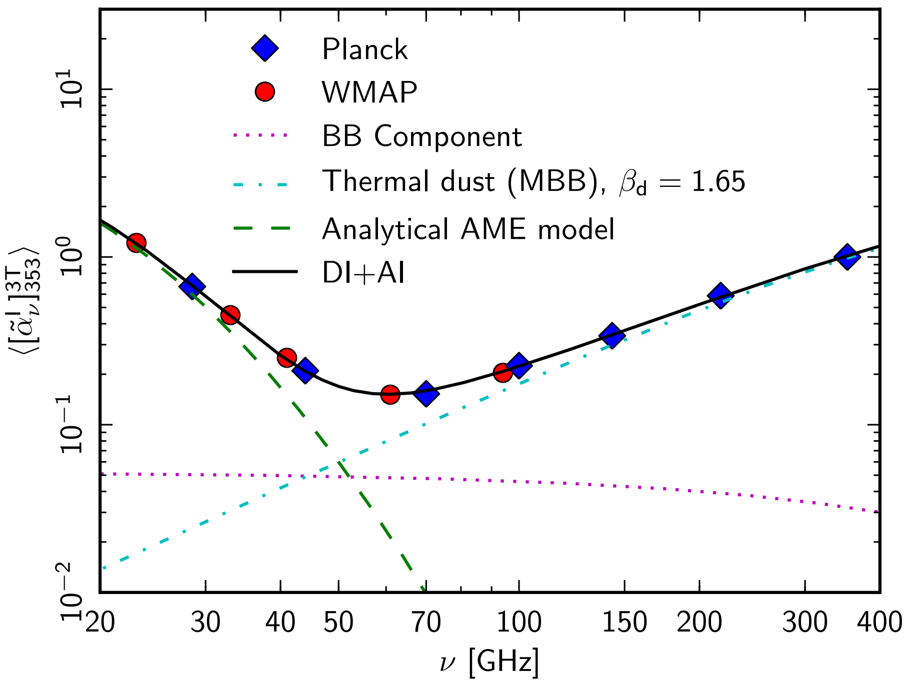
- WMAP polarised intensity in
  - W (60 GHz)
  - V (90 GHz)
- correlate with ILC9
- ratio of average intensities in Loop I region: 1.7
- spectral index: ~1.3

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

Evidence for magnetised dust I

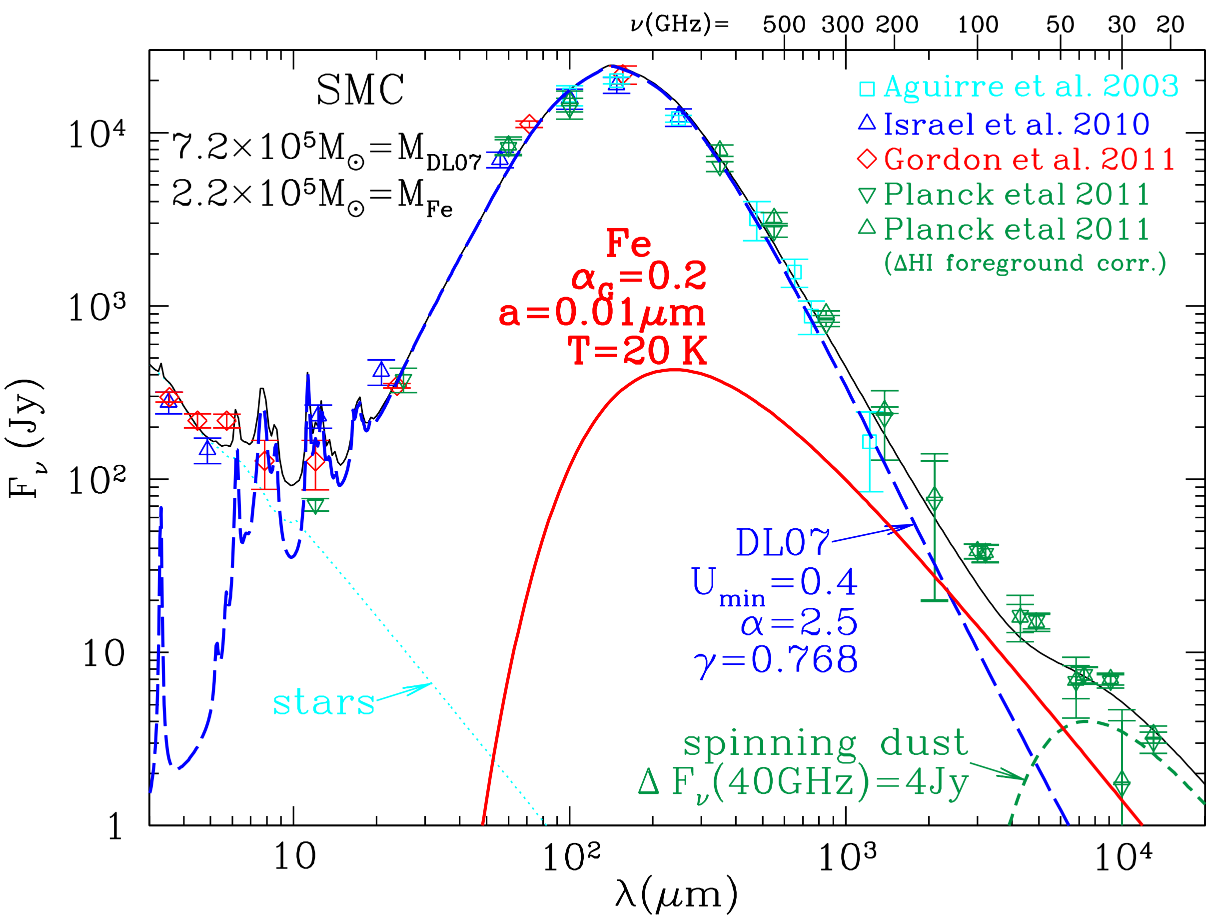
- correlation $\alpha_{353}(\nu)$ of WMAP and *Planck* frequency maps with dust template (353 GHz) in intensity and polarisation
- model as
  - CMB: achromatic
  - synchrotron: $A_s \nu^{\beta_s}$
  - thermal dust: $A_d \nu^{\beta_d} B(\nu, T_d)$
  - AME: spinning dust
- in intensity: $T_d \simeq 19\,\mathrm{K}$ 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?!



Ade *et al.*, arXiv:1405.0874

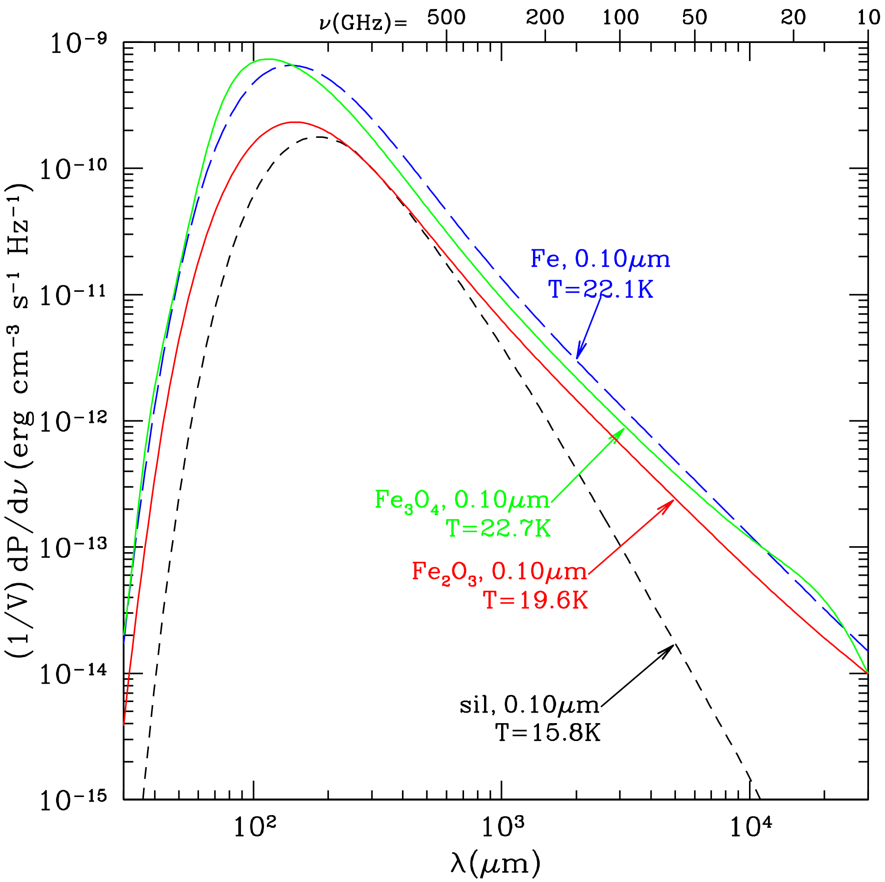
Evidence for magnetised dust II

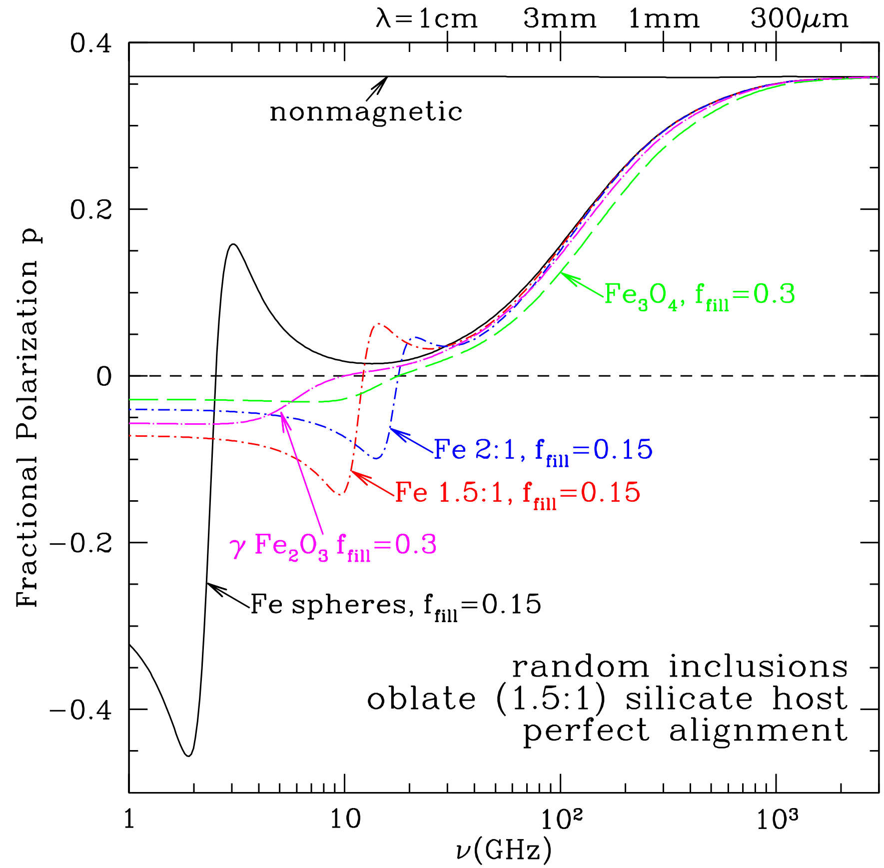


- thermal dust
  typical $\beta \sim 1.6 \ldots 1.7$
- spinning dust
  low-ν foreground
- magnetic dust
  very flat spectra,
  $\beta \sim 0$;
  dependence on compound, grain size, shape…

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

Significance for cosmology

temperature anisotropies

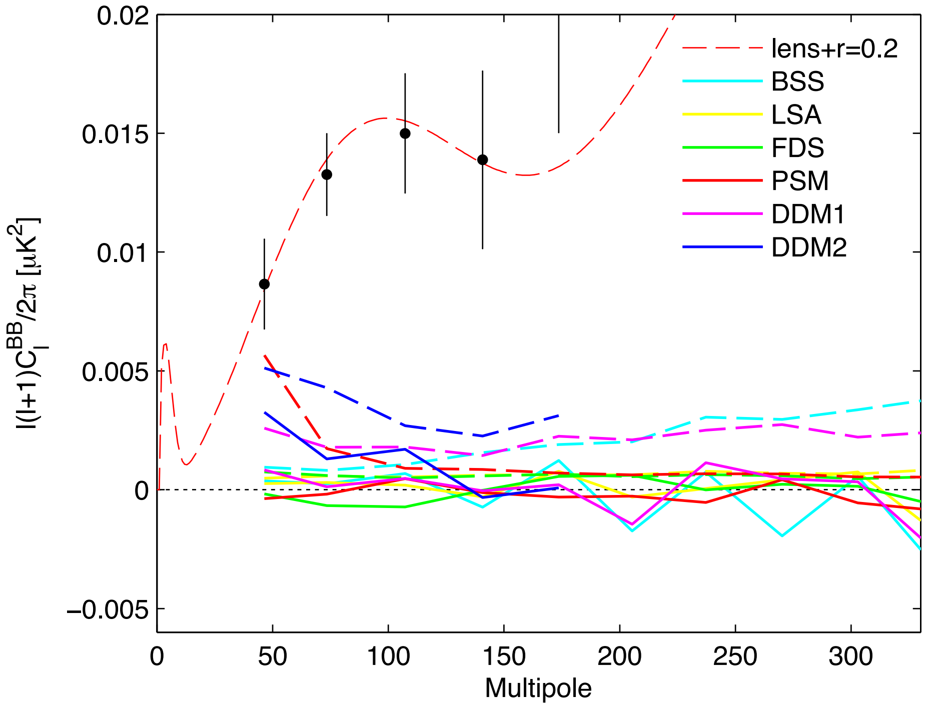
- *observed* loops contribute mostly at $\ell \lesssim 100$

→ no impact at large ℓ?

- low-ℓ anomalies (power deficit, $\ell = 2$, $\ell = 2, 3$ alignment, parity asymmetry
- CMB power even lower than observed?!

polarisation

- not a power law in ℓ
- dangerous frequency behaviour: BB!
- possibility of small-scale turbulence in loops ➔ variation of polarisation fraction and angle
- none of the "dust models" covers this



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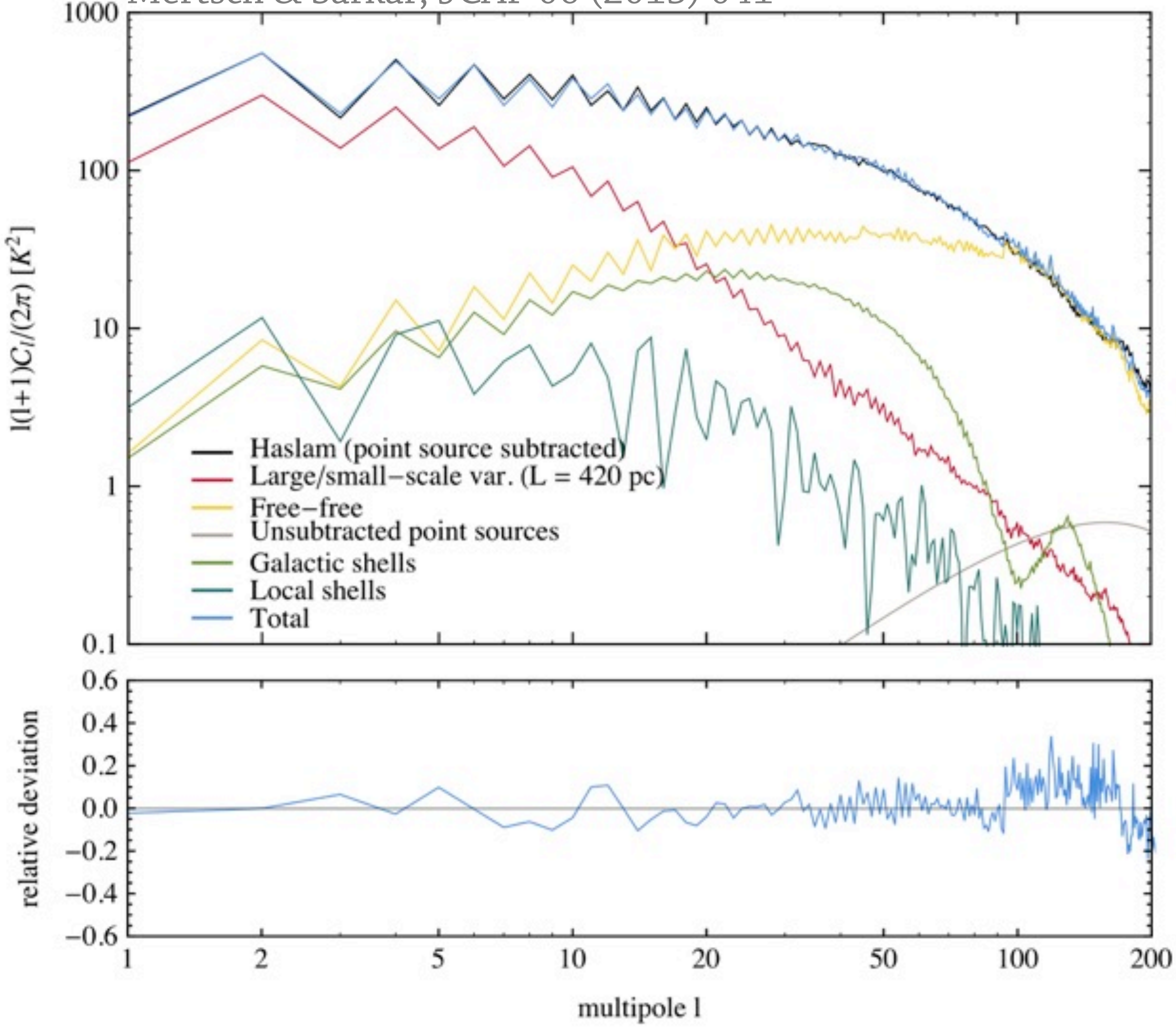
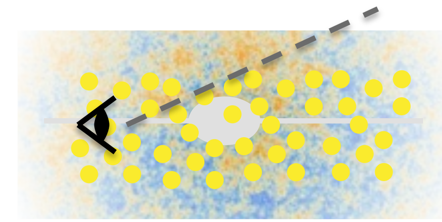
Mertsch & Sarkar, JCAP 06 (2013) 041





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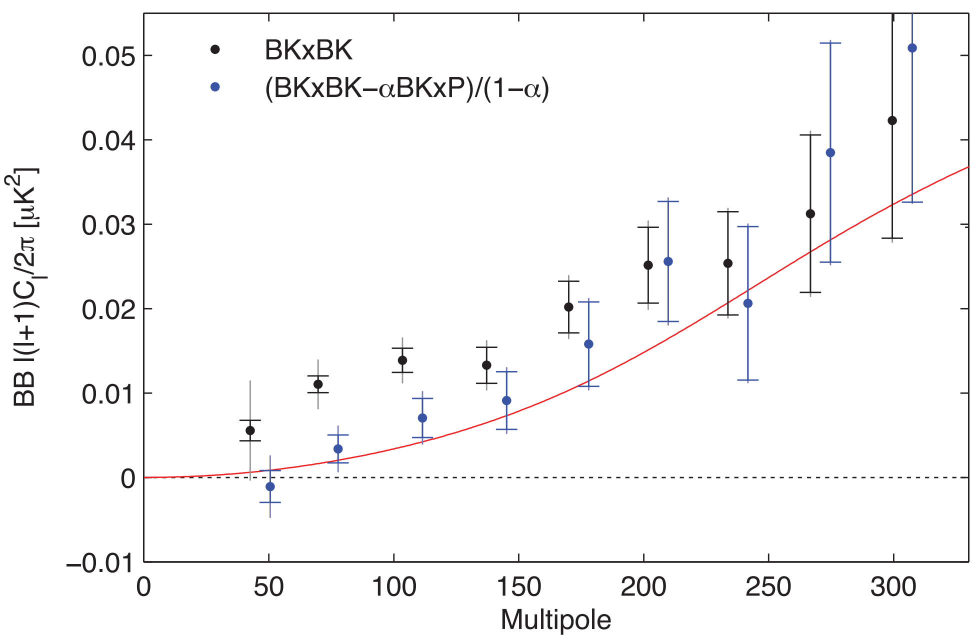
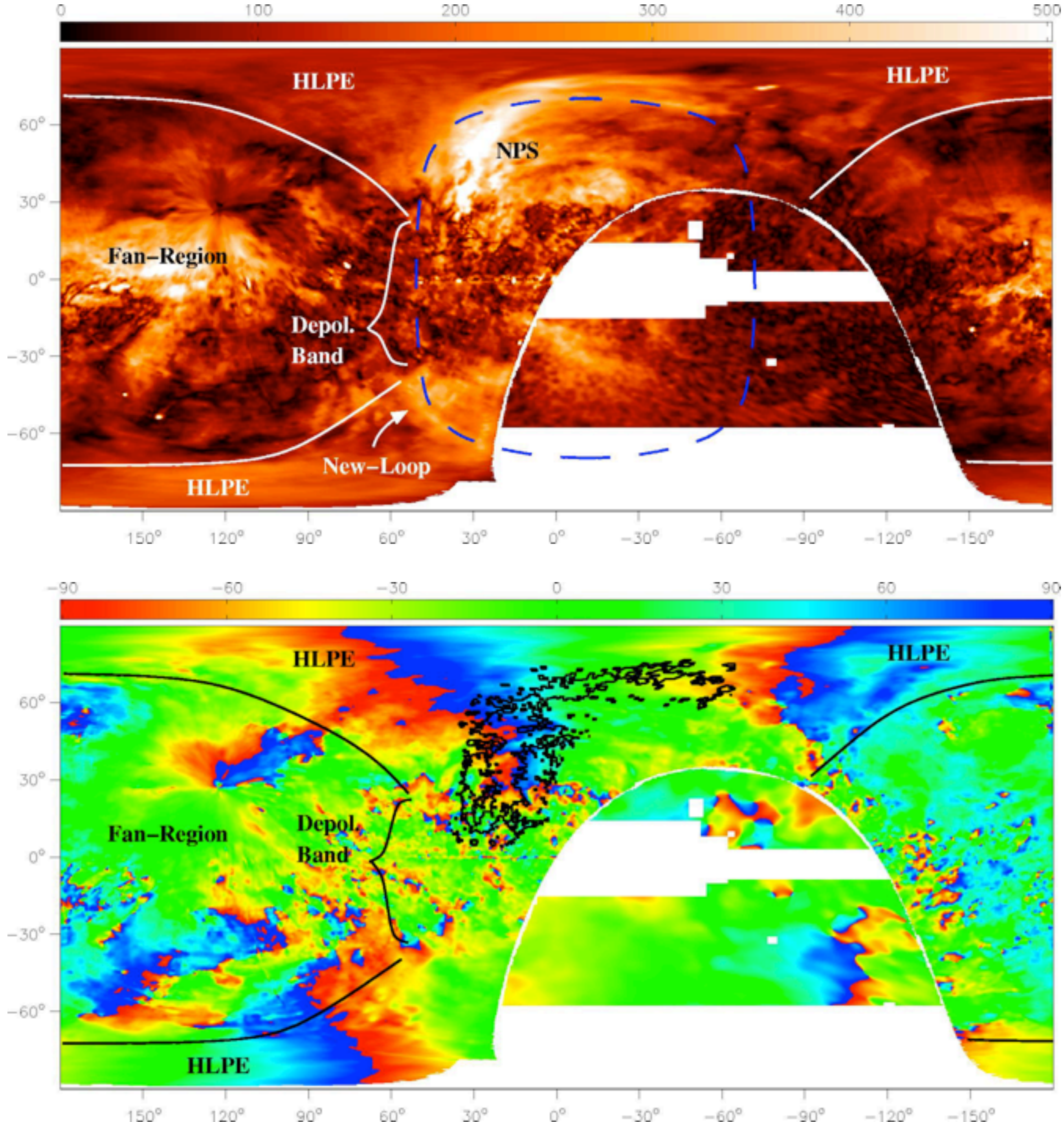


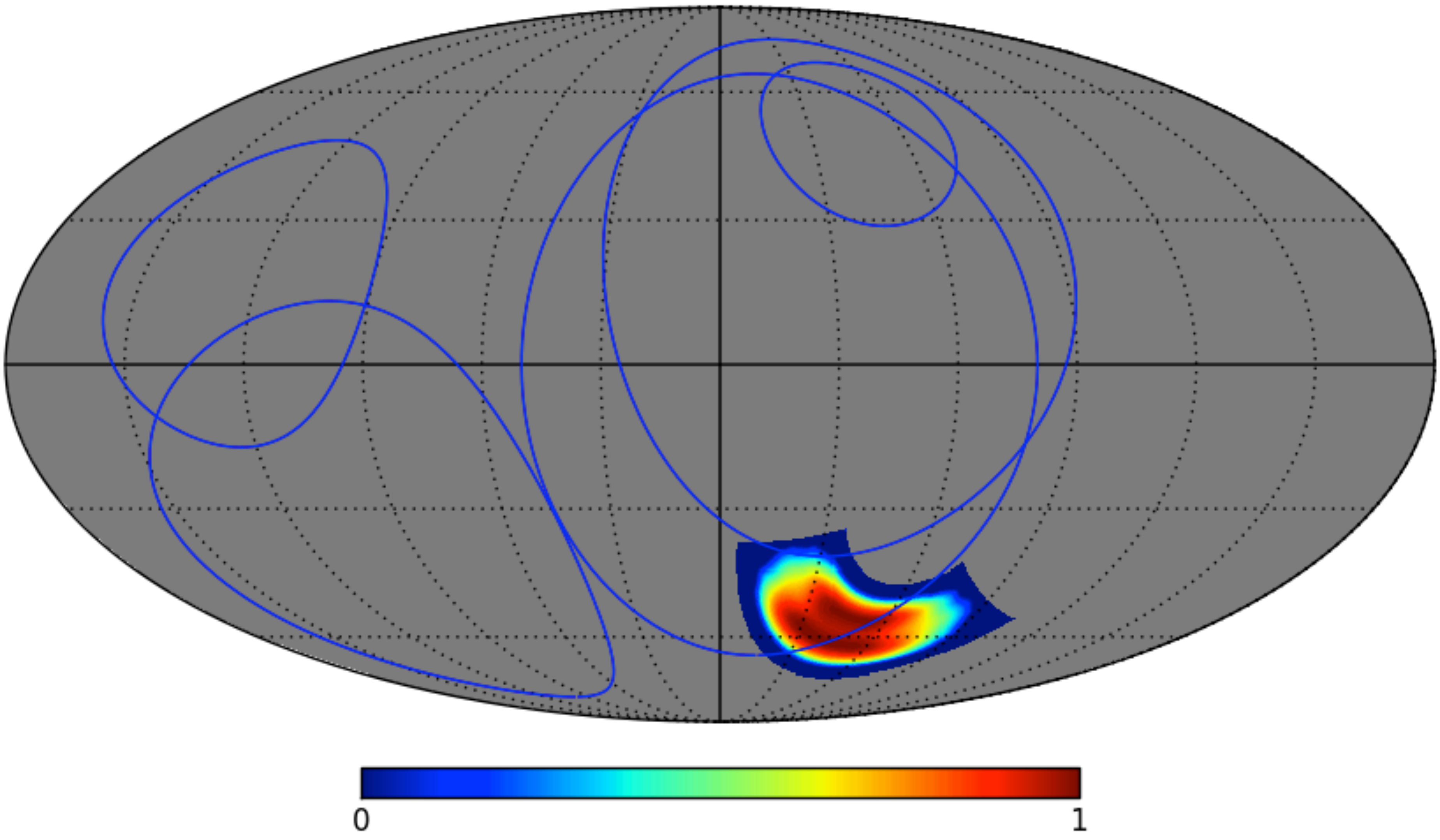
Wolleben, ApJ **664** (2007) 349



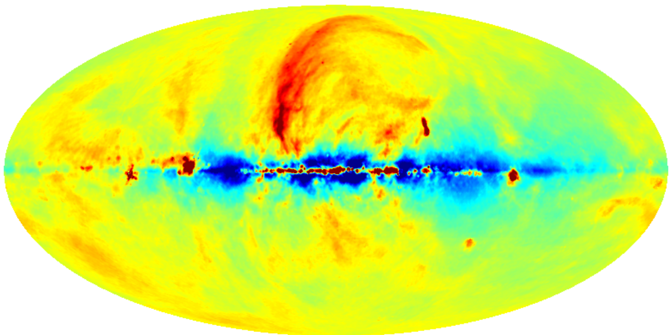
polarisation
(1.4 and 23 GHz)

polarisation angle

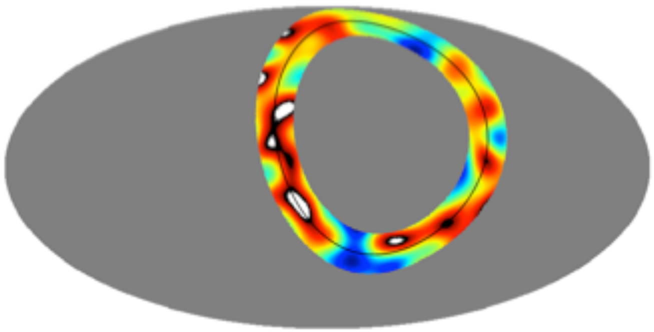
BICEP2 variance-weight map & loops



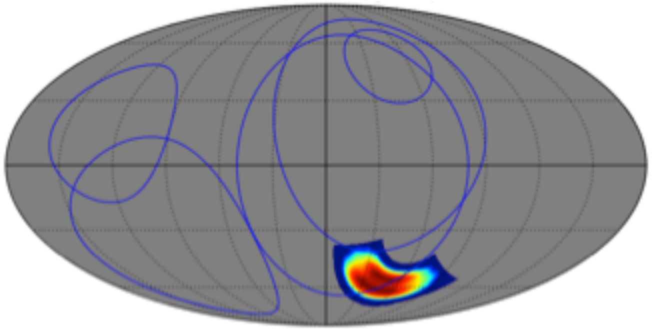
Conlcusion



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