ANISOTROPIC CR DIFFUSION IN THE GALAXY

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GG, Kachelriess & Semikoz, JCAP 07, 051 (2018) [arXiv:1710.08205]
Lopez-Coto & GG, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

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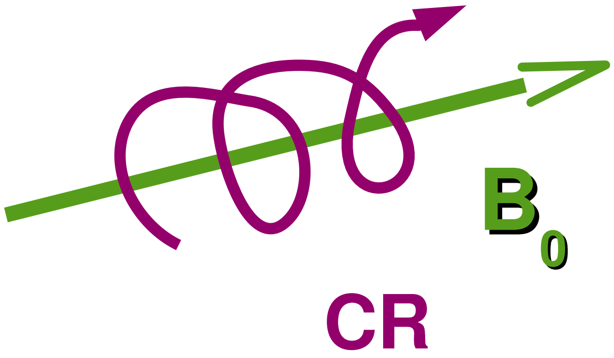
OUTLINE :

I – γ-ray emission around Geminga as a probe of the surrounding turbulence

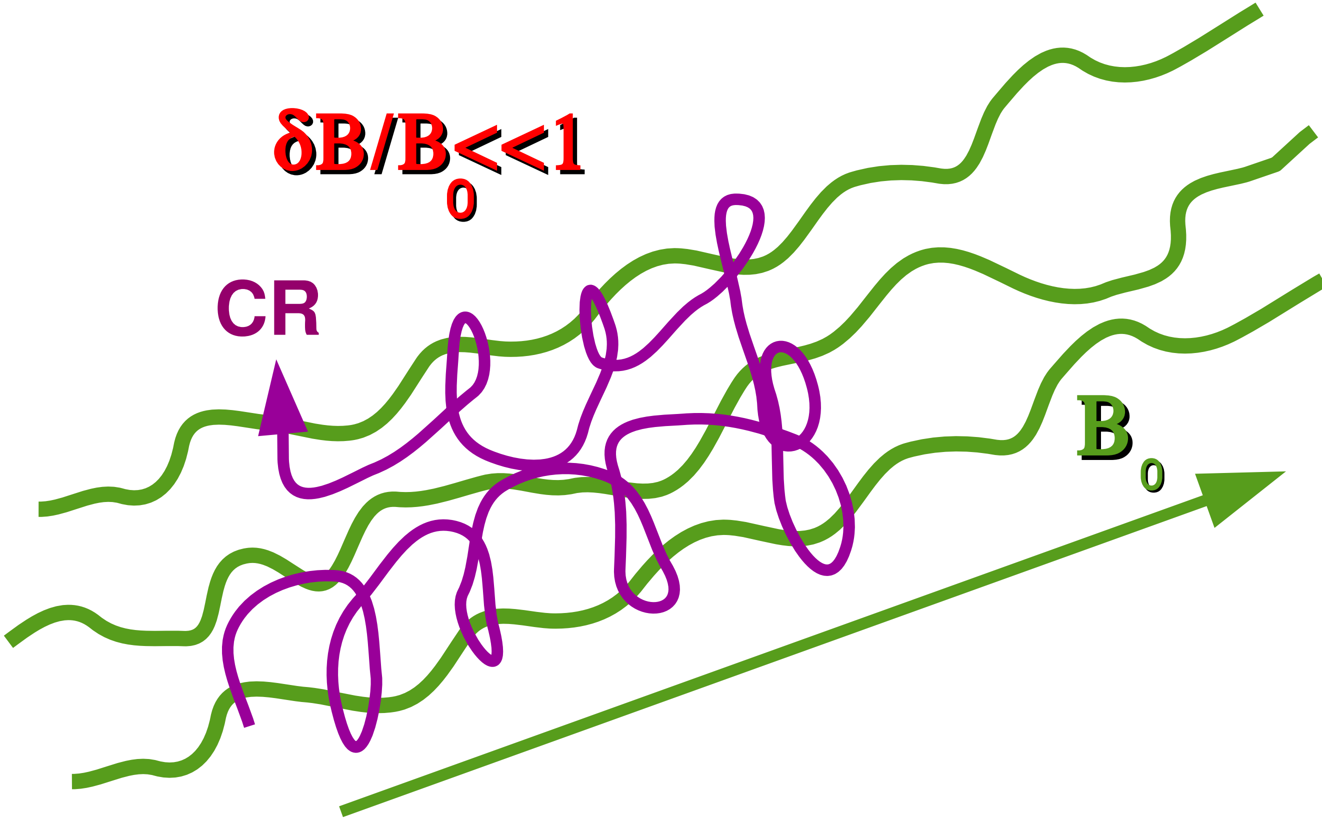
II – Anisotropic CR diffusion in the Milky Way and Galactic magnetic field models

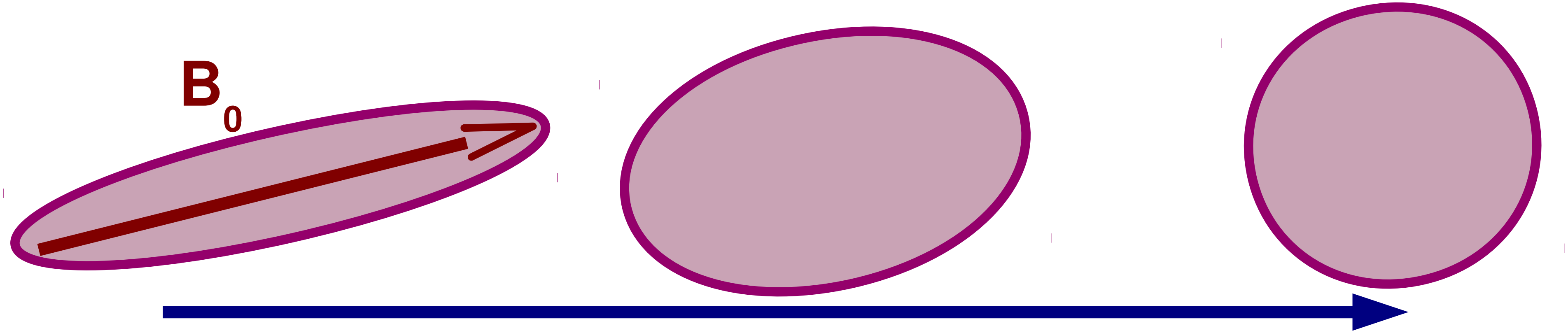
Perpendicular/Parallel diffusion coeffs.

$\delta B = 0$



$\delta B/B_0 << 1$





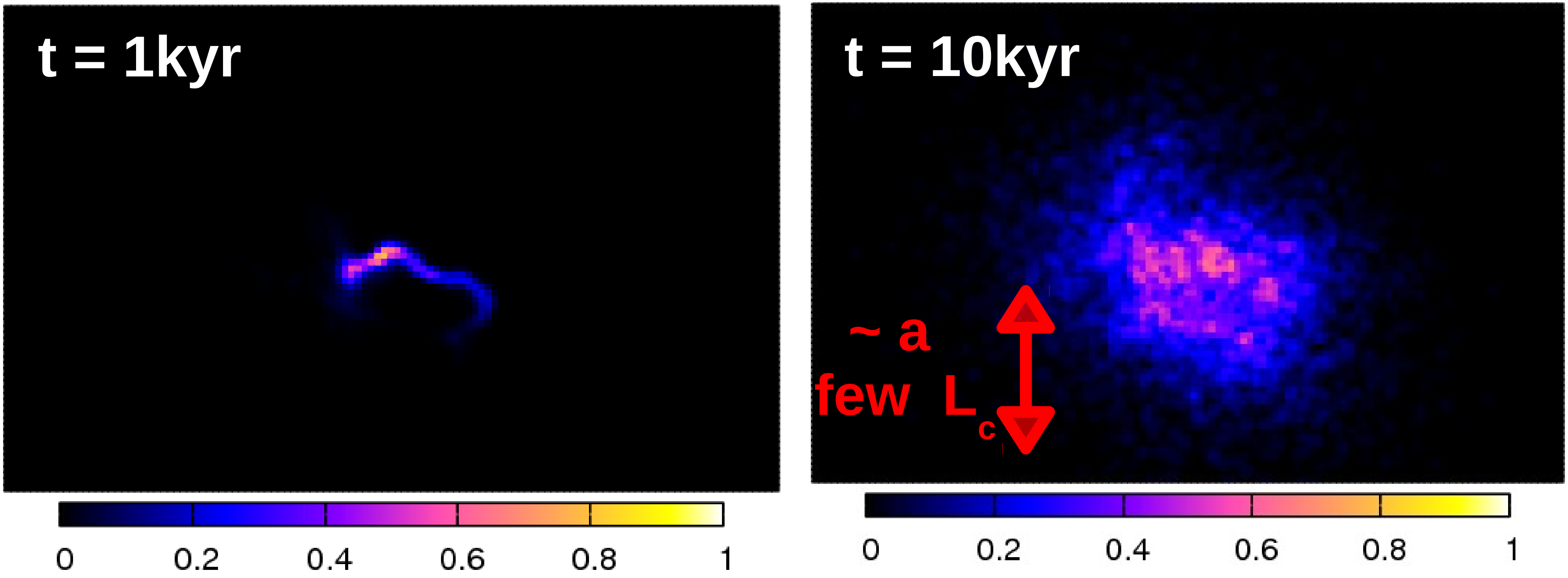
$\delta B/B_0 << 1$ **Increasing turbulence** $\delta B/B_0 >> 1$

Anisotropic diff. in *isotropic* turbulence

PRL **108,** 261101 (2012) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2012

Filamentary Diffusion of Cosmic Rays on Small Scales

G. Giacinti,[1] M. Kachelrieß,[1] and D. V. Semikoz[2,3]



E/Z = 1 PeV, Kolmogorov spectrum, *L_{max} = 150 pc, Plot size : 400 pc*

... then starts to tend towards the $r \propto t^{1/2}$ behaviour.

The Galactic turbulent magnetic field

Satisfies: $\langle\mathbf{B}(\mathbf{x})\rangle = \mathbf{0}$, $\langle\mathbf{B}(\mathbf{x})^2\rangle = B_{rms}^2$

Power spectrum (if iso.): $\mathcal{P}(k) \propto k^{-\alpha}$ (e.g. α = 5/3, 3/2)

for $2\pi/L_{max} \leq k \leq 2\pi/L_{min}$ with L_{min}<1 AU, **L_{max} ~ few-100pc**

Fourier transform: $B_i(\mathbf{x}) = \int \frac{\mathrm{d}^3k}{(2\pi)^3} B_i(\mathbf{k}) e^{i(\mathbf{k}\cdot\mathbf{x}+\phi_\mathbf{i}(\mathbf{k}))}$

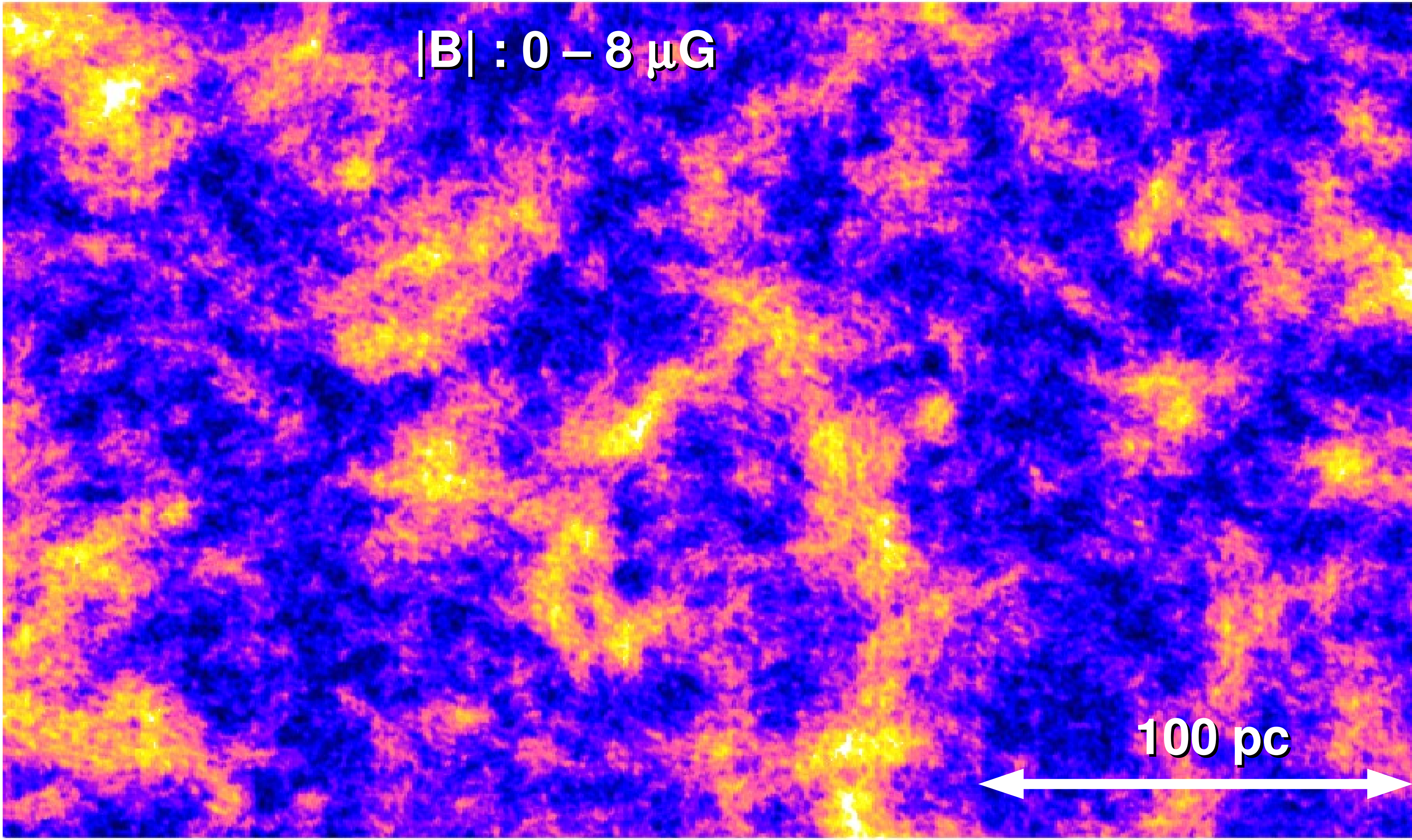
with $|\boldsymbol{B}(\boldsymbol{k})|^2 \propto k^{-\alpha-2}$

Coherence length: $\int_{-\infty}^{\infty} \mathrm{d}L \langle\mathbf{B}(0)\cdot\mathbf{B}(\mathbf{x}(L))\rangle \equiv L_c B_{rms}^2$

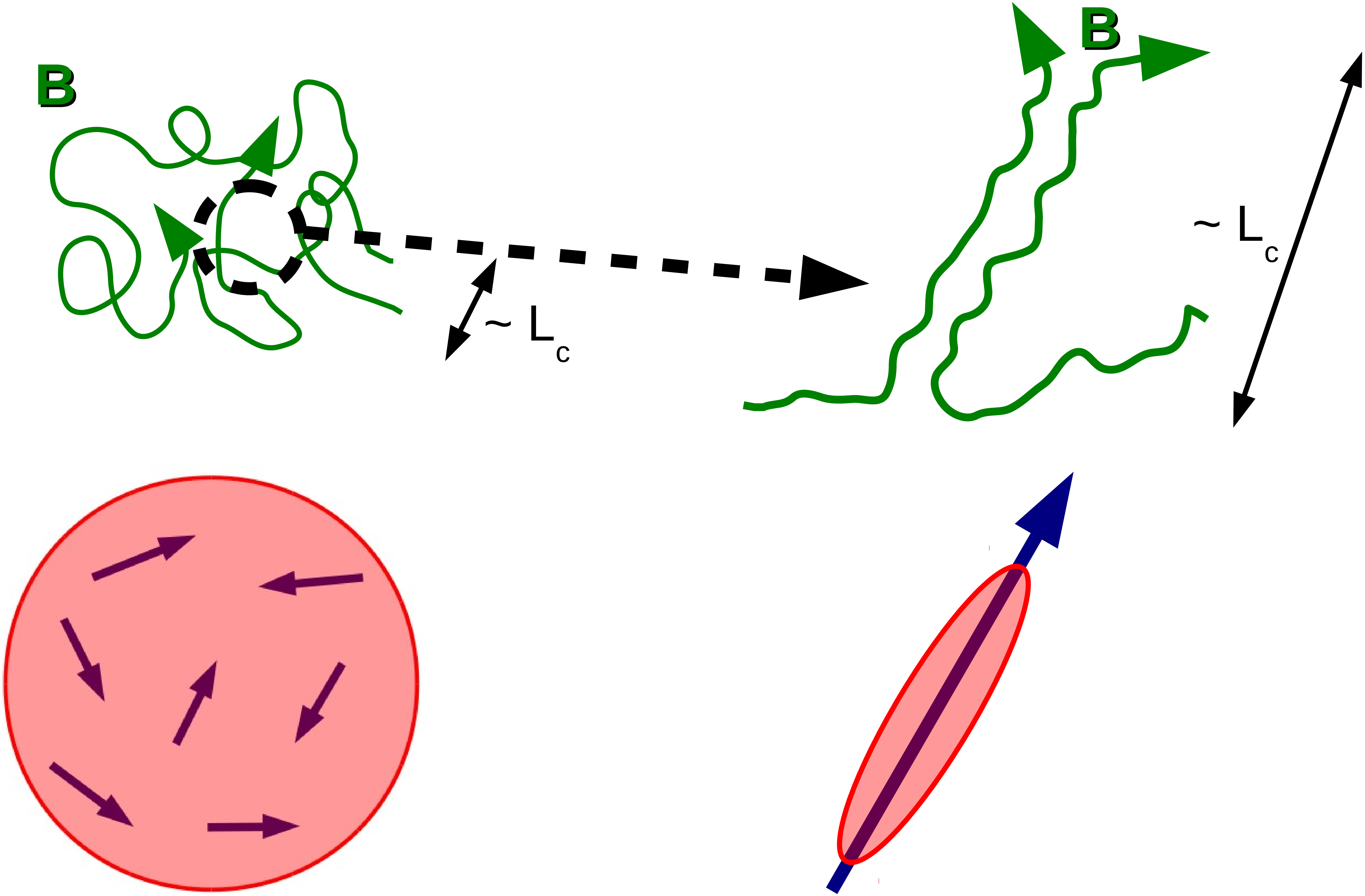
=> $L_c = \frac{1}{2} L_{max} \frac{n-1}{n} \frac{1-(L_{min}/L_{max})^n}{1-(L_{min}/L_{max})^{n-1}}$ ~ 1 – 10s pc

$r_L \ll L_c$

Kolmogorov turbulence



Anisotropic diff. in *isotropic* turbulence

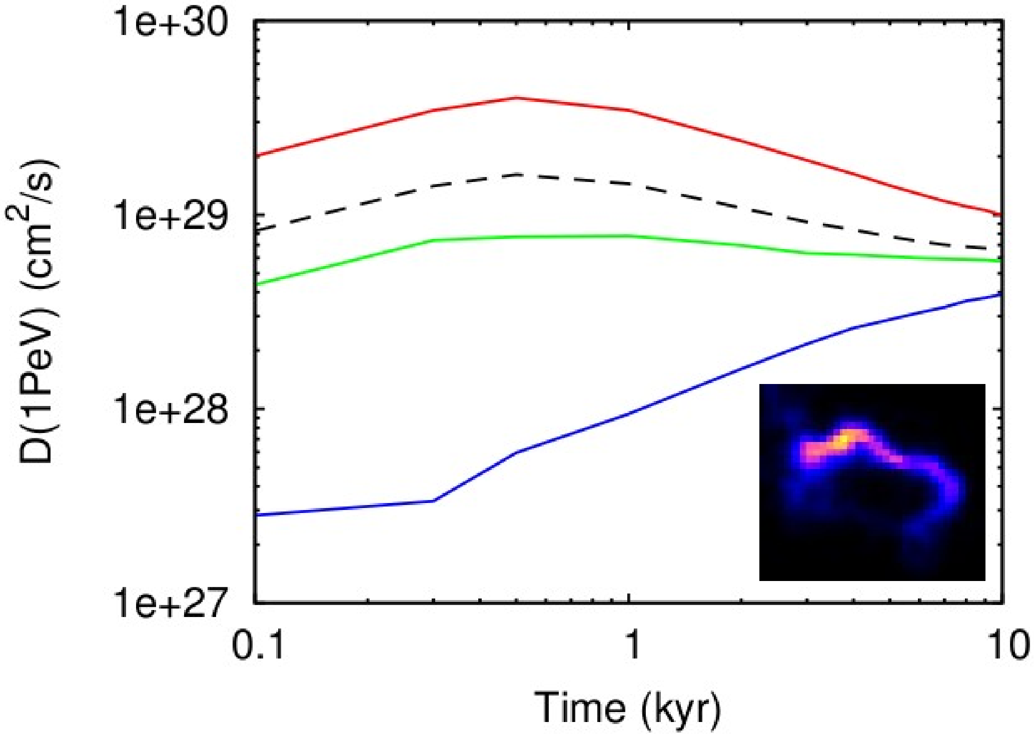


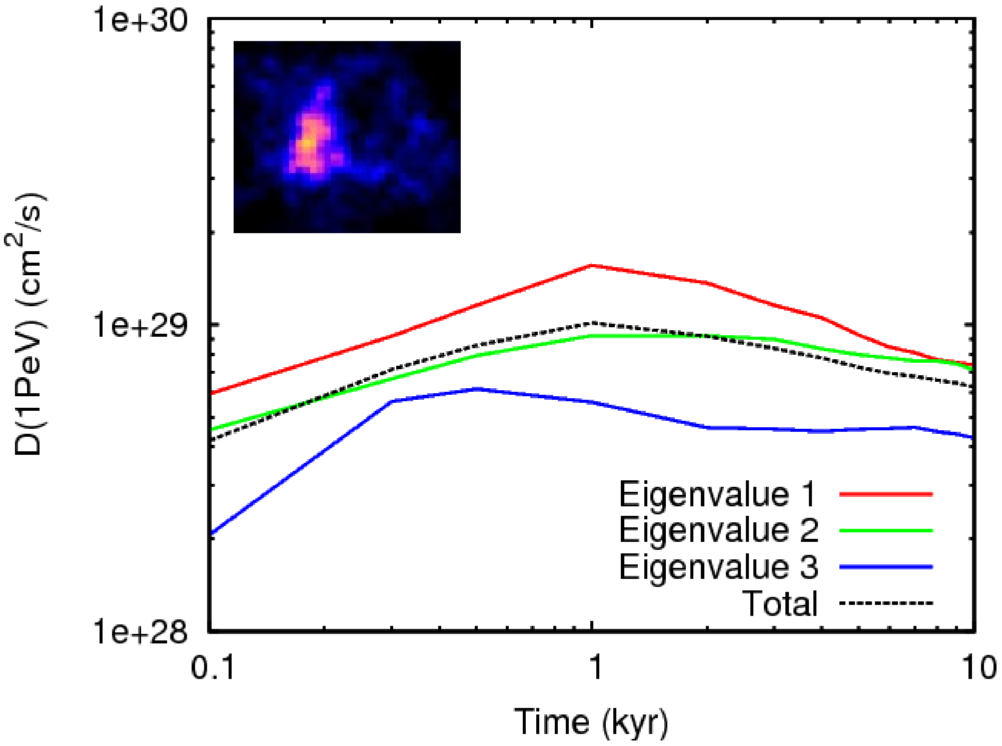
Eigenvalues of the diffusion tensor

Inject N particles at **x** = **0** in ***one single*** B field realization '*b*'

Calculate $$D_{ij}^{(b)} = \frac{1}{N}\sum_{a=1}^{N}\frac{x_i^{(a)}x_j^{(a)}}{2t}$$ ($i, j = X, Y, Z$)

Compute its eigenvalues : $d_1^{(b)} < d_2^{(b)} < d_3^{(b)}$

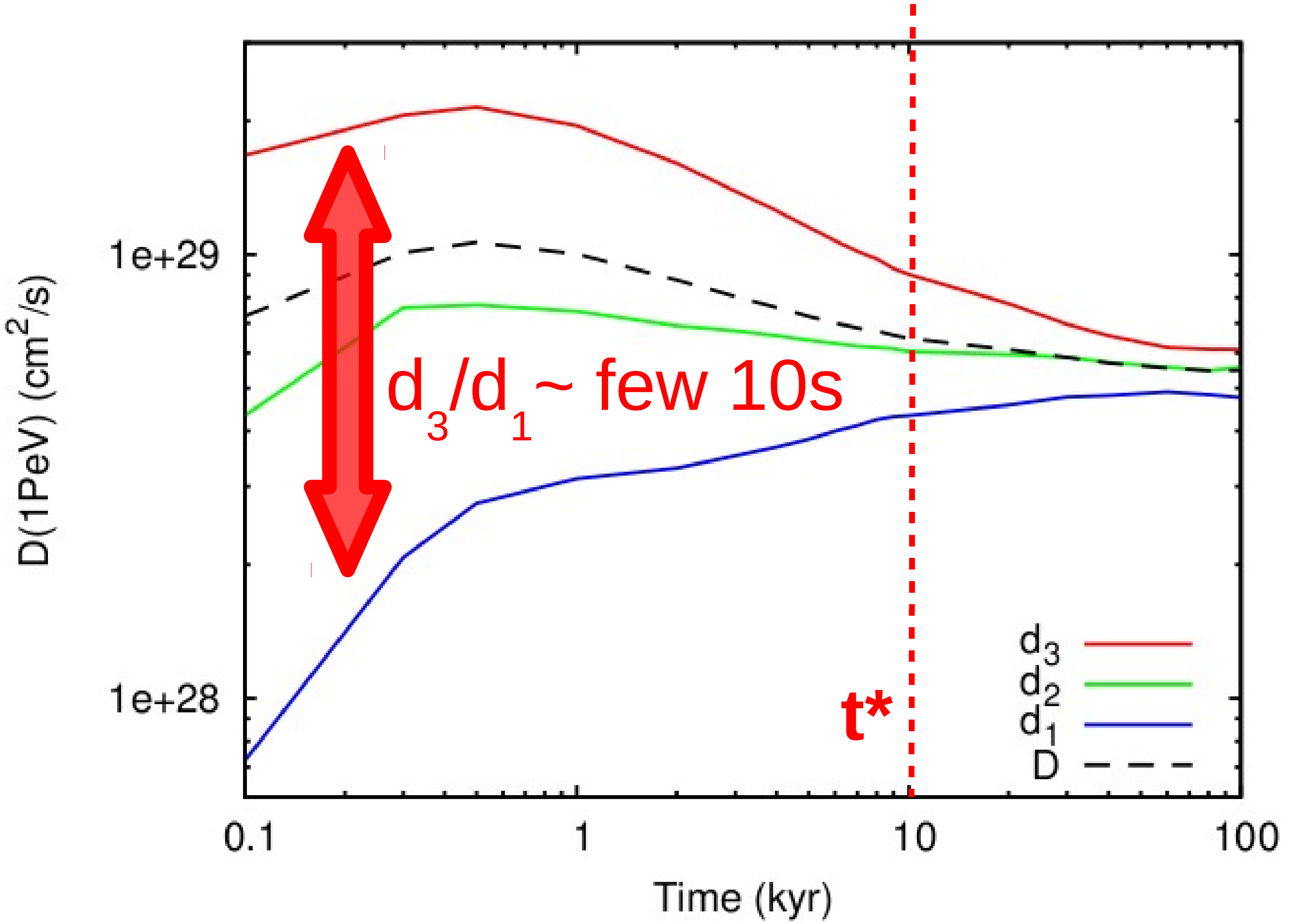




Eigenvalues of the diffusion tensor

Average $d_i^{(b)}$ over *M* field realizations: $d_i = \frac{1}{M}\sum_{b=1}^{M} d_i^{(b)}$

(i=1,2,3)



$d_3/d_1 \sim$ few 10s

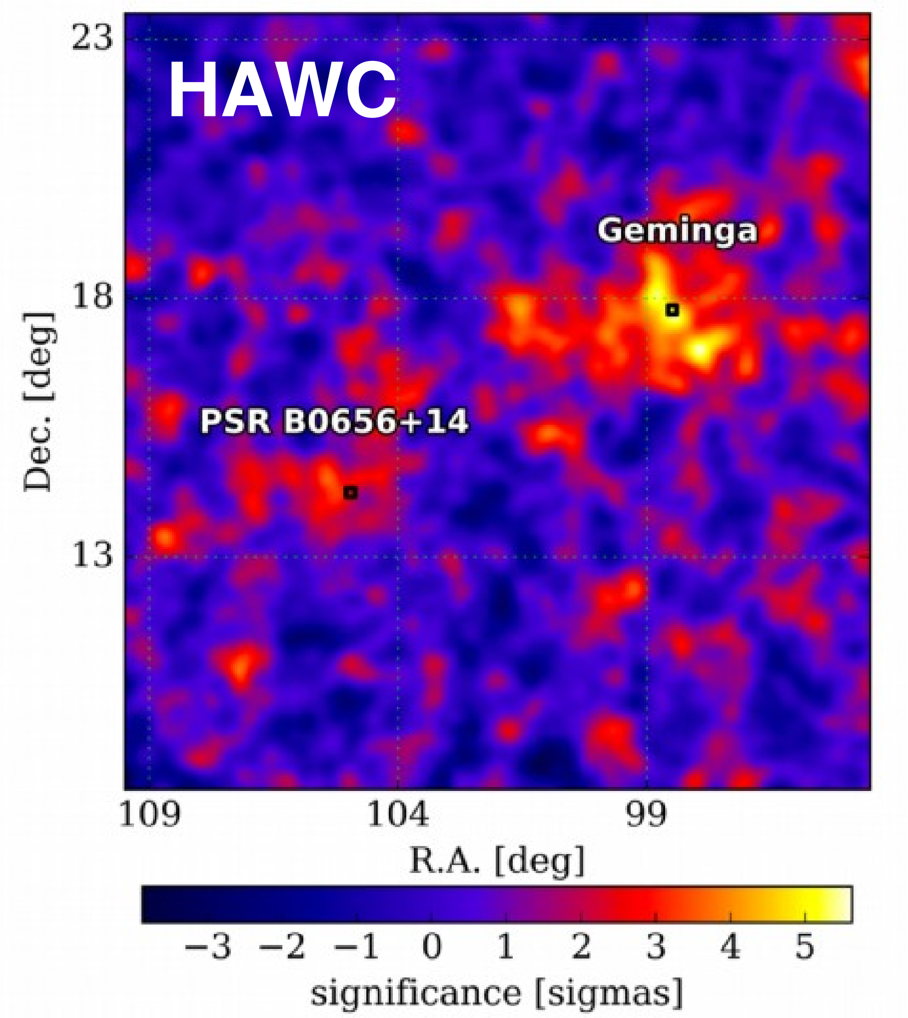
$$t_* \sim \underline{10^4\,\mathrm{yr}}\,(l_{\max}/150\,\mathrm{pc})^{\beta}\,(E/\mathrm{PeV})^{-\gamma}\,(B_{\mathrm{rms}}/4\,\mu\mathrm{G})^{\gamma}$$

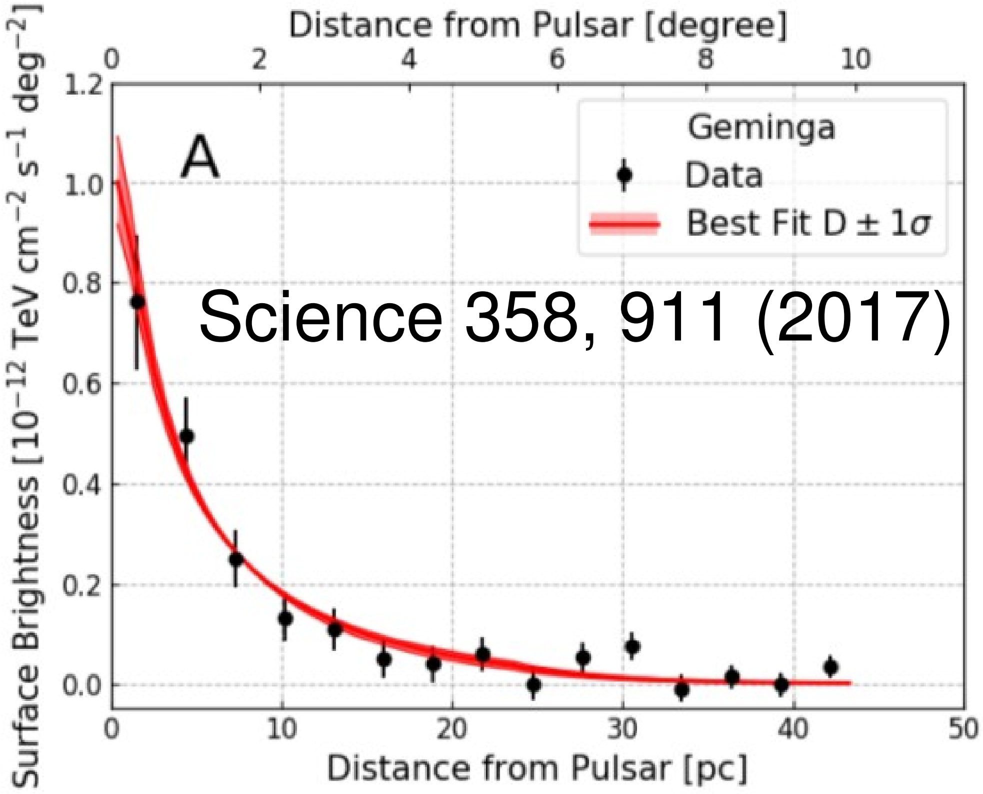
with $\beta \simeq 2$ and $\gamma = 0.25$–0.5

I – Extended gamma-ray emission around Geminga

Lopez-Coto & GG, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

HAWC observations of Geminga region





Science 358, 911 (2017)

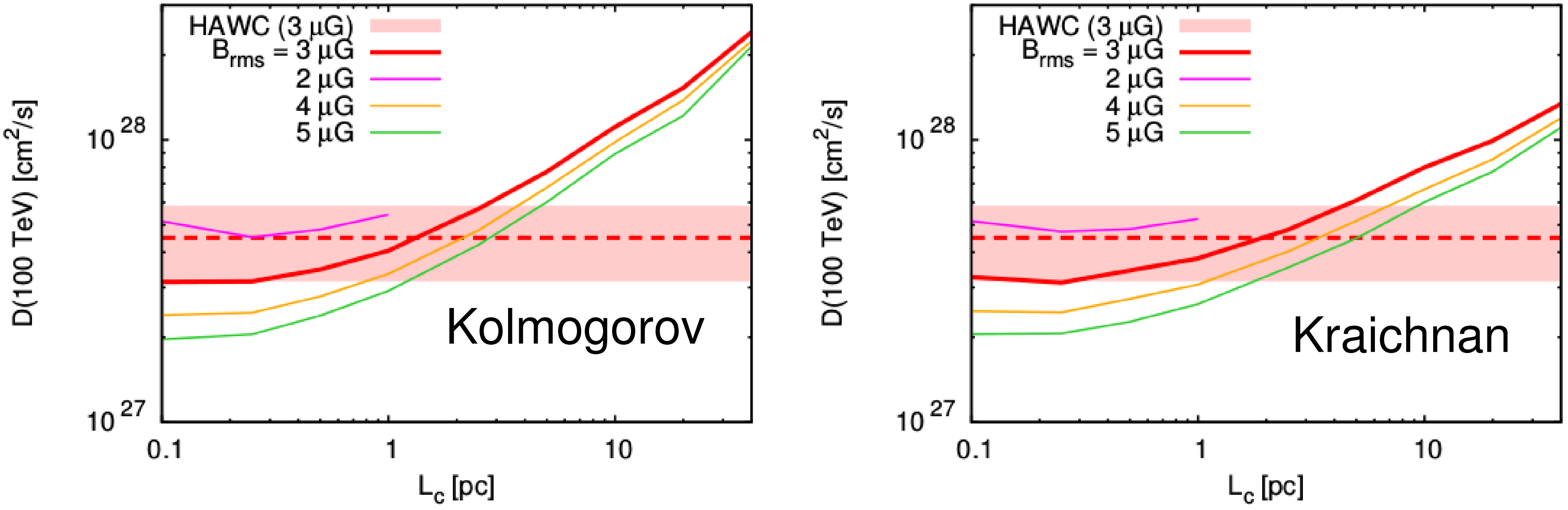
$B = 3$ μG

$$D_{100} = (4.5 \pm 1.2) \times 10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$$

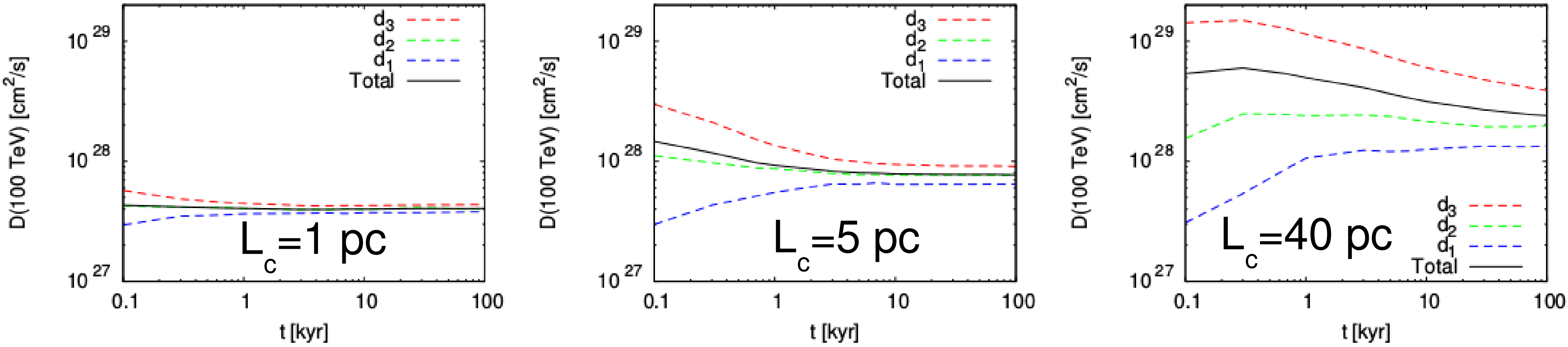
at 100 TeV.

If emission ~ symmetric: Can already put <u>upper limits</u> on the <u>coherence length</u> of the turbulence

100 TeV protons



Eigenvalues (Kolmogorov spectrum, B_{rms}=3 μG):



Simulations

→ Inject 5000 electrons (40 – 500 TeV) :

$$dN/dE = f_{\rm e}(E/E_0)^{-\alpha} \text{ with } \alpha = 2.24$$

→ Propagate in 3D realizations of B turbulence :

(62x10 cases) : $\{\mathcal{P}(k), L_{\rm c}, B_{\rm rms}\}$ $B_{\rm rms} \equiv \sqrt{\langle B^2 \rangle}$.

→ Synchrotron + IC losses (/CMB) :

$$\left|\frac{dE}{dt}\right| \simeq 2.53 \times 10^{-15}\,\mathrm{TeV/s}\left[\left(\frac{B}{\mu\mathrm{G}}\right)^2 + 10.1\left(1+\frac{E}{99\,\mathrm{TeV}}\right)^{-1.5}\right]\left(\frac{E}{\mathrm{TeV}}\right)^2$$

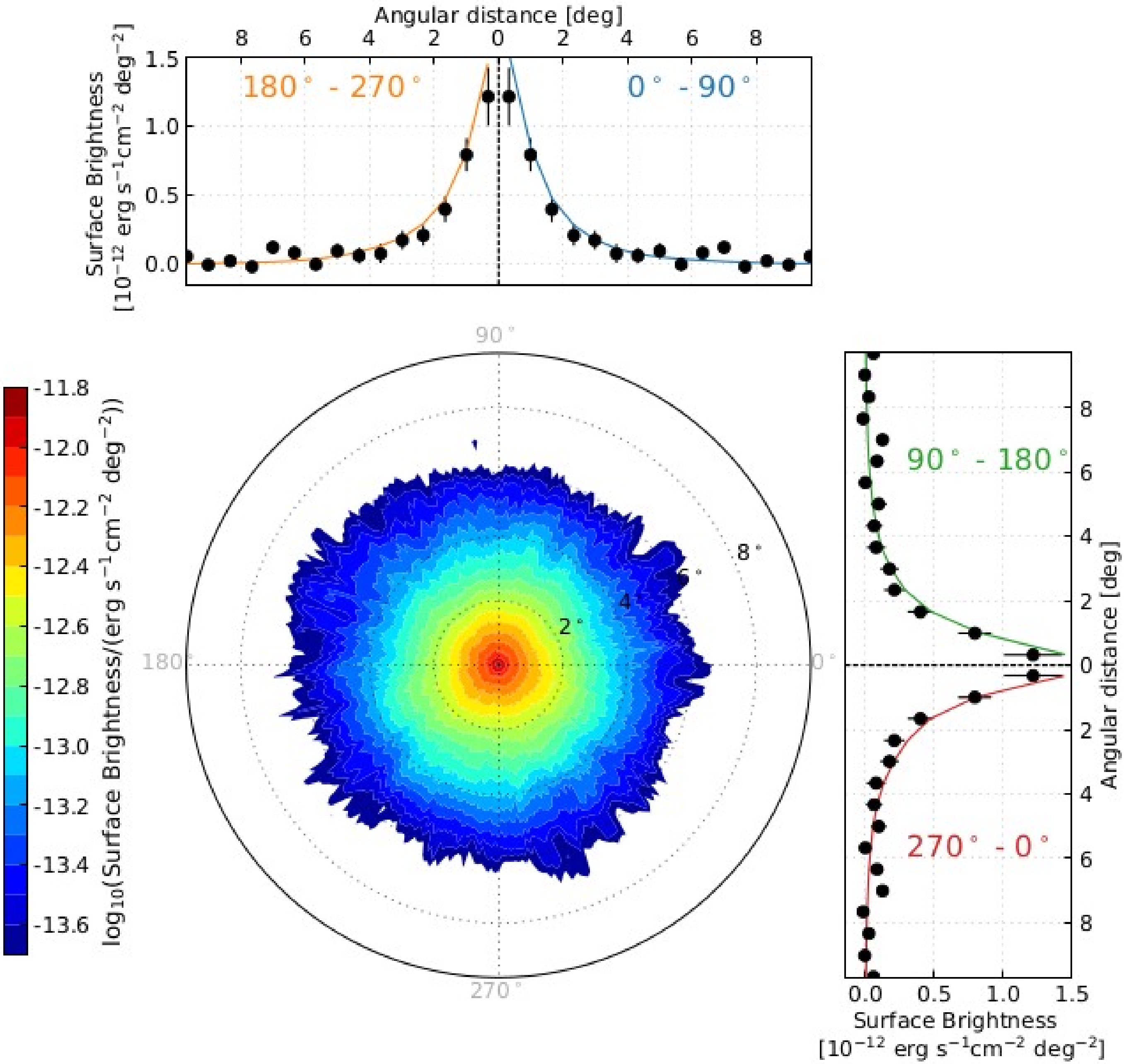
→ Calculate gamma-ray emission : IC on CMB photons.
(full Klein-Nishina treatment of the cross section)

Predicted γ-ray surface brightness

Kolmogorov

B_{rms}=3 μG

L_c = 0.25 pc

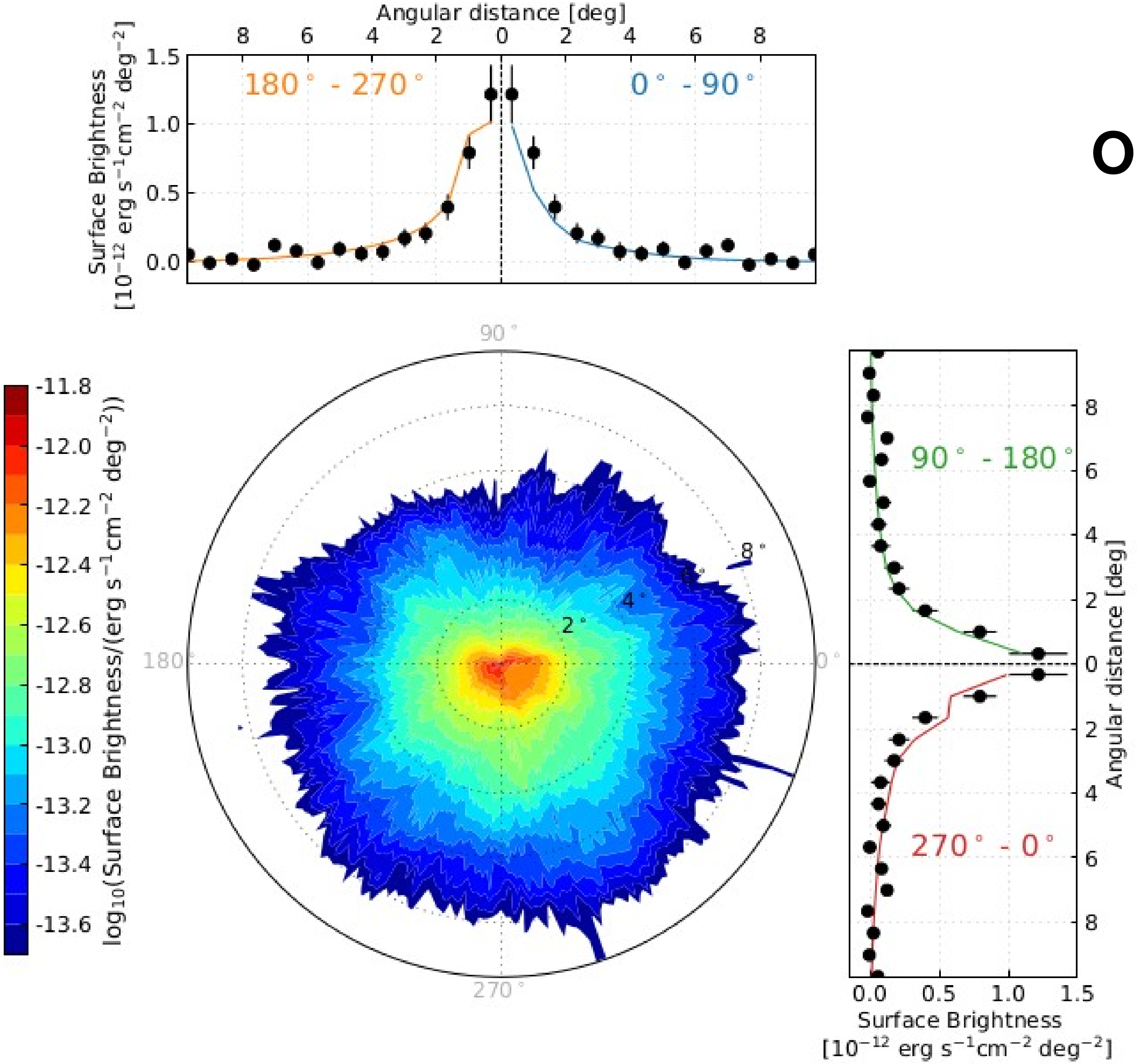


Predicted γ-ray surface brightness

Kolmogorov

B_{rms}=3 μG

L_c = 5 pc



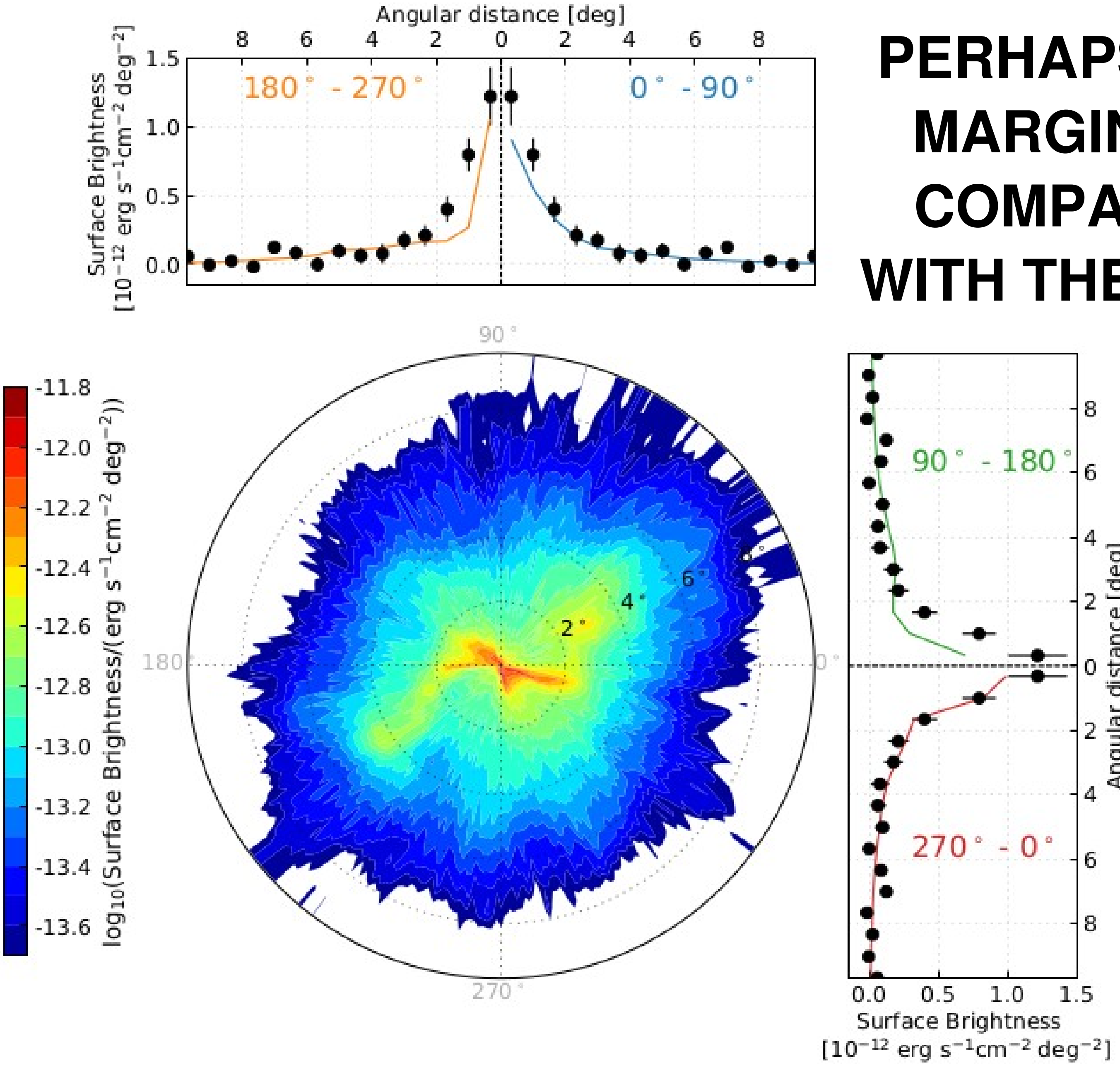
OK

Predicted γ-ray surface brightness

Kolmogorov

B_{rms}=3 μG

L_c = 10 pc



PERHAPS STILL MARGINALLY COMPATIBLE WITH THE DATA?

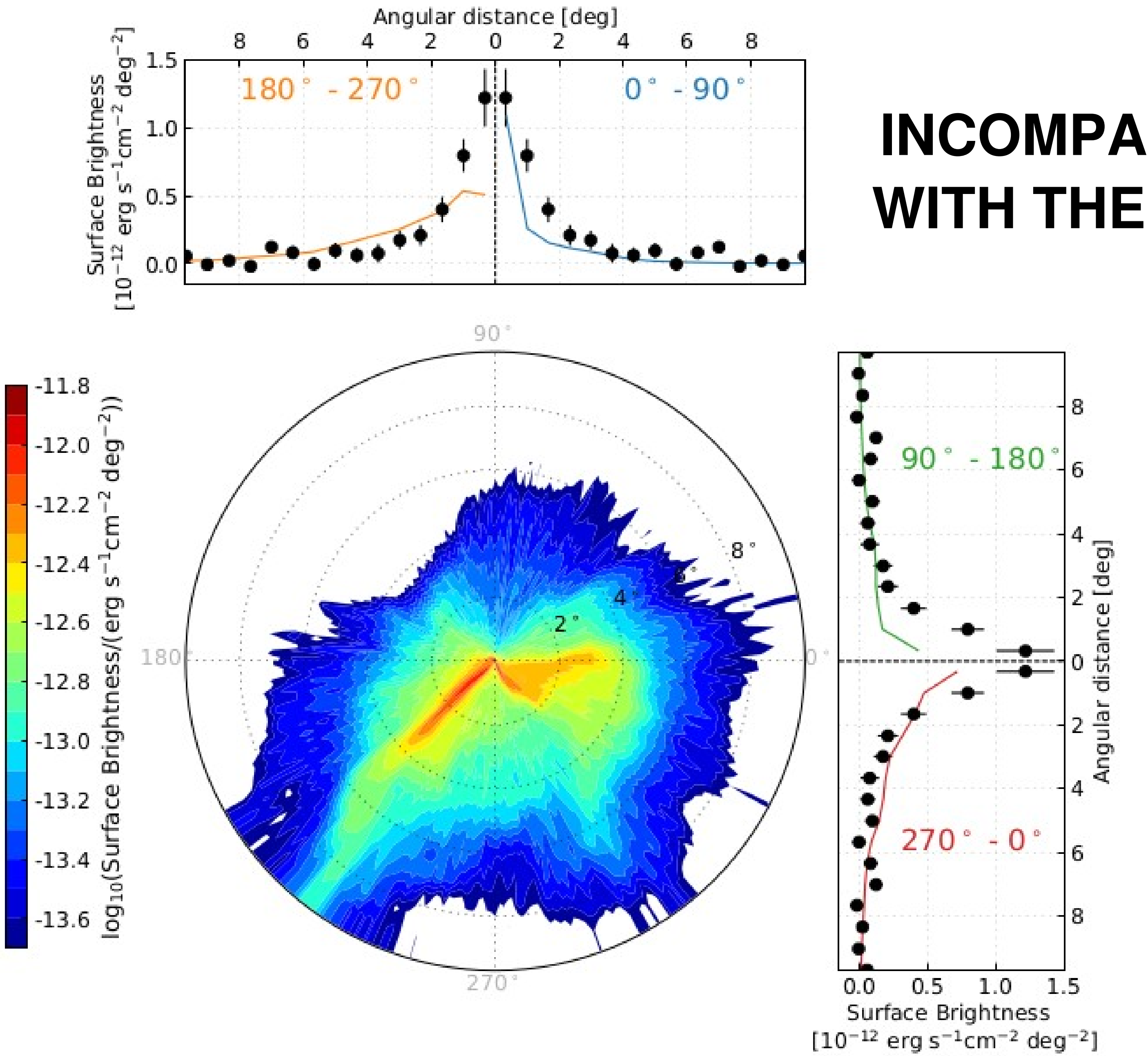
Predicted γ-ray surface brightness

INCOMPATIBLE WITH THE DATA

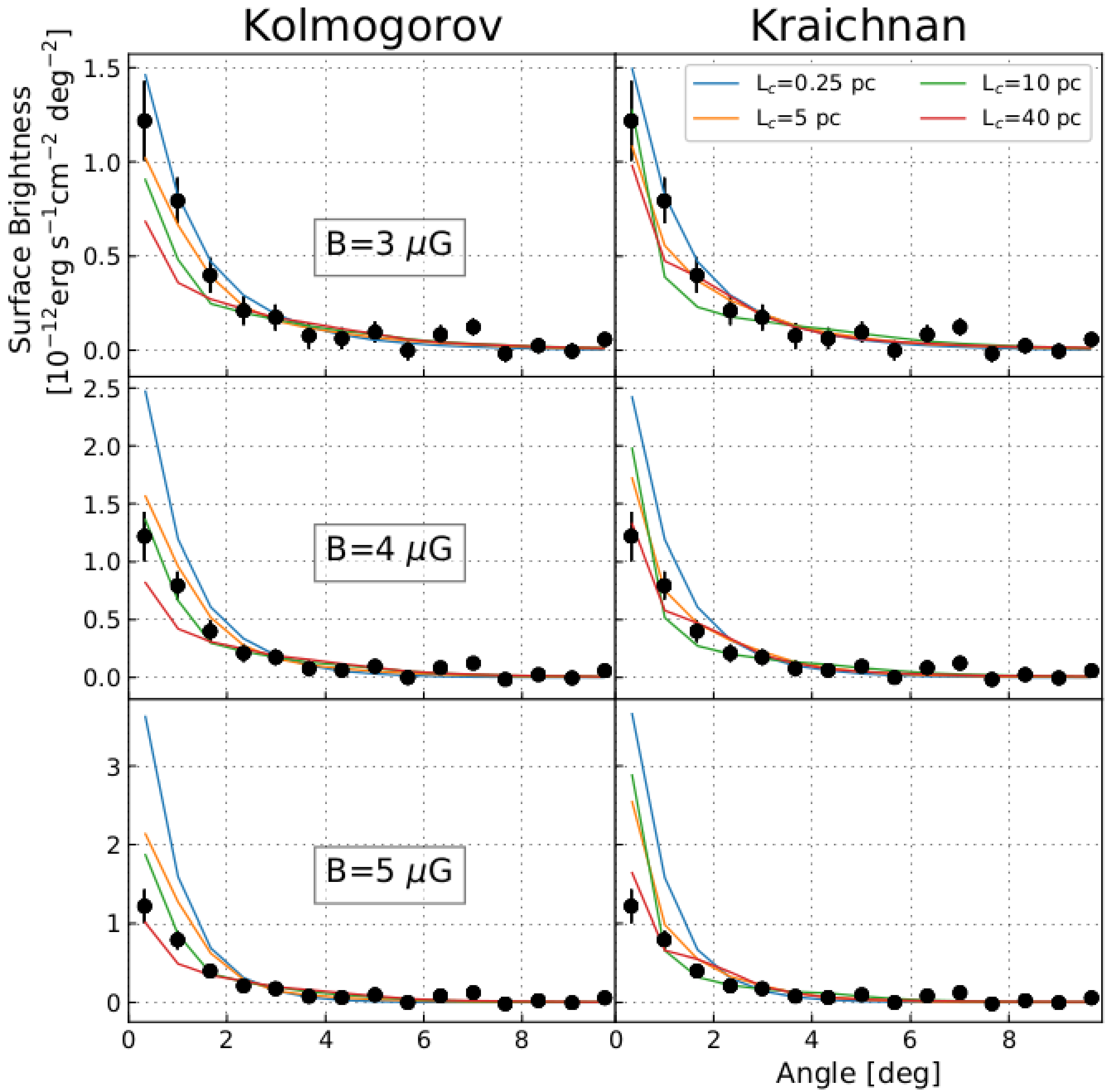
Kolmogorov

B_{rms}=3 μG

L_c = 40 pc

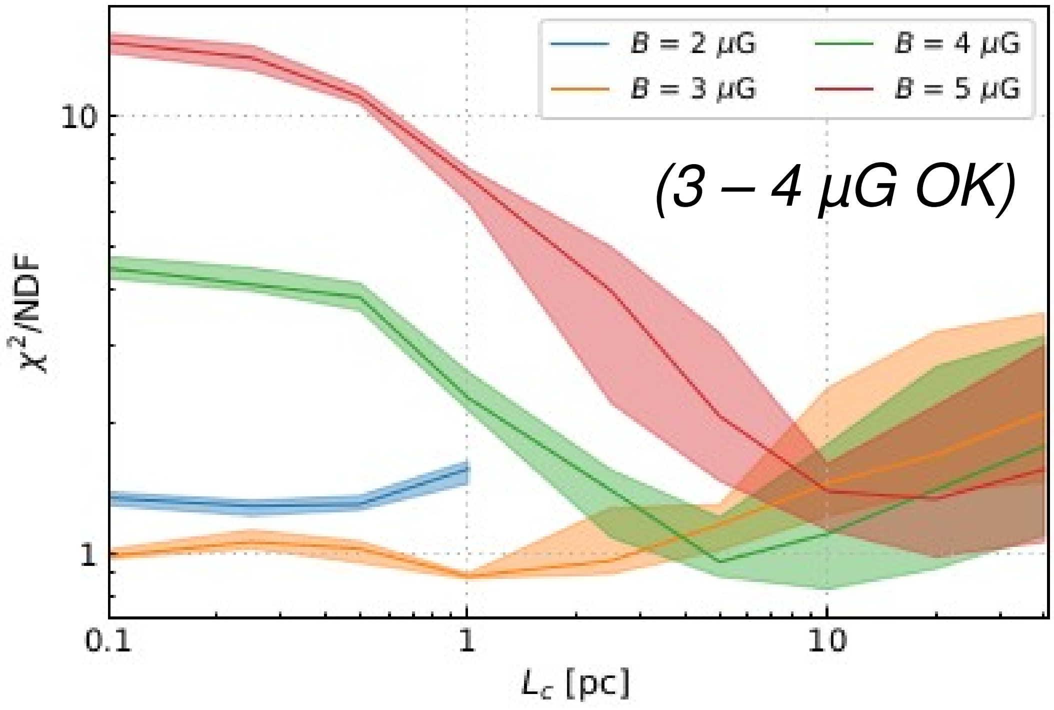


Surface brightness vs dist. to Geminga



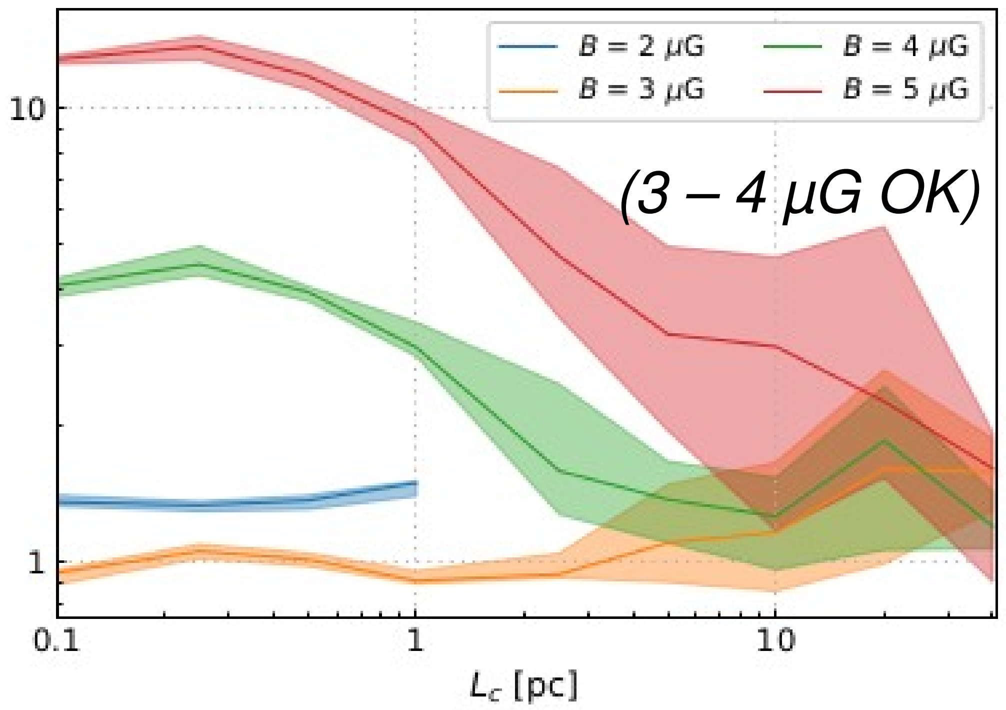
χ^2/ndf as a function of L_c

Kolmogorov



(3 – 4 μG OK)

Kraichnan



(3 – 4 μG OK)

Kolmogorov	$2\,\mu$G	$3\,\mu$G	$4\,\mu$G	$5\,\mu$G
0.1 pc	20.1/15	14.8/15	67.1/15	220/15
0.25 pc	19.2/15	15.9/15	61.6/15	203/15
0.5 pc	19.5/15	15.4/15	57.6/15	165/15
1 pc	23.4/15	13.3/15	34.0/15	108/15
2.5 pc	N/A	14.4/15	20.9/15	59.6/15
5 pc	N/A	17.5/15	14.4/15	30.9/15
10 pc	N/A	21.7/15	16.7/15	20.8/15
20 pc	N/A	25.2/15	21.0/15	20.0/15
40 pc	N/A	31.4/15	26.4/15	23.4/15

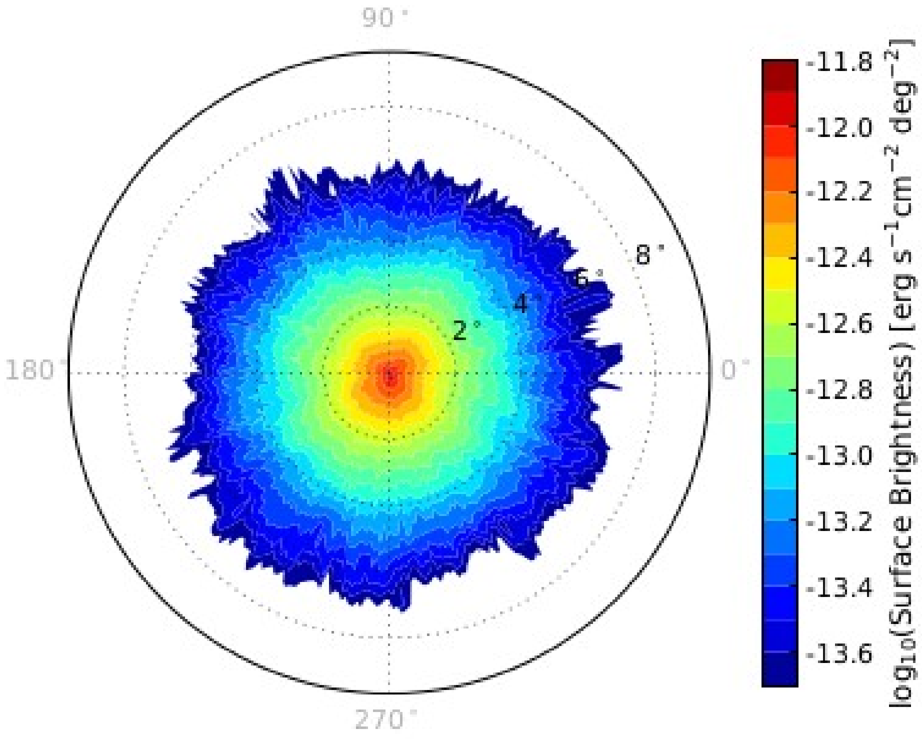
Kraichnan	$2\,\mu$G	$3\,\mu$G	$4\,\mu$G	$5\,\mu$G
0.1 pc	20.3/15	14.1/15	61.0/15	193/15
0.25 pc	20.0/15	15.8/15	67.9/15	205/15
0.5 pc	20.5/15	15.1/15	59.0/15	177/15
1 pc	22.4/15	13.6/15	44.5/15	137/15
2.5 pc	N/A	14.1/15	23.8/15	70.8/15
5 pc	N/A	16.5/15	20.5/15	47.6/15
10 pc	N/A	17.4/15	18.8/15	44.7/15
20 pc	N/A	24.0/15	27.7/15	33.8/15
40 pc	N/A	23.6/15	18.0/15	24.0/15

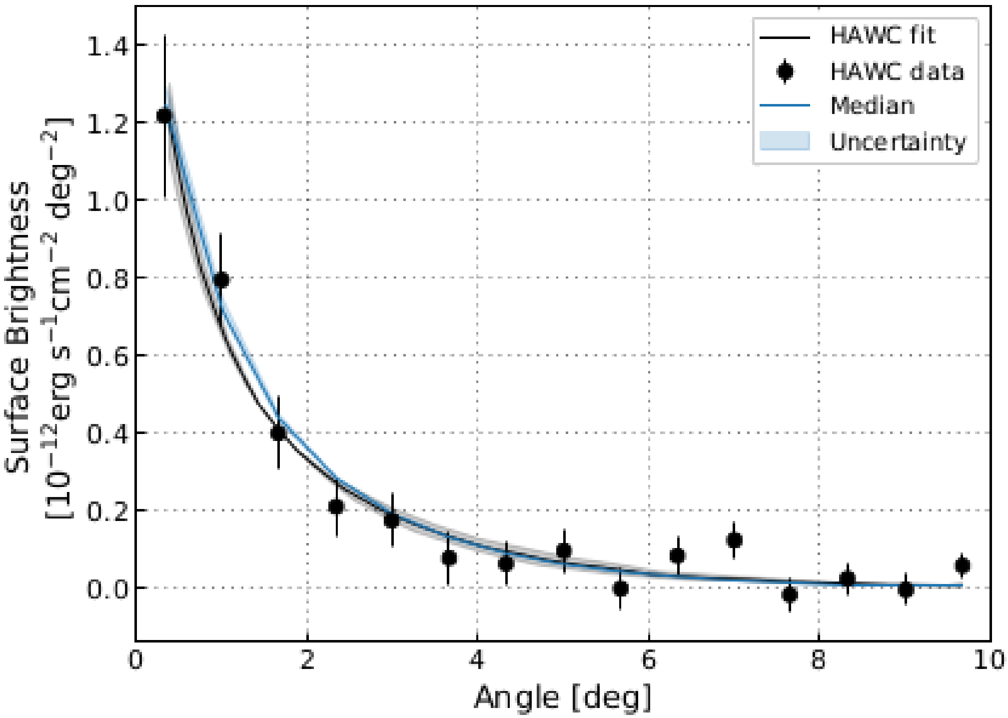
Our best fit to HAWC measurements

Kolmogorov
(Kraichnan)

$B_{rms} = 3\ \mu G$

$L_c = 1\ pc$

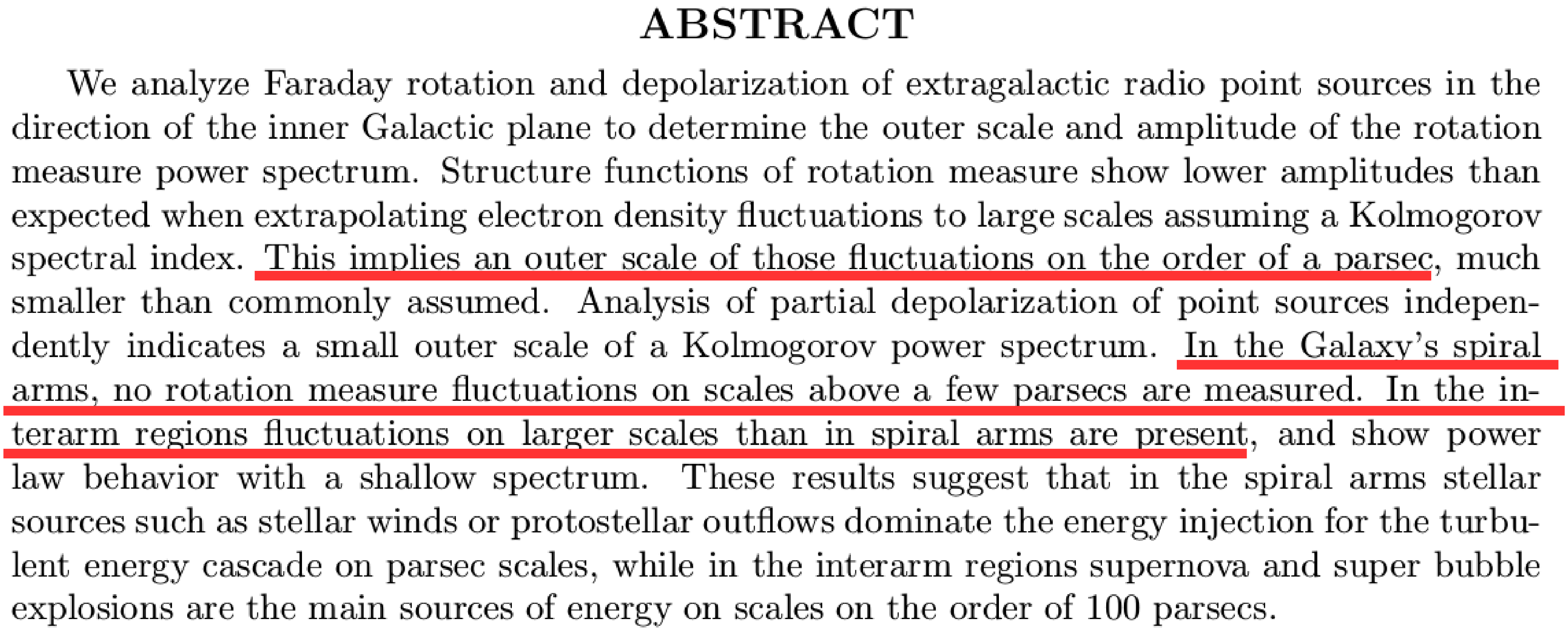




Radio observations

Radio observations suggest that L_c in the spiral arms of our Galaxy is equal to only a few parsecs, which is very close to our best fit value. $L_{max} = 5L_c$ for Kolmogorov turbulence) is ≤ 20 pc according to e.g.

Haverkorn et al., ApJ **680**, 362 (2008) :



ABSTRACT

We analyze Faraday rotation and depolarization of extragalactic radio point sources in the direction of the inner Galactic plane to determine the outer scale and amplitude of the rotation measure power spectrum. Structure functions of rotation measure show lower amplitudes than expected when extrapolating electron density fluctuations to large scales assuming a Kolmogorov spectral index. This implies an outer scale of those fluctuations on the order of a parsec, much smaller than commonly assumed. Analysis of partial depolarization of point sources independently indicates a small outer scale of a Kolmogorov power spectrum. In the Galaxy's spiral arms, no rotation measure fluctuations on scales above a few parsecs are measured. In the interarm regions fluctuations on larger scales than in spiral arms are present, and show power law behavior with a shallow spectrum. These results suggest that in the spiral arms stellar sources such as stellar winds or protostellar outflows dominate the energy injection for the turbulent energy cascade on parsec scales, while in the interarm regions supernova and super bubble explosions are the main sources of energy on scales on the order of 100 parsecs.

See also Iacobelli M et al A&A **558**, A72 (2013)

Part I: Conclusions and perspectives

- "**Anisotropic" propagation** of CRs in the ISM must be taken into account on scales <~ several L_c.

- **HAWC measurements for Geminga**
  → **Constraints on the surrounding turbulence.**

- **γ-ray observatories as a probe of** :
  → **Turbulent interstellar magnetic fields**
  → Future : CR-driven instabilities around CR sources.

- Implications of a small D for B/C, all-electron spectrum.

II – Anisotropic CR diffusion and Galactic magnetic field models

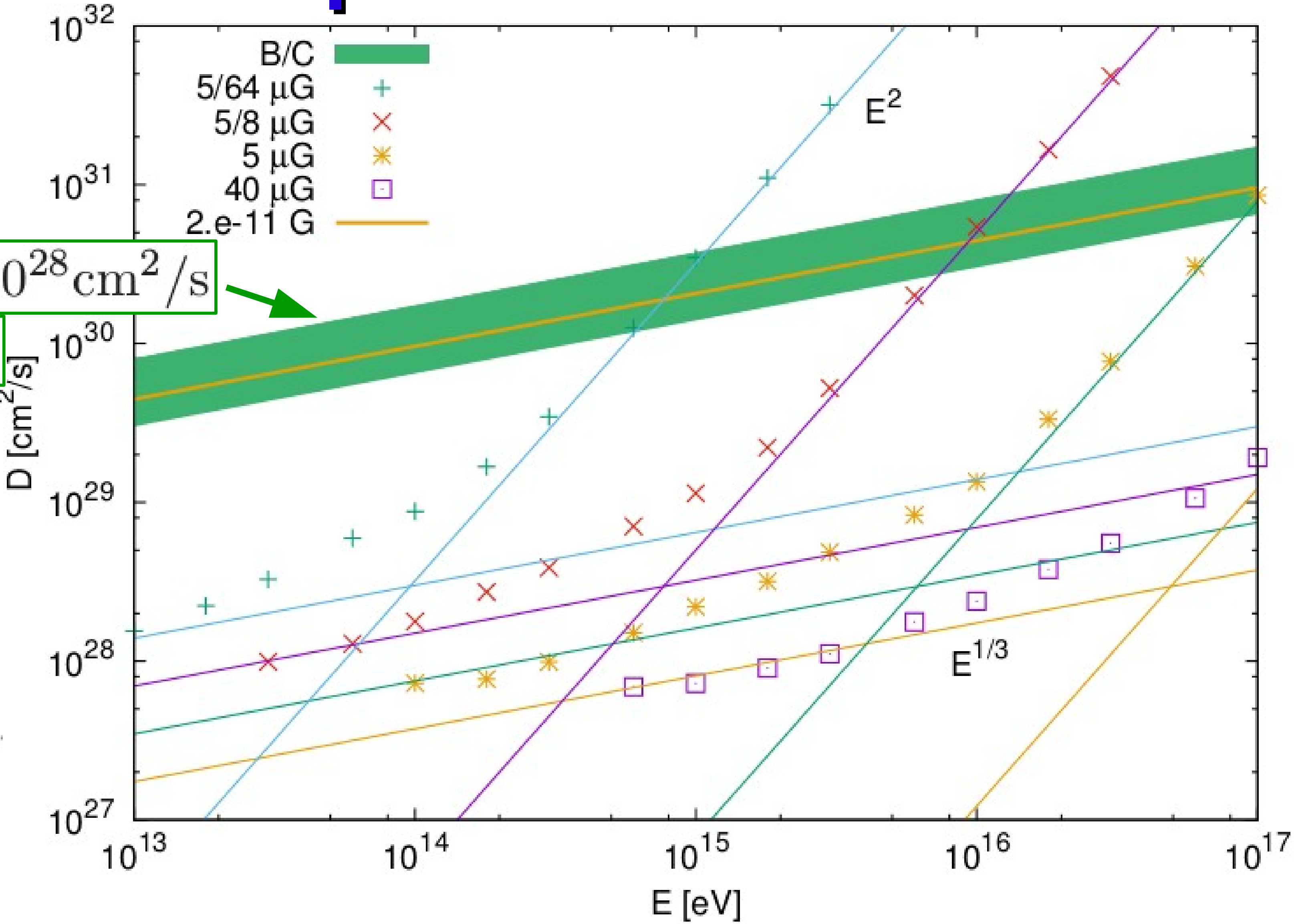
GG, Kachelriess & Semikoz,
JCAP 07, 051 (2018) [arXiv:1710.08205]

Isotropic diffusion

$D_0 = (3-8)\times 10^{28}\,\mathrm{cm}^2/\mathrm{s}$

$\text{at } E_0 = 10\,\mathrm{GeV}$

$H \simeq 5\,\mathrm{kpc}$



$\mathcal{P}(k) \propto k^{-5/3}$

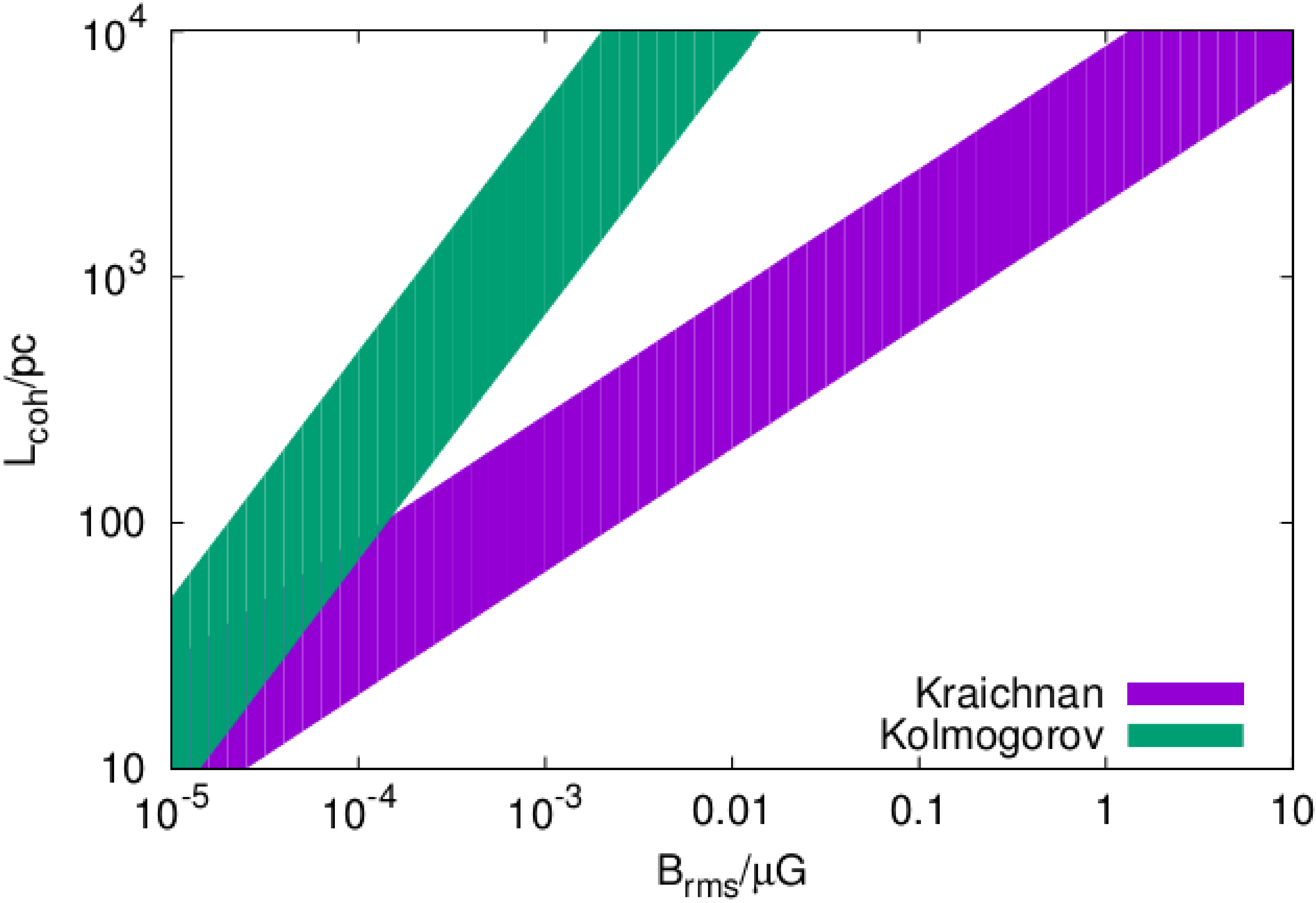
$L_{\rm coh} = L_{\rm max}/5$

$L_{\rm max} = 25\,\mathrm{pc}$

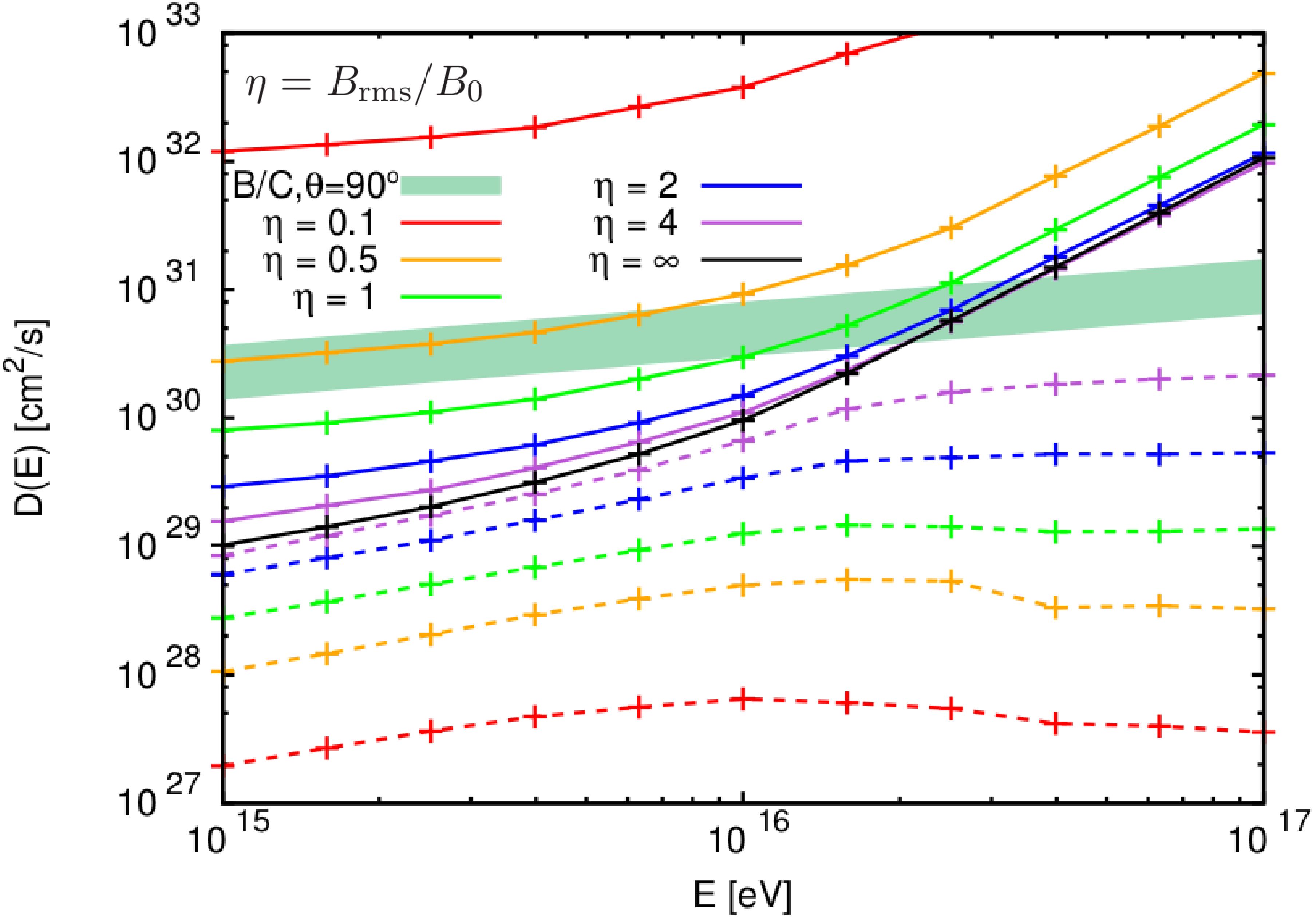
$$D = \frac{cL_0}{3}\left[(R_{\rm L}/L_0)^{2-\alpha} + (R_{\rm L}/L_0)^2\right]\ ,\ \ L_0 \simeq L_{\rm coh}/(2\pi)$$

Isotropic diffusion

Allowed ranges of $B_{\rm rms}$ and $L_{\rm coh}$ compatible with $D_0 = (3-8)\times 10^{28}\,{\rm cm}^2/{\rm s}$ at $E_0 = 10\,{\rm GeV}$



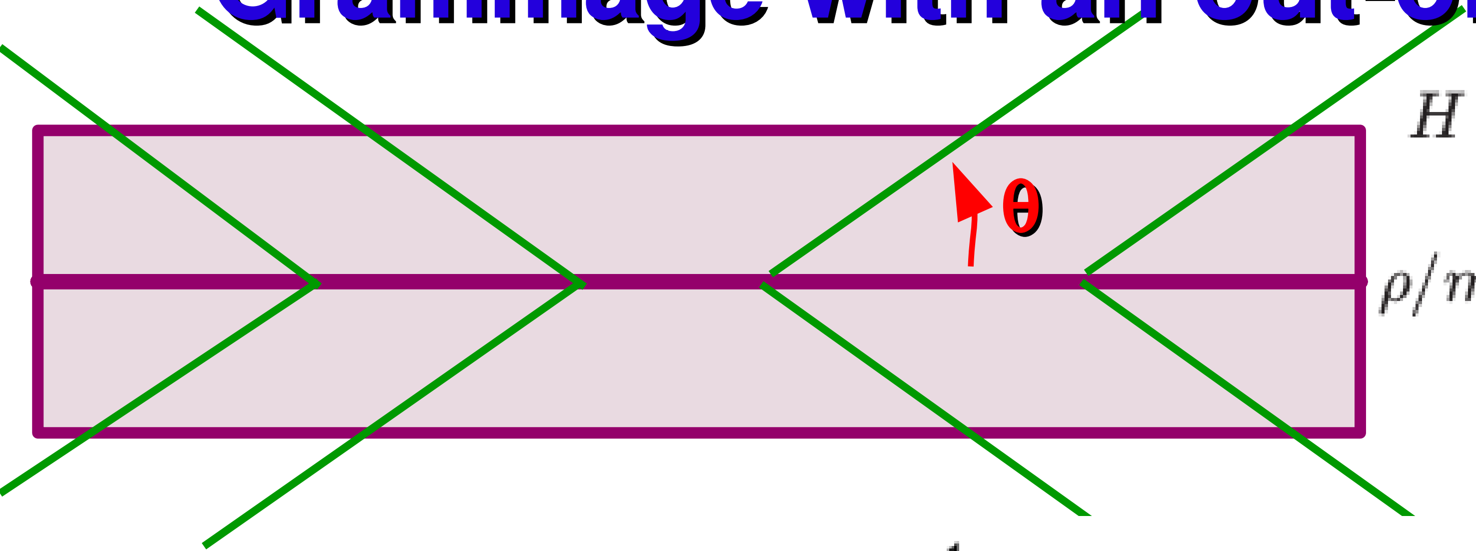
Anisotropic diffusion



$L_{\rm max} = 100\,{\rm pc}$

$B_{\rm tot} = \sqrt{B_{\rm rms}^2 + B_0^2} = 1\,\mu{\rm G}$

Grammage with an out-of-plane B

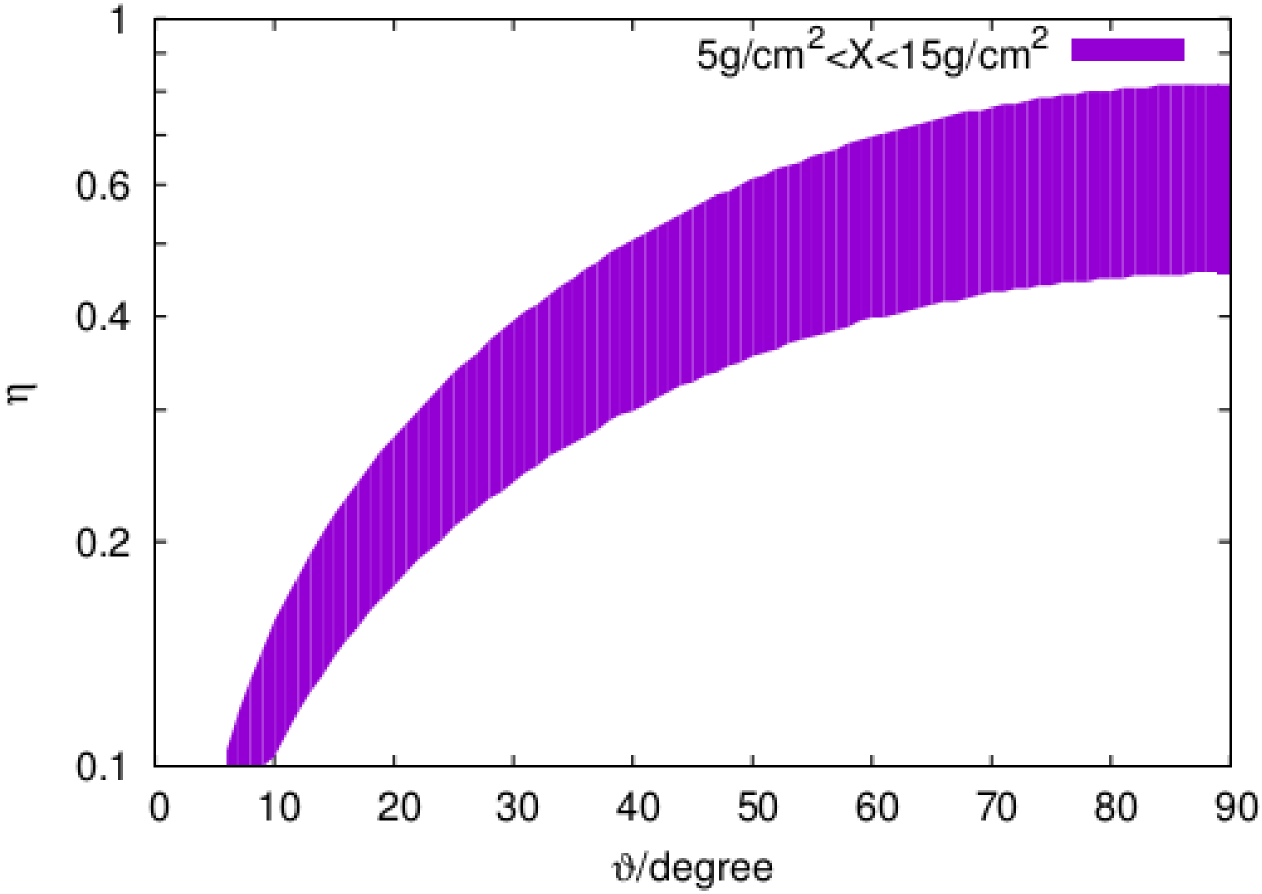


$H = 5\,\mathrm{kpc}$

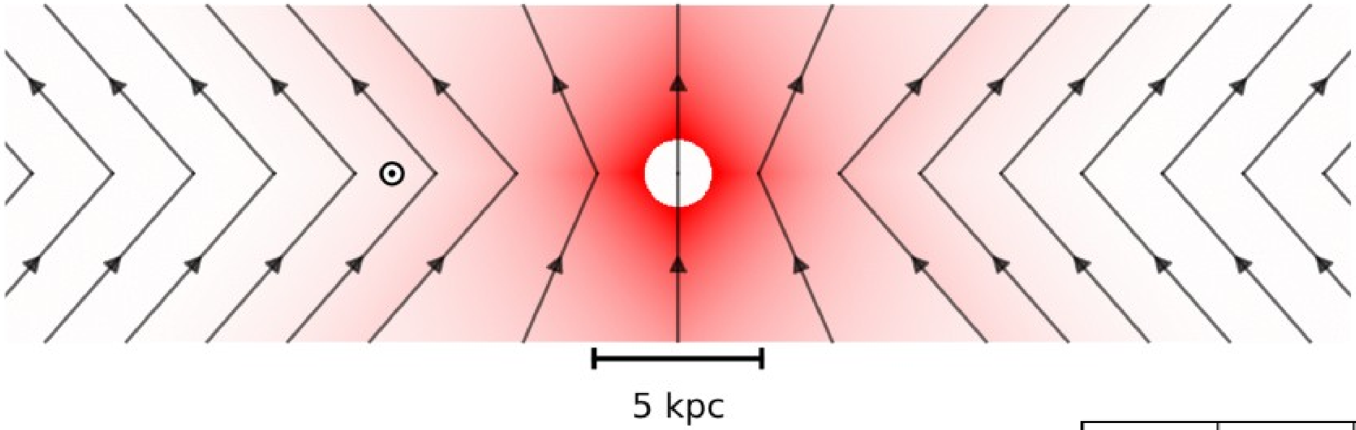
$\rho/m_{\mathrm{p}} \simeq 1/\mathrm{cm}^3$ $h = 150\,\mathrm{pc}$

$$X = c\rho h H/D_z$$

$$D_z = D_\perp \cos^2\vartheta + D_\| \sin^2\vartheta$$



Jansson & Farrar GMF model



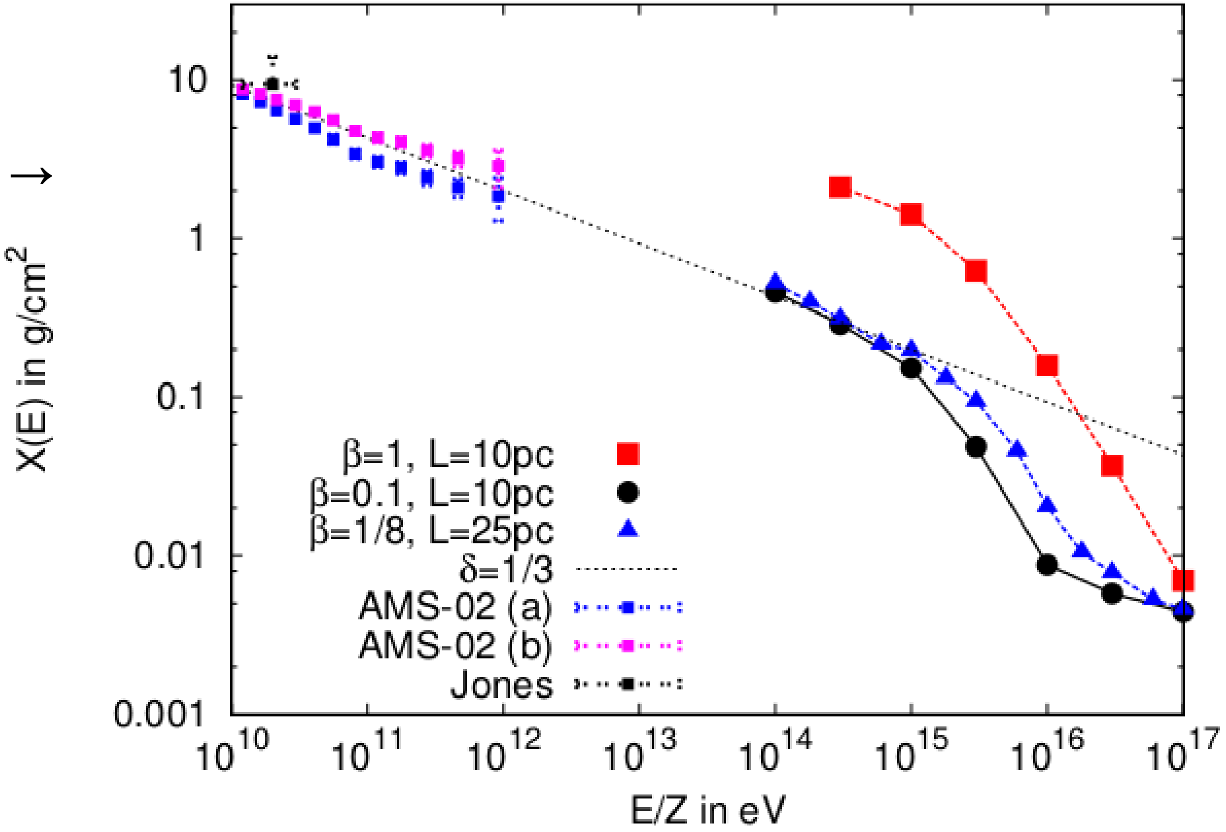
“X-field”

=> CRs go in the halo

X(E) reproduced if TF reduced by a factor ≈ 8–10 →

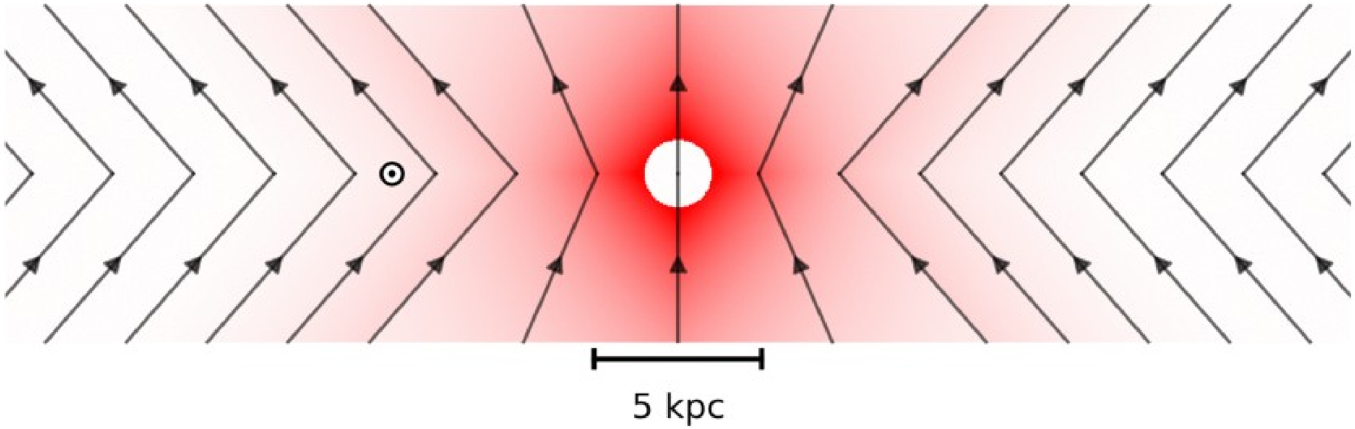
(1) Avg turb. level η ≃ 0.25 along CR trajectories

(2) typically, Θ ≈ 20°



GG, Kachelriess & Semikoz, Phys. Rev. D **91**, 083009 (2015)

Jansson & Farrar GMF model



"X-field"

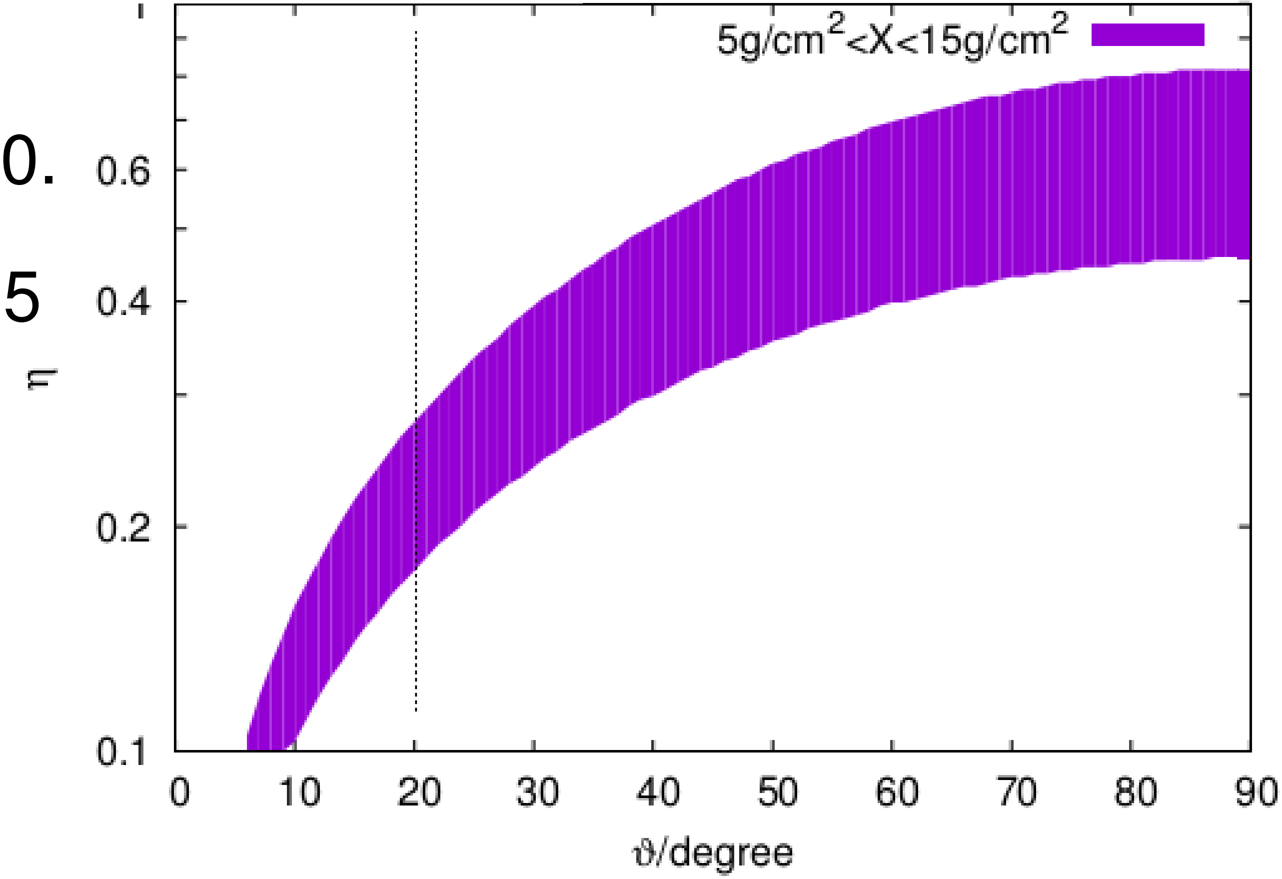
=> CRs go in the halo

X(E) reproduced if TF reduced by a factor ≈ 8–10.

(1) Avg turb. level $\eta \simeq 0.25$ along CR trajectories

(2) typically, $\Theta \approx 20^\circ$

=> Consistent picture



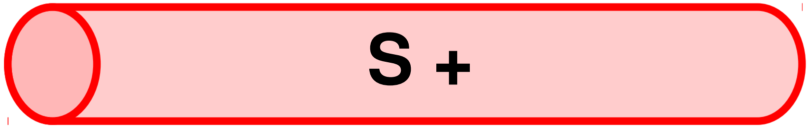
Breakdown of the steady-state picture at low E >~ 1 TeV?
Can a single 2–3 Myr source dominate the CR flux at 10 TeV?

CR flux from a source at distance L and age t, after release :

$10^{50}\,\mathrm{erg}$ $\qquad Q(E) = Q_0 (E/E_0)^{-\alpha}$ $\qquad \alpha \simeq 2.2$

(1) At $2Dt \lesssim L^2$ flux suppressed.

(2) Later : $I(E) \simeq \dfrac{c}{4\pi}\dfrac{Q(E)}{V(t)}$



$V(t) = \pi^{3/2} D_\perp D_{||}^{1/2} t^{3/2}$ where $2Dt \sim L^2$

(3) Even later : Escape from the Galaxy.

Case of isotropic diffusion:

$D_{\rm iso}(E_*) \sim 5 \times 10^{29} {\rm cm}^2/{\rm s}$ satisfying the B/C constraints (H~5kpc)

$E_* = 10\,{\rm TeV}$

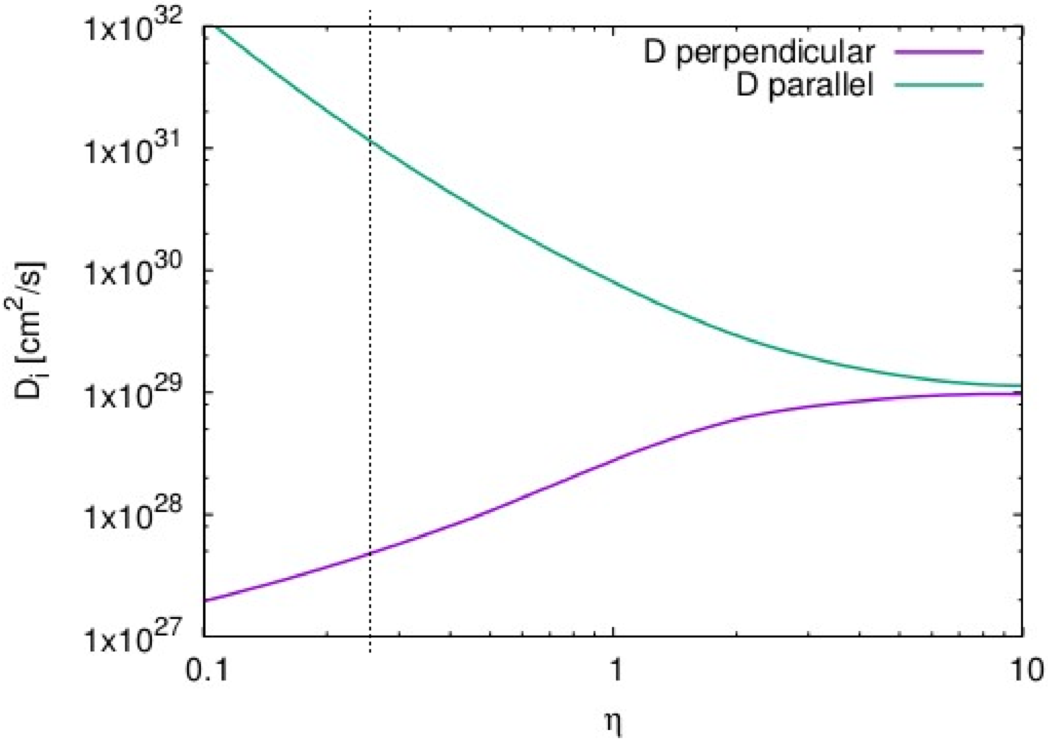
Size of the diffusion front at t = 2 Myr : $L(t) = \sqrt{2Dt} \simeq 2.5\,{\rm kpc}$

$$E_*^{2.8} I(E_*) \simeq 200\,{\rm GeV}^{1.8}\,{\rm sr}^{-1}\,{\rm s}^{-1}\,{\rm m}^{-2}$$

→ Only 1/100 of observed CR intensity at E_*

=> NO! Large number of sources contribute to the CR flux.

Anisotropic diffusion (with JF GMF model):



$$\eta = 0.25 \text{ and } D_{\rm iso} \simeq 2 \times 10^{30} {\rm cm}^2/{\rm s}$$

$$\text{valid at } E = 10^{15}\,{\rm eV}$$

=> $D_{\|} \simeq 5 D_{\rm iso}$

and $D_{\perp} \simeq D_{\rm iso}/500$

the volume $V(t) = \pi^{3/2} D_{\perp} D_{\|}^{1/2} t^{3/2}$ is reduced by $500/\sqrt{5} \simeq 200$

=> A single source can contribute a fraction of order O(1) to the total CR intensity at such E.

Part II: Conclusions and perspectives

- Isotropic Kolmogorov (Kraichnan) turbulence: Overproduce secondary nuclei (e.g. B) for any reasonable L_c, B_{rms}

- Strongly **anisotropic propagation** of CRs in the Milky Way: **Anisotropic diffusion** (+ Anisotropic turbulence ?)

- **-** Geometry of **regular Galactic magnetic field** important
  - Nb sources contributing to CR flux reduced by ~ 100
  - Single source may start to dominate at >~ TeV energies