CONSTRAINING THE PROPERTIES OF THE INTERSTELLAR TURBULENCE AROUND GEMINGA USING HAWC MEASUREMENTS

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& Ruben Lopez-Coto (Padova)

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

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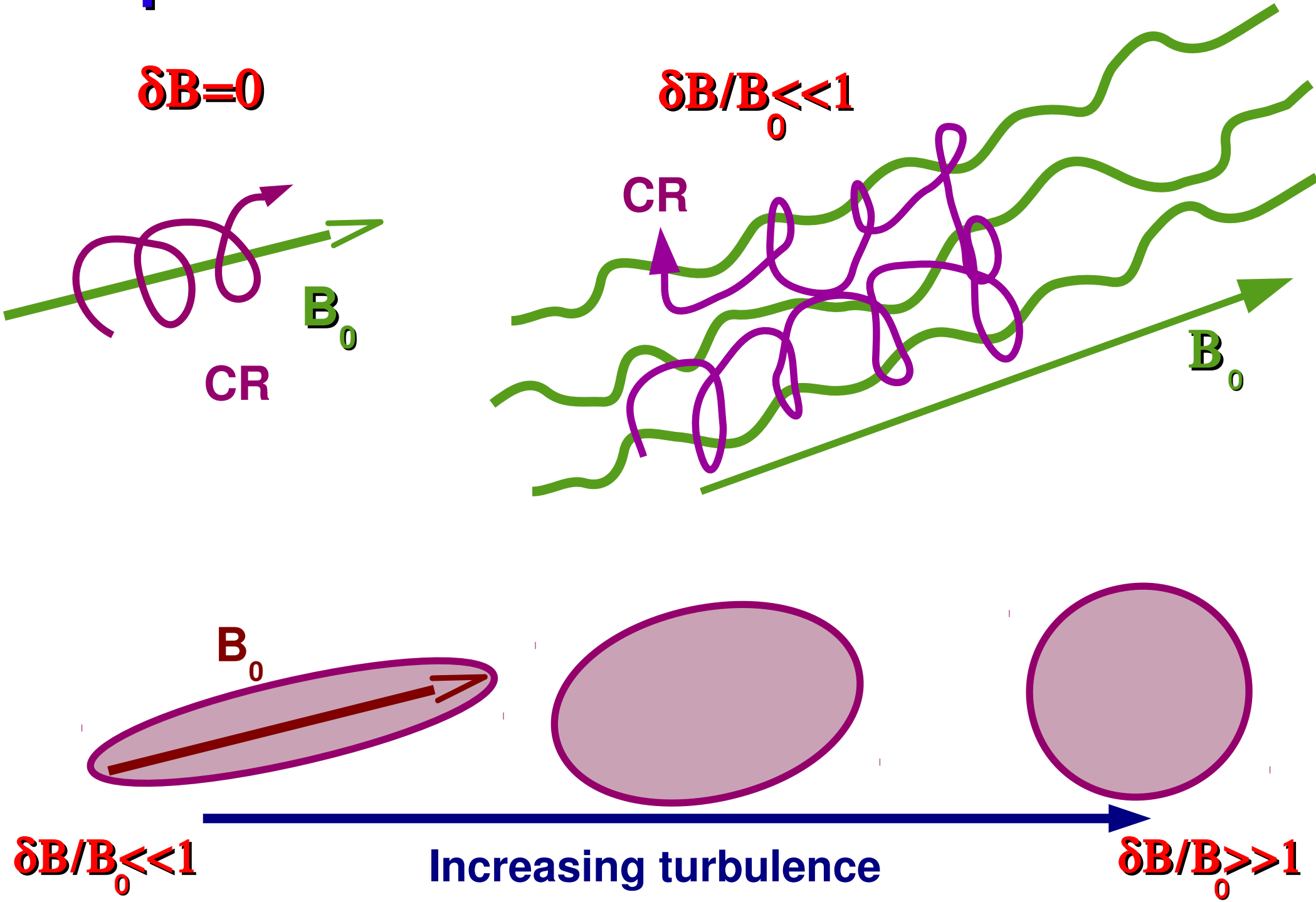
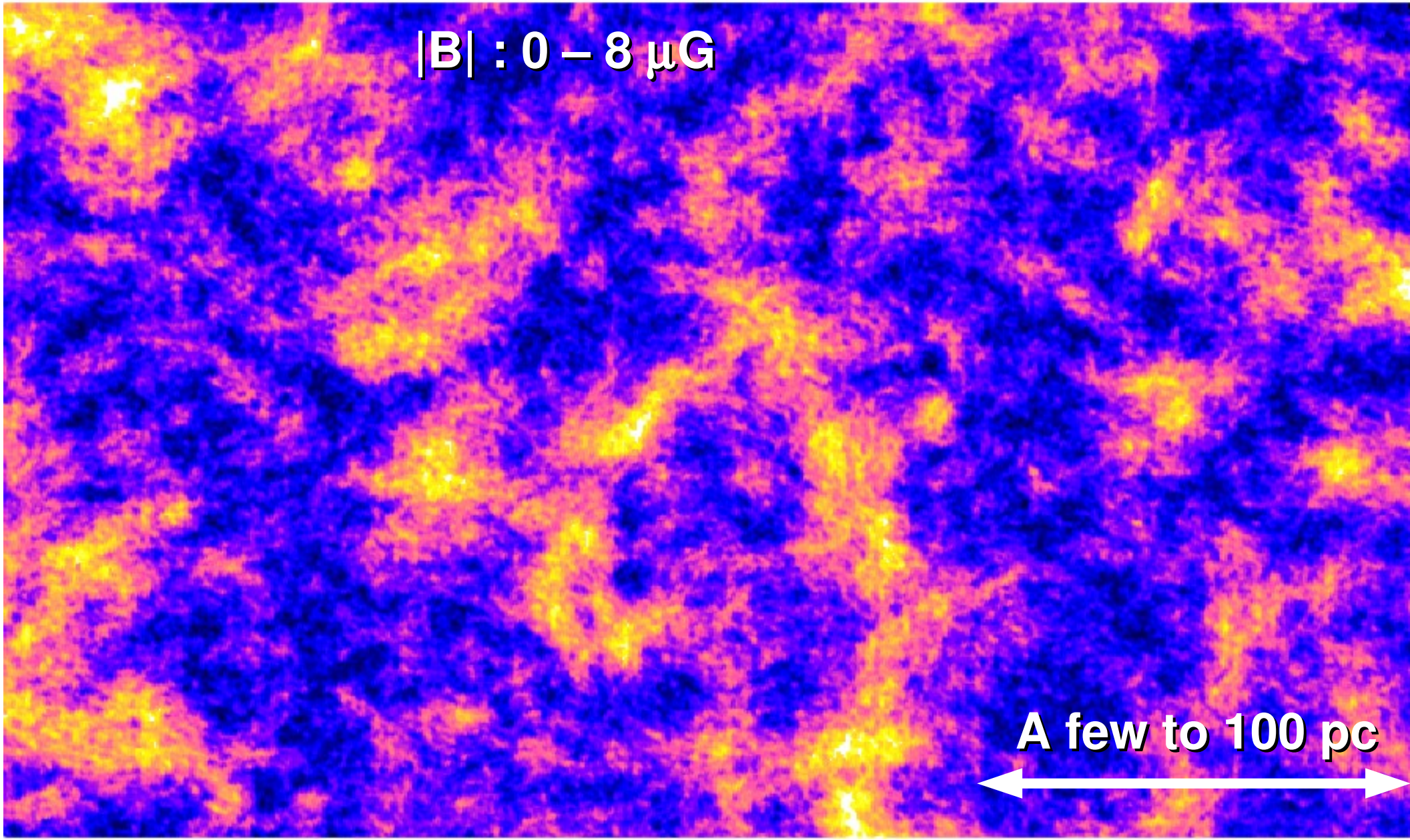
Perpendicular/Parallel diffusion coeffs.



Kolmogorov turbulence

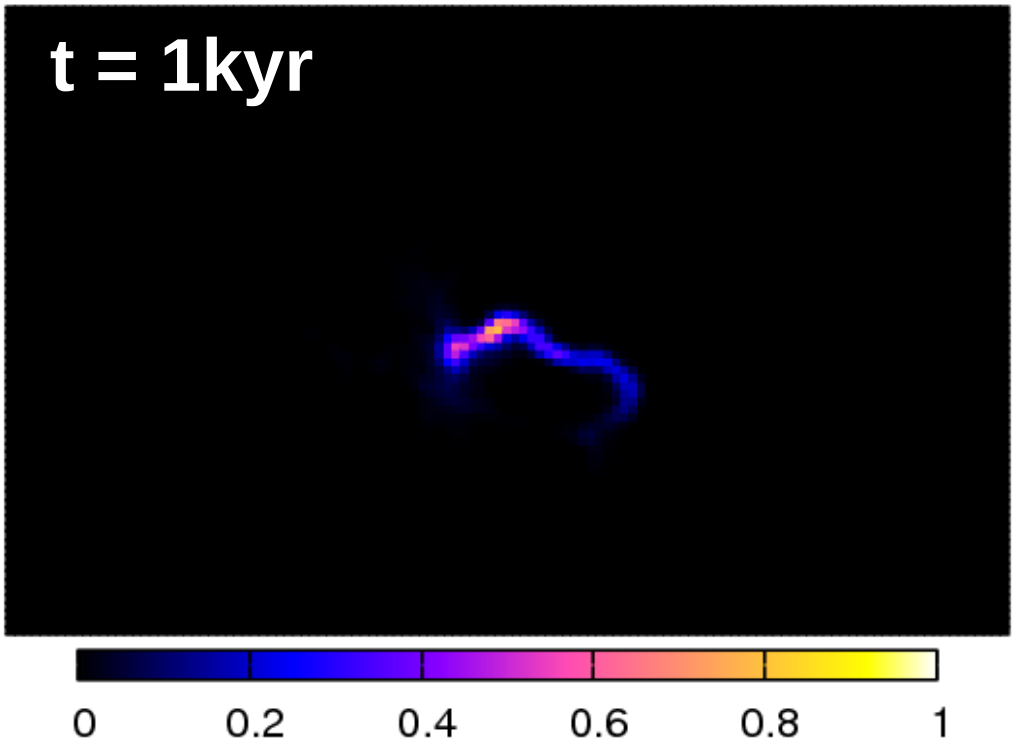


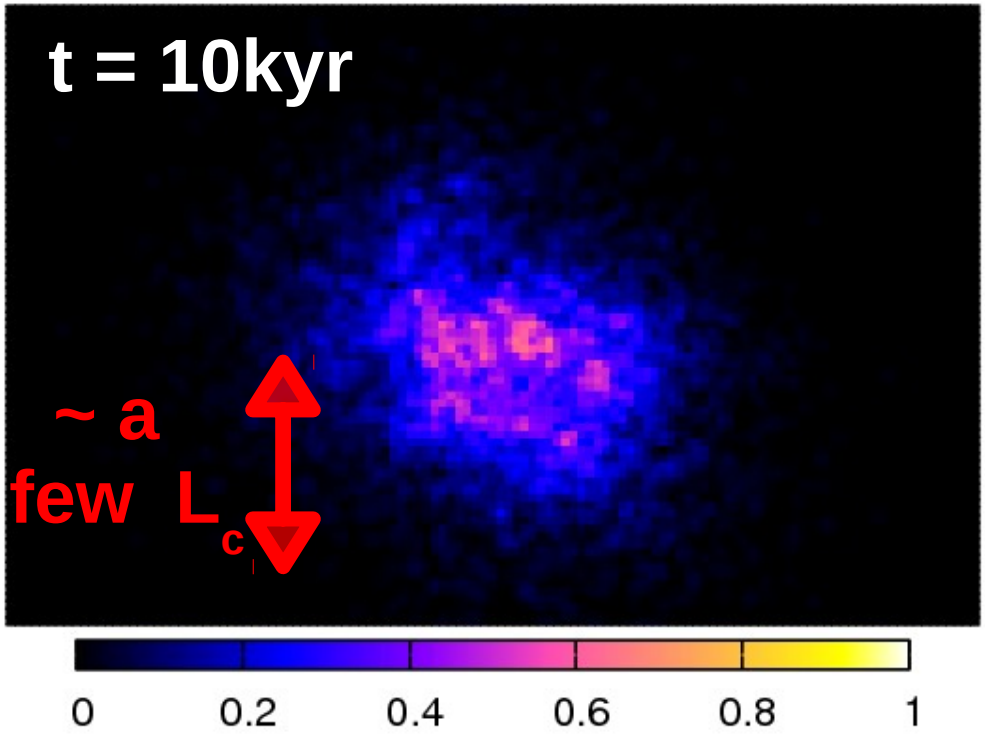
Anisotropic diff. in *isotropic* turbulence

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

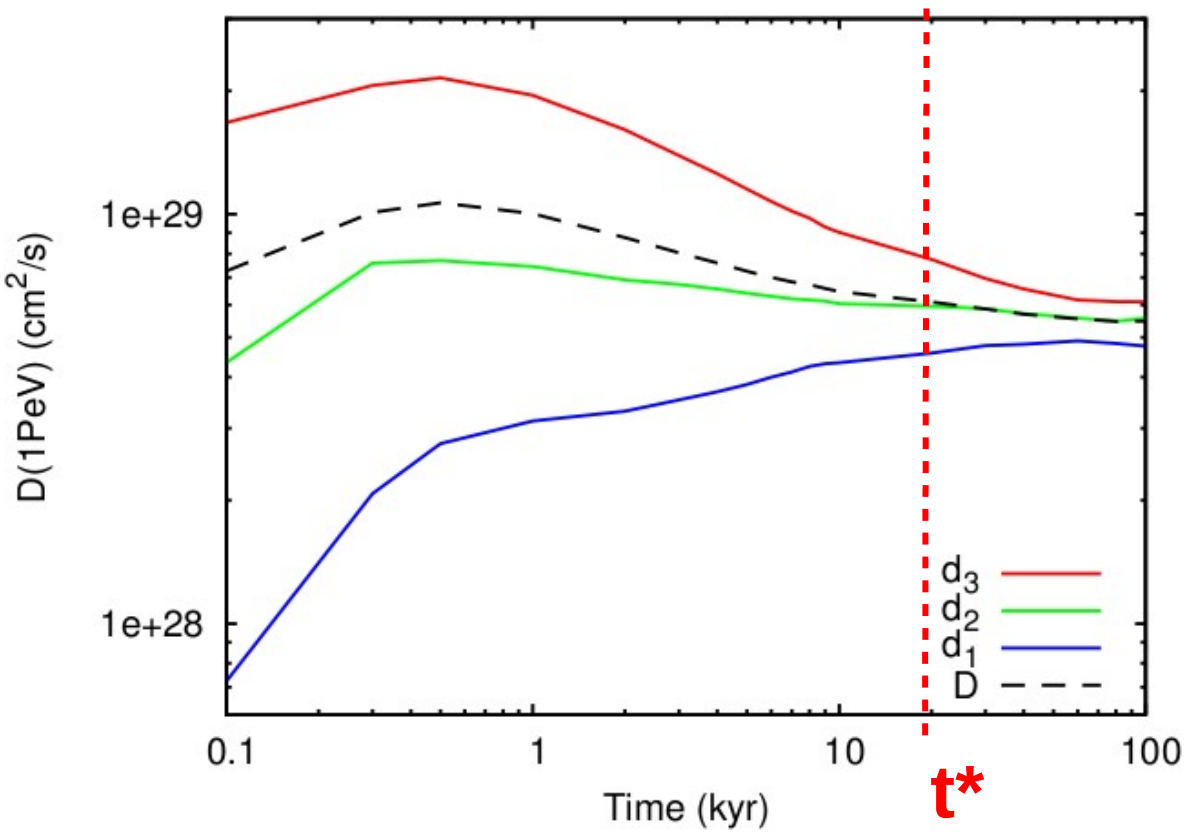
$r \propto t^{1/2}$ behaviour.

Eigenvalues of the diffusion tensor

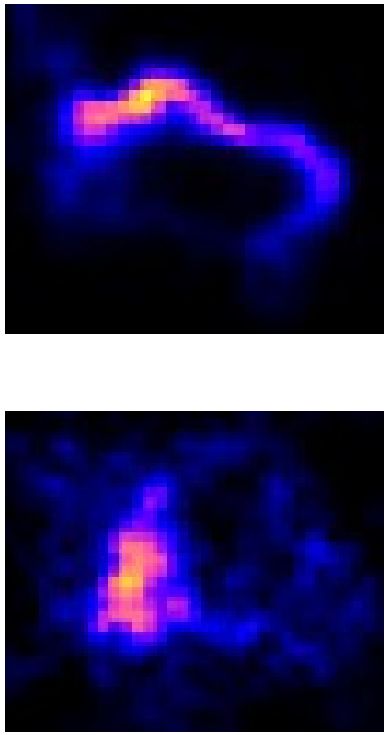
Inject N particles at **x** = **0** in ***one*** field realization

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

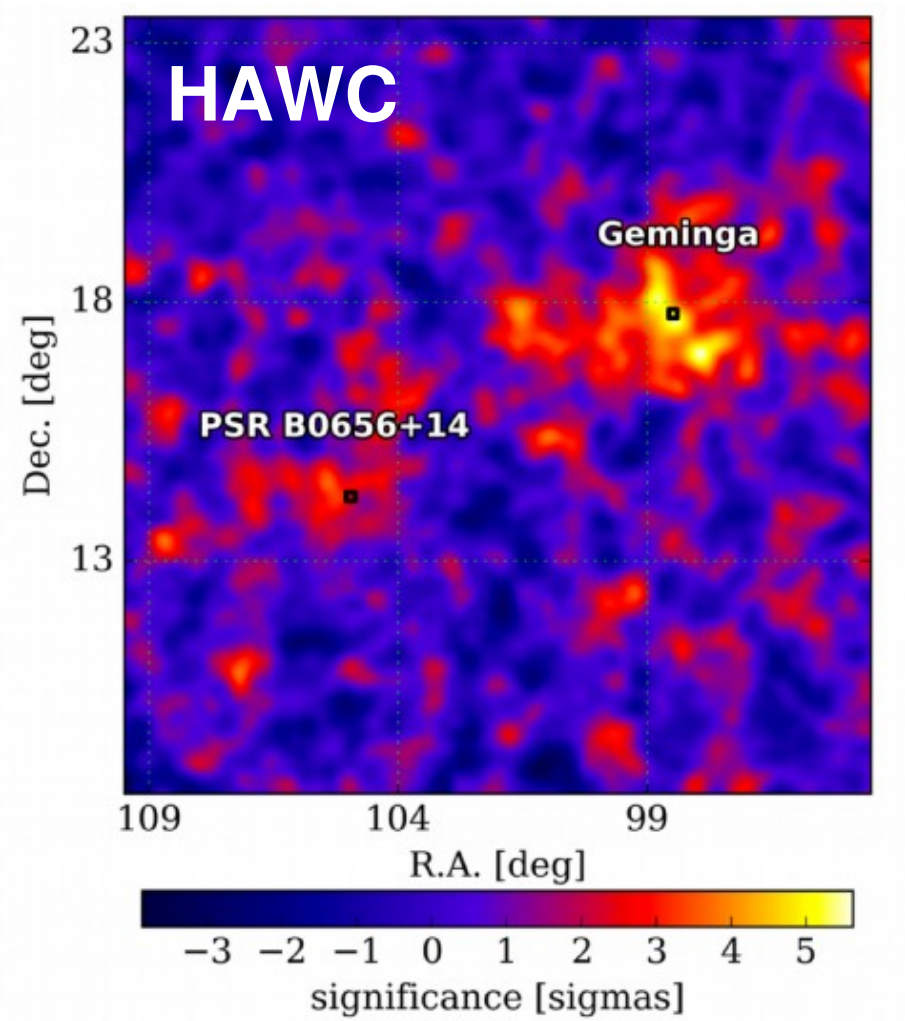
Average over M realizations:

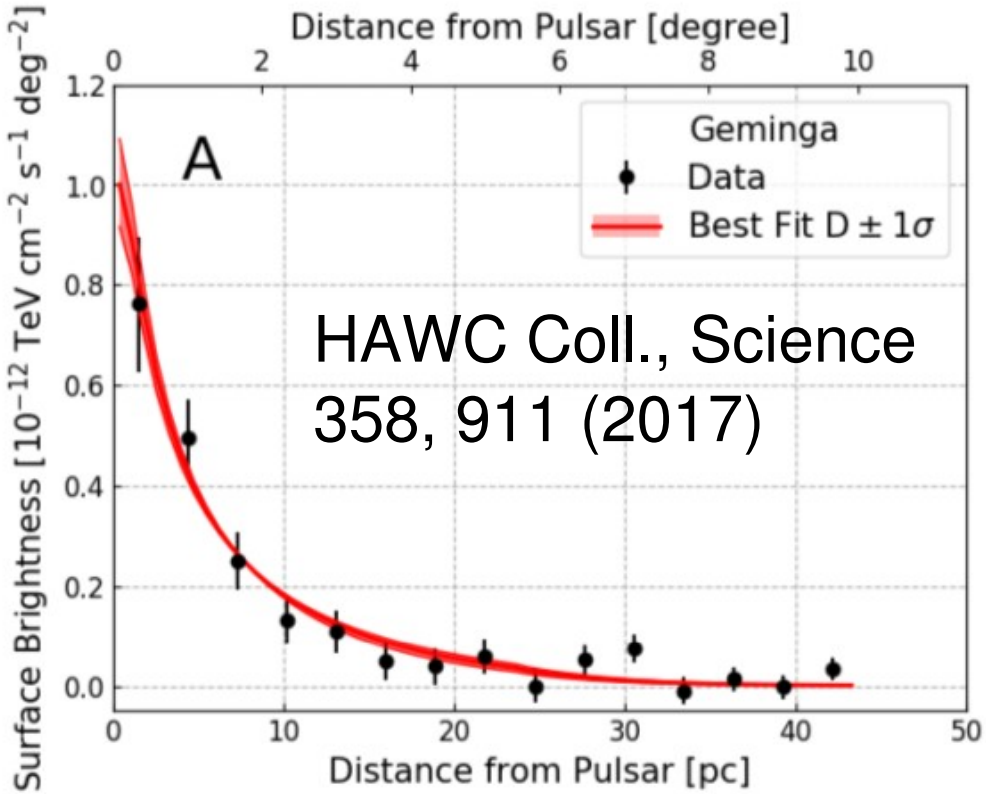


Individual realizations:



HAWC observations of Geminga region





HAWC Coll., Science 358, 911 (2017)

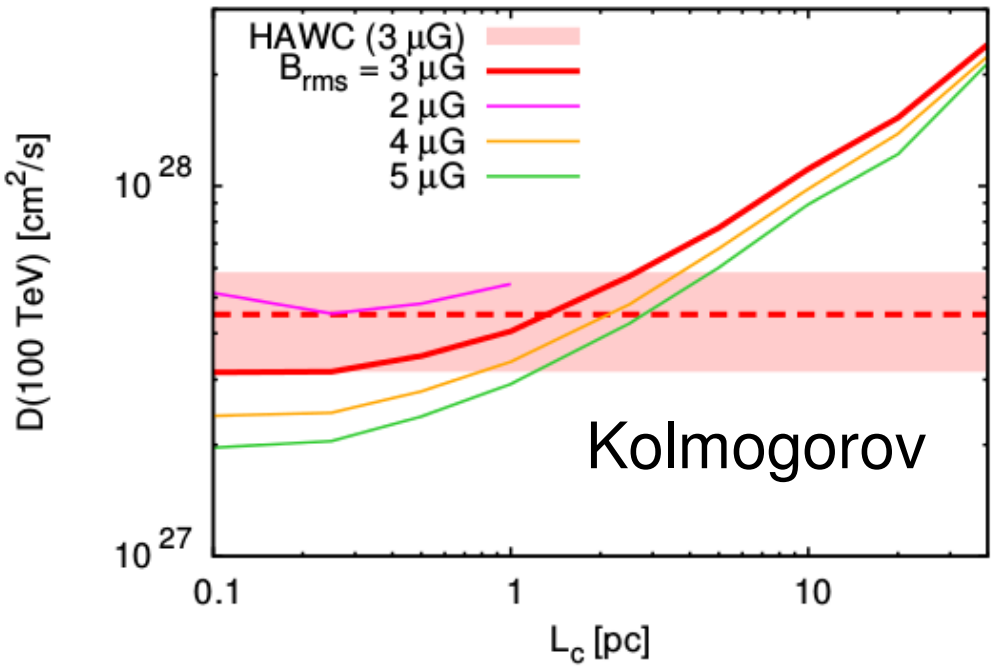
$B = 3\ \mu G$

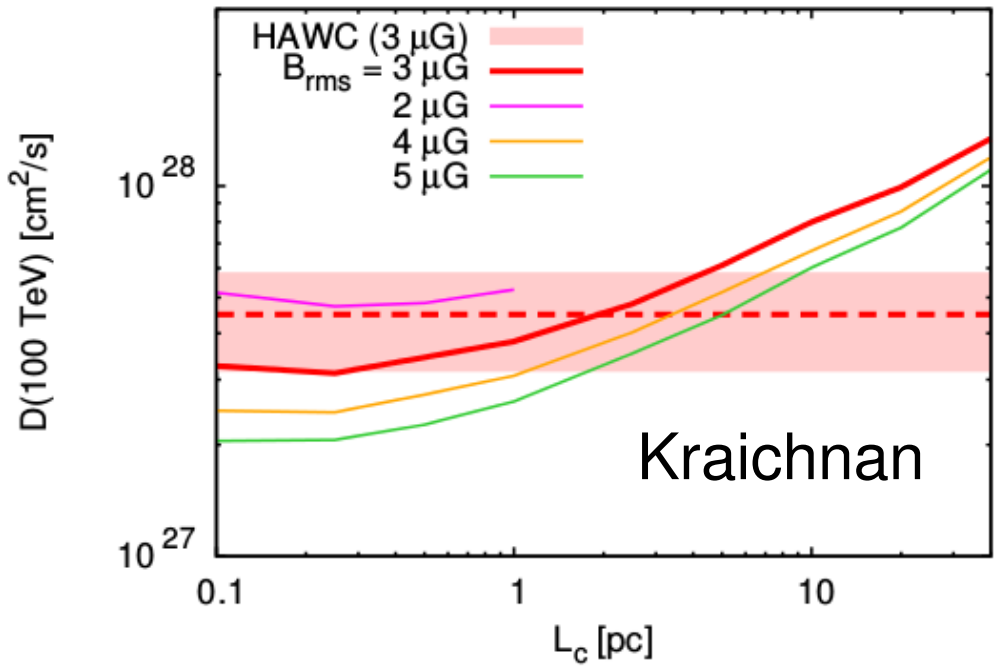
$$D_{100} = (4.5 \pm 1.2) \times 10^{27}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$

at 100TeV. See review talk on July, 30.

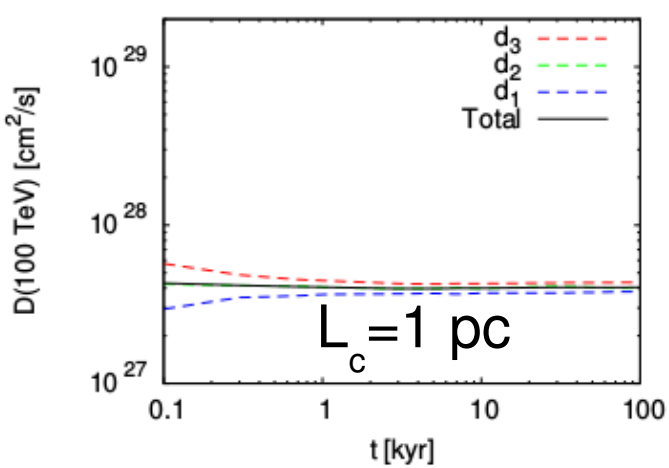
If emission ~ symmetric: Can already put <u>upper limits</u> on the <u>coherence length</u> of the turbulence

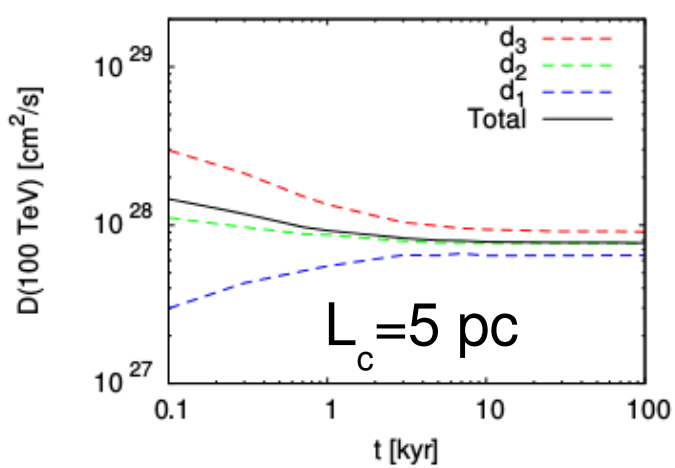
100 TeV protons

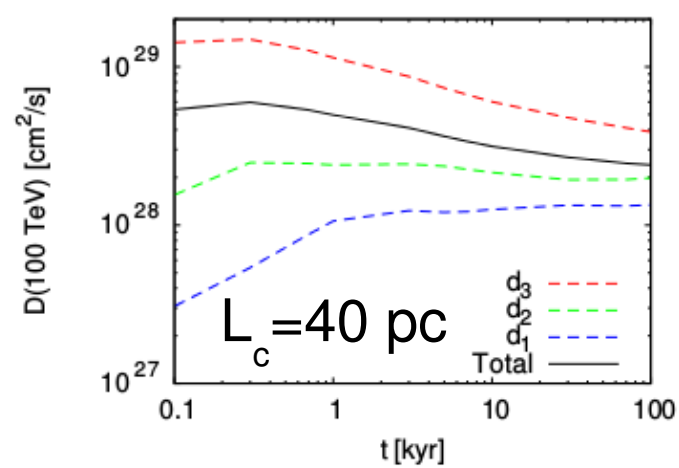




Eigenvalues (Kolmogorov spectrum, B_{rms}=3 μG):







Simulations

→ Inject 5000 electrons (40 – 500 TeV) :

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

→ Propagate in 3D realizations of B turbulence :

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

→ Synchrotron + IC losses (/CMB) :

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

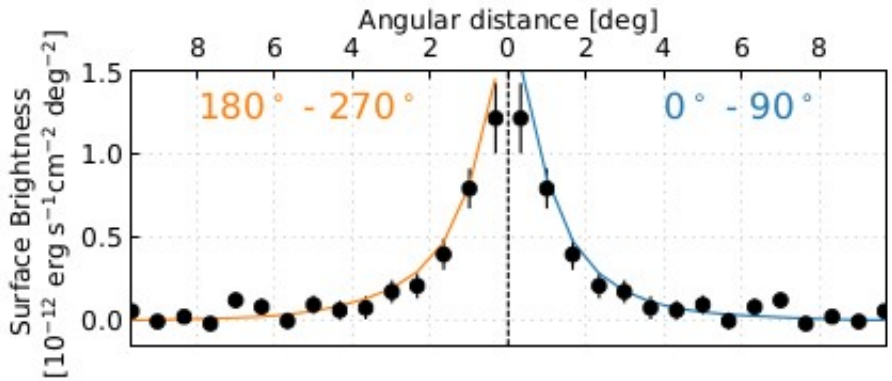
→ Calculate gamma-ray emission : IC on CMB photons.
(full Klein-Nishina treatment of the cross section)

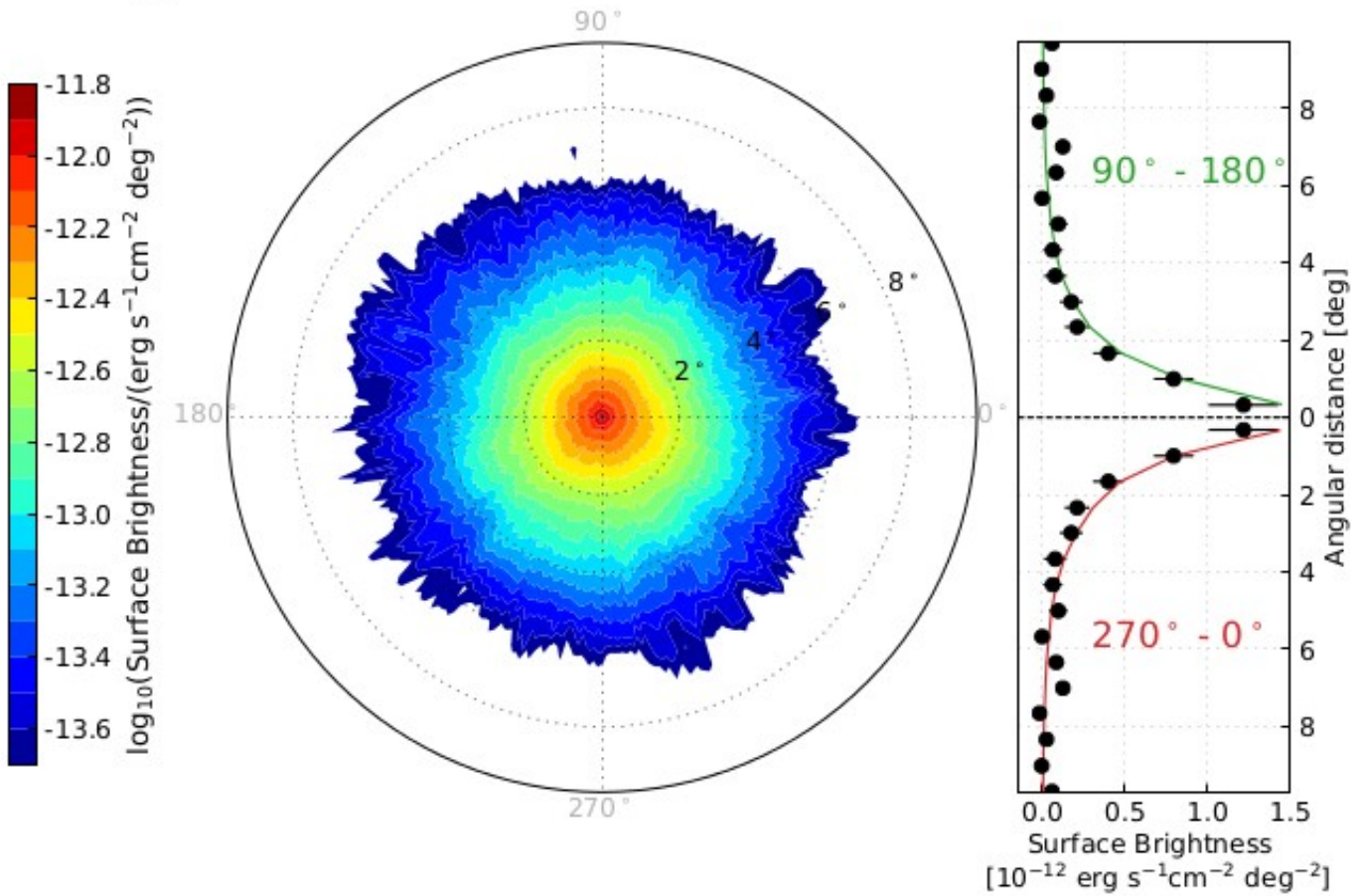
Predicted γ-ray surface brightness

Kolmogorov

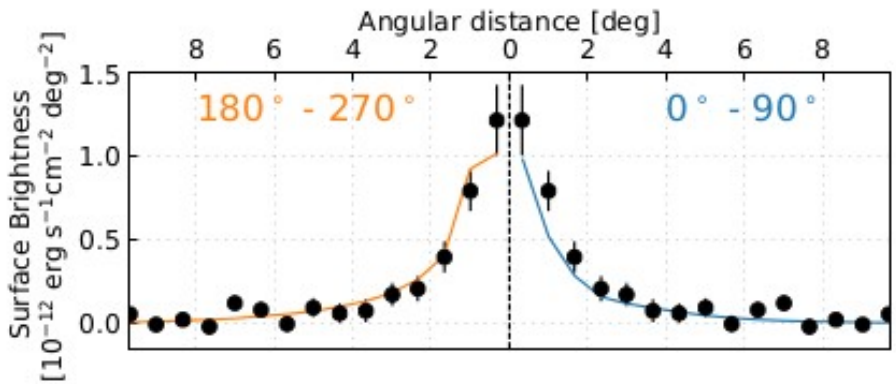
B_{rms}=3 μG

L_c = 0.25 pc





Predicted γ-ray surface brightness

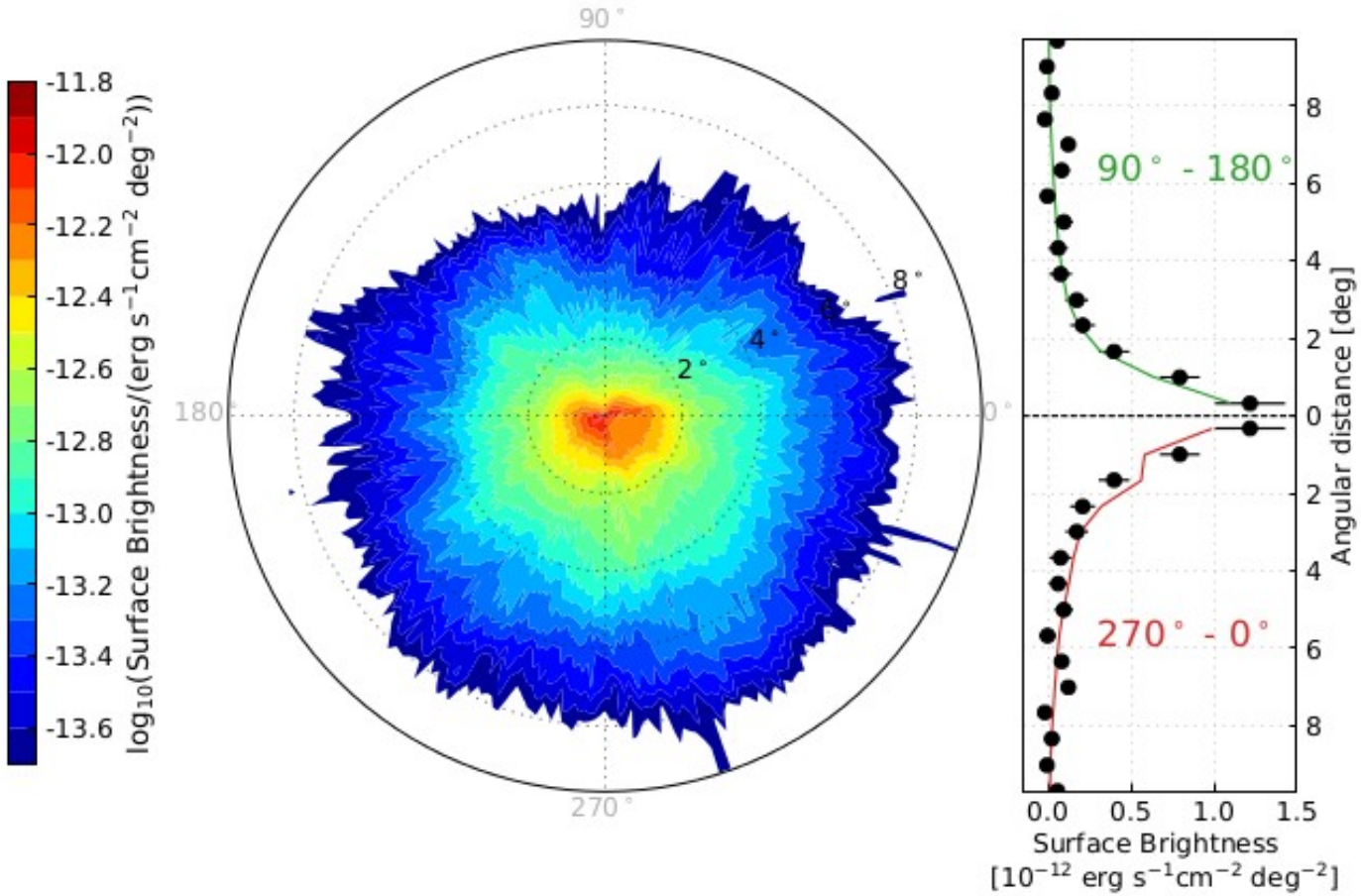


OK

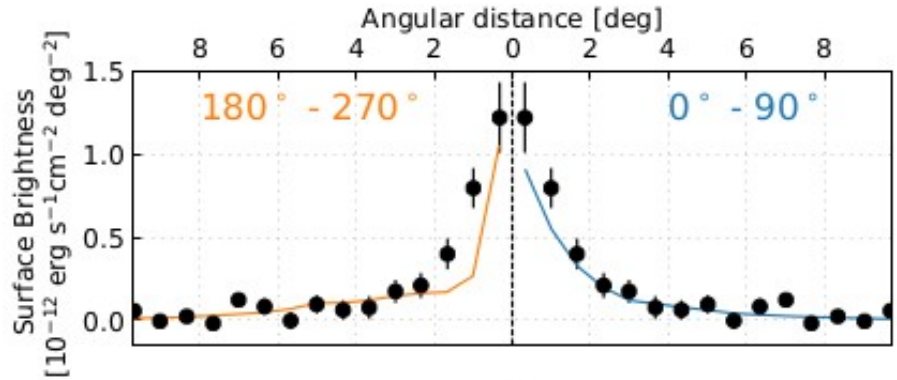
Kolmogorov

B_{rms}=3 μG

L_c = 5 pc



Predicted γ-ray surface brightness

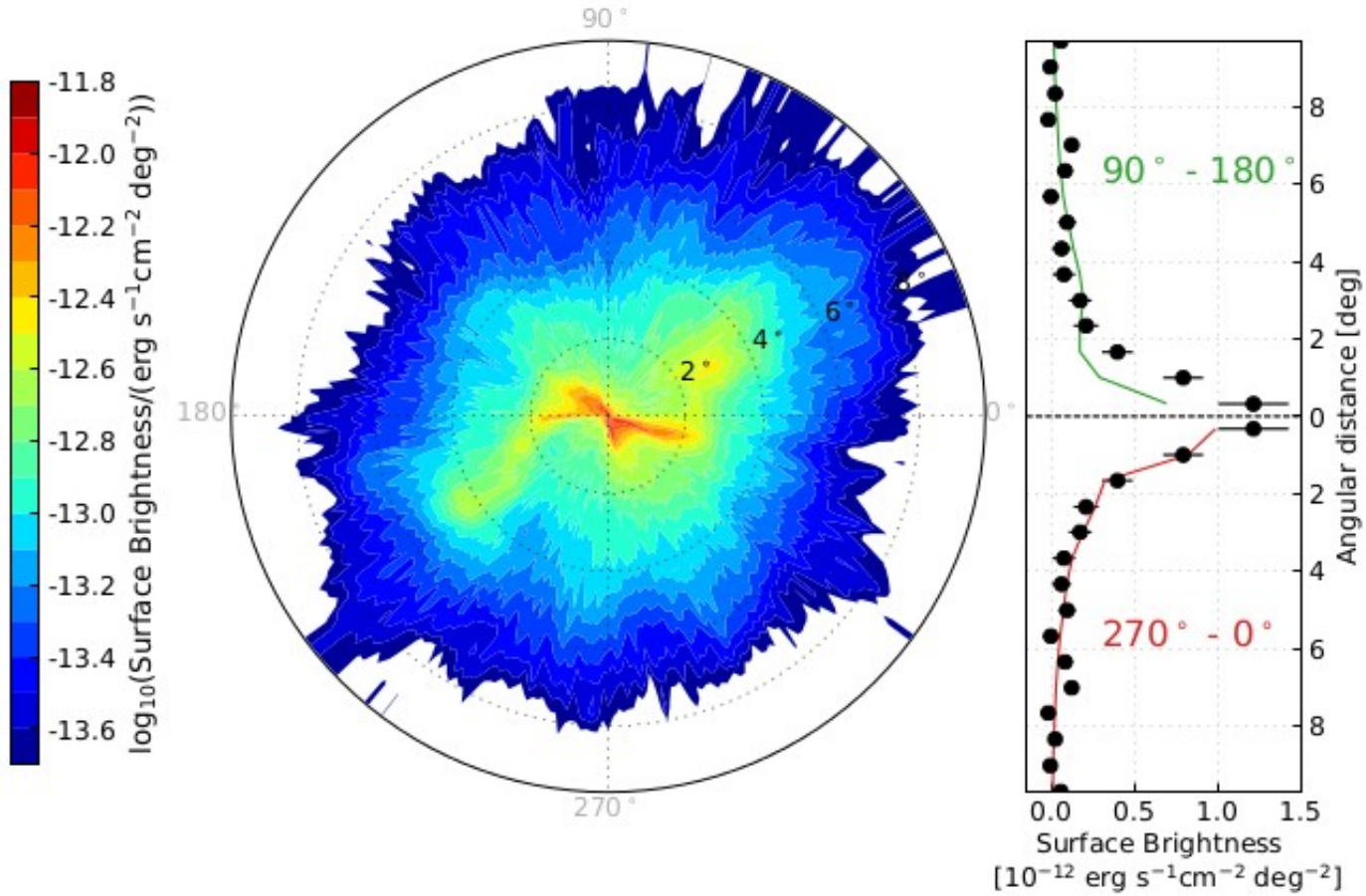


PERHAPS STILL MARGINALLY COMPATIBLE WITH THE DATA?

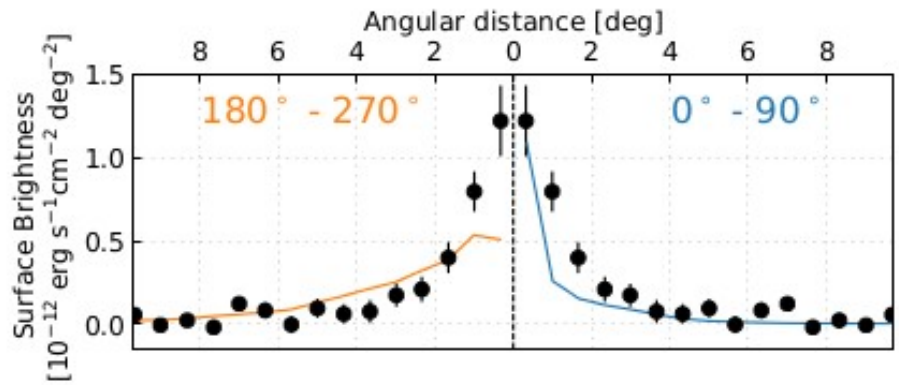
Kolmogorov

B_{rms}=3 μG

L_c = 10 pc



Predicted γ-ray surface brightness

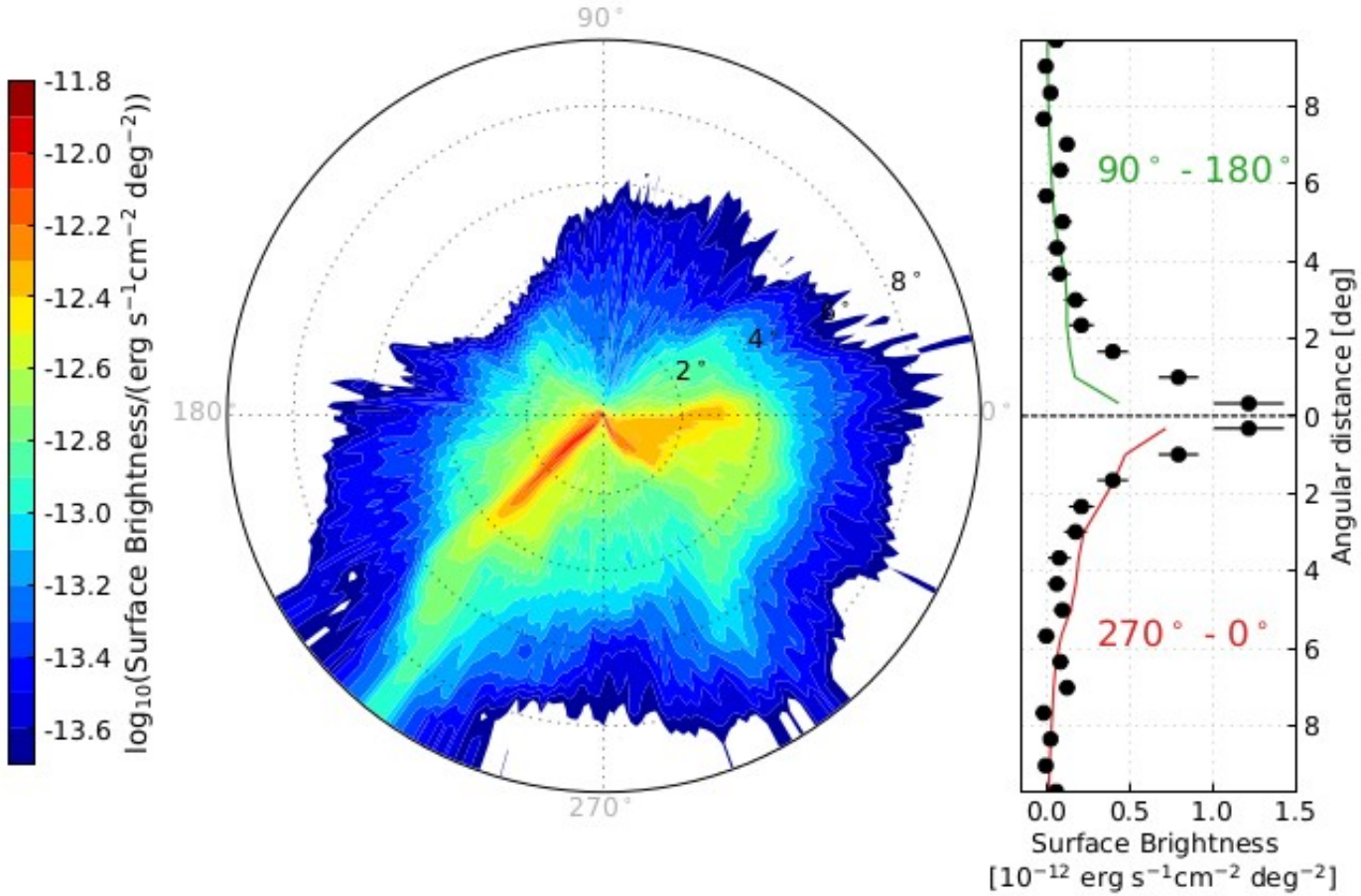


INCOMPATIBLE WITH THE DATA

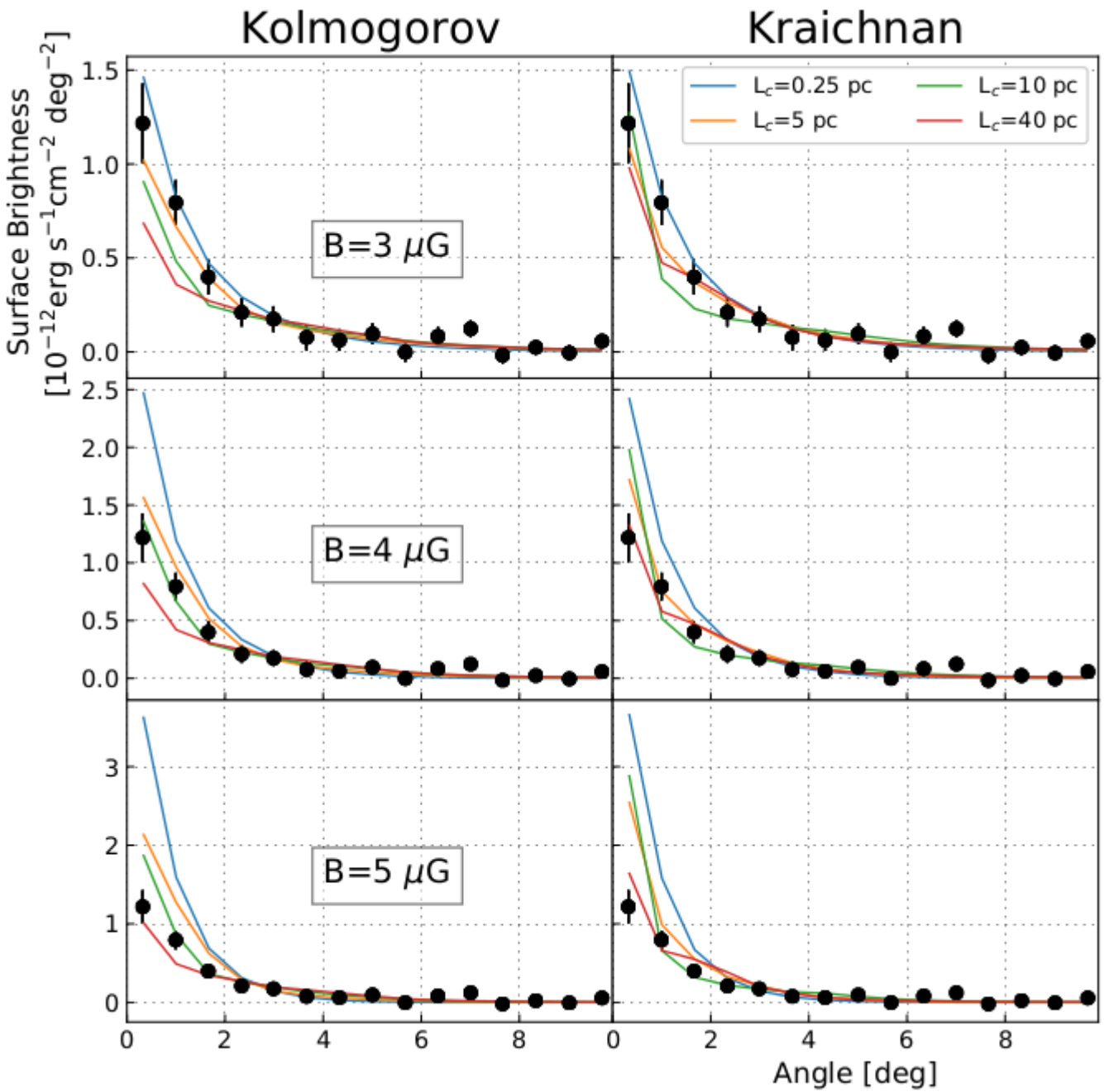
Kolmogorov

B_{rms}=3 μG

L_c = 40 pc

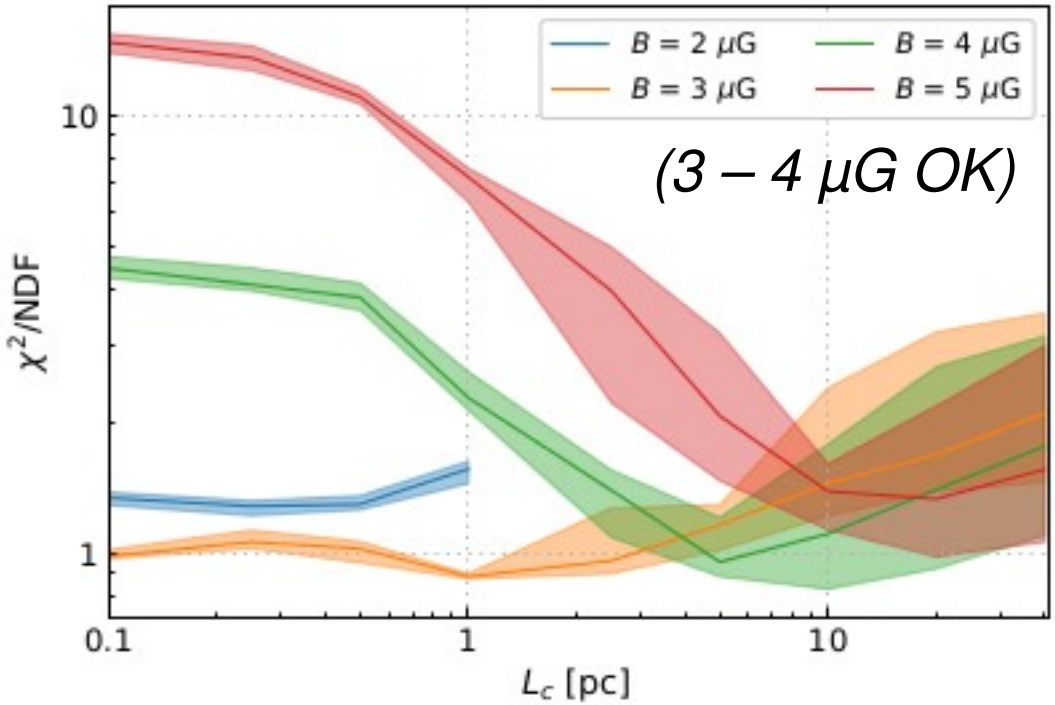


Surface brightness vs dist. to Geminga

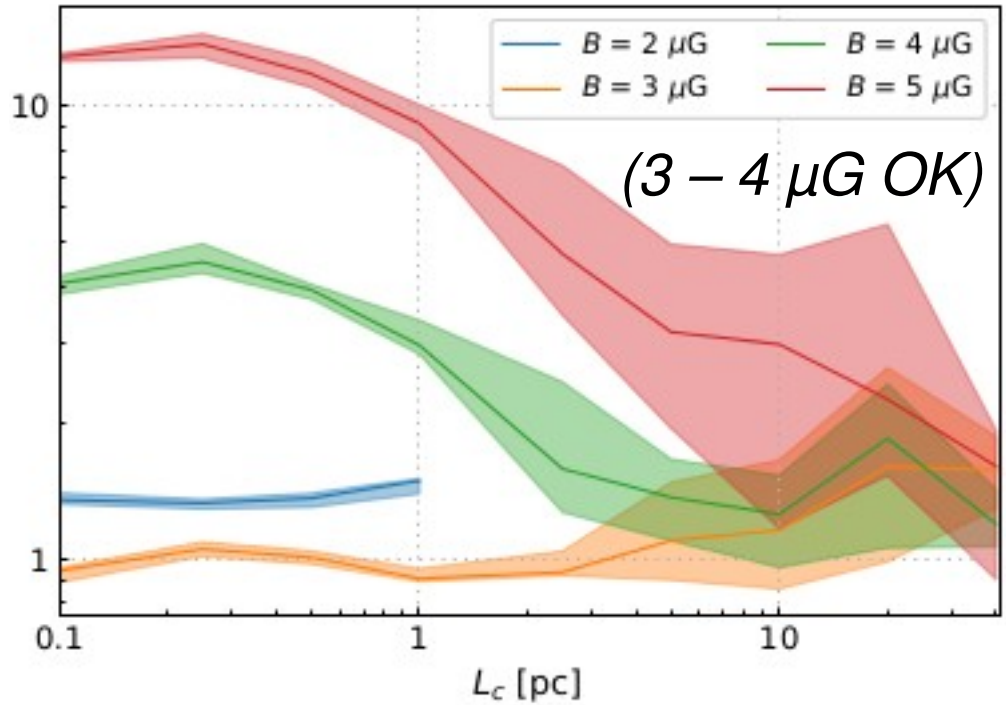


χ^2/ndf as a function of L_c

Kolmogorov



Kraichnan



Kolmogorov	2 μG	3 μG	4 μG	5 μG
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

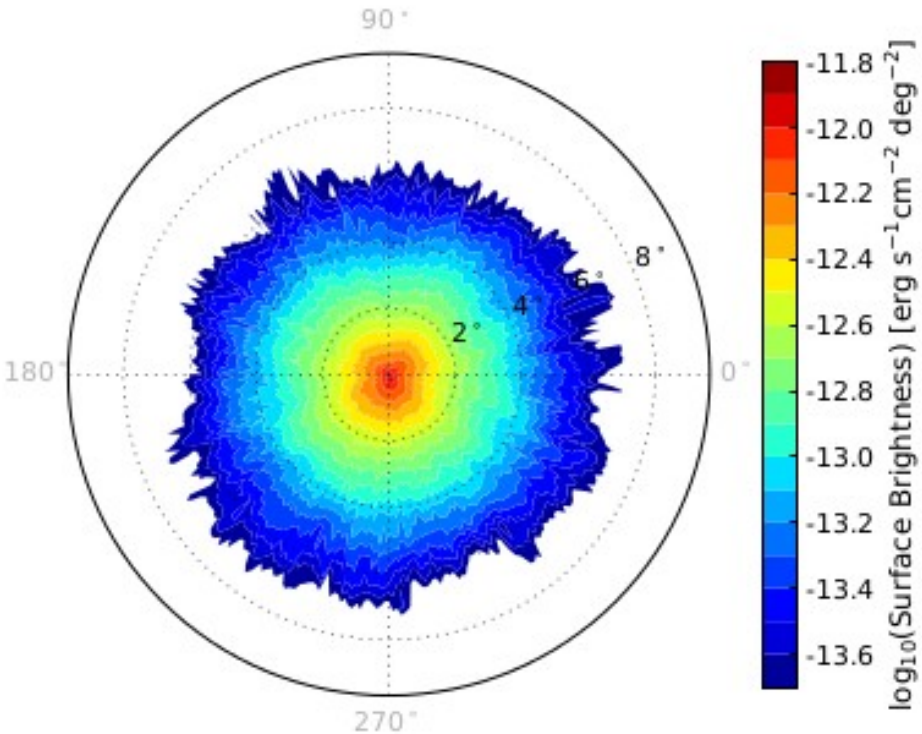
Kraichnan	2 μG	3 μG	4 μG	5 μG
0.1 pc	20.3/15	14.1/15	61.0/15	193/15
0.25 pc	20.0/15	15.8/15	67.9/15	205/15
0.5 pc	20.5/15	15.1/15	59.0/15	177/15
1 pc	22.4/15	13.6/15	44.5/15	137/15
2.5 pc	N/A	14.1/15	23.8/15	70.8/15
5 pc	N/A	16.5/15	20.5/15	47.6/15
10 pc	N/A	17.4/15	18.8/15	44.7/15
20 pc	N/A	24.0/15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

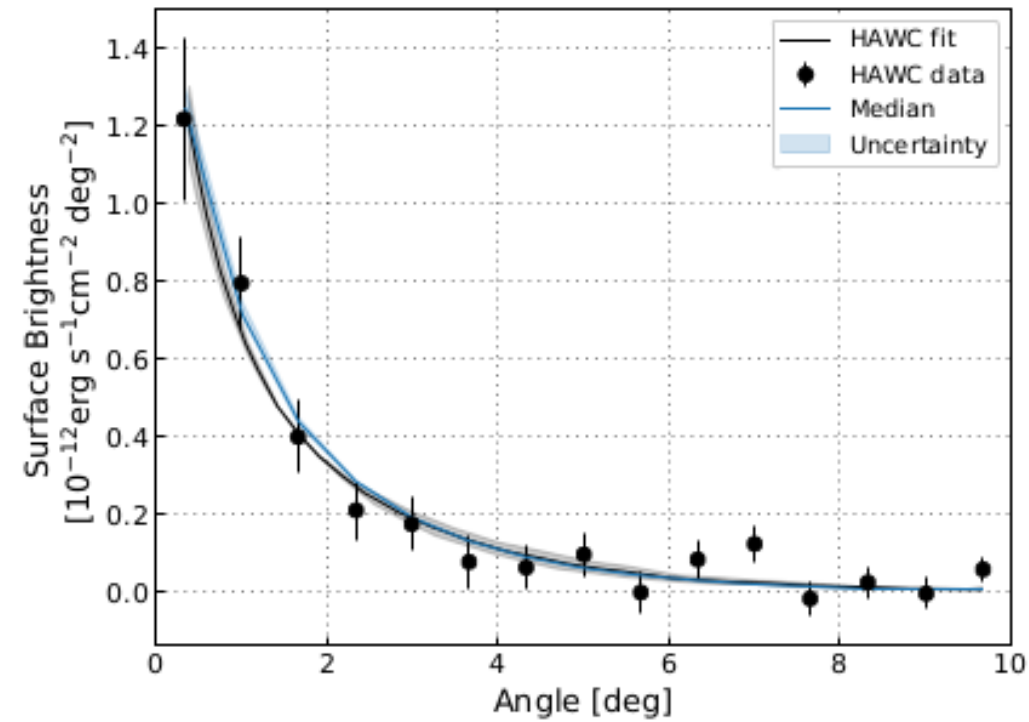
Our best fit to HAWC measurements

Kolmogorov (Kraichnan)

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

$L_c = 1$ pc





Radio observations: L_c in the spiral arms of our Galaxy is equal to only a few pc, which is very close to our best fit value. Cf. Haverkorn et al., ApJ **680**, 362 (2008): L_{max} (= $5L_c$ for Kolmogorov turbulence) is ≤ 20 pc.

Conclusions and perspectives

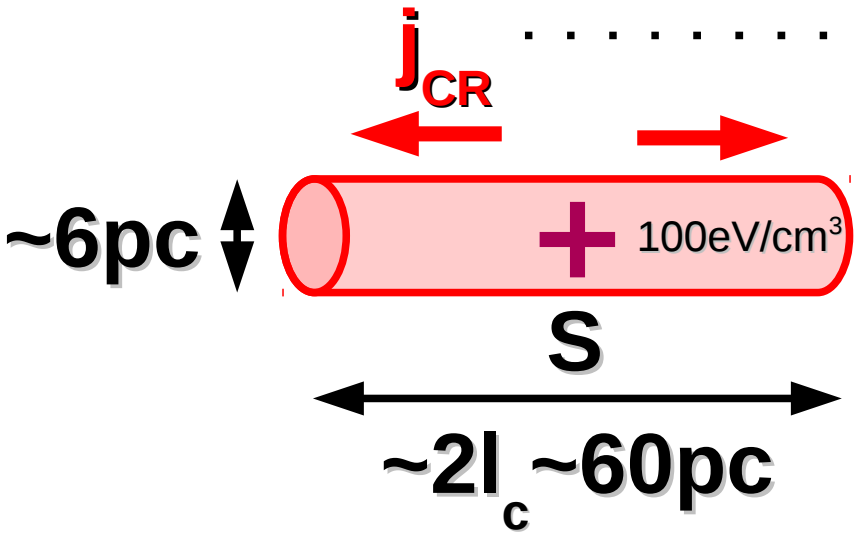
- "**Anisotropic" propagation** of CRs in the ISM must be taken into account on scales <~ several L_c.

- **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.

EXTRA SLIDES

CR-driven instabilities



$$\sim U_{\rm CR} e D/(E l_{\rm c})$$

$$5\Gamma_{\rm BNRH}^{-1} \approx 10\sqrt{\rho_{\rm ISM}/\mu_0}\, E^{2/3} l_{\rm c}/(U_{\rm CR} e D_0)$$
$$\approx 1.4,\ 3.1,\ 14 \text{ and } 67\,\text{kyr}$$
$$3,\ 10,\ 100 \text{ and } 1000\,\text{TeV CRs}$$

$$t_{\rm c} \sim l_{\rm c}^2/D$$

If e.g. 1 % neutrals
→ damp. ~ 1kyr

$$E \gtrsim 0.1\sqrt{\mu_0/\rho_{\rm ISM}}\, U_{\rm CR} e l_{\rm c} \approx 40\,\text{TeV}$$

NB : The CR pressure does not widen the filaments

$$\rho_{\rm ISM} du/dt = |\nabla P_{\rm CR}| \sim 100\,\text{eV}\cdot\text{cm}^{-3}/3\,\text{pc}$$

$$t_{10k}^2 du/dt \approx 0.3\,\text{pc}$$

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Filamentary Diffusion of Cosmic Rays on Small Scales

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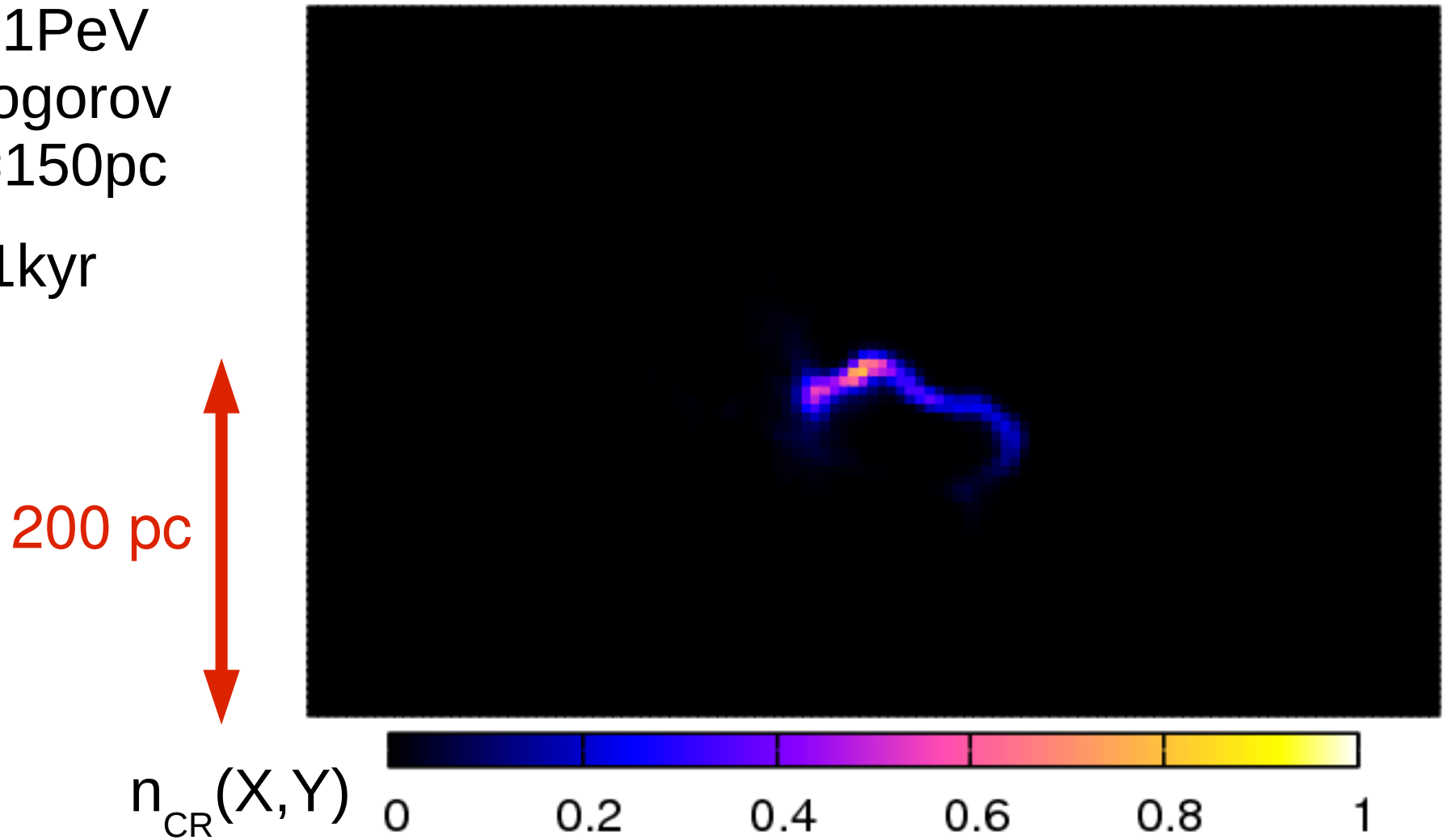
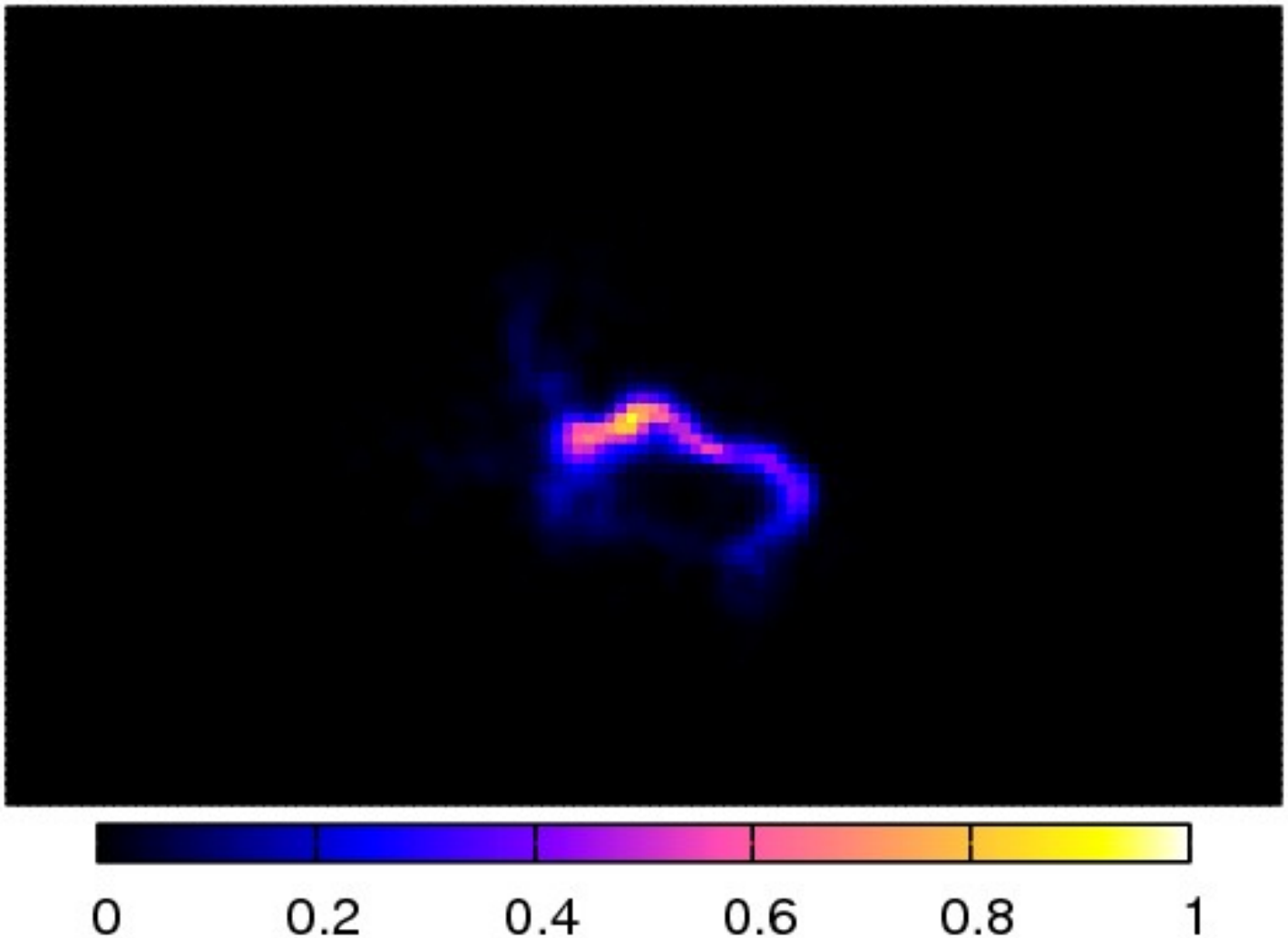
+ GG et al., Phys. Rev. D **88**, 023010 (2013)

E/Z=1PeV
Kolmogorov
L_{max}=150pc
t = 1kyr



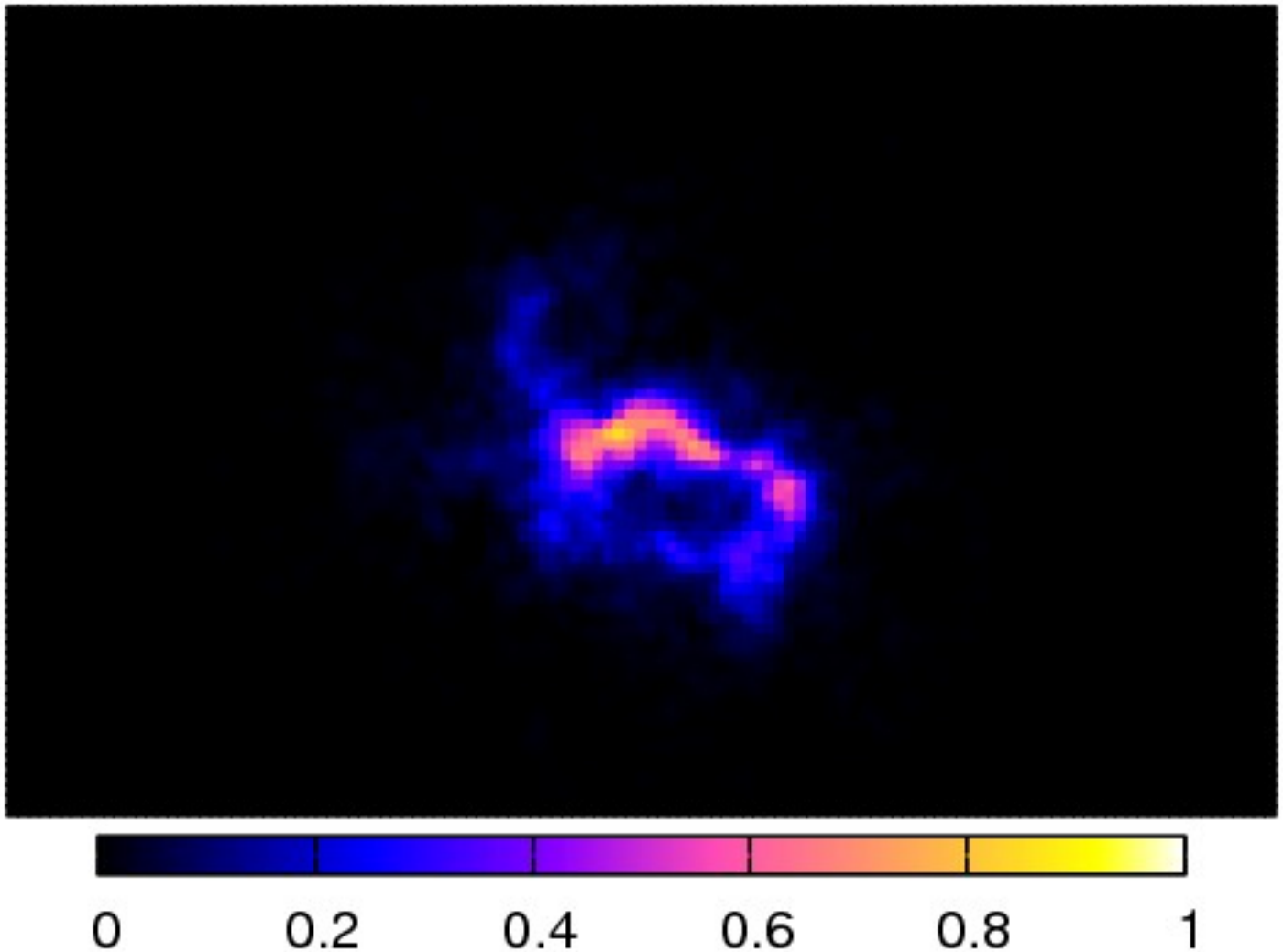
Results of numerical simulations

t = 2kyr



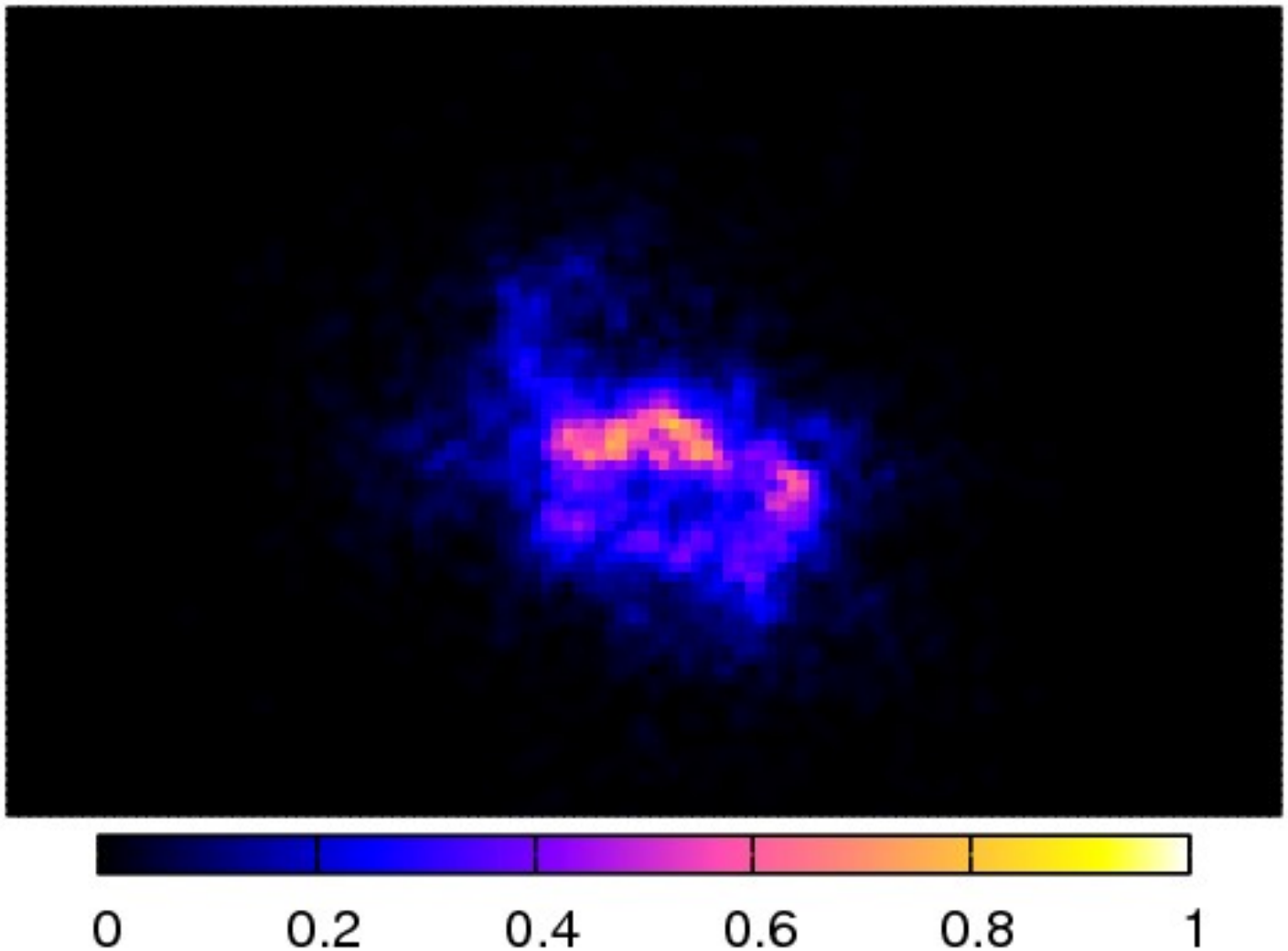
Results of numerical simulations

t = 4kyr



Results of numerical simulations

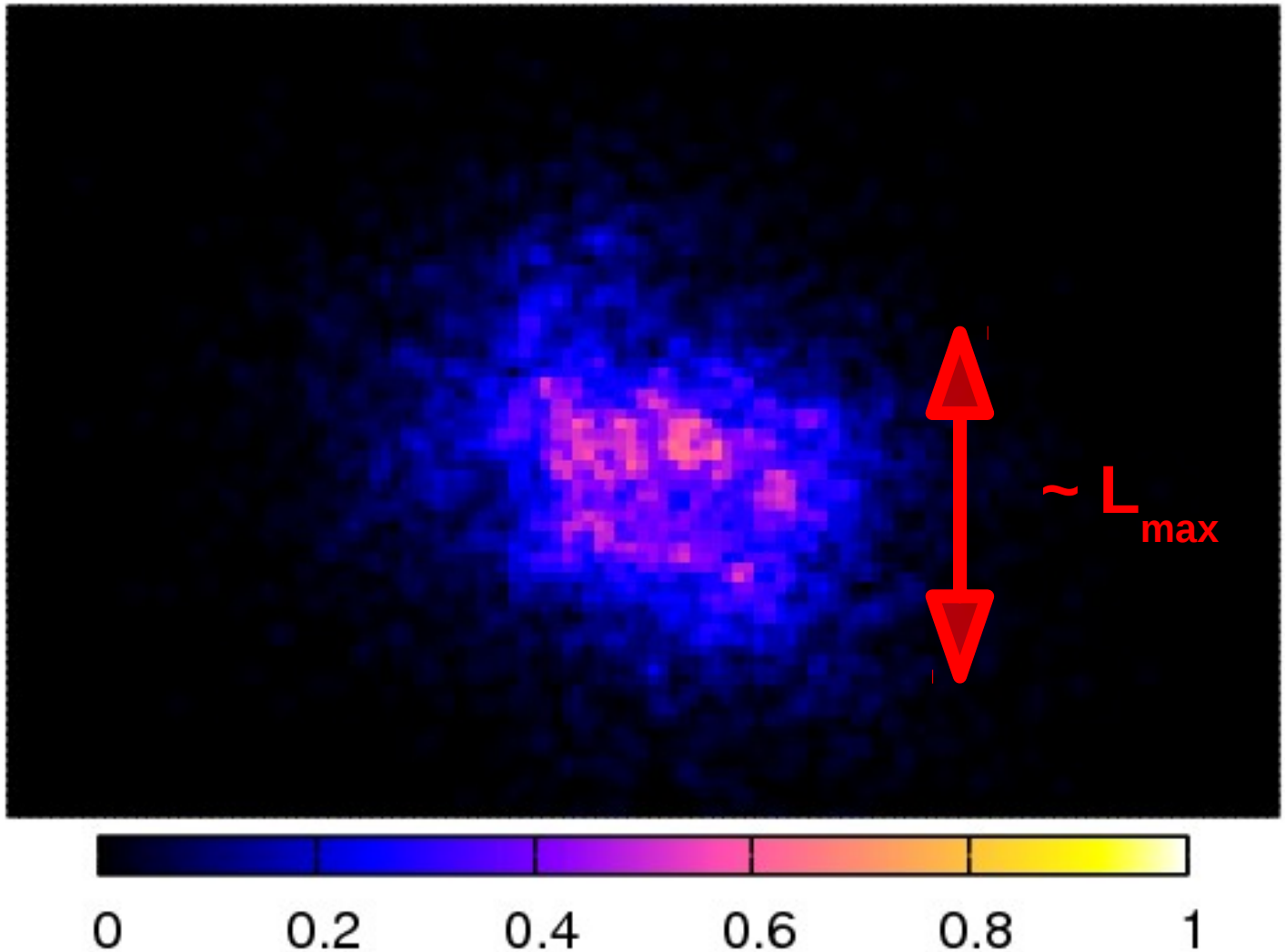
t = 6kyr



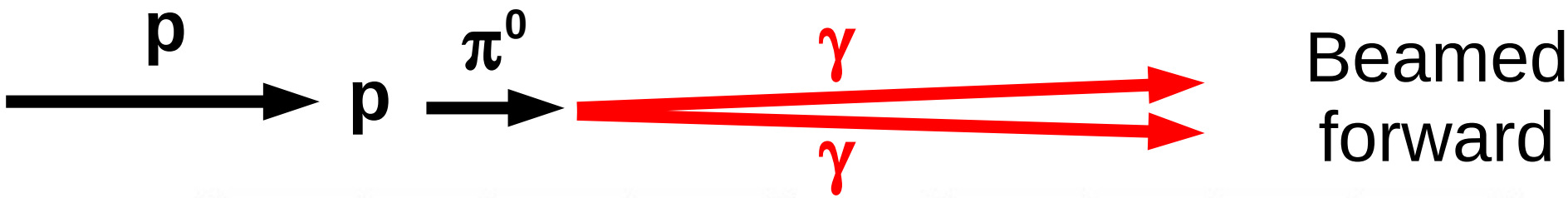
Results of numerical simulations

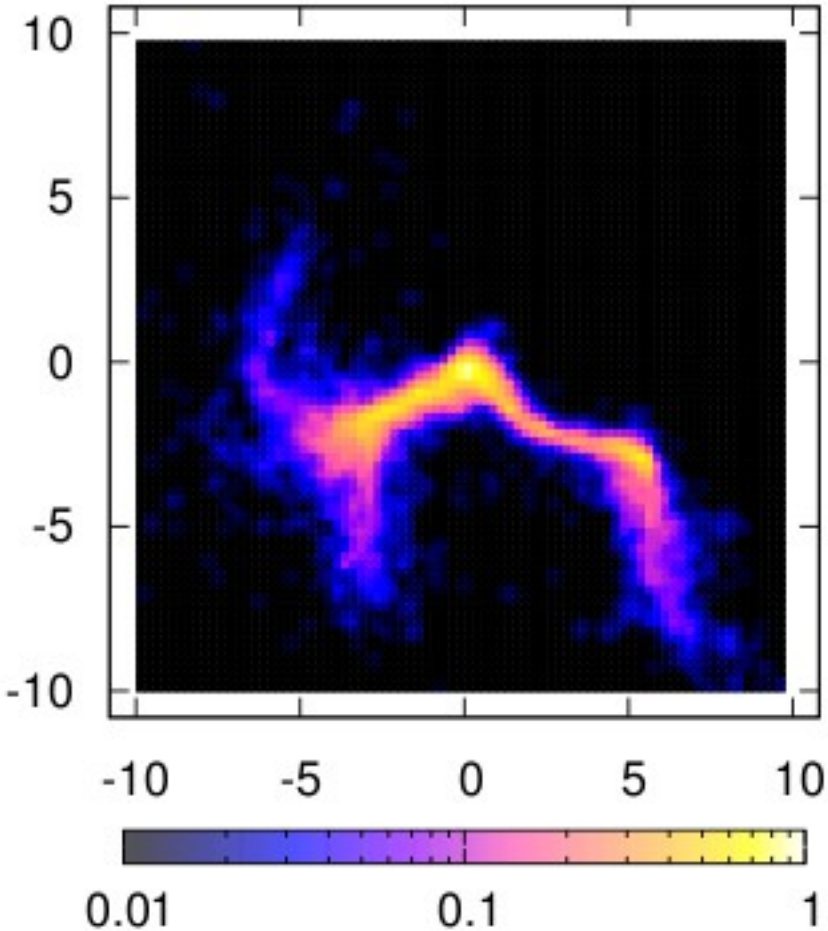
... then starts to tend towards the $r \propto t^{1/2}$ behaviour

t = 10kyr

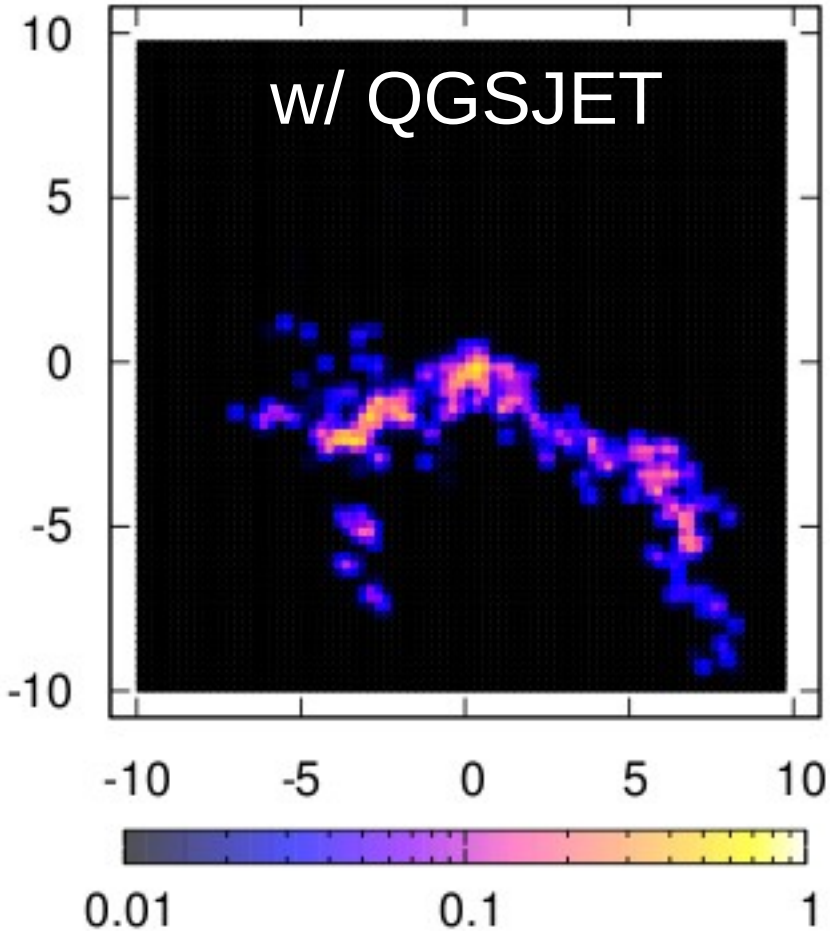


CR map ↔ γ–ray map



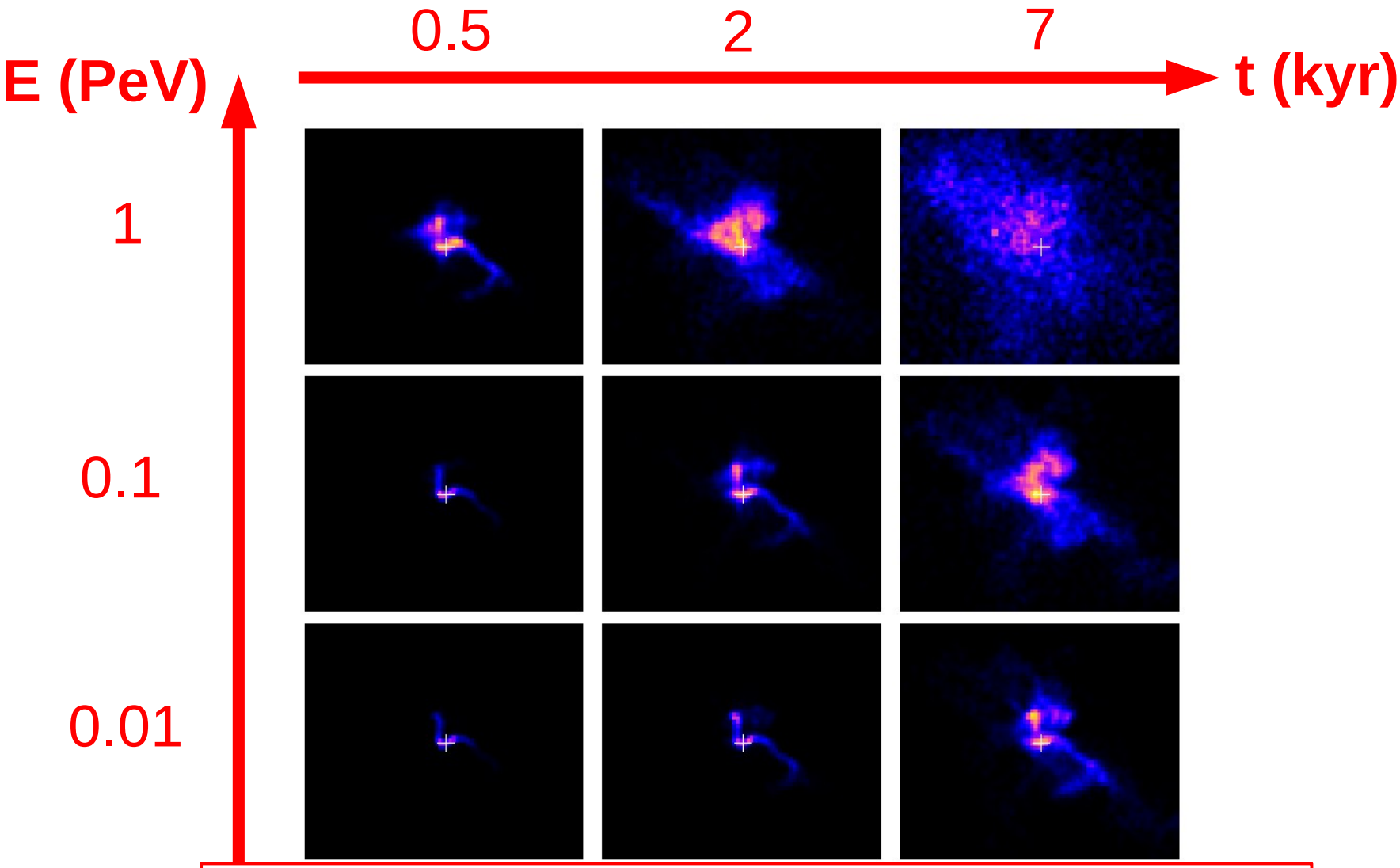


CR column density



γ ray emissivity

Dependence on parameters



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

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