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CR PROPAGATION IN THE GALAXY: INSIGHTS FROM TeV HALOS AND THE DIFFUSE γ-RAY EMISSION

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In collaboration with Yiwei Bao and Samy Kaci

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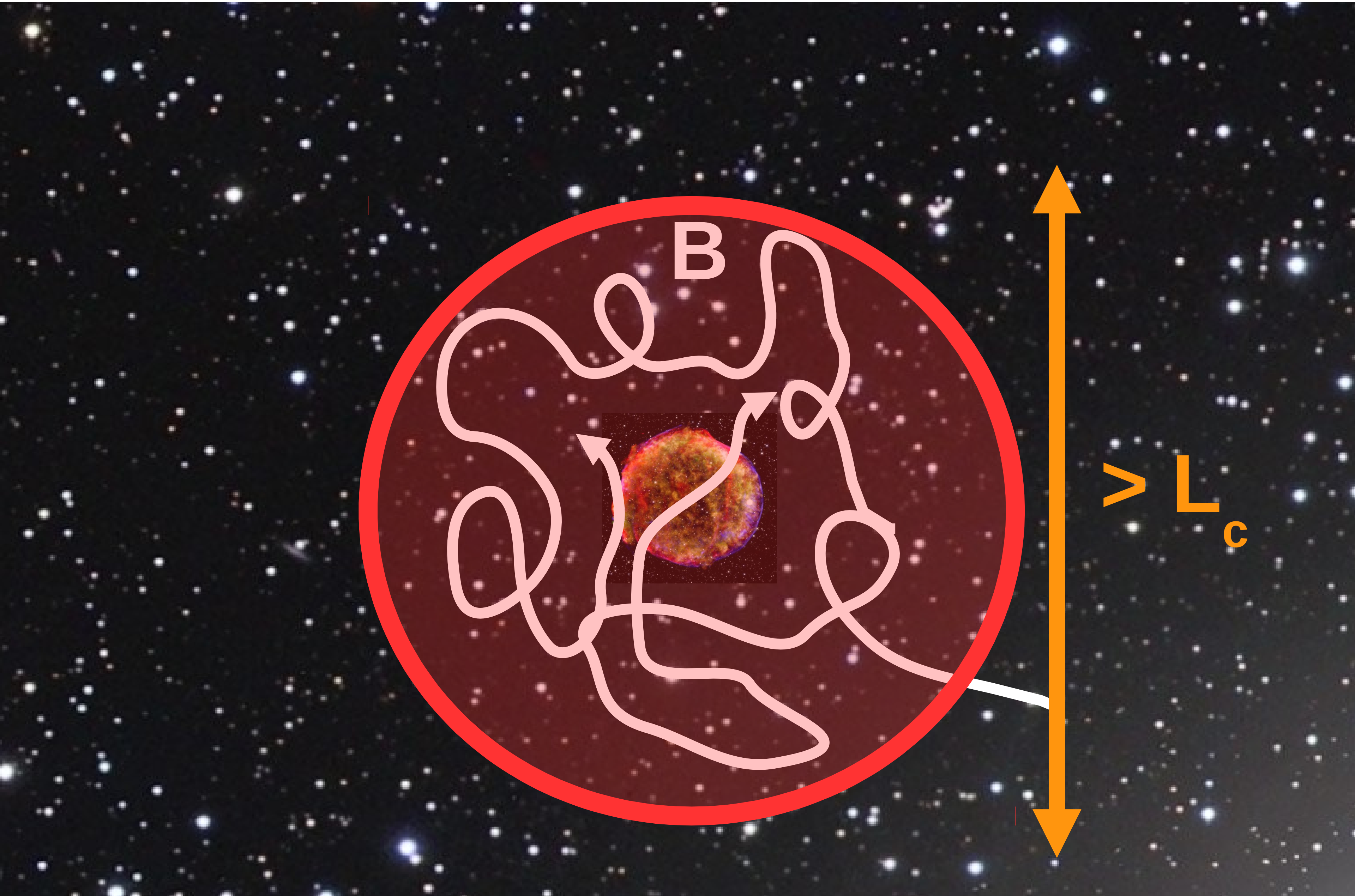
1 – TeV halos as a probe of CR propagation in the ISM

Giacinti et al., A&A 636, A113 (2020),
Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018)

Is CR diffusion (ever) isotropic ?



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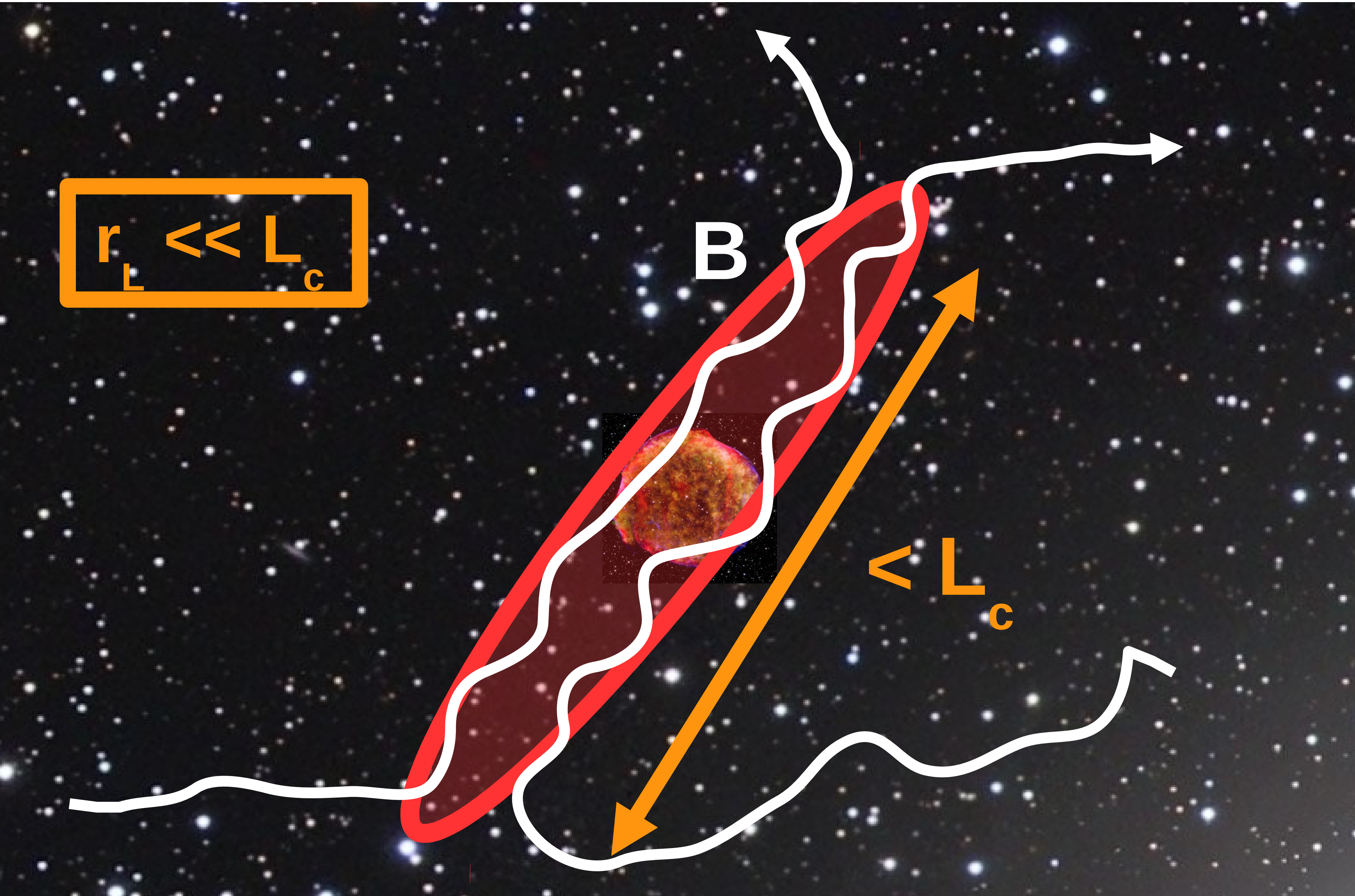
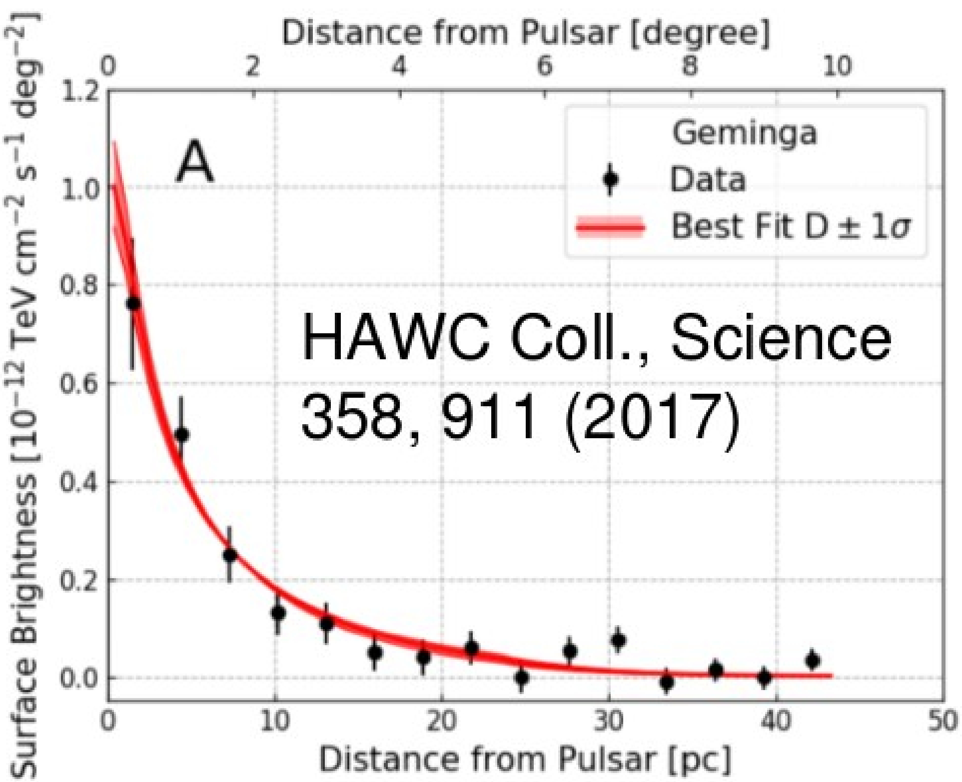


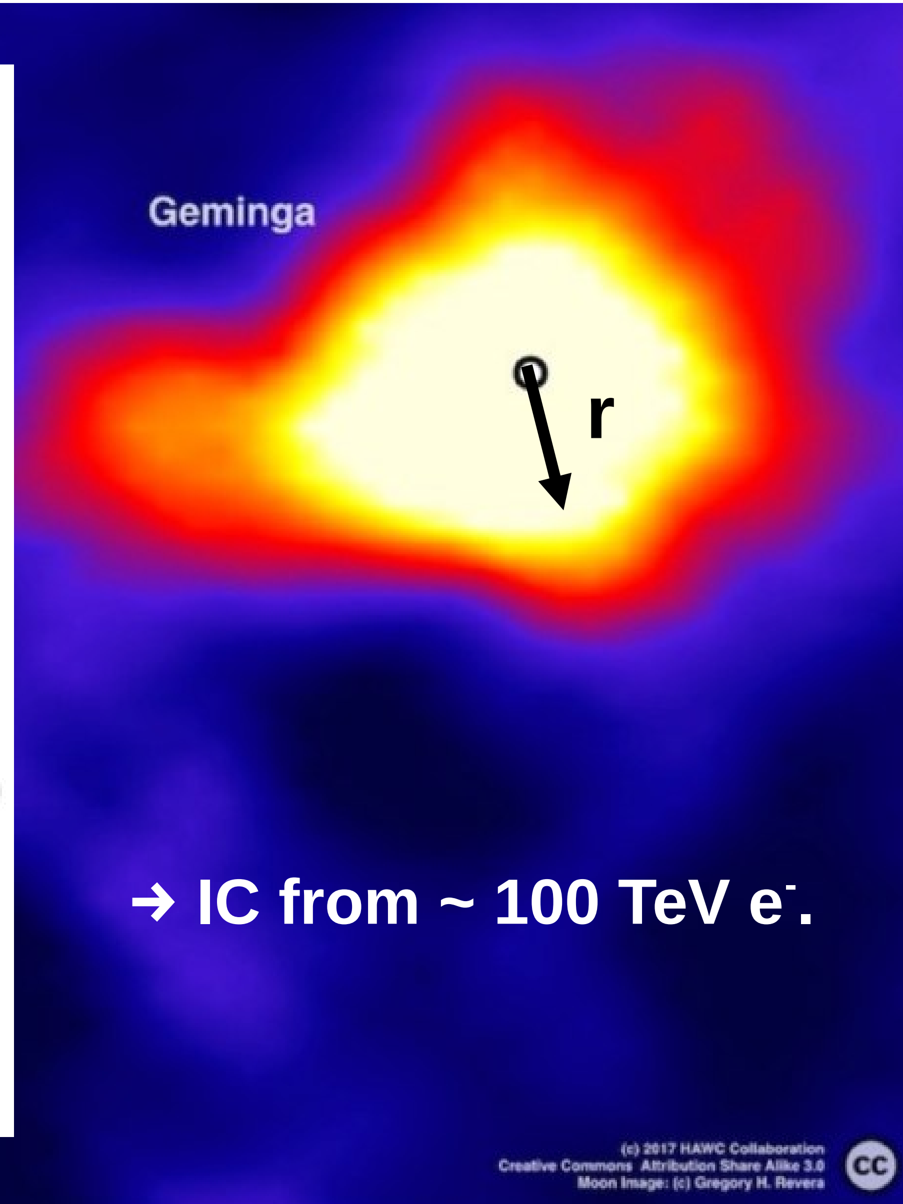
HAWC observ. of Geminga & Monogem



HAWC Coll., Science 358, 911 (2017)

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

at 100TeV.

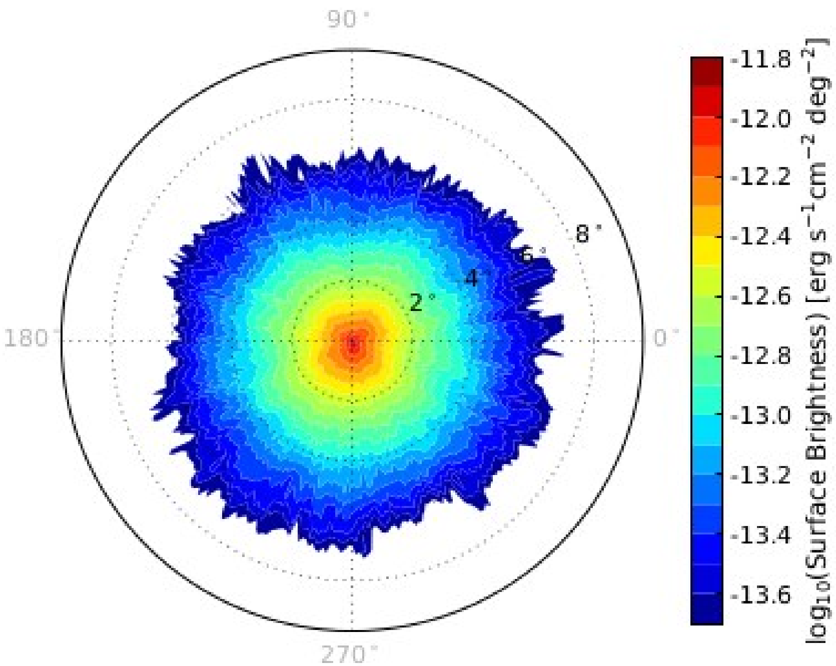


→ IC from ~ 100 TeV e^-.

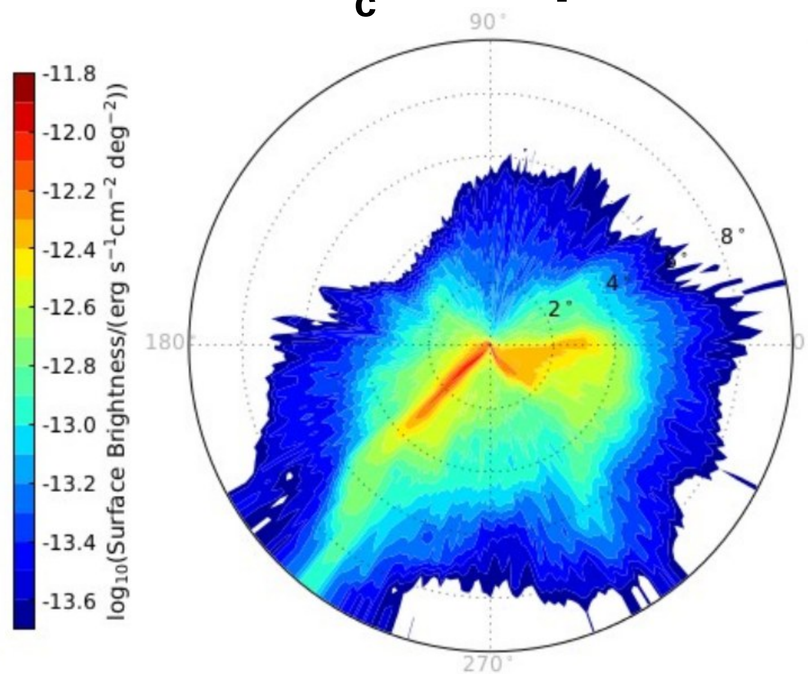
Predicted γ-ray surface brightness

Kolmogorov, B_{rms}=3 μG

L_c = 1 pc (best fit)



L_c = 40 pc



Large coherence lengths (> 10 pc) ruled out (Too asymmetric)

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

"Mirage" sources and large offsets: Asymmetric CR diffusion around sources

Works from Yiwei Bao

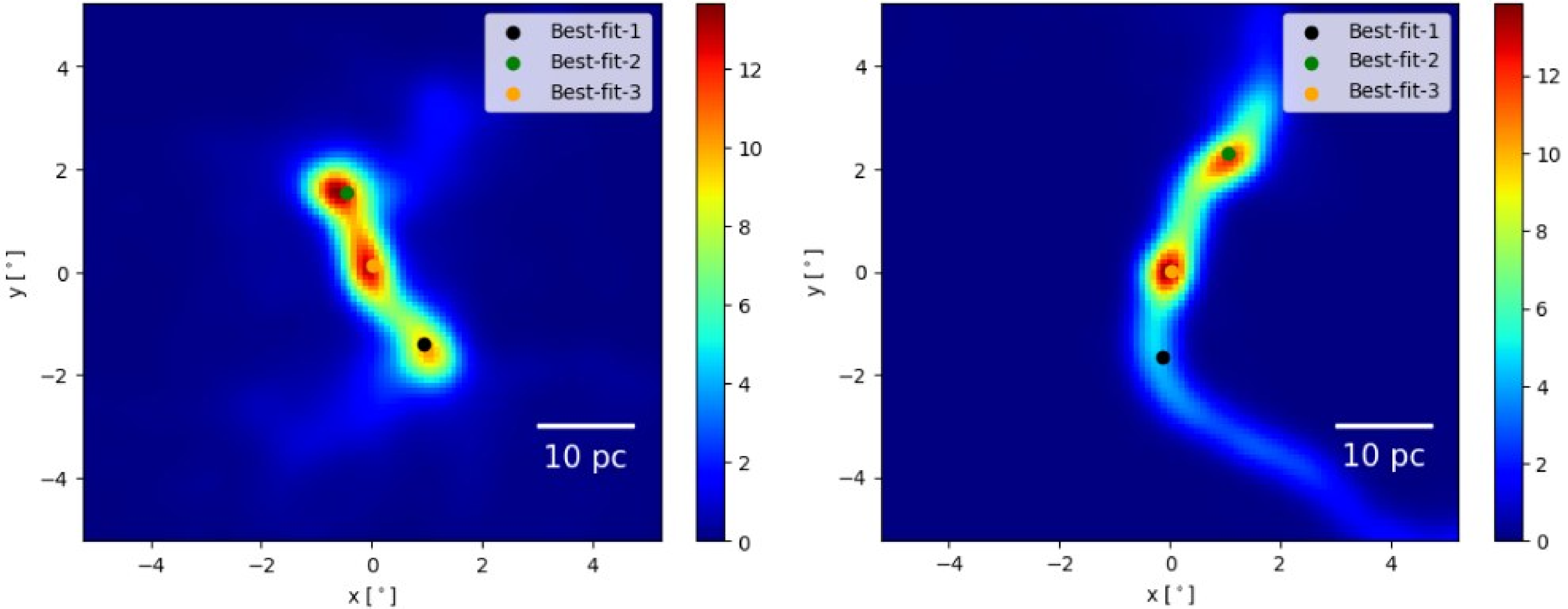
References:

Bao, Giacinti, Liu, Zhang & Chen, arXiv:2407.02478 (Submitted to PRL)

Bao, Liu, Giacinti, Zhang & Chen, arXiv:2407.02829 (Submitted to PRD)

Appearance of additional ("mirage") sources:

They may appear around astrophysical sources.

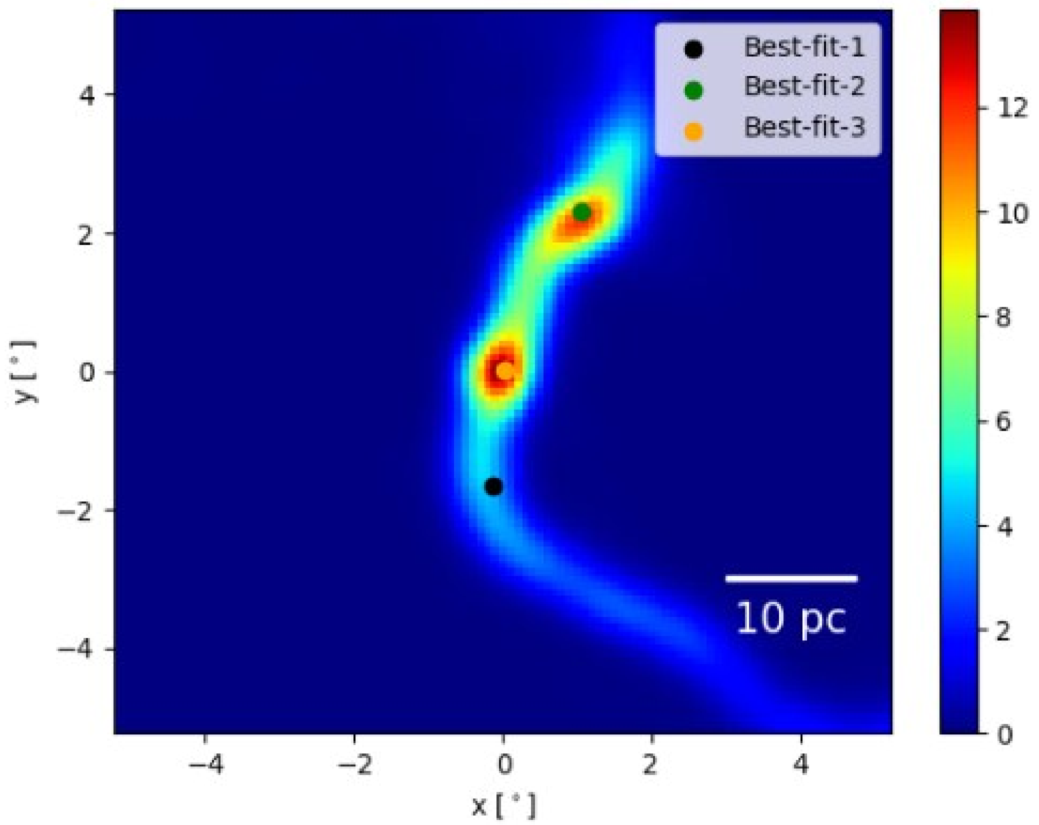


L_c = 40pc ; B_{turb} = 3 μG ; B_{reg} = 0 μG; Kolmogorov turbulence ; (8192 particles)

Appearance of additional ("mirage") sources:

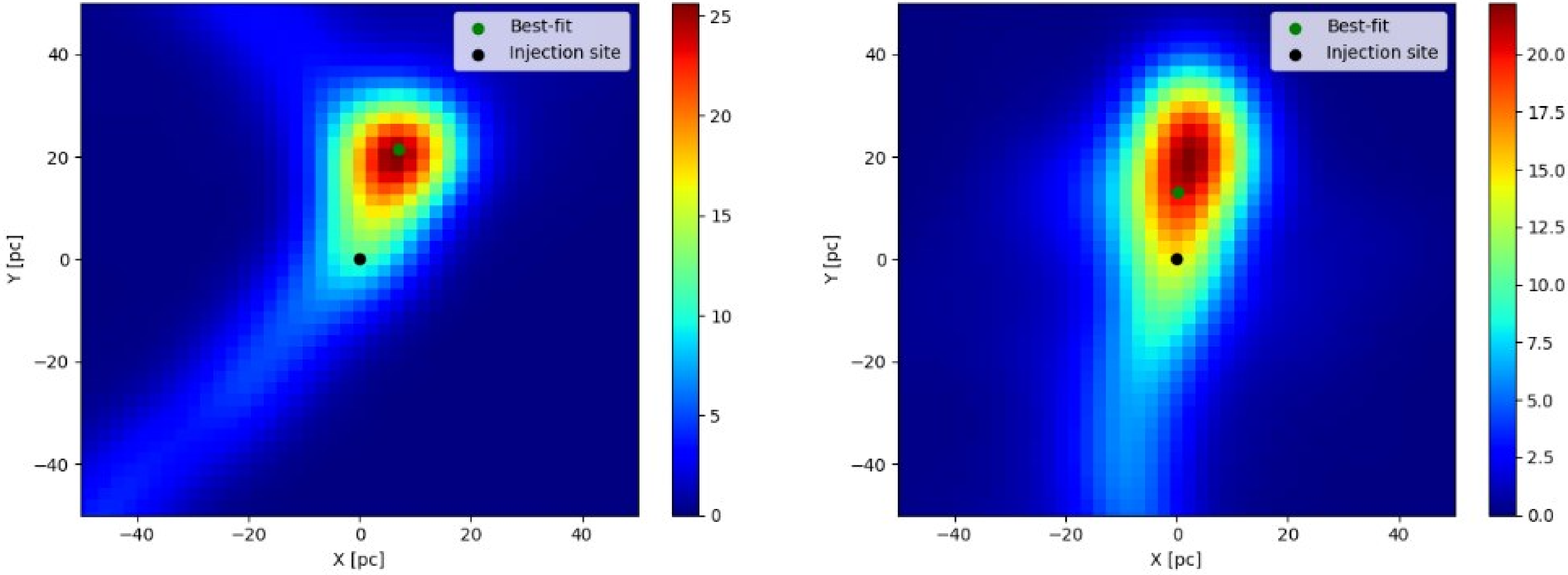
The second source is a "**mirage**", where the magnetic field bends inwards /outwards, wrt/ observer.

(Prediction: X-ray emission at the mirage source fainter than that at the connecting structure.)



Large offsets:

Large offsets may exist between real source and detected source

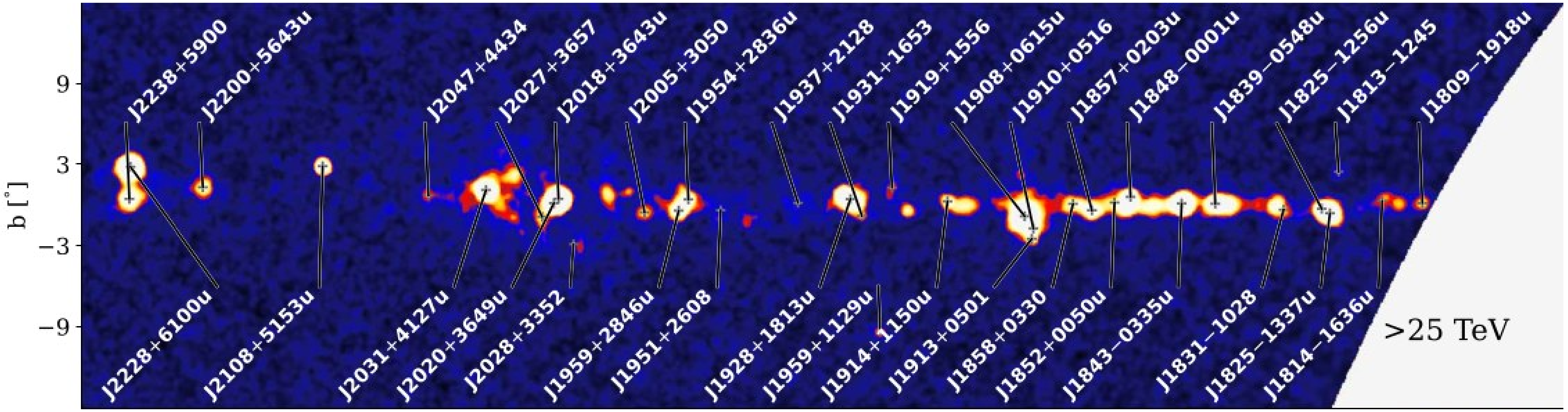


B_{turb} ~ 1 µG ; B_{reg} = 0 µG ; L_c = 200 pc ; Kolmogorov turbulence ; (8192 particles)

May explain LHAASO observations

LHAASO Collaboration, ApJS 271, 25 (2024)

Many **extended sources** w/ **irregular shapes:**



Large offsets between sources and center

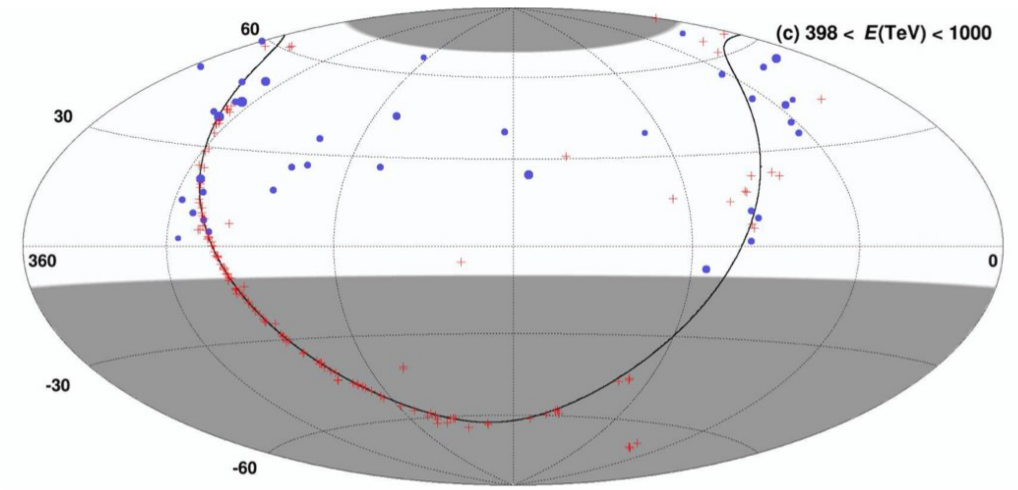
Table 4. 1LHAASO sources associated pulsars

Source name	PSR name	Sep.(°)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	-	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	-	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Halo
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	

No counterparts?

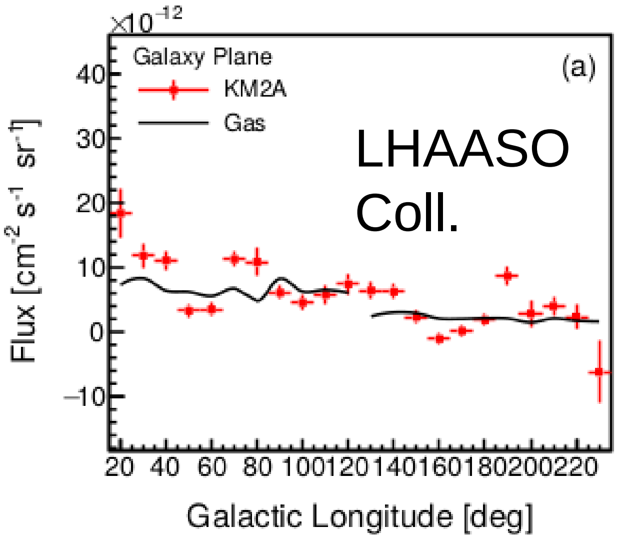
2 – Diffuse VHE γ-ray emission

Diffuse from AS-γ (400 TeV – 1 PeV)



AS-γ Collaboration,
arXiv:2104.05181

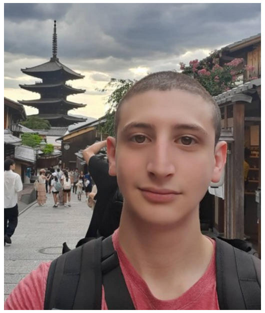
Diffuse from LHAASO (10 TeV – 1 PeV)



→ **Emission in Galactic longitude does not follow target gas…**
=> Stochasticity of CR injection?

Diffuse VHE emission from discrete CR sources

<u>Work by Samy Kaci</u>



Based on:
Kaci & Giacinti,arXiv:
2406.11015, Submitted to JCAP

Our simulation

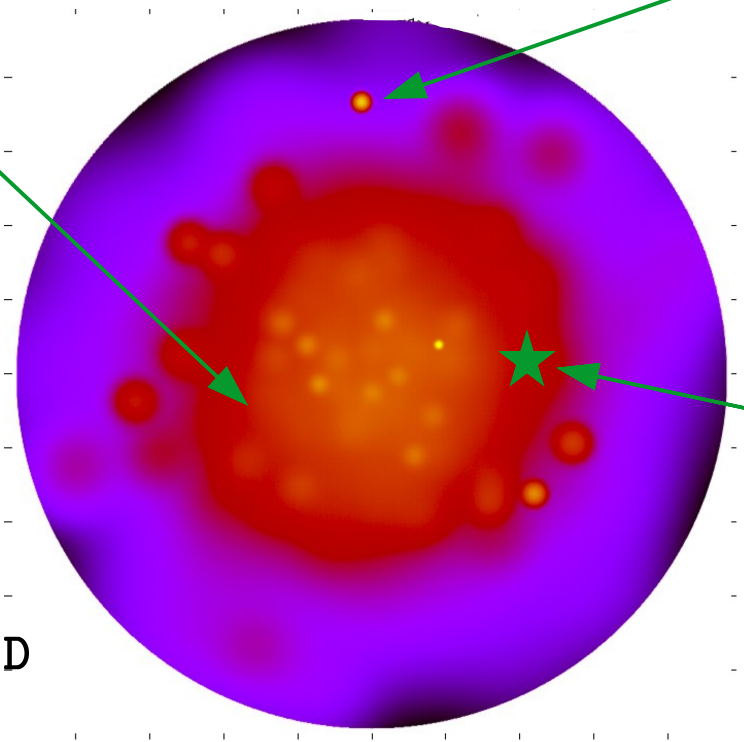
Isotropic and homogeneous diffusion

1) GALPROP-like (d=1/3) :

$$D(E) = 10^{28} D_{28} \left(\frac{R}{3GV}\right)^{\delta} cm^2/s$$

$$D_{28} = 1.33 \times \frac{H}{kpc}$$

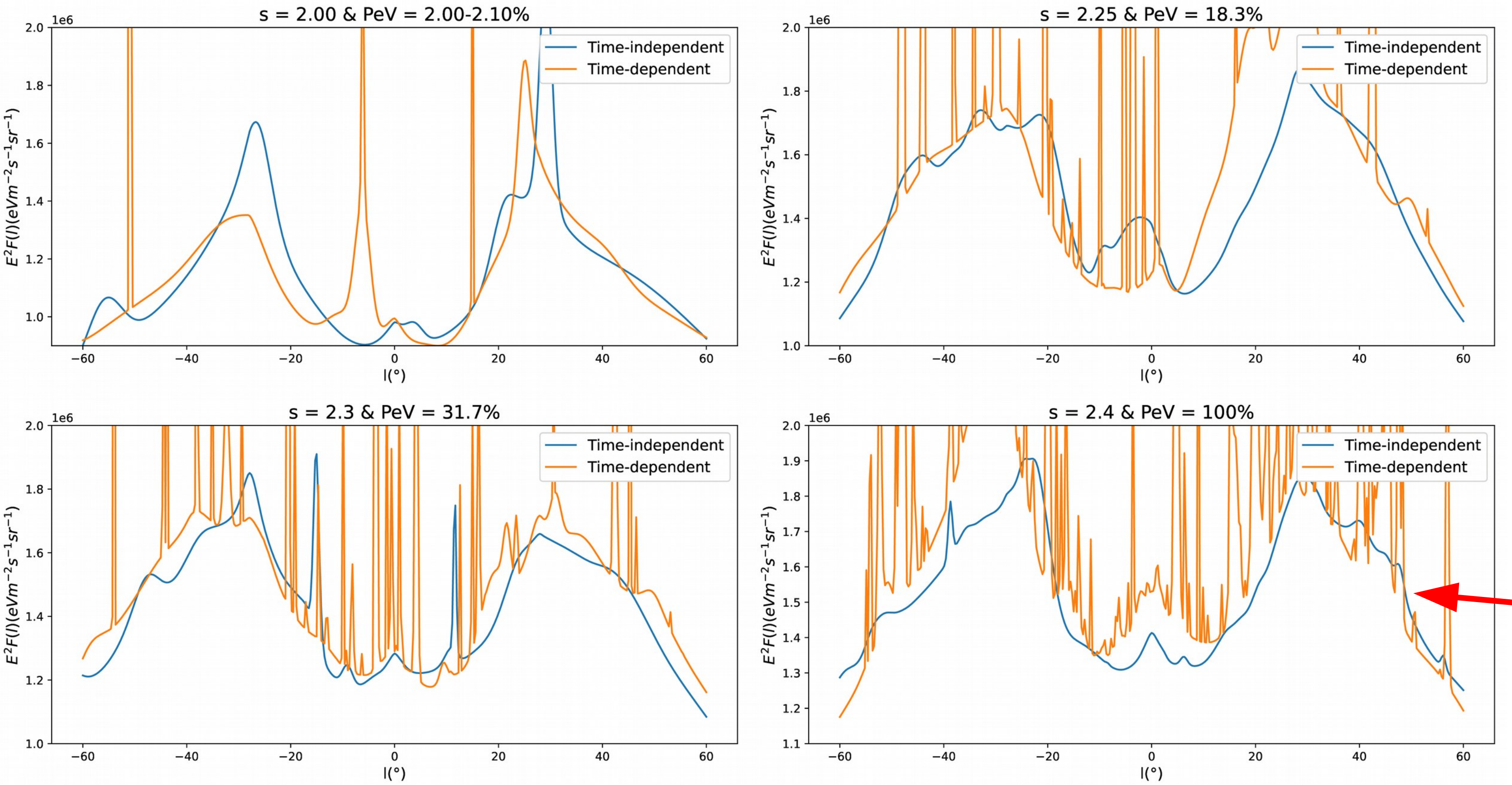
2) Time-dependent (mimics self-confinement): 1/100 x D around sources for 10 kyr.



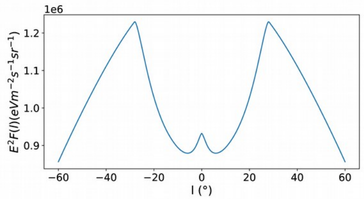
Discrete injection of cosmic rays

Cosmic-ray flux at Earth and B/C ratio

Clumps in the gamma-ray flux



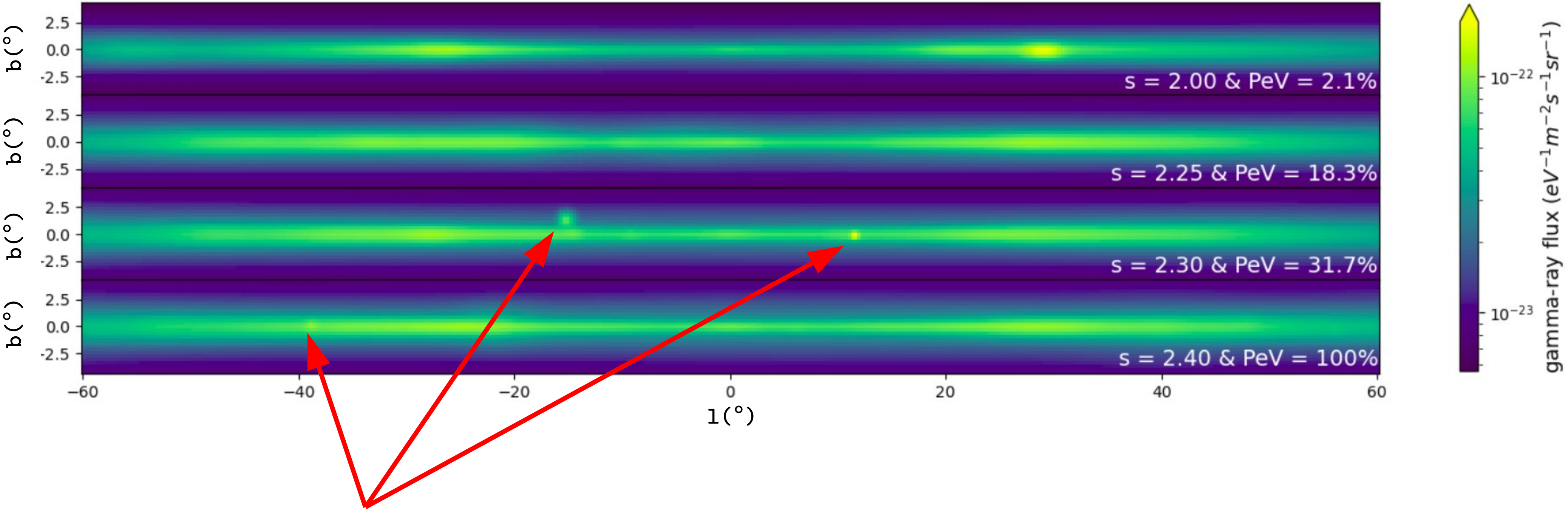
General shape like Lipari & Vernetto



But both cases present large bumps

Slide from Samy Kaci

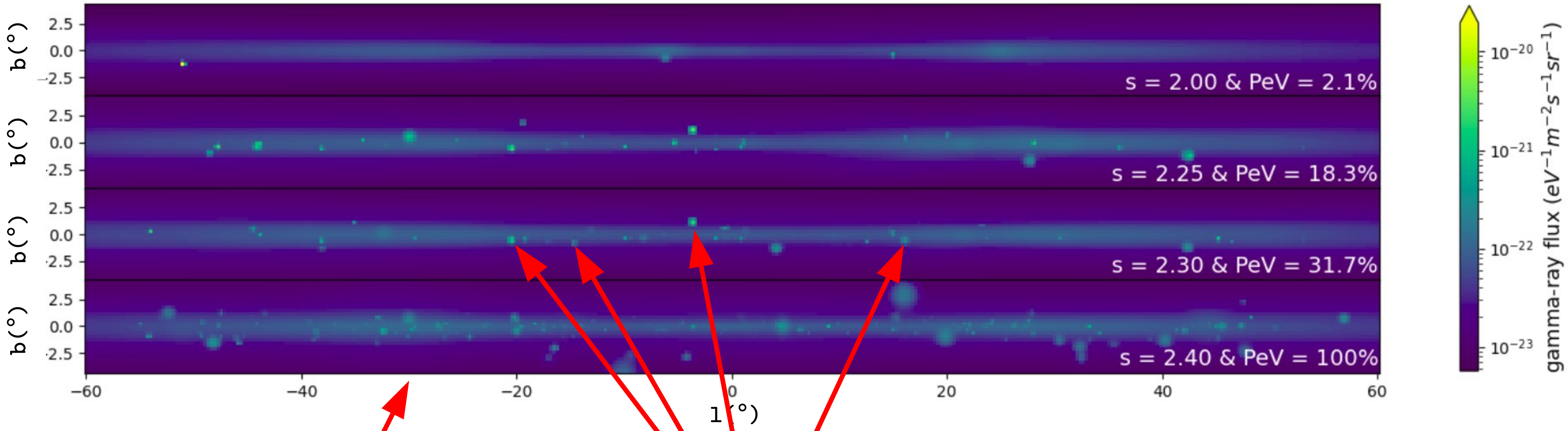
Sky Maps and sources (case 1)



Very few visible sources for case 1

Slide from Samy Kaci

Sky Maps and sources (case 2)



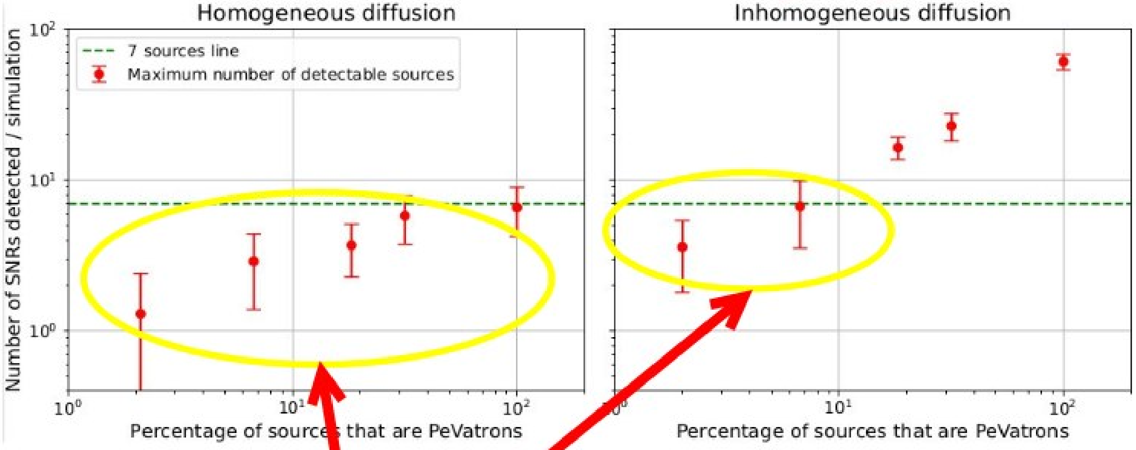
Completely different morphology for the two cases

Many more visible sources

Is this situation realistic?

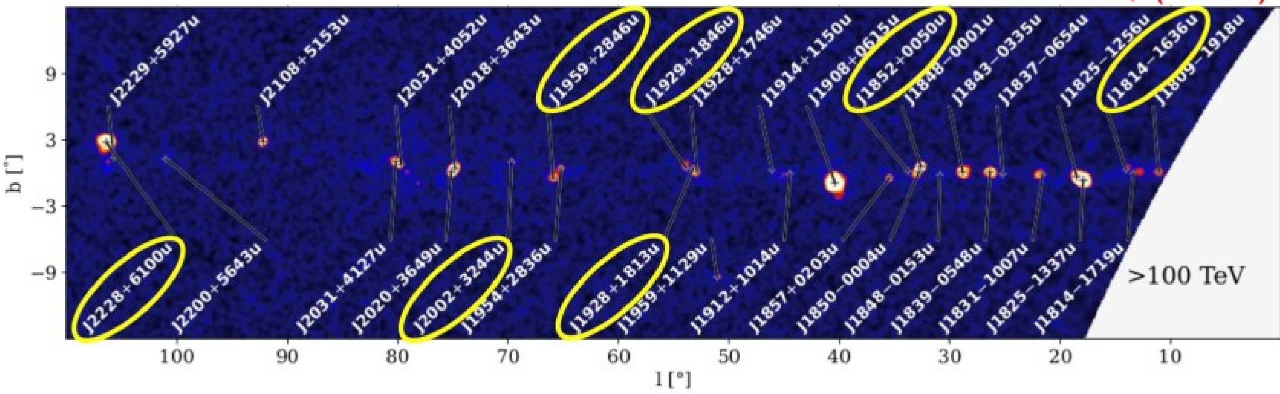
Number of detectable sources

S. Kaci & G. Giacinti (2024)



- Two diffusion regimes lead to different results concerning the detectability of sources.
- Homogeneous diffusion strongly limits the detectability of sources.
- Some parts of the space paramters can already be excluded.

Z. Cao et al., (2023)



There is still some degeneracy between the two cases

Can be disentangled from clumpiness of diffuse bkg

Summary & Conclusion

- Diffuse gamma-ray flux clumpy at VHE.
- The sky map morphology is very sensitive to the propagation mechanism.
- For standard (GALPROP) isotropic diffusion, few PeVatrons detectable.
- With short period of suppressed diffusion, more sources detectable.
- Inhomogeneous diffusion implies a PeVatron SNR rate < 3.6/kyr.

Slide from Samy Kaci