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

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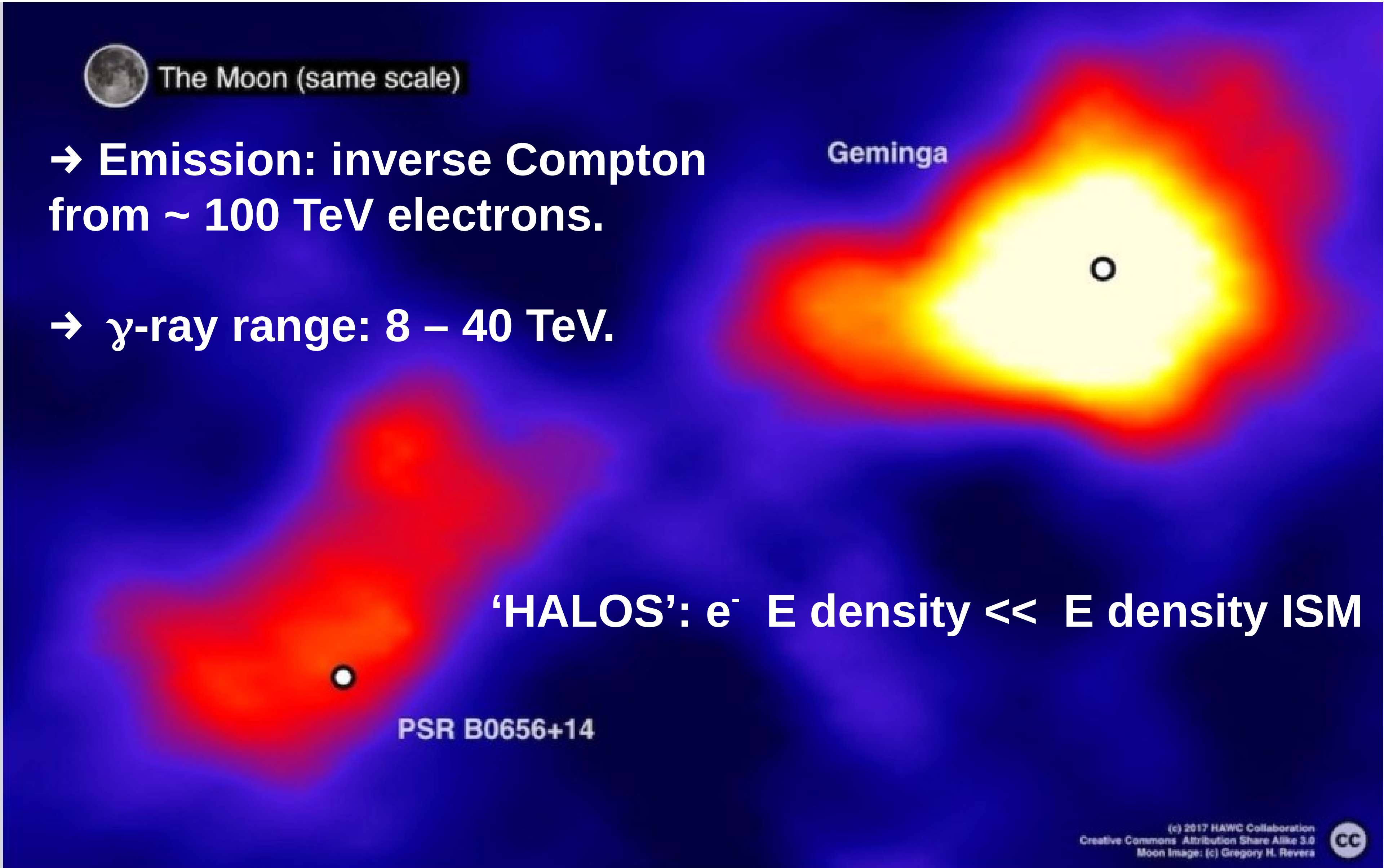
1 – TeV halos as a probe of CR propagation in the ISM

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

HAWC observ. of Geminga & Monogem

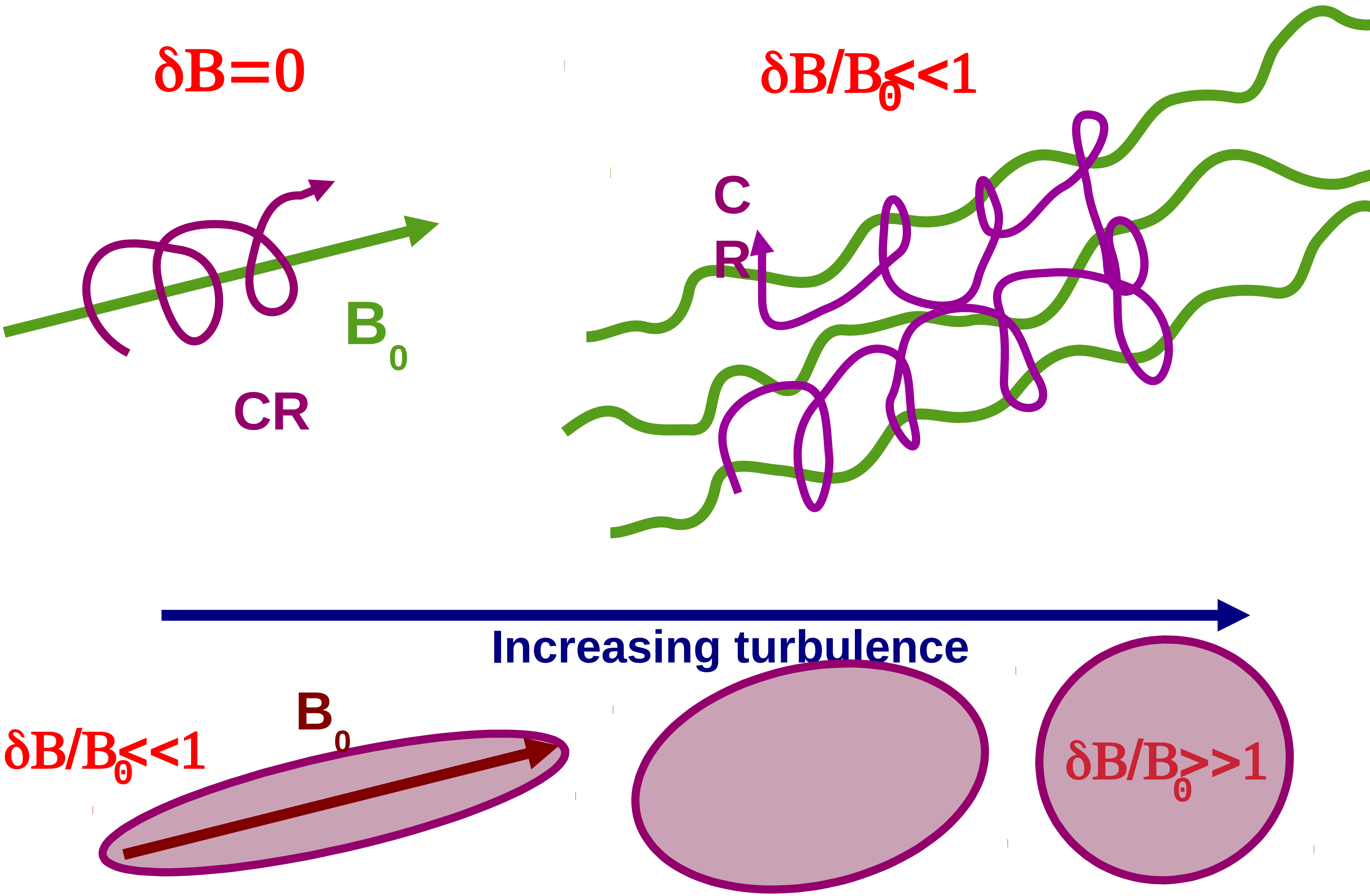


→ **Emission: inverse Compton from ~ 100 TeV electrons.**

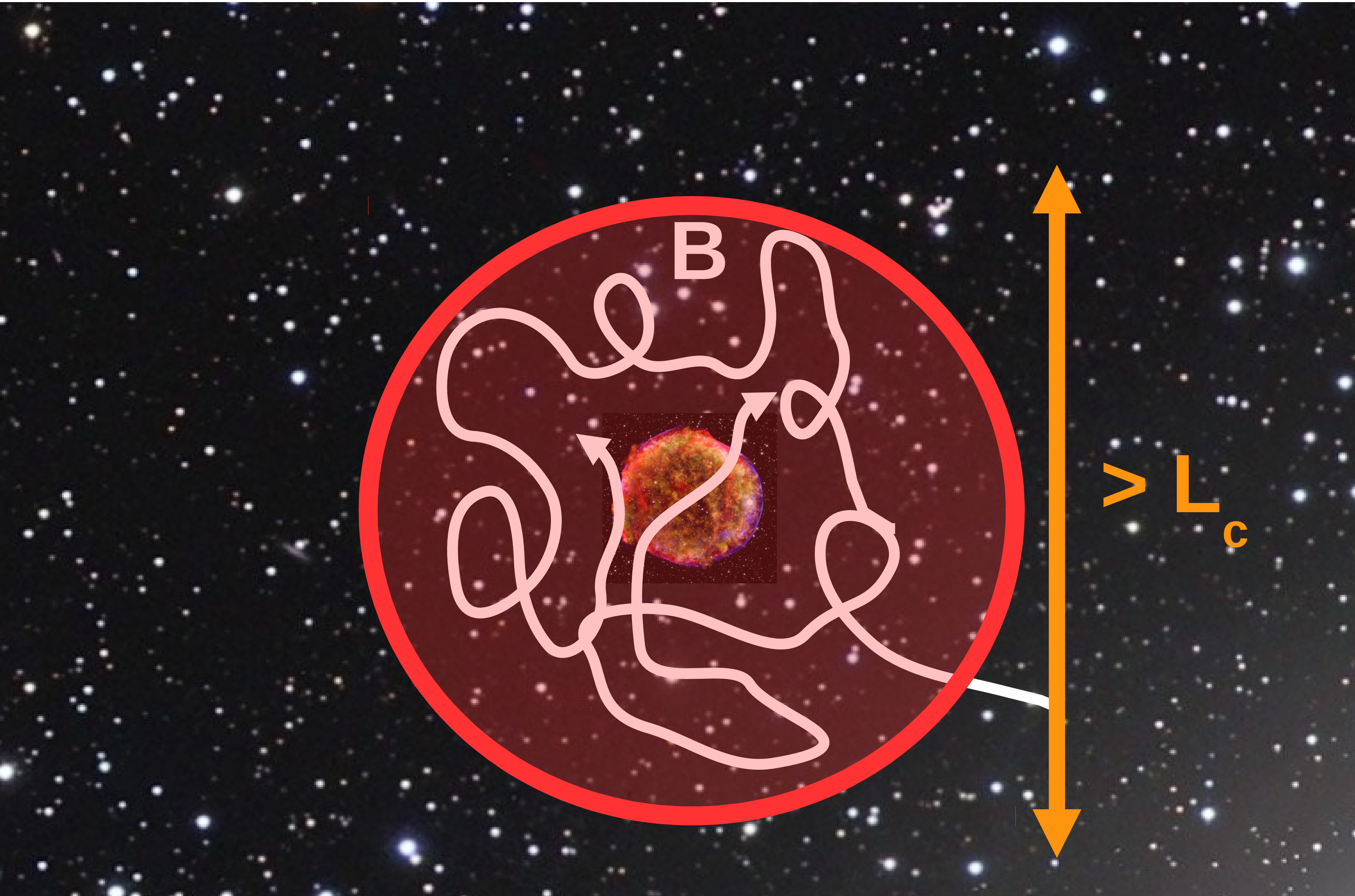
→ **γ-ray range: 8 – 40 TeV.**

'HALOS': e^- E density << E density ISM

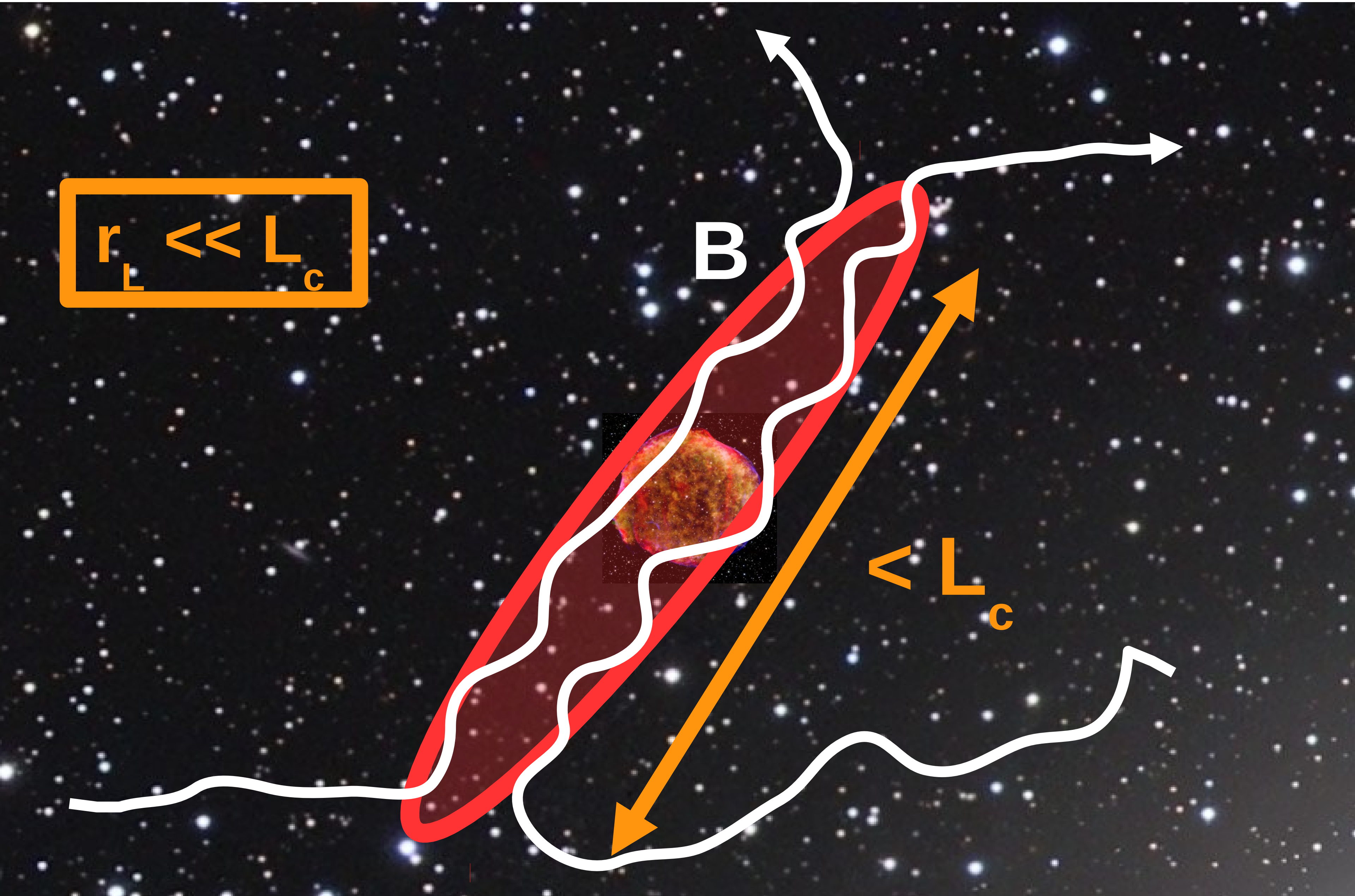
CR diffusion



But is CR diffusion (ever) isotropic ?

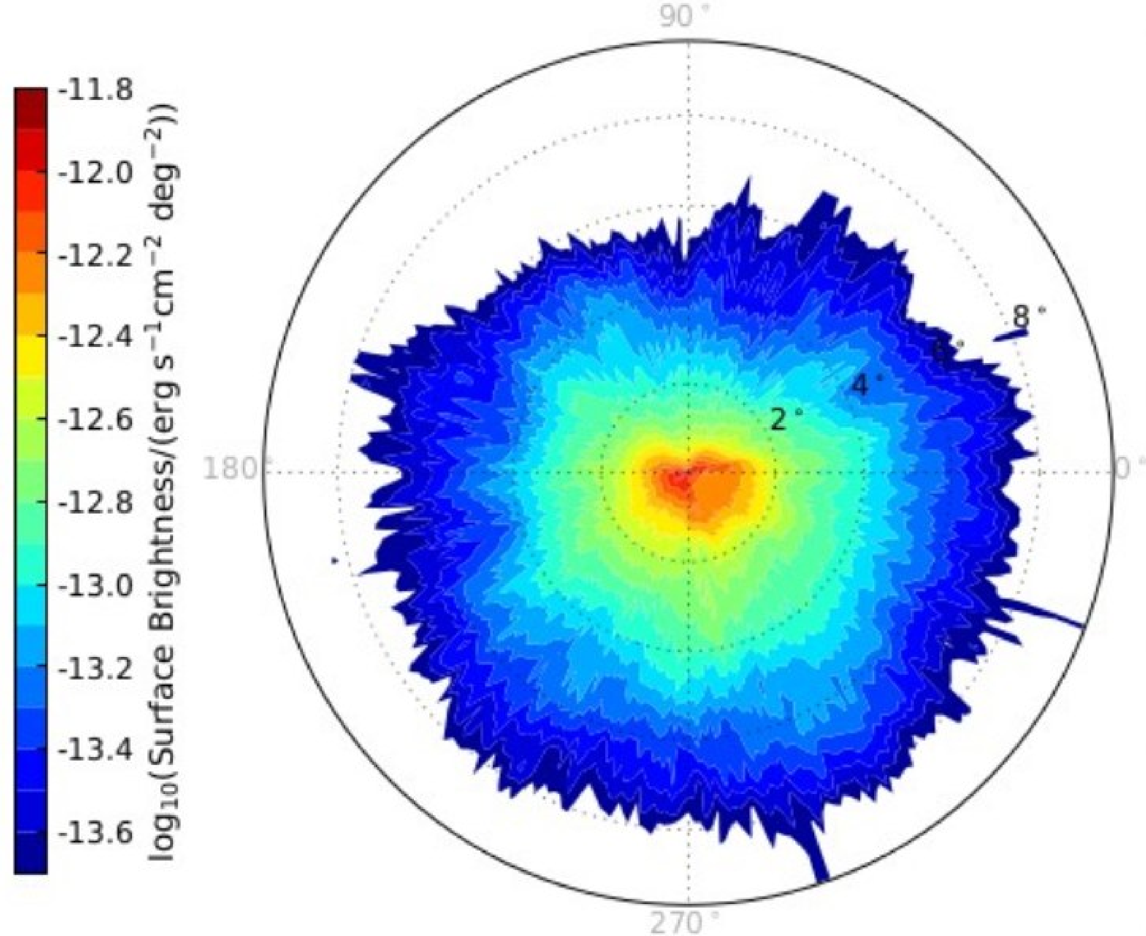


But is CR diffusion (ever) isotropic ?



Predicted γ-ray surface brightness

Kolmogorov, B_{rms}=3 μG, $\mathbf{L_c}$ **= 5 pc** :

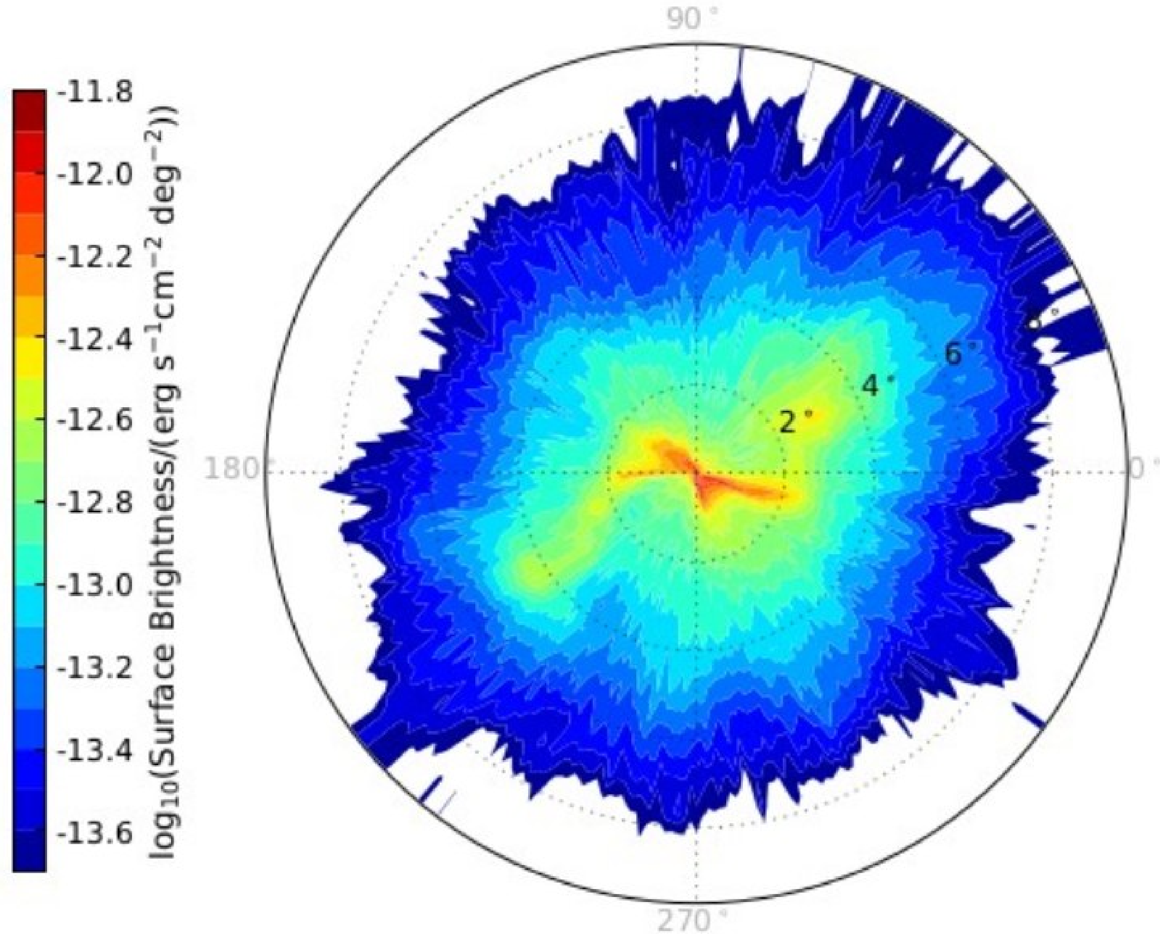


OK

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

Predicted γ-ray surface brightness

Kolmogorov, B_{rms}=3 μG, **L_c = 10 pc** :

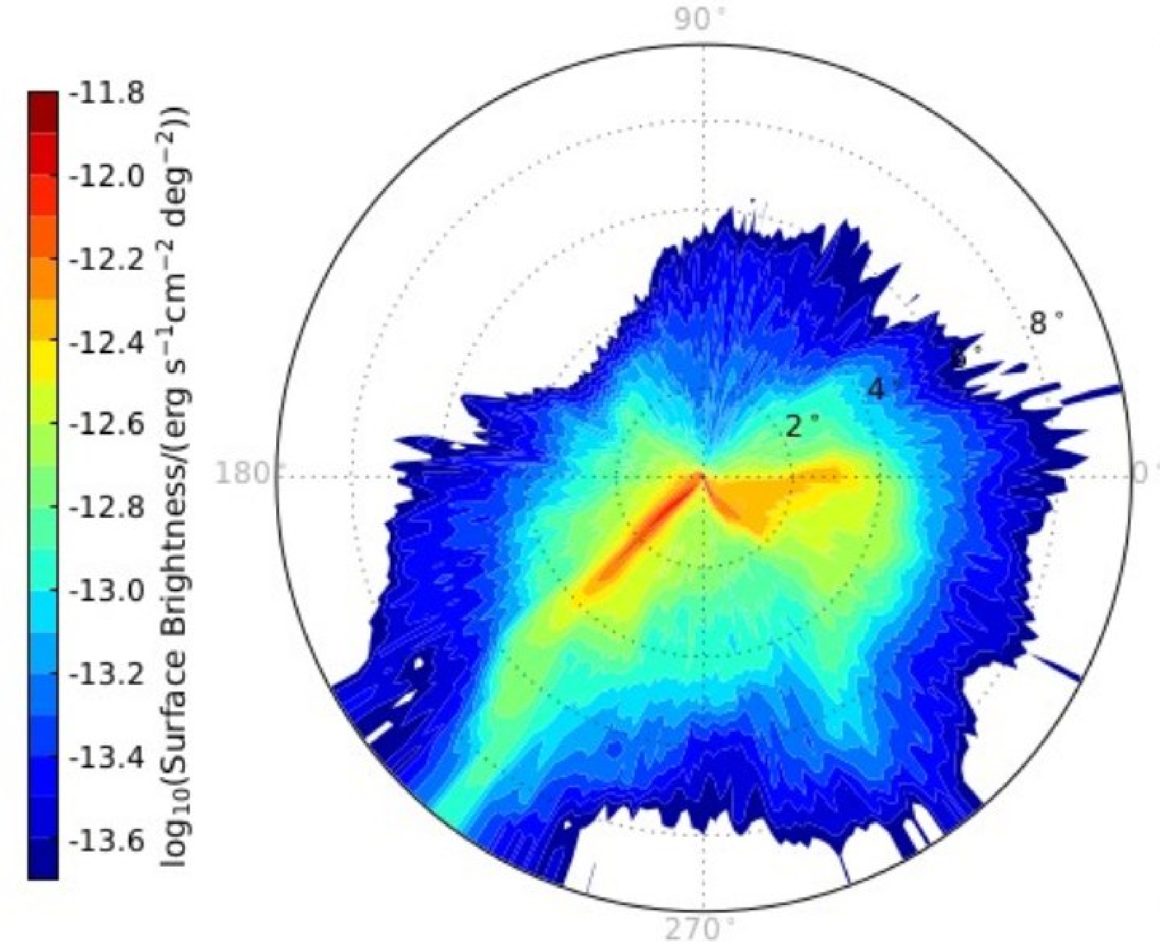


ALMOST INCOMPATIBLE WITH HAWC MEASUREMENTS

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

Predicted γ-ray surface brightness

Kolmogorov, B_{rms}=3 μG, $\mathbf{L_c}$ **= 40 pc** :



INCOMPATIBLE WITH HAWC MEASUREMENTS

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

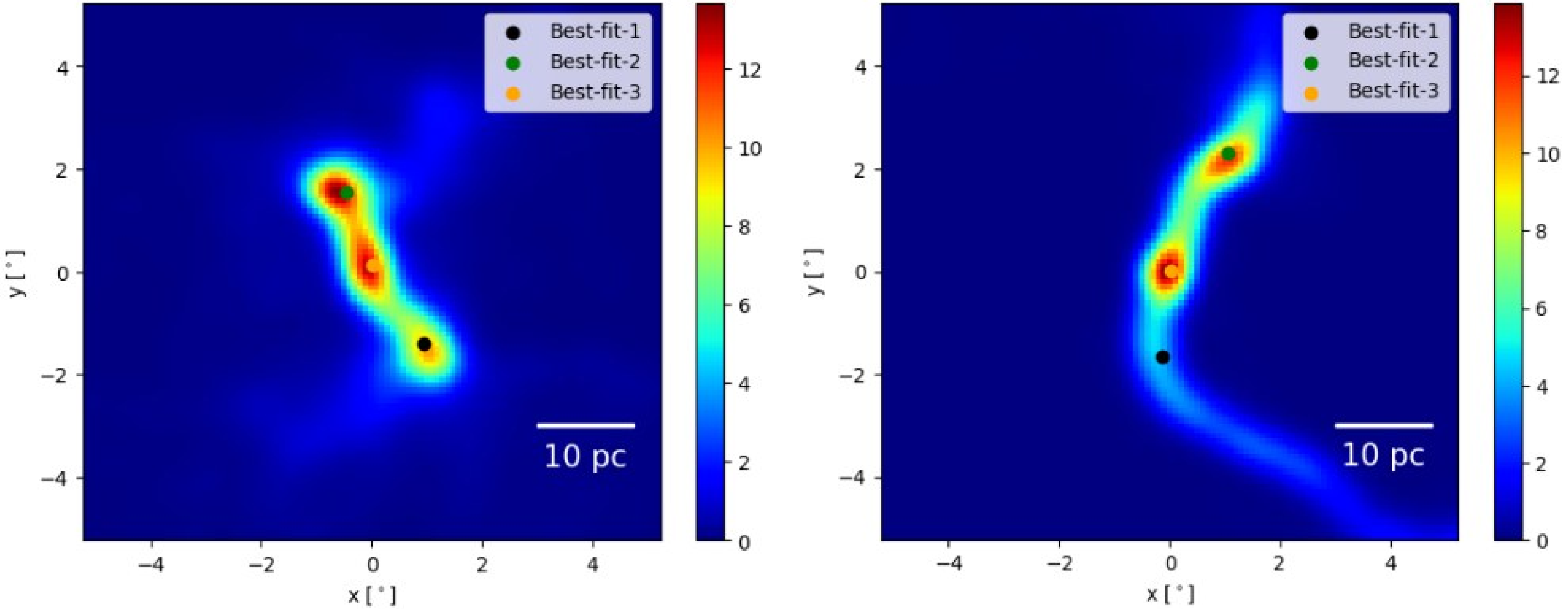
TeV Halos: "Mirage" sources and large offsets

Works by Yiwei Bao

Bao, Giacinti, Liu, Zhang & Chen, arXiv:2407.02478 (Submitted)
Bao, Liu, Giacinti, Zhang & Chen, arXiv:2407.02829 (Submitted)

Appearance of additional (“mirage”) sources:

They may appear around astrophysical sources.

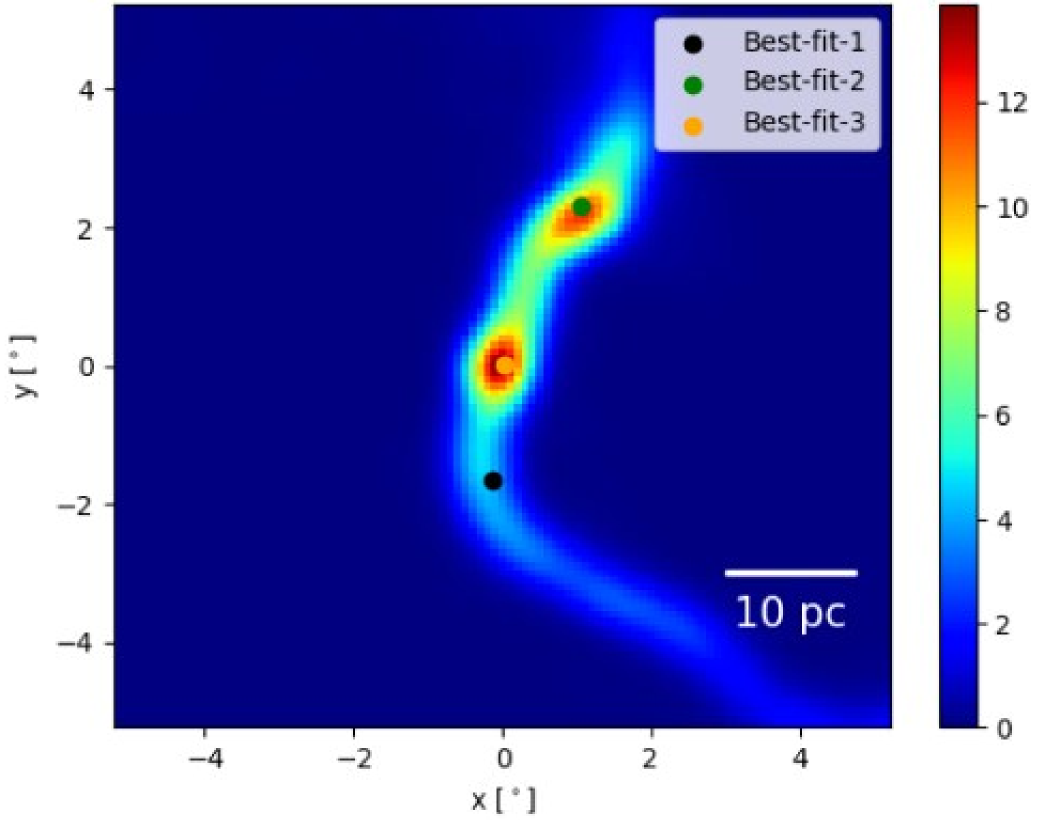


L_c = 40pc ; B_{turb} = 3 μG ; B_{reg} = 0 μG; Kolmogorov turbulence ; (8192 particles)

Appearance of additional ("mirage") sources:

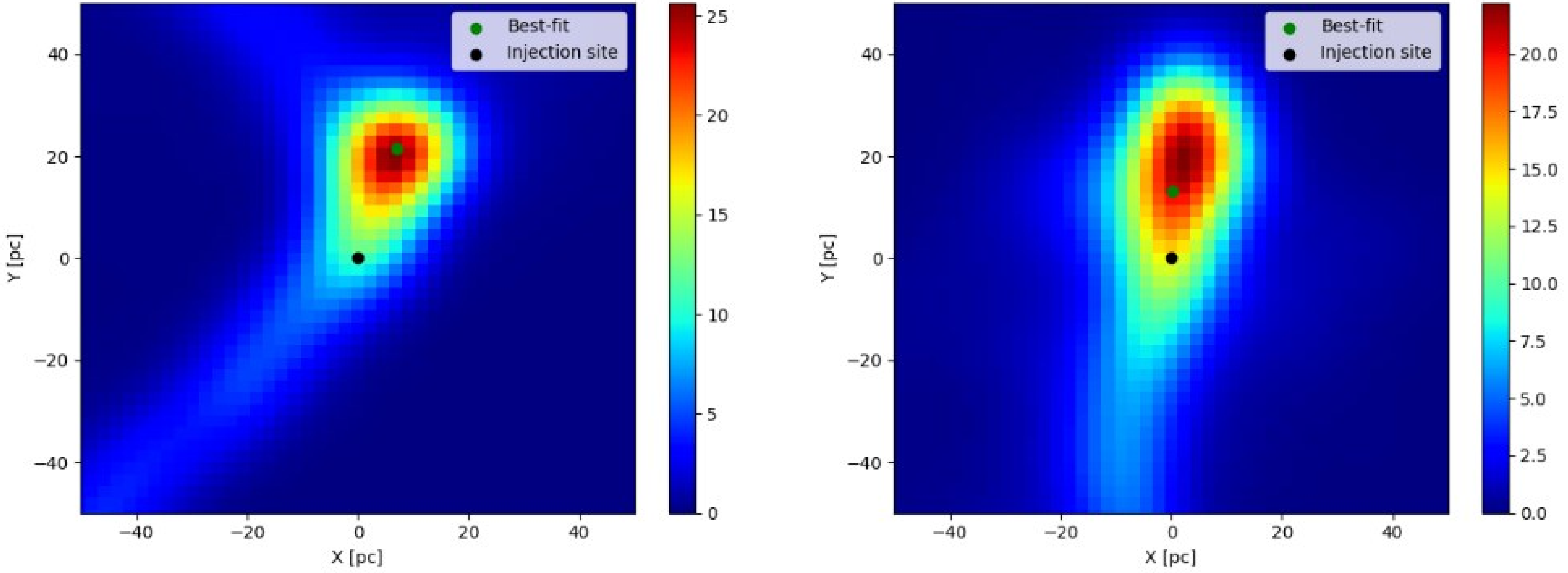
The second source is a "**mirage**", where the magnetic field bends inwards /outwards, wrt/ observer.

(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

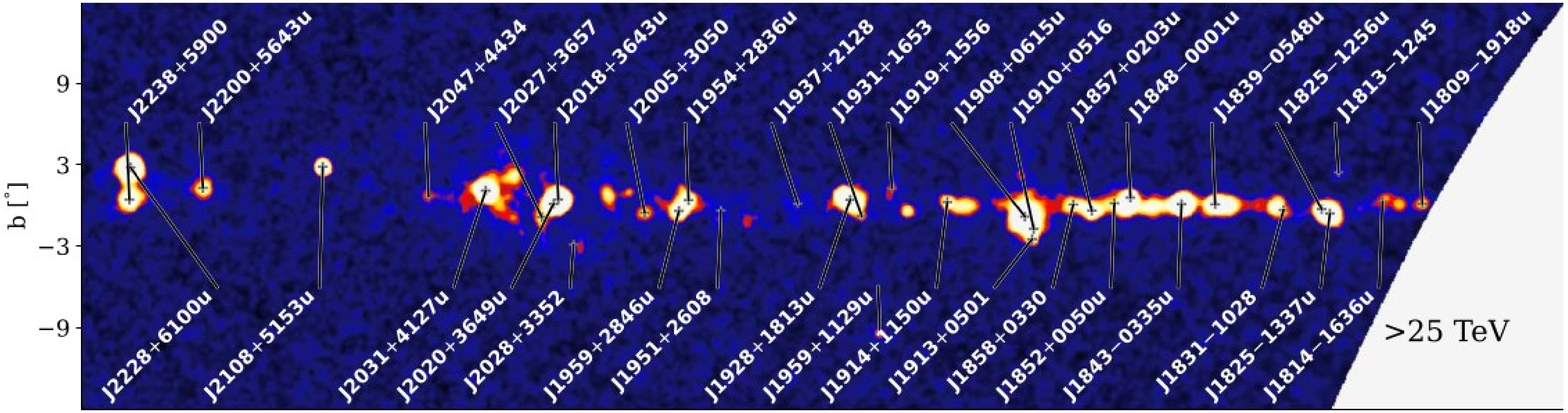


B_{turb} ~ 1 μG ; B_{reg} = 0 μG ; L_c = 200 pc ; Kolmogorov turbulence ; (8192 particles)

May explain LHAASO observations

LHAASO Collaboration, ApJS 271, 25 (2024)

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



No counterparts?

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	

Summary:

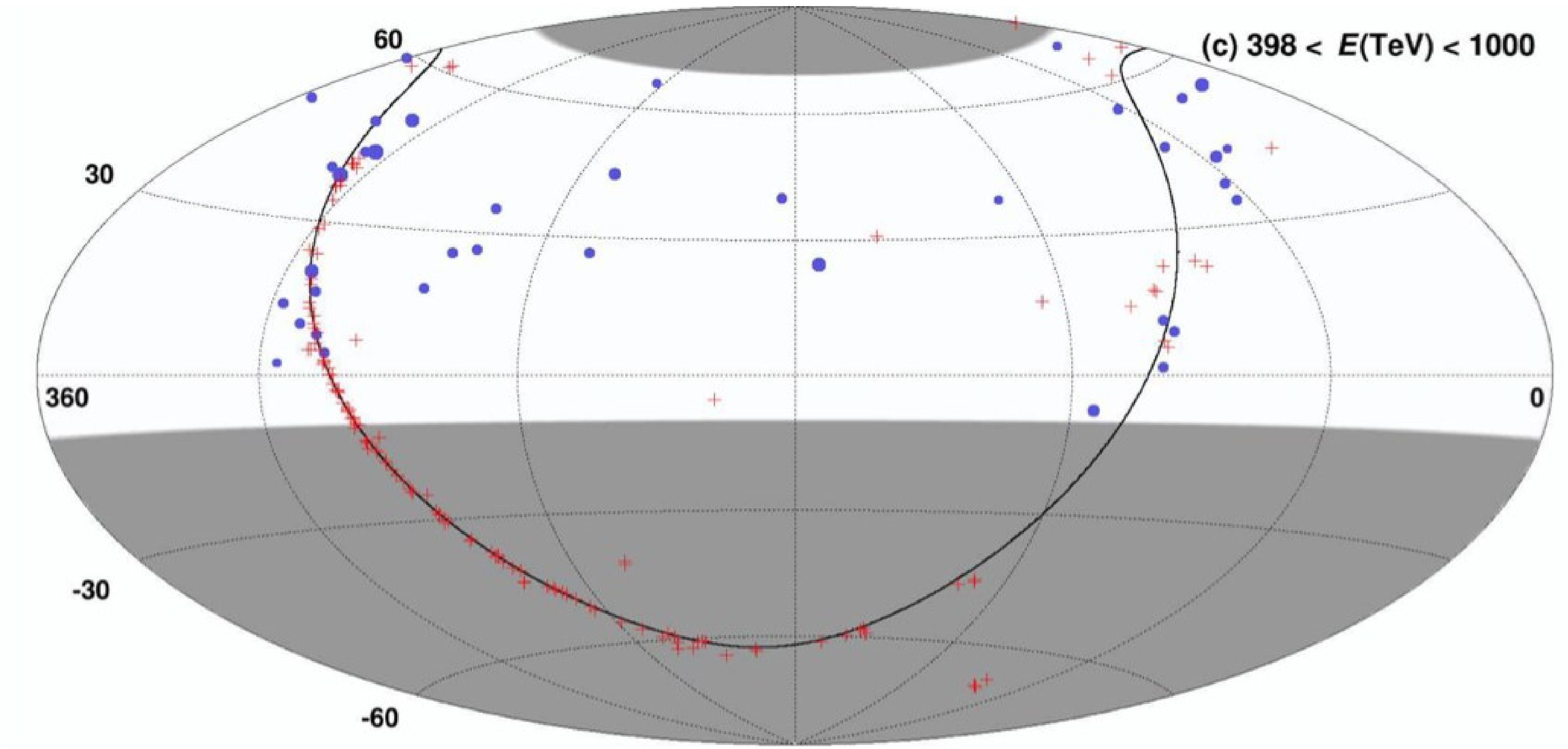
→ **Very extended hadronic sources** from **past PeVatrons** may exist.

→ **“Mirage” sources** may appear **around (and far from) astrophysical sources.**

→ **Large offsets** may exist between the **real source** and the **detected source**, due to B field structure in the ISM around the source.

2 – Diffuse γ-ray emission

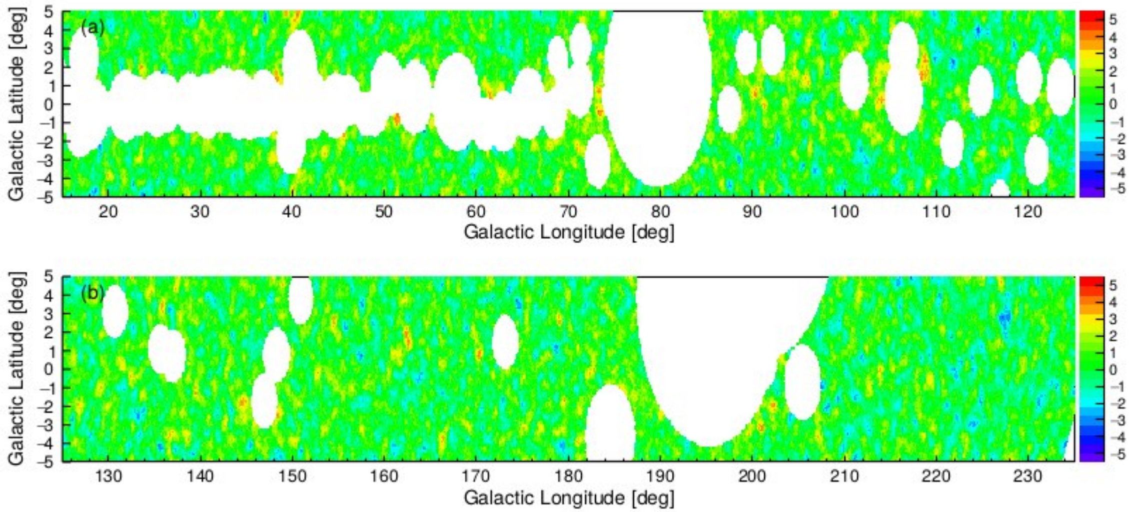
The sky at ~ 400 TeV – 1 PeV: Diffuse emission from AS-γ

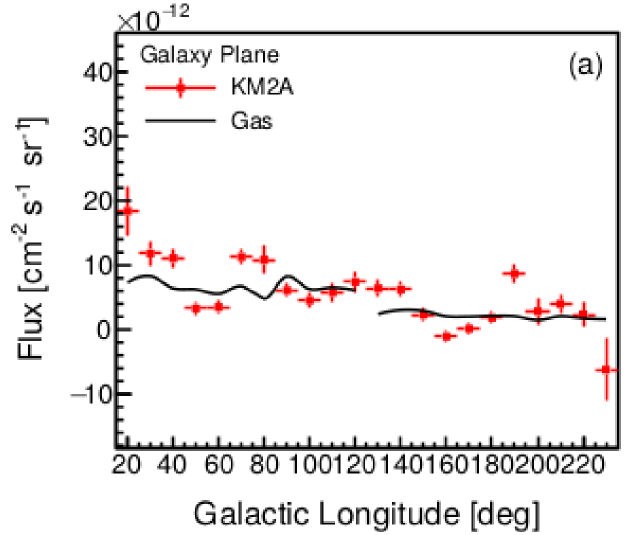


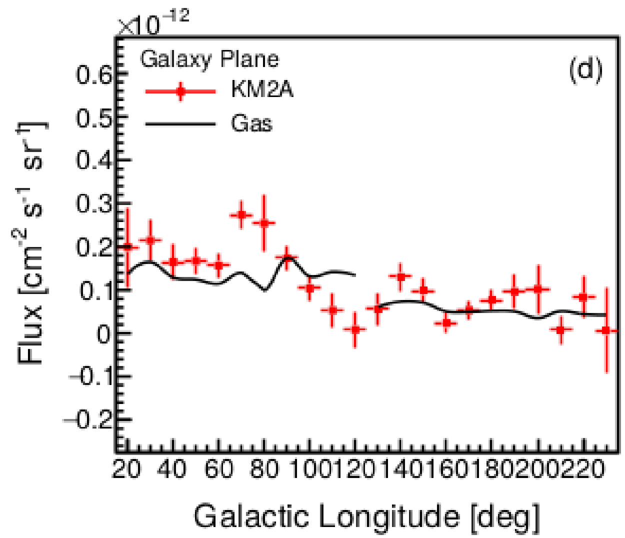
AS-γ Collaboration,
arXiv:2104.05181

The sky at ~ 10 TeV – 1 PeV: Diffuse emission from LHAASO

LHAASO Collaboration, arXiv:2305.05372





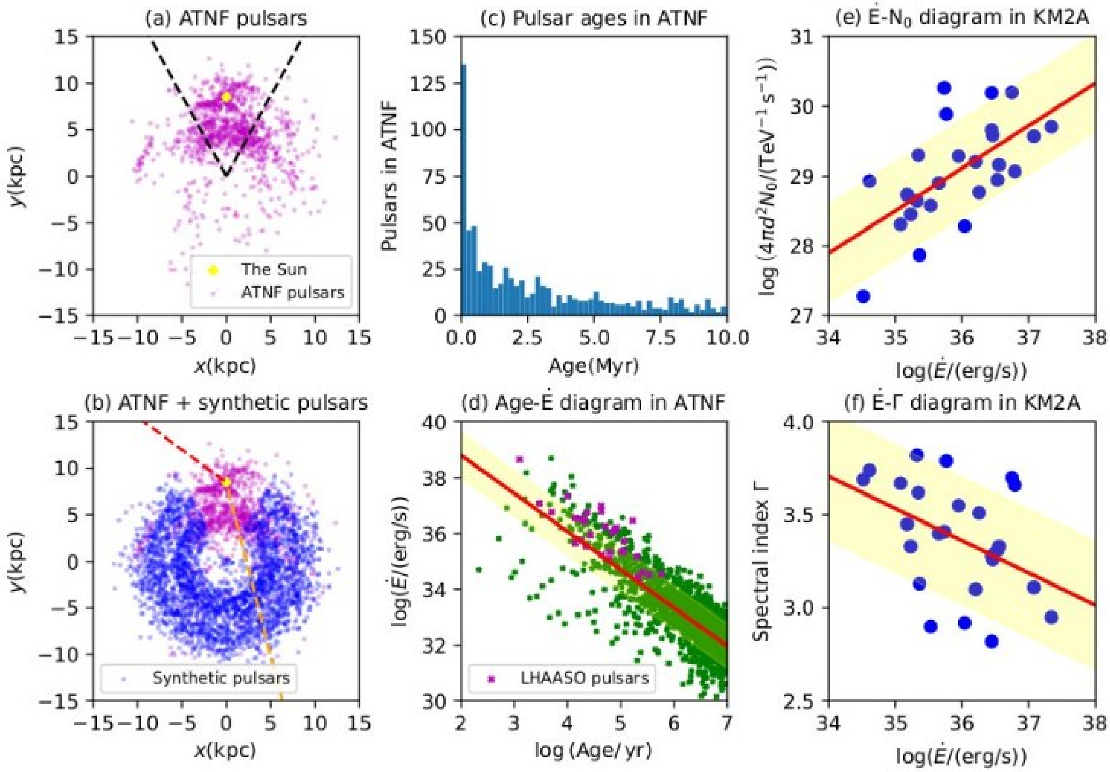


→ **Emission in Galactic longitude does not follow target gas…**
=> Stochasticity of CR injection?

Impact of unresolved sources (PWNe)

TSUNG-DAO LEE INSTITUTE

S. Kaci, G. Giacinti, D. Semikoz (2024) ApJ Lett., Accepted, arXiv:2407.20186

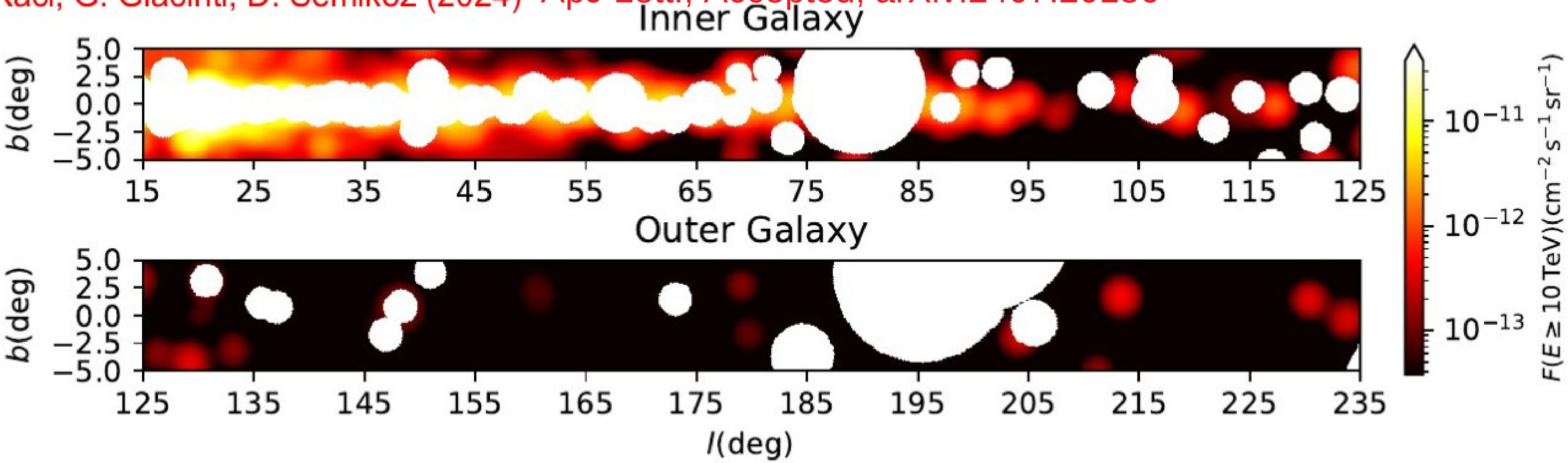


- Use ATNF catalog and complete it.
- Generate a VHE gamma-ray emission similar to that measured by KM2A for each source.
- Constrain the gamma-ray emission to be below KM2A sensitivity.
- Use the same masks as LHAASO.
- Compare the contribution of unresolved sources to the total flux measured by KM2A.

Slide S. Kaci

Impact of unresolved sources (PWNe)

S. Kaci, G. Giacinti, D. Semikoz (2024) ApJ Lett., Accepted, arXiv:2407.20186

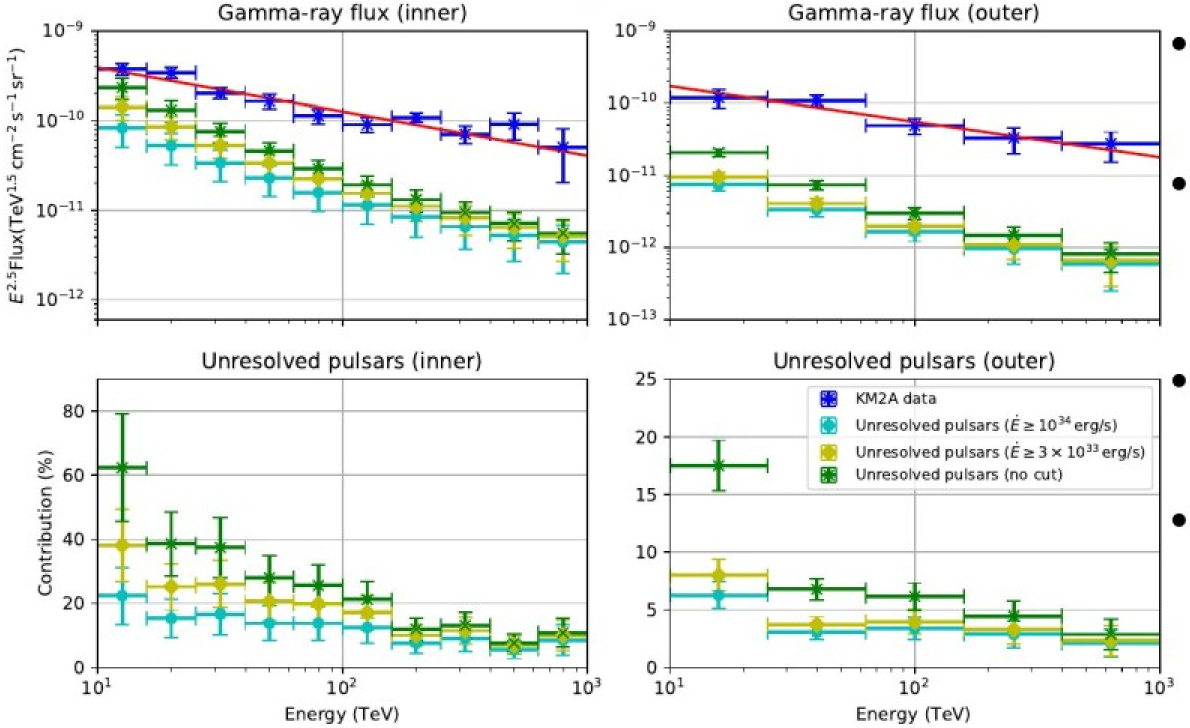


Slide S. Kaci

Impact of unresolved sources (PWNe)

李政道研究所 Tsung-Dao Lee Institute

S. Kaci, G. Giacinti, D. Semikoz (2024) ApJ Lett., Accepted, arXiv:2407.20186

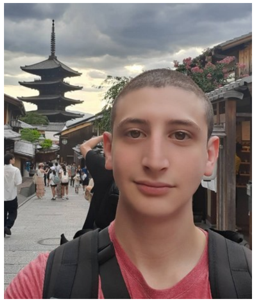


- Unresolved pulsars almost do not contribute in the outer Galaxy.
- Their contribution in the inner Galaxy depends on the cut in spindown power.
- Their contribution is negligeable above 100TeV.
- Unresolved pulsars may account for at most ~50% of the diffuse flux under ~30TeV in the inner Galaxy..

Slide S. Kaci

Diffuse gamma-ray emission at VHE from discrete CR sources

Works by Samy Kaci



Based on:
Kaci & Giacinti, arXiv: 2406.11015, Accepted by JCAP

Our simulation

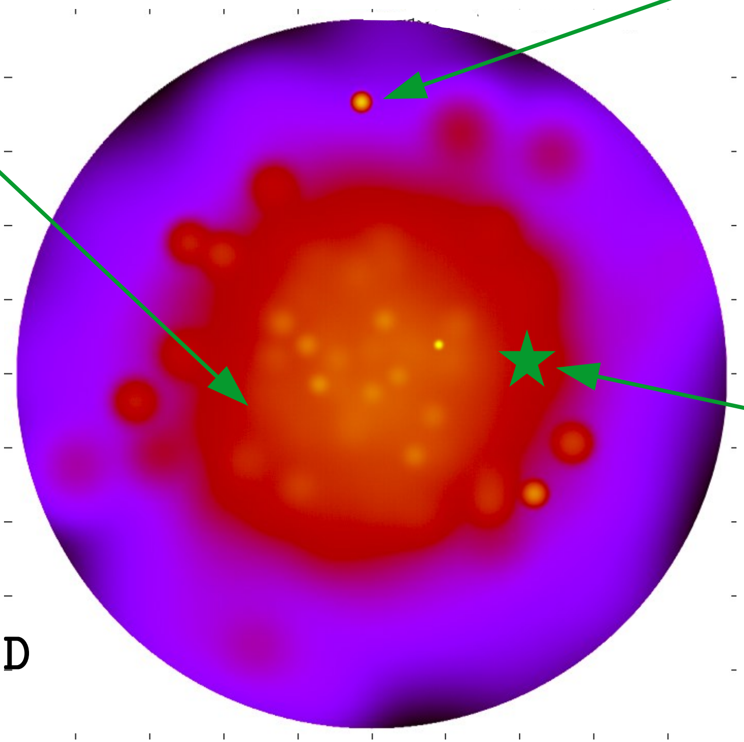
Isotropic and homogeneous diffusion

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.

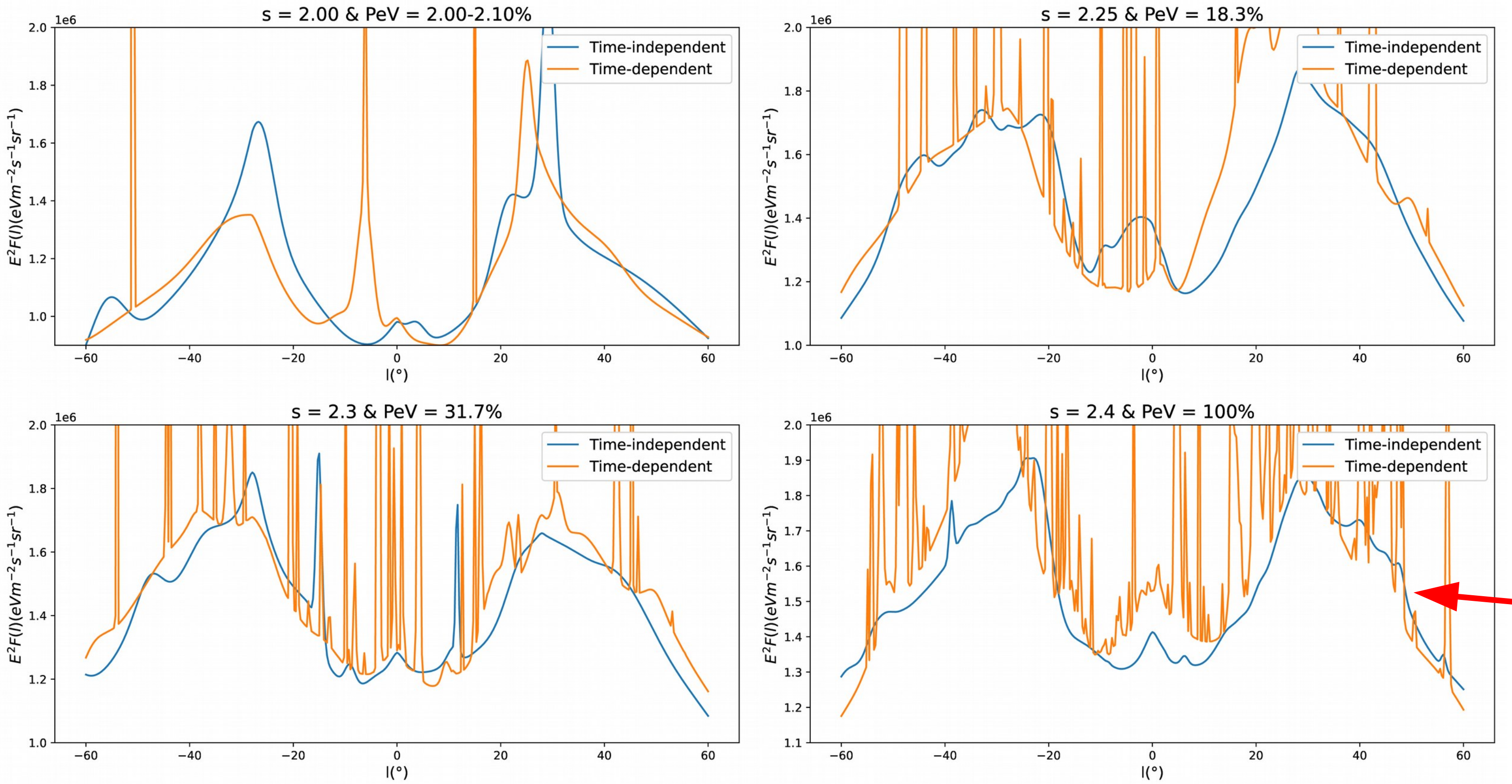


Discrete injection of cosmic rays

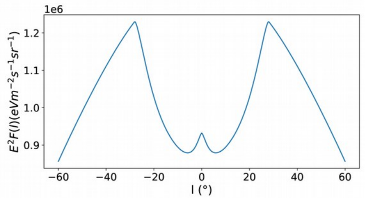
Cosmic-ray flux at Earth and B/C ratio

Slide from Samy Kaci

Clumps in the gamma-ray flux



General shape like Lipari & Vernetto



But both cases present large bumps

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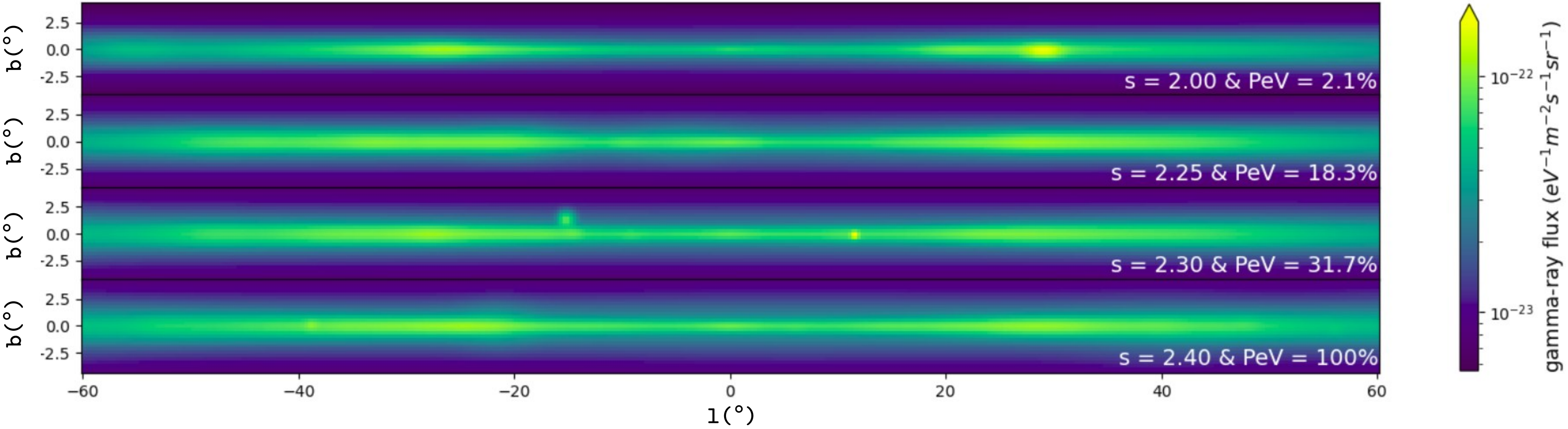
Sky Maps and sources (case 1)



Slide from Samy Kaci

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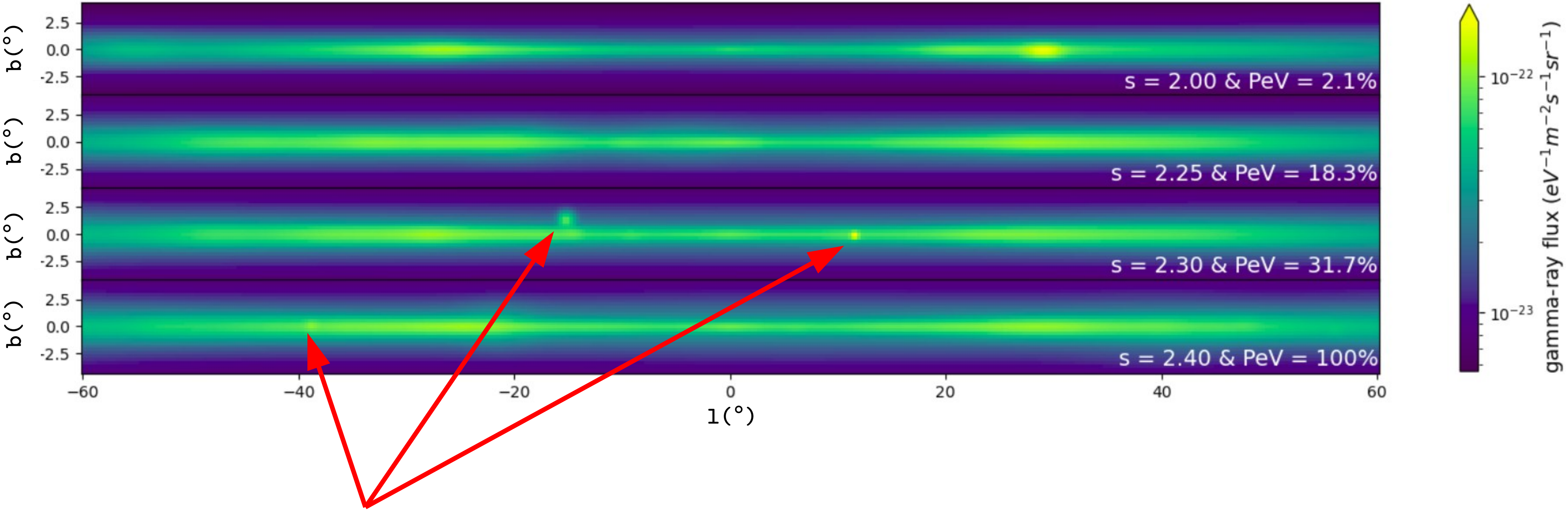

Very few visible sources for case 1

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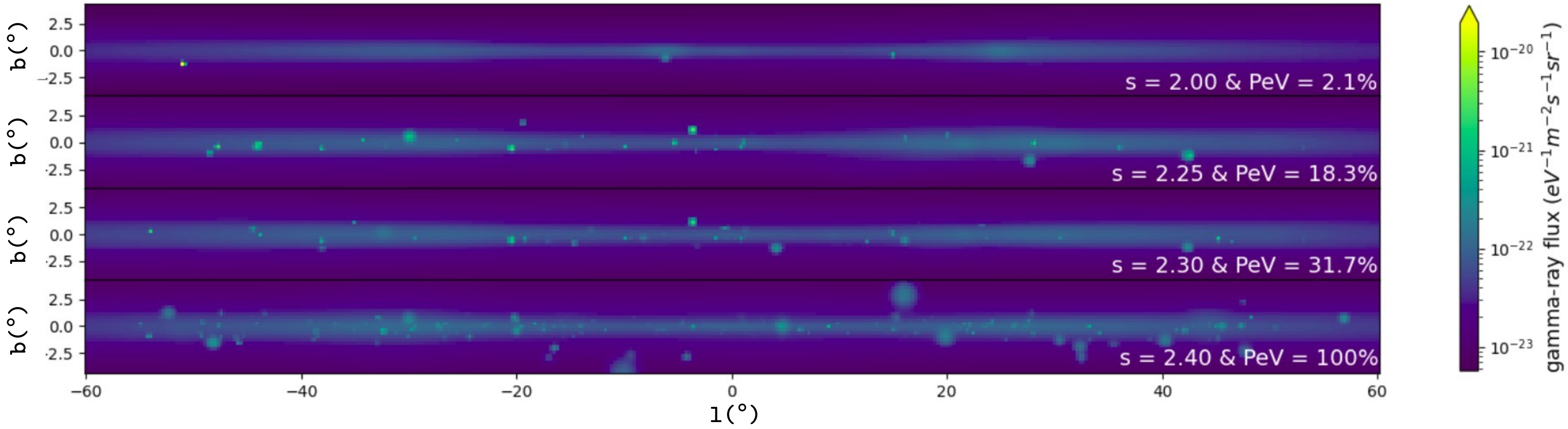
Sky Maps and sources (case 2)



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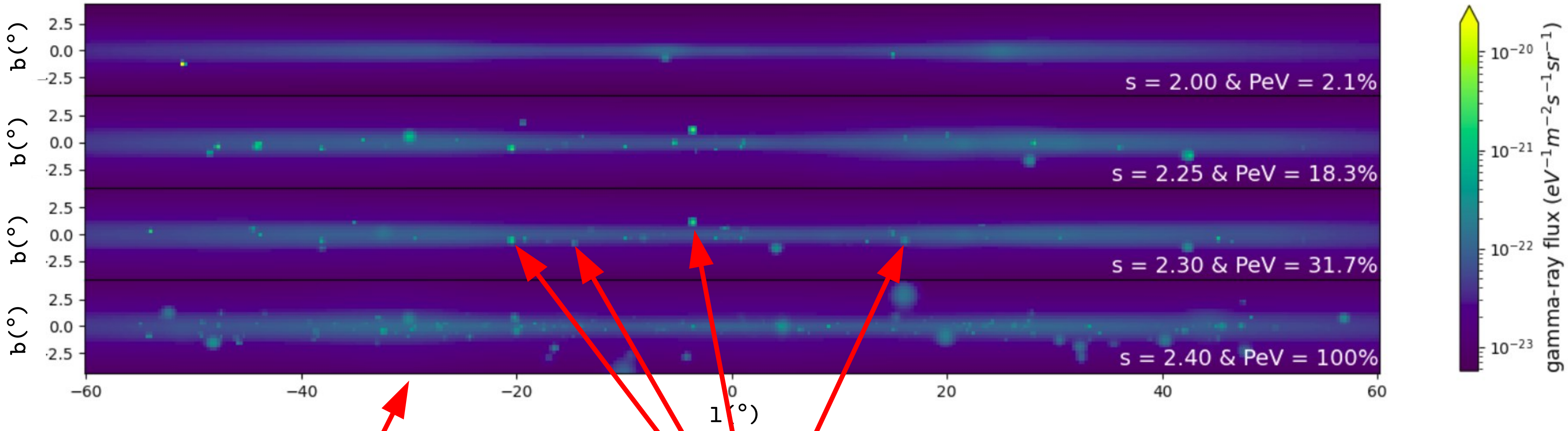
Sky Maps and sources (case 2)



Completely different morphology for the two cases

Many more visible sources

Is this situation realistic?

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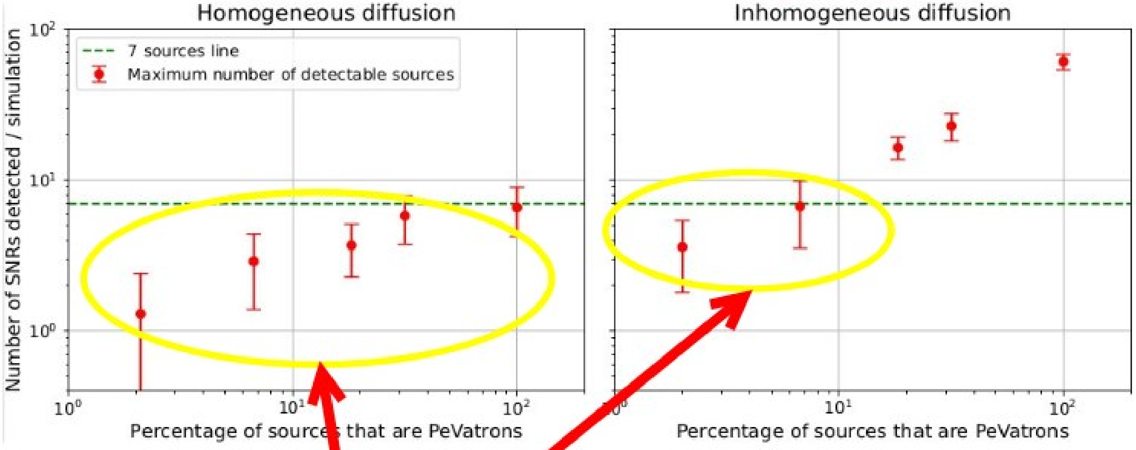
Number of detectable sources

S. Kaci & G. Giacinti (2024)

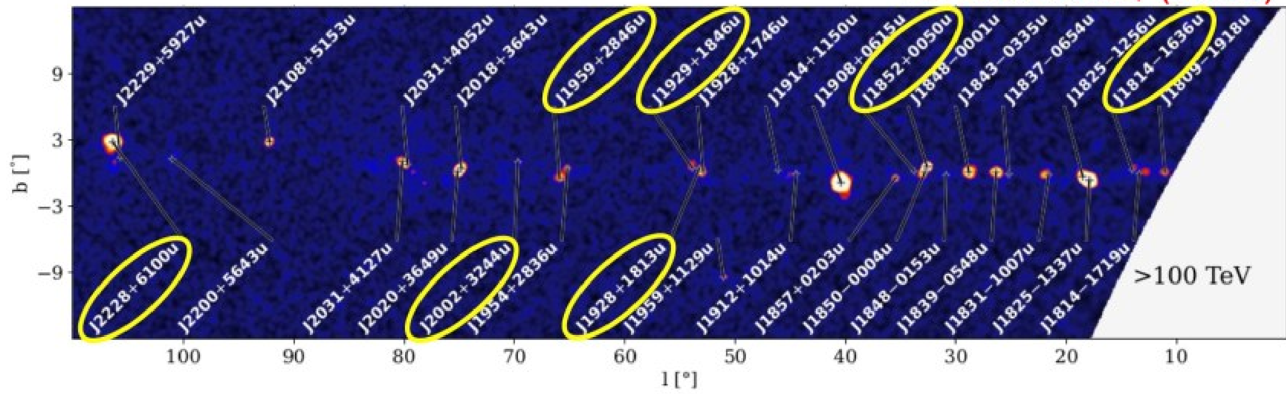


- Two diffusion regimes lead to different results concerning the detectability of sources.
- Homogeneous diffusion strongly limits the detectability of sources.
- Some parts of the space paramters can already be excluded.

There is still some degeneracy between the two cases

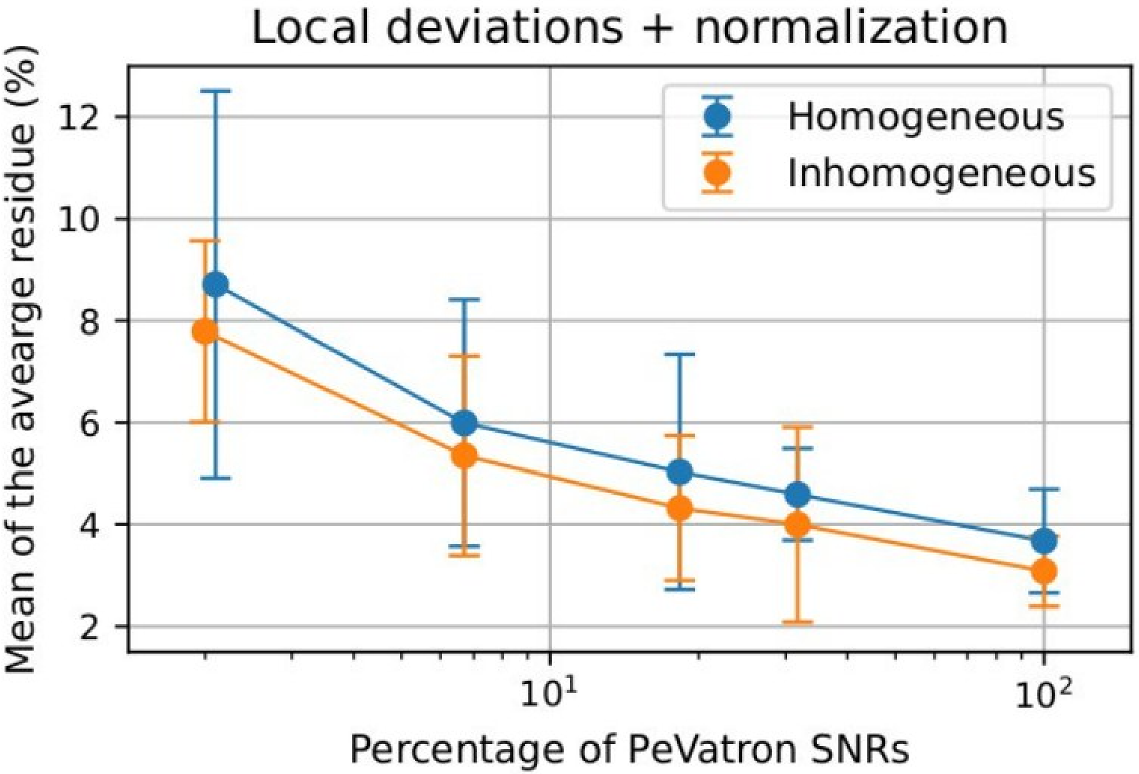
Can be disentangled from clumpiness of diffuse bkg

Z. Cao et al., (2023)



Morphology of the diffuse background

S. Kaci & G. Giacinti (2024)



- The diffusion mechanism does not really impact the diffuse background.
- At VHE there are always deviations from the expected morphology.
- Variations are more important for small numbers of SNRs.
- The morphology of the diffuse background can help to alleviate the degeneracy between the diffusion mechanisms.

Summary & Conclusion

- Gamma-ray flux can be quite clumpy.
- Case 1: CRs diffuse very fast and most sources quickly become invisible.
- The sky map morphology is very sensitive to the propagation mechanism.
- For standard (GALPROP) isotropic diffusion few sources are detectable.
- Assuming a short period of suppressed diffusion several sources appear.
- Inhomogeneous diffusion implies a PeVatron SNR rate $< 3.6/\mathrm{kyr}$.