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

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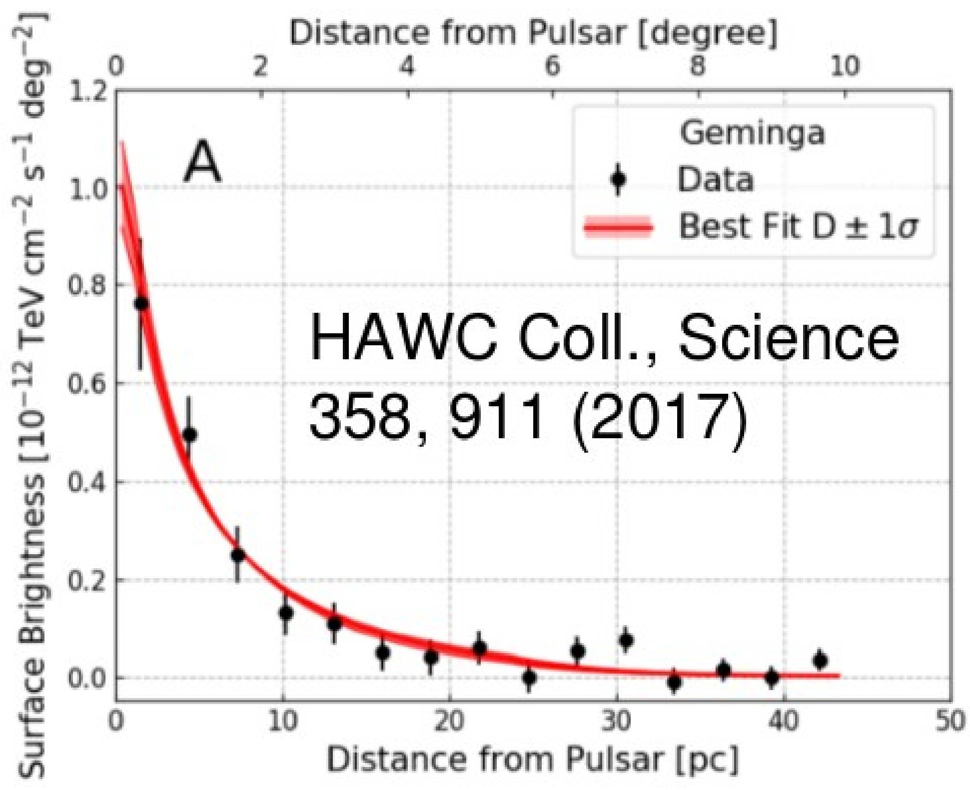
1 – TeV halos as a probe of CR propagation in the ISM

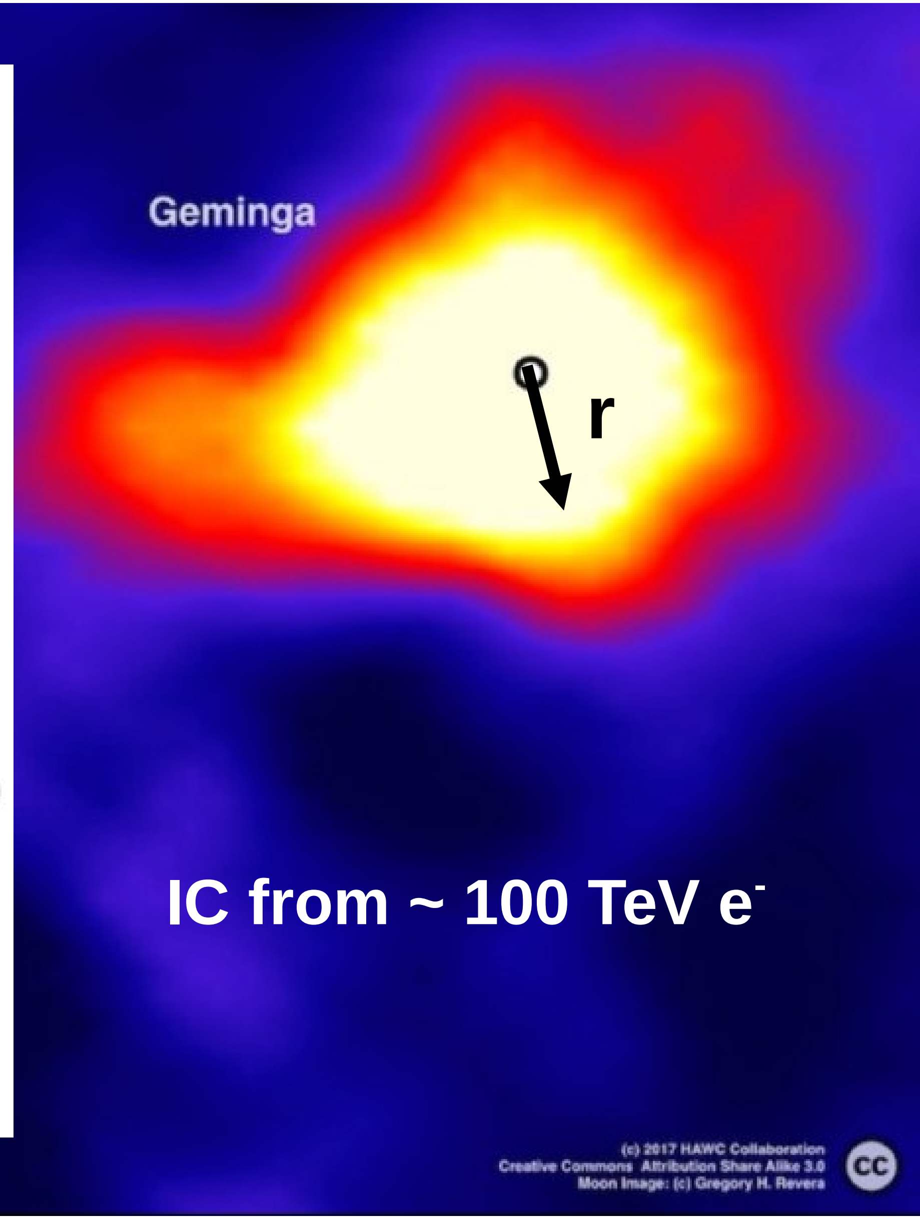
Giacinti et al., A&A 636, A113 (2020),
Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018)

HAWC observ. of Geminga & Monogem



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

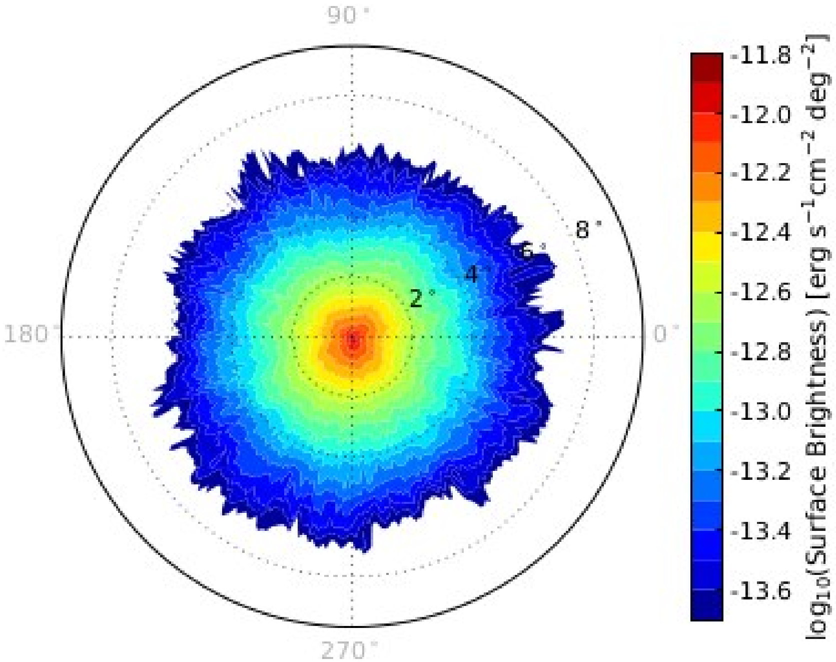
at 100TeV.



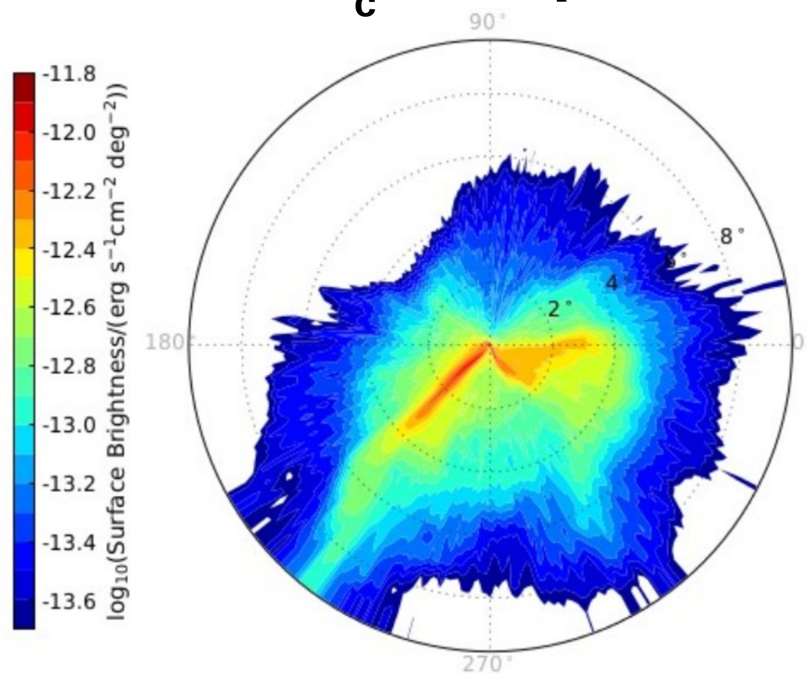
Predicted γ-ray surface brightness

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]

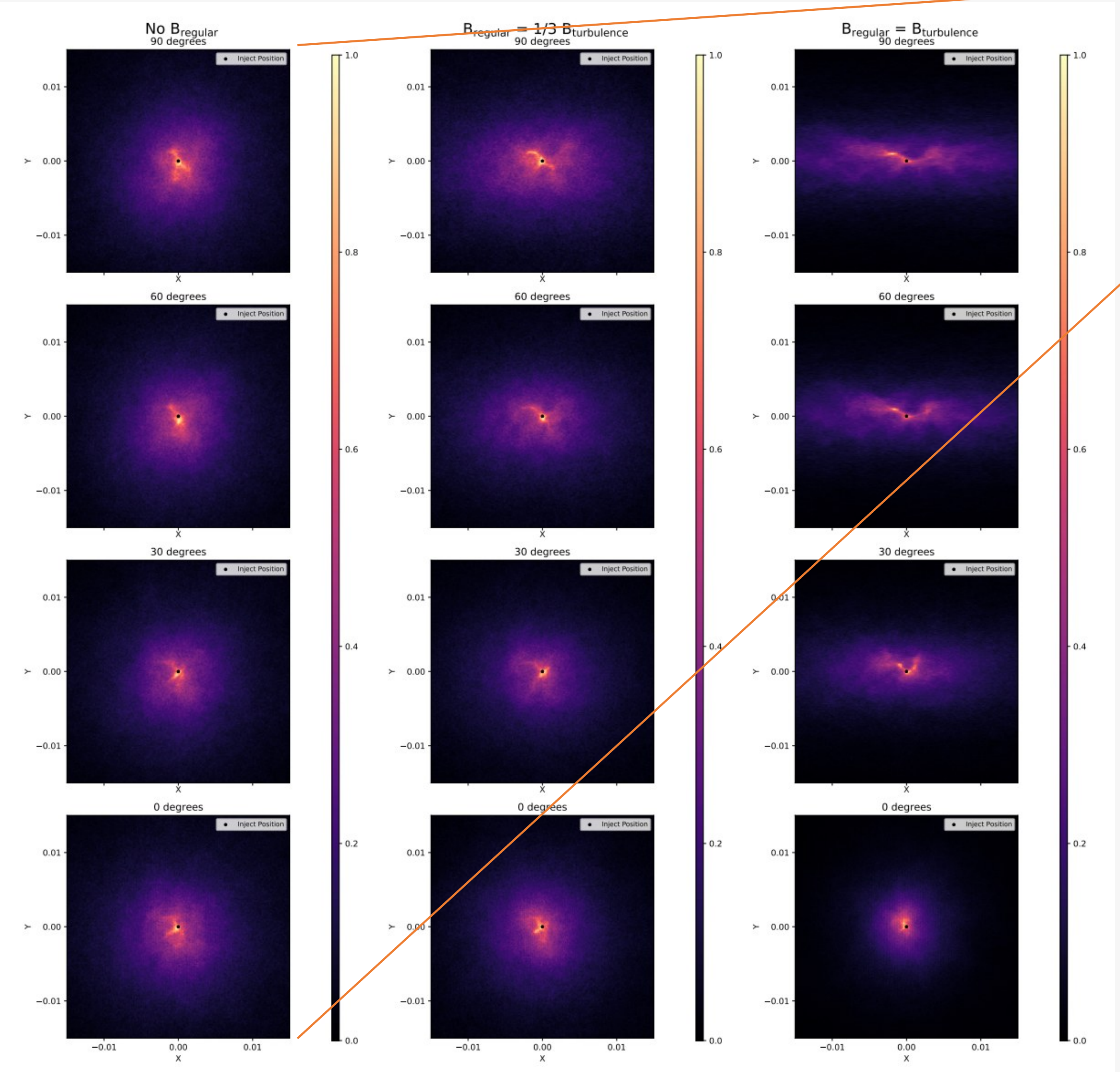
Li, Giacinti & Lopez-Coto, To be submitted (2025)

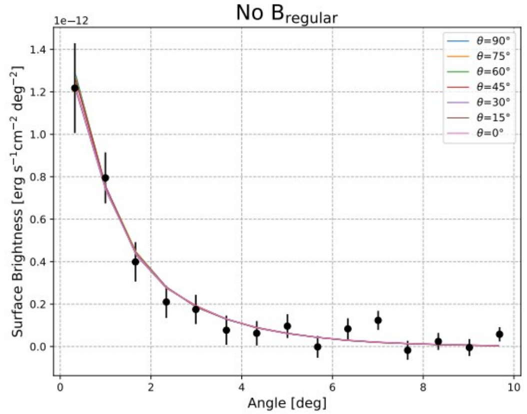
Yuan Li

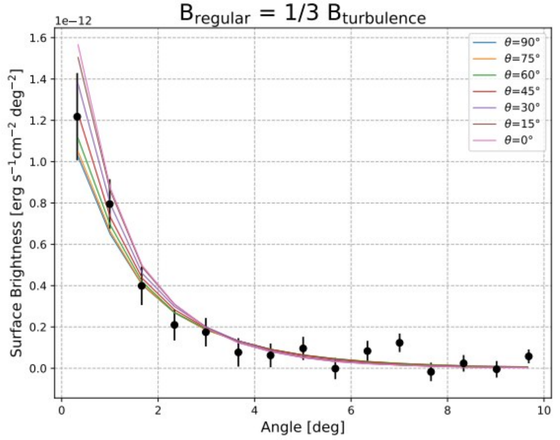
→ **POSTER**

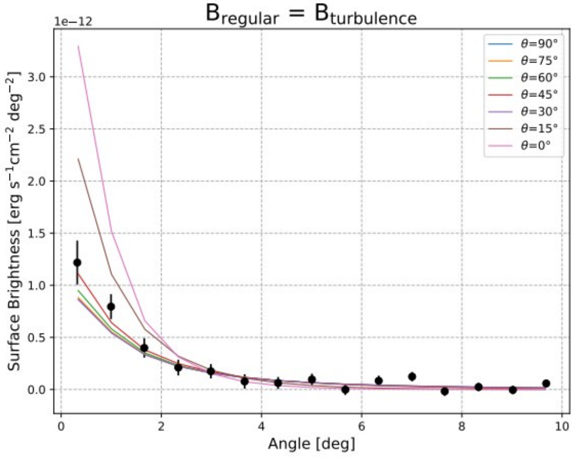
Best fits around
L_c=1-5 pc,
B_{rms}=3-4 μG

Kolmogorov,
L_c=1 pc,
B_{rms}=3 μG









Li, Giacinti & Lopez-Coto, To be submitted (2025)

Yuan Li

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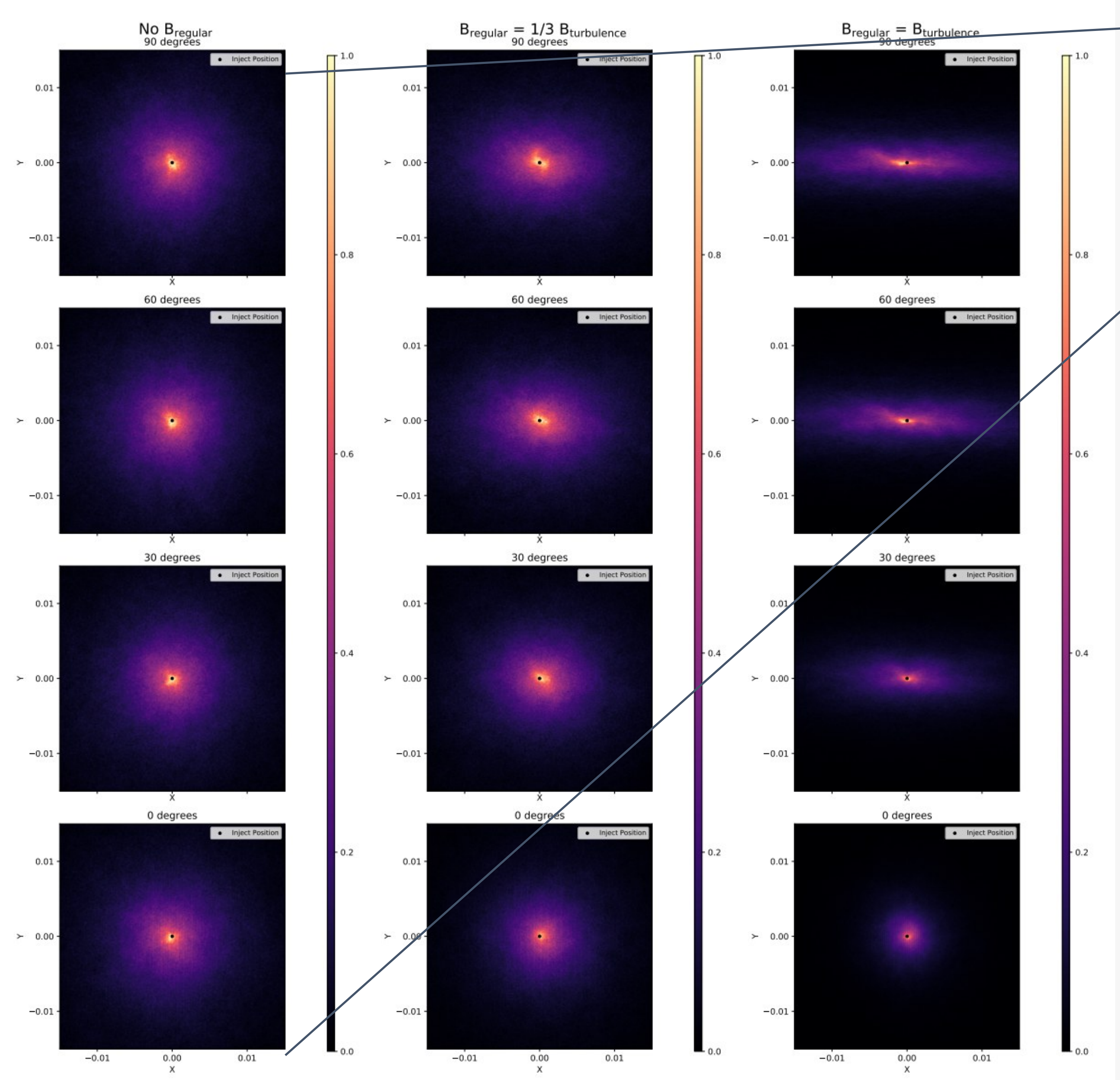
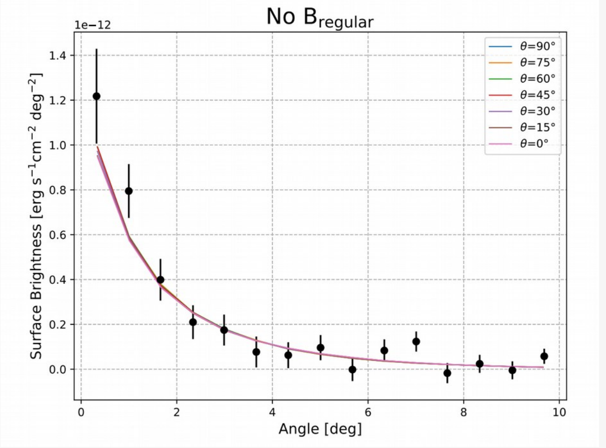
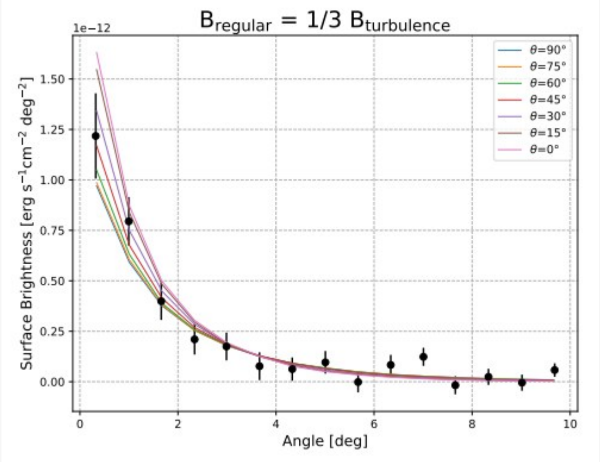
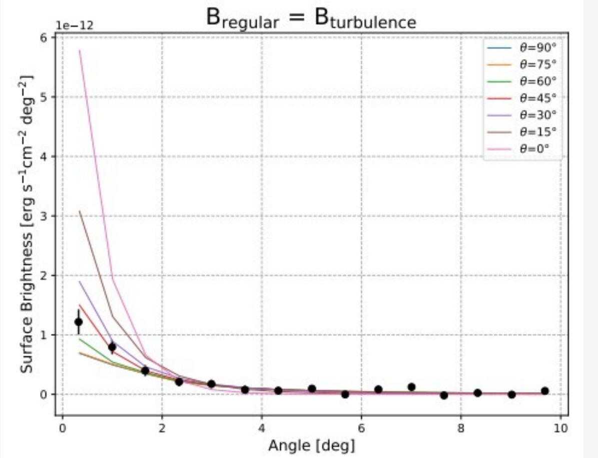


Best fits around L_c=1-5 pc, B_{rms}=3-4 μG

Bohm, L_{max}=5 pc, B_{rms}=3 μG

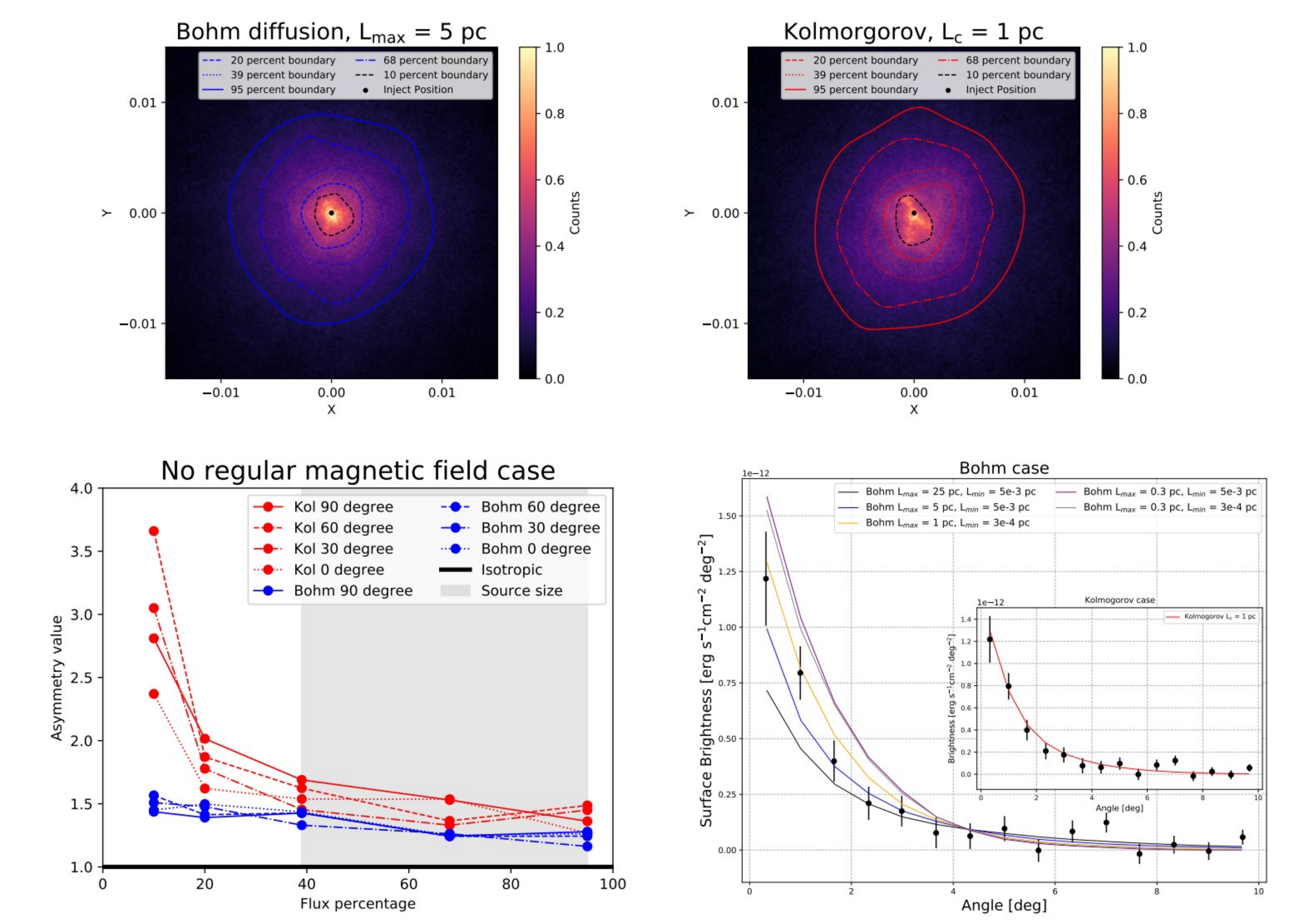






Asymmetry results ($B_{regular} = 0$):

Li, Giacinti & Lopez-Coto, To be submitted (2025)



Yiwei Bao

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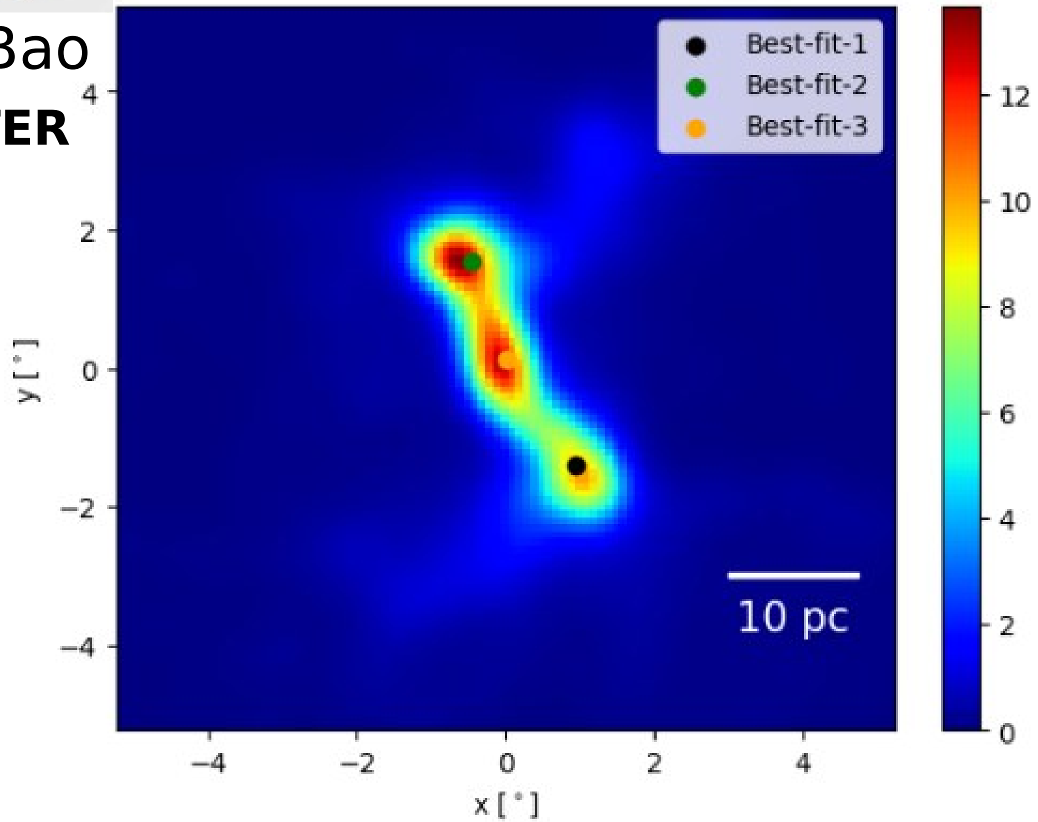
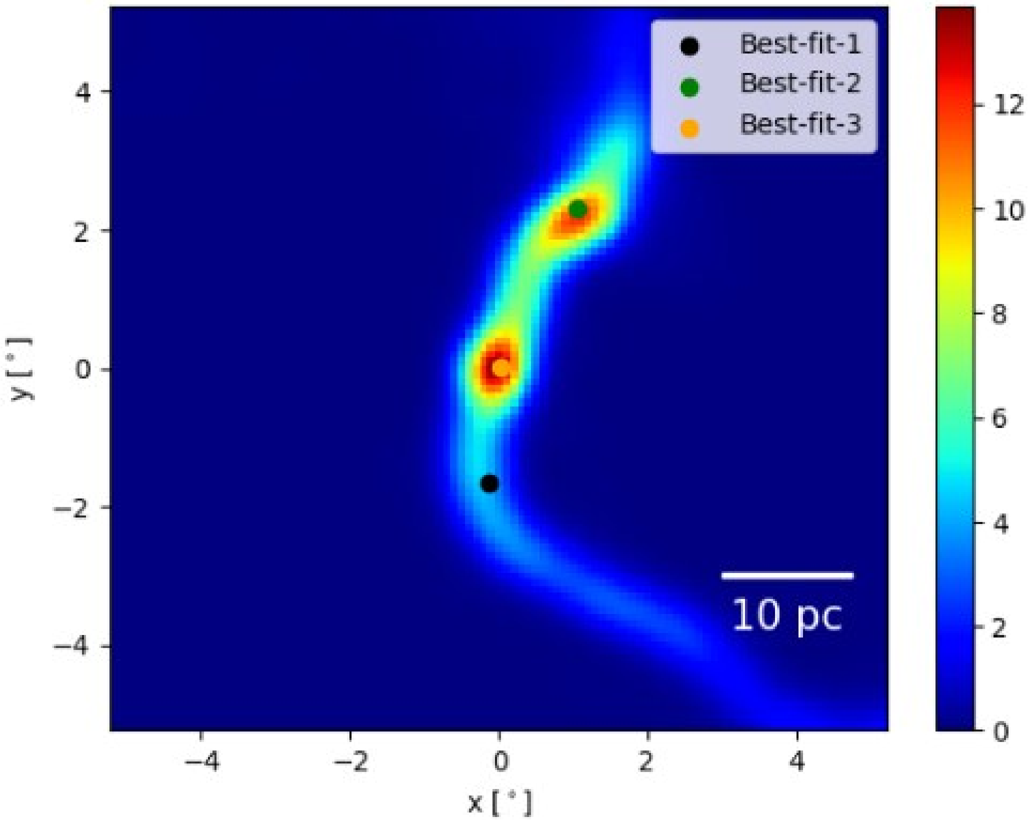
Appearance of “mirage” sources:

They may appear around astrophysical sources.





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

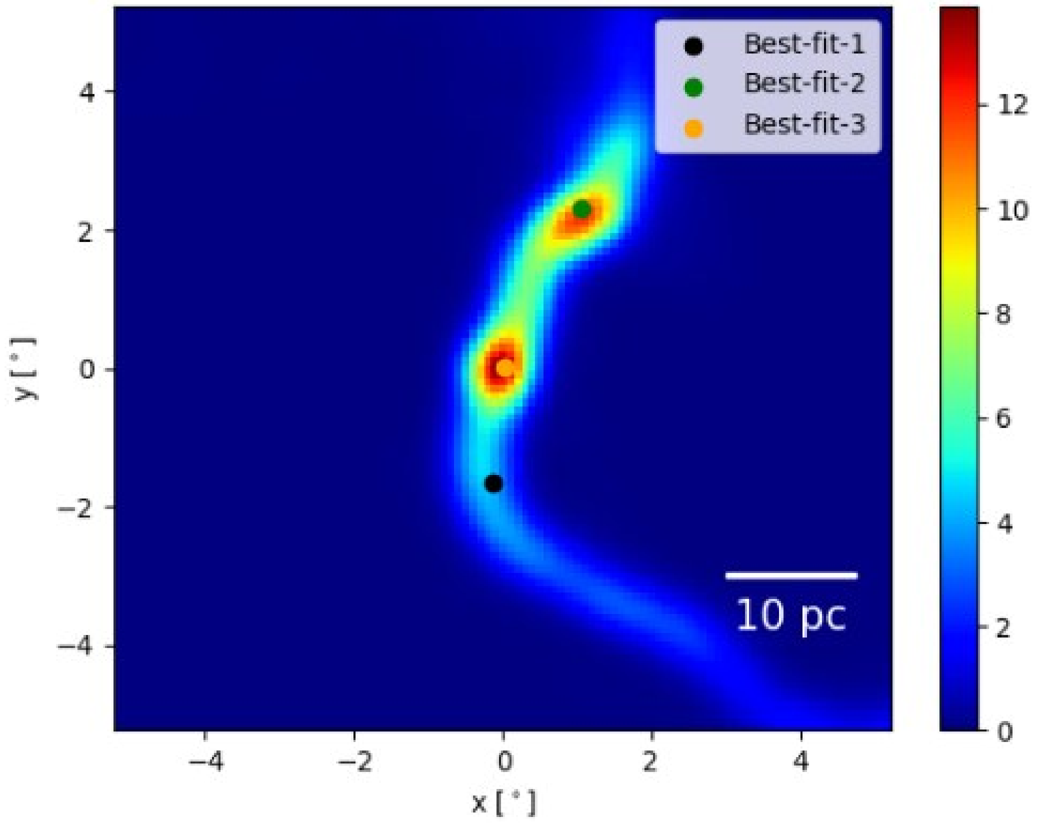
Bao, Giacinti, Liu, Zhang & Chen, arXiv:2407.02478
Bao, Liu, Giacinti, Zhang & Chen, arXiv:2407.02829

Yiwei Bao

Appearance of “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.)

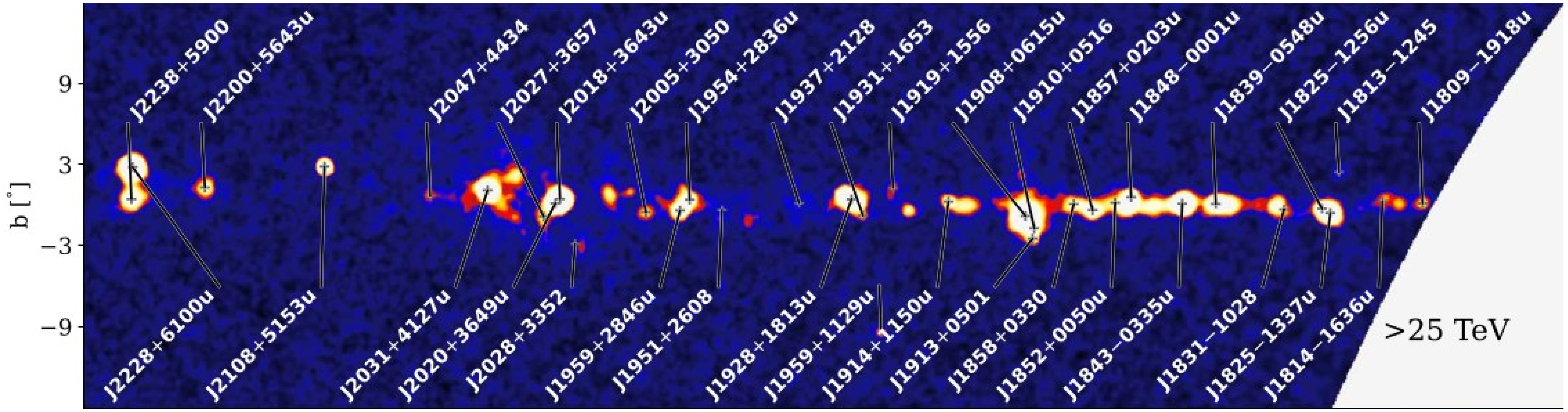


Bao, Giacinti, Liu, Zhang & Chen, arXiv:2407.02478
Bao, Liu, Giacinti, Zhang & Chen, arXiv:2407.02829

Could explain LHAASO observations

LHAASO Collaboration, ApJS 271, 25 (2024)

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



Large offsets between sources and center

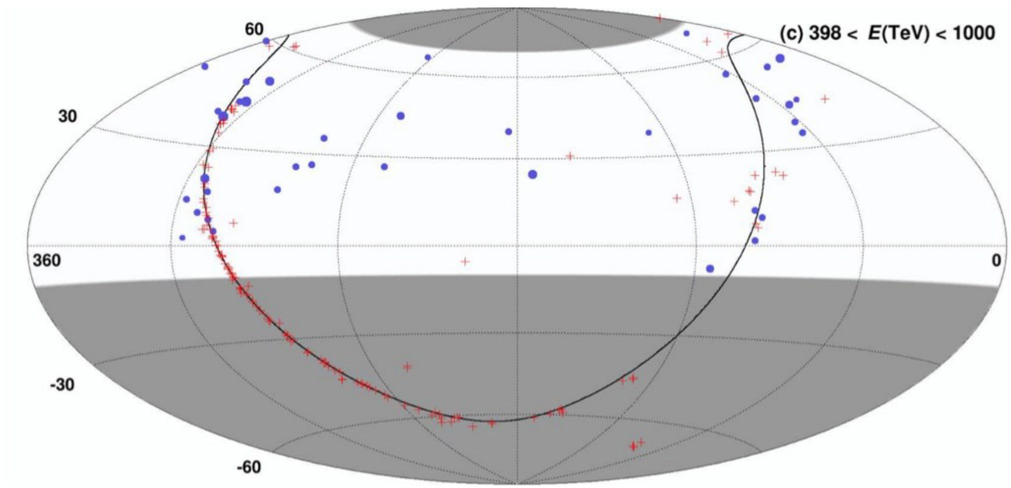
No counterparts?

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	

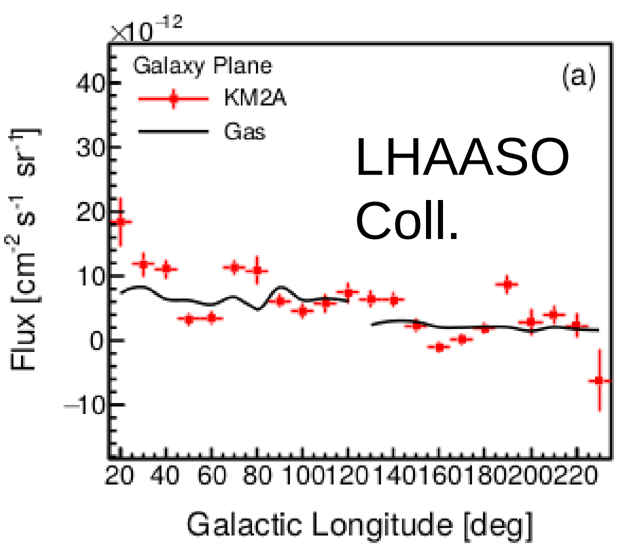
2 – Diffuse VHE γ-ray emission

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 γ-ray emission from discrete sources

SIMULATION:

Kaci & Giacinti, JCAP 01, 049 (2025)

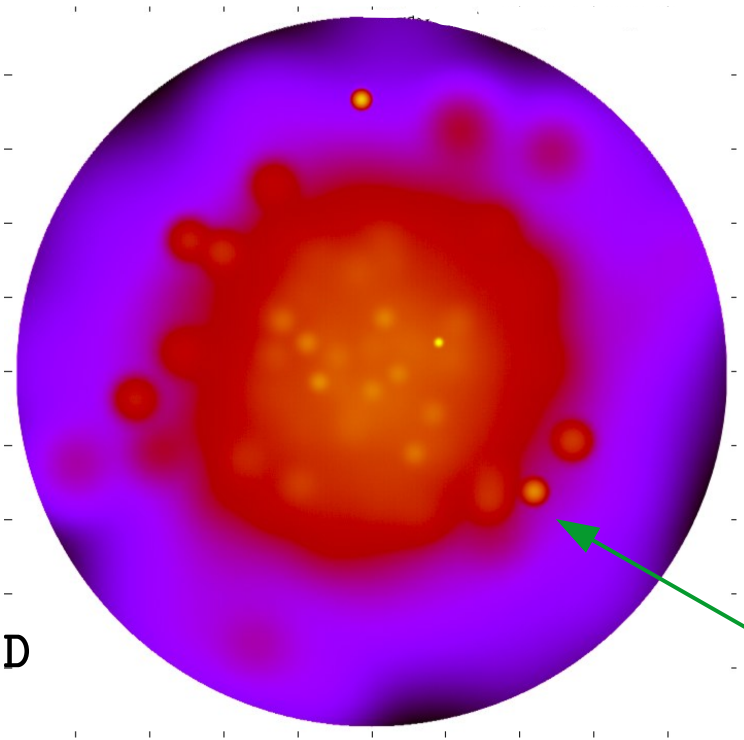
Isotropic and homogeneous diffusion

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

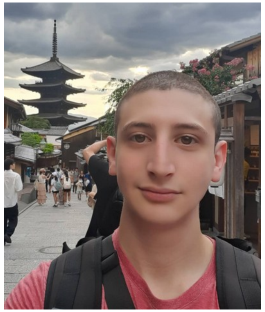
$$D(E) = 10^{28} D_{28} \left(\frac{R}{3GV}\right)^{\delta} cm^2/s$$

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

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



Discrete injection of cosmic rays

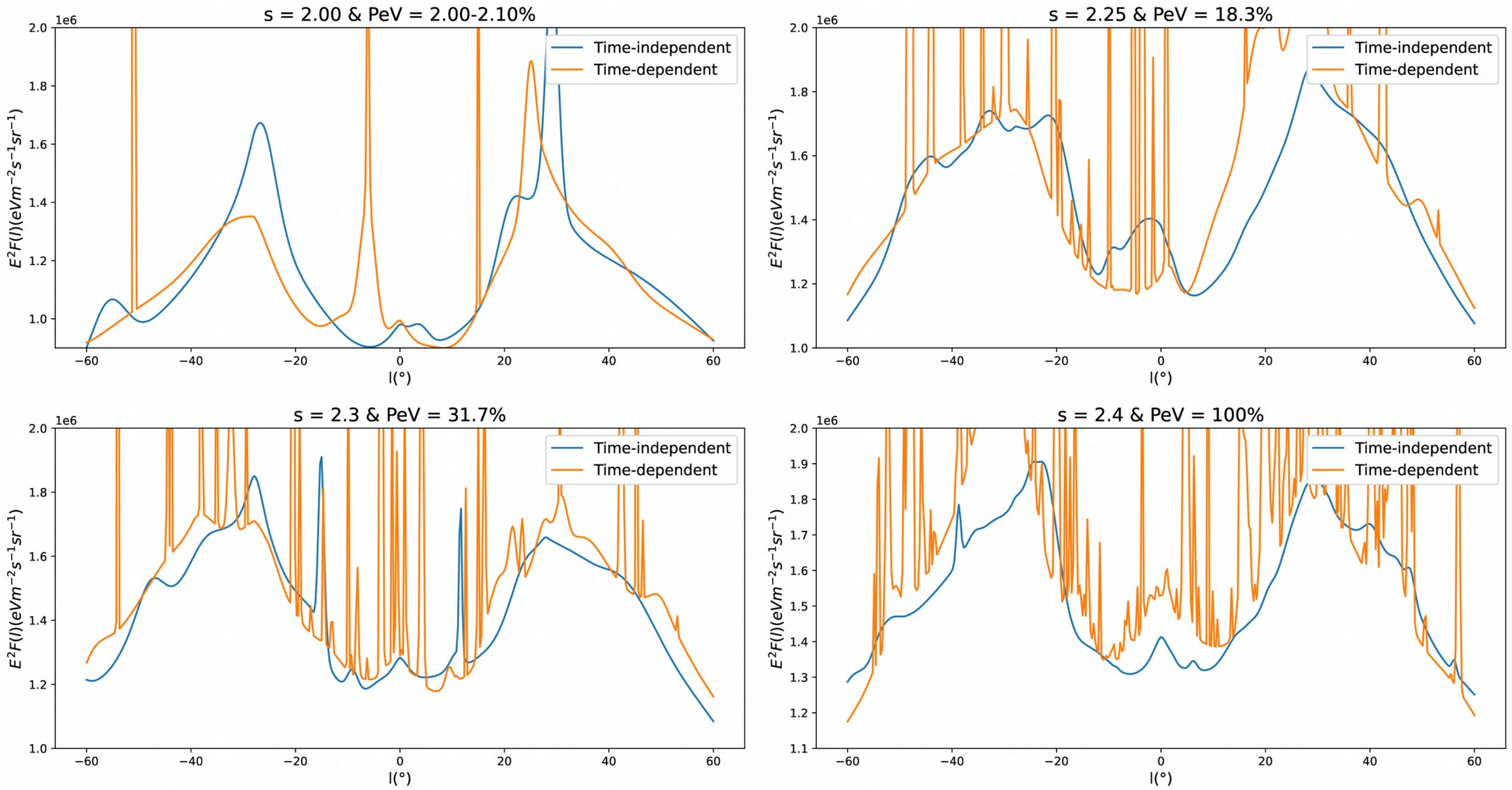


Samy Kaci

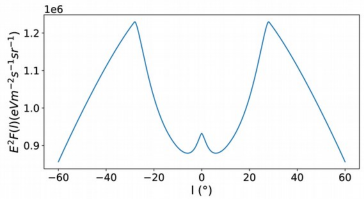
Cosmic-ray flux at Earth and B/C ratio satisfied

Clumps in the gamma-ray flux

Kaci & Giacinti, JCAP 01, 049 (2025)



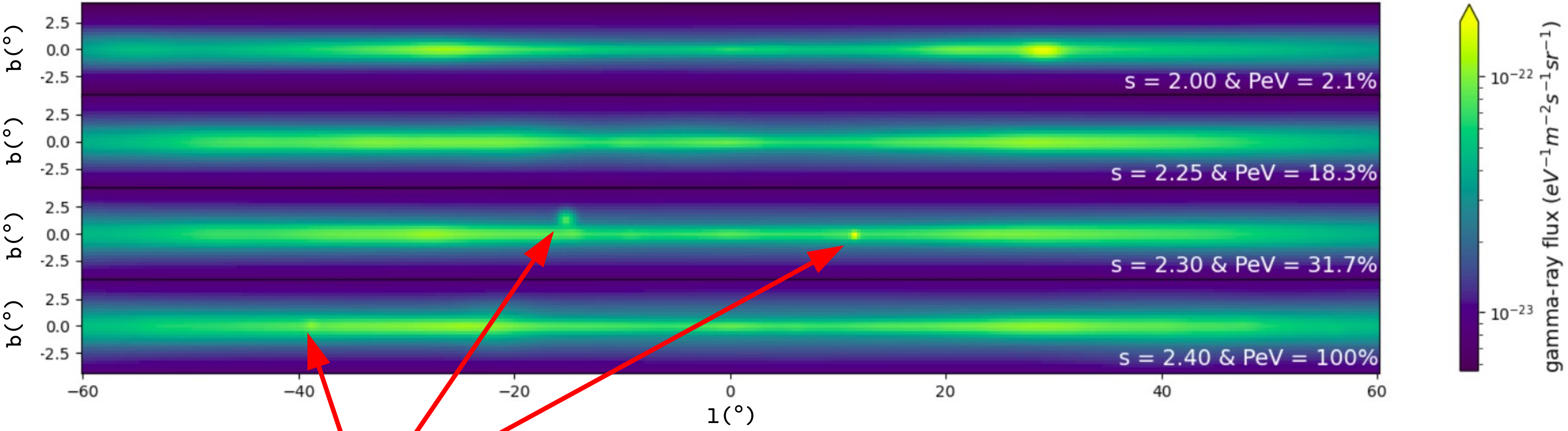
General shape like Lipari & Vernetto



Diffuse gamma-ray flux clumpy at VHE

Slide from Samy Kaci

Sky Maps and sources (case 1)



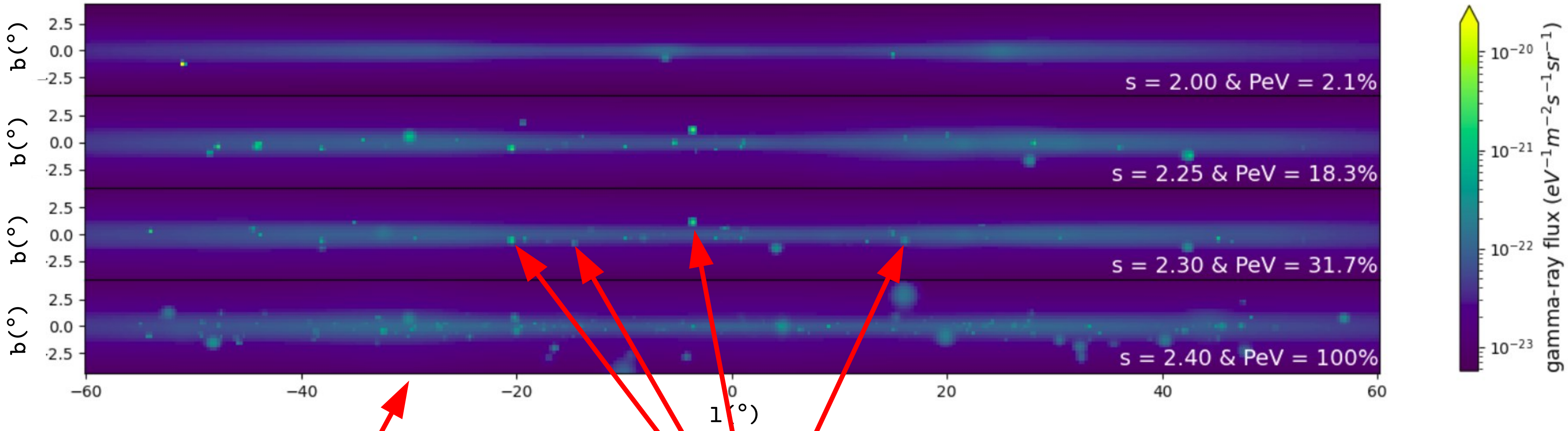
Very few visible sources for case 1

For standard isotropic diffusion, few PeVatrons are detectable

Kaci & Giacinti, JCAP 01, 049 (2025)

Slide from Samy Kaci

Sky Maps and sources (case 2)



Sky map very sensitive to CR propagation assumptions

Many more visible sources

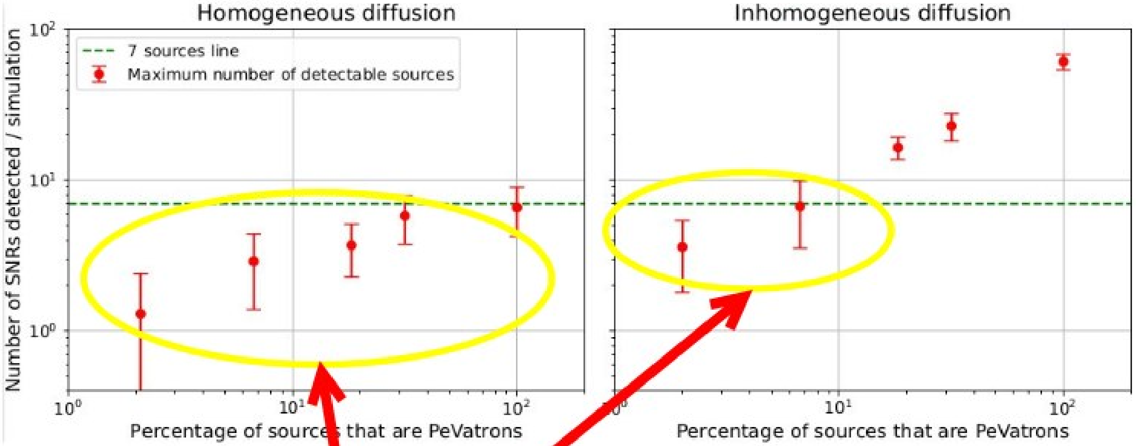
Implies a PeVatron SNR rate < 3.6/kyr

Kaci & Giacinti, JCAP 01, 049 (2025)

Slide from Samy Kaci

Number of detectable sources

Kaci & Giacinti, JCAP 01, 049 (2025)

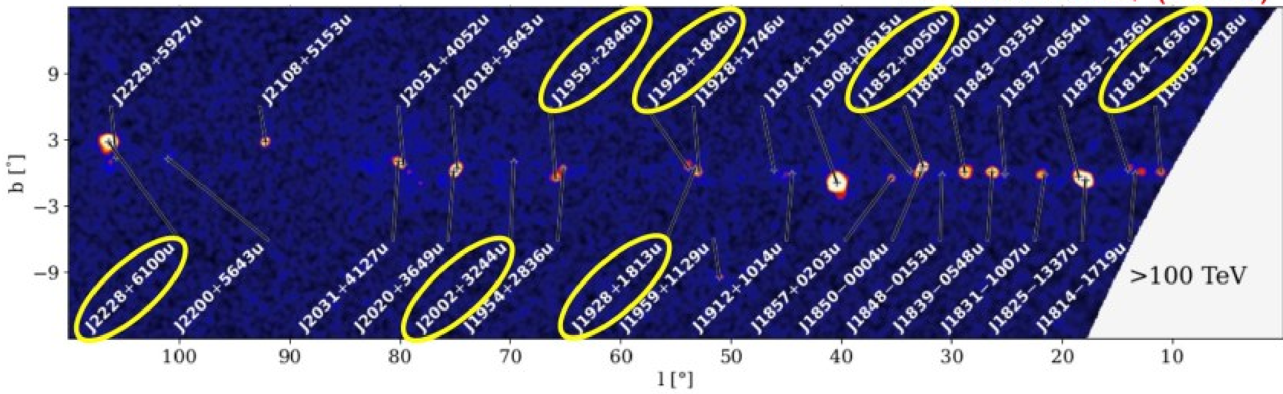


- Two diffusion regimes lead to different results concerning the detectability of sources.
- Homogeneous diffusion strongly limits the detectability of sources.
- Some parts of the space paramters can already be excluded.

There is still some degeneracy between the two cases

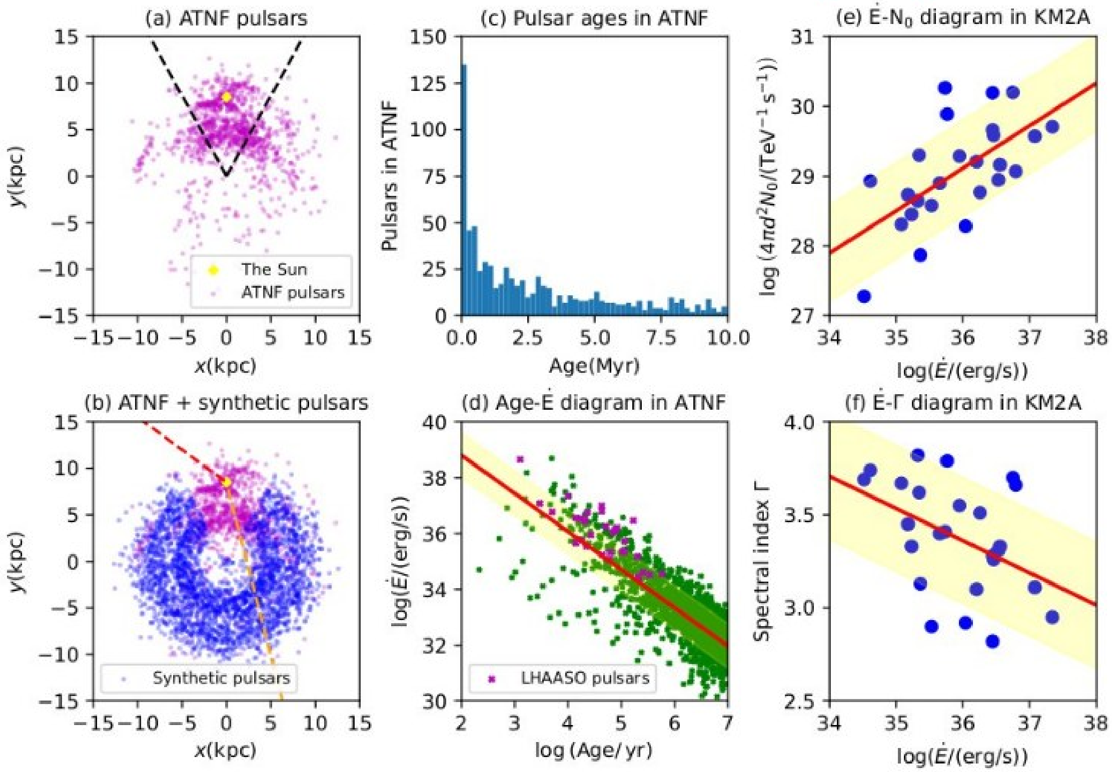
Can be disentangled from clumpiness of diffuse bkg

Z. Cao et al., (2023)



Impact of unresolved sources (PWNe)

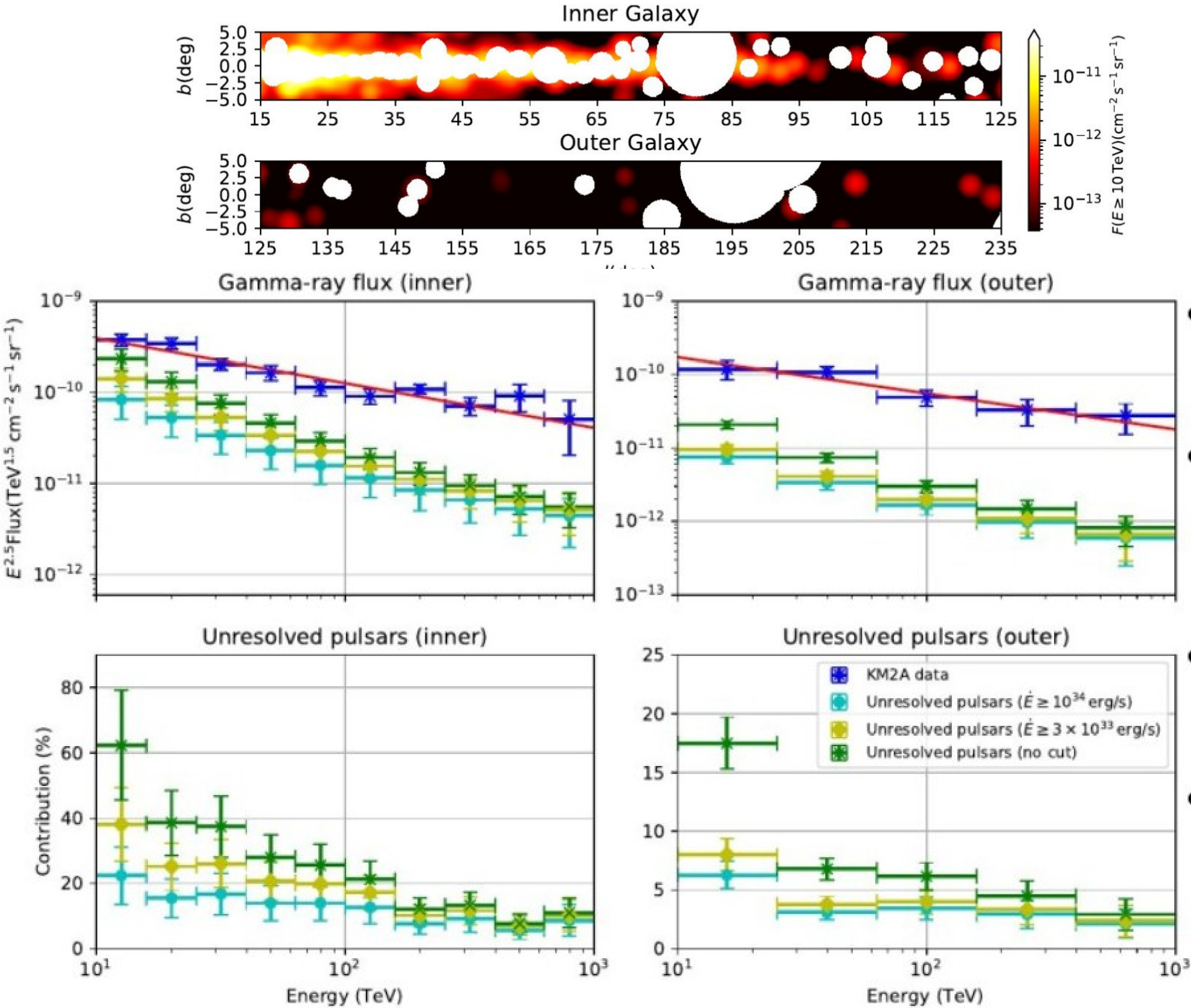
Kaci, Giacinti, Semikoz, ApJ Lett. 975, L6 (2024)



- 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.

Upper Limits unresolved PWNe/halos

Kaci, Giacinti, Semikoz,
ApJ Lett. 975, L6 (2024)



Microquasars as Galactic super-PeVatrons

Kaci, Giacinti et al., To be submitted (2025)

→ **POSTER 8**

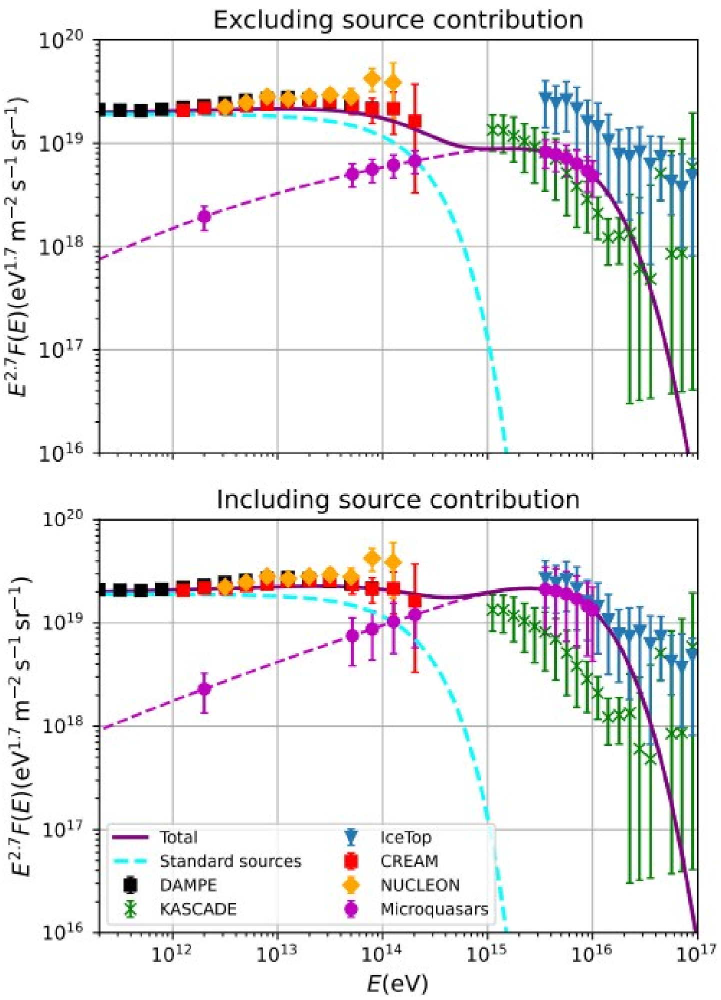
Microquasars: inj. -2 spectrum, cutoff at 10 PeV, 100 kyr lifetime, 0.1/kyr rate, power $10^{39\text{-}40}$ erg/s.

(Standard/SNR sources: -2.7 Power-law & exponential cutoff at 150TeV.)

-Up: Lower limit by excluding the existence of any active source within 4 kpc in the last 500 kyr.

- Down: No source younger than 100 kyr within 2.2 kpc. Only objects reported by BlackCat at r < 2.2 kpc, in the FoV of LHAASO and no detection by LHAASO.

→ Fits the knee and the 10TeV bump.



Microquasars as Galactic super-PeVatrons

Kaci, Giacinti et al., To be submitted (2025)

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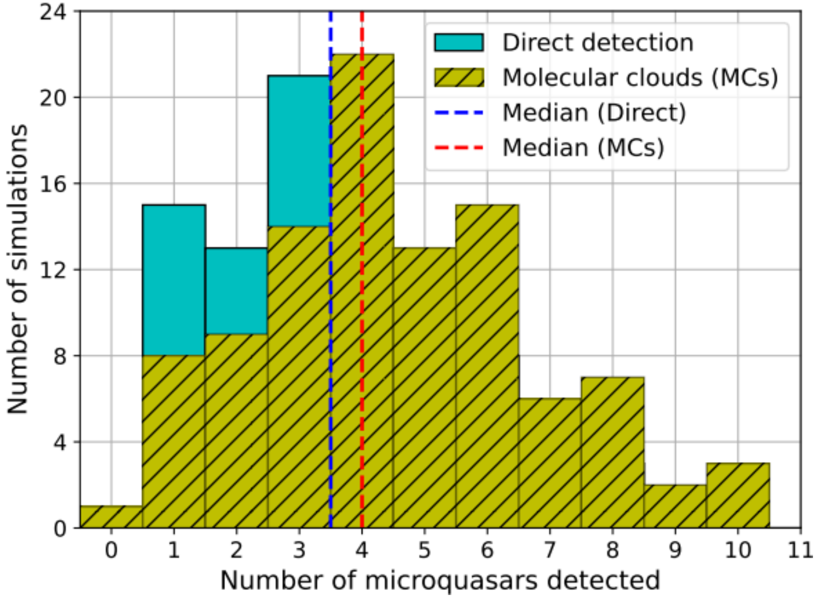
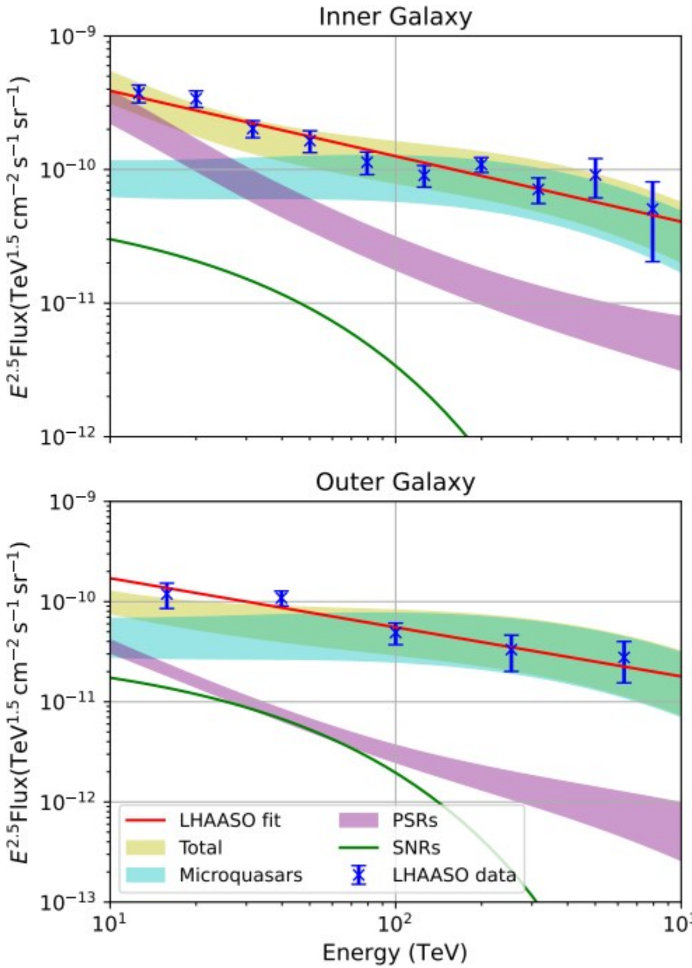
On average 3-4 sources detectable:



molecular clouds similar to that around SS433
(uniform sphere with r = 20pc and n=30cm^{-3})

Contribution to the diffuse emission:



Conclusions & Perspectives

→ **TeV halos** and **diffuse γ-ray emission** constrain CR propagation & sources:

→ **Best fit** parameters for **Geminga**. **LHAASO will help refine them.**
Inner asymmetries can help disentangle between Kolmogorov (slightly favored) and Bohm,

→ **“Mirage” sources**: **Could explain some LHAASO sources.**

→ New code for **stochastic CR injection** in the Galaxy: **Clumpy diffuse background at VHE**
=> LHAASO constraints on PeVatron frequency / CR propagation,

→ **Unresolved PWNe/halos**: Minor contribution to LHAASO diffuse emission at > a few 10 TeV,

→ ~ 10 powerful **microquasars** can fit the CR spectrum and LHAASO diffuse emission.