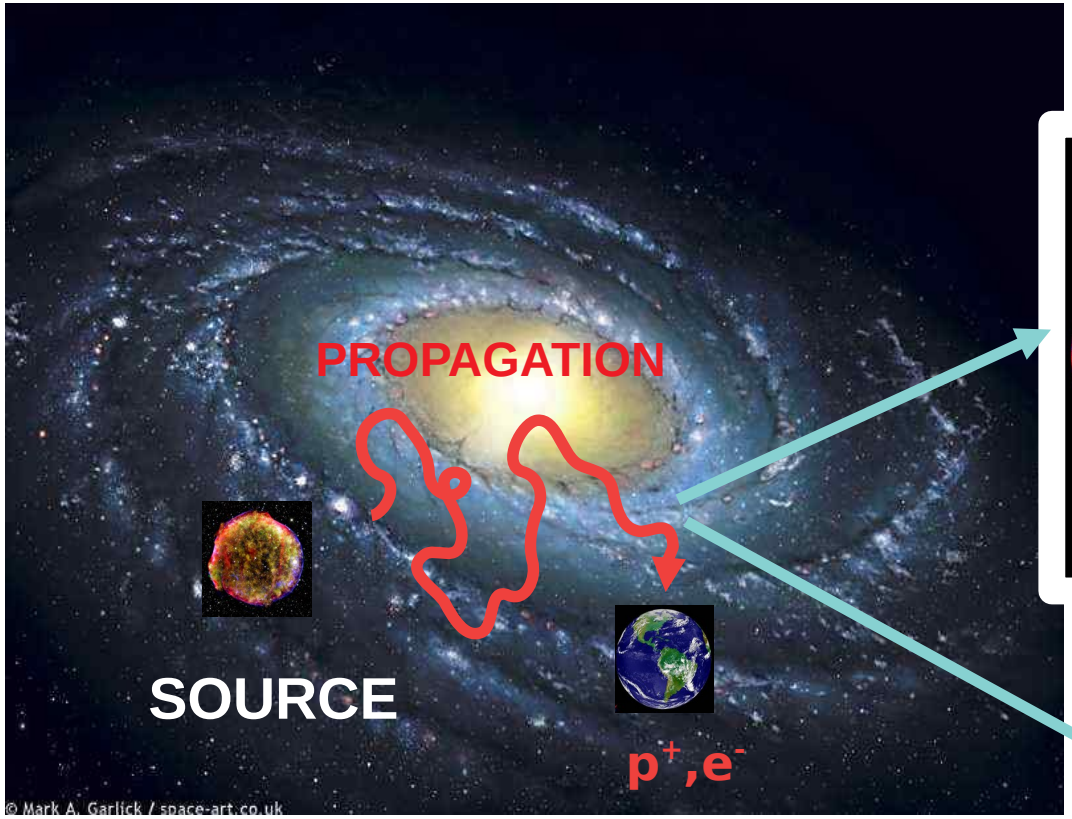
CR PROPAGATION IN THE GALAXY: INSIGHTS FROM TeV HALOS, THE DIFFUSE γ-RAY EMISSION, AND THE CR ANISOTROPY

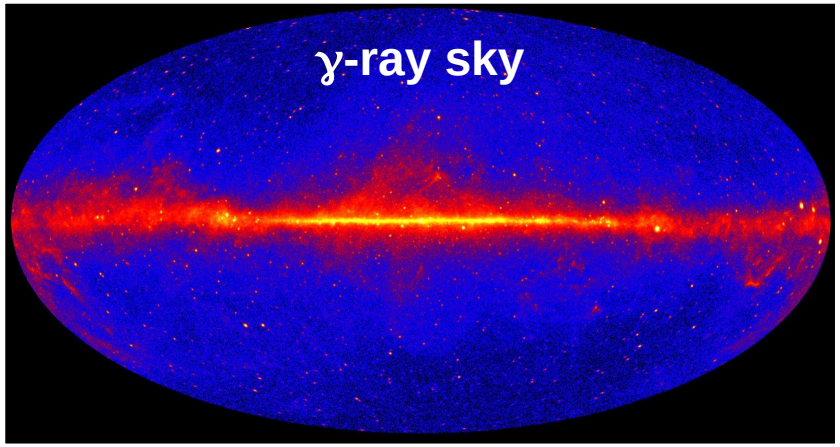
Gwenael Giacinti
(APC Paris, CNRS)

Collaborators include:
Maksim Kleimenov, Samy Kaci, Yuan Li, Yiwei Bao

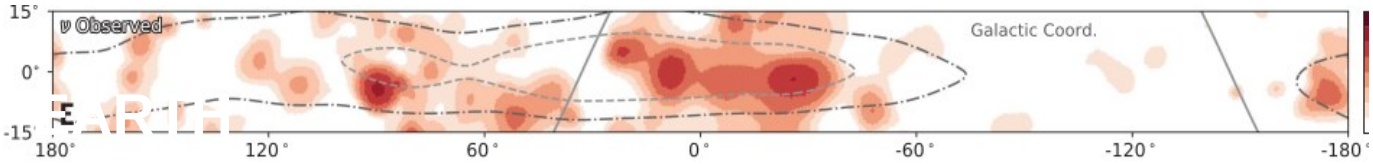
Cosmic-rays & their secondaries :



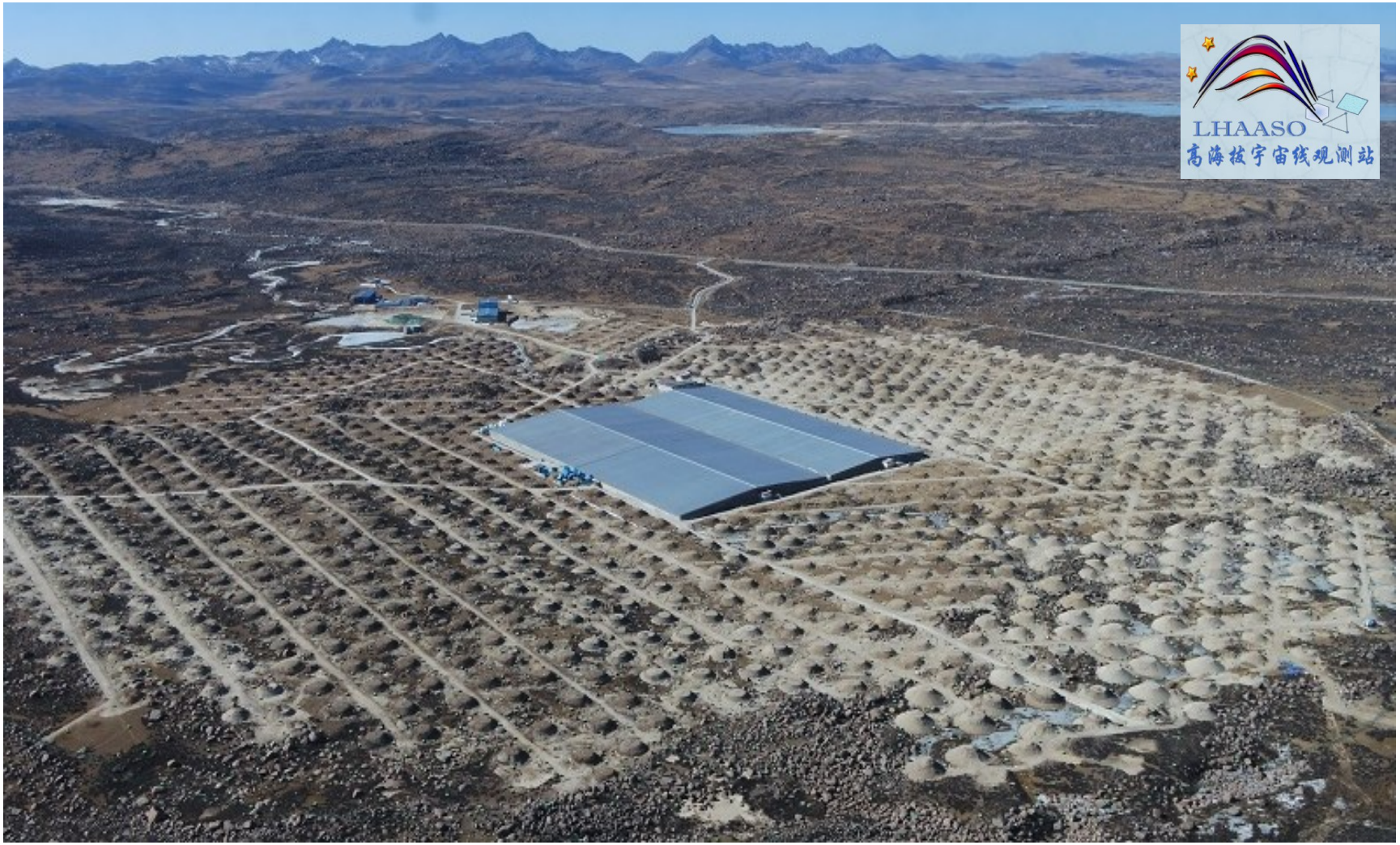
Produce γ-rays, neutrinos:



ν sky

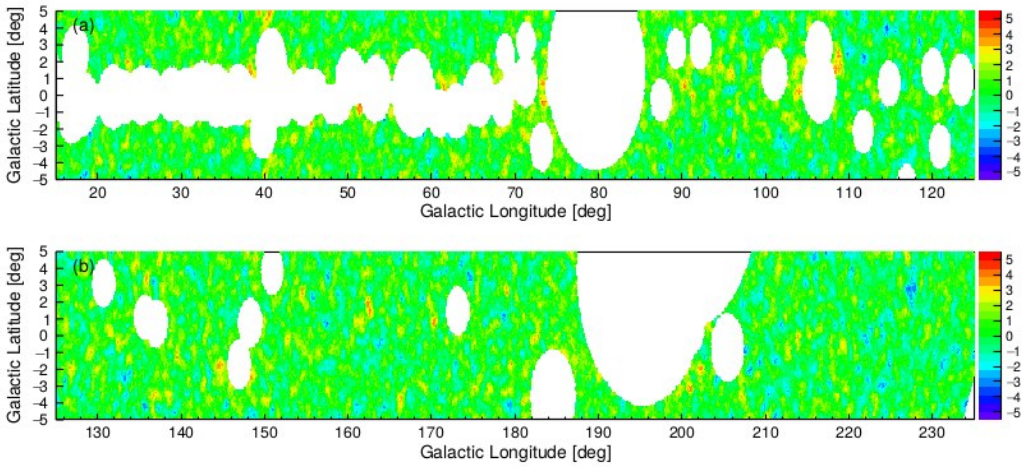


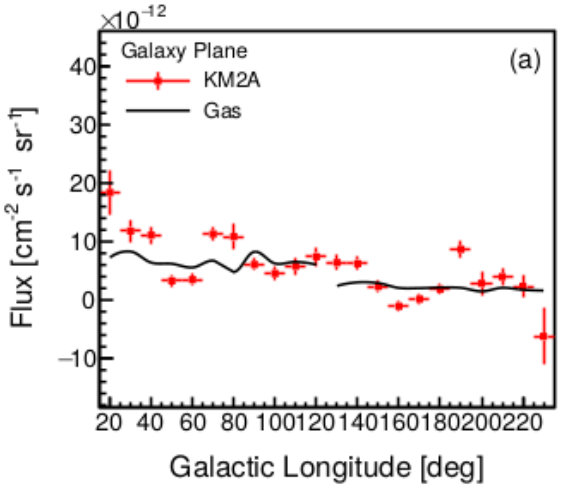
PeV Gamma-Ray Astronomy: LHAASO



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

LHAASO Collaboration, Phys. Rev. Lett. 131, 151001 (2023)

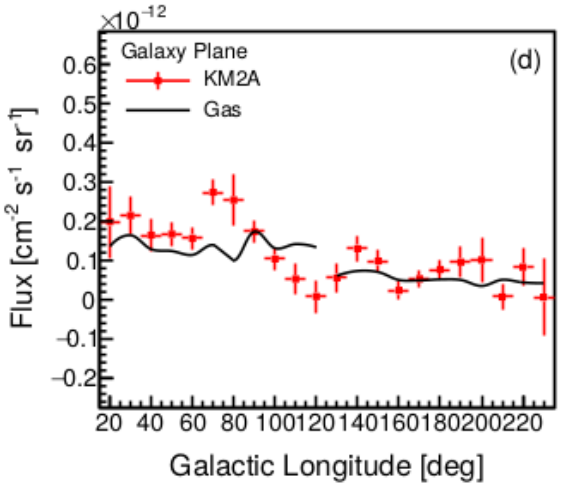




Emission in Galactic longitude does not follow target gas…

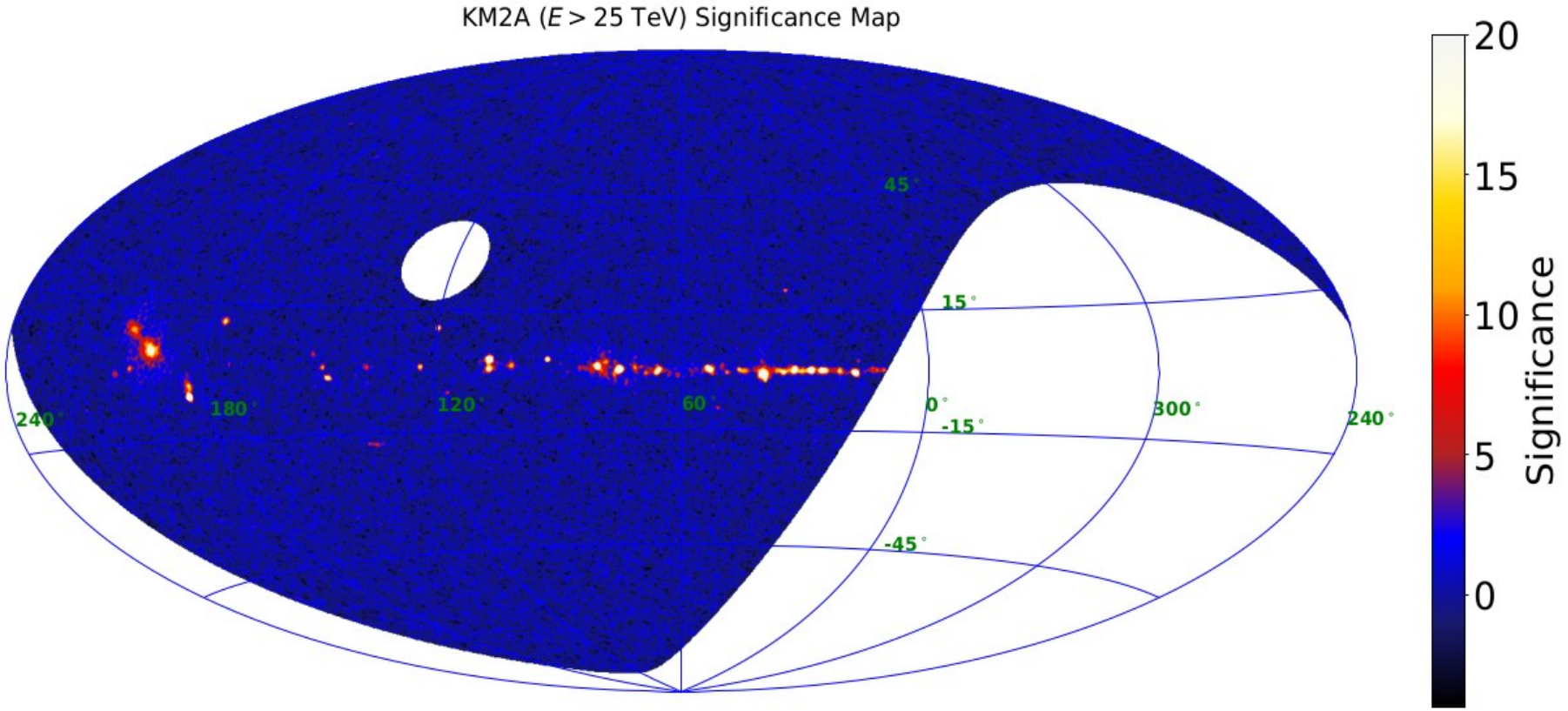
→ Leptonic origin?

→ Stochasticity of CR injection?



Sky at 25 TeV – 1 PeV with LHAASO

LHAASO Collaboration

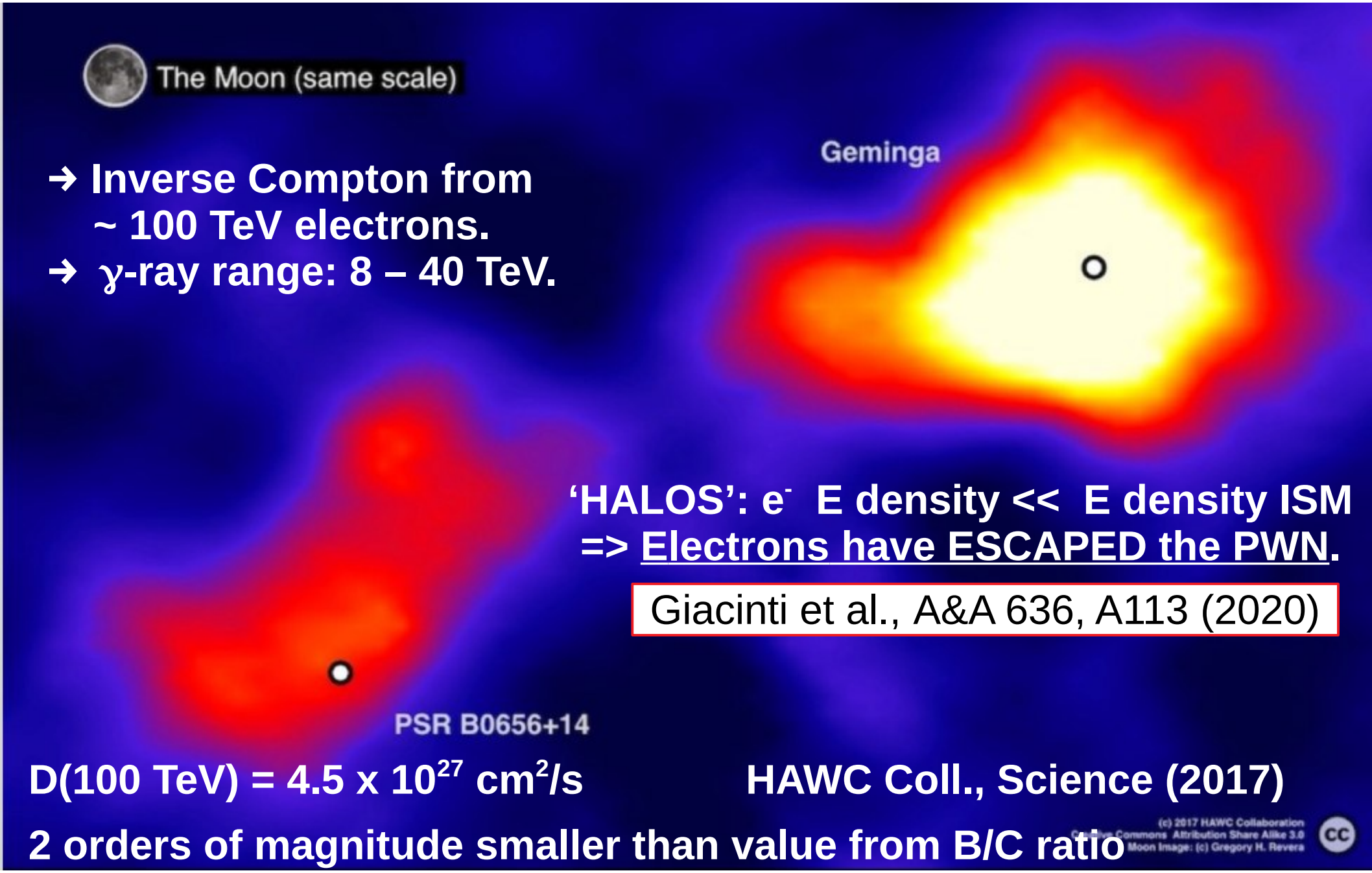


> Dozen of PeVatrons

~ 35 **PWNe & TeV Halos** (leptonic); ~ 7 **SNRs** (hadronic);
A **stellar cluster** (hadronic); 5 **Microquasars** (hadronic/leptonic?)

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

HAWC observ. of Geminga & Monogem



➜ Inverse Compton from ~ 100 TeV electrons.

➜ γ-ray range: 8 – 40 TeV.

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

=> Electrons have ESCAPED the PWN.

Giacinti et al., A&A 636, A113 (2020)

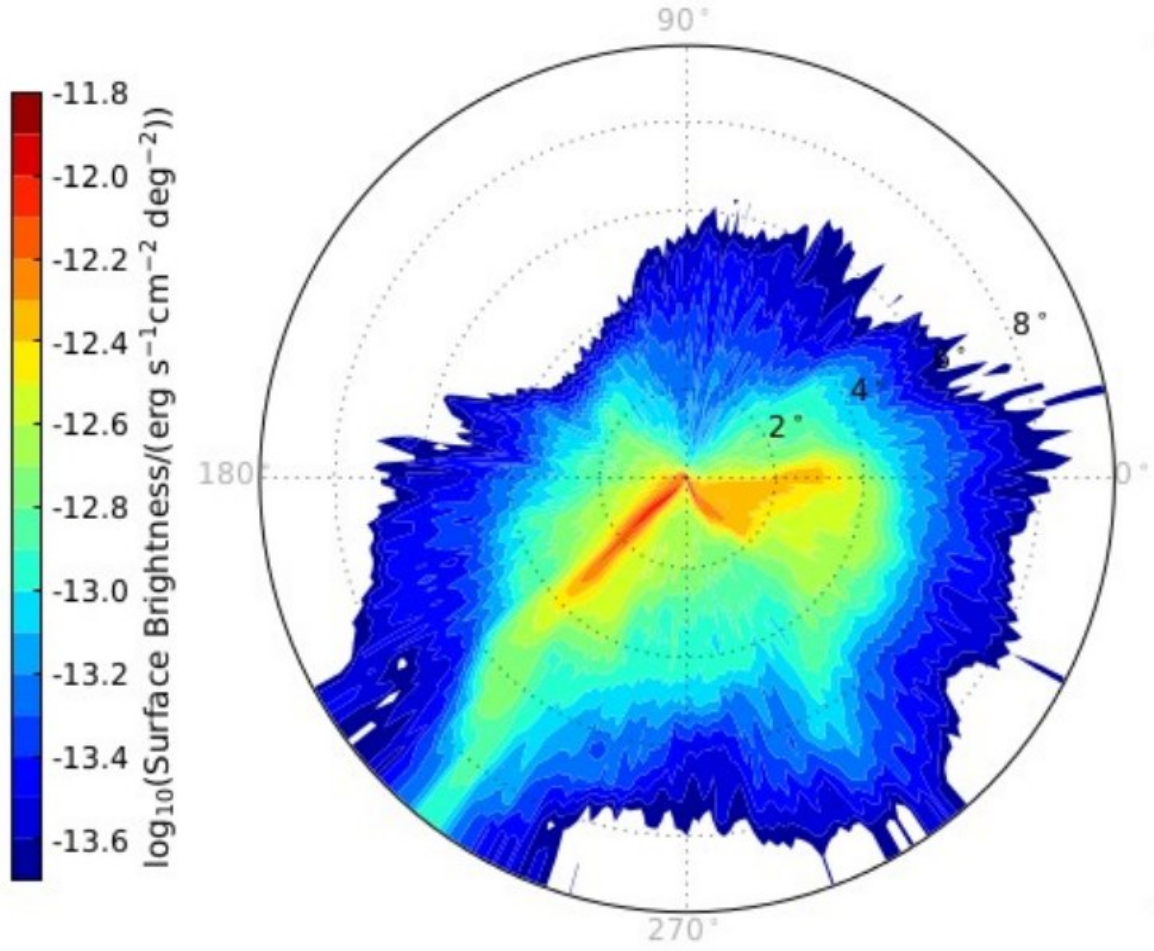
$D(100\ \text{TeV}) = 4.5 \times 10^{27}\ \text{cm}^2/\text{s}$

HAWC Coll., Science (2017)

2 orders of magnitude smaller than value from B/C ratio

Predicted γ-ray surface brightness

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

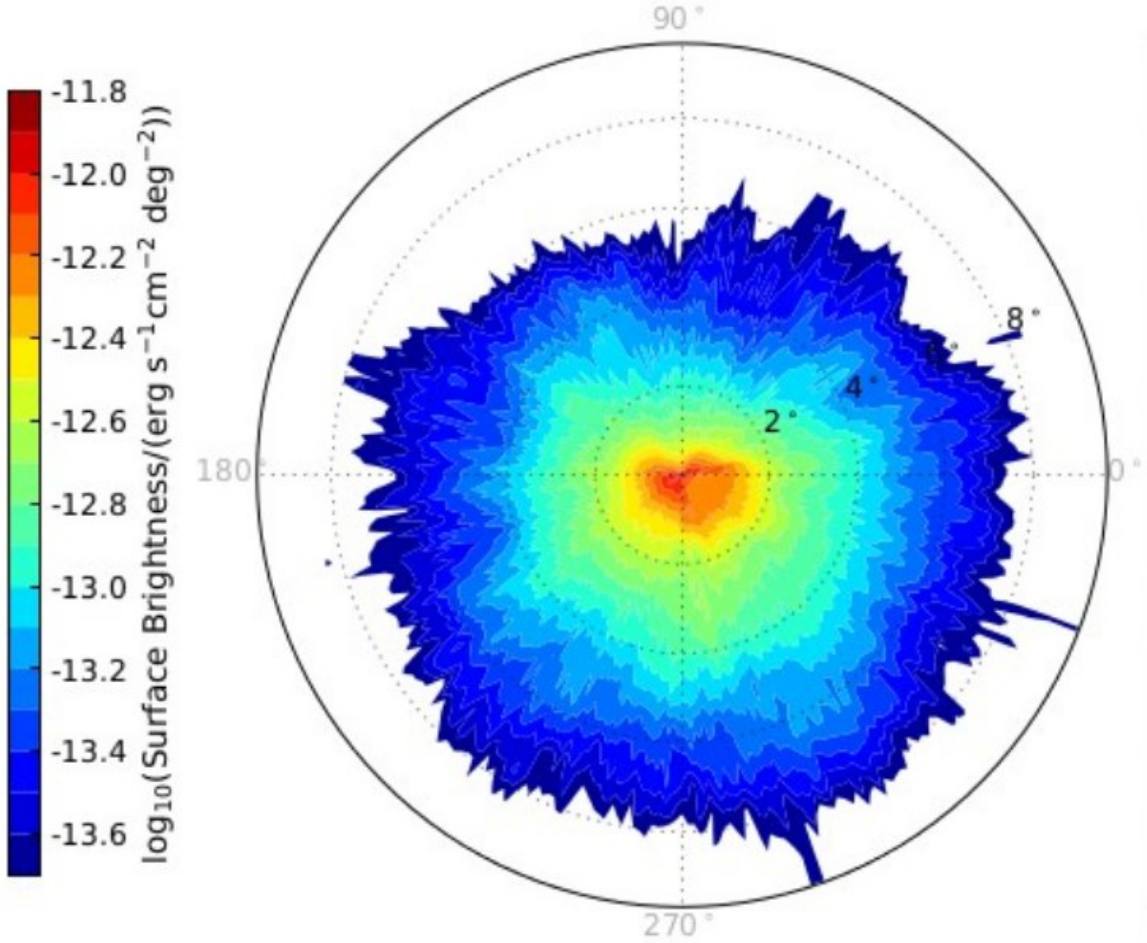


INCOMPATIBLE WITH HAWC MEASUREMENTS

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

Predicted γ-ray surface brightness

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

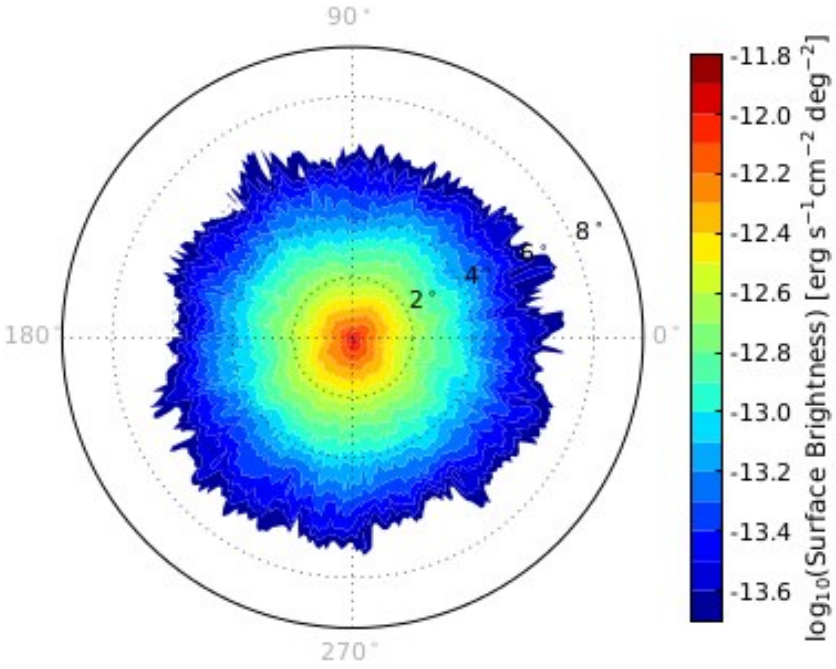


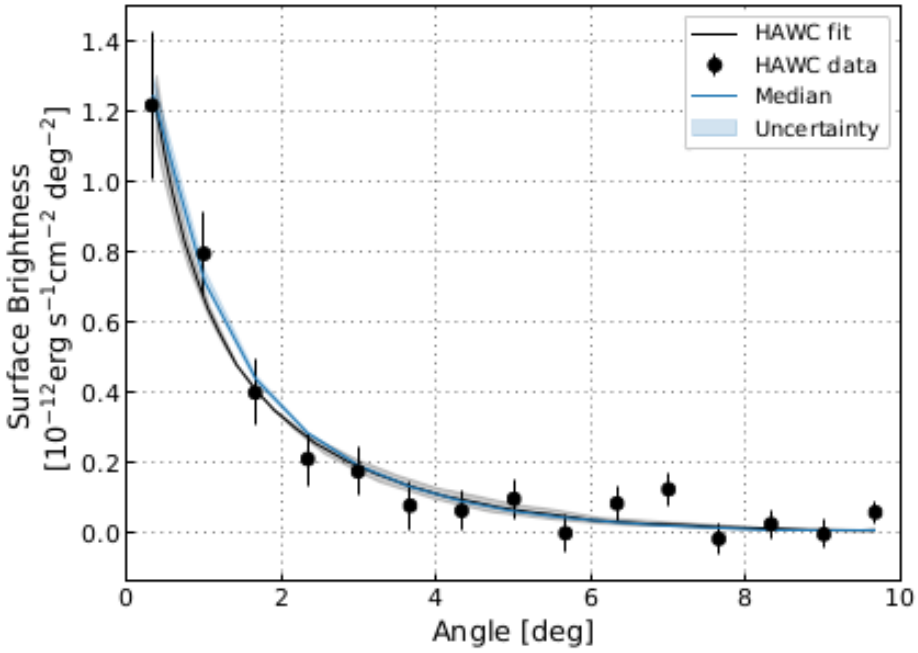
OK

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

Best fit to HAWC measurements (χ^2/ndf<1)

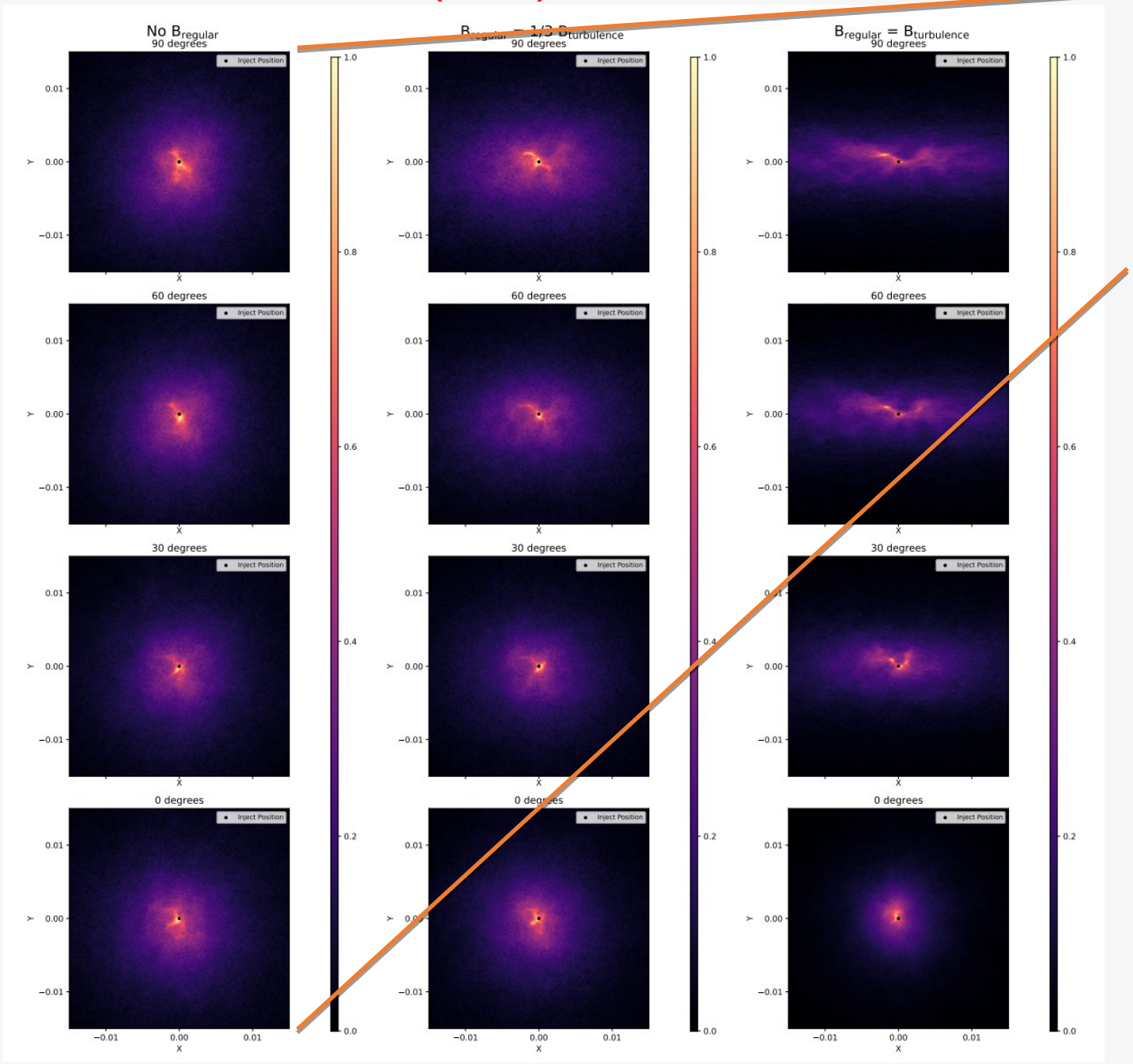
→ Kolmogorov / Kraichnan, B = 3 μG, L_c = 1 pc

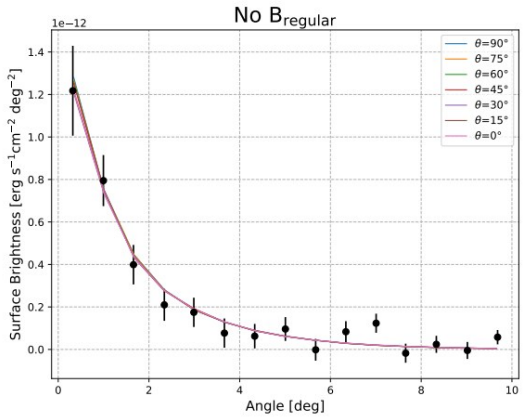


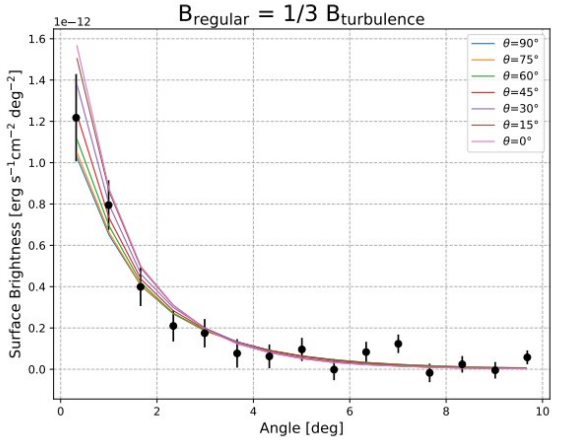


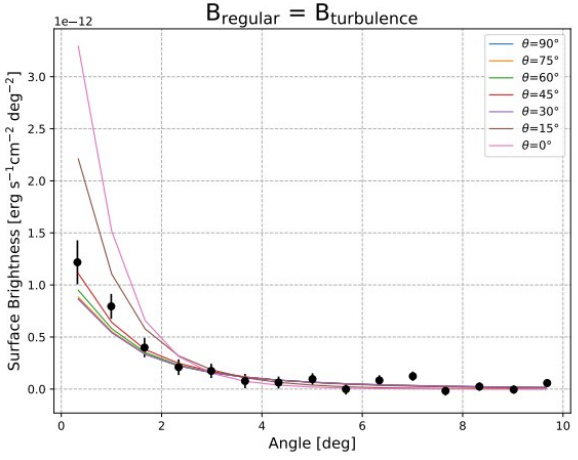
Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

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







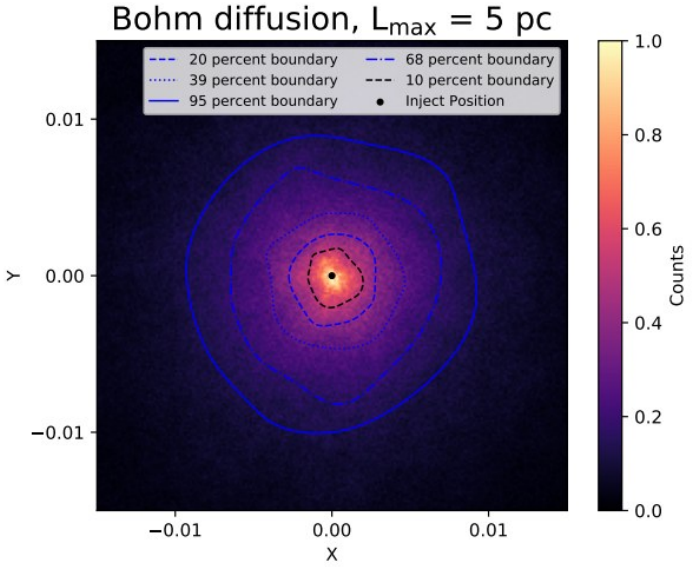


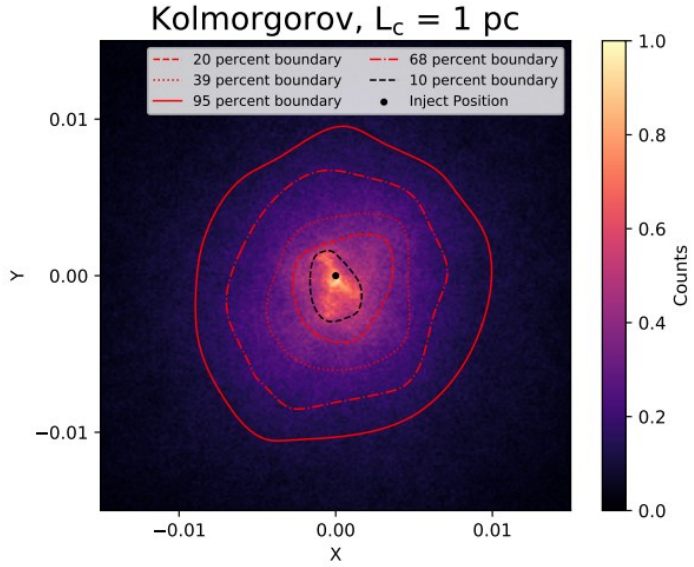
Best fits around
L_c=1-5 pc,
B_{rms}=3-4 μG

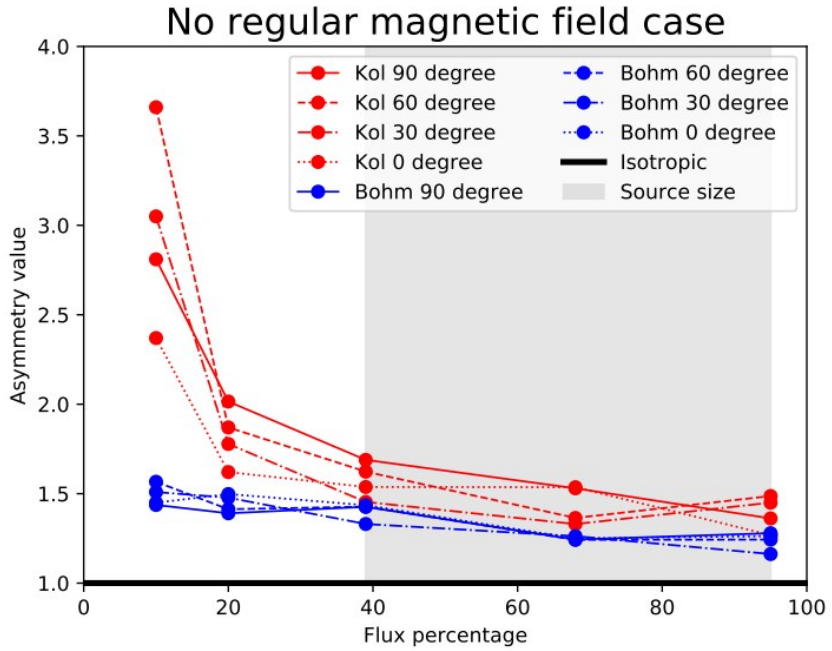
Kolmogorov,
L_c=1 pc,
B_{rms}=3 μG

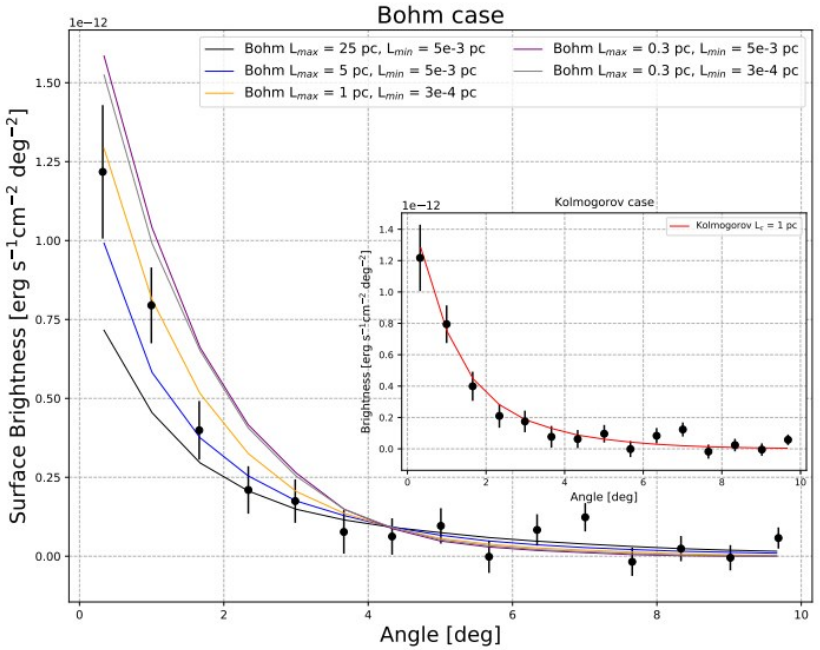
Asymmetry results ($B_{regular} = 0$):

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

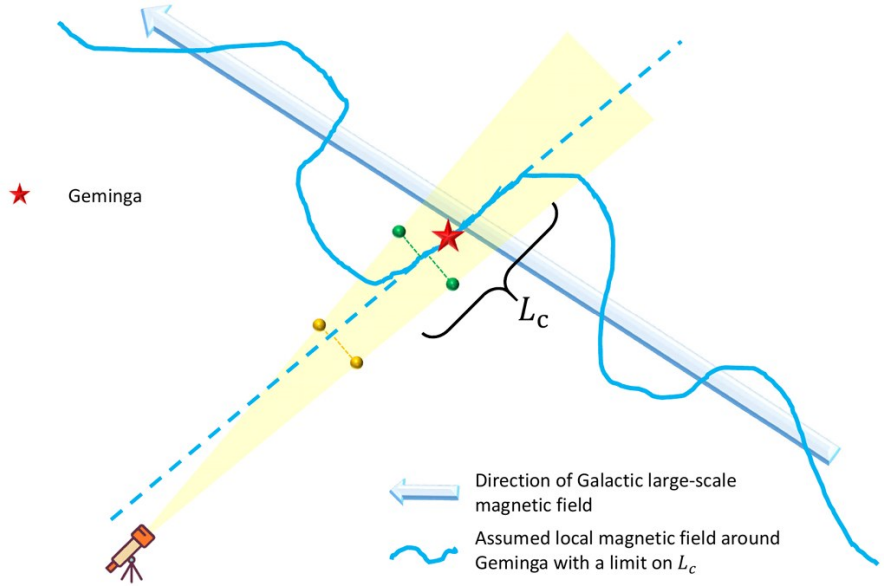


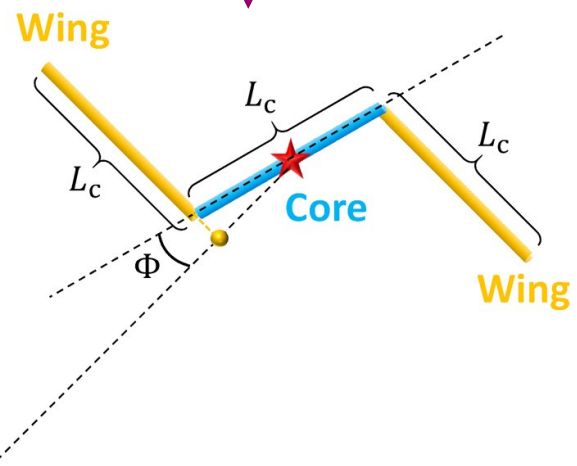




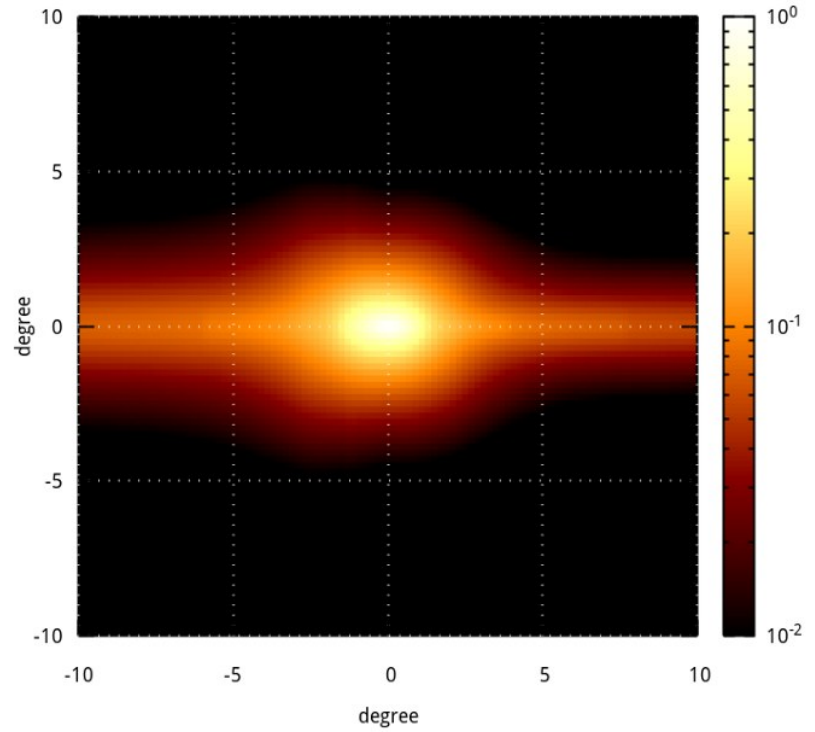


Or could the local L_c be >> 10 pc ?





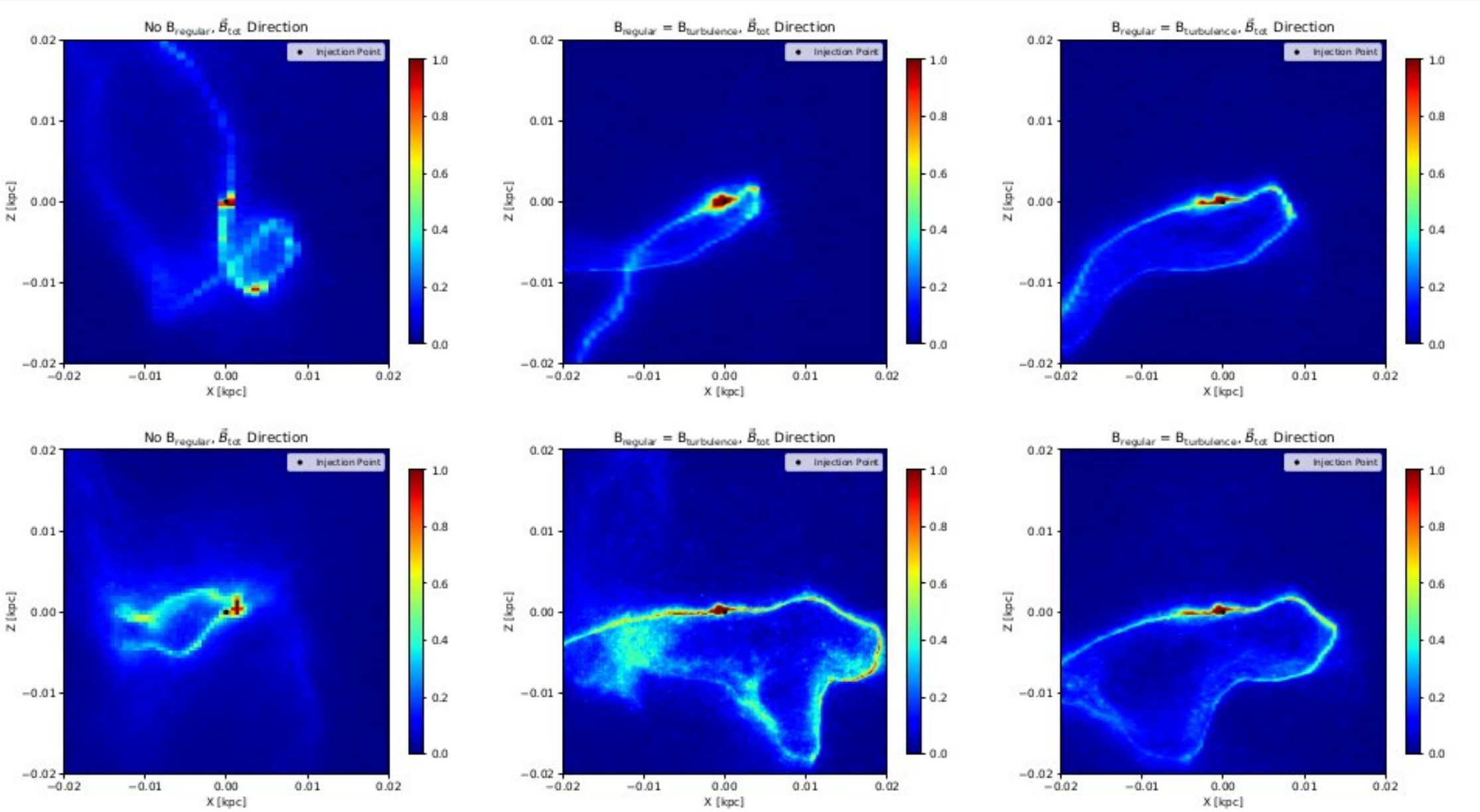
Fang et al., PRD (2023)



Large coherence lengths:

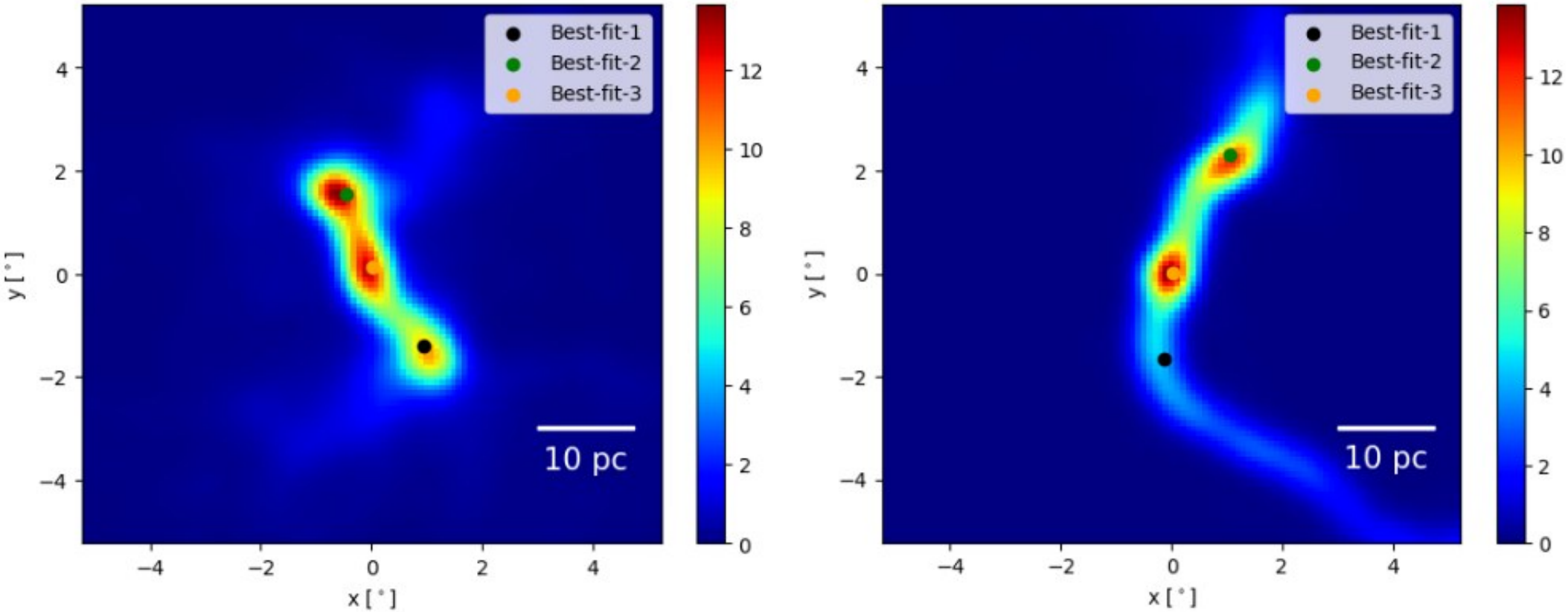
Li, Giacinti & Lopez-Coto, To be submitted (2025)

L c = 100 pc and B rms = 3 μG



Appearance of “mirage” sources:

They may appear around astrophysical sources.



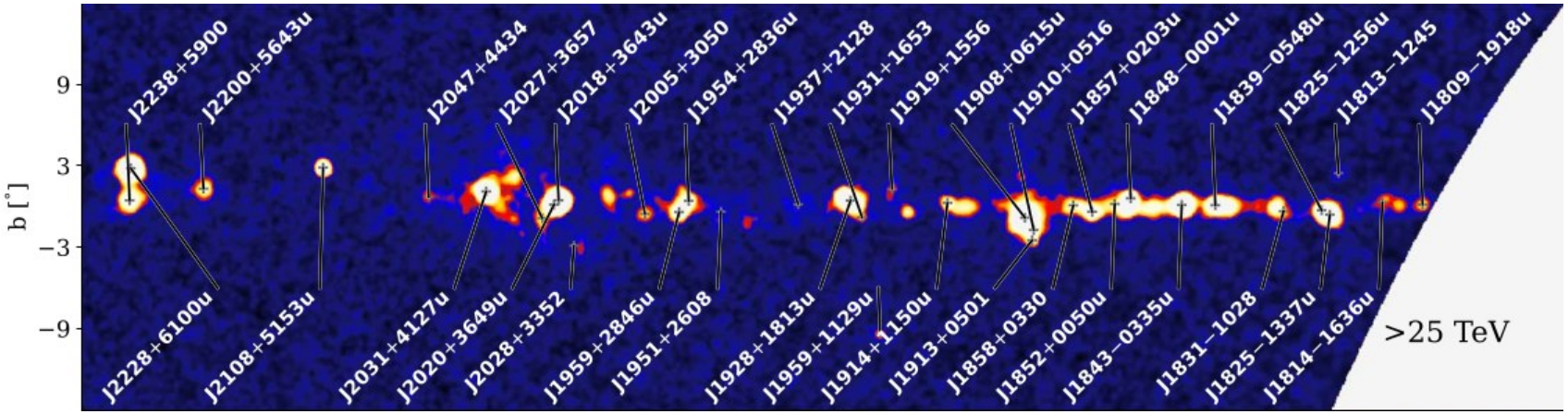
L_c = 40pc ; B_{turb} = 3 μG ; B_{reg} = 0 μG; Kolmogorov turbulence ; (8192 particles)

Bao, Giacinti, Liu, Zhang & Chen, Phys. Rev. Lett. (2025)
Bao, Liu, Giacinti, Zhang & Chen, Phys. Rev. D (2025)

Could explain LHAASO observations

LHAASO Collaboration, ApJS 271, 25 (2024)

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



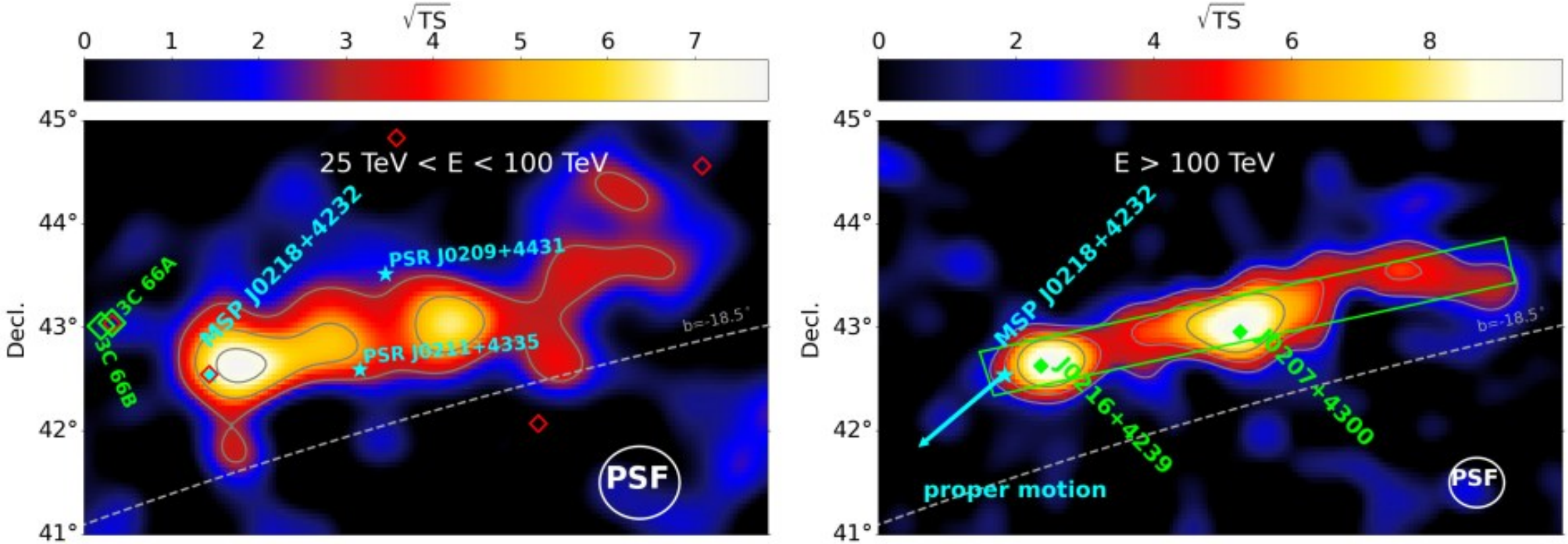
Large offsets between sources and center

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	

LHAASO's Peanut

LHAASO Coll.,
arXiv:2510.06786



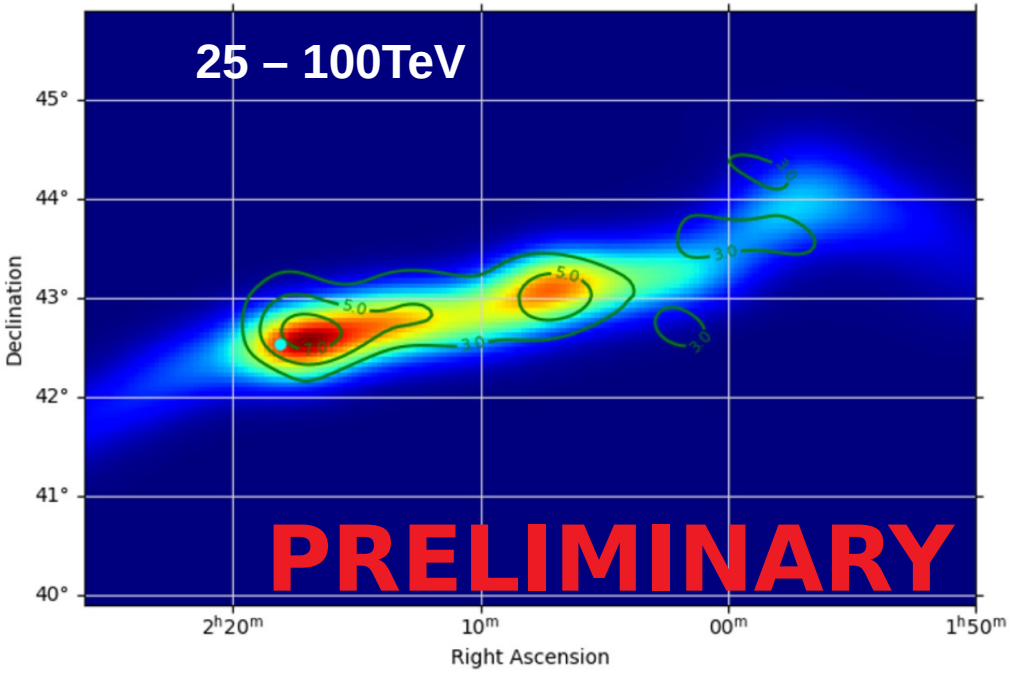
LHAASO's Peanut

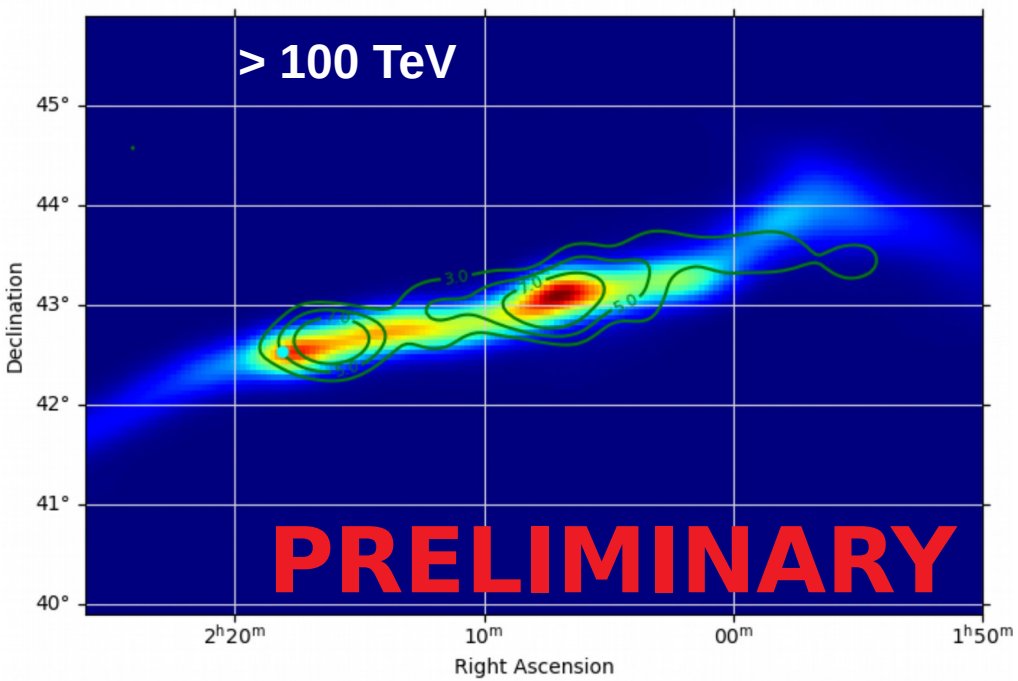
Kolmogorov turbulence, dB/B0 ~ 1, B ~ 1 microG, Lc ~ 100-200 pc

Or

Goldreich-Sridhar turbulence, dB/B0 ~ 1, B ~ few microG, Lc ~ 100-200 pc

Kleimenov, Li, GG Semikoz, In prep (2026)

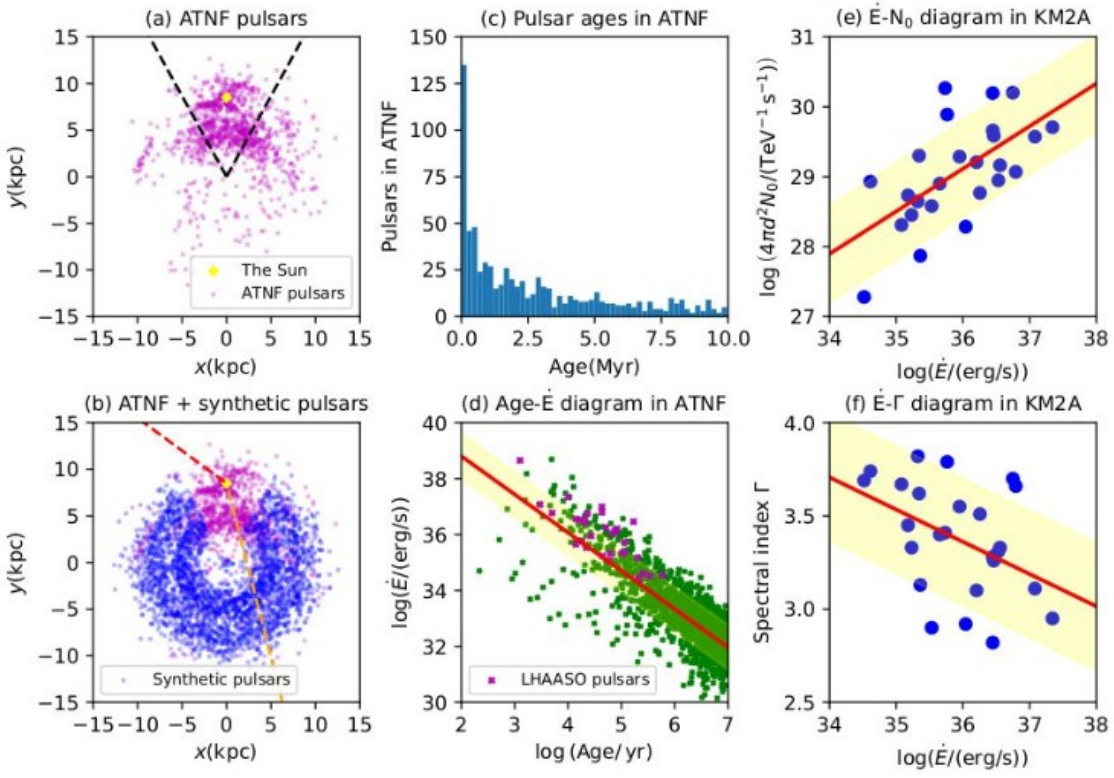




2 – Diffuse VHE γ-ray emission:

Impact of unresolved sources (PWNe)

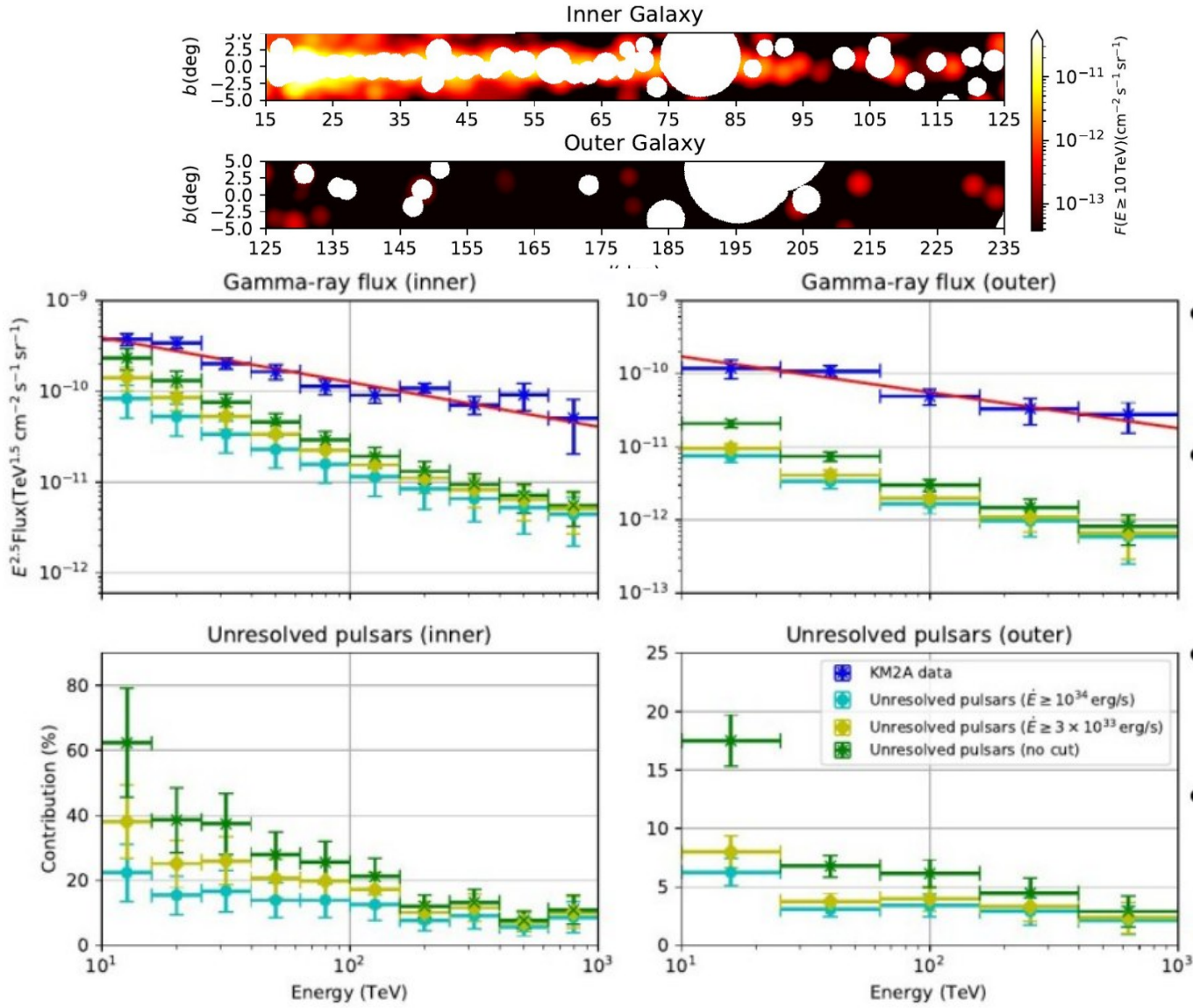
Kaci, Giacinti, Semikoz, ApJ Lett. 975, L6 (2024)



- 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.

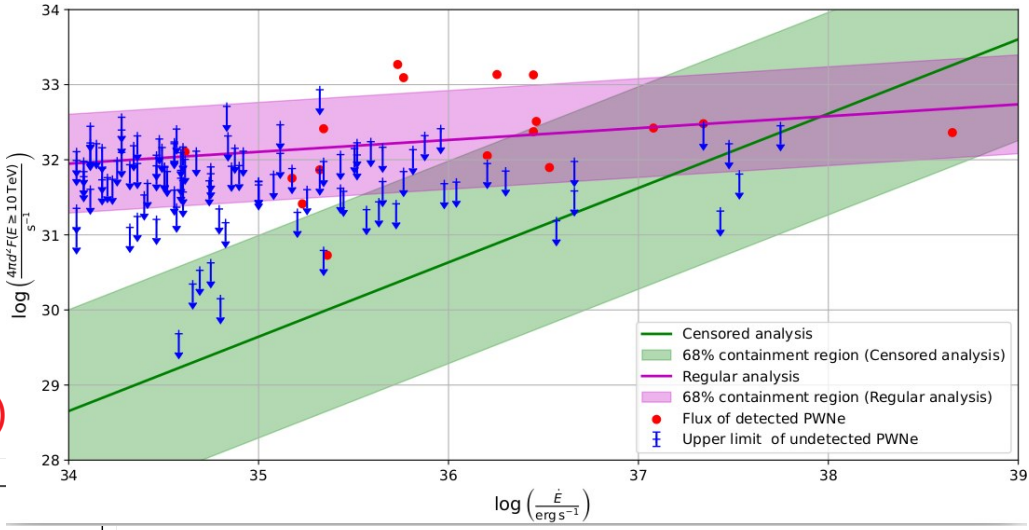
Upper Limits unresolved PWNe/halos

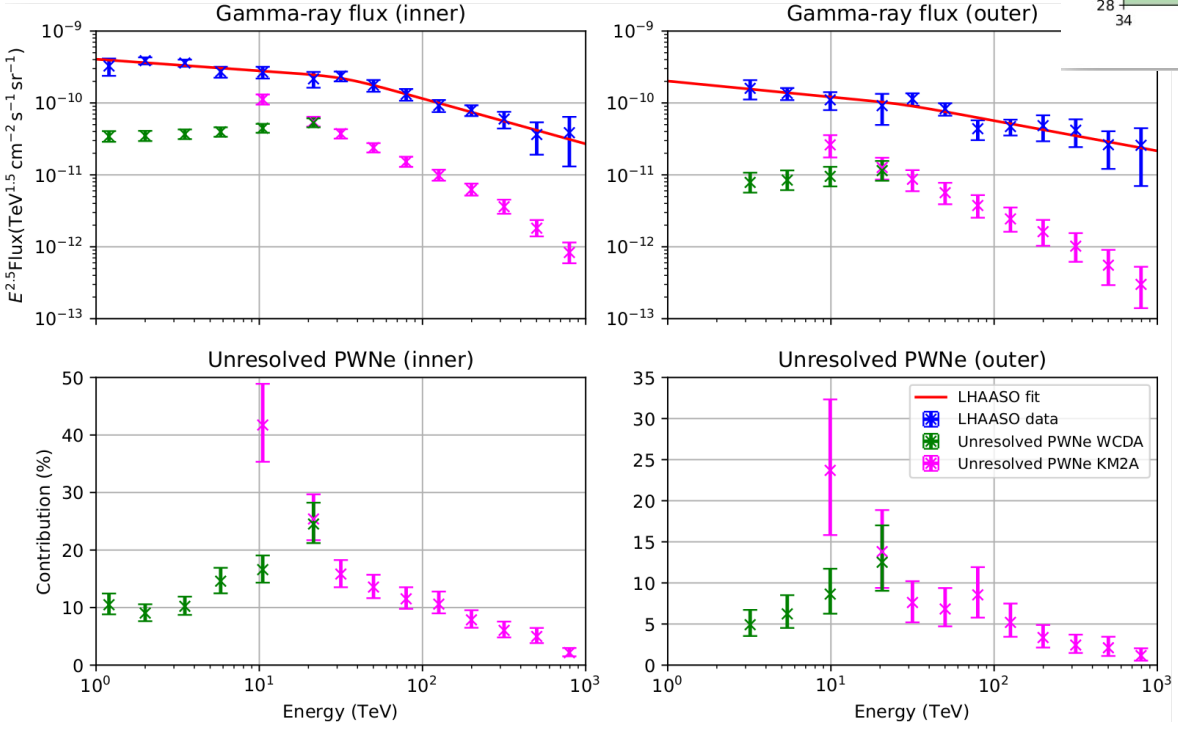
Kaci, Giacinti, Semikoz,
ApJ Lett. 975, L6 (2024)



Upper Limits unresolved PWNe/halos

Kaci, Giacinti, Semikoz, Submitted (2026)





→ The contribution of PWNe to the diffuse background is rather negligible.

→ It peaks at 30% at most at 25TeV in the inner Galaxy.

Diffuse VHE γ-ray emission from discrete sources

SIMULATION:

Kaci & Giacinti, JCAP 01, 049 (2025)

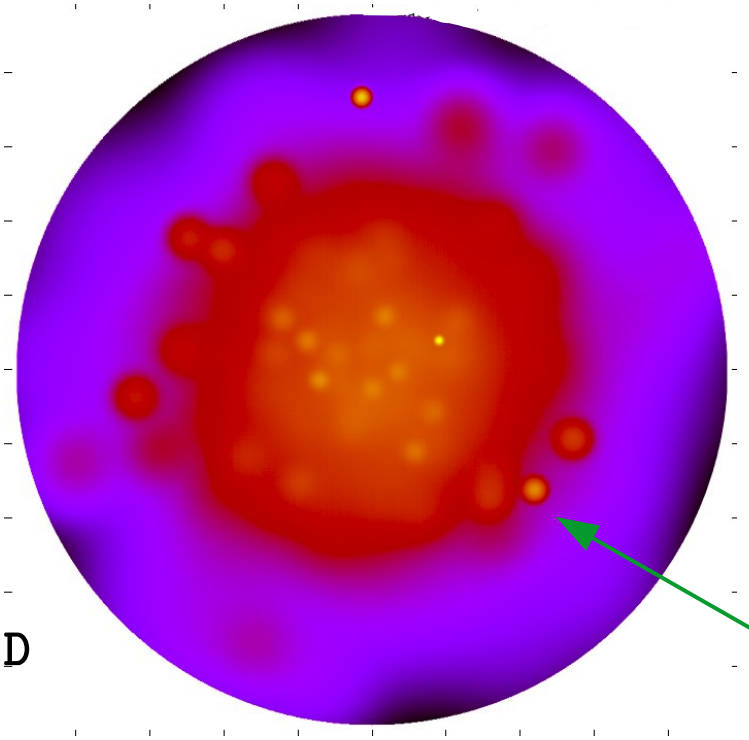
Isotropic and homogeneous diffusion

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.

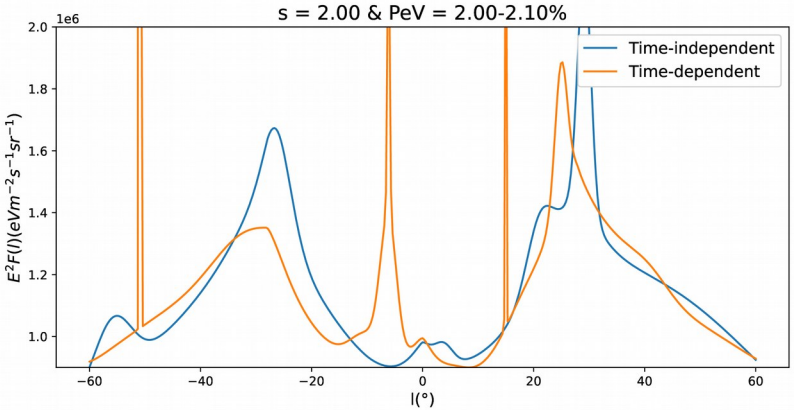


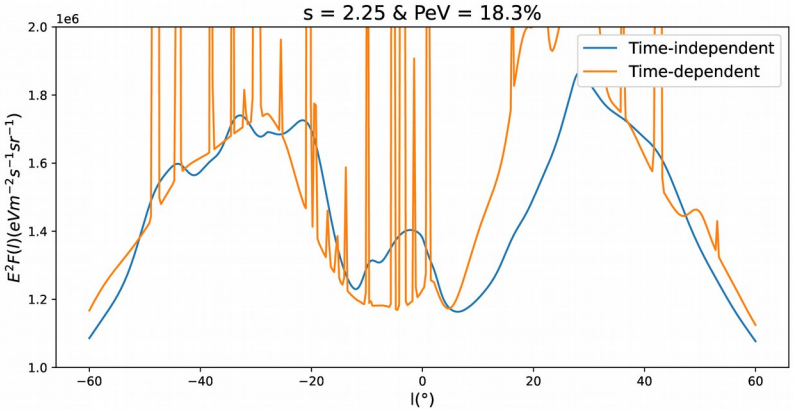
Cosmic-ray flux at Earth and B/C ratio satisfied

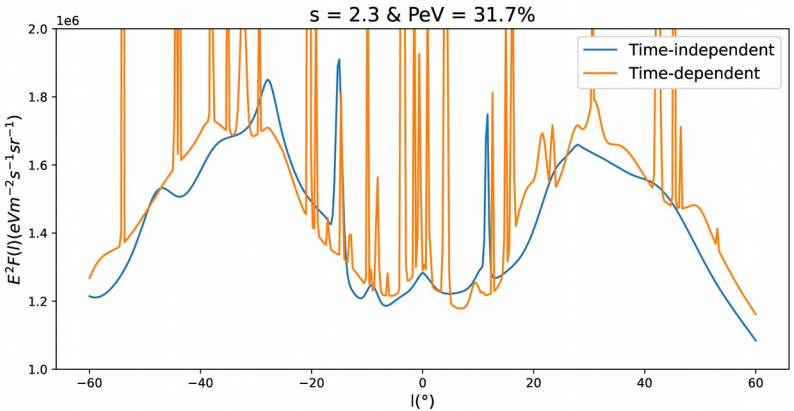
Discrete injection of cosmic rays

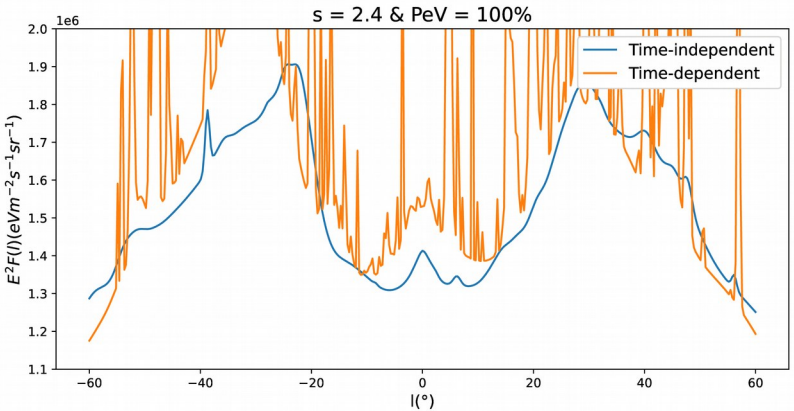
Clumps in the gamma-ray flux

Kaci & Giacinti, JCAP 01, 049 (2025)

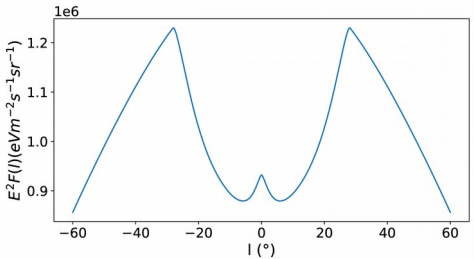






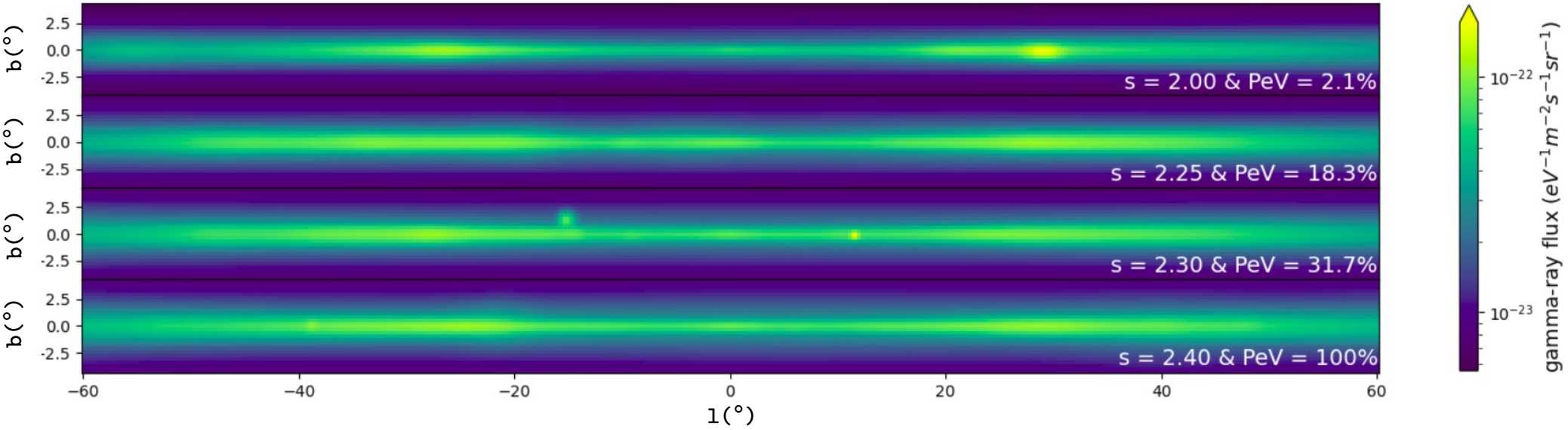


Vs shape from Lipari & Vernetto(2018):



Diffuse gamma-ray flux clumpy at VHE

Sky Maps and sources (case 1)



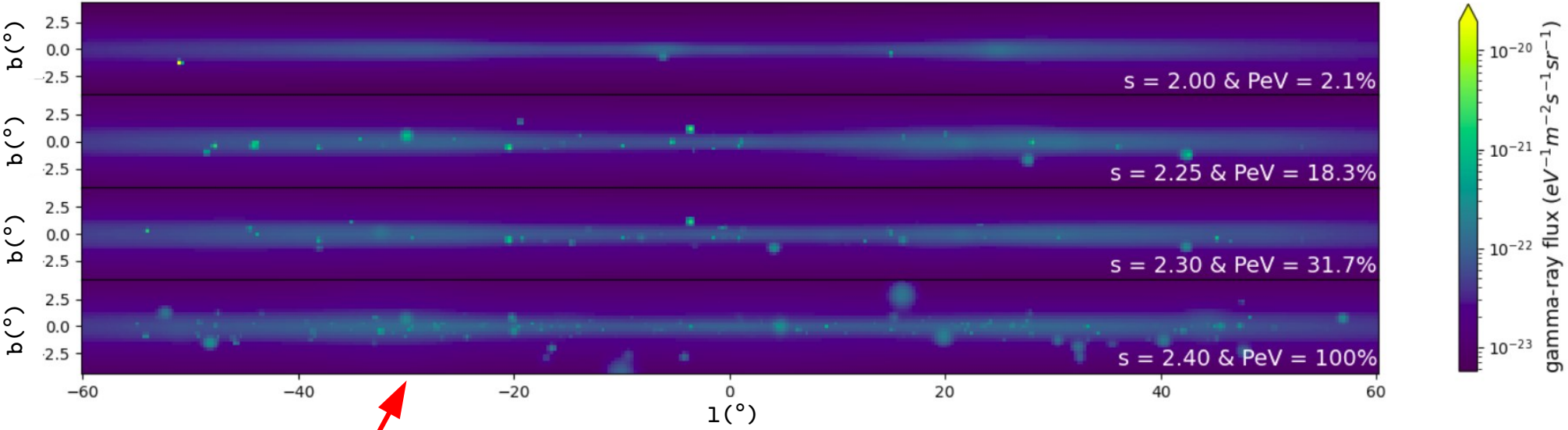
Very few visible sources for case 1

For standard isotropic diffusion, few PeVatrons are detectable

Slide from Samy Kaci

Kaci & Giacinti, JCAP 01, 049 (2025)

Sky Maps and sources (case 2)



Sky map very sensitive to CR propagation assumptions

Many more visible sources

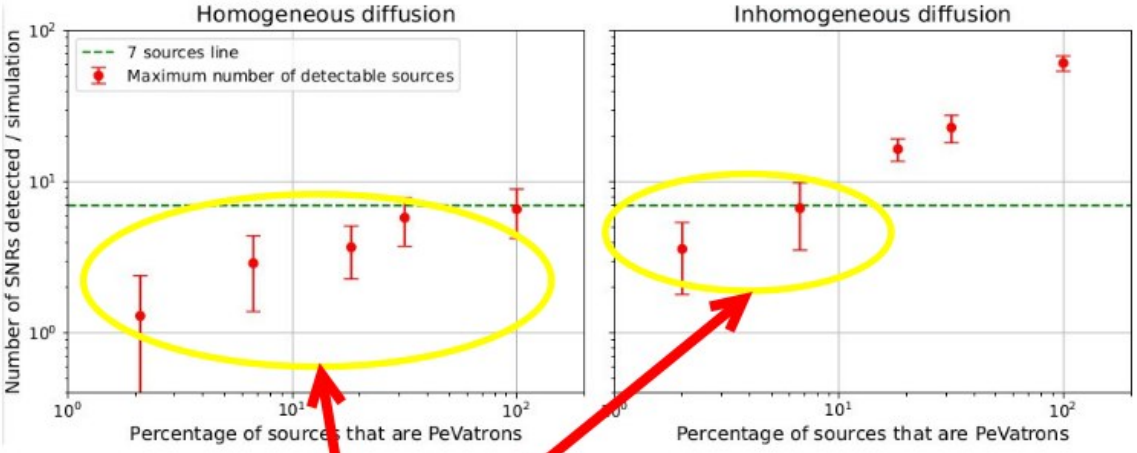
Implies a PeVatron SNR rate < 3.6/kyr

Slide from Samy Kaci

Kaci & Giacinti, JCAP 01, 049 (2025)

Number of detectable sources

Kaci & Giacinti, JCAP 01, 049 (2025)

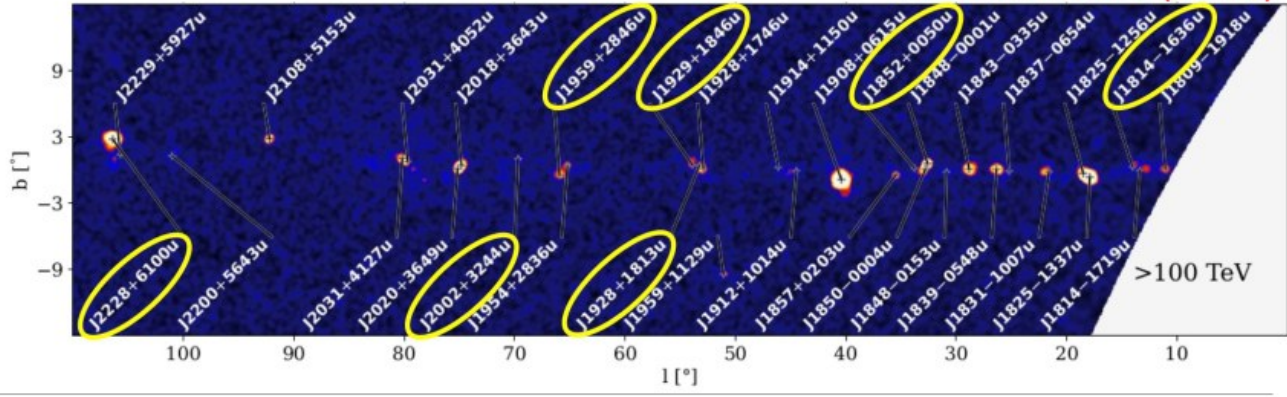


There is still some degeneracy between the two cases

Can be disentangled from clumpiness of diffuse bkg

- 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)

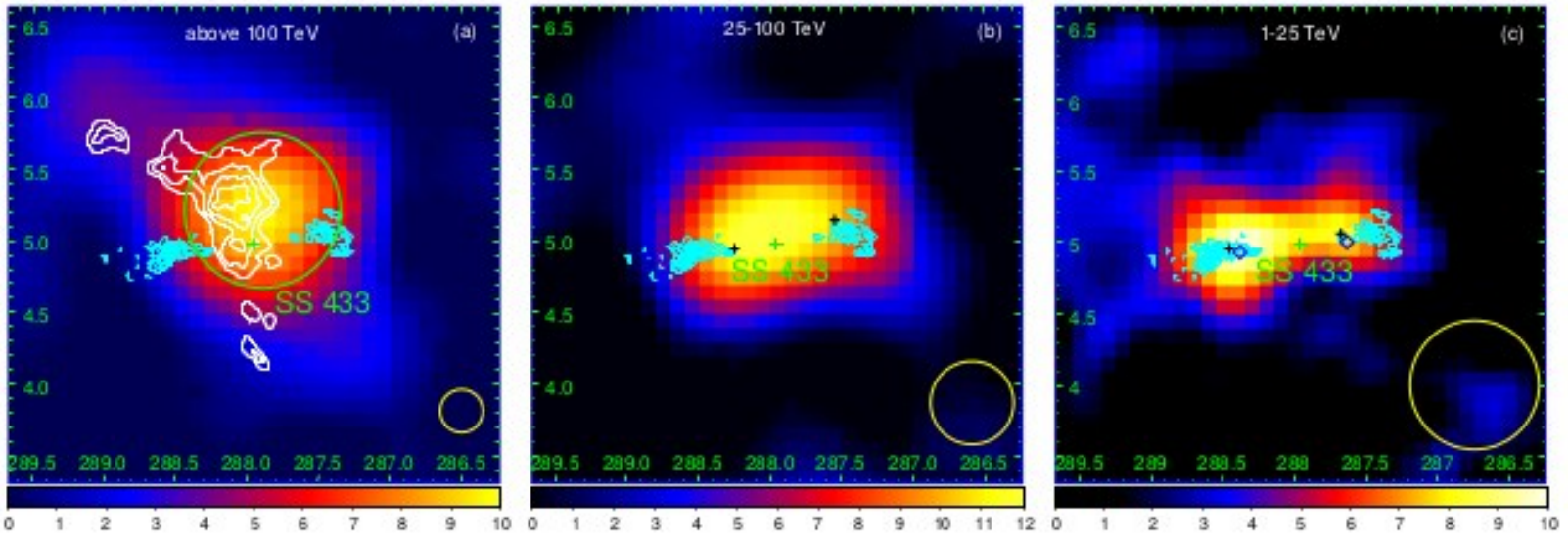


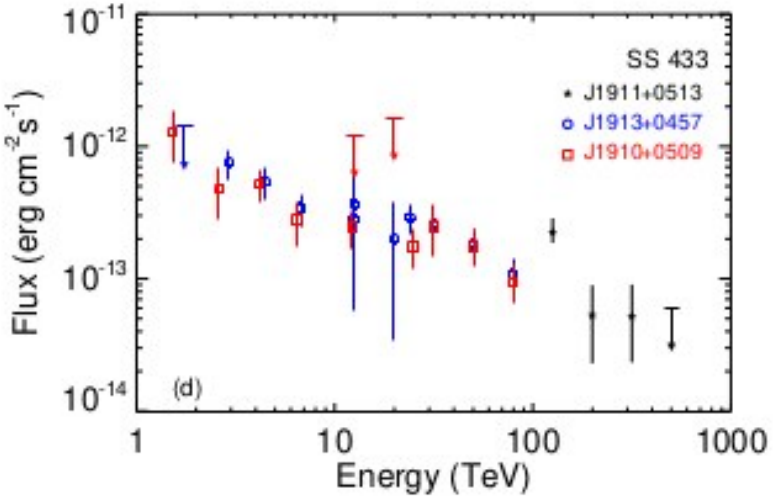
Microquasars ?

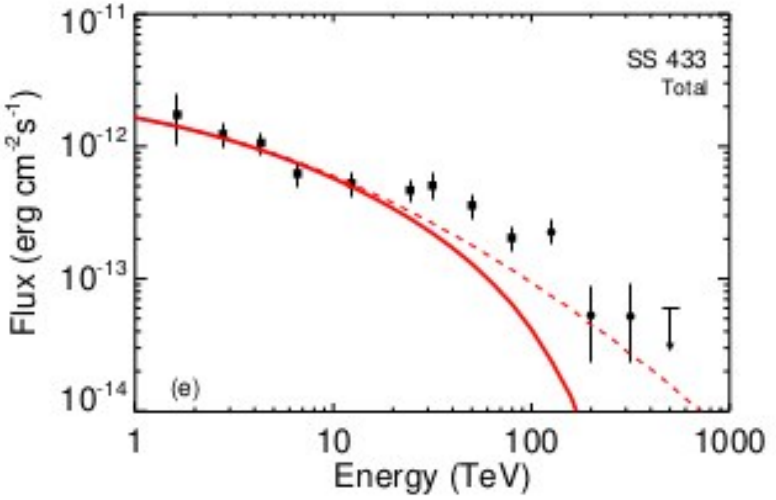
Kaci, Giacinti, Aharonian & Wang, Phys. Rev. Lett. (2026)

LHAASO's PeVatron microquasars

LHAASO Collaboration, National Science Review (2025)

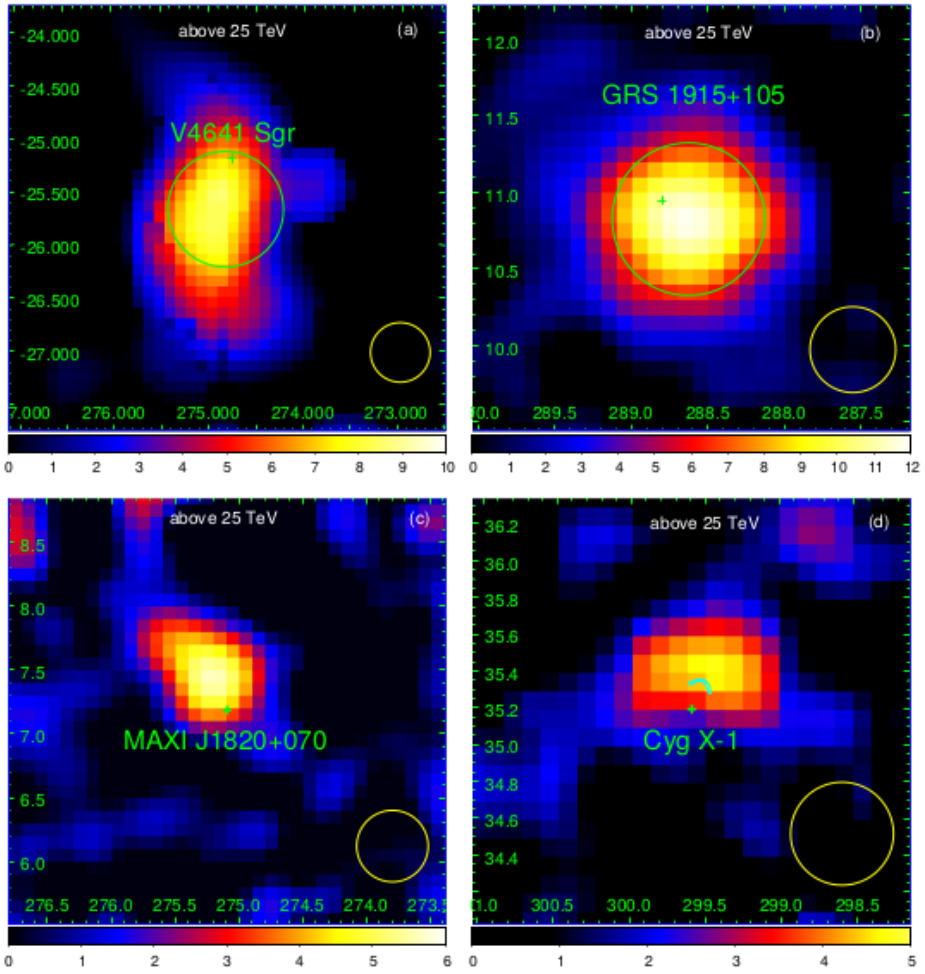


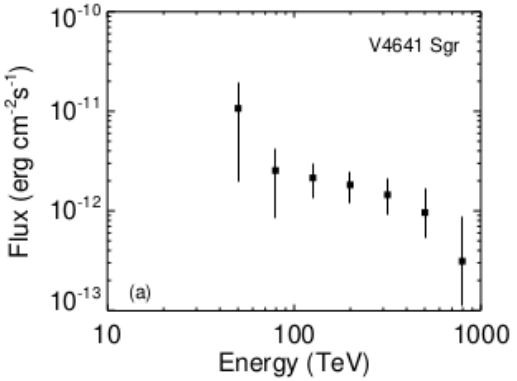


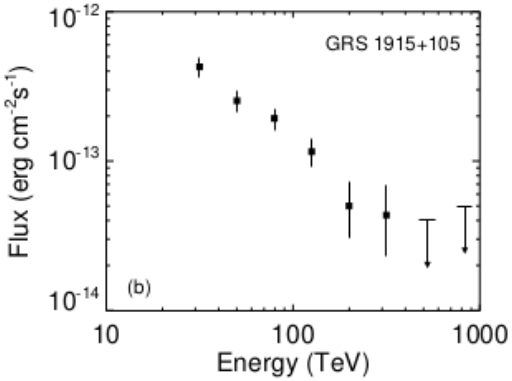


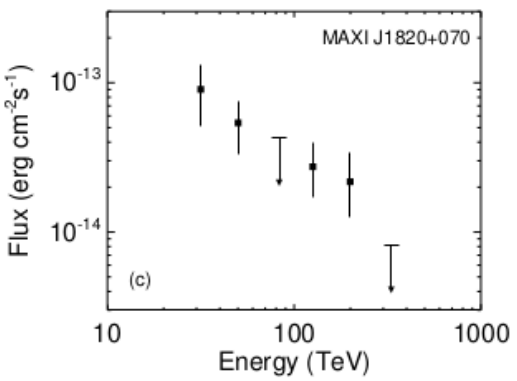
LHAASO's PeVatron microquasars

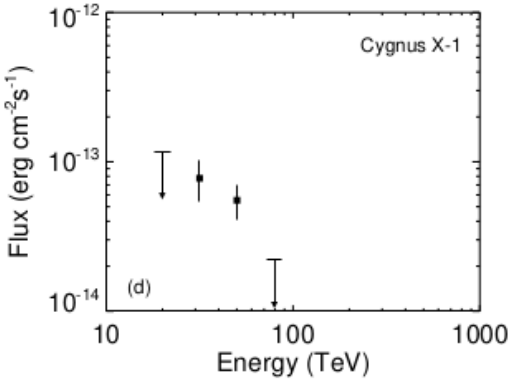
LHAASO Collaboration, National Science Review (2025)



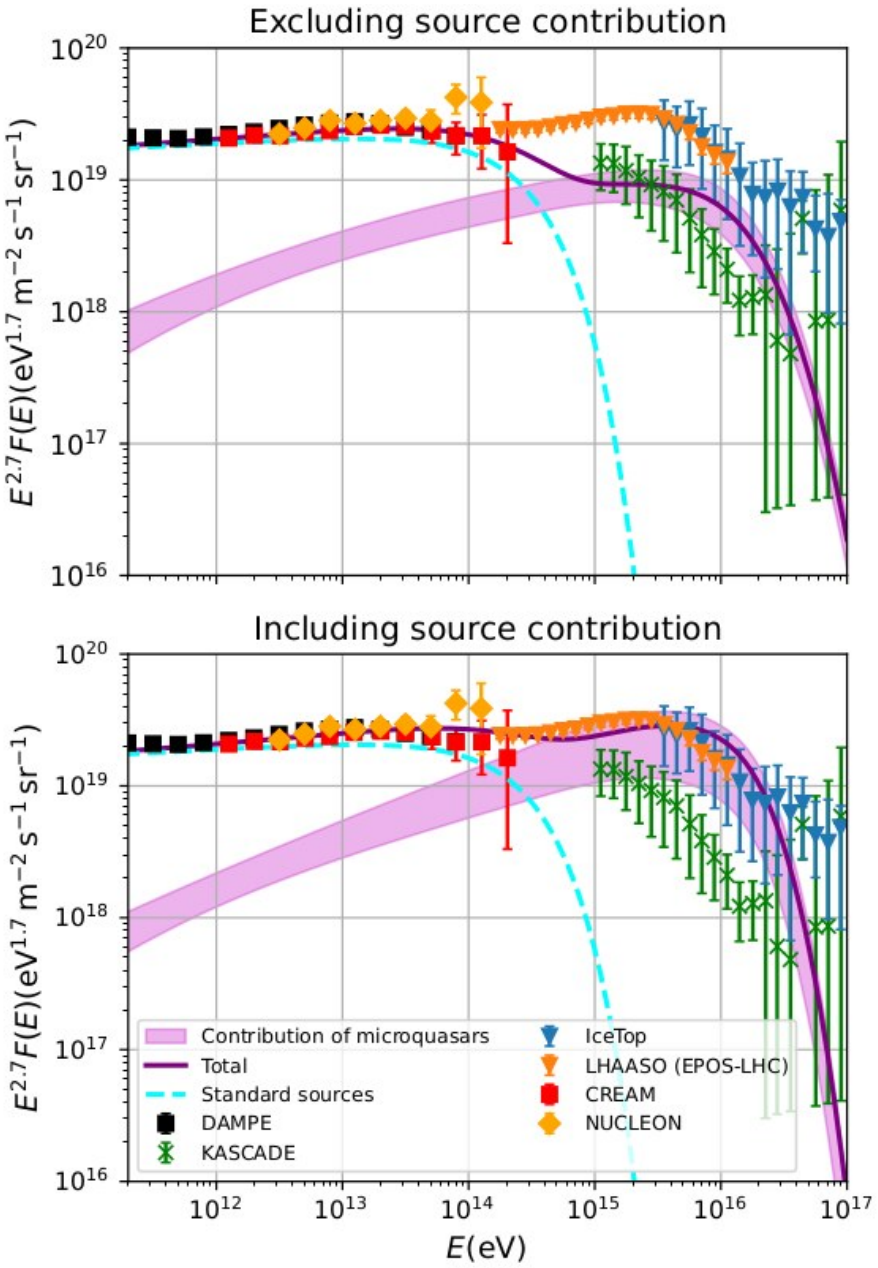








Cosmic-ray spectrum



Kaci, et al., PRL (2026)

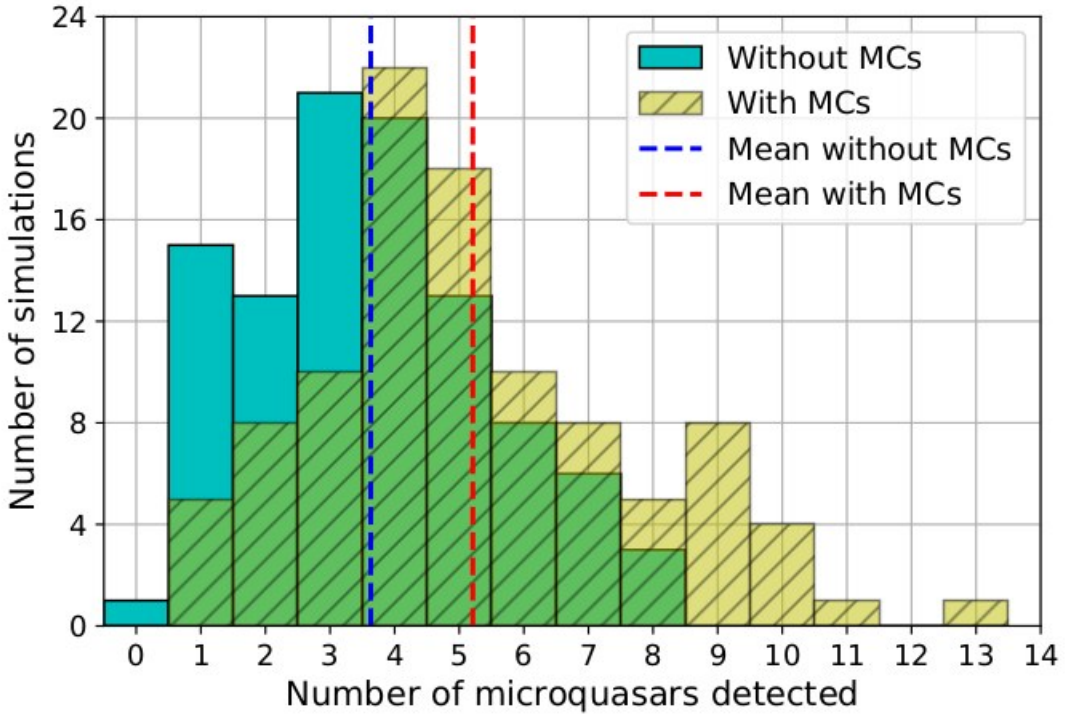
Microquasars: inj. -2 spectrum, cutoff at 10 PeV, 100 kyr lifetime, 0.1/kyr rate, power $10^{39\text{-}40}$ erg/s.

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

→ **Fits the ~ 10TeV bump, ~ 100 TeV hardening and the knee**

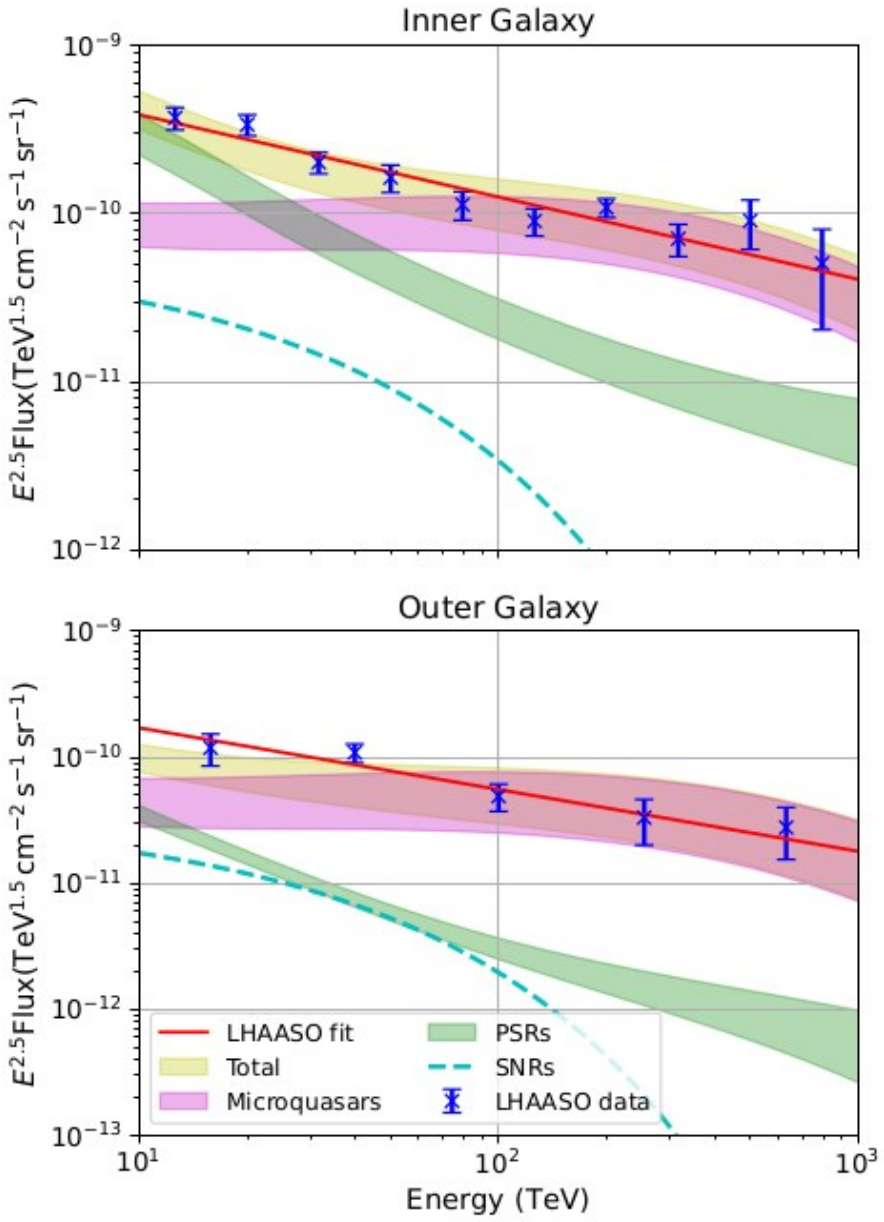
Detectable sources

Kaci, et al., PRL (2026)



- The number of detectable microquasars in the Galaxy with and without molecular clouds above 100TeV is compatible with the LHAASO observation of 6 sources.

Diffuse gamma-ray emission



Kaci et al., PRL (2026)

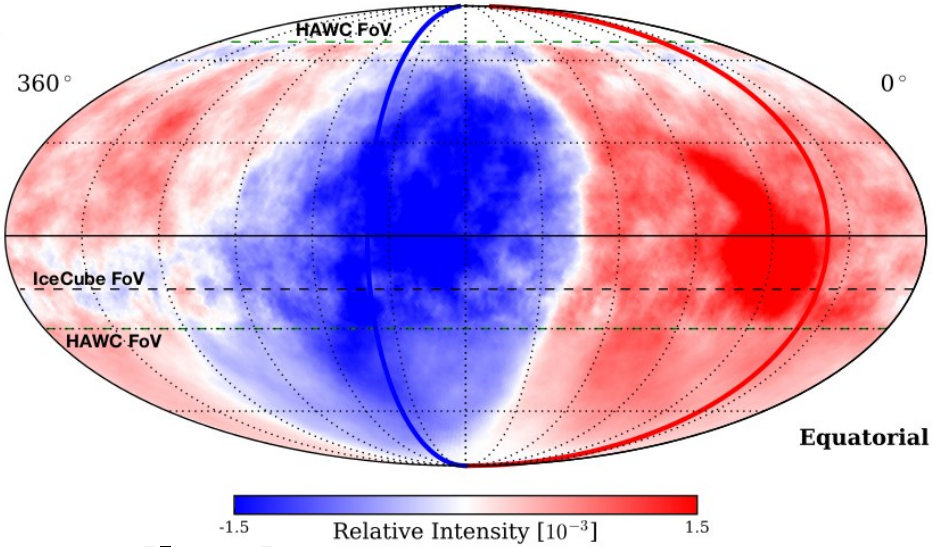
- In the outer Galaxy the contribution of microquasars almost entirely account for the diffuse gamma-ray flux.
- In the inner Galaxy, microquasars can explain gamma-ray data with a minimal contribution from unresolved pulsars above 50TeV.

3 – CR anisotropy

Bian, Giacinti & Reville, ApJ 979, 197 (2025)

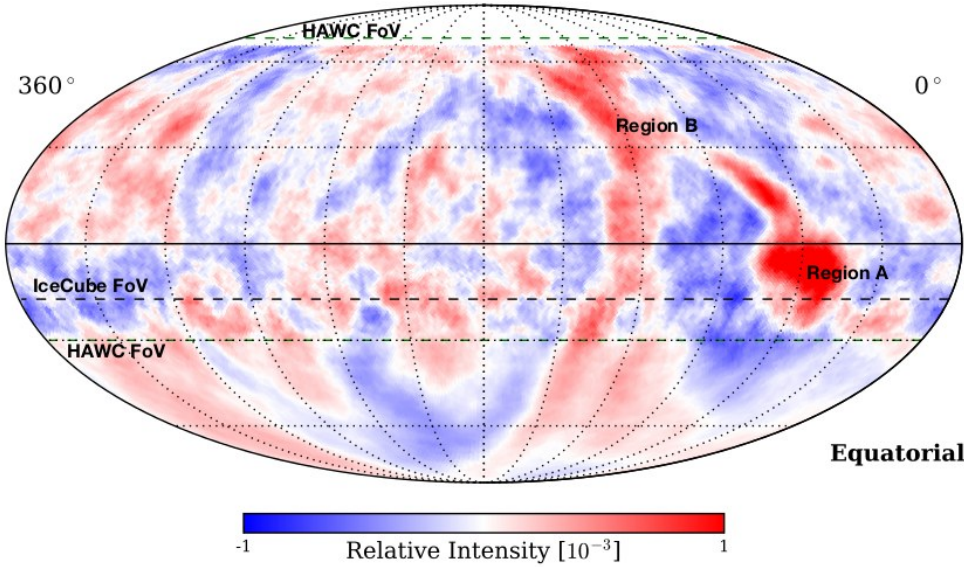
HAWC + IceCube Collab., ApJ (2018) [arXiv:1812.05682]:

Large Scale Anisotropy (~0.1%) :

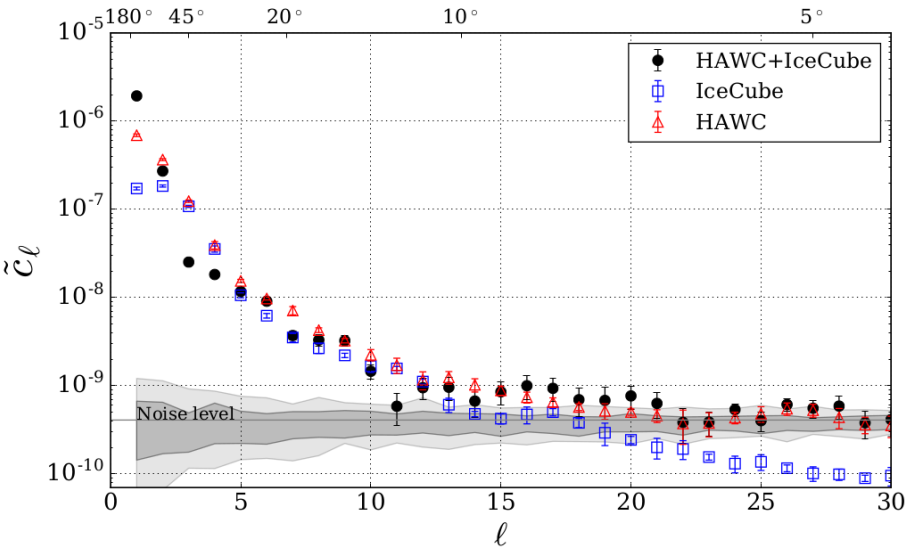


In the direction of field line

SSA (I>3):



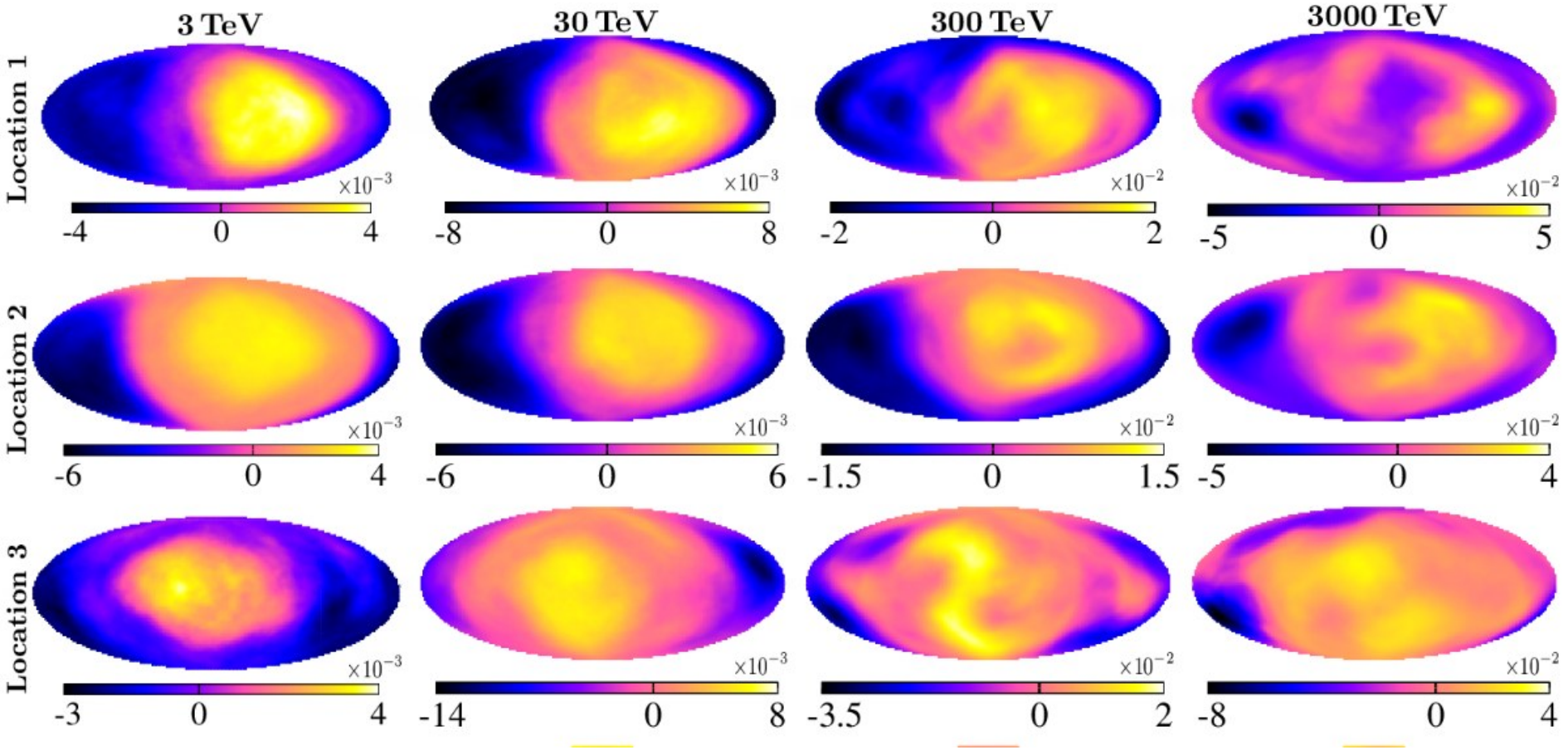
Angular power spectrum:



CR anisotropy down to 3 TeV

Bian, Giacinti & Reville, ApJ (2025)

Simulations now reach TeV energies

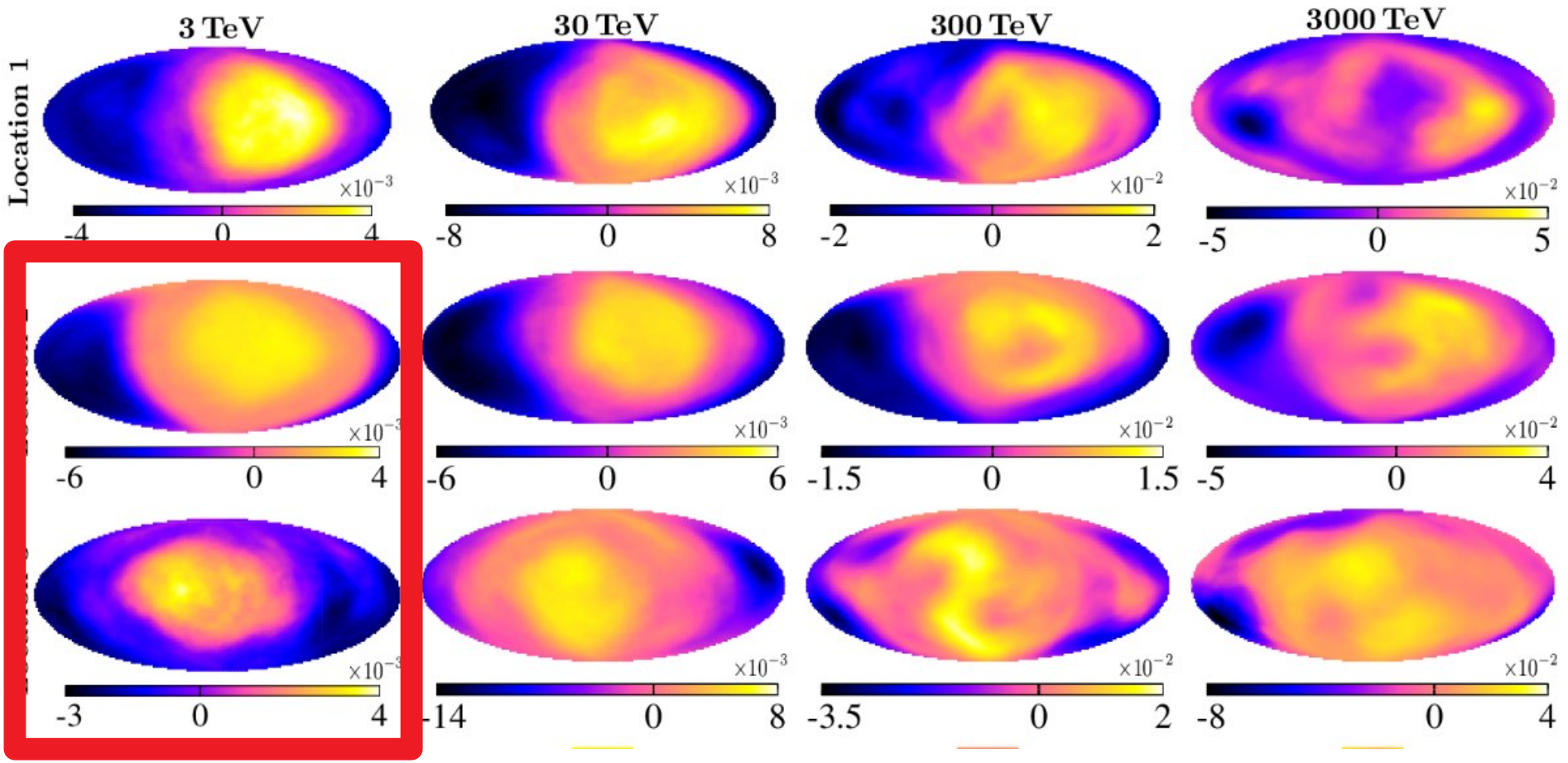


Outer scale turbulence L_{max} = 150 pc, Kolmogorov turbulence

CR anisotropy down to 3 TeV

Bian, Giacinti & Reville, ApJ (2025)

Simulations now reach TeV energies

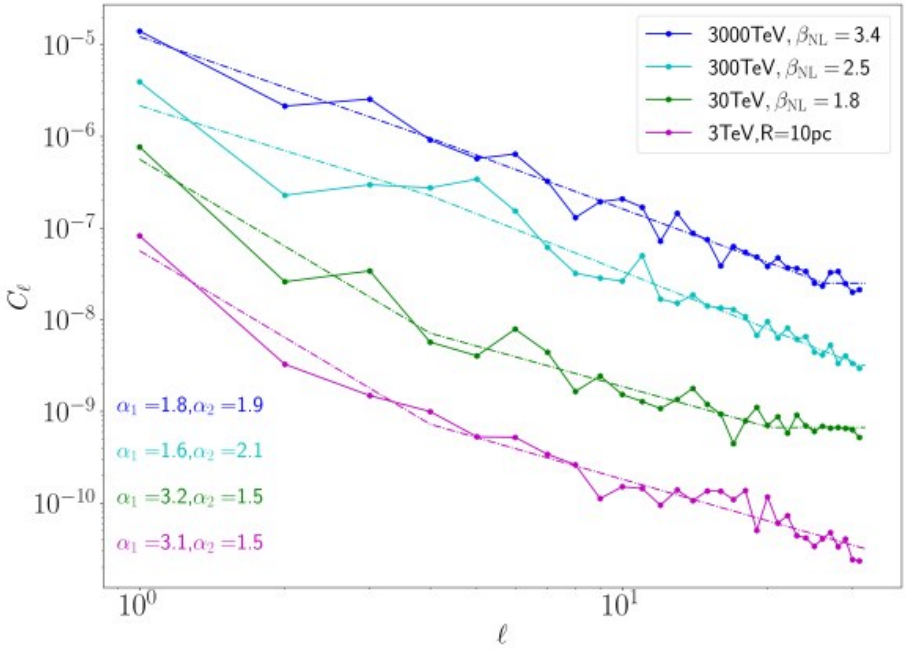


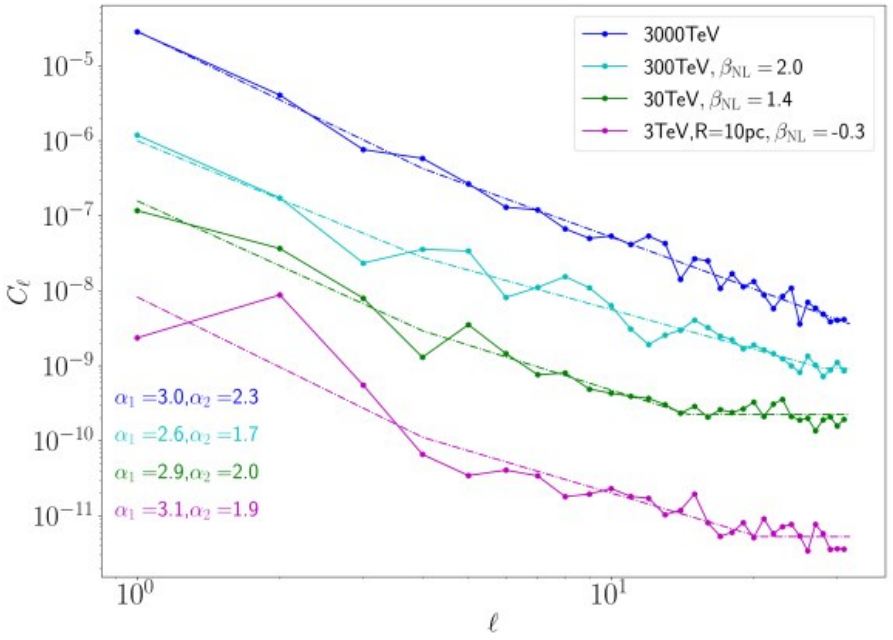
Amplitude SSA/LSA related to local

Power spectrum versus CR energy

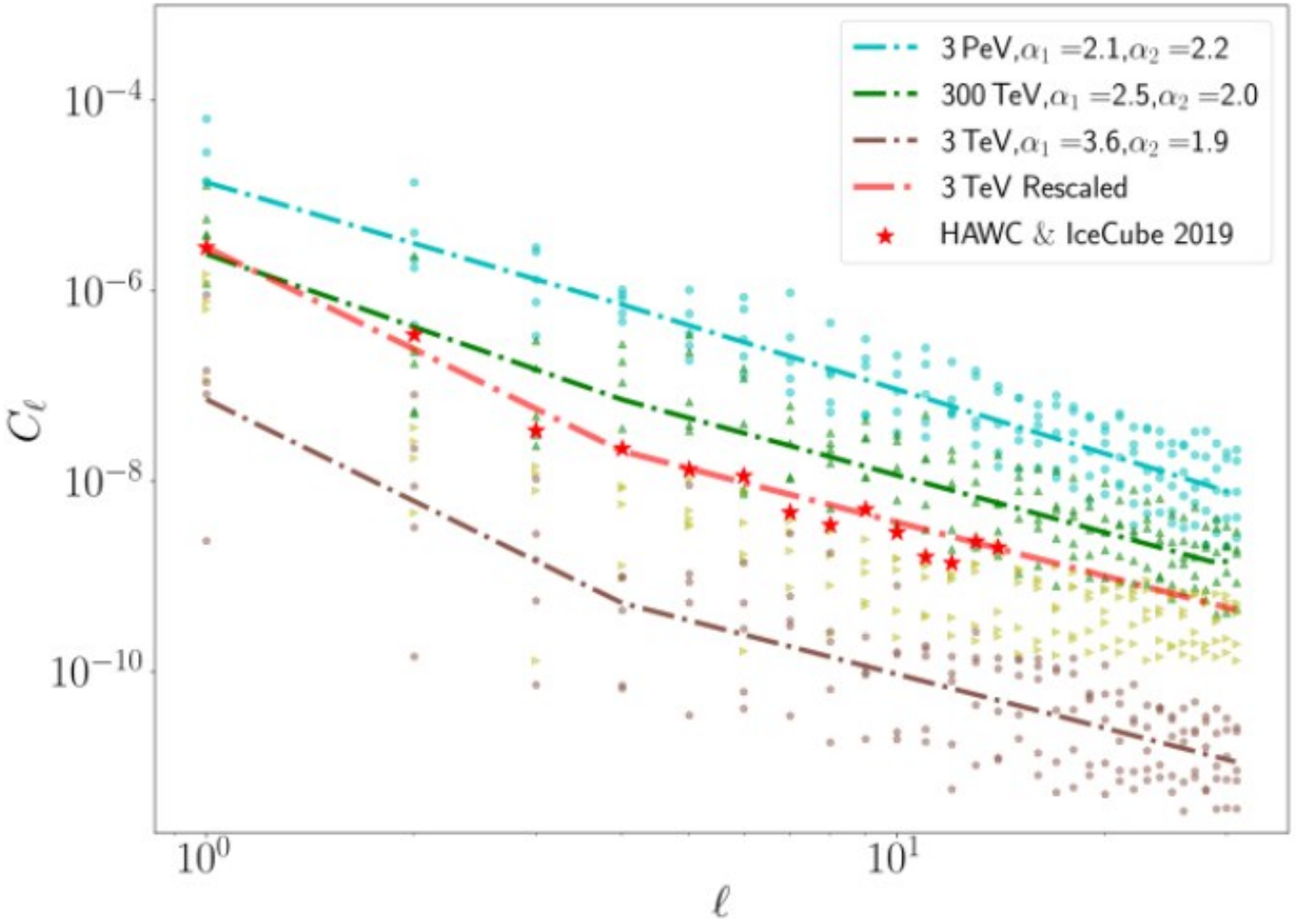
Spherical harmonics: $$f(E,\mu,\phi) = \sum_{\ell=0}^{L_{max}} \sum_{m=-\ell}^{\ell} f_\ell^m(E) Y_\ell^m(\mu,\phi)$$

Angular power spectrum: $$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |f_\ell^m|^2$$





Power spectrum versus CR energy



Excellent agreement with HAWC & IceCube measurements

Conclusions & Perspectives

→ **TeV halos** constrain CR propagation around middle-aged pulsars,

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

→ **“Mirage” sources, asymmetric γ-ray sources**: **Could explain some LHAASO sources,**

→ **Clumpy diffuse γ-ray background at VHE,**

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

→ Observations not incompatible with frequent transient PeVatrons with standard CR diffusion coefficient,

→ ~ 10 powerful **microquasars can fit CR spectrum and LHAASO diffuse γ-ray emission.**