上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

CR PROPAGATION & GMF: INSIGHTS FROM DIFFUSE γ-RAY EMISSION, TeV HALOS & CR ANISOTROPY

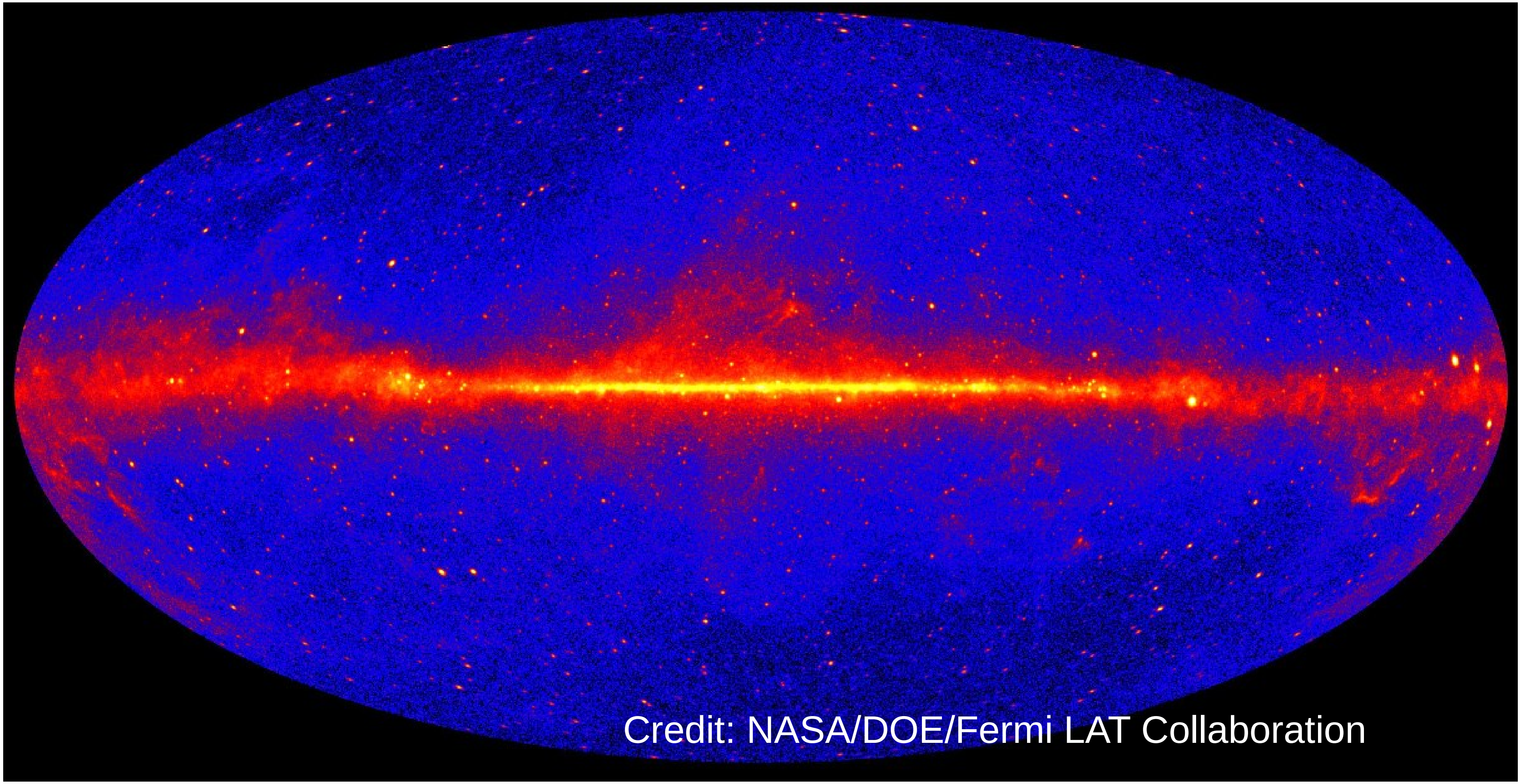
Gwenael Giacinti (贾鸿宇)

Tsung-Dao Lee Institute & Shanghai Jiao Tong University

GG, Abounnasr, Neronov & Semikoz, PRD 106, 123029 (2022)
Kaci, GG & Semikoz, ApJ Lett (2024), arXiv:2407.20186
Kaci & GG, Submitted (2024), arXiv:2406.11015
Bian, GG & Reville, Submitted (2024), arXiv:2410.09634
GG & Semikoz, Submitted (2024), arXiv:2305.10251
GG, Koldobskiy & Semikoz, In prep. (2024)

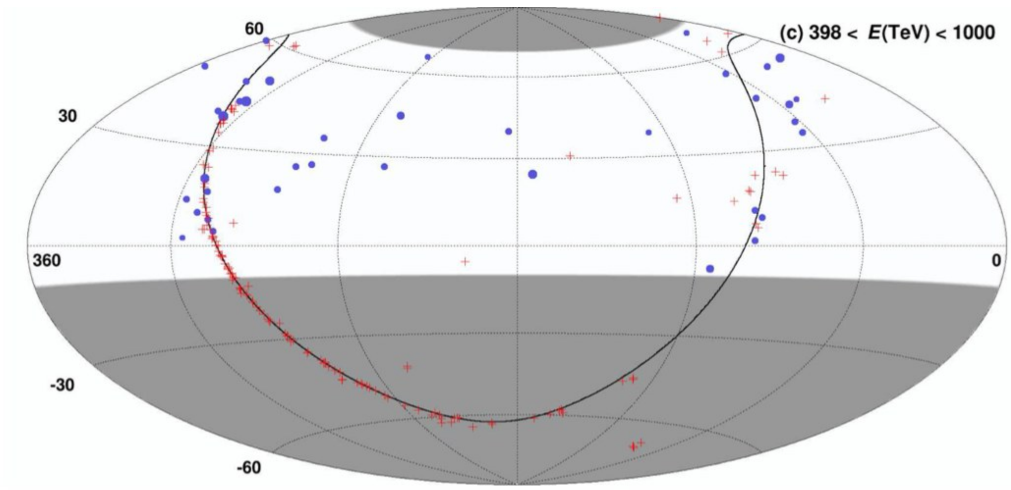
1 – Diffuse γ-ray emission

The sky at GeV energies



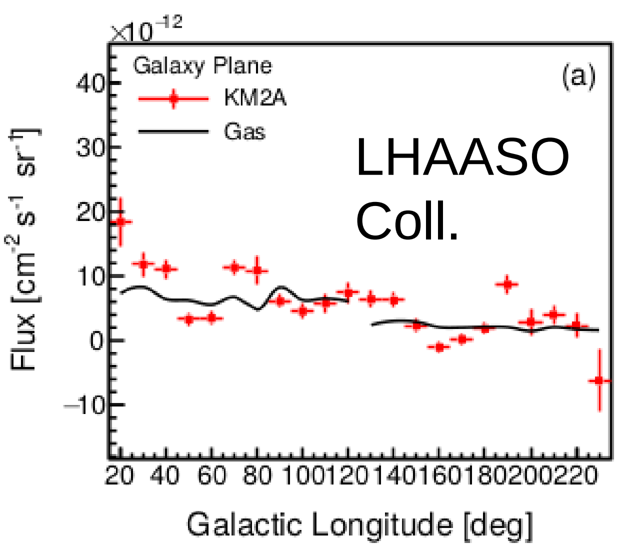
(Fermi, 2008 – 2017)

Diffuse from AS-γ (400 TeV – 1 PeV)



AS-γ Collaboration,
arXiv:2104.05181

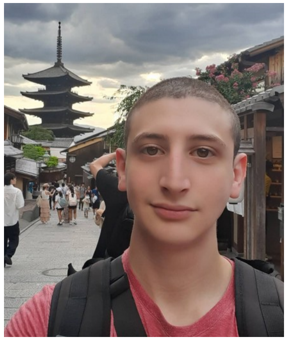
Diffuse from LHAASO (10 TeV – 1 PeV)



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

Diffuse gamma-ray emission at VHE from discrete CR sources

<u>Works by Samy Kaci</u>



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

Our simulation

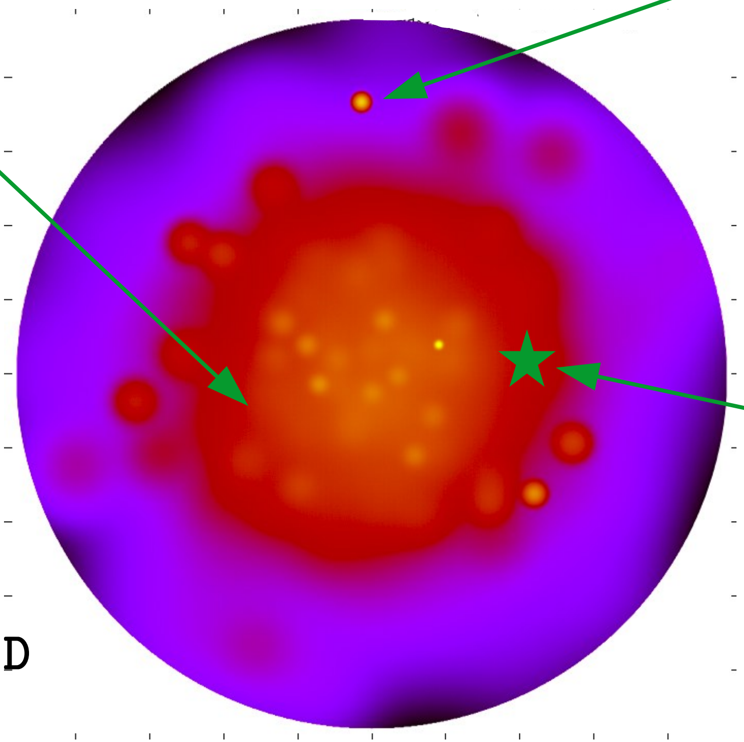
Isotropic and
homogeneous diffusion

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

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

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

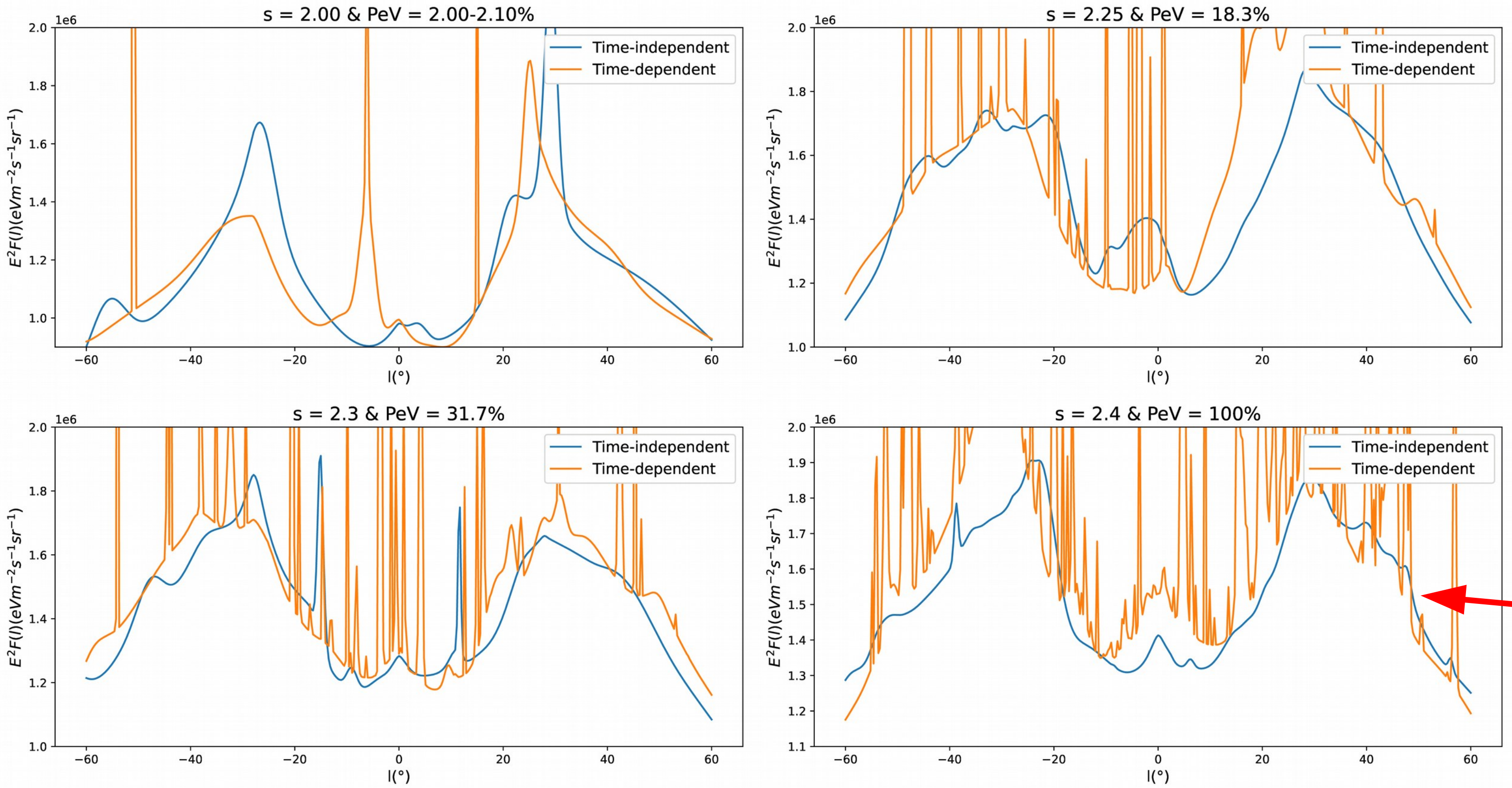
2) Time-dependent (mimics self-confinement): 1/100 x D around sources for 10 kyr.



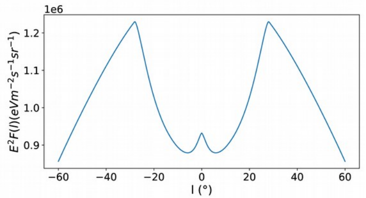
Discrete injection
of cosmic rays

Cosmic-ray flux at
Earth and B/C ratio

Clumps in the gamma-ray flux



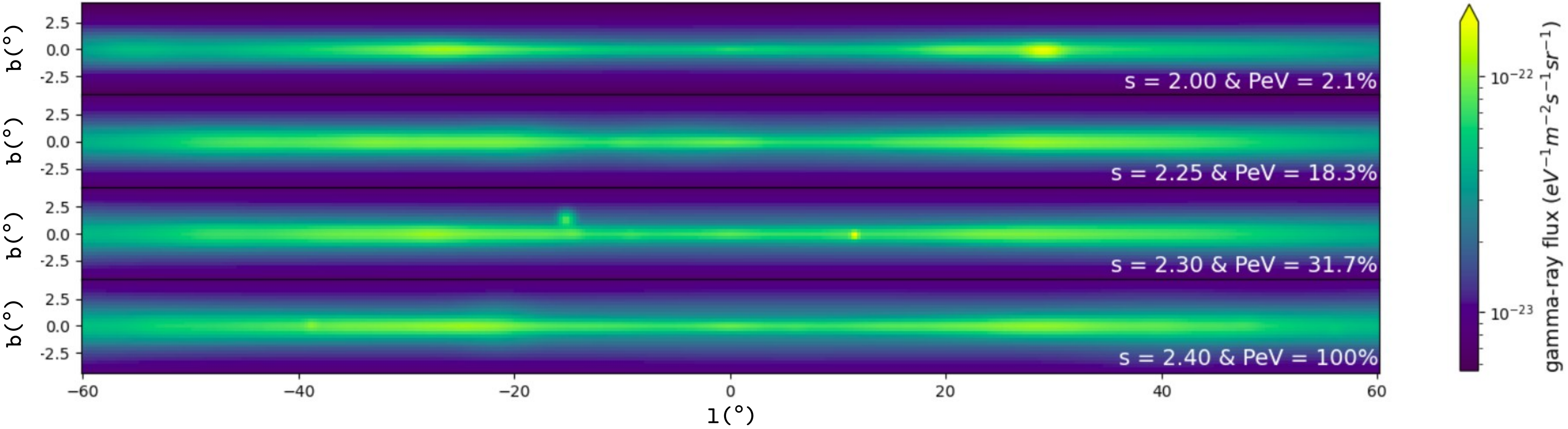
General shape like Lipari & Vernetto



But both cases present large bumps

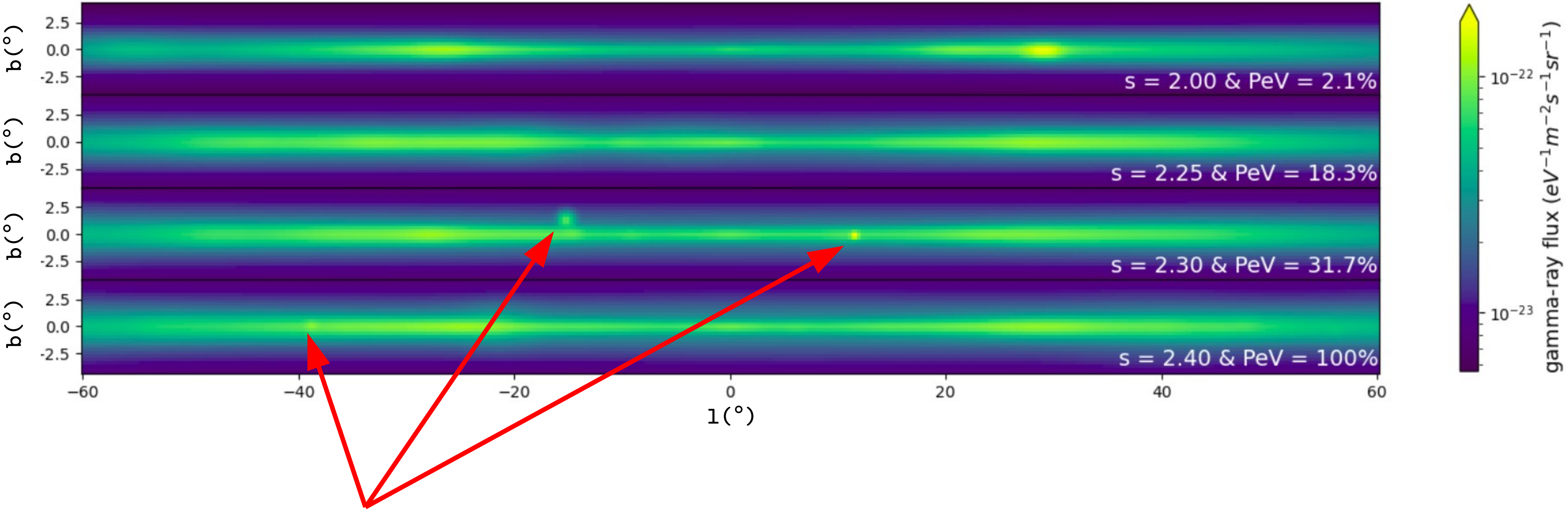
Slide from Samy Kaci

Sky Maps and sources (case 1)



Slide from Samy Kaci

Sky Maps and sources (case 1)



Very few visible sources for case 1

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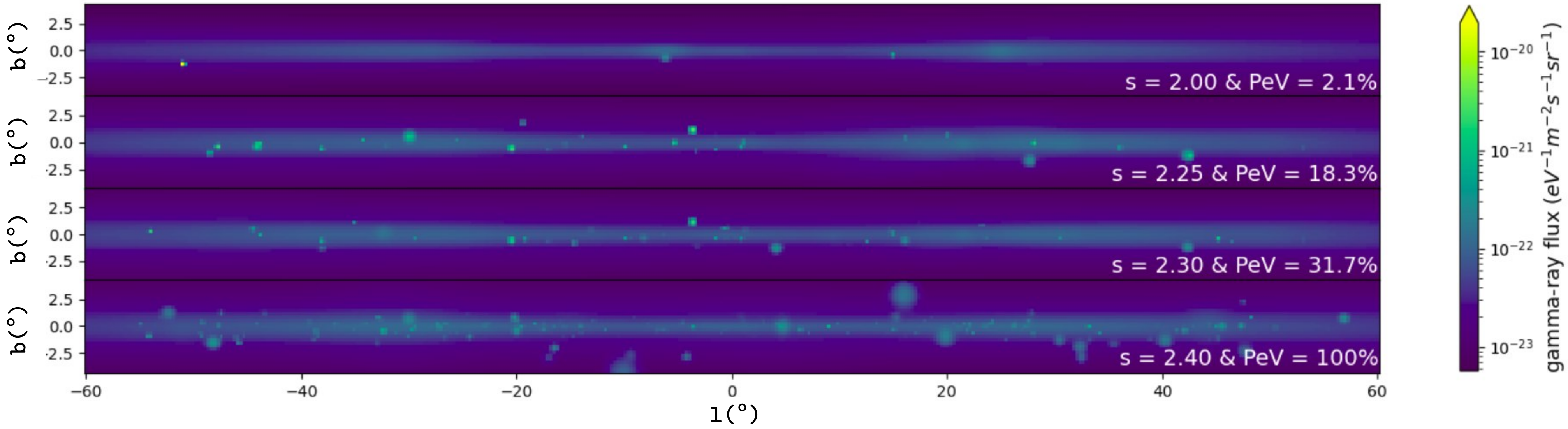
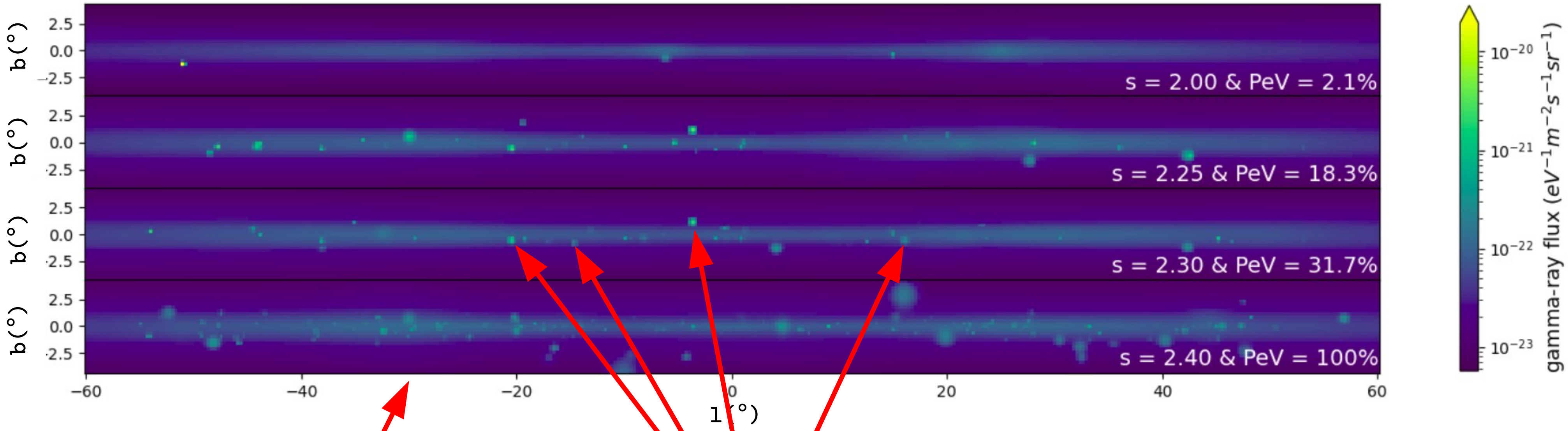
Sky Maps and sources (case 2)



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?

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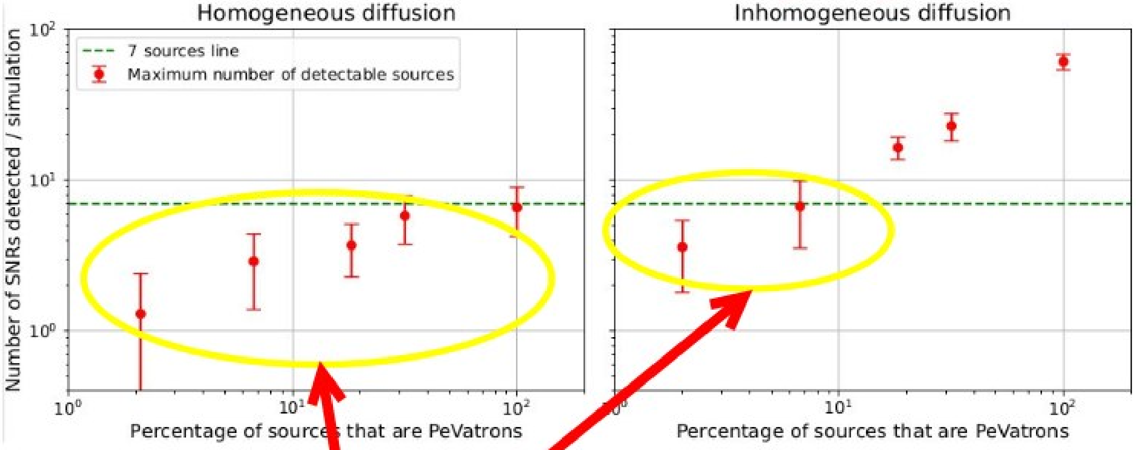
Number of detectable sources

S. Kaci & G. Giacinti (2024)

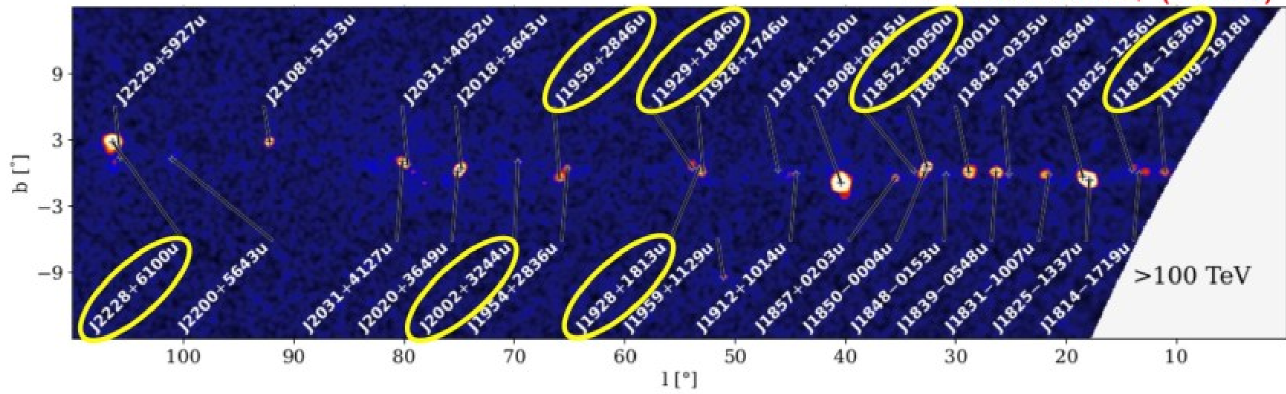


- Two diffusion regimes lead to different results concerning the detectability of sources.
- Homogeneous diffusion strongly limits the detectability of sources.
- Some parts of the space paramters can already be excluded.

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

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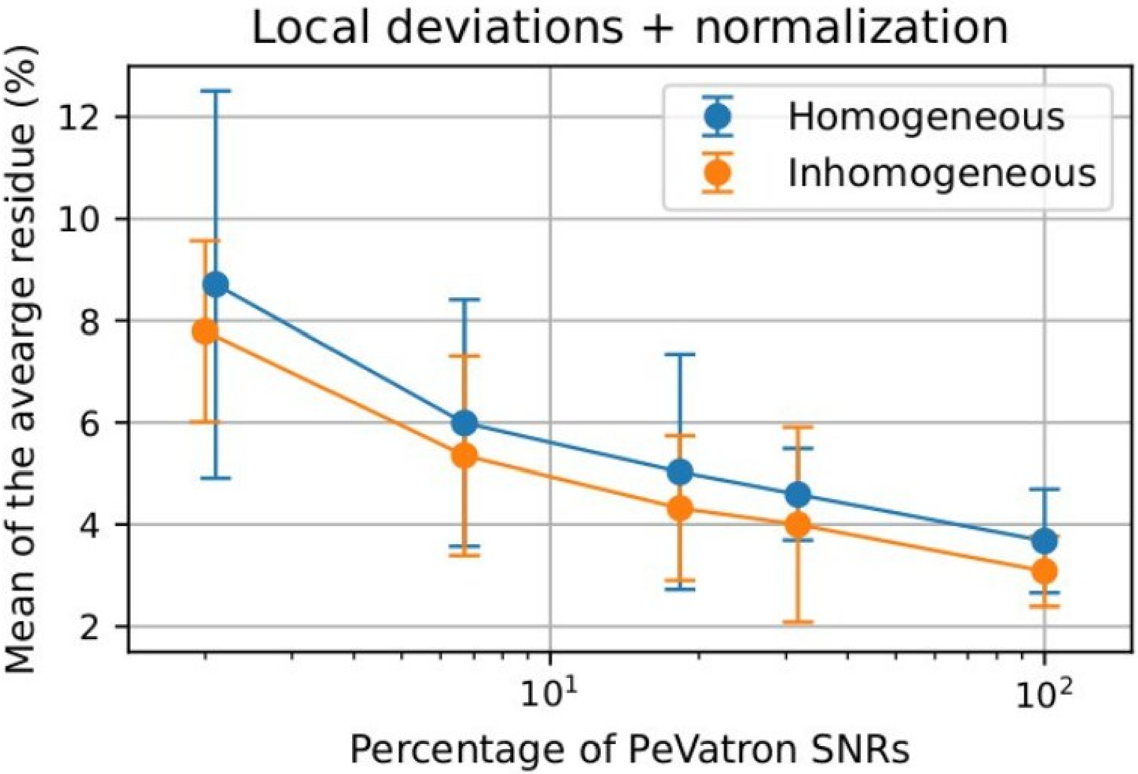
S. Kaci & G. Giacinti (2024)



- 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.

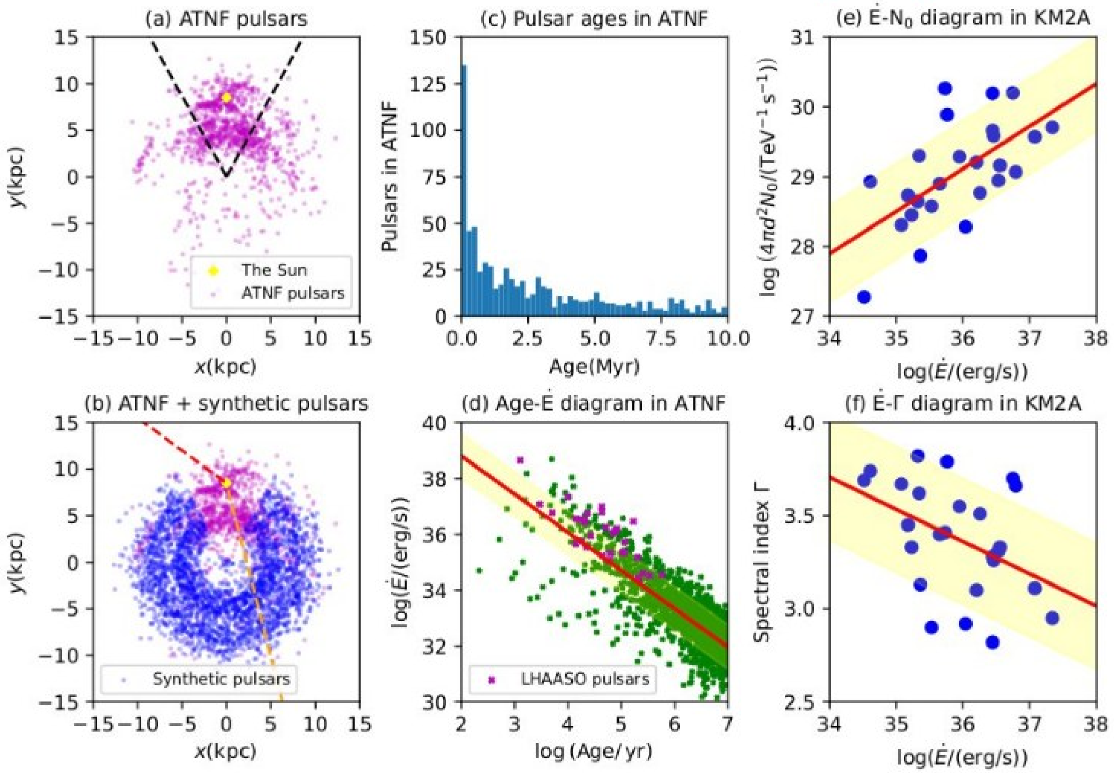
Summary & Conclusion

- The 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/kyr.

Slide from Samy Kaci

Impact of unresolved sources (PWNe)

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)

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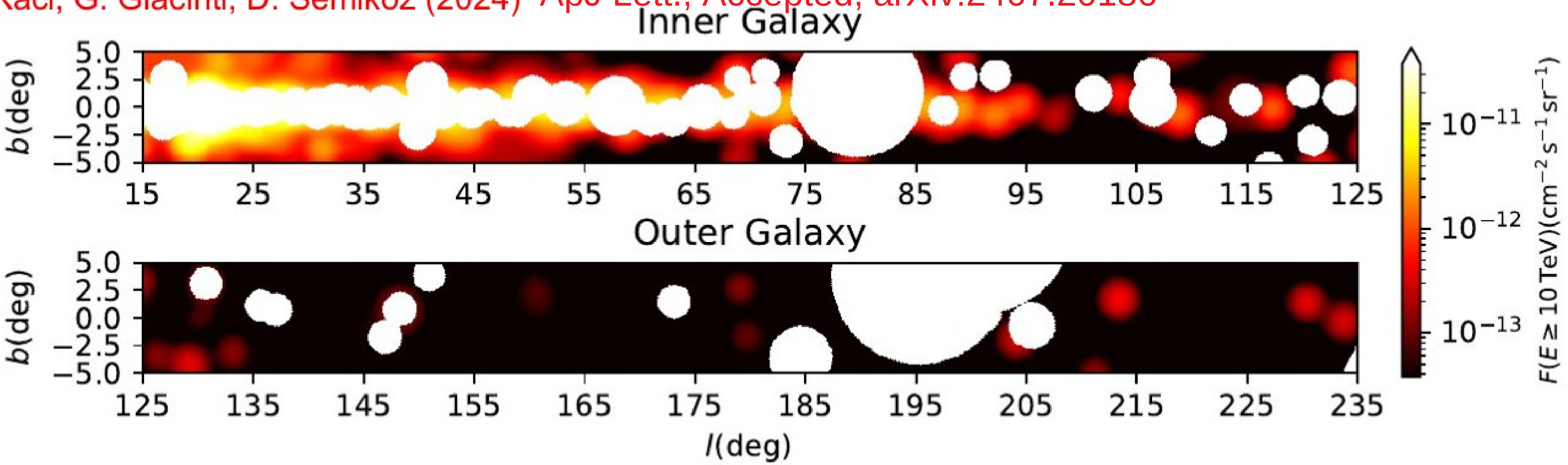
S. Kaci, G. Giacinti, D. Semikoz (2024) ApJ Lett., Accepted, arXiv:2407.20186



Slide S. Kaci

Impact of unresolved sources (PWNe)

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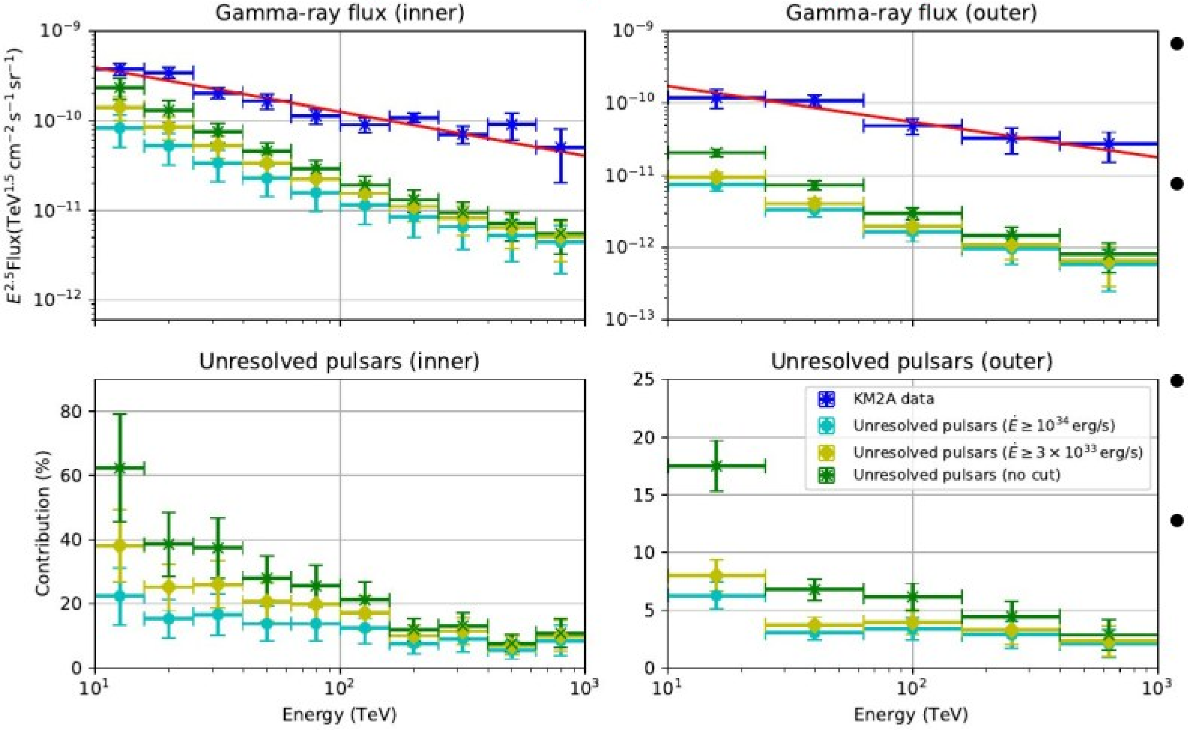


- Unresolved pulsars almost do not contribute in the outer Galaxy.
- Their contribution in the inner Galaxy depends on the cut in spindown power.
- Their contribution is negligeable above 100TeV.
- Unresolved pulsars may account for at most ~50% of the diffuse flux under ~30TeV in the inner Galaxy..

Slide S. Kaci

Anisotropic CR propagation & Galactic diffuse γ-ray emission

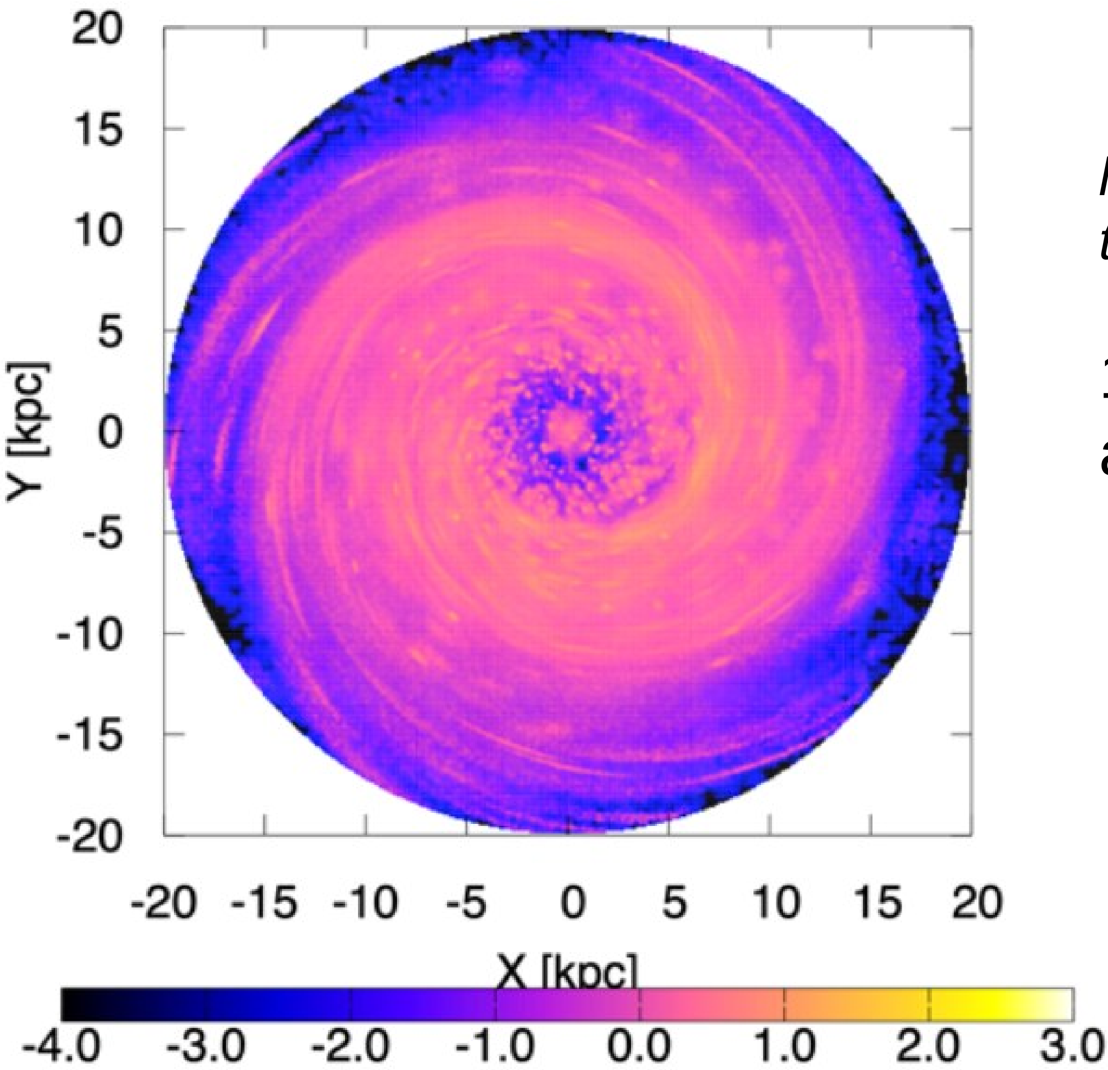
Giacinti & Semikoz, Submitted, arXiv:2305.10251

→ Propagate CRs in “Jansson &Farrar” Galactic magnetic field model.

→ **Stochastic** PeV CR **injection** at SNe.

source distribution from Green, arXiv:1309.3072: $n(r) \propto (r/R_{\odot})^{0.7} \exp\left[-3.5(r-R_{\odot})/R_{\odot}\right]$

1 PeV CR density in the Gal. plane



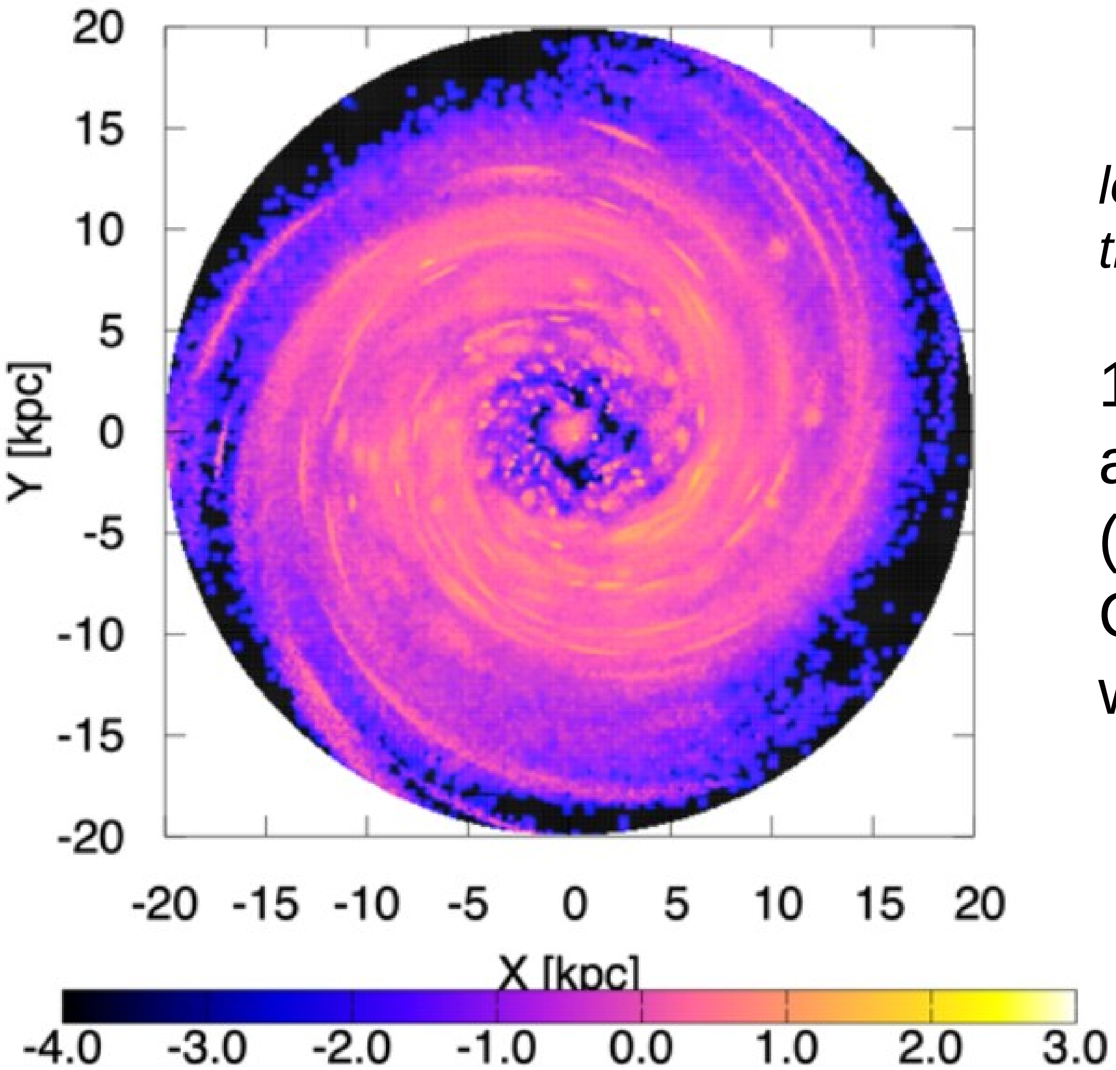
log(CR density) in the Galactic plane

10% of all SNe are PeVatrons

PATCHY

G.Giacinti and D.Semikoz, Submitted, arXiv:2305.10251

1 PeV CR density in the Gal. plane



log(CR density) in the Galactic plane

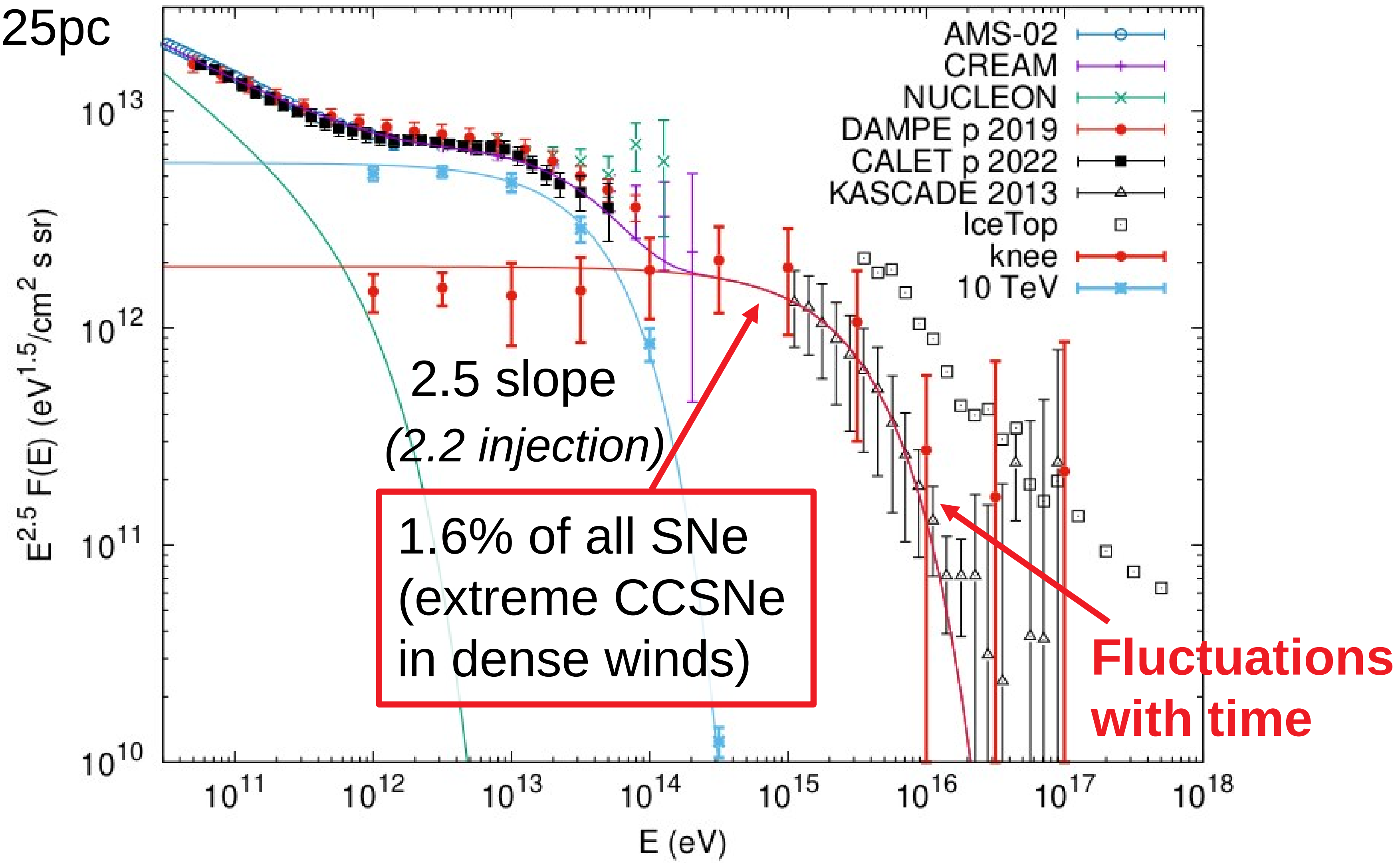
1.6% of all SNe are PeVatrons (rare, extreme CCSNe in dense winds)

EXTREMELY PATCHY!

G.Giacinti and D.Semikoz, Submitted, arXiv:2305.10251

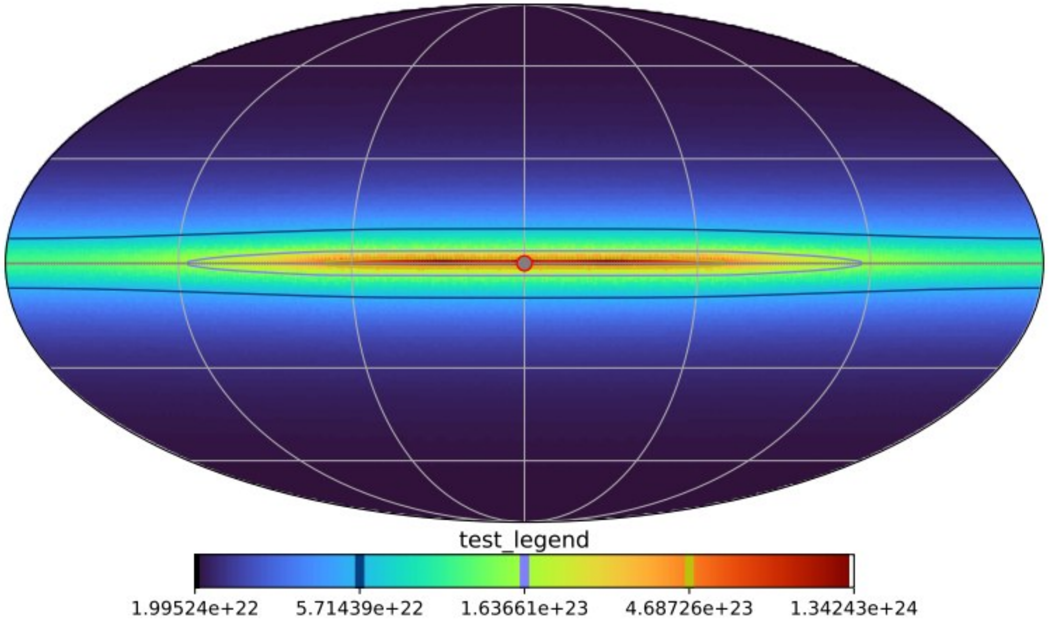
Proton flux at the knee

L_{max}=25pc



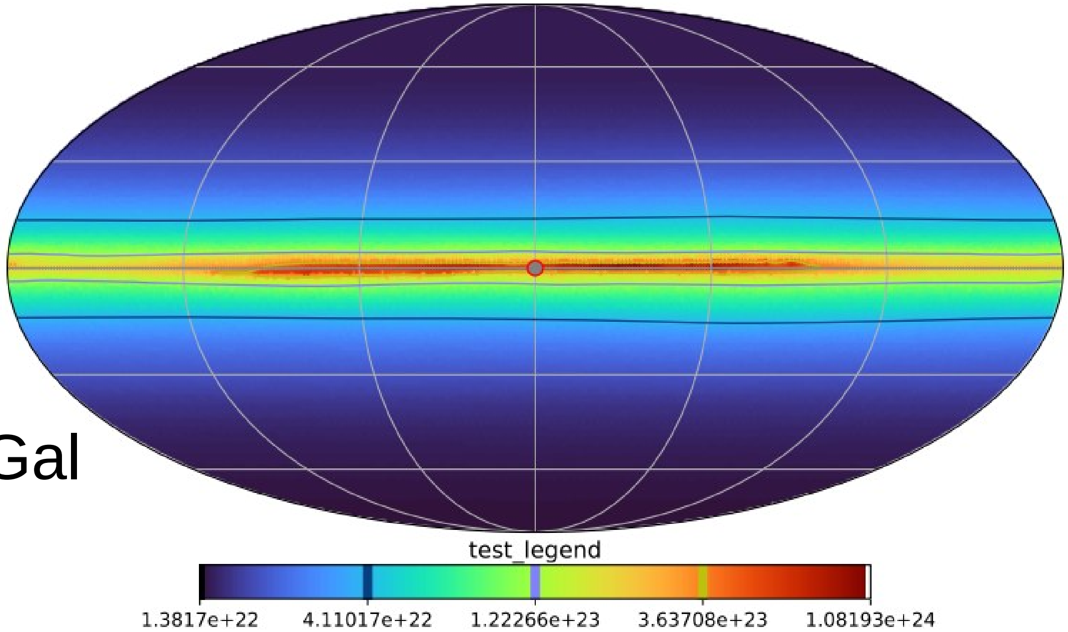
G.Giacinti and D.Semikoz, Submitted, arXiv:2305.10251

Diffuse 100 TeV γ-ray emission



Lipari & Vernetto (2018)

Giacinti, Koldobskiy & Semikoz, In prep. (2024)

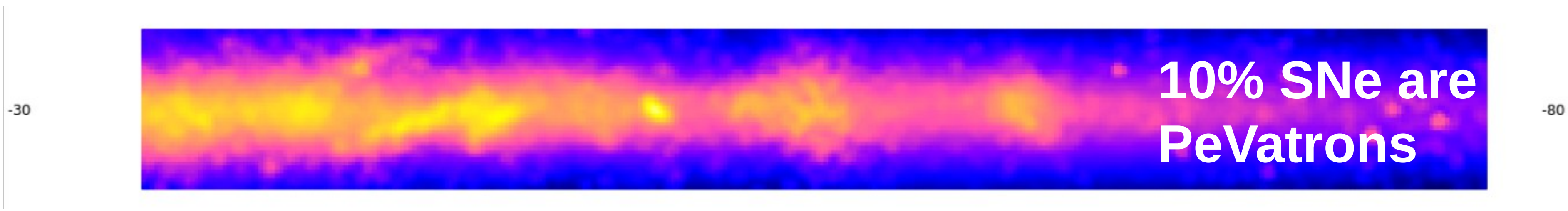


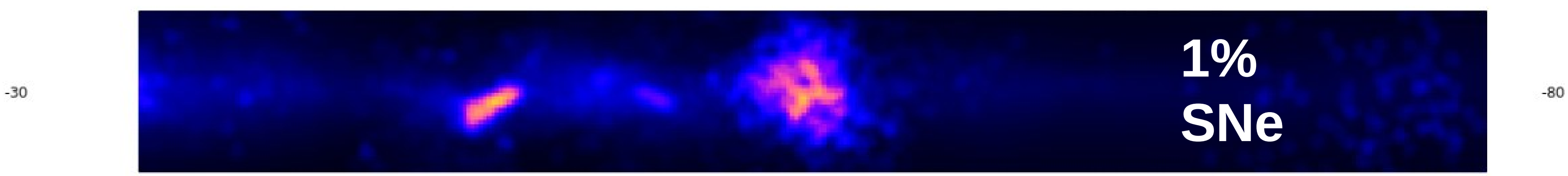
→ Less contrast inner/outer Gal
→ Broader in some places.

Zoom on our simulated Gal. plane

Giacinti, Koldobskiy & Semikoz, In prep. (2024)

Galactic plane survey ($|b| < 3^o$) at E_γ = 100 TeV in the simulation:

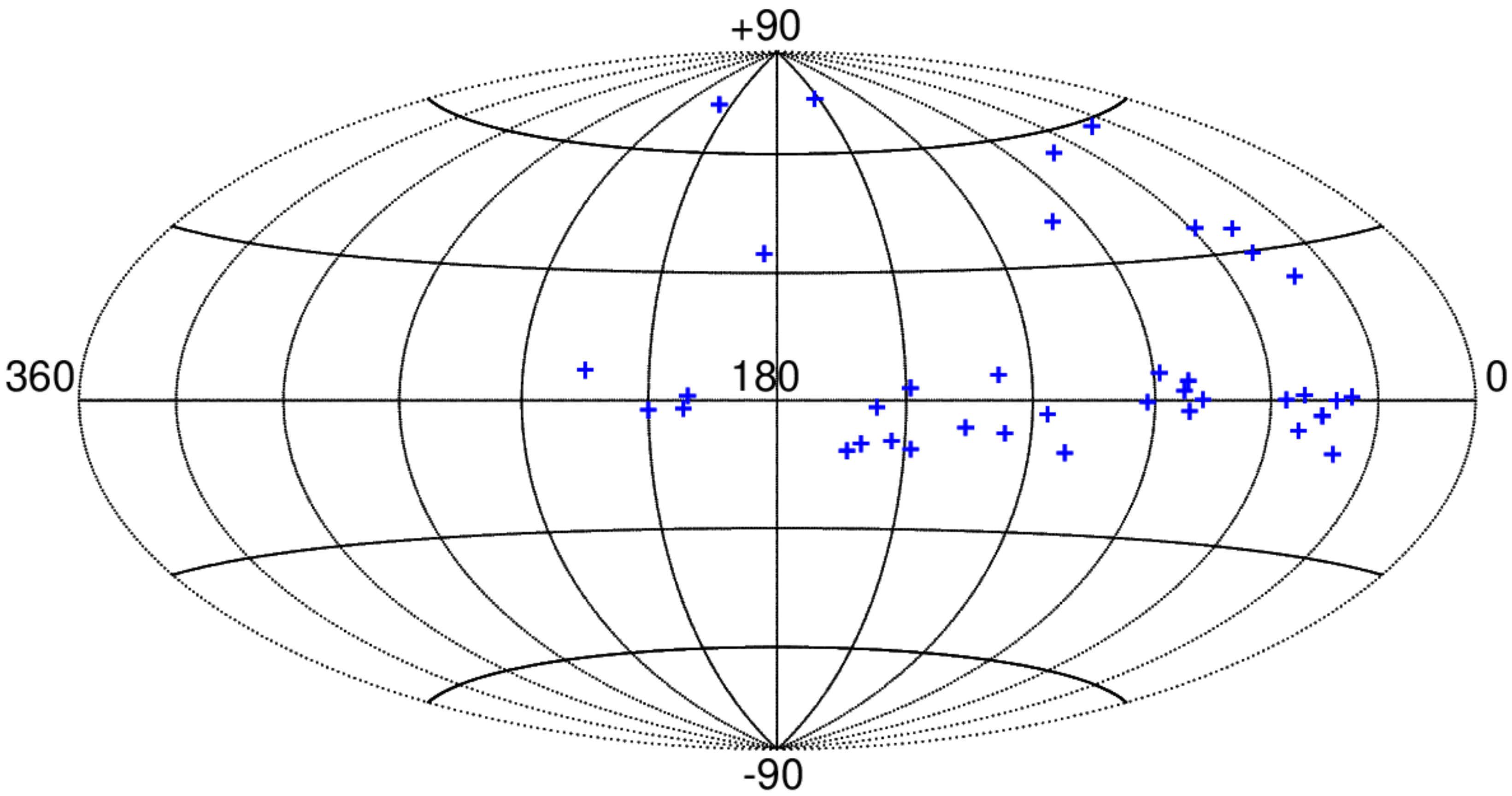




Updated our model of CR propagation (dynamical now).
Compare with LHAASO data => Infos on PeVatrons & GMF

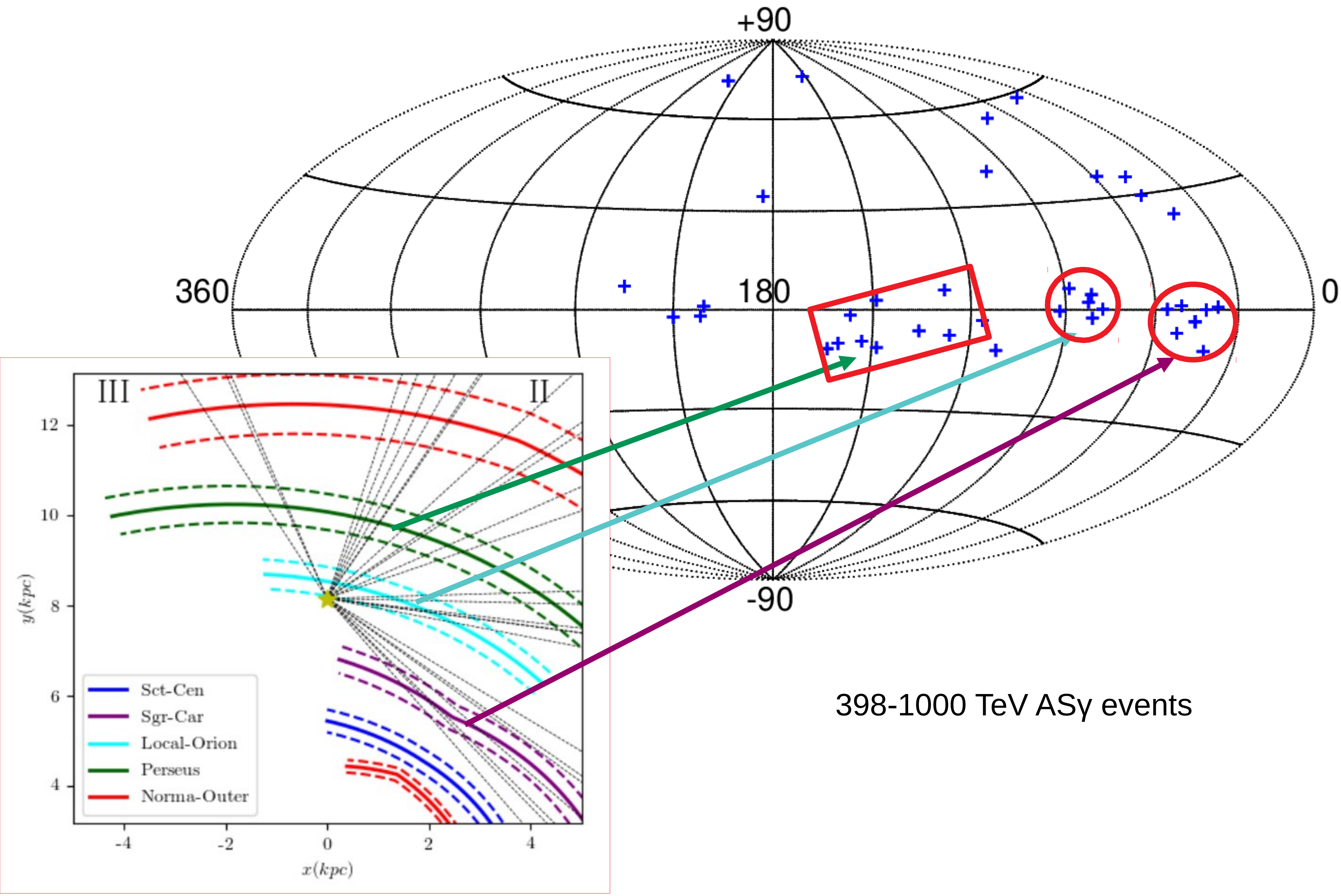
2 – Extended γ-ray sources from past / current PeVatrons (p^+/e^-, incl. TeV halos)

Extended sources in ASγ data ?



398-1000 TeV ASγ events

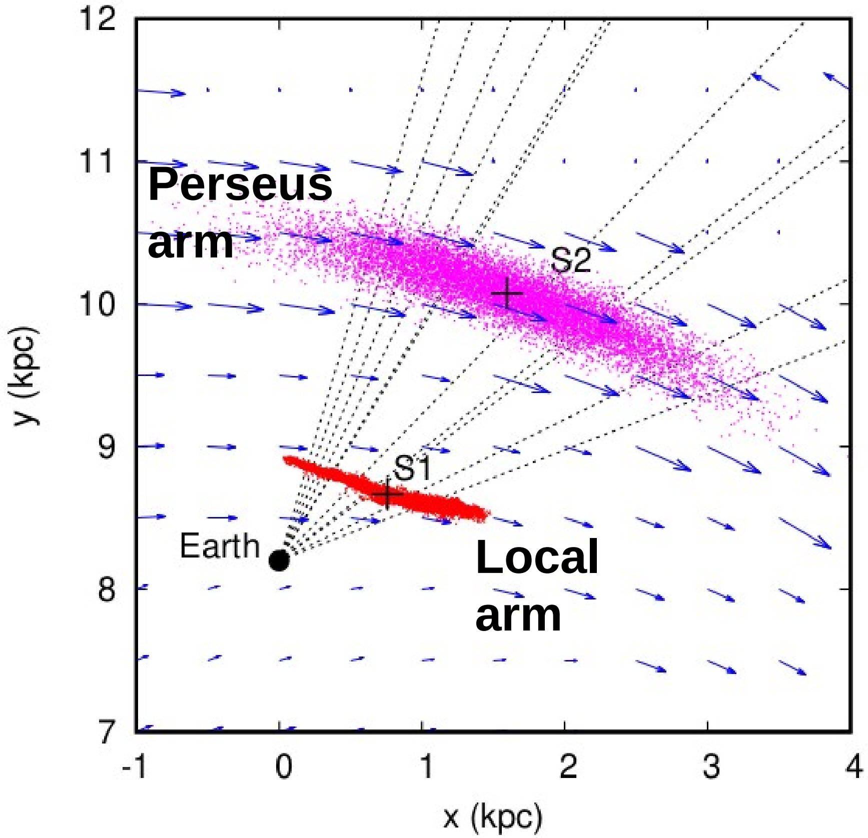
Extended sources in ASγ data ?



398-1000 TeV ASγ events

Extended sources in ASγ data ?

Giacinti, Abounnasr, Neronov & Semikoz, Phys. Rev. D 106, 123029 (2022), arXiv:2203.11052



→ Propagate CRs in “Jansson & Farrar” Galactic B field model.

S1: (x, y, z) = (0.758 kpc, 8.67 kpc, 0) & t = 3 kyr.

S2: (1.60 kpc, 10.1 kpc, −250 pc) & t = 30 kyr.

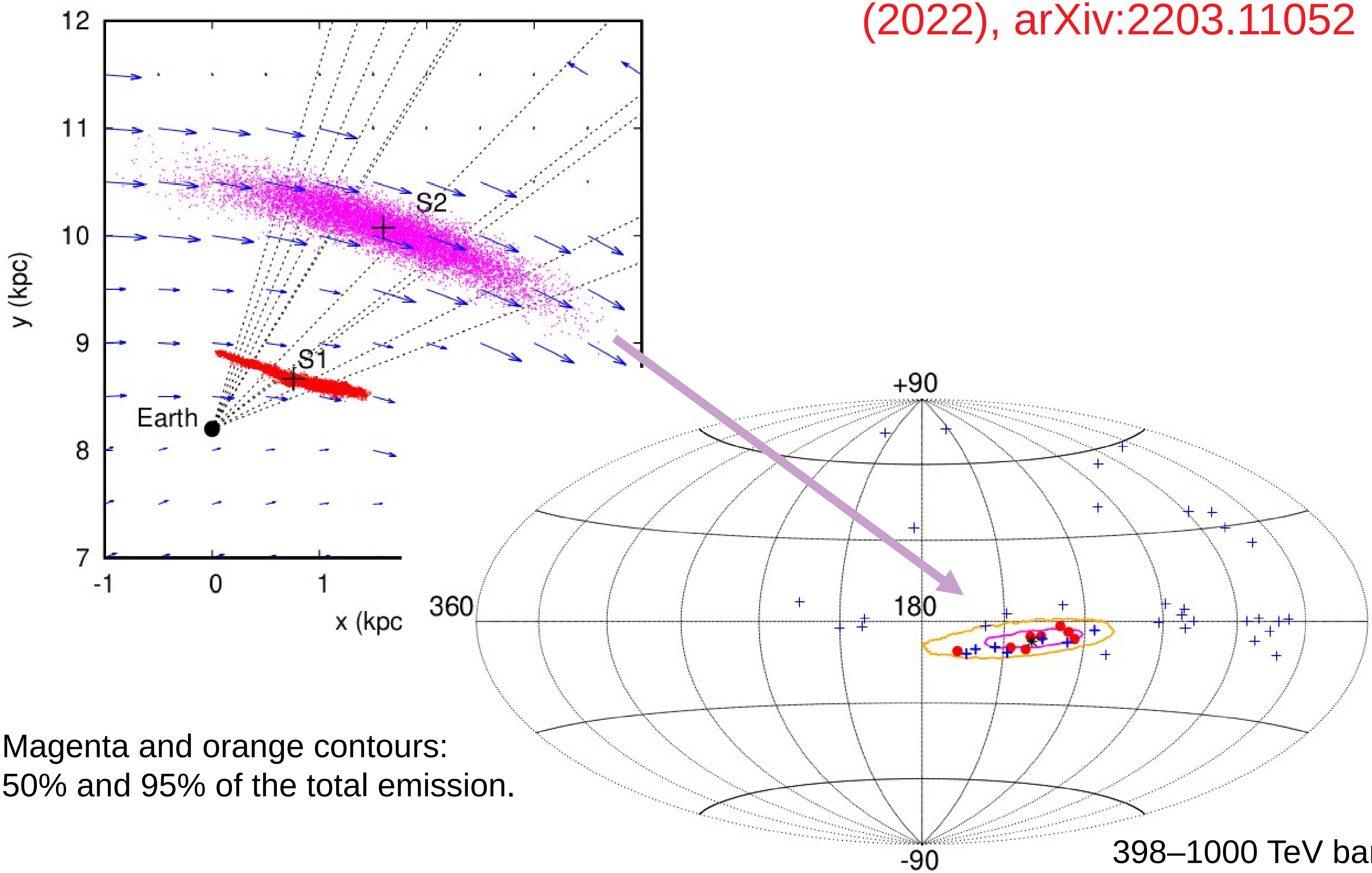
$n_1 \sim 0.33\ \mathrm{cm}^{-3}$

$n_2 \sim 1.5\ \mathrm{cm}^{-3}$

=> 7 ± 3 photons in the 398-1000 TeV range

Extended sources in ASγ data ?

Giacinti, Abounnasr, Neronov & Semikoz, Phys. Rev. D 106, 123029 (2022), arXiv:2203.11052



Magenta and orange contours:
50% and 95% of the total emission.

398–1000 TeV band

TeV Halos: "Mirage" sources and large offsets

Works from Yiwei Bao

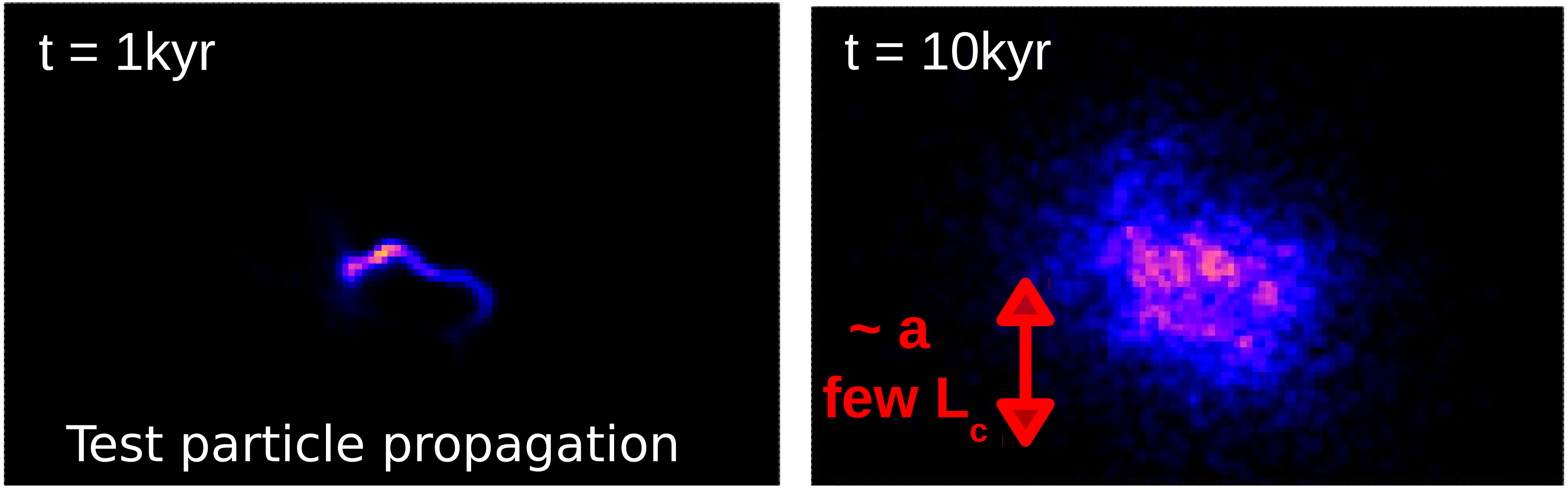
Bao, Giacinti, Liu, Zhang & Chen, arXiv:2407.02478 (Submitted)
Bao, Liu, Giacinti, Zhang & Chen, arXiv:2407.02829 (Submitted)

Anisotropic diffusion 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]

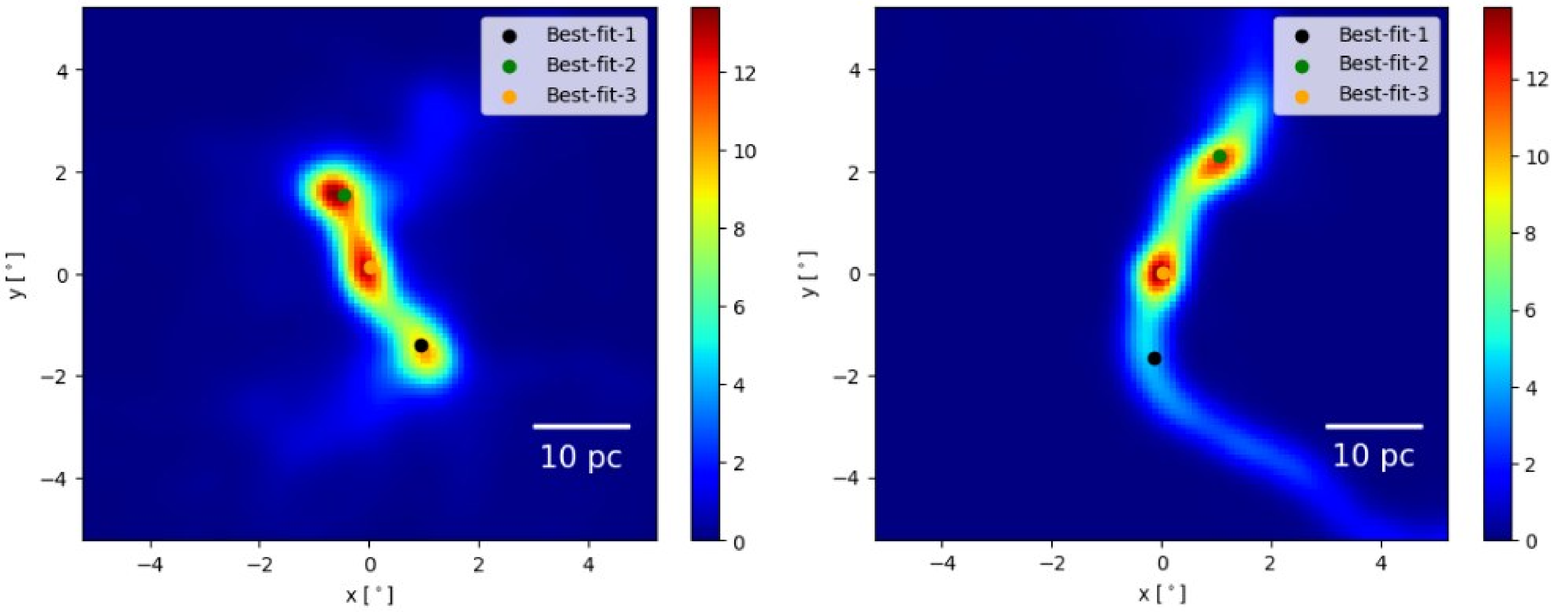


1 PeV CRs in 3D Kolmogorov turbulence (L_{max} = 150 pc, Plot size: 400 pc)

=> Expect intrinsically ASYMMETRIC emissions too.

Appearance of additional ("mirage") sources:

They may appear around astrophysical sources.

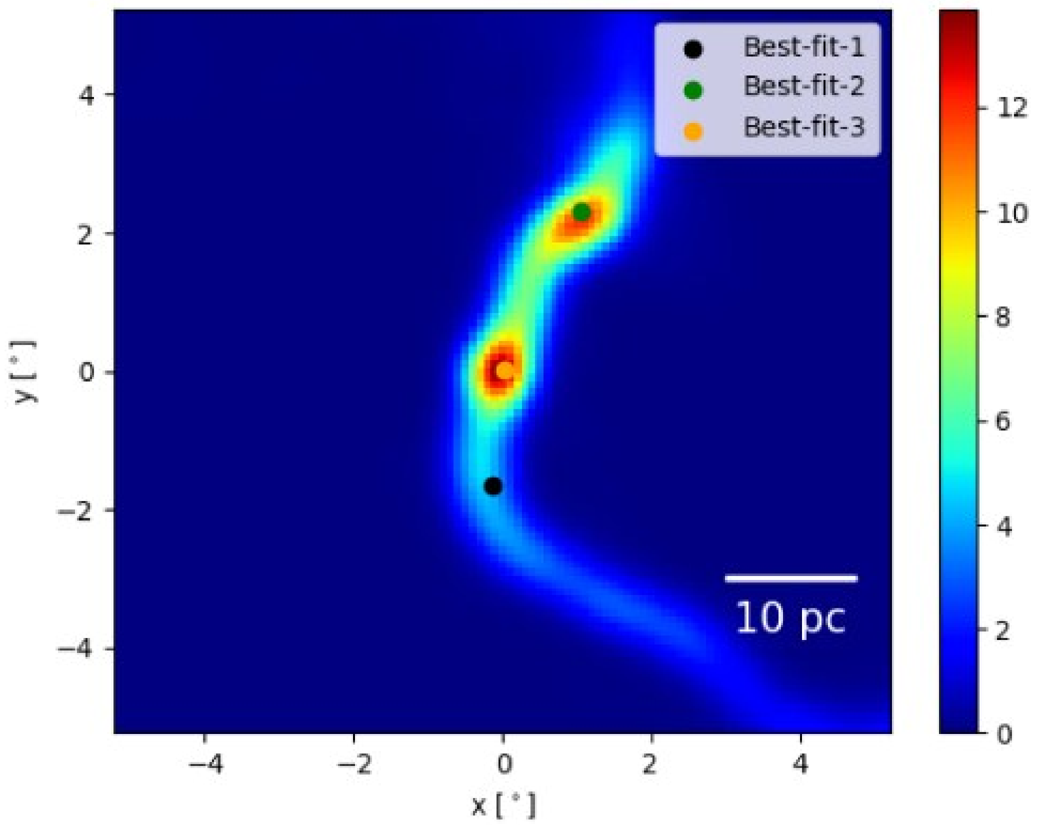


L_c = 40pc ; B_{turb} = 3 μG ; B_{reg} = 0 μG; Kolmogorov turbulence ; (8192 particles)

Appearance of additional (“mirage”) sources:

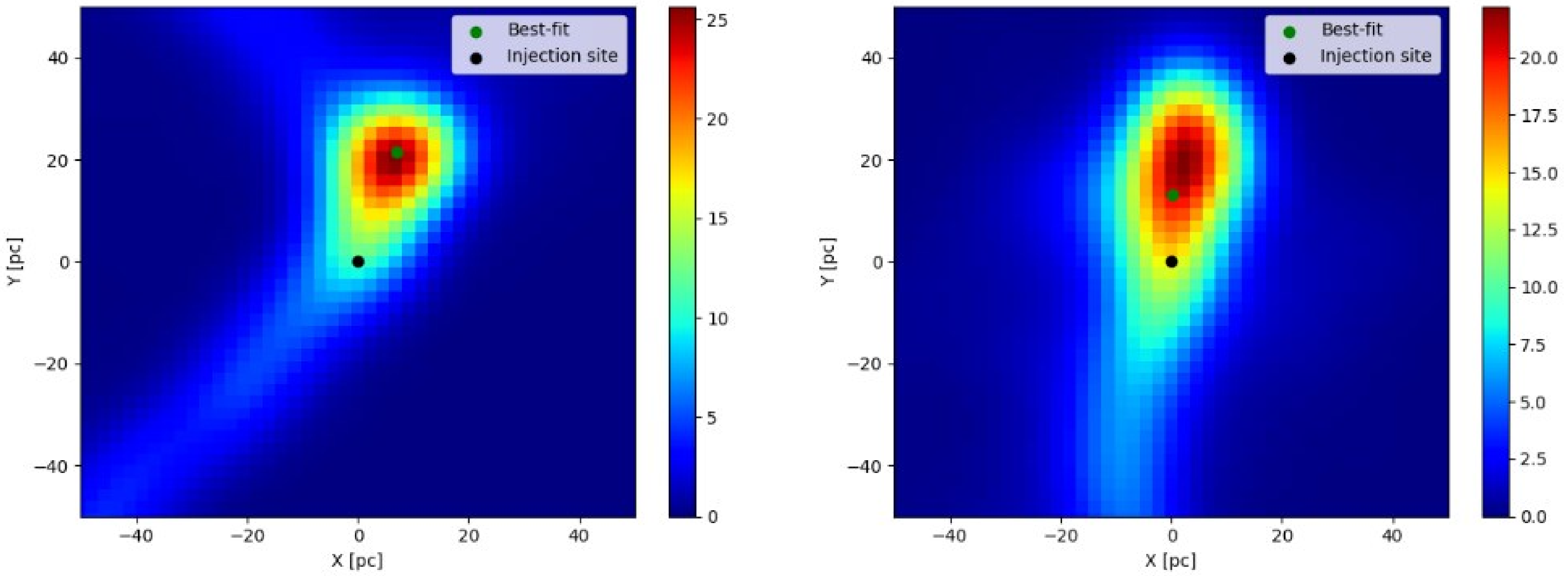
The second source is a "**mirage**", where the magnetic field bends inwards /outwards, wrt/ observer.

(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

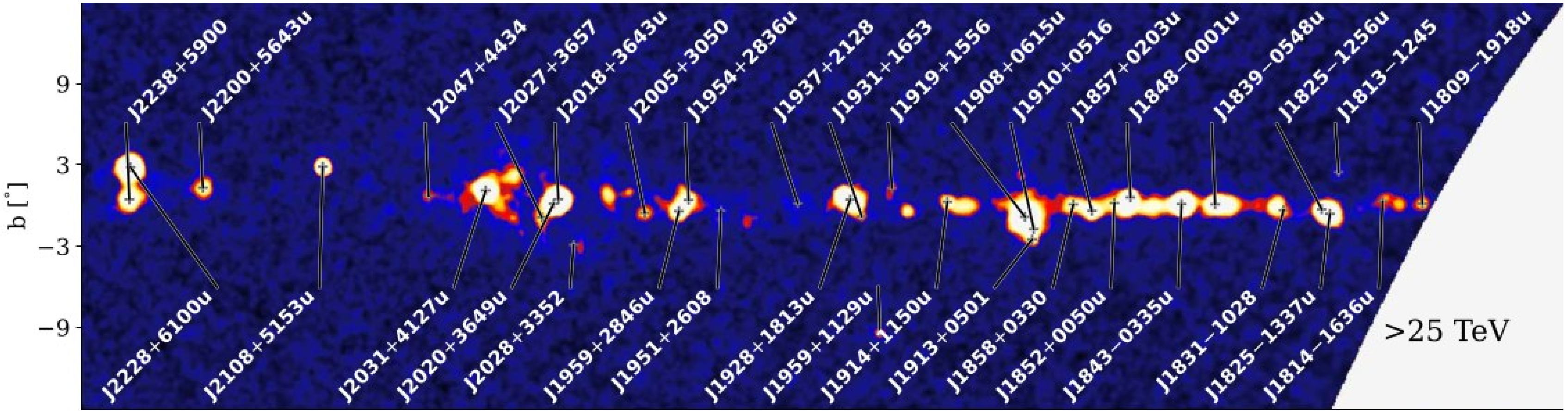


B_{turb} ~ 1 µG ; B_{reg} = 0 µG ; L_c = 200 pc ; Kolmogorov turbulence ; (8192 particles)

May explain LHAASO observations

LHAASO Collaboration, ApJS 271, 25 (2024)

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



Large offsets between sources and center

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	

Summary:

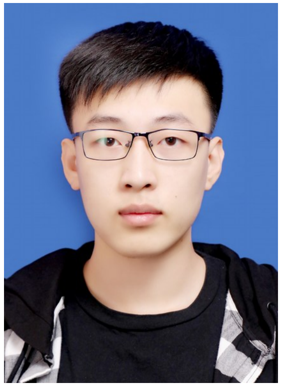
→ **Very extended hadronic sources** from **past PeVatrons** may exist.

→ **“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.

3 – CR anisotropy

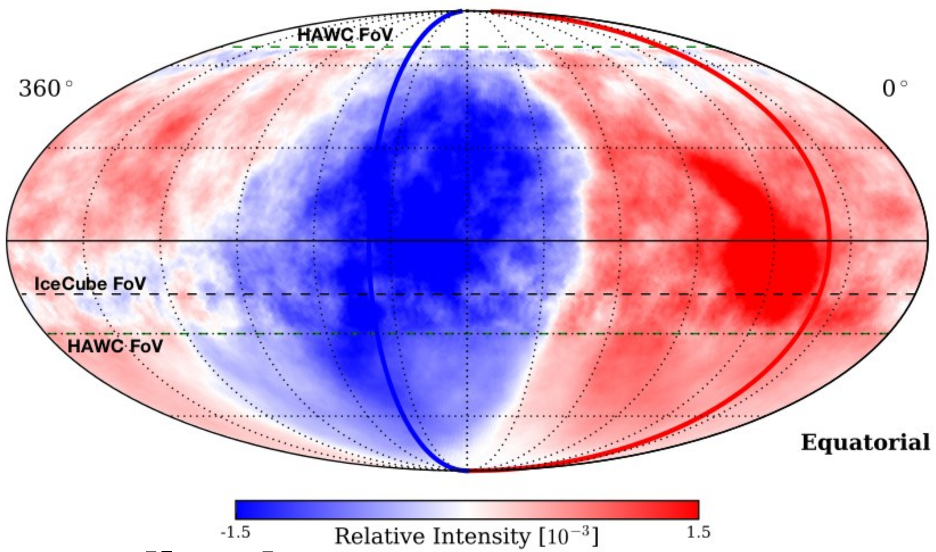
Work by Wenyi Bian (边稳懿)



Bian, Giacinti & Reville, Submitted, arXiv:2410.09634

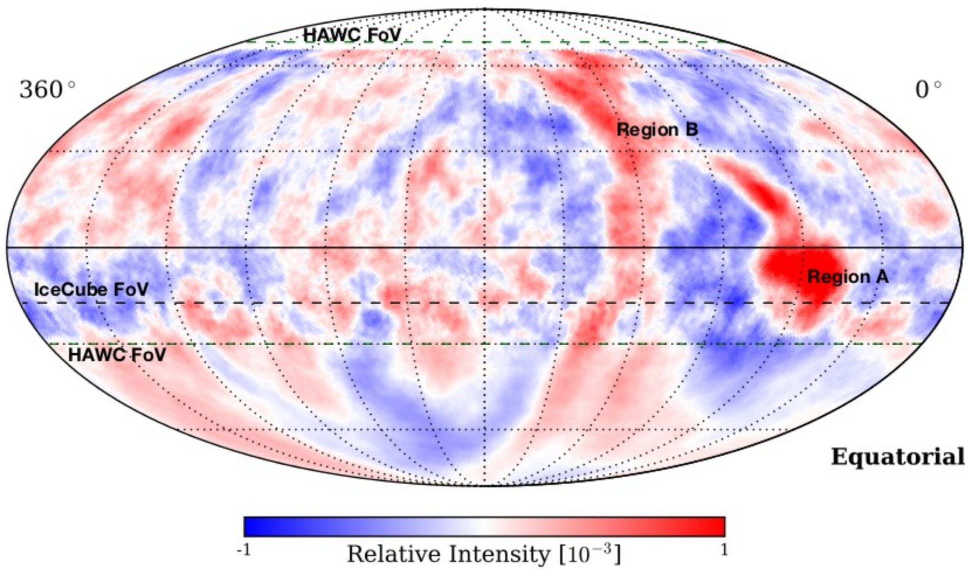
HAWC + IceCube Collab., ApJ (2018) [arXiv:1812.05682]:

Large Scale Anisotropy (~0.1%) :

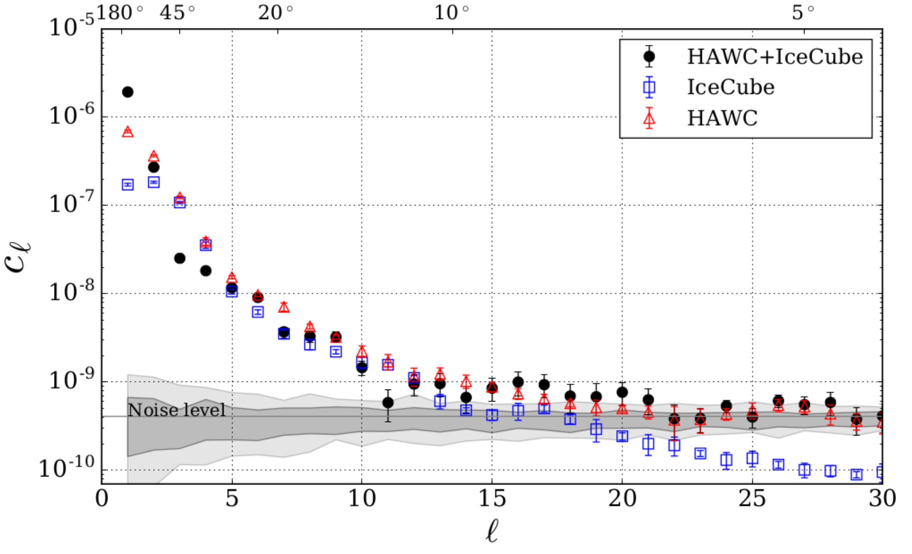


In the direction of field line

SSA (l>3):

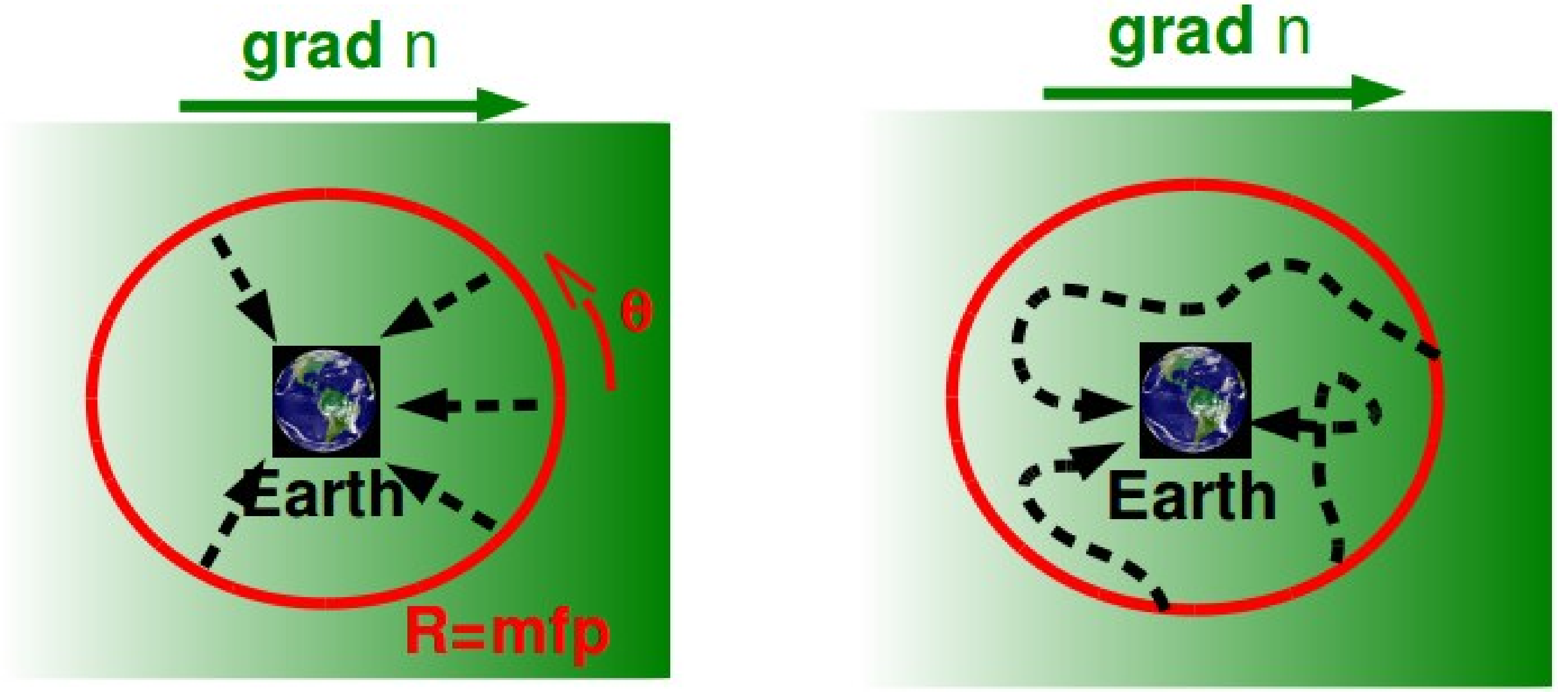


Angular power spectrum:



Small-scale anisotropies

Giacinti & Sigl, Phys. Rev. Lett. (2012), arXiv:1111.2536



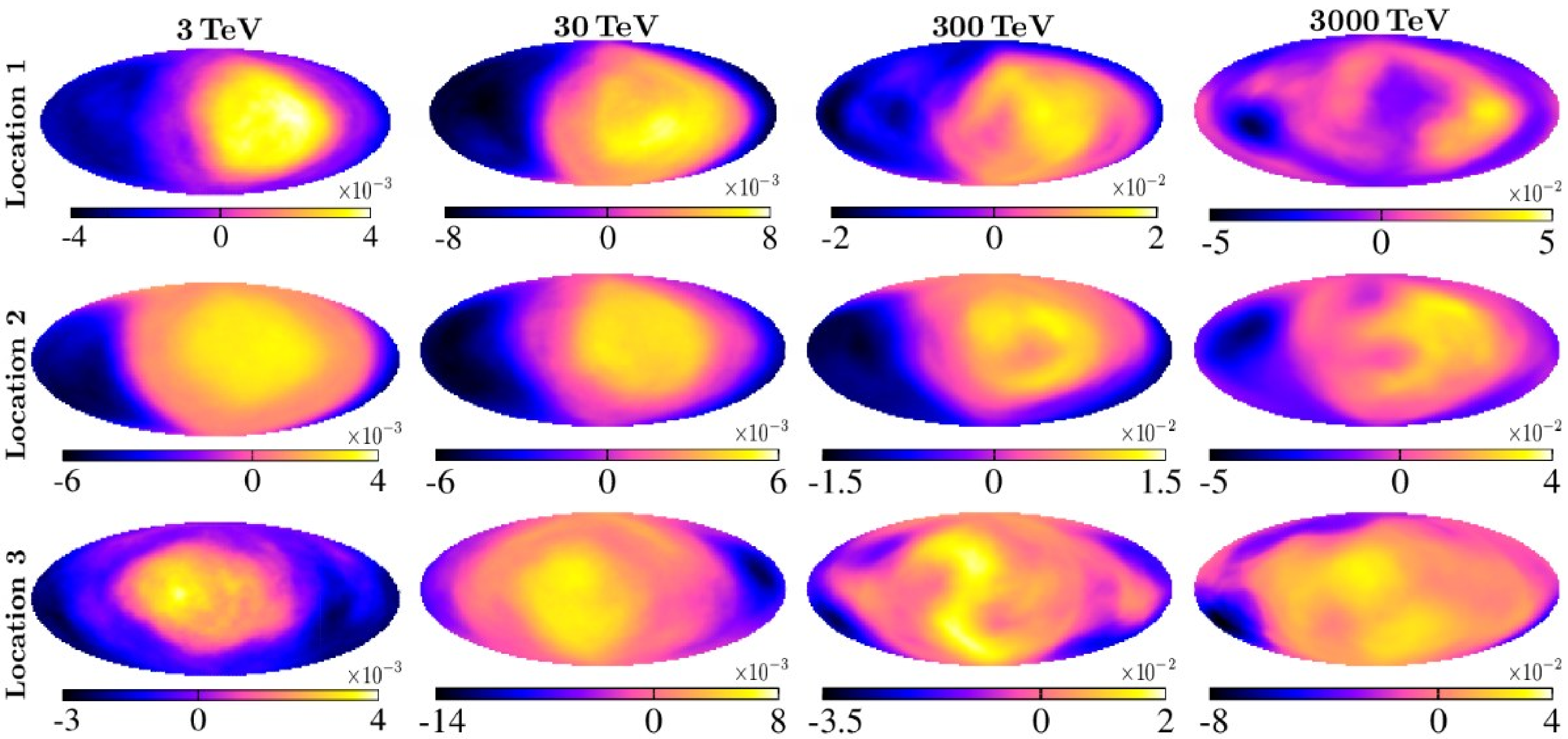
$$F = F_0\,(1 + \delta \cos \theta)$$

SSA due to the local realization of the ISM turbulent field, within a CR MFP around Earth.

CR anisotropy down to 3 TeV

Bian, Giacinti & Reville, arXiv:2410.09634

Simulations now reach TeV energies

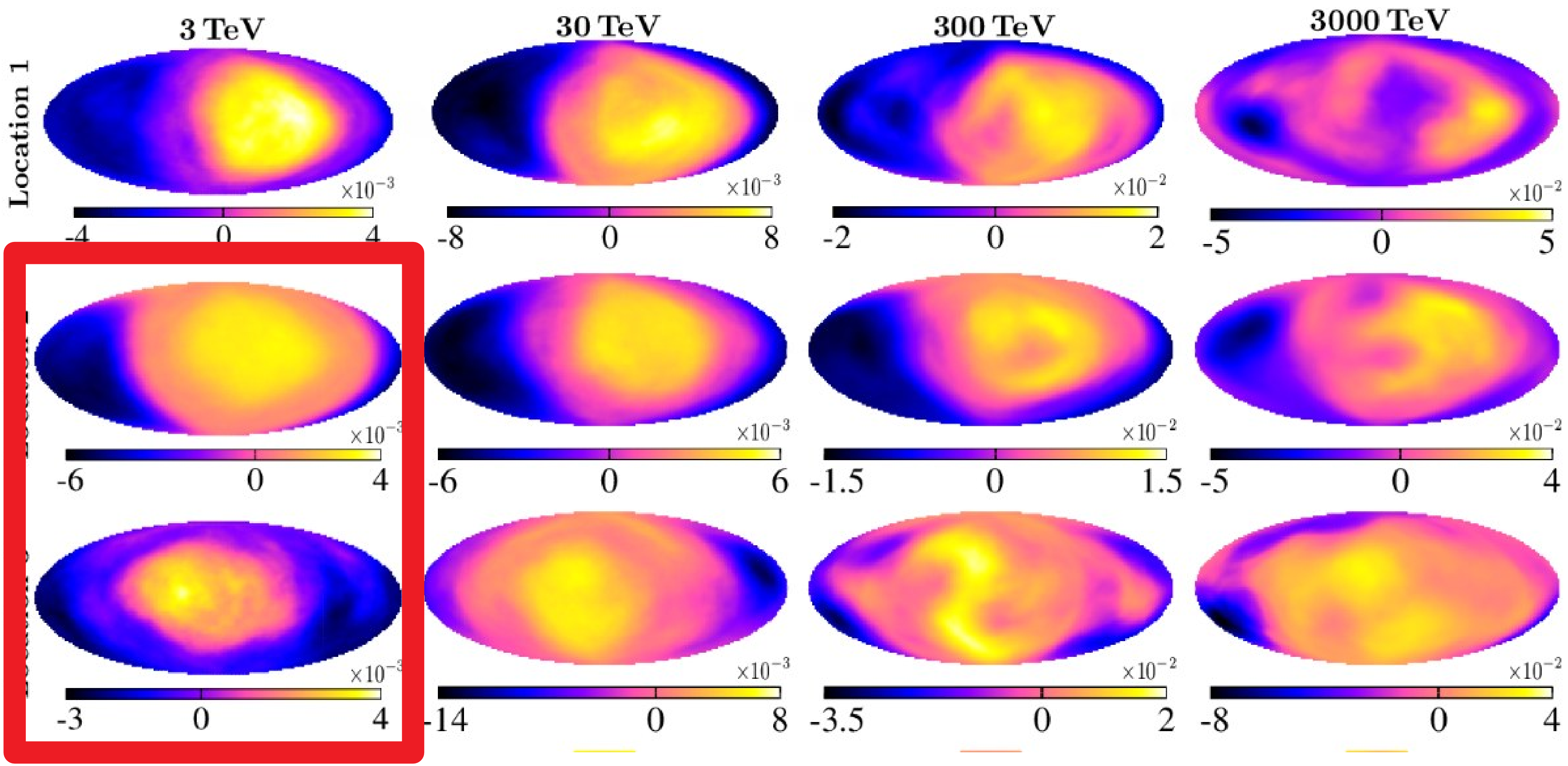


Outer scale turbulence L_{max} = 150 pc, Kolmogorov turbulence

CR anisotropy down to 3 TeV

Bian, Giacinti & Reville, arXiv:2410.09634

Simulations now reach TeV energies

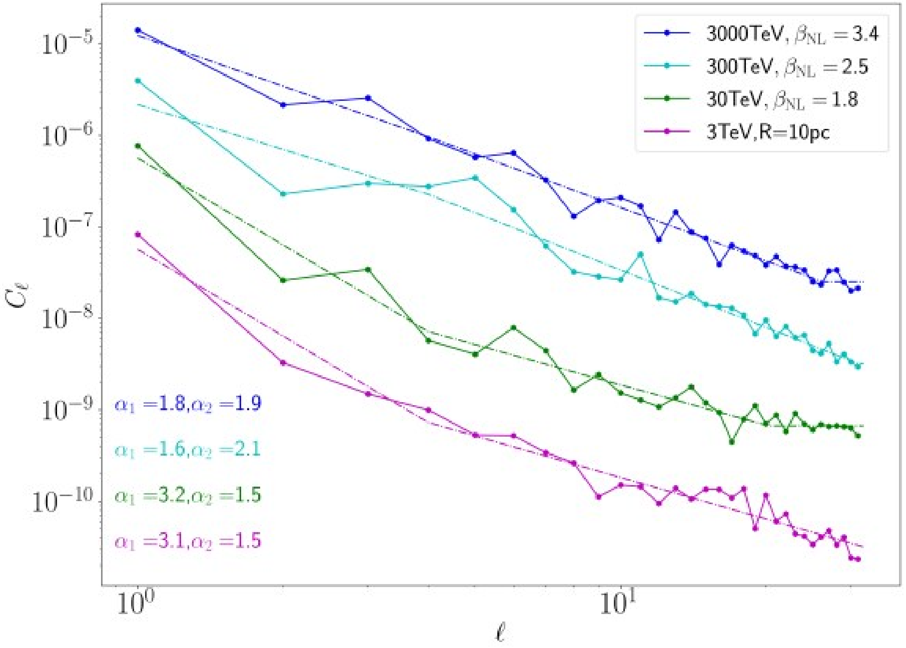


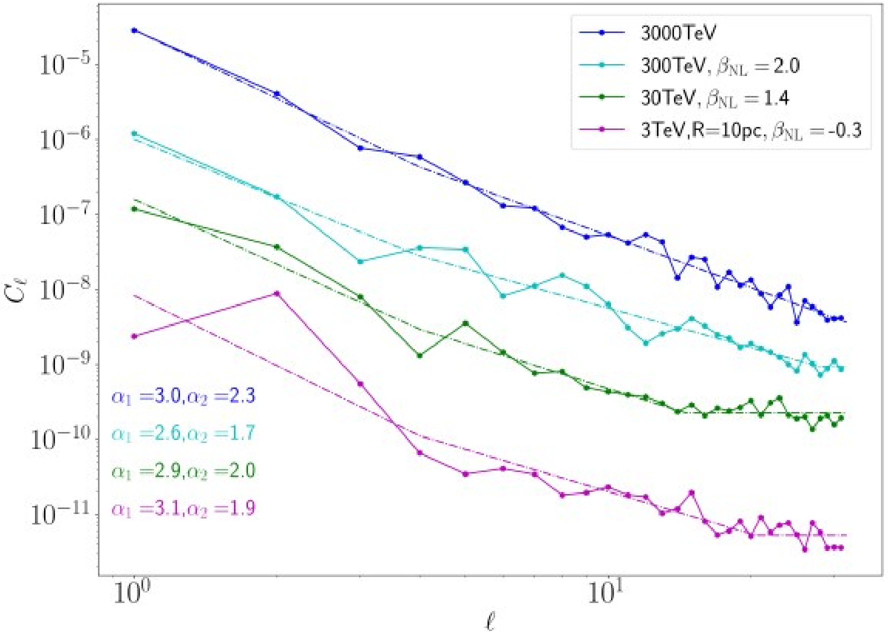
Amplitude SSA/LSA related to local δB/B.

Power spectrum versus CR energy

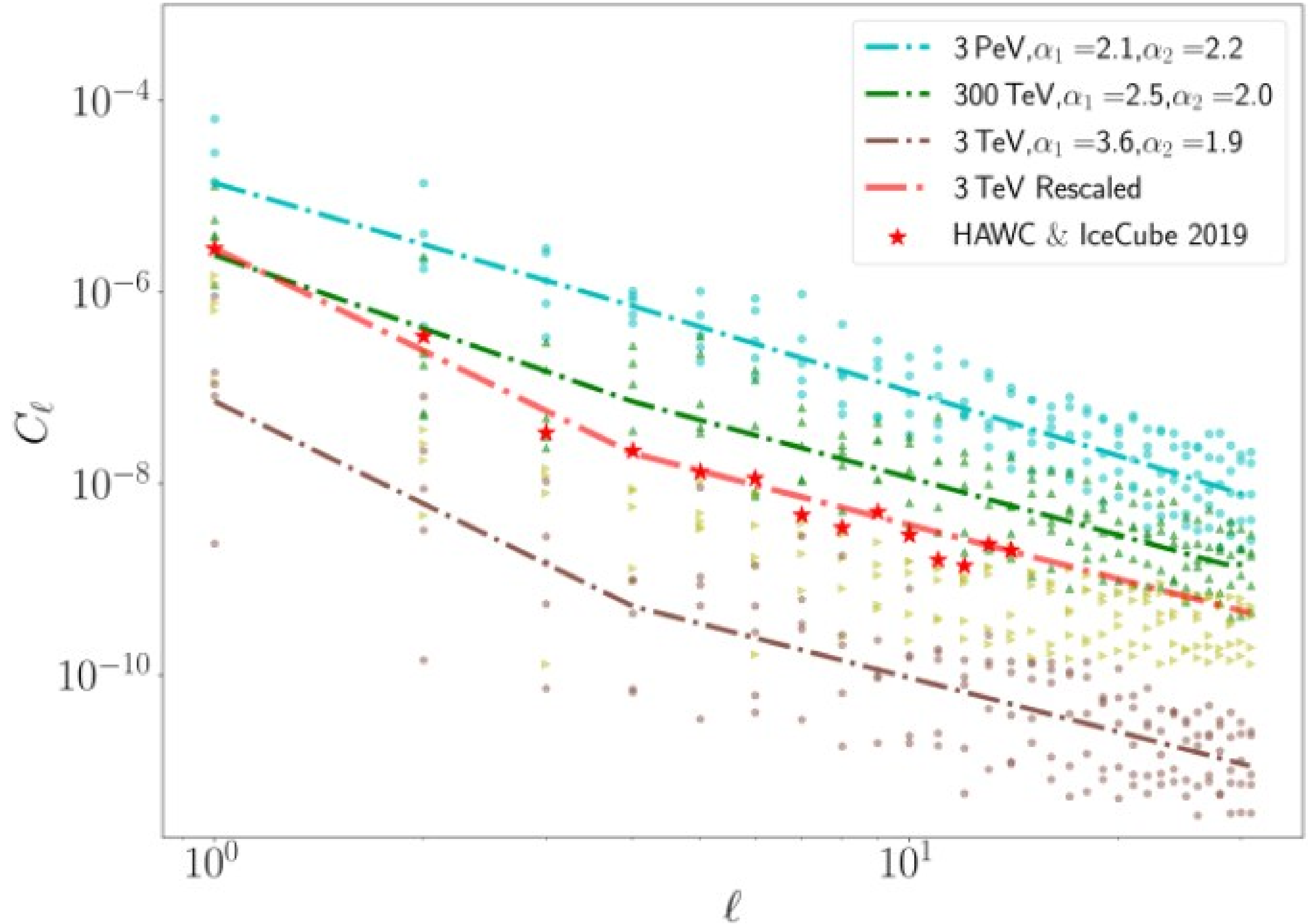
Spherical harmonics: $$f(E,\mu,\phi) = \sum_{\ell=0}^{L_{max}} \sum_{m=-\ell}^{\ell} f_\ell^m(E) Y_\ell^m(\mu,\phi)$$

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



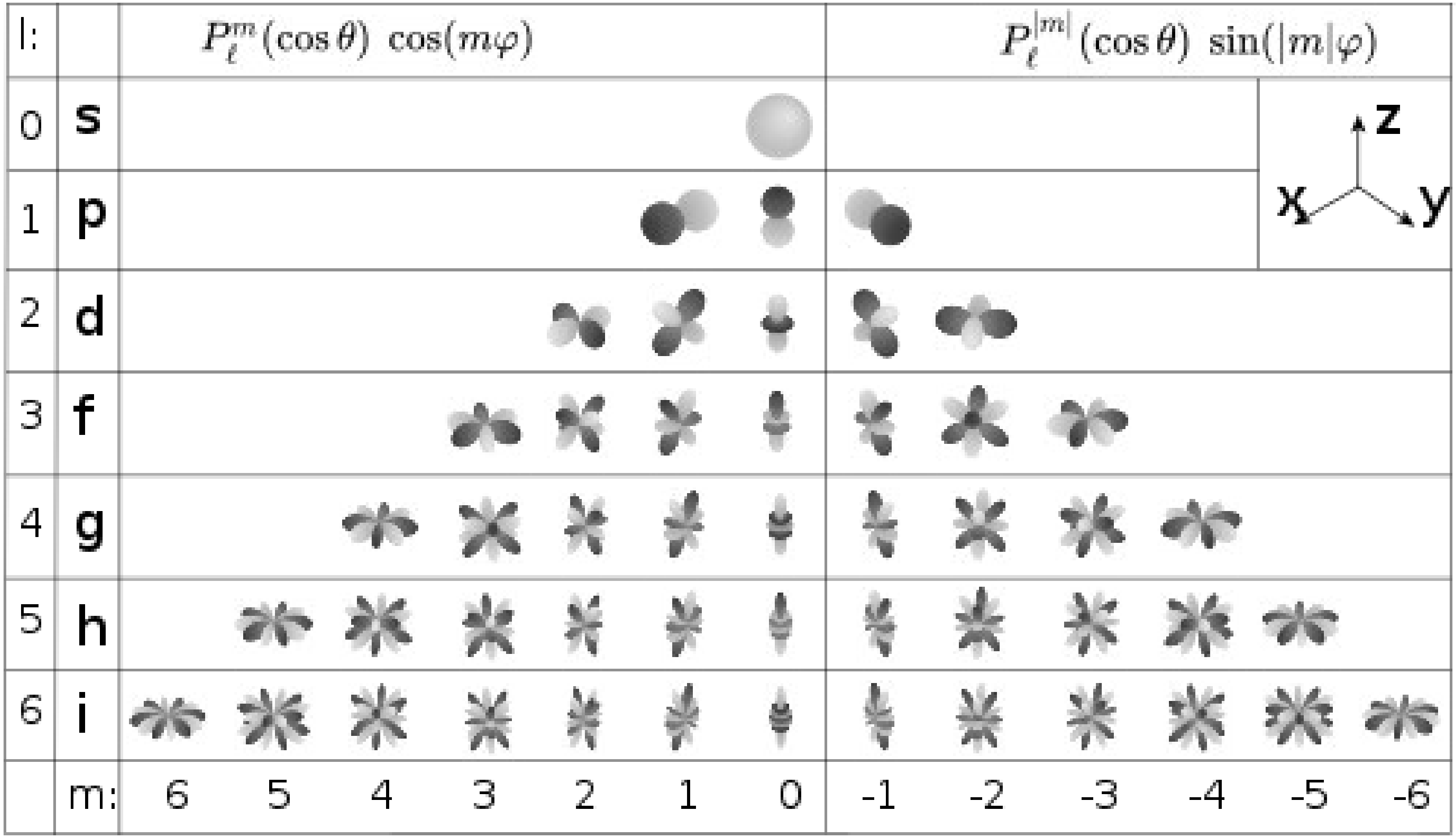


Power spectrum versus CR energy

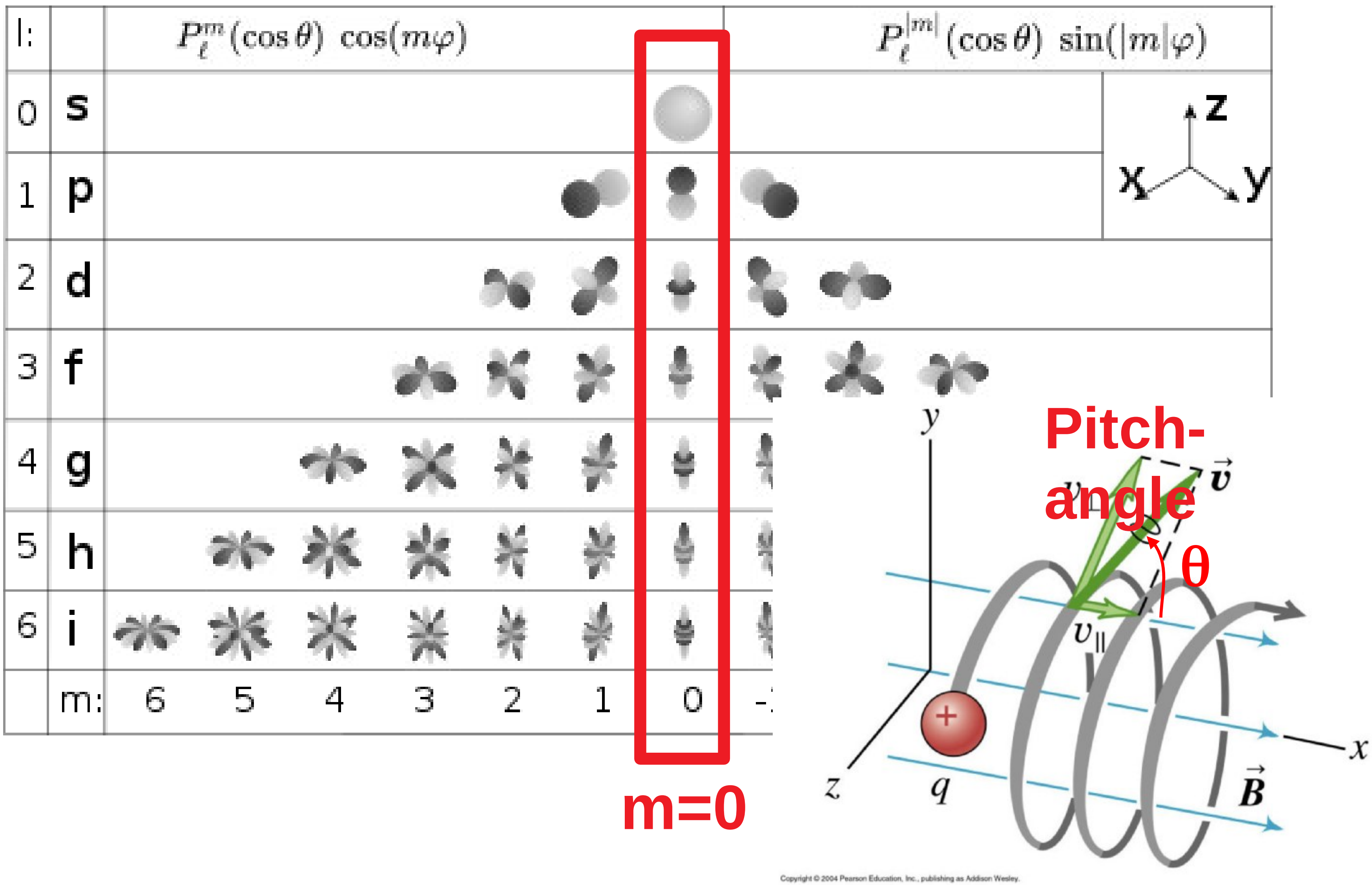


Excellent agreement with HAWC & IceCube measurements

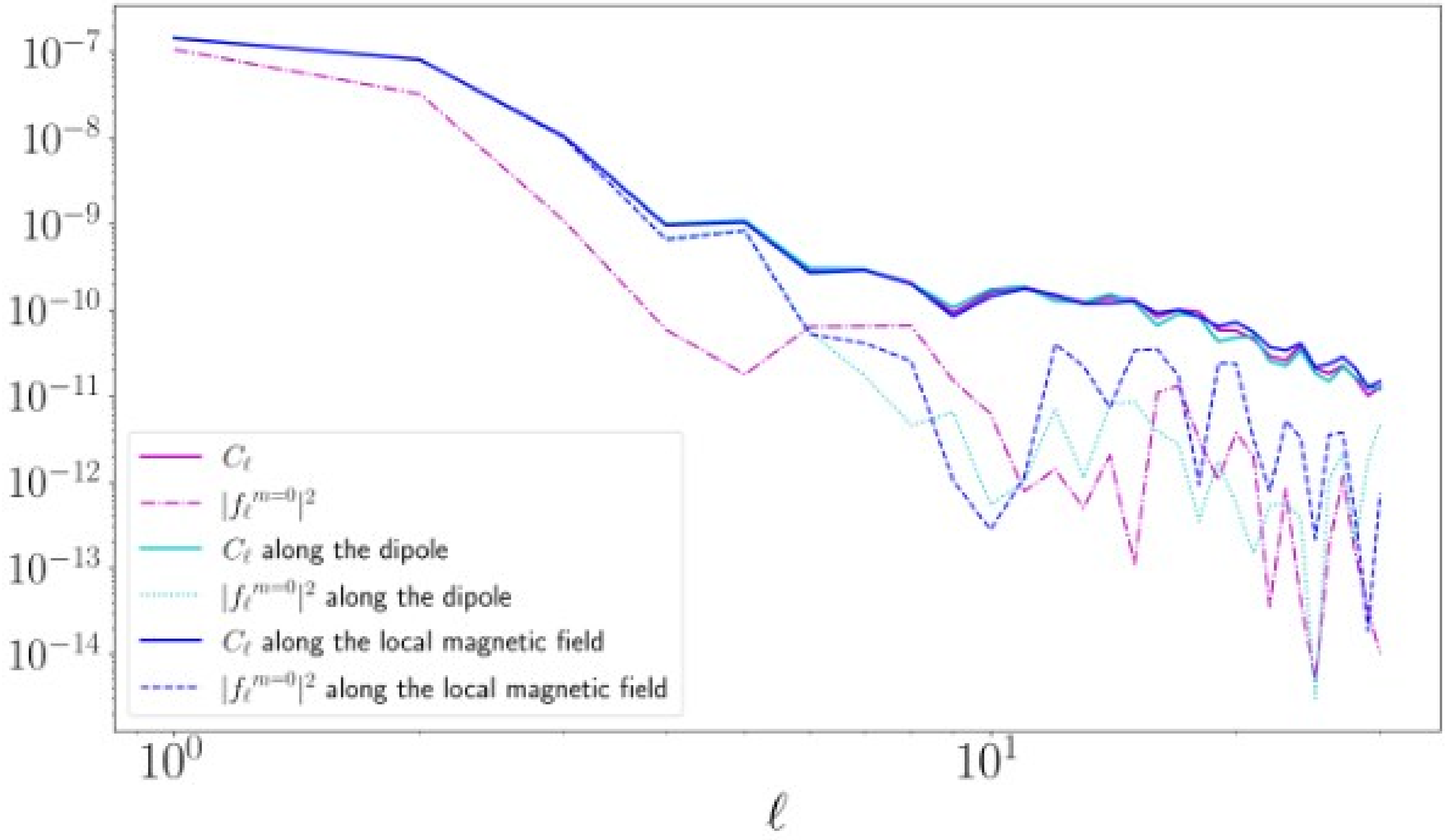
Spherical harmonics



Spherical harmonics



Power along the direction of the dipole / B field



More **gyrotropic** at: (1) Low energies and (2) small l.

Conclusions

→First numerical simulations **down to 3 TeV.**

→ New dependence of the angular power spectrum on **CR energy: Good fit to HAWC + IceCube measurements.**

→ Aligns well with the local B field direction.

→ More **gyrotropic** at: (1) Low energies and (2) small l.

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