TURBULENCE AND COSMIC RAY PROPAGATION

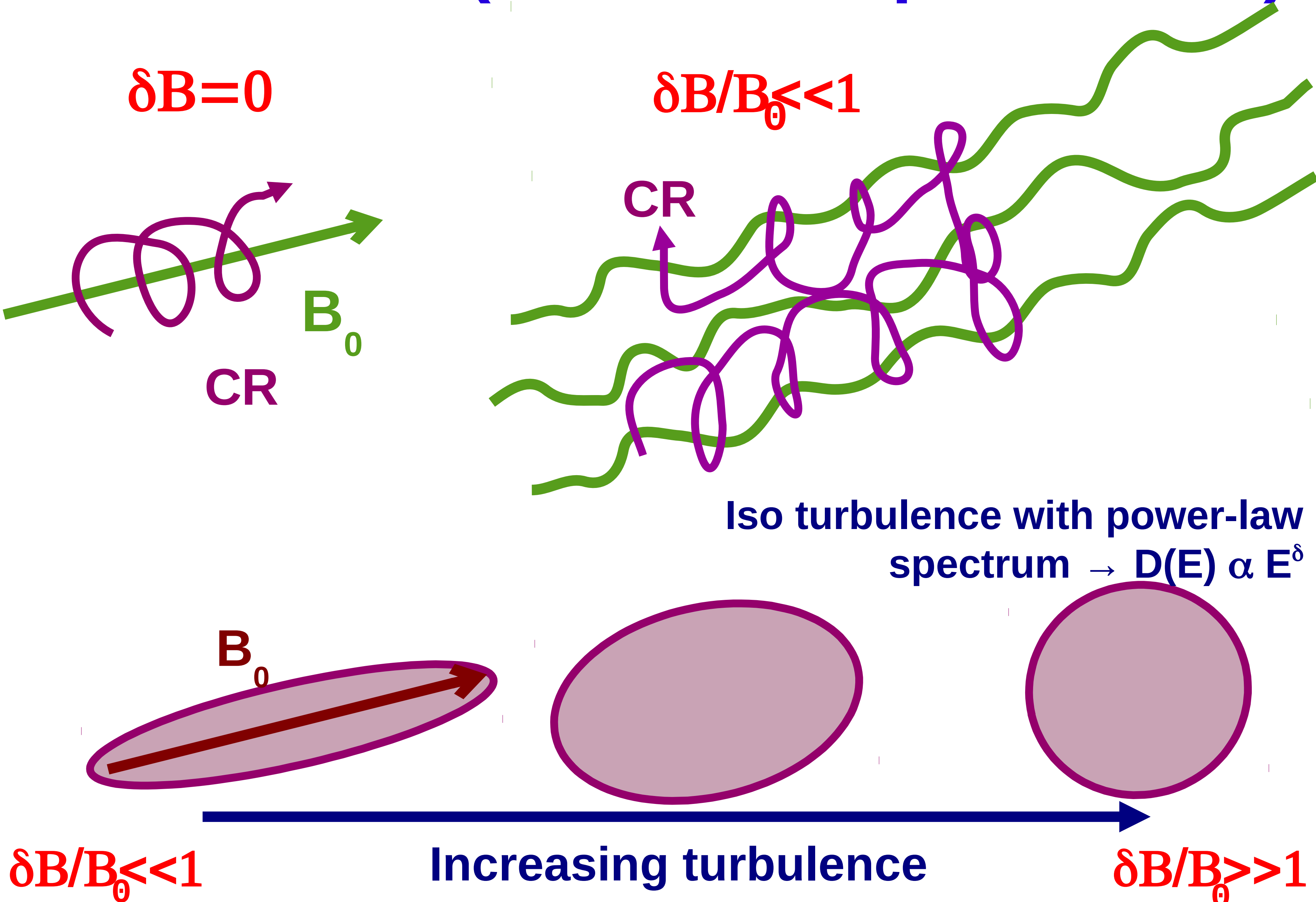
Gwenael Giacinti (贾鸿宇)

Tsung-Dao Lee Inst., Shanghai Jiao Tong U.
上海交通大学 李政道研究所

gwenael.giacinti@sjtu.edu.cn

Collaboration w/: D. Semikoz, A. Neronov (APC), S. Koldobskiy (Oulu), T. Abounnasr (ICRR).

CR diffusion (Parallel/Perpendicular)



Is CR diffusion (ever) isotropic ?

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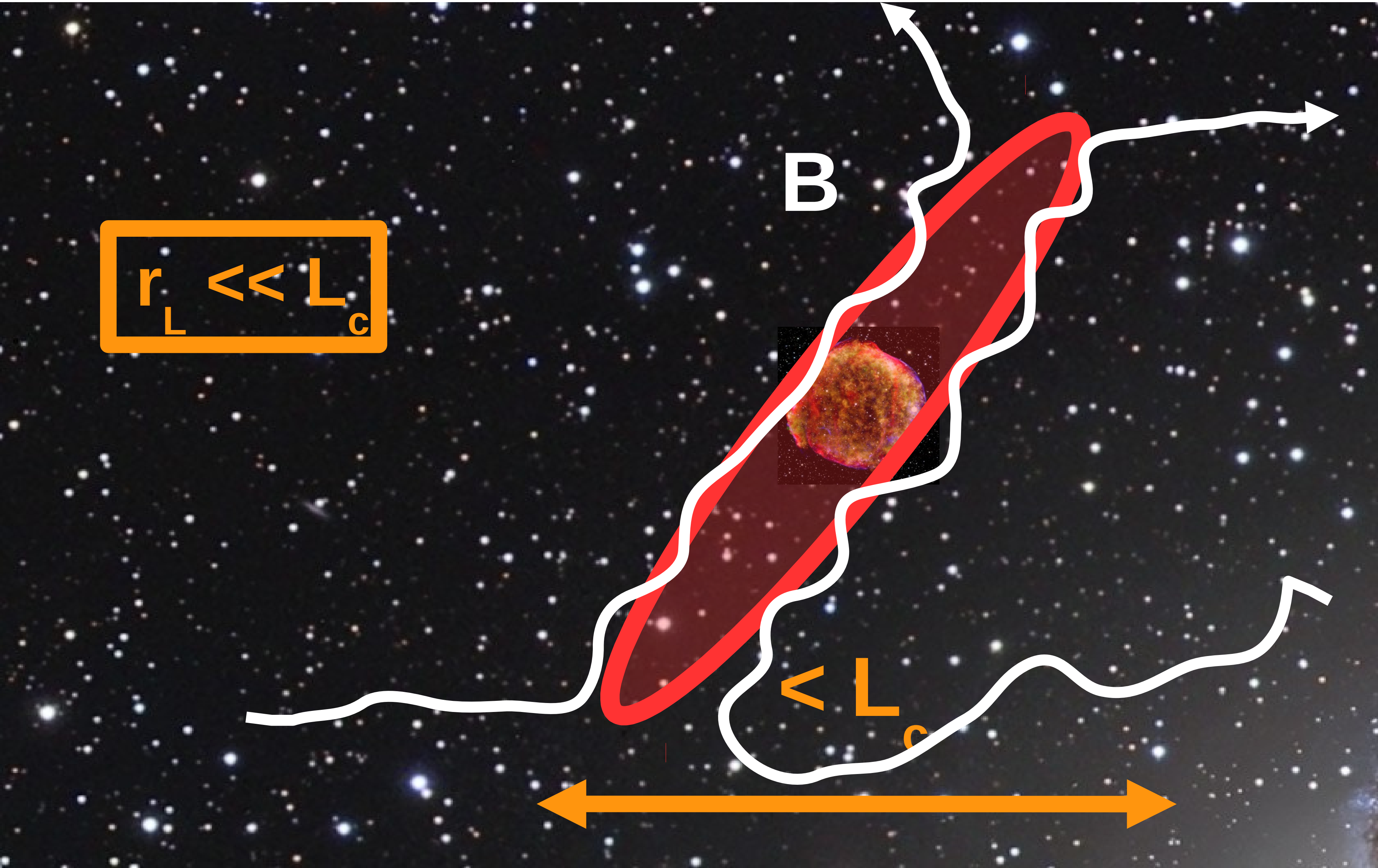
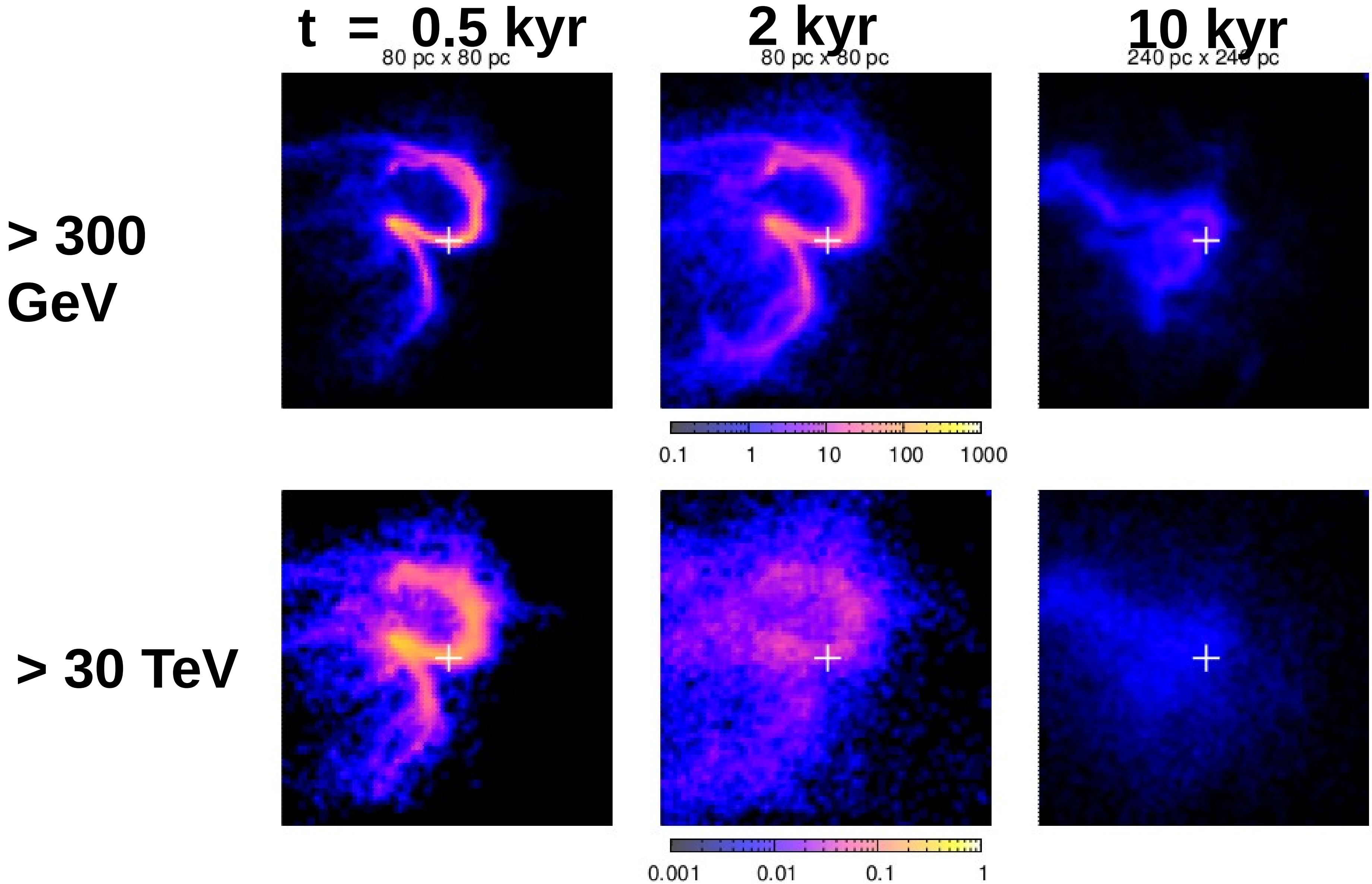
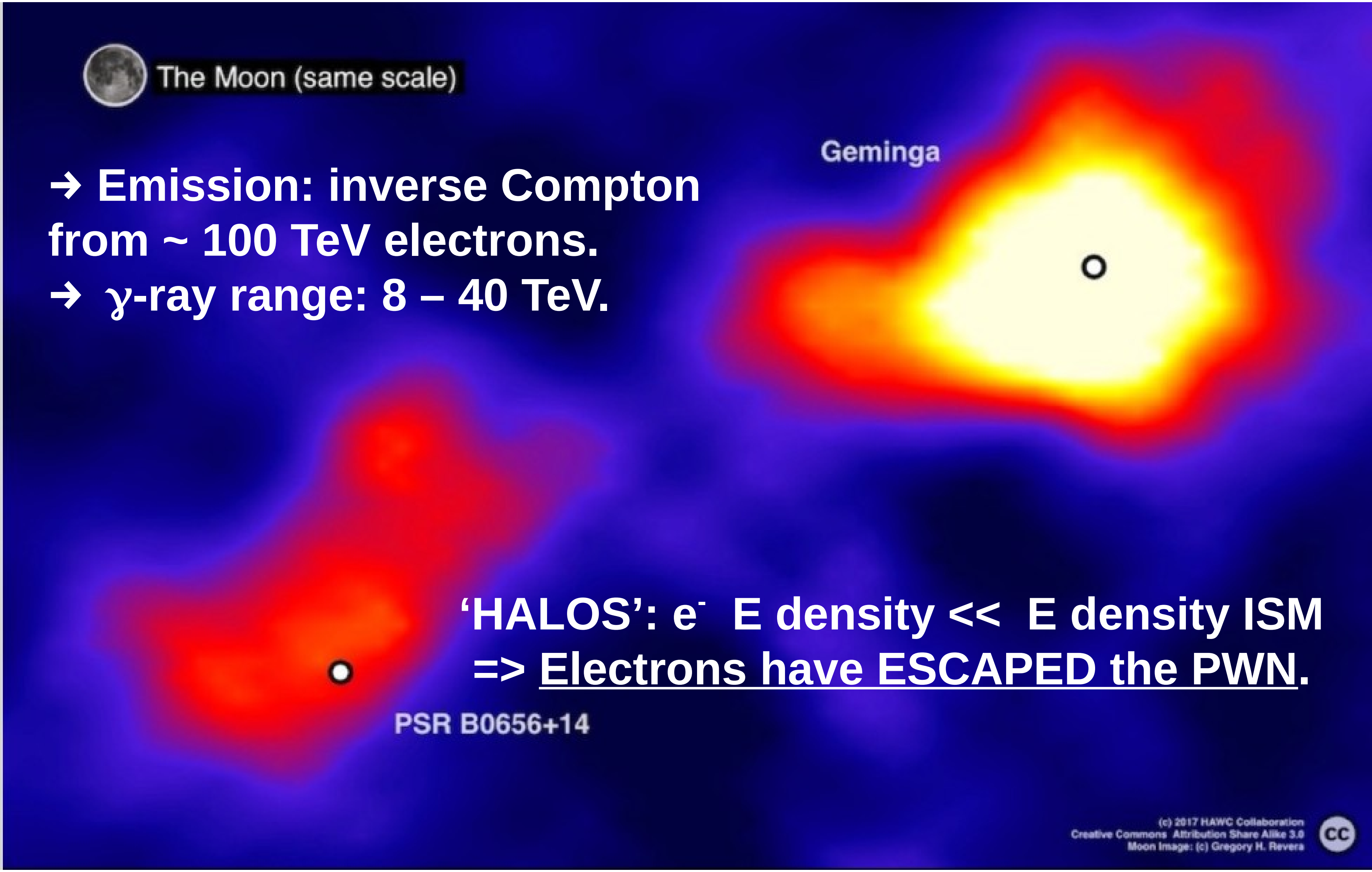


Simulated γ-ray images of a source

GG, Kachelriess, Semikoz, PRD (2013)



HAWC - Geminga & Monogem



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

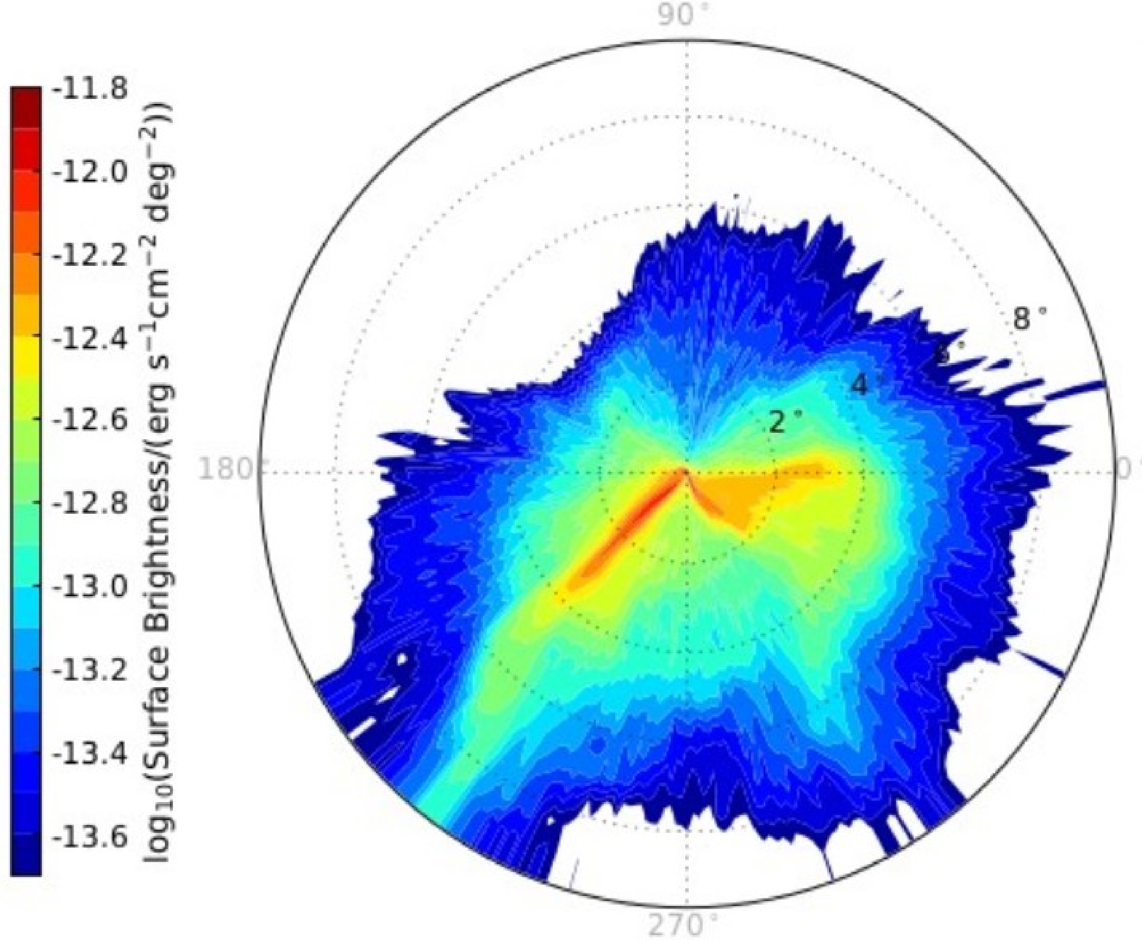
→ **γ-ray range: 8 – 40 TeV.**

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

=> Electrons have ESCAPED the PWN.

Predicted γ-ray surface brightness

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

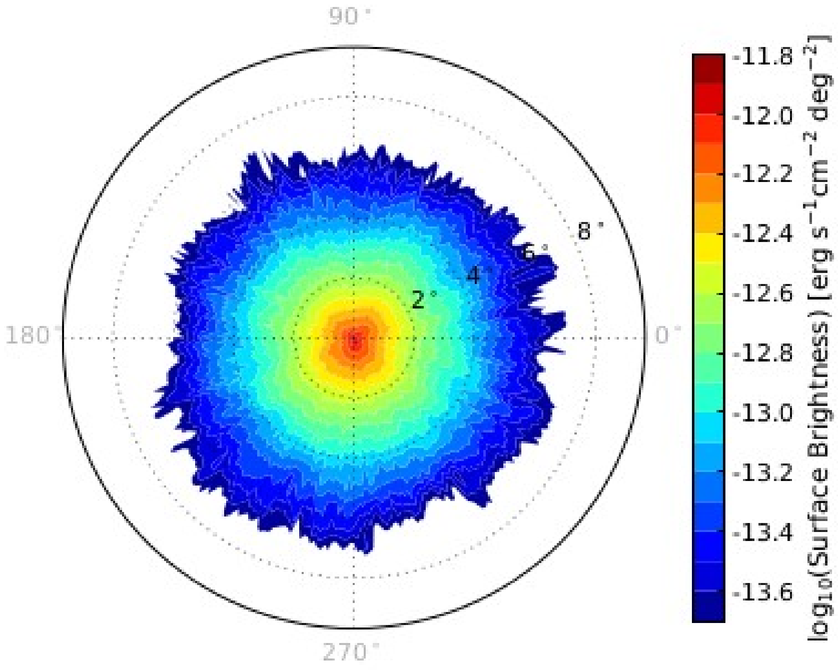


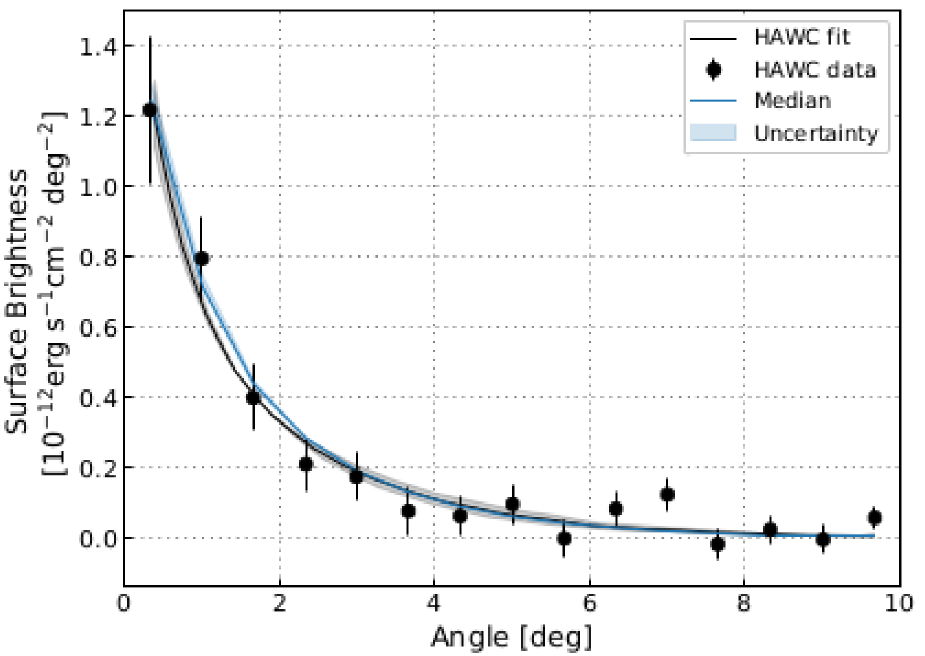
INCOMPATIBLE WITH HAWC MEASUREMENTS

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

Best fit to HAWC measurements

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

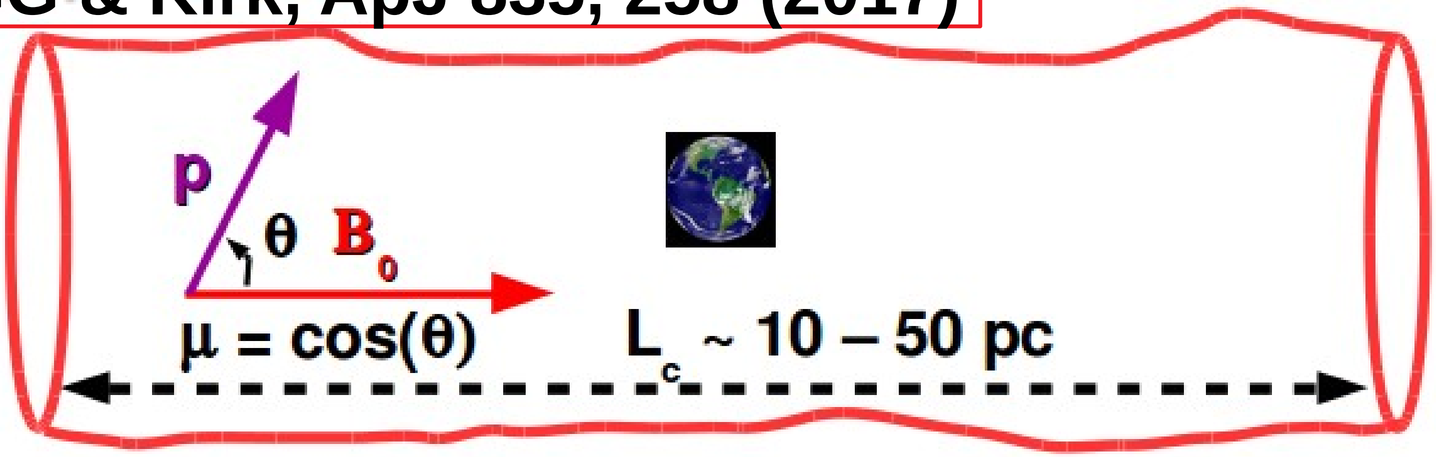




Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018)

CR Anisotropy: Probe of turbulence

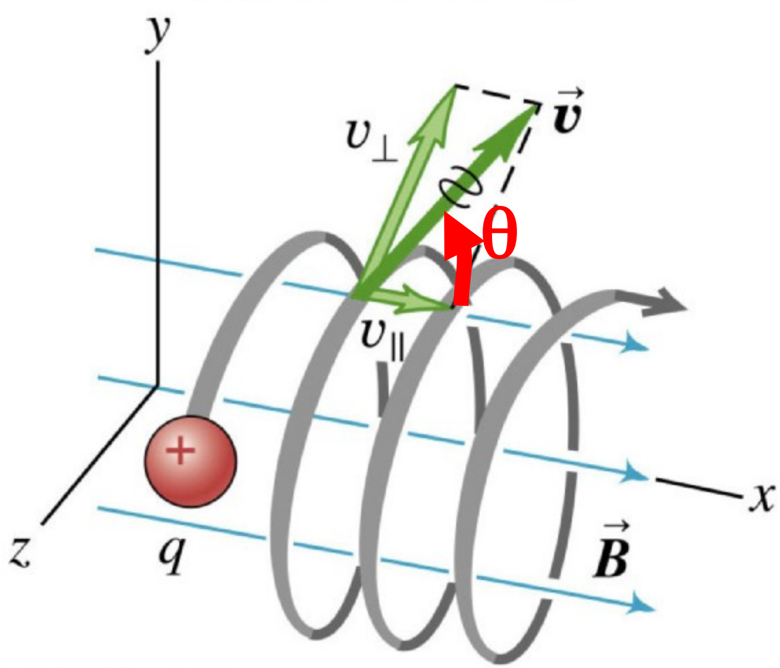
GG & Kirk, ApJ 835, 258 (2017)



$$\mu v \frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)$$

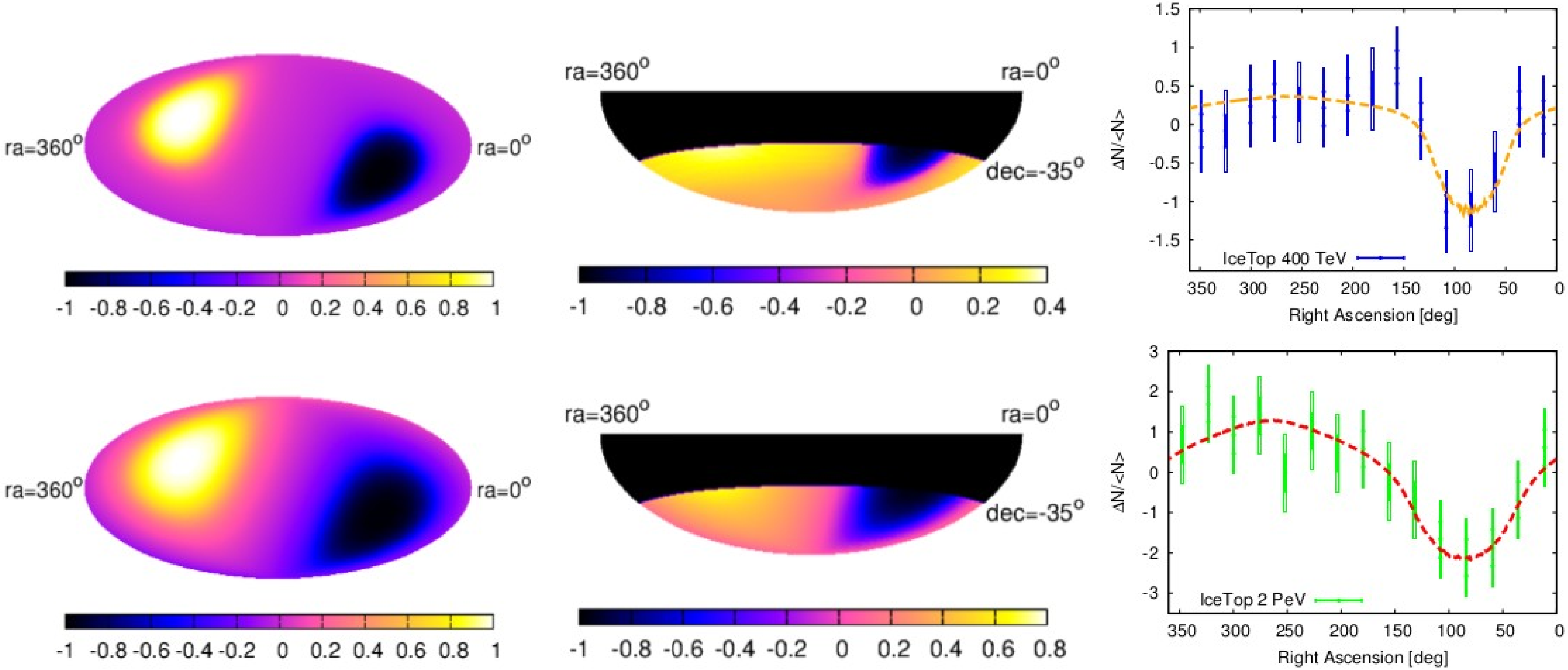
Pitch-angle diffusion

(gyrophase-averaged)



G-S turbulence with a broad RF

GG & Kirk, ApJ 835, 258 (2017)

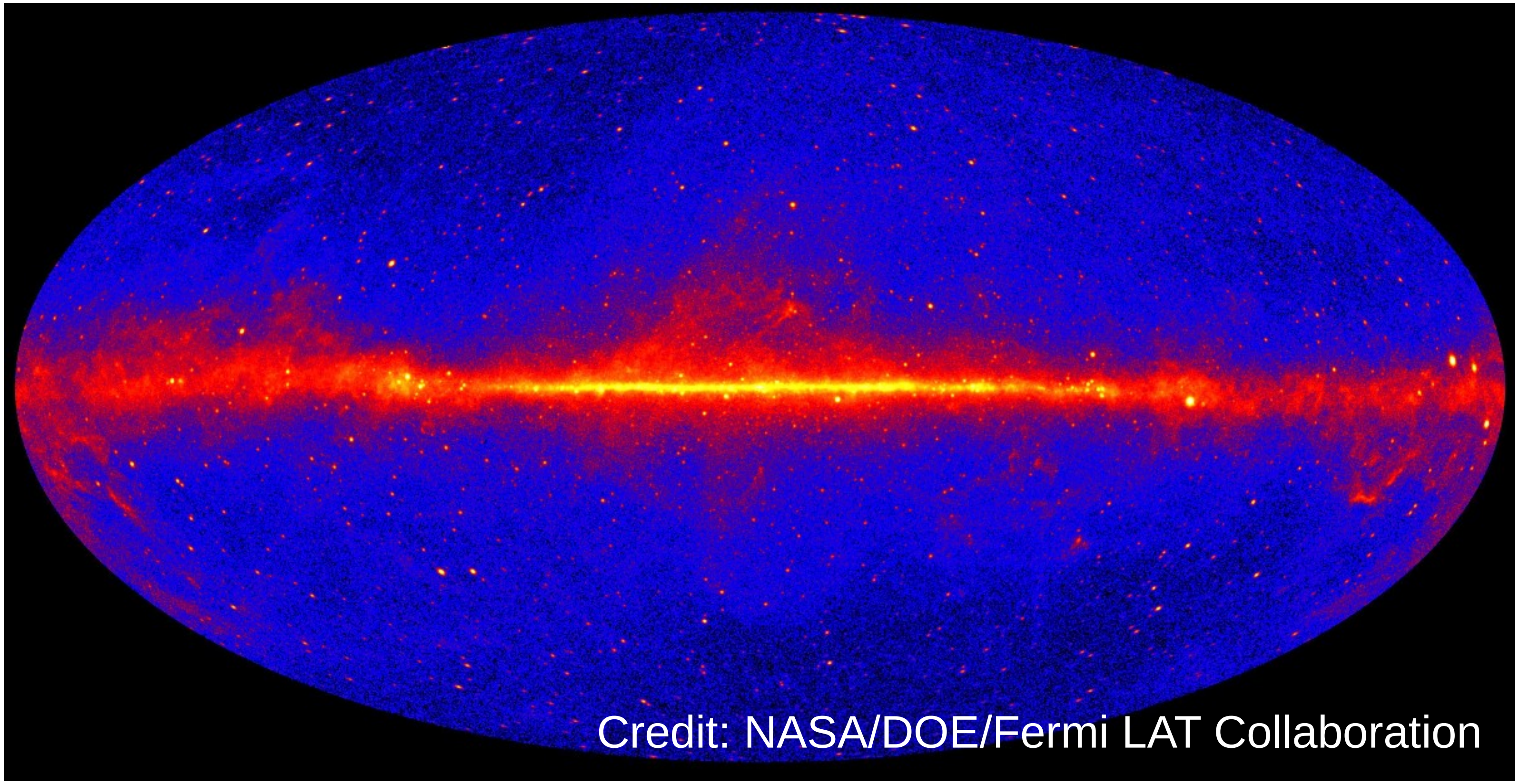


Can fit well the 400 TeV and the 2 PeV data.

Energy-dependence reproduced for fixed turbulence parameters.

Constraints from the VHE Galactic diffuse γ-ray emission at >100 TeV?

The sky at GeV energies



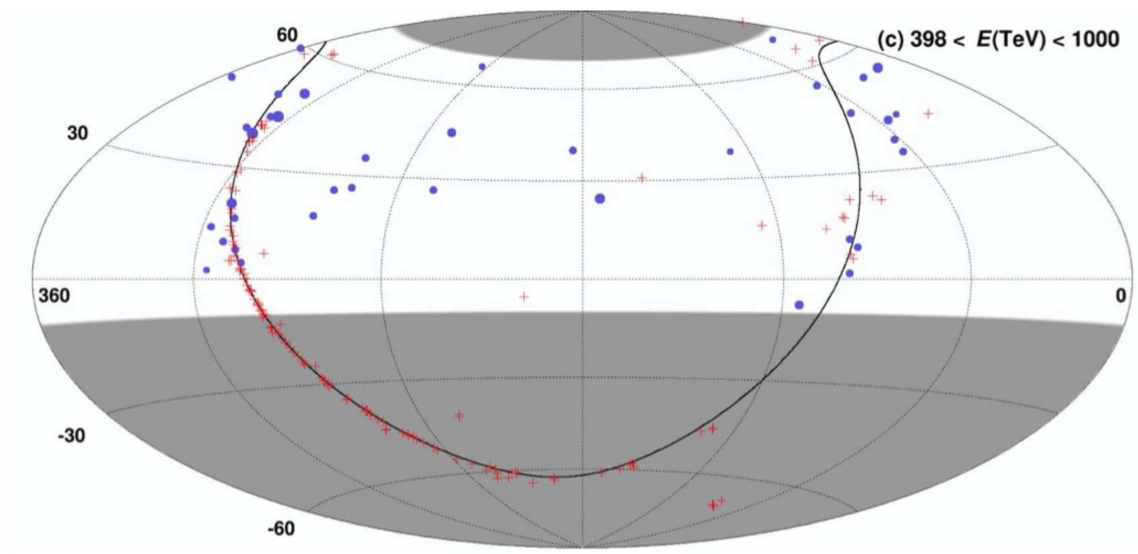
(Fermi, 2008 – 2017)

→ **Point sources** (CR accelerators) + **Diffuse emission**.

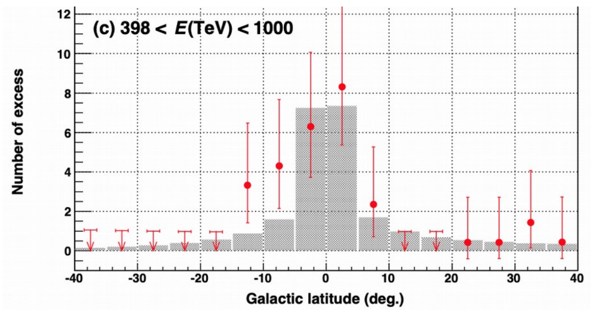
→ Diffuse emission: - Narrow band (a few degrees) around GP,

- Inner Galaxy vs outer Galaxy.

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



Tibet AS-γ Collaboration, arXiv:2104.05181

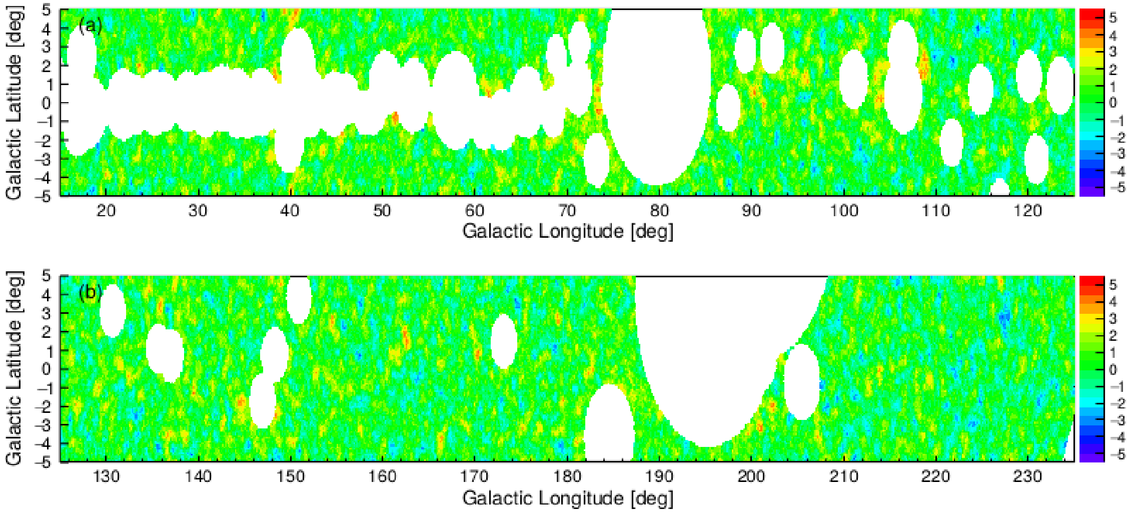


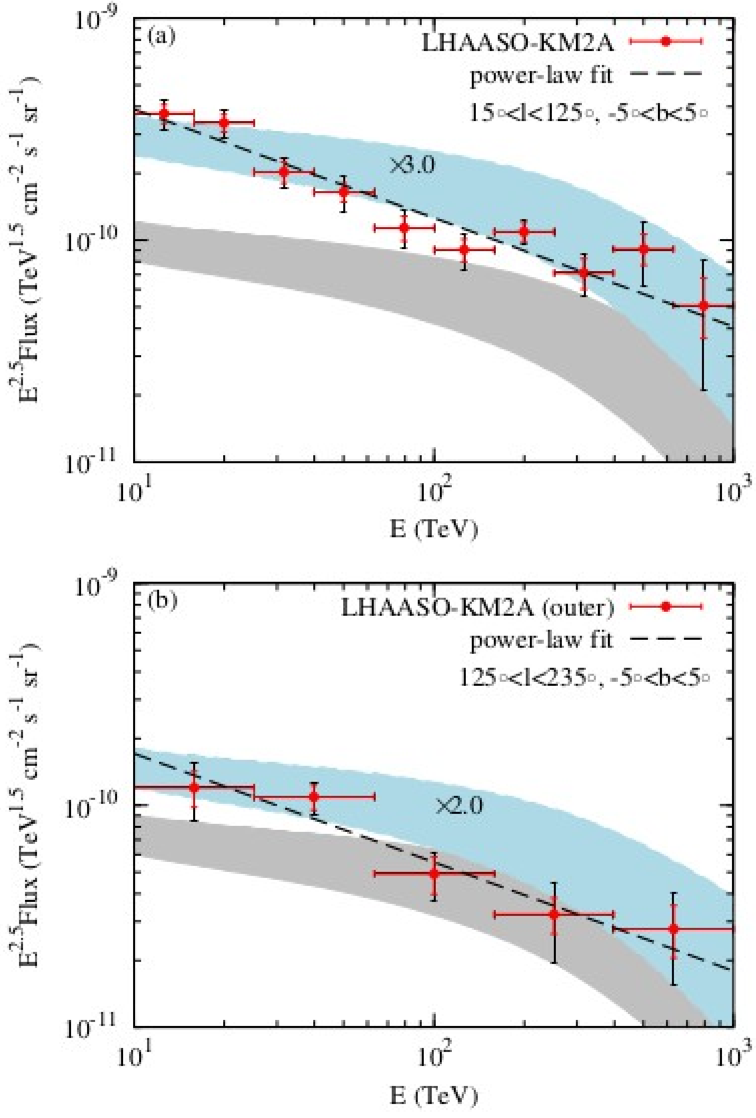
→ Diffuse emission: - **Broader** band around GP?
- **Inner vs outer Galaxy**

→ **A new type of very extended sources?** (Between point sources and true diffuse emission).

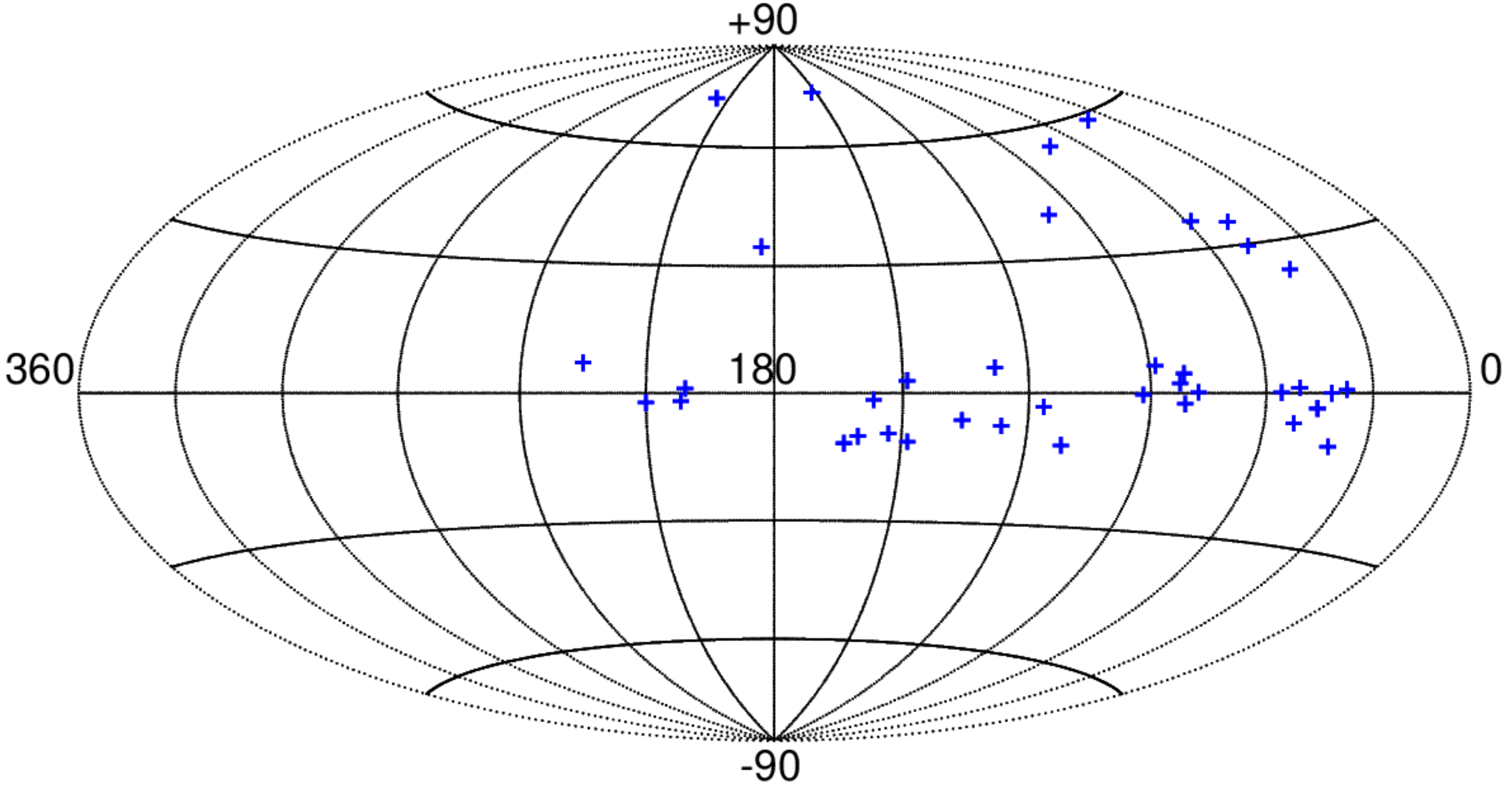
The sky at ~ 10 TeV – 1 PeV: Diffuse Galactic emission from LHAASO

LHAASO Collaboration, arXiv:2305.05372



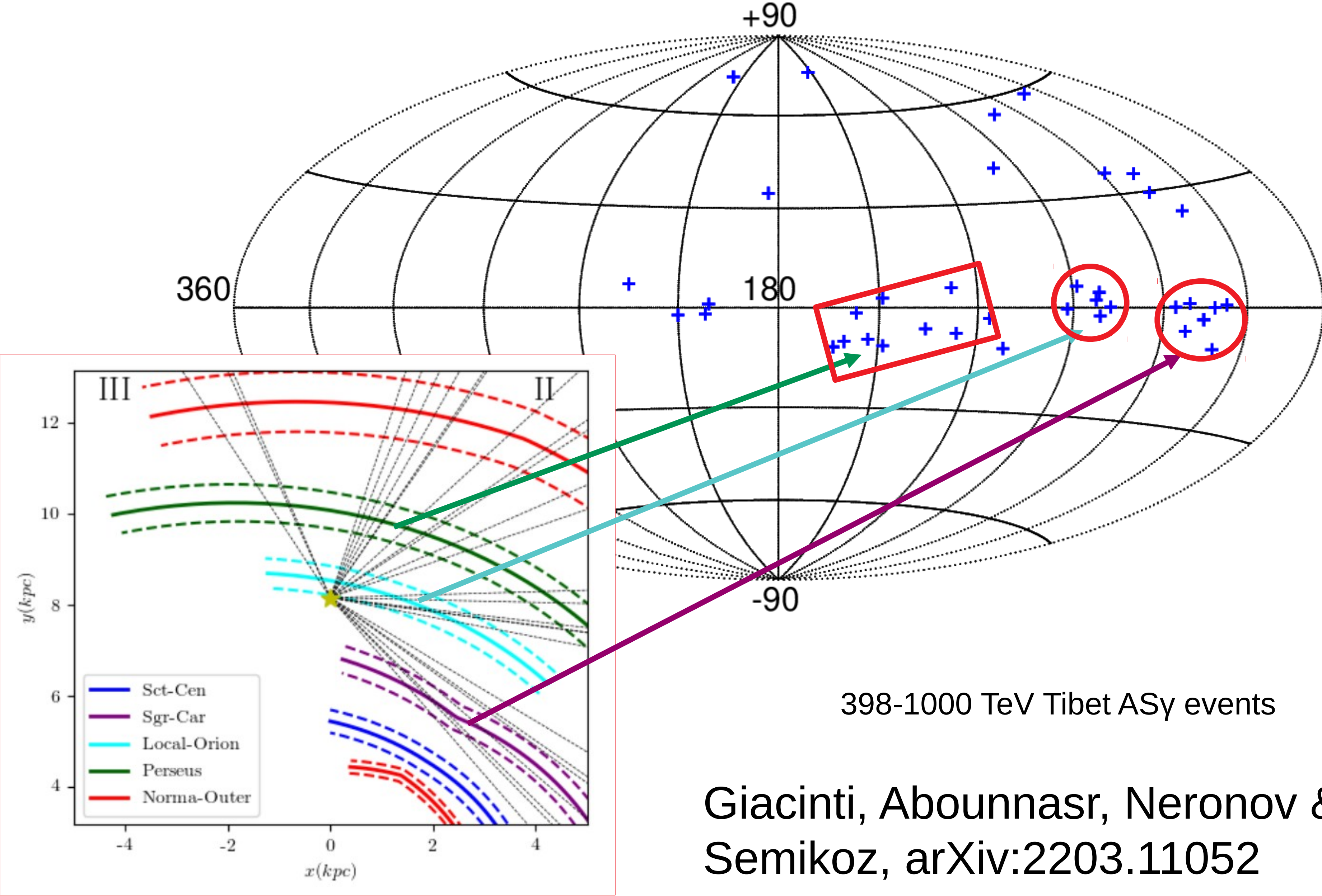


Diffuse Galactic VHE γ-ray emission



398-1000 TeV Tibet ASγ events

Extended sources in Tibet ASγ data ?

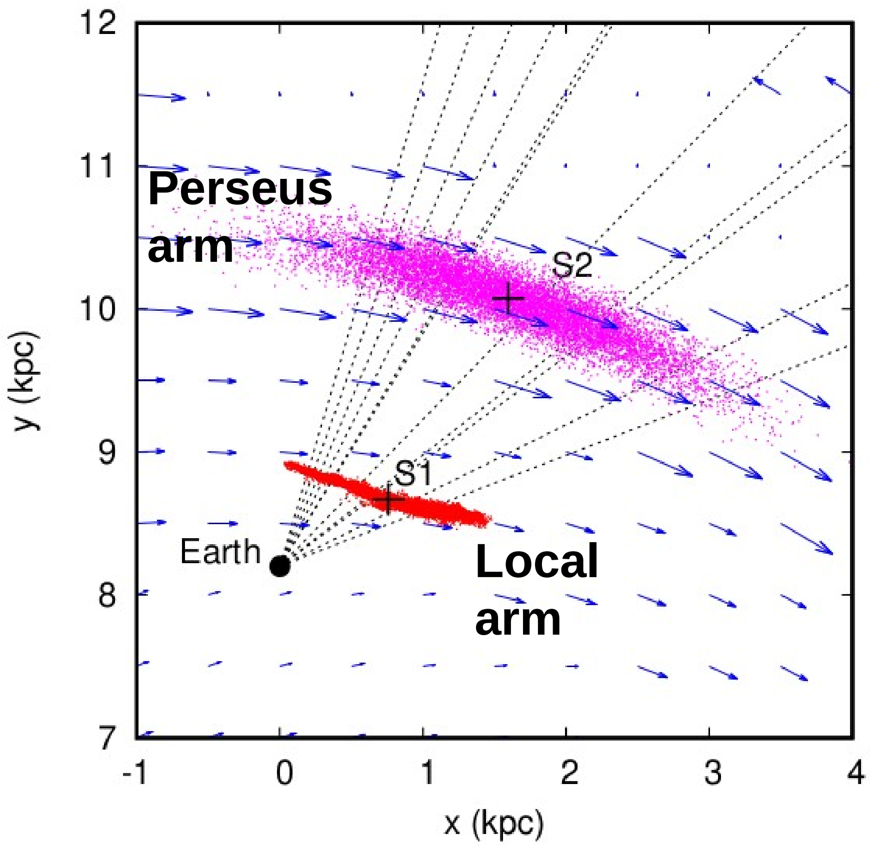


398-1000 TeV Tibet ASγ events

Giacinti, Abounnasr, Neronov & Semikoz, arXiv:2203.11052

Extended sources in Tibet 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.

(E_{CR} between 1 GeV and 10 PeV)

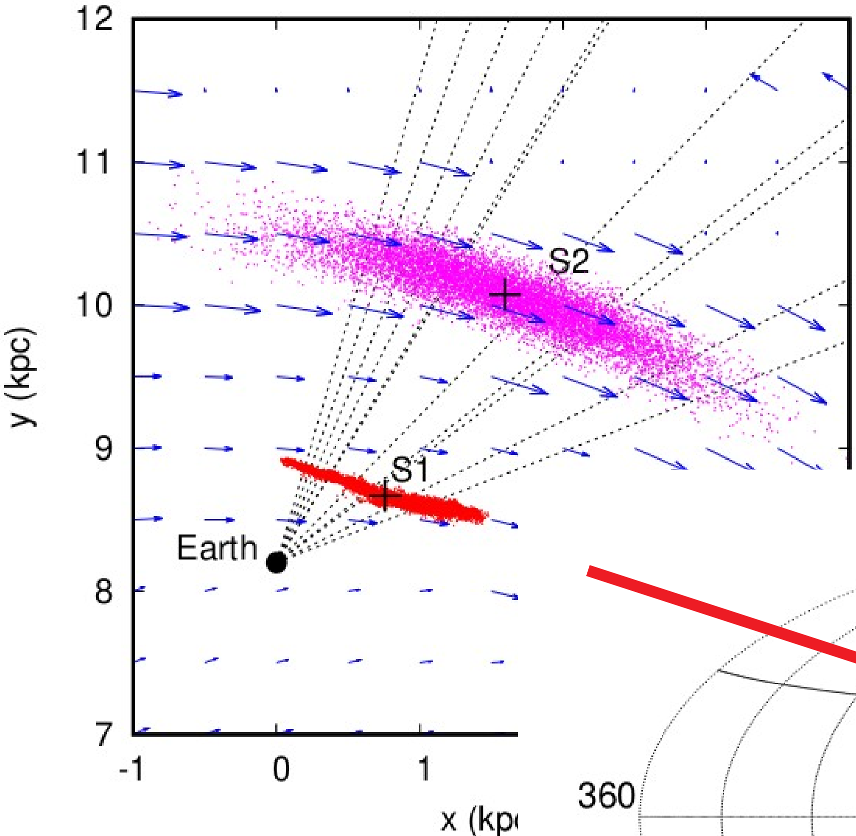
$n_1 \sim 0.33((10^{50}\ \text{erg})/E_{CR})\ \text{cm}^{-3}$ in the Local arm;

$n_2 \sim 1.5((3\cdot10^{50}\ \text{erg})/E_{CR})\ \text{cm}^{-3}$ in the Perseus arm.

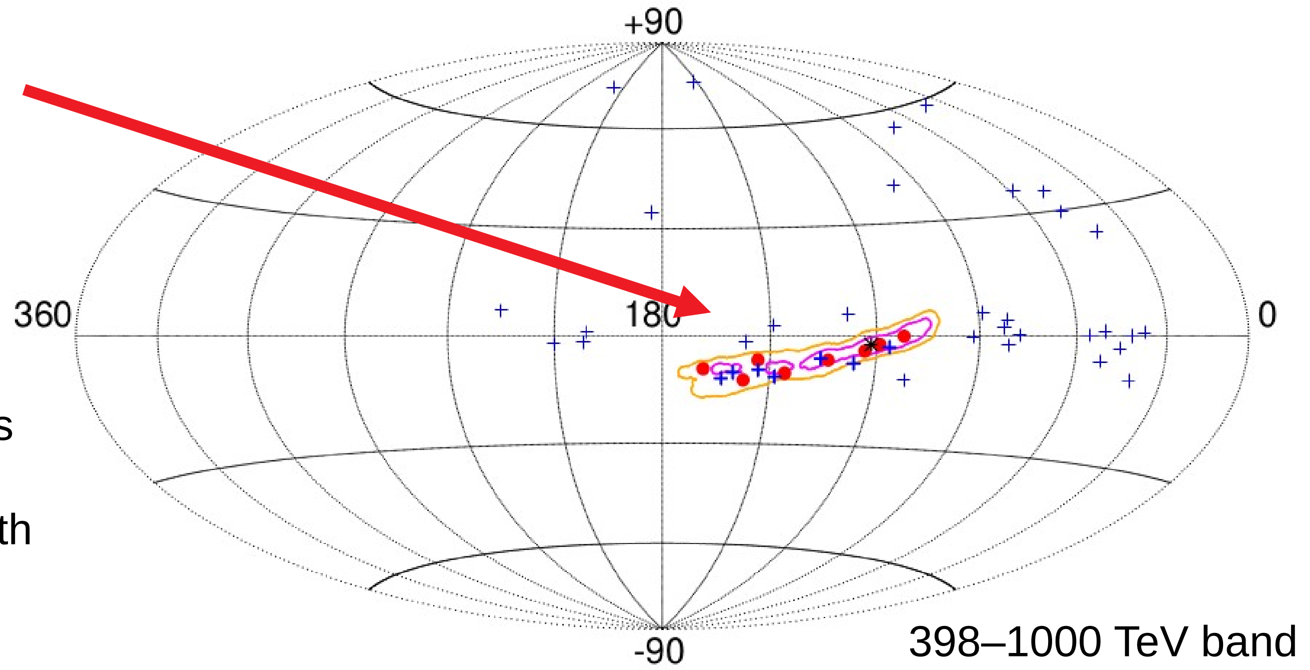
& Gas density scale height from Reid et al., ApJ **885**, 131 (2019)

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

Extended sources in Tibet ASγ data ?



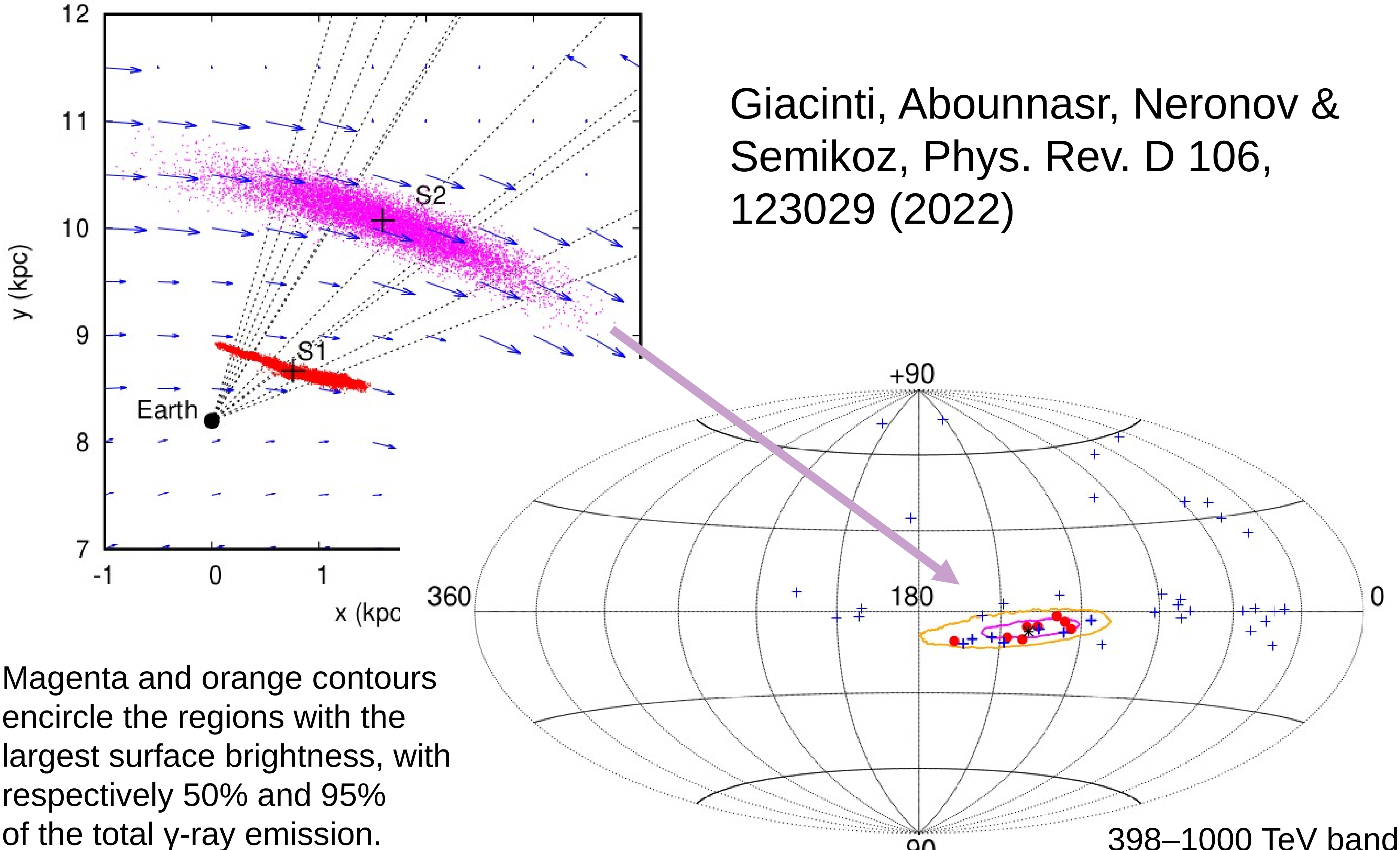
Giacinti, Abounnasr, Neronov & Semikoz, Phys. Rev. D 106, 123029 (2022)



Magenta and orange contours encircle the regions with the largest surface brightness, with respectively 50% and 95% of the total γ-ray emission.

Extended sources in Tibet ASγ data ?

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



Magenta and orange contours encircle the regions with the largest surface brightness, with respectively 50% and 95% of the total γ-ray emission.

398–1000 TeV band

A new model for VHE CRs in the Galaxy, and their secondary γ-rays

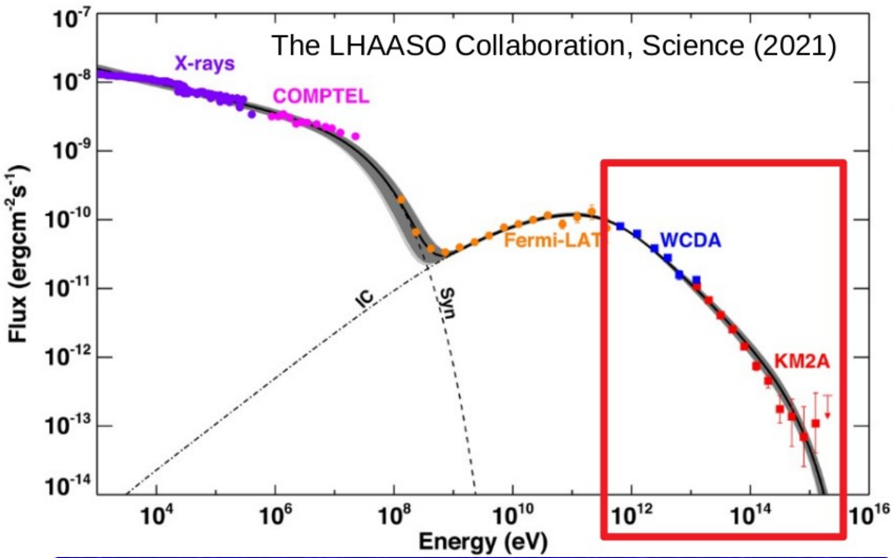
Galactic CR prop. codes vs VHE

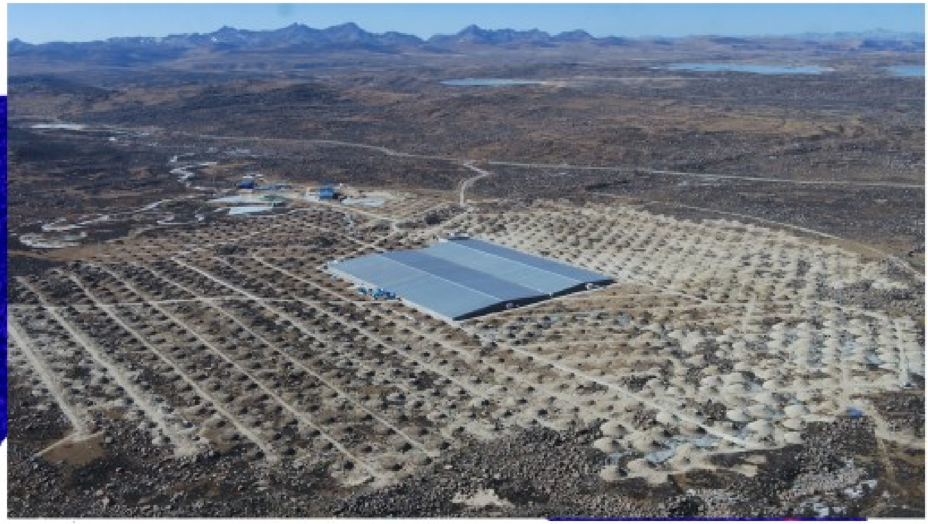
→ Usually assume homogeneous and continuous CR injection in the GP. But **stochasticity of CR sources crucial at VHE,** because: (1) CR confinement time short, (2) Frequency of PeVatrons a priori (much) smaller than that of supernovae:

* Observations: - Many SNRs are not PeVatrons,
  - Very few PeVatrons, and might be leptonic

* Theory: Only a small subset of supernovae are PeVatrons.

LHAASO PeVatrons :

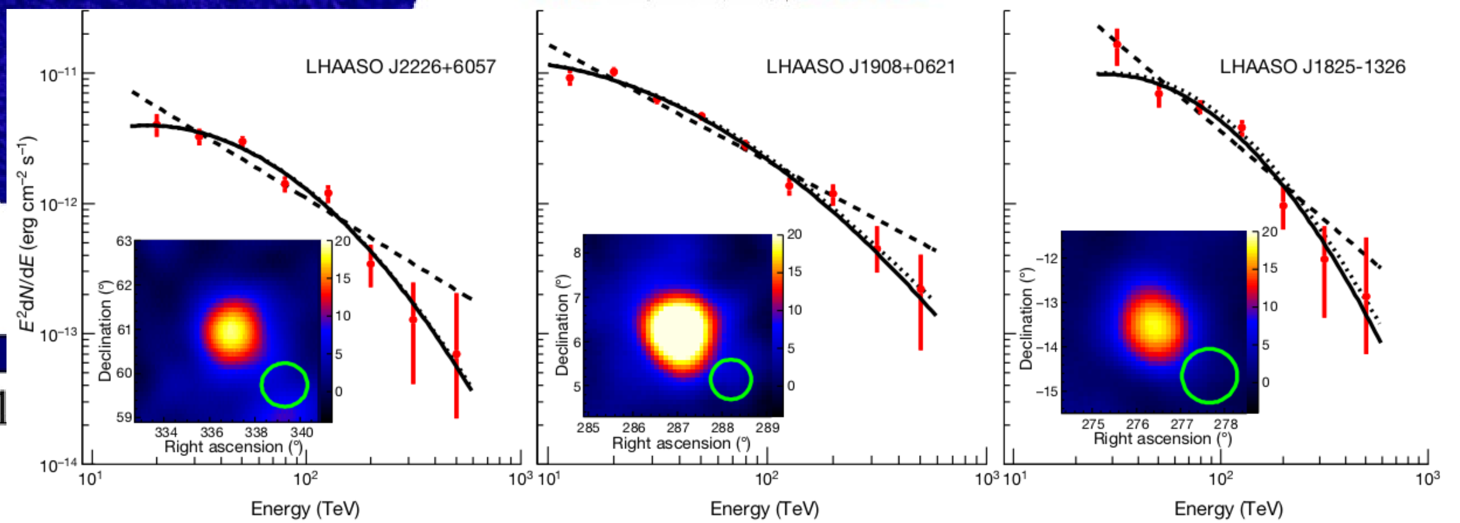


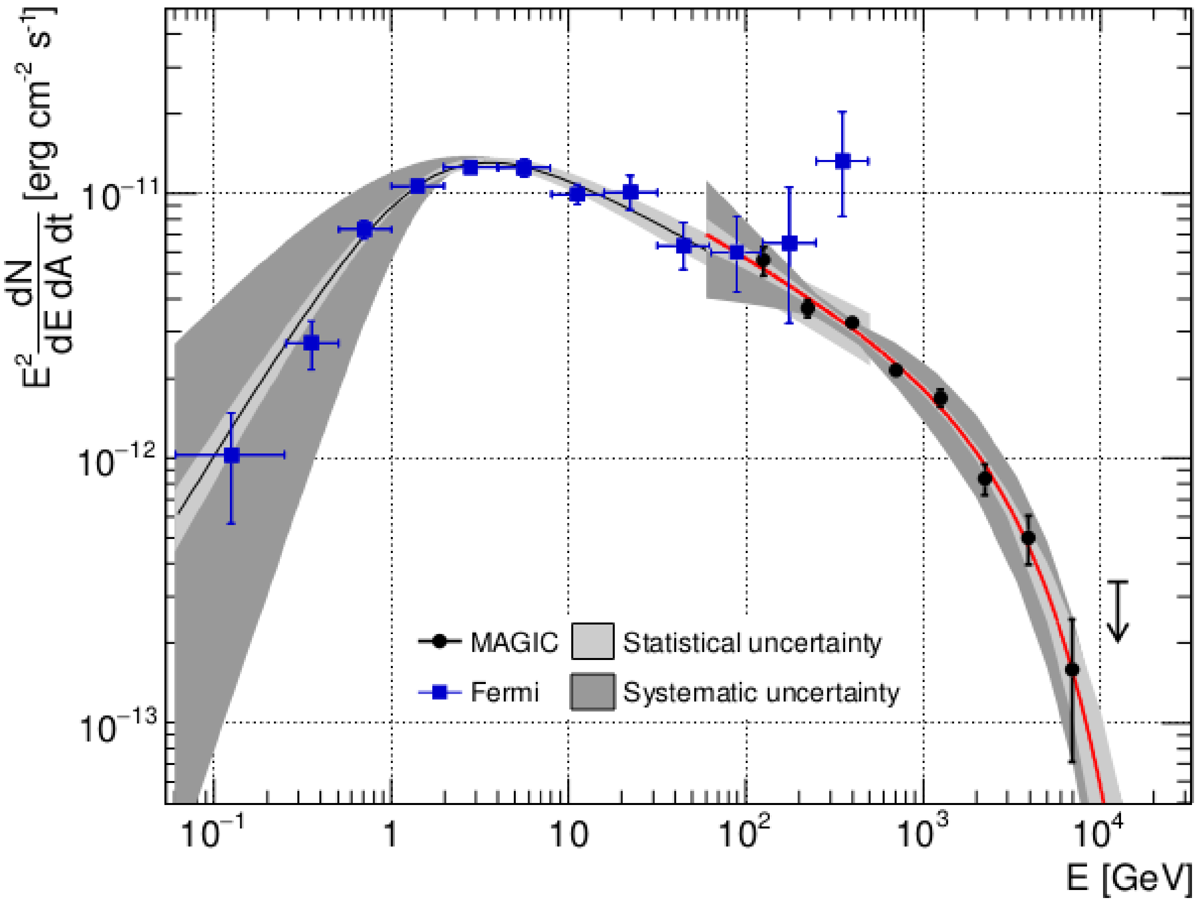


Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, […]X. Zuo

Nature **594**, 33–36 (2021) | Cite this article



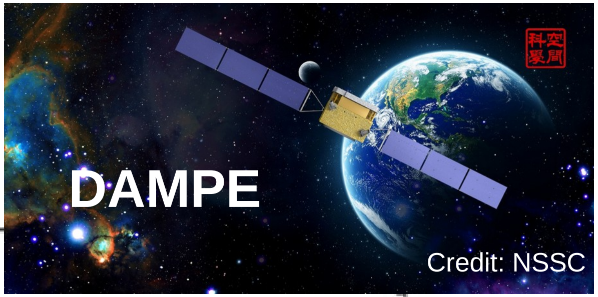


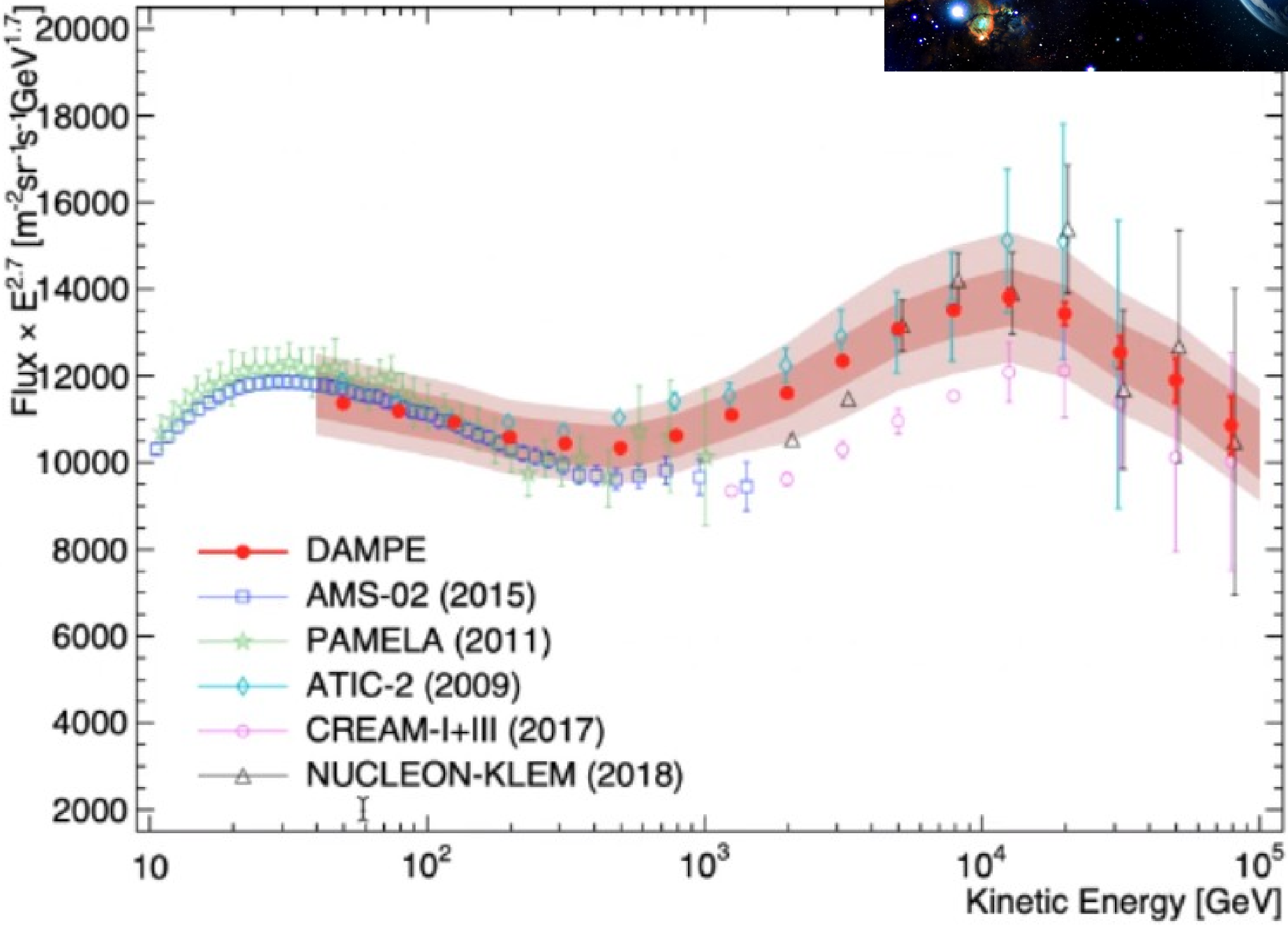
Spectrum of Cas A [ArXiv:1709.00280]

Bell et al. (2013) : **Only some supernovae in dense winds can reach multi-PeV energies.**

Tatischeff, A&A (2013) : SN 1993 J a PeVatron for 10 yr.

Bump in CR spectrum at ~ 10 TeV?



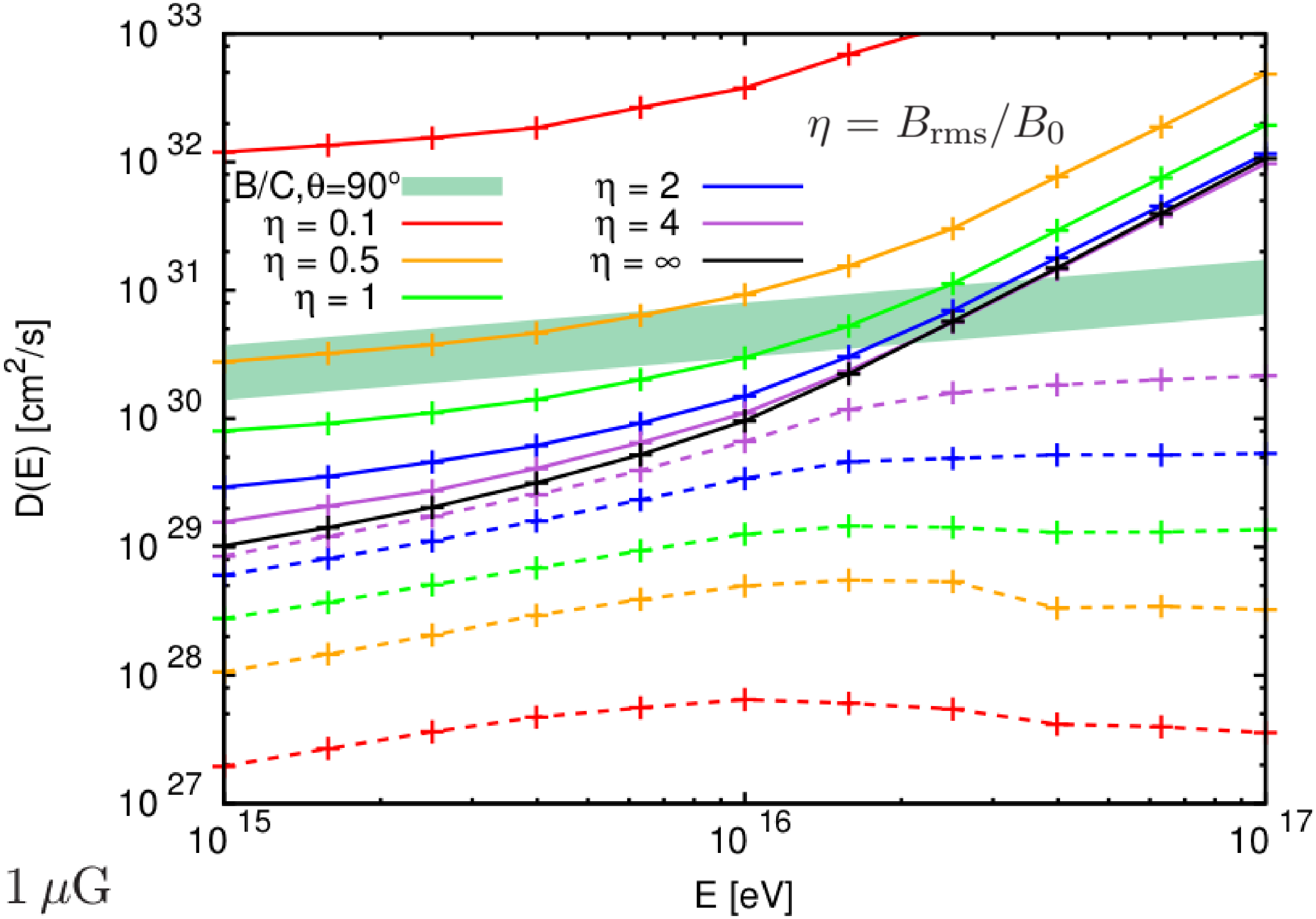


Proton spectrum with DAMPE (arXiv:1909.12860)

Standard picture of isotropic CR propagation with a large D ~ 10^{30} cm^2/s is in strong tension with ISMF observations & CR propagation theory.

=> Need for **anisotropic diffusion.**

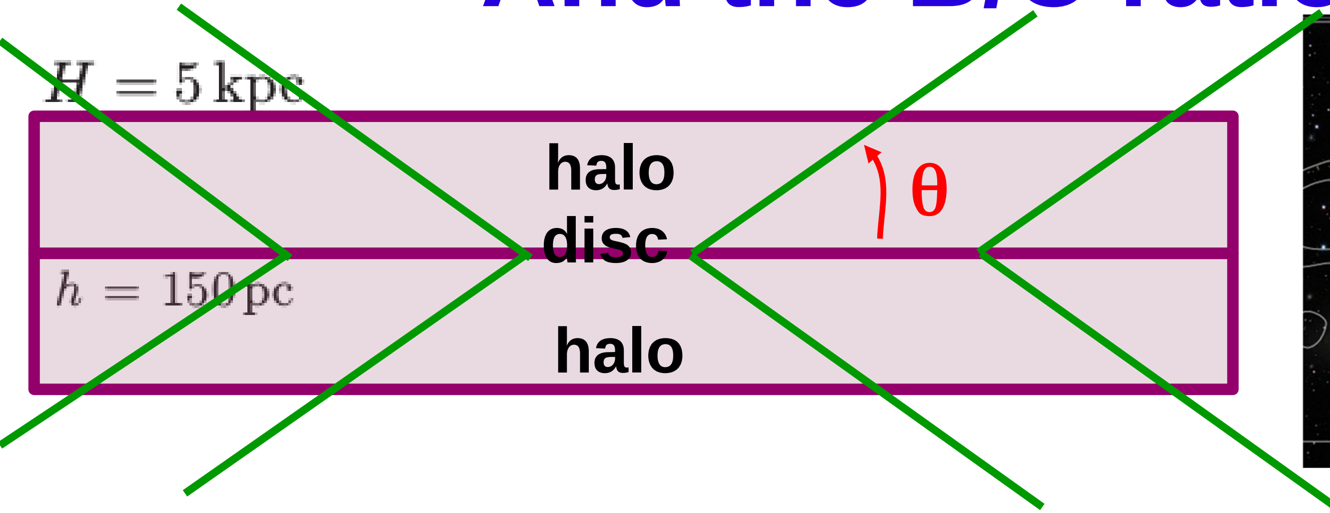
Giacinti et al., JCAP (2018), 1710.08205

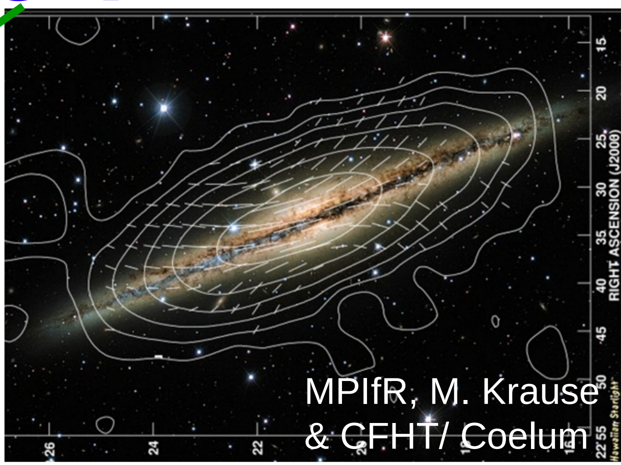


$$L_{\max} = 100\,\mathrm{pc}$$

$$B_{\rm tot} = \sqrt{B_{\rm rms}^2 + B_0^2} = 1\,\mu\mathrm{G}$$

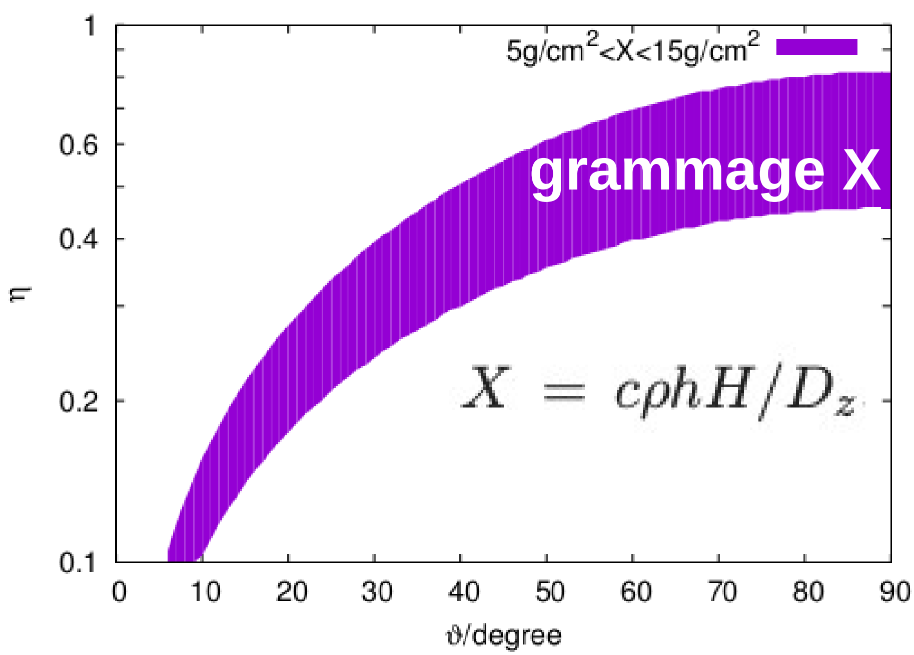
And the B/C ratio ?



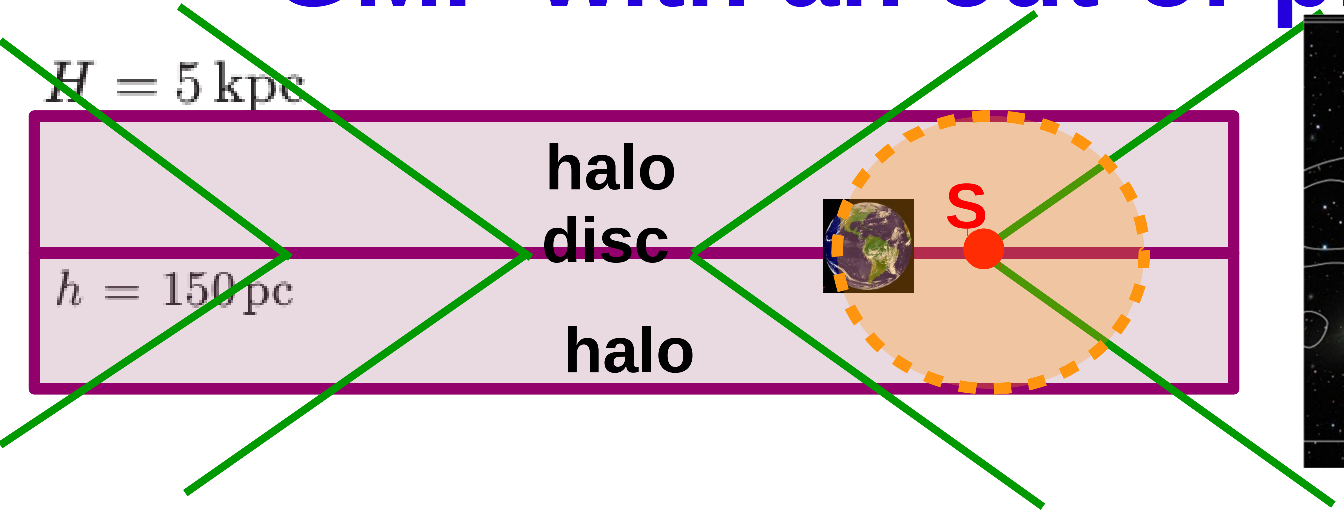


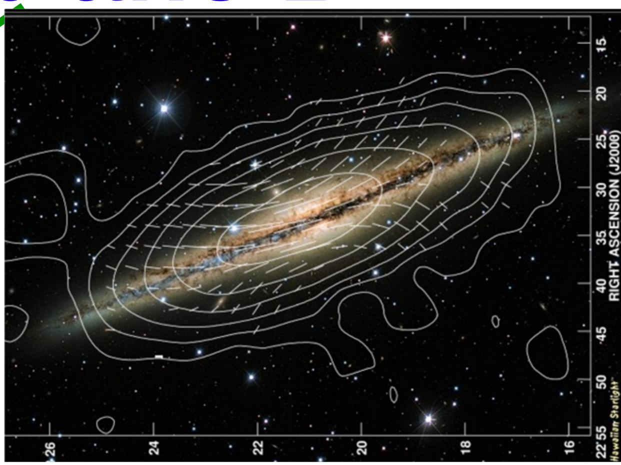
Giacinti, Kachelriess & Semikoz, JCAP (2018)

$$\eta = B_{\rm rms}/B_0$$



GMF with an out-of-plane B



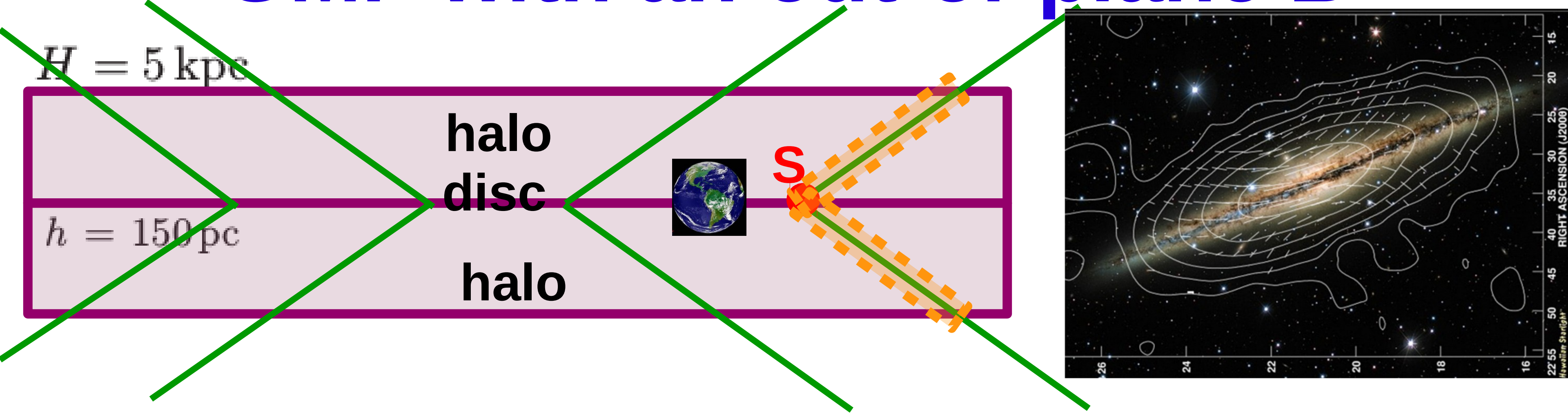


Giacinti, Kachelriess & Semikoz, JCAP (2018)

<u>Isotropic diffusion:</u>

Needs > 1000s sources for the local > 10 TeV CR flux.

GMF with an out-of-plane B



Giacinti, Kachelriess & Semikoz, JCAP (2018)

Isotropic diffusion:

Needs > 1000s sources for the local > 10 TeV CR flux.

Anisotropic diffusion:

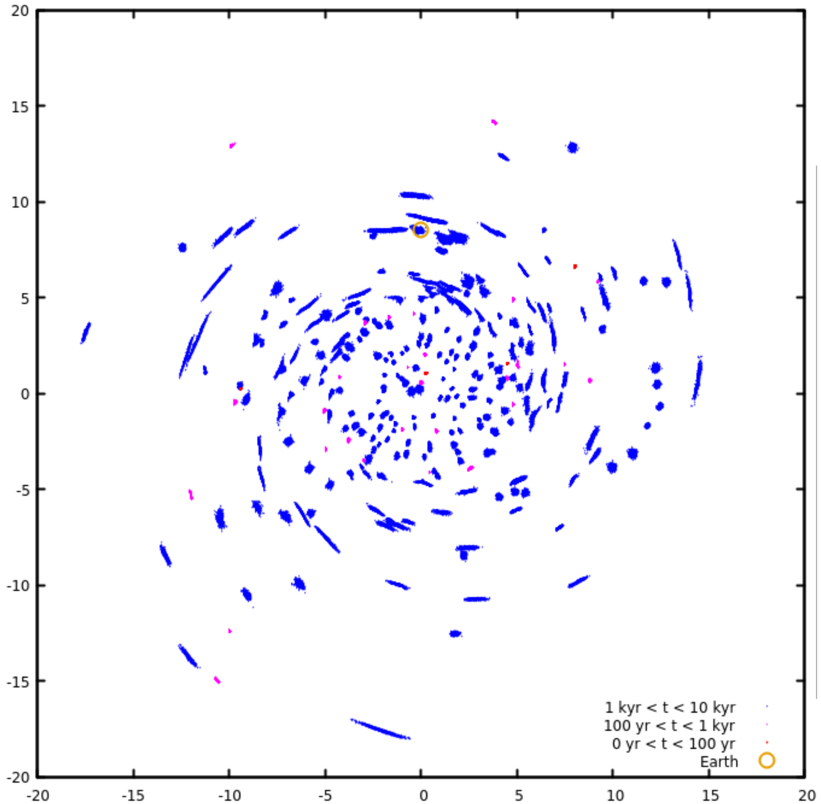
Only ~ (a few) 10s of local sources (~ 200pc) may dominate the CR flux at > 10TeV +

New code for CR propagation at VHE

Giacinti & Semikoz, arXiv:…. (tomorrow)

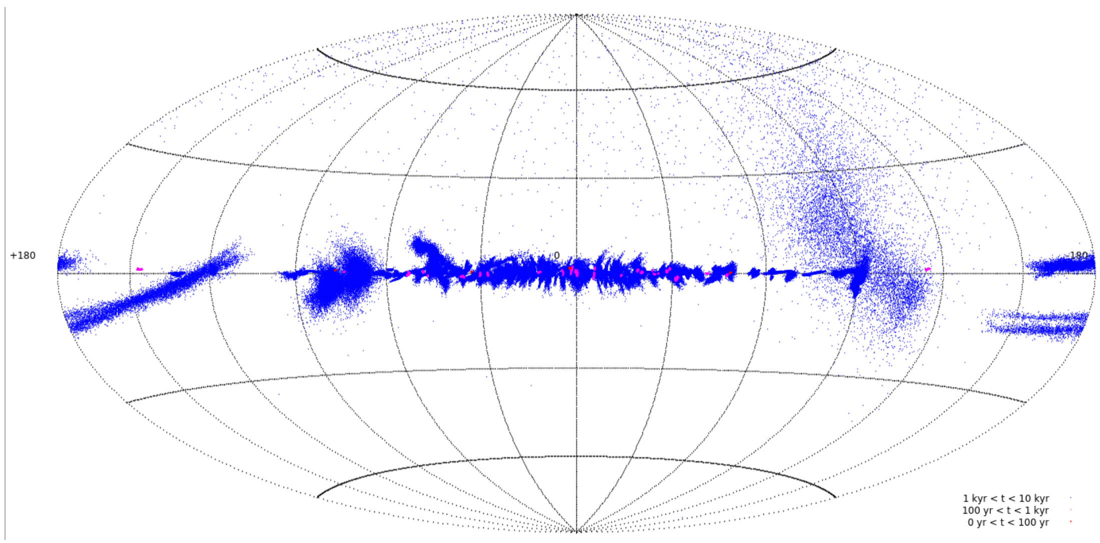
→ Propagate CRs in “Jansson &Farrar” Galactic magnetic field model.

→ Stochastic PeV CR injection at SNe.
Better than continuous injection at E>~100TeV



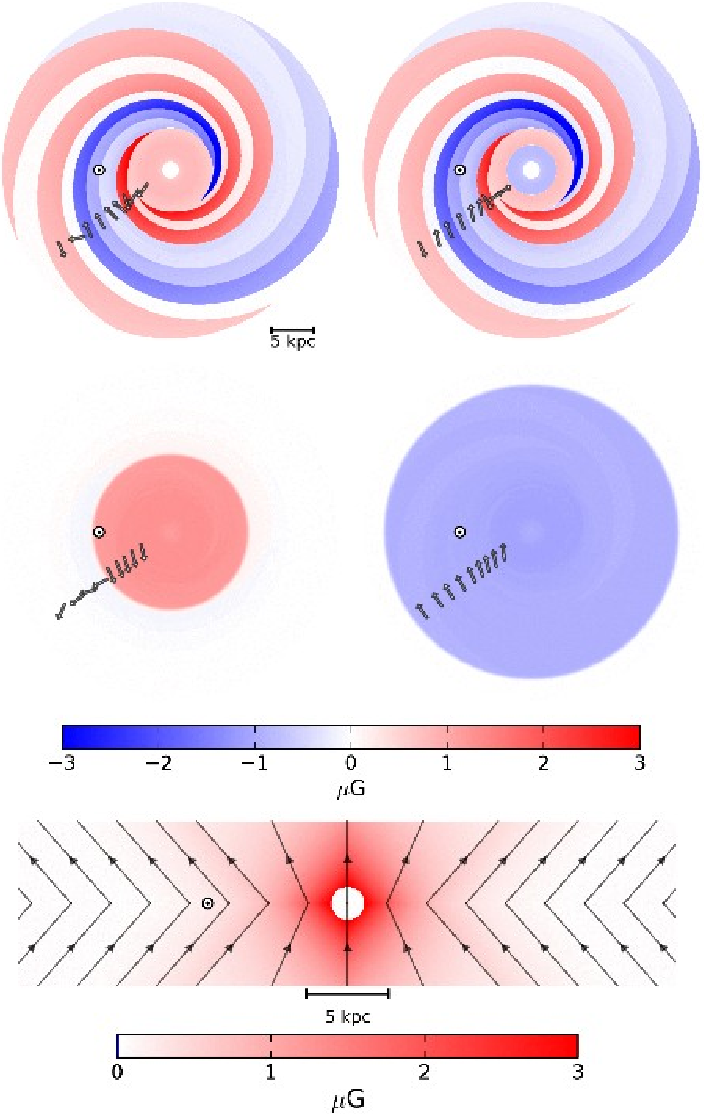
W/ source distribution from Green, arXiv:1309.3072 :

$$n(r) \propto (r/R_\odot)^{0.7} \exp\left[-3.5(r - R_\odot)/R_\odot\right]$$



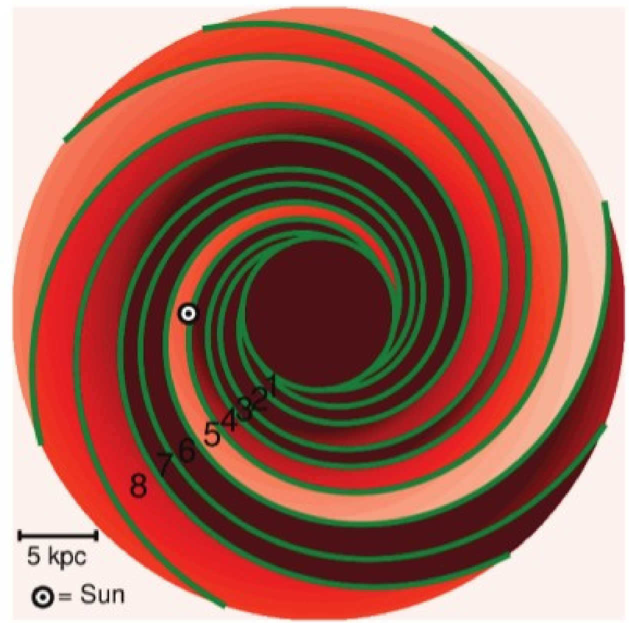
Regular MF:

Jansson & Farrar, ApJ 757, 14 (2012)



Turbulent MF:

Jansson & Farrar, ApJ 761, L11 (2012)



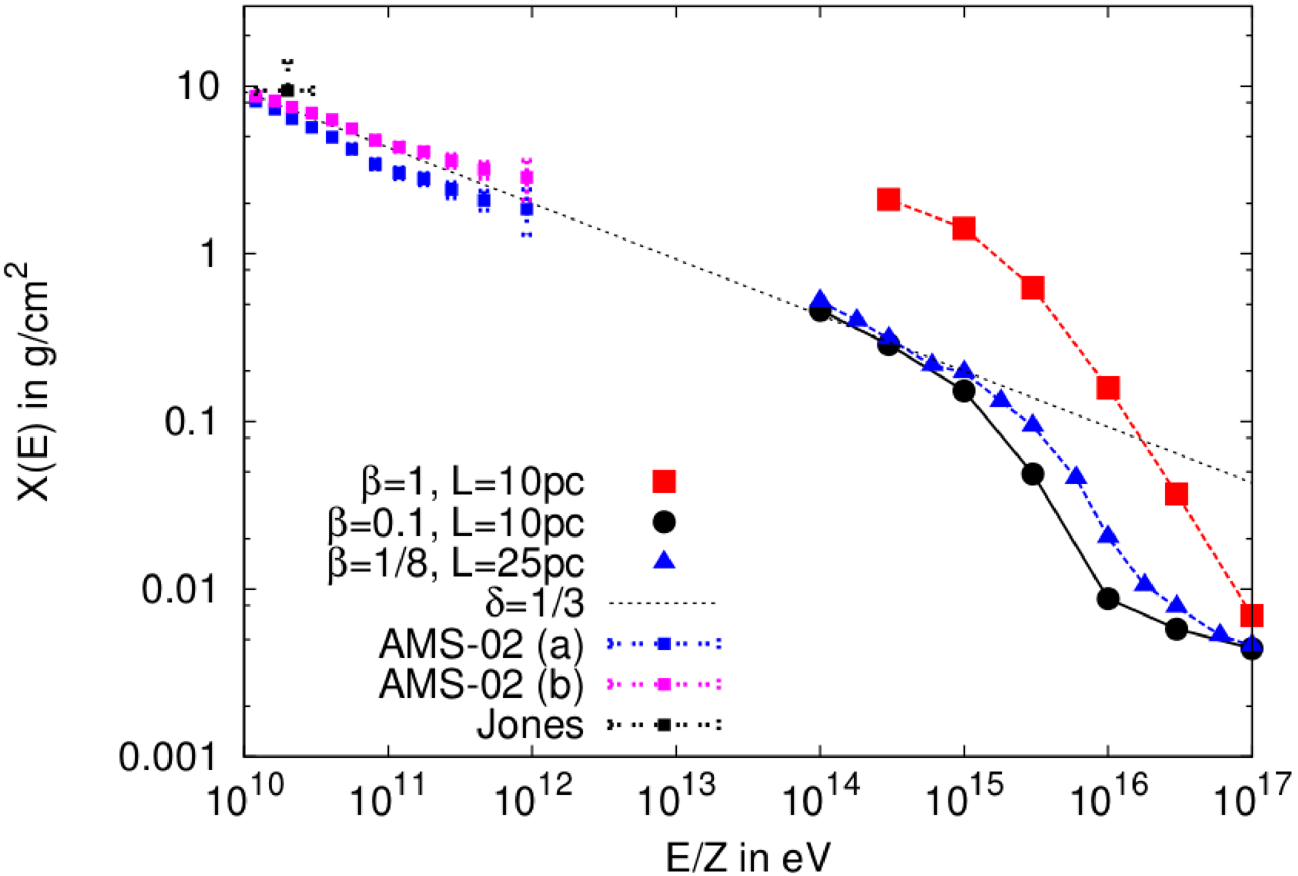
We use l_c = 1 pc to 10 pc & Kolmogorov spectrum

Grammage

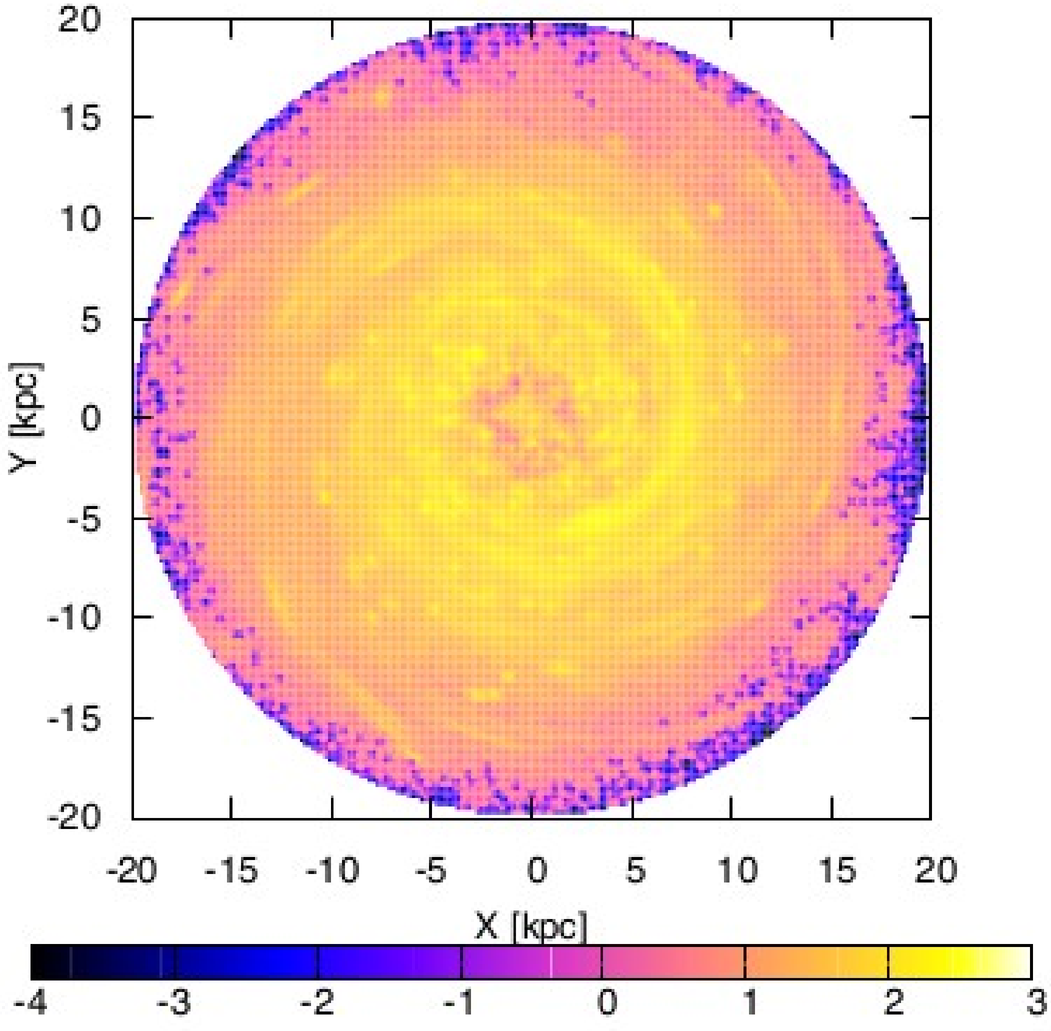
GG, Kachelriess & Semikoz, Phys. Rev. D **91**, 083009 (2015)

Gas distribution : $n(z) = n_0 \exp(-(z/z_{1/2})^2)$ with $n_0 = 0.3/\mathrm{cm}^3$ at $R_\odot$ and $z_{1/2} = 0.21\,\mathrm{kpc}$

$n = 10^{-4}\mathrm{g/cm}^3$ ↔ Minimum, up to z = +/- 10 kpc



1 PeV CR density in the Gal. plane



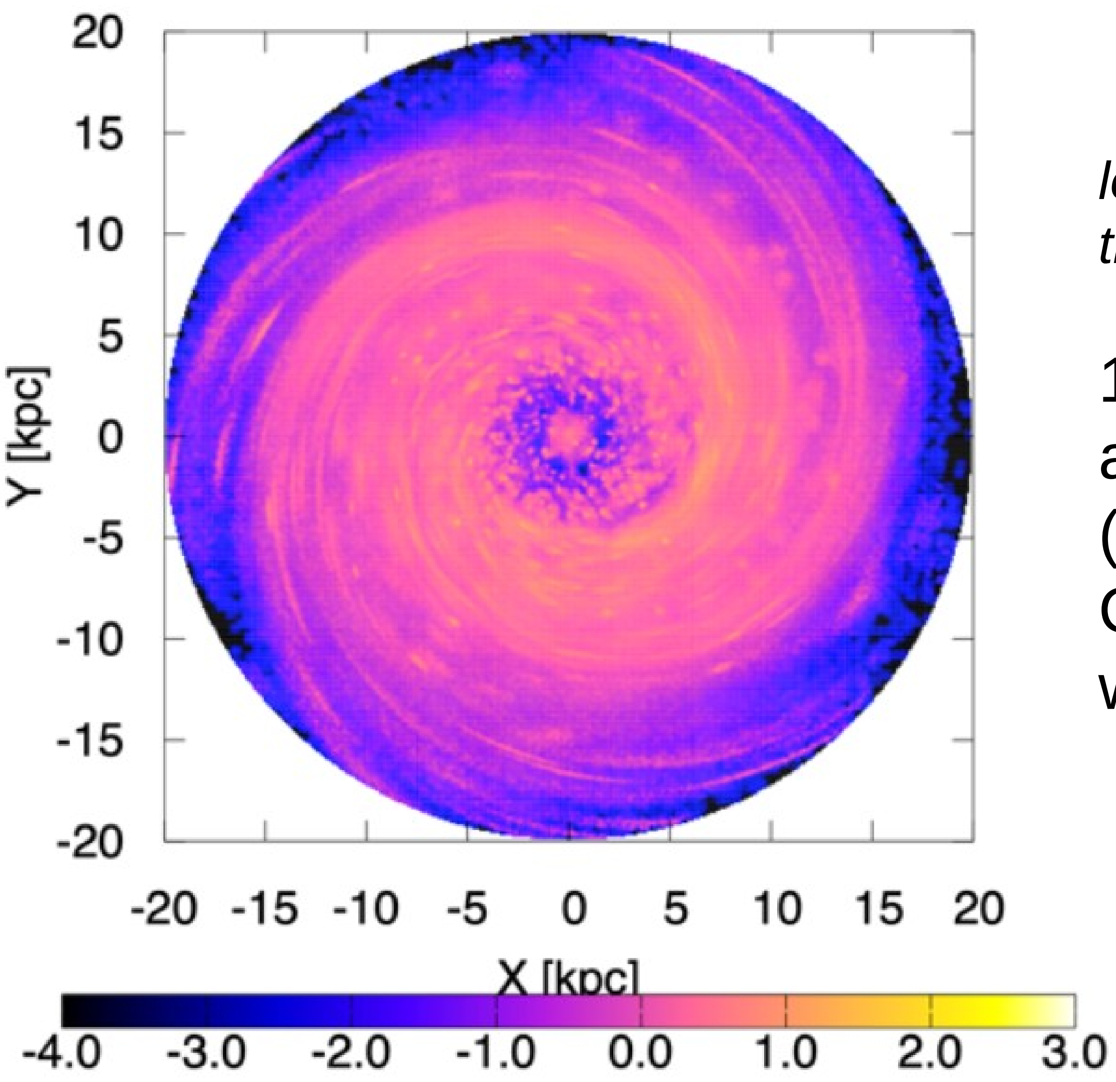
log(CR density) in the Galactic plane

1/3 of all SNe are PeVatrons (all CCSNe)

~ 'SMOOTH'? BUT MUCH MORE PATCHY THAN WITH ISO DIFF

G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

1 PeV CR density in the Gal. plane

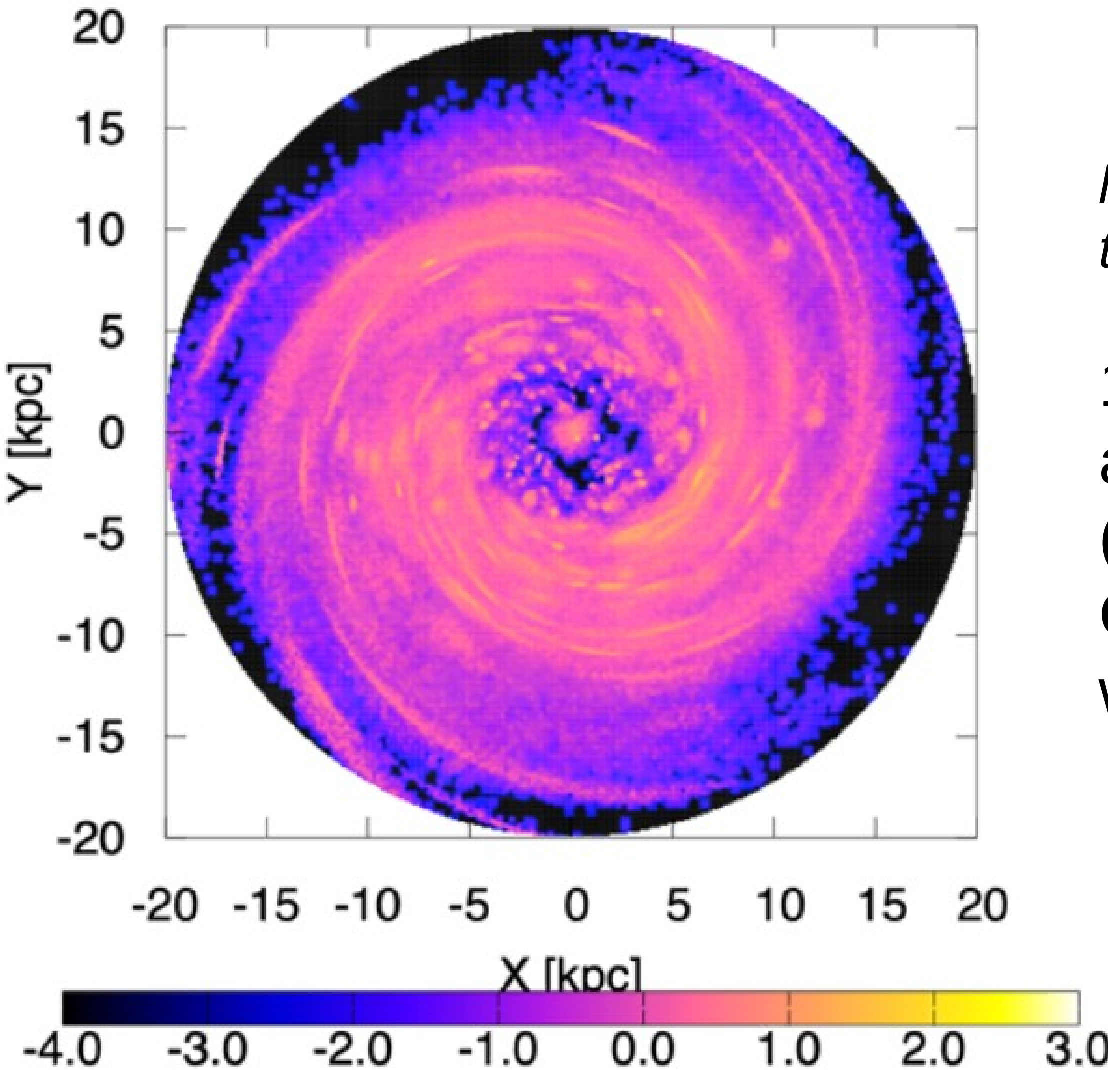


log(CR density) in the Galactic plane

10% of all SNe are PeVatrons (rare, extreme CCSNe in dense winds)

G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

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)

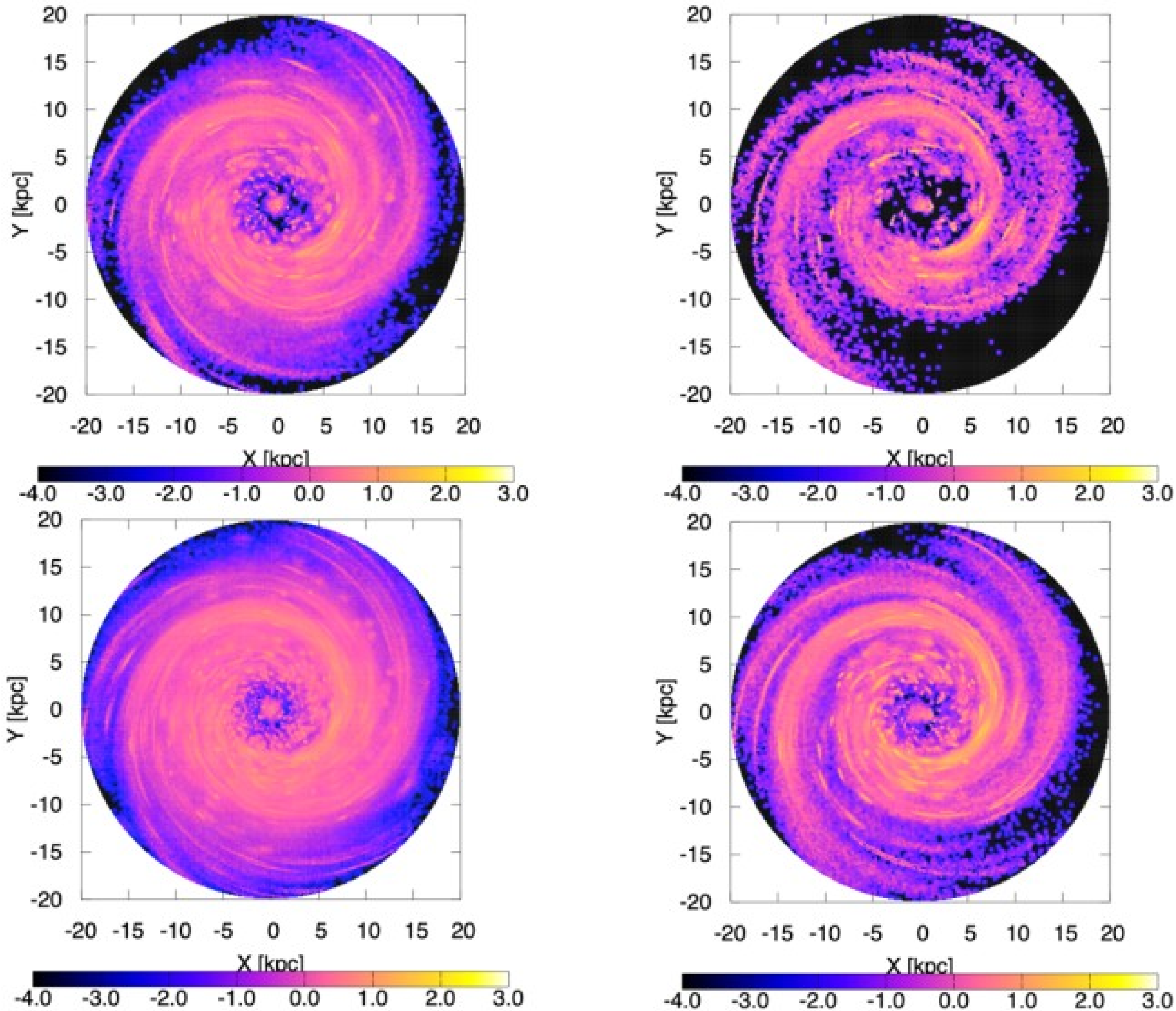
EXTREMELY PATCHY!

G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

1 PeV   10 PeV

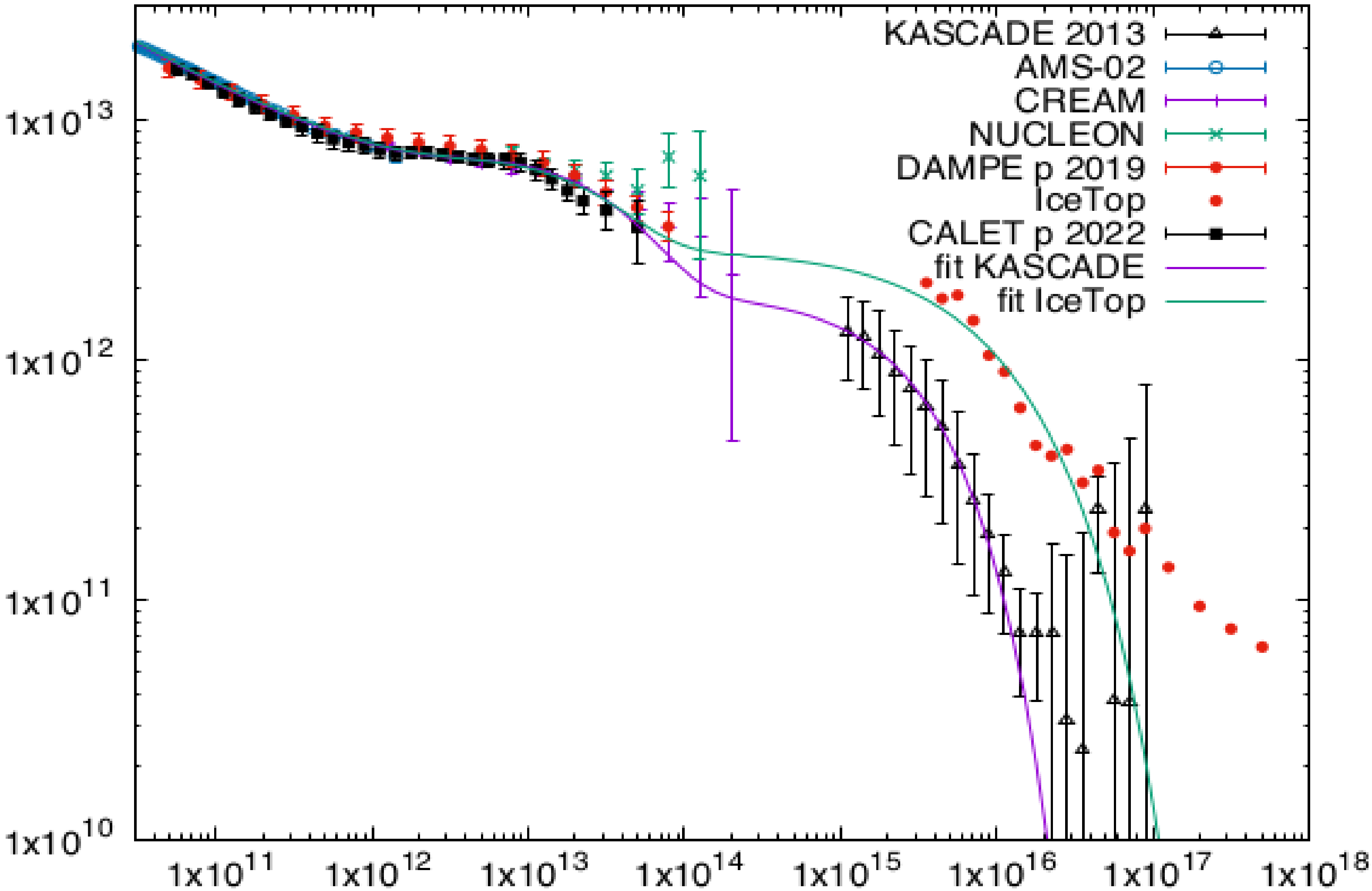
1.6%

10%



G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

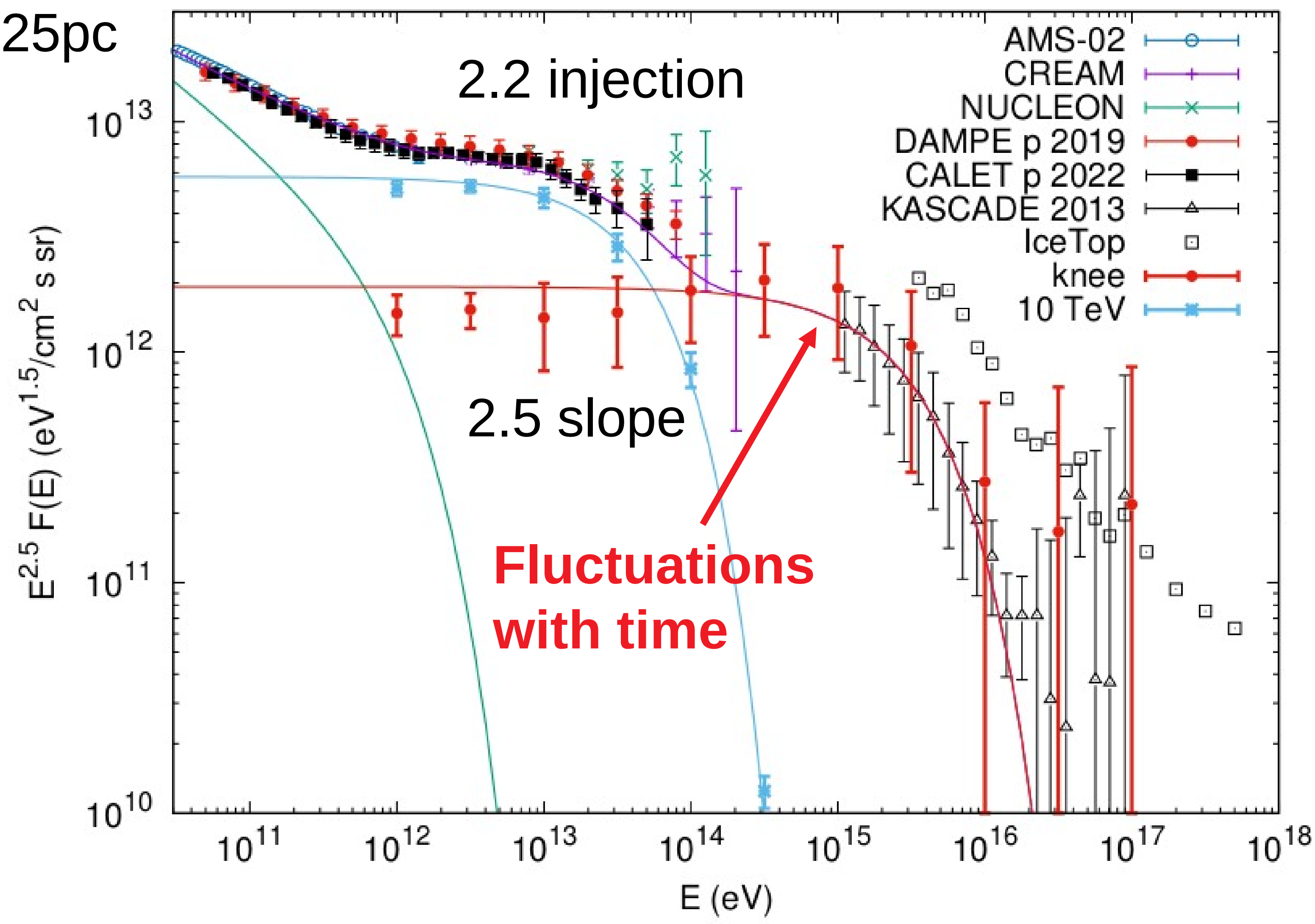
Proton flux at the knee



G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

Proton flux at the knee

L_{max}=25pc



G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

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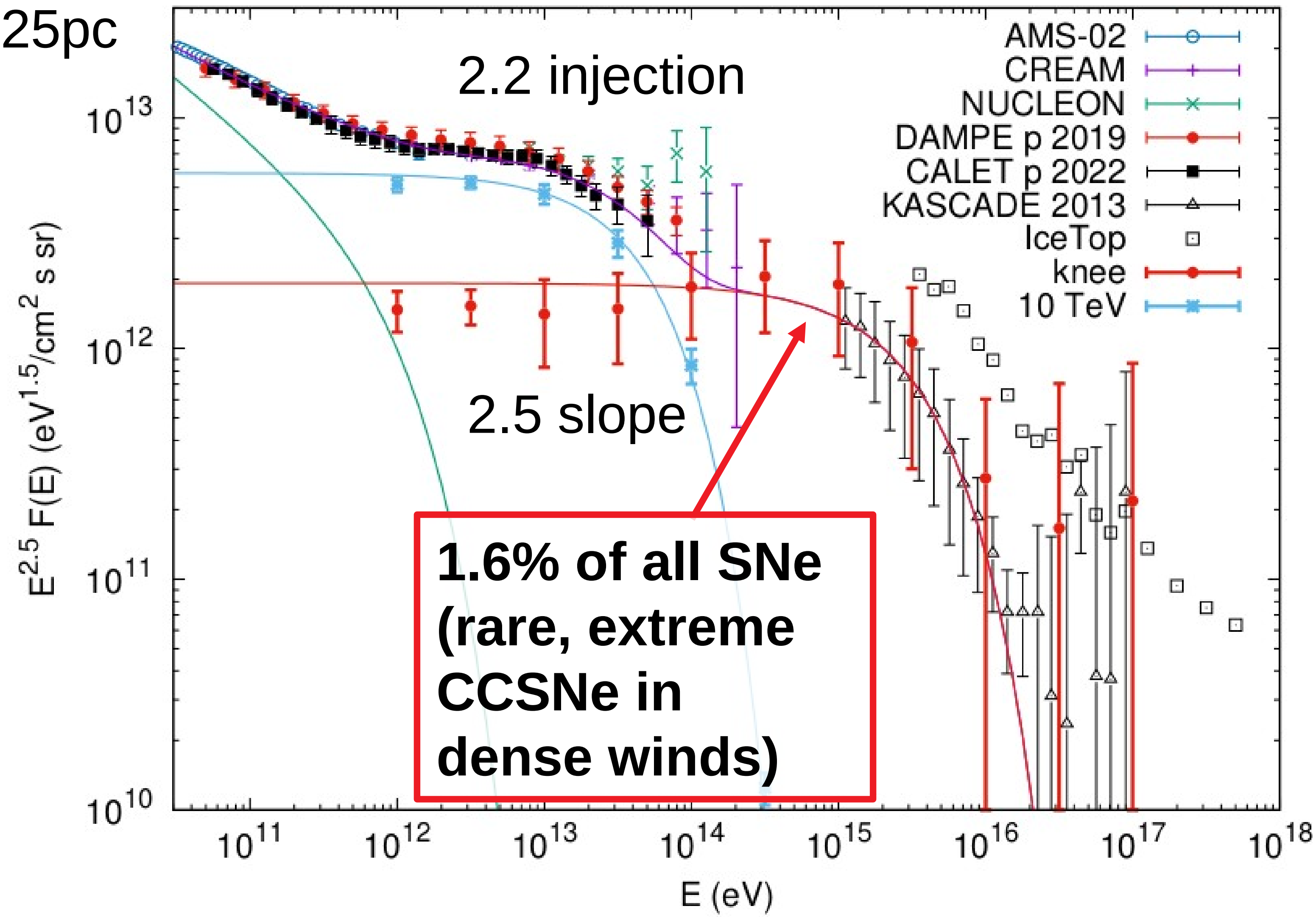

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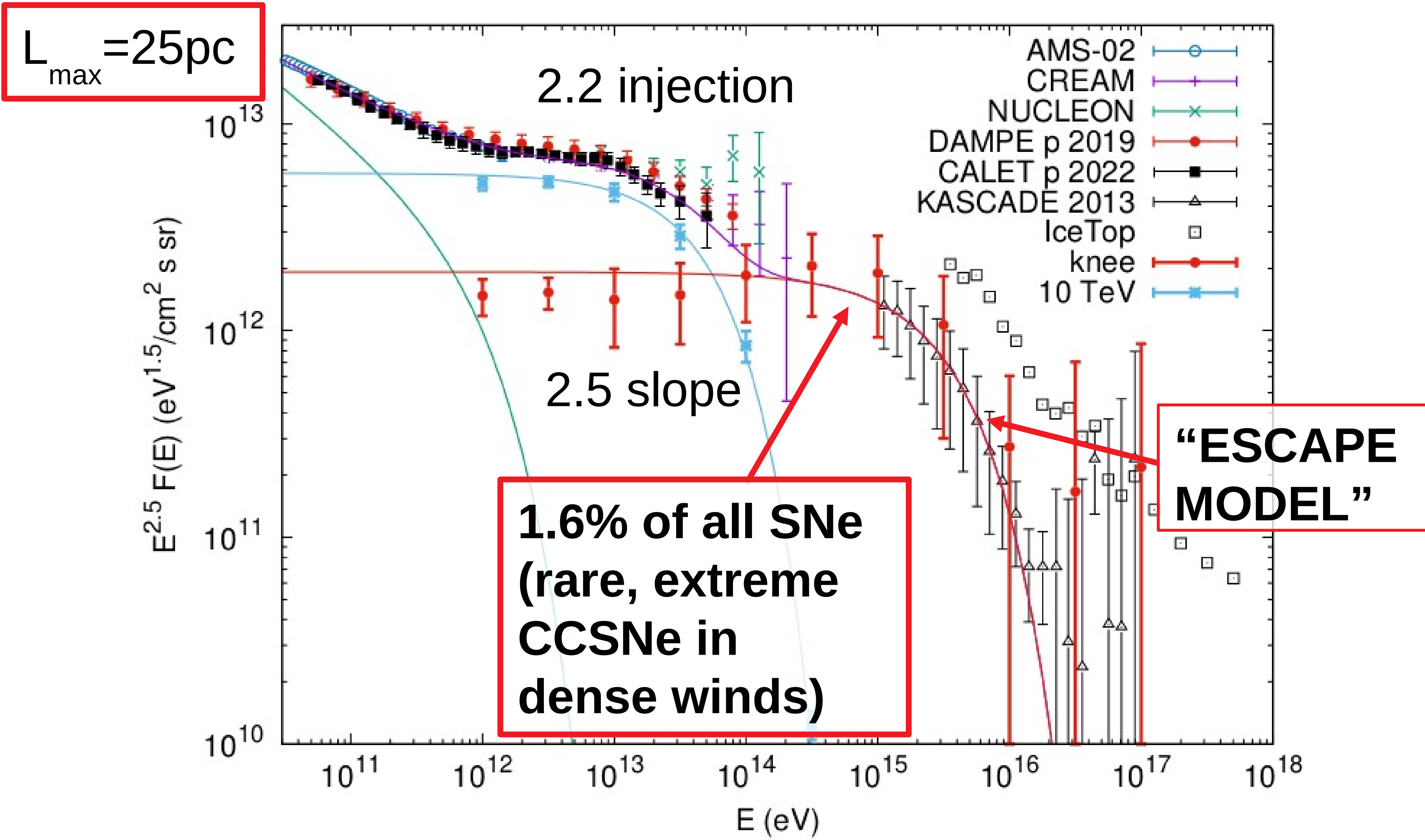

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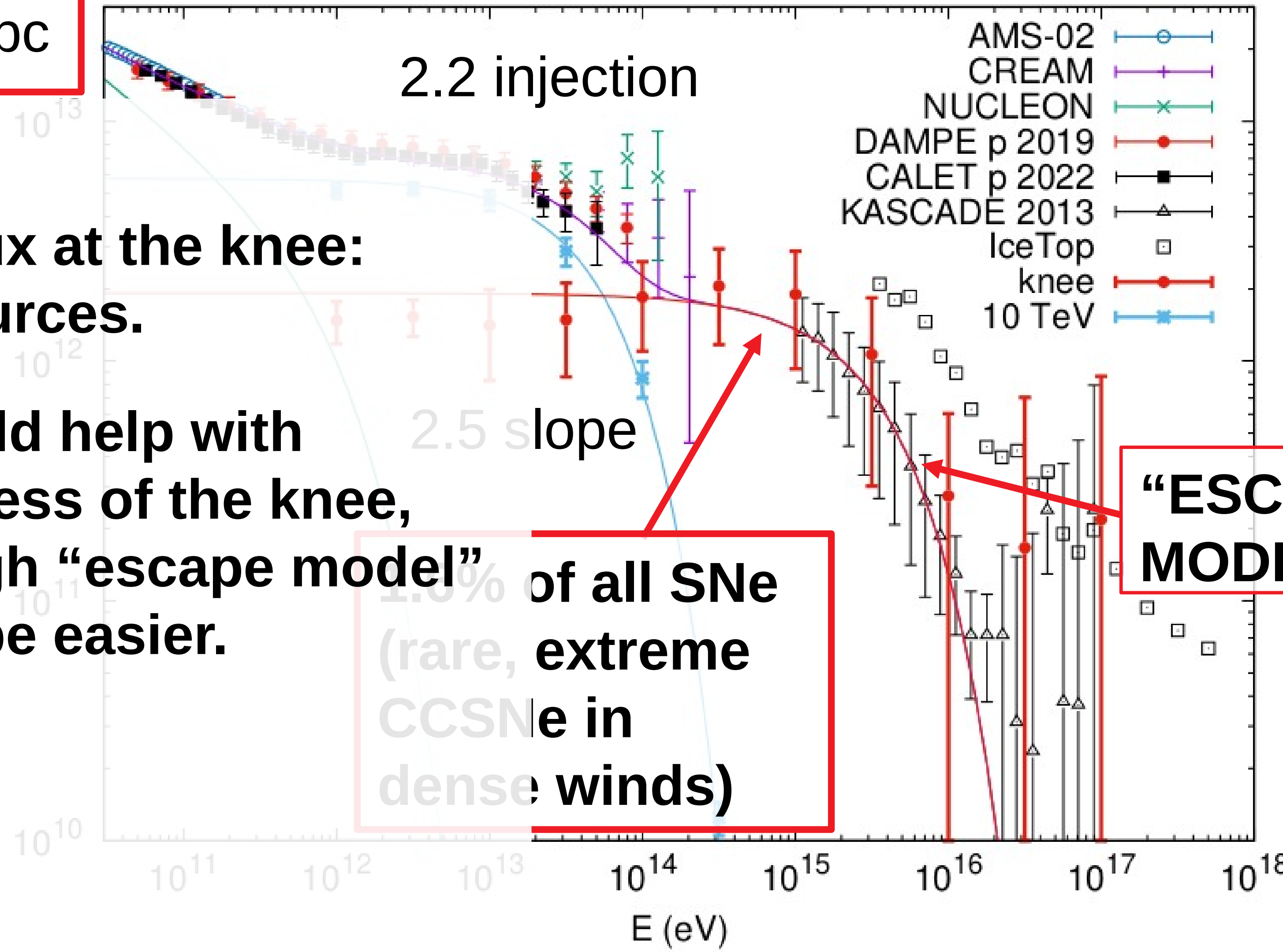


*** CR flux at the knee: ~10 sources.**

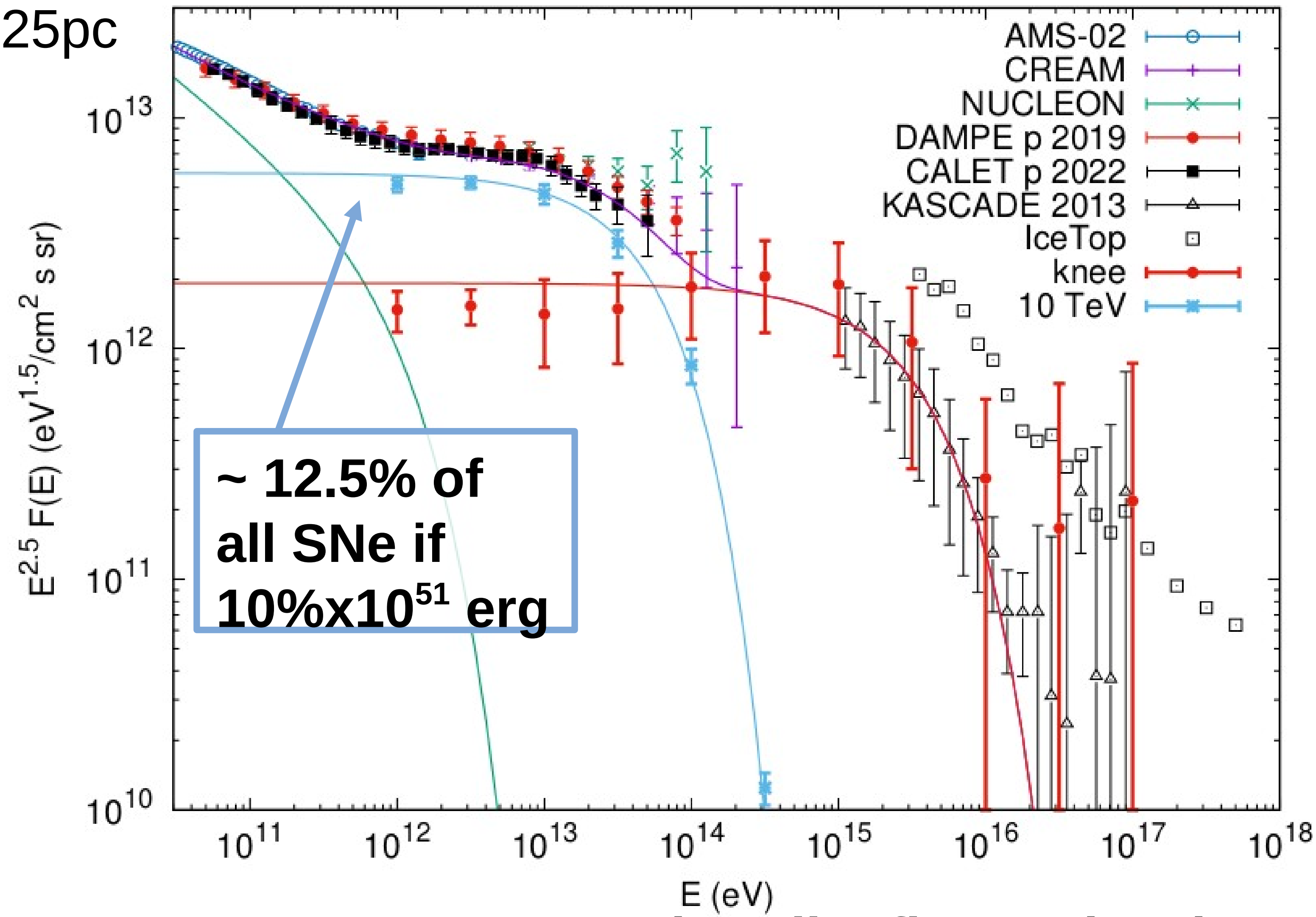
=> Could help with sharpness of the knee, although “escape model” might be easier.

1.0% of all SNe (rare, extreme CCSNe in dense winds)

G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

Proton flux at the knee

L_{max}=25pc



At 10 TeV: ~100 sources (smaller fluctuations)

G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

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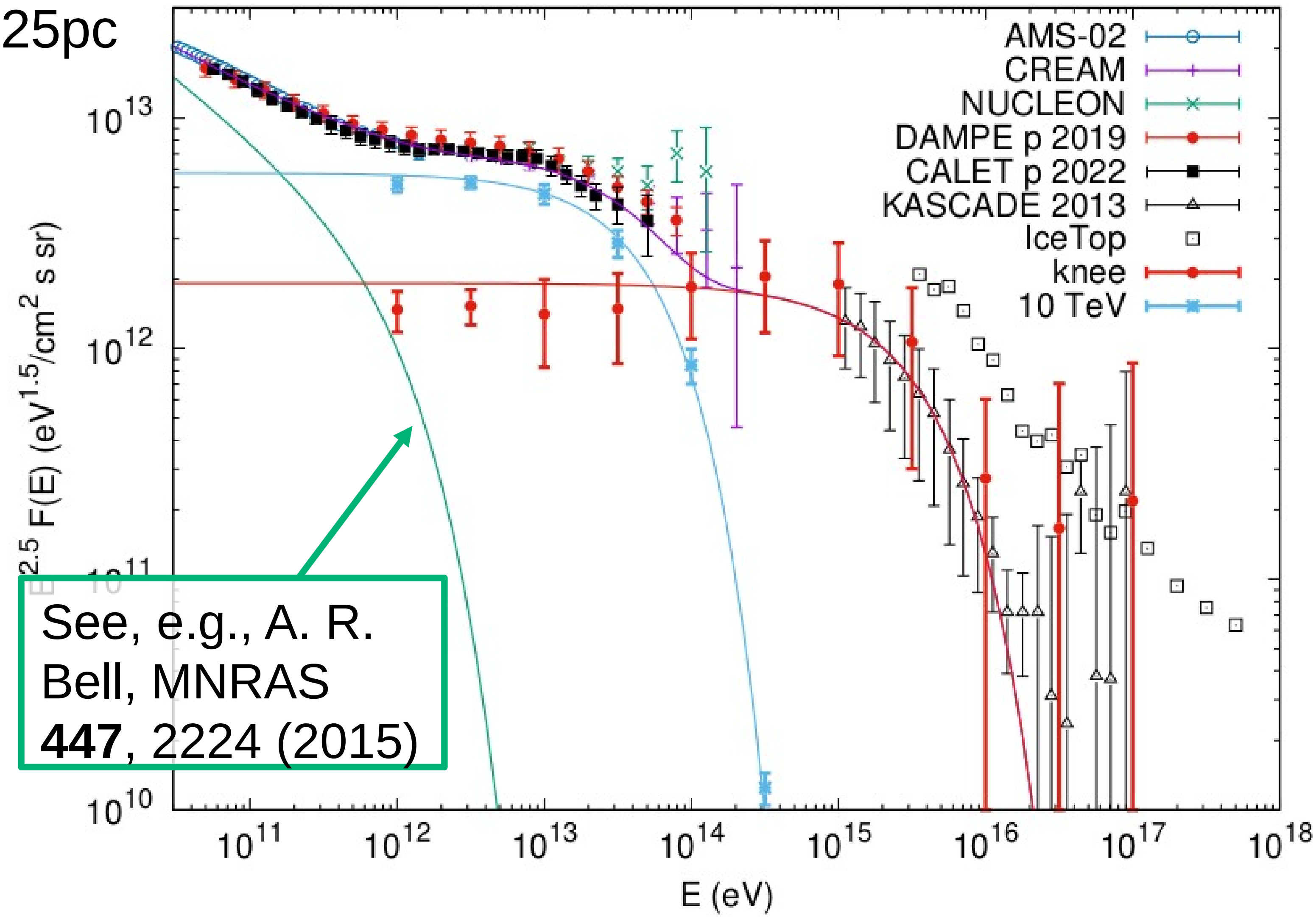

G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

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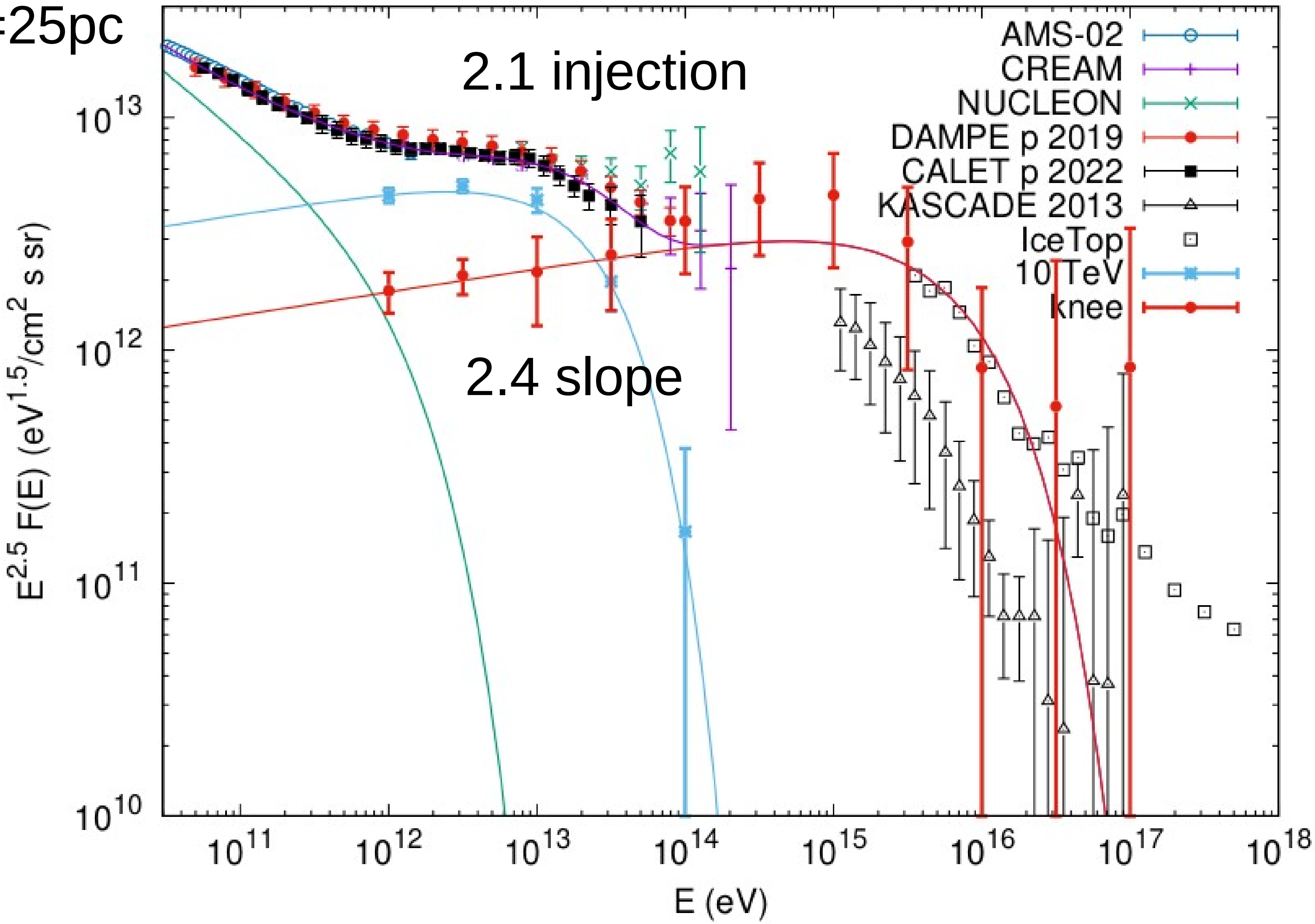
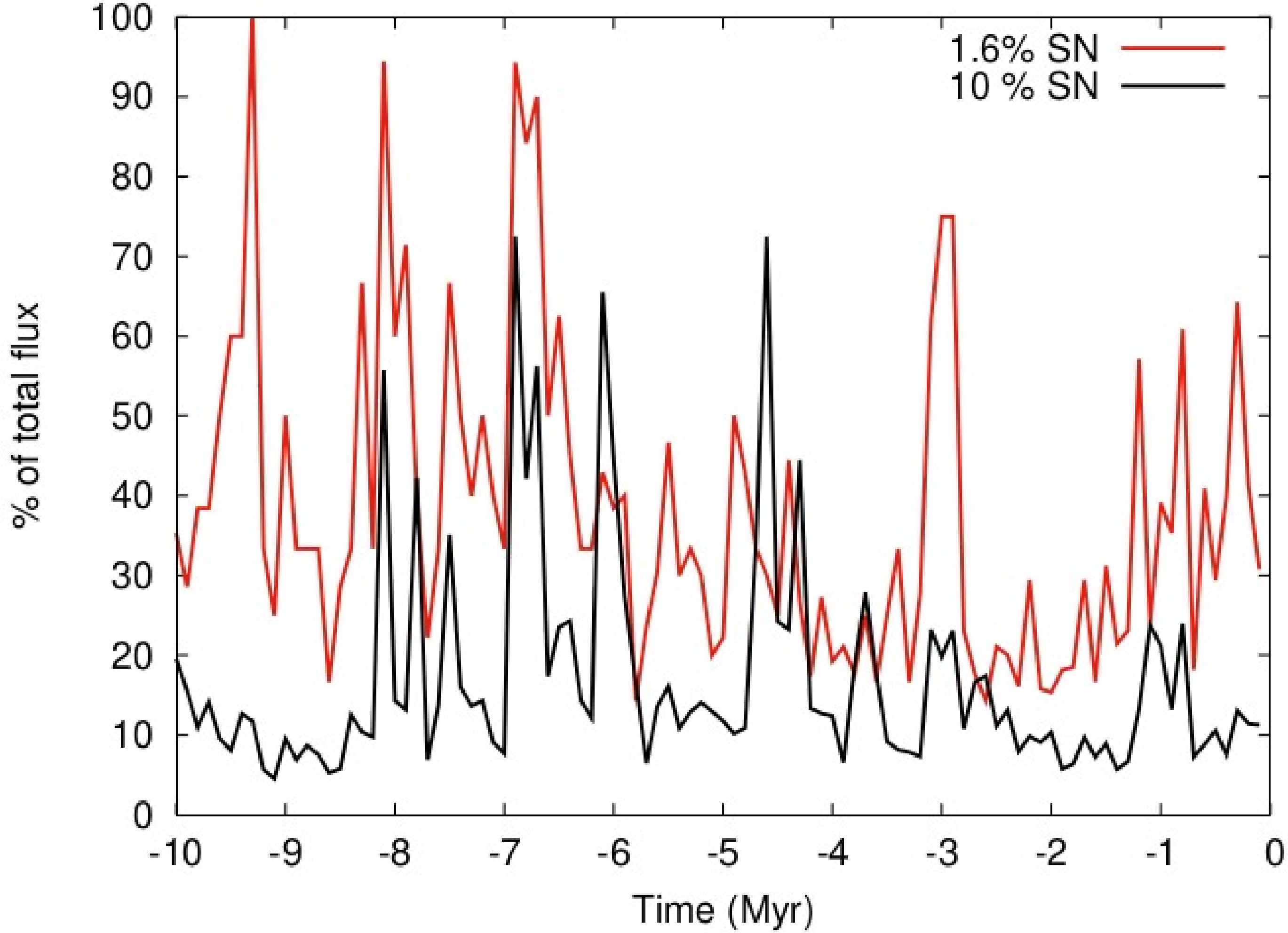


G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

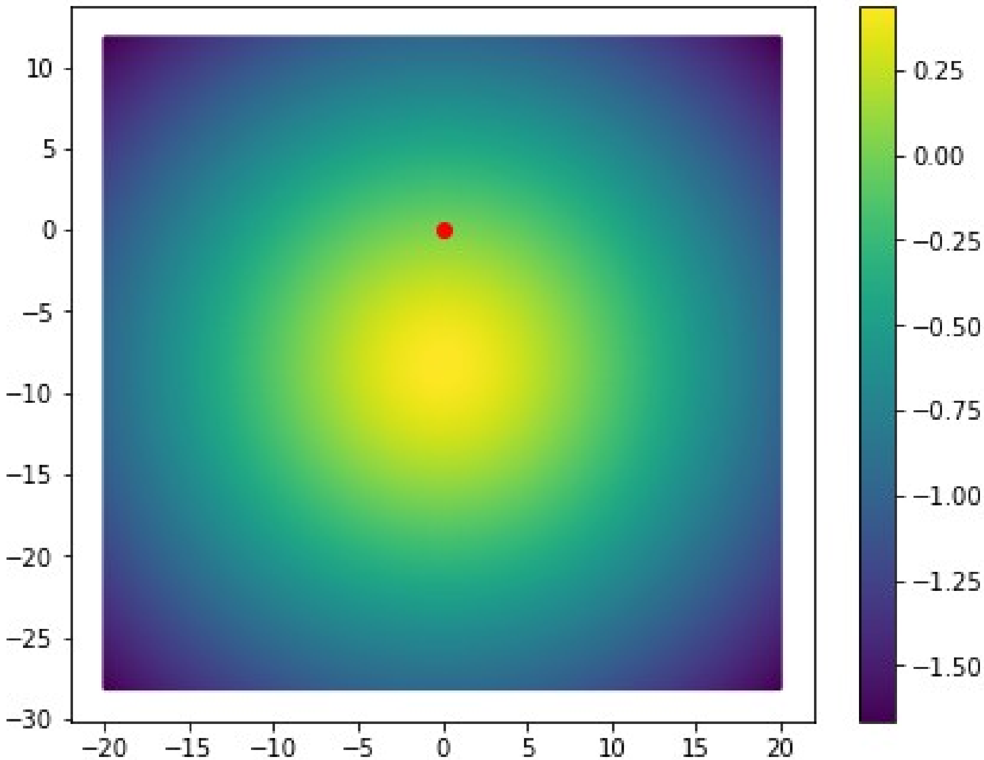
Dominant source contribution to total flux at 1PeV



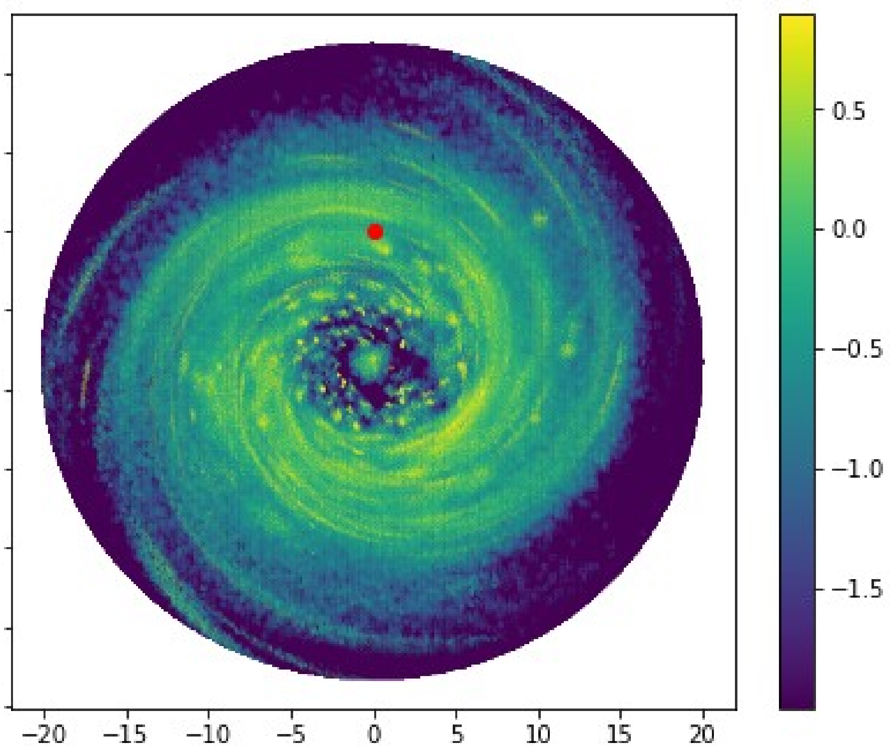
G.Giacinti and D.Semikoz, arXiv:…….. (Tomorrow)

1 PeV CR density in the Gal. plane

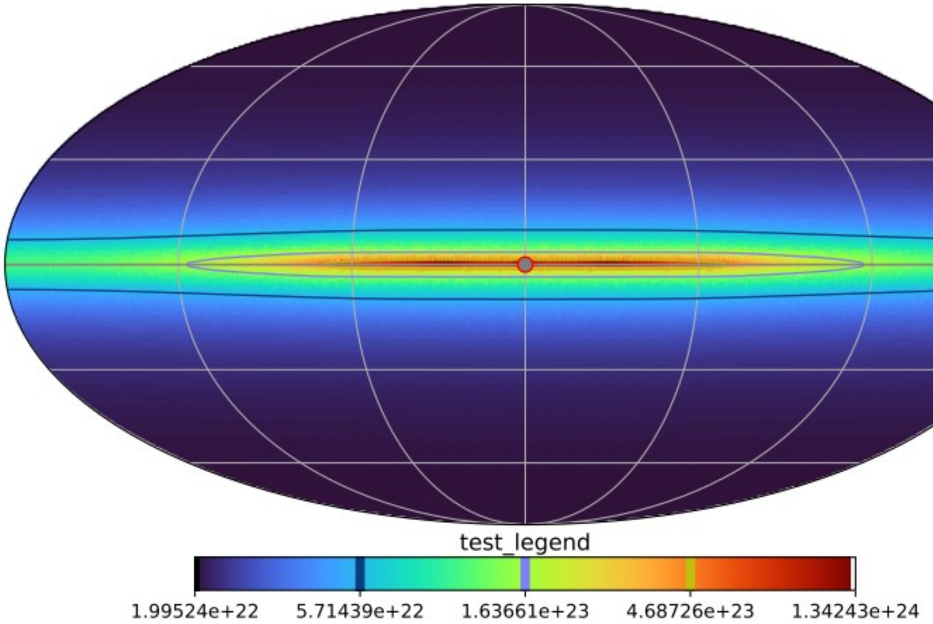
Lipari & Vernetto (2018)



Giacinti, Semikoz, Koldobskiy, Neronov +, In prep. (2023)

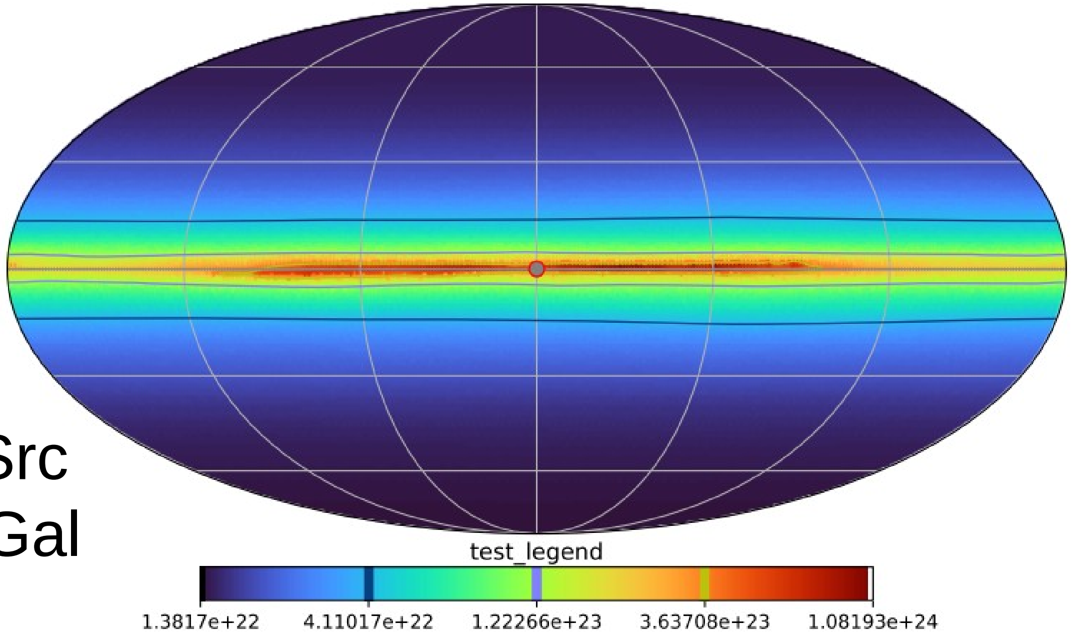


Diffuse 100 TeV γ-ray emission



Lipari & Vernetto (2018)

Giacinti, Semikoz, Koldobskiy, Neronov +, In prep. (2023)

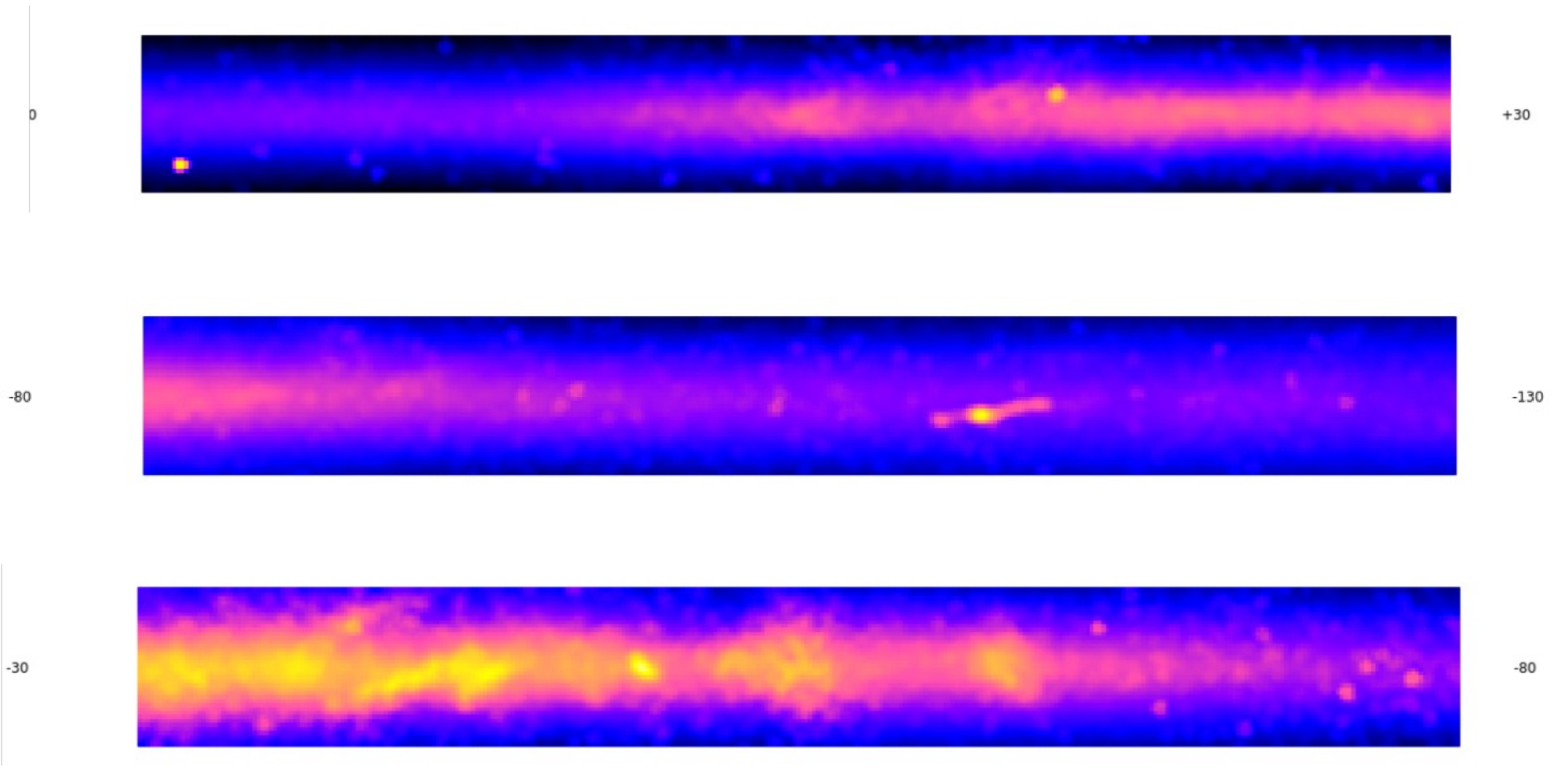


→ More patchy + Extended Src
→ Less contrast inner/outer Gal
→ Broader in some places.

Zoom on our simulated Gal. plane

Giacinti, Semikoz, Koldobskiy, Neronov, et al., In prep.

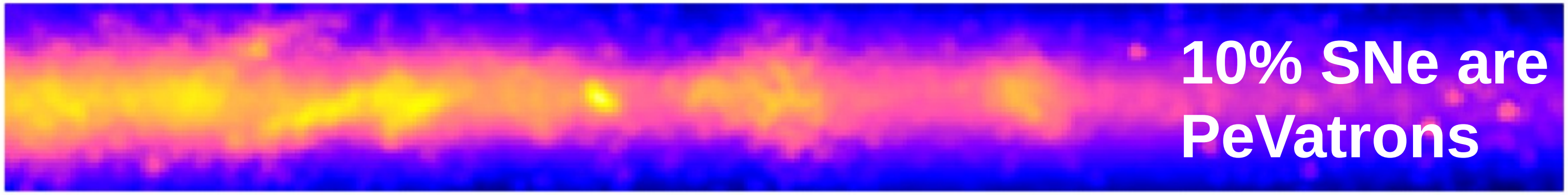
Galactic plane survey ($|b| < 3^o$) at E_γ = 100 TeV in the simulation:

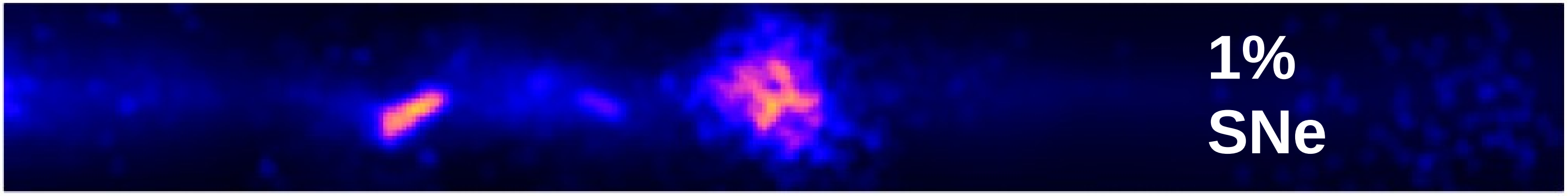


Zoom on our simulated Gal. plane

Giacinti, Semikoz, Koldobskiy, Neronov, et al., In prep.

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

-30  -80

-30  -80

Comparison with LHAASO data => Infos on PeVatrons & GMF

Summary & Perspectives

- Very extended sources = New class of sources
  → Between point sources and true diffuse emission,
  → Signatures of past PeVatrons invisible otherwise,
  → New way of probing CR transport in the IS Turb.

- Galaxy NOT uniformly filled with CRs at PeV energies (very different from GeV); Knee is strongly variable.

- Updated our model of CR propagation in the Galaxy (dynamical now); 2 classes of sources (~10/100TeV).
  → Descr. of the knee & New model for the Galactic diffuse VHE emission. Can compare with LHAASO.