Latin-American School on CTA Science

Supernovae Remnants and PeVatrons: Acceleration and Propagation

Pierre Auger Observatory image courtesy Steven Saffi

Dra. Rita de Cassia dos Anjos

PALOTINA UFPR 30 anos
O FUTURO SE FORMA AQUI

UFPR - Palotina
March 31, 2023

cta cherenkov telescope array

ICTP The Abdus Salam International Centre for Theoretical Physics
Associate

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Hess 1912

CTA Observatory image courtesy G. Perez, IAC

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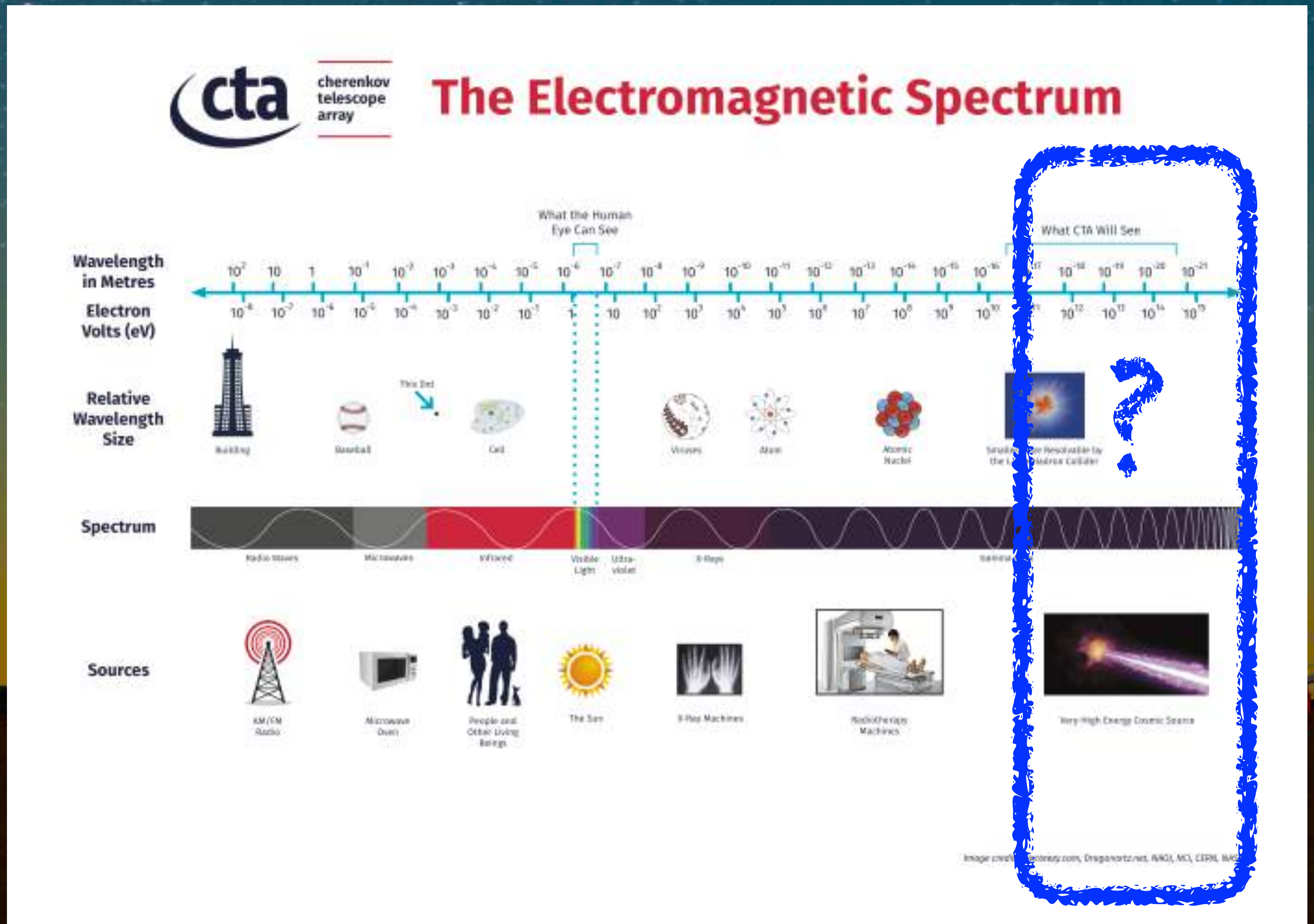

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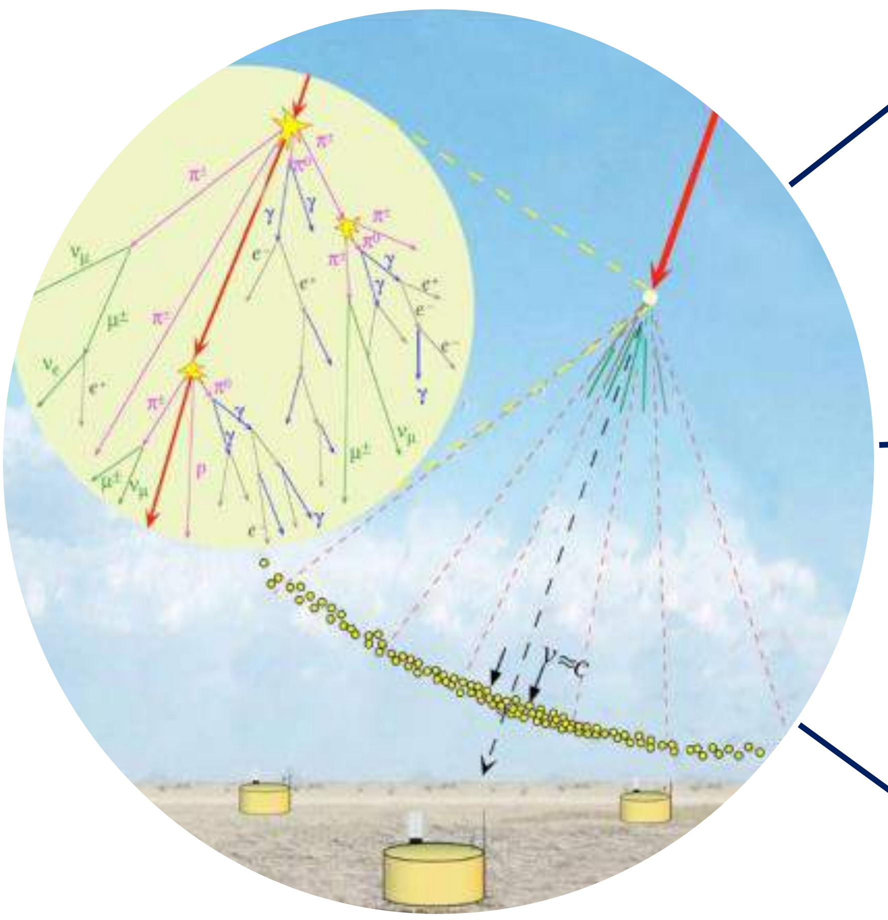
Overview

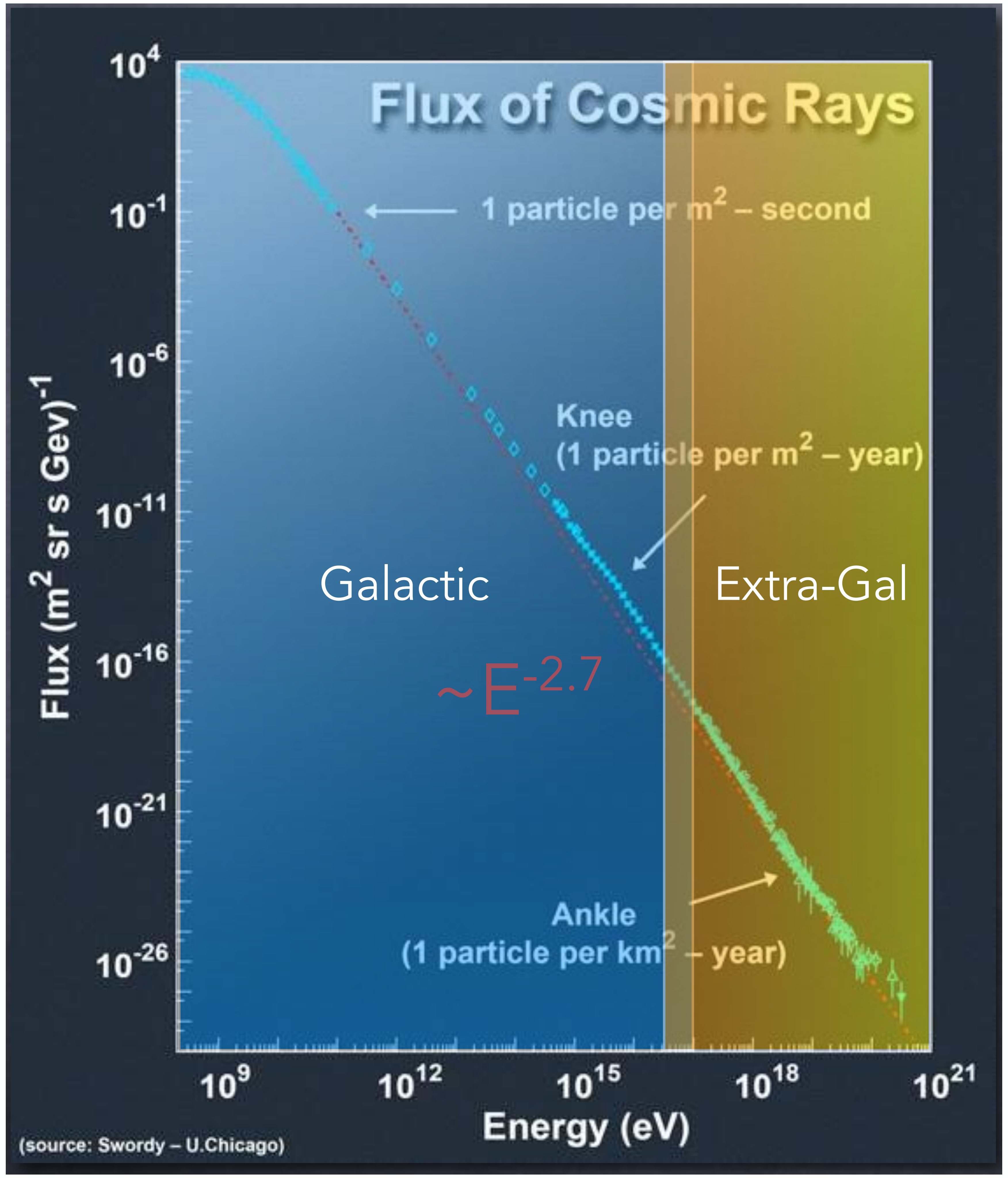
- Motivation and state-of-the-art
- What are PeVatrons?
- Cosmic-ray acceleration in SNRs
- Multimessenger propagation inside/outside Galaxy
- Galactic PeVatron Candidates
- Conclusion

• Motivation and State-of-the-art

What do we have?



Energy Spectrum



• Motivation and State-of-the-art

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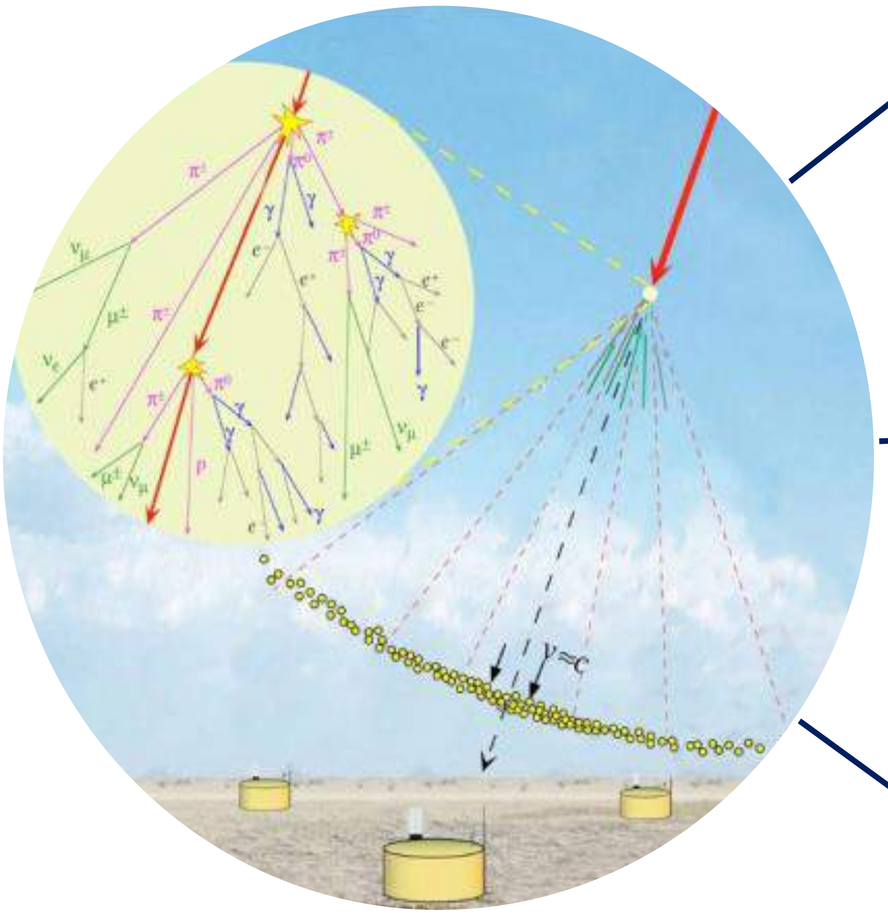

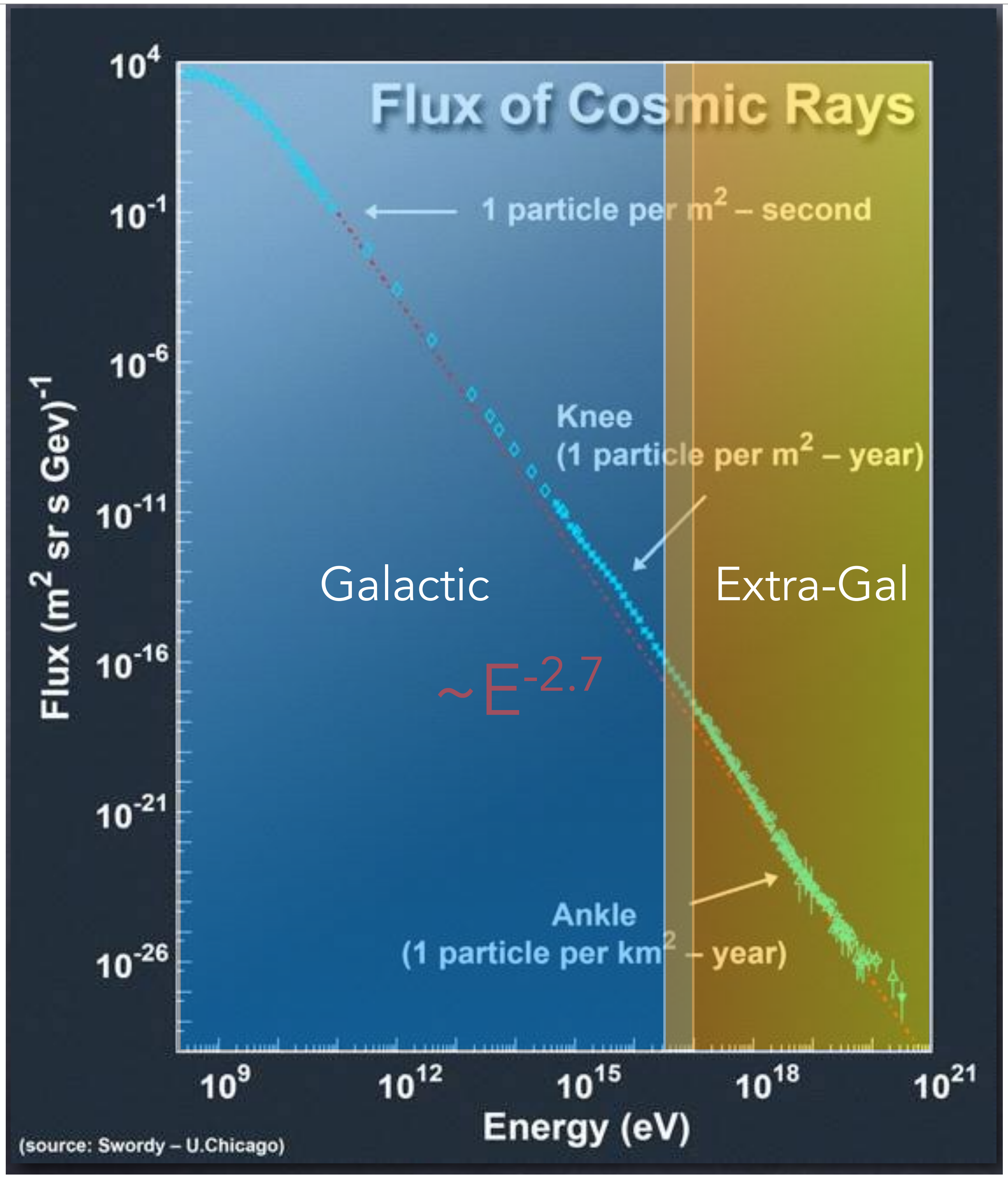

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{-\alpha}$$

Spectrum shape:

- Different composition
- Different sources (Gal x Extragal)
- Interaction with cosmic radiations

• Motivation and State-of-the-art

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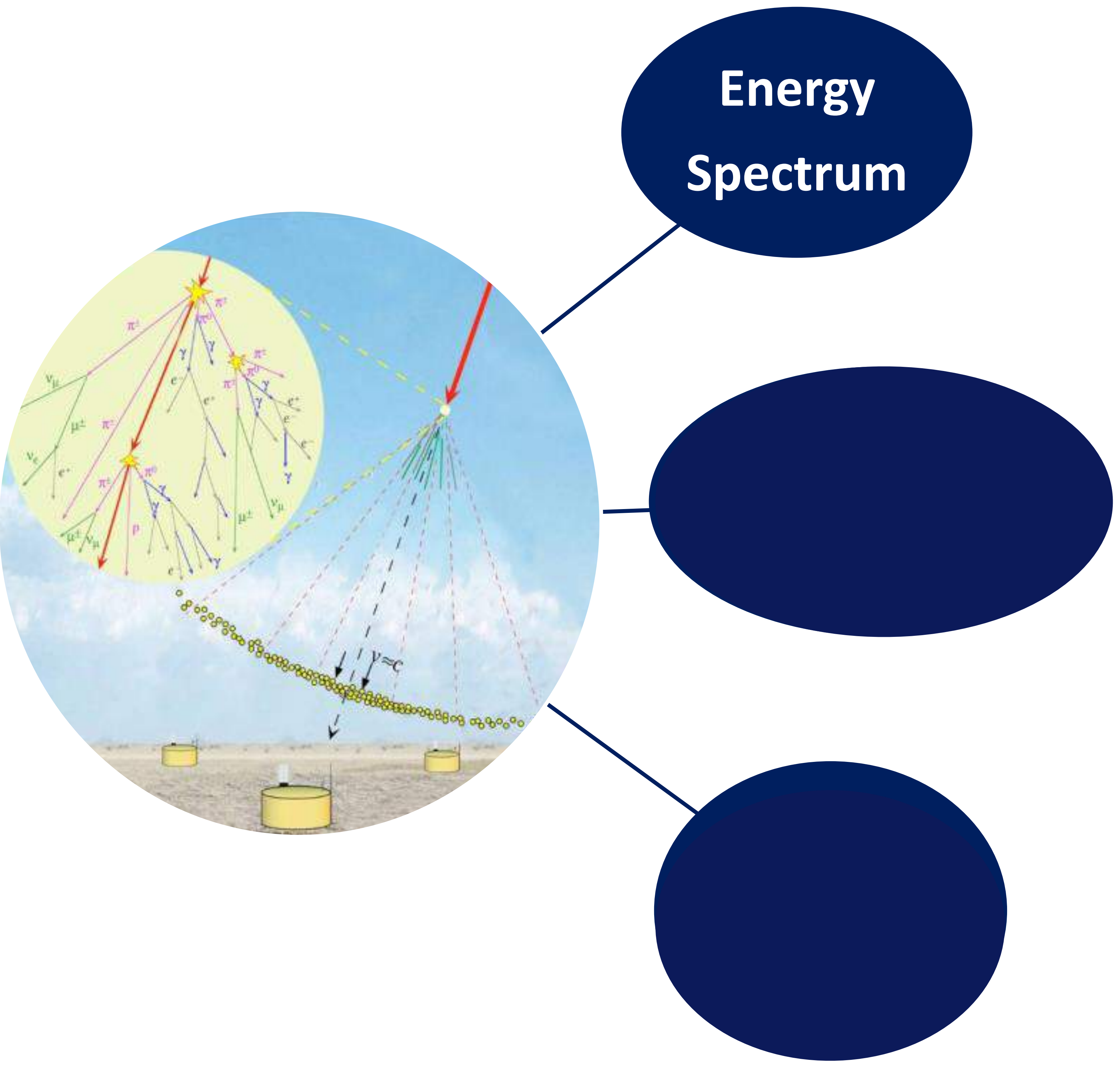

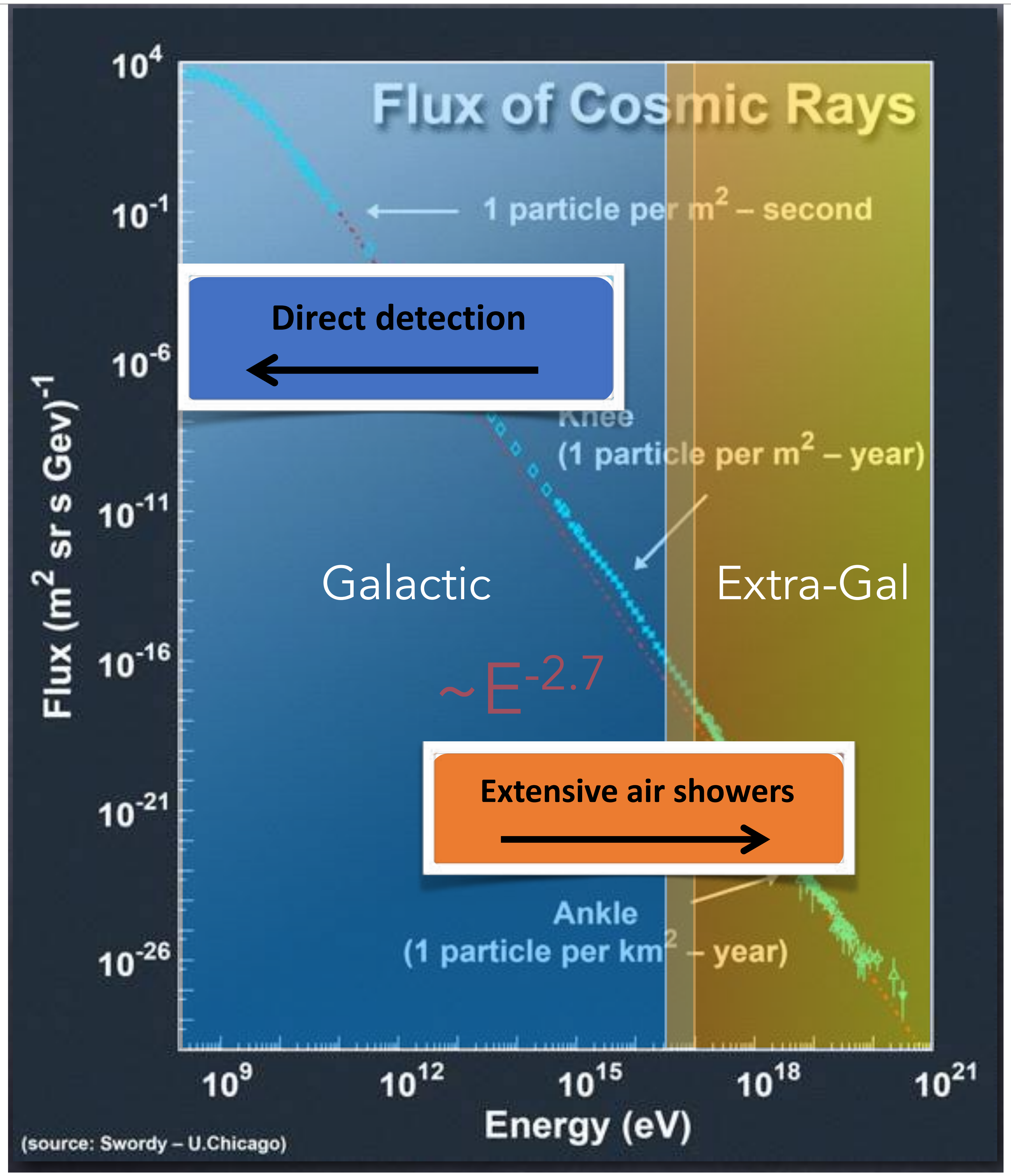

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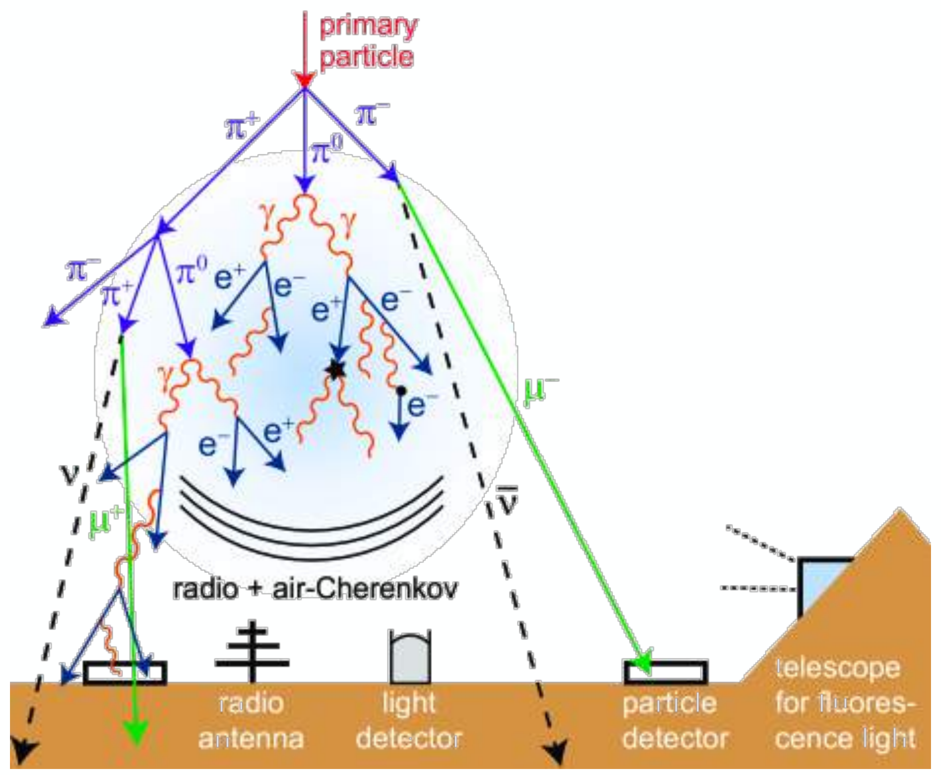

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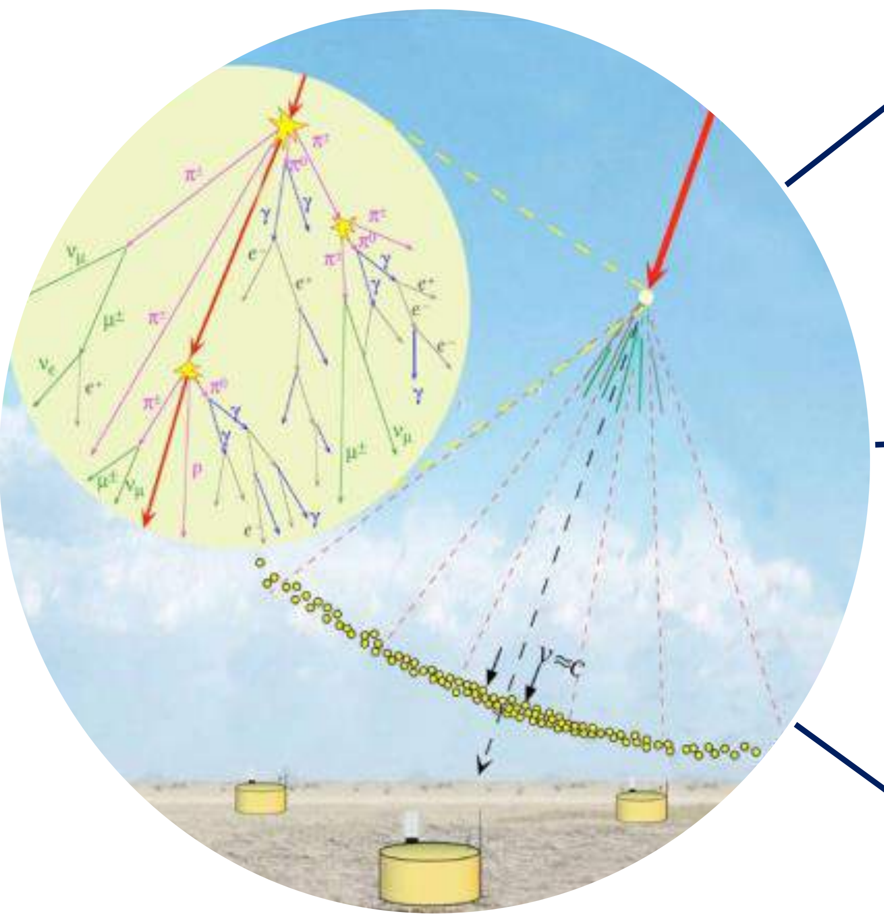
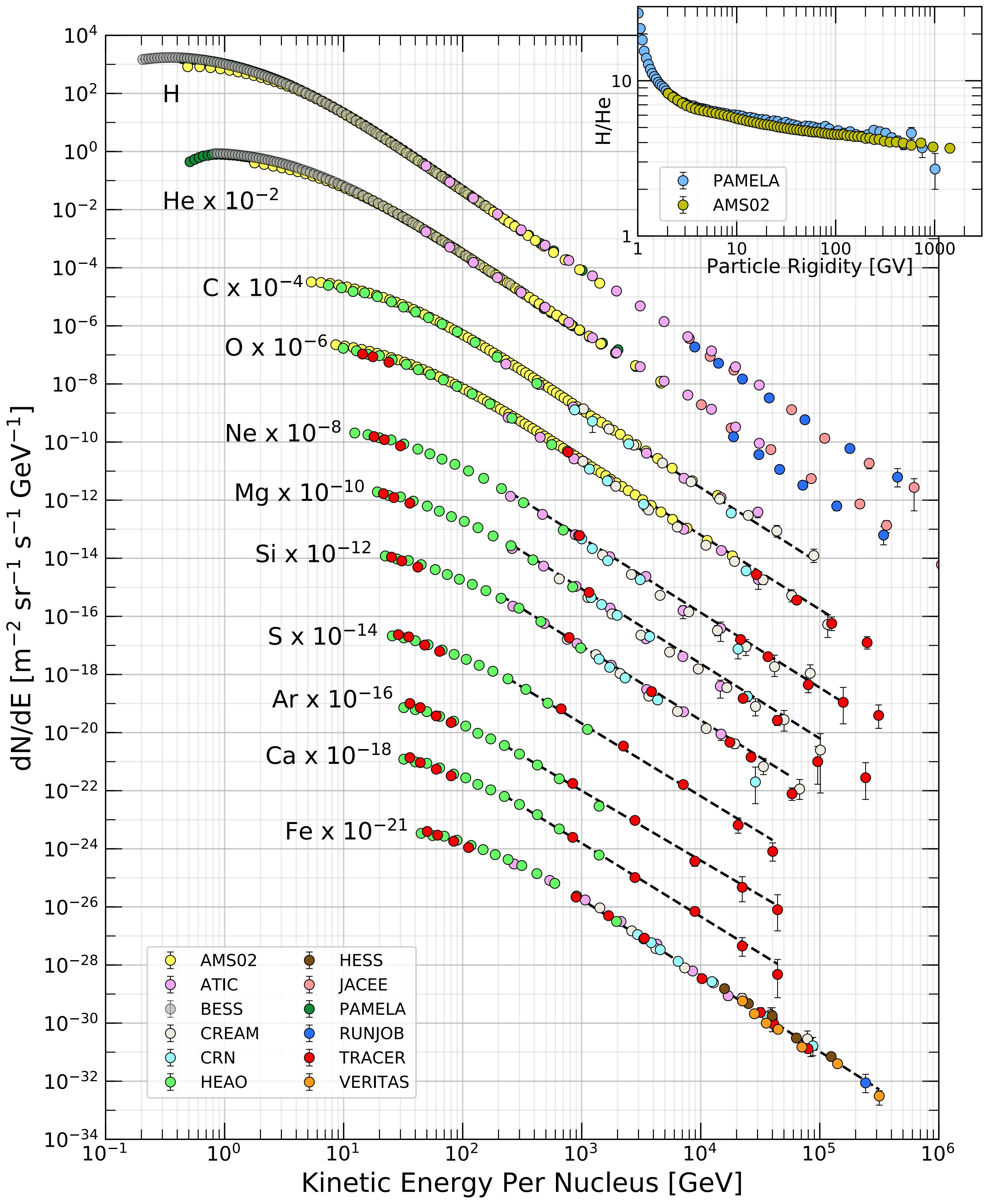


Energy Spectrum

Chemical Composition



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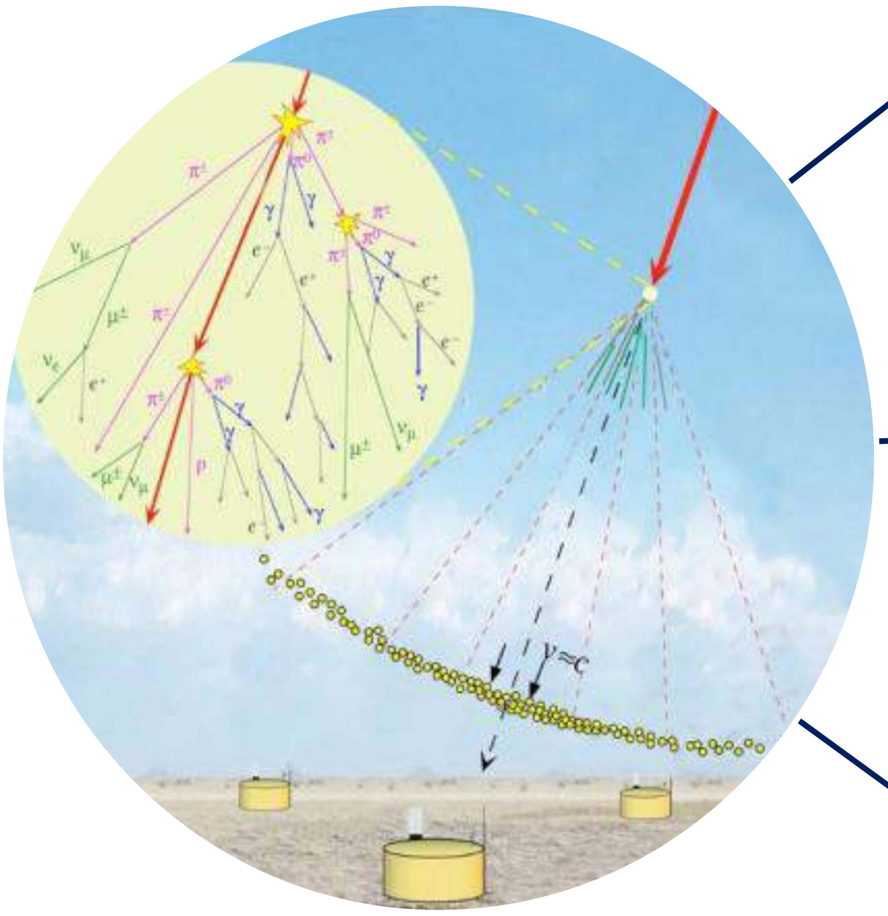
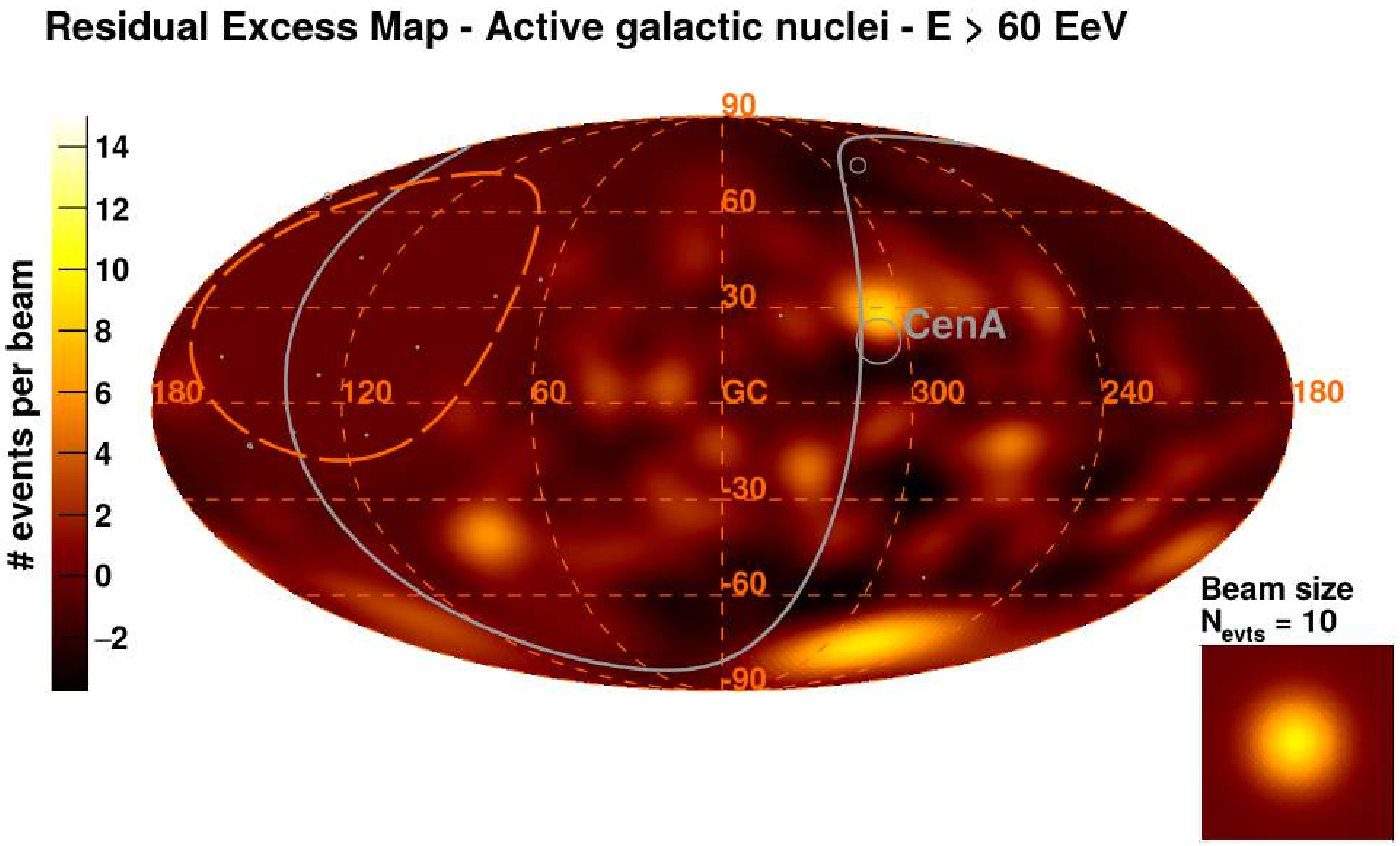


Energy Spectrum

Chemical Composition

Arrival Directions



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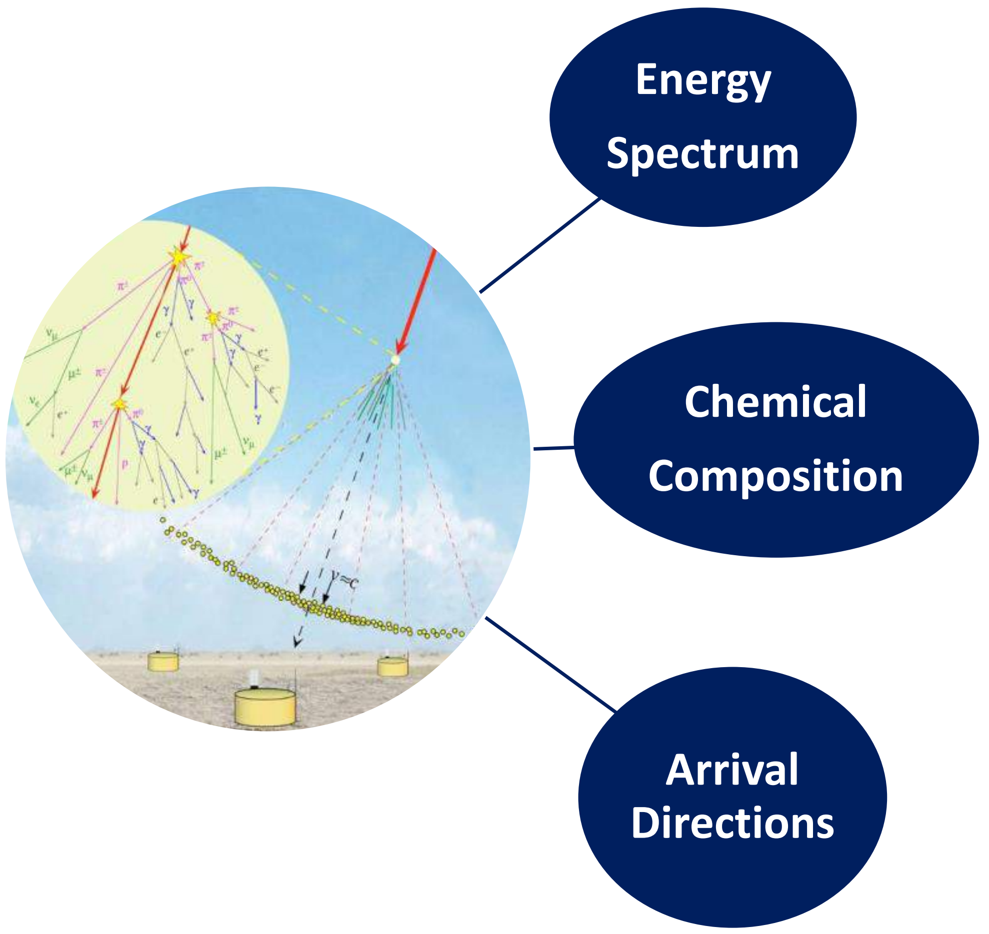
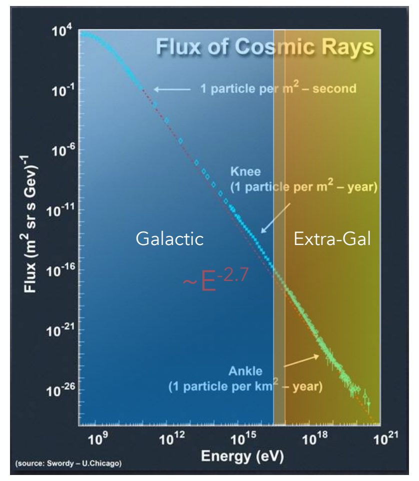
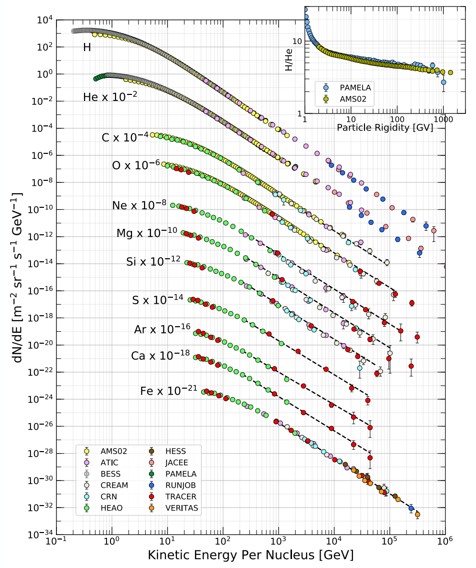
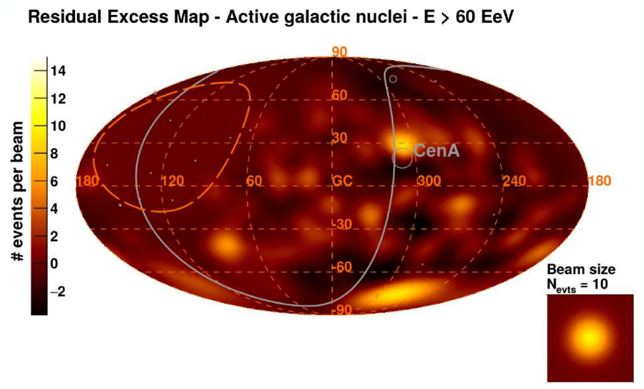
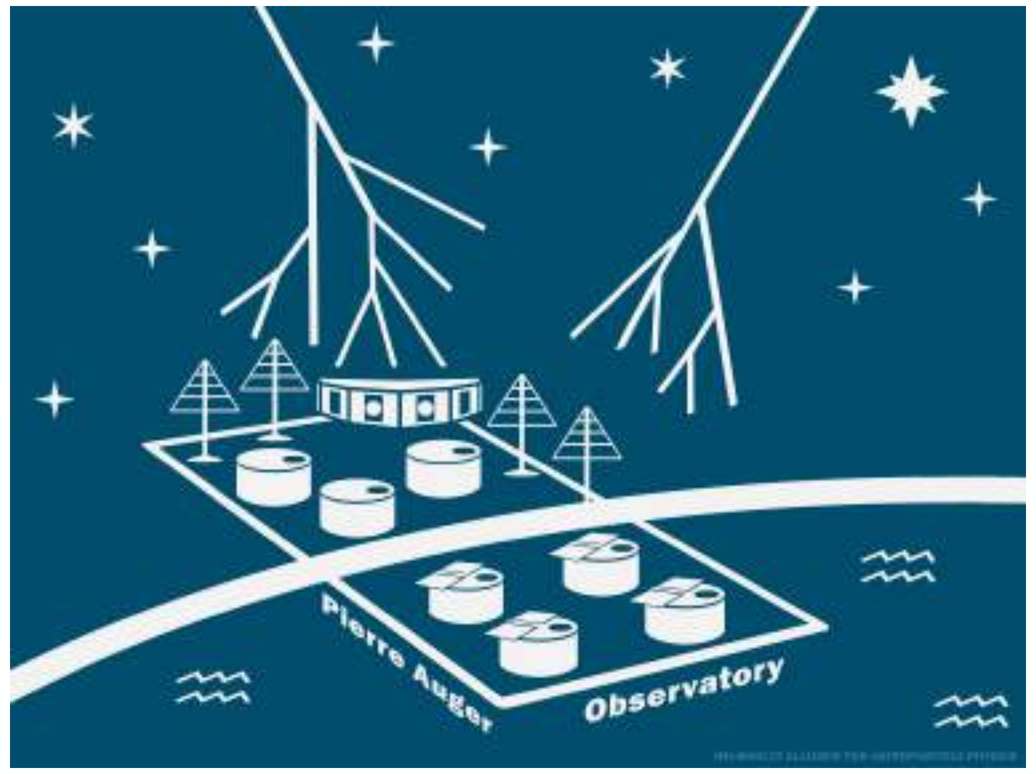


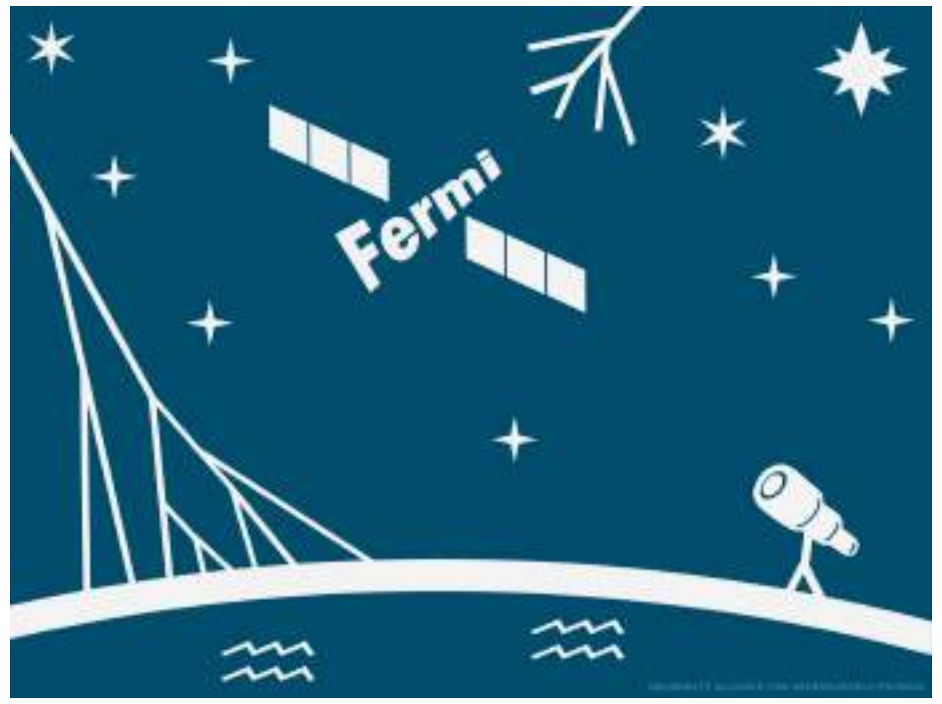


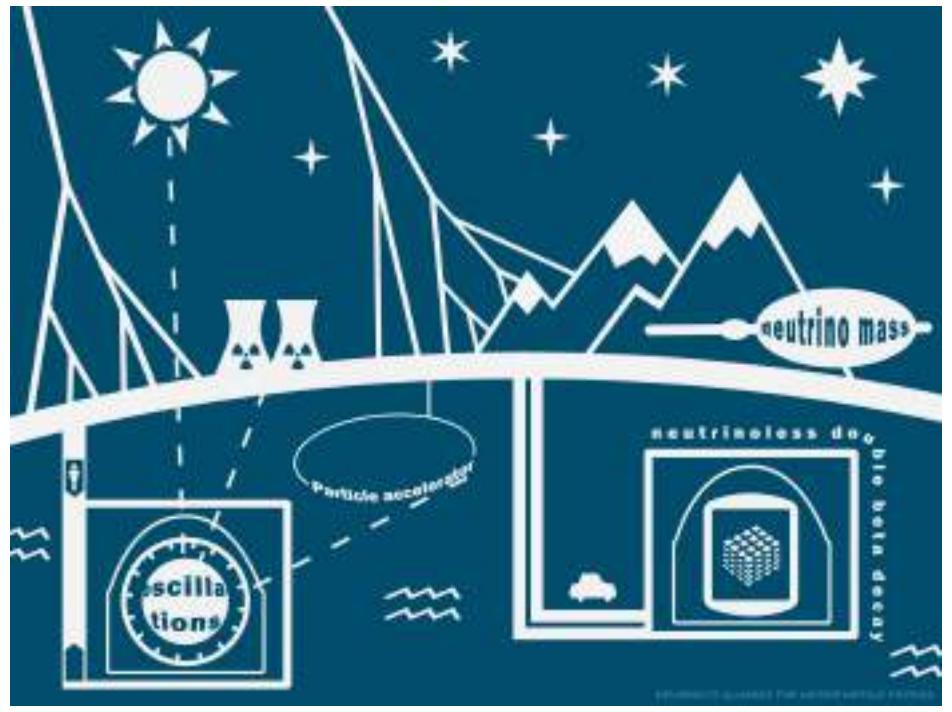




Thanks to all Observatories







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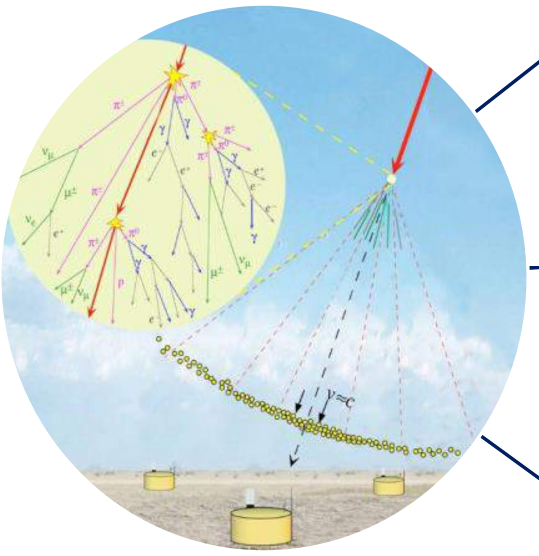

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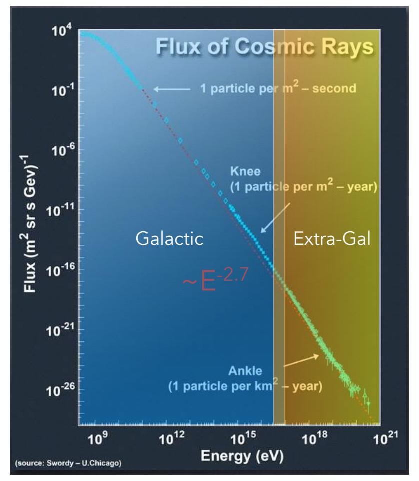

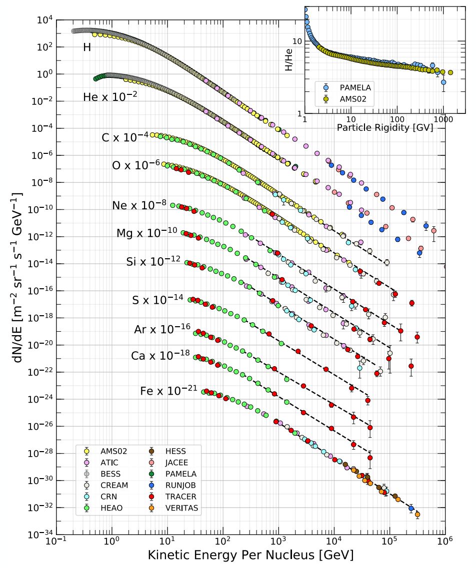

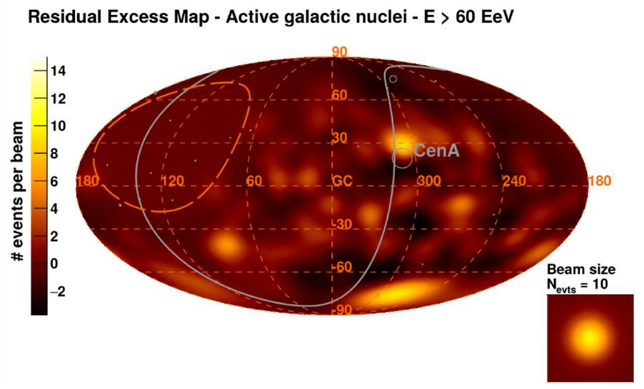

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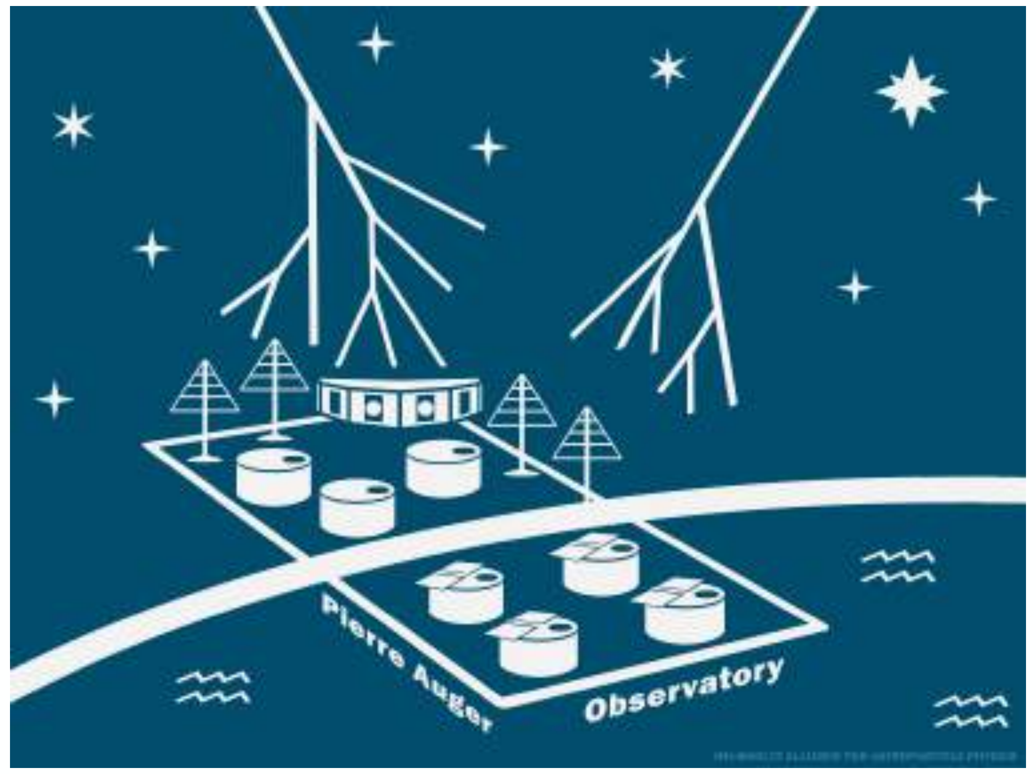

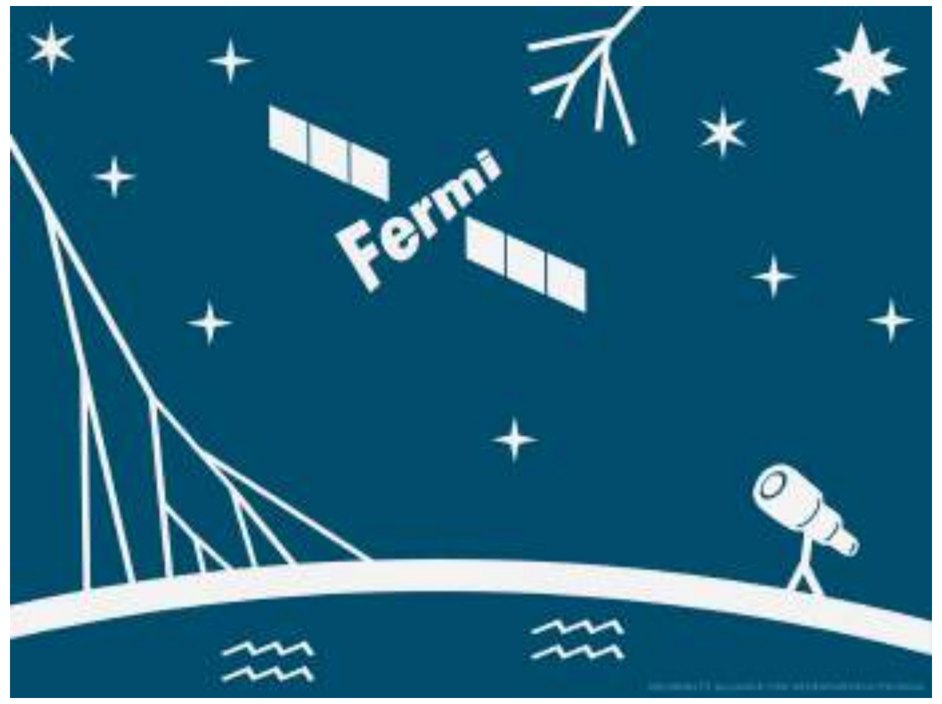

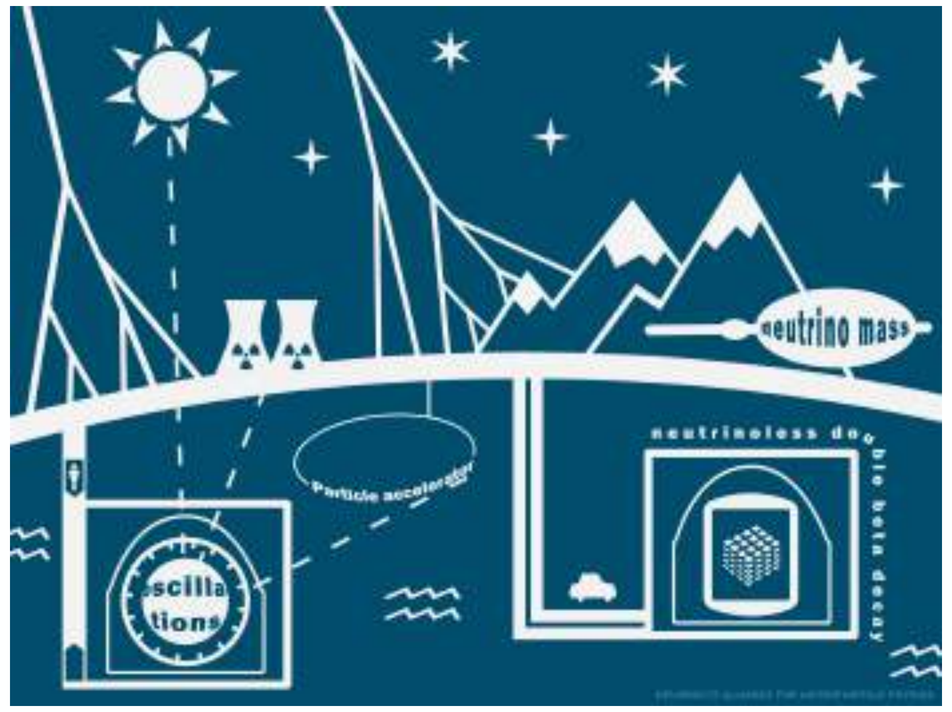

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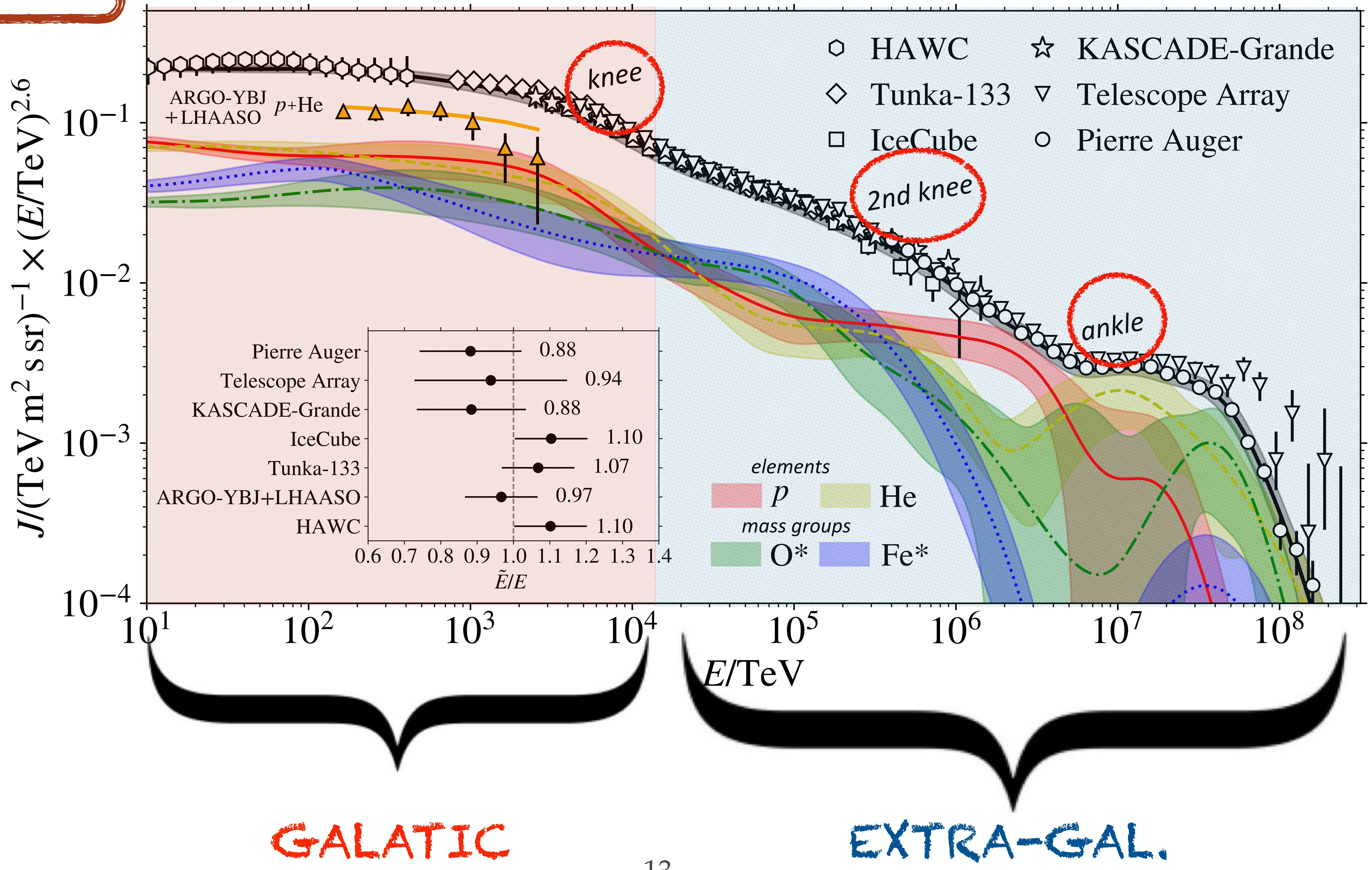
What do we know?



arXiv:1903.07713v1, arXiv:1301.6824

PAOl. Science 2017;357:1266-1270

Anjos et al 2018

Björn Eichmann, UHECR2018, Paris

• Motivation and State-of-the-art

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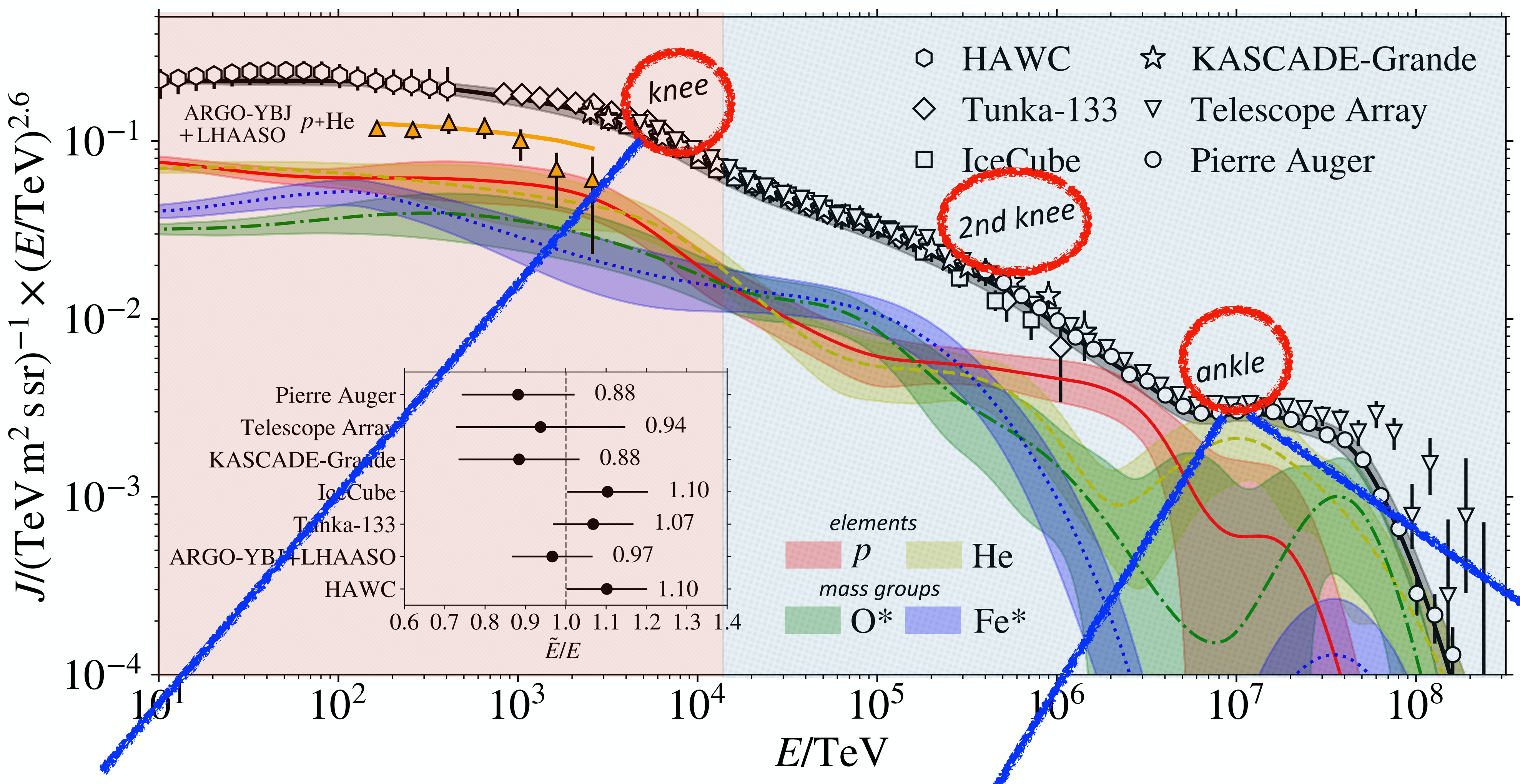

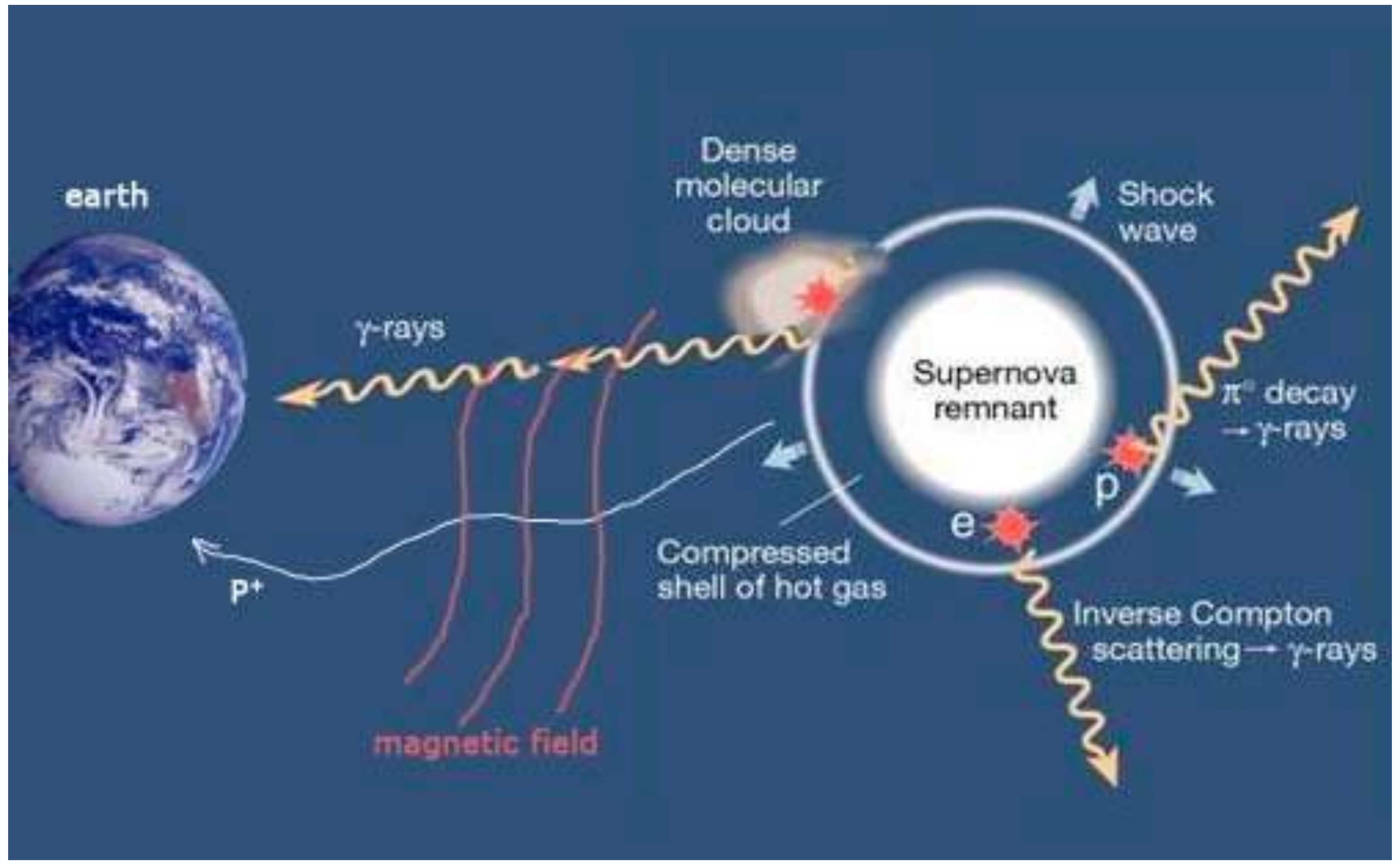

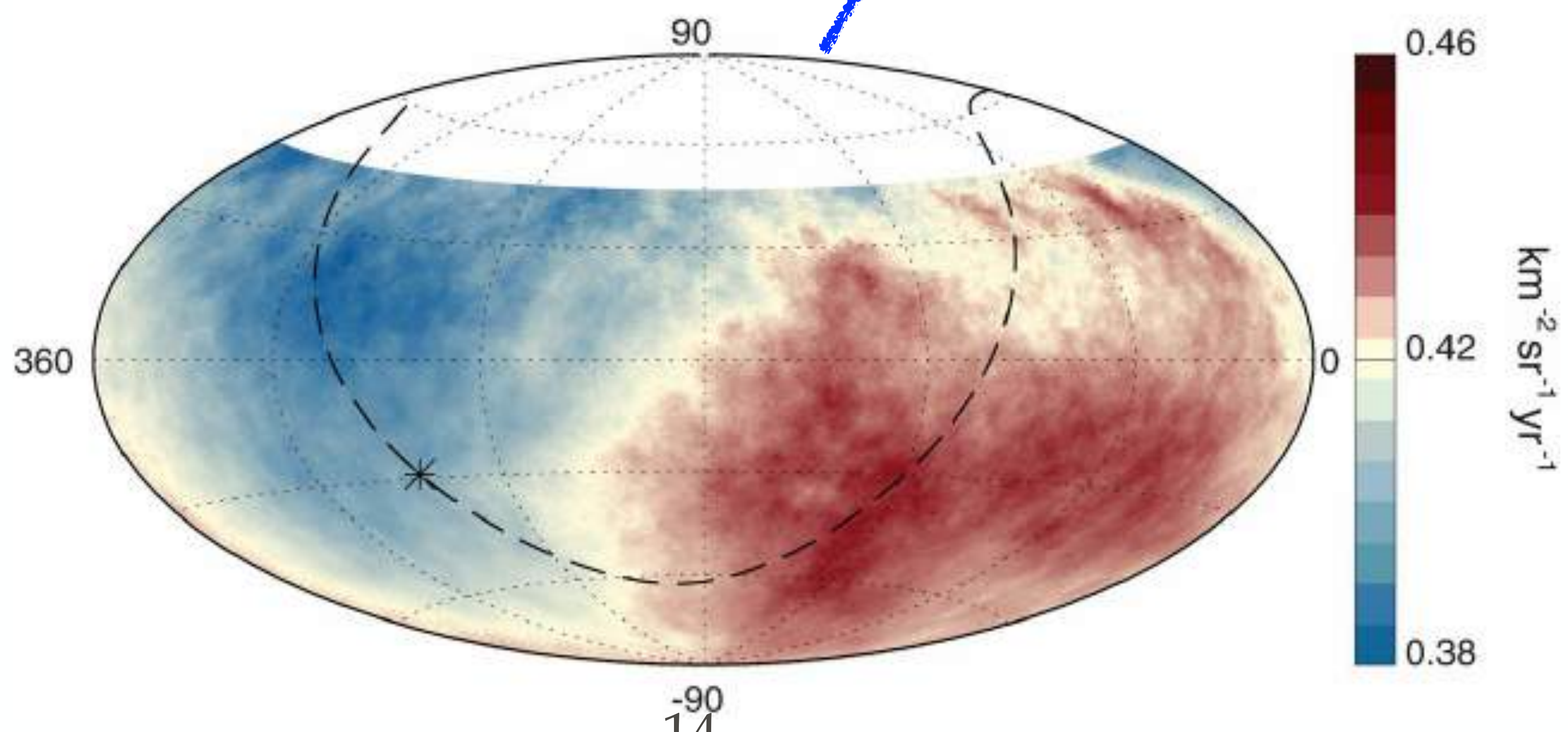

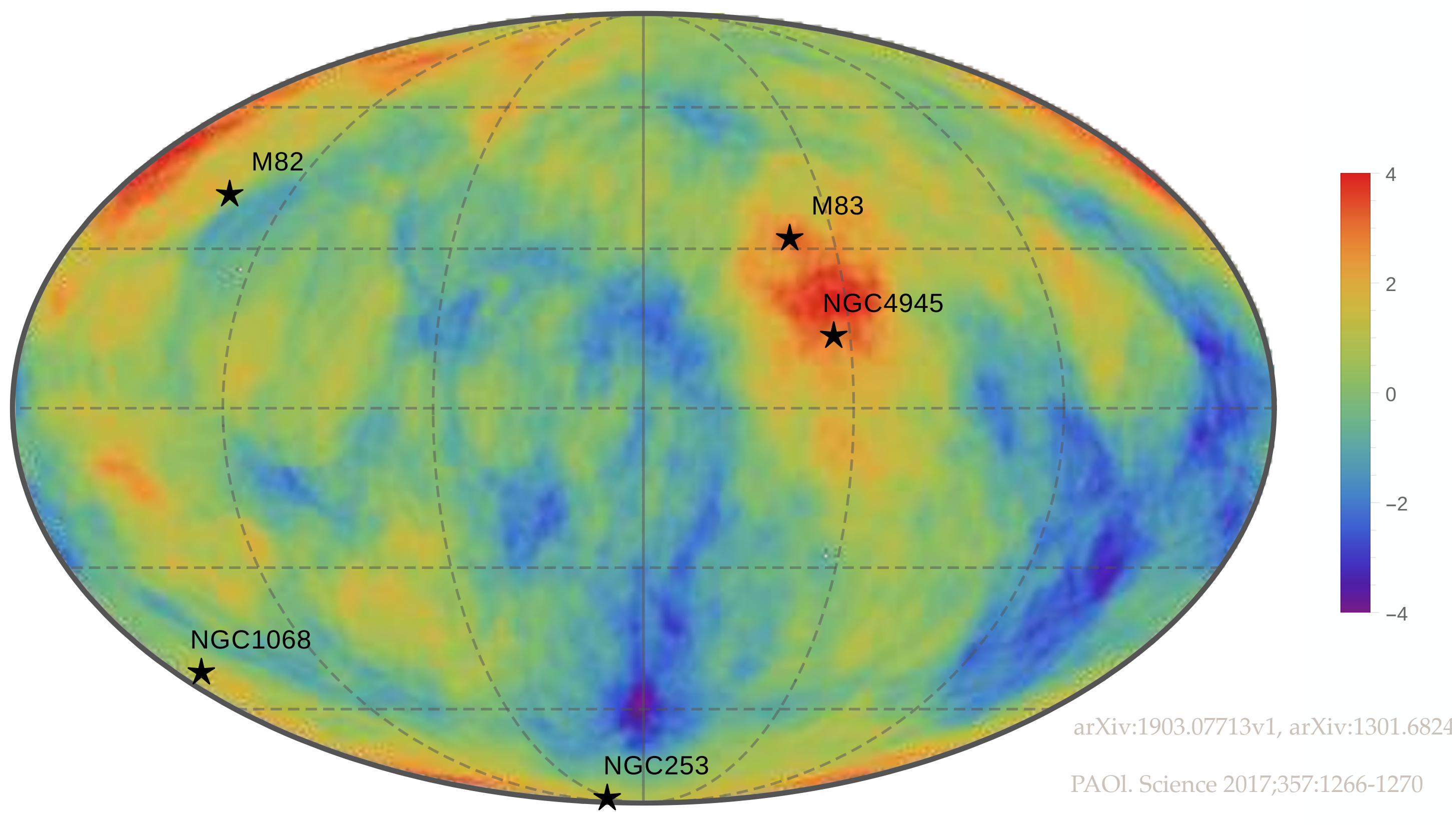

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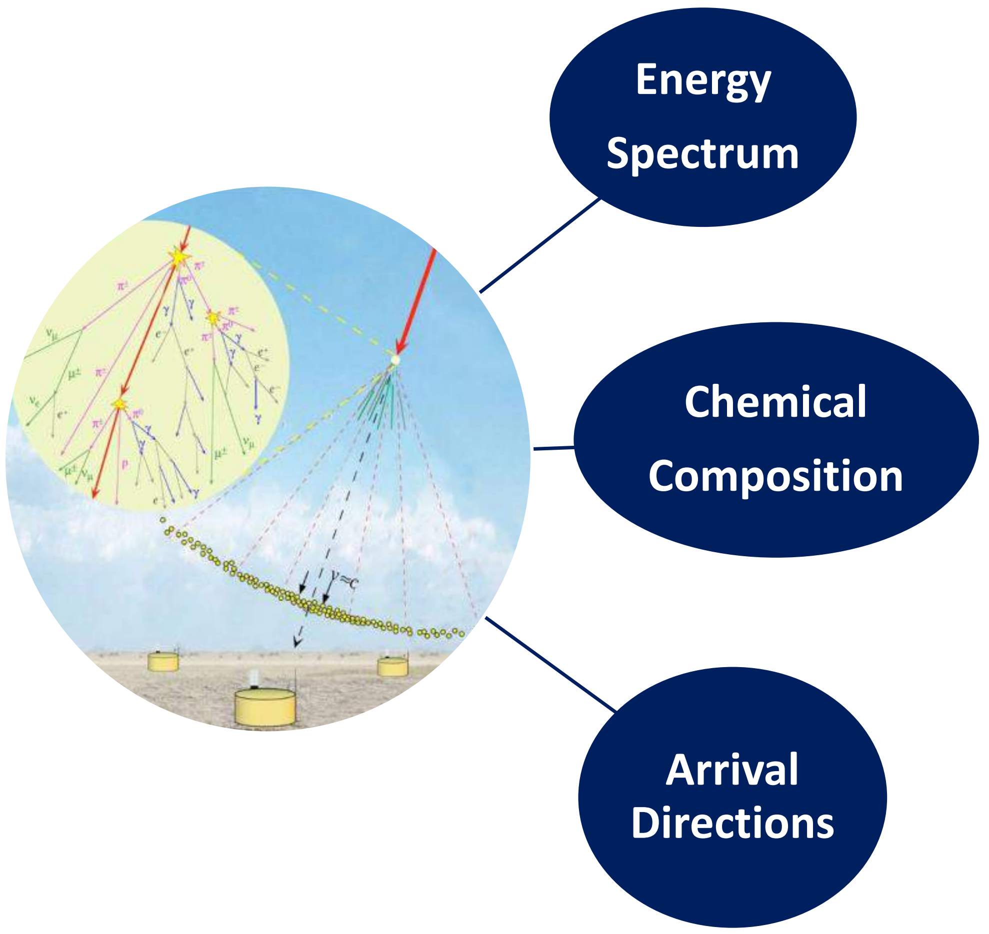

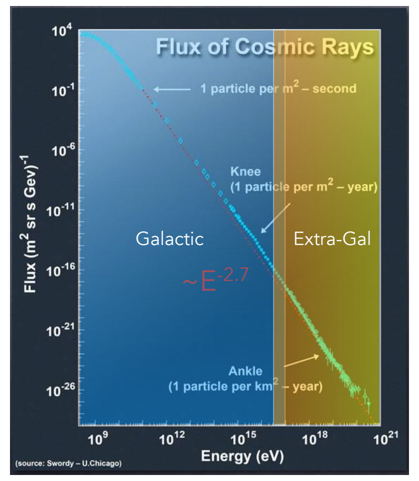

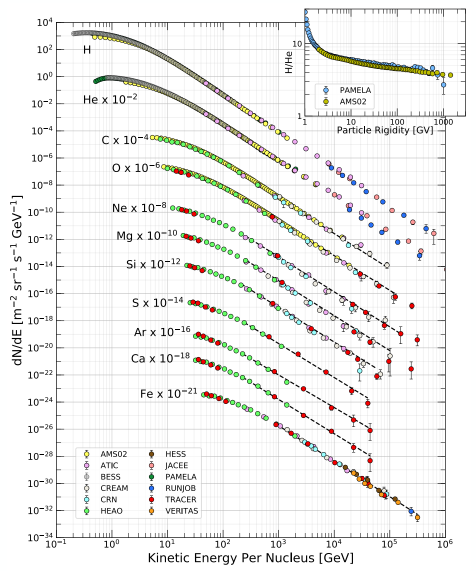

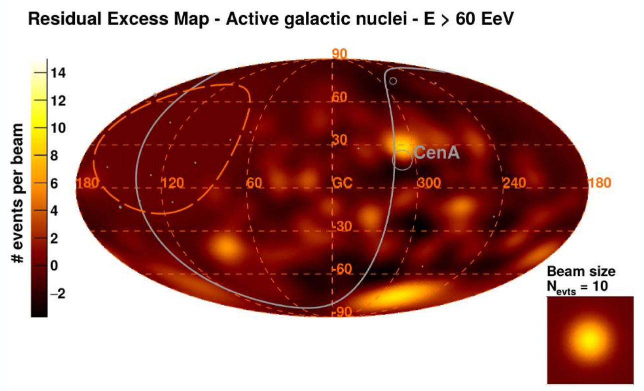

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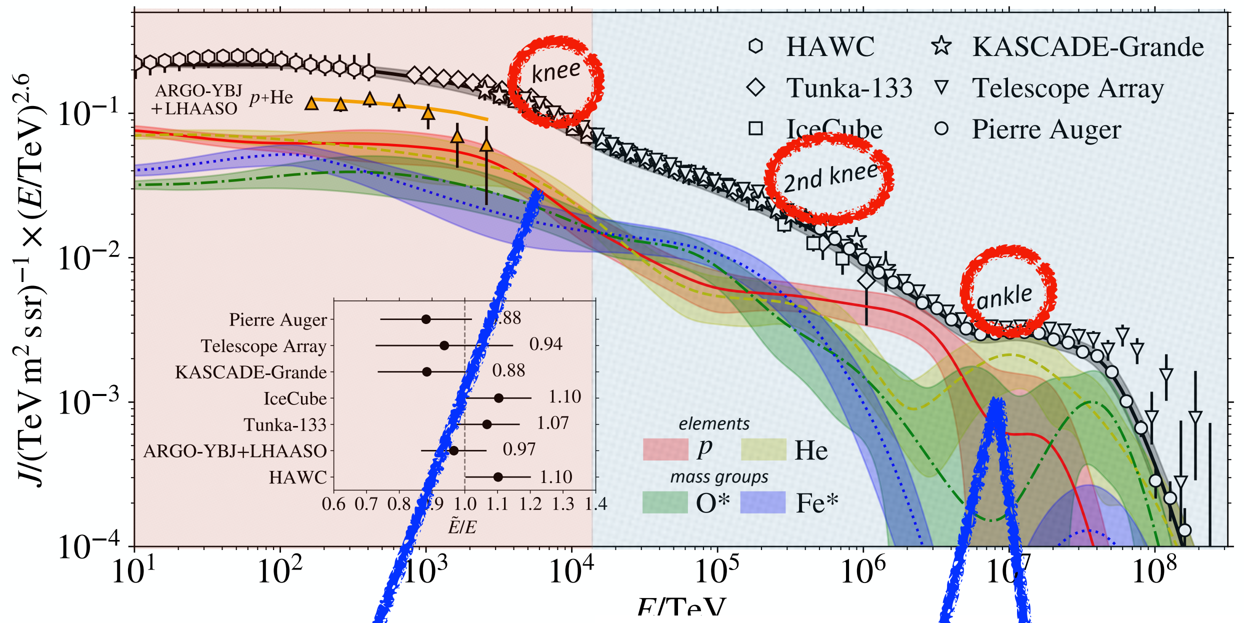

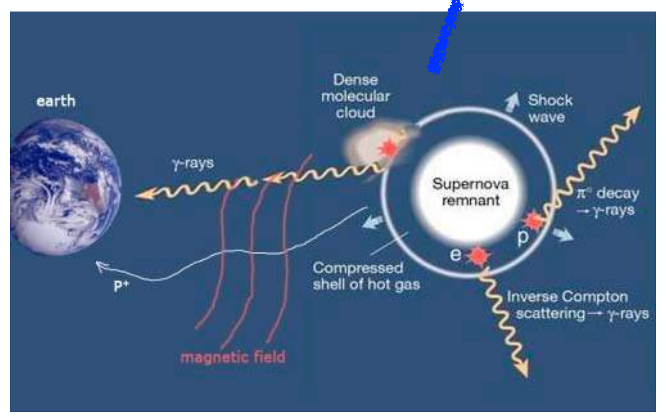

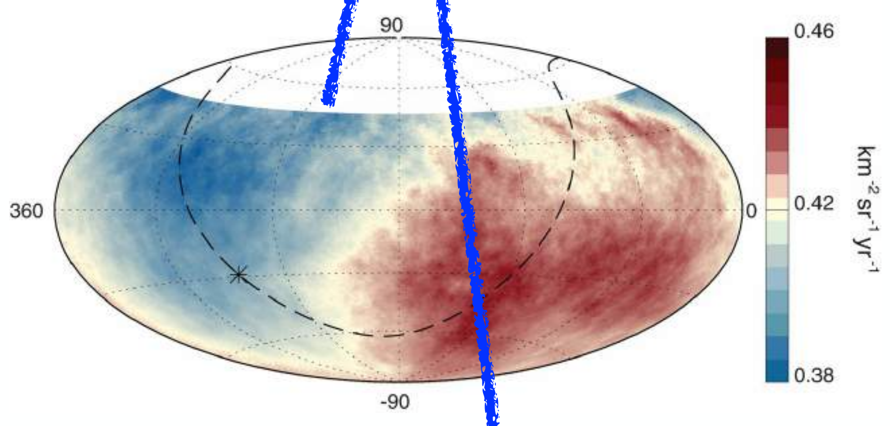

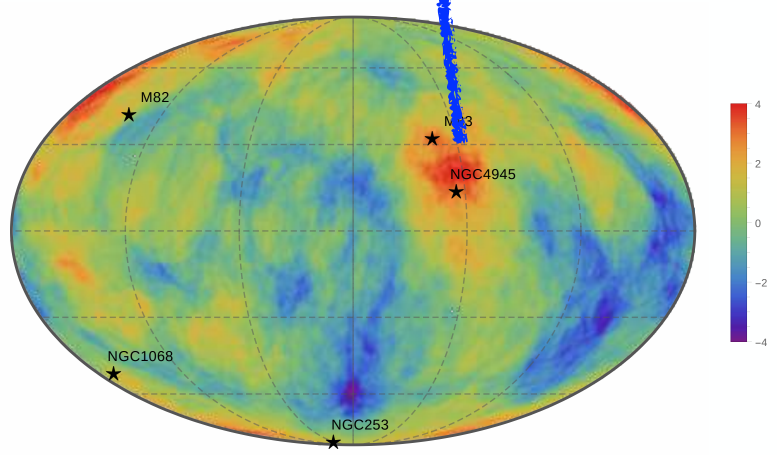

What do we want to answer?

- The big questions and goals
  1. What sources can accelerate CRs to PeV energies?
  2. How do SNRs contribute to Galactic CRs up to the knee?
  3. What physical processes are involved at PeVatrons and in their close environment?
  4. How do accelerated particles escape their accelerator?
  5. ……

arXiv:1903.07713v1, arXiv:1301.6824

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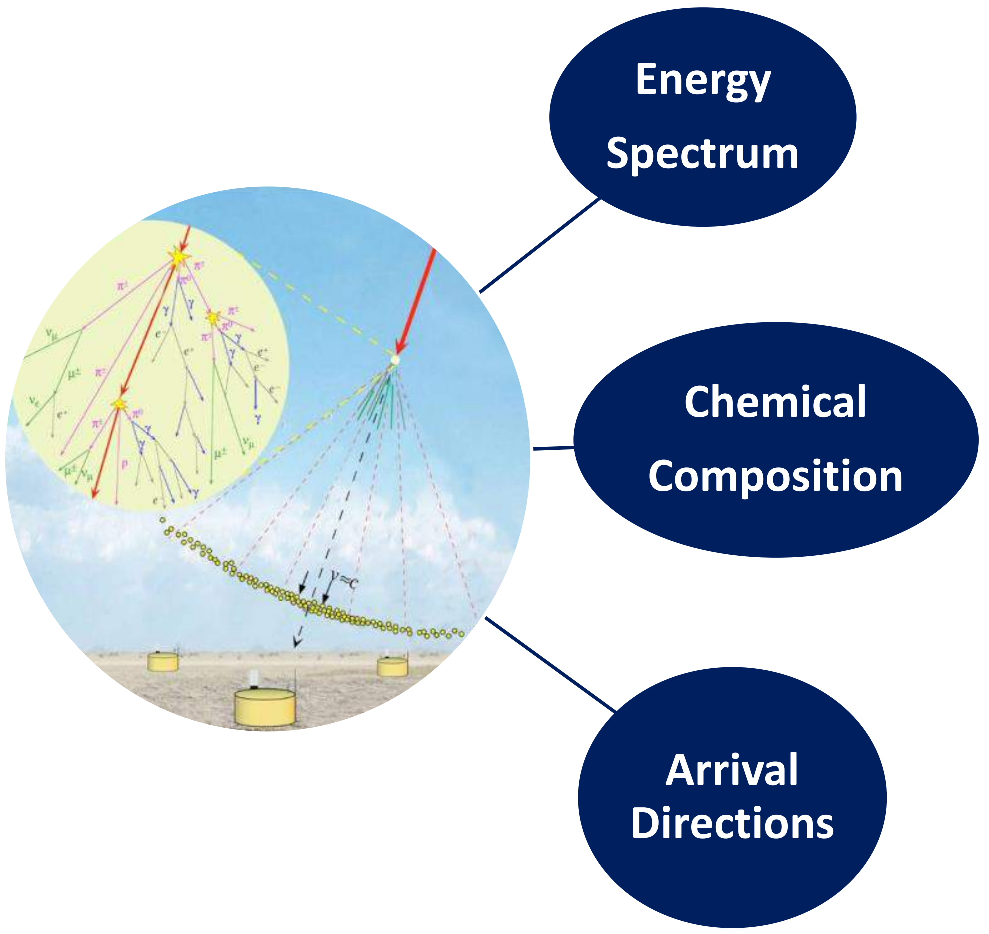
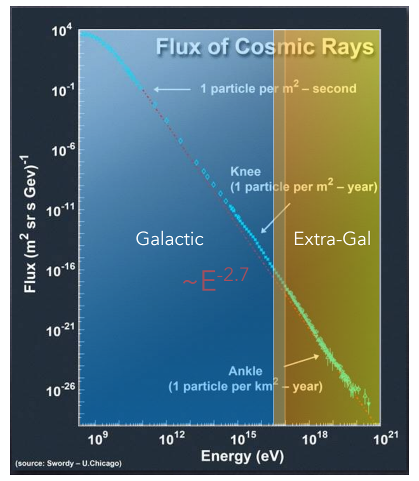
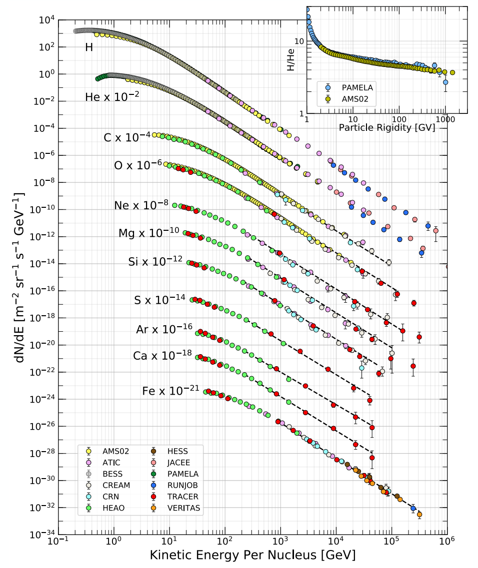
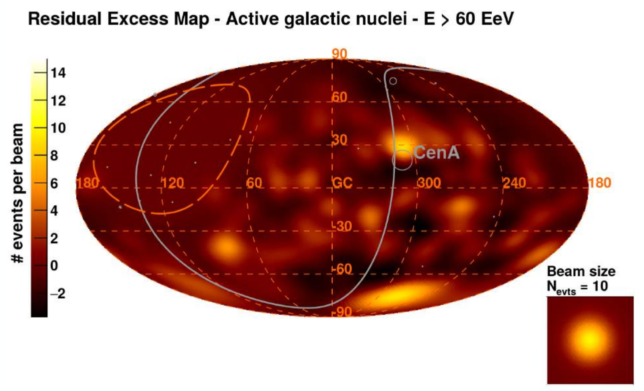
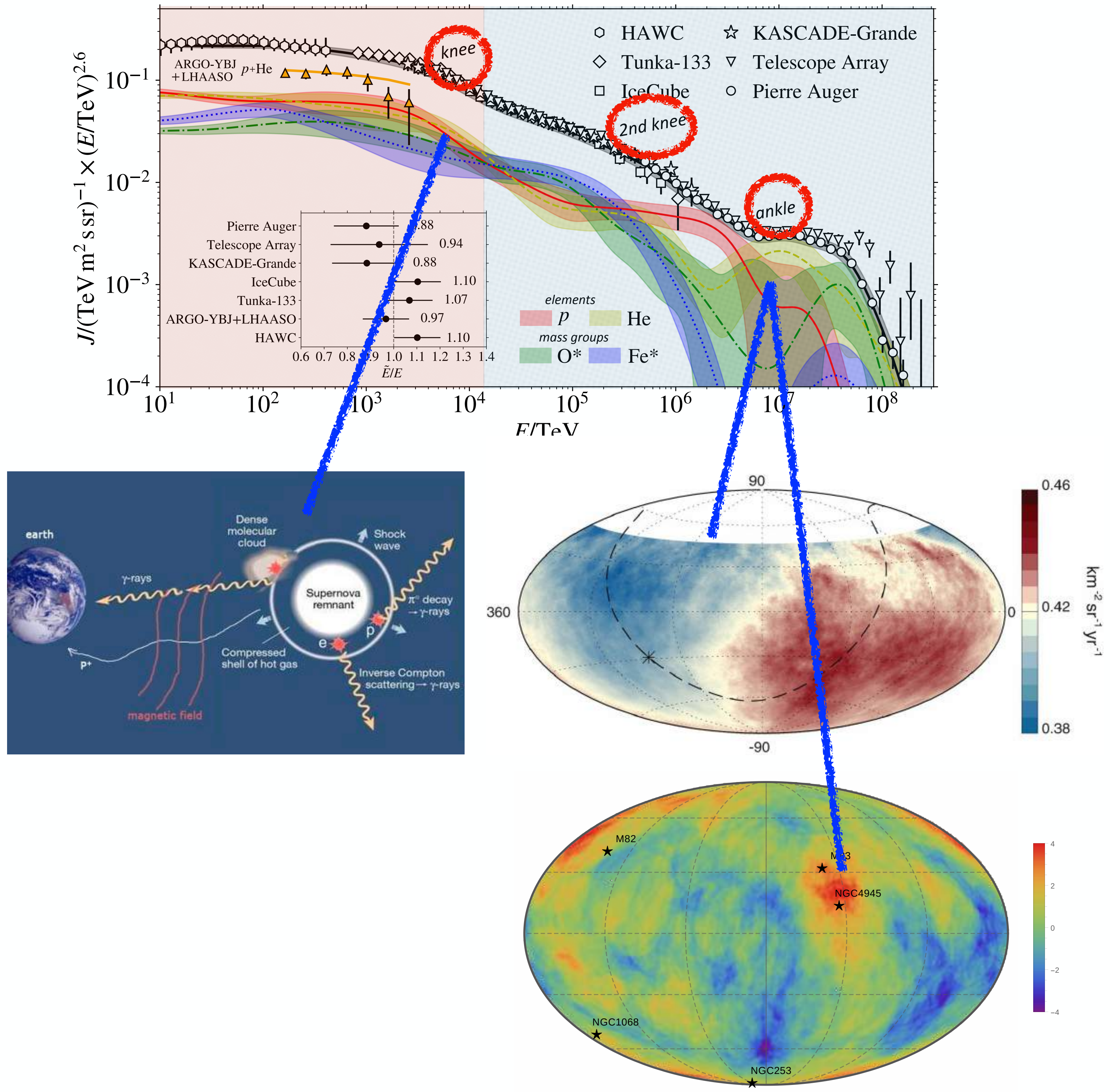








What do we know?



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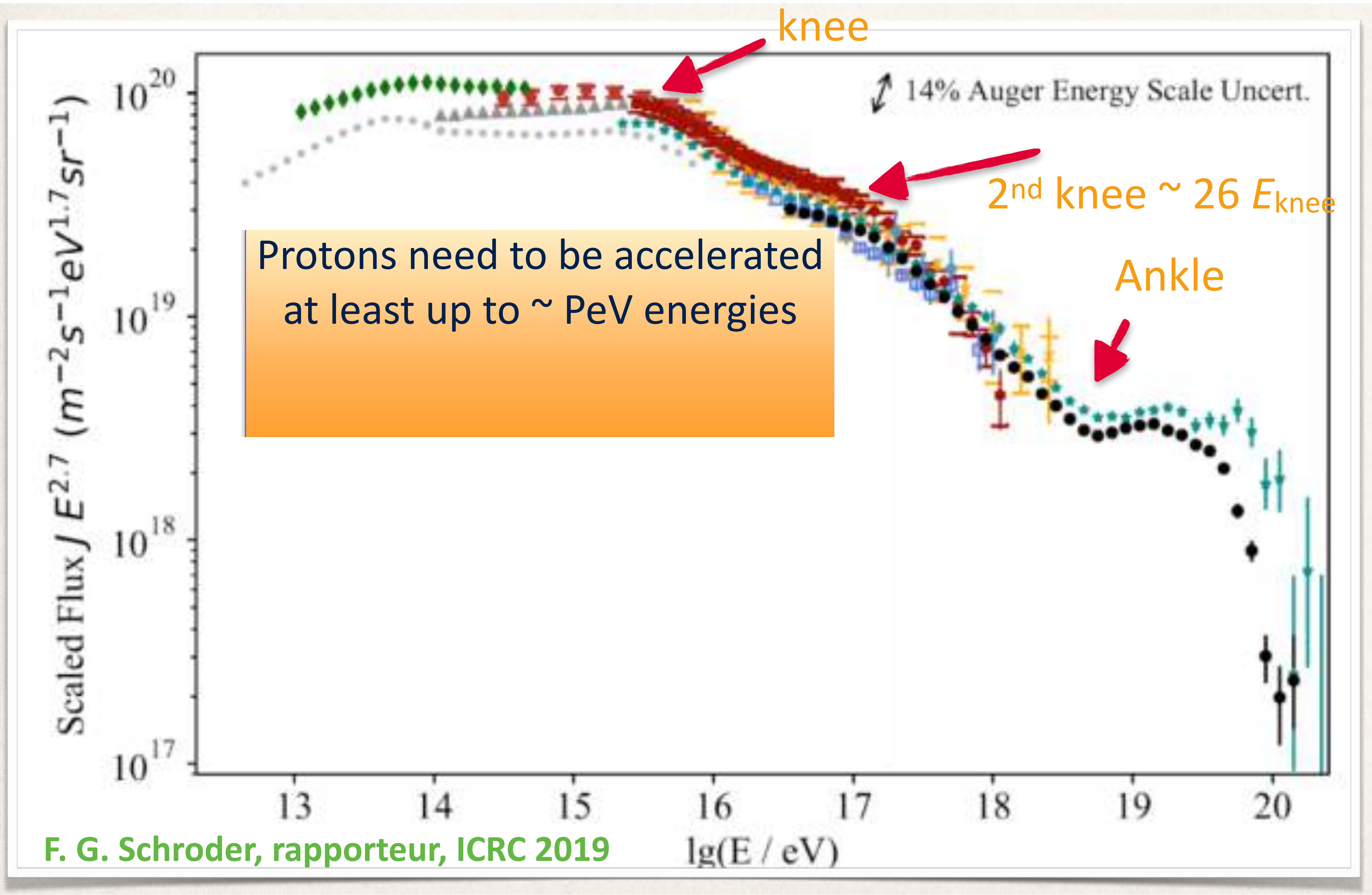
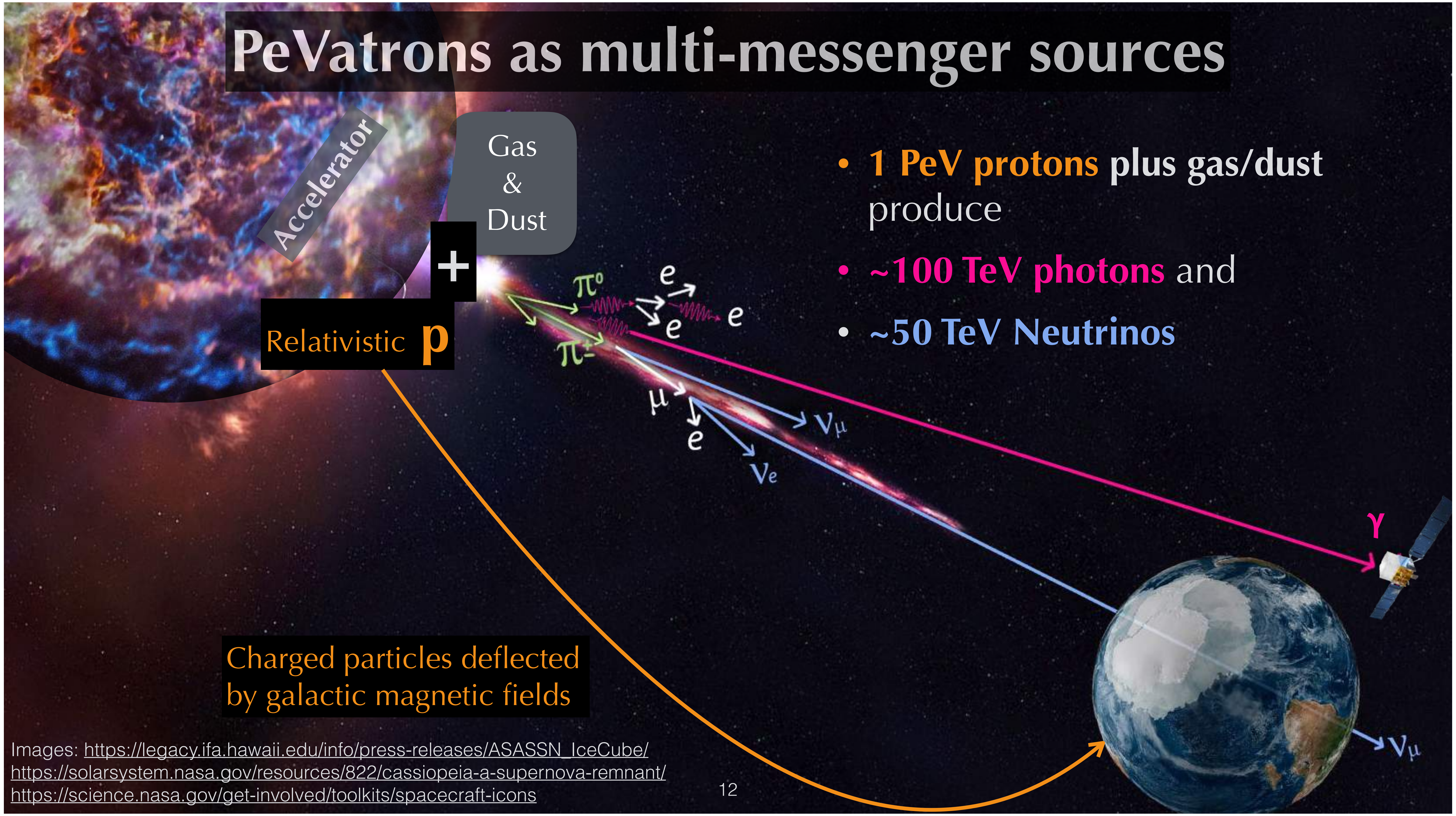
• What are PeVatrons?



PeVatrons are:

- Galactic CR sources
- accelerating protons to PeV energies (10^{15} eV)

- What are PeVatrons?



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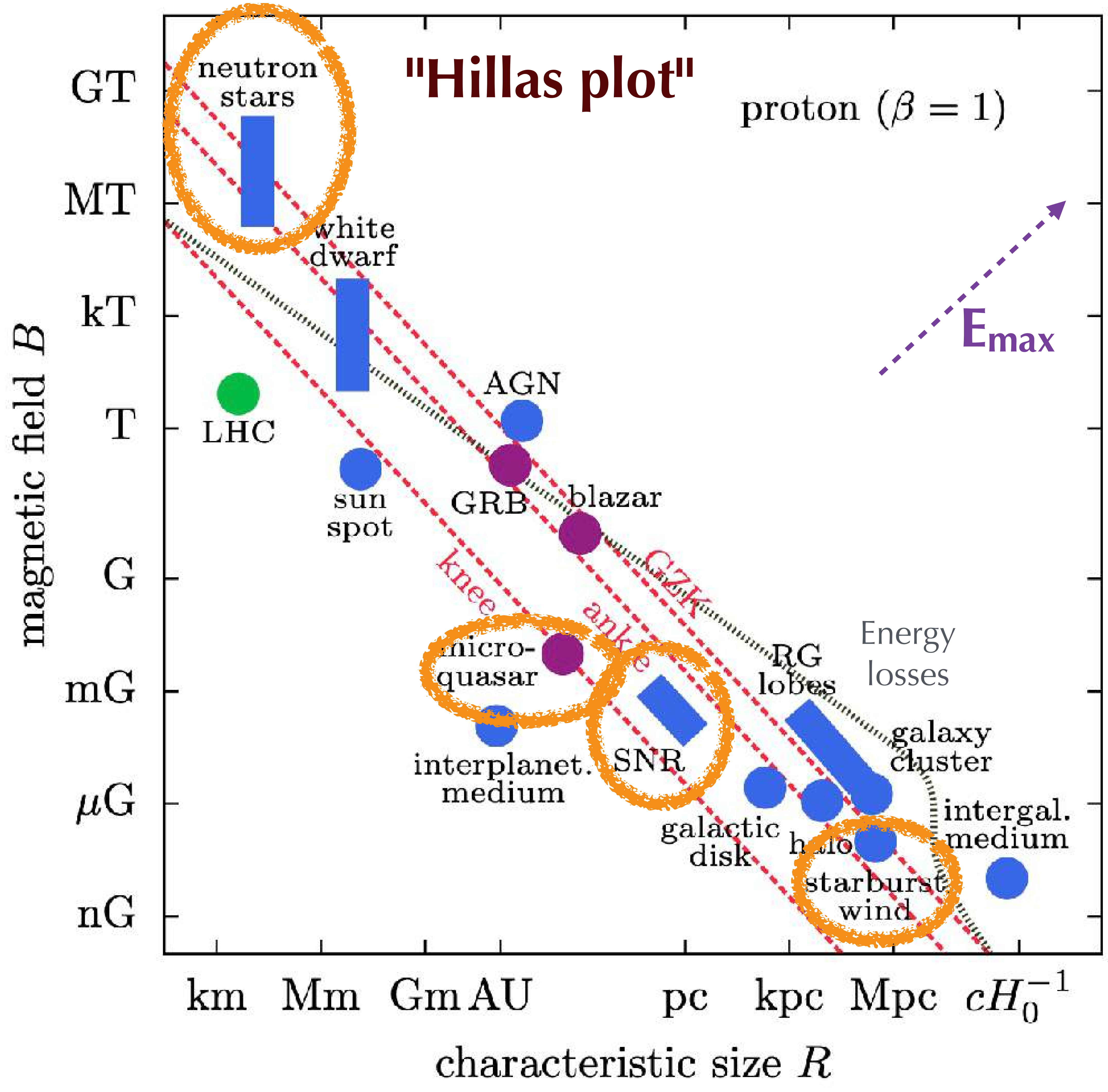
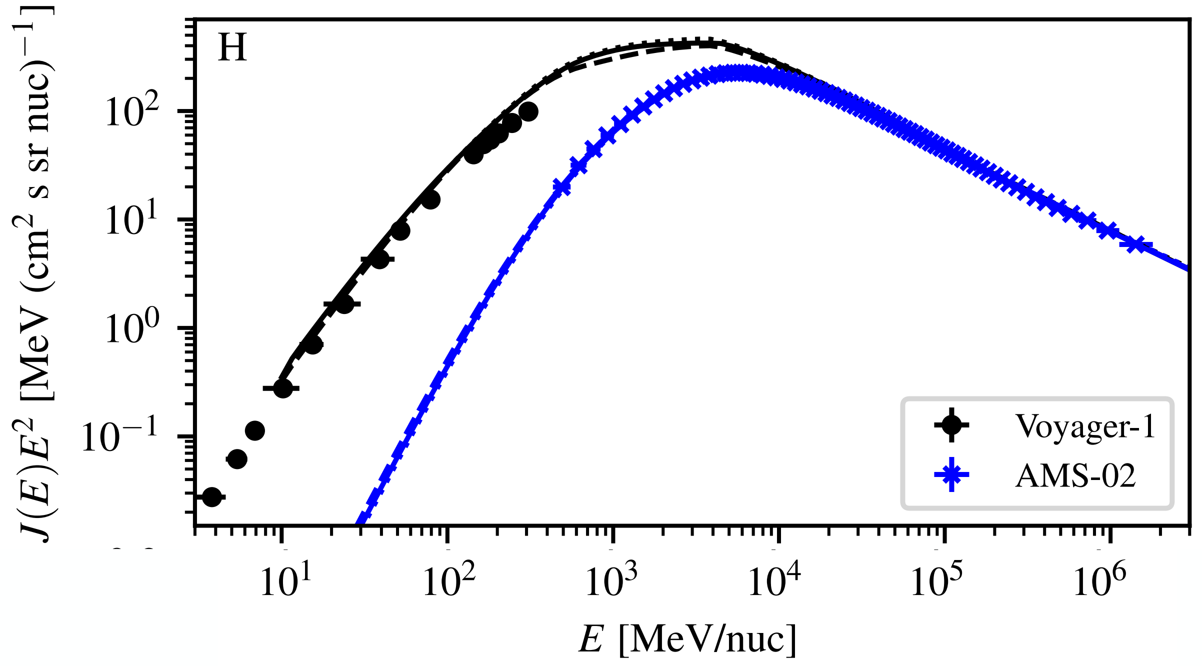
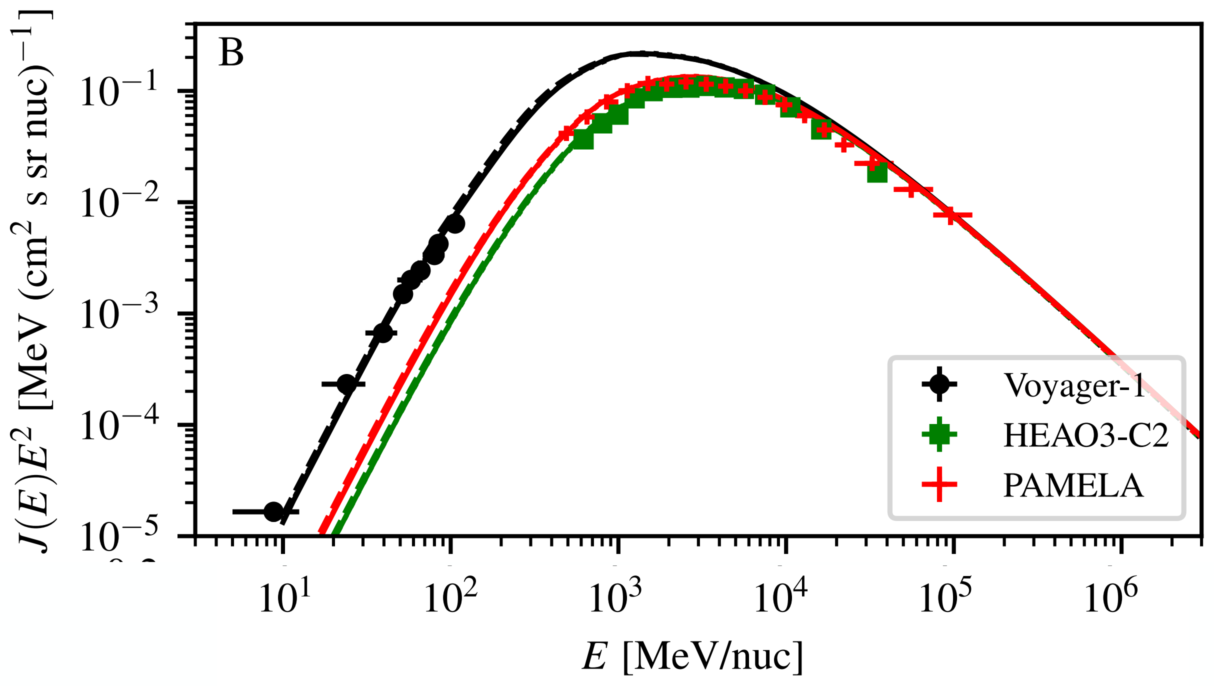


Candidates source classes:

- Supernova remnants

Tycho's SNR





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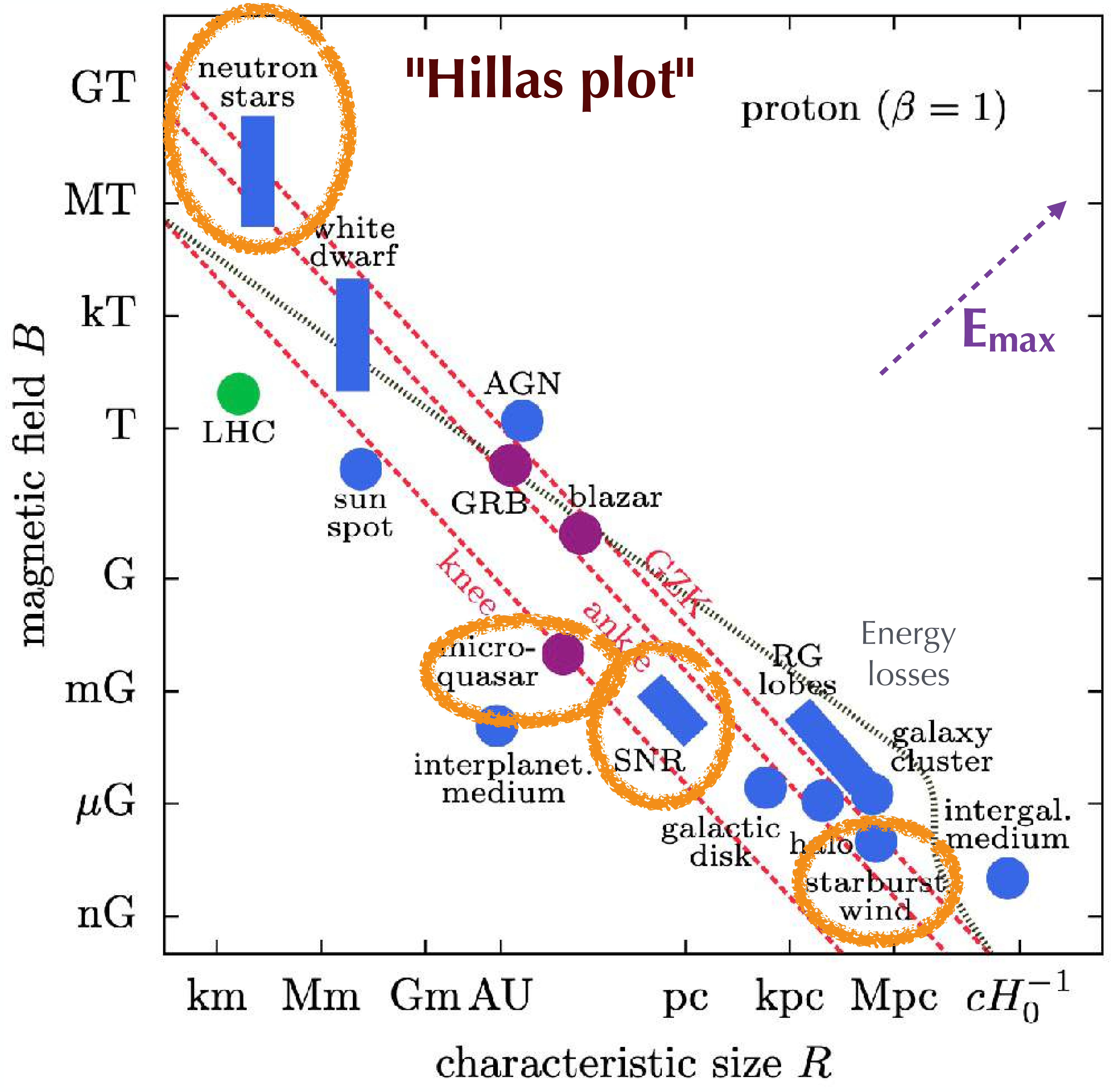
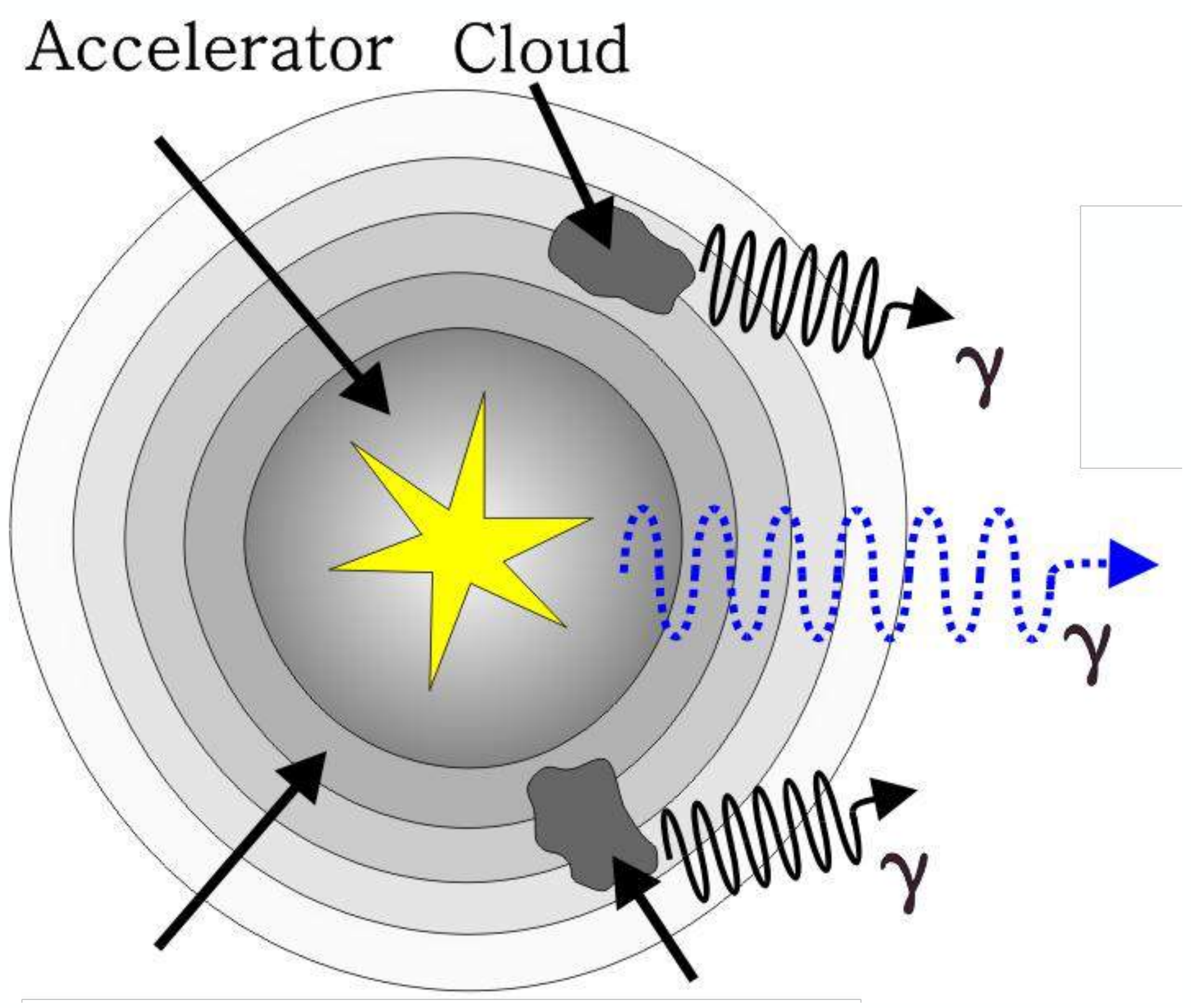


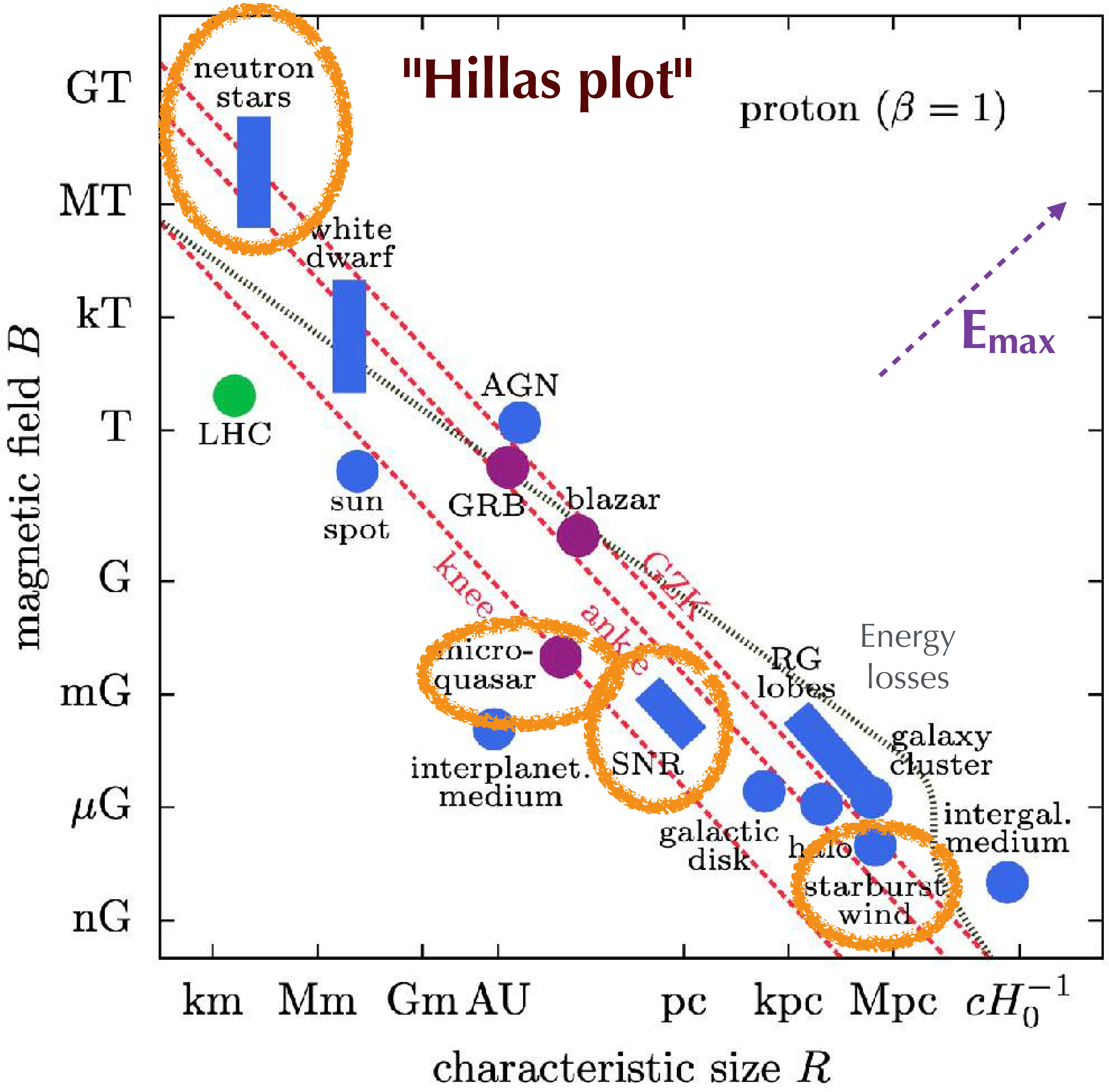
Candidates source classes:

- Pulsars and pulsar wind nebulae



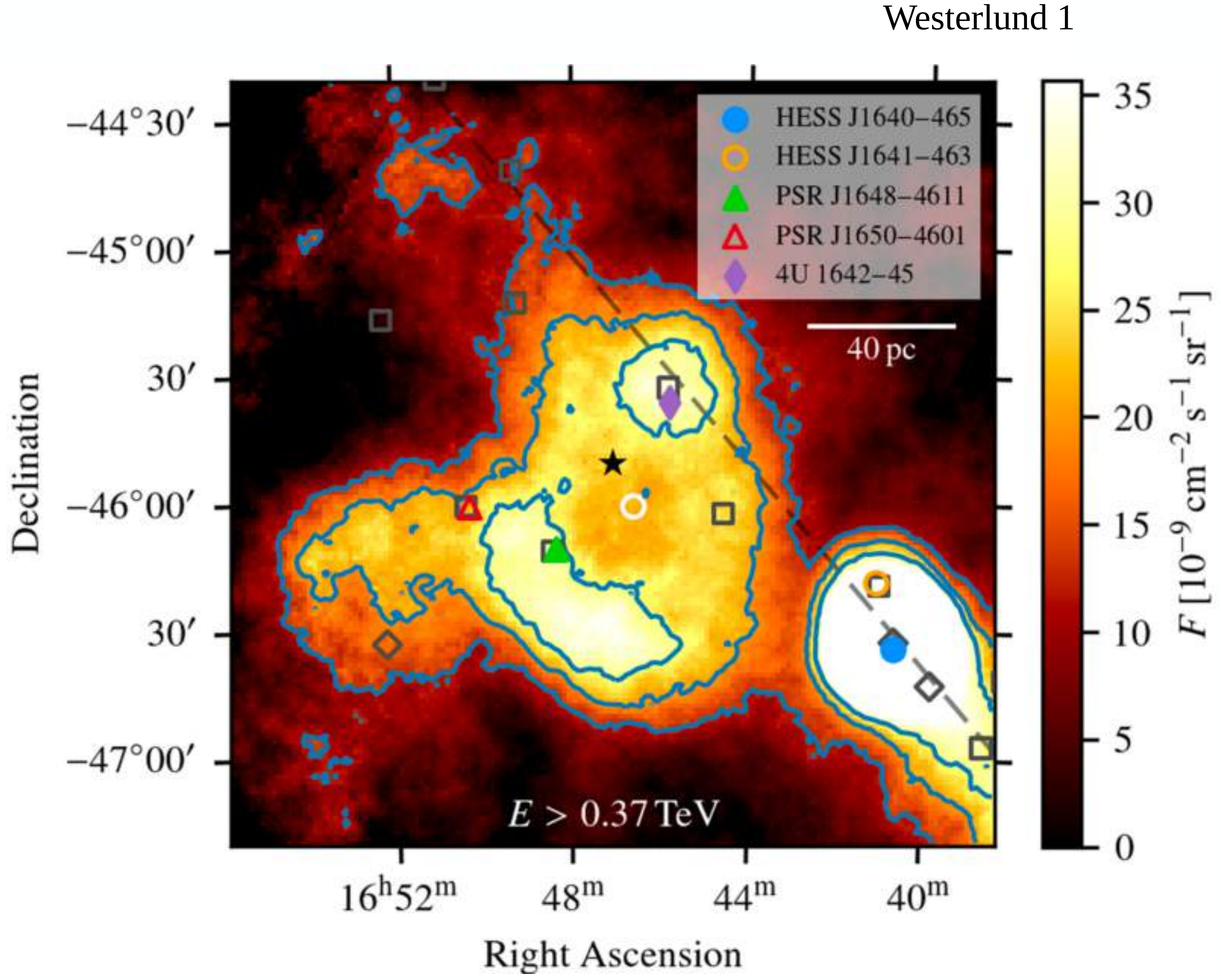
Slide Henrike Fleishhack

- # What are PeVatrons?



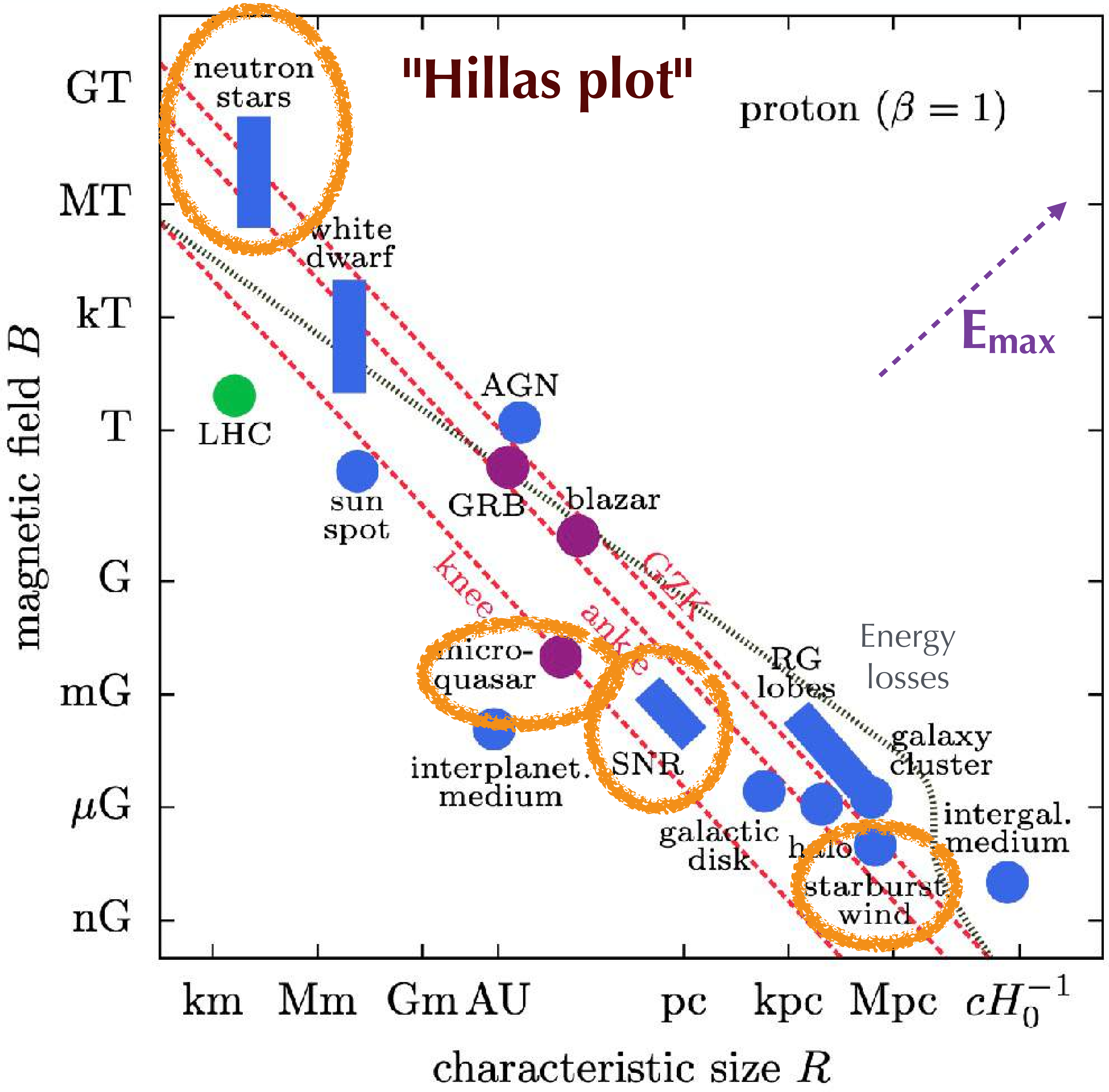
Candidates source classes:

- Starforming regions



Gamma-ray map of the HESS J1646–458 region

• What are PeVatrons?



Requirements:

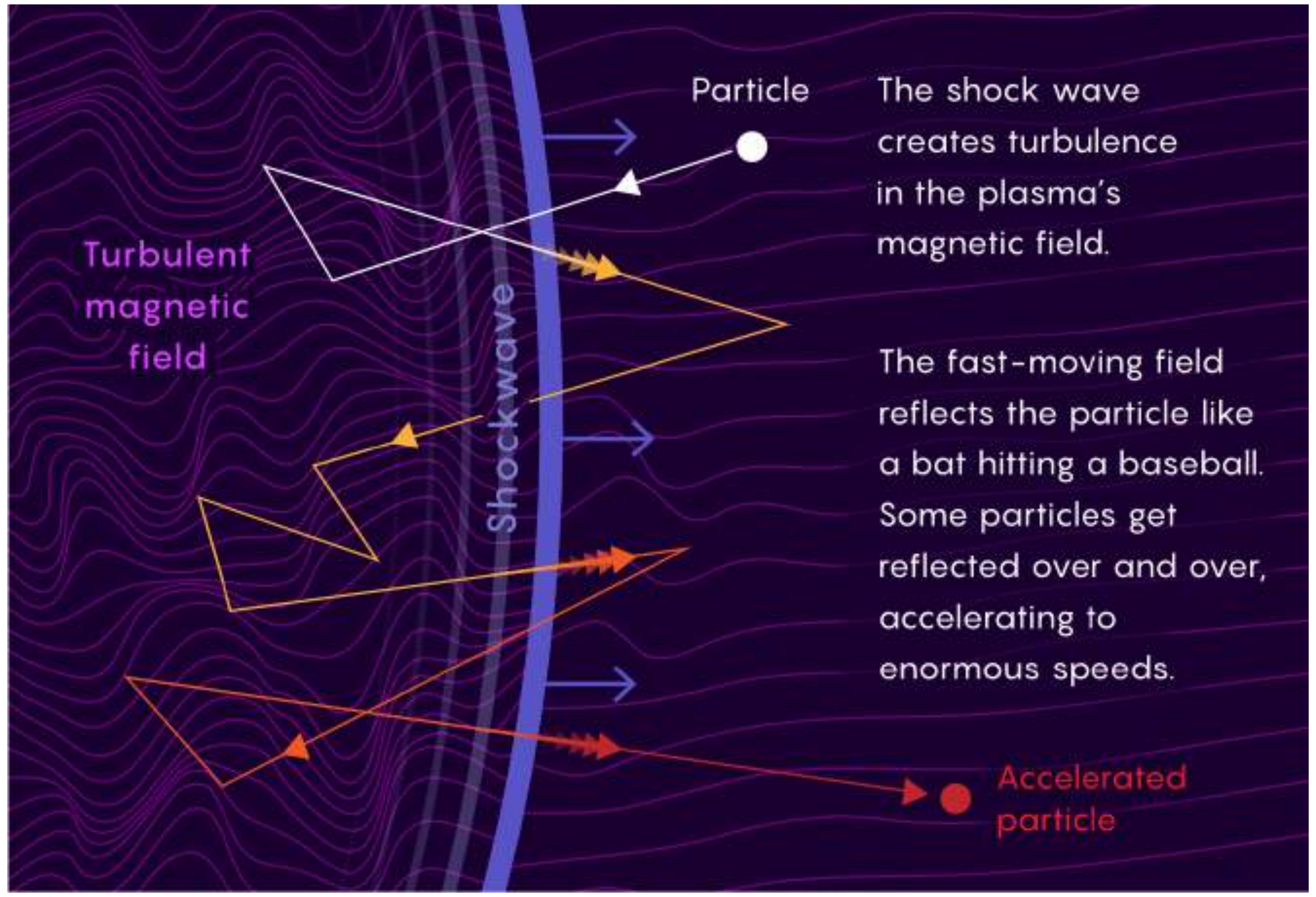
- Engine: Shocks
- Fuel: Charged particles
- Container: magnetic field (confinement)

• Cosmic-ray acceleration in SNRs

SNRs likely produce the bulk of Galactic CR:

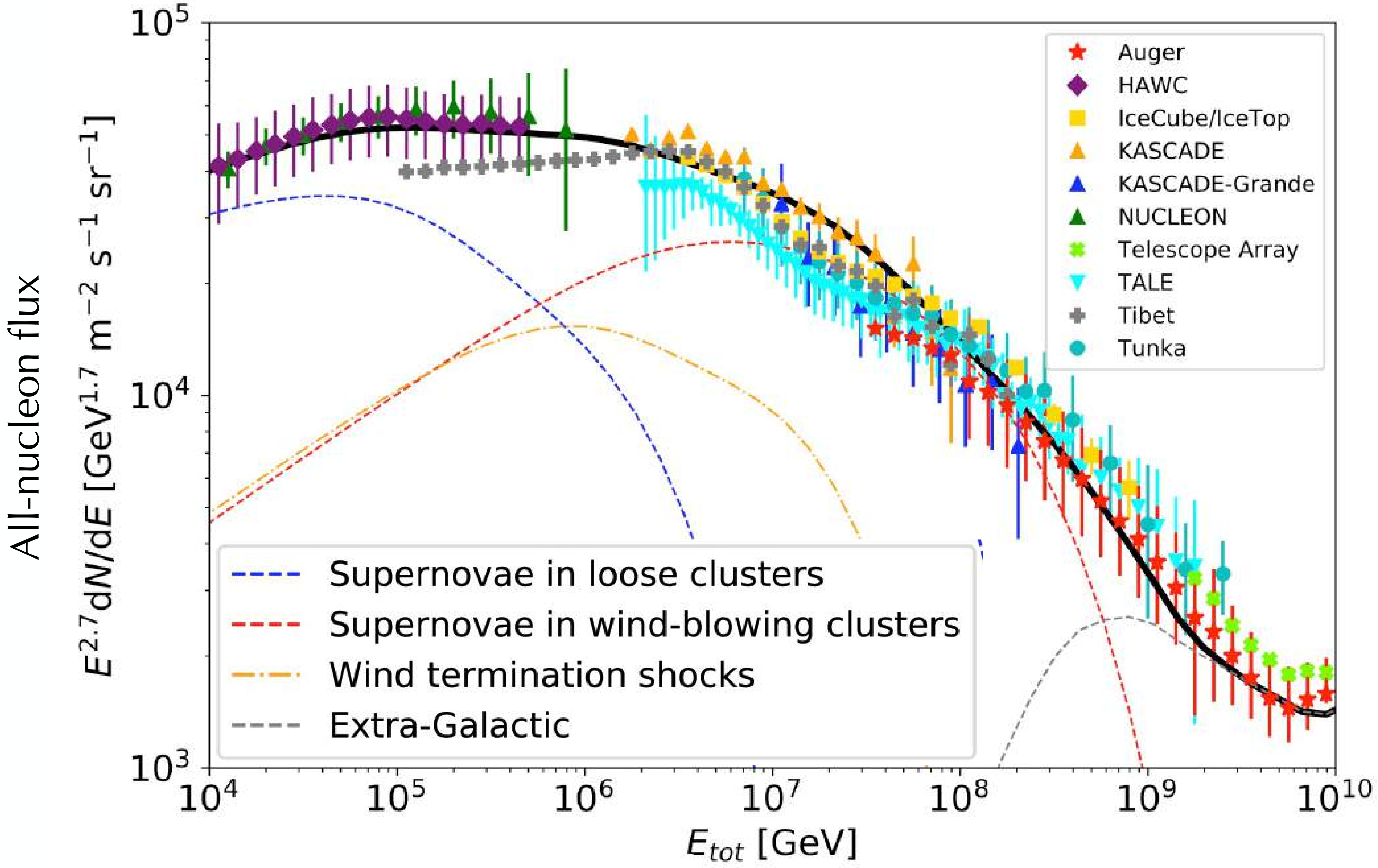
- Strong shocks → diffusive shock acceleration - I order Fermi acceleration
- Isolated SNRs can accelerate CR up to TeV energies.

Cas A



• Cosmic-ray acceleration in SNRs

SNR shocks within massive star clusters can reproduce the knee and 2nd knee



T. Vieu, B. Reville 2022: https://doi.org/10.1093/mnras/stac3469

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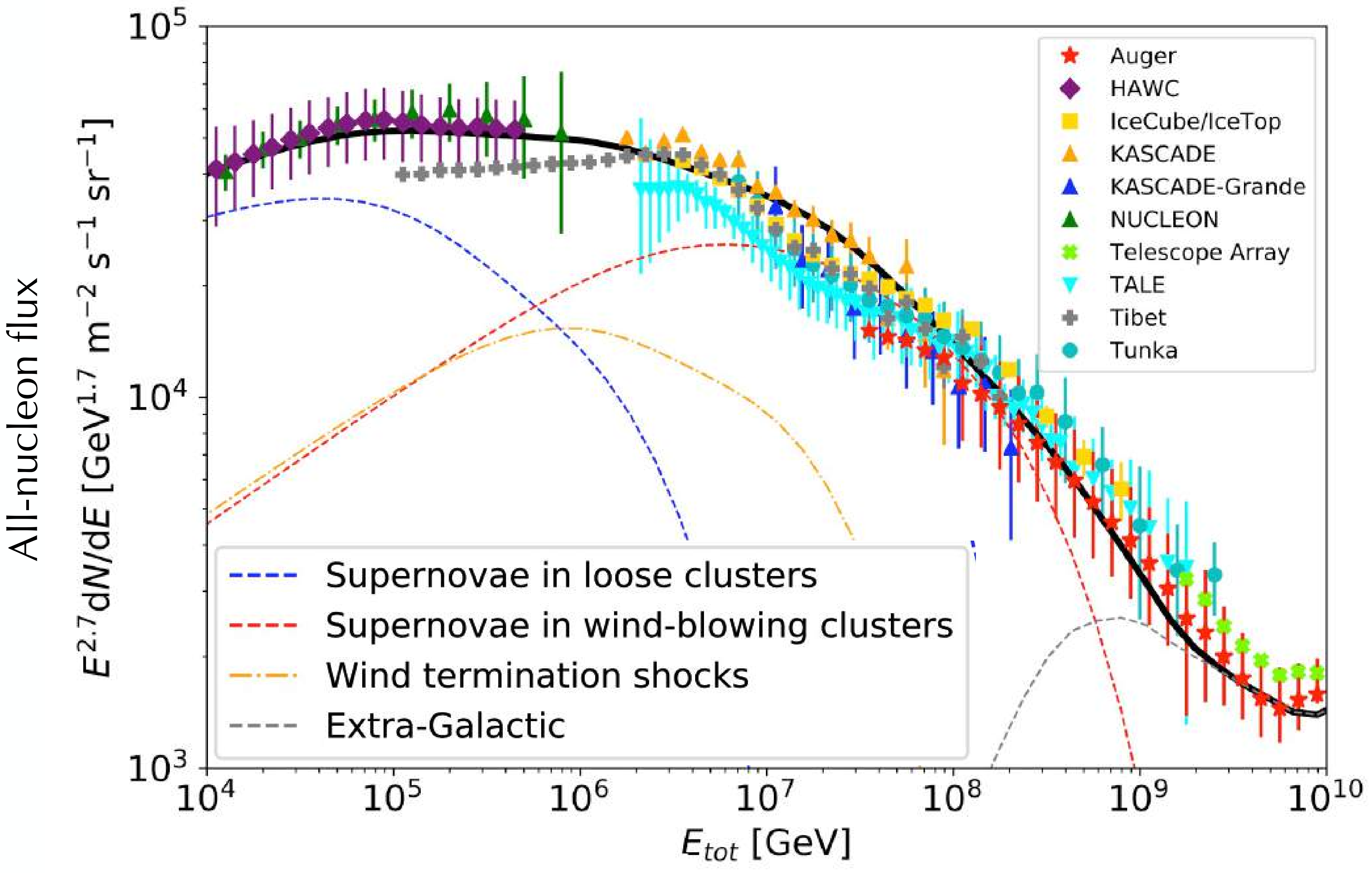

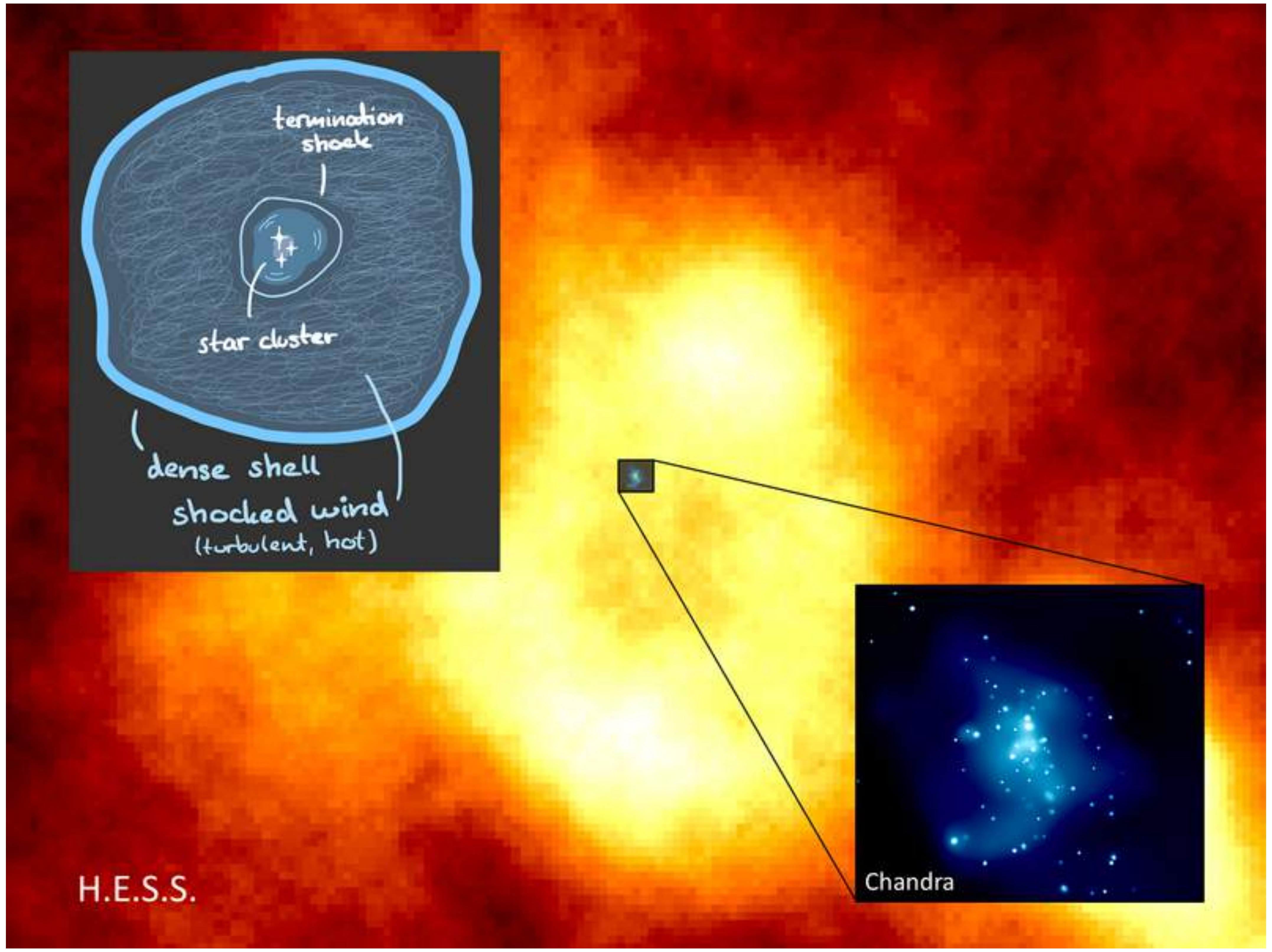

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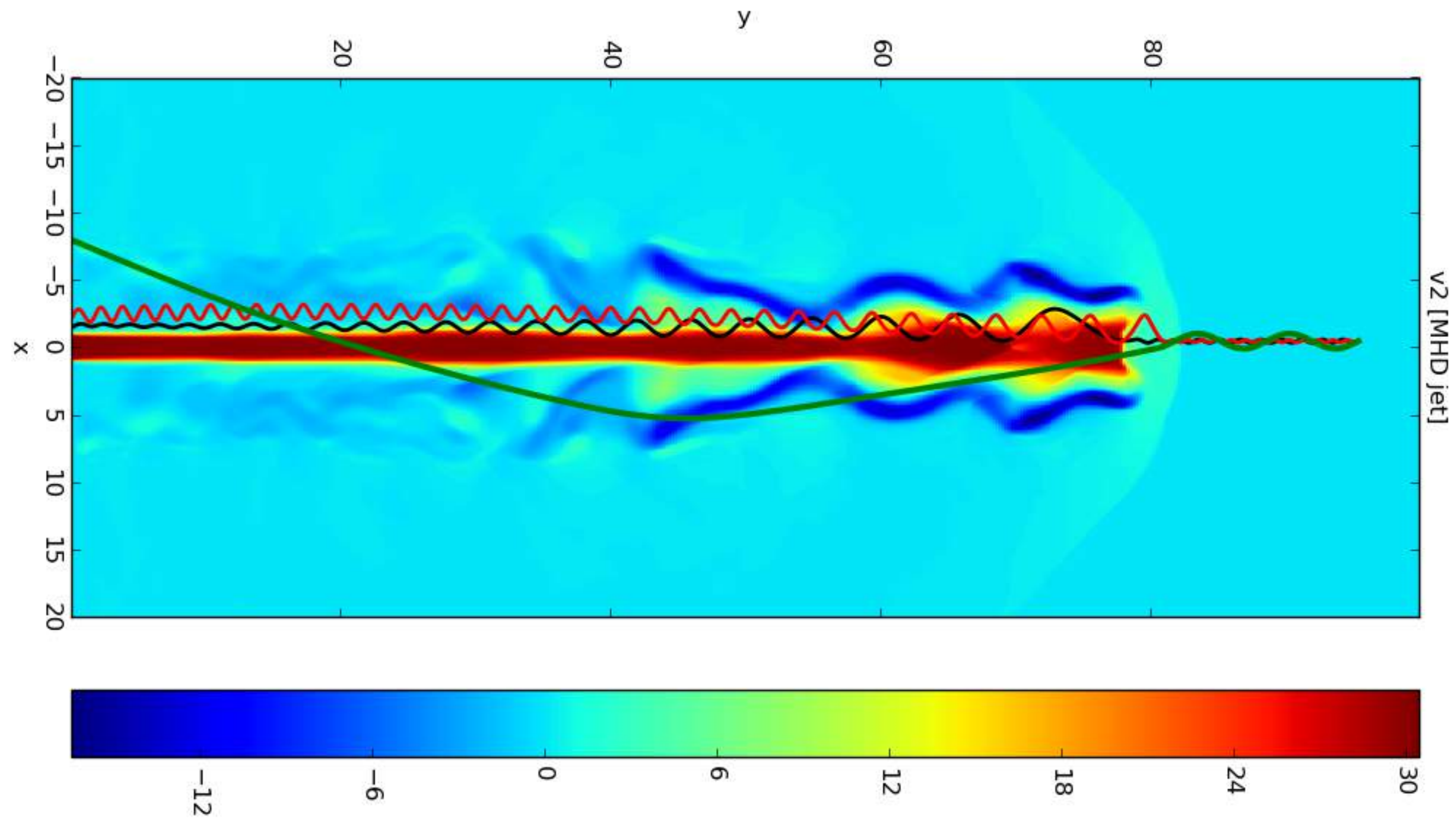
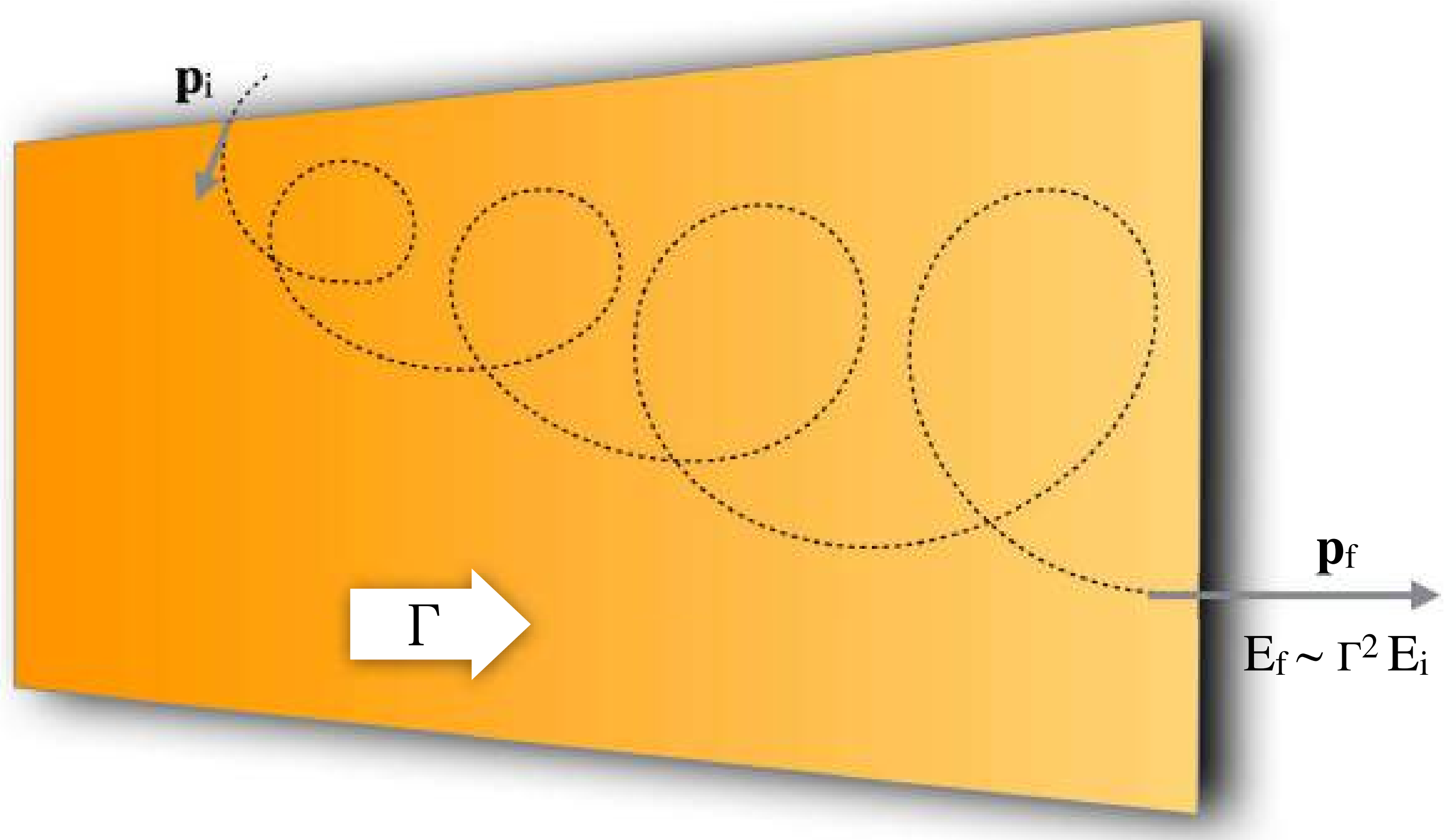
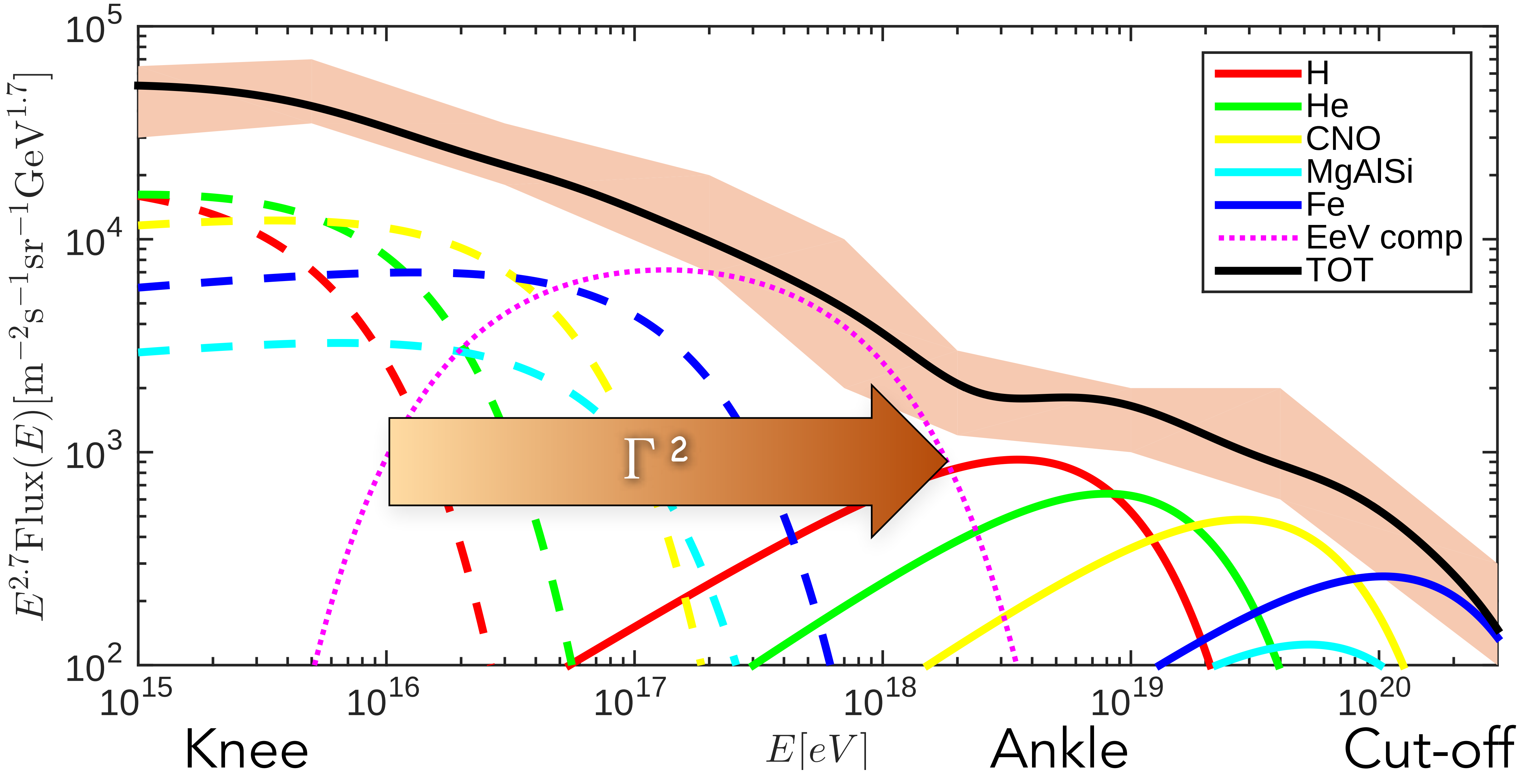
• Cosmic-ray acceleration - extragalactic transition



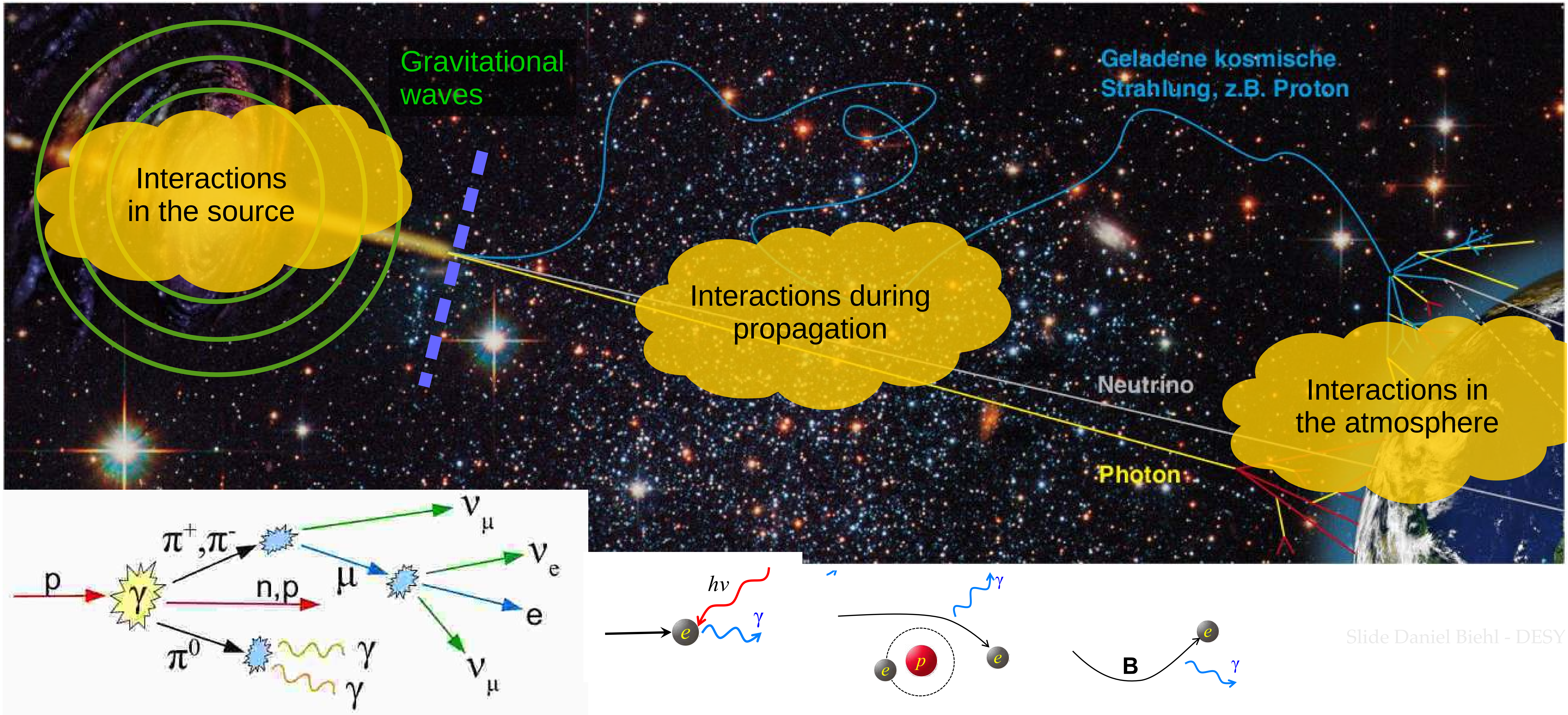


Schematic trajectory of a galactic CR reaccelerated by a relativistic jet

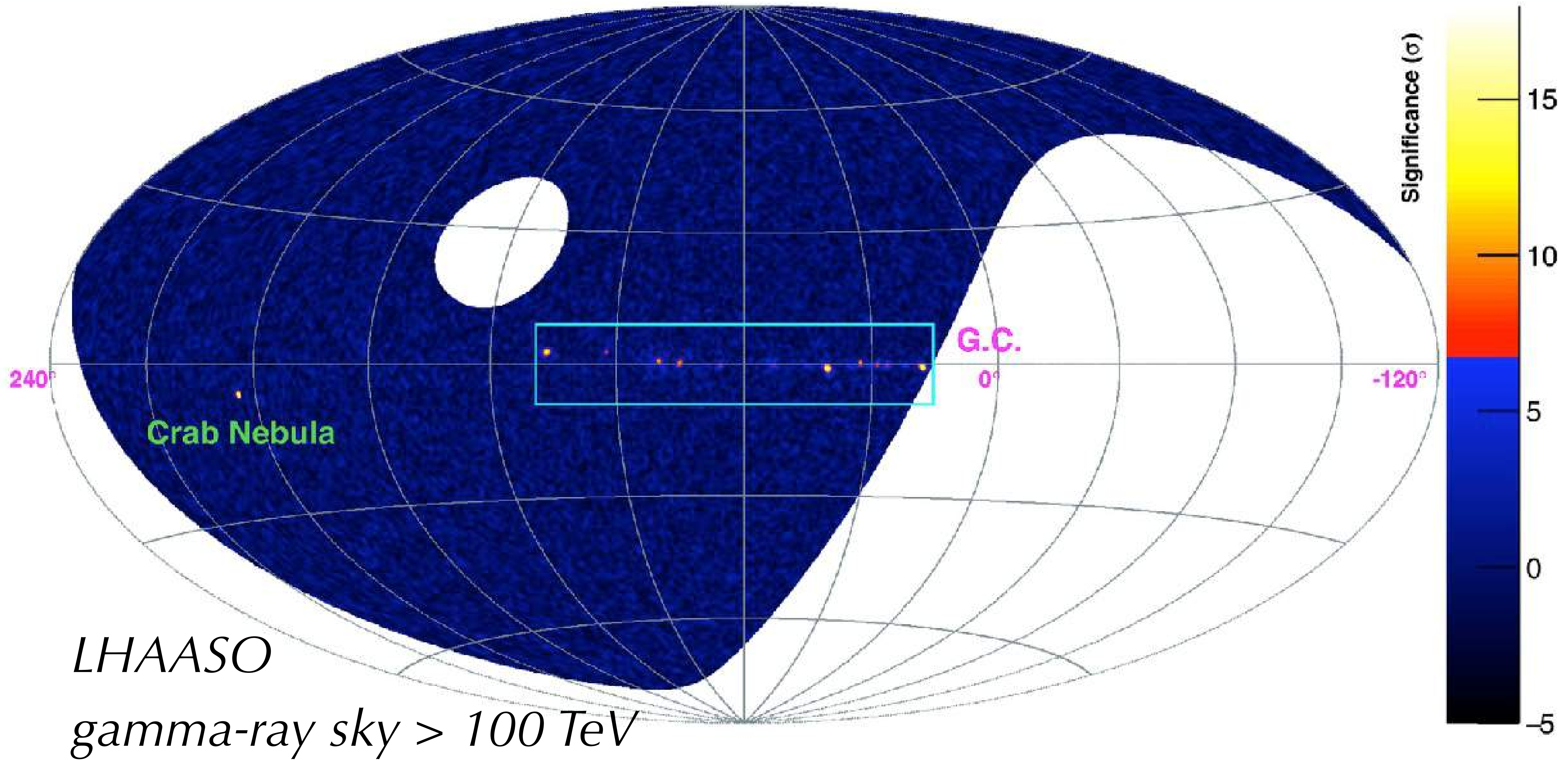


Particle fluxes above 10^{15} eV for different species. Dashed lines correspond to CRs accelerated in SNRs and solid lines to UHECRs produced via espresso acceleration in AGN jets with $\Gamma \approx 30$

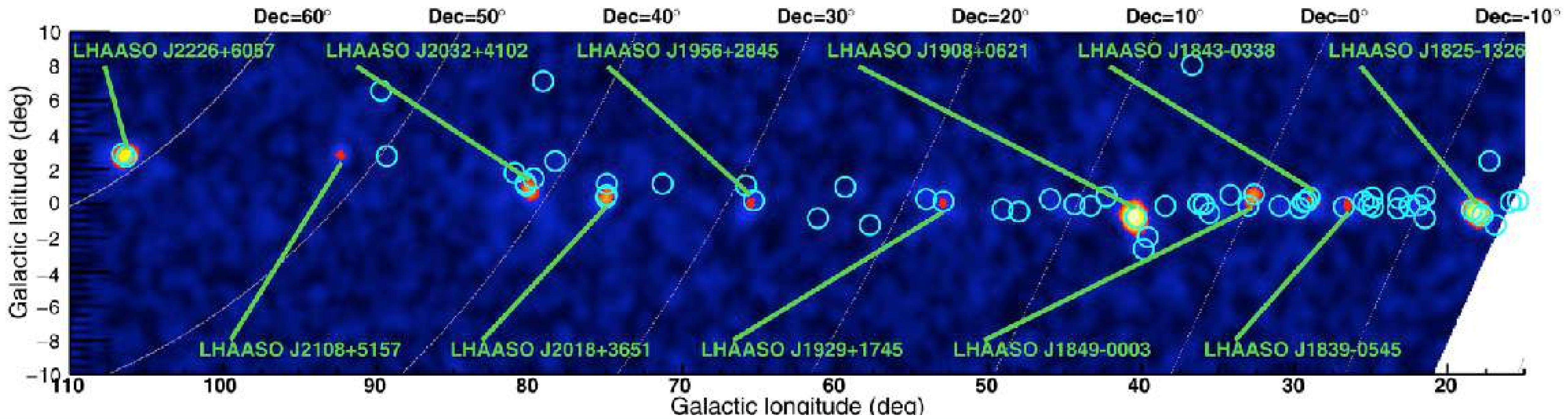
• Multimessenger propagation inside/outside Galaxy



• Galactic Pevatron Candidates

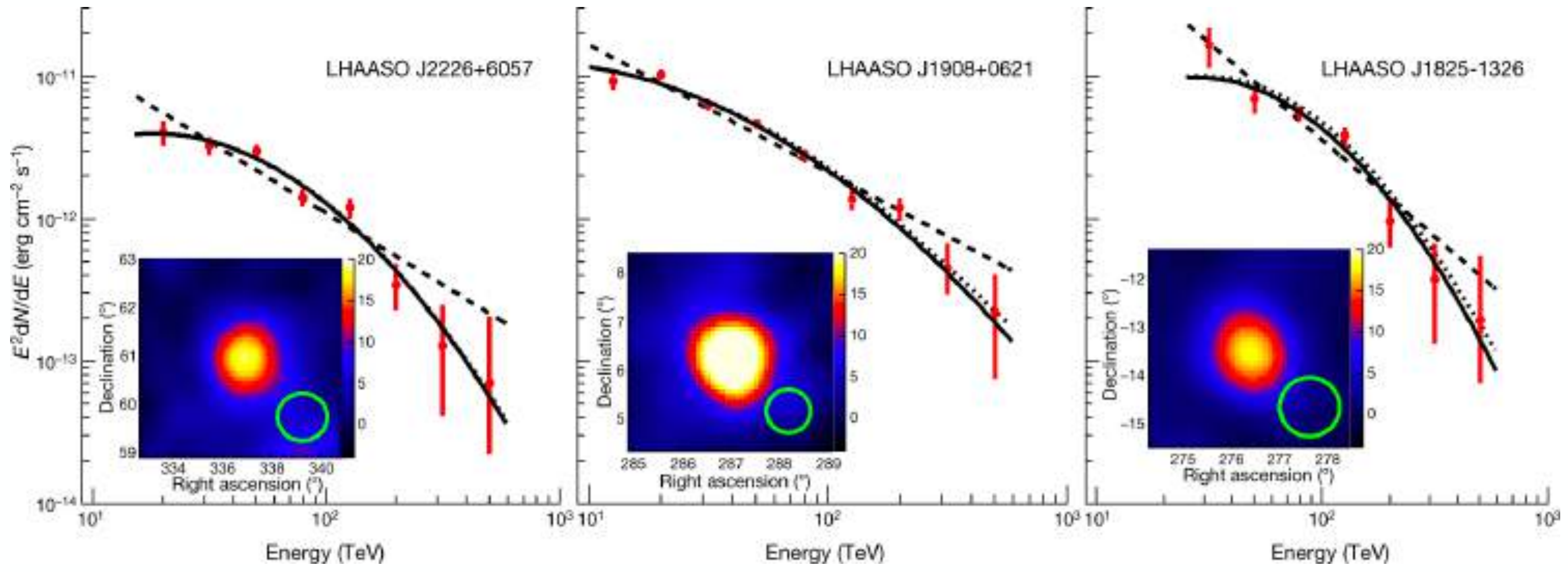


LHAASO
gamma-ray sky > 100 TeV



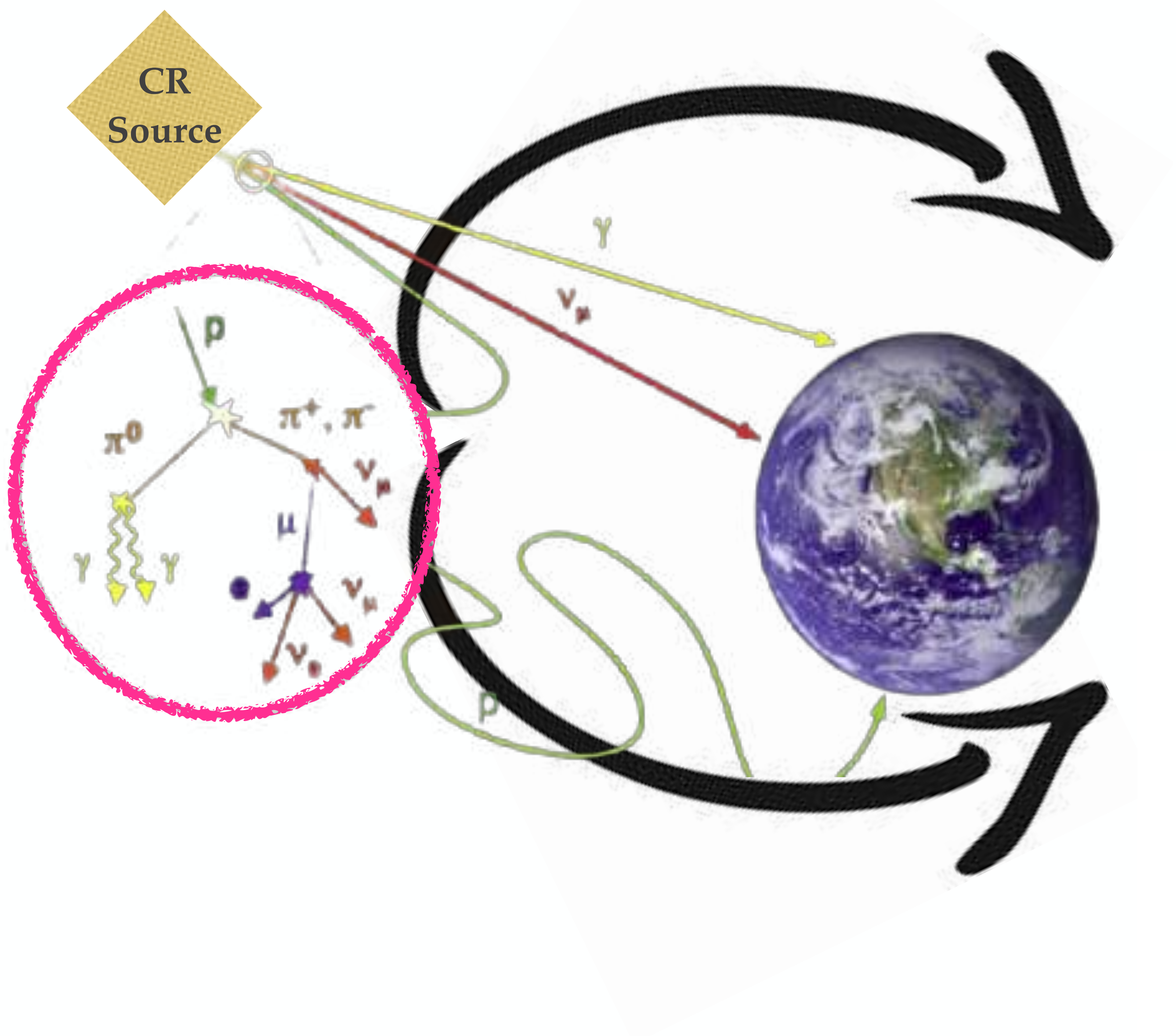
100 TeV -> PeVatron

>10 known sources >100 TeV

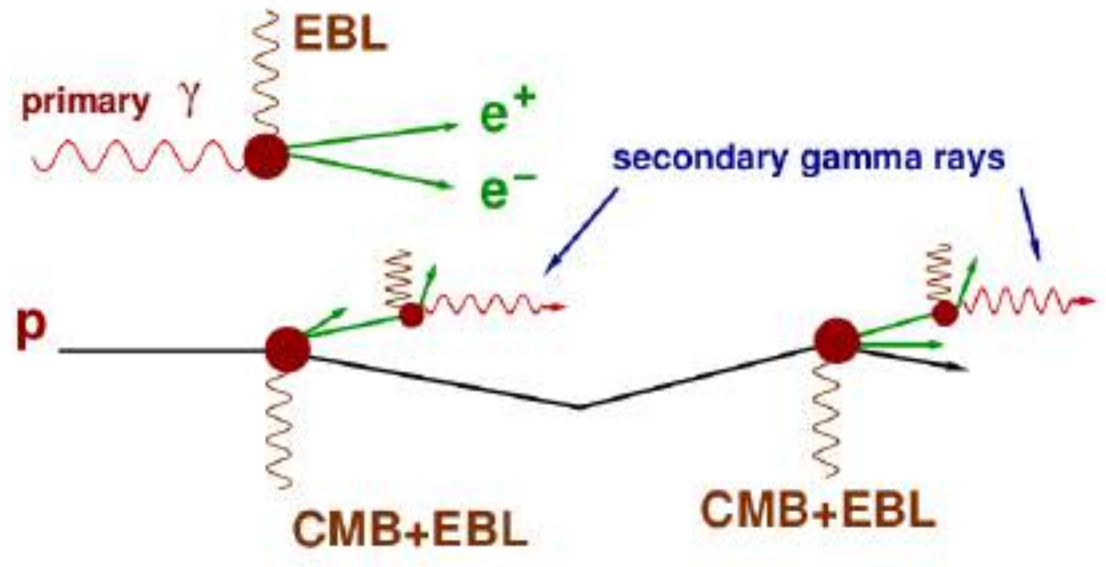


• Multimessenger propagation inside/outside Galaxy

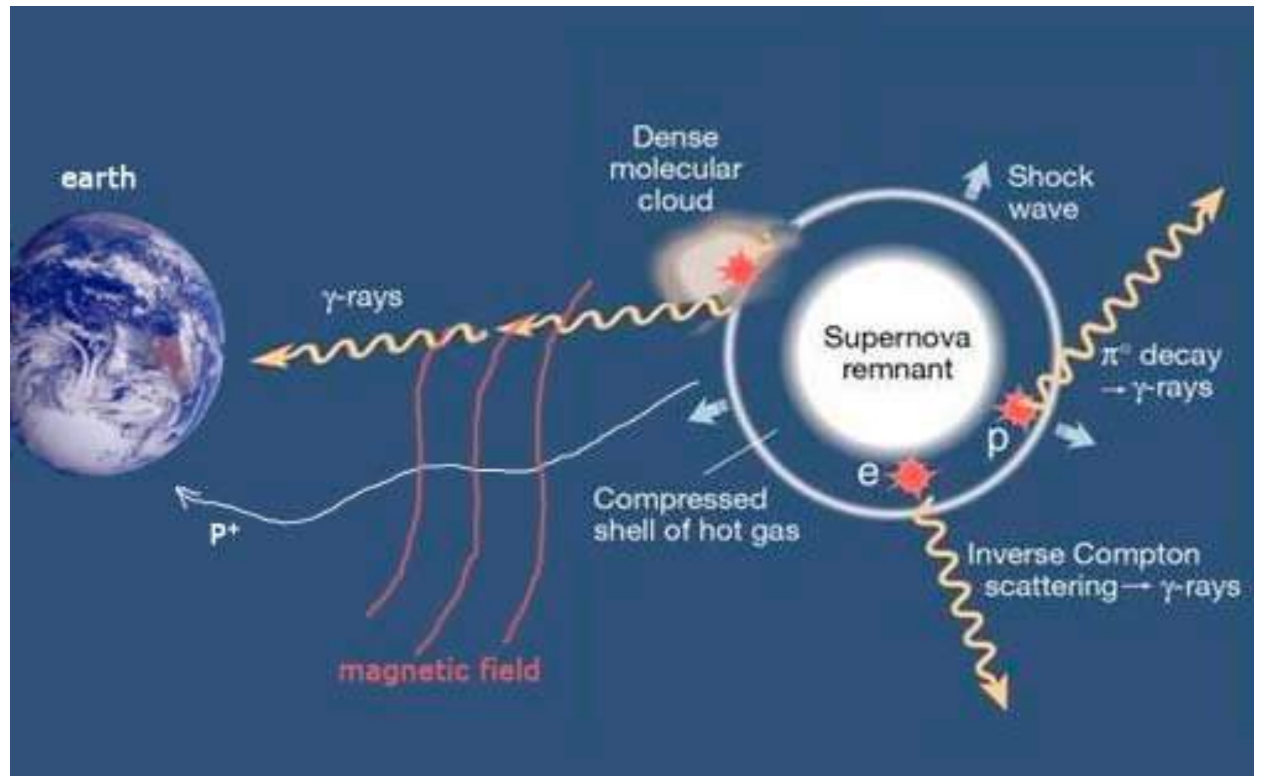
Multimessenger modeling

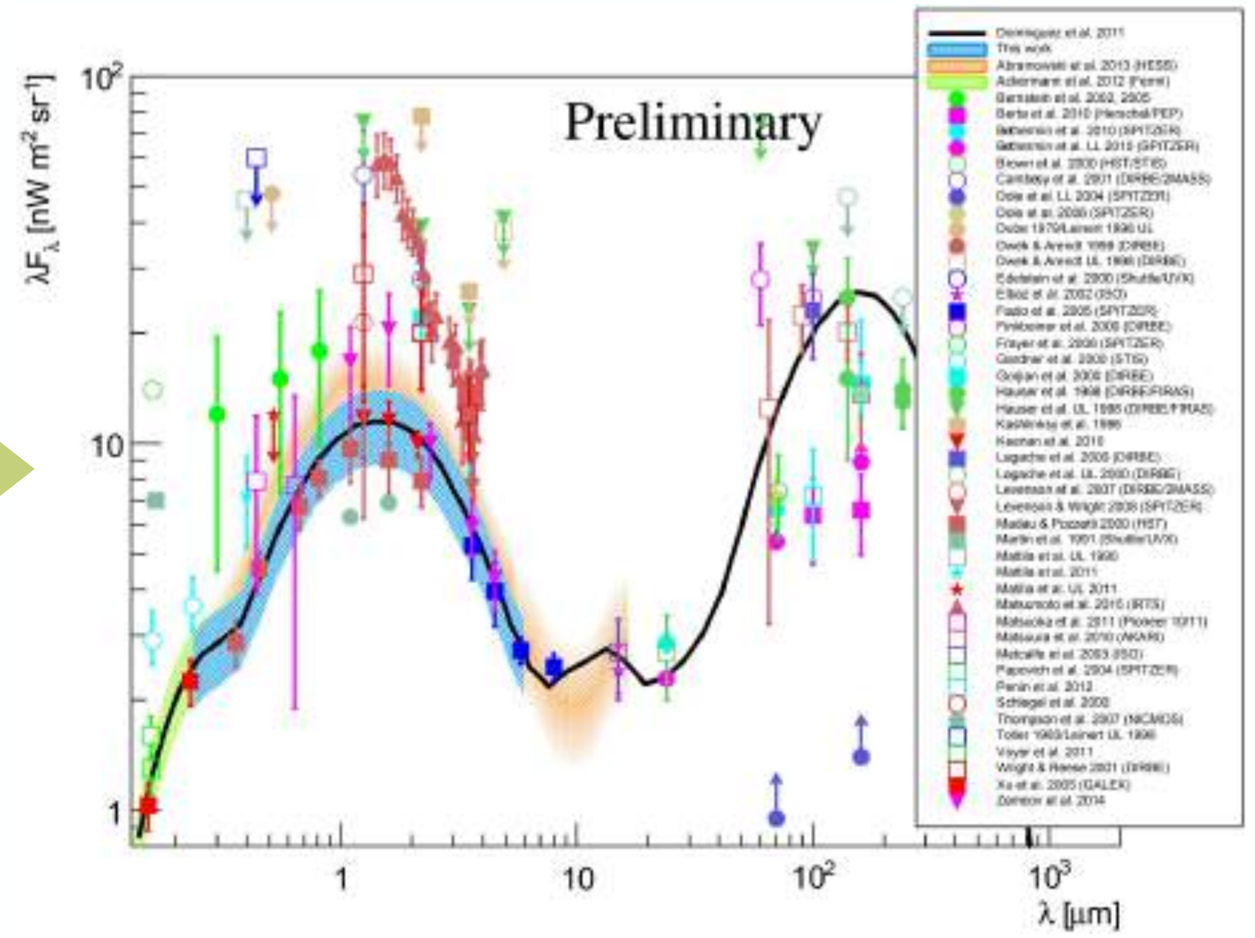


Extra



Galactic





+ impact of CRs interactions with different radiation models, gas and dust

arXiv:1903.07713v1, arXiv:1301.6824
Front. Astron. Space Sci., 22 November 2017
Anjos 2014
https://slideplayer.com/slide/8801439/

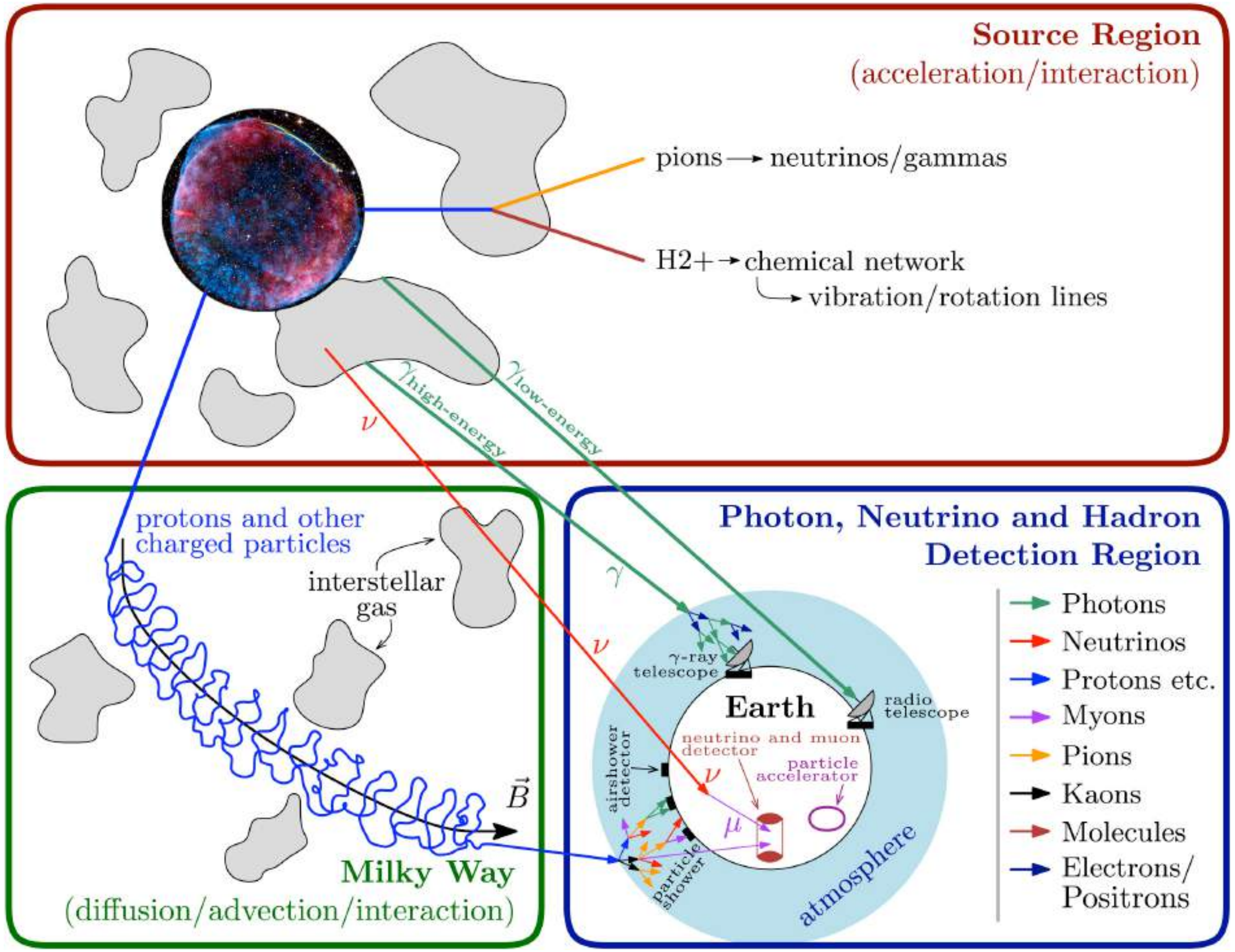
• Multimessenger propagation inside Galaxy

GALPROP

Solves transport equation

- Nuclei up to Z = 28
- Includes estimation of interstellar gas distributions, dust, nuclear interaction, diffusion, convection, fragmentation…
- Propagation parameters can be fitted to available data.

Other codes: DRAGON, PICARD



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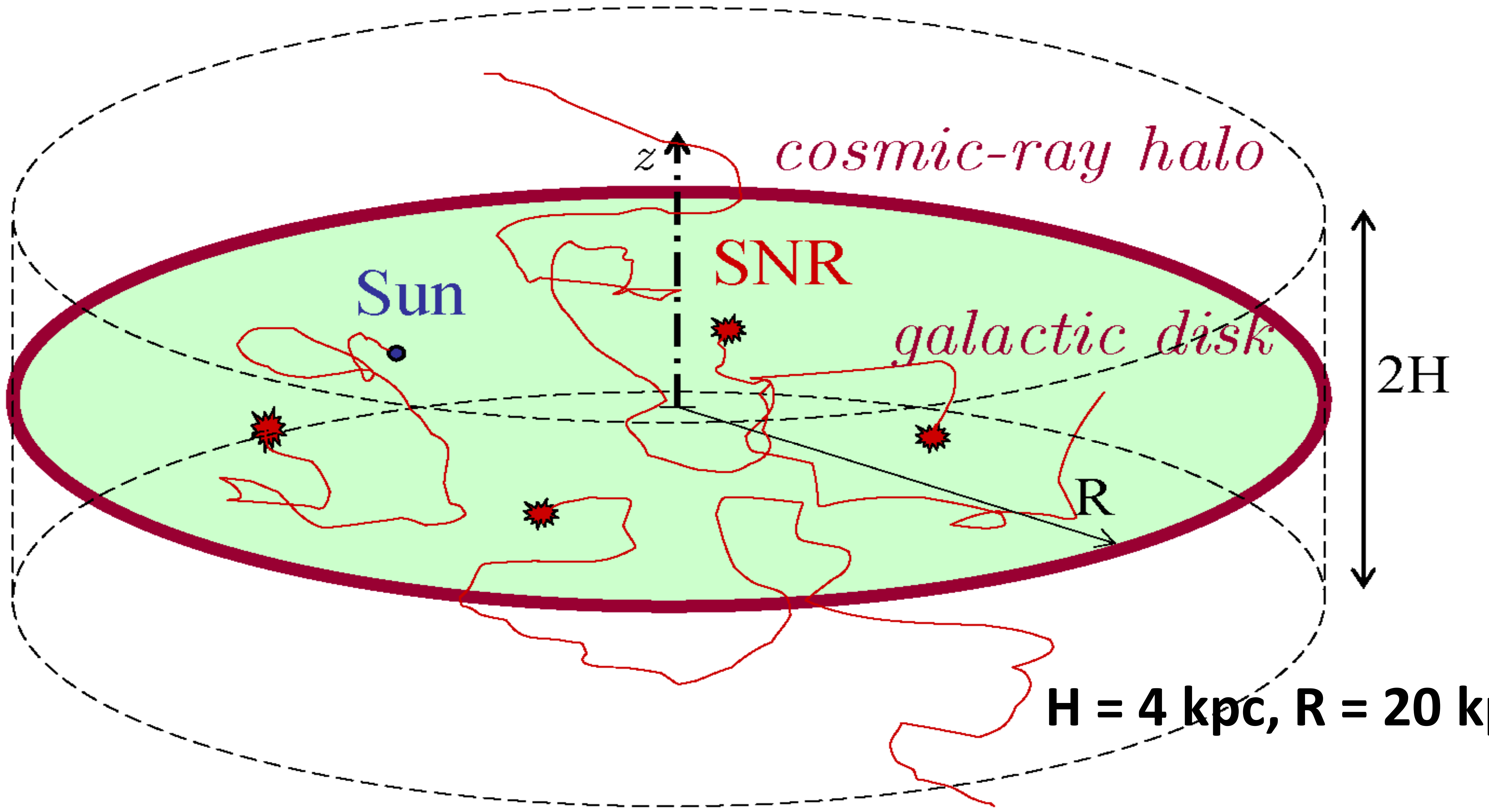
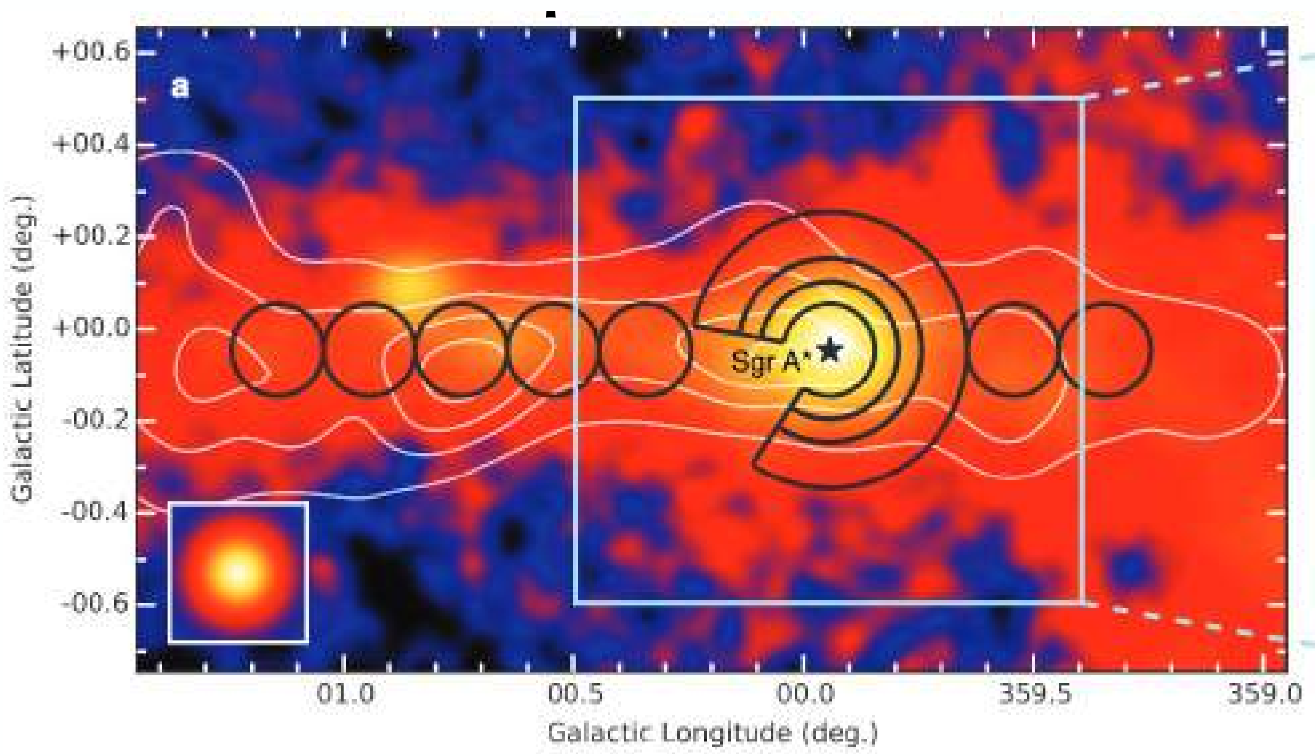


H = 4 kpc, R = 20 kpc

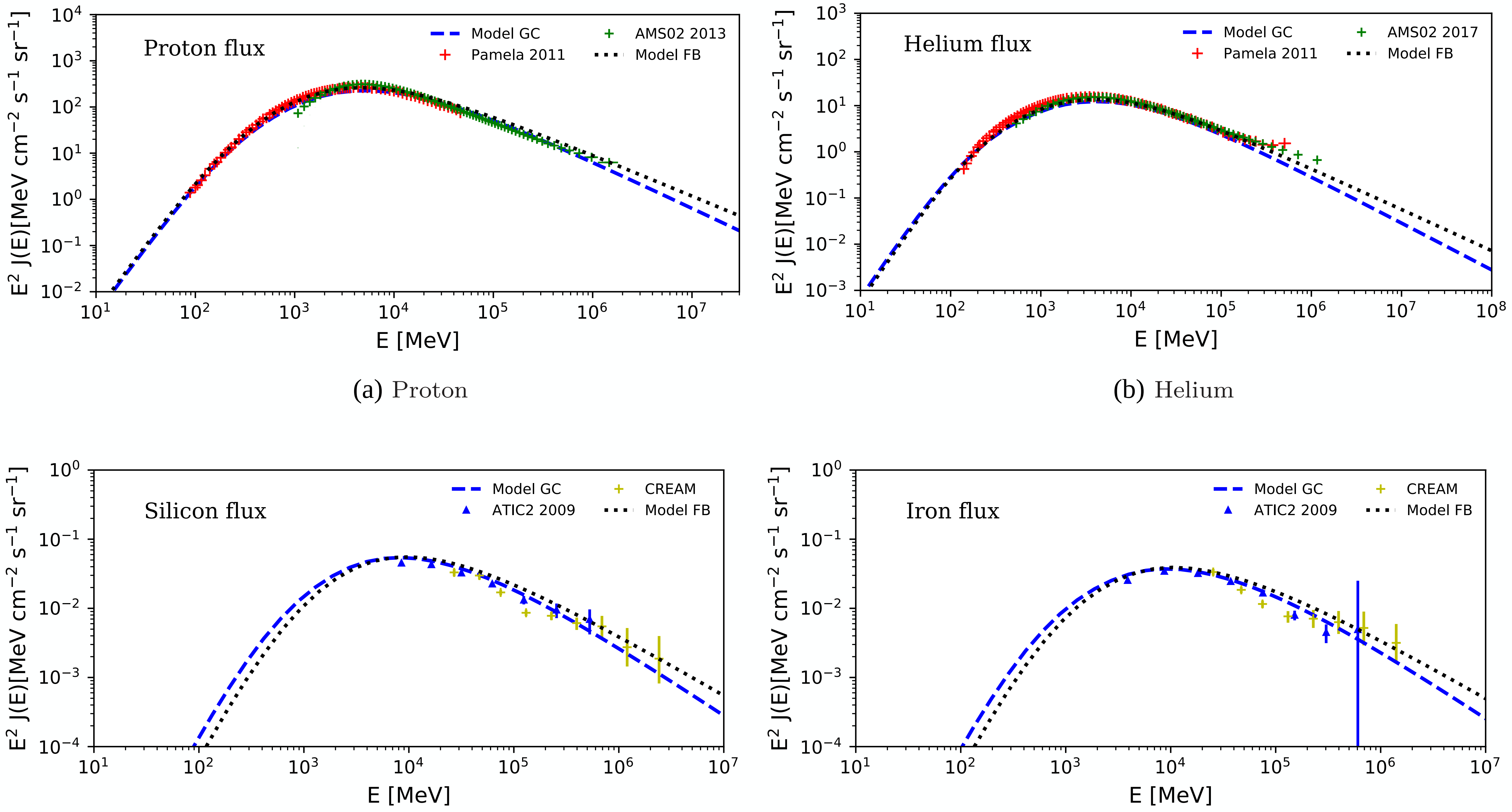
https://www.researchgate.net/figure/The-journey-of-the-cosmic-rays-from-their-source-to-their-detection13_fig2_310831062

• Galactic Pevatron Candidate - Galactic Center

Gamma-rays > 50 TeV -> PeV protons



- Continuous δ function source of energetic particles at the center of the Galaxy
- Period of 1E7 yr
- Injection power ~ 1E41 erg/s



(a) Proton (b) Helium

(e) Silicon (f) Iron

H.E.S.S. 2016: https://www.nature.com/articles/nature17147

• Galactic Pevatron Candidate - Galactic Center

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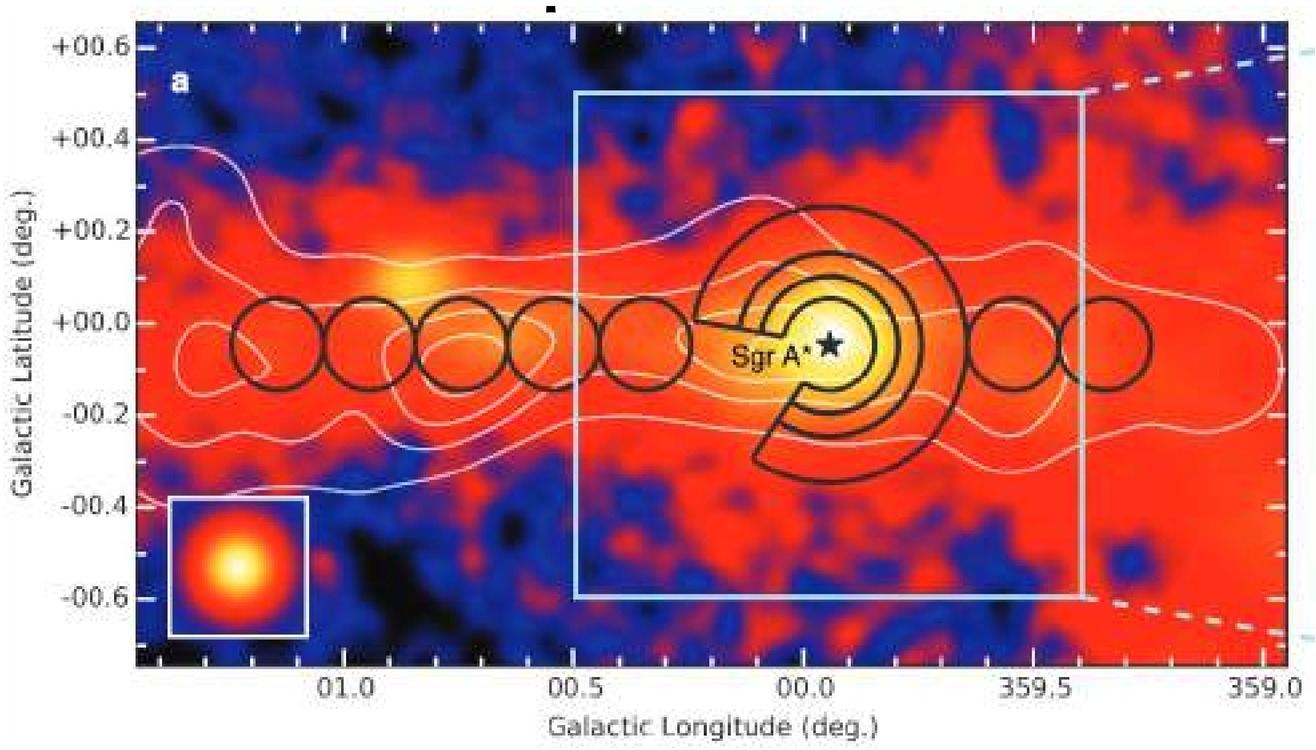

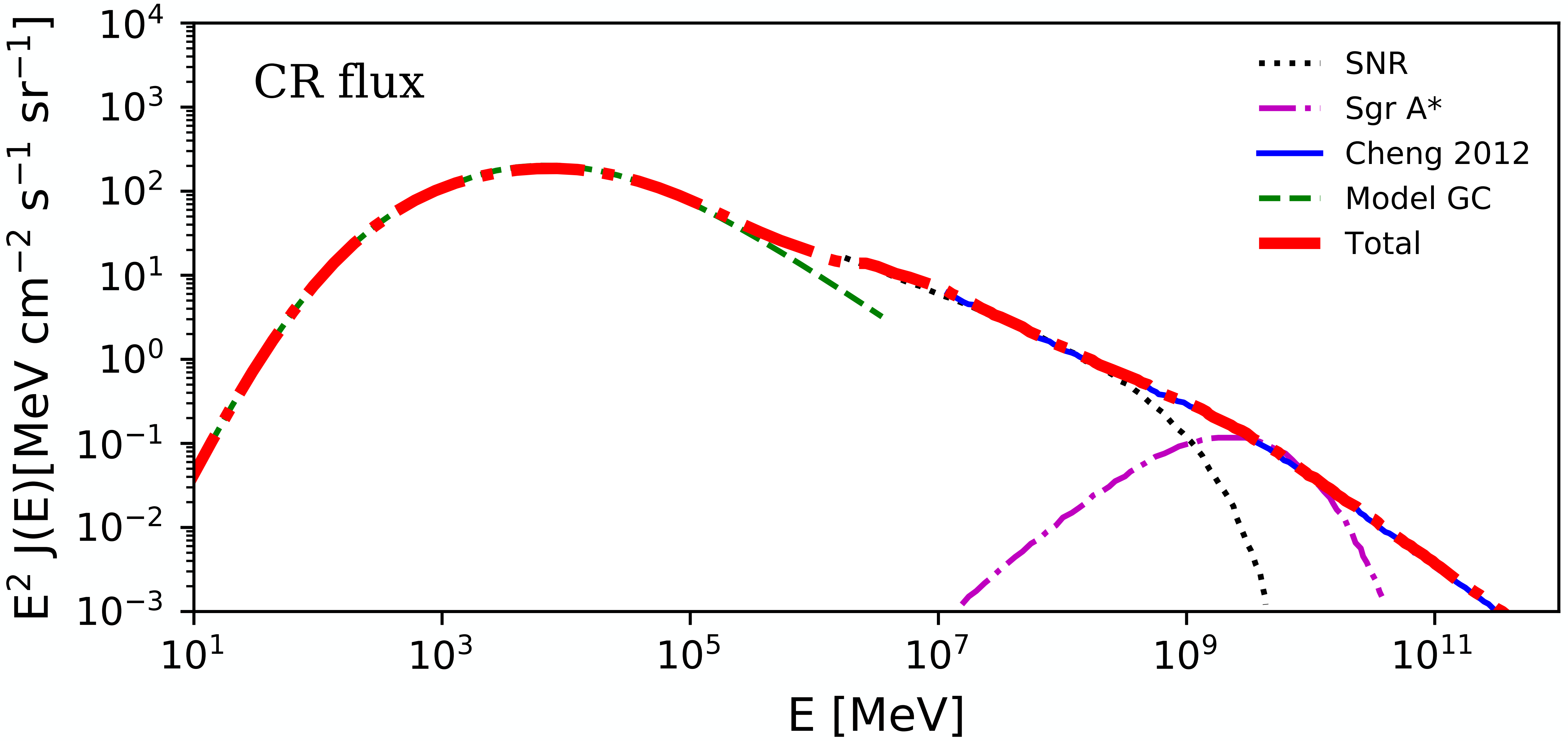

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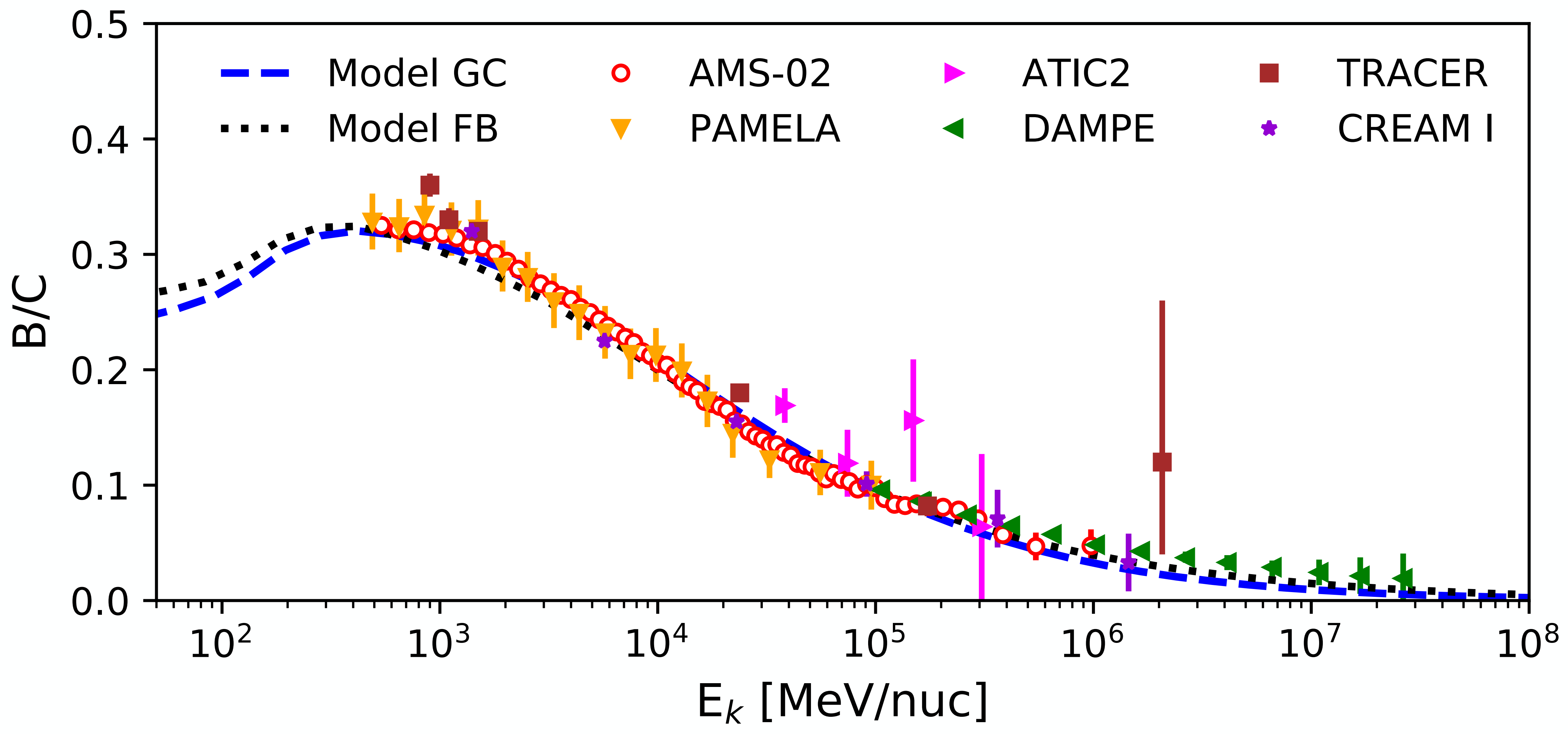
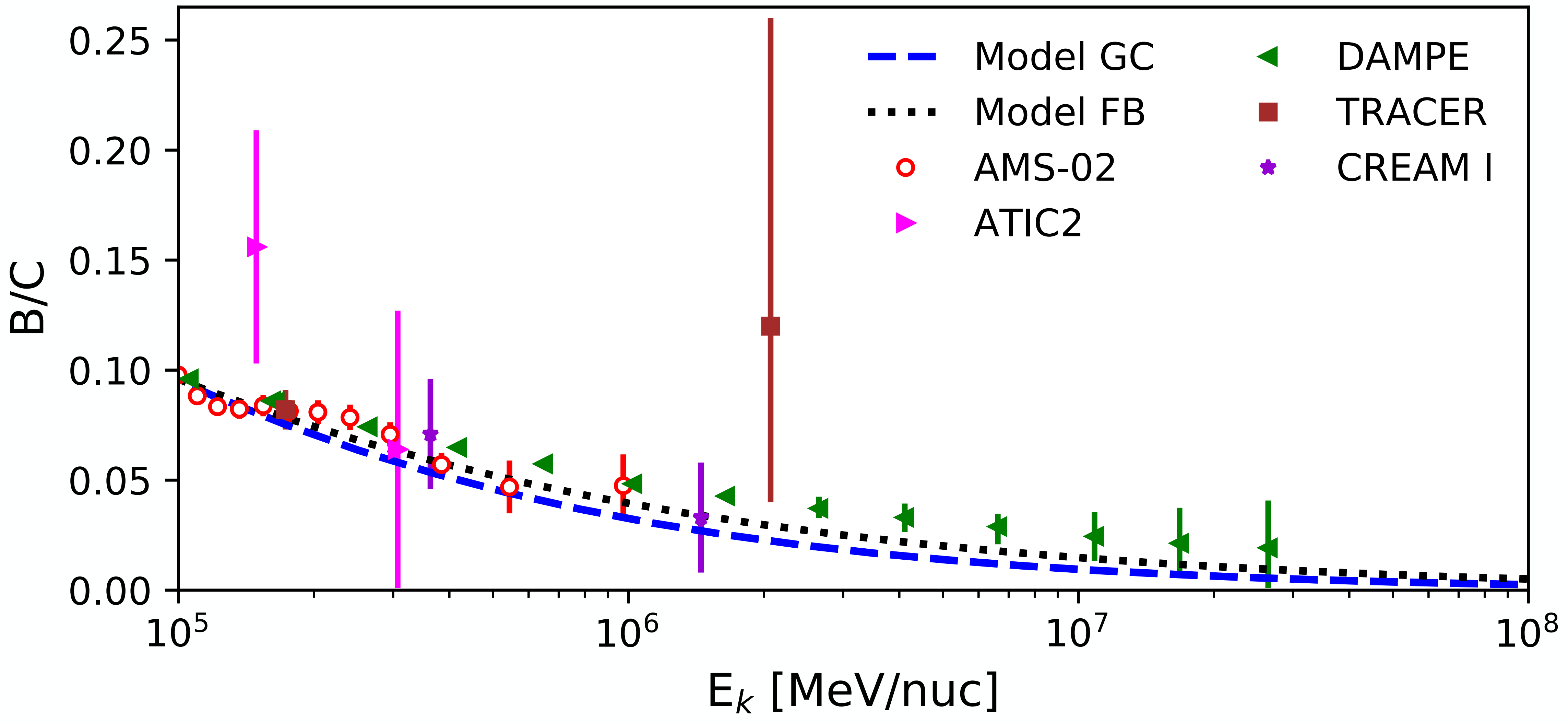
• Galactic Pevatron Candidate - Galactic Center



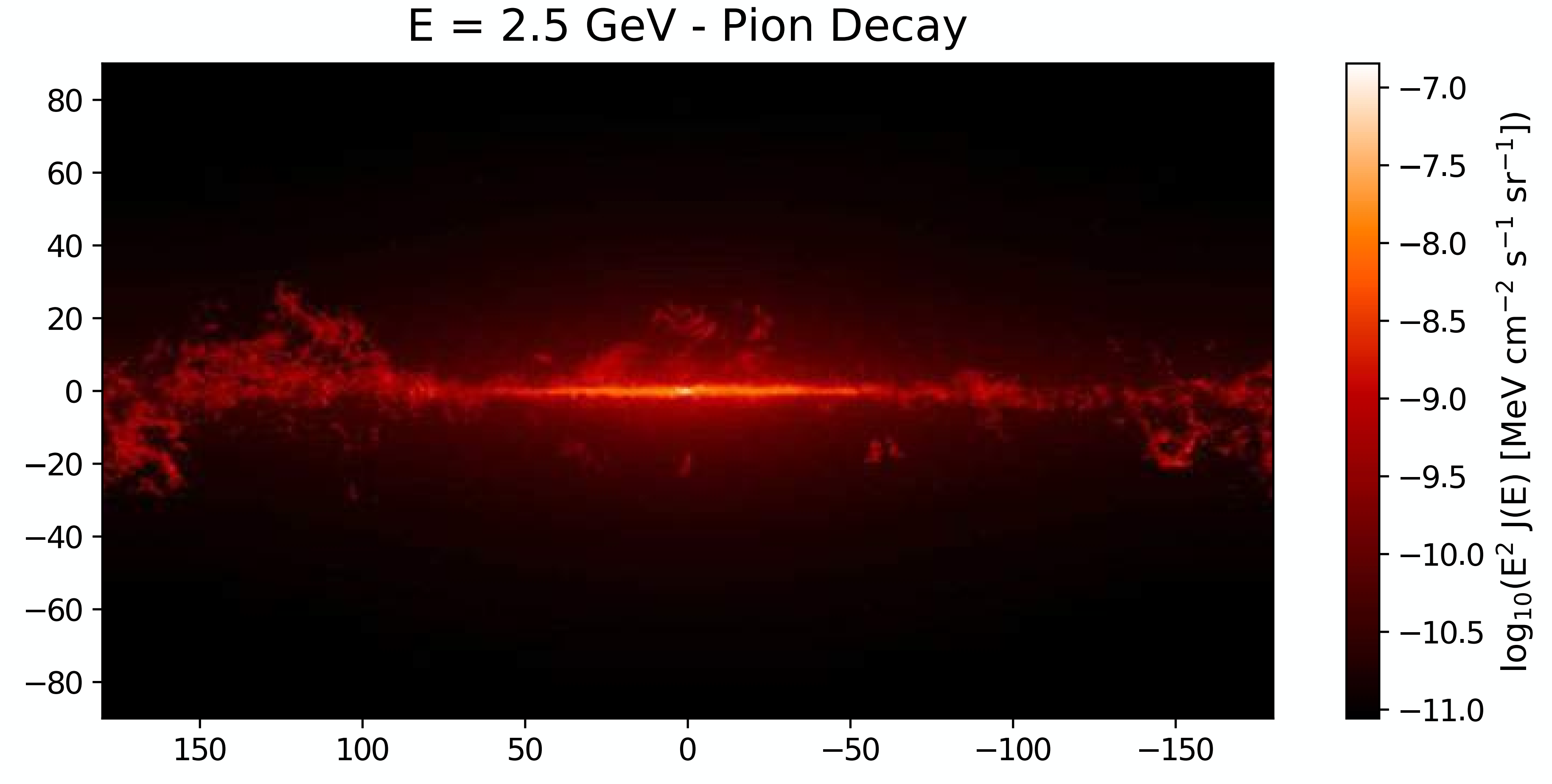
(a) Boron to Carbon ratio



(b) Boron to Carbon ratio at high energy ($K \geq 10^5$ MeV)

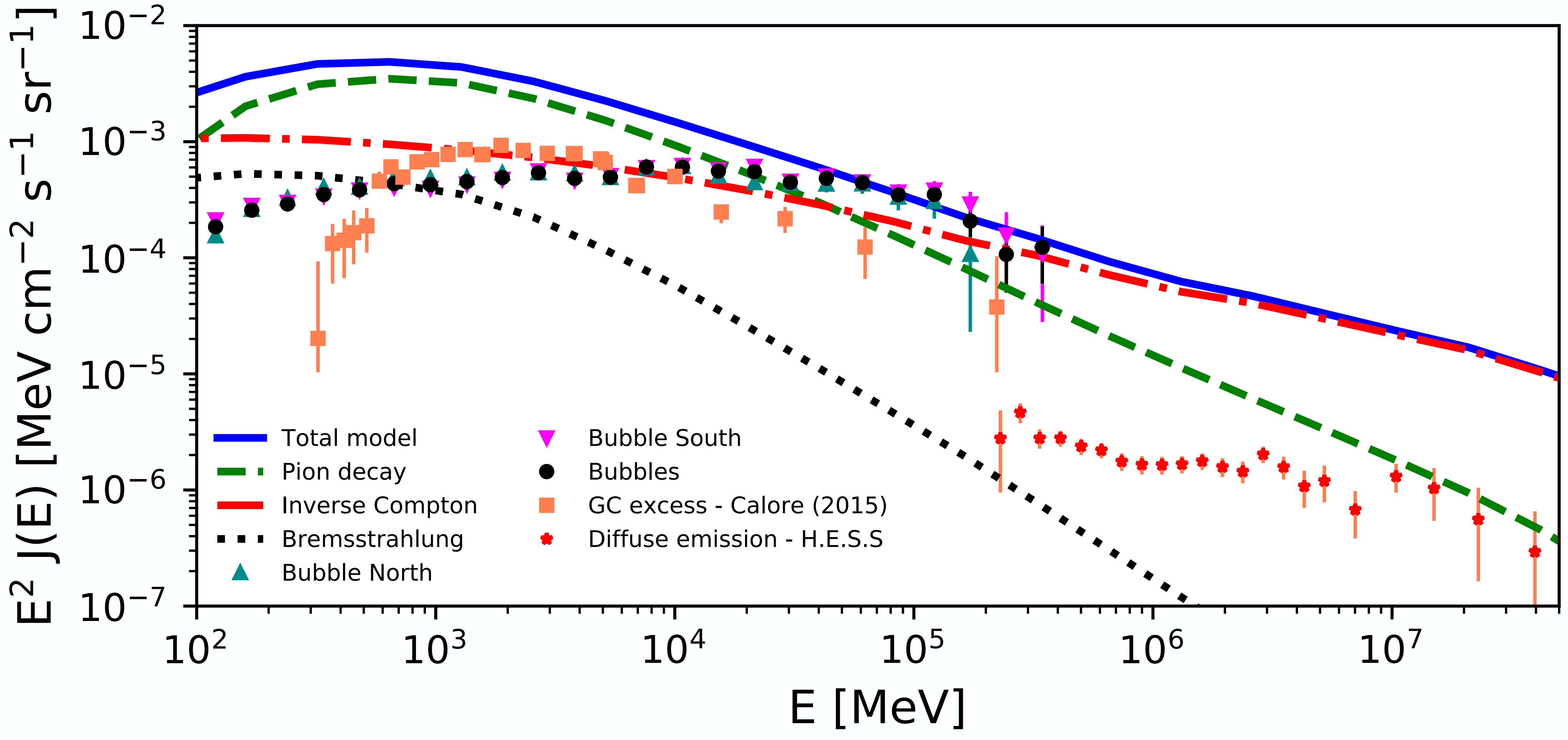
Parameters	Units	Model GC	Model FB
Source	···	GC	Fermi bubbles
D_0	$\mathrm{cm^2\,s^{-1}}$	2.7×10^{28}	2.0×10^{28}
δ	···	0.6	0.6
L	kpc	10.0	10.0
z	kpc	20.0	20.0
v_a	$\mathrm{km\,s^{-1}}$	28.0	28.0
dv/dz	$\mathrm{km\,s^{-1}\,kpc^{-1}}$	10.0	10.0
α	···	2.4	2.4

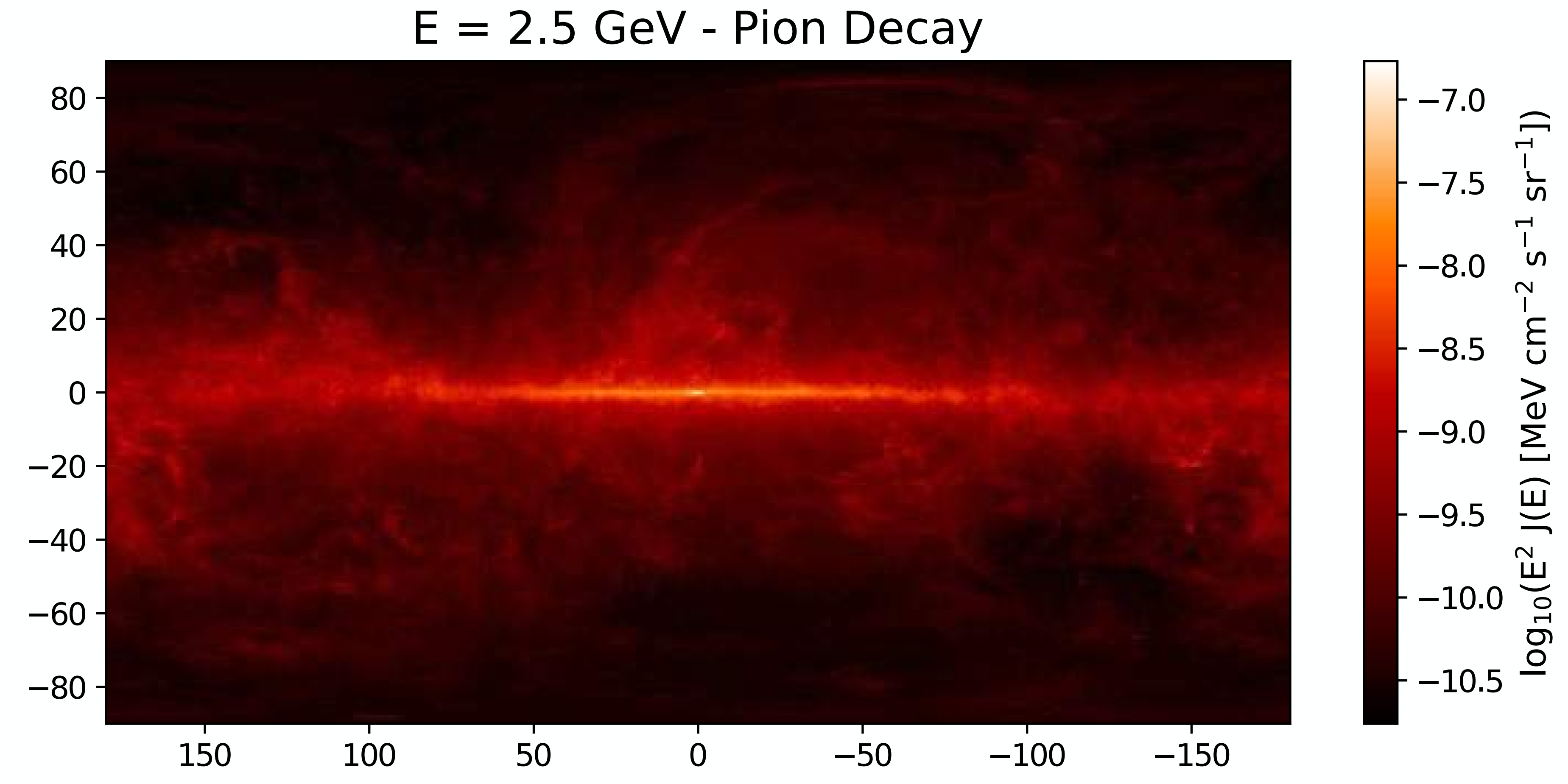
• Galactic Pevatron Candidate - Galactic Center



(g) Pion decay

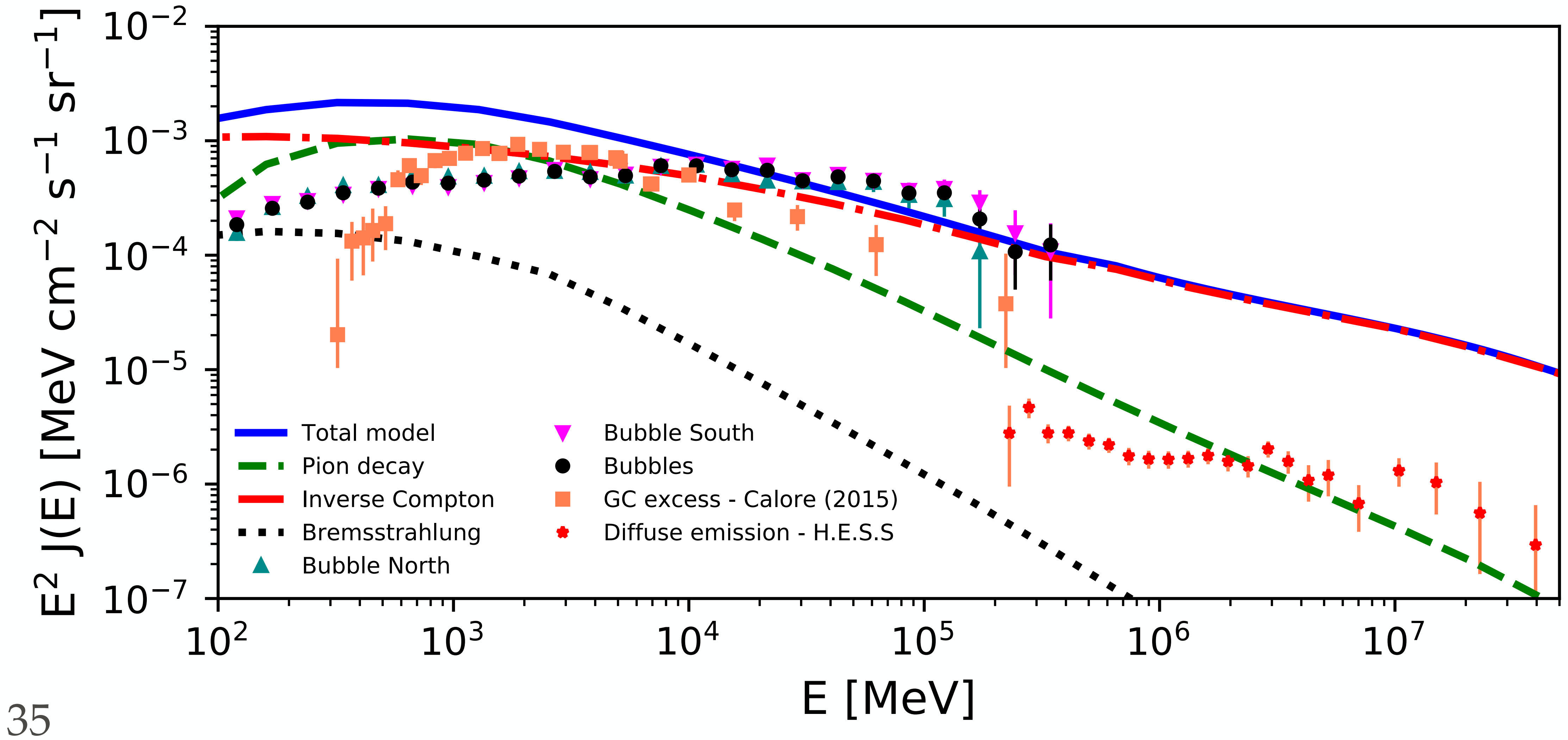
Fermi-LAT Collaboration



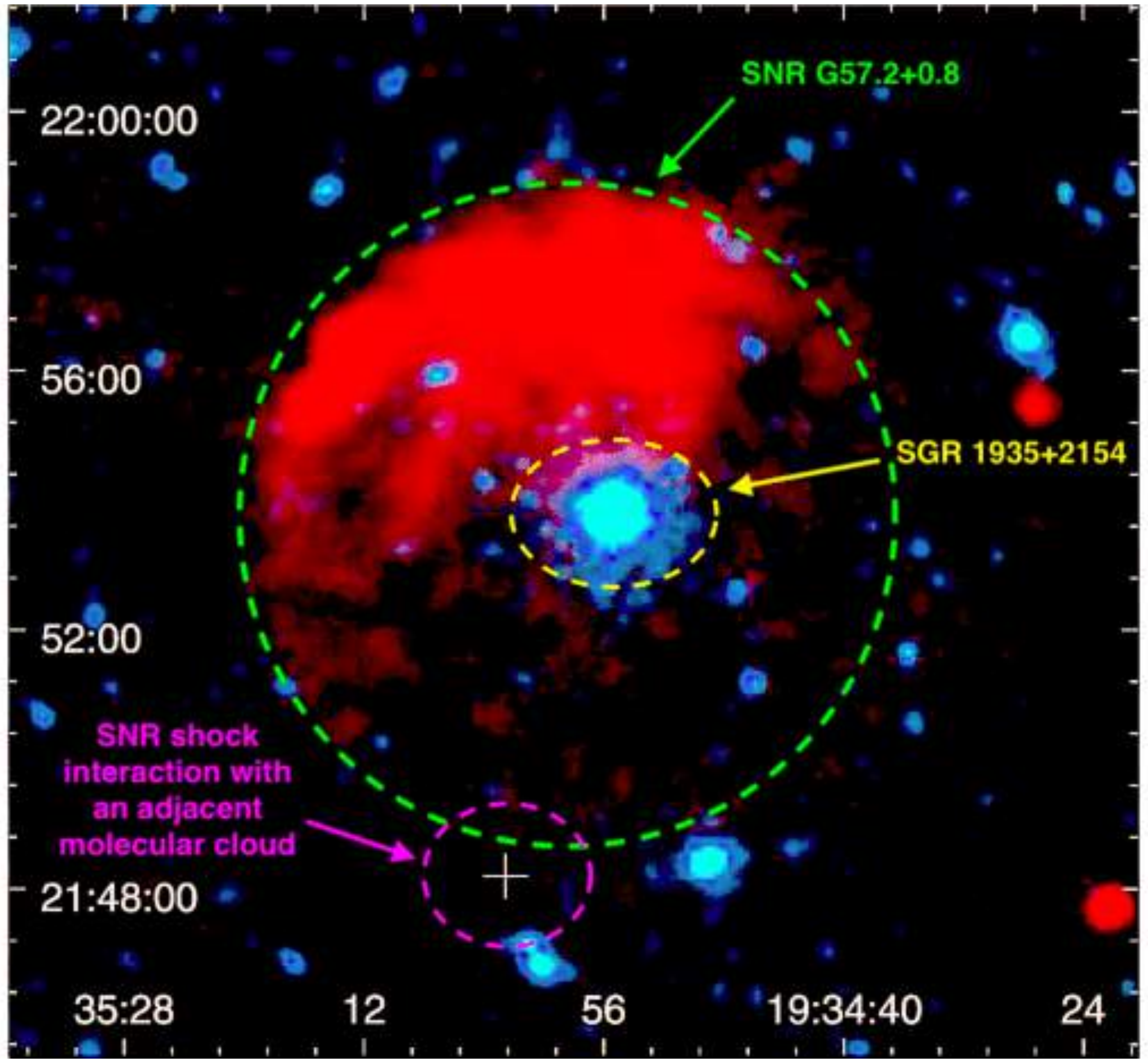


(g) Pion decay

2D gas distribution galactic ensemble component

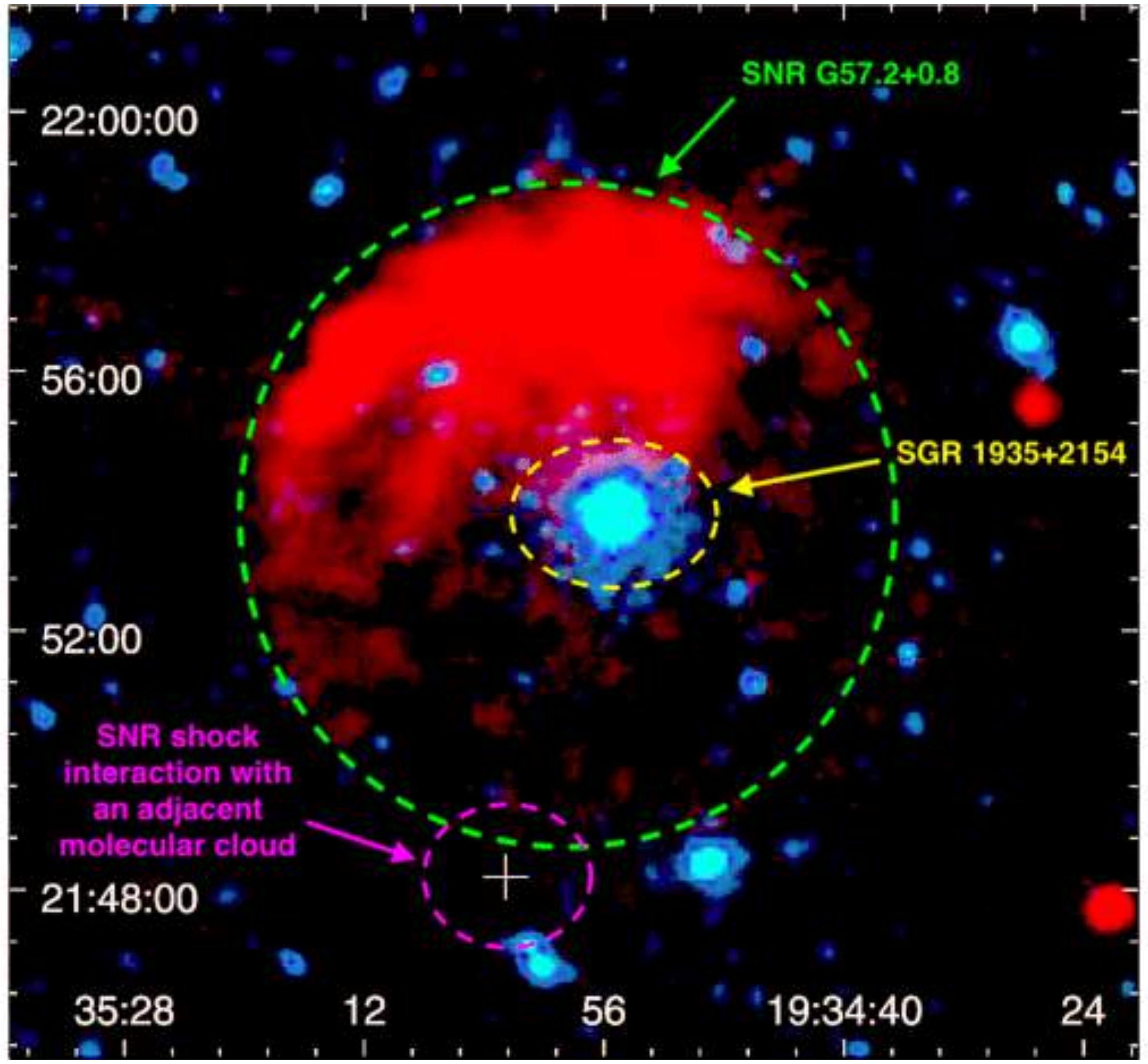


• Galactic Pevatron Candidate - SNR G57.2+0.8 hosting SGR J1935+2154



- SGRs present rotation and strong magnetic field
- Molecular cloud can amplify the emission produced by CRs accelerated around the source.
- Highest energy protons escape and contribute to gamma-ray production.

- Galactic Pevatron Candidate - SNR G57.2+0.8 hosting SGR J1935+2154



$$L_{\rm CR} \approx 10^{41} {\rm erg/s} \left(\frac{\eta}{0.1}\right)\left(\frac{\dot{n}}{0.02\ {\rm yr}^{-1}}\right)\left(\frac{E_{\rm SN}}{10^{50}\ {\rm erg}}\right)$$

$$L_\gamma(E_\gamma) = n_{\rm gas}\frac{W_{CR}}{4\pi d^2\langle E_0\rangle}K_\gamma P_\gamma(E_\gamma)$$

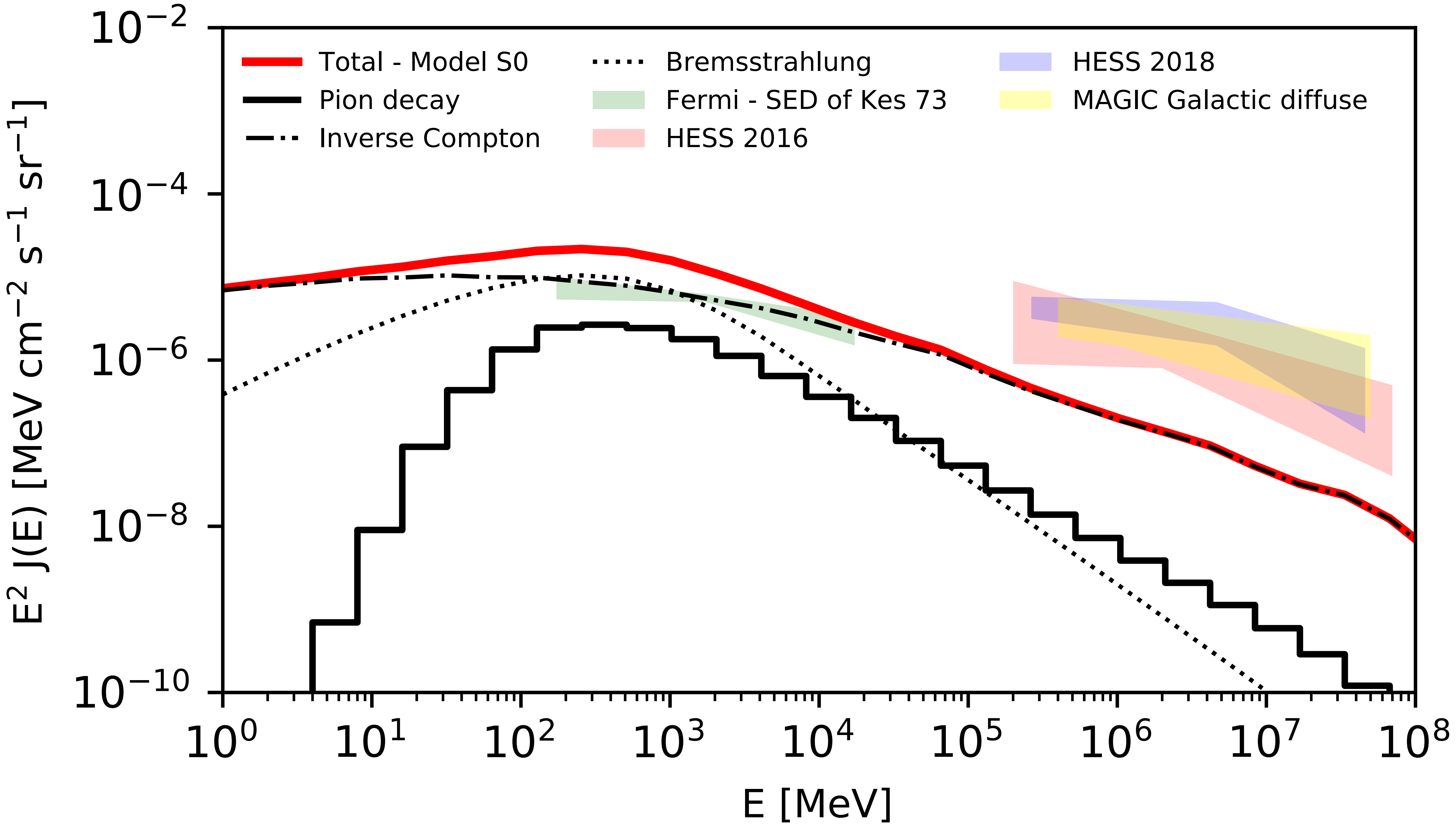
- Galactic Pevatron Candidate - SNR G57.2+0.8 hosting SGR J1935+2154

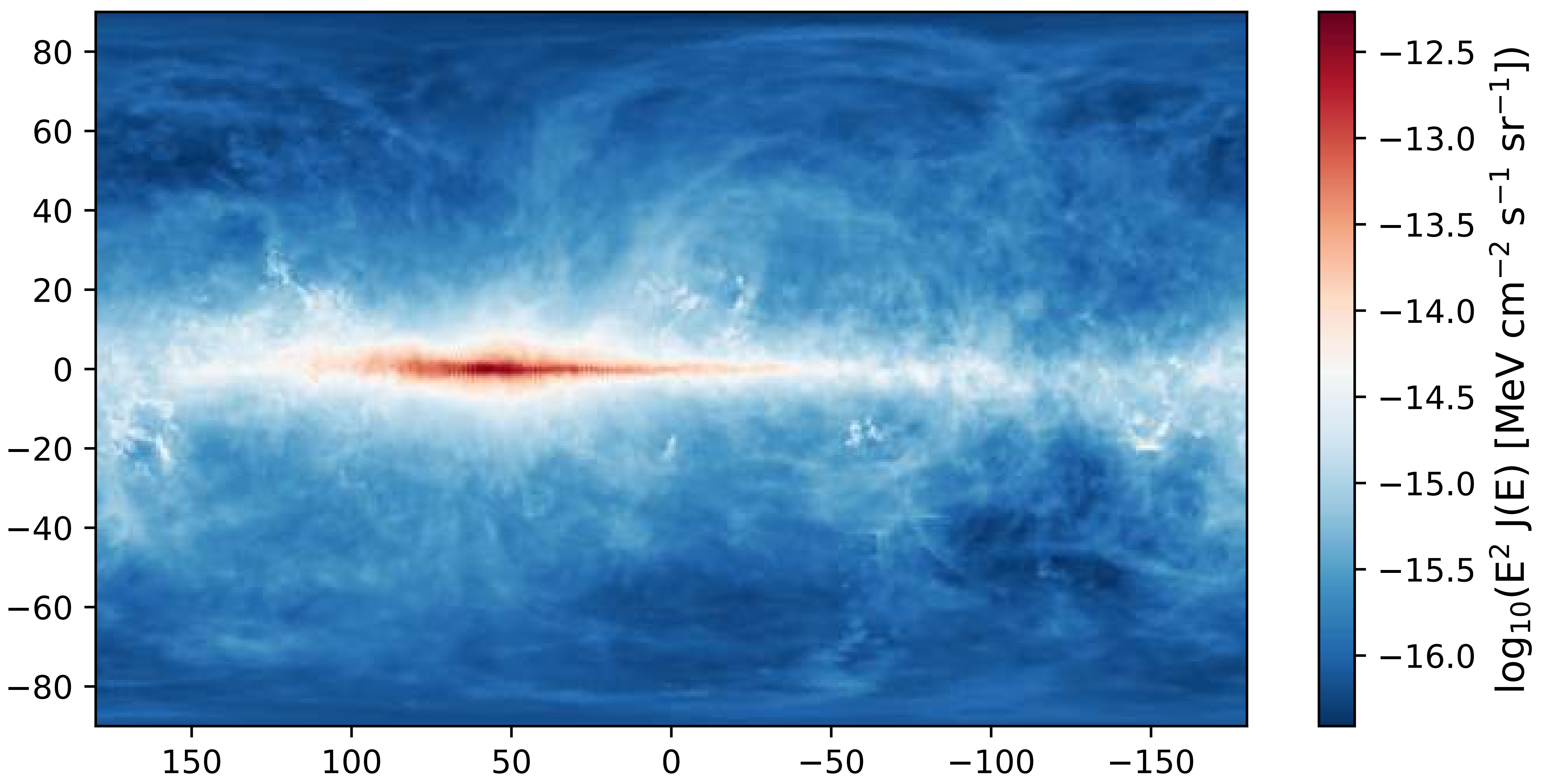
Upper limits on the total cosmic-ray luminosity of individual sources

Conservative

Depends on the injection spectrum
at source (Ecut, spectral index)

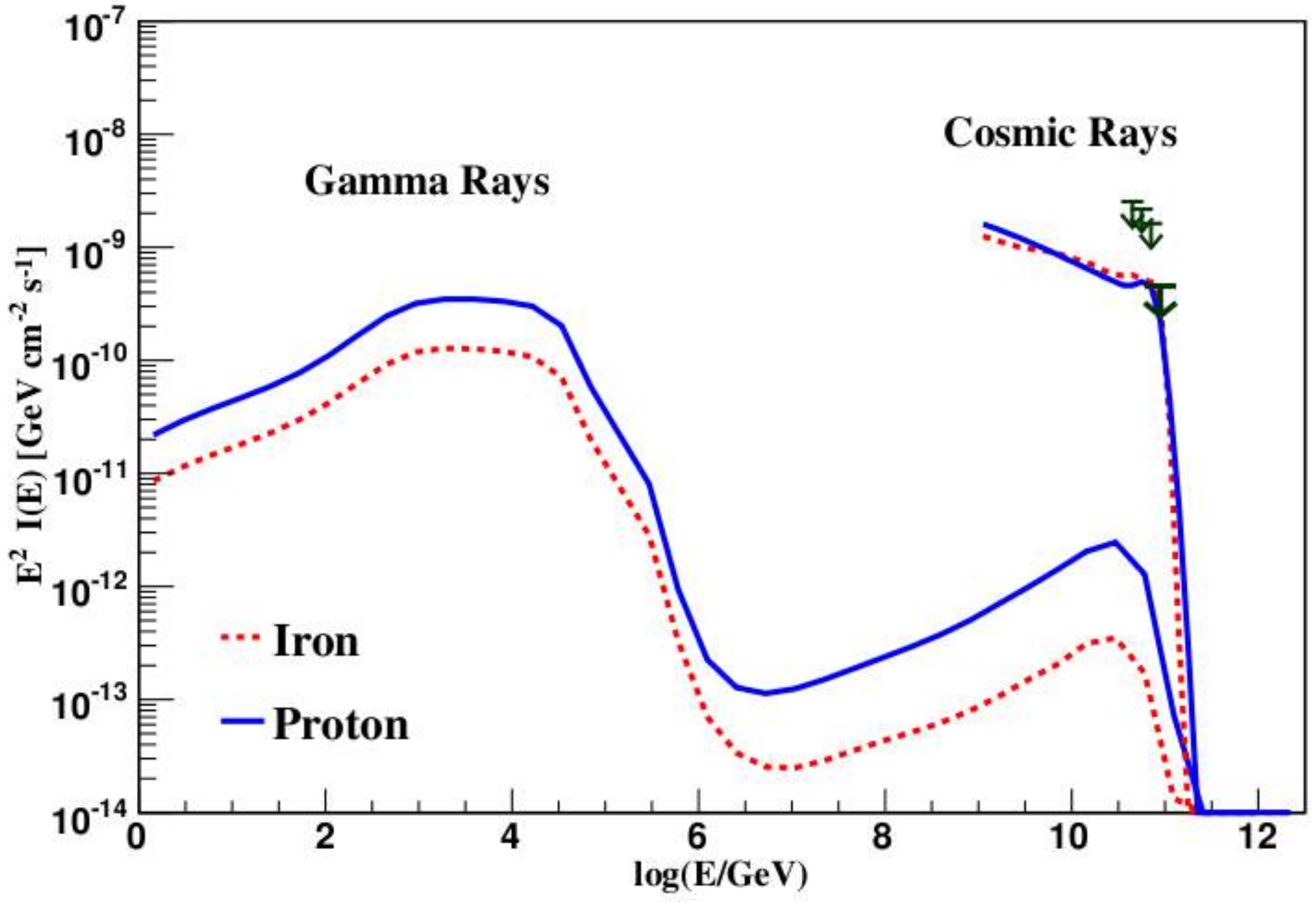
- Galactic Pevatron Candidate - SNR G57.2+0.8 hosting SGR J1935+2154



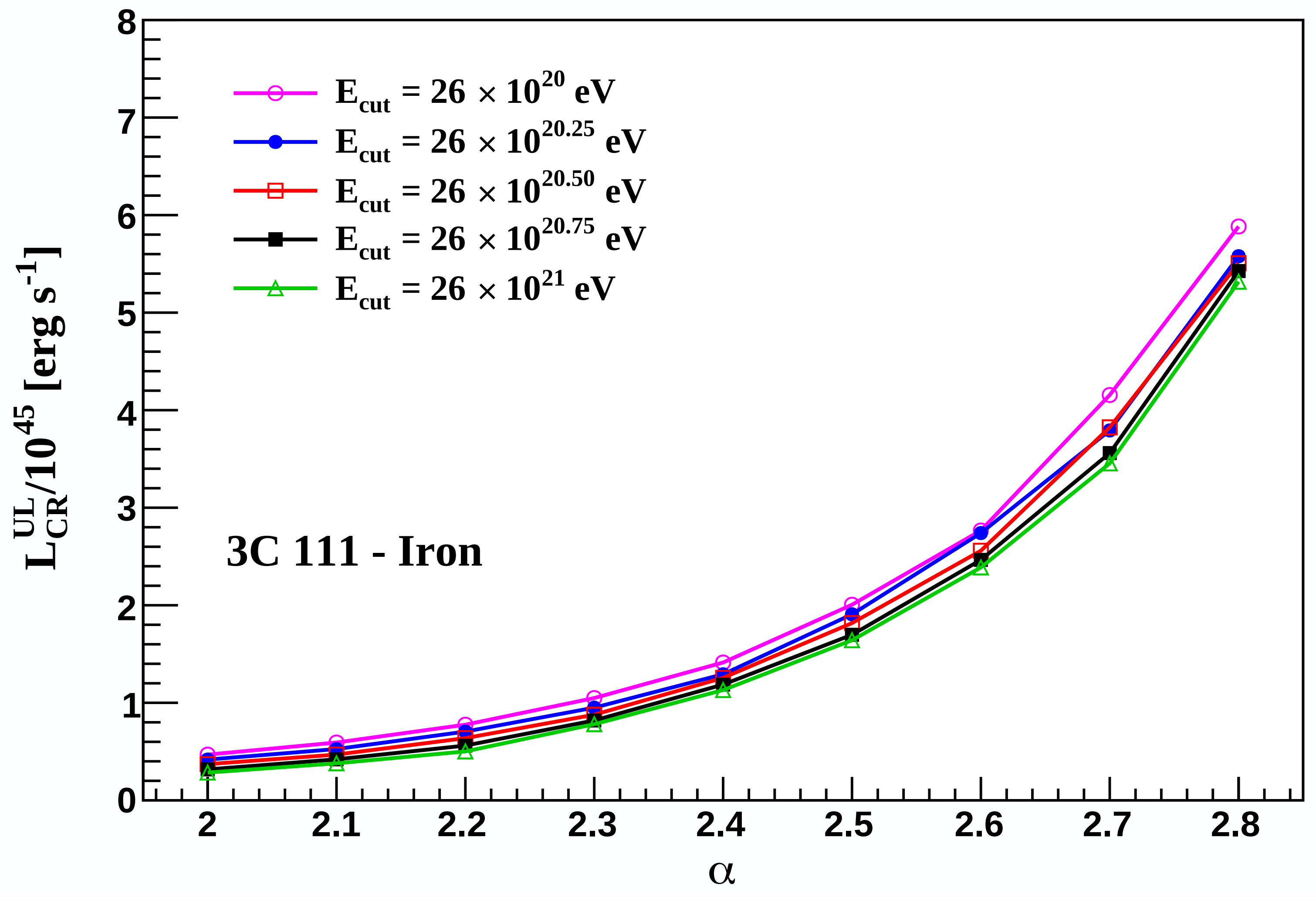


(c) Pion Decay

• Looking for Galactic Pevatron Candidates



$$L_{CR}^{UL} = \frac{4\pi D_s^2 (1+z_s)\langle E\rangle_0}{K_\gamma \int_{E_{th}}^{\infty} dE_\gamma \; P_\gamma(E_\gamma)} \; I_\gamma^{UL}(> E_\gamma^{th})$$



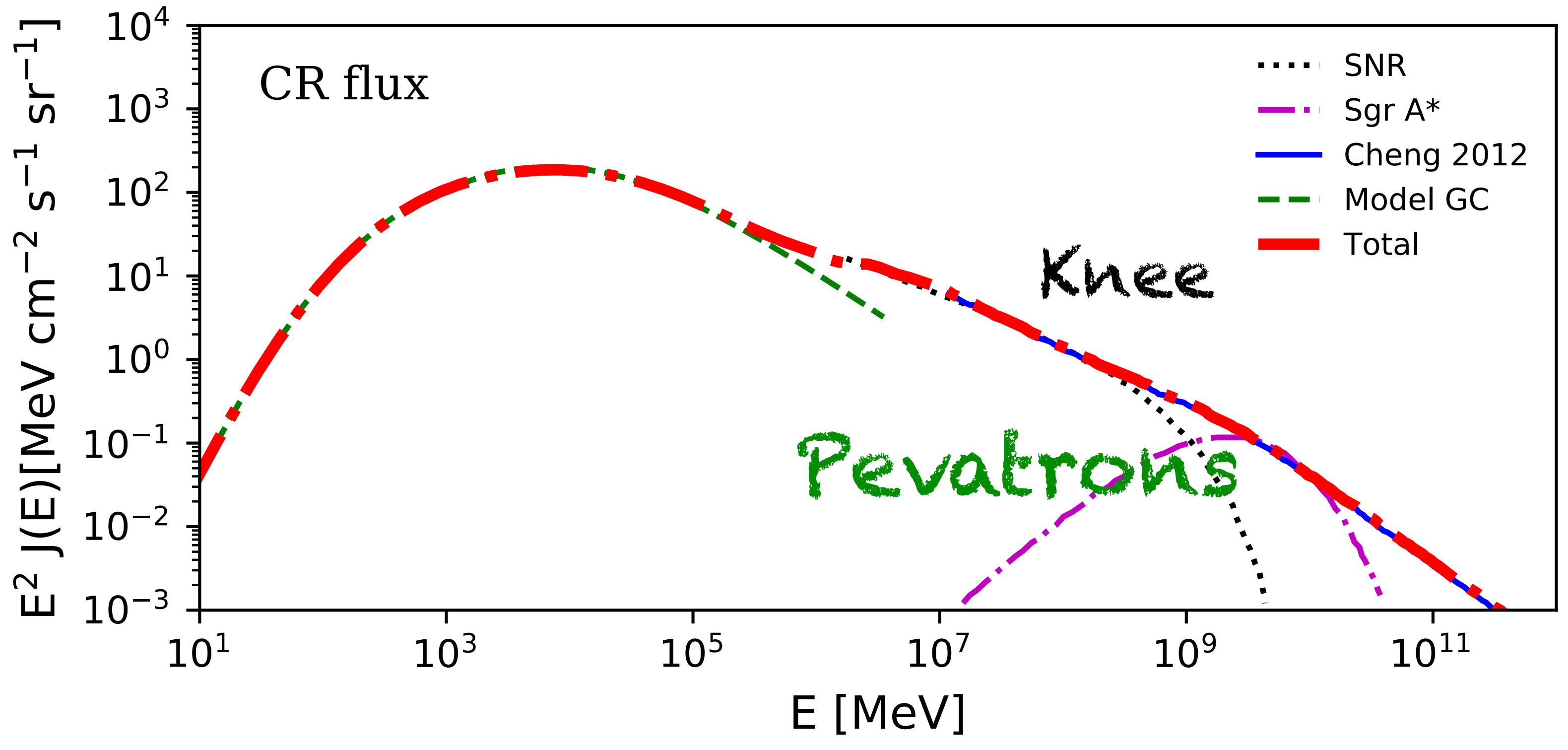
+ Neutrinos -> LCR

Anjos, 2014

• Conclusion

Acceleration up to knee and beyond energies

- PeVatron Sources (Magnetars, Pulsar wind nebulae, clusters Galactic center and Fermi Bubbles) with molecular cloud, winds …
- Multimessenger and magnetic fields
- Acceleration mechanism at source
- Distributions of interstellar gas
- Anisotropic diffusion



- Conclusion

Next Generation VHE Gamma-ray observatories

GeV-TeV coverage by near-future instruments

Improve the models with Galactic and Extra-galactic CRs and γ-ray fluxes from Observatories with different PeVatrons

https://www.cta-observatory.org/what-propogation-of-energetic-light-can-tell-us/

Associate