PeVatrons: Where are they hiding?

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CUA/NASA GSFC/CRESST II
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https://www.nature.com/articles/490024a

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Motivation

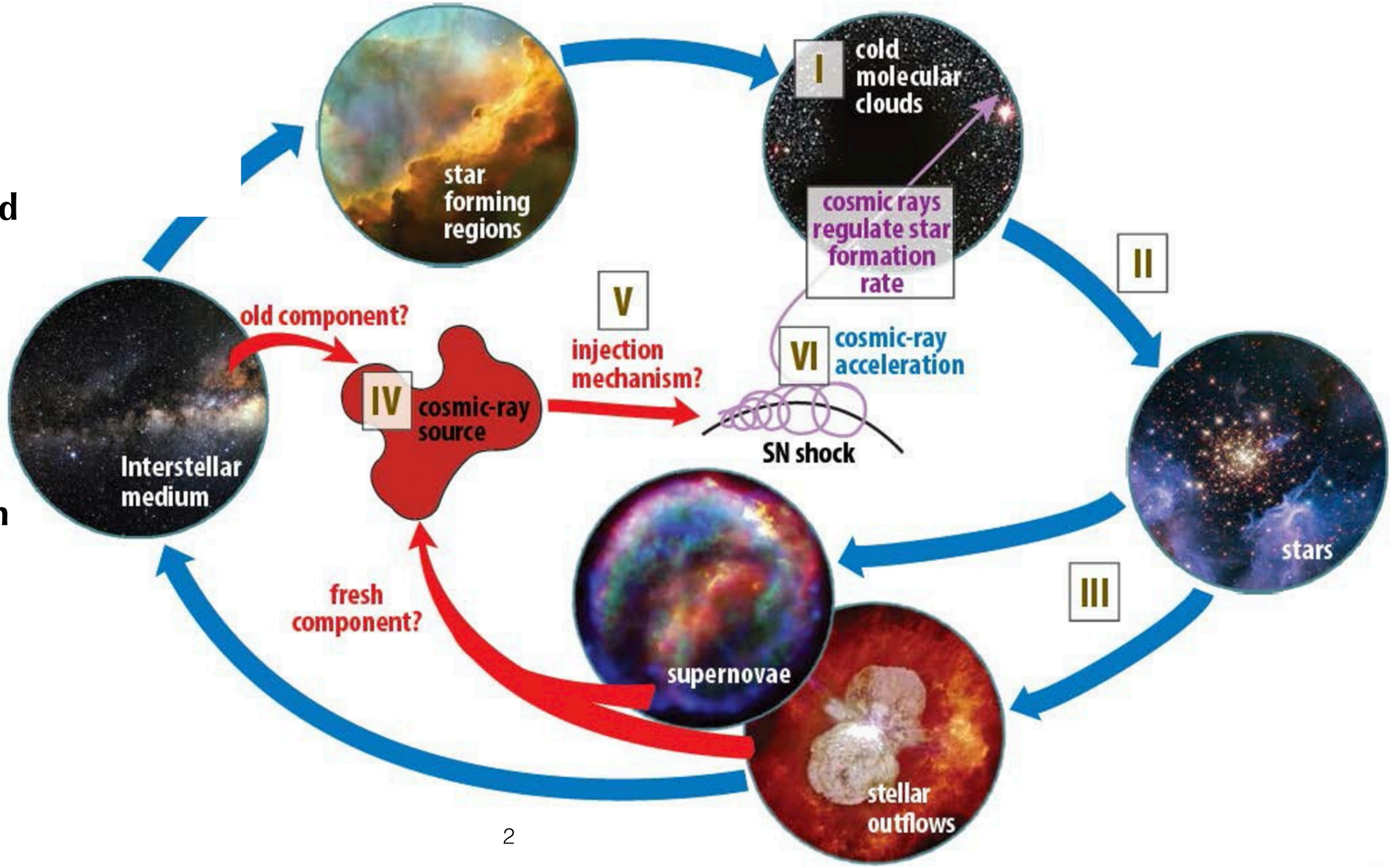
Cosmic rays affect and are affected by:

- Star formation,
- Magnetic fields,

and

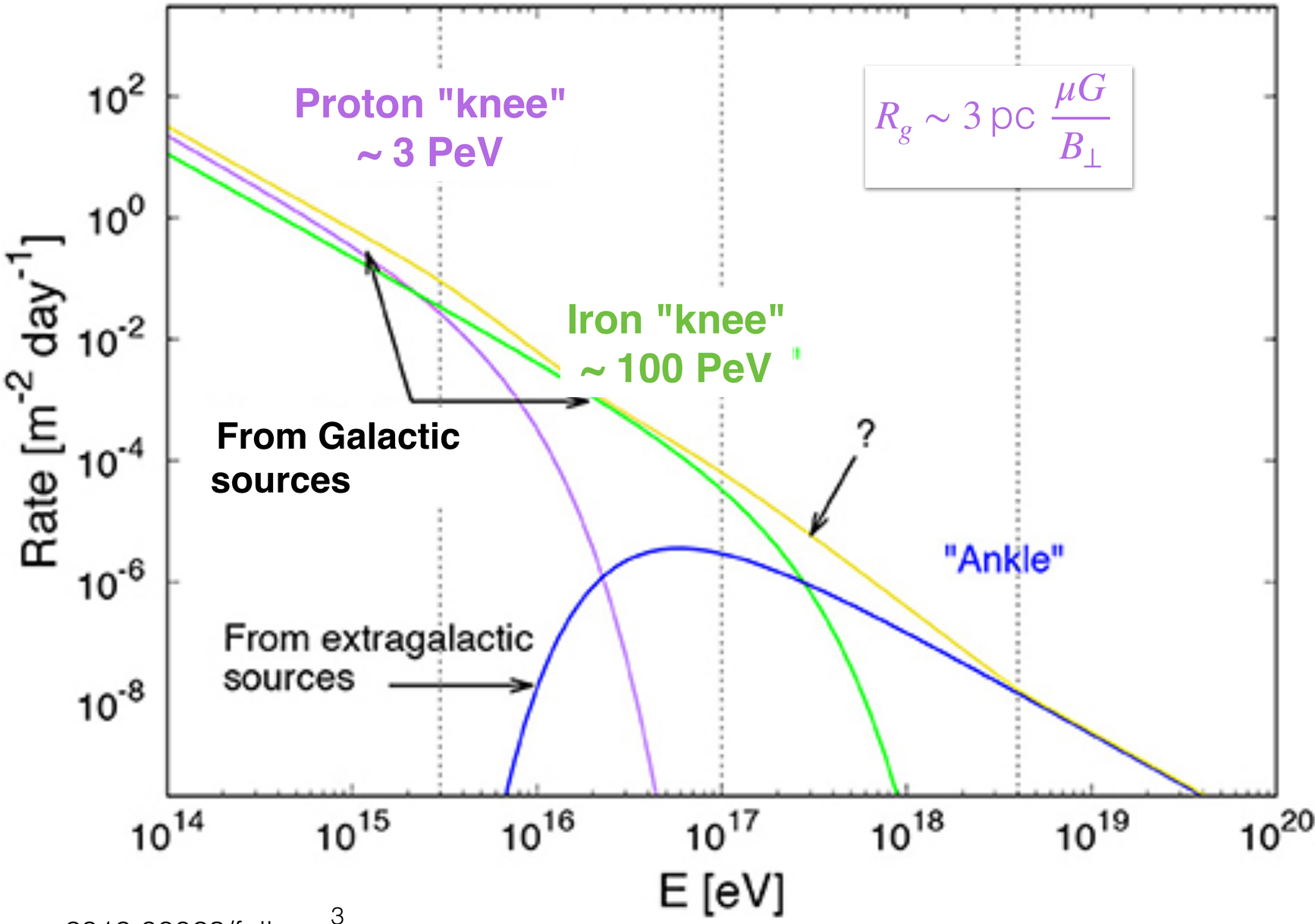
- Structure formation

In the Galaxy



https://pos.sissa.it/395/087/

The Cosmic Ray Spectrum at Earth

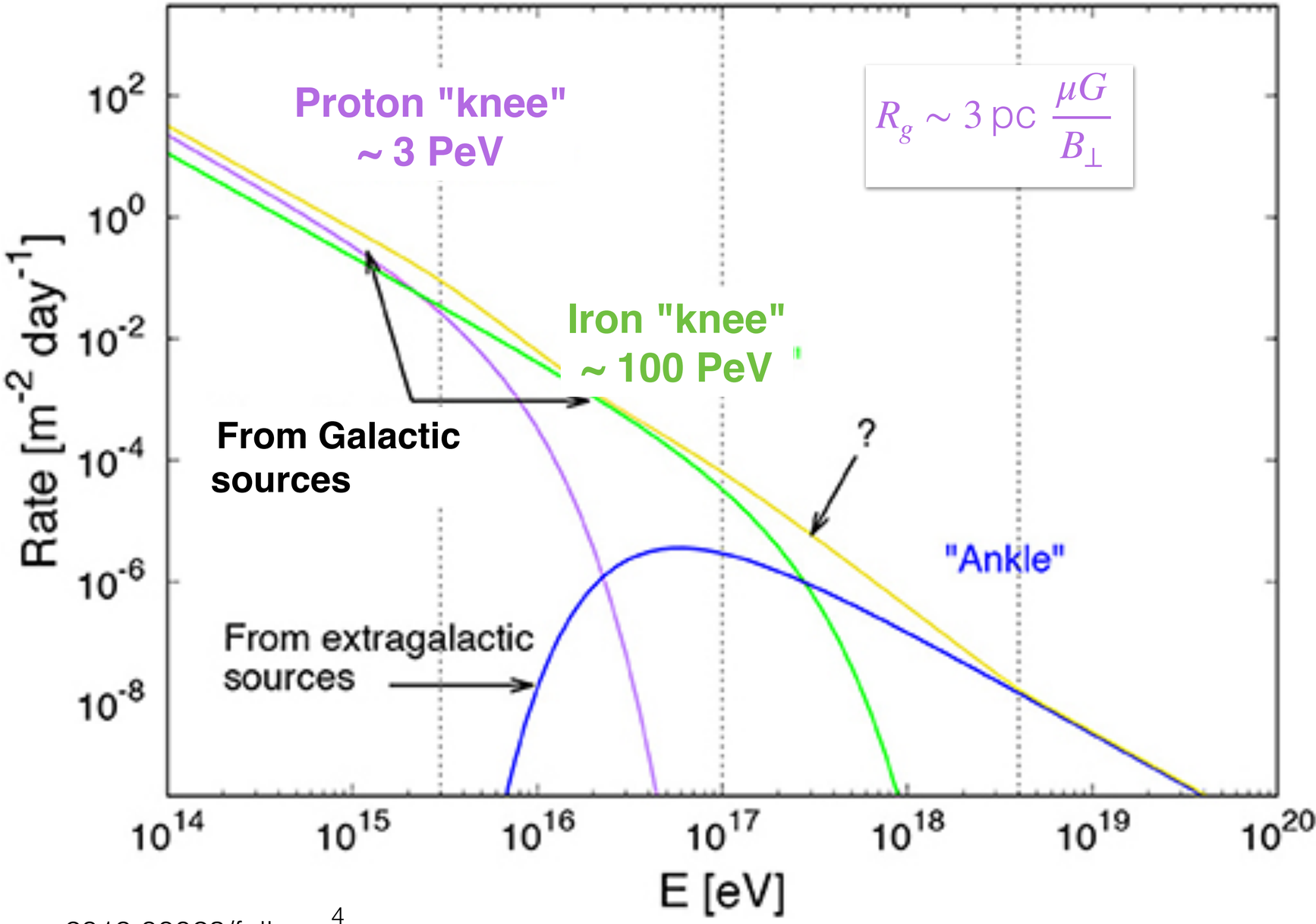


https://www.frontiersin.org/articles/10.3389/fspas.2019.00023/full

The Cosmic Ray Spectrum at Earth

PeVatrons are:

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



https://www.frontiersin.org/articles/10.3389/fspas.2019.00023/full

Cosmic Accelerators

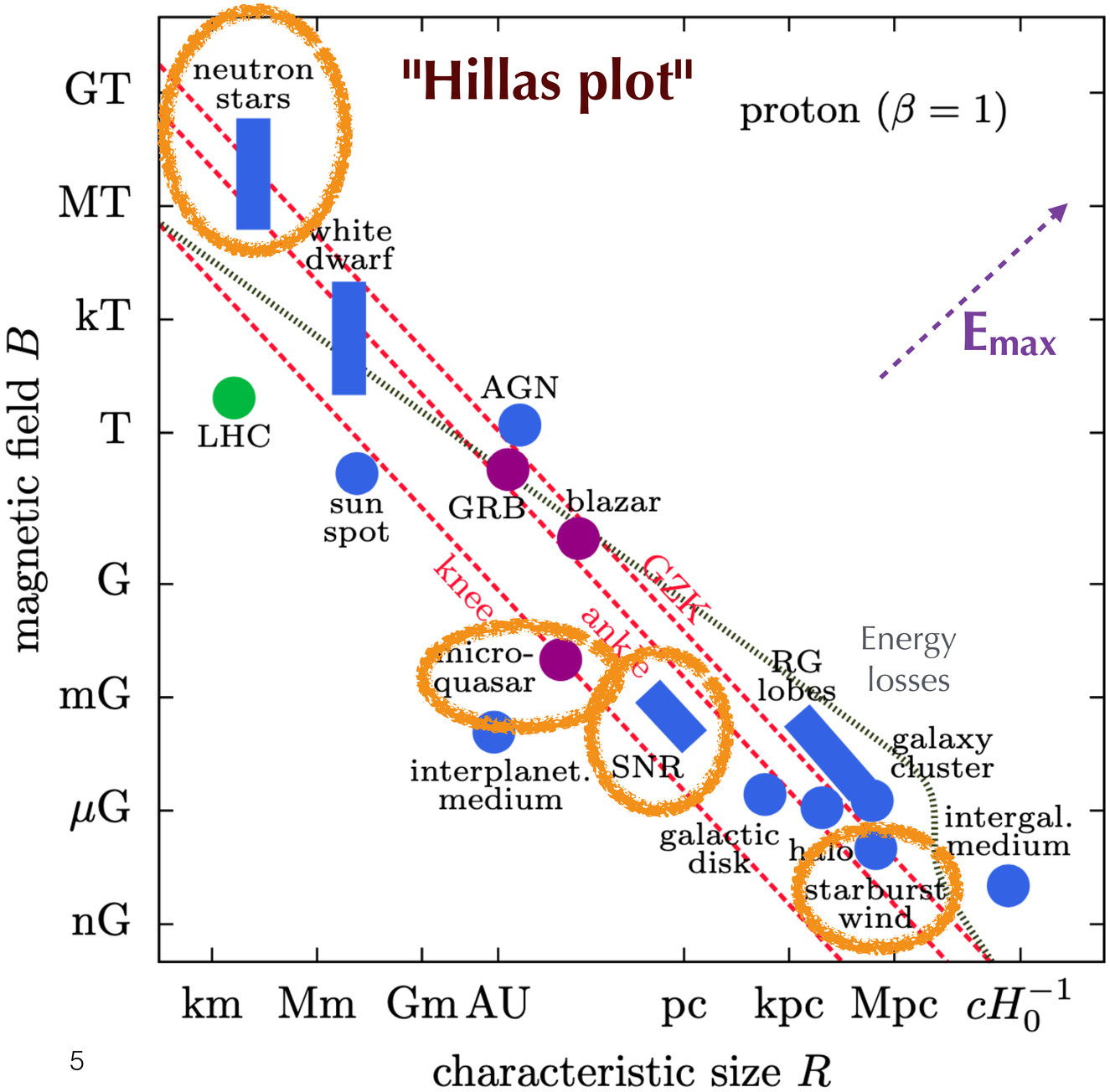
https://www.sciencedirect.com/science/article/pii/S0273117717303757

Requirements:

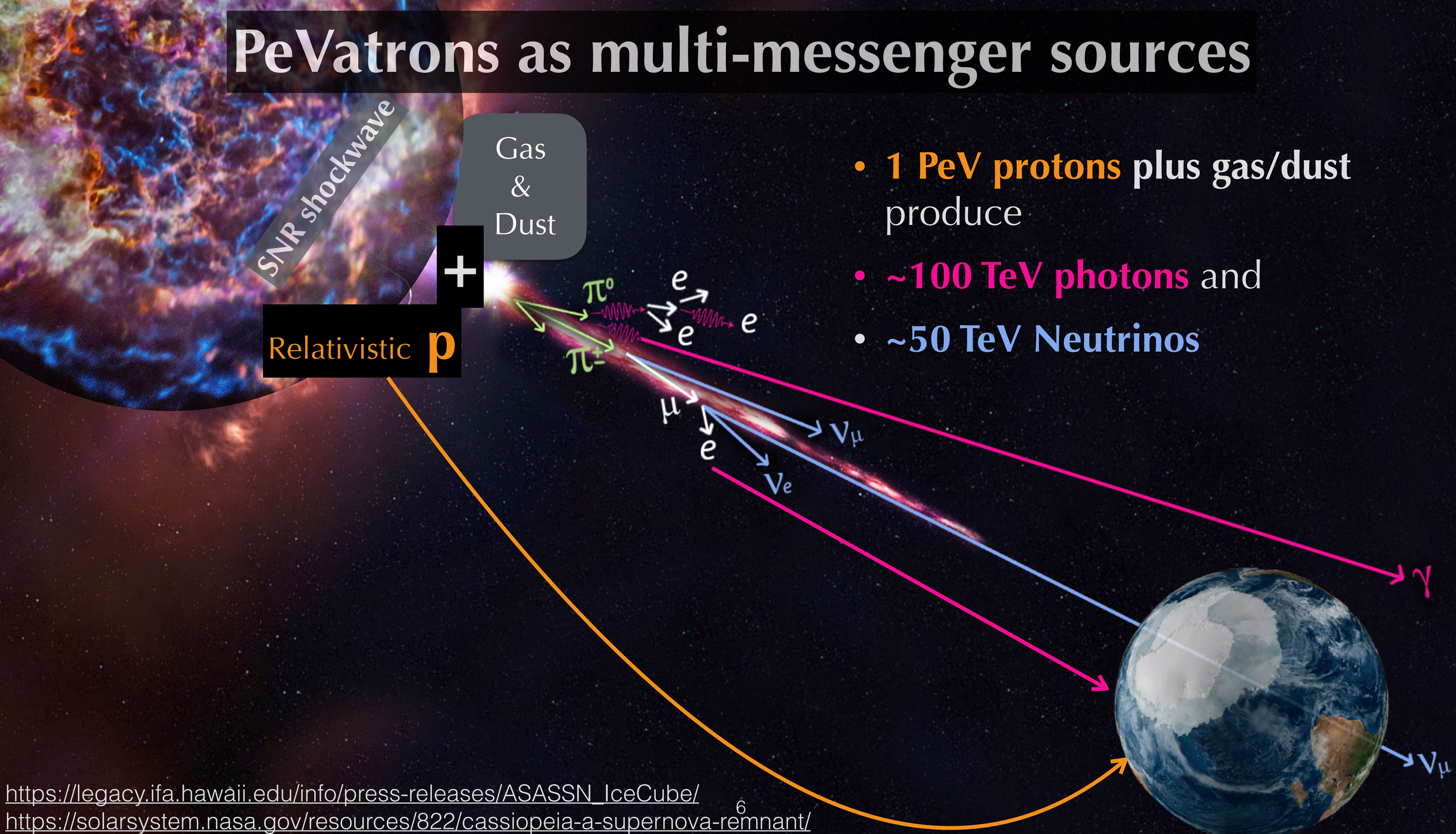
- Engine: Shocks or magnetic reconnection
- Charged particles
- Magnetic field (confinement)
- Energy budget
- Lifetime

Source candidates:

- Supernova remnants
- Pulsars and pulsar wind nebulae
- Starforming regions



PeVatrons as multi-messenger sources



- **1 PeV protons plus gas/dust** produce
- **~100 TeV photons** and
- **~50 TeV Neutrinos**

https://legacy.ifa.hawaii.edu/info/press-releases/ASASSN_IceCube/
https://solarsystem.nasa.gov/resources/822/cassiopeia-a-supernova-remnant/

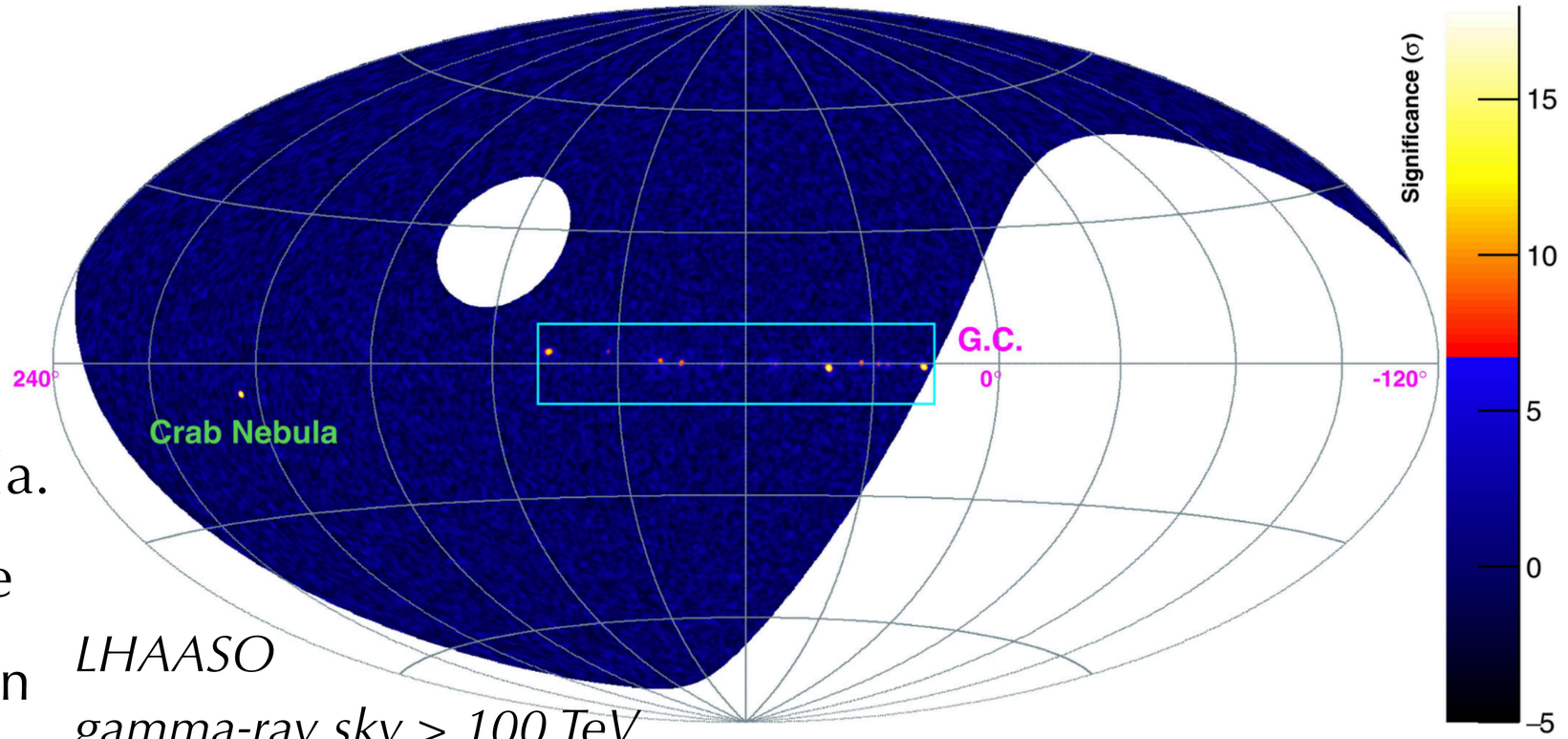
How to find PeVatrons

How **not** to find PeVatrons

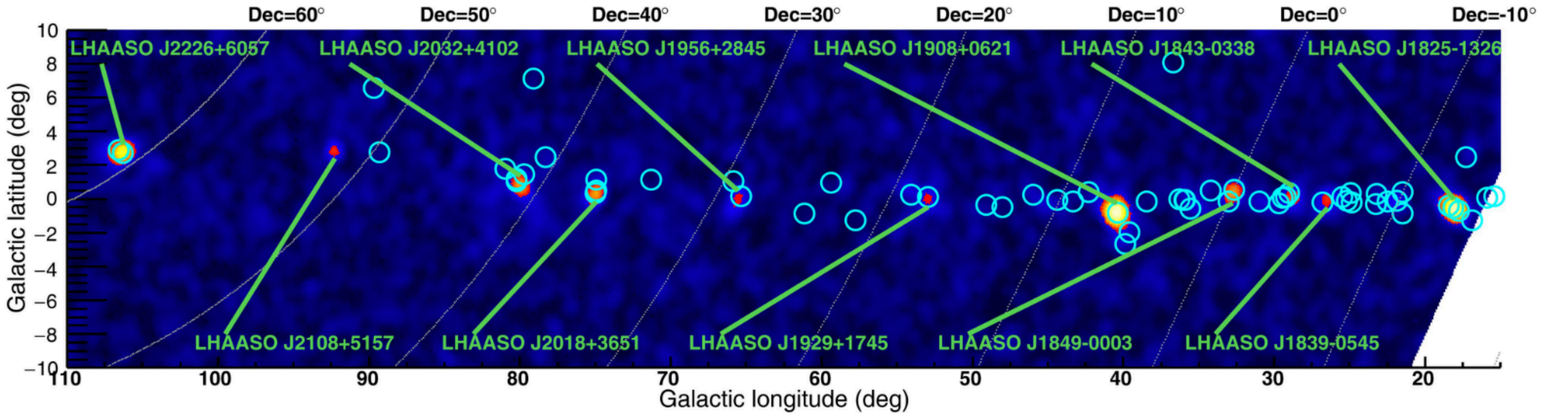
Myth 1: Emission > 100 TeV makes a PeVatron

- >10 known sources >100 TeV.
- Many show entirely leptonic emission (**leptonic PeVatrons**)
- Example: Crab pulsar wind nebula.
- Most UHE LHAASO sources have at least one **bright young pulsar** in the vicinity. (Correlation ≠ causation!)

  (E. de Oña Wilhelmi et al 2022)
- **Need in-depth MW spectral and spatial studies.**



LHAASO gamma-ray sky > 100 TeV



https://www.nature.com/articles/s41586-021-03498-z

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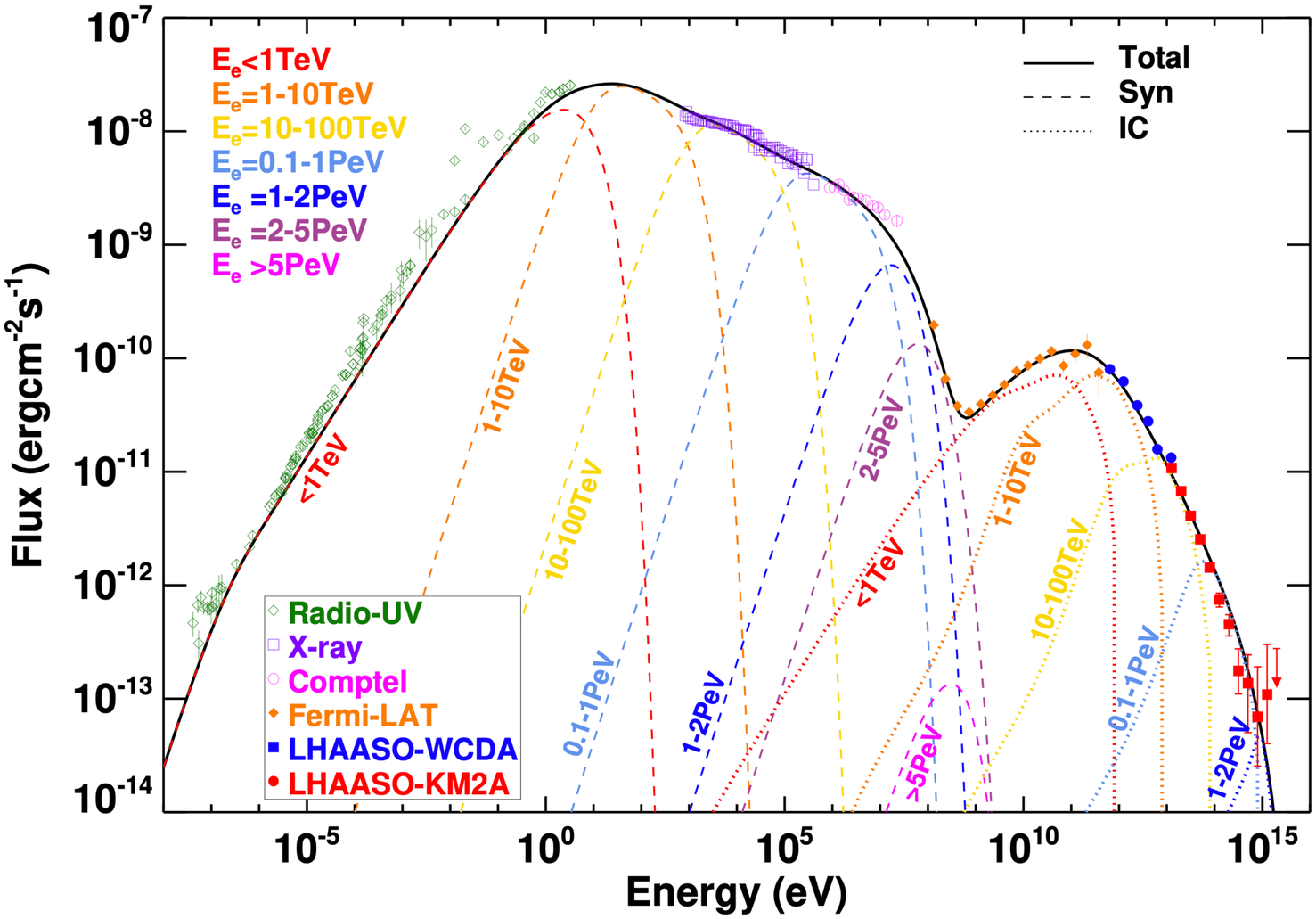
Crab nebula energy spectrum and leptonic model

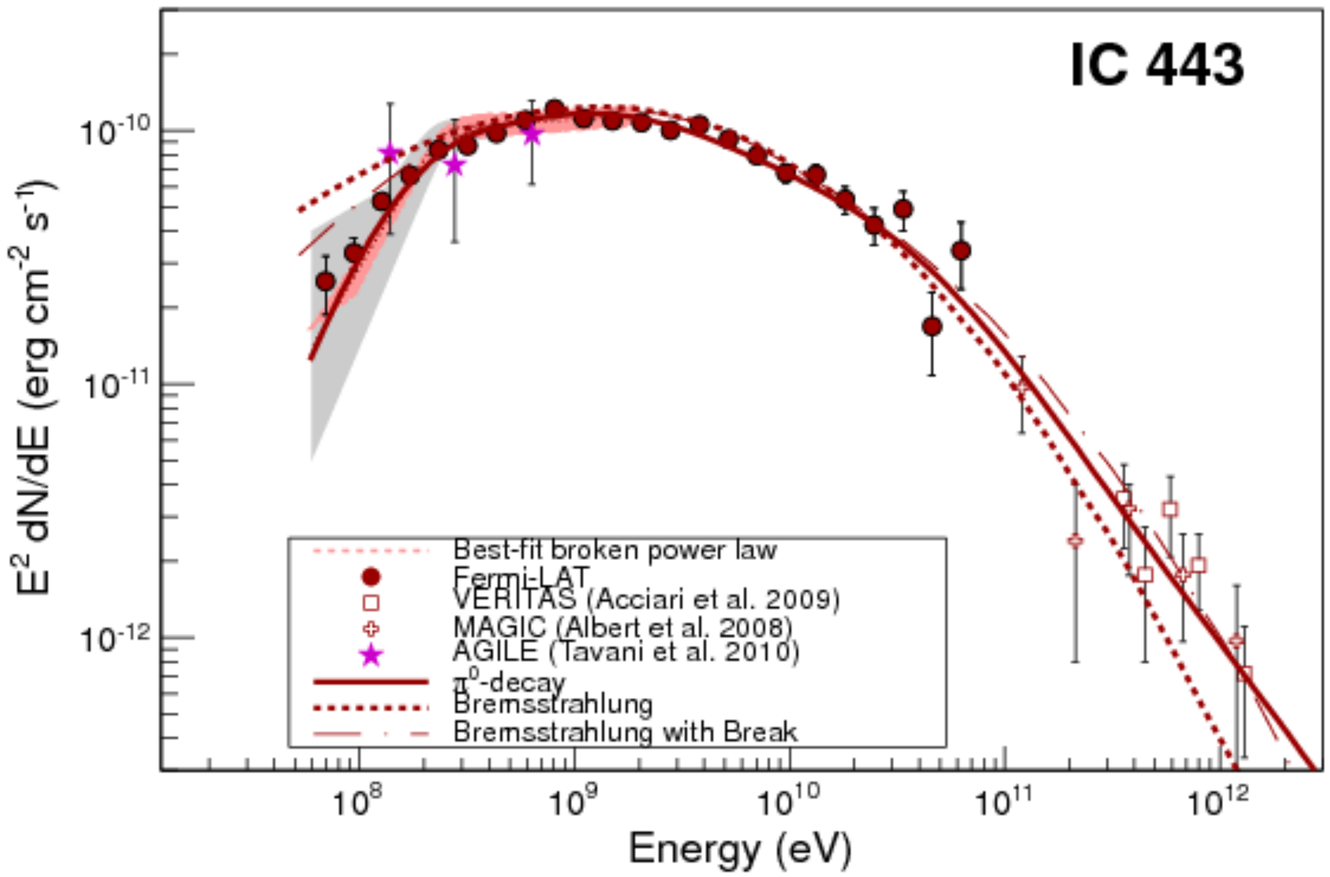


https://www.science.org/doi/10.1126/science.abg5137

Myth 2: The pion bump feature

- Pion decay production mode: spectral break at $E \sim 2 \cdot m_\pi \sim 280$ MeV.
- Disentangle hadronic and leptonic emission modes.
- Pion bumps observed in multiple SNR spectra.
- None of them emit > TeV energies!
- **Pion bump more prominent in soft-spectrum sources.**

https://www.science.org/doi/10.1126/science.1231160



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https://www.annualreviews.org/doi/full/10.1146/annurev-nucl-102014-022036

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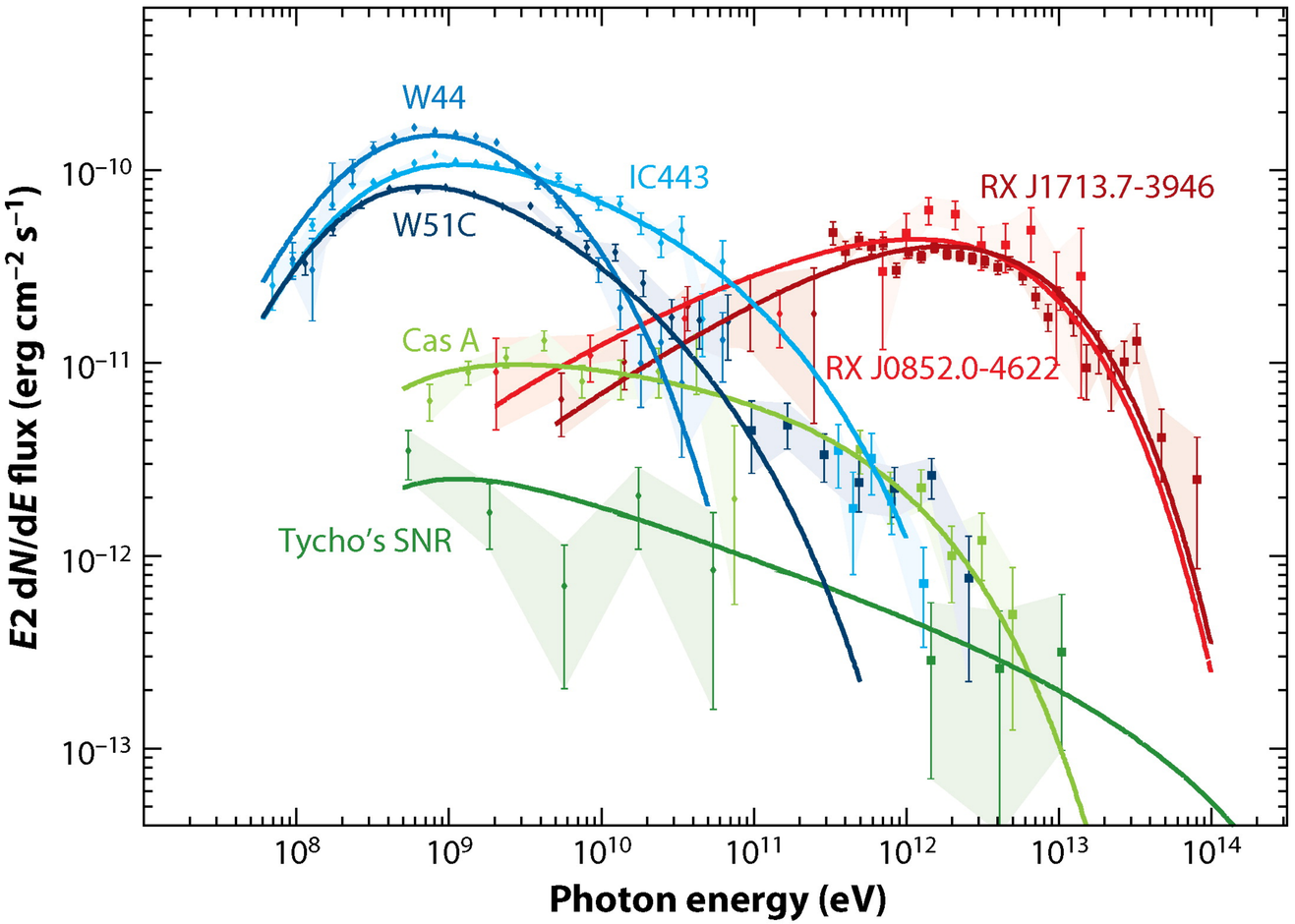
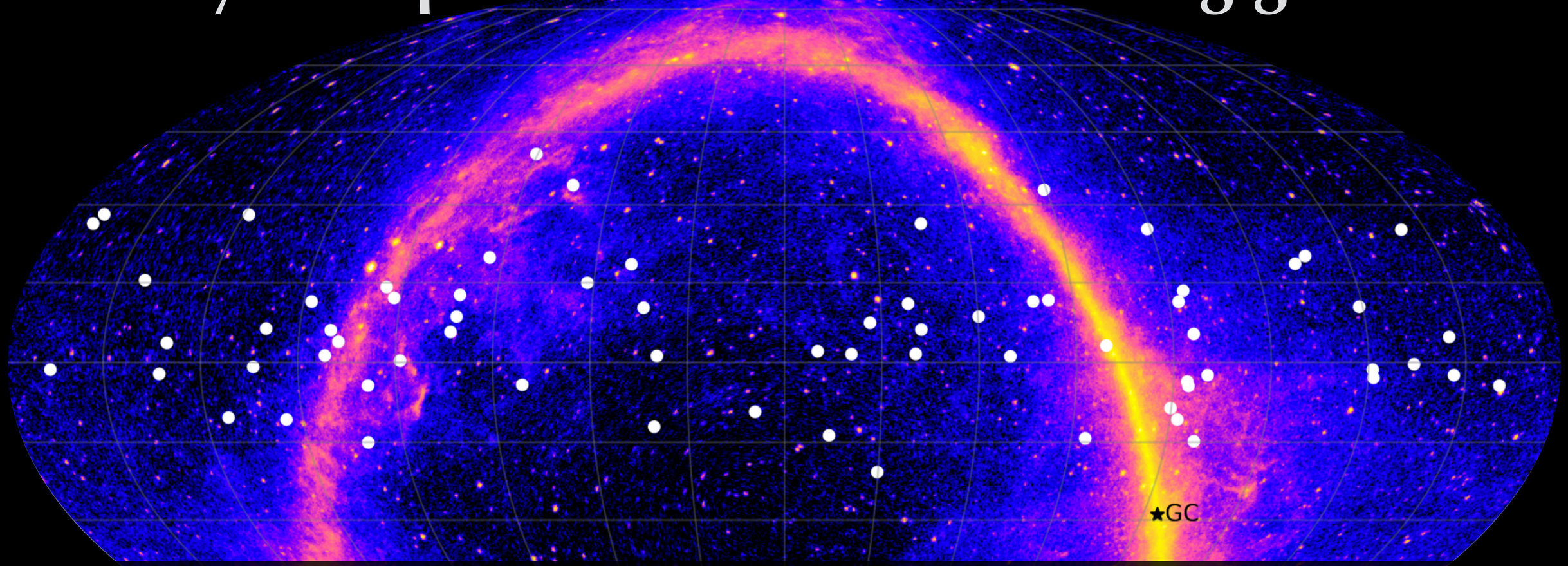


~~Myth~~ Hope 3: Neutrinos as smoking guns?

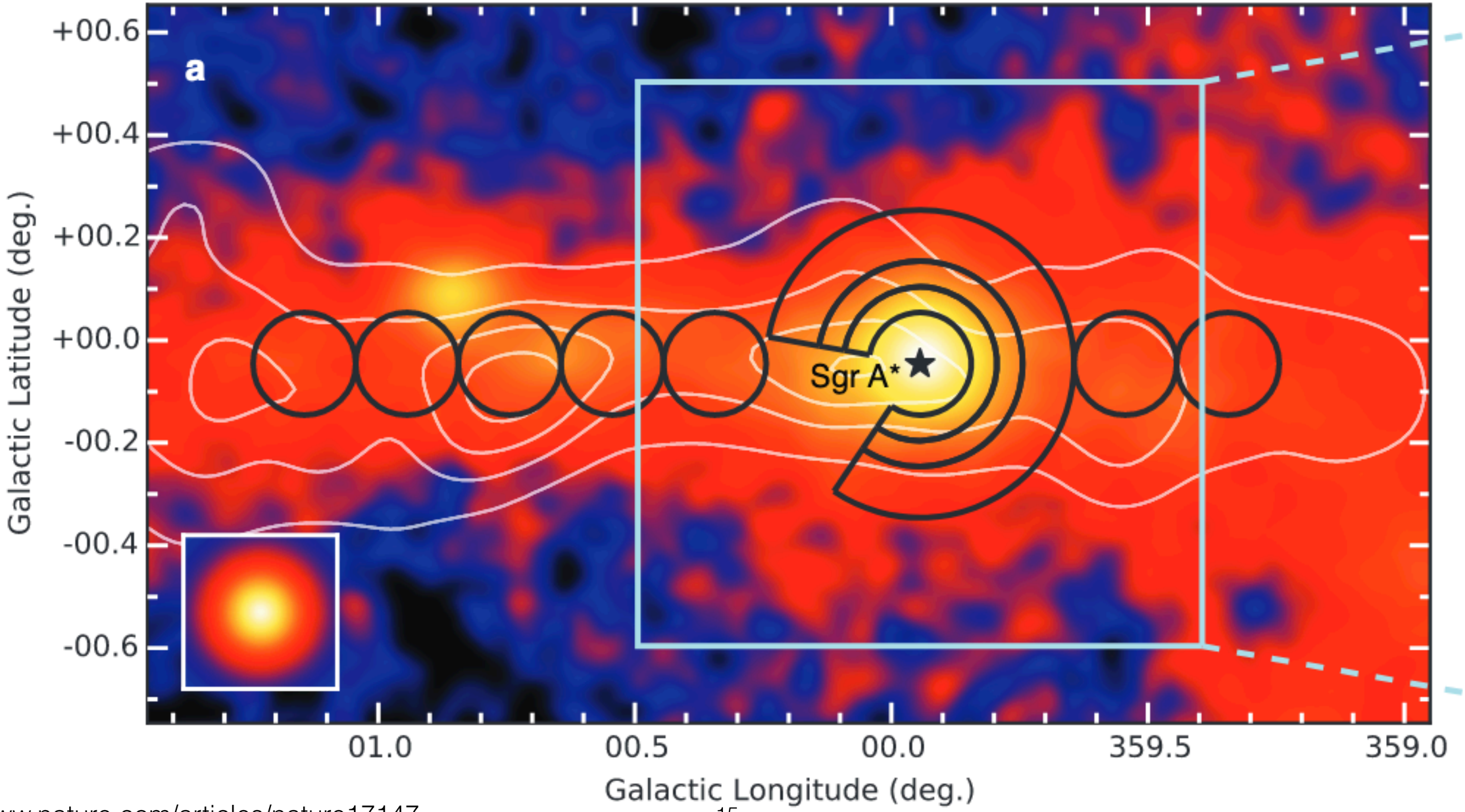


- ~50 TeV neutrinos guaranteed to accompany ~100 TeV photons from PeVatrons.
- First evidence (4.1σ) for diffuse neutrino signal >200 TeV from Galaxy.
- Current neutrino observatories lack sensitivity to individual PeVatrons.

https://arxiv.org/abs/2208.08423

How to find PeVatrons

Diffuse PeV protons near the GC

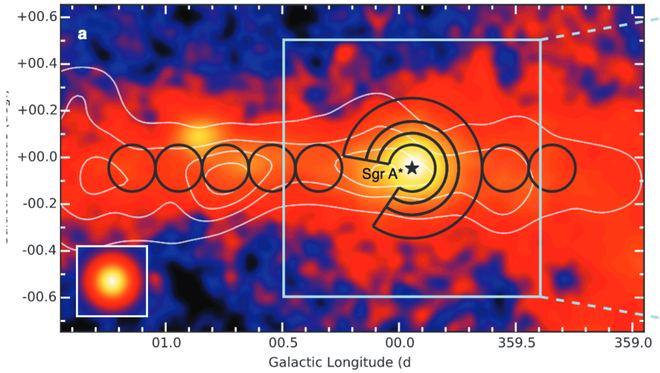


https://www.nature.com/articles/nature17147

Diffuse PeV protons near the GC

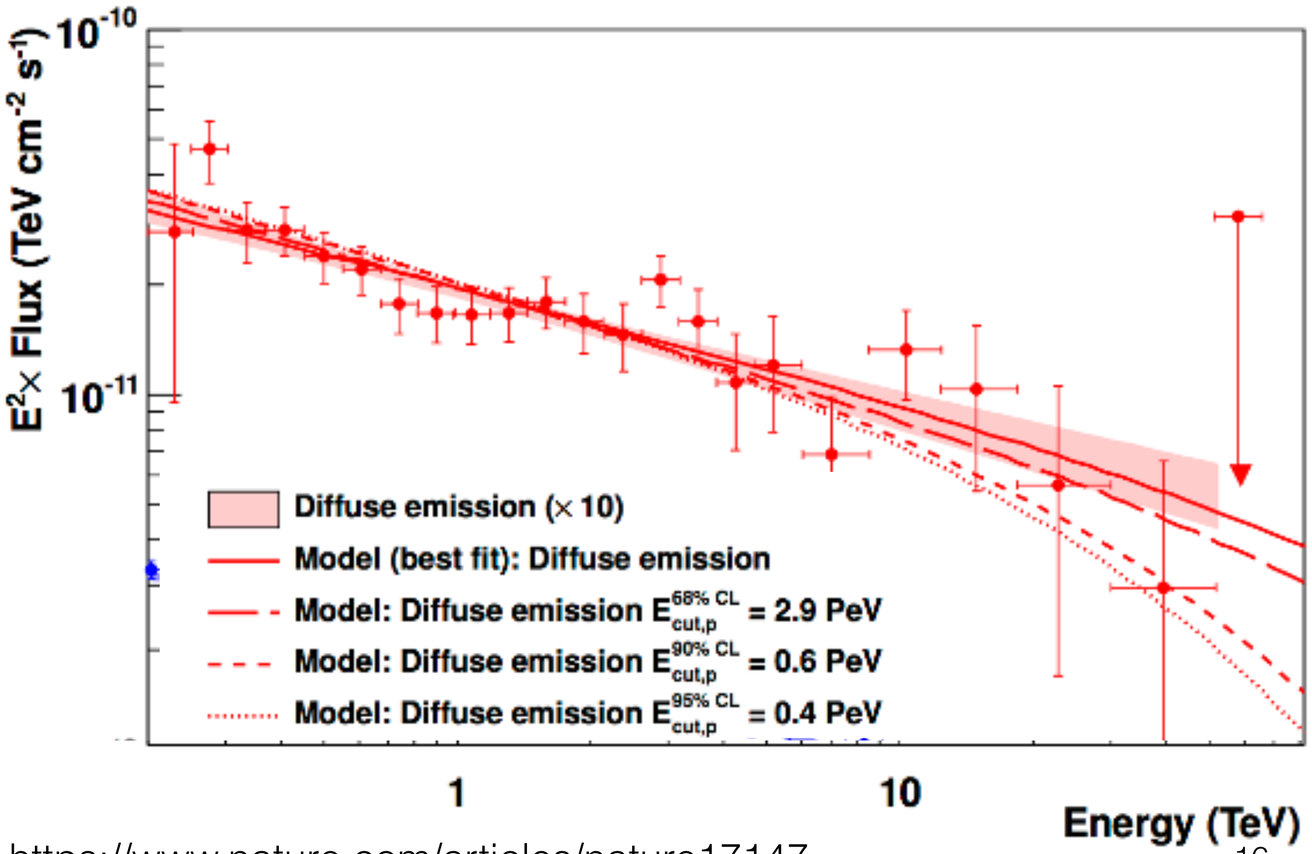
Gamma-rays >50 TeV:

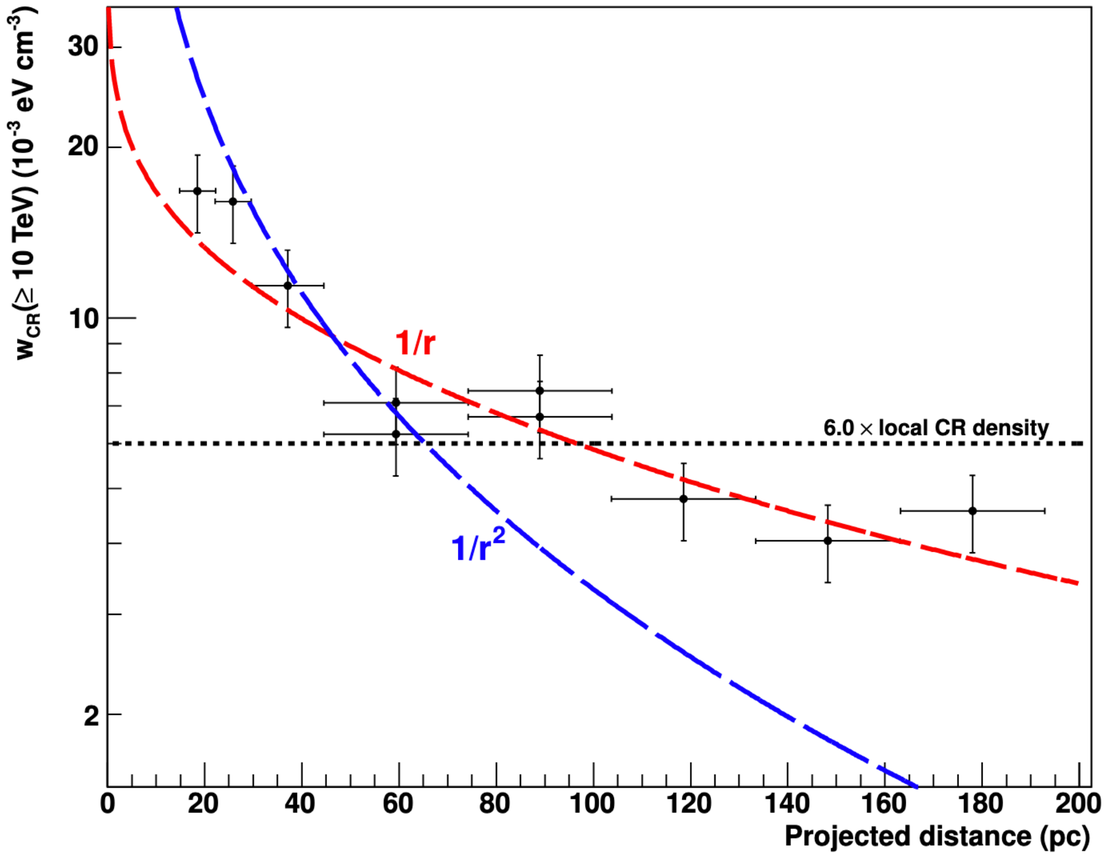
PeV protons



Gamma-ray **morphology**:

Proton **diffusion** from Sag A*





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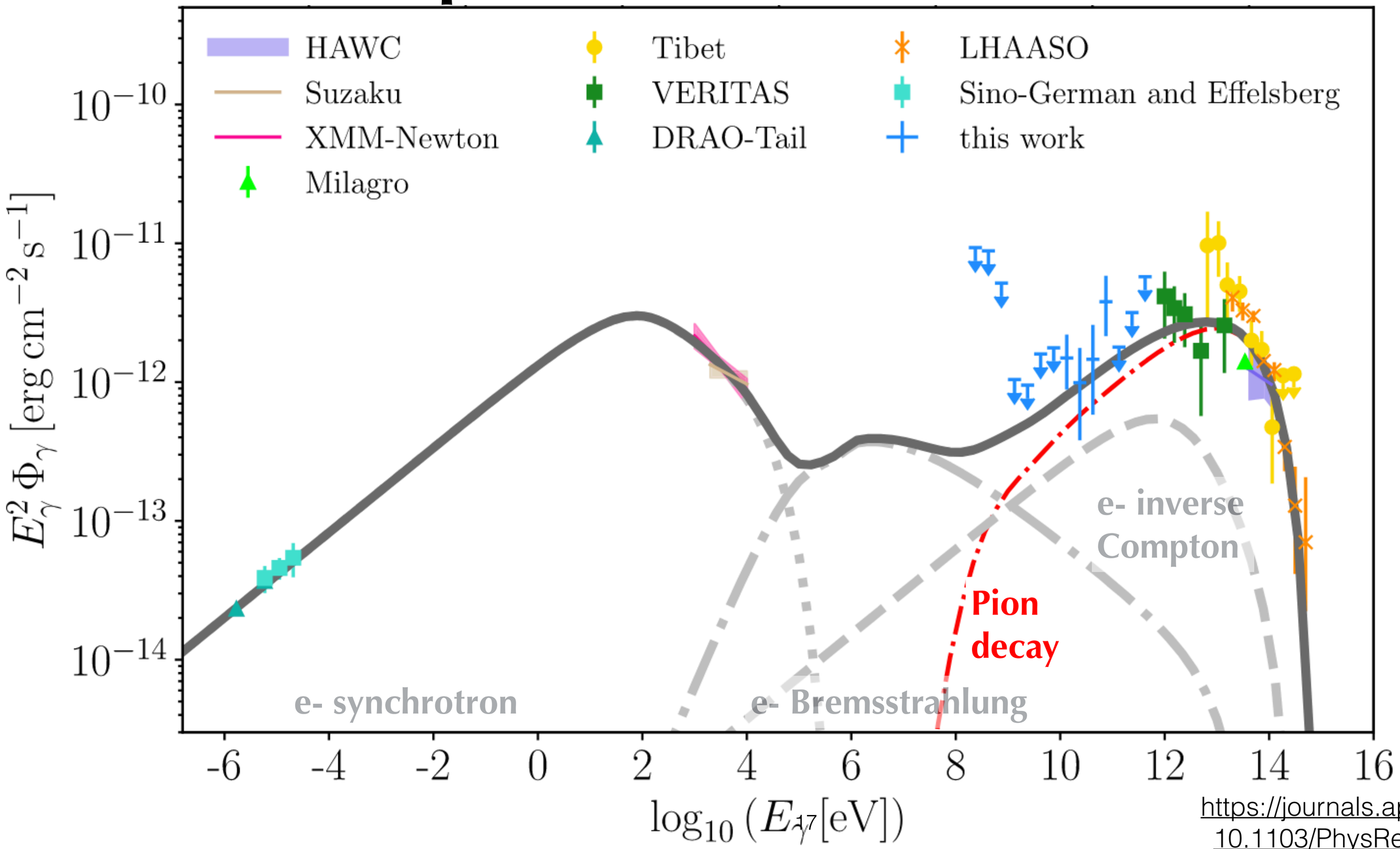
PeV protons in SNR G106.3 +2.7



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

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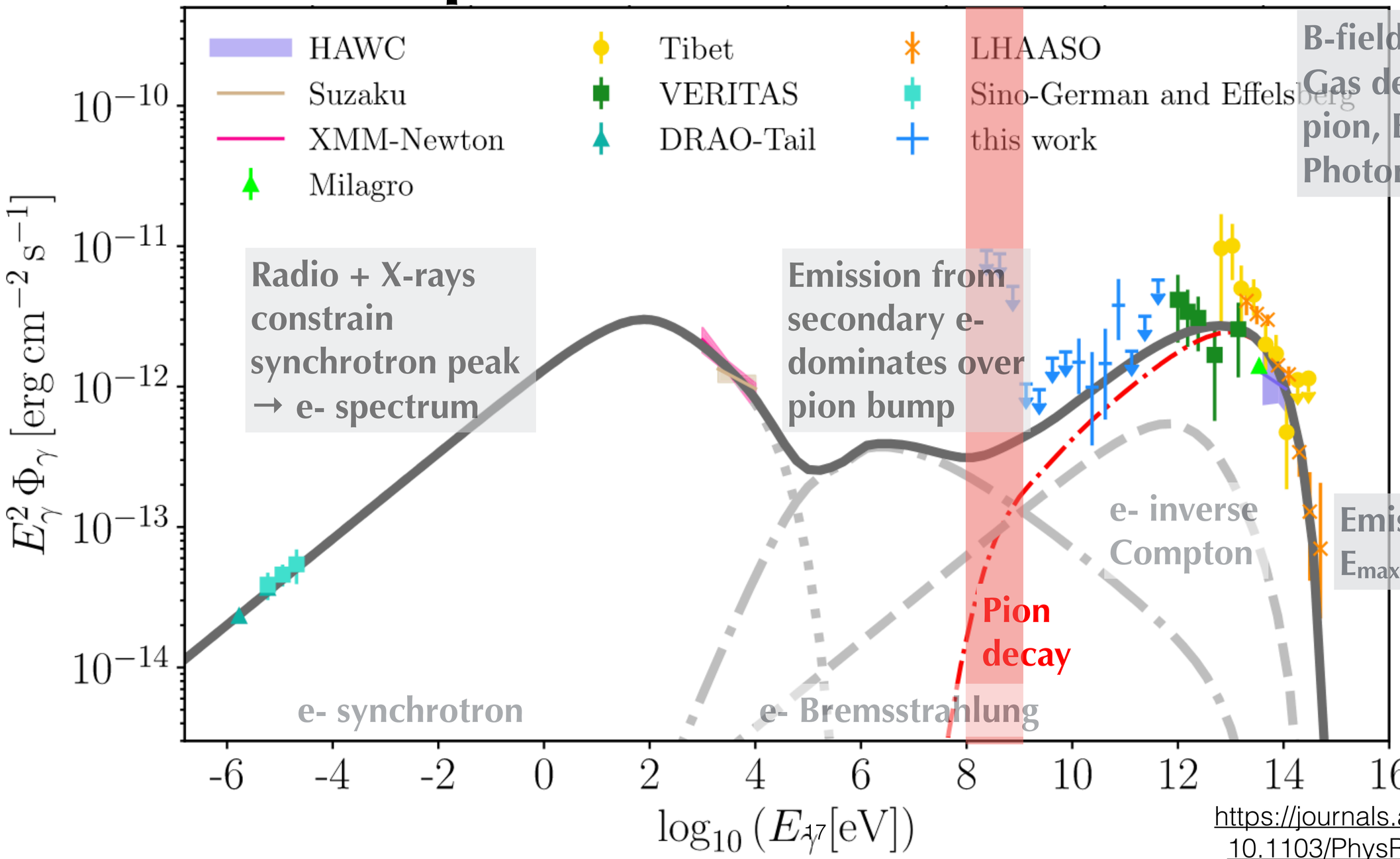


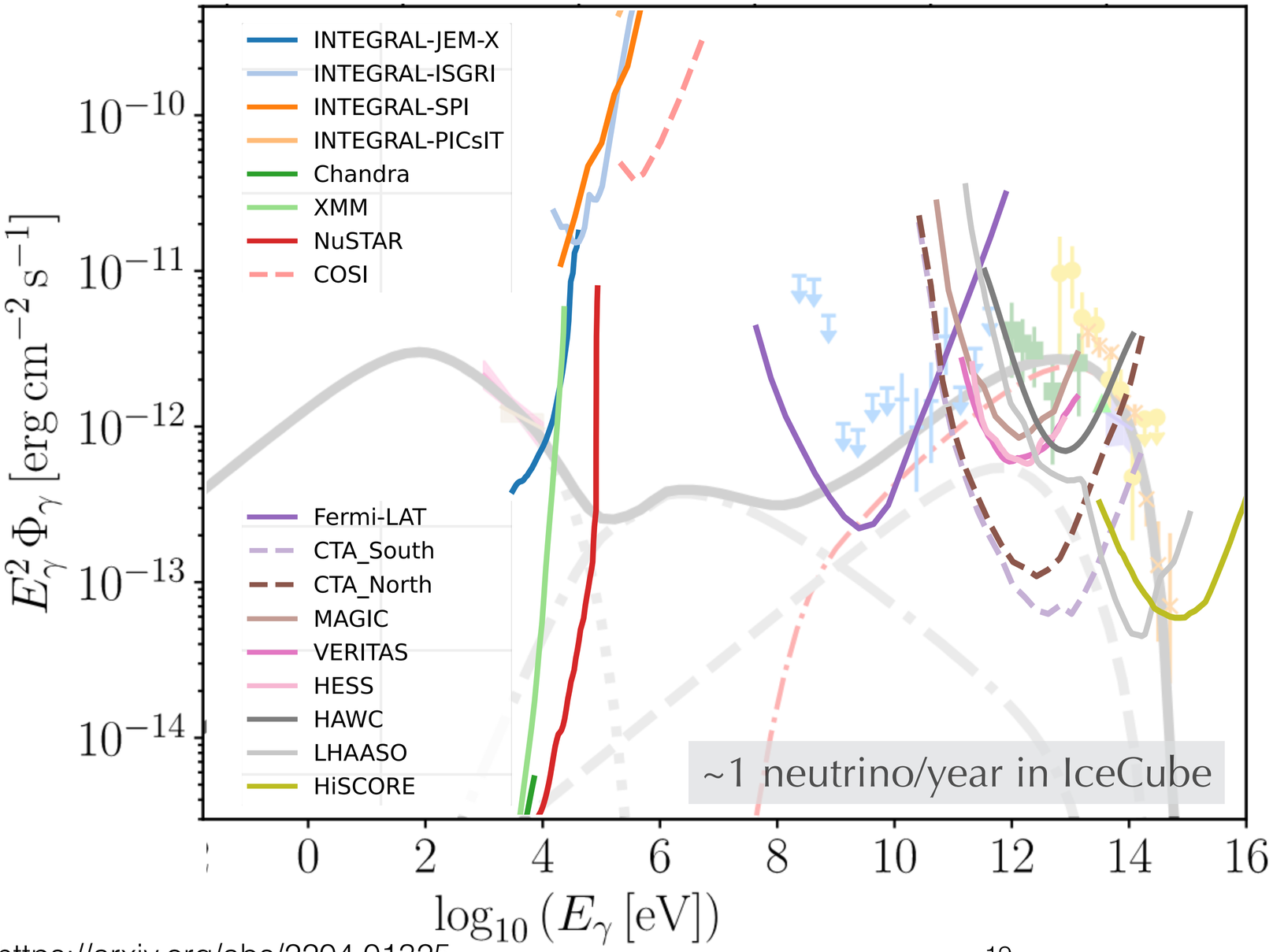
B-field → synchrotron
Gas density → pion, Bremsstrahlung
Photon fields → IC

Emission 100 TeV: E_{max} ~ 1 PeV

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

What's Next?

More of the same?



- **Gamma rays (and neutrinos) generic features of shock acceleration.**
- Excellent GeV-TeV coverage by near-future instruments.
- Contamination from Galactic diffuse gamma-ray background and other sources.
- X-ray limited by source confusion and source size.
- MeV band (Bremsstrahlung) challenging.
- Neutrino detection requires larger instrumented volume.

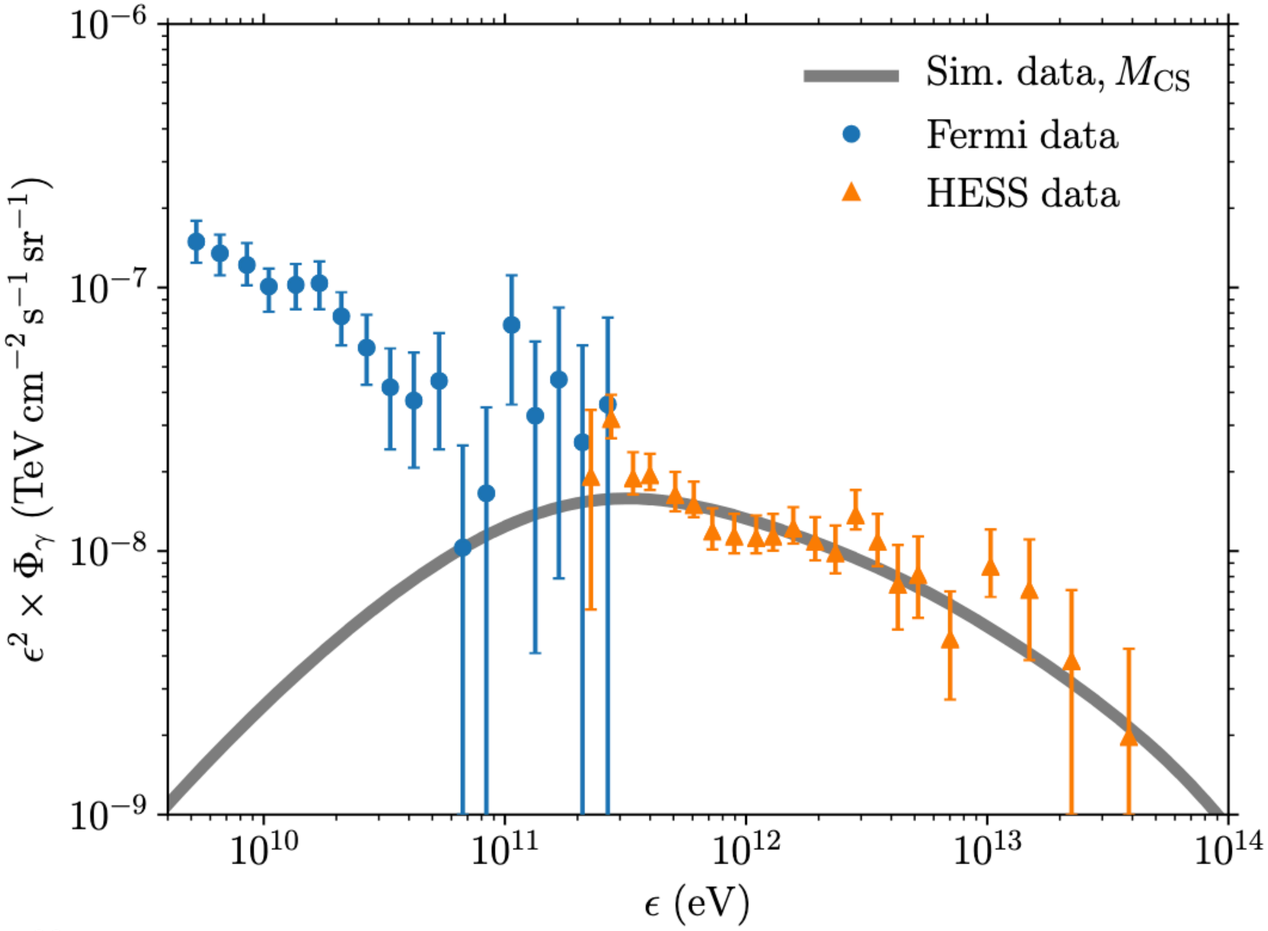
https://arxiv.org/abs/2204.01325

What if: Dark Accelerators

- "Naked" PeVatrons? (e.g. isolated pulsars)
- No gas → no pions →no ɣ, no ν ☹️😞
- But: Bright IC emission from e-
- **If pulsars dominate PeV cosmic rays, many of them must be PeVatrons.**
- **Globular clusters have many pulsars.**
- Search for pion decay photons and neutrinos from molecular clouds near globular clusters.
- Other ideas?

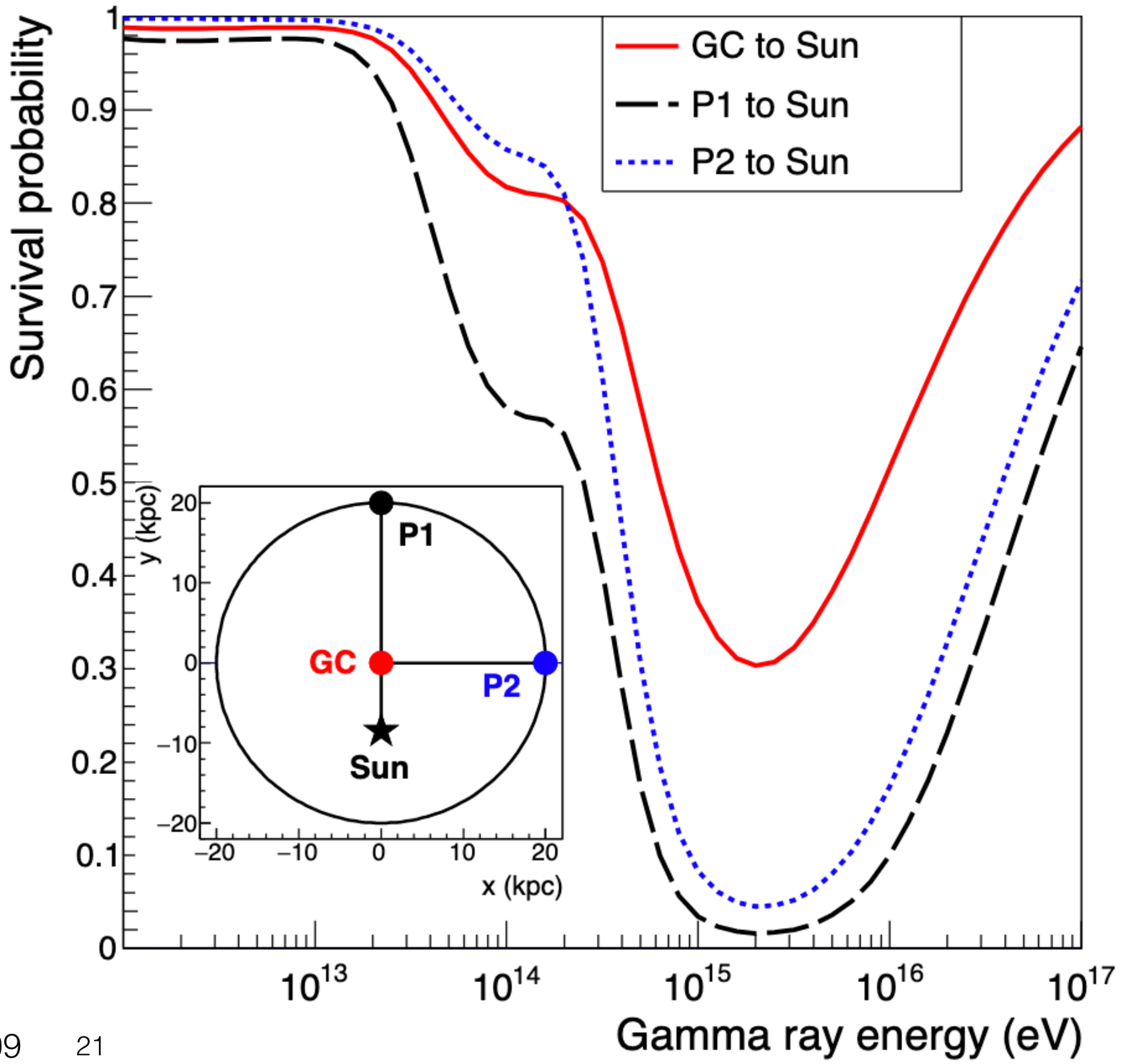
Proton acceleration by **milli-second pulsars** explains GC PeVatron.

https://iopscience.iop.org/article/10.1088/1475-7516/2018/07/042



Gamma-ray absorption

- **Photons > 100 TeV absorbed by starlight (IR) and CMB.**
- Can be accounted for given photon fields and cross sections.
- Build bigger instruments?
- Neutrinos are **not** absorbed.



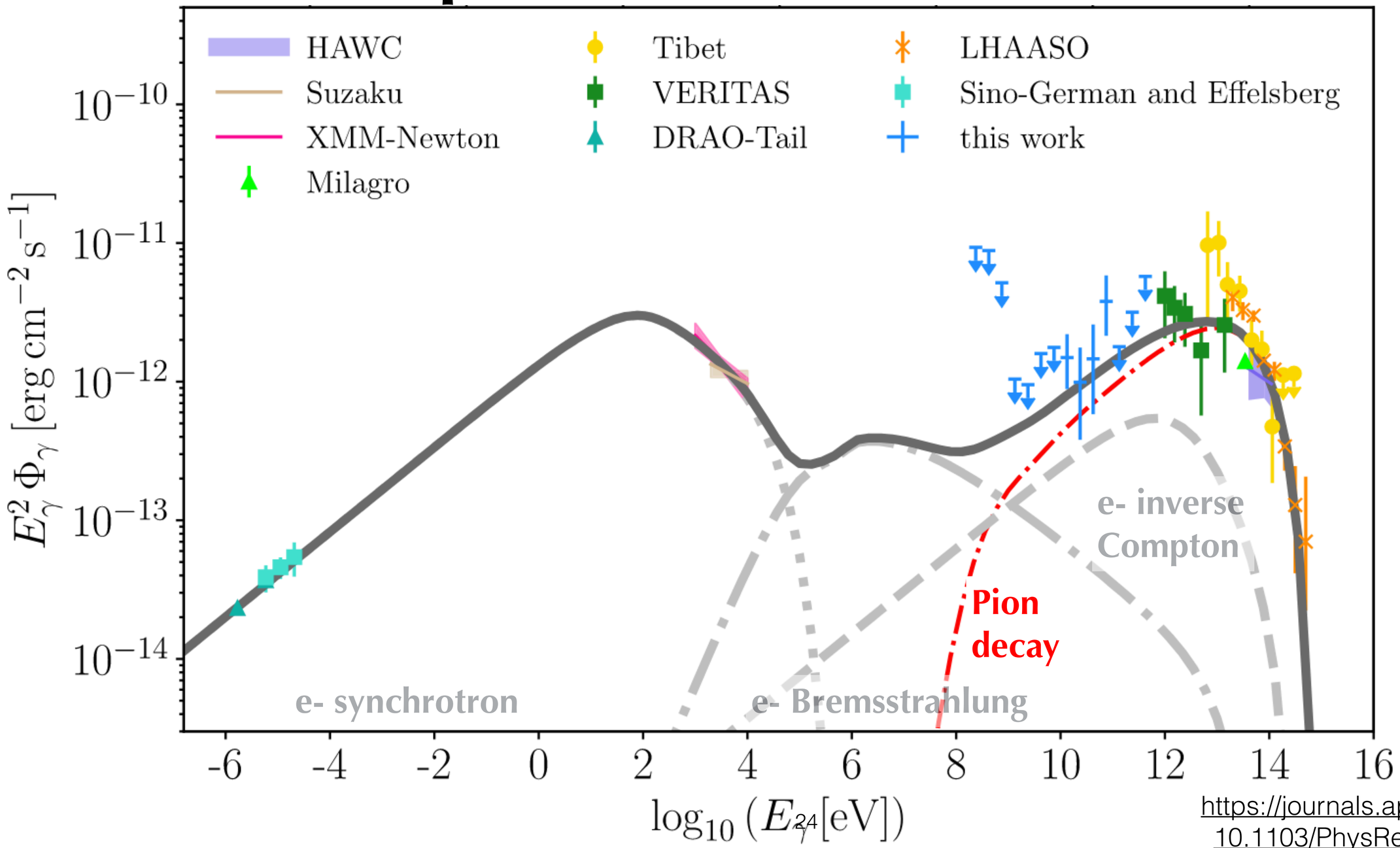
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.94.063009

A Wishlist

- Round them up: **Sensitive Galactic survey in TeV - PeV photons**
- Weed out the leptons: **Multi-wavelength coverage** with >degree FoV to constrain secondary electron population and source environment.
- Study in depth: ≤ **arcmin angular resolution in TeV - PeV**
  - Source position: source identification
  - Source morphology: Acceleration process, source evolution.
- Understand the environment: **3D gas distribution** and photon fields in Milky Way.
- Cross checks: **Diffuse gamma-ray** emission, **direct CR** measurements.
- Cherry on top: **PeV neutrinos** from galactic sources.

Backup

PeV protons in SNR G106.3 +2.7



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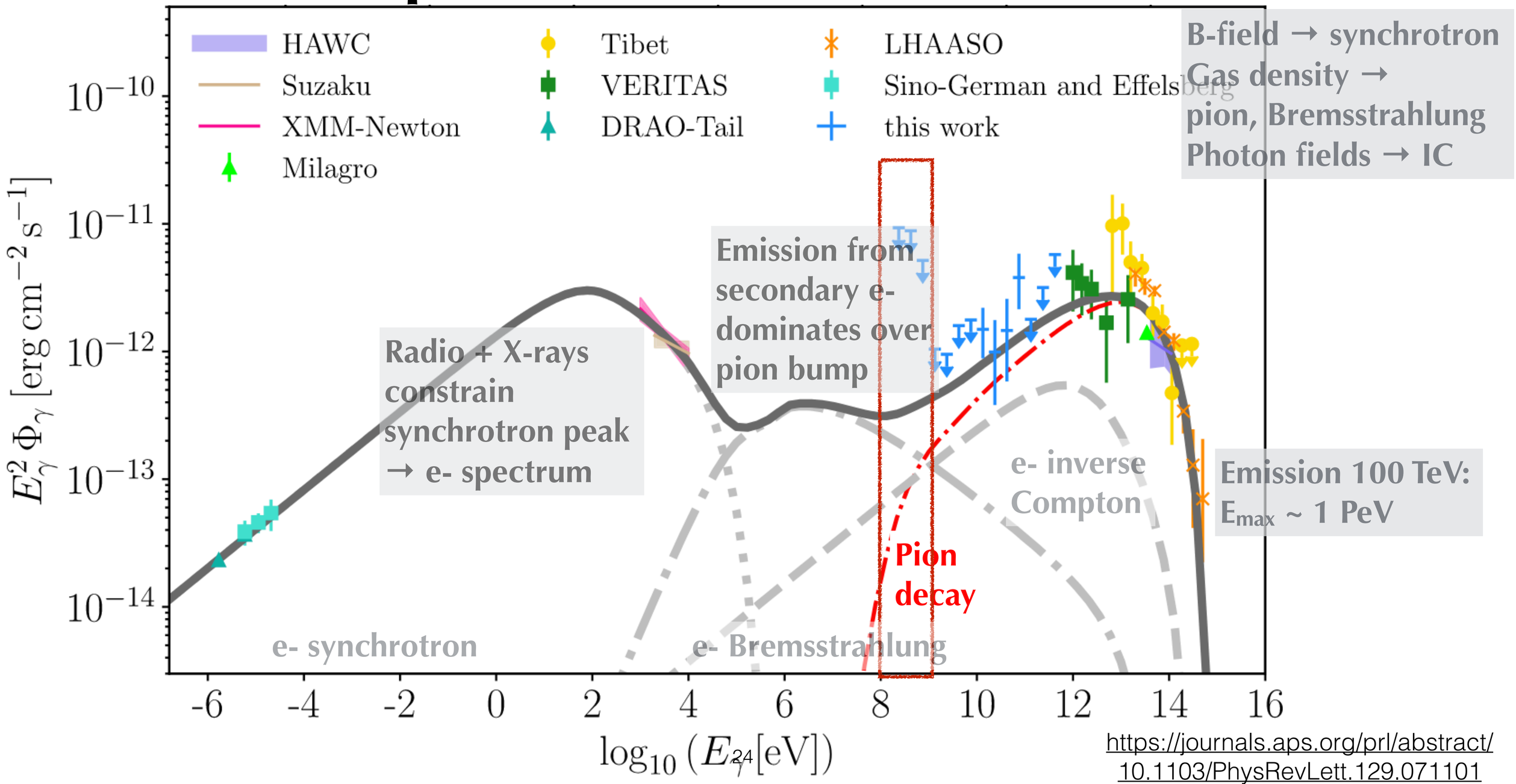

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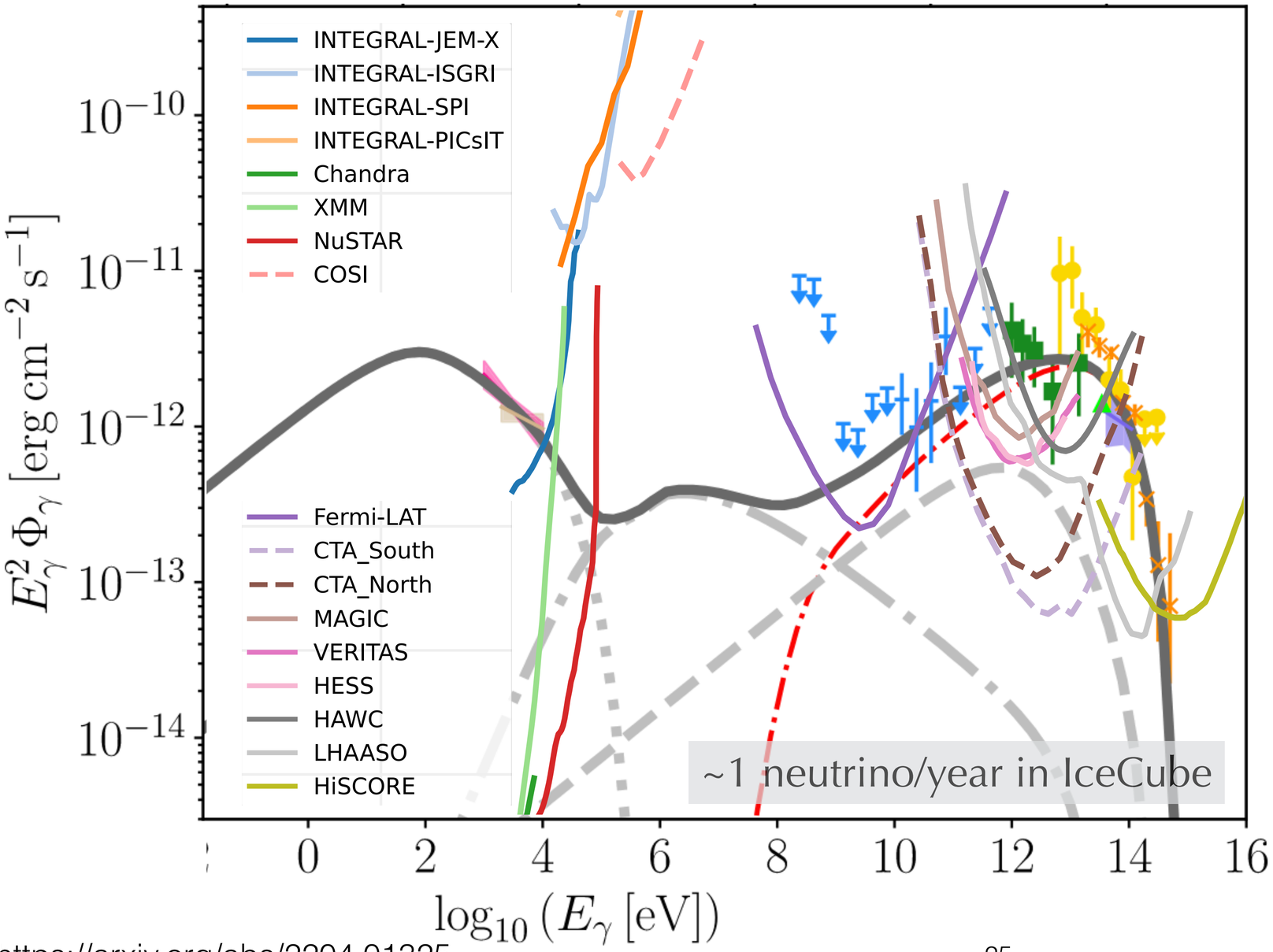

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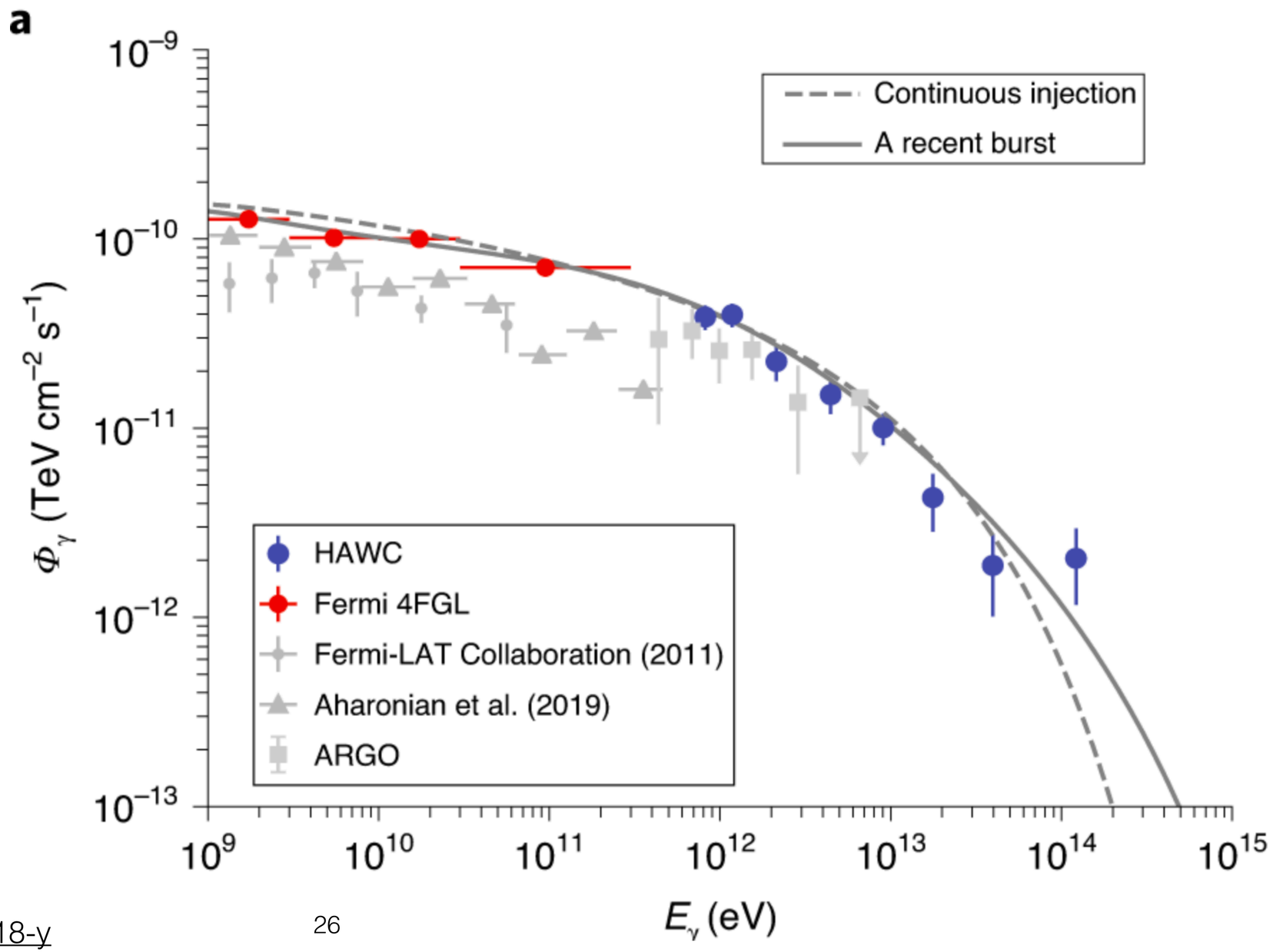
>100 TeV Protons in Cygnus OB2 association

- **Protons >100 TeV** explain gamma-ray emission**.**
- X-ray/radio observations disfavor leptonic origin.
- Continuous acceleration or "recent" starburst activity.
- **~1% of the kinetic energy in stellar winds** is converted to relativistic protons.



https://www.nature.com/articles/s41550-021-01318-y

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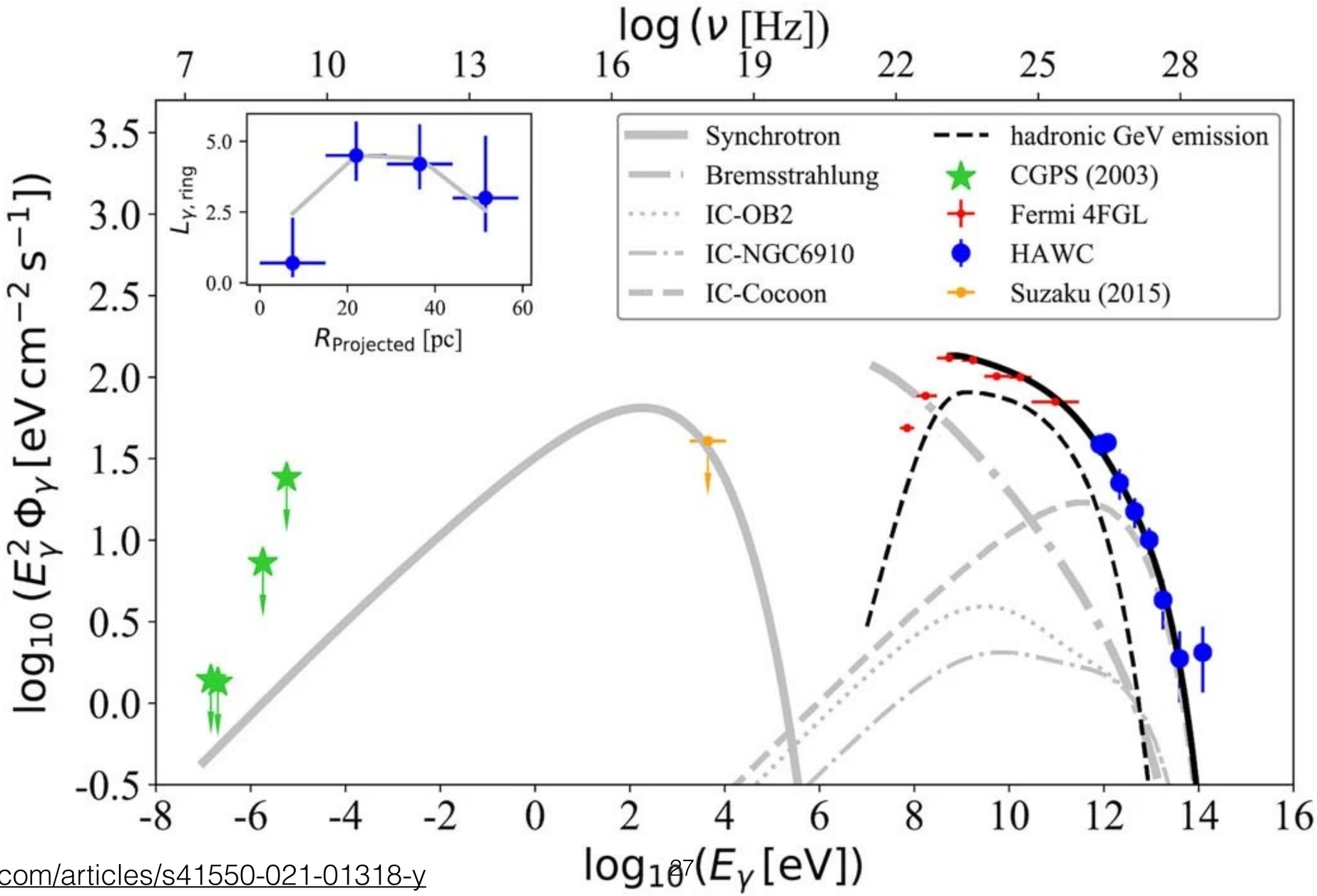


https://www.nature.com/articles/s41550-021-01318-y

OB2 as Origin of Cocoon?

- GeV-TeV spectrum well fit by a pion decay spectrum.
- Leptonic origin unlikely.
- Required energy in CR protons >1GeV : ~10^{49} erg [preliminary!]
- Kinetic wind Power in OB2: ~10^{39} erg/s over 2Myr.
- Need < 1% acceleration efficiency to power gamma-ray emission from Cocoon.
- First evidence for ~100 TeV protons in star-forming regions?
- Stay tuned for publication!

Gamma-ray absorption

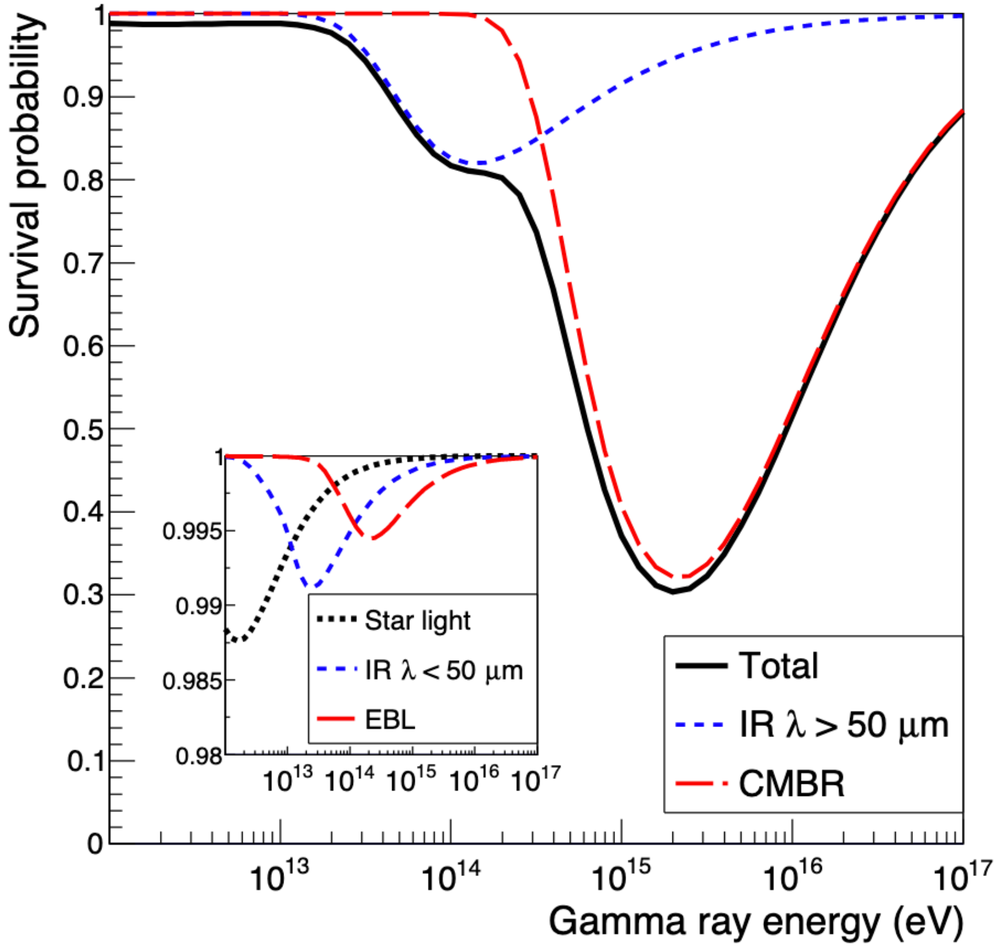


FIG. 12: Survival probability of gamma rays for a trajectory from the GC to the Sun, plotted as a function of the gamma ray energy. The contributions of different radiation fields are shown. The inset shows the contributions of starlight, infrared radiation with wavelength $\lambda < 50\ \mu$m and EBL.

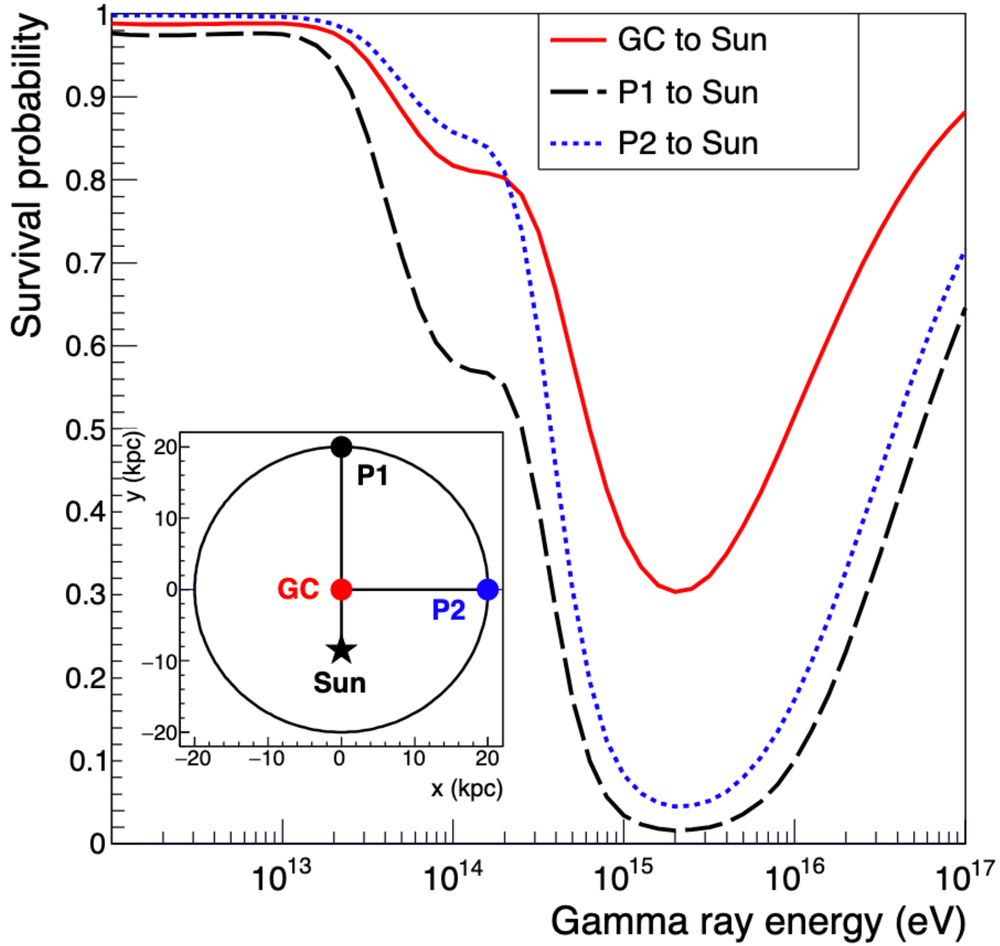
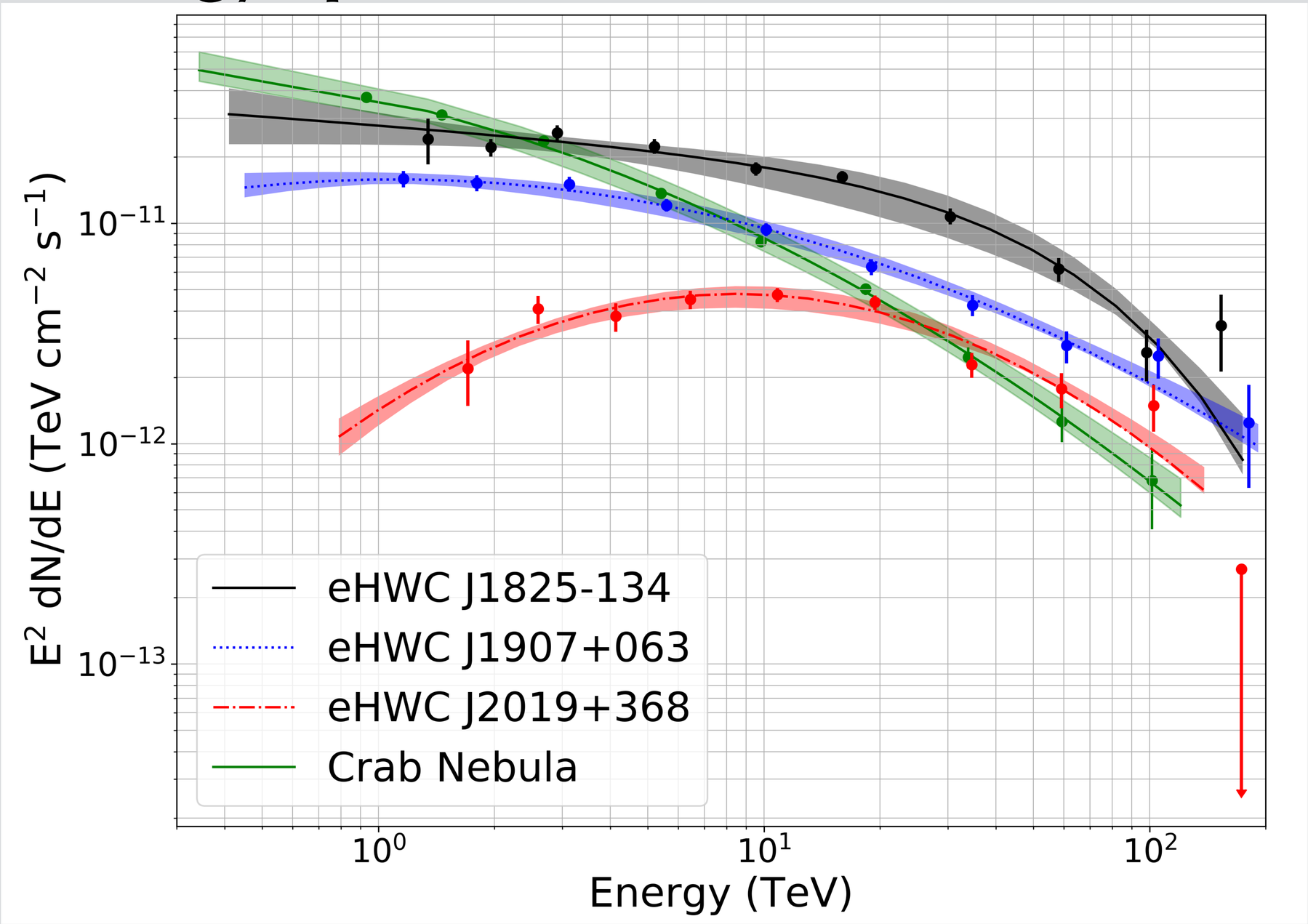
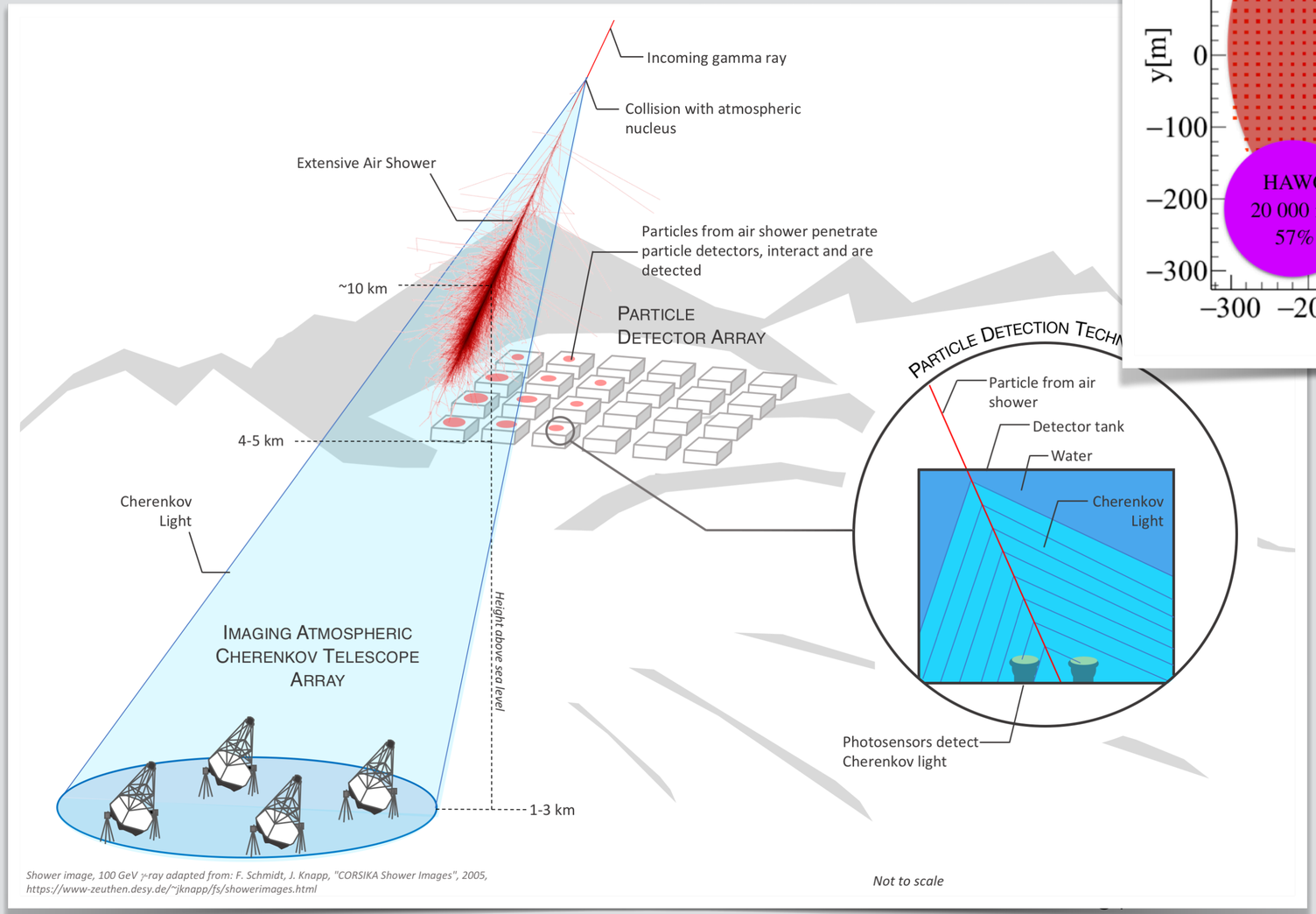


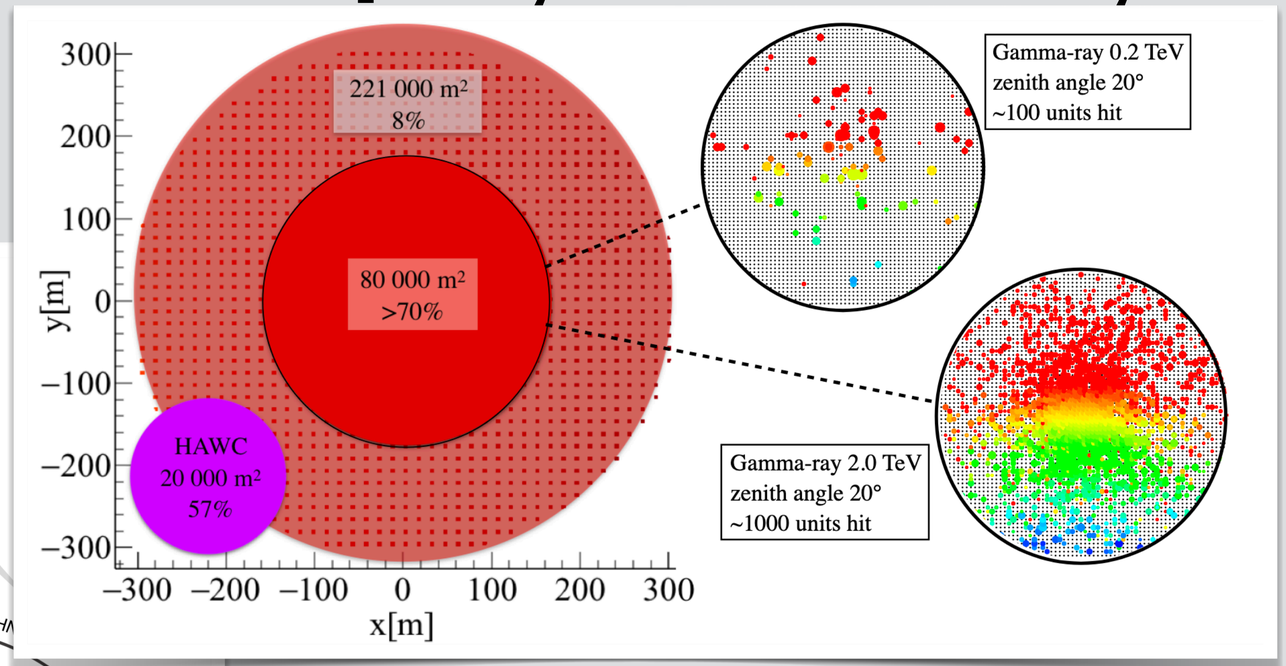
FIG. 13: Survival probability of gamma rays for three different trajectories in the Galactic plane, plotted as a function of the gamma ray energy. The inset shows the position of the sources.

Energy spectra of > 100 TeV sources



SWGO: A next-generation VHE γ-ray observatory





Looking for institutional members and supporting scientists!

More info: https://www.swgo.org

Cosmic Rays and Gamma Rays

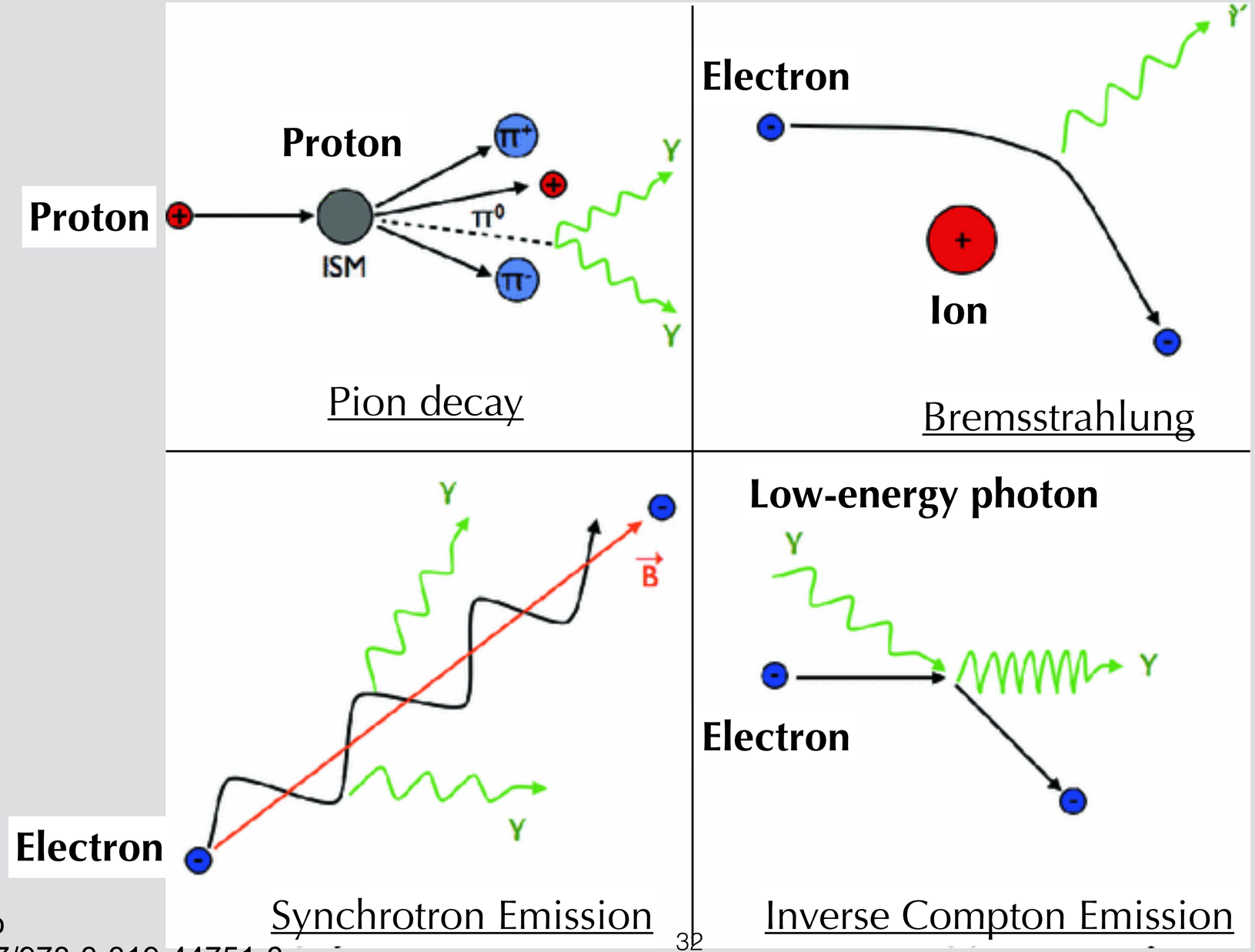
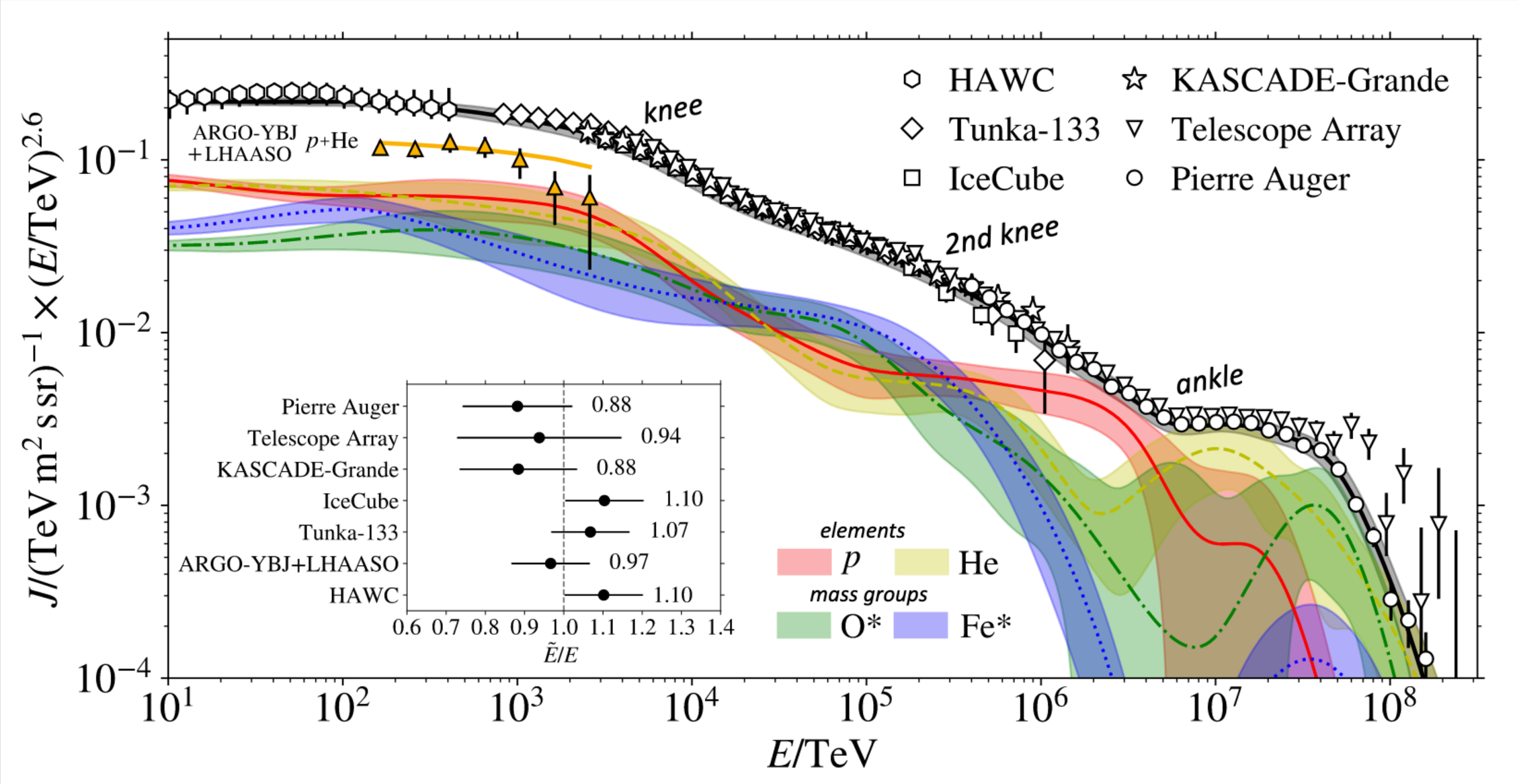
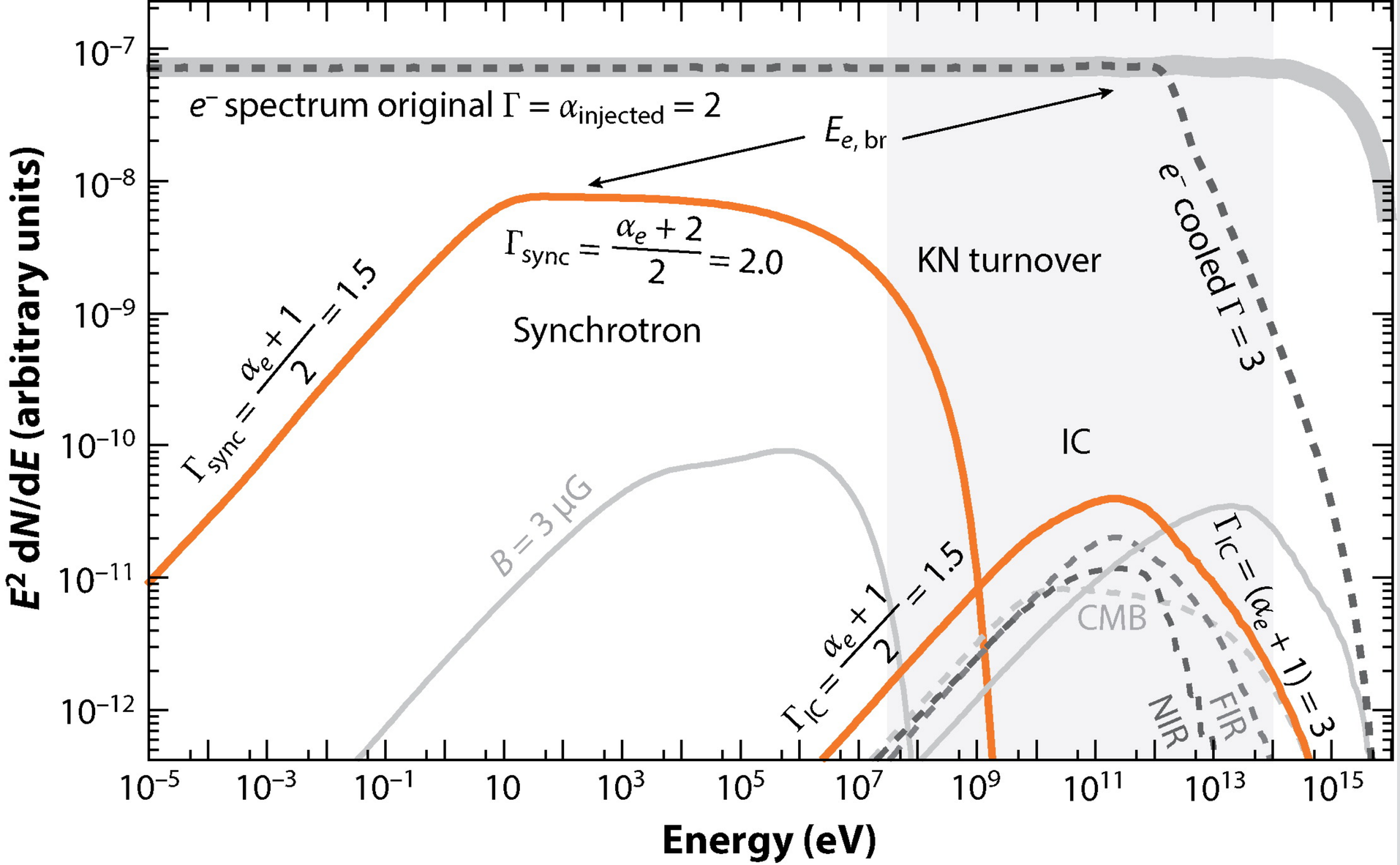


Image: R. Lopez-Coto
https://doi.org/10.1007/978-3-319-44751-3

Motivation: The Cosmic Ray Spectrum

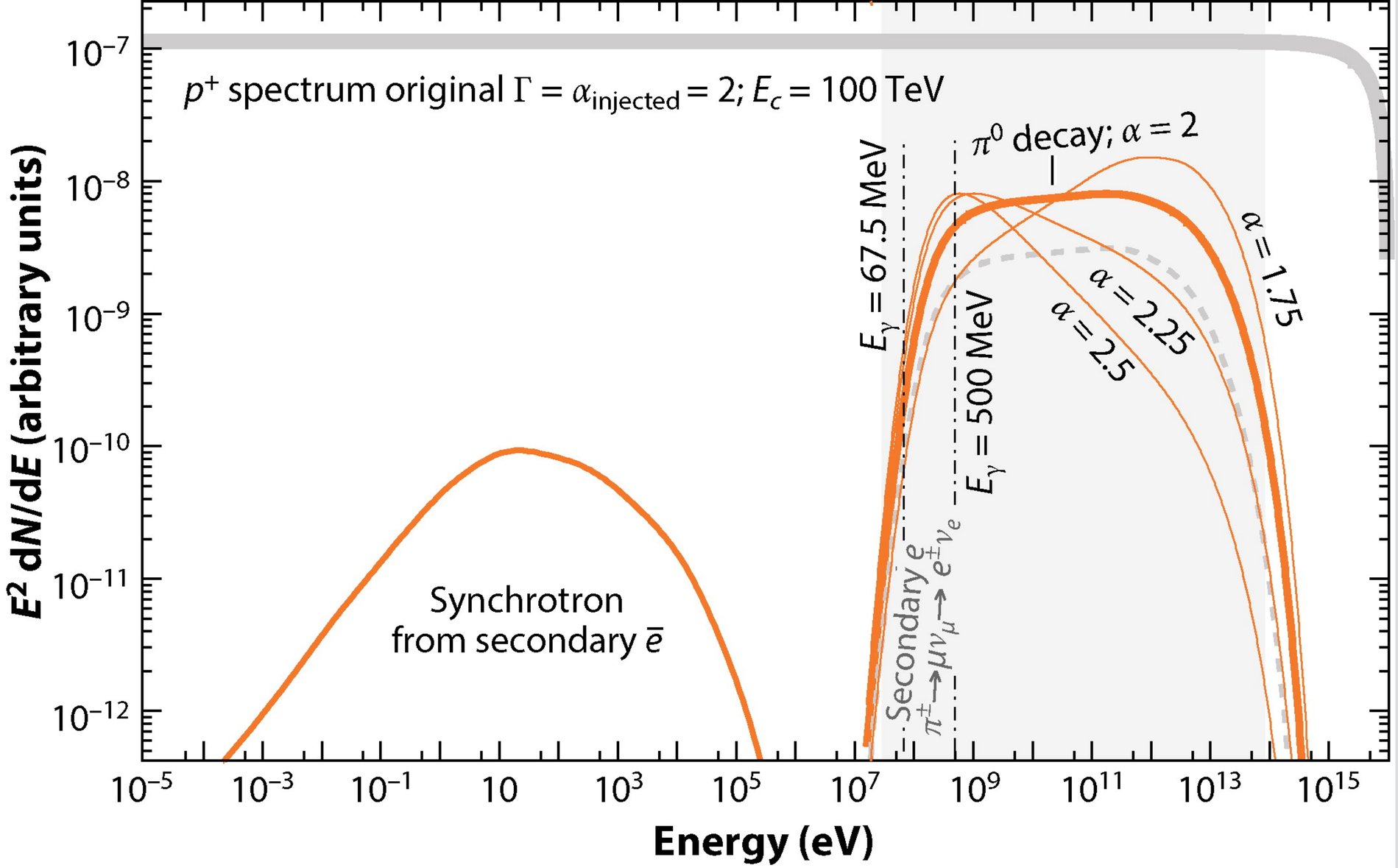


https://arxiv.org/abs/1903.07713



Funk S. 2015.

Annu. Rev. Nucl. Part. Sci. 65:245–77



Funk S. 2015.

Annu. Rev. Nucl. Part. Sci. 65:245–77

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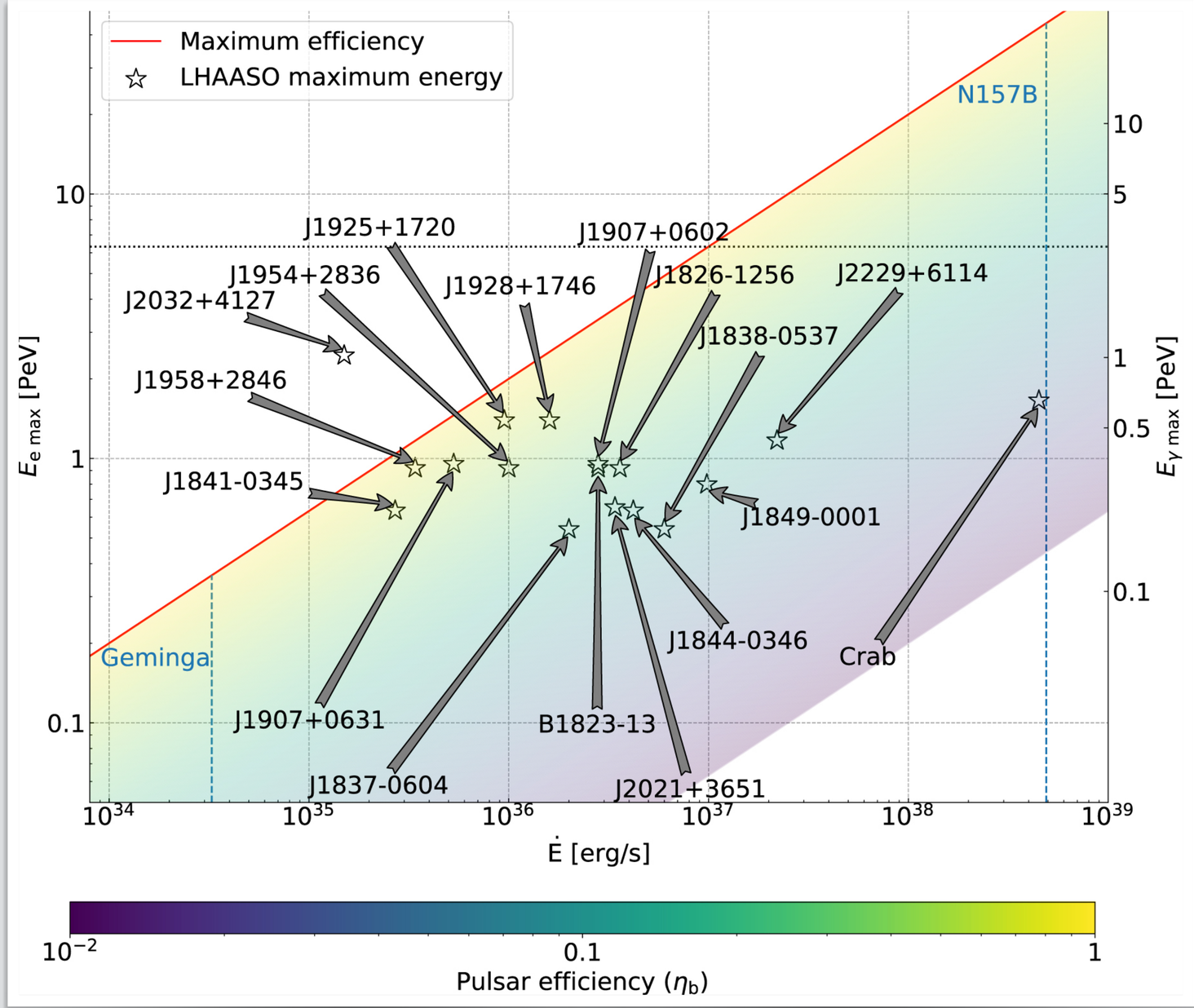
M. Breuhaus et al 2021:

- **Pulsar wind nebula** origin of 3 UHE LHAASO sources.

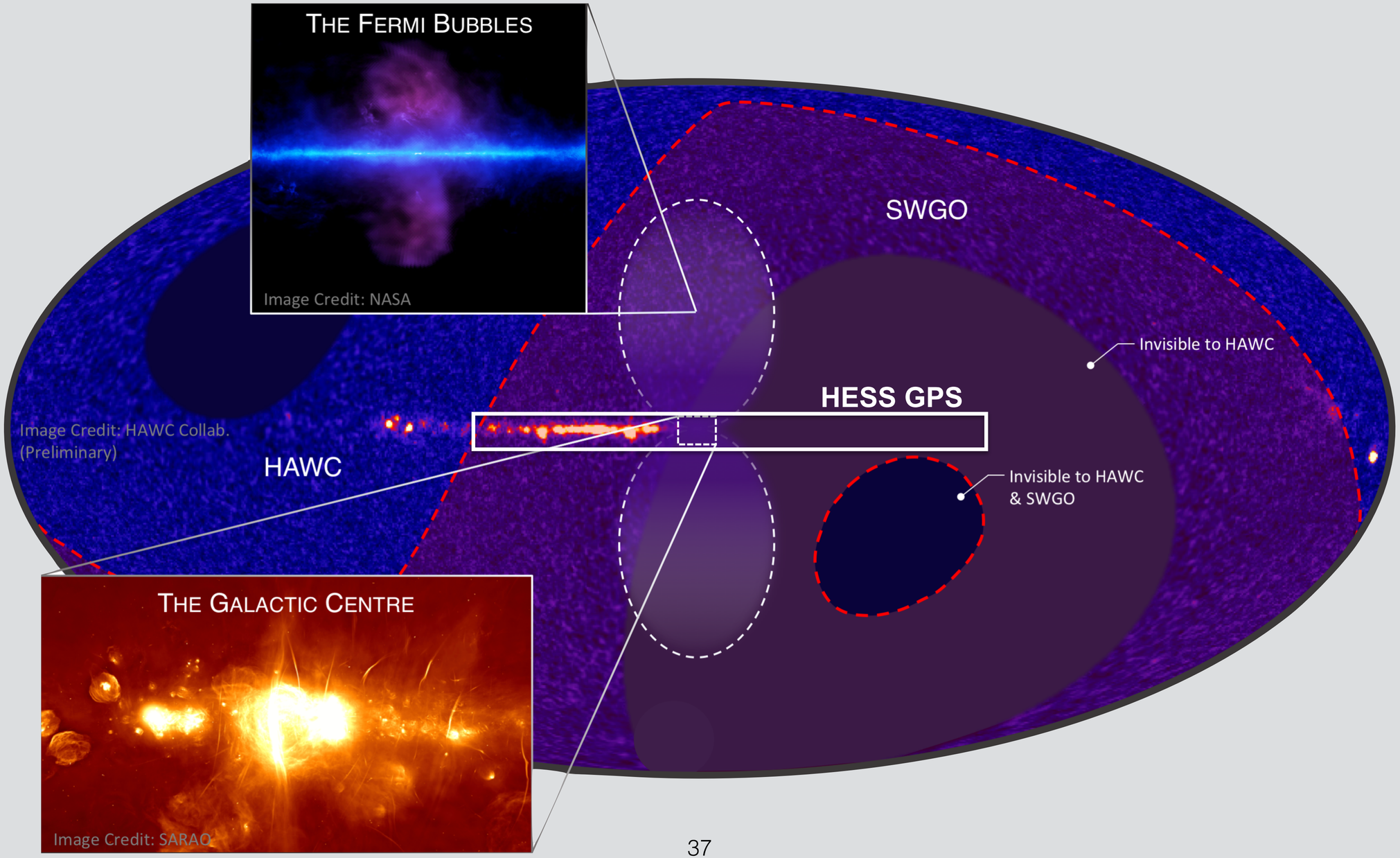
E. de Oña Wilhelmi et al 2022:

- Most UHE LHAASO sources have at least one **bright young pulsar** in the vicinity
- Only exception: LHAASO J2108+5157

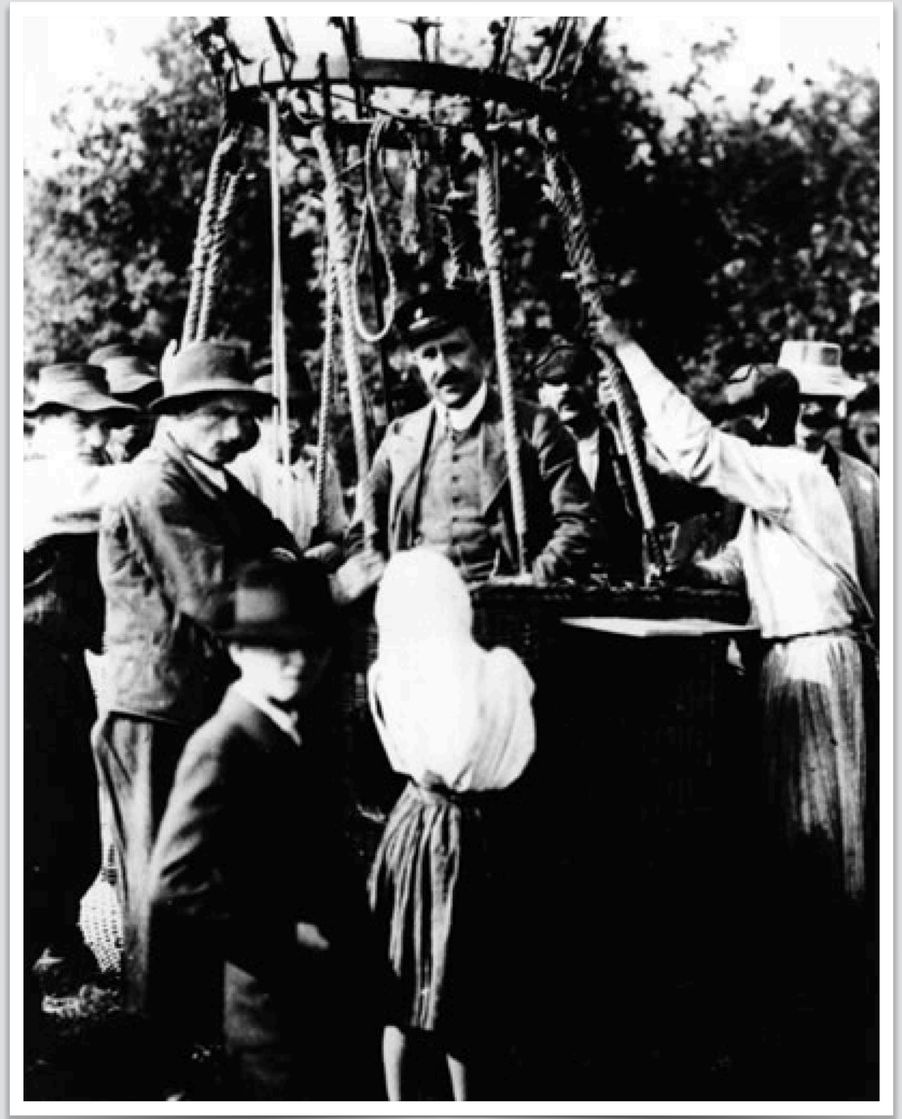
Leptonic PeVatrons are rampant!?

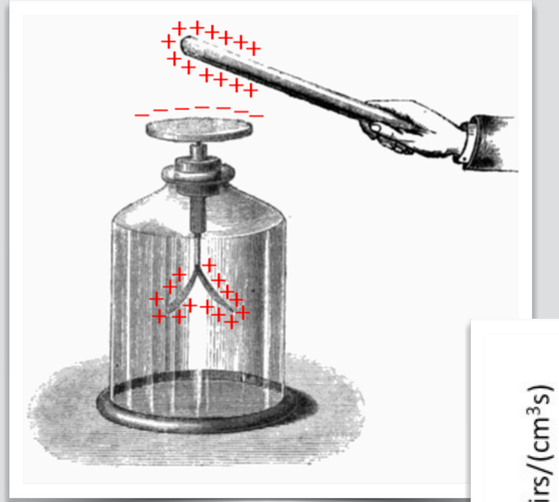


The Southern Gamma-Ray Sky

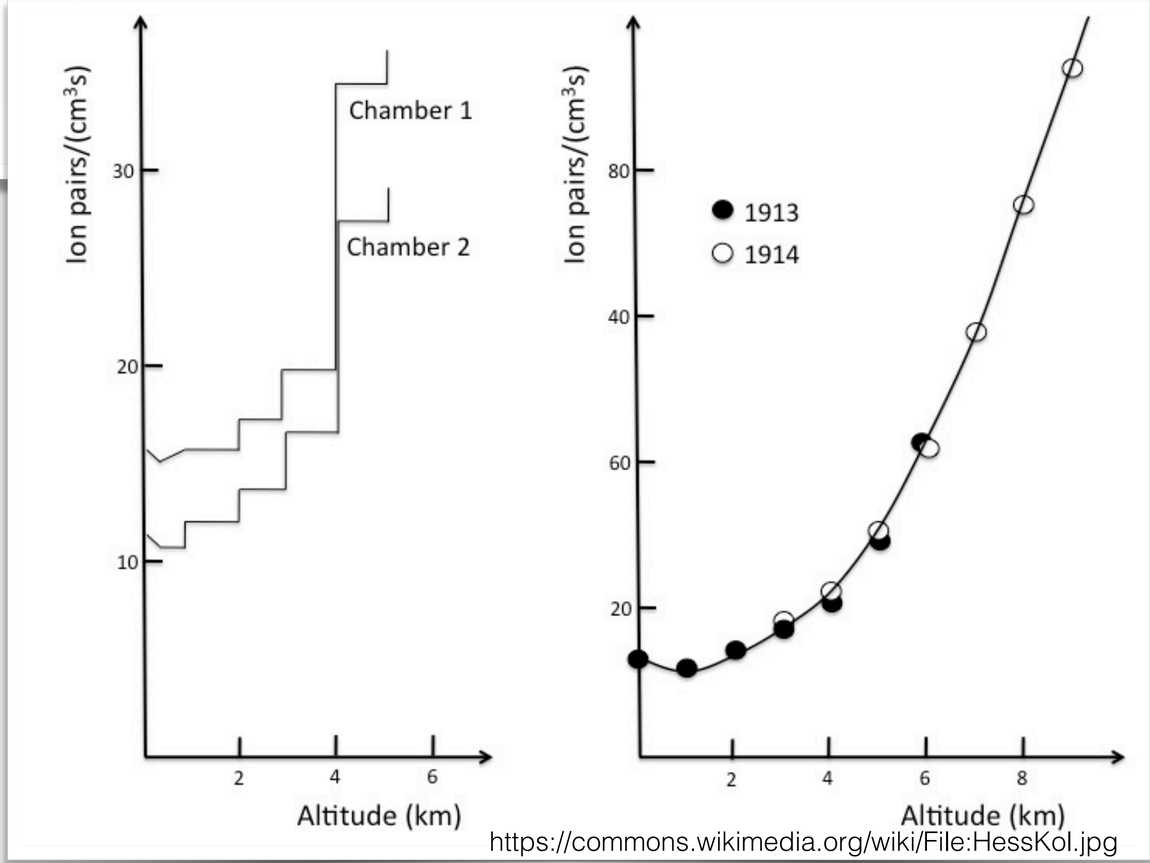


Hess & Kolhörster 1912





Ionizing radiation rate increases with altitude

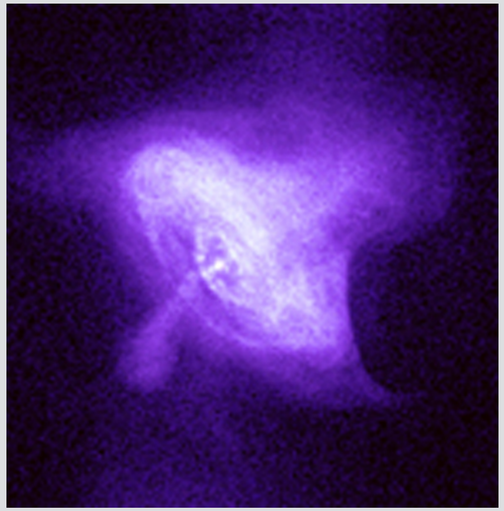


https://commons.wikimedia.org/wiki/File:HessKol.jpg

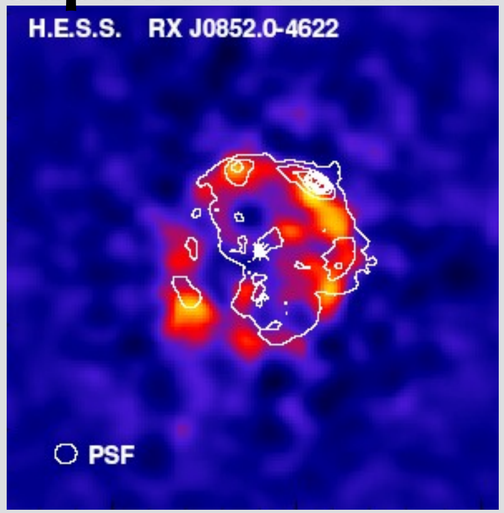
Particle Accelerators in Nature

Galactic

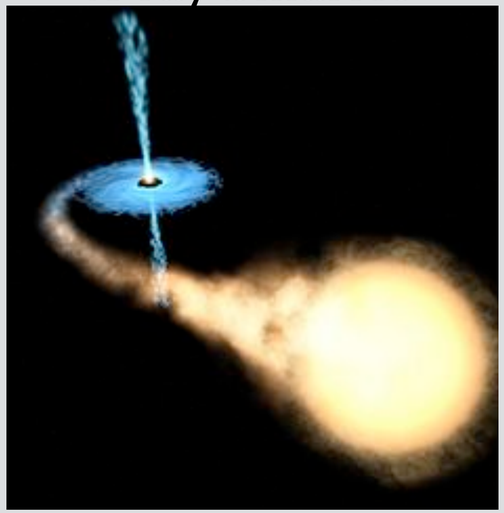
Pulsar Wind Nebulae



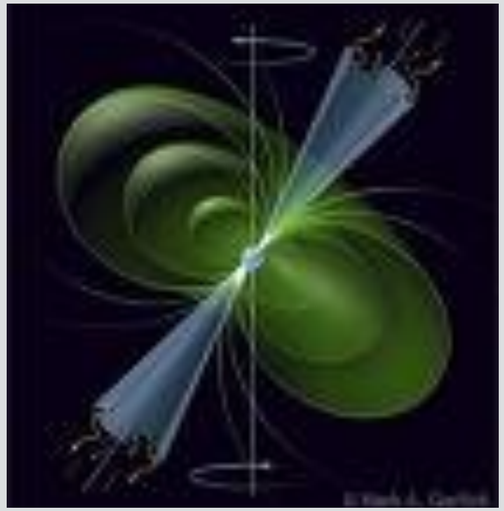
Supernova Remnants



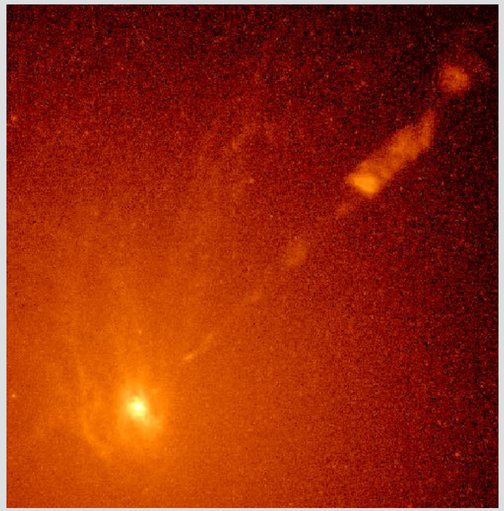
X-ray binaries



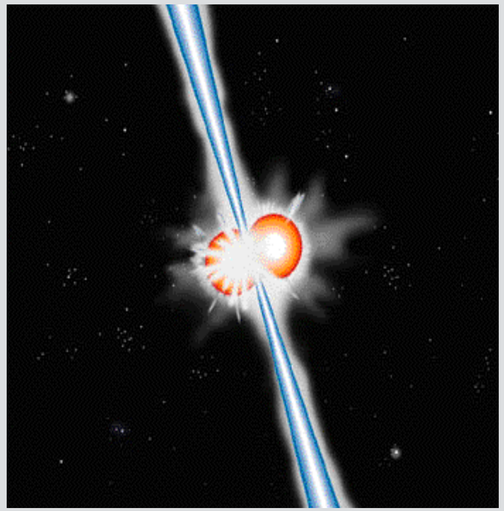
Pulsars



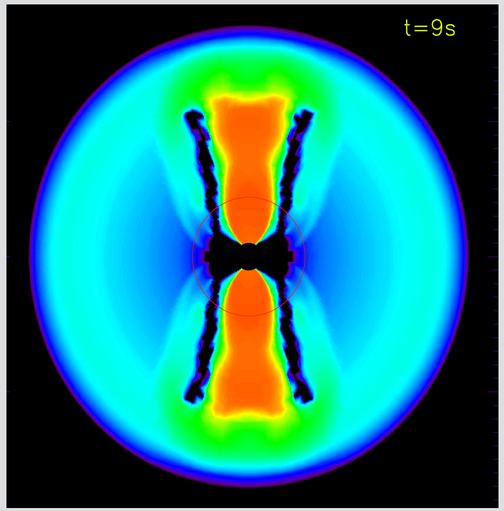
Extragalactic



Active Galaxies



Short γ-ray Bursts



Long γ-ray Bursts

Starburst Galaxies