Title: Where are Milky Wayâ€™s Hadronic PeVatrons?

Speakers: Takahiro Sudo

Series: Particle Physics

Date: October 11, 2022 - 1:00 PM

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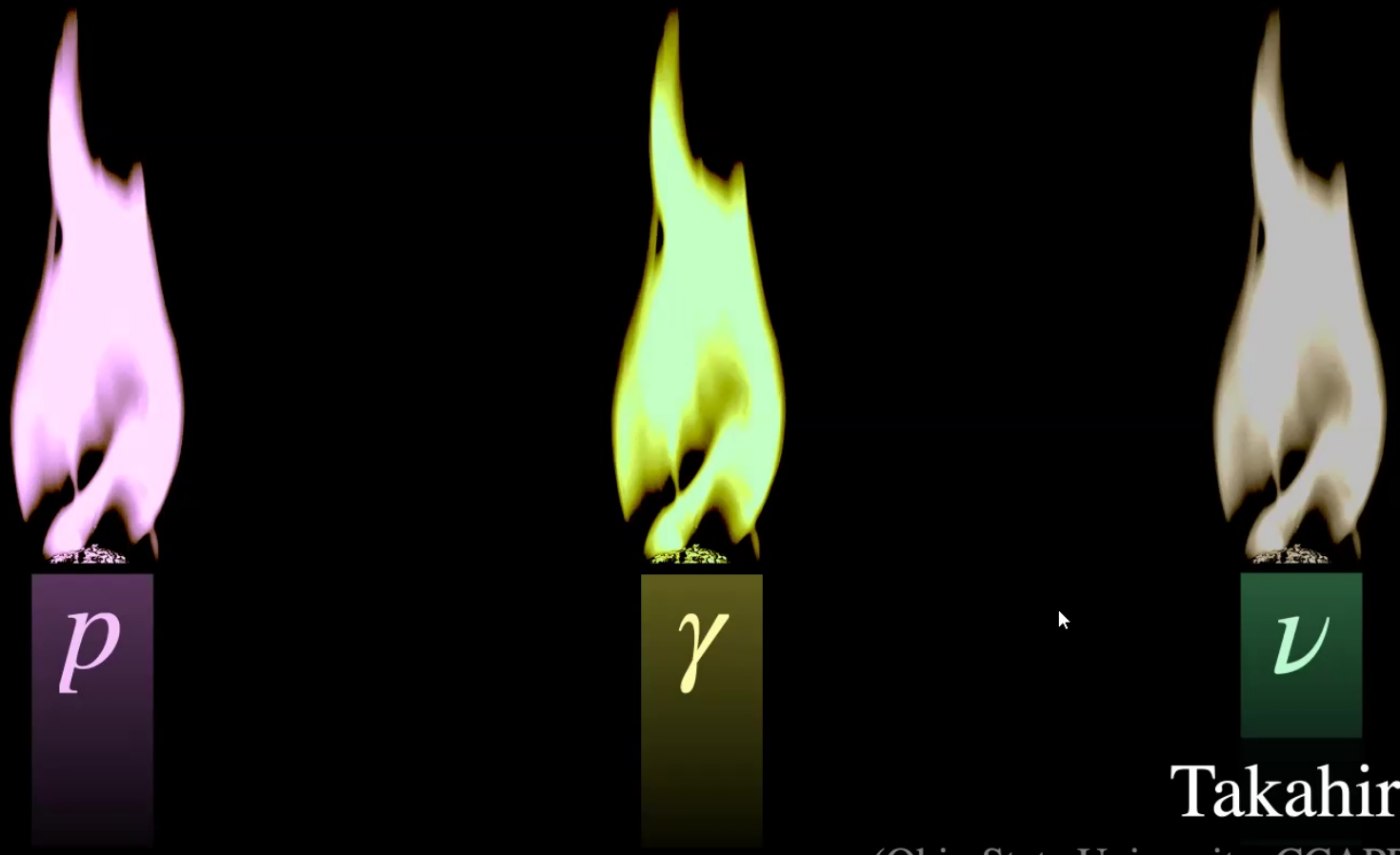
Abstract: Observations indicate the existence of natural particle accelerators in the Milky Way, capable of producing PeV cosmic rays ("PeVatrons"). Observations also indicate the existence of extreme sources in the Milky Way, capable of producing gamma-ray radiations above 100 TeV. If these gamma-ray sources are hadronic cosmic-ray accelerators, then they must also be neutrino sources. However, no neutrino sources have been detected. How can we consistently understand the observations of cosmic rays, gamma rays, and neutrinos? We point out two extreme scenarios are allowed: (1) the hadronic cosmic-ray accelerators and the gamma-ray sources are the same objects, so that neutrino sources exist and improved telescopes can detect them, versus (2) the hadronic cosmic-ray accelerators and the gamma-ray sources are distinct, so that there are no detectable neutrino sources. We discuss the nature of Milky Way's highest energy gamma-ray sources and outline future prospects toward understanding the origin of hadronic cosmic rays.

Zoom link: https://pitp.zoom.us/j/91390039665?pwd=dGJ2b3VCbVFhUVpSelpjYzJHdk1Gdz09

Where are Milky Way's Hadronic PeVatrons?



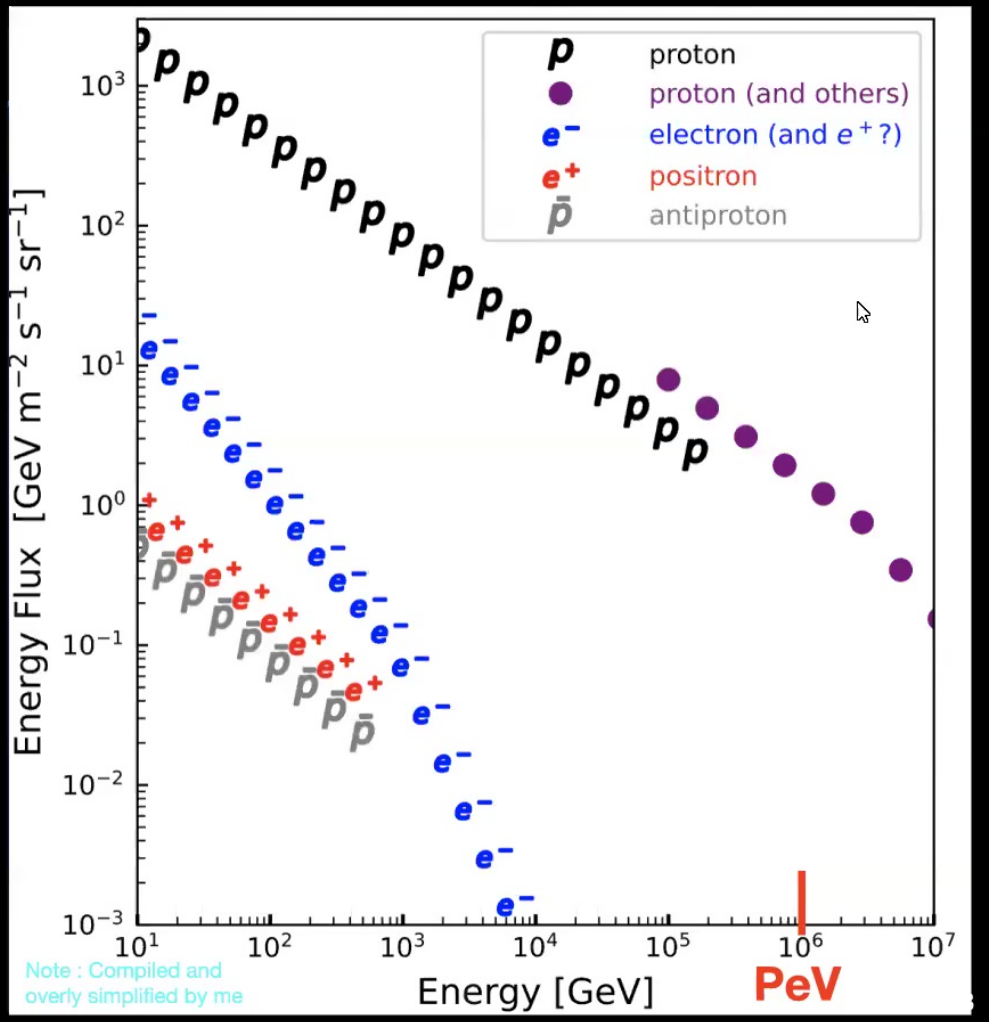
Takahiro Sudoh

(Ohio State University, CCAPP/JSPS Fellow)

Based on work with John Beacom (Ohio State), Tim Linden (Stockholm), Dan Hooper (Fermilab)

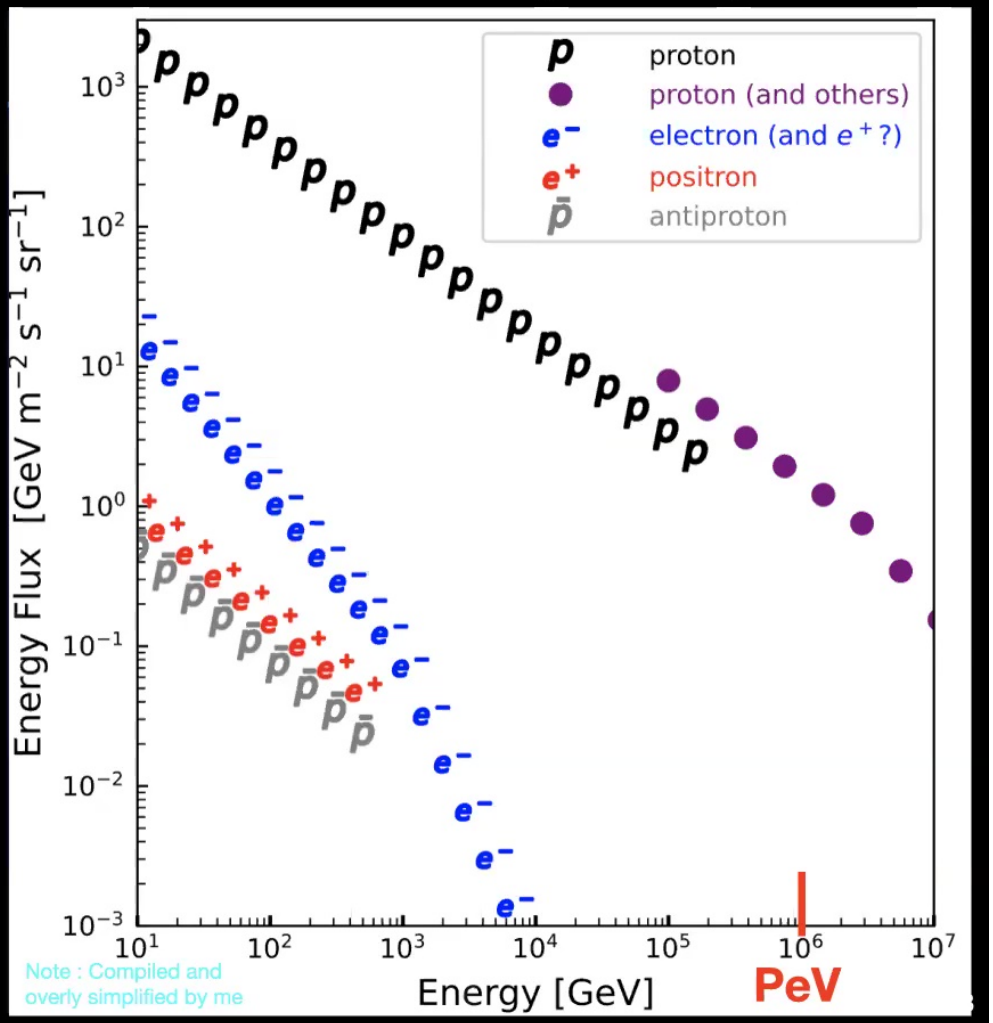
Hadronic PeVatrons exist in the Milky Way

- Somewhere in the Milky Way protons (and nuclei) are accelerated to at least PeV energies



Hadronic PeVatrons exist in the Milky Way

- Somewhere in the Milky Way protons (and nuclei) are accelerated to at least PeV energies
- Many source classes accelerate protons to GeV - TeV
- Mysterious : which one(s) can reach PeV energies? **(Hadronic "PeVatrons")**



PeVatrons Candidates

- Supernova Remnants (SNRs) :
  - Best candidate for decades, but some challenges

    (1) Theoretically difficult to reach a PeV

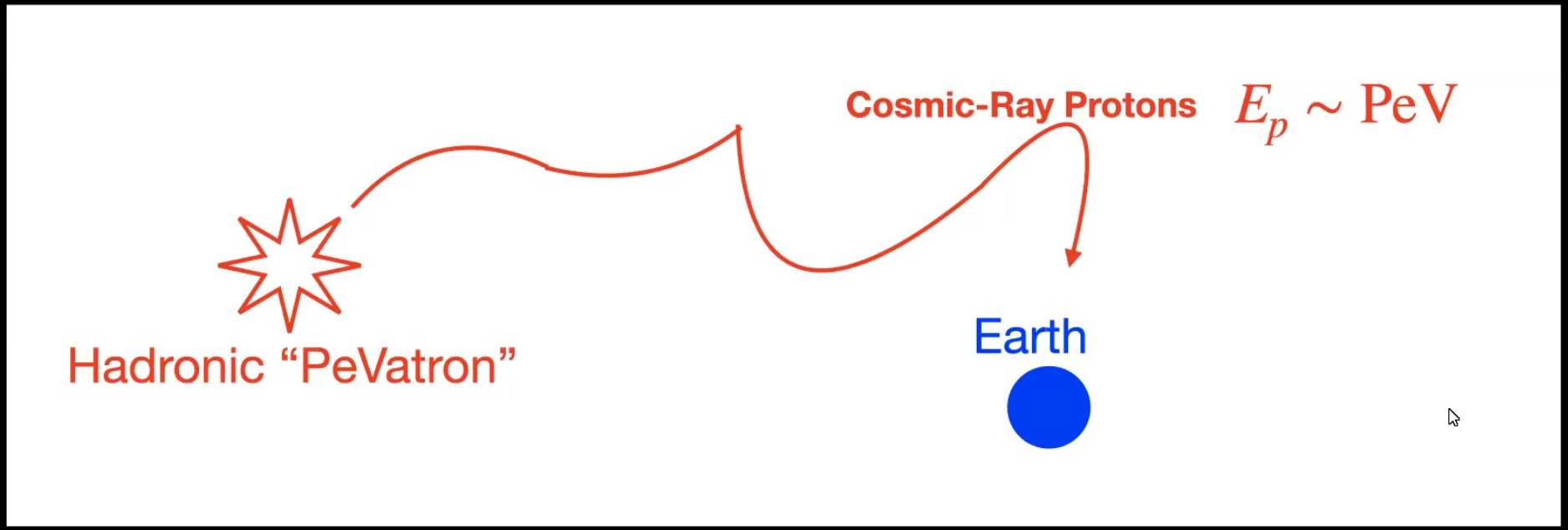
    (2) No 100 TeV gamma ray observed (see next slide)
- Young star clusters
- Super Massive Black Hole
- X-ray binaries (jet and accretion disk)

⋮

- Various candidates have been proposed; no clear identification thus far.

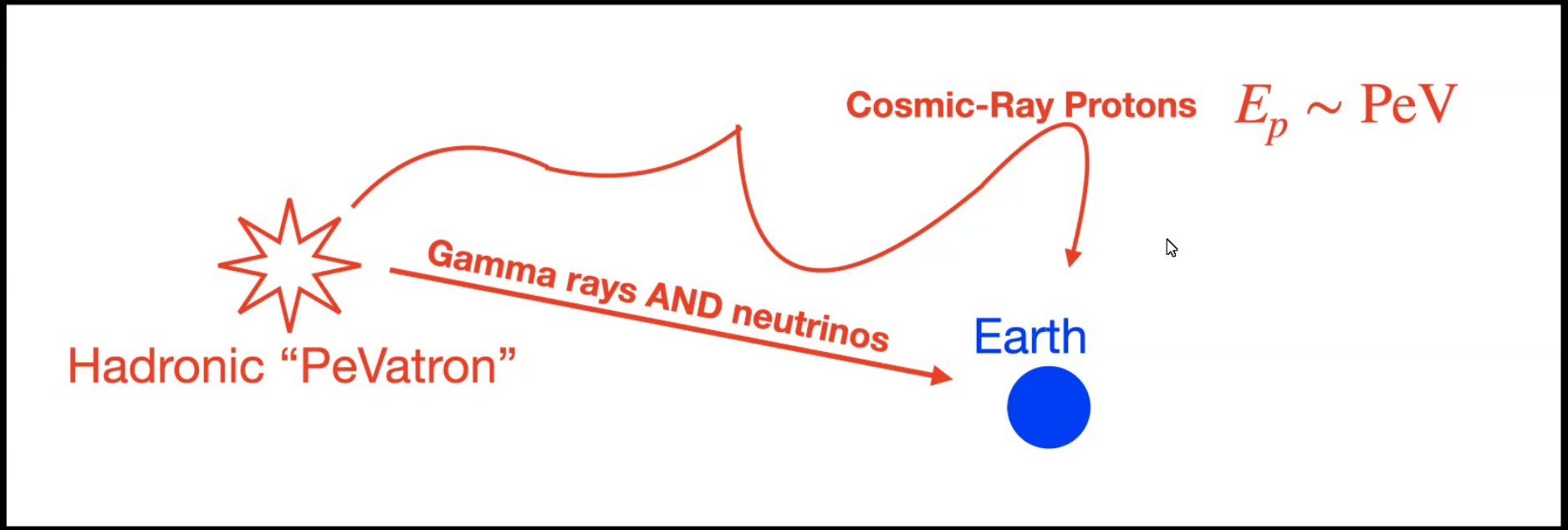
How to find PeVatrons?

- Difficulty : Interstellar magnetic field randomly deflects particles
- Because of this, cosmic-ray arrival direction is (almost) isotropic



How to find PeVatrons?

- Collision between protons and gases produce gamma rays and neutrinos
- Emission is the key to identity the Milky Way's "PeVatron"



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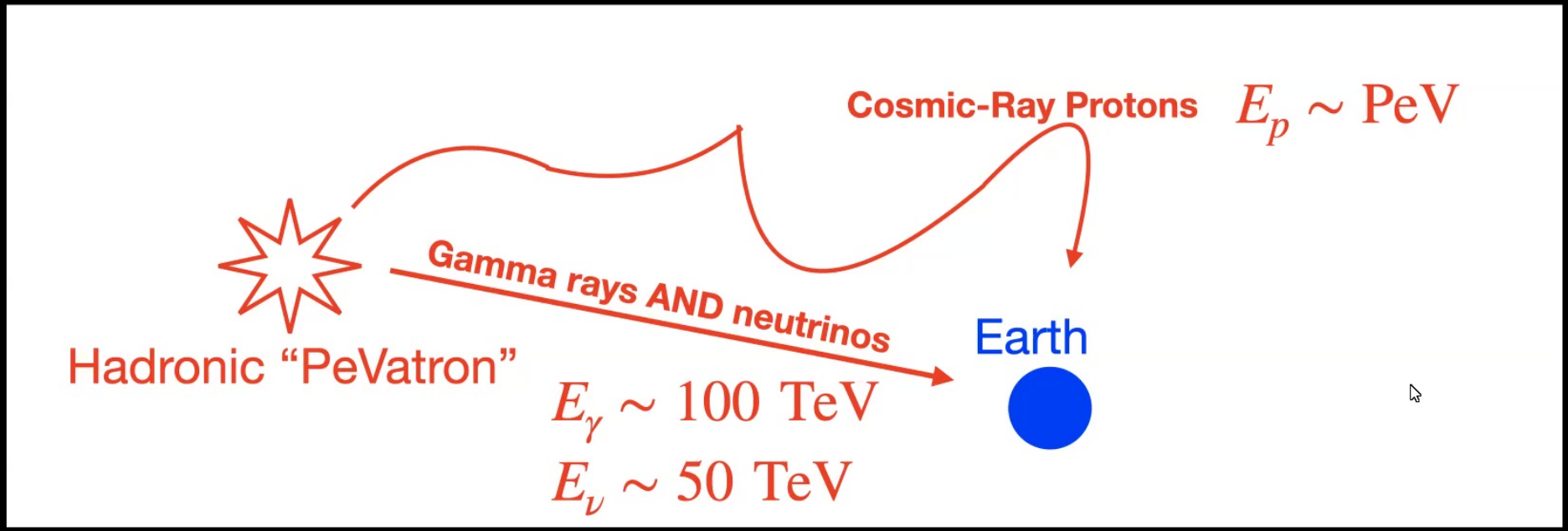
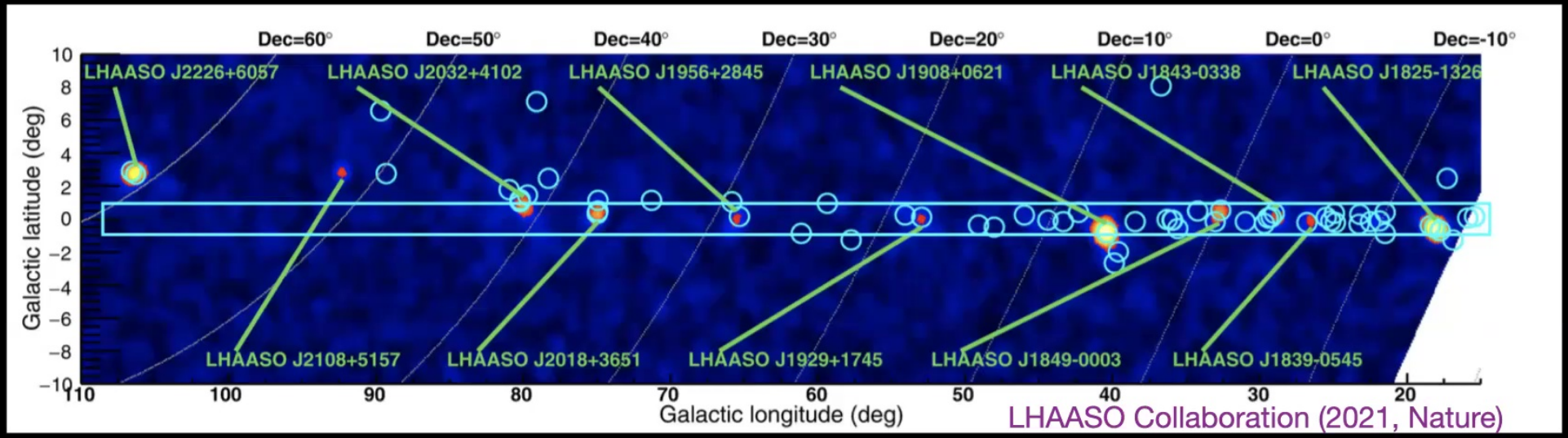
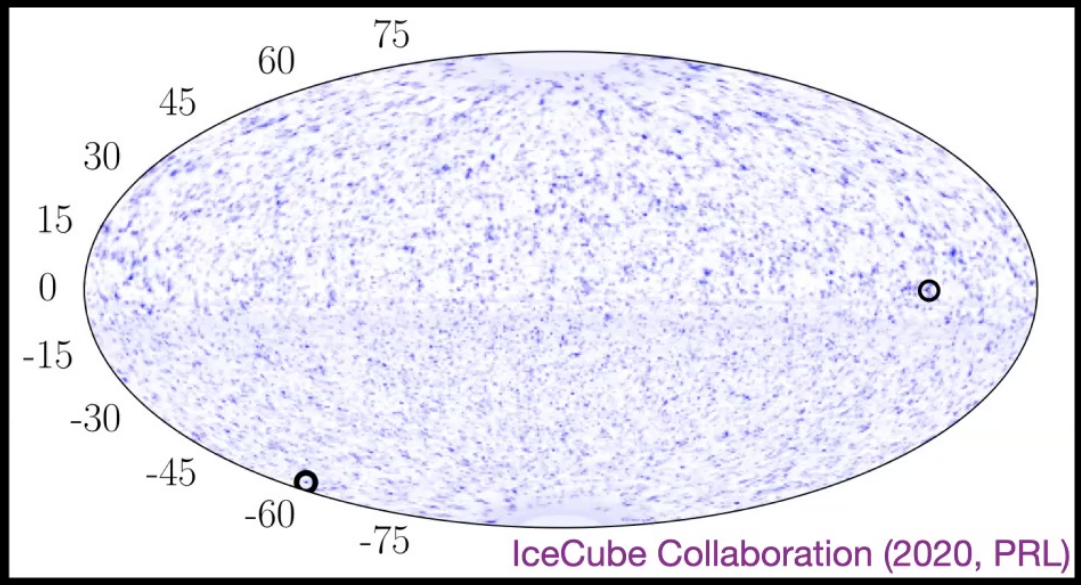


100-TeV gamma rays : A Dozen of MW sources



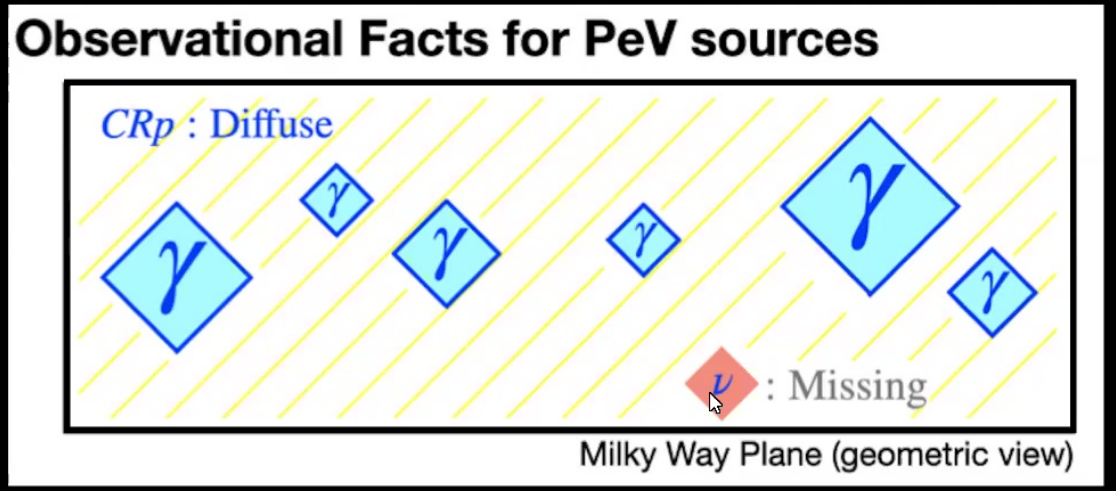
- Gamma-ray observations are now reaching such high energies!
- A dozen of sources are already detected above 100 TeV
- They are good candidate for hadronic PeVatrons

TeV - PeV Neutrinos : No MW source yet



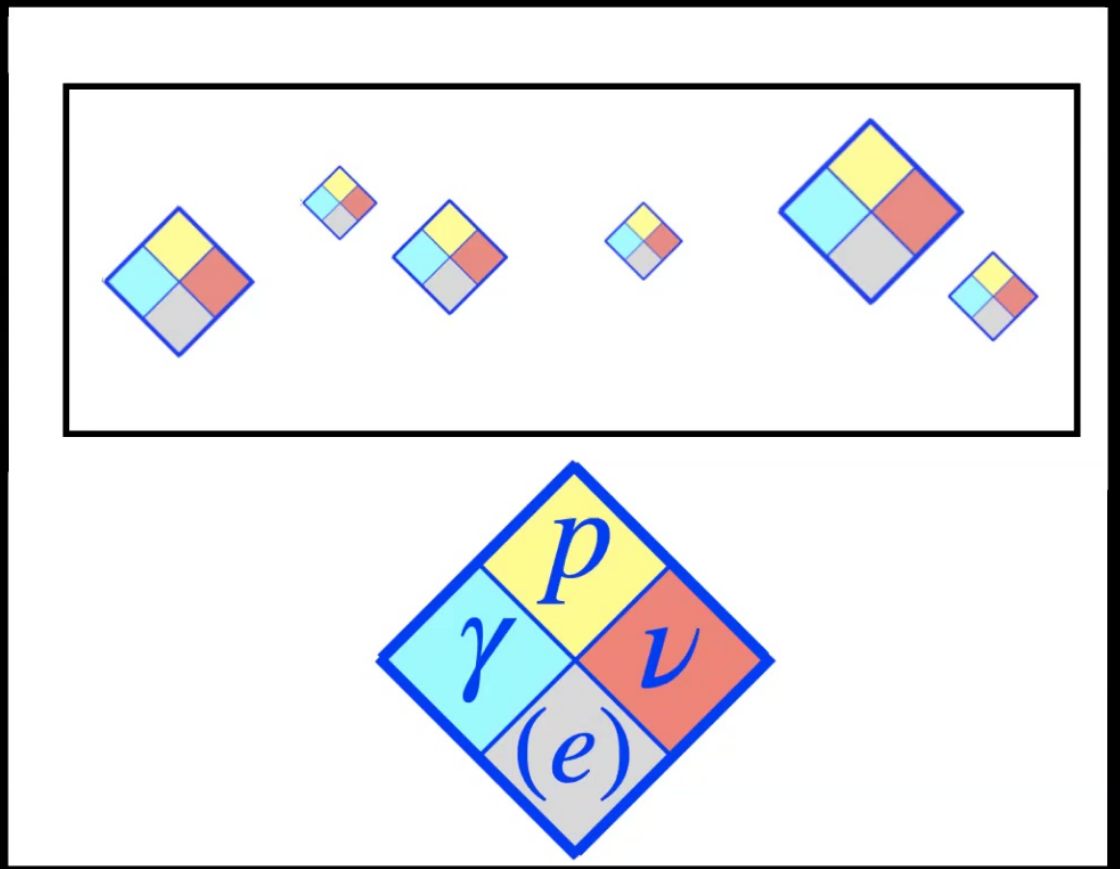
- No Milky-Way neutrino sources are found by IceCube searches
- Maybe because current sensitivities are just short
- Future telescopes should soon find Milky Way's PeVatrons

- Observational Facts:
  - Diffuse protons
  - Many gamma-ray sources
  - No neutrino sources



Optimistic Interpretation

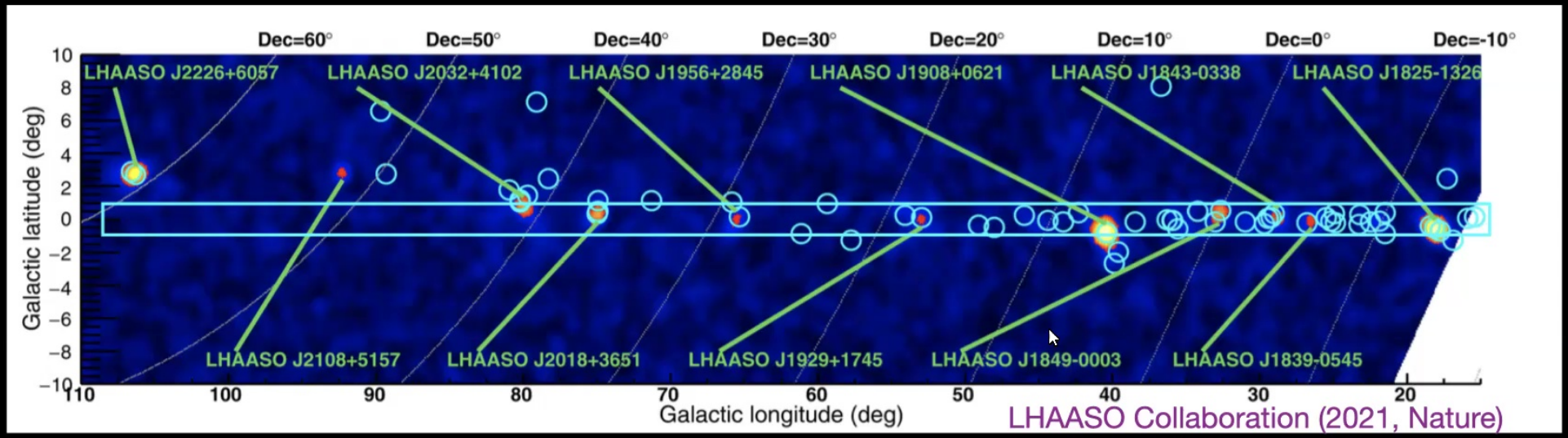
- Gamma-ray sources are hadronic cosmic-ray accelerators
- Future neutrino telescopes will soon find them



100-TeV gamma rays : Leptonic mechanism

- Hadronic mechanism (pion production and decay) :
  - Protons + gases —> gamma rays AND neutrinos
  - $E_\gamma \sim 0.1 E_p$
- Leptonic mechanism (inverse-Compton scattering) :
  - Electrons + photons —> gamma rays (NO neutrinos)
  - $E_\gamma \sim E_e$ (in the highest energies)

What do we see in the 100-TeV gamma-ray sky?



- In principle, all of these gamma-ray sources could be leptonic

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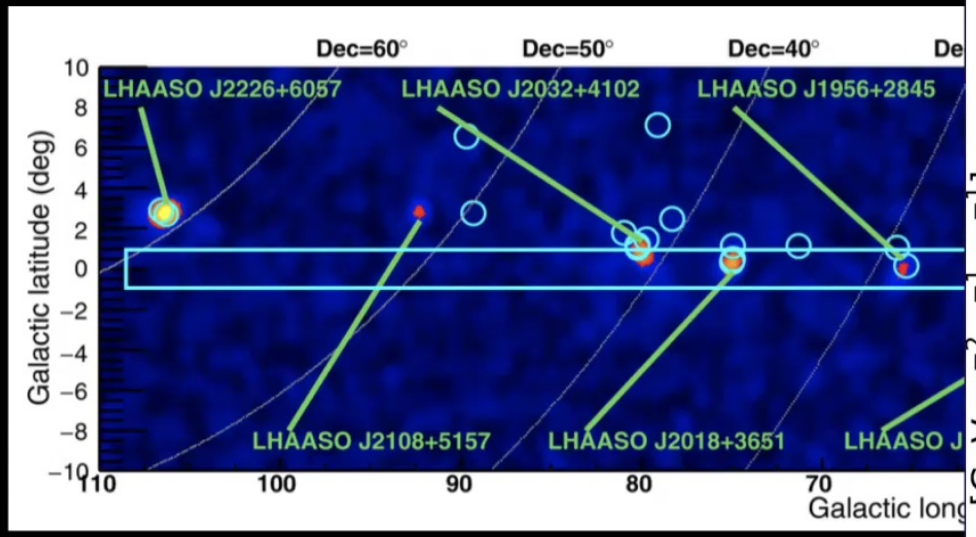
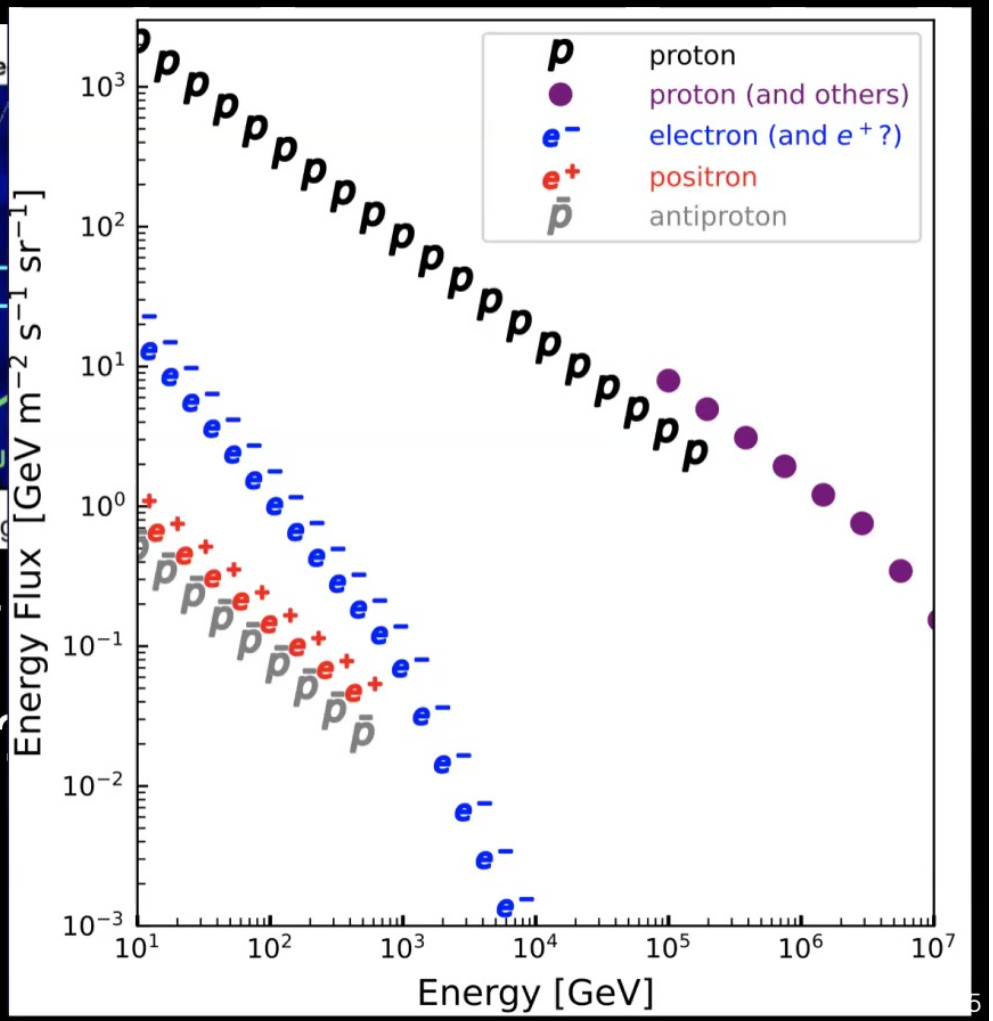
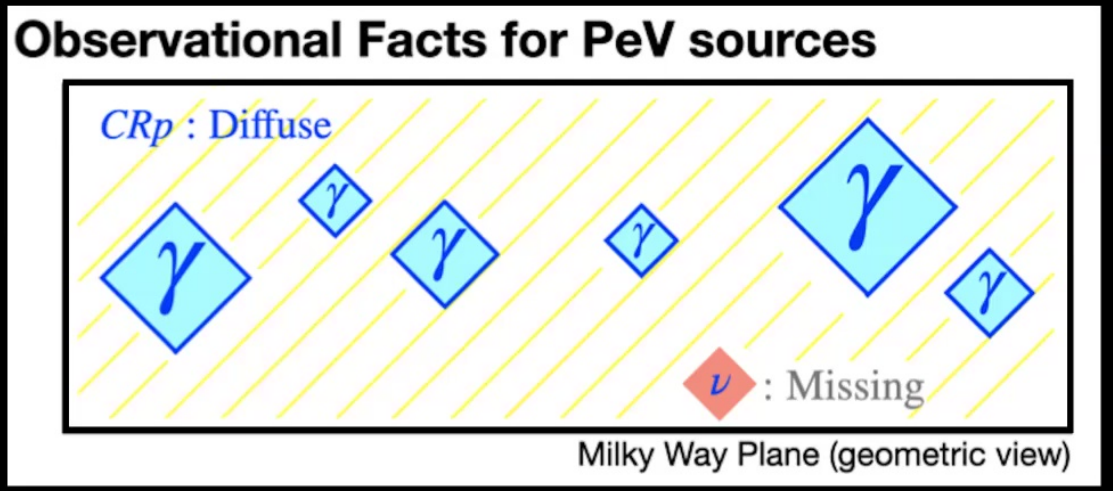




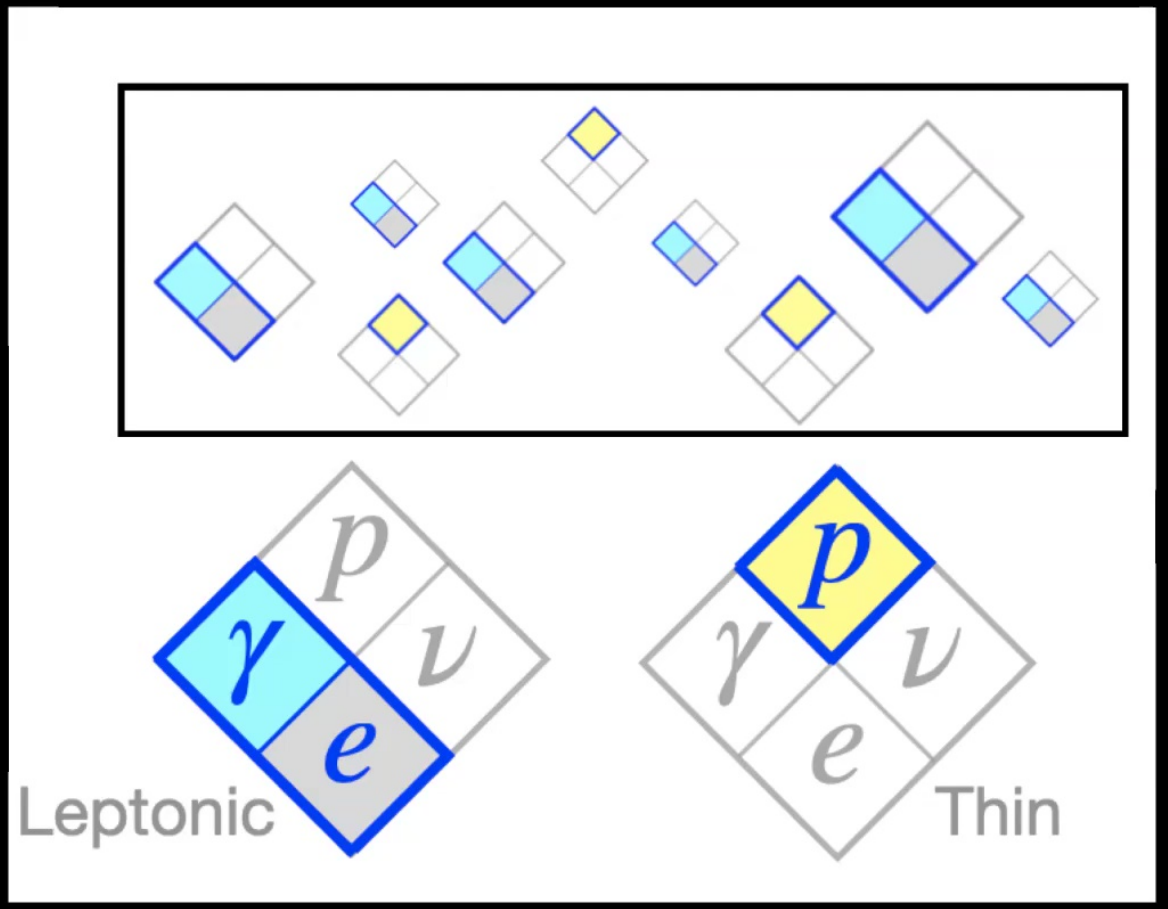
- In principle, all of these gamma-
- What about hadronic PeVatrons?

- Observational Facts:
  - Diffuse protons
  - Many gamma-ray sources
  - No neutrino sources



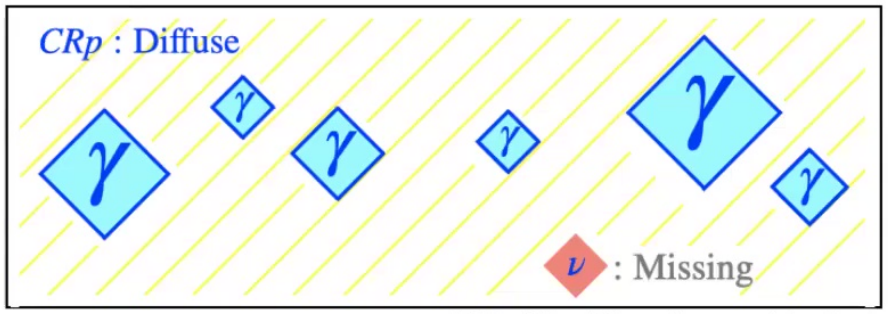
Pessimistic Interpretation

- Gamma-ray sources are all leptonic
- Hadronic cosmic-ray accelerators are thin and make little emission
- No detectable neutrino sources exist



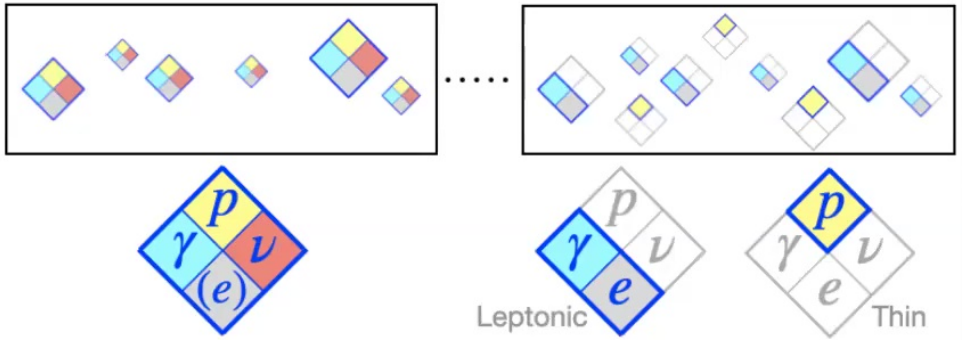
Range of Possibility : What is allowed?

Observational Facts for PeV sources



Milky Way Plane (geometric view)

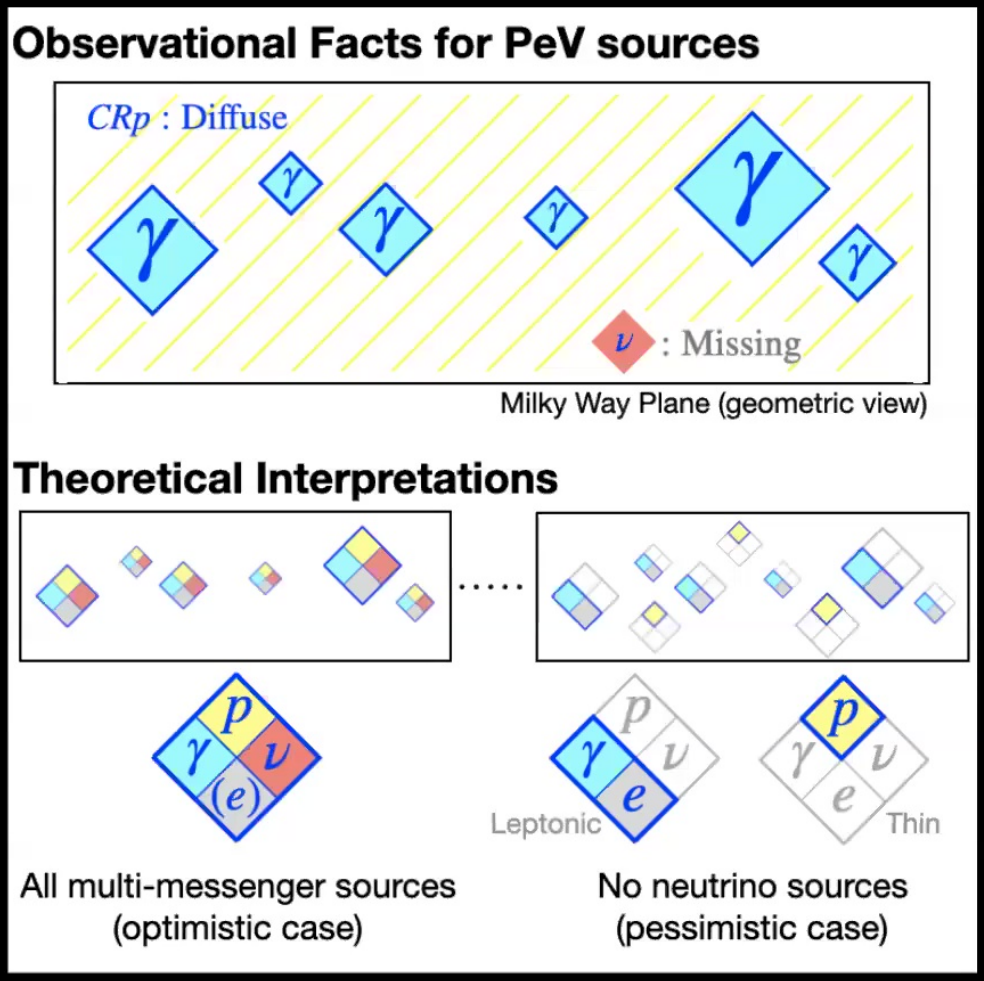
Theoretical Interpretations



All multi-messenger sources (optimistic case)

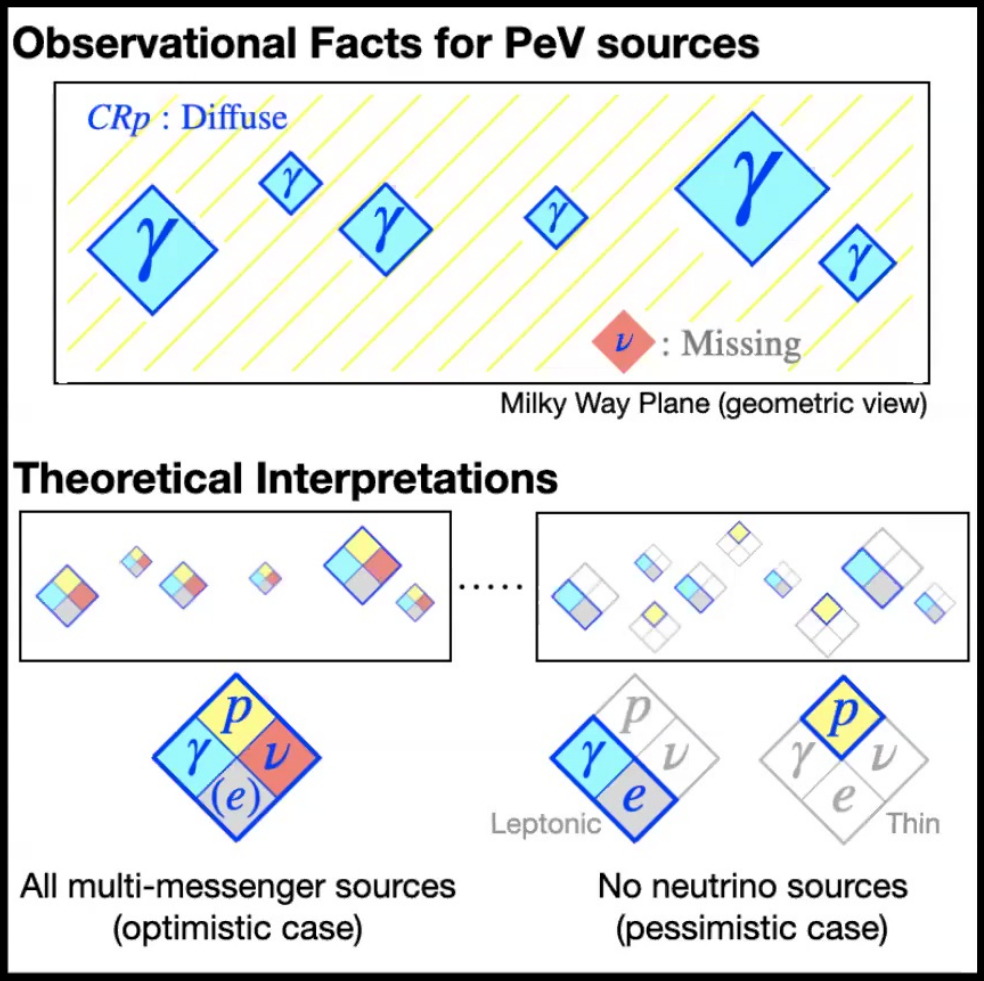
No neutrino sources (pessimistic case)

Range of Possibility : What is allowed?



- Leptonic sources :
  - Does the Milky Way have leptonic accelerators powerful enough to potentially explain all gamma-ray sources?
- Hadronic sources :
  - Where the Milky Way's hadronic accelerators lie between those extremes?

Range of Possibility : What is allowed?



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Leptonic Sources

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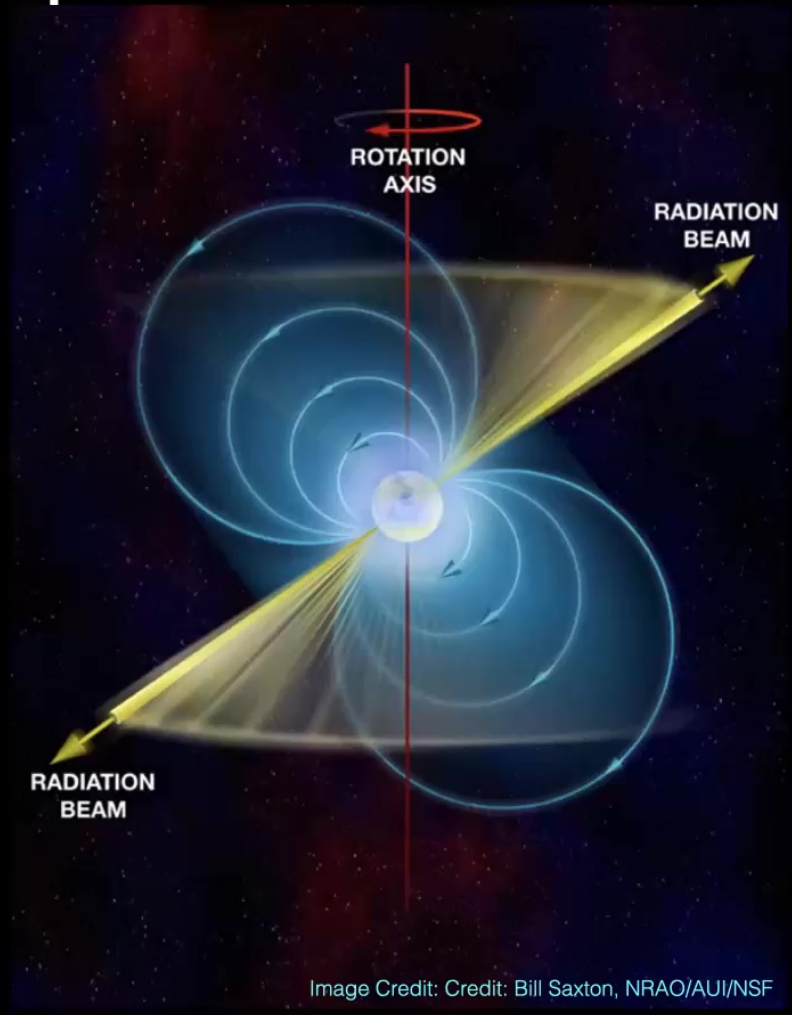
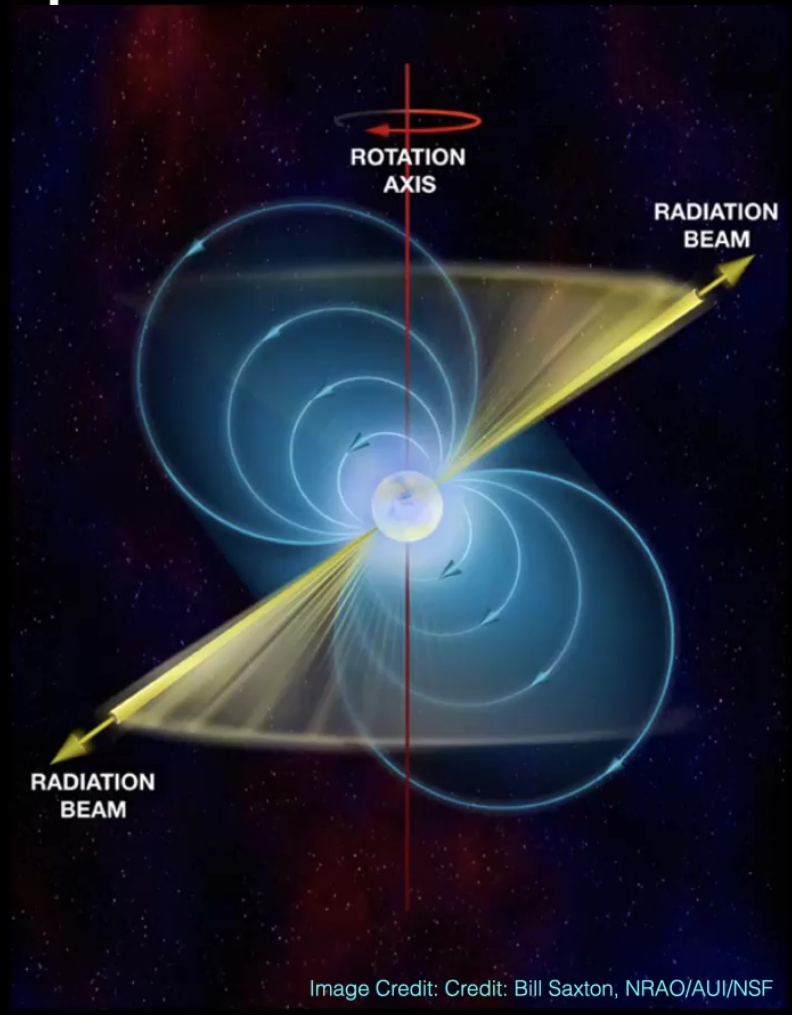
- Pulsars can be a source of very-high-energy electrons.
- Magnetosphere release electrons and positrons as a relativistic “pulsar wind”



100-TeV gamma rays : Leptonic mechanism

- Pulsars can be a source of very-high-energy electrons.
- Magnetosphere release electrons and positrons as a relativistic “pulsar wind”
- These $e^{\pm}$ are further accelerated when the pulsar wind is stopped by the surrounding medium



Young pulsars as e+- accelerator

Amato & Olmi (2021)
Left : National Radio Astronomy Observatory (M. Bietenholz, T. Burchell , B. Schoening)
Right : Chandra X-ray Observatory (F.Seward et al.)

- Crab Nebula (1000 yr old) : Multi-wavelength emission produced by electrons

Young pulsars as e+- accelerator

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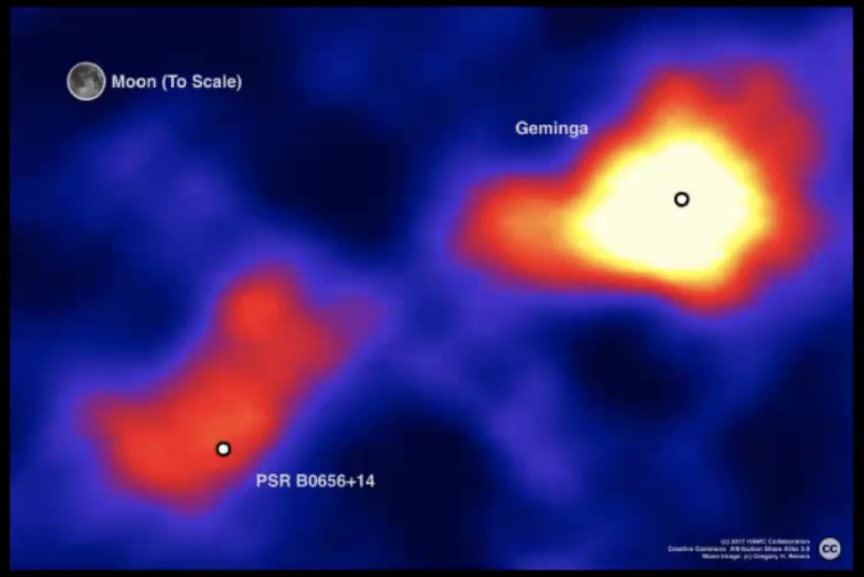
- Crab Nebula (1000 yr old) : Multi-wavelength emission produced by electrons
- Gamma rays now seen above 1 PeV !
- Indicates the presence of PeV electrons — a leptonic “PeVatron”

Middle-aged pulsars as e+- accelerator

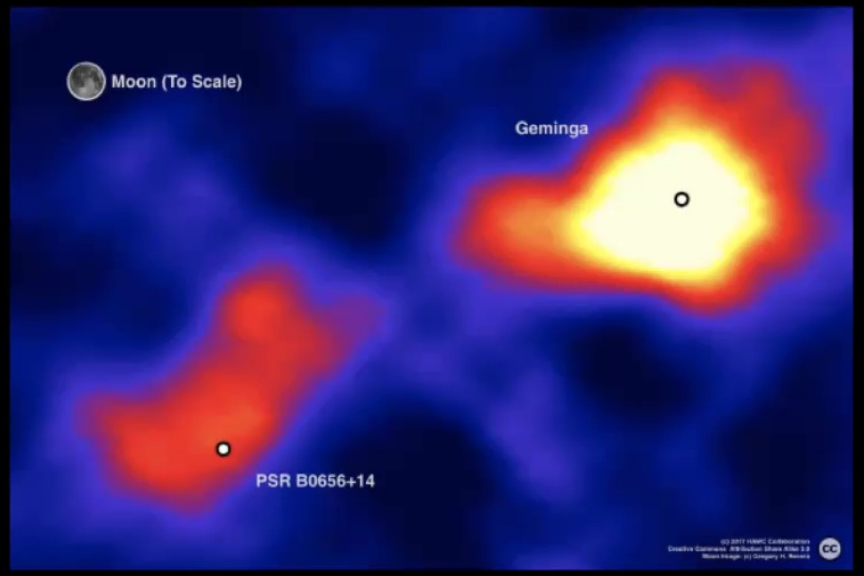
- Recently, largely extended emission of TeV gamma rays are discovered around middle-aged (> 100 kyr) pulsars — “TeV Halos”



HAWC Collaboration
Image : John Pretz

Middle-aged pulsars as e+- accelerator

- Recently, largely extended emission of TeV gamma rays are discovered around middle-aged (> 100 kyr) pulsars — “TeV Halos”
- Middle-aged pulsars are efficiently producing > 50 TeV electrons



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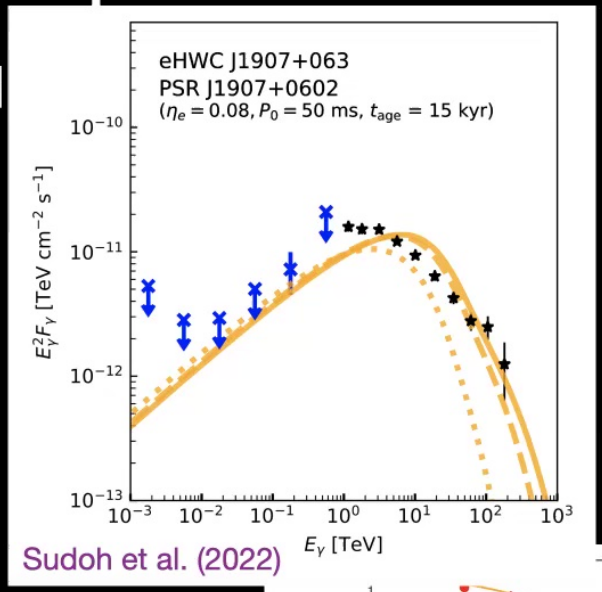
100-TeV gamma rays : Leptonic mechanism

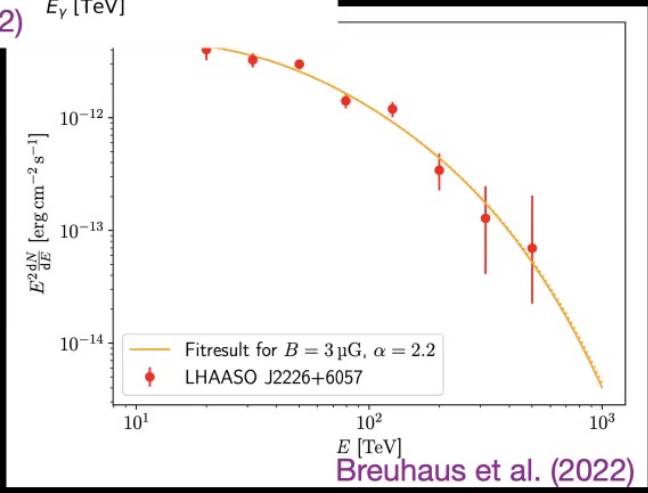
- Various types of pulsars are established as a source of very-high-energy electrons.
- Many gamma-ray sources are located in the vicinity of young, powerful pulsars.

100-TeV gamma rays : Leptonic mechanism

- Various types of pulsars are established as a source of very-high-energy electrons.
- Many gamma-ray sources are located in the vicinity of young, powerful pulsars.
- Radiation field can be provided by CMB (everywhere)
- We find that highest energy gamma-ray sources can be easily explained as leptonic, pulsar-powered emission.

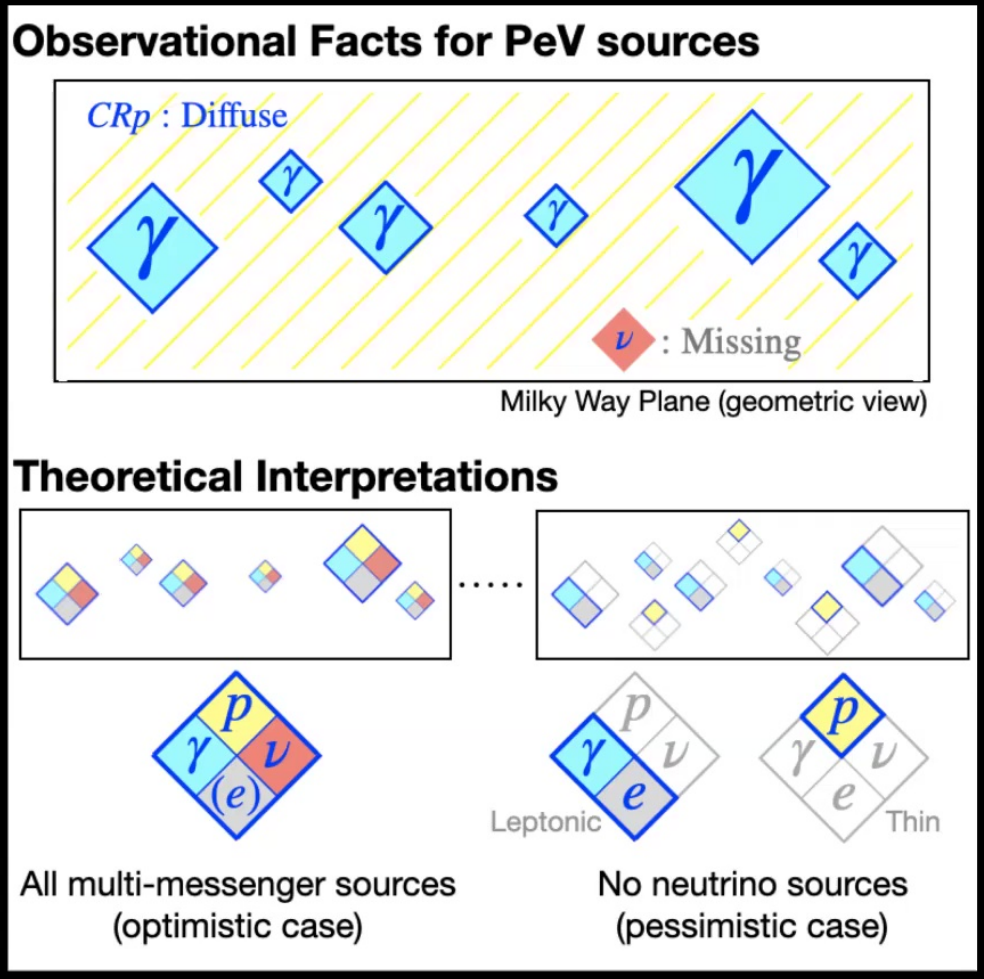


Sudoh et al. (2022)



Breuhaus et al. (2022)

Range of Possibility : What is allowed?



- Leptonic sources :
  - Pulsars are powerful leptonic emitter, and potentially explain all highest-energy gamma-ray sources
- Hadronic sources :
  - Where the Milky Way's hadronic accelerators lie between those extremes?

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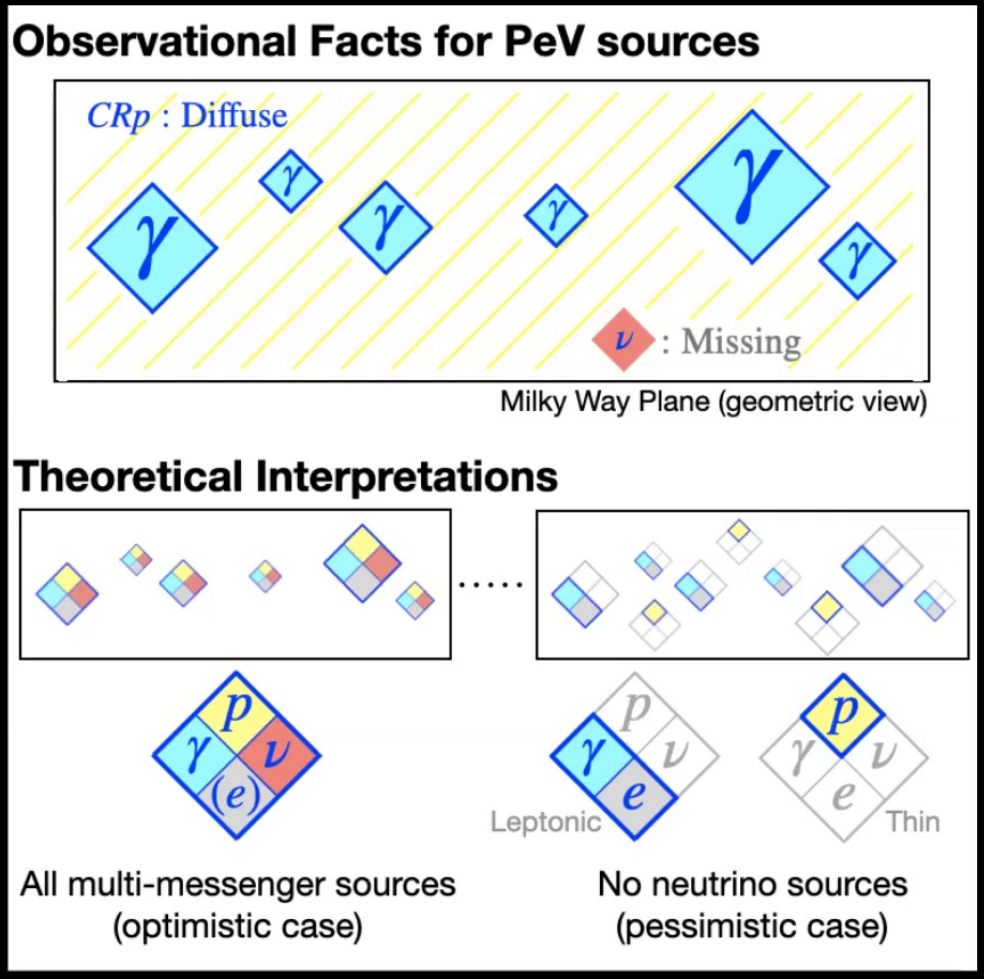

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Hadronic Emission from PeVatrons

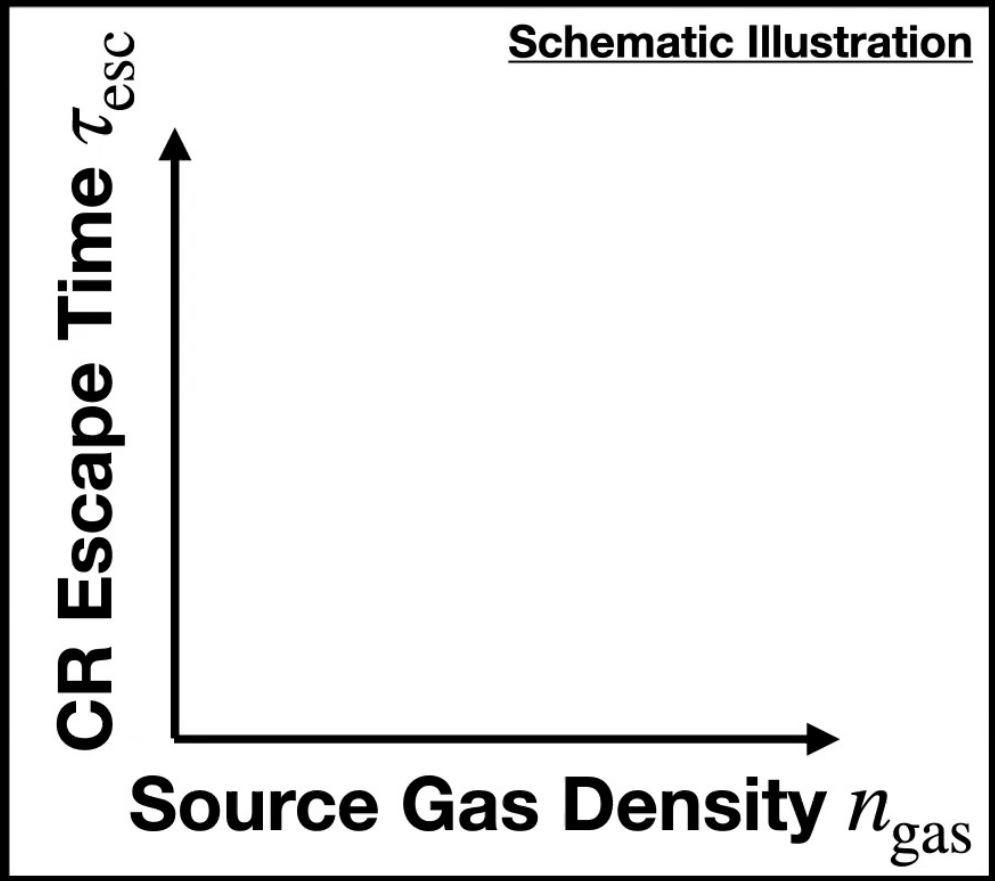
- The key if hadronic PeVatron produce emission is :
  - Energy budget of PeV hadrons
  - Amount of target gas
  - Length of cosmic-ray confinement

Hadronic Emission from PeVatrons

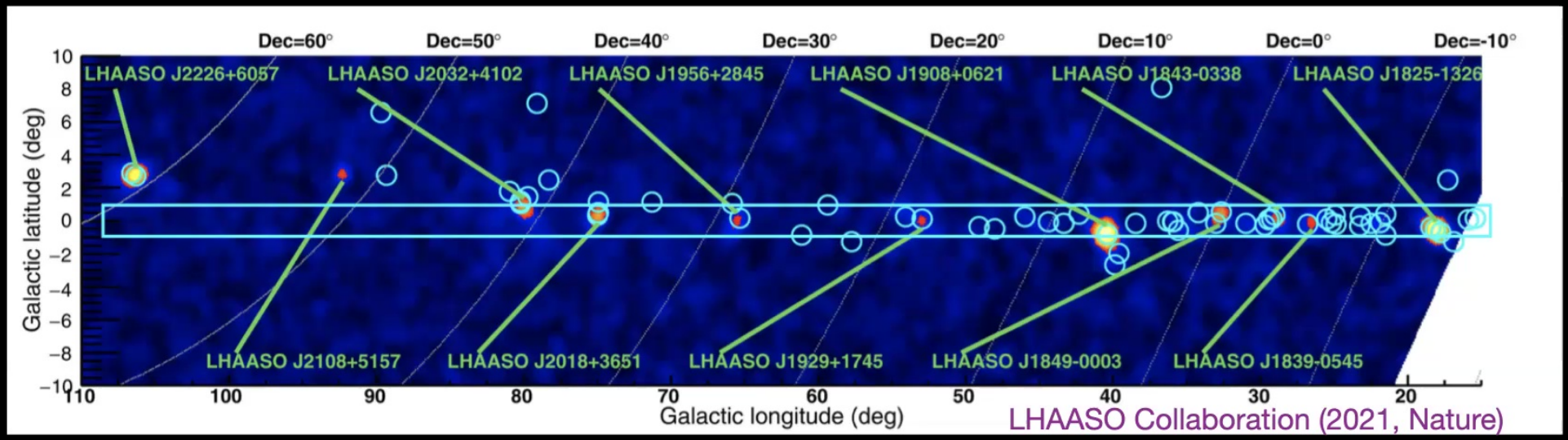
- The key if hadronic PeVatron produce emission is :
  - Energy budget of PeV hadrons ⟶ Fixed based on CR data
  - Amount of target gas : n
  - Length of cosmic-ray confinement : τ

Both n and τ ⟶ Important source Property

“n — tau” plane


Schematic Illustration
CR Escape Time τ_{esc}
Source Gas Density n_{gas}

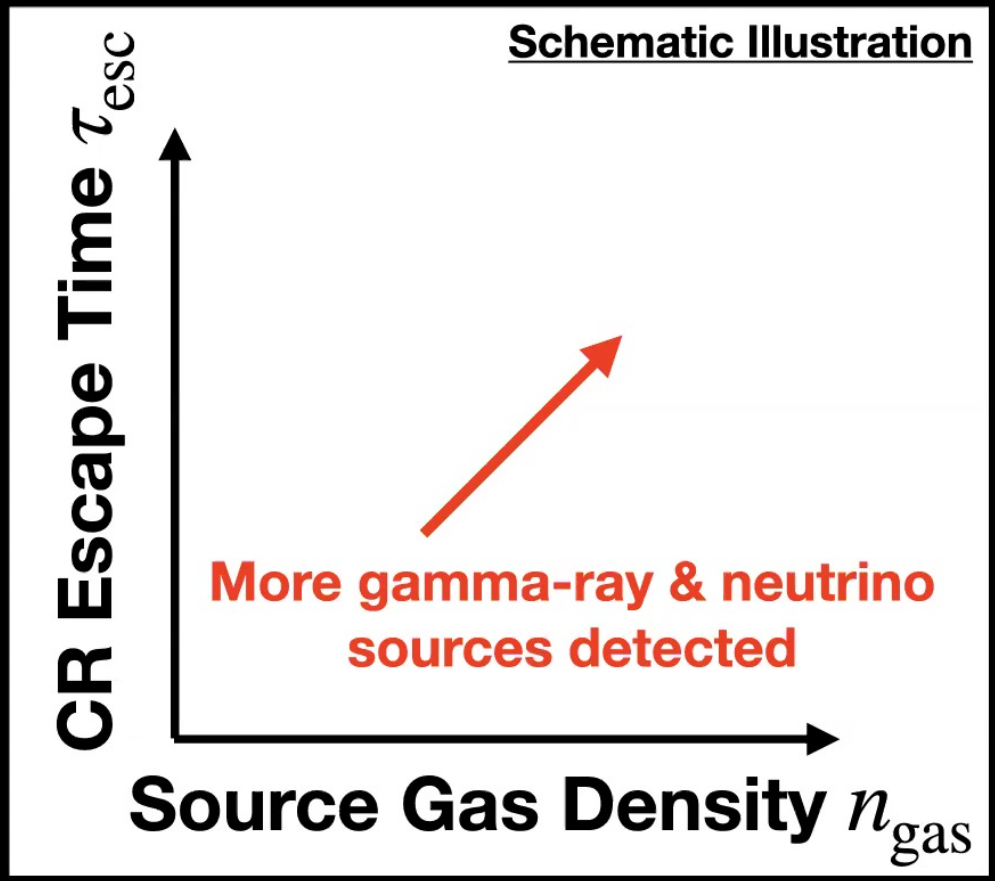
Data



- CR : Various observations
- Gamma ray : Twelve sources above 100 TeV by LHAASO
- Neutrino : Non-detection by IceCube

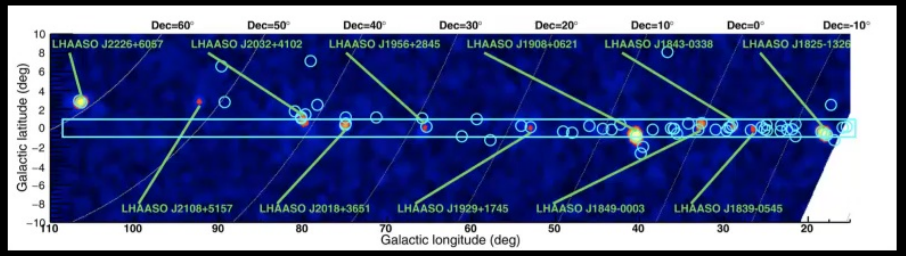
“n — tau” plane

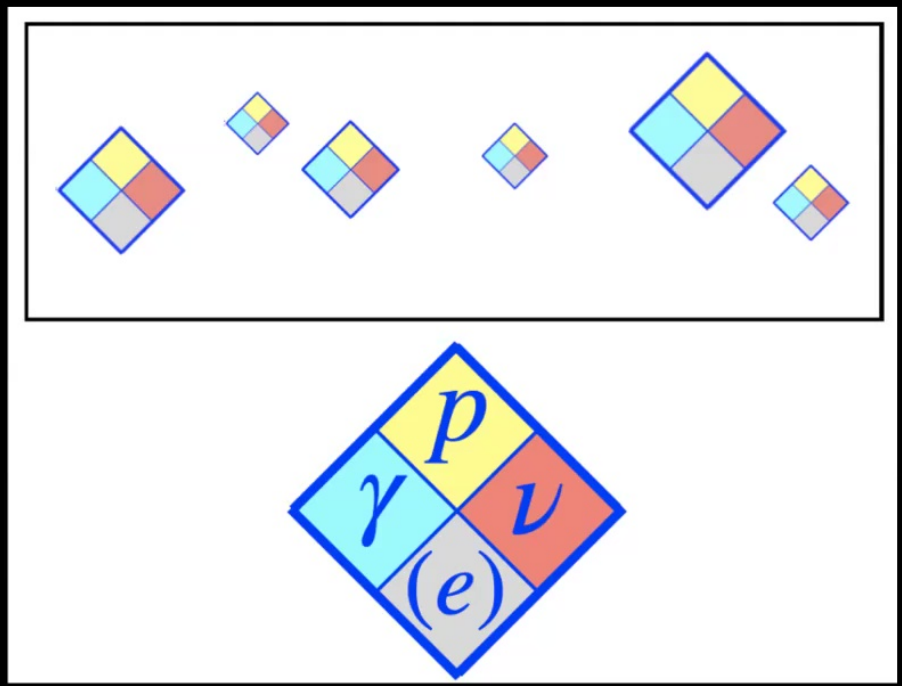
- Observations can constrain parameter space on this plane



100-TeV gamma-ray sources

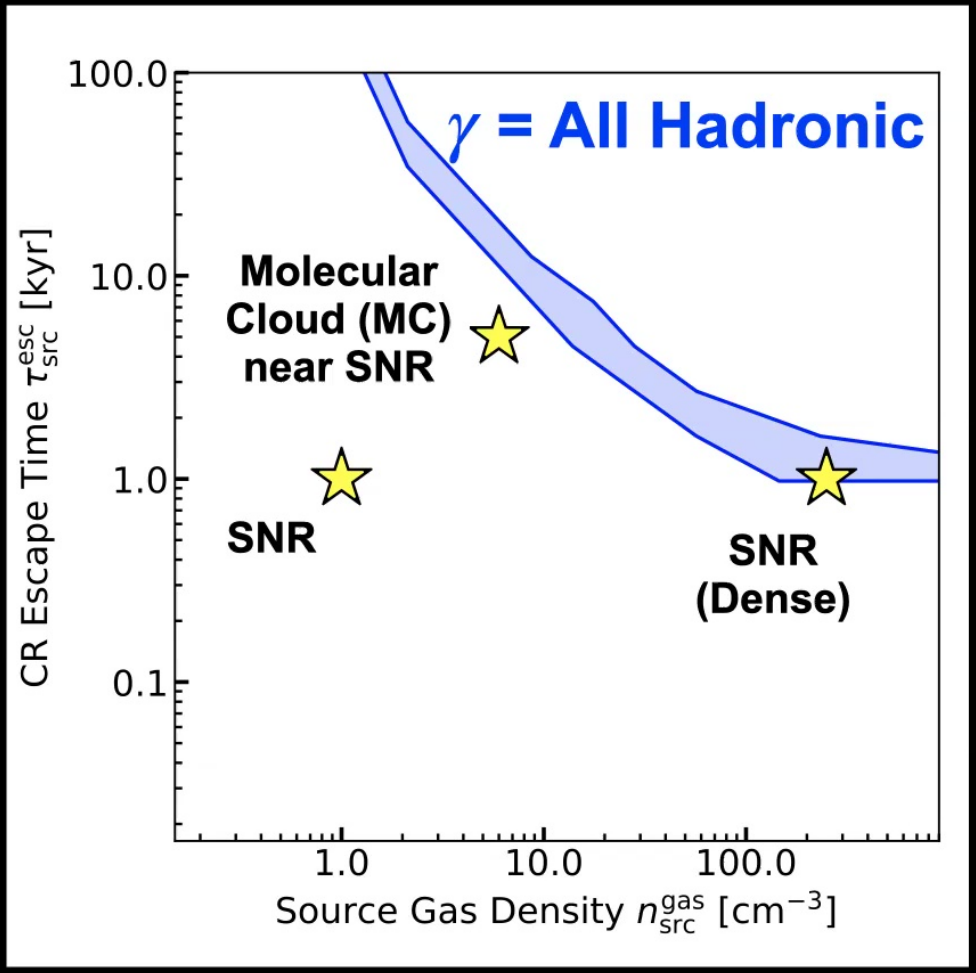
- Can highest-energy gamma-ray sources be **all hadronic** ?





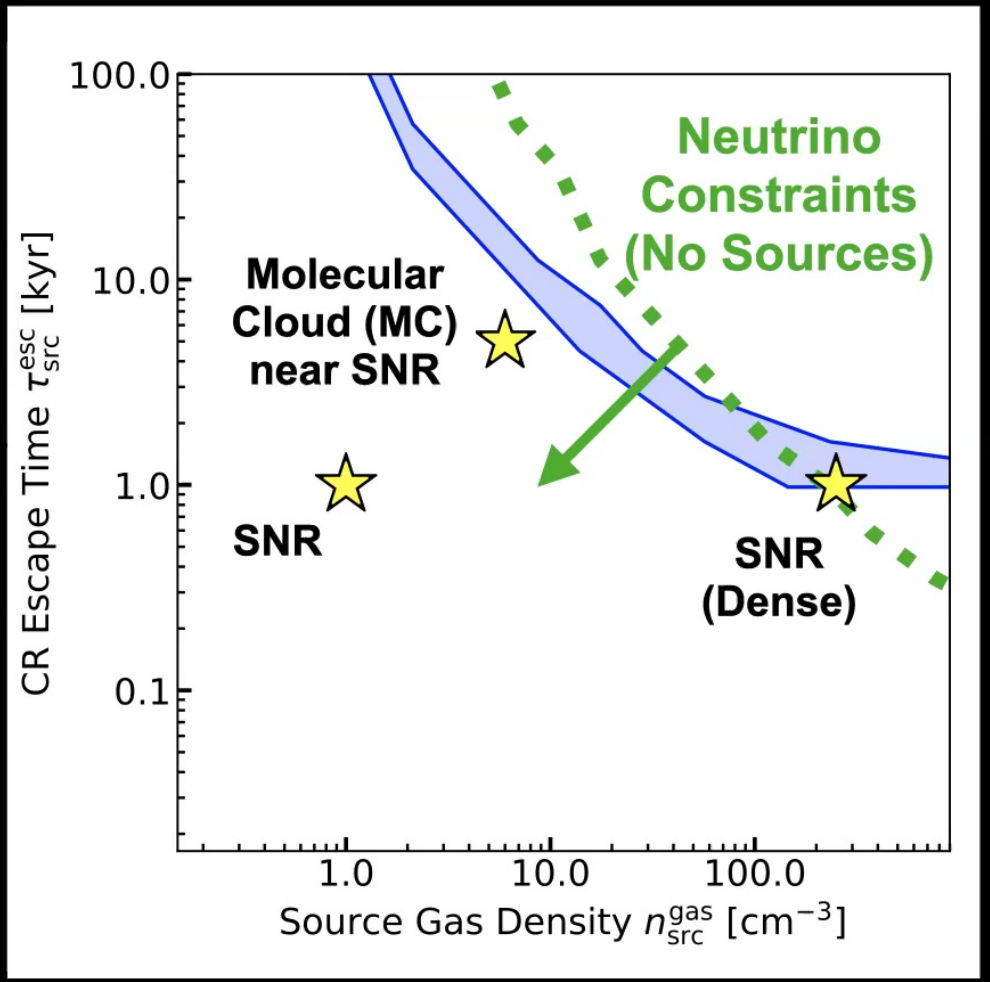
100-TeV gamma-ray sources

- Can highest-energy gamma-ray sources be **all hadronic** ?
- **Yes!**
- Require high gas density and confinement time



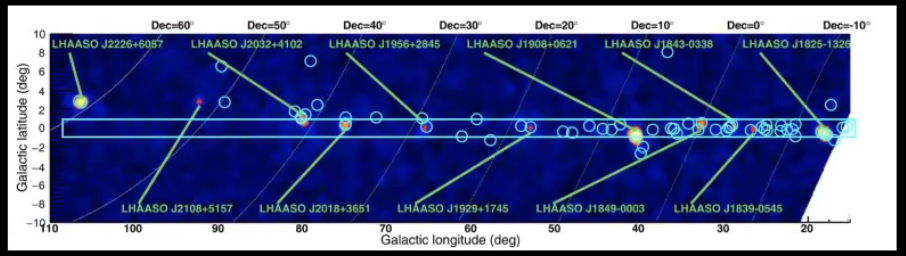
100-TeV gamma-ray sources

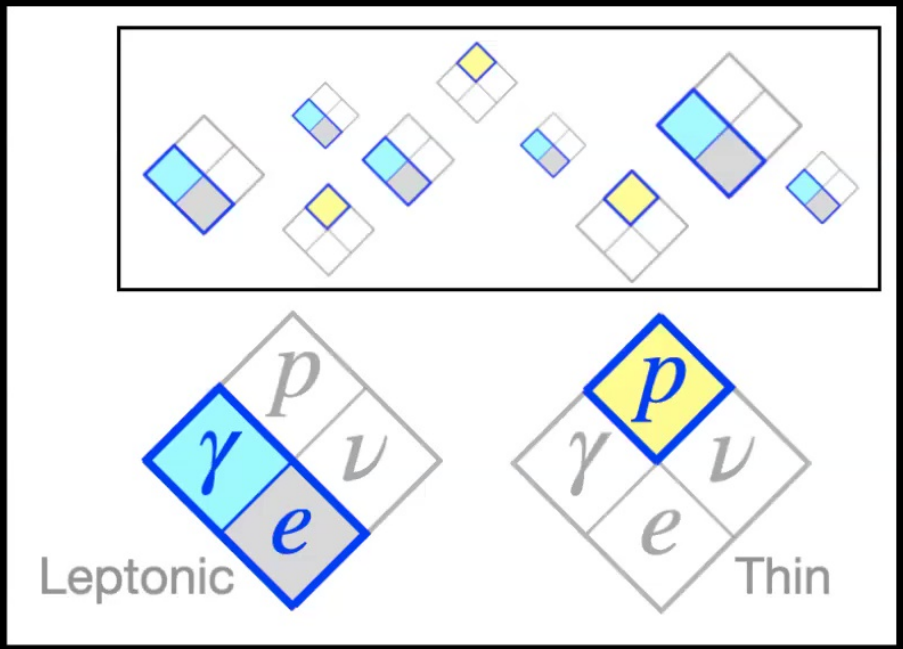
- Can highest-energy gamma-ray sources be **all hadronic** ?
- **Yes!**
- Require high gas density and confinement time
- **"SNR (Dense)"** is ruled out by non-detection of MW's neutrino sources



100-TeV gamma-ray sources

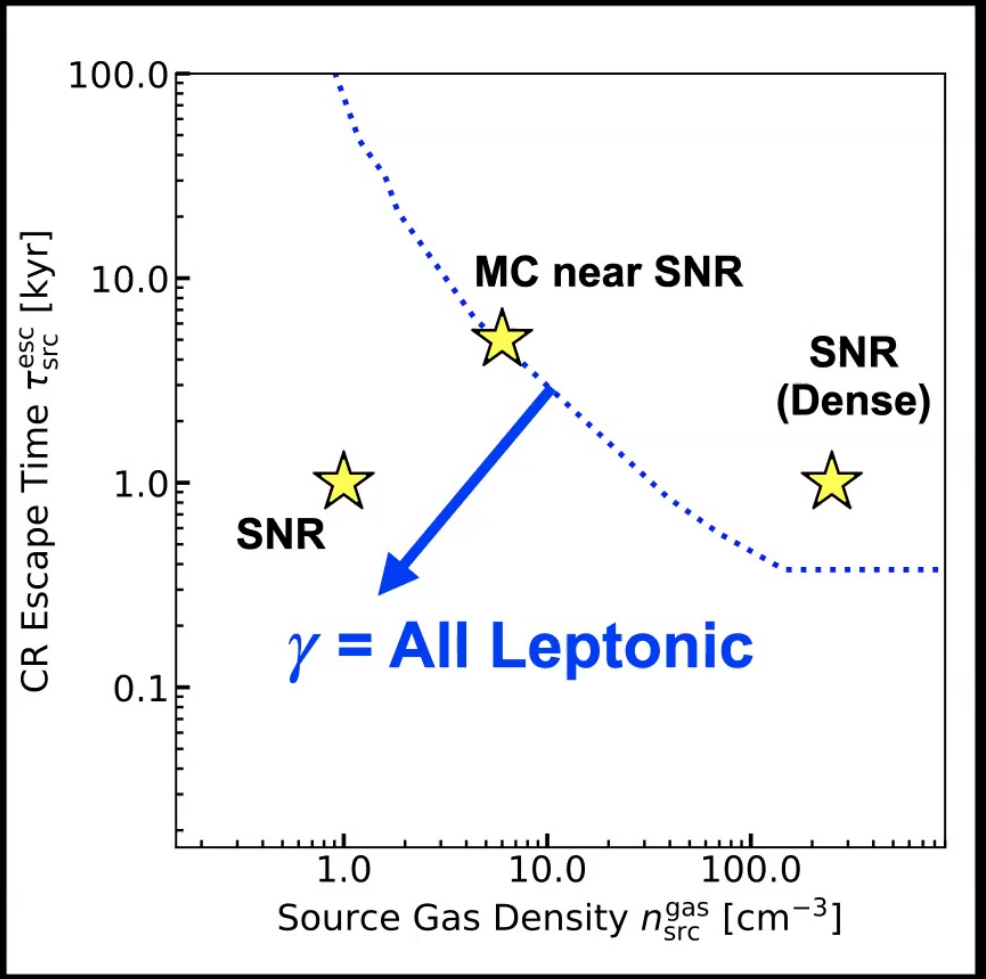
- Can highest-energy gamma-ray sources be **all leptonic** ?





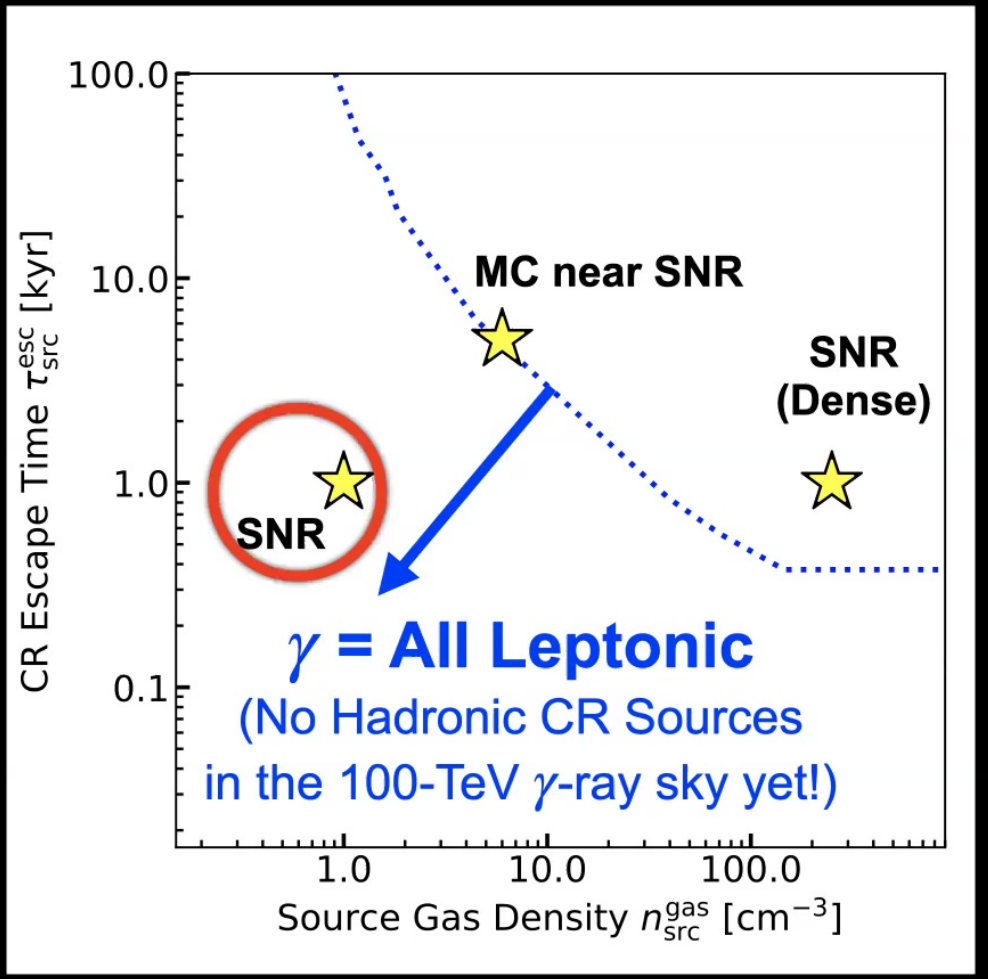
100-TeV gamma-ray sources

- Can highest-energy gamma-ray sources be **all leptonic** ?
- **Yes!**
- A wide range of models is consistent with such scenario!



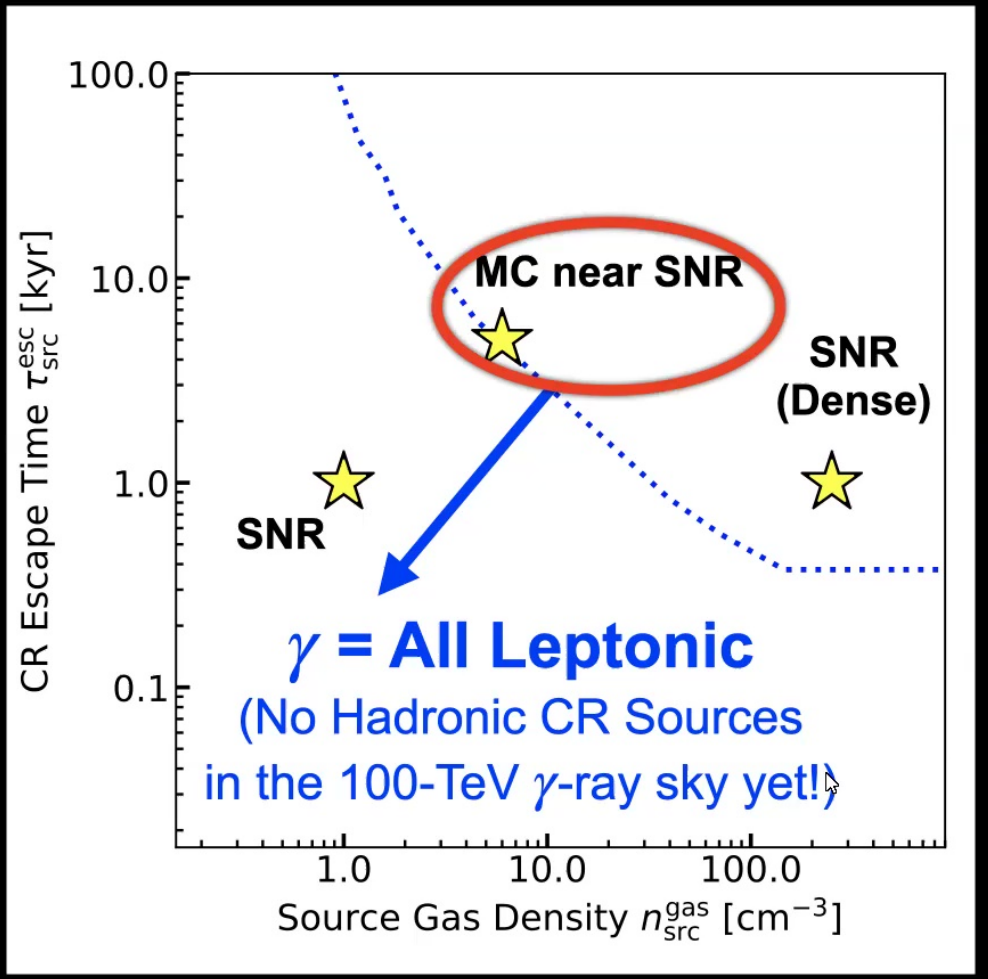
100-TeV gamma-ray sources

- Remark : Models are normalized to CR data.
- Even if ordinary SNRs are PeV CR sources, it is natural we do not yet see them in 100 TeV gamma rays

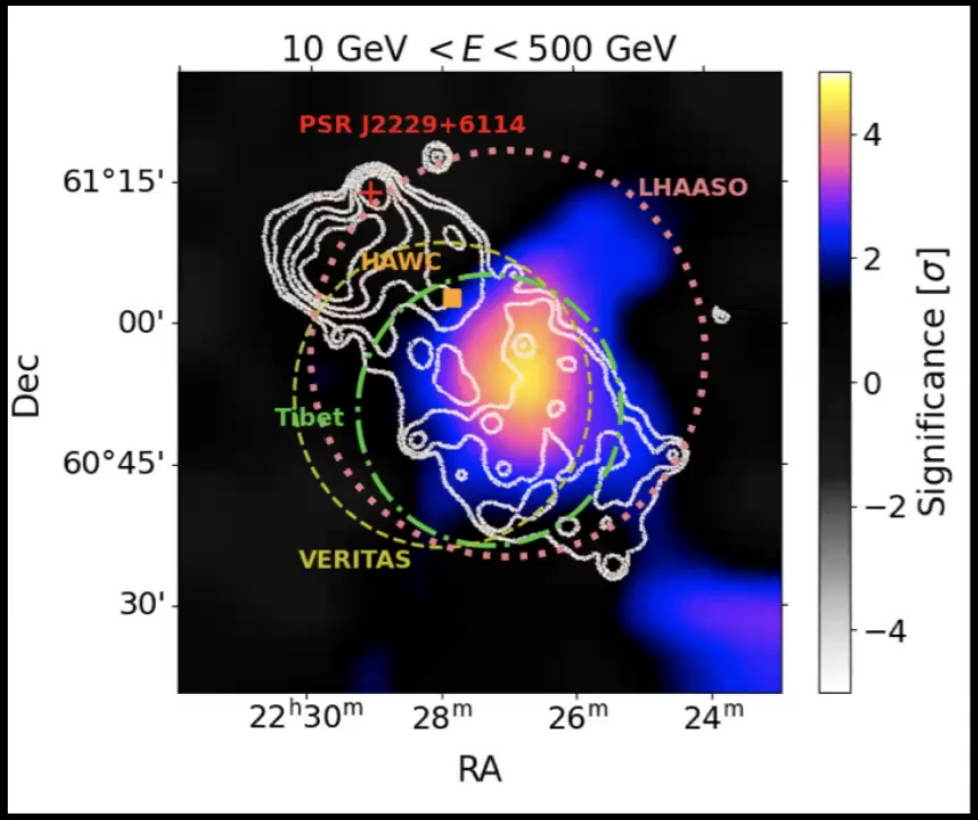


100-TeV gamma-ray sources

- The existing survey starts to probe models where SNRs are in the vicinity of a giant molecular cloud (MC)



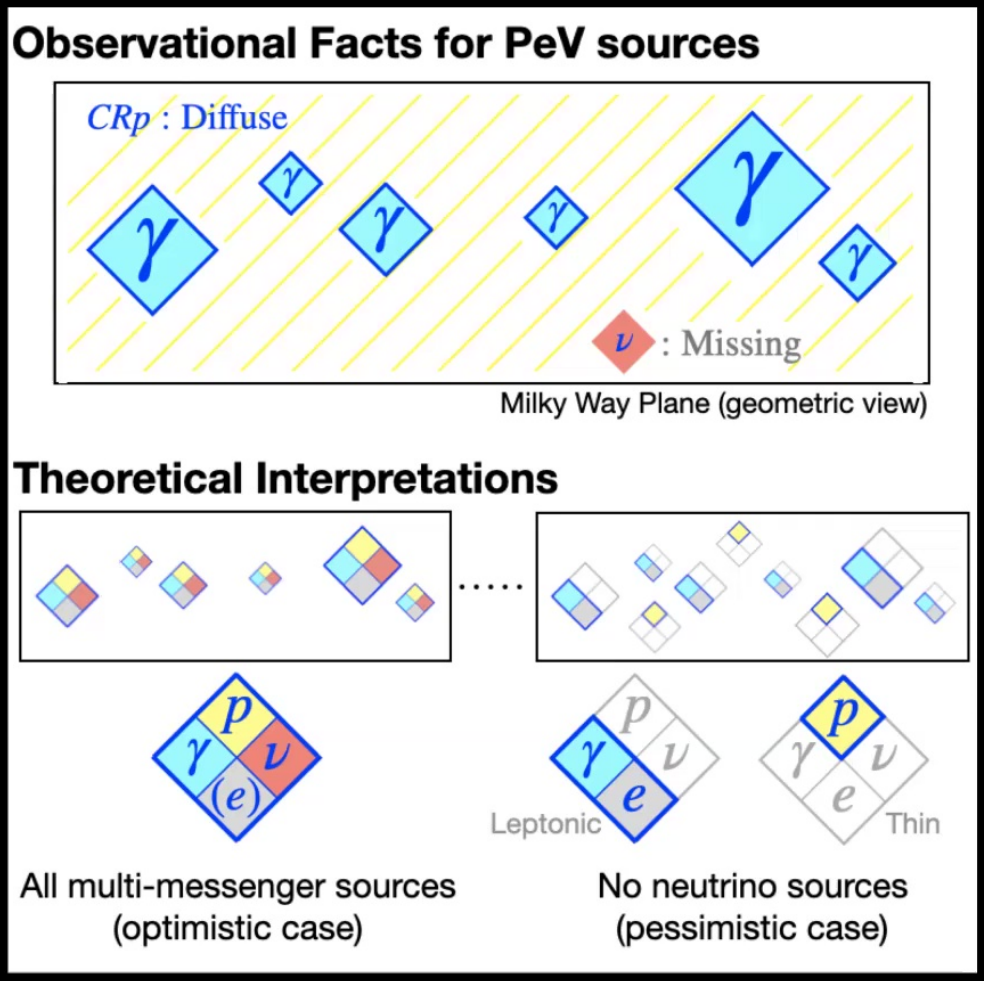
Interesting System : SNR G 106.3 +2.7



- Promising hadronic PeVatron candidate
- Associated with a middle-aged SNR
- Emission correlates with gas clouds
- Leptonic (pulsar-powered) scenarios have also been proposed

Figure from Fang et al. (2022, PRL)
See also papers by HAWC, Tibet ASγ, LHAASO, VERITAS

Wide range of possibility is allowed



- Leptonic sources :
  - Pulsars are powerful leptonic emitter, and potentially explain all highest-energy gamma-ray sources
- Hadronic sources :
  - Both extreme scenarios for PeV source are viable

How to progress?
(1) Neutrinos

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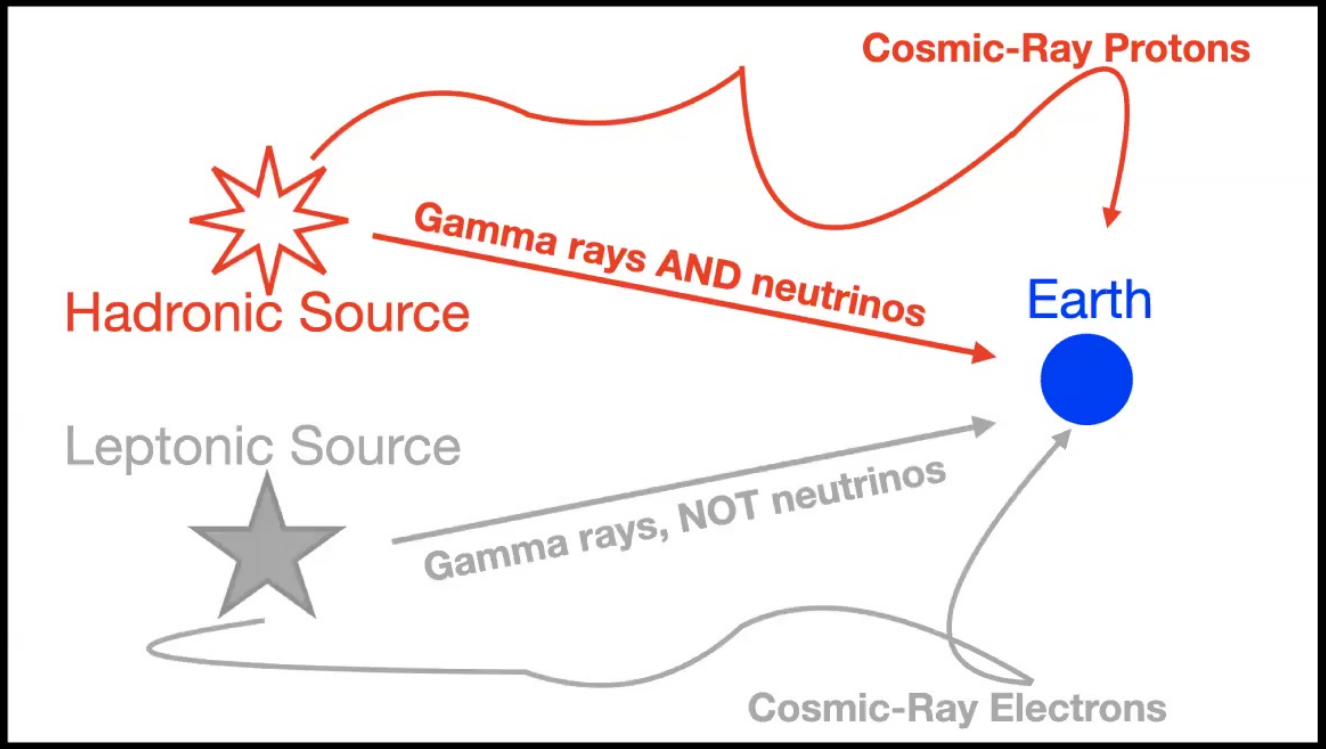
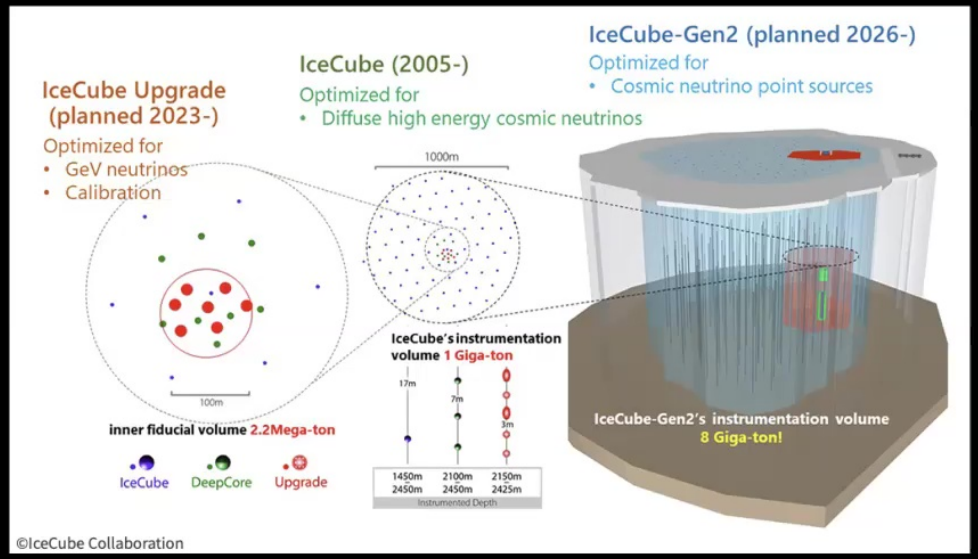
(1) Neutrinos

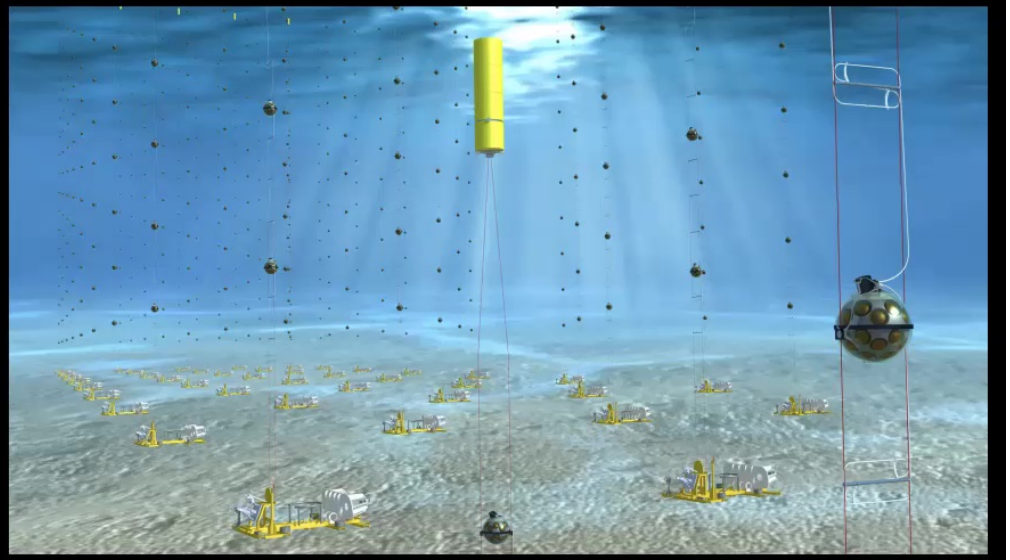
Neutrinos are smoking-gun

- A decisive way to detect hadronic sources are neutrinos



Future telescopes



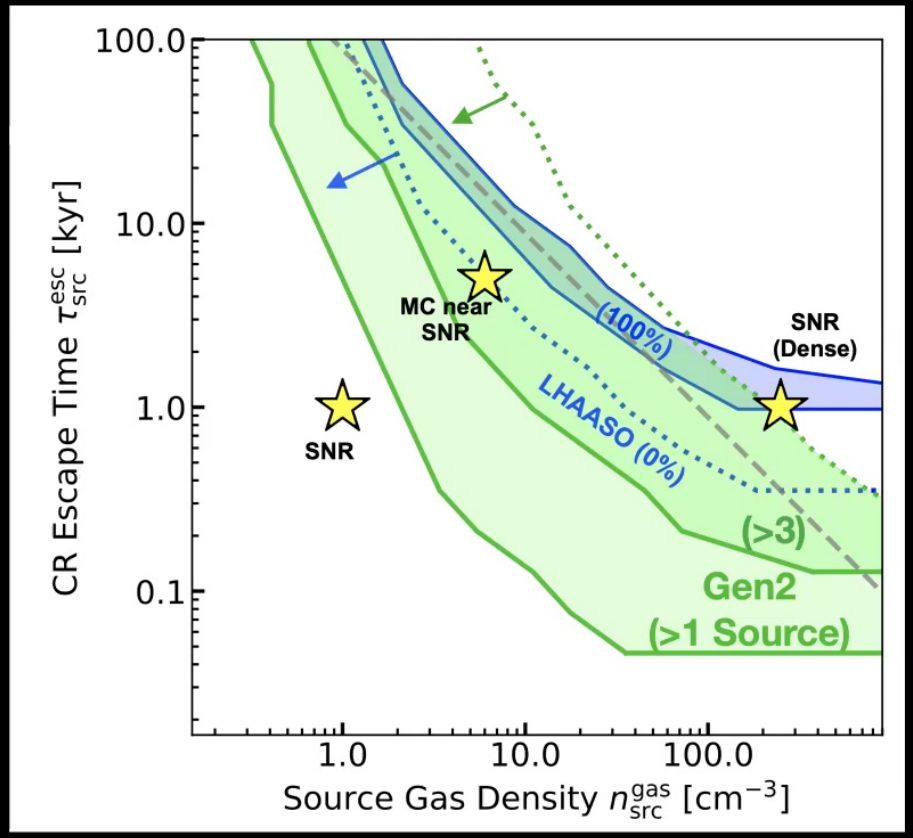


- IceCube Gen2
- Increased volume by a factor of 8

- KM3NeT
- Ocean-based

Prospects for Gen2

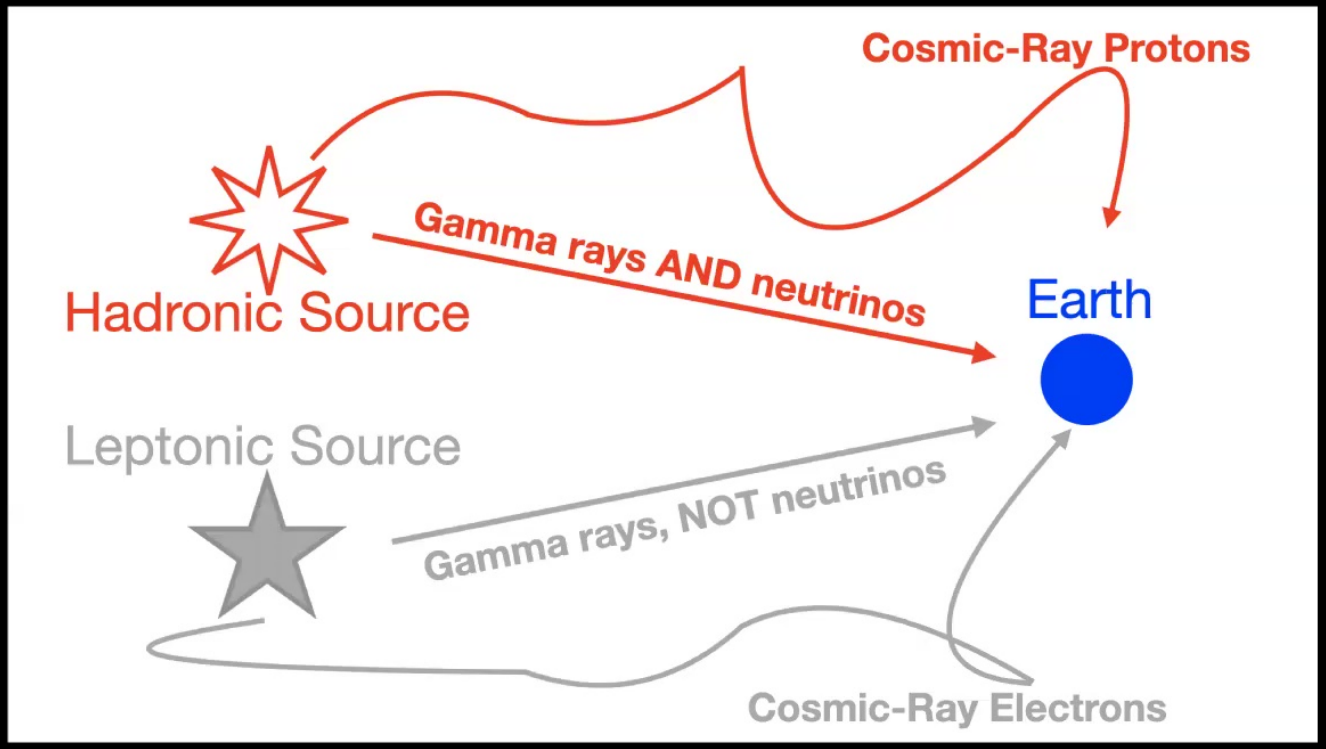
- It is promising that Gen-2 find one or more hadronic PeVatrons
- But it may find zero, if PeVatrons are thin



How to progress?
(2) Finding nearby sources

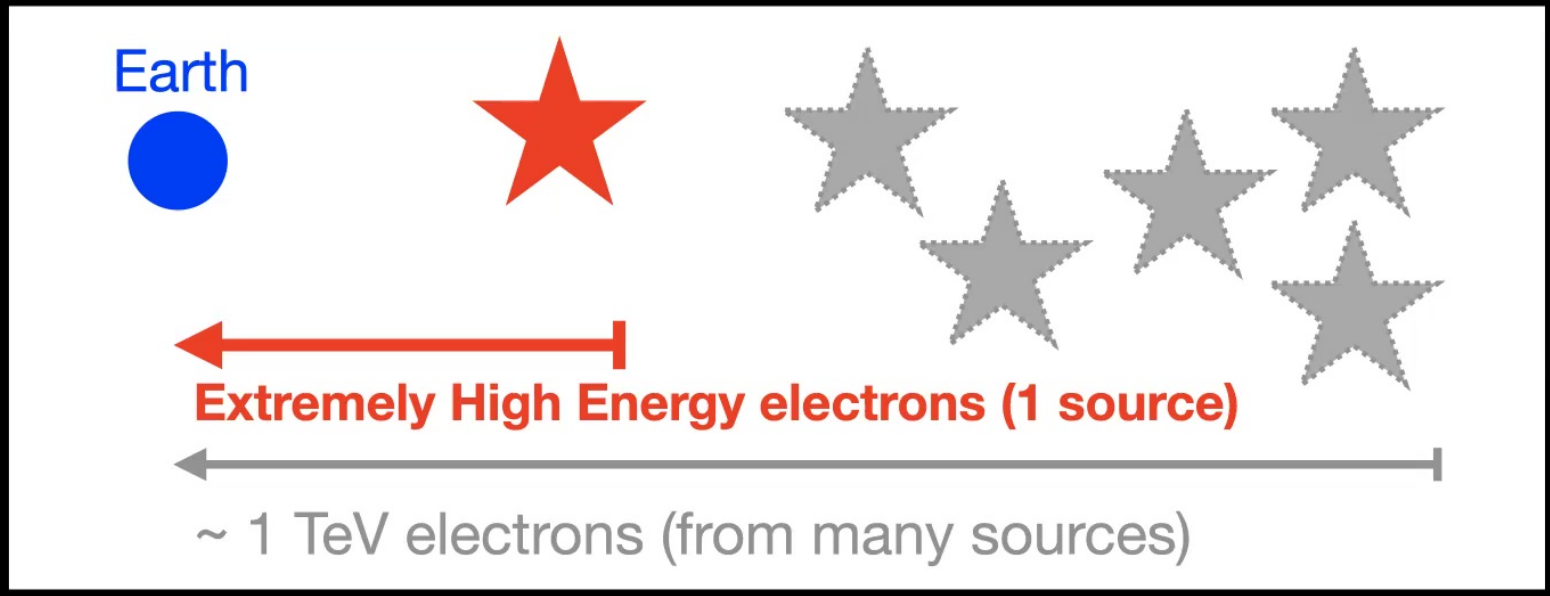
Identifying cosmic-ray sources

- Identifying cosmic-ray sources are hard due to random deflections



Identifying nearby cosmic-ray sources

- Higher energy electrons cool faster = come from nearby
- At extremely high energies, only one source contributes to the observed flux
- We could identify that source by, e.g., anisotropy in arrival direction



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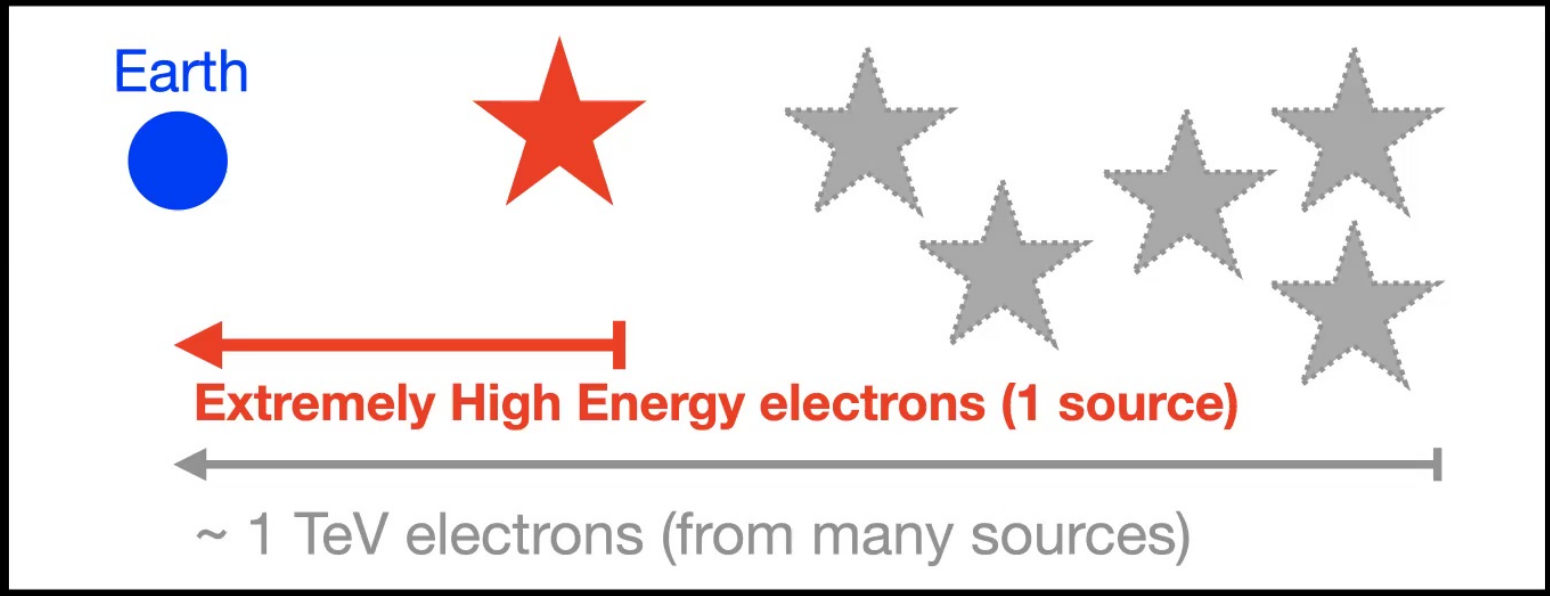
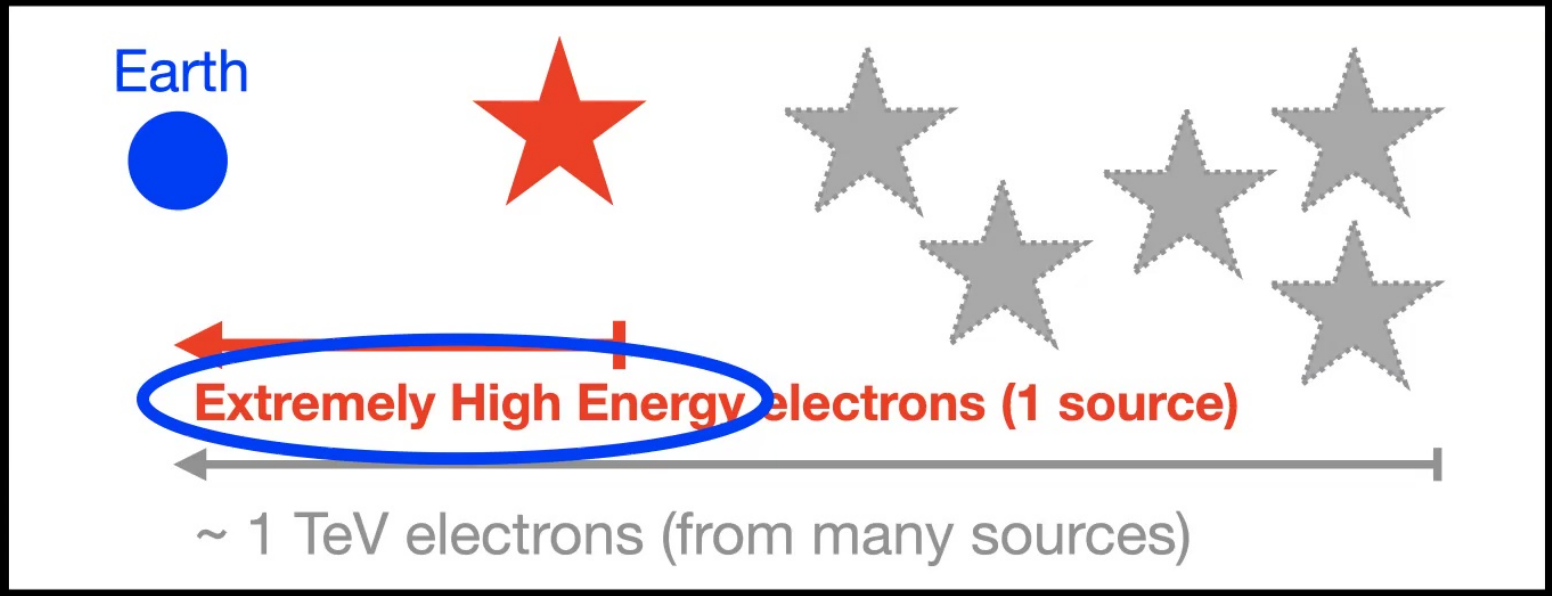


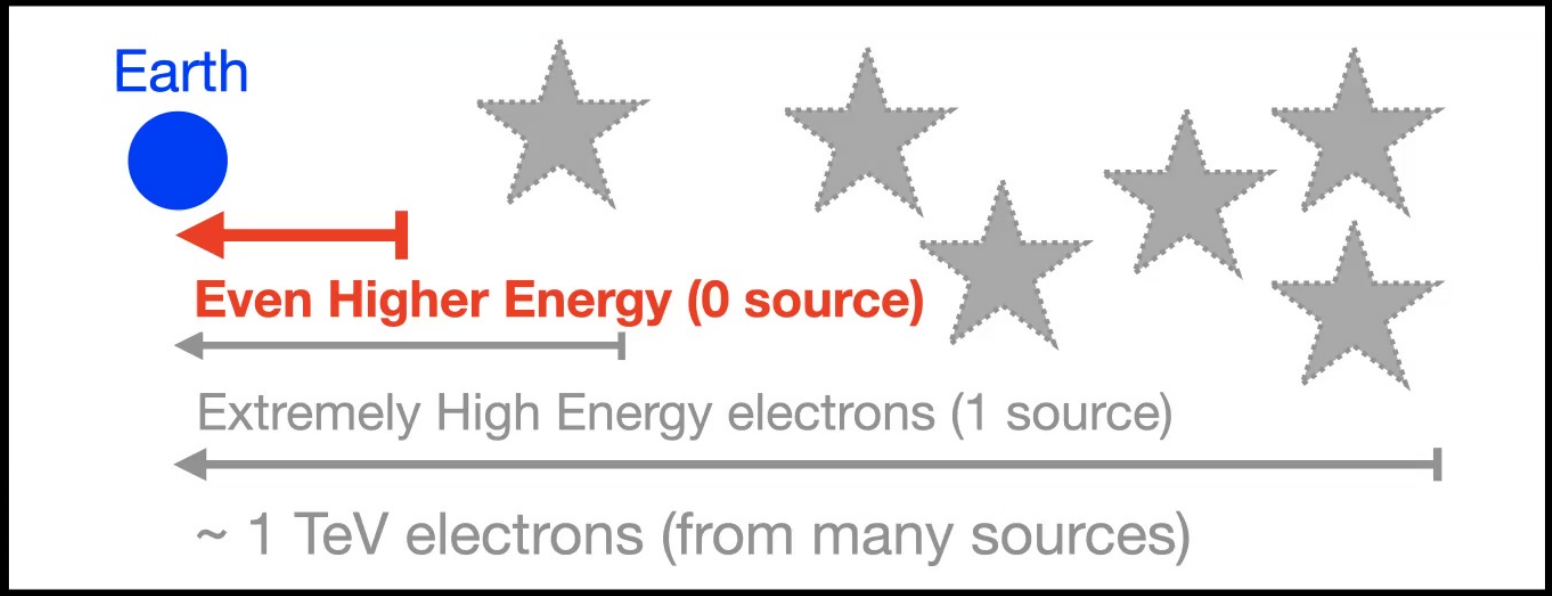
Identifying nearby cosmic-ray sources

- What is the energy range where only one source contributes?
- We currently work on this to see if it is within reach of future observations.
- Very preliminary; the “end” of CR electrons could be observed soon.



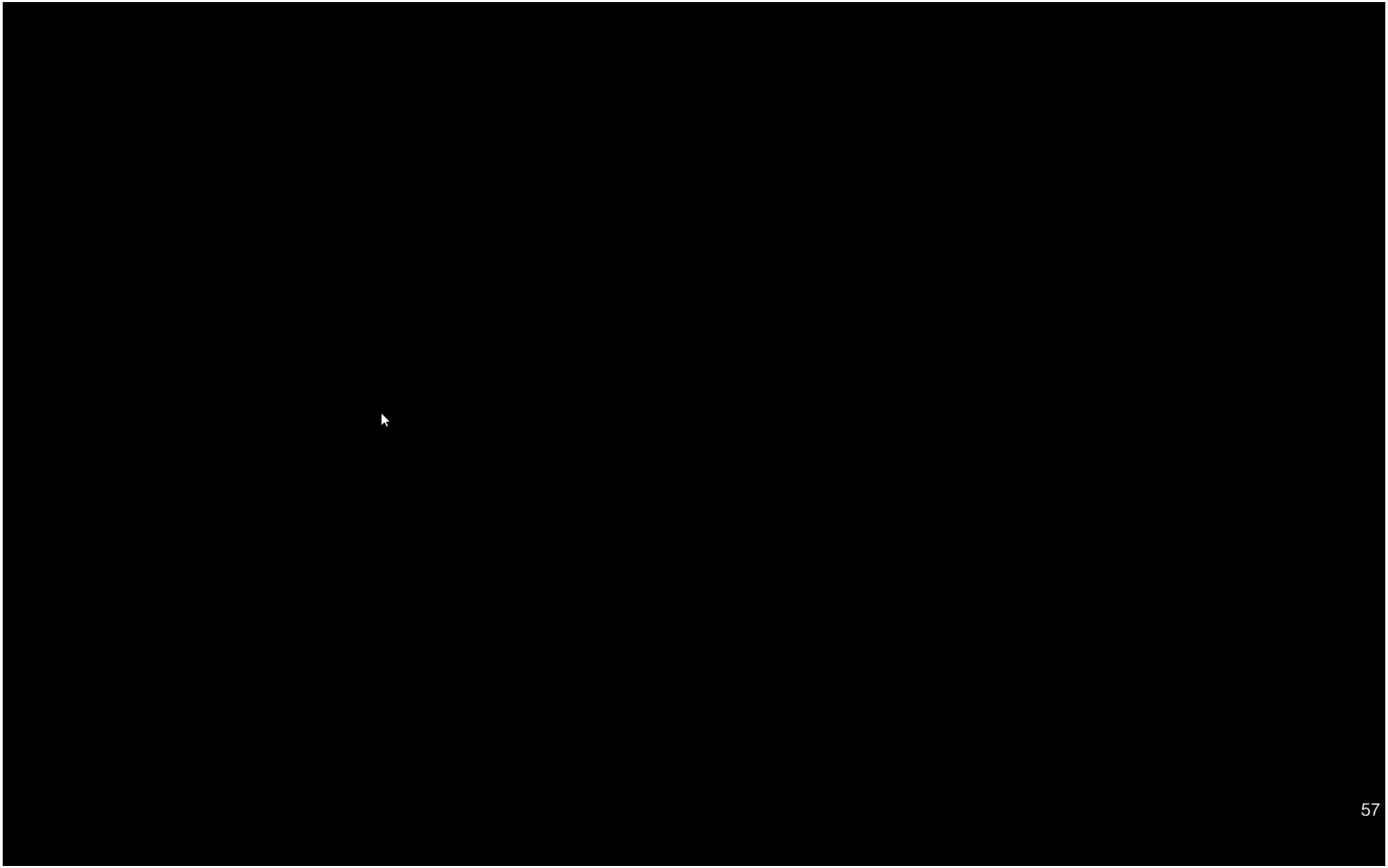
Identifying nearby cosmic-ray sources

- At even higher energies, no electron from astro source reach the Earth
- The only contribution is from exotic scenarios, e.g., decay of dark matters
- Clean window to search for the dark-matter signals !?



Conclusions

- We see PeV hadronic cosmic rays, we see 100-TeV gamma-ray sources, but no neutrino source — Where are Galactic PeVatrons?
- Optimistically, the highest-energy gamma-ray sources are hadronic PeVatrons that produce neutrinos, making them excellent multi-messenger sources.
- We point out that an alternate pessimistic exist : the origins of CRs and highest-energy gamma-ray sources might be disjoint, and there is no detectable neutrino source.
- Improvements in neutrinos are key to isolate these scenarios.
- Extremely high-energy electrons could be used for the direct detection of a cosmic-ray source (and a unique window for DM searches).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