Where are Milky Way's Hadronic PeVatrons?

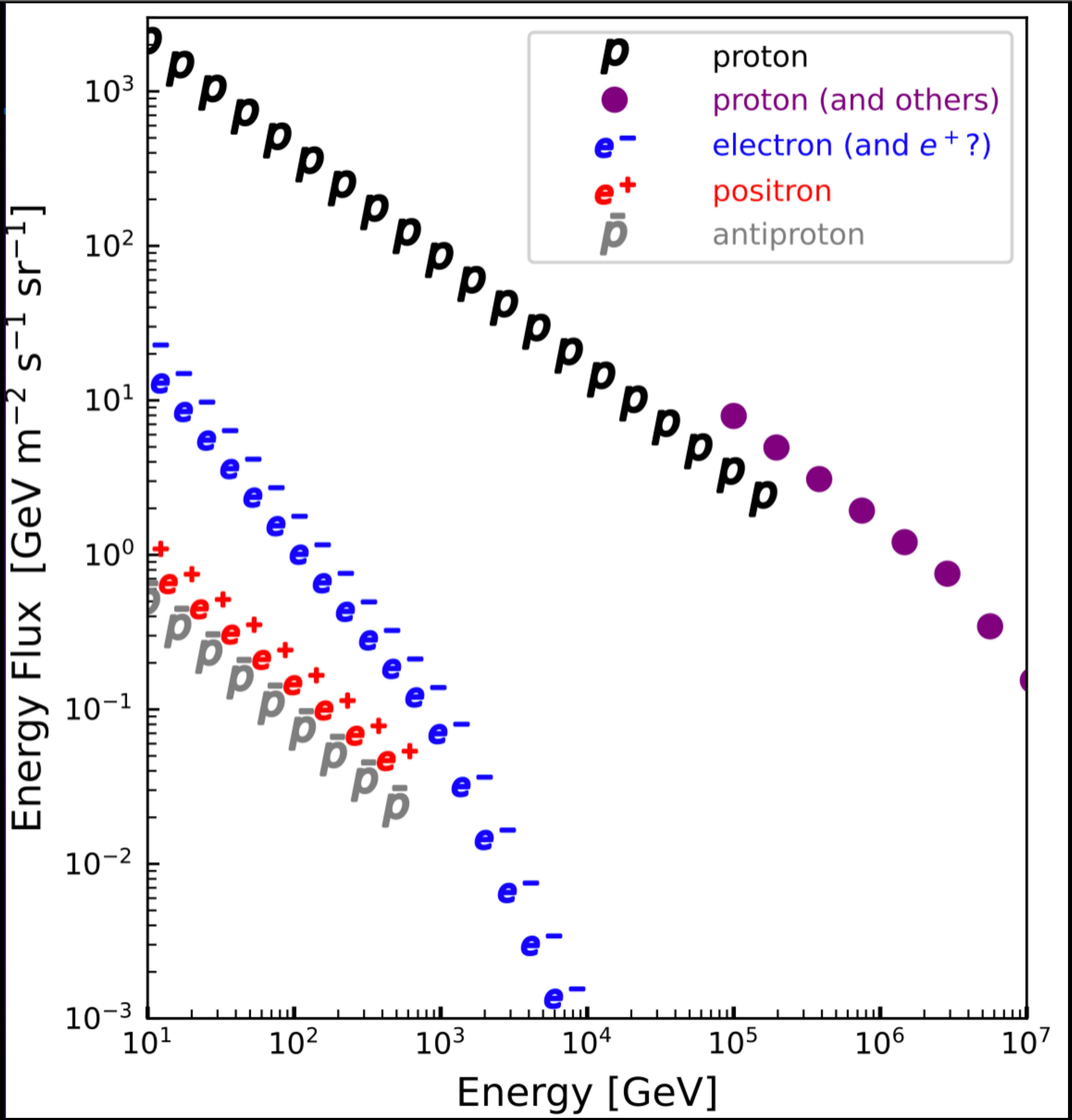
Takahiro Sudoh

(Ohio State University)

Introduction

Hadronic PeVatrons exist in the Milky Way

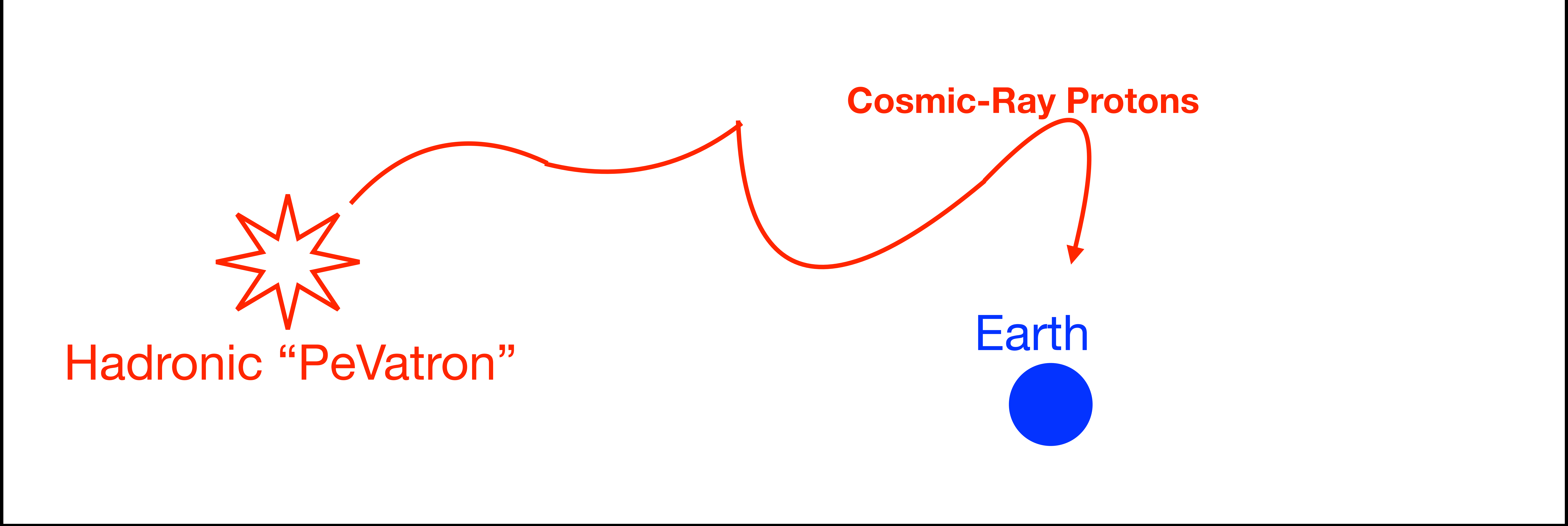
- Unidentified sources in the Milky Way accelerate hadrons to PeV energies = **Hadronic "PeVatrons"**
- Finding hadronic PeVatrons has been a long-standing goal



Note : Compiled and overly simplified by me

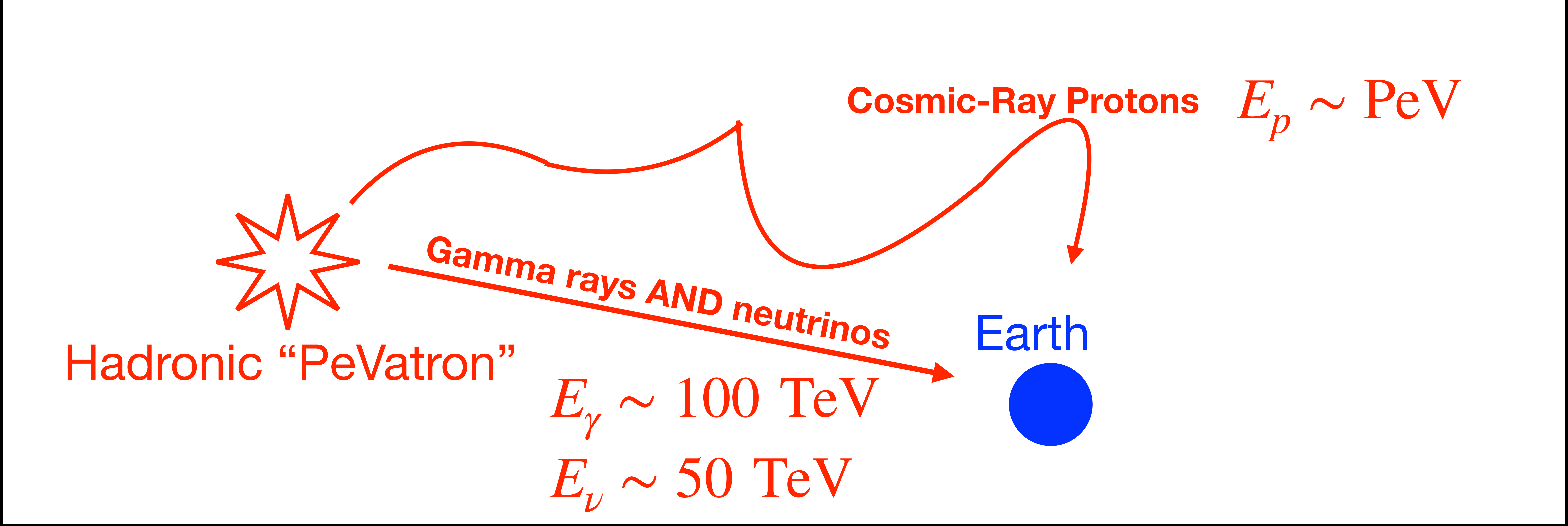
But PeVatrons cannot be identified directly via CRs

- Cosmic rays (CRs) are charged particles and randomly deflected by magnetic field

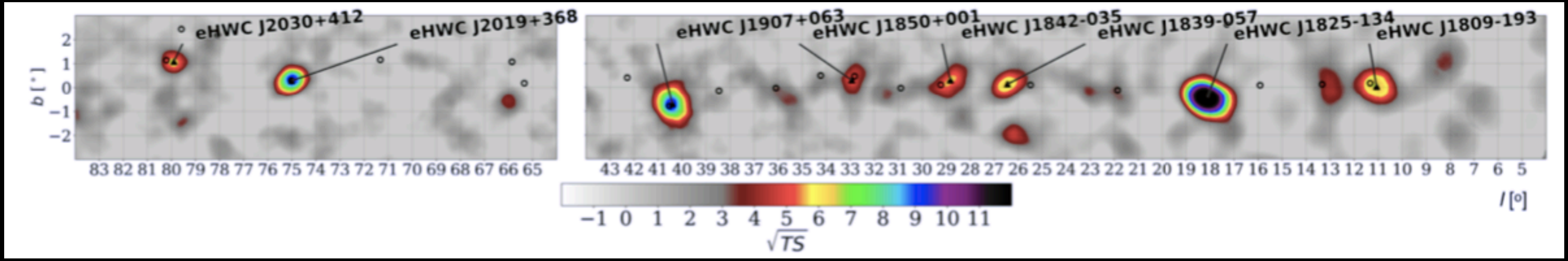


PeVatrons can be identified via gamma ray and neutrino

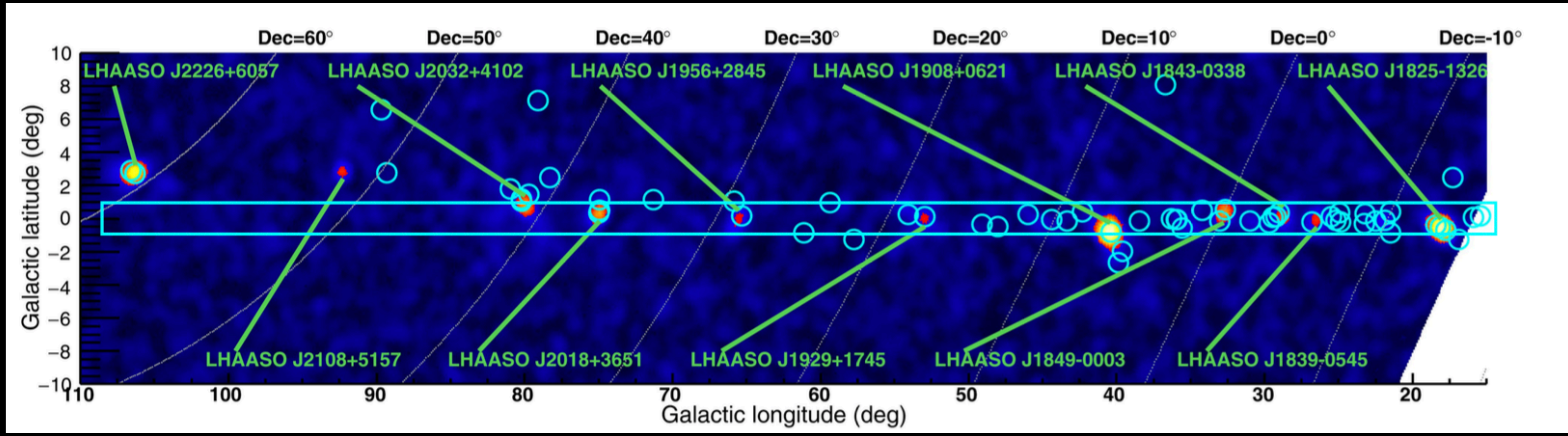
- Protons interact with gases to emit gamma rays and neutrinos
- Emission is the key to identity the Milky Way's PeVatron



Gamma rays sources are detected above 100 TeV



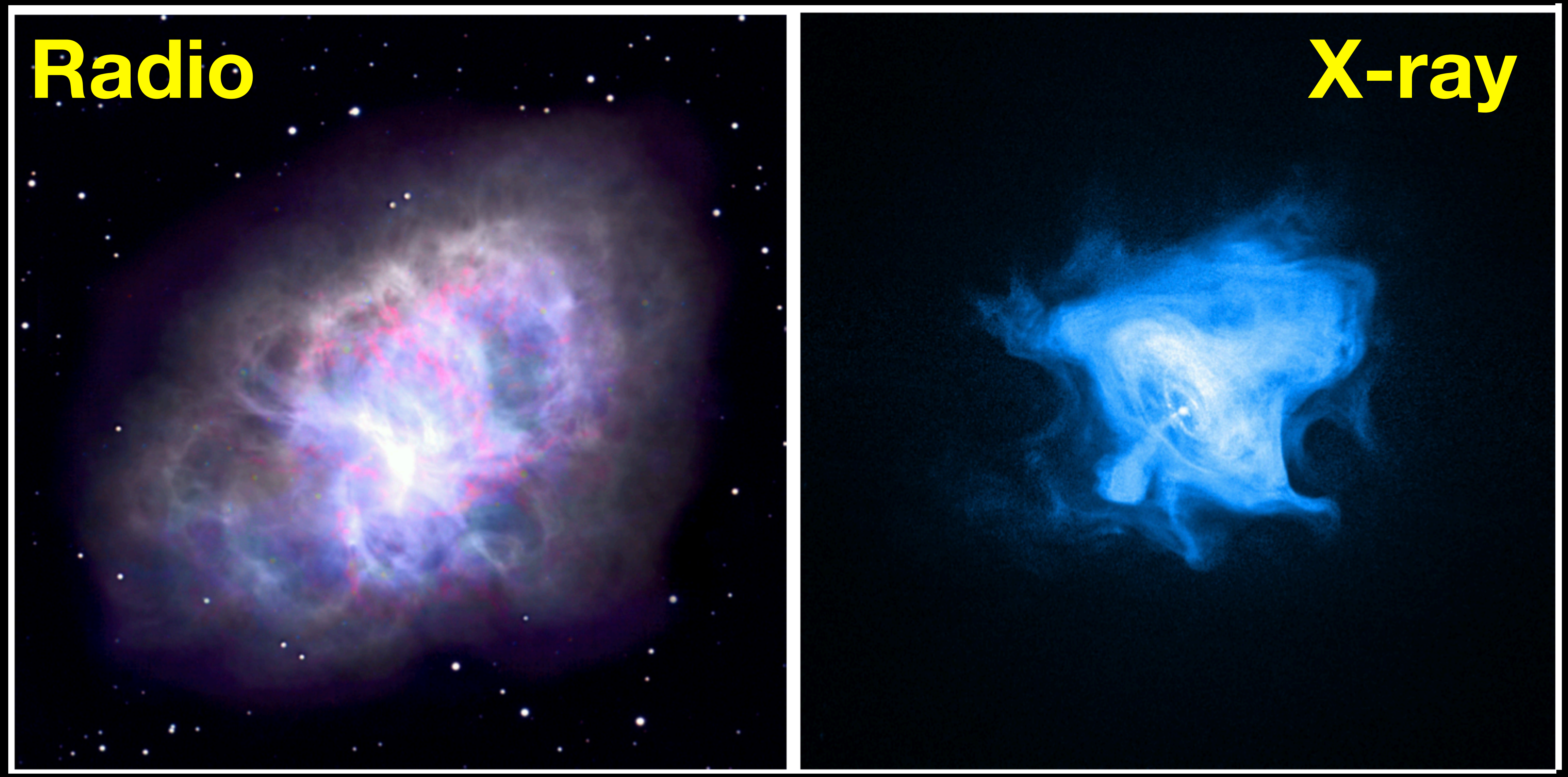
HAWC Collaboration (2020, PRL)



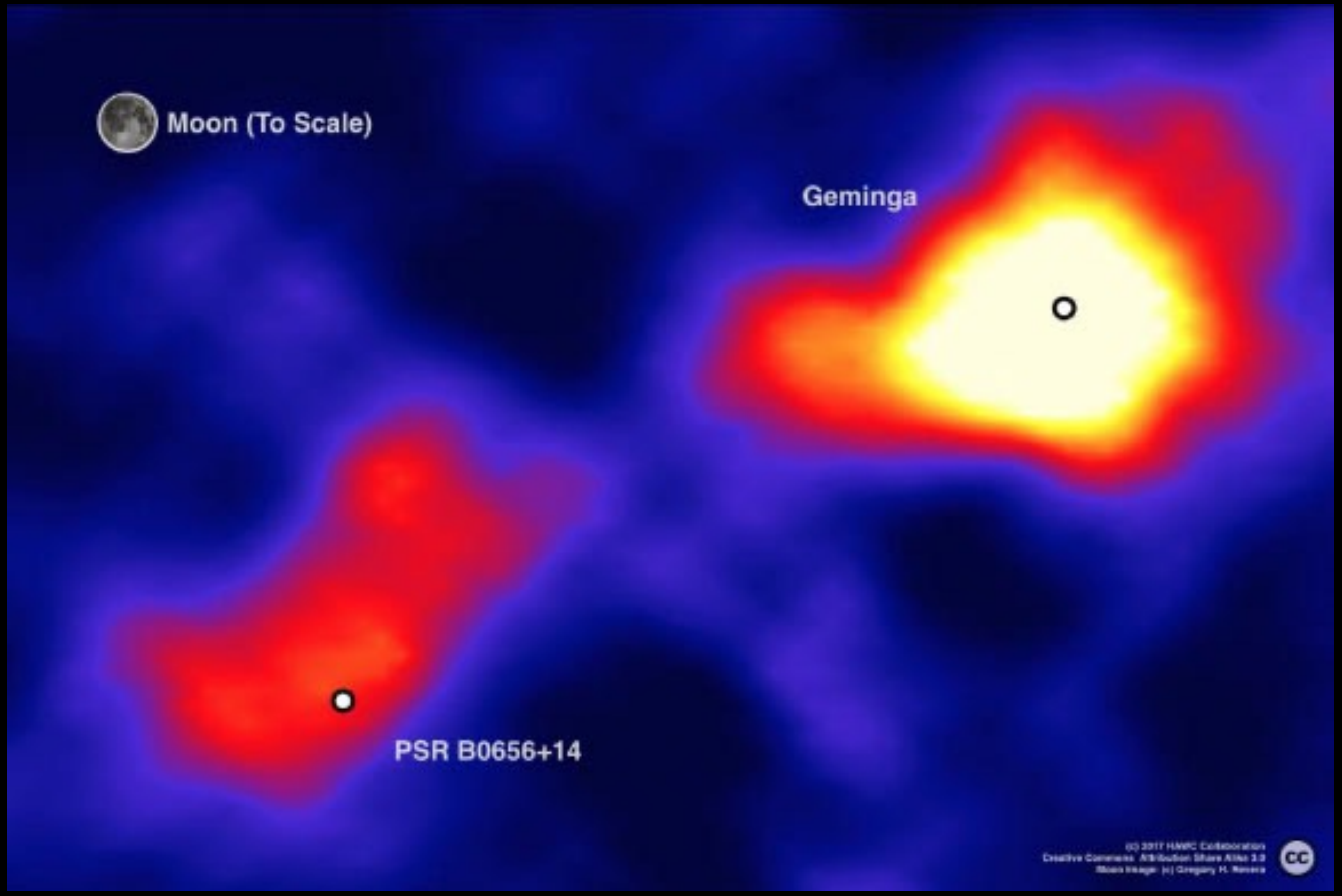
LHAASO Collaboration (2021, Nature)

- More than a dozen of sources are detected above 100 TeV
- They are good candidate for hadronic PeVatrons

But gamma rays may instead be leptonic



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

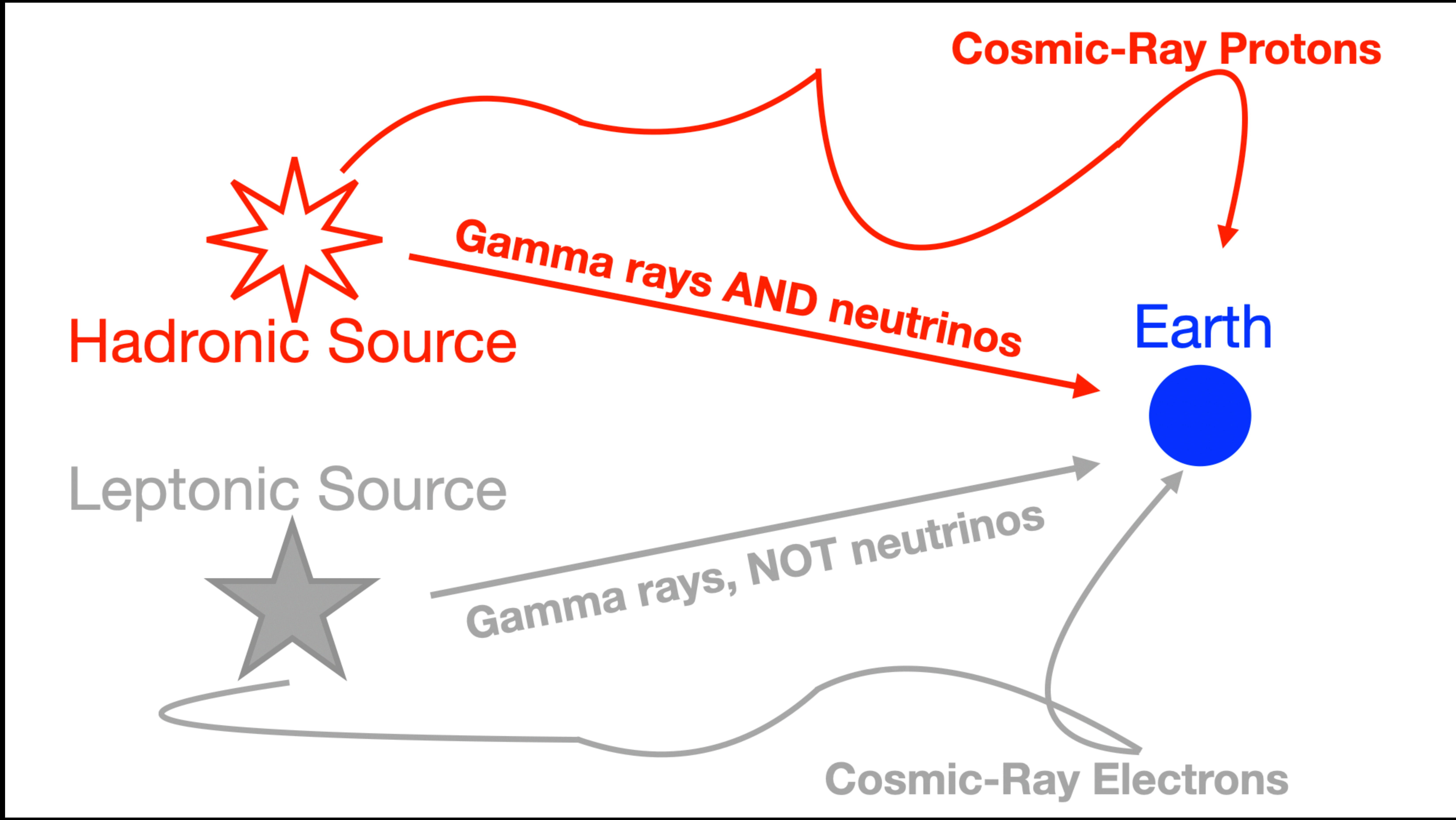


HAWC Collaboration
Image : John Pretz

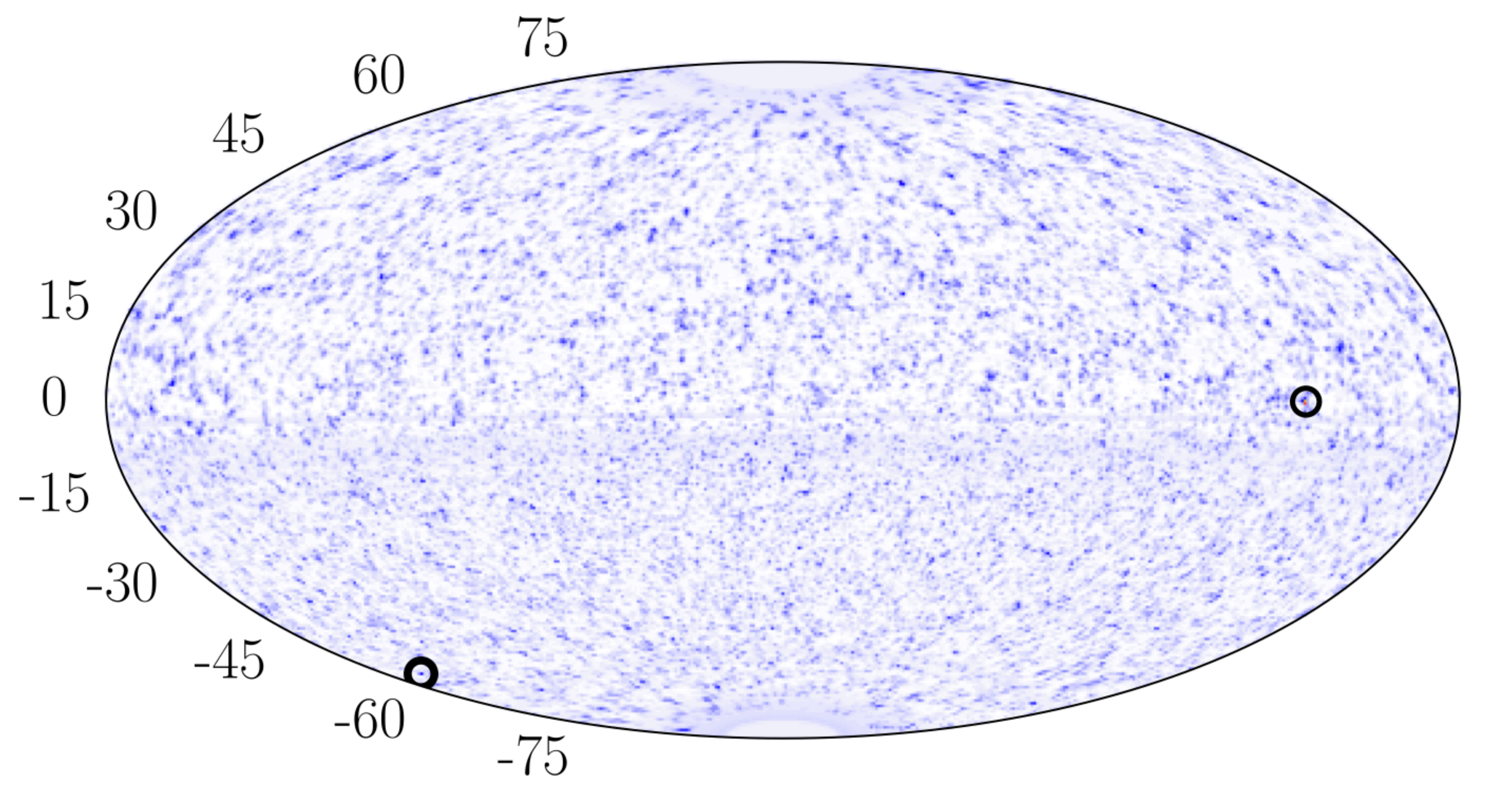
- Gamma ray can be instead produced by leptonic mechanism
- Pulsars at various ages produce TeV - PeV electrons

Hadronic source can be identified via neutrino

- Neutrino detection would decisively identify hadronic accelerators



But TeV - PeV MW neutrino sources are not yet found



IceCube Collaboration (2020)
See also work by ANTARES

- Excellent progresses in extragalactic neutrino sources by IceCube
- No TeV - PeV neutrino sources are detected in the Milky Way

Summary of TeV - PeV Messengers

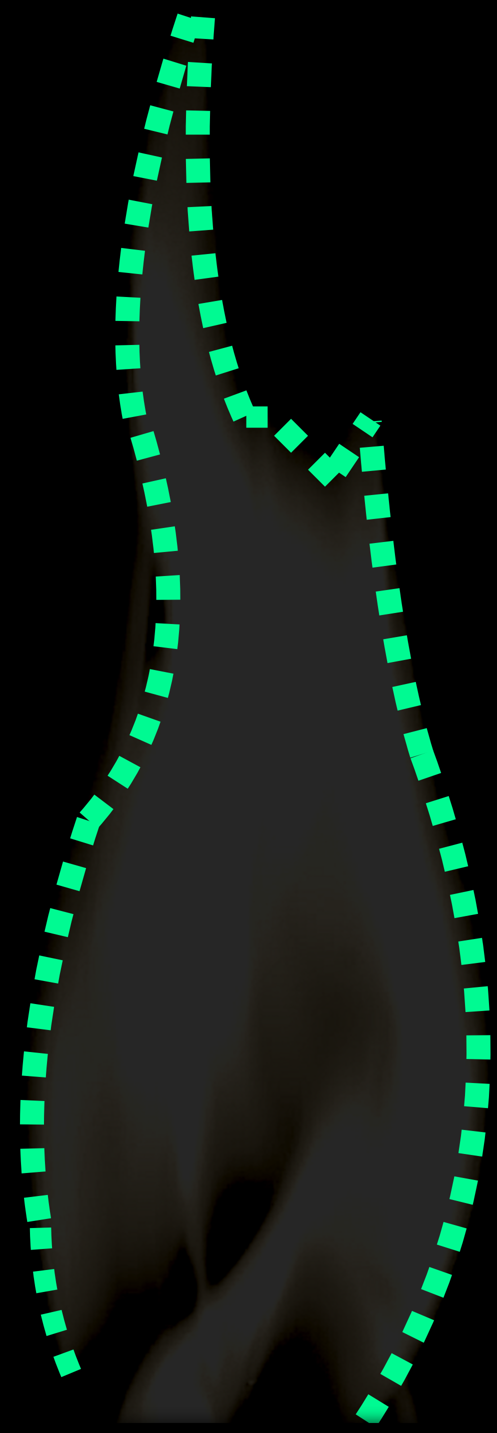
Cosmic Rays

- ✓ Energy Budget
- ✗ Diffuse Only

Gamma Rays

- ✓ Point to Sources
- ✗ Hadrons or Leptons?

Neutrinos



- ✓ Decisively Hadrons
- ✗ No MW Sources Yet

This talk

✔ Introduction

TeV - PeV gamma-ray sources : Can leptons explain them?

TeV - PeV gamma-ray sources : Where are hadronic PeVatrons?

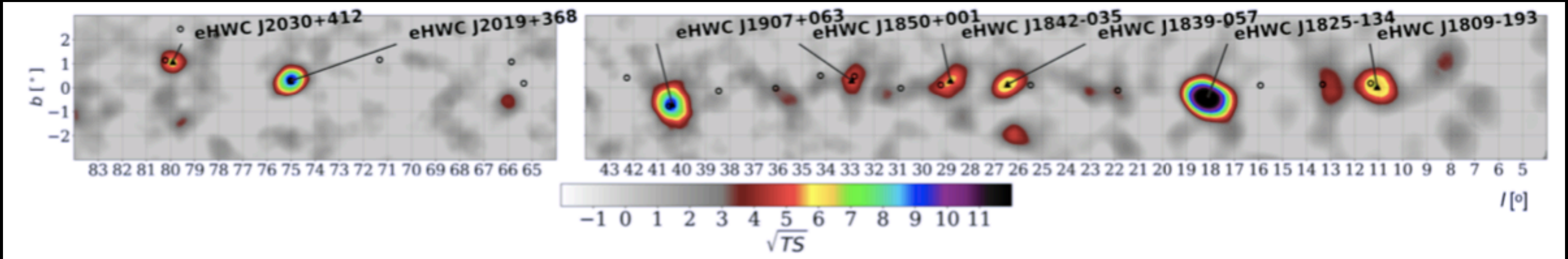
TeV - PeV neutrino sources : What to expect in the future?

Summary

TeV - PeV gamma-ray sources :

Can leptons explain them?

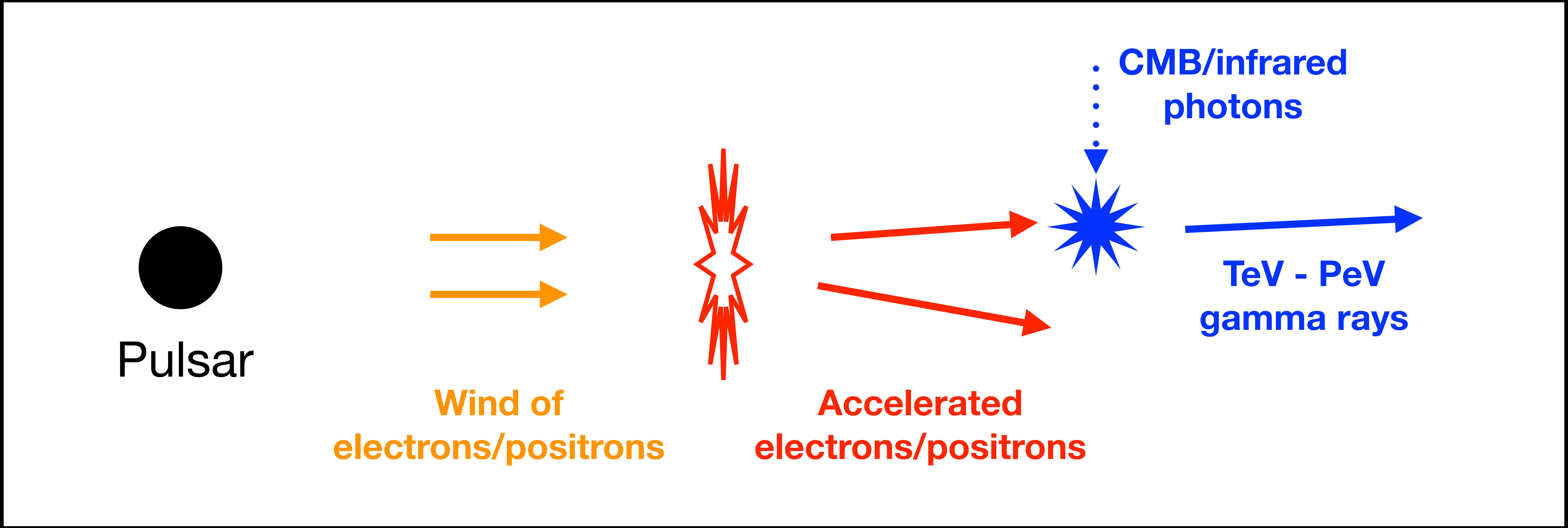
Can leptons explain extreme gamma-ray sources?



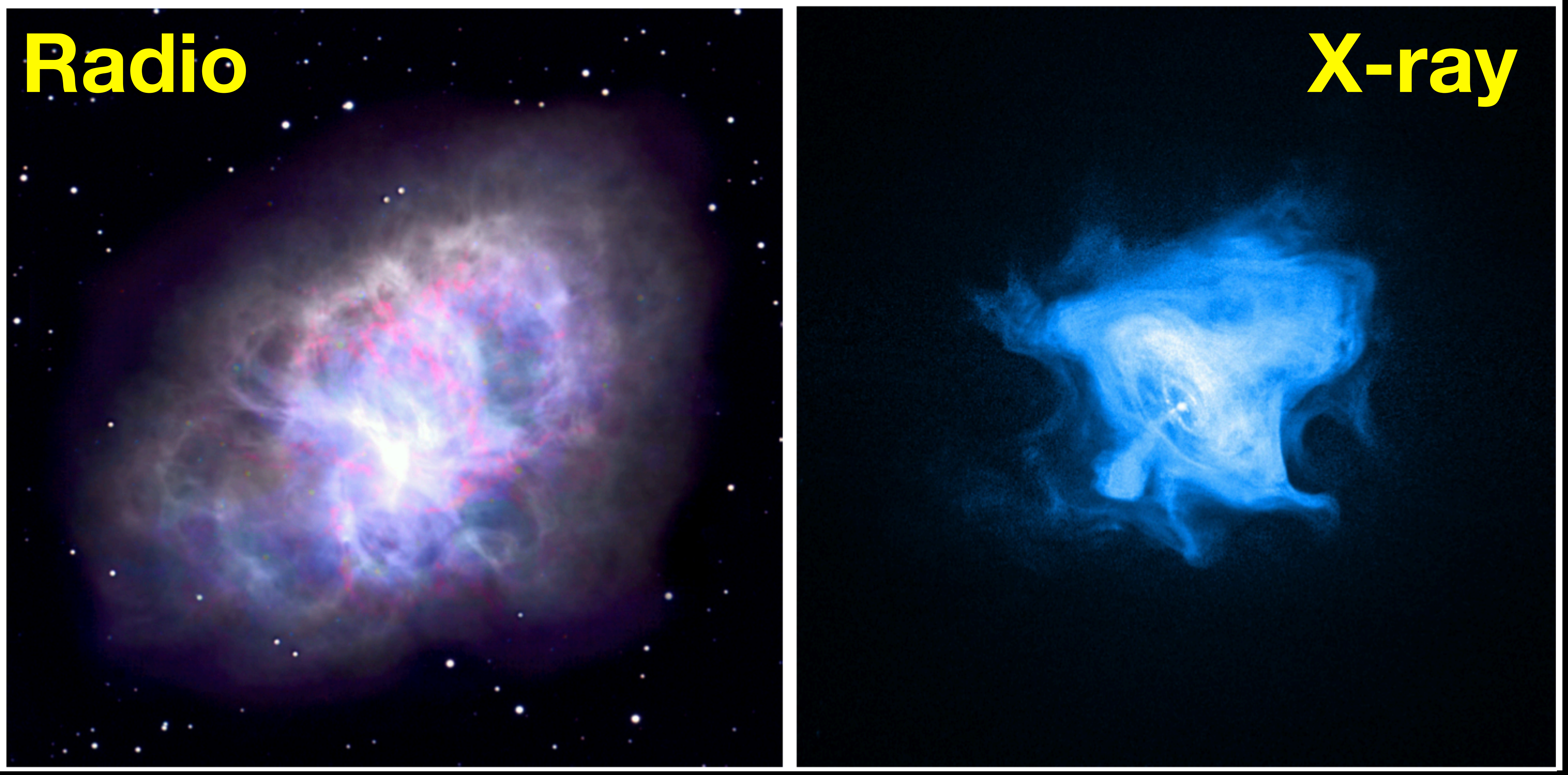
HAWC Collaboration (2020, PRL)

- We study HAWC sources (> 56 TeV); other authors obtain similar results for LHAASO sources (> 100 TeV)
- HAWC reported nine sources above 56 TeV; all of them are located within 0.5 degree of known pulsars
- Pulsars are efficient leptonic gamma-ray emitters (next slides)

Pulsars are efficient leptonic emitters



Pulsars are efficient leptonic emitters



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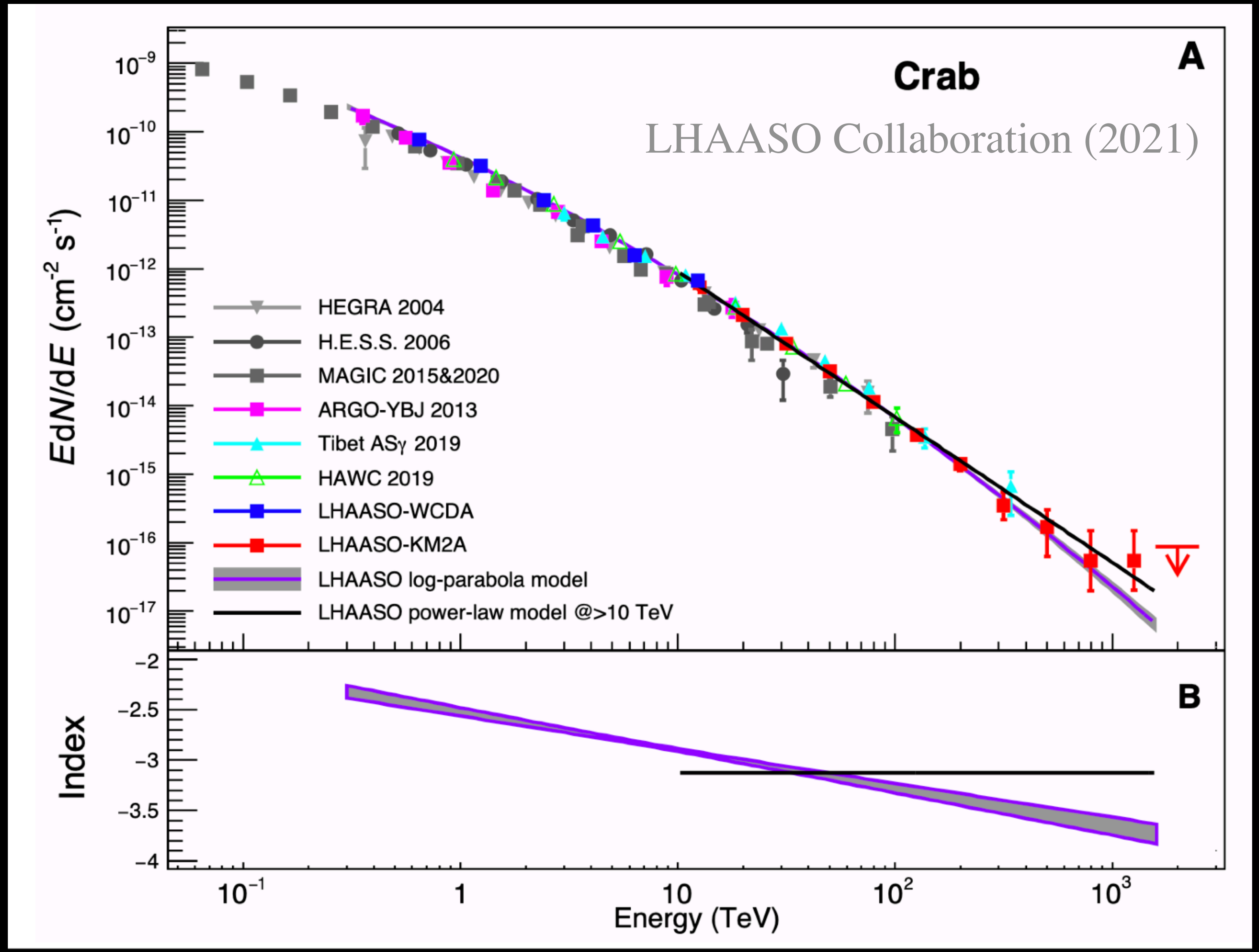
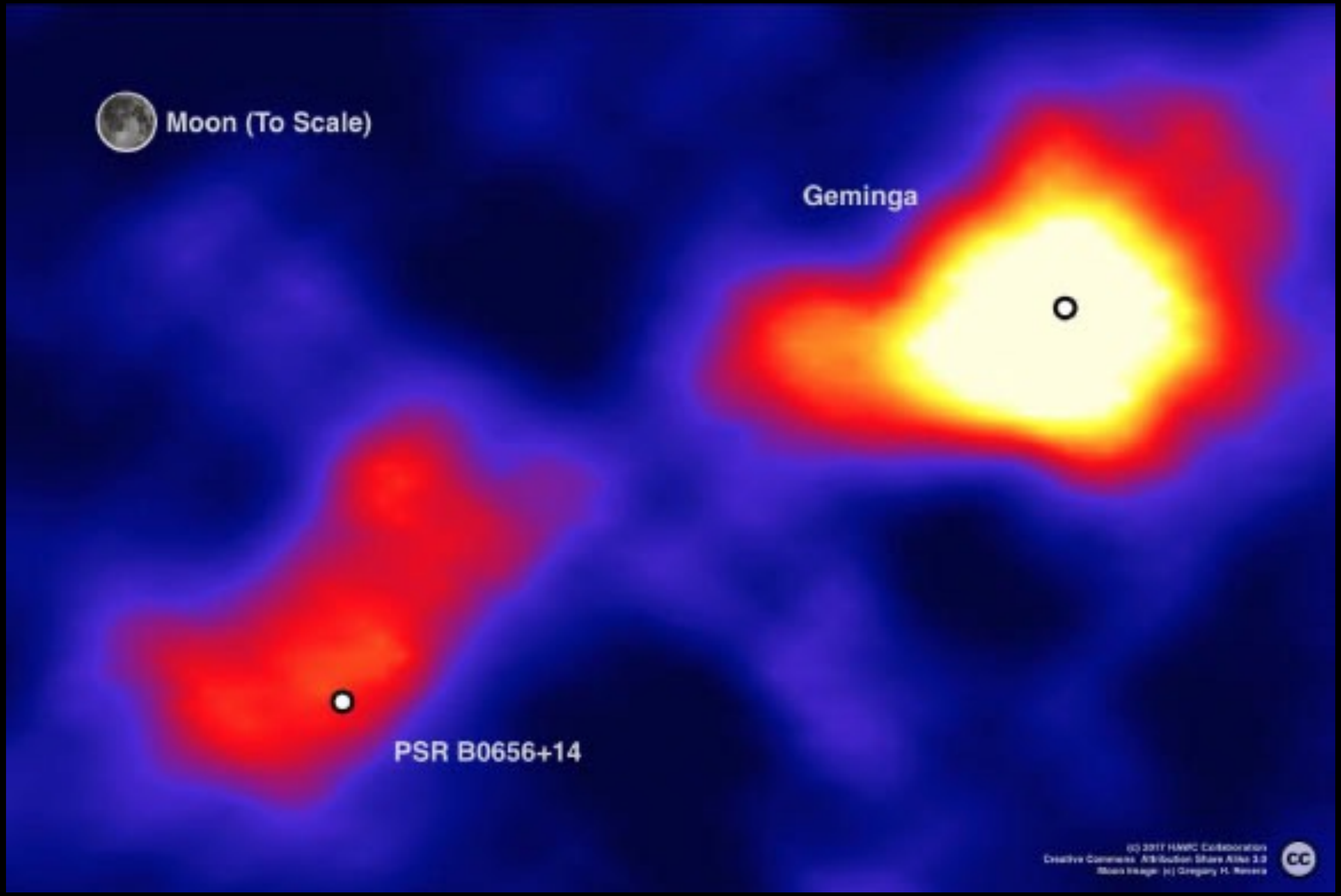


- Crab Nebula : Multi-wavelength emission produced by electrons
- Gamma rays now seen above 1 PeV !
- Indicates the presence of PeV electrons — a leptonic “PeVatron”

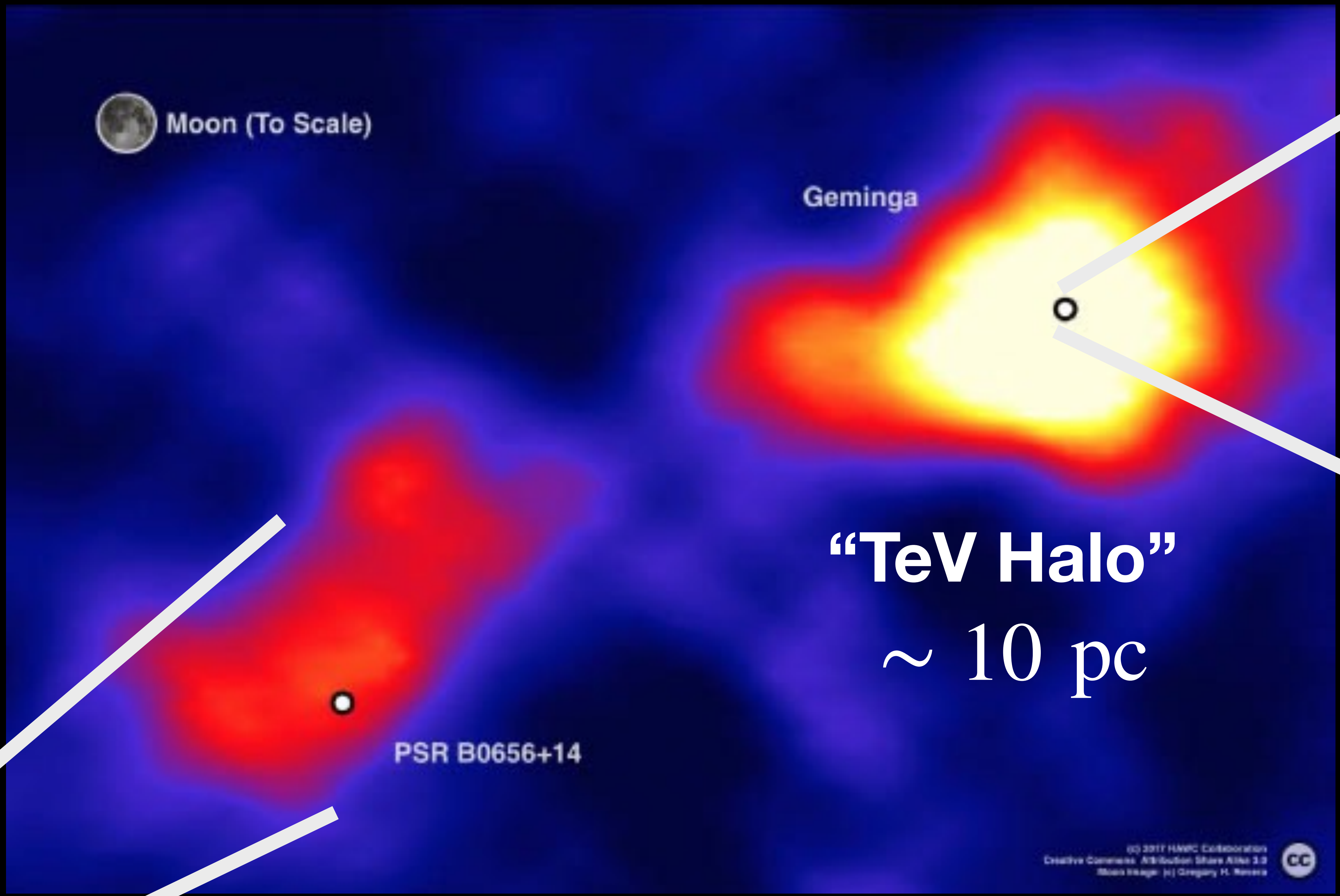
Pulsars are efficient leptonic emitters



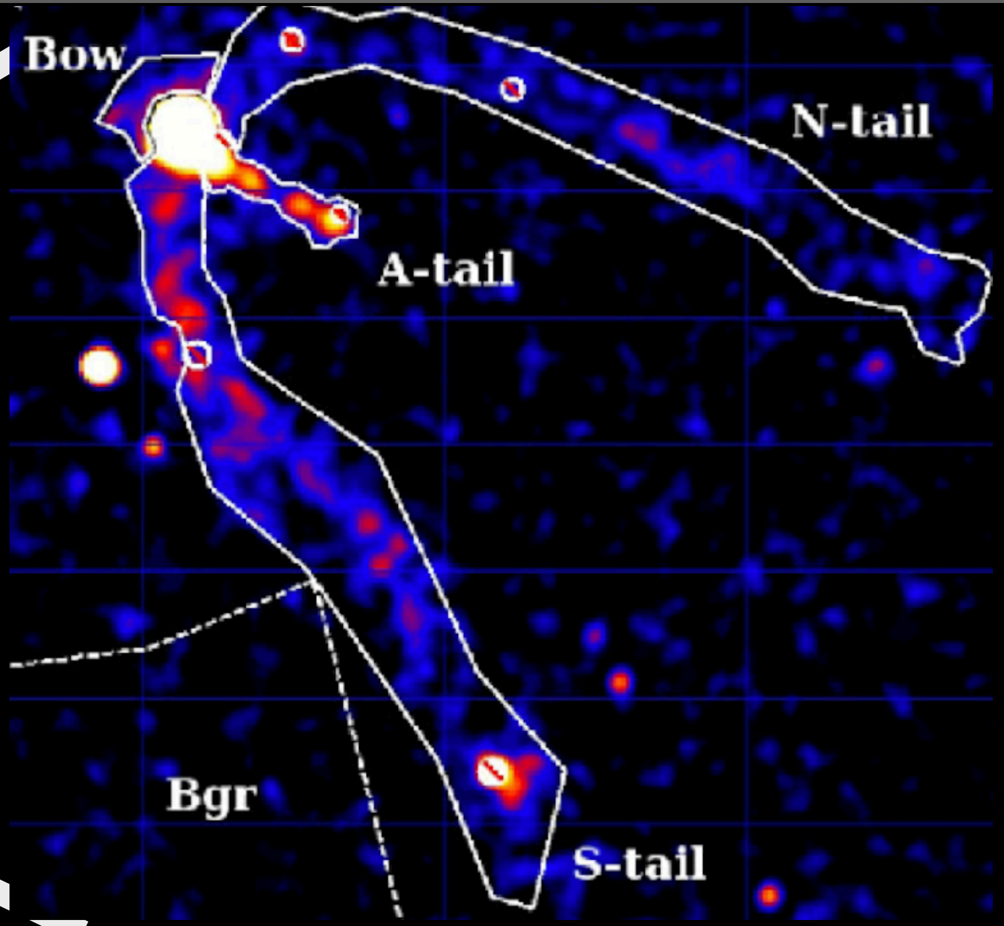
HAWC Collaboration
Image Credir : John Pretz

- Middle-aged pulsars form a “halo” of TeV gamma rays

Pulsars as efficient leptonic emitters



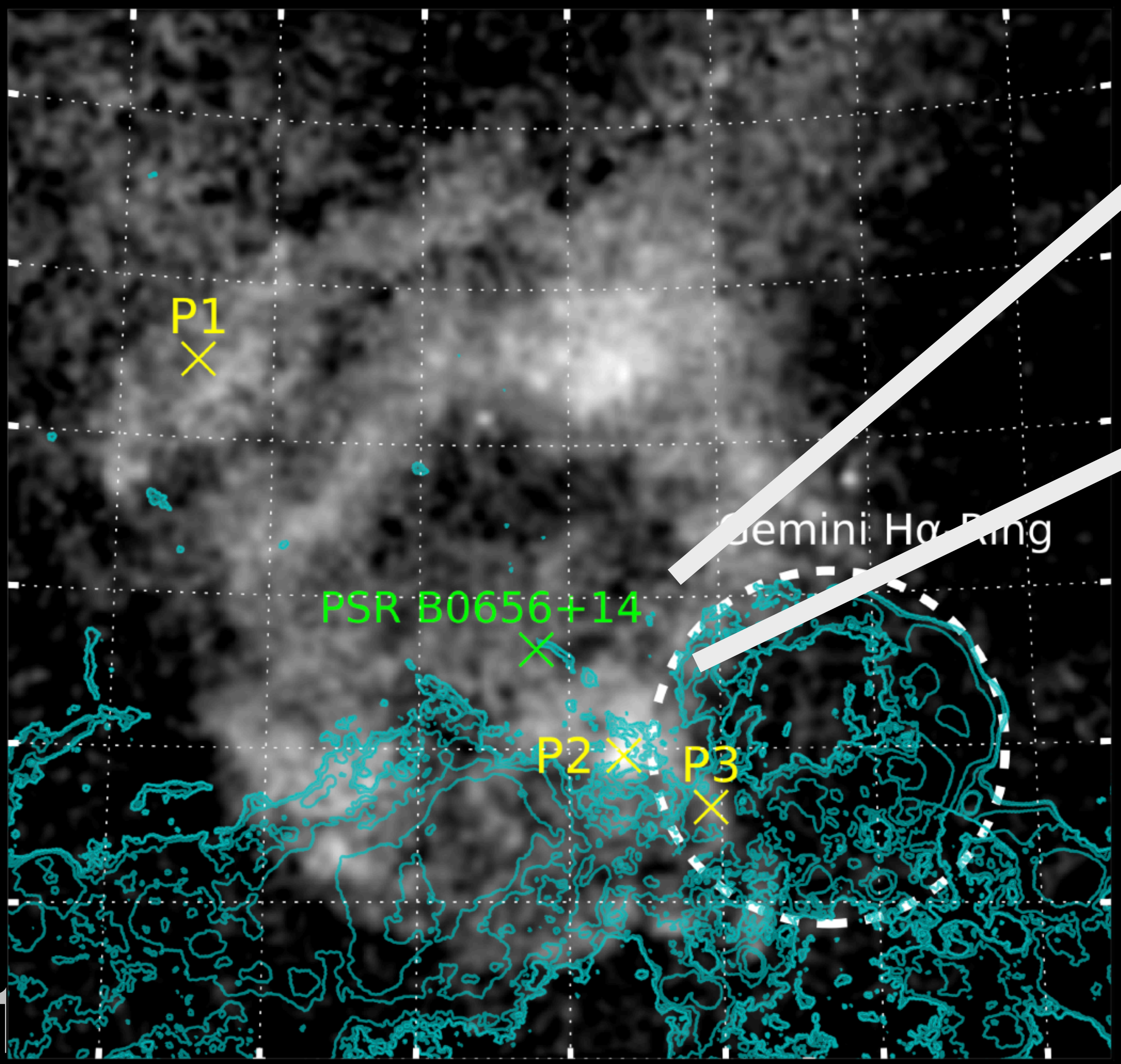
"TeV Halo"
~ 10 pc



Pulsar Wind Nebula
~ 0.1 pc
(for Geminga)

Posselt et al. (2017)

Supernova Remnant
~ 100 pc
(for PSR B0656+14)

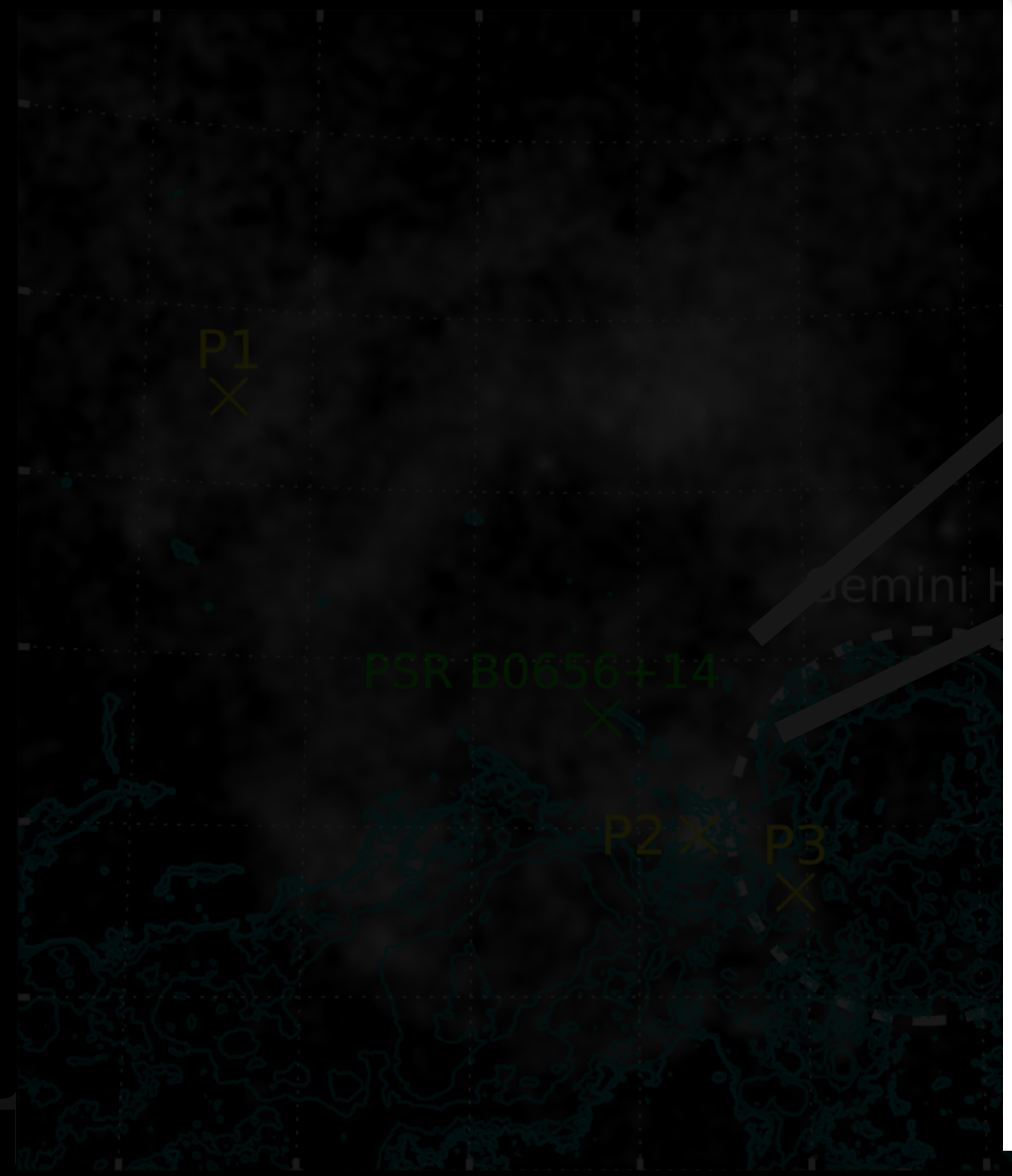


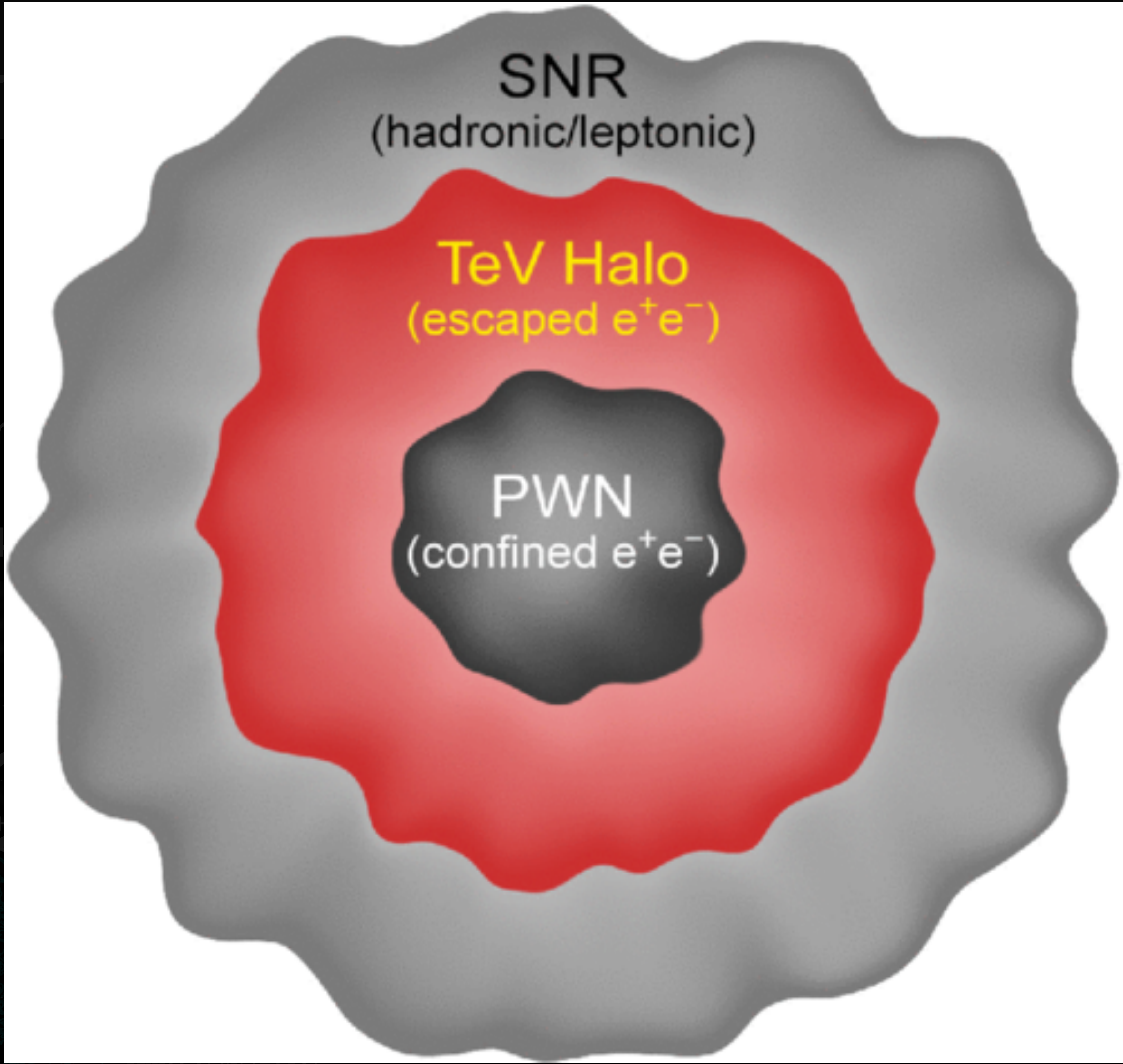
Knies et al. (2018)

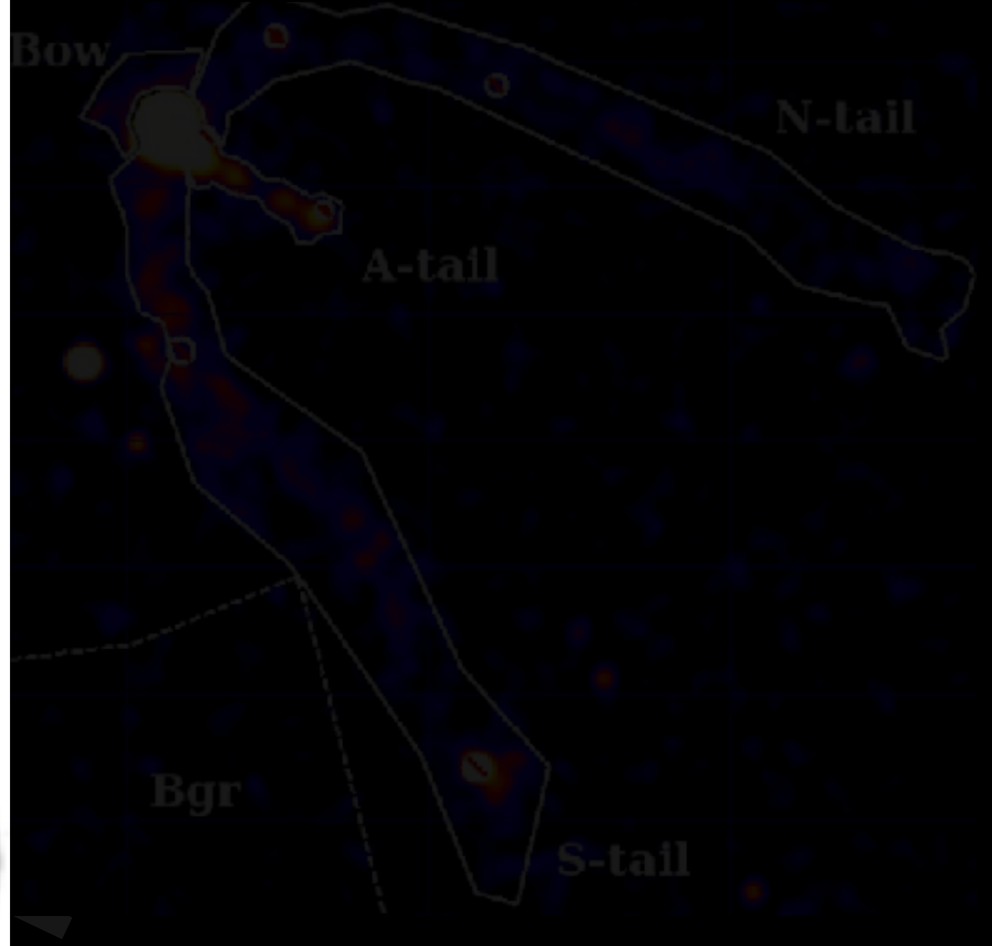
Supernova Remnan

~ 100 pc

(for PSR B0656+14







Pulsar Wind Nebula

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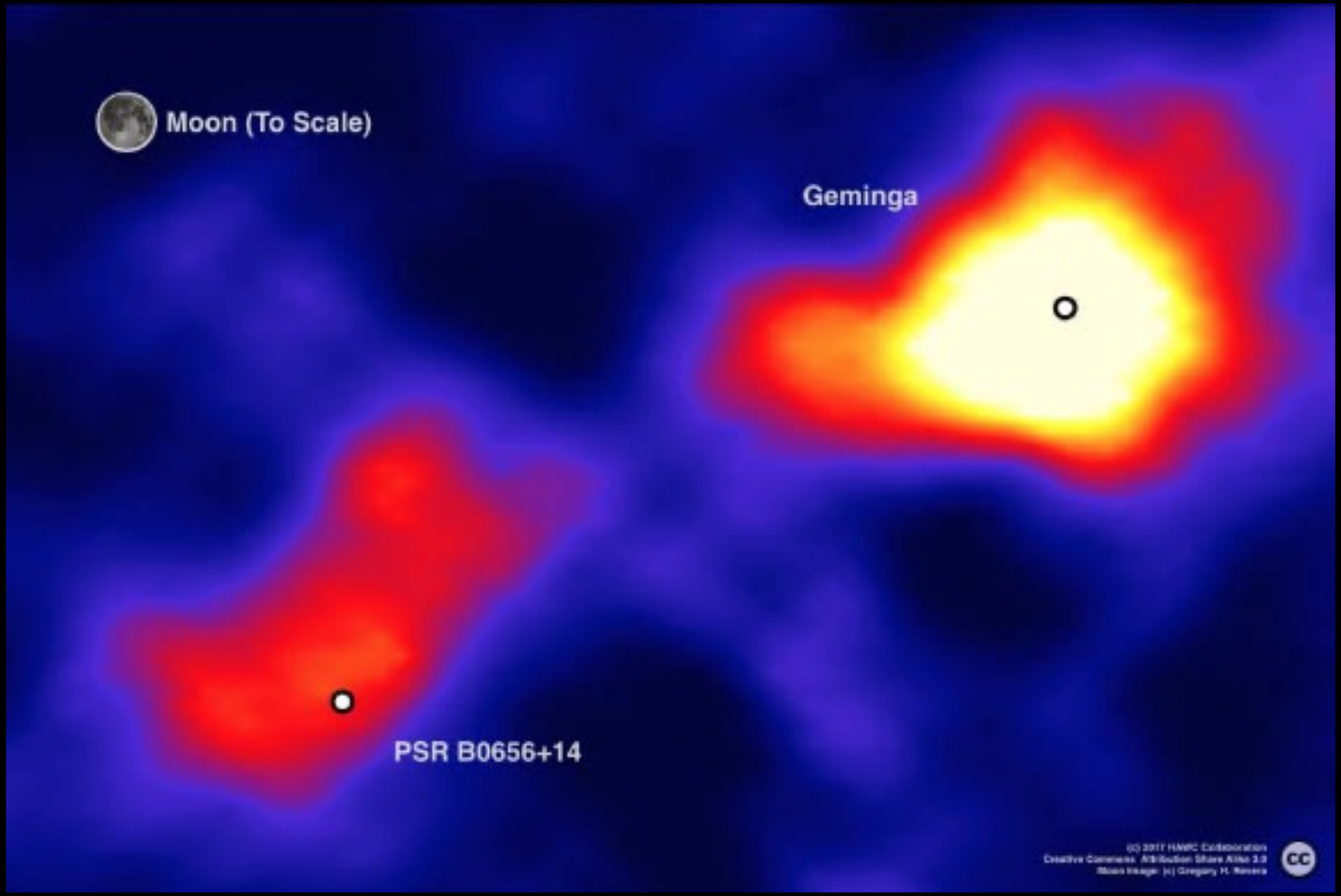
Posselt et al. (2017)

Sudoh, Linden, Beacom (2019)

Pulsars as efficient leptonic emitters

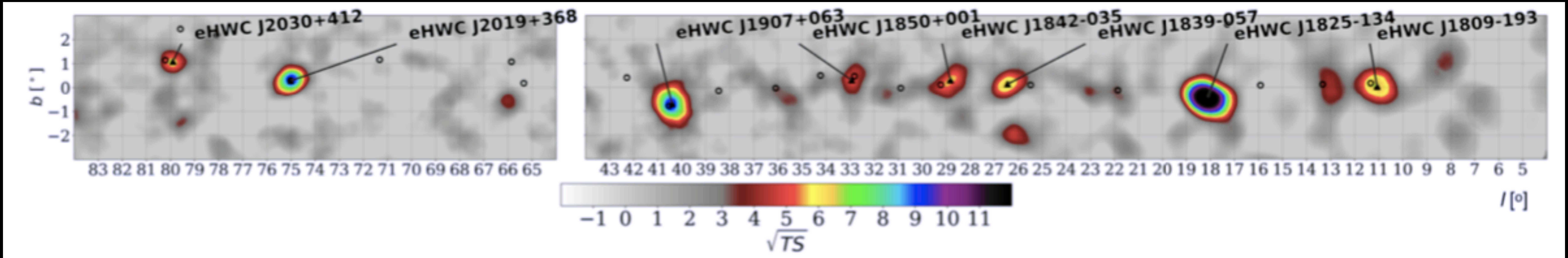


HAWC Collaboration
Image Credir : John Pretz

- Middle-aged pulsars produce > 10 TeV electrons with high efficiency and hard spectra

- These electrons are (somehow) efficiently confined in the source vicinity and lose energies to gamma-ray emission

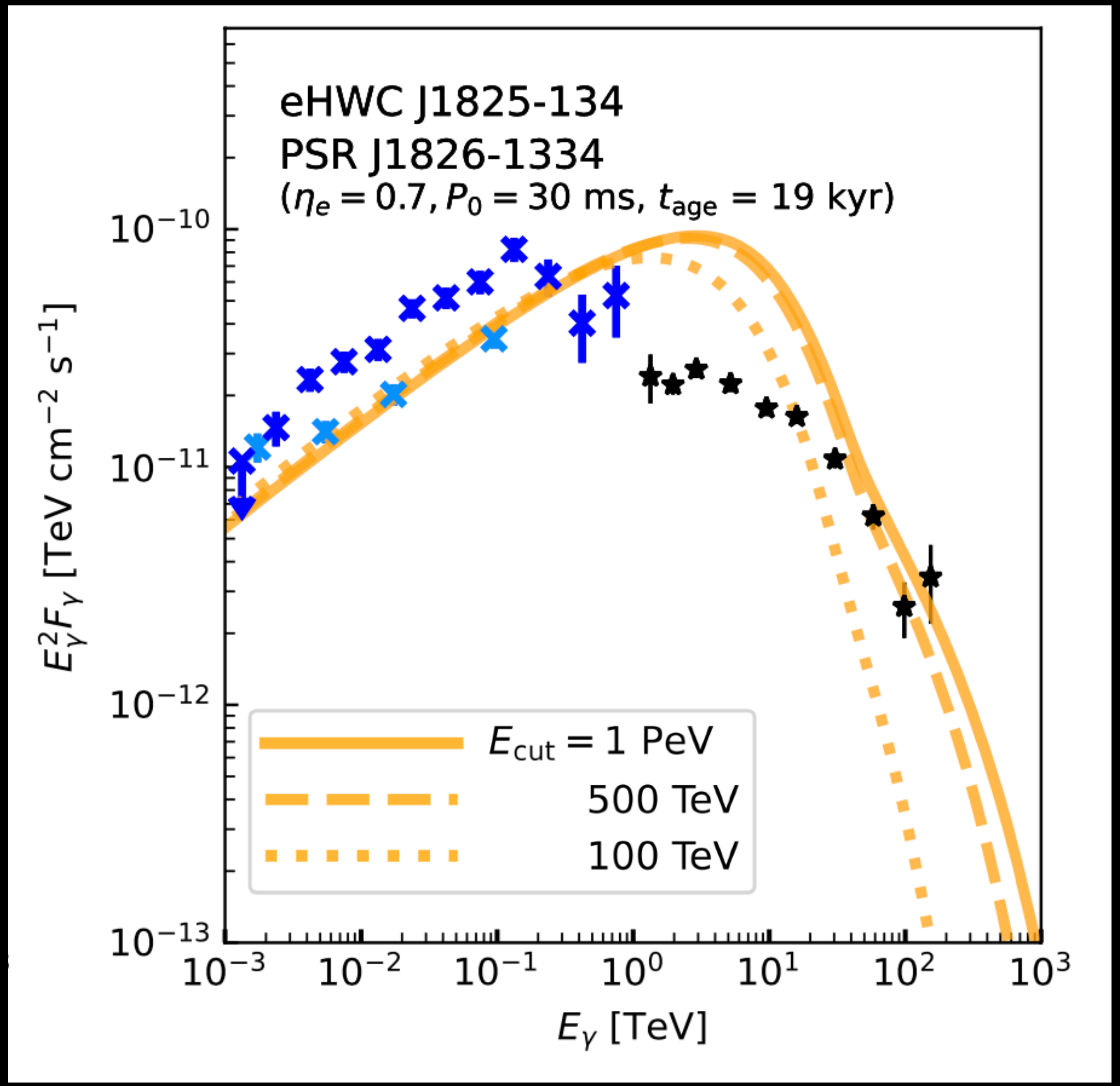
Can leptons explain extreme gamma-ray sources?

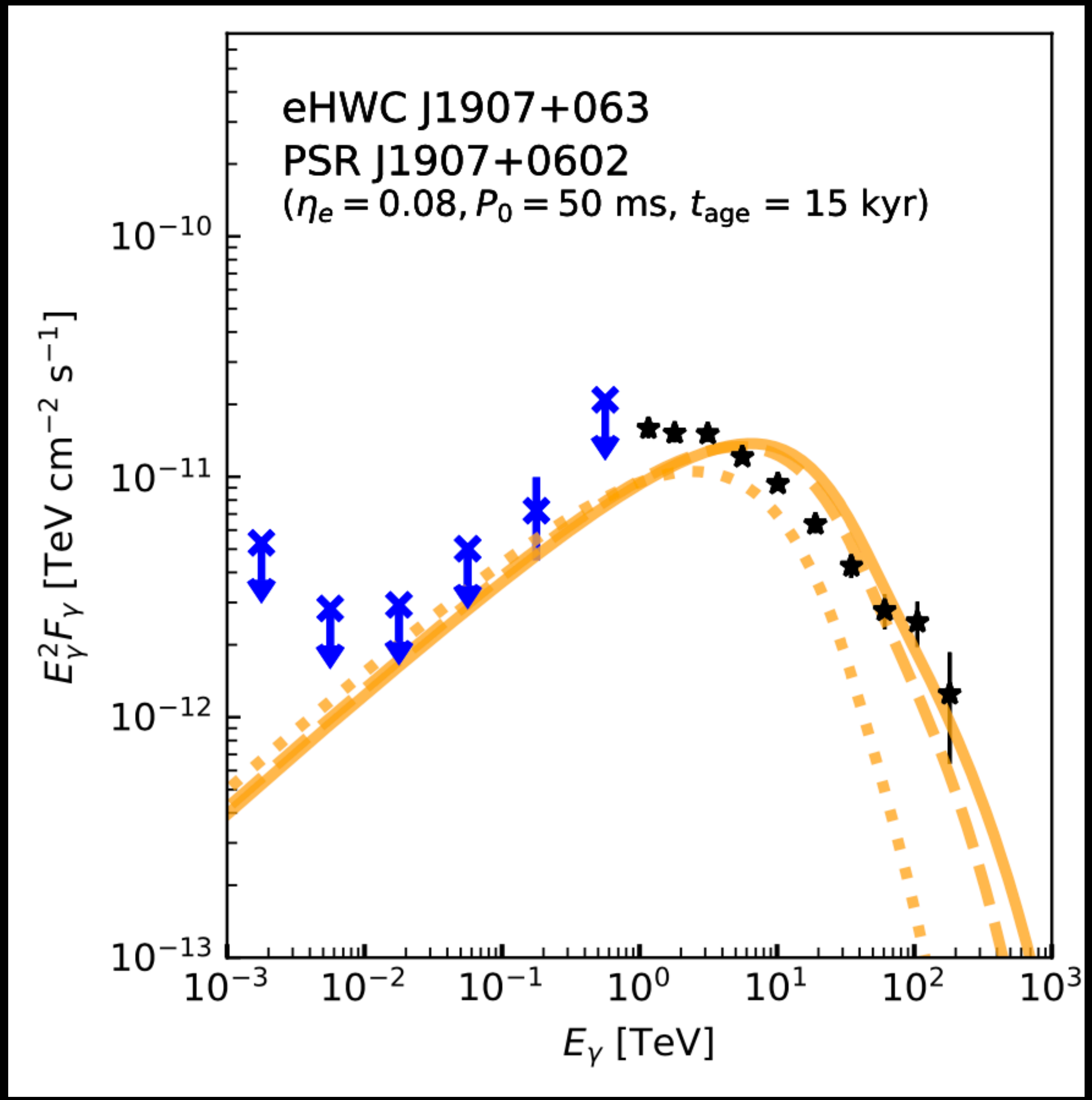


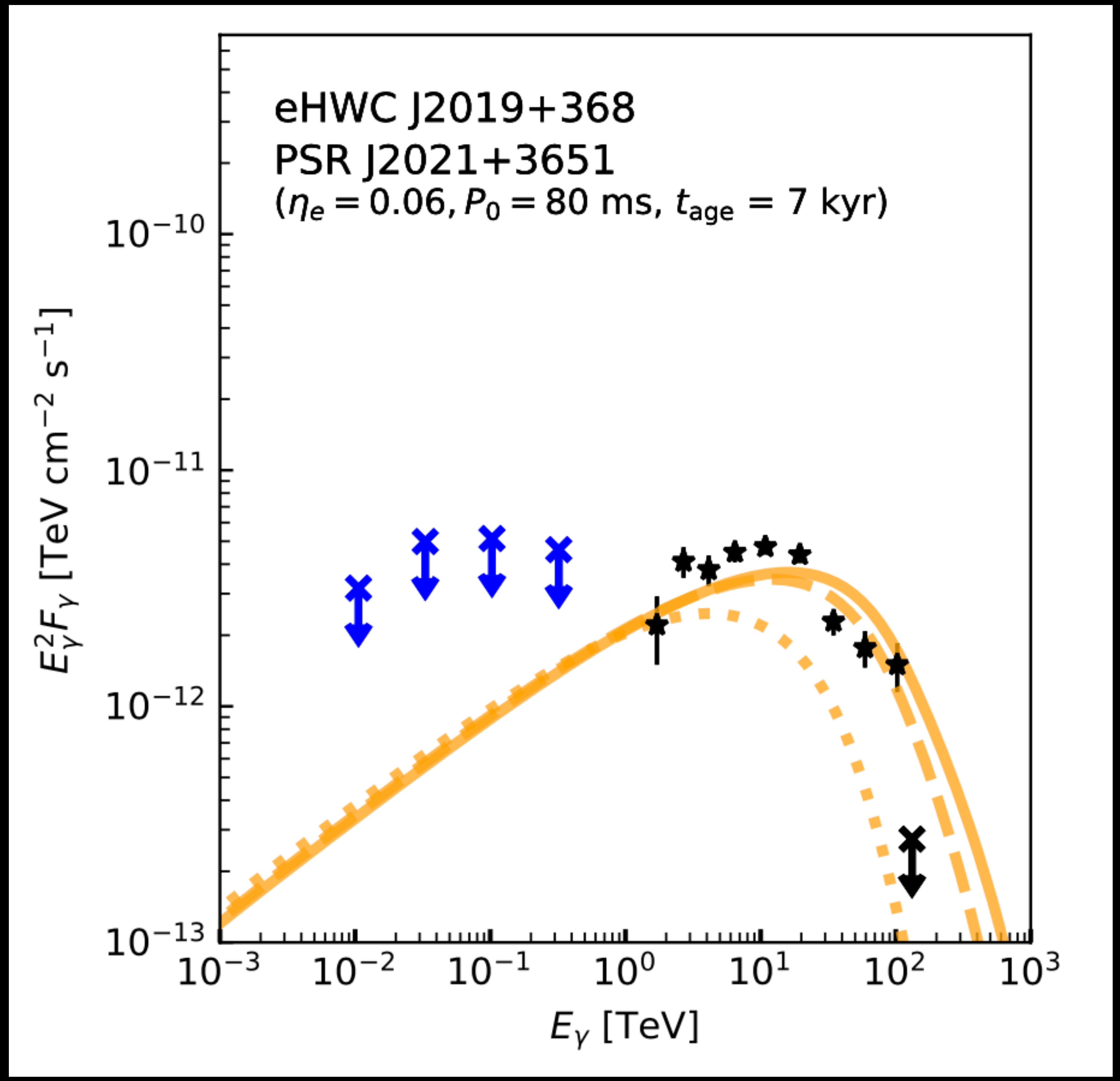
HAWC Collaboration (2020, PRL)

- Pulsars are efficient leptonic gamma-ray emitters (previous slides)
- HAWC reported nine sources above 56 TeV; all of them are located within 0.5 degree of known pulsars
- We examine if these pulsars can explain the luminosities and spectra (if available) of the HAWC sources

Leptons can explain extreme gamma-ray sources



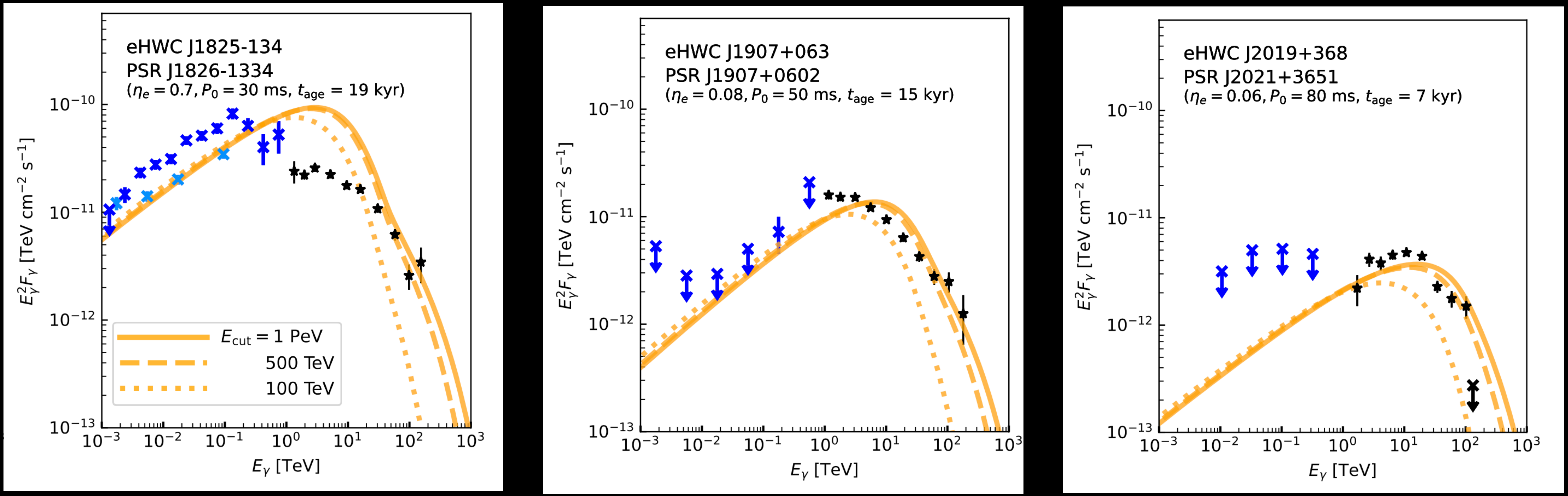




Sudoh, Linden, Hooper (2021, JCAP)

- Three HAWC sources have detailed spectra
- Apply standard one-zone model of pulsar wind nebulae radiation

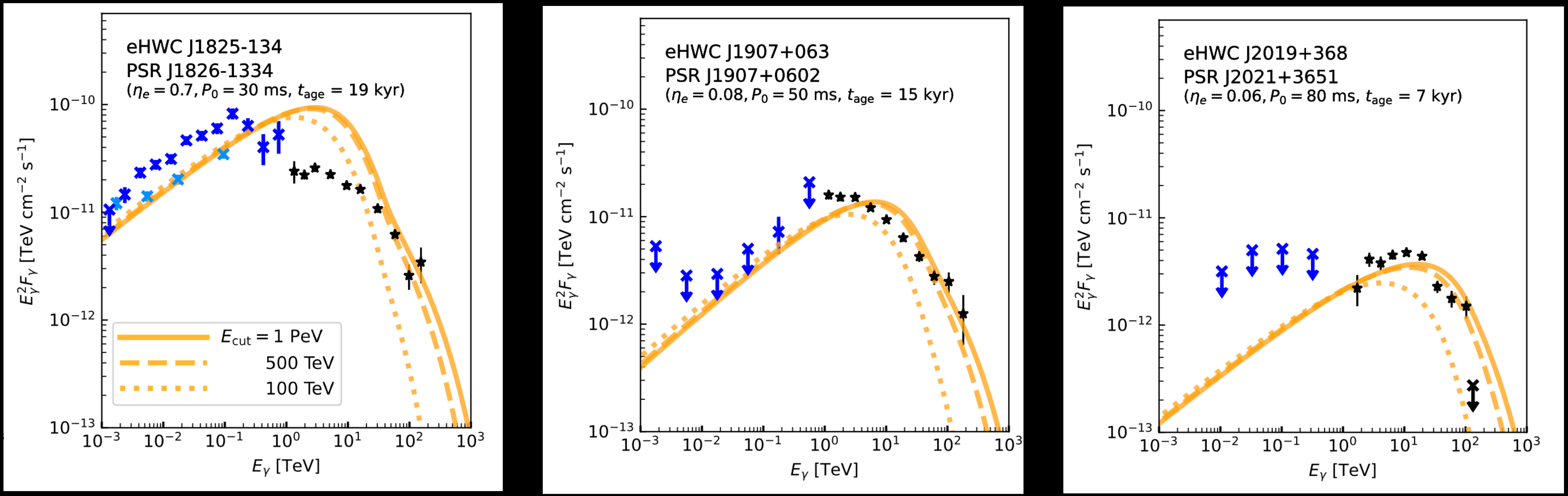
Leptons can explain extreme gamma-ray sources



Sudoh, Linden, Hooper (2021, JCAP)

- Free : Initial spin, $e^{\pm}$efficiency (~ 10%), $e^{\pm}$ spectrum (~ 2.1)
- Fixed : Magnetic field (3 μG), escape (Neglected)

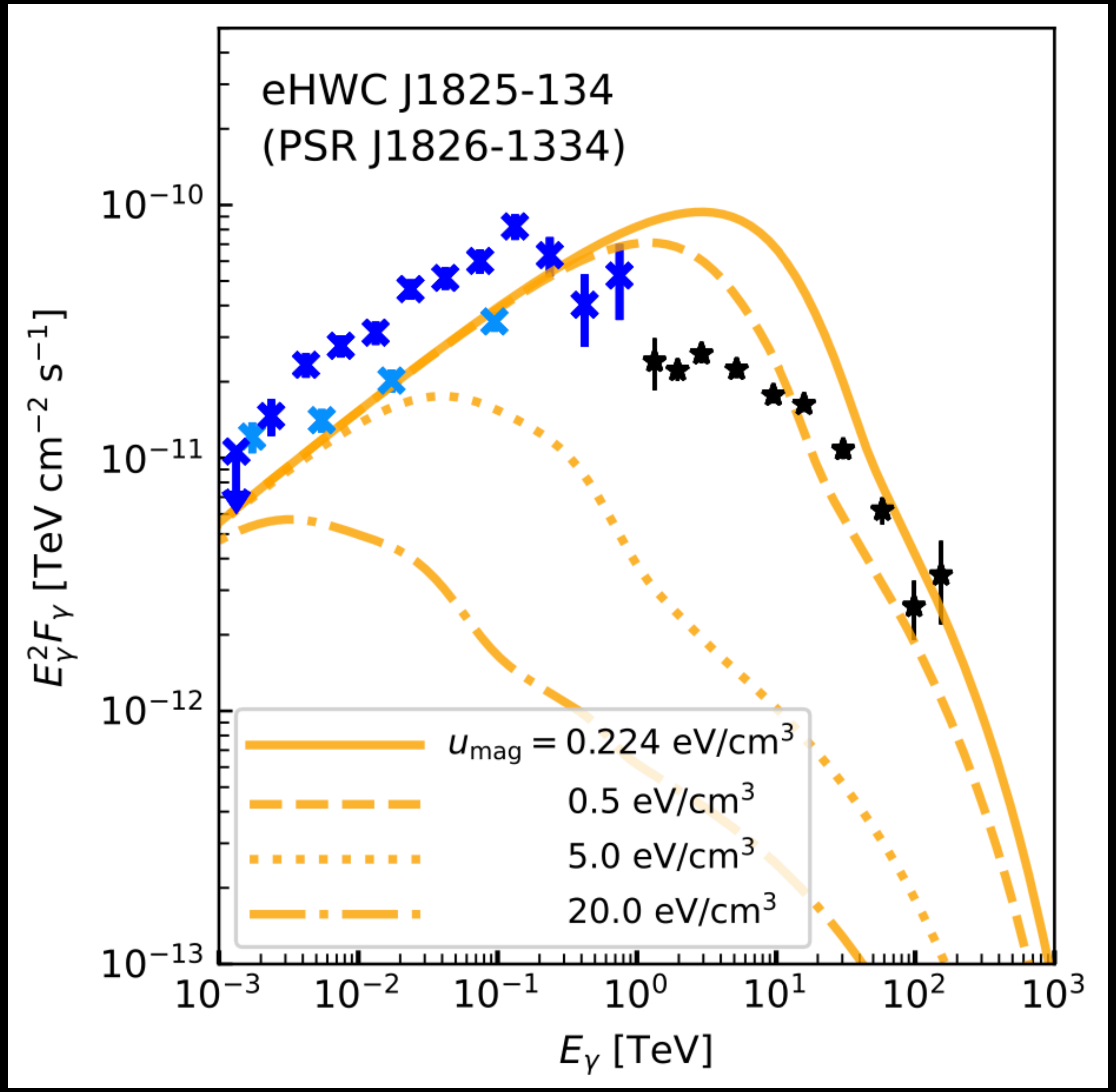
Leptons can explain extreme gamma-ray sources

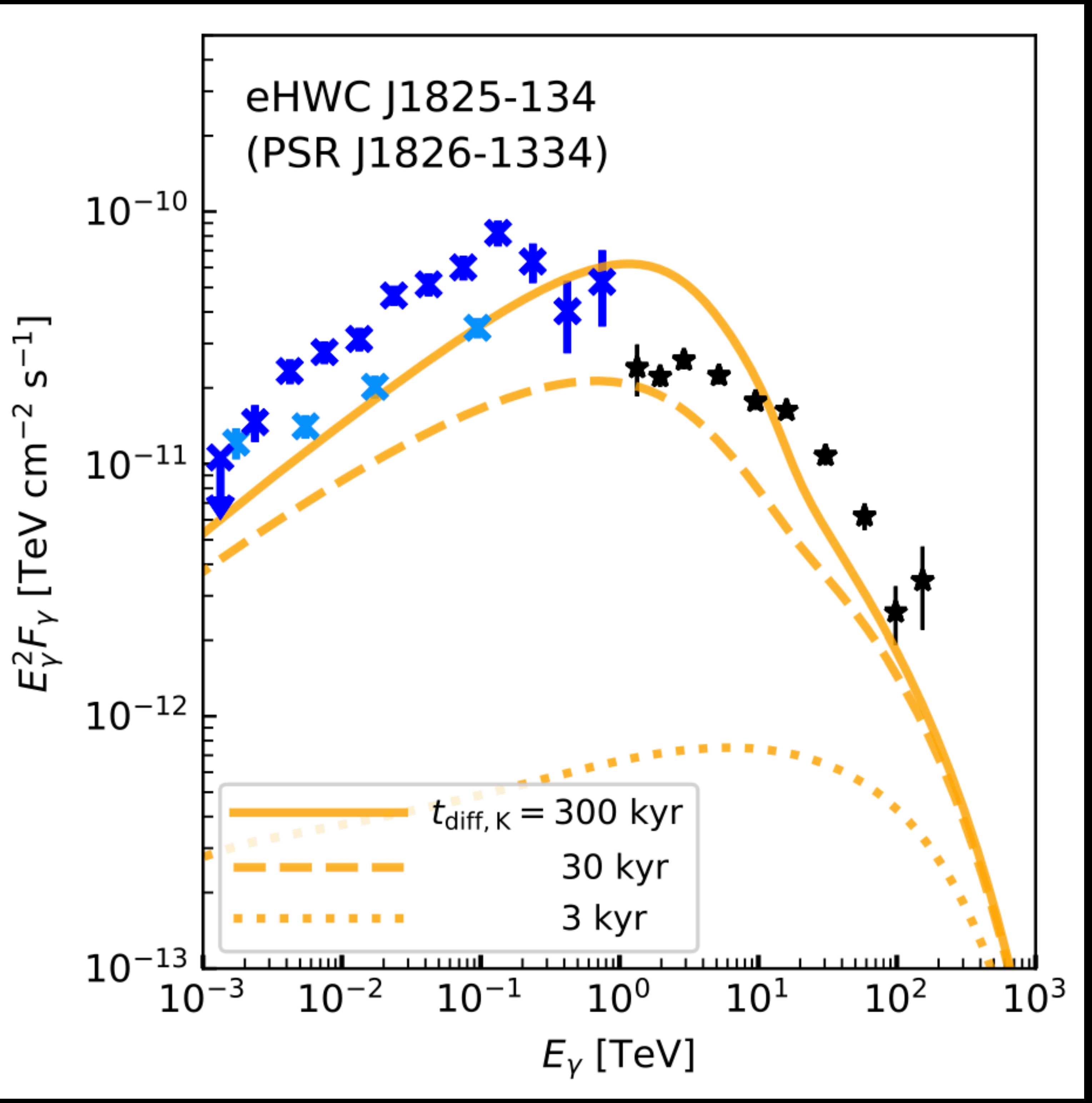


Sudoh, Linden, Hooper (2021, JCAP)

- For three sources with full GeV - 100 TeV spectral data, fair fit can be obtained with reasonable parameters

Leptons can explain extreme gamma-ray sources

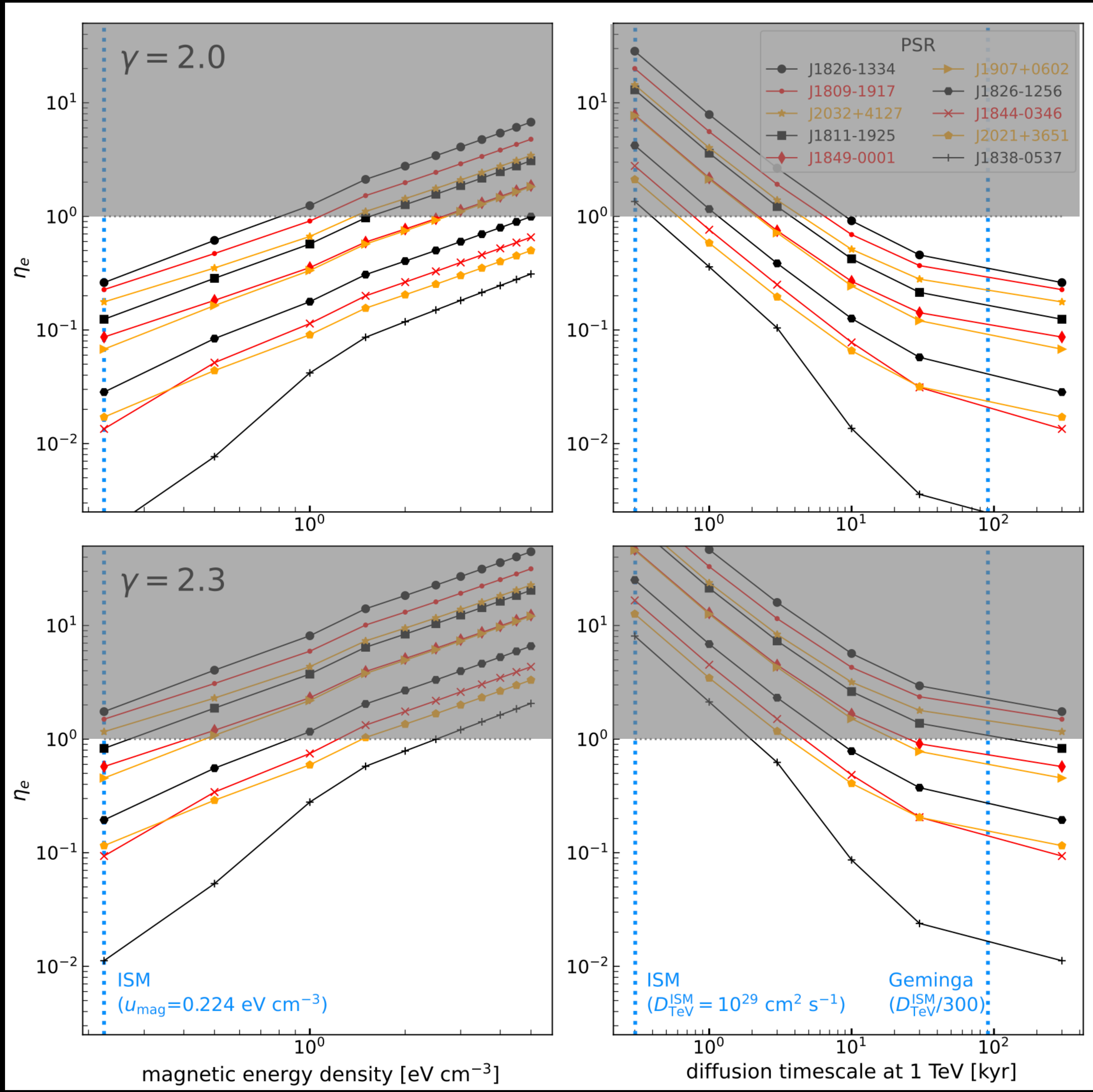




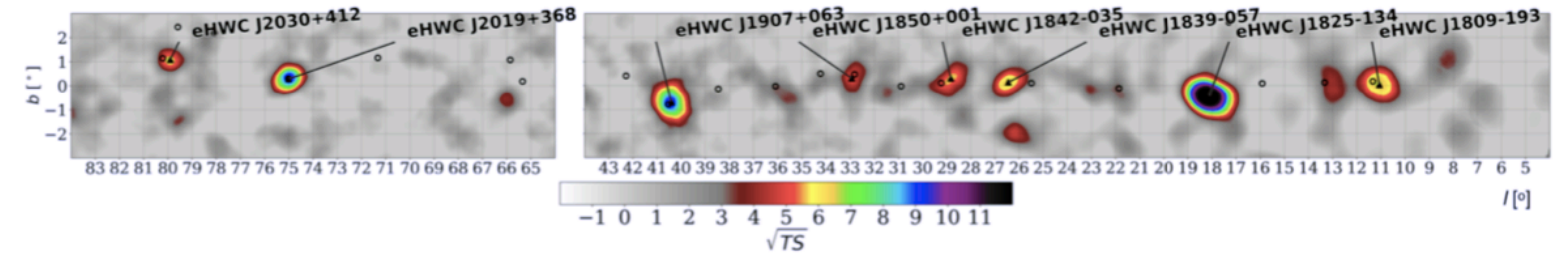
- Stronger B field or faster escape would make it more difficult to explain the gamma-ray data
- B-field can be constrained by X-ray data

Leptons can explain extreme gamma-ray sources

- Parameter study for all nine sources
  - Y-axis : fraction of pulsar power to $e^{\pm}$
  - X-axis :
    - (Left) Magnetic field
    - (Right) Escape time
  - (Top) $dN_e/dE_e \propto (E_e)^{-2}$ injection
  - (Bottom) $dN_e/dE_e \propto (E_e)^{-2.3}$ injection
- Pulsars explain HAWC data; if the injection is hard, the emission site has small B-field, and confinement is efficient.

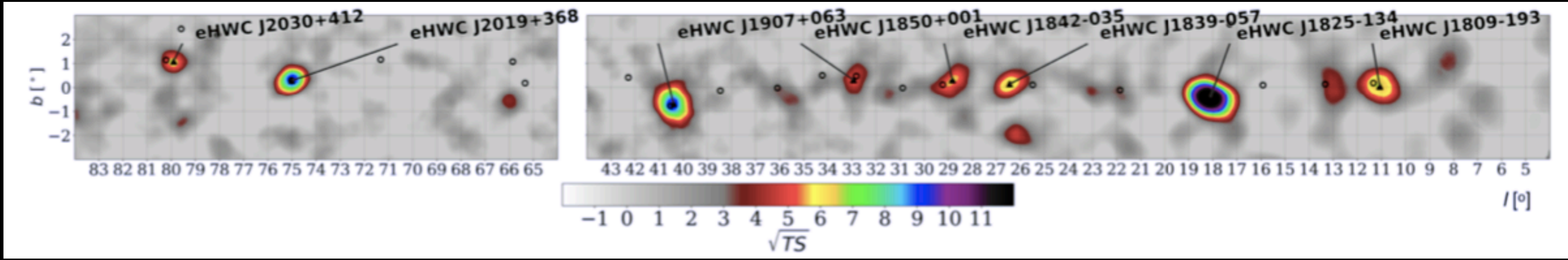


Leptons can explain extreme gamma-ray sources



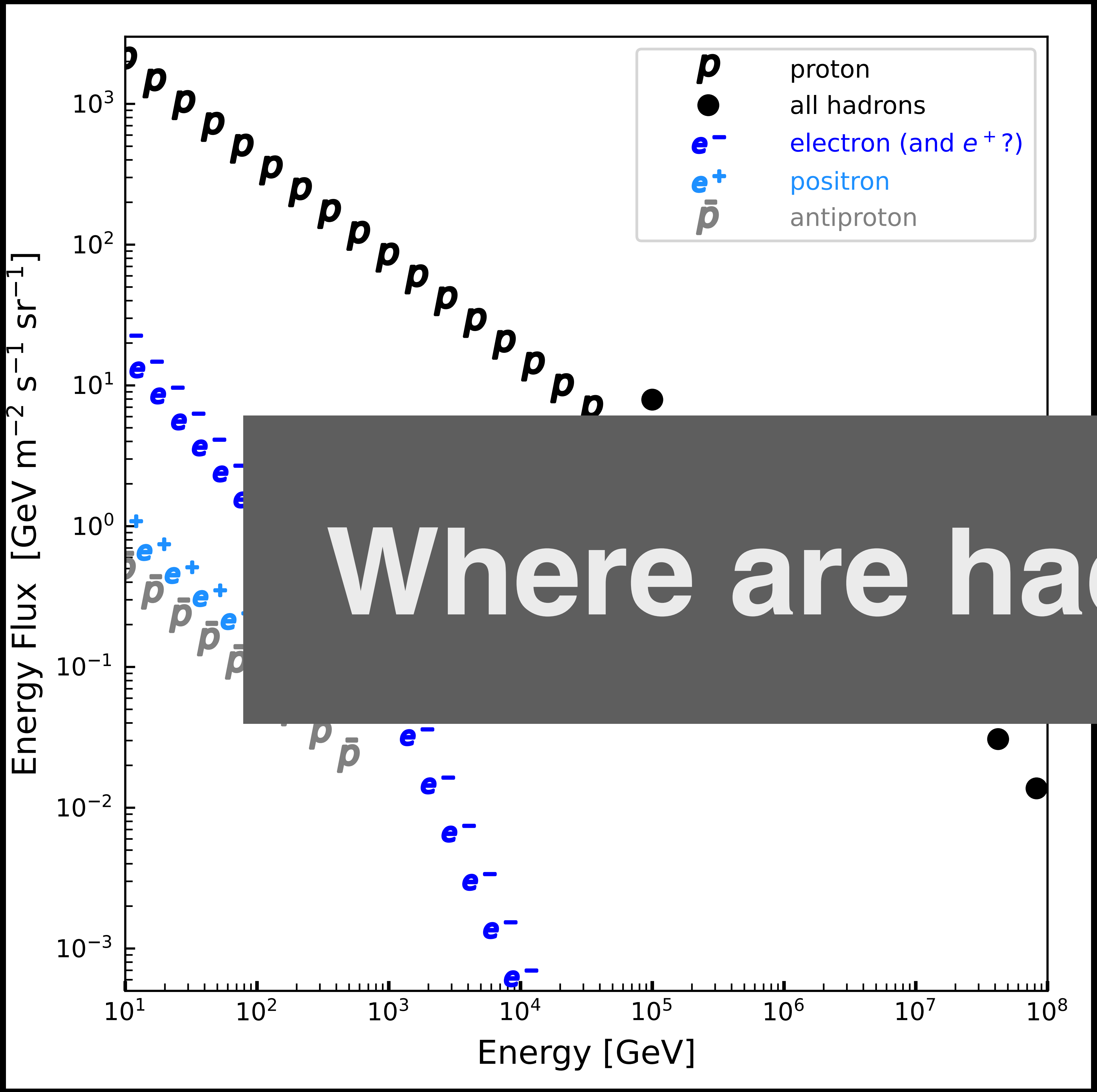
- Nearby pulsars can explain luminosities and spectra
- We only studied *necessary condition*! More studies are needed
    - Morphology (multi-zone modeling)
    - Multi-messenger data will be the key (in particular, X-rays)

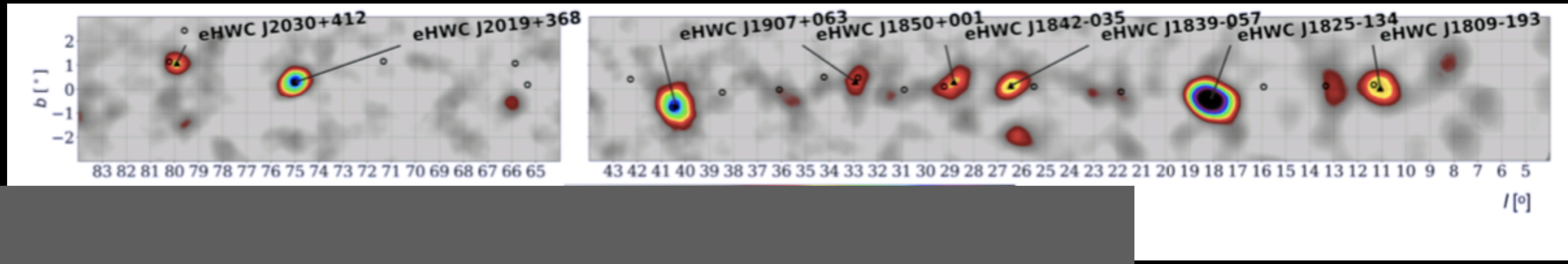
Leptons can explain extreme gamma-ray sources

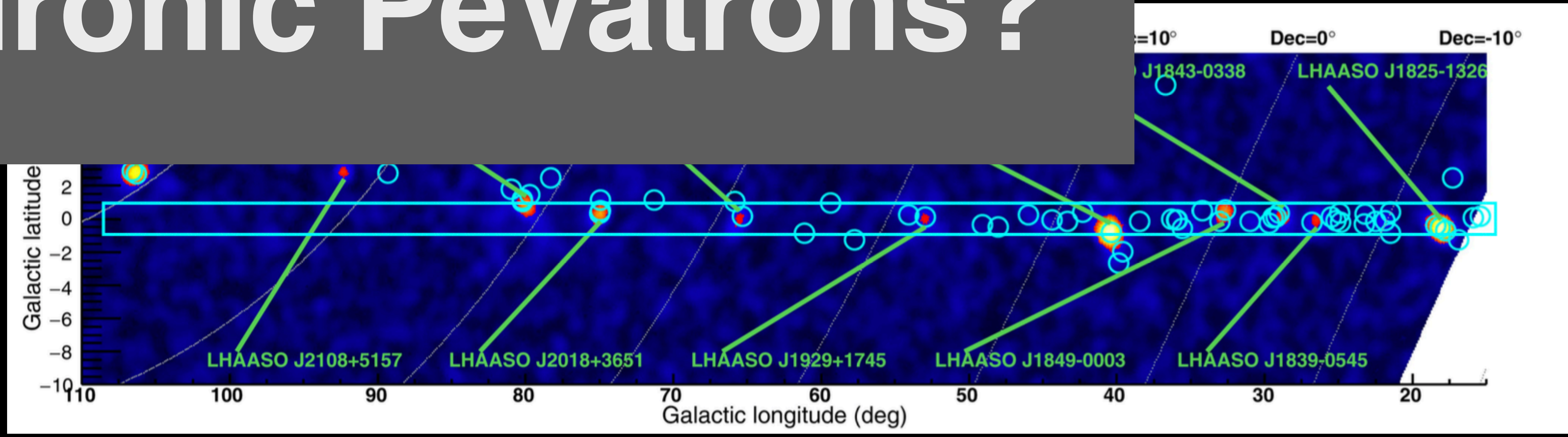


- Leptonic mechanism look convincing for majority of HAWC sources

A natural question







Where are hadronic PeVatrons?

Hadron, Hadron, Hadron,…

Lepton, Lepton, Lepton, …

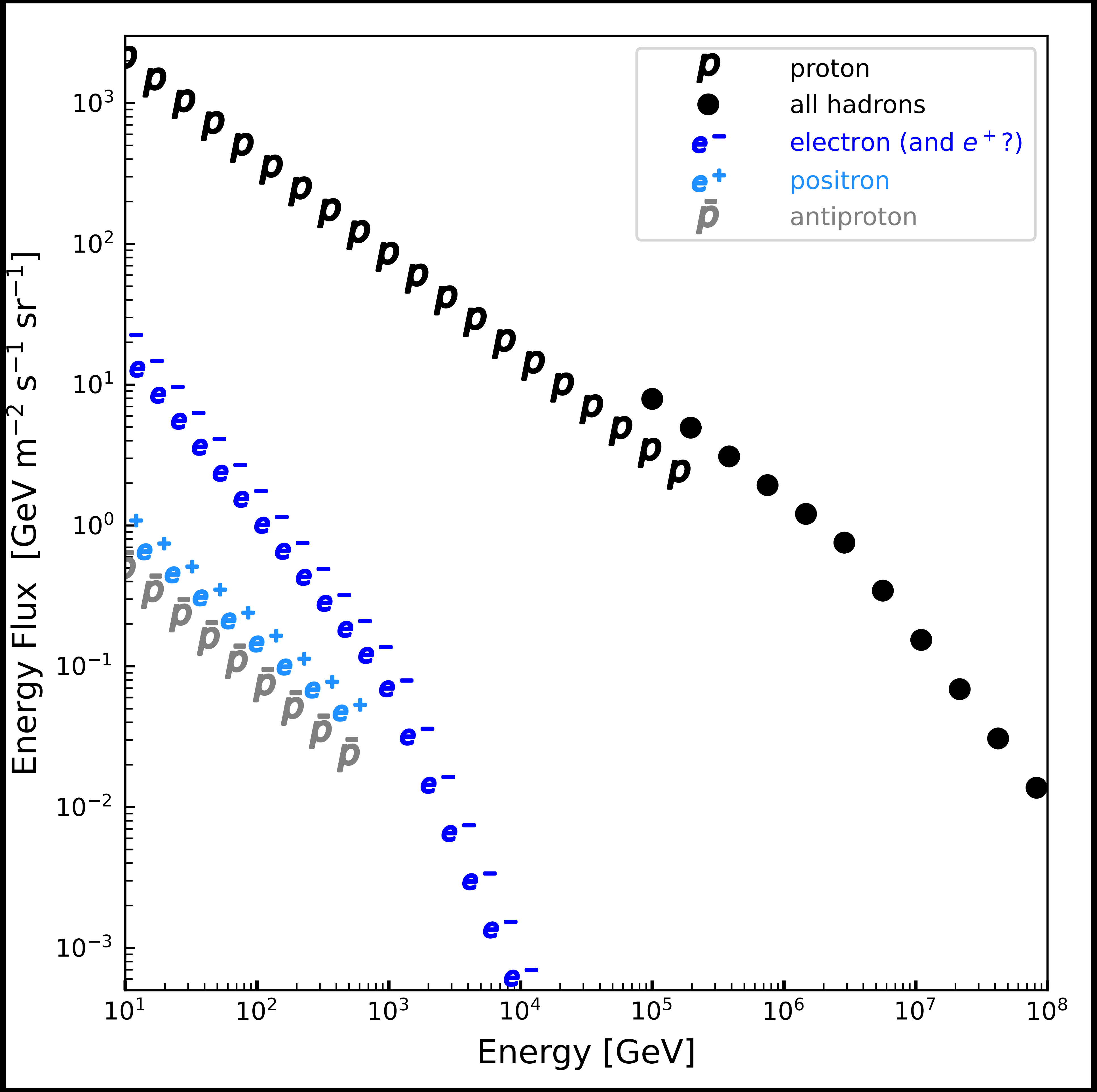
This talk : three questions

- ✓ Introduction
- ✓ TeV - PeV gamma-ray sources : Can leptons explain them?
- TeV - PeV gamma-ray sources : Where are hadronic PeVatrons?
- TeV - PeV neutrino sources : What to expect in the future?
- Summary

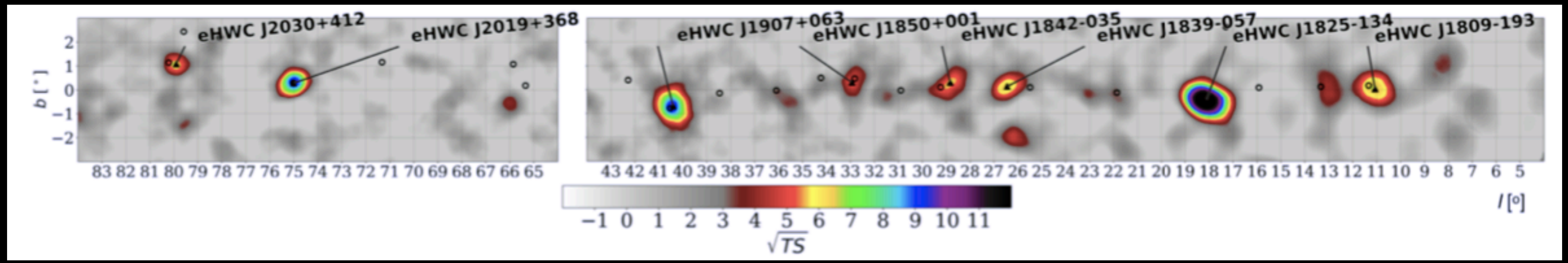
TeV - PeV gamma-ray sources :

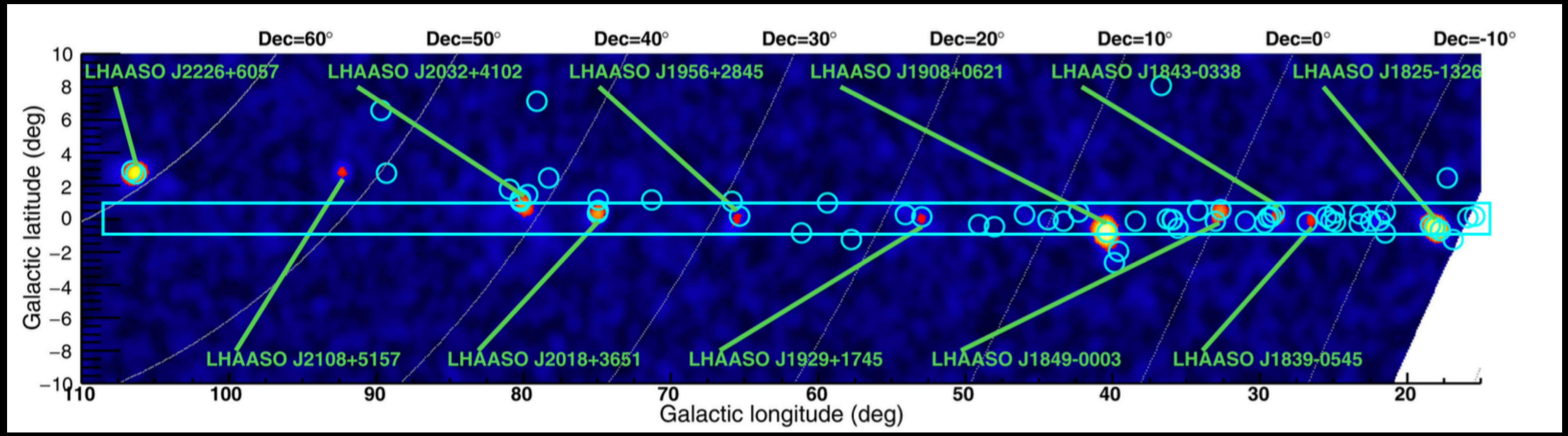
Where are hadronic PeVatrons?

Where are hadronic PeVatrons?



Hadrons dominate up to ~ PeV





Leptons may dominate at > 100 TeV

Cosmic-ray sources and gamma-ray sources

- *Gamma-ray sources may not be ideal cosmic-ray sources*

  Strong energy-losses make a source bright in gamma rays but may kill all charged particles

- *Cosmic-ray sources may not be ideal gamma-ray sources*

  Little energy-losses make a source dim in gamma rays but allow charged particles to be "cosmic rays"

Cosmic-ray sources and gamma-ray sources

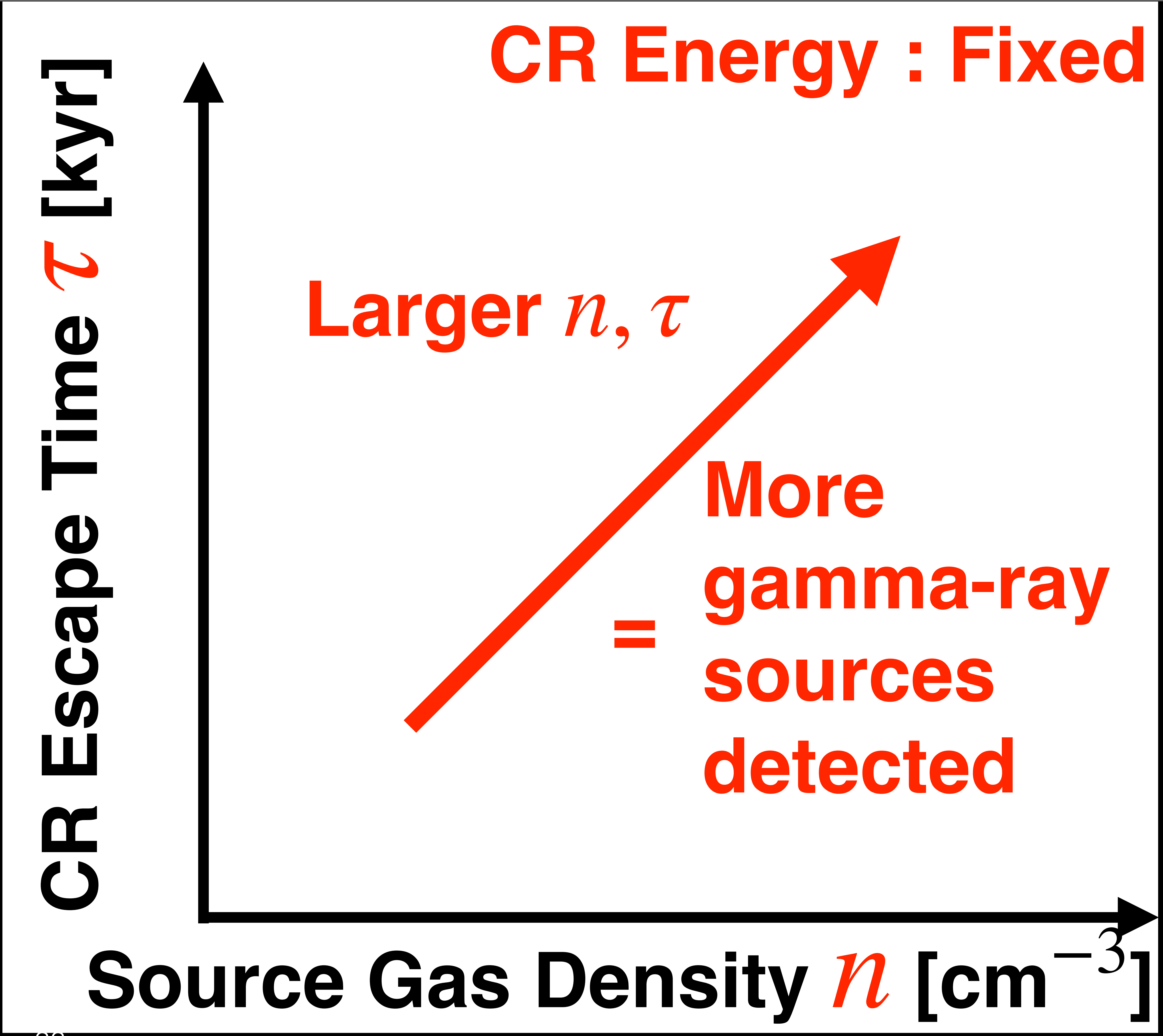
- *What defines the link between CR and gamma-ray sources?*

  Energy loss (pp) at the source

- *What defines energy loss at the source?*

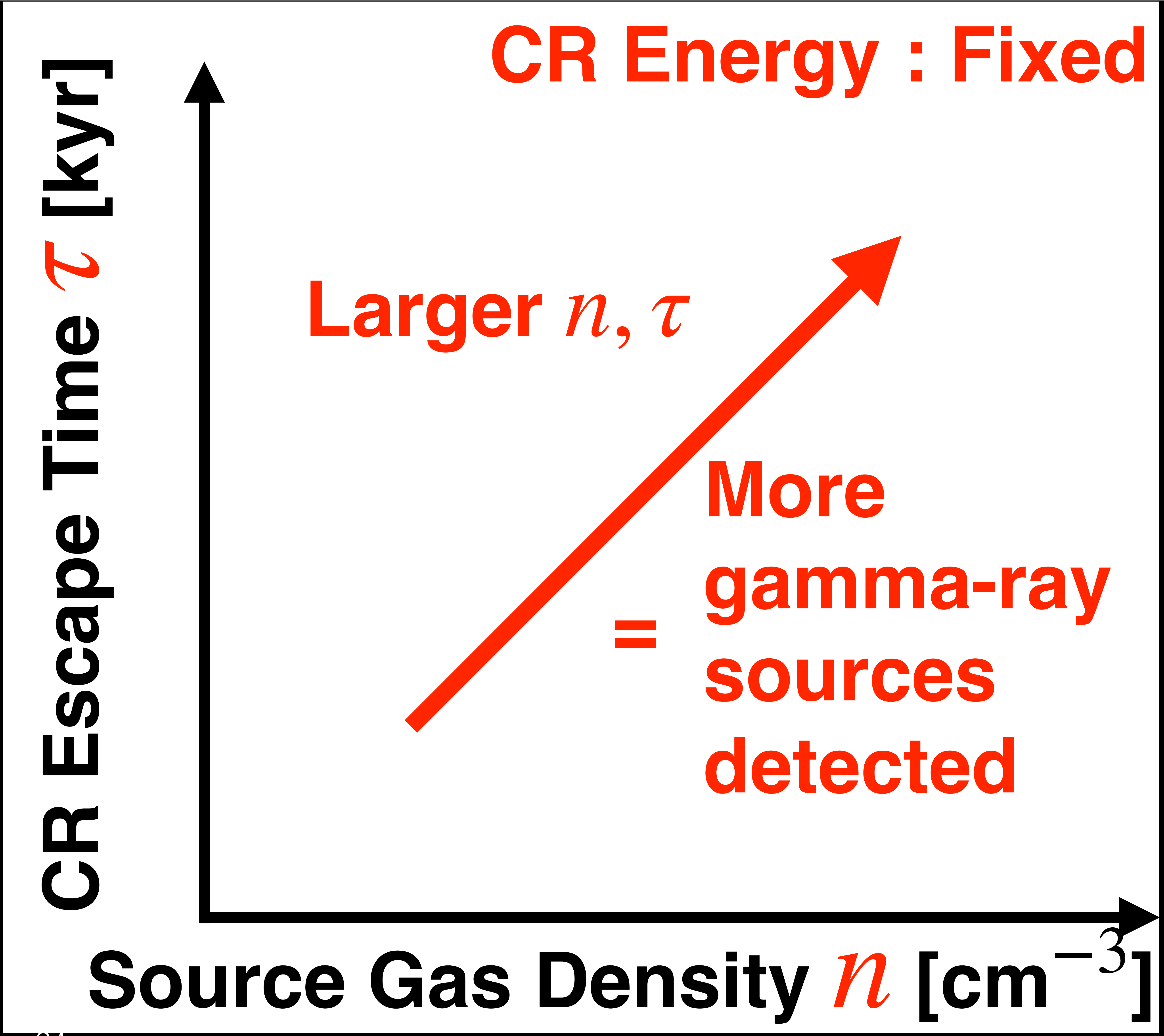
  n : gas density at the source

  τ : how long particles are confined by the source



Cosmic-ray sources and gamma-ray sources

- We introduce "$n - \tau$ plane"
- *Semi-model-independent :* can treat any PeVatron models
- *Population-based :* complements individual source studies



Some technical details

- Observed hadronic CR flux : $E_{\rm CR}^2 \Phi_{\rm CR}$

Boron to Carbon data

- Energy-dependent CR luminosity [erg/s] : $L_{\rm CR}$

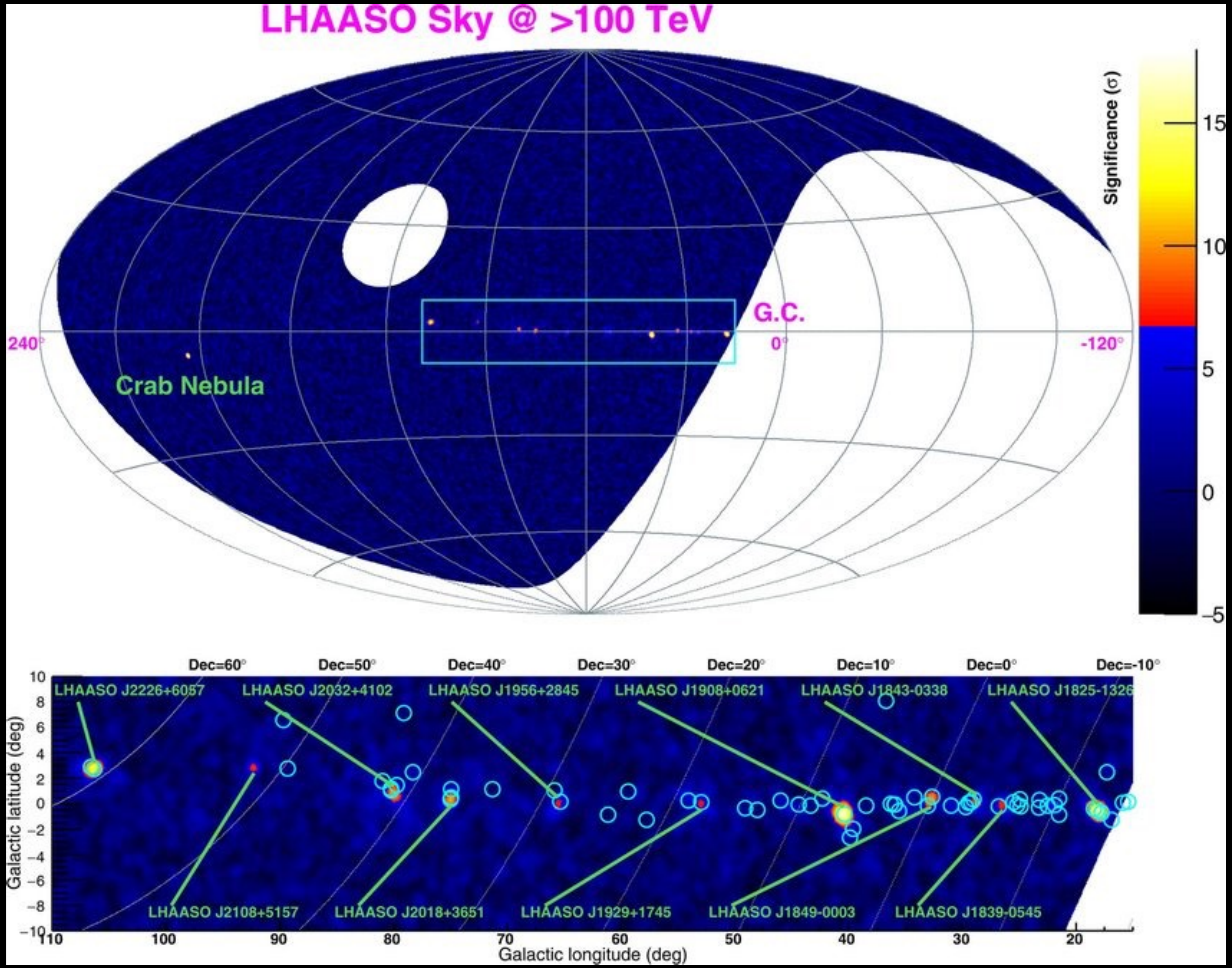
Event Rate $\Gamma_{\rm CR}$

- Energy-dependent CR energy per source [erg] : $\mathscr{E}_{\rm CR} = \dfrac{L_{\rm CR}}{\Gamma_{\rm CR}}$

Some technical details

- CR energy per source $\mathcal{E}_{\rm CR}$: Fixed (previous slide).
- Properties as gamma-ray and neutrino sources :
  - Luminosities : $\mathcal{E}_{\rm CR}/t_{pp}$, where $t_{pp} \sim (n\sigma_{pp}c)^{-1}$
  - Duration of emission : τ
- Run MC simulation that take source distribution and detector properties into account to predict the **expected number of hadronic PeVatrons detected in gamma rays and neutrinos**

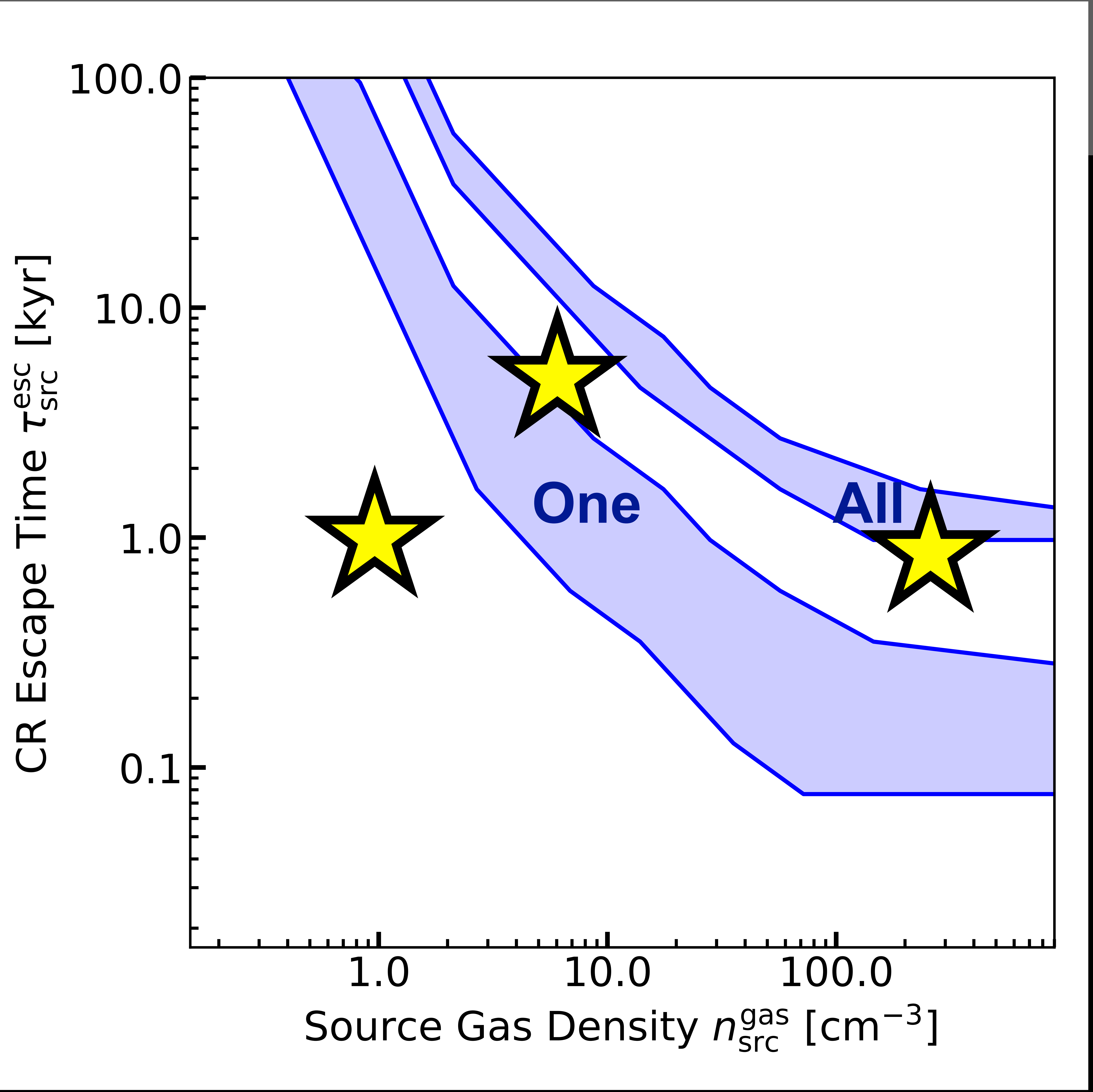
Cosmic-ray sources and gamma-ray sources



LHAASO Collaboration (2020)
See also earlier work by HAWC and Tibet ASγ

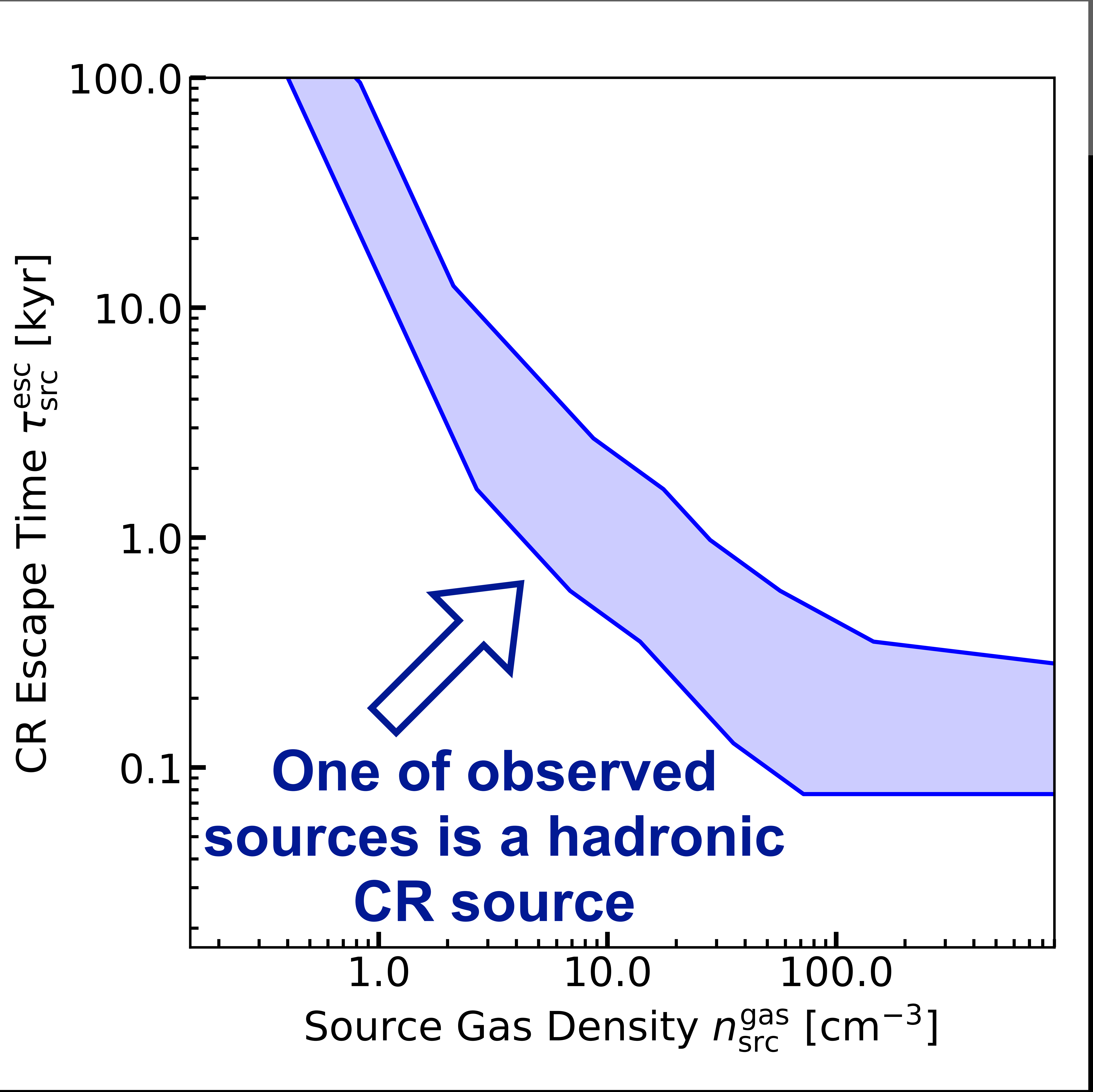
- We focus on > 100 TeV sources by LHAASO
- Twelve sources are observed by this survey
- How many hadronic PeVatrons should be there?

$n-\tau$ plane



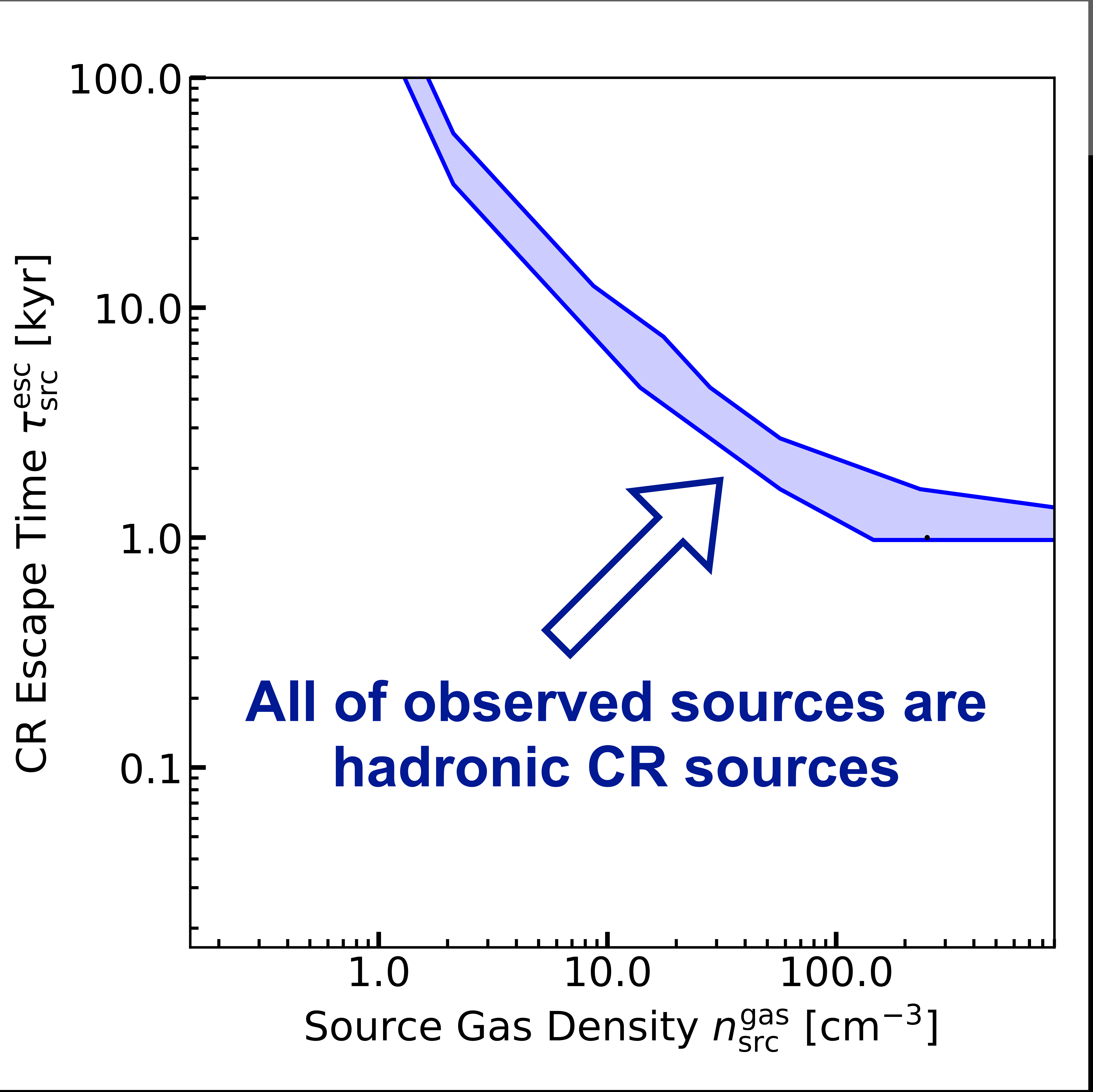
For details : Sudoh & Beacom (2022, PRD)

$n - \tau$ plane



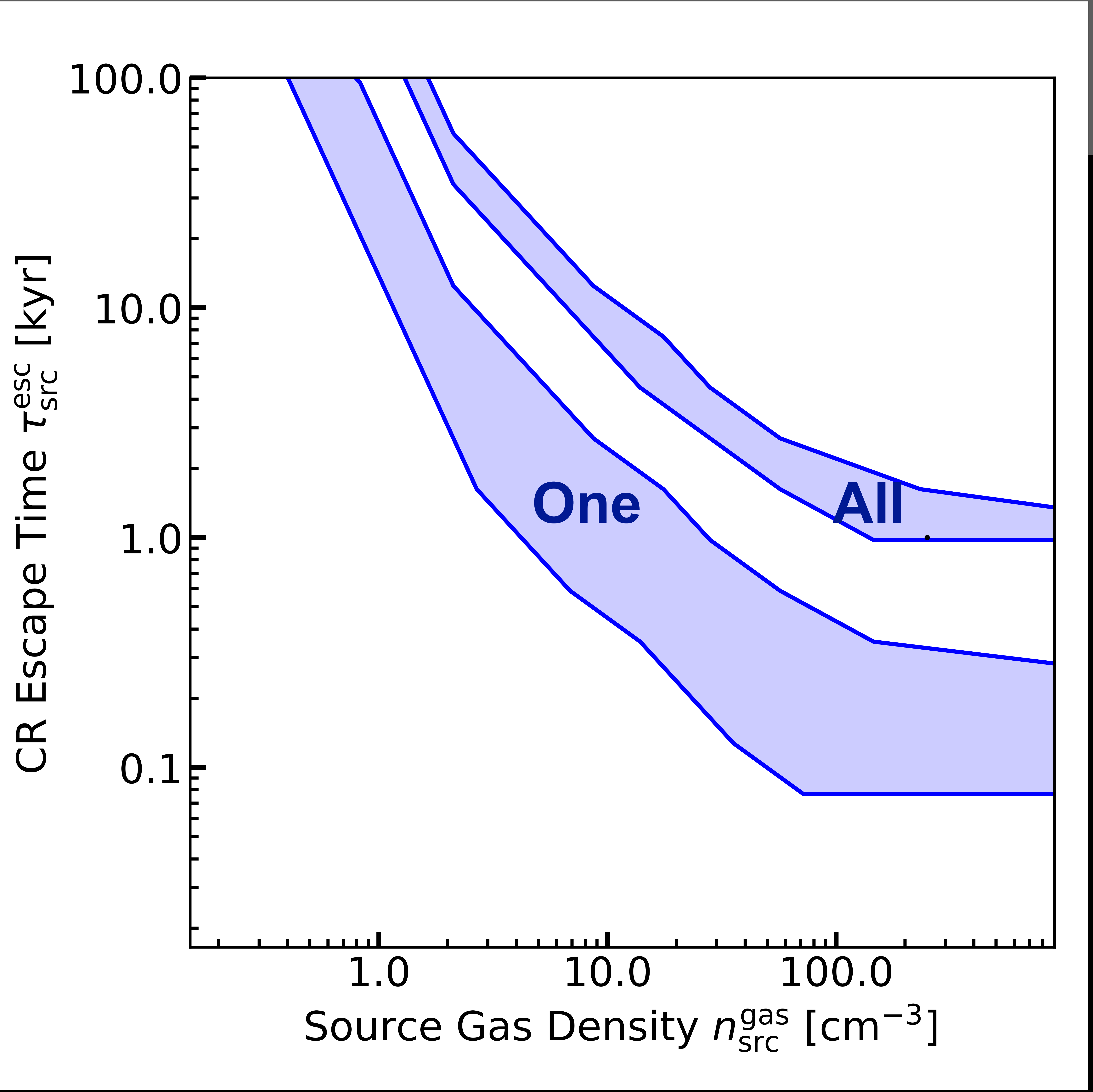
100.0
10.0
1.0
0.1
CR Escape Time τ_{src}^{esc} [kyr]
1.0
10.0
100.0
Source Gas Density n_{src}^{gas} [cm^{-3}]
One of observed sources is a hadronic CR source

$n - \tau$ plane



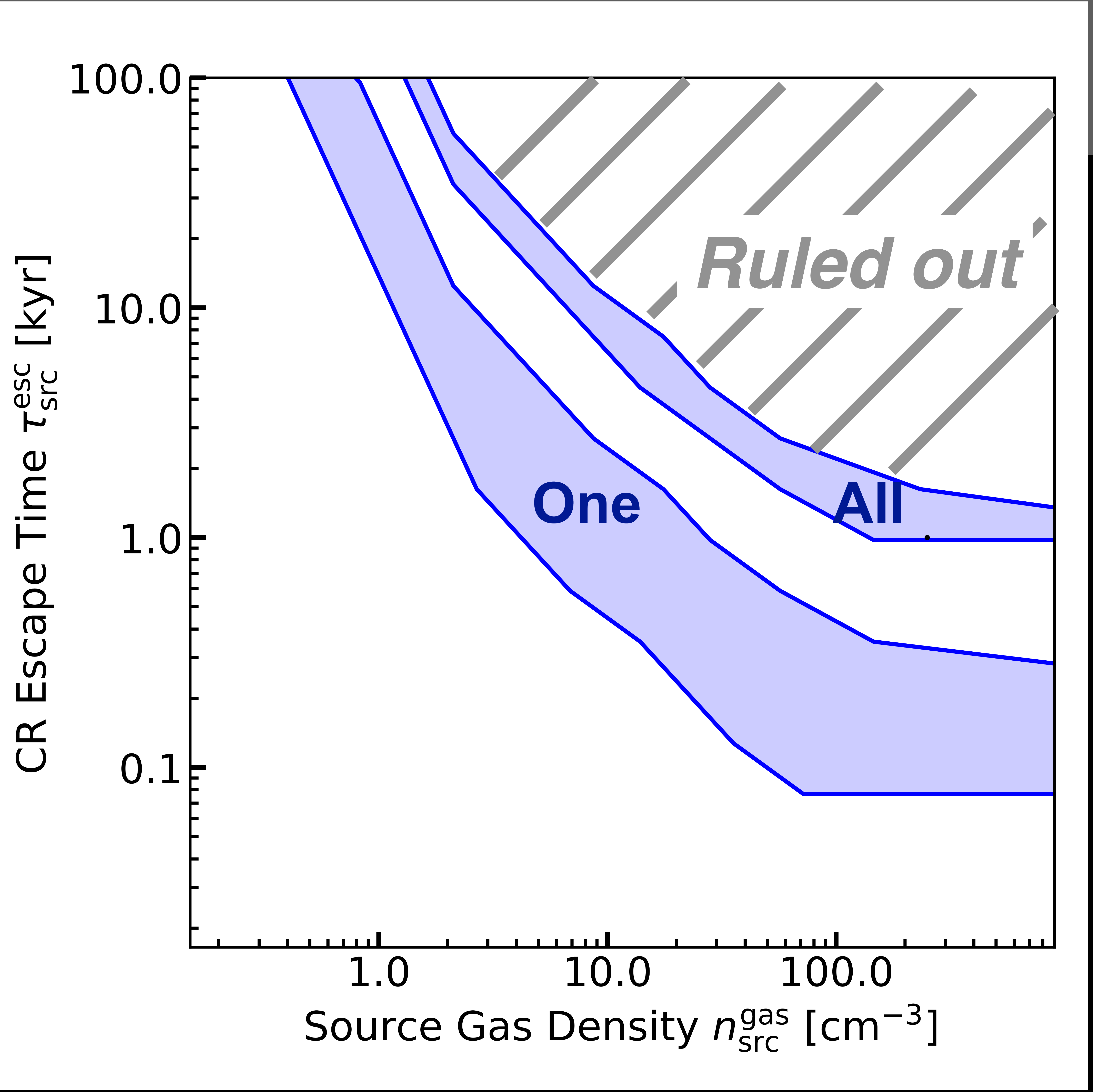
100.0
10.0
1.0
0.1
CR Escape Time τ_{src}^{esc} [kyr]
1.0
10.0
100.0
Source Gas Density n_{src}^{gas} [cm^{-3}]
All of observed sources are hadronic CR sources

$n - \tau$ plane



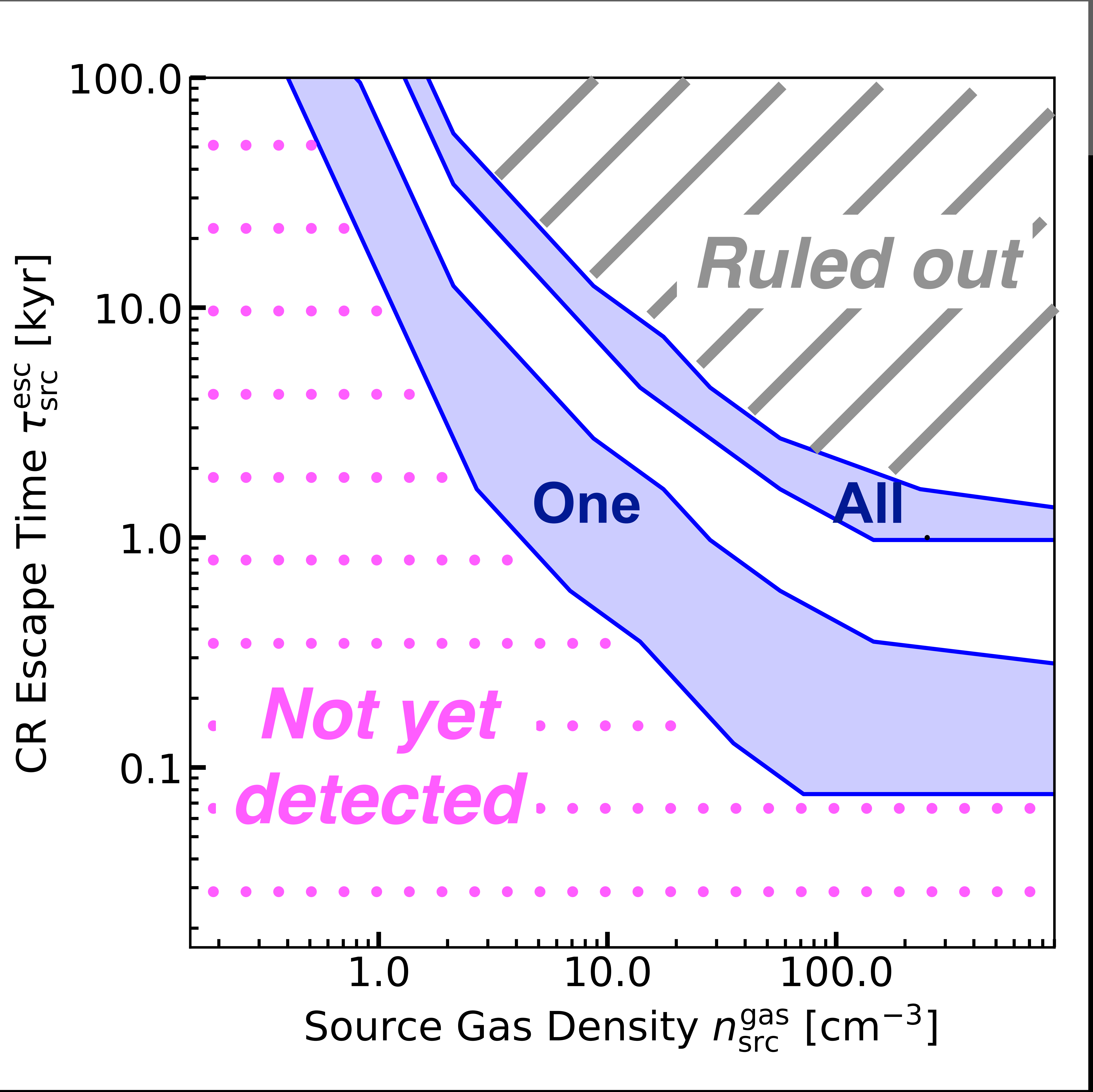
CR Escape Time τ_{src}^{esc} [kyr]
100.0
10.0
1.0
0.1
One
All
1.0
10.0
100.0
Source Gas Density n_{src}^{gas} [cm^{-3}]

$n - \tau$ plane



100.0
10.0
1.0
0.1
1.0
10.0
100.0
CR Escape Time τ_{src}^{esc} [kyr]
Source Gas Density n_{src}^{gas} [cm^{-3}]
Ruled out
One
All

$n - \tau$ plane

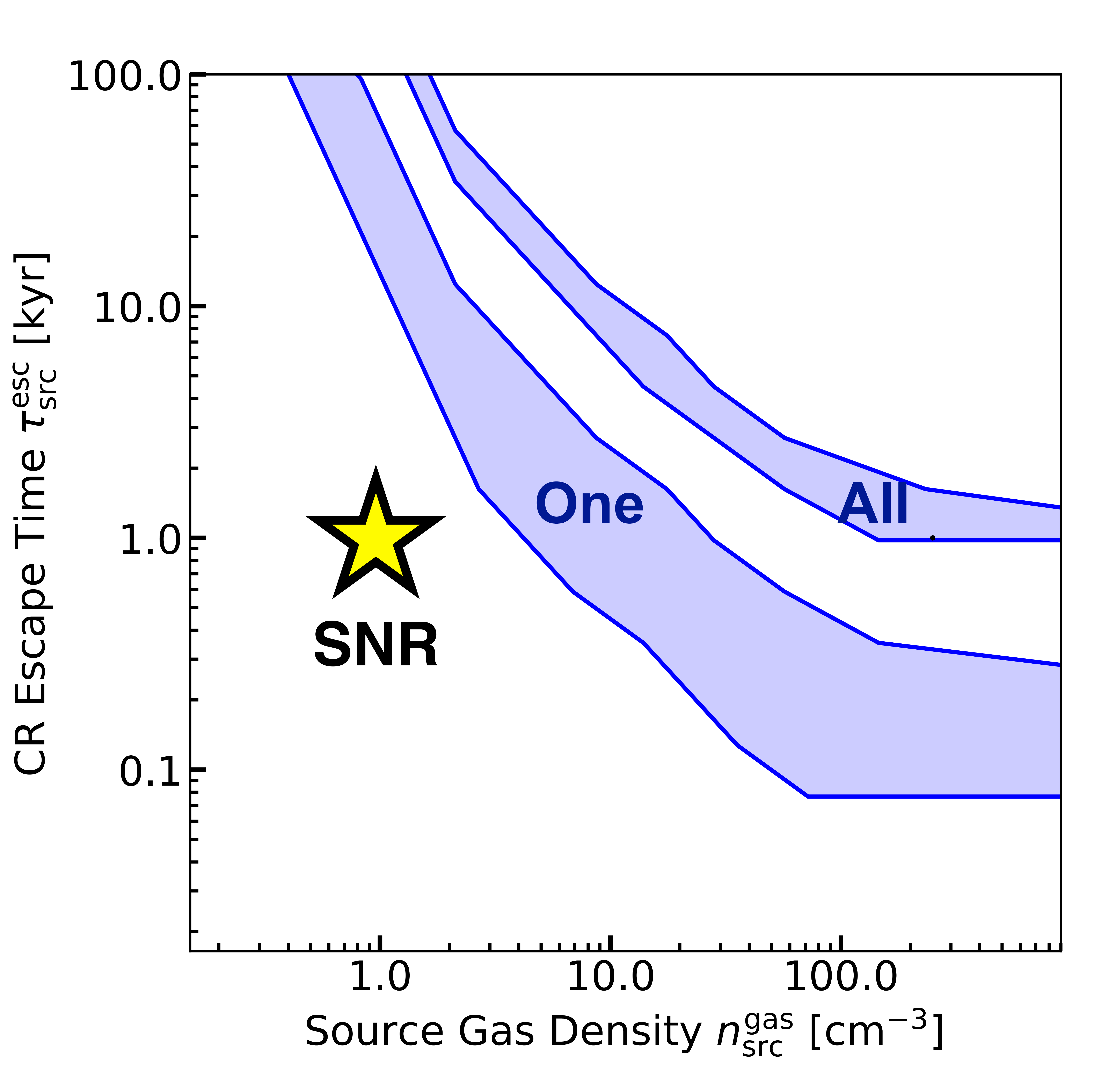

Ruled out
One
All
Not yet detected
CR Escape Time τ_{src}^{esc} [kyr]
Source Gas Density n_{src}^{gas} [cm^{-3}]
100.0
10.0
1.0
0.1
1.0
10.0
100.0

$n - \tau$ plane

If SNRs are the origin of cosmic rays,

we expect **ZERO** detection by highest-energy gamma rays.

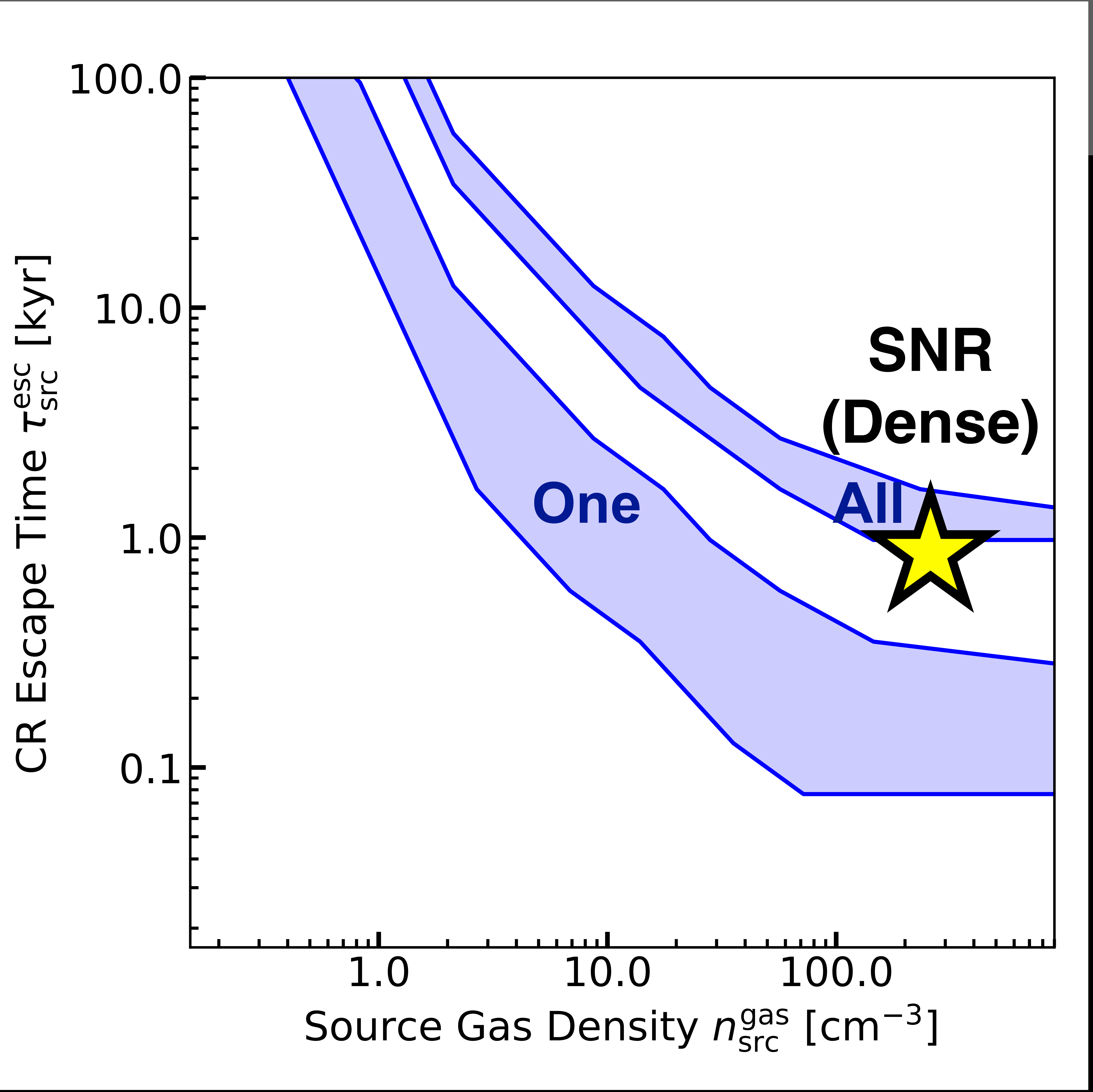
(Note : Our focus is above 100 TeV)



$n - \tau$ plane

…unless the typical gas density is very high

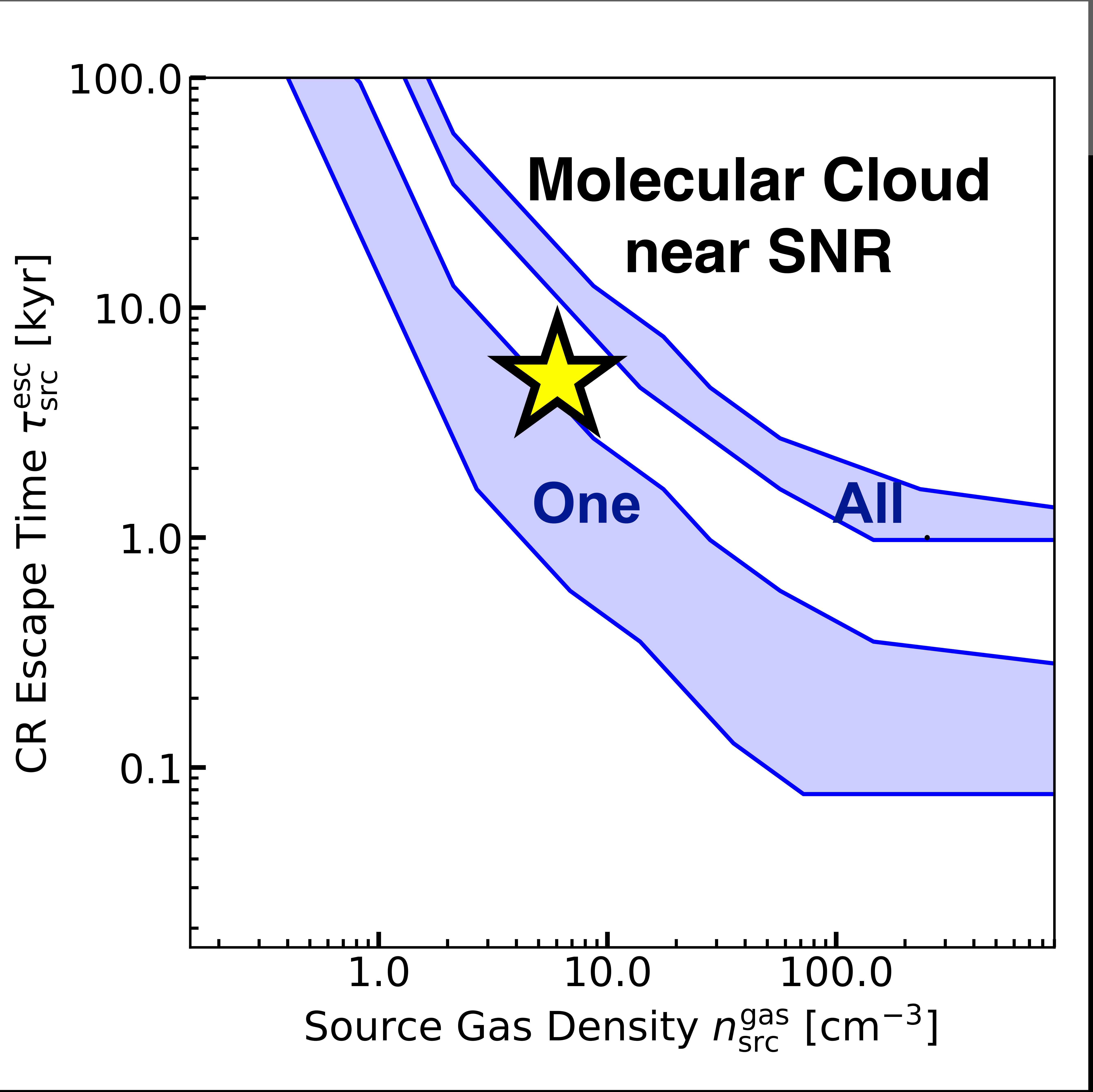
(Another note : An escape time 1 kyr could be optimistic)



$n - \tau$ plane

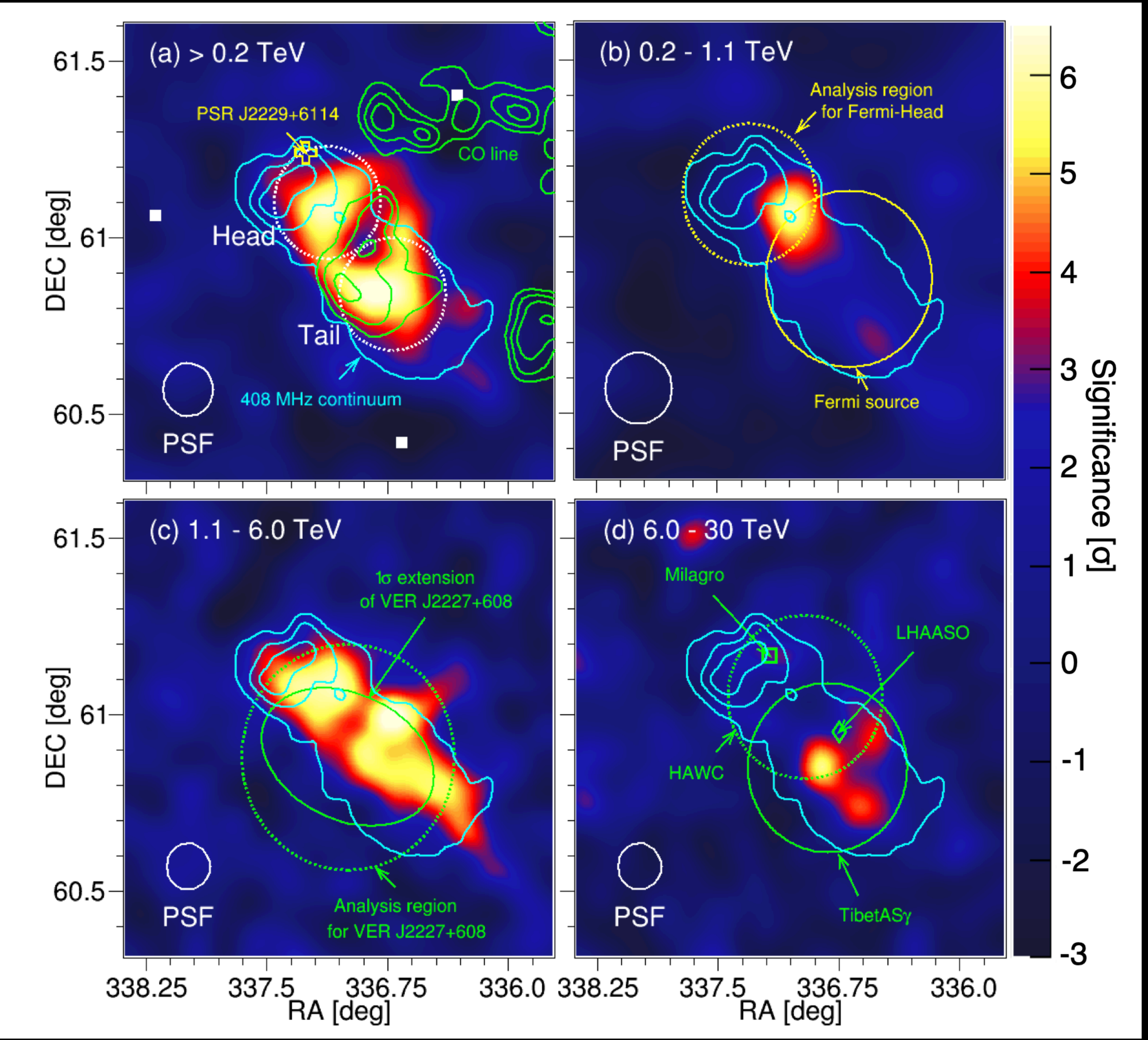
If normal SNRs are CR sources and they have a nearby giant molecular cloud,

we expect **one (or a few)** detection by highest-energy gamma rays



A Promising PeVatron : SNR G106.3+2.7

- A system of SNR + Molecular Cloud
- Recent data strongly support hadronic interpretation



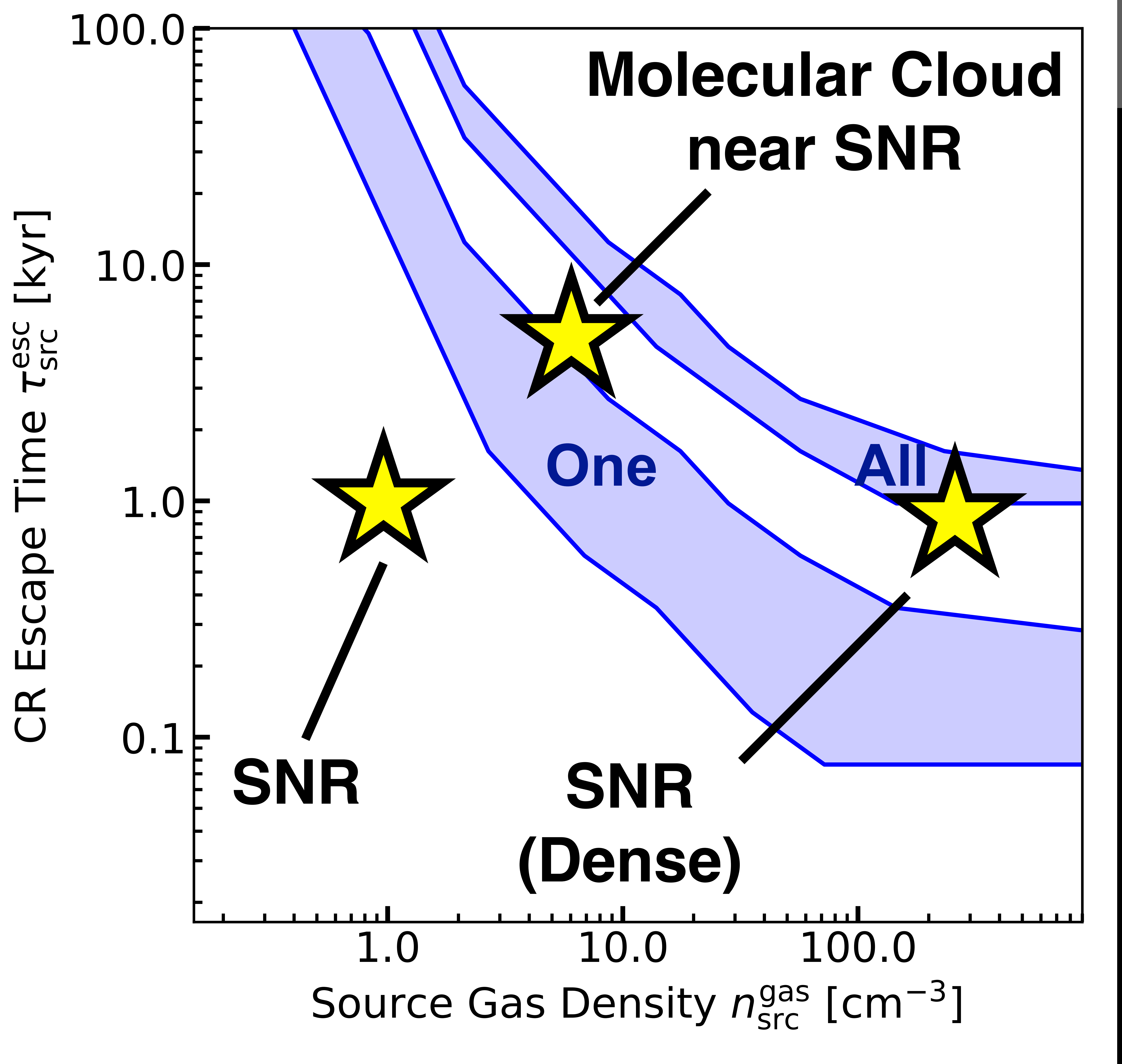
MAGIC Collaboration (2022)
+ Fermi, VERITAS, Milagro, Tibet ASγ, HAWC, LHAASO

$n - \tau$ plane

- We showed a "$n - \tau$ plane" taking SNRs as an example

- If normal SNRs are CR sources, we may not yet see them directly, but could find systems of cloud + SNR

- These results agree well with individual studies.



For details : Sudoh & Beacom (2022, PRD)

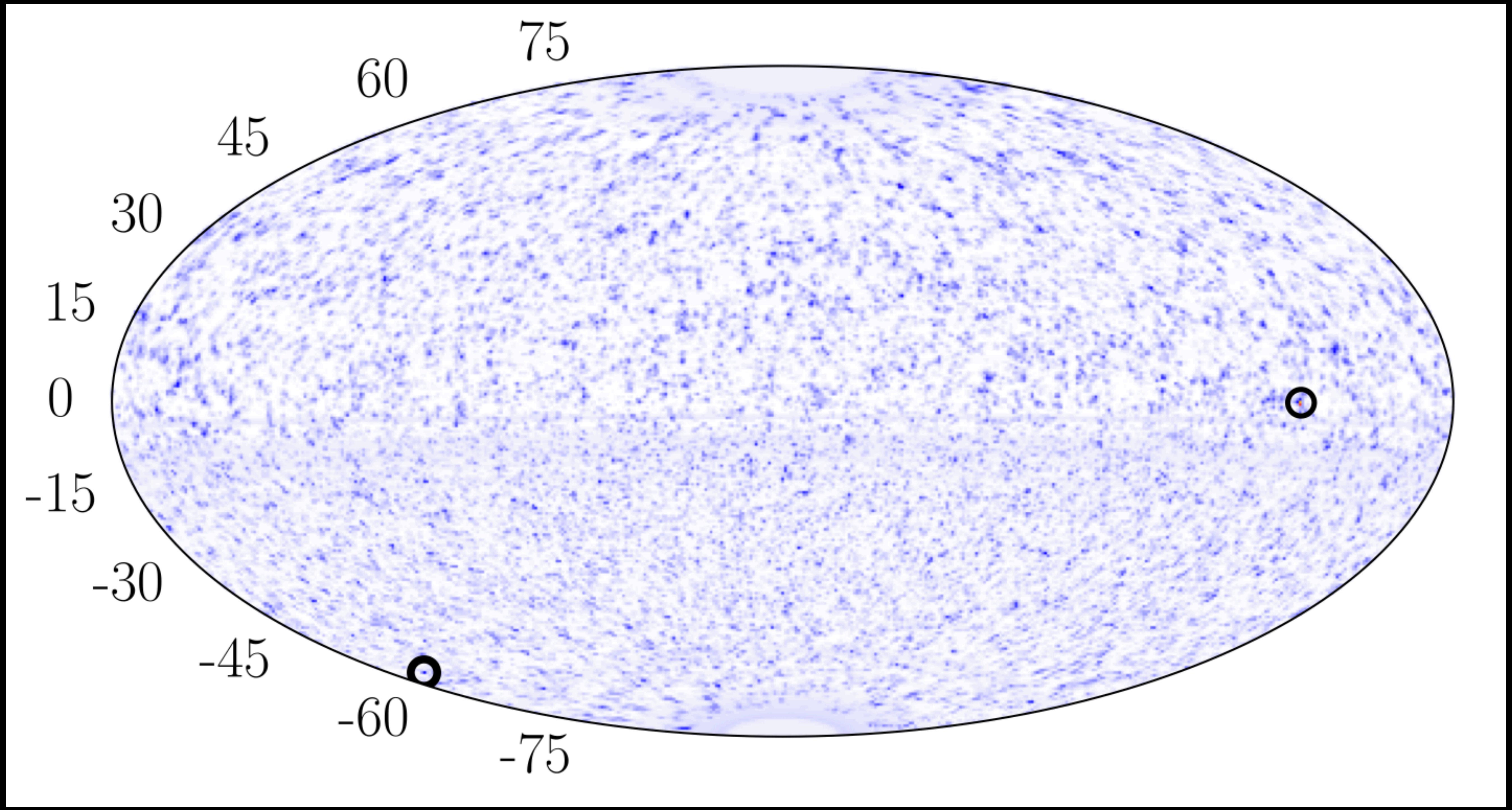
This talk

- ✓ Introduction
- ✓ TeV - PeV gamma-ray sources : Can leptons explain them?
- ✓ TeV - PeV gamma-ray sources : Where are hadronic PeVatrons?
- TeV - PeV neutrino sources : What to expect in the future?
- Summary

TeV - PeV neutrino sources :

What to expect in the future?

TeV - PeV Neutrinos : Present Status



IceCube Collaboration (2020)
See also work by ANTARES

- No TeV - PeV neutrino sources are detected in the Milky Way
- What non-detection tell us about the nature of hadronic PeVatrons?

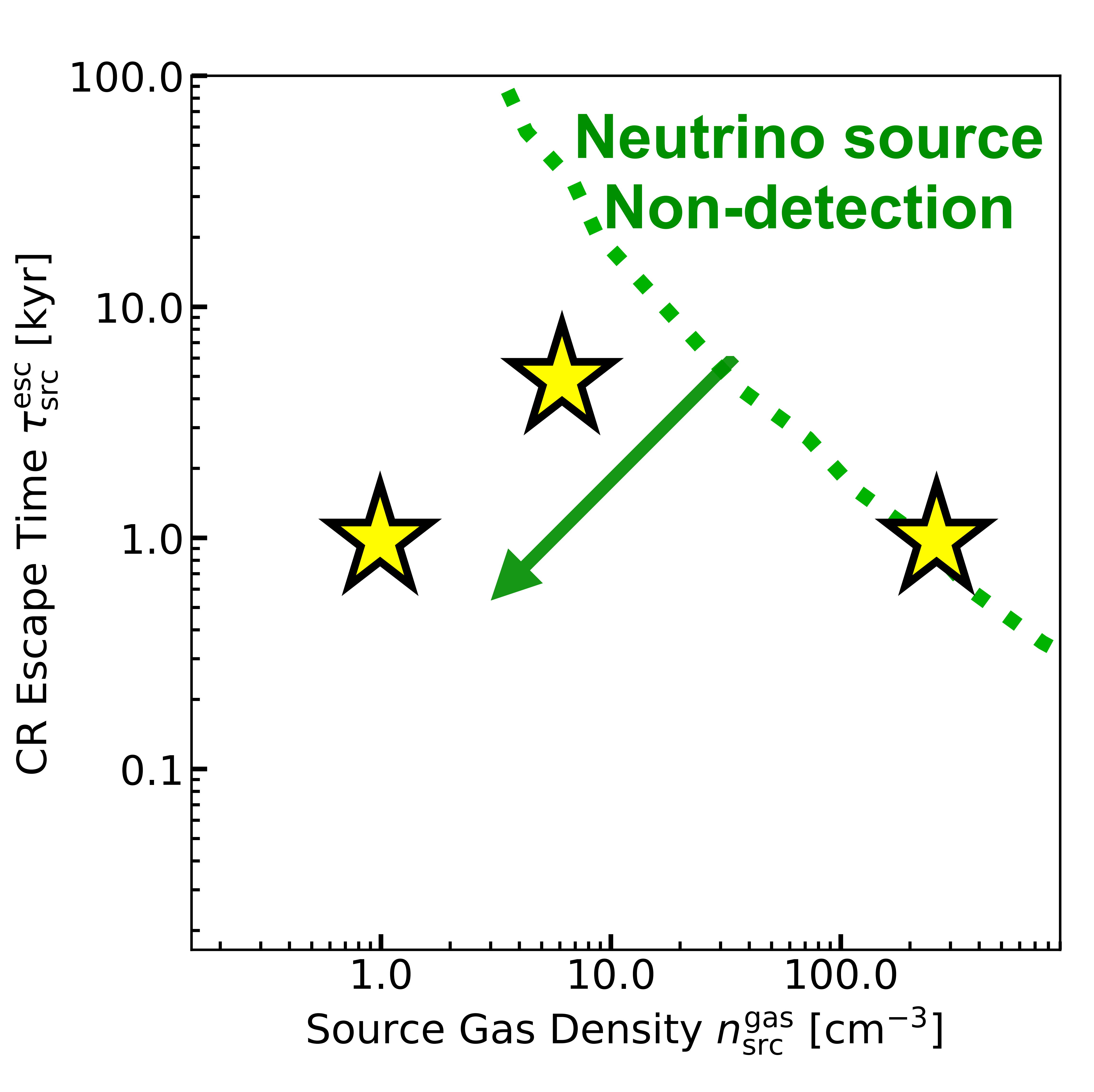
TeV - PeV Neutrinos : Present Status

- Non-detection translates into an upper bound in the $n - \tau$ plane

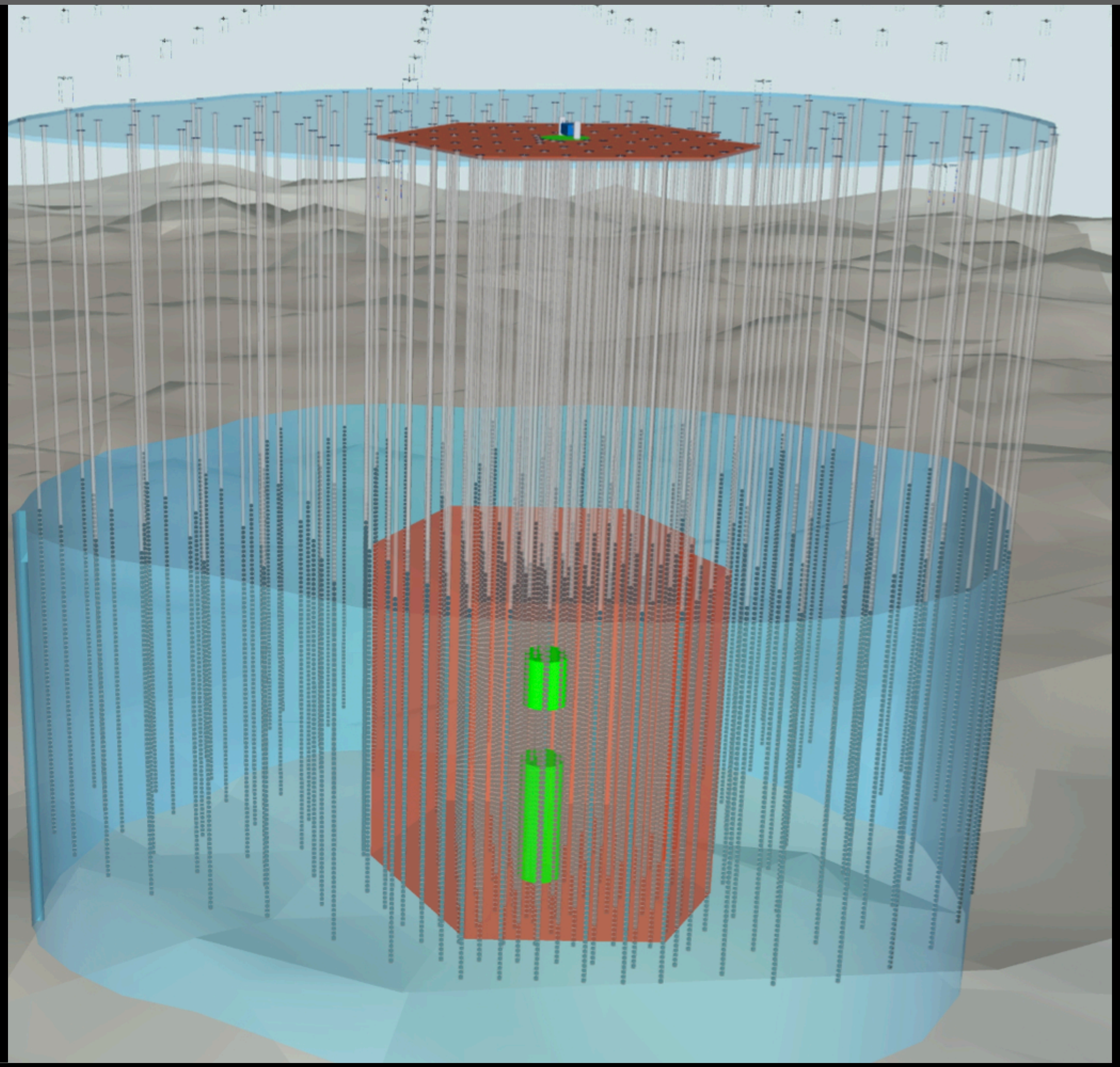
- IceCube rules out a model of very high gas density

- A large parameter space is still open

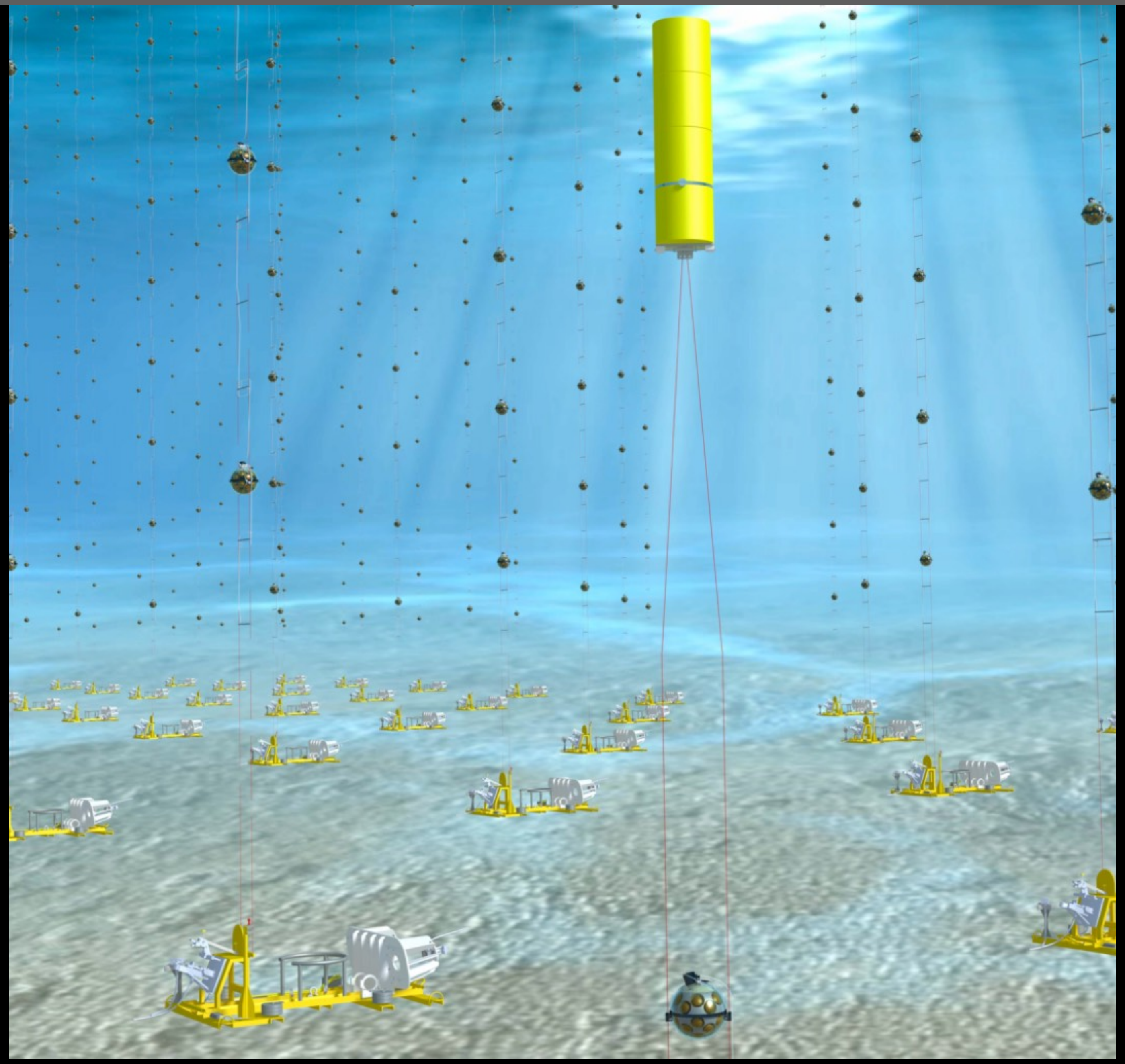
- How to progress?



TeV - PeV Neutrinos : Future



IceCube Gen-2 Collaboration (2020)

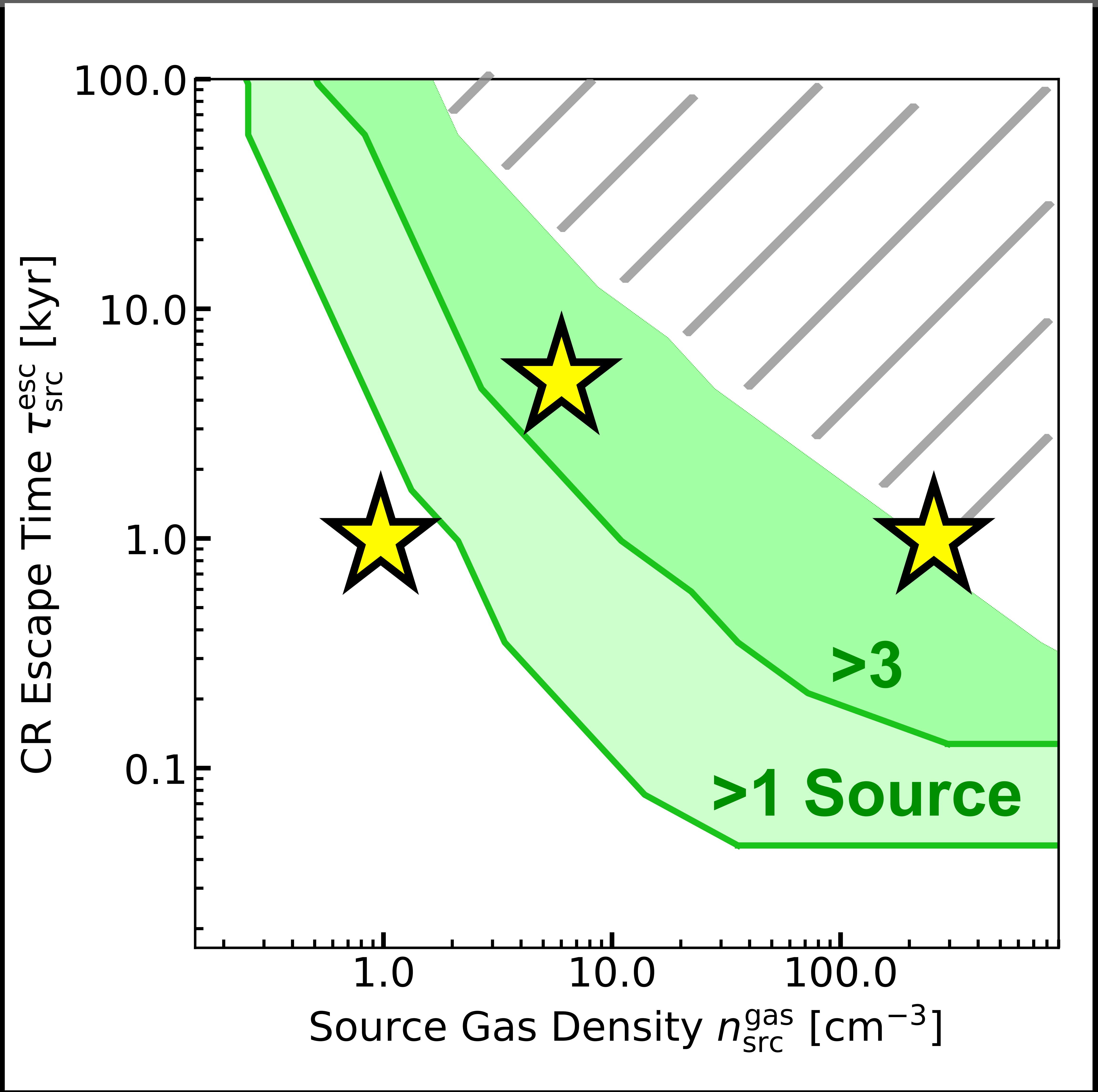


KM3NeT Official Website

IceCube Gen-2	KM3NeT
Ice-based	Ocean-based
Large-volume	Good angular resolution
South Pole	Northern Hemisphere

TeV - PeV Neutrinos : Future

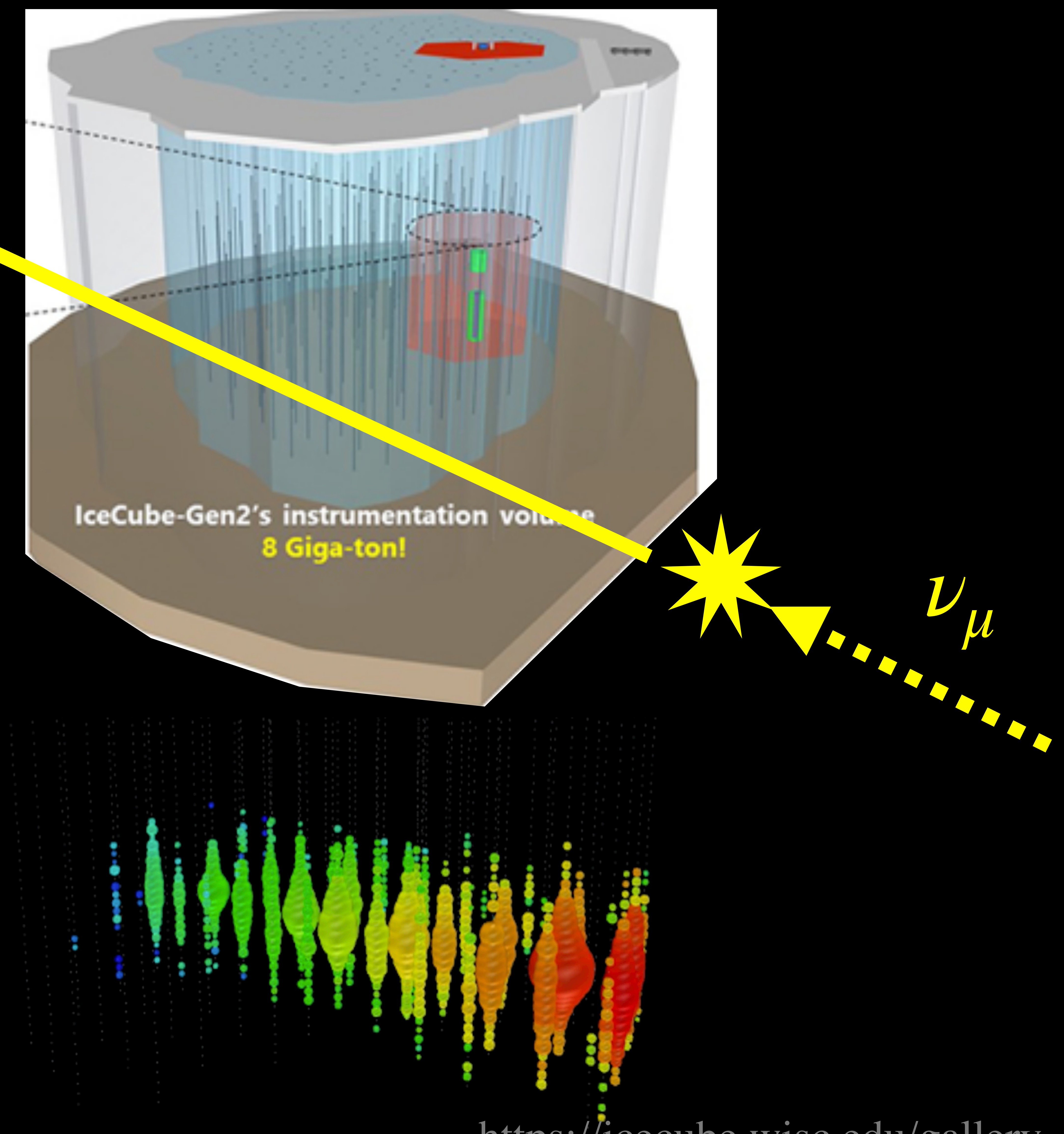
- Gen2 will have promising potential to find hadronic PeVatrons
- Can we further improve the sensitivity?



How to improve sensitivity? : Importance of showers

How to improve sensitivity? : Importance of showers

- In source studies, muon-induced *tracks* are often best suited due to the high angular resolution

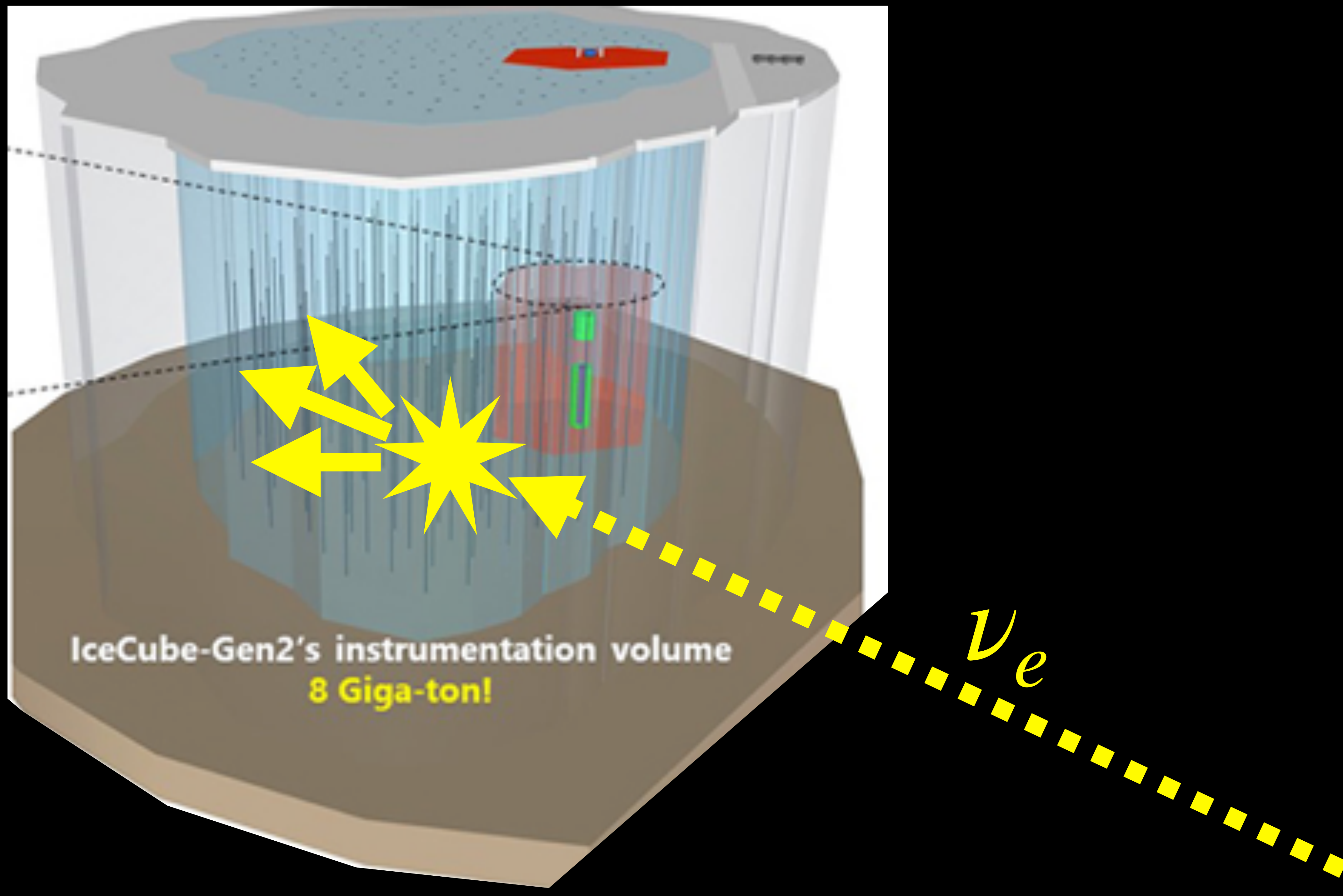


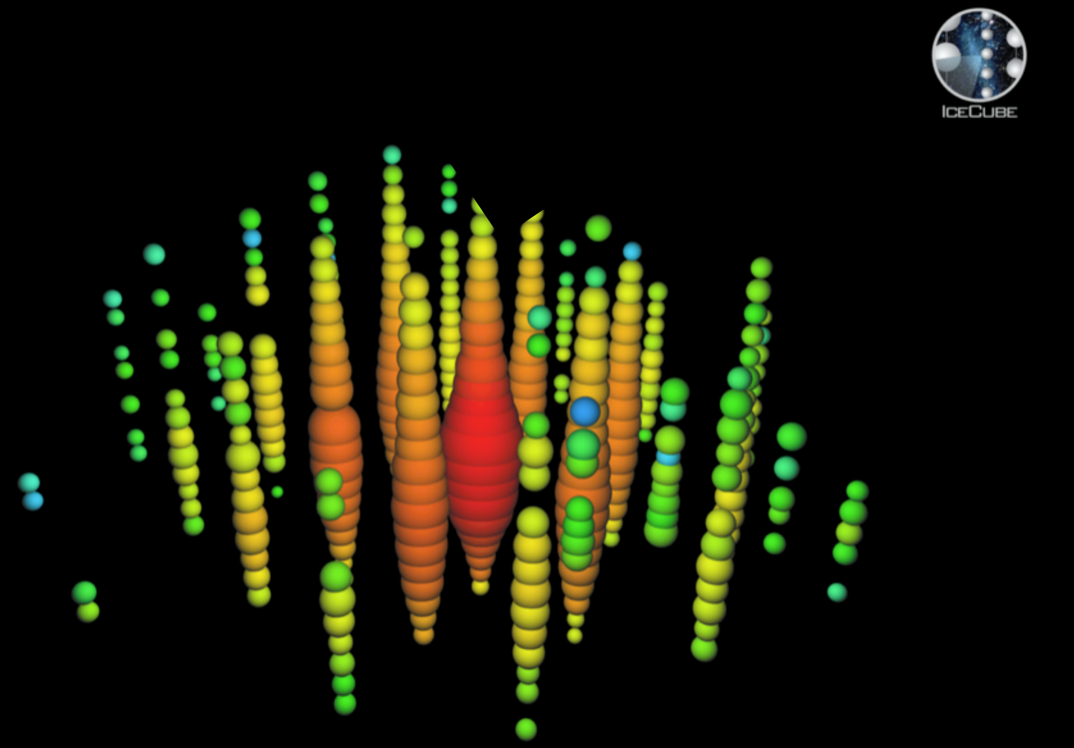
https://icecube.wisc.edu/gallery

How to improve sensitivity? : Importance of showers

- In source studies, muon-induced *tracks* are often best suited due to the high angular resolution

- *Showers* have much lower atmospheric background but have poor angular resolution

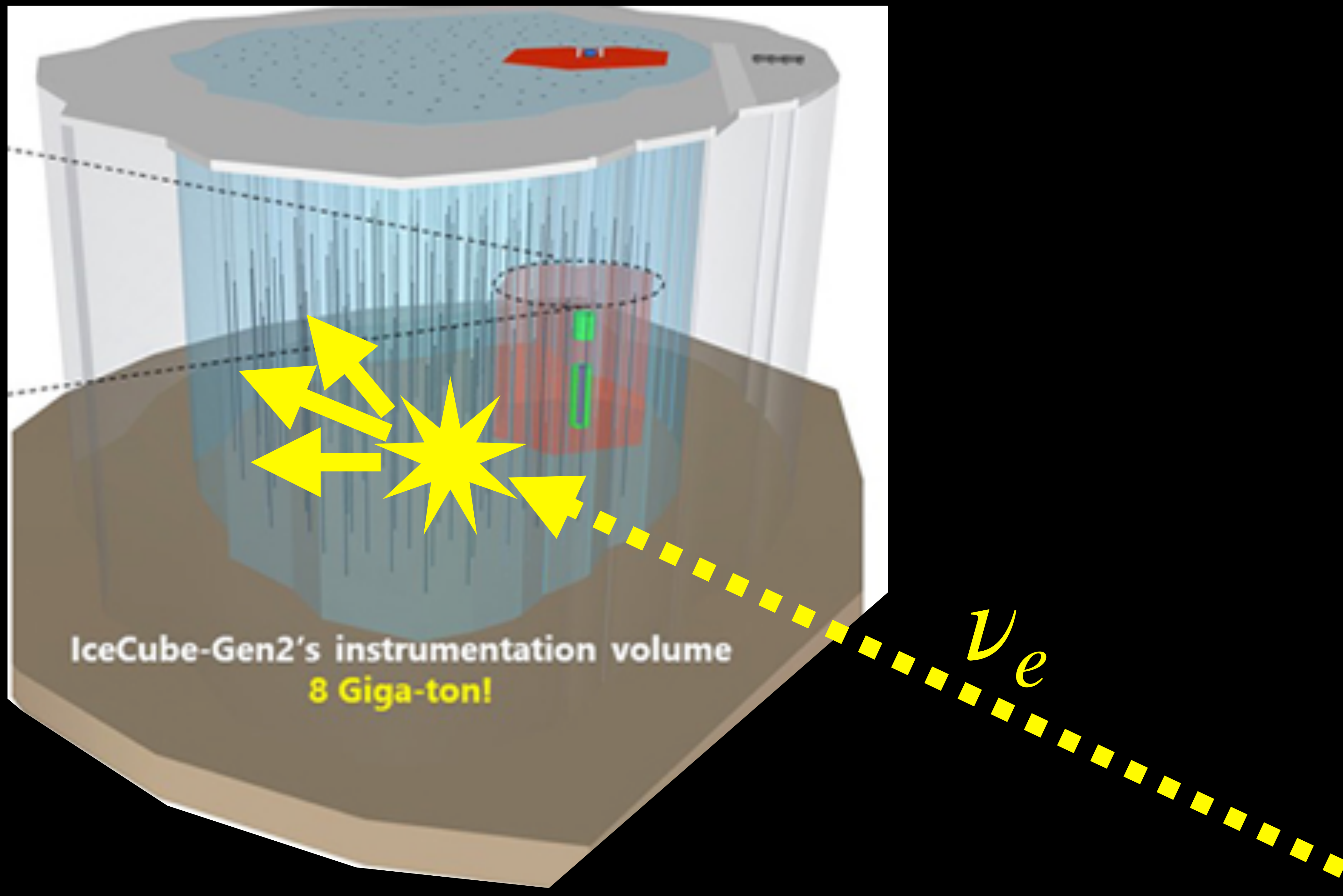


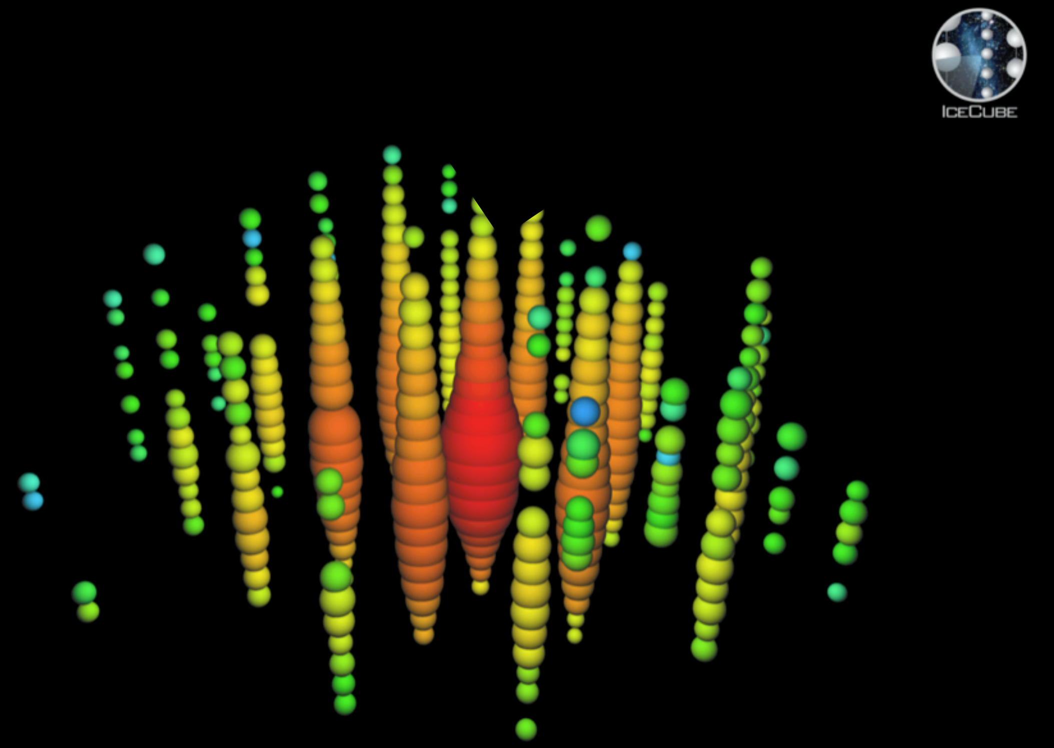


https://icecube.wisc.edu/gallery

How to improve sensitivity? : Importance of showers

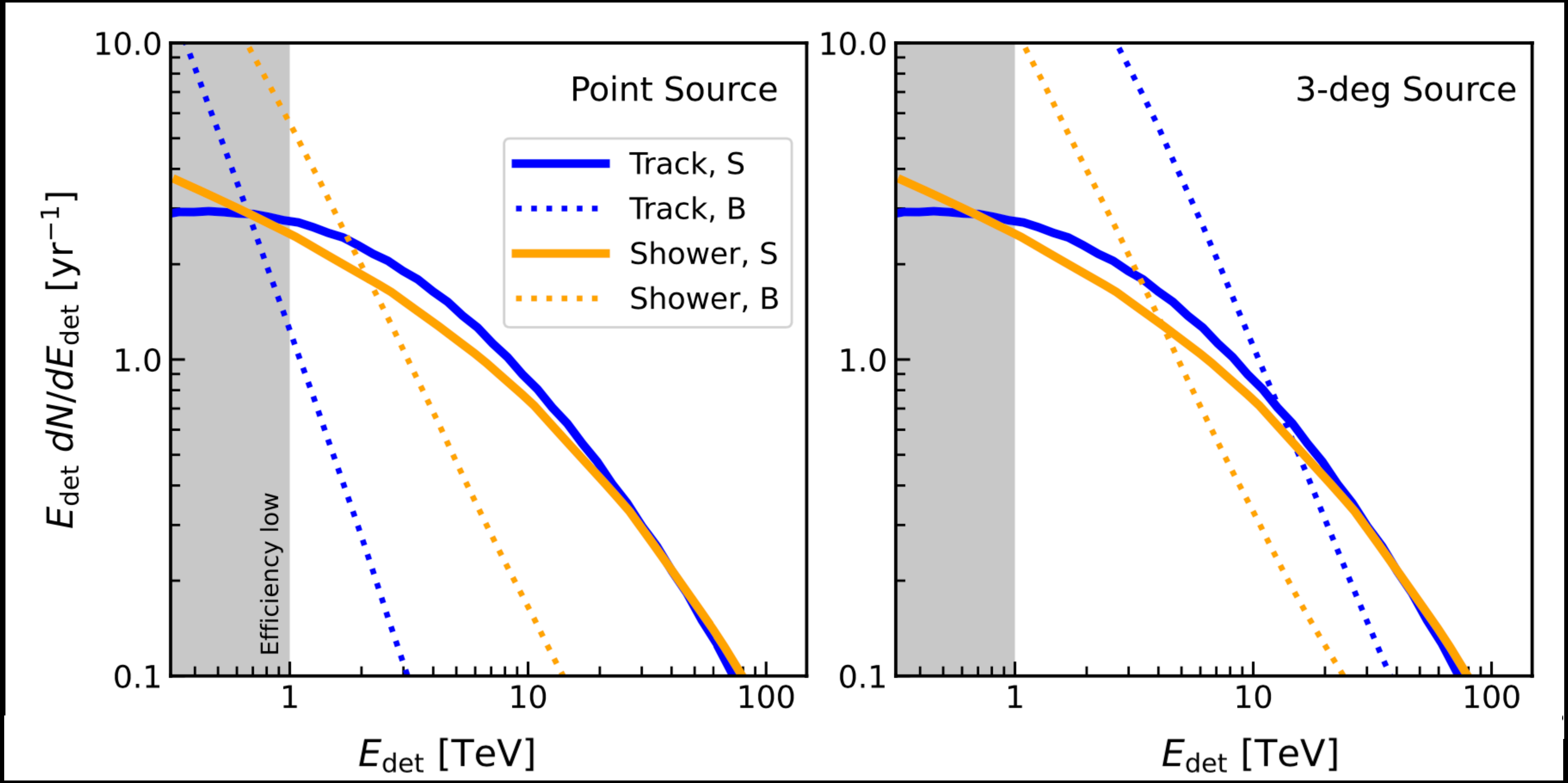
- Shower angular resolution is ~20° for IceCube, but this is due to the light scattering in ice
- Water-based detectors could achieve ~2°
- Showers are intrinsically directional!





https://icecube.wisc.edu/gallery

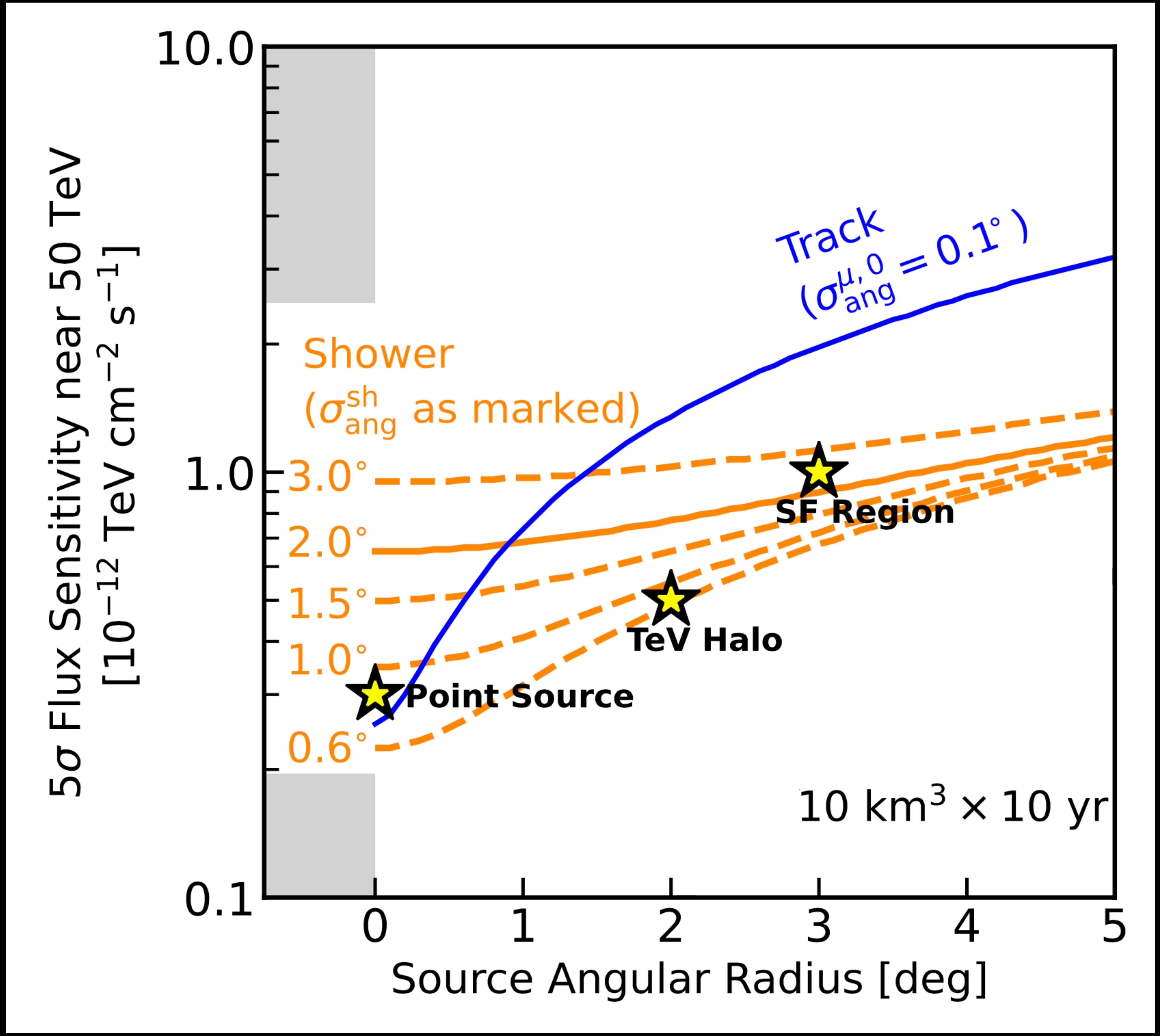
How to improve sensitivity? : Importance of showers



- Showers have lower background flux per solid angle

Sudoh & Beacom, in prep.

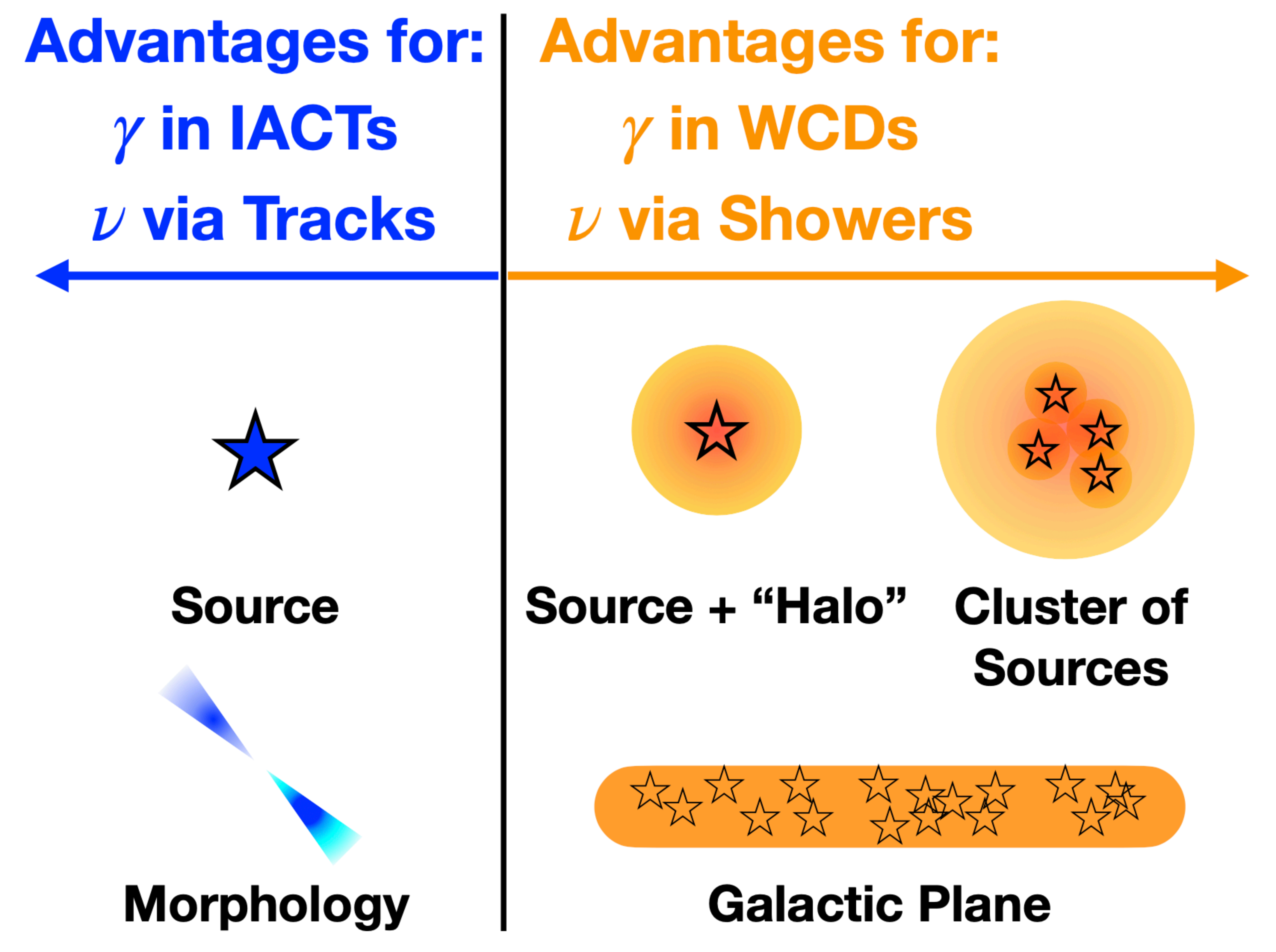
How to improve sensitivity? : Importance of showers



- Showers perform better for extended sources

Sudoh & Beacom, in prep.

How to improve sensitivity? : Importance of showers



- Shower channel should be an important part of the Milky Way's source searches!

Sudoh & Beacom, in prep.

This talk

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Summary

Summary

TeV - PeV gamma-ray sources : Can leptons explain them?

Yes for almost all cases. Further multi-zone modeling and multi-messenger data are crucial.

TeV - PeV gamma-ray sources : Where are hadronic PeVatrons?

We introduce a concept of “n-tau” plane to address this;
Minority of gamma-ray sources might be hadronic

TeV - PeV neutrino sources : What to expect in the future?

We quantify constraints and prospects in the “n-tau” plane;
Gen2 + KM3 is promising to find PeVatron sources

Appendix

Properties of HAWC sources

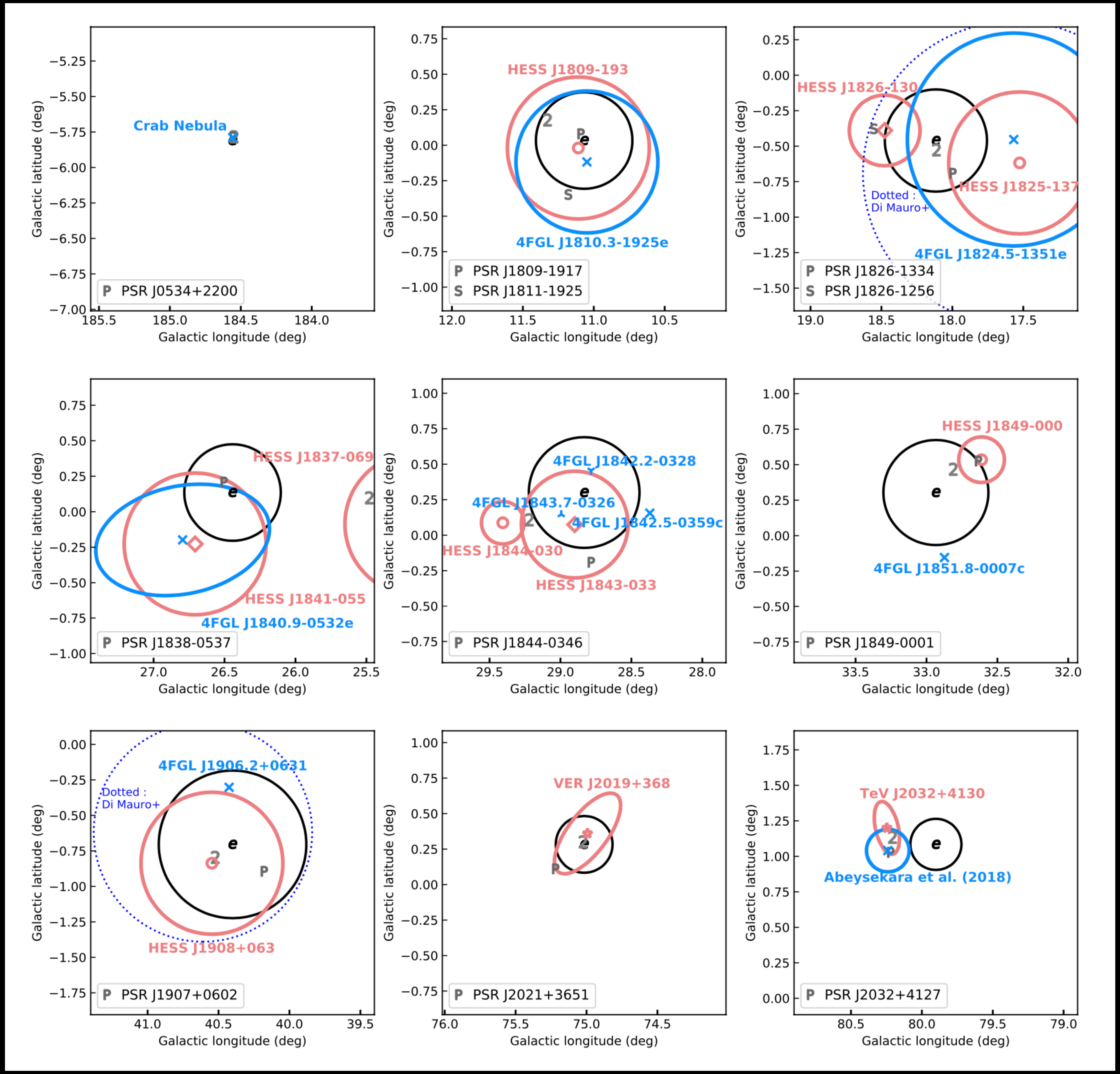
HAWC source	PSR name	$\dot{E}$ (erg/s)	Age ($\frac{P}{2\dot{P}}$) (kyr)	Distance to Earth (kpc)	Distance between HAWC source and PSR [° (pc)]	HAWC source extent (pc)
eHWC J0534+220	J0534+2200	4.5×10^{38}	1.3	2.00	0.03 (1.05)	-
eHWC J1809-193	J1809-1917	1.8×10^{36}	51.3	3.27	0.05 (2.86)	19.4
-	J1811-1925	6.4×10^{36}	23.3	5.00	0.40 (34.9)	29.7
eHWC J1825-134	J1826-1334	2.8×10^{36}	21.4	3.61	0.26 (16.4)	22.1
-	J1826-1256	3.6×10^{36}	14.4	1.55	0.45 (12.2)	9.47
eHWC J1839-057	J1838-0537	6.0×10^{36}	4.89	2.0[a]	0.10 (3.50)	11.9
eHWC J1842-035	J1844-0346	4.2×10^{36}	11.6	2.40[b]	0.49 (20.5)	16.3
eHWC J1850+001	J1849-0001	9.8×10^{36}	42.9	7.00[c]	0.37 (45.2)	45.2
eHWC J1907+063	J1907+0602	2.8×10^{36}	19.5	2.37	0.29 (12.0)	21.5
eHWC J2019+368	J2021+3651	3.4×10^{36}	17.2	1.80	0.27 (8.48)	6.28
eHWC J2030+412	J2032+4127	1.5×10^{35}	201	1.33	0.33 (7.66)	4.18

[a] Pseudo-distance from [38]
[b] Pseudo-distance from Eq. 3 of [39]
[c] Distance estimate from [40]

TABLE III. Information on all pulsars with $\dot{E} > 10^{36}$ erg/s within 0.5 degree of each source. The only pulsar within 0.5 degree of eHWC J2030+412 has an $\dot{E}$ below this threshold; it is included here for completeness. All pulsar parameters come from the ATNF database, version 1.60 [34] unless specified. The distance between the pulsar and the HAWC source as well as the HAWC high-energy source extent (from Table I) are given in parsecs here, assuming that the HAWC source is the same distance from the Earth as the pulsar.

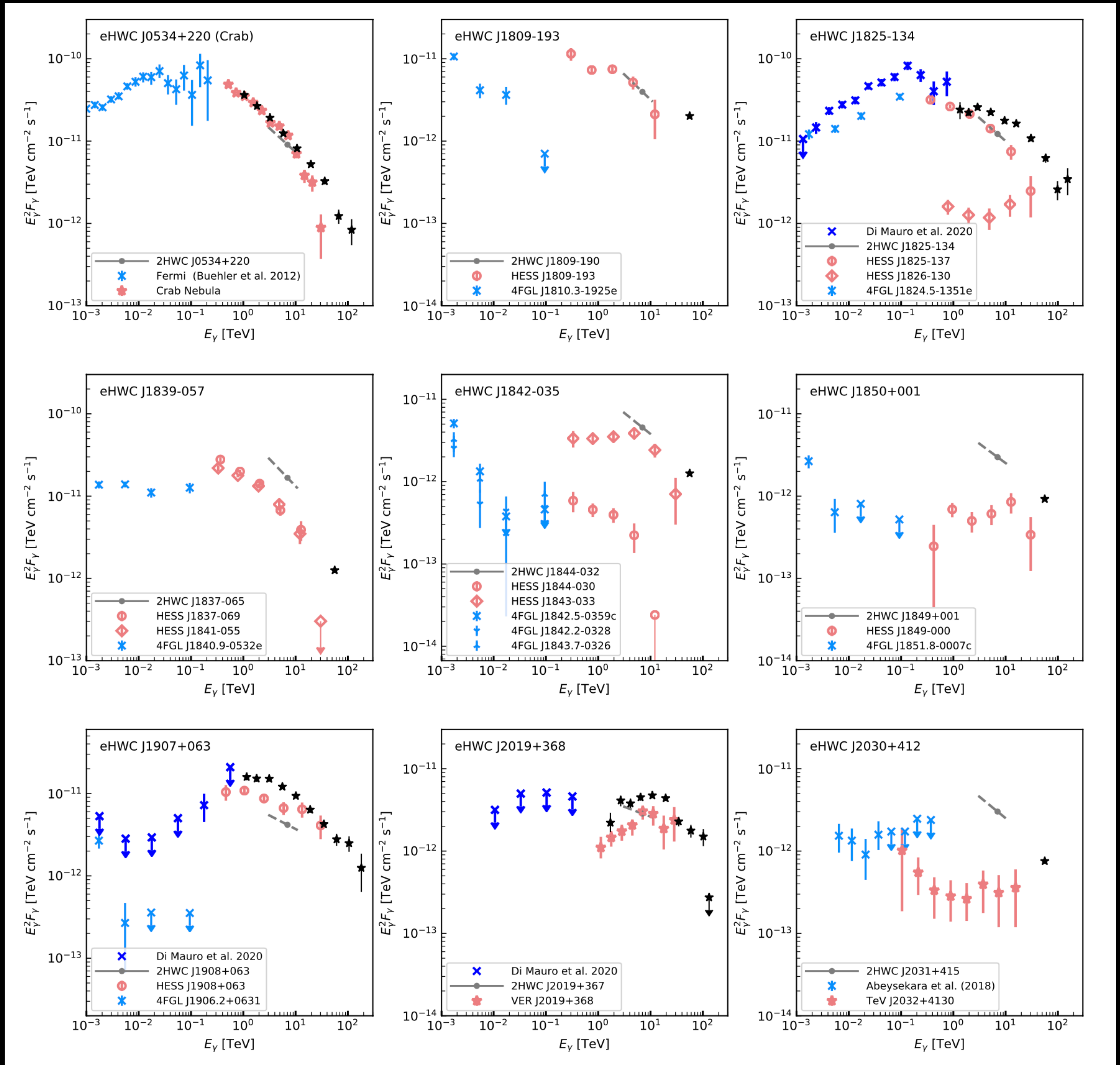
HAWC Collaboration (2020, PRL)

Properties of HAWC sources



Sudoh, Linden, Hooper (2021, JCAP)

Properties of HAWC sources



Sudoh, Linden, Hooper (2021, JCAP)

$n - \tau$ plane : Rare sources

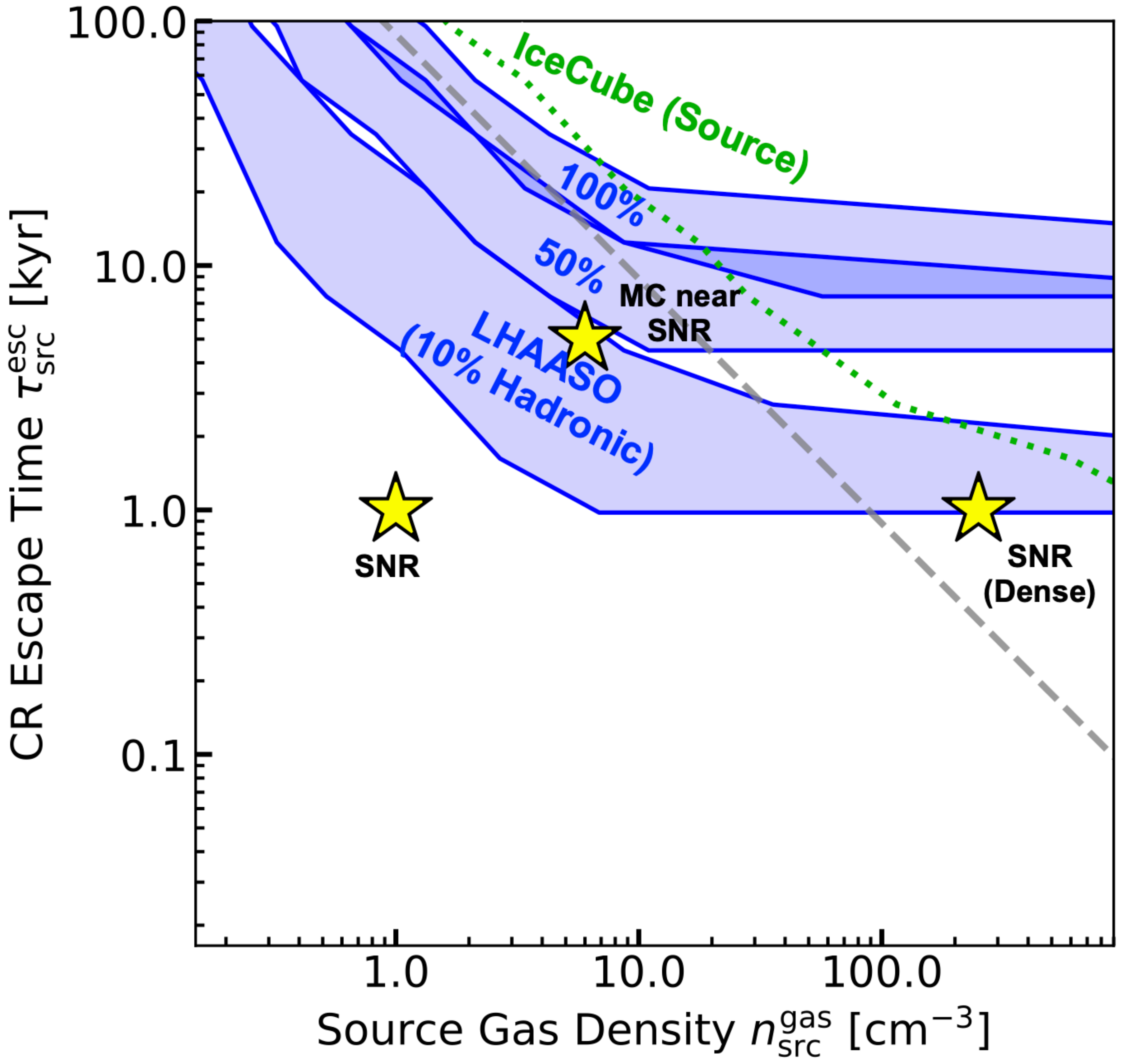


FIG. 9. Same as Fig. 3 (right panel), but for $\Gamma_{CR} = 0.003\ yr^{-1}$.

$n - \tau$ plane : Larger size (30 pc)

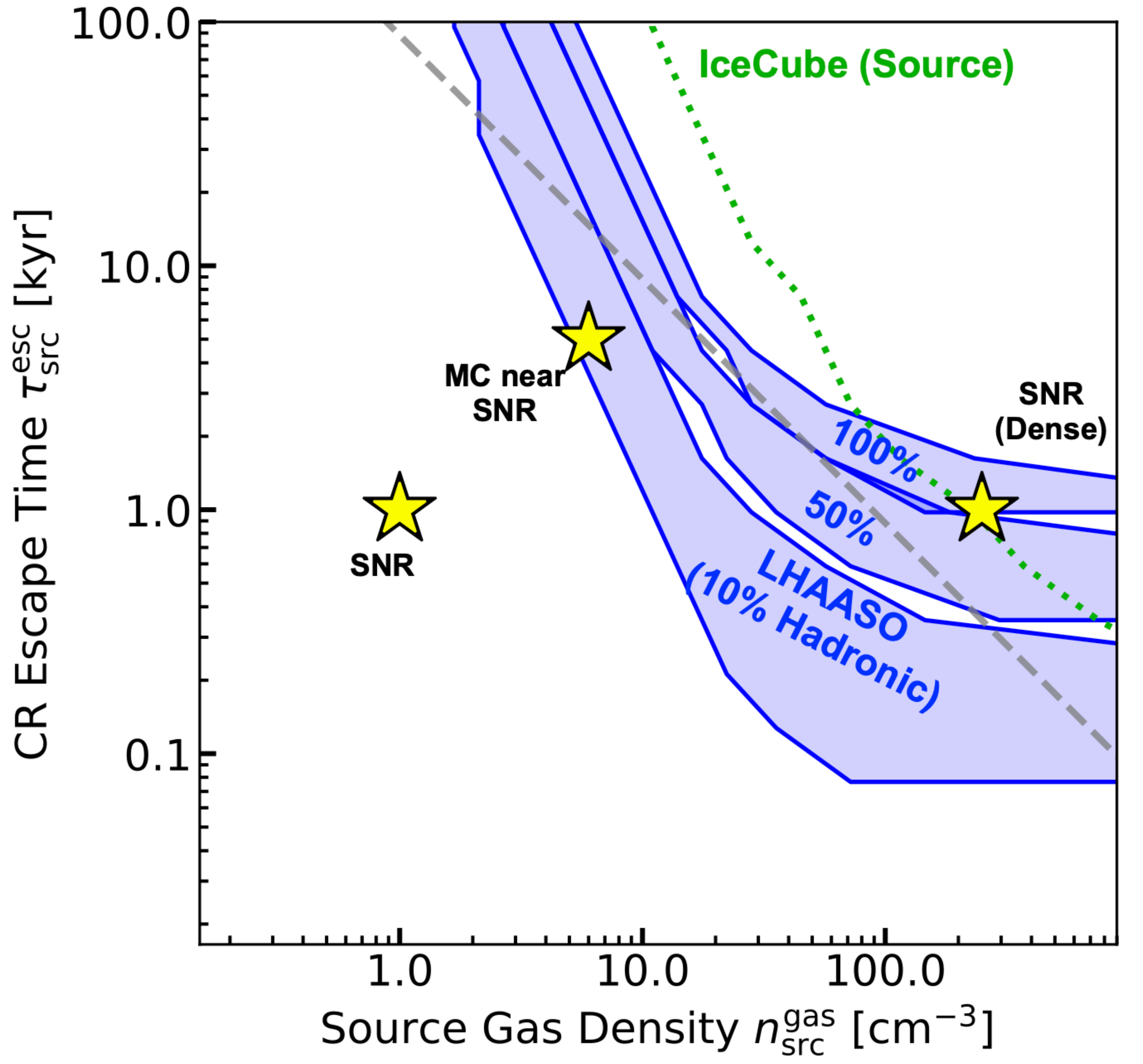


FIG. 10. Same as Fig. 3 (right panel), but for $R_{src} = 30$ pc.

$n - \tau$ plane : Steady source

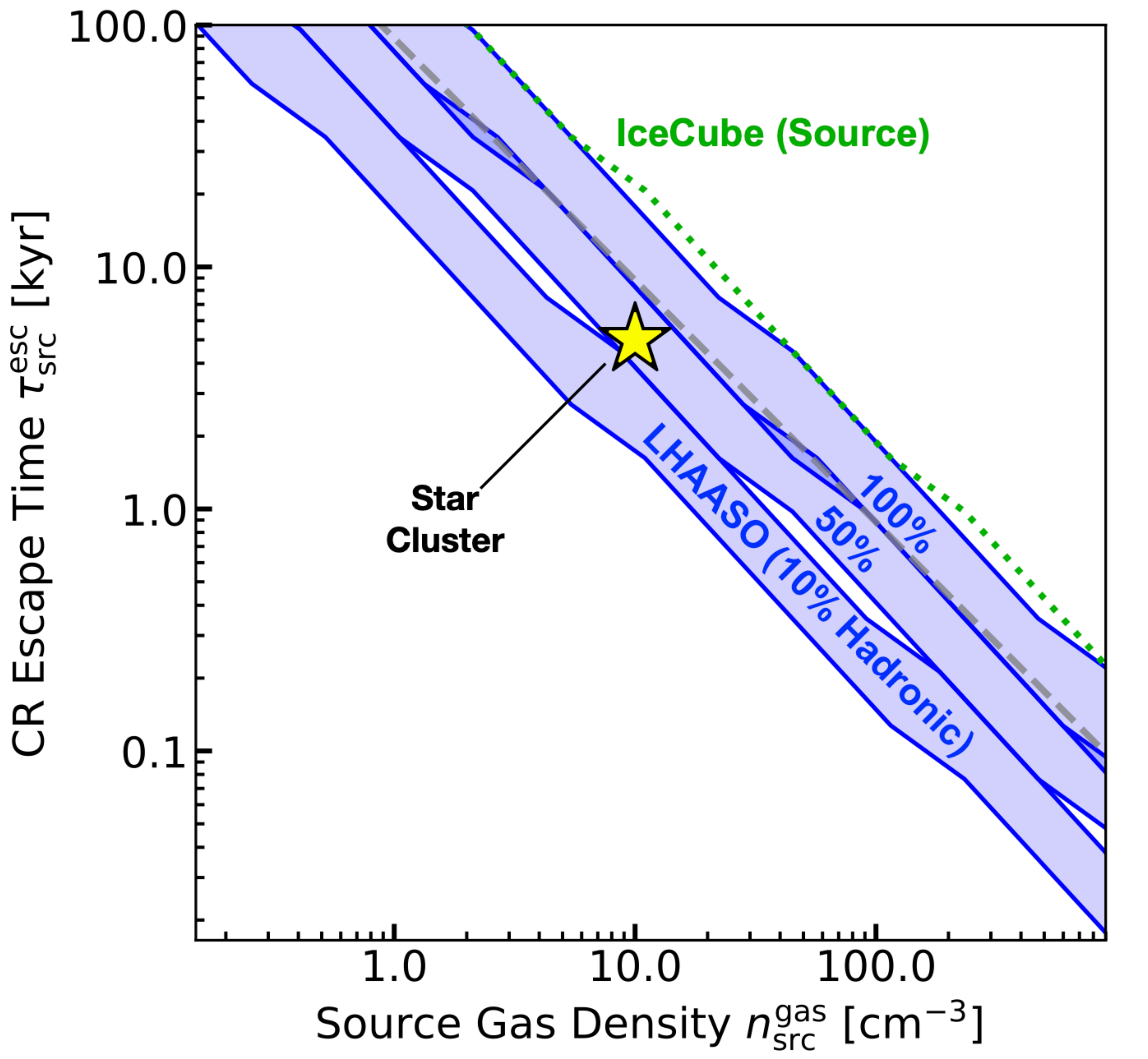


FIG. 11. Same as Fig. 3 (right panel), but for the case of continuous CR injection with $\mathcal{N}_{\rm CR} = 10^2$ and $R_{\rm src} = 30$ pc.

$n - \tau$ plane : Models

1. **SNR**: The most plausible candidate for the source of PeV hadrons are SNRs. Indeed, both GeV and TeV data support the scenario where SNRs accelerate protons to TeV scales [158–161], although it remains unknown if the maximum energy can reach the PeV range. If produced, PeV protons are expected to escape in the very early phase of the SNR evolution, $\tau_{\rm src}^{\rm esc} \sim 1$ kyr, comparable to when the Sedov-Taylor phase starts, although many details are uncertain [162–171]. Acceleration to the PeV scale might take place on timescales much shorter than kiloyears [172–176] and $\tau_{\rm src}^{\rm esc}$ includes the time particles are in the vicinity of the accelerator. This choice of $\tau_{\rm src}^{\rm esc}$ is likely optimistic, given the escape of PeV particles from the shock might be as short as $\sim$10 yrs [173] and the escape from the larger surroundings are highly uncertain. If PeV protons interact with the average gas densities in the ISM, then $n_{\rm src}^{\rm gas} \sim 1$ cm^{-3}.

2. **SNR (Dense)**: For a handful of shell-type SNRs, TeV gamma rays are spatially coincident with gas clouds, supporting a hadronic origin for the gamma rays: RX 1713.7-3946 [177–179], Vela Jr. [180], HESS J1731-347 [181], and RCW86 [182]. They are young ($\simeq$ 1–5 kyr) and have high target gas densities of $\gtrsim$10–100 cm^{-3}, although the latter significantly depends on the volume filling factor of dense gas, which is usually highly uncertain. Here, we take RX J1713.7-3946 as an example case. Multi-wavelength modeling of this SNR suggests high-density (2.5×10^4 cm^{-3}) clumps with a volume filling factor 10^{-2}, embedded in low-density gas ($\sim$ 10^{-2} cm^{-3}), for an average density of $n_{\rm src}^{\rm gas} \sim 250$ cm^{-3} in the 10-pc shell [183] (see also Ref. [144] for a detailed numerical study). The escape of PeV particles is model-dependent. Given the lack of > 10 TeV gamma-ray emission from this object, $\tau_{\rm src}^{\rm esc}$ is likely smaller than its age (1.4 kyr). If the escape time coincides with the Sedov time, it would be smaller for SNRs in dense environments (as $\propto (n_{\rm src}^{\rm gas})^{-1/3}$). The actual escape time might be even shorter, as discussed above. We optimistically take $\tau_{\rm src}^{\rm esc} = 1$ kyr , as in the previous case, but the above uncertainties should be kept in mind.

3. **MC near SNR**: Emission may be produced by CRs that escape from the accelerators and diffuse around them, interacting with a massive gas cloud or clouds. The duration is determined by the local propagation of CRs. As a reference, we consider a molecular cloud with a mass of $M_{\rm cl} = 10^5\ M_\odot$ and a size of $R_{\rm cl} = 20$ pc at

a distance of $d_{\rm cl} = 50$ pc from an SNR. With a diffusion coefficient of $D = 10^{29}$ cm^2 s^{-1} at 1 PeV (ten times smaller than the ISM average), the diffusion time is $\tau_{\rm src}^{\rm esc} \sim (d_{\rm cl})^2/D \sim 5$ kyr. (Note that the use of an isotropic diffusion coefficient can be a crude approximation close to the source; more work is needed to theoretically evaluate the propagation of PeV particles in the source vicinity.) The gas density of this MC is very high, $\simeq$ 100 cm^{-3}, but the volume filling fraction of this is $\sim (R_{\rm cl}/d_{\rm cl})^3 \sim 0.06$, resulting in a modest value of $n_{\rm src}^{\rm gas} \sim 6$ cm^{-3}.