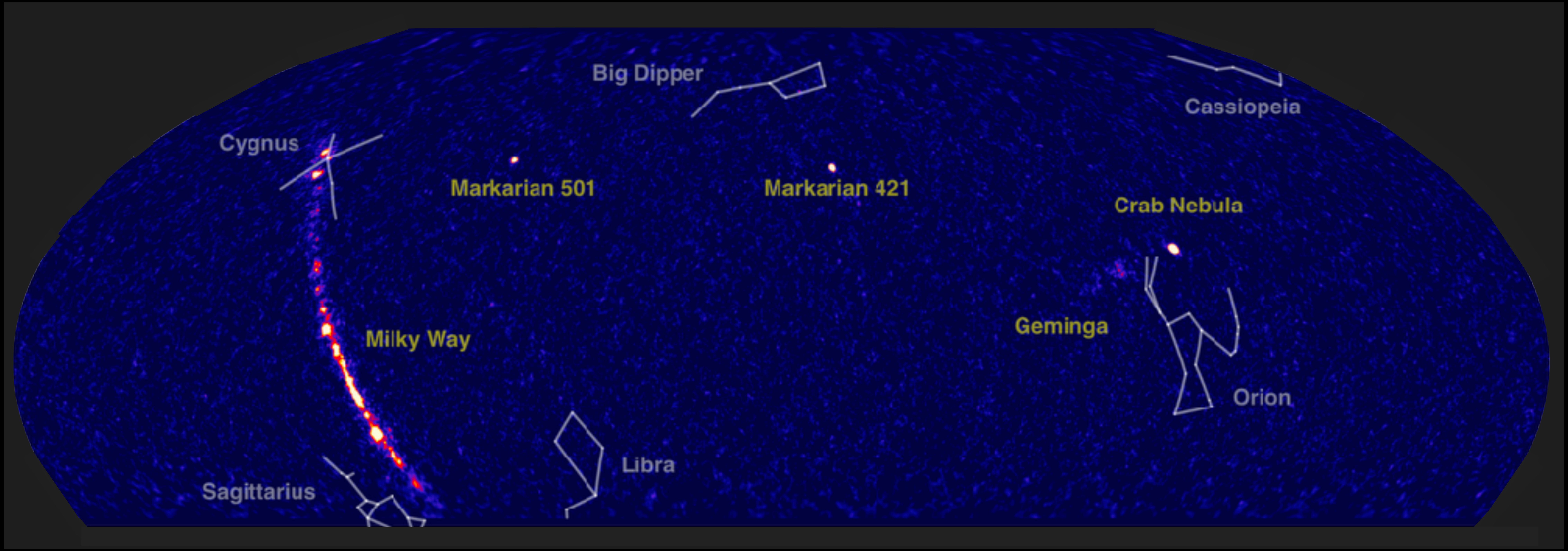
Where are the Galactic "PeVatrons"?



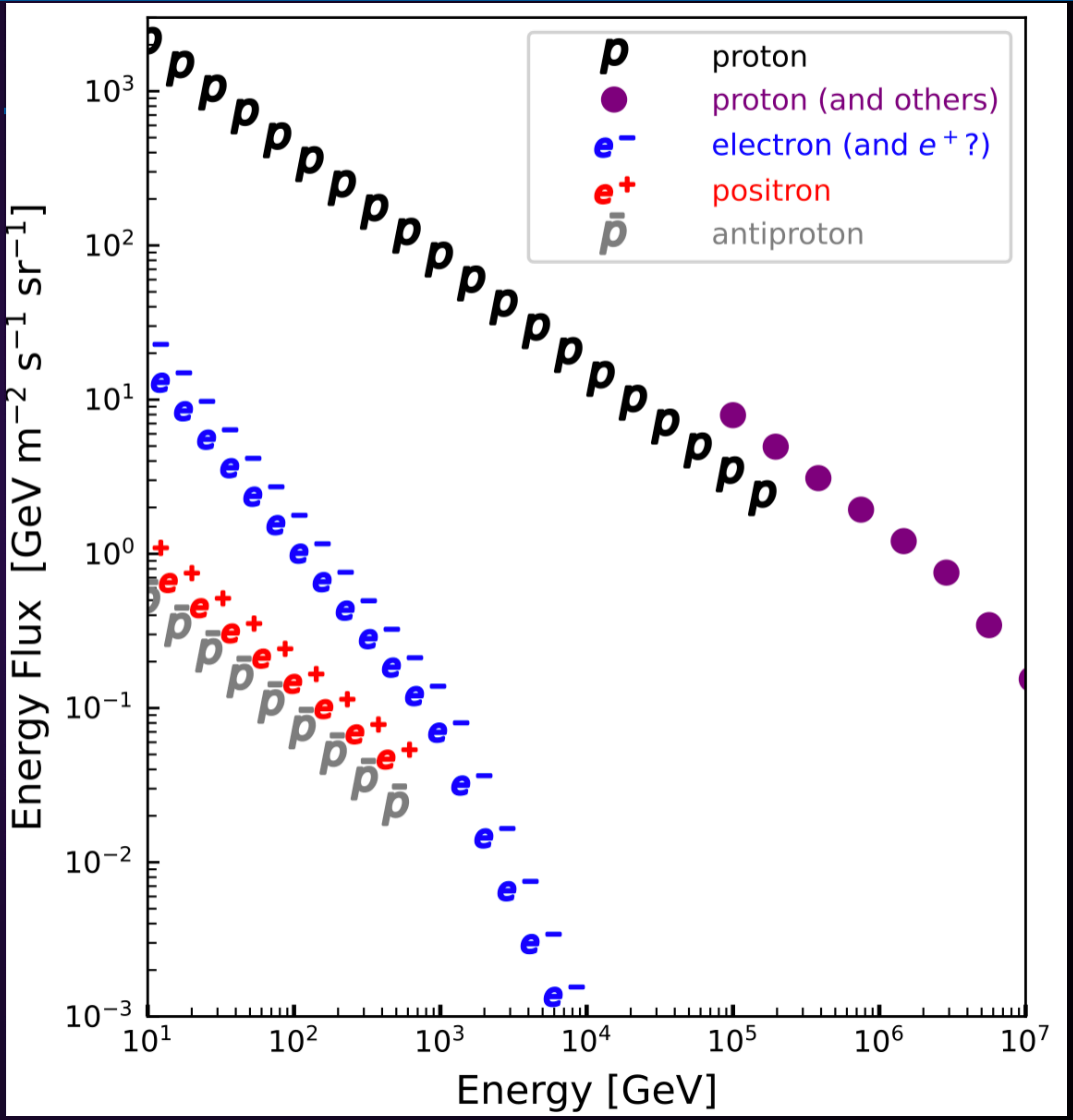
Takahiro Sudoh (須藤 貴弘)

Ohio State University
JSPS Overseas Fellow

Milky Way’s High-Energy Sources

Cosmic rays

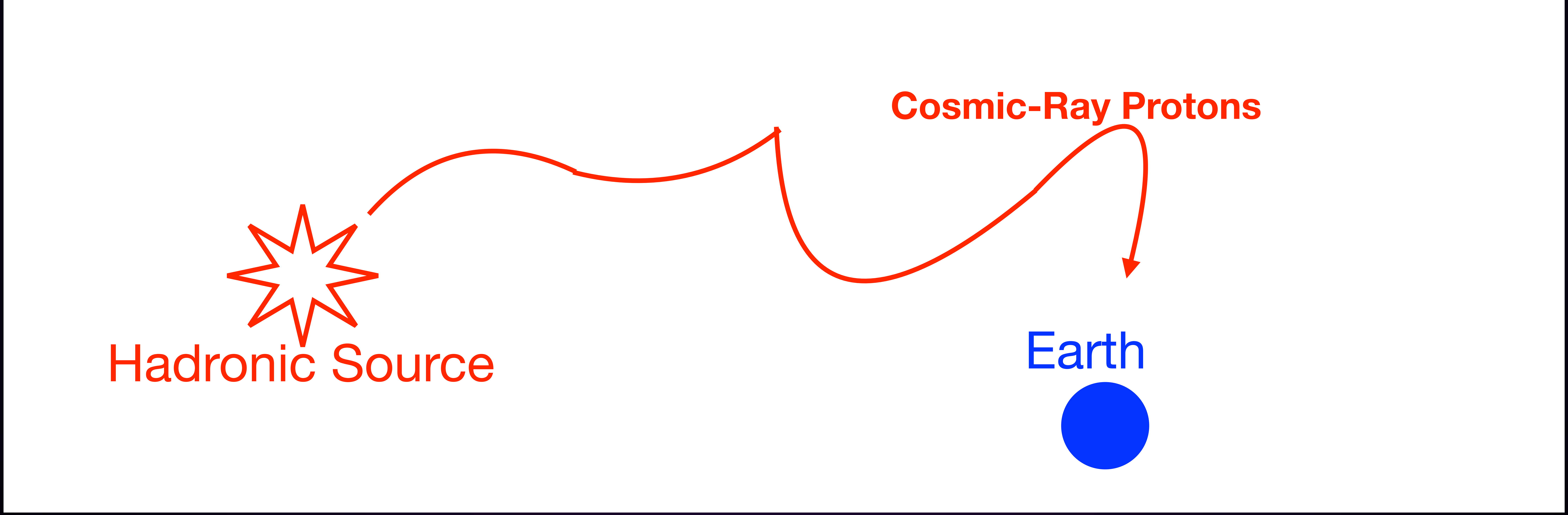
- High energy particles from the sky
- Believed to be from Milky Way's sources up to PeV (10^{15} eV)
- Many source classes seem to accelerate GeV - TeV hadrons
- Mysterious : which ones can reach PeV energies ("hadronic PeVatrons")



Note : Compiled and overly simplified for visualization!

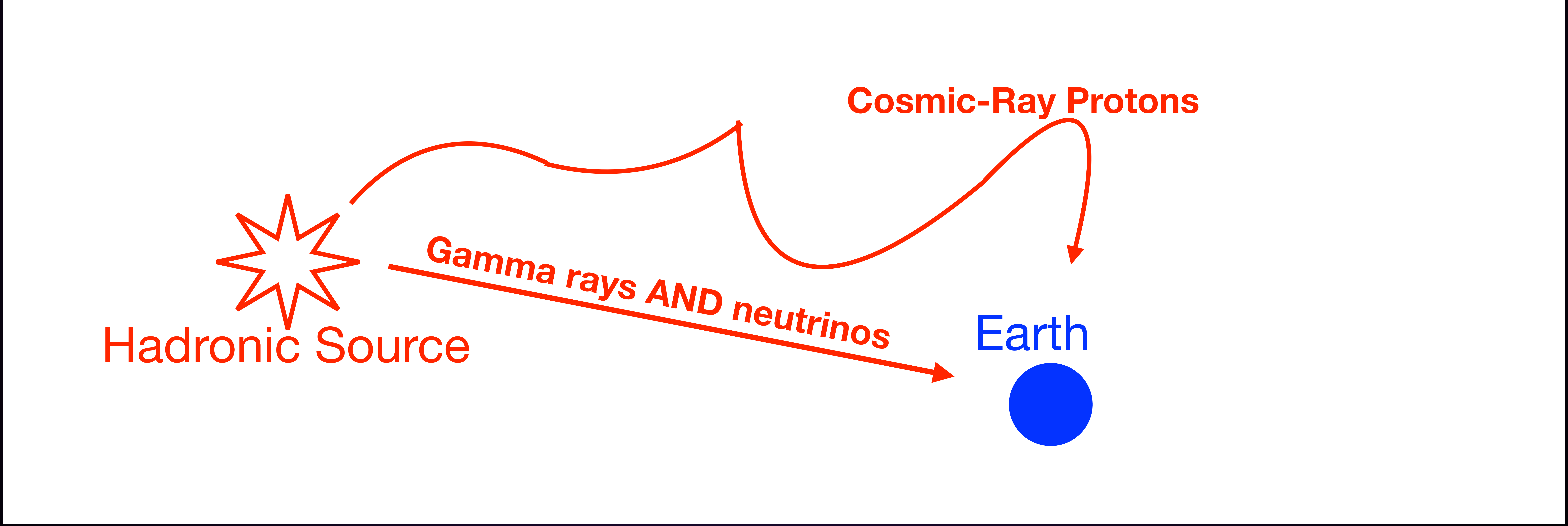
Identify cosmic PeVatrons

- Magnetic fields change the direction of particles

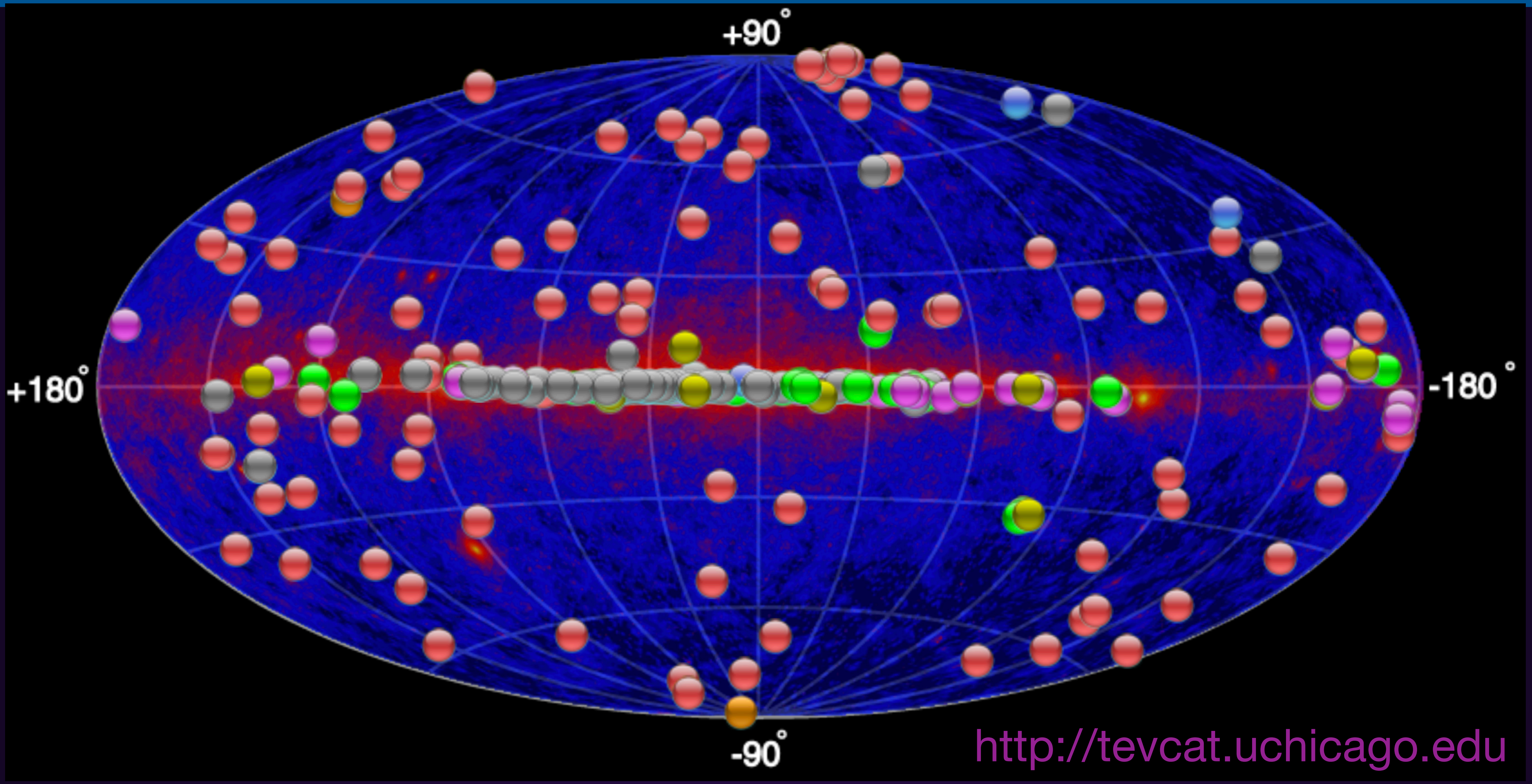


Identify cosmic PeVatrons

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

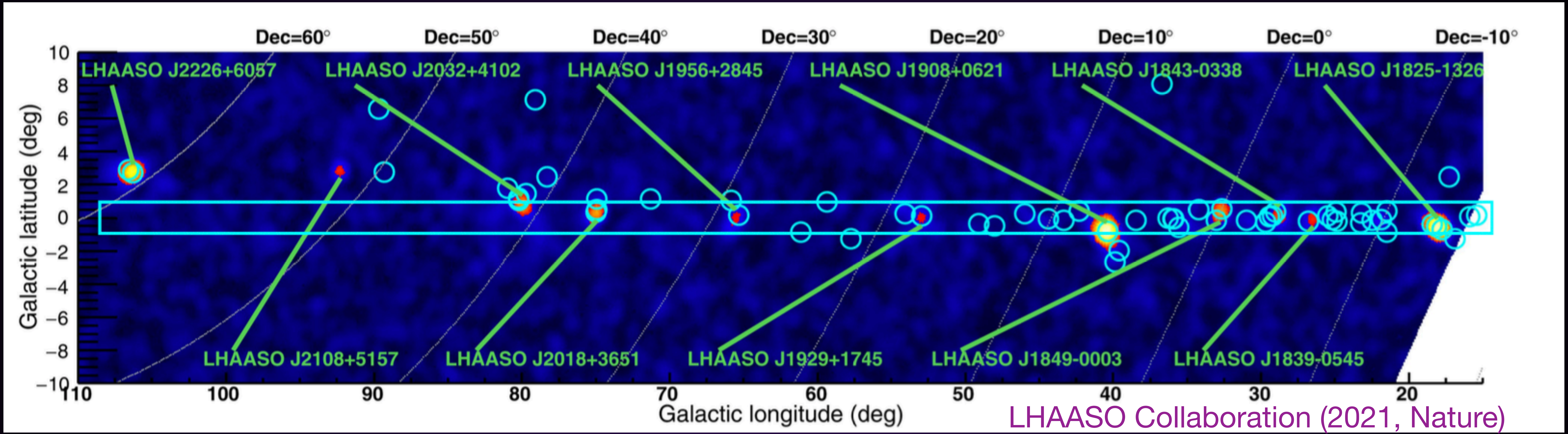


Gamma-ray sources at TeV energies



- HESS, MAGIC, VERITAS have detected more than a hundred sources in TeV gamma rays.
- Hadronic PeVatrons would produce gamma rays and neutrino with energies of $\sim$ 100 TeV

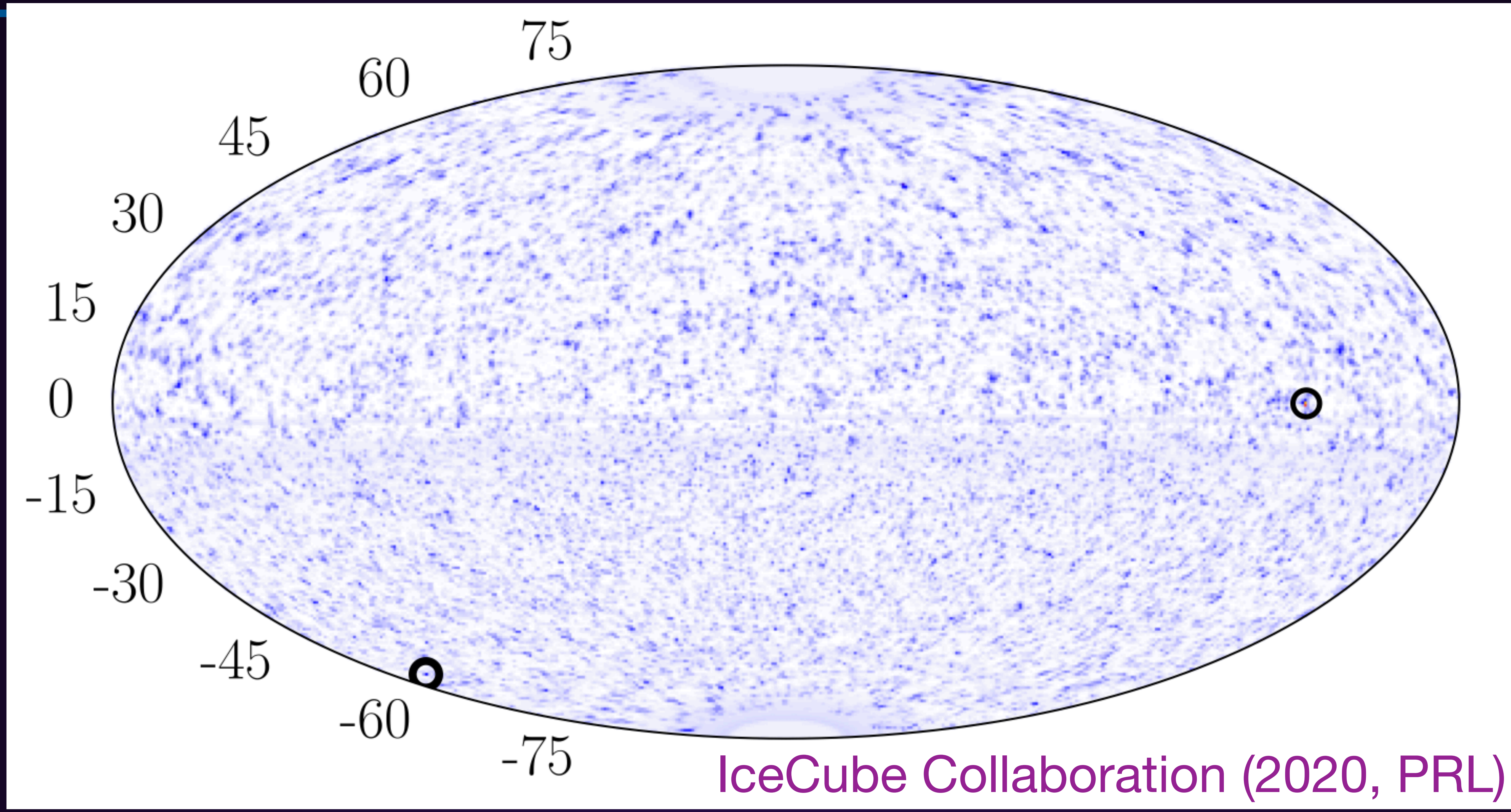
Gamma-ray sources beyond 100 TeV



LHAASO Collaboration (2021, Nature)

- And observations are now reaching such high energies!
- Tibet ASγ, HAWC, and LHAASO have detected photons above 100 TeV, some of which reaching a PeV.
- Are they hadronic PeVatrons?

Neutrino sources at TeV energies

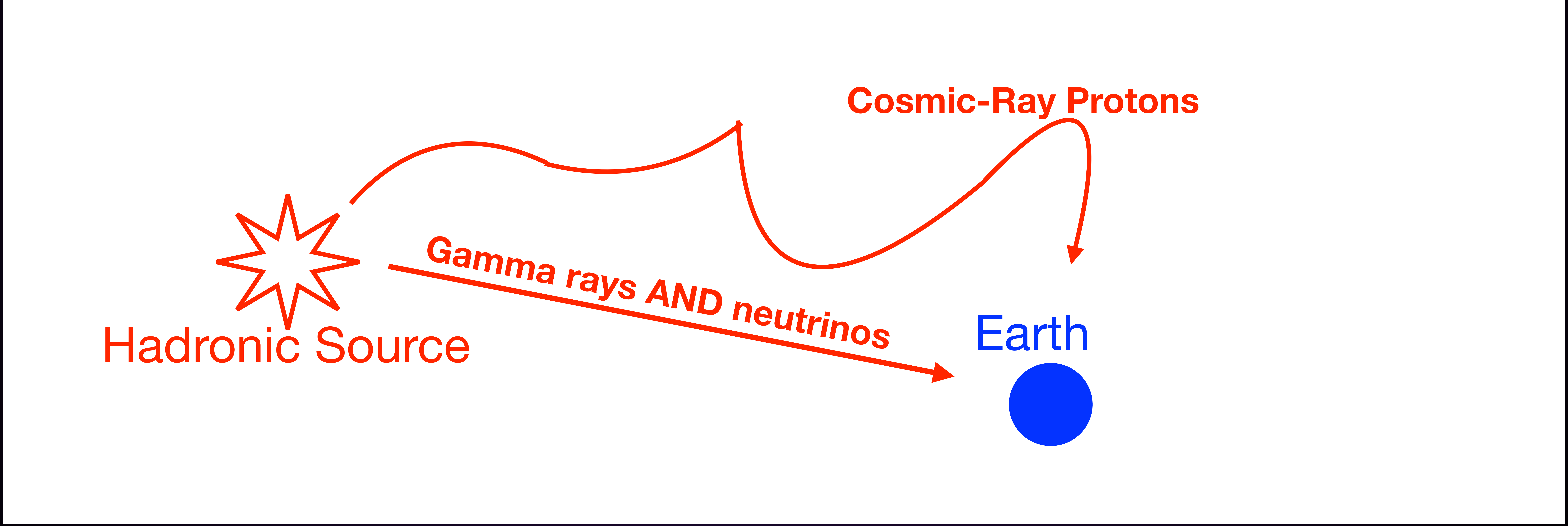


- No Galactic neutrino sources are found by a decade of IceCube searches
- Just a lack of sensitivity?
- Or … PeVatrons are thin and particles escape without interacting gases (= little gamma rays and neutrinos)?

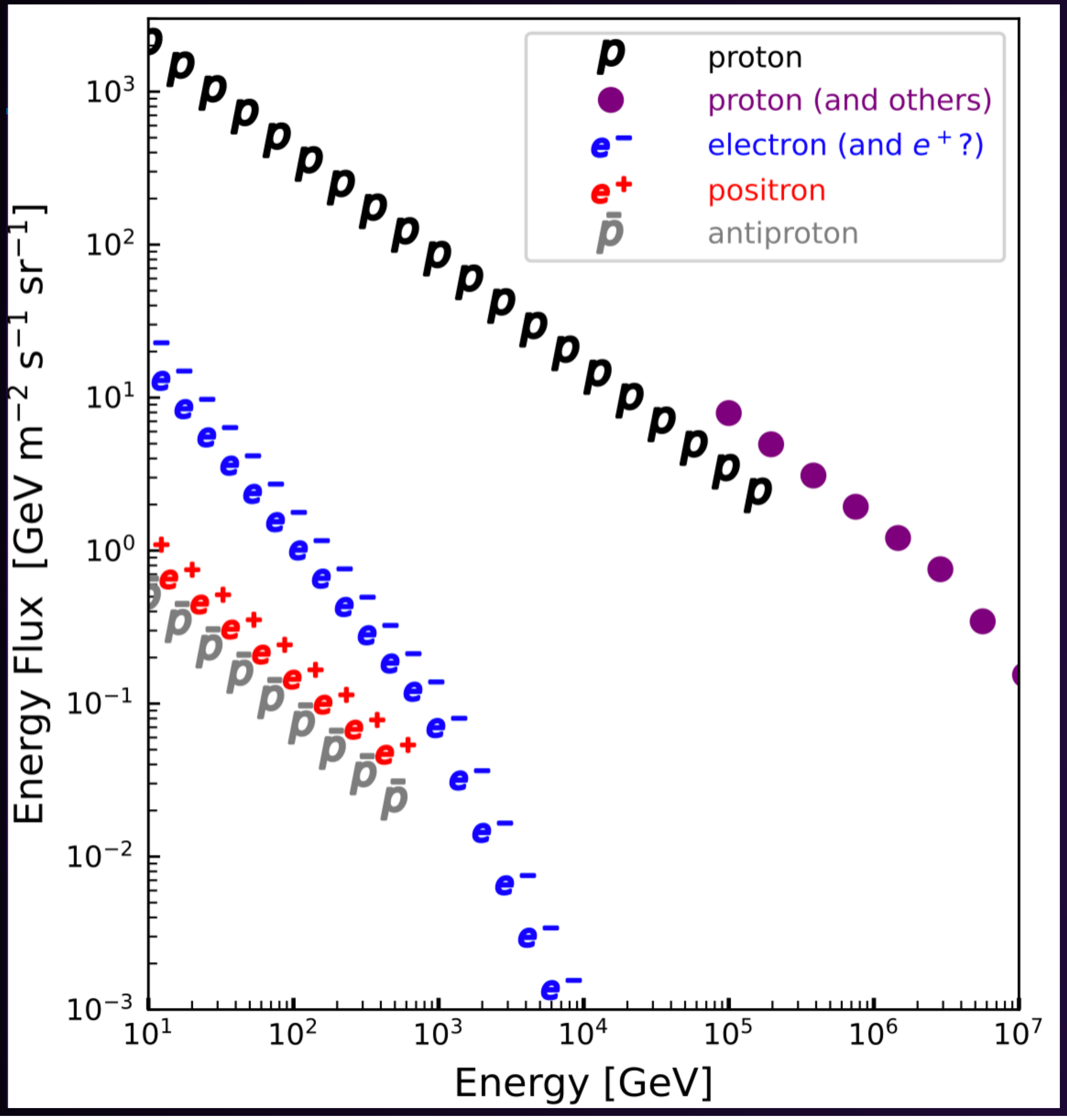
Identify cosmic PeVatrons

- Collision between protons and gases produce gamma rays and neutrinos

- Emission is the key to identity the Milky Way's "PeVatron".

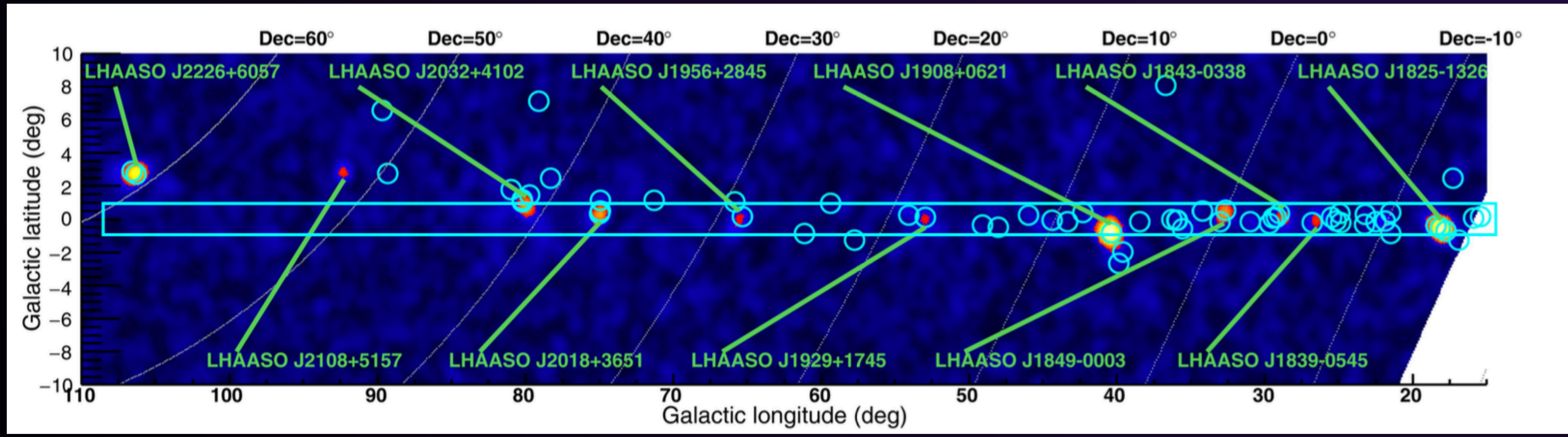


Connection between CR - gamma - nu ?



- Bright diffuse hadronic cosmic rays (CR) beyond 1 PeV

How to consistently understand CR, gamma rays, and neutrinos?

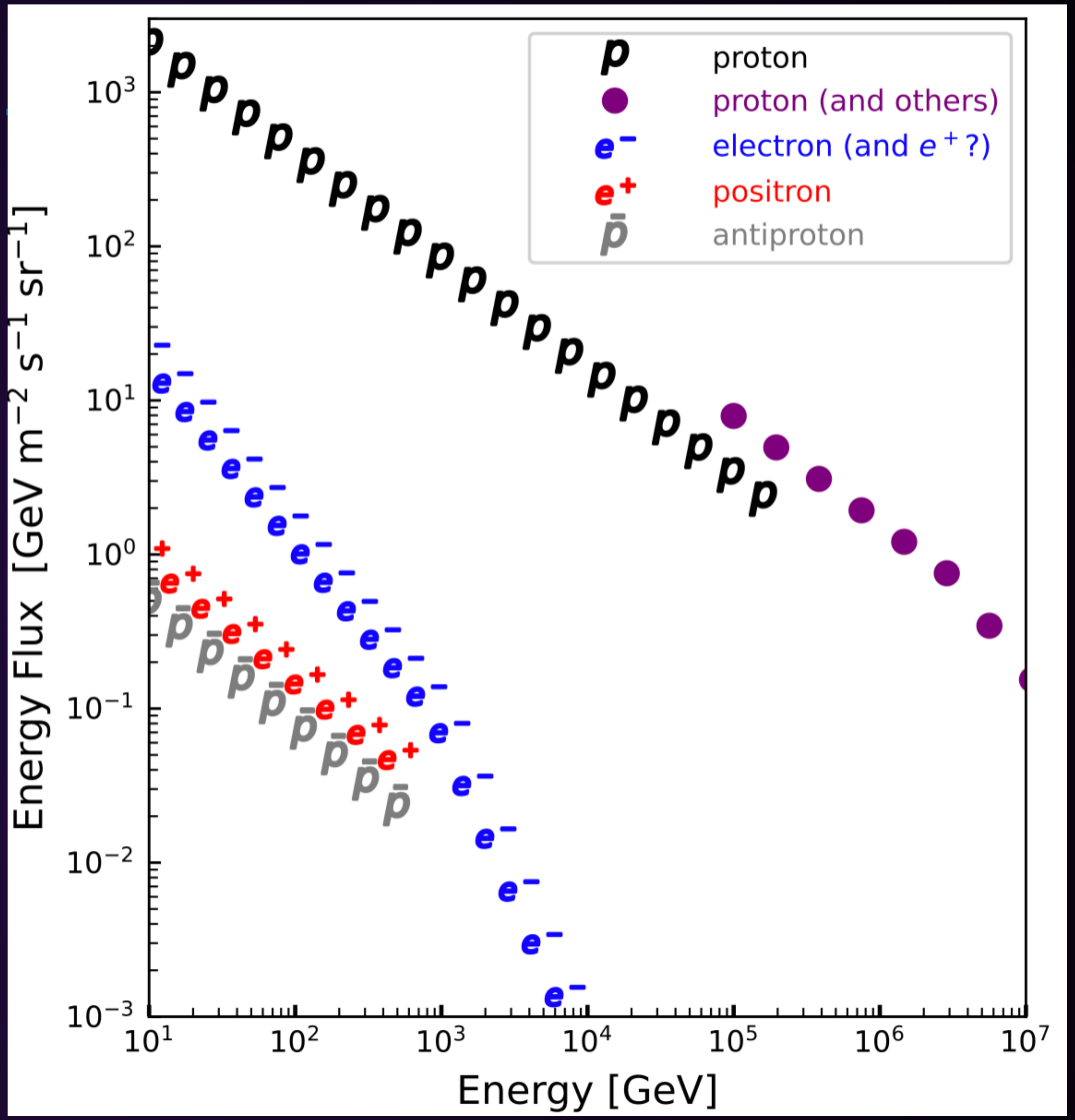


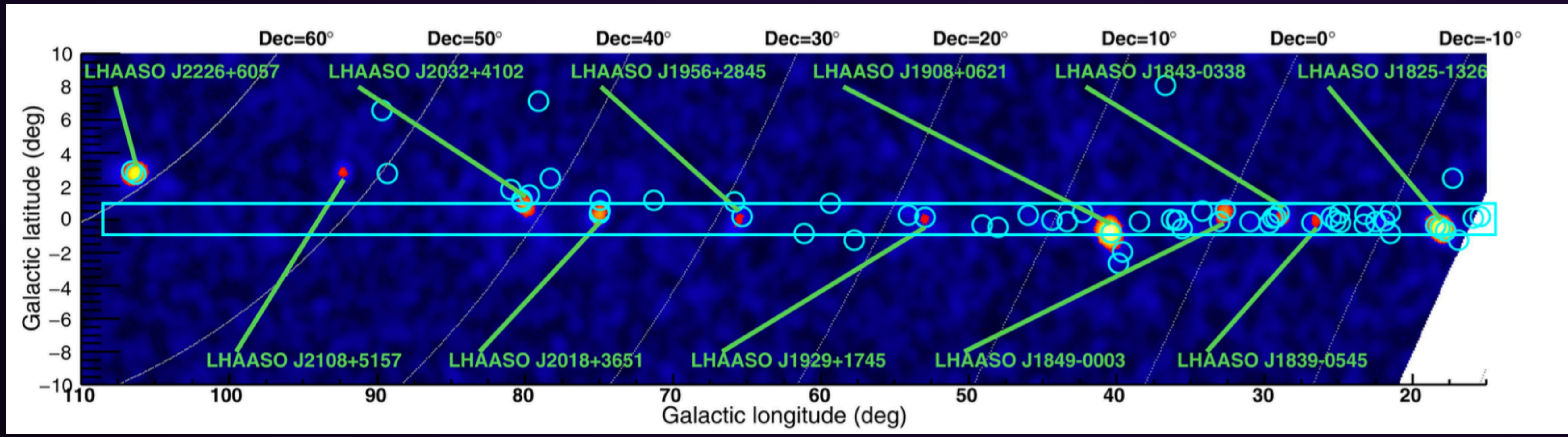
- Gamma-ray sources above 100 TeV (but no neutrinos!)

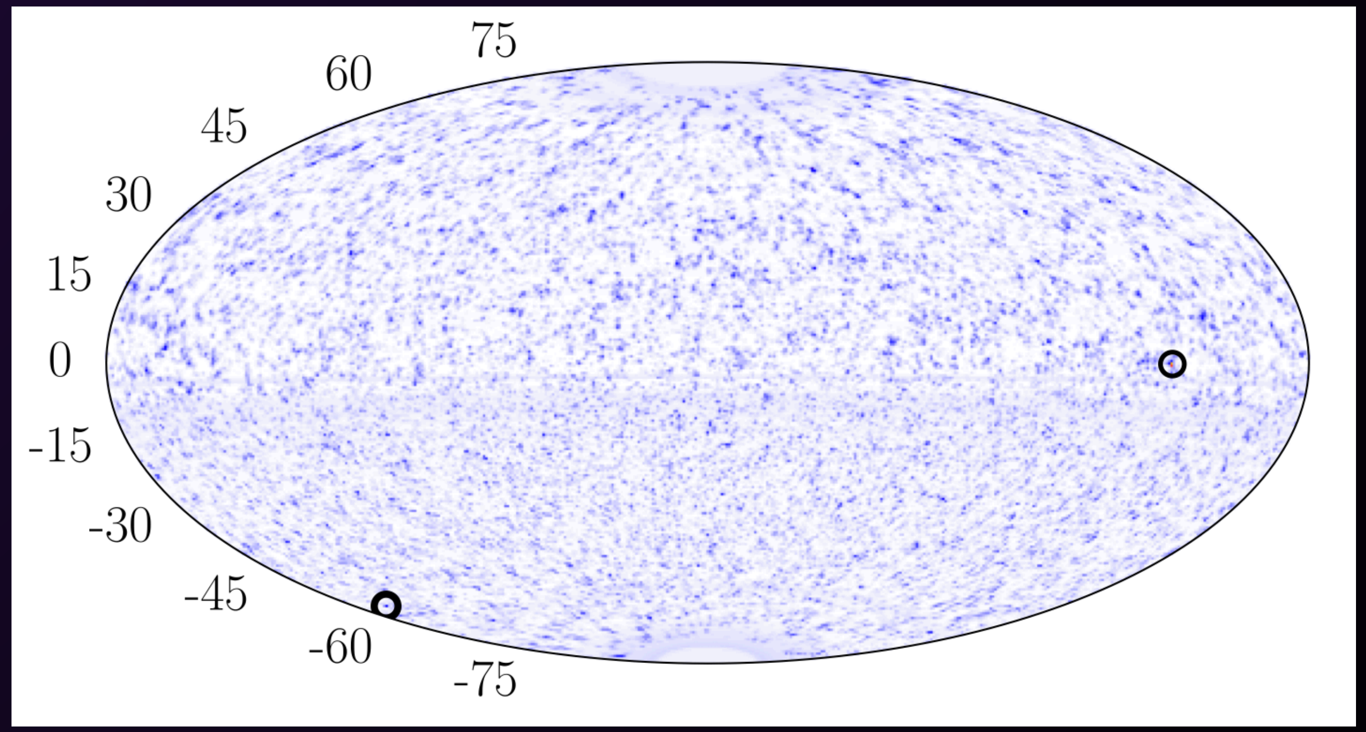
Understanding High-Energy Multi-Messengers

Understanding Multi Messengers

- **Goal :** Consistent understanding of
  - Hadronic diffuse CR flux
  - Gamma-ray sources (+ diffuse emission)
  - Neutrino non-detection (+ diffuse emission)







Cosmic-ray Sources

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

- Boron to Carbon data

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

- **Event Rate** Γ_{CR}

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

Gamma-ray and neutrino sources

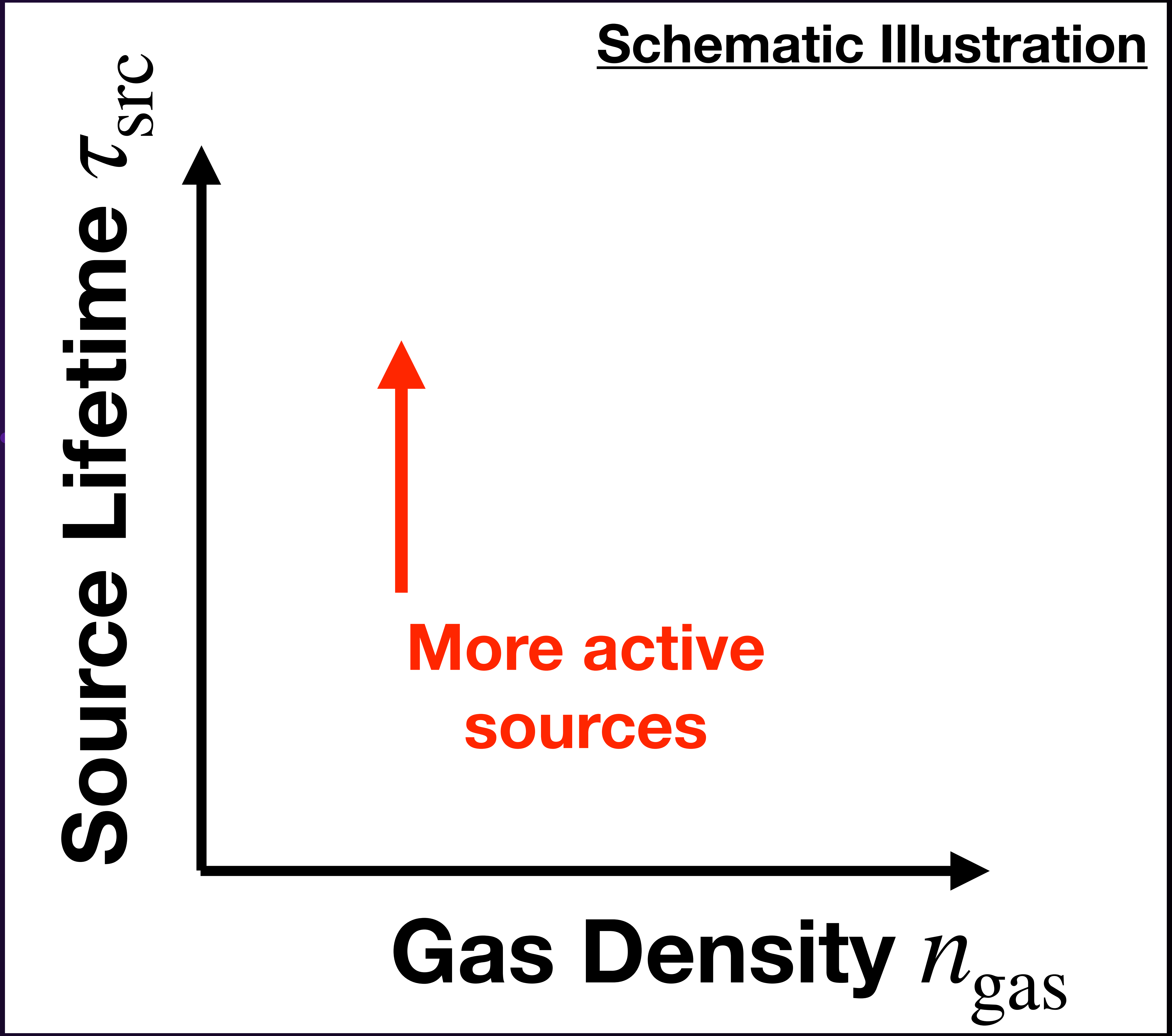
- CR energy per source $\mathscr{E}_{\rm CR}$: Calculated from the CR data (previous slide).
- Properties as gamma-ray and neutrino sources :
  - Luminosities : $\mathscr{E}_{\rm CR}/\tau_{pp}$
    - $\tau_{pp} \sim (n_{\rm gas}\sigma_{pp}c)^{-1}$ is the energy-loss time of protons via collisions with ambient gases, which produce gamma rays and neutrinos
  - Duration of emission : $\tau_{\rm src}$

Gas density around/in the source

Lifetime as a source (≃ particle confinement timescale)

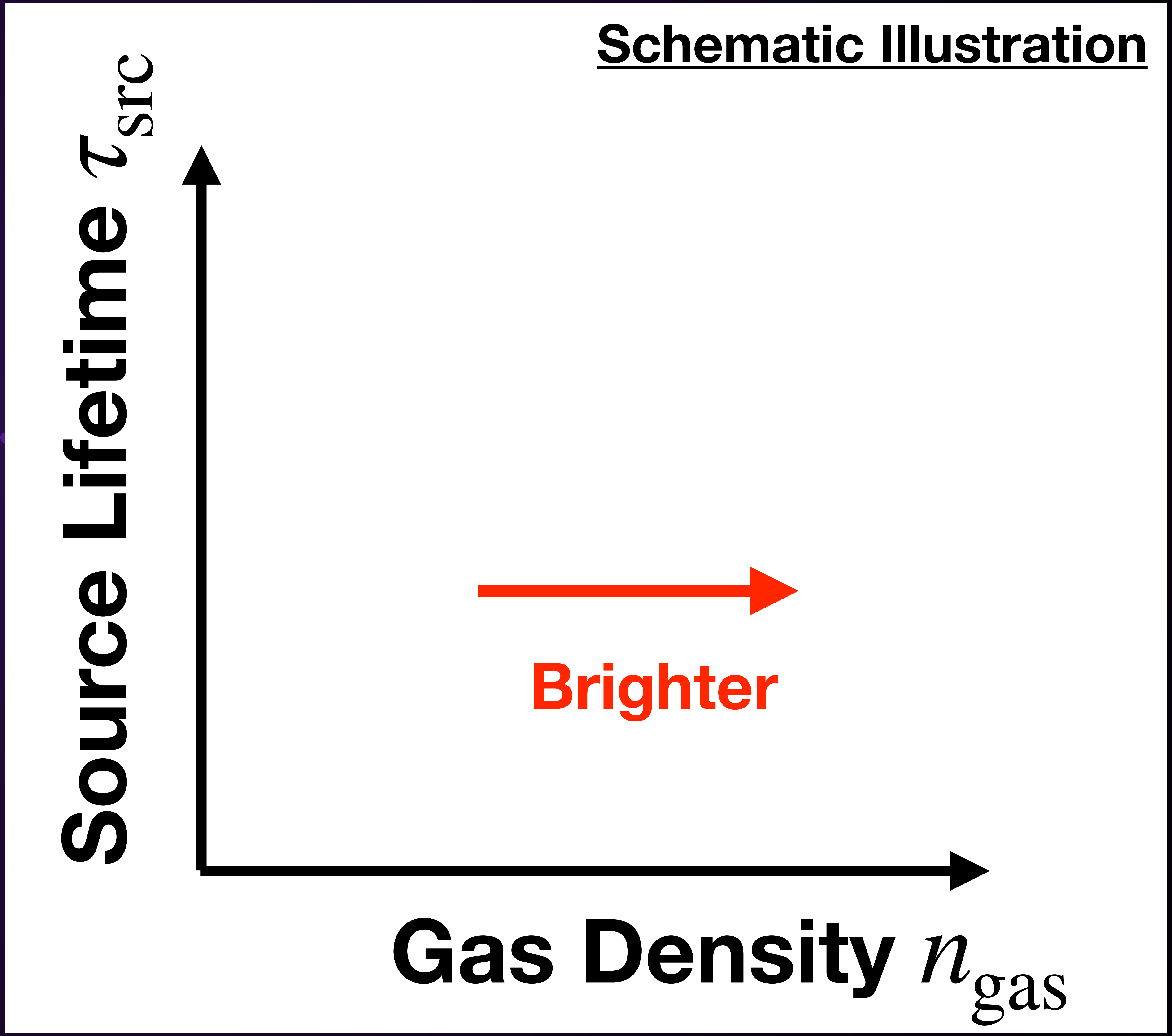
Introducing "n-tau" plane

- Two key parameter : n_{gas} and τ_{src}



Introducing “n-tau” plane

- Two key parameter : $n_{\rm gas}$ and $\tau_{\rm src}$



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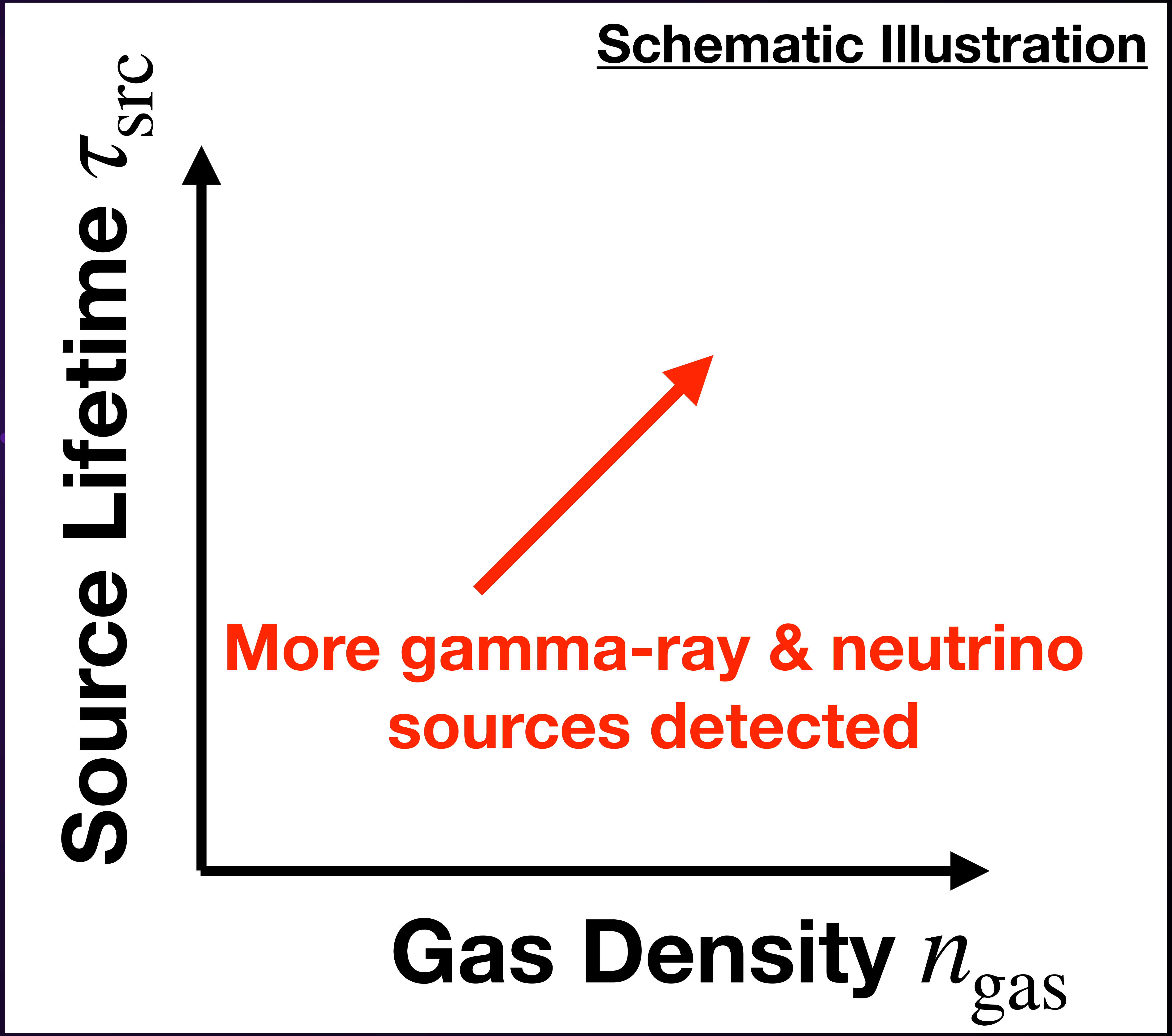
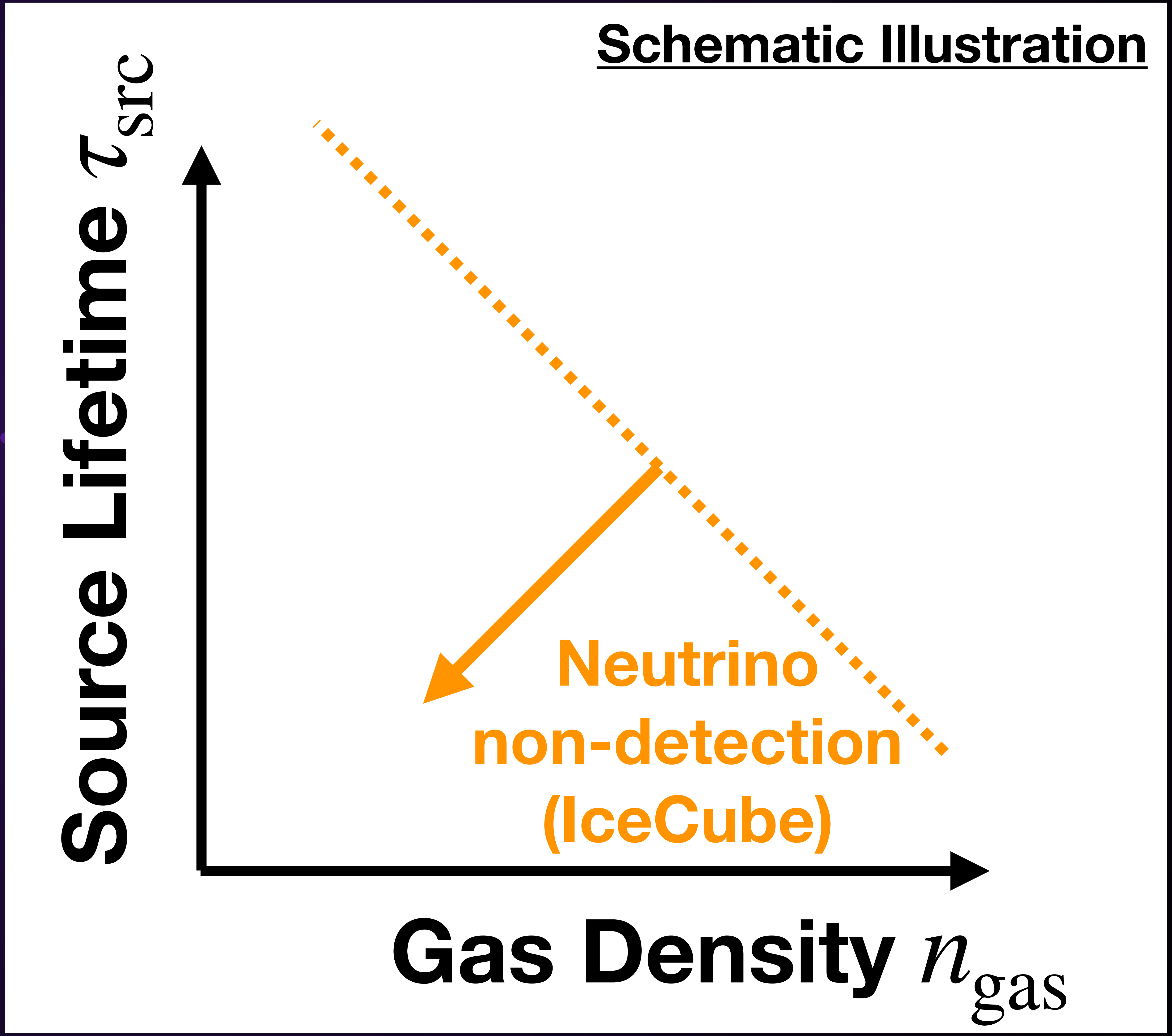


Introducing "n-tau" plane

- Upper limit from neutrino non-detection



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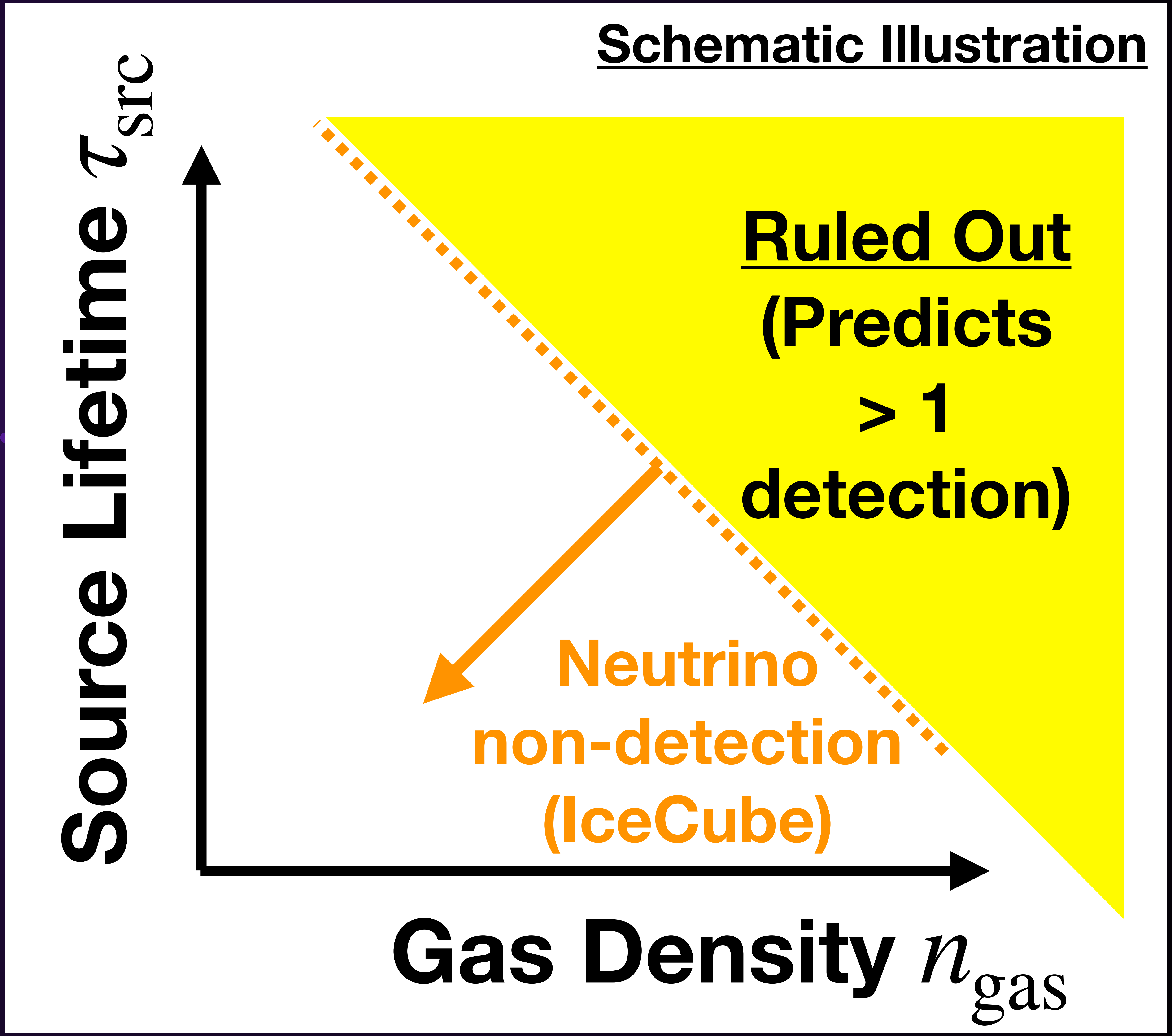

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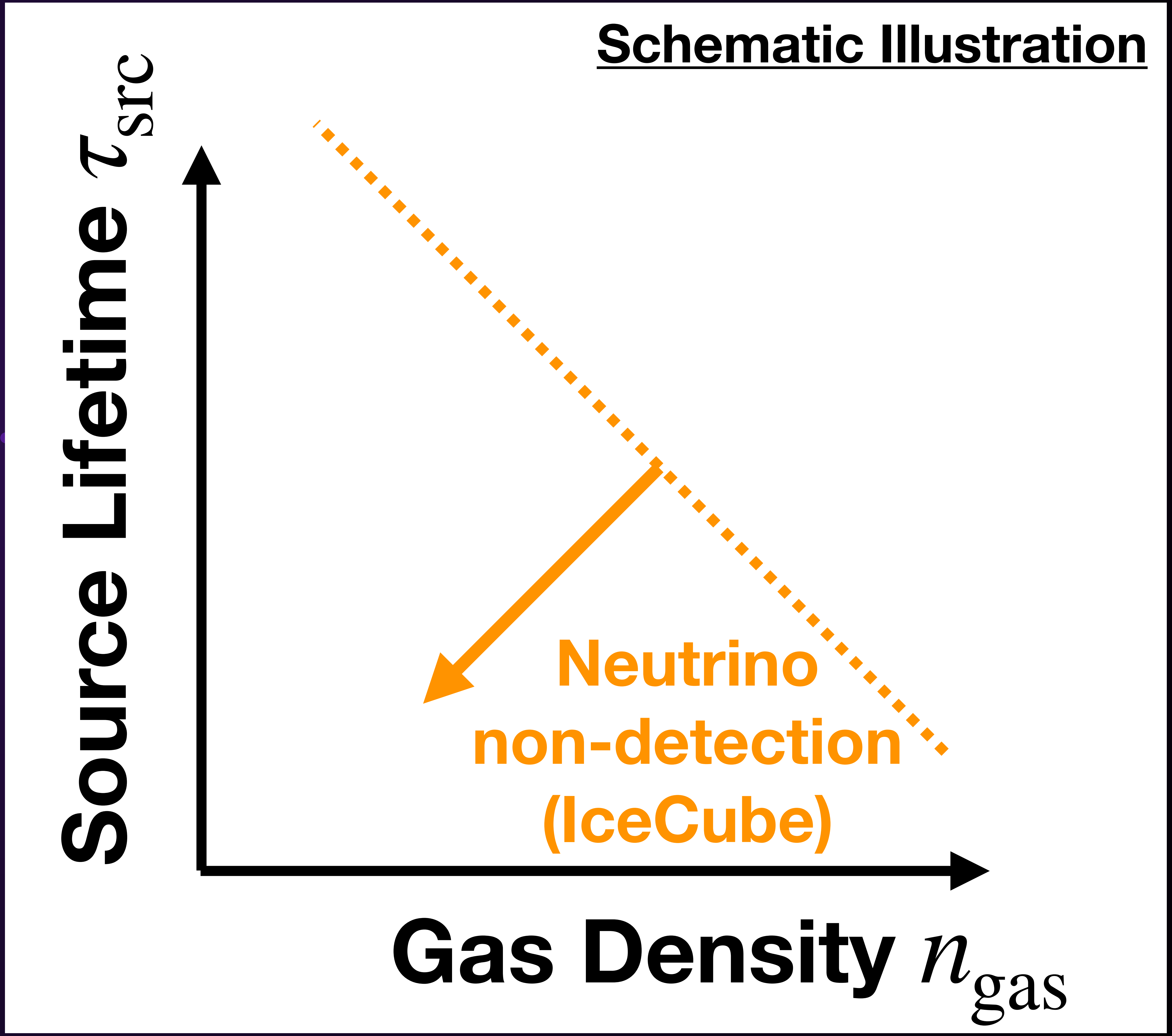
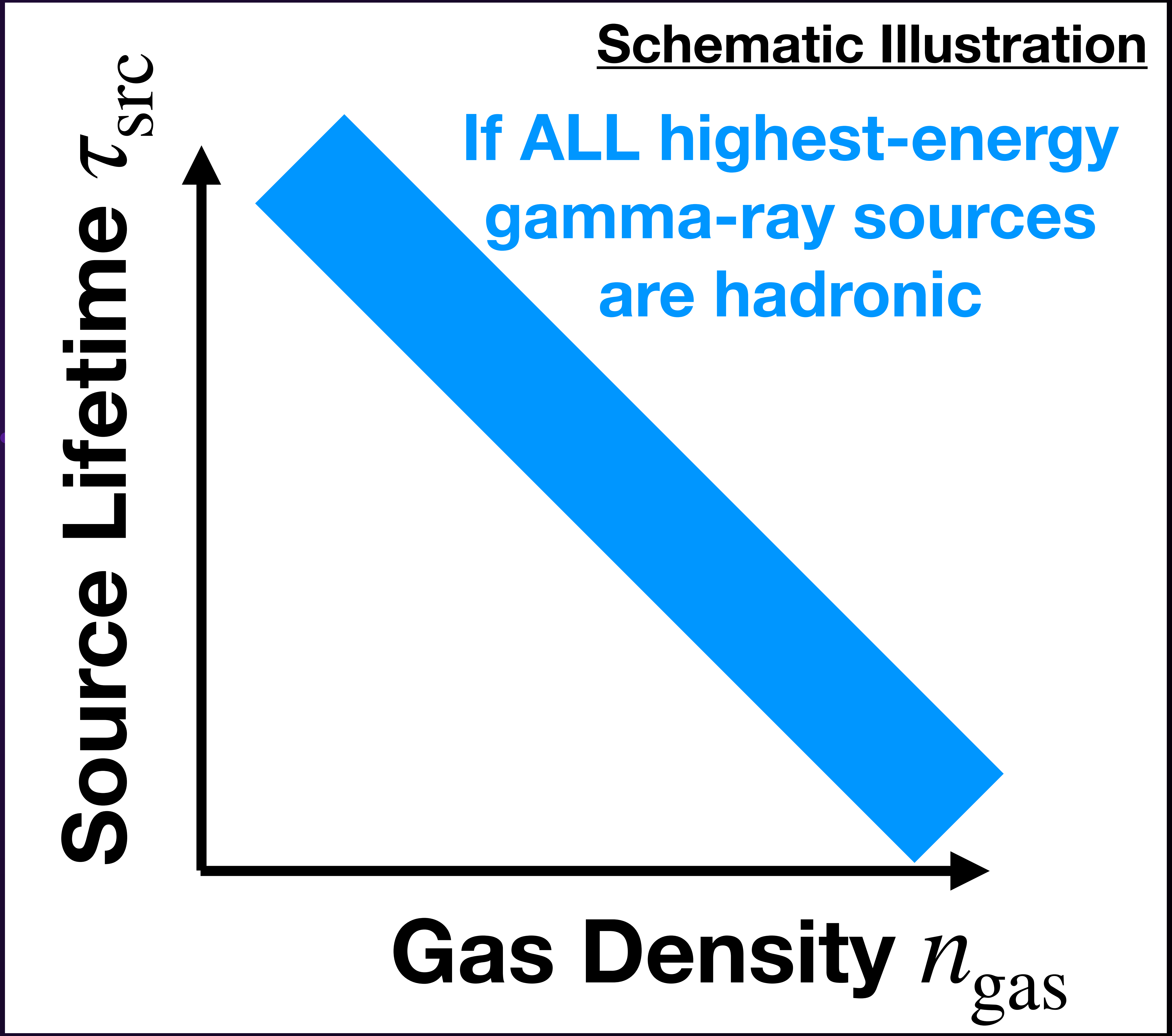


Introducing "n-tau" plane

- LHAASO detected 12 sources above 100 TeV ("highest-energy gamma-ray sources")
- We do not know how many of them are hadronic PeVatrons
- If ALL of them are hadronic, then {n, tau} should be in the blue region



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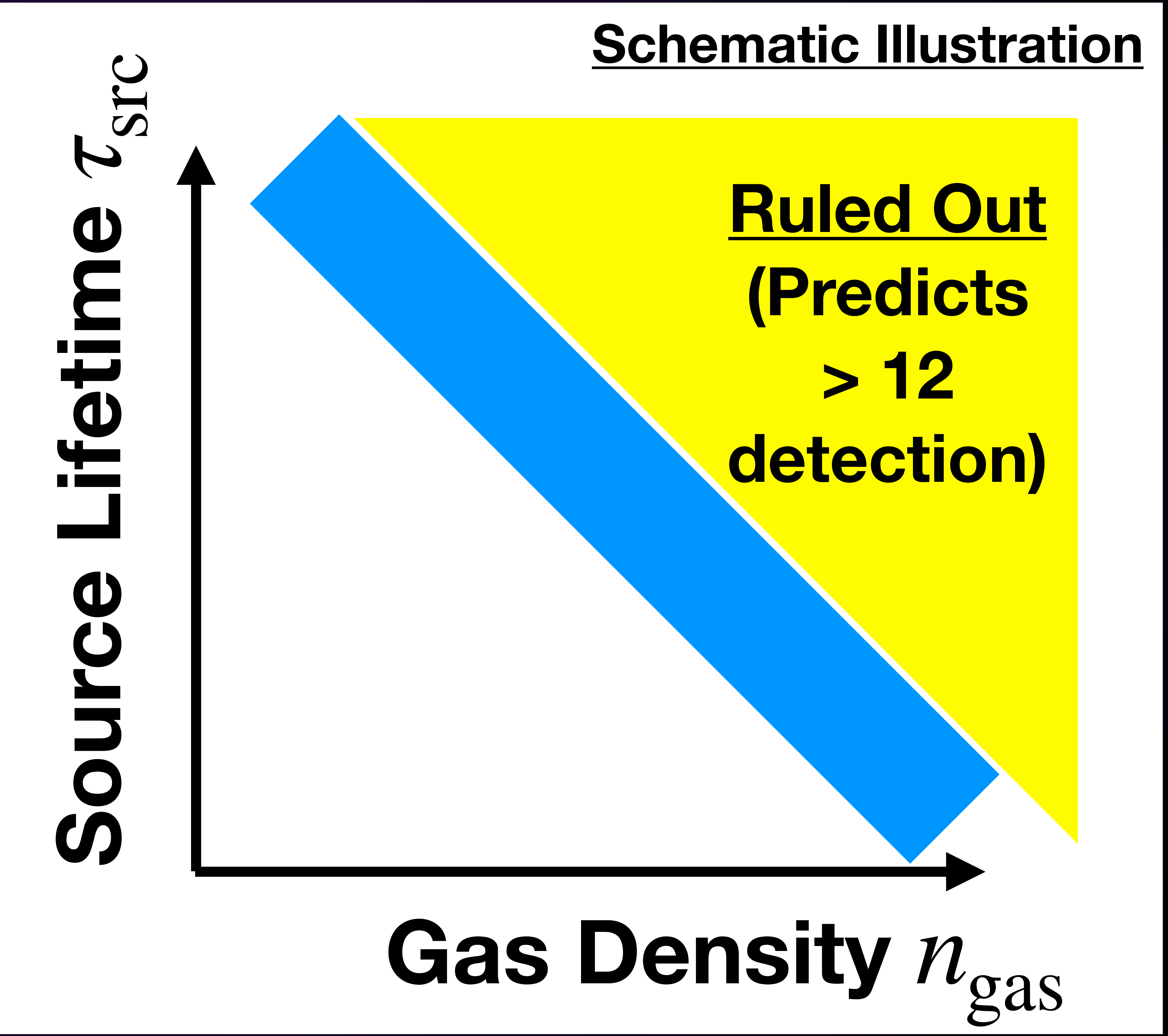

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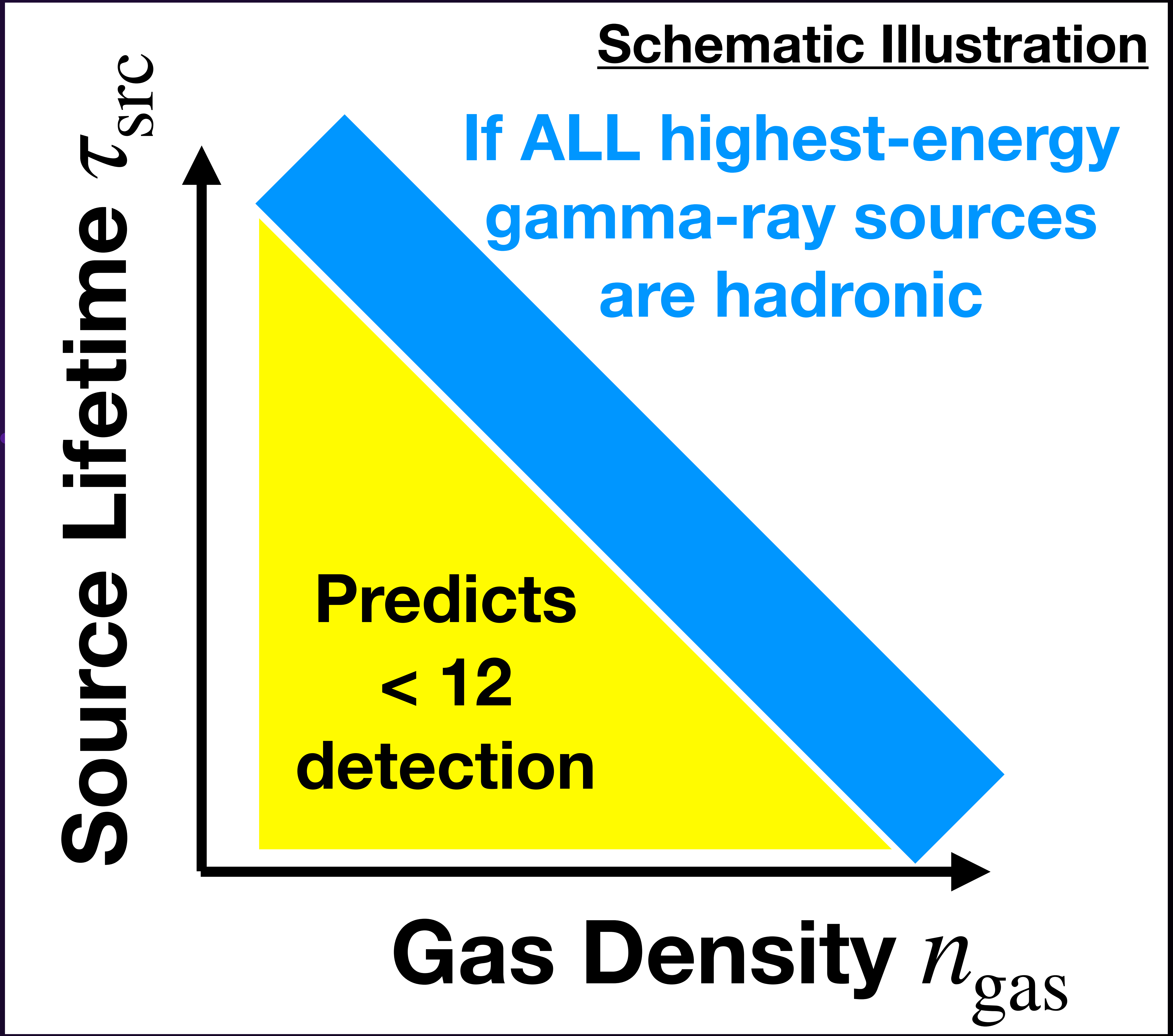
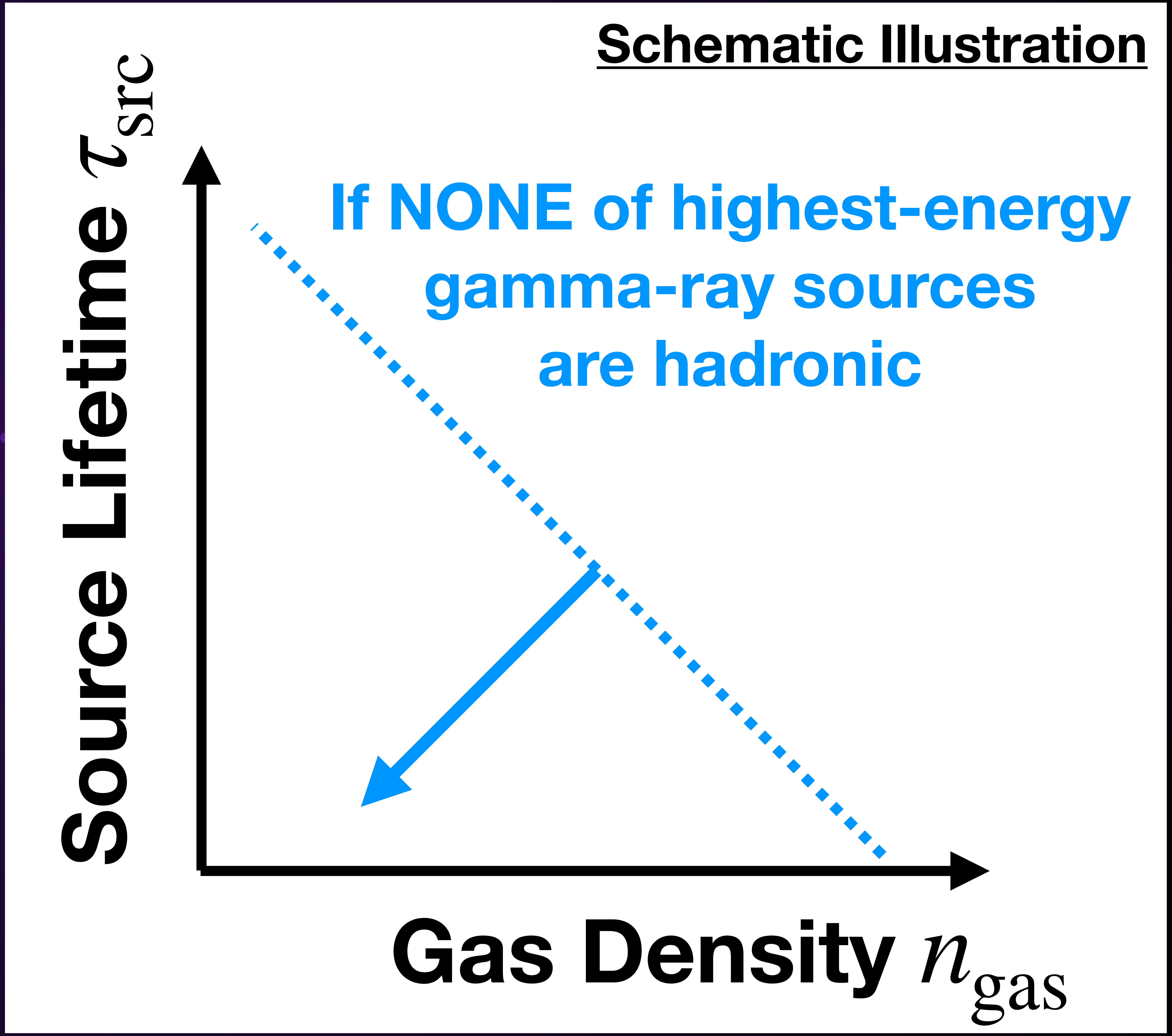


Introducing “n-tau” plane

- LHAASO detected 12 sources above 100 TeV
- If NONE are hadronic, {n, tau} should be below the line



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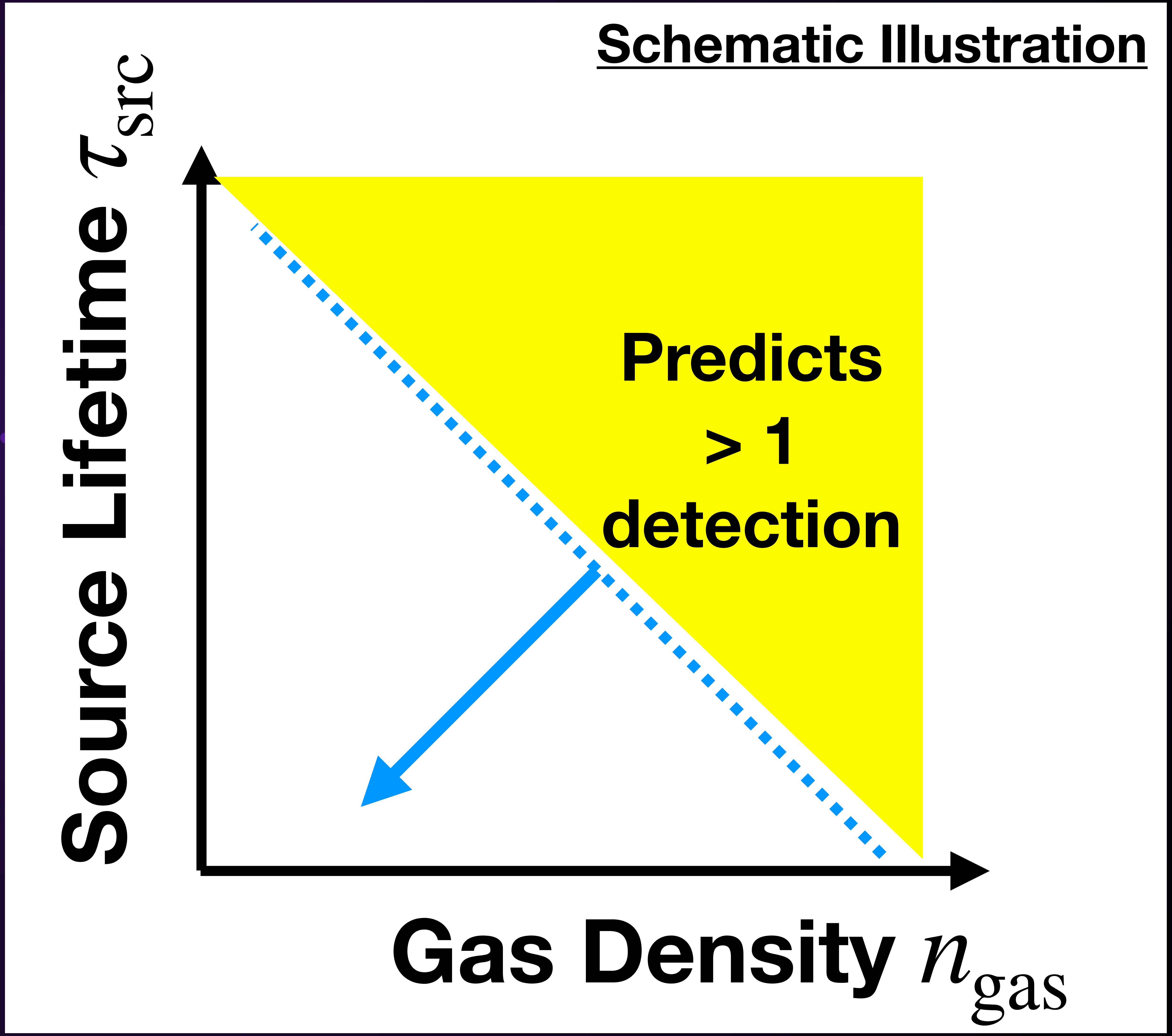
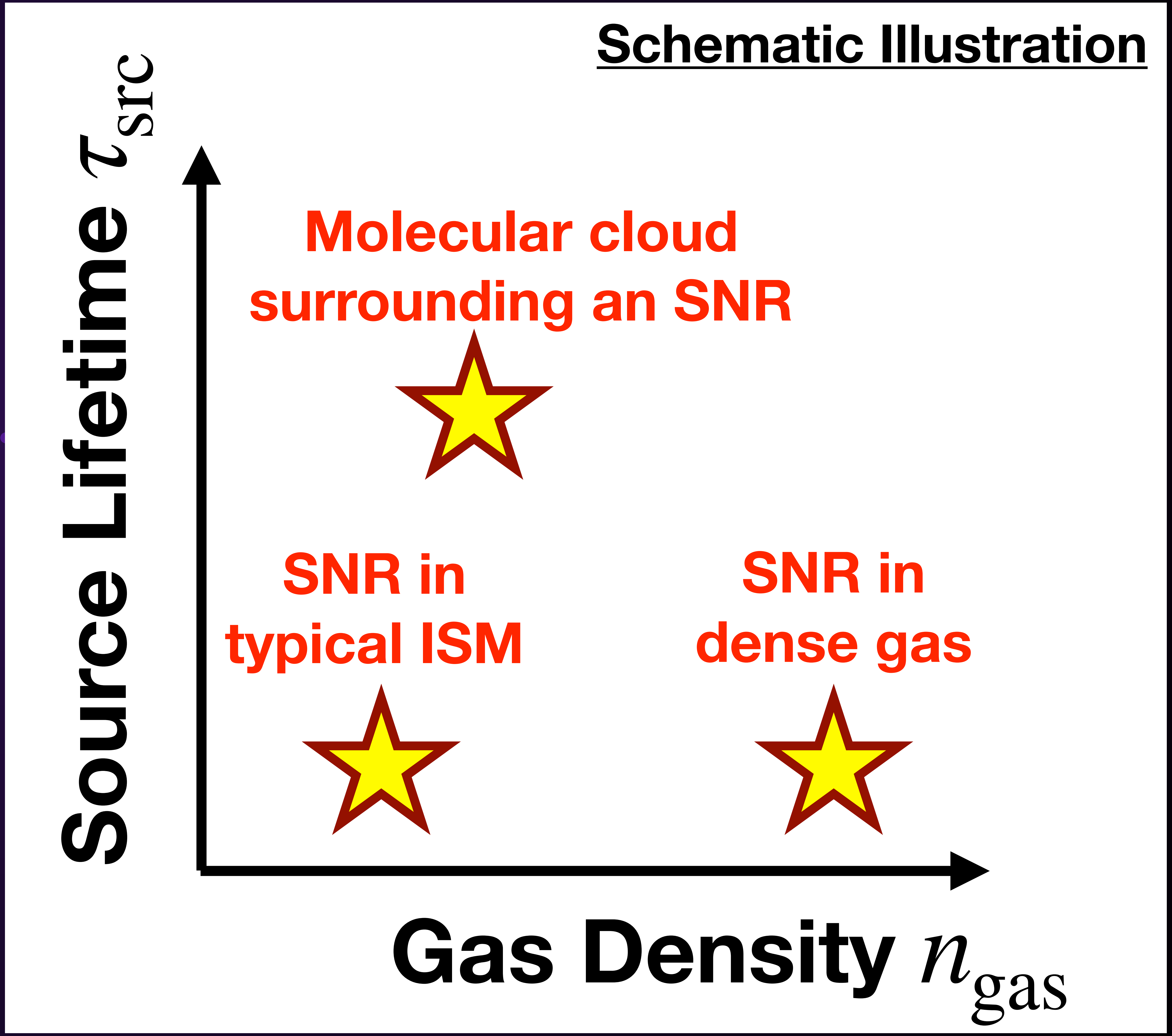


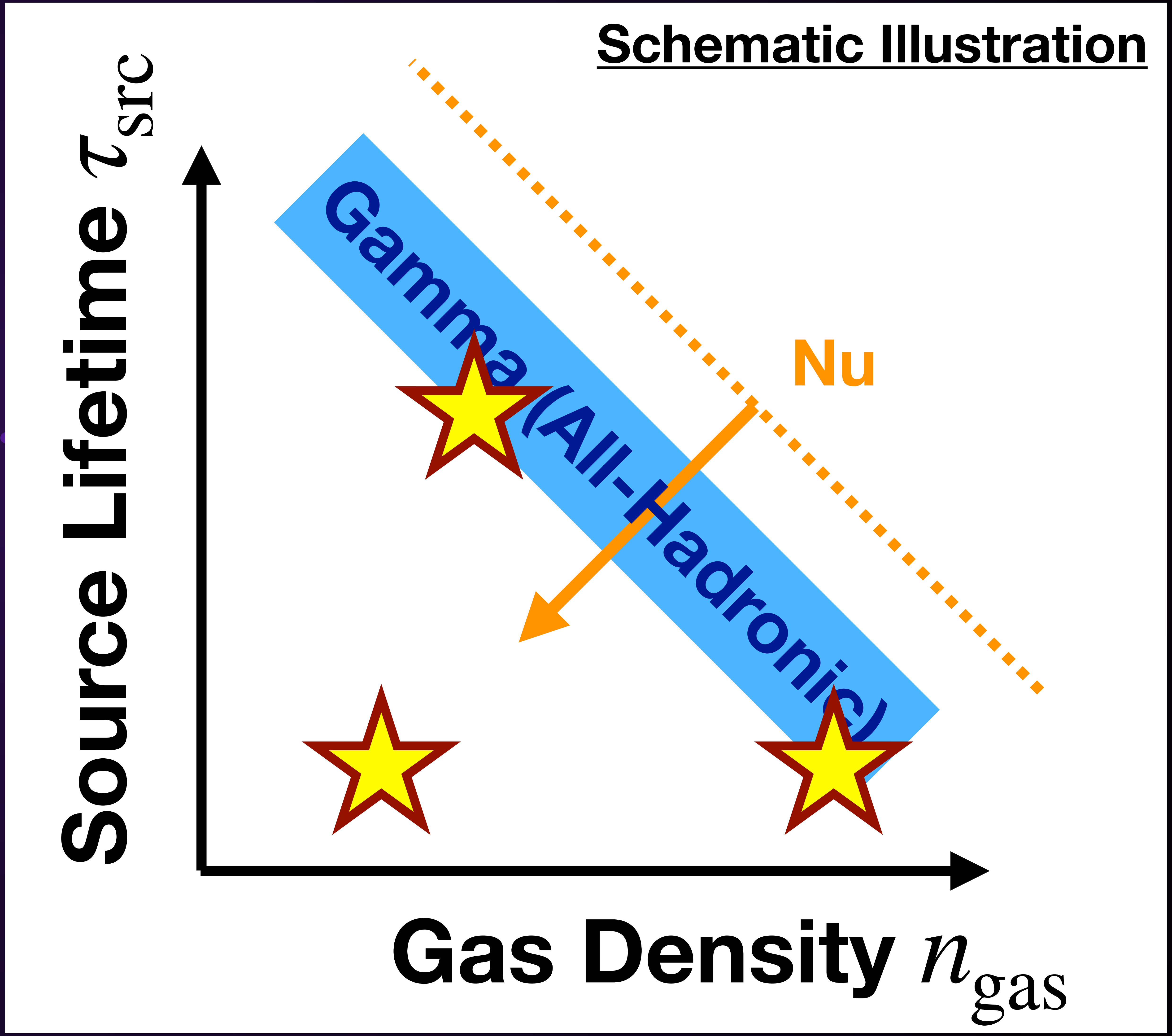
Introducing "n-tau" plane

- The gas density is the average value PeV protons encounter
- The source lifetime is the timescale for which PeV protons are confined in / around the source



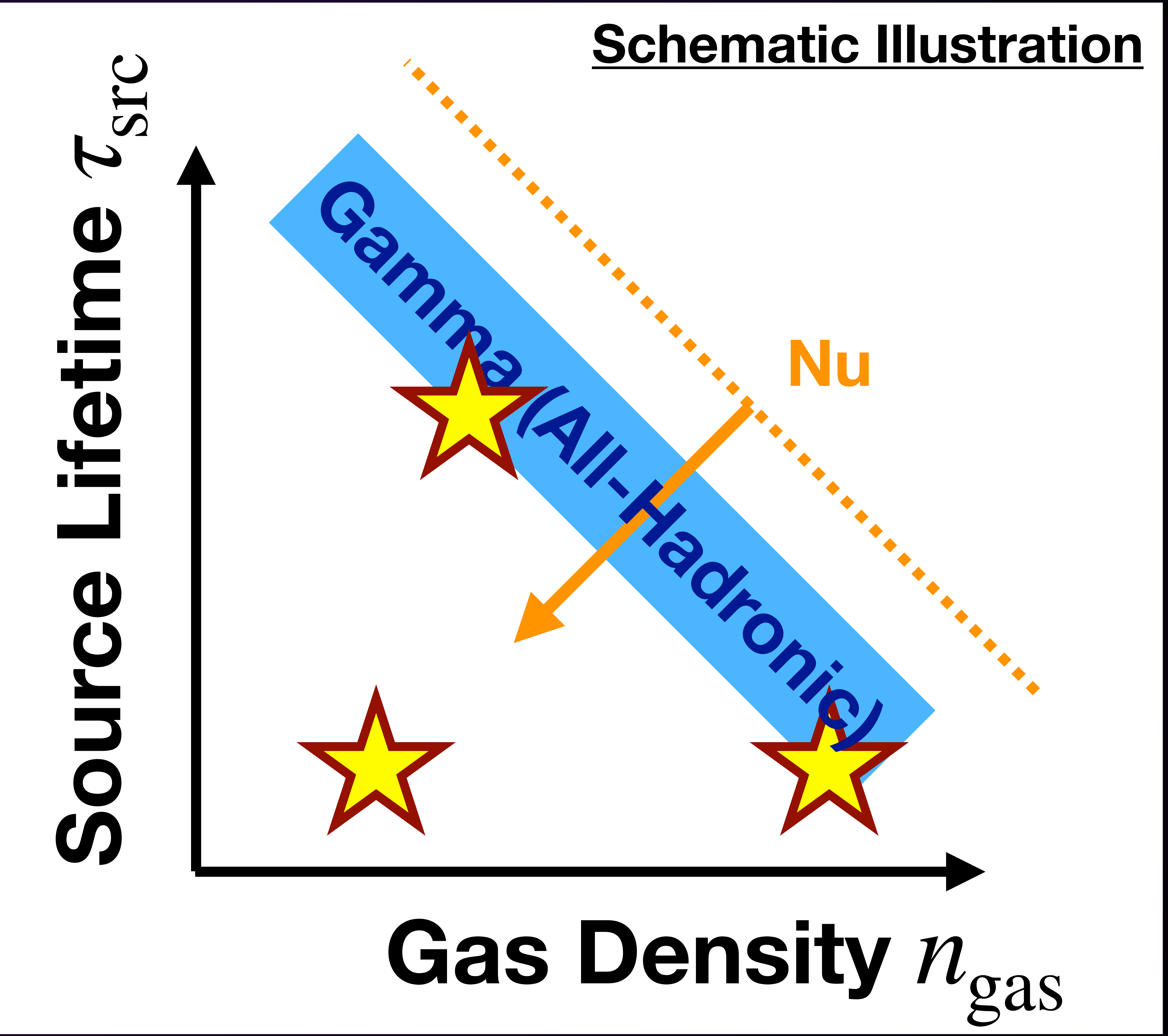
Introducing "n-tau" plane

- Compare various observations and theoretical models
- We can also calculate diffuse gamma rays and neutrino from unresolved sources (not shown in the schematic figure)



Introducing "n-tau" plane

- Key Points:
- Demand consistency with diffuse and source data on cosmic rays, gamma rays, and neutrinos.
- Quantify properties of PeVatrons in a semi-model-independent plane of source density and lifetime.



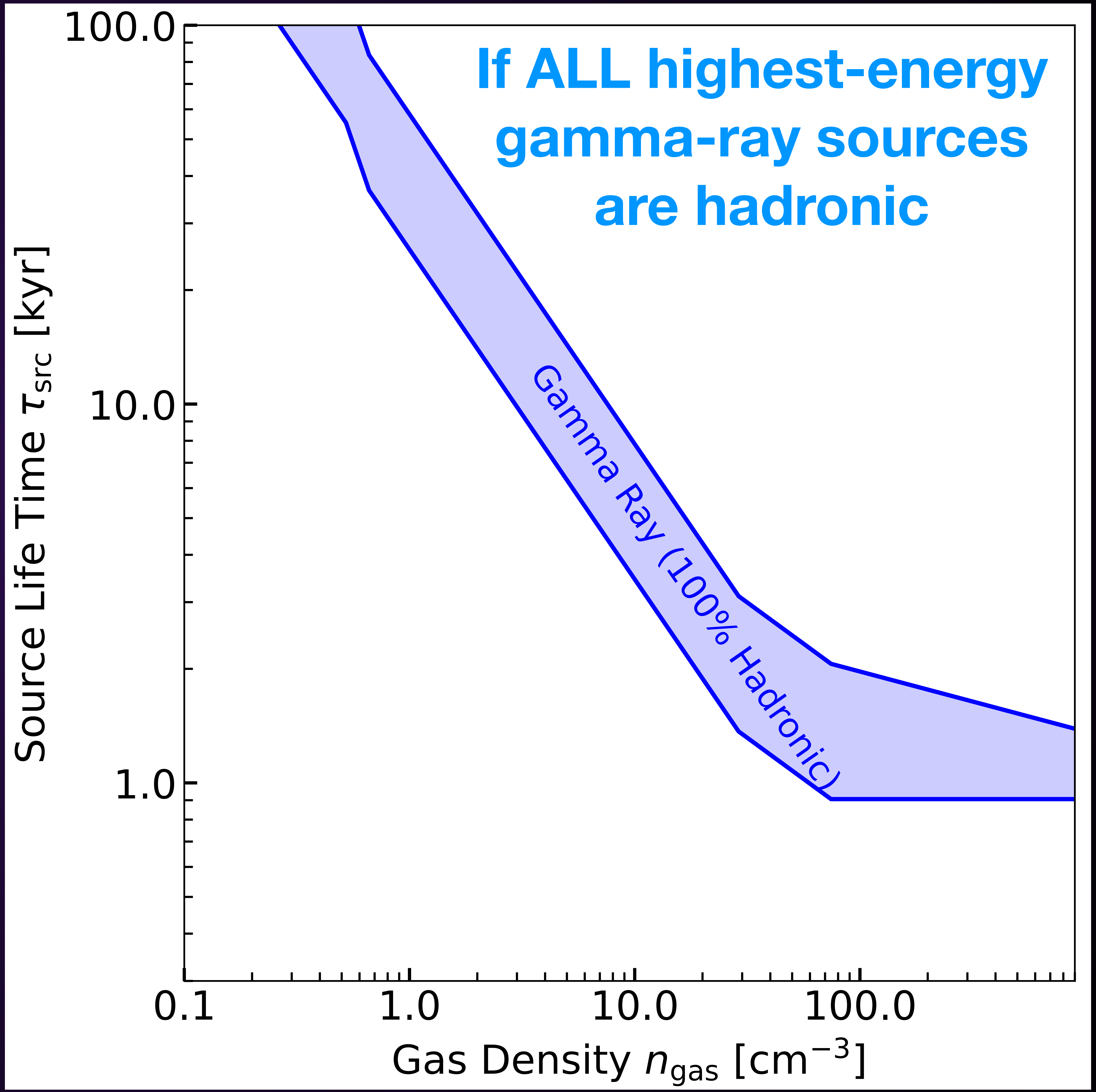
Population model

- We carry out Monte-Carlo simulation to obtain the existing constraints in the n - tau plane.
    - Gamma-ray / neutrino spectrum
    - Detector properties
    - Source size and spatial distribution
    - Assume Γ_{CR} = SN rate
- Retain simple descriptions with gas densities & source lifetime

Gamma-ray implications

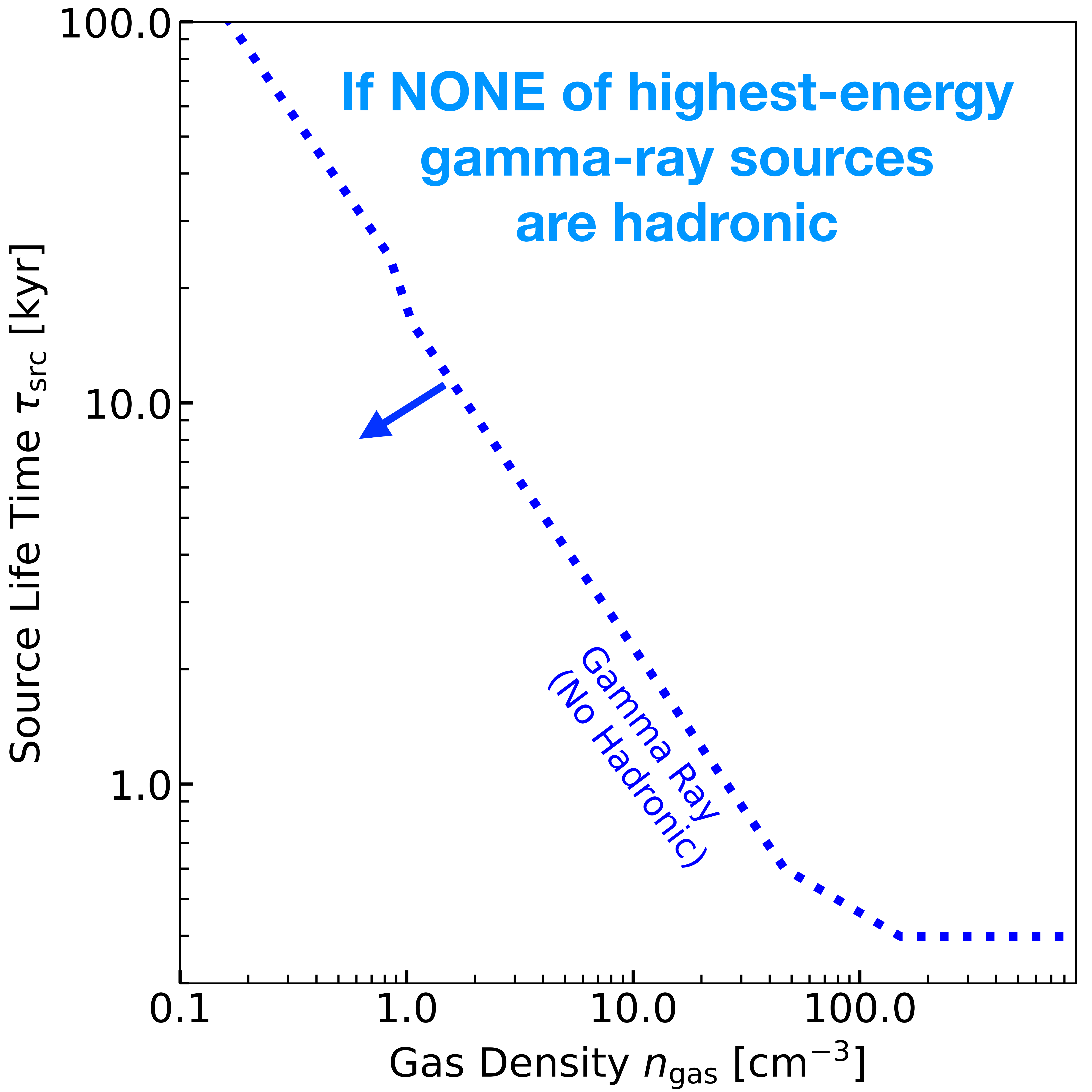
- Most of highest-energy gamma-ray source could be hadronic PeVatrons

- Require long lifetime and/or high gas densities



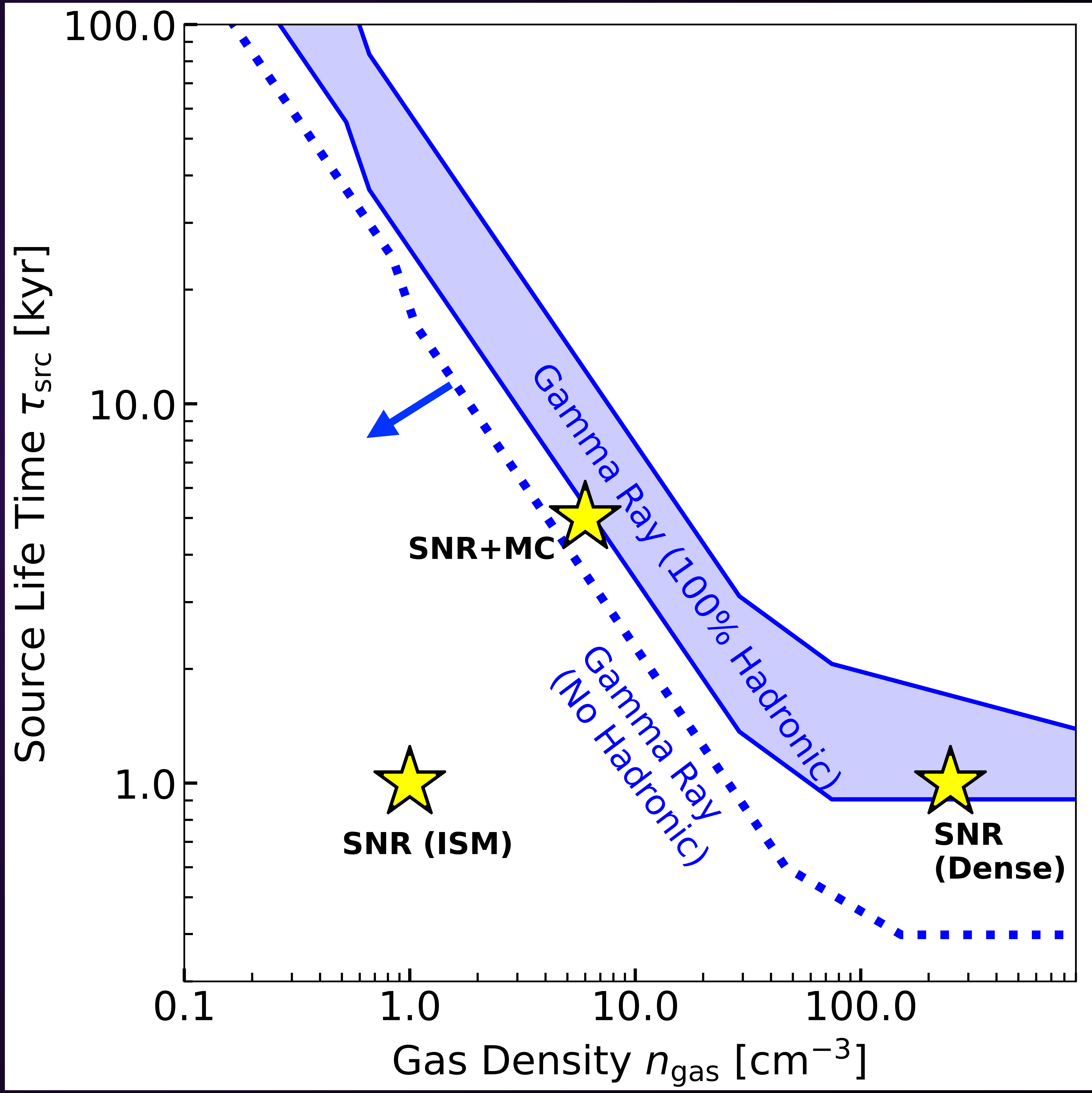
Gamma-ray implications

- A wide range of n and tau is consistent with 0% being hadronic accelerators
- Highest-energy gamma-ray sources might be irrelevant to the origin of CR hadrons.



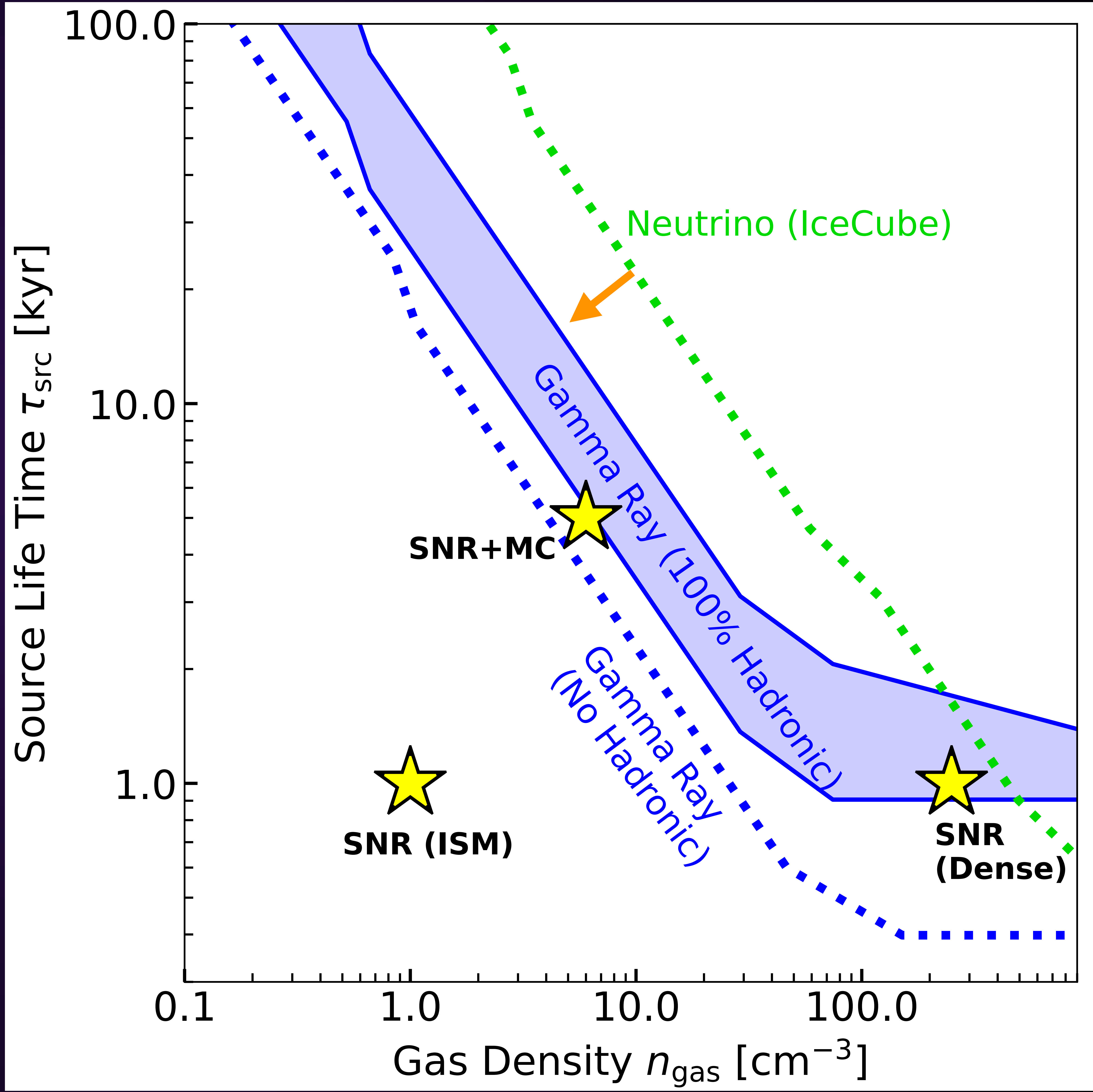
Gamma-ray implications

- Representative models
  - SNRs in 1 cm^{-3} gas
  - SNRs with dense shell
  - Molecular clouds (MC) surrounding SNRs
- Confinement time is unknown and model-dependent
  - Very optimistic values are plotted



Neutrino implications

- IceCube constraints still allow a large parameter space



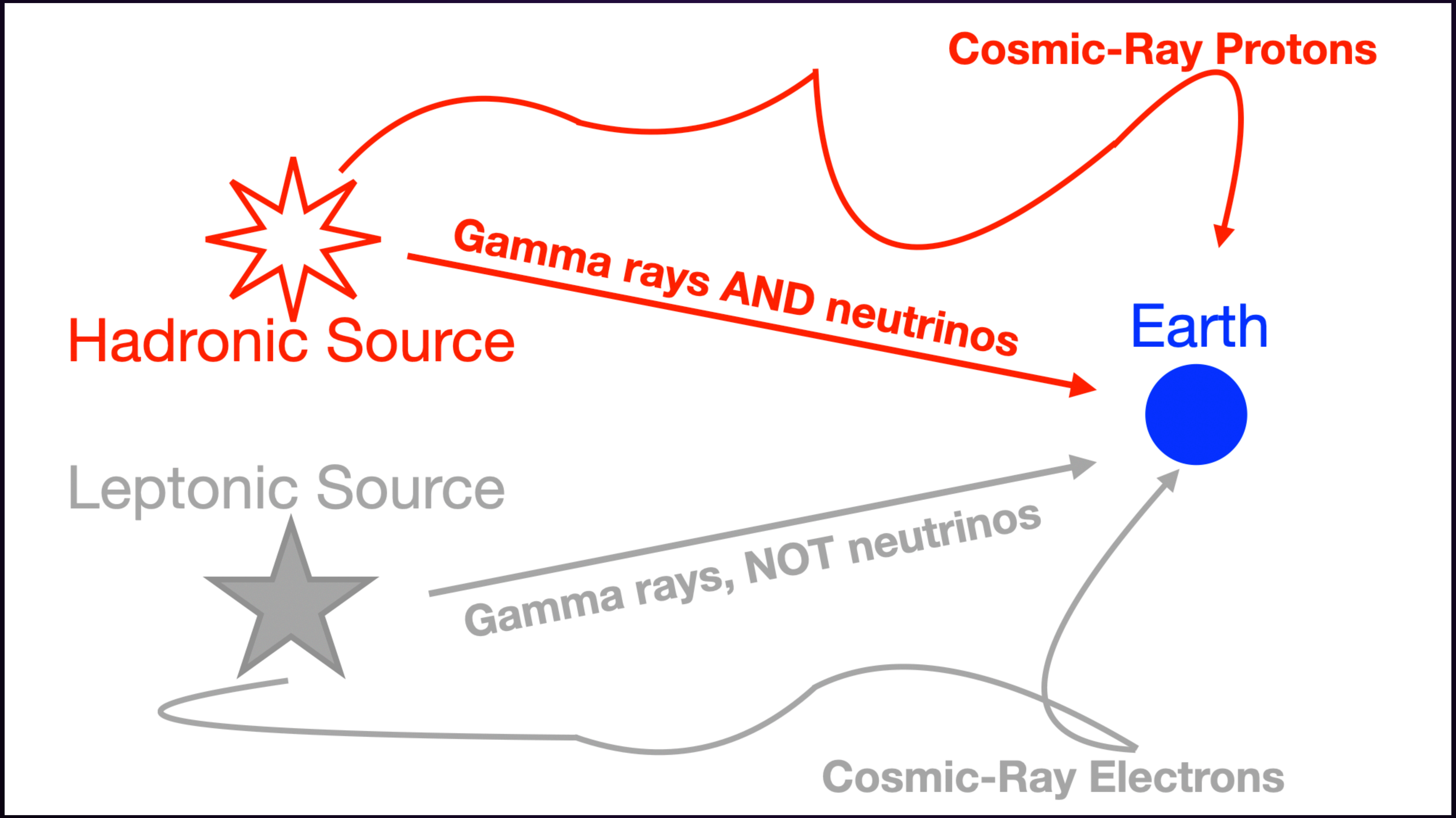
Summary 1

- We introduce n - tau plane to consistently understand measurements of CR, gamma rays, and neutrinos.
- Existing neutrino constraints are still weak
- Optimistic models : highest-energy gamma-ray sources are hadronic PeVatrons.
- A wide range of models : none of highest-energy gamma-ray sources might be hadronic PeVatrons.
- Then, what could be those gamma-ray sources?

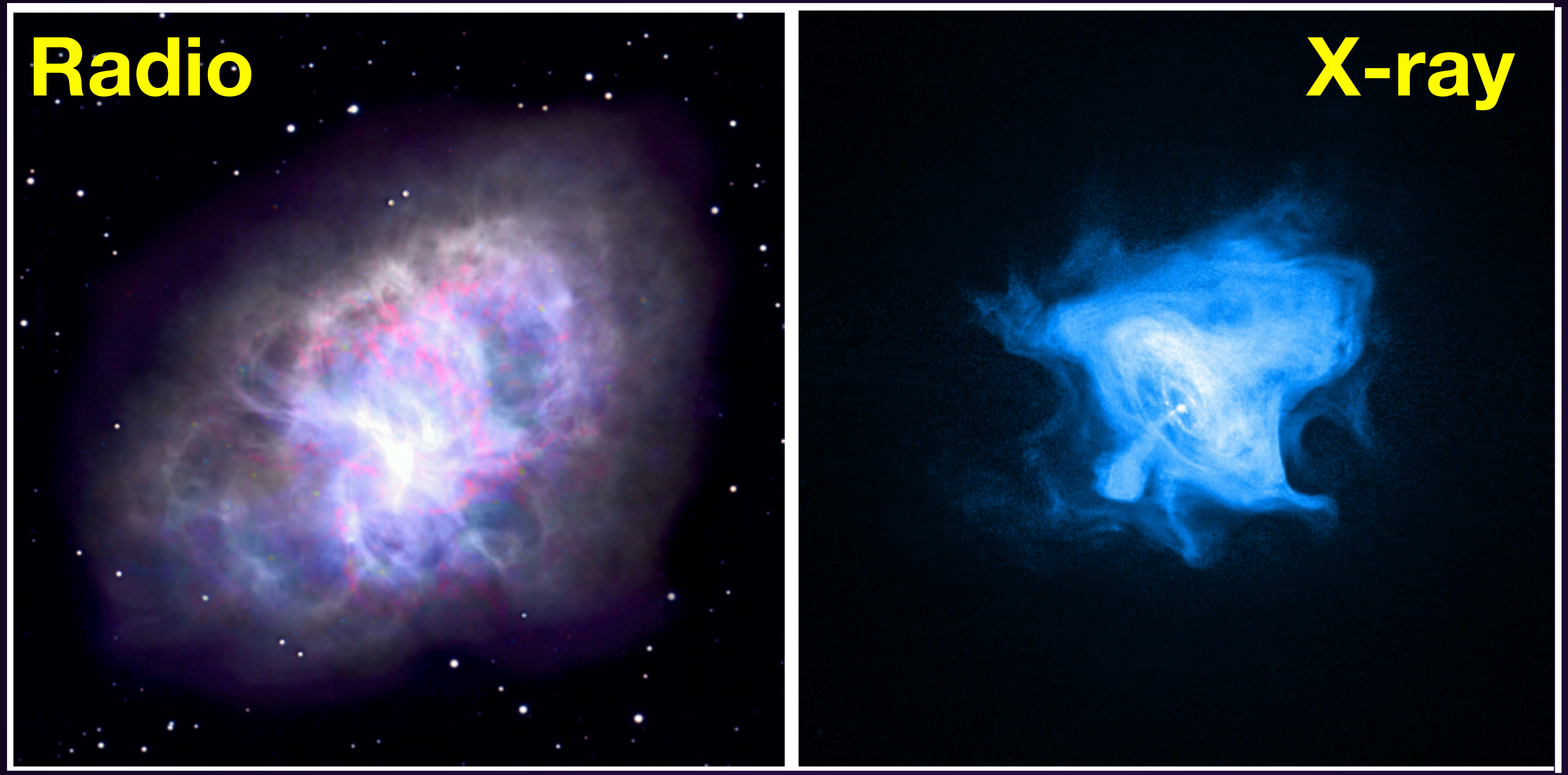
What are the nature of gamma-ray sources?

Two Gamma-Ray Production Mechanisms

- Hadronic : Protons collide with gases to make gamma rays and neutrinos
- Leptonic : Electrons scatter ambient photons to make gamma rays



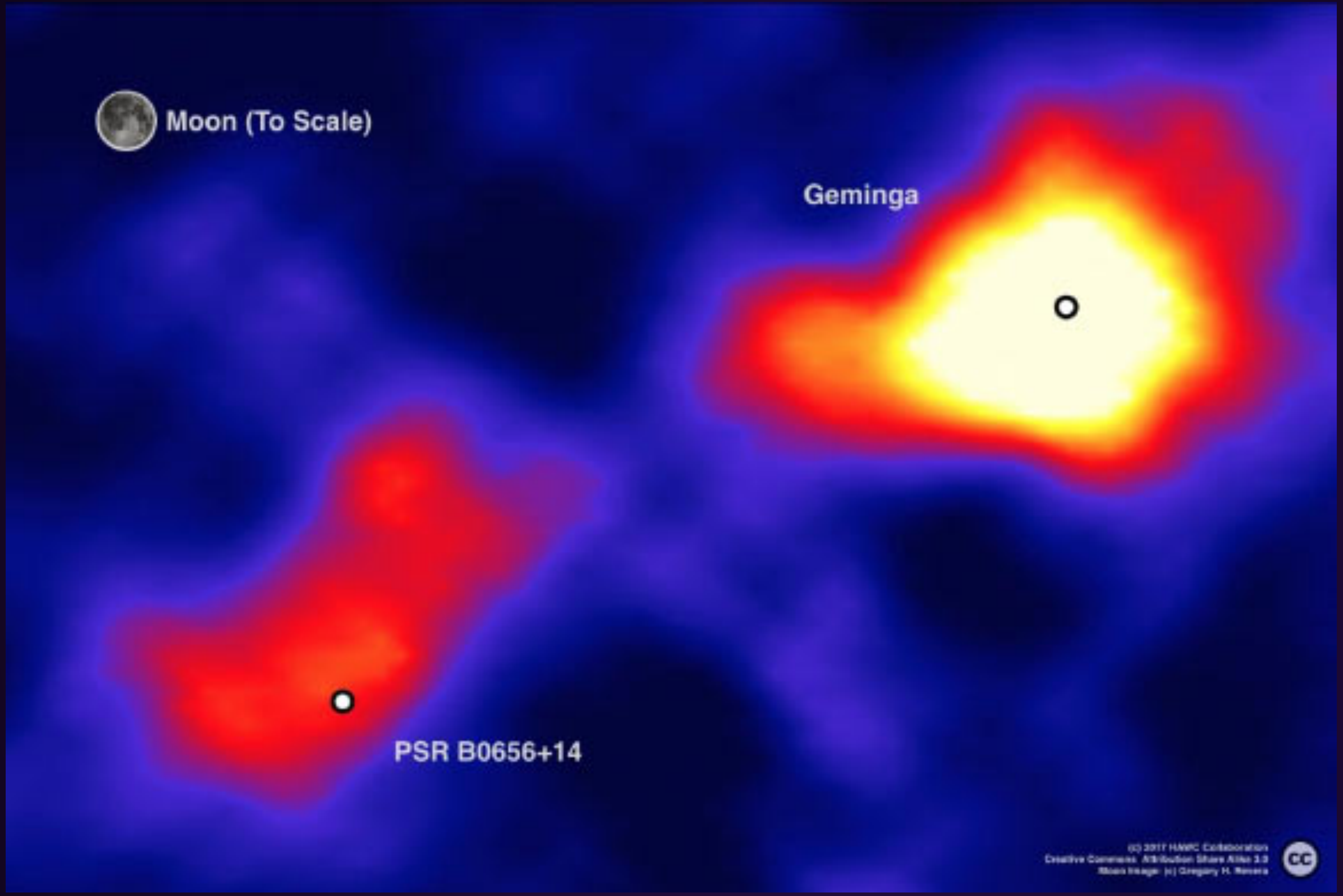
Young pulsars as e+- accelerator



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 by electrons
- Gamma rays now seen above 1 PeV !
- Indicates the production of > PeV electrons — a leptonic “PeVatron”

Middle-aged pulsars as e+- accelerator



HAWC Collaboration
Image : John Pretz

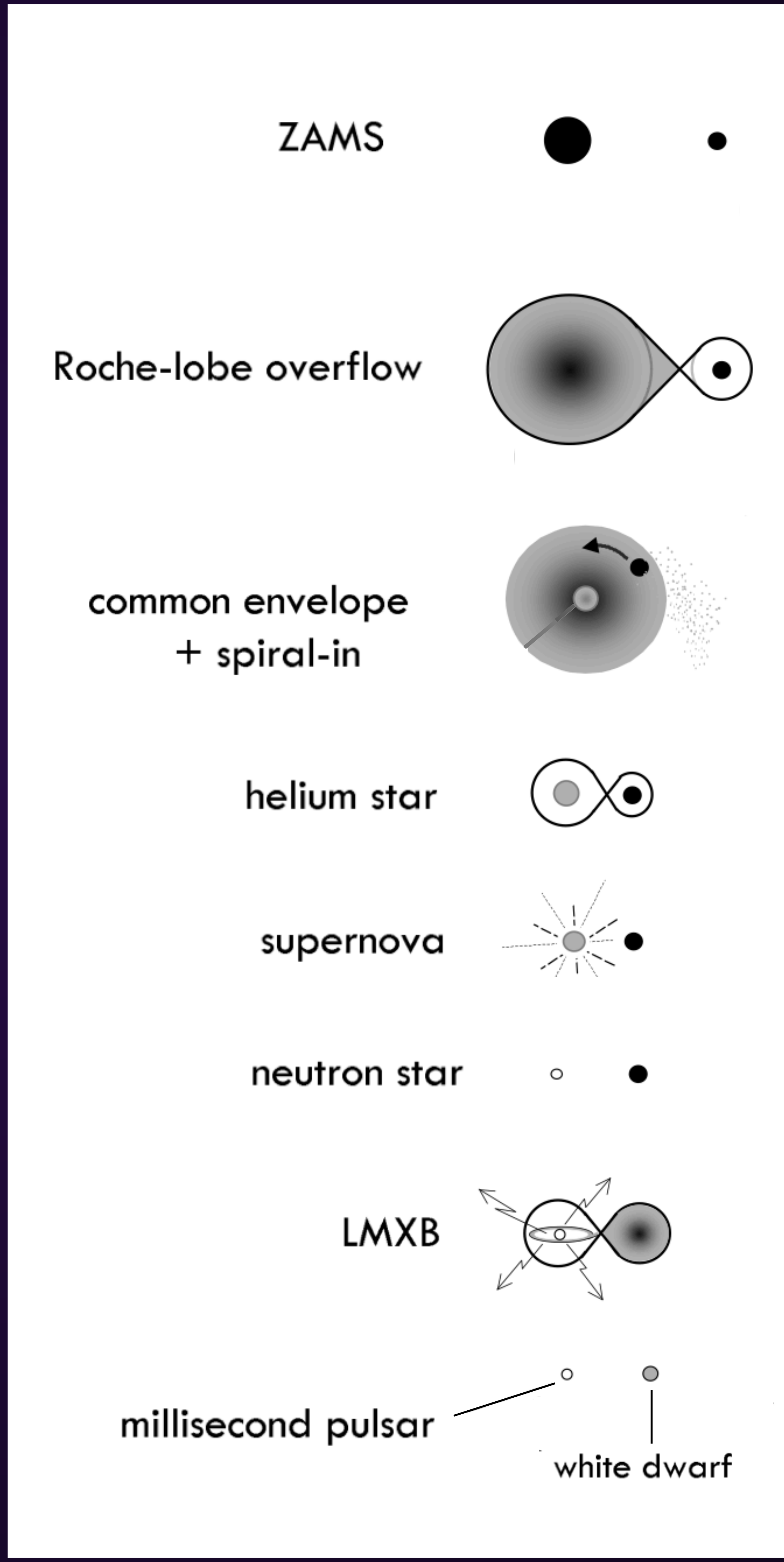
- Recently, largely extended emission of TeV gamma rays are discovered around middle-aged (> 100 kyr) pulsars — “TeV Halos”

- Middle-aged pulsars are efficiently producing > 50 TeV electrons

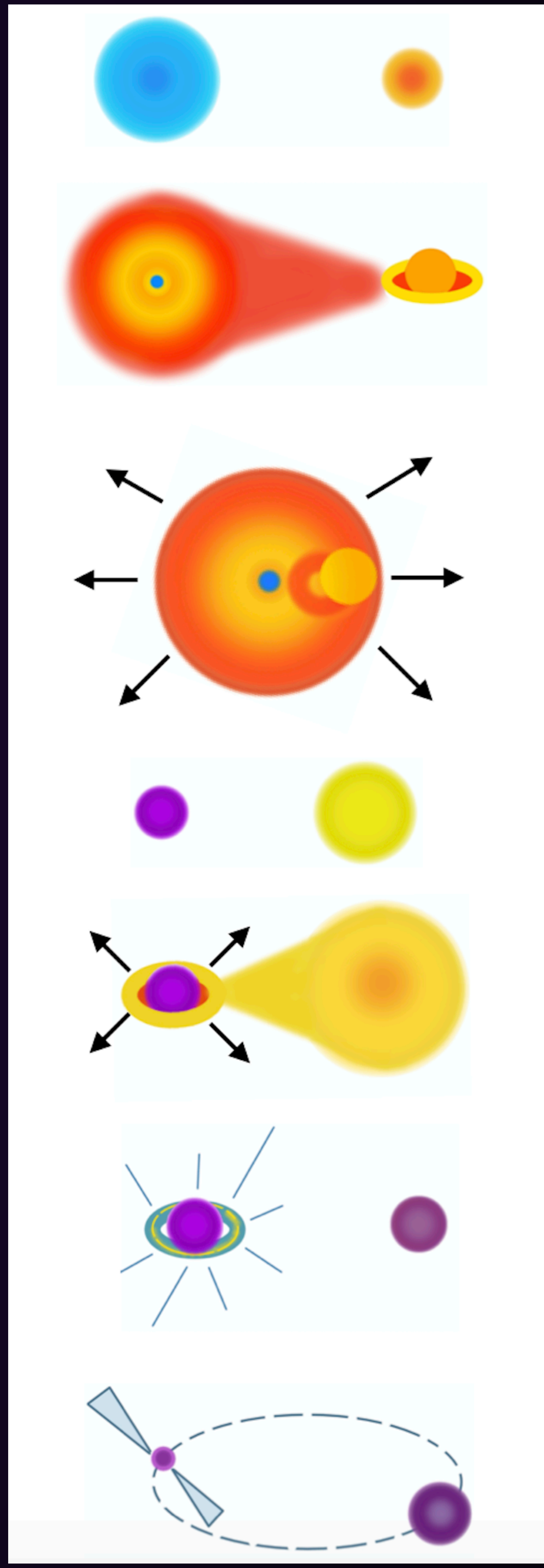
Millisecond pulsars as e+- accelerator

- “Normal” Pulsars : formed at core-collapse and spin down over ~ kyr
- **Millisecond Pulsars (MSPs)** : formed in binary and spin down over ~ Gyr
- Recent data suggest MSPs can produce e+- efficiently.
- They can be important in understanding nonthermal emission from old galaxies.

Sudoh, Linden, Beacom (2021, PRD)



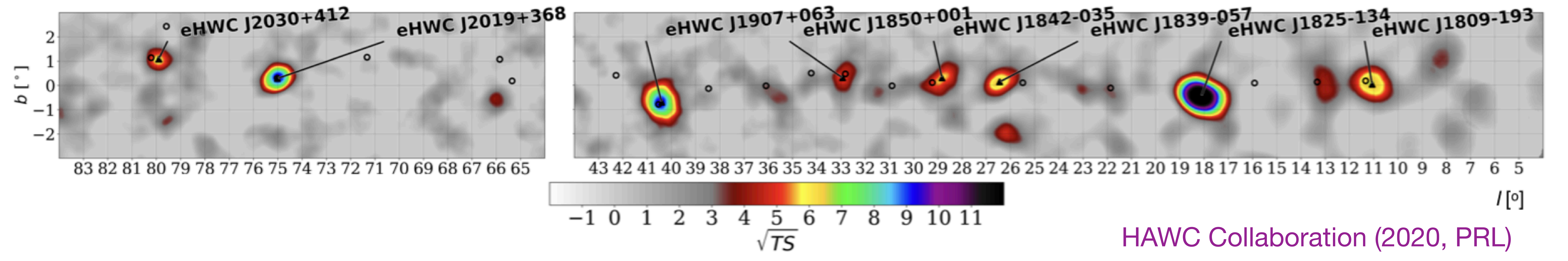
Tauris & van den Heuvel (2006), slightly modified



Gautam et al. (2022, Nature Astronomy)

Pulsars fit 100 TeV gamma-ray data

- Various types of pulsars are established as electron/positron sources, which can radiate gamma rays by scattering ambient photons.

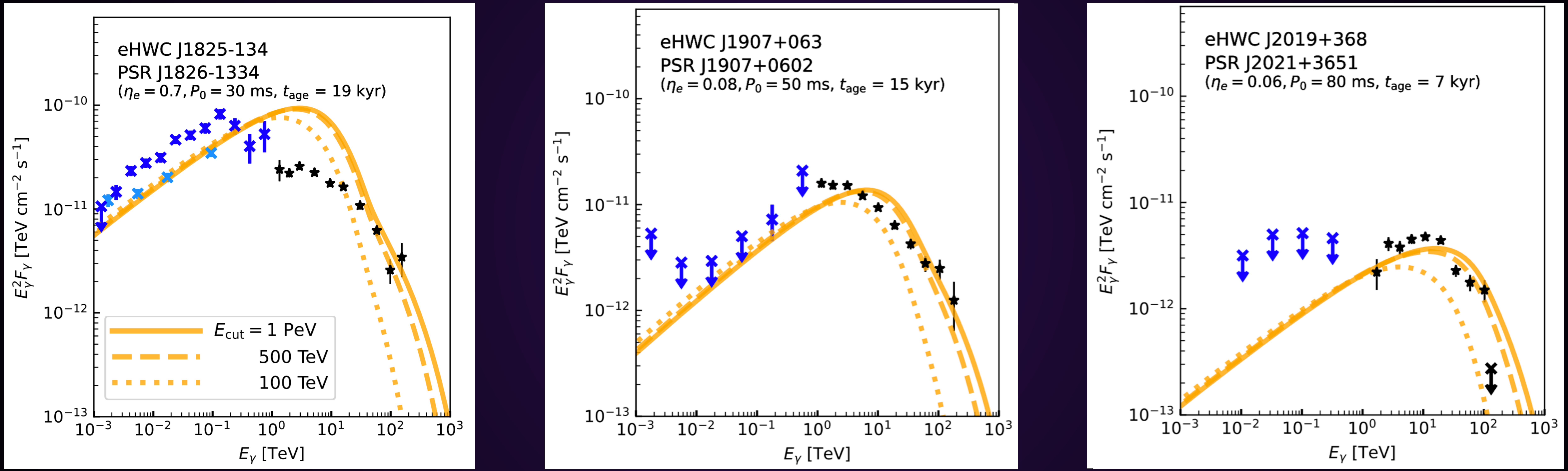


HAWC Collaboration (2020, PRL)

- Most of highest-energy gamma-ray sources are within 0.5 degree from young energetic pulsars.

Pulsars fit 100 TeV gamma-ray data

- Simple pulsar models fit spectra of three brightest sources.

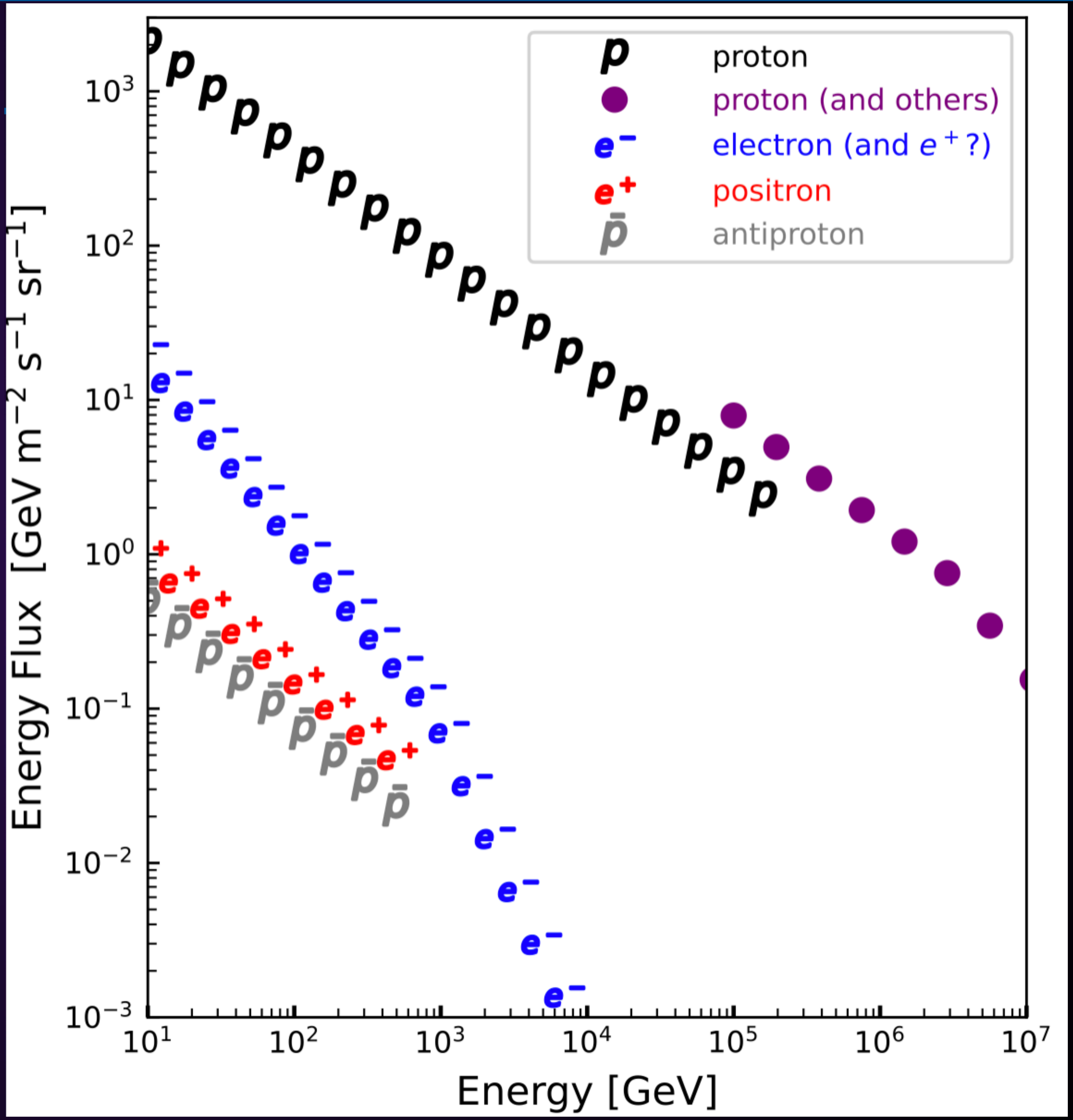


Sudoh, Linden, Hooper (2021, JCAP)

- Suggest dominance of pulsars in the highest-energy gamma-ray sky

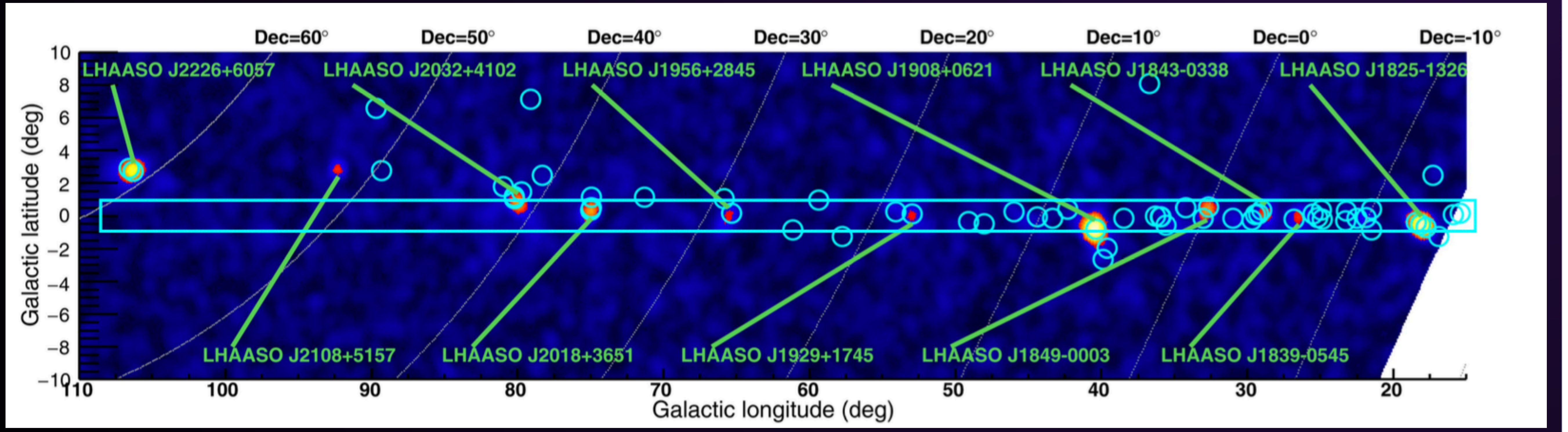
Implications for cosmic rays

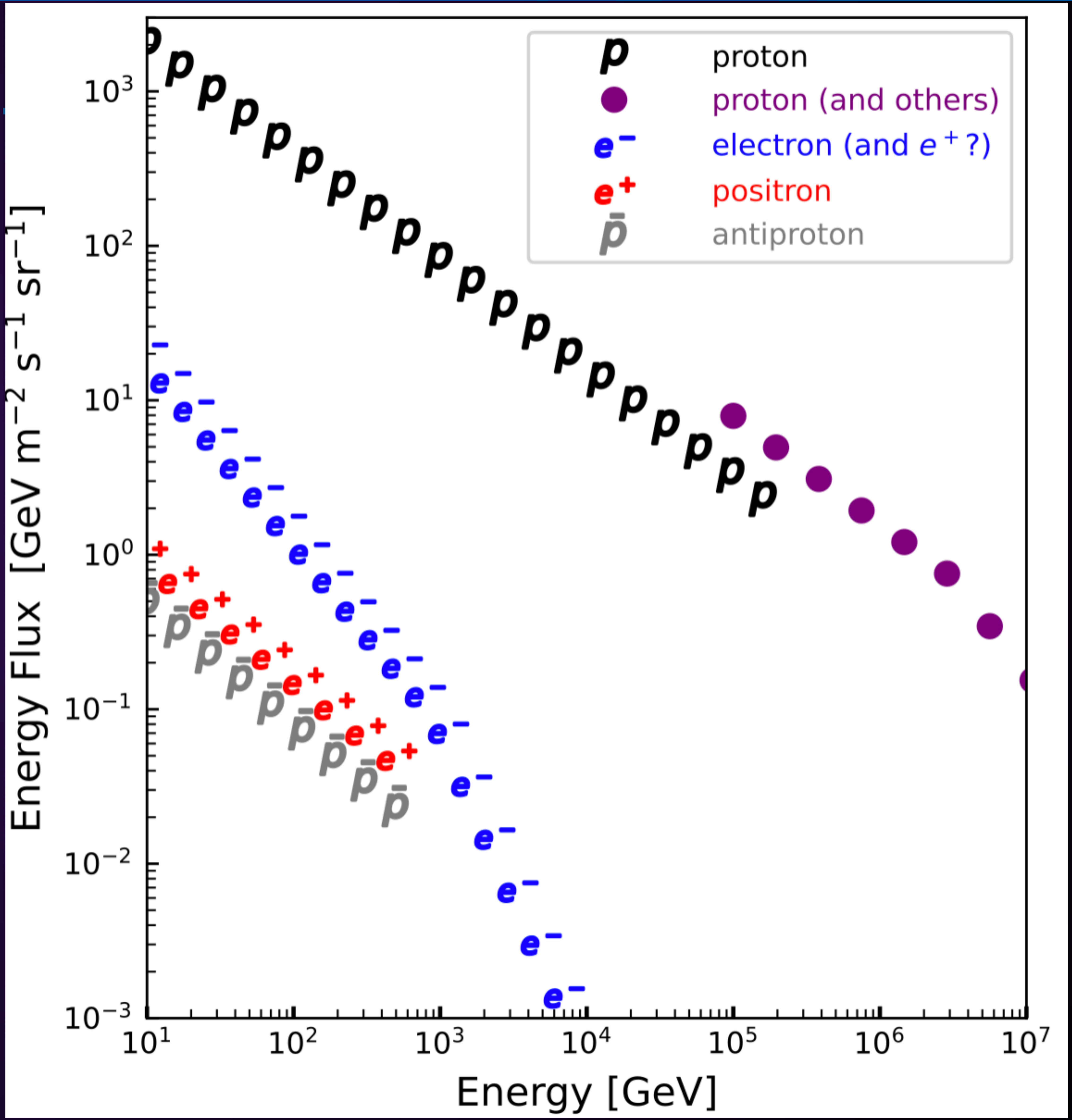
- Contributions from pulsars to the e- flux is thought to be small.
- Positrons may be dominated by pulsars.



Implications for cosmic rays

- Extreme scenario?
  - CR (p & e-) : SNR
  - Gamma-ray sources : pulsar
- Gamma-ray sources may be disjoint from the origin of CRs!
- Natural that we see no neutrino source





Summary 2

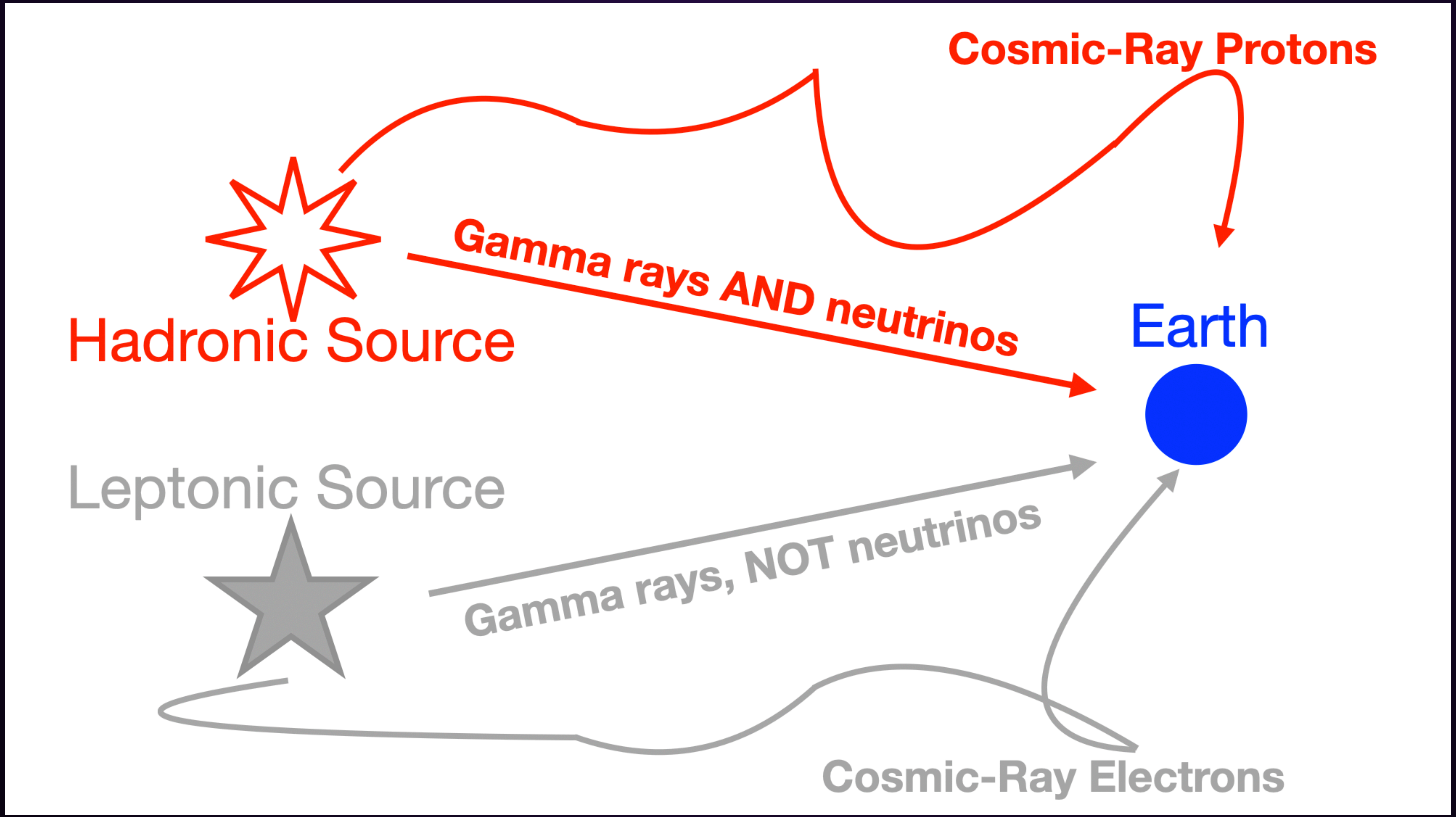
- The TeV gamma-ray sky might be dominated by leptonic sources originated from pulsars.
- They can make important contribution to the positron flux, although the exact level is under debate.
- Most of gamma-ray source could be irrelevant to the observed CR!
- Then, how should we find CR sources?

How to find CR sources?

Solid idea : Neutrinos

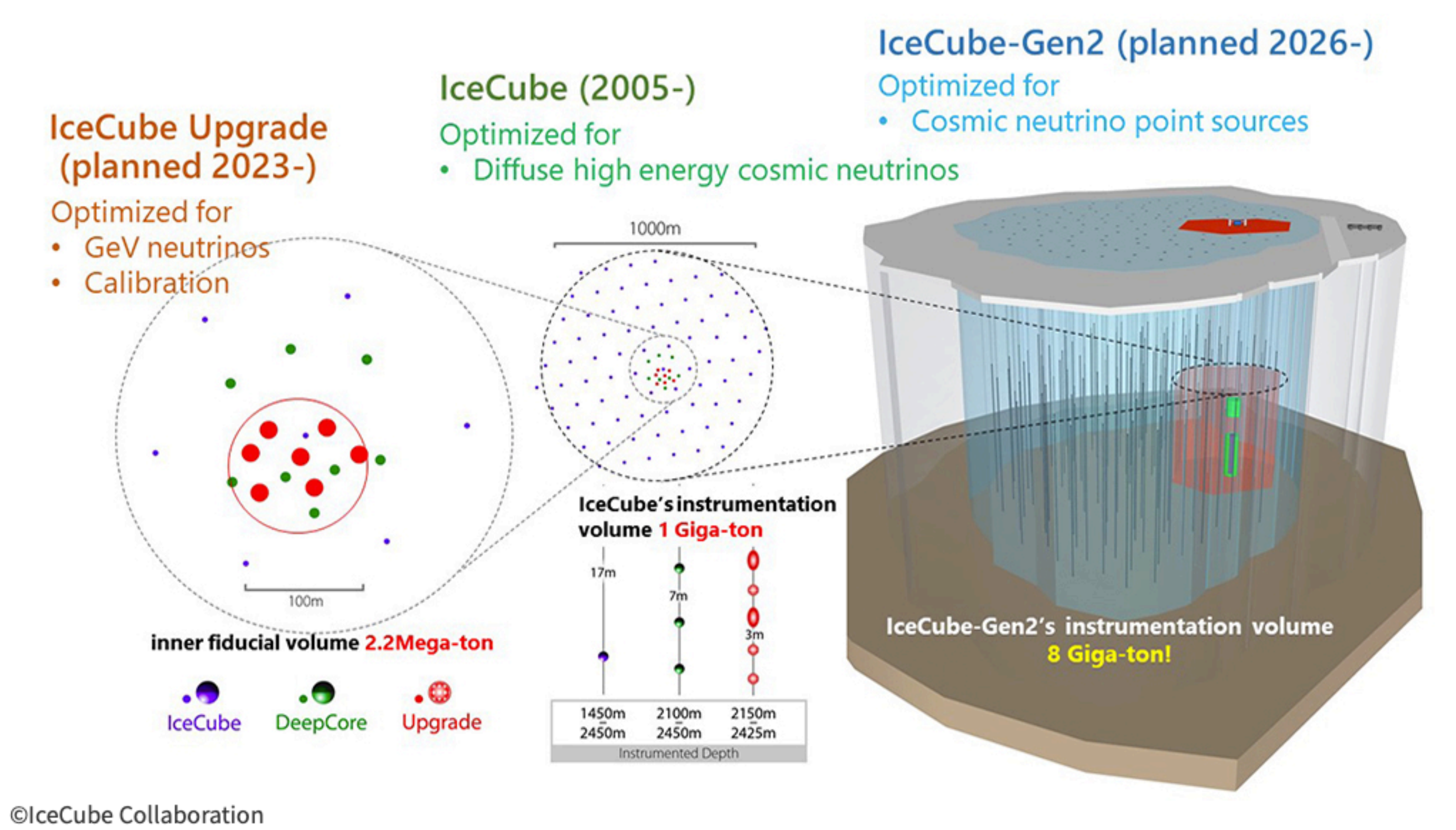
Neutrinos are smoking-gun

- Neutrinos are produced only by hadronic sources
- A decisive way to detect hadronic PeVatron



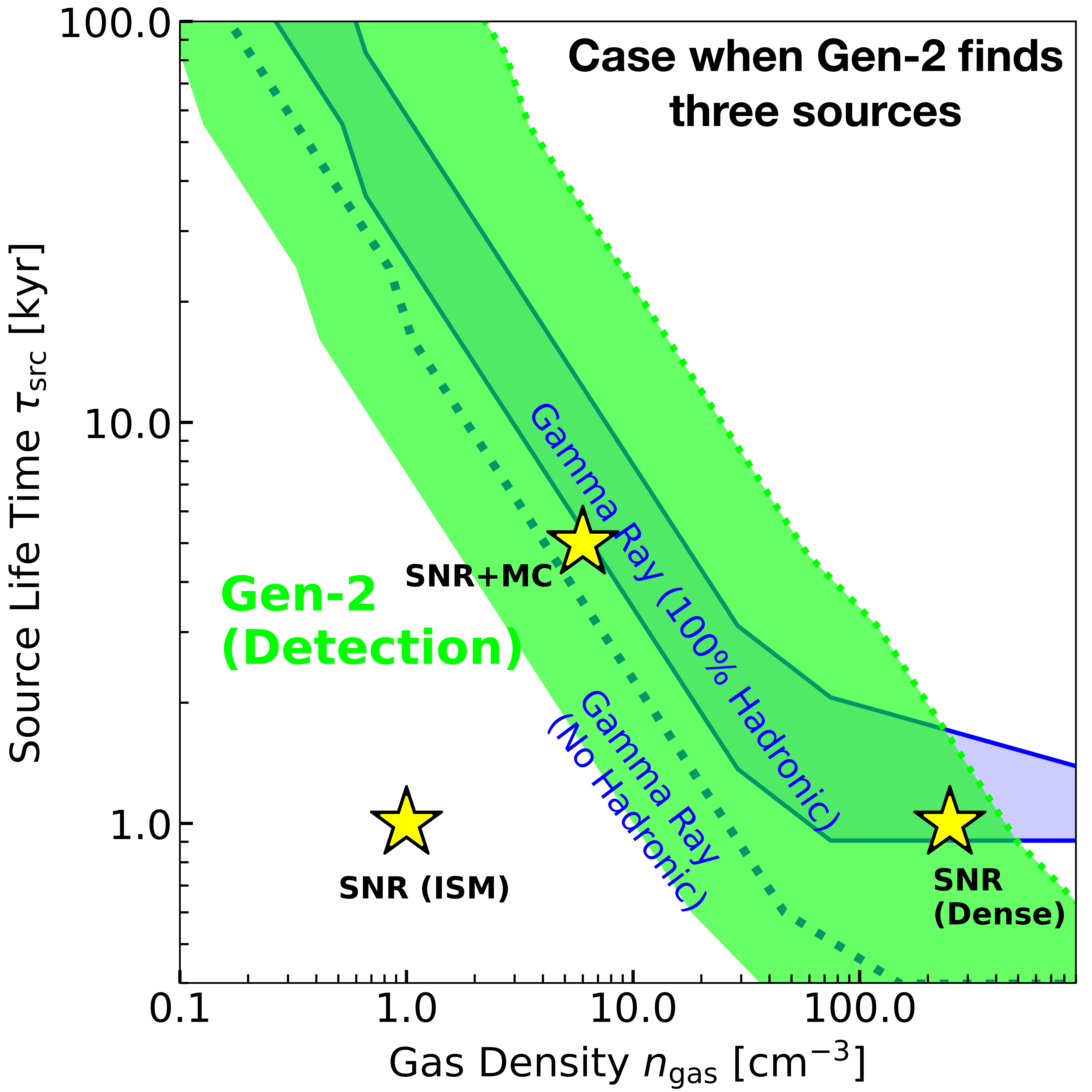
IceCube Gen-2

- Planned upgrade to the IceCube



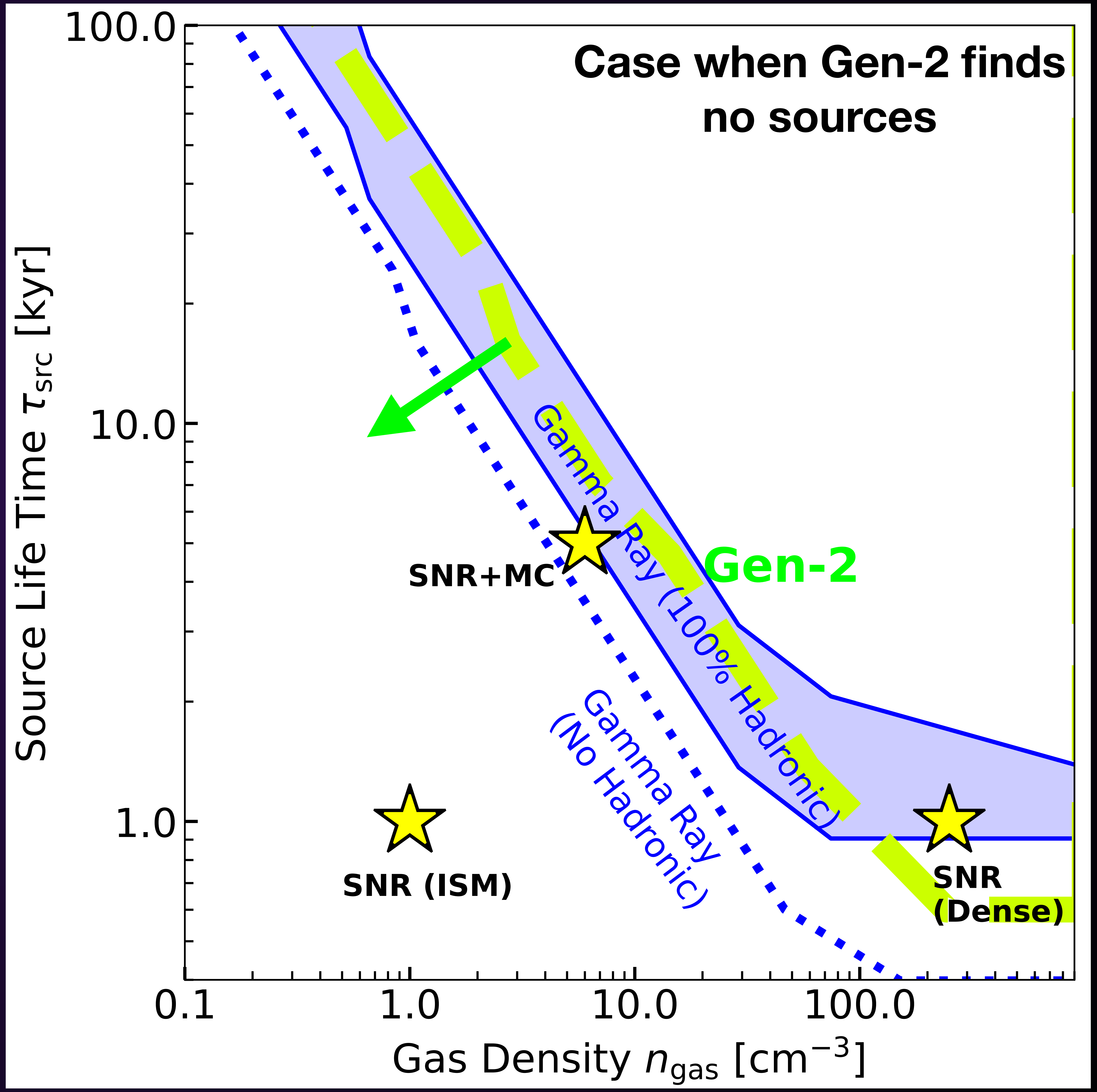
IceCube Gen-2

- Detection of neutrino sources by Gen-2 would constrain the parameter space in the green band.



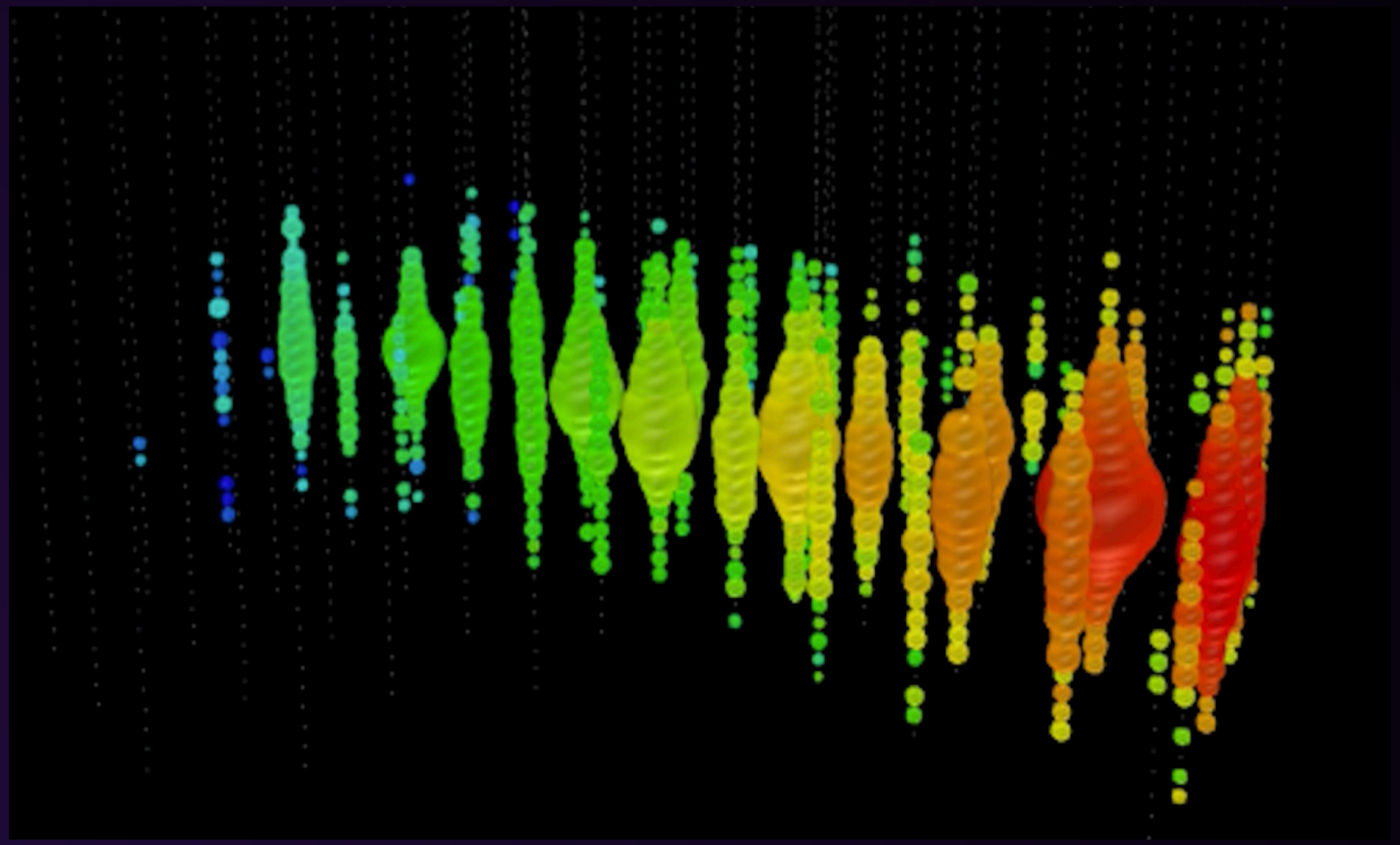
IceCube Gen-2

- Non-detection by Gen-2 still allows a wide range of PeVatron models.
- Improvements in sensitivities are needed to rule out interesting scenarios. … How?

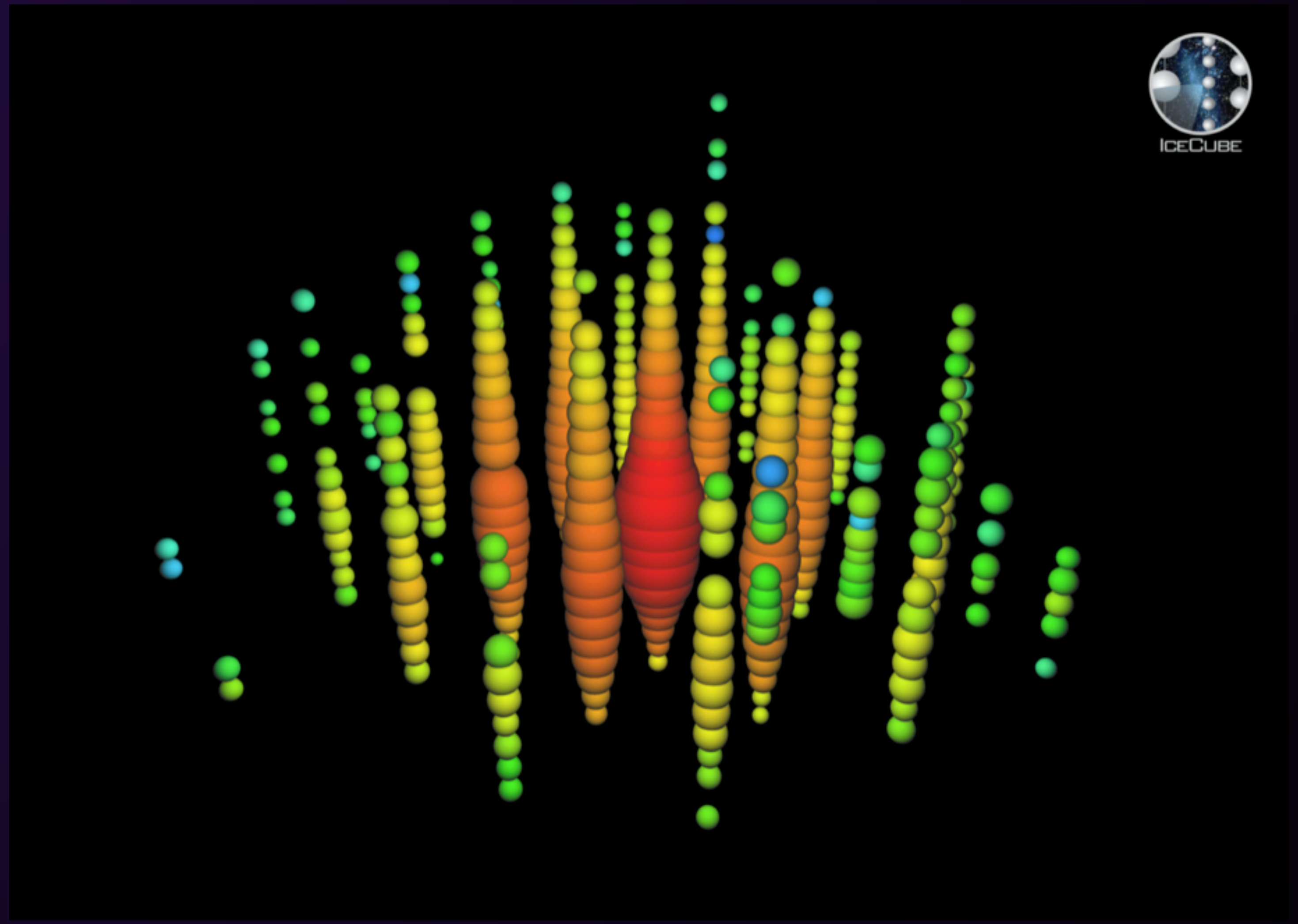


Importance of Shower

- Normally, muon events have better sensitivities for source searches due to better angular resolution.



- In principle, shower events can work better than muons!
  - Smaller bkg, large source size, steep spectrum
  - Needs future work to improve the angular resolution

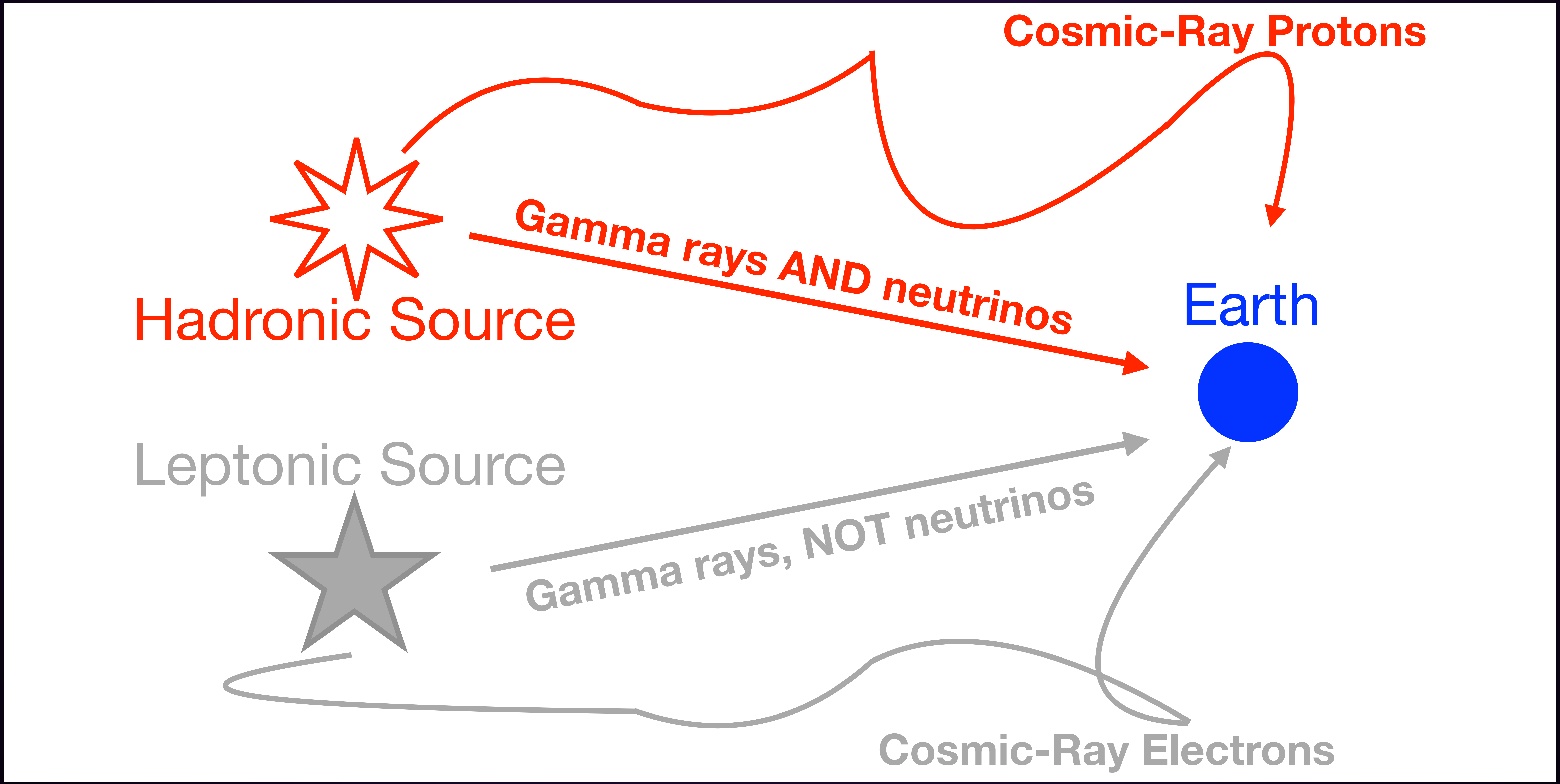


How to find CR sources?

Ambitious idea : Nearby source

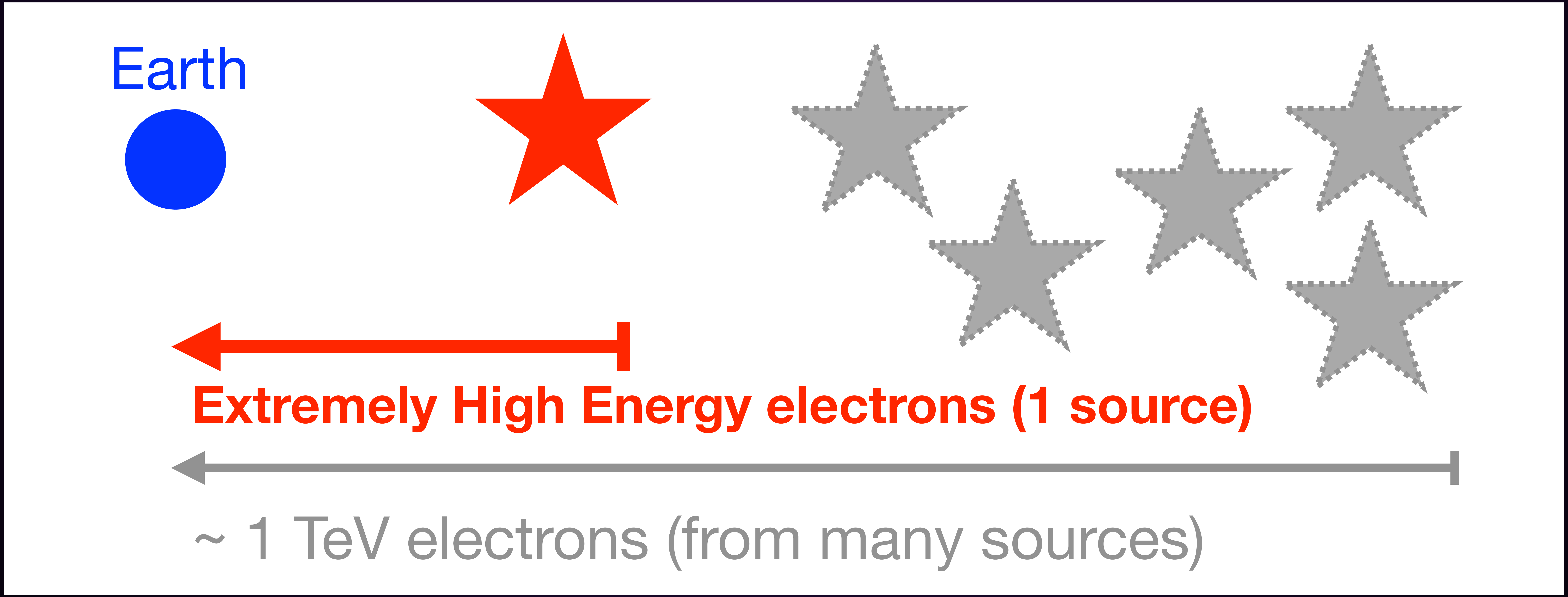
Identify cosmic-ray sources

- Hard to identity a source



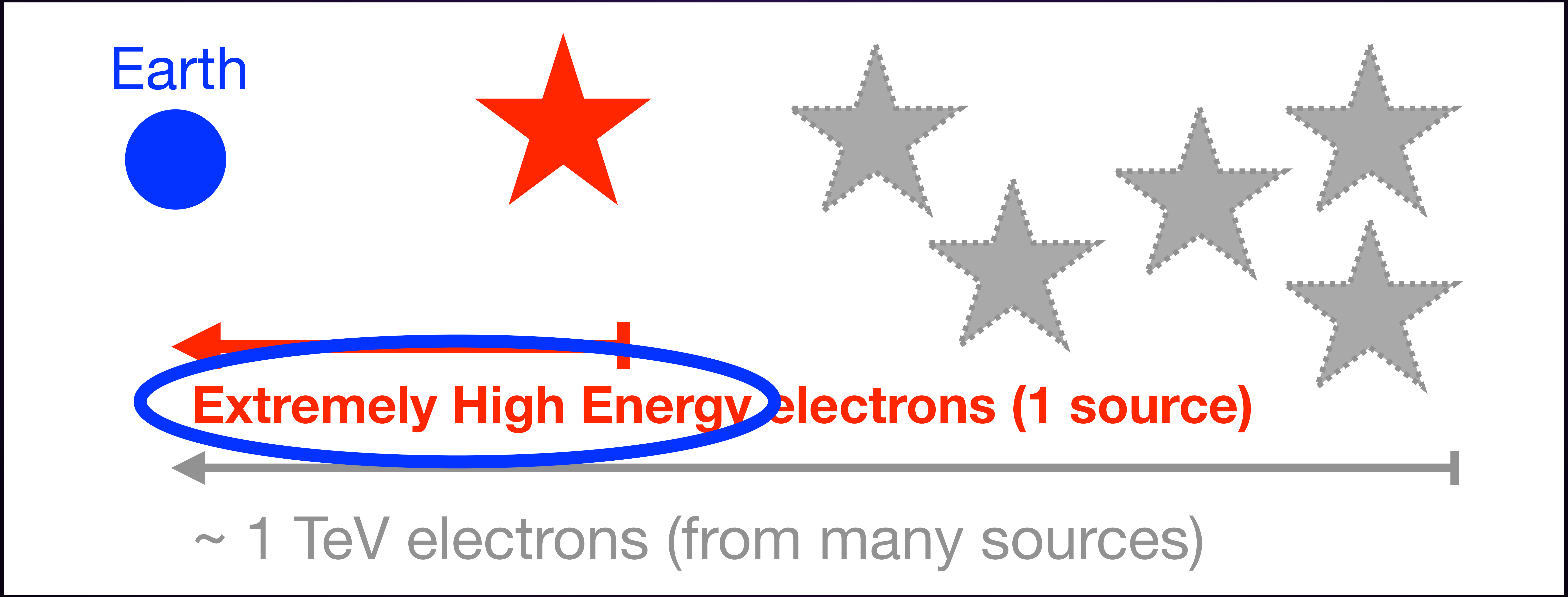
Leptons cool fast

- 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



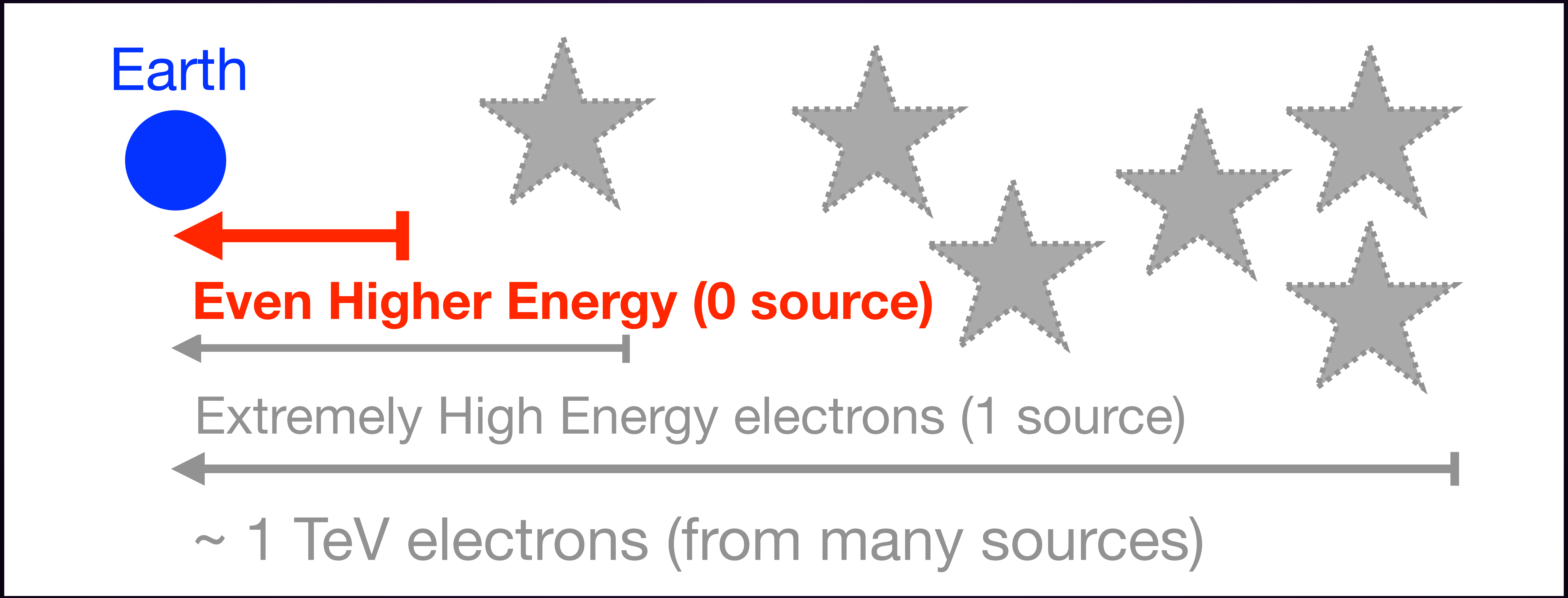
Where the CR electron spectrum ends?

- 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.



Beyond the end of CR electron spectrum

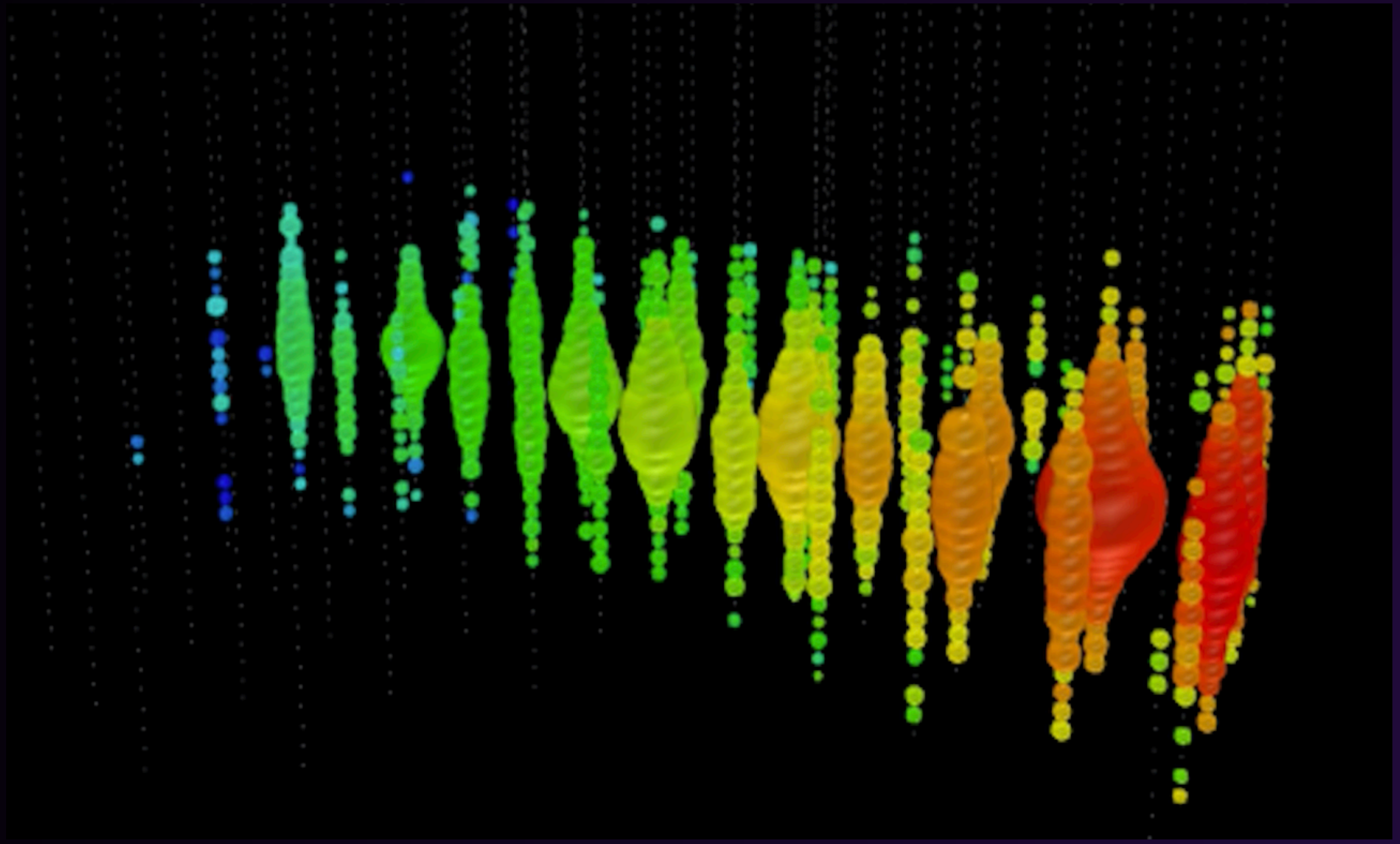
- At even higher energies, no electron from astro source reach the Earth
- The only contribution is from exotic scenarios, e.g., decay of dark matters
- Clean window to search for the dark-matter signals !?



Summary

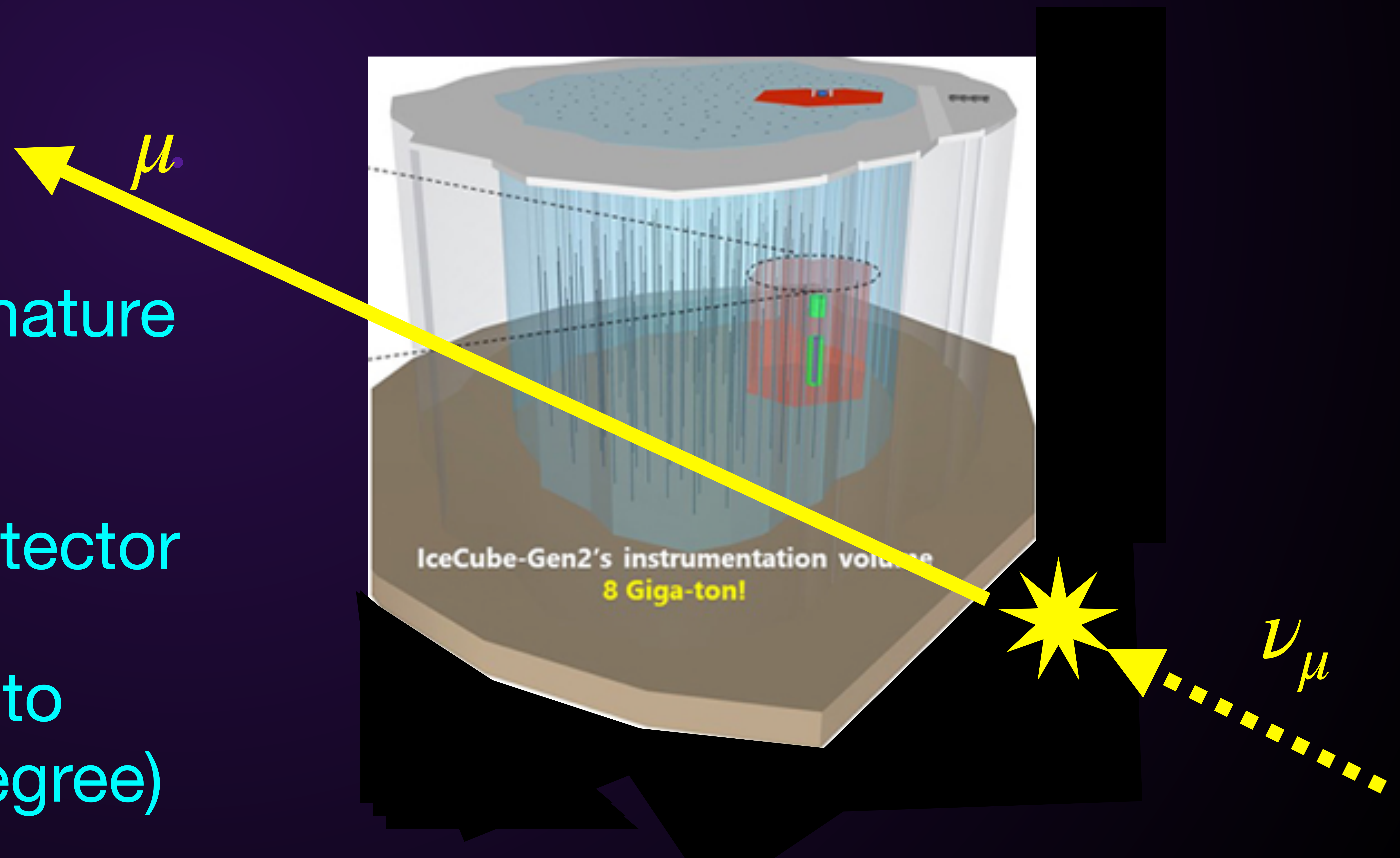
- We see hadronic flux, we see sub-PeV gamma-ray sources, and we see no neutrino source — Where are Galactic PeVatrons?
- Optimistically, the highest-energy gamma-ray sources are hadronic PeVatrons that produce neutrinos, making them excellent multi-messenger sources.
- We point out that the origins 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 CR source (and a unique window for DM searches).

Searches for Milky Way's sources



https://icecube.wisc.edu/gallery

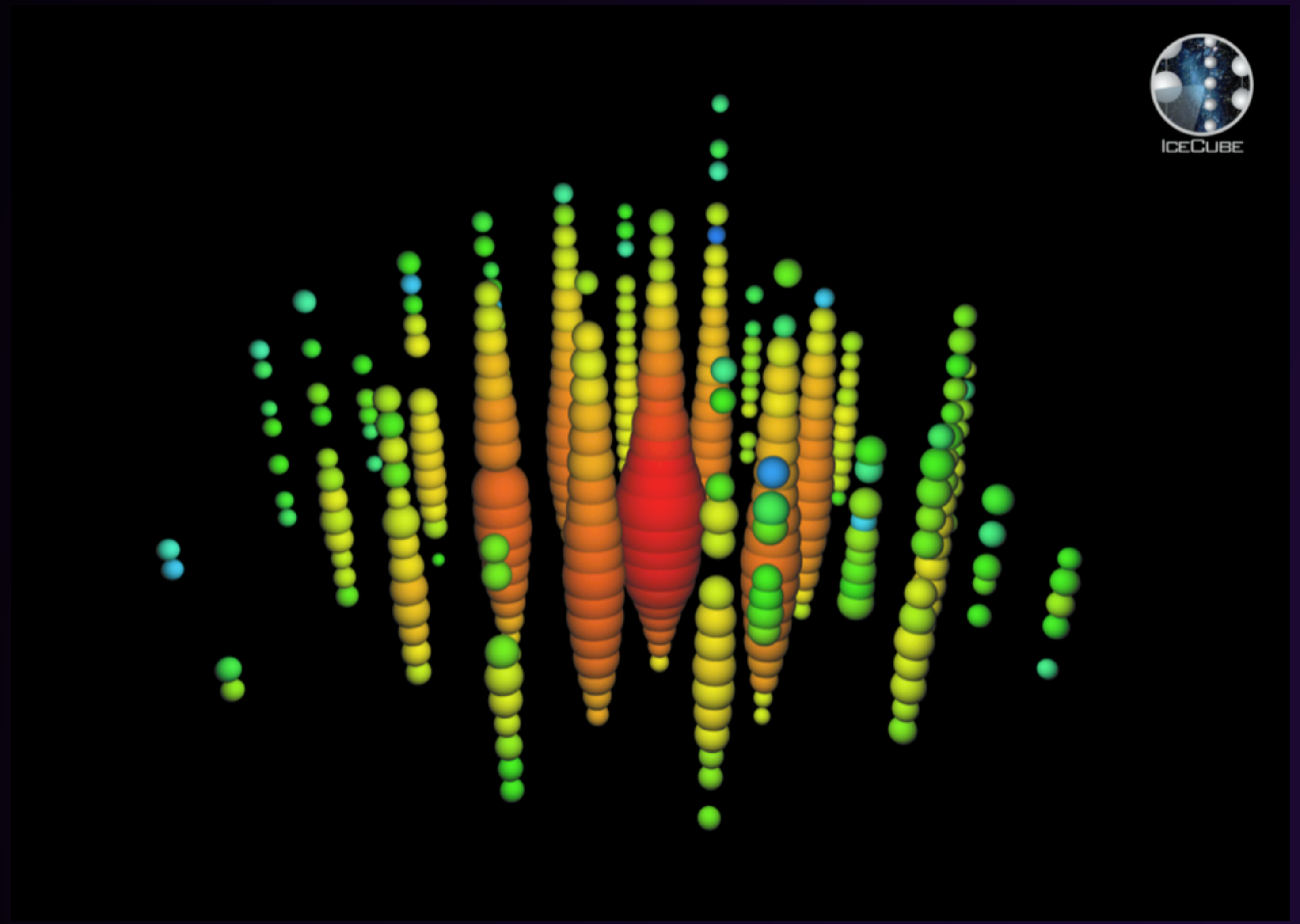
$$E_\mu < E_\nu$$



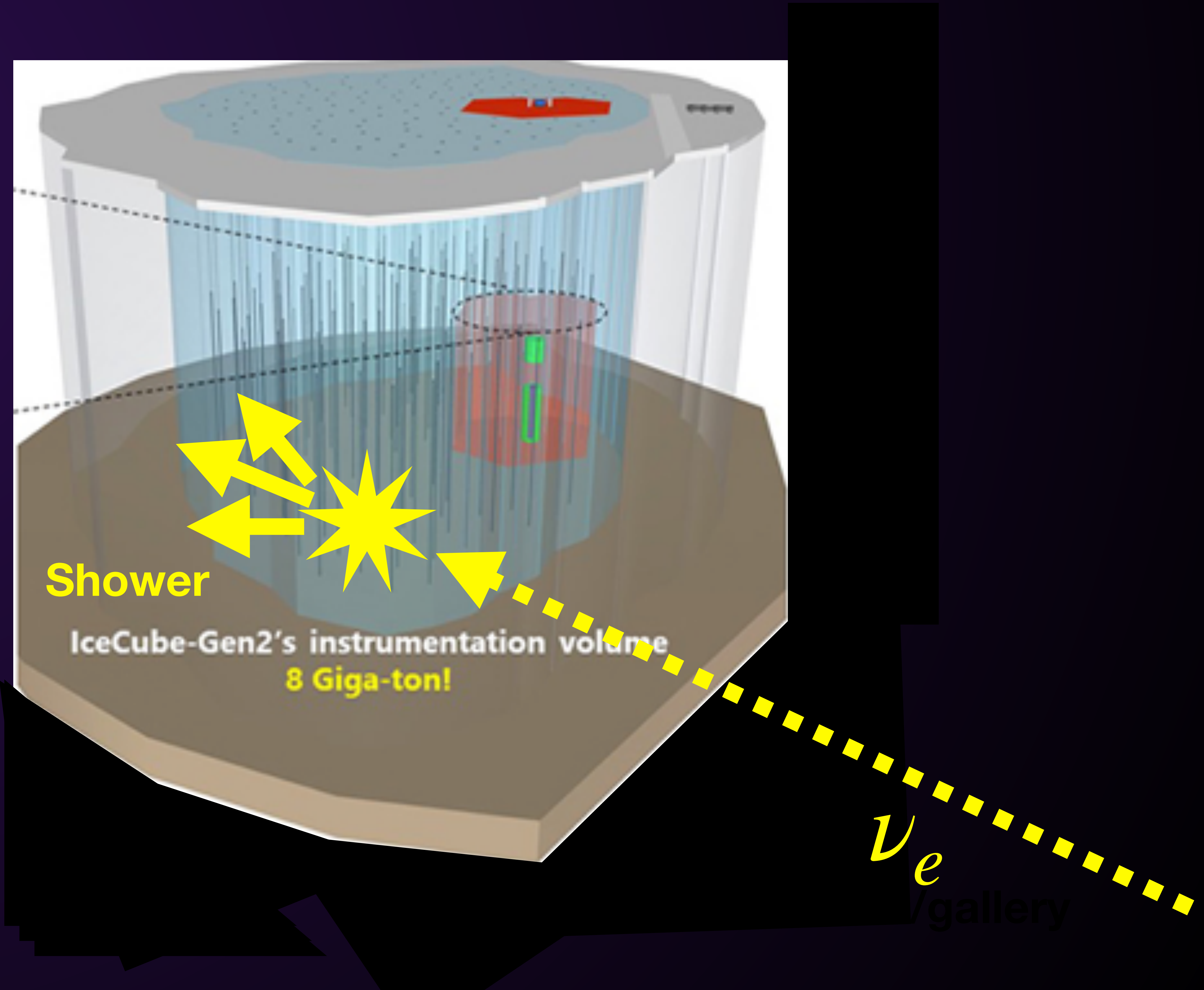
- Muons leave long track-like signature
- Observe muon neutrinos that interacted inside/outside the detector
- Useful for source searches due to good angular resolution (sub-degree)

Searches for Milky Way’s sources

https://icecube.wisc.edu/gallery



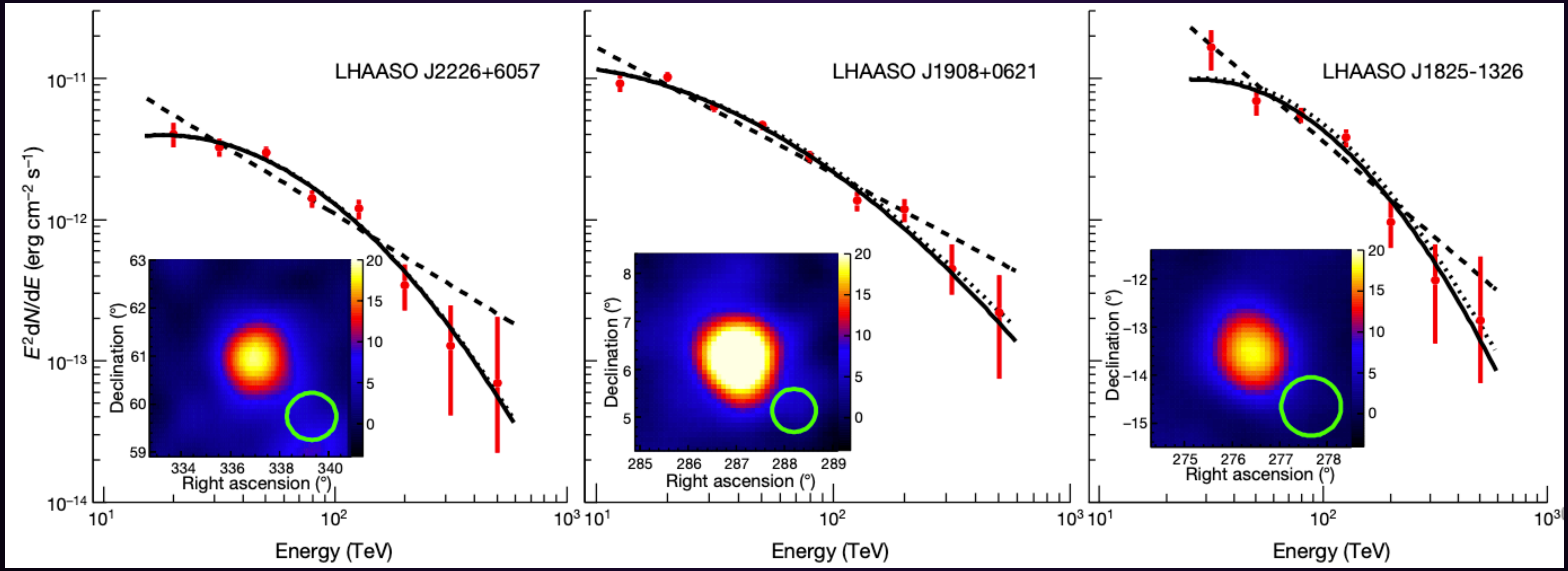
$$E_{\mathrm{sh}} \simeq E_\nu$$



- Electrons produce short-range shower of hadronic/electromagnetic
- Observe electron neutrinos that interacted inside the detector
- Spherical due to light scattering by the ice

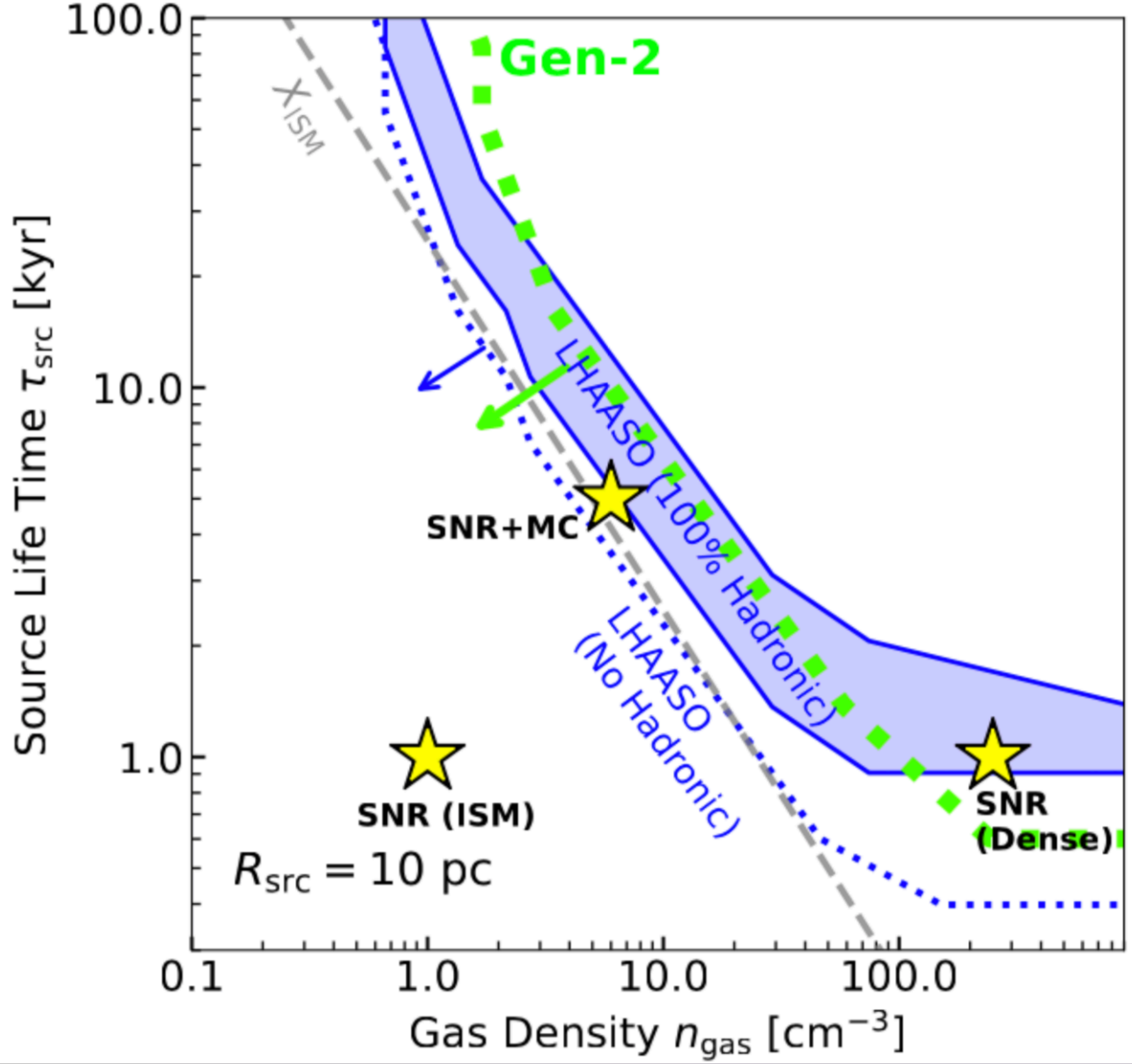
Features of gamma-ray sources

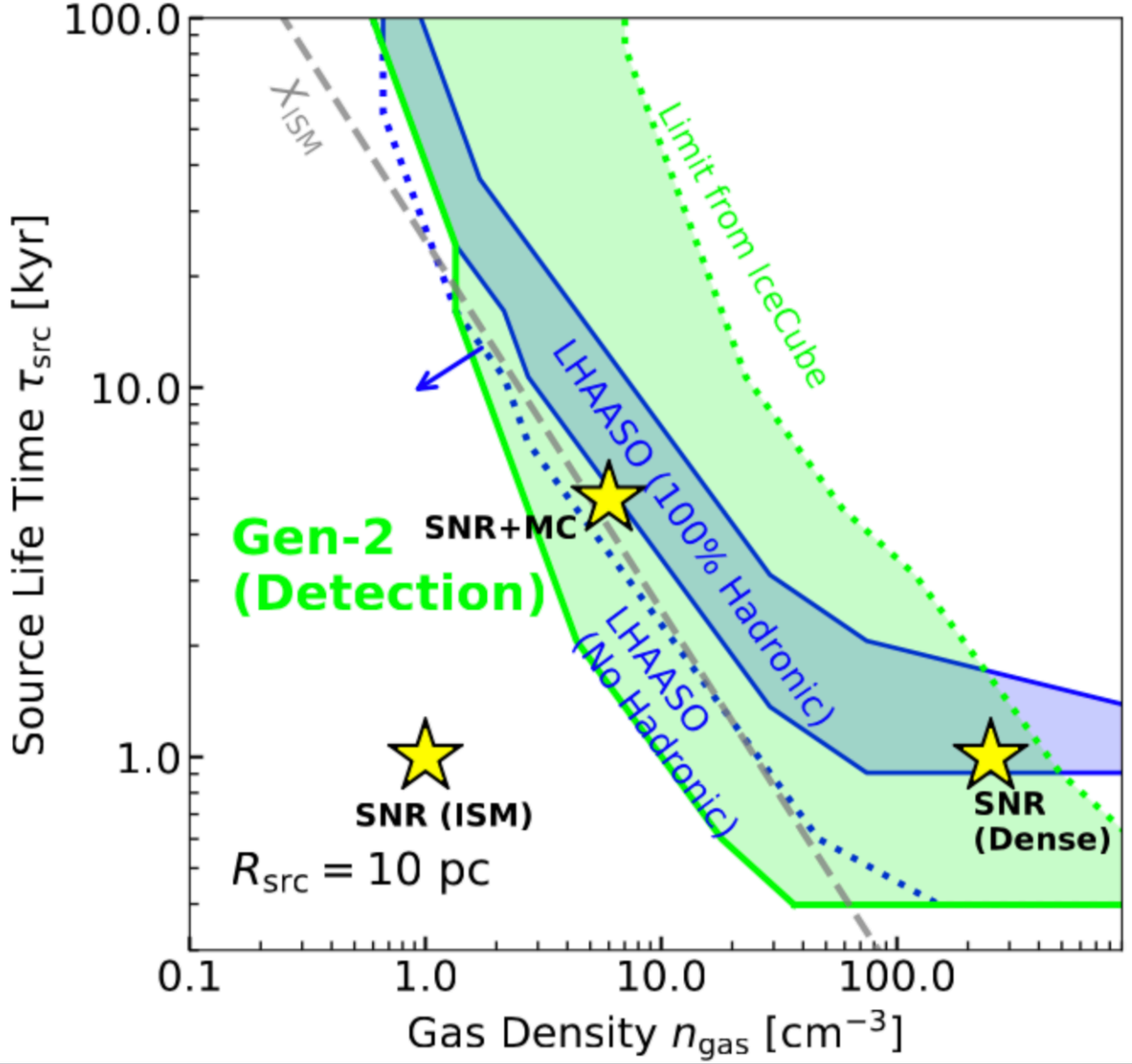
- LHAASO observed twelve gamma-ray sources above 100 TeV. Three brightest sources are :
  - Spatially extended
  - increasingly stepping spectra



LHAASO Collaboration (2021, Nature)

Source Size

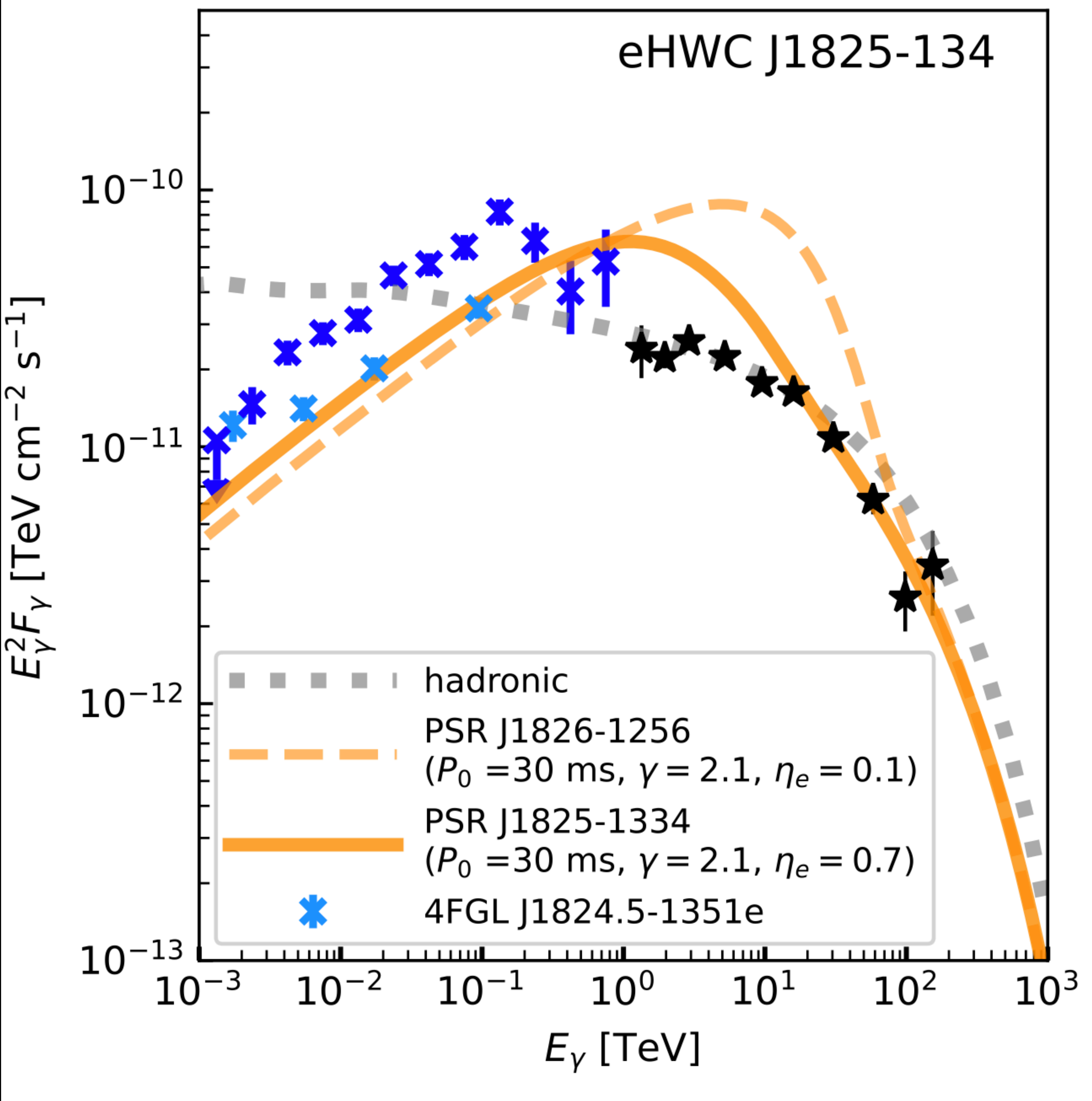

100.0
10.0
1.0
0.1
1.0
10.0
100.0
Source Life Time τ_{src} [kyr]
Gas Density n_{gas} [cm^{-3}]
X_{ISM}
Gen-2
LHAASO (100% Hadronic)
LHAASO (No Hadronic)
SNR+MC
SNR (ISM)
SNR (Dense)
R_{src} = 10 pc


100.0
10.0
1.0
0.1
1.0
10.0
100.0
Source Life Time τ_{src} [kyr]
Gas Density n_{gas} [cm^{-3}]
X_{ISM}
Limit from IceCube
LHAASO (100% Hadronic)
LHAASO (No Hadronic)
Gen-2 (Detection)
SNR+MC
SNR (ISM)
SNR (Dense)
R_{src} = 10 pc

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

LHAASO Collaboration (2021, Nature)



eHWC J1825-134
$E_\gamma^2 F_\gamma$ [TeV cm^{-2} s^{-1}]
E_γ [TeV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
hadronic
PSR J1826-1256
(P_0 =30 ms, $\gamma = 2.1$, $\eta_e = 0.1$)
PSR J1825-1334
(P_0 =30 ms, $\gamma = 2.1$, $\eta_e = 0.7$)
4FGL J1824.5-1351e