Where are hadronic PeVatrons? – Constraints and Prospects

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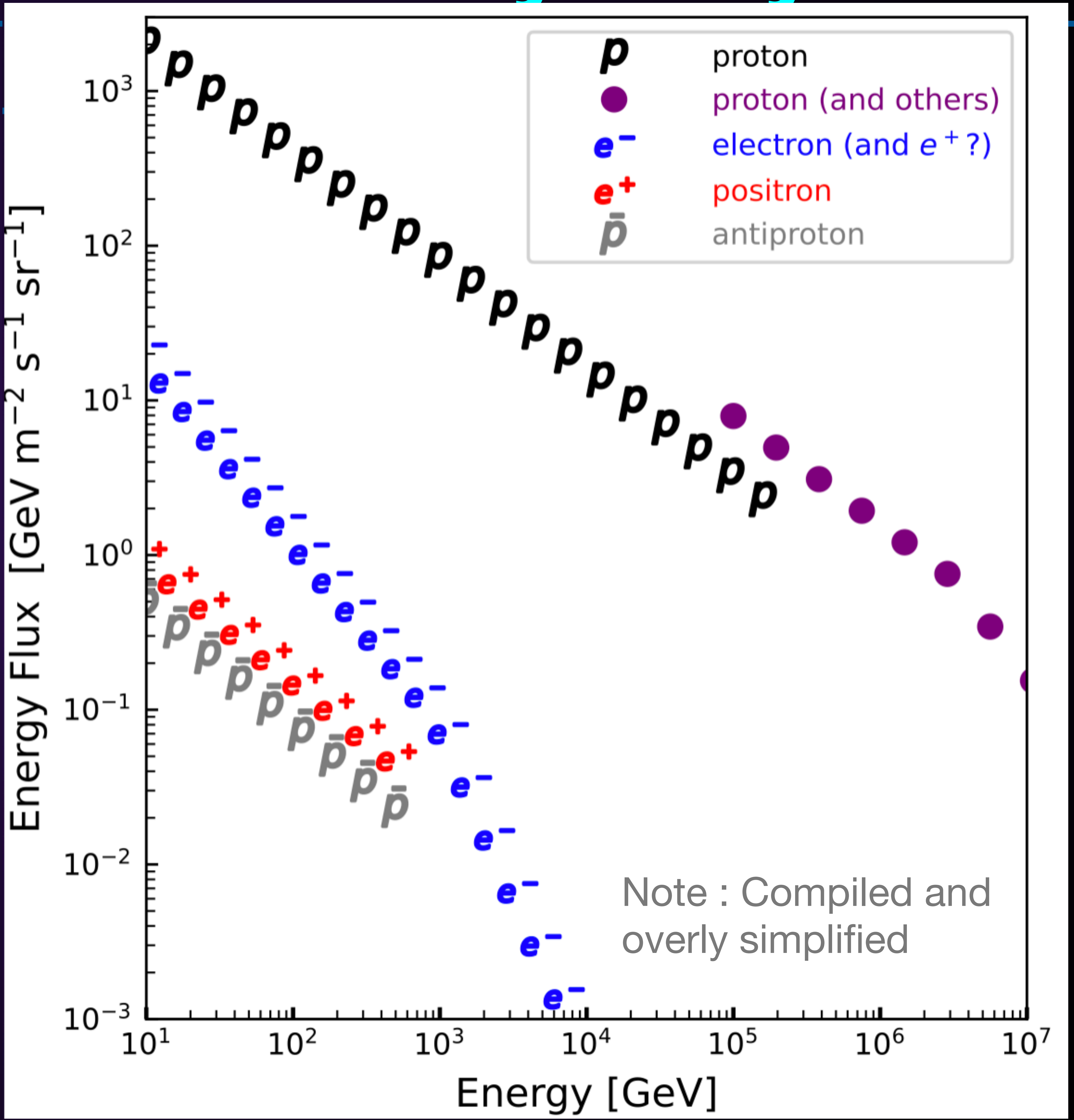
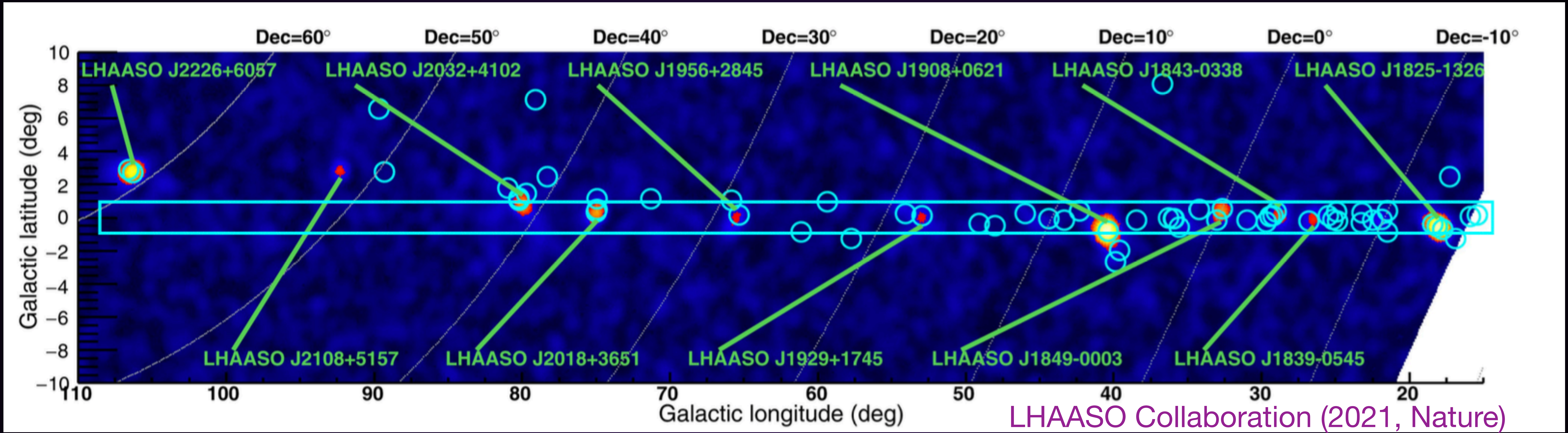
In collaboration with : John F. Beacom (OSU)

Hadronic PeVatrons in the Milky Way

- PeV hadrons from the Milky Way's sources
- Many source classes seem to accelerate GeV - TeV hadrons
- Mysterious : which ones can reach PeV energies ("PeVatrons")

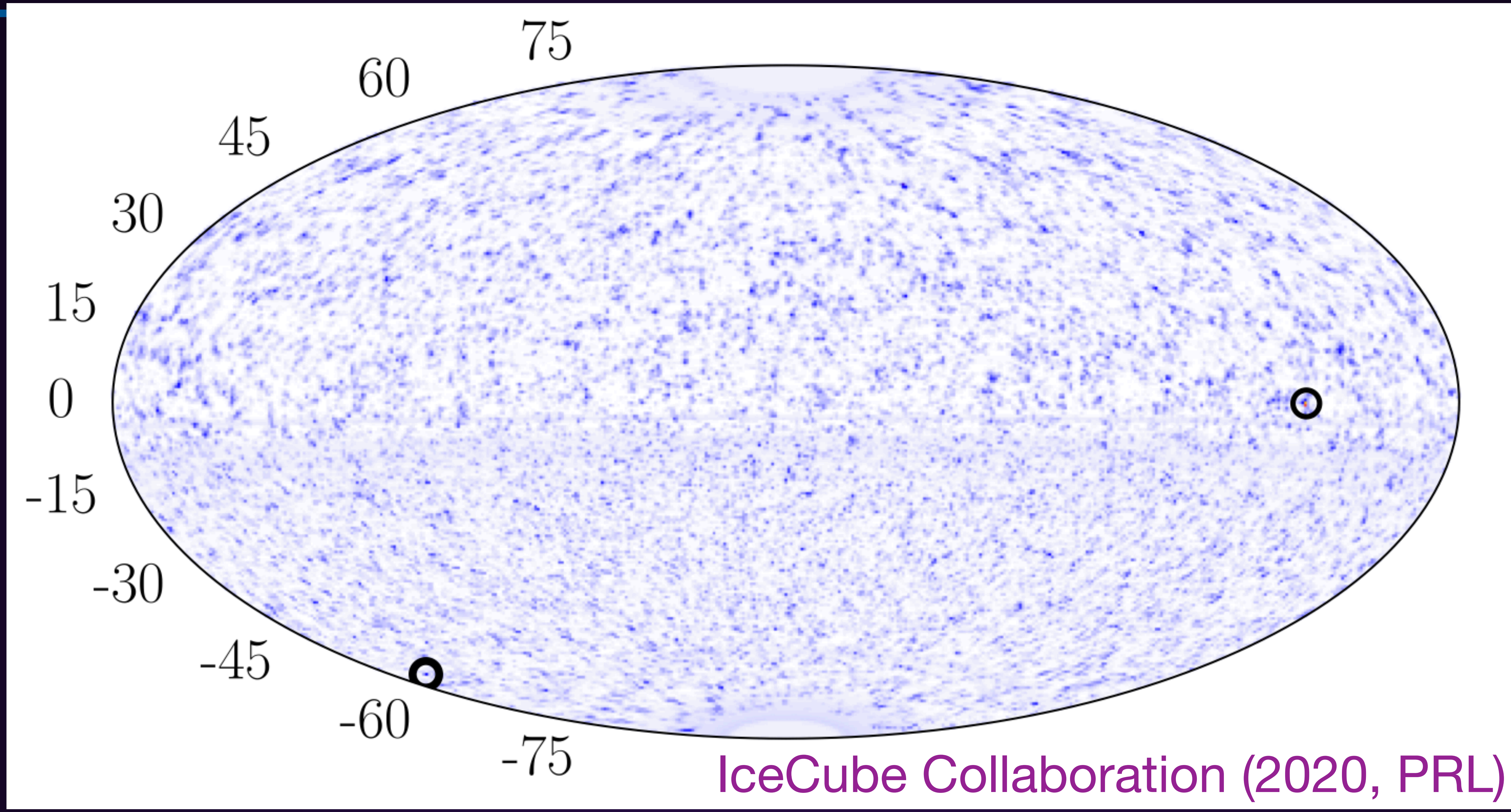


Gamma-ray sources beyond 100 TeV



- Hadronic PeVatrons produce ~ 100 TeV gamma rays
- Tibet ASγ, HAWC, and LHAASO observe sources at such high energies!
- Promising candidates for hadronic PeVatrons

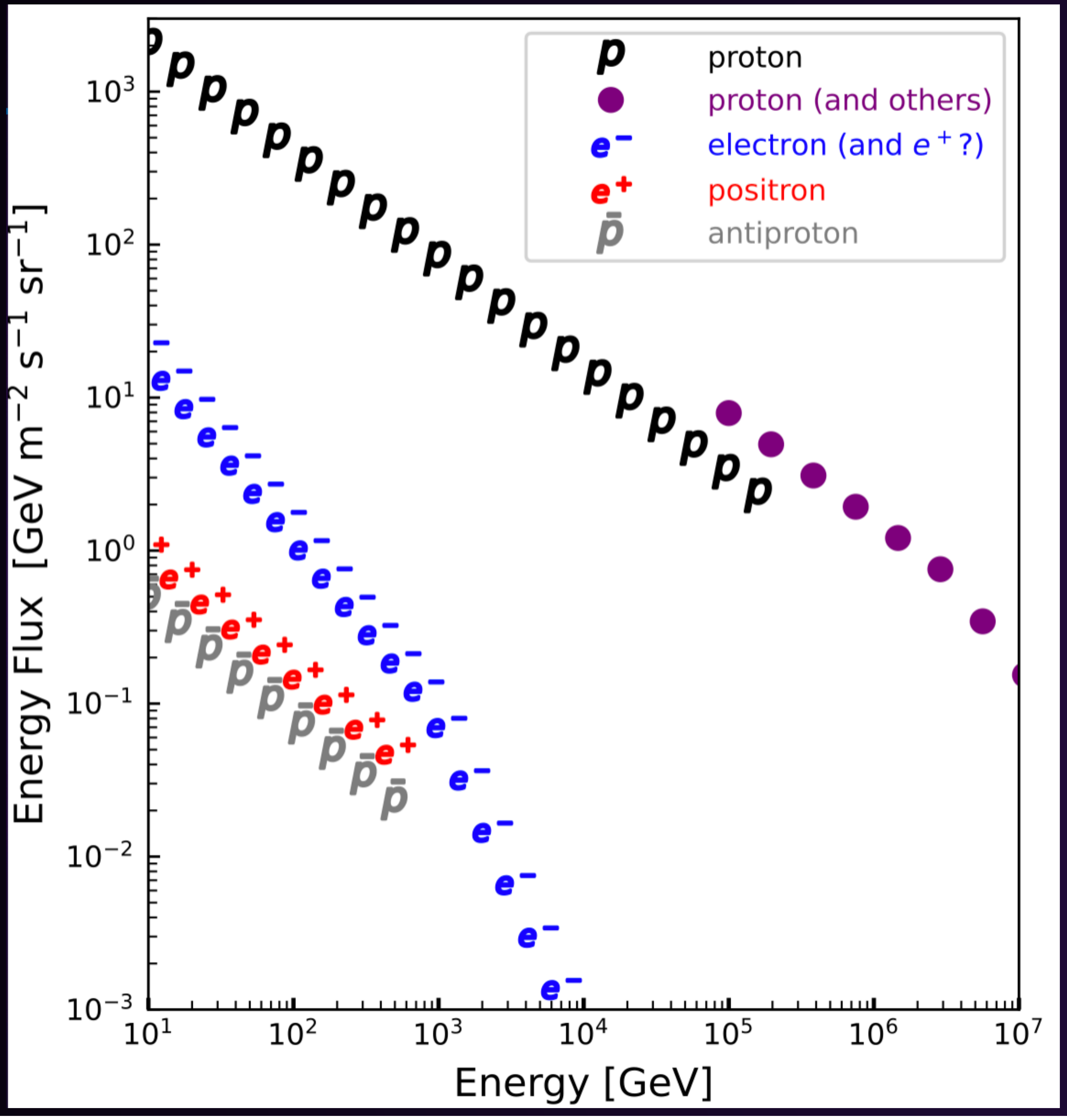
Neutrino sources at TeV - PeV energies



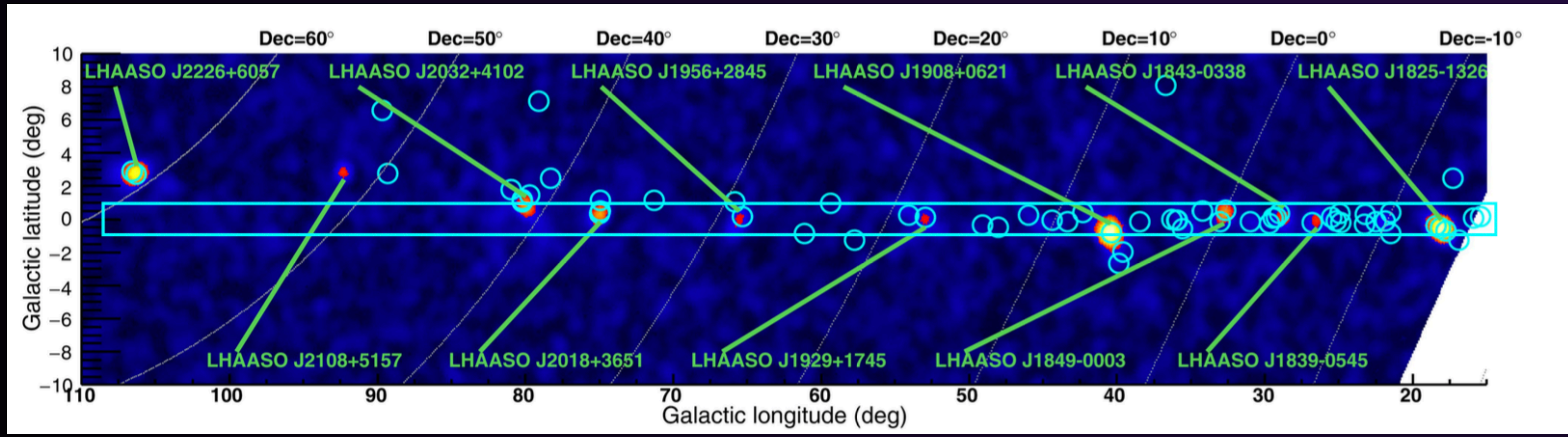
IceCube Collaboration (2020, PRL)

- Hadronic PeVatrons produce ~ 100 TeV neutrinos
- Non detection of Milky Way's sources
- Where are hadronic PeVatrons?

Connection between CR - gamma - nu ?



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



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

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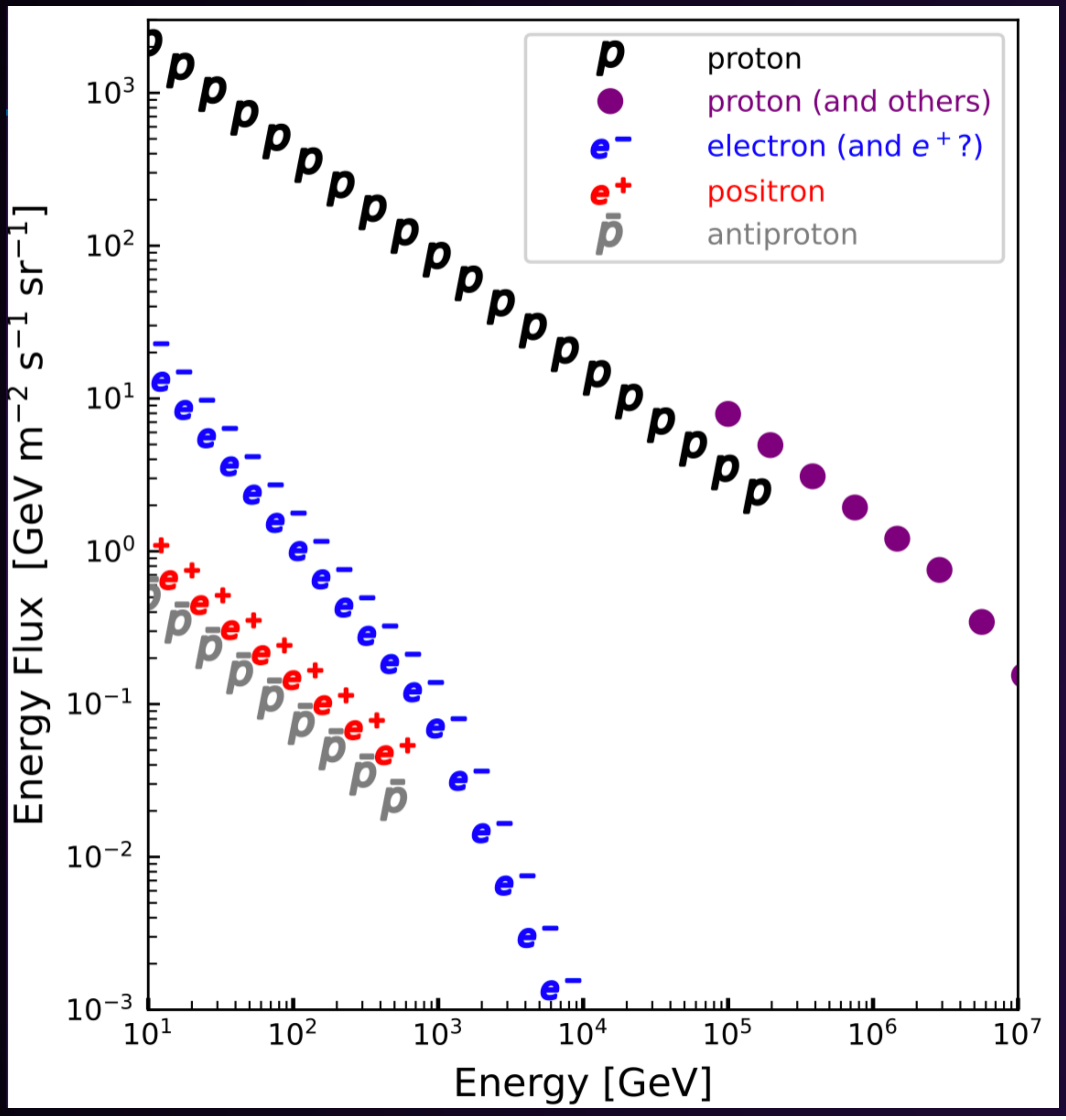

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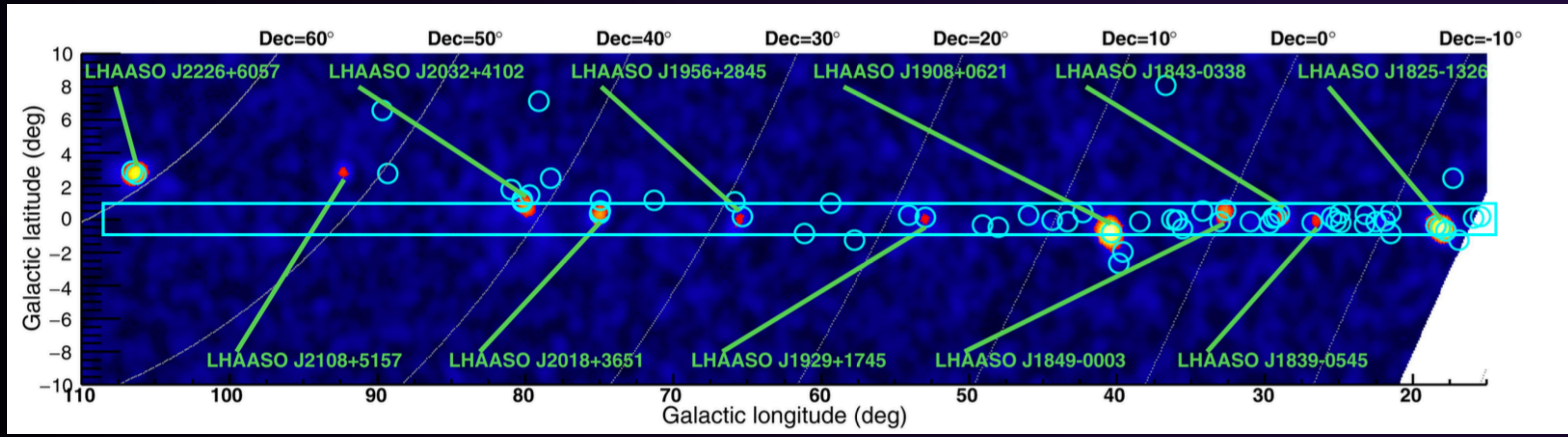
How to consistently understand CR, gamma rays, and neutrinos?



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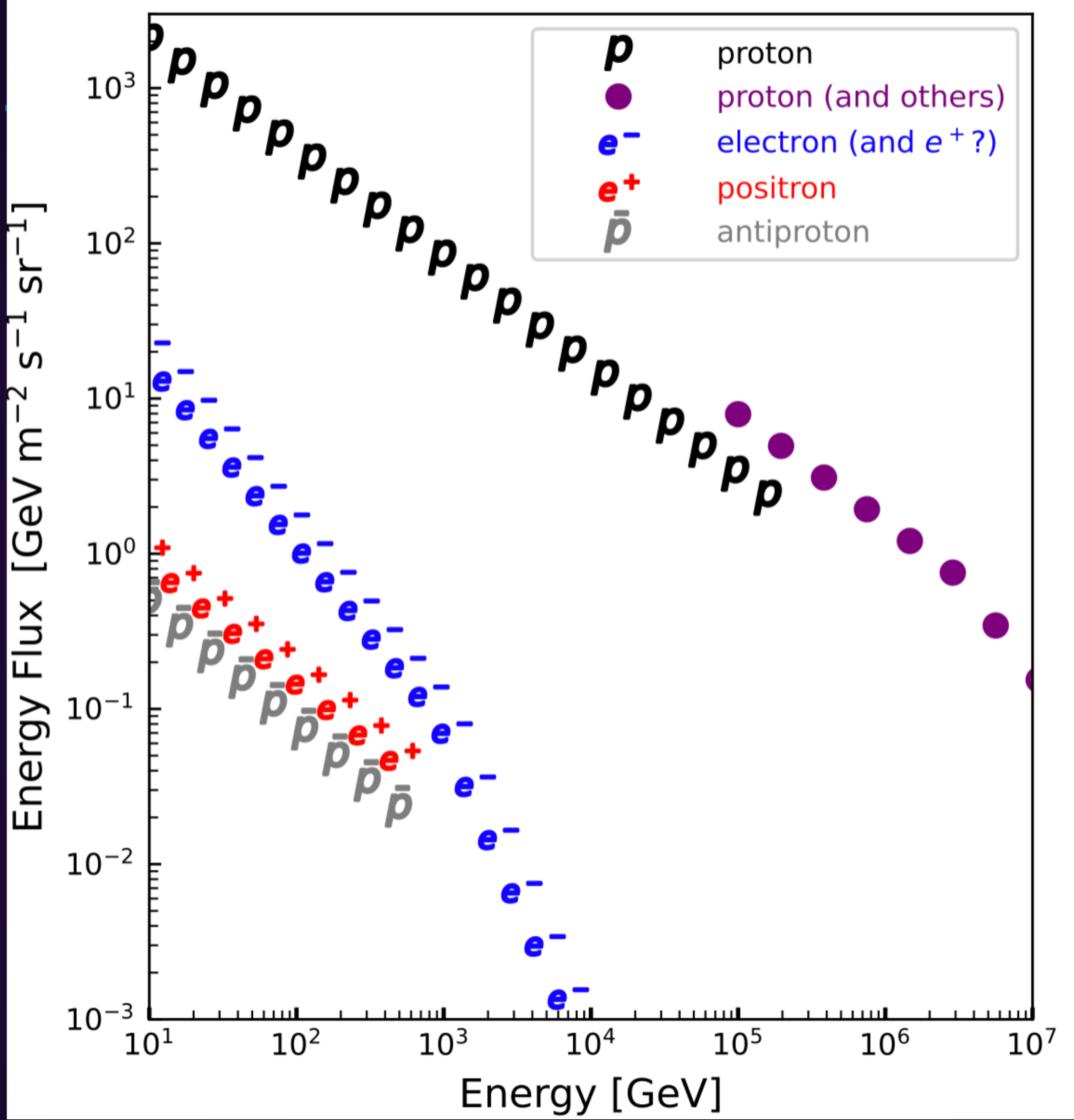
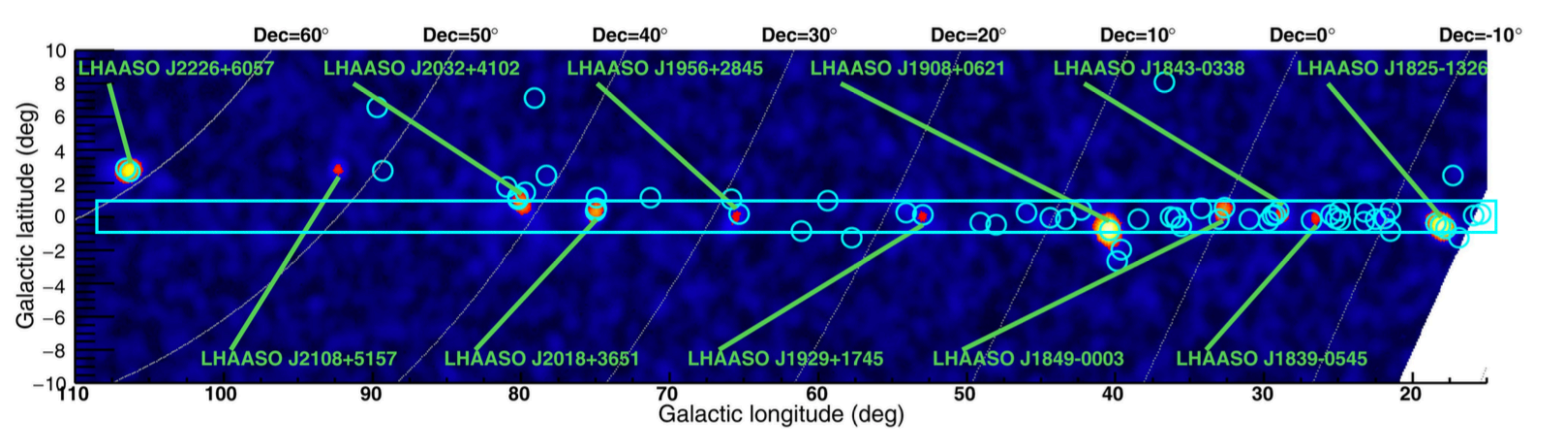
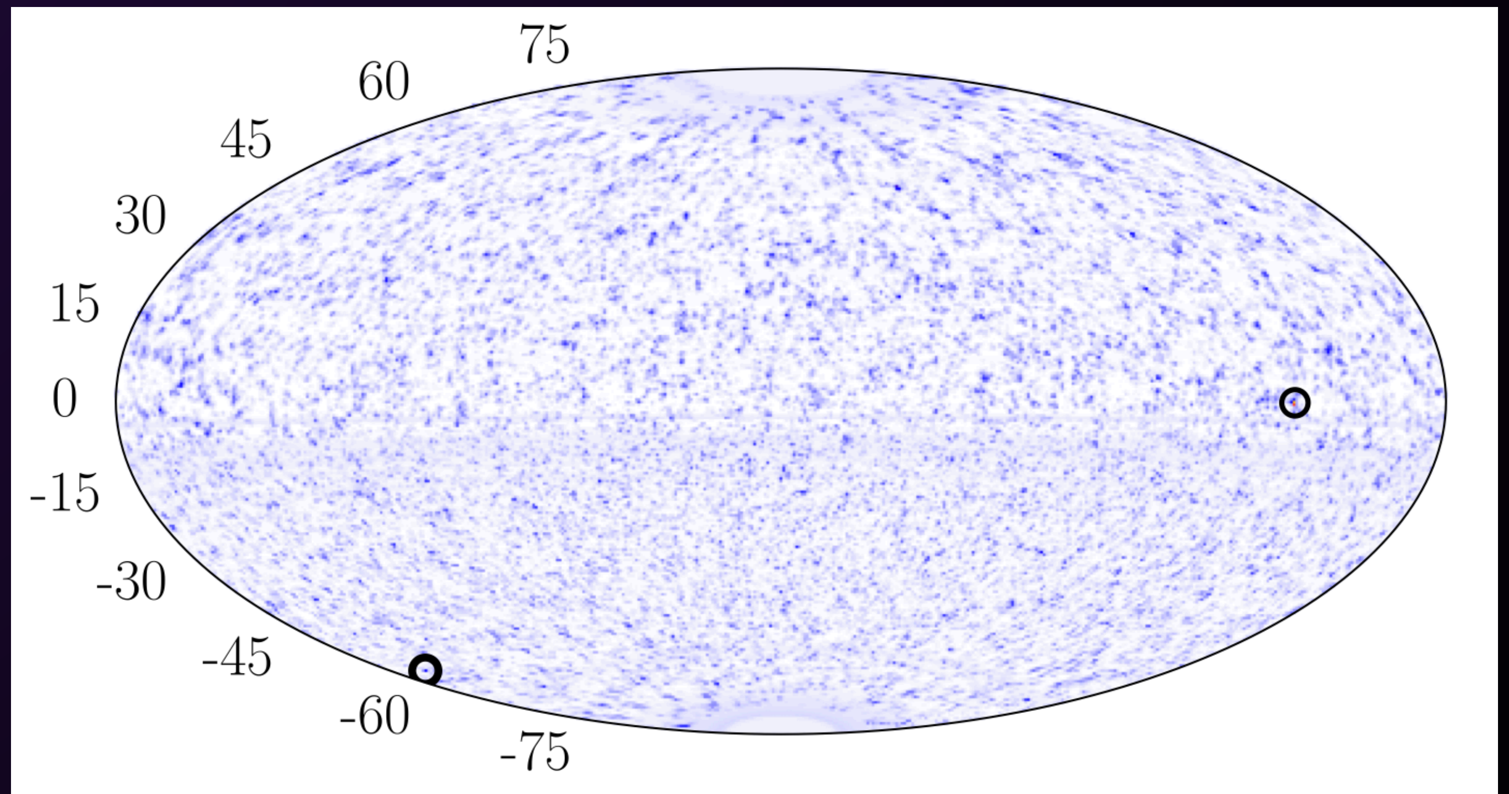
Understanding High-Energy Multi-Messengers

Understanding multi messengers

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







Cosmic-ray sources

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

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↓ Boron to Carbon data

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

Cosmic-ray sources

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

↓ Event Rate $\Gamma_{\rm CR}$

Cosmic-ray sources

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

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- 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).

Gamma-ray and neutrino sources

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Gas density around/in the source

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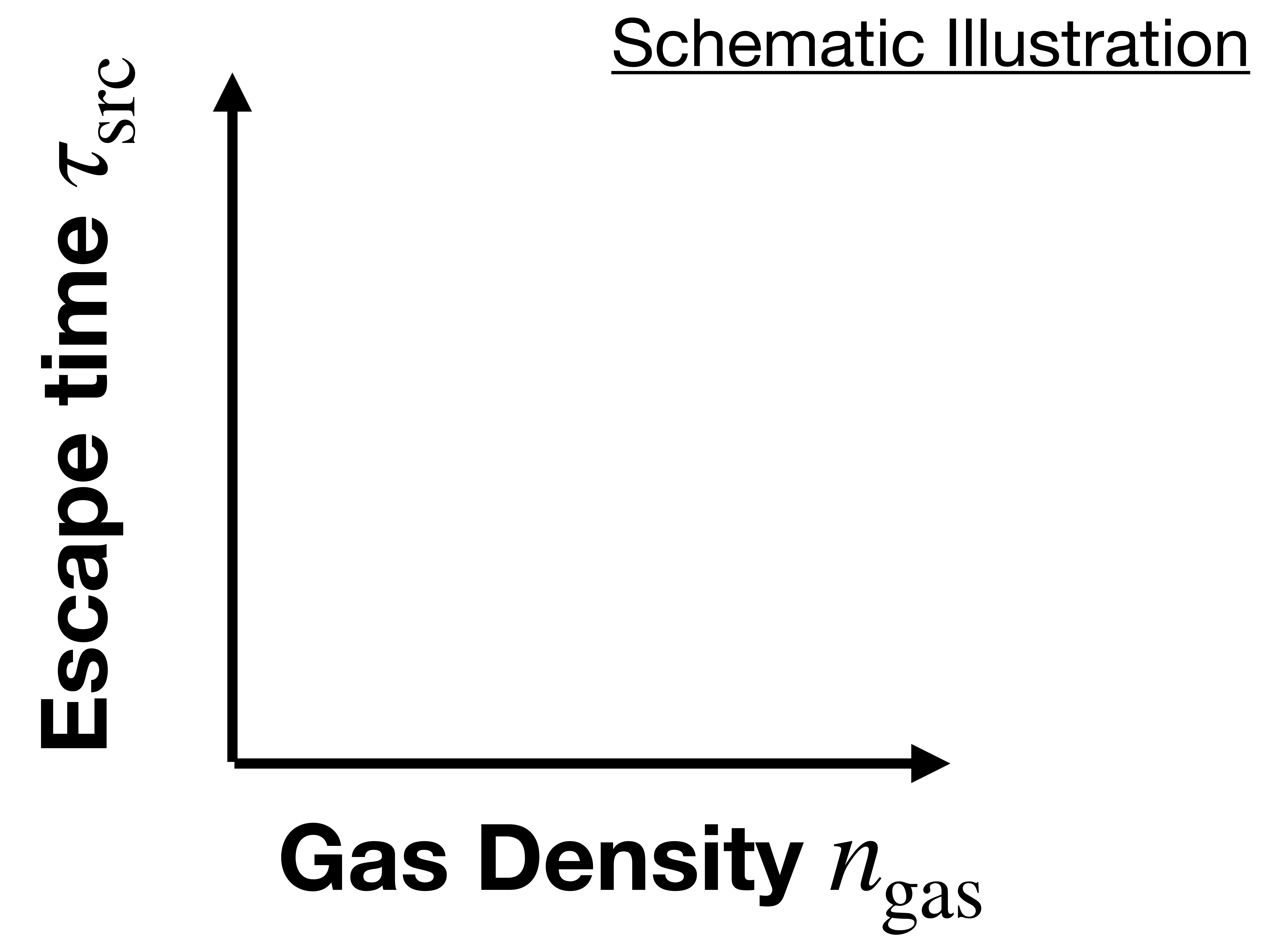
Gas density around/in the source

particle confinement timescale

Introducing "n-tau" plane



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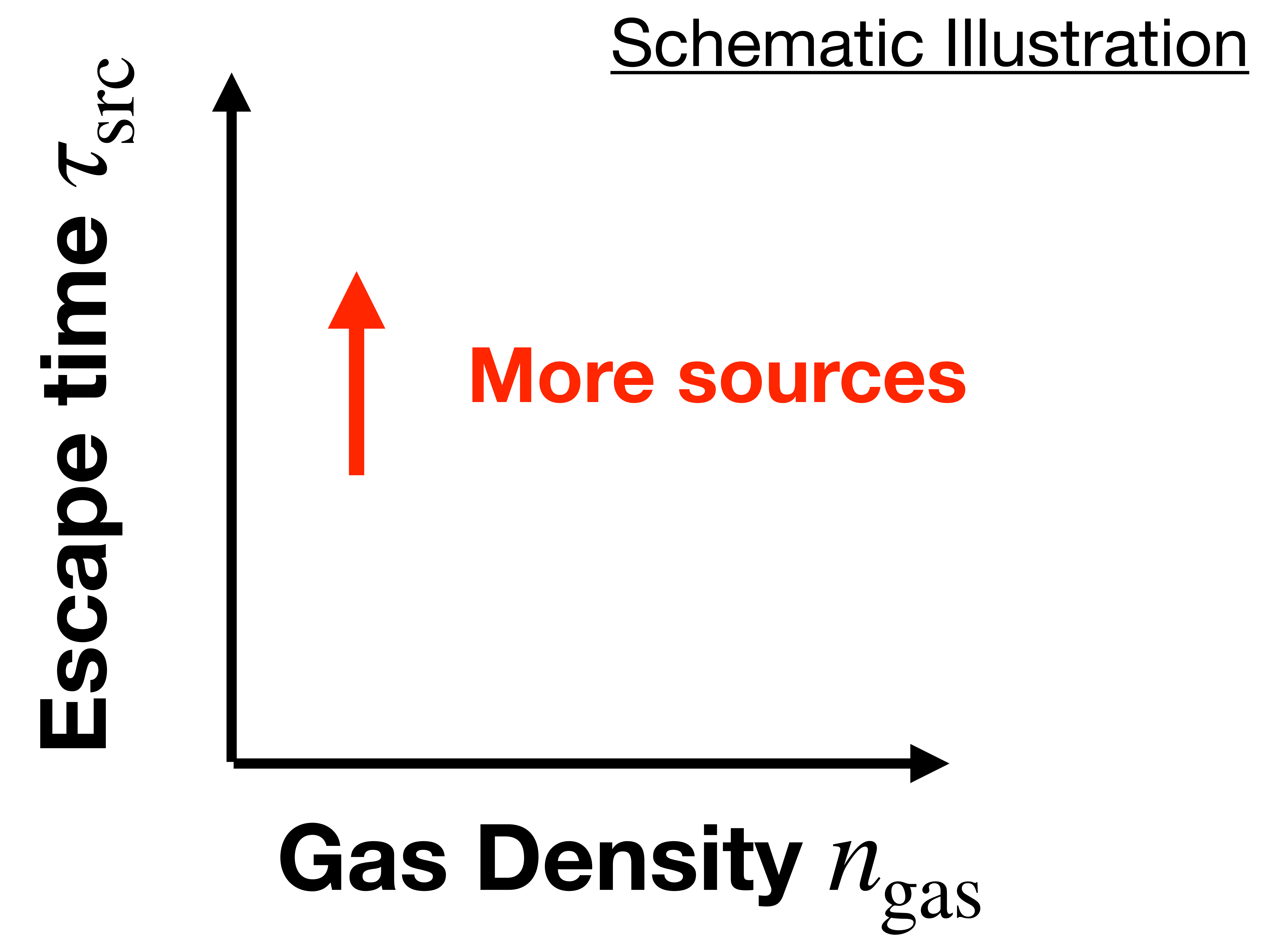

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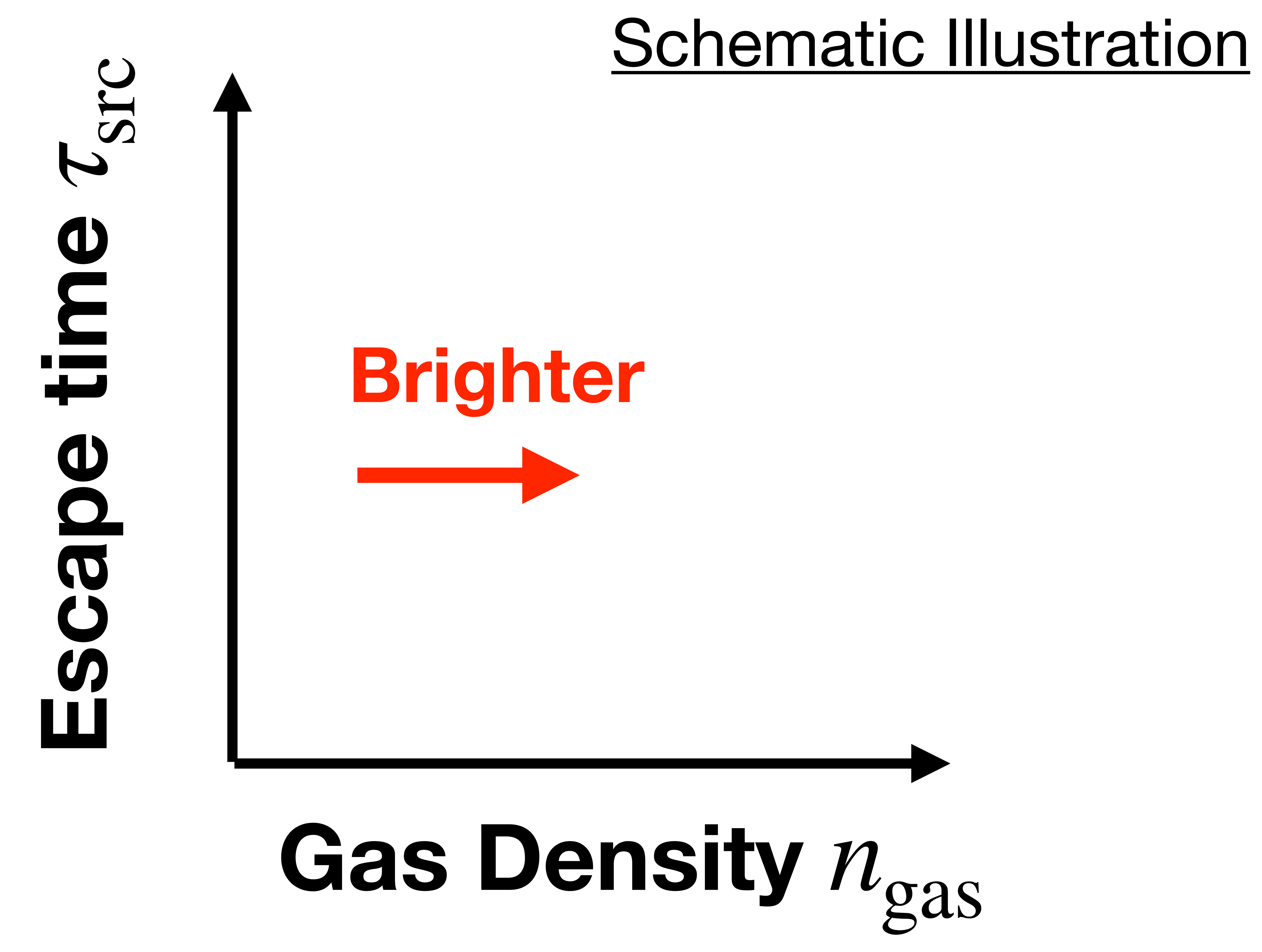

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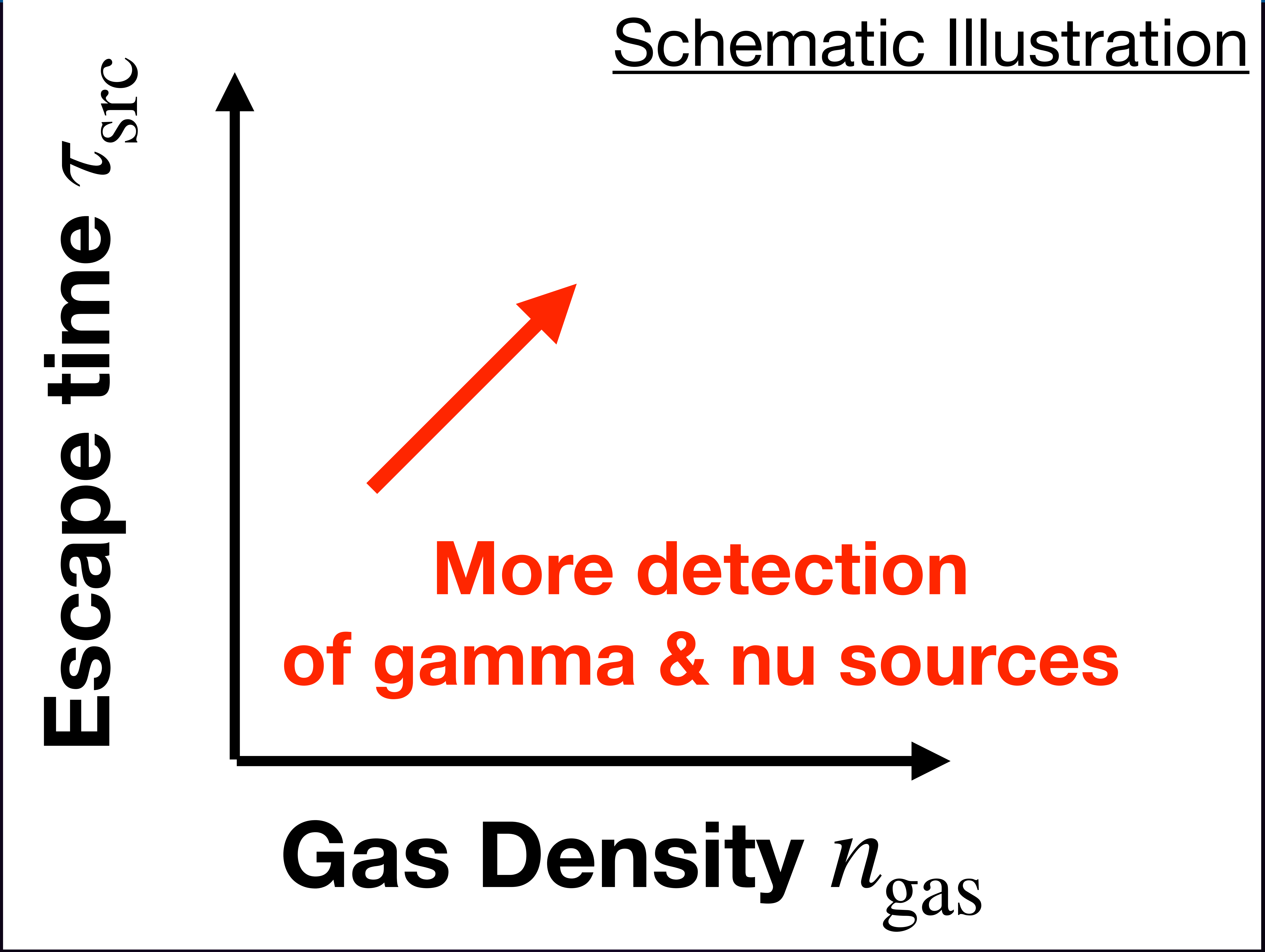

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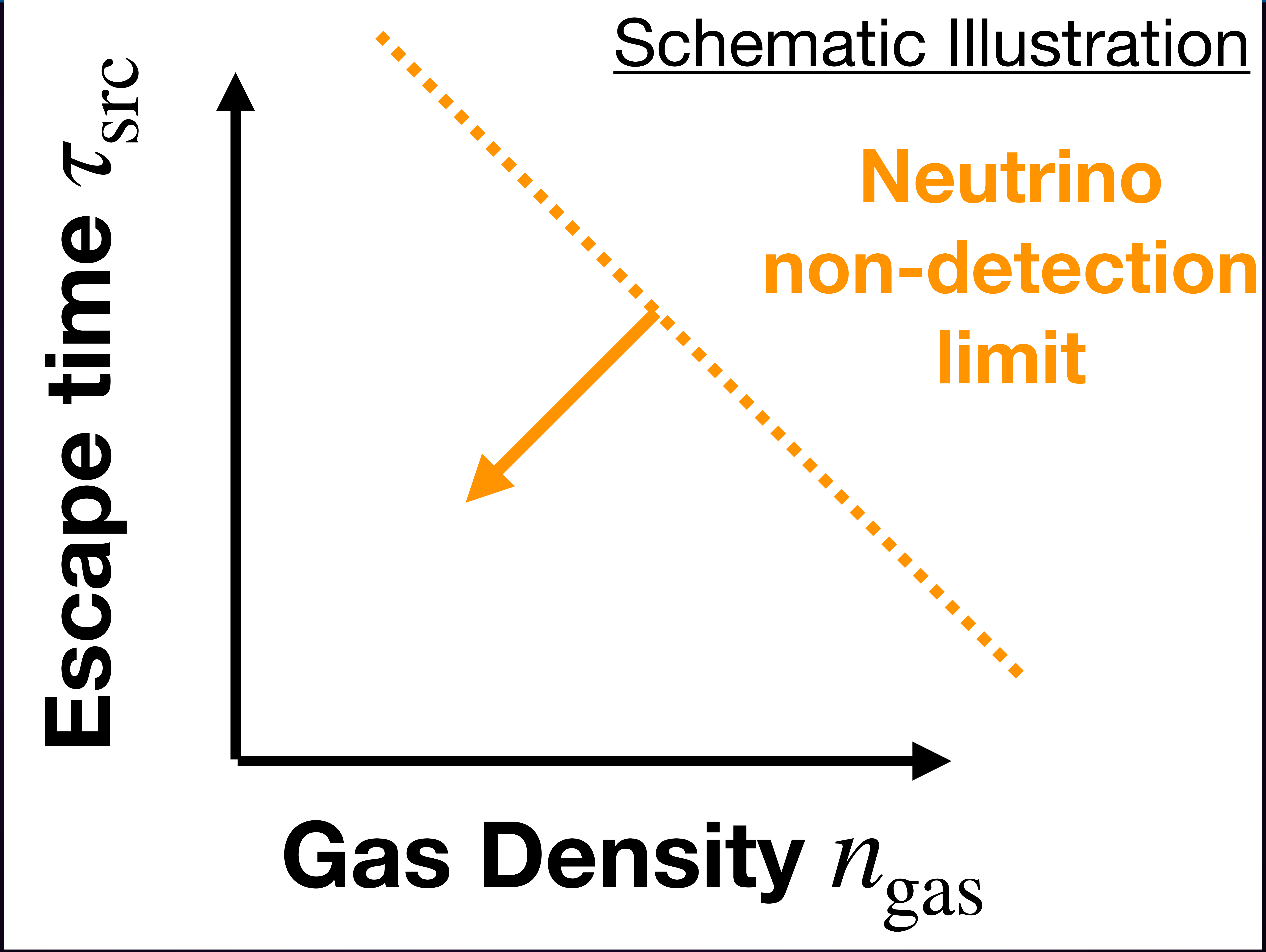

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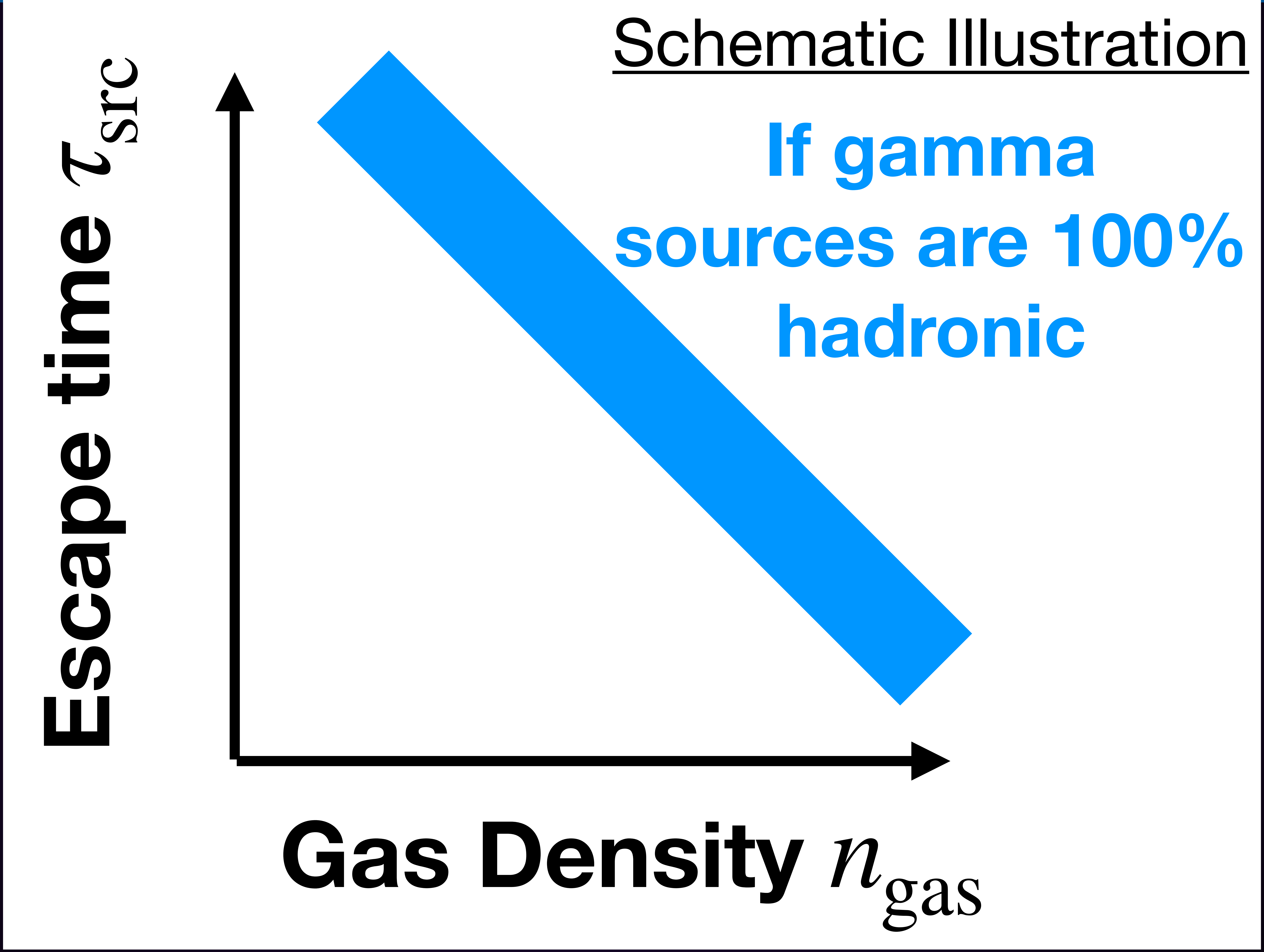

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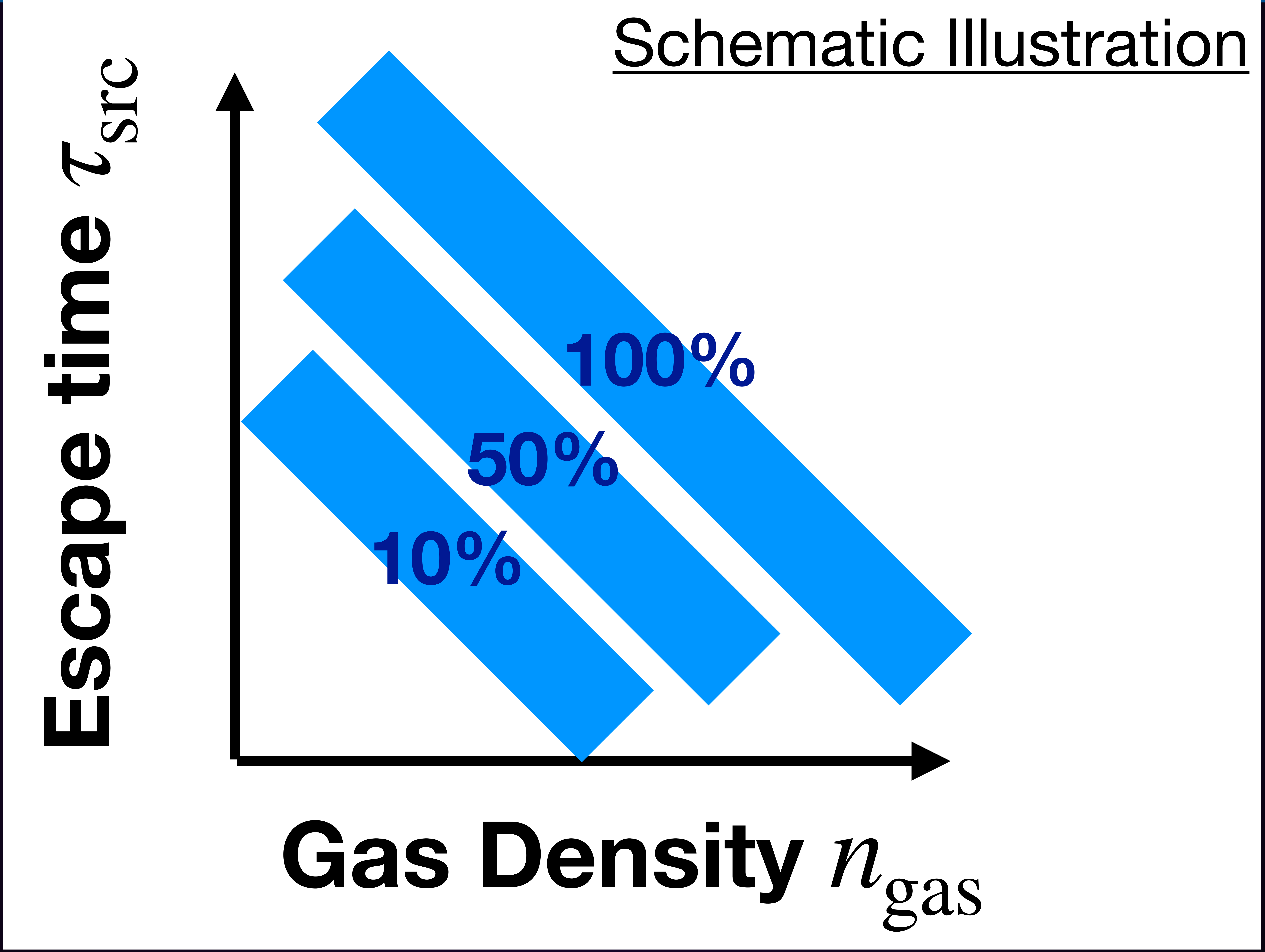

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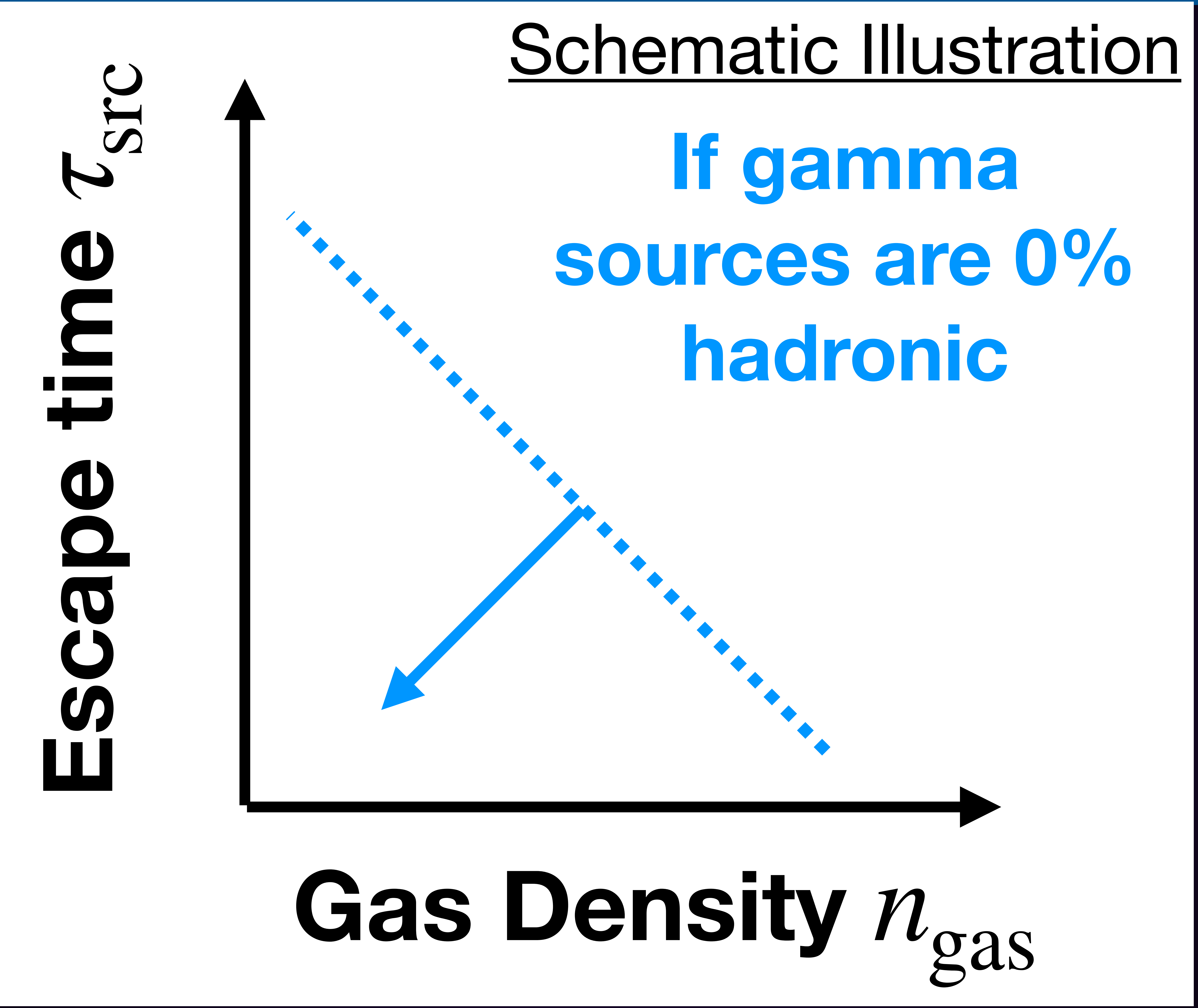

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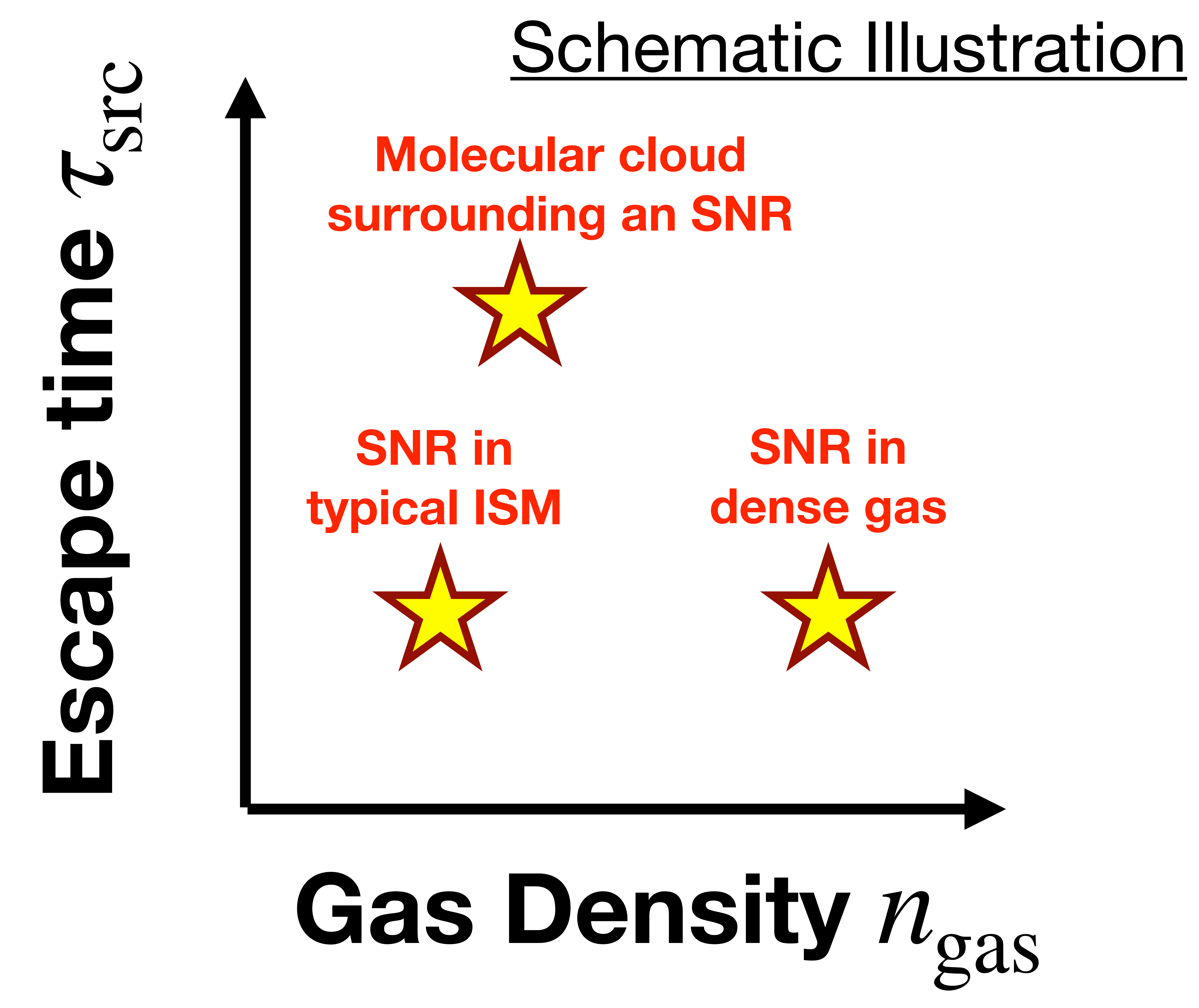
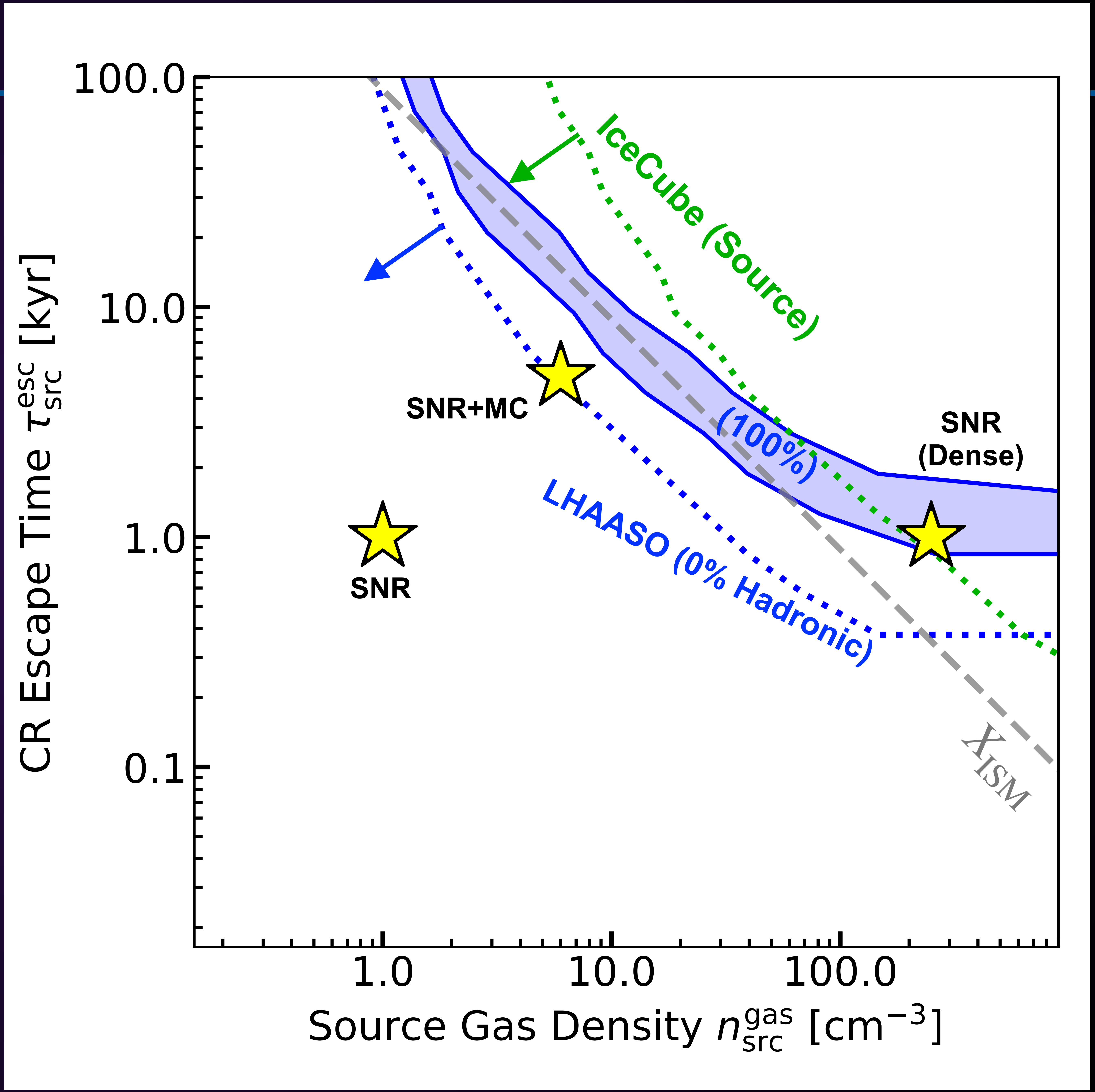


Population model

- Monte-Carlo simulation to obtain constraints in the n - tau plane.
  - Gamma-ray and neutrino spectra, detector properties, source size (10 pc) and spatial distribution (NS birthplace)
  - Assume Γ_{CR} = SN rate
- Gamma rays : LHAASO observations of 12 sources above 100 TeV
- Neutrinos : IceCube non-detection after decade of searches
- Reminder : **The n - tau plane is calibrated to the CR data.**
- Aim at consistent understanding of CR + gamma + nu

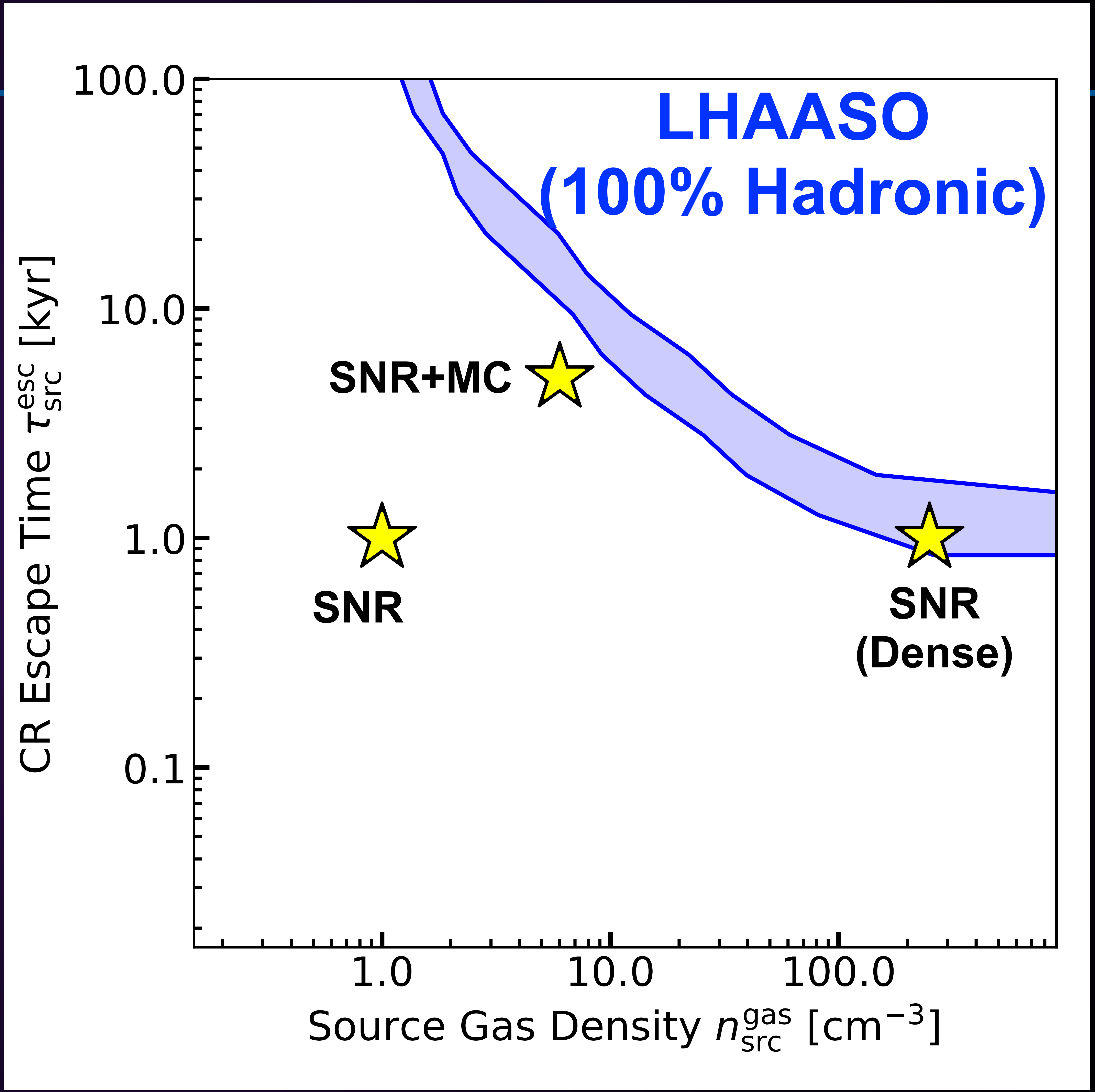
Main Results



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}]
IceCube (Source)
(100%)
LHAASO (0% Hadronic)
SNR+MC
SNR
SNR
(Dense)
X_{ISM}

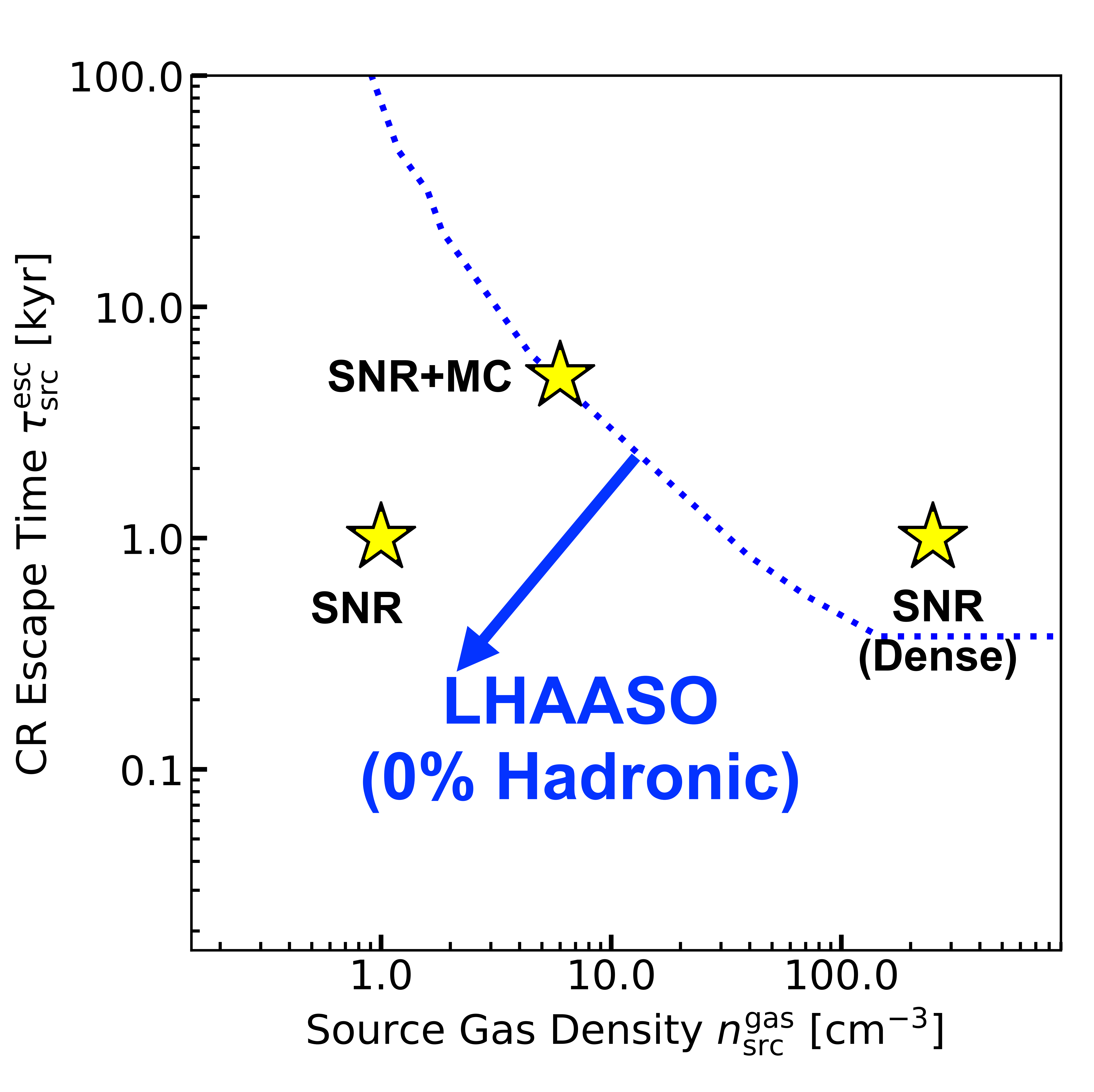
Gamma-ray

- Can all of LHAASO sources be **hadronic?**
- Yes!
- Rather high gas densities and confinement time.



Gamma-ray

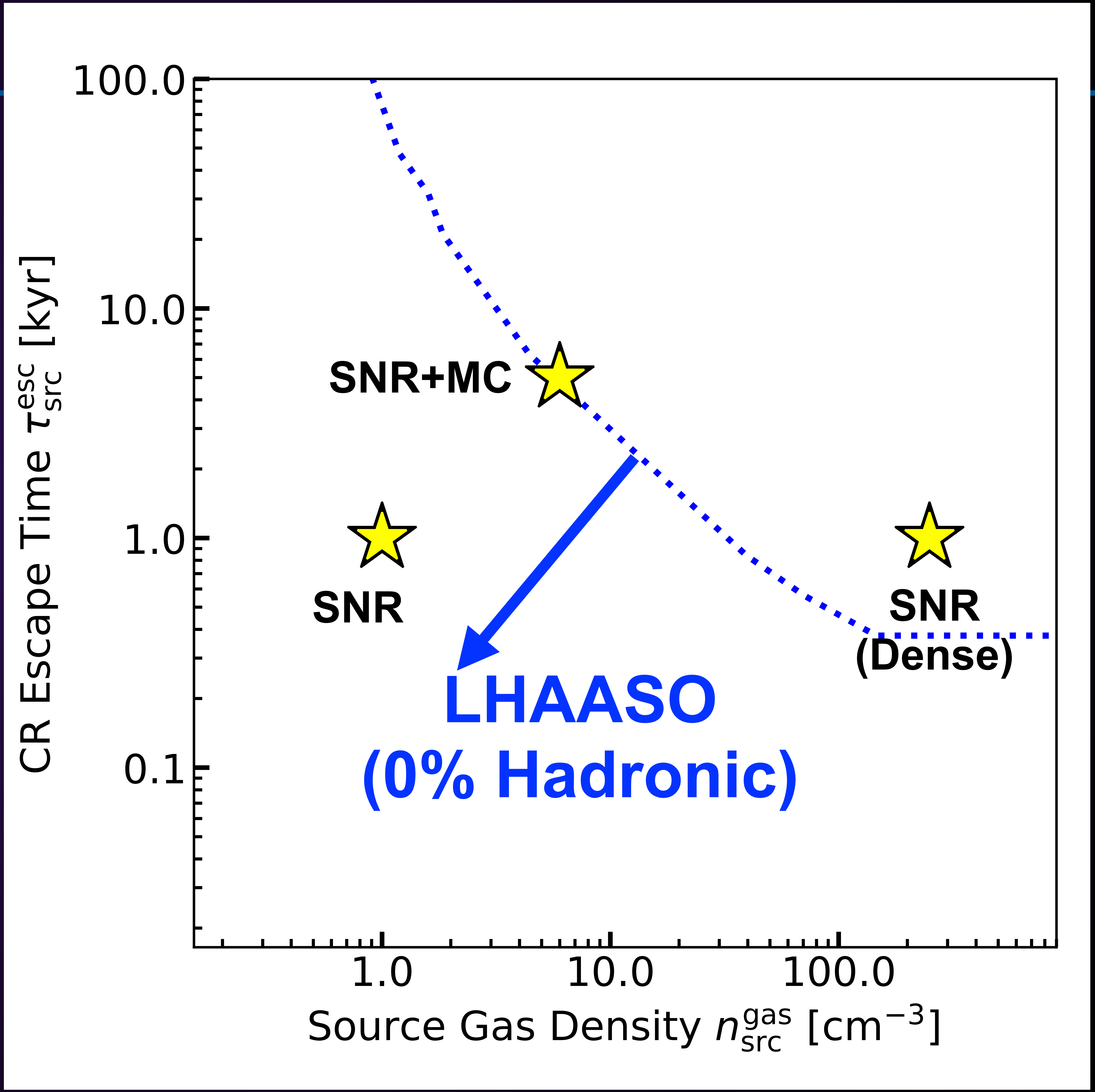
- Can all of LHAASO sources be **leptonic?**
- Yes!
- A wide range of models is consistent with such scenario



Gamma-ray

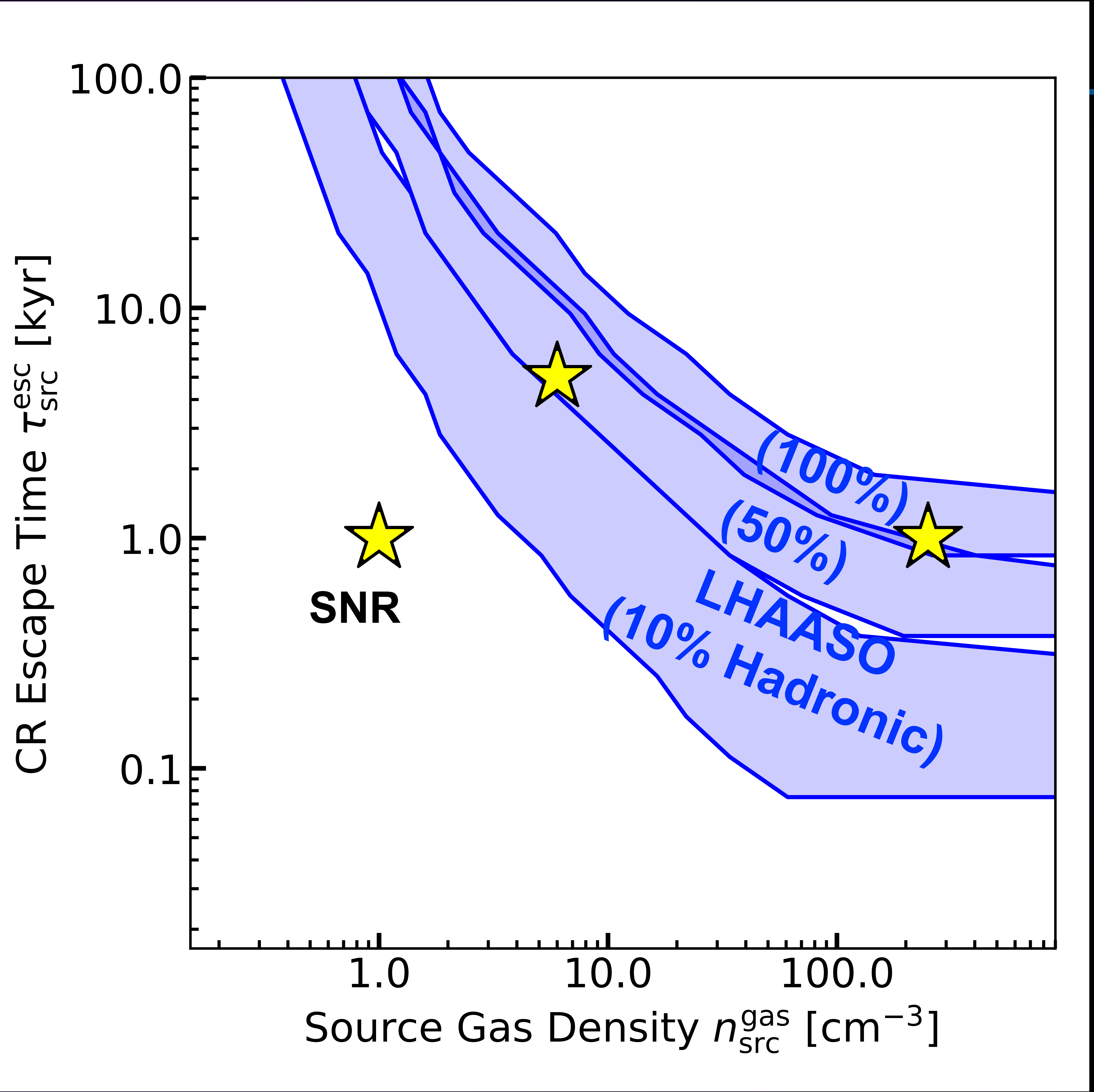
- Although no SNRs are established as 100 TeV gamma-ray source yet,

  SNRs can still be a viable PeVatron candidate



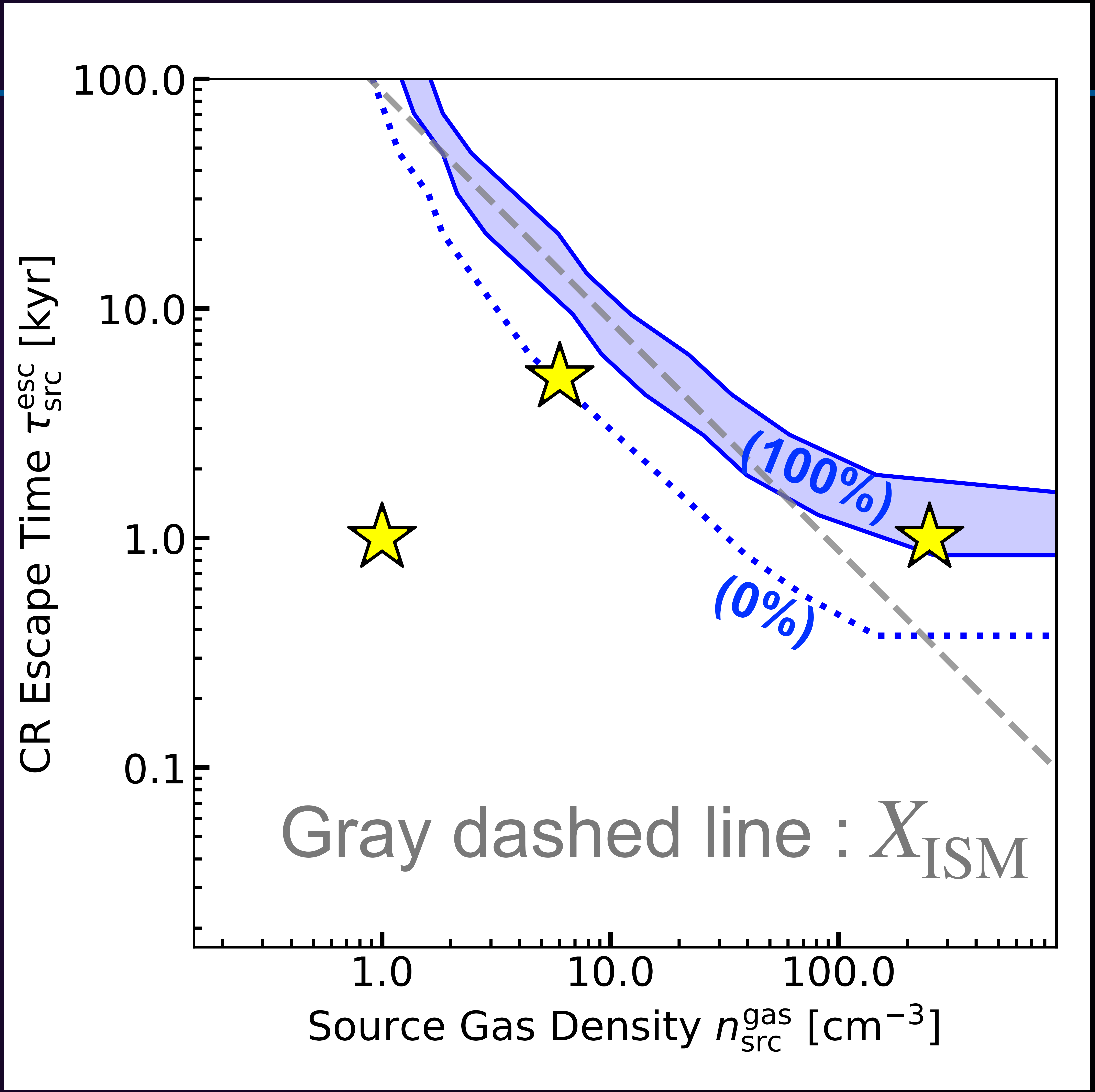
Gamma-ray

- More details on LHAASO hadronic fraction
- It is probable that one (or even a few) of them could be hadronic.



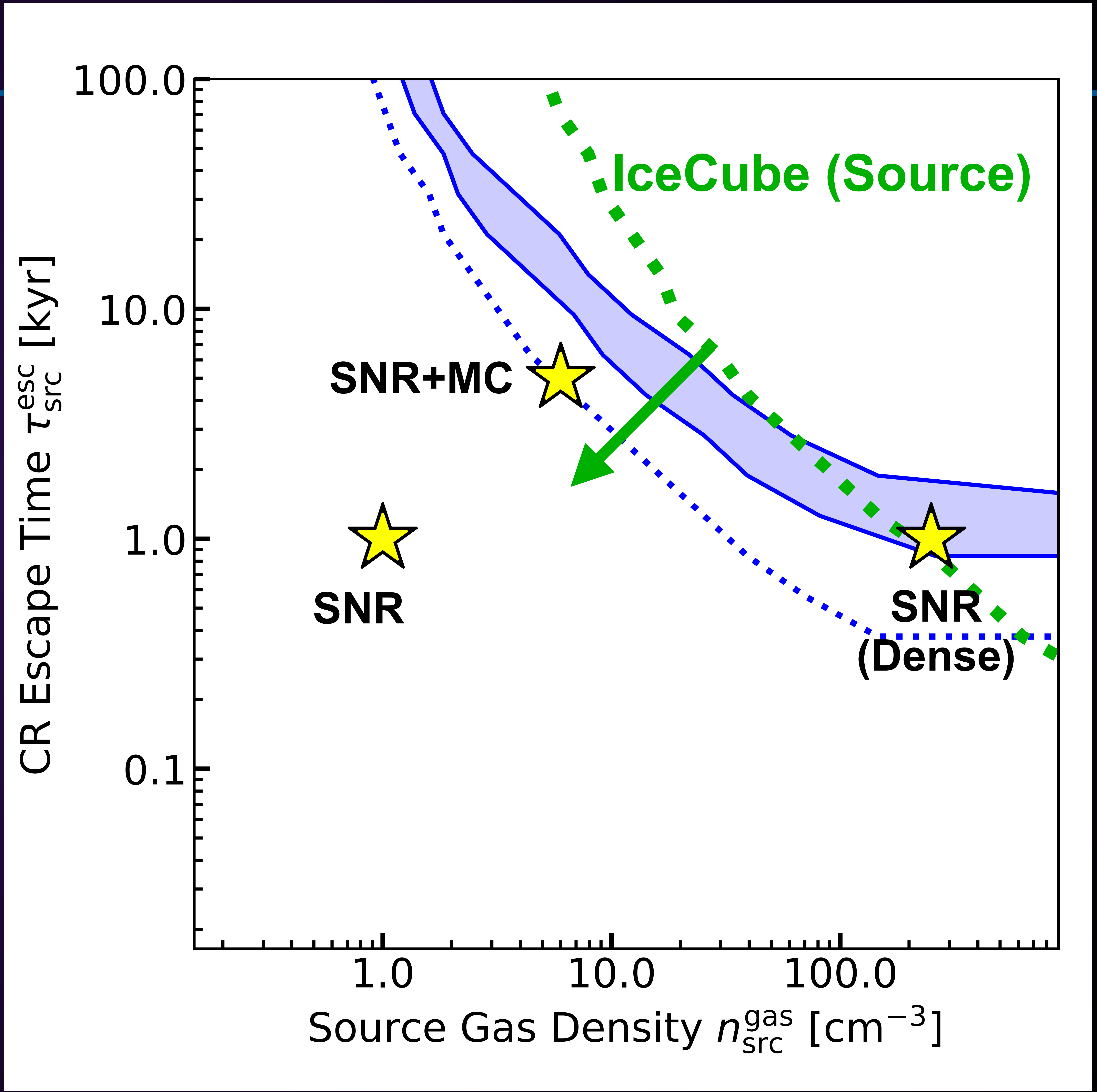
Source vs ISM

- Can (unresolved) sources important for **diffuse** gamma-ray emission?
- Yes!
- Compare grammage at the source vs ISM



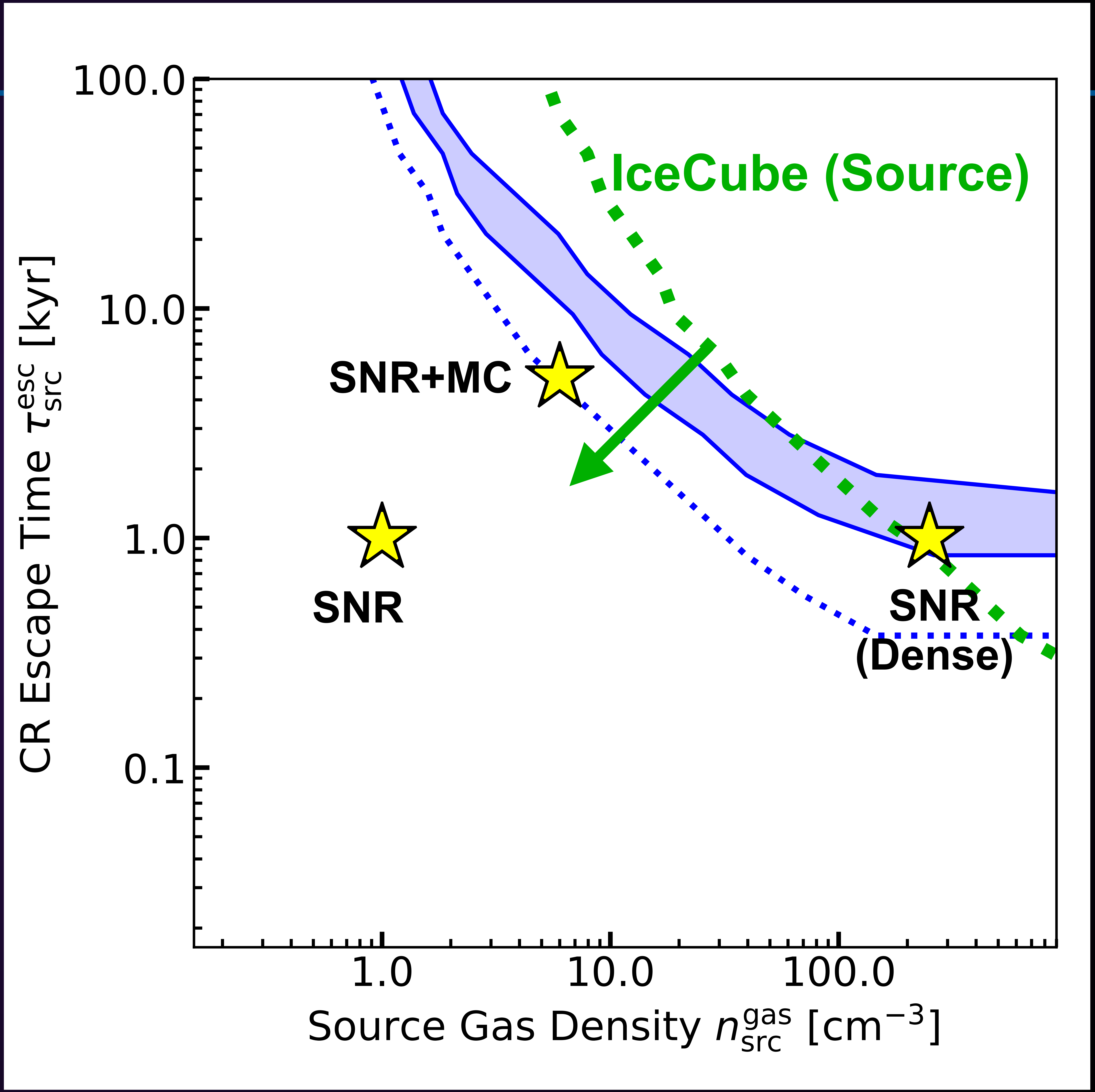
Neutrino

- **Does IceCube non-detection help?**
- Yes!
- Rule out regions of high gas densities.



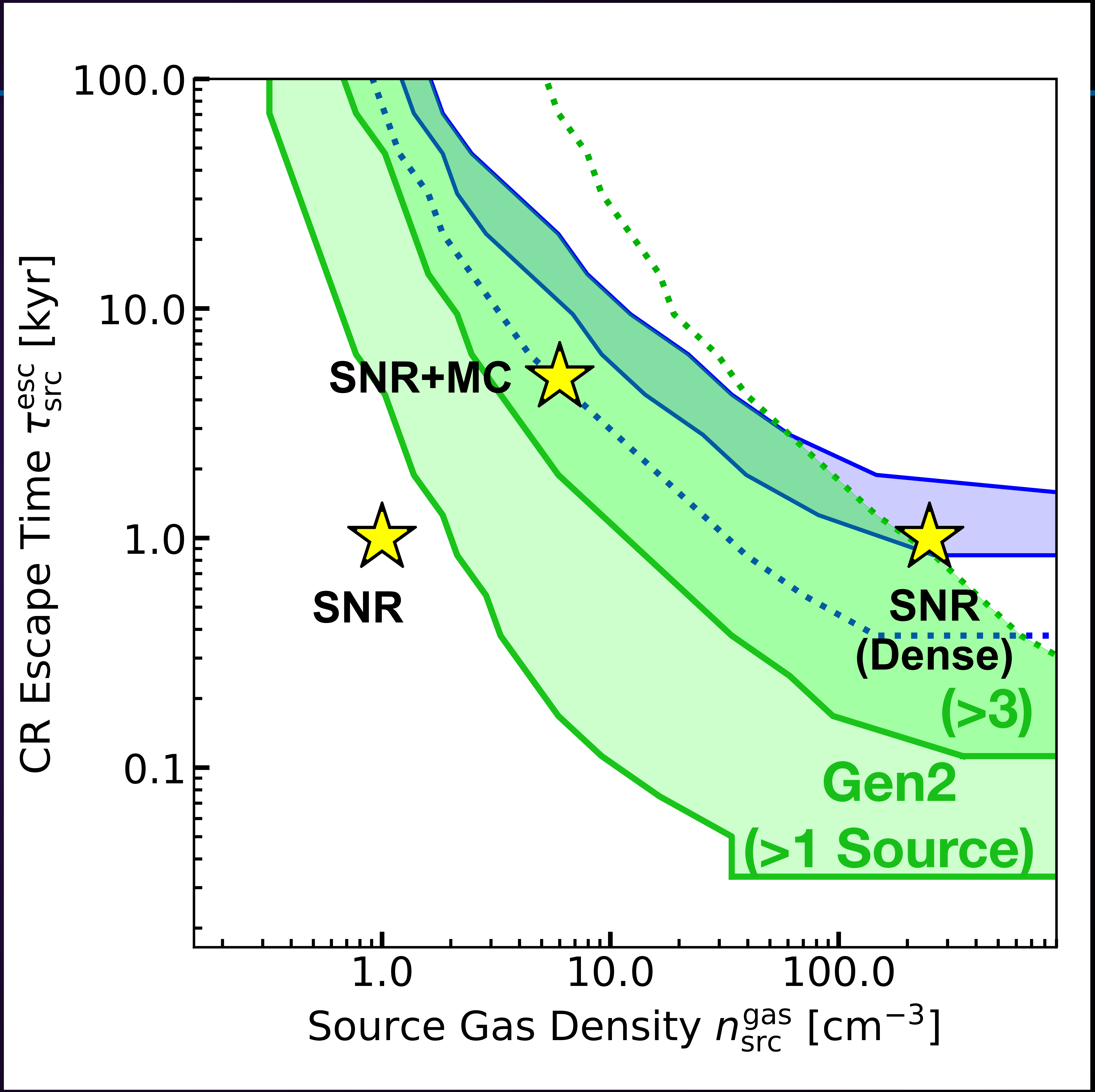
Neutrino

- **Is IceCube enough?**
- No!
- Still wide parameter space is open.



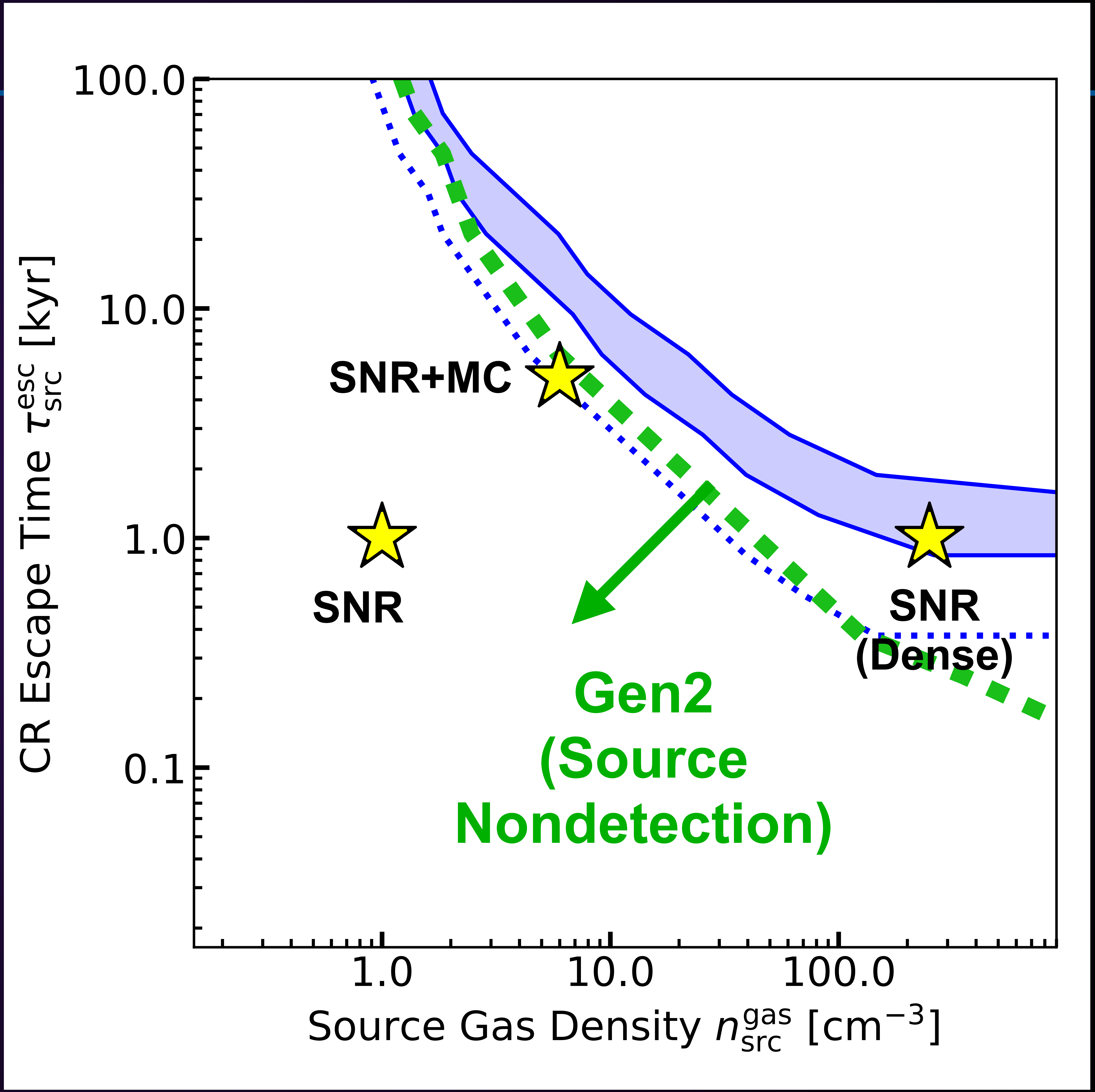
Future neutrino

- **Is Gen2 promising to observe PeVatrons?**
- Yes!
- A wide parameter range is consistent with Gen2 source detection



Future neutrino

- **Is Gen2 enough?**
- No!
- Non-detection could still allow a wide range of models.



How to improve neutrino sensitivities?

- Improved sensitivities are needed for neutrinos
- Most searches thus far obtain best sensitivities with track-like events
- Source searches with **cascade events** might be important
    - Lower atmospheric background
    - Sources may have steep spectra
    - Cascade angular resolution in principle can be improved by a lot
- Ocean-based future telescopes are promising

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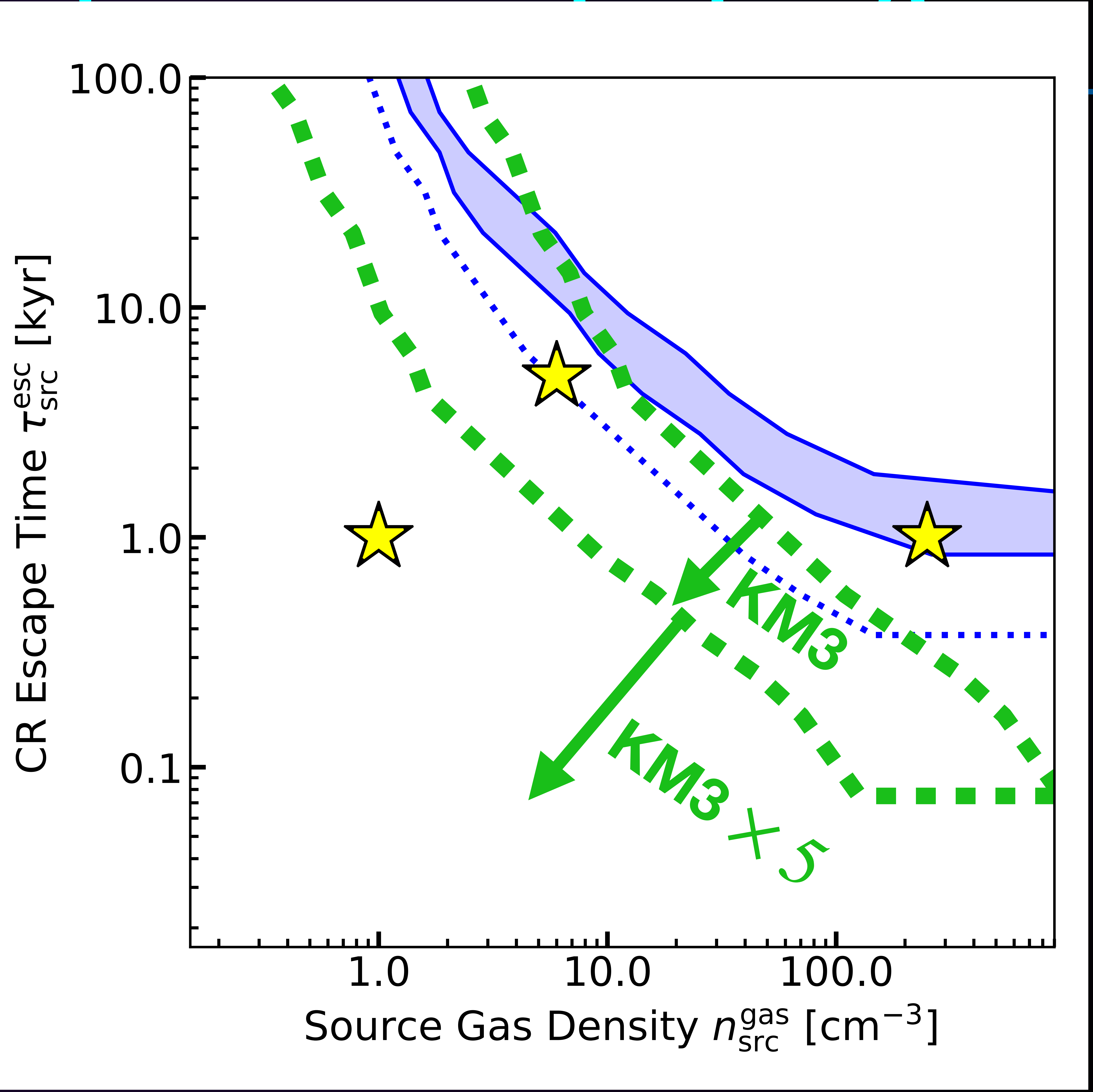


Conclusions

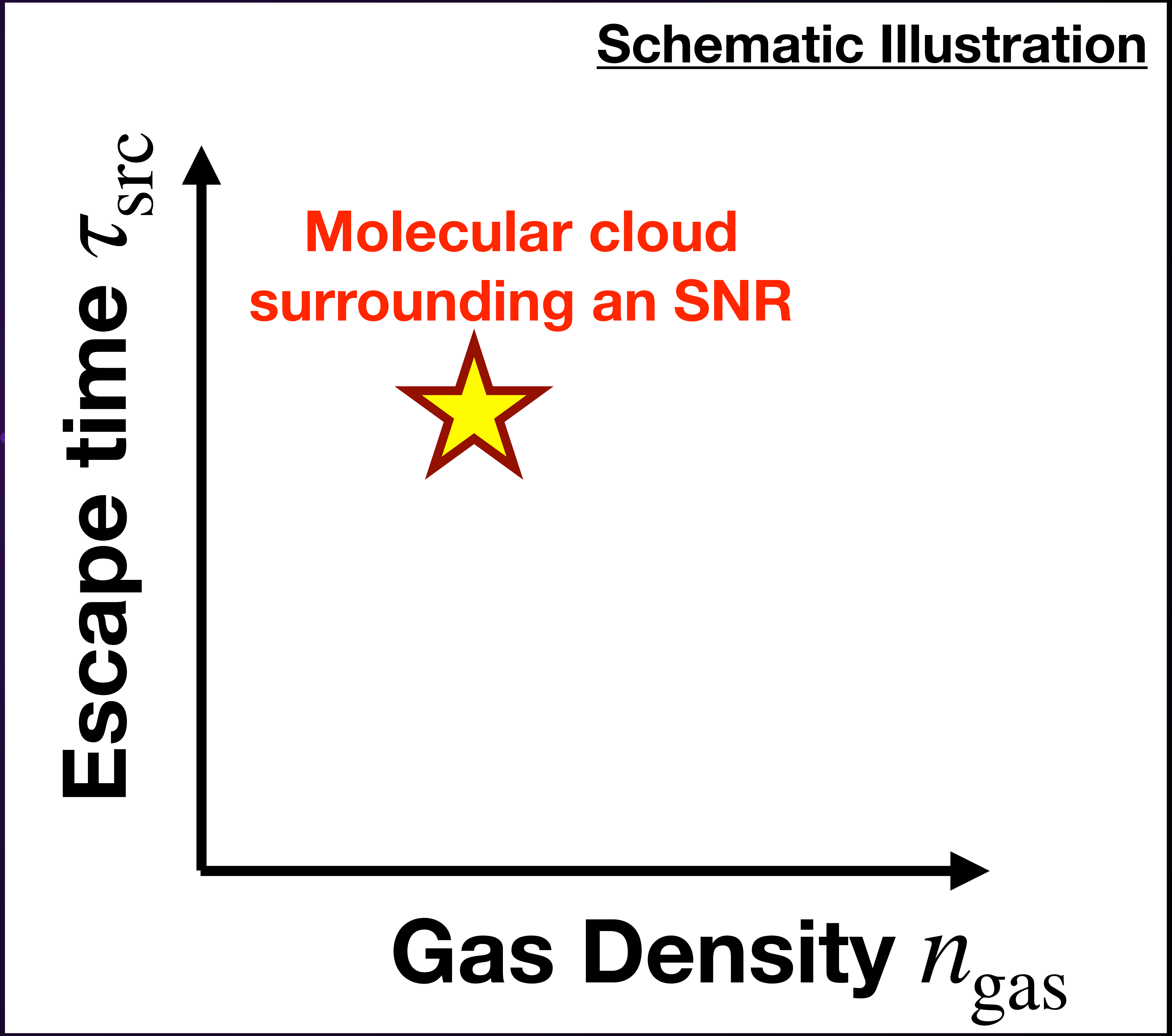
Summary

- We introduced a new population-based approach to consistently understand the data of cosmic rays, gamma rays, and neutrinos
- We quantified the existing constraints on a semi model-independent plane of gas densities and particle confinement time
- LHAASO sources could be all hadronic, but dense gas and strong confinement are needed
- LHAASO sources could be all leptonic, for a wide range of parameters
- IceCube non-detection still allows a large parameter space
- Gen2 is promising to find PeVatrons

Appendix

Introducing “n-tau” plane

- SNR + MC :
  - M_cloud, gas = 1e5 M_sun
  - R_cloud = 20 pc
  - Distance from SNR = 50 pc
  - Diffusion = 1e29 cm^2/s
- Volume filling ~ (20/50)^3



Introducing “n-tau” plane

- SNR (Dense) :
  - RX J1713.7-3946
  - Gas clump ~ 2.5e4 cm^-3
  - Volume filling ~ 0.01
  - Age ~ 1.4 kyr
- Escape time for PeV protons are uncertain, but the lack of > 10 TeV suggest $\tau < 1.4$ kyr.