Microquasar Origin of PeV Cosmic Rays and Constraints on the Diffuse Neutrino Sky

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References:

Paper I: B.T. Zhang and S. Yu, 2026, arXiv- 2602.08940

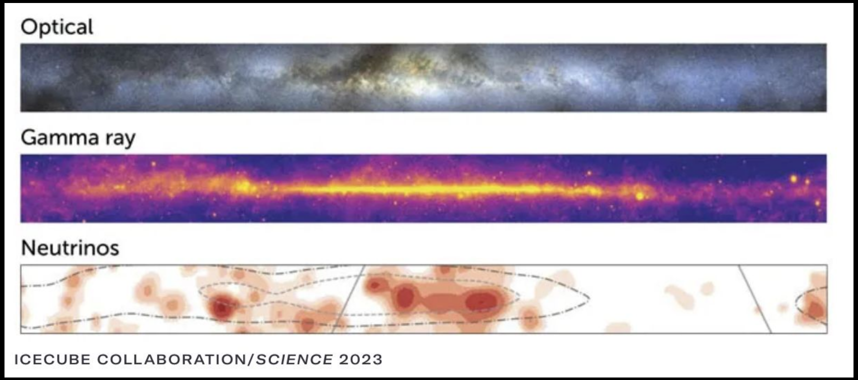
"Microquasar Remnants as PeVatrons Illuminating the Galactic Cosmic Ray Knee"

Paper II: S. Yu and B.T. Zhang, 2026, arXiv- 2608.22374

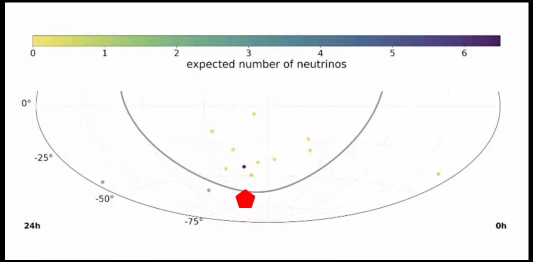
"Galactic Microquasar and Supernova Remnants Imprinting on the Diffuse Neutrino Sky"

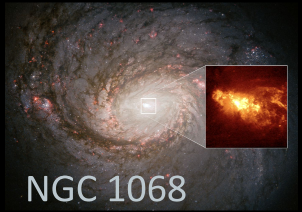
TeVPA, Japan | Sep 1, 2026

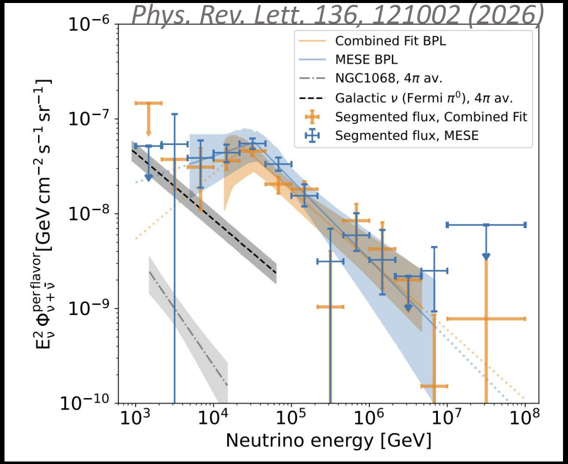
Evidences of High-energy Astrophysical Neutrinos



Astrophysical neutrinos have been detected from both extragalactic and galactic sources.







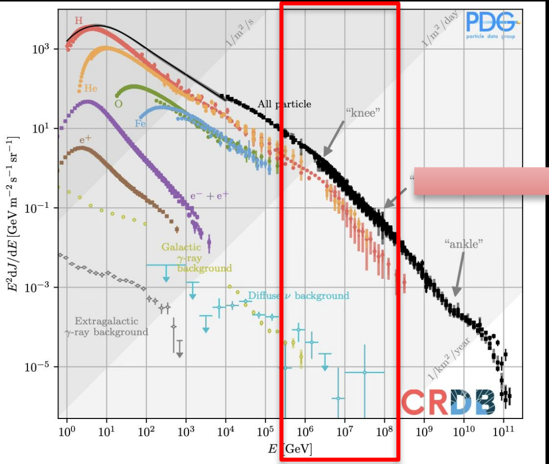
Top candidate: Circinus Galaxy sky position close to GP (b = -3.8°), significance is 3.1 σ (pre-trial)

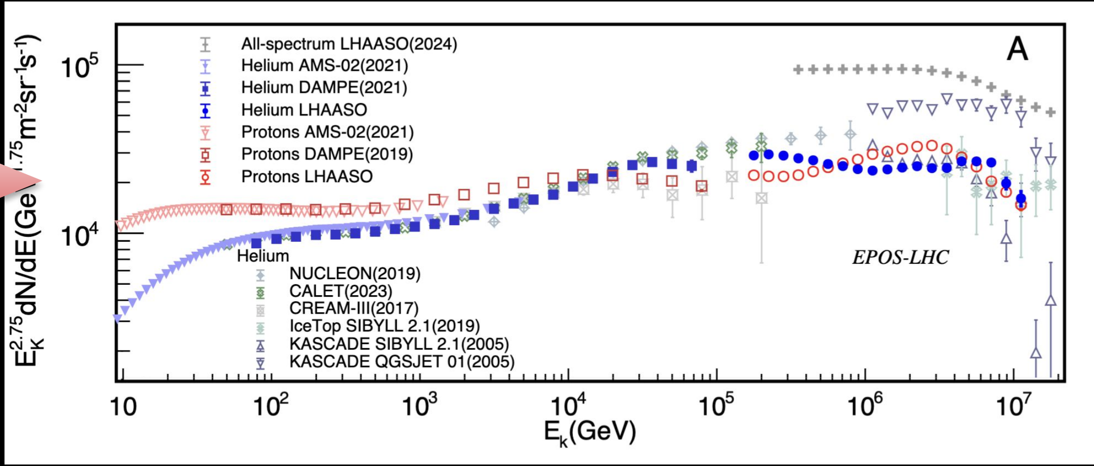
Inspired extensive theoretical modeling…

Why Galactic diffuse is pressing topic?

CR Knee: An Unresolved Challenge

Since 1958…





[LHAASO Collab., Sci. Bull. 2025; PRL, 2026]

- PeV proton ``bump": the all-particle knee links directly to proton spectrum.
- Galactic CR (GCR) protons show complex hardening and steepening behaviors.

What are the CR accelerator candidates in the Milky Way?

Supernova Remnant (SNR)

Credit: NASA

Supernova Remnants as Galactic CR sources were proposed in 1934 by Baade & Zwicky [Proc Natl Acad Sci USA 20, 254–259 (1934), Phys. Rev. 55, 986]

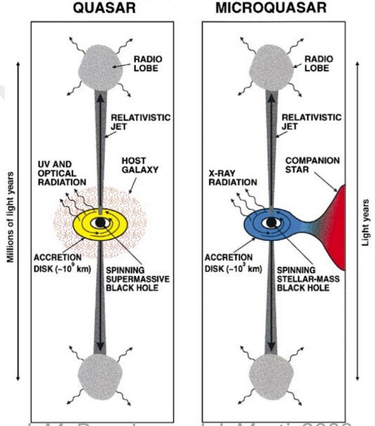
Required Energetics: Local CR energy density is explained if ~10% of SNR shock kinetic energy is converted to GCRs [Strong, 2010]

Acceleration to VHE energies via diffusive shock acceleration is possible [Drury,1983; Blandford & Eichler, 1987]

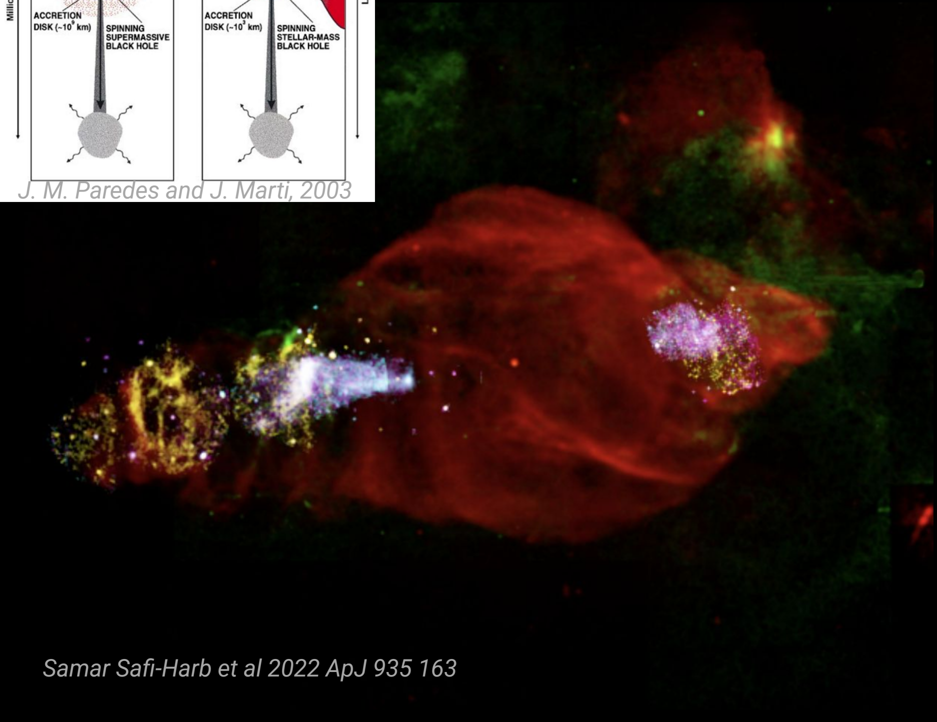
However, SNRs as sources of PeV CRs are challenged by both theory and observations.

Recent work interprets <100 TeV CR p/He spectra using SNRs [Aharonian & Zhang, 2026 ApJ 1006 211]

Microquasar (MQ)



J. M. Paredes and J. Marti, 2003

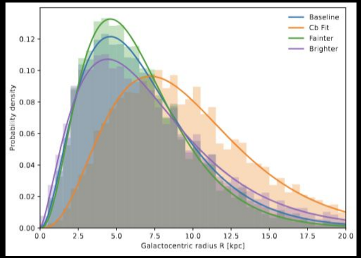


Samar Safi-Harb et al 2022 ApJ 935 163

Binary systems consisting of a compact object (usually a black hole) and a companion star, functioning as scaled-down Active Galactic Nuclei.

Extreme environments to accelerate particles beyond PeV.

Random Sampled MQ Population



R-distributions
[2015, MNRAS, 454, 1517]

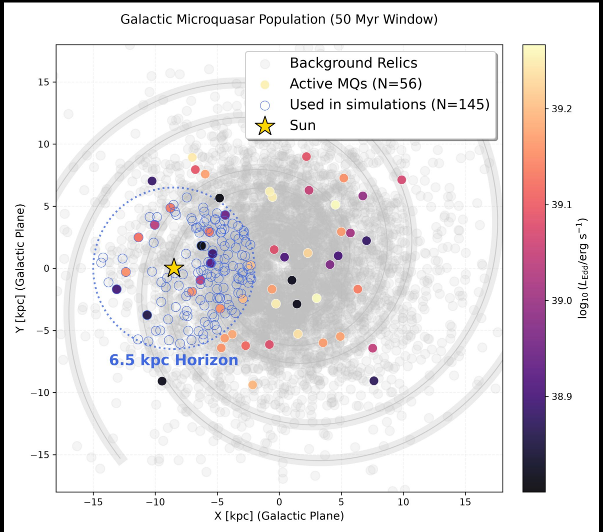
TABLE S2. Parameters used in the microquasar catalog generation and CRPropa simulation setup.

Parameter (Symbol)	Value / Distribution
Constants	
Birth Rate	1×10^{-4} yr^{-1}
CR Loading Efficiency Baseline (η_{cr})	0.1 (nominal)
Simulation Cutoff	6 Myr & non-active
Sample Ensembles	
Lookback Time ($t_{\rm lookback}$)	$\mathcal{U}(0, 50)$ Myr
Jet Duration ($t_{\rm duration}$)	$\mathcal{U}(0.1, 1.0)$ Myr
Black Hole Mass ($M_{\rm BH}$)	$\mathcal{U}(5, 15)$ $M_\odot$
Galactocentric Radius Distribution($r_{\rm gc}$)	Green15
Vertical Height ($z_{\rm gc}$) [JCAP01(2012)010]	$\pm$Exp($h_z = 0.15$ kpc)

Stochastically sample MQ distributions in the Milky Way: 200 realizations.

→to capture spatial and temporal distributions.

Inject 25 million protons in [0.1, 100] PeV each MQ.



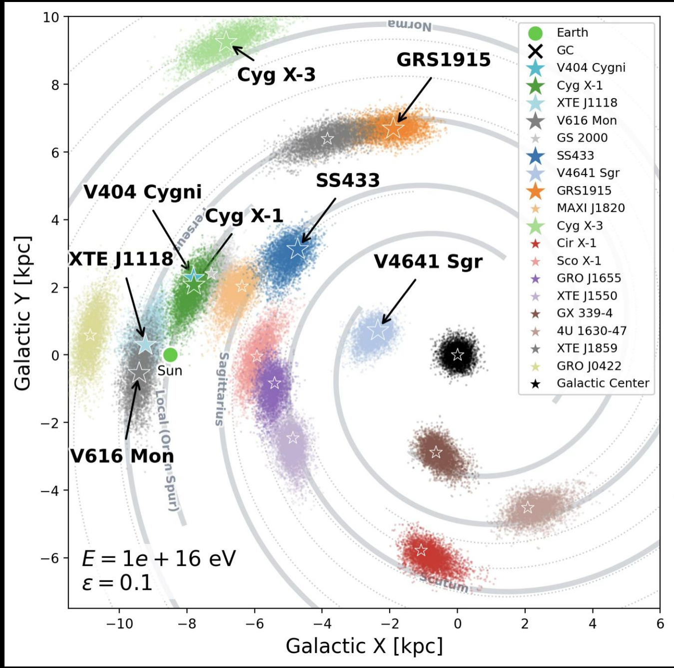
Each ``Milky Way" contains ~5k MQs with random ages, jet durations, and black hole masses, etc.

$$L_{\rm cr} = \eta_{\rm cr,MQ} L_{\rm Edd}$$

Injected proton estimated from $L_{\rm Edd}$

** CRs escape (τ_{esc}< 1Myr at E >1 TeV) prior to significant pp loss with τ_{loss}~ 50/(n_{gas}/1cm^{-3}) Myr and reach steady state << 20 Myr.*

Anisotropic Diffusion under GMF



Simulation tool: **CRPropa3.2**
[JCAP (2022) no. 09, 035]

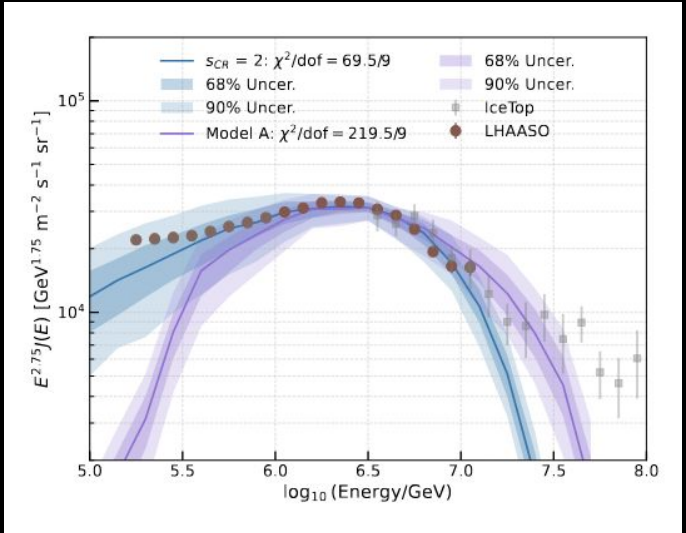
Simulated 1 PeV CR protons induced from locations of ~20 identified Galactic MQs.

Solenoidal **JF12 Galactic Magnetic Field** model defining the ordered field [Jansson & Farrar, APJL. 761, L11, 2012].

Anisotropic transport modeled via the DiffusionSDE module by diffusion coefficient ε=0.1:

$$D_{\parallel} = 6.1 \times 10^{28} (E/4\ \mathrm{GeV})^{1/3}\ \mathrm{cm}^2\ \mathrm{s}^{-1} \qquad D_{\perp} = \varepsilon D_{\parallel}$$

Fit to Proton Bump Data



Model A : hard injection spectrum assuming jet-related acceleration [Zhang, Kimura & Murase, PRD, 2025]

Power law: scr=2, Emax=6PeV [Aharonian & Zhang, ApJ, 2026]

Fit to LHAASO data in [1, 10] PeV, around the bump.

CR released by stochasticly sampled MQs in the past can reproduce the observed proton bump.

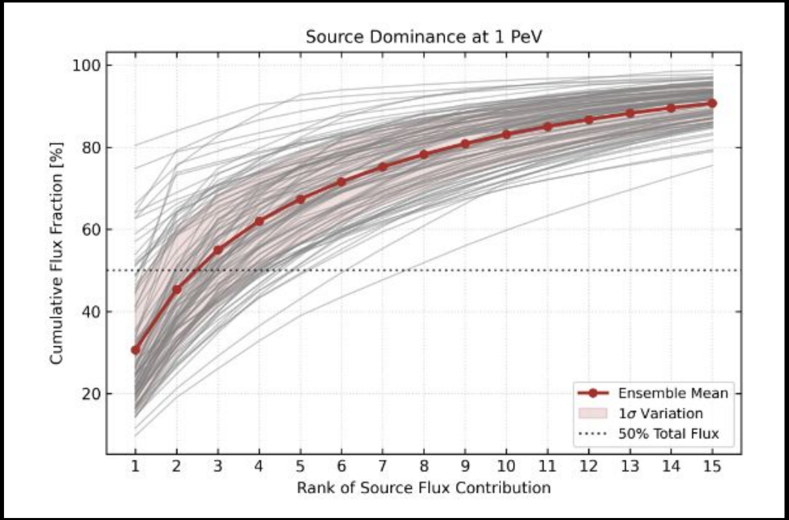
Best-fit value of CR acceleration efficiency:

- ➔ Model A : η_{cr} ≃ 0.3–1.5%
- ➔ **Power-law : η_{cr} ≃ 2–10%**

η_{cr} value degenerated with local source(s) proximity.

*CR fit results yield a Solar neighborhood average, further Galactic sources, including unresolved and active sources, can be inferred from population distribution and traced by neutrinos and gamma rays → need multi-messenger constraints.

Recent and Nearby MQ Ramnents



Cumulative fraction of the local CR flux at 1 PeV vs. source ranked by their individual flux contributions.

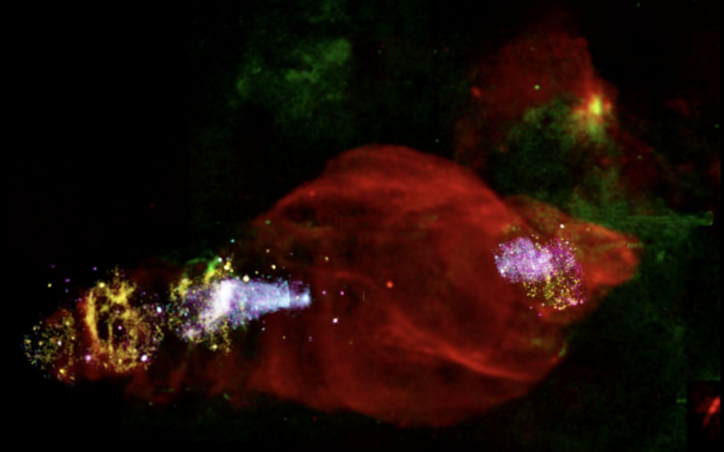
The local PeV CR flux could be dominated by a few recent and nearby MQ remnants.

- ➔ No more than 4 sources are needed to explain 50% of the observed flux at 1 PeV.
- ➔ The top 10 sources contribute approximately 80% of the total flux.

Galactic Microquasar and SNRs

Imprinting on the

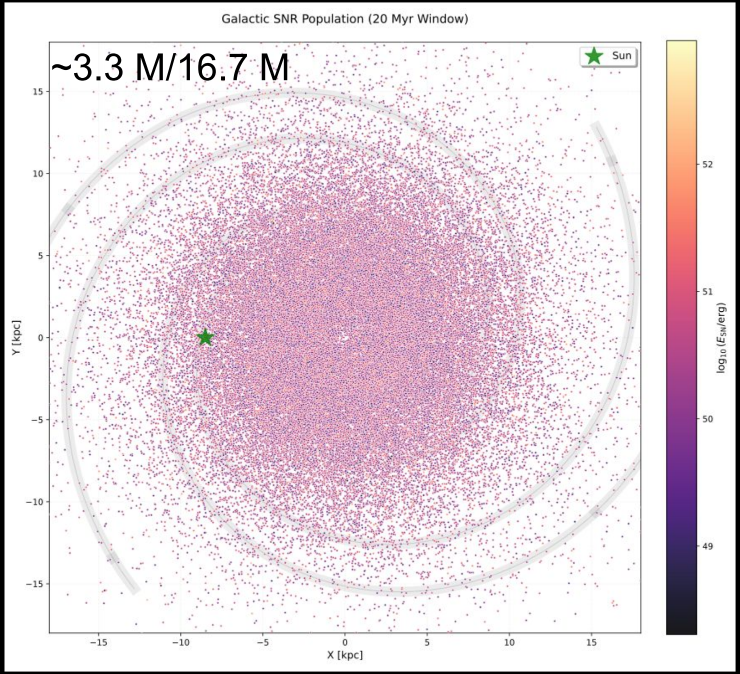
Diffuse Neutrino and Gamma-ray Sky

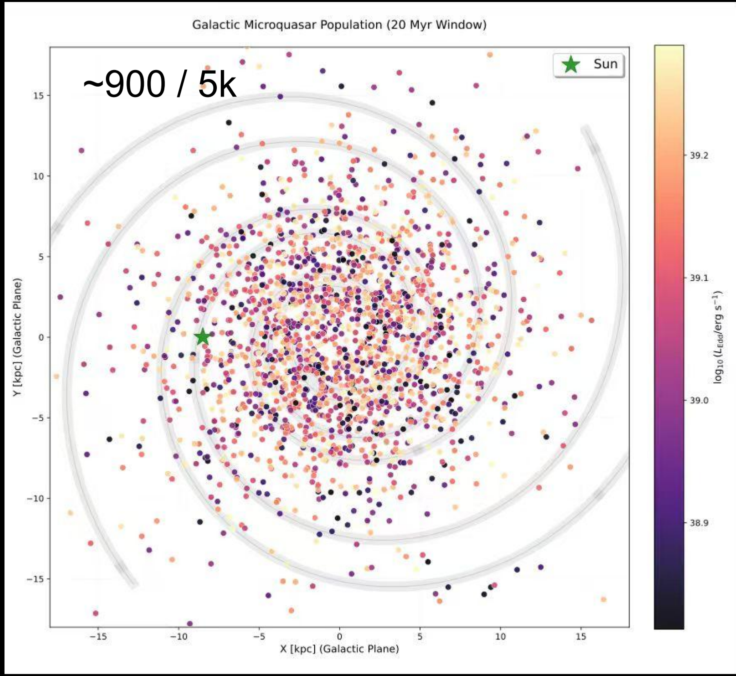


Population Distribution

SNR

MQ





Anchor in CR Data

Simultaneous fit of **MQ** and **SNR** components to **p** and **He** spectra from LHAASO [Z. Cao et al. 2025b, 2026b] and DAMPE [F. Alemanno et al. 2025]

➔ Cosmic-ray acceleration efficiencies $\eta_{\rm CR}$ corresponds to CR injection rate:

$$\mathcal{E}_{\rm cr} = \eta_{\rm cr,SN}\mathcal{E}_{\rm SN}$$

$$L_{\rm cr} = \eta_{\rm cr,MQ}L_{\rm Edd}$$

Component	Parameter	Fitted Value (%)
Microquasars	$\eta_{p,\rm MQ}$	9.59 ± 0.18
	$\eta_{\rm He,\ MQ}$	2.96 ± 0.08
SNRs	$\eta_{p,\rm SN}$	6.00 ± 0.27
	$\eta_{\rm He,\ SN}$	2.00 ± 0.08

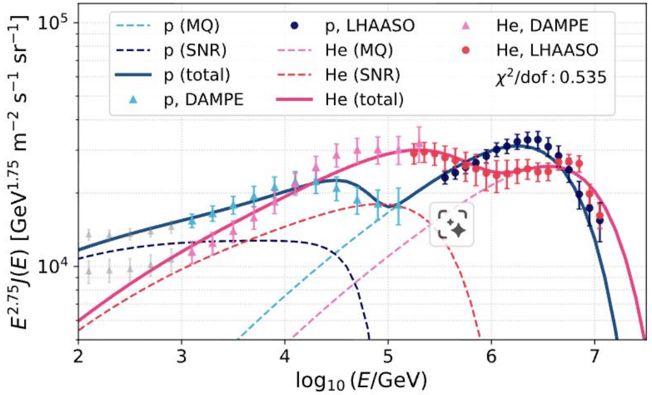


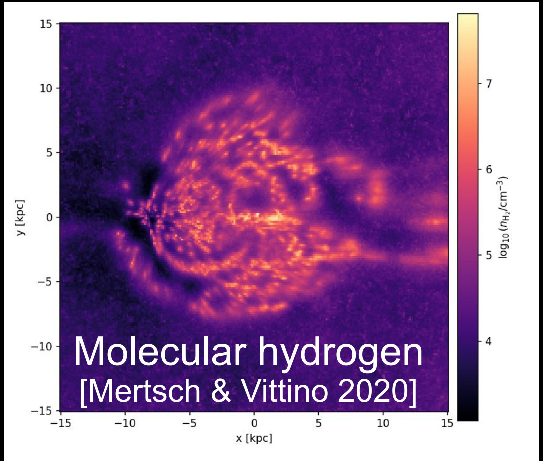
Figure 1. Best-fit spectra for proton (blue) and helium (pink) components from microquasar (light dashed) and SNR (dark dashed) populations, compared against DAMPE (dark spot) (F. Alemanno et al. 2025) and LHAASO (light triangle) (Z. Cao et al. 2025b, 2026b) observations. Sub-TeV data (gray) are excluded from the fit and displayed for completeness.

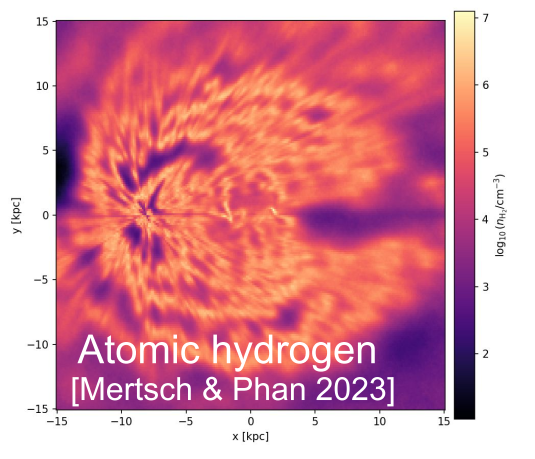
*All ingredients of **proton** and **Helium** from **MQ** & **SNR** can nicely reproduce data!*

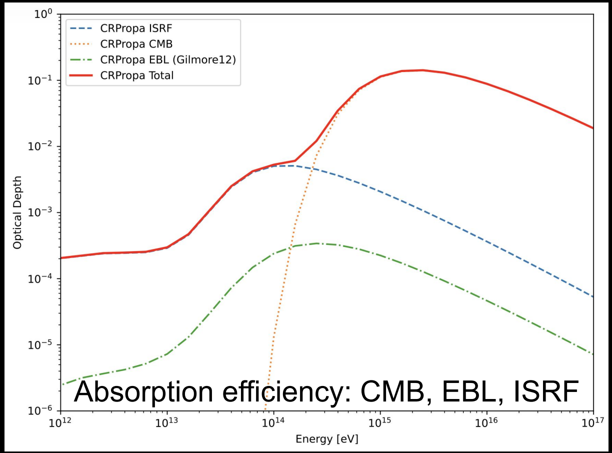
3D InterStellar Radiation and Gas Fields

Line-of-sight (LOS) integrations over gas and photon maps to estimate resulting ν^* and γ-ray emission

- **pp and He-p interaction** with gas nuclei via AAFRAG [Comput.Phys.Commun. 245 (2019) 106846], with heavier nucleus scaled by 1.42 [Castro et. al., 2025]
- $\gamma\gamma$ **absorption** accounts for CMB, EBL, and ISRF photon fields [Vernetto & Lipari 2016, Robitaille 2012]







$$* \quad \phi_\nu(E_\nu,\Omega) = \frac{1}{4\pi}\int dE_{\rm p}\,\beta c\,\sigma_{pp}(E_{\rm p})\,\frac{dN_\nu}{dE_\nu}(E_\nu,E_{\rm p})\,X(\Omega,E_{\rm p}),$$

$$X(\Omega,E_{\rm p}) = \int_0^\infty ds\, n_{\rm gas}(\mathbf{r})\, n_{\rm p}(E_{\rm p},\mathbf{r})$$

Predicted Diffuse Neutrinos

Comparison between nominal template predictions and IceCube best fits reveals distinct energy regimes.

➔ **Sub-TeV regime: SNR dominant.**

➔ **Above 10 TeV: MQ-dominated**

- **KRA**:
  - *no constraints from recent CR data*
- CRINGE:
  - *utilize rigidity-dependent diffusion breaks instead of source-driven cutoffs*

Our spectral transition is driven by MQ and SNR populations and their distinct features.

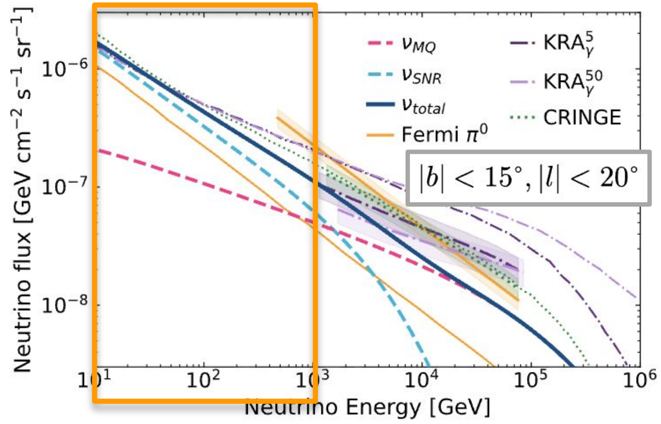


Figure 2. Total predicted per-flavor Galactic diffuse neutrino spectra for the inner Galaxy (dark blue), decomposed into microquasar (light pink) and SNR (light blue) populations, compared with IceCube measurements and nominal spectra of Fermi-π^0, CRINGE, KRA^5_γ and KRA^{50}_γ models (R. Abbasi et al. 2026a).

Room for other sources or physical process. High-precision data are essential for model comparison and constraint.

Predicted Diffuse Gamma Rays

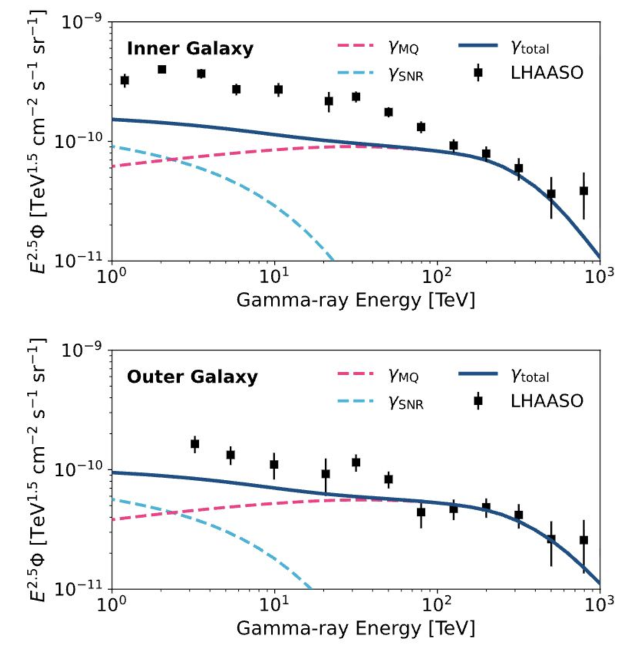


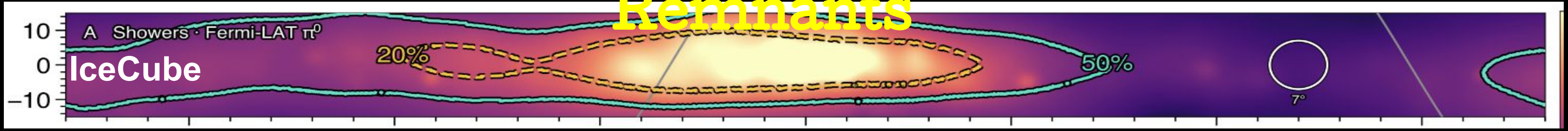
Figure 3. Diffuse gamma-ray flux integrated over the inner (top) and outer (bottom) Galactic regions within $|b| \leq 5°$, compared with LHAASO measurements. The same sky mask as in Z. Cao et al. (2025c) is applied.

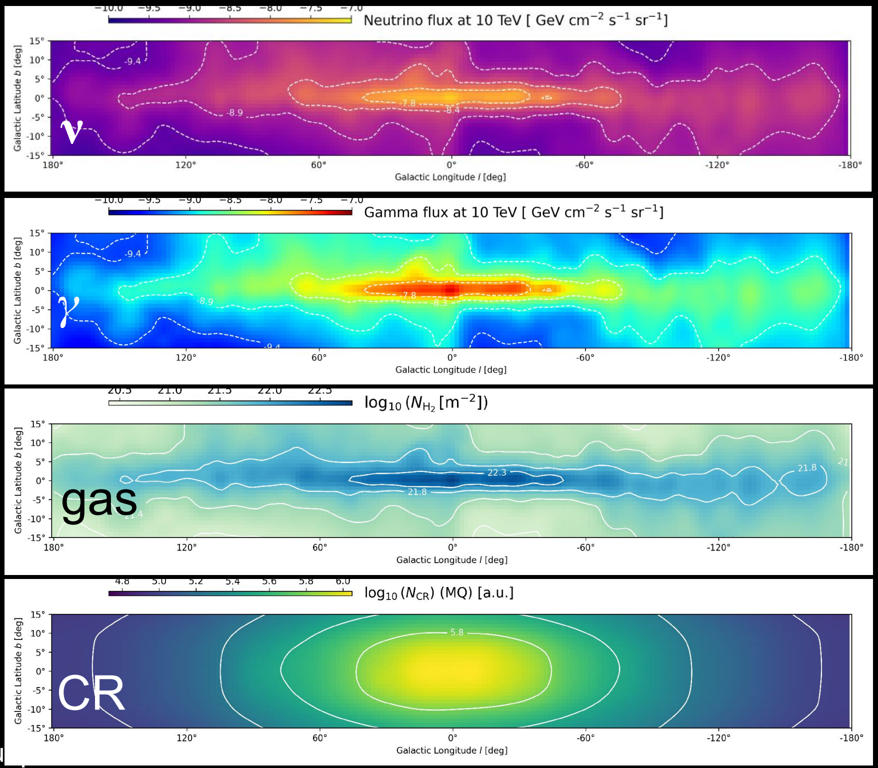
Consistent with LHAASO data.

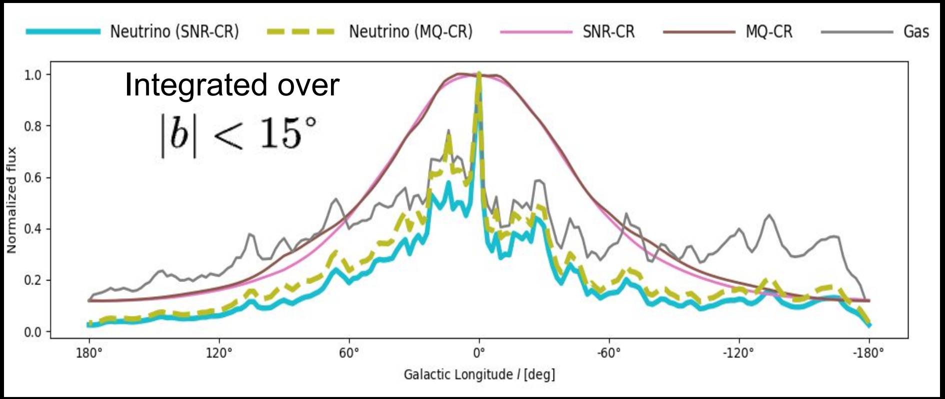
➔ Below 100 TeV, a residual excess in the gamma-ray data suggests possible additional contributions:
- ◆ Unresolved, faint source populations
- ◆ Unmodeled leptonic processes, such as inverse Compton by high-energy electrons

➔ Above 100 TeV: pure hadronic regime

Diffuse Sky Maps Imprinted by MQ and SN Remnants







Secondary particle profiles closely track LOS target gas distribution.

Discussion & Outlook

Paper I, MC Simulations
"Microquasar Remnants as PeVatrons Illuminating the Galactic Cosmic Ray Knee"

- The local PeV CR flux is shaped by the integrated history of MQs in the Milky Way
  - and could be stochastically dominated by less than 4 nearby remnants (10 sources explains ~80% of the flux).
- Fitting LHAASO data yields CR loading efficiencies: 2–10% (power-law: s=2, Emax=6PeV).

Paper II, analytical framework
"Galactic Microquasar and Supernova Remnants Imprinting on the Diffuse Neutrino Sky"

- Galactice MQ and SNR populations contribute jointly at distinct energy regimes.
- MQ-induced protons successfully reproduce the CR proton bump with a loading factor of ~10%.

Outlook:

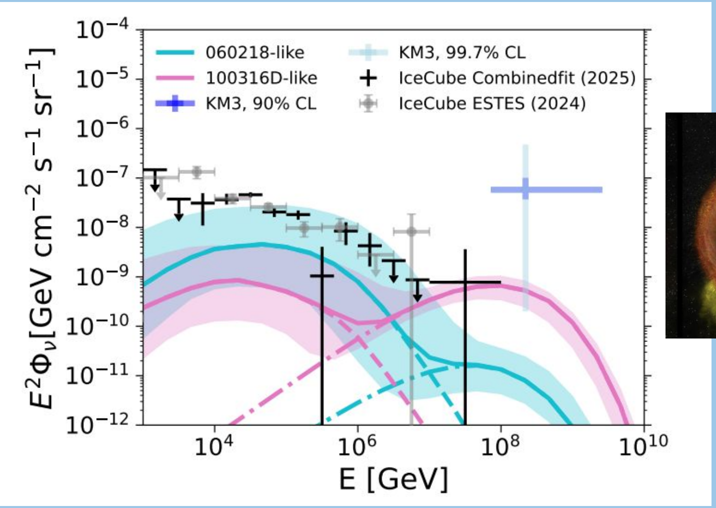
- Active sources or recent remnants temporarily confine CRs in local magnetic environments, driving additional gas interactions and multi-messenger signatures not covered in these work.
- Next Steps: detailed simulations for neutrino and gamma-ray predictions; evaluate systematics uncertainties.

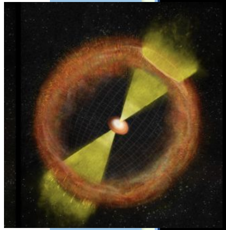
Open to collaborating across all relevant fields!

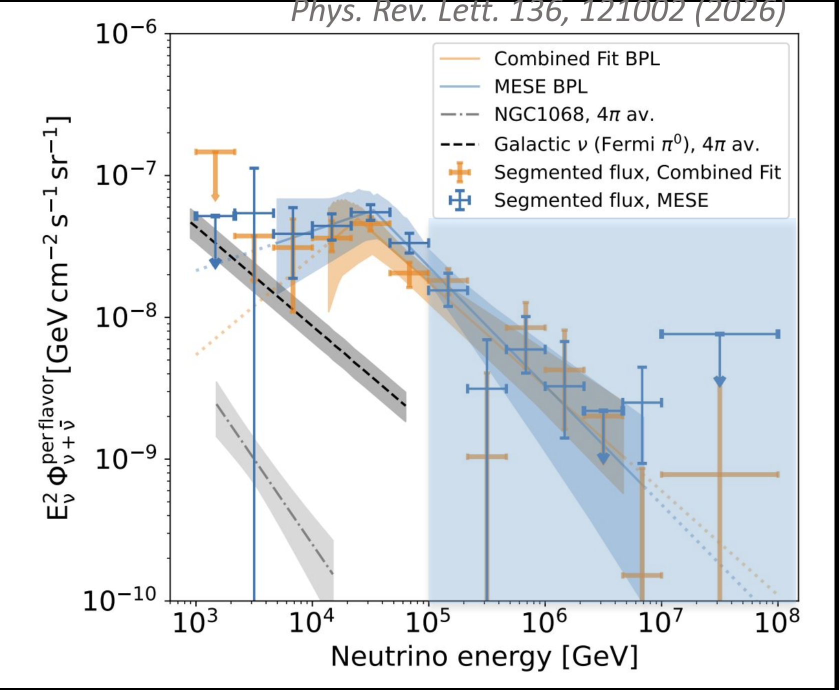
Models of High-energy Astrophysical Neutrinos

Low-luminosity gamma-ray bursts
are viable candidates for >100 TeV.

Astrophys.J.Lett. 1002 (2026) 2, L45
2026 ApJ 998 275







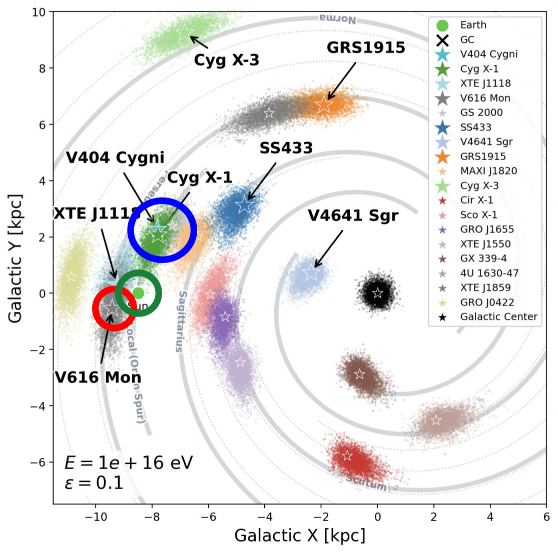
Future searches can be benefited from multi-messenger modeling.

Thank you!

Anisotropic Diffusion

Individual active sources exhibit significantly harder spectral features and higher flux levels.

Magnetic connection (ε = 0.01) has a stronger impact than physical distance to **Earth**.



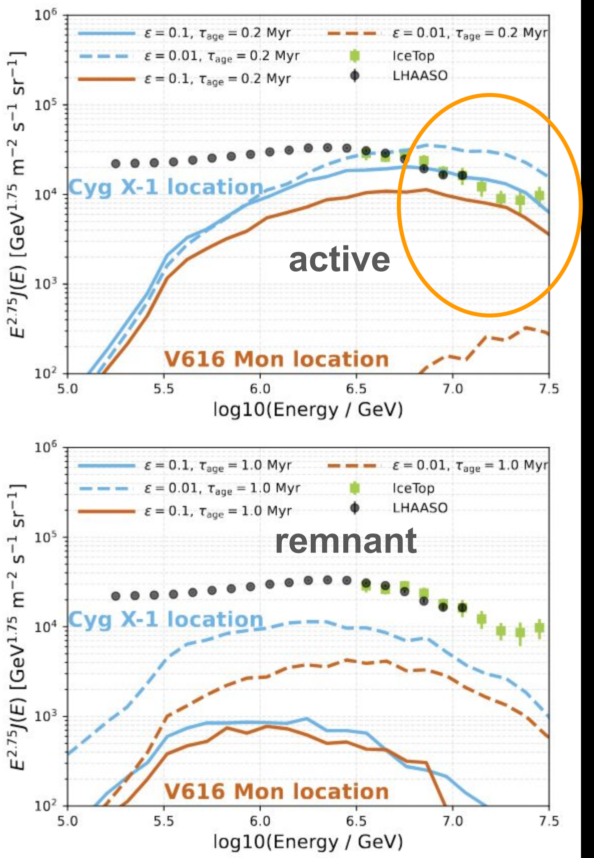
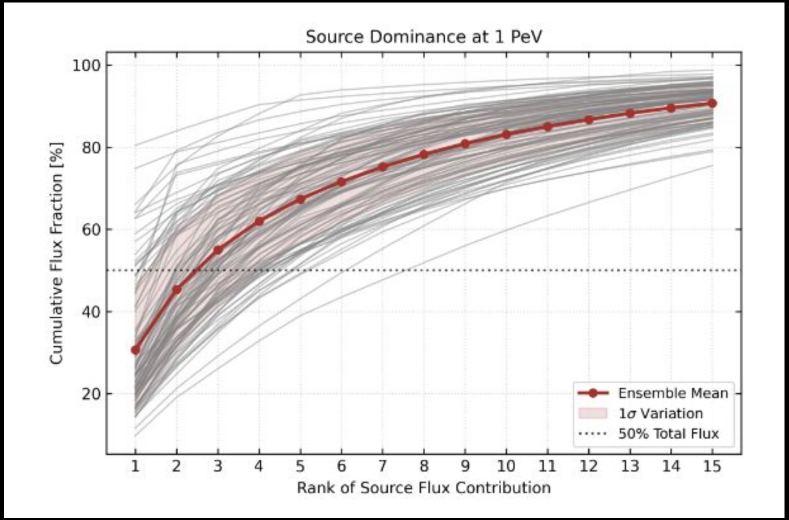


FIG. 2. Predicted CR spectra from Cyg X-1 and V616 Mon locations compared with LHAASO [1] and IceTop [30] data. Results show anisotropic diffusion ($\varepsilon = 0.1, 0.01$) at $\tau_{\rm age} = 0.2$ Myr (top) and $\tau_{\rm age} = 1$ Myr (bottom). We assume Model A injection with $M_{\rm BH} = 10 M_\odot$, $\tau_{\rm dur} = 0.2$ Myr, and $\eta_{\rm cr} = 0.005$.

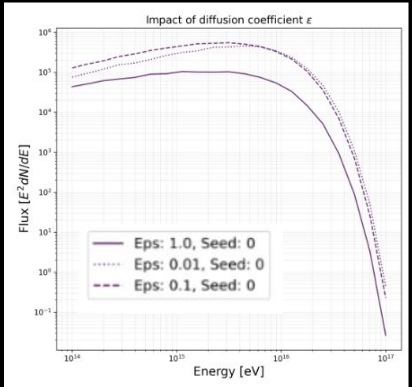
Recent and Nearby MQ Ramnents



Cumulative fraction of the local CR flux at 1 PeV as a function of source rank, with sources ordered by their individual flux contributions.

The local PeV CR flux could be dominated by a few recent and nearby MQ remnants.

- ➔ No more than 4 sources are needed to explain 50% of the observed flux at 1 PeV.
- ➔ The top 10 sources contribute approximately 80% of the total flux.



Impact from diffusion coefficient is less pronounced than the stochastic impact from local source distribution.

method following [Blasi & Amato, JCAP01(2012)011]

GCR Isotropic Diffusion

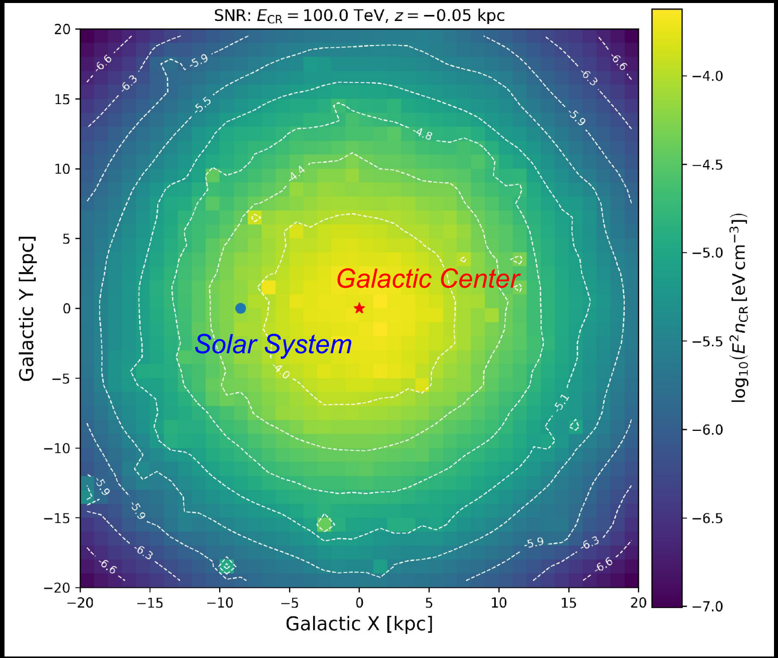


Illustration of steady-state CR density distribution of SNR at z=-0.05 kpc.

Isotropic diffusion (ε=1*) for each source, solving for the CR number density via the propagator P:

$$n_{\rm cr}(E, \mathbf{r}, \tau_{\rm lookback}) = L_{\rm cr} \int_{\tau_{\rm min}}^{\tau_{\rm lookback}} \mathcal{P}(\mathbf{r}, E, \tau)\, d\tau$$

$$\mathcal{P}(\mathbf{r}, z, E, \tau) = \frac{1}{(4\pi D(E)\tau)^{3/2}} \exp\left(-\frac{r^2}{4D(E)\tau}\right) \mathcal{V}(z, \tau, E)$$

with a free-escape boundary of Galactic Halo at H=4kpc:

$$\mathcal{V}(z, \tau, E) = \sum_{n=-\infty}^{+\infty} (-1)^n \exp\left(-\frac{(z - z_n')^2}{4D(E)\tau}\right), \quad z_n' = z_s + 2nH$$

*energy-dependent isotropic diffusion with constant ε=1:

$$D_\parallel = 6.1 \times 10^{28} (E/4\ \mathrm{GeV})^{1/3}\ \mathrm{cm^2\ s^{-1}} \quad D_\perp = \varepsilon D_\parallel$$

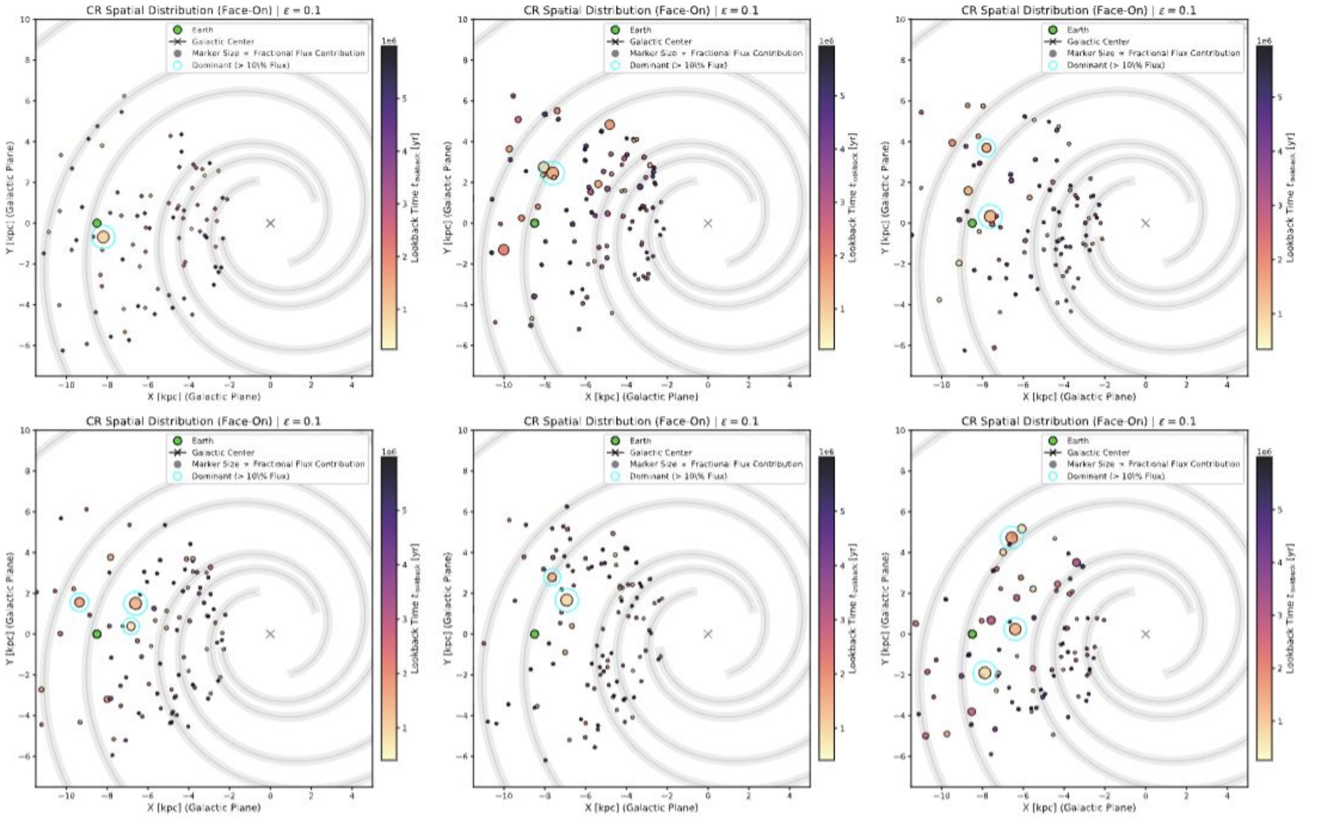


Figure 3: Spatial distribution of microquasar remnants for the first 6 sample realizations. Symbol size corresponds to fractional flux contribution at 1 PeV; bright green circles mark dominant sources contributing > 20% to the total local flux.

Can we be more realistic?

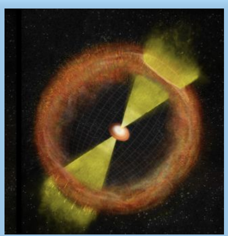
This physically motivated framework can be naturally extended to incorporate richer physical ingredients:

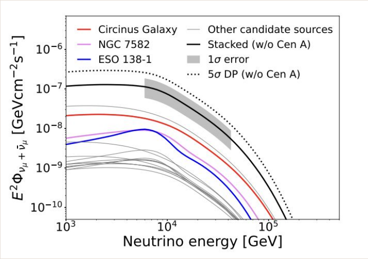
- ✓ Galactic Magnetic Fields?
- ✓ Population variations?
- ✓ Refined source acceleration models?
- ✓ 3D Gas models?
- Active source contributions?
- …

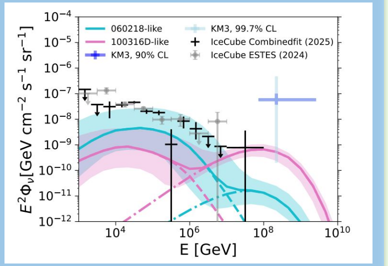
Models of High-energy Astrophysical Neutrinos

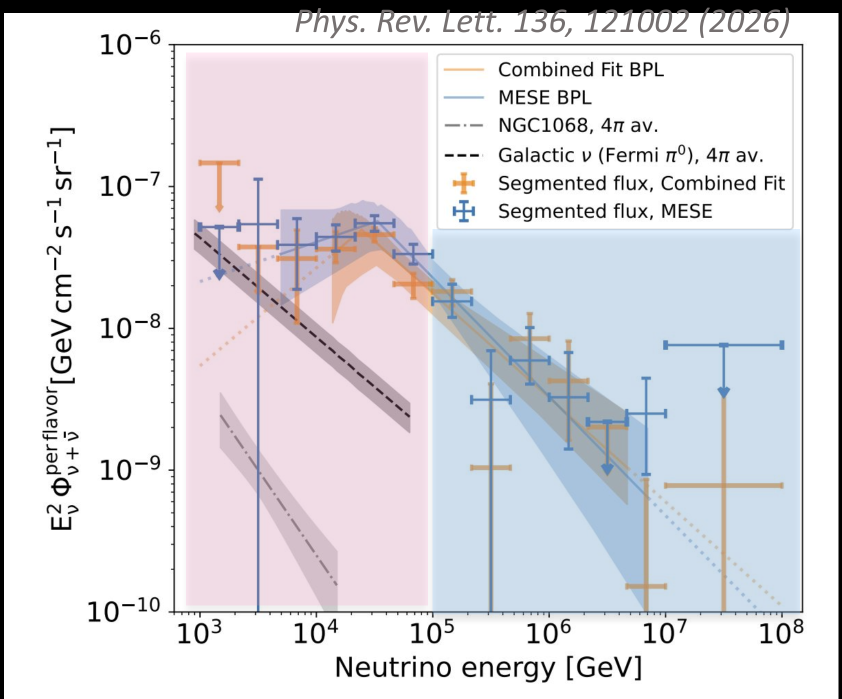
Majority is still largely unclear.

- ➔ *Some associations to AGNs have been found in the <100 TeV.*
- ➔ *Low-luminosity gamma-ray bursts are viable candidates for >100 TeV.*









Future searches can be benefited from multi-messenger modeling.

GCR Source Modeling

Injection spectral parameters for MQs and SNRs follow [Aharonian & Zhang, 2026 ApJ 1006 211]

Protons and helium are injected and propagated independently

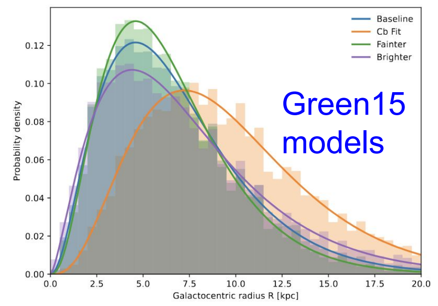
Heavier nuclei are scaled to helium following rigidity dependence

Table 2. Parameters for Population Distributions and CR Injection of MQs and SNRs.

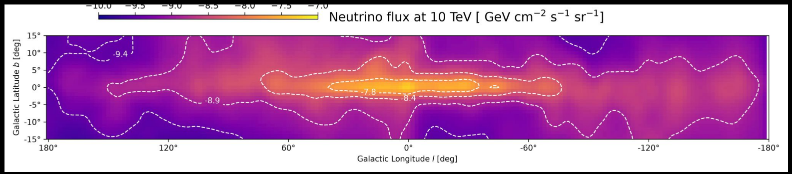
Source	MQ	SNR
Shared Parameters		
Radial Distribution Parameters	$\alpha = 1.09, \quad \beta = 3.87$ Green15 nominal	
Pivot Height (h_z)	$P(z) = \frac{1}{2h_z} \exp\left(-\frac{\lvert z \rvert}{h_z}\right)$, 0.15 kpc	
Solar System Radius ($R_\odot$)	8.5 kpc	
Max. Lookback	20 Myr*	
Distinct Parameters		
Birth Rate ($\mathcal{R}$)	1×10^{-4} yr^{-1}	$1/30$ yr^{-1} [a]
Jet Duration (τ_{dur})	Uniform(0.1, 1.0 Myr)	–
CR Injection Index (s)	2.0	2.4 (2.24) for p (He)
CR Maximum Energy (s)	6 PeV	68(468) TeV for p (He)
Mass / Kinetic Energetics	$M_{BH} \sim$ Uniform(5.0, 15.0) $M_\odot$	$\frac{E_{SN}}{erg} \sim$ Log-Norm(50.5, 0.53^2) [b]

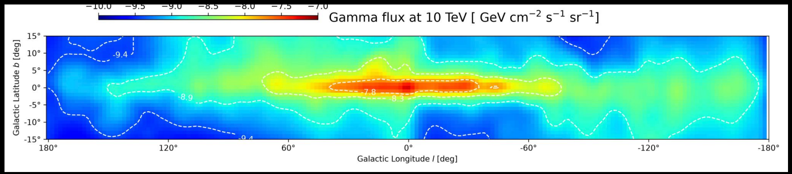
[a] P. Blasi & E. Amato (2012).
[b] D. A. Leahy et al. (2022).

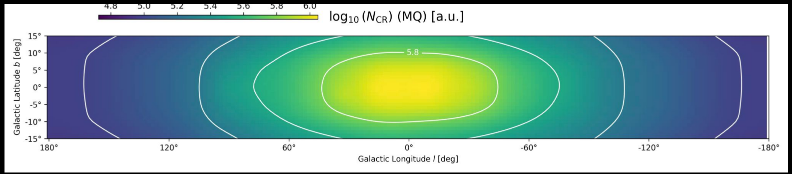
R-distributions from [2015, MNRAS, 454, 1517]

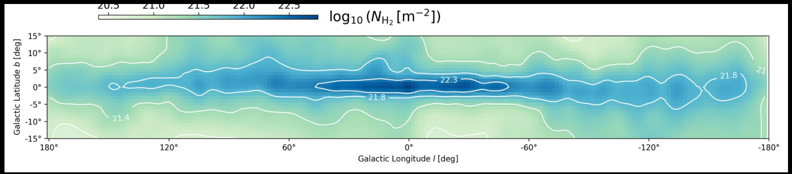


** CRs escape (τ_{esc}< 1Myr at E >1 TeV) prior to significant pp loss with τ_{loss}~ 50/(n_{gas}/1cm^{-3}) Myr and reach steady state << 20 Myr.*









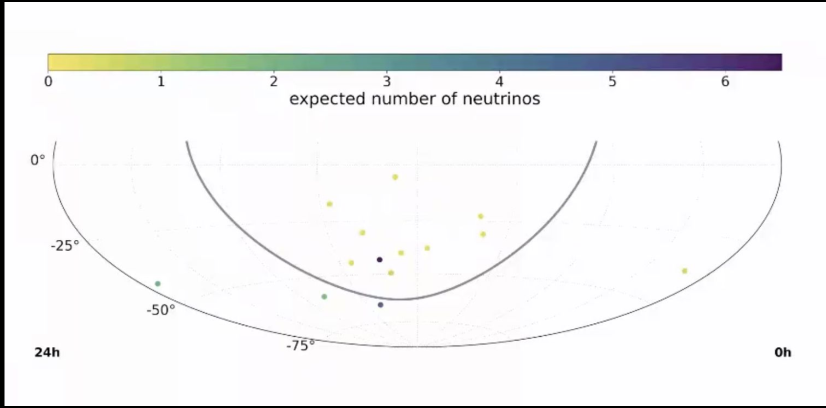
Galactic CRs : Origin of Neutrinos and Gamma Rays

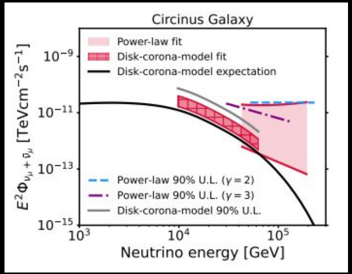
Foundations:

➔ **Source population:** Galactic CR sea is dominated by past injections from SNR and MQ populations.

➔ **Fit to CR data:** Spatial and spectral neutrino and gamma-ray emission templates are anchored on observed Galactic CR data.

ν Evidence in Southern Hemisphere





Top candidate: Circinus Galaxy sky position close to GP (b = -3.8°), significance is 3.1 σ (pre-trial)

Galactic Plane (GP) contaminates point-like source searches:

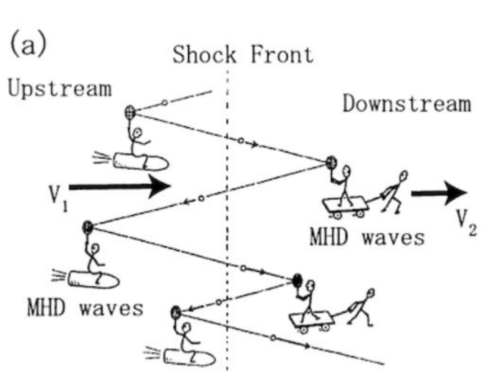
- ➔ *Evidence of **collective neutrino emission** from the extragalactic AGNs in the Southern Hemisphere, some top candidates are located close to the GP.*
- ➔ *Novel background modeling method developed for GP based on π_0 template.*
- ➔ *Better understanding GP contribution as background is critical in future point-like source searches in Southern Hemisphere.*

Acceleration in Supernova Remnant

SNRs as the dominant source population responsible for Galactic CRs

Observations of SNRs oftentimes show power law spectra non-thermal emission of X-rays

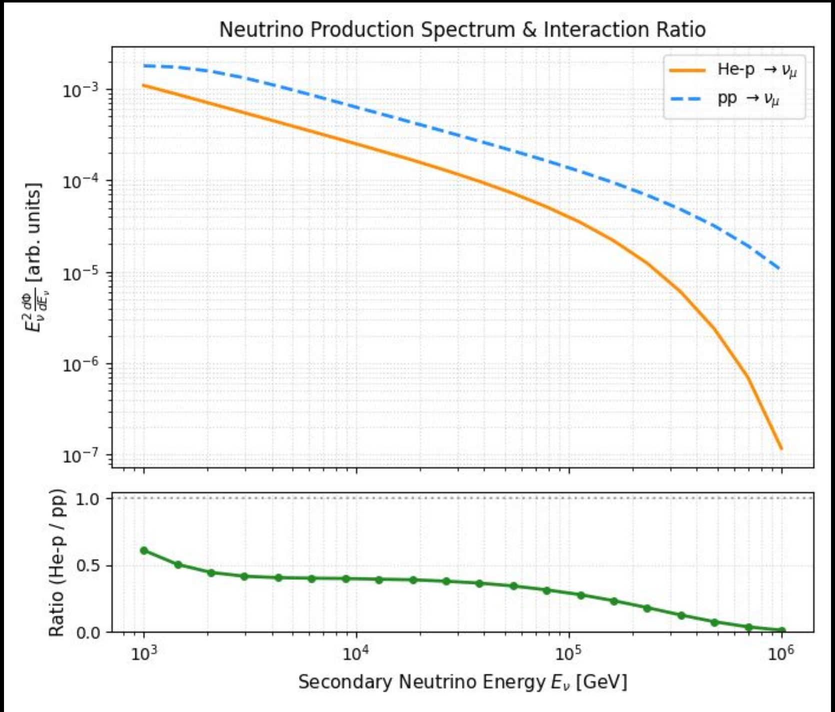
Diffusive shock acceleration work in SNR's blastwave



Hoshino, PTPS, 2001

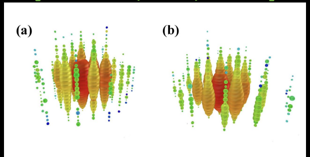
Hadronic Interaction

He-p and pp cross sections produce secondary neutrinos utilizing AAFRAG.

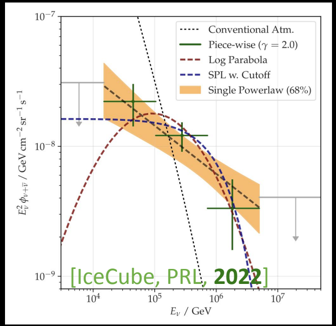


Detection of High-energy Astrophysical Neutrinos

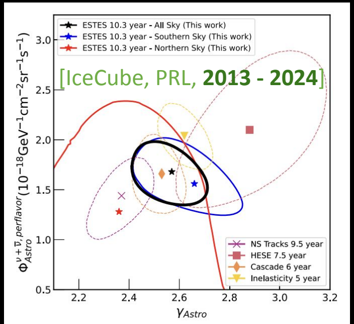
[IceCube, PRL, **2013**]



First PeV neutrinos observed



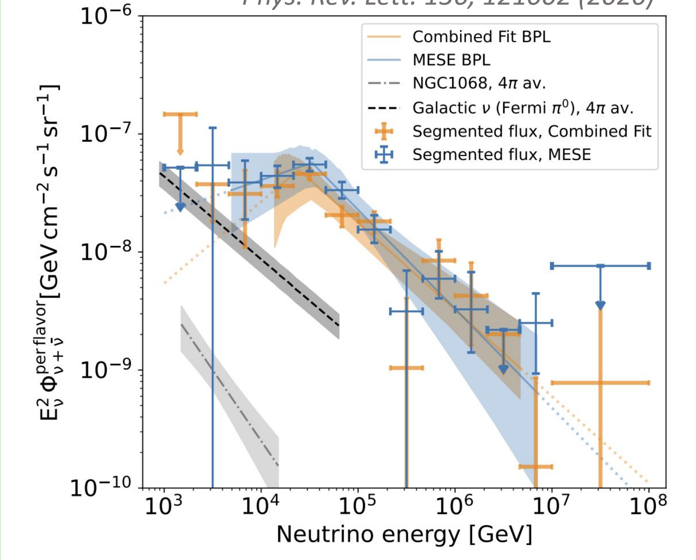
Different event selections and cumulative statistics



- Prefer single power-law (PL) hypothesis
- Substructure may be hidden in the low- and high-energy regions

Evidence of diffuse neutrino spectrum preferring broken power law instead of single power law.

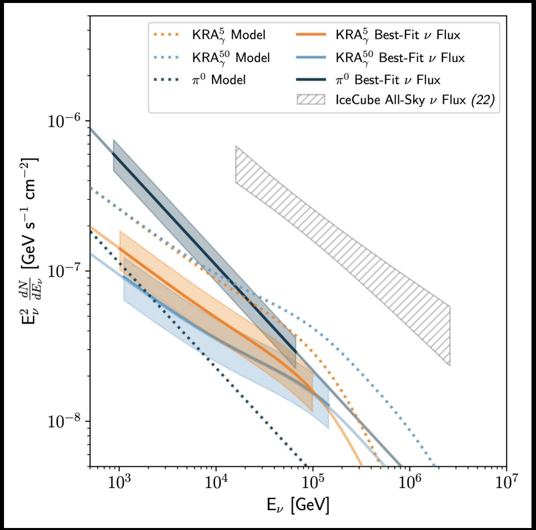
Phys. Rev. Lett. 136, 121002 (2026)



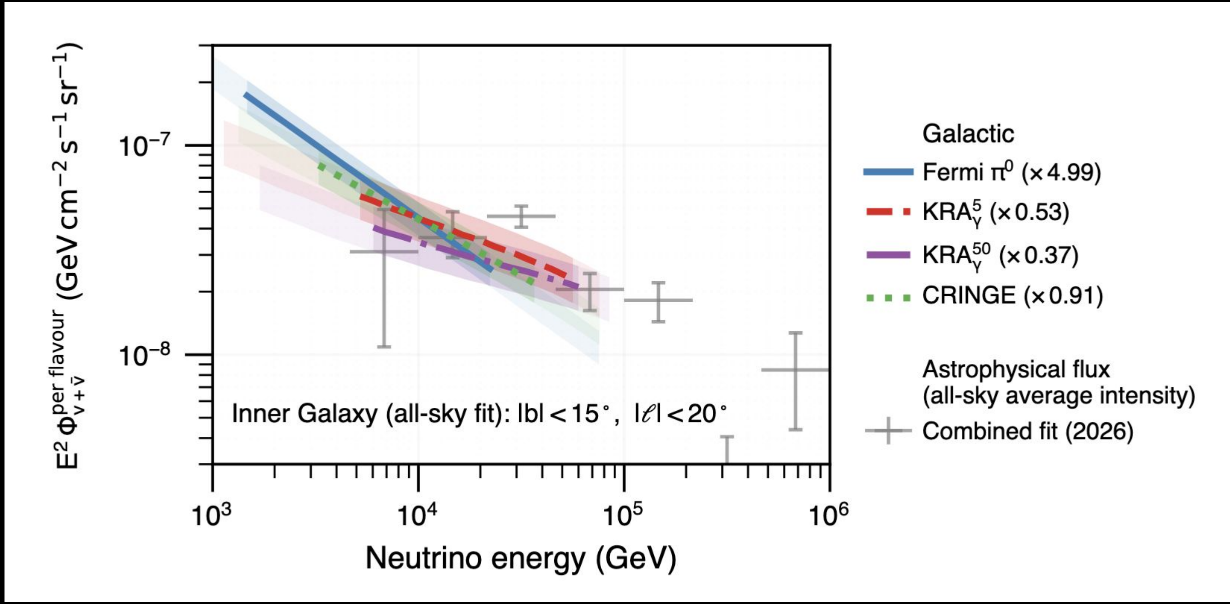
Understand origins of astrophysical neutrinos is a pressing challenge!

High-energy Neutrino Spectra

IceCube Collab. 2023



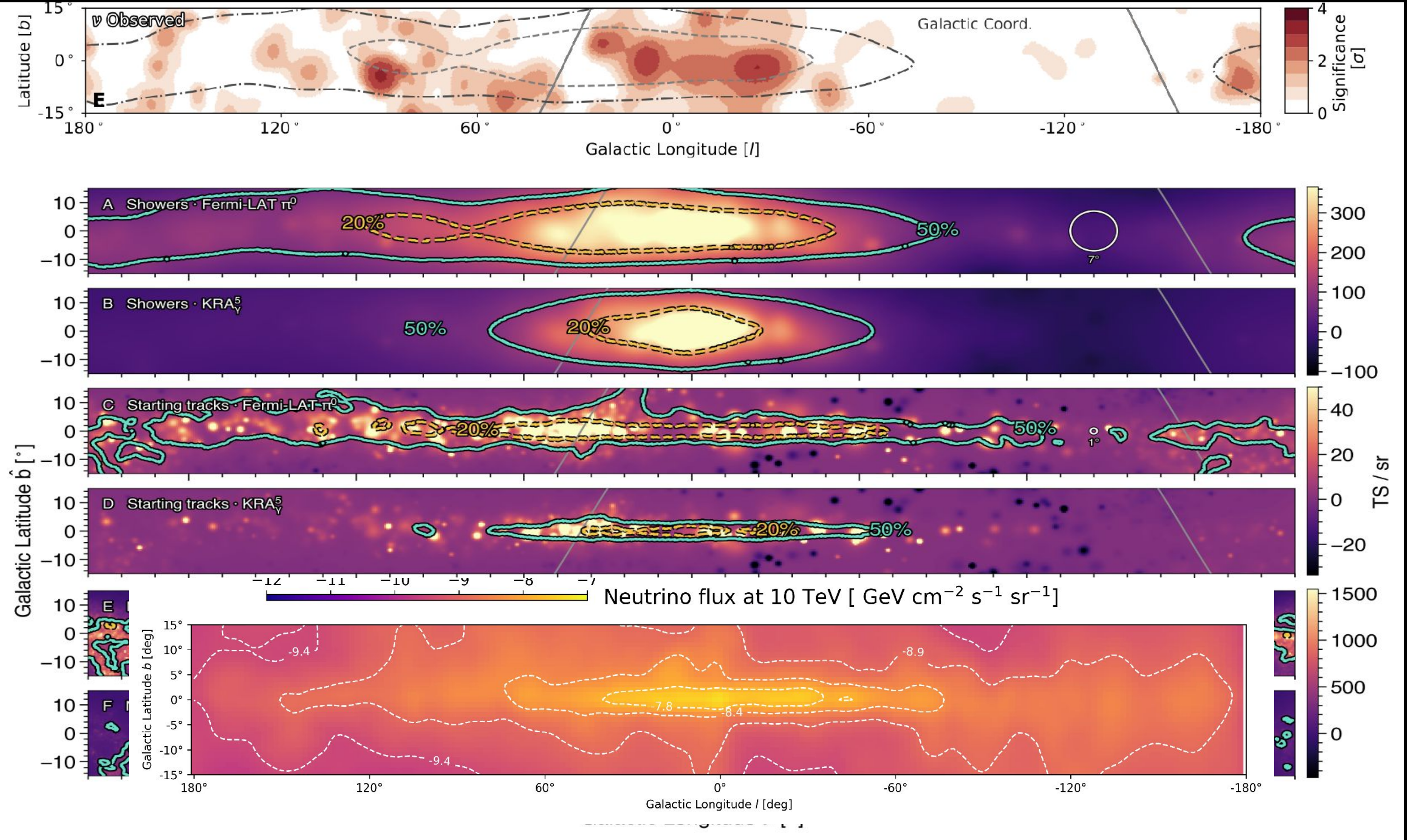
IceCube Collab. 2026



- Based on the all-sky (4π sr) template and are presented as an all-sky flux

- Diffuse Galactic neutrino spectra averaged over the Inner Galaxy
- Comparable to the all-sky averaged astrophysical intensity

Detection of High-energy Astrophysical Neutrinos



IceCube Collab. 2023

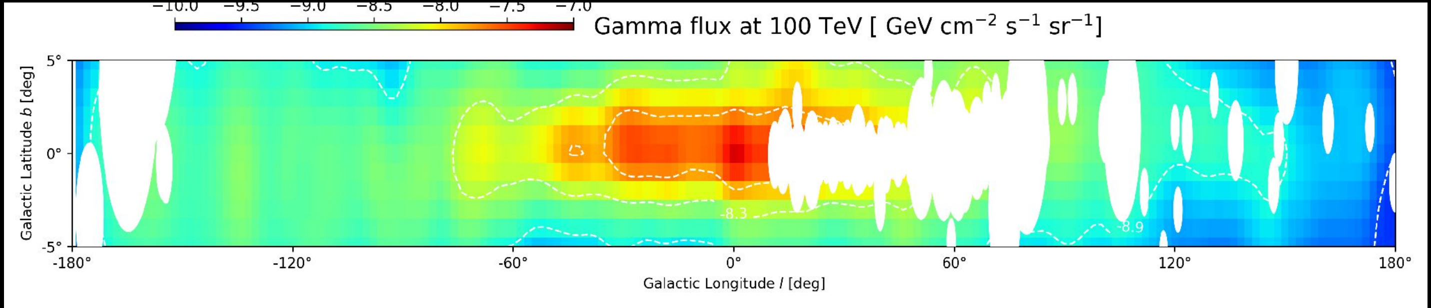
IceCube Collab. 2026

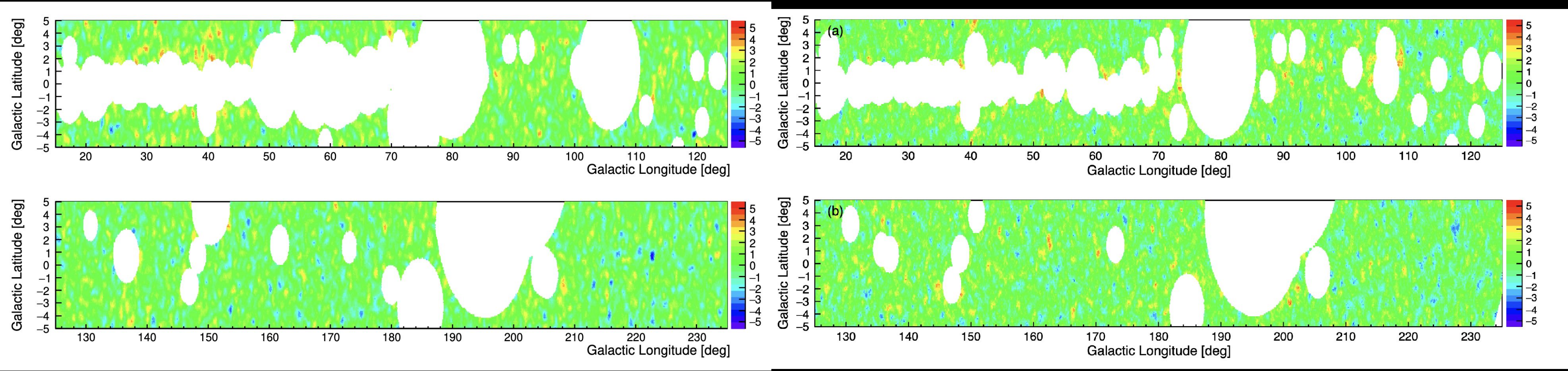
Shower samples (A, B)

Starting-track samples (C, D)

Northern-track samples (E, F)

LHAASO Detection of High-energy Gamma Ray

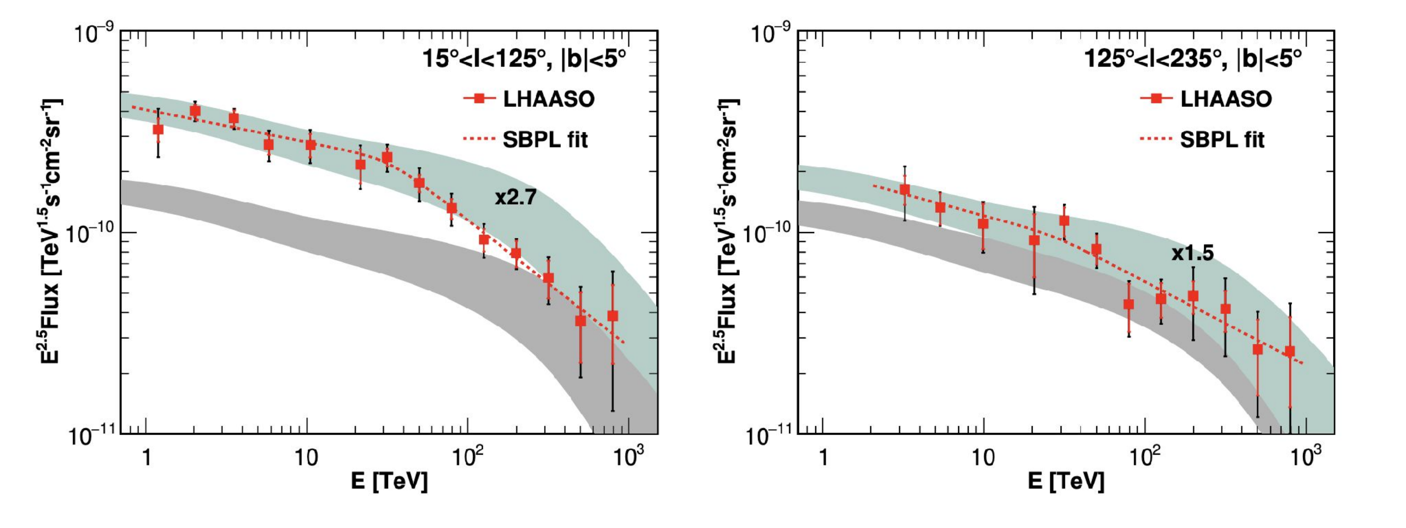




WCDA KM2A

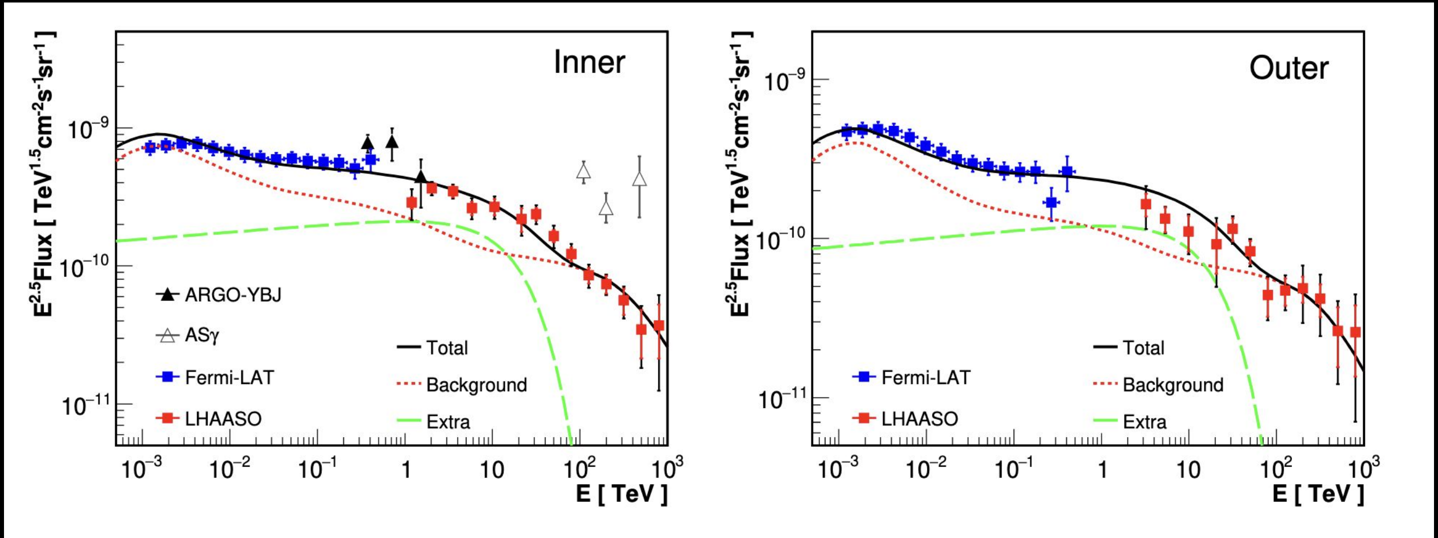
- The significance maps in Galactic coordinate of the inner Galaxy region (top panel) and outer Galaxy region (bottom panel))

“Assume that the CR intensity is uniform in the Galaxy, and calculate the γ-ray emission using the local CR spectra and the line-of-sight integrated gas content” --- LHAASO Collab. 2025



The grey shaded bands show the predicted diffuse fluxes from local CR intensities and the LOS integrated gas.

Wide-band fluxes of diffuse γ-ray emission in the inner and outer Galaxy regions



Microquasars as UHE gamma-ray sources