CosPA 2026 / ACGRG 13

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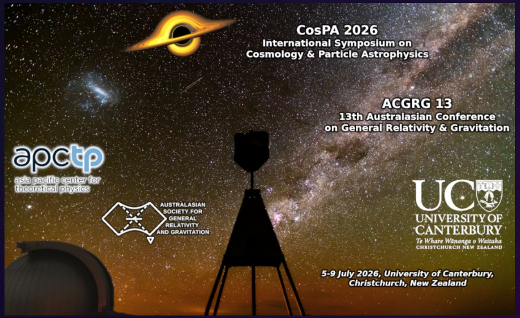
Galactic Neutrino Source Searches in the Multi-Messenger Era

Ankur Sharma | Rhia Hewett



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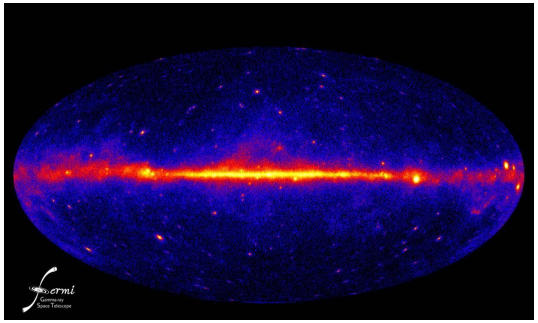
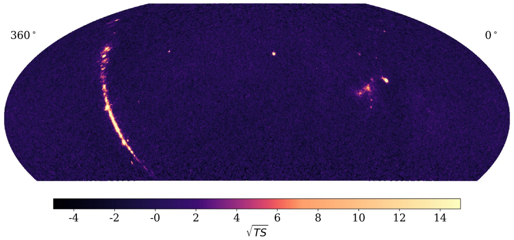
Galactic gamma-ray abundance

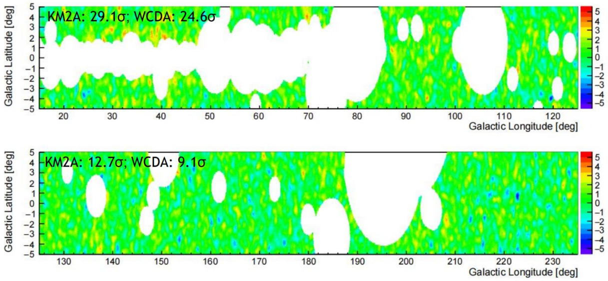
Galactic plane is a bright emitter of **GeV–PeV γ rays**, containing hundreds of resolved sources together with strong diffuse emission



HAWC



LHAASO



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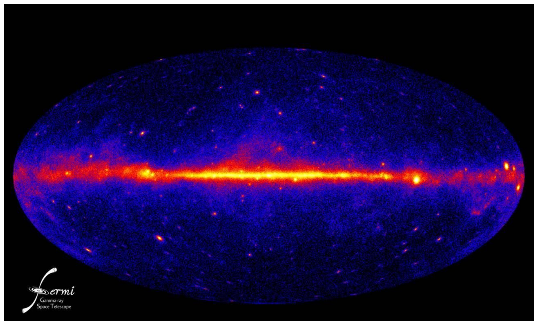
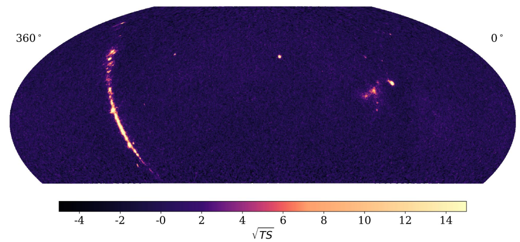


HAWC



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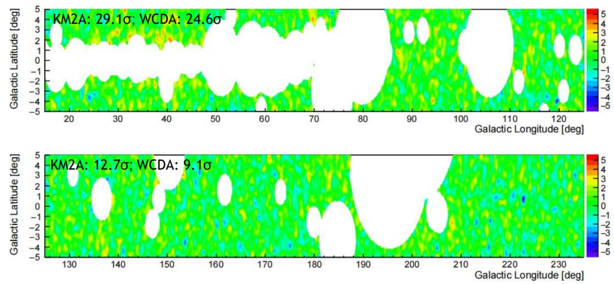
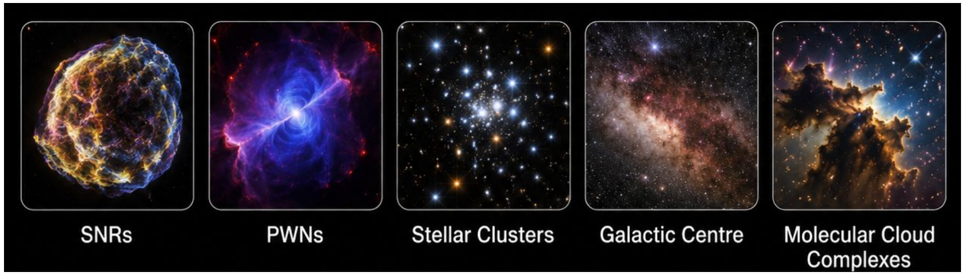


Candidate Galactic PeVatrons include **SNRs**, **PWNs**, **stellar clusters**, the **Galactic Centre**, and **molecular cloud complexes** illuminated by nearby accelerators



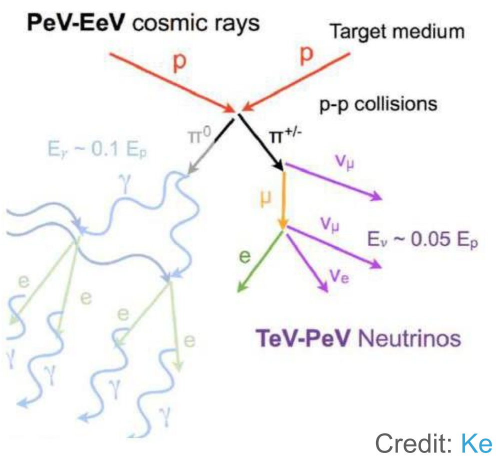
➔ Diffuse emission consistent with cosmic-ray (CR) interactions throughout the interstellar medium, while individual TeV sources trace localized acceleration sites

If these γ-rays are hadronic, high-energy neutrinos should accompany them!

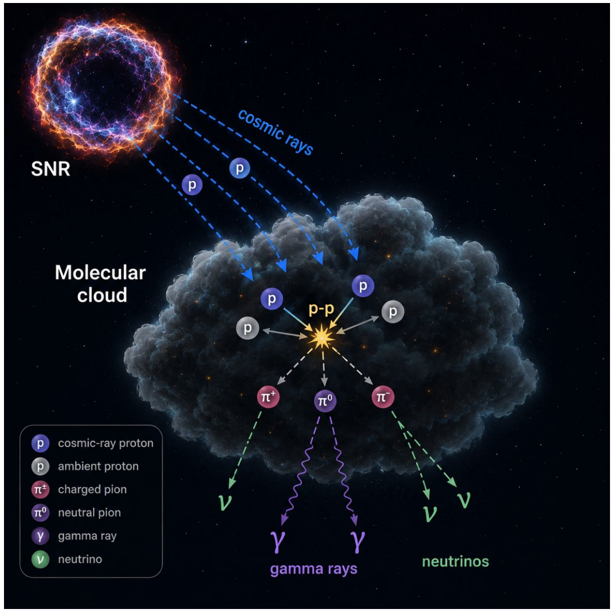
Gamma-rays are not enough!

Gamma-rays point to the neighborhood; neutrinos point to the crime

- ➢ Galactic plane is a source-rich environment, not a single emitter
- ➢ Gamma rays identify energetic regions, not always the emission channel -> **Neutrinos are the clean hadronic tag**



Credit: Ke Fang



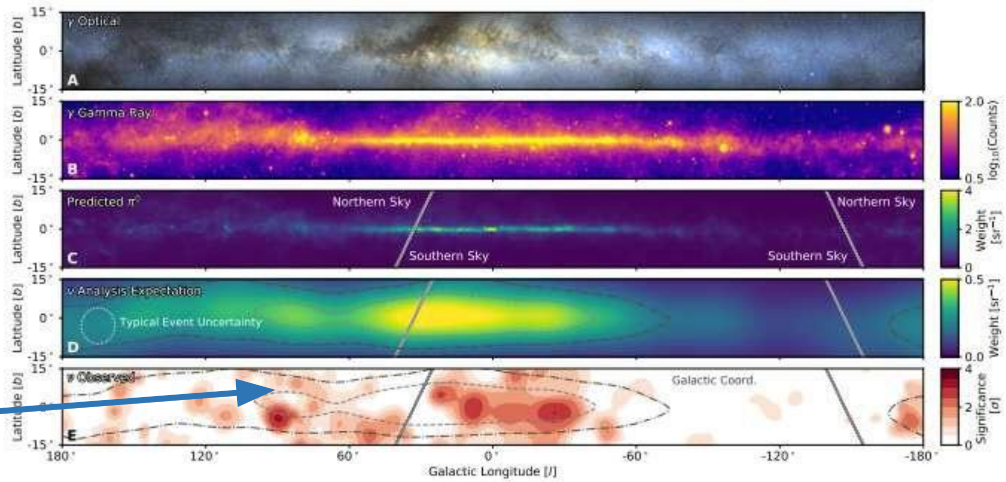
Gamma-ray observations provide spatial/spectral priors for targeted neutrino searches

So… where's the party at?

Despite a rich Galactic γ-ray sky, no steady Galactic neutrino source has yet been conclusively identified

- ➢ **Diffuse emission** from Galactic plane observed by **IceCube at 4.5σ**
- ➢ However, individual sources powering this emission remain unidentified

Truly diffuse emission, or combined glow of many unresolved accelerators?

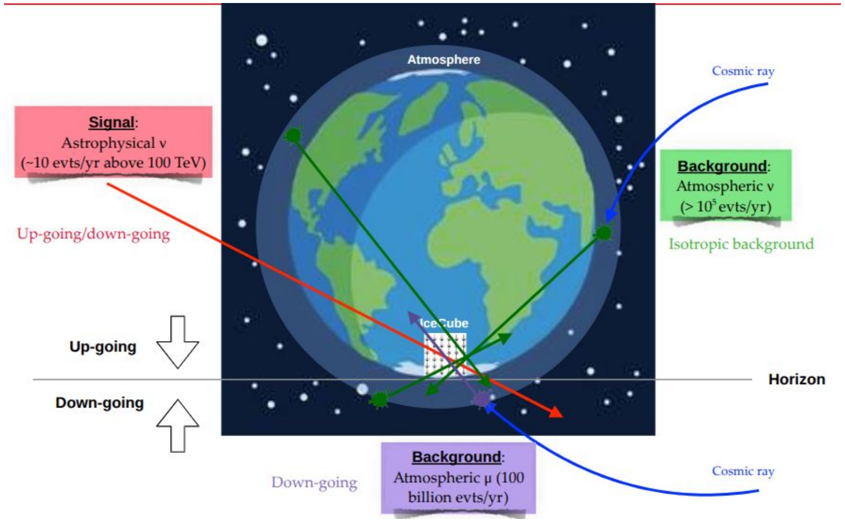


[IceCube 2023, Science 380:6652]

Identifying the sources is now one of the central goals of Galactic neutrino astronomy

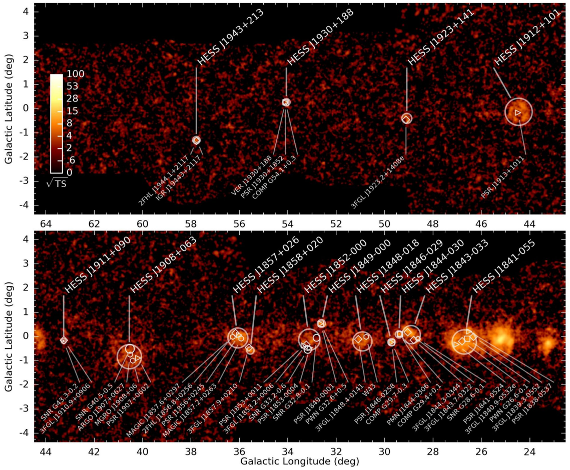
Party poopers!

- Neutrinos are intrinsically rare
- Atmospheric backgrounds dominate

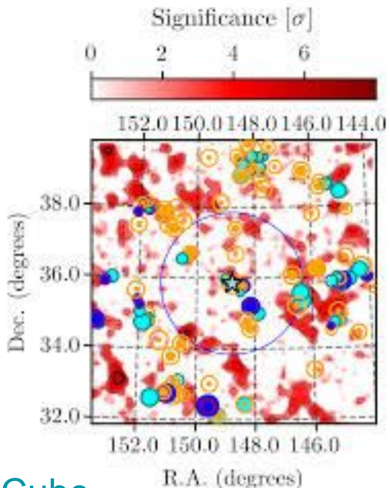


- The Galactic plane is crowded
- Sources may be spatially extended

HESS



- Detector angular resolution limits localization

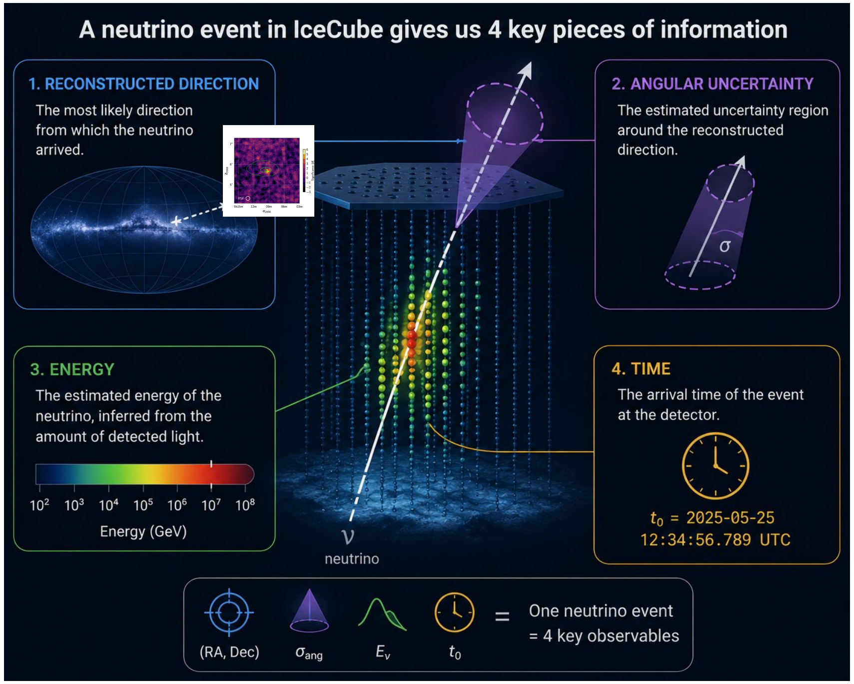


IceCube

Following the music

So how does IceCube search for neutrino sources?

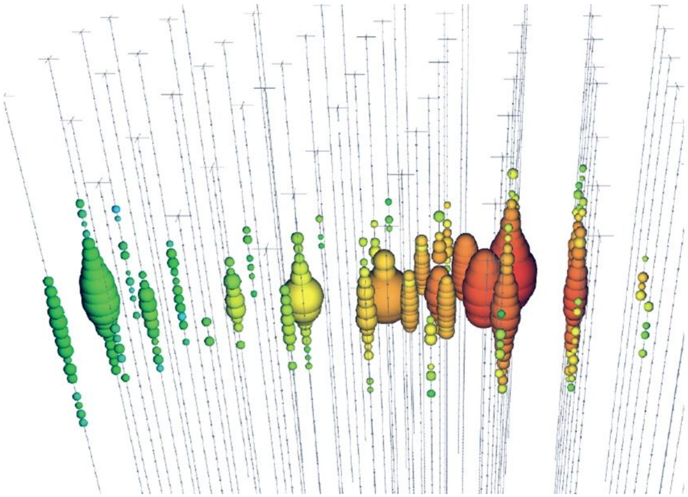
- Directional reconstruction and its uncertainty quantify the spatial association with a candidate source
- Energy info helps probabilistically discriminate an astrophysical signal from atmospheric backgrounds
- A likelihood framework combines the spatial and energy information from all events to evaluate competing source hypotheses



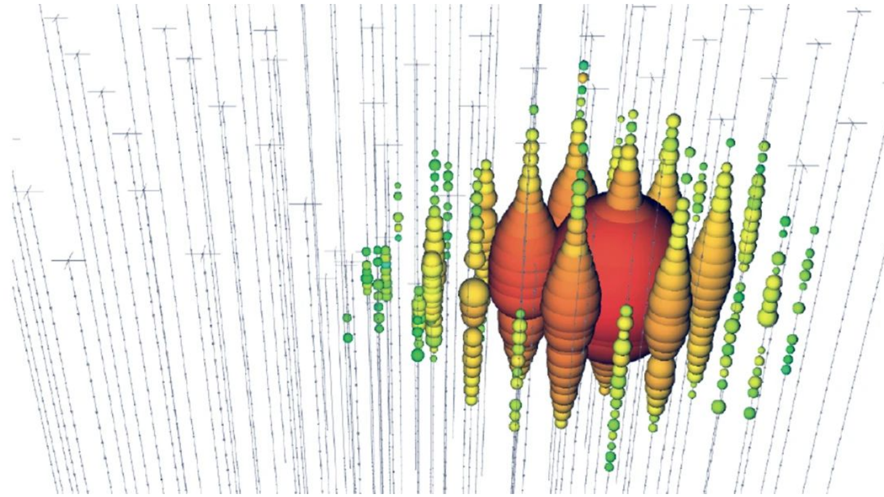
Different source morphologies favour different event topologies and analysis strategies

Event signatures in IceCube

Complementary views of the high-energy neutrino sky:



Through-going track



Cascade

- Produced primarily by charged-current ν_μ interactions
- Provide superior angular resolution (~ 1° @ TeV)
- Ideal for point-source searches and source localization

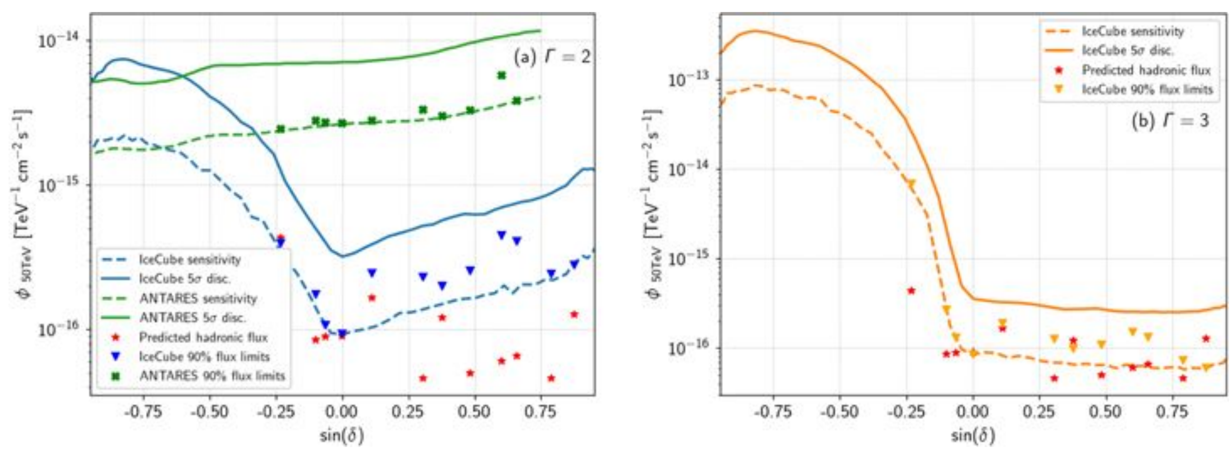
- Produced by ν_e , ν_τ and neutral-current interactions
- Compact light pattern gives excellent energy reconstruction (~ 10% energy resolution) but poorer angular precision (~ 10° - 15°)
- Provide strong sensitivity to diffuse and extended Galactic emission

Beyond diffuse emission: Sources

Current IceCube searches probe a range of source hypotheses, from individual accelerators to extended Galactic structures

★ **Individual Sources:** Can a single Galactic accelerator produce a detectable neutrino signal?
- Searches target promising Galactic PeVatrons (e.g. SNRs, PWNe, LHAASO sources)
- No steady Galactic neutrino source has yet been conclusively identified
- IceCube searches of LHAASO >100 TeV catalog found no significant neutrino counterpart from any individual source, placing increasingly stringent constraints on hadronic emission models

[IceCube 2023, ApJ Lett. 945, L8]



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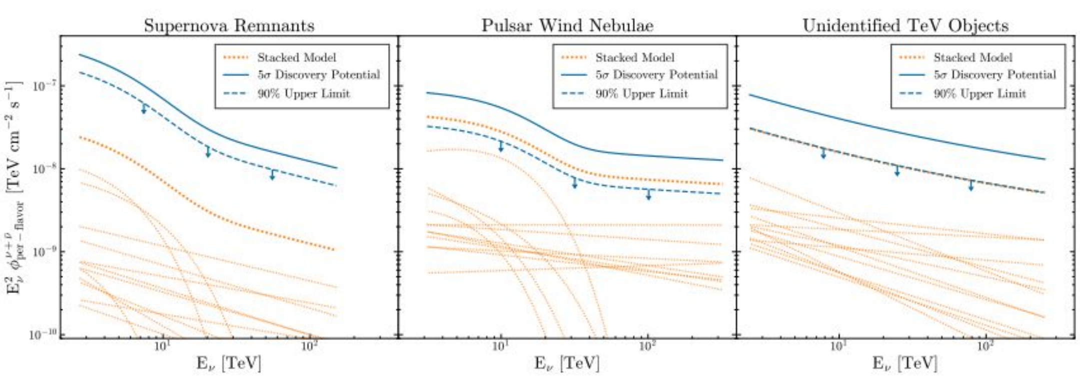
★ **Source Populations:** *Are many individually faint sources producing the observed signal collectively?*

- Stacking analyses test entire source populations rather than individual objects
- No significant population has been detected so far
- Stacking analyses of >100 TeV LHAASO sources show that currently known Galactic PeVatron population is insufficient to explain the observed Galactic neutrinos, contributing no more than ~20% of the total

IceCube ESTES (2025)



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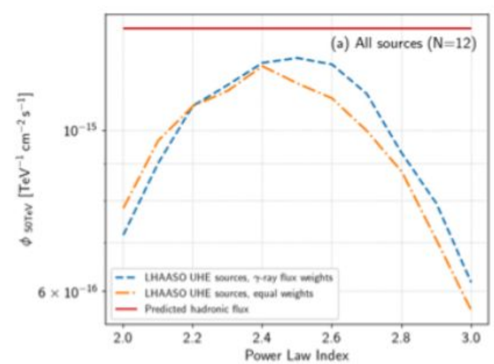

Beyond diffuse emission: Sources

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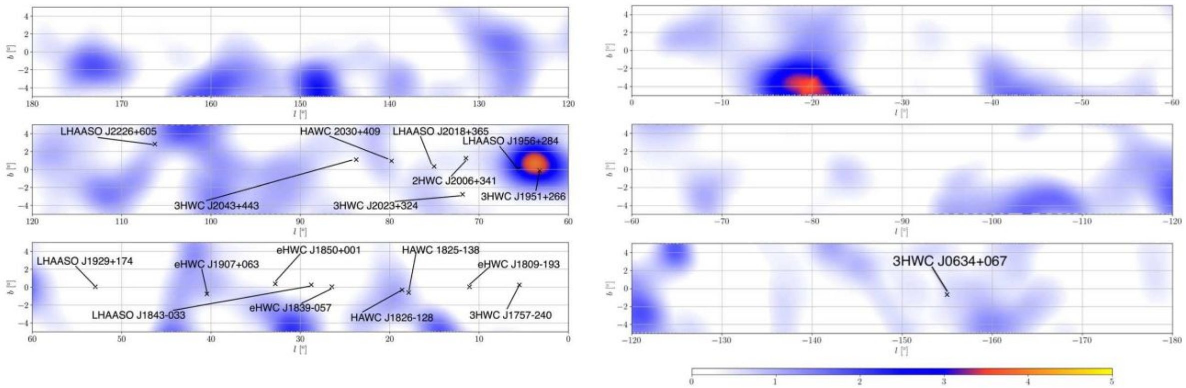
- ★ **Extended Structures:** *Does neutrino emission follow large-scale Galactic structures?*
  - Spatially extended regions, such as the Galactic plane and known TeV complexes, targeted
  - Recent IceCube searches for spatially extended Galactic sources found no significant excess above background, placing improved constraints on several TeV source regions and **reinforcing that source morphology and environment modelling remain an open challenge!**

[IceCube 2023, ApJ 956:20]

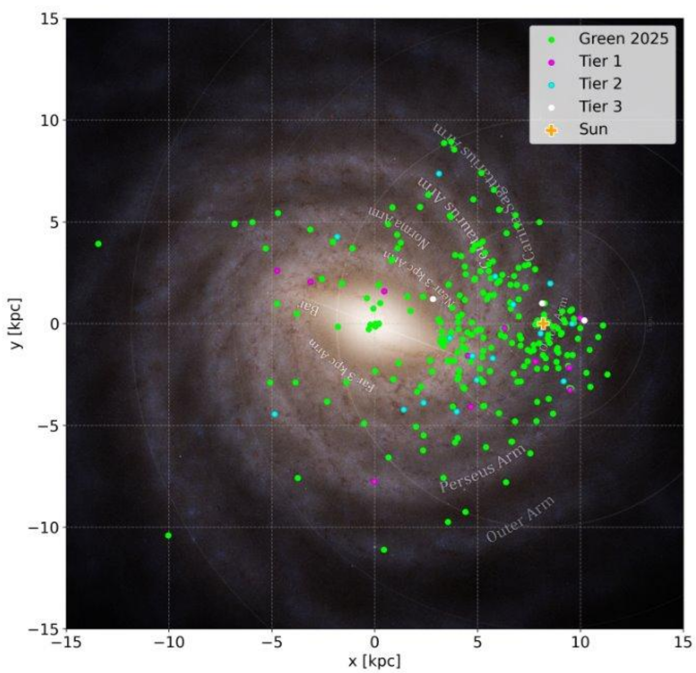


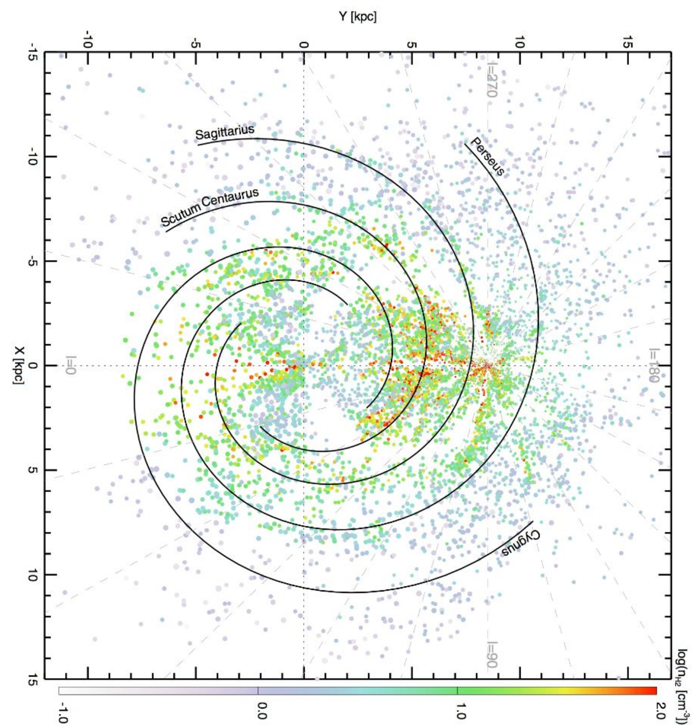
Searching for neutrino emission from molecular clouds near cosmic-ray accelerators

Source selection

Search for molecular clouds near potential accelerators based on CR transport modelling

- Supernova remnants from SNRCat: Ferrand & Safi-Harb (2012) paired with molecular cloud catalogues (Rice et al. 2016, Miville-Deschenes et al. 2017)





(see References)

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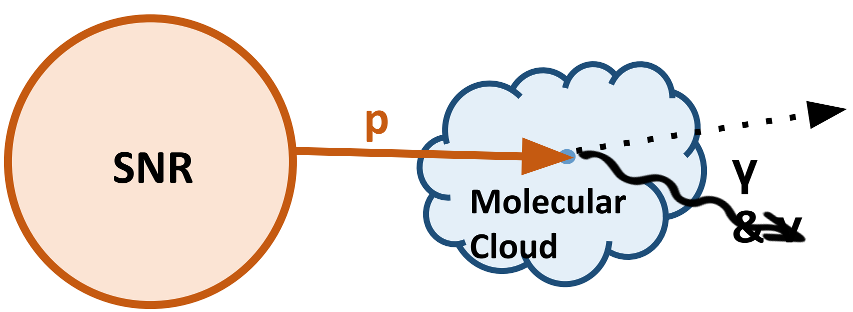
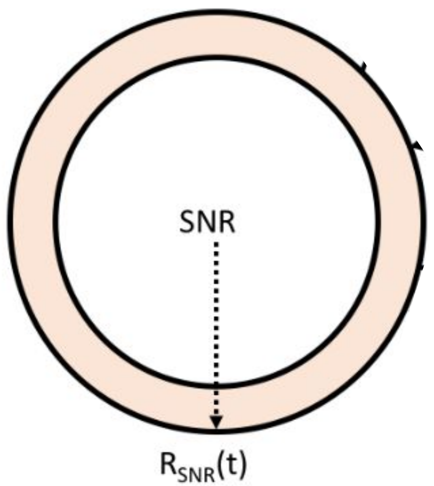
- Supernova remnants from SNRCat: Ferrand & Safi-Harb (2012) paired with molecular cloud catalogues (Rice et al. 2016, Miville-Deschenes et al. 2017)
- Model CR diffusion from release to cloud and predict resulting nu/gamma flux - using implementation based on Burley et al. (2023) and Einecke et al. (2023)
- Select top regions of interest for catalogue search and weight stacking contribution according to predicted flux
- Regions of interest defined as extended sources centred on brightest cloud



(see References)

CR transport modelling



Schematic from Mitchell et al. (2021)

Energy dependent release from SNR:

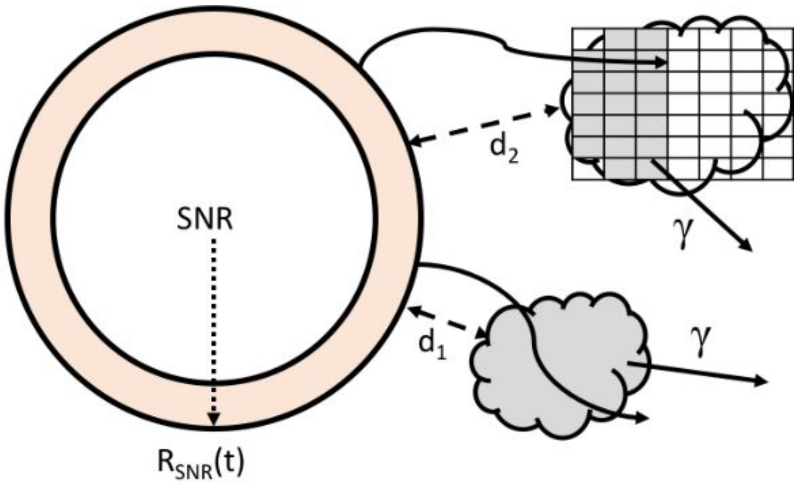
$$R_{SNR} = 0.31\left(\frac{E_{SN}/10^{51}}{n_0\mu}\right)^{1/5} t^{2/5}$$

$$t_{esc} = t_{sedov}\left(\frac{E_p}{E_{p-max}}\right)^{-1/\beta}$$

Adiabatic expansion in Sedov-Taylor phase from Celli et al. (2019)

(see References)

CR transport modelling



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CR diffusion in ISM:

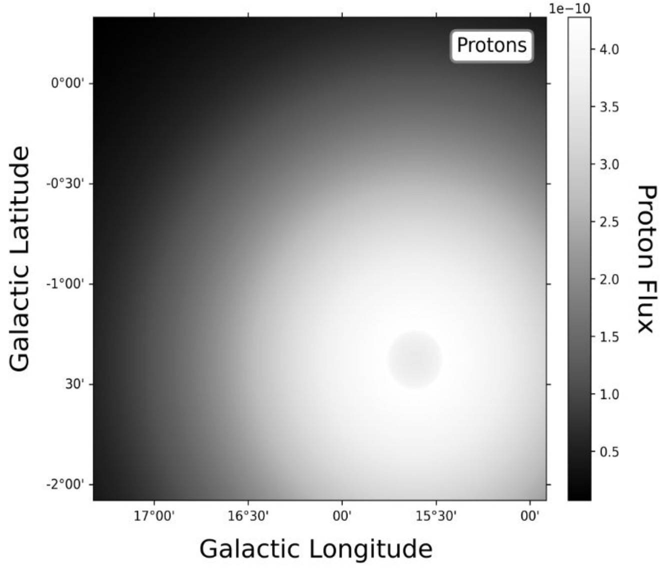
$$J_p(E, r', t') = N_0 \cdot E_p^{\alpha} \cdot f(E, r', t')$$

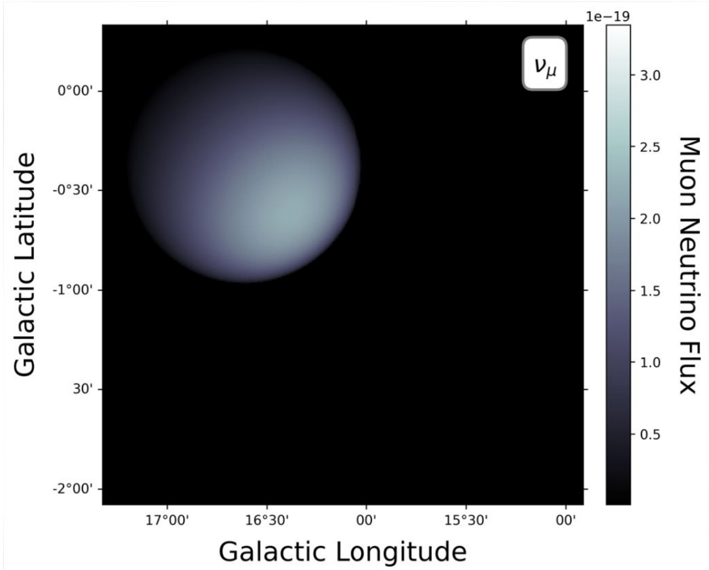
$$f(E_p, r', t') = \frac{f_0}{\pi^{3/2} R_d^3} \exp\left(-\frac{(\alpha - 1)t'}{\tau_{pp}} - \frac{r'^2}{R_d}\right)$$

Analytic solution from Aharonian & Atoyan (1996) to transport equation for isotropic, homogeneous diffusion from impulsive injector

(see References)

CR transport modelling





Figures from Burley et al. (2023)

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Analytic solution from Aharonian & Atoyan (1996) to transport equation for isotropic, homogeneous diffusion from impulsive injector

Neutrino/gamma ray production:

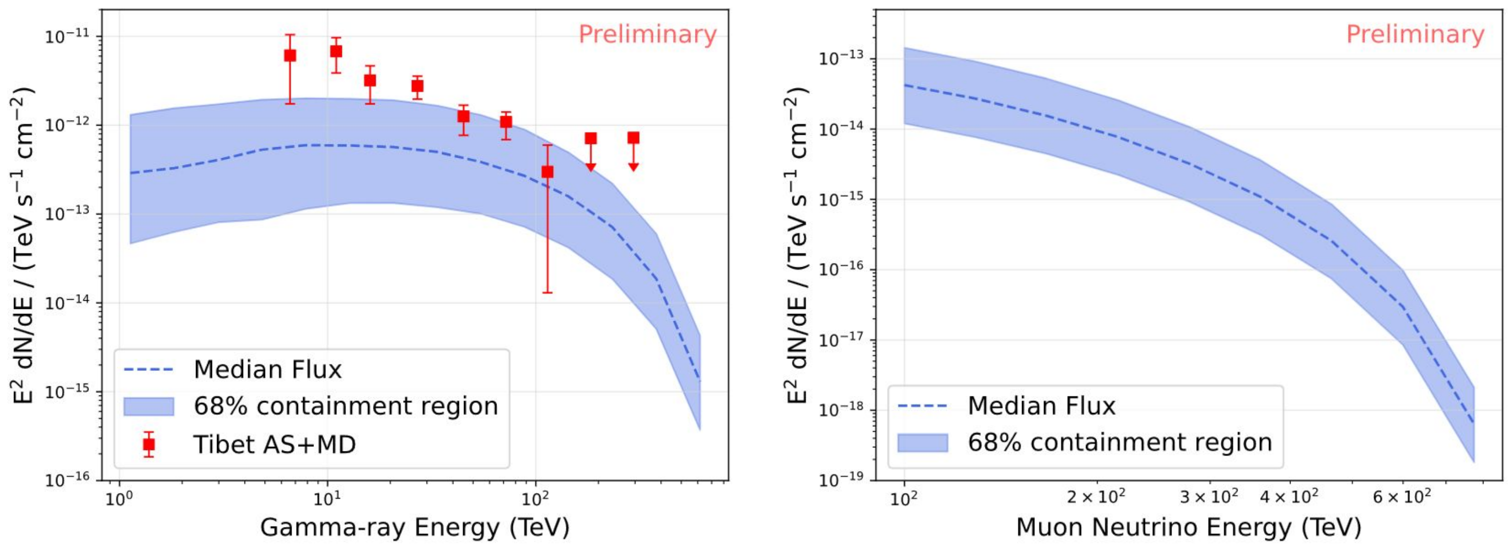
$$\phi_\nu(E_\nu, R', t')$$
$$= cn \int_{E_\nu}^{\infty} \sigma_{\mathrm{inel}}(E_p) J_p(E_p, R', t') F_\nu\left(\frac{E_\nu}{E_p}, E_p\right) \frac{dE_p}{E_p}$$

Neutrino/gamma-ray flux from pion decay using pp inelastic cross section by Kafexhiu et al. (2014) and neutrino spectrum by Kelner et al. (2006)

(see References)

Restricting the parameter space

Place constraints on system parameters based on gamma-ray observation limits



$$D(E_{\rm p}) = \chi D_0 \left(\frac{E_{\rm p}/{\rm GeV}}{B/3\mu{\rm G}} \right)^{\delta}$$

Model Parameter	Values
χ	0.1, 0.01, 0.001
δ	0.3, 0.5
η	0.1, 0.3
$E_{\rm p,max}$	1 PeV, 5 PeV
α	2, 2.2
$E_{\rm SN}, M_{\rm ej}$	(10^{51} erg, 1.4 $M_\odot$), (10^{51} erg, 10 $M_\odot$), (10^{52} erg, 20 $M_\odot$)

With suppression factor χ, diffusion coefficient at 1 GeV, D_0 (3×10^{-27}cm^{-2} s^{-1}), magnetic field B tuned for MC, and 3μG in the interstellar medium), and diffusion index δ.

Figure and table from Burley et al. (2023)

(see References)

Disentangling sources from the diffuse Galactic flux

The typical likelihood used for point-source hypothesis testing:

$$\mathcal{L}(n_s, \gamma; \vec{x_i}, E_i) = \prod_i \left(\frac{n_s}{N} \mathcal{S}(\vec{x_i}, \vec{x_s}, \sigma_i, E_i; \gamma) + (1 - \frac{n_s}{N}) \mathcal{B}(\delta_i, E_i) \right)$$

- Maximise with respect to the number of signal events, n_s and spectral index, γ
- Background TS distribution from scrambled data assuming isotropic background
- But observed diffuse Galactic flux shows astrophysical background is not isotropic -> need careful treatment
- Current solution: also fit a diffuse template with floating normalization

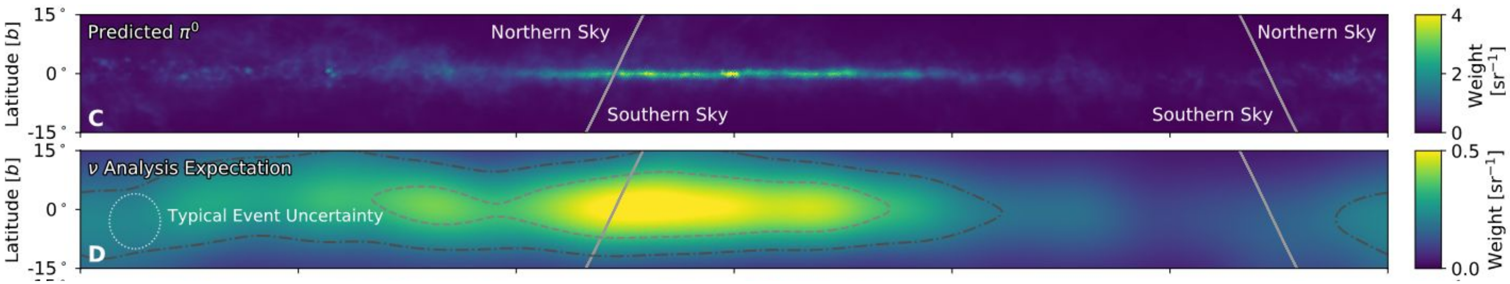


Figure from IceCube Collaboration (2023)

More work to be done!

Conclusions

- The Galaxy is rich in high-energy γ-ray sources, but their neutrino counterparts remain largely unidentified
- Neither known source populations nor simple source models can fully explain the observed Galactic emission
- Ongoing efforts increasingly combine multi-messenger source templates, spatial segmentation, and complementary neutrino event samples to probe its origin
- Morphology-informed analyses provide a natural framework for the next generation of Galactic neutrino source searches to resolve spatial origin

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