Search for neutrino signals from the Galactic Plane and Cygnus Bubble based on LHAASO γ-ray observations

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Outline

1. Introduction

- LHAASO observation of Galactic plane & Cygnus Bubble

2. Detectors & Datasets

- IceCube publicly available 7 years of track data with the full detector
- LHAASO diffuse Galactic γ-ray flux templates

3. Analyses & Results

- Template searches
- Scan searches

4. Summary & Outlook

Introduction

- Origin of cosmic rays?
- Cosmic rays interact with the interstellar medium (ISM) should produce pions ($\pi^0/\pi^{\pm}$) which decay into γ-rays and neutrinos.

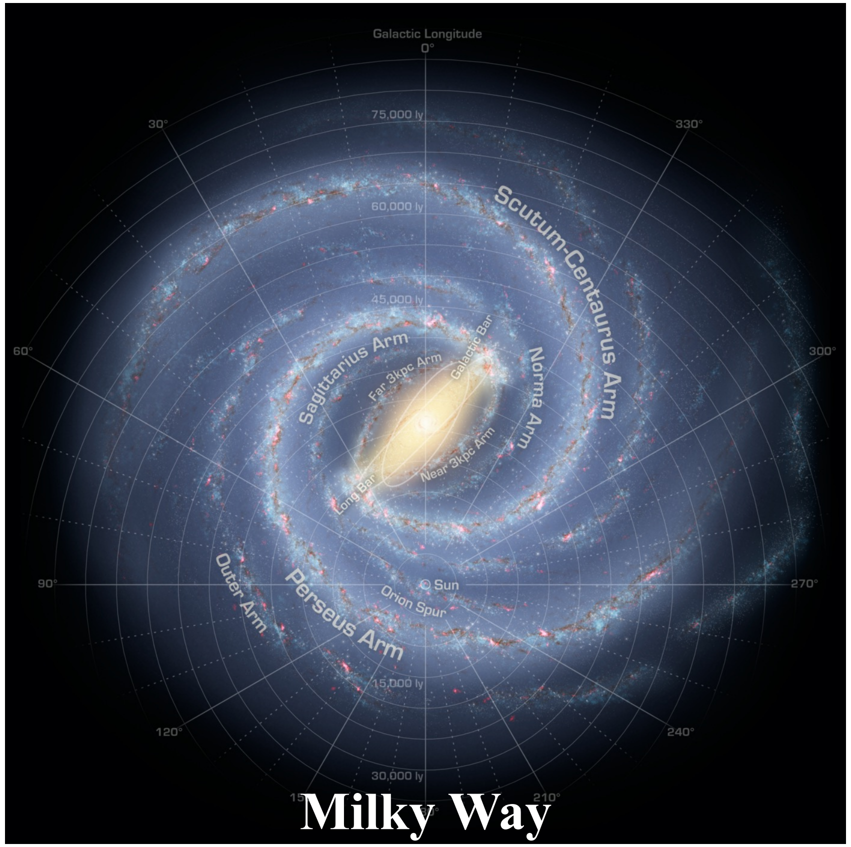


Figure credit: Wikipedia

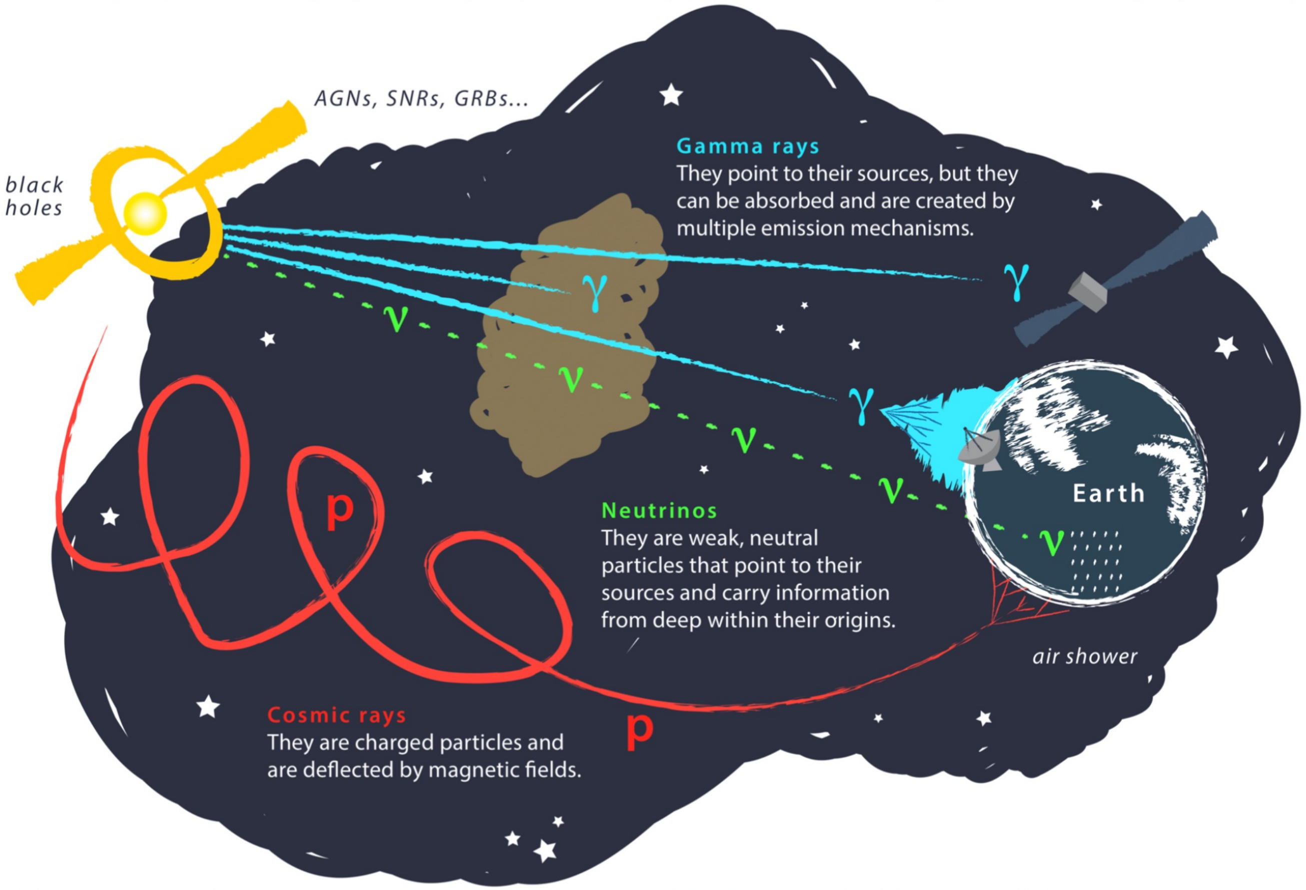


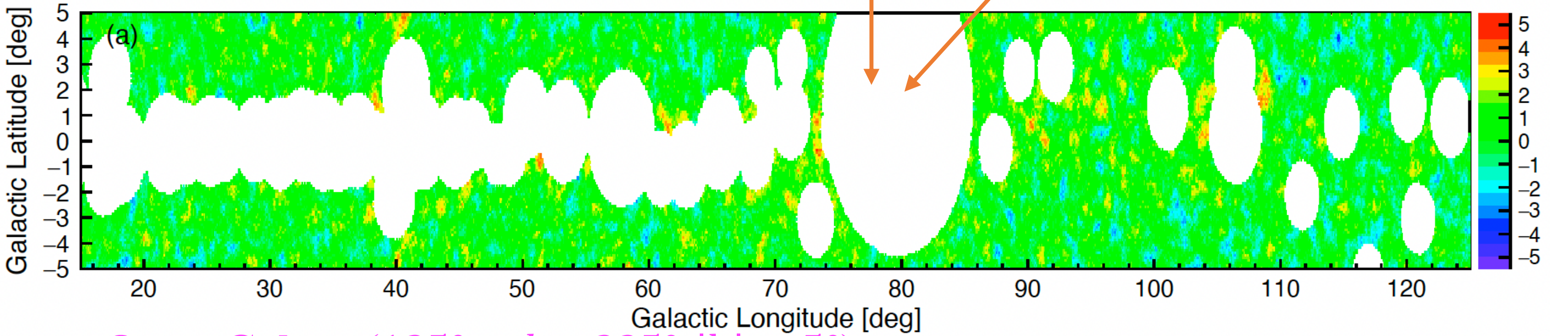
Figure credit: Juan Antonio Aguilar and Jamie Yang

LHAASO Observation of Diffuse Galactic γ-ray Emission (DGE)

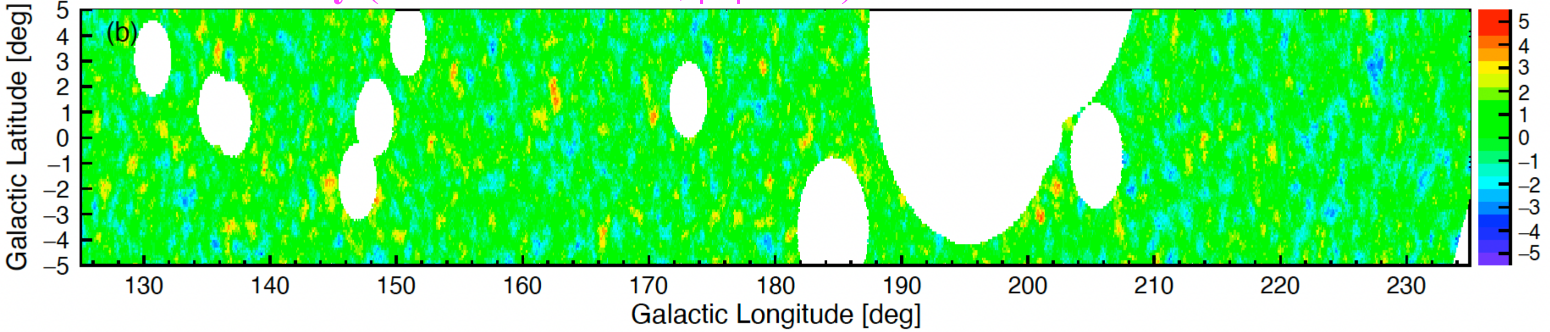
- LHAASO measured diffuse γ-rays from the Galactic plane with energies from sub-TeV to 1 PeV
  - ✓ Conducted in two regions: the inner region ($15° < l < 125°$, $|b| < 5°$) and the outer region ($125° < l < 235°$, $|b| < 5°$)
  - ✓ All known point-like and extended sources are masked in the analysis

Cygnus region (6°) was masked in the DGE measurement

Inner Galaxy ($15° < l < 125°$, $|b| < 5°$)



Outer Galaxy ($125° < l < 235°$, $|b| < 5°$)



LHAASO Collaboration, Phys.Rev.Lett. 131 (2023) 15, 15

- KM2A (10TeV-1PeV): the diffuse γ-rays follow a power-law spectrum $dN/dE \propto E^{-2.99}$ for both inner and outer regions

- WCDA (sub-TeV to 20 TeV): the diffuse γ-rays follow an $E^{-2.64}$ ($E^{-2.60}$) spectrum in the **inner (outer)** region

PoS ICRC2023 (2023), 672

Datasets and Method

- **LHAASO data:** diffuse Galactic γ-ray flux map and significance map of KM2A
  - Use the γ-ray flux map (Δl=2°, Δb=1°) observed by LHAASO-KM2A as the weighting for neutrino emission
  - Apply significance cuts ($0.5\sigma, 1\sigma, 1.5\sigma, 2\sigma$) to the flux map

- **IceCube data:** publicly released 7 years of track events with the IceCube full detector
  - IC86-I (2011-2012), IC86-II (2012-2018)
  - Experimental data events, instrument response functions, and detector uptime

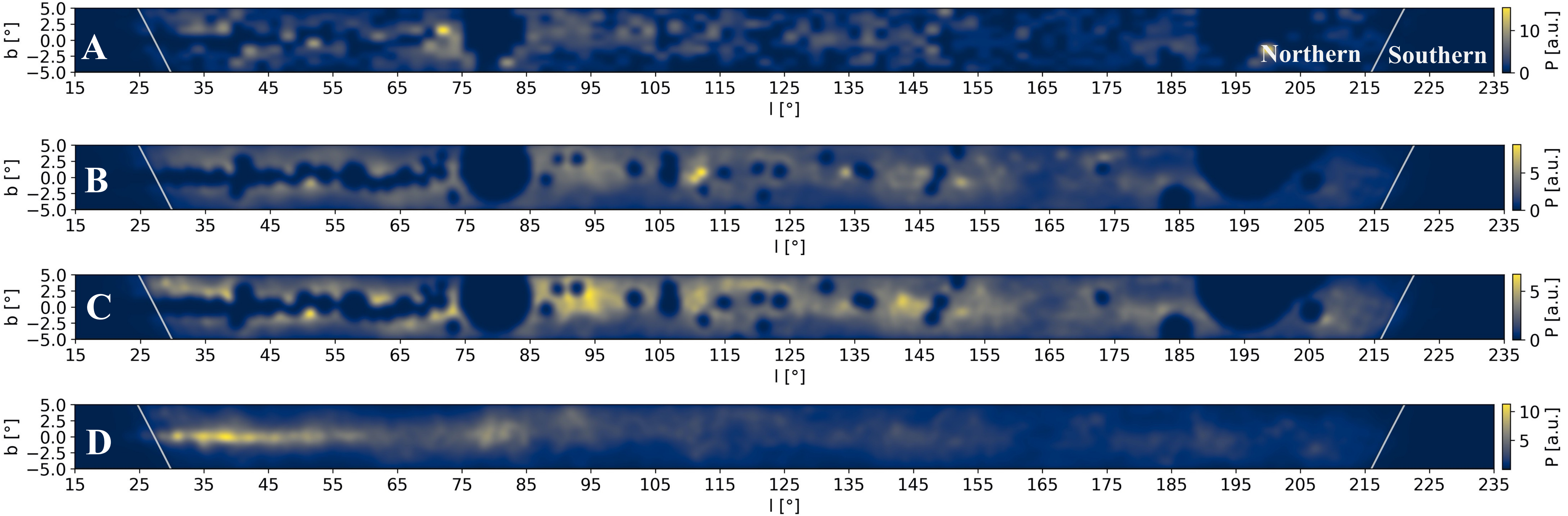
- **Method:** time-integrated template analysis

$$L(n_s,\gamma) = \prod_{i=1}^{N}\left(\frac{n_s}{N}S_i(\mathbf{x}_i,\sigma_i,E_i;\gamma) + \tilde{D}_i(sin\delta_i,E_i) - \frac{n_s}{N}\tilde{S}_i(sin\delta_i,E_i)\right)$$

$$TS = 2\ln\left[\frac{L(\hat{n}_s)}{L(n_s=0)}\right] = 2\sum_{i}^{N}\ln\left[\frac{n_s}{N}\left(\frac{S_i}{\widetilde{D}_i} - \frac{\widetilde{S}_i}{\widetilde{D}_i}\right)+1\right]$$

- **Interpreting results:** neutrino flux/upper limits, hadronic fraction constraints

Templates/Signal PDFs



- From top to bottom: **(A)** LHAASO γ-ray flux map (0.5σ), **(B)** π^0 (with mask), **(C)** gas (with mask), **(D)** gas
- Each template was convolved with the IceCube detector acceptance and then smeared with Gaussian distributions representing a typical uncertainty of 0.5°. The color scale is in arbitrary units (a.u.)

$$S_i^{\text{spat}}(\mathbf{x}_i|\sigma_i,\gamma) = (T_{\text{spat}}(\mathbf{x}) \times M_{\text{acc}}(\mathbf{x},\gamma) * Gaussian_{\text{2D}}(\sigma_i))(\mathbf{x}_i)$$

Template Search Results

➢ **γ-ray flux** templates

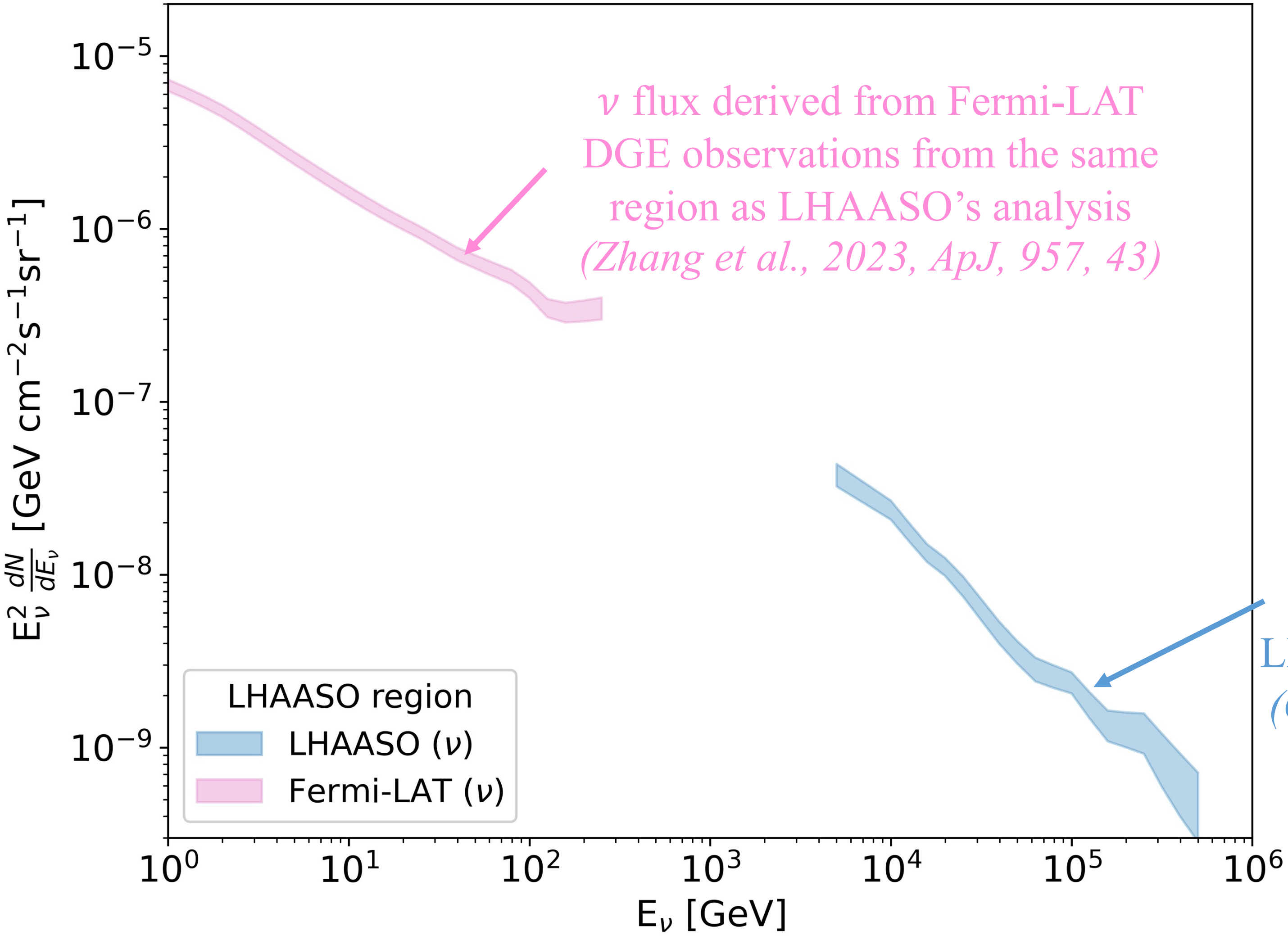
Flux at E_ν=25 TeV in units of $TeV^{-1}cm^{-2}s^{-1}$

Spatial Template	$\hat{n}_s$	Pretrial p-value (σ_{pre})	Best-fit flux $\pm 1\sigma$	Upper Limit $\phi_{90\%}$	$\phi_{90\%}/\phi_\nu$
γ-ray flux map (0.5σ)	311.4	0.029 (1.9σ)	$1.78^{+0.95}_{-0.94}\times10^{-14}$	3.00×10^{-14}	2.9
γ-ray flux map (1.0σ)	278.8	0.036 (1.8σ)	$1.56^{+0.88}_{-0.87}\times10^{-14}$	2.68×10^{-14}	2.9
γ-ray flux map (1.5σ)	244.5	0.040 (1.8σ)	$1.34^{+0.78}_{-0.77}\times10^{-14}$	2.35×10^{-14}	3.0
γ-ray flux map (2.0σ)	182.5	0.064 (1.5σ)	$0.98^{+0.66}_{-0.65}\times10^{-14}$	1.82×10^{-14}	3.2

- The neutrino spectral shape γ is fixed, assuming it follows the KM2A spectral index above 5 TeV (with $E_\gamma = 2E_\nu$) and the WCDA spectral index below it, while only fits $\hat{n}_s$ in the likelihood maximization

- The most significant result is obtained using the γ-ray flux map with >0.5σ detection, at 1.9σ pre-trials
- The 90% C.L. upper limits are approximately three times higher than the expected neutrino flux assuming that all diffuse γ-rays originate from hadronic interactions

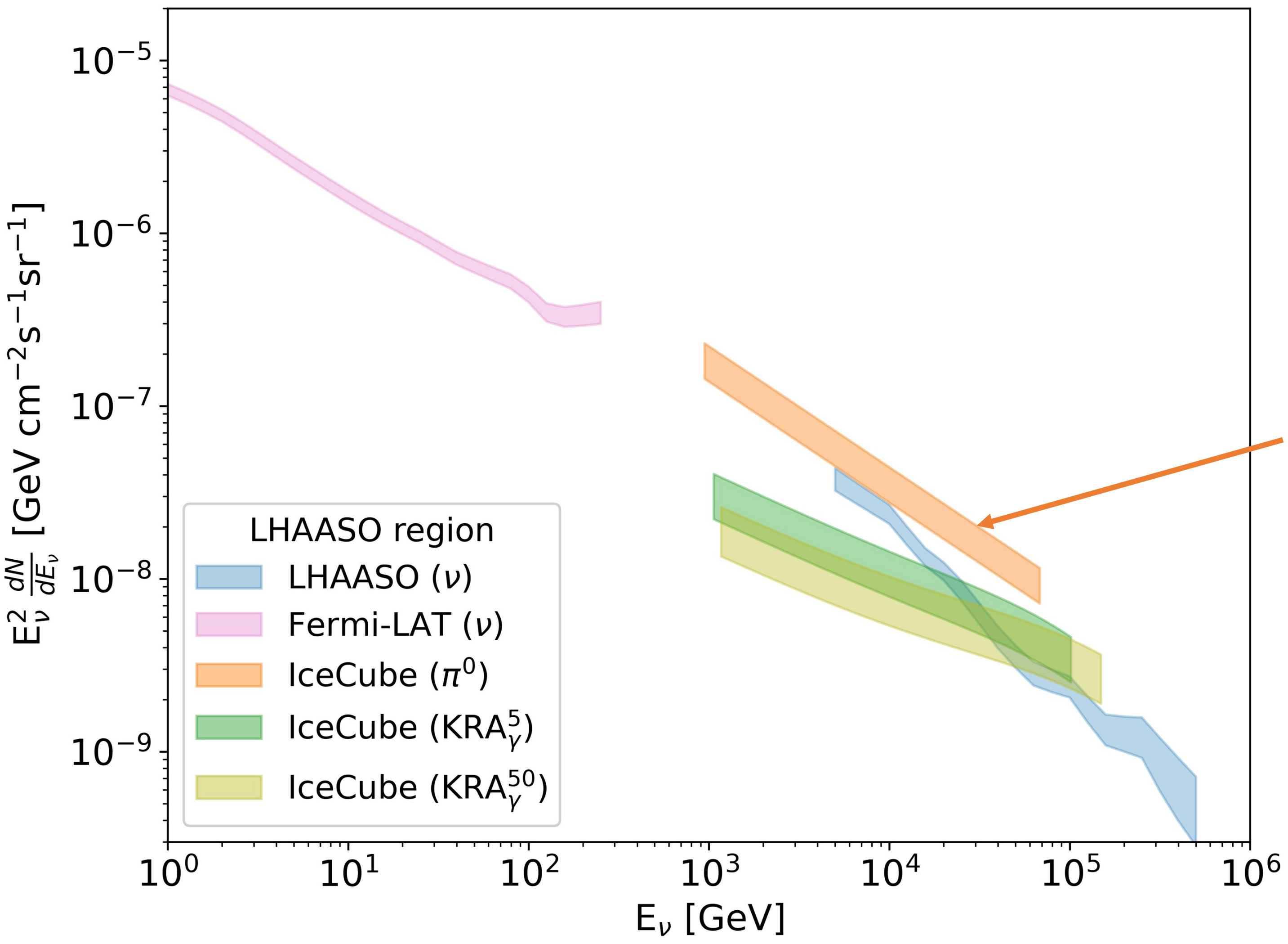
Template Search Results



ν flux derived from Fermi-LAT DGE observations from the same region as LHAASO's analysis *(Zhang et al., 2023, ApJ, 957, 43)*

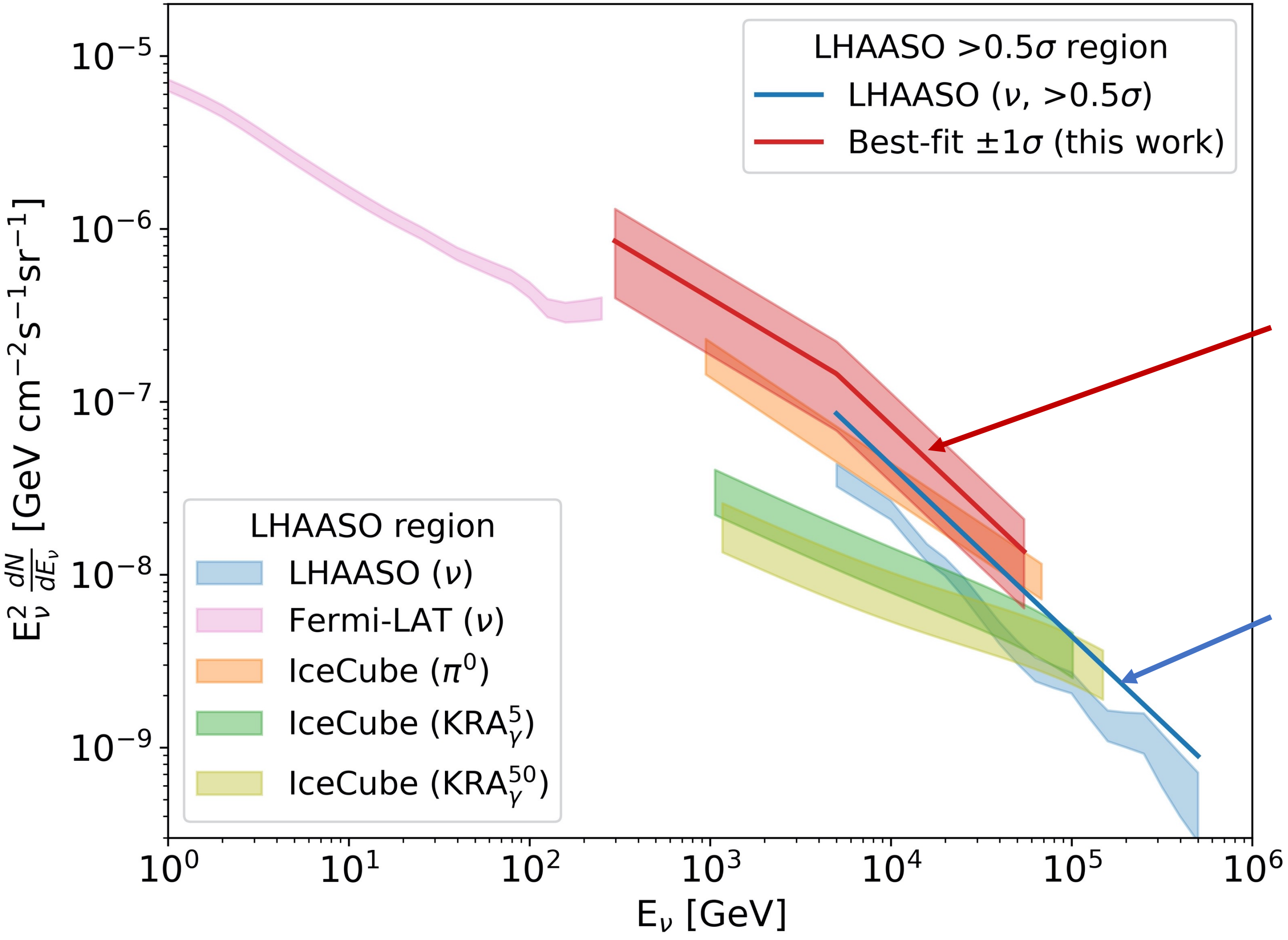
ν flux derived from LHAASO DGE observations *(Cao et al., 2023, PRL, 131, 151001)*

Template Search Results



IceCube flux scaled to the same region as LHAASO's analysis *(Abbasi et al., 2023, Science, 380, 6652)*

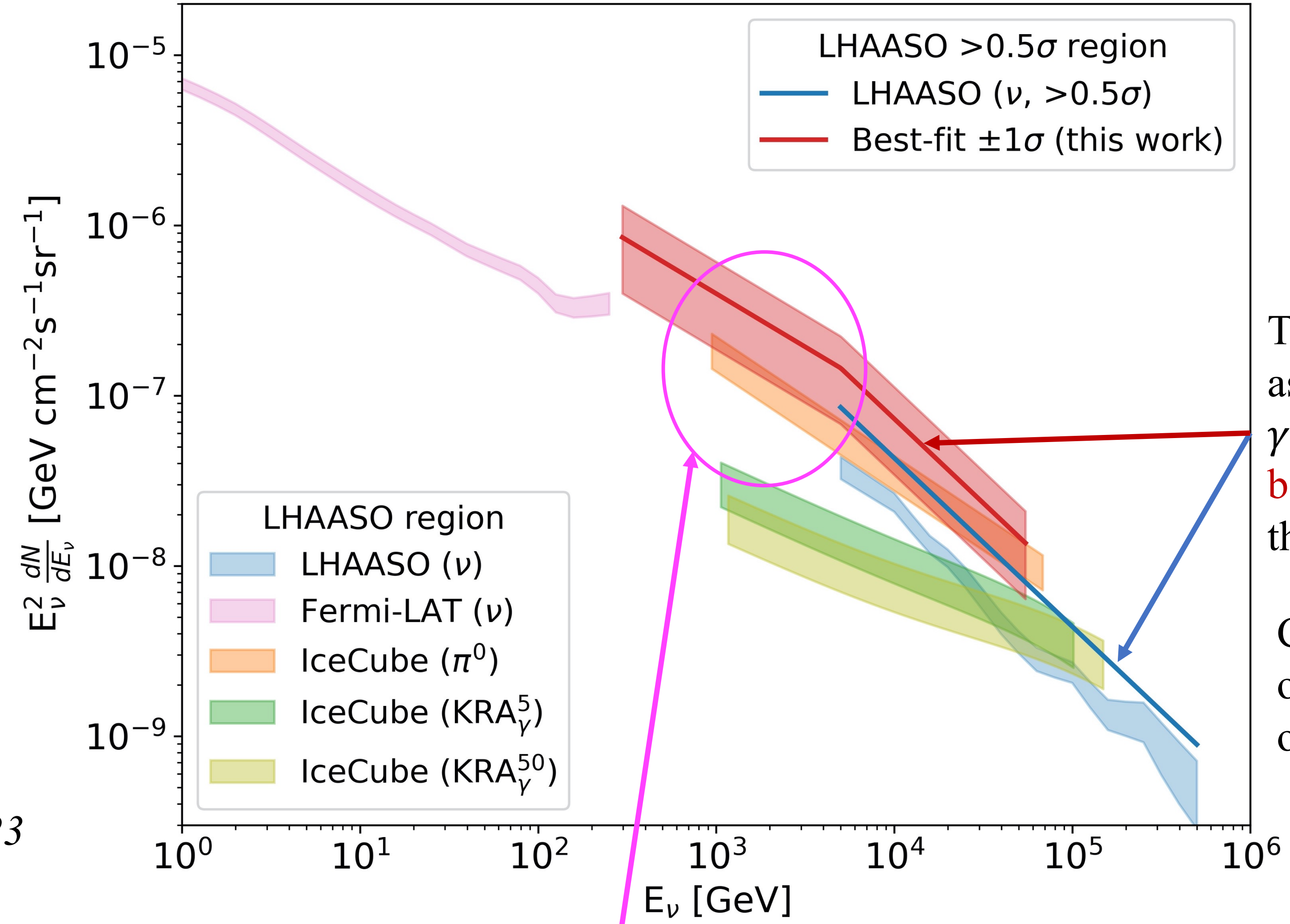
Template Search Results



Best-fit ν flux obtained using the **γ-ray flux map with >0.5σ detection**

Theoretically predicted ***ν* flux after applying a 0.5σ significance cut** on the flux map

Template Search Results



arXiv: 2408.12123

The expected neutrino flux assuming hadronic origins of γ-ray emission is within the best-fit flux 1σ uncertainty in the LHAASO >0.5σ region

Consistent with the hadronic origin of the diffuse γ-rays observed by LHAASO

The deviation from the measurements of IceCube at lower energy range is probably due to differences in energy spectra, neutrino data samples, and sky regions

Template Search Results

➢ Other templates

✓ Uniform, gas, π^0, KRA_γ^5, and KRA_γ^{50} model templates

Flux is given at E_ν=25 TeV in units of $TeV^{-1}cm^{-2}s^{-1}$

Spatial Template	γ	$\hat{n}_s$	Pretrial p-value (σ_{pre})	Best-fit flux $\pm1\sigma$	Upper Limit $\phi_{90\%}$
Uniform (with mask)	γ_{LHAASO}	208.9	0.15 (1.0σ)	$1.21^{+1.16}_{-1.16}\times10^{-14}$	2.71×10^{-14}
Gas (with mask)	γ_{LHAASO}	181.2	0.16 (1.0σ)	1.03×10^{-14}	2.36×10^{-14}
π^0 (with mask)	$E^{-2.70}$	198.0	0.14 (1.1σ)	$1.45^{+1.34}_{-1.33}\times10^{-14}$	3.17×10^{-14}
KRA_γ^5 (with mask)	γ_{model}^5	145.4	0.15 (1.0σ)	$0.20^{+0.20}_{-0.20}\times MF$	$0.46\times MF$
KRA_γ^{50} (with mask)	γ_{model}^{50}	113.8	0.19 (0.9σ)	$0.14\times MF$	$0.35\times MF$
Uniform ($15° < l < 235°, \lvert b\rvert < 5°$)	γ_{LHAASO}	336.8	0.069 (1.5σ)	$1.92^{+1.30}_{-1.29}\times10^{-14}$	3.58×10^{-14}
Gas ($15° < l < 235°, \lvert b\rvert < 5°$)	γ_{LHAASO}	276.5	0.067 (1.5σ)	$1.62^{+1.09}_{-1.08}\times10^{-14}$	3.01×10^{-14}
π^0 (all-sky)	$E^{-2.70}$	606.3	0.062 (1.5σ)	$7.02^{+4.61}_{-4.58}\times10^{-14}$	1.29×10^{-13}
KRA_γ^5 (all-sky)	γ_{model}^5	209.5	0.15 (1.0σ)	$0.61^{+0.61}_{-0.60}\times MF$	$1.39\times MF$
KRA_γ^{50} (all-sky)	γ_{model}^{50}	155.8	0.19 (0.9σ)	$0.42\times MF$	$1.05\times MF$

Flux in units of the model flux (MF)

- The results obtained using the γ-ray flux maps are more significant than those obtained using the gas, uniform, and model templates.

Galactic Plane Scan Results

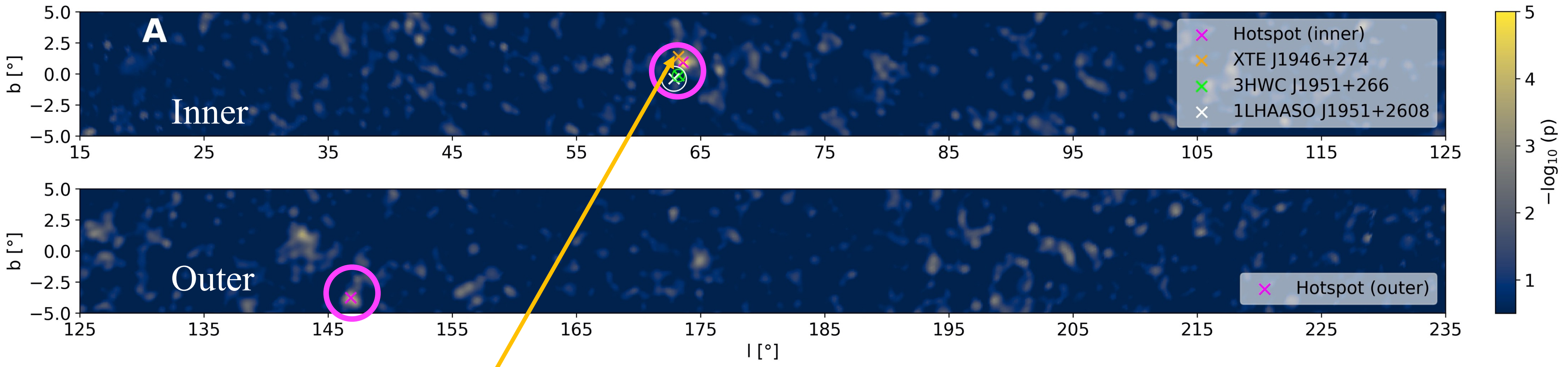
➢ Hotspot

Trial factors corrected for the inner region ↓

Trial factors corrected for inner and outer regions ↓

Name	l [°]	b [°]	$\hat{\gamma}$	$\hat{n}_s$	p_{pre} (σ_{pre})	p_{post} (σ_{post})	p_{post} (σ_{post})
Hotspot (inner)	63.57	0.93	3.00	56.2	1.9×10^{-6} (4.6σ)	0.018(2.1σ)	0.038(1.8σ)
Hotspot (outer)	146.81	-3.77	3.10	43.3	1.1×10^{-4} (3.7σ)	/	0.069

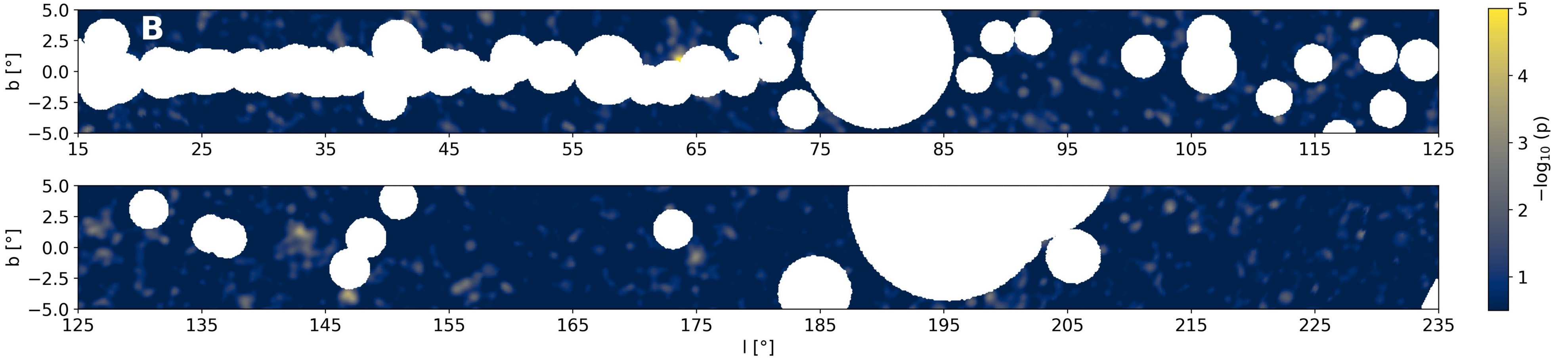
➢ Neutrino pretrial p-value $(-log_{10}p)$ sky map



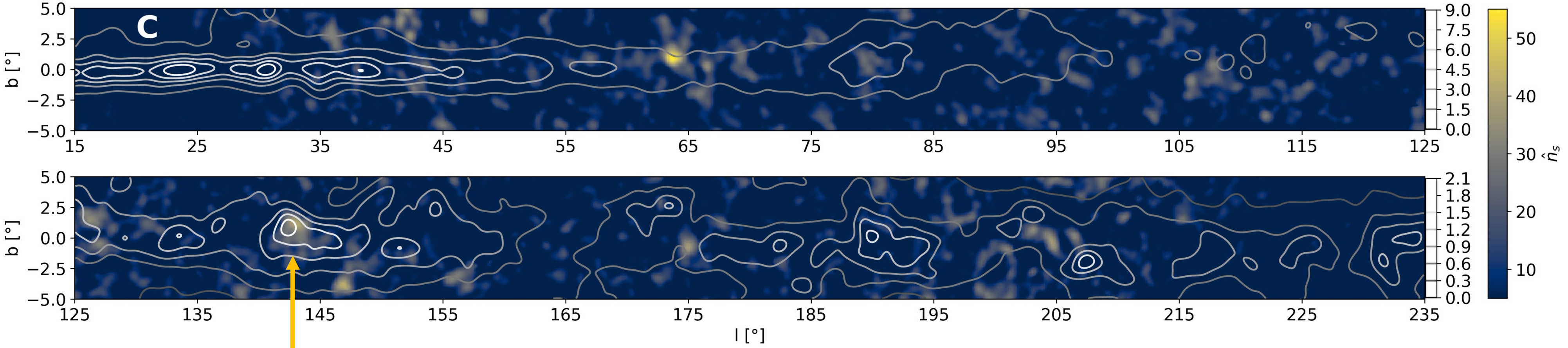
- A X-ray binary, XTE J1946+274 (l = 63.21°, b = 1.40°), is located 0.6° away from the inner hotspot
- This source is found with a pretrial p-value of 2.6×10^{-3} (2.8σ) with $\hat{n}_s = 36.1$ and $\hat{\gamma} = 2.98$

Galactic Plane Scan Results

- Neutrino pretrial p-value sky map and masked region in LHAASO’s analysis



- Neutrino excess ($\hat{n}_s$) map and gas contour

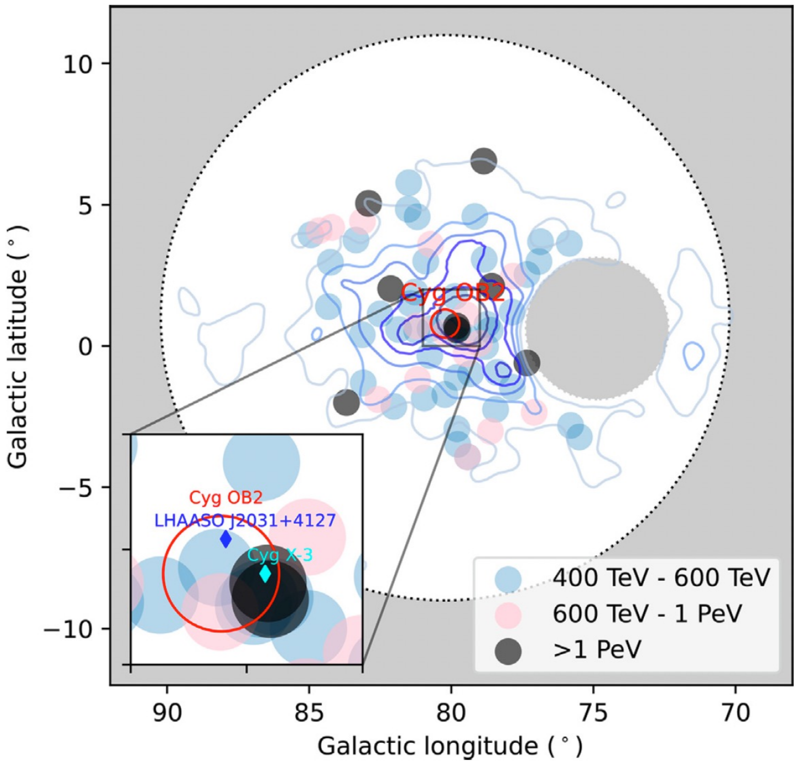


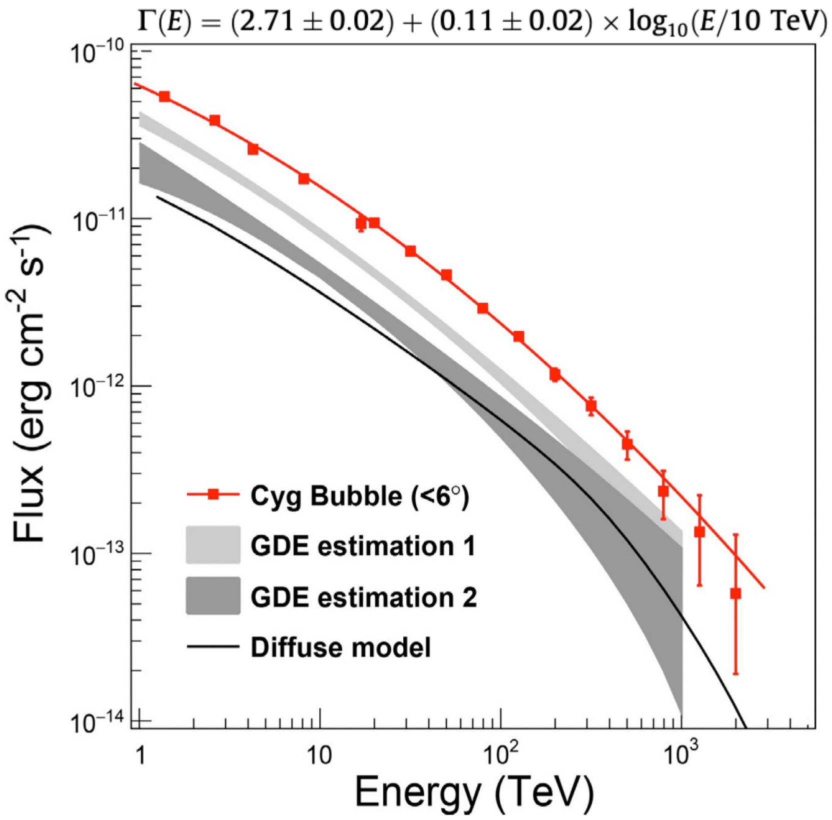
- A cluster of neutrino warm spots near 138°<l<142°, |b|<2.5° is associated with a large gas clump. However, the cluster is not significant

Neutrinos from the Cygnus region?

LHAASO Observation of Cygnus Bubble

- LHAASO detected an enormous γ-ray bubble (at least 6°) in the direction of the star-forming region Cygnus X
  - ✓ The SED extends up to 2 PeV → indicating the presence of Super PeVatron(s)
  - ✓ Hot spots associated with massive molecular clouds → indicating a hadronic origin of photons in the Bubble
- Conduct template searches using the γ-ray flux map as the neutrino emission template
  - ✓ Composed of the MC, HI gas, LHAASO J2027+4119, and LHAASO J2031+4057





LHAASO Collaboration, Sci.Bull. 69 (2024) 4, 449-457

Template Search Results

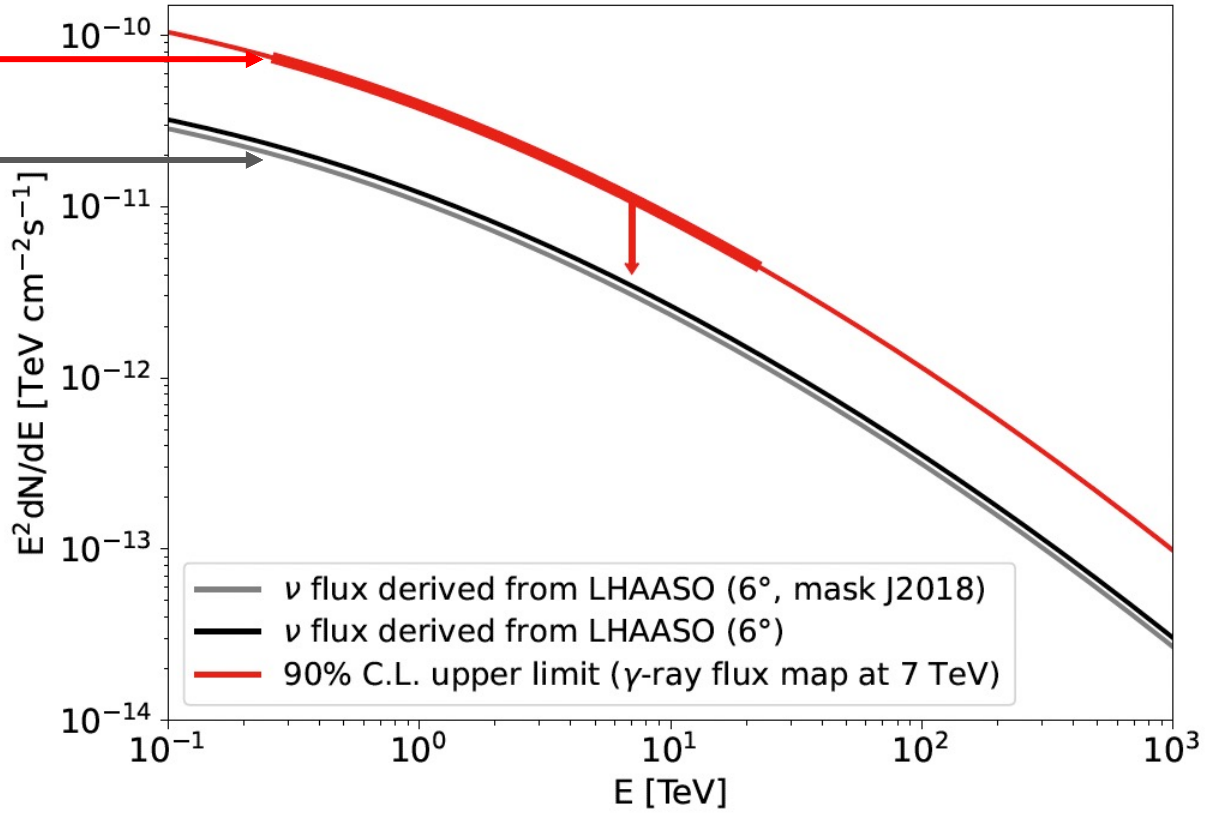
- **Cygnus Bubble** γ-ray flux templates (6°)

$\phi_{90\%}$ at 5 TeV in units of $TeV^{-1}cm^{-2}s^{-1}$

Spatial Template	$\hat{n}_s$	Pretrial p-value	Upper Limit $\phi_{90\%}$
γ-ray flux map at 50 TeV	29.9	0.243	5.31×10^{-13}
γ-ray flux map at 7 TeV	39.4	0.176 (0.9σ)	5.69×10^{-13}

90% CL upper limit

Theoretically predicted ***ν* flux** assuming all γ-rays are of hadronic origin



Li et al., 2024, ApJ, 969, 6

Template Search Results

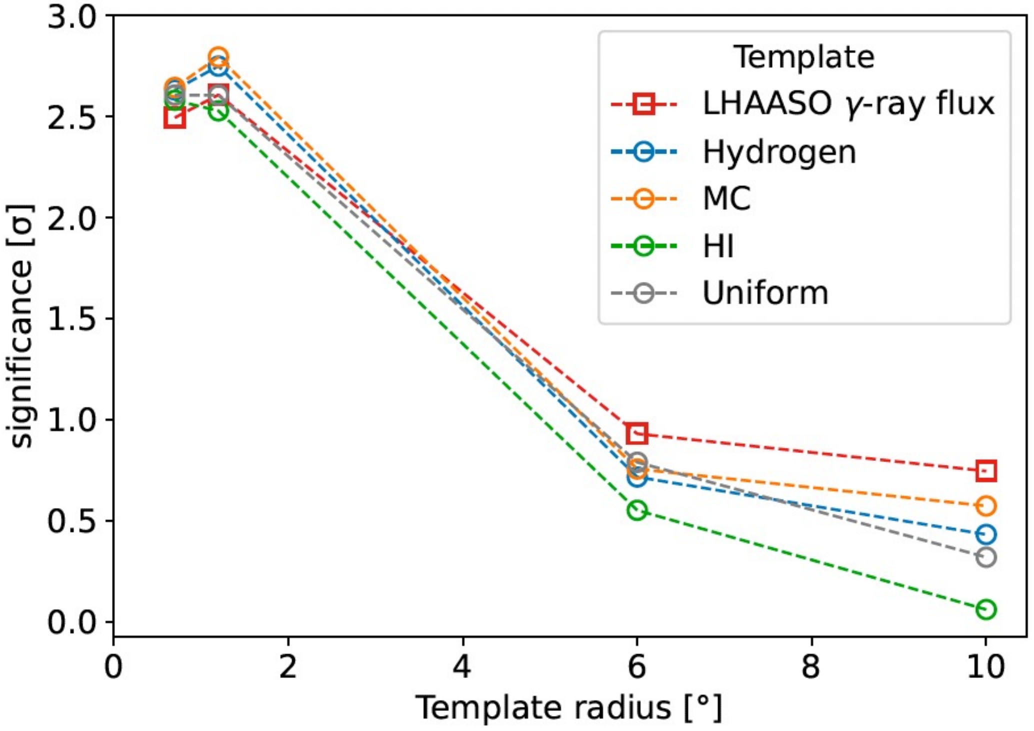
➢ **Results** of other templates

Spatial Template	$\hat{n}_s$	p_{pre} (σ_{pre})	UL ($\phi_{90\%}$)
MC (6°)	31.8	0.225	5.32×10^{-13}
HI (6°)	27.3	0.291	5.75×10^{-13}
Hydrogen (6°)	32.2	0.237	5.58×10^{-13}
Uniform (6°)	41.6	0.215	6.68×10^{-13}
LHAASO J2027+4119 (σ = 2.28°)	22.9	0.278	4.61×10^{-13}
LHAASO J2031+4057 (σ = 0.33°)	34.0	0.007 (2.4σ)	3.16×10^{-13}

$\phi_{90\%}$ at E_ν=5 TeV in units of $TeV^{-1}cm^{-2}s^{-1}$

- The most significant is Gaussian template for LHAASO J2031+4057 with σ = 0.33°, at 2.4σ pre-trials

➢ **Results (significance)** for various template radii **(0.7°, 1.2°, 6°, and 10°)**



- The molecular cloud (MC) template (r =1.2°) yields the most significant result, at 2.8σ pre-trials
- At larger radii of 6° and 10°, the neutrino excess of γ-ray flux template at 7 TeV is more significant

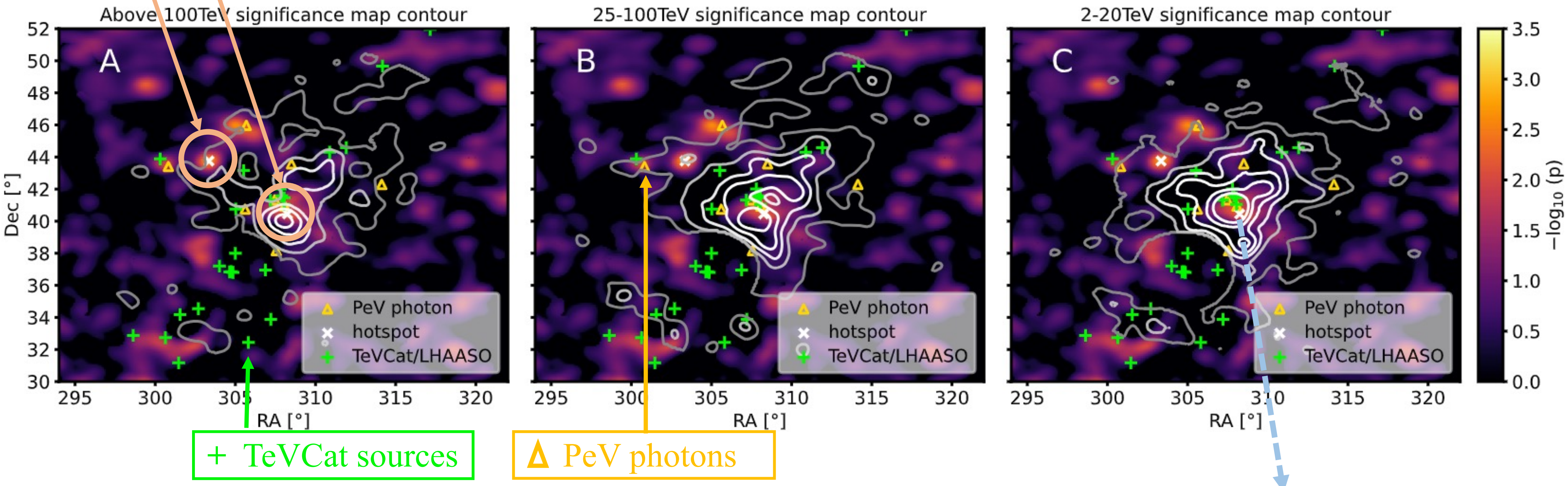
Cygnus Bubble Scan Results

$$S^{spat}(\mathbf{x}_i|\mathbf{x}_s,\sigma_s,\sigma_i)=\frac{1}{2\pi(\sigma_i^2+\sigma_s^2)}e^{-\frac{|\mathbf{x}_s-\mathbf{x}_i|^2}{2(\sigma_i^2+\sigma_s^2)}}$$

- **Hotspot**

Name	RA [°]	Dec [°]	Ext σ_s [°]	$\hat{\gamma}$	$\hat{n}_s$	p_{pre} (σ_{pre})	p_{post}
Hotspot (entire scan region)	303.35	43.75	0.3	2.3	22.2	2.2×10^{-3} (2.9σ)	0.84
Hotspot (central 2° region)	308.25	40.45	0.3	4.0	31.7	6.3×10^{-3} (2.5σ)	0.18

- Neutrino pretrial p-value sky map and γ-ray significance map contour



The neutrino hotspot in the bubble center is spatially associated with the γ-ray hotspot below 20 TeV

Summary & Outlook

Summary

- Conducted template and scan searches of the Galactic Plane and Cygnus Bubble using 7 years of public IceCube track data with the full detector
- Neutrinos from the Galactic Plane:
  - ✓ In the scan , the hottest spot is found at l=63.57° and b=0.93° with a pre- (post-) significance of 4.6σ (1.8σ)
  - ✓ In the template search, the most significant result is found using the LHAASO diffuse γ-ray flux map with >0.5σ detection, yielding a pretrial significance of 1.9σ
- Neutrinos from the Cygnus Bubble:
  - ✓ The MC template in 1.2° radius yields the most significant result, with a pretrial significance of 2.8σ
- Our findings are consistent with the hadronic origin of the γ-ray emission from the diffuse Galactic Plane and Cygnus Bubble, as the 90ULs exceed the theoretically predicted ν flux assuming hadronic interactions

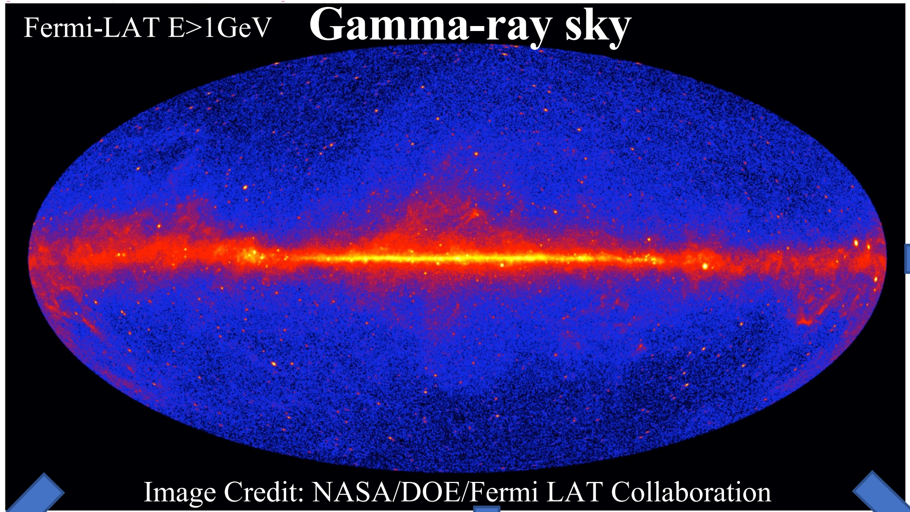
Outlook

- More templates can be investigated in the future (e.g., LHAASO-WCDA diffuse γ-ray flux templates, GC)
- Combined analyses using more data, including both tracks and cascades observed by current and future neutrino telescopes, will elucidate the origin and propagation of cosmic rays in the Galaxy

Thanks for listening!

Backup

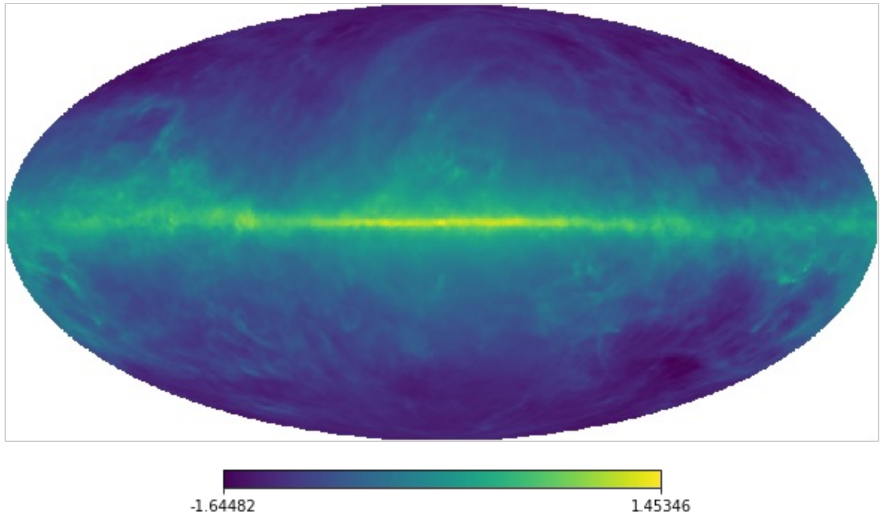
Diffuse Galactic γ-ray Emission (DGE)



Isotropic Background

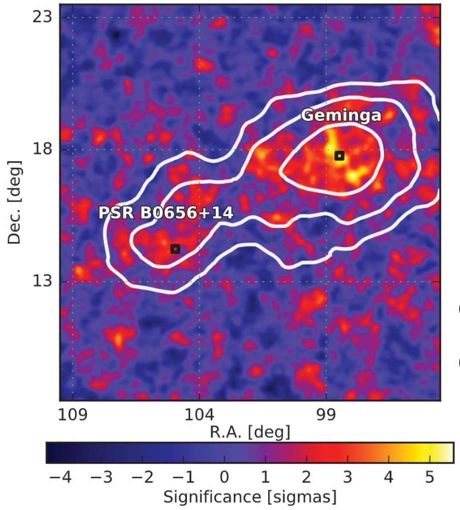
- π^0 decay: $p, \alpha + ISM \rightarrow \pi^0 \rightarrow \gamma$
- Inverse Compton scattering (IC): $e^{\pm} + ISRF \rightarrow \gamma$
- Bremsstrahlung: $e^{\pm} + ISM \rightarrow \gamma$

Diffuse Emission



Fermi diffuse model

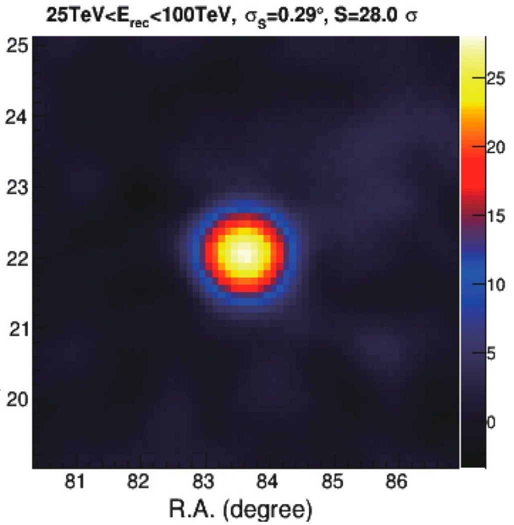
Extended Sources



Geminga and Cygnus-X region

Science 358, 911-914 (2017)

Point Sources

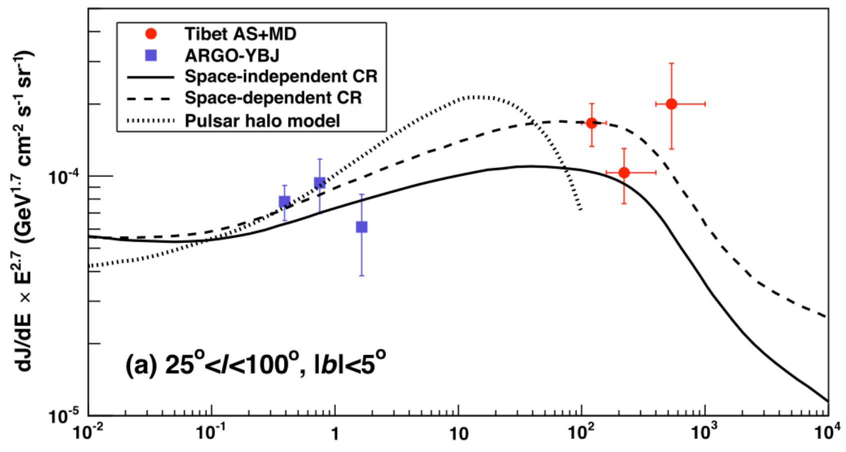


Chin. Phys C 45, 025002 (2021)

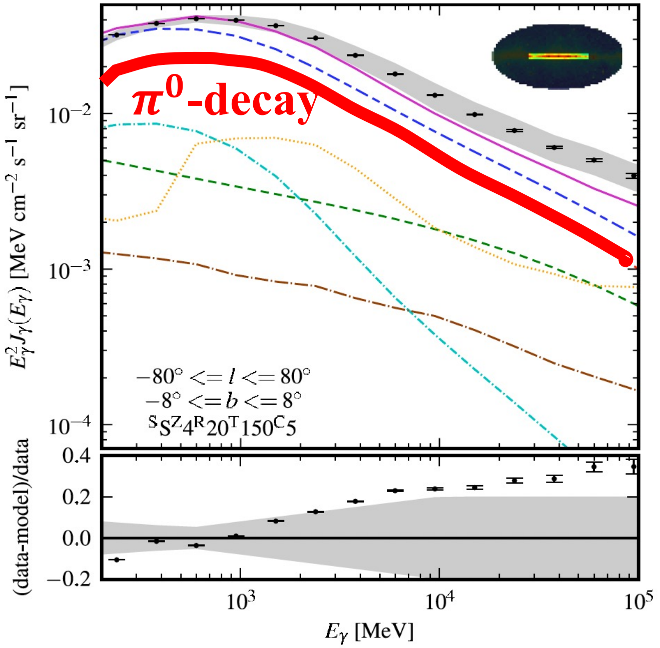
DGE Observation & Model

Tibet ASγ collaboration, PRL 126, 141101 (2021)

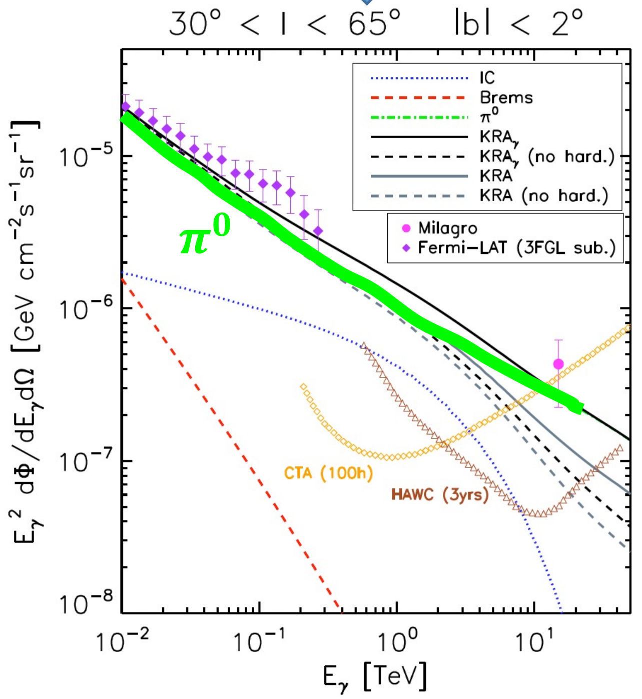
- DGE has been measured by Fermi, Milagro, HESS, ARGO-YBJ, Tibet ASγ, HAWC, and recently by LHAASO from sub-GeV to PeV.



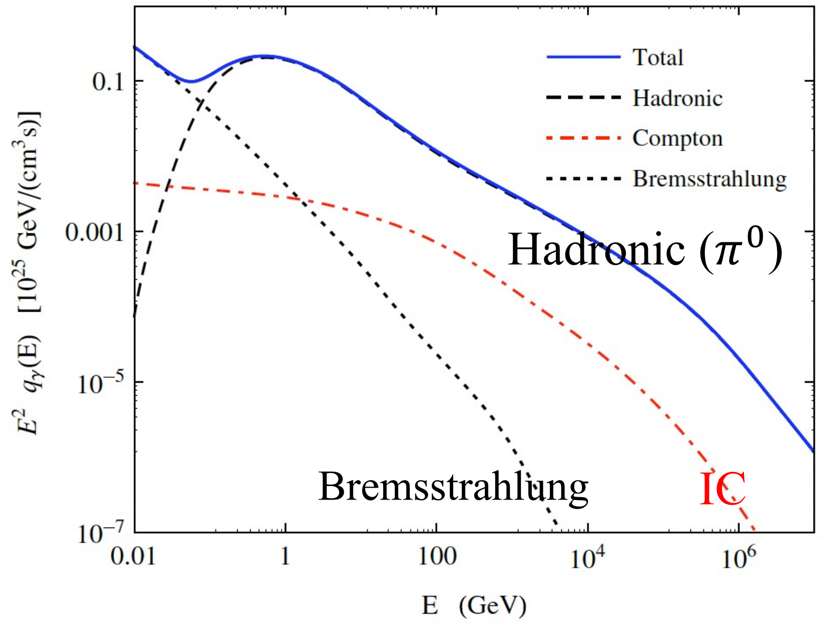
- This flux could be modeled using CR and γ-ray observations:
  - *Fermi*-LAT $\boldsymbol{\pi^0}$, **KRA-$\boldsymbol{\gamma}$** model…
  - Diffuse Galactic γ-ray emission is dominated by $\boldsymbol{\pi^0}$**-decay** flux



Ackermann et al., 2012, ApJ, 750, 3



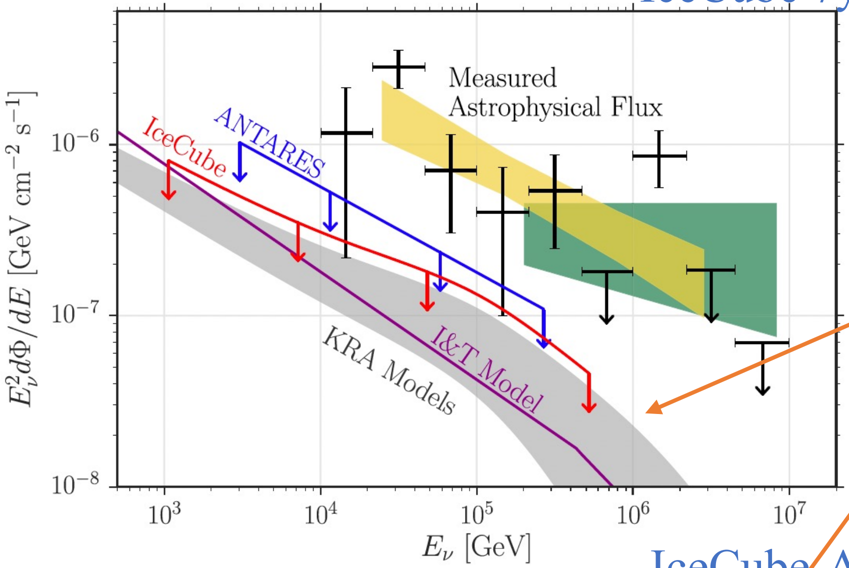
Gaggero et al., 2015, ApJL, 815, L25



P. Lipari&S. Vernetto, PRD, 98, 043003 (2018)

Previous Template Searches (Galactic Plane)

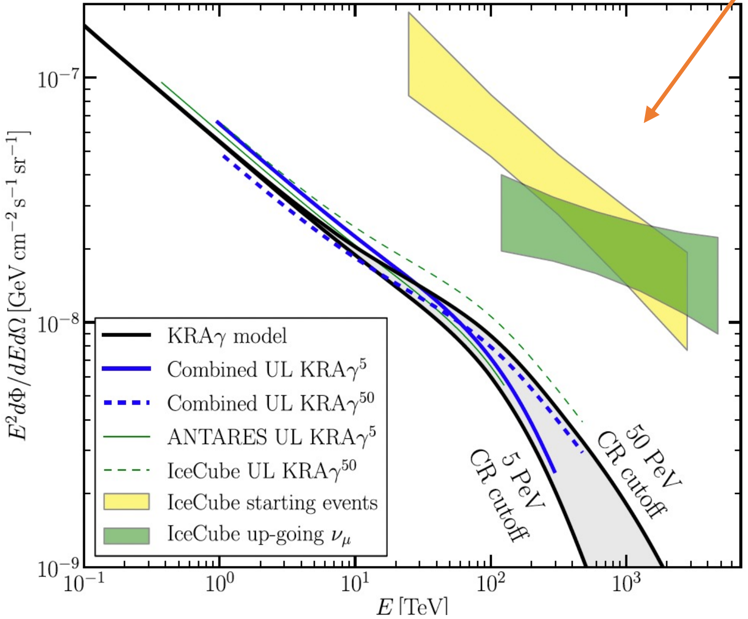
IceCube 7yr Tracks (2017)



Aartsen et al., 2017, ApJ, 849, 67

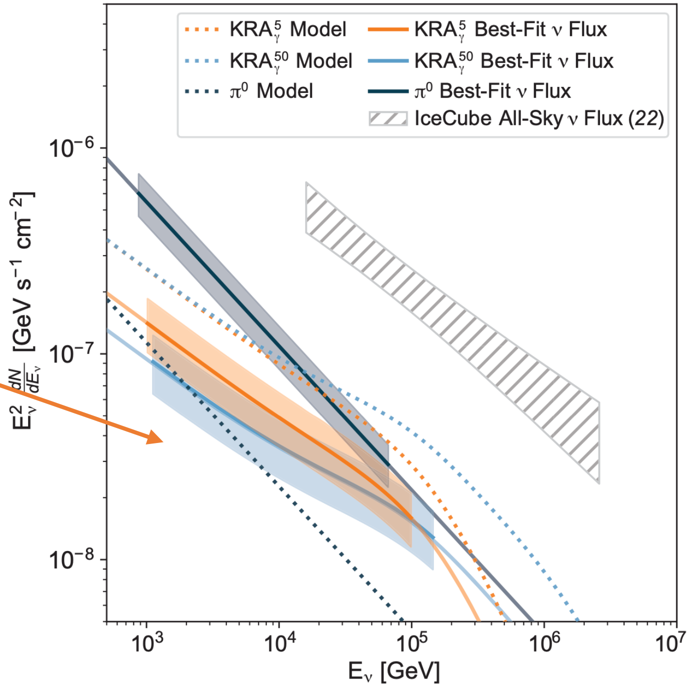
π^0, KRA_γ^5, and KRA_γ^{50} model templates

IceCube-ANTARES (2018)



Albert et al., 2018, ApJL, 868, L20

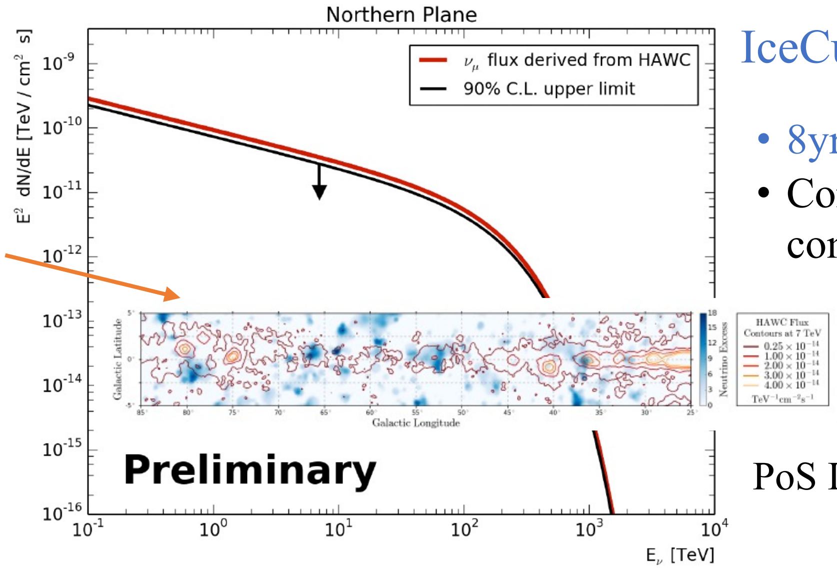
IceCube 10yr Cascades (2023)



- **Strong evidence (4.5σ)** for the Milky Way as a source of high-energy neutrinos

IceCube Collaboration, Science380, 1338-1343 (2023)

γ-ray flux templates



IceCube-HAWC (2019)

- 8yr Northern tracks
- Constrain hadronic component < 80%

PoS ICRC2019 (2020), 932

Previous Searches (Cygnus Region)

IceCube 7.5yr Tracks (2022)

Point-source Search

Abbasi et al. 2022, ApJL, 930, L24

Table of the Most Significant Sources

Analysis	Source	TS	$\hat{n}_s$	$\hat{\gamma}$	p-value
Periodic	V635 Cas	9.07	50.5	4	0.25 (0.0052)
Flare	V404 Cyg	8.28	5.4	4	0.75 (0.014)
Time-integrated	Cyg X-3	6.81	44.6	3.25	0.036 (0.009)

- A pretrial significance of 2.4σ for Cyg X-3

IceCube-LHAASO 11yr Tracks (2023)

Point-source Search

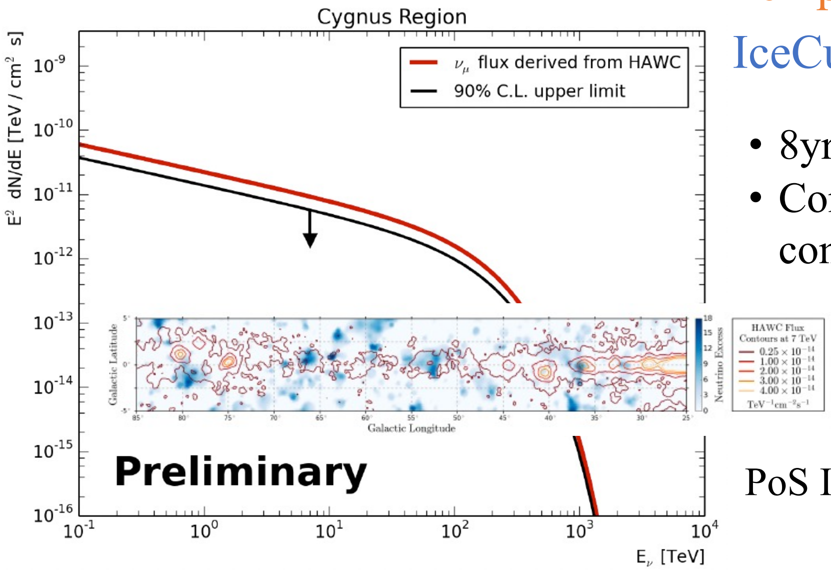
Abbasi et al. 2023, ApJL, 945, L8

Table 1
Table of Best-fit Parameters with Corresponding Test Statistic (TS) and p-value of the Catalog Search

Source	R.A.	Decl.	γ-Ray Flux[CU]	Possible Association	n_s	Γ	TS	Pretrial p-value	$\phi_{90\%}$
LHAASOJ1825-1326	276.45	−13.45	3.57	PWN	1.00	3.33	0.02	0.42	4.0
LHAASOJ1839-0545	279.95	−5.75	0.7	PWN	9.34	3.12	1.43	0.46	1.8
LHAASOJ1843-0338	280.75	−3.65	0.73	SNR	0.00	⋯	0.00	1.0	0.99
LHAASOJ1849-0003	282.35	−0.05	0.74	PWN/YMC	0.00	⋯	0.00	1.0	0.90
LHAASOJ1908+0621	287.05	6.35	1.36	SNR/PWN	6.83	2.11	4.06	0.046	2.5
LHAASOJ1929+1745	292.25	17.75	0.38	SNR/PWN	16.0	2.63	1.34	0.18	2.3
LHAASOJ0534+2202	83.55	22.05	1.0	PWN	14.0	4.0	1.22	0.19	2.0
LHAASOJ1956+2845	299.05	28.75	0.41	SNR	17.6	3.05	1.16	0.21	2.5
LHAASOJ2018+3651	304.75	36.85	0.5	PWN/YMC	18.7	2.67	3.62	0.045	4.5
LHAASOJ2032+4102	308.05	41.05	0.54	SNR/PWN/YMC	24.8	3.98	2.81	0.075	4.1
LHAASOJ2108+5157	317.15	51.95	0.38	⋯	10.6	2.96	0.84	0.26	2.4
LHAASOJ2226+6057	336.75	60.95	1.05	SNR/PWN	0.00	⋯	0.00	1.0	2.9

- A pretrial significance of 1.4σ for LHAASO J2032+4102
- Constrain hadronic component from Crab Nebula < ~80%

Huang & Li 2022

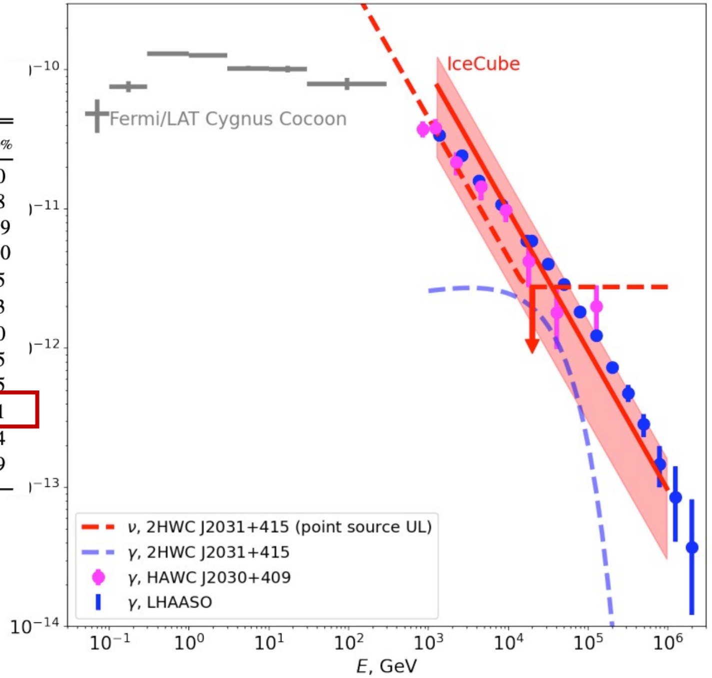


Template Search

IceCube-HAWC (2019)

- 8yr Northern tracks
- Constrain hadronic component < 60%

PoS ICRC2019 (2020), 932



Extended-source Search

7yr Tracks (2023)

- A 3σ excess of neutrino events from an extended Cygnus Cocoon (~ 1°)

Neronov et al., arXiv: 2311.13711

Cygnus Bubble Scan Results

LHAASO γ-ray significance map contour

> 100 TeV | 25-100 TeV | 2-20 TeV

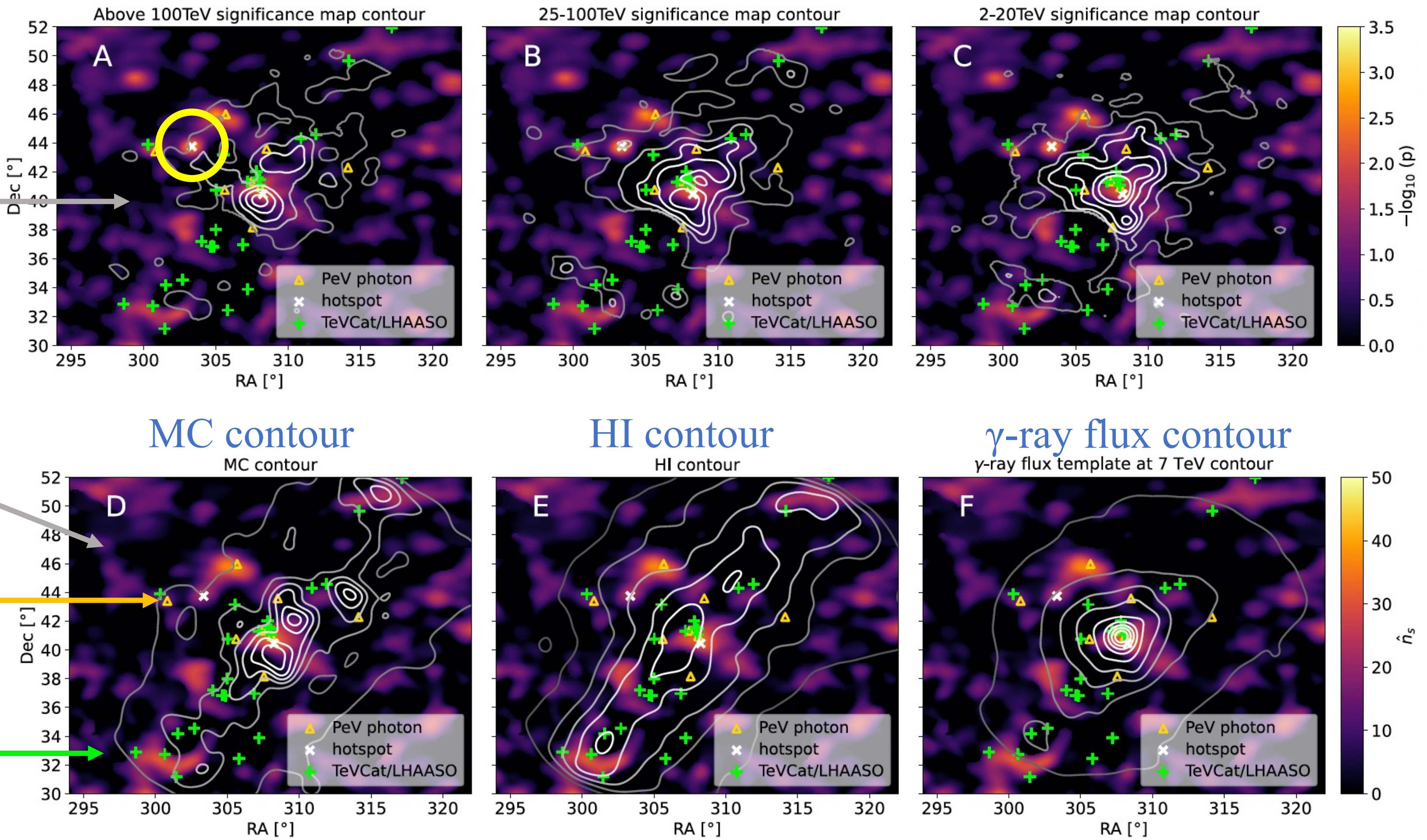
Neutrino pretrial p-value map

MC contour | HI contour | γ-ray flux contour

Neutrino excess (n_s) map

▲ 8 PeV photons

+ TeVCat sources



- The neutrino significance (excess) map lacks a clear correlation with the γ-ray significance map (gas and γ-ray flux distribution)