# Search for Astrophysical Neutrinos from the 4FGL Galactic Plane Sources with the Pion Bump Signature

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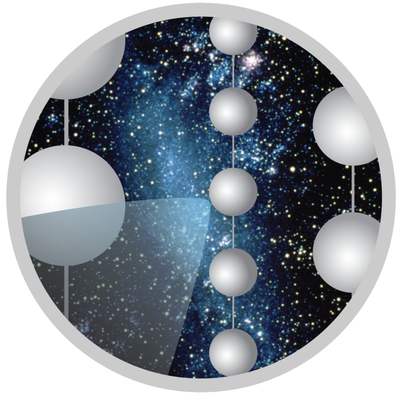

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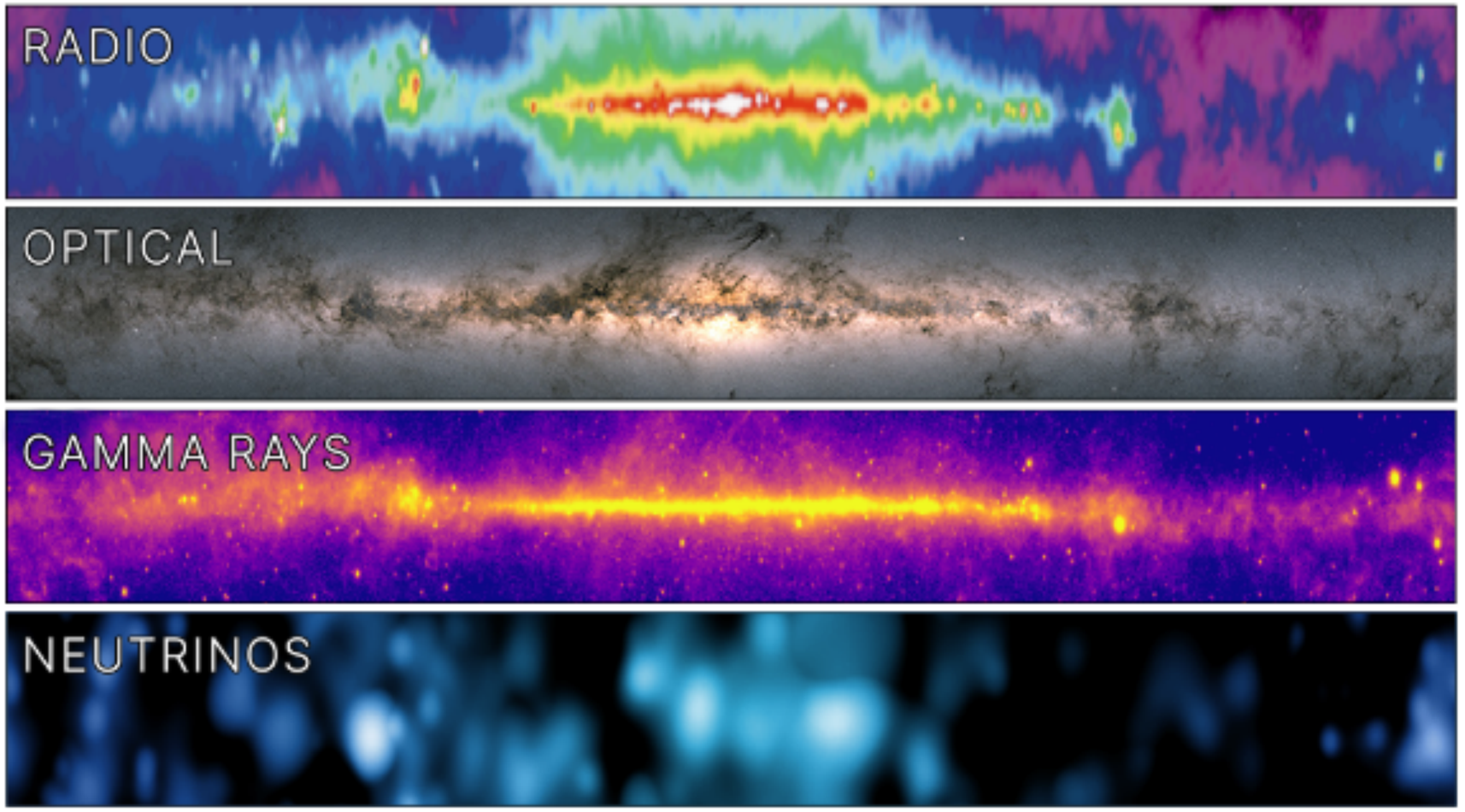
# Galactic Diffuse Neutrino Sky




- Observation of a diffuse neutrino flux concentrated along the Galactic Plane (see Steve Sclafani's talk Parallel 11A)
- $\pi^0$ spatial model : spatial template that incorporates the MeV to GeV $\pi^0$ component, inferred from the gamma-ray emission.
- Where are the galactic sources of neutrinos?
- What is the exact nature of correlations between gamma rays and neutrinos?

IceCube Collaboration, "Observation of high-energy neutrinos from the Galactic plane", vol. 380, no. 6652, pp. 1338–1343, 2023

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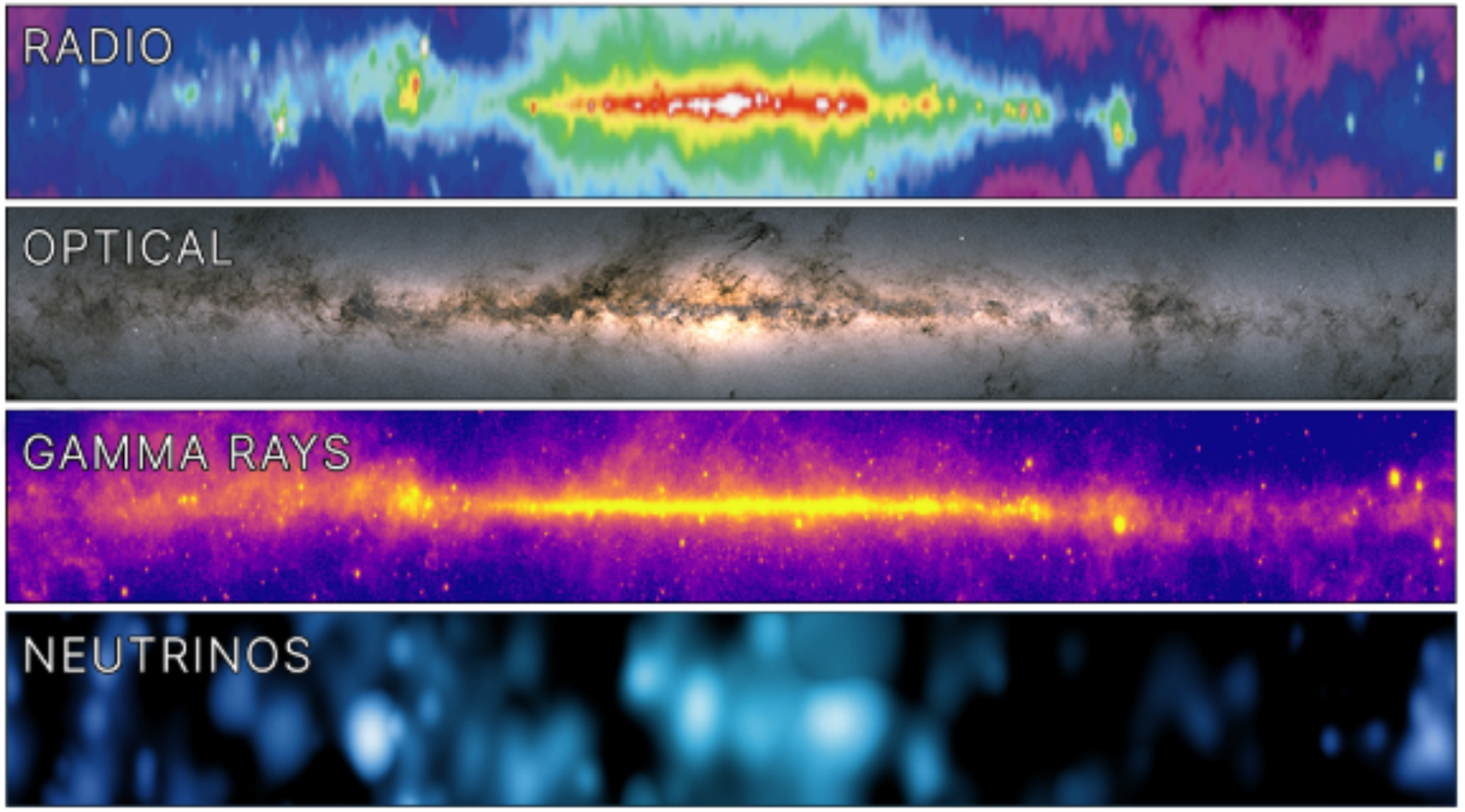


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**Unresolved sources?**

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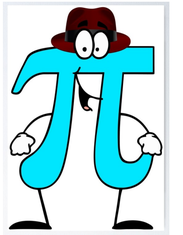
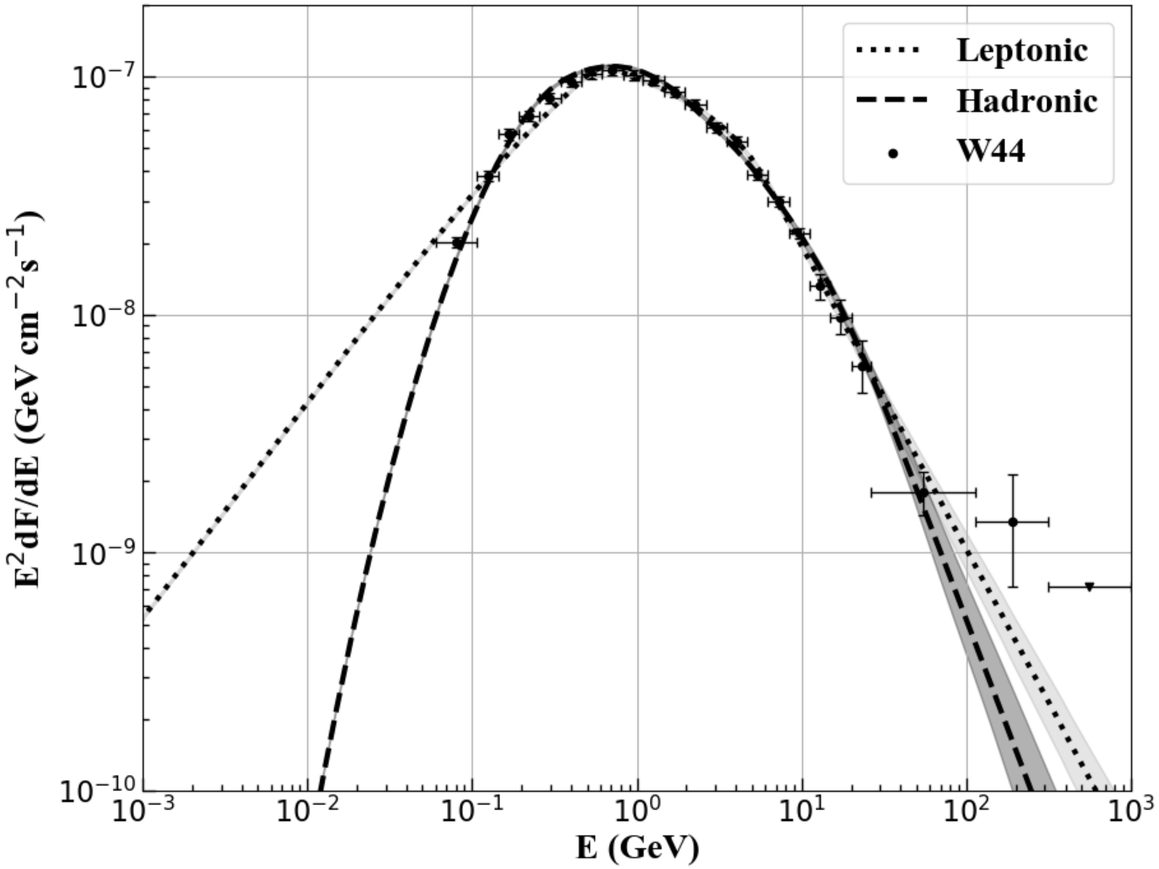
# From the $\pi^0$ Template to the $\pi^0$ bump

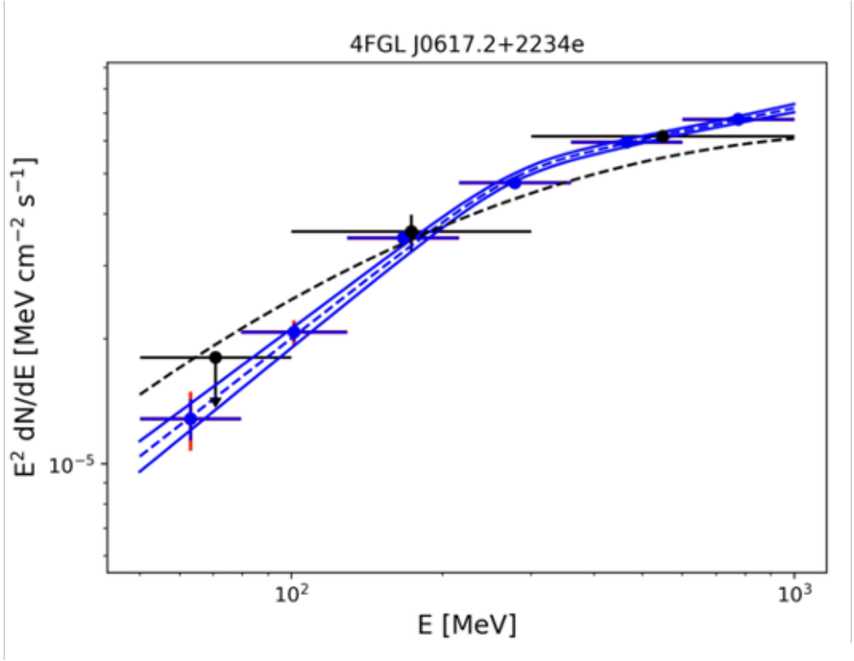


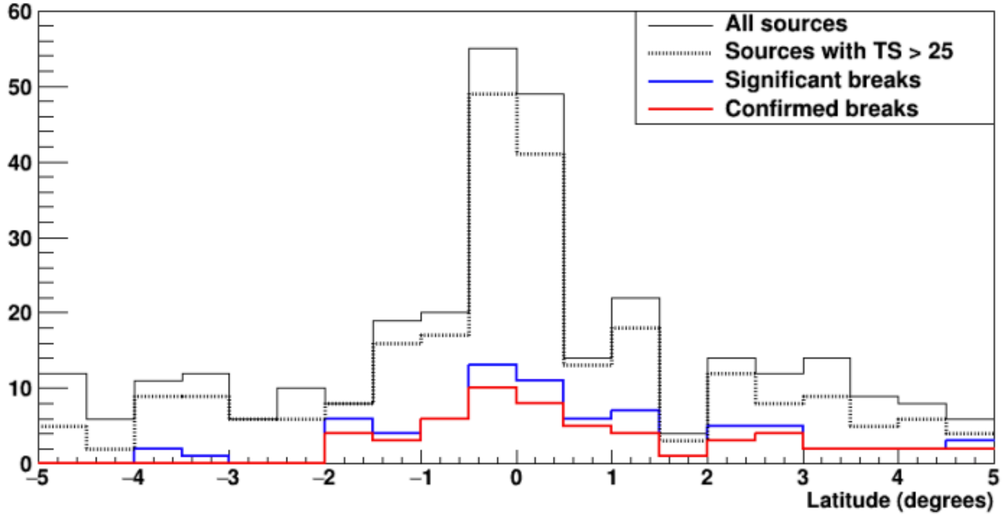
- **Distinct signature of hadronic gamma rays**
- **Hard to detect with Fermi-LAT's energy dispersion.**
- **Energy resolution of LAT above 1 GeV: <10%**
- **~20% at 100 MeV and ~28% at 30 MeV**
- **Previously Observed around SNRs (IC443, W44)**
- **Can manifest as low-energy spectral break in sources around 200 MeV**




arXiv: 2406.03691

# Confirmed Low-energy Spectral Breaks in 4FGL Sources



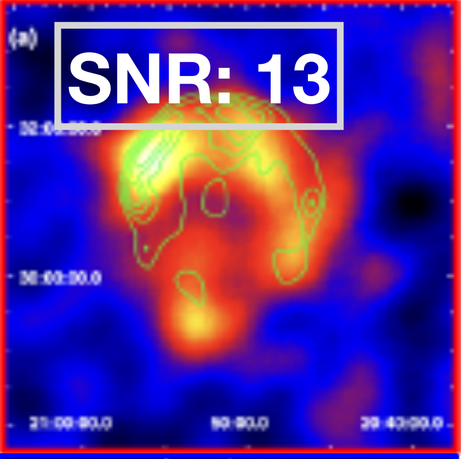

- **Updated LAT analysis confirmed characteristic break in 56 sources between 50 MeV and 1 GeV**

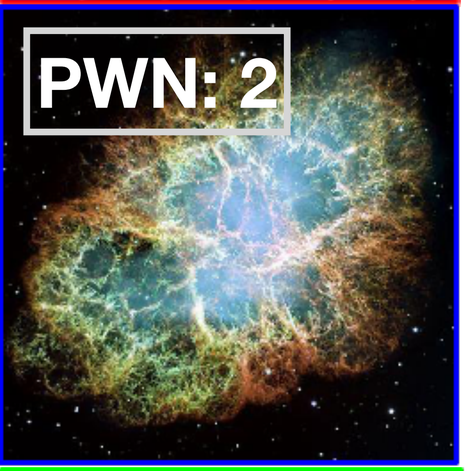
Abdollahi, S., "Search for New Cosmic-Ray Acceleration Sites within the 4FGL Catalog Galactic Plane Sources",*The Astrophysical Journal, Vol. 933, No. 2, 2022.*

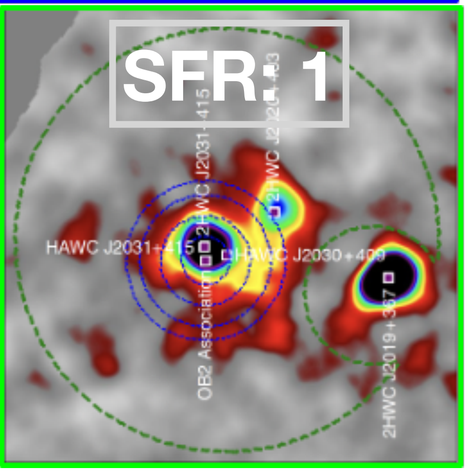
**Table 4**. Spectral parameters of all confirmed sources showing a significant break

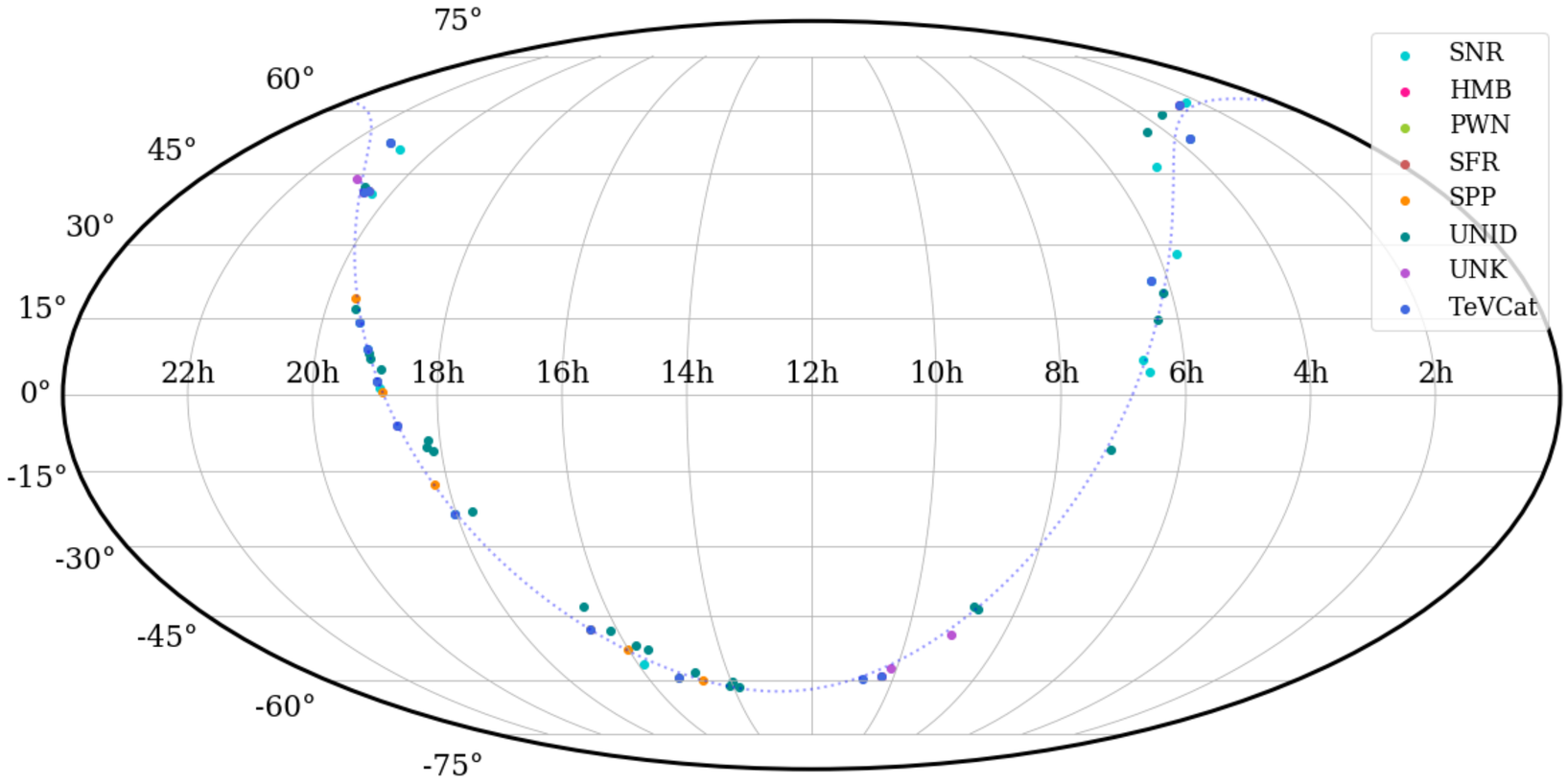
| 4FGL Name | I(50 − 1000) $10^{-6}$ (MeV/cm$^2$/s) | ΔI(50 − 1000) stat/syst | $E_{break}$ (MeV) | $\Delta E_{break}$ stat/syst | $\Gamma_1$ | $\Delta\Gamma_1$ stat/syst | $\Gamma_2$ | $\Delta\Gamma_2$ stat/syst |
|---|---|---|---|---|---|---|---|---|
| 4FGL J0222.4+6156e | 47.8 | 2.7/0.6 | 465 | 78/40 | 1.35 | 0.14/0.03 | 2.34 | 0.21/0.14 |
| 4FGL J0240.5+6113 | 237.6 | 1.9/6.6 | 142 | 10/74 | 1.63 | 0.03/0.36 | 2.10 | 0.02/0.10 |
| 4FGL J0330.7+5845 | 3.2 | 0.5/0.3 | 367 | 38/52 | −0.68 | 0.75/0.81 | 3.42 | 0.64/0.21 |
| 4FGL J0340.4+5302 | 34.1 | 1.3/5.8 | 284 | 43/116 | 1.60 | 0.14/0.38 | 3.27 | 0.23/0.35 |
| 4FGL J0426.5+5434 | 15.1 | 0.8/0.9 | 338 | 47/80 | 1.25 | 0.16/0.35 | 2.50 | 0.18/0.07 |
| 4FGL J0500.3+4639e | 11.6 | 1.0/1.6 | 252 | 43/107 | 0.14 | 0.61/1.06 | 2.17 | 0.19/0.08 |
| 4FGL J0540.3+2756e | 14.8 | 1.5/4.8 | 493 | 82/146 | 0.90 | 0.25/0.54 | 2.64 | 0.52/0.37 |
| 4FGL J0609.0+2006 | 4.7 | 0.7/0.8 | 499 | 134/59 | 0.11 | 0.67/0.56 | 3.52 | 0.66/0.35 |
| 4FGL J0617.2+2234e | 122.5 | 2.4/1.1 | 276 | 19/3 | 1.06 | 0.05/0.03 | 1.75 | 0.03/0.03 |
| 4FGL J0620.4+1445 | 3.2 | 0.6/0.4 | 355 | 36/55 | 0.26 | 0.44/0.36 | 4.03 | 0.71/0.63 |
| 4FGL J0634.2+0436e | 24.1 | 1.4/15.5 | 243 | 41/121 | 1.07 | 0.13/0.50 | 2.00 | 0.13/0.26 |
| 4FGL J0639.4+0655e | 36.6 | 3.3/19.2 | 233 | 31/167 | −0.13 | 0.66/0.95 | 2.51 | 0.23/0.59 |
| 4FGL J0709.1−1034 | 5.1 | 0.8/2.2 | 351 | 57/23 | 0.06 | 0.90/0.25 | 3.40 | 0.56/0.36 |
| 4FGL J0844.1−4330 | 15.2 | 2.6/2.4 | 159 | 28/76 | 0.35 | 0.19/0.46 | 3.28 | 0.20/0.41 |
| 4FGL J0850.8−4239 | 10.8 | 1.4/1.7 | 424 | 83/26 | 1.24 | 0.12/0.11 | 3.71 | 0.30/0.03 |
| 4FGL J0904.7−4908c | 10.6 | 0.7/1.4 | 402 | 12/173 | 1.10 | 0.07/1.19 | 2.99 | 0.16/0.71 |
| 4FGL J1008.1−5706c | 12.3 | 1.6/5.1 | 409 | 76/37 | 0.96 | 0.43/0.55 | 3.40 | 0.64/0.33 |
| 4FGL J1018.9−5856 | 130.0 | 3.4/11.9 | 73 | 1/24 | 0.32 | 0.02/0.31 | 1.98 | 0.02/0.05 |
| 4FGL J1045.1−5940 | 49.8 | 2.3/6.0 | 525 | 26/178 | 1.12 | 0.05/0.17 | 2.12 | 0.11/0.14 |
| 4FGL J1351.6−6142 | 26.9 | 2.7/12.5 | 125 | 8/22 | −0.87 | 0.17/0.59 | 2.37 | 0.12/0.30 |

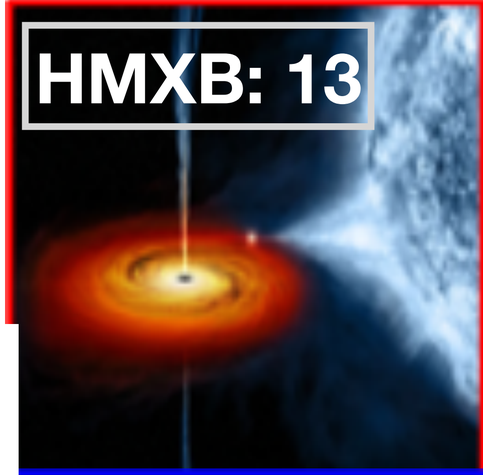
# Source Properties

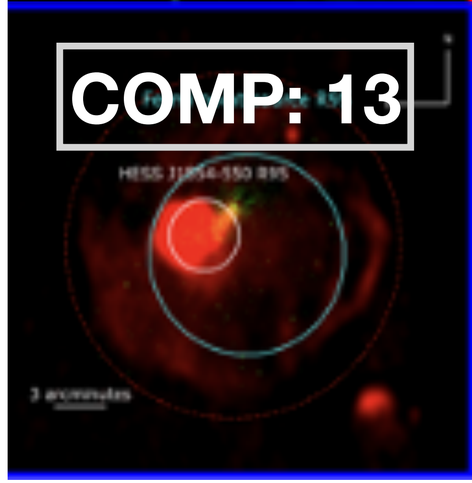


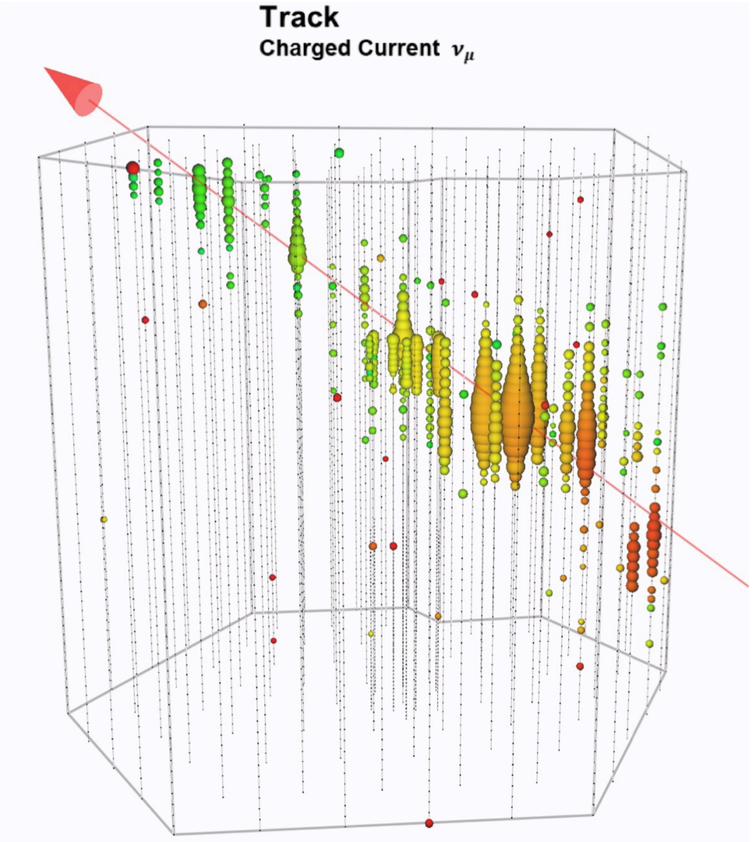



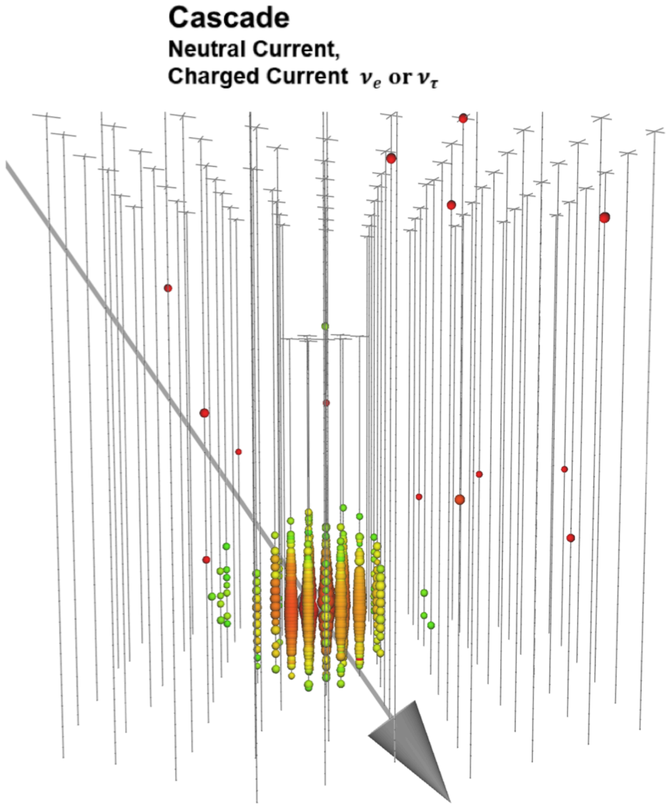




**TeV associations: 16**

**UNK:4**
**UNID: 26**

# IceCube Analysis




- Combined dataset of 11 years of tracks and 10 years of cascade events
- Stacking various source classes, weighted by source gamma-ray flux
- Catalog search with all 56 sources

Pointing

Signal

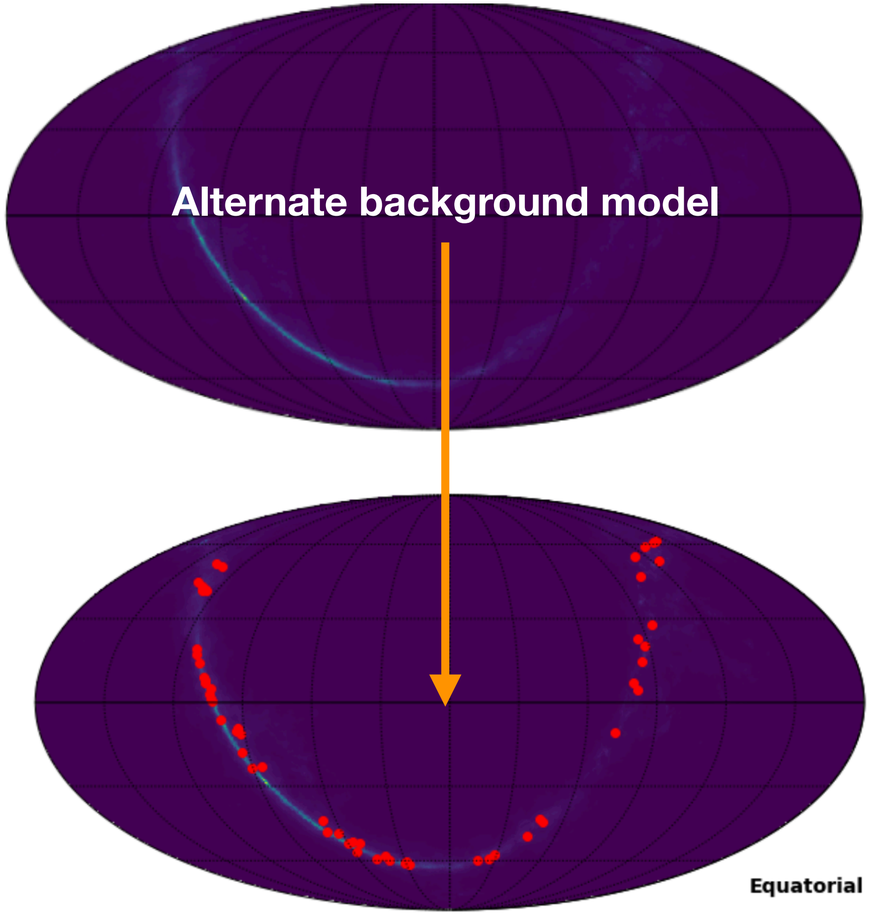
Point-source signal?

# Analysis Details

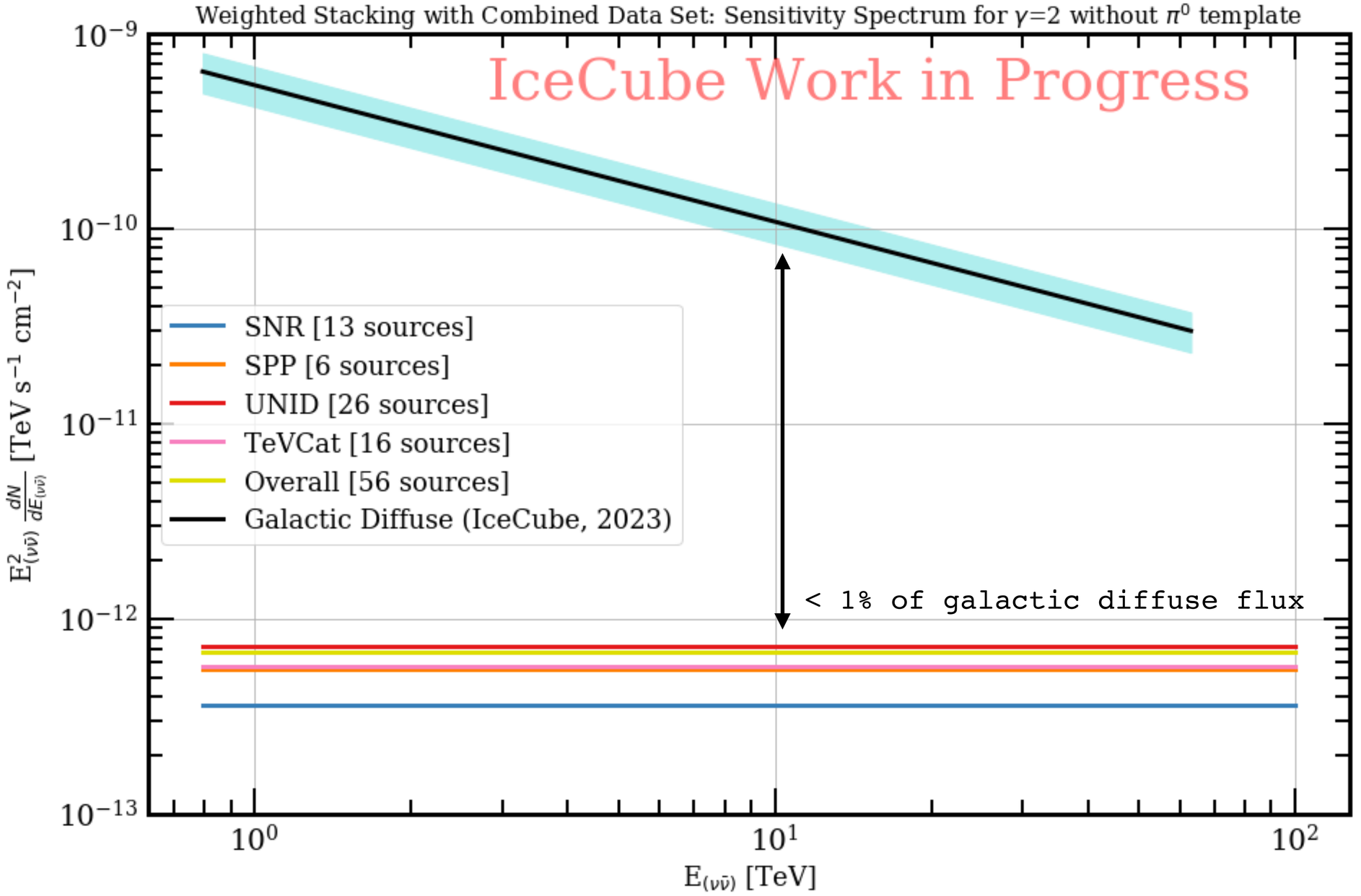
- **Catalog Analysis:**
  - All 56 sources
  - No Fermi-LAT $\pi^0$ template
  - Test sensitivity for $\gamma$=2, $\gamma$=3 and $\gamma$=$\gamma$ of the 4FGL source after the break

- **Stacking Analysis:**
  - Source classes with no of sources > 5
  - Two different approaches:
    - Fermi-LAT $\pi^0$ template (as additional background events)
    - No Fermi-LAT $\pi^0$ template (baseline)
  - Weighted with respect to individual MeV flux
  - Test sensitivity for $\gamma$=2, $\gamma$=3

**Sensitivity flux:** Flux which 90% of the time generates a TS greater than the median TS of the bkg only simulations.



# Sensitivity: Stacking Search



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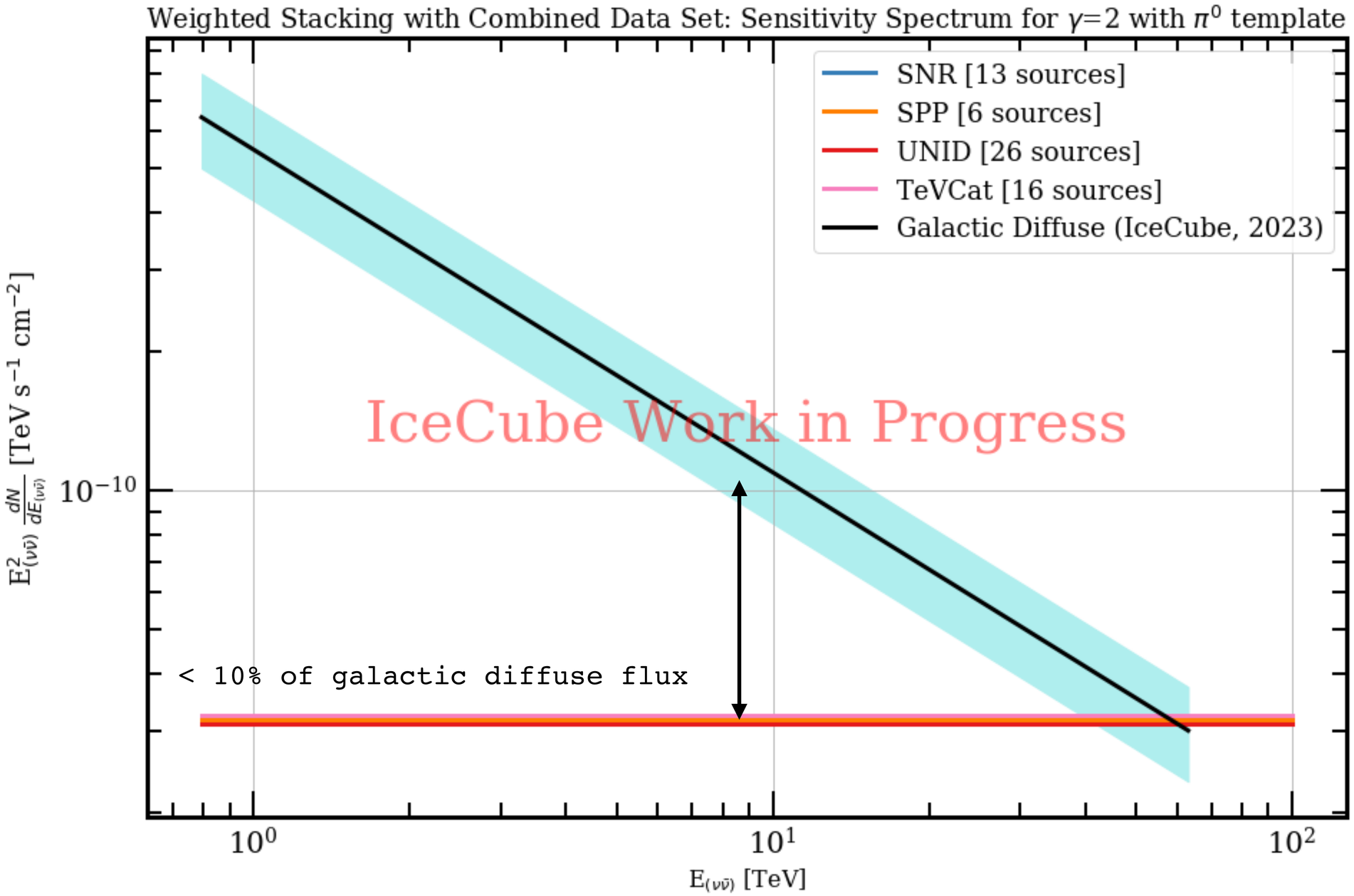
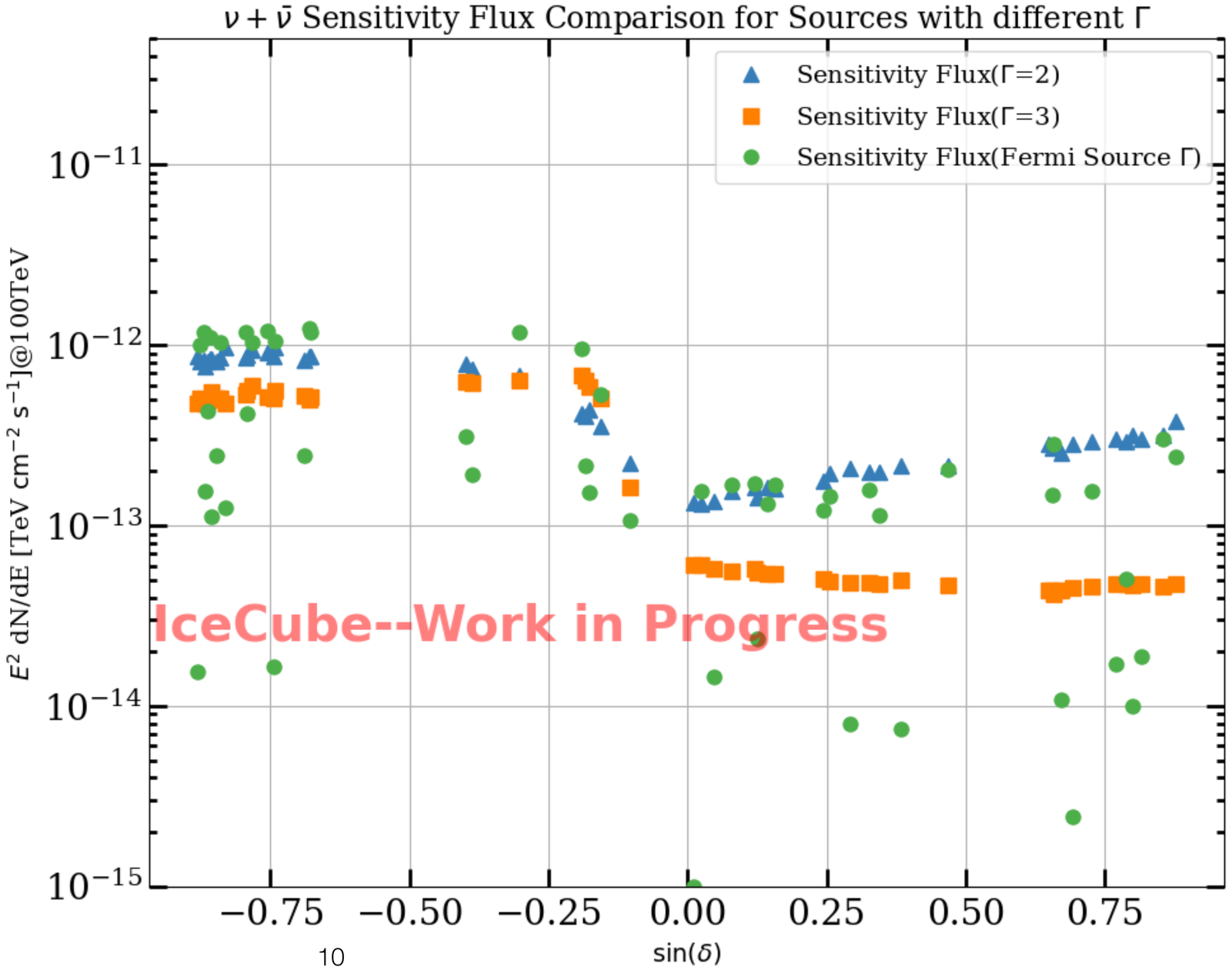


# Sensitivity: Catalog Search

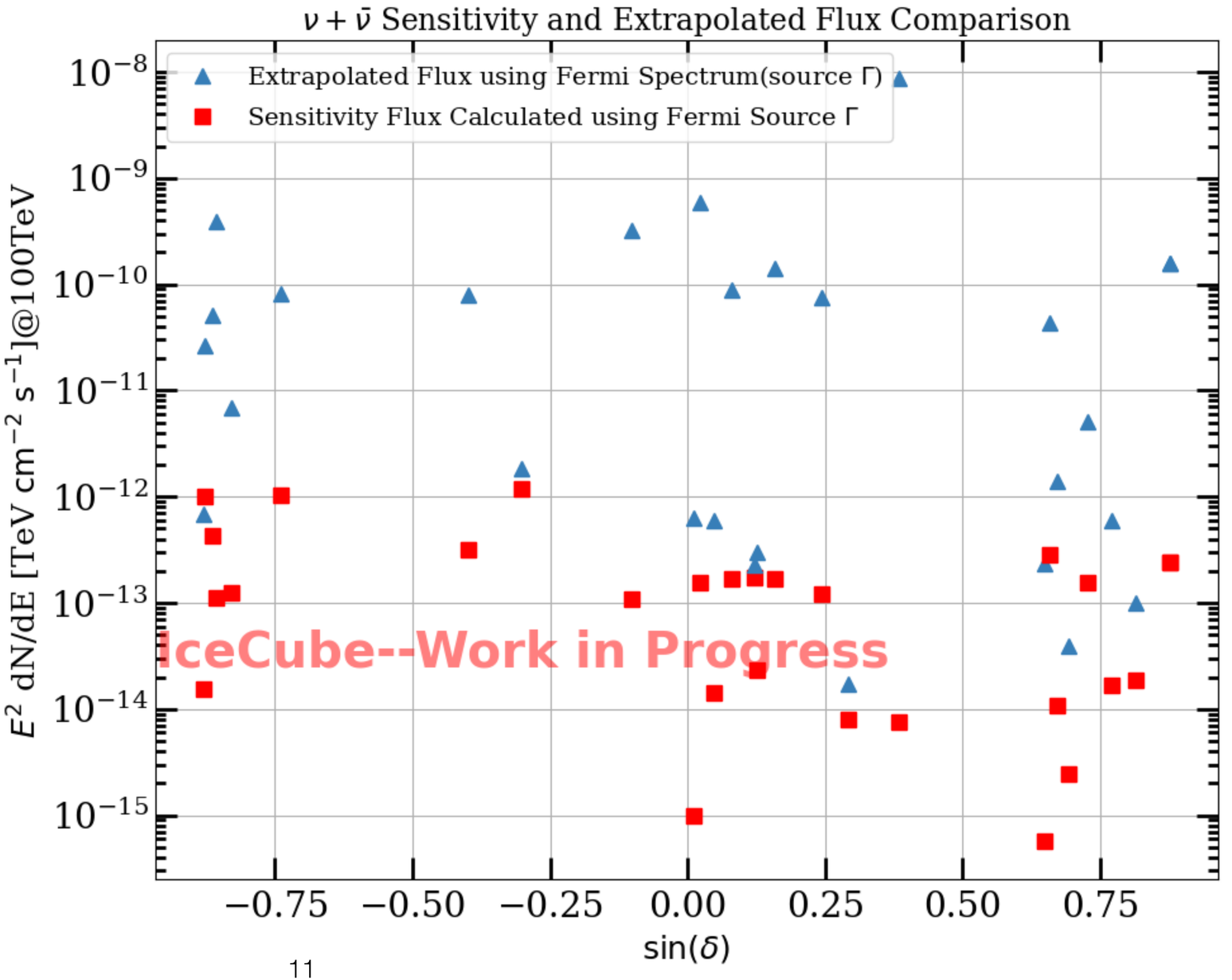
Comparison of $\nu+\bar{\nu}$ all-flavor Sensitivity Spectra for all 56 sources with different indices at 100 TeV

Fermi spectral indices
$1.75 < \gamma < 4.68$



# Sensitivity: Catalog Search

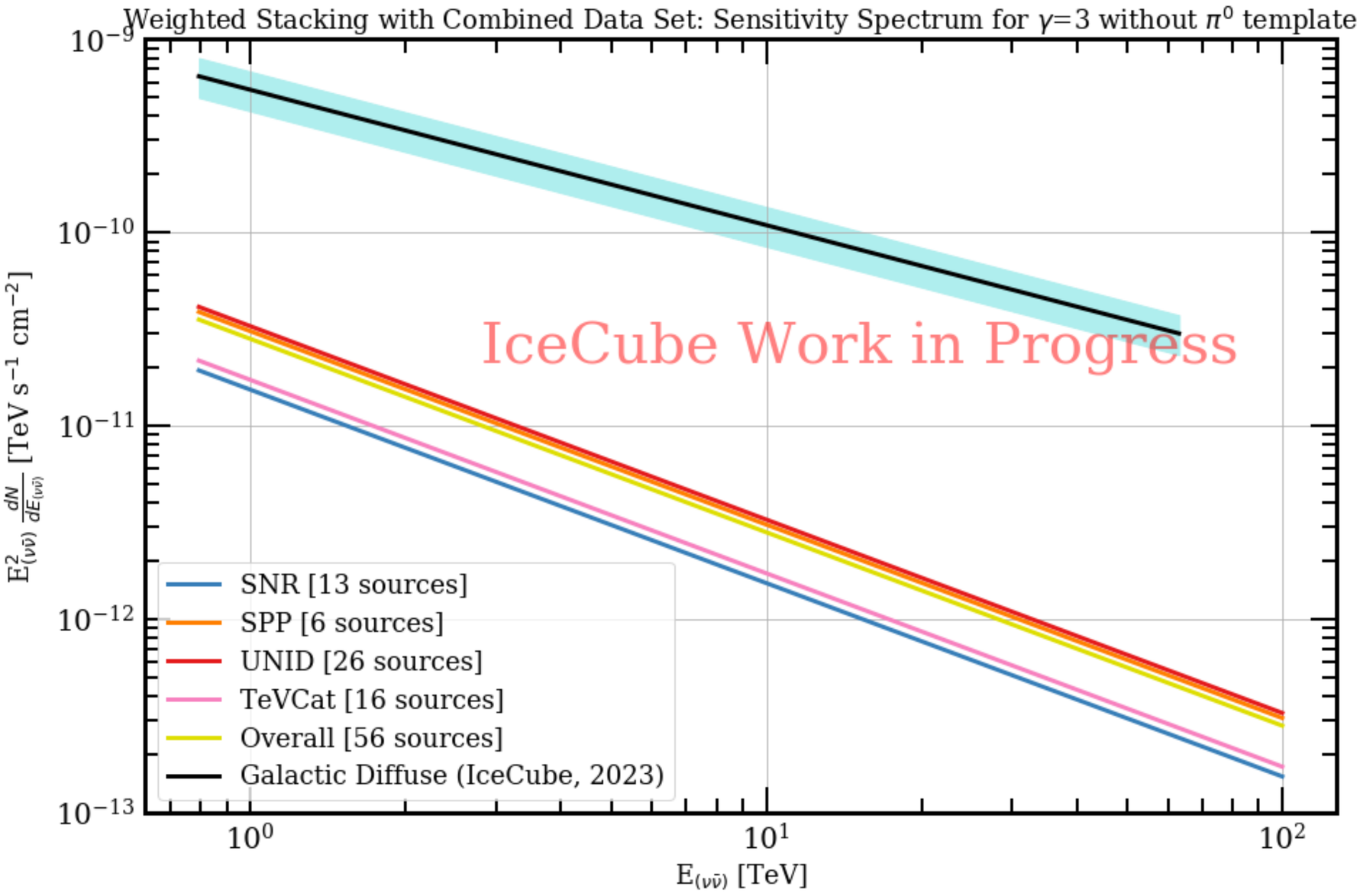
- Calculate predicted neutrino flux by extrapolating the MeV $\gamma$-ray flux to 100 TeV with simple power-law
- Predicted flux for 29 out of 56 sources falls below the sensitivity
- Compare the Sensitivity Spectra for 27 sources

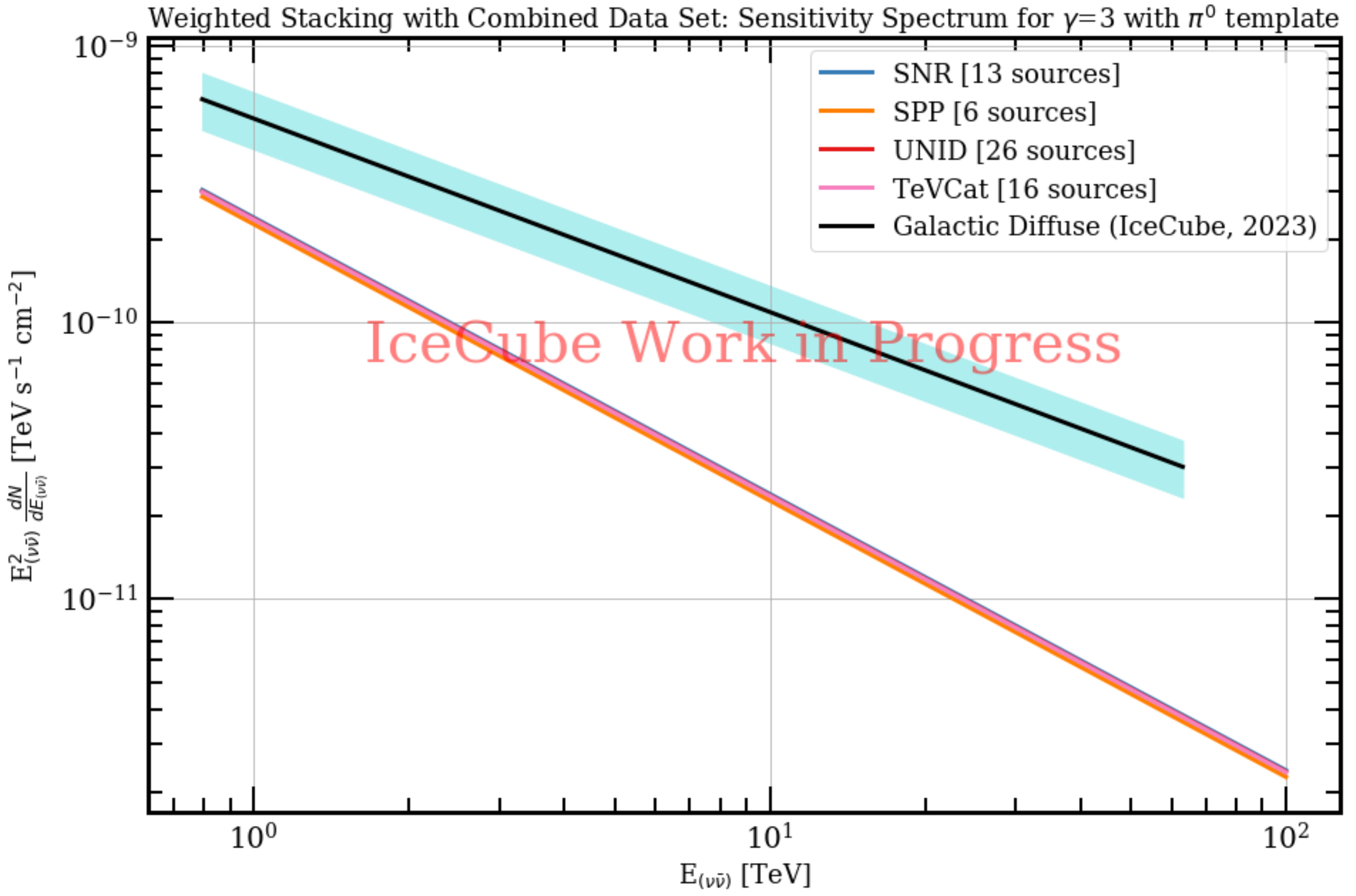


# Summary and Outlook

- Sources showing the characteristic pion bump signature can be explored for potential hadronic activity.
- Probe GeV-TeV $\gamma$-ray obscured sources
- Performed initial sensitivity studies on scrambled data
  - Stacking search
  - Catalog search
- Using 10 years of IceCube data, the contribution from these sources could be constrained to less than 10% of the galactic diffuse flux
- Next steps: determine sensitive energy ranges, handle source confusion.
- Work in progress. Stay Tuned!

# Back up


Weighted Stacking with Combined Data Set: Sensitivity Spectrum for $\gamma$=3 without $\pi^0$ template
IceCube Work in Progress
$E^2_{(\nu\bar{\nu})} \frac{dN}{dE_{(\nu\bar{\nu})}}$ [TeV s$^{-1}$ cm$^{-2}$]
$E_{(\nu\bar{\nu})}$ [TeV]
SNR [13 sources]
SPP [6 sources]
UNID [26 sources]
TeVCat [16 sources]
Overall [56 sources]
Galactic Diffuse (IceCube, 2023)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SNR [13 sources]
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Galactic Diffuse (IceCube, 2023)
IceCube Work in Progress
$10^{-9}$
$10^{-10}$
$10^{-11}$
$E^2_{(\nu\bar{\nu})} \frac{dN}{dE_{(\nu\bar{\nu})}}$ [TeV s$^{-1}$ cm$^{-2}$]
$10^0$
$10^1$
$10^2$
$E_{(\nu\bar{\nu})}$ [TeV]