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

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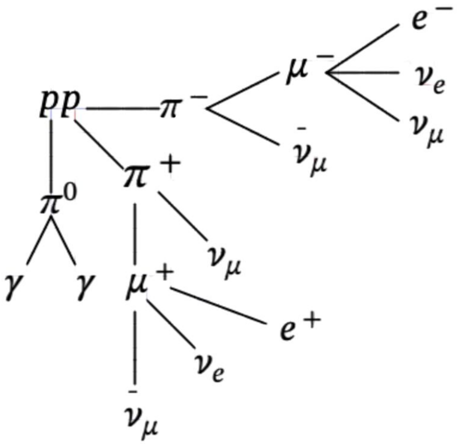
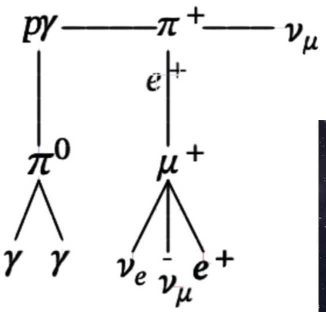
TeVPA 2024 Conference
Chicago

Motivation: Search for Neutrino Sources to study Cosmic-ray Accelerators

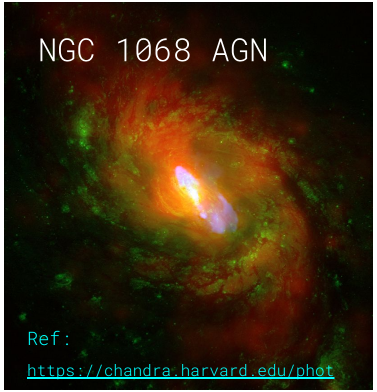
Physics behind neutrino production:





Possible sources:

- SNRs
- GRBs
- Active Galactic Nuclei
  - Blazars
  - Galaxies
- More?



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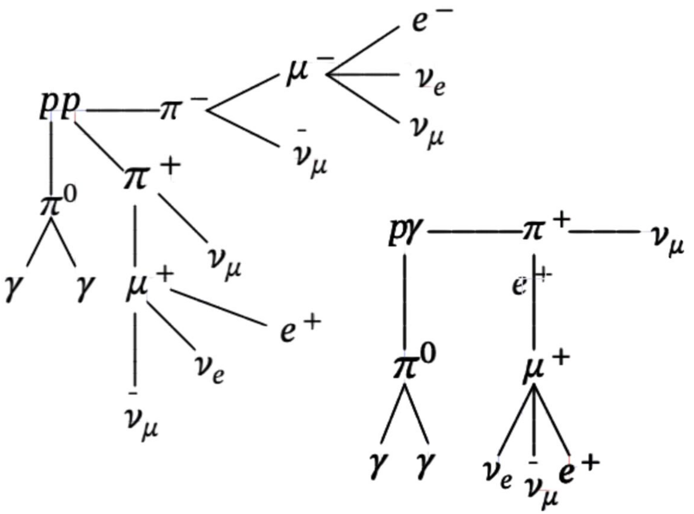
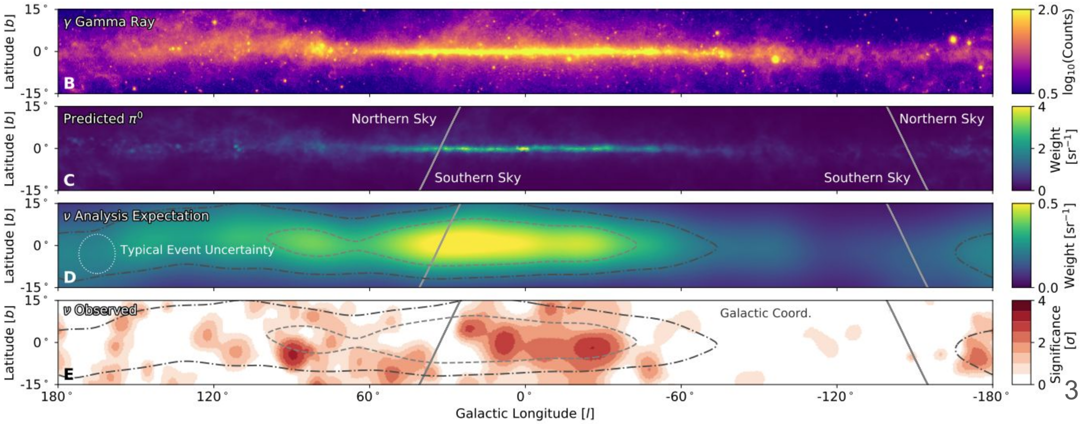
Motivation: Diffuse Neutrino Background

Physics behind neutrino production:



Ref: Icecube Collaboration, “Observation of high-energy neutrinos from the Galactic plane”, vol. 380, no. 6652, pp. 1338–1343, 2023

- Gamma-rays and Neutrinos are produced from the decay of pions
  - Expect a diffuse neutrino flux concentrated along the Galactic Plane
- π^0 spatial model : spatial template that incorporates the MeV to GeV π^0 component, inferred from the gamma-ray emission
- Can we observe unresolved sources on top of these diffuse emissions?



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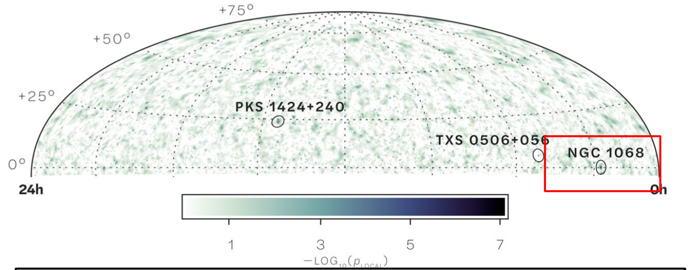
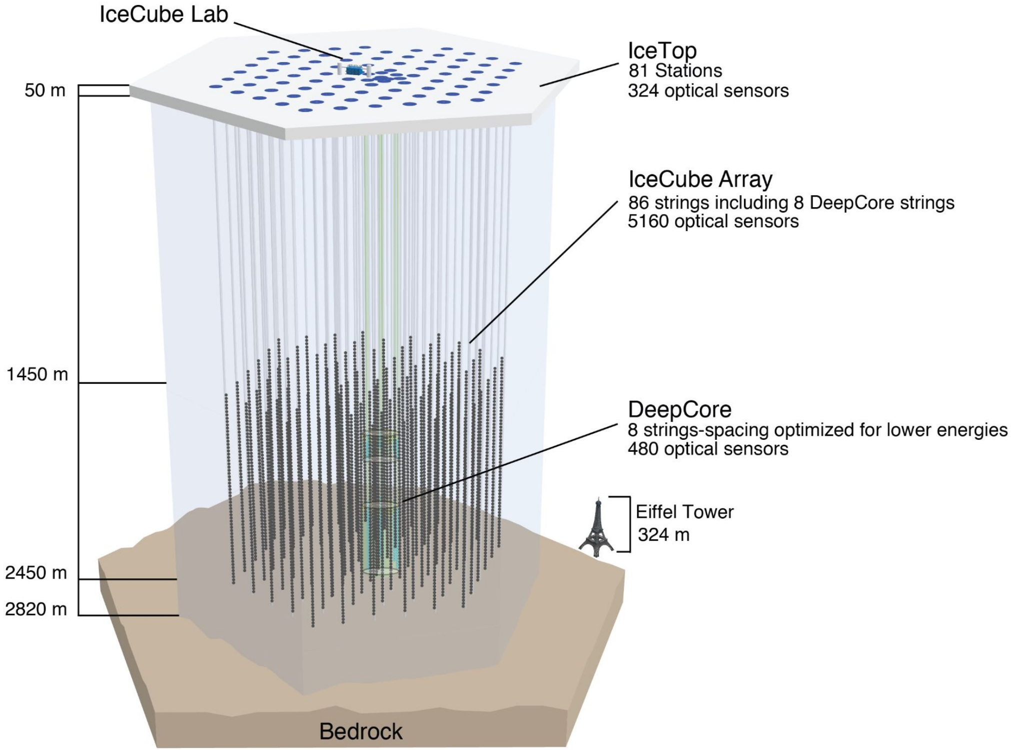
IceCube Observatory

- Identified and presented evidence for detecting astrophysical neutrinos for NGC 1068
- Still searching for astrophysical neutrinos from both galactic and extragalactic sources



Ref: IceCube Collaboration, "Evidence for neutrino emission from the nearby active galaxy NGC 1068", Science, vol. 378, no. 6619, pp. 538–543, 2022



Low-energy Spectral Breaks in 4FGL Sources

- **Fermi-LAT Collaboration** studied the effect of energy dispersion in Pass 8 of their data release.
- <10% above 1 GeV
- ~20% at 100 MeV and ~28% at 30 MeV
- Performed simulations on the spectrum of IC443
- Chose a finer binning scheme to capture the energy dependence at low energies
- Searched 8 years of data for low-energy spectral breaks in the sources

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

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Table B2. List of selected Galactic plane candidates

4FGL Name	GLON (°)	GLAT (°)	4FGL SigCurv	4FGL $\sqrt{TS}$ (0.3 – 1 GeV)	4FGL Class	TS	TS_{LP}	TS_{SBPL}	TS_{SBPL2}
4FGL J0034.6+6438	121.13	1.83	2.6	3.9		7.6			
4FGL J0039.1+6257	121.54	0.12	7.0	5.2		43.8	7.0		
4FGL J0129.0+6312	127.16	0.65	3.1	5.7	spp	55.9	5.1		
4FGL J0142.5+6650	127.93	4.46	3.4	3.6		6.4			
4FGL J0144.3+5959	129.51	−2.20	0.6	3.4		4.9			
4FGL J0211.5+6219	132.09	0.89	1.1	3.5		0.3			
4FGL J0221.4+6241e	133.05	1.60	5.7	8.8	SNR	75.9	0.5		
⋆4FGL J0222.4+6156e	133.42	0.94	14.3	30.7	snr	1307.1	27.2	34.8	32.4
4FGL J0235.3+5650	136.82	−3.19	4.1	7.6		77.1	3.7		
⋆4FGL J0240.5+6113	135.68	1.09	28.2	107.3	HMB	39495.7	127.8	127.3	100.9
4FGL J0302.7+5717	139.97	−1.17	0.8	3.3		20.3			
4FGL J0328.5+6114	140.71	3.92	1.4	3.9		12.3			
4FGL J0330.1+5038	146.91	−4.70	4.7	6.1		34.8	2.7		
⋆4FGL J0330.7+5845	142.35	2.02	4.7	6.2		43.2	16.1	18.0	14.2
⋆4FGL J0340.4+5302	146.79	−1.82	12.3	23.4		1329.3	149.4	143.6	139.0
⋆4FGL J0426.5+5434	150.88	3.82	9.8	18.1		704.1	19.6	25.2	18.9
4FGL J0452.9+5117	155.99	4.63	2.8	5.6		26.4	8.0		

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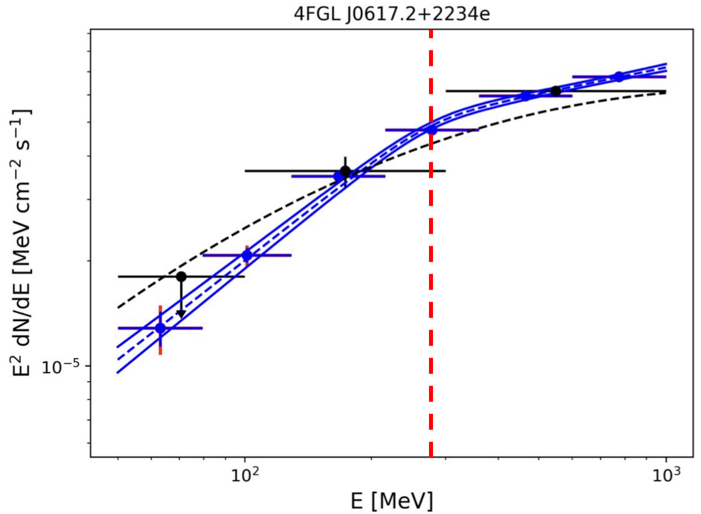
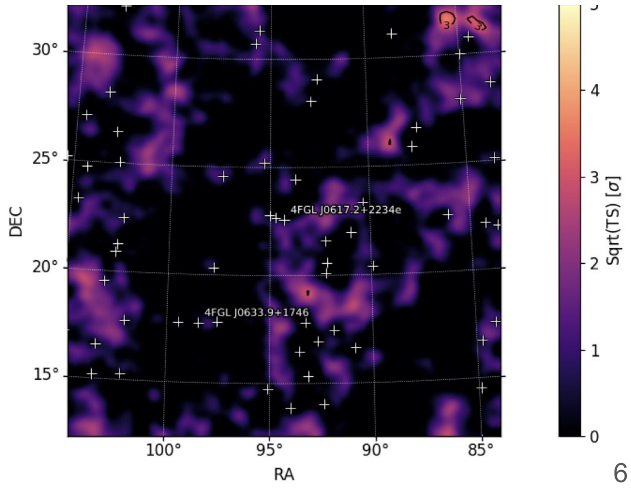
Confirmed Low-energy Spectral Breaks in 4FGL Sources

- The **result of the study** confirmed a characteristic spectral break in 56 sources using 8 years of data between 50 MeV and 1 GeV.
- Characteristic of a Hadronic Spectrum: Spectral break
  - Observed around SNRs (IC443, W44)
  - Low-energy break ~ 200 MeV
- Neutrino detection from these sources: “smoking gun” signature for hadronic activity





4FGL J0617.2+2234e (IC 443) showing a spectral break at ~465 MeV
Ref: Abdollahi, S., “Search for New Cosmic-Ray Acceleration Sites within the 4FGL Catalog Galactic Plane Sources”,The Astrophysical Journal, Vol. 933, No. 2, 2022.

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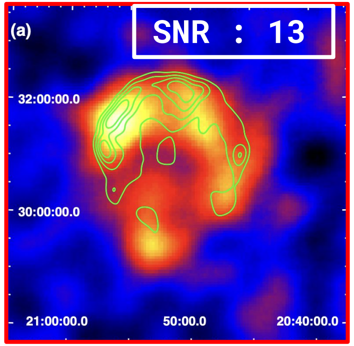
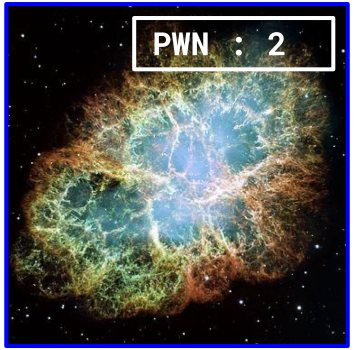
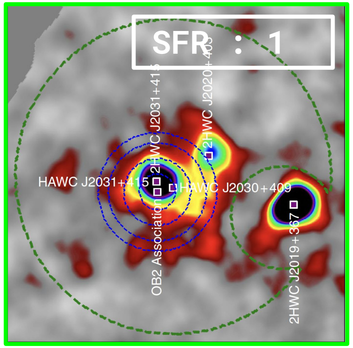
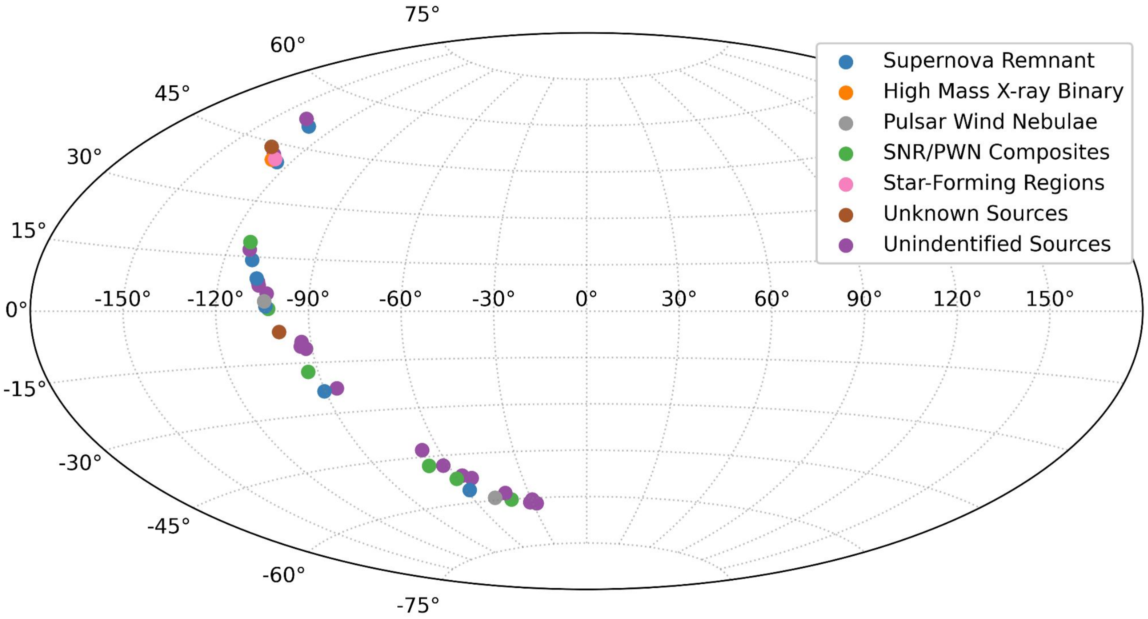
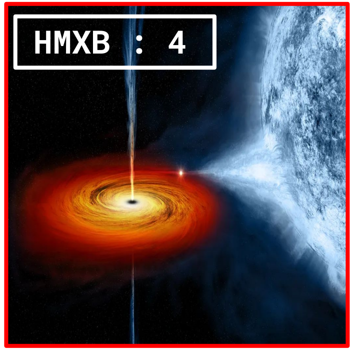
IceCube Search: Source Candidates

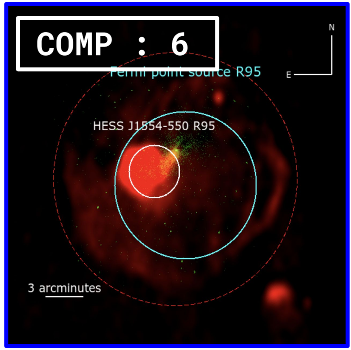




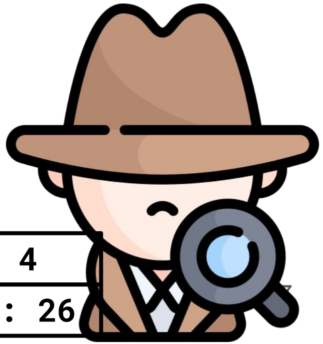








Distributed throughout Northern and Southern sky



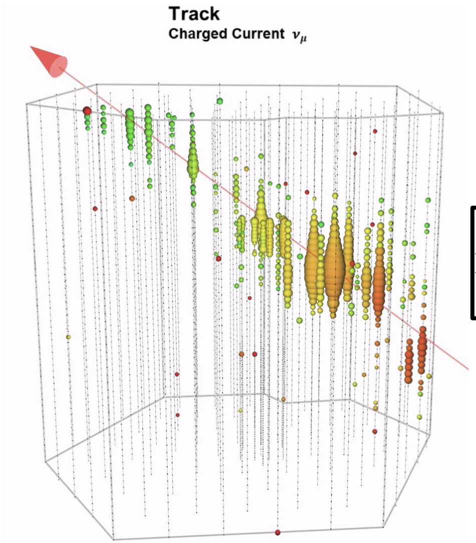
UNK : 4

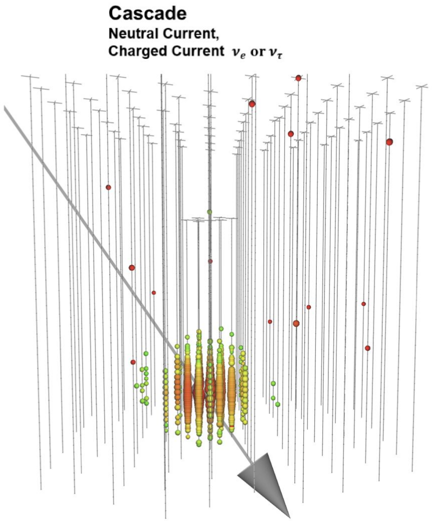
UNID : 26

IceCube Analysis Schema

Starting + Throughgoing Track Events: 11 years dataset

Cascade Event: 10 years dataset





$$\log \mathcal{L} = \sum_{i=1}^{N} \log\left(\frac{n_s}{N} \cdot S(\delta_i, \alpha_i, \sigma_i, E_i; \gamma) + \left(1 - \frac{n_s}{N}\right) B(\delta_i, E_i)\right)$$

Stacking Analysis for source classes

Catalog Analysis on all 56 sources

n_s: No of signal neutrinos
S: Signal PDF
B: Background PDF
γ: Spectral Index
w_k: Weights

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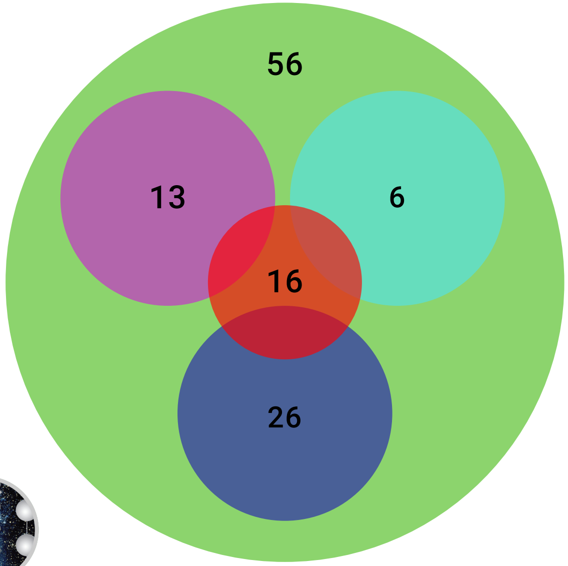
Analysis Details

$$\mathrm{TS} = 2\frac{\log L(\mathrm{n_s} = \mathrm{n_{s,max}})}{\log L(\mathrm{n_s} = 0)}$$

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



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

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

56 - All sources
16 - Sources with TeV counterparts [TeVCat]
13 - Supernova Remnants [SNR]
26 - Unidentified Sources [UNK]
6 - Composites [SPP]

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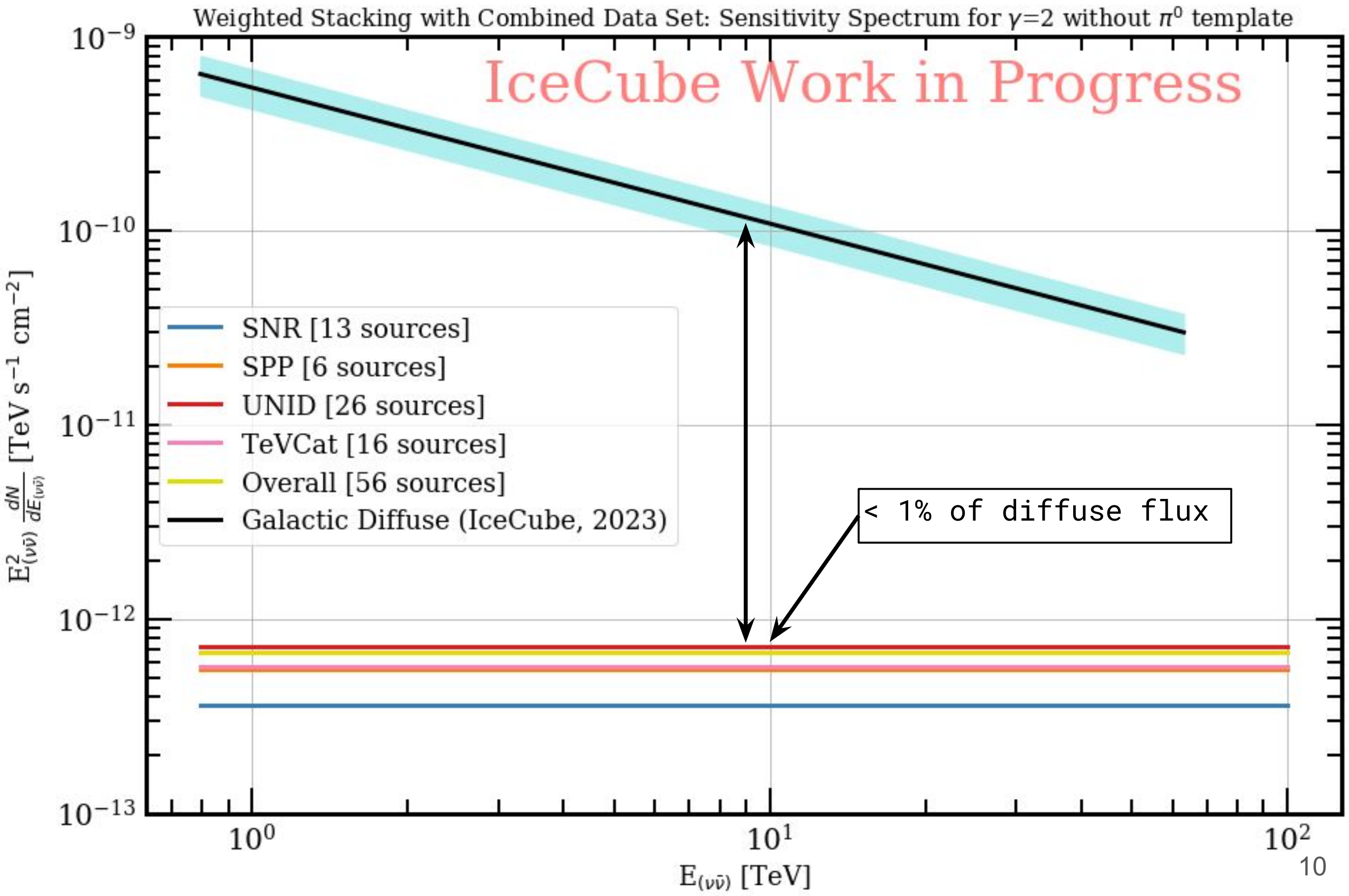
Sensitivity from Stacking Search

Stacked Sensitivity Spectra (γ=2)
No π^0-template injected in background.



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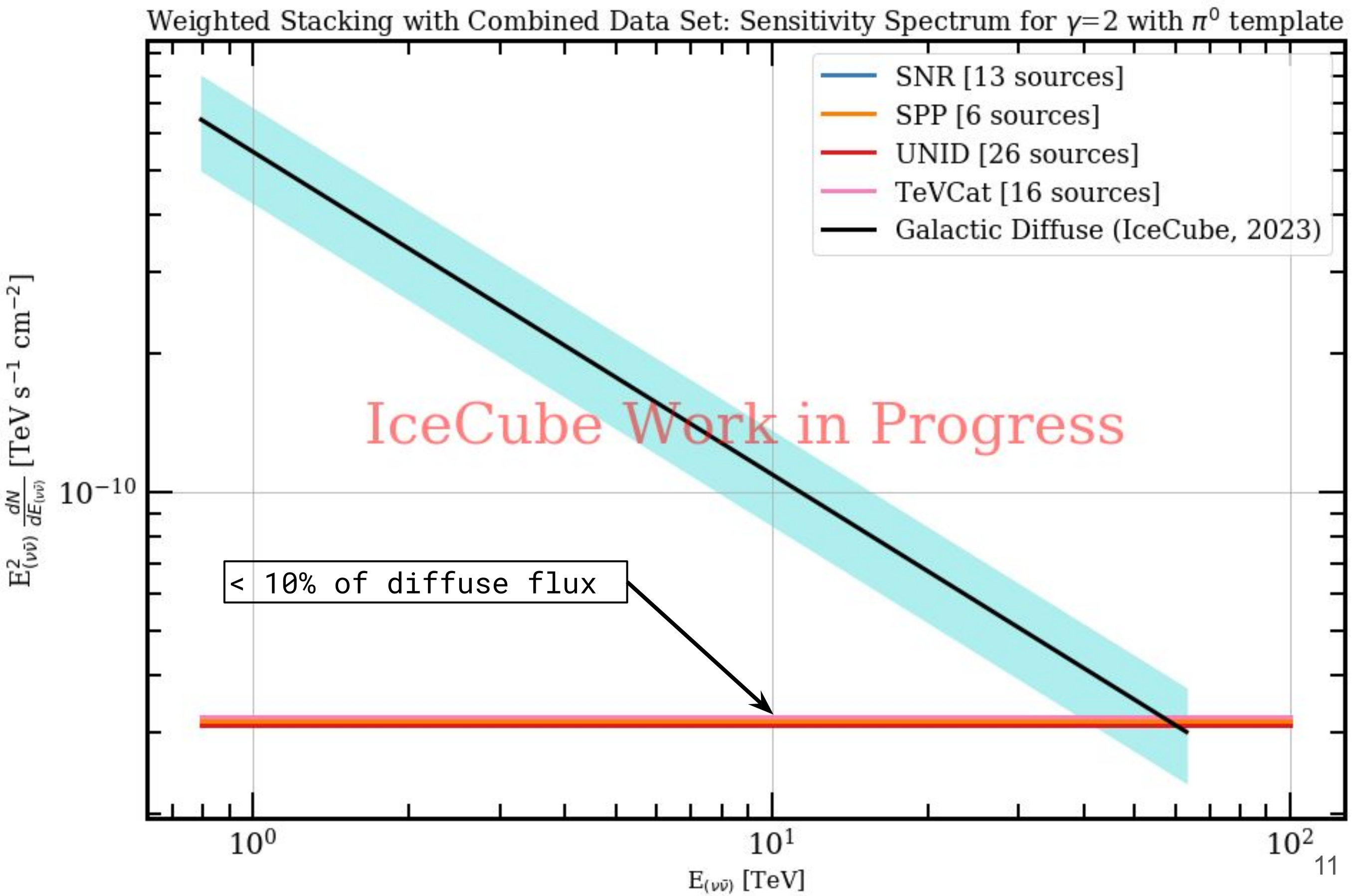
Sensitivity from Stacking Search

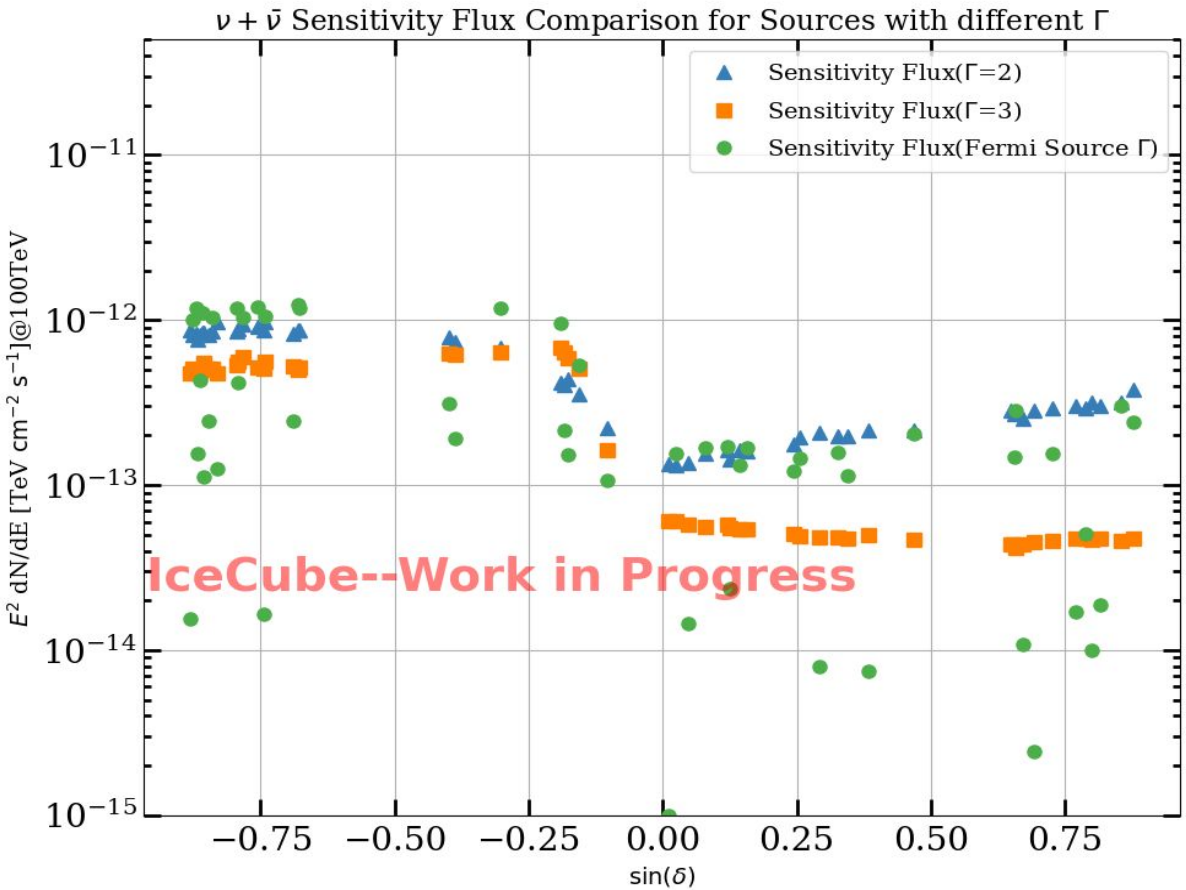
Stacked Sensitivity Spectra (γ=2) π^0-template injected in background.



Sensitivity from Catalog Search

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

Fermi spectral indices
$1.75 < \gamma < 4.68$

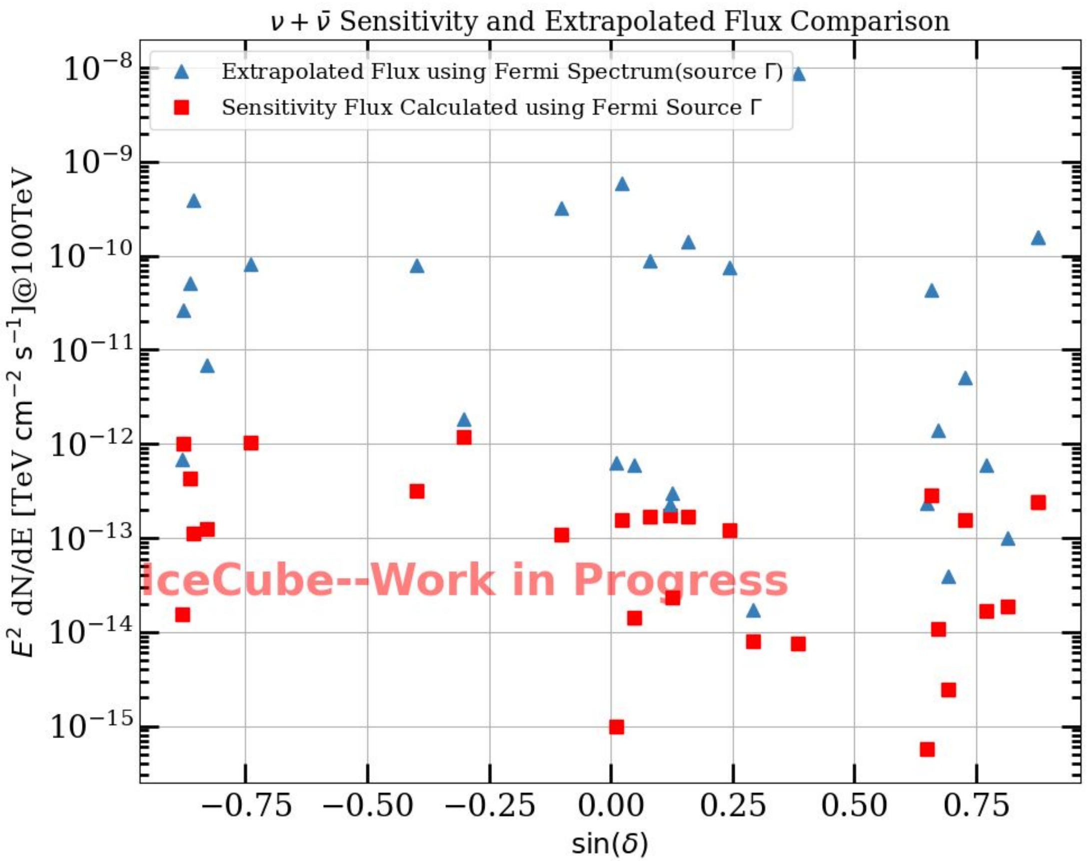


Sensitivity from Catalog Search

Comparison of Sensitivity Spectra for 27 sources (predicted flux greater than the sensitivity flux) assuming source γ after the spectral break

▲ : Predicted Flux obtained by extrapolating the MeV flux after the spectral break using a simple power-law to 100 TeV

■ : Sensitivity Flux calculated using the Fermi Source γ



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Summary and Outlook

- Sources showing a characteristic pion bump signature can be explored for potential hadronic activity.
- 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
- Work in progress!

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Thank you!!

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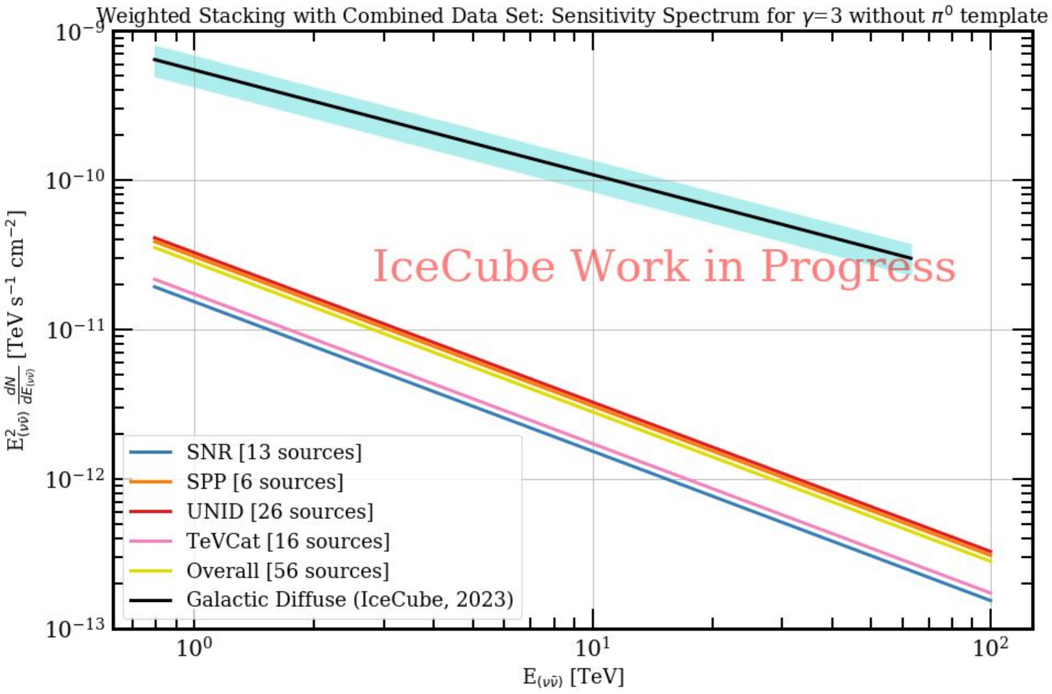
Backup

Results from Stacking Search(backup?)



Sensitivity Spectra for each of the sources classes for γ=3 with no pi0-template injected in background.

- No pi0 template diffuse neutrinos injected into the fit
- The pi0 best fit diffuse flux is higher than each of the source class sensitivity flux.

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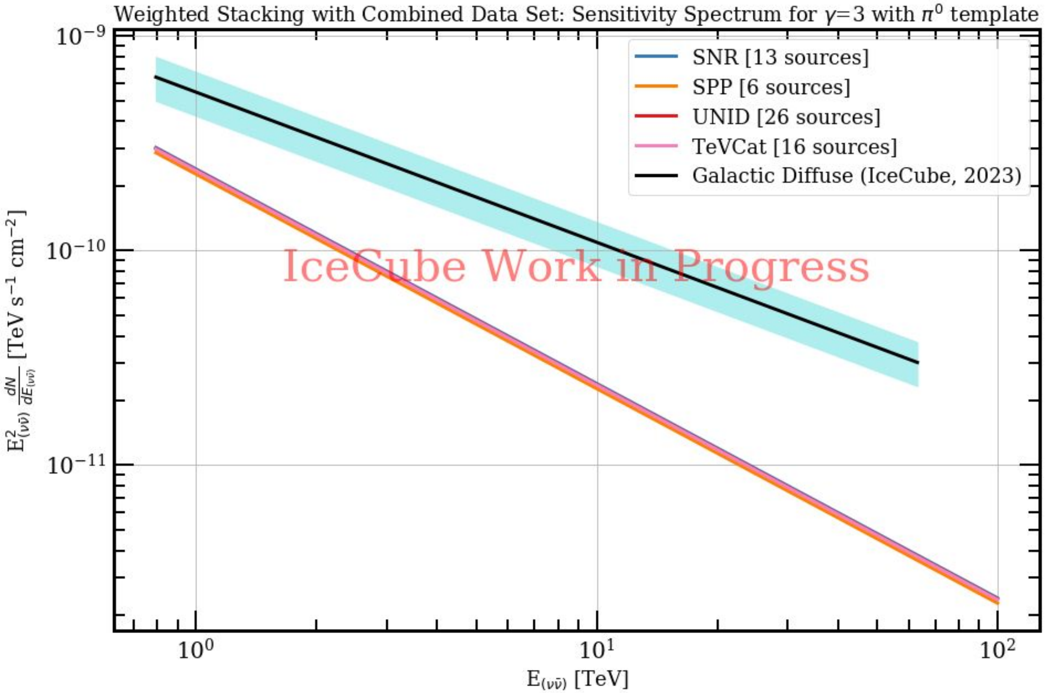
Results from Stacking Search(backup?)

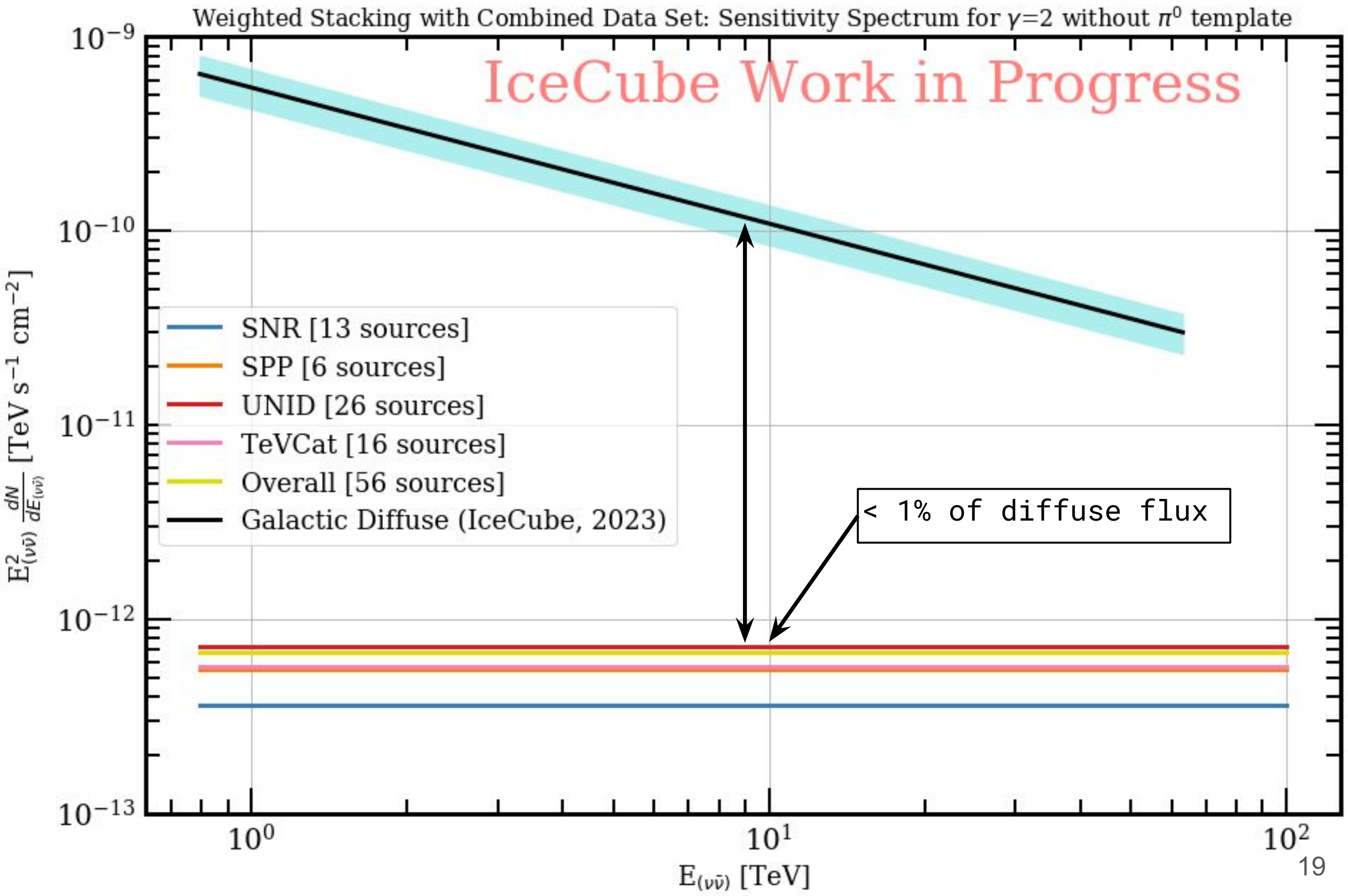


Sensitivity Spectra for each of the sources classes for γ=3 with pi0-template injected in background.

- Pi0 template diffuse neutrinos injected into the fit
- The pi0 best fit diffuse flux is higher than each of the source class sensitivity flux.

Sensitivity from Stacking Search

Sensitivity Spectra for each of the sources classes for γ=2 with no π^0-template injected in background.



Analysis Schema

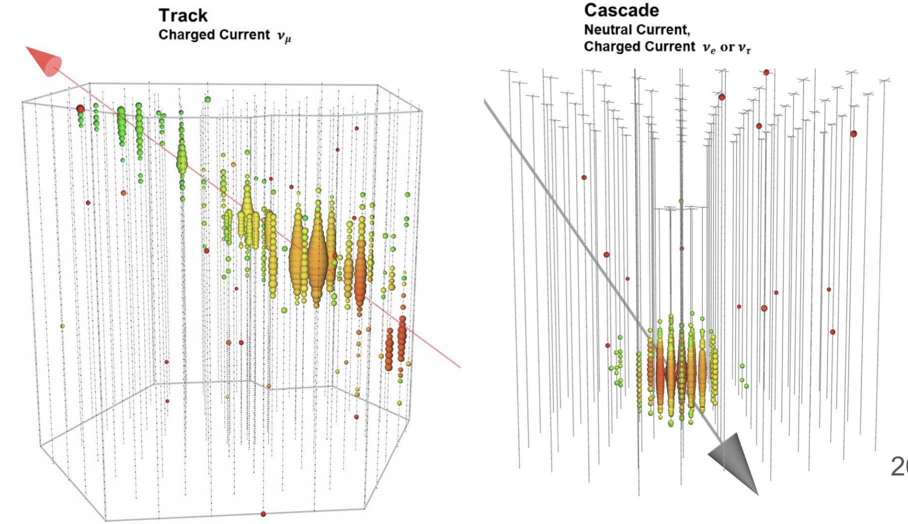
- Use a combined data of 11 years of starting and throughgoing tracks and 10 years of cascades dataset
- **Stacking Analysis** for source classes
- **Catalog Analysis** on all 56 sources in the Fermi source list

$$\log \mathcal{L} = \sum_{i=1}^{N} \log \left(\frac{n_s}{N} \cdot S(\delta_i, \alpha_i, \sigma_i, E_i; \gamma) + \left(1 - \frac{n_s}{N}\right) B(\delta_i, E_i) \right)$$

We perform stacking of M sources with weights

$$S(\delta_i, \alpha_i, \sigma_i, E_i; \gamma) = \sum_{k=1}^{M} w_k S_k(\delta_i, \alpha_i, \sigma_i, E_i; \gamma)$$

- n_s: No of signal neutrinos
- S: Signal PDF
- B: Background PDF
- γ: Spectral Index
- w_k: Weights



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

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  - Perform two different analyses:
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    - No Fermi-LAT π^0 template
  - Weighted with respect to their MeV flux (w_k **= source flux**)
  - Test sensitivity for γ=2, γ=3
- **Catalog Analysis**:
  - All sources
  - Test sensitivity for γ=2, γ=3 and γ=γ of the 4FGL source after the break
  - No Fermi-LAT π^0 template

Source Class	No of Sources
SNR	13
SPP	6
UNID	26
TeVCat	16
All sources	56

Source classes (with no of sources > 5) used in the stacking search

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IceCube Search for Neutrinos from the 4FGL Spectral Break List

- **56 sources** have been identified by Fermi-LAT
  - **Supernova**(SNR) - 13
  - **Pulsar Wind Nebulae**(PWN) - 2
  - **Composites** - 6
  - **Star-forming Region** - 1
  - **Unknown Sources** - 4
  - **High-Mass X-ray Binary** - 4
  - **Unidentified Sources** - 26
- Distributed throughout Northern and Southern sky