Search for Neutrino Sources with Cascade Events in IceCube

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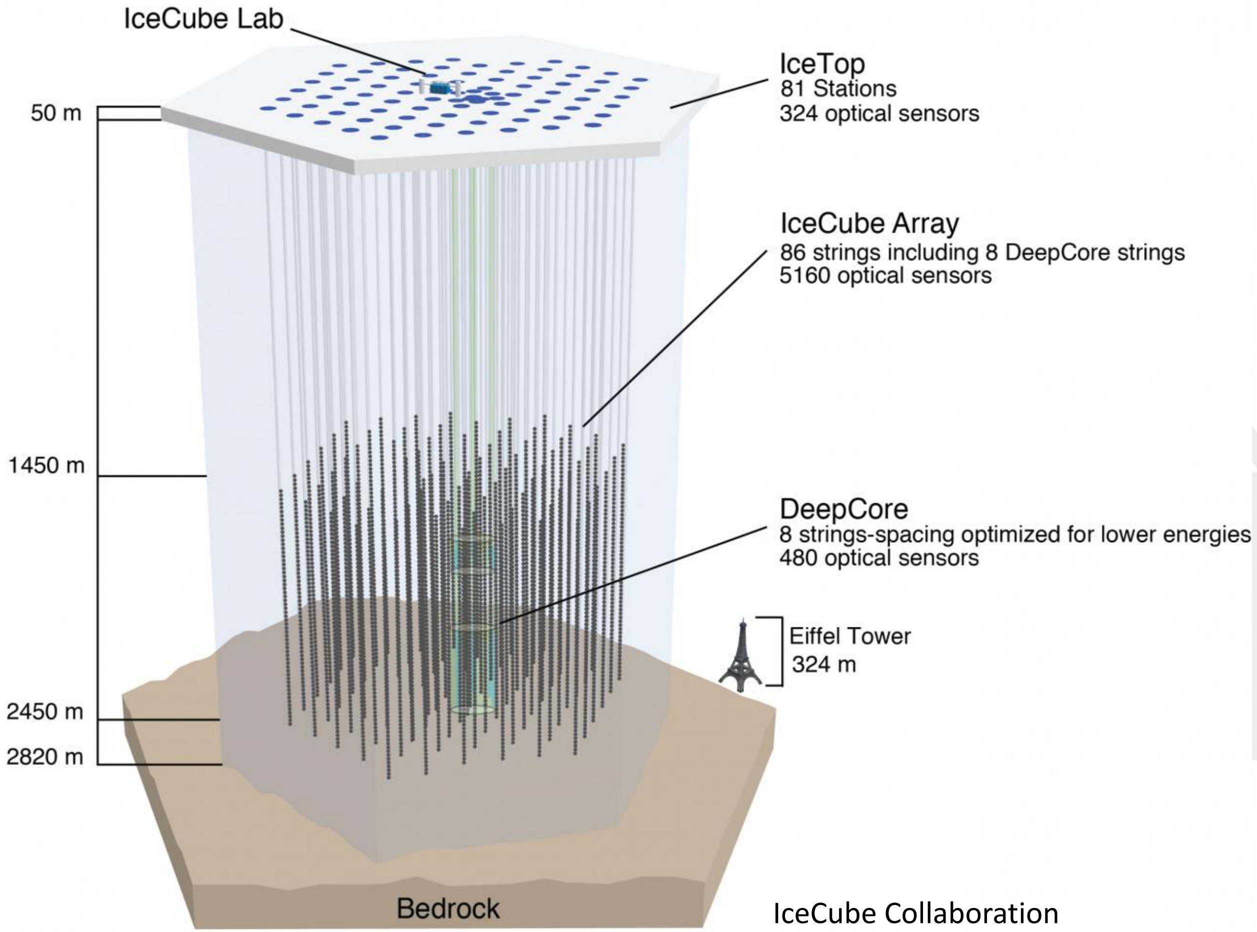
DFG
NSF
Federal Ministry of Education and Research
IceCube South Pole Neutrino Observatory

IceCube

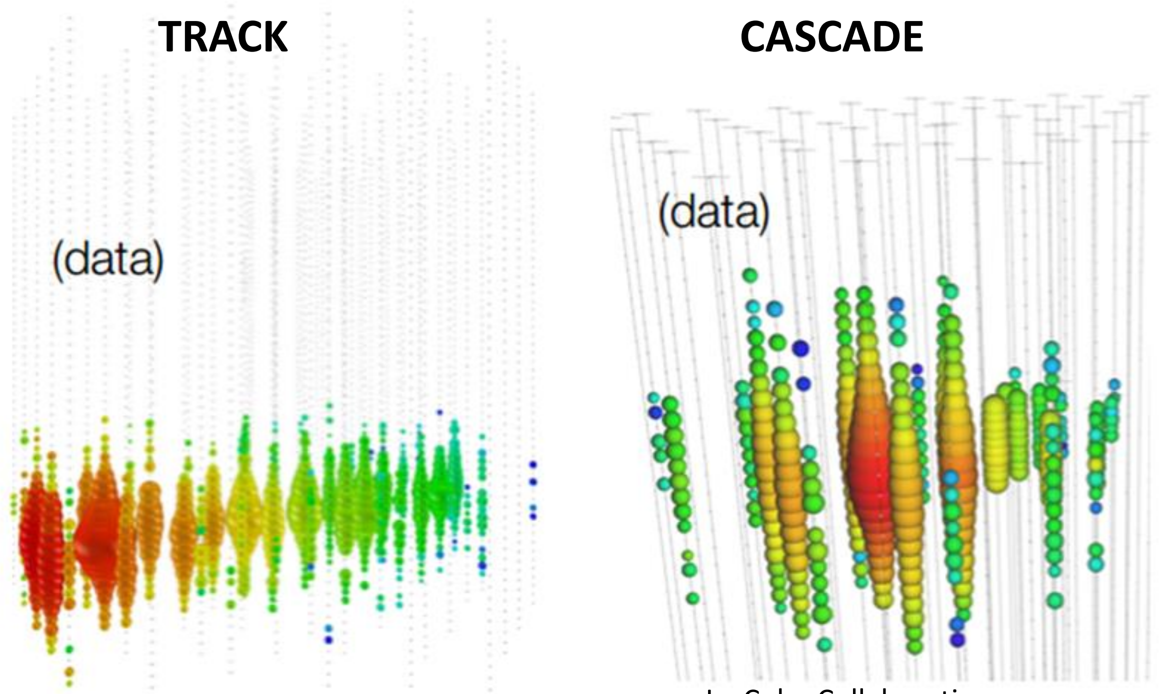
- Located at Geographic South Pole.
- 5160 Digital Optical Modules on 86 Strings
- Use Cherenkov light from interactions to search for the sources of astrophysical neutrinos
- Source neutrino backgrounds are a function of declination



IceCube Collaboration

Track vs Cascade

- Two primary topologies of events, tracks and cascades
- Tracks from CC-ν_{μ} interactions, Cascades from NC and CC interactions from other flavors
- Tracks angular resolution (0.1°-1°) much better than cascades angular resolution (5°-15°)



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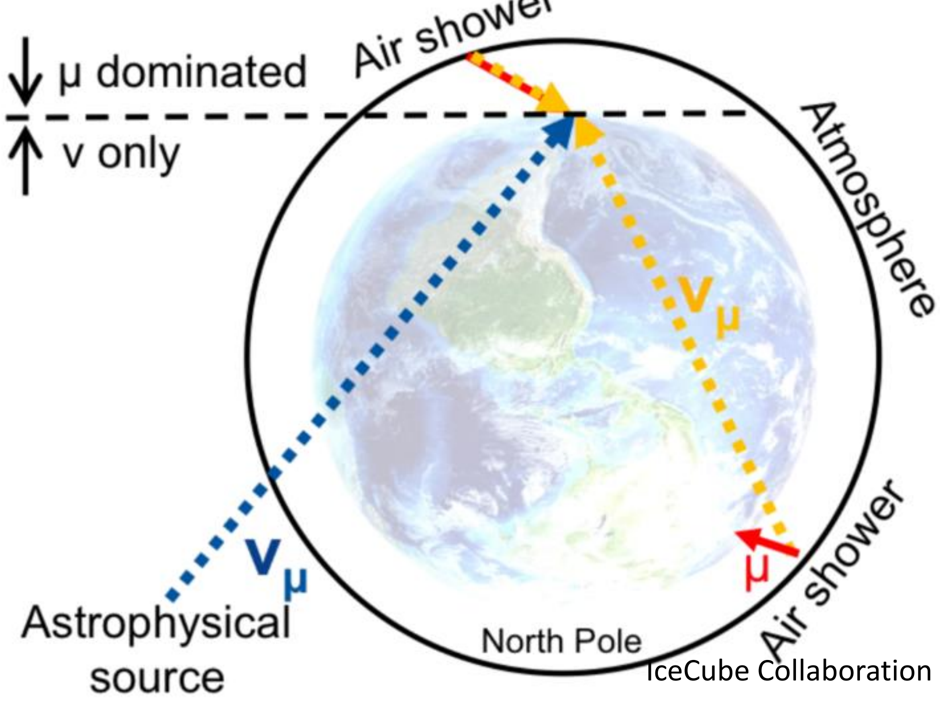
Track vs Cascade

- Backgrounds are very different in Southern Sky
- Track event selections use energy to discriminate background: High energy threshold
- Cascade event selections can reduce the energy threshold
  - Benefit for southern sources, soft spectrum sources, and extended sources
- Very low event overlap between samples
- Previous cascade datasets not optimized for source searches



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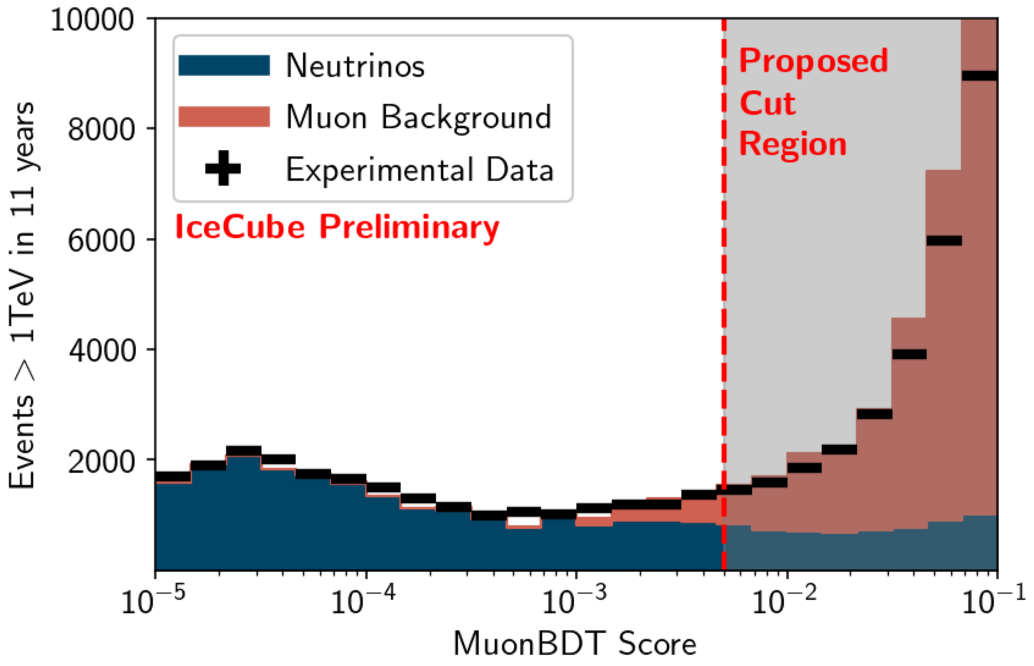
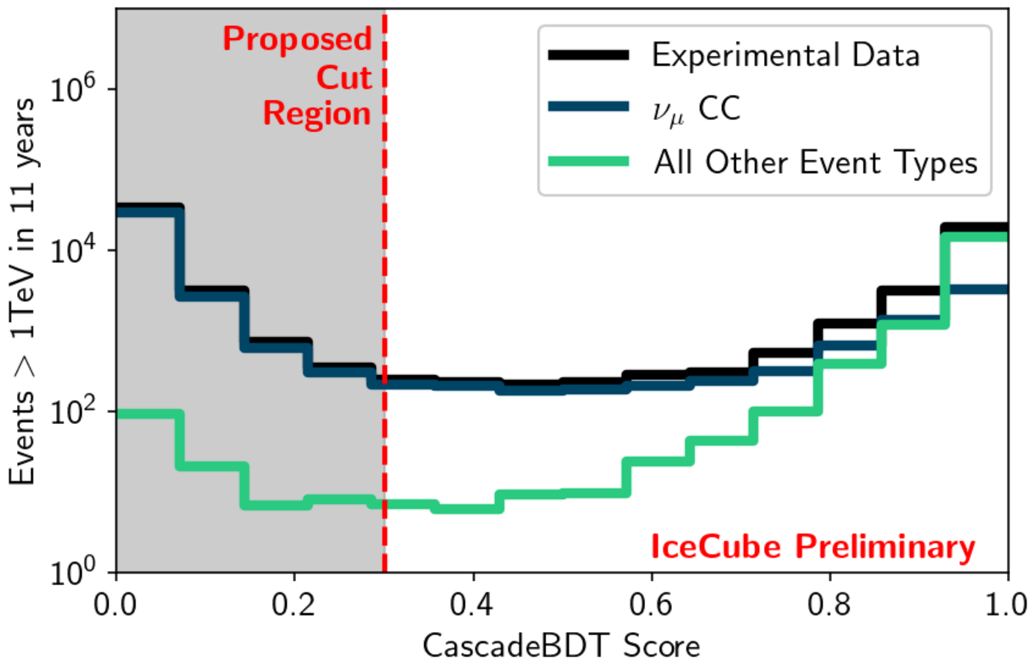
Event Selection

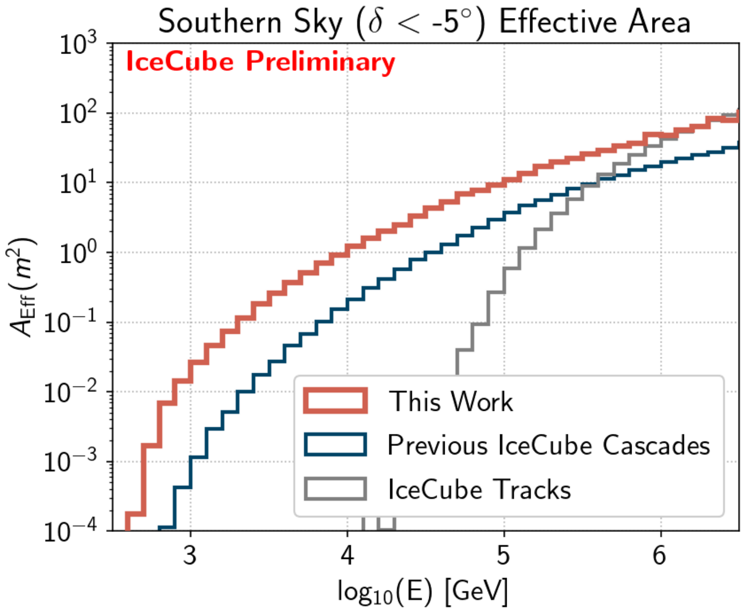
- Neural-Net Architecture for features and precuts
- Look for:
  - Events contained in the detector
  - Low track length
  - Reject incoming events
- Final selection via BDTs trained for Muon and Cascade classification
- Selection can be done in real-time
- Novel Reconstruction combining LLH and DNN architecture [See PoS 1065]

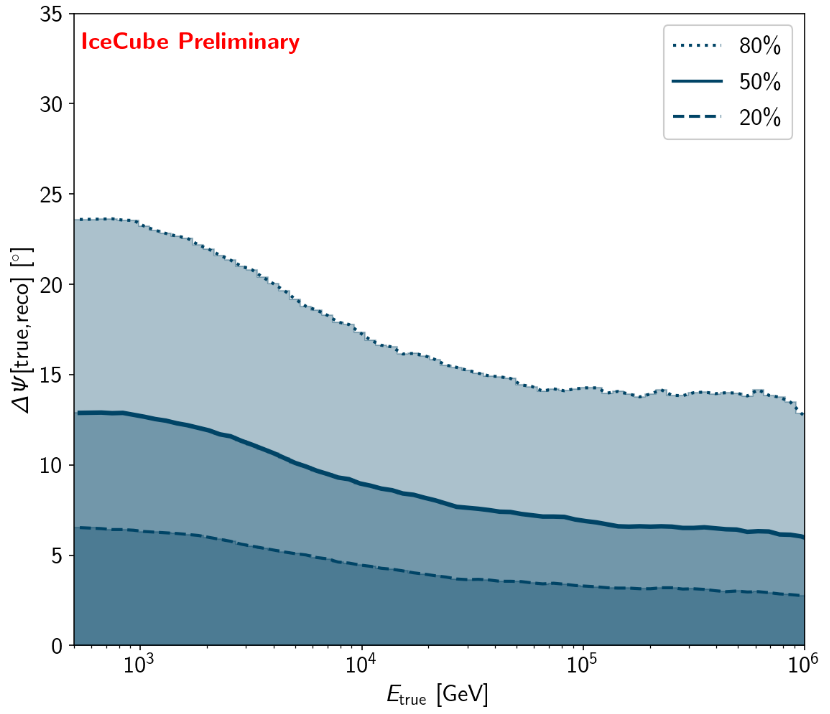




Dataset Statistics

- 10 years of Data (2011-2021)
- ~45,000 Cascade-like events
- $\mathcal{O}(100)$ atmospheric muon background events
- Median Energy ~ 1 TeV
- Increase in effective area for declinations in the southern sky when compared to previous cascades[1] or tracks[2]





1. IceCube Collaboration, M. G. Aartsen et al.,Astrophys. J.886(2019) 12
2. IceCube Collaboration, M. G. Aartsen et al.,Phys. Rev. Lett.124(2020) 051103

Hypothesis – Diffuse Galactic Emission

- Cosmic Rays are produced in our galaxy and interact with galactic media to produce pions:
  - $\Pi^+ \rightarrow \nu_u + u^+ \rightarrow e^+ + \boldsymbol{\nu_u} + \boldsymbol{\nu_e} + \boldsymbol{\bar{\nu}_u}$
  - $\Pi^- \rightarrow \bar{\nu}_u + u^- \rightarrow e^- + \boldsymbol{\nu_u} + \boldsymbol{\bar{\nu}_e} + \boldsymbol{\bar{\nu}_u}$
  - $\Pi^0 \rightarrow 2\gamma$
- Use gamma ray data to construct templates for neutrino emission
- Neutrino flux is spread through the sky, but majority is in southern sky and expected to follow soft spectrum
- Strong improvement in sensitivity

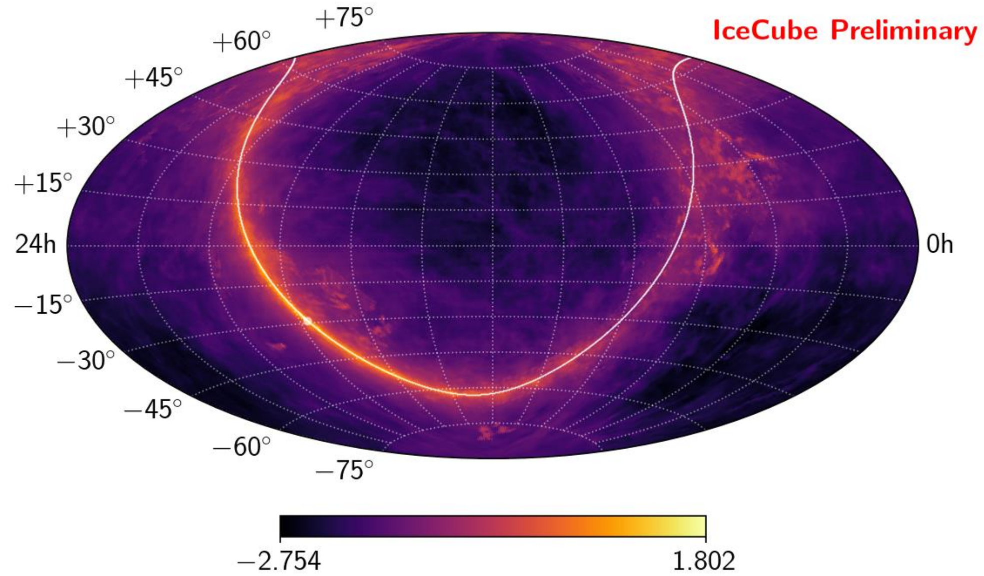


Figure: The spatial template for the KRA-γ model with 5 PeV cutoff.

Template	This Work	IceCube / ANTARES[3]	Previous IceCube Cascades[2]
KRA-γ 5 PeV[1]	0.17	0.81	0.58
KRA-γ 50 PeV[1]	0.12	0.57	0.35
Fermi π^0 [2]	0.82×10^{-18}	--	2.2×10^{-18}

Sensitivity to various models. Units for KRA-γ in multiples of Model Flux. Fermi π^0 are in GeV $s^{-1}cm^{-2}$ at 100 TeV

1. D. Gaggero, D. Grasso, A. Marinelli, A. Urbano, and M. Valli, Astrophys. J. Lett.815(2015) L25
   D.Gaggero, D. Grasso, A. Marinelli, M. Taoso, and A. Urbano, Phys. Rev. Lett.119(Jul,2017) 031101.
2. IceCube Collaboration, M. G. Aartsen et al.,Astrophys. J.886(2019) 12
3. ANTARES, IceCube Collaboration, A. Albert et al.,Astrophys. J. Lett.868(2018) L20

Hypothesis – Stacking Source Classes

- Various Galactic Source Classes are expected to be sources of neutrinos
- Test emission from source class by stacking sources: Supernova Remnants, Pulsar Wind Nebulae, and Unidentified Galactic Sources[2]
- Catalog of 12 sources from each class
- Sources selected based on observed Gamma-Ray emission
- Fit for number of signal events, spectrum

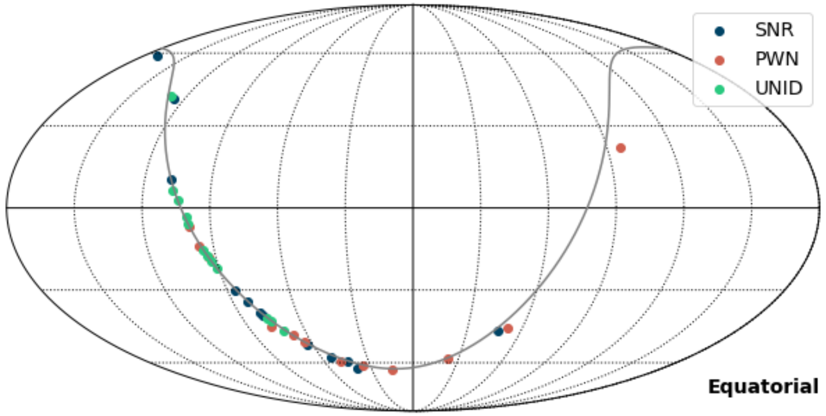


Figure: Source Locations for sources included in the Stacking Catalogs[2]

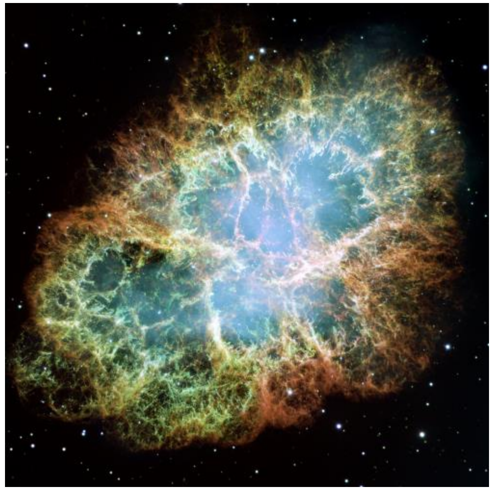


Figure: Crab Nebula, Hubble Telescope

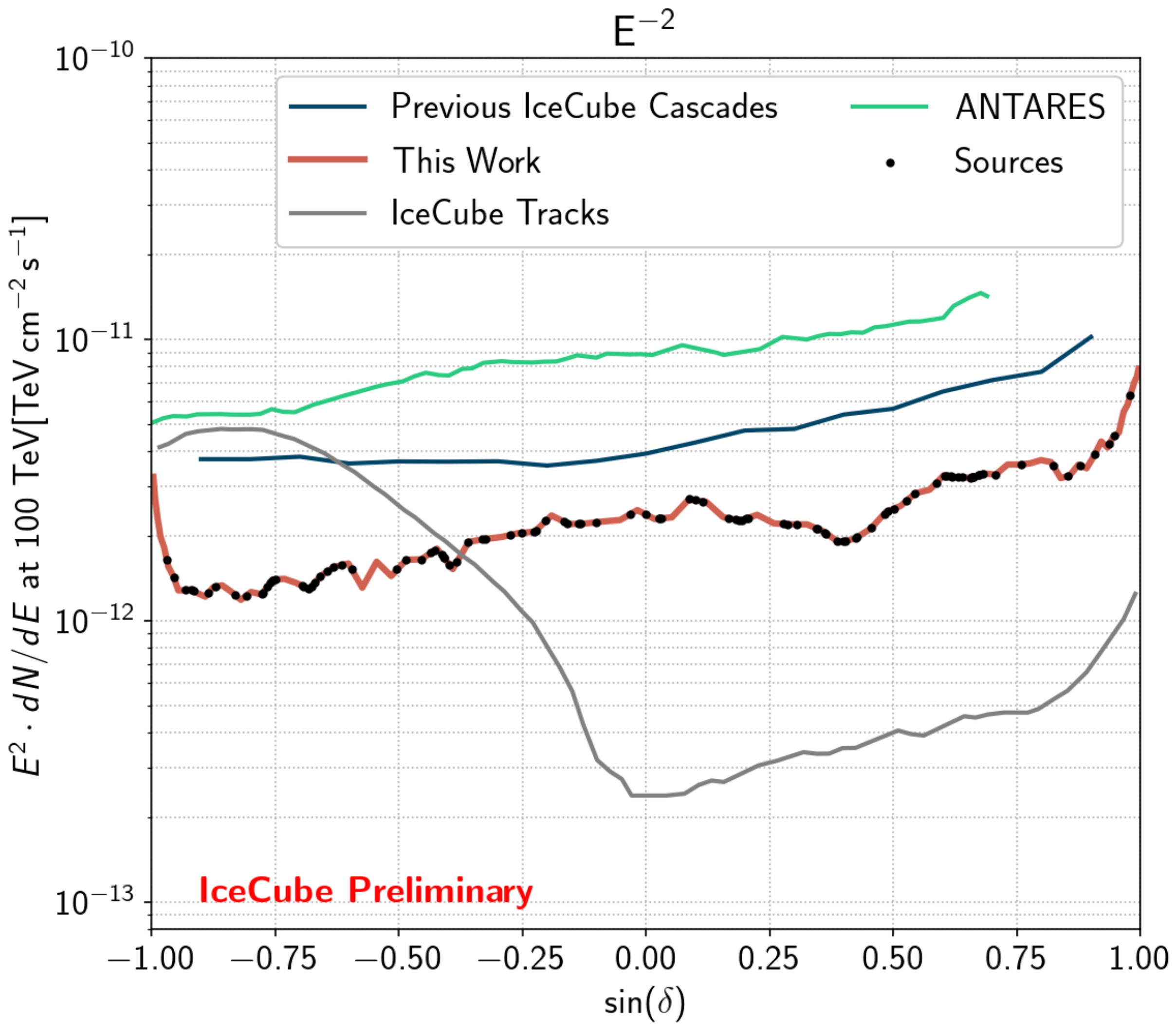
Catalog	Sensitivity (E^{-2})[1]	Sensitivity ($E^{-2.5}$)[1]
Supernova Remnants	3.4	3.3
Pulsar Wind Nebulae	4.0	3.5
Unidentified Galactic Sources	3.9	3.2

1. E^2 dN/dE x 10^{-12} at 100 TeV [TeV s^{-1} cm^{-2}]

2. Full Catalogs in Backup Slides

All Sky Scan and Source List

- Catalog of 110 likely galactic and extragalactic sources
- Scan the sky and identify any hotpots in data
- Significant boost in sensitivity when compared with previous analyses[1234]



1. ANTARESCollaboration, J. Aublin, G. Illuminati, and S. Navas, PoS(ICRC2019)920117(2020).
2. ANTARESCollaboration, A. Albert et al.,Phys. Rev. D96(2017) 082001.
3. IceCubeCollaboration, M. G. Aartsen et al.,Phys. Rev. Lett.124(2020) 05110
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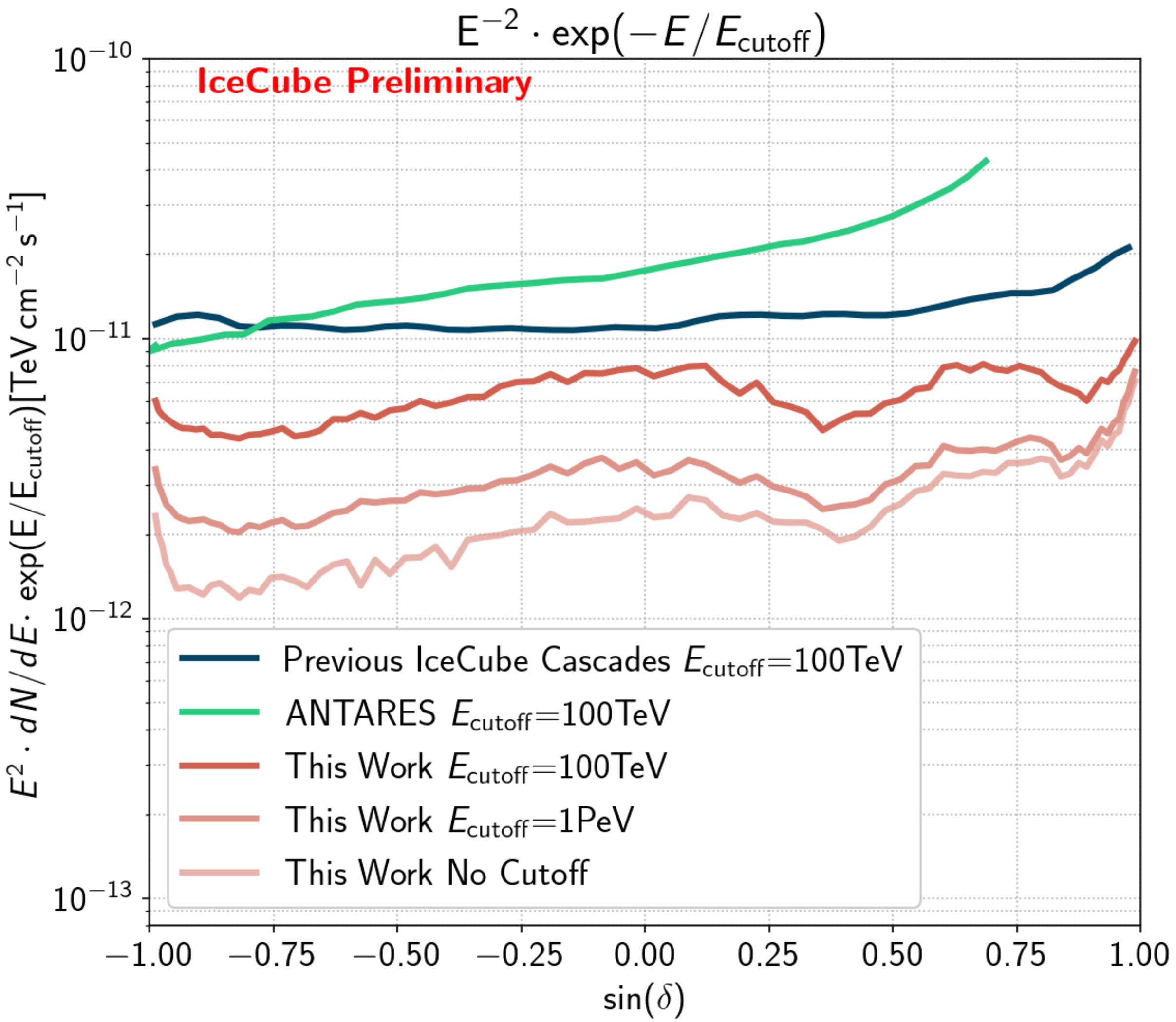

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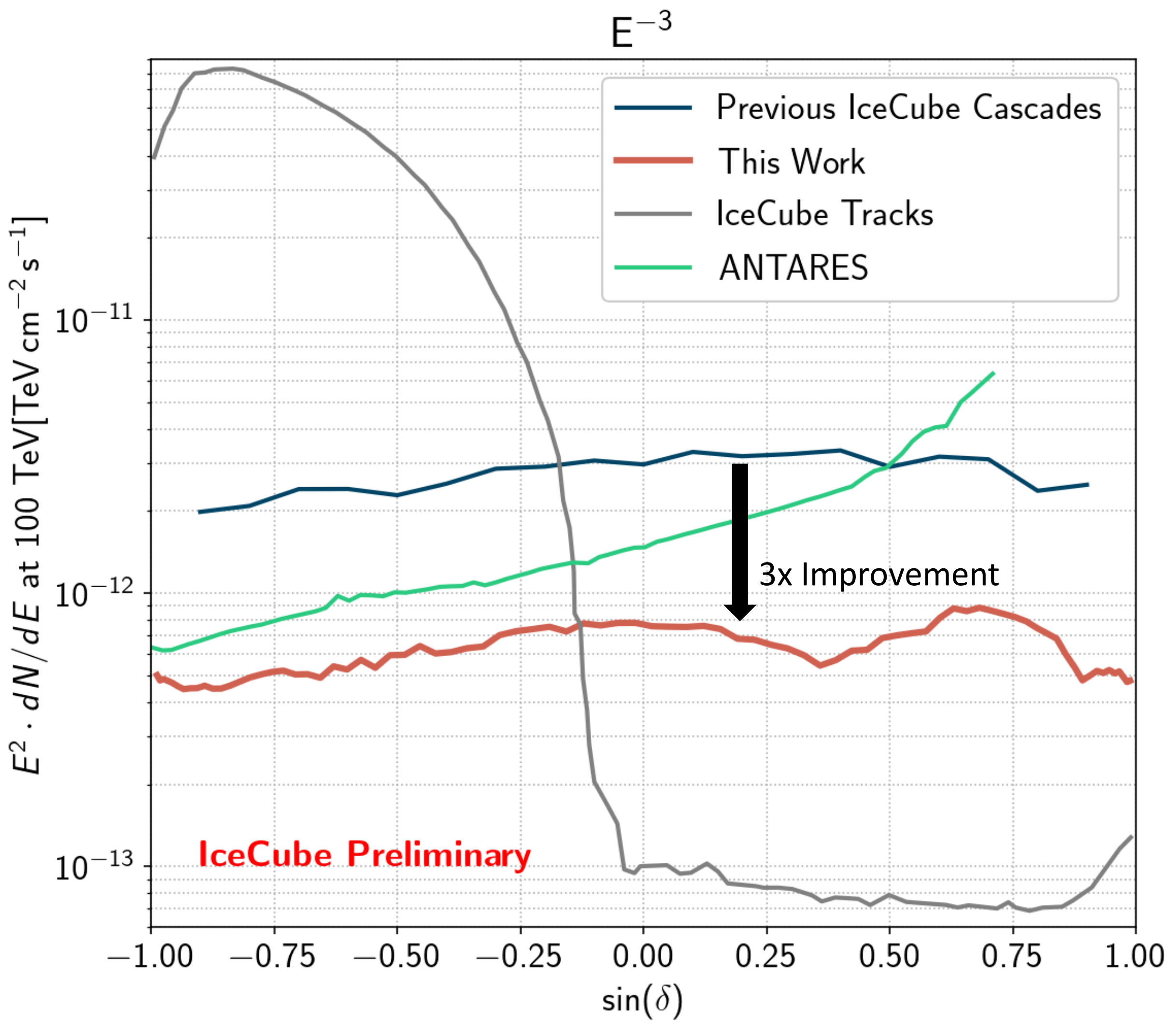

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Conclusions

- IceCube is extending its reach and can use cascade-based datasets to search for sources
- Particularly promising for softer, more southern, or extended sources
- Selection can be run in real-time with few resources
- Presenting a sensitivity study; stay tuned for physics results soon
- Can combine naturally with track-based datasets in the future.

BACKUP

Full Stacking Catalogs

Catalog	Name	α[deg]	δ[deg]	Catalog	Name	α[deg]	δ[deg]
PWN	Vela X	128.29	-45.19	SNR	Vela Junior	133.0	-46.33
	Crab nebula	83.63	22.01		RX J1713.7-2946	258.36	-39.77
	HESS J1708-443	257.0	-44.3		HESS J1614-518	243.56	-51.82
	HESS J1825-137	276.55	-13.58		HESS J1457-593	223.7	-59.07
	HESS J1632-478	248.01	-47.87		SNR G323.7-01.0	233.63	-57.2
	MSH 15-52	228.53	-59.16		HESS J1731-347	262.98	-34.71
	HESS J1813-178	273.36	-17.86		Gamma Cygni	305.27	40.52
	HESS J1303-631	195.75	-63.2		RCW 86	220.12	-62.65
	HESS J1616-508	244.06	-50.91		HESS J1912+101	288.33	10.19
	Kookaburra	214.69	-60.98		HESS J1745-303	266.3	-30.2
	HESS J1837-069	279.43	-6.93		Cassiopeia A	350.85	58.81
	HESS J1026-582	157.17	-58.29		CTB 37A	258.64	-38.545
UNID	MGRO J1908+06	133.0	6.32				
	Westerlund 1	258.36	-45.8				
	HESS J1702-420	243.56	-42.02				
	2HWC J1814-173	223.7	-17.31				
	HESS J1841-055	233.63	-5.55				
	2HWC J1819-150	262.98	-15.06				
	HESS J1804-216	305.27	-21.73				
	HESS J1809-193	220.12	-19.3				
	HESS J1843-033	288.33	-3.3				
	TeV J2032+4130	266.3	41.51				
	HESS J1708-410	350.85	-41.09				
	HESS J1857+026	258.64	2.67				