

TXS 0506+056 Through a New Neutrino Lens

William Luszczyk (OSU/CCAPP)

PIKIMO 2022

November 12, 2022

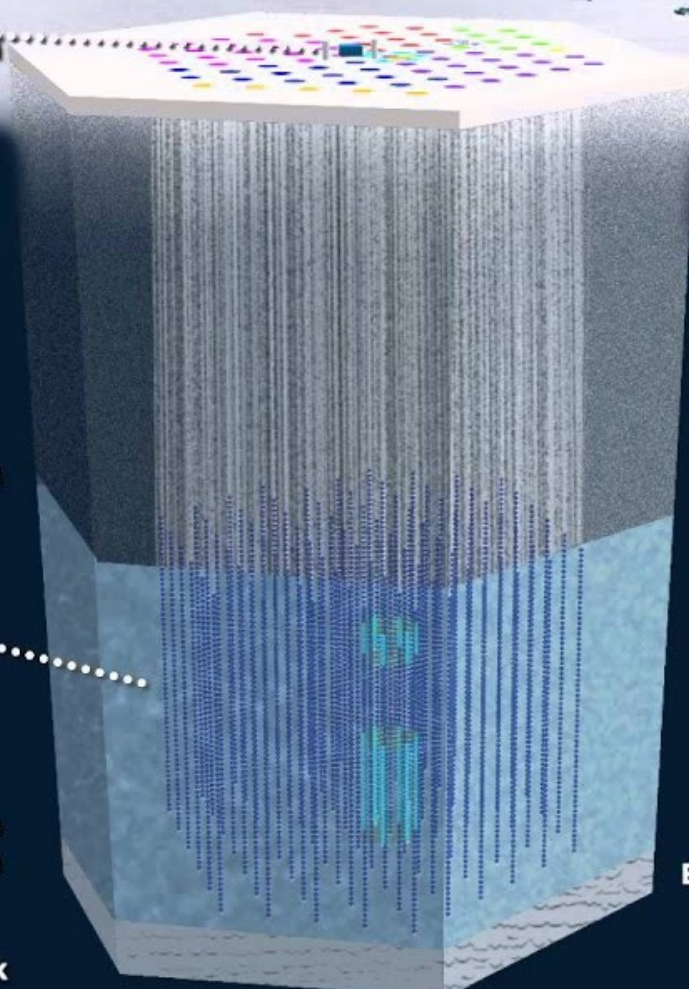


ICECUBE
NEUTRINO OBSERVATORY



**IceCube
Laboratory**

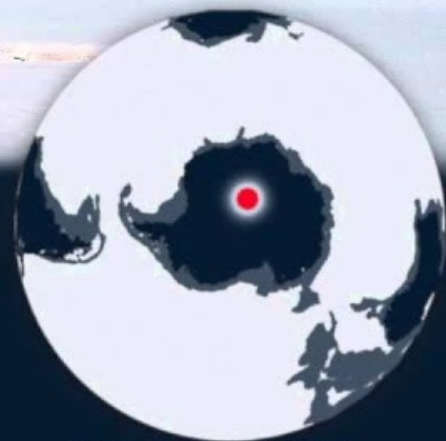
50 m



1450 m

2450 m
2820 m

bedrock



**Amundsen-Scott
South Pole
Station
Antarctica**

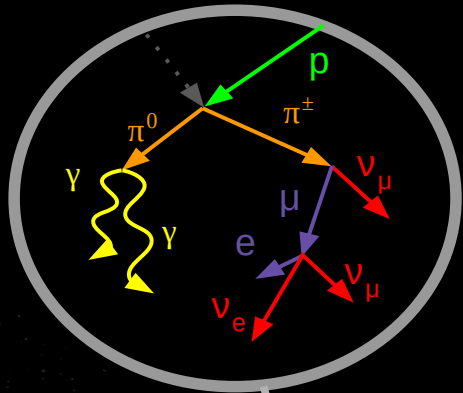


**Digital Optical Module
DOM
86 strings
5160 optical sensors**



Eiffel Tower 324 m

Multi-messenger Astronomy

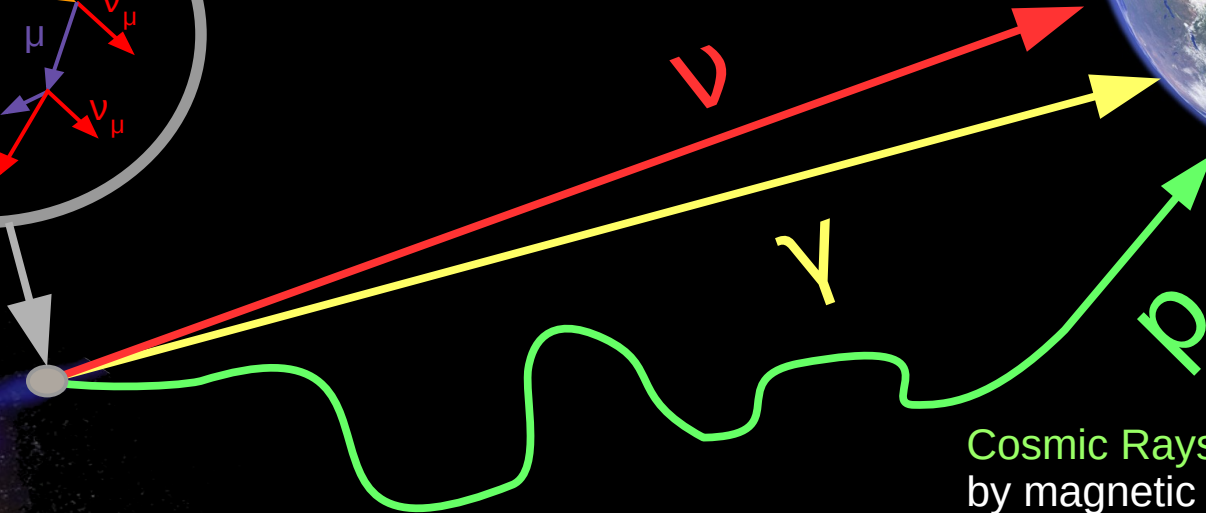
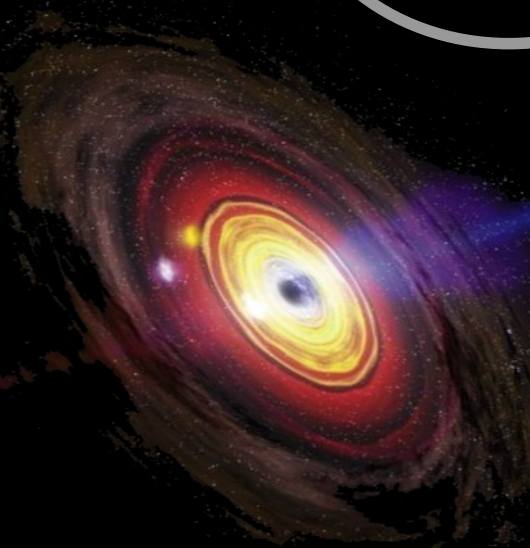


Neutrinos: Not bent by magnetic fields, produced in hadronic interactions

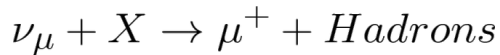
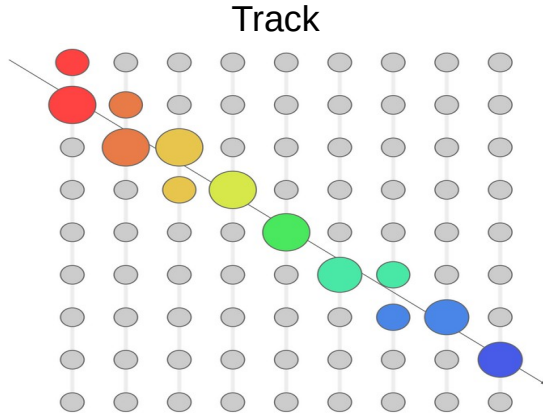


Gamma Rays: Scattered/absorbed by dust in the galaxy, universe is opaque at high energy, multiple production mechanisms

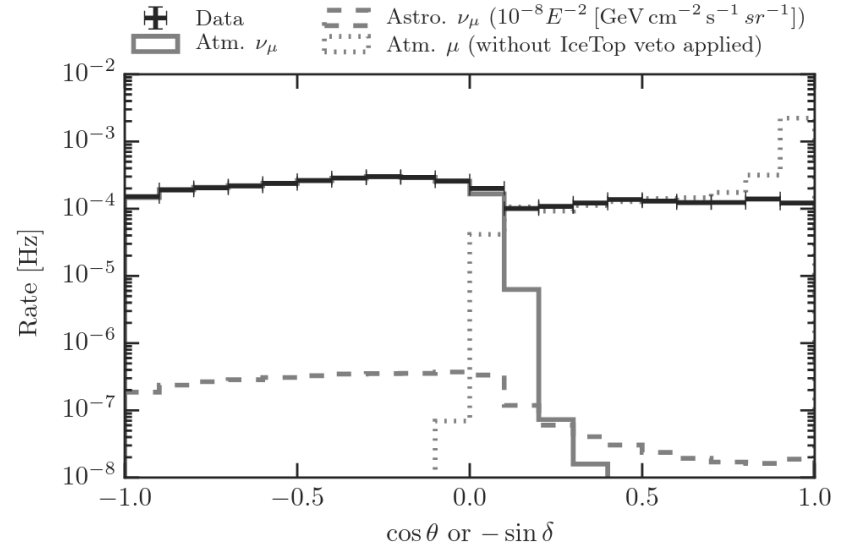
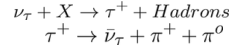
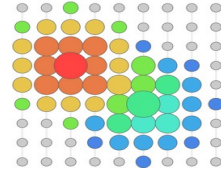
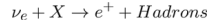
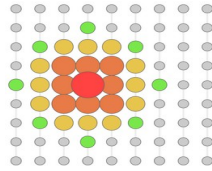
Cosmic Rays: Paths are bent by magnetic fields, may not point directly back to source



What's In An IceCube Event Sample?



Factor of ~2 energy resolution
< 1 degree angular resolution
Great for point sources!



- Use muon neutrinos to do astronomy
- Atmospheric neutrino and atmospheric muon events are primary background
- Design event samples to include large amount of background, use statistical methods to identify clustering near source candidates

Publicly Available IceCube Data

IceCube has release 10 years of data for public use: [link](#)

- ~1 million events between 2008 and 2018
- Astrophysical muon neutrinos, atmospheric muon neutrinos, and atmospheric muons
- Slightly different selection processes above/below $\text{dec}=5^\circ$
- Tabulated effective areas and smearing matrices included to describe detector response
- Arxiv document describing the sample properties: <https://arxiv.org/pdf/2101.09836.pdf>

Can be used for non-point-source studies as well!

All-sky point-source IceCube data: years 2008-2018

Posted on January 26, 2021

Introduction

IceCube has performed several searches for point-like sources of neutrinos. The events contained in this release make up the sample used in IceCube's 10-year time-integrated neutrino point source search [1]. Events in the sample are track-like neutrino candidates detected by IceCube between April 2008 and July 2008.

The data contained in this release of IceCube's point source sample shows 3.3σ evidence of a cumulative excess of events from a catalogue of 110 potential sources, primarily driven by four sources (NGC 1068, TXS 0506+056, PKS 1424+240, and GB6 J1542+6129). NGC 1068 gives the largest excess and appears in spatial coincidence with the hottest spot in the full Northern sky search [1].

IceCube's 10-year neutrino point source event sample includes updated processing for events between April 2012 and May 2015, leading to differences in significances of some sources, including TXS 0506+056. For more information, please refer to [2].

This release contains data beginning in 2008 (IC40) until the spring of 2018 (IC86-VII). In order to standardize the release format of IceCube's point source candidate events, this release duplicates and supplants previously released data from 2012 and earlier. Events from this release cannot be combined with other IceCube public data releases.

Data release

Suggested citation for this dataset:

IceCube Collaboration (2021): All-sky point-source IceCube data: years 2008-2018. Dataset. DOI: <http://doi.org/DOI:10.21234/sxvs-mt83>

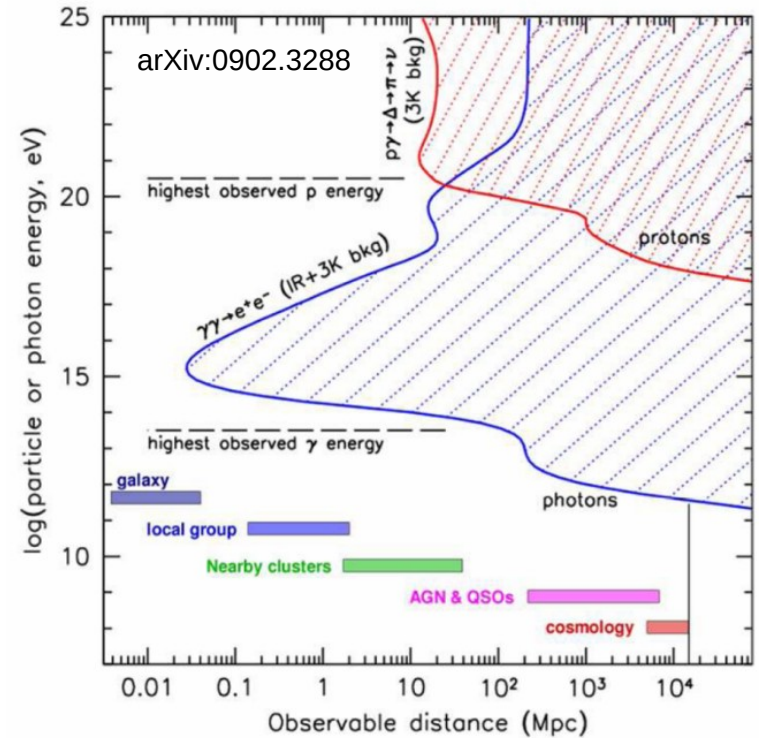
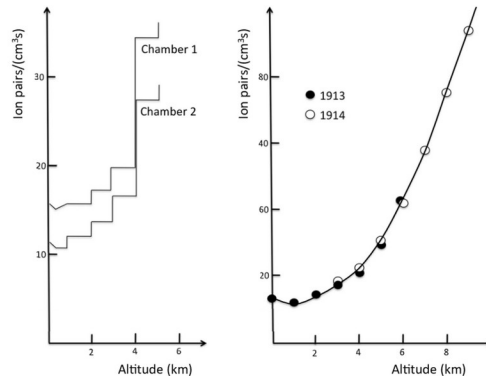
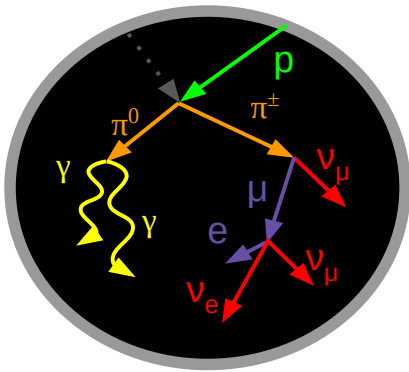
Click [here](#) to download (.zip, 35 MB)

Included in the download are the following files:

Data files

What Is TXS 0506+056 and Why Are We Talking About It?

- If we identify an astrophysical neutrino point source, it must also be a source of cosmic rays
 - The source of cosmic rays has been an open question since 1912 (!)
- Neutrinos would allow us to explore regions of the universe opaque to other messengers



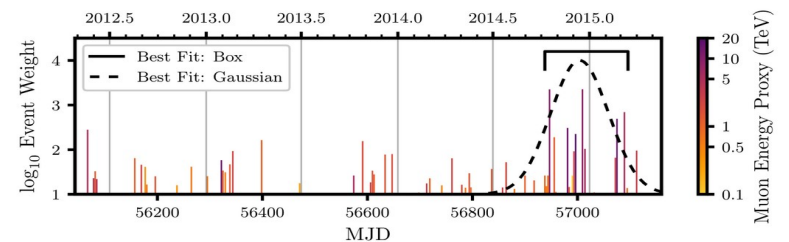
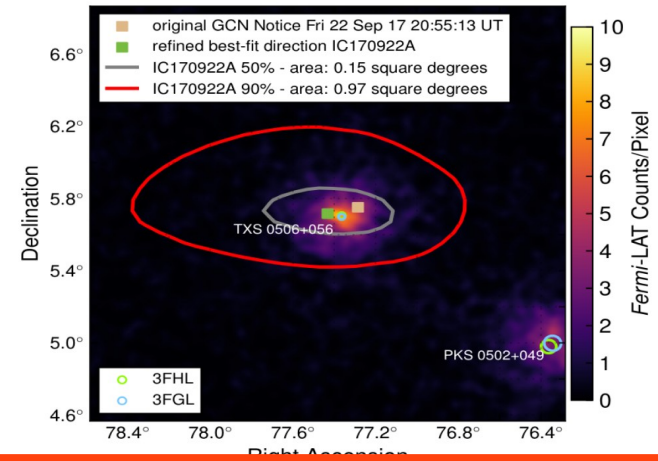
What Is TXS 0506+056 and Why Are We Talking About It?

- **2017 high energy neutrino alert event from the direction of TXS 0506+056**

- 3 sigma coincidence of EHE alert with multi-messenger data

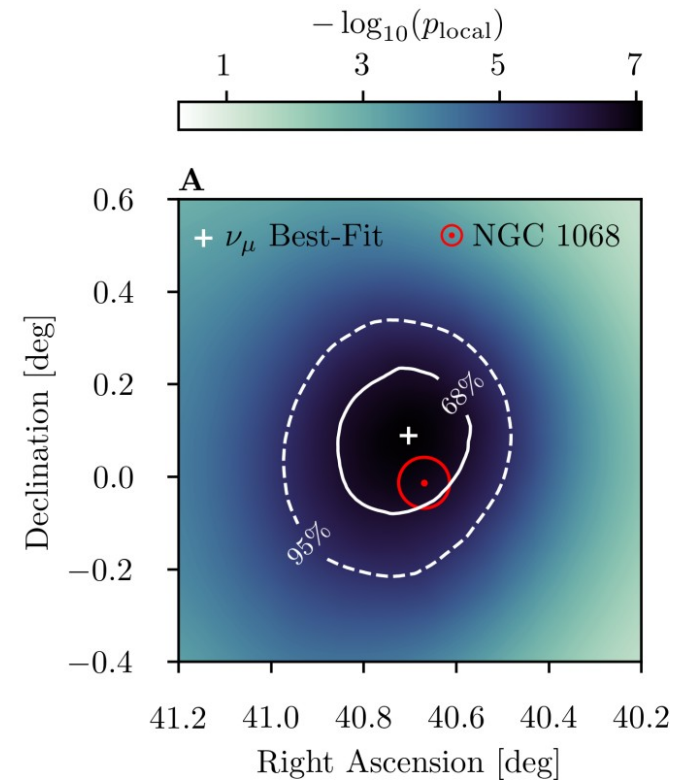
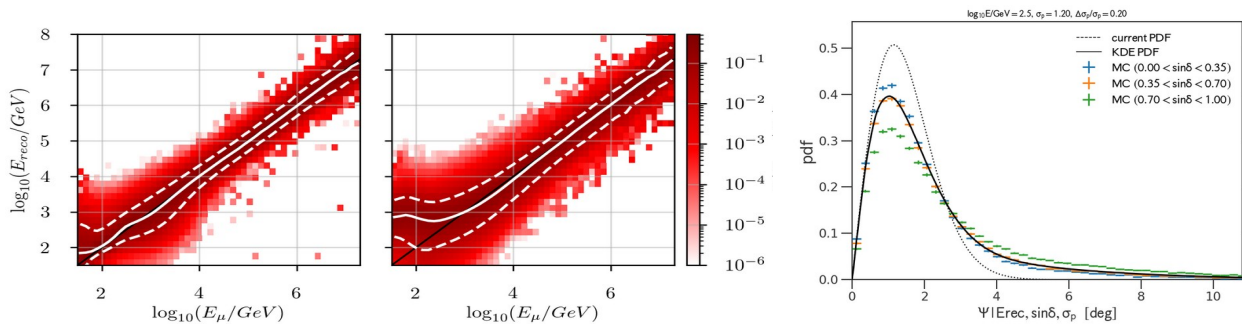
- **Archival follow-up at this location identifies elevated emission in 2014/15**

- 3.5 sigma significance for the 2014/15 flare candidate

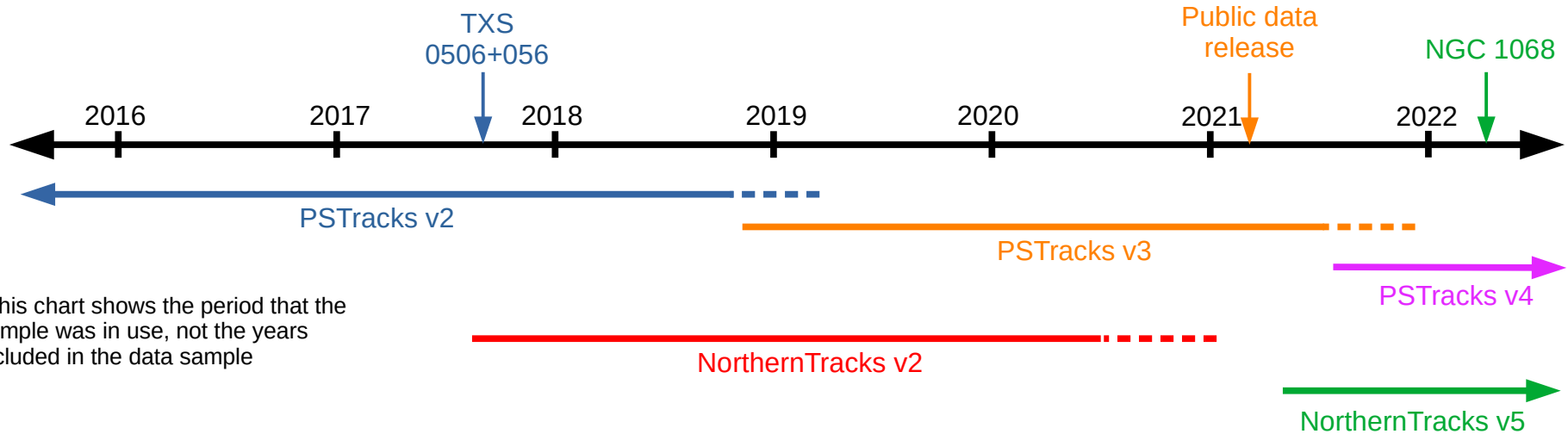


Updates Since the Original TXS 0506+056 Result

- Recalibration of detector response (“Pass 2”)
- Misreconstructed cascade-like background events removed
- DNN based energy reconstruction
- Improved angular error description via KDEs*
- **Another source candidate (NGC 1068)!**



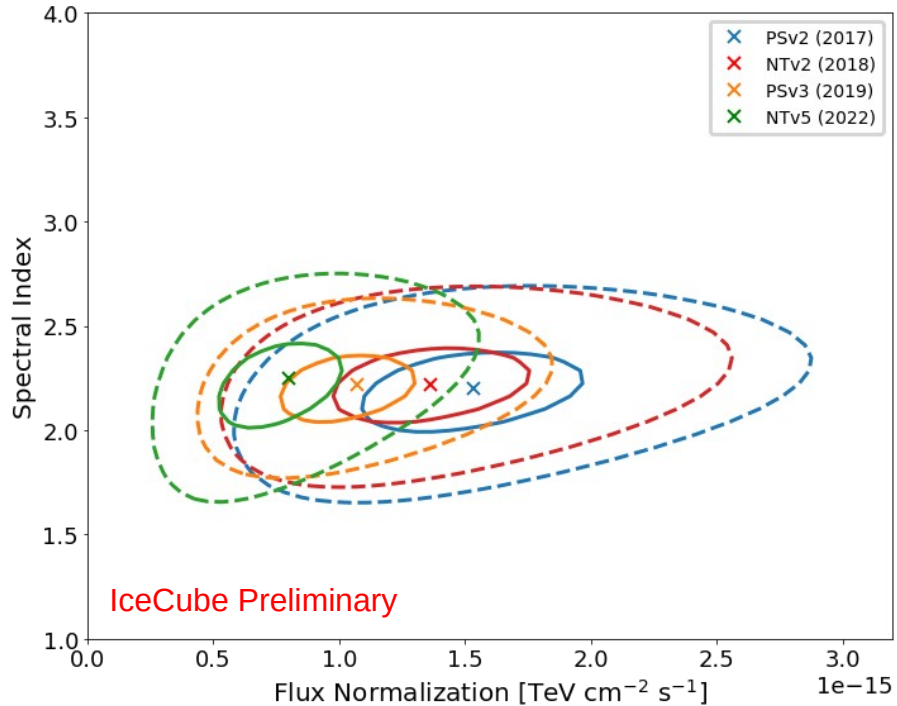
Event Samples Timeline



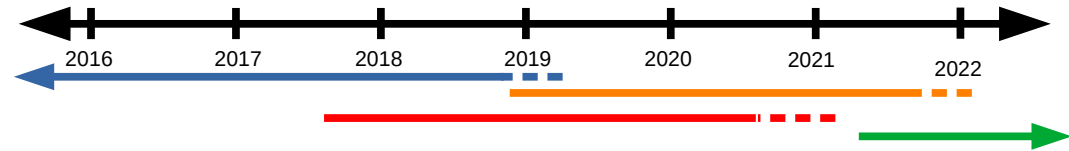
*This chart shows the period that the sample was in use, not the years included in the data sample

- Names not important, just note the progression
- Newer samples have large (but not complete) overlap with older ones
- Many different approaches with similar goals
- This list isn't even complete! There are event selections targeted at cascades, starting tracks, double cascades, atmospheric nu, and many more!

TXS 0506+056 Through The Years



- Fitted flux normalization lower in newer samples
- Best fit # of signal events: ~ 14 (original) $\rightarrow 9$ (newest)
- Spectral index fairly constant



Takeaways

Use our public data!

<https://icecube.wisc.edu/science/data-releases/>

- IceCube analyses are hard, consult an IceCuber before publishing anything dramatic

IceCube's data samples/methods have changed a lot over the past ~decade

- These changes matter!
- Lots of space for improvement, even with just the current livetime
- Old results are not incorrect!

Newer methods give updated flux fits TXS 0506+056

- Not inconsistent with previous samples
- Should keep an eye on TXS 0506+056 as we improve our data/methods
- We're getting better at neutrino astronomy! Better flux fits and more sources=more opportunity for exciting science!

13 Sep 2022

TUM-HEP 1418/22

New constraints on the dark matter-neutrino and dark matter-photon scattering cross sections from Blazar constraints on neutrino-dark matter scattering

Francesc Ferre
¹Department of Physics
²Physik-Department, Te

James M. Cline, Shan Gao, Fangyi Guo, Zhonghan Lin, Shiyao Liu, Matteo Puel, Phillip Todd, and Tianzhuo Xiao
McGill University, Department of Physics, 3600 University St., Montréal, QC H3A2T8 Canada

Neutrino emission in astrophysics with gamma-ray has been observed from the blazar TXS 0506+056 associated with a high-energy neutrino. The detection of such a neutrino implies a function of DM mass. The cross section rises linearly as high as possible, depending on details

THE ASTROPHYSICAL JOURNAL LETTERS, 863:L10 (10pp), 2018 August 10
© 2018. The American Astronomical Society.
<https://doi.org/10.3847/2041-8213/aad083>

OPEN ACCESS

The Blazar TXS 0506+056 Associated with a High-energy Neutrino: Insights into Extragalactic Jets and Cosmic-Ray Acceleration

S. Ansoldi^{1,2}, L. A. Antonelli¹, C. Arcaro¹, D. Baack⁵, A. Babic⁶, B. Banerjee⁷, P. Bangale⁸, U. Barres de Almeida^{8,24}, J. A. Barrio⁹, J. Becerra González¹⁰, W. Bednarek¹¹, E. Bernardini^{4,12,13}, R. Ch. Berse³, A. Berti^{1,25}, J. Besenrieder⁸, W. Bhattacharyya^{1,2}, C. Bigongiari³, A. Biland¹⁴, O. Blanch¹⁵, G. Bonnoli¹⁶, R. Carosi¹⁷, G. Ceribella⁸, A. Chatterjee⁸, S. M. Colak¹, P. Col
P. Da Vela¹⁰, F. A. Dominguez⁸, D. A. Fattorini¹, A. Fernández S. Gallozzi¹, R. J. G. D. Hadasch², A. Hahn¹

Dimuons in Neutrino Telescopes: New Predictions and First Search in IceCube

Bei Zhou^{1,*} and John F. Beacom^{2,3,4,†}
¹William H. Miller III Department of Physics and Astronomy, IFIC/17-52

Neutrino tomography of the Earth

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¹Instituto de Física Corpuscular, CSIC-Universitat de València, Apartado de Correos 22085, E-46071 València, Spain
²Institut de Ciències del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain

Cosmic-ray interactions with the nuclei of the Earth's atmosphere produce a flux of neutrinos in all directions with energies extending above the TeV scale [1]. However, the Earth is not a fully transparent medium for neutrinos with energies above a few TeV. At these energies, the charged-current neutrino nuclear cross section is large enough so that the neutrino mean free path in a medium with

Backup Slides

A History of Neutrino Astronomy in Antarctica



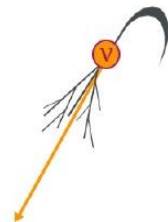
1988

Telescope in the Ice Envisioned



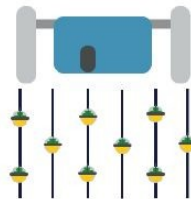
2000

AMANDA Completed



2001

Atmospheric Neutrinos Detected



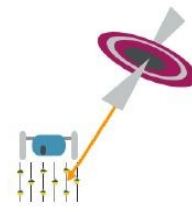
2011

IceCube Completed



2013

Astrophysical Neutrinos Discovered



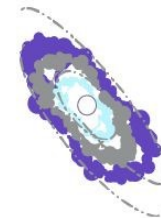
2018

First Source TXS 0506+056 Identified



2021

Glashow Resonance Neutrino Identified

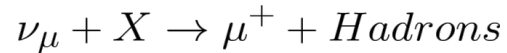
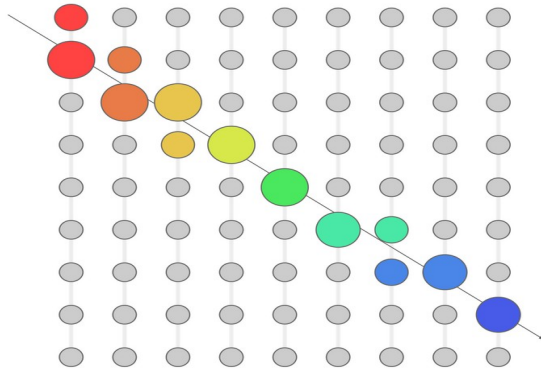


2022

Second Source NGC 1068 Identified

IceCube Event Types

Track

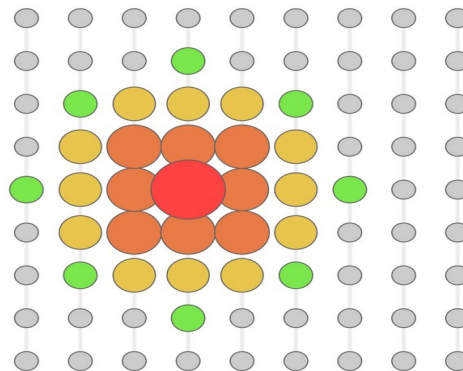


Factor of ~2 energy resolution

< 1 degree angular resolution

Great for point sources!

Cascade

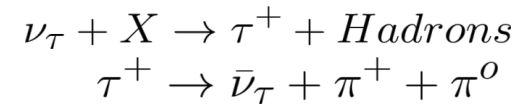
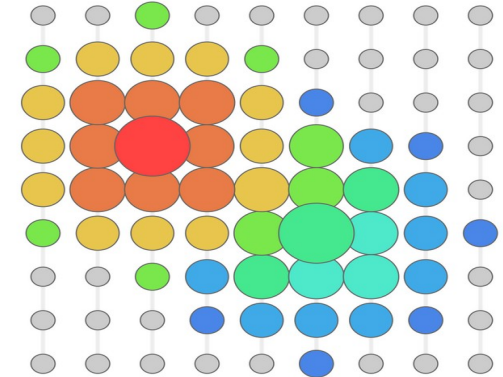


15% deposited energy resolution

~10 degree angular resolution above 100 TeV

Great for extended sources!

Double Cascade



Decay length is 50m/PeV

Mostly look like cascades

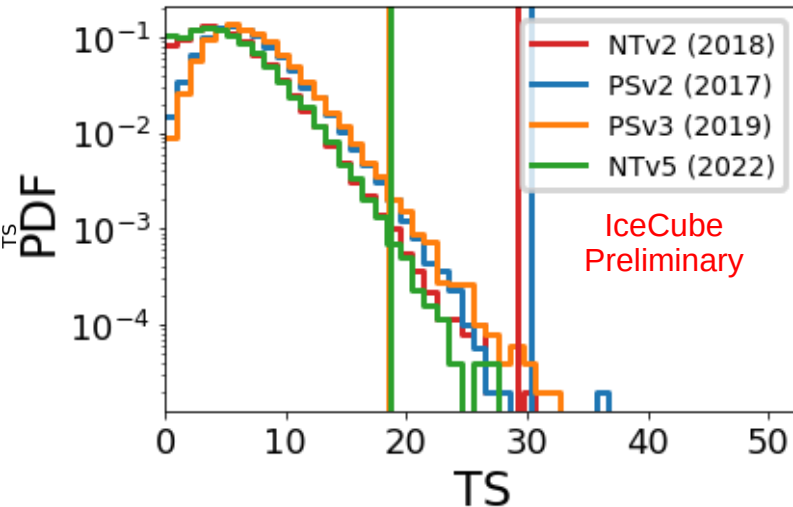
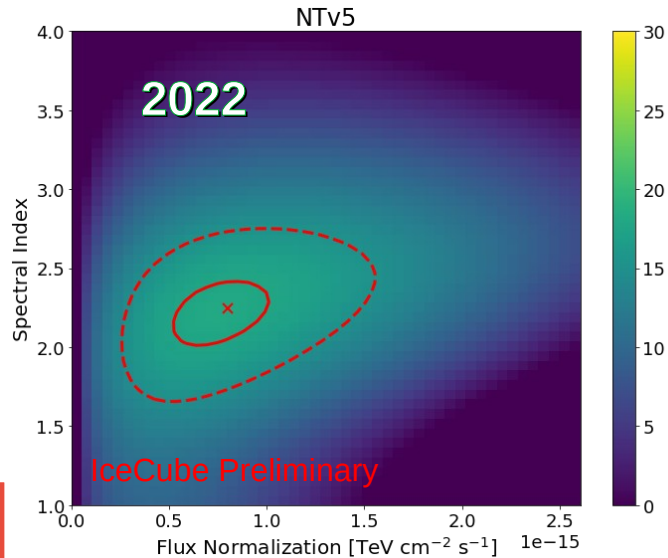
Too rare to be of much use for source searches

Early \longrightarrow Late



TXS 0506+056 Through The Years

	T_{start}	T_{stop}	TS	n_s	γ	p	Flux ($\times 10^{-15} \text{ TeV}^{-1} \text{ cm}^{-1} \text{ s}^{-1}$)
PSv2 (2017)	56937.81	57096.22	30.34	14.39	2.20	$7e-5$	1.6
NTv2 (2018)	56927.86	57096.20	29.14	14.07	2.22	$6.8e-5$	1.44
PSv3 (2019)	56927.86	57116.76	18.52	11.87	2.22	$8e-3$	1.07
NTv5 (2022)	56927.86	57091.33	18.7	9.21	2.24	$1e-3$	0.76

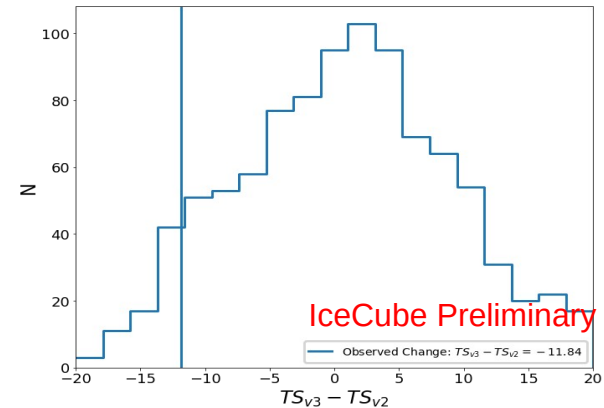
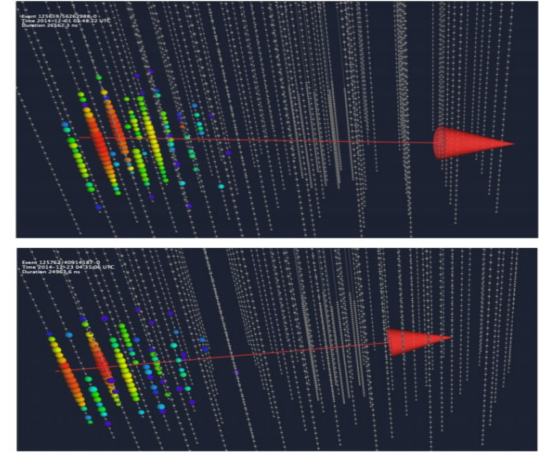


*Reminder: These checks with updated data are not blind; each row in the table is highly correlated with the others

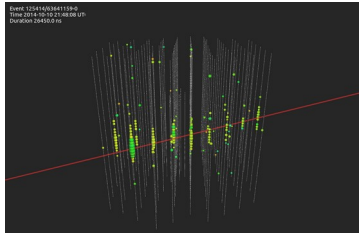
This is Unsurprising

Older event sample contains cascade events that were originally misidentified as tracks

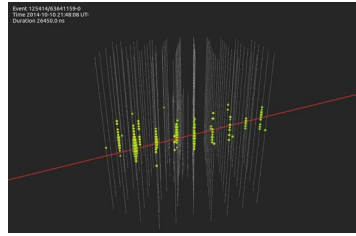
- These events previously handled by the likelihood instead of the event selection
- See <https://arxiv.org/abs/2101.09836> for more details
- Newer results are still consistent with older results



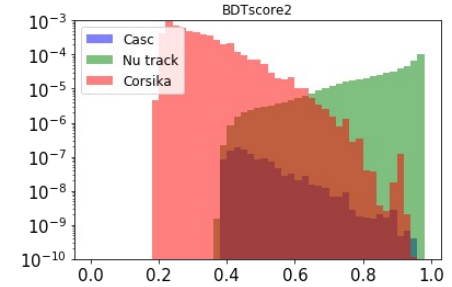
How IceCube Data Becomes a (Point Source) Result



Raw data



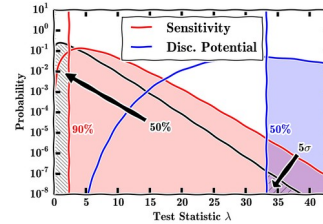
Hit cleaning and reconstruction



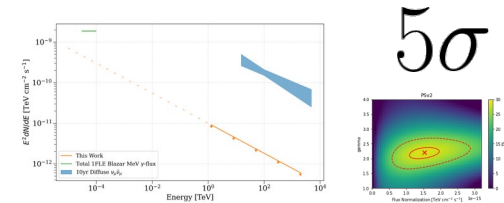
Event classification and selection

$$\mathcal{L}(n_s) = \prod_{i=1}^N \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right]$$

Evaluate likelihood

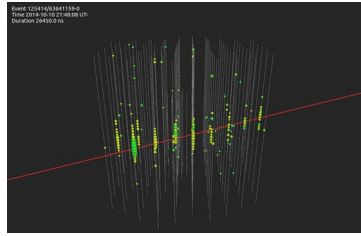


Calculate TS and significance



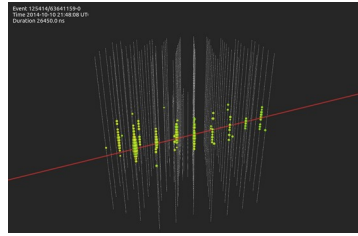
Report significance/flux fit or upper limits (and maybe have a press conference)

How IceCube Data Becomes a (Point Source) Result

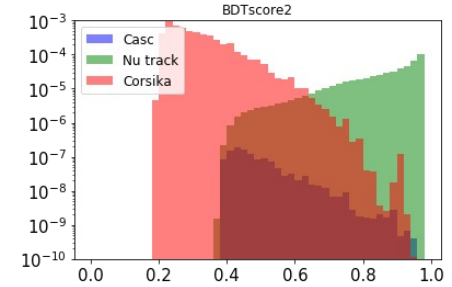


Raw data

“Standardized”



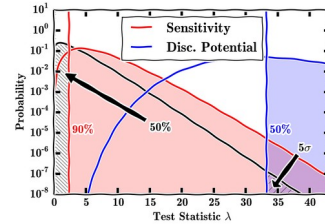
Hit cleaning and reconstruction



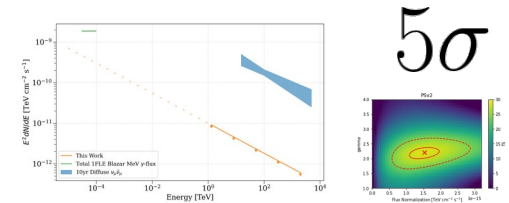
Event classification and selection

$$\mathcal{L}(n_s) = \prod_{i=1}^N \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right]$$

Evaluate likelihood



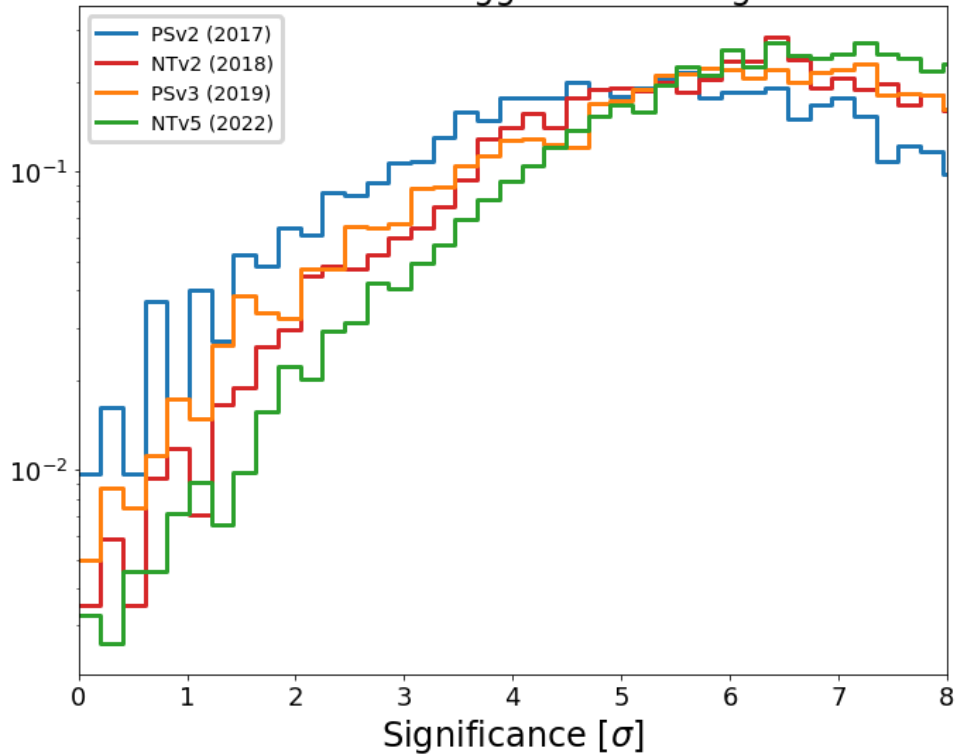
Calculate TS and significance



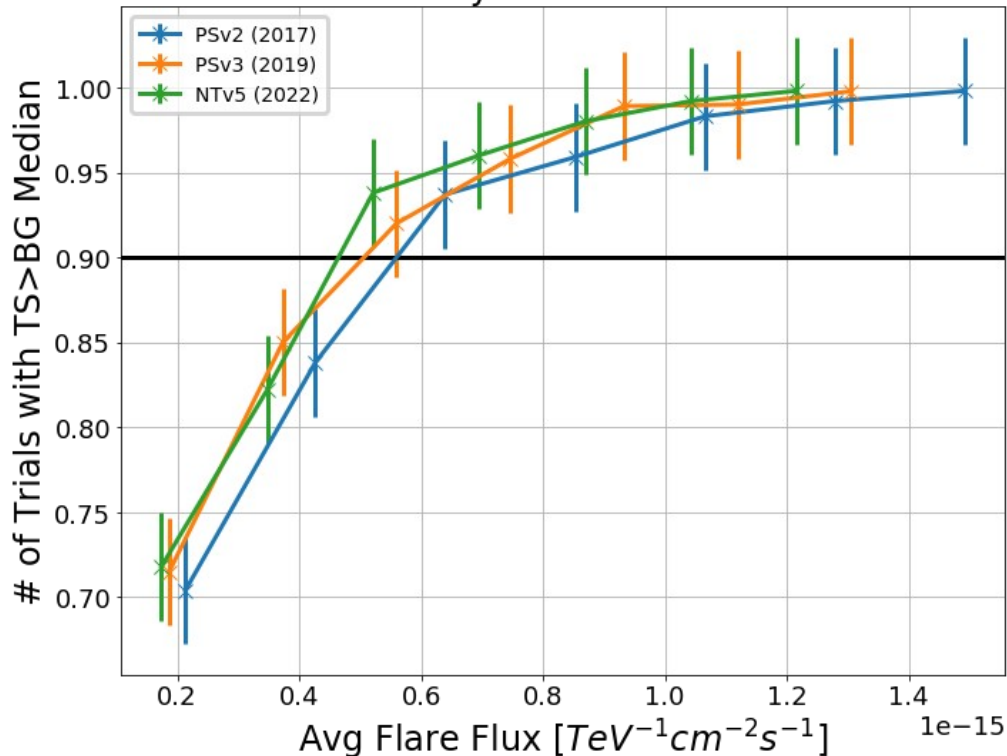
Report significance/flux fit or upper limits (and maybe have a press conference)

We're Getting Better at This (At Least a Little)

TXS 0506+056 Untriggered Flare Significance



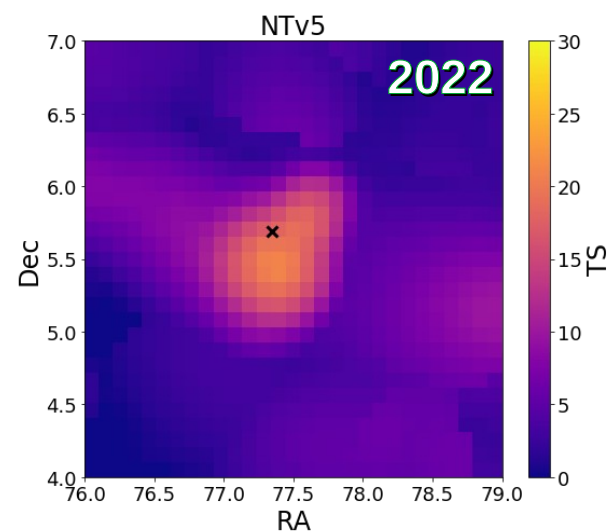
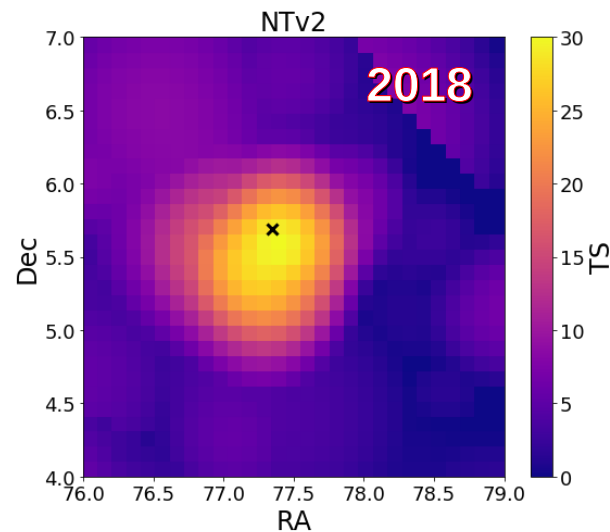
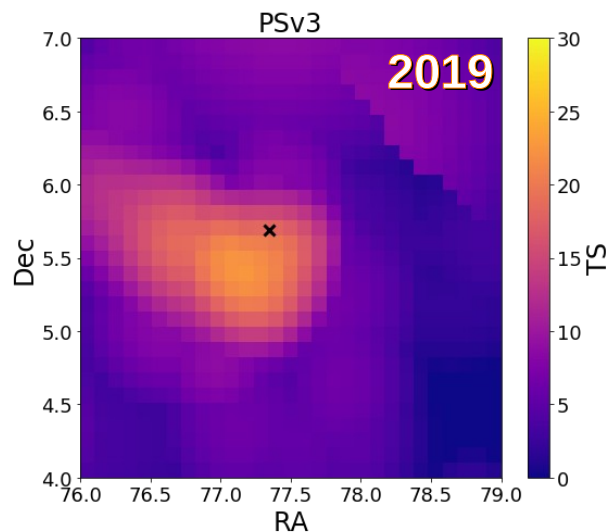
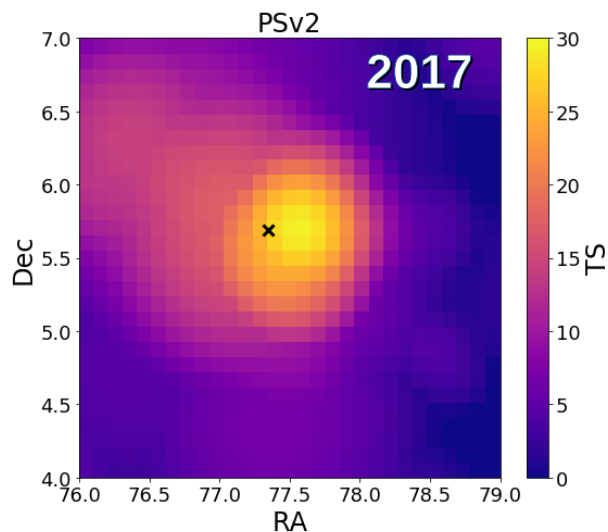
Sensitivity to a TXS-like Flare



Event Samples Comparison

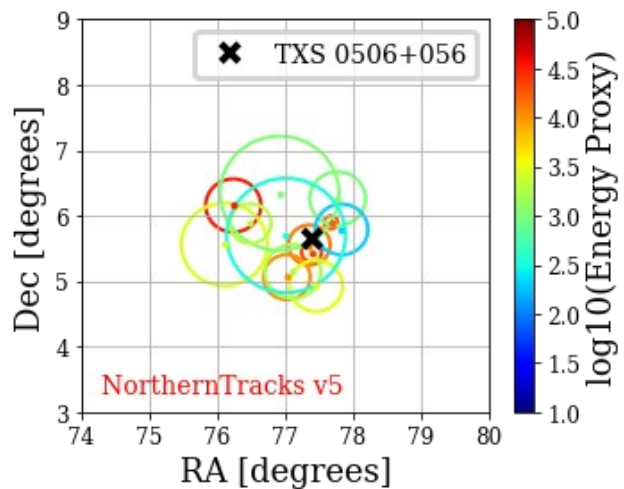
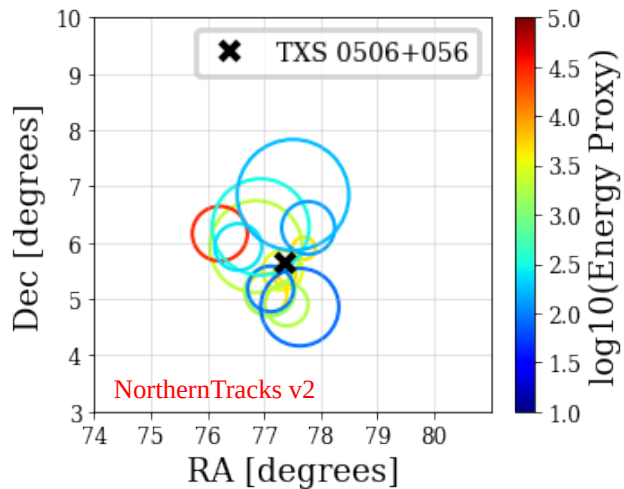
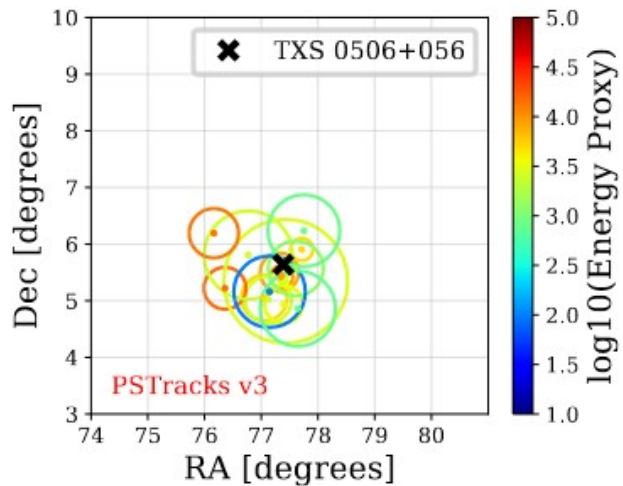
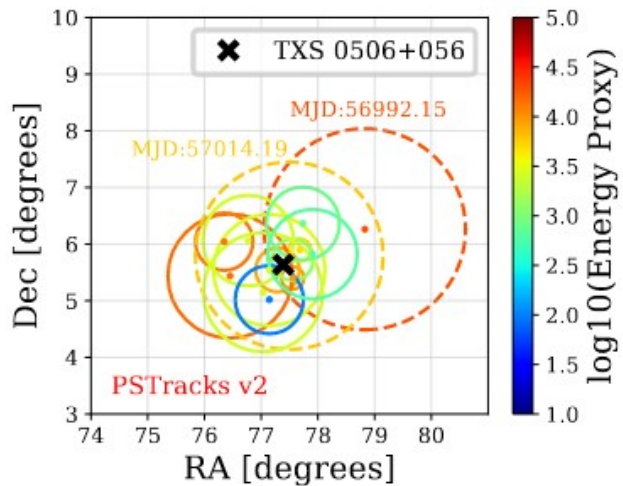
Publicly available

	PSTracks v2	PSTracks v3	NorthernTracks v2	NorthernTracks v5
Processing	Pass 1	Pass 1	Pass 1	Pass 2
Pre-cuts	No	Yes	Yes	Yes
BDT 1	Selects tracks	Selects tracks and rejects cascades	Selects tracks	Selects tracks
BDT 2	None	None	Rejects cascades	Rejects cascades
Signal training set	Simulation	Simulation	Simulation	Simulation
Background training set	Data	Data	Simulation	Simulation
Direction reconstruction	SplineMPE (“plain”)	SplineMPE (“plain”) × 2	SplineMPE (“max”)	SplineMPE (“max”?)
Angular error estimator	Paraboloid	Paraboloid	Paraboloid	KDE
Energy estimator	MuEX	MuEX	TruncatedEnergy	DNN
DeepCore included?	Yes	Yes	No	No
Livetime	7 years (2008-2014)	10 years (2008-2017)	8 years (2009-2016)	11 years (2011-2021)
Declination Range	$-90^\circ < \delta < 90^\circ$	$-90^\circ < \delta < 90^\circ$	$-5^\circ < \delta < 90^\circ$	$-5^\circ < \delta < 90^\circ$
Events	711,878	1,134,451	493,252	794,301

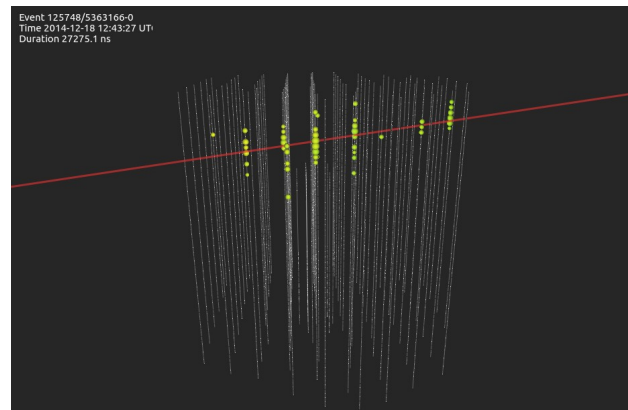
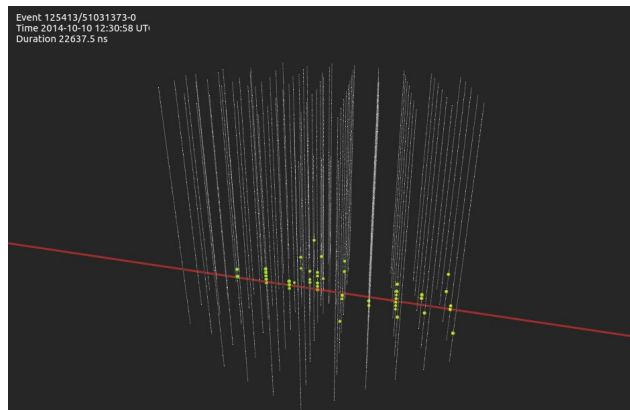
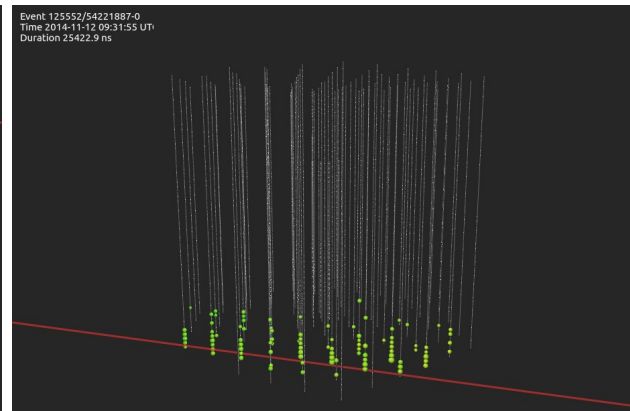
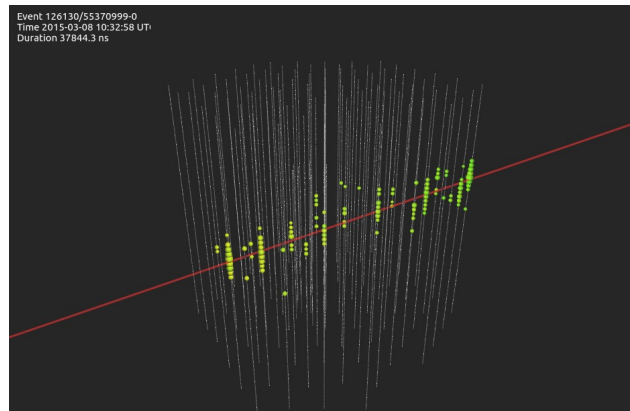
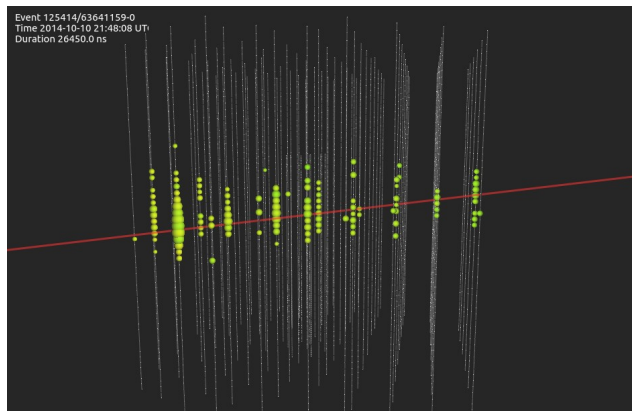


→ Hotspot is slightly dimmer in newer samples

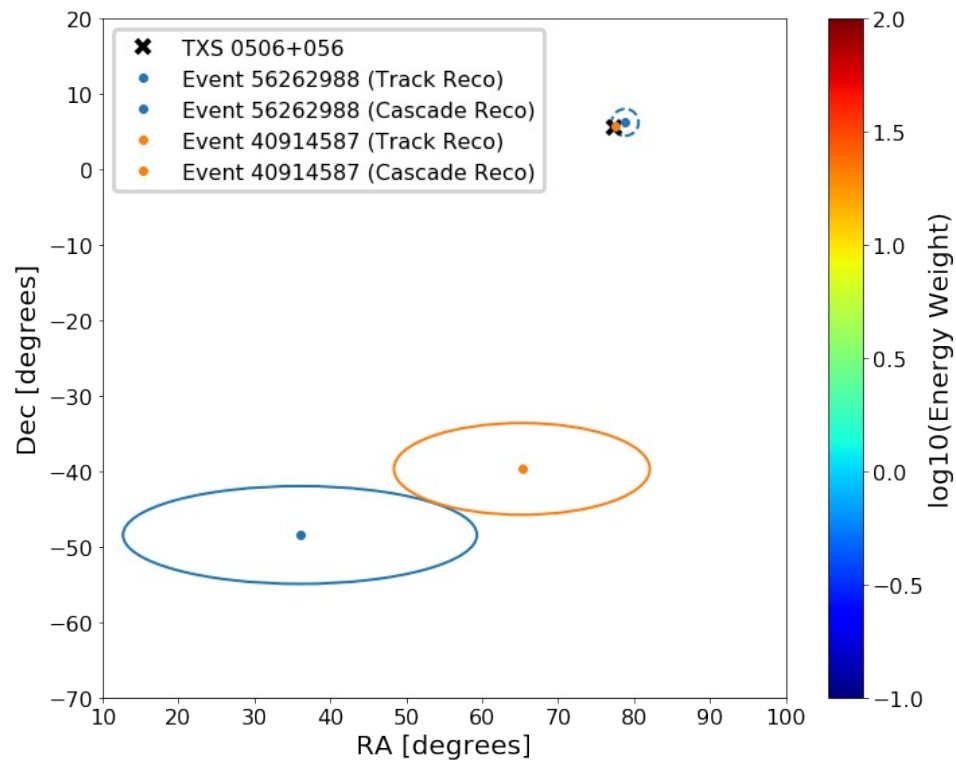
→ Small shift in overall position in PSv2 → v3 move was probably because of removal of misreconstructed cascades



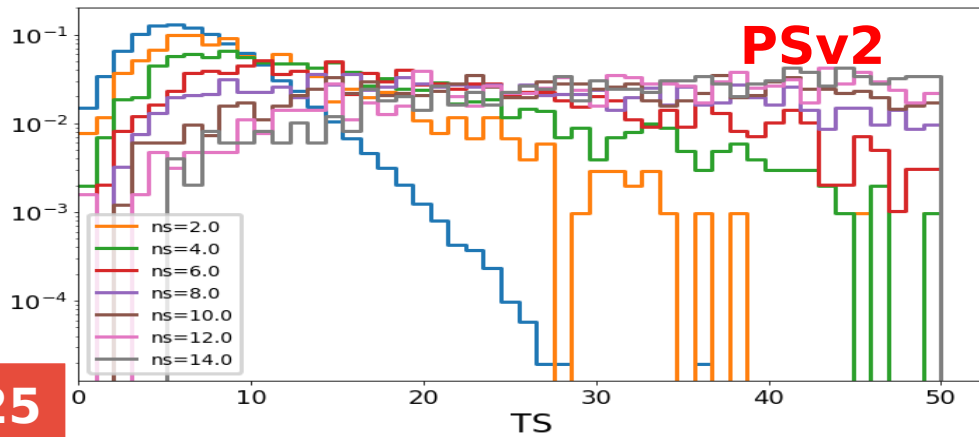
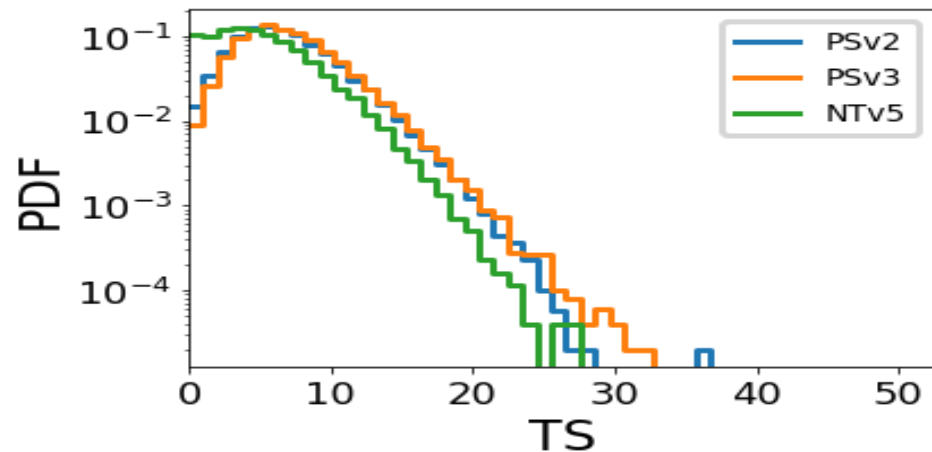
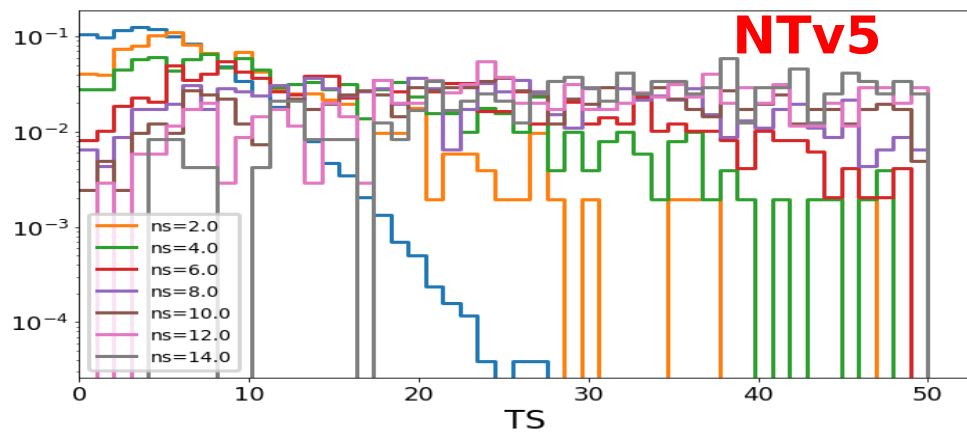
Event Views



“But what if you reconstructed them as cascades?”



NTv5 TS Distributions



Reminder: Fitted Parameter Distributions

→ Fit bias plots show the median, but remember there's an underlying distribution at each point

→ It is entirely possible to do everything correctly and end up with fitted parameters that are very different from what was injected

