For the IceCube collaboration

image credit

IceCube Search for High Energy Neutrino Emission from X-ray Bright Seyfert Galaxies

Shiqi Yu, U of Utah/MSU
Theo Glauch, TUM
Ali Kheirandish, UNLV
Tomas Kontrimas, TUM
Qinrui Liu, Queen's U
Hans Niederhausen, MSU

TeVPA Chicago 2024

August 27th, 2024

TeVPA 2024, U of Chicago, U.S.

Science **378**,538-543(2022)

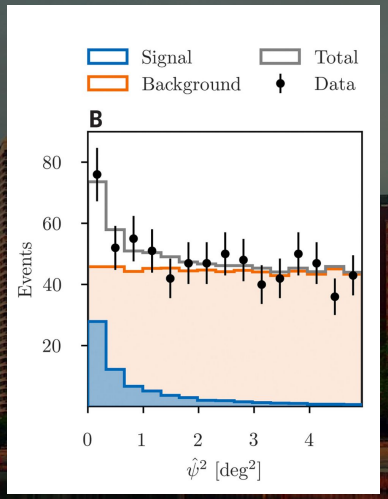
Motivation: NGC 1068

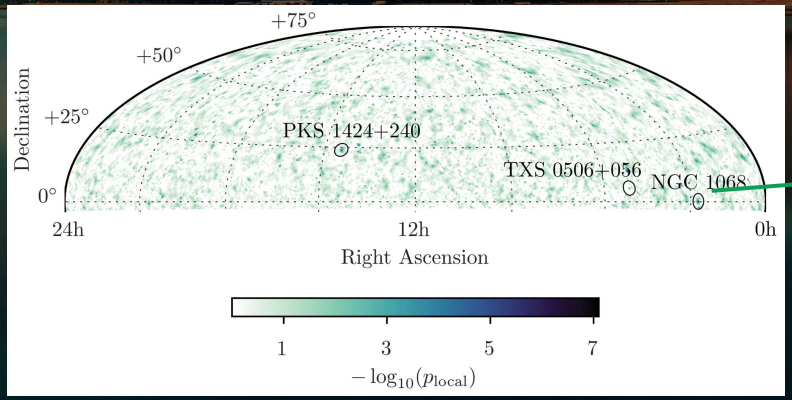
All-sky scan found hot spot at NGC 1068 location.

In catalog search (110 sources), at NGC 1068:

- ➢ 79 candidates; spectral index = 3.2 ± 0.2
- ➢ single source significance 5.2 σ (local)

4.2 σ post-trial significance of evidence!





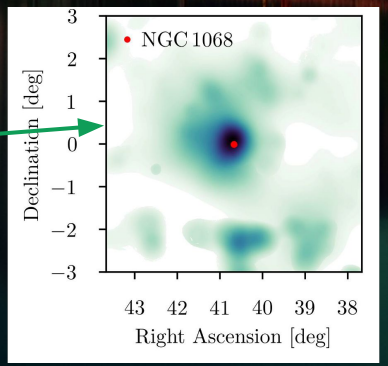
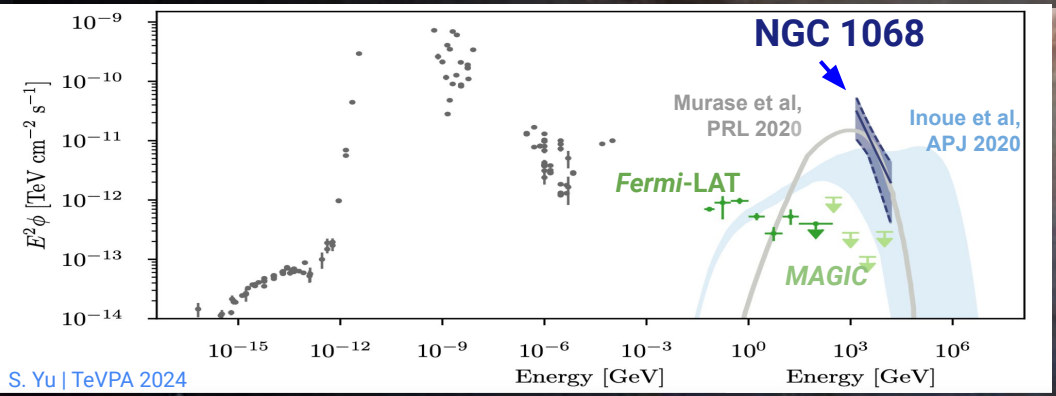


Image credit: NASA

Why NGC 1068?

- Seyfert galaxy
- Compton thick environment, column density ~10^{25} cm^{-2}
- High level of star formation
- Bright in X-ray
- High-energy gamma-ray likely to be obscured
- Proposed possible source of high-energy CR and neutrinos: *Silberberg, Shapiro (1979, 1983)*



Where could neutrinos be produced?

Murase and Stecker arXiv:2202.03381

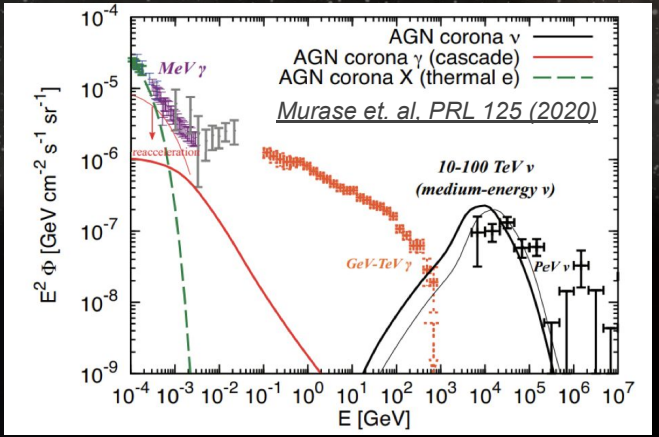
- starburst activity
- AGN outflows/winds
- faint jet
- AGN core region (e.g. corona)

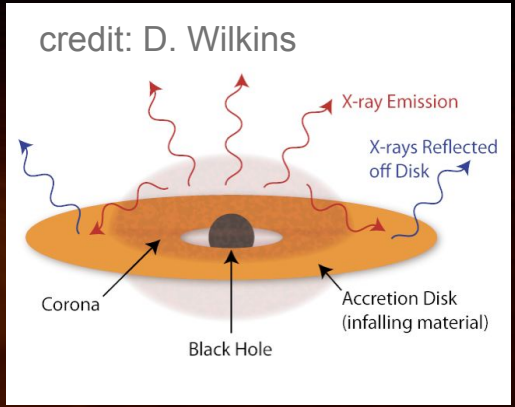
Find more similar sources! More model-dependent studies on neutrino emission are needed!

Image credit: NASA/JPL-Caltech

Disk-corona Model

- In Seyfert galaxies, magnetized coronae are formed due to accretion and magnetic dissipation;
- The disk-corona model* suggests coronae are best neutrino source candidates where ions are accelerated while high-energy gamma rays are absorbed;
- Intrinsic X-ray luminosity is used to predict neutrino flux: $L_\nu \propto L_{\text{X-ray (intrinsic)}}$





Bright X-ray emission

*Kheirandish+ ApJ 2021

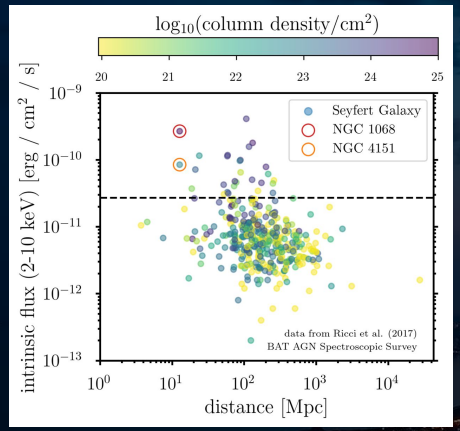
Source Selection

The BAT AGN Spectroscopic Survey

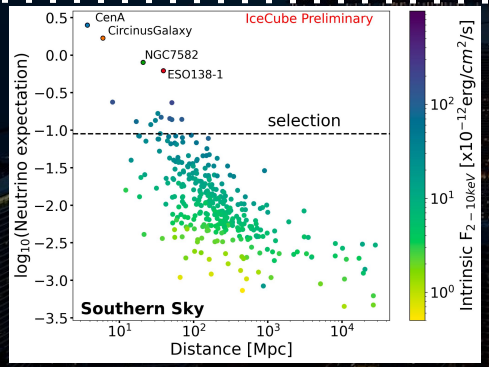
An all-sky study of the brightest and most powerful hard X-ray detected AGN

Select from BASS
- ➔ Seyfert Galaxies
- ➔ Bright in 2-10 keV X-ray

27 (+NGC 1068) sources

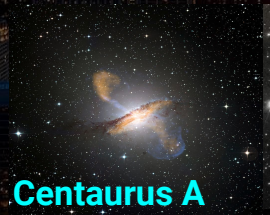


Northern Sky



Southern Sky

14 sources



arXiv:2406.07601

image credit

Northern Sky

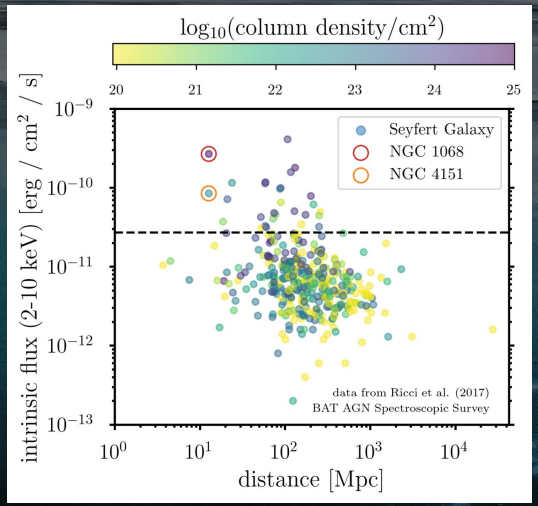
- Same Northern Sky Muon Track sample as IceCube Science 2022 with ~1.7 yr more data (~20% increase in statistics);
  - See talk by Tomas, Aug 26th, TeVPA2024

Catalog:

- Disk-corona model vs. power-law spectrum

Stacking:

- Disk-corona model with weights = n_{exp}

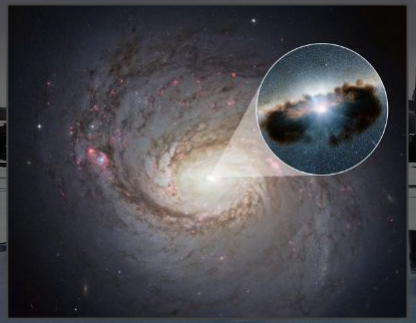


* NGC 1068 is excluded (27 sources) to avoid bias.

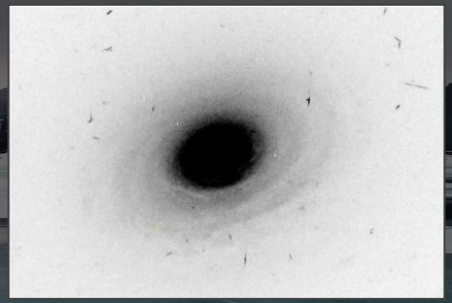
arXiv:2406.07601

Northern Sky Result Highlight

In addition to NGC 1068, 2 sources have pre-trial significances above 3σ.



NGC 1068
~14 Mpc
~7 $\mathrm{Log}(M_{BH}/M_{\odot})$
$\mathrm{LogL_X}^{2\text{-}10keV}$~42.9 erg/s
(NuSTAR and XMM-Newton:
$\mathrm{LogL_X}^{2\text{-}10keV}$~43.8 erg/s)



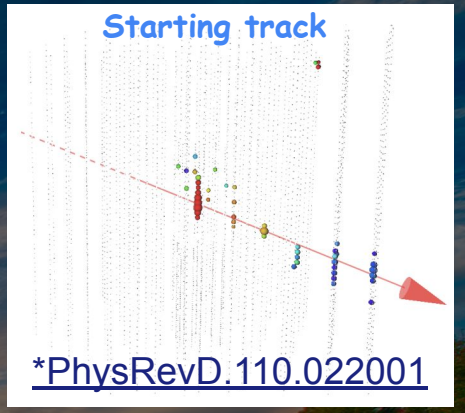
CGCG 420-015
~130 Mpc
~8.3 $\mathrm{Log}(M_{BH}/M_{\odot})$
$\mathrm{LogL_X}^{2\text{-}10keV}$~44 erg/s

NGC 4151
~16 Mpc
~7.6 $\mathrm{Log}(M_{BH}/M_{\odot})$
$\mathrm{LogL_X}^{2\text{-}10keV}$~42.3 erg/s

Image credit: Fermilab

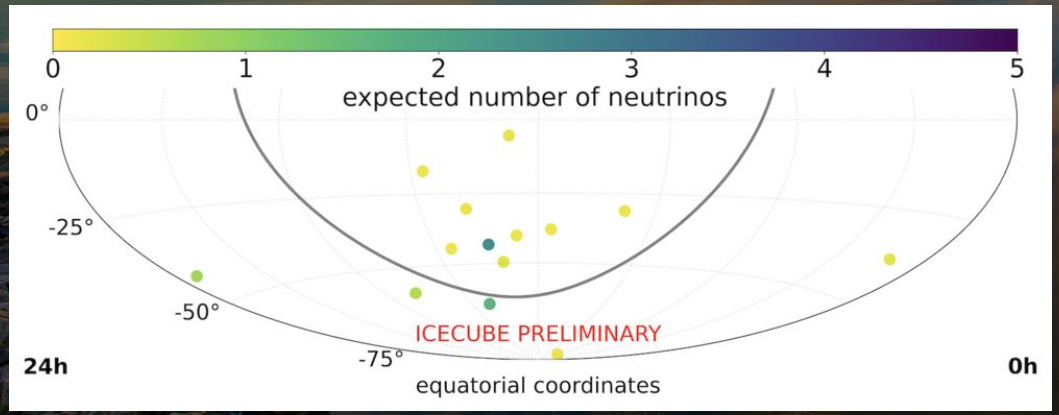
Southern Sky Analyses

- Use starting track events (ESTES sample)*
- Improved analysis methods are applied:
  - Some sources are close to the galactic plane
  - Mask out galactic plane region (+/- 10 deg) before background scrambling
  - Inject Monte-Carlo events using IceCube result** as the realization of galactic plane



*PhysRevD.110.022001

**Science 380,1338-1343(2023)



Catalog:

- Disk-corona model vs. power-law spectrum

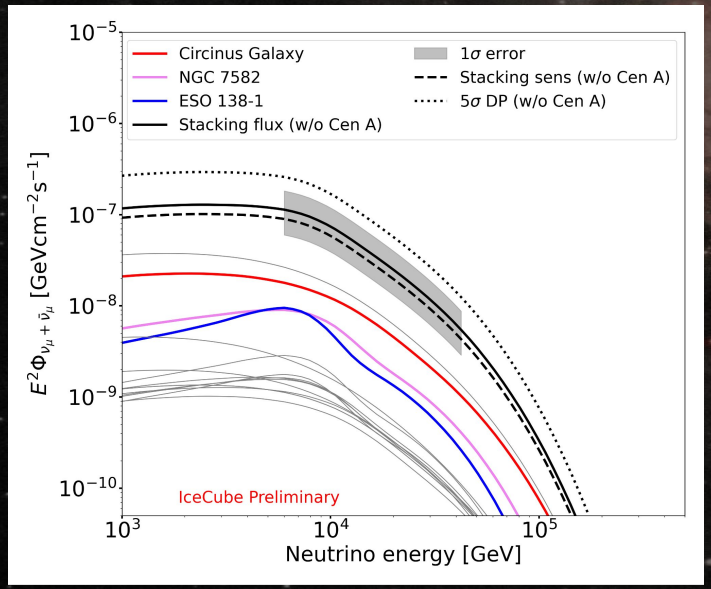
Stacking*:

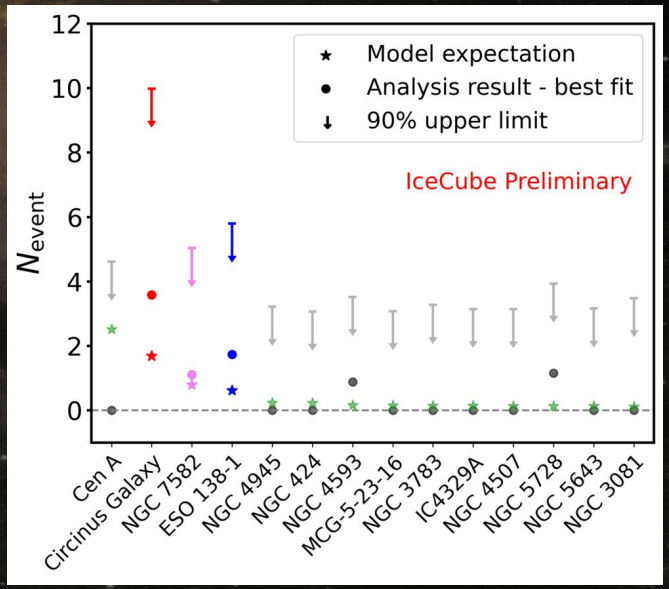
- Disk-corona model with weights = n_{exp}

* CenA is excluded from stacking to avoid bias.

Southern Sky Results: stacking & catalog

- 3.0σ excess (ns=6.7) in stacking using model flux and expectations as weights (shade shows error)
  - Top three sources (excluding CenA) have mild excess





Southern Sky Result: Catalog Search

- See mild excess from the top three sources in the selected catalog with both flux assumptions;
- Southern hemisphere suffers from low-statistics.

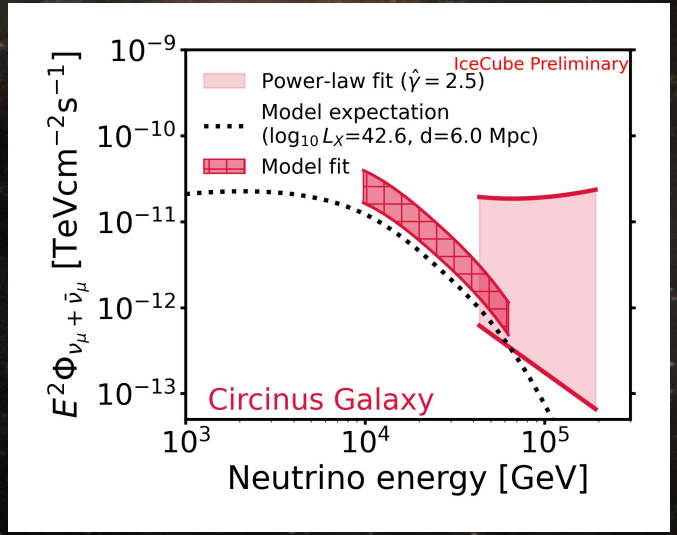
	$n_{\rm exp}$	TS	$\hat{n}_{\rm s}$	$\hat{\gamma}$	$p_{\rm local}$	$p_{\rm global}$	90% U.L.
Disk-corona							n_{event}
Circinus Galaxy	1.7	6.7	3.6	–	$0.003\,(2.7\,\sigma)$	$0.042\,(1.7\,\sigma)$	10.0
ESO 138-1	0.6	3.0	1.7	–	$0.03\,(1.9\,\sigma)$	–	5.7
NGC 7582	0.8	1.4	1.1	–	$0.05\,(1.6\,\sigma)$	–	5.1
Power-law							$\Phi(\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 1TeV)
Circinus Galaxy	–	10.4	3.1	2.5	$0.001\,(3.1\,\sigma)$	$0.017\,(2.1\,\sigma)$	63.8×10^{-11}
NGC 7582	–	1.7	1.7	4.0	$0.05\,(1.6\,\sigma)$	–	25.6×10^{-11}
ESO 138-1	–	3.0	1.9	3.6	$0.06\,(1.6\,\sigma)$	–	29.7×10^{-11}

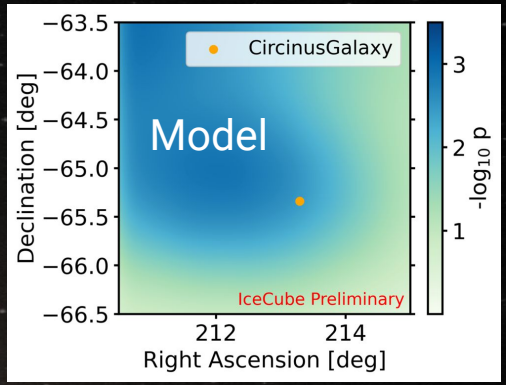
Hottest source: 3.1σ -> 2.1σ (14 sources)=> post-trials 1.8σ (2 flux assumptions)

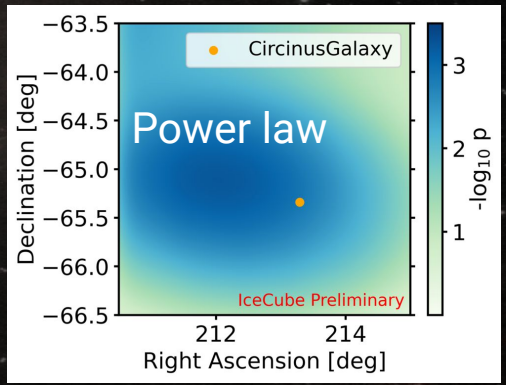
Southern Sky Result: Circinus Galaxy

Circinus Galaxy has pre-trial significance at 3σ using power-law flux.

- ~6 Mpc
- ~11 $\mathrm{Log}(M_{BH}/M_{\odot})$
- X-ray luminosity of $\mathrm{Log}L_X^{2\text{-}10\mathrm{keV}}$ ~42.6 erg/s
- $L_\gamma/L_X < 3.1\%$







Southern Sky Result: Discussions

- There are no individual bright sources from the catalog search result using ESTES sample in the Southern hemisphere likely due to limited statistics;
  - A follow-up analysis will combine the cascade and starting track events aim to improve the discovery potential in the Southern hemisphere.
- Using disk-corona model in stacking shows 3.0σ excess suggests there might be a population of Seyfert as candidates of cosmic-ray accelerator.

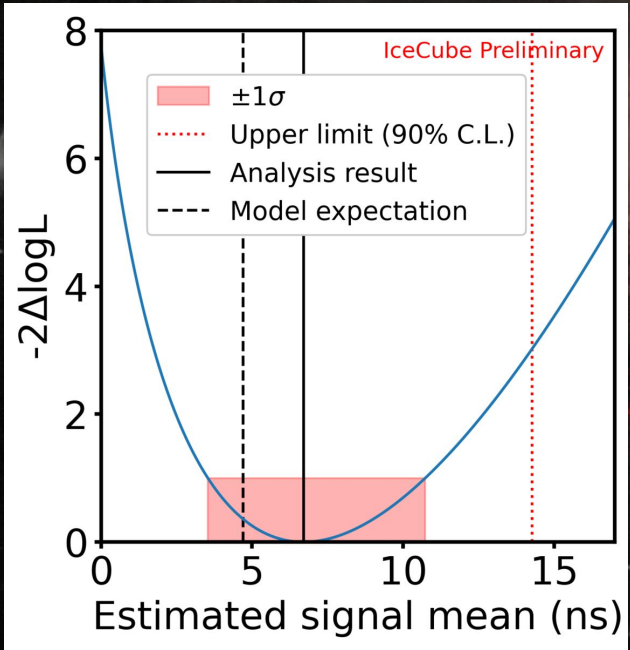
Summary and Outlook

- ➔ Disk-corona model is employed in catalog and stacking searches to study high-energy neutrino emission from X-ray bright Seyfert galaxies.
- ➔ In Northern hemisphere: arXiv:2406.07601
  - ◆ Catalog search hints two additional sources: NGC 4151 and CGCG 420-015 with 2.7σ while no significant excess observed in stacking search;
    - More high-energy neutrino sources in other IceCube talks *See talks by Tomas (Aug 26) and Sreetama (Aug 29)
- ➔ In Southern hemisphere:
  - ◆ 3.0σ excess from stacking search while no significant excess observed with the individual;
    - Suggests emerging picture of X-ray bright Seyfert galaxies as candidates of cosmic-ray accelerator.
  - ◆ **Follow-up analysis** combines cascade and track events aim to improve the searching sensitivity.
- ➔ Future identification is promising with input from **multi-messenger data** and **next-generation** neutrino telescopes.

Thank you!

Overflow slides

Southern Sky Result: Stacking



Best-fit ns: 6.7

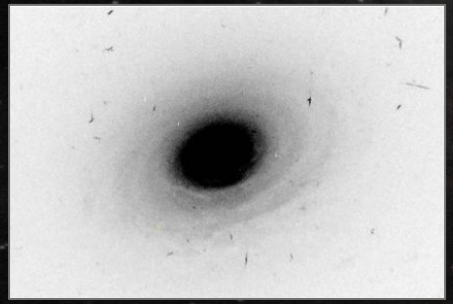
1σ error: [3.5, 10.7]

U.L.: 14.3

Significance: 3.0 sigma

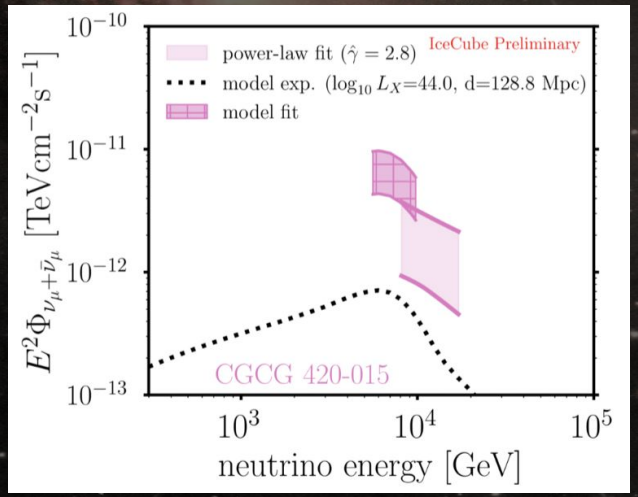
1σ error: [3.002, 3.006]

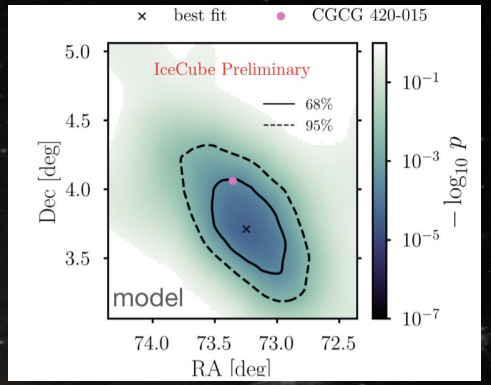
Northern Sky Result: CGCG 420-015

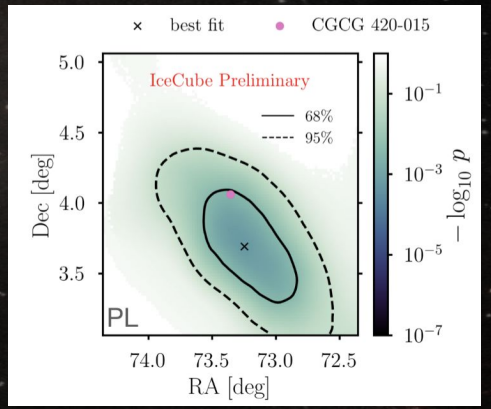


- Quite far (~130 Mpc)
- Supermassive BH: 2×10^8 $M_\odot$
- High X-ray luminosity ($LogL_X^{2\text{-}10keV}$ ~44 erg/s)
- Compton thick, highly obscured

- Model fit finds better significance and localization.
- The best-fit flux is a factor of ~10 larger than the expectation





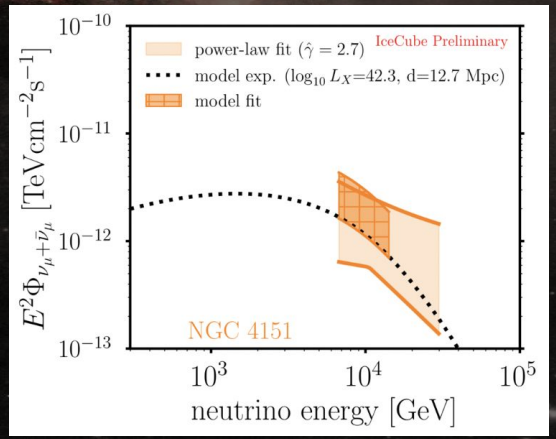


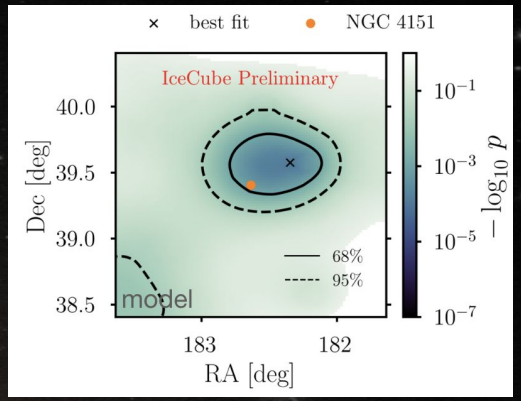
Northern Sky Result: NGC 4151

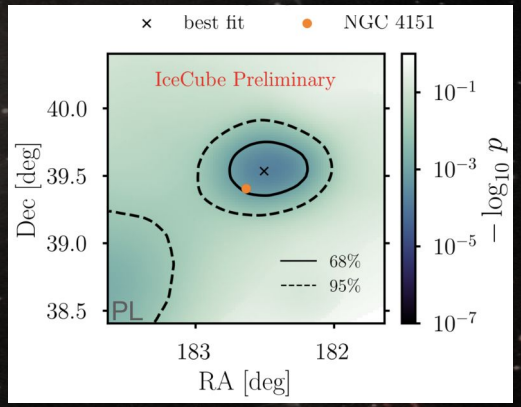
- Most significant in power-law analysis, comparable significance in both flux assumptions.
- Also seen in hard X-ray catalog*

*See talks by Tomas (Aug 26) and Sreetama (Aug 29)

- ~16 Mpc
- ~4×10^7 $M_\odot$
- X-ray luminosity of $\mathrm{Log}L_X^{2\text{-}10\mathrm{keV}}$ ~42.3 erg/s
- $L_\gamma / L_X < 0.25\%$







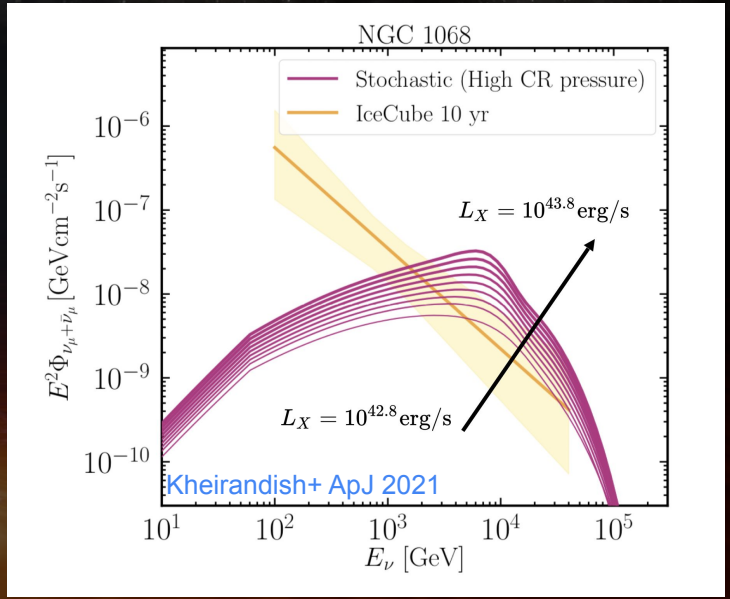
Northern Sky Result: Stacking

	spectral model	$n_{\rm exp}$	TS	$\hat{n}_{\rm s}$	$\hat{\gamma}$	$p_{\rm local}$	$p_{\rm global}$	$n_{\rm UL}$
Stacking Searches								
Stacking (excl.)	disk-corona	154	0.1	5	–	$2.4 \times 10^{-1}\,(0.7\,\sigma)$	$2.4 \times 10^{-1}\,(0.7\,\sigma)$	51.1
Stacking (incl.) (*)	disk-corona	199	11.2	77	–	$1.1 \times 10^{-4}\,(3.7\,\sigma)$	–	128

- **No significant emission** is found in the stacking search excluding NGC 1068.
- The upper limit constrains the collective emission to ~30% of the expectation.

Disk-corona Model

- Neutrino flux predictions based on the High CR pressure scenario of the disk-corona model.
  - Most promising for identification with current data.
- Thermal X-ray luminosity serves as the proxy of CR injection and neutrino emission: $L_\nu \propto L_\gamma \propto L_{CR}$
  - Spectra normalized by CR pressure.
  - CR injection function: $F_{p,\,inj} \propto f_{inj} L_{X\text{-ray}}$
  - Injection fraction: CR to thermal ratio $f_{inj} \propto P_{CR}/P_{th}$
    - CR to thermal pressure ratio



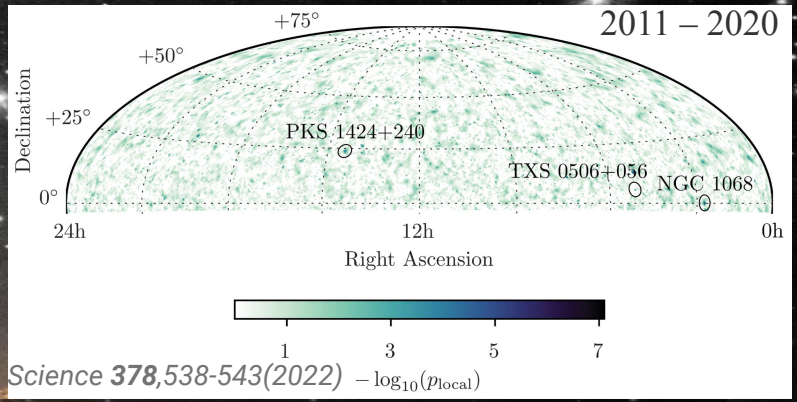
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

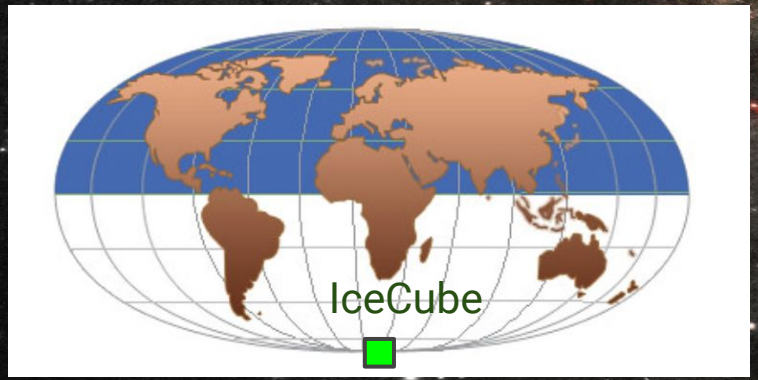
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

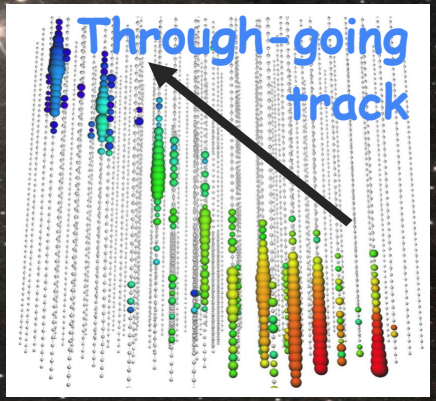


Science **378**,538-543(2022)

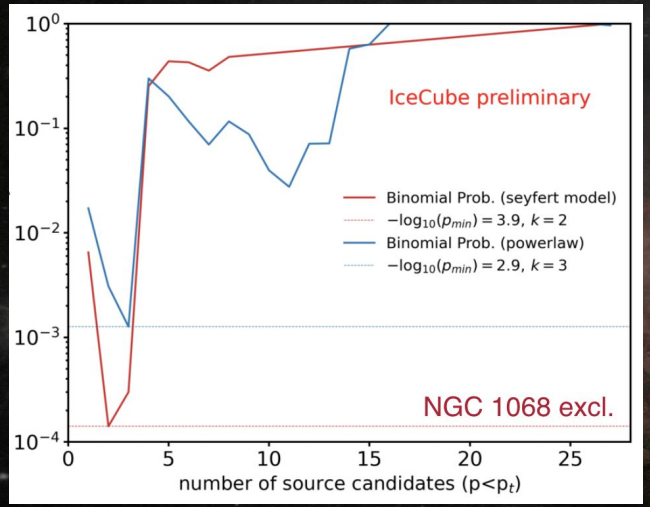
Motivation: NGC 1068



Earth absorption helps removing muon background



Northern Sky Result: Binomial Test



- The significance of observing an excess of k sources with local p-values below or equal to a chosen threshold p_k for the two flux assumptions analyzed.
- Optimized to search for a smaller number of emitters in a source list.

- Larger significance with the model fit
- 2.9σ excess in the binomial test using model fit
  - k=2: *CGCG 420-015* and *NGC 4151*
  - 2.7σ of post-trial significance

*Would be 4σ if NGC 1068 was included

Northern Sky Result: Discussions

- It's possible that some Seyfert galaxies have similar flux to NGC 1068 but not all. More flux assumptions (extending to high-energy) can be tested with next-generation neutrino telescopes (Gen-2, for example).

- Intrinsic X-ray flux measurements have large uncertainties on galaxies with high column densities, which affect neutrino expectations and weights in stacking.
  - e.g. for NGC 1068, NuSTAR & XMM-Newton report higher $L_{X\text{-}ray}$ than BASS, which leads to more moderate CR pressure which will reduce the expectations of other sources.

- Need more studies on the multi-wavelength emission to find more sources and verify the neutrino flux models.

Northern Sky Results

				model				powerlaw				
Source	DEC	RA	$F^{\rm intr}_{2-10{\rm keV}}$	$n_{\rm exp}$	$\hat{n}_s$	-$\log_{10}p$	$n_{\rm UL}$	$\hat{n}_s$	$\hat{\gamma}$	-$\log_{10}p$	$\phi^{E^{-2}}_{90\%}$	$\phi^{E^{-3}}_{90\%}$
NGC 1068	−0.0	40.7	268.3	44.5	47.5	6.5	61.4	94.1	3.3	7.1	8.5	39.0
NGC 4388	12.7	186.4	71.7	21.4	0.0	0.0	13.0	2.0	1.9	0.9	3.9	16.7
NGC 6240	2.4	253.2	411.1	16.8	0.0	0.0	13.4	0.0	4.3	0.0	1.5	5.8
NGC 4151	39.4	182.6	84.8	13.1	22.5	3.2	39.5	30.1	2.7	3.2	10.9	38.7
Z164-19	27.0	221.4	179.5	8.6	0.0	0.0	12.0	3.3	2.0	0.7	4.2	15.7
UGC 11910	10.2	331.8	157.5	8.5	0.0	0.0	12.9	6.4	4.3	0.3	2.2	8.5
NGC 5506	−3.2	213.3	115.6	8.1	0.0	0.0	9.0	0.0	1.6	0.0	1.9	6.4
NGC 1194	−1.1	46.0	117.8	7.6	4.4	0.6	15.2	27.7	3.7	0.9	2.9	13.1
Mrk3	71.0	93.9	113.6	7.4	0.0	0.0	10.9	0.0	4.3	0.0	4.4	11.4
MCG+8-3-18	50.1	20.6	99.4	6.3	0.0	0.0	10.8	0.0	4.3	0.0	3.3	9.3
UGC 3374	46.4	88.7	65.1	4.6	0.0	0.0	11.0	0.0	4.3	0.0	3.2	9.0
NGC 3227	19.9	155.9	37.2	4.0	0.0	0.0	14.5	0.0	1.7	0.0	2.1	6.8
4C+50.55	51.0	321.2	97.0	4.0	4.6	0.8	14.9	9.7	3.2	0.5	5.0	15.9
NGC 7682	3.5	352.3	47.9	4.0	2.3	0.7	18.8	0.0	4.3	0.0	1.6	6.2
IRAS05078+1626	16.5	77.7	46.1	4.0	0.0	0.0	12.2	0.0	4.3	0.0	2.0	6.9
2MASXJ20145928+2523010	25.4	303.7	78.6	3.8	0.0	0.0	11.9	0.0	4.3	0.0	2.3	7.6
Mrk 1040	31.3	37.1	40.6	3.7	0.0	0.0	11.7	32.9	4.3	0.9	5.1	19.1
LEDA136991	68.4	6.4	42.6	3.7	0.0	0.0	11.4	3.8	4.1	0.2	5.0	13.4
Mrk 1210	5.1	121.0	32.9	3.2	0.0	0.0	13.3	0.0	4.3	0.0	1.7	6.4
CGCG 420-15	4.1	73.4	50.5	3.2	30.7	3.6	46.4	35.5	2.8	2.5	5.2	25.9
MCG+4-48-2	25.7	307.1	31.6	3.1	22.1	2.3	31.8	45.2	3.2	2.1	7.2	29.0
3C111	38.0	64.6	61.5	3.1	0.0	0.0	11.6	15.7	4.3	0.5	4.2	13.6
UGC 5101	61.4	144.0	45.4	2.6	4.8	1.0	17.6	8.7	3.0	0.7	6.9	21.7
3C382	32.7	278.8	49.4	2.4	0.0	0.0	11.6	34.9	4.3	1.0	5.4	20.1
Mrk 110	52.3	141.3	34.4	2.1	0.0	0.0	10.9	0.0	4.3	0.0	3.4	9.6
3C 390.3	79.8	280.5	44.4	1.8	0.0	0.0	12.6	0.0	4.3	0.0	6.9	19.7
NGC 3516	72.6	166.7	30.7	1.6	0.0	0.0	11.8	30.0	4.3	0.6	8.8	26.0
Cygnus A	40.7	299.9	32.1	1.6	3.7	0.7	15.2	2.9	2.1	0.7	5.3	18.2

Intrinsic X-ray flux is

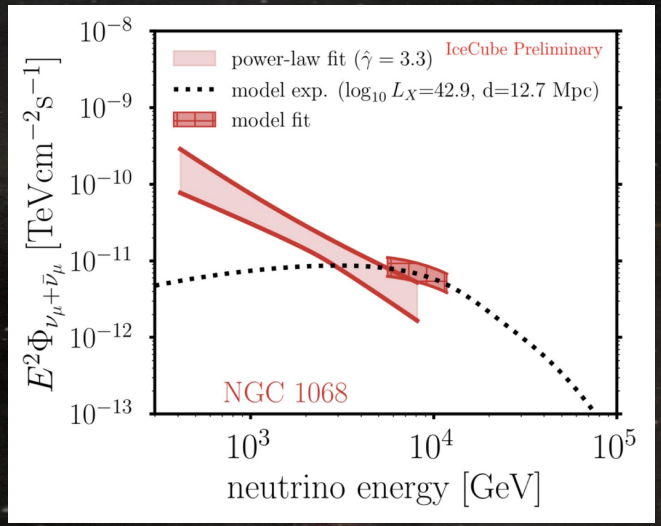
$$F^{\rm intr}_{2-10{\rm keV}} \times 10^{-12} {\rm erg\,cm^{-2}\,s^{-1}}$$

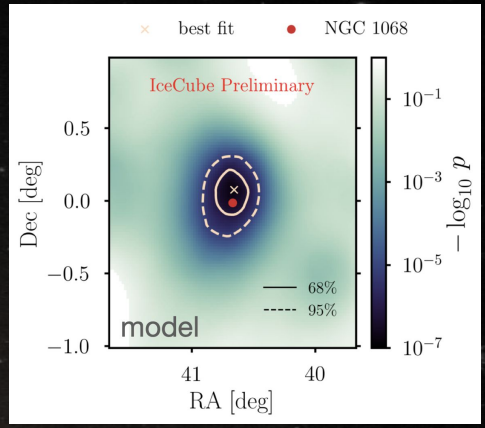
upper limit fluxes

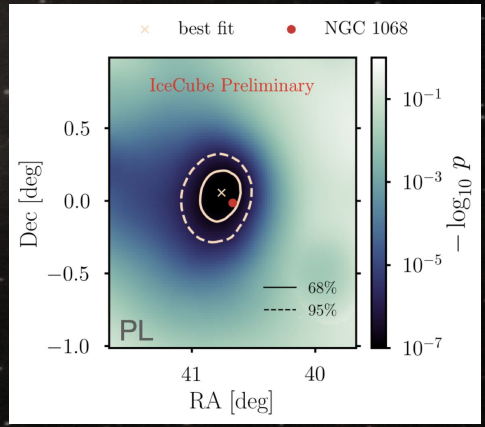
$$\phi^{-\gamma}_{90\%}\,(E/1{\rm TeV})^{-\gamma} \times 10^{-13}\,{\rm TeV^{-1}cm^{-2}\,s^{-1}}$$

Northern Sky Result: NGC 1068

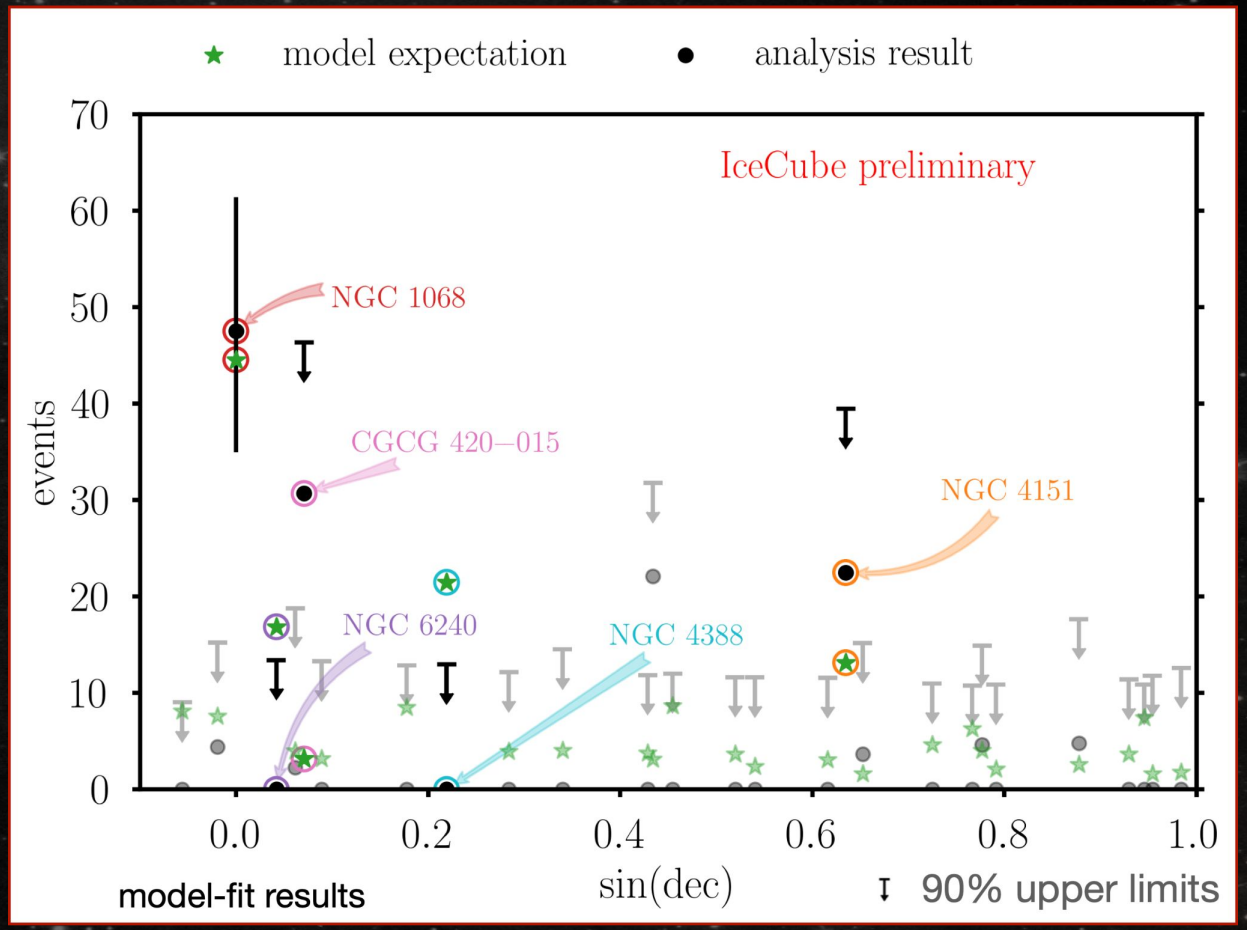
- ~14 Mpc
- ~10^7 $M_\odot$
- X-ray luminosity of $LogL_X^{2\text{-}10keV}$ ~42.9 erg/s



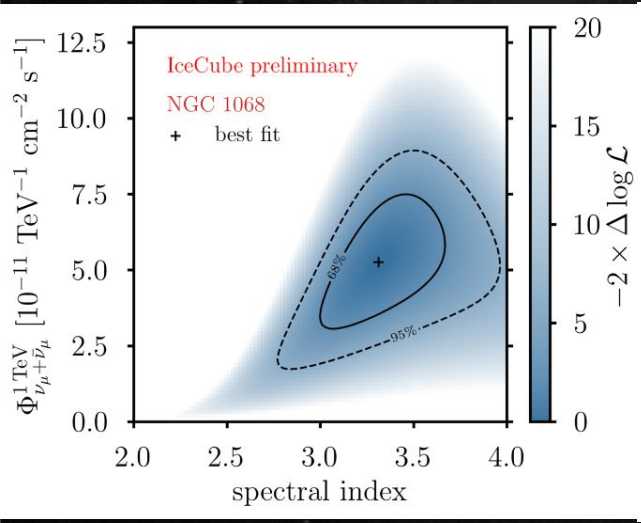


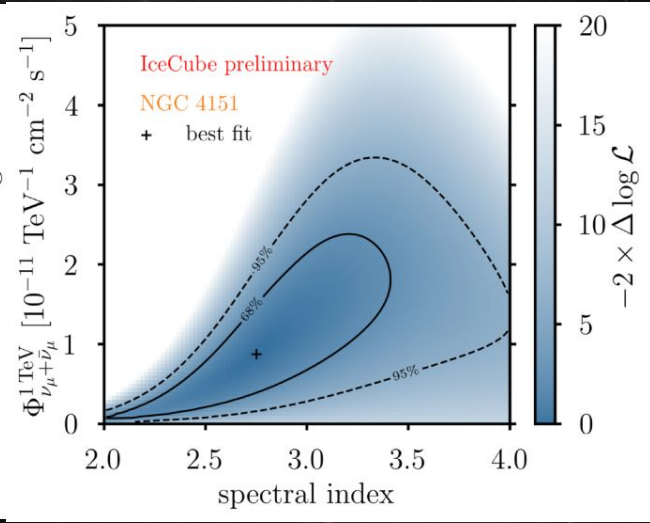


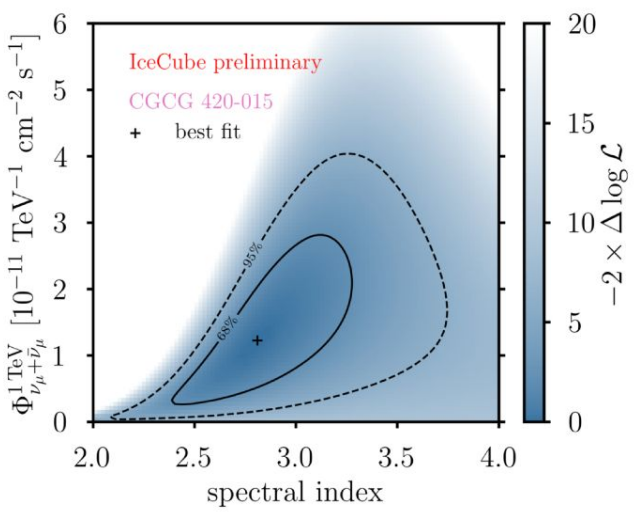
Northern Sky Results



Likelihood Scans

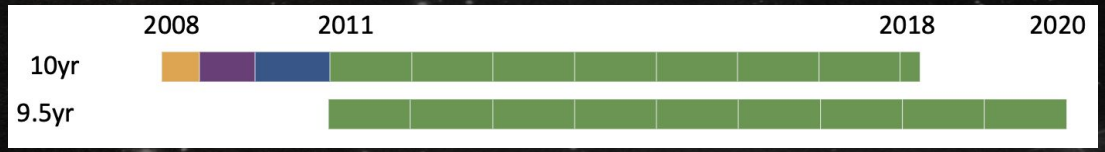


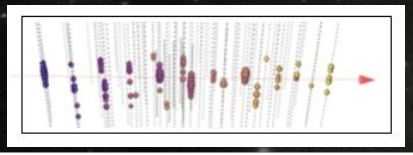


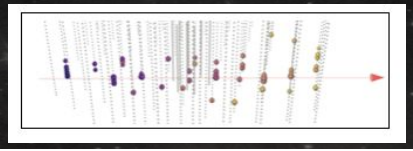


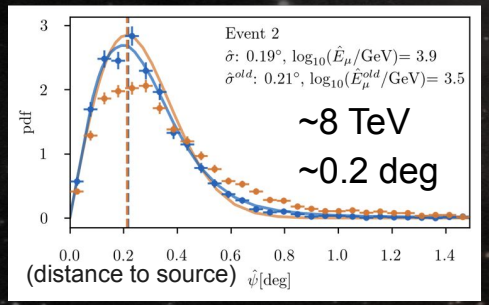
Profile likelihood scans for the flux parameters for the top sources with the power-law fit.

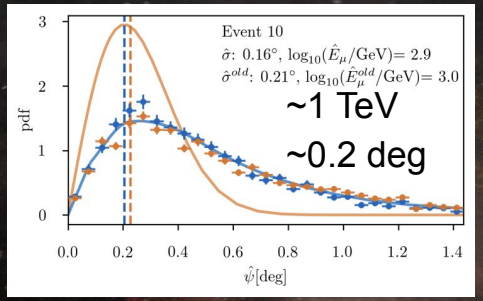
NGC 1068





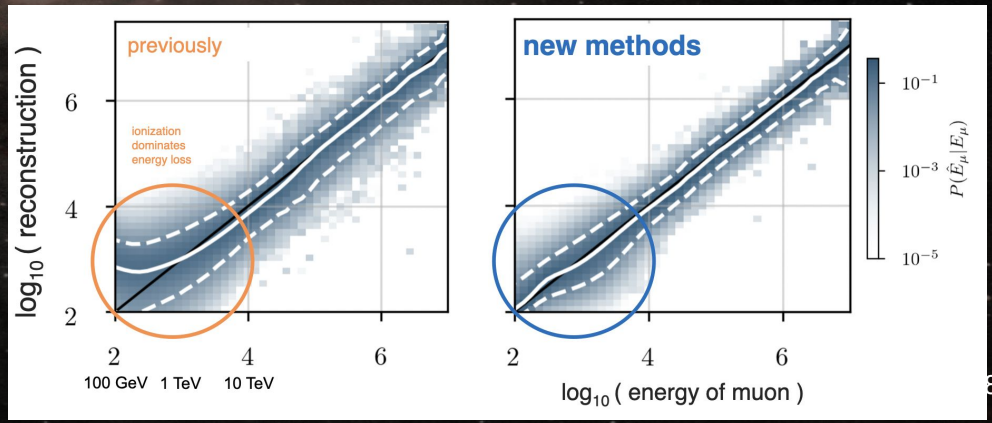




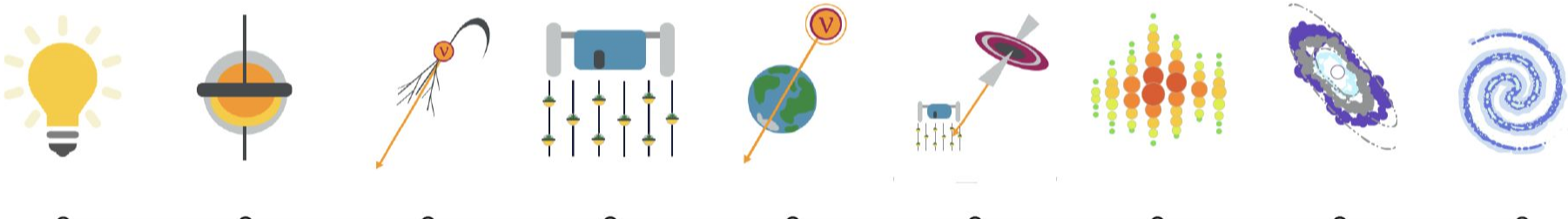


better modeling of directional distributions of individual neutrinos in particular well reconstructed events (at TeV energies)

energy reconstruction: neural network provides more accurate and more precise energy estimates especially at TeV energies



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

2023 — Third Source Milky Way Identified