For the IceCube collaboration

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

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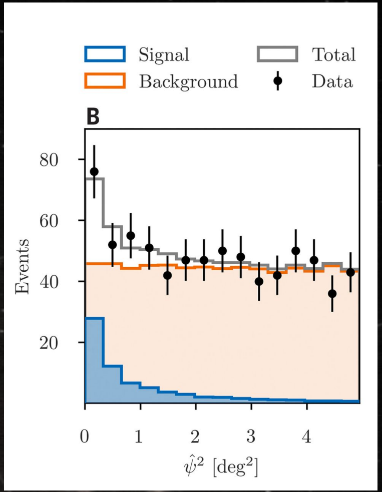
Science **378**,538-543(2022)

Motivation: NGC 1068

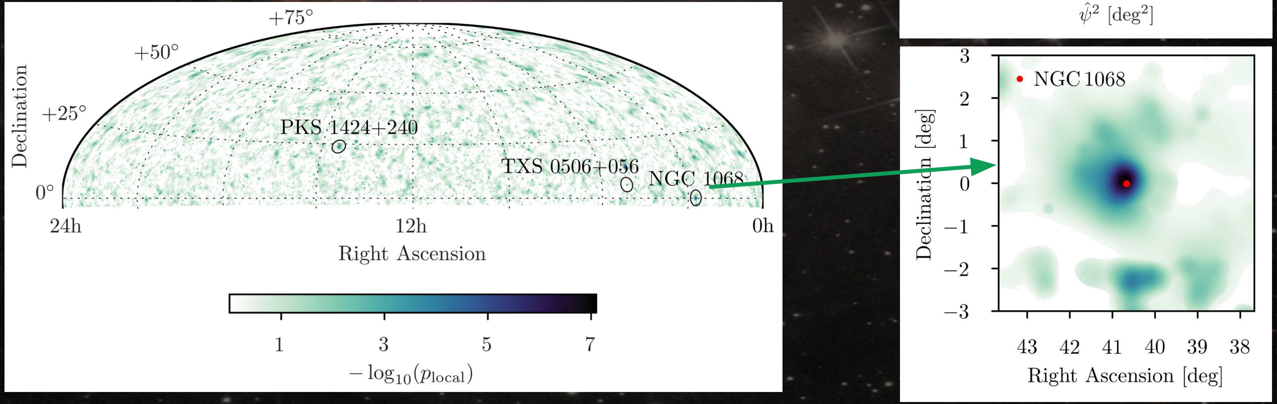
All-sky scan found hot spot at NGC 1068 location.

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

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

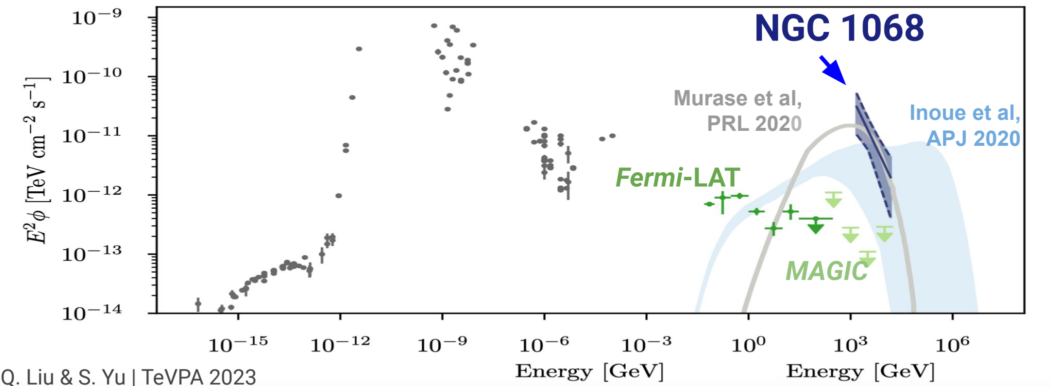


4.2 σ post-trial significance of evidence!



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?

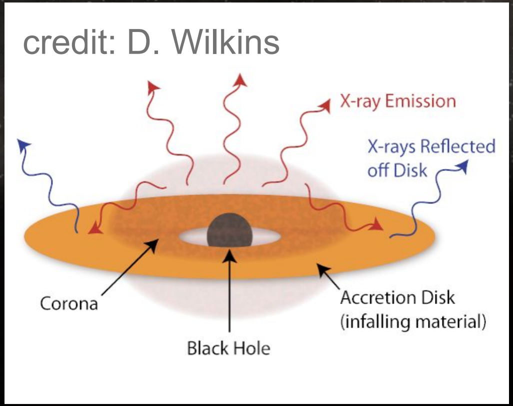
Murase and Stecker arXiv:2202.03381

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

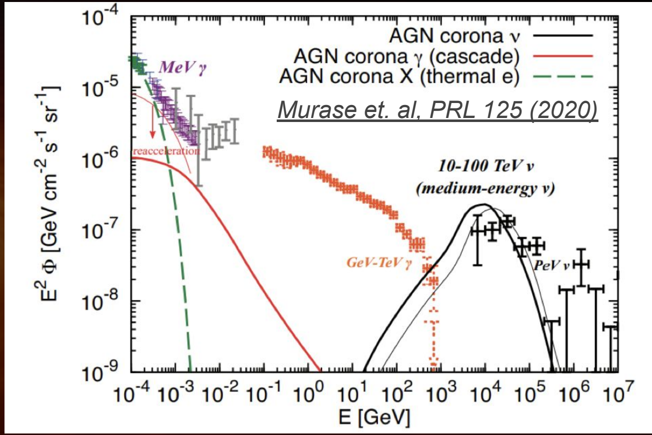
Find more similar sources! More model-dependent studies on neutrino emission are needed!

Disk-corona Model

- AGN cores optically thick for GeV-TeV gamma rays are one of the best neutrino source candidates.
- Acceleration of ions via stochastic and/or magnetic reconnection processes.
- In Seyfert galaxies, magnetized coronae can be formed due to accretion and magnetic dissipation.
- The disk-corona model can accommodate neutrino flux at medium energies (~30 TeV).

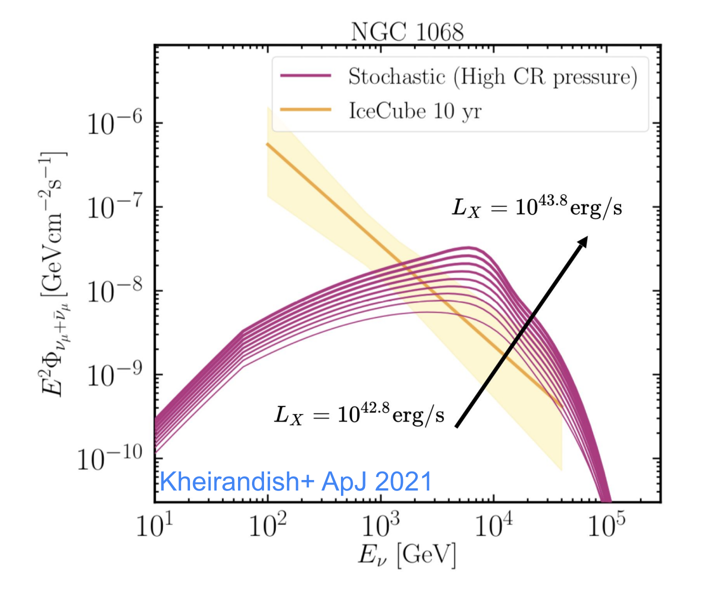


Bright X-ray emission



Disk-corona Model

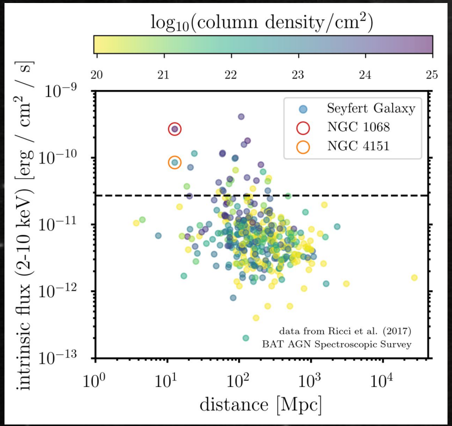
- Neutrino flux predictions based on the High CR pressure scenario of the disk-corona model.
  - Most promising for identification with current data.
- Thermal X-ray luminosity serves as the proxy of CR injection and neutrino emission: $L_\nu \propto L_\gamma \propto L_{CR}$
  - Spectra normalized by 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



Source Selection

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

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

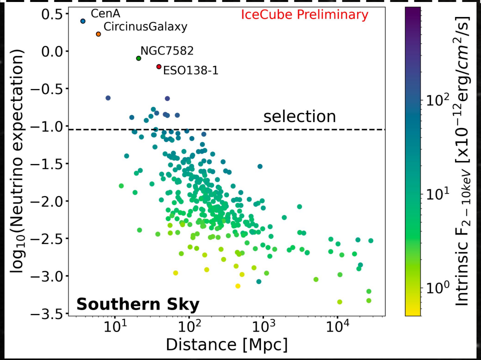


27 (+NGC 1068) sources

Northern Sky

Southern Sky

14 sources



Northern Sky Analyses: Catalog & Stacking Searches

Catalog:

- Using disk-corona model, parameter: n_s
- Using the power-law spectrum, parameter: n_s, γ

Stacking:

- Using disk-corona model with weights = n_{exp}

- Same Northern Sky Muon Track sample as IceCube Science 2022 with ~1.7 yr more data. ~20% increase in statistics.
- Improved analysis method (kernel density estimation) is also applied.

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

Northern Sky Result: Catalog Search

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

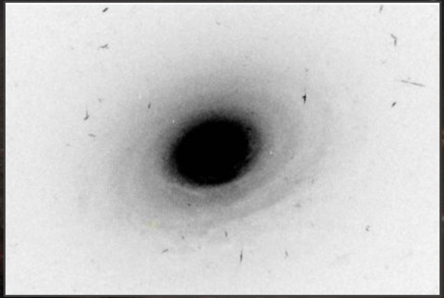
	spectral model	n_{exp}	TS	$\hat{n}_s$	$\hat{\gamma}$	p_{local}	p_{global}	n_{UL}
Catalog Search 1								
CGCG 420-015	disk-corona	3.2	11.0	31	–	2.4×10^{-4} (3.5 σ)	6.5×10^{-3} (2.5 σ)	46.4
NGC 4151	disk-corona	13.1	9.0	23	–	6.4×10^{-4} (3.2 σ)	–	39.5
NGC 1068 (*)	disk-corona	44.6	23.4	48	–	3.0×10^{-7} (5.0 σ)	–	61.4
Catalog Search 2								
NGC 4151	power-law	–	7.4	30	2.7	6.4×10^{-4} (3.2 σ)	1.7×10^{-2} (2.1 σ)	61.4
CGCG 420-015	power-law	–	9.2	35	2.8	3.0×10^{-3} (2.7 σ)	–	62.1
NGC 1068 (*)	power-law	–	29.5	94	3.3	8.0×10^{-8} (5.2 σ)	–	94.9

*3.5σ -> 2.5σ (27 sources)=> post-trials **2.3σ** (2 flux assumptions)*

Northern Sky Result: Catalog Search

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

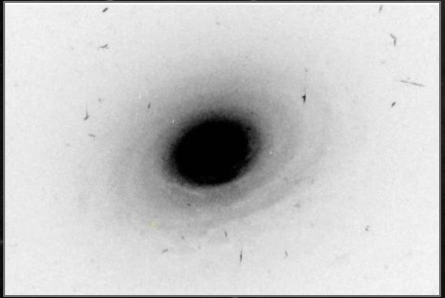
NGC 1068
~14 Mpc
~7 Log(M/M⊙)
$\mathrm{Log}L_X^{2\text{-}10\mathrm{keV}}$~42.9 erg/s
(NuSTAR and XMM-Newton:
$\mathrm{Log}L_X^{2\text{-}10\mathrm{keV}}$~43.8 erg/s)



CGCG 420-015
~130 Mpc
~8.3 Log(M/M⊙)
$\mathrm{Log}L_X^{2\text{-}10\mathrm{keV}}$~44 erg/s

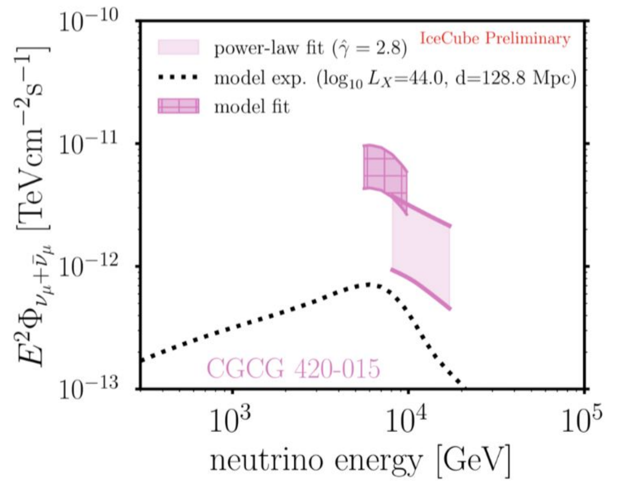
NGC4151
~16 Mpc
~7.6 Log(M/M⊙)
$\mathrm{Log}L_X^{2\text{-}10\mathrm{keV}}$~42.3 erg/s

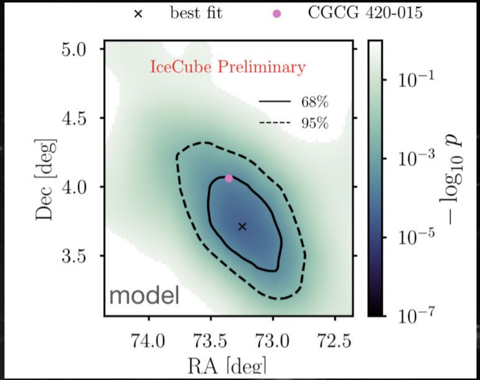
Northern Sky Result: CGCG 420-015

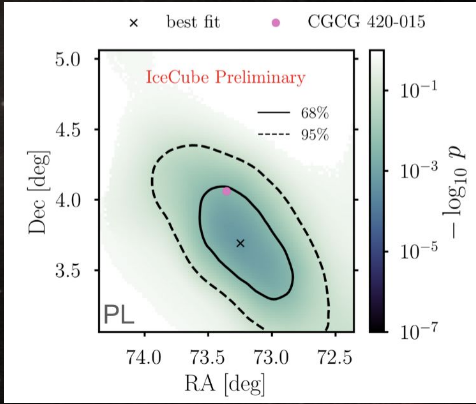


- Quite far (~130 Mpc)
- Supermassive BH: 2x10^{8} M⊙
- High X-ray luminosity (Log$L_X^{2\text{-}10keV}$ ~44 erg/s)
- Compton thick, highly obscured

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

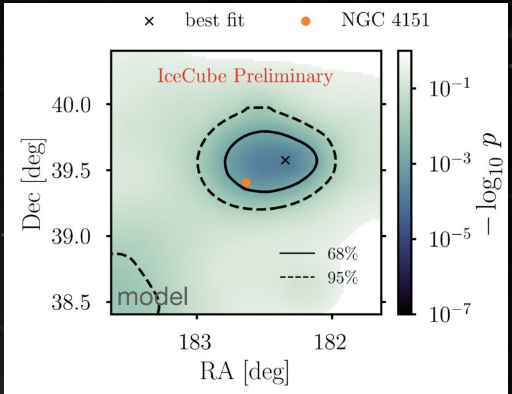




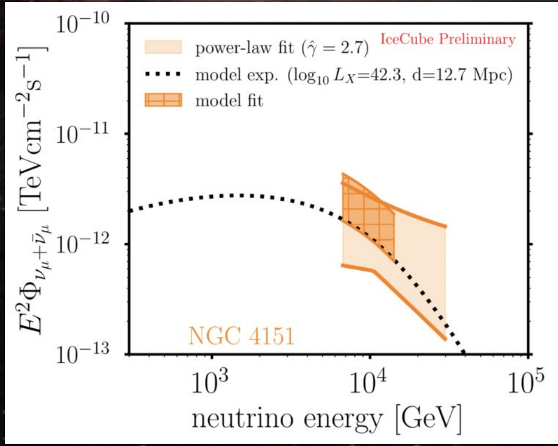


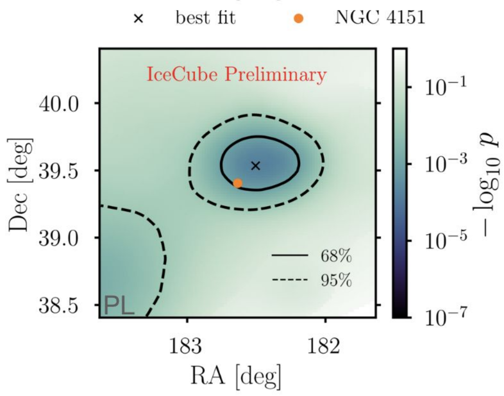
Northern Sky Result: NGC 4151

- ~0.18 degree from the 4th hottest spot in IceCube Science 2022
- Most significant in power-law analysis, comparable significance in both flux assumptions.

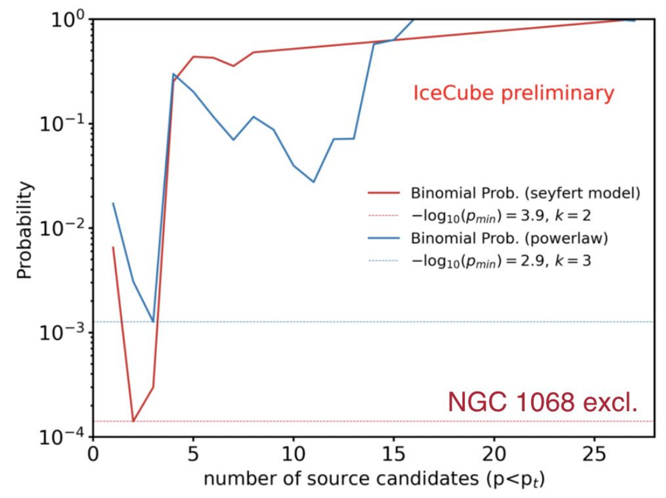


- ~16 Mpc
- ~4x10^7 M☉
- X-ray luminosity of Log$L_X^{2\text{-}10keV}$ ~42.3 erg/s
- L_γ/L_X < 0.25%





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 included

Northern Sky Result: Stacking

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

Northern Sky Result: Discussions

- It's possible that there is a subset of sources that have high CR-thermal pressure (optimistic scenario) similar to NGC 1068. But it's also possible that there are not many that share similar properties. Moderate scenarios are only testable with next-generation neutrino telescopes.

- In environments with high levels of column densities, there is a large uncertainty on the intrinsic X-ray flux measurements which can significantly change expectations.
  - e.g. for NGC 1068, NuSTAR & XMM-Newton report higher L_X than BASS, which leads to more moderate CR pressure which will reduce the expectations of other sources.

- In order to find more sources and verify the models, we need more studies on the multi-wavelength emission of the sources.

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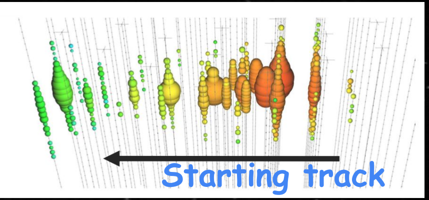
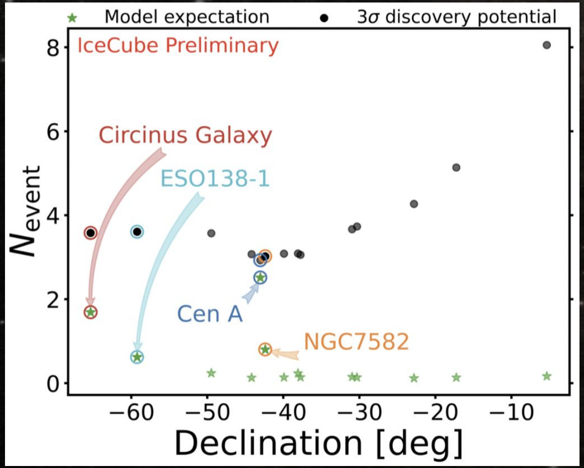
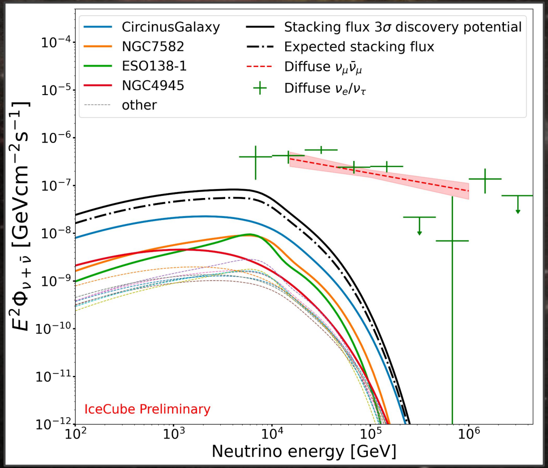
Southern Sky Sensitivities



A similar study focusing on the Southern Sky is performed with an improved track selection technique.





Stacking analysis (w/o Cen A) expect to see a strong signal → selected sources together produce 10% of the measured diffuse flux at 10 TeV

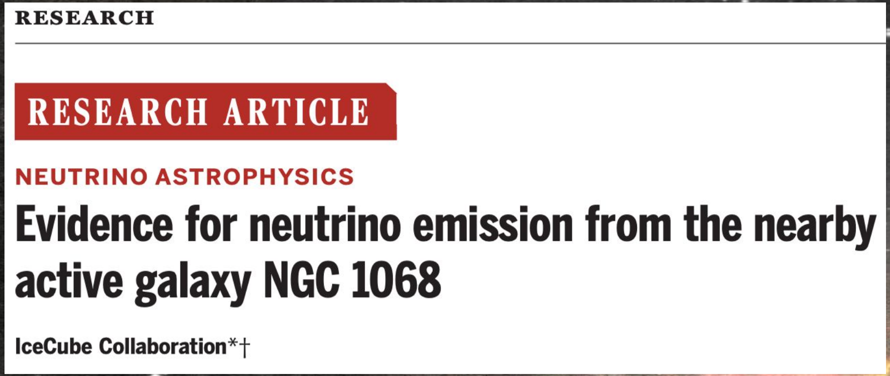
(space for other potential sources!)

Summary and Outlook

- ➔ We incorporate the disk-corona model for catalog and stacking searches to study high-energy neutrino emission from X-ray bright Seyfert galaxies. The generic power-law spectrum is also studied for a catalog search.
- ➔ With Northern Sky:
  - ◆ No significant excess observed in the stacking search, we constrain the collective neutrino emission from those sources.
  - ◆ Our results hint at neutrino emission from two sources in addition to NGC 1068, i.e. NGC 4151 and *CGCG* 420-015 with 2.7σ.
- ➔ With Southern Sky: similar studies are performed with an improved track selection technique and sensitivities are shown.
- ➔ Future identification is promising, with important multi-messenger input.
- ➔ The next-generation detectors with improved sensitivities covering the whole sky will advance searches in the upcoming years.

Thank you!

Overflow slides

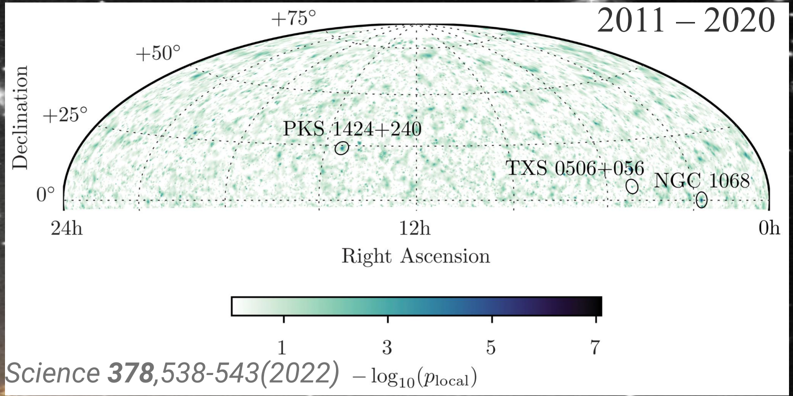

RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

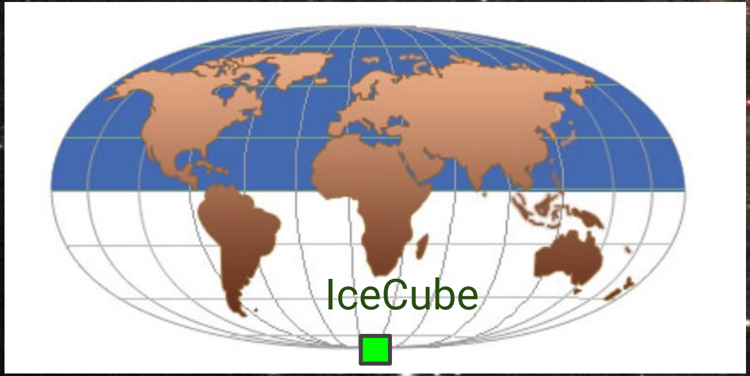
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

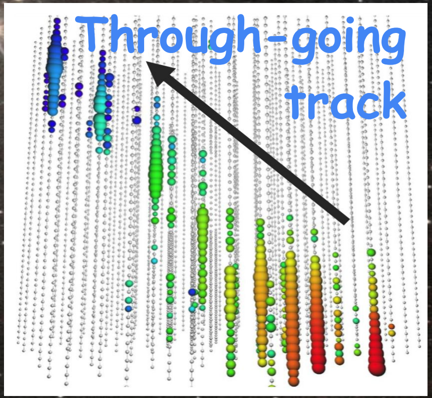


Science **378**,538-543(2022)

Motivation: NGC 1068



Earth absorption helps removing muon background



Northern Sky Results

Source	DEC	RA	$F^{\rm intr}_{2-10\rm keV}$	$n_{\rm exp}$	model			powerlaw				
					$\hat{n}_s$	-$\log_{10}p$	$n_{\rm UL}$	$\hat{n}_s$	$\hat{\gamma}$	-$\log_{10}p$	$\phi^{E^{-2}}_{90\%}$	$\phi^{E^{-3}}_{90\%}$
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

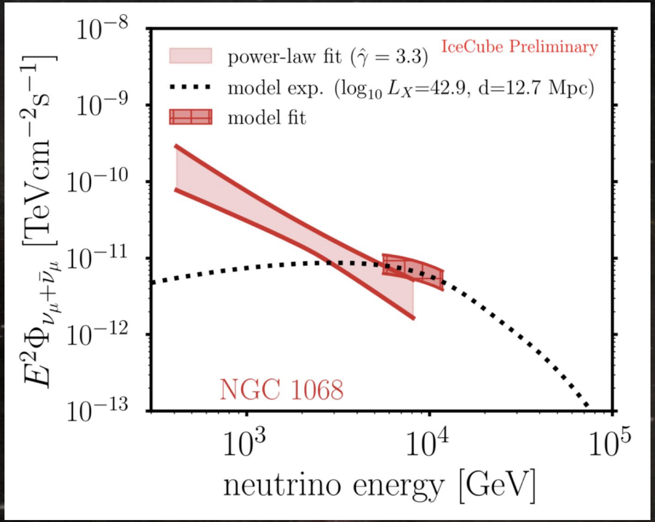
Intrinsic X-ray flux is

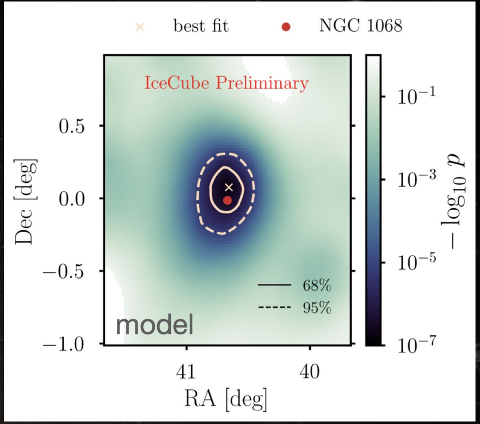
$F^{\rm intr}_{2-10\rm keV} \times 10^{-12} \rm erg\, cm^{-2}\, s^{-1}$

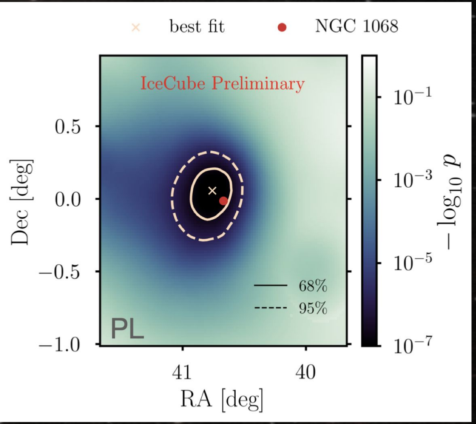
upper limit fluxes

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

Northern Sky Result: NGC 1068

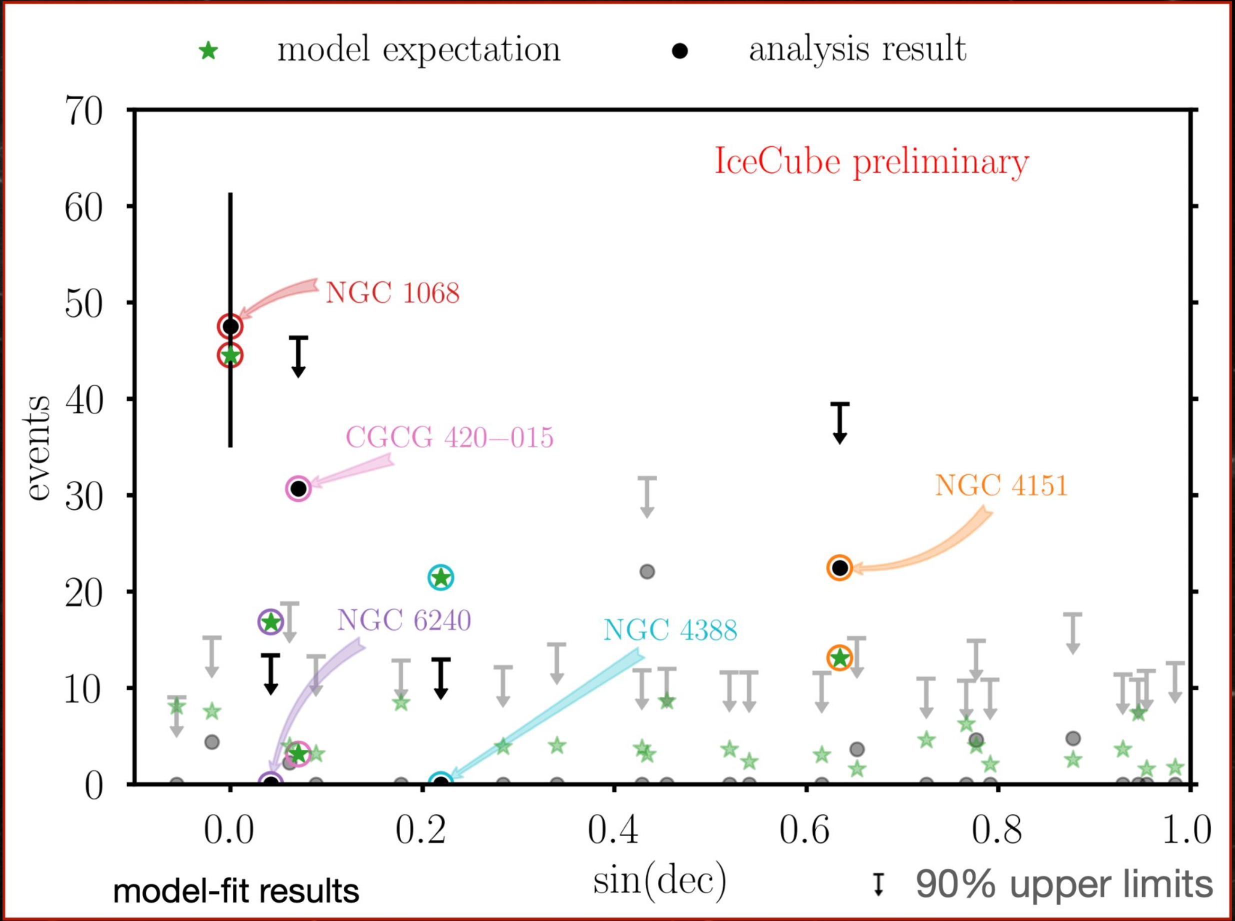




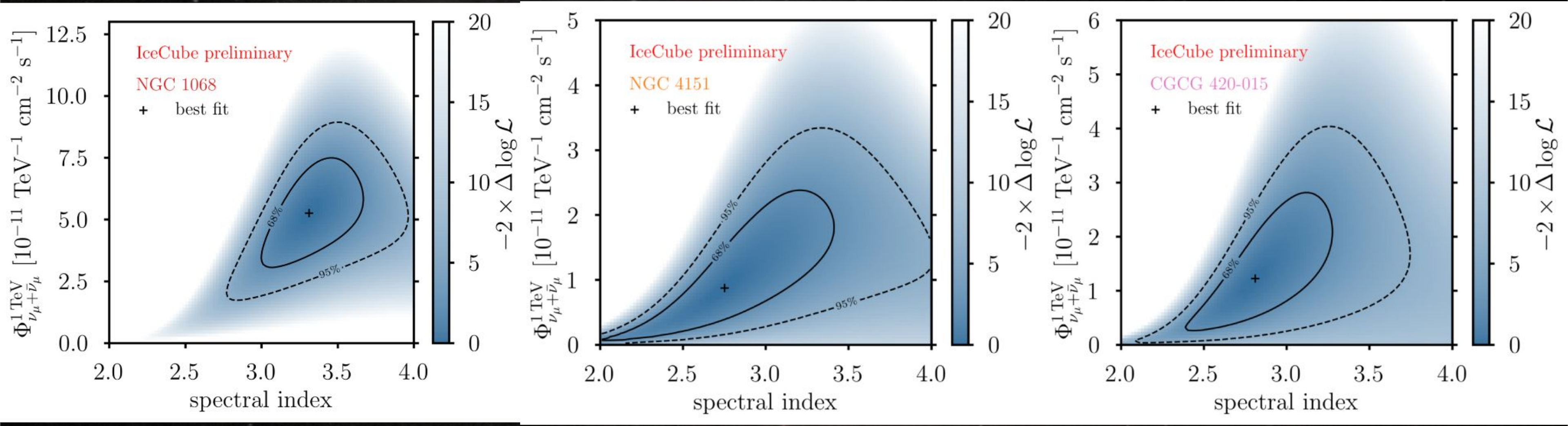


- ~14 Mpc
- ~10^7 M☉
- X-ray luminosity of $\text{Log}L_X^{2\text{-}10\text{keV}}$ ~42.9 erg/s

Northern Sky Results

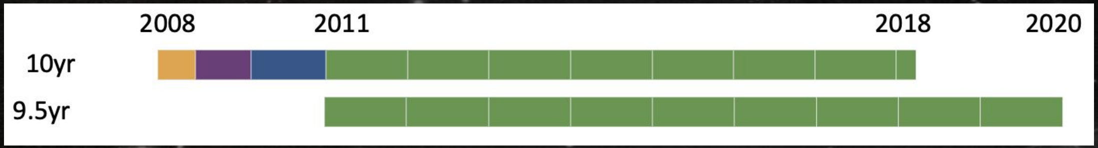


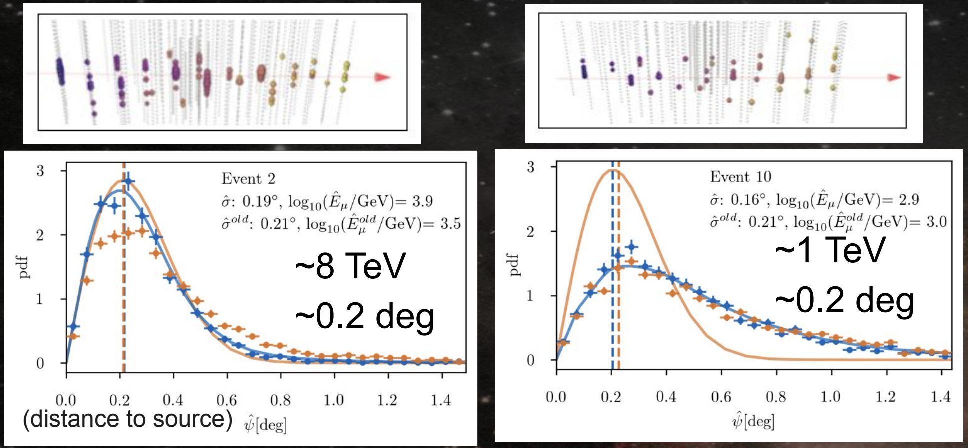
Likelihood Scans



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

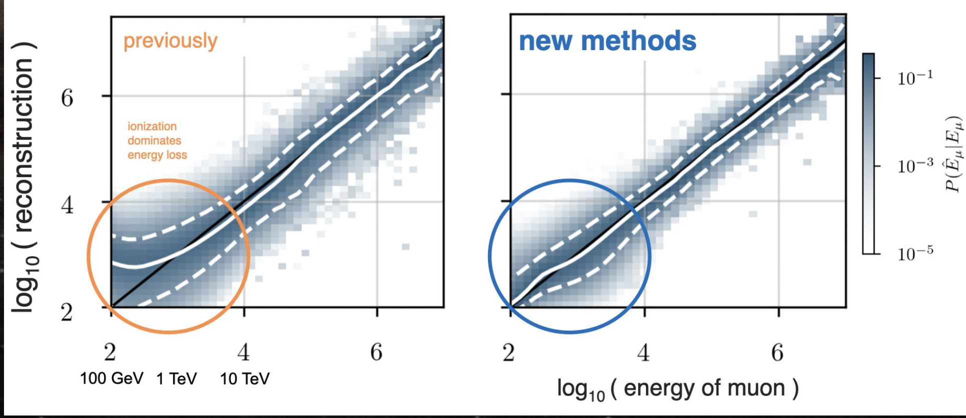
NGC 1068





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