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

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for the IceCube Collaboration

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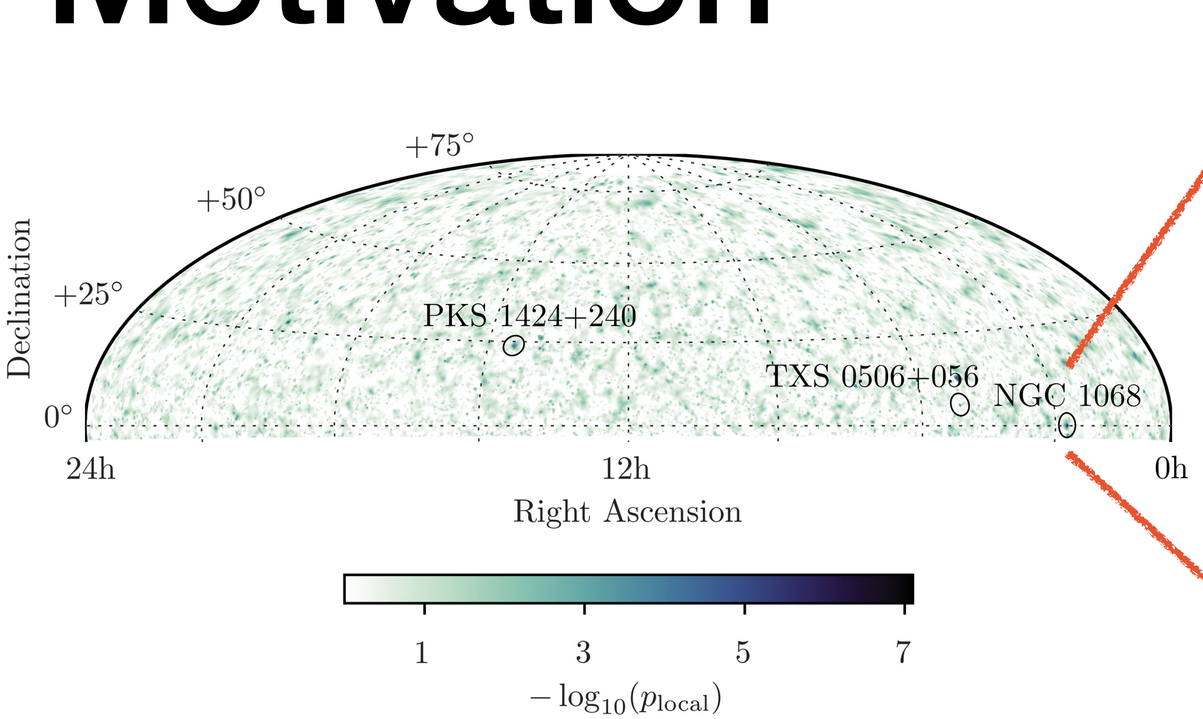
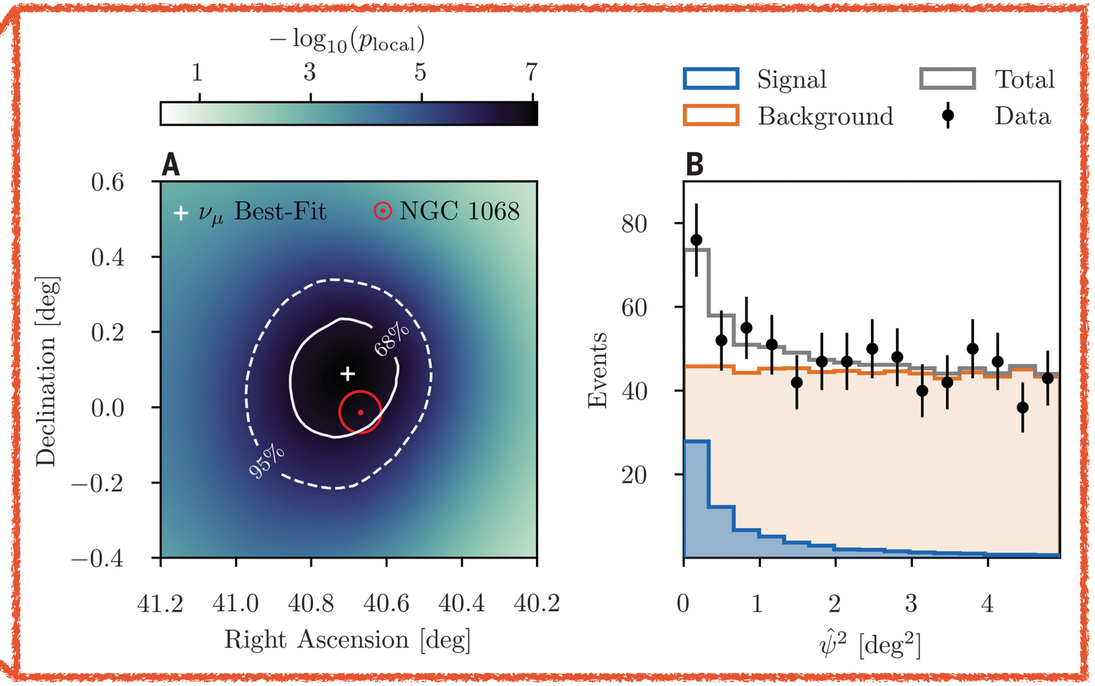
Motivation





IceCube Science 2022

- IceCube identified neutrino emission from a nearby Seyfert 2 galaxy (NGC 1068) at $4.2\,\sigma$ post-trial significance with soft best-fit spectrum
  - Mean # of signal events $\hat{n}_s = 79^{+22}_{-20}$; Spectral index $\hat{\gamma} = 3.2 \pm 0.2$
  - Single source significance $5.2\,\sigma$ (local)

Why NGC 1068?

Profile of NGC 1068:

- Seyfert Galaxy
- Compton thick environment, column density $\sim 10^{25}\,\mathrm{cm}^{-2}$
- High level of star formation
- Observed gamma-ray flux can not accommodate the neutrino flux, likely to be obscured
- Bright in X-ray
- It is close! (~14 Mpc)

Proposed possible source of high-energy cosmic rays and neutrinos: Silberberg, Shapiro (1979, 1983)

TABLE 1. Estimated Numbers of Neutrinos ($E > 4 \times 10^{12}$ eV) Detected Underwater per Year from NGC 1068 in an Array* of 1 km^3

Neutrino Events per year	Parameters of Spectrum ($E^{-\alpha}$)	
~100	α = 2.35	$E_o = 10^9$ eV
10^3-10^4	α = 2.00	$E_o = 10^9$ eV
10^2-10^3	α = 2 to 2.4	$E_o = 10^{17}$ eV

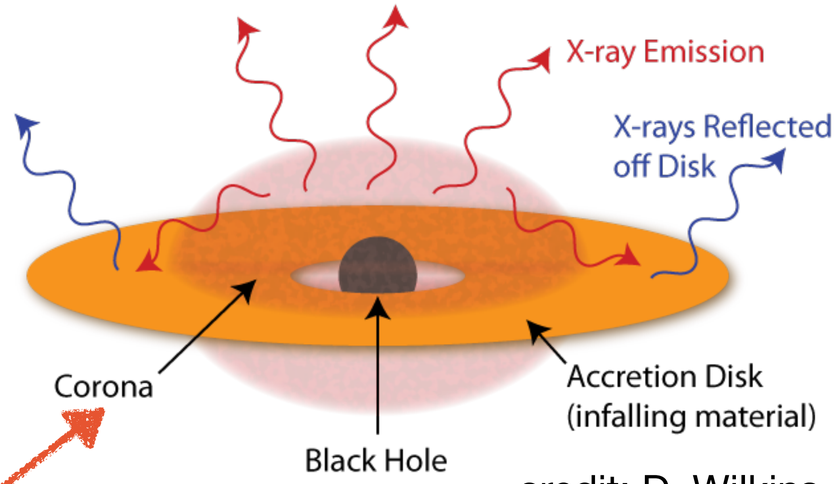
*The effective volume for detection of ν_μ is estimated to be ~10 km^3 owing to muon-generating events occurring near the array; see F. Reines, Proc. 1978 DUMAND Workshop, 2, 147, ed. A. Roberts, Scripps Inst. of Oceanography.

†If the observed value is $\ll 10^2$, it may be concluded that the energy source of NGC 1068 is thermal, (or, if non-thermal, the particles are not accelerated to energies above 10^{13} eV).

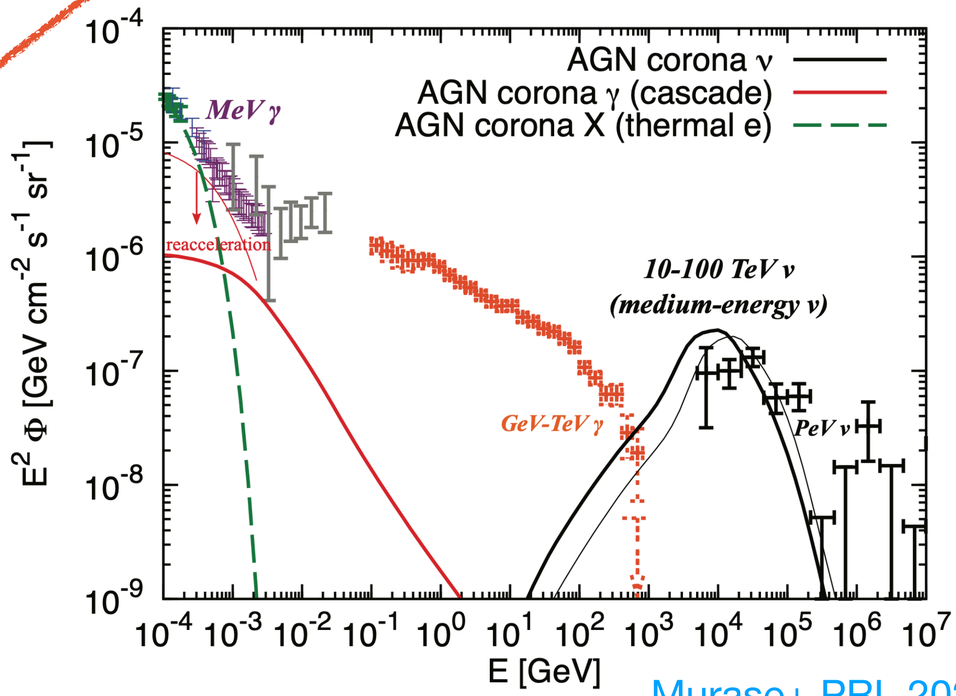
Find more similar sources!
More model-dependent studies on neutrino emission are needed!

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, a magnetized corona above the disk can be formed due to accretion and magnetic dissipation
- The disk-corona model can accommodate neutrino flux at medium energies (~30 TeV)



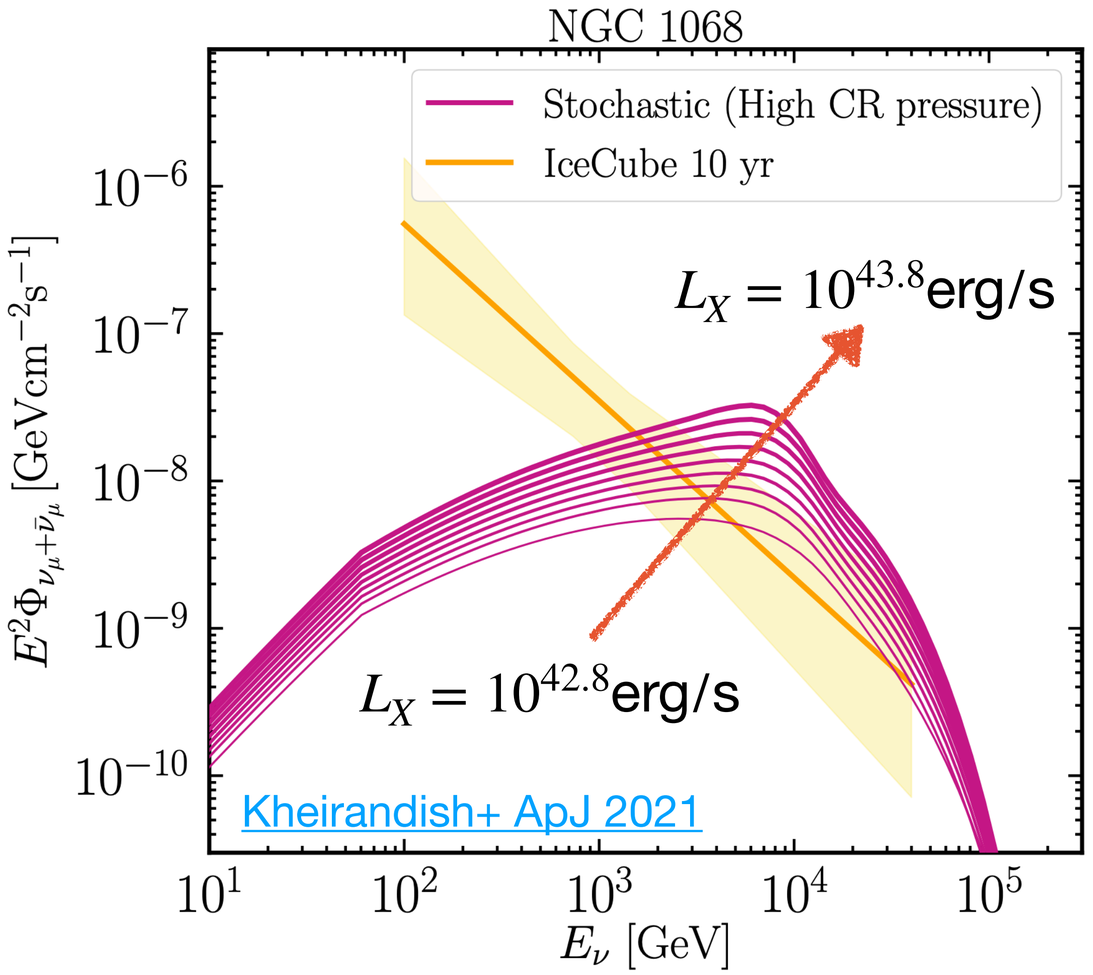
credit: D. Wilkins



Murase+ PRL 2020

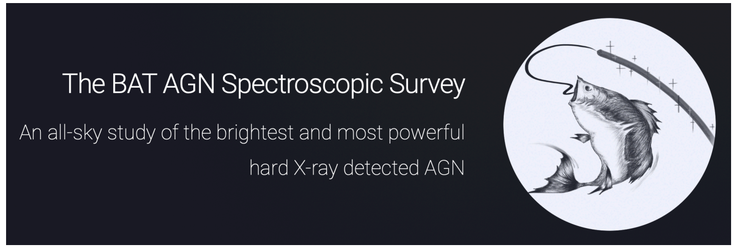
Thermal X-ray ~ Neutrinos

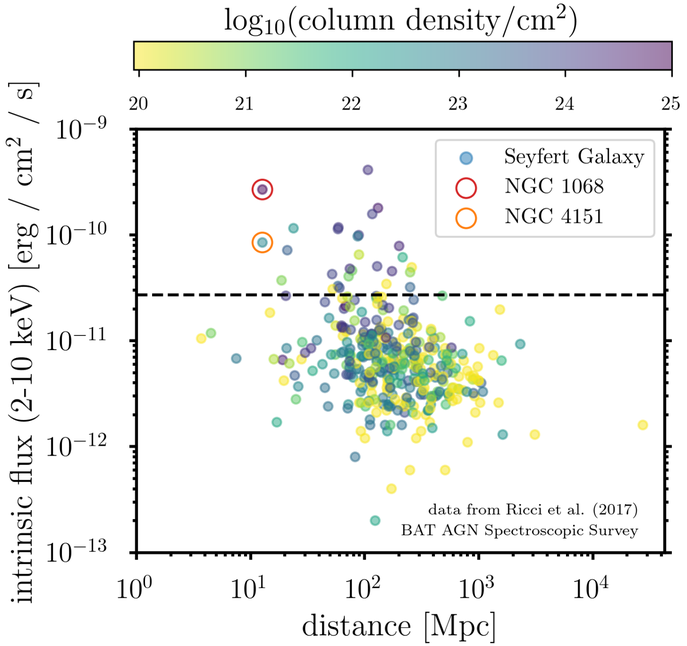
- Neutrino flux predictions based on the High CR pressure scenario of the disk-corona model. The most promising for identification with current data
- Parameter: thermal X-ray luminosity, the proxy of cosmic ray injection and neutrino emission
  $L_\nu \propto L_{CR} \propto L_X$
- Normalization of the neutrino spectrum depends on CR pressure:
  - CR injection function: $F_{p,\mathrm{inj}} \propto f_{\mathrm{inj}} L_X$
  - Injection fraction — CR to thermal pressure ratio: $f_{\mathrm{inj}} \propto P_{CR}/P_{th}$
- Studying Seyfert galaxies bright in intrinsic X-ray



Northern Sky Source Selection

- Select bright Seyfert galaxies in 2-10 keV X-ray from BASS
- The brightness threshold is 10% of NGC 1068 intrinsic 2-10 keV X-ray flux





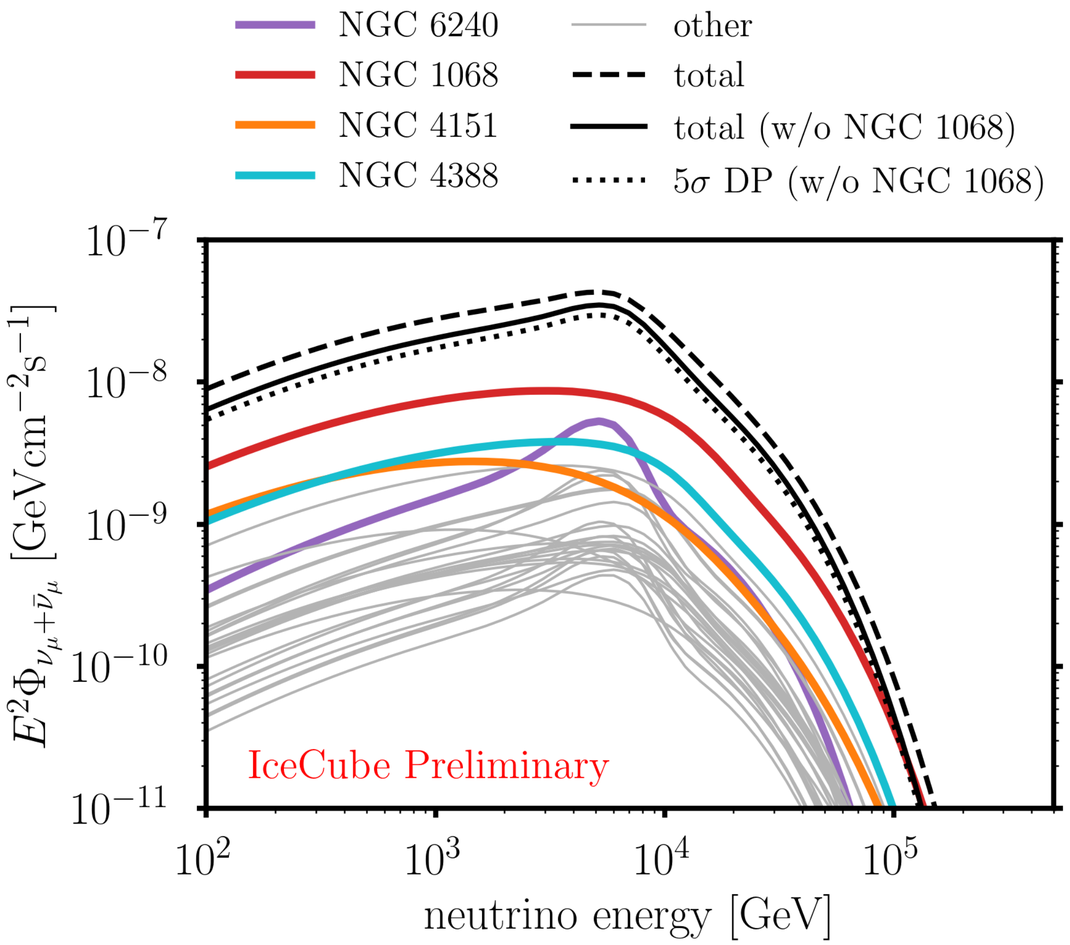
Source	Decl.	R.A.	$F^{\rm intr}_{2-10\rm keV}$	$n_{\rm exp}$
NGC 1068	−0.0	40.7	268.3	44.5
NGC 4388	12.7	186.4	71.7	21.4
NGC 6240	2.4	253.2	411.1	16.8
NGC 4151	39.4	182.6	84.8	13.1
Z164-19	27.0	221.4	179.5	8.6
UGC 11910	10.2	331.8	157.5	8.5
NGC 5506	−3.2	213.3	115.6	8.1
NGC 1194	−1.1	46.0	117.8	7.6
Mrk3	71.0	93.9	113.6	7.4
MCG+8-3-18	50.1	20.6	99.4	6.3

27 (+NGC 1068) sources in the Northern Sky

Analysis Overview

- Same Northern Sky Muon Track sample as IceCube Science 2022 with ~1.7 yr more data (~20% increase in statistics)
- **Method**:
  - The (kernel density estimation) KDE method presented in the IceCube NGC 1068 analysis
  - KDE is applied to the disk-corona model fluxes
- **Catalog search**:
  - Using disk-corona model, parameter: $\hat{n}_s$
  - Using the power-law spectrum, parameter: $\hat{n}_s, \hat{\gamma}$
- **Binomial tests** for significant sources in the catalog
- **Stacking**:
  - Using disk-corona model with weights $= n_{exp*}$

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



expected fluxes vs stacking discovery potential

Results - Catalog Search

Catalog Search 1								
CGCG 420-015	disk-corona	3.2	11.0	31	–	$2.4 \times 10^{-4}\,(3.5\,\sigma)$	$6.5 \times 10^{-3}\,(2.5\,\sigma)$	46.4
NGC 4151	disk-corona	13.1	9.0	23	–	$6.4 \times 10^{-4}\,(3.2\,\sigma)$	–	39.5
NGC 1068 (*)	disk-corona	44.6	23.4	48	–	$3.0 \times 10^{-7}\,(5.0\,\sigma)$	–	61.4
Catalog Search 2								
NGC 4151	power-law	–	7.4	30	2.7	$6.4 \times 10^{-4}\,(3.2\,\sigma)$	$1.7 \times 10^{-2}\,(2.1\,\sigma)$	61.4
CGCG 420-015	power-law	–	9.2	35	2.8	$3.0 \times 10^{-3}\,(2.7\,\sigma)$	–	62.1
NGC 1068 (*)	power-law	–	29.5	94	3.3	$8.0 \times 10^{-8}\,(5.2\,\sigma)$	–	94.9

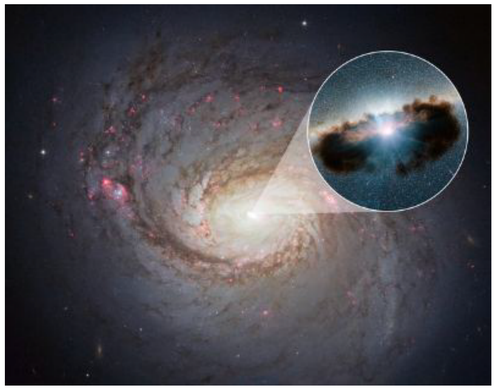
- In addition to NGC 1068, 2 sources have pre-trial significances above $3\,\sigma$
- $3.5\,\sigma$ -> $2.5\,\sigma$ (27 sources) => post-trial $2.3\,\sigma$ (2 flux assumptions)

Results marked with * are provided for completeness

Catalog Search

- In addition to NGC 1068, 2 sources have pre-trial significances above $3\,\sigma$

NGC 1068



~ 14 Mpc

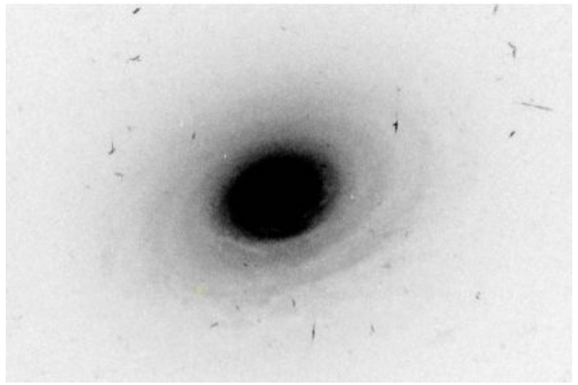
$\sim 7\ \log(\mathrm{M}/\mathrm{M}_\odot)$

$\log L_X^{2-10\,\mathrm{keV}} \sim 42.9\,\mathrm{erg/s}$

$\log L_X^{2-10\,\mathrm{keV}} \sim 43.8\,\mathrm{erg/s}$

NuSTAR and XMM-Newton

CGCG 420-015



Quite far ~ 130 Mpc

$\sim 8.3\ \log(\mathrm{M}/\mathrm{M}_\odot)$

$\log L_X^{2-10\,\mathrm{keV}} \sim 44.0\,\mathrm{erg/s}$

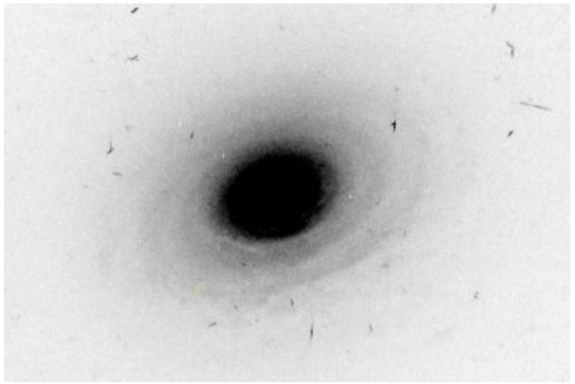
NGC 4151

~ 16 Mpc

$\sim 7.6\ \log(\mathrm{M}/\mathrm{M}_\odot)$

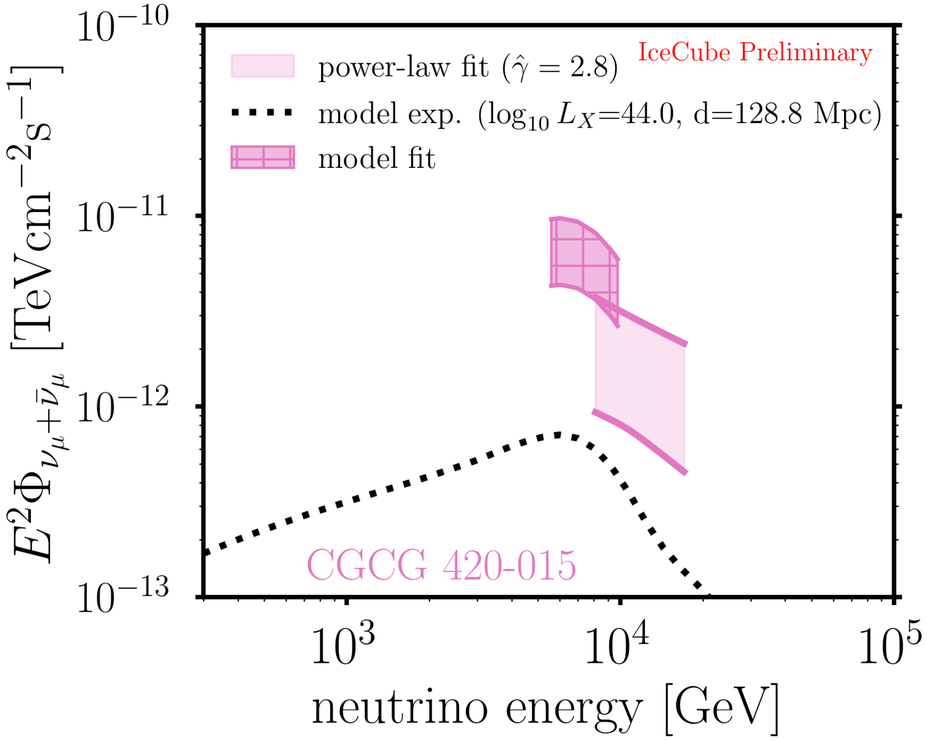
$\log L_X^{2-10\,\mathrm{keV}} \sim 42.3\,\mathrm{erg/s}$

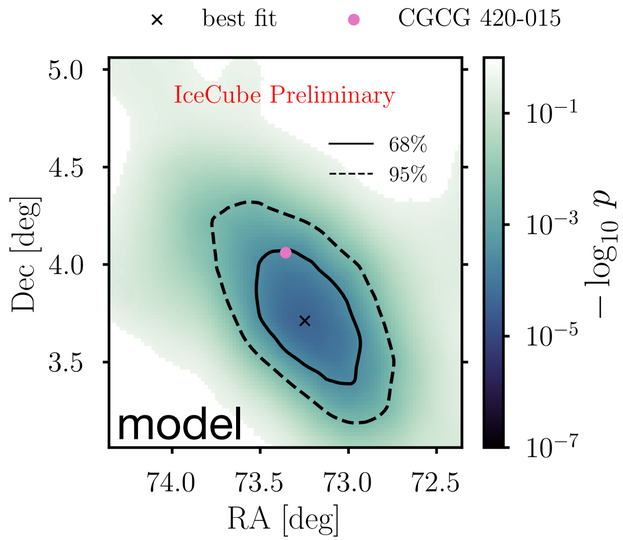
Catalog Search: CGCG 420-015

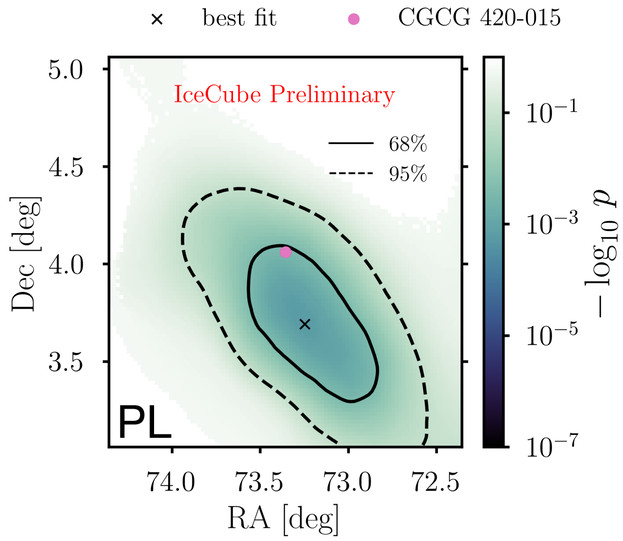


- High X-ray luminosity
  $\sim 10^{44}\,\mathrm{erg/s}$
- Compton thick, highly obscured

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



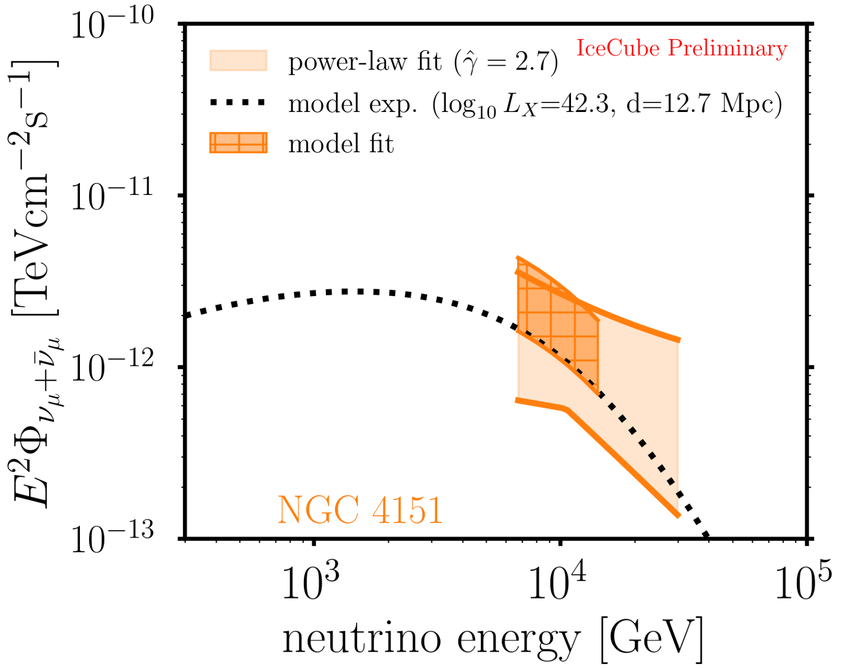


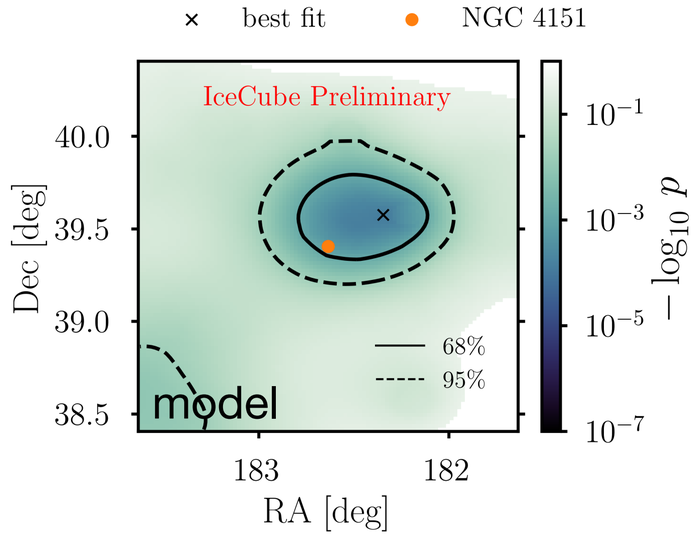


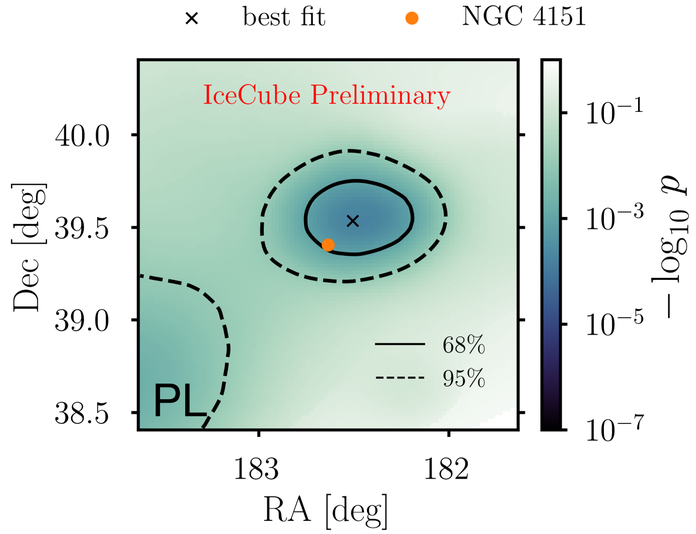
Catalog Search: NGC 4151

- $\sim 0.18^{\circ}$ from the 4th hottest spot in [IceCube Science 2022]
- Most significant in power-law analysis, comparable significance in both flux assumptions

- X-ray luminosity $\sim 10^{42.3}\,\mathrm{erg/s}$
- $L_\gamma / L_X < 0.25\,\%$







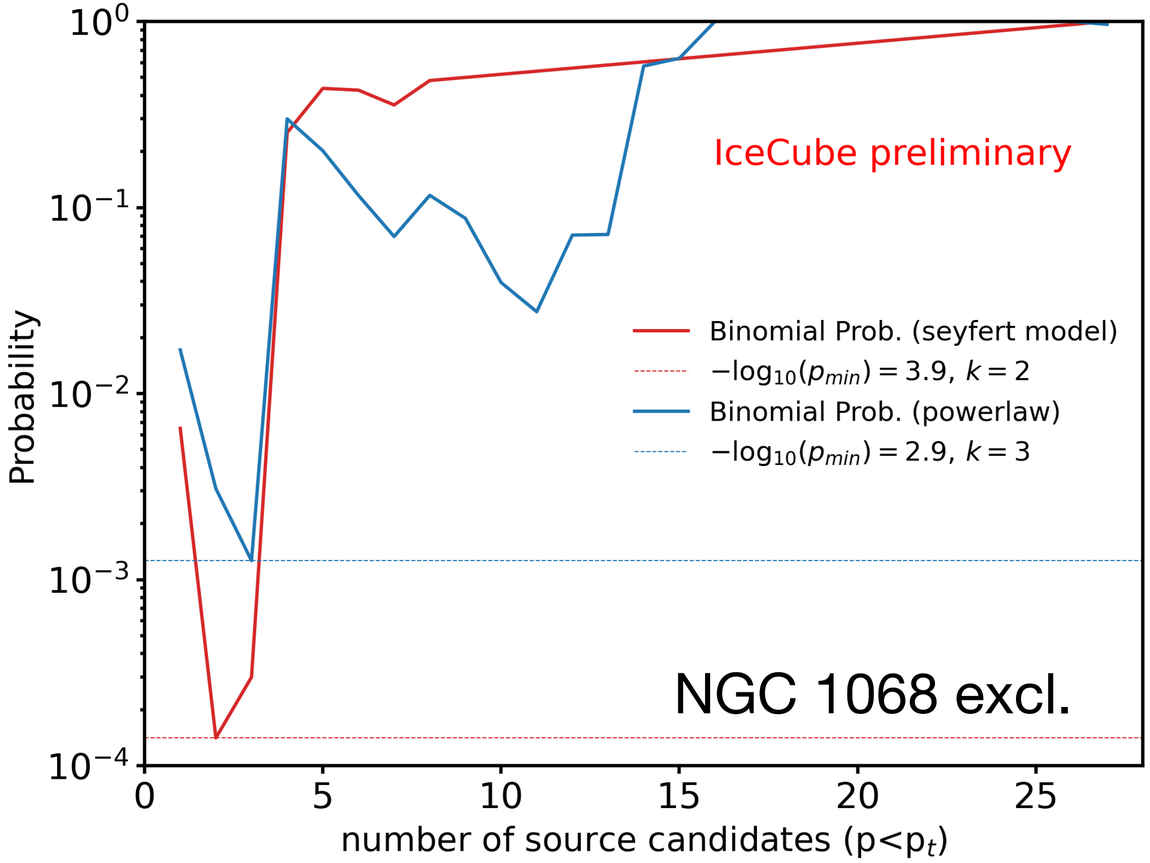
Results - Binomial Test

- 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 scenarios is analyzed

- Optimized to search for a smaller number of emitters in a source list

- Larger significance with the model fit
- $2.9\,\sigma$ excess in the binomial test using model fit, k=2:
  CGCG 420-015 and **NGC 4151**
- Significance reduces to $2.7\,\sigma$ post-trial

* (Would be $4\,\sigma$ when including NGC 1068)



Results - Stacking Search

	spectral model	n_{exp}	TS	$\hat{n}_{\mathrm{s}}$	$\hat{\gamma}$	p_{local}	p_{global}	n_{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

Results marked with * are provided for completeness

What do we learn?

- 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, leading to more moderate CR pressure which reduces the expectations of the 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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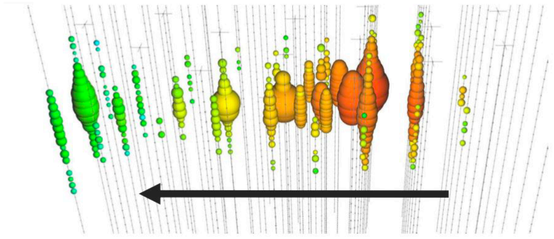
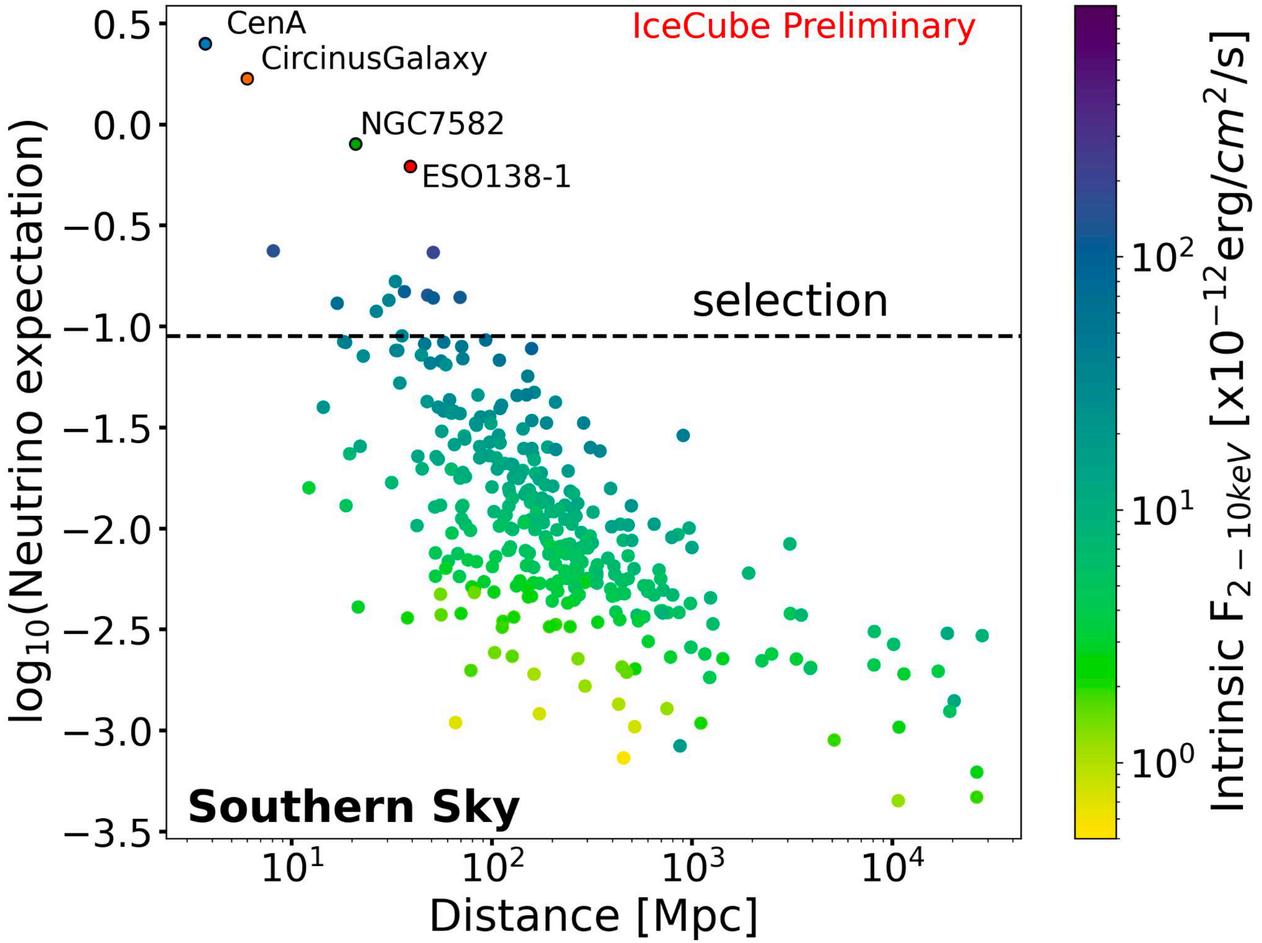
Southern Sky Source Selection

- A similar study focusing on the Southern Sky is performed with an improved track selection technique
- Selected 14 sources



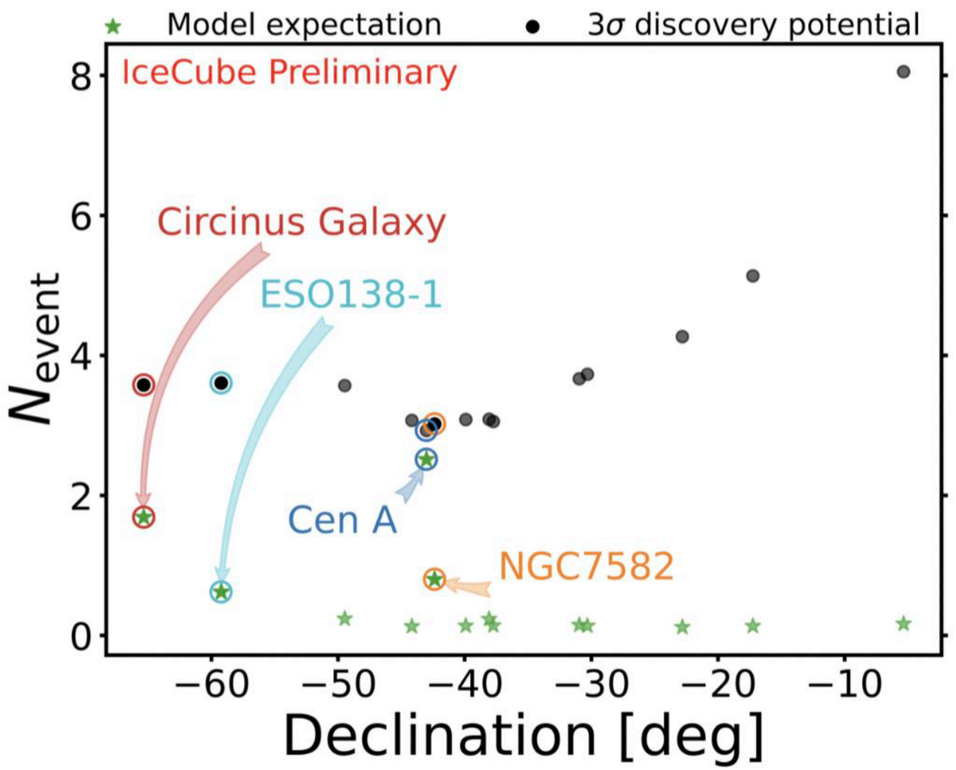
Starting track

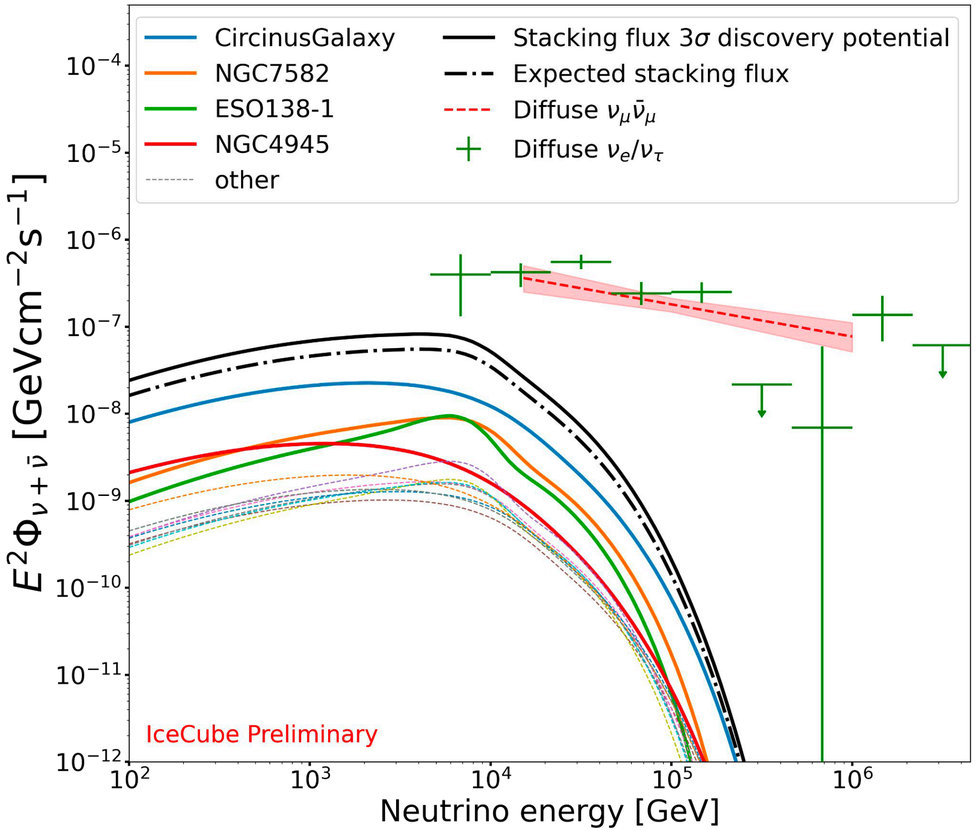


Southern Sky Sensitivities

Stay tuned for results!

- Stacking analysis (w/o Cen A) expects to see a strong signal
- Selected sources together produce 10% of the measured diffuse flux at 10 TeV (space for other potential sources!)





Summary

- We incorporate the disk-corona model for a catalog search and a stacking search to study high-energy neutrino emission from X-ray bright Seyfert galaxies in the Northern Sky. The generic power-law spectrum is also studied for a catalog search.

- With 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, i.e. **NGC 4151** and **CGCG 420-015** in addition to NGC 1068 with $2.7\,\sigma$. Future identification is promising, with important multi-messenger input.

- The majority of X-ray bright Seyfert galaxies are in the Southern Sky. We also perform a similar study focusing on the Southern Sky with an improved track selection technique and sensitivities are shown.

- The next-generation detectors with improved sensitivities covering the whole sky will advance searches in the upcoming years.

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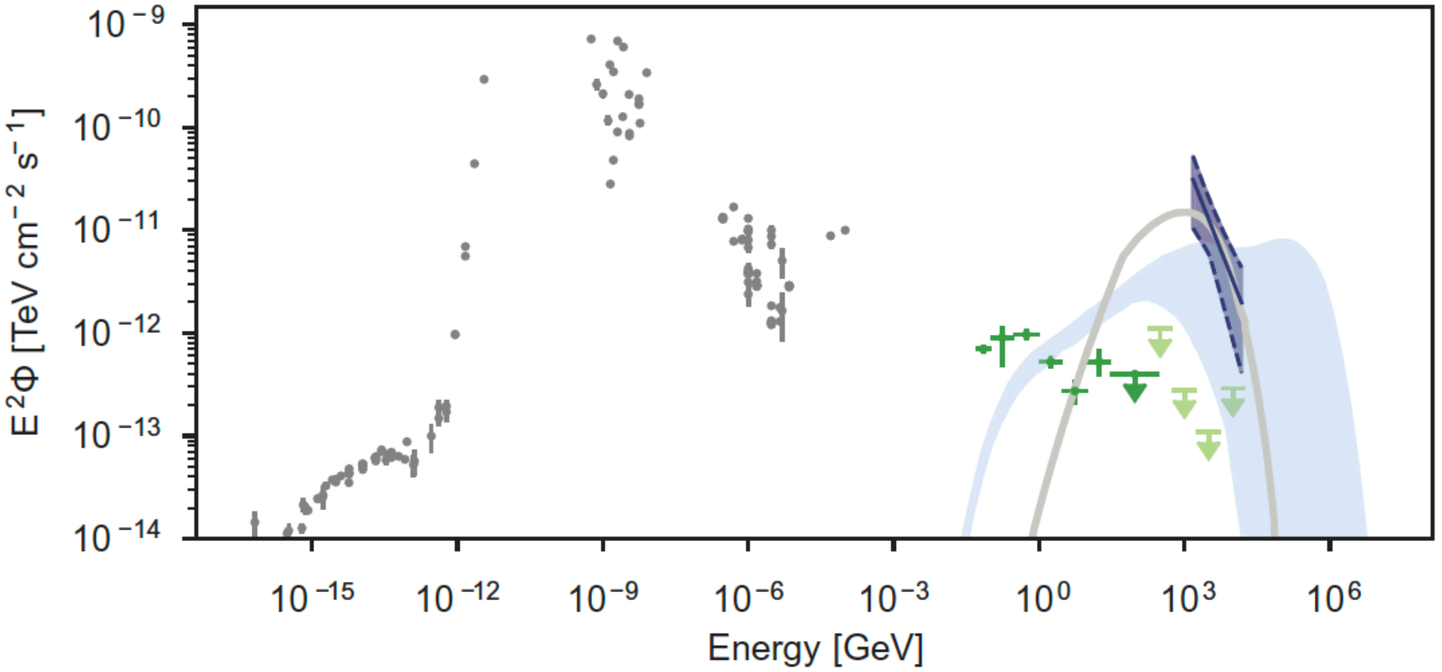
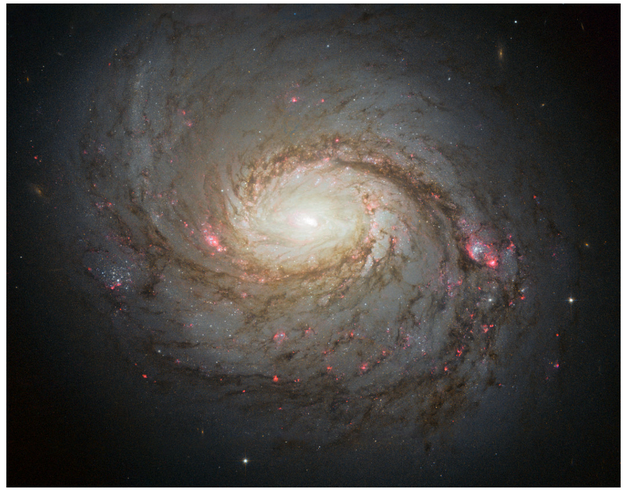
Backup

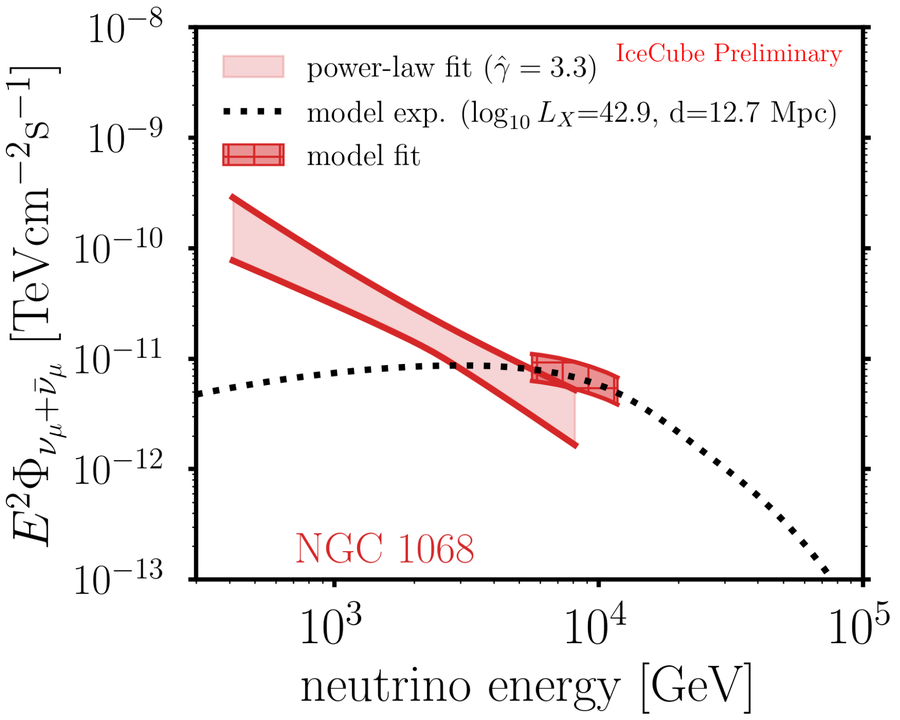
NGC 1068 Spectrum

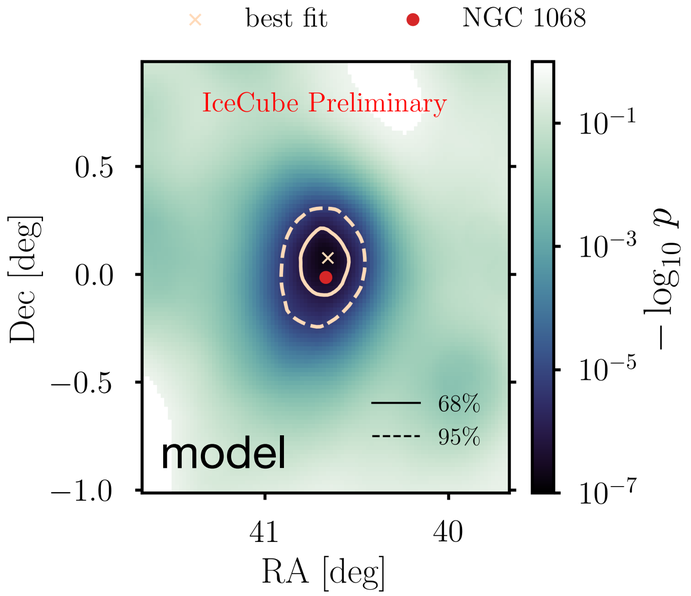


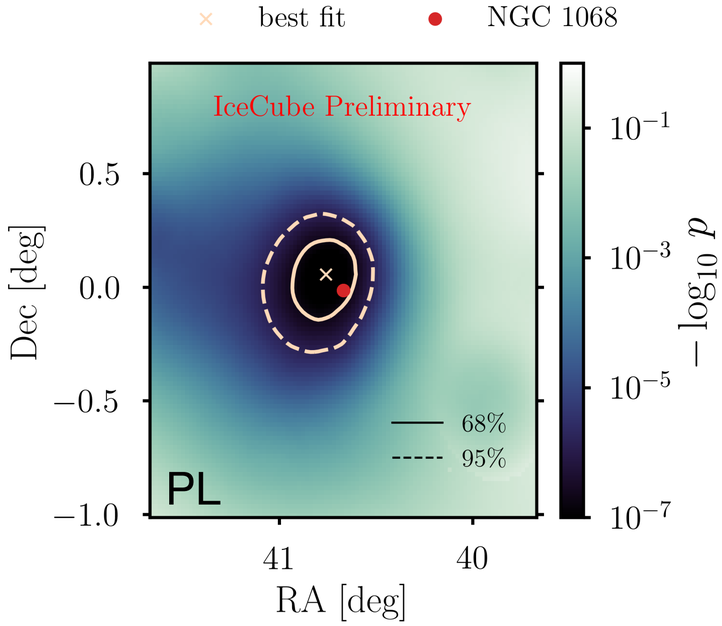
- The neutrino flux is much higher than the observed gamma-ray flux.
- Models built on measured gamma-ray flux cannot accommodate the neutrino flux.
- Significant gamma-ray absorption at the sources is expected, gamma-ray obscure source.

NGC 1068

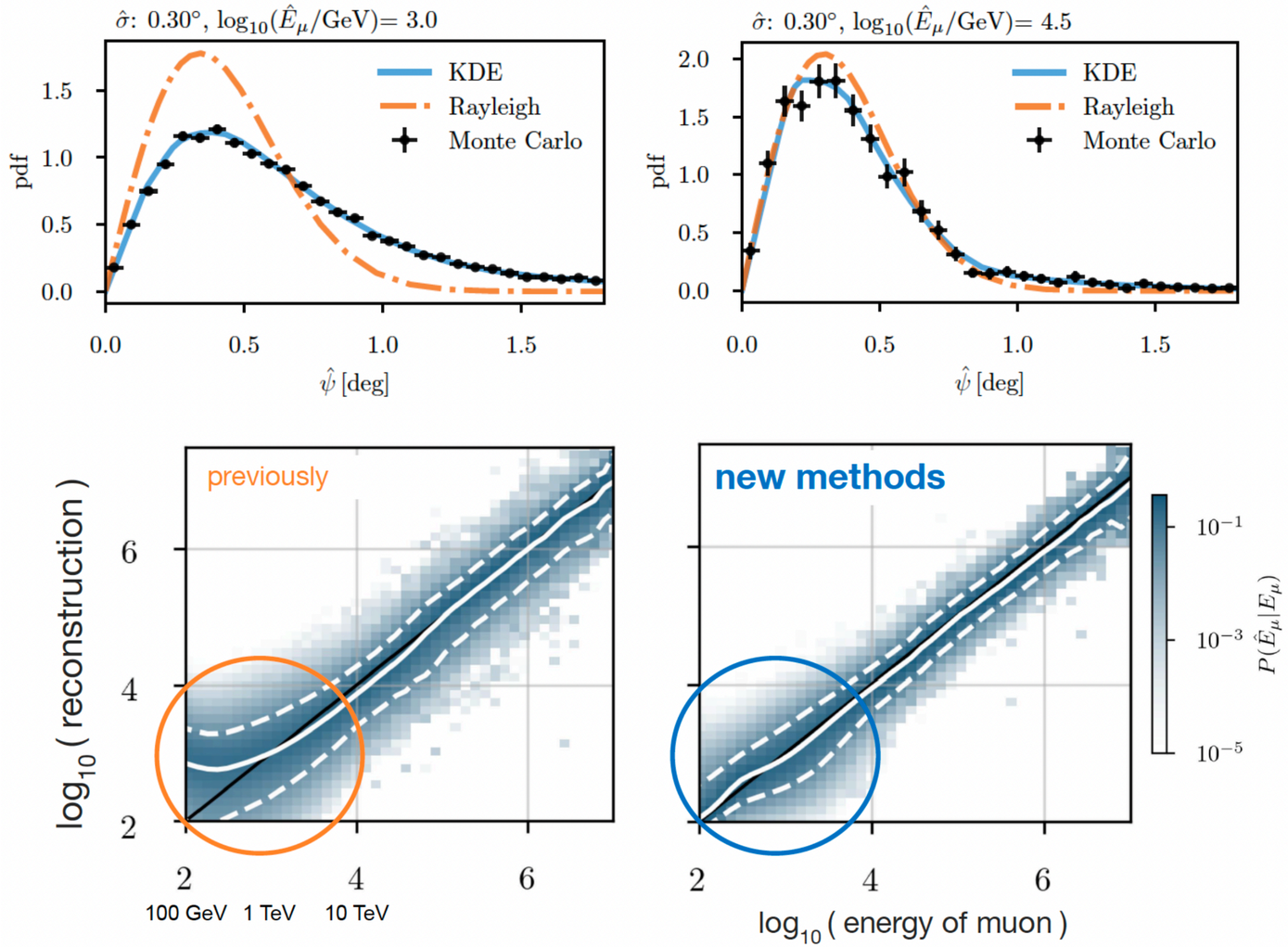



IceCube Preliminary
power-law fit ($\hat{\gamma} = 3.3$)
model exp. ($\log_{10} L_X$=42.9, d=12.7 Mpc)
model fit
NGC 1068
$E^2\Phi_{\nu_\mu+\bar{\nu}_\mu}$ [TeVcm^{-2}s^{-1}]
neutrino energy [GeV]


best fit
NGC 1068
IceCube Preliminary
model
68%
95%
Dec [deg]
RA [deg]
$-\log_{10} p$


best fit
NGC 1068
IceCube Preliminary
PL
68%
95%
Dec [deg]
RA [deg]
$-\log_{10} p$

Method improvements



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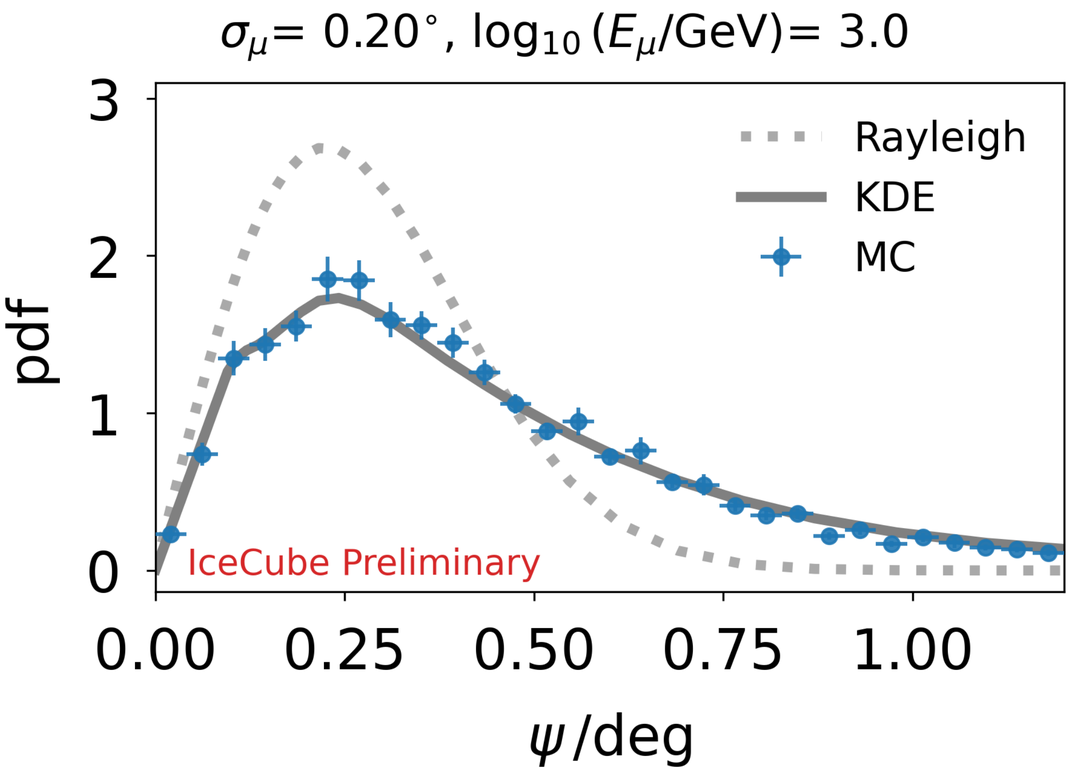
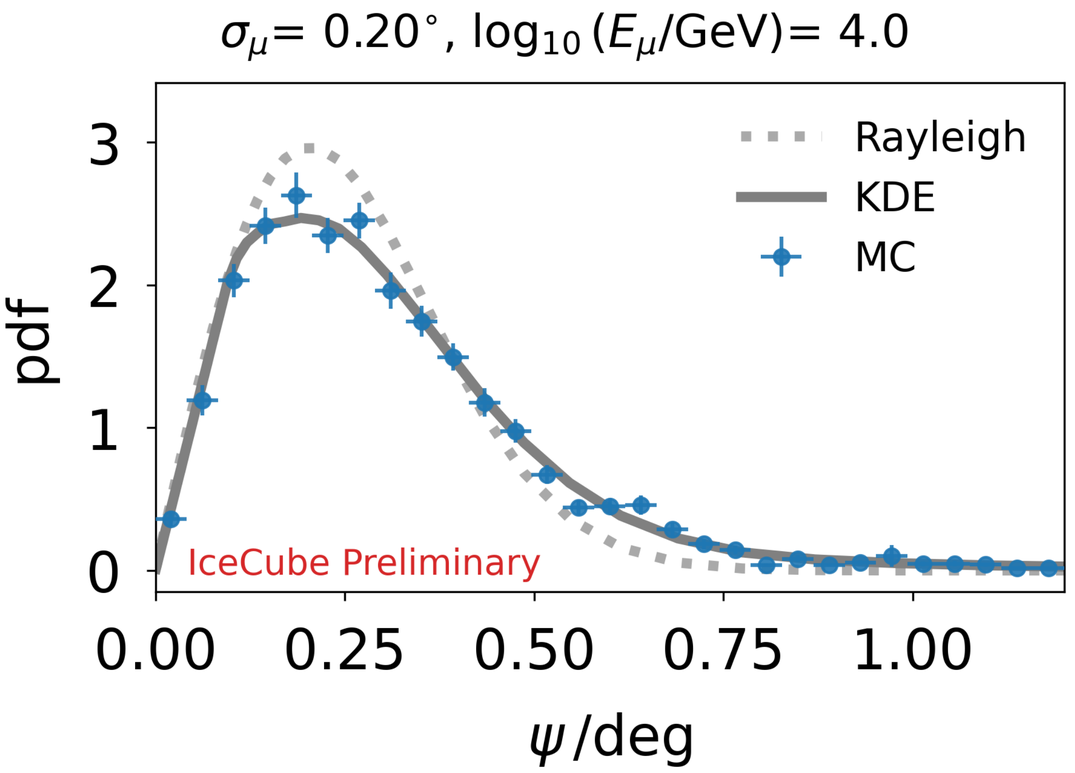
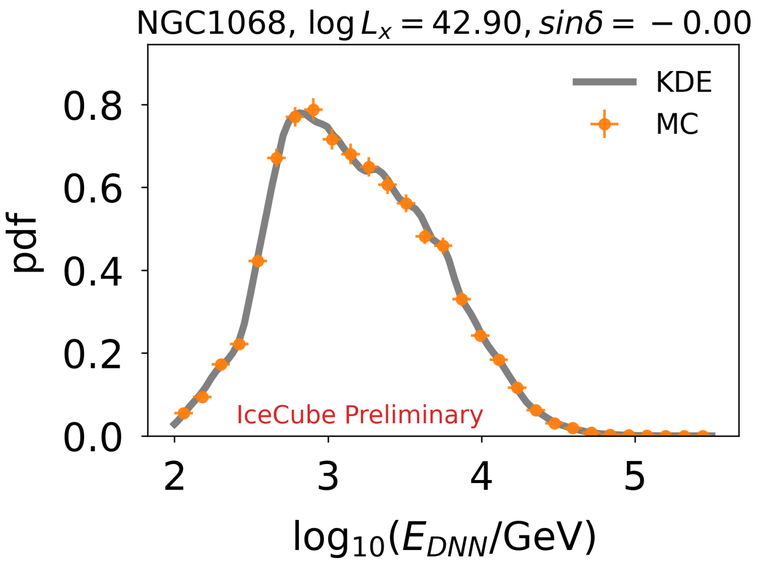
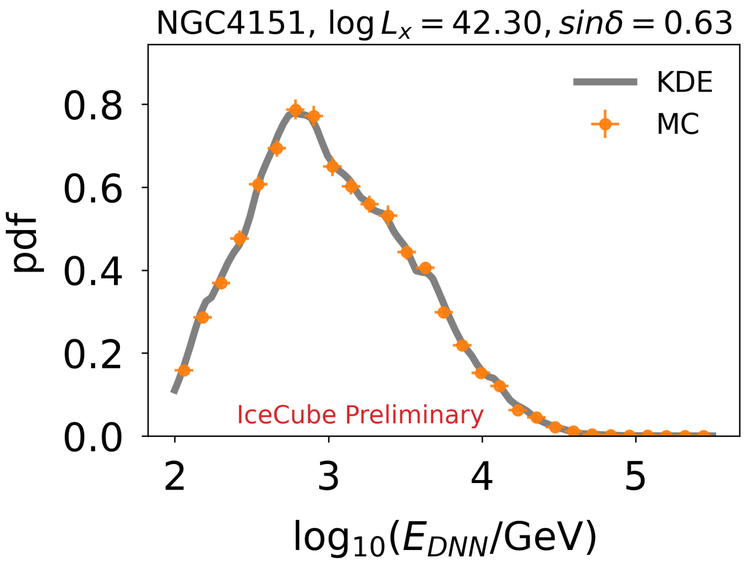
Model Spatial PDFs

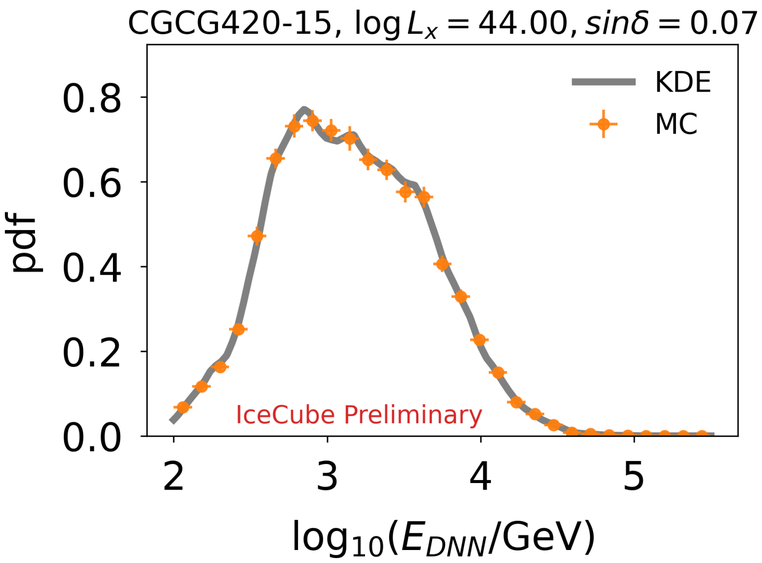




Model Energy PDFs







Results for individual seyfert galaxies assuming the disc-corona model as function of the source declination