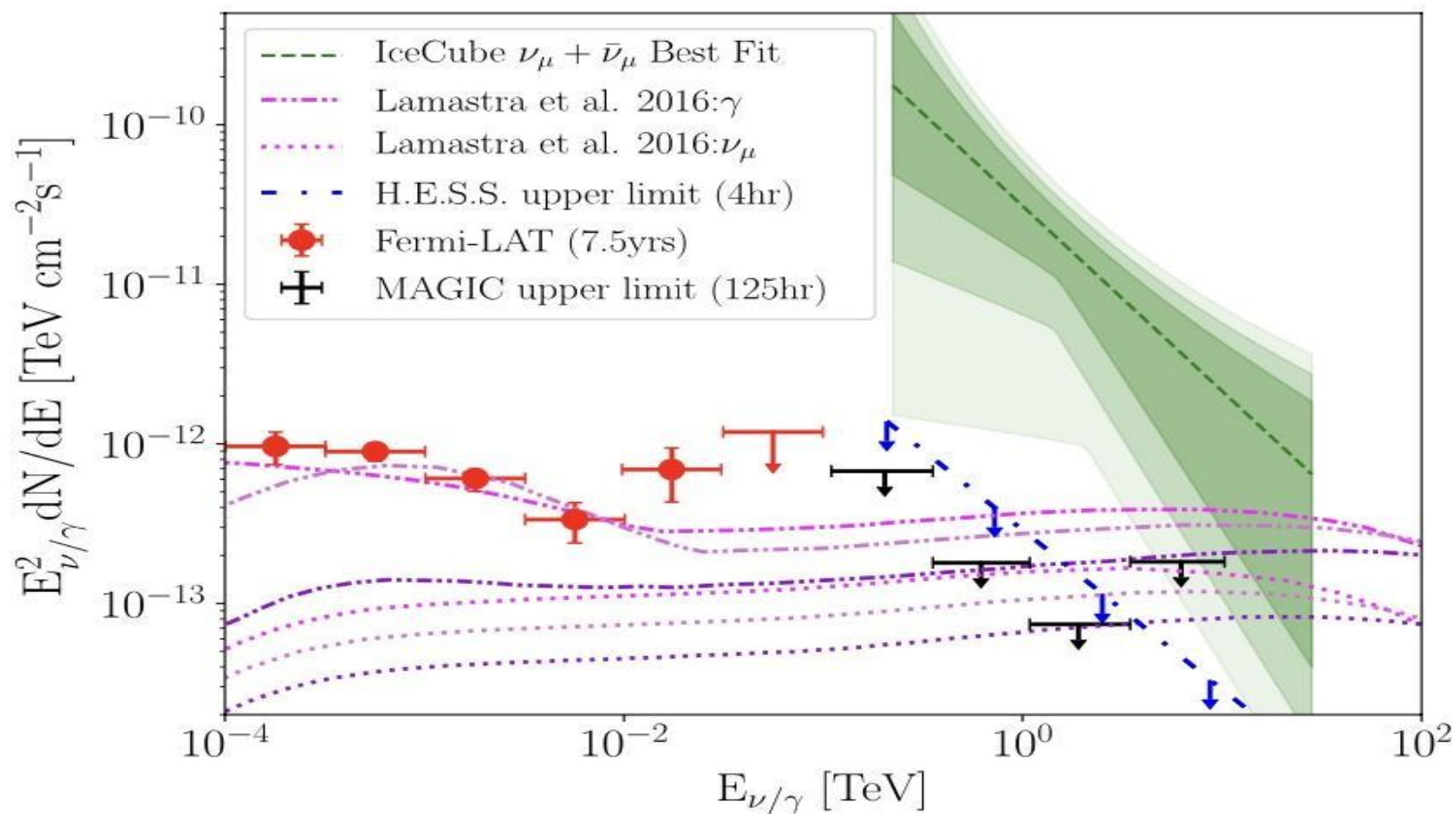


Neutrinos from Seyfert galaxies in 10 years of muon data

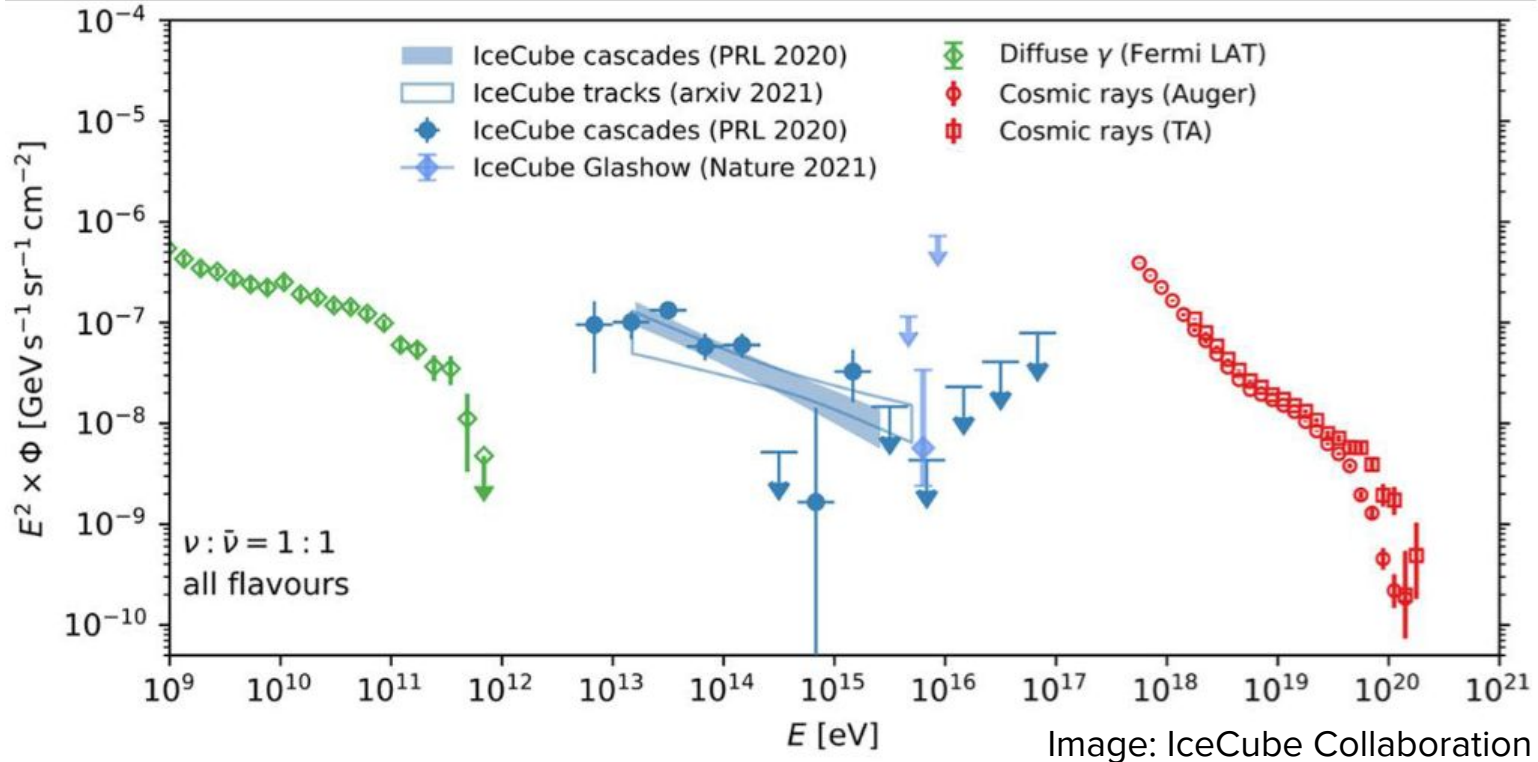
Denys Savchenko, APC Paris

based on Andrii Neronov, D.S., Dmitri Semikoz, arXiv:2306.09018

“Unexpected” neutrinos from NGC 1068



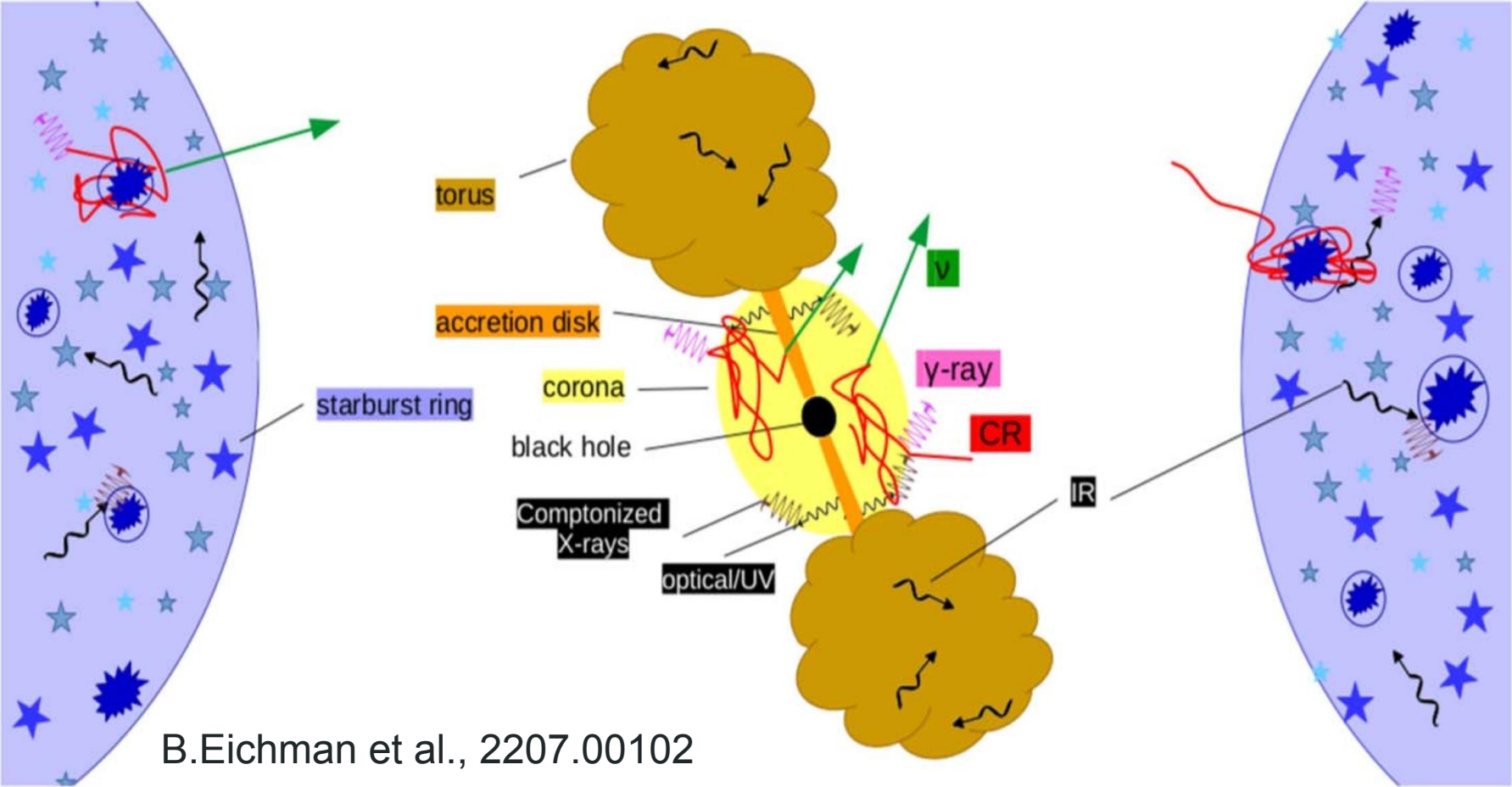
IceCube neutrinos are from “hidden” sources?



- Corresponding gamma-rays will saturate/exceed the diffuse gamma
- (Almost) no correlation with observed gamma sources

Significant part of astrophysical neutrinos are from obscured sources

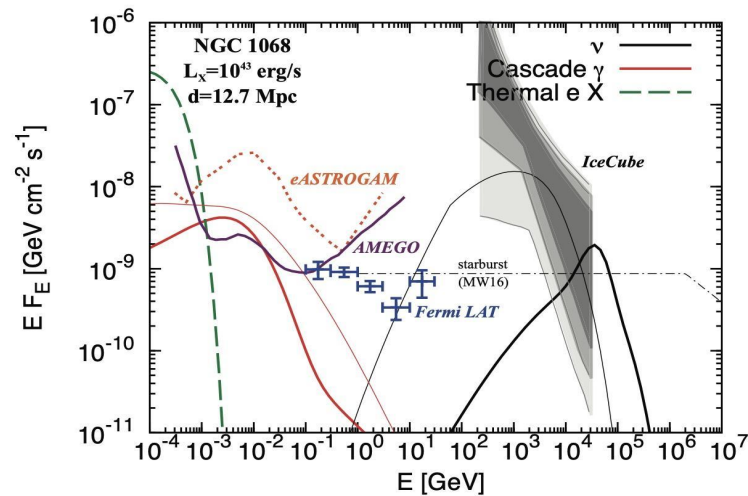
Seyfert AGN



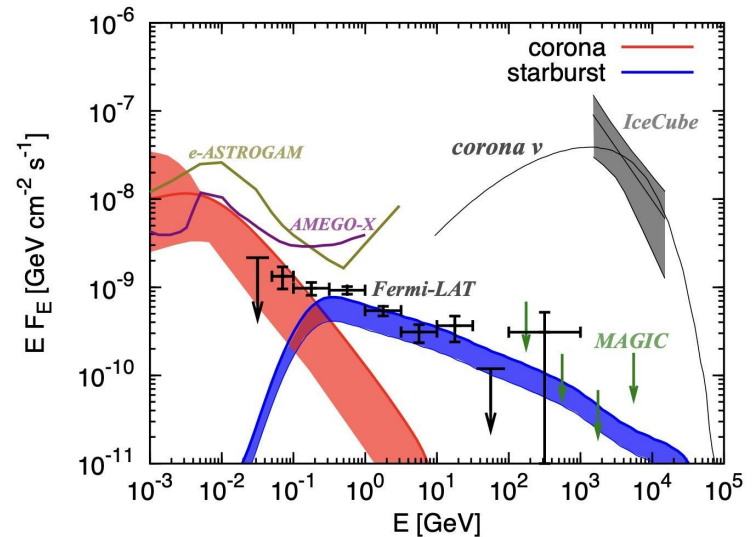
B.Eichman et al., 2207.00102

Neutrino production in Corona

- CR acceleration mechanism is unclear (spontaneous acceleration in magnetized plasma, magnetic reconnection, winds, weak jets?)
- Bethe-Heitler process $p+\gamma \rightarrow p+(e^+e^-)$
- Pair production \rightarrow IC, synchrotron emission
- Power in electromagnetic channel goes to low energies due to cascades

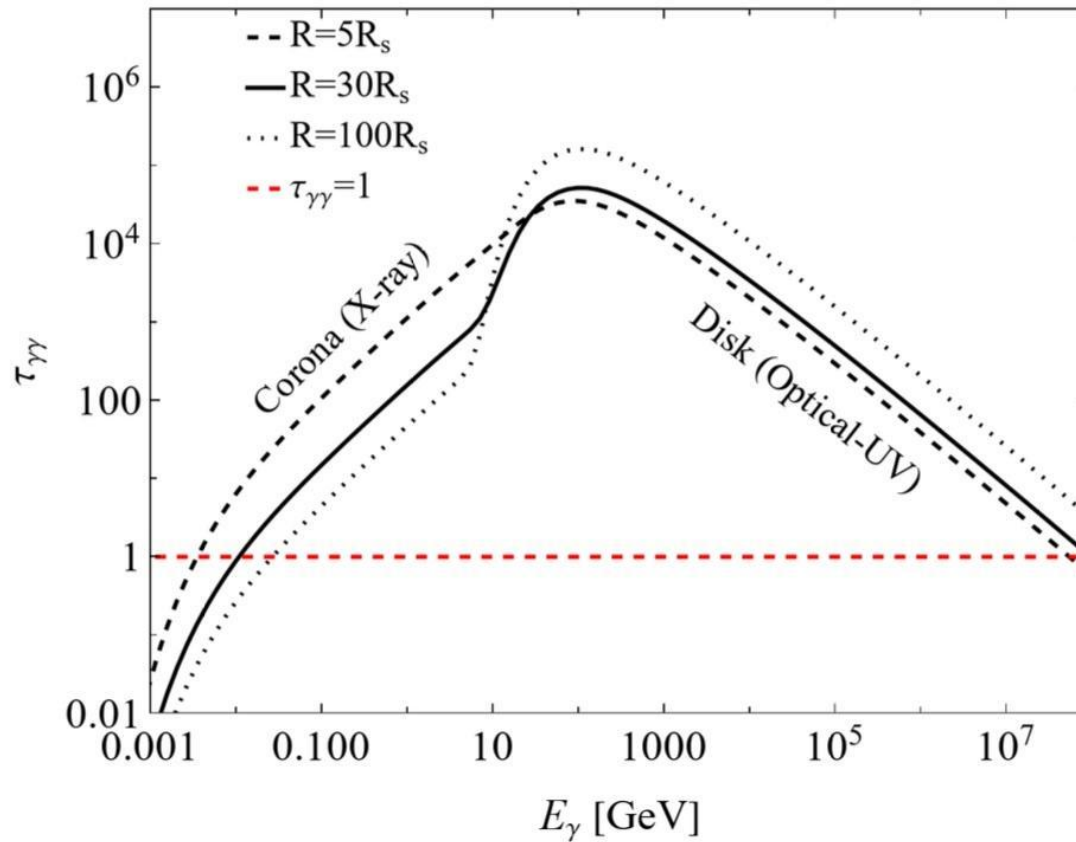


K.Murase et al arXiv:1904.04226



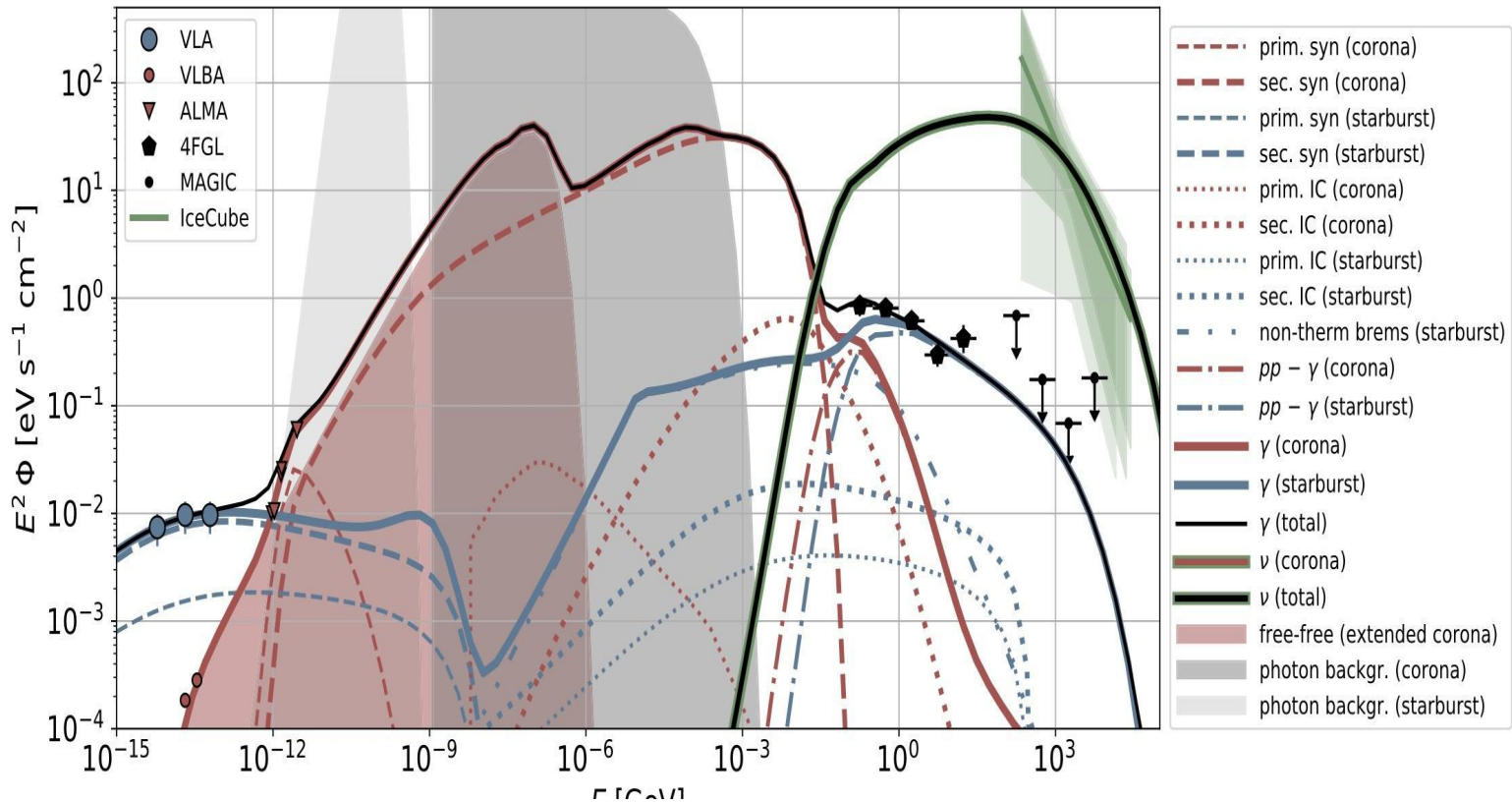
M.Ajello et al, arXiv:2307.02333

Optical depth disk-corona NGC 1068



From C. Blanco et al, arXiv:2307.03259

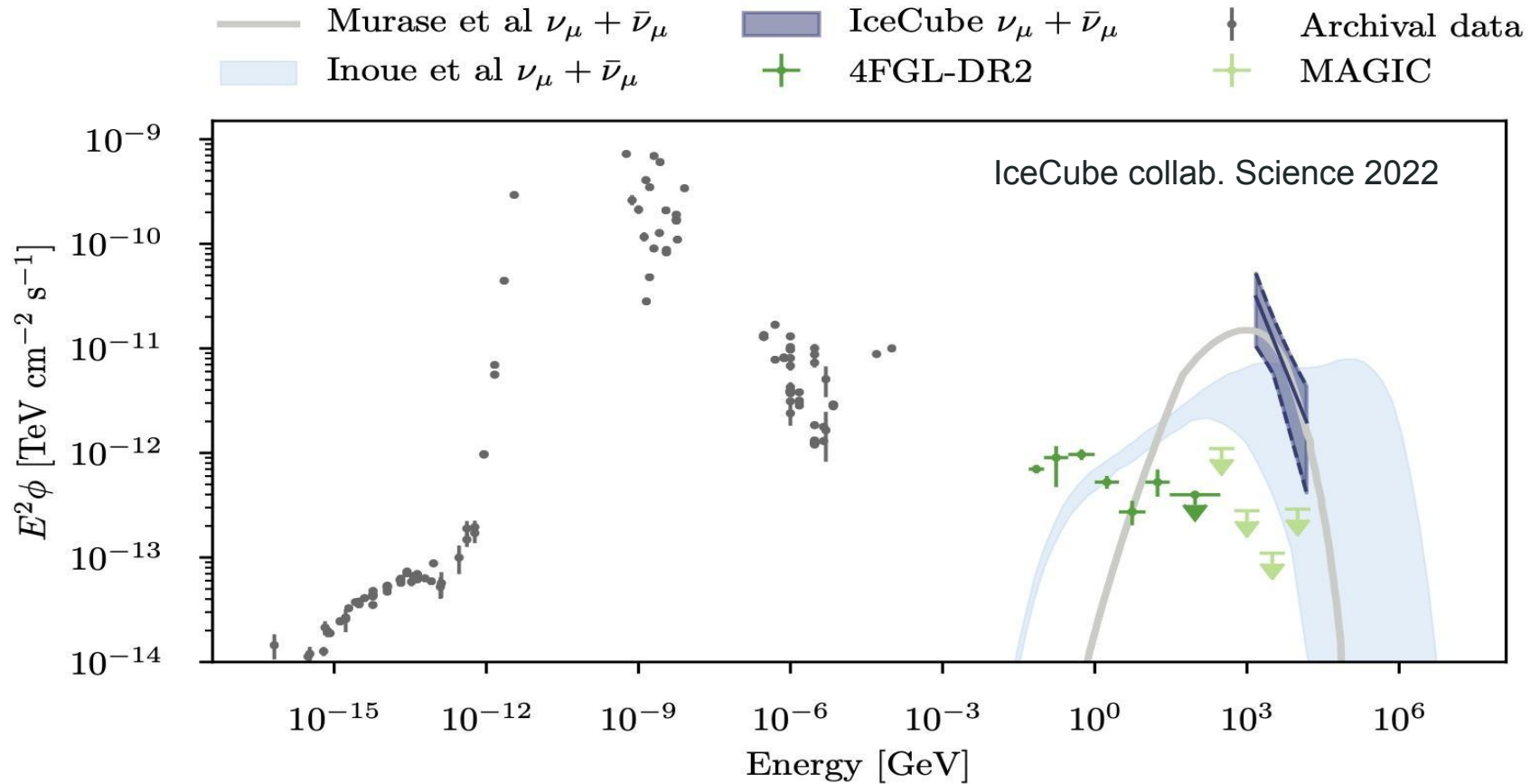
Example multimessenger model of NGC 1068



B.Eichman et al., 2207.00102

Cascade emission flux in hard X-rays is of the order of neutrino flux in the GeV-TeV range

Neutrino flux from NGC 1068



Is NGC 1068 a representative of a population?

Seyfert galaxies selection

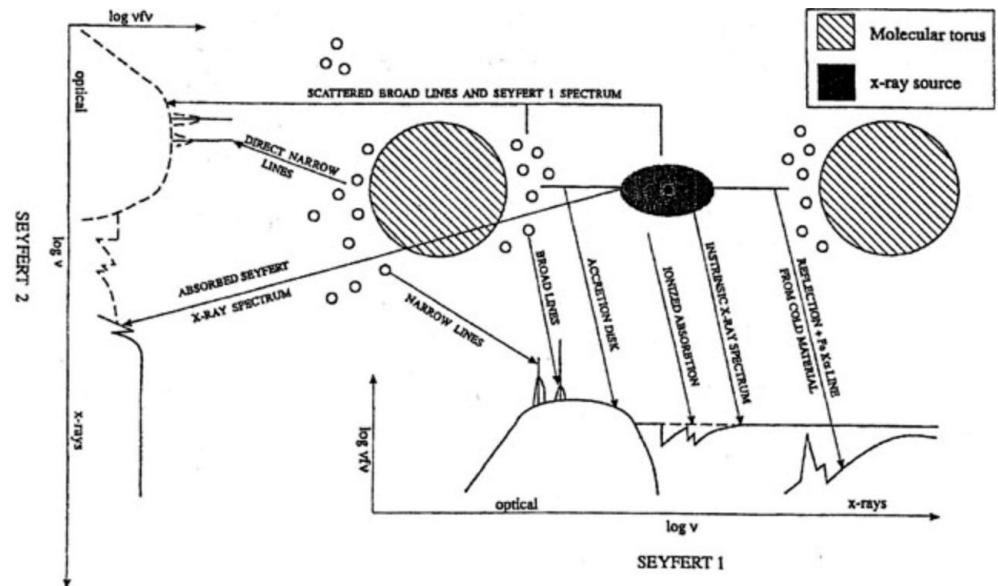
- Volume complete sample $R < 40$ Mpc of SWIFT-BAT Galaxies with high X-ray flux in 14 – 195 keV band following T. C. Fischer et al. [arXiv:2011.06570]

(25 Seyferts)

- $-5^\circ < \text{DEC} < 60^\circ$ moderate background in muon ν ; no strong absorption by the Earth

(13 Seyferts)

- NGC 1068, NGC 1320, NGC3079, NGC 7479 Compton-thick
 NGC 4388, NGC 5899 $N_{\text{H}} > 10^{23} \text{ cm}^2$
 → intrinsic hard X-ray luminosity from detailed modelling of the NUSTAR spectra



Mushotzky+ 1993

Seyfert galaxies with high intrinsic hard X-ray luminosity within 40 Mpc distance

Name	<i>RA</i>	<i>Dec</i>	<i>D</i>	<i>F_{hX}</i>	<i>L_{hX0}</i>	<i>N_H</i>	Type
				14-195 keV	14-195 keV		
			Mpc	$10^{-11} \frac{\text{erg}}{\text{cm}^2\text{s}}$	$10^{43} \frac{\text{erg}}{\text{s}}$	10^{24} cm^2	
NGC 1068	40.6696342	-0.01323785	16.3	3.79	5 – 22 [3]	> 10 [4]	Sy2
NGC 1320	51.2028681	-3.04226840	38.4	1.31	0.27 [5] ^a	3 – 6 [6]	Sy2
IC 2461	139.9914308	+37.19100007	32.3	1.91		0.08 [7]	Sy2
NGC 3079	150.4908469	+55.67979744	15.9	3.67	1.0 – 1.6 [5]	2.5 [8], 3.2 [4], 8.5[1]	Sy2
NGC 3227	155.8774015	+19.86505766	16.8	11.24		0.009 – 0.07 [7]	Sy1
NGC 3786	174.9271391	+31.90942732	38.4	1.46		0.02 [7]	Sy2
NGC 4151	182.6357547	+39.40584860	14.2	61.89		0.08 [8]	Sy1
NGC 4235	184.2911678	+7.19157597	34.5	3.86		0.003 [8]	Sy1
NGC 4388	186.4449188	+12.66215153	36.2	27.89	1.4 – 1.5 [5]	0.5 [8]	Sy2
NGC 5290	206.3297085	+41.71241871	37.1	1.49		0.0095 [8]	Sy2
NGC 5506	213.3119888	-3.20768334	26.7	23.94		0.012 [8]	Sy1.9
NGC 5899	228.7634964	+42.04991289	37.1	2.04	0.3 [5]	0.11 [8]	Sy2
NGC 7479	346.2359605	+12.32295297	34.0	1.69	0.9 [9]	5.7 [8]	Sy2

^aRecalculated to 14-195 keV assuming E^{-2} spectrum.

Volume complete sample of Seyfert galaxies with luminosity $L_{\text{hX}} > 10^{42}$ erg/s in $-5^\circ < \delta < 60^\circ$ declination strip.

IceCube 10 years open data Likelihood analysis

IceCube 10 years open data, muon events [arXiv:2101.09836]:

- event lists
- tabulated effective area
- tabulated MC data → spatial and energy distribution of background

Likelihood analysis:

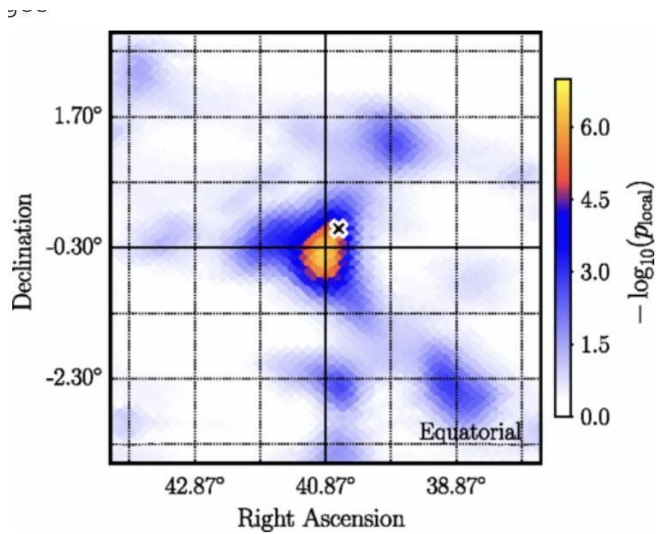
$$\mathcal{S}(\mathbf{x}_S, \mathbf{x}_i, \sigma_i, E_i; \gamma) = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S(E_i, \sin \delta_i; \gamma)$$

$$\mathcal{B}(\sin \delta_i, E_i) = \mathcal{P}_B(\sin \delta_i) \times \mathcal{E}_B(E_i, \sin \delta_i)$$

$$\log L(N_s) = \sum_i \log \left(\frac{N_s}{N_t} S_i + \left(1 - \frac{N_s}{N_t}\right) B_i \right)$$

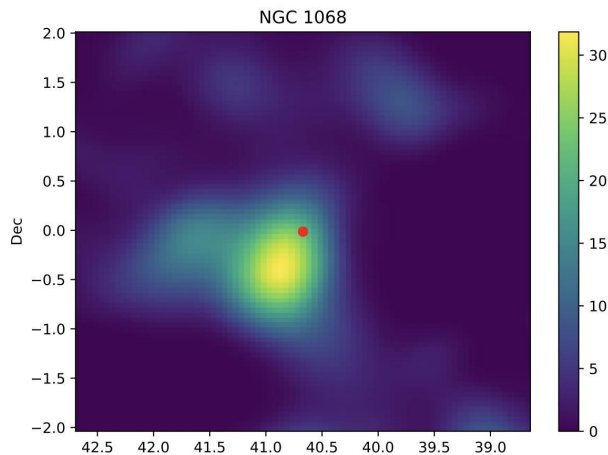
$$TS(N_s) = 2(\log L(N_s) - \log L(0))$$

IceCube data analysis NGC 1068: significance map



$$\log L(N_s) = \sum_i \log \left(\frac{N_s}{N_t} S_i + \left(1 - \frac{N_s}{N_t} \right) B_i \right)$$

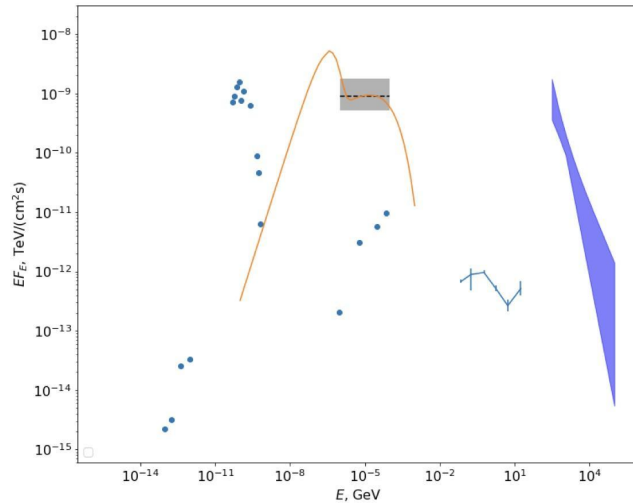
IceCube 2020 Phys. Rev. Lett. **124**, 051103



Our analysis of public 10 yr IceCube data

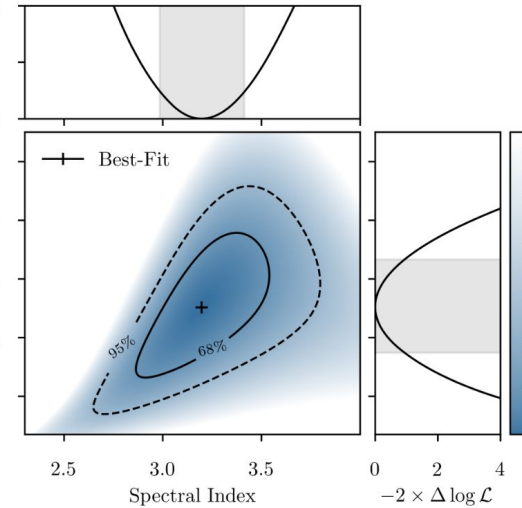
$$TS(N_s) = 2(\log L(N_s) - \log L(0))$$

IceCube data analysis NGC 1068: spectrum



Our analysis of IceCube 10-year data

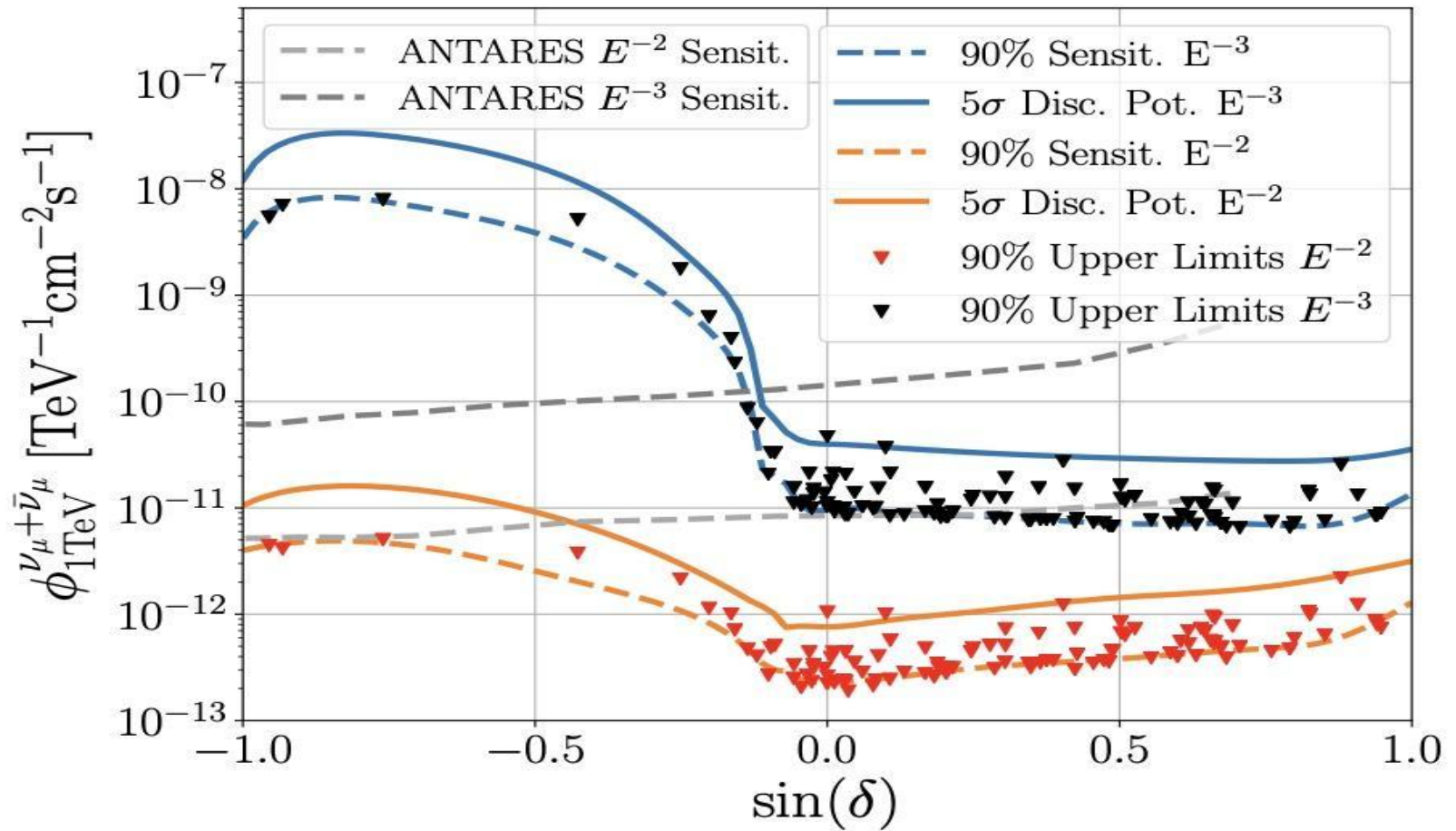
$$G = 3.3 \pm 0.3$$



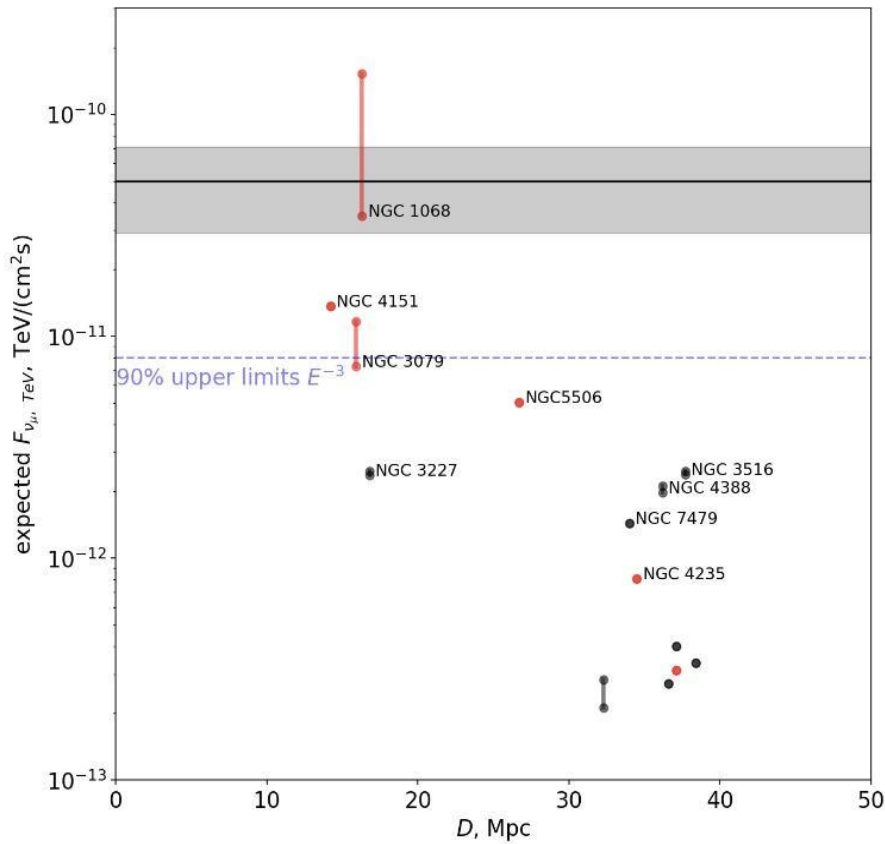
IceCube Science, arXiv:2211.09972

$$G = 3.2 \pm 0.2$$

IceCube sensitivity



Final catalog: ν sources above detection threshold



X-ray – ν correspondance from NGC1068

$$F_{\nu_{\mu}, TeV} \sim \frac{0.02 L_{hX0}}{4\pi D^2}$$

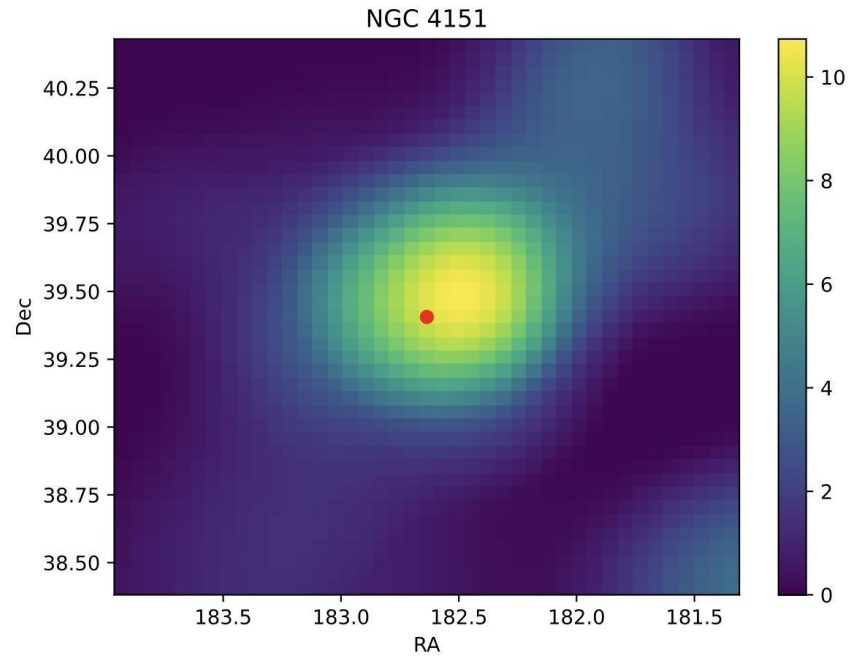
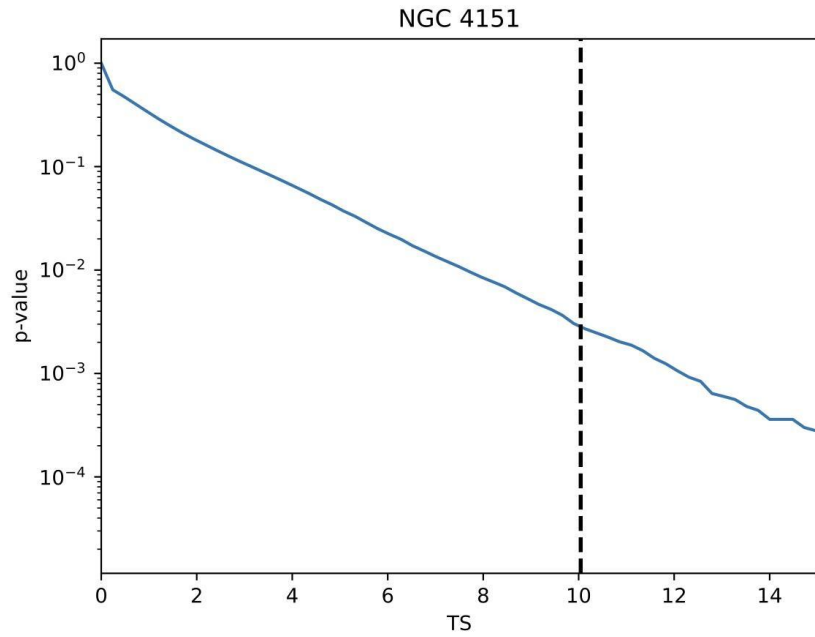
Only 3 sources above detection threshold

We exclude NGC1068
(was used to formulate the hypothesis)

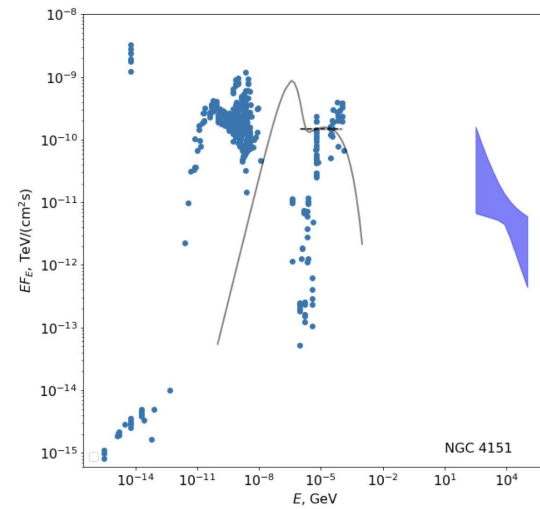
Final catalog:

2 sources
NGC 4151
NGC 3079

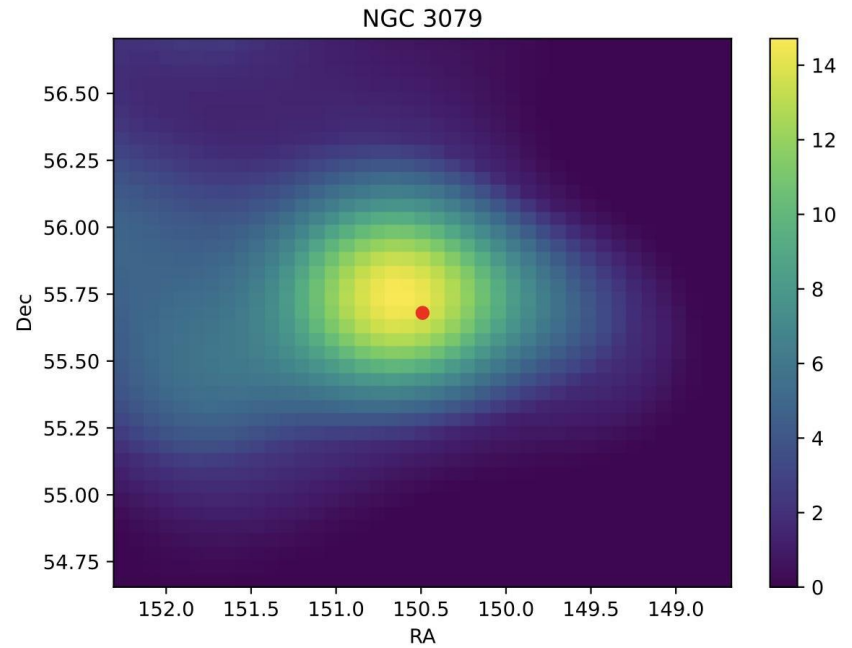
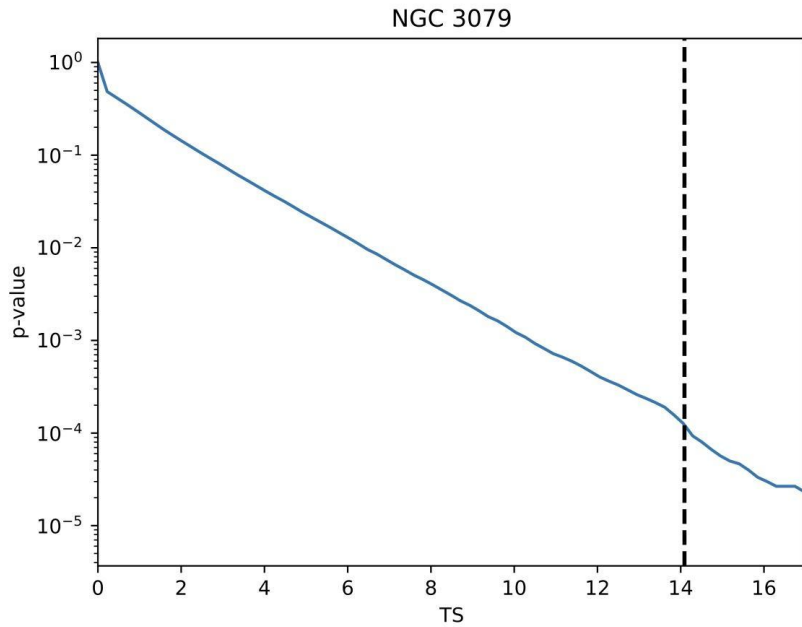
NGC 4151



$$P_{4151} = 2.7 \cdot 10^{-3}$$

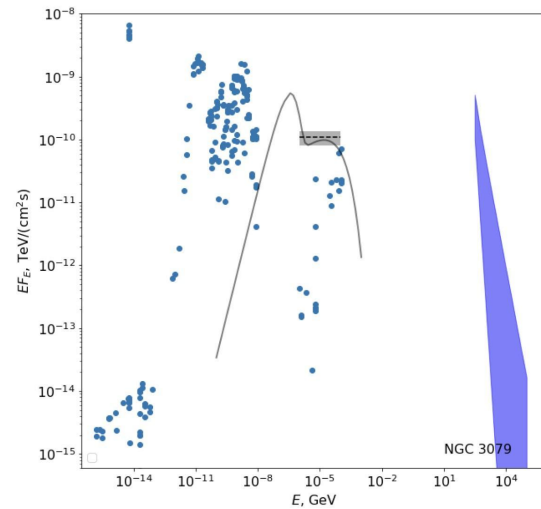


NGC 3079

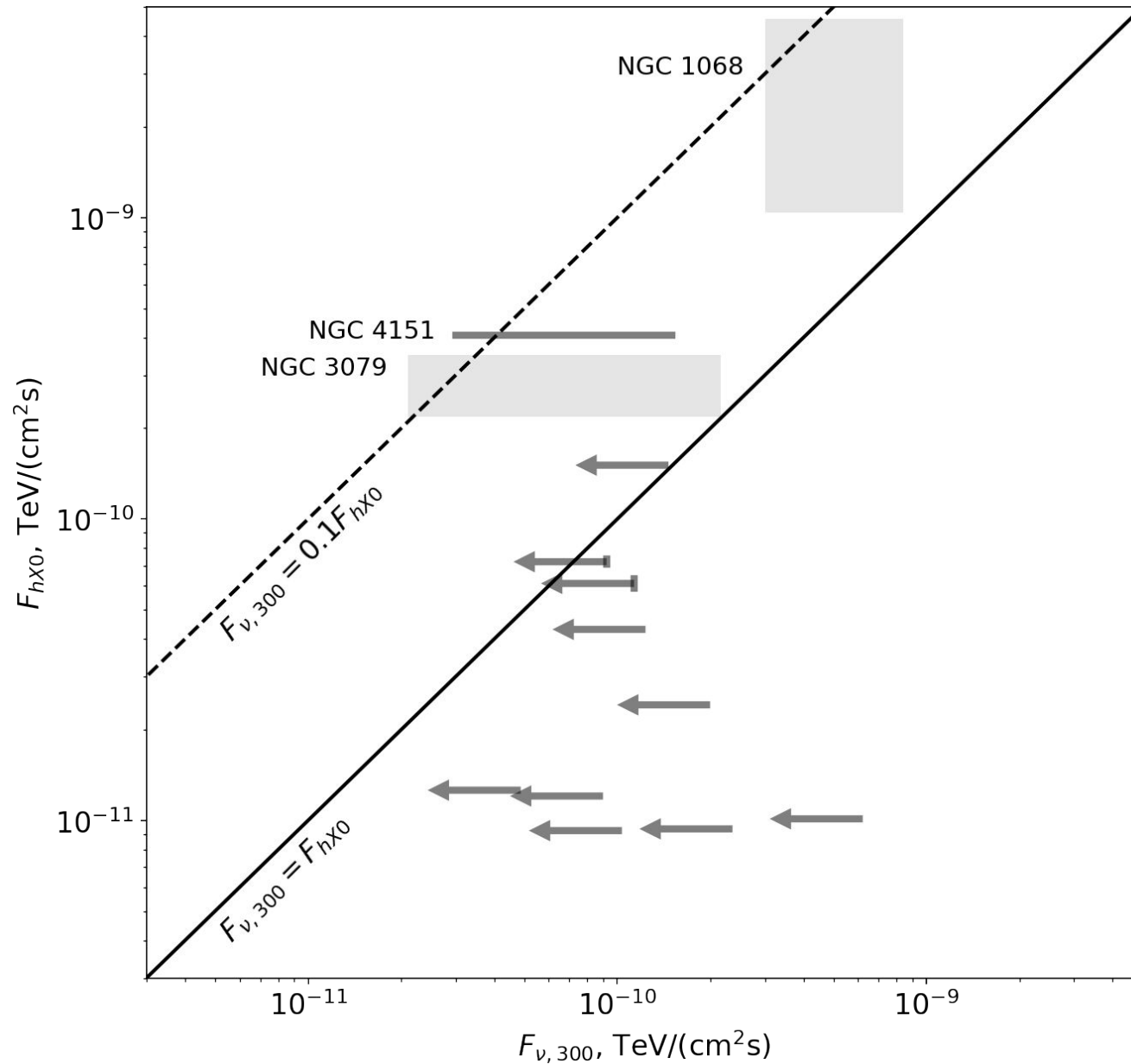


$$P_{3079} = 9.3 \cdot 10^{-5}$$

Total probability $P_{\text{tot}} < 2.6 \cdot 10^{-7}$



No neutrino signal from other Seyferts



Summary

- We selected volume complete sample of Seyfert galaxies with high intrinsic hard X-ray luminosity within 40 Mpc from Milky Way and pre-selected 13 sources potentially visible to IceCube.
- Based on NGC 1068 model, we predicted that 3 of 13 sources can be detected with 10 years of IceCube data above 90% CL.
This includes NGC 1068, NGC 3079 and NGC 4051
- We excluded NGC 1068 from analysis. Final catalogue has only 2 sources.
- In 10-years public catalogue of IceCube muon neutrinos, we searched for neutrino signal from NGC 3079 and NGC 4051. Using likelihood analysis, we found that both sources show evidence of neutrino flux with p-values $9.3 \cdot 10^{-5}$ and $2.7 \cdot 10^{-3}$
- Combined probability $< 2.6 \cdot 10^{-7}$
- Thus, we established that Seyfert galaxies with high intrinsic hard X-ray luminosity are sources of astrophysical neutrinos