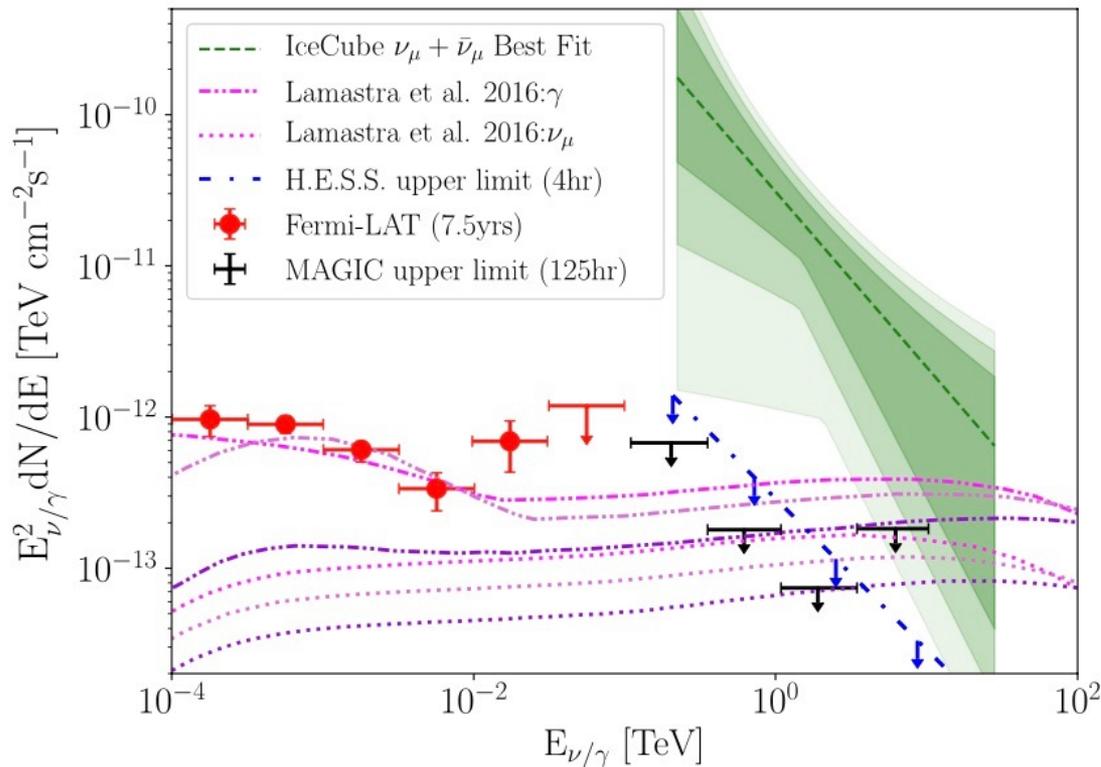


Neutrinos from Seyfert galaxies

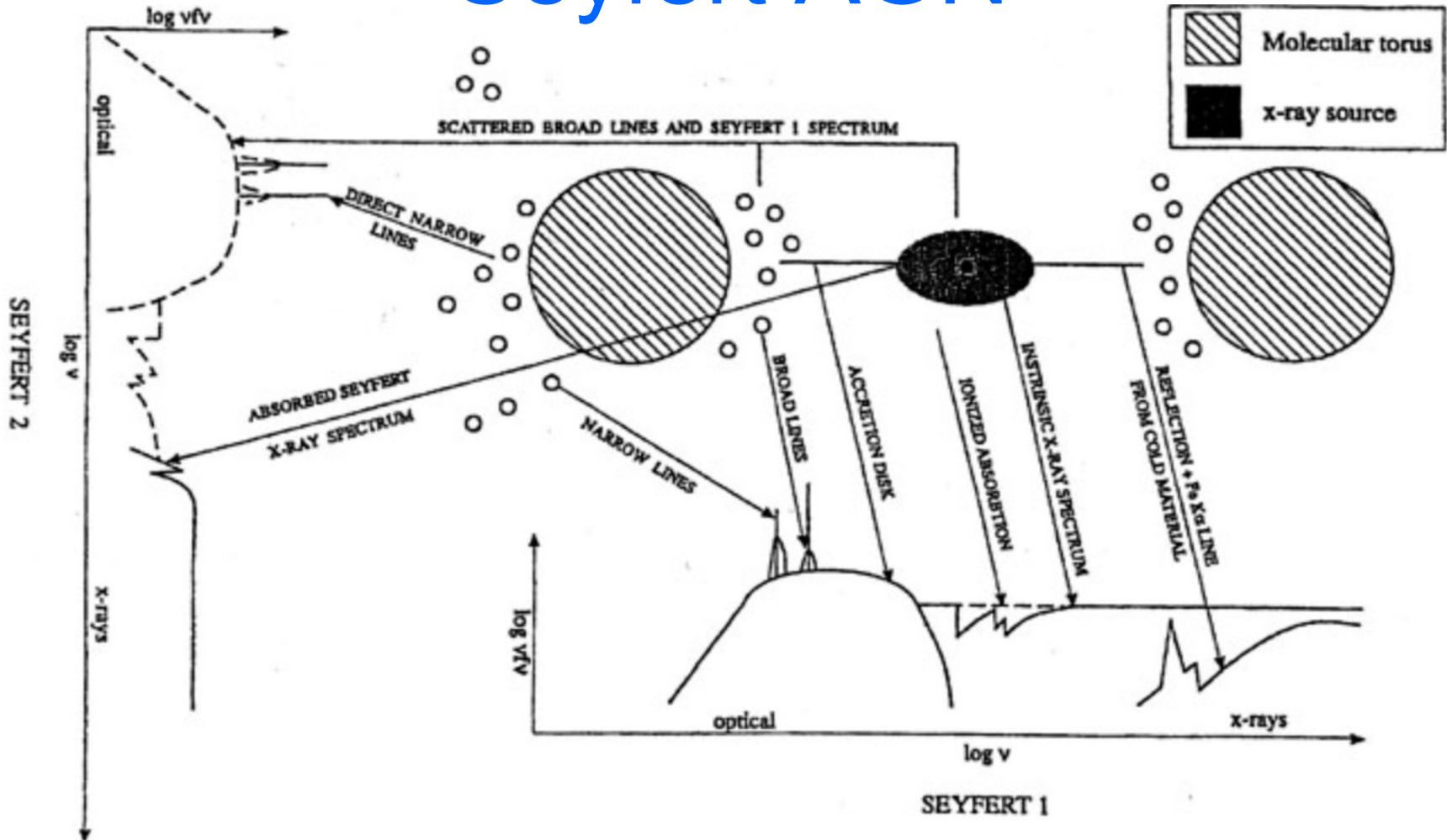
Dmitri Semikoz
APC, Paris

Based on Andrii Neronov, Denis Savchenko
and D. S., arXiv: 2306.09018

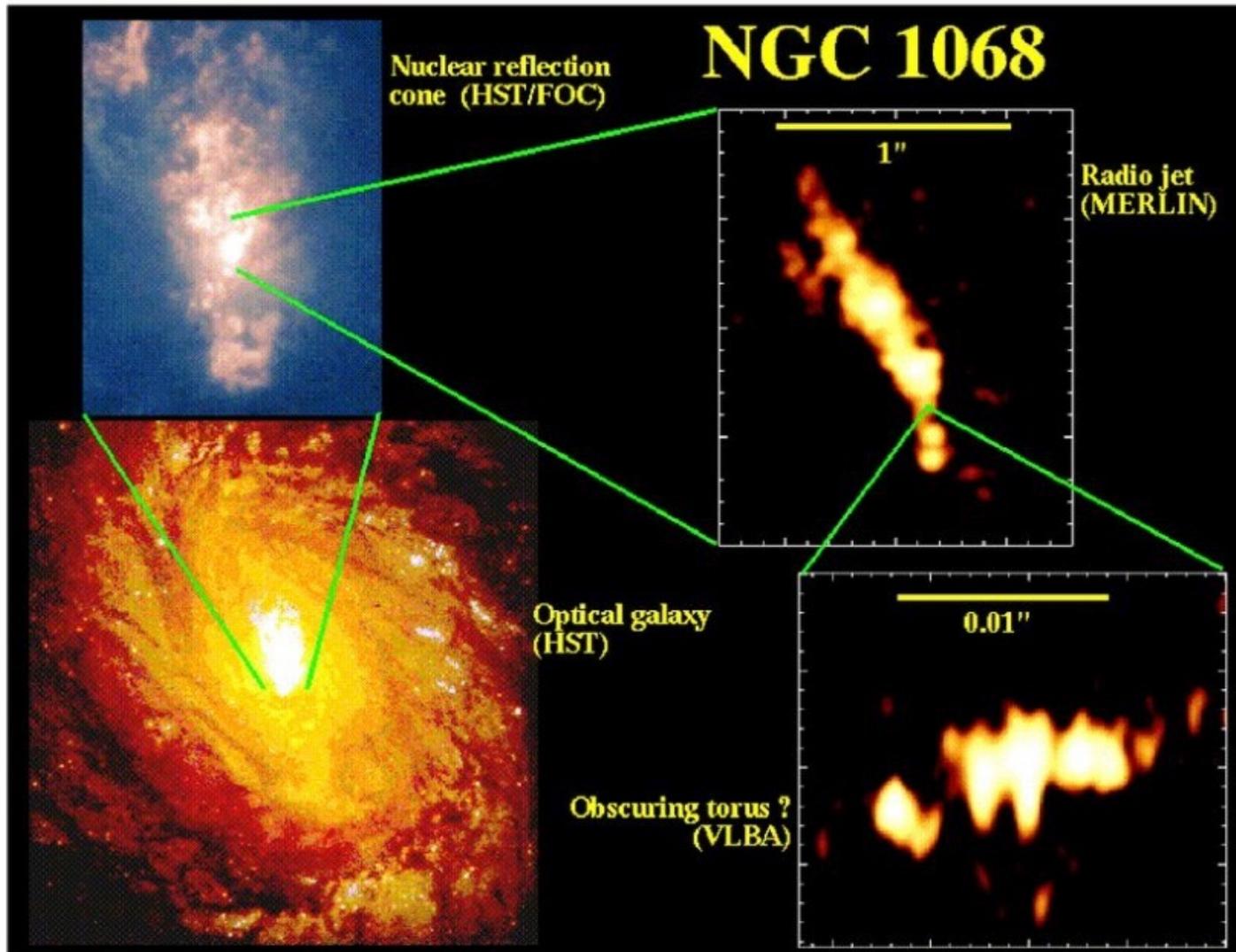
“Unexpected” neutrinos from NGC 1068



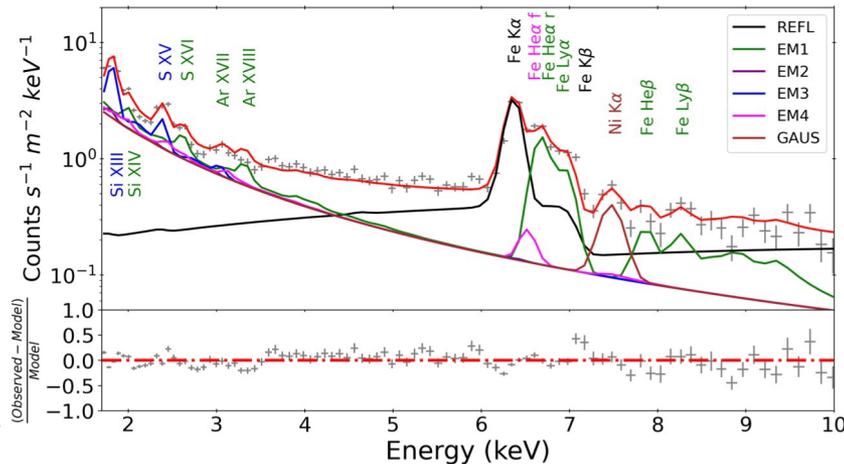
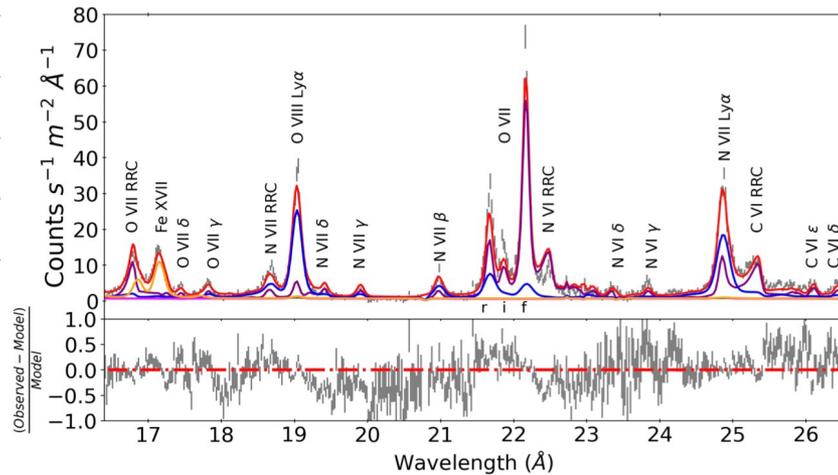
Seyfert AGN



NGC 1068 radio observations



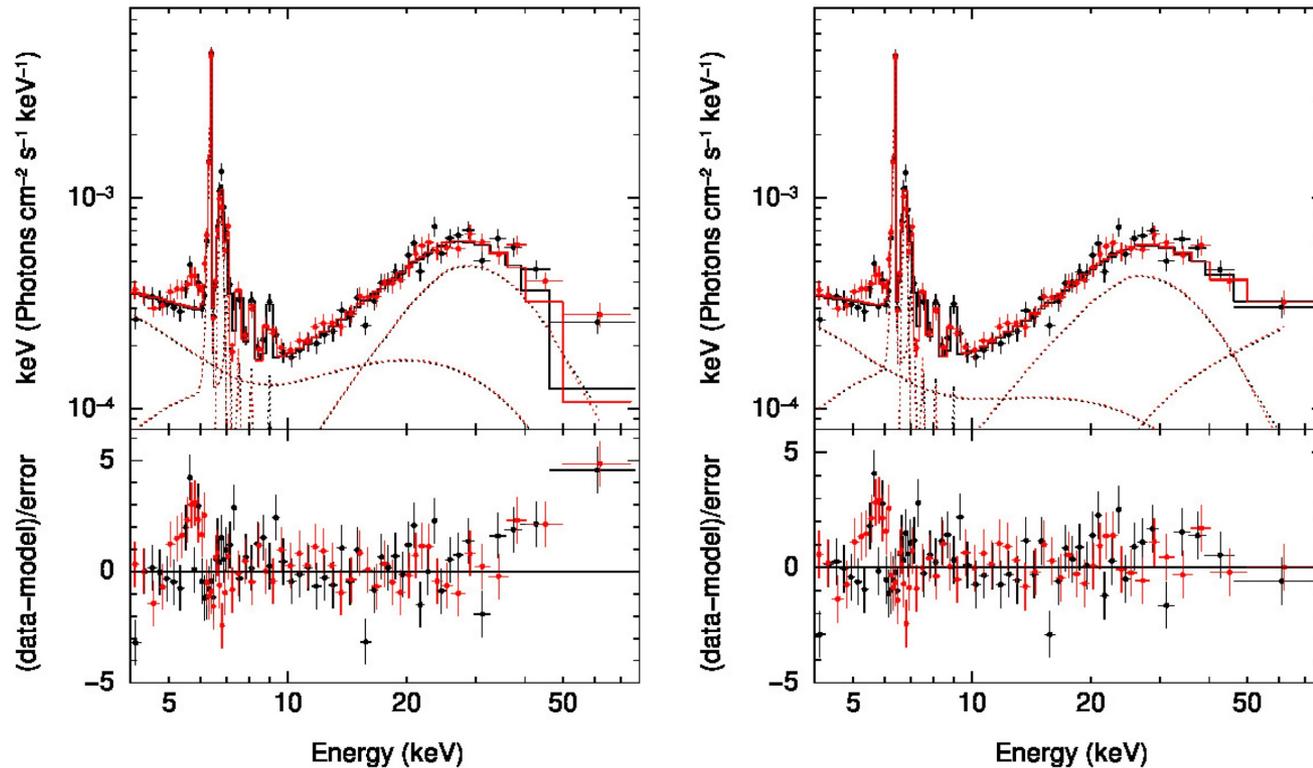
X-ray flux from NGC 1068: lines



photoionised X-ray
emission line regions
Does not change in time
2000 -2014

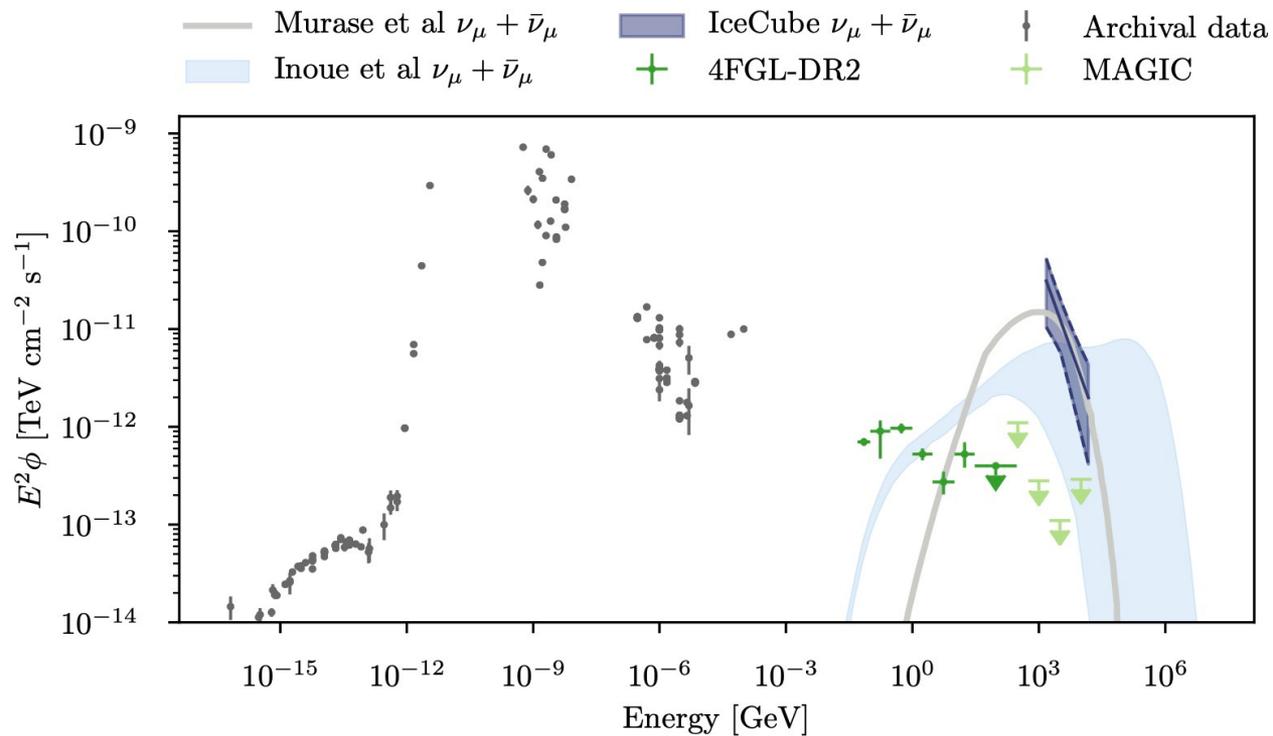
S. Grafton-Waters
et al, 2103.13374

Hard X-ray flux from NGC 1068: reflected emission



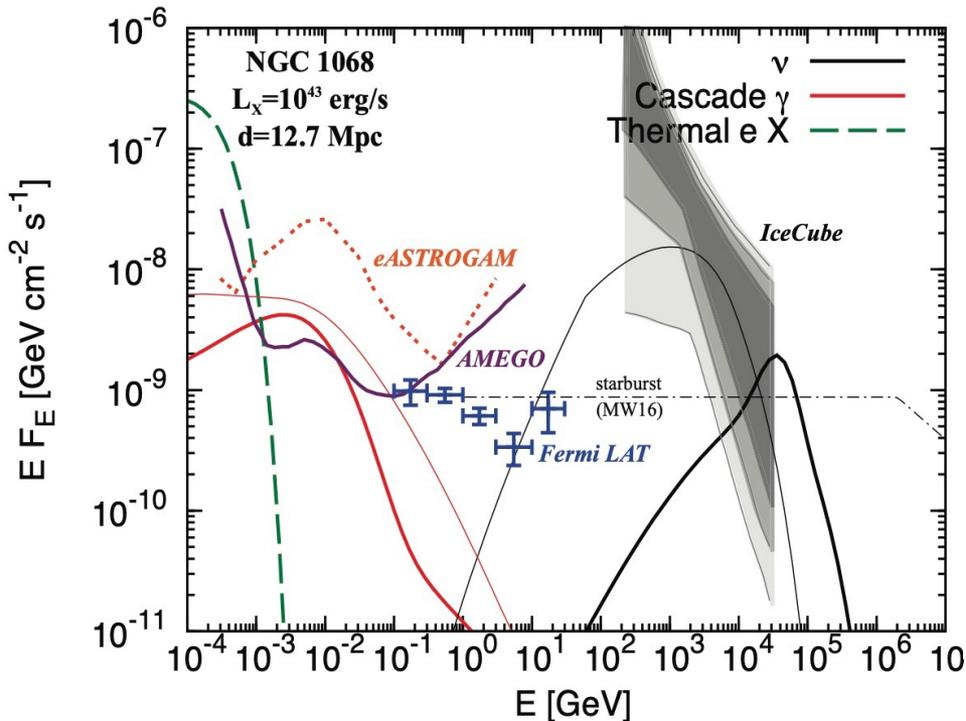
Corona temperature $T_c=9$ keV
I.Pal et al, 2209.10261

Neutrino flux from NGC 1068

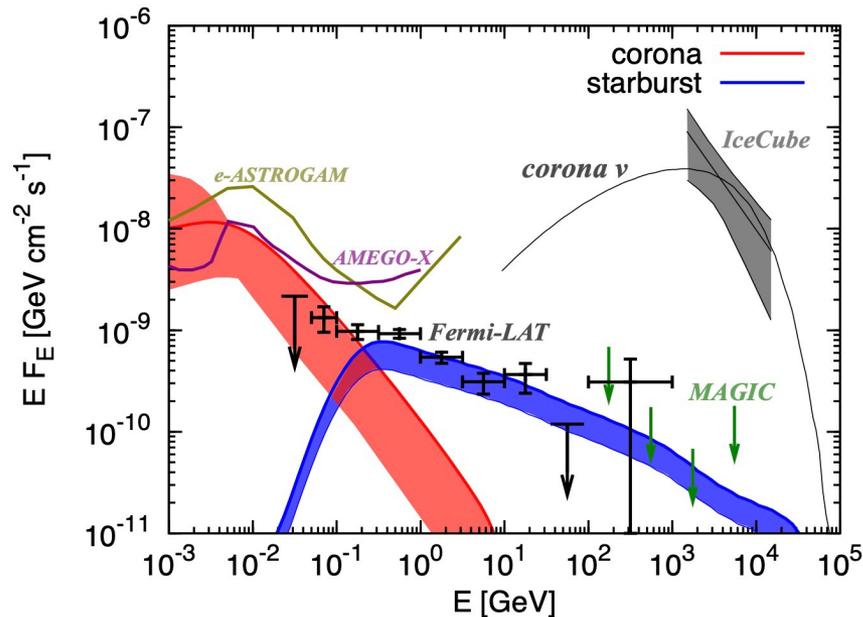


IceCube collab. Science 2022, [arXiv:2211.09972]

Bethe-Heitler process $p+\gamma \rightarrow p+(e^+ e^-)$



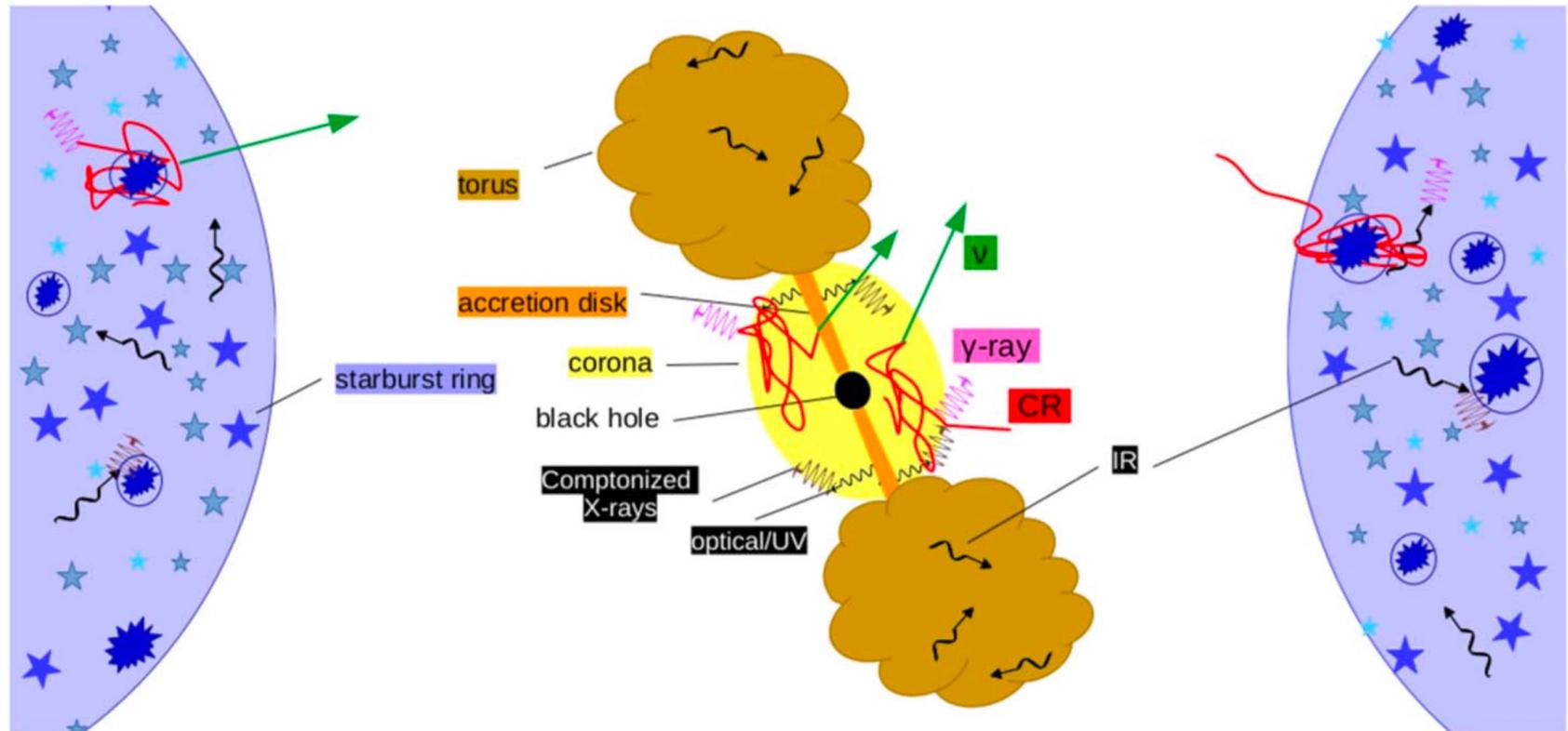
K.Murase et al arXiv:1904.04226



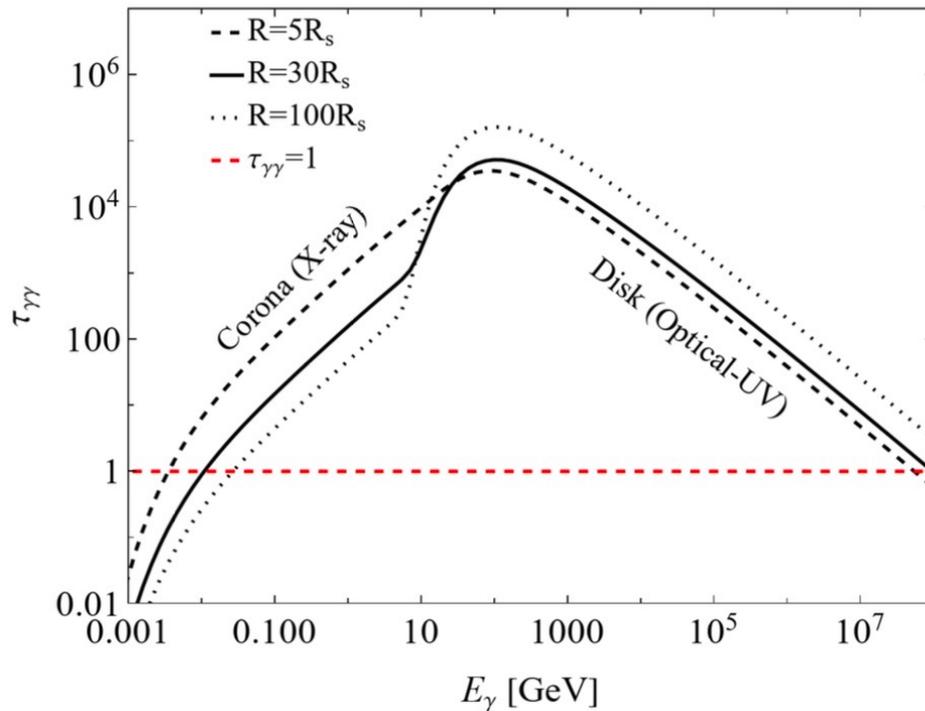
M.Ajello et al, arXiv:2307.02333

At low energies protons loose energy due to e^+e^- production

Seyfert AGN

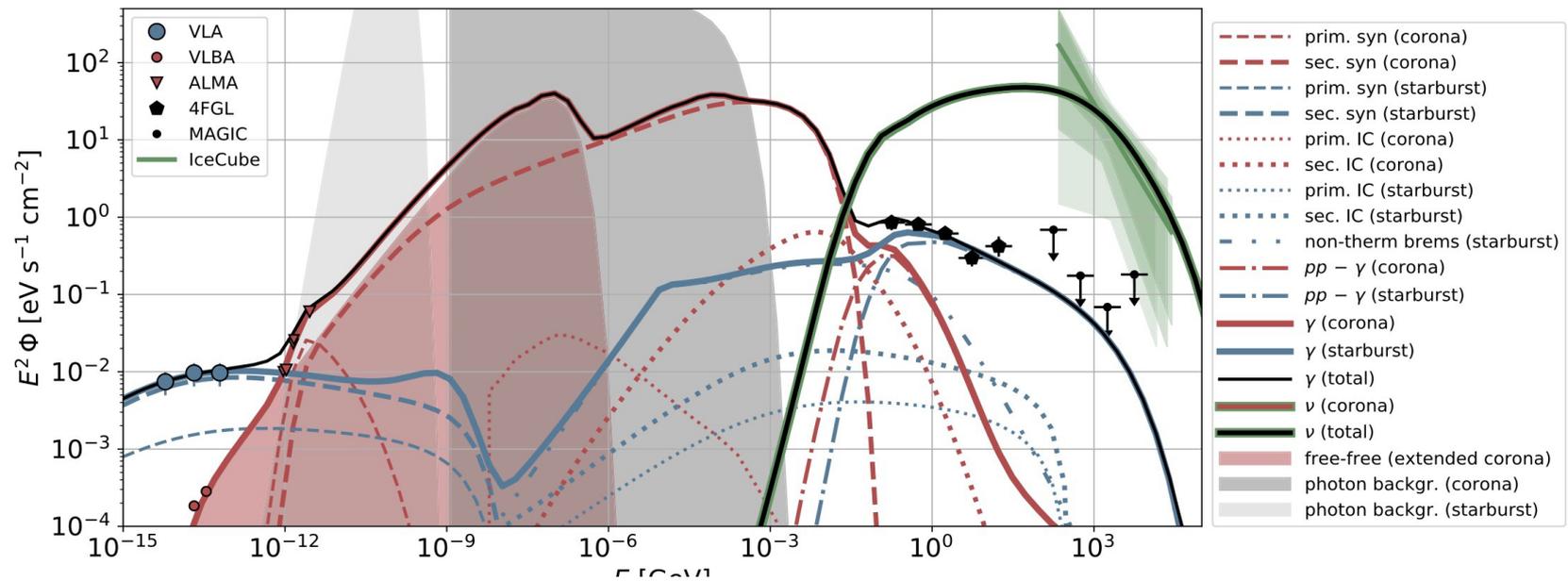


Optical depth disk-corona NGC 1068



From C. Blanco et al, arXiv:2307.03259

Neutrino flux from NGC 1068



B.Eichman et al, 2207.00102

Seyfert galaxies selection

- We took 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
- We took $DEC > 5$ deg in order to have good IceCube background rejection and $DEC < 60$ dec to not have absorption in Earth at high energies. End up with 13 sources

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

Name	<i>RA</i>	<i>Dec</i>	<i>D</i>	F_{hX}	L_{hX0}	N_H	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.

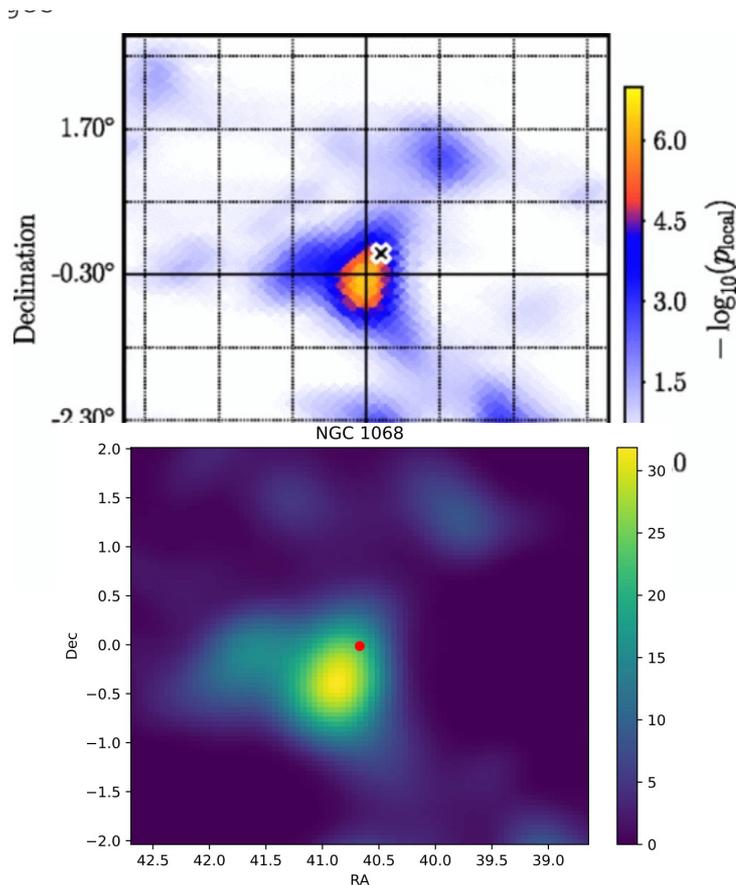
TABLE I: Volume complete sample of Seyfert galaxies with luminosity $L_{hX} > 10^{42}$ erg/s in $-5^\circ < \delta < 60^\circ$ declination strip, from Ref. [1]. *Ra*, *Dec*, distances *D* and Seyfert types are from [1]. 14-195 keV fluxes F_{hX} are from [10].

$$N_H \gtrsim \sigma_T^{-1} = 1.5 \times 10^{24} \text{ cm}^{-2}$$

Neutrino analysis NGC 1068: sky map

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

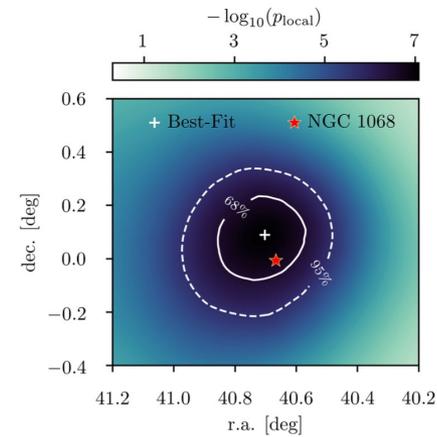
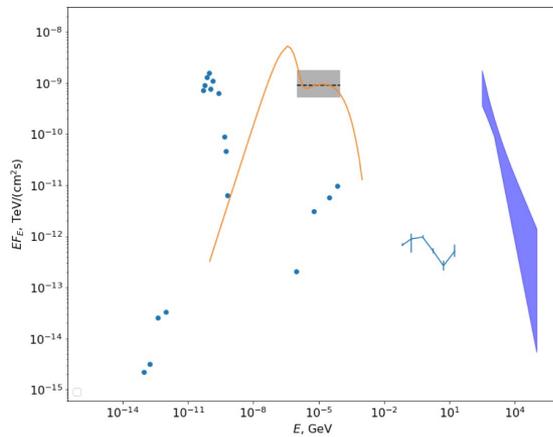
10 years catalog muon neutrinos
IceCube 2020 Phys. Rev. Lett. **124**, 051103



Our analysis of IceCube
public 10-years catalog muon neutrinos

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

Neutrino analysis NGC 1068: spectrum



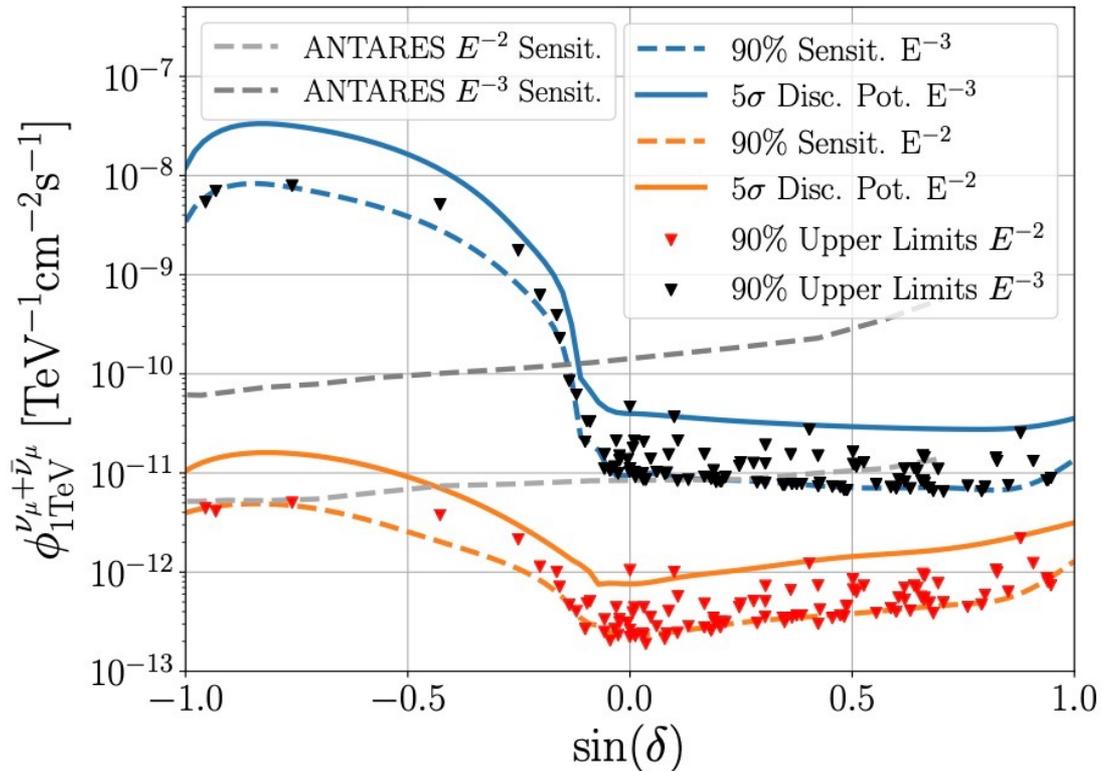
Our analysis of IceCube 10-years catalog

$$G = 3.3 \pm 0.3$$

IceCube Science, arXiv:2211.09972

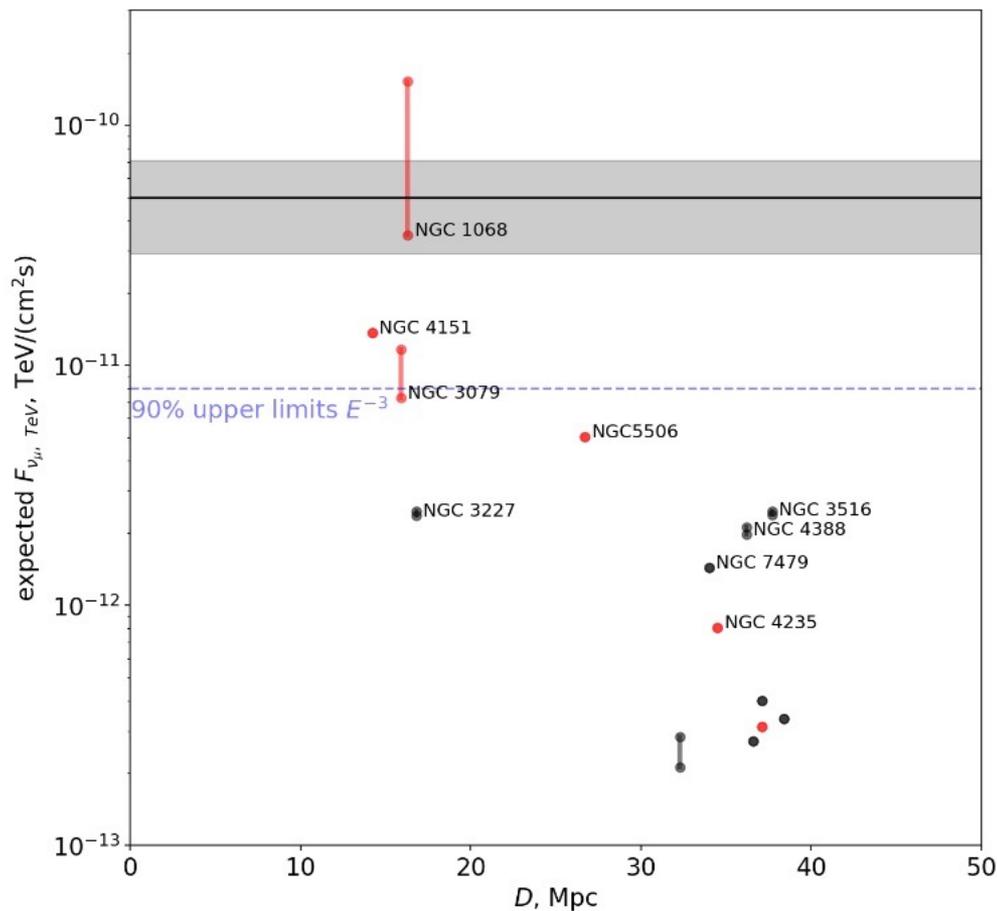
$$G = 3.2 \pm 0.2$$

90 % limits point sources



Estimate of neutrino flux from our list of Seyfert galaxies: only 3 above detection threshold

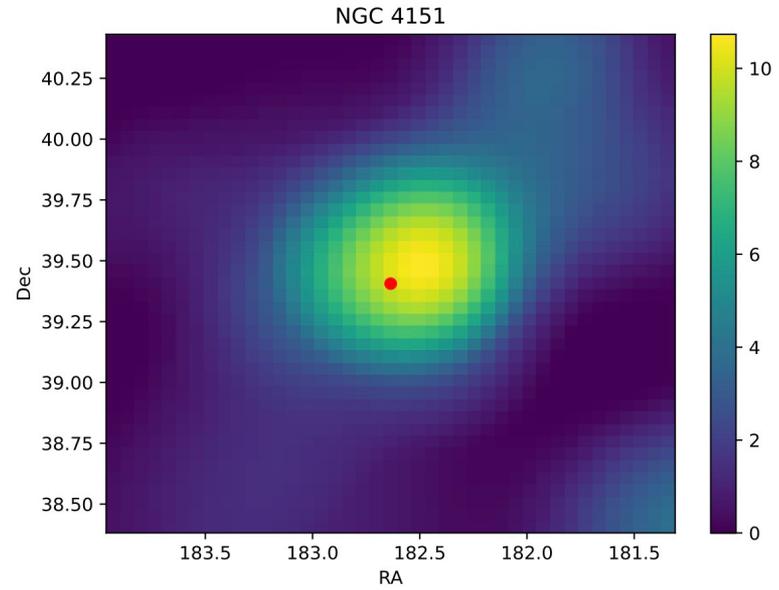
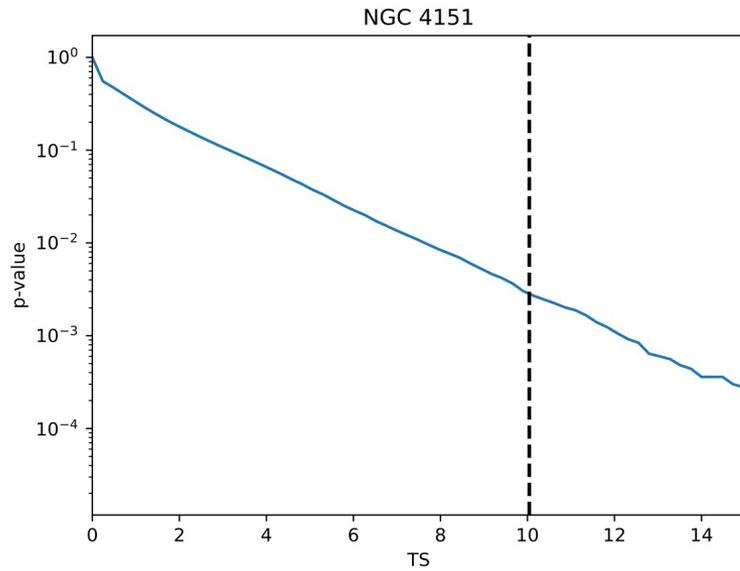
$$F_{\nu_{\mu}, TeV} \sim \frac{0.02 L_{hX0}}{4\pi D^2}$$



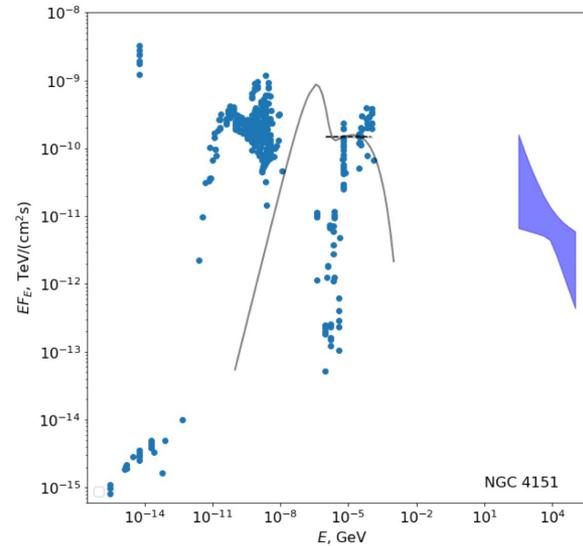
Final catalog:

2 sources
 NGC 4151
 NGC 3079

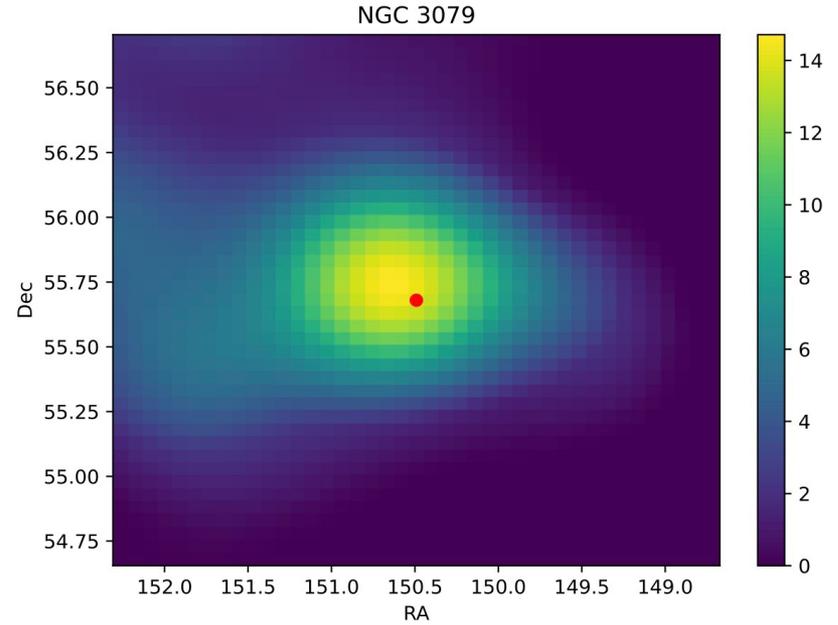
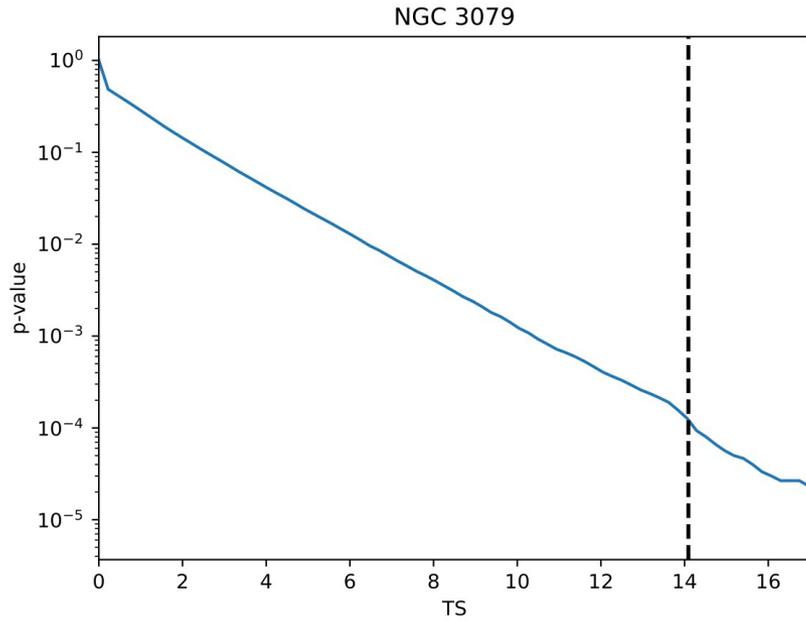
NGC 4151



$P_{4151} = 2.7e-3$

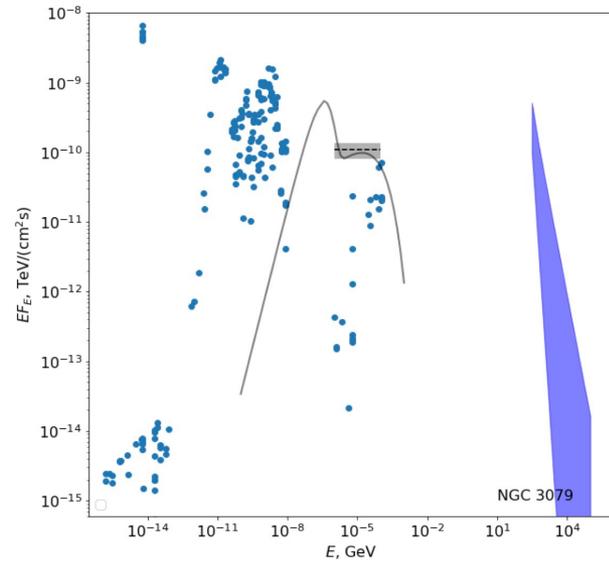


NGC 3079



$$P_{3079} = 9.3e-5$$

$$\text{Total probability } P_{\text{tot}} = 2.5e-7$$



Summary

- We selected volume complete sample of Seyfert galaxies with high hard X-ray flux 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 include NGC 1068, NGC 3079 and NGC 4051
- We excluded NGC 1068 from analysis. Final catalog has 2 sources.
- In 10-years public catalog 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 $9.3e-5$ and $2.7e-3$
- Combined probability is $2.5e-7$
- Thus, we established that Seyfert galaxies with high hard X-ray flux are sources of astrophysical neutrinos