Seyfert Galaxies as Astrophysical Neutrino Sources

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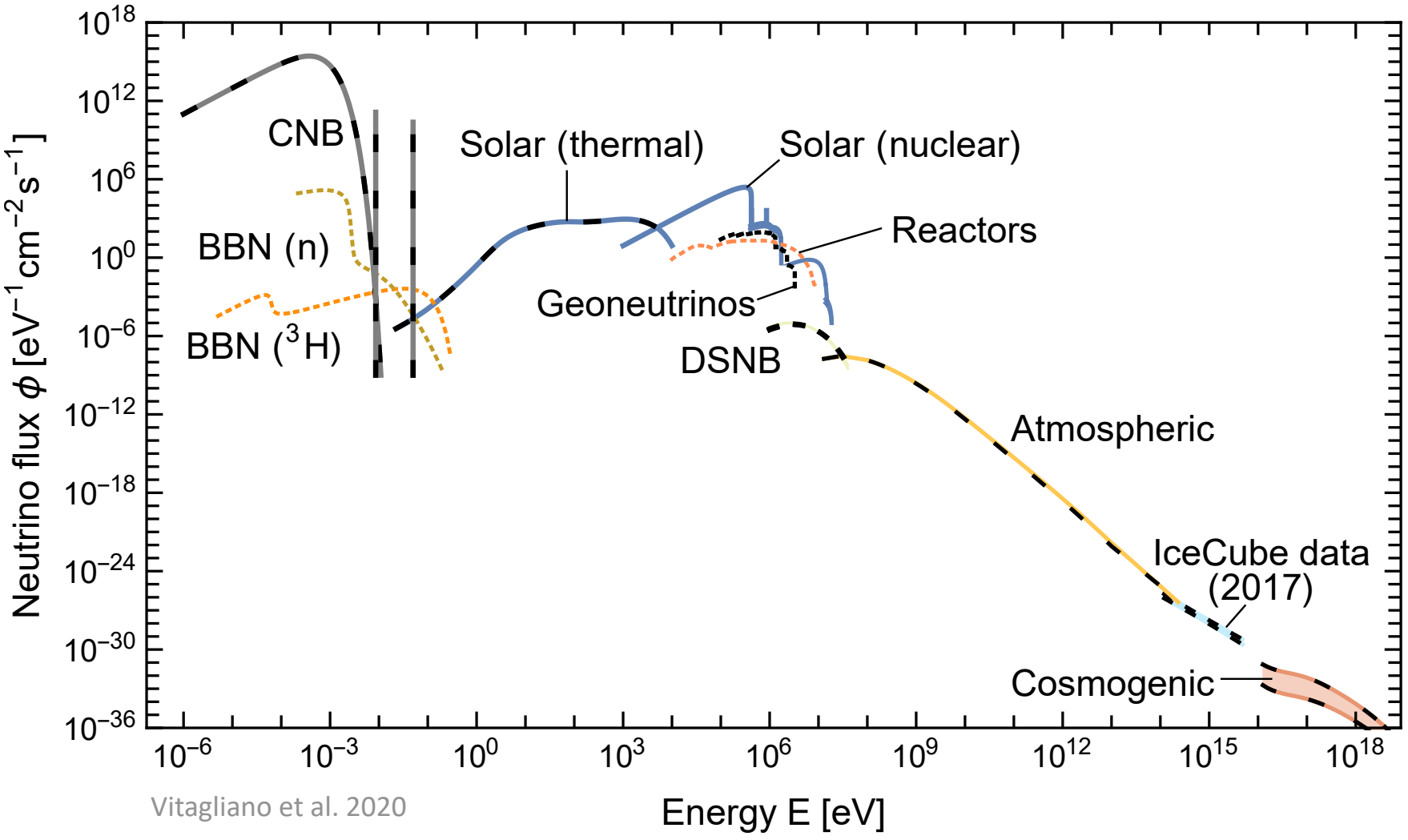
Astro & Theory Seminar NTNU

13th February 2024

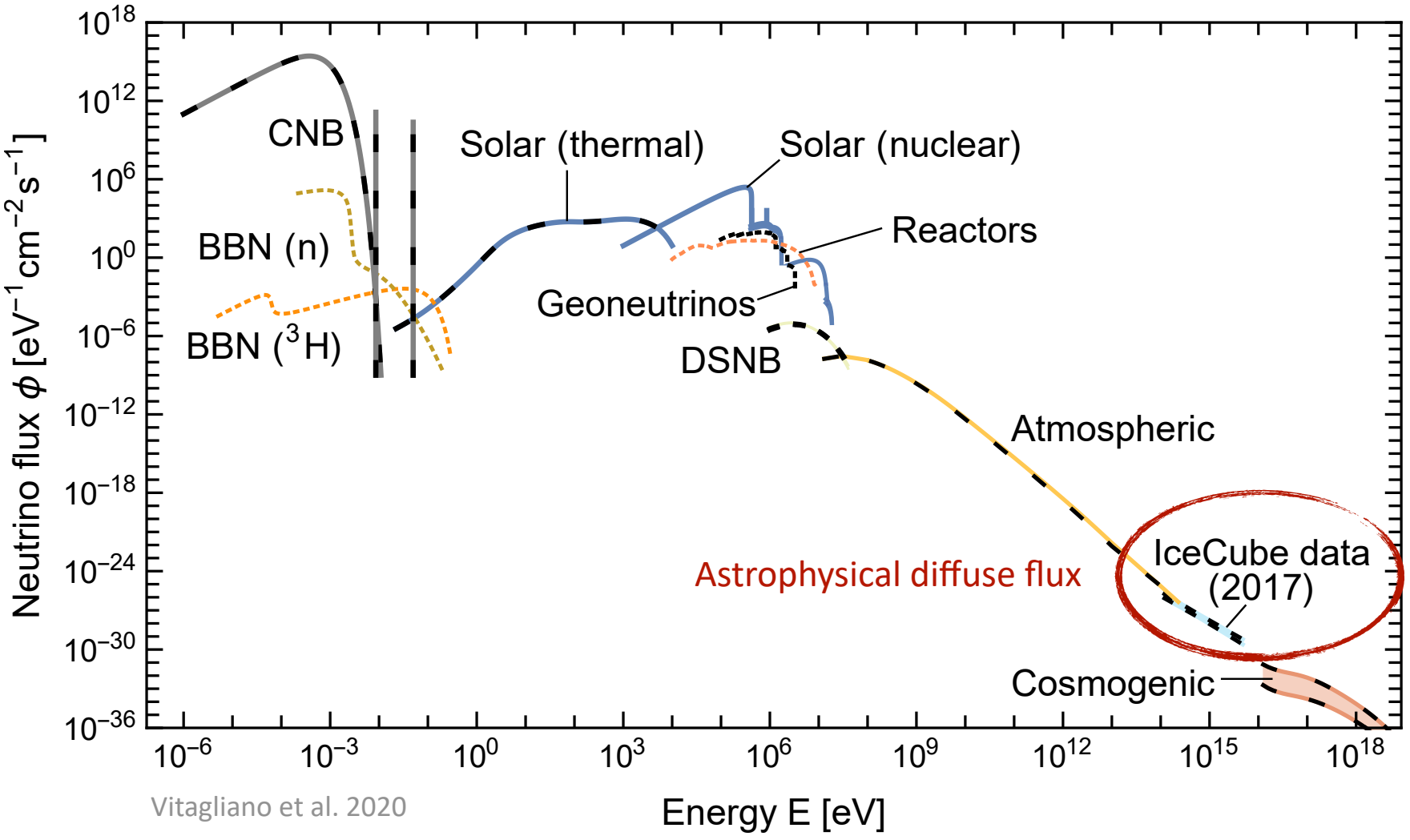
MAX-PLANCK-INSTITUT
FÜR PHYSIK

Grand Unified Neutrino Spectrum



Vitagliano et al. 2020

Grand Unified Neutrino Spectrum



Vitagliano et al. 2020

IceCube

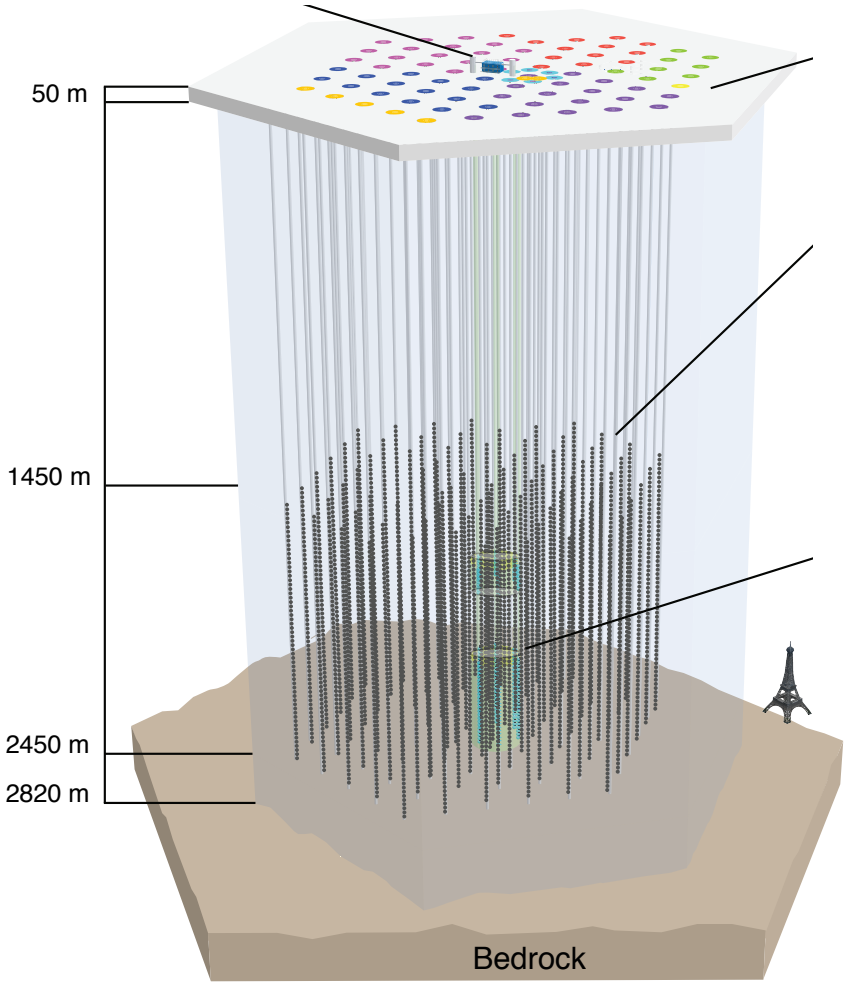
- In-ice neutrino telescope at the South Pole operating in the **TeV - PeV** range

- 2 different types of **neutrino-nucleus interactions**

  charged current: $\nu_l + N \rightarrow l + X$

  neutral current: $\nu_l + N \rightarrow \nu_l + X$

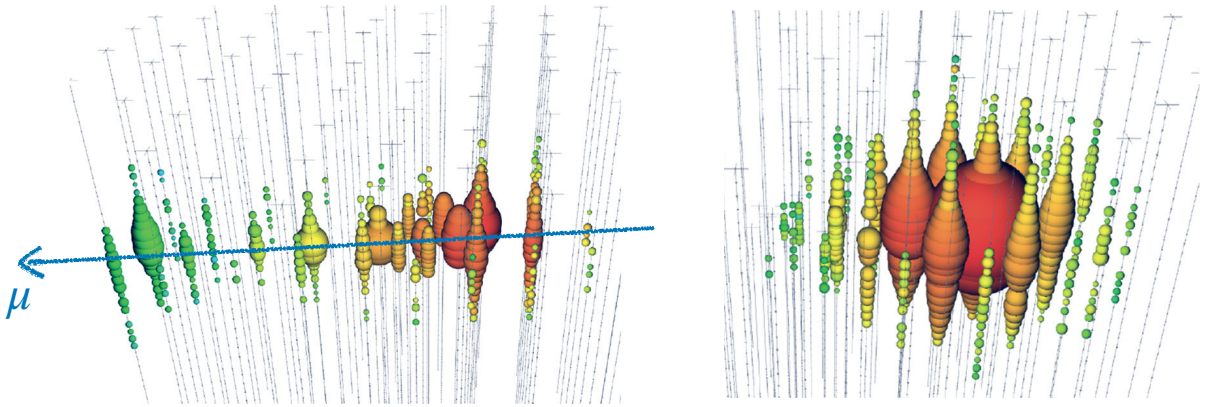
- Optical modules measure **Cherenkov radiation** emitted by secondary particles



Aartsen et al. 2017

IceCube

- 2 different types of events:

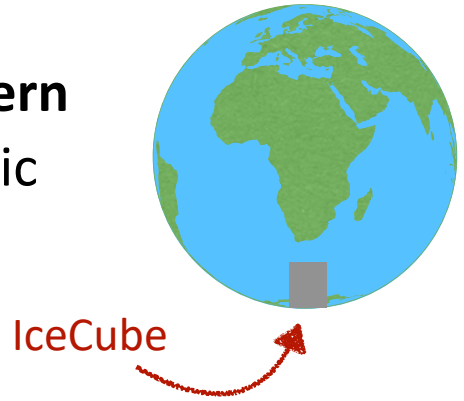


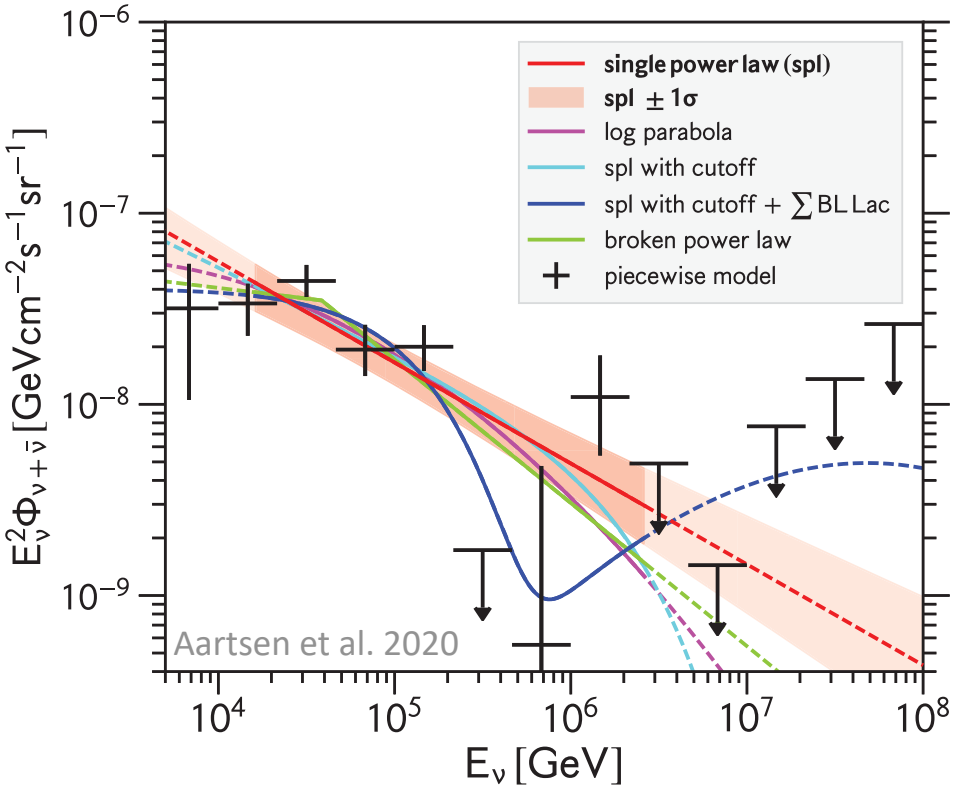
Ahlers et al. 2017

muon track

cascade

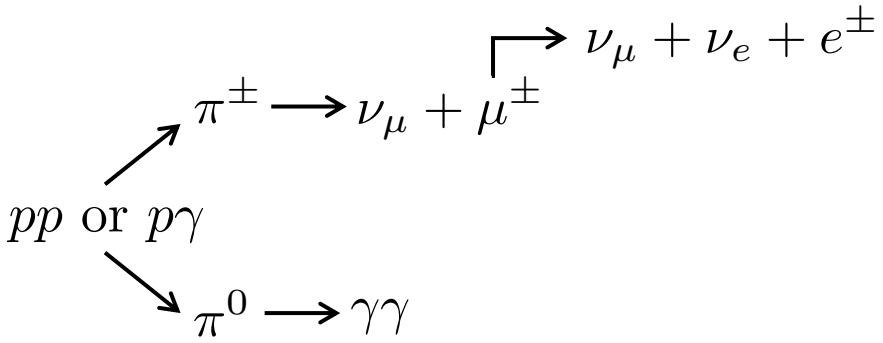
- Higher sensitivity in the **Northern hemisphere** due to atmospheric muons





Diffuse astrophysical neutrino flux

Sources of astrophysical neutrinos



Source candidates

AGNs → blazars, Seyfert galaxies

transients → GRBs, TDEs

…

Sources of astrophysical neutrinos

$$pp \text{ or } p\gamma \begin{cases} \pi^{\pm} \longrightarrow \nu_\mu + \mu^{\pm} \begin{cases} \longrightarrow \nu_\mu + \nu_e + e^{\pm} \end{cases} \\ \pi^0 \longrightarrow \gamma\gamma \end{cases}$$

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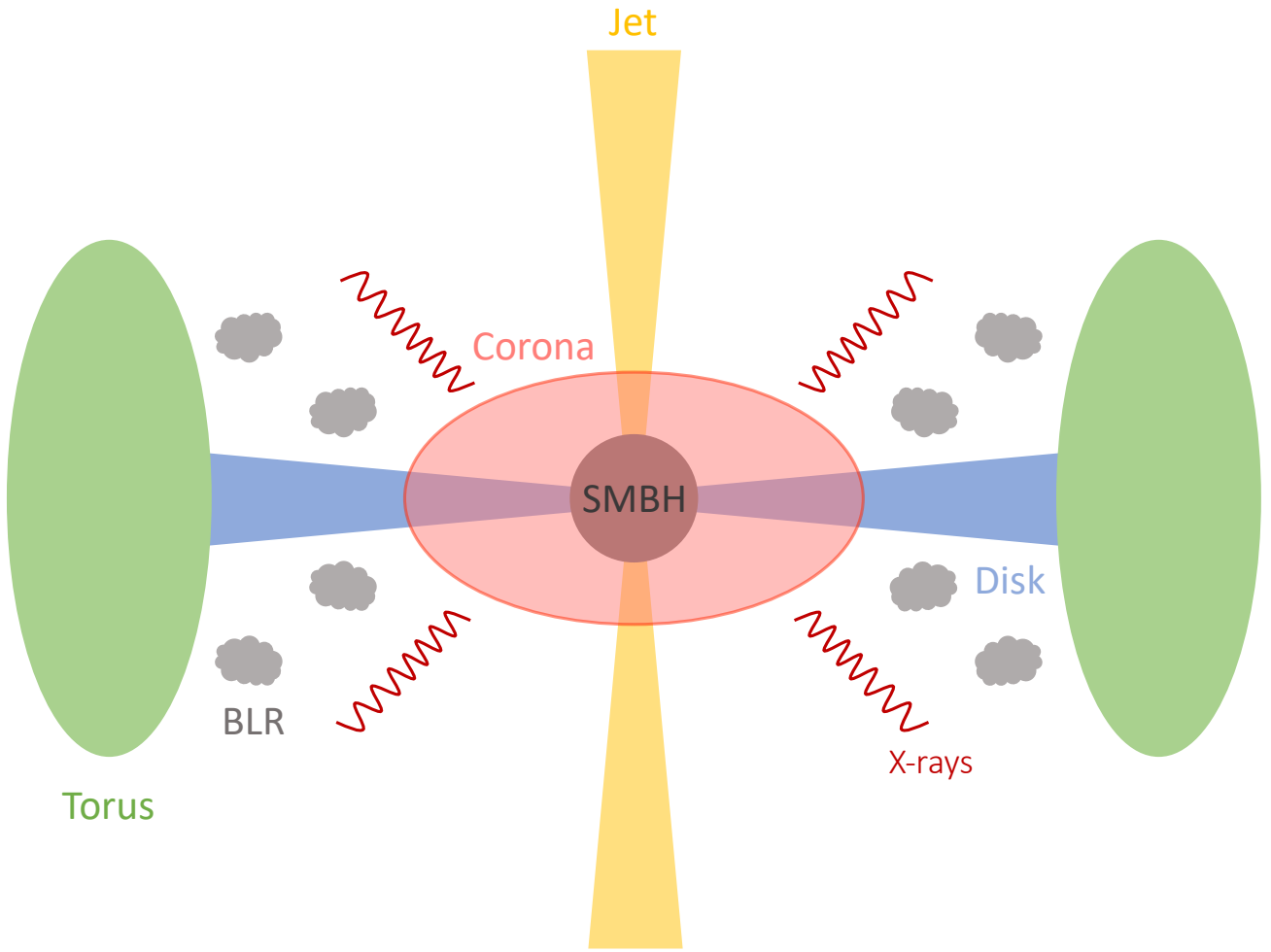

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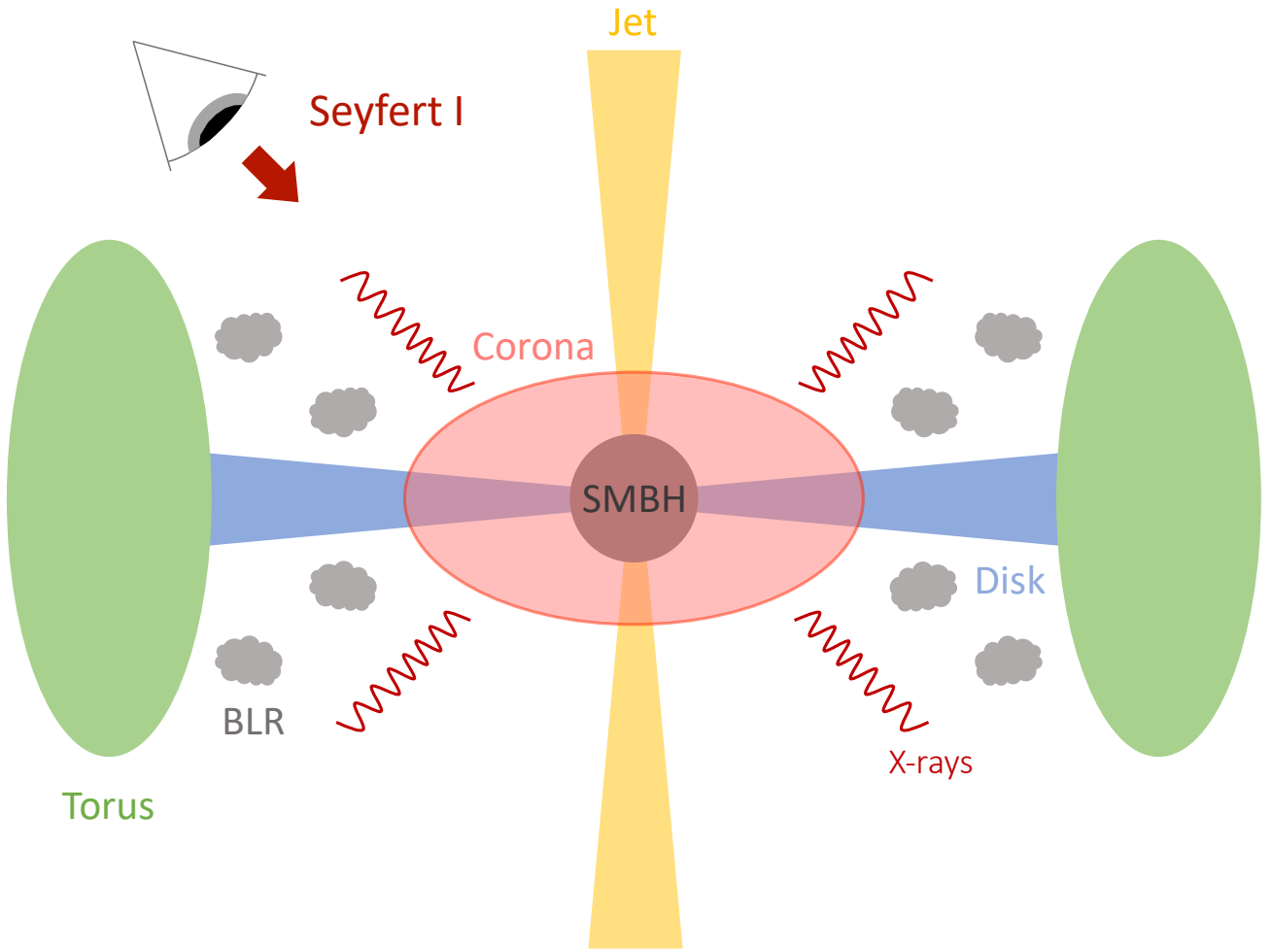

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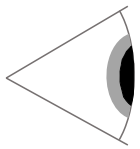
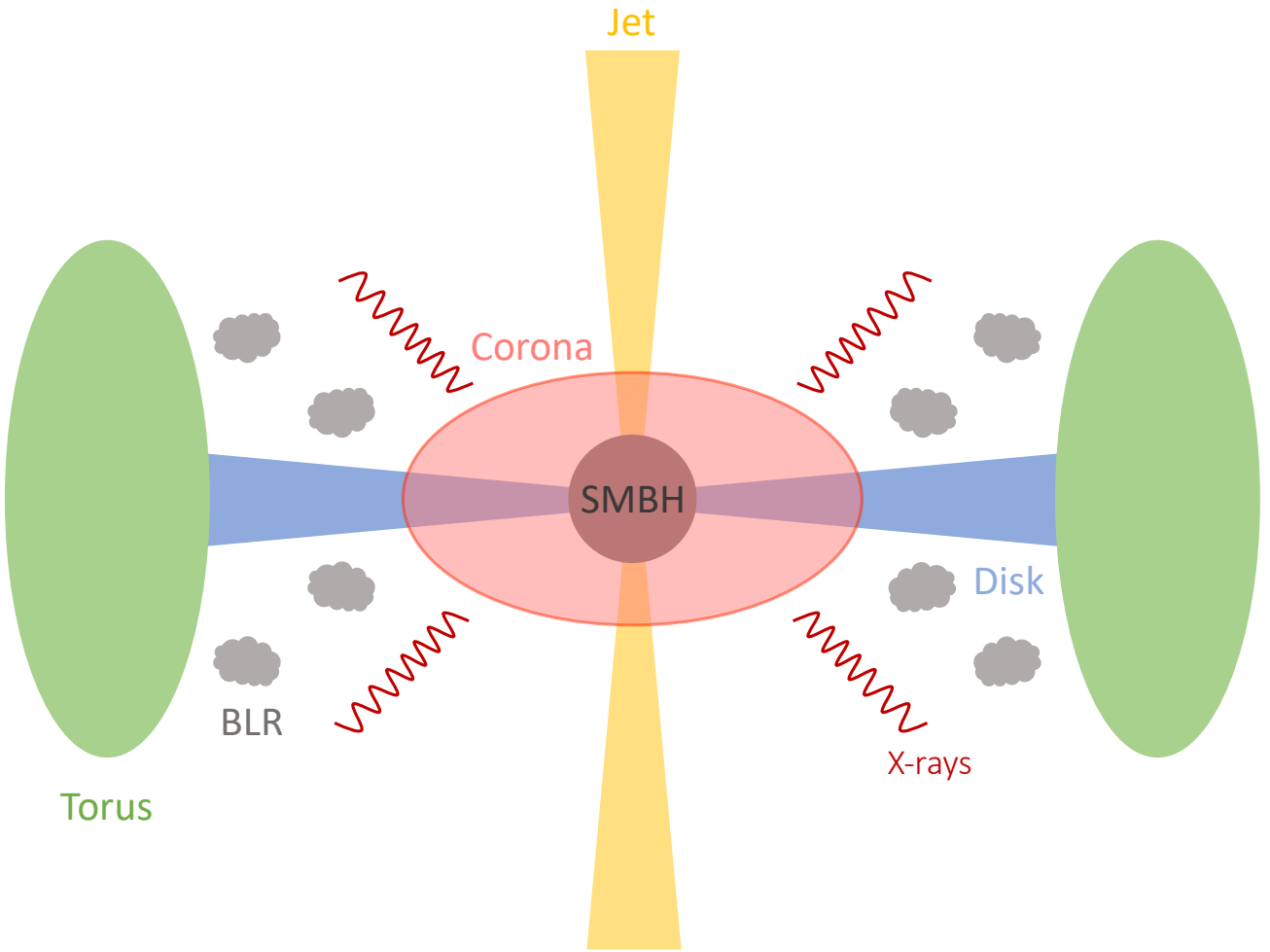


Seyfert II



IceCube observations of NGC 1068

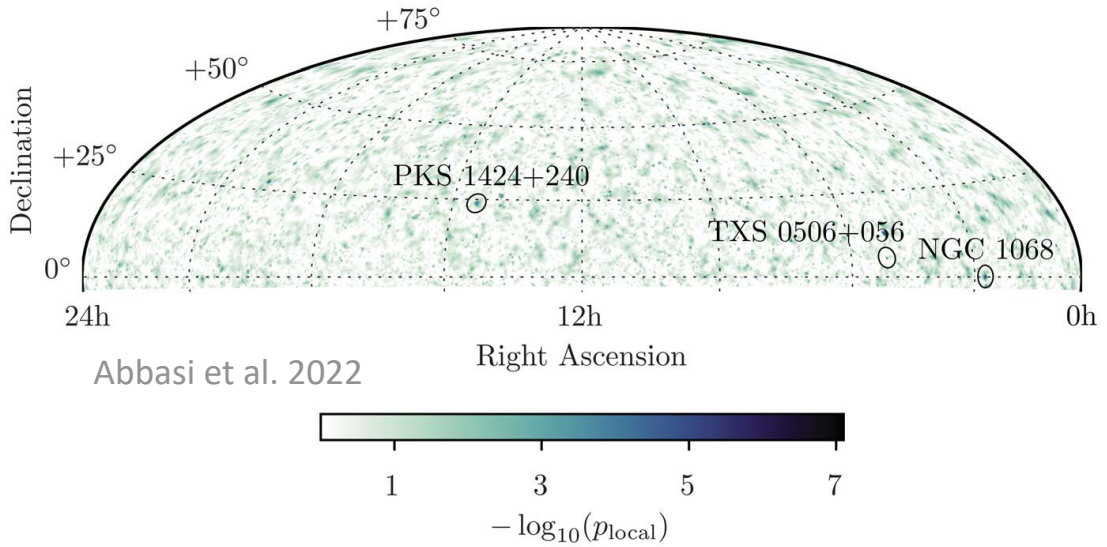
NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

A supermassive black hole, obscured by cosmic dust, powers the nearby active galaxy NGC 1068. Neutrinos, which rarely interact with matter, could provide information on the galaxy's active core. We searched for neutrino emission from astrophysical objects using data recorded with the IceCube neutrino detector between 2011 and 2020. The positions of 110 known gamma-ray sources were individually searched for neutrino detections above atmospheric and cosmic backgrounds. We found that NGC 1068 has an excess of 79^{+22}_{-20} neutrinos at tera–electron volt energies, with a global significance of 4.2σ, which we interpret as associated with the active galaxy. The flux of high-energy neutrinos that we measured from NGC 1068 is more than an order of magnitude higher than the upper limit on emissions of tera–electron volt gamma rays from this source.

Abbasi et al. 2022



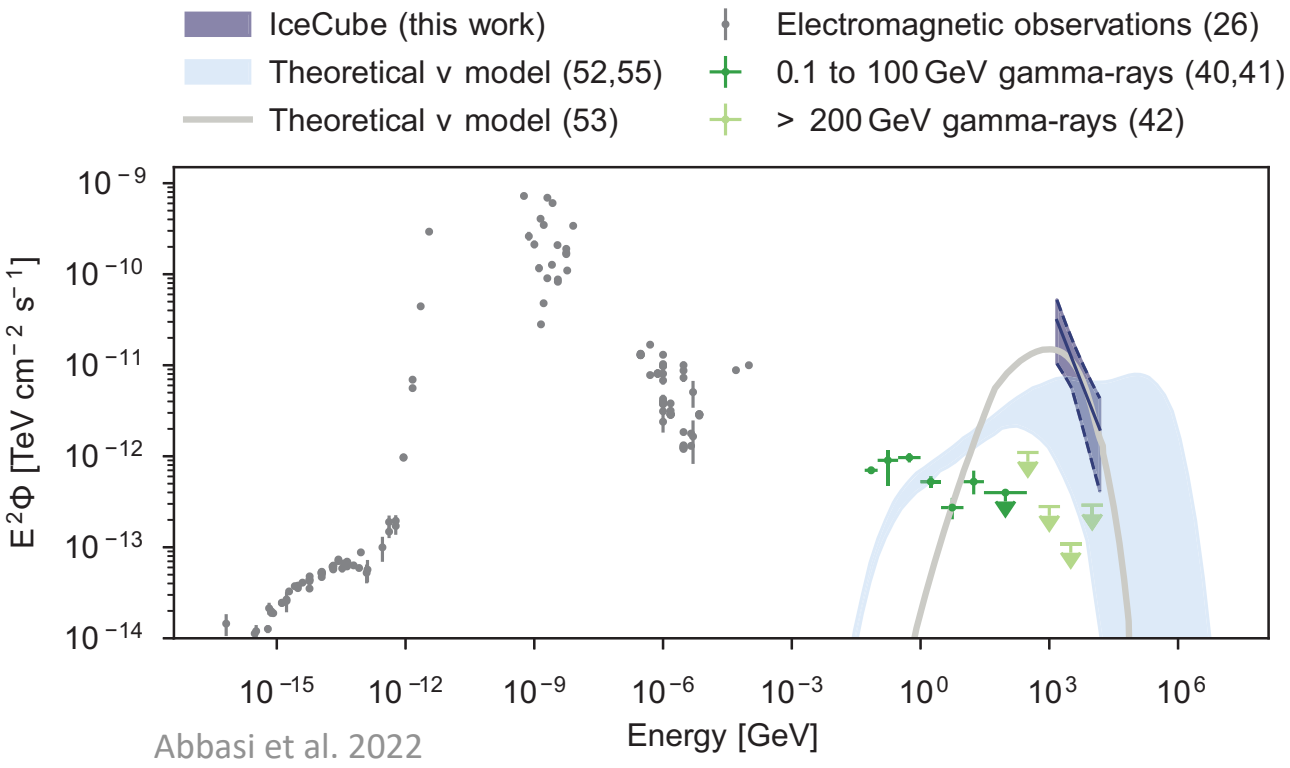
Abbasi et al. 2022

- distance: $d_L = 11.1\,\mathrm{Mpc}$
  Tikhonov & Galazutdinova 2021
- column density: $N_H \simeq 10^{25}\,\mathrm{cm}^{-2}$
  Marinucci et al. 2016
- X-ray luminosity: $L_X = 4.2 \times 10^{43}\,\mathrm{erg\,s}^{-1}$
  Marinucci et al. 2016

→ Seyfert galaxy with the **highest intrinsic X-ray flux** in the Northern hemisphere!

Ricci et al. 2017

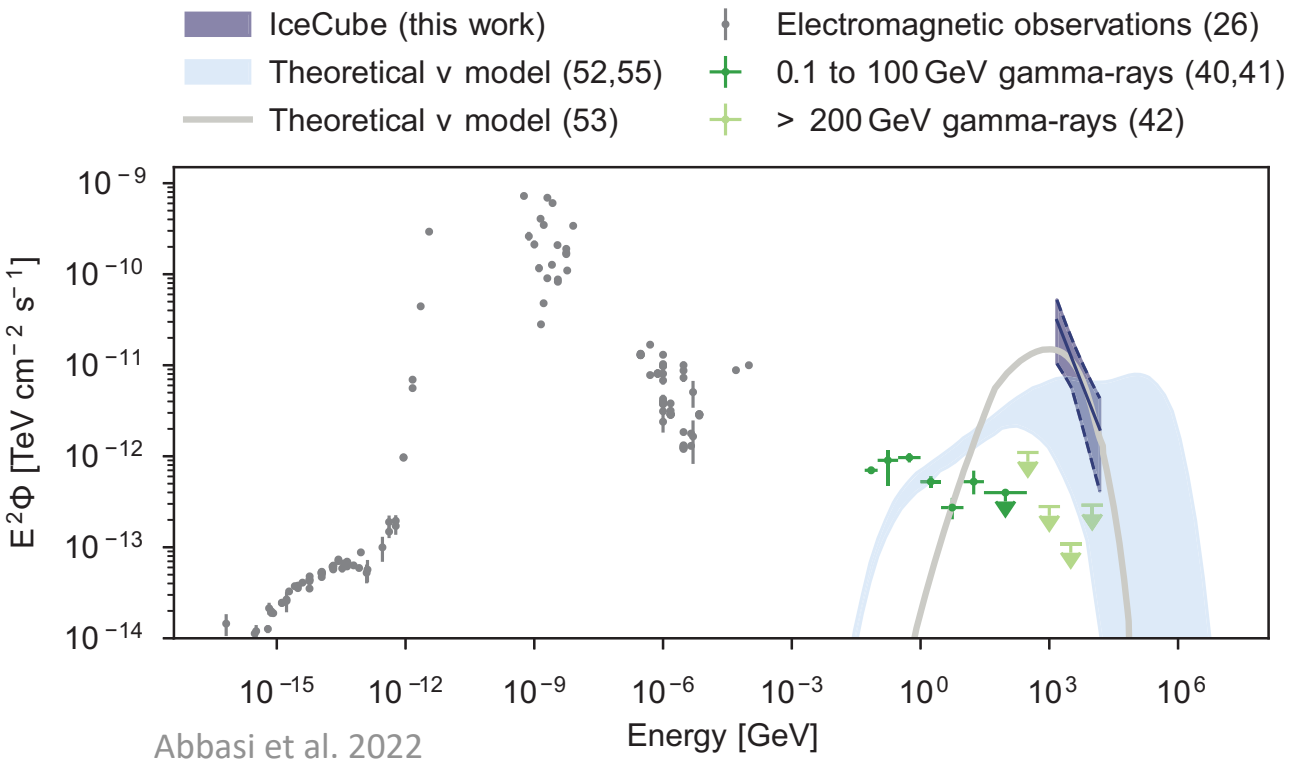
IceCube observations of NGC 1068



Abbasi et al. 2022

$L_\gamma \ll L_\nu$ → Hidden neutrino source

IceCube observations of NGC 1068 & other Seyferts



Abbasi et al. 2022

$L_\gamma \ll L_\nu$ → Hidden neutrino source

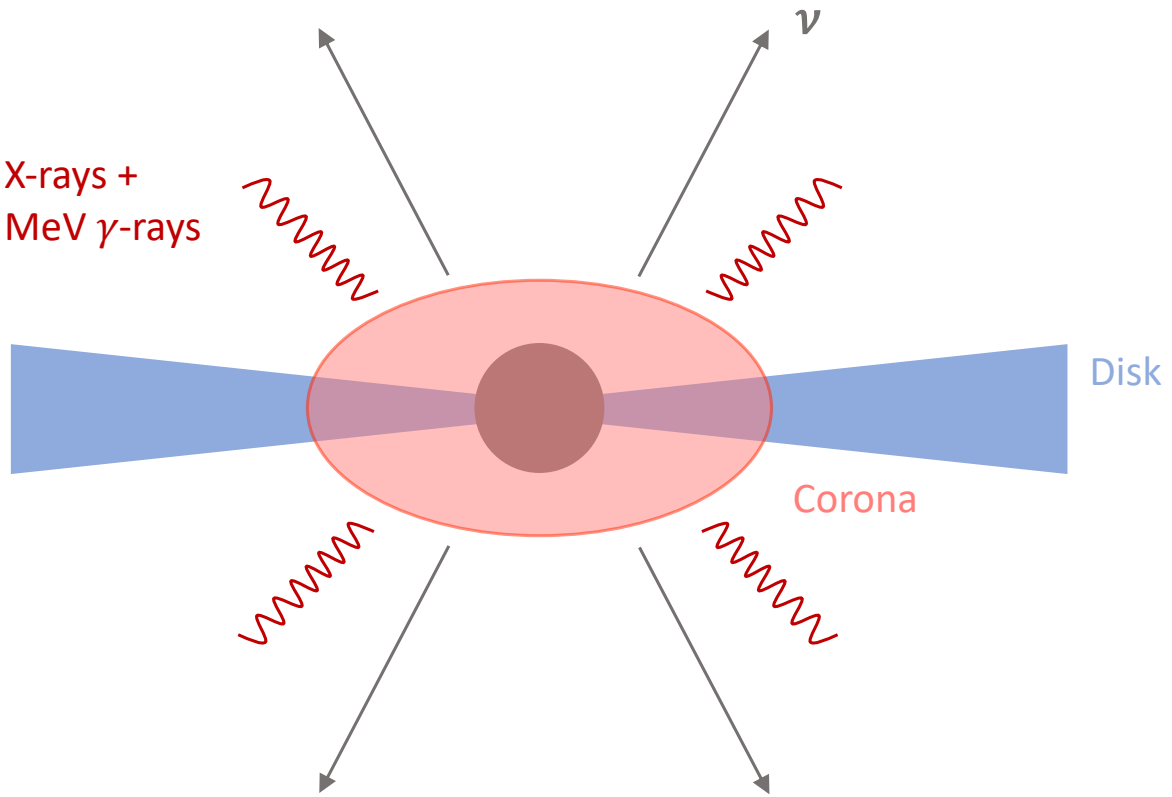
Evidence for neutrino emission from two other Seyfert galaxies:

- NGC 4151 at 2.9σ
  Goswami et al. 2023
- CGCG 420-015 at 2.5σ
  Glauch et al. 2023

The disk-corona model

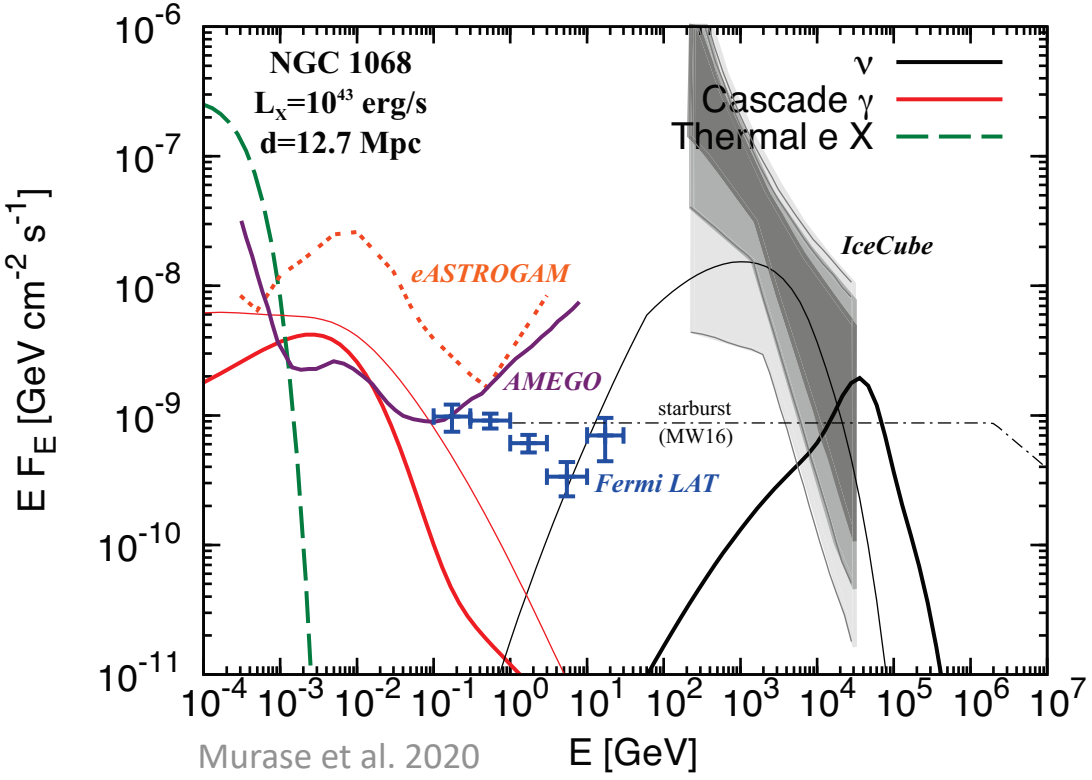
Inoue et al. 2019 & 2020, Murase et al. 2020 & 2022, Kheirandish et al. 2021, Eichmann et al. 2022

- Protons are accelerated inside the **corona**
  - → stochastic acceleration
  - → acceleration via magnetic reconnections
- Neutrinos and γ-rays are produced in **pp and/or pγ interactions**
- γ-rays are attenuated in $\gamma\gamma$ interactions with X-rays
  - → should be observable in the **MeV range**

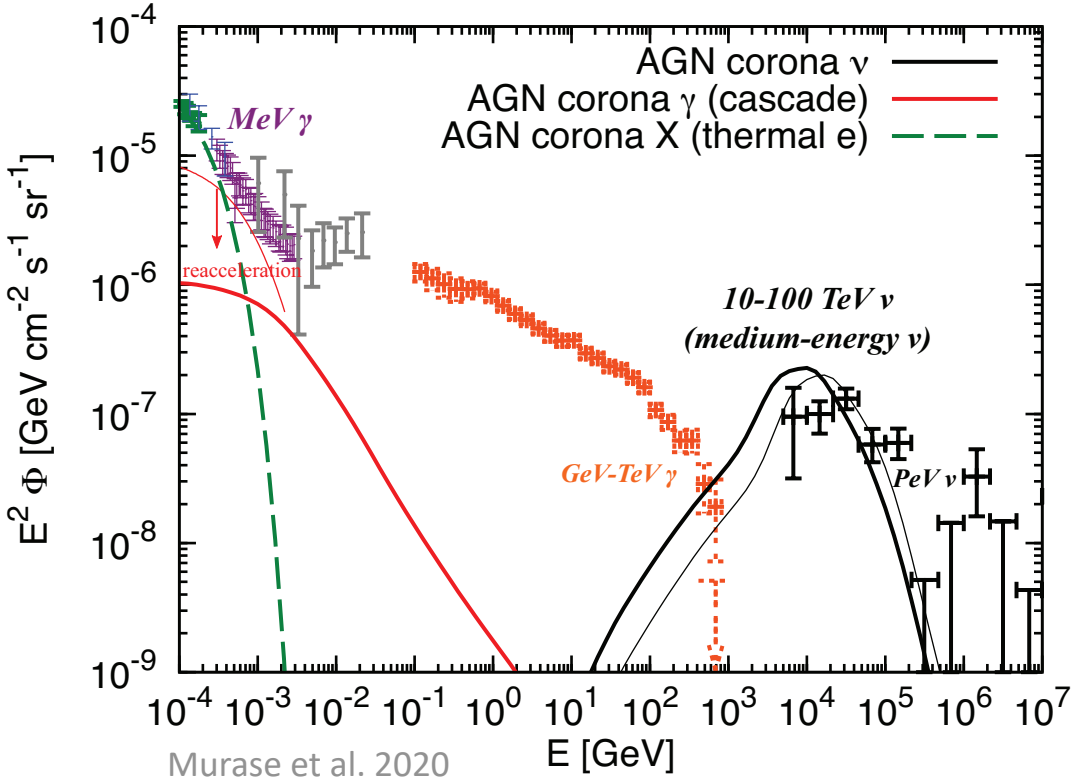


Murase et al. 2020 & 2022

Resulting neutrino and MeV γ-ray spectra depend only on L_X



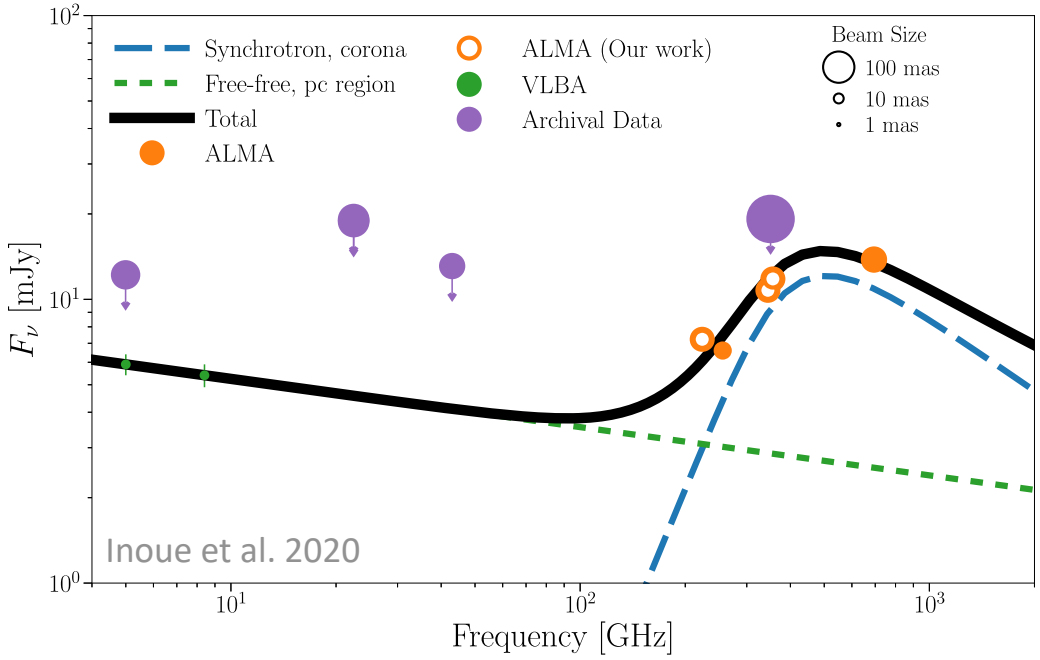
NGC 1068

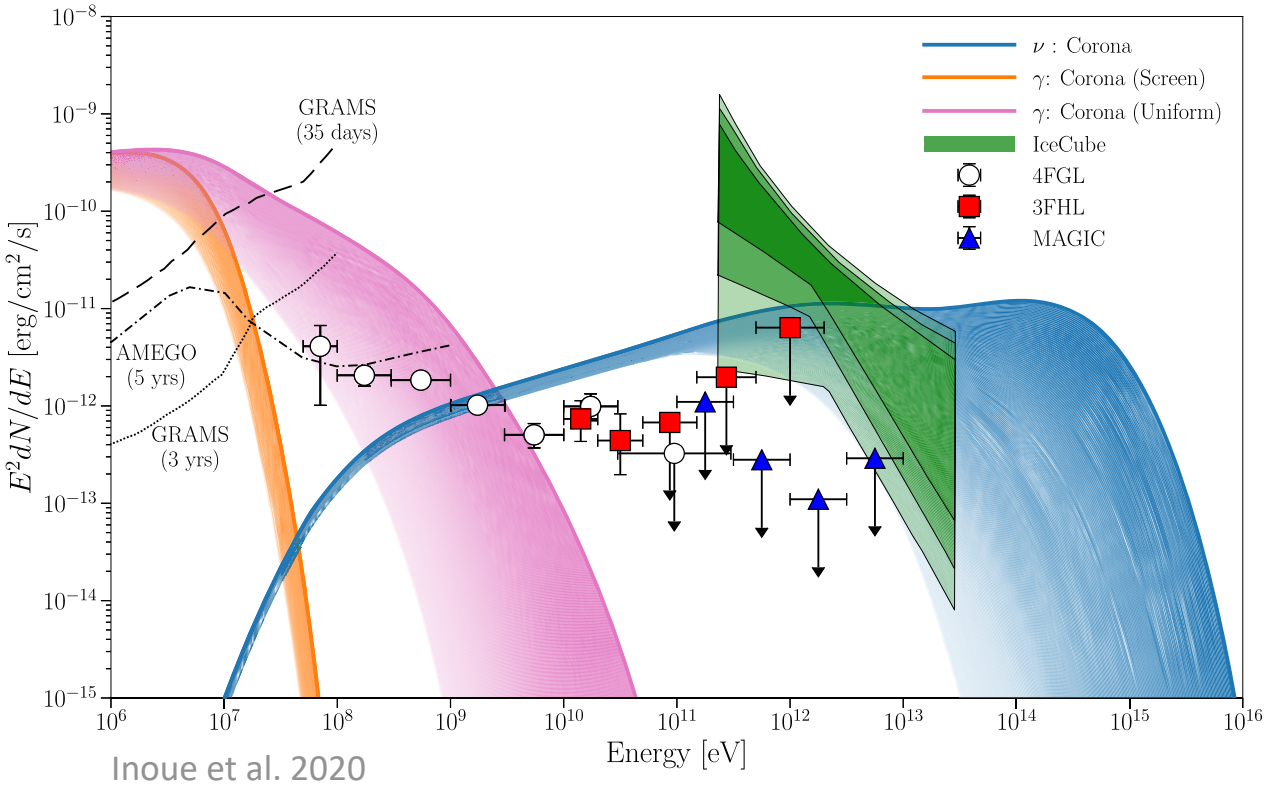


source population

Inoue et al. 2019 & 2020

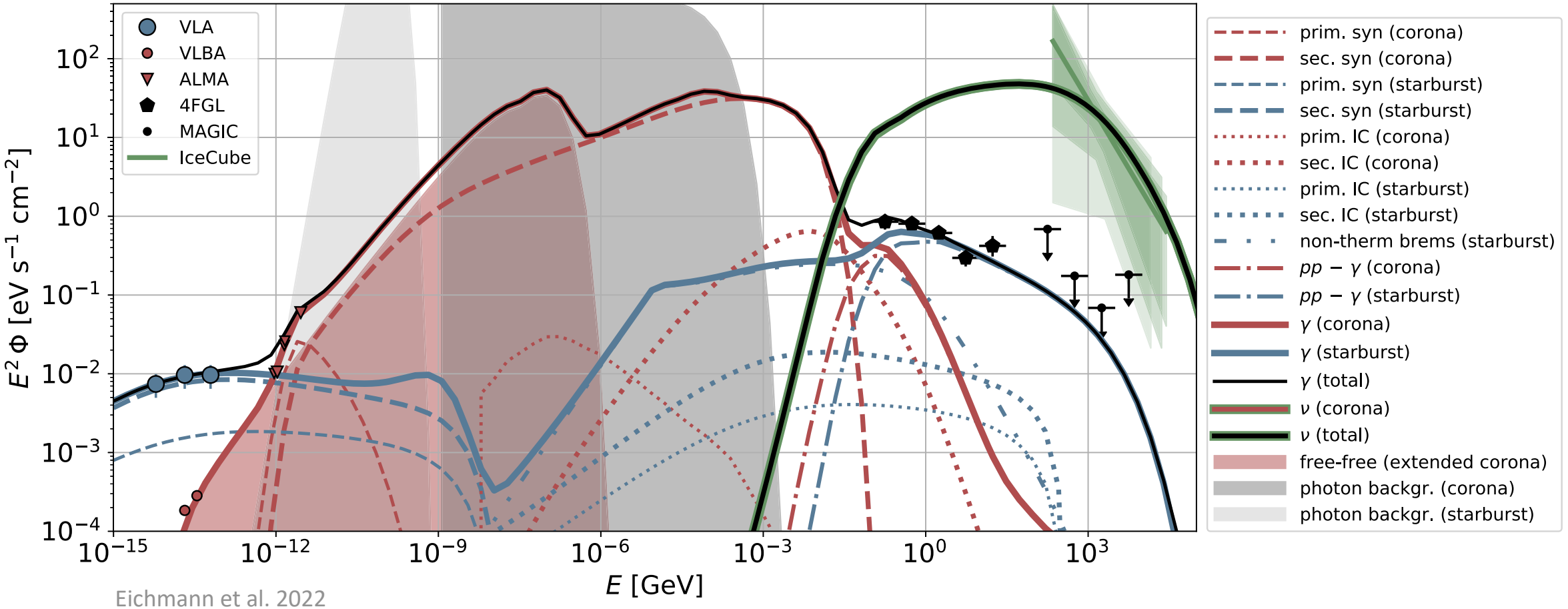
Model based on radio observations of **synchrotron radiation** from accelerated electrons





Eichmann et al. 2022

2-zone model of starburst region + AGN corona



Eichmann et al. 2022

Other models

- particle acceleration in ultra-fast outflows Lamastra et al. 2016, Peretti et al 2023
- interactions of failed winds with the obscuring torus Inoue et al. 2022
- jet interactions with the interstellar medium Fang et al. 2023
- muon pair production in the AGN core Hooper & Plant 2023
- jets of stellar-mass black holes embedded in the AGN accretion disk Tagawa et al. 2023

Goals of our project

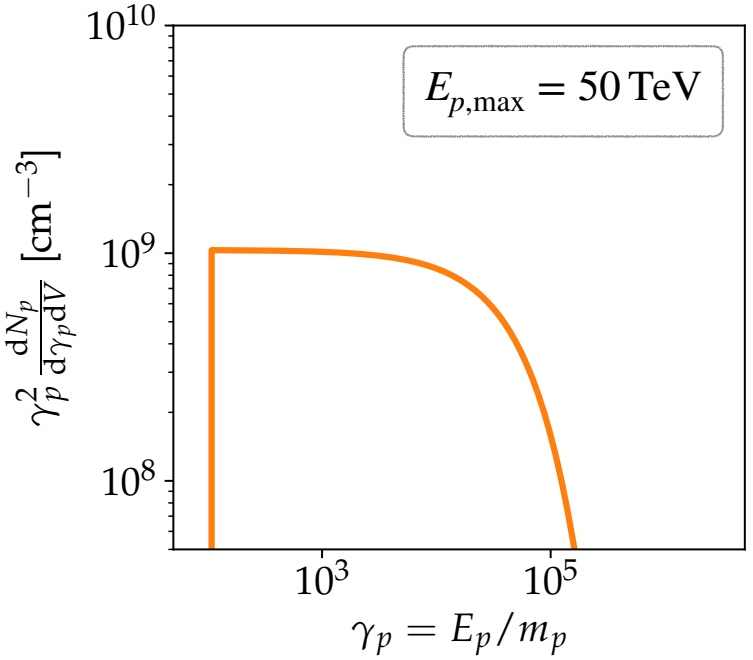
What are the prospects of observing other individual Seyfert galaxies in the near future?

How much could the neutrino emission from Seyfert galaxies contribute to the observed diffuse neutrino flux?

Look at individual **point sources** and an entire **population of sources**

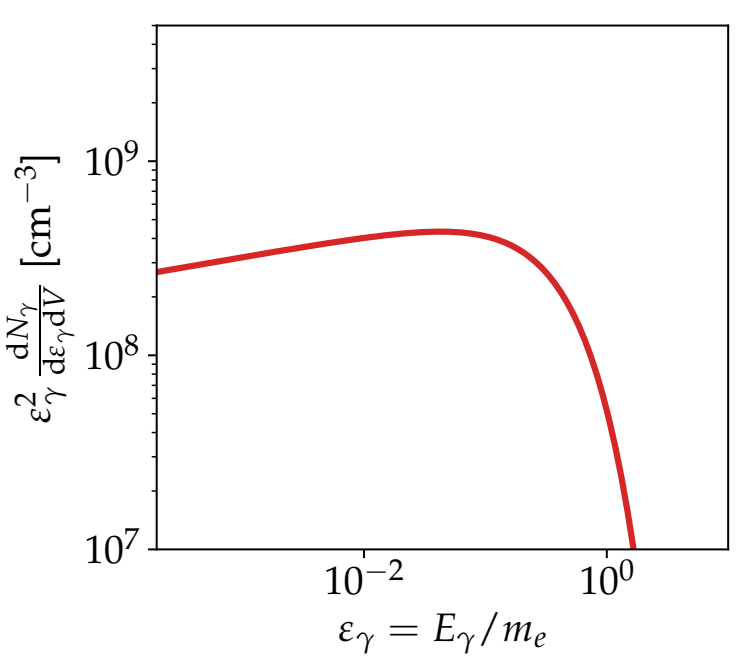
Our spectral model - Ingredients

Assumption: Neutrinos are mainly produced in **pγ interactions** of accelerated protons with coronal X-rays



proton spectrum

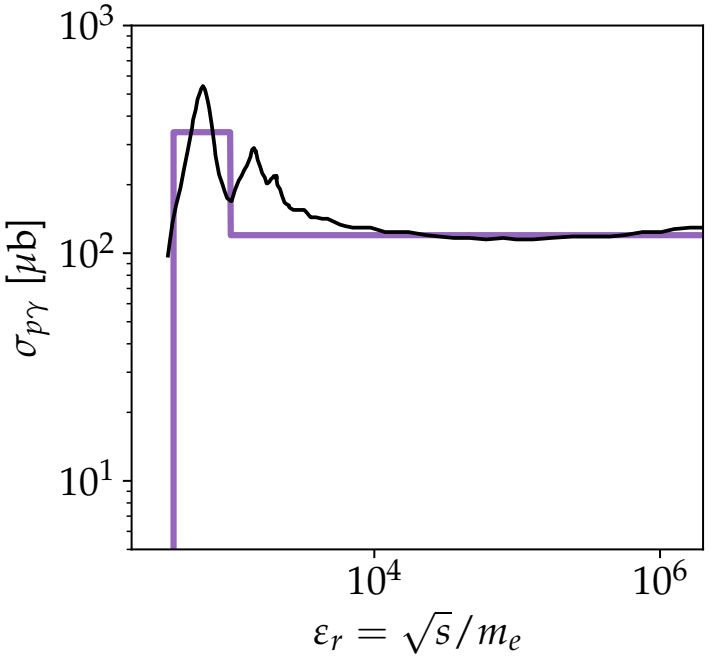
×



coronal X-ray spectrum

Murase et al. 2020

×

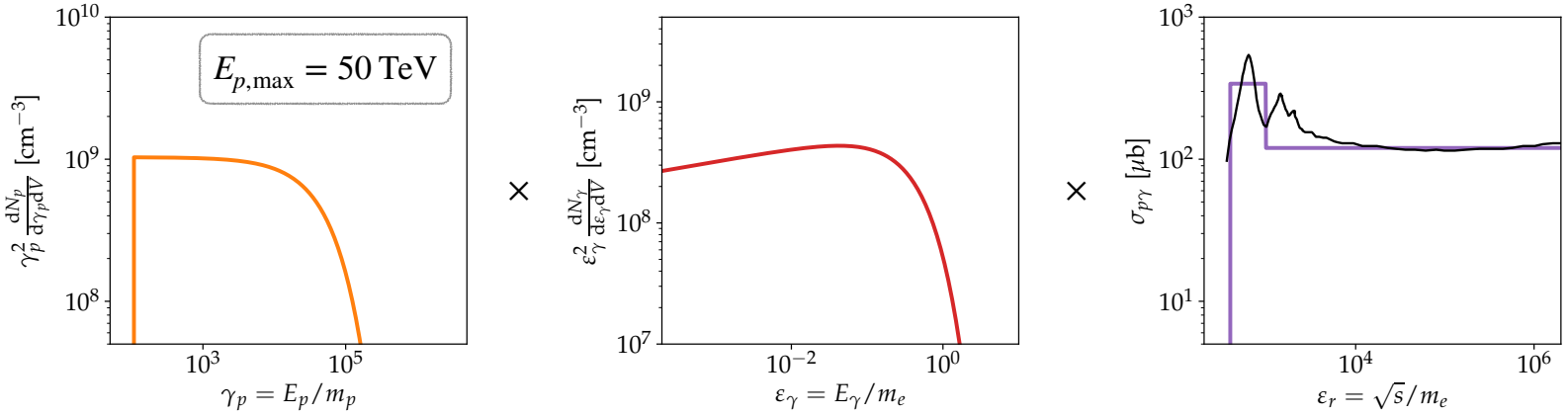


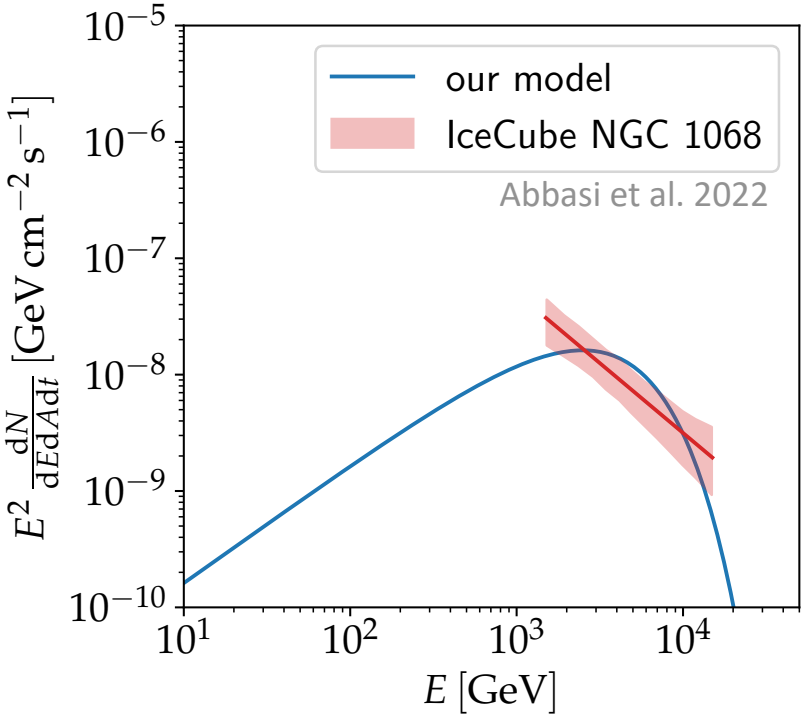
$p\gamma$ cross section

Dermer & Menon 2009

Mücke et al. 2000

Our spectral model - Neutrino spectrum

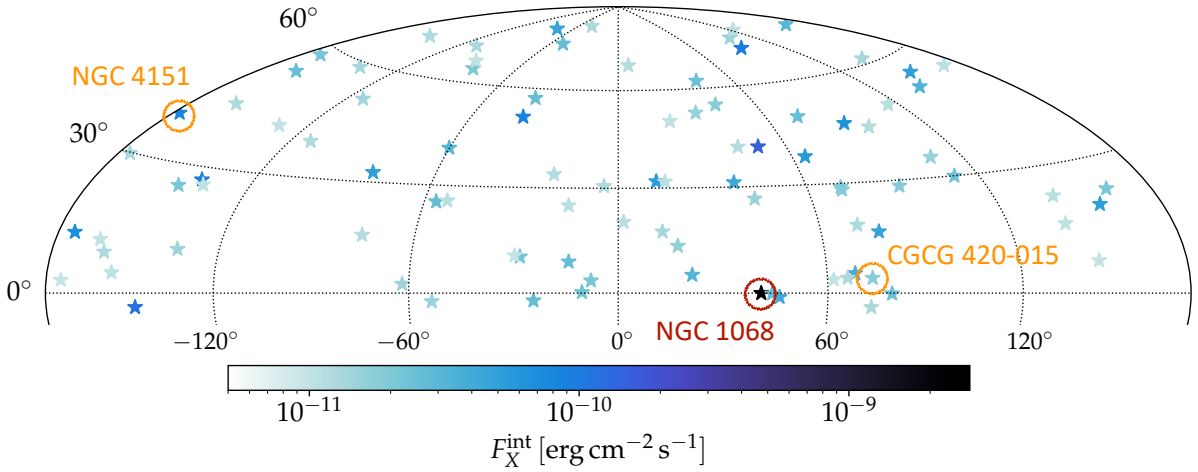




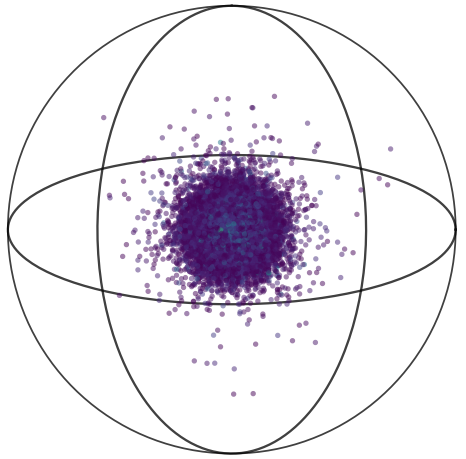
neutrino spectrum of NGC 1068

Other nearby sources & source population

92 additional nearby sources from the BASS catalogue Ricci et al. 2017



Simulate a population of Seyfert galaxies using **popsynth**[1] Burgess & Capel 2021



$\sim$ 19 million sources up to $z = 5$

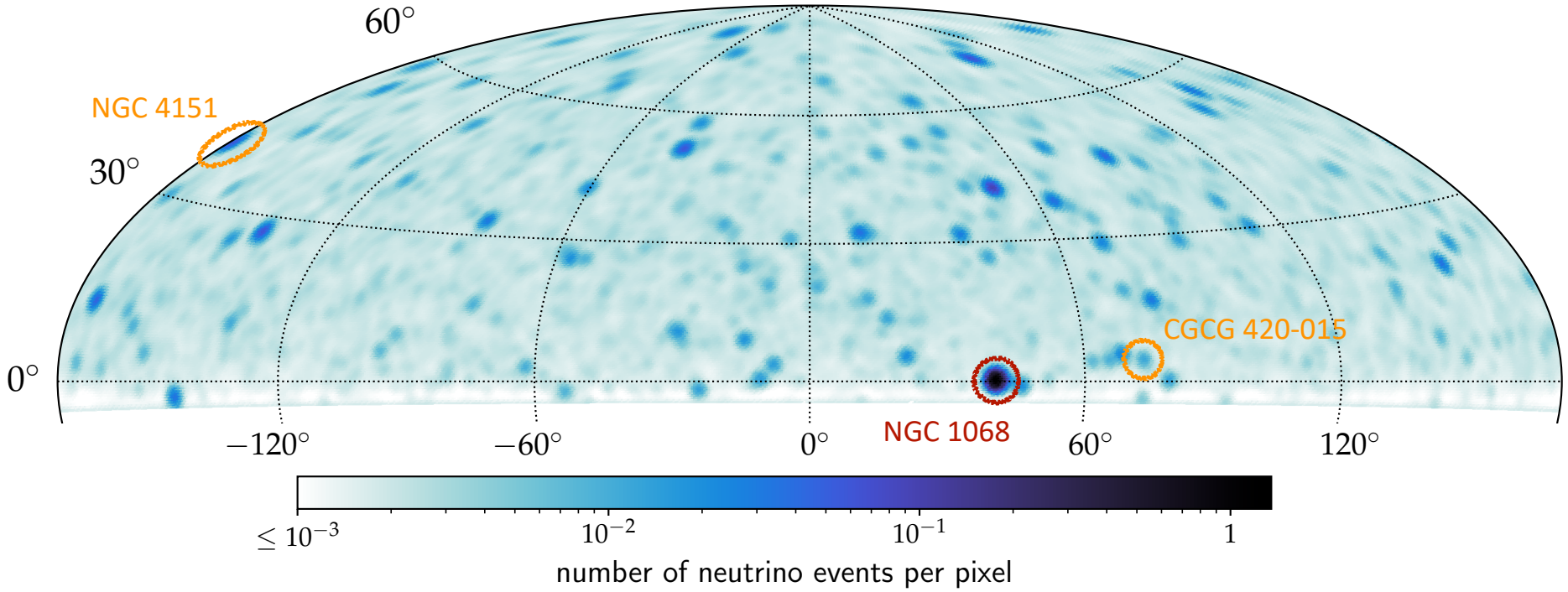
[1]https://github.com/grburgess/popsynth

$$L_\nu \propto L_X \text{ and } E_{p,\max} = 50\,\text{TeV} = \text{const}$$

Neutrino events in 10 years of IceCube

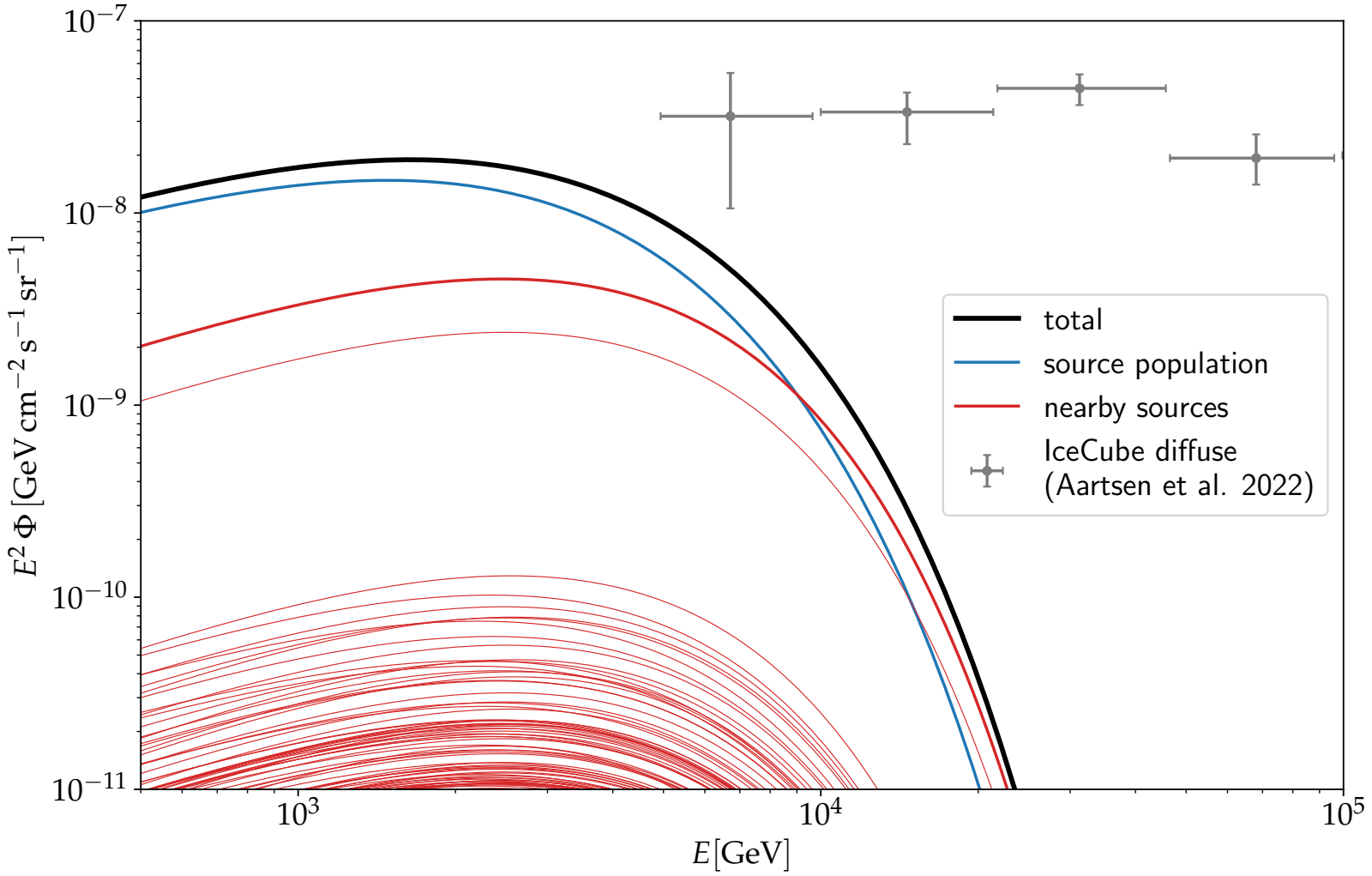
For all sources: calculate the expected **number of neutrino events** using **icecube_tools**[1]

→ use A_{eff} from the 10-year IceCube data set of track-like events Abbasi et al. 2021



[1]https://github.com/cescalara/icecube_tools

Diffuse neutrino flux

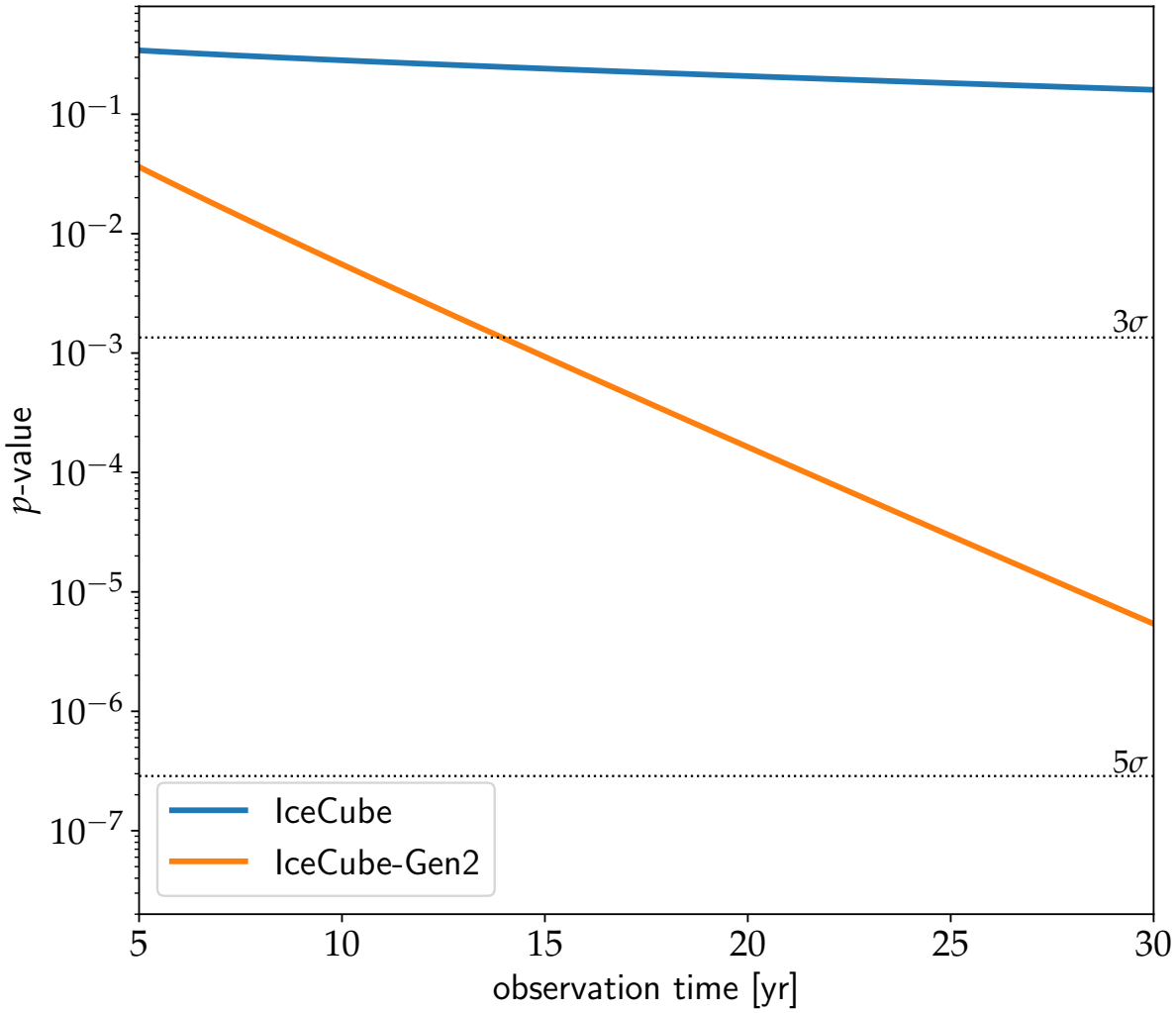


Seyfert galaxies could be responsible for $\sim 15\,\%$ of the total diffuse neutrino flux at TeV energies!

Detectability of individual sources

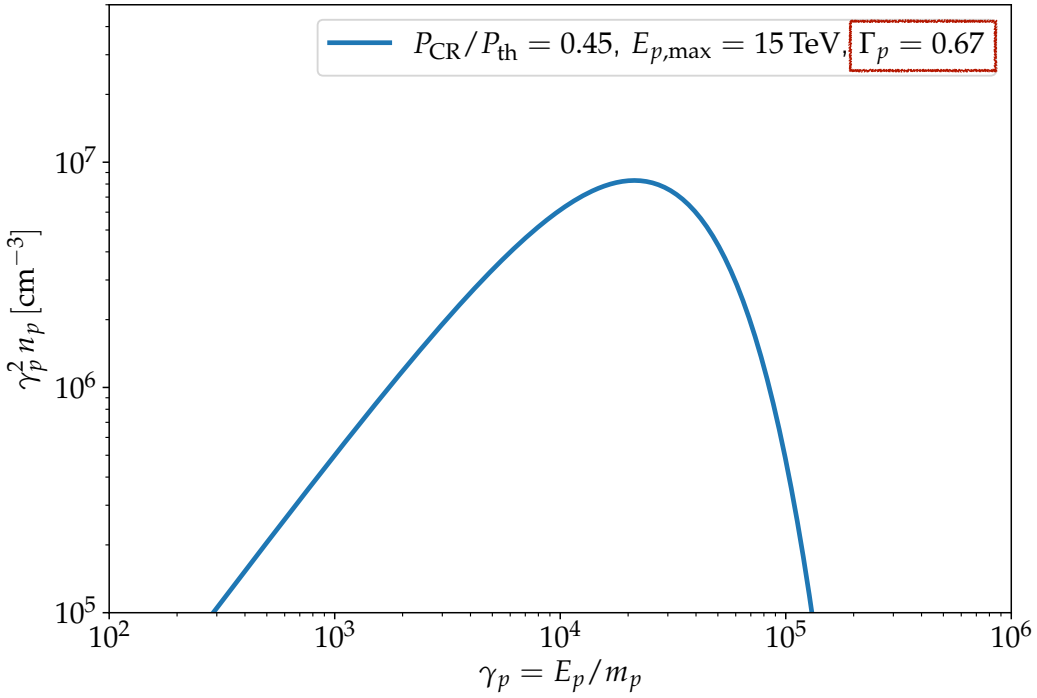
Kheirandish et al. 2021

- NGC 1068 is the **brightest** source: $p = 8 \times 10^{-5}\,(3.7\sigma)$ after 10 years of IceCube
- All other nearby sources are **unlikely to be observed**, neither by IceCube nor by IceCube-Gen2
- **Stacking analysis**: 3σ after 14 years of IceCube-Gen2

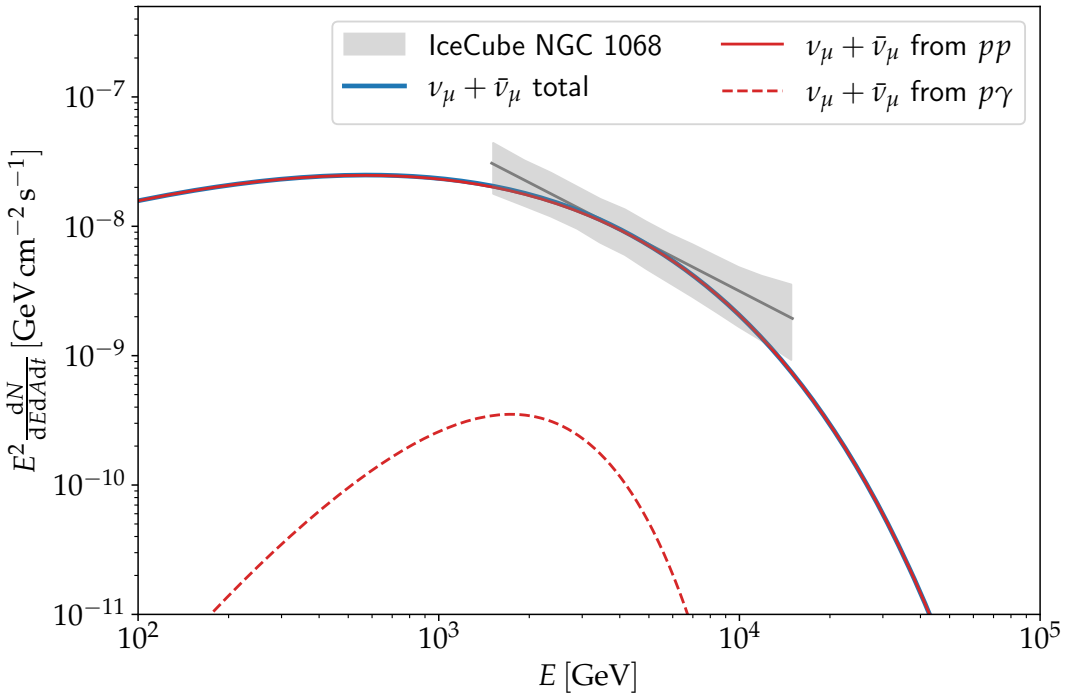


Neutrinos from pp interactions

Calculate the neutrino spectrum from **pp interactions** using **aafragpy** Koldobskiy et al. 2021



proton spectrum NGC 1068



neutrino spectrum NGC 1068

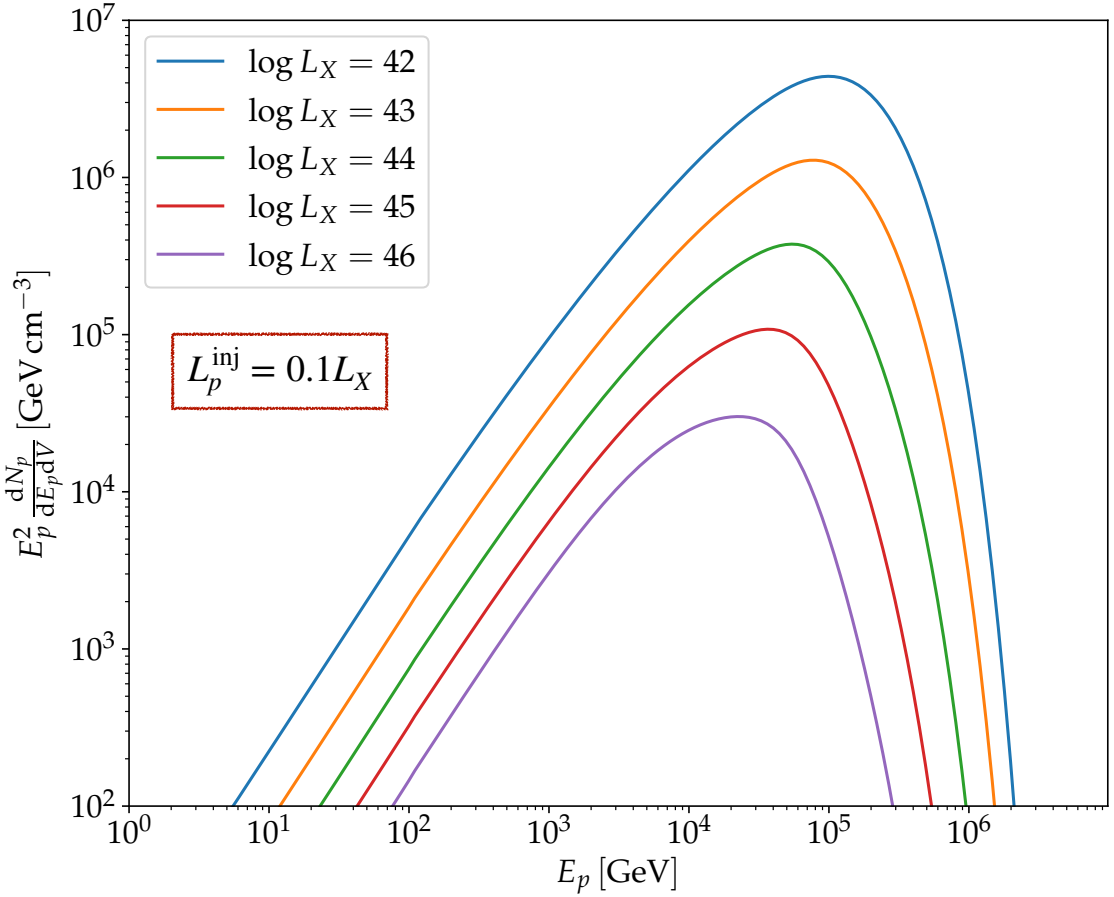
pp interactions seem to be the **dominant** neutrino production mechanism!

L_X-dependence of the proton spectrum

- **AM³**: software to simulate multimessenger emission from AGNs
  Klinger et al. 2023

- inject a power-law spectrum with $\Gamma = 2/3$ and cutoff at $t_{\rm acc} = t_{\rm loss}$
  Murase et al. 2020

- calculate the proton spectrum after energy + escape losses



Conclusions

NGC 1068 is by far the brightest neutrino source, all **other Seyfert galaxies** are expected to be **much fainter**.

Seyfert galaxies could contribute significantly to the observed **diffuse neutrino flux**.

Next steps:

- Repeat the calculation using the **improved proton spectra**
- Take into account uncertainties in the **cosmological evolution** of Seyferts