Characterizing High-Energy Neutrino Emission Parameters in Bright Seyfert Galaxies and Quasars

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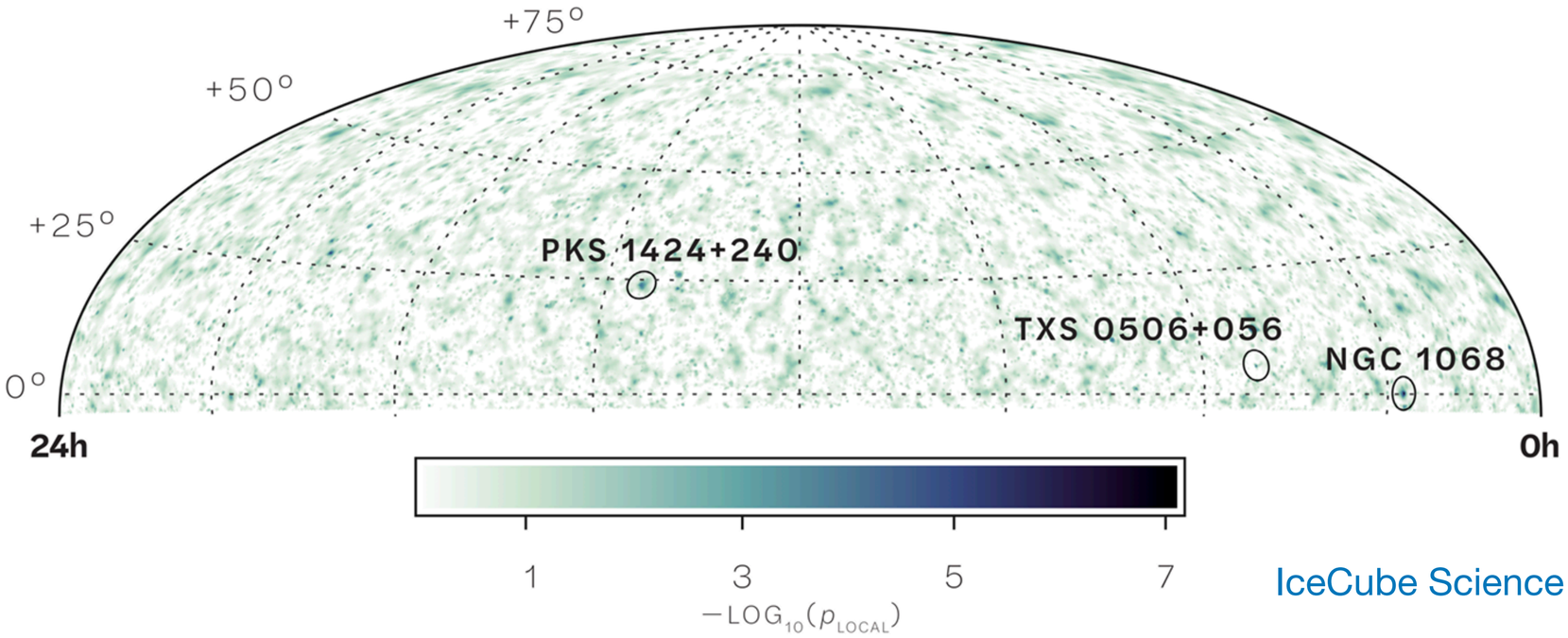
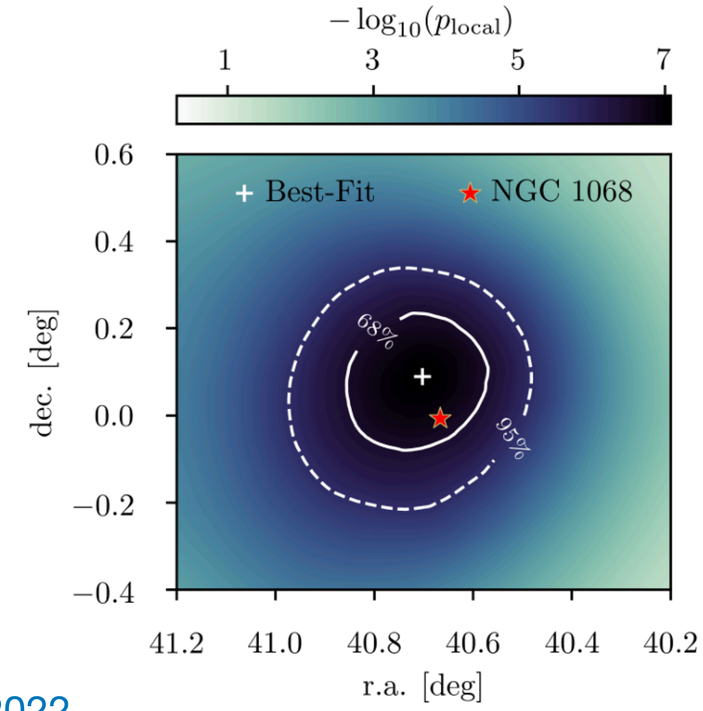
NCfA

Neutrino emission from Seyfert galaxies

- **Steady** sources powered by supermassive black holes (SMBHs). Strong radiation emitters.
- NGC 1068 is the most significant neutrino point source in the Northern Sky (4.2σ post-trial)





IceCube Science 2022

- Followup stacking searches with Seyfert Galaxies showed no significant excess.
- Among Seyferts, the most significant sources are NGC 1068, NGC 4151 and CGCG 420-015 (IceCube 2024).
- Seyferts can be X-ray bright, but **γ-ray opaque**

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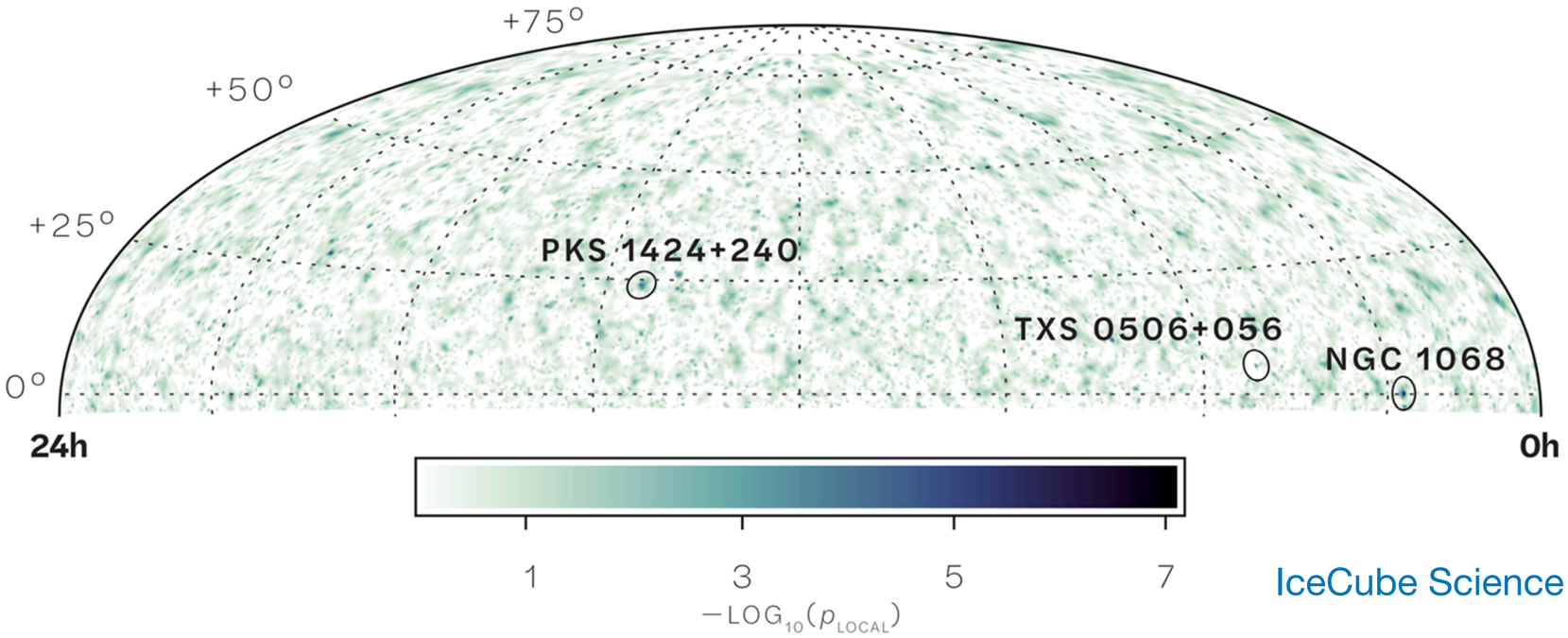

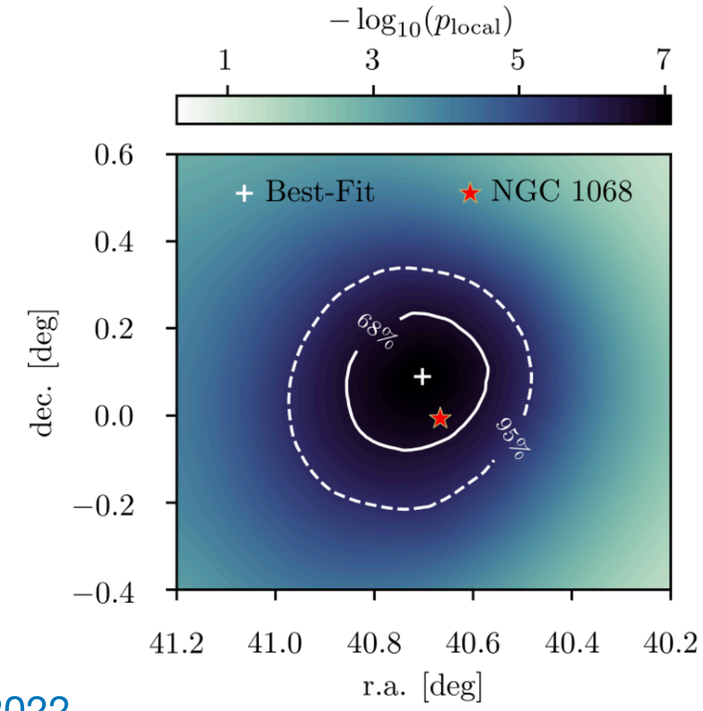

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Why is a γ-ray opaque neutrino source interesting?

The gamma-ray and neutrino connection

Cosmic-ray (proton) accelerators produce high-energy νs via pp and/or $p\gamma$ interactions

$$p + \gamma \longrightarrow n + \pi^+ \longrightarrow e^+ + (\nu_\mu + \bar{\nu}_\mu) + \nu_e$$

$$\longrightarrow p + \pi^0 \longrightarrow \gamma + \gamma$$

A γ-ray for every muon neutrino!

$$E_\nu \approx \frac{1}{4} E_{\pi^+} \qquad E_\gamma \approx \frac{1}{2} E_{\pi^0}$$

Comparable neutrino and photon energies

Both pp and $p\gamma$ create π^+ and π^0

IceCube TeV neutrinos from NGC 1068 should be accompanied by a **comparable flux** of TeV $\gamma-$rays

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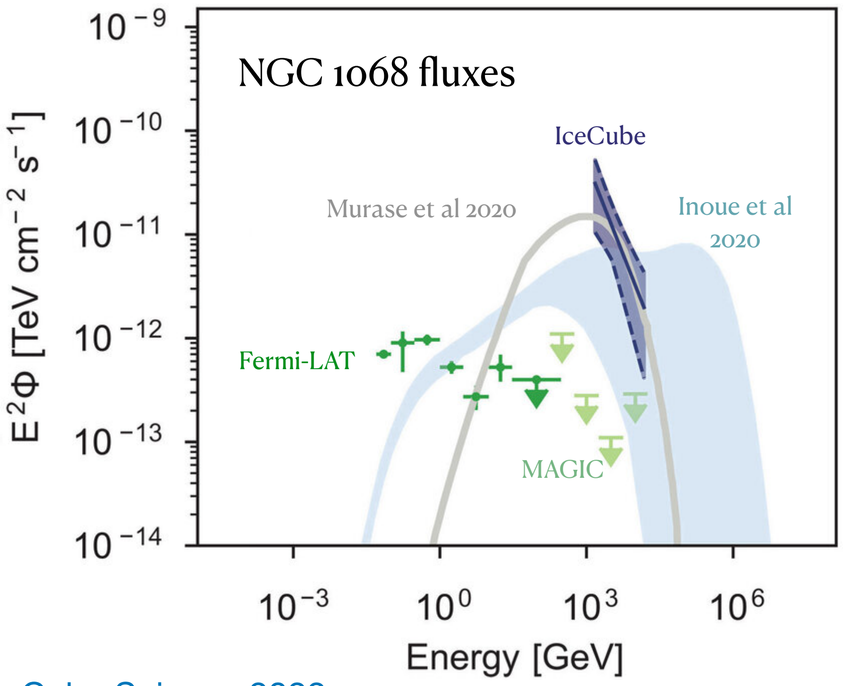
Where are the TeV photons?

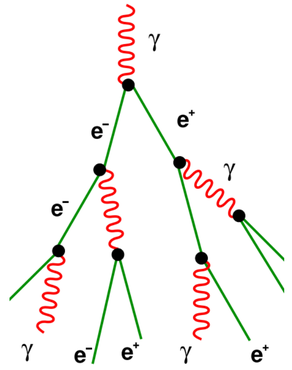


IceCube Science 2022

Cascade initiated via

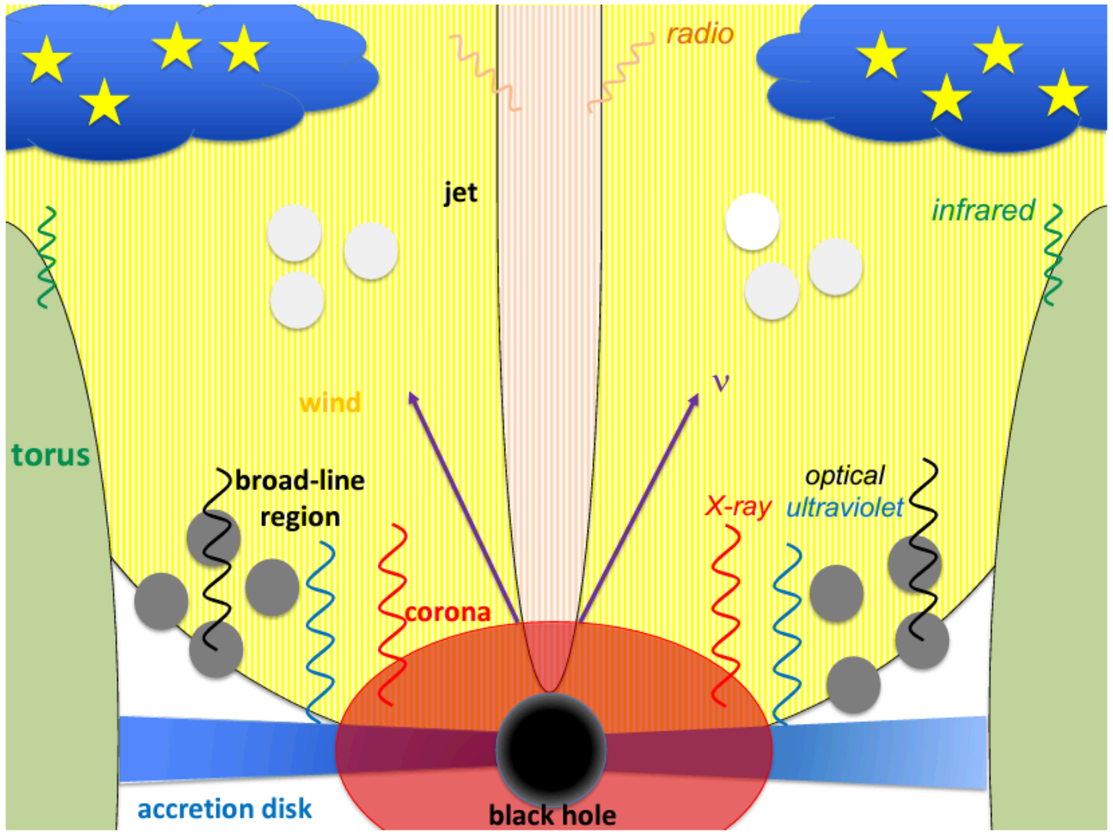
$$\gamma + \gamma \rightarrow e^+ + e^-$$

TeV photons are **cascading down** to $\sim$ GeV energies

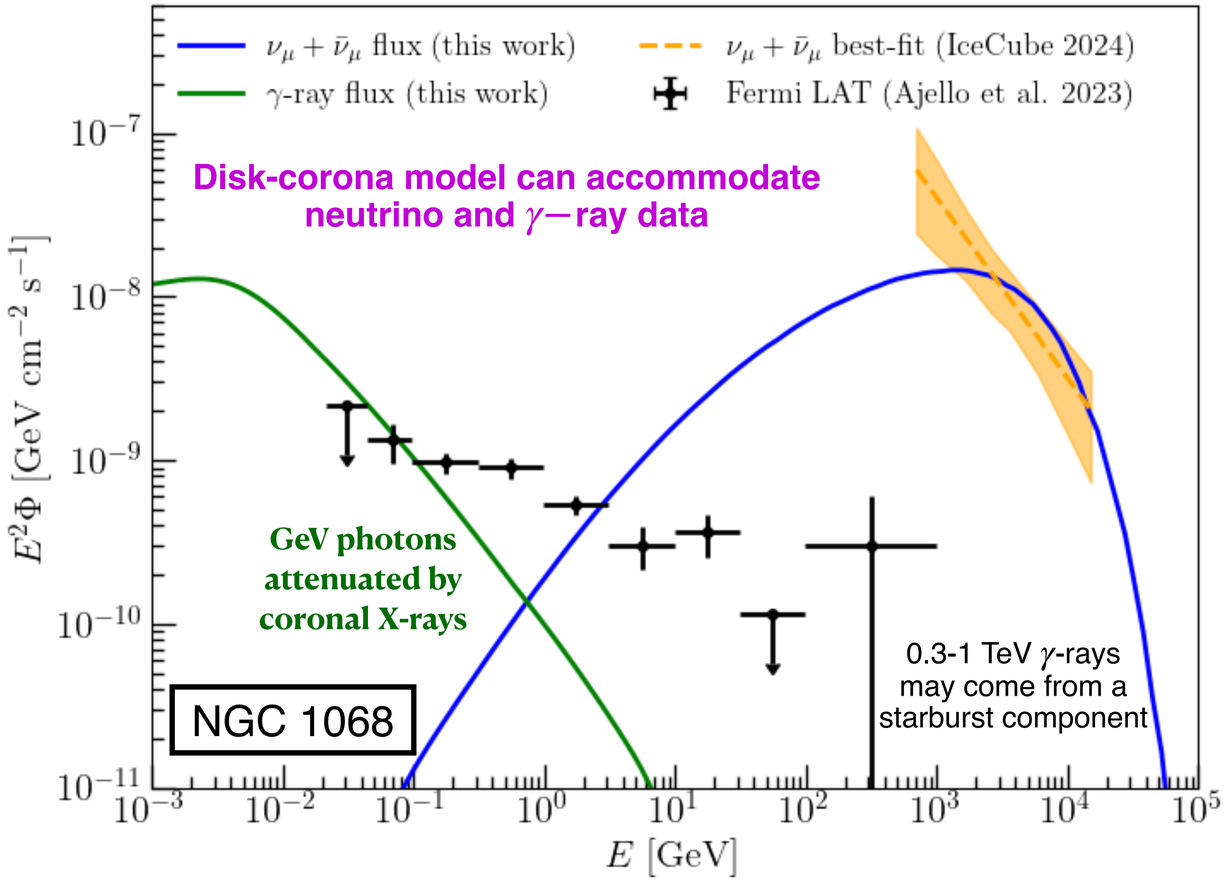


Mollerach & Roulet 2018

AGNs - the multimessenger picture



Murase 2022



Cosmic ray (CR) acceleration

- **Stochastic particle acceleration** in the corona
- CR energy cutoff at ∼ PeV energies

Targets

Coronal X-rays and protons **(main targets for pp and $p\gamma$)**

Features

Non-power law neutrino spectra

Hadronic explanation for high-energy γ-rays

Identifying source parameters

We study the two **most prominent** AGN neutrino sources: NGC 1068 and NGC 4151.

- Neutrino data from IceCube 2024. **See Sreetama Goswami's talk**
- *Fermi*-LAT data (Abdollahi et al 2022) from the analyses in Ajello et al 2023, Murase et al 2024

Studying source parameters via models helps us understand:

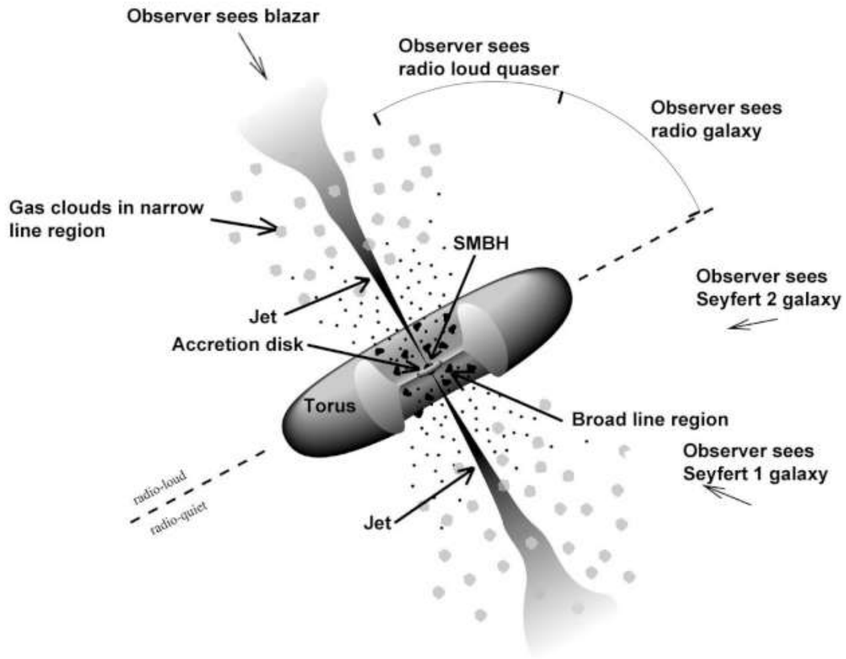
- Cosmic-ray acceleration mechanisms in AGN (beyond power-law)
- Multi-wavelength emission
- The origin of IceCube neutrinos in the $\sim 10 - 100$ TeV range

NGC 1068

SMBH mass: $1.8 \times 10^7 M_\odot$
Distance: 10 Mpc
Type 2 Seyfert
IceCube power-law fit: $E^{-3.1}$

NGC 4151

SMBH mass: $1.7 \times 10^7 M_\odot$
Distance: 15.8 Mpc
Type 1.5 Seyfert
IceCube power-law fit: $E^{-2.83}$



One difference between NGC 1068 and NGC 4151 is the viewing angle

Neutrino and γ-ray fluxes from disk-corona model

Parameters

Intrinsic X-ray luminosity L_X

CR to thermal pressure ratio

} Provide the CR **normalization**

$P_{\rm CR}/P_{\rm vir} \leq 0.5$

Emission radius → Determines injection spectra and optical depths

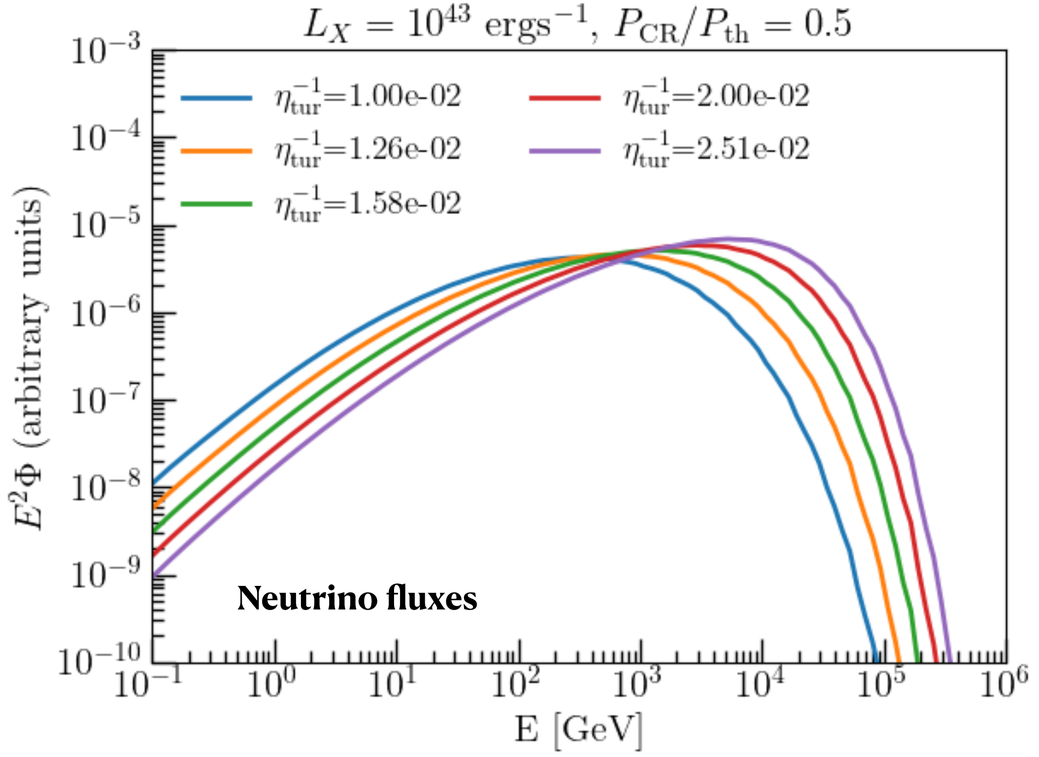
Turbulence strength $\eta_{\rm tur}$ → Determines **maximum** CR energy

$\eta_{\rm tur} \propto t_{\rm acc}$, where $t_{\rm acc}$ is the CR acceleration time

Large $\eta_{\rm tur}^{-1}$ (short $t_{\rm acc}$) require **shorter cooling times** to prevent efficient acceleration

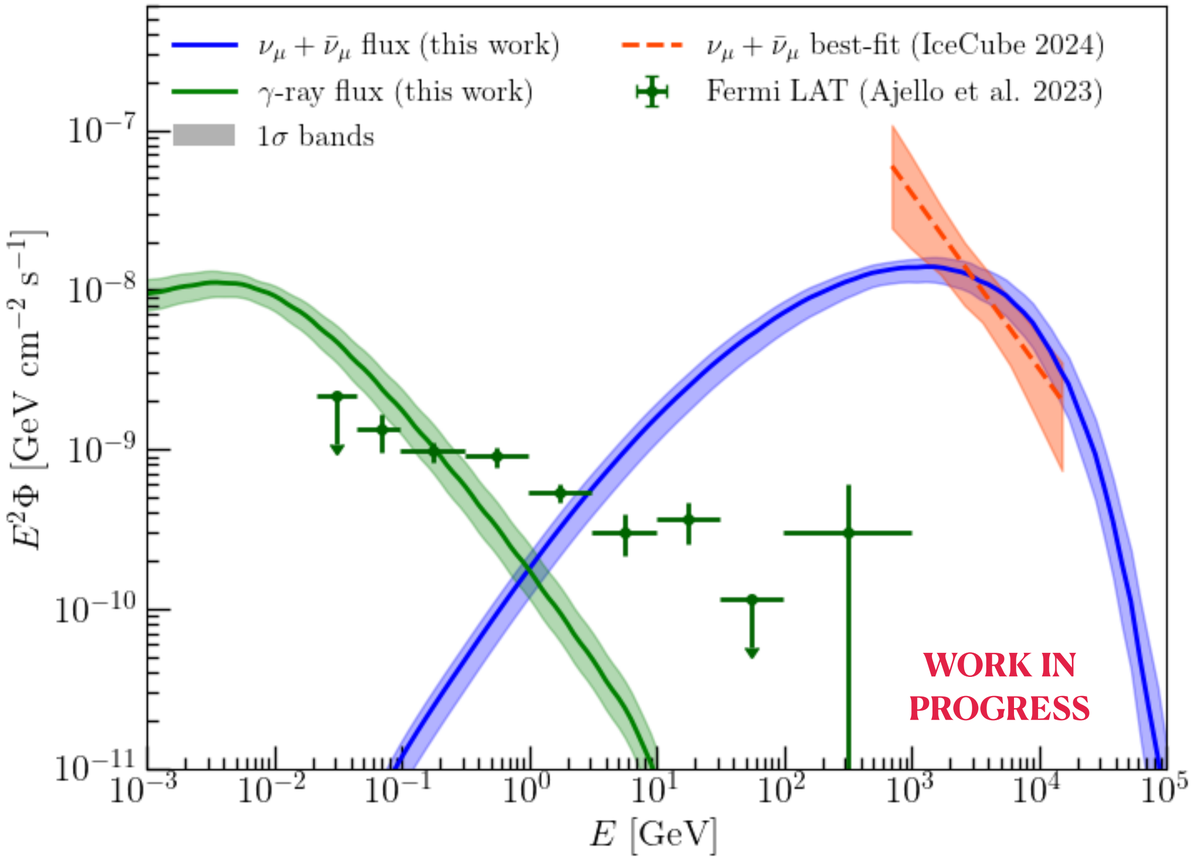
↓

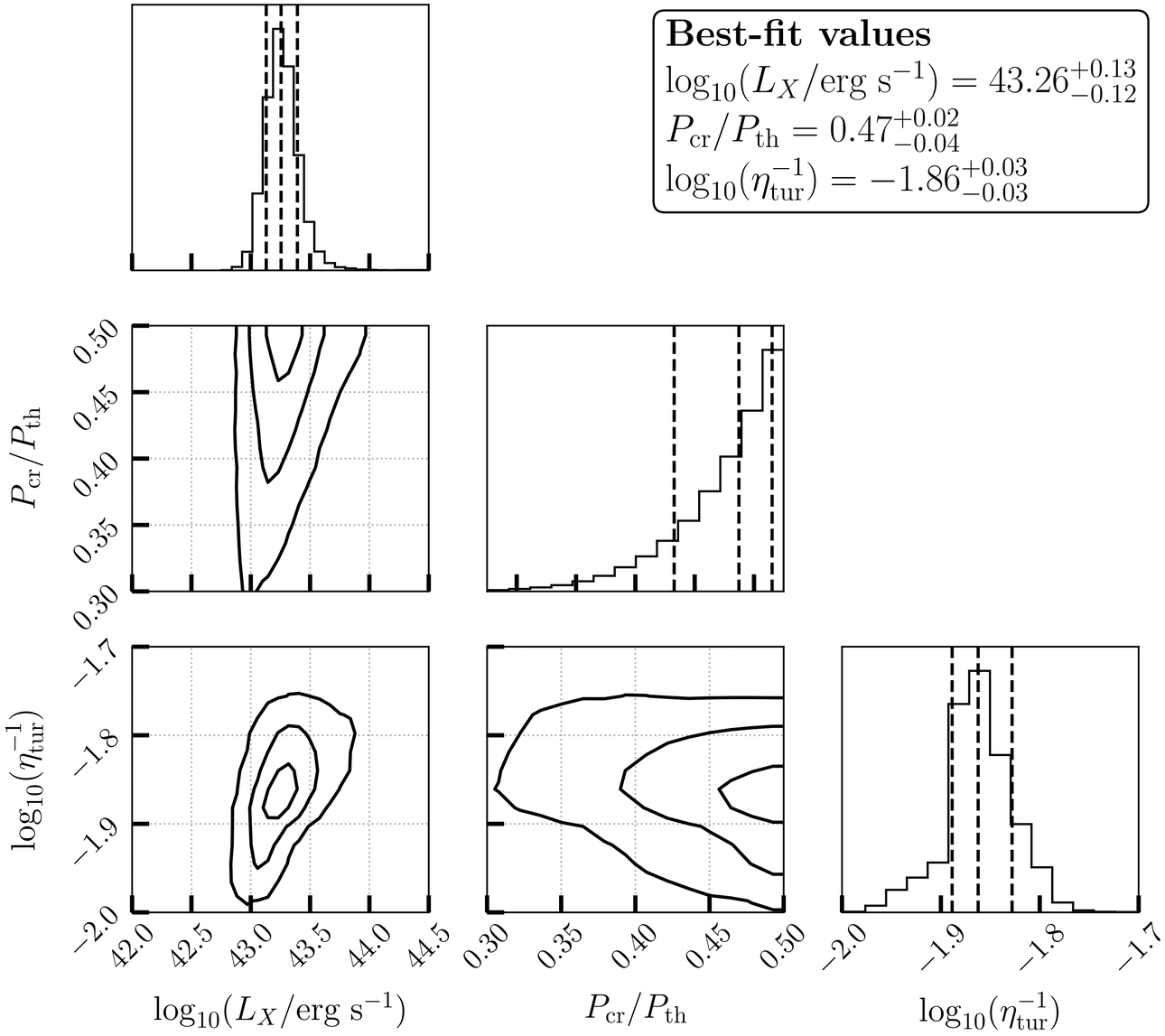
Proton energy **cutoff** occurs at higher energies



NGC 1068

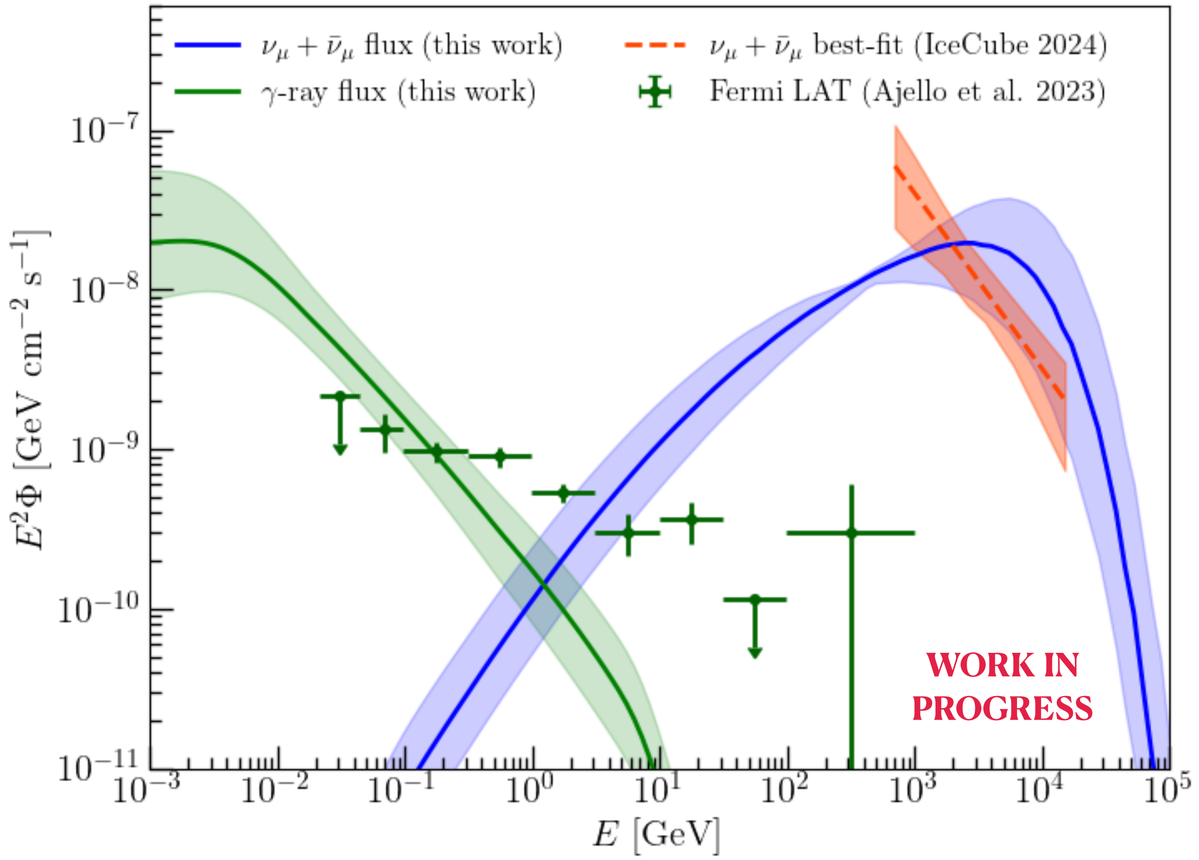
SMBH mass: $1.8 \times 10^7 M_\odot$
Emission radius: $R = 30 R_S$
Distance: 10 Mpc

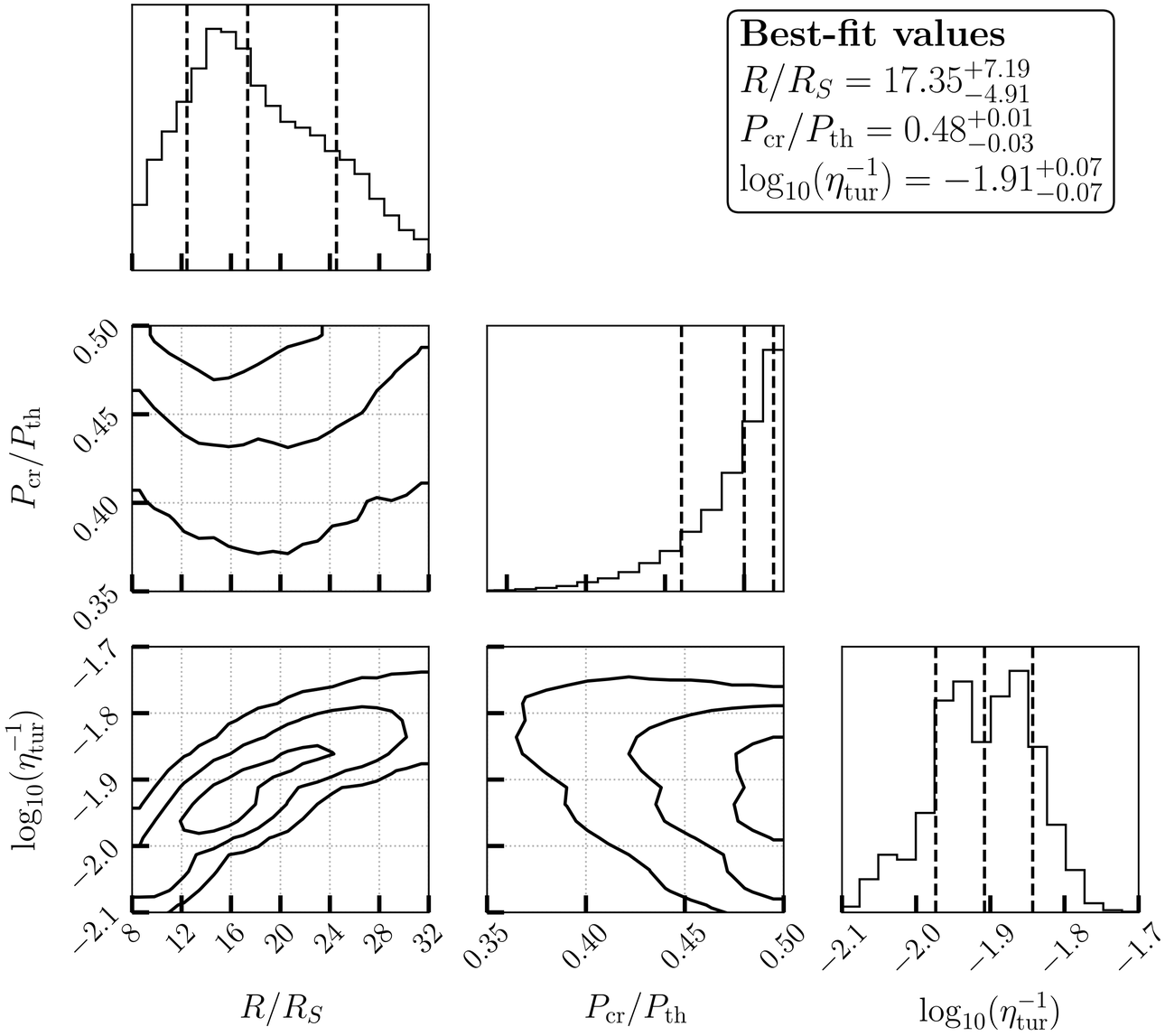




NGC 1068

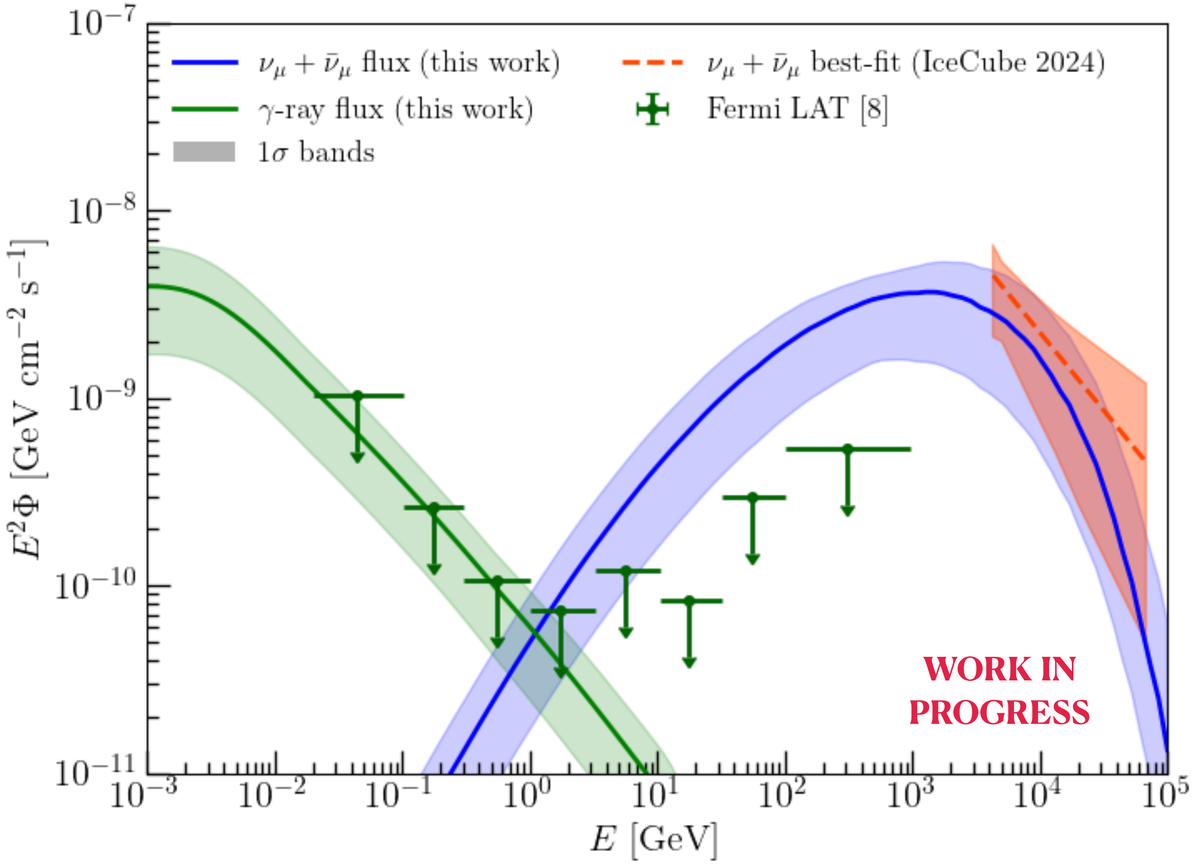
SMBH mass: $1.8 \times 10^7 M_\odot$
Intrinsic X-ray luminosity: 3×10^{43} erg s^{-1}
Distance: 10 Mpc

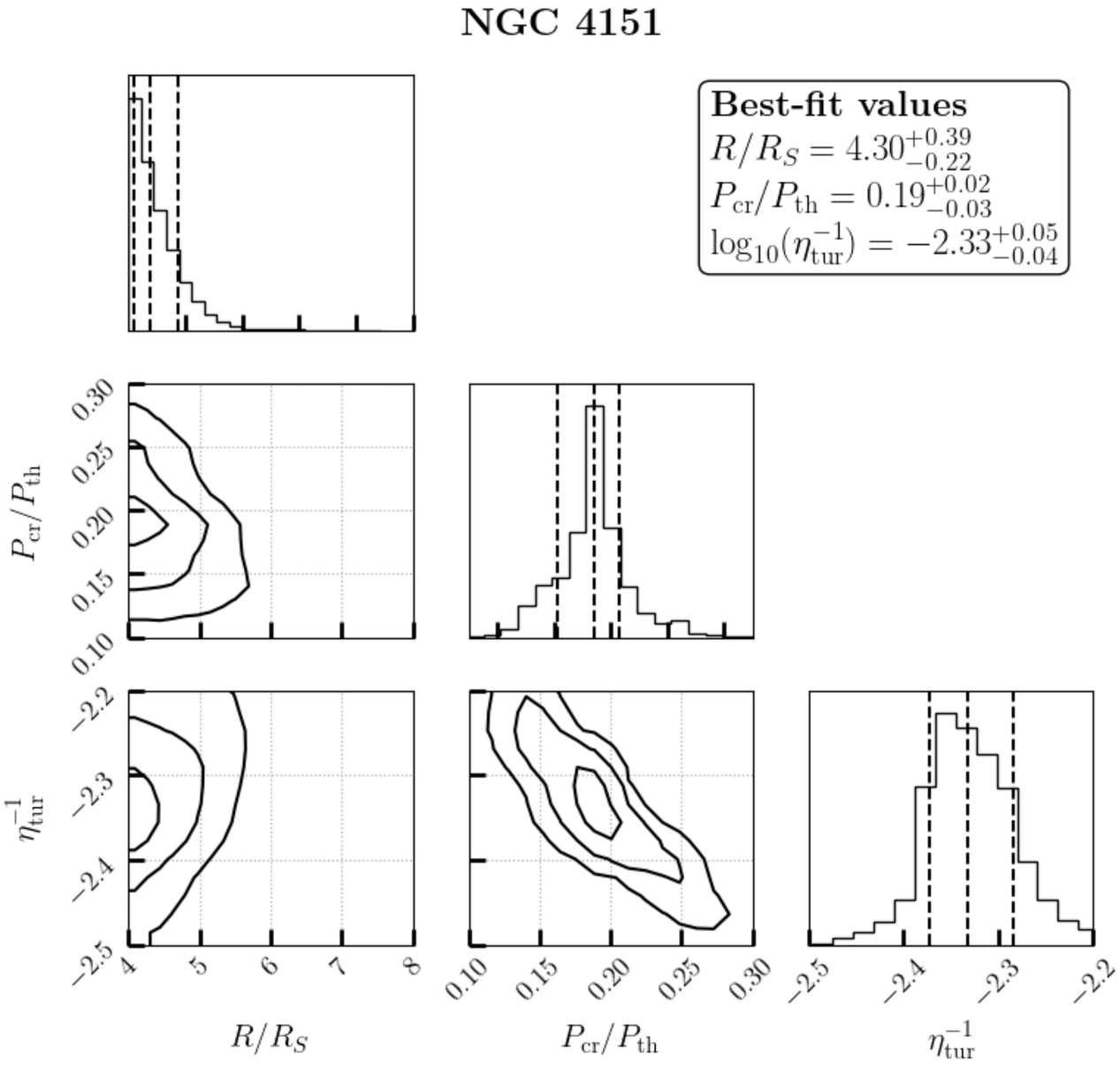




NGC 4151

SMBH mass: $1.7 \times 10^7 M_\odot$
Intrinsic X-ray luminosity: 2.6×10^{42} erg s^{-1}
Distance: 15.8 Mpc
IceCube neutrino power-law: $E^{-2.83}$ (IceCube 2024)





Summary

- Neutrinos give us a unique opportunity to **probe particle acceleration** in hidden sources
- Inclusion of γ-rays lead to **additional constraints** on L_X and $P_{\rm CR}/P_{\rm th}$
- This multimessenger approach can be useful to understand AGN contributions to the diffuse neutrino flux
- Combining these results with X-ray data can help us explore the relationship between L_X and bolometric luminosity.
- The use of more detailed models can **guide future targeted analyses**