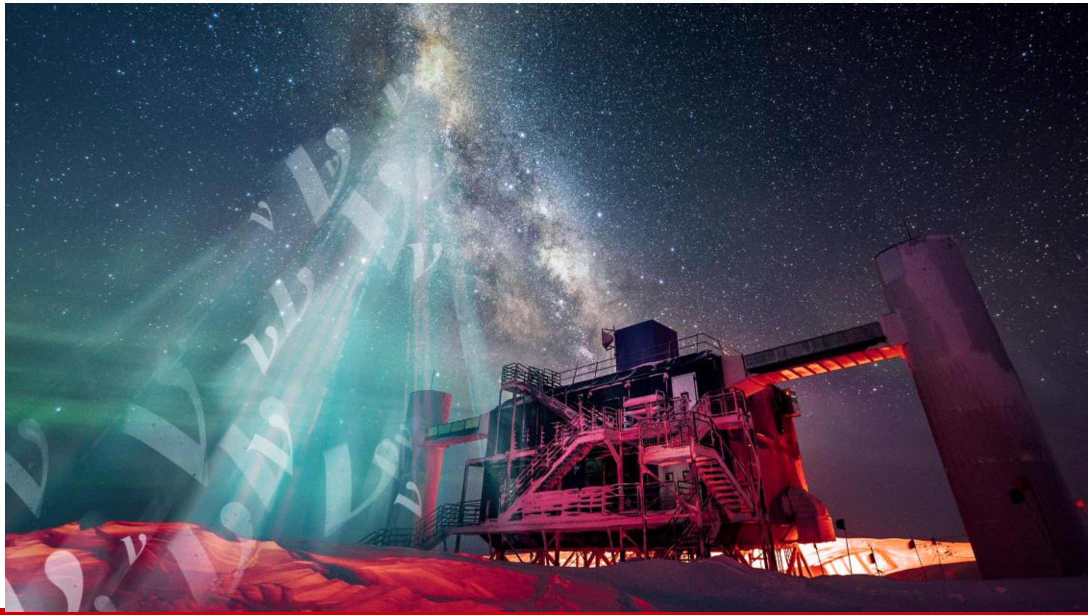
# Connecting the Dots: Neutrino Emission in TXS 0506+056 and NGC 1068

Lepton-Photon 2025,

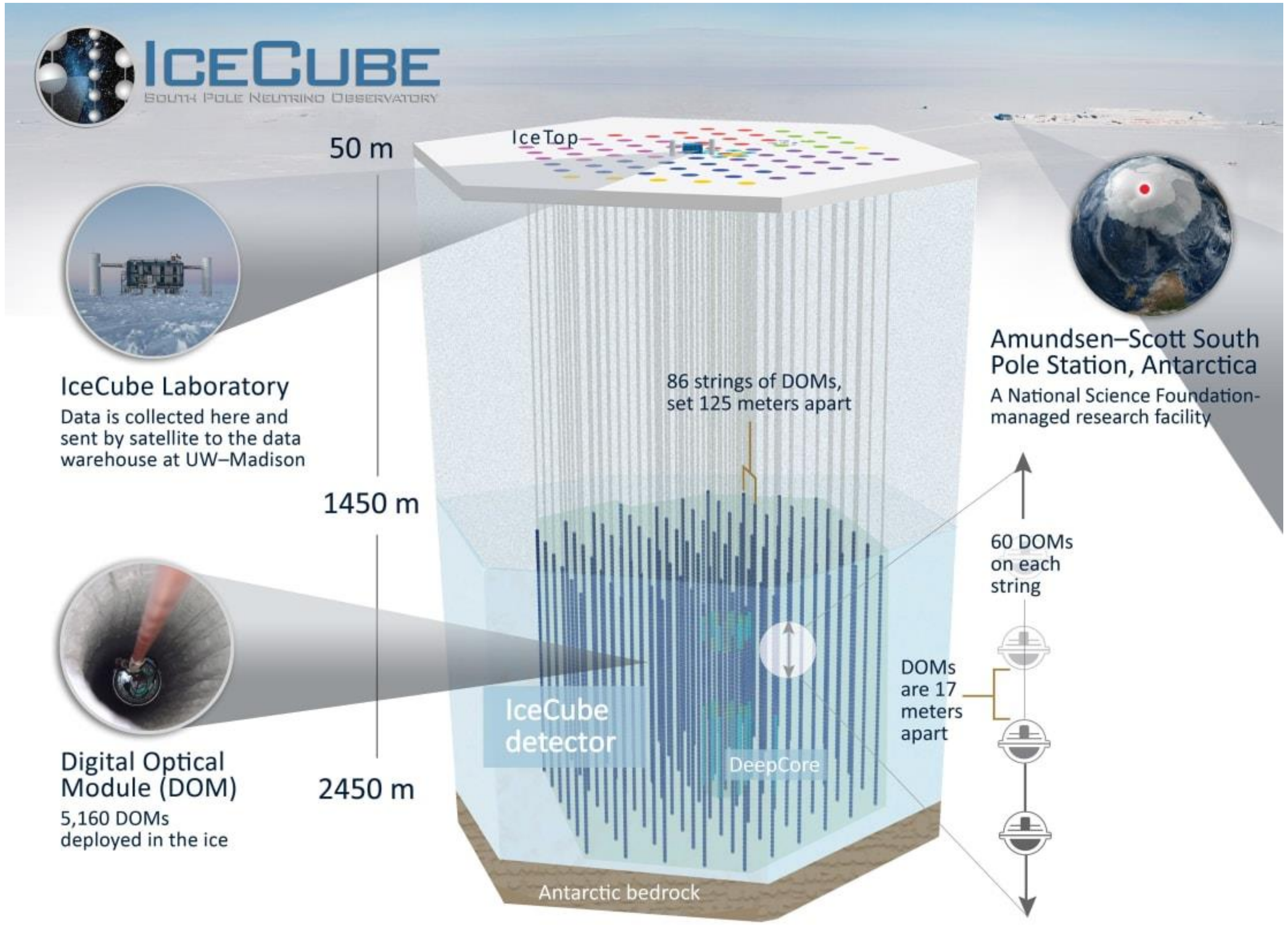
Madison, Wisconsin

27 Aug 2025



**Arifa Khatee Zathul, PhD student, University of Wisconsin-Madison**

# The IceCube Neutrino Observatory




- Neutrino detector embedded in 1 $km^3$ of Antarctic ice
- 5160 Digital Optical Modules (DOMs) deployed on 86 strings ~1.5-2.5km below the surface
- Detects Cherenkov light produced when neutrinos interact with ice
- Energy sensitivity: TeV to PeV

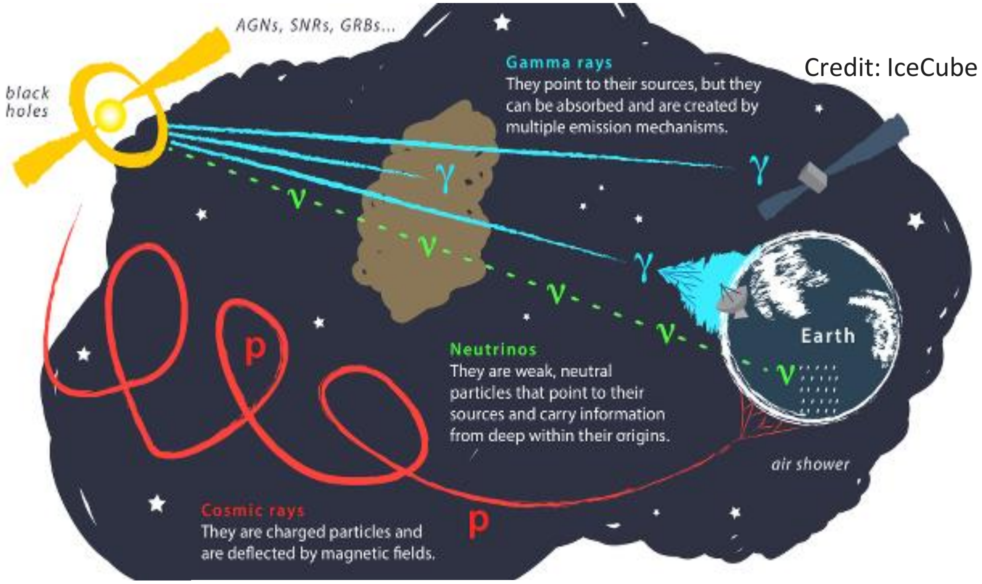
# Astrophysical Neutrino Production

- Produced alongside gamma-rays in *hadronic processes:*
  - Photohadron production (pγ) via $\Delta^+$ channel:

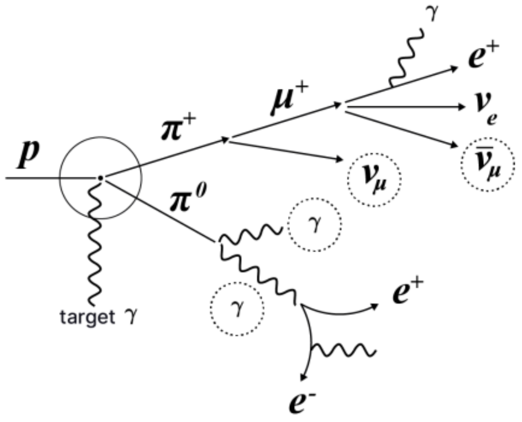
$$p + \gamma \longrightarrow n + \pi^+$$
$$p + \gamma \longrightarrow p + \pi^0$$

- Pionic neutrinos and gamma-rays:

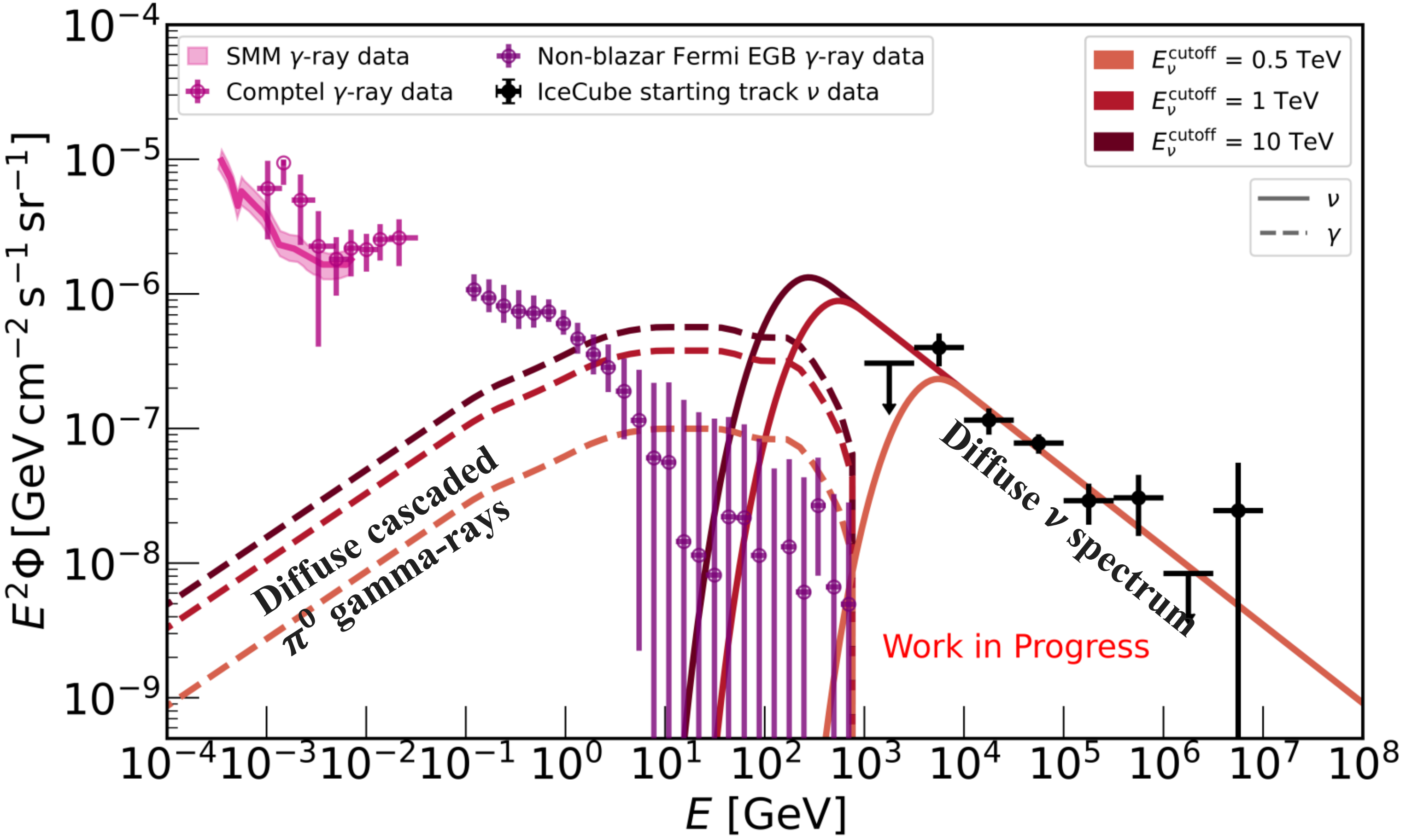
$$\pi^+ \longrightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$
$$\pi^- \longrightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^0 \longrightarrow \gamma + \gamma$$




Credit: IceCube Collaboration



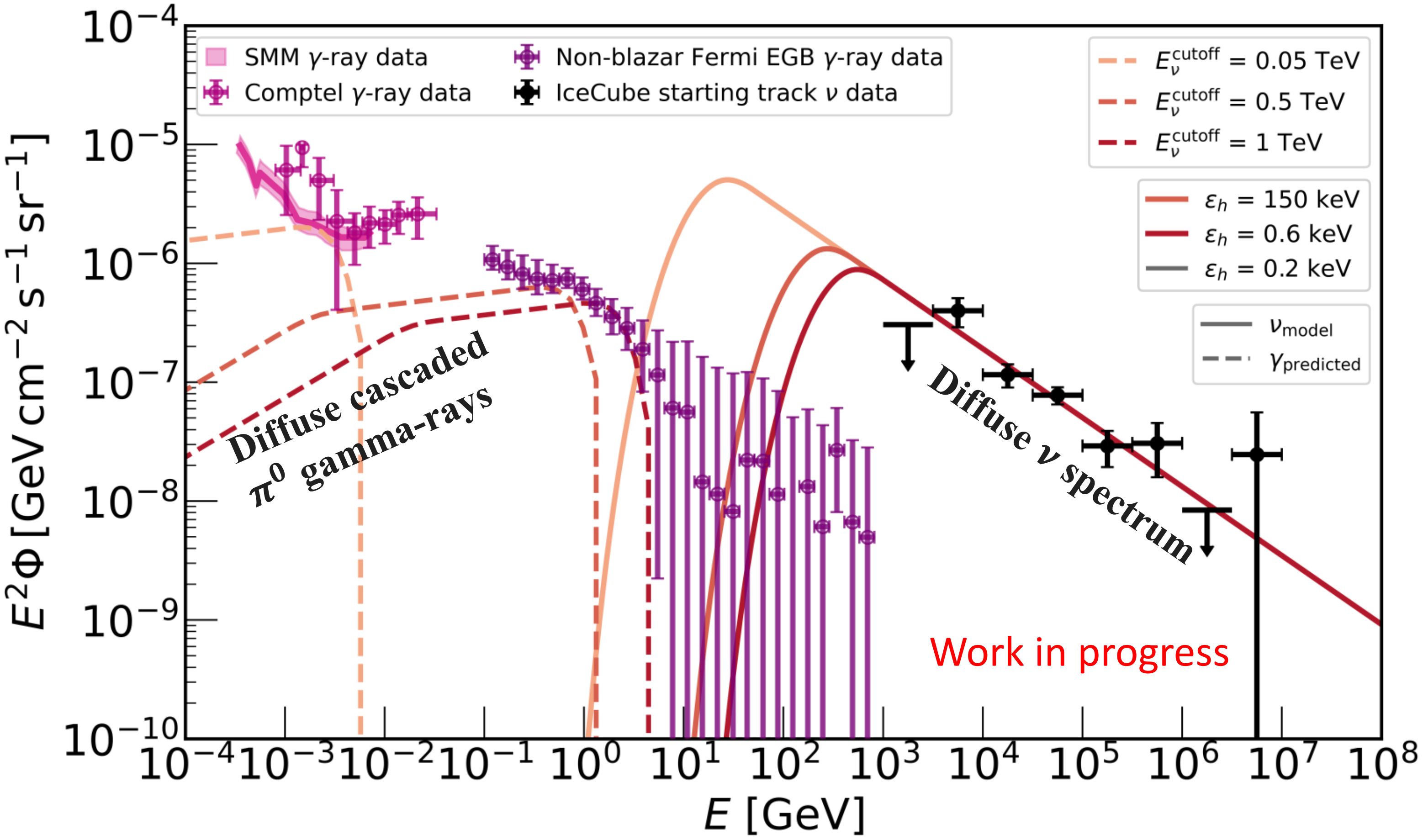
# In Gamma-ray transparent sources, calculated $\gamma$-rays exceed Fermi data




- **Gamma-ray transparent sources:**
  - Gamma-rays produced with neutrinos leave the sources without attenuation
  - They pair-produce with the extragalactic background light to produce cascades in GeV-TeV range
  - However, ~100% of EGB are from blazar jet emissions at $E > 50$ GeV [Qu et al (2019)]

# In Gamma-ray obscured sources, calculated $\gamma$-rays saturate data

- **Gamma-ray obscured sources:**
  - Gamma-rays produced with neutrinos pair-produce with radiation fields in the source
  - Produce cascades in MeV-GeV range, which are then propagated
  - Require source radiation field in X-ray energies
  - Could explain sub-GeV Fermi-LAT EGB data

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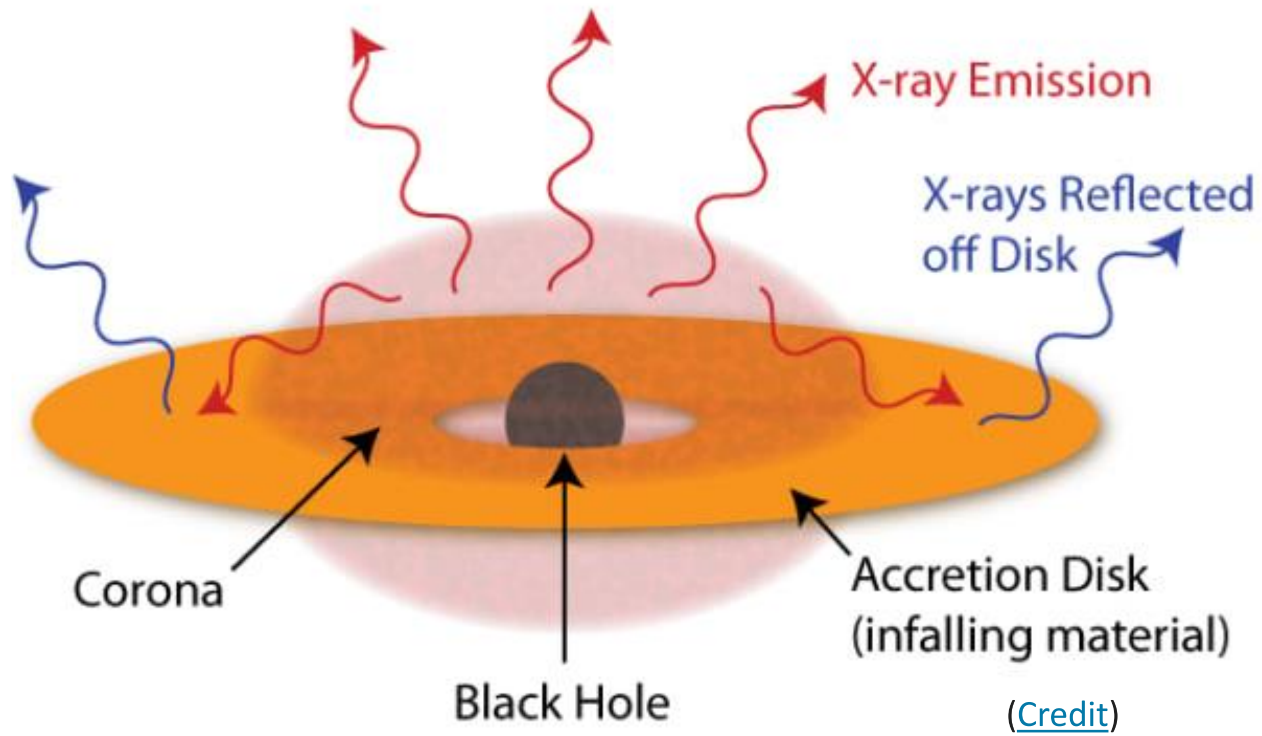
**Typical astrophysical neutrino sources are**

- **gamma-ray obscured**
- **X-ray dense**

# Active Galactic Nucleus (AGN) as an accelerator and a target:



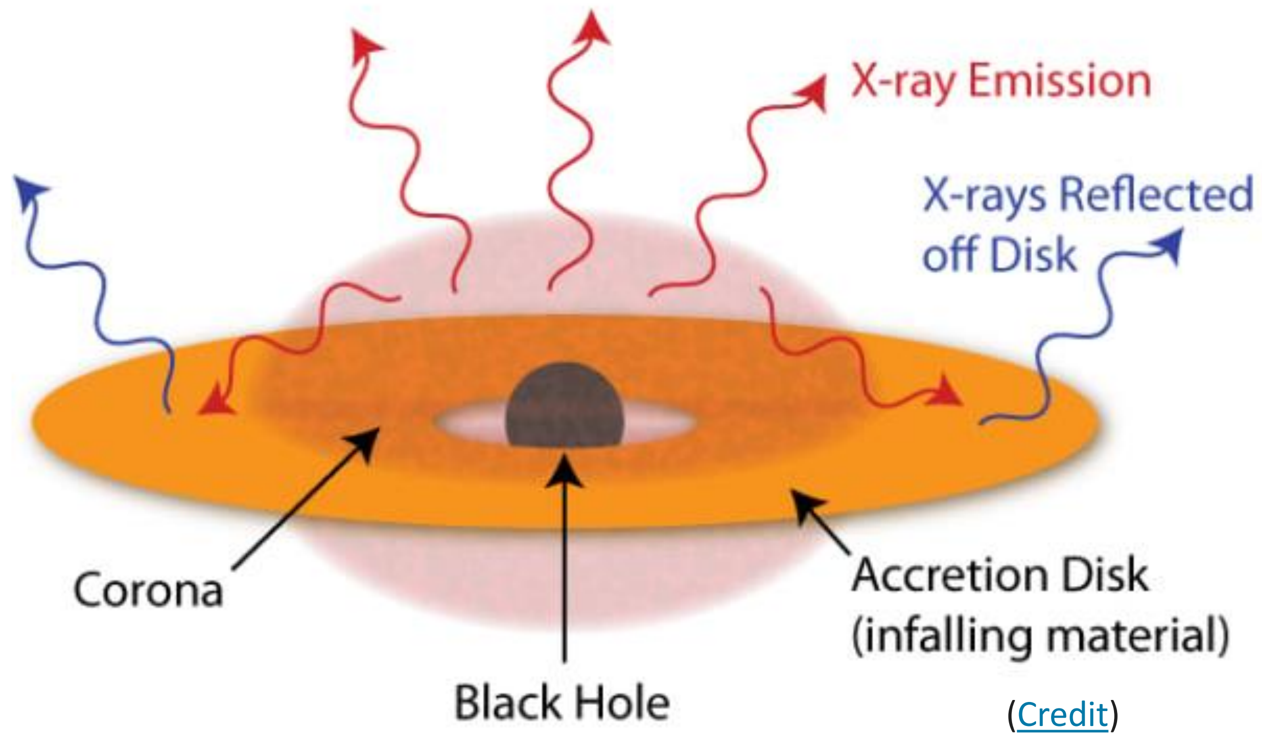

(Credit)

- Supermassive black holes in the center of *active* galaxies:
  - accelerate protons
  - produce neutrinos in the dense targets surrounding them

**Accelerator:** turbulent magnetic fields associated with accretion disk, in-fall of matter around the black hole disks can accelerate protons.

**Targets:** Dense X-ray fields of corona act as photon targets for accelerated protons to produce neutrinos ($p\gamma$).

# AGNs as X-ray sources



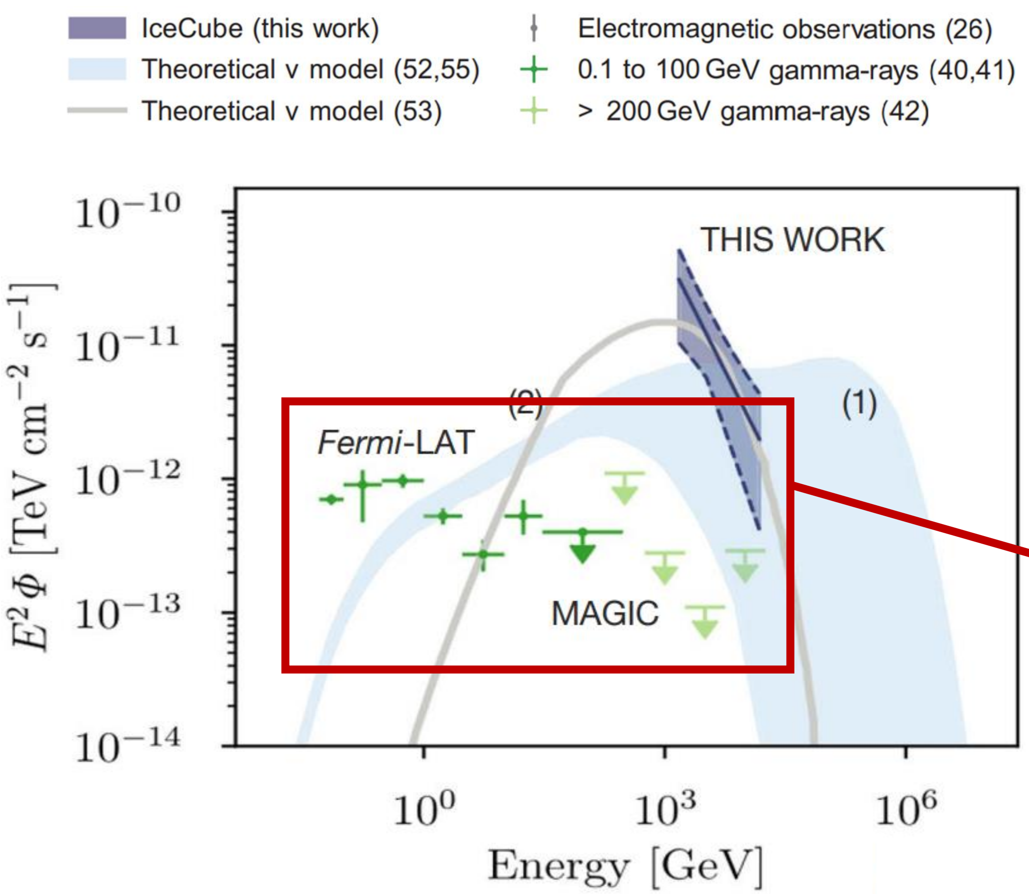

(Credit)

Significant energy in AGNs emitted in the form of X-rays

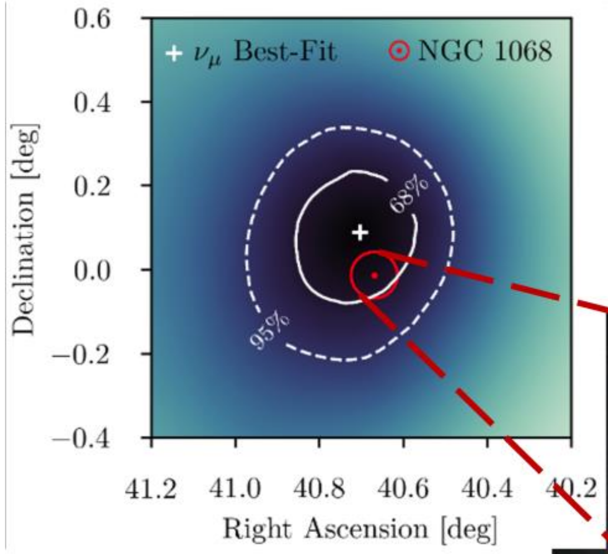
Rapid X-ray variability on time scales of hours to days → emission comes from the innermost region.

X-rays primarily produced by **inverse Compton interaction** between UV/optical photons and highly energetic electrons ($10^9$ K) emitted from the corona.

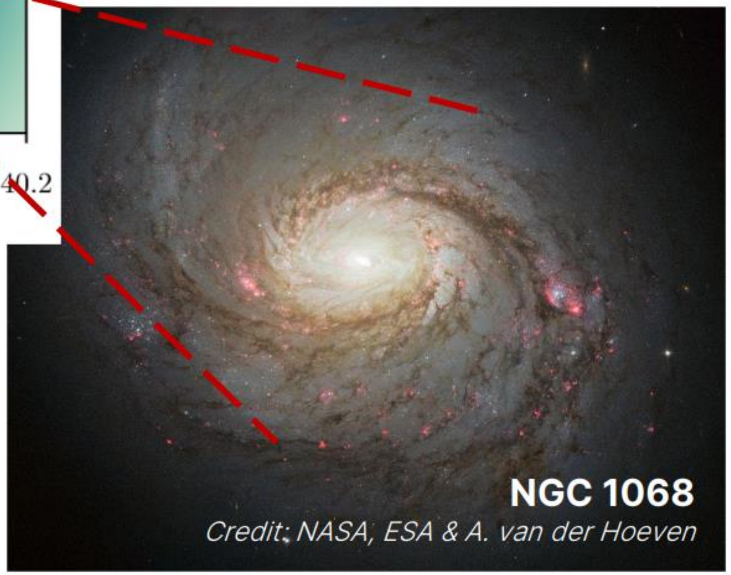
# NGC 1068




ArXiv:2211.09972)




- Seyfert 2
  - $z = 0.0038$
  - Steady source
  - 2011-2020: $79^{+22}_{-20}$ neutrinos




These MeV-GeV $\gamma$-rays are cascades that were produced in gamma-ray-obscured target.

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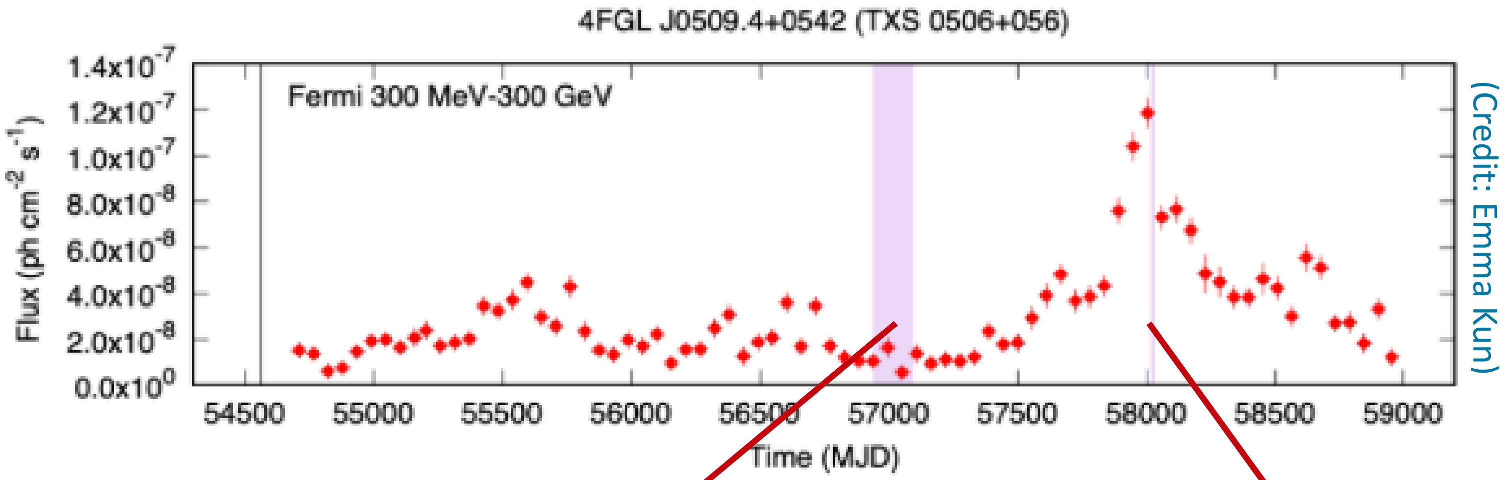
# TXS 0506+056

- IceCube point source, blazar located at z=0.3365.



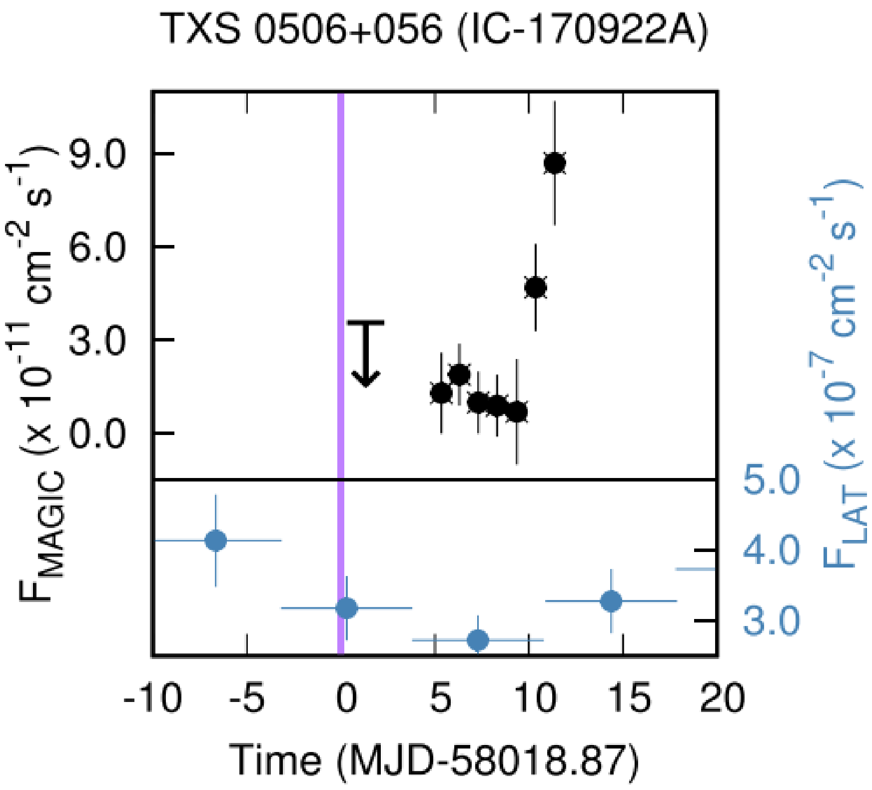

**2014–2015 neutrino excess (archival search finding)**

- An excess of $13 \pm 5$ neutrino events
- Steady emission
- Faint in gamma rays

**IC-170922A (22 Sep 2017)**

- A single, high-energy muon neutrino event (~290 TeV)
- Transient
- Coincident with a bright gamma-ray flare

# A deeper look into IC-170922A: $\gamma$-ray activity




arXiv:2305.06729

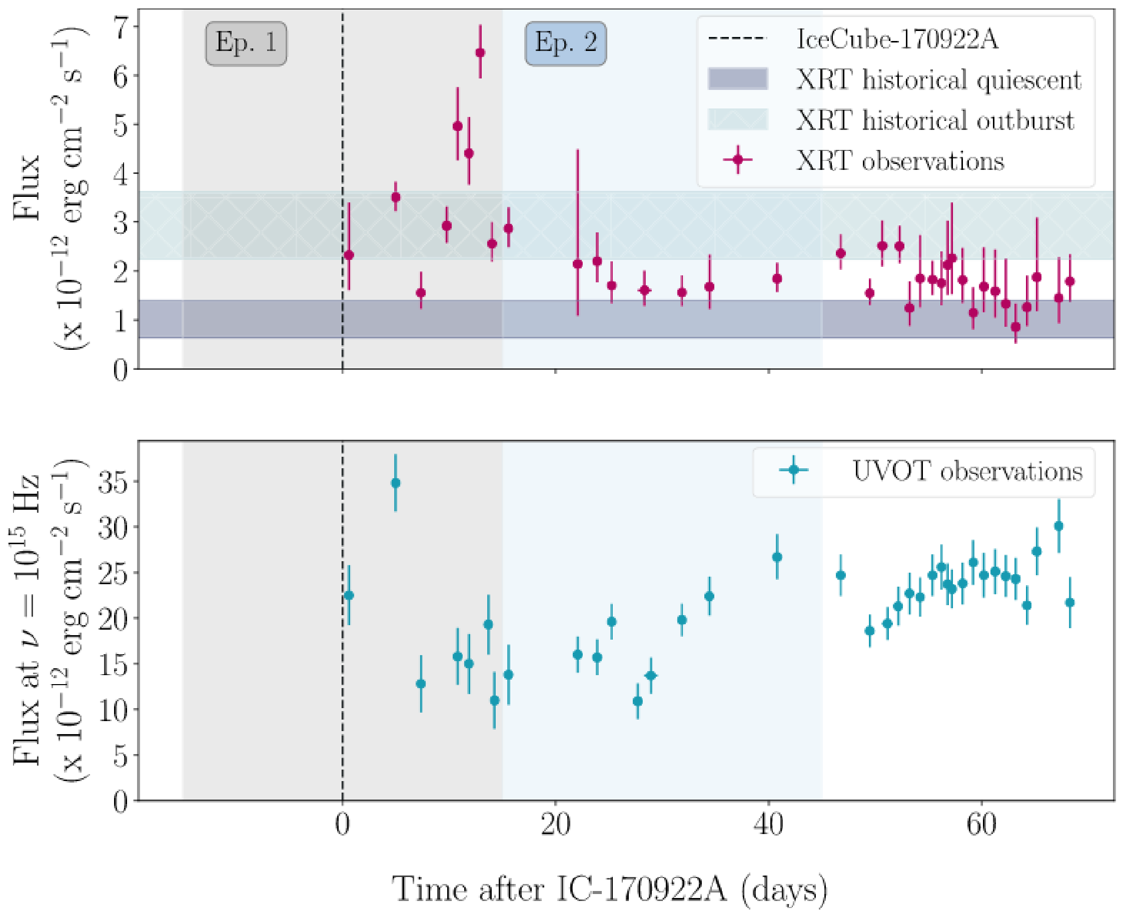
- γ-ray behaviour around neutrino time:
  - Fermi-LAT: ~30% drop in flux just before neutrino, rise within 2 weeks during large flare
  - MAGIC: undetectable at neutrino time, ×10 increase within 2 weeks
  - Optical: rapid brightening hours after neutrino
- TXS 0506+056 may have been gamma-ray obscured over a short period (possibly hours)

# A deeper look into IC-170922A: X-ray activity

- TXS 0506+056 in active X-ray flaring state
  - $F_{0.3-10\ \mathrm{keV}} \sim 2.27 \times 10^{-12}$ erg/cm²/s.
  - Could represent a temporarily enhanced emission from an accretion disk corona
- Historical *Swift*-XRT X-ray measurements:
  - Typical flux $F_{0.3-10\ \mathrm{keV}} \lesssim 1 \times 10^{-12}$ erg/cm²/s.
  - Past outburst $F_{0.3-10\ \mathrm{keV}} \sim 2.8 \times 10^{-12}$ erg/cm²/s.

Ep. 1: [−15 days, +15 days]
Ep. 2: [+15 days, +45 days]

Swift-XRT light curve (soft X-rays, 0.3–10 keV) of TXS 0506+056.




arXiv:1807.04537

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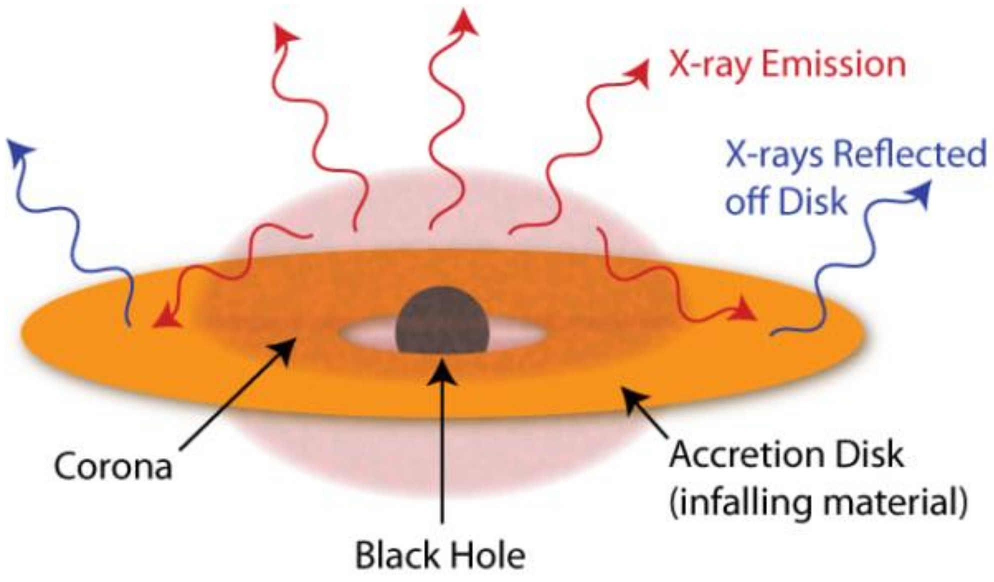
# Photomesonic optical depths

**Corona-Disk Model:**




(Credit)

- X-ray measurements show that corona is compact and extended object (Sotirov 2024)
- X-ray energy density of corona of radius $R$:

$$u_X = n_X E_X = \left(\frac{L_X}{4\pi R^2 c}\right)$$

- Proton's opacity for interacting in the coronal field:

$$\tau_{p\gamma} = \frac{\kappa_{p\gamma} c t_{esc}}{\lambda_{p\gamma}} \simeq n_X \kappa_{p\gamma} \sigma_{p\gamma} c t_{esc}$$

$$\simeq \frac{\kappa_{p\gamma}\sigma_{p\gamma}}{4\pi c}\left(\frac{c}{v_{esc}}\right)\left(\frac{1}{R}\right)\left(\frac{L_X}{E_X}\right)$$

where $\kappa_{p\gamma} \equiv E_\pi / E_p \simeq 0.2, \sigma_{p\gamma} \simeq 5 \times 10^{-28} \mathrm{cm}^2$

- Charged particles escape from the corona on a timescale $t_{esc} = 100\ R/c$ (Stathopoulos et al. 2024)

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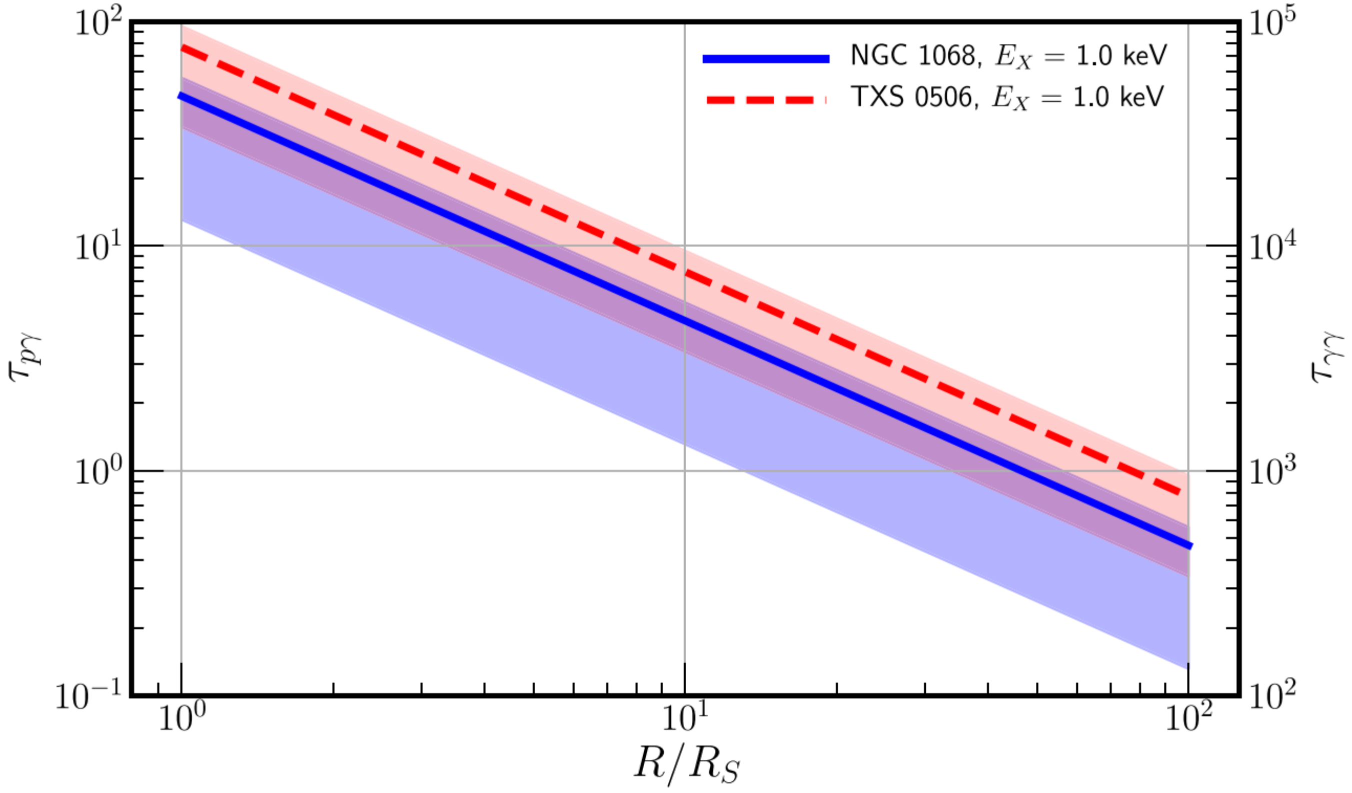
# Optical depths of NGC 1068 & TXS 0506+056

$p\gamma$ and $\gamma\gamma$ opacities against emission radii




A Khatee Zathul et al. (ApJ)
arXiv:2411.14598

- Rewriting opacity:

$$\tau_{p\gamma} \simeq 70 \left(\frac{c}{v_{esc}}\right)\left(\frac{R}{R_S}\right)^{-1}\left(\frac{E_X}{1\ \mathrm{keV}}\right)^{-1}\left(\frac{L_X}{L_{edd}}\right)$$

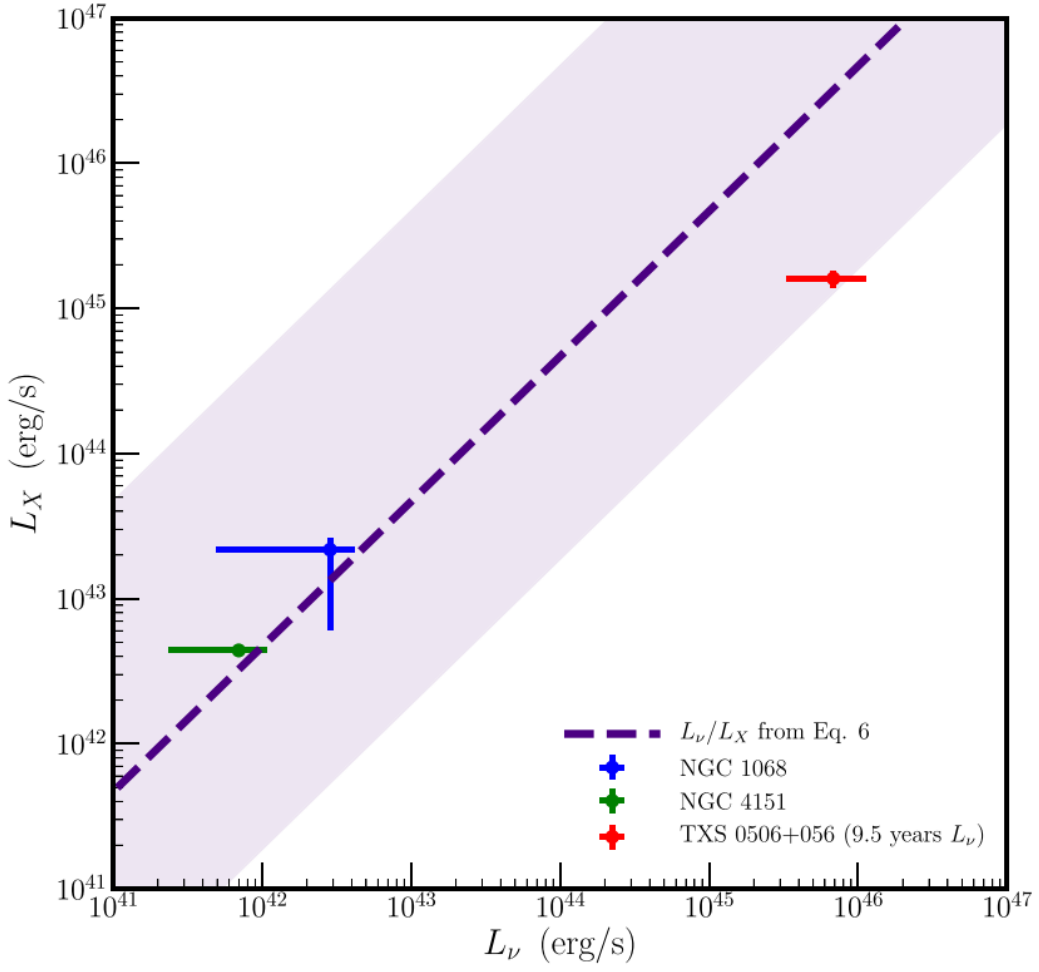
- Important parameters:
  - Soft X-ray band: 0.3 – 10 keV
  - NGC1068 $L_X^{intr} = 2.2^{+0.4}_{-1.7} \times 10^{43}$ erg/s
  - TXS0506+056 $L_X^{intr} = 8.5^{+2.0}_{-4.8} \times 10^{44}$ erg/s
- At $R = 10\ R_S,\ \tau_{p\gamma} \sim 1 - 10$,
  - Neutrino efficiency $f_{p\gamma} = 1 - e^{-\tau_{p\gamma}} = 63\% - 100\%$
  - High optical thickness → $p\gamma$ interactions efficient in producing neutrinos

# Linear scaling between X-ray and $\nu$ luminosity

- Knowing the proton luminosity, we can derive the linear relationship:

$$L_\nu \approx \frac{\kappa_{p\gamma}\sigma_{p\gamma}}{4\pi v_{esc}} \frac{L_p}{RE_X} L_X \sim 700 \frac{L_p}{L_{edd}} \left(\frac{R}{R_S}\right)^{-1} \left(\frac{E_X}{1\ \mathrm{keV}}\right)^{-1} L_X$$

- Error regions:
  - $10^{-3} \leq \frac{L_p}{L_{edd}} \leq 1,$
  - $10 \leq \frac{R}{R_S} \leq 100$
- Using X-ray flux/luminosity observations to look for other potential neutrino sources

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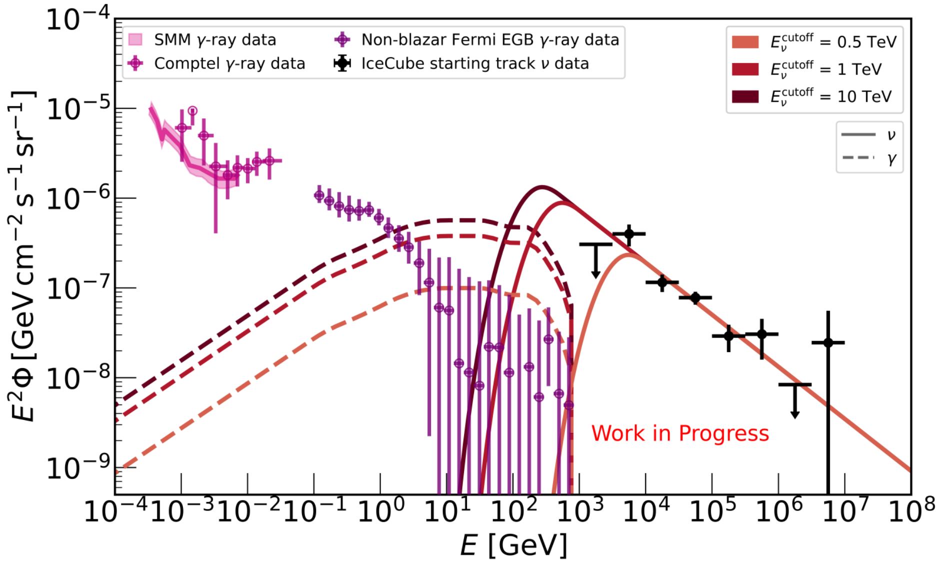
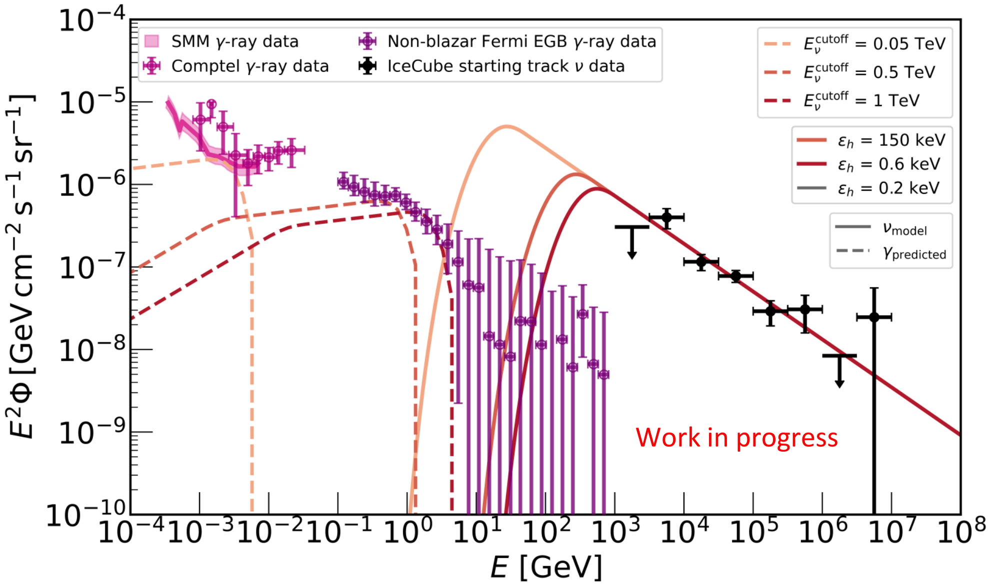
# Conclusion and Outlook

- Neutrino sources are X-ray bright and gamma-ray obscured
- AGNs are a class of sources that IceCube has seen
- Futurework: Population studies using IceCube



IceCube
Neutrino Observatory

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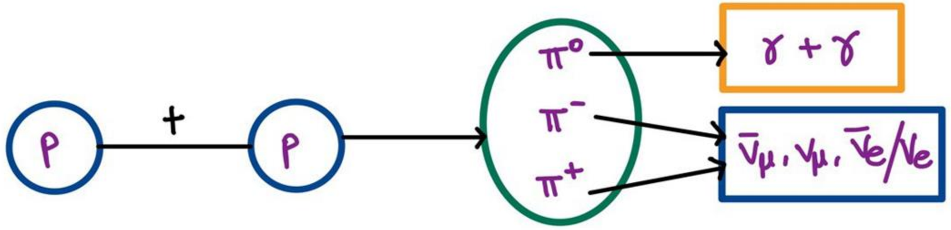
# Astrophysical Neutrino Production

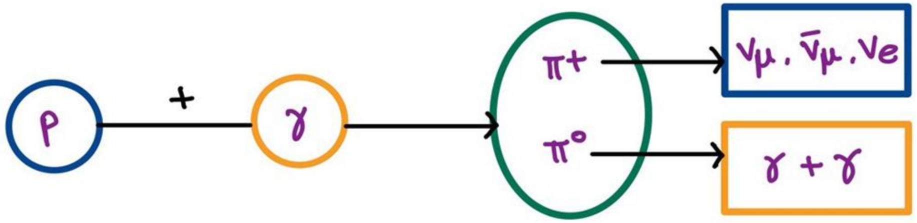
- Produced alongside gamma-rays in *hadronic processes*, primarily via these 2 channels:
  1. Inelastic proton-proton collision (pp):

$$p + p \longrightarrow n_\pi \left(\pi^0 + \pi^+ + \pi^-\right) + X$$




  2. Photohadron production (pγ) via $\Delta^+$ channel:

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

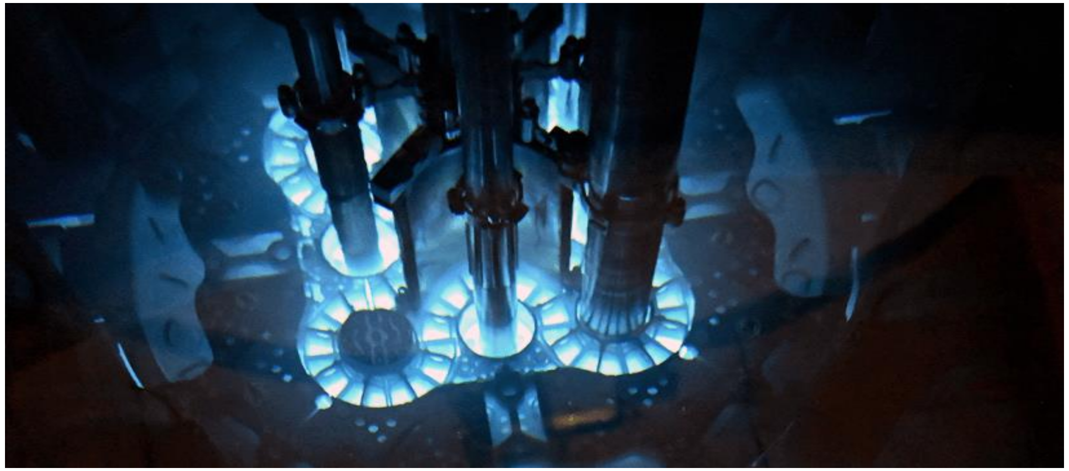



- Pionic neutrinos and gamma-rays:

$$\pi^+ \longrightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$
$$\pi^- \longrightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^0 \longrightarrow \gamma + \gamma$$

# Cherenkov radiation

- Emitted when charged particle moves faster than the speed of light in a given medium of refractive index $n \left(v > \frac{c}{n} \rightarrow \beta > \frac{1}{n}\right)$
- Emission in UV–blue spectrum, at an angle: $\cos\theta_c = (n\beta)^{-1}$
- For visible light: $n_{ice} \simeq 1.32,\ \theta_c \simeq 41^\circ$ for relativistic particles



After a time $t$,

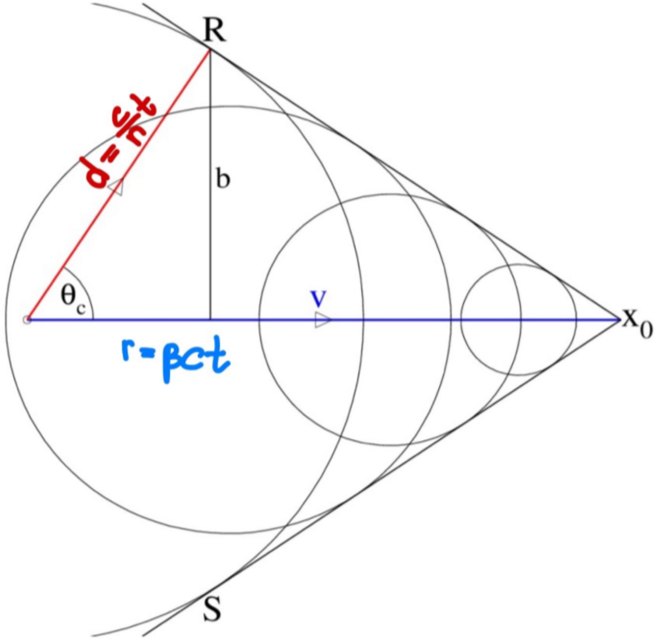
- Charged particle travelled

$d = \frac{c}{n} t$

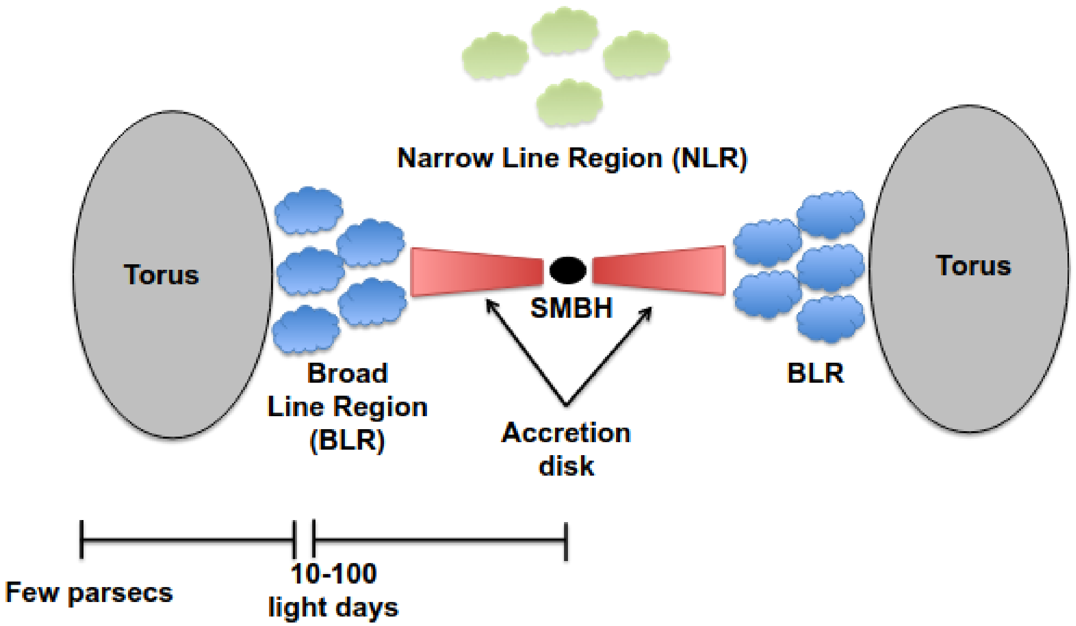
- Light wave-front travelled

$r = \beta c t$

$$\boxed{\therefore \cos\theta_c = \frac{\cancel{c}}{n}\cancel{t} \times \frac{1}{\beta\cancel{c}\cancel{t}} = \frac{1}{n\beta}}$$



# Anatomy of a typical AGN

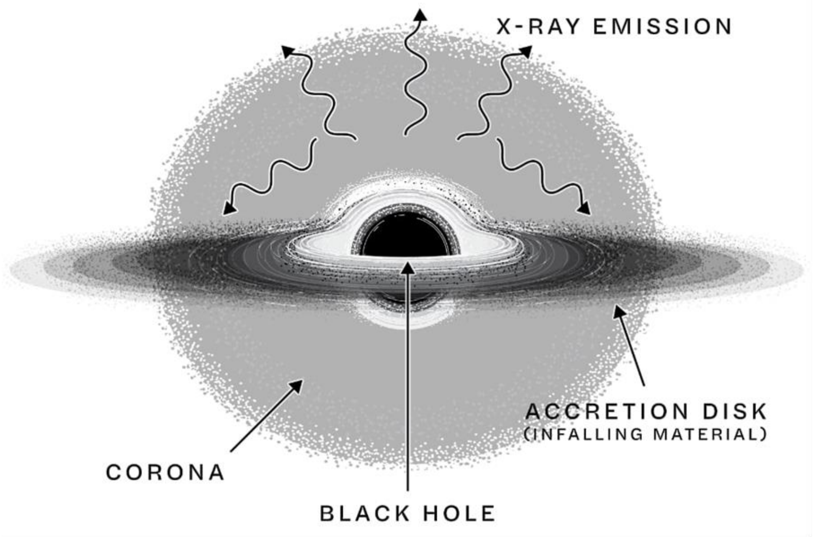



Credit: Claudio Ricci, taken from [thesis name]

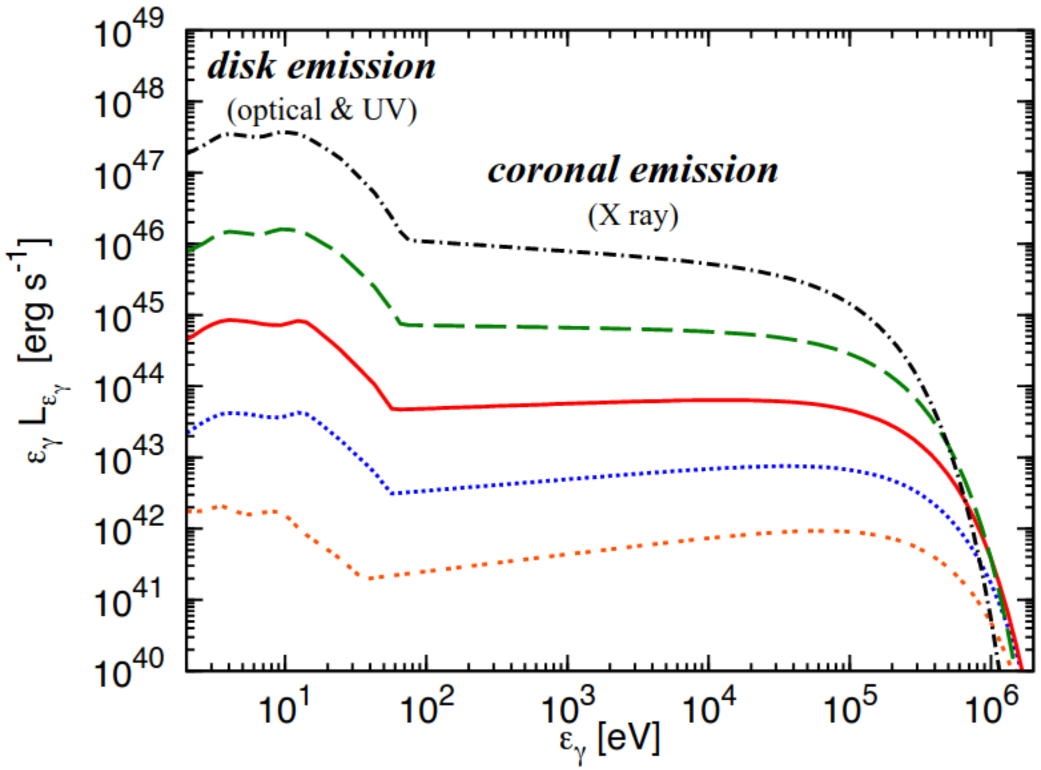
- Central engine:
  - SMBH → gravitational engine
  - Accretion disk → optical/UV (blue bump)
  - Corona → hot magnetized plasma, responsible for most of the X-ray emission [S. Laha 2025]
- Broad line region (BLR):
  - High-velocity gas clouds photoionized by energy from central engine
  - Doppler-broadened emission lines
- Dusty torus:
  - Boundary of BLR region
- Narrow line region (NLR):
  - Low-velocity gas clouds
  - Narrow emission lines

# Corona-disk Model

- Accretion disk:
  - Thermal black body spectrum that peaks at T~10 eV (UV)
- X-ray corona:
  - Formed due to accretion and magnetic dissipation
  - Disk photons undergo inverse Compton scattering on the hot electrons (100 keV)
  - Power-law spectrum from soft X-rays (~0.1 keV) to hard X-rays (>100 keV)




(Credit: F. Halzen, ArXiv:2305.07086)



# Energetics of NGC 1068 & TXS 0506+056

- We can compute the proton luminosity at the source given the neutrino data:

$$E_\nu^2 Q_\nu^2 = (1 - e^{-\tau_{p\gamma}}) E_p^2 Q_p^2$$

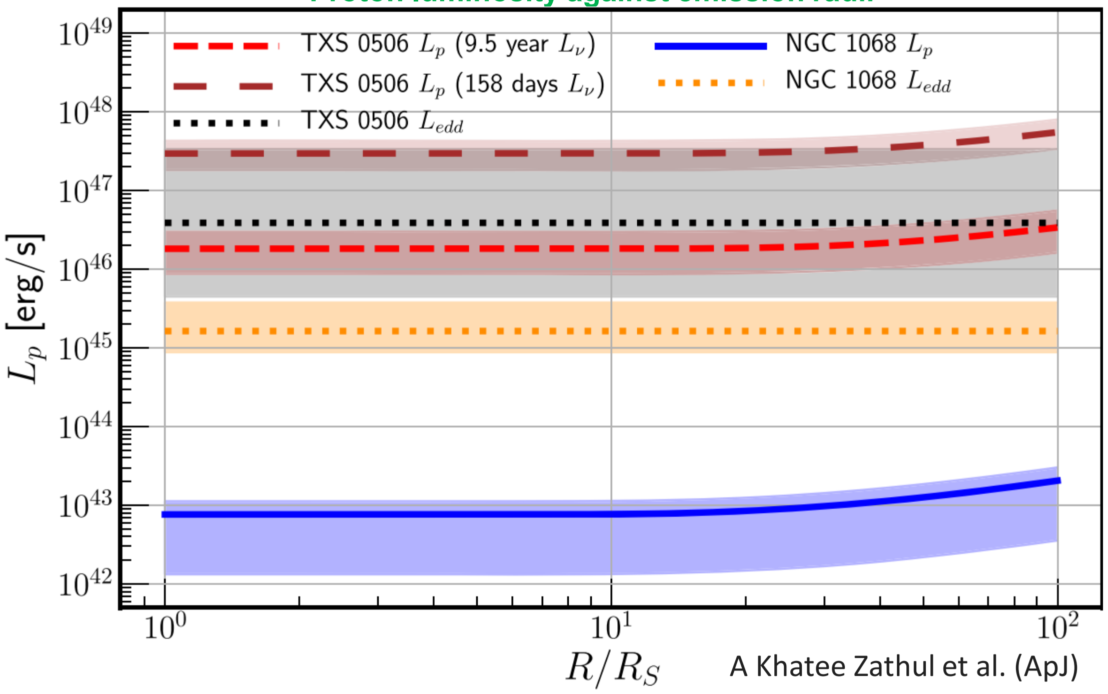
- Eddington luminosity

$$L_{edd} \approx \frac{4\pi G m_p c}{\sigma_T} M = 1.3 \times 10^{38}\ \mathrm{erg/s} \left(\frac{M}{M_\odot}\right)$$

- Results:
  - NGC 1068: $L_p \ll L_{Edd}$
  - TXS 0506 (9.5 year average): $L_p \sim L_{edd}$
  - TXS 0506 (158-days in 2014-2015): $L_p \gg L_{edd}$

| Parameter | NGC 1068 | TXS 0506+056 |
|---|---|---|
| Eddington luminosity, $L_{\mathrm{edd}}$ (erg s$^{-1}$) | $1.6^{+2.1}_{-0.8} \times 10^{45}$ | $3.9^{+29.9}_{-3.4} \times 10^{46}$ |
| Neutrino luminosity, $L_\nu$ (erg s$^{-1}$) | $2.9^{+1.4}_{-2.4} \times 10^{42}$ | $6.8^{+4.4}_{-3.6} \times 10^{45}$ (9.5 yr duration), $1.1^{+0.5}_{-0.4} \times 10^{47}$ (158 days duration) |

Proton luminosity against emission radii

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