Multi-messenger models of AGN jets and coronae

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DEPARTMENT OF PHYSICS

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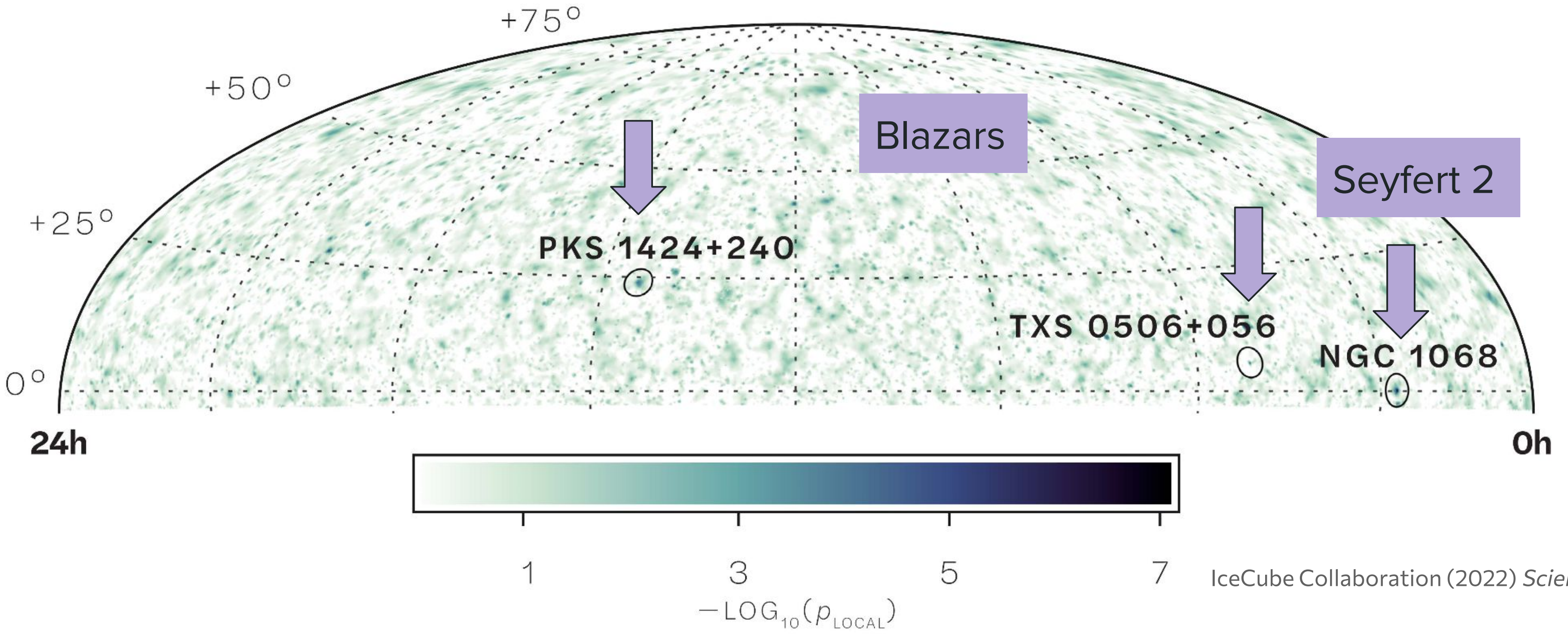
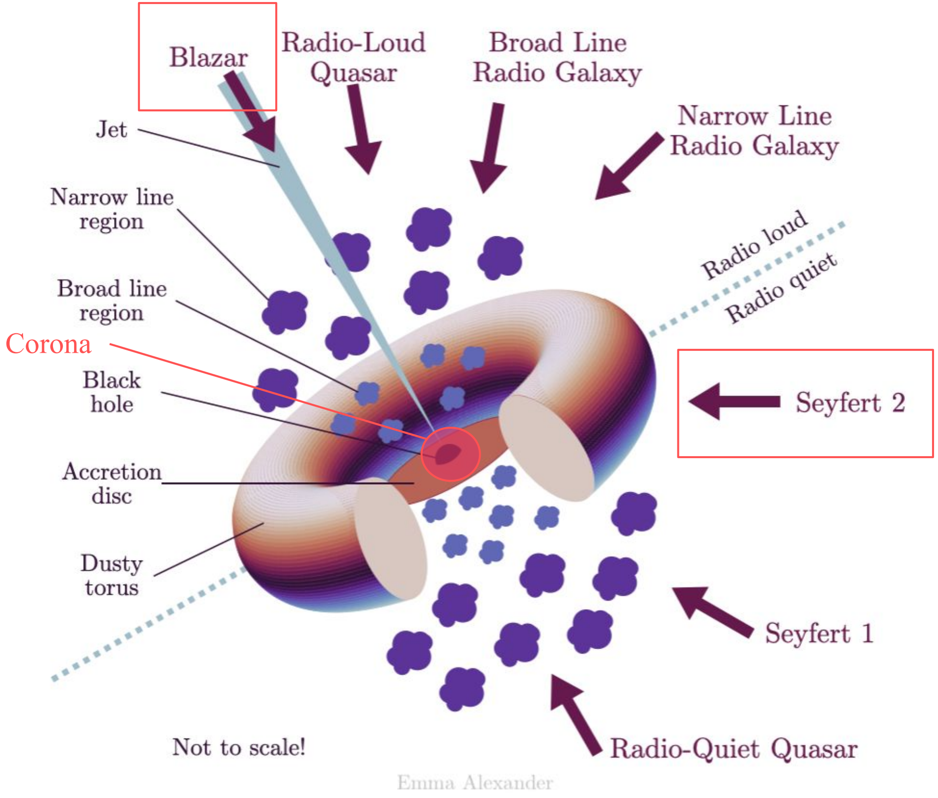
Neutrino associations with Active Galactic Nuclei

10 year IceCube neutrino sky map

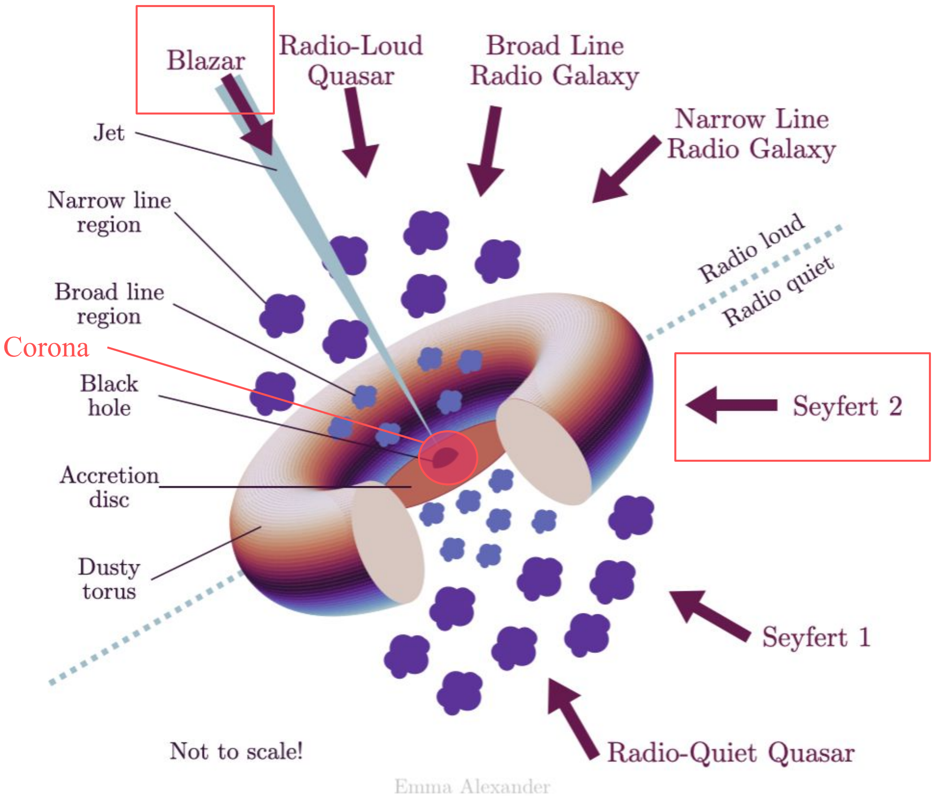


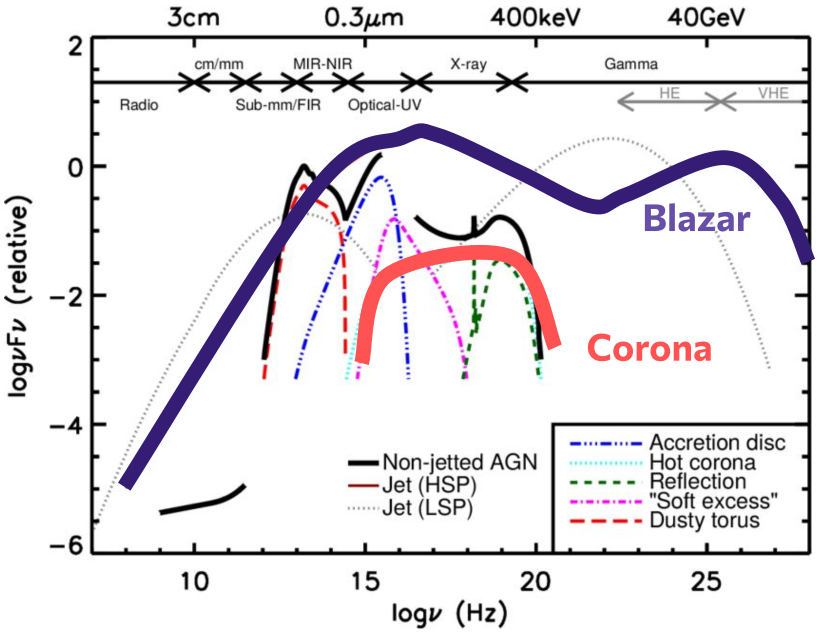
IceCube Collaboration (2022) *Science*

Active Galactic Nuclei



Active Galactic Nuclei

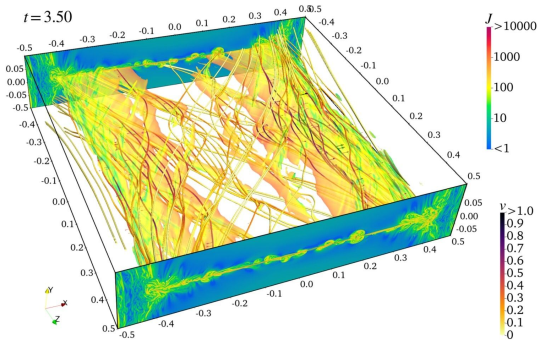




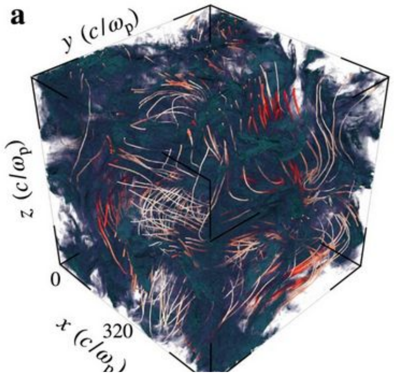
Ingredients of AGN multi-messenger models

- **Acceleration:** shocks, shear flows, magnetic reconnection, turbulence

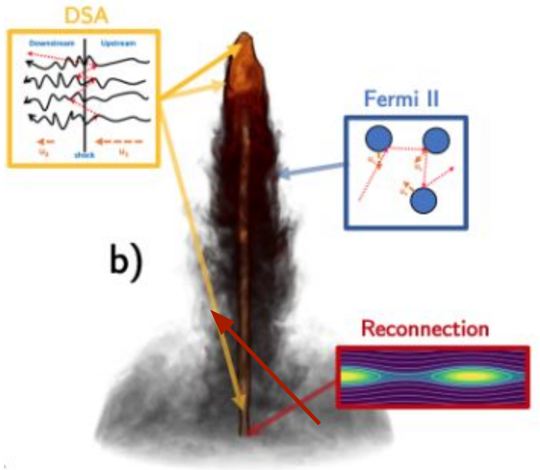
Matthews, Bell, Blundell (2020) *NewAR*



Huang, Y. M. (2023). *Radiation Effects and Defects in Solids*, *178*



Nättilä, J. (2024) *Nat. Commun.* **15**, 7026



- **Radiation fields:** IR (dusty torus), OUV (disk + BLR), X-rays (corona), MW (jet)
- **Proton interaction channels:** pγ (photomeson) - BH (Bethe-Heitler) - pp

The ν-γ connection

Murase, Guetta, Ahlers (2016) *ApJ*

Neutrino luminosity

$$E_\nu L_{\nu+\bar{\nu}}(E_\nu) \approx \eta \cdot \left[f_i(E_p) \cdot E_p L_p(E_p) \right]_{E_p \approx 20\, E_\nu}$$

Acceleration physics

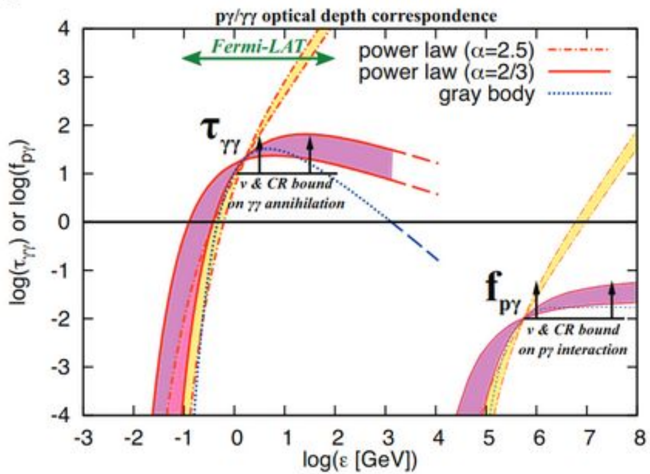
Interaction physics (branching ratio, proton energy)

Interaction physics + Source properties

Escaping γ-ray luminosity

$$E_\gamma L_{\gamma,esc}(E_\gamma) \approx \eta' \cdot \left[f_i(E_p) \cdot E_p L_p(E_p) \right]_{E_p \approx 10\, E_\gamma} e^{-\tau_{\gamma\gamma}(E_\gamma)}$$

Radiation fields + Source properties



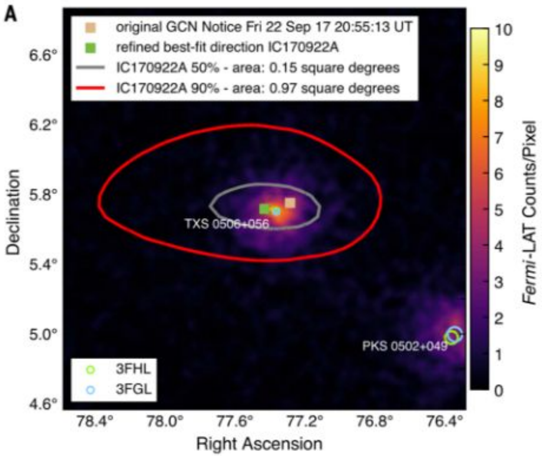
IMPLICATIONS

Sources that are efficient neutrino producers are opaque to γ-rays.

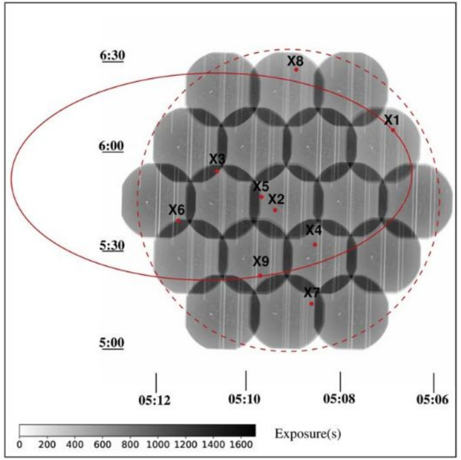
The absorbed γ-ray luminosity emerges at lower energies via electromagnetic cascades.

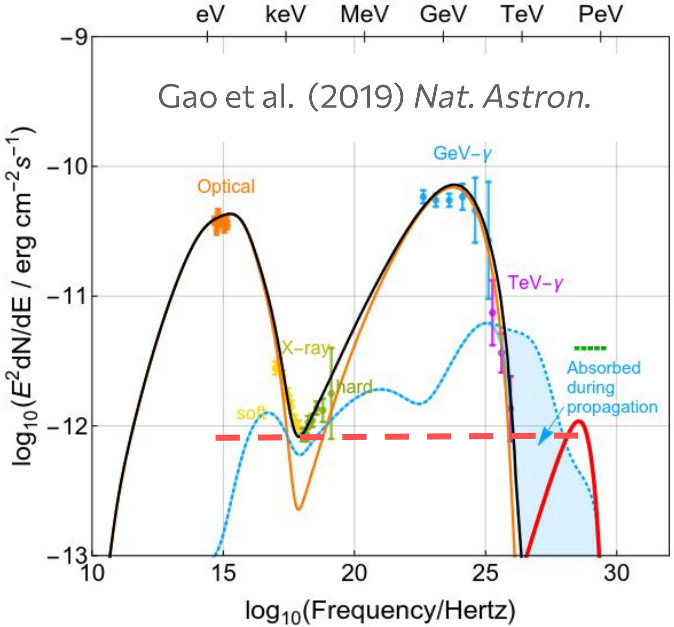
TXS 0506+056

IceCube Collaboration (2018), Science



Keivani et al. (2018), ApJ



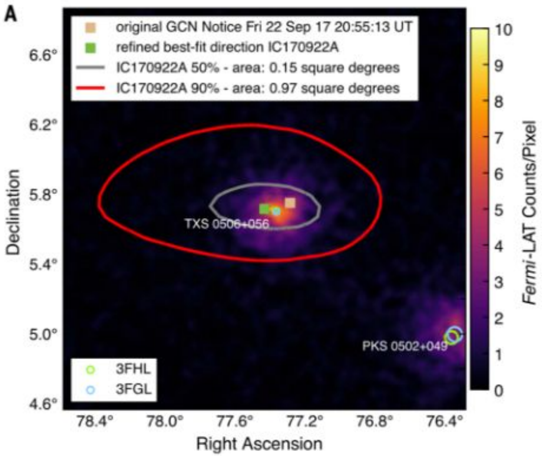


- Unspecified acceleration mechanism
- Neutrinos: pγ interactions - GeV γ-rays: ICS interactions
- Production site in jet at ~ 0.1 - 1 pc
- EM cascade saturates X-ray flux → $L_\nu < L_X \sim 4\ 10^{44} - 10^{45}$ erg/s

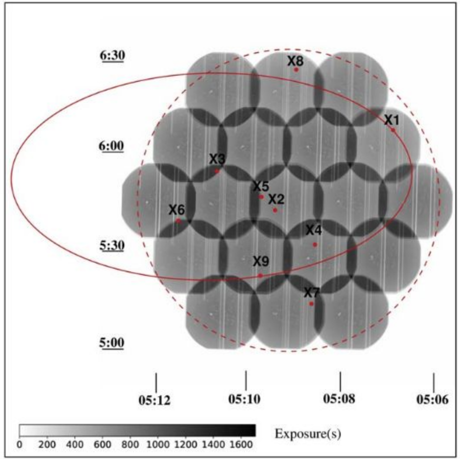
Similar findings: Keivani et al. (2018) *ApJ*; Murase et al. (2018), *ApJ*; Cerruti et al. (2019) *MNRAS*; Gao et al. (2019) *Nat. Astron.*; Sahakyan et al. (2018) *ApJ*

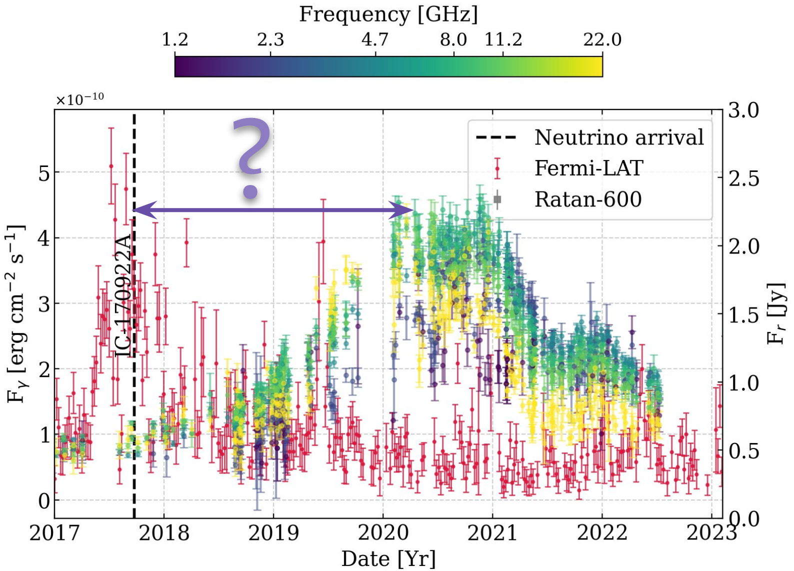
TXS 0506+056

IceCube Collaboration (2018), Science



Keivani et al. (2018), ApJ





Stathopoulos et al. (2026) *ApJL*

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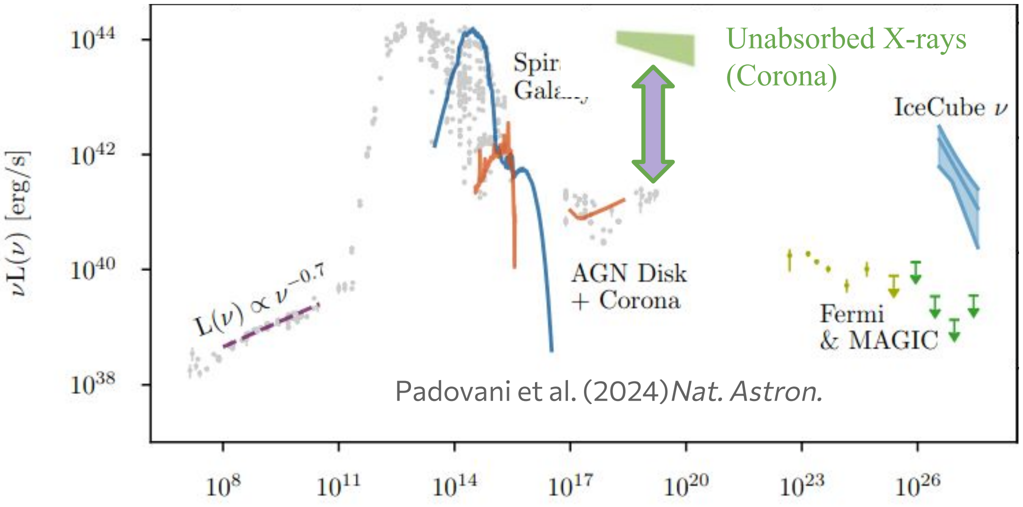
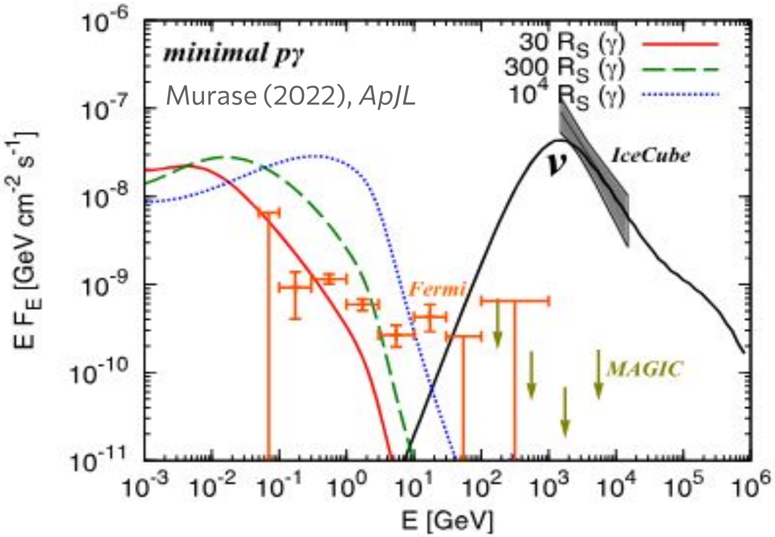
Check talk by Stathopoulos (Sep 3)

Similar findings: Keivani et al. (2018) *ApJ*; Murase et al. (2018), *ApJ*; Cerruti et al. (2019) *MNRAS*; Gao et al. (2019) *Nat. Astron.*; Sahakyan et al. (2018) *ApJ*

NGC 1068



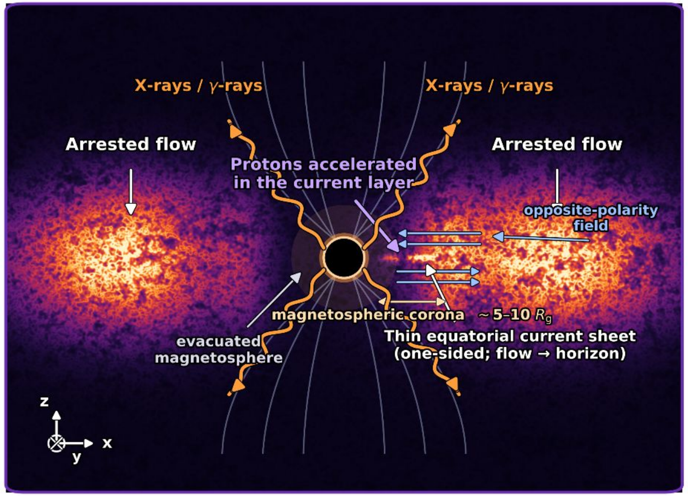


- Neutrinos likely produced in corona
- Fermi-LAT observations set model-independent constraints on coronal size: $R < (60\text{-}200)\, R_g$ [Murase (2022), *ApJL*; Murase et al. (2020) *ApJ*; Ajello *et al*. (2023), *ApJL*]

- ~79 ± 20 events with soft spectrum ($\Gamma = 3.4$)
- $L_\nu >> L_{\gamma,\,TeV}$ → source opaque to TeV γ rays
- $L_X \sim 10^{43} - 10^{44}$ erg/s (unabsorbed X ray emission)

A - Magnetic reconnection model

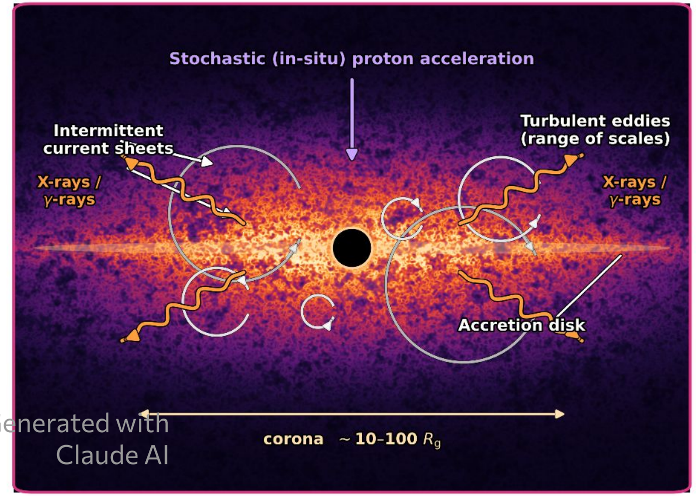
Equatorial current sheet between arrested flow and horizon



- Macroscopic current sheet on the equatorial plane, between the edge of the arrested flow and the black-hole horizon
- Systematic acceleration in reconnection sites
- Very high magnetization ($\sigma_p \sim 10^3$–10^5)
- Non-thermal protons carry a large fraction of the Poynting luminosity ($P_p \sim L_{Poynting}$)
- Pair-dominated plasma ($n_e \gg n_p$)

B - Magnetized turbulence model

Turbulent corona = puffed-up inner accretion flow



- MHD turbulence generates intermittent current sheets throughout the corona
- Stochastic (non-resonant) particle acceleration
- Low-to-moderate magnetization ($\sigma_p \sim 0.1$–1)
- Proton luminosity a fraction of the turbulent power ($P_p \lesssim L_{turb}$)
- No forced pair dominance ($n_e \sim n_p$ or $n_e \geq n_p$)

$$\sigma_i = \frac{B^2}{4\pi\, n_i\, m_i\, c^2}$$

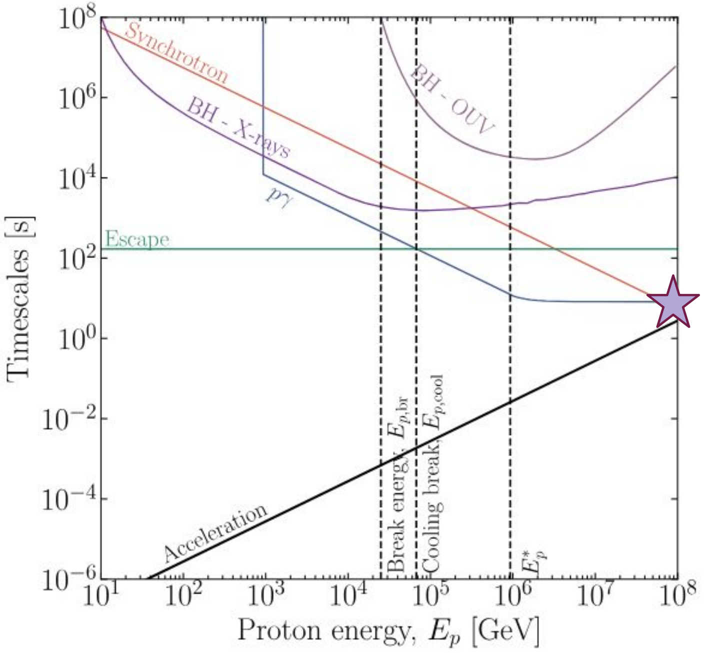
Relevant Studies

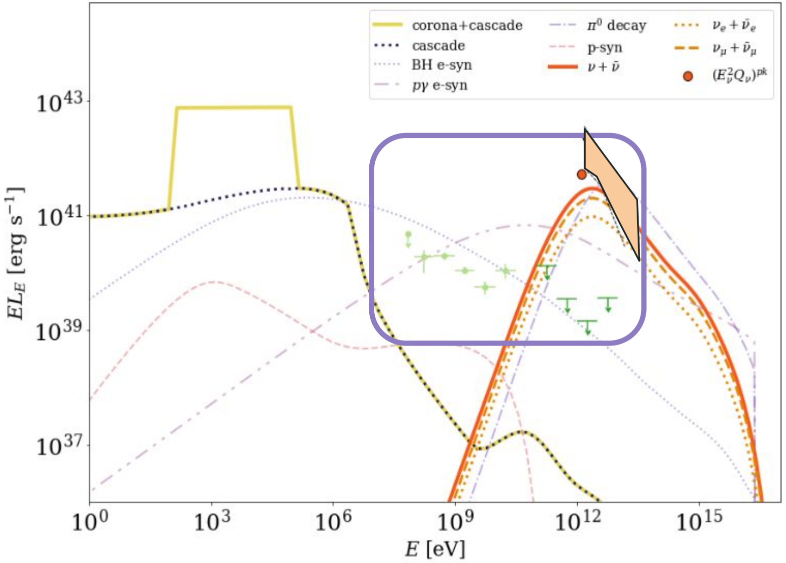
A - Fiorillo et al. (2024) *ApJL*; Karavola et al. (2025) *JCAP*; Karavola et al. (2026) *A&A*; Mbarek et al. (2024) [2-step acceleration model]; Passos-Reis et al. (arXiv:2604.10847) [turbulence-driven reconnection]

B - Murase, Kimura, Meszaros (2020); Kheirandish, Murase, Kimura (2021); Lemoine & Rieger (2025); Fiorillo et al. (2024) *ApJ*; Testagrossa et al. (2026) *ApJ*; Yang et al. (2026) *ApJ*

$R_g = GM/c^2$: gravitational radius $\sigma_p = B^2/(4\pi n_p m_p c^2)$: magnetization P_p : power in non-thermal protons $L_{Poynting}$: large-scale-field power L_{turb} : turbulent magnetic power

Magnetospheric reconnection model for NGC 1068





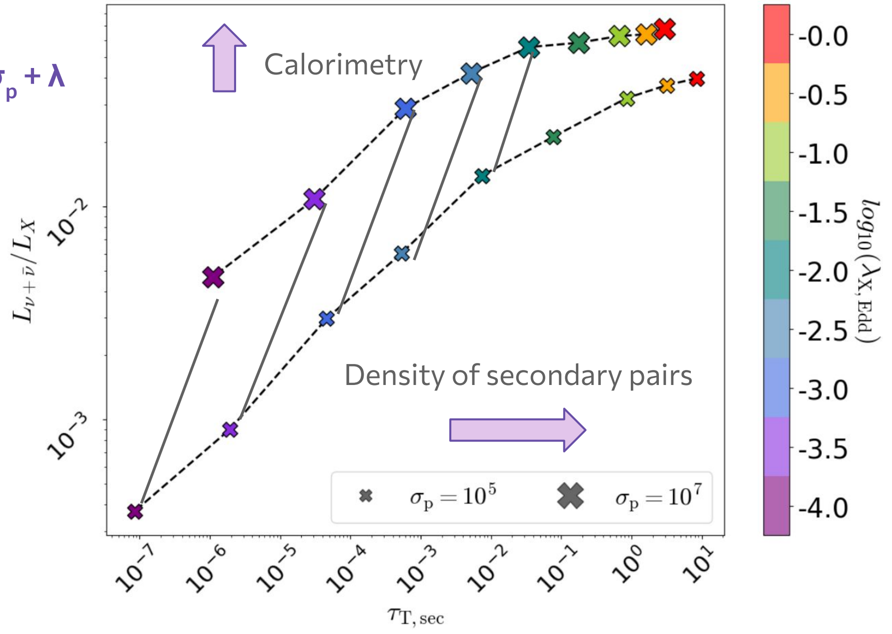
Fiorillo et al. (2024) *ApJL*, **961**

KEY FINDINGS (NGC 1068)

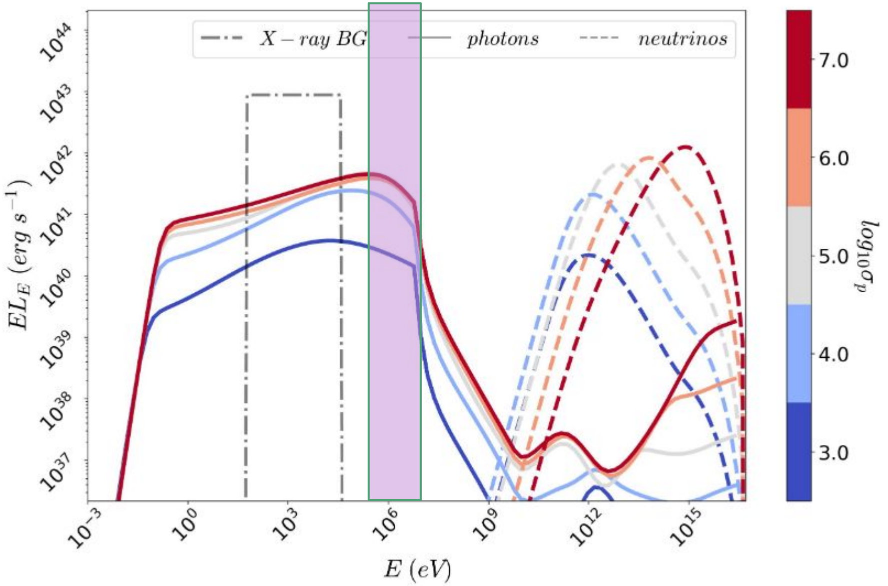
- Proton luminosity: $L_p \sim L_X$
- Neutrino luminosity: $L_\nu <\sim L_p \sim L_X$
- Compact corona: $R = (3\text{-}10)\, R_g$
- Highly magnetized corona: $\sigma_p = 10^5$ ($\sigma_e = 100$)

Parametric study

Dependence on $\sigma_p + \lambda$



Dependence on σ_p

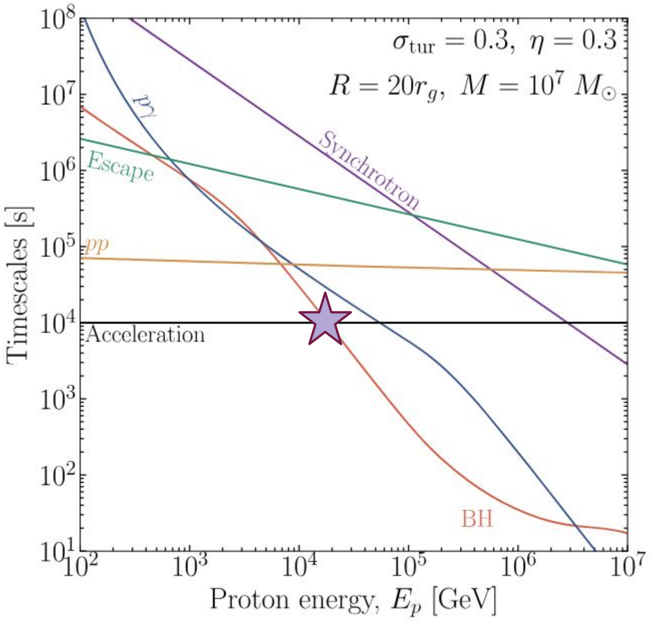


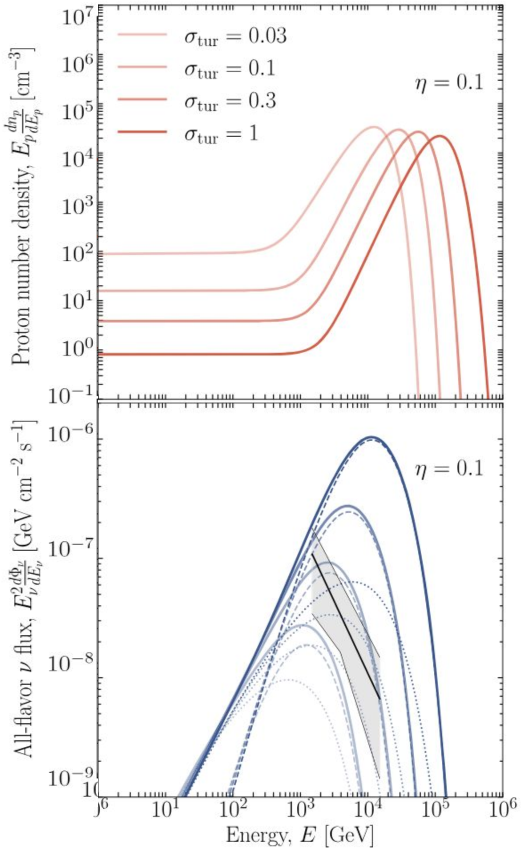
KEY FINDINGS

- **Two key parameters: σ_p , $\lambda = L_X/L_{Edd}$**
- Peak neutrino energy and luminosity increase with increasing σ_p
- Cascade emission peaks ~ 1-10 MeV; weak dependence on σ_p

Karavola et al. (2025) *JCAP*

Turbulent coronal model for NGC 1068





Fiorillo et al. (2024) *ApJ*, **974**

KEY FINDINGS

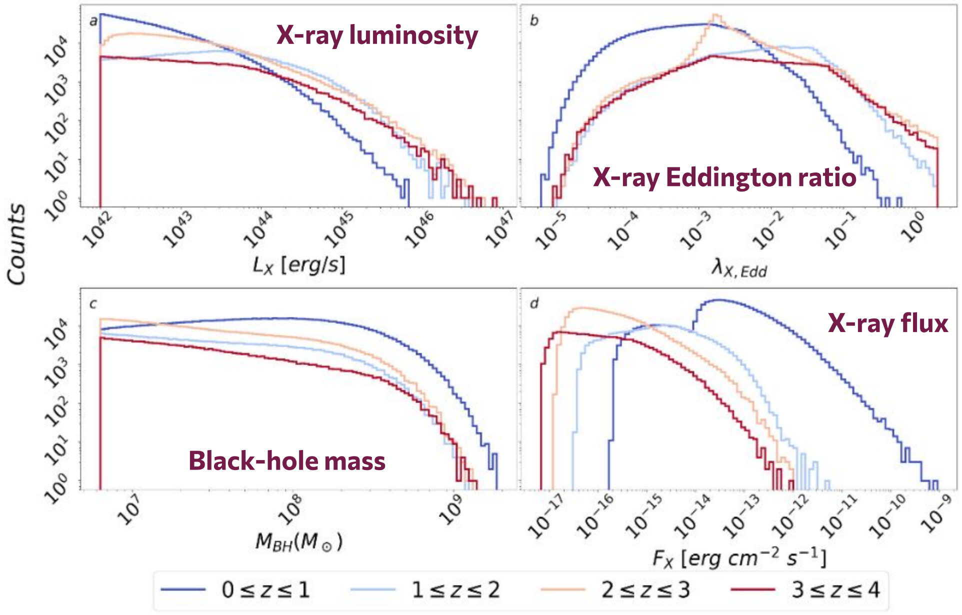
- **Two key parameters: σ_{tur}, $\eta = l_{tur}/R$**
- Peak neutrino energy and peak neutrino flux increase with increasing σ_{tur} and decreasing η
- Sensitive to disk+coronal SEDs → implicit dependence on accretion rate

Population synthesis

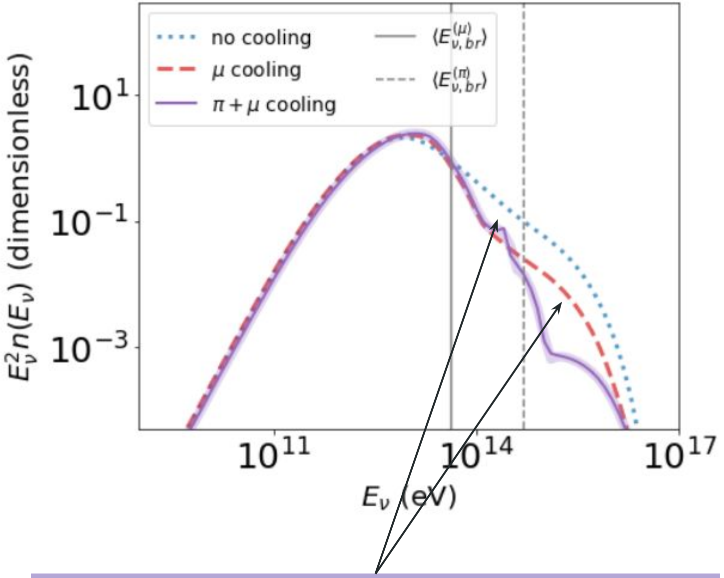
https://github.com/Des0053/Coronal_neutrinos

Mock AGN catalog

(Georgakakis, Ruiz, LaMassa 2020)



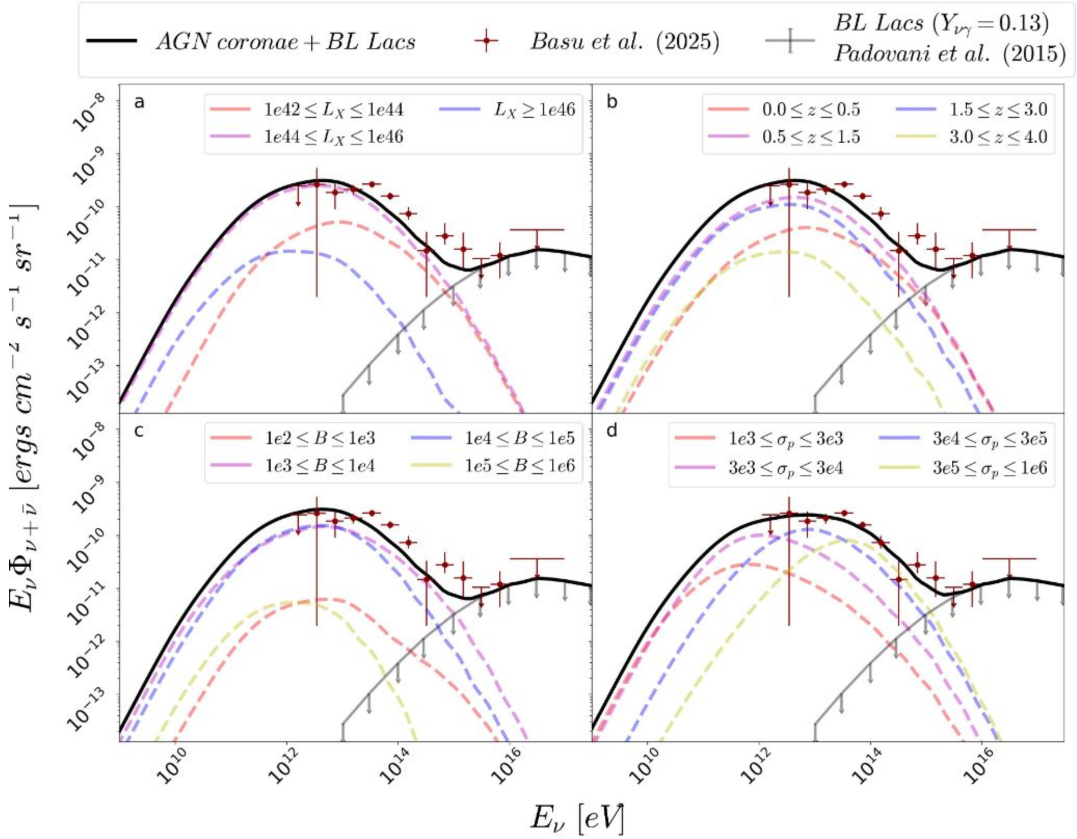
AGN Neutrino Spectral Template



NEW!
Synchrotron pion/muon cooling suppression

Karavola et al. (2026) *A&A*

Diffuse flux from magnetospheric reconnection model



KEY FINDINGS

- Universal $\sigma_p \sim 10^5$ overshoots by ~8 × at 10 TeV → ~10% of AGN
- These ~10% of AGN make almost all the ~30 TeV diffuse flux
- AGN properties making up most of the flux are:
  - $0.5 < z < 3$
  - $1e+44 < L_X < 1e+46$
  - B ~ 1 kG - 1 MG
- Jetted AGN (blazars) may contribute to fluxes >0.1 PeV

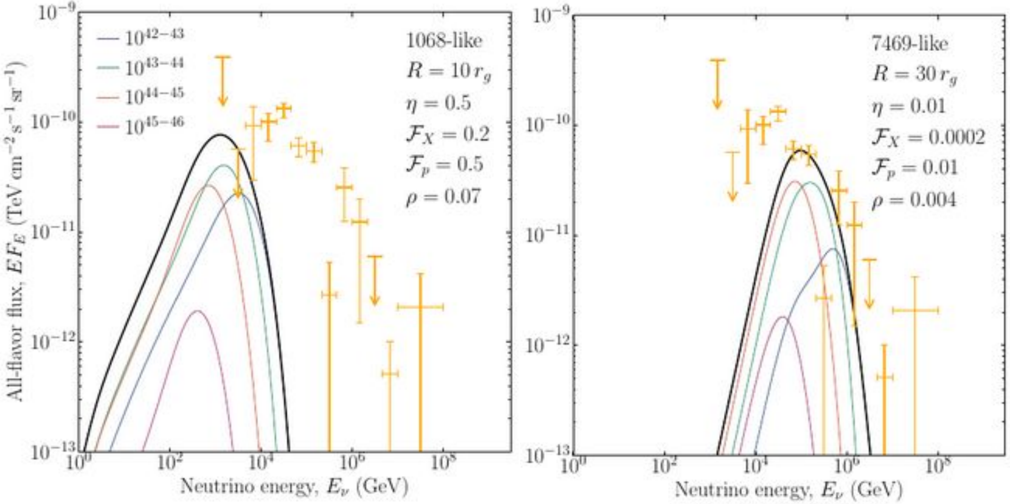
Karavola et al. (2026) *A&A*

Diffuse flux from turbulent magnetized coronae

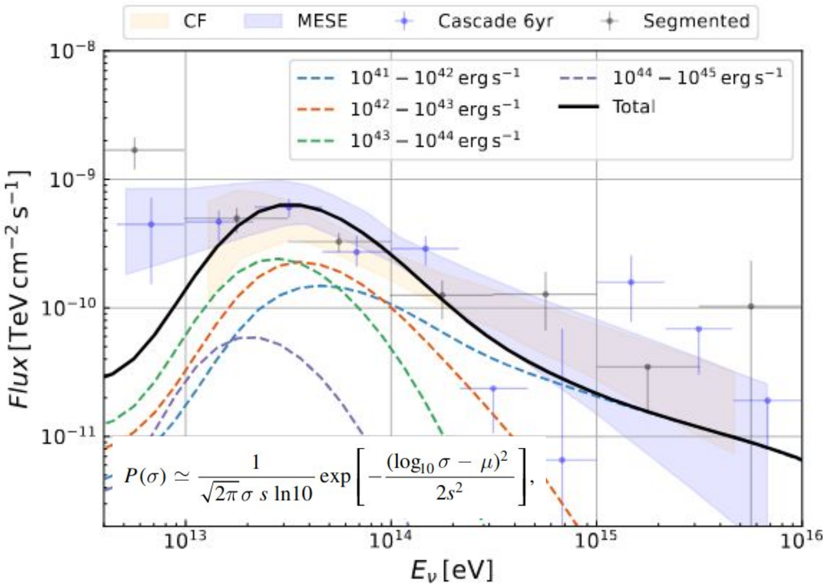
Check talks by Yang, Mbarek (Sep 3)

AGN Neutrino Spectral Template

https://github.com/federicotes/Turbulent-corona-emission



Testagrossa et al. (2026) *ApJ*



Yang et al. (2026) *ApJ*

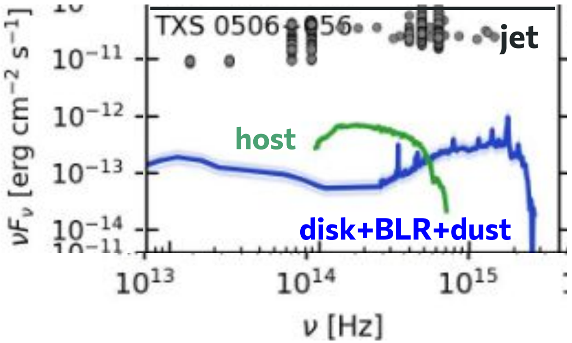
Could TXS 0506+056 neutrinos be of coronal origin?

NGC 1068 showed that AGN cores can be efficient neutrino emitters. Could TXS neutrinos be coronal too? Recent works proposed this: Khatee Zathul et al. 2025; Yang et al. 2025

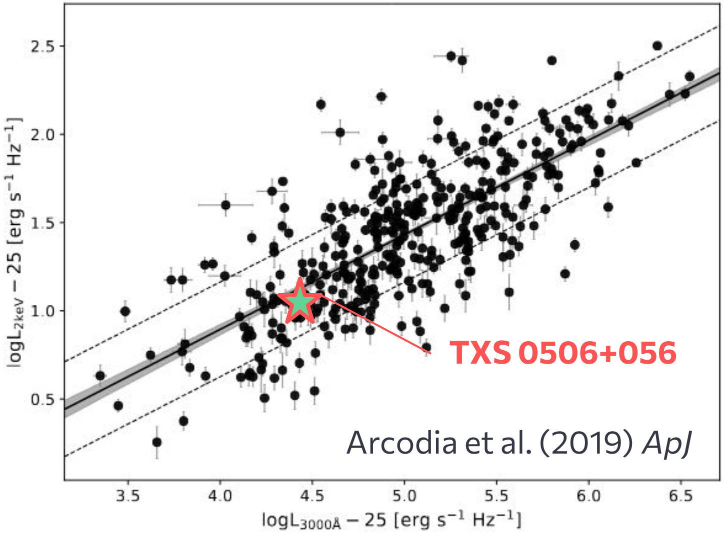
We also put the hypothesis to the test!

TXS 0506+056: a masquerading BL Lac

Rodrigues et al. (2024) *MNRAS*



- Optical spectrum resembles a Seyfert 2 AGN
  [line ratios, Paiano et al. (2018)]
- L_{bol} ~ 10^{45} erg/s and L_{bol} / L_{Edd} ~ 0.04 (standard α-disk)
  [Padovani et al. (2019) *MNRAS Letters*]

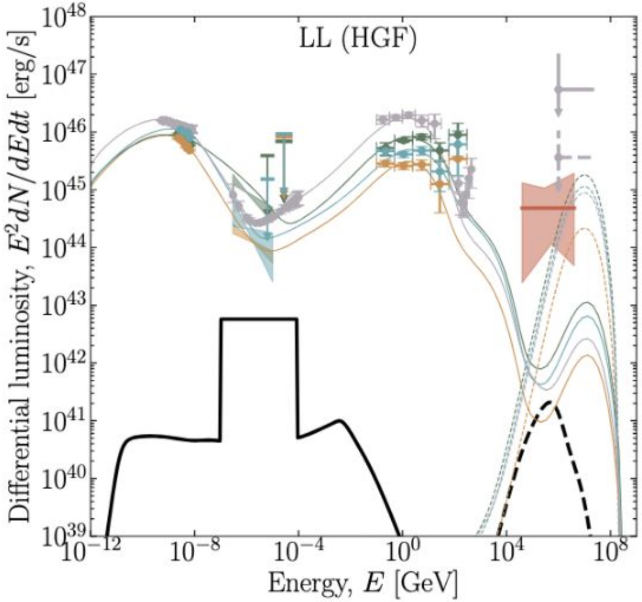


KEY FINDING

- Predicted coronal L_X @ 2 keV ~ 6e+43 erg/s
- L_X **(0.1-100 keV) ~4e+44 erg/s** or **4e+43 erg/s** (based on a radio-loud AGN sample)

Coronal emission from TXS 0506+056

L_X = 4e+43 erg/s, L_p = 0.2 L_X



Fiorillo, Testagrossa, **PM**, Winter (2025) *ApJ*

KEY FINDING

- Coronal origin fails for TXS 0506+056:
  - observed X-rays → jet origin → upper limit on coronal L_X
  - no observational evidence for super-Eddington accretion
- A jet origin remains the most plausible explanation

Note. Colored lines are jet models from multi-epoch modeling of TXS [PM et al. (2020), *ApJ*]

SUMMARY

- **AGN are promising neutrino sources from TeV to PeV energies.**
- **Jetted AGN:** neutrinos likely arise in relativistic jets → GeV γ-ray–bright.
- **Non-jetted AGN:** neutrinos likely arise in coronae → GeV–TeV γ-ray–dark.
- **Two viable coronal scenarios:** magnetic reconnection and magnetized turbulence.
- **Both can explain the ~20–30 TeV flux;** reconnection can extend the spectrum toward PeV.

OPEN QUESTIONS & OUTLOOK

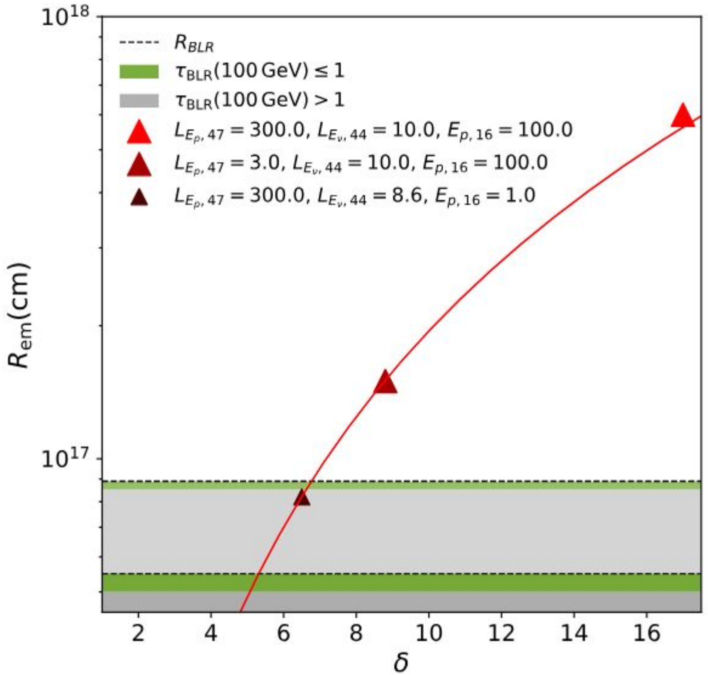
- **What sets the coronal magnetization?**
- How can we **distinguish the two scenarios** observationally?
- **When will the next jetted AGN neutrino source be found?**
- Inform models with **local and global plasma** simulations.
- Search for **cascade signatures** with MeV γ-ray telescopes (COSI, AMEGO-X).
- **Increase neutrino sensitivity** to point sources.

Thank you - Questions?

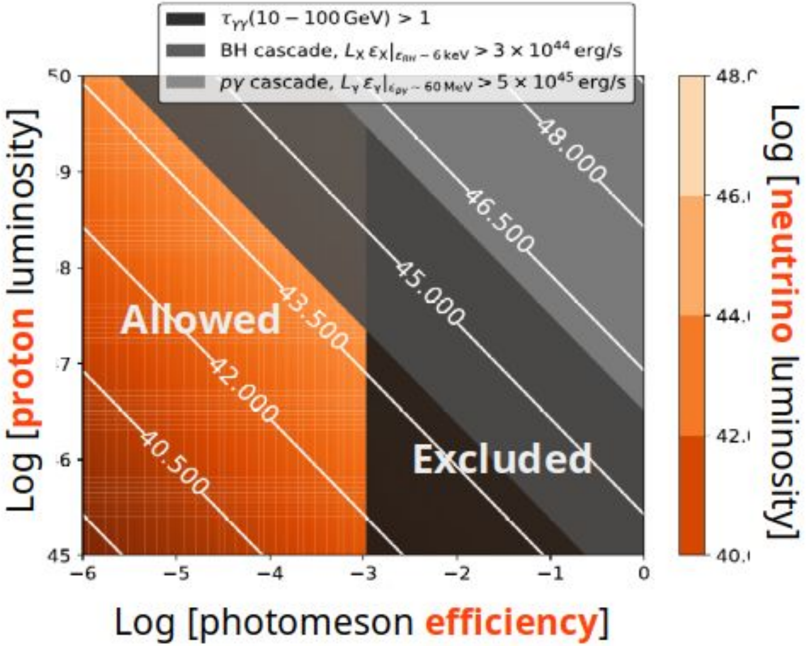
Backup slides

Physical constraints on TXS 0506+056

Location of emitting region



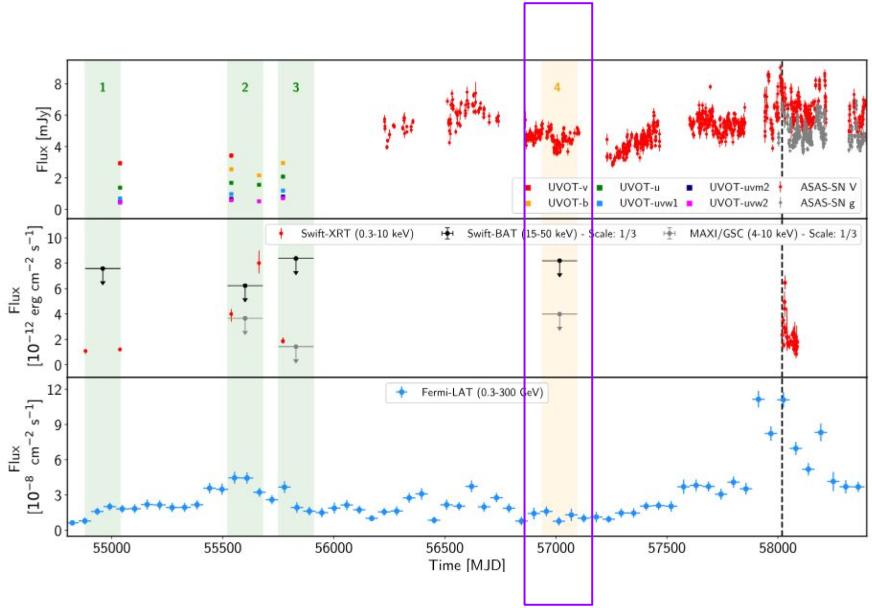
Proton luminosity

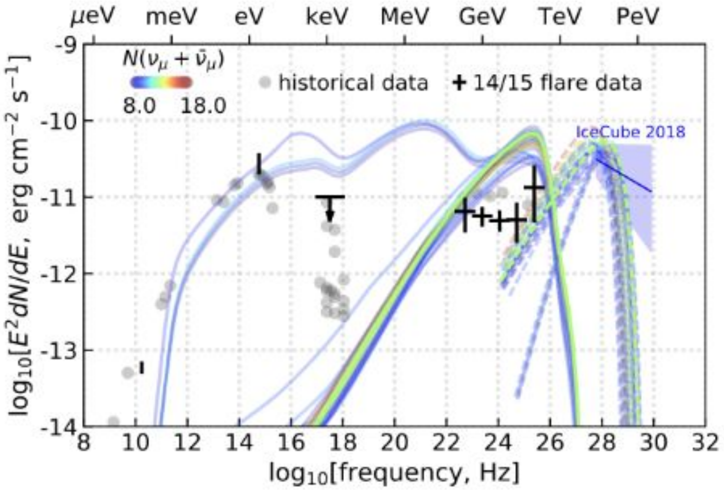


Padovani et al. (2019) MNRAS Letters

TXS 0506+056

The puzzling 2014-15 neutrino excess

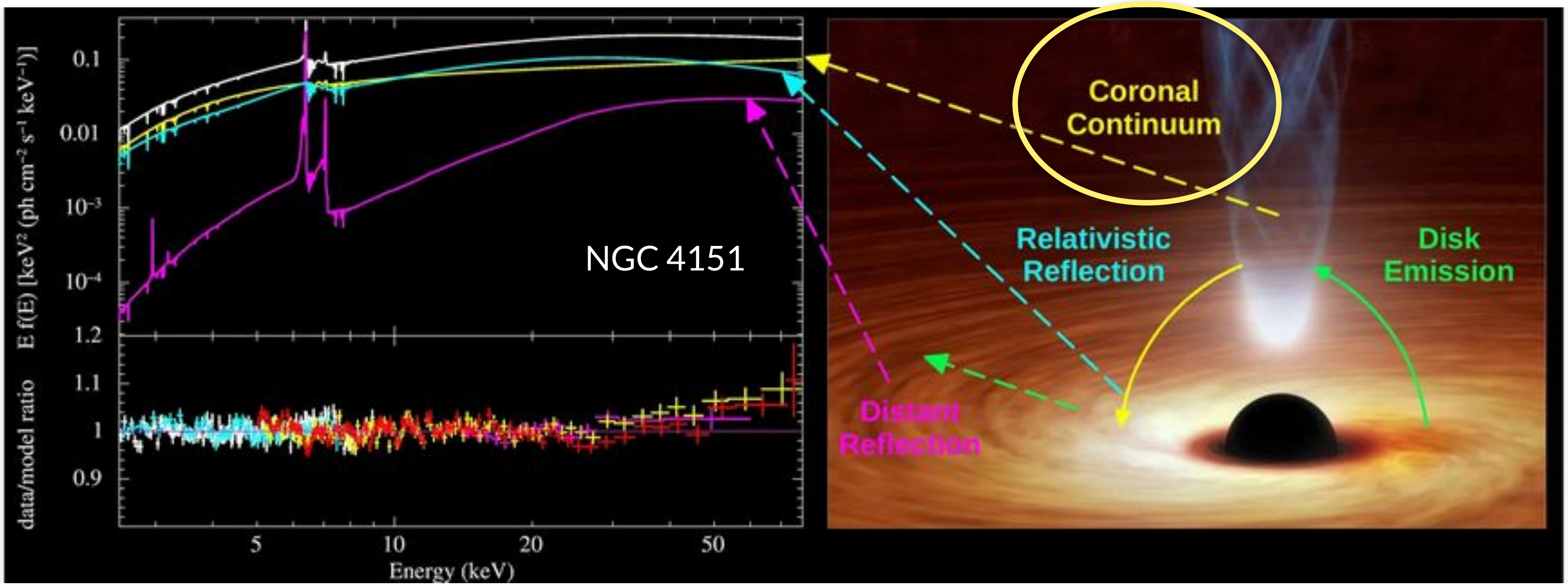




Rodrigues et al. (2019), *ApJ*

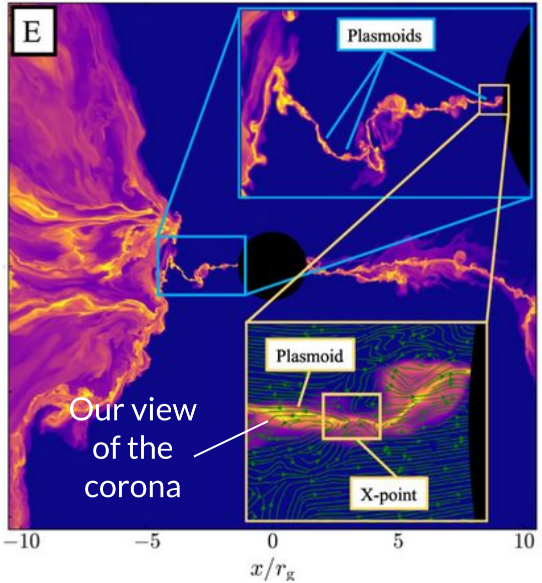
- 13 ± 5 events **without** γ-ray counterpart → $L_\nu \sim 10^{46}$ erg/s >> L_X, L_γ
- One-zone models fail; ν from γ-ray opaque region or neutron beams? [Reimer et al. (2019) *ApJ*; Rodrigues et al. (2019), *ApJ*; **PM** et al. (2020) *ApJ*; Zhang et al. (2020) *ApJ*]

X-ray spectra of non-jetted AGN



Danekhar (2024), Front. Astron. Space Sci.

Magnetospheric reconnection model



Ripperda et al. (2022)

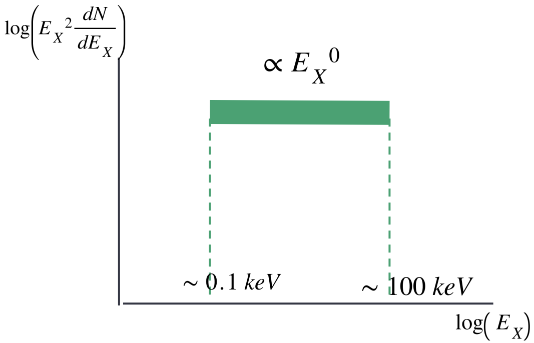
Poynting flux

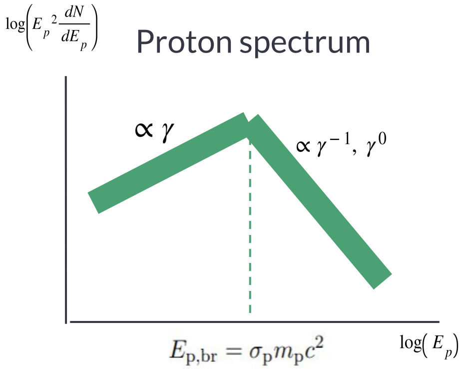
Comptonized X-ray luminosity	Relativistic proton luminosity
$L_X = \eta_X S_P A$	$L_p = \eta_p S_P A = \frac{\eta_p}{\eta_X} L_X.$
+	+
Corona spectrum	Proton spectrum

p-γ collisions

Neutrino spectrum

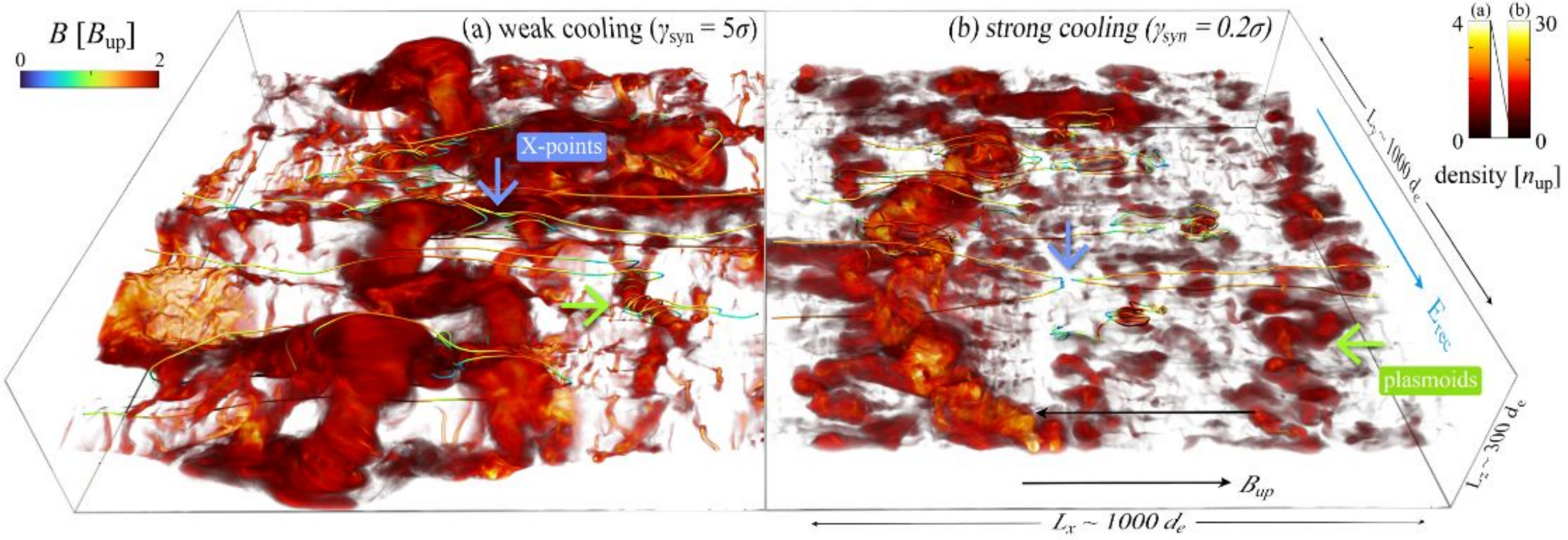
Corona spectrum





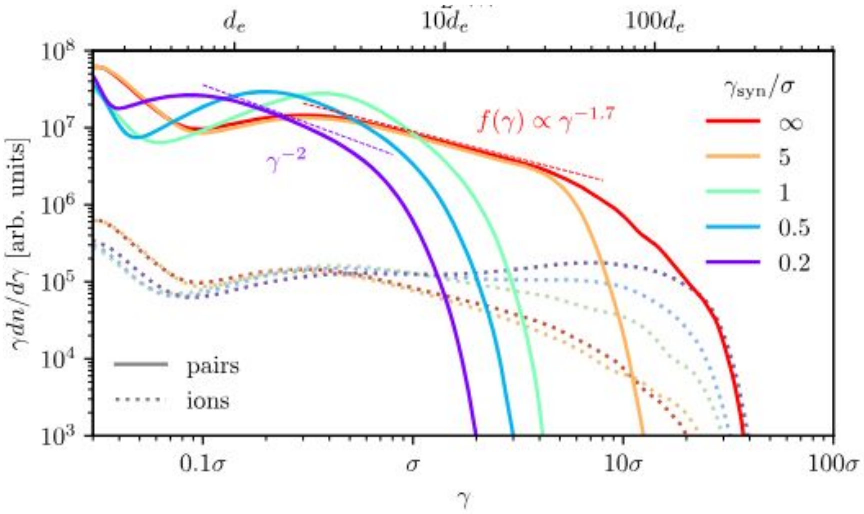
For particle acceleration check : Werner & Uzdensky 2017, Chernoglazov et al. 2023, Zhang et al. 2021, 2023

Relativistic magnetic reconnection

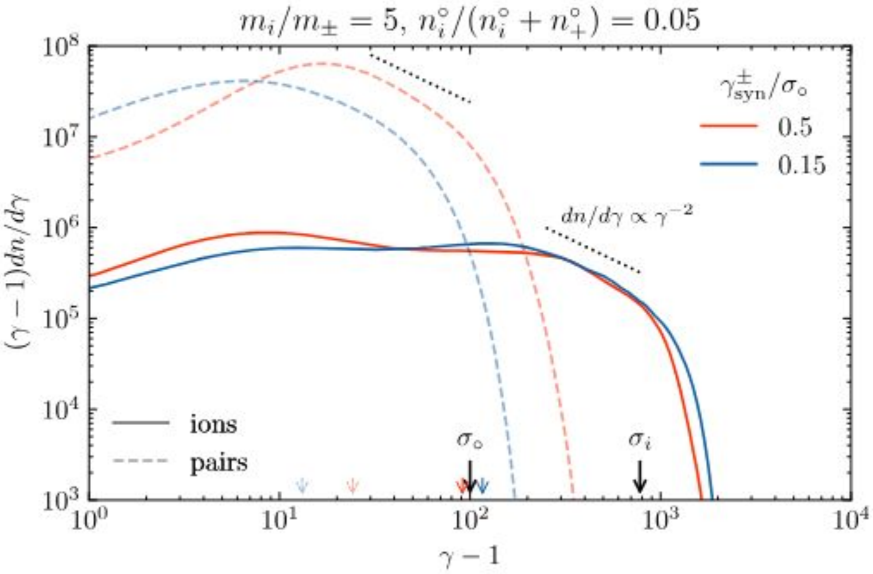


Chernoglazov et al. (2023) *ApJ*

Particle spectra from relativistic magnetic reconnection

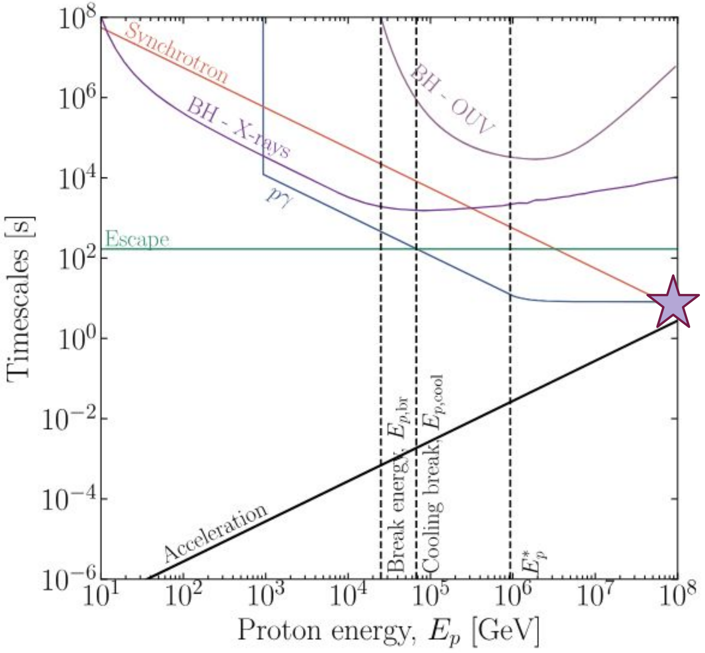


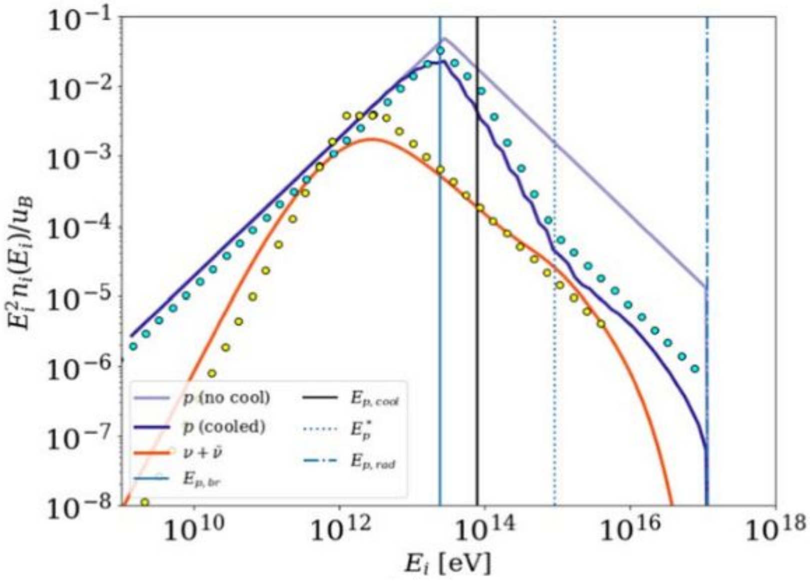
Chernoglazov et al. (2023) *ApJ*



Hakobyan et al. (2025) *ApJL*, **995**

Magnetospheric reconnection model for NGC 1068



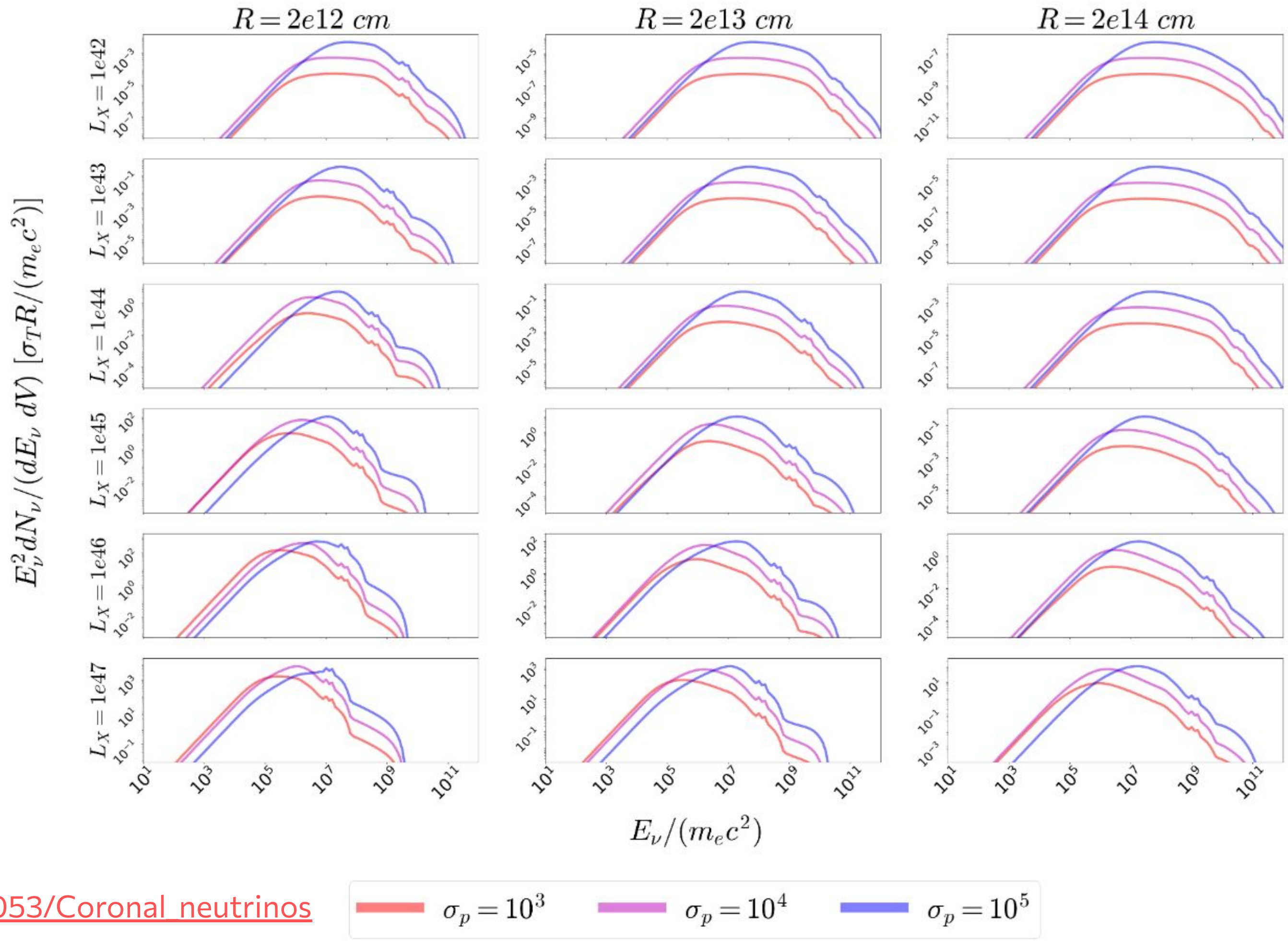


Fiorillo et al. (2024) *ApJL*, **961**

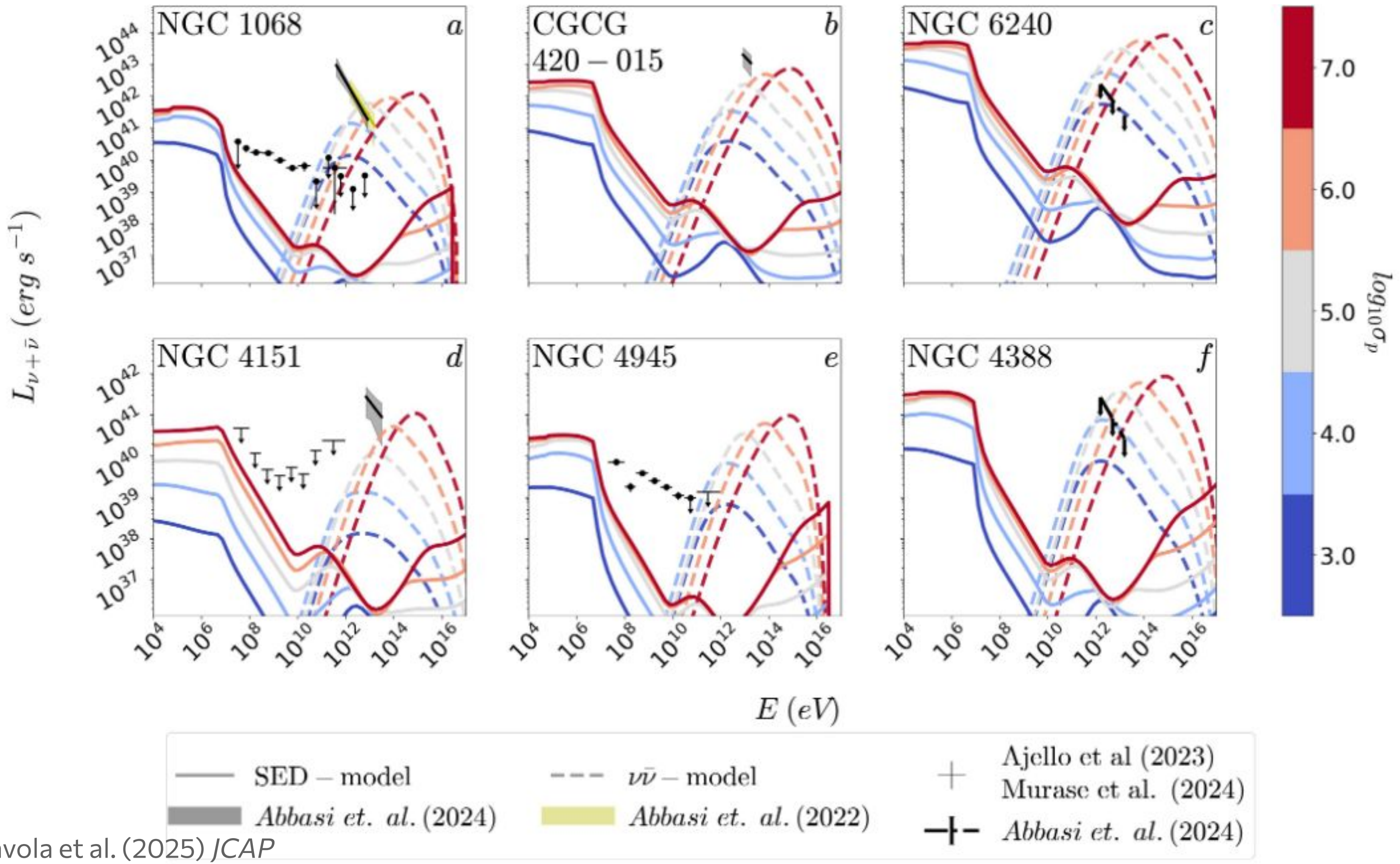
KEY FINDINGS (NGC 1068)

- Proton luminosity: $L_p \sim L_X$
- Neutrino luminosity: $L_\nu <\sim L_p \sim L_X$
- Compact corona: $R = (3\text{-}10)\, R_g$
- Highly magnetized corona: $\sigma_p = 10^5$ ($\sigma_e = 100$)

All-flavor neutrino spectral templates



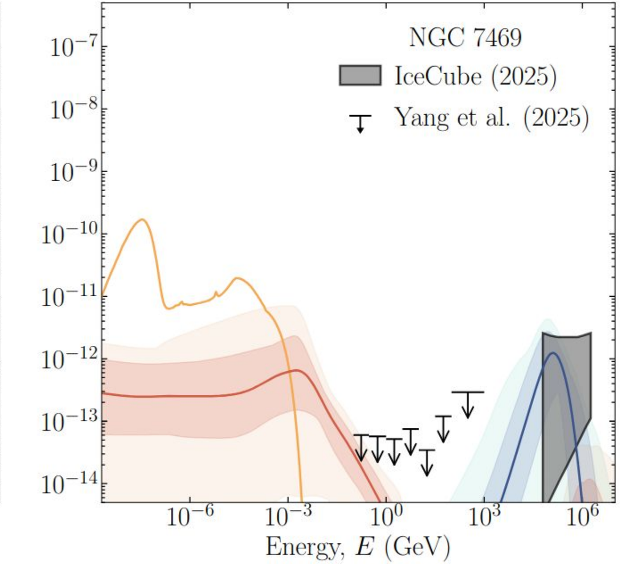
https://github.com/Des0053/Coronal_neutrinos



Karavola et al. (2025) *JCAP*

Constraining coronal parameters

$$t_{\rm acc} \simeq \frac{10\,\eta R}{\sigma_{\rm tur}\,c}, \quad L_p = \frac{8\pi c R^2 U_p \sigma_{\rm tur}}{15\eta}.$$



$$\chi^2_\nu(\boldsymbol{\theta}, \mathcal{B}) = 2 \sum_{E_i^{\rm reco}, \psi_j^2} [\mu_{ij}(\boldsymbol{\theta}, \mathcal{B}) - k_{ij} \ln(\mu_{ij}(\boldsymbol{\theta}, \mathcal{B}))].$$

$$\chi^2_\gamma(\boldsymbol{\theta}) = \sum_n \frac{\phi_{\gamma,n}(\boldsymbol{\theta})^2}{(\Phi_n/2)^2}.$$

$$\Upsilon(\boldsymbol{\theta}) = \min_{\mathcal{B}} [\chi^2_\nu(\boldsymbol{\theta}, \mathcal{B}) + \chi^2_\gamma(\boldsymbol{\theta})].$$

Table 2

Best-fit Values for the Model Parameters $\sigma_{\rm tur}$, η, R/r_g, $\mathcal{F}_p$ for All of the Galaxies Considered

Galaxy	$\sigma_{\rm tur}$	η	R/r_g	$\mathcal{F}_p$	$\mathcal{F}_X$	β	$U_{p,\rm nth}/U_{B,\,\rm tur}$
NGC 1068	1	0.5	10	0.5	0.2	0.07	0.125
NGC 7469	1	0.01	30	0.01	2×10^{-4}	0.02	3×10^{-3}
NGC 4151	0.8	1	10	0.15	0.04	0.08	0.04
CGCG 420-015	0.6	1	13	0.14	0.04	0.08	0.04

Diffuse neutrino flux from turbulent magnetized coronae

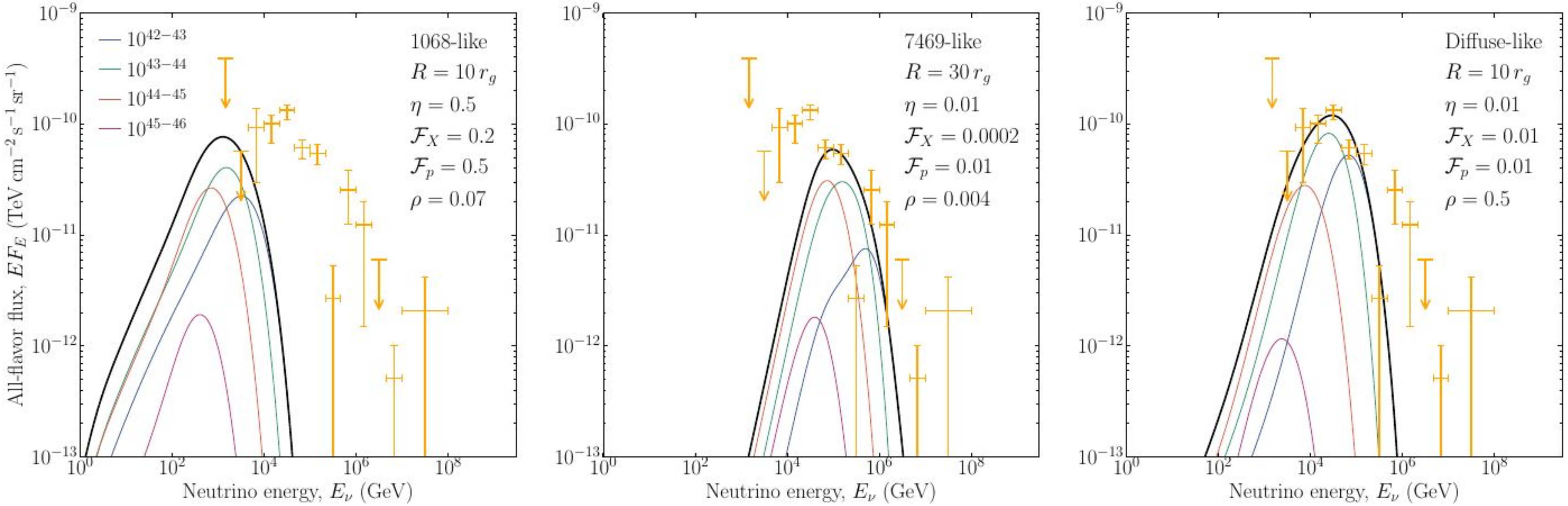
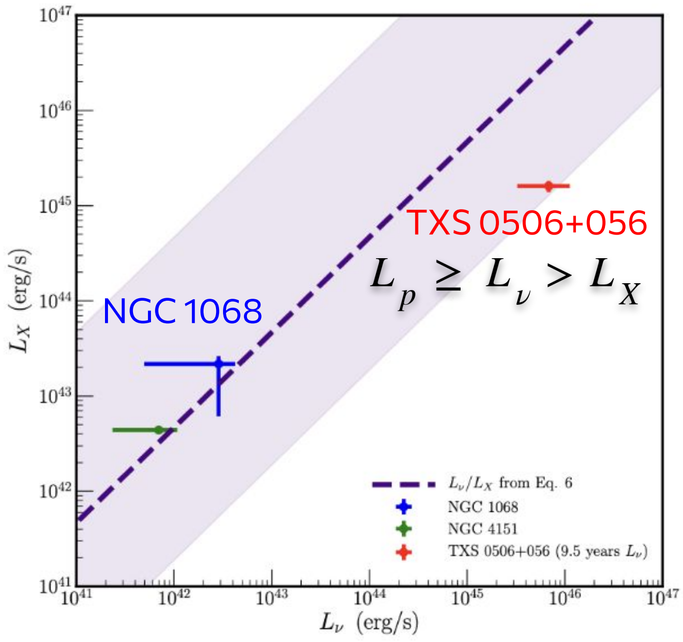


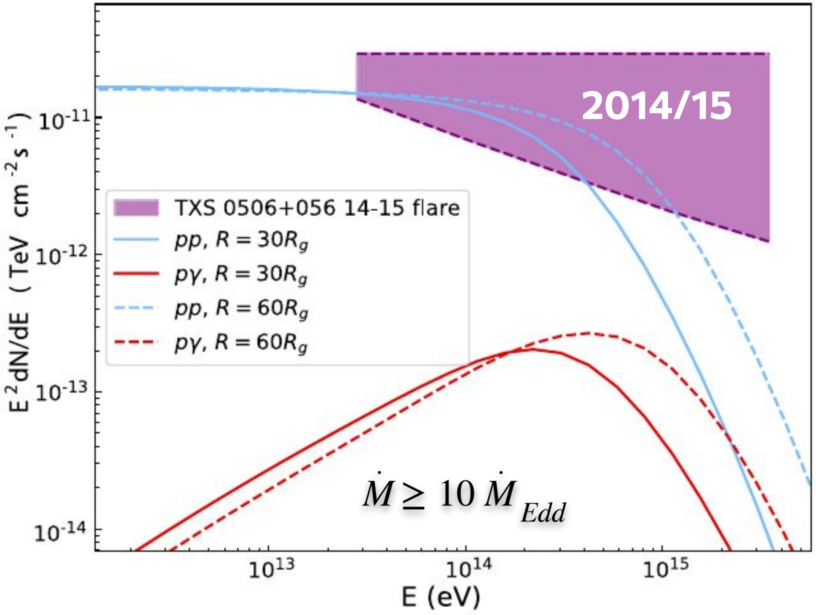
Figure 4. Predicted diffuse neutrino flux from a population of Seyfert galaxies with coronal parameters informed by our fit for NGC 1068 (left), NGC 7469 (center), and intermediate properties that fit by eye the spectral break of the diffuse flux (right). Different colors indicate the contribution of coronae of different $L_X^{2-10\,\mathrm{keV}}$, in erg s^{-1}, as indicated in the legend. In all cases, we rescale the total flux by a factor $\rho < 1$, to match the normalization of the diffuse flux observed by IceCube. Measured flux points are taken from R. Abbasi et al. (2025b).

A coronal origin of neutrinos in TXS 0506+056 ?

Common hypothesis: observed X-rays are from the corona and not the jet



Khatee Zathul et al. (2025) ApJ



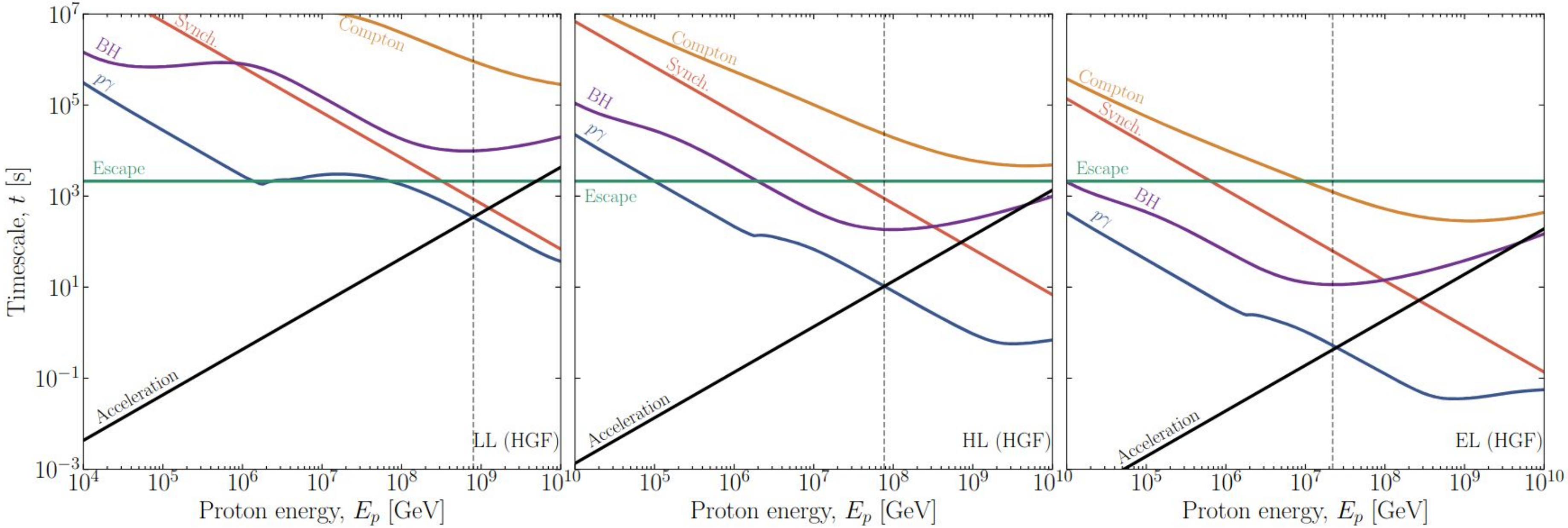
Yang, Liu, Wang (2025) ApJ

Model parameters

Parameter	TXS (LL)	TXS (HL)	TXS (EL)
L_X [10^{43} erg/s]	4	40	2×10^3
L_p [10^{43} erg/s]	0.8	80	4×10^3
B [kG]	2.6	8.1	57.3
η_p	0.1	1	1

Table 1. Astrophysical parameters for TXS 0506+056, in the three scenarios discussed in the text. For all cases, we use a coronal size $R \simeq 1.4 r_g = 6.4 \times 10^{13}$ cm, corresponding to $L = 5 r_g$.

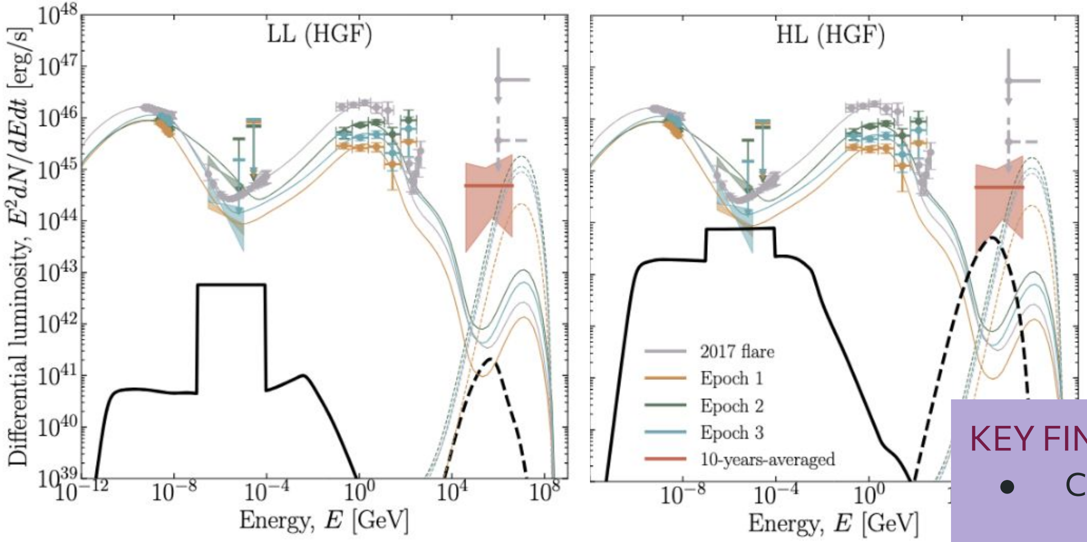
Proton timescales in magnetized turbulent corona: application to TXS 0506+056



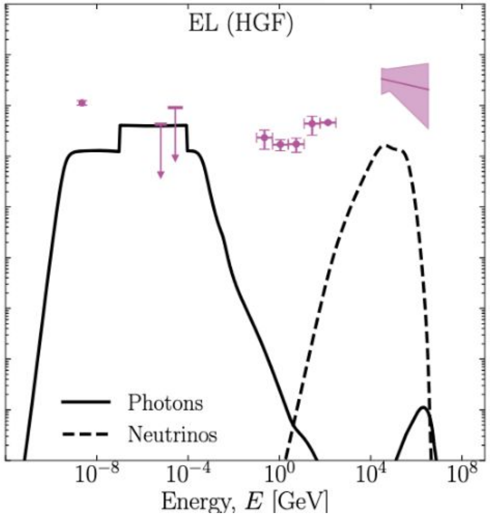
Coronal emission from TXS 0506+056

L_X = 4e+43 erg/s, L_p = 0.2 L_X

L_X = 4e+44 erg/s, L_p = 0.2 L_X



L_X = 4e+44 erg/s, L_p = 2 L_X



Fiorillo, Testagrossa, **PM**, Winter (2025) *ApJ*

KEY FINDING

- Coronal origin fails for TXS 0506+056
  - observed X-rays → jet origin
  - no observational evidence for super-Eddington accretion
- A jet origin remains the most plausible explanation

TXS 0506+056: a masquerading BL Lac

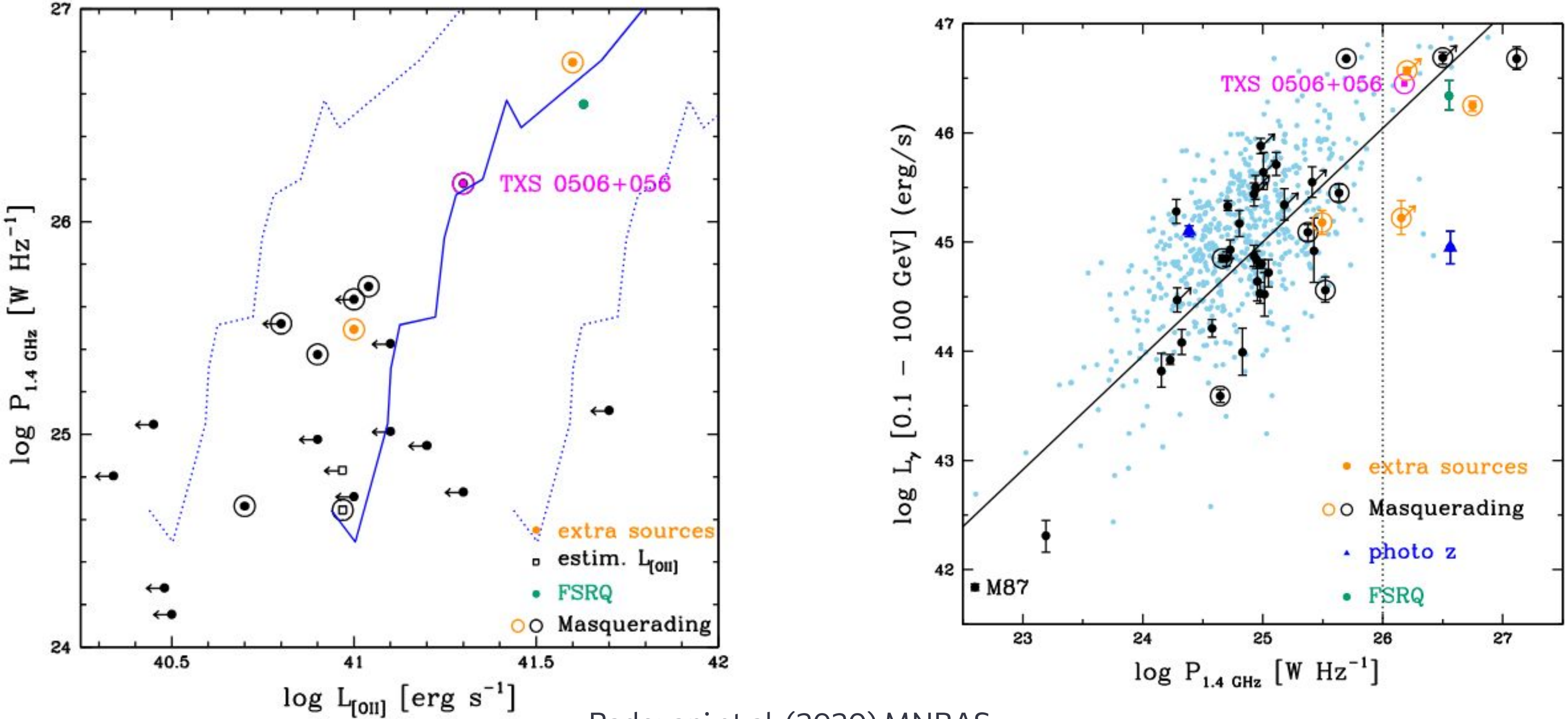
(i) Its radio power ($P_{1.4\rm GHz} \sim 1.8 \times 10^{26}$ W Hz^{-1}) and O II luminosity ($L_{\rm O\,II} \sim 2 \times 10^{41}$ erg s^{-1}: Paiano et al. 2018) put this source right in the middle of the locus of jetted (radio-loud) quasars (fig. 4 of Kalfountzou et al. 2012). Moreover, HEGs become the dominant population in the radio sky above $P_{1.4\rm GHz} \sim 10^{26}$ W Hz^{-1} (Heckman & Best 2014);

(ii) The optical spectrum of TXS 0506+056 resembles that of a Seyfert 2 galaxy from the point of view of the emission line ratios (Paiano et al. 2018), which implies it is a HEG;

(iii) Its $L/L_{\rm Edd}$ is >0.01. We estimate the black hole mass by assuming the host galaxy to be a typical giant elliptical with absolute R-band magnitude $M(R) \sim -22.9$ (Paiano et al. 2018) and then by using the McLure & Dunlop (2002) relationship between black hole mass and bulge $M(R)$ to derive $M_{\rm BH} \approx 3 \times 10^8$ M$_\odot$. This translates into $L_{\rm Edd} \approx 4 \times 10^{46}$ erg s^{-1}. We note that the true value cannot be much larger than this. Paiano et al. (2018) have in fact estimated a lower limit on the redshift >0.3 based on the lack of absorption features due to the host galaxy. Given the closeness of this value to the measured redshift this means that the host galaxy can only be at the same level, or fainter, than assumed, which in turns means that the black hole mass cannot be much higher than estimated and that the resulting $L/L_{\rm Edd}$ is a lower limit. As for the (thermal) bolometric luminosity, we use the relationships between $L_{\rm bol}$ and $L_{\rm O\,II}$ and $L_{\rm O\,III}$ (Punsly & Zhang 2011) to derive $L_{\rm bol} \sim 9 \times 10^{45}$ erg s^{-1} and $L_{\rm bol} \sim 3 \times 10^{45}$ erg s^{-1}, respectively. Since Punsly & Zhang (2011) have shown that these values are overestimated for jetted (radio-loud) quasars because of a sizeable jet-induced contribution we conservatively divide the logarithmic average by 3 (based on their fig. 3), which gives $L_{\rm bol} \sim 1.7 \times 10^{45}$ erg s^{-1}. We finally obtain $L/L_{\rm Edd} \gtrsim 0.04$.

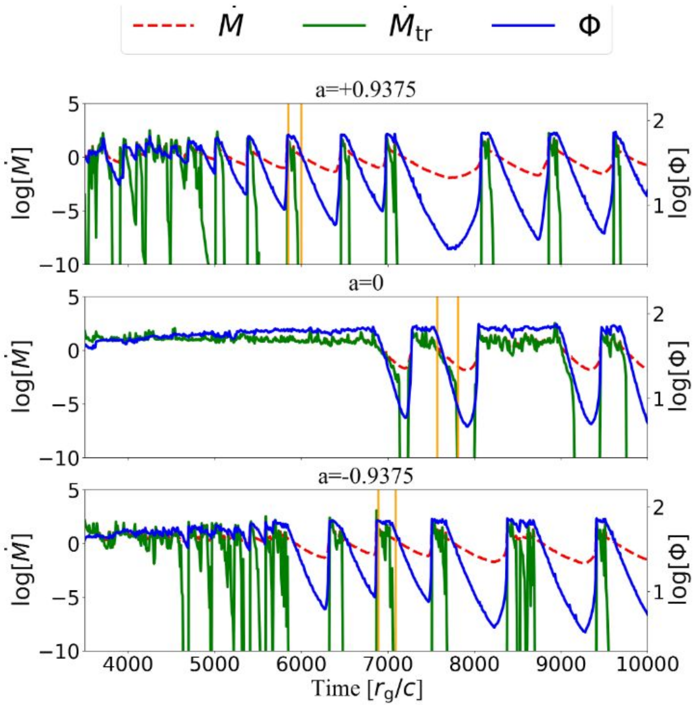
Padovani et al. (2019) MNRAS Letters

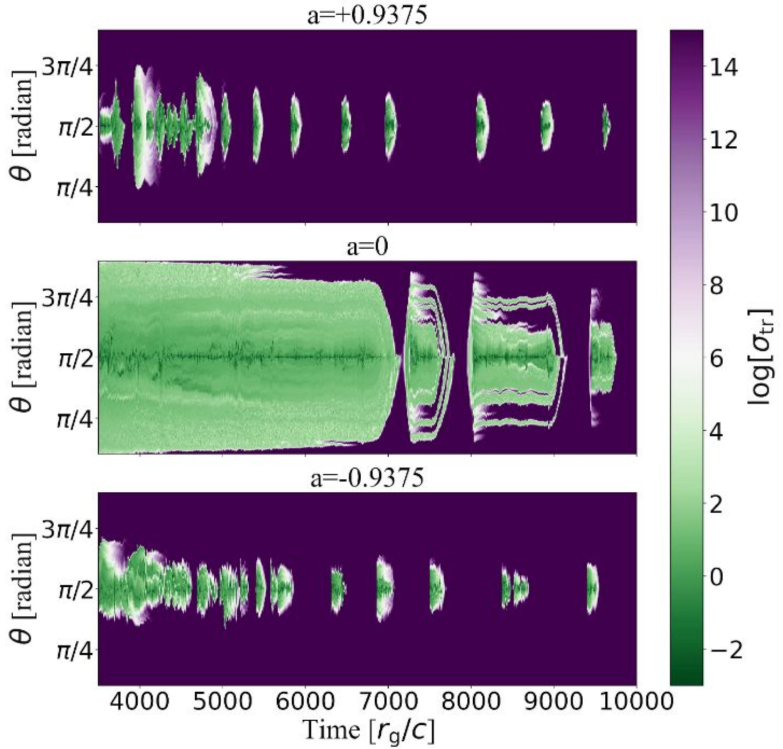
TXS 0506+056: a masquerading BL Lac



Padovani et al. (2020) MNRAS

Baryon-poor magnetospheric regions

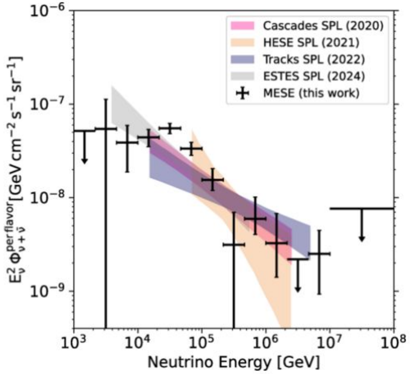




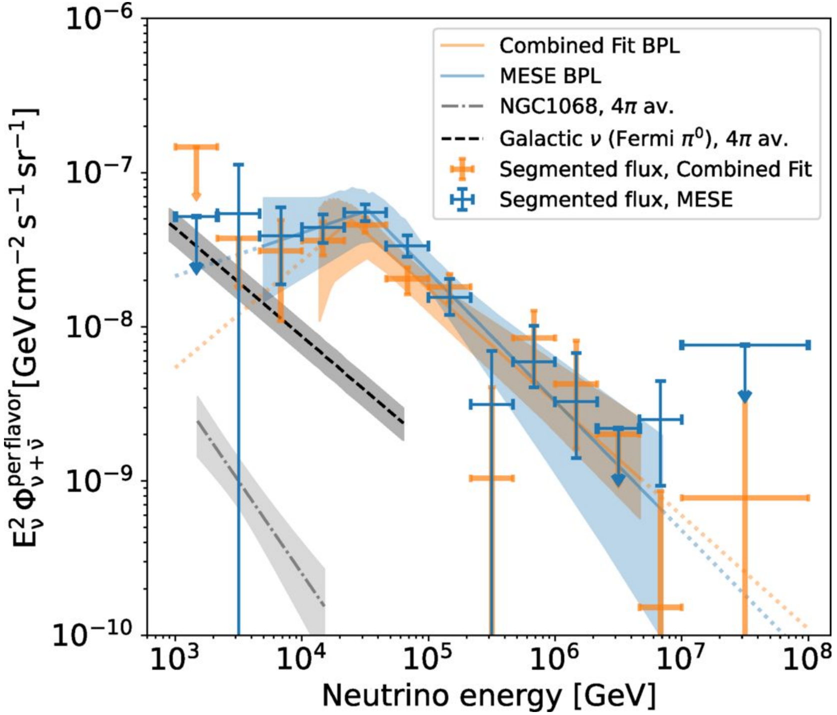
Chow et al. 2026 (arXiv: 2603.10122)

The diffuse neutrino spectrum

Abbasi et al. (2026) *Phys. Rev. D*



Abbasi et al. (2026) *Phys. Rev. Lett.*



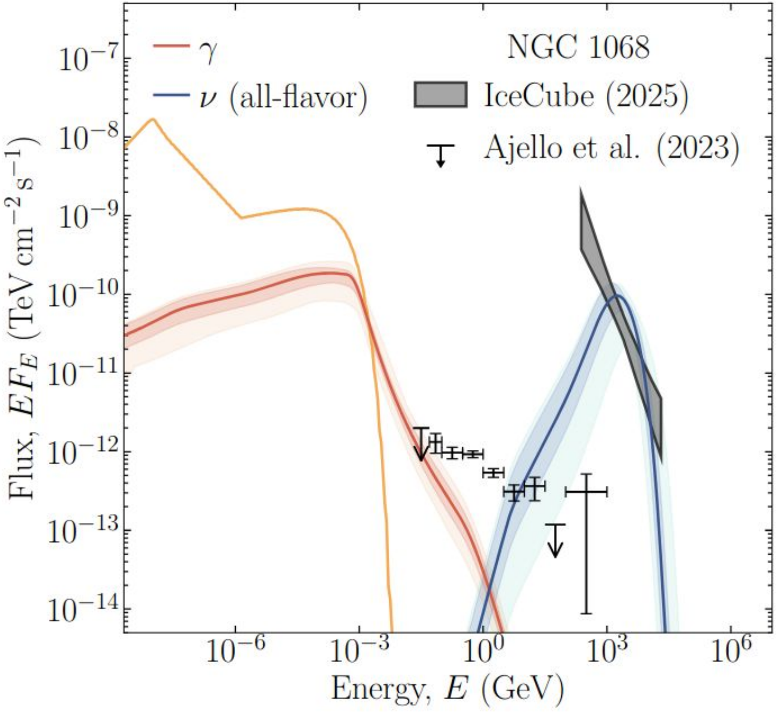
- ~10 yr IceCube data (1 TeV - 10 PeV) analyzed in two ways [Abbasi et al. (2026) *Phys. Rev. Lett.;* Abbasi et al. (2026) *Phys. Rev. D*]
- Simple Power Law (SPL) rejected at > 4σ in favor of Broken Power Law (BPL)
- Evidence of break at ~20-30 TeV

Constraining coronal properties

- 4 free parameters **$\theta = (\sigma_{tur}, \eta, R, F_p)$**
- **Combined ν+γ fit:** mock ν via PLEνM, Fermi as 2σ ULs

KEY FINDINGS

- NGC 1068: compact ($R \sim 10\ R_g$), strongly magnetized corona ($\sigma_{tur} \sim 1$) with a large turbulence coherence length ($l_{tur} \sim R/2$)
- Coronal properties differ among Seyferts



Testagrossa et al. (2026) *ApJ*