Review on extragalactic neutrinos in the multi-messenger context

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H.F.R.I.
Hellenic Foundation for Research & Innovation

The astrophysical neutrino flux

= sum of Galactic and extragalactic components

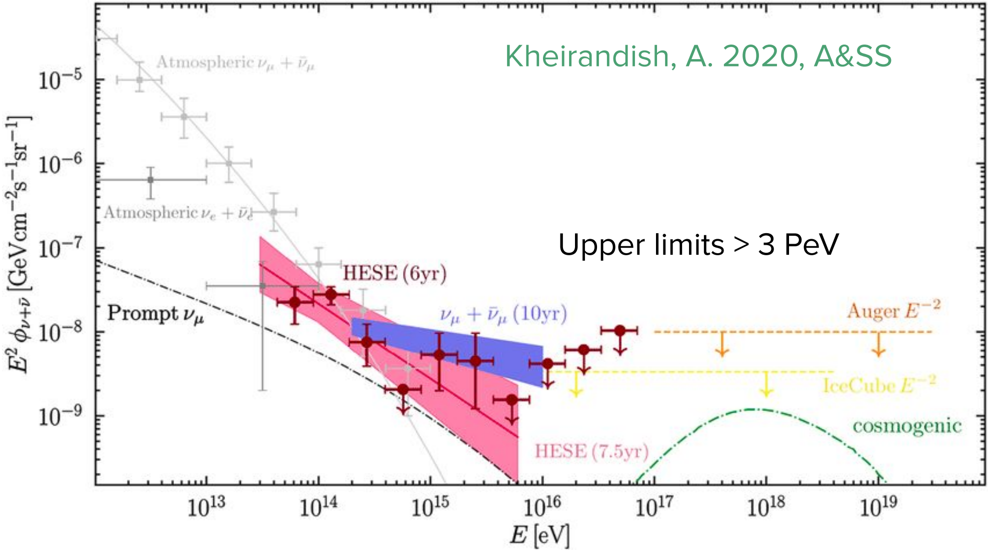
(talk by A. Neronov)

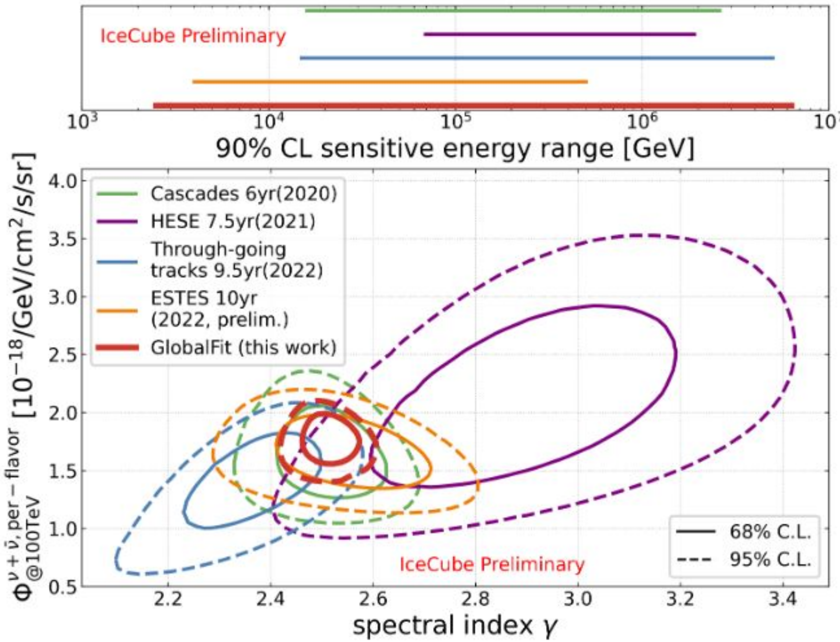
PoS-ICRC2023-1064

Galactic contribution at 100 TeV is ~10%

Kheirandish, A. 2020, A&SS

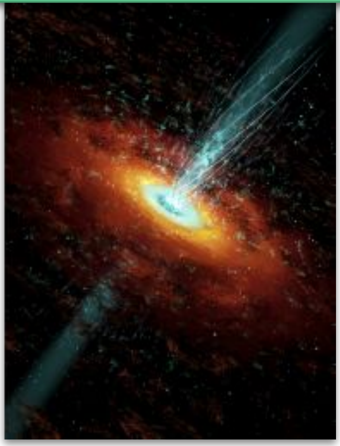
Upper limits > 3 PeV





Hunting for extragalactic neutrino point sources

Jetted AGN



Steady but variable

(e.g. Eichler 1979, Mannheim, Stanev, and Biermann 1992, Halzen & Zas 1997, Atoyan & Dermer 2001, 2003, Murase et al. 2014, Petropoulou et al. 2015, +++; see also review Murase & Stecker 2023)

Non-jetted AGN, starbursts

Steady*

* accretion disk emission is variable

(e.g. Loeb and Waxman 2006, Stecker 2007, Tamborra et al. 2014, Bechtol et al. 2017, Peretti et al. 2020; see also review Murase & Stecker 2023)

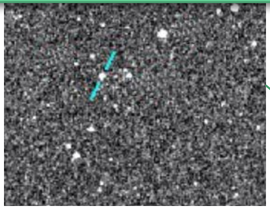
Gamma-Ray Bursts, TDEs, ...

Transients

(e.g. Waxman & Bahcall 1999, Murase 2008, Petropoulou et al. 2014, Bustamante et al. 2017, Stein et al. 2021, +++)

Highlights*

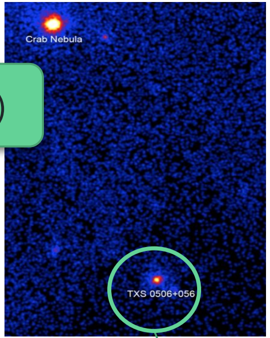
Blazar (D$_L$ > 3.5 Gpc)



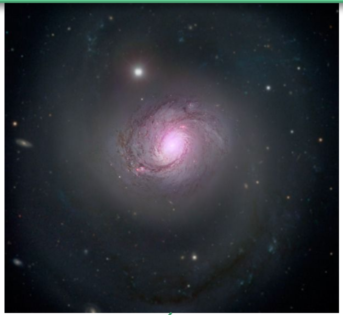
Credit: Perugia Blazar List

Blazar (D$_L$ ~ 1.8 Gpc)

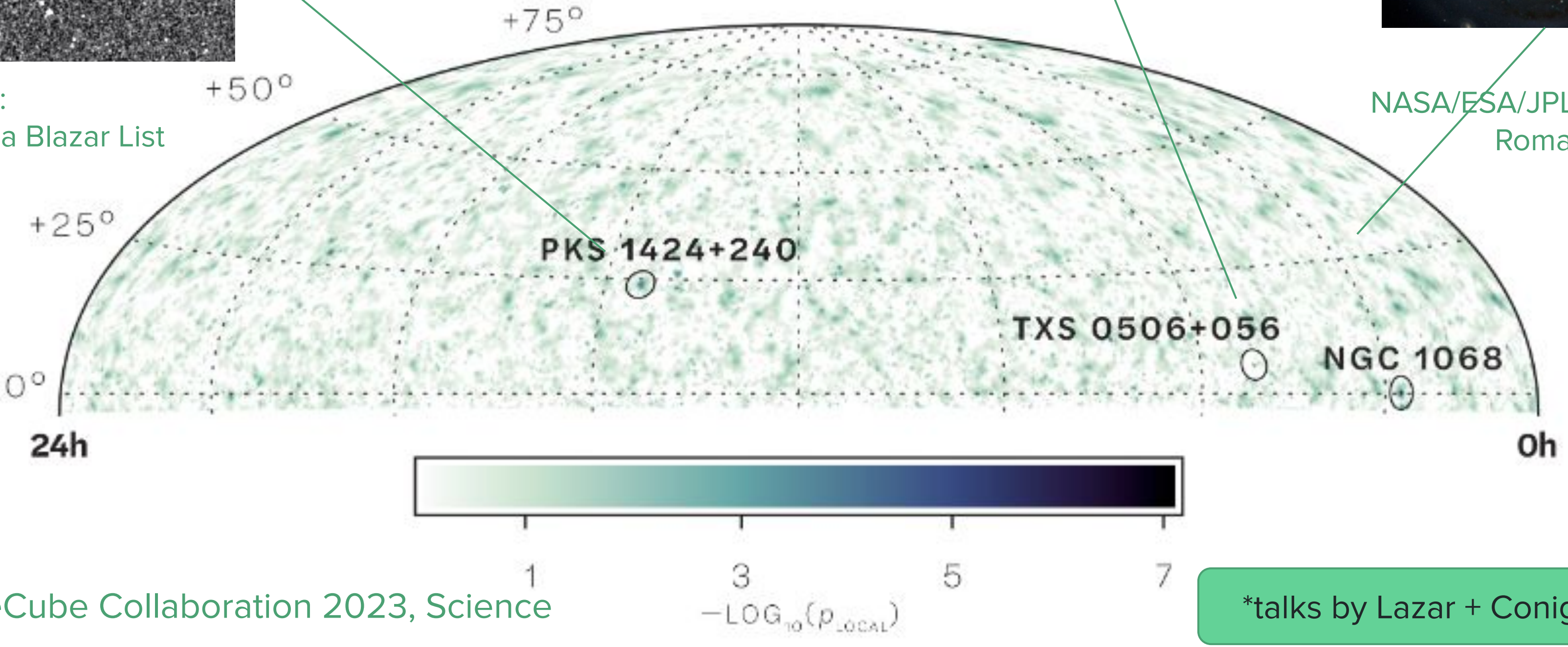
Credit: NASA/DOE/Fermi LAT Collaboration



Seyfert 2 (D$_L$ ~ 10 Mpc)



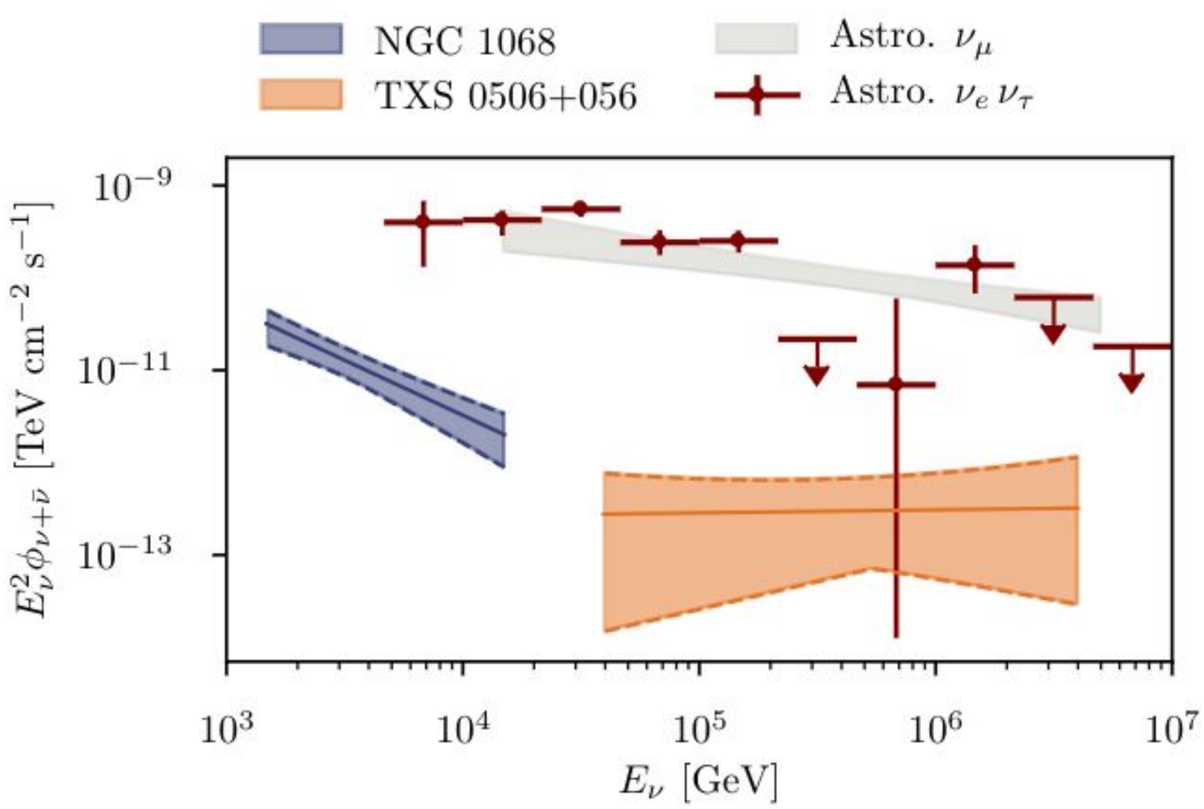
Credit: NASA/ESA/JPL-Caltech/ Roma Tre Univ.



IceCube Collaboration 2023, Science

*talks by Lazar + Coniglione

Highlights



IceCube Collaboration 2023, Science

- Are neutrino spectra of non-jetted and jetted AGN *different*, and why?
- Are *all* jetted AGN neutrino emitters, or only those sharing common properties with TXS 0506+056?
- Can we explain the diffuse flux with a *combination* of jetted and non-jetted AGN?

Physical models for neutrino point sources

Source Physics

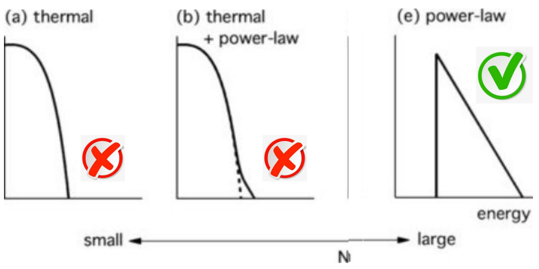
Observations and experiments

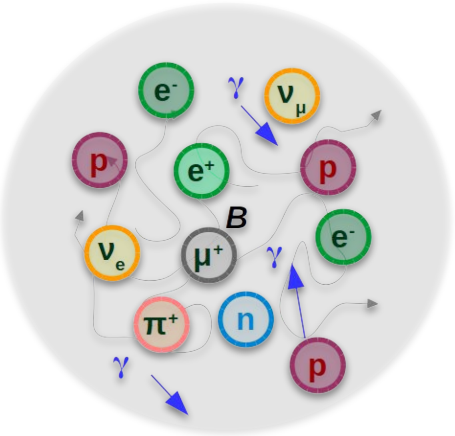
Acceleration

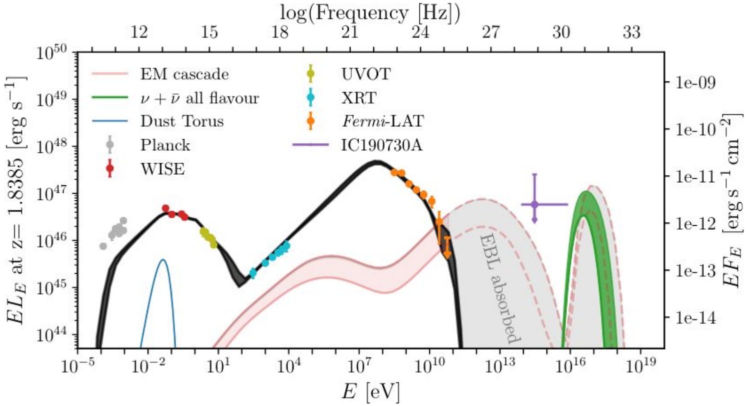
Radiation

Observables

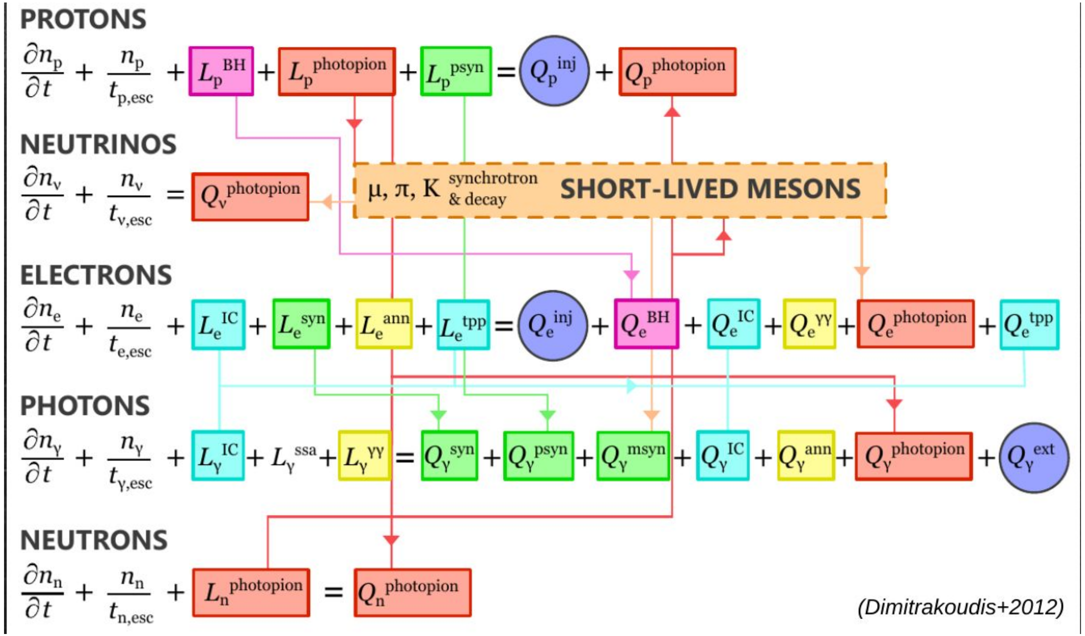
Heating   Acceleration







Numerical models for neutrino point sources



- Python code (implicit scheme)
- Processes: adiabatic expansion, p-p collisions, p-γ interactions, Bethe-Heitler pair production +++
- Features: time-dependent, non-linear cascades from secondaries, SED fitting with MCMC

Stathopoulos S. I. et al. 2024, A&A

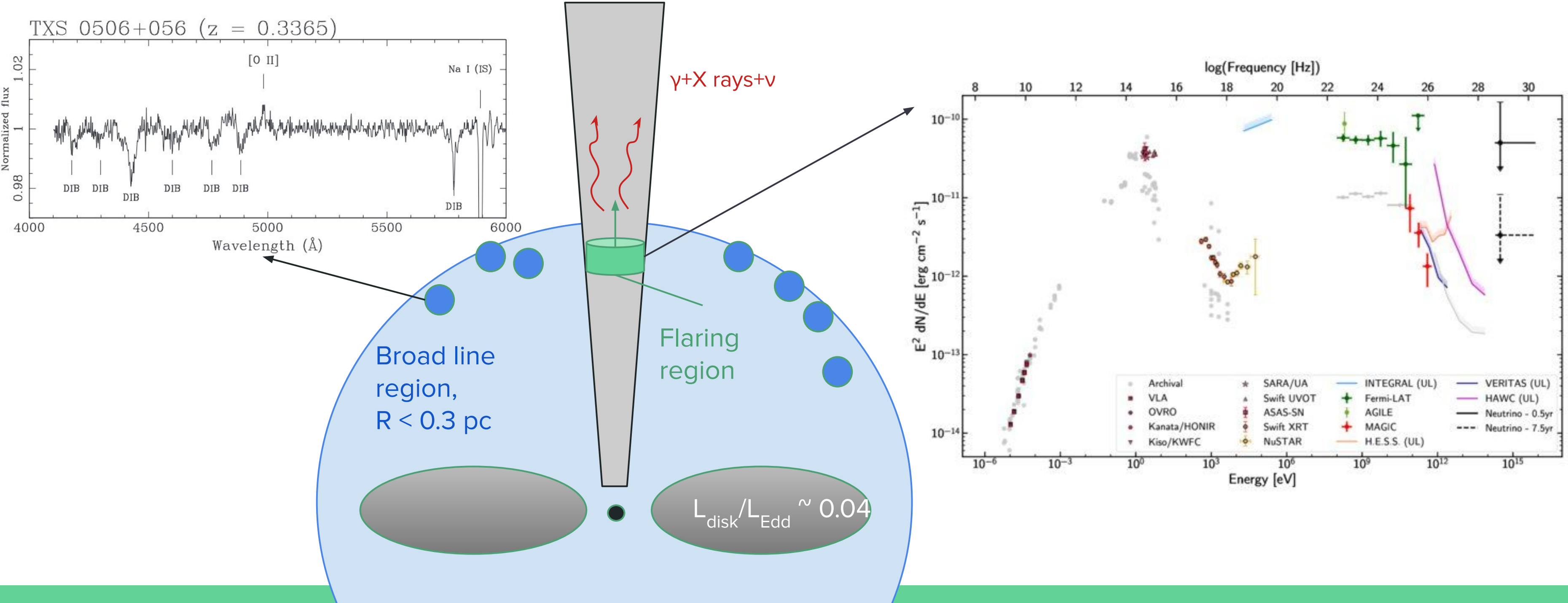
TRY...

Code available: https://github.com/mariapetro/LeHaMoC.git

(See also: AM^3, Klinger et al., 2023, arXiv:2312.13371)

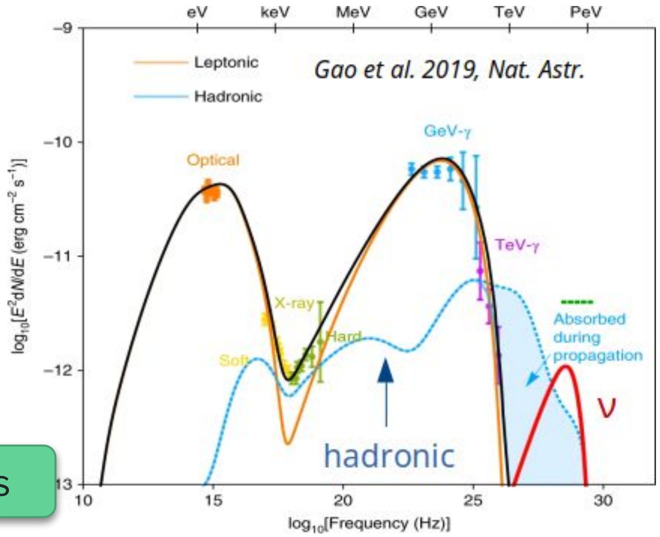
TXS 0506+056 / IC 170922A

- Blazar at z = 0.3365 from weak emission lines (Paiano et al. 2018, ApJL)
- Masquerading BL Lac with Esyn,pk < 4 eV [IBL] ➔ hidden broad line region (Padovani et al. 2019, MNRAS)
- IC 170922A (~ 290 TeV) detected during a 6 month-long flare (IceCube collaboration 2018, Science)

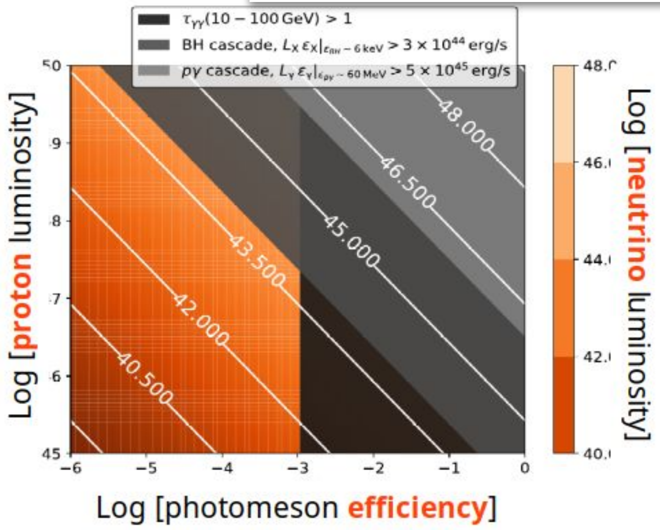


Modeling of the 2017 flare

$$E_\nu L_{E_\nu} \lesssim 10^{45}\ \mathrm{erg\ s^{-1}}\ \frac{L_{\mathrm{X,lim}}}{3\times 10^{44}\ \mathrm{erg\ s^{-1}}}\ \frac{0.1}{f_x}$$



Main results

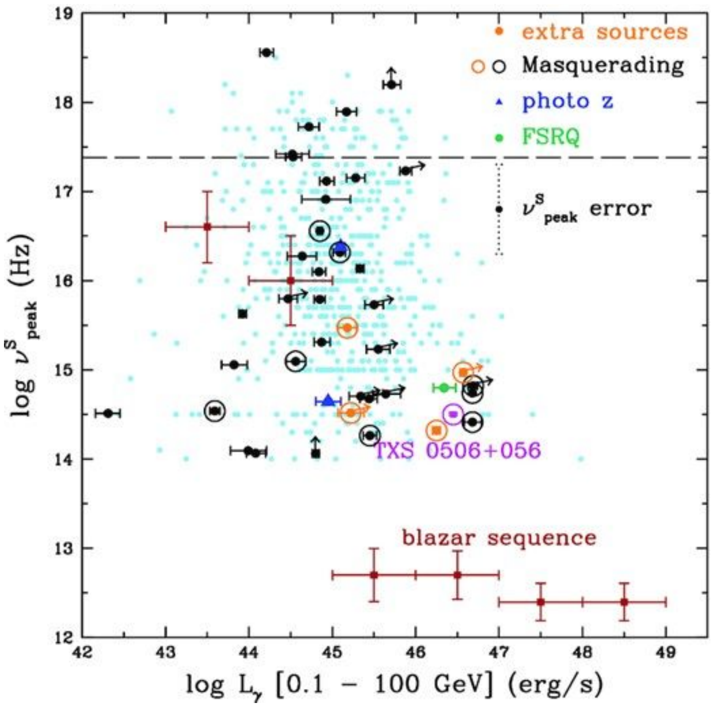


- Leptonic γ-rays ➔ inverse Compton scat. radiation of accelerated electrons (Ansoldi et al. 2018, Keivani et al. 2018, Cerruti et al. 2019, Gao et al. 2019)
- “Hidden” hadronic emission ➔ Hybrid model (e.g. Keivani et al. 2018, Gao et al. 2019)
- Max. neutrino flux is set by the X-ray flux (Murase, Oikonomou,Petropoulou 2018)
- Max. proton energies below EeV ➔ not an UHECR accelerator

The SIN* project

Main goals are:

- measure redshifts of BL Lacs,
- search for masquerading blazars,
- build SEDs, and
- apply physical models to test these correlations.



Padovani et al. 2021

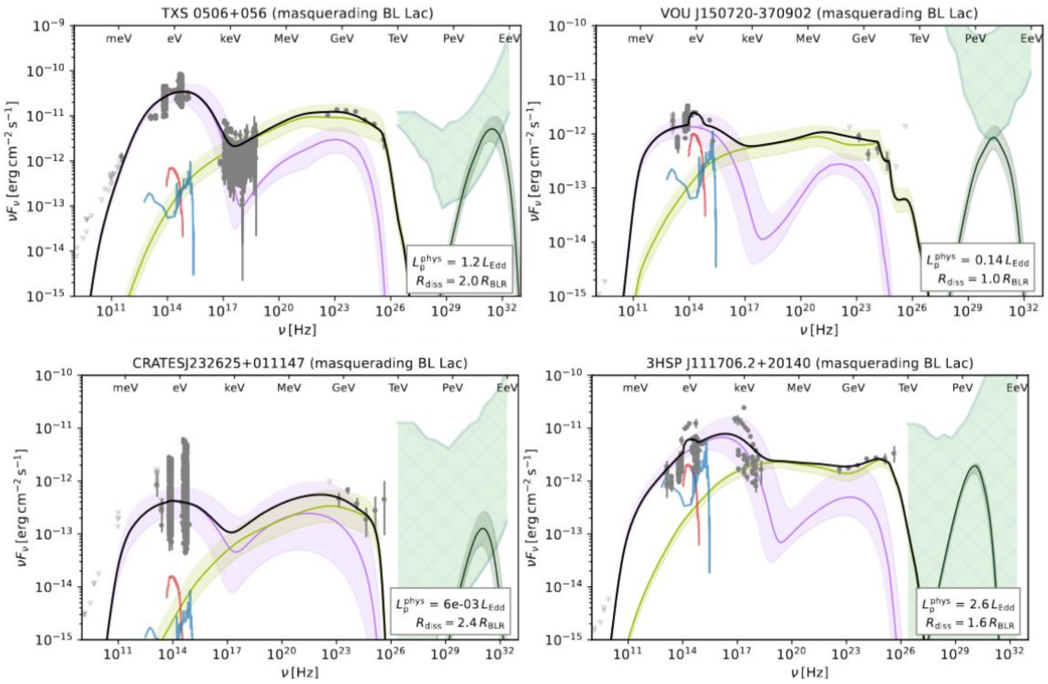
Sample: 36 blazars (IBL/HBL) with redshifts, within error ellipse of 70 high-energy neutrino tracks, off the Galactic plane (Giommi et al. 2020) + 4 more including M87 and 3HSP J095507.9+35510

→ 9 masquerading BL Lacs, 8 true BL Lacs, rest unidentified

*The spectra of IceCube Neutrino (SIN) candidate sources. (P. Padovani and collaborators)

Lepto-hadronic modeling of SIN sources

SED fitting of 34 IHBLs accounting for host galaxy + disk + BLR contributions, and IceCube point-source neutrino fluxes derived using a physical spectral template from public IC data of 10 years

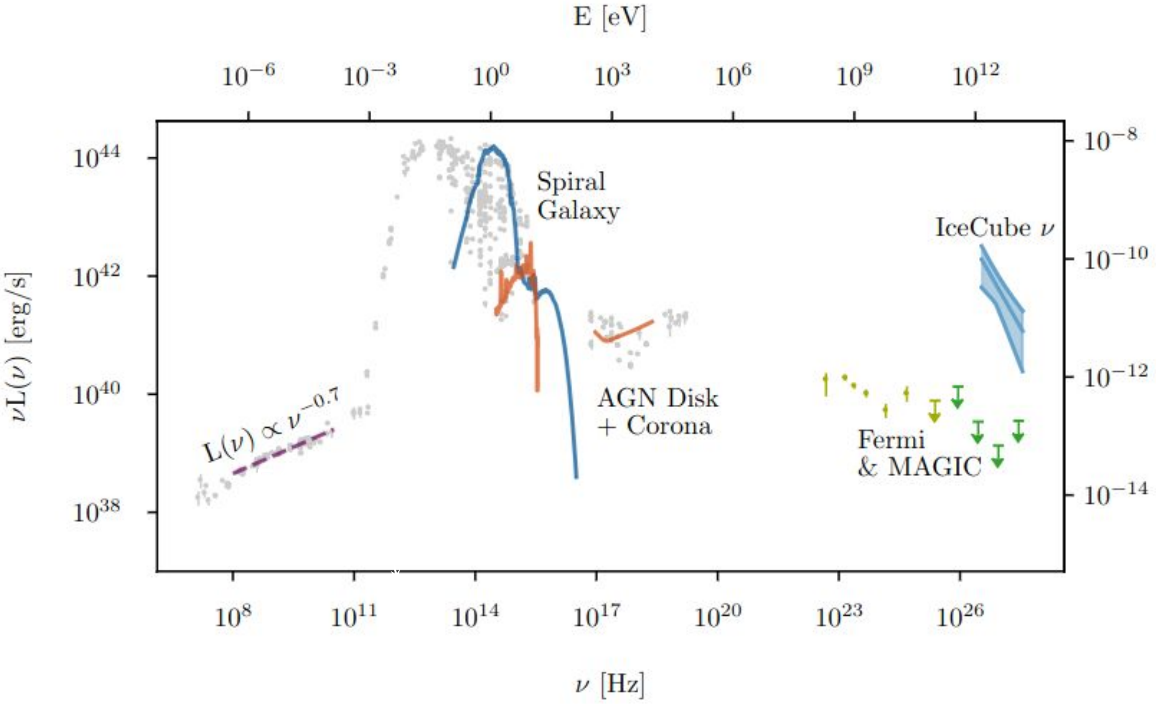


Main results

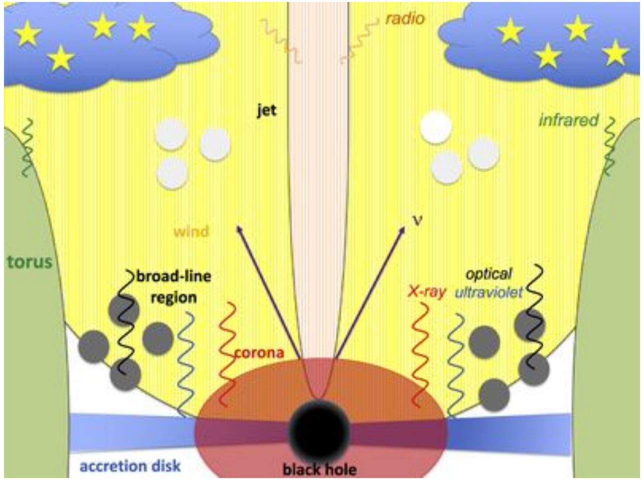
- 12/34 IHBLs with non-zero minimum neutrino flux at the 68% c.l. (*5 masquerading, 3 true, 4 undetermined*)
- Neutrino production site is close to the BLR
- Mix of hadronic + leptonic GeV γ-ray emission <Yνγ> ~0.8 (see also Petropoulou+2015)
- Hadronic emission expected in hard X-rays + MeV γ-rays in all sources.
- Peak neutrino energy > 10 PeV (see also Padovani+2015)

Rodrigues, Karl et al. 2024, arXiv:2406.06667

NGC 1068: a multi-messenger view



Many potential sites for proton acceleration and neutrino production



Murase 2022

Padovani et al. 2014, to appear in Nat. Ast. (arXiv:2405.20146)

NGC 1068 models: pick your flavor

Different hypotheses

- CR acceleration:
    - Stochastic acceleration in turbulence (Murase+2020, Murase 2022, Eichmann+2022, Fiorillo+2024b)
    - Diffuse shock acceleration (Inoue et al. 2019, 2020, Eichmann+2022)
    - Magnetic reconnection (Kheirandish+2021, Fiorillo+2024a)

Common results

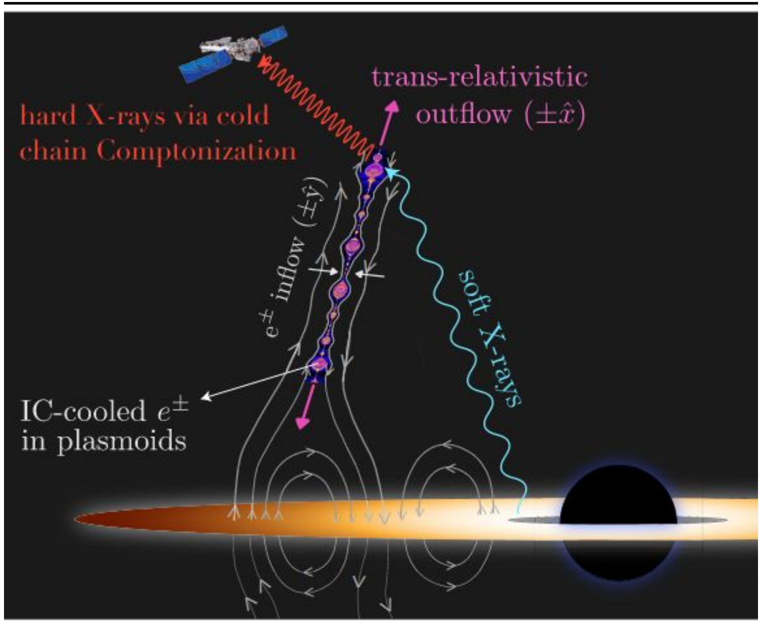
- Neutrino production site:
    - inner disk and/or corona
    - opaque to TeV γ-rays ➔ constraints on coronal size
- GeV γ-rays: starburst
- MeV γ-rays: hadronic cascade

Different results

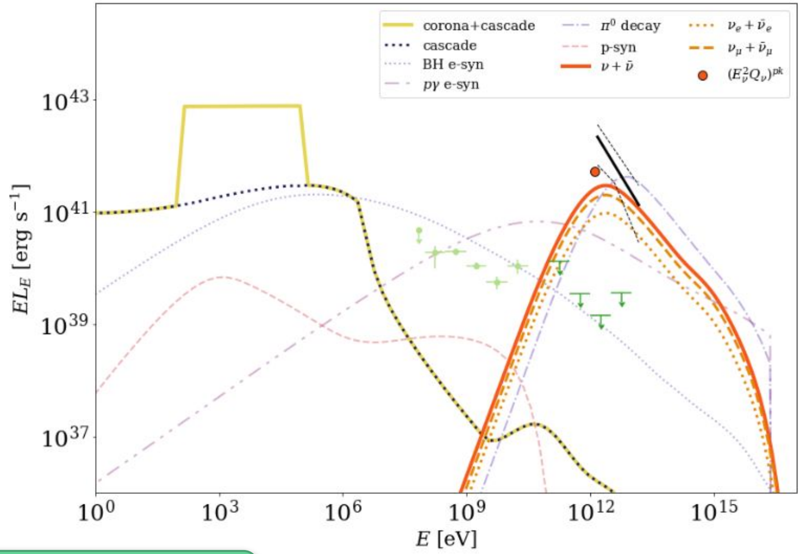
- Properties of corona:
    - Pair dominated plasma
    - Electron-proton plasma
    - Plasma magnetization
    - Size

Proposal No. 1: reconnection layers

Fiorillo et al., 2024a



Shridhar, Sironi, Beloborodov, 2021



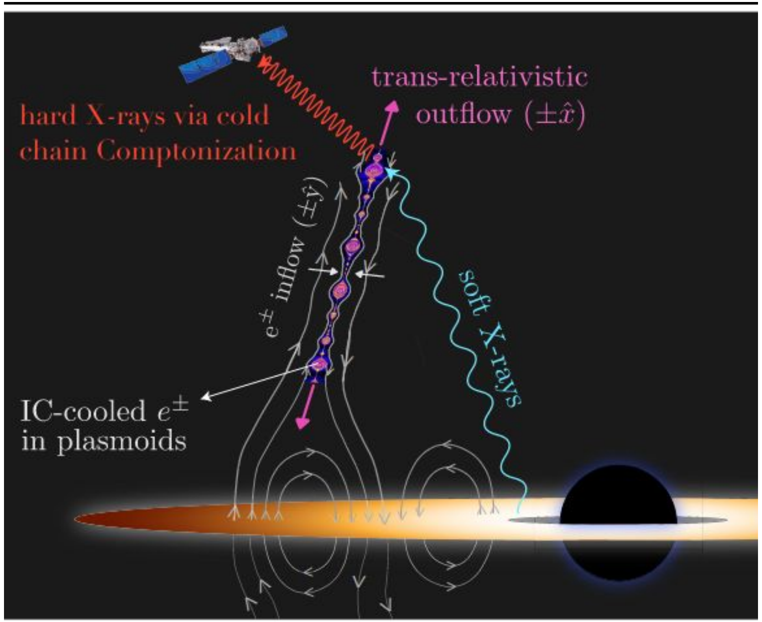
Main results

- Compact corona: L ~ (3-10)*R_g
- Pair dominated corona: n_{ee}/ n_p ~10^{6-7}
- Highly magnetized corona: σ_e ~ 10^2 and σ_p ~ 10^5
- Non-thermal-to-thermal proton fraction: ~1

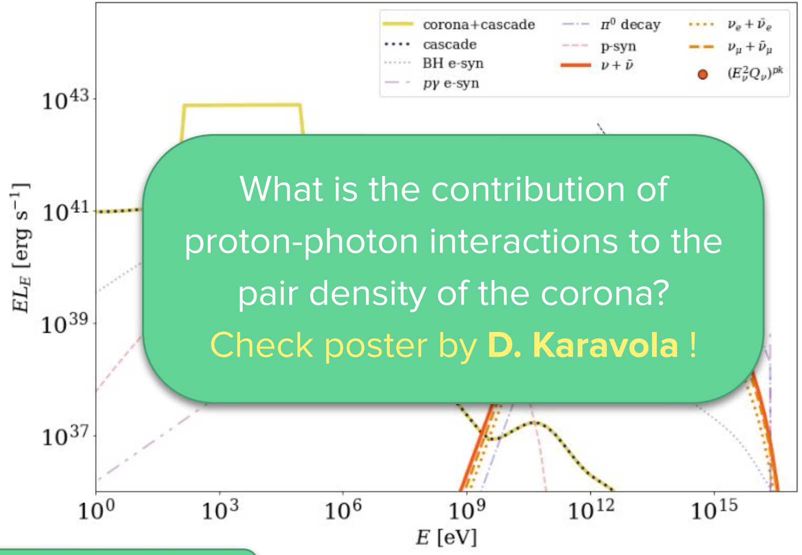
For particle acceleration see : Werner & Uzdensky 2017, Chernoglazov et al. 2023, Zhang et al. 2021, 2023

Proposal No. 1: reconnection layers

Fiorillo et al., 2024a



Shridhar, Sironi, Beloborodov, 2021

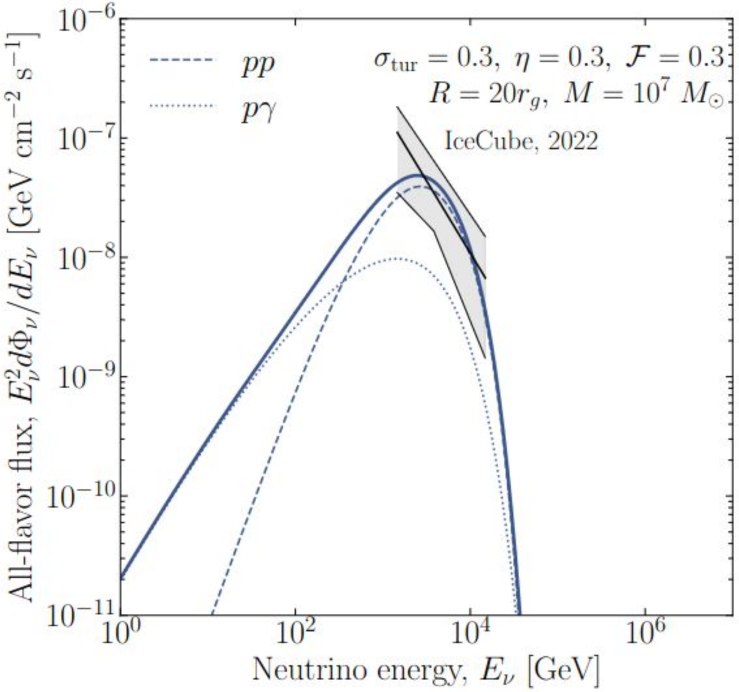


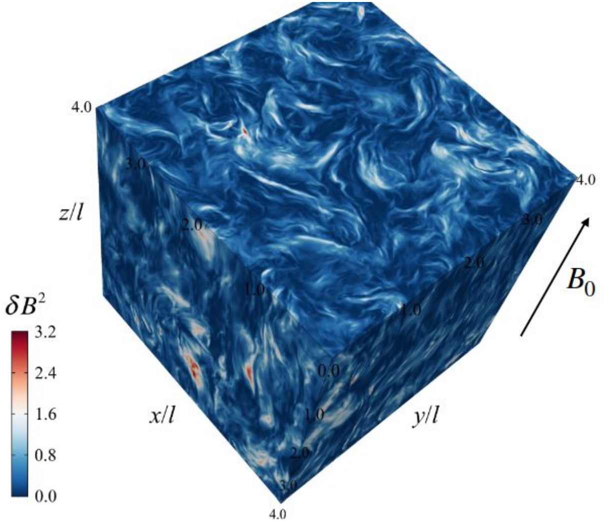
What is the contribution of proton-photon interactions to the pair density of the corona?
Check poster by **D. Karavola** !

Main results

- Compact corona: L ~ (3-10)*R_g
- Pair dominated corona: $n_{ee}/n_p \sim 10^{6-7}$
- Highly magnetized corona: $\sigma_e \sim 10^2$ and $\sigma_p \sim 10^5$
- Non-thermal-to-thermal proton fraction: ~1

Proposal No. 2: strong turbulence





Main results

- Compact corona: $L \sim 20\ R_g$
- Strong turbulence: $\delta B/B_o \sim 1$
- Electron-proton corona: $n_e/\ n_p \sim 1$
- Weakly magnetized corona: $\sigma_e \sim \sigma_p < 1$
- Non-thermal-to-thermal fraction: $\sim 10^{-6}$

Fiorillo et al., 2024b, in prep.

For particle acceleration, see: Comisso & Sironi 2019

New questions

Jetted AGN

- Is neutrino production in jets *steady* or *transient* ?
- Are there *different* neutrino production *sites* in a jet ? If so, how does neutrino production depend on *jet conditions* ?
- What is the contribution of γ-ray flaring blazars to diffuse neutrino flux ? (Yoshida et al. 2023)

Non-jetted AGN

- How can we *distinguish* between competing physical *models* of NGC 1068 ?
- What is the contribution of *hadronic* interactions to the *pair content* of the corona ?
- Are *all* AGN coronae neutrino emitters ?

Conclusions & Outlook

- The most compelling astrophysical neutrino point sources today are: a jetted AGN (TXS 0506+056) and a Seyfert galaxy (NGC 1068).

- There are hints that masquerading BL Lacs, like TXS 0506+056, are more efficient neutrino emitters than true, lower power BL Lacs. Neutrino production site is located close to the BLR.

- The most promising neutrino production site in NGC 1068 is the corona, but it's properties are very different among models.

- Hadronic emissions are expected in the MeV γ-ray range. *All-sky sensitive MeV satellite ???*
- Detailed neutrino spectra may unveil the physics of proton acceleration. *IceCube-Gen2 ?*
- More physical input to the neutrino source models is needed !

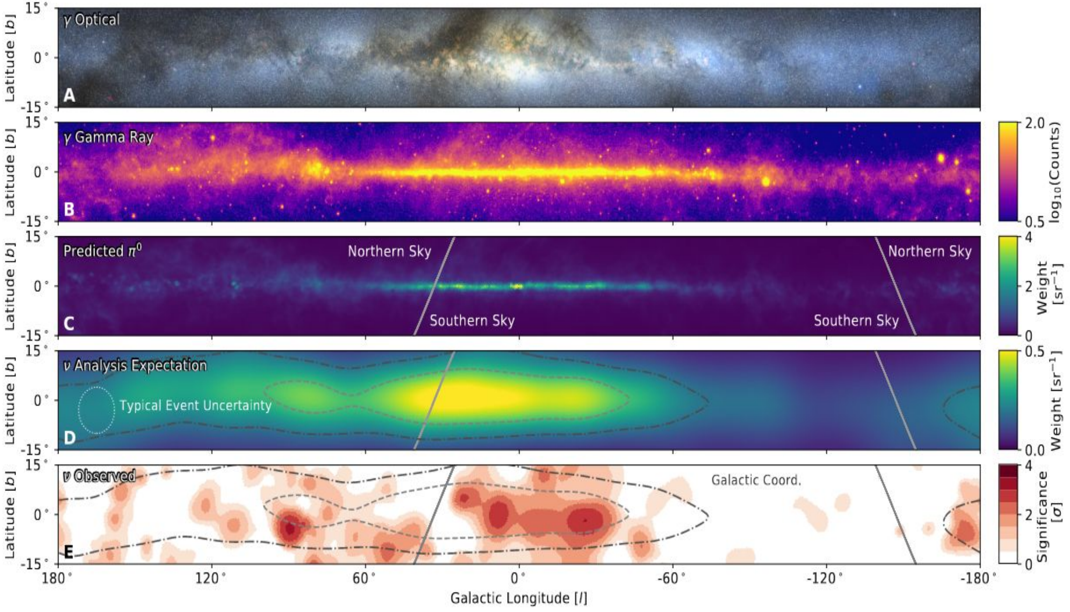
Thank you!

Backup slides

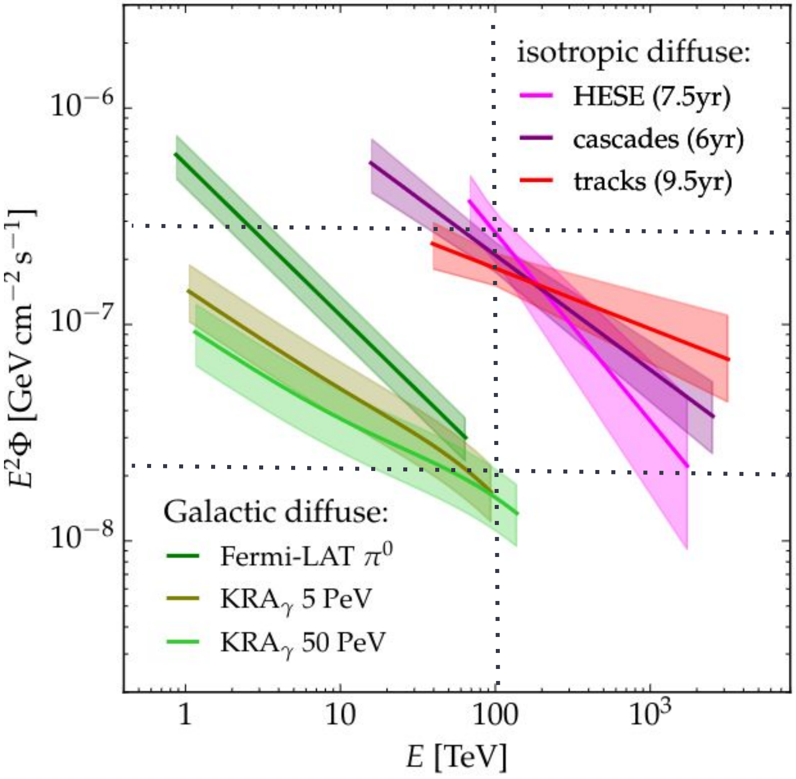
The Galactic neutrino emission

(talk by A. Neronov)

= diffuse from p-p CR interactions and/or unresolved point sources (e.g. SNRs, PWNe)



Icecube Collaboration, 2023, Science

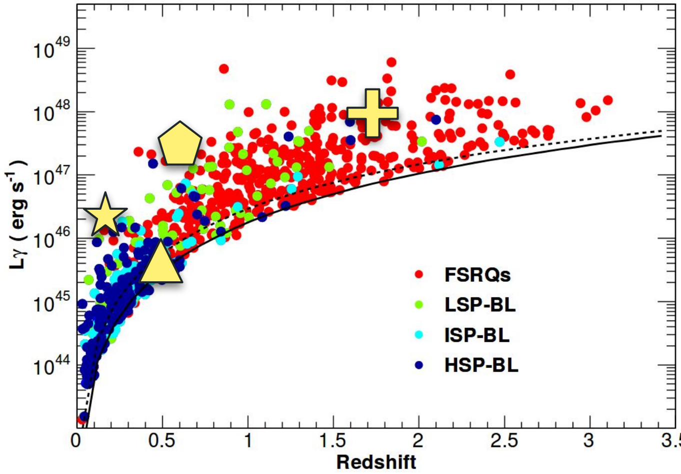


Ambrosone et al., 2024, Phys. Rev. D

A summary of interesting neutrino alerts & blazars

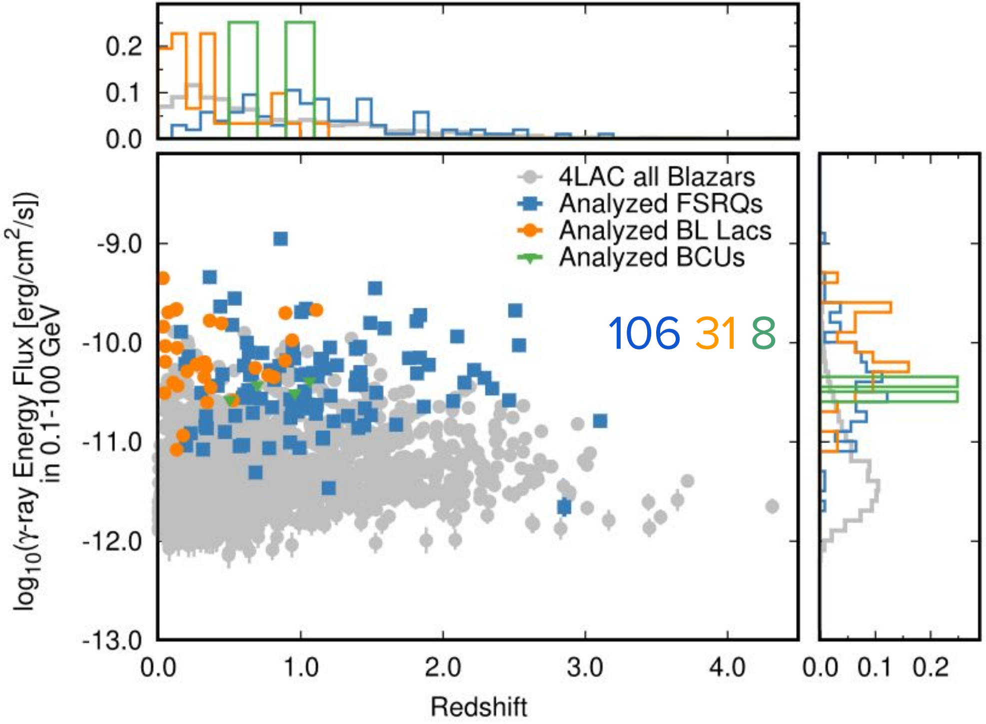
- TXS 0506+056 / IC - 170922A (IceCube collaboration 2018, Science)
  - Masquerading BL Lac with Esyn,pk < 4 eV [ISP] (Padovani et al. 2019, MNRAS)
  - Neutrino (~ 290 TeV) detected during a MW 6 month-long flare
- 3HSP J095507.9+35510 / IC-200107 (Giommi et al. 2020, MNRAS; Paliya et al. 2020, ApJ)
  - BL Lac with Esyn,pk > 1 keV ["extreme" HSP]
  - Neutrino (??) detected 1 day before a hard X-ray flare in 2020 - no γ-ray flare
- PKS 0735+178 / IC-211208A (Sahakyan,... MP ... 2022, arXiv:2204.05060)
  - Masquerading BL Lac with Esyn,pk < 4 eV [ISP]
  - IC neutrino (~ 172 TeV)detected at peak of a 3-week γ-ray flare
  - Lower energy neutrinos detected by Baikal, KM3Net (low significance)
- PKS 1502+106 / IC-190730A (Franckowiak et al. 2020, ApJ)
  - FSRQ with Esyn,pk < 0.4 eV [LSP]
  - Neutrino (~ 300 TeV) detected during period of low MW activity (no flare)

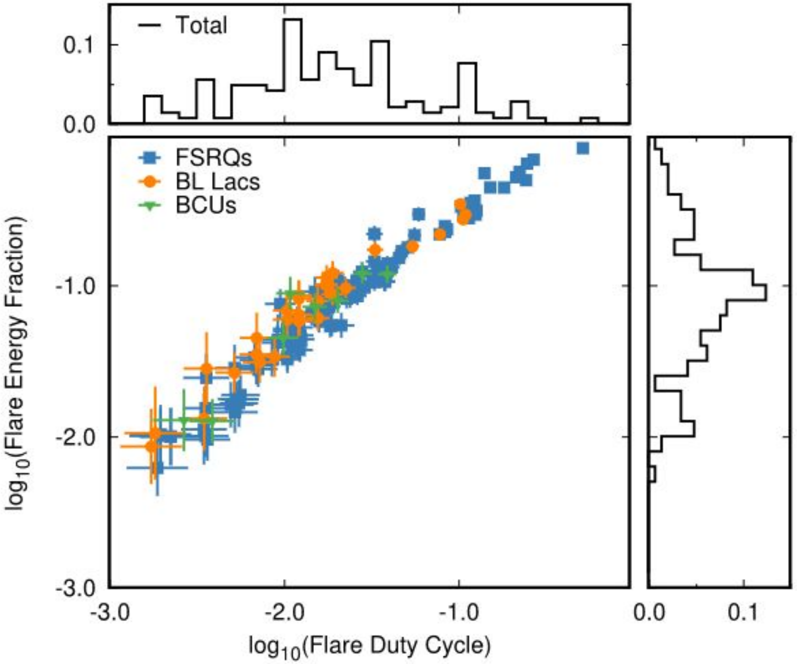
Fermi 3LAC (2015)



Gamma-ray flaring blazars in Fermi 4LAC

Yoshida et al. 2023, ApJ



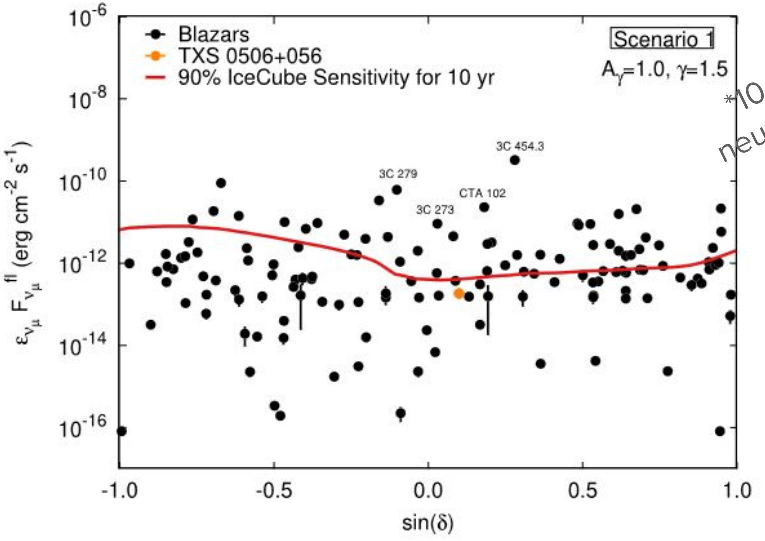


Gamma-ray flaring blazars in Fermi 4LAC

Yoshida et al. 2023, ApJ

Scenario 1

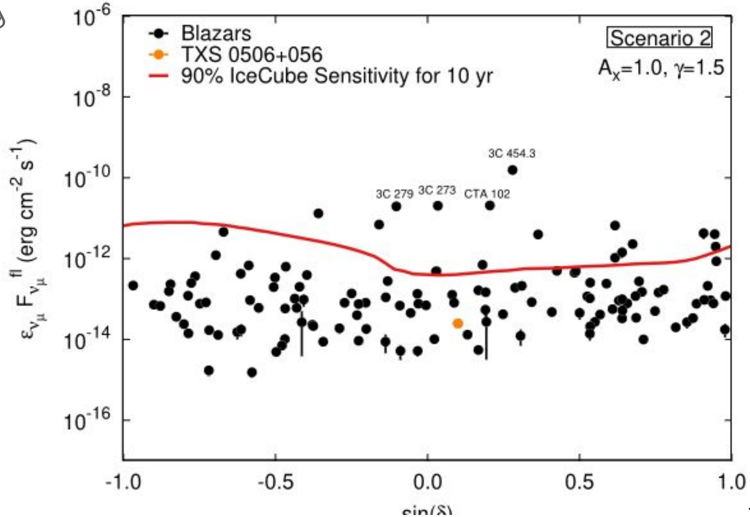
$$E_{\nu_\mu} F^{\rm fl}_{E_{\nu_\mu}} = E_{\nu_\mu} F^{q}_{E_{\nu_\mu}} \left(\frac{F^{\rm fl}_\gamma}{F^q_\gamma}\right)^\gamma = A_\gamma \frac{E_\gamma F^q_{E_\gamma}}{3} \left(\frac{F^{\rm fl}_\gamma}{F^q_\gamma}\right)^\gamma ,$$



*10 yr averages of weekly neutrino flare fluxes with zero fluxes during non-flaring states

Scenario 2

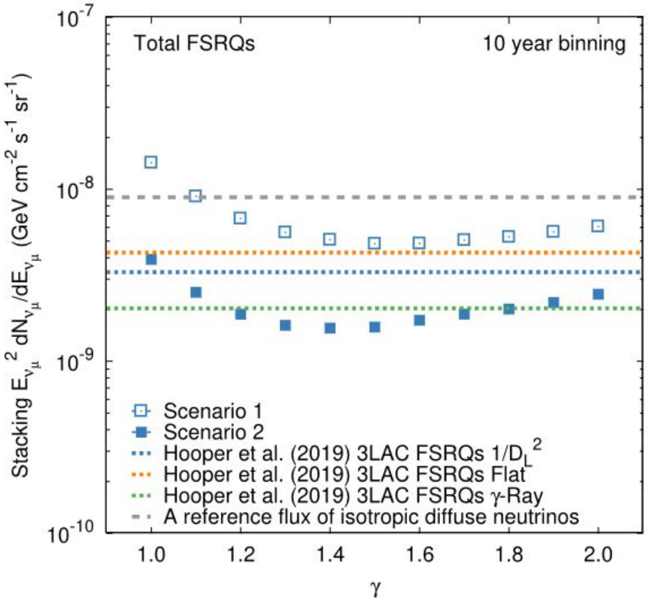
$$E_{\nu_\mu} F^{\rm fl}_{\nu_\mu} = E_{\nu_\mu} F^{q}_{E_{\nu_\mu}} \left(\frac{F^{\rm fl}_\gamma}{F^q_\gamma}\right)^\gamma = A_X \frac{E_X F^q_{E_X}}{3} \left(\frac{F^{\rm fl}_\gamma}{F^q_\gamma}\right)^\gamma$$

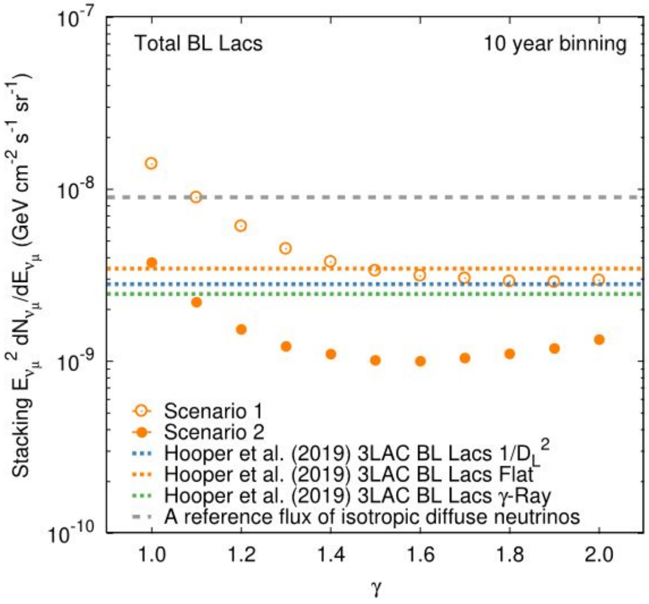


Gamma-ray flaring blazars in Fermi 4LAC

Yoshida et al. 2023, ApJ

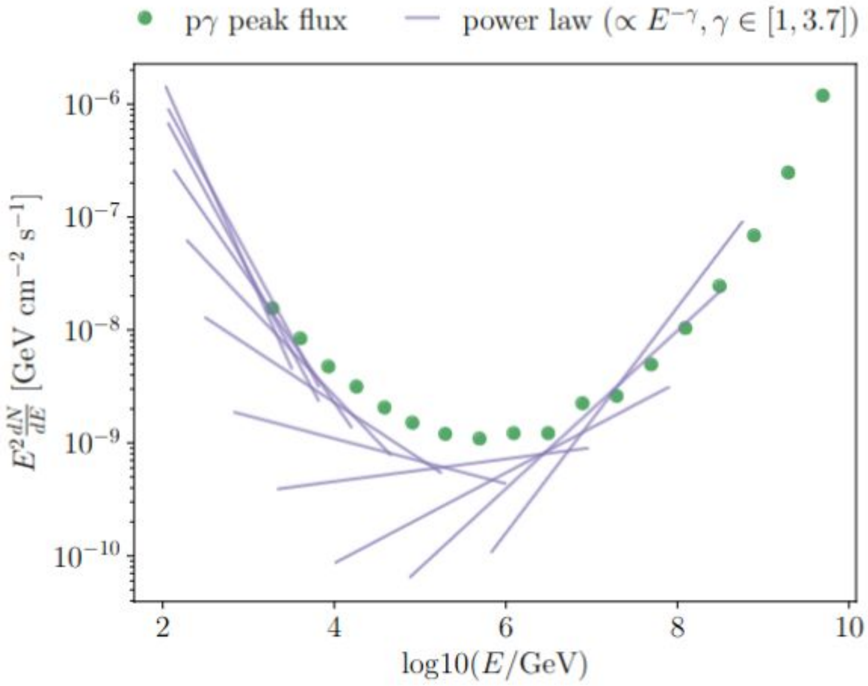
The origin of all-sky neutrinos observed in IceCube is one of the most important puzzles in high-energy neutrino astrophysics. We found that scenarios (1) and (2) suggest that no more than ∼50% and ∼14% of the all-sky neutrino flux can originate from gamma-ray flares of FSRQs and BL Lac objects, respectively. A more realistic neutrino spectrum than the usual E_ν^{-2} power law yields upper limits of the all-sky diffuse neutrino flux that are a factor of 2 more constraining. The upper limits are consistent with those obtained the previous literature despite different methods and assumptions.

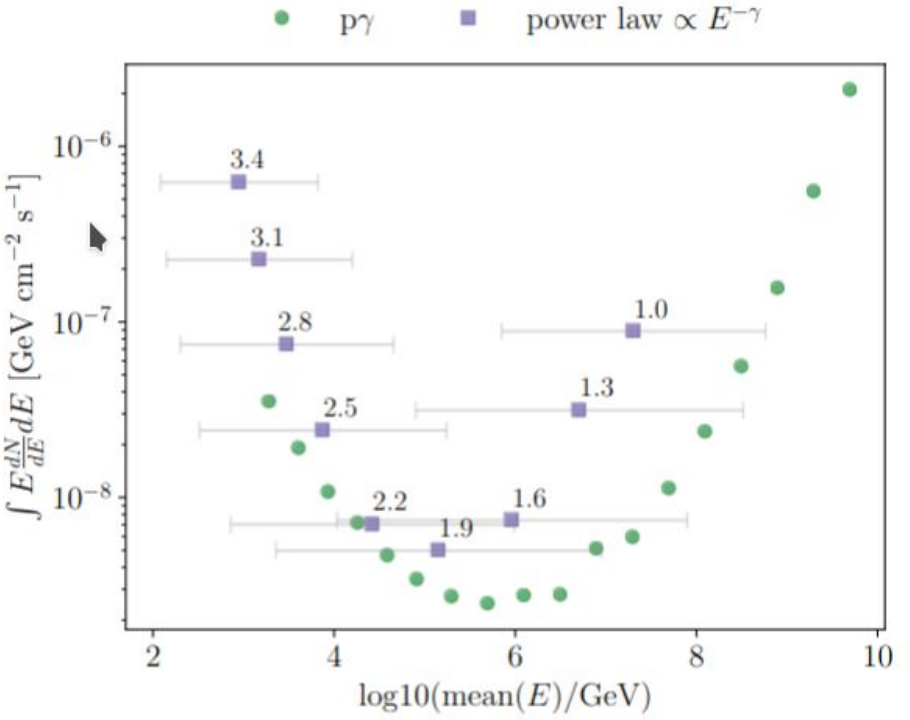




3σ neutrino discovery potential* at location of TXS 0506+056

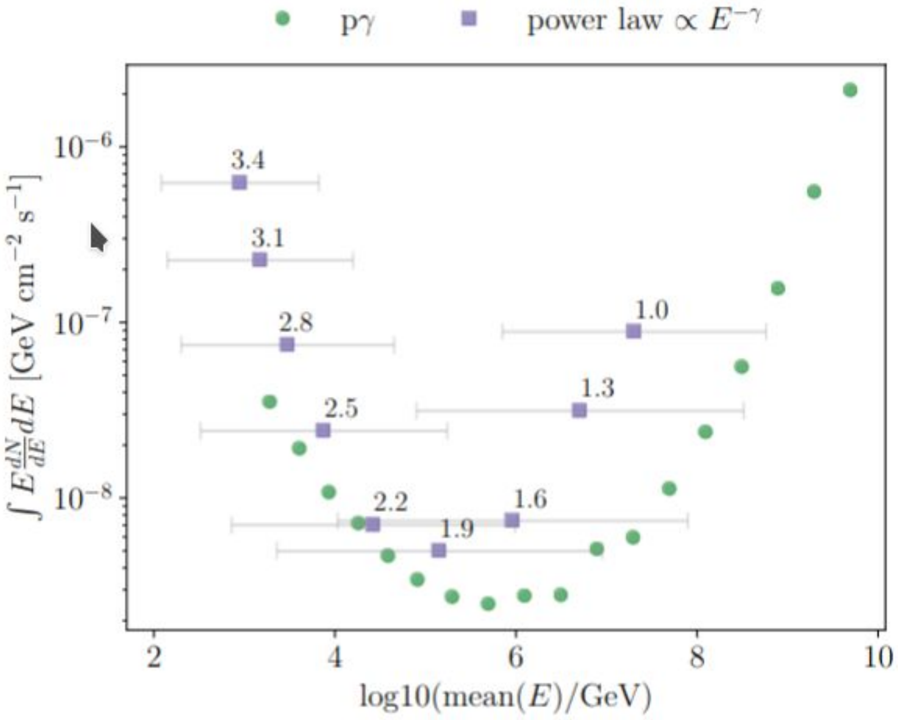
* source flux in order to have a 50% chance to be detected with 3σ significance

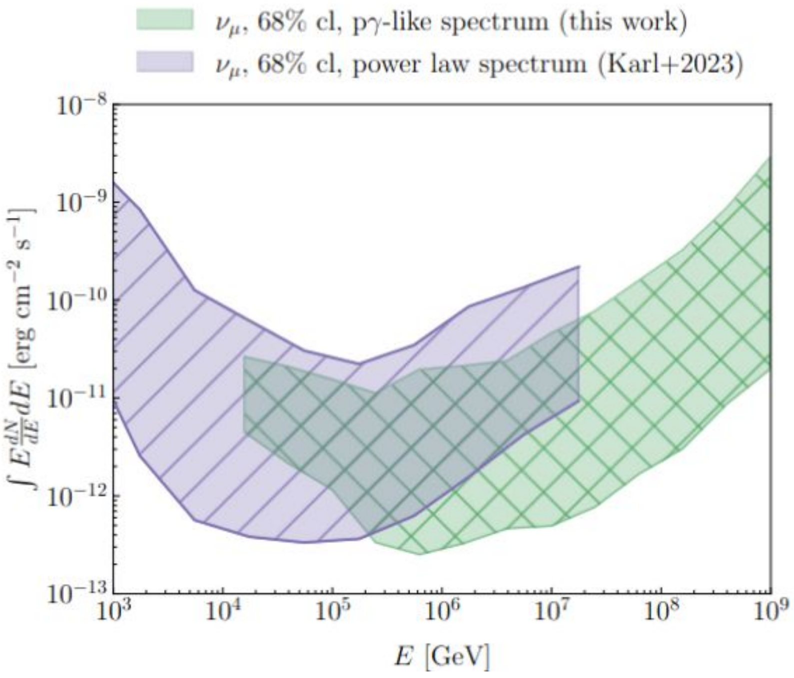




Rodrigues, Karl et al. 2024, arXiv:2406.06667

Differential neutrino point-source fluxes

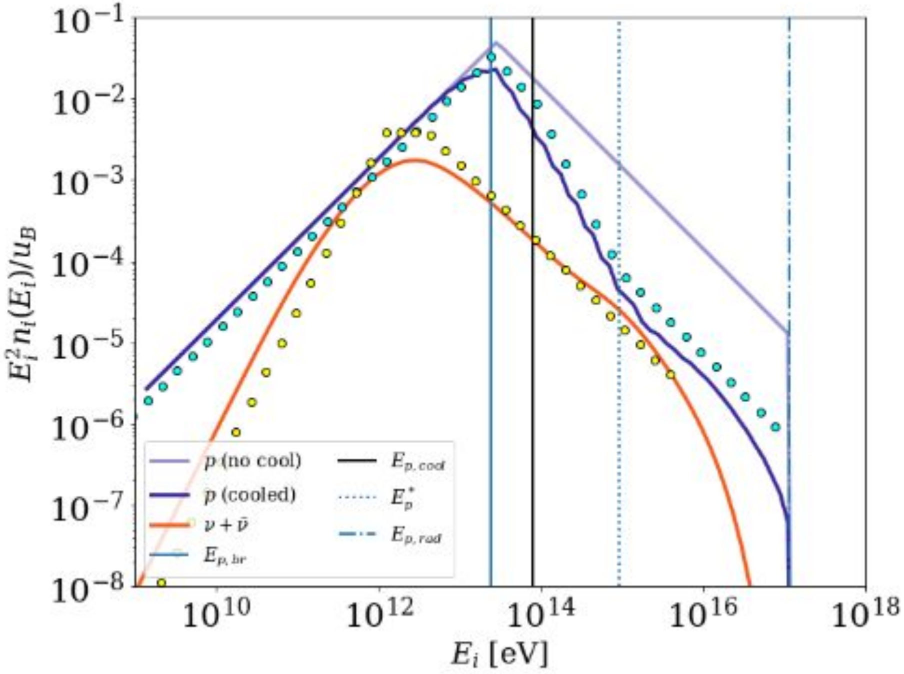


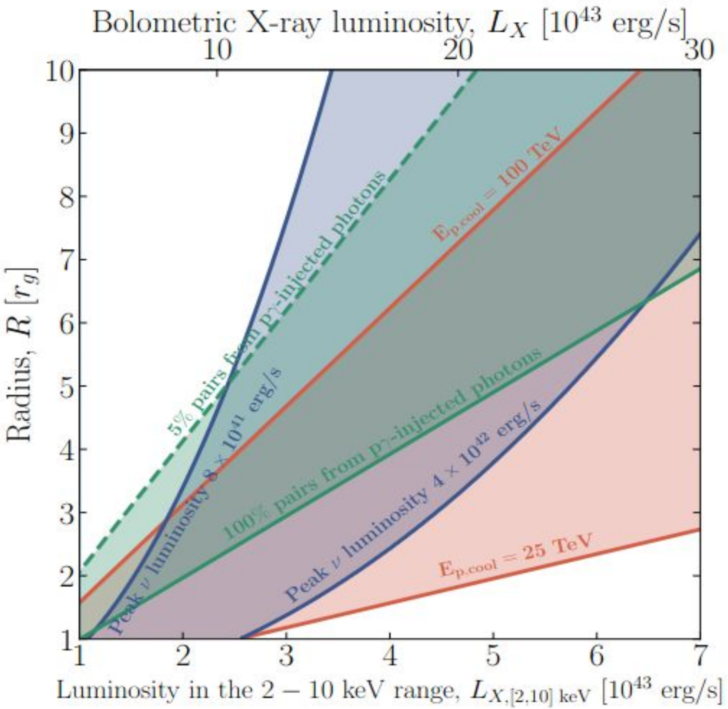


Rodrigues, Karl et al. 2024, arXiv:2406.06667

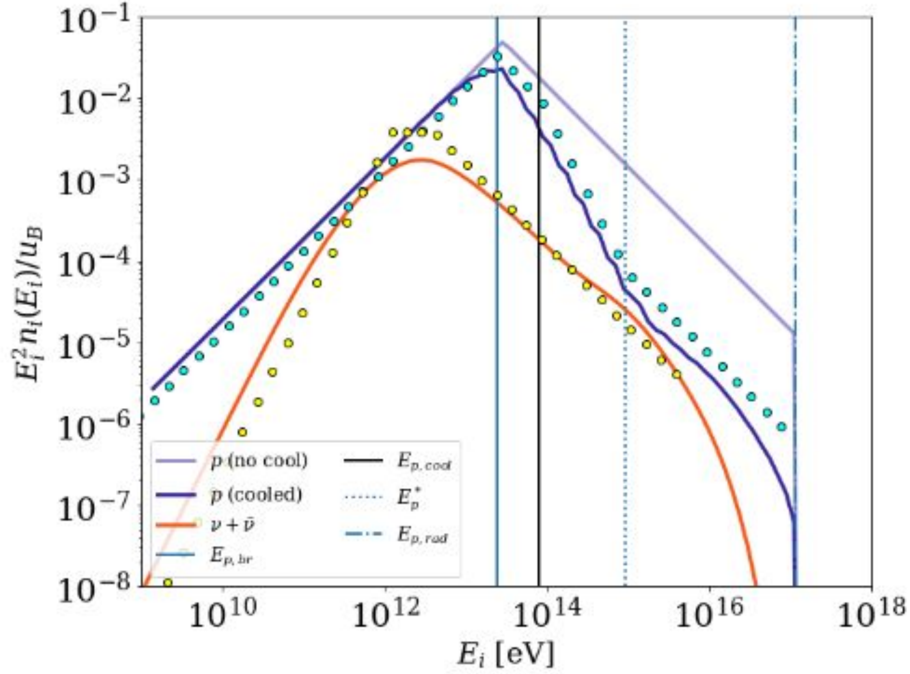
Proton and neutrino spectra from NGC 1068

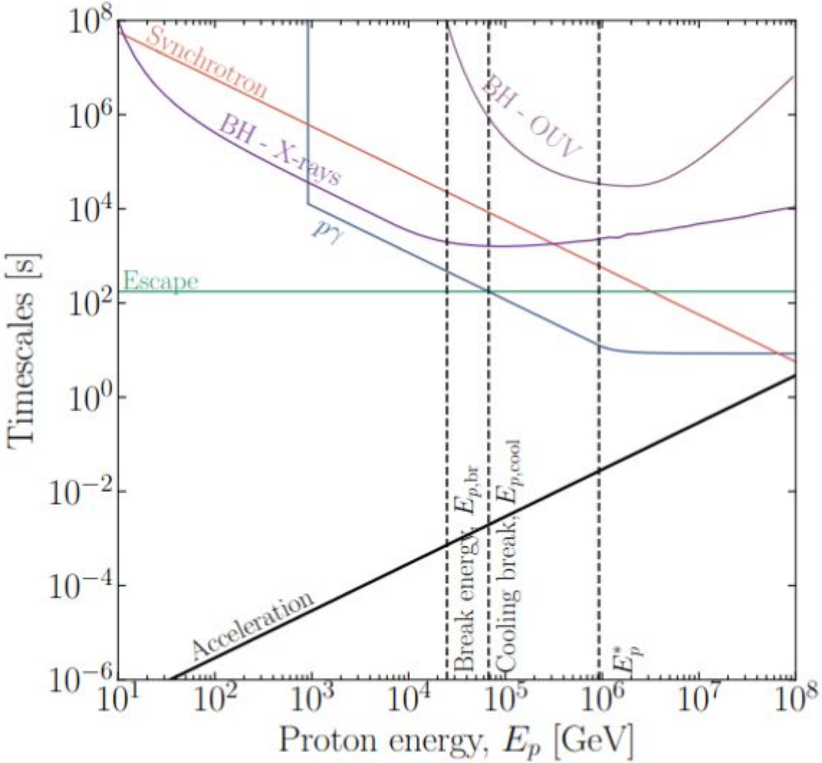
Fiorillo et al., 2024a

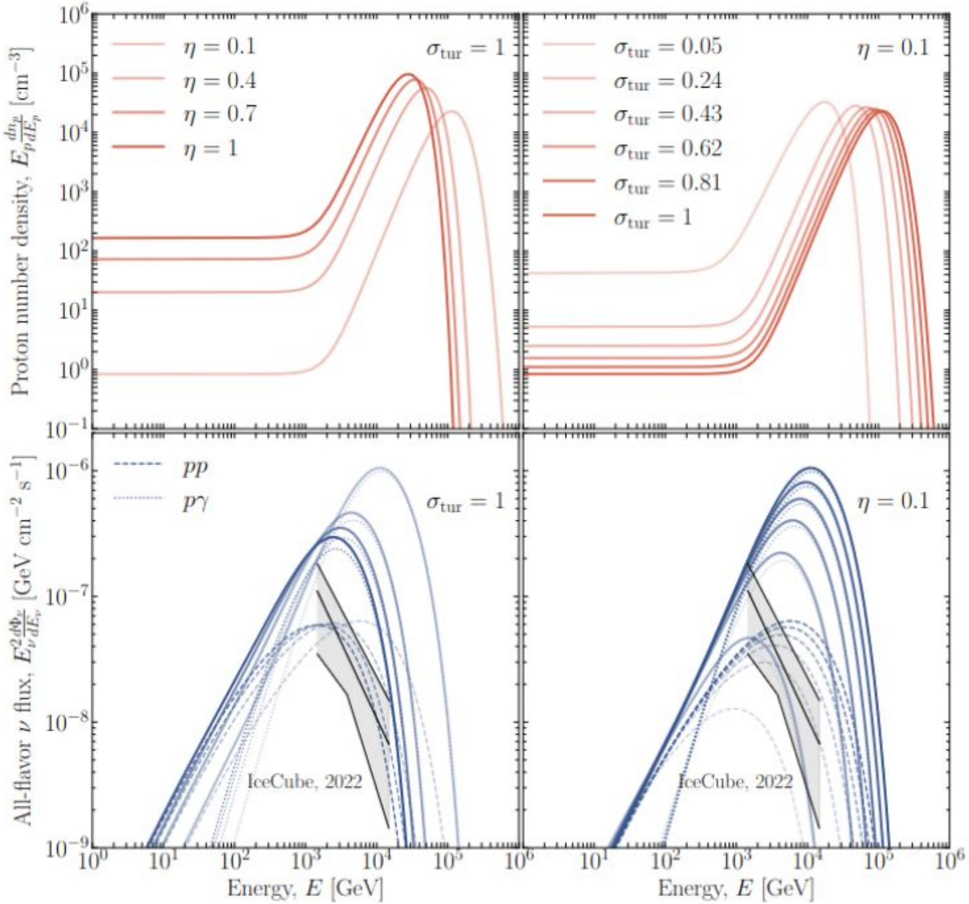




Fiorillo et al., 2024a







Fiorillo et al., 2024b

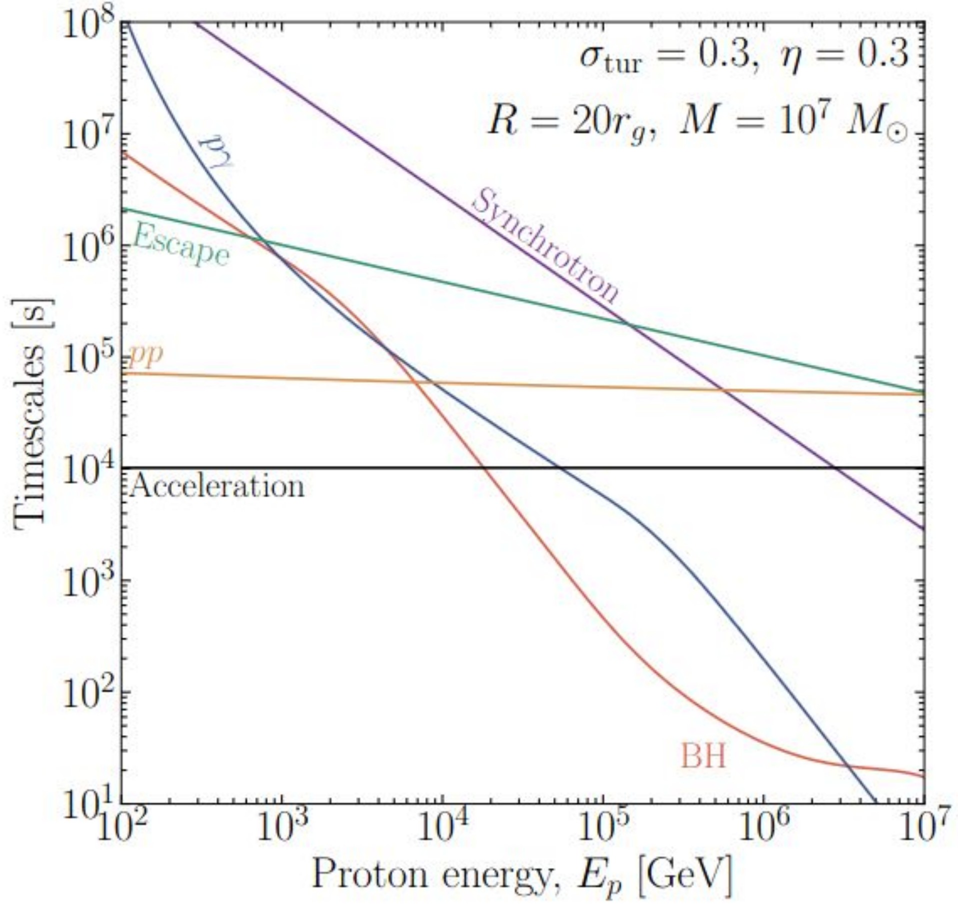
Dependence of proton (top) and neutrino (bottom) distributions on two main model parameters:

– plasma magnetization σ_{tur}
– coherence length of turbulence/corona size η

$$\frac{\partial f_p}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[\frac{p^4}{t_{acc}}\frac{\partial f_p}{\partial p}\right] + \frac{1}{p^2}\frac{\partial}{\partial p}\left[\frac{p^3}{t_{cool}(p)} f_p\right] - \frac{f_p}{t_{esc}} + q_p(p).$$

$$t_{acc} \equiv \frac{p^2}{D_p} \simeq \frac{10}{\sigma_{tur}}\frac{\ell}{c}. \qquad t_{esc} \simeq \frac{R}{c}\max\left[1, \frac{R}{\ell}\left(\frac{eB\ell}{E_p}\right)^{1/3}\right],$$

$$t_{cool}^{-1} = t_{p\gamma}^{-1} + t_{BH}^{-1} + t_{pp}^{-1} + t_{synch}^{-1}.$$



Proton Timescale vs. Energy plot

$$t_{\rm acc} \equiv \frac{p^2}{D_p} \simeq \frac{10}{\sigma_{\rm tur}} \frac{\ell}{c}\,.$$

$$t_{\rm esc} \simeq \frac{R}{c} \max\left[1, \frac{R}{\ell}\left(\frac{eB\ell}{E_p}\right)^{1/3}\right],$$

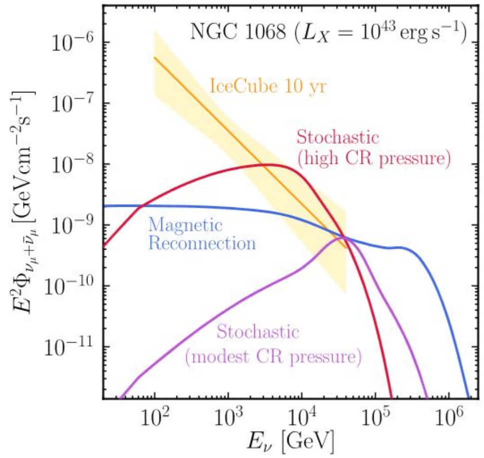
$$t_{\rm cool}^{-1} = t_{p\gamma}^{-1} + t_{\rm BH}^{-1} + t_{pp}^{-1} + t_{\rm synch}^{-1}.$$

Fiorillo et al., 2024b

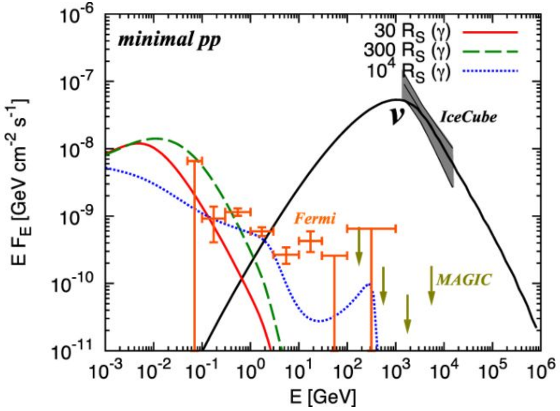
Coronal/disk models

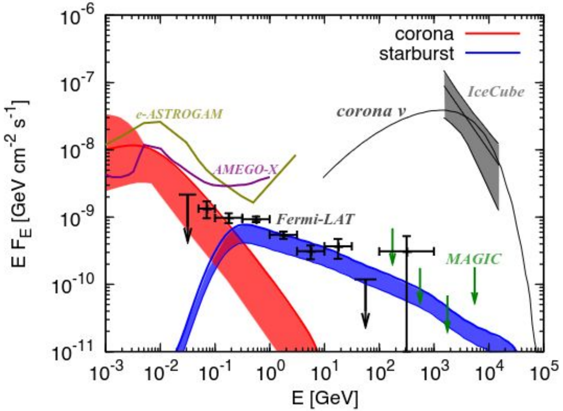
- Neutrinos produced in inner disk and/or corona, opaque to TeV γ rays ➔ constraints on coronal size
- CR acceleration: stochastic acceleration in turbulence or magnetic reconnection or shock acceleration

Kheirandish, Murase, & Kimura



Generic acceleration / pp or pγ

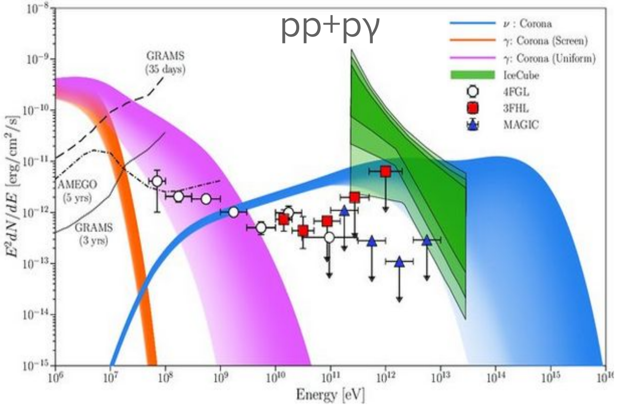




Murase 2022; Ajello, Murase, McDaniel, 2023

Diffusive shock acceleration (DSA)

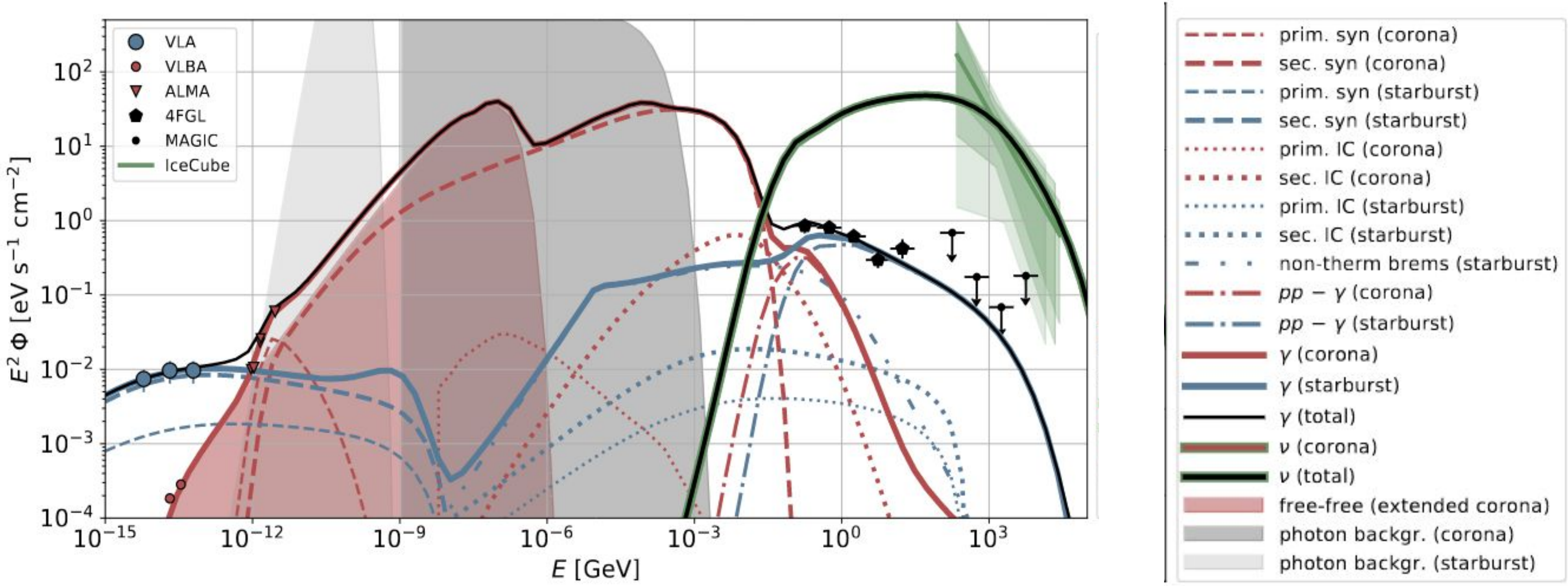
pp+pγ



Inoue, Khangulyan, Doi, 2020, ApJ
(Inoue et al. 2019)

“Two-zone” models

- Neutrinos produced in inner disk and/or corona (<< pc)
- radio/IR/GeV γ-rays from starburst region (kpc)
- CR acceleration: gyro-resonant scattering in turbulence (corona) + DSA (starburst)



Eichmann et al. 2022

See also Inoue, Cerruti et al. (arXiv:2207.02097)