High-energy neutrinos

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Introduction

- Associations with sources and coincidences
- Particle acceleration
- Example AGNS:
    1. Energetics
    2. Source of photons
    3. Maximum energy

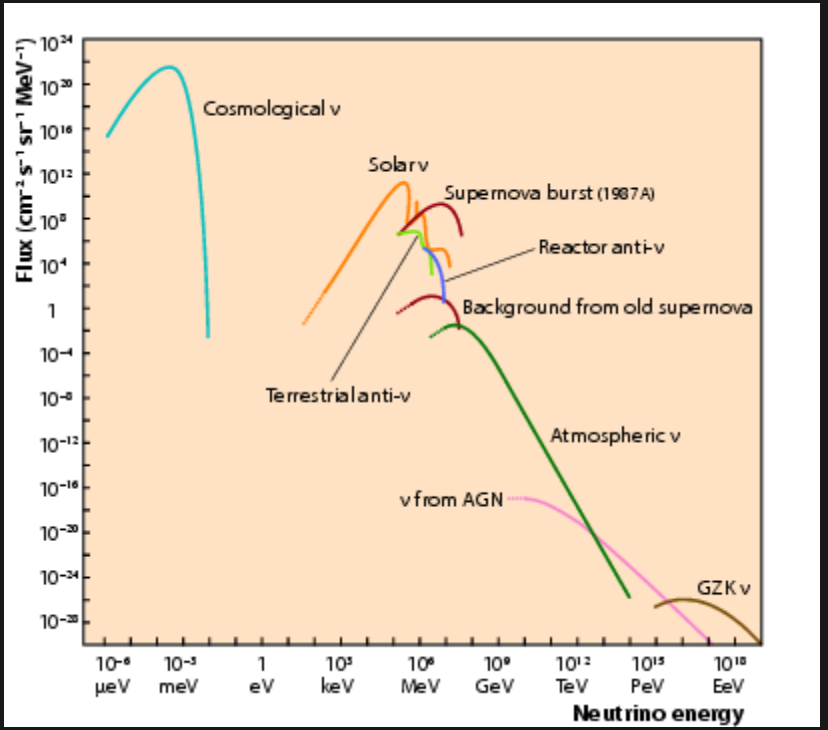
High-energy neutrinos

Neutrinos from cosmic sources

Pro: Negligible absorption
(Small cross section)

Contra: Hard to detect
(Small cross section)

Problem: Atmospheric background

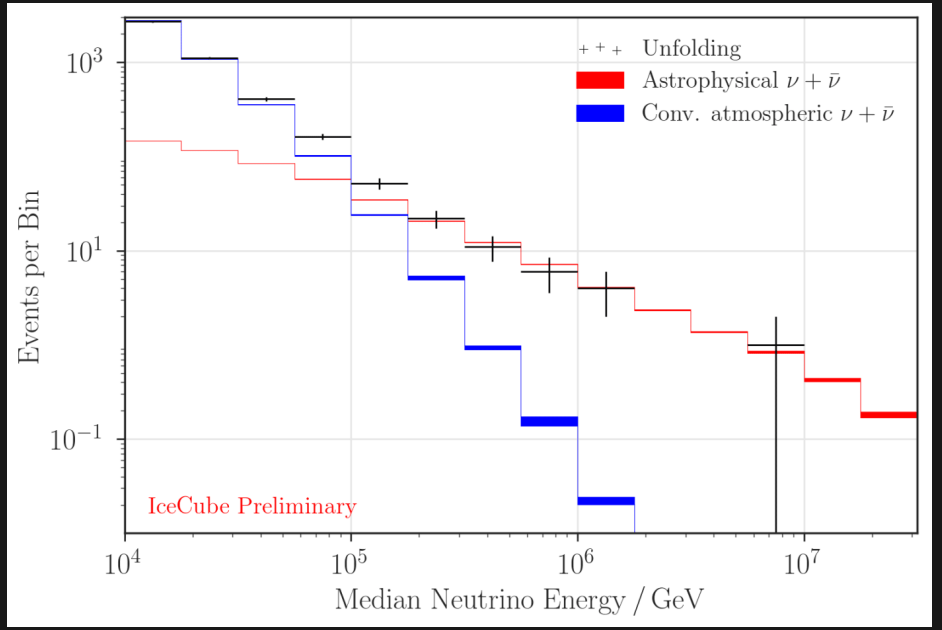


High-energy neutrinos

Cosmic neutrinos

seen as significant excess intensity

Statistically consistent with isotropy



High-energy neutrinos

Directional uncertainy is half a square degree

Lots of potential counterparts in the uncertainty region

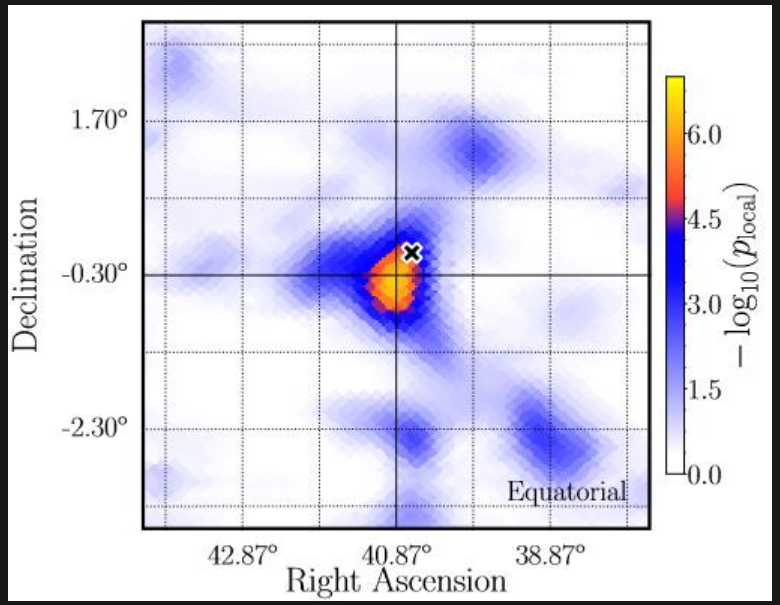
Potential improvement for transient events

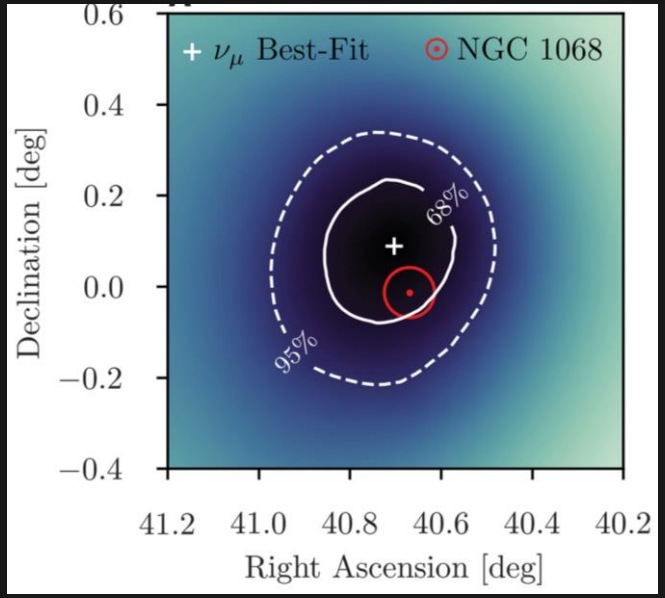
Honest estimate of the trials factor is required

Flux-flux correlation may still give more events in off-phase

Associations

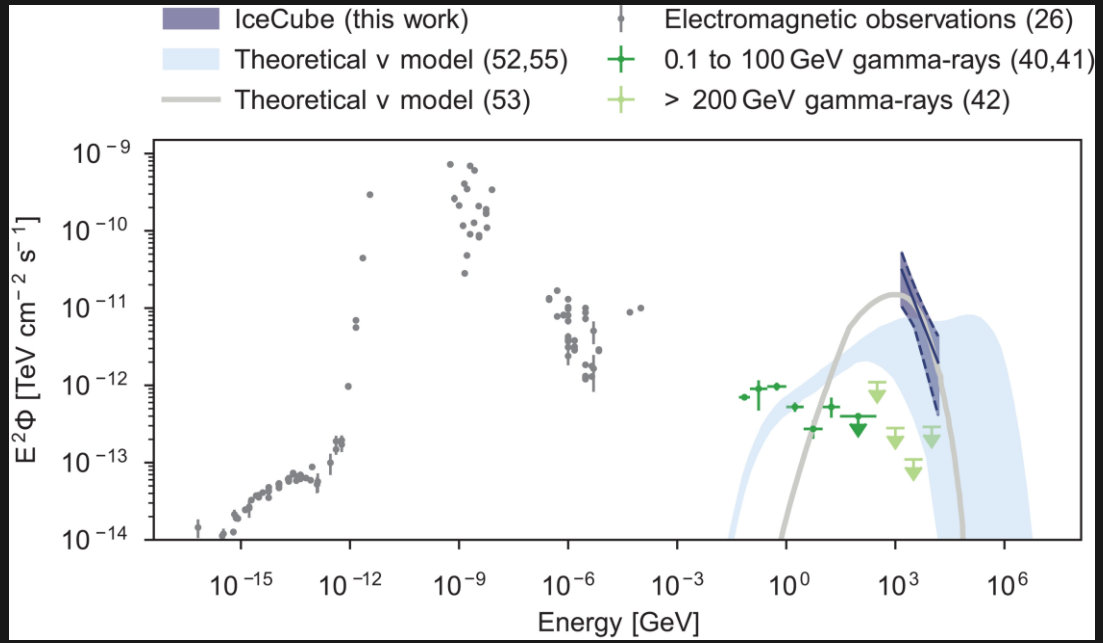
NGC 1068





Associations

NGC 1068



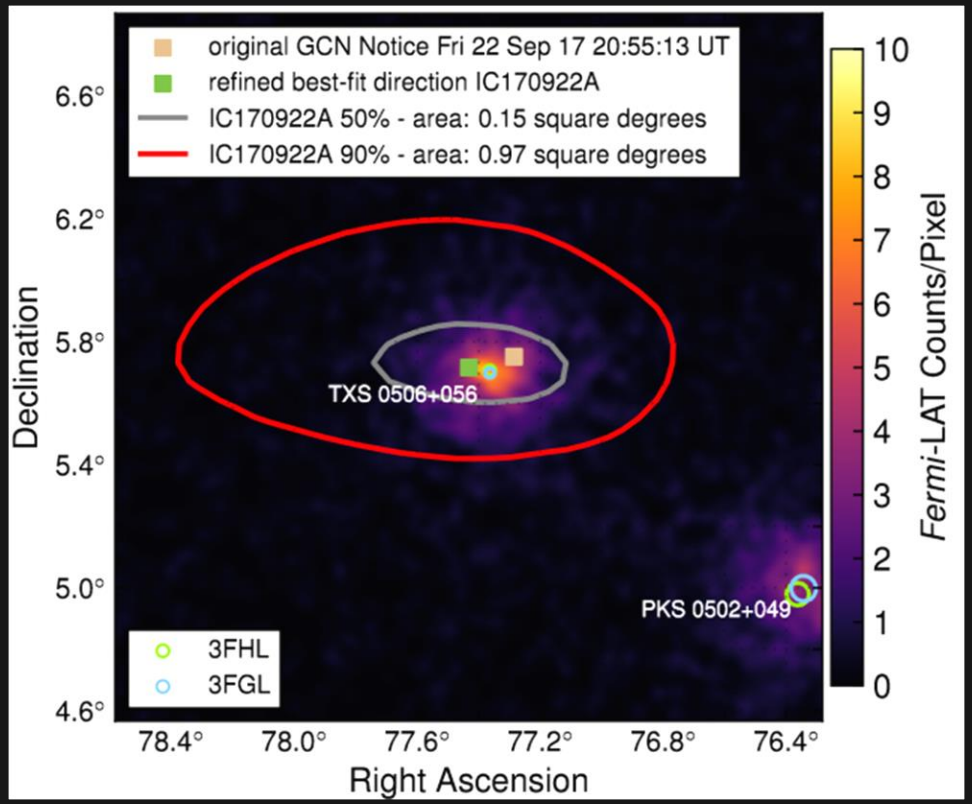
Associations

Search for coincidences

Here TXS 0506+056

Half-year long GeV flare

Association still only 3σ (officially)



Associations: TXS 0506+056

Half-year long GeV flare before the neutrino event

... and for a few months after it

MAGIC sees TeV gamma rays within a week

VERITAS sees TeV gamma rays over the next five months

Which coincidence time window do we want to use?

Associations: TXS 0506+056

A gamma-neutrino correlation?

Which gamma-ray flux do we want to use?

A linear correlation? Then fluence matters

→ We should see neutrinos outside of flare periods

Associations: TXS 0506+056

All selections need to be defined before the event, and not like ...

- At this time it was among the ten brightest gamma-ray emitters
- MAGIC‘s TeV detection was within a week
- The LAT high state has already lasted for half a year
- The coincidence renders associations at low state trials-free

Associations: TXS 0506+056

The issue with the trial factor:

It is not defined by the state you saw
at the time of the neutrino event

It is rather defined by the meekest state you would have accepted before giving up

Particle acceleration

Neutrino emission from blazars requires

- High energy density in energetic protons
- High maximum energy of at least a few hundred TeV
- Sustained activity of weeks in observer time
- Desirable is a hard spectrum with index $s < 2$

Particle acceleration

Reconnection may produce hard spectra

but preferentially accelerate electrons

Maximum Lorentz factor is commensurate with the ion sigma parameter

Where do we have this?

Power requirement 1.e45 erg/s

Needs at least B = 25 G for 1.e16 cm radius

Not terribly likely

Particle acceleration

Shocks are know to accelerate ions

Low radiation efficiency requires very good confinement

$t_{acc} / t_{esc} \sim 1 / v_s^2$ → mildly relativistic shocks

$t_{esc} / t_{\gamma p}$ is low, and so is the radiation efficiency

Problem: Downstream temperature of the order $m_p c^2$

→ sideways expansion quickly dilutes the medium

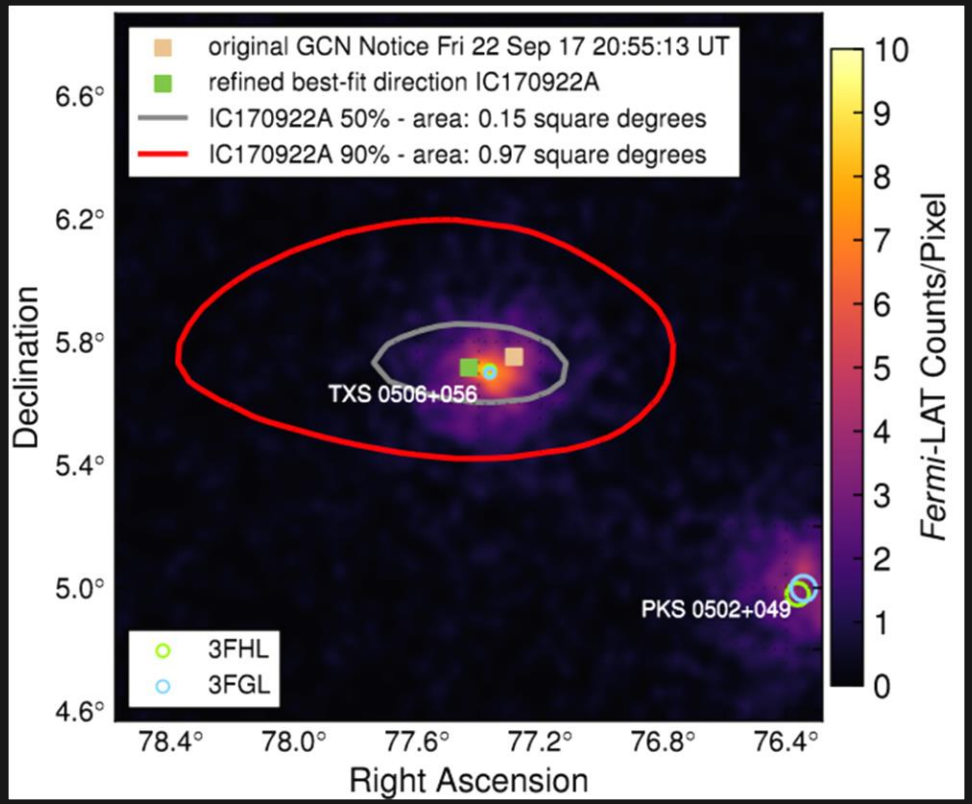
Neutrinos from AGN

Search for coincidences

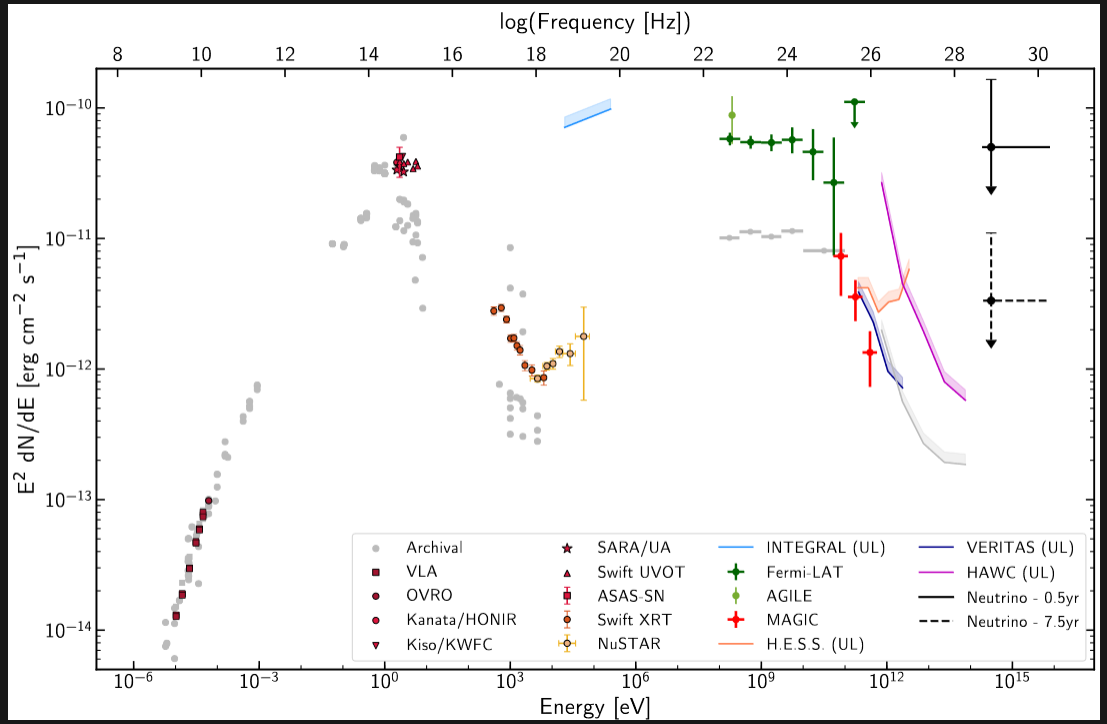
Here TXS 0506+056

Half-year long GeV flare

Association still only 3σ



TXS 0506+056


log(Frequency [Hz])
8
10
12
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16
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20
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26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr

Statistics

n=1 event measured

Need to know expectation value λ

Probability $P_\lambda(n) = \frac{\lambda^n}{n!}\exp(-\lambda)$

Need inversion $P_n(\lambda) = \frac{P_\lambda(n)P(\lambda)}{P(n)}$

P(n=1)=1

No prior knowledge on λ, hence P(λ) = const.

Probability distribution is an incomplete Gamma function

$P_{n=1}(>\lambda) = \int_\lambda^\infty ds\ \ s\exp(s)$

→ 2σ range for true value λ is [0.36 , 4.74]

Simple estimate λ=1

Flux scales inversely with activity time

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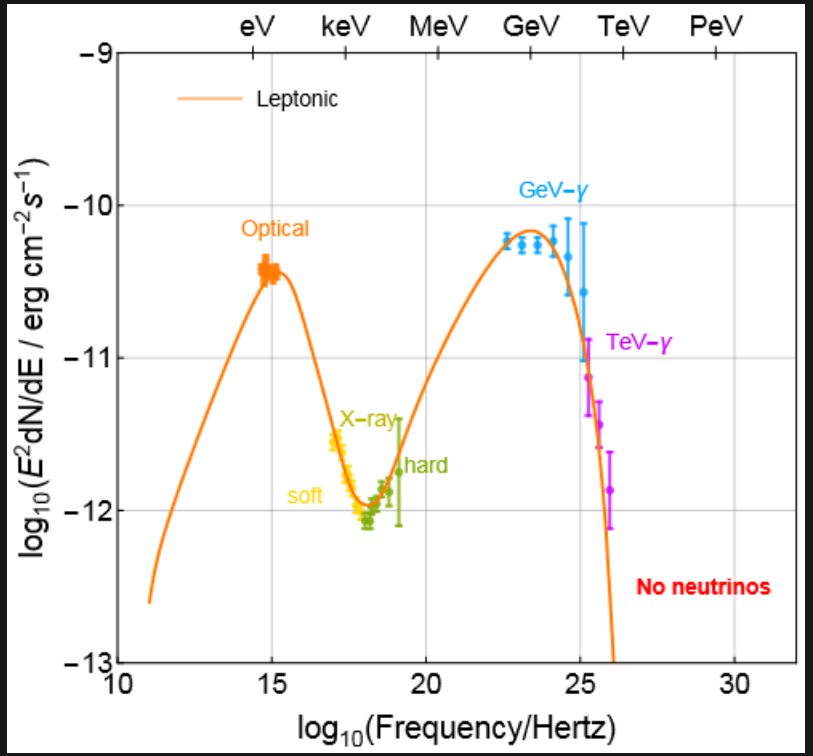
Can construct a one-zone Synchr./Compton model,

but not a fully hadronic model

Gao et al. 2019



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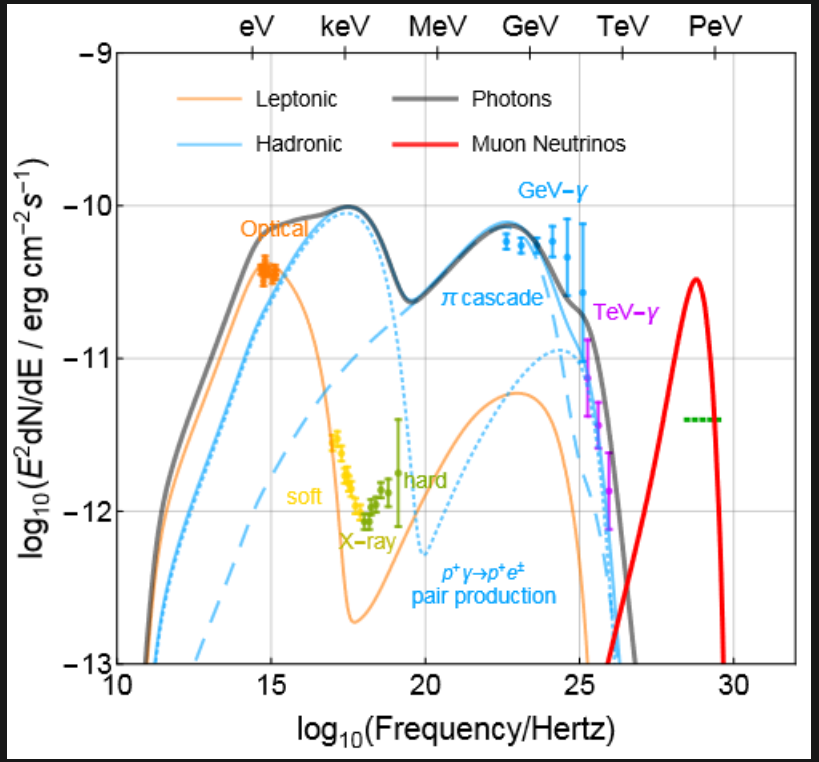
Purely hadronic model:

Radiation flux from pairs is prohibitively high

Explaining neutrino requires hybrid leptonic/hadronic model



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Observed neutrino energy $E_\nu = 170\ \mathrm{TeV}$

Doppler factor for energy $D = \frac{1}{\Gamma(1-\beta\cos\theta)} \approx 20 \quad \rightarrow \quad E_\nu^{jet} = 8.5\ \mathrm{TeV}$

Producing proton has 20 times that → Lorentzfactor $\gamma_p^{jet} \approx 2 \cdot 10^5$

Energy of interacting photons $\varepsilon_{target}^{jet} \approx 0.5\ \mathrm{keV}$ or $\varepsilon_{target} \approx 10\ \mathrm{keV}$

→ Hard X rays, near the minimum in SED

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Electrons from charged pions

- same energy as neutrinos
- Compton radiation is Klein-Nishina suppressed
- Synchrotron radiation MeV scale

Electrons from pair production

- Energy only 100 GeV or so
- Synchrotron radiation in X-ray band
- Compton radiation moderately suppressed

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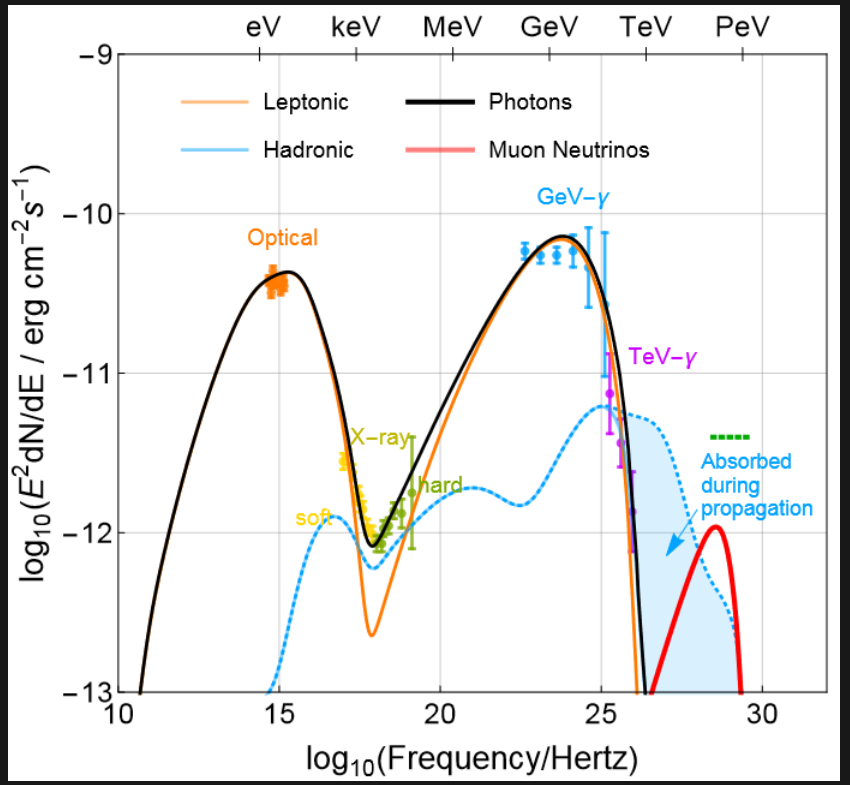
Lepto-hadronic scenario

X-rays constrain the model

Only low neutrino yield

$$\lambda_\nu \approx 0.1$$



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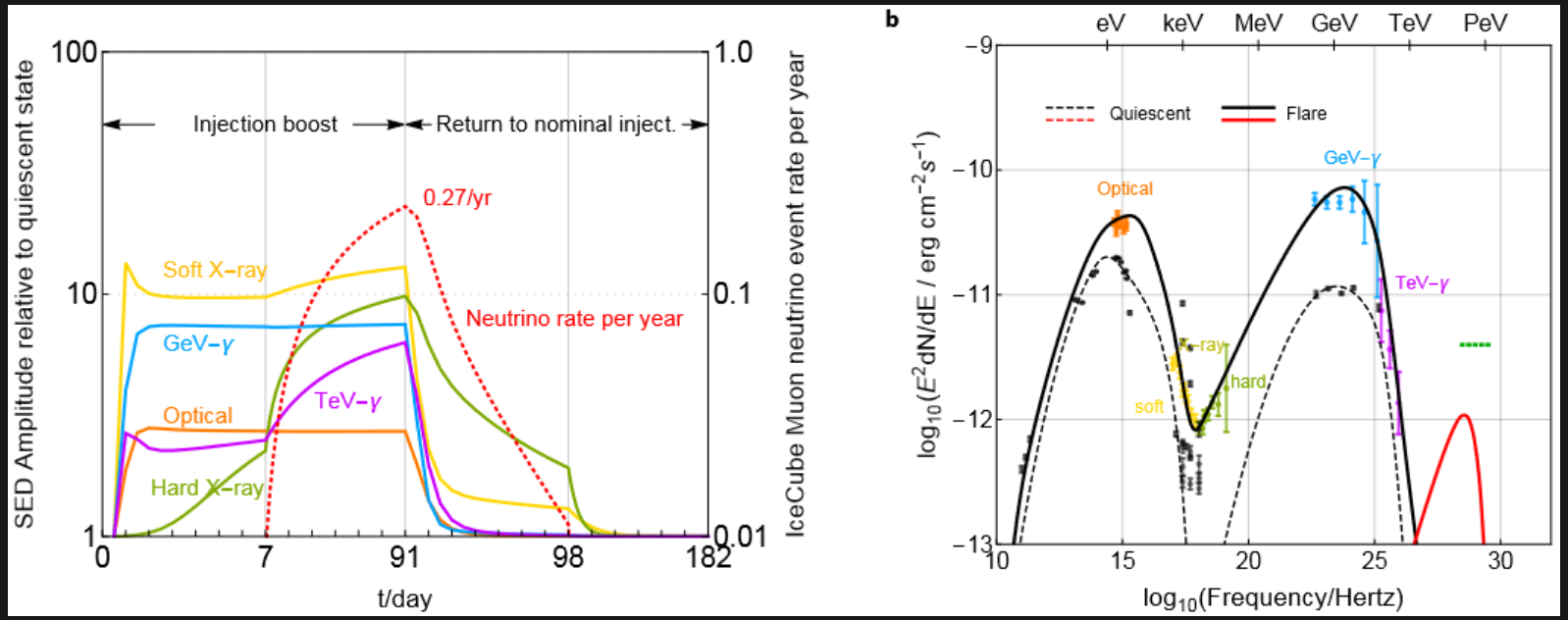
Variability for 180 days of enhanced activity



Issues of hadronic scenario

Low interaction rate of energetic ions

- **Most ions escape and do not radiate**
- **Radiative inefficiency increases the required ion source power**
- **Hugh pressure should lead to expansion**
- **Jet power exceeds Eddington limit**

External photons

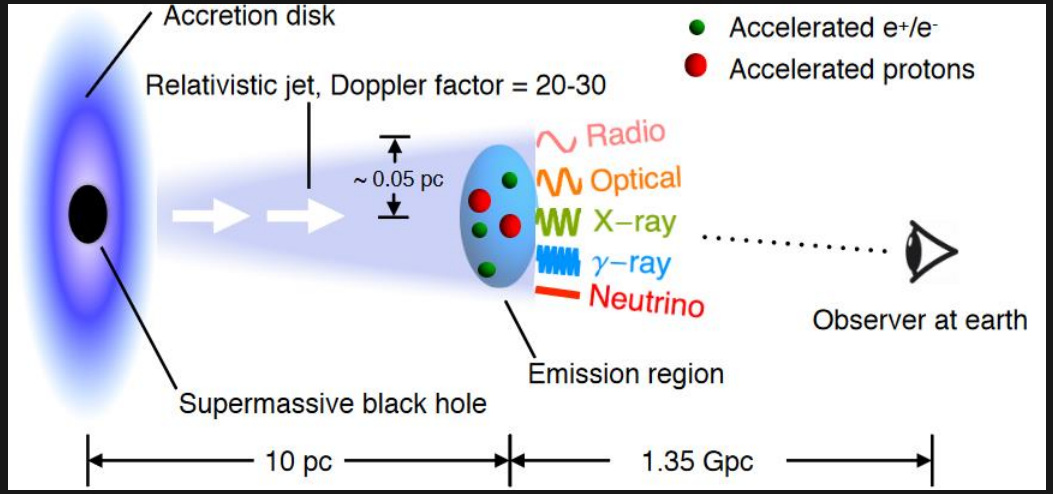
- **Spine-sheath models** (e.g., Tavecchio)
- **BLR / NLR photons** (e.g., Sahakyan)

External photons are Doppler-boosted in jet frame

Increases interaction rate and reduces power requirement

The problem is retardation

External photons



Problem: Pathlength is $2\,\Gamma^2\,ct > 100$ pc

Is the spine-sheath system really that long?

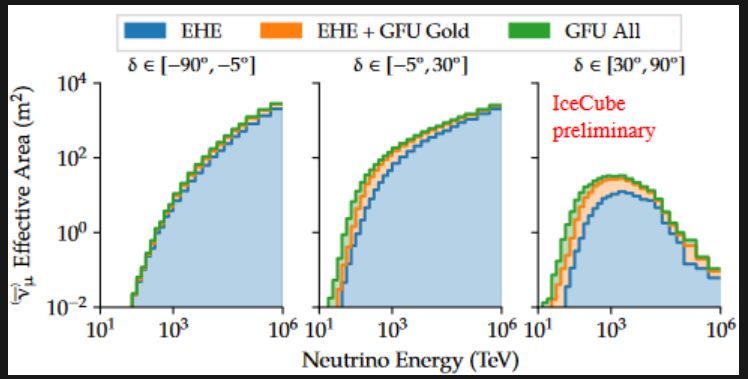
Maximum energy

Neutrino spectra are fairly peaked

The neutrino energy scales with the proton energy

Effective area increases as well

Blaufuss et al. (2019)



→ We should see highest-energy neutrinos

→ No evidence for link to UHECRs

Summary

Do AGN, etc., efficiently accelerate ions?

- Neutrinos are smoking gun
- Reported associations are theoretically challenging
- Tremenduous power requirements
- Site and process of acceleration unclear
- Link to ultra-high-energy cosmic rays is very tenuous