

Neutrino-Emitting Seyfert candidates in the VHE gamma-ray sky

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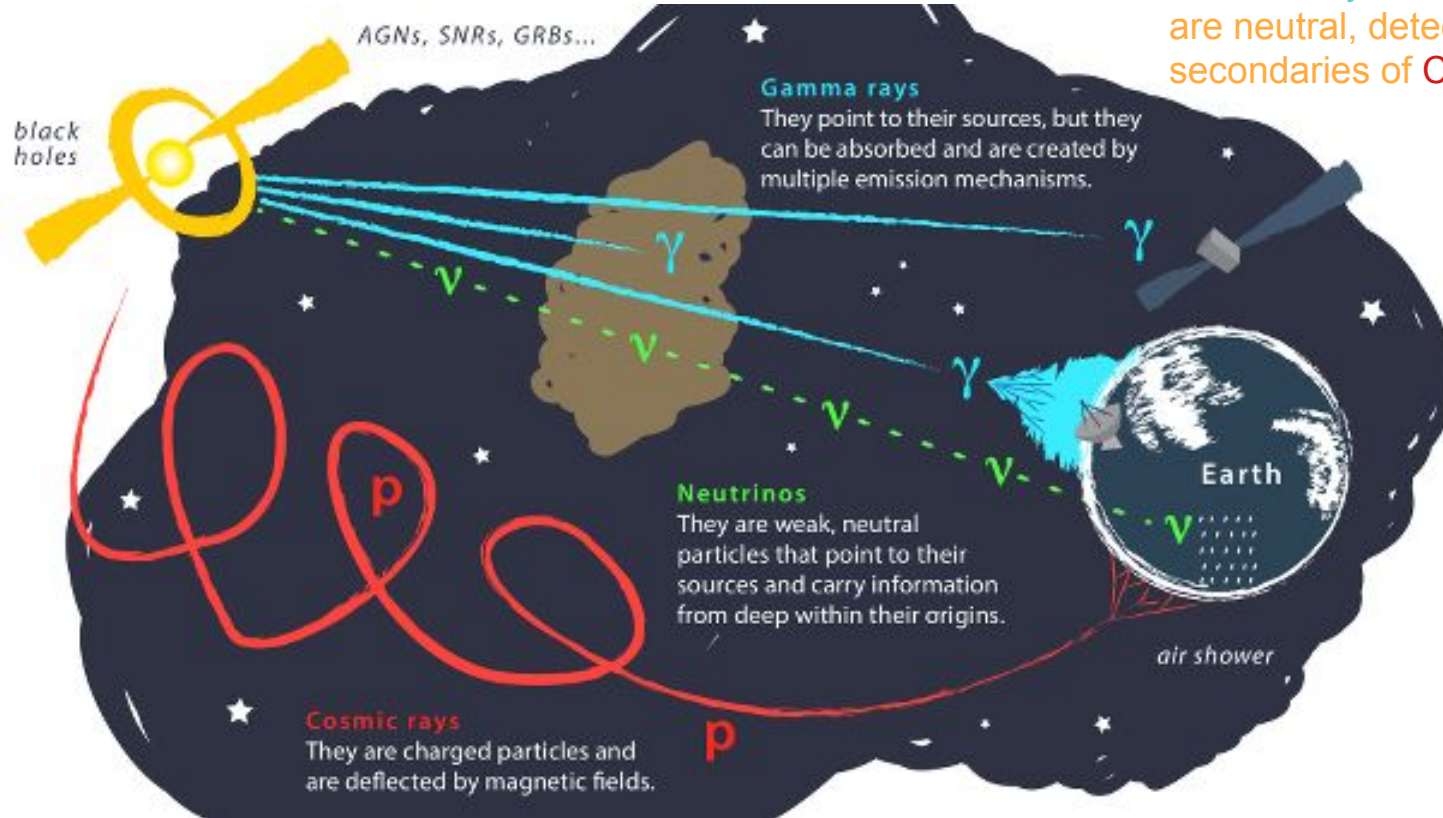
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For A. Lamastra, S. Mangano, F. G. Saturni, G. Peron and E. Peretti

Collaborations: MAGIC

Multi-messenger Astronomy

Gamma rays and neutrinos
are neutral, detectable
secondaries of Cosmic Rays



First hint of gamma obscured accelerators?

Comparable energy budgets of diffuse
Gamma, neutrino and cosmic rays (IceCube coll. 2021)

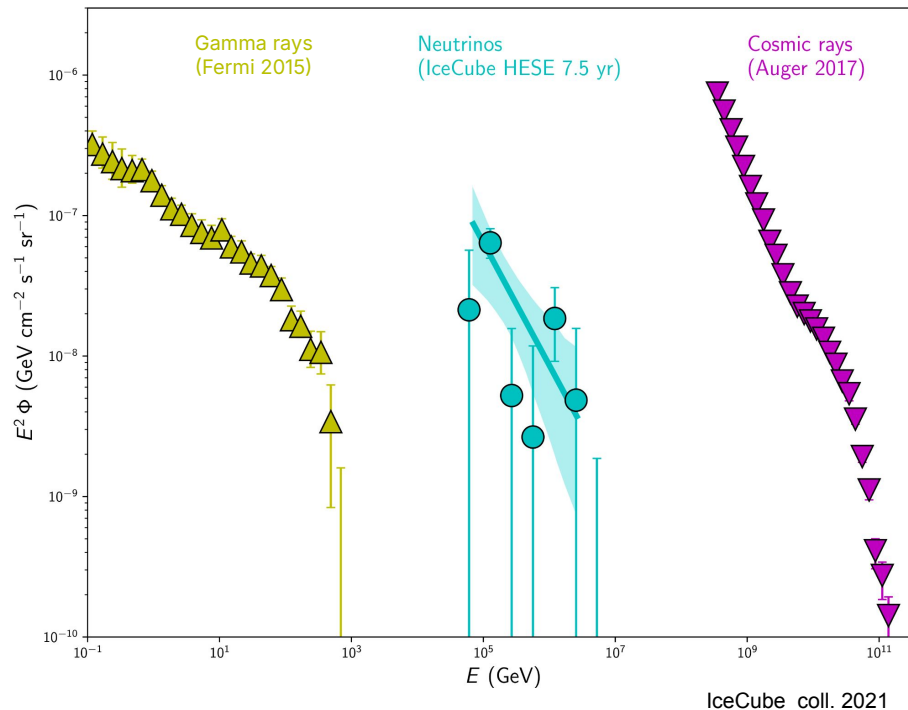
⇒ similar unresolved sources ?

Hadronic interactions produce gamma rays
and neutrinos at the comparable levels

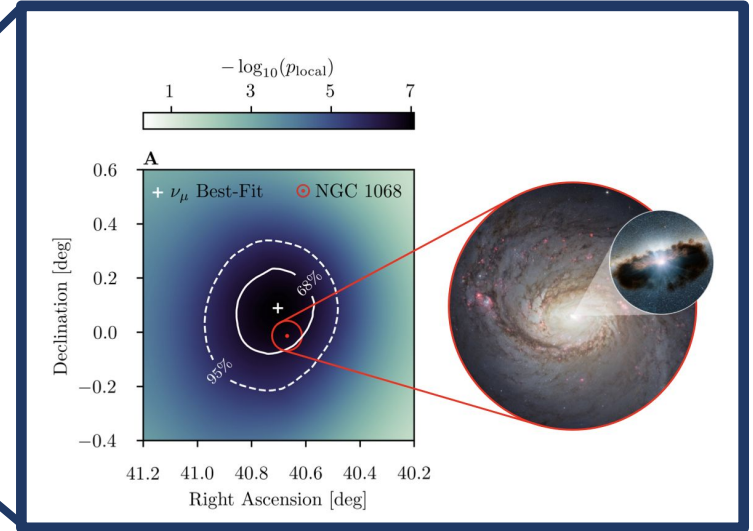
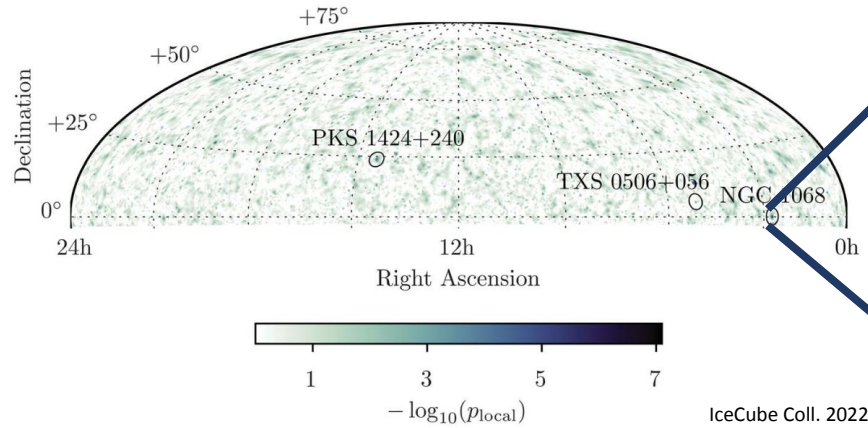
$$E_\nu \approx E_\gamma / 2$$

Gamma rays co-produced with neutrinos <
100 TeV overpredicts Fermi-LAT isotropic
gamma ray background (Murase+ 23, Murase et al. 2013; Aartsen
et al. 2015, 2020b; Fang et al. 2022)

⇒ Gamma obscured accelerators produce
neutrino flux < 100 TeV?



First Evidence of neutrino emission from NGC 1068



NGC 1068 global significance 4.2σ (IceCube coll. 2022)

TXS 0506+056 global significance 3.0σ

The Galactic plane global significance 4.5σ

4

At the NGC 1068 location:

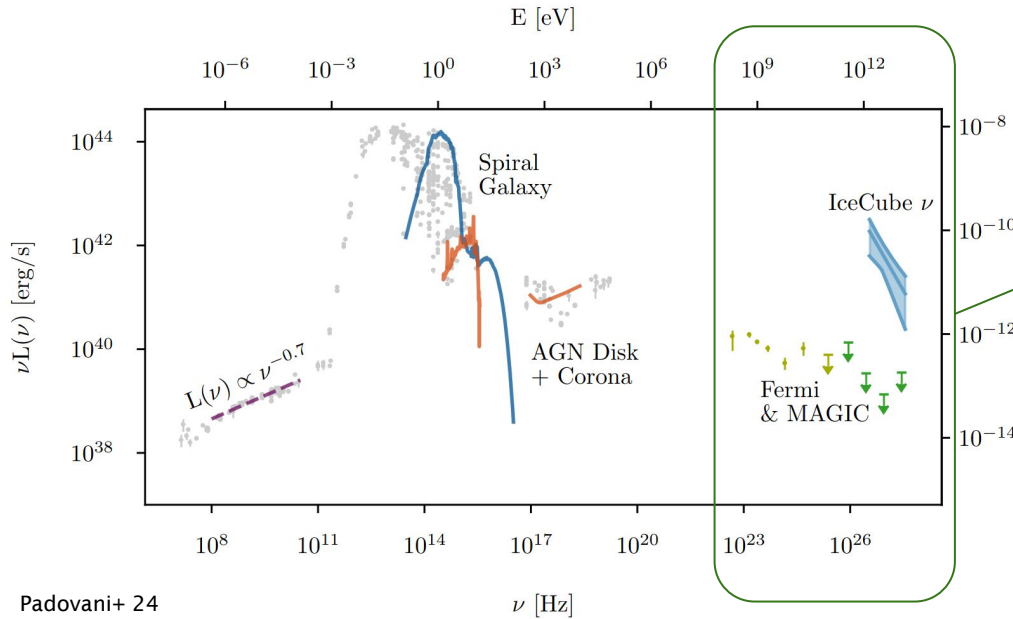
- Astrophysical neutrino events = 79 ± 22

- Energy: (1.5 - 15.0) TeV

- Flux: $\Phi_\nu = 5 \times 10^{-11} (E/\text{TeV})^{-3.2} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \Rightarrow$ All-flavour isotropic neutrino

luminosity $L_\nu = 1.3 \times 10^{42} \text{ erg s}^{-1}$

Multimessenger Spectral Energy Distribution of NGC 1068

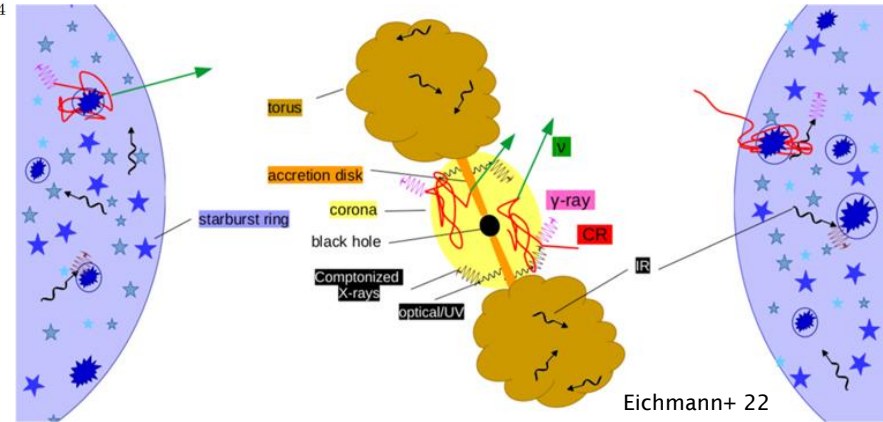


Padovani+ 24

Orders of magnitude difference in
VHE γ -rays and ν

⇒

Neutrinos produced at a site
opaque to VHE gamma rays



Eichmann+ 22

Current Multimessenger Synergies with neutrinos

Possible IceCube neutrino sources :

TXS 0506+05

PKS 1424+240 ...

Possible IceCube neutrino sources :

NGC 1068 (4.2σ)

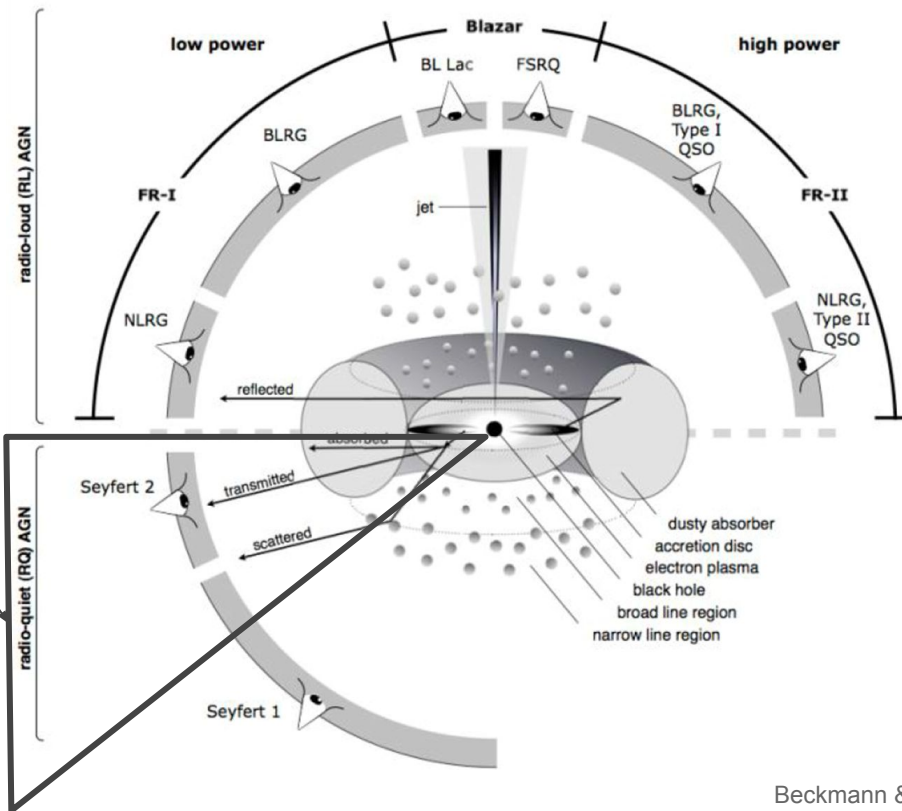
NGC 4151 (3σ)

CGCG 420-015 (3σ)

NGC 3079 (3σ)

NGC 7469, Circinus

...



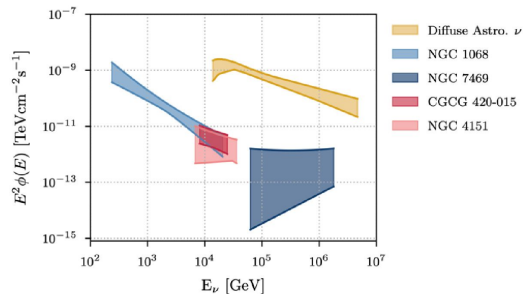
Several acceleration sites e.g. accretion disk, corona, winds, weak jets etc...

+Starburst regions for composites!

Beckmann & Schrader 12

Prototype Seyfert 2 NGC 1068 indicative of an emerging class of neutrino emitters or peculiar?

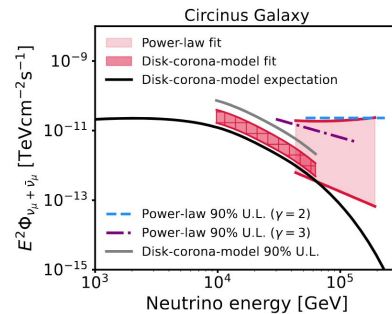
Most significant neutrino candidates: Seyferts



Northern hemisphere

Source Name	$\hat{n}_s$	$\hat{\gamma}$	TS	p_{local}
NGC 1068	102.2	3.4	27.1	2.2×10^{-7} (5.0 σ)
NGC 7469	5.5	1.9	15.5	9.8×10^{-5} (3.7 σ)
NGC 4151	27.6	2.7	10.8	1.1×10^{-3} (3.1 σ)
CGCG 420-015	35.3	2.7	8.4	3.6×10^{-3} (2.7 σ)
Cygnus A	3.4	1.6	7.4	6.5×10^{-3} (2.5 σ)
LEDA 166445	57.1	4.4	5.2	0.02 (2.1 σ)
NGC 4992	27.3	2.9	5.0	0.02 (2.0 σ)
NGC 1194	43.2	4.4	4.1	0.03 (1.8 σ)
Mrk 1498	39.9	3.6	3.7	0.04 (1.7 σ)
MCG+4-48-2	36.7	3.2	4.1	0.04 (1.7 σ)
NGC 3079	33.8	3.6	3.3	0.05 (1.7 σ)
Mrk 417	4.4	1.9	3.5	0.05 (1.6 σ)

IceCube 25



Southern hemisphere

Source	n_{exp}	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p$
Centaurus A	2.5	0.0	4.0	0.0
Circinus Galaxy	1.7	3.1	2.5	2.9
NGC 7582	0.8	1.7	4.0	1.3
ESO 138-1	0.6	1.9	3.6	1.2
NGC 4945	0.2	0.0	4.0	0.0
NGC 424	0.2	0.0	2.2	0.0
NGC 4593	0.2	0.6	2.9	0.4
MCG-5-23-16	0.1	1.0	1.7	1.0
NGC 3783	0.1	0.0	4.0	0.0
IC4329A	0.1	0.0	3.8	0.0
NGC 4507	0.1	0.0	3.8	0.0
NGC 5728	0.1	1.9	4.0	0.9
NGC 5643	0.1	0.0	4.0	0.0
NGC 3081	0.1	0.0	4.0	0.0

IceCube 26

Stacked analysis of 11 X-ray bright AGN (North) $\rightarrow$

$\sim 3 \sigma$

Stacked analysis of 13 X-ray bright AGN (South) $\rightarrow$

$\sim 3 \sigma$

Current Multimessenger Synergies with neutrinos

Possible IceCube neutrino sources :

TXS 0506+05

PKS 1424+240 ...

Possible IceCube neutrino sources :

NGC 1068 (4.2σ)

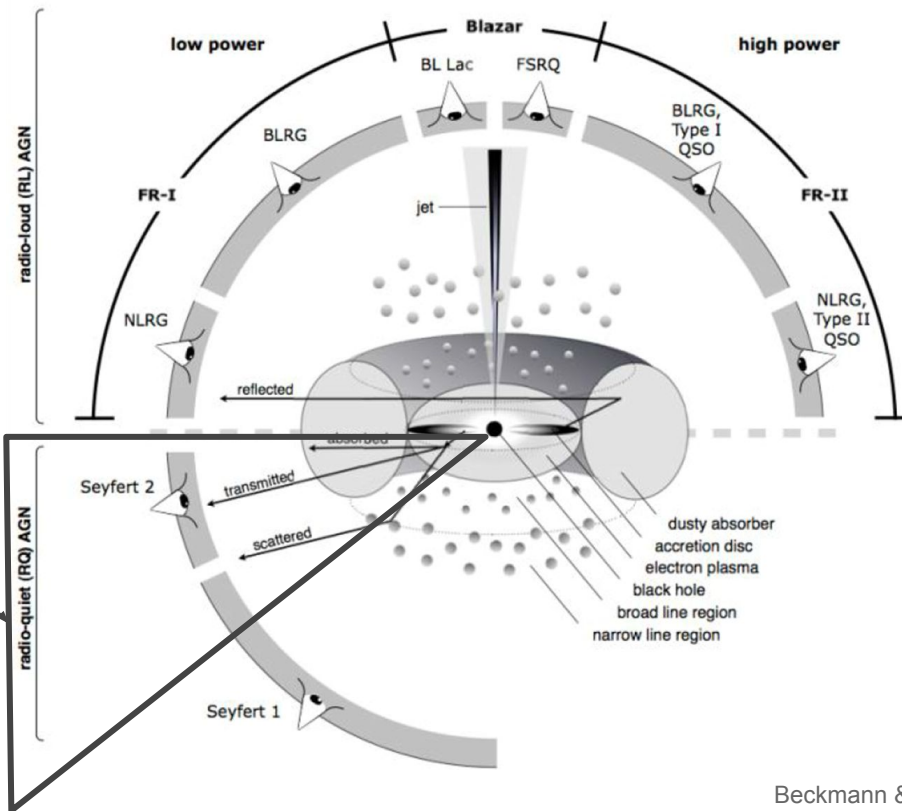
NGC 4151 (3σ)

CGCG 420-015 (3σ)

NGC 3079 (3σ)

NGC 7469, Circinus

...



**Deepest ULs
already available
for NGC 1068 with
MAGIC**

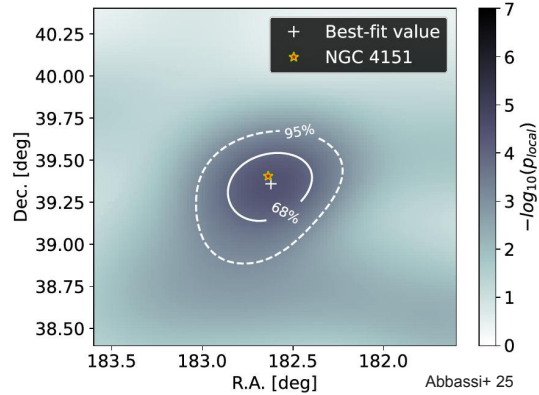
→ We now move on
NGC 4151- the
second most
probable neutrino
Seyfert consistently
in the list

Beckmann & Schrader 12

Prototype Seyfert 2 NGC 1068 indicative of an emerging class of neutrino emitters or peculiar?

NGC 4151

NGC 4151



NGC 4151

Abbasi+ 25:

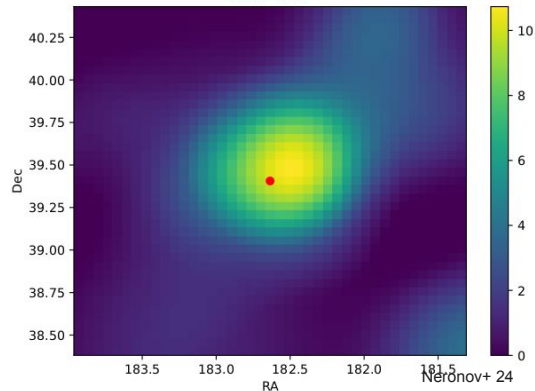
Source probability: $\sim 2.9 \sigma$

Neutrinos: 50

Energy: (4.3 – 65.2) TeV

Flux $\phi_\nu = 1.51 \times 10^{-11} (E_\nu/\text{TeV})^{-2.83}$
 $\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$

NGC 4151



NGC 4151

Neronov+ 24:

Source probability: $\sim 2.9 \sigma$

Energy: (0.3 - 100.0) TeV

Flux $\phi_\nu = 1 \times 10^{-11} (E_\nu/\text{TeV})^{-3.0}$
 $\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$



RA|DEC:12h 10m 32.6s | +39° 24' 21"

Seyfert 1 @ 15.8 Mpc

Fermi source assoc: 4FGL J1210.3+3928(6 σ)
Blazar@ z= 0.6

Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC)

Two telescope system @ La Palma, Canary Islands

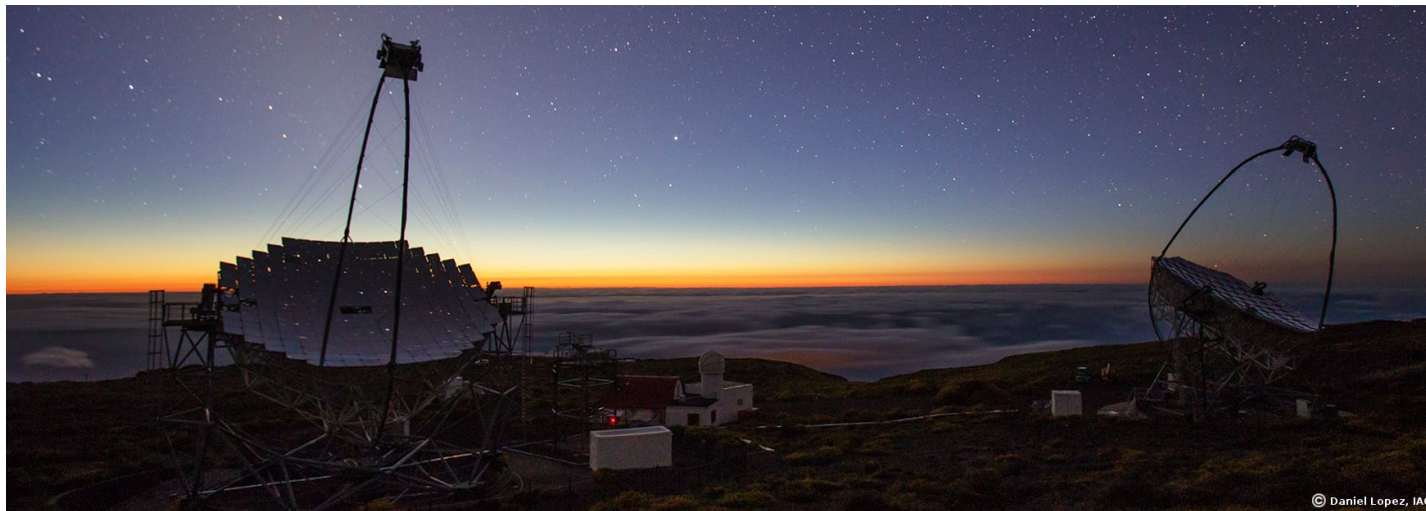
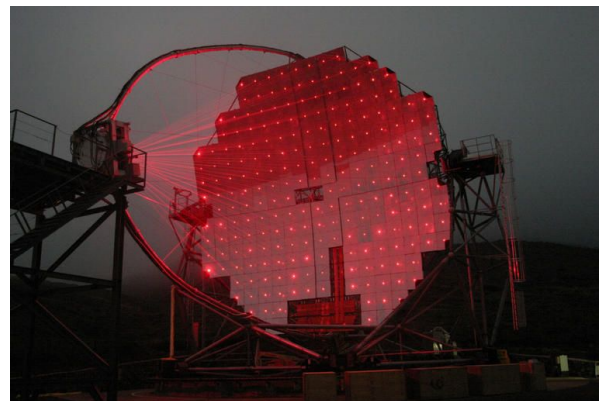
Energy Threshold > 30 GeV

Diameter : 17 m

FOV: 3.5°

Angular resolution: 0.06° @ 300 GeV

Sensitivity (5σ in 50 h) 0.8% CU flux for $E > 250$ GeV



MAGIC observations of NGC 4151

RA DEC:12 10 32.6 +39 24 21

Seyfert 1 / 1.5 @ 15.8 Mpc

Hours of observation by MAGIC: 29 h

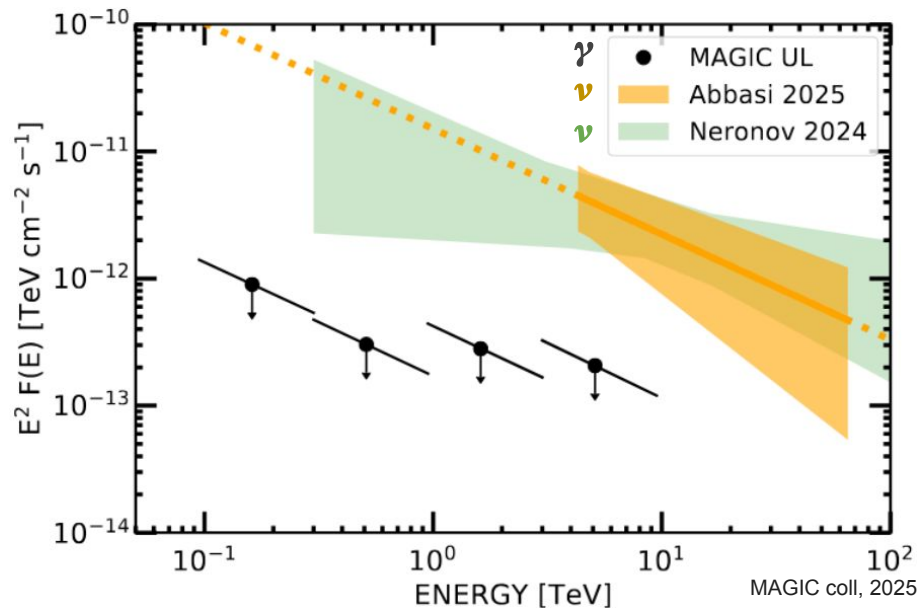
Conditions: Dark (25.6 h) + weak moon(3.4 h)

Assumed spectral model:

Power law with spectral index 2.83

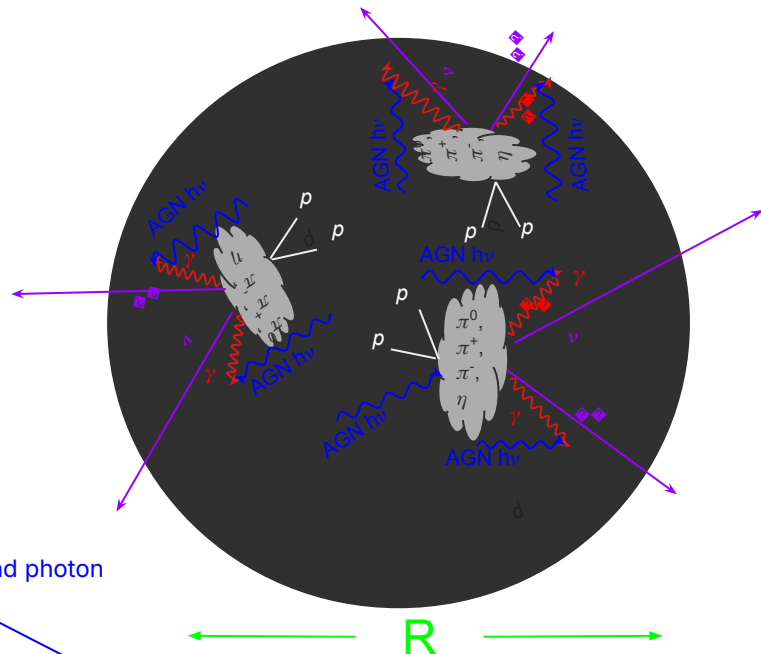
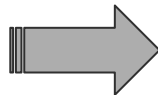
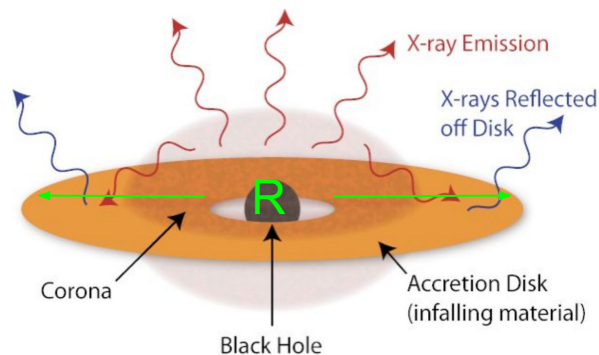
Non detection indicative of gamma-ray absorption

⇒ Another obscured accelerator?



Exploiting the gamma - neutrino connection

credit: D. Wilkins



Optical depth

$$\tau_{\gamma\gamma}(E_\gamma) = R \int_{\epsilon_{\min}}^{\infty} d\epsilon n_{\text{ph}}(\epsilon) \sigma_{\gamma\gamma}(E_\gamma, \epsilon)$$

$\tau_{\gamma\gamma}(E_\gamma)$: gamma ray energy
 R : emission region radius
 $\epsilon_{\min} = m_e^2 c^4 / E_\gamma$: Pair production threshold energy
 $\sigma_{\gamma\gamma}(E_\gamma, \epsilon)$: Pair production cross section
Aharonian+ 2009)

Exploiting the gamma - neutrino connection

gamma ray energy

emission
region radius

AGN background photon
density at ϵ

$$\tau_{\gamma\gamma}(E_\gamma) = R \int_{\epsilon_{\min}}^{\infty} d\epsilon n_{\text{ph}}(\epsilon) \sigma_{\gamma\gamma}(E_\gamma, \epsilon)$$

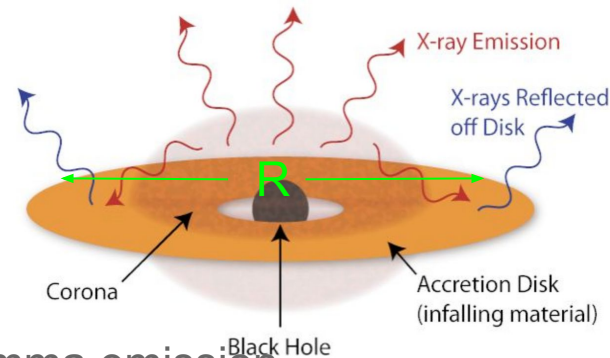
Pair
production
cross section

For a homogeneous region of emission

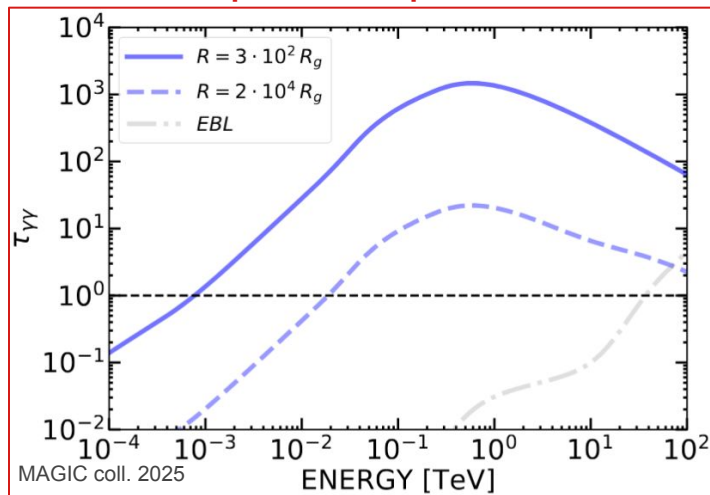
$$n_{\text{ph}}(\epsilon) \propto R^{-2}$$

$$\Rightarrow \tau_{\gamma\gamma} \propto 1/R$$

credit: D. Wilkins



Optical depth



Intrinsic Multipion gamma emission

(Murase+ 16)

$$E_\nu \approx E_\gamma / 2$$

pp interactions (K=2)
p γ interactions (K=1)

$$E_\gamma^2 Q_\gamma(E_\gamma) \approx \frac{4}{3K} E_\nu^2 Q_\nu(E_\nu)$$

production rate of
 γ -rays

production rate of
all-flavor ν



Constraints on emission region of NGC 4151

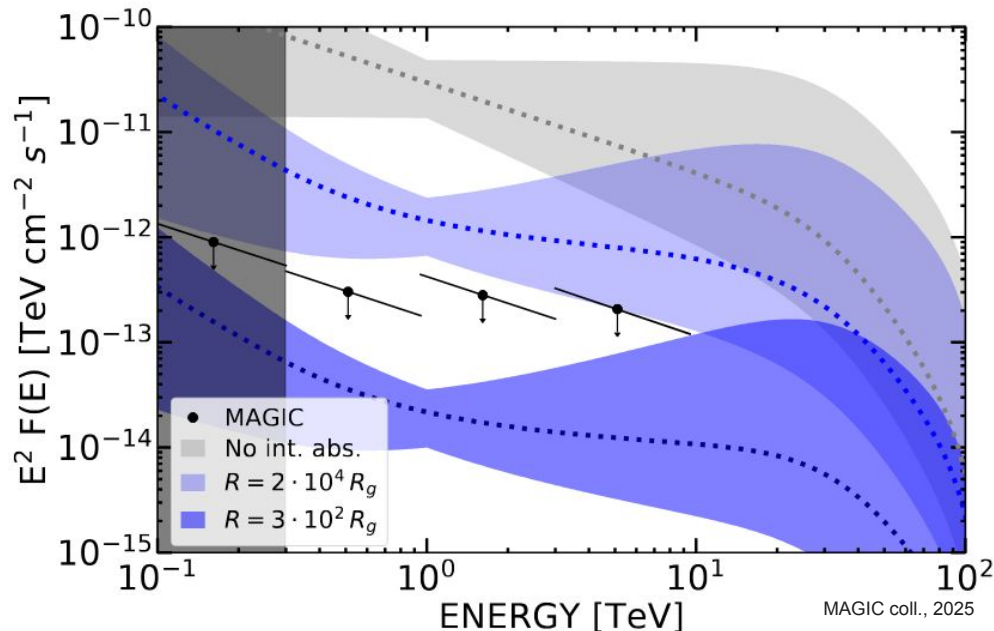
$$\tau_{\gamma\gamma} \propto 1/R$$

$$\Rightarrow R < 10^4 R_g$$

$\Rightarrow$ Site close to the central engine

Sites of acceleration for this class based on NGC 1068

$\rightarrow$ AGN disk-corona? Dense radiation field that absorb gamma rays (Ajello+ 23, Eichmann+ 22, Murase+ 23, Fiorillo +24, Fiorillo +25)



The dotted lines are derived using flux normalization and spectral index 2.83 values from Abbasi+ 25, and the error band is calculated from their respective uncertainties

Summary

Second probable neutrino source, NGC 4151, probed with MAGIC after NGC 1068

Non-detection after observation with MAGIC for 29 h $\Rightarrow$ First ULs! $\Rightarrow$ Indication of another gamma-ray obscured candidate neutrino source!

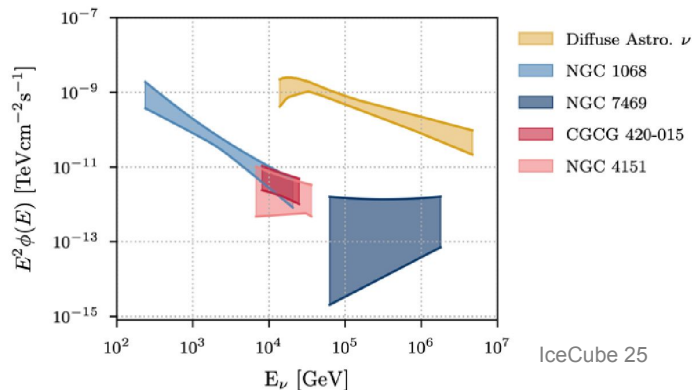
Using simple opacity arguments, NGC 4151 emission region constrained to $10^4 R_g \Rightarrow$ Regions close to central engine such as disk-corona, failed winds, ...

Confirmation of NGC 4151 as a source by current and new generation of neutrino telescopes needed!

Two types of seyferts with similar characteristic in terms of gamma ray opacity $\Rightarrow$ Hidden neutrino source class possibly dominating the diffuse neutrino background?

Now an A&A publication!
<https://doi.org/10.1051/0004-6361/202554723>

Characterizing Seyferts as hidden accelerators?



Optical obscuration $\nRightarrow$ Gamma ray obscuration

+

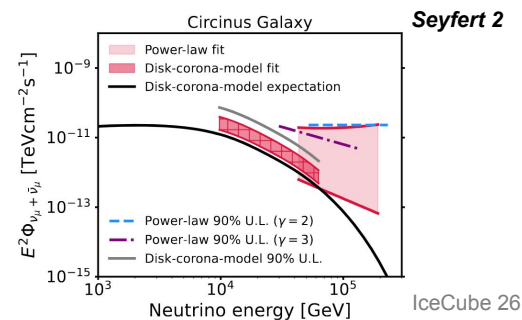
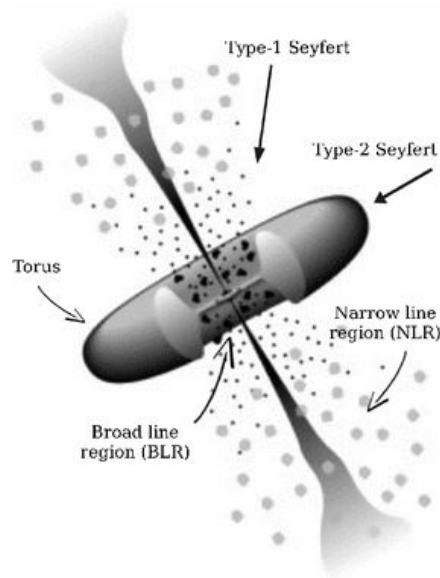
More Seyferts with different optical obscuration

$\Rightarrow$

More opportunities to probe how different environments affect gamma emission and/or

Obtain size of emission region?

Seyfert 2
Seyfert 1
Seyfert 2
Seyfert 1/1.5

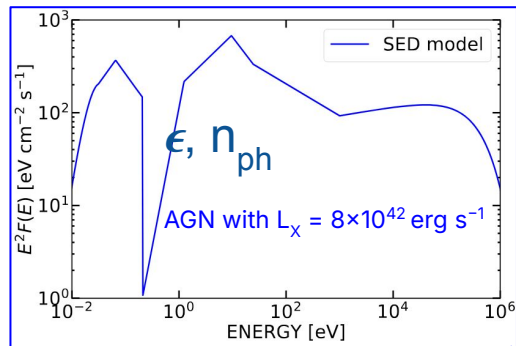


Seyferts with different neutrino and gamma spectra

$\Rightarrow$

Different underlying acceleration mechanisms?

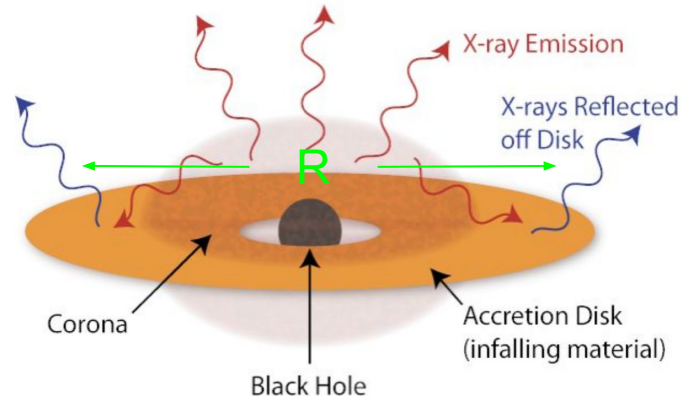
BACK UP: Exploiting the gamma - neutrino connection



Pair production cross section

$$\sigma_{\gamma\gamma}(E_\gamma, \epsilon) = \frac{3\sigma_T}{2s^2} \left[\left(s + \frac{1}{2} \ln(s) - \frac{1}{6} + \frac{1}{2s} \right) \ln(\sqrt{s} + \sqrt{s-1}) - \left(s + \frac{4}{9} - \frac{1}{9s} \right) \left(\sqrt{1 - \frac{1}{s}} \right) \right], s = \epsilon E_\gamma / (m_e^2 c^4)$$

credit: D. Wilkins



gamma ray energy

emission region radius

AGN background photon density at ϵ

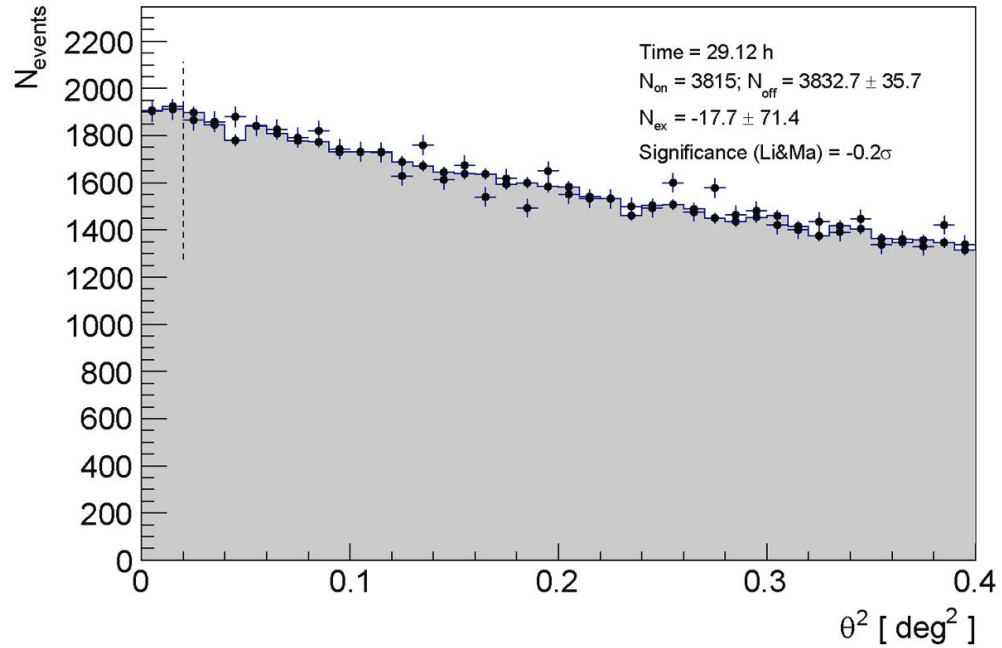
Optical depth

$$\tau_{\gamma\gamma}(E_\gamma) = R \int_{\epsilon_{\min}}^{\infty} d\epsilon n_{ph}(\epsilon) \sigma_{\gamma\gamma}(E_\gamma, \epsilon)$$

$\epsilon_{\min} = m_e^2 c^4 / E_\gamma$

Aharonian+ 2009)

BACK UP: MAGIC non detection



Back up: NGC 4151

RA,DEC:12 10 32.6 +39 24 21

Seyfert 1 @ 15.8 Mpc

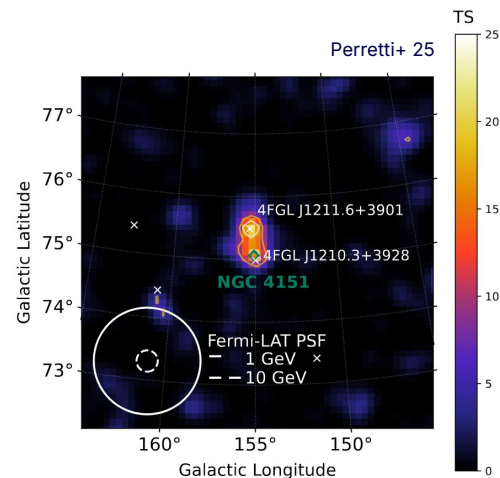
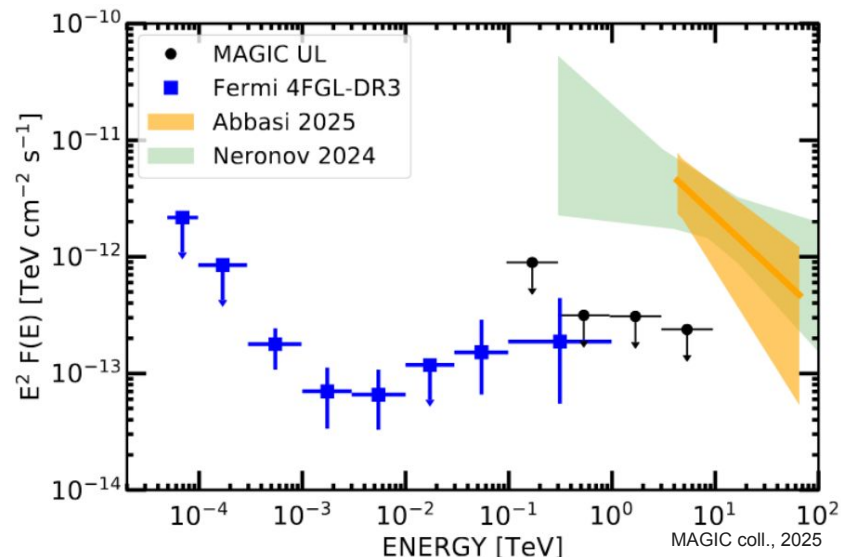
Fermi source: 4FGL J1210.3+3928(6 sig)

Blazar@ z= 0.6

Offset 4.747 arcmin to NGC 4151

Energy range under investigation here: 0.03- 1 TeV

Blazars too far to be associated with > 300 GeV photons(In Peretti+25 0.1-1 TeV flux point turns to a UL)



Back up: IceCube 2026 list

source	σ_{post}	n_s	flux [$\times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$]	data sample
(Abbasi et al. 2022)				
NGC 1068	4.2σ	—	$5.0^{+1.5}_{-1.5}$ (best-fit)	May 2011 to May 2020 (NT)
(Neronov et al. 2024)				
NGC 3079	$\sim 3 \sigma$	—	$3.2^{+4.0}_{-2.5}$ (best-fit)	Apr 2008 to Jul 2018 (PS)
(Abbasi et al. 2025c)				
NGC 4151	2.9σ	—	$1.51^{+0.99}_{-0.81}$ (UL)	Apr 2008 to May 2020 (PS)
(Abbasi et al. 2025a)				
CGCG 420-015	2.3σ	46.4 (UL)	—	May 2011 to Feb 2022 (NT)
binomial test	2.7σ	—	—	
(Abbasi et al. 2025d)				
binomial test	3.3σ	—	—	May 2011 to Nov 2023 (NT)
(this work)				
Circinus Galaxy	1.8σ	—	63.8 (UL)	May 2011 to Jan 2022 (ST)
stacking w/o CenA	3.0σ	14.3 (best-fit)	—	