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

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Collaborations: MAGIC

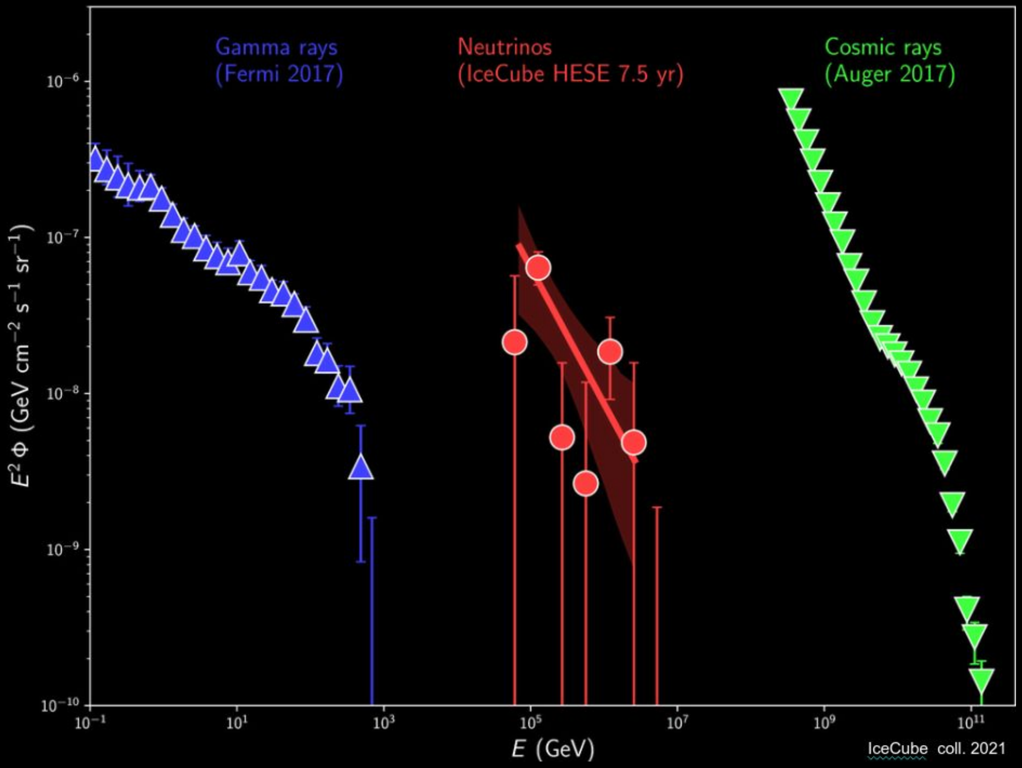
First hint of gamma obscured accelerators?

Comparable energy budgets of diffuse Gamma, neutrino and cosmic rays(IceCube coll. 2021)
⇒ similar unresolved sources > 100 TeV-PeV range?

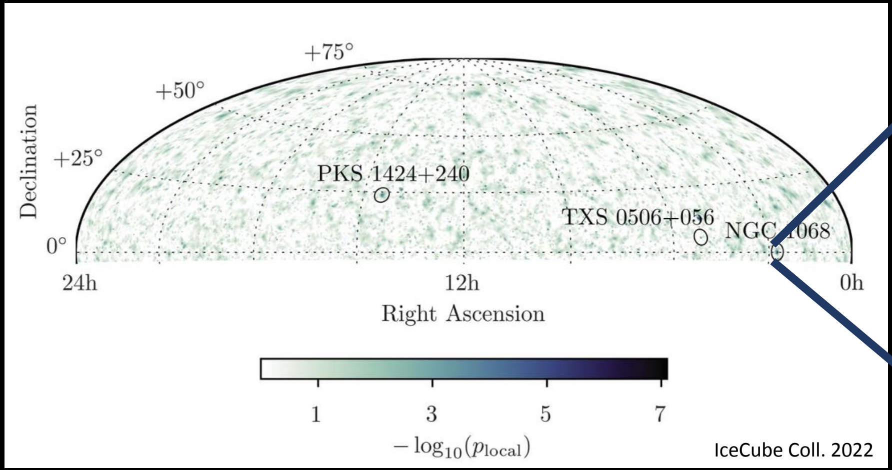
Hadronic interactions produce gamma rays and neutrinos at the comparable levels
$E_\nu \approx E_\gamma/2$

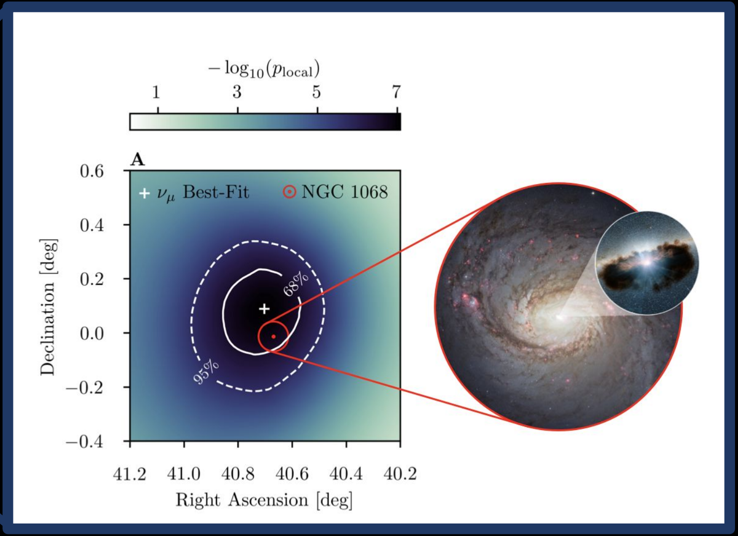
Gamma rays co-produced with neutrinos < 100 TeV overpredicts Fermi-LAT isotropic gamma ray background(Murase+ 23,Murase et al. 2013; Aartsen et al. 2015, 2020b; Fang et al. 2022)

⇒Gamma obscured accelerators produce neutrino flux < 100 TeV?



Evidence of neutrino emission from NGC 1068



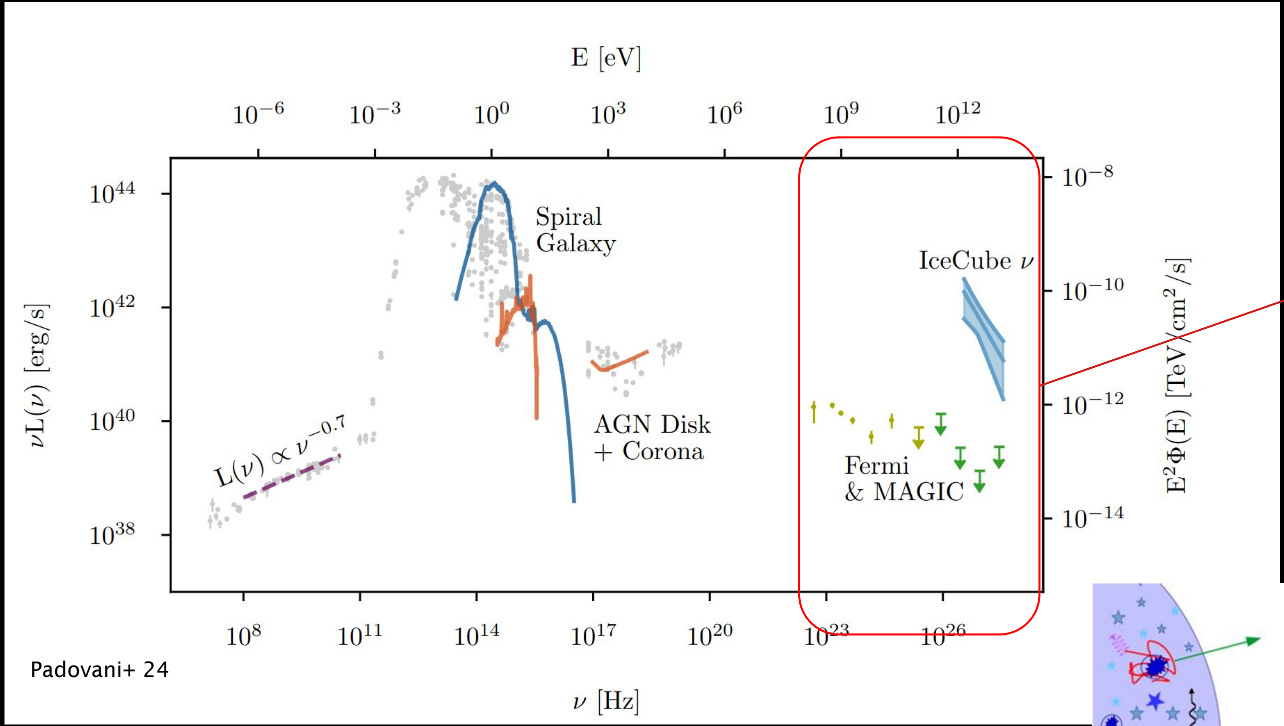


NGC 1068 global significance 4.2 σ (IceCube coll. 2022)
TXS 0506+056 global significance 3.0 σ
The Galactic plane global significance 4.5 σ

IceCube can't resolve the region of the neutrino production

At the NGC 1068 location:
- Astrophysical neutrino events = 79^{+22}_{-20}
- Energy: (1.5 - 15.0) TeV
- Flux: $\phi_\nu = 5 \times 10^{-11} (E_\nu/\mathrm{TeV})^{-3.2}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ => All-flavour isotropic neutrino luminosity $L_\nu = 1.3 \times 10^{42}\ \mathrm{erg\ s}^{-1}$

Multimessenger Spectral Energy Distribution of NGC 1068

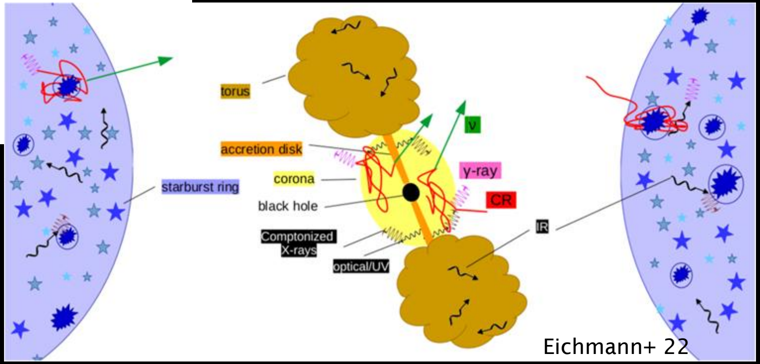


Padovani+ 24

Orders of magnitude difference in VHE γ-rays and ν

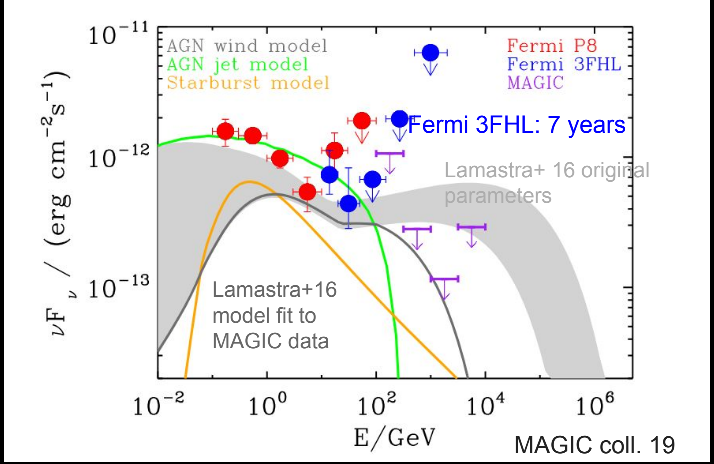
$\Rightarrow$

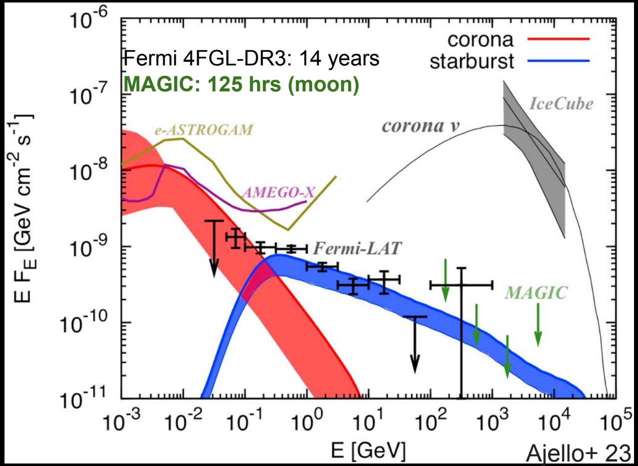
Neutrinos produced at a site opaque to VHE gamma rays



Eichmann+ 22

Gamma-ray investigations of NGC 1068





Most constraining ULs in VHE γ-rays: MAGIC+ 2019

MAGIC: 125 hrs(moon) from Jan 2016 to Jan 2019;

Fermi 4FGL-DR3: 14 yrs from 2008 - 2022

Constrained models of gamma ray production like the wind models

Neutrinos from Coronal regions(Eichmann+22,Ajello+23), Failed wind(Inoue+23)

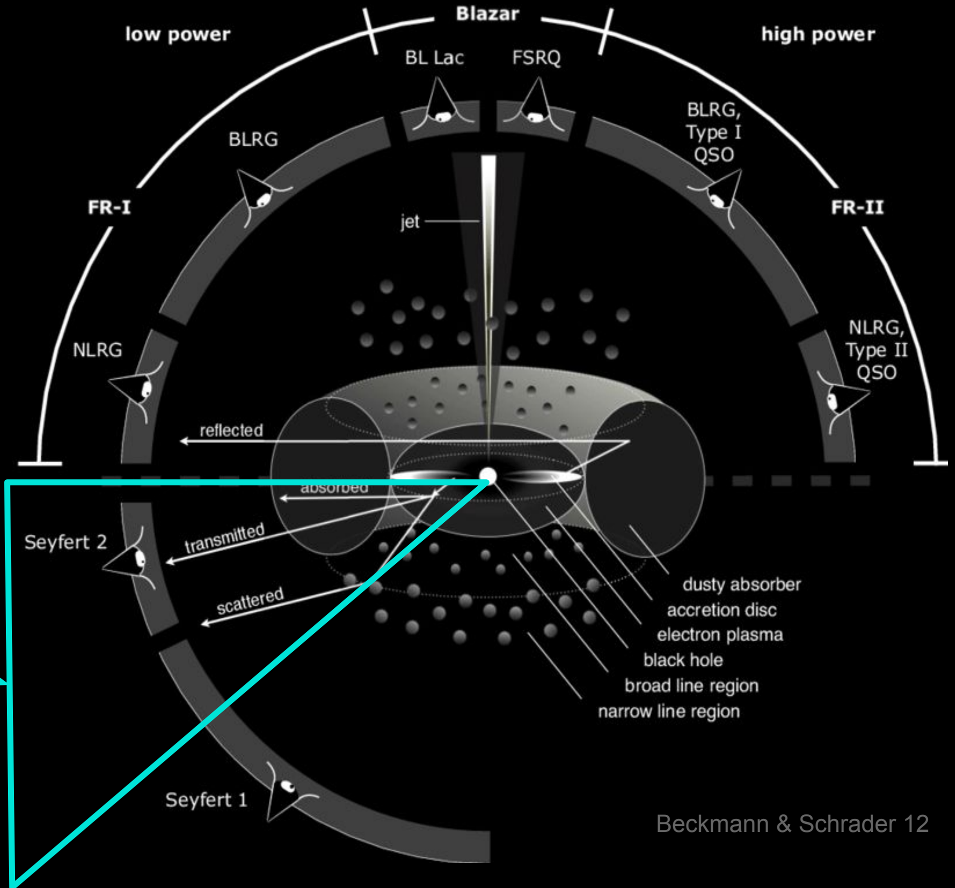
Gamma-rays primarily attributed to starburst activity

Need for improvement in ~10 GeV – TeV energy range to constrain models ⇒ Perfect job for the newest generation of telescopes: CTAO LST

Current Multimessenger Synergies with neutrinos

Possible IceCube neutrino sources :
TXS 0506+05
PKS 1424+240

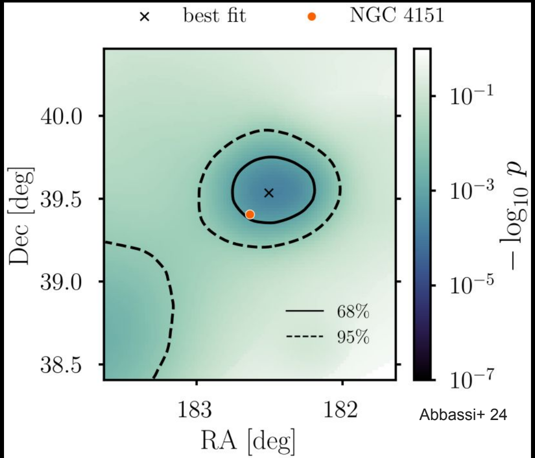
Possible IceCube neutrino sources :
NGC 1068 (4.2 σ)
NGC 4151 (3 σ)
CGCG 420-015 (3 σ)
NGC 3079 (3 σ)



Beckmann & Schrader 12

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

Seyferts as possible neutrino emitting sources



NGC 4151

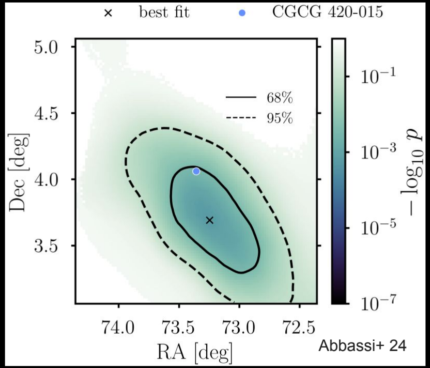
Abbasi+24:

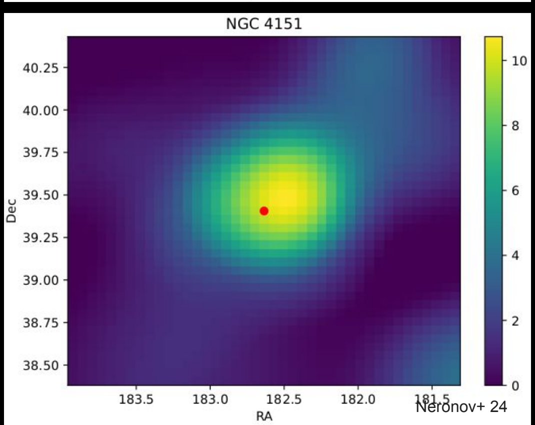
Source probability: ~ 3.2 σ
Neutrinos: 30
Energy: (7 - 300) TeV
Flux ϕ_ν=1 x 10^{-11} $(E_\nu/\mathrm{TeV})^{-2.7}$ TeV^{-1} cm^{-2} s^{-1}

CGCG 420-015

Abbasi+24:

Source probability: ~ 2.7 σ
Neutrinos: 35
Energy: (8 - 200) TeV
Flux ϕ_ν=1.2 x 10^{-11} $(E_\nu/\mathrm{TeV})^{-2.8}$ TeV^{-1} cm^{-2} s^{-1}





NGC 4151

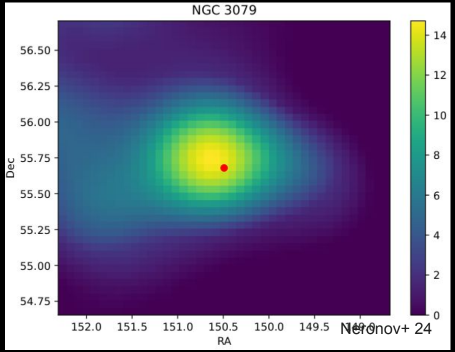
Neronov +24:

Source probability: ~ 2.9 σ
Neutrinos:
Energy: (0.3 - 100.0) TeV
Flux ϕ_ν=1 x 10^{-11} $(E_\nu/\mathrm{TeV})^{-3.0}$ TeV^{-1} cm^{-2} s^{-1}

NGC 3079

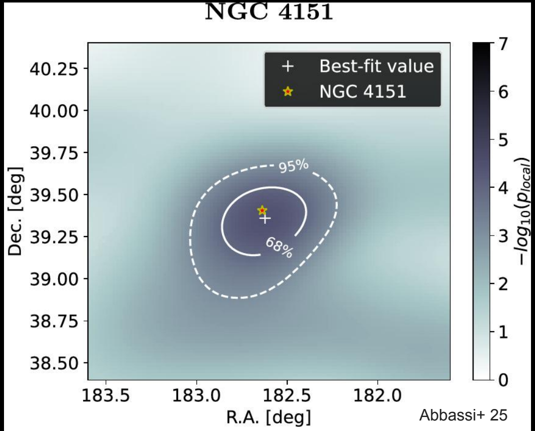
Neronov +24:

Source probability: ~ 2.9 σ
neutrinos:
Energy: (0.3 - 100.0) TeV
Flux ϕ_ν=0.8 x 10^{-11} $(E_\nu/\mathrm{TeV})^{-3.0}$ TeV^{-1} cm^{-2} s^{-1}



Nernov+ 24

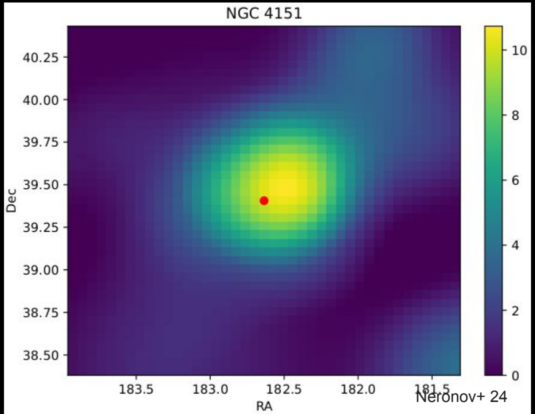
NGC 4151: Second most probable neutrino emitting Seyfert



NGC 4151
Abbasi+ 25:

Source probability: ~ 2.9 σ
Neutrinos: 50
Energy: (4.3 – 65.2) TeV
Flux $\phi_\nu = 1.51 \times 10^{-11} (E_\nu/\mathrm{TeV})^{-2.83}$ $\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

See also Abbasi+ 24



NGC 4151
Neronov+ 24:

Source probability: ~ 2.9 σ
Neutrinos:
Energy: (0.3 - 100.0) TeV
Flux $\phi_\nu = 1 \times 10^{-11} (E_\nu/\mathrm{TeV})^{-3.0}$ $\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Neutrino hotspot correlation from two independent searches:

A second possible source!!!

MAGIC observations of NGC 4151

RA DEC:12 10 32.6 +39 24 21

Seyfert 1 / 1.5 @ 15.8 Mpc

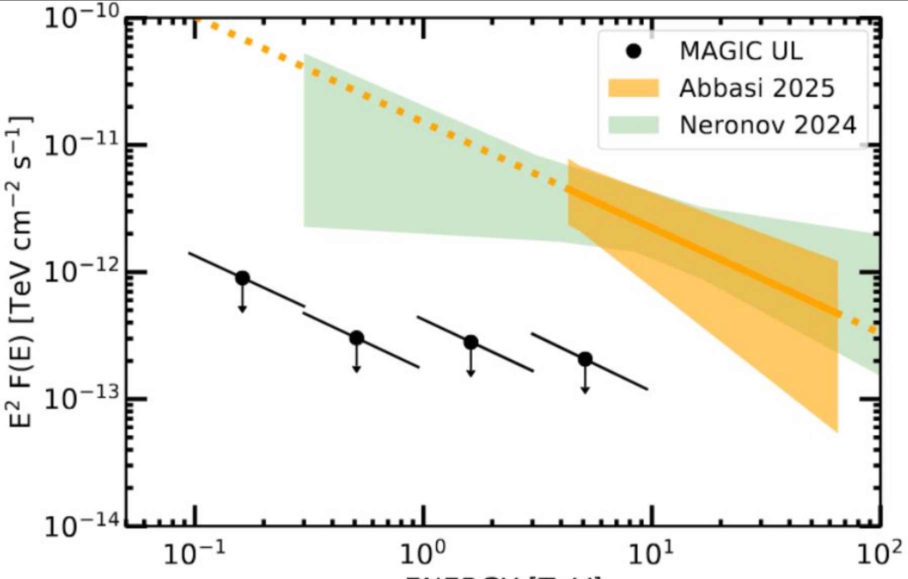
Hours of observation by MAGIC: 29 h

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

Assumed spectral model:
Power law with spectral index 2.83

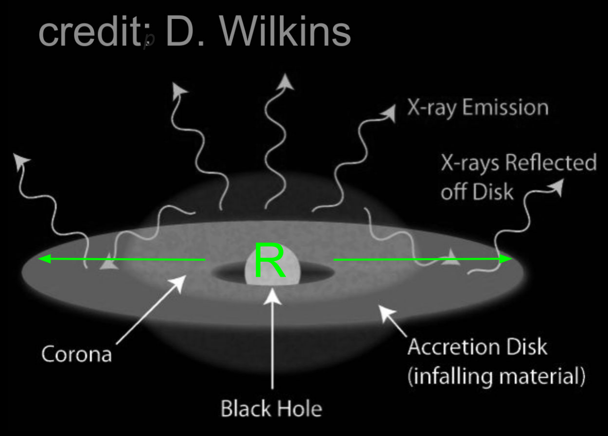
Non detection indicative of gamma-ray absorption

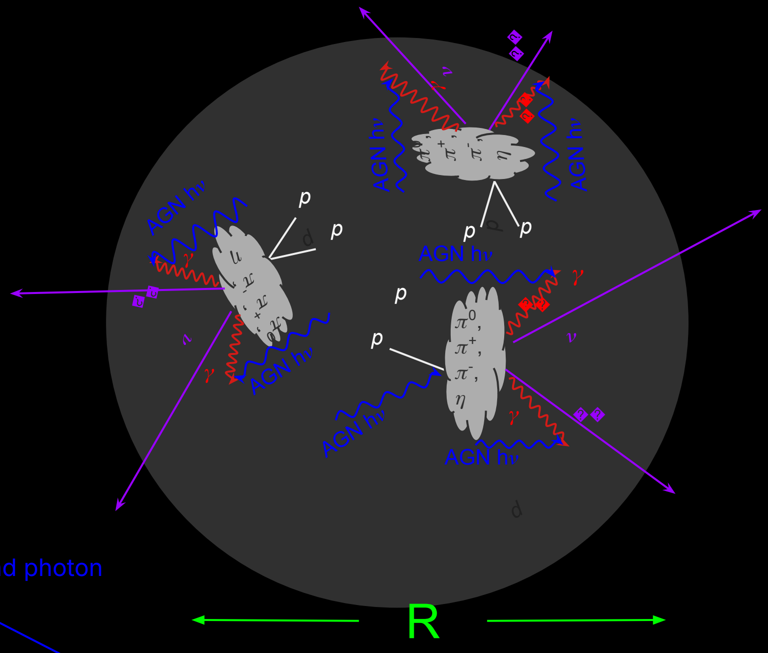
⇒ Another obscured accelerator?



MAGIC coll. A&A, accepted

Exploiting the gamma - neutrino connection





AGN background photon density at ϵ

Optical depth

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

gamma ray energy

emission region radius

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

Aharonian+ 2009)

Pair production cross section

Exploiting the gamma - neutrino connection

gamma ray energy

emission region radius

AGN background photon density at ϵ

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

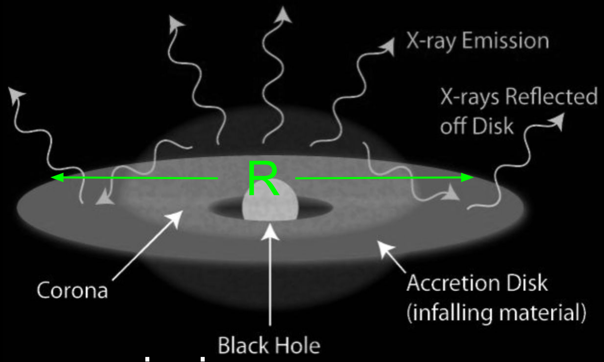
Pair production cross section

For a homogeneous region of emission:

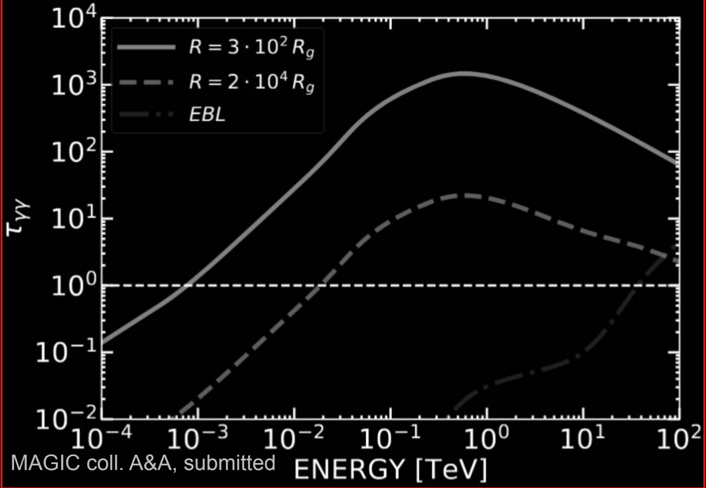
$$n_{\mathrm{ph}}(\epsilon) \propto R^{-2}$$

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

credit: D. Wilkins



Optical depth



MAGIC coll. A&A, submitted

X

Intrinsic Multipion gamma emission

(Murase+ 16)

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

pp interactions (K=2)
pγ interactions (K=1)

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

production rate of γ-rays

production rate of all-flavor ν

Constraints on emission region of NGC 4151

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

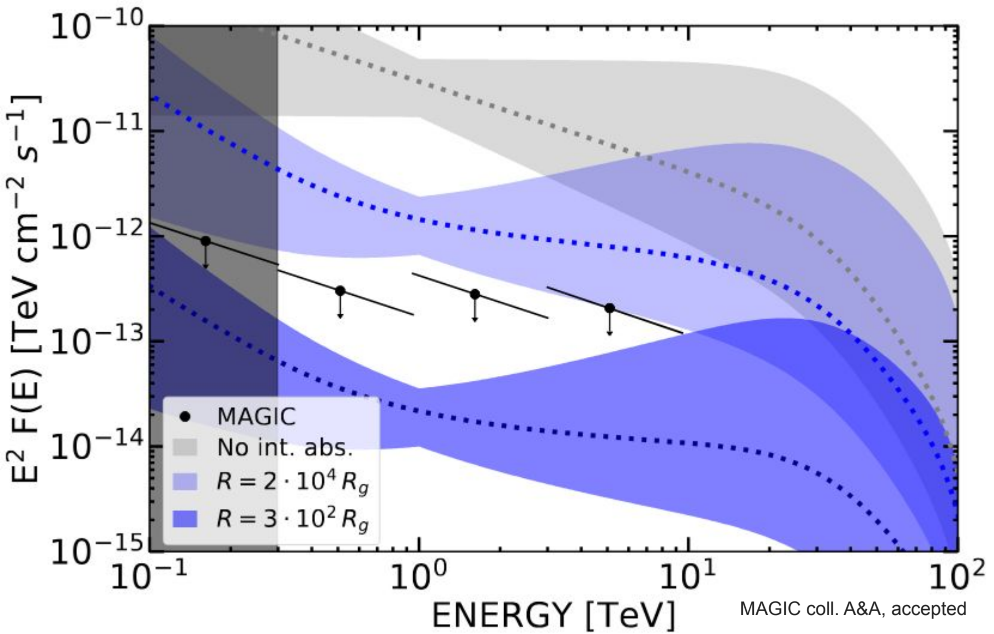
$\Rightarrow R < 10^4\ R_g$

$\Rightarrow$ Site close to the central engine

Sites of acceleration for this class based on NGC 1068

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

→Failed inner winds? (Inoue 2022)



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 ⇒ First ULs! ⇒ Indication of another gamma-ray obscured candidate neutrino source!

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

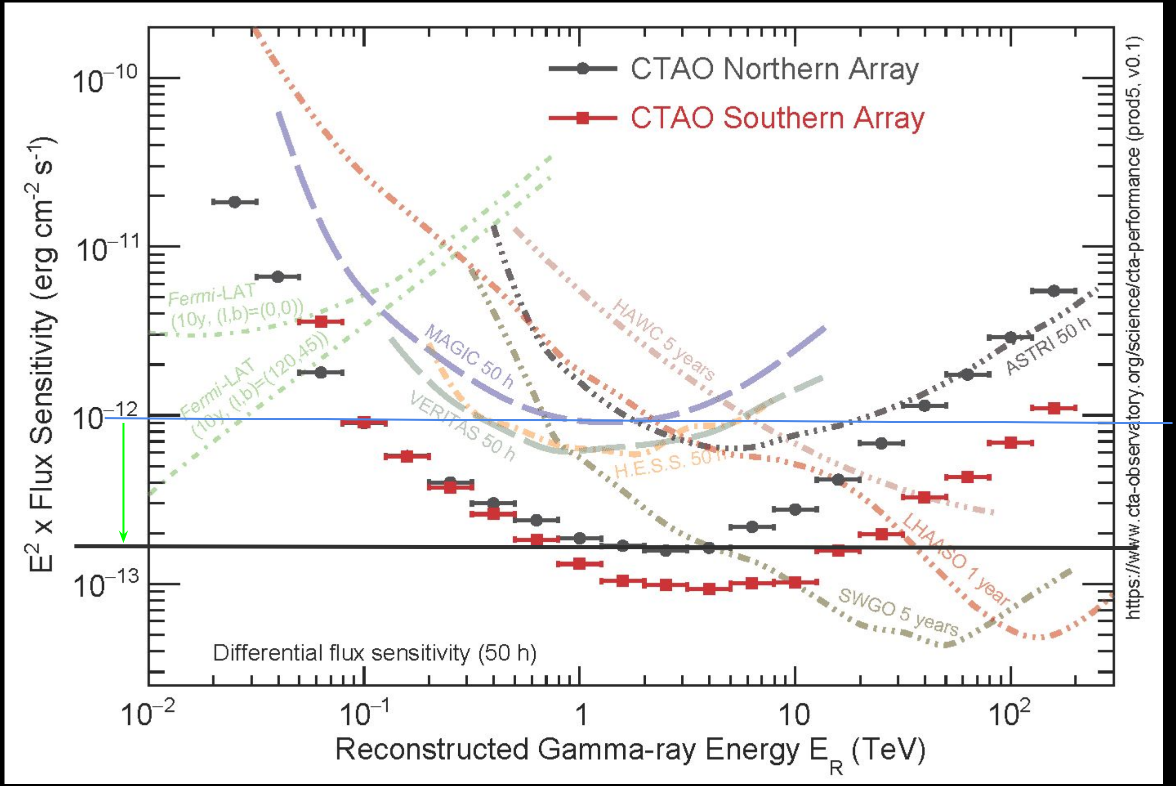
Confirmation of NGC 4151 as a source by current and new generation of neutrino telescopes needed!

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

This work has been accepted to A&A!

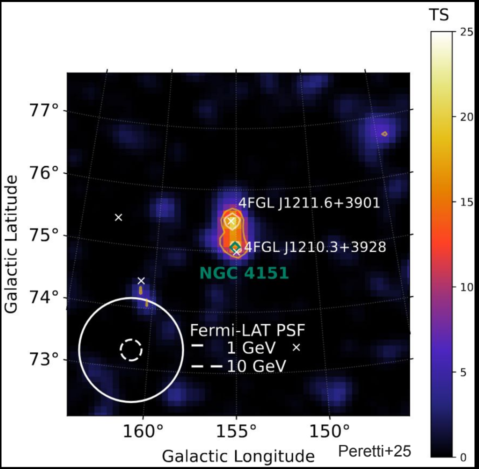
Improved Sensitivity with CTAO

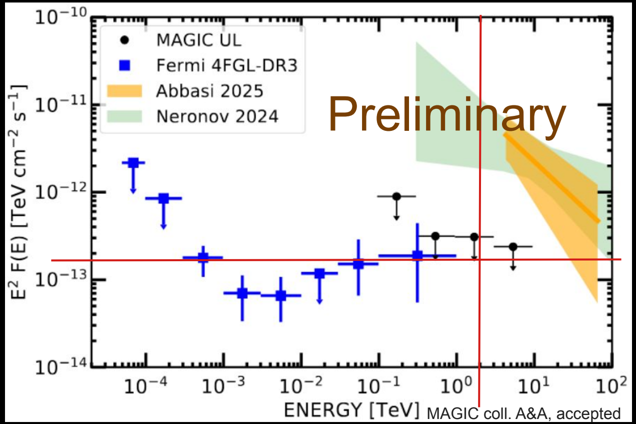
Order of magnitude improvement compared to MAGIC!

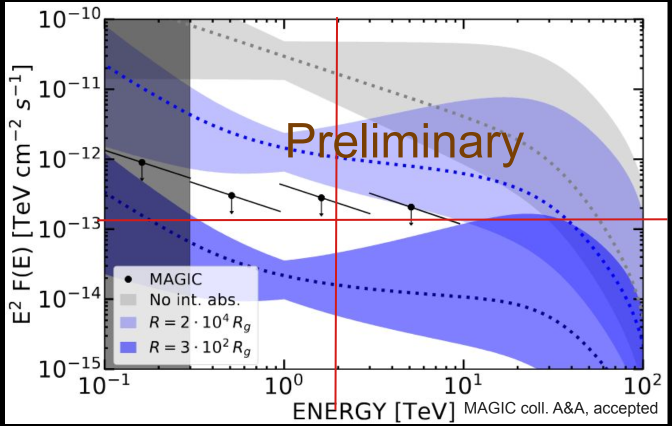


Prospects with CTAO : Deeper Studies with NGC 4151

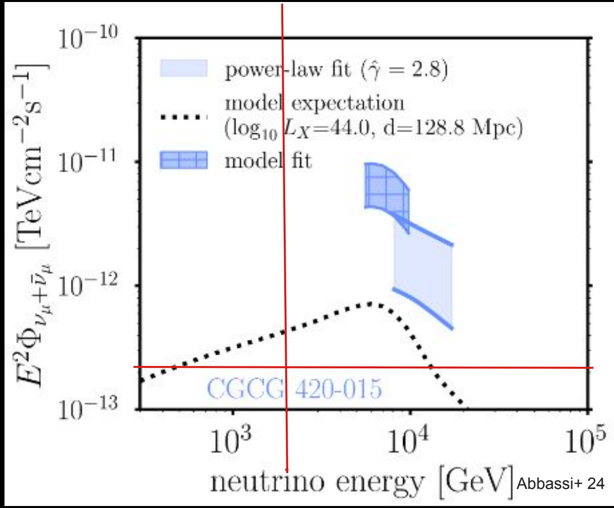
- Extend the Fermi spectrum
- Alleviate source confusion: Two blazars @ z~ 0.6
- Further constraints on the size

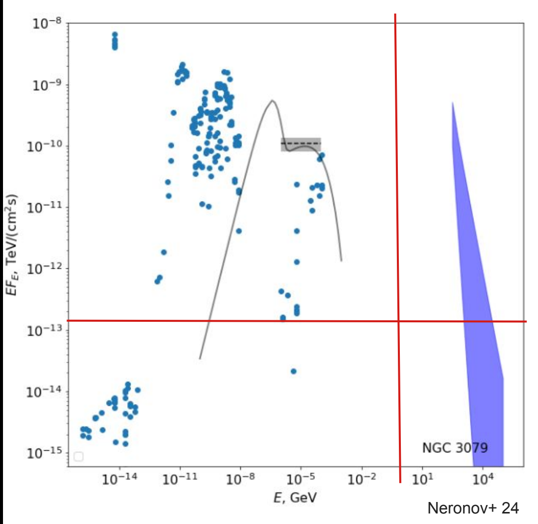






Prospects with CTAO : Prospects of study of other Seyferts



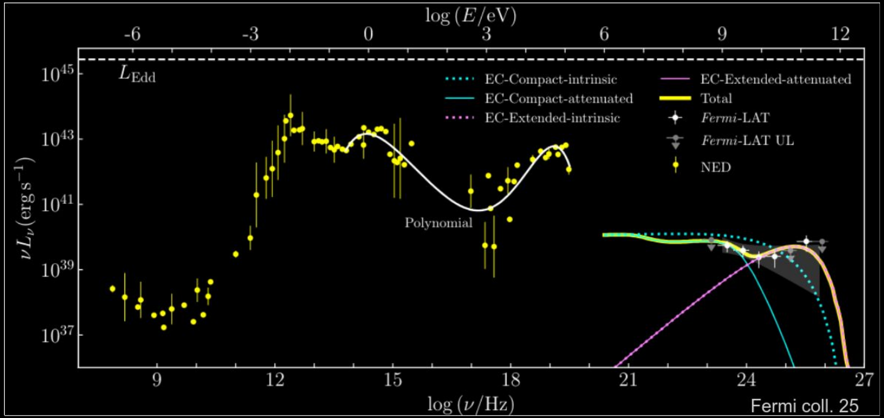


- Simulation of Neutrino emitting Seyfert candidates: NGC 3079, CGCG 420-015 etc.
- Simulation of Southern targets relevant for KM3Net.

Prospects with CTAO: Fermi Spectrum of Seyferts

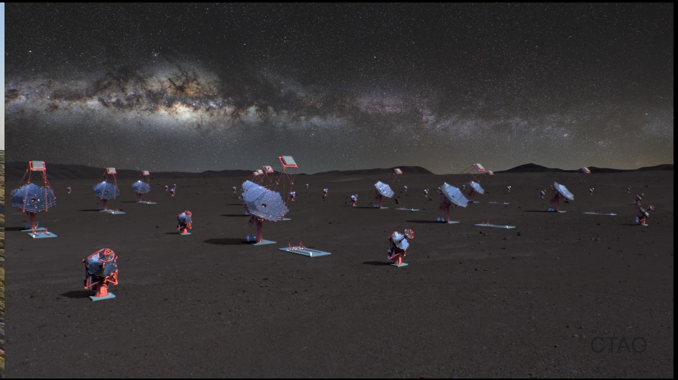
Results from Fermi Stacking of Seyferts ⇒ Detection of signal!

NEEDS INVESTIGATION in VHE gamma rays for extend the spectral coverage and potentially detect a high-energy cutoff, which provide information about the maximum energy of the accelerated particles



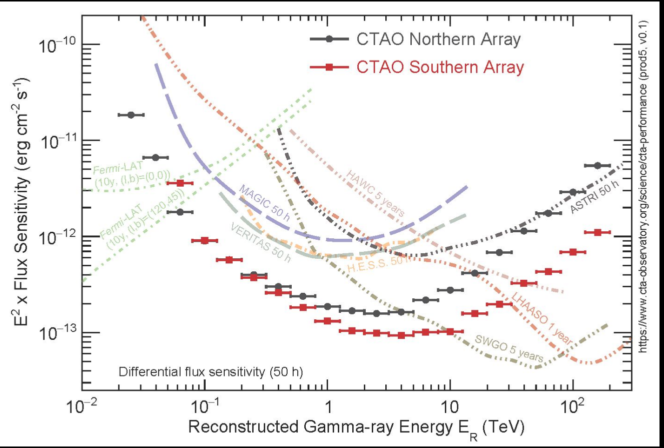
Fermi coll. 25

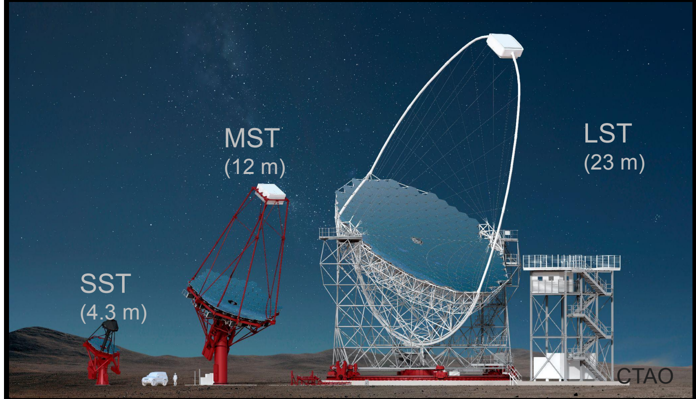
Cherenkov Telescope Array Observatory



CTAO North: La Palma, Spain
4 Large Sized Telescope
9 Medium Sized Telescope

CTAO South: Paranal, Chile
14 Medium Sized Telescope
37 Small Sized Telescope





- + Full sky coverage
- + Sensitive to wider energy range of gamma rays
- + Gain in sensitivity by an order of magnitude

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)

Offset 4.747 (NGC 4151)

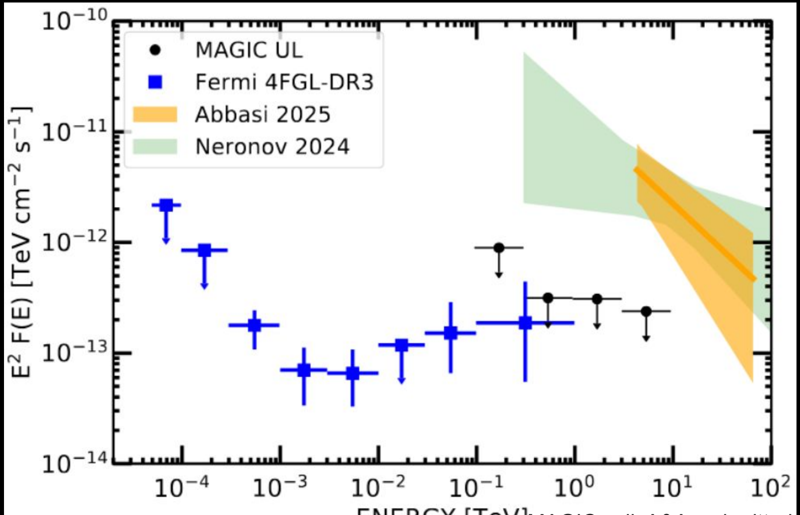
Hours of observation by MAGIC: 29 h

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

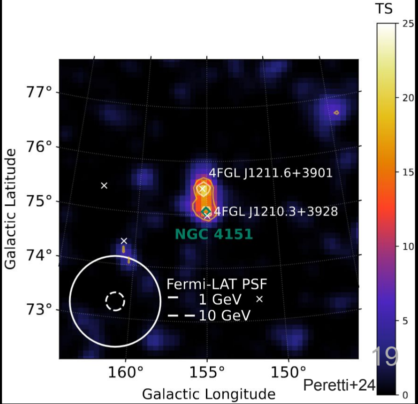
Assumed spectral model: Power law with spectral index 2.0

Non-detection indicative of gamma-ray absorption

⇒ Another obscured accelerator?

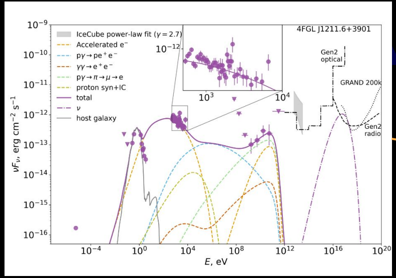


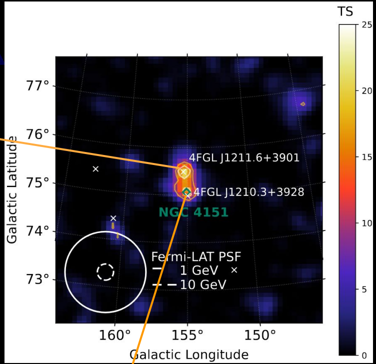
MAGIC coll. A&A, submitted



Peretti+24

Back up: Blazars in FoV and source confusion



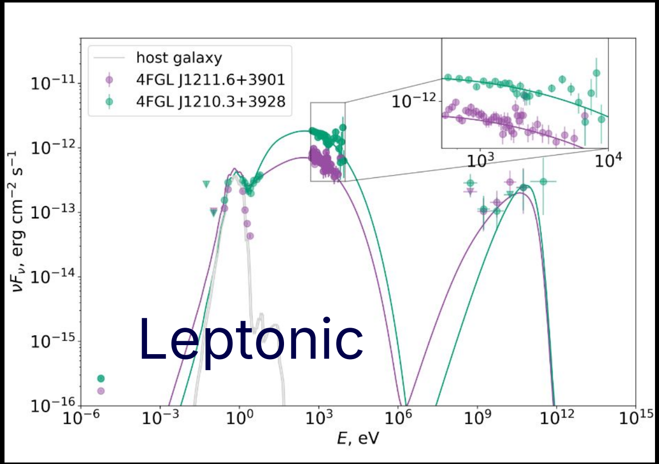


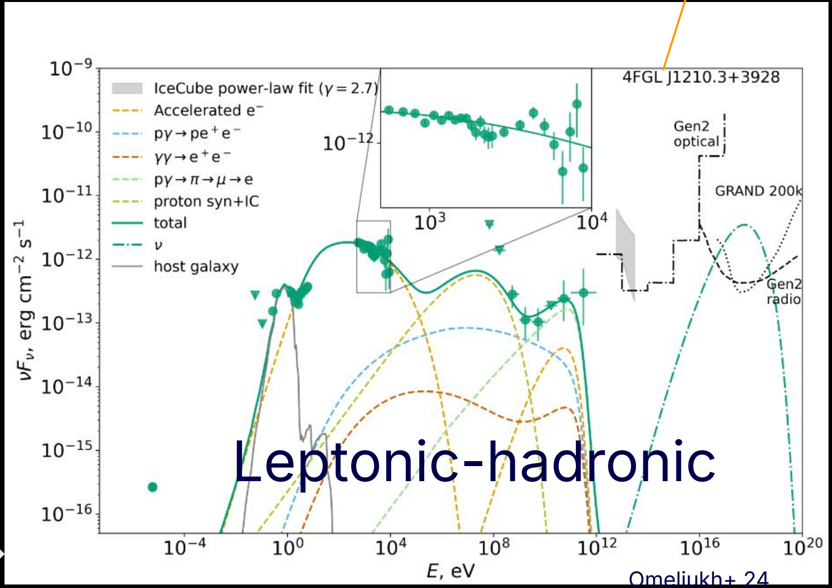
4FGL J1210.3+3928(~0.08°) 4FGL J1211.6+3901(~0.4°) in NGC 4151 FoV

Sharp cutoffs at 1 TeV → Only UL above TeV for Blazar(EBL motivated cut off @ z~0.6) 4FGL J1210.3+3928

4FGL J1211.6+3901 Can also be spatially resolved by MAGIC/LST

Confirmation of last Fermi Point → NGC 4151

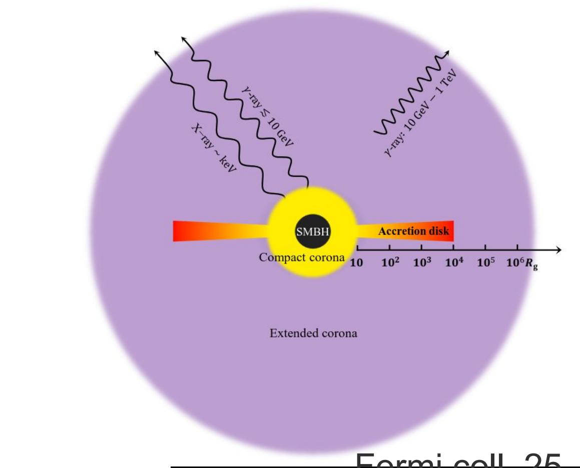




Our tailored 14-year Fermi data analysis put the last Fermi spectral point in question(Peretti +24) → observations with low threshold MAGIC+LST

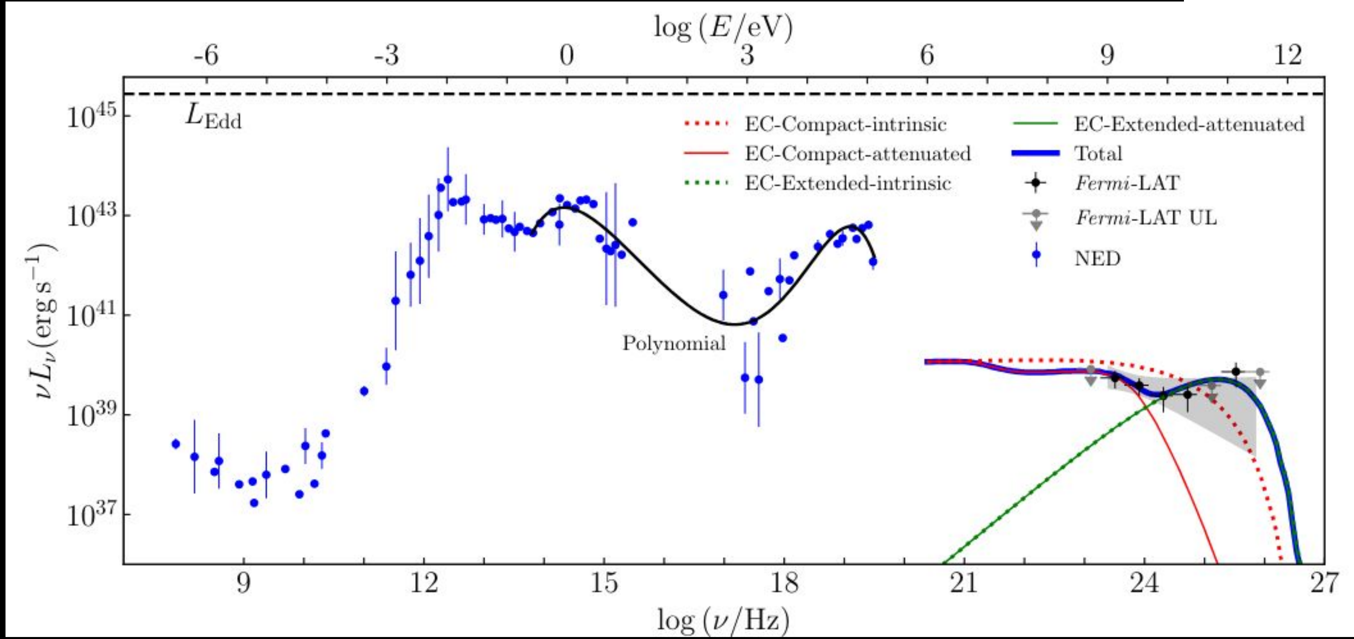
Seyferts as possible neutrino emitting source

VHE telescopes probe the energy range of IceCube⇒
ULs from other potential candidates ⇒New class of obscured accelerator



ORATION

Fermi coll. 25



Fermi coll. 25

Blazars in FoV and source confusion

4FGL J1210.3+3928(~0.08°) 4FGL J1211.6+3901(~0.4°) in NGC 4151 FoV

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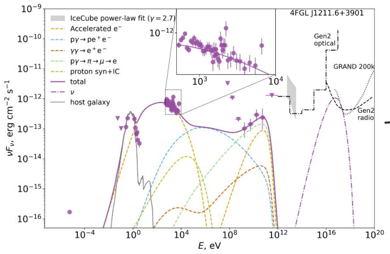
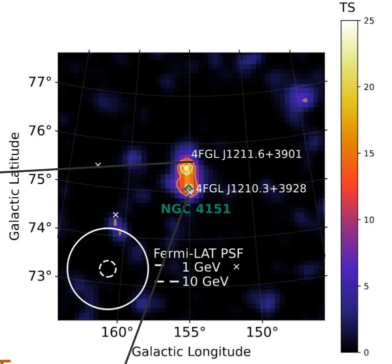
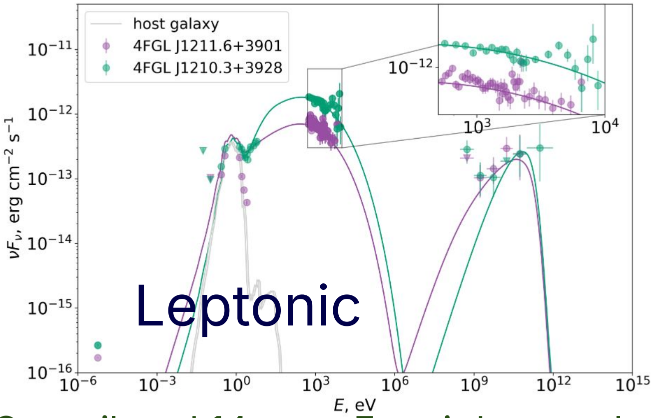
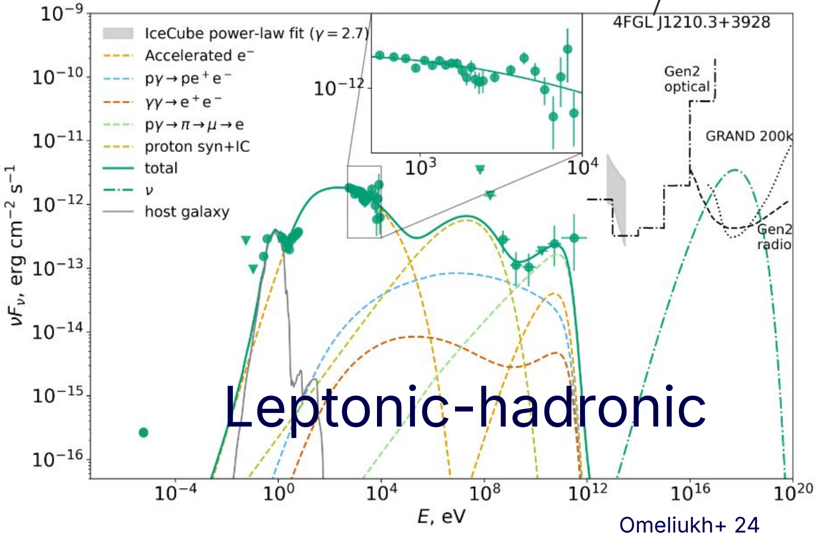




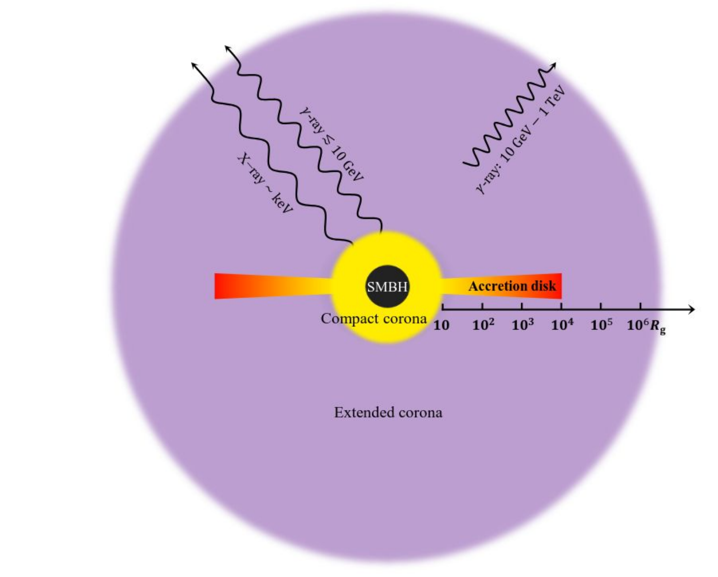
4FGL J1211.6+3901 Can also be spatially resolved by MAGIC/LST





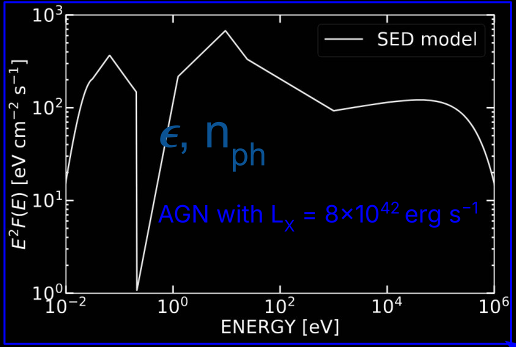
Omeliukh+ 24

Our tailored 14-year Fermi data analysis put the last Fermi spectral point in question(Peretti +24) → observations with low threshold MAGIC+LST



X-ray ~ keV
γ-ray ≤ 10 GeV
γ-ray: 10 GeV – 1 TeV
SMBH
Accretion disk
Compact corona
10 10^2 10^3 10^4 10^5 $10^6 R_g$
Extended corona

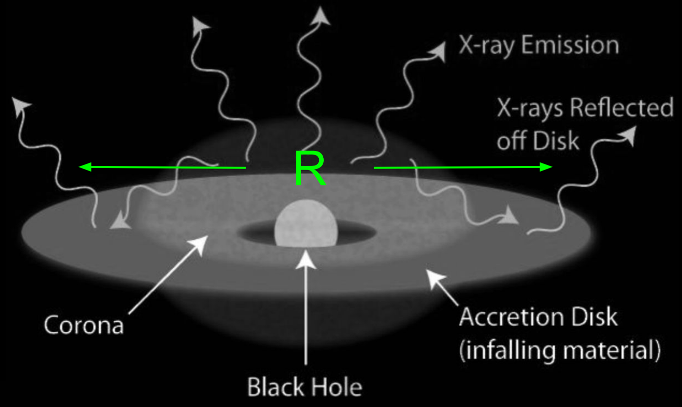
Exploiting the gamma - neutrino connection



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

opacity

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

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

Aharonian+ 2009)