Possible photohadronic origin of the IC-201114A alert

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Cosmic Messenger Connection

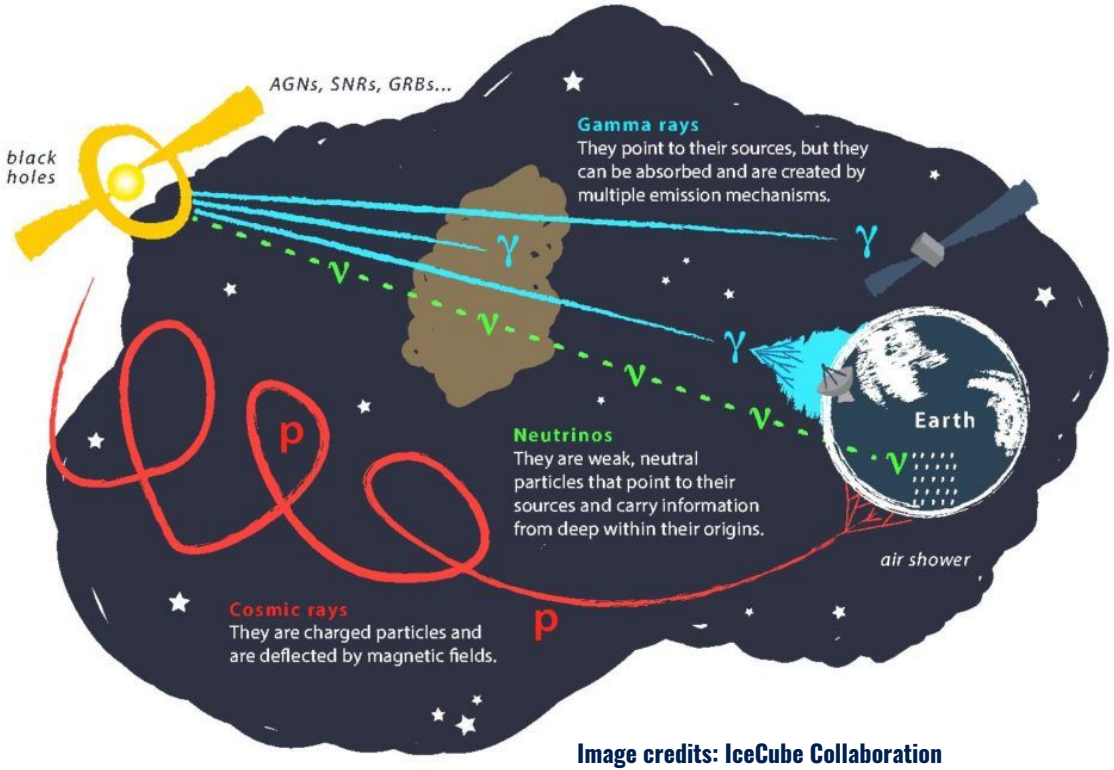
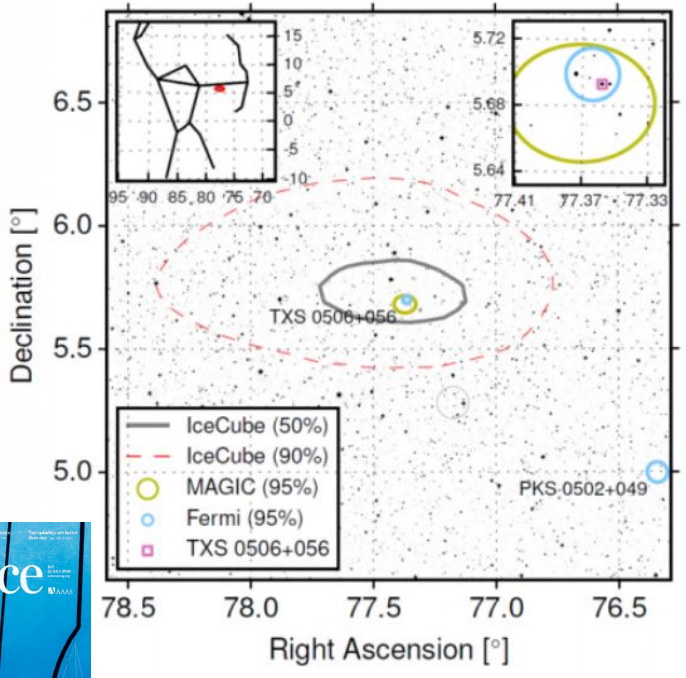


Image credits: IceCube Collaboration

A neutrino/gamma-ray connection is expected if hadronic processes occurs in astrophysical sources (such as AGN)

Neutrinos are considered ideal cosmic messengers and 'smoking gun' for hadronic interactions

IceCube-170922A & TXS 0506+056



Science 361, 147 (2018)

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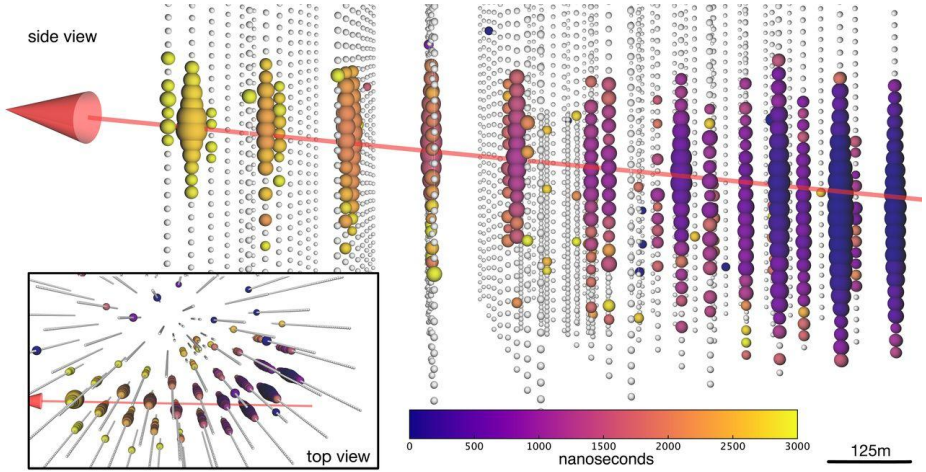
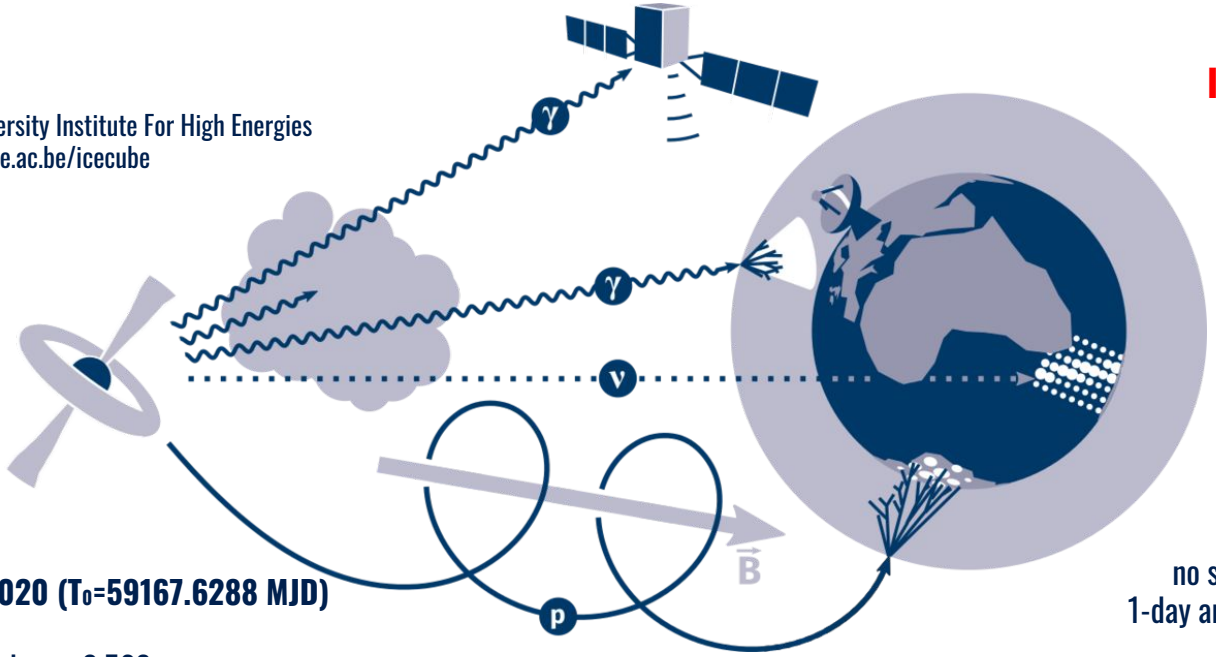


2017: 3σ correlation between a muon neutrino event with a reconstructed energy of 290 TeV and the flaring source TXS-0506+056.

2014-2015: Excess of HE neutrino events coming from the direction of the source at significance level of 3.5σ

Multi-messenger astronomy

Image Credit: Inter-University Institute For High Energies
www.iihe.ac.be/icecube



Improved IC alert system:

Gold alerts: 50%
Bronze alerts: 30%
astrophysical origin

Blaufuss et al. (2019)

November 14th, 2020 (T_0=59167.6288 MJD)

signalness=0.562
false alarm rate=0.92 events/year
R.A.=105.25° +1.28°/-1.12°; Dec=6.05°±0.95°
E~ 214.29 TeV

Alert distributed worldwide

4FGL J0658.6+0636 (NVSS J065844+063711)

Blazar, HSP, z >0.5
0.8° away from the best-fit event position
Identified as a VHE (E>20 GeV) source

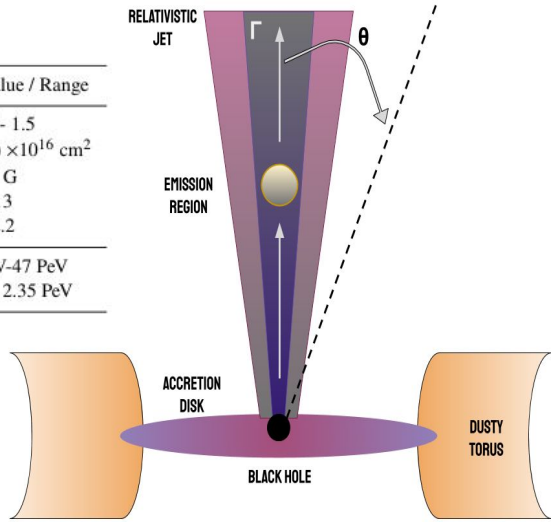
Fermi-LAT reported:
no significant detection of the source
1-day and 1-month prior to the neutrino alert

Follow Up Observations:
X-RAY: Swift, NICER, eROSITA
Radio: MPIfR

Photohadronic contributions

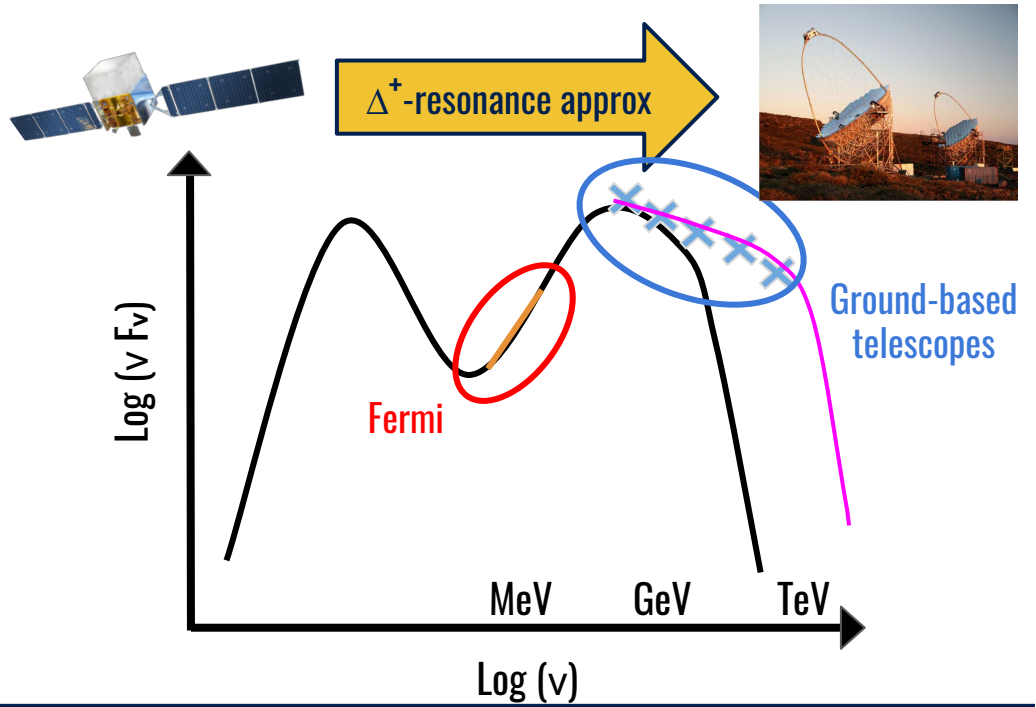
Let's assume the standard interpretation of the leptonic model:
Standard Leptonic = electron-synchrotron + SSC
Physical Parameters: {R_f, δ, Γ, B}

Parameter	Typical Value / Range
z	0.5 - 1.5
R'_f	(1.35-2.25) $\times 10^{16}$ cm^2
B	1 G
$\mathcal{D}$	13
α	2.2
E_p	663 GeV-47 PeV
E_ν	30 GeV- 2.35 PeV



Hadronic (pγ) contributions at VHE:

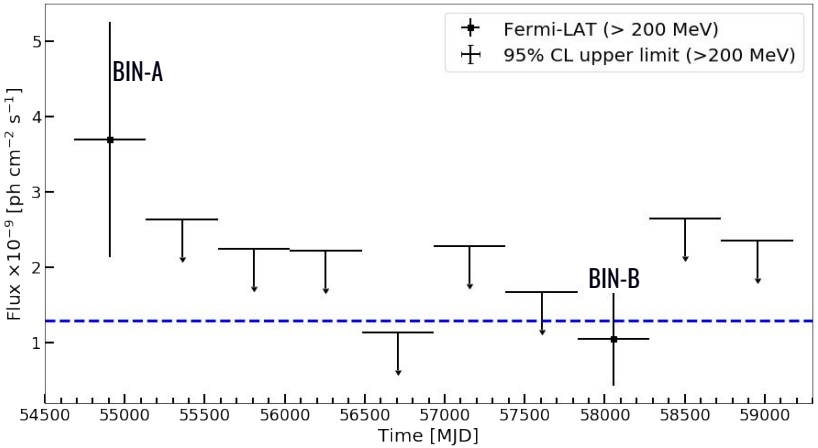
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\pi^0,\ \pi^0 \rightarrow \gamma\gamma \\ n\pi^+,\ \pi^+ \rightarrow \mu^+\nu_\mu,\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$



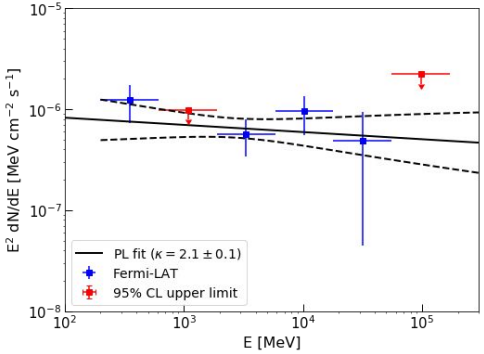
Fermi-LAT analysis

12.3-year data set: 54683-59178 MJD
IRFs: Pass8v6 & 4FGL-DR2 catalog
Energy range: 200 MeV - 300 GeV
RoI: 15°; bin size=0.1°/pixel
'SOURCE' class events (evclass=128 & evtype=3)

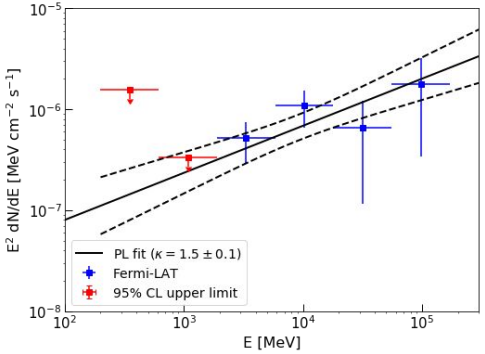
12.3 year data set light curve



BIN-A: (2008/08/04 - 2009/10/28)



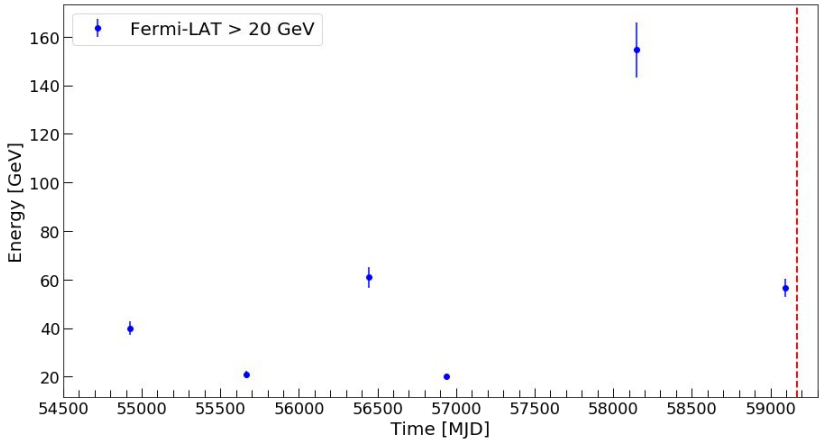
BIN-B: (2017/03/17 - 2018/06/10)



Power-Law (PL):

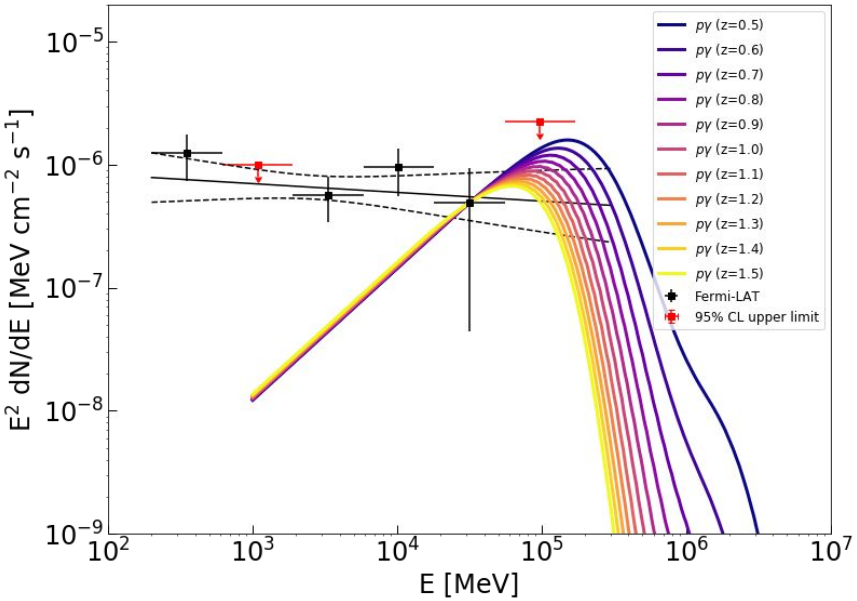
$$\frac{dN}{d\epsilon_\gamma} = N_{PL}\left(\frac{\epsilon_\gamma}{\epsilon_0}\right)^{-\kappa}$$

VHE photons associated with 4FGL J0658.6+0636 (≥ 90%)

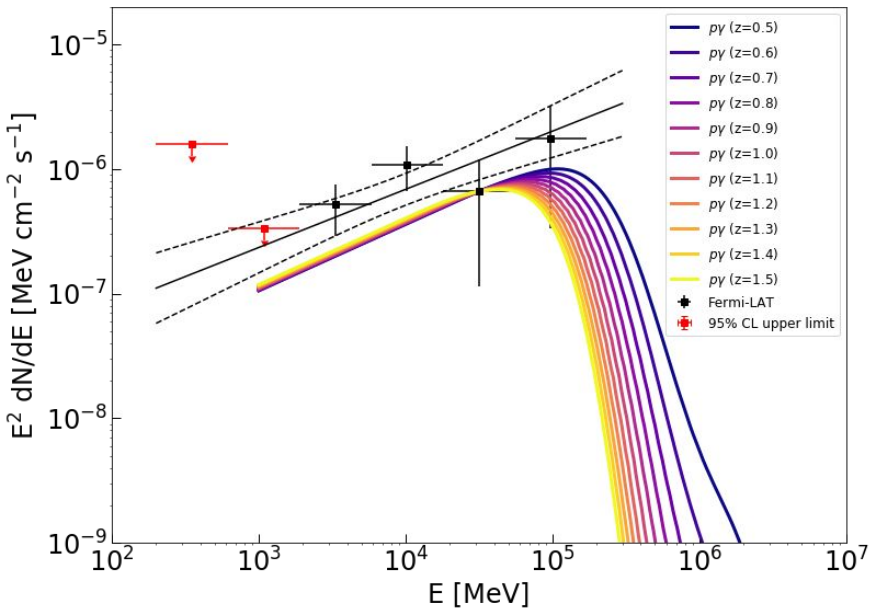


Photohadronic contribution for:

BIN-A



BIN-B



BIN	TS	Flux 10^{-9} [ph cm^{-2} s^{-1}]	N_{PL} 10^{-14} [MeV cm^{-2} s^{-1}]	κ	A_γ 10^{-2}	A_ν 10^{-12} [TeV cm^{-2} s^{-1}]	**MDT** Time [days]	$F_{\nu,\mathrm{int}}$ 10^{-5} [TeV cm^{-2}]
BIN-A	38	3.69 ± 1.56	8.9 ± 2.2	2.1 ± 0.2	1.85 - 1.92	6.35 - 6.93	160 (IC40) 100 (IC59)	8.66 - 9.46 5.54 - 6.05
BIN-B	34	1.04 ± 0.61	4.6 ± 2.1	1.5 ± 0.2	29.9 - 53.9	186.15 - 352.21	2.5 (IC86)	4.02 - 7.61

Minimum Detection Time (**MDT**): the estimated time elapsed for IceCube to detect a couple of neutrino events during an active state of the source.

Results

- For BIN-B: a dominant photohadronic contribution is compatible with the SED behaviour of the source
  MDT~2.5-days is expected and coincides with the most energetic VHE photon registered (E = 155~GeV)
  About 16-days to emulate the 13 excess events from 2014-15 neutrino flare of TXS 0506+056

- For BIN-A: the predicted spectrum does not match the Fermi-LAT data
  Low-level gamma-ray emission over an extended period
  Expected MDT between 100-160-days

Fermi Gamma-ray Space Telescope

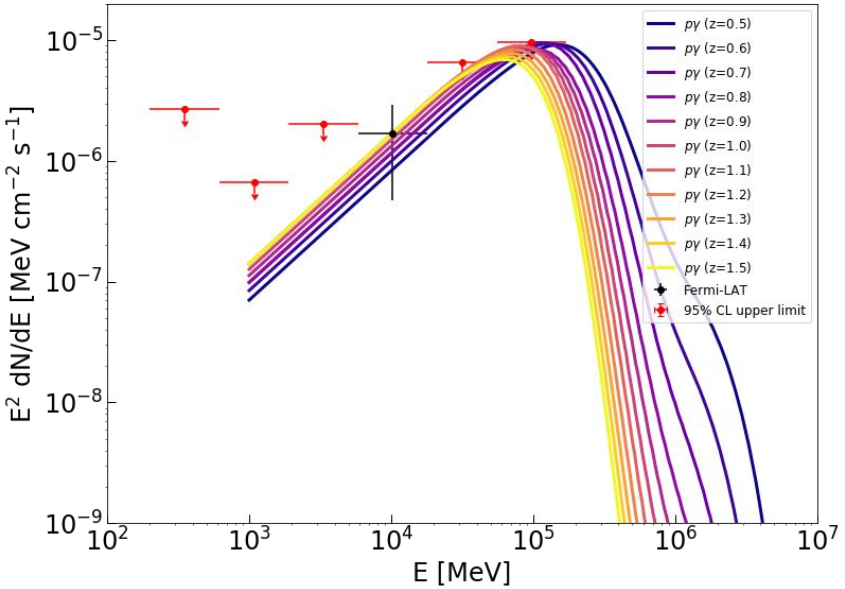
4-month data set: 59108-59228 MJD
centered at the time of the neutrino alert
IRFs: Pass8v6 & 4FGL-DR2 catalog
Energy range: 200 MeV - 300 GeV
RoI: 15° ; bin size=0.1°/pixel
'SOURCE' class events (evclass=128 & evtype=3)

No significant gamma-ray activity during this time window.
Assuming a photon target spectrum similar to
BIN-A or BIN-B

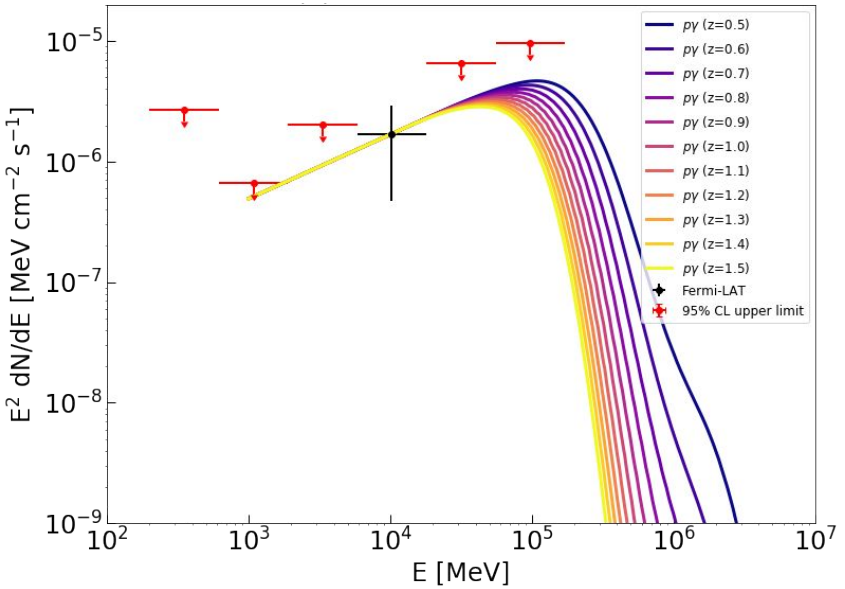
Photohadronic contribution for IC-20114A

Photohadronic contributions around IC-201114A

BIN-A like spectrum



BIN-B like spectrum



Assumed Behaviour	A_γ	A_ν [TeV cm^{-2} s^{-1}]	MDT	$F_{\nu,\mathrm{int}}$ $\times 10^{-5}$ [TeV cm^{-2}]
BIN-A like	0.11 - 0.20	$(3.66 - 7.15)\times 10^{-11}$	12-days	3.80- 7.42
BIN-B like	1.39 - 2.24	$(1.05 - 1.78)\times 10^{-8}$	~ 1-hour	3.79 - 6.41

Conclusions and Outlook

Two significant periods of gamma-ray activity were found (BIN-A and BIN-B) which were studied using the photohadronic approximation:

- BIN-B fit is compatible with the behaviour of the source:
  Harder gamma-ray spectrum and coincide with the highest VHE photon from the source (E = 155~GeV)
  MDT~2.5-days: the detection of neutrino events in this period is plausible

- BIN-A the predicted spectrum does not match the Fermi-LAT data, and the MDT>100-days
  This may indicate that other components are dominant and necessary to explain fully the emission

- Time window around IC-201114A, no significant gamma-ray activity detected with Fermi-LAT:
  The prediction for the gamma-ray emission and the MDT using the photohadronic approx is compatible
  If the opacity is too large, then a possible neutrino detection will not be accompanied by an enhanced gamma-ray flux

- More evidence is needed to confirm 4FGL J0658.6+0636 as a neutrino emitter

- We are living the DAWN of Multimessenger Astronomy: Next generation of observatories (CTA, IceCube-Gen2) will play crucial role

Durham University

Thanks for your attention

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