The population of neutrino blazar candidates from real-time high-energy neutrino alerts

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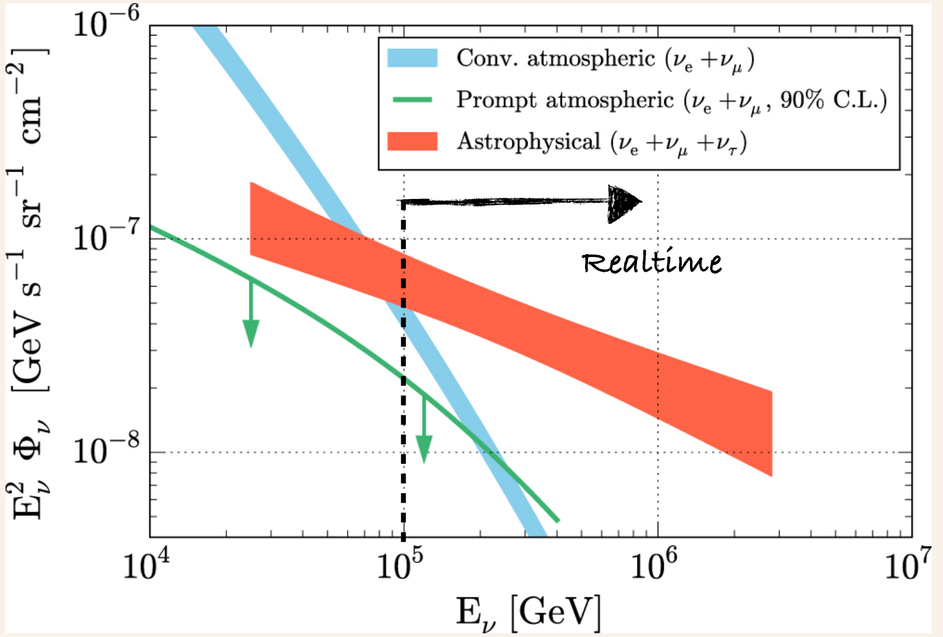
RUB

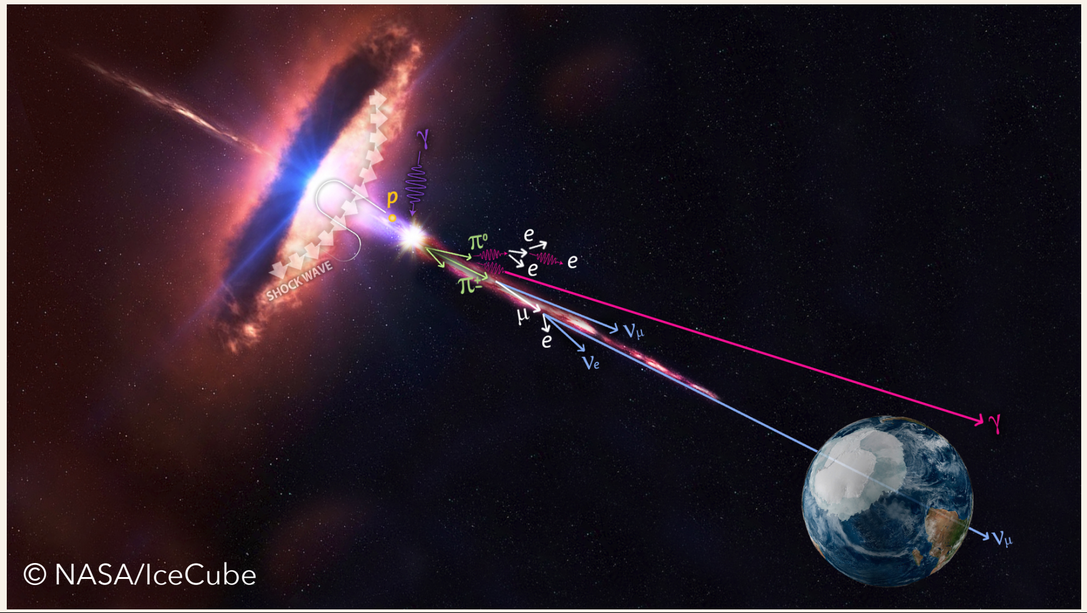
Fermi Gamma-ray Space Telescope

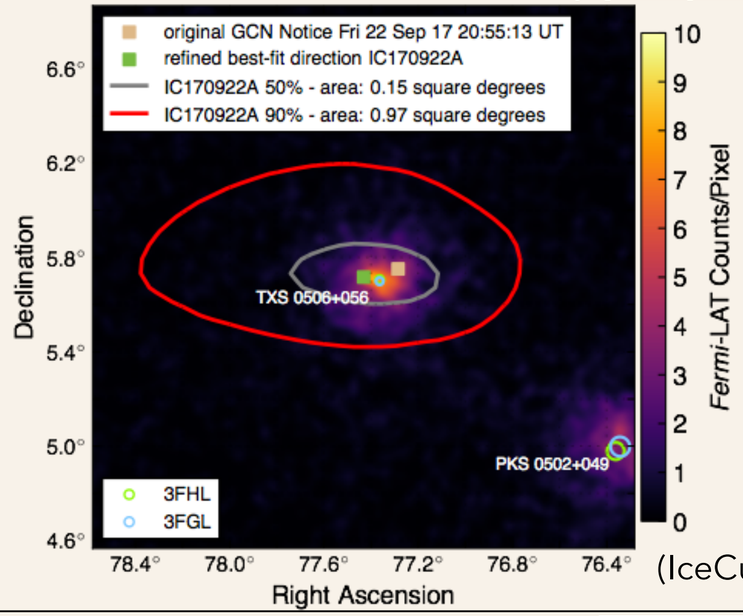
Motivation

(Aartsen et al. 2015)

- High-energy (>100 TeV) events play an important role in the search for the sources of the astrophysical neutrino flux.
- After TXS 0506+056, several other neutrino source candidates have been proposed thanks to multi-wavelength realtime follow-ups.
- Main challenge: spatial resolution of neutrino telescopes are far from ideal for astronomy.
- *Fermi*-LAT realtime observations have a key role in these searches.



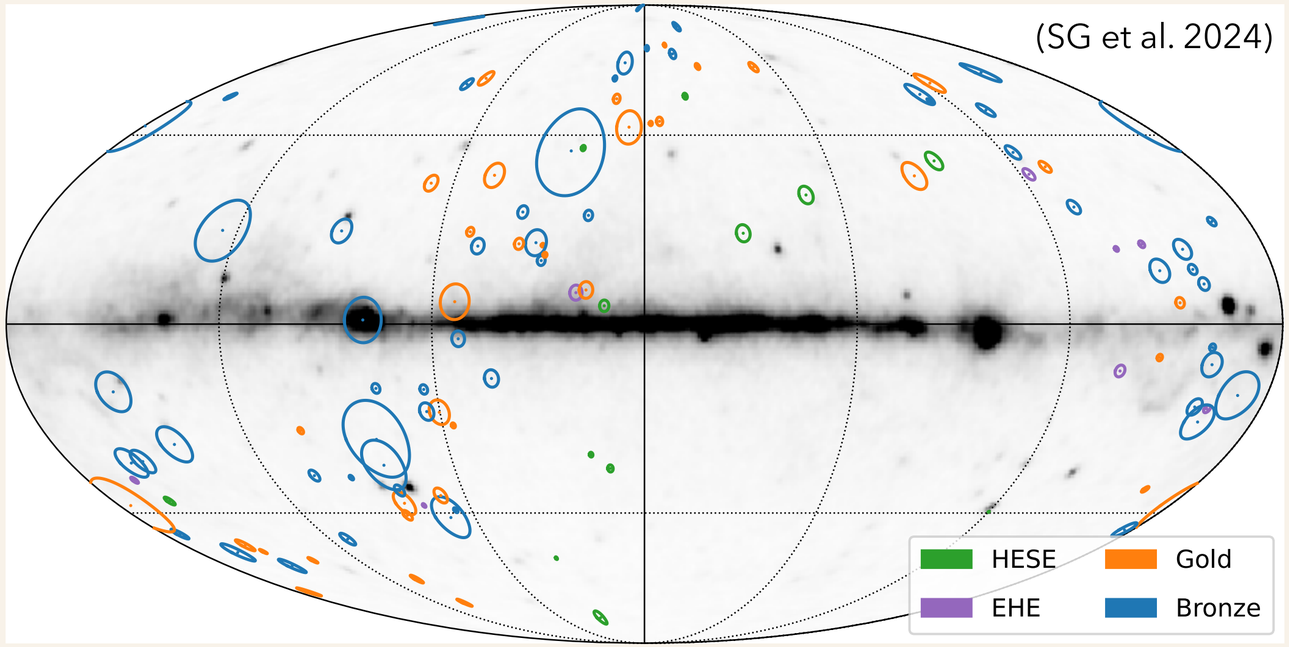




(IceCube coll. et al. 2018)

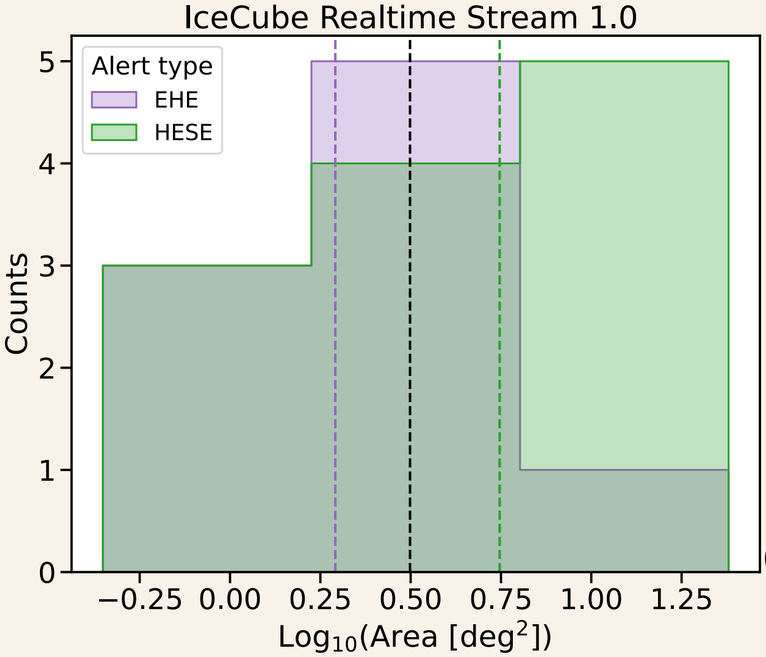
Realtime neutrino follow-up observations with *Fermi*-LAT

- Systematic analysis of sky regions around the neutrino direction
- We investigate 3 timescales during a standard follow-up (T_0 = neutrino detection time):
  - 1-day before T_0: Detect fast, bright transients coincident with the neutrino
  - 1-month before T_0: Detect recent transients, sources in bright state (with time lags consistent with the most credited models)
  - Full-mission data: Detect weak gamma-ray sources out of LAT catalogs and coincident with neutrino position
- In the case of significant detection of a transient at 1-day or 1-month timescales, dedicated light curve analyses are performed up to 1-year timescale before T_0.
- In the case of a non-detection at the best-fit position of the neutrino, 95% CL upper limits are reported, corresponding to the detection of a power-law source (index 2.0).
- Reports are sent via GCN Circulars/ATels.

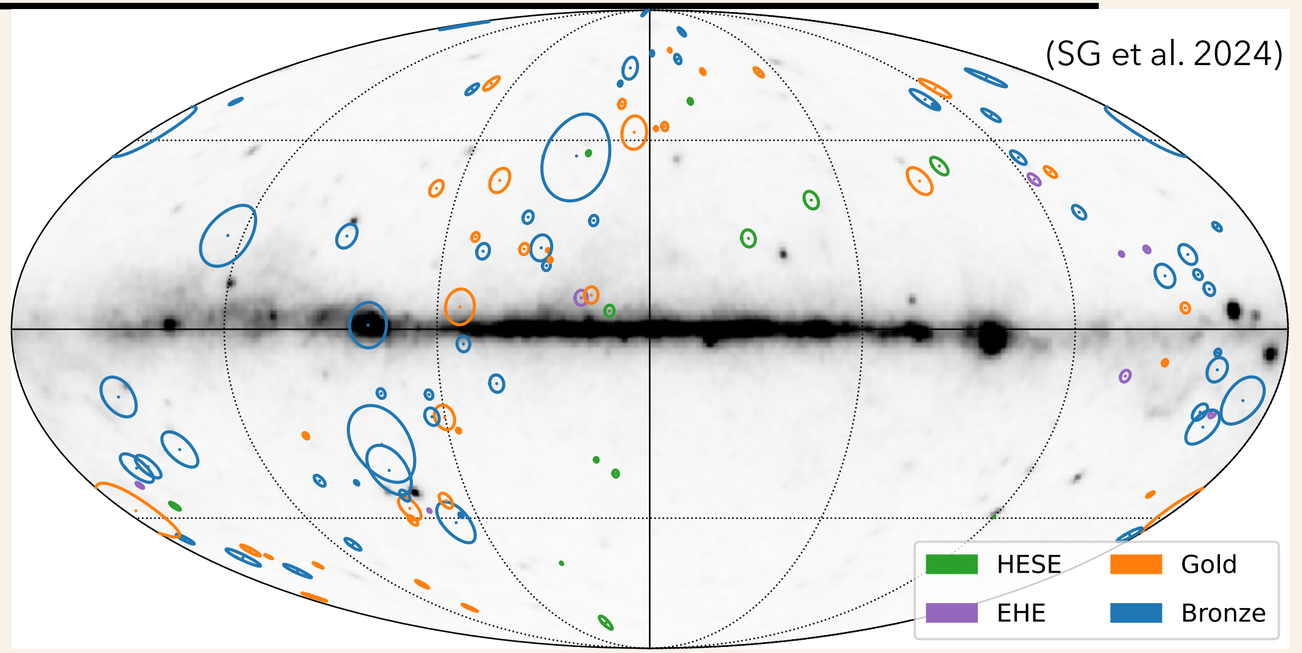


Realtime neutrino follow-up observations with *Fermi*-LAT

- Follow-up of 21 alerts from Realtime Stream 1.0 (2016-2019)
- $A_{90\%}$ (angular unc.) from 0.4 - 24 deg^2.
- Median extensions:
  - 1.96 deg^2 for EHE alerts and 5.6 deg^2 for HESE.
- Only 3 events have a single coincident LAT source, while 13 have no coincidence.



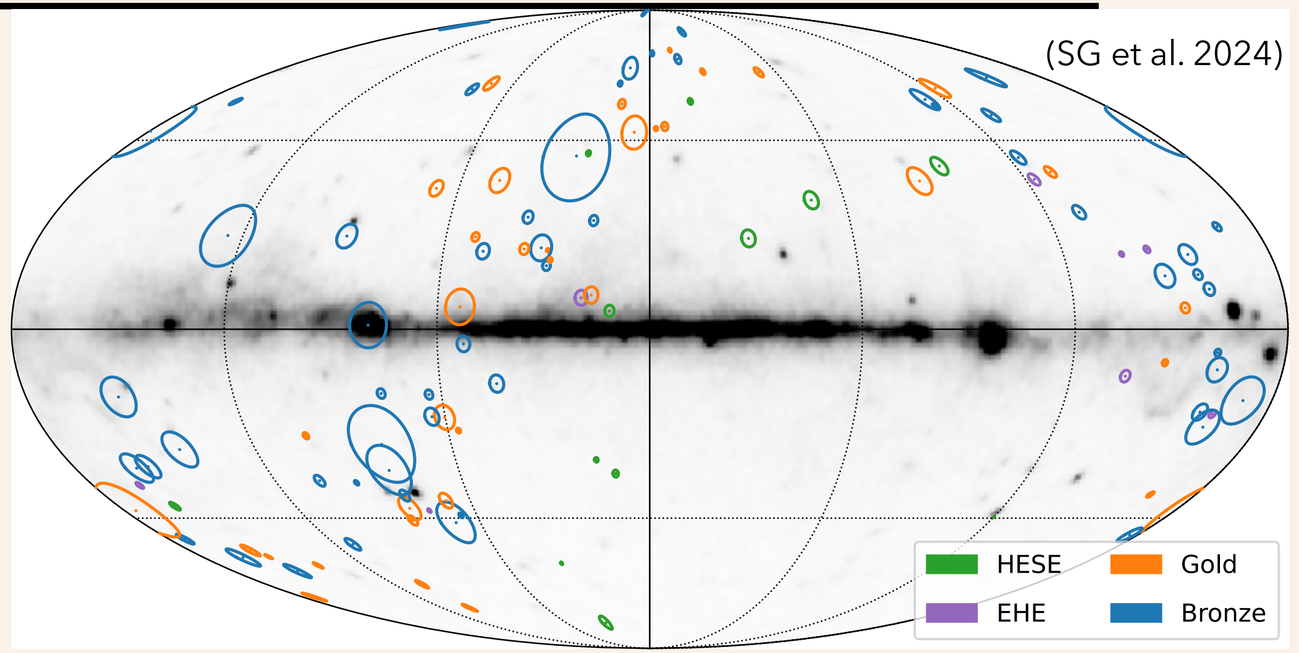
(SG et al. 2024)

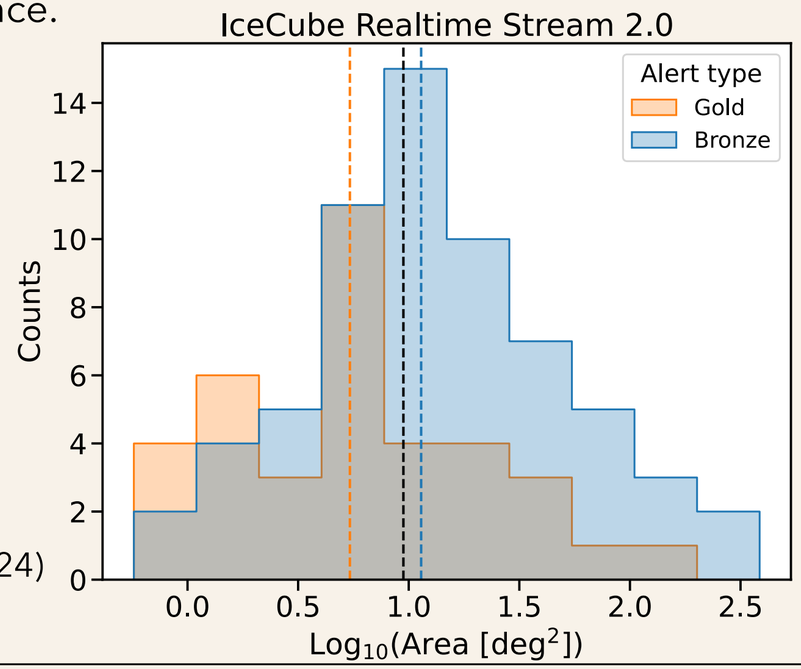


(SG et al. 2024)

Realtime neutrino follow-up observations with *Fermi*-LAT

- Follow-up of 101 alerts from the IceCube Realtime Stream 2.0 (June 2019 - May 2023).
- $A_{90\%}$ (angular unc.) from 0.57 - 385 deg^2.
- Median extensions:
  - 5.4 deg^2 for Gold (S_{av} > 50%) alerts and 11.15 deg^2 for Bronze (S_{av} > 30%).
- Only 17 events have a single coincident LAT source, while 44 have no coincidence.

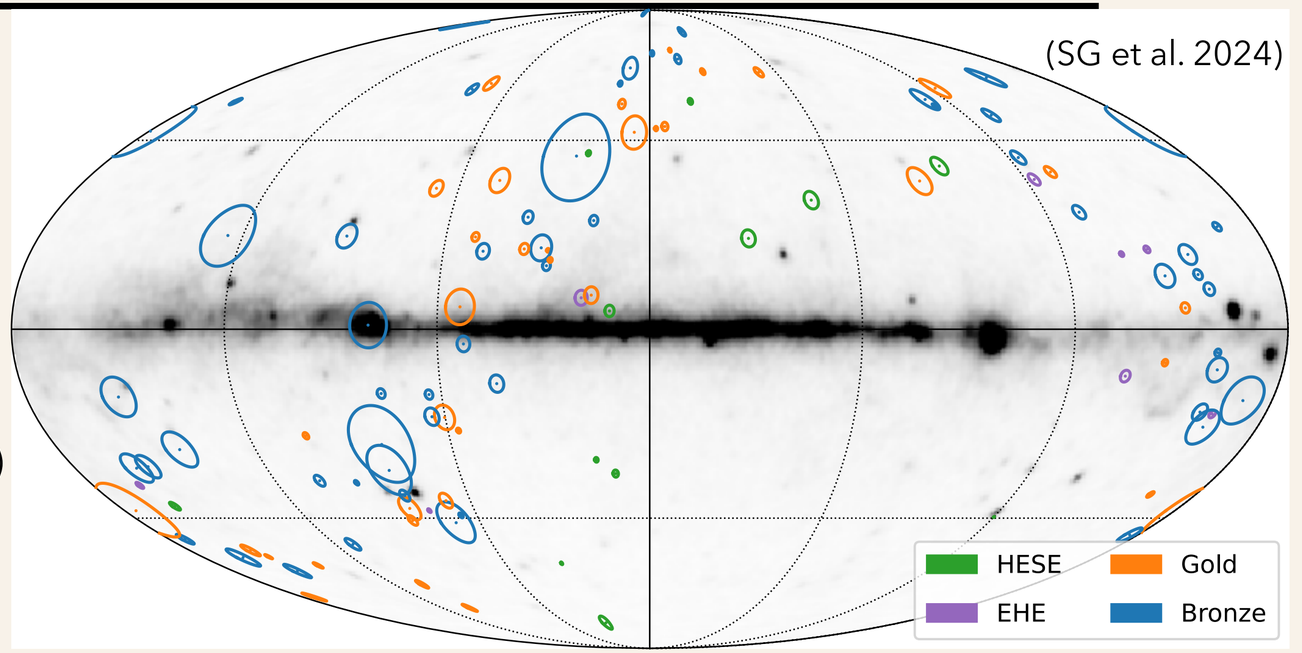




(SG et al. 2024)

Multiple neutrino coincidences with *Fermi*-LAT sources

- We add also 225 archival alerts from the ICECAT-1 catalog (Abbasi+ 2023)
  - 115 4FGL-DR3 sources are coincident with >1 neutrino.
  - 11 sources with ≥ 3 neutrinos.
  - One has 4 coincidences: PKS B2224+006, FSRQ at z = 2.25 (Albareti+ 2017)
- The two neutrino candidates TXS 0506+056 (IceCube+2018) and GB6 J1040+0617 (SG et al. 2019) also have a double coincidence, but no temporal correlation.
- A lot of poorly-reconstructed events…



4FGL Name	Class	IceCube names	Area (deg^2)
J0203.9+8120	–	IC190629A, IC140103A, IC140410A	161.6, 837.6, 3143.8
J0228.1+8208	bcu	IC190629A, IC140103A, IC140410A	161.6, 837.6, 3143.8
J2223.3+0102	bll	IC200523A, IC110807A, IC180612A	90.6, 5.7, 70.4
J2226.6+0210	bcu	IC200523A, IC110807A, IC180612A	90.6, 5.7, 70.4
J2226.8+0051	fsrq	IC200523A, IC110807A, IC140114A, IC180612A	90.6, 5.7, 2.7, 70.4
J2227.9+0036	bll	IC200523A, IC140114A, IC180612A	90.6, 2.7, 70.4
J0506.9+0323	bcu	IC220918A, IC161117A, IC190317A	50.9, 13.9, 95.0
J0509.4+0542	bll	IC220918A, IC170922A, IC190317A	50.9, 1.3, 95.0
J1019.7+0511	bcu	IC130627A, IC170308A, IC190415A	4.9, 6.0, 33.8
J0839.7+3540	bll	IC140122A, IC140223A, IC181121A	55.1, 368.2, 111.2
J0244.7+1316	bcu	IC161103A, IC170824A, IC180613A	3.2, 18.2, 91.5

After simulations, the number of multiple neutrino coincidences is still consistent with random chance!

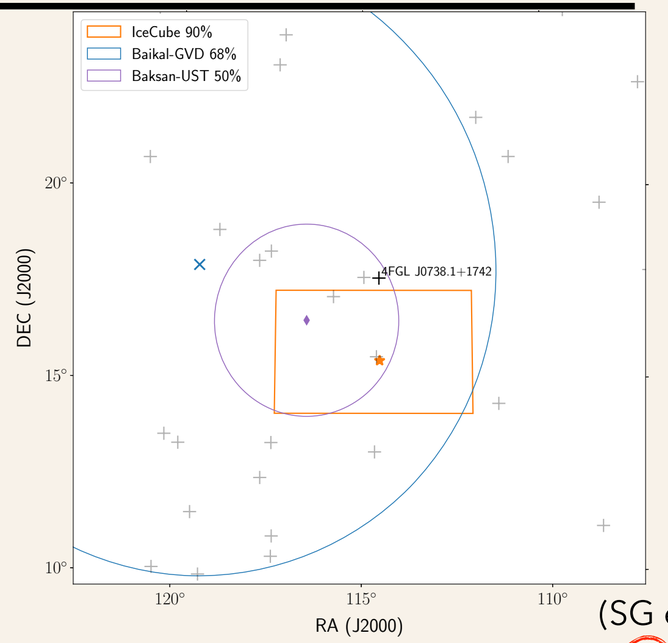
A blazar in temporal coincidence with multiple neutrinos

IceCube-211208A:
- Bronze Alert
- Signalness = 50%
- Energy = 172 TeV

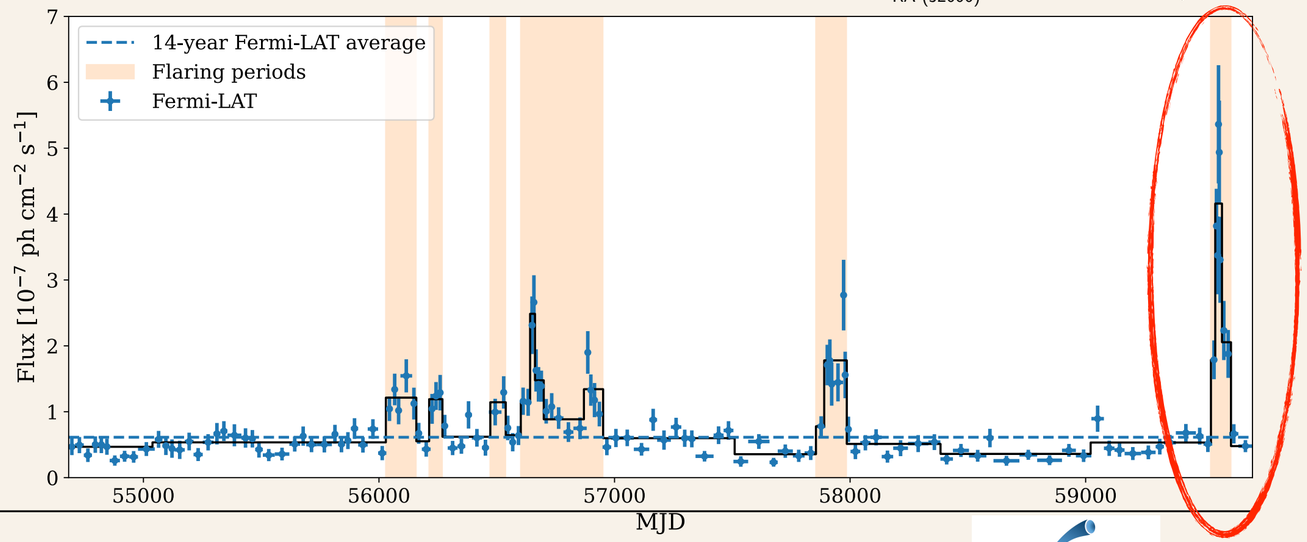
Baikal-GVD event (ATel #15112)
- Event type: Cascade
- Detected 3.95 hours after the IceCube event
- Energy 43 TeV
- Chance coincidence excluded at 2.85σ

Baksan-UST event (ATel #15143)
- Event type: Track
- Detected 4 days before the IceCube event
- Energy > 1 GeV
- Chance coincidence excluded at 3σ

PKS 0735+17
- Class: BL Lac
- z = 0.45 (Gattano+ 2018)
- Variability duty cycle: ~16%



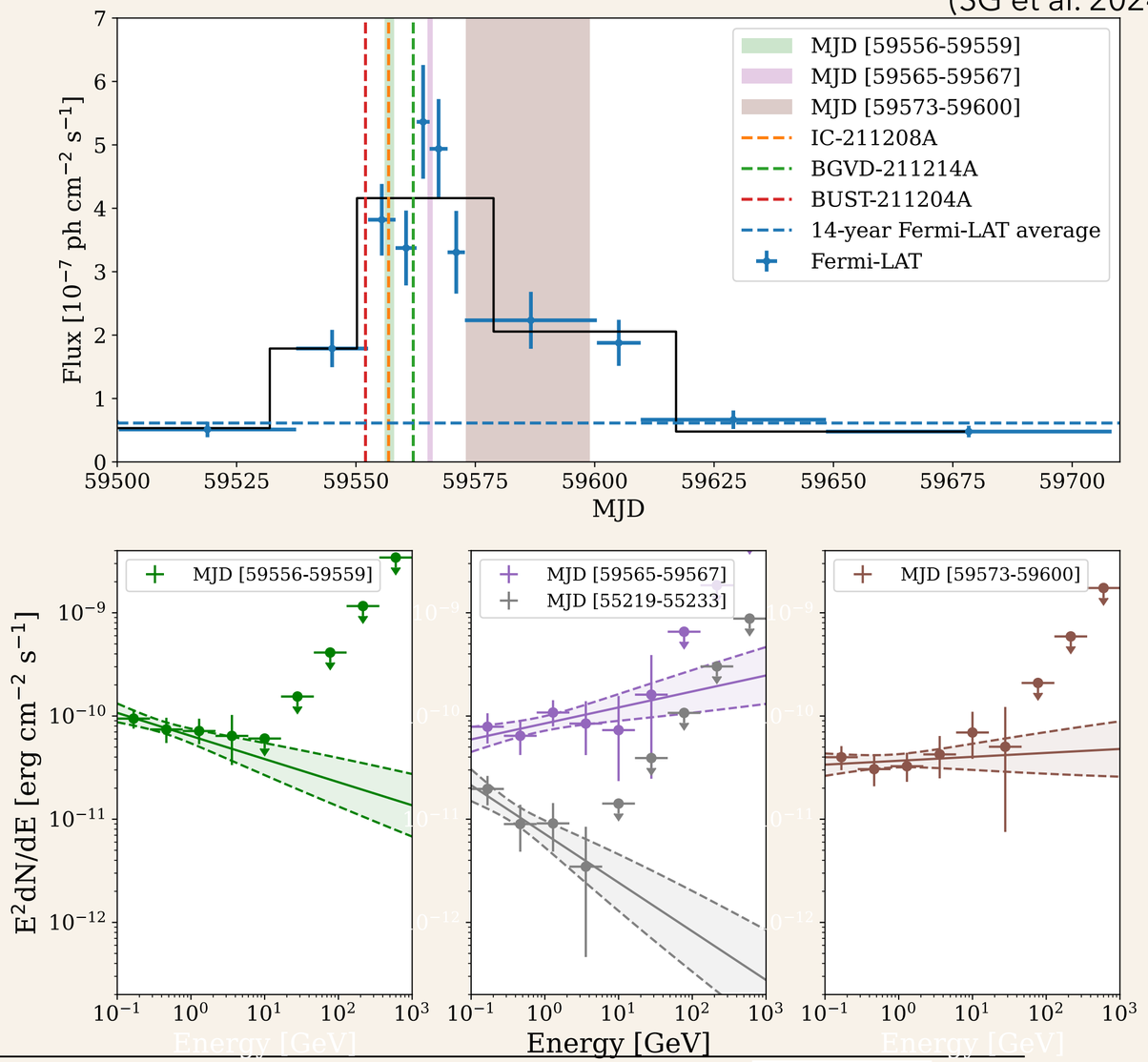
(SG et al. 2024)



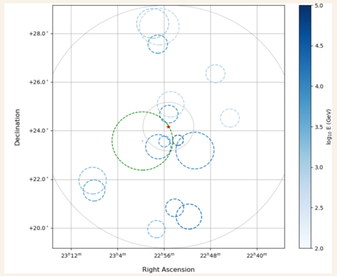
A blazar in temporal coincidence with multiple neutrinos

- The brightest gamma-ray activity in *Fermi*-LAT data for PKS 0735+17.
- All 3 neutrinos during the raising period of the gamma-ray flare.
- Shortest variability timescale: ~14.4 days (R_g ~10^{15} cm)
- Lepto-hadronic modeling predicts up to 0.2 muon neutrinos in 50days (Omeliukh, SG et al. 2024).
- In the quiescent state, the neutrino rate is ~2 orders of magnitude lower (Omeliukh, SG et al. 2024).
- Similar predictions during flare in Sahakyan et al. (2023), Acharyya et al. (2023).

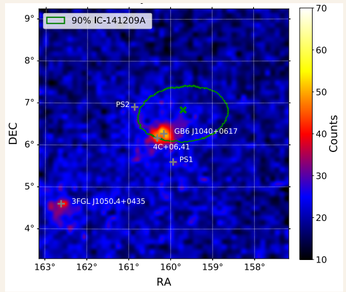
(SG et al. 2024)



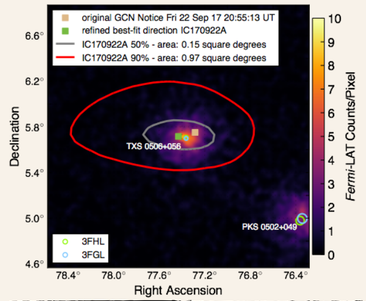
Blazars as high-energy neutrino sources



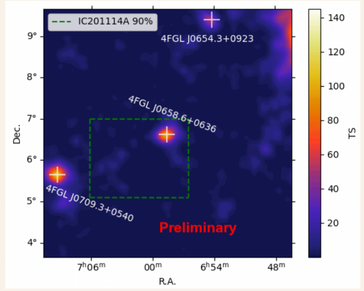
IC-100608A and MG3 J225517+2409
Flaring: Yes
ANTARES Coll. et al. 2021



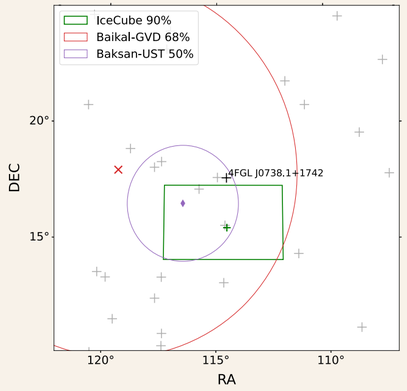
IC-141209A and GB6 J1040+0617
Flaring: Yes
SG et al. 2019



IC-170922A and TXS 0506+056
Flaring: Yes
IceCube Coll. et al. 2018



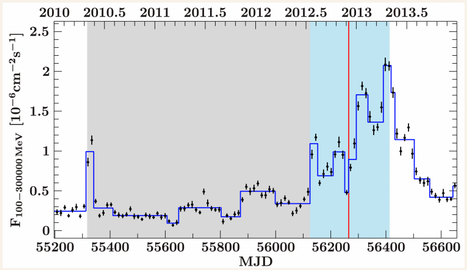
IC-201114A and 4FGL J0658.6+0636
Flaring: No
de Menezes et al. 2021



IC-211208A and PKS 0735+17
Flaring: Yes
SG et al. 2021, ATel #15099
Sahakyan et al. 2022

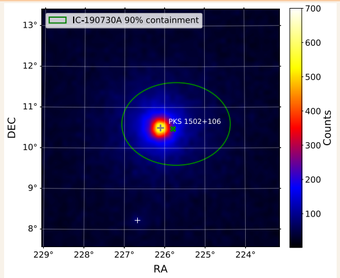
2010 2012 2014 2016 2018 2020 2022

Year

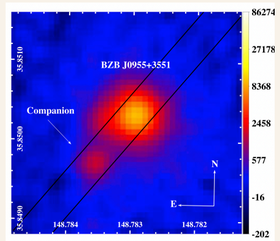


IC-35 and PKS 1424-41
Flaring: Yes
Kadler et al. 2016

IceCube Realtime alert stream



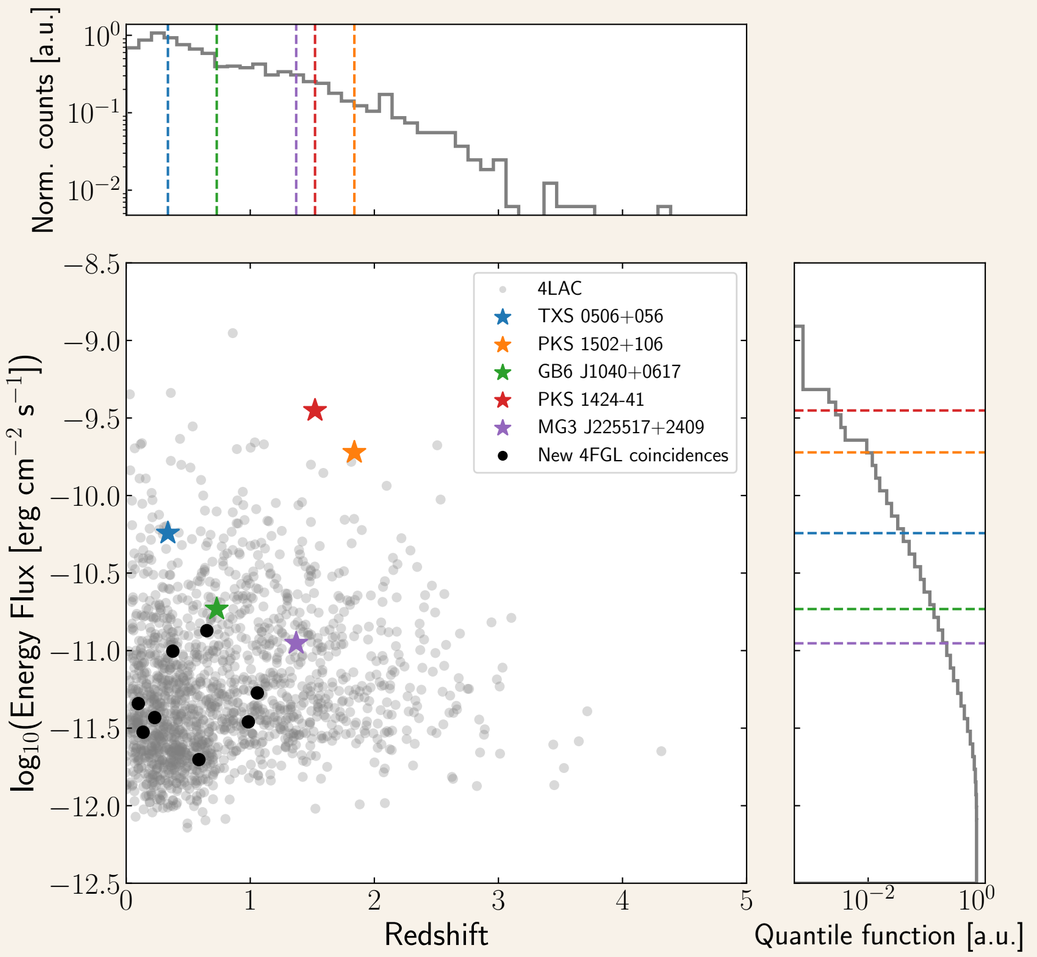
IC-190730A and PKS 1502+106
Flaring: No
Franckowiak, SG et al. 2019



IC-200107A and BZB J0955+3551
Flaring: No
Paliya et al. 2020

Blazars as high-energy neutrino sources

- Expected simultaneous activity is not always observed!
- Alternative tracer: **intrinsic gamma-ray properties?**
- Necessary to select well-reconstructed alerts:
  - RS1.0: median area HESE (5.6 deg^2)
  - RS2.0: median area Gold (5.4 deg^2)
- 16 well-reconstructed events have a single LAT counterpart.
- We also include 2 neutrino-blazar candidates proposed in MWL studies.
- Total sample of 18 blazars:
  (3 FSRQ, 9 BL Lac, 6 BCU)

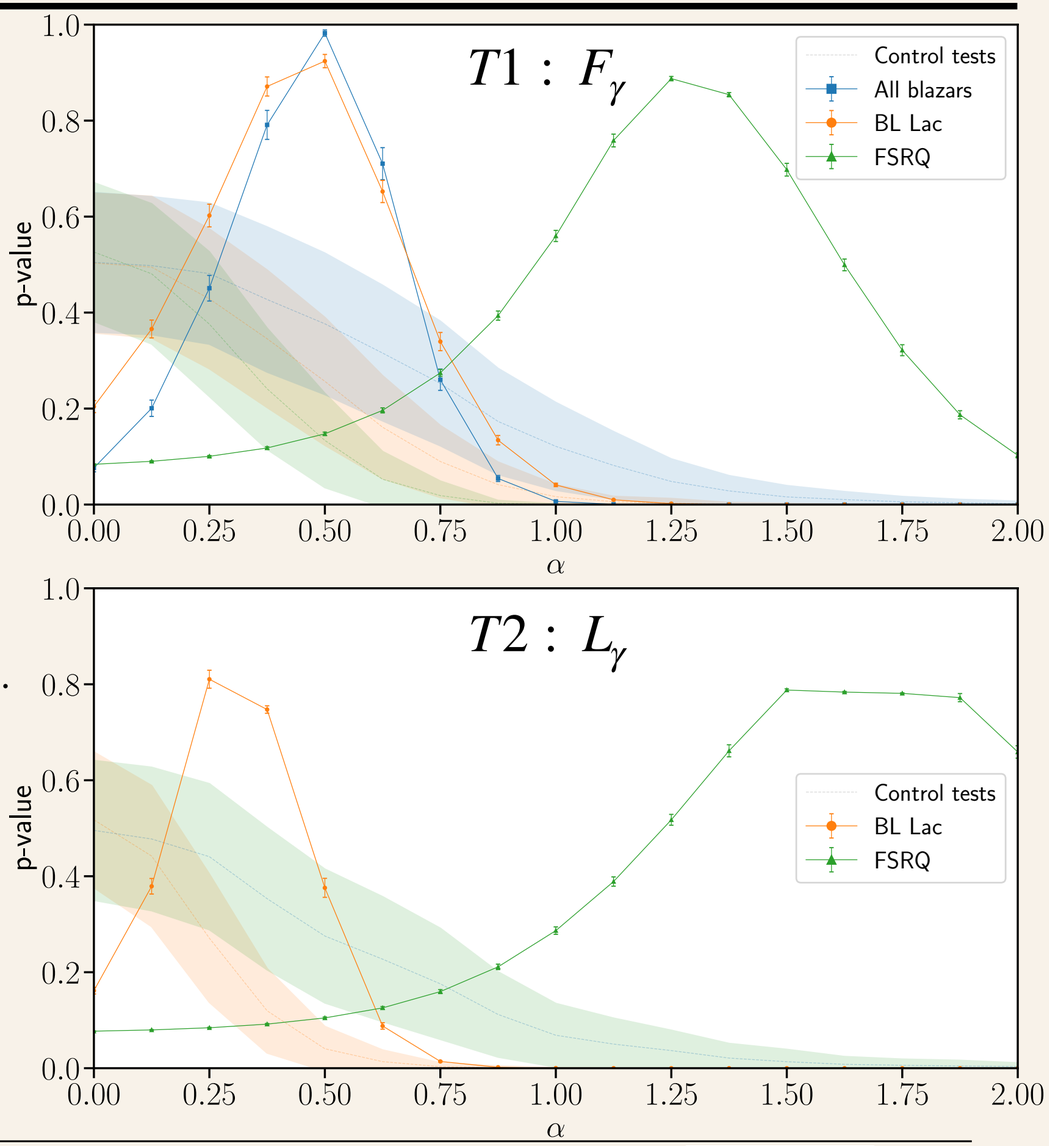


(SG et al. 2024)

Testing the gamma-ray / neutrino connection

(SG et al. 2024)

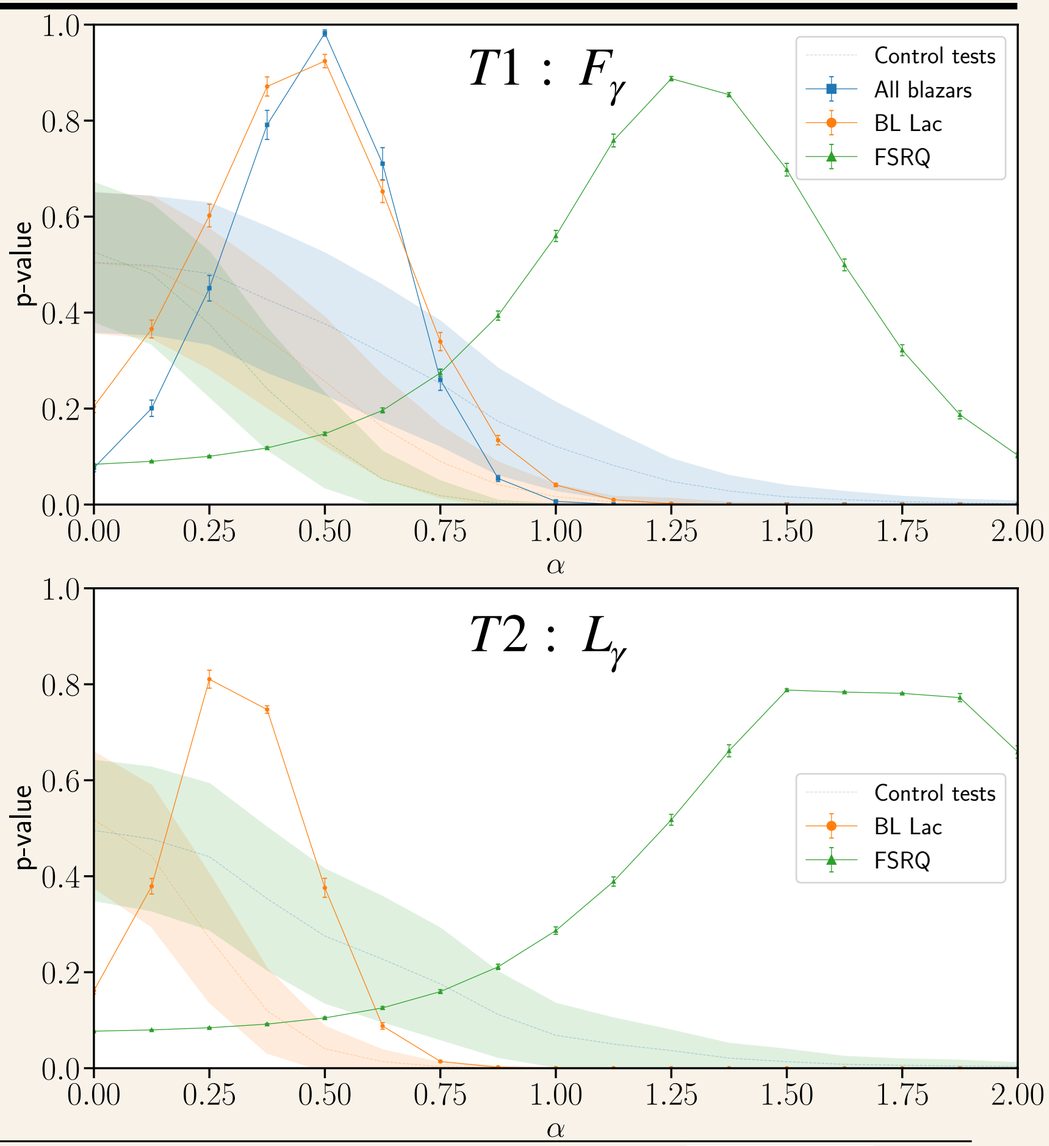
- Two ways to test the general relation $L_\nu \propto L_\gamma^\alpha$
  - **T1**: Use gamma-ray energy flux as proxy for luminosity.
  - **T2**: Use gamma-ray luminosity for sources with measured redshift.
- We test a grid of α values from 0 to 2 (steps of 0.125)
- For each α:
  - Draw a weighted random distributions from 4LAC-DR2 with $p_i = \frac{F_i^\alpha}{\sum_i F_i^\alpha}$
  - Apply a 2-sample K-S test between the neutrino candidates distribution and the weighted distribution sampled from 4LAC-DR2.
  - Each test repeated 10^3 times for average p-value and standard deviation.
- CONTROL TEST:
  - Repeat the same exercise 10^3 times for each α using randomly sampled of dummy neutrino blazars, with same size as the original samples.



Testing the gamma-ray / neutrino connection

(SG et al. 2024)

- Theoretical expectations for the lumionsity relation depend on the blazar class.
  - Discussed in several works (e.g. Murase & Waxman 2016, Tavecchio & Ghisellini 2015, Murase+ 2013, Petropolou+ 2015)
- **FSRQ**:
  - Photomeson production efficiency $f_{p\gamma} \propto L_{AD}^{1/2}$ (from optical-IR data)
    - In the simplest assumption $L_{CR} \propto L_{AD}$
    - Therefore $L_\nu \propto L_{CR} \times L_{AD}^{1/2} \propto L_\gamma^{3/2} \quad \rightarrow \quad \alpha = 1.5$
- **BL Lac:**
  - Given the absence of external photon fields, the main target is the synchrotron radiation in jets.
  - Therefore, in general less constrained and can typically vary between
    - $\alpha = 1$ (target photons only dependent from the low-frequency bump)
    - $\alpha = 2$ (target photons proportional to the high-frequency bump)



Summary

- Although likely not responsible for the majority of the neutrino flux, individual gamma-ray blazars can still be promising candidate counterparts of high-energy neutrinos.
- The realtime programs are essential to identify interesting candidates and trigger multi-wavelength campaigns.
  - *Fermi*-LAT still plays a key role in these realtime activities.
- The blazar PKS 0735+17 is one of the most recent examples of candidate found in spatial and temporal coincidence.
  - Theoretical modelings find efficient neutrino production during the bright gamma-ray flare.
- After several years, we have a large statistics of alerts, but only a small fraction pinpoints to single sources.
- While the theoretical and observational evidences of gamma-ray/neutrino connection are still debated, the intrinsic gamma-ray properties of neutrino blazar candidates can be an alternative tracer.
  - First trends in the gamma-ray/neutrino correlation can be observed in the population of neutrino blazar candidates, but a larger number of candidates is necessary.