Patterns in the multi-wavelength behavior of neutrino emitting blazar candidates

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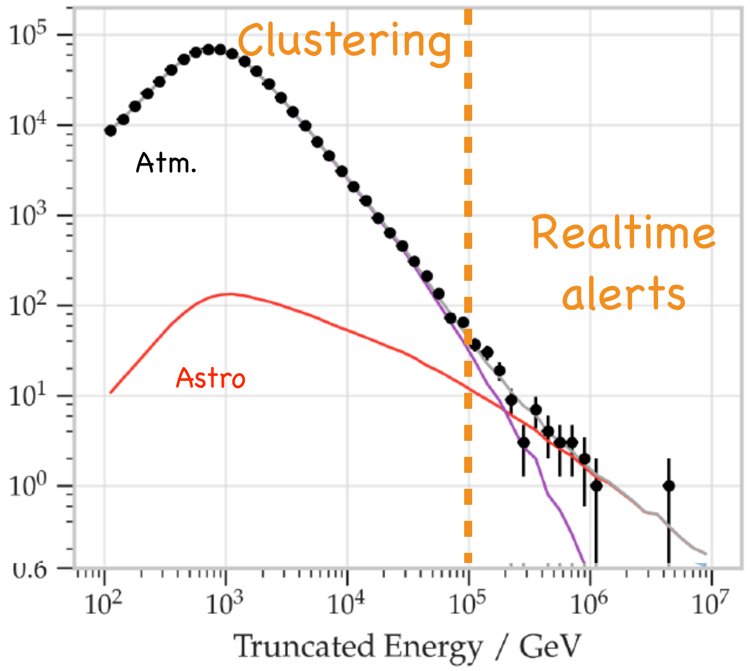
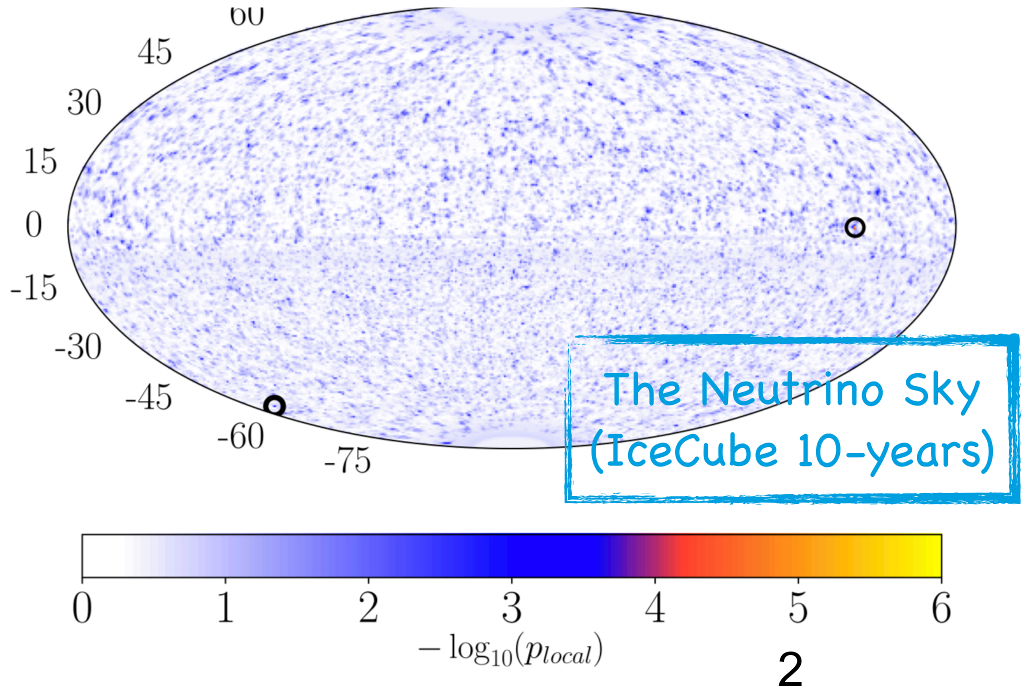
The sources of the IceCube diffuse flux

Motivation behind this work

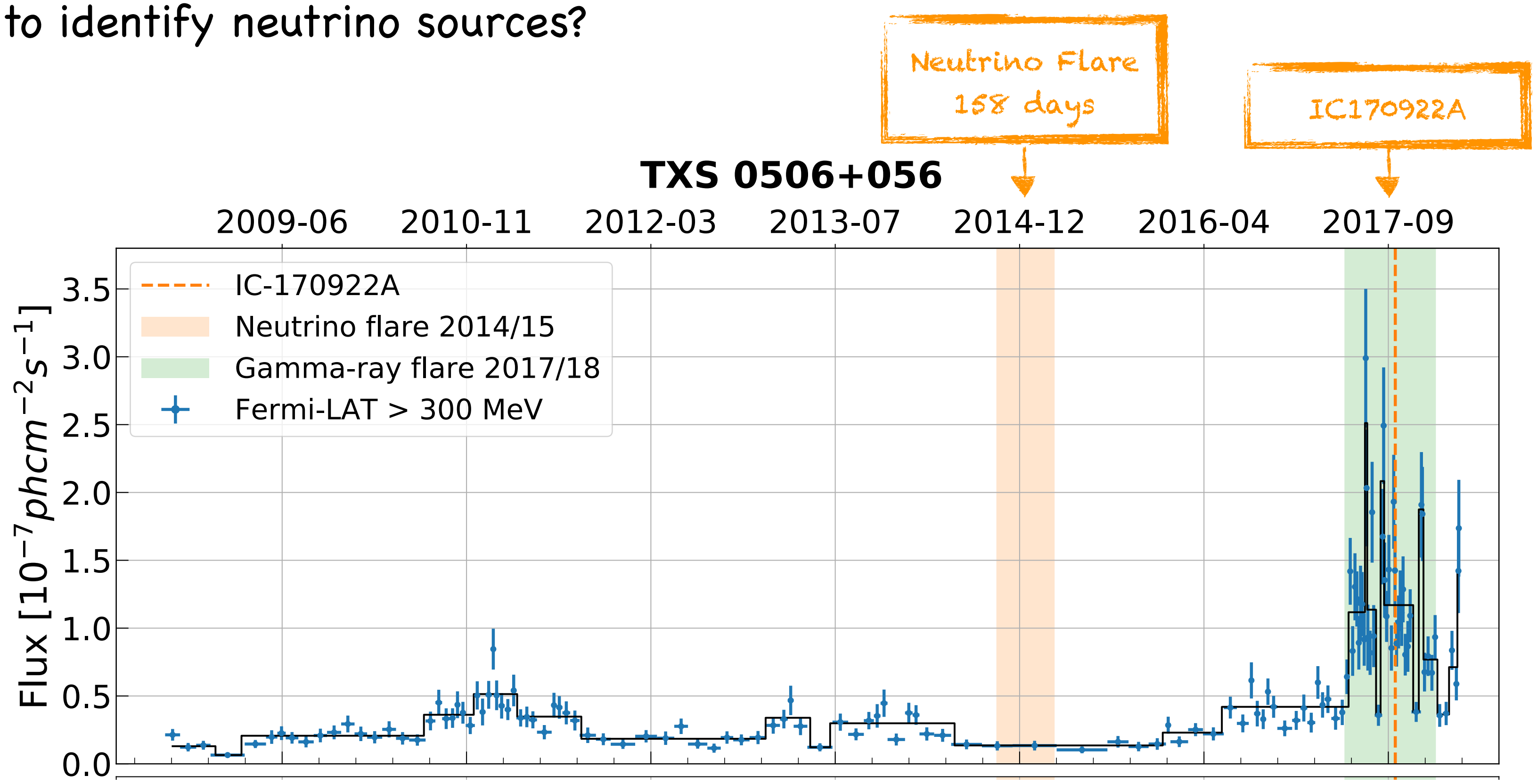
- An astrophysical neutrino flux was detected by IceCube in 2013
- Two different strategies in the point-sources search:
  - Single detection of high-energy events (Realtime alerts since 2016)
  - Clustering of low-energy events with high atmospheric background
- Several MWL efforts to identify the counterparts of these events:
  - The gamma-ray blazar TXS 0506+056 is so far the most significant candidate counterpart to IceCube neutrino events





The puzzling case of TXS 0506+056

- We have two different behaviors in gamma-rays for TXS 0506+056 in coincidence with a single high-energy neutrino and with a 'neutrino flare'. Is it always the case?
- Are gamma-rays the best tracer to identify neutrino sources?

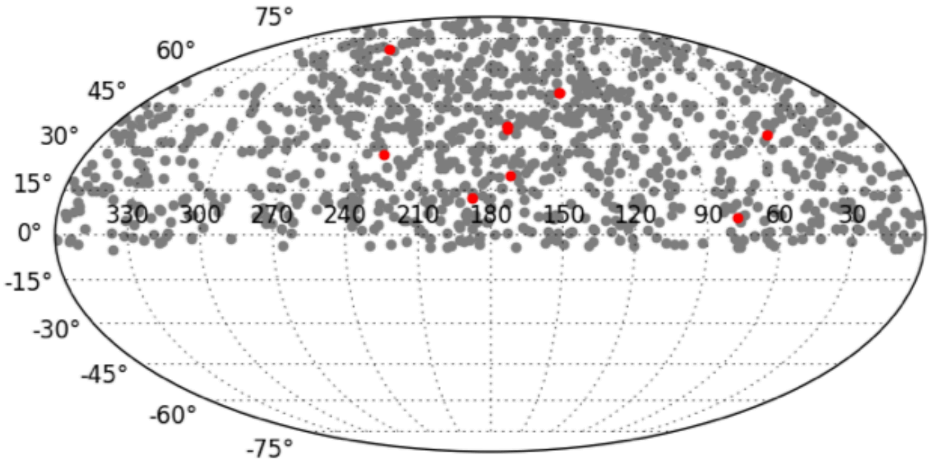


SG, S. Buson, A. Franckowiak et al. 2019, ApJ 880 103

Neutrino Flares

Spatial and temporal clusterings of neutrino events

- We used the sample of 10 blazars with the most significant 'neutrino flares' found in (O'Sullivan and Finley, 2019)
- Neutrino flare durations span from ~seconds to ~100 days
- No remarkable gamma-ray/MWL simultaneous activity



(O'Sullivan and Finley 2019, arXiv:1908.05526v1)

A. Franckowiak, SG et al. 2020, ApJ 893, 2, 162

Source Name	4FGL Name	Class	redshift	T_0 [MJD]	T_w [days]	p_γ	$T_{\gamma,\nu}$[MJD]	L_γ [erg]
Neutrino flare candidates								
4C +20.25	J1125.9+2005	FSRQ	0.133	56464.1	5.2	0.64	[56369.45, 57248.31]	1.6×10^{44}
CRATES J112916+370317	J1129.1+3703	BL Lac	0.445	56501.385	6.0×10^{-2}	0.45	[56404.68, 57066.59]	2.9×10^{46}
MG2 J112758+3620	J1127.8+3618	FSRQ	0.884	56501.385	6.0×10^{-2}	0.24	[56482.90, 56555.93]	5.5×10^{46}
TXS 0506+056	J0509.4+0542	BL Lac	0.336	57000	120	0.92	[56965.28, 57089.28]	2.2×10^{46}
1H 0323+342	J0324.8+3412	nlsy1	0.061	57326.2938	1.7×10^{-3}	0.08	[57326.10, 57333.17]	2.0×10^{44}
RBS 1467	J1508.8+2708	BL Lac	0.27	57440	170	0.53	[56474.88, 58633.01]	6.3×10^{44}
S4 1716+68	J1716.1+6836	FSRQ	0.777	57469.17919	5.4×10^{-5}	0.48	[57378.18, 57510.76]	2.1×10^{46}
M 87	J1230.8+1223	radio galaxy	0.00428	57730.0307	2.7×10^{-3}	0.55	[57724.77, 57847.51]	6.9×10^{41}
GB6 J0929+5013	J0929.3+5014	BL Lac	0.37	57758.0	1.2	0.44	[57647.78, 57759.66]	5.6×10^{45}
1ES 0927+500	J0930.5+4951	BL Lac	0.187	57758.0	1.2	0.49	[57031.36, 58633.01]	2.2×10^{44}

Neutrino Flares

Spatial and temporal clusterings of neutrino events

- The NLSy1 galaxy 1H 0323+342 (z = 0.061) shows mild flaring activity coincident with the neutrino flare
- Probability to find the source in a higher gamma-ray state is p_γ = 8%

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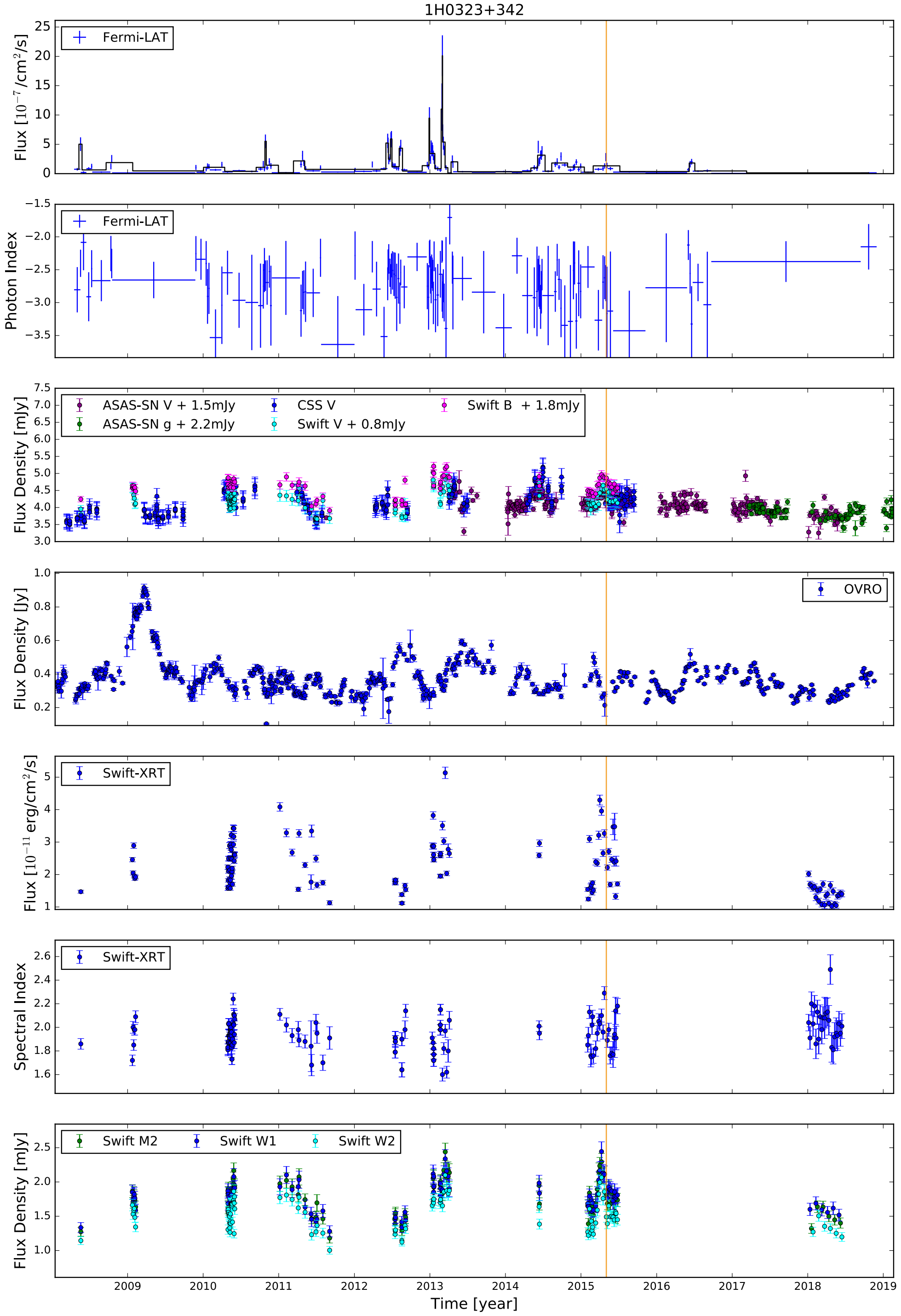
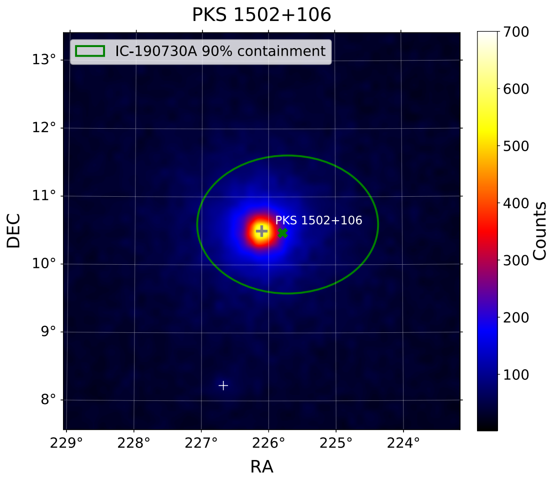


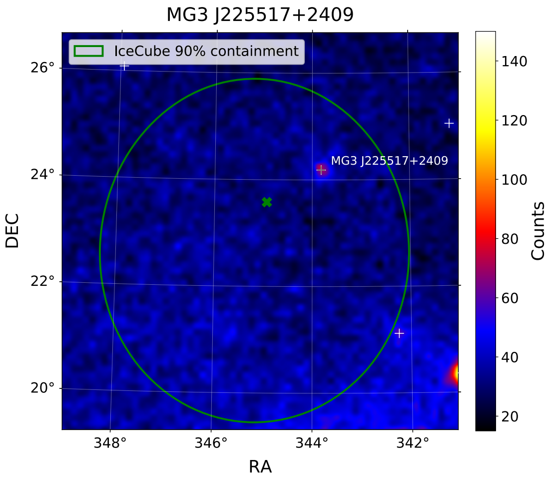
DESY.

Single HE neutrinos coincidences

Counterparts to realtime neutrino alerts

- Selection criterium: 90% error less than 5 deg^2
  - 44 out of 75 events survive after selection
- 6 coincident sources (including TXS 0506+056 and GB6 J1040+0617)
- MG3 J225517+2409 (Antares Coll. 2019) added to the list, but would not pass the selection ($A_{90\%}$ > 5 deg^2)





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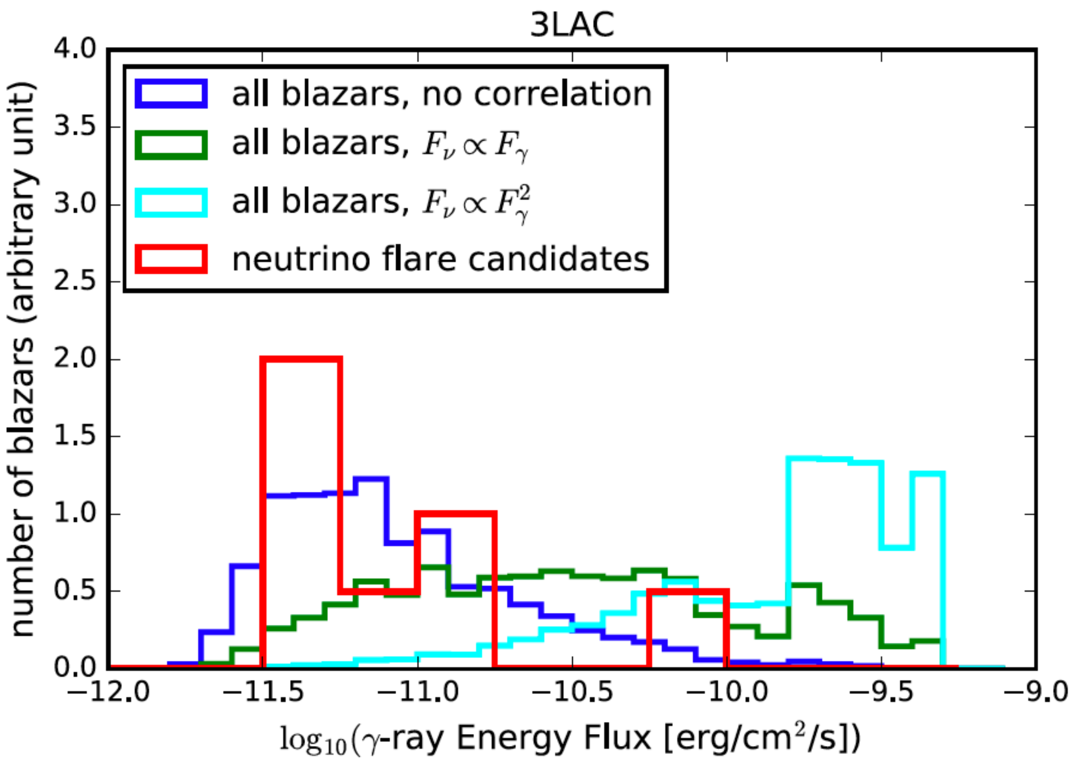
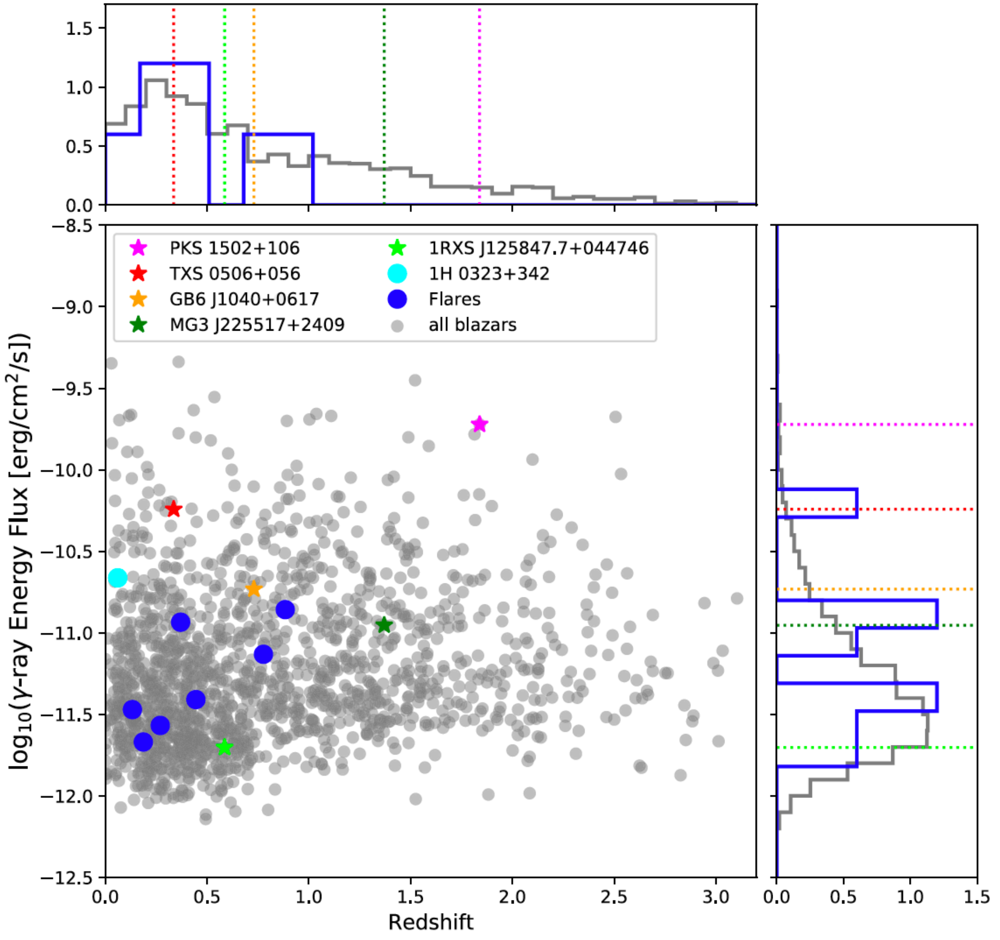
Source Name	4FGL Name	Class	Redshift	T_0 (MJD)	T_w (days)	p_γ	$T_{\gamma,\nu}$ (MJD)	L_γ (erg s^{-1})
				Single High-energy Neutrinos				
MG3 J225517+2409	J2255.2+2411	BL Lac	1.37	55,355.49	···	0.04	[55,346.73, 55,403.54]	1.3×10^{47}
GB6 J1040+0617	J1040.5+0617	BL Lac	0.73	57,000.14311	···	0.17	[56,997.67, 57,055.08]	4.6×10^{46}
1RXS J125847.7–044746	J1258.7–0452	BL Lac	0.586	57,291.90119	···	···	···	2.9×10^{45}
GB6 J0244+1320	J0244.7+1316	BCU	···	57,695.38	···	···	···	···
TXS 0506+056	J0509.4+0542	BL Lac	0.336	58,018.87	···	0.009	[58,016.57, 58,019.94]	2.2×10^{46}
AT20G J175841–161703	J1758.7–1621	BCU	···	58,535.35	···	0.39	[58,304.43, 58,633.01]	···
PKS 1502+106	J1504.4+1029	FSRQ	1.839	58,694.8685	···	0.75	[58,603.54, 58,695.14]	4.7×10^{48}

Candidate neutrino sources as population

Connecting neutrino sources to their gamma-ray properties

- Candidate **neutrino-flare sources** show a good match with random distribution (p = 39%)
- Less well-described by energy-flux weighted distributions (p = 0.4%-2.1%)



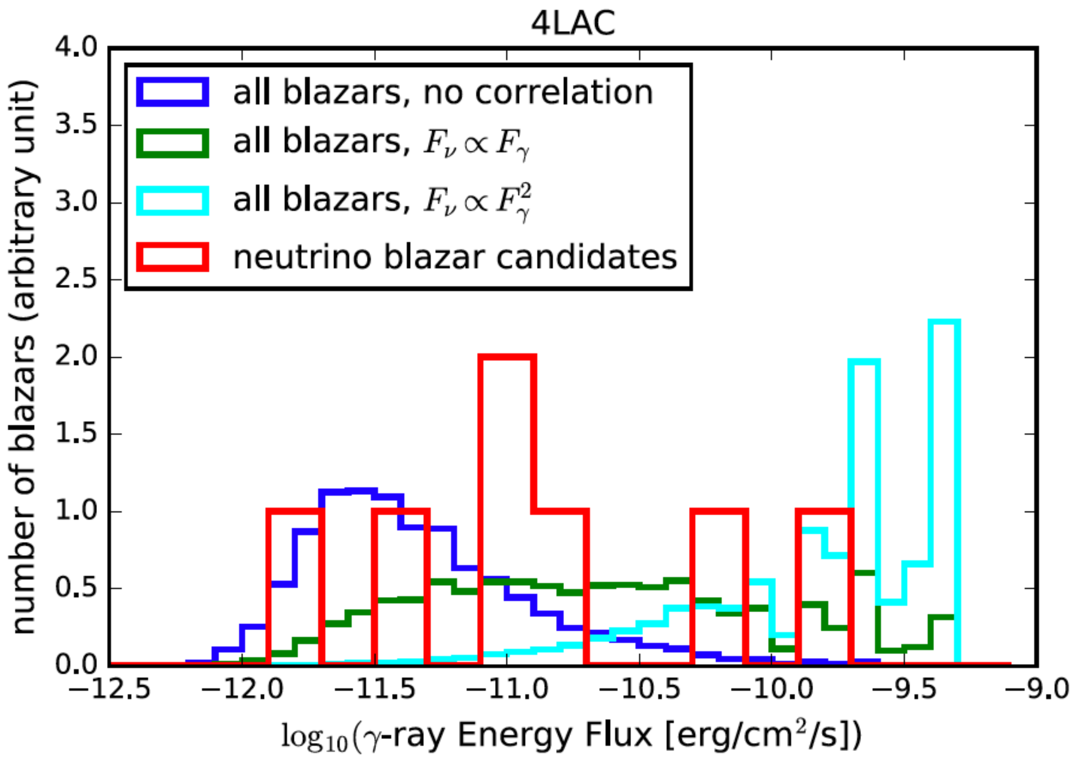


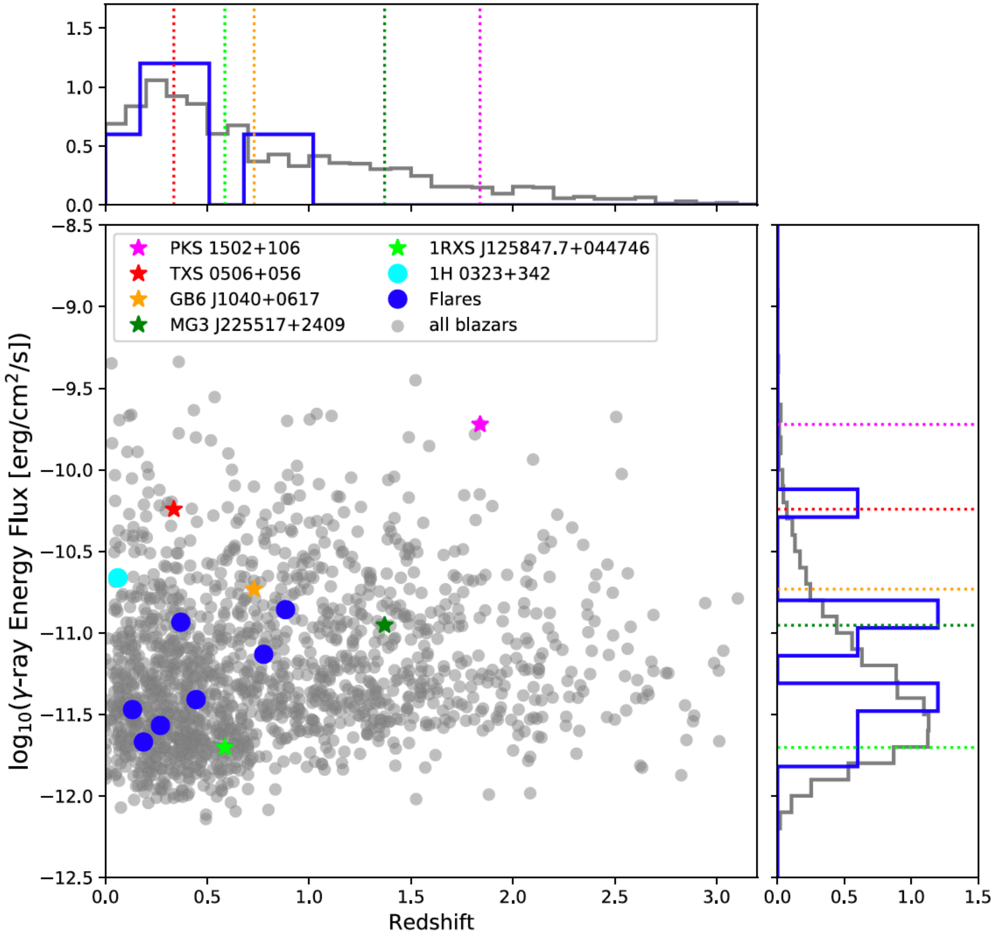
A. Franckowiak, SG et al. 2020, ApJ 893, 2, 162

Candidate neutrino sources as population

Connecting neutrino sources to their gamma-ray properties

- Candidate **single HE neutrino sources** show an indication of linear correlation with gamma-ray energy flux (p = 64%)
- Mismatch with quadratic energy-flux correlation (p = 0.03%)





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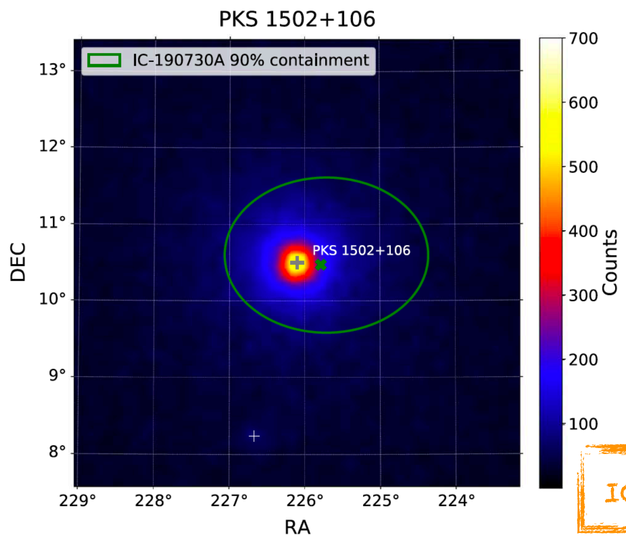
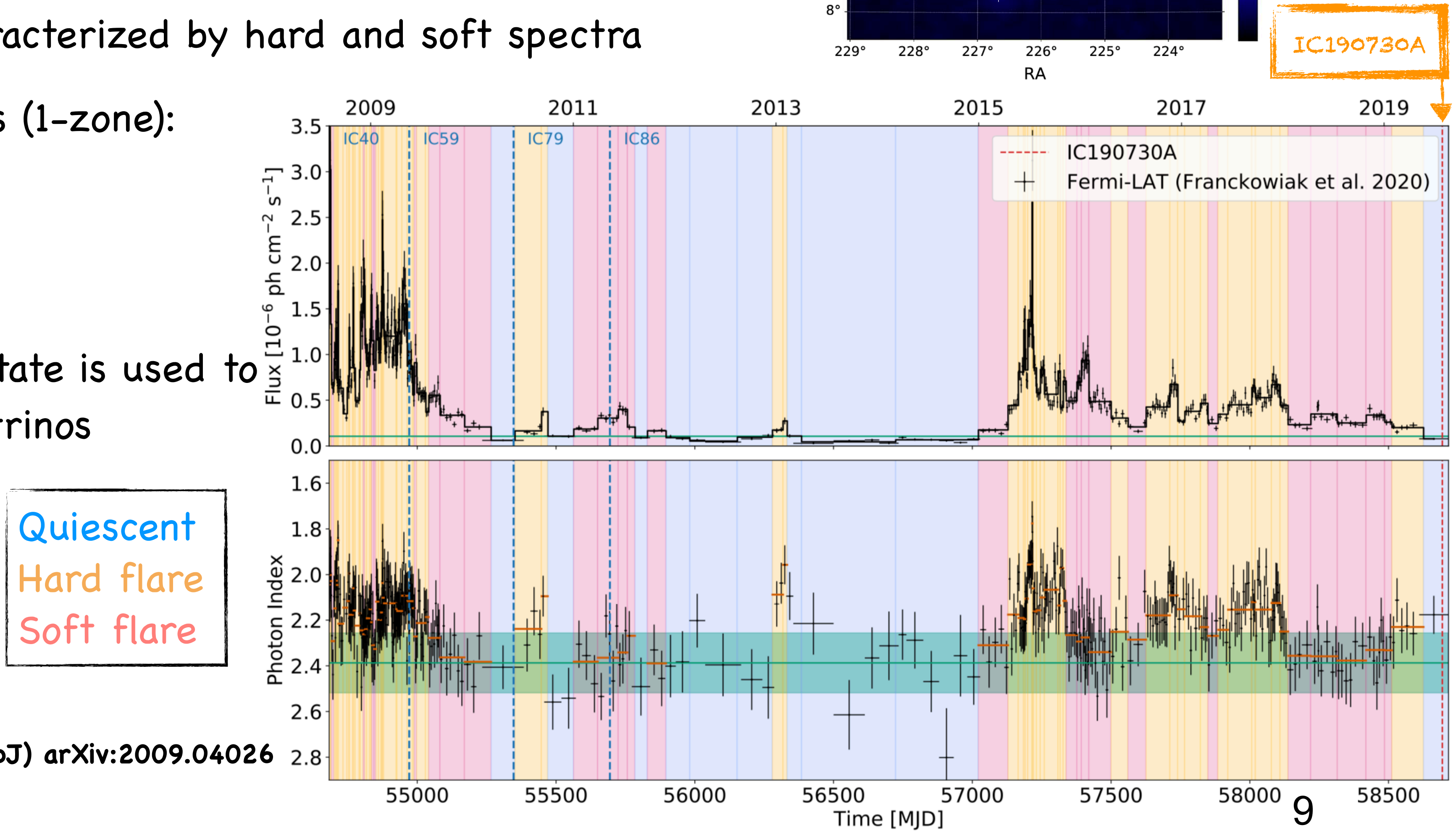
PKS 1502+106: an outstanding laboratory

Coincident with the HE event IceCube-190730A



- The 15th brightest LAT blazar (FSRQ at z = 1.84)
- In low gamma-ray state at the arrival of IC190730A
- Gamma-ray flares are characterized by hard and soft spectra
- SED model in two scenarios (1-zone):
  - Lepto-hadronic
  - Proton Synchrotron
- The total fluence in each state is used to compute the expected neutrinos

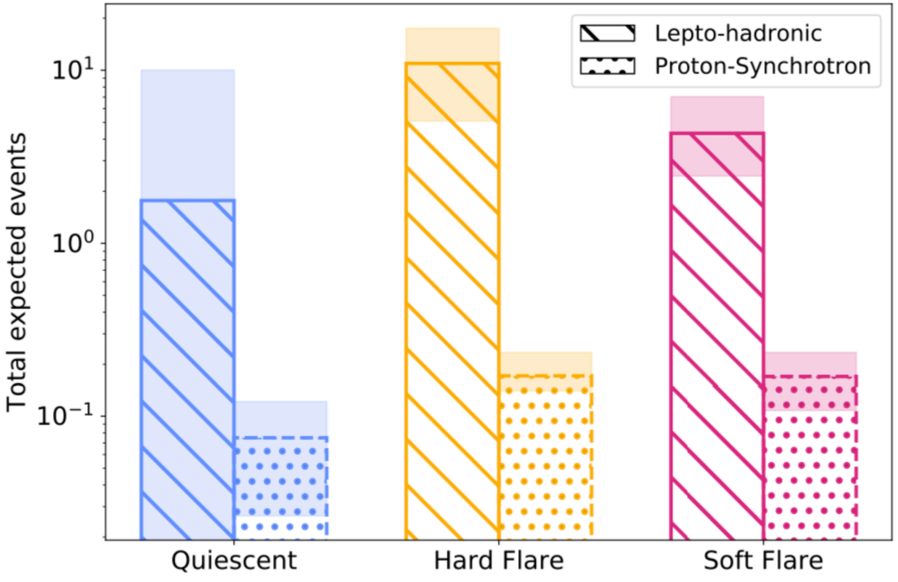


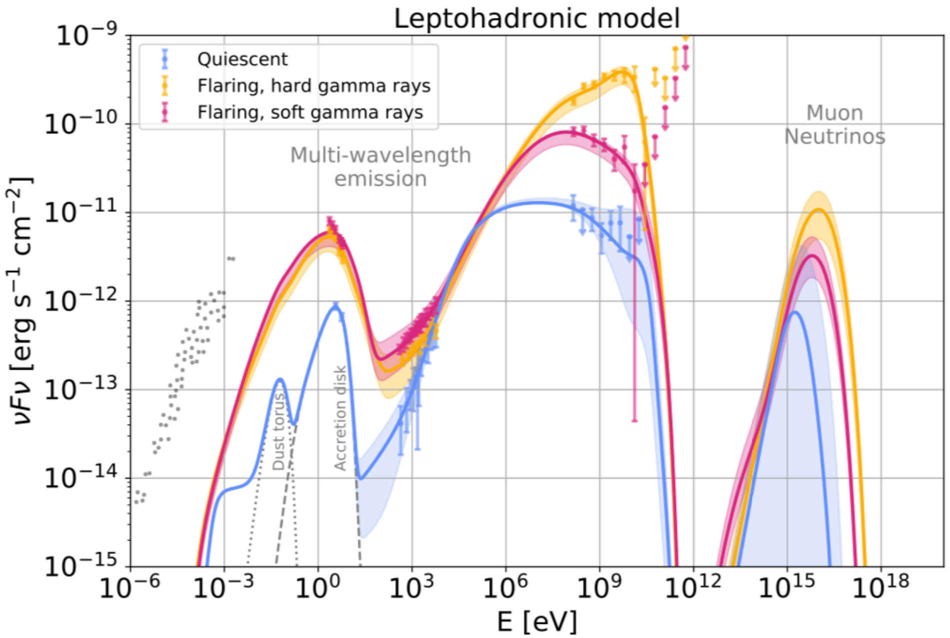
X. Rodrigues, SG et al. 2021, (accepted in ApJ) arXiv:2009.04026

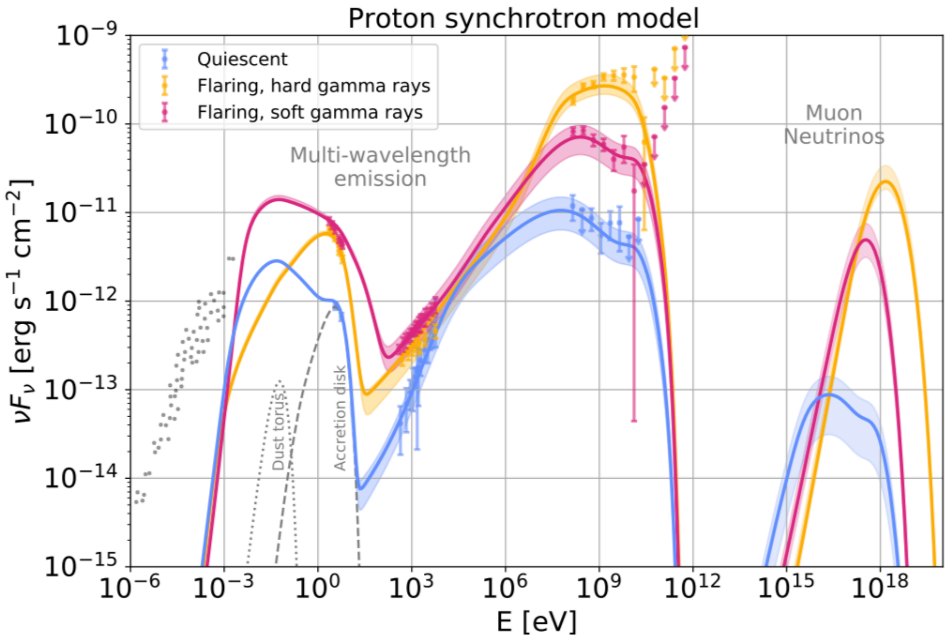
PKS 1502+106: an outstanding laboratory

Coincident with the HE event IceCube-190730A

- All models are compatible with PKS 1502+106 as a neutrino source
    - Flaring states are not properly fitted in pure leptonic scenario
- Proton synchrotron models have low expected rate (~0.14 events)
    - Consistent with a single observed event (e.g. Eddington bias)
- Mild tension for the high efficiency of lepto-hadronic models in flaring states (up to ~10 events)







What do we learn from PKS 1502+106?

Signatures of hadronic interactions

- The quiescent state is consistent overall with a pure leptonic model (left) except for **E > 1GeV**
- The proton-synchrotron model describes the full second SED hump
- The two models require very different source properties, starting from the magnetic field (B ≤ 1G, B ≥ 10G respectively)

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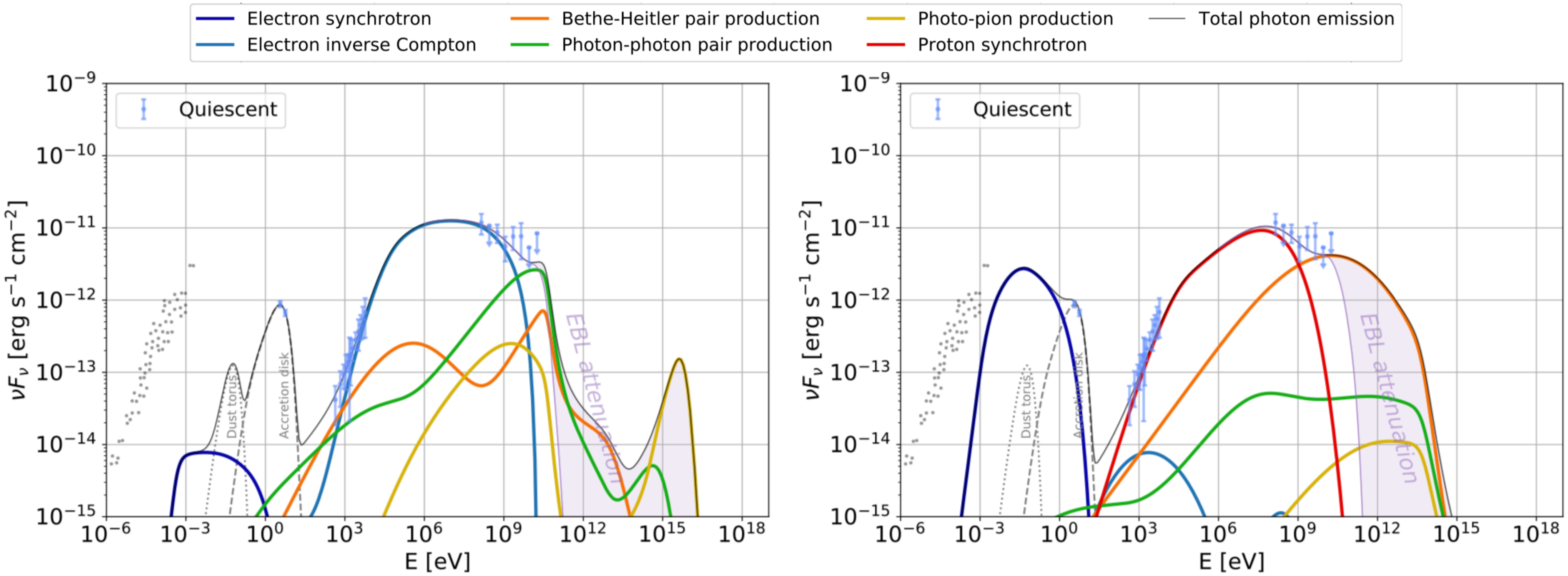

What do we learn from PKS 1502+106?

Signatures of hadronic interactions

- For flaring states, the **X-ray band** is a good tracer to rule-out purely leptonic models
  - e.m. cascades initiated by HE protons

- **Simultaneous multi-wavelength observations are crucial to probe these models. Findings in PKS 1502+106 are confirming important science-cases that require synergies between X-Ray and gamma-ray observatories up to VHE.**

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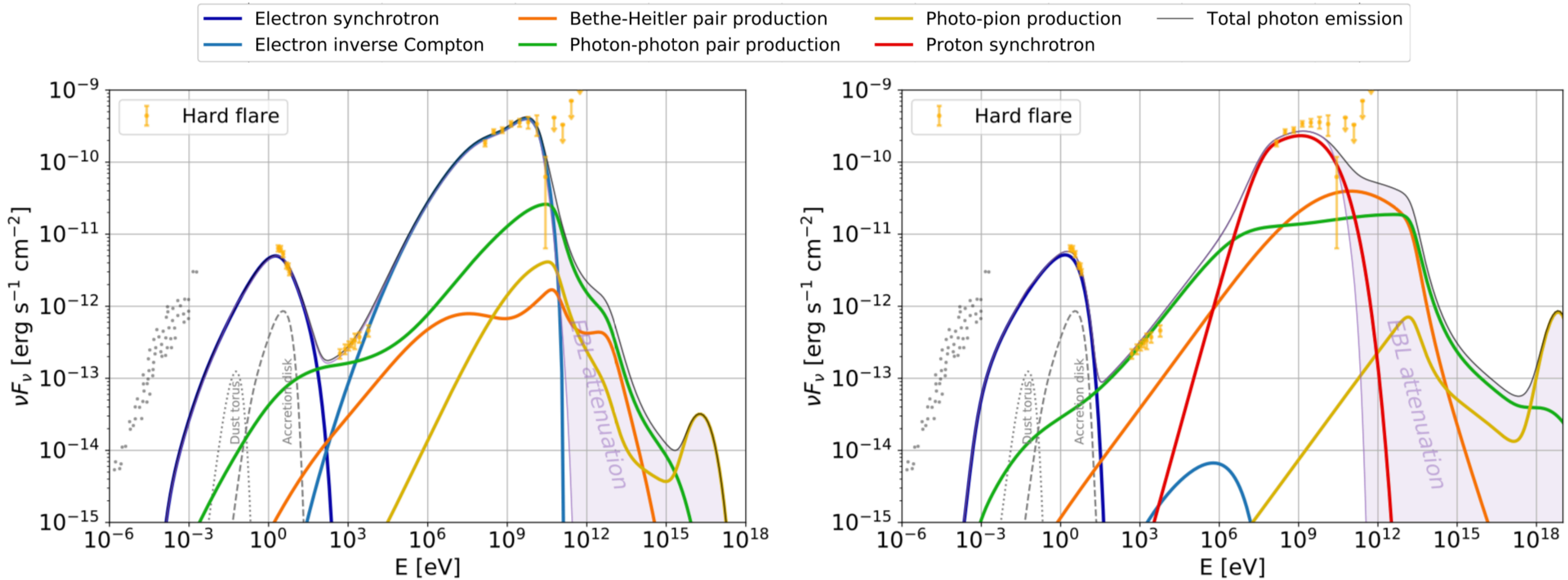

Summary

- We have studied the behavior of potential neutrino counterparts individually and as a population:
  - Sources coincident with high-energy neutrinos are in agreement with a linear correlation between neutrino and gamma-ray flux
  - Neutrino flare source candidates are in agreement with the assumption of no correlation between neutrino and gamma-ray flux
- The study of candidate neutrino source PKS 1502+106 shows the key role of Fermi-LAT in the identification of neutrino counterparts
  - Spectral features in simultaneous observations in the gamma and X-ray bands are essential to probe hadronic interaction models in blazars

Thank you.