Multiwavelength Follow-up Observations of Astrophysical Neutrino Events

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Celebrating 20 Years of Swift Discoveries
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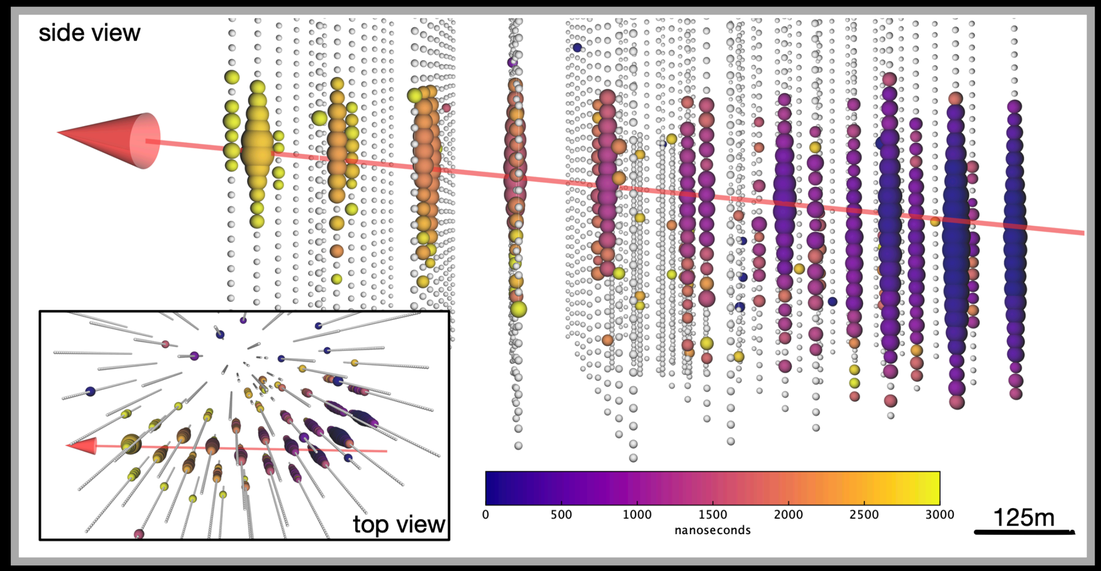
IceCube and Astrophysical Neutrinos

- IceCube Neutrino Observatory has detected a high-energy diffuse neutrino flux.
  - No sources have been identified at the 5σ level.
  - 4.2σ association of neutrino excess with NGC 1068 announced in 2022.
- IceCube real time alert system allows for multiwavelength follow-ups.
  - Gold events have ~50% average likelihood of being astrophysical in origin.

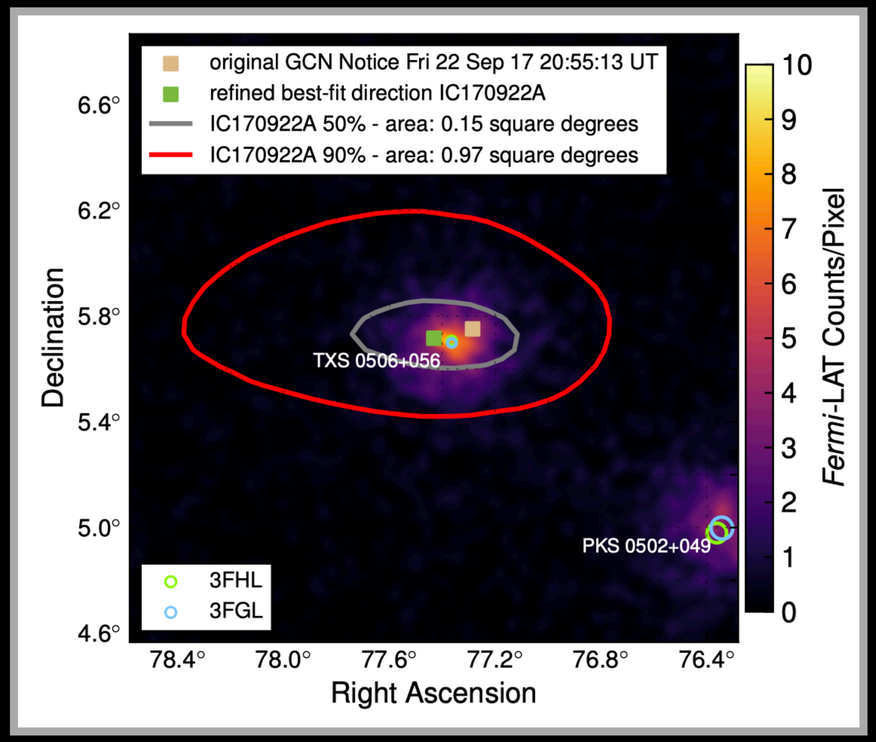


Event display for the neutrino event IC170922A

Aartsen M. G., et al., 2018, Science, 361, eaat1378

Counterparts to Astrophysical Neutrinos

- The blazar TXS 0506+056 was found to be in the 50% containment region of the neutrino alert IC170922A.
- Archival analysis found evidence of a "neutrino flare" at the 3.5σ level at the location of this source in 2014-2015.
- Connections between astrophysical neutrinos and high energy photons could help explain acceleration mechanisms in AGN jets.



Fermi-LAT observation of TXS 0506+056 showing its location within the 50% containment region of IC170922A

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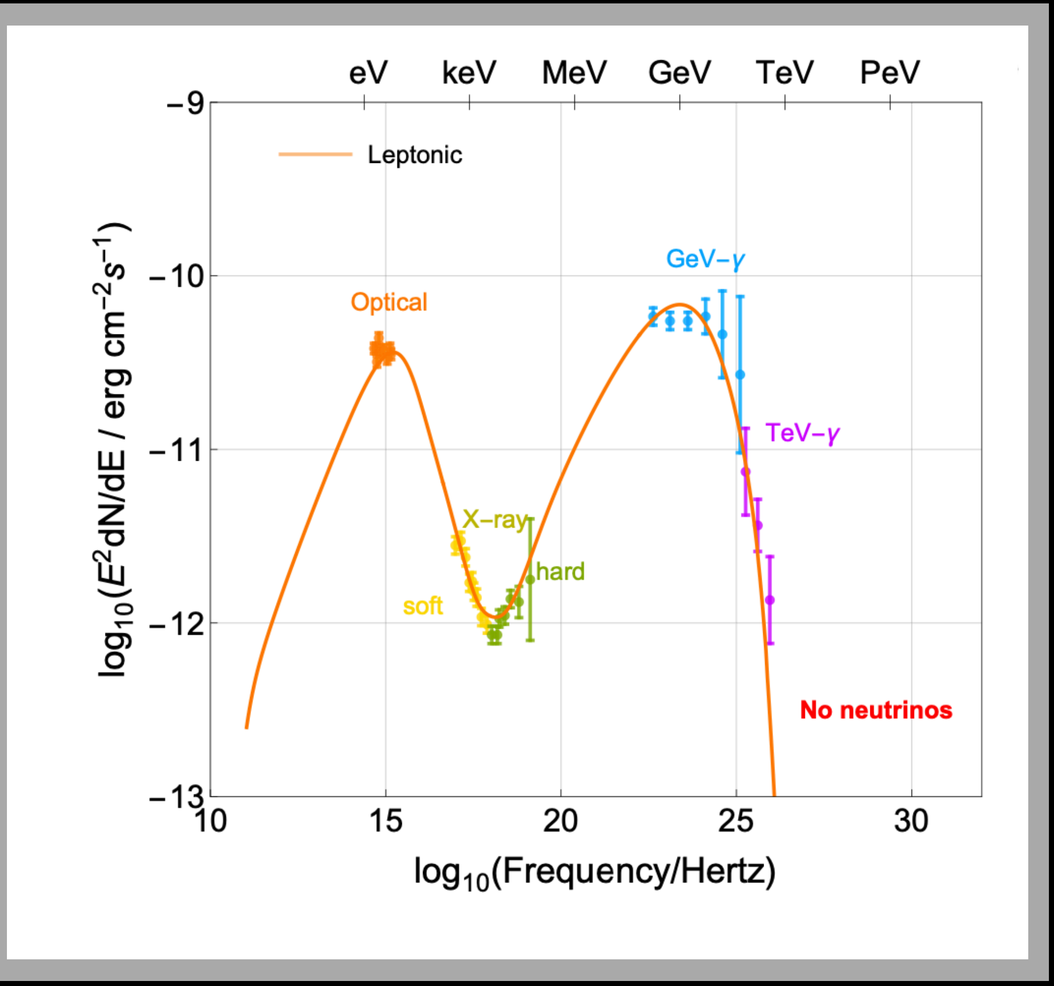
Leptonic vs. Hadronic Models



Gao, S., Fedynitch, A., Winter, W., & Pohl, M. 2019, Nature Astronomy, 3, 88

- Leptonic Model
  - Lower energy hump modeled by electron synchrotron radiation.
  - Higher energy hump modeled by inverse Compton scattering.
  - Fits EM observations well.
  - Has no mechanism for producing neutrinos.

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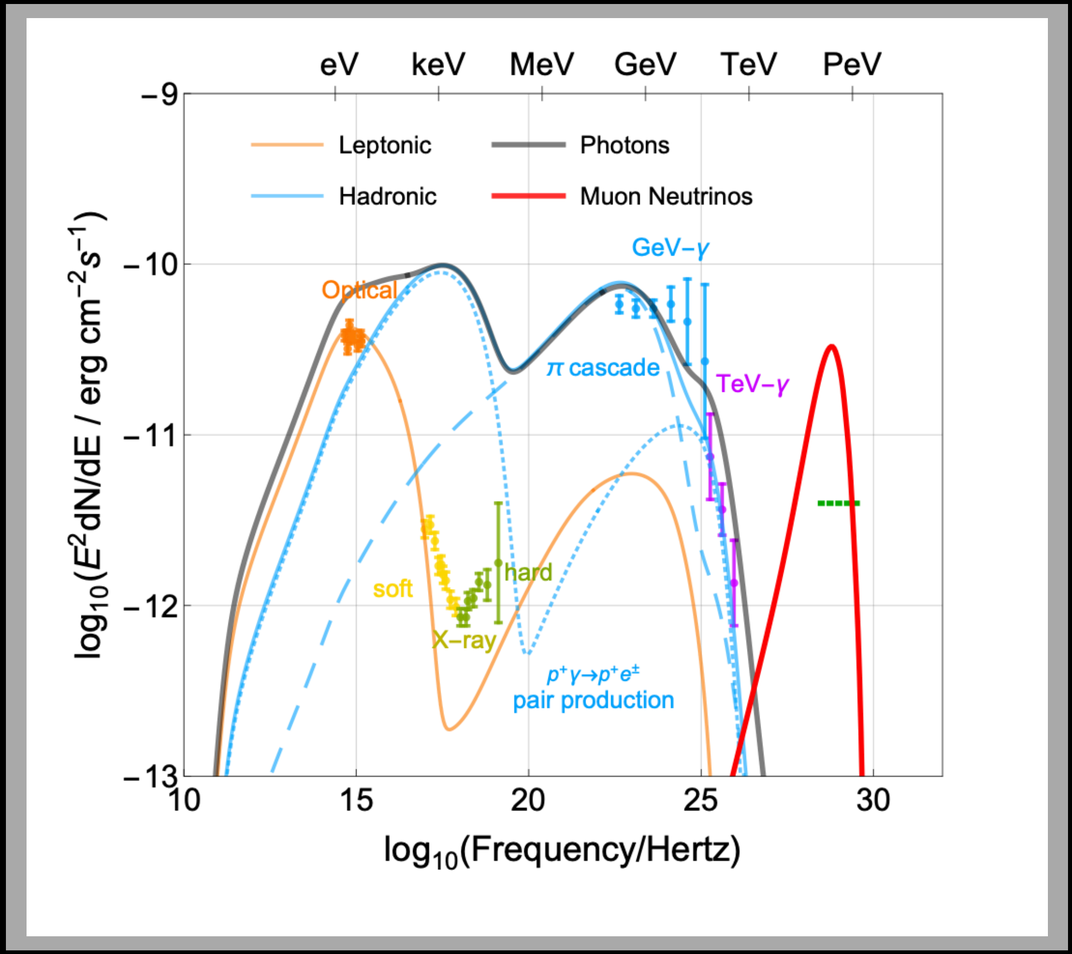

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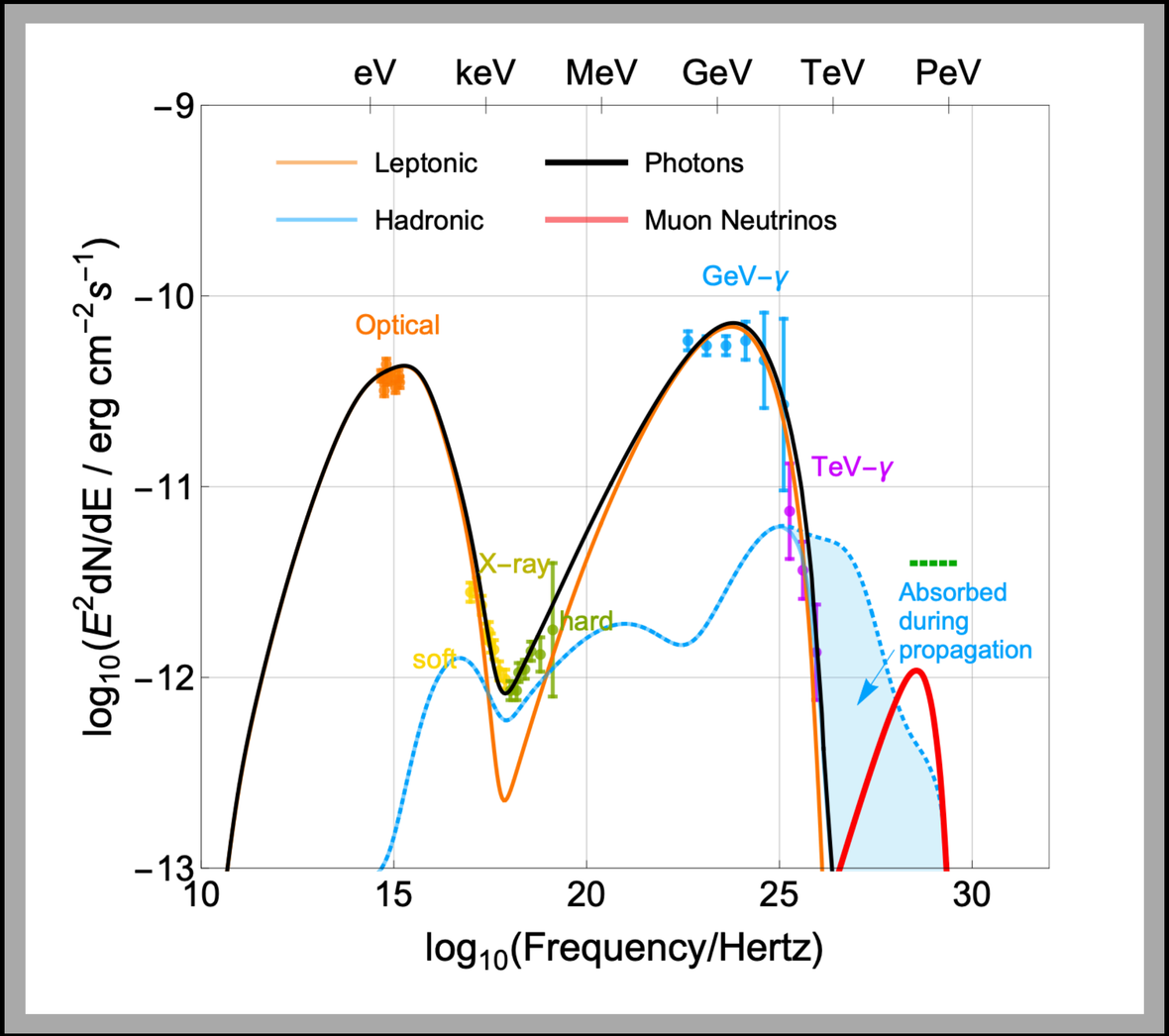
- Hadronic Model
  - Lower energy hump modeled by electron synchrotron radiation.
  - Higher energy hump modeled by proton interactions producing π^0 and $\pi^{\pm}$.
    - Charged pion decay products include neutrinos.
  - Overestimates EM flux, especially in X-rays and ~MeV gamma-rays

Leptonic vs. Hadronic Models

- A hybrid lepto-hadronic model can solve the issues found in both individual models.
- X-rays are key in constraining the contributions of both model components.



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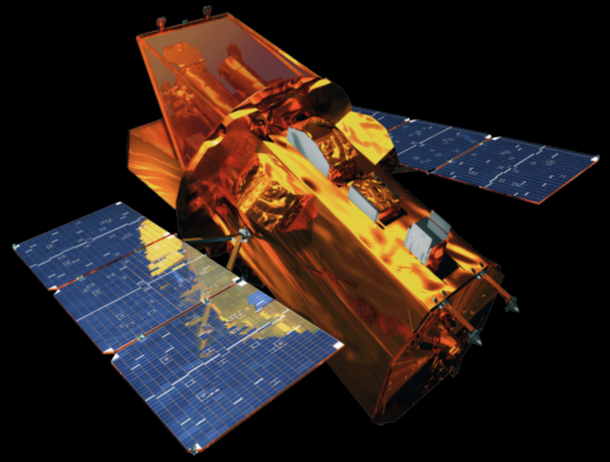
Swift Follow-up Campaigns

- Follow-up program targeting sources similar to TXS 0506+056:
  - Began in Swift Guest Investigator Cycle 16 (2020), and continues to present.
  - Prompt observations of Fermi-detected sources located within the error region of an IceCube Gold alert.
    - Collect 4 ks as quickly as possible after neutrino detection.
    - 4 ks more ~48 hrs later to look for fast variability.
    - 4 ks more ~few weeks later to look for longer time-scale variability.



NASA E/PO, Sonoma State University/Aurore Simonnet

Swift Follow-up Observations

Neutrino Event	Signalness	Source
IC190704A	48.6%	**1WHSP J104516.2+275133**
IC190730A	67.2%	**PKS 1502+106**
IC200530A	59.2%	**4FGL J1702.2+2642**
		4FGL J1659.0+2627
IC201114A	56.2%	**4FGL J0658.6+0636**
IC211208A	50.2%	**PKS 0735+17**
IC220425A	49.7%	**NVSS J175236-101145**
IC220624A	60.9%	**Fermi J1458.0+4119**
IC220629A	30.1%	**IceCube-220629A**
IC221223A	79.5%	**TXS 2320+343**
IC230724A	52.7%	**4FGL J0212.2-0219**
IC231027A	62.5%	**4FGL J1740.0+4737**
		4FGL J1750.2+4704
		4FGL J1747.9+4704
IC231211A	27.7%	**PKS 2047+098**
IC240105A	30.1%	**PKS 0446+11**
IC240307A	60.6%	**4FGL J1557.2+3822**
IC240424A	50.8%	**4FGL J2149.6+0323**

- Signalness provided by IceCube gives a measure of how likely it is that each neutrino is of astrophysical origin.
- Swift ToO observations typically performed within hours of neutrino detection.

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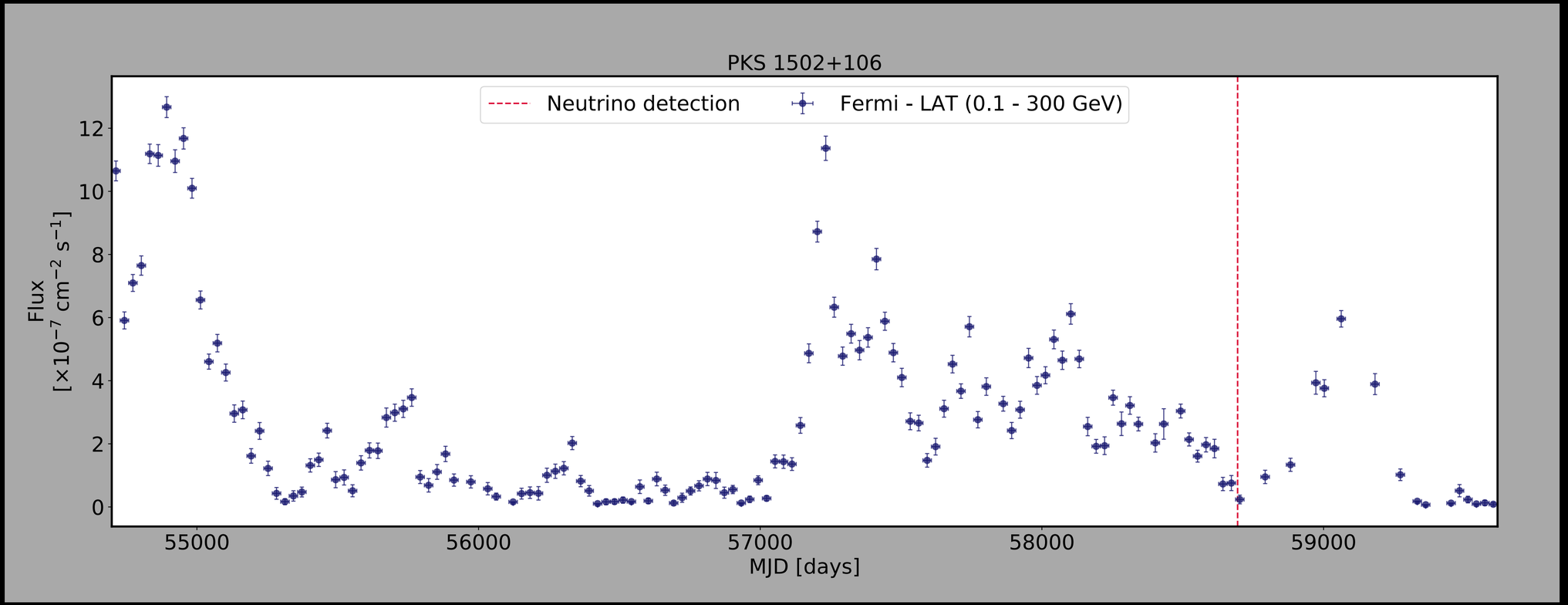
IC190730A and PKS 1502+106



- High energy neutrino detected during a period of decreasing gamma-ray and X-ray flux between two potential flares.

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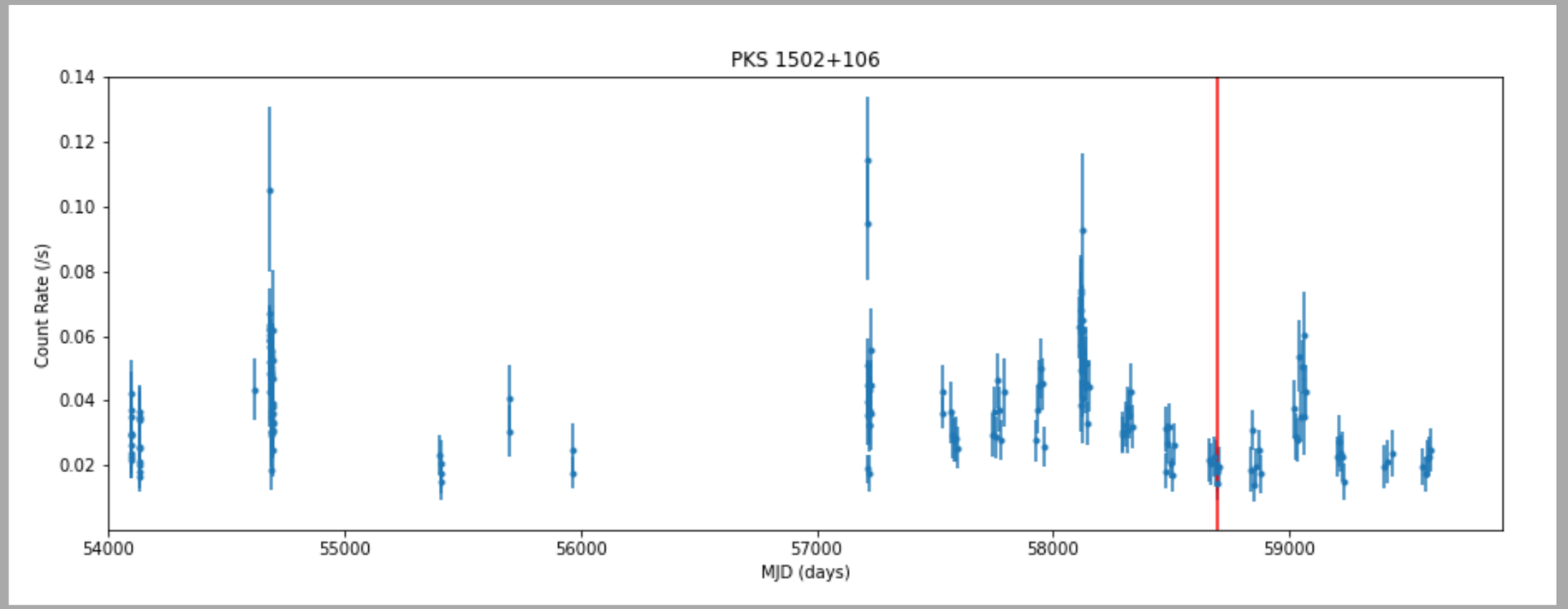

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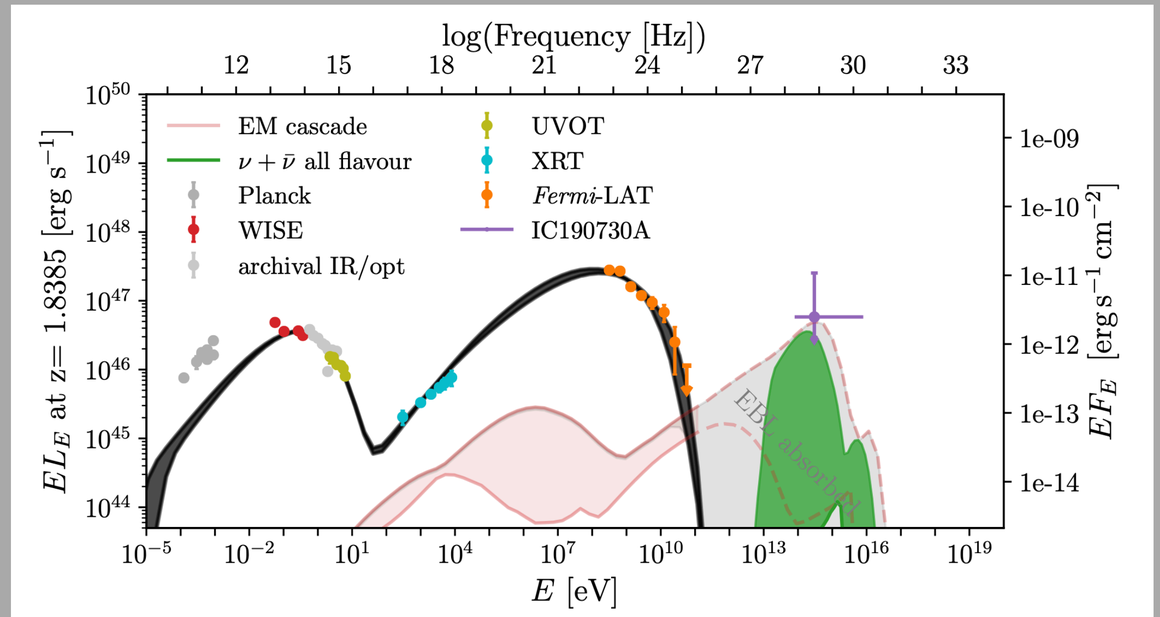
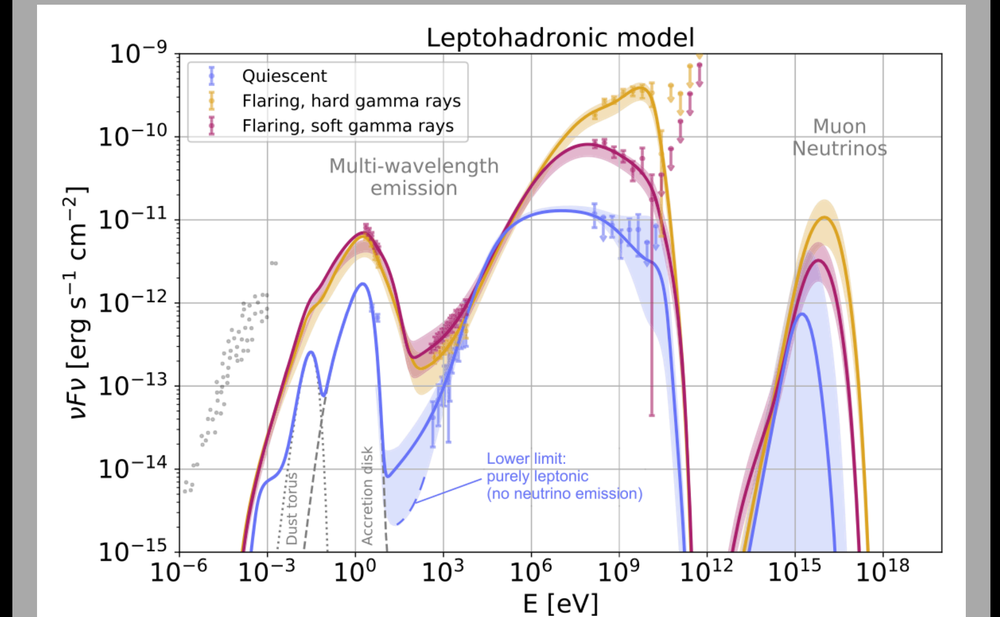


Oikonomou et al. 2021



- Oikonomou et al. 2021 found that a leptohadronic model works well to fit the SED of the source in its average long-term state.
- Rodrigues et al. 2021 found that both leptohadronic and proton synchrotron models can explain the high-energy emission at the time of the neutrino event.

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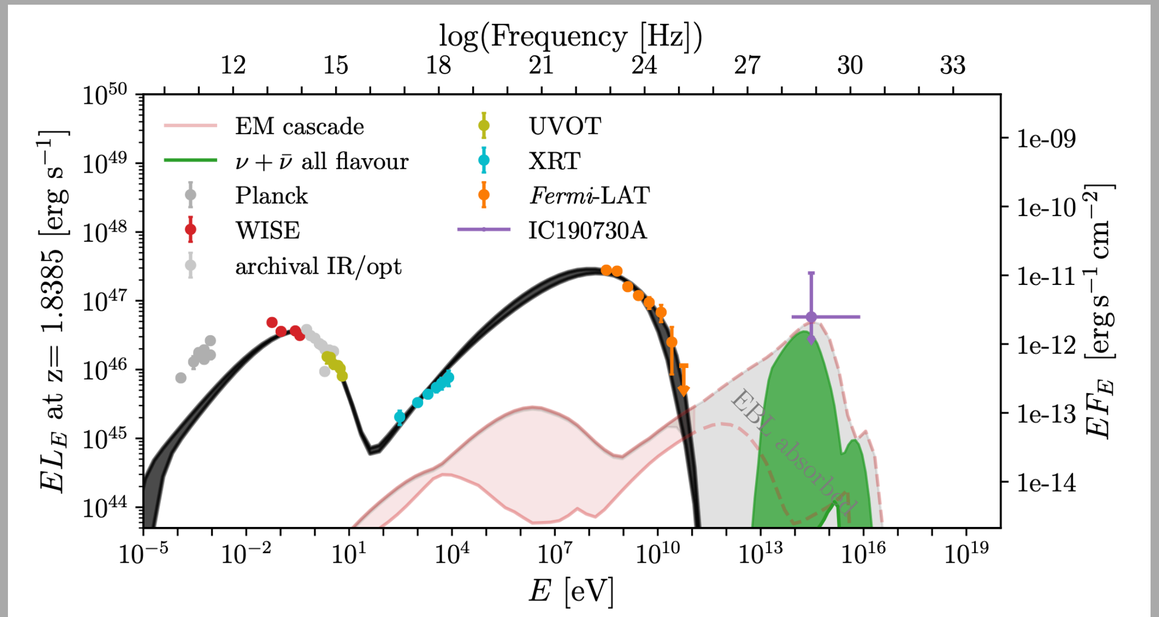

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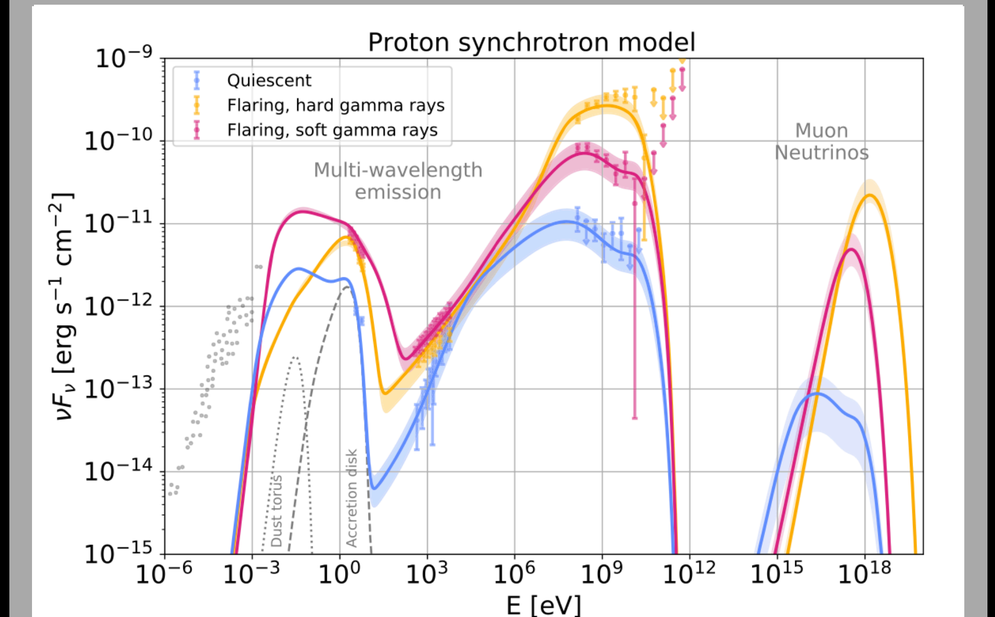

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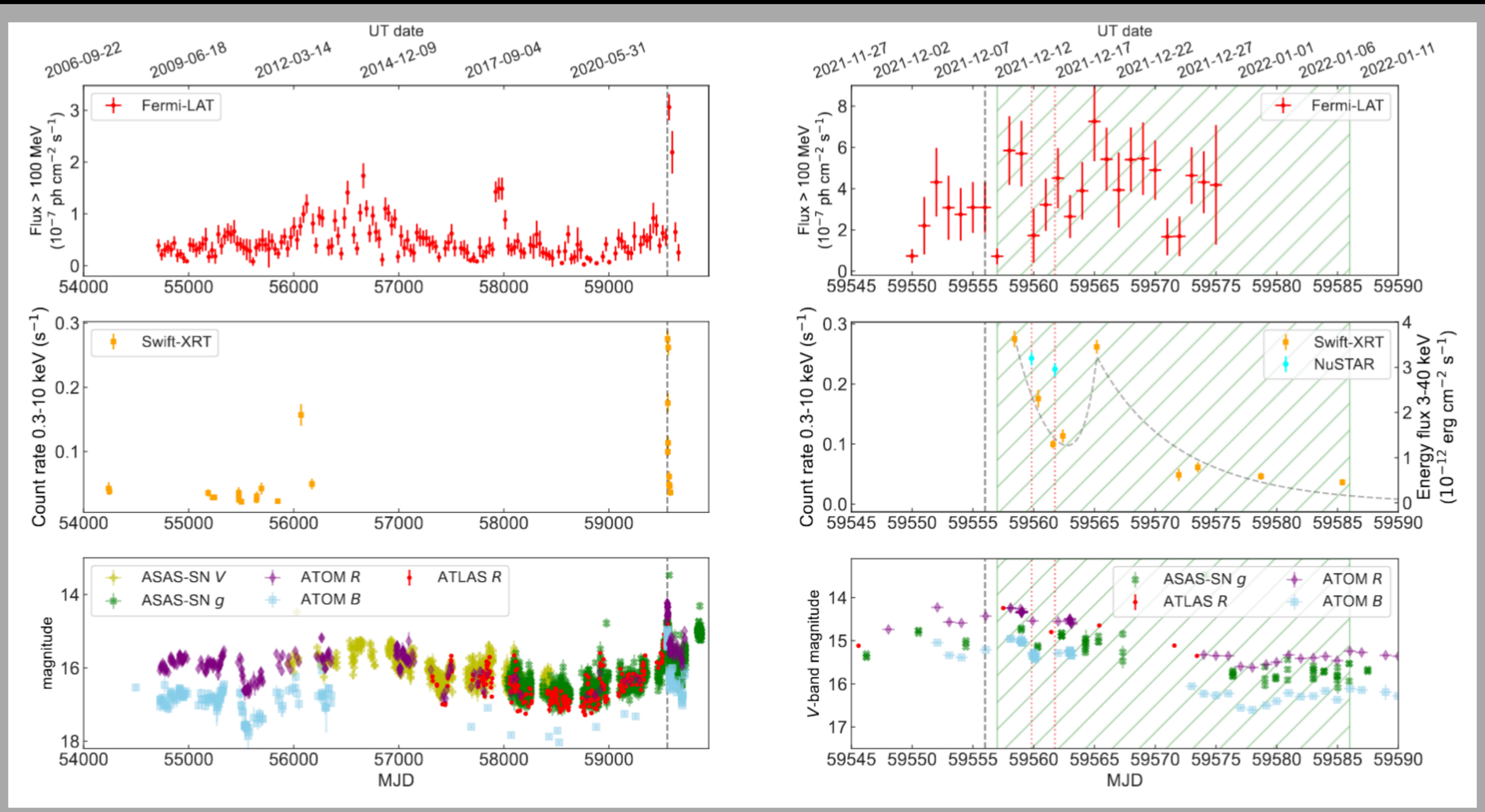
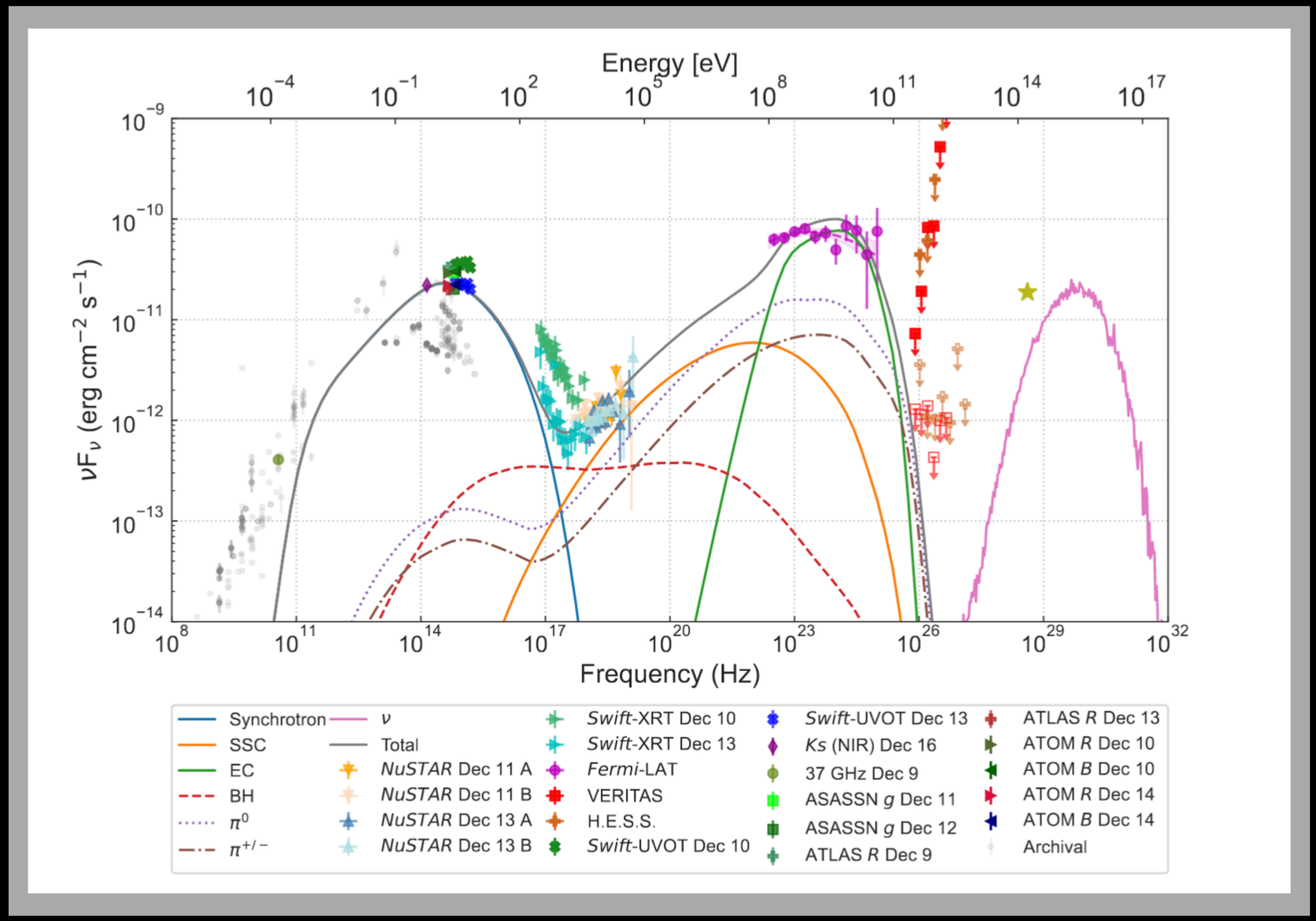


- Source located outside 90% uncertainty region for location of IceCube neutrino.
- High energy neutrino detected preceding a period of enhanced gamma ray and X-ray flux.

VERITAS Collaboration et al. 2023

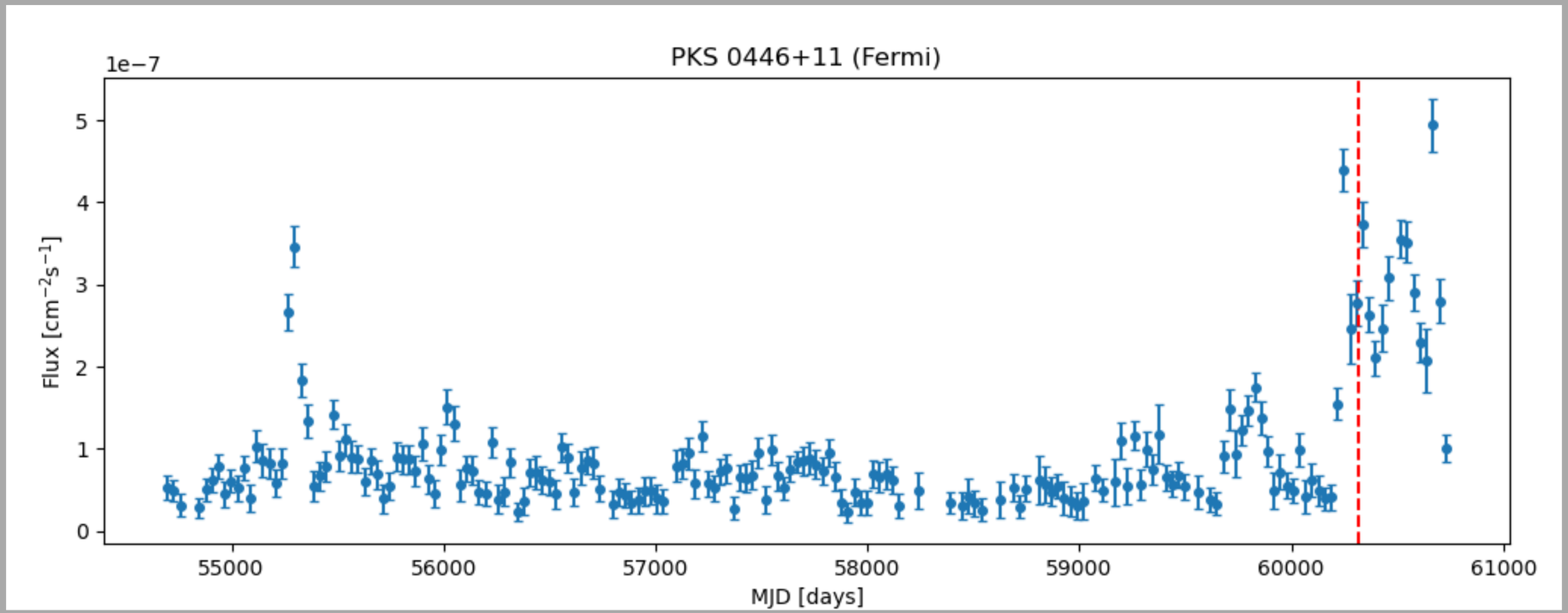
IC211208A and PKS 0735+17

- SED can be fit with lepto-hadronic model with external photon field.
- SSC model doesn't fit unless the synchrotron peak extends into the far-UV band that the observations do not cover.



VERITAS Collaboration et al. 2023

IC240105A and PKS 0446+11



- High energy neutrino detected preceding a period of enhanced gamma ray and X-ray flux.
- Work to model the SED for this source is currently in progress, including data from Swift XRT/UVOT, NuSTAR, Fermi and VERITAS.

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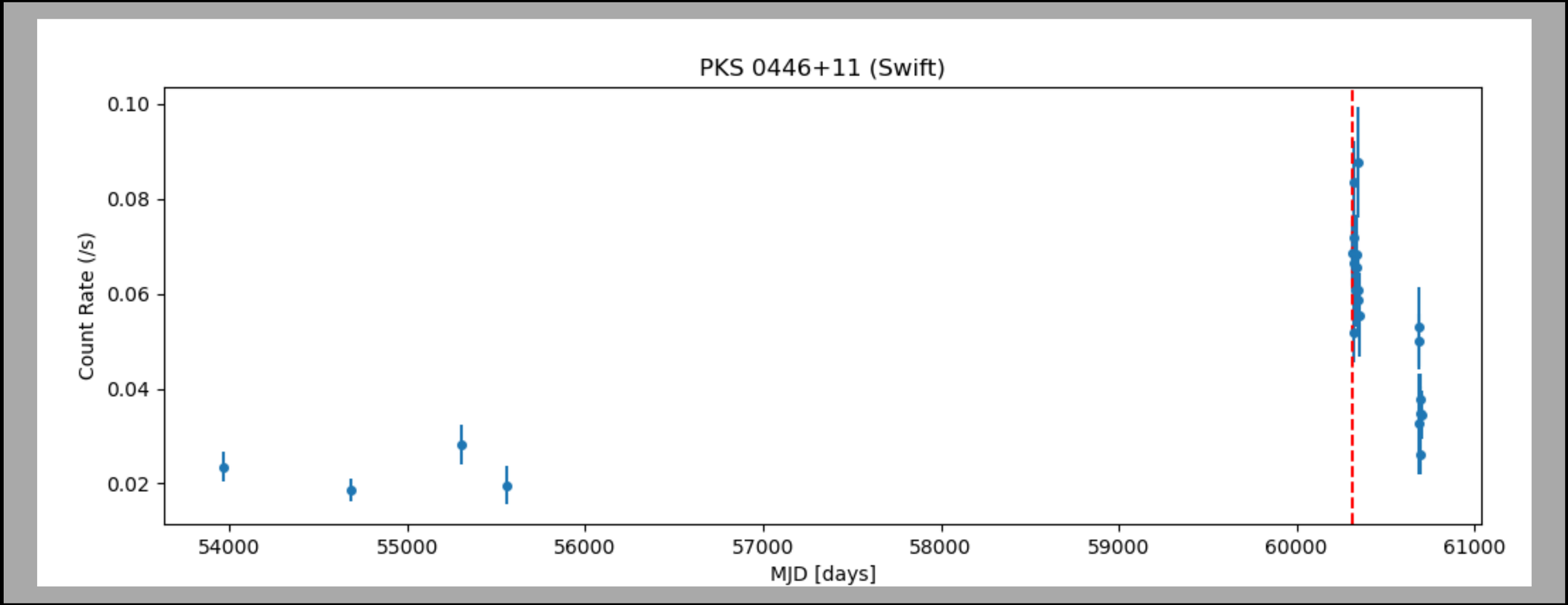

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Conclusions

- The sources of high energy neutrinos detected by IceCube remain unknown.
- Blazars are potential sources for individual high-energy neutrinos.
- X-rays are a key component in determining production mechanisms for neutrinos emitted by blazars/
- Thank you to the Swift team!

Martin Wolf IceCube/NSF