



Multiwavelength Follow-up Observations of Astrophysical Neutrino Events

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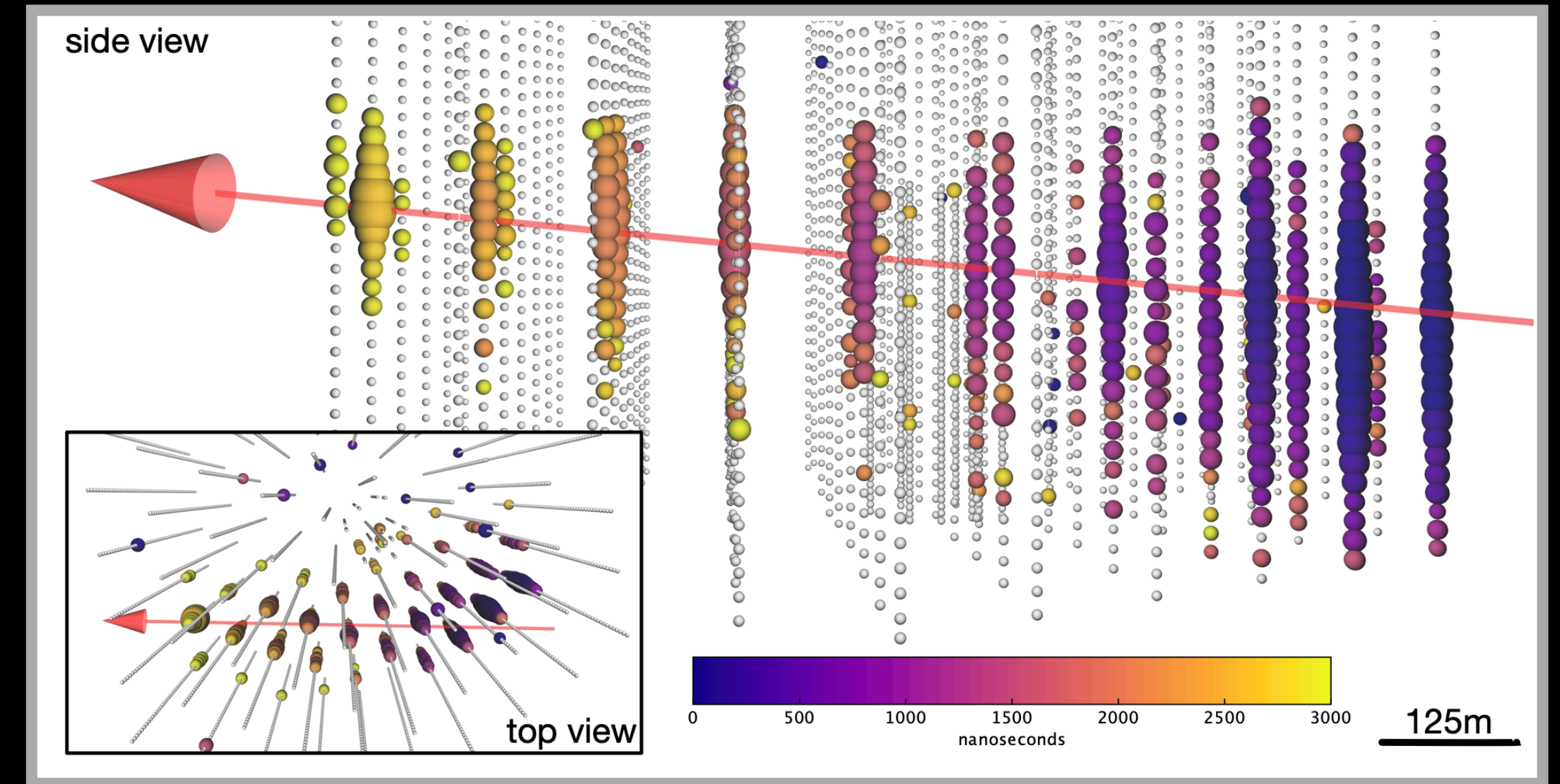
The Transient Universe 2023

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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.
 - Active galactic nuclei (AGN) are promising candidate sources.
- IceCube real time alert system allows for multiwavelength follow-ups.
 - Gold events have $\sim 50\%$ average likelihood of being astrophysical in origin.

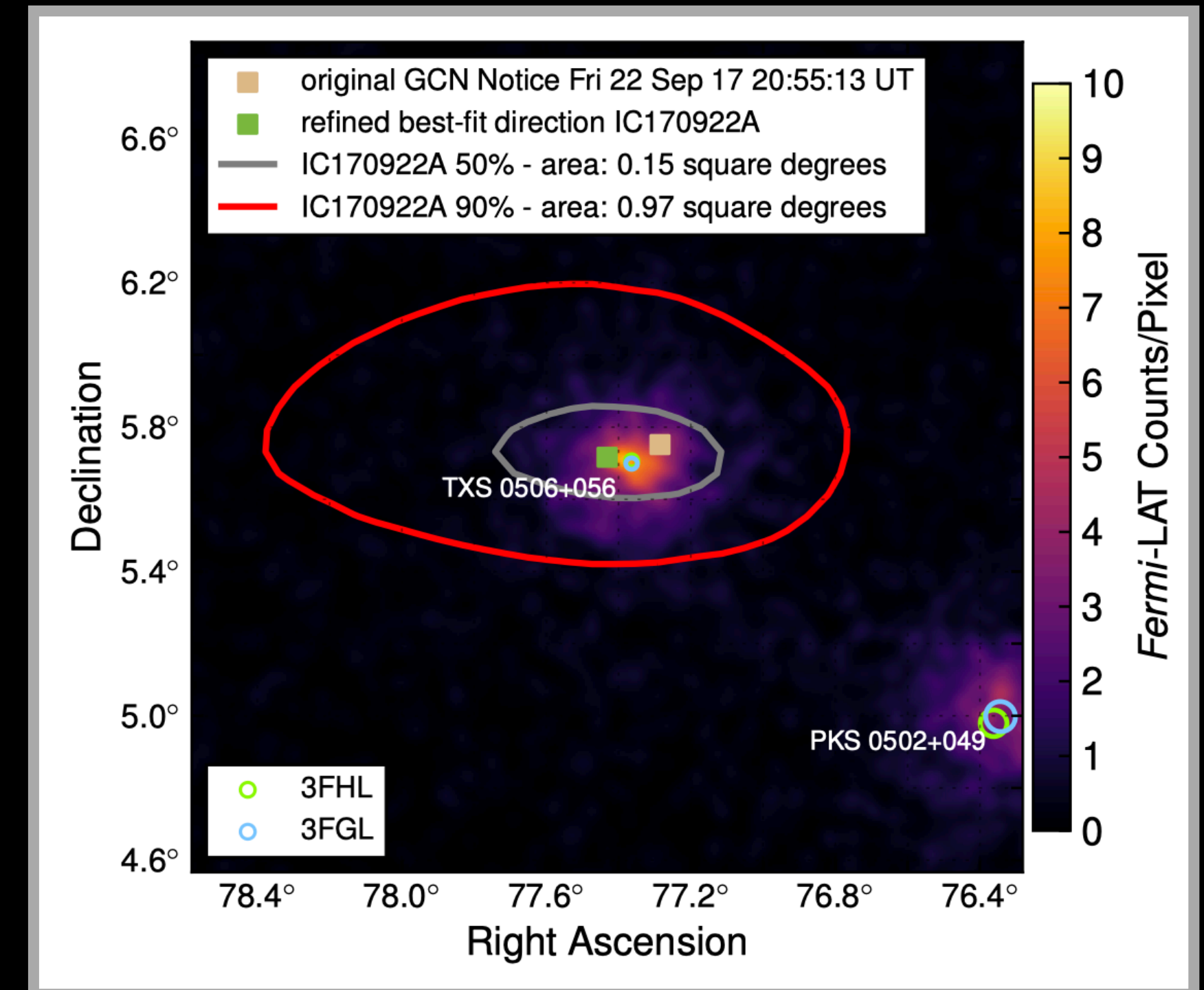


Event display for the neutrino event IC170922A

[Aartsen M. G., et al., 2018, Science, 361, eaat1378](#)

Counterparts to Astrophysical Neutrinos

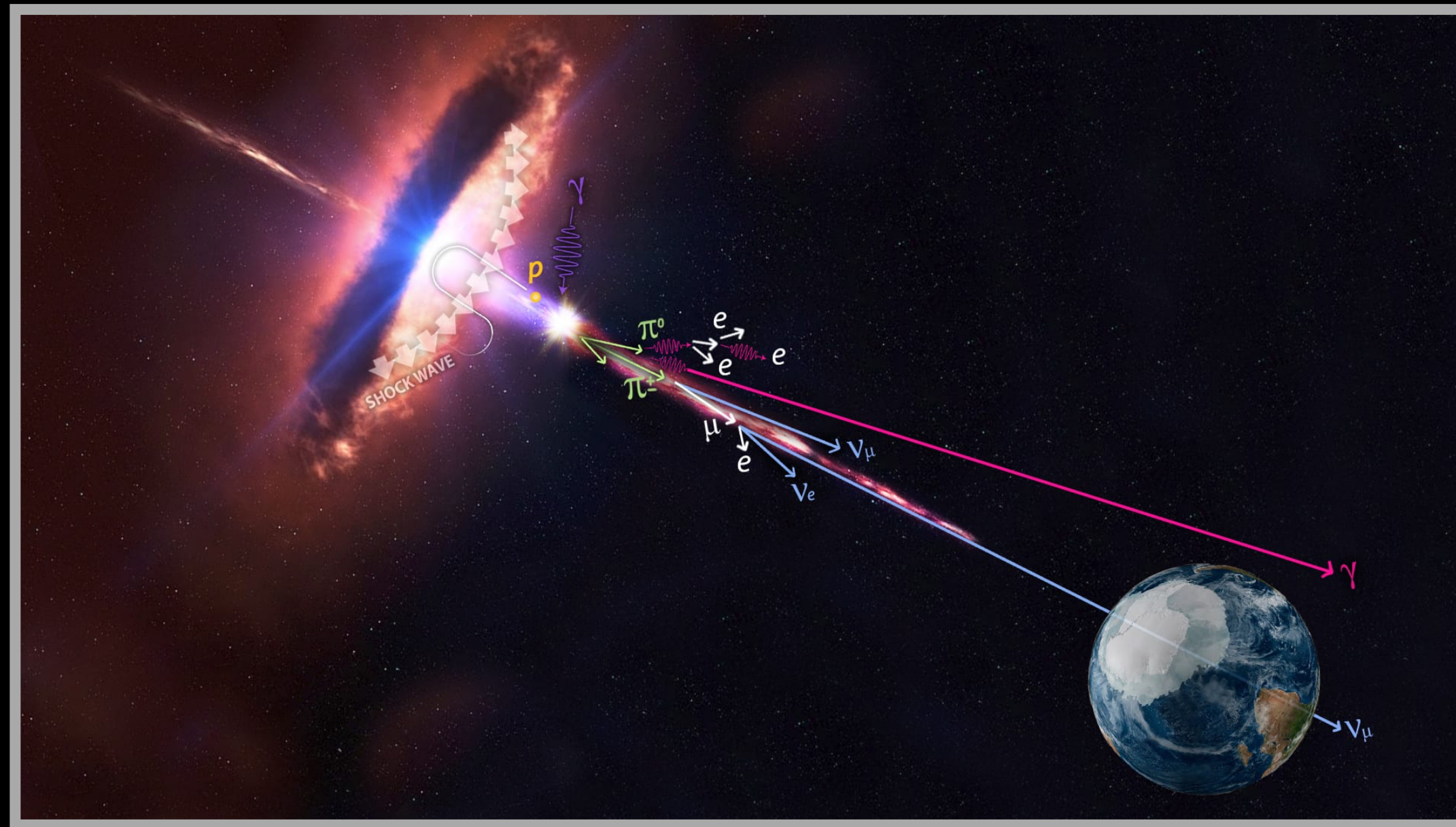
- The blazar TXS 0506+056 was found to be in the 50% containment region of the neutrino alert IC170922A.
- Archival analysis found evidence of a “neutrino flare” at the 3.5σ level at the location of this source in 2014-2015.
- Connections between astrophysical neutrinos and high energy photons could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



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

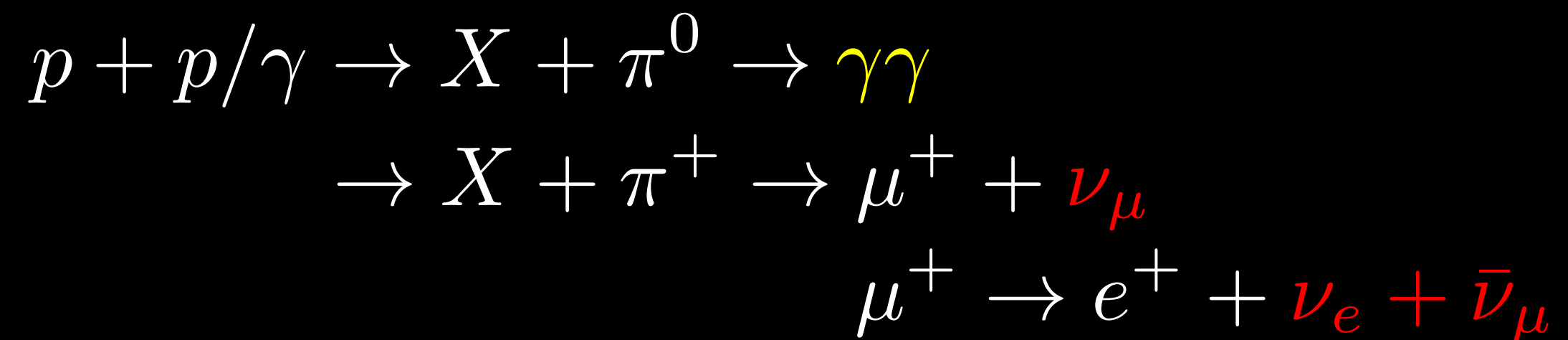
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Connecting Cosmic Rays and Neutrinos from AGN



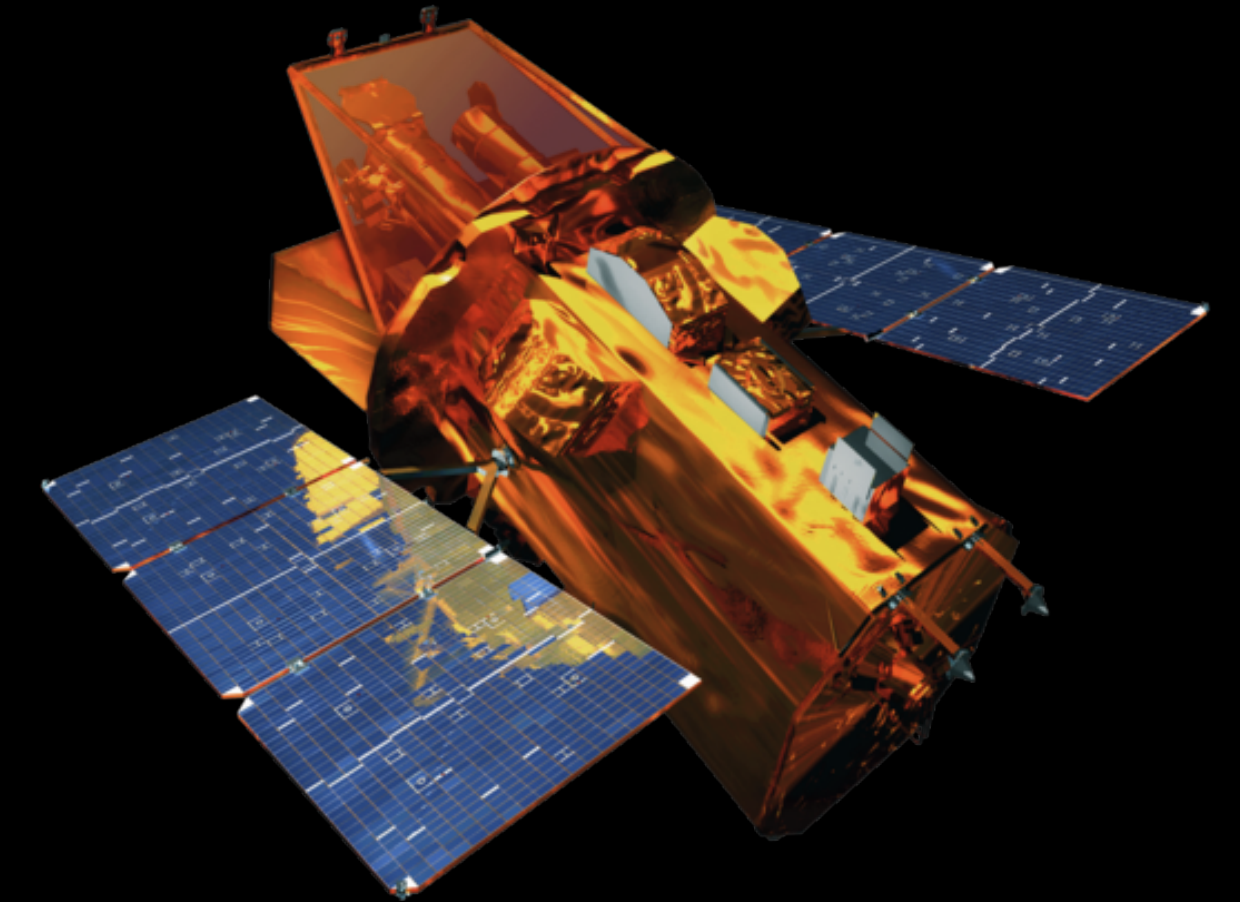
IceCube/NASA

- Lepto-hadronic models
 - Cosmic rays in jet interact with radiation fields to create neutral and charged pions.
 - Gamma rays emitted through neutral pion decay.
 - Neutrinos emitted through charged pion decay.
- AGN as point sources of neutrinos would be evidence supporting lepto-hadronic models.
- Cascading produced by the interaction of gamma-rays and photon fields in the AGN can lead to the production of X-rays and MeV gamma-rays.



Swift Follow-up Campaigns

- Follow-up program targeting sources similar to TXS 0506+056:
 - Began in Swift Guest Investigator Cycle 16, and continued in Cycles 17, 18, and 19 (through March 2024).
 - 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.
 - 4ks more ~few weeks later to look for longer time-scale variability.



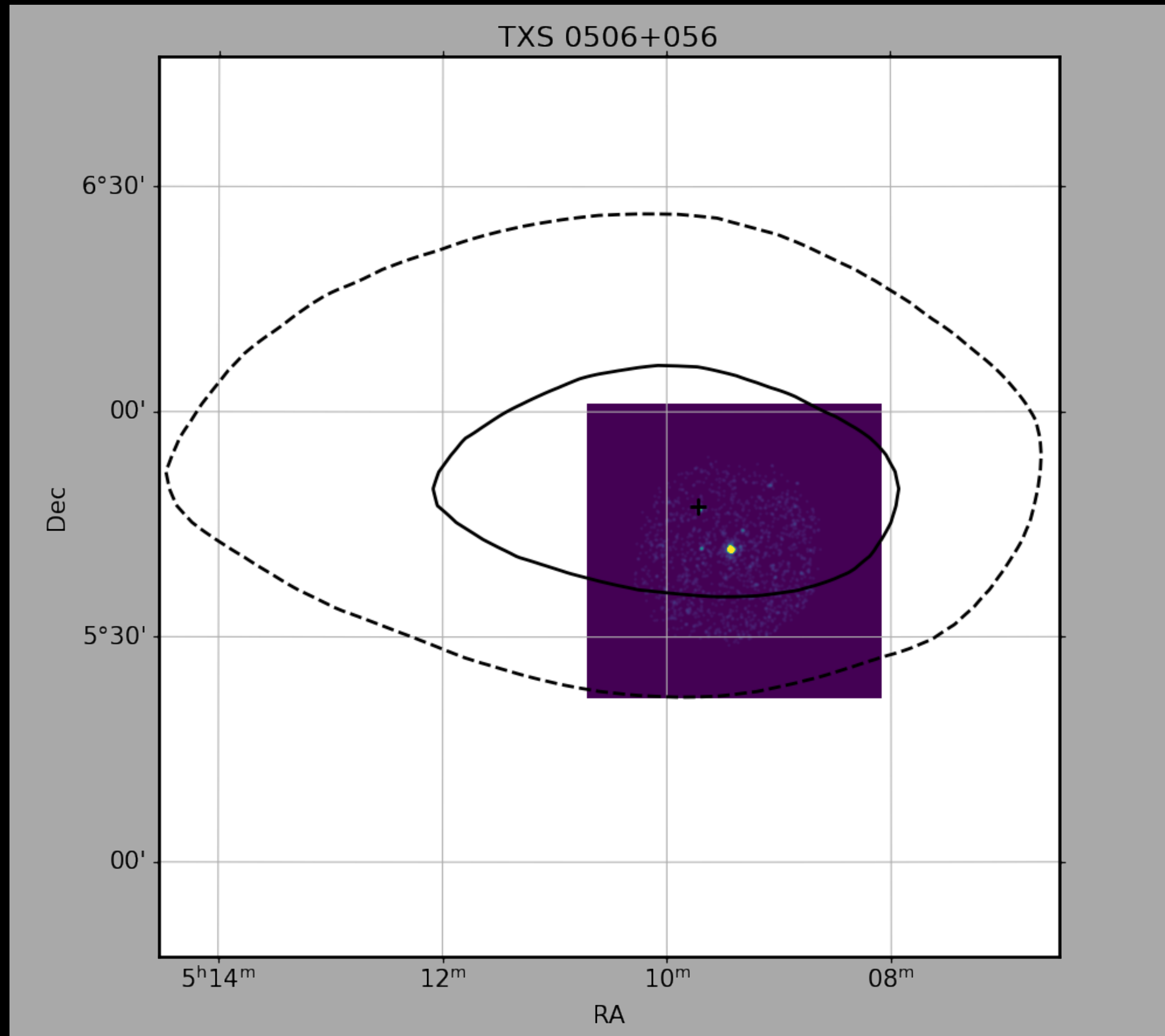
Neil Gehrels Swift Observatory
[NASA E/PO, Sonoma State University/Aurore Simonnet](#)

Swift Follow-up Observations

Source	Neutrino Event	Signalness	Swift Response Time [hr]
1WHSP J104516.2+275133	IC190704A	48.6%	99.0
PKS 1502+106	IC190730A	67.2%	1.1
4FGL J1702.2+2642	IC200530A	59.2%	8.5
4FGL J1659.0+2627	IC200530A	59.2%	2.3
4FGL J0658.6+0636	IC201114A	56.2%	17.2
PKS 0735+17	IC211208A	50.2%	36.9
NVSS J175236-101145	IC220425A	49.7%	110.0
Fermi J1458.0+4119	IC220624A	60.9%	3.9
IceCube-220629A	IC220629A	30.1%	18.9
TXS 2320+343	IC221223A	79.5%	24.3

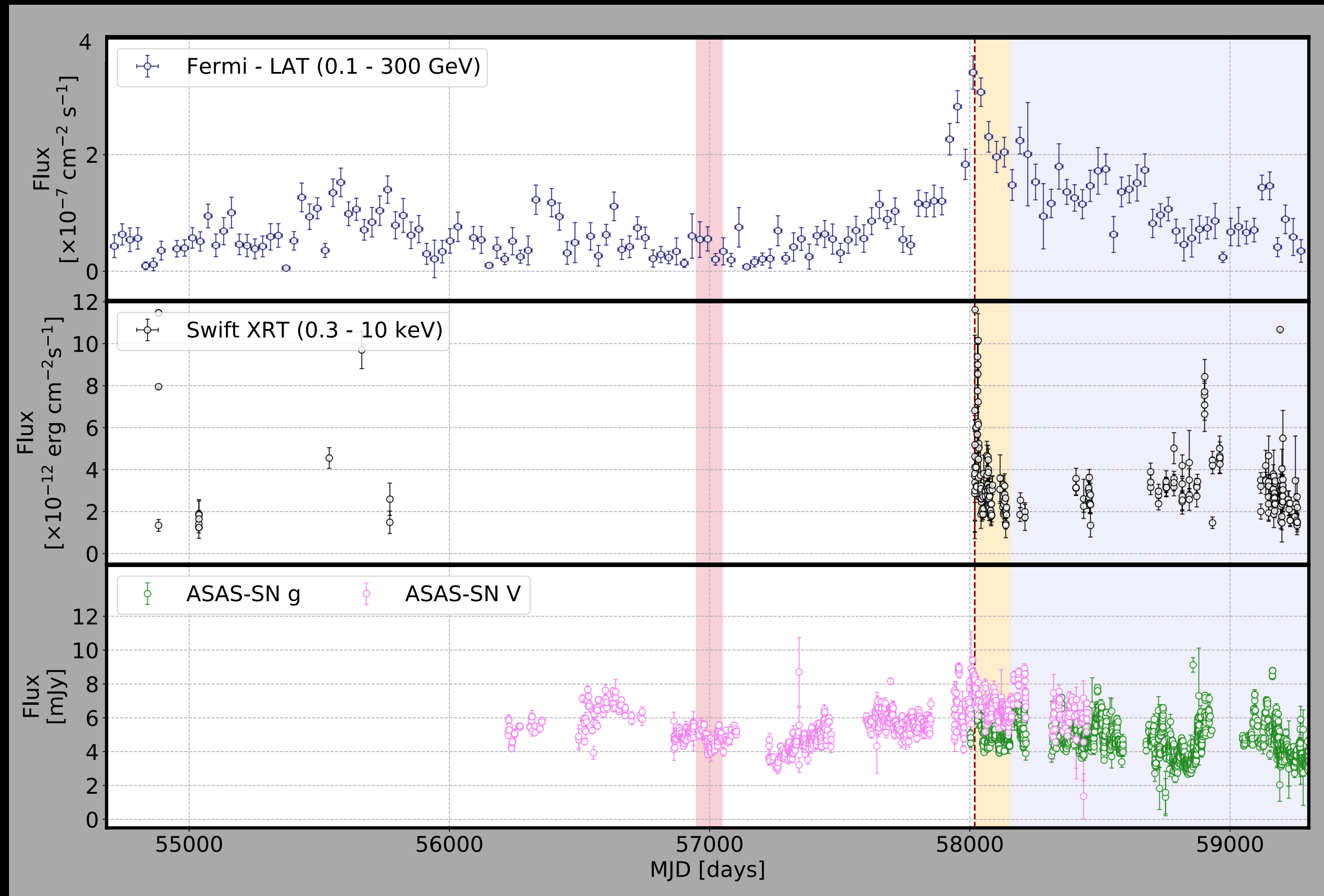
- Signalness provided by IceCube gives a measure of how likely it is that each neutrino is of astrophysical origin.
- Swift ToO observations typically performed within hours of neutrino detection.

IC170922A and TXS 0506+056



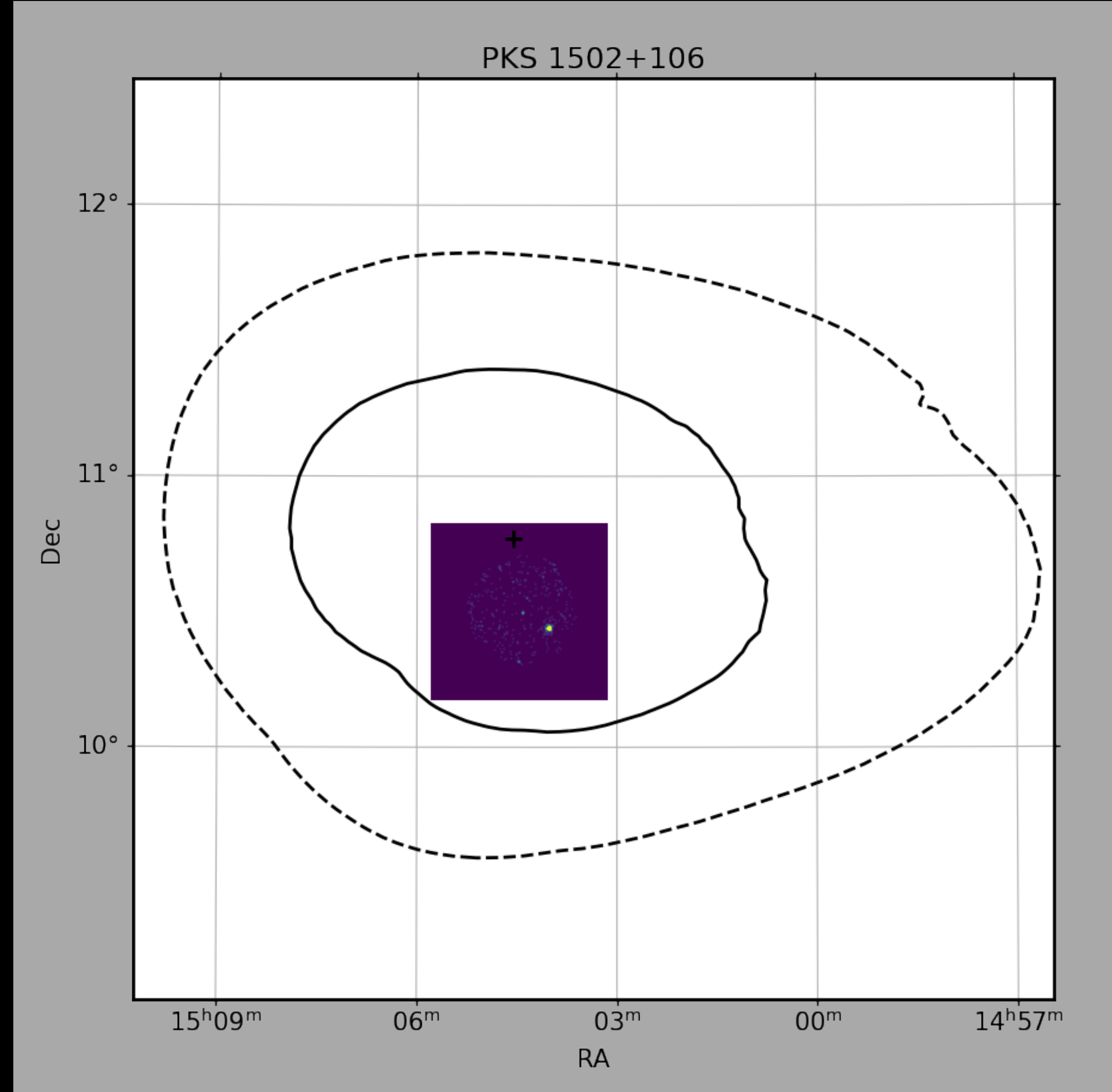
- Enhanced gamma-ray and X-ray flux around detection of IC170922A.
- No evidence of enhanced flux during the neutrino flare in 2014-2015.
- Increased multiwavelength monitoring of this source.
- Models for emission mechanisms can be found in [Keivani et al. \(2018\)](#), [Petropoulou et al. \(2020\)](#).

IC170922A and TXS 0506+056

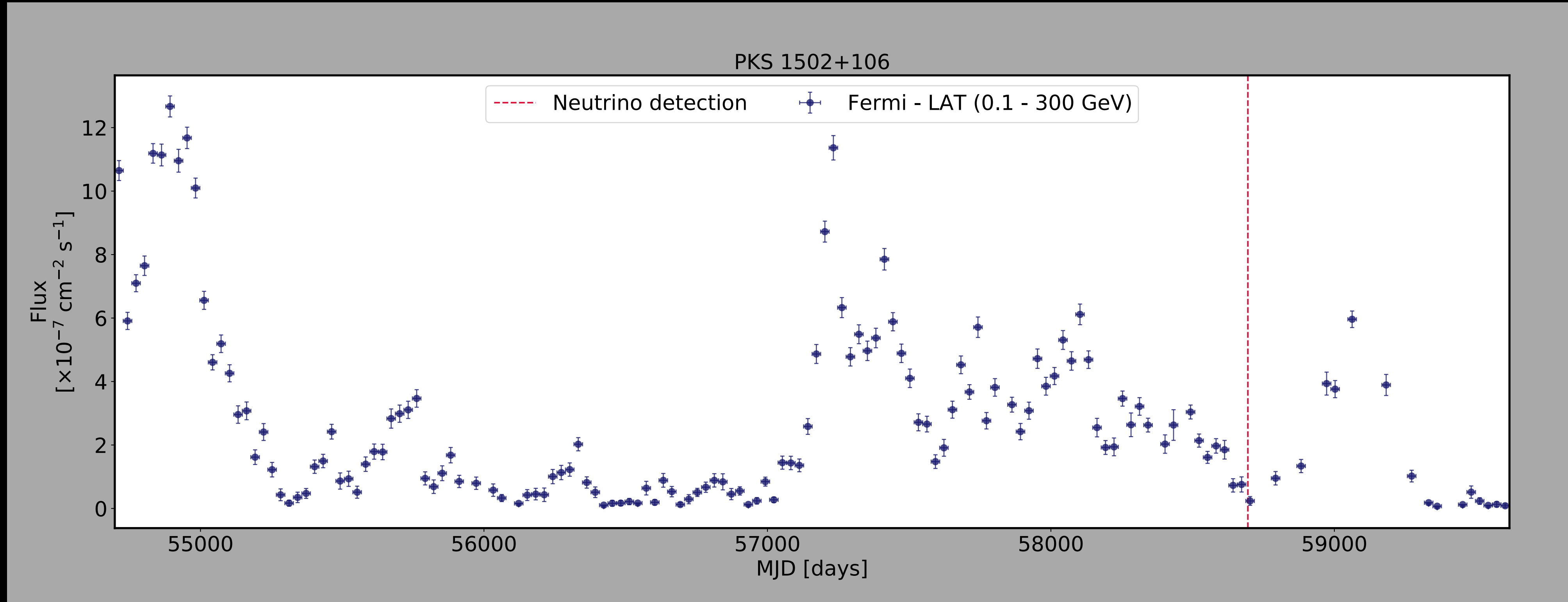


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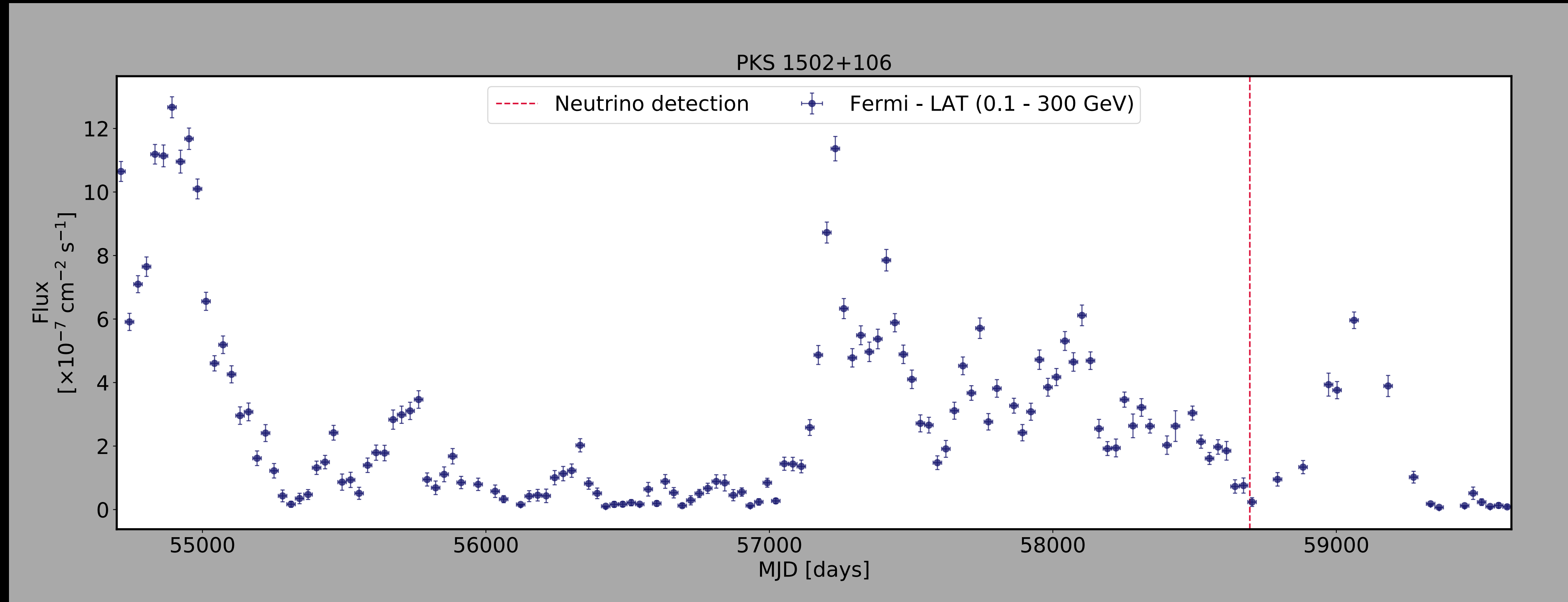
IC190730A and PKS 1502+106



IC190730A and PKS 1502+106

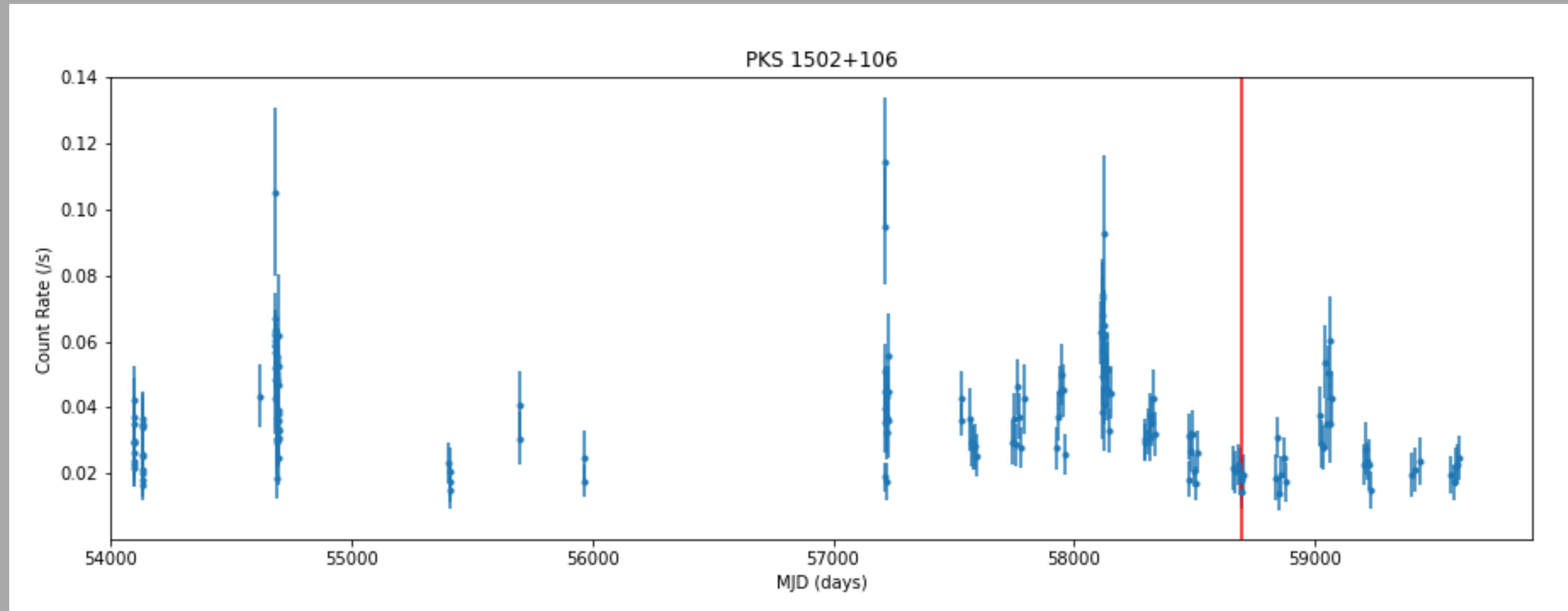


IC190730A and PKS 1502+106



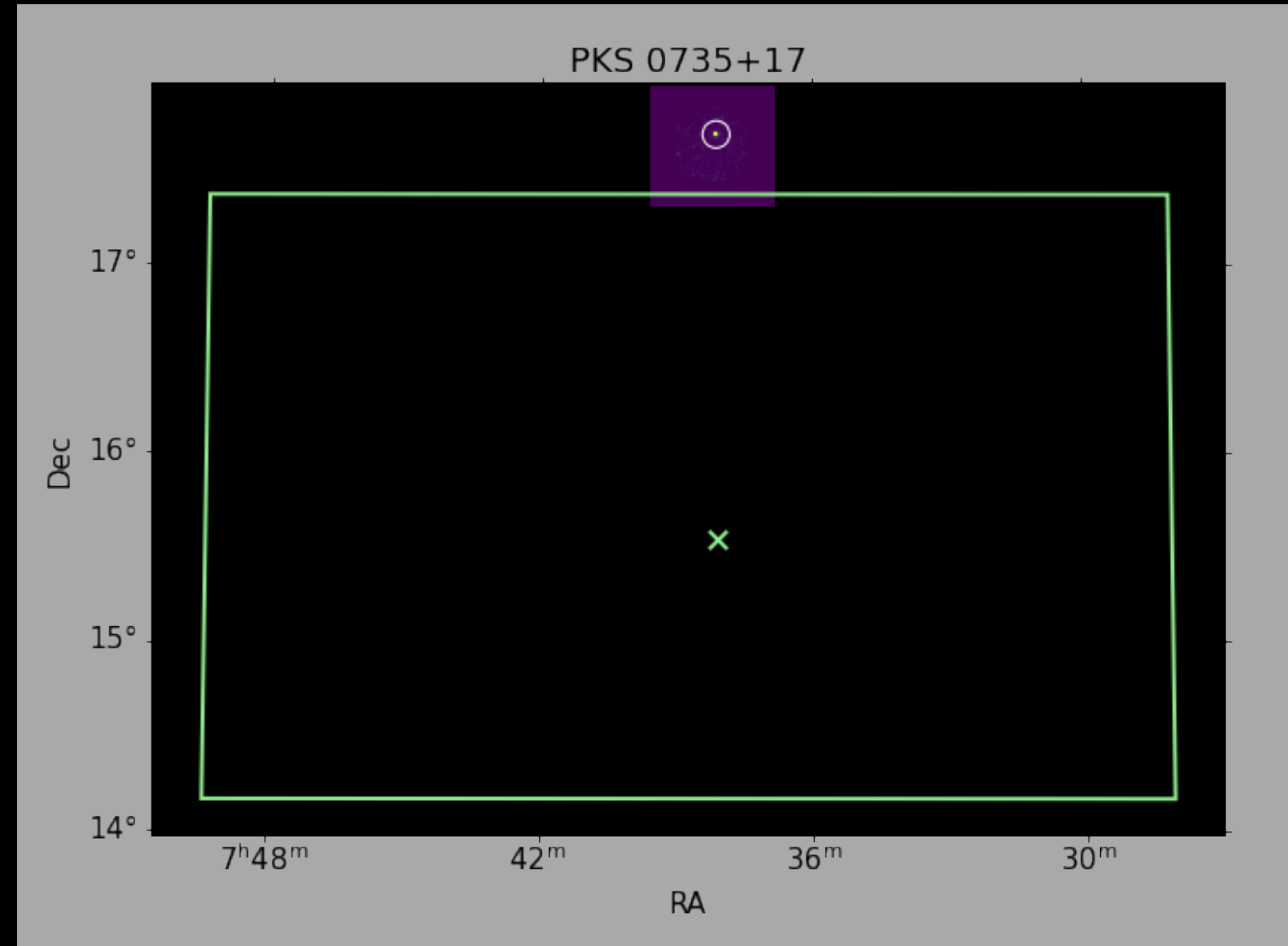
- High energy neutrino detected during a period of decreasing gamma-ray and X-ray flux between two potential flares.
- Models for emission mechanisms can be found in [Oikonomou et al. 2021](#).

IC190730A and PKS 1502+106

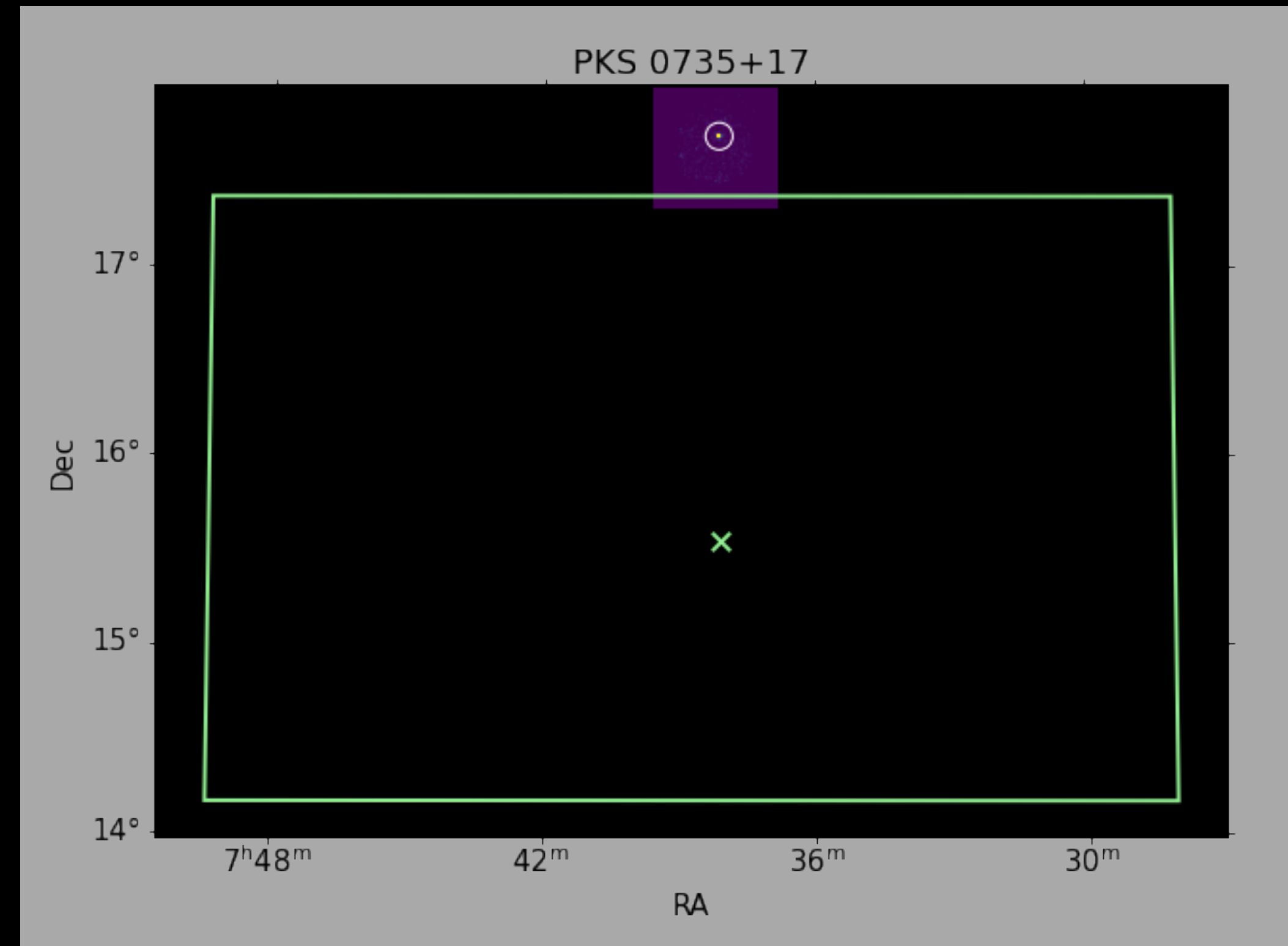


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IC211208A and PKS 0735+17

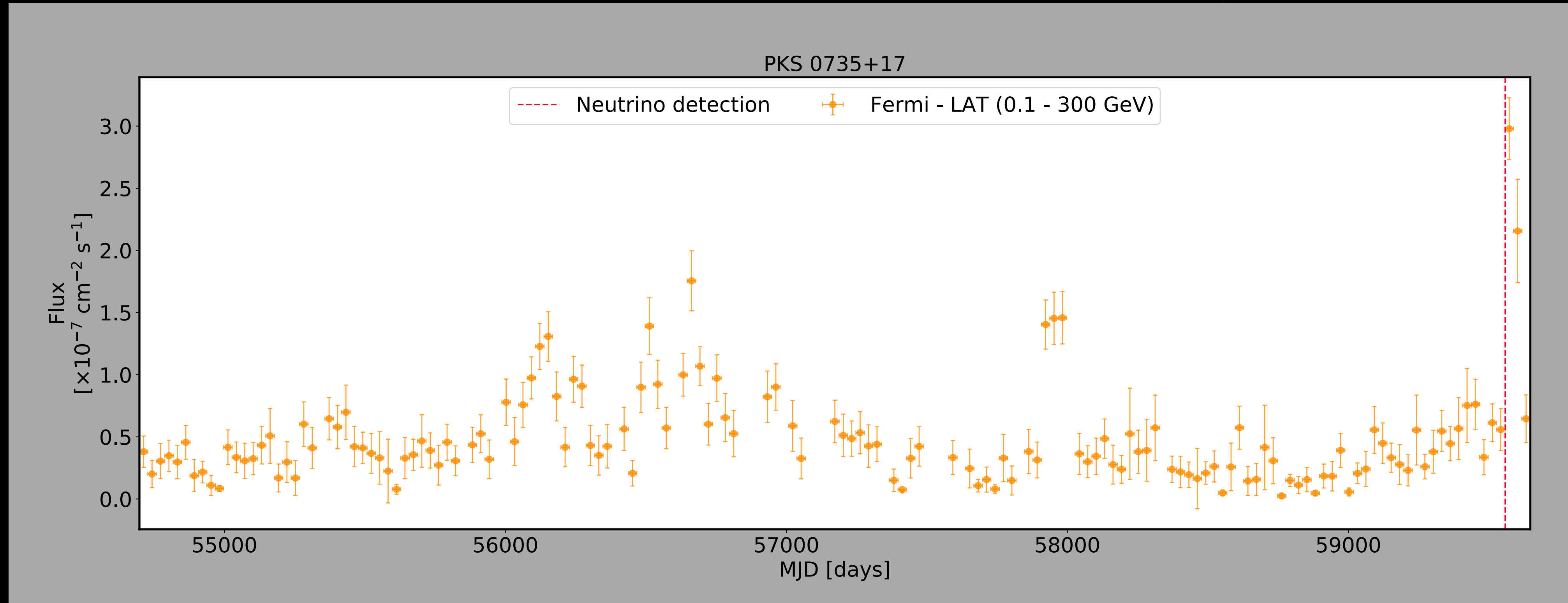


IC211208A and PKS 0735+17



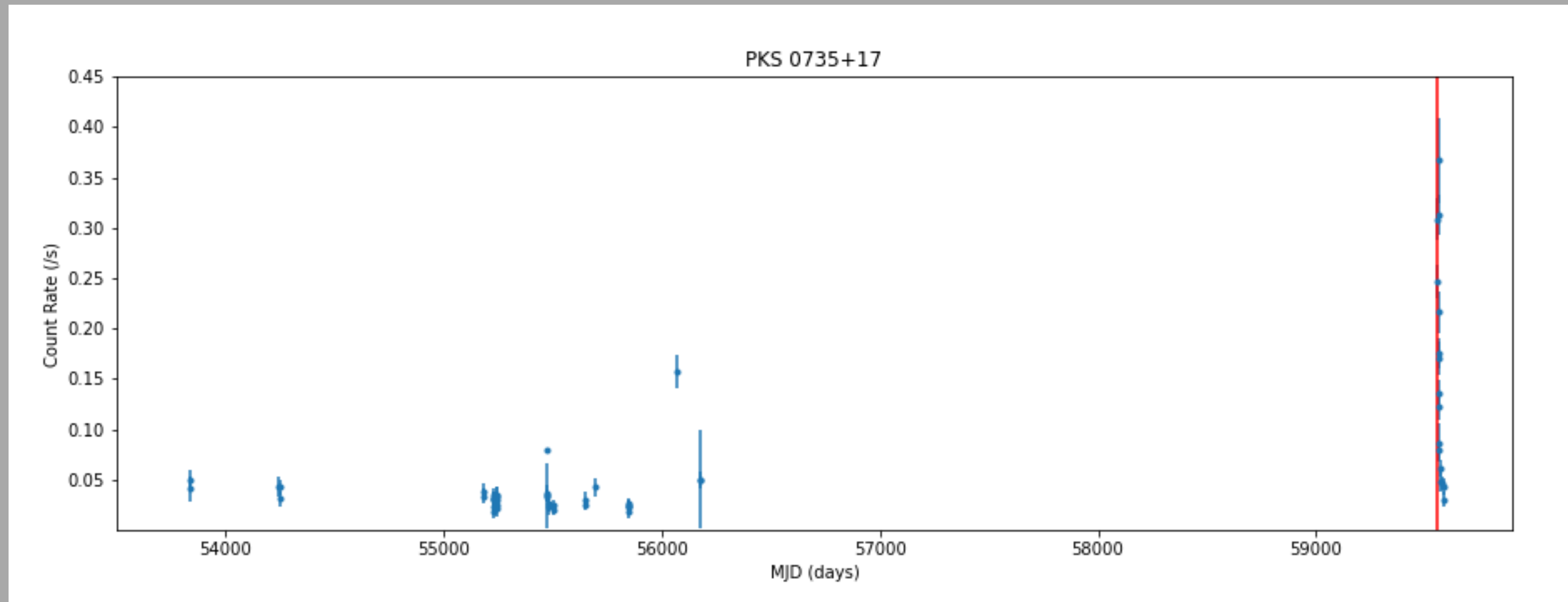
- Source located outside uncertainty region for location of IceCube neutrino.
- High energy neutrino detected preceding a period of enhanced gamma ray and X-ray flux.

IC211208A and PKS 0735+17



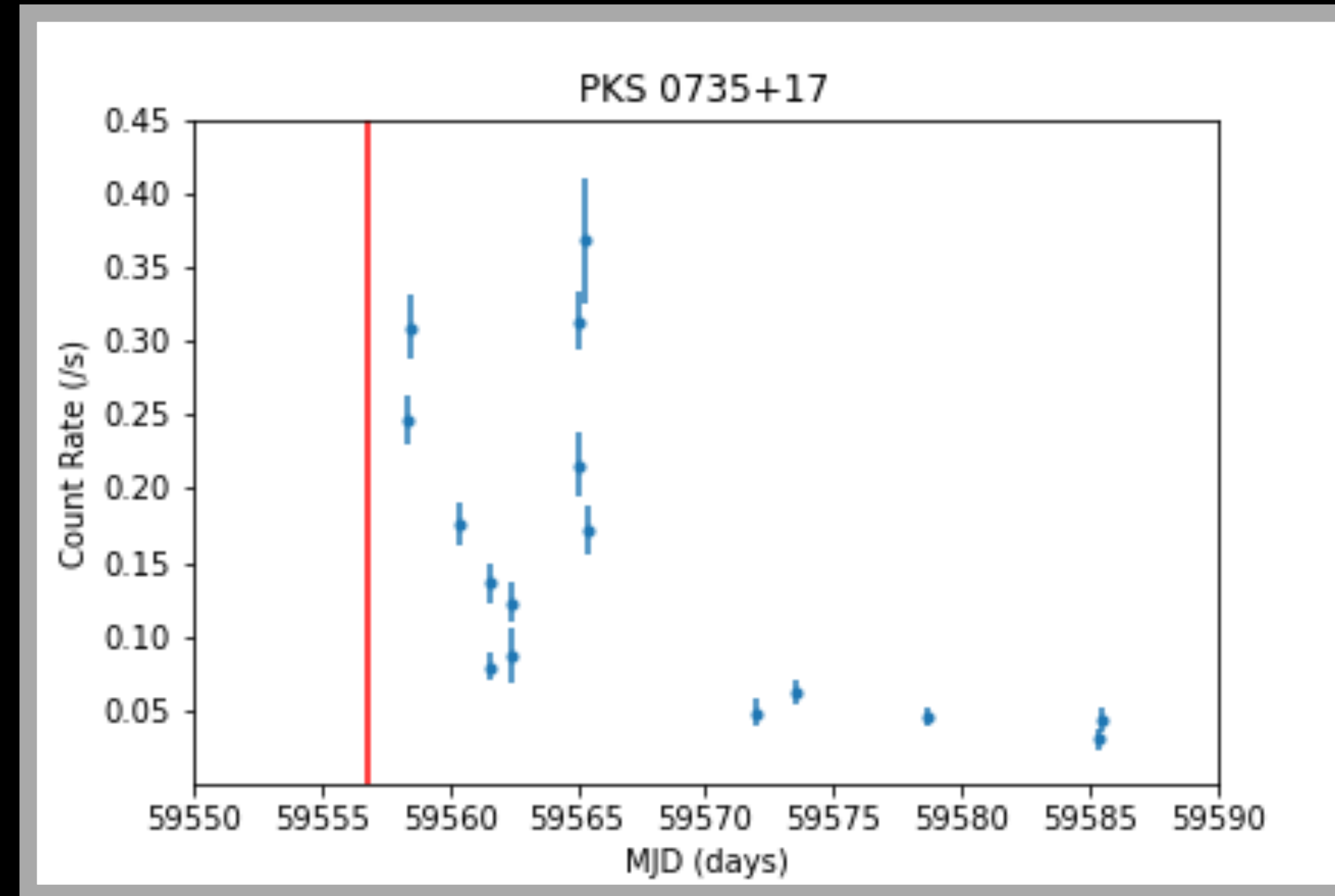
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IC211208A and PKS 0735+17



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Conclusions and outlook

- Continue Swift follow-up observations of Gold neutrino detections.
- Determine when/if sources are flaring at the time of the neutrino detection.
- Characterize the spectral shape of neutrino counterparts and determine if spectral index changes.
- Future work includes determining chance correlation for flaring X-ray sources with neutrino events.



Martin Wolf IceCube/NSF