Search for gamma-ray counterparts to IceCube neutrinos with *Fermi*-LAT

Simone Garrappa

Multi-frequency to Multi-messenger: The new sight of the Universe
Perugia, May 16-18, 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

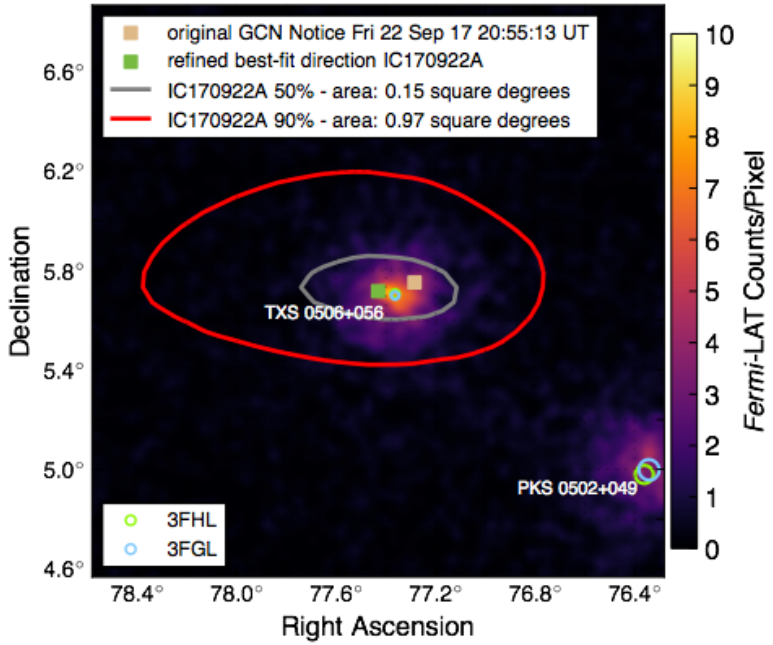
HELMHOLTZ Young Investigators

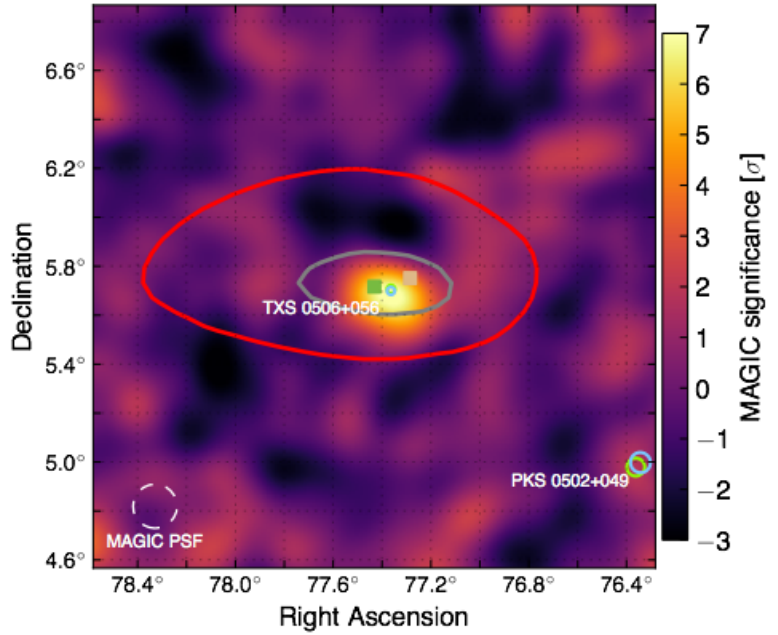
DESY.

September 22nd, 2017

A first compelling evidence

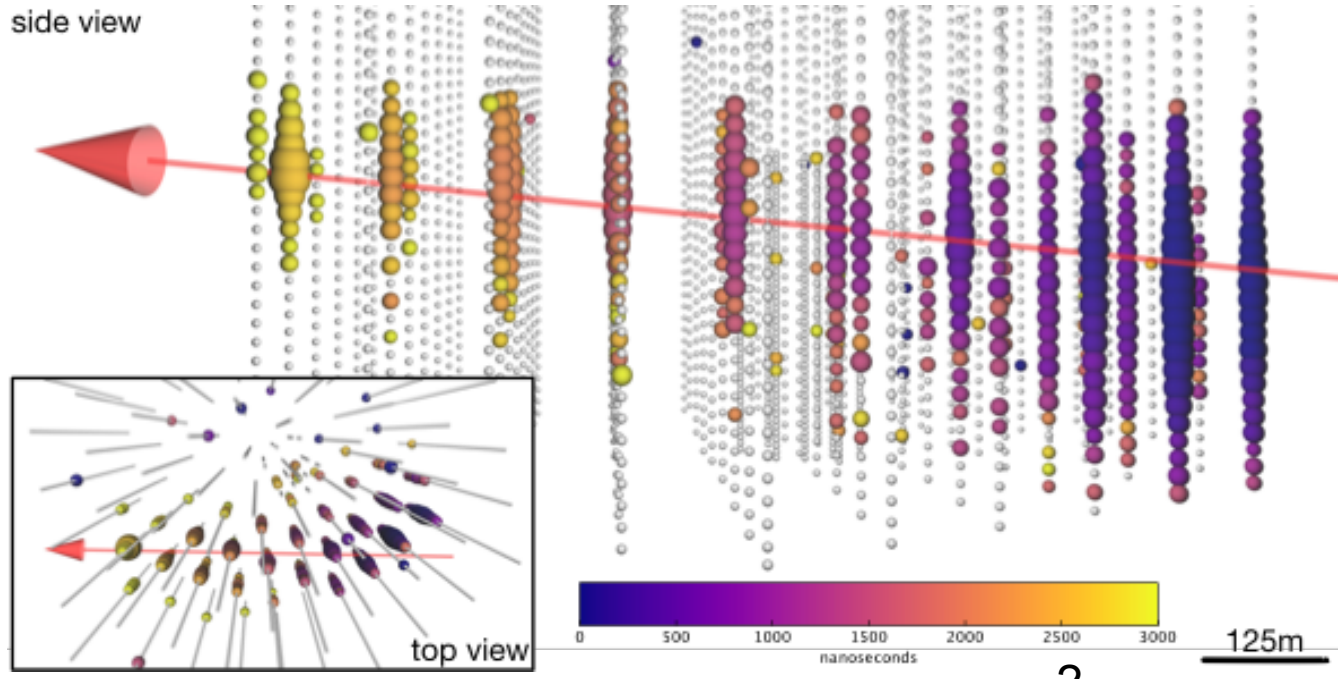
- A 290 TeV EHE event detected by IceCube
- Known blazar TXS 0506+056:
  - Spatial coincidence with IC170922A
  - Strong MWL flaring activity
  - 3σ chance coincidence





Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

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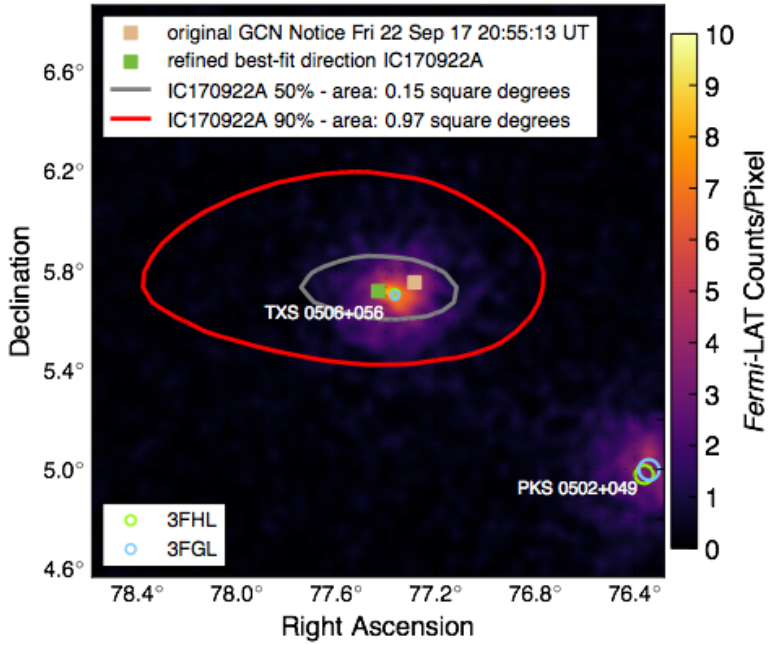
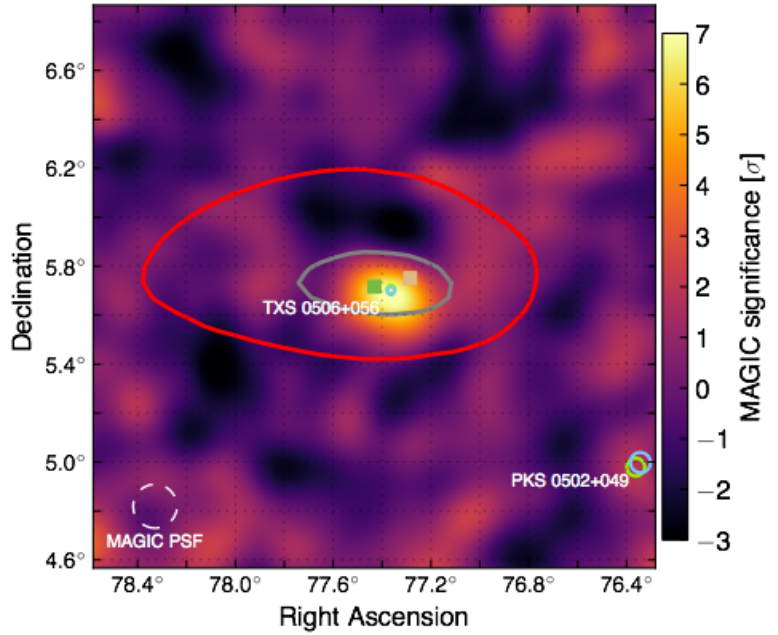




Looking back to archival IC data…

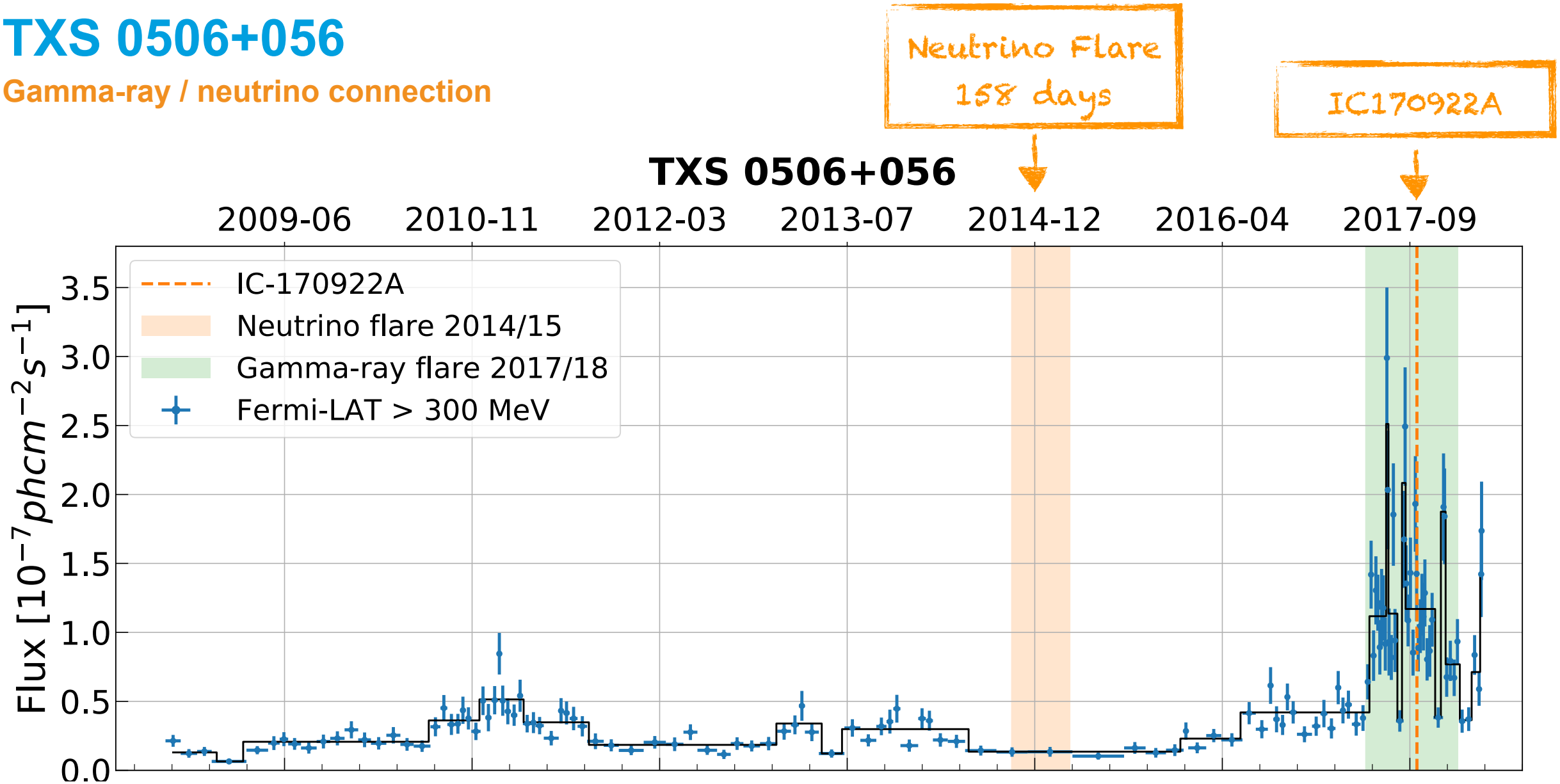
a 3.5σ neutrino excess of 13 ± 5 events above

atmospheric background in a time window of 158 days

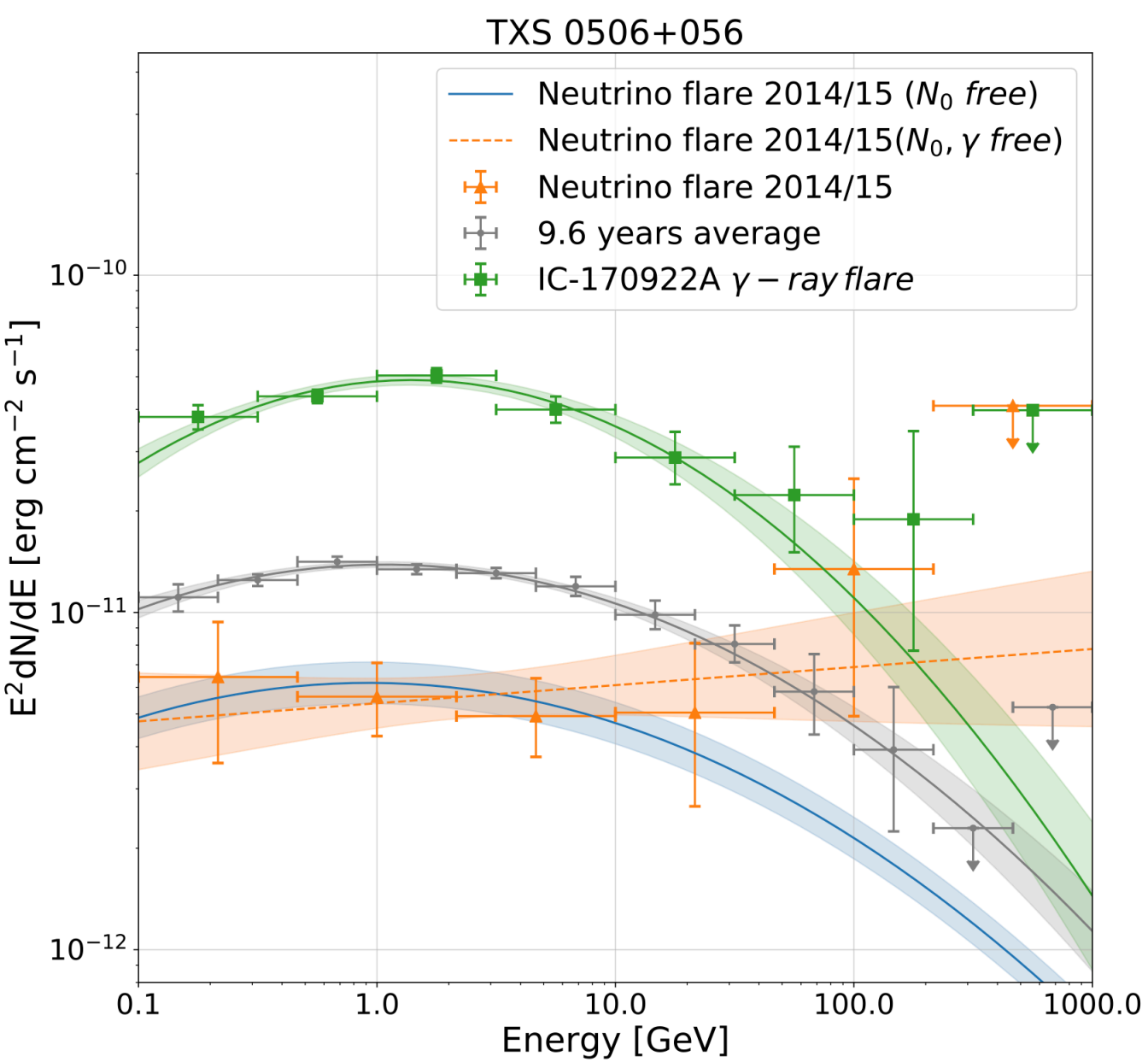
between 2014/15

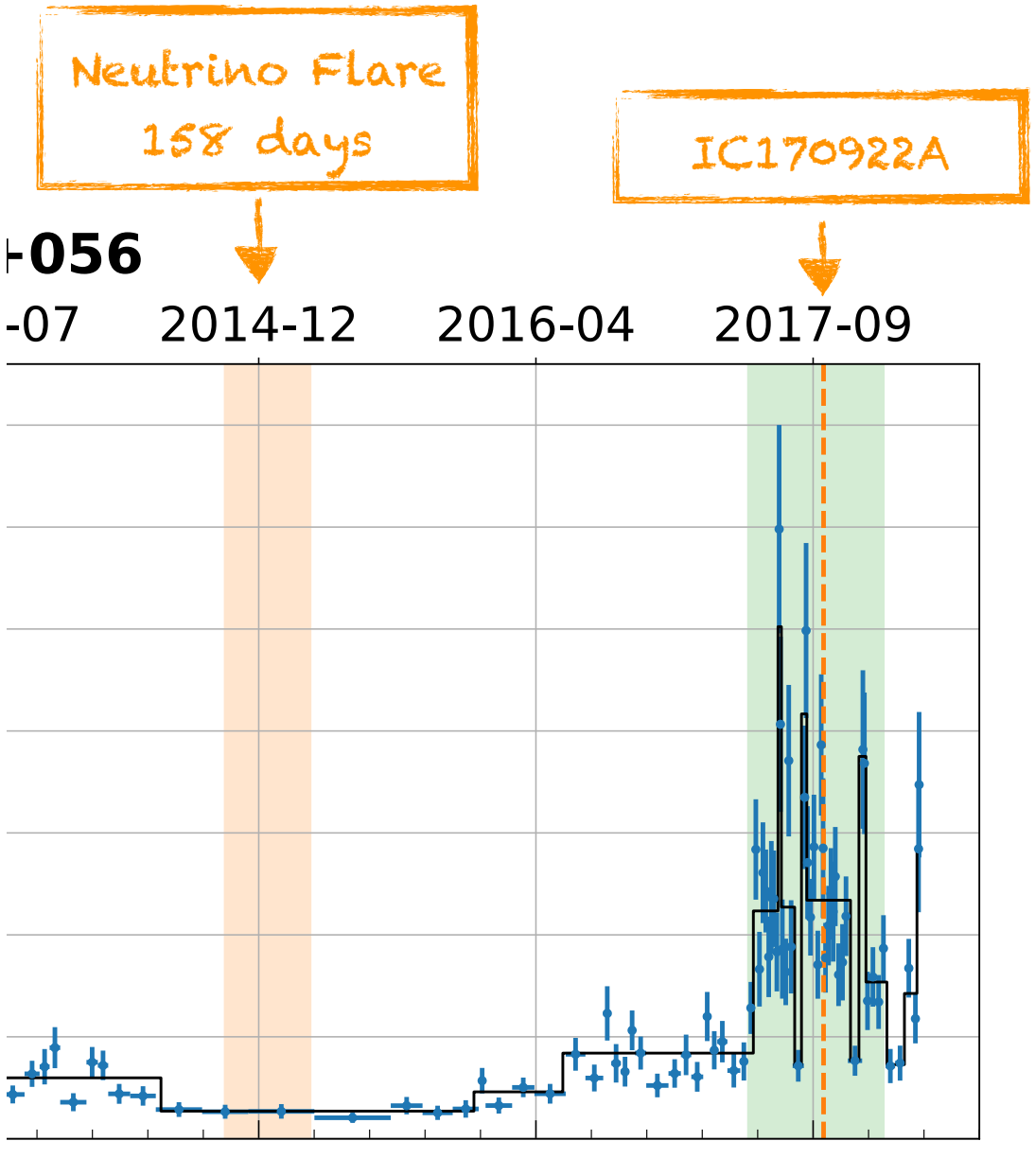
TXS 0506+056

Gamma-ray / neutrino connection



(SG, S. Buson, A. Franckowiak, ASAS-SN coll., IceCube coll. , 2019)





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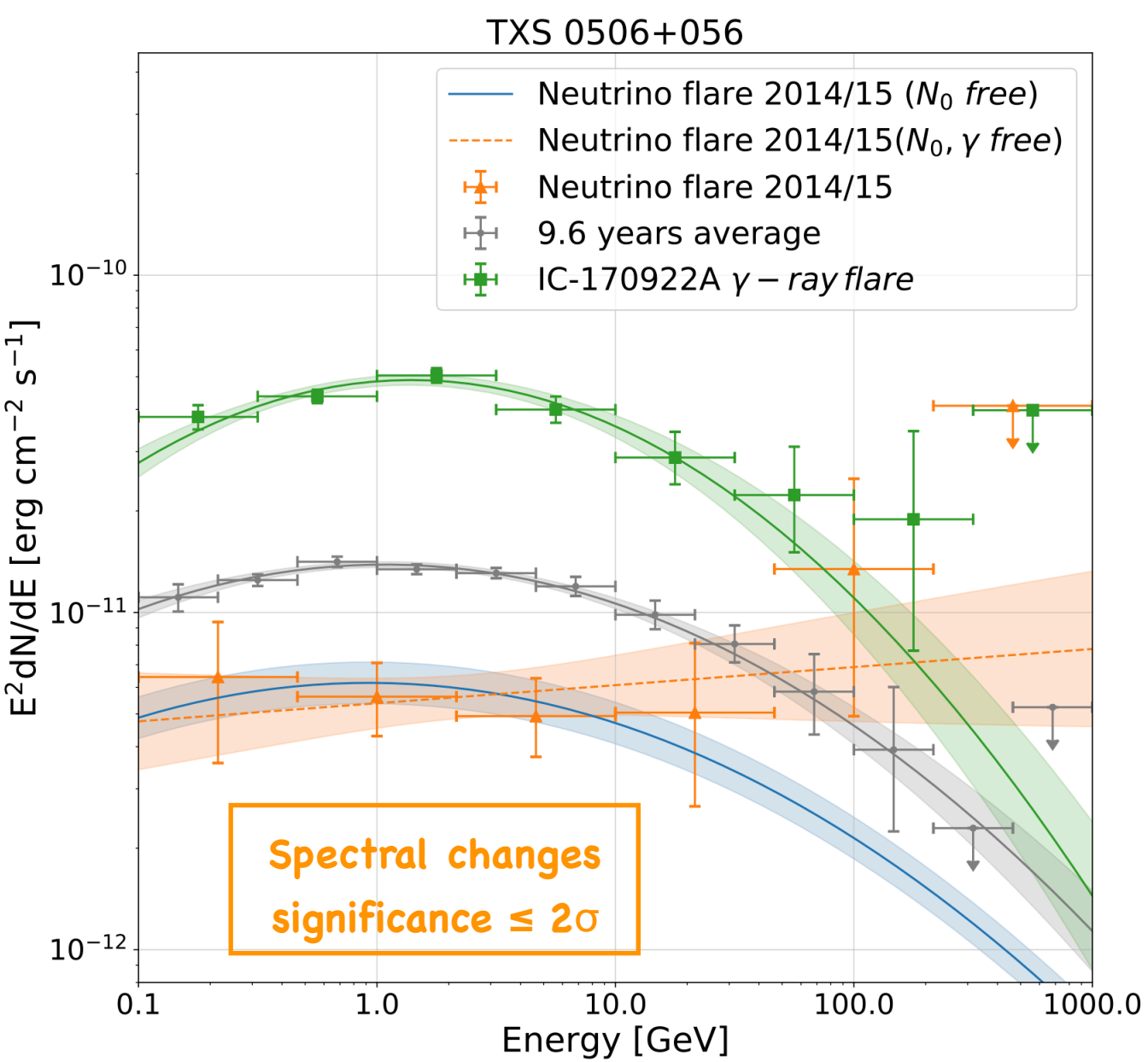
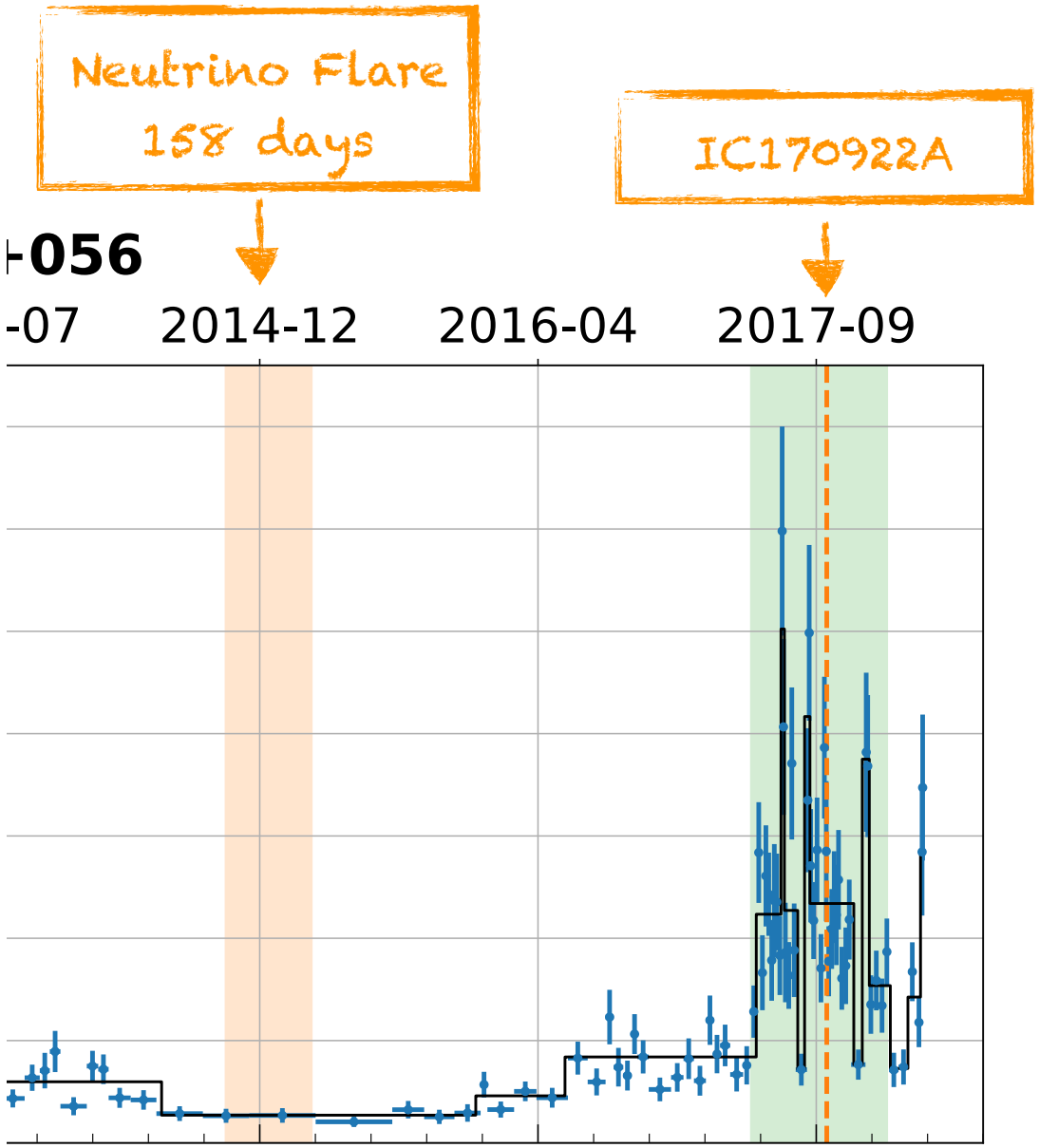


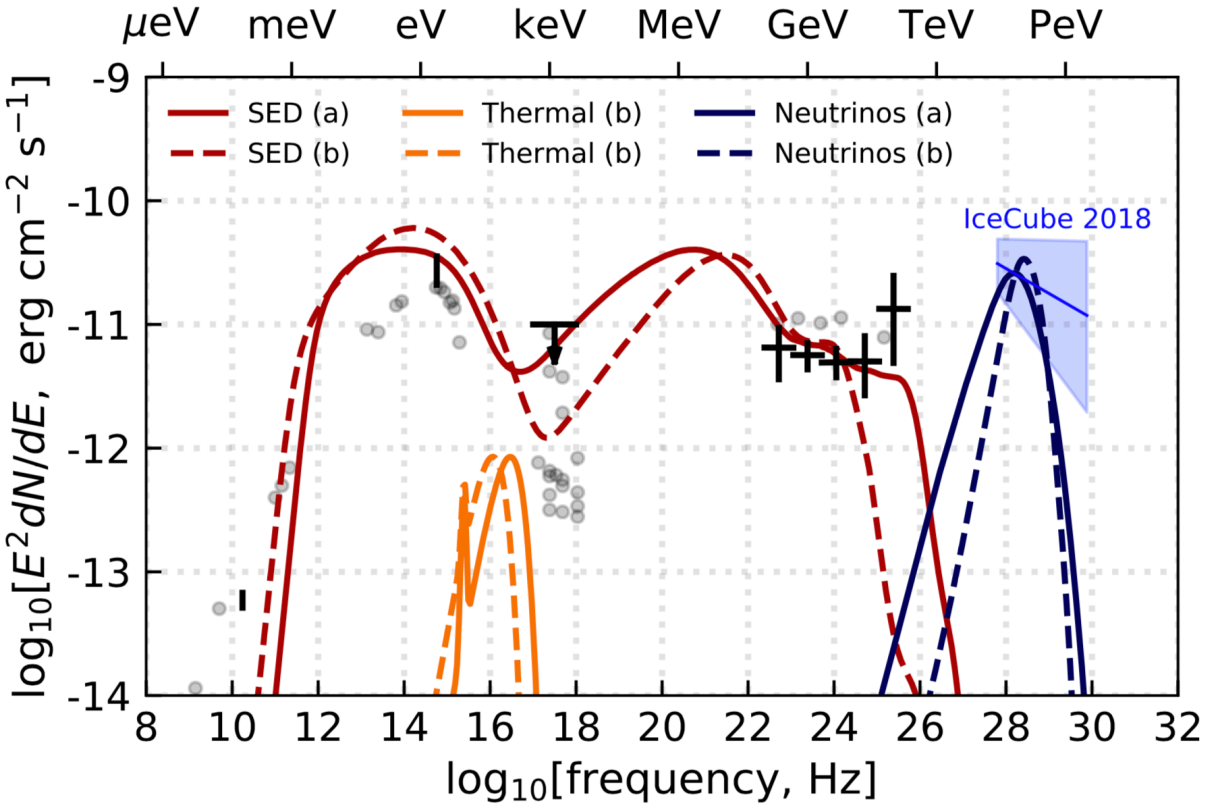


(SG, S. Buson, A. Franckowiak, ASAS-SN coll., IceCube coll. , 2019)

The neutrino / gamma-ray connection in blazars

A complicated puzzle

- Approaches to explain different gamma-ray behavior:
  - Absorption at source (Liu et al. 2018)
  - Hybrid models (Murase et al. 2018, Gao et al. 2018, Rodrigues et al. 2018, Keivani et al. 2018)
  - Different scaling of neutrino flux with e.m. emission (Reimer et al. 2018)
- Source properties are crucial:
  - TXS is not a BL Lac? (Padovani et al. 2019)
  - Different scenarios lead to substantial changes in the expected neutrino production rate
  - Gamma-ray observations give strong constraints to these scenarios



(X. Rodrigues et al. 2018)

Are there more gamma-ray sources coincident with high-energy IceCube neutrinos?

Search for high-energy neutrinos coincident with gamma-ray sources

Look into realtime and historical events

- Sample of high-energy neutrino events:
  - Observed from 2010 to 2017 (up to IC-170922A)
  - Satisfy realtime trigger criteria

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- Angular uncertainty cut:
  - Events with 90% angular uncertainty > 5deg^2 —> removed!

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One additional match out of 37 events: 3FGL J1040.4+0615 (GB6 J1040+0617)

GB6 J1040+0617

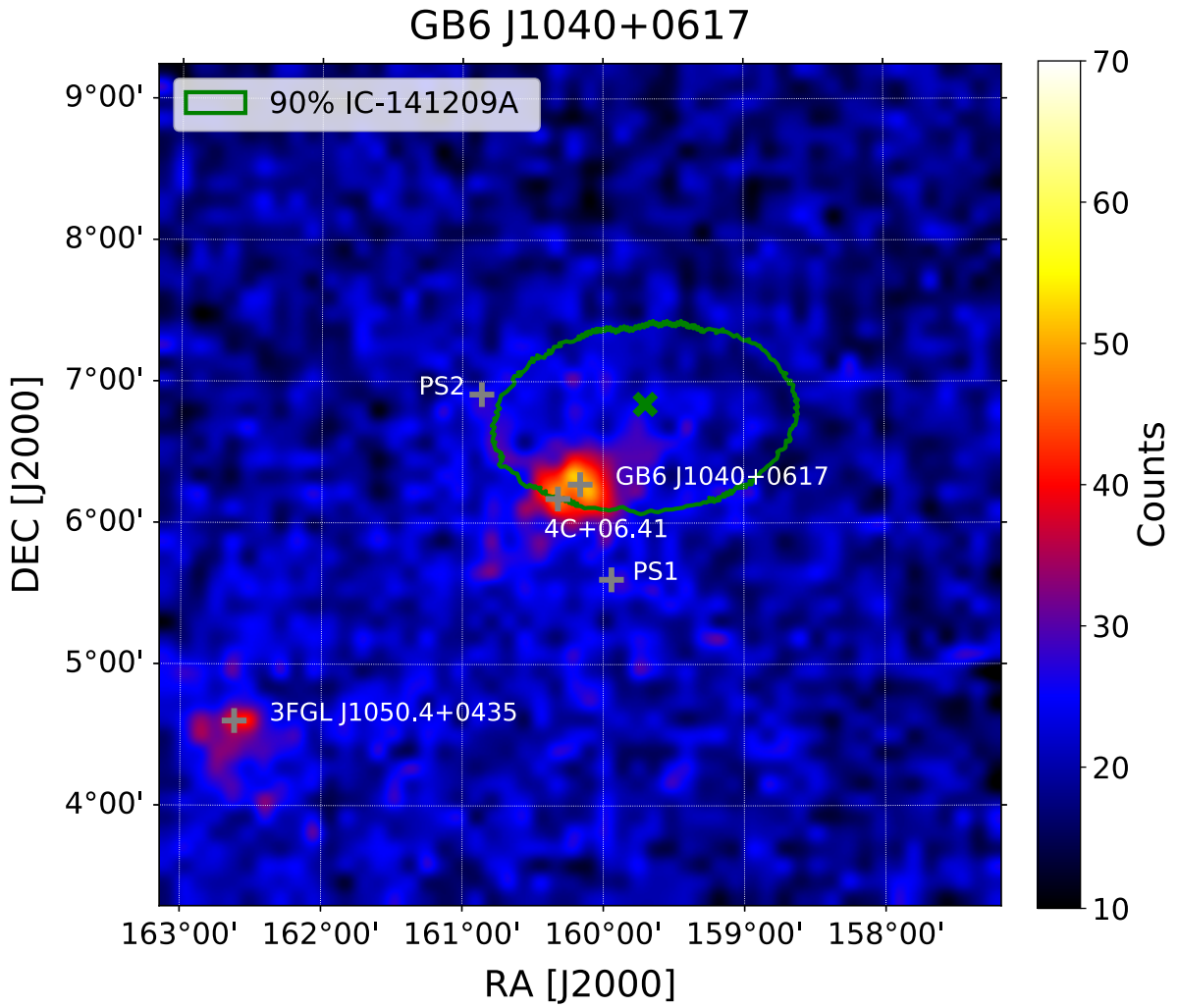
Counterpart for IC-141209A

IC-141209A

- December 9th, 2014
- Ang. Err.(90%): 2.24 deg^2
- Signalness: 29%

GB6 J1040+0617

- BL Lac, LSP
- z = 0.7351 ± 0.0045
- Dist. from IC-141209A: 0.7°



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GB6 J1040+0617

Counterpart for IC-141209A

GB6 J1040+0617

- Type: BL Lac, LSP
- 3FGL J1040.4+0615
- z = 0.7351 ± 0.0045
- Dist. from IC-141209A: 0.7°

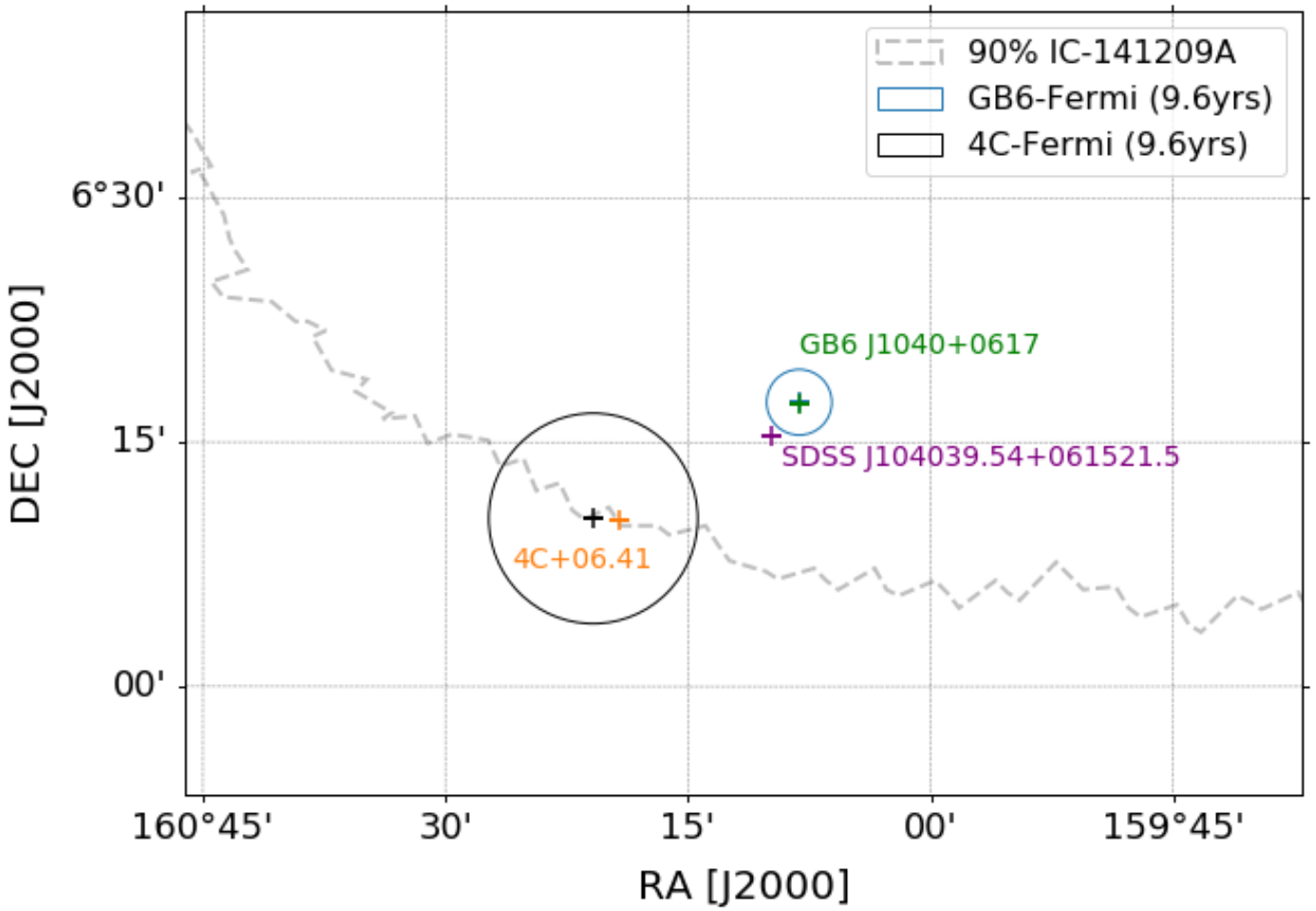
4C+06.41

- Type: FSRQ
- z = 1.27
- Dist. from GB6: 0.22°

SDSS J104039.54+061521.5

- Type: FSRQ
- No gamma-ray detection

9.6 years

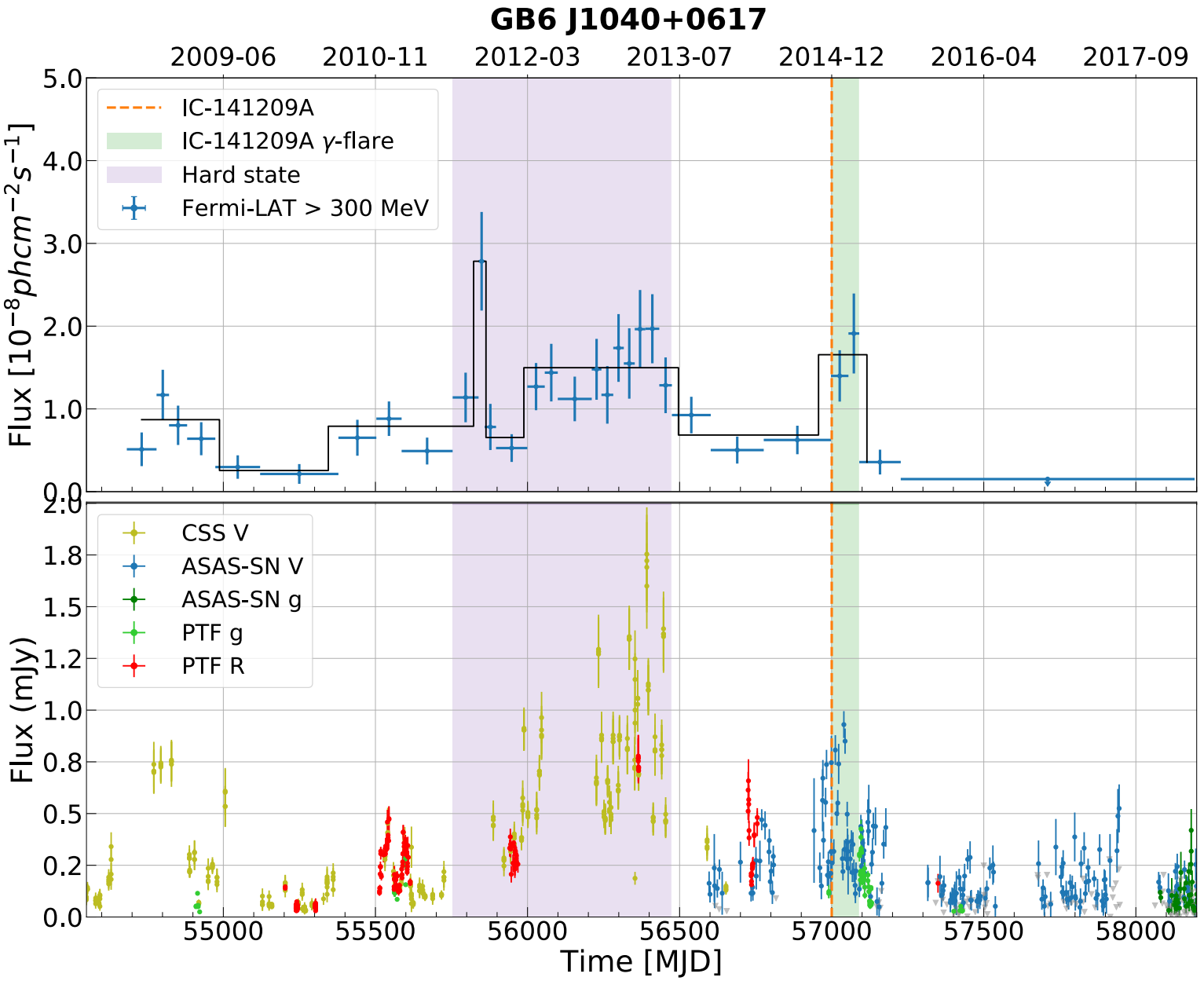


(SG, S. Buson, A. Franckowiak, ASAS-SN coll., IceCube coll. , 2019)

GB J1040+0617

Lightcurve Analysis

- **Gamma-ray data:**
  - Moderate flare starting few days before IC-141209A
  - Flare duration ~ 100 days
- **Optical data:**
  - Flaring activities match with gamma-ray data



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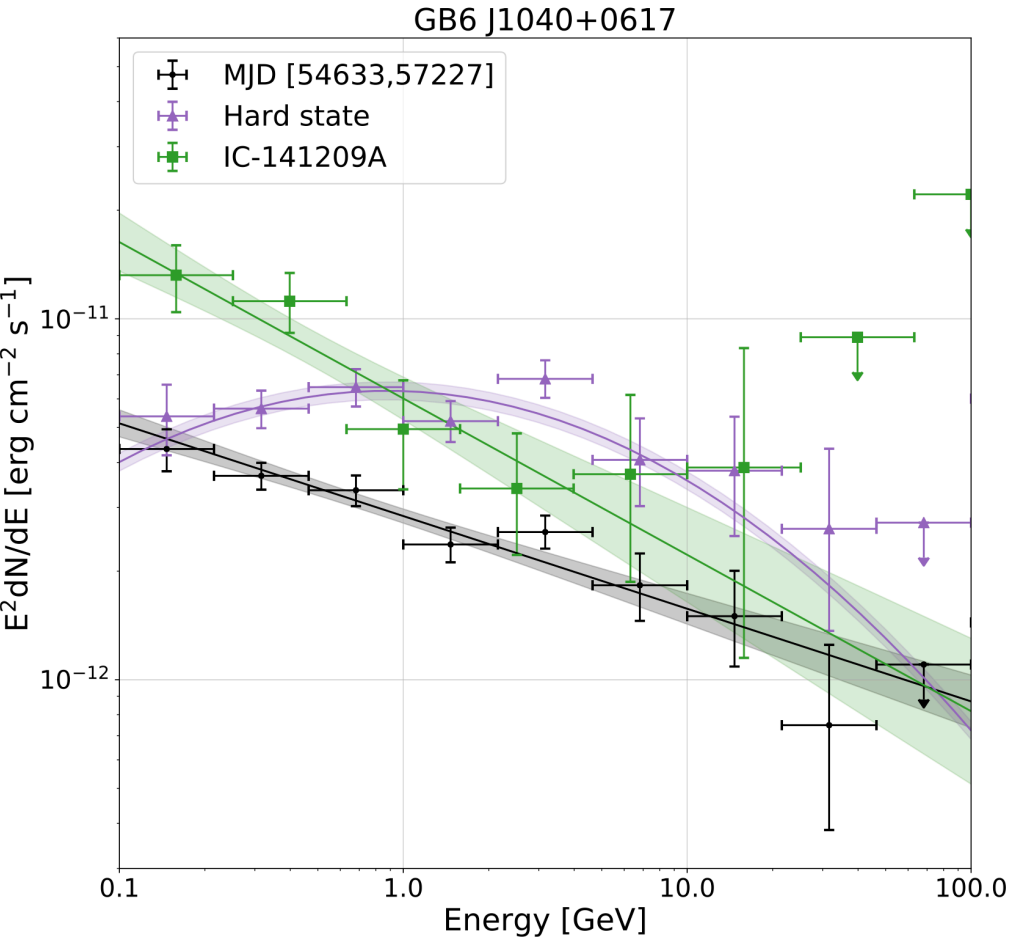
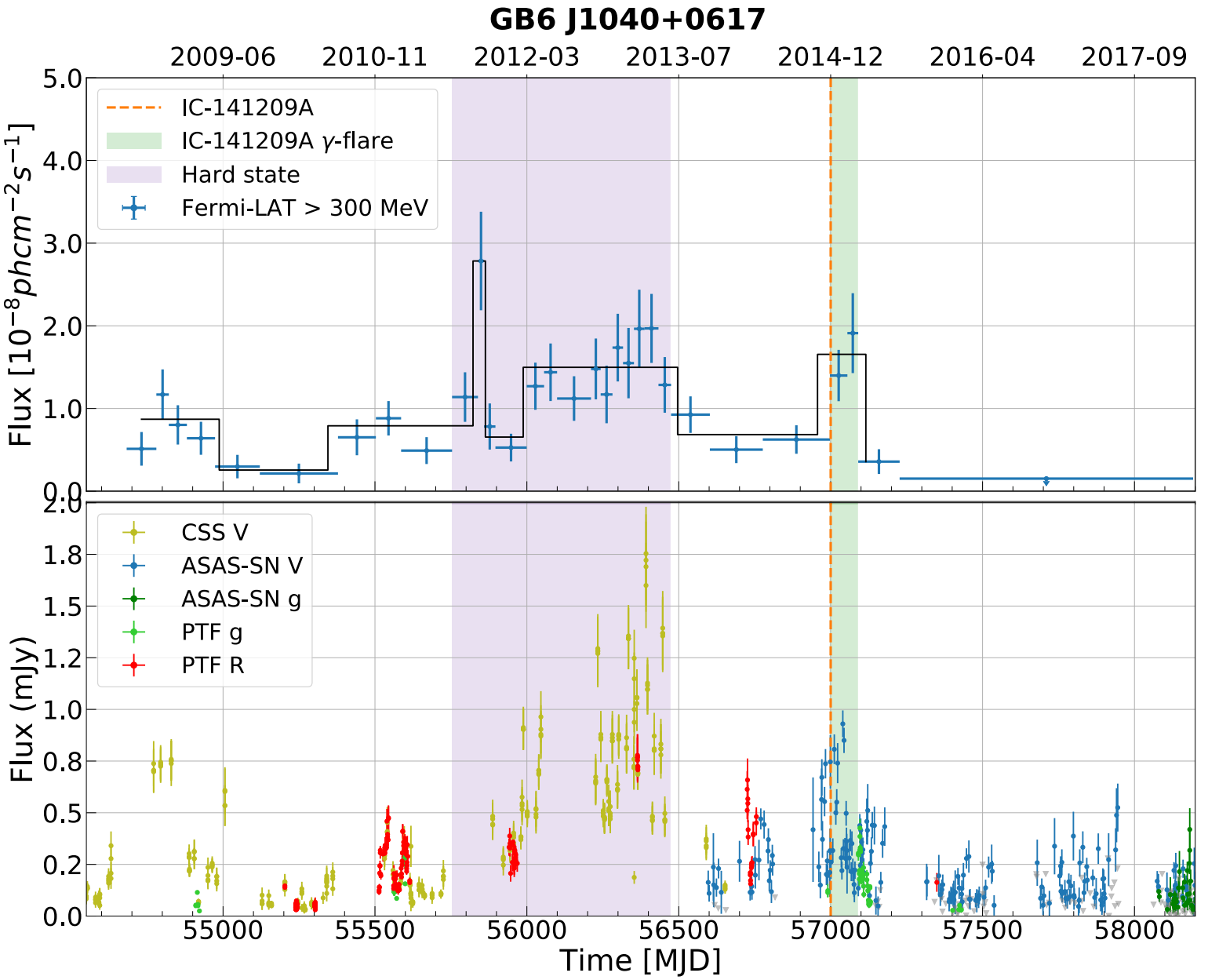
GB6 J1040+0617

Fermi-LAT 9.6 years





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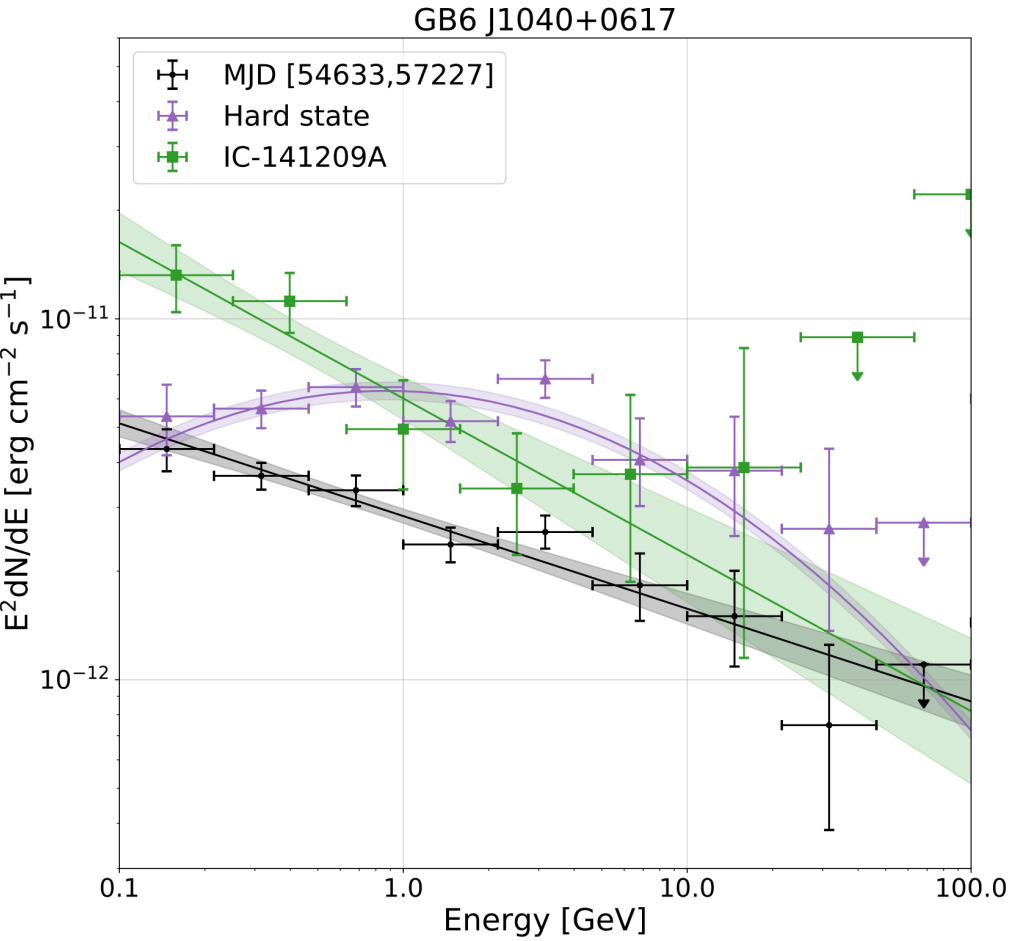

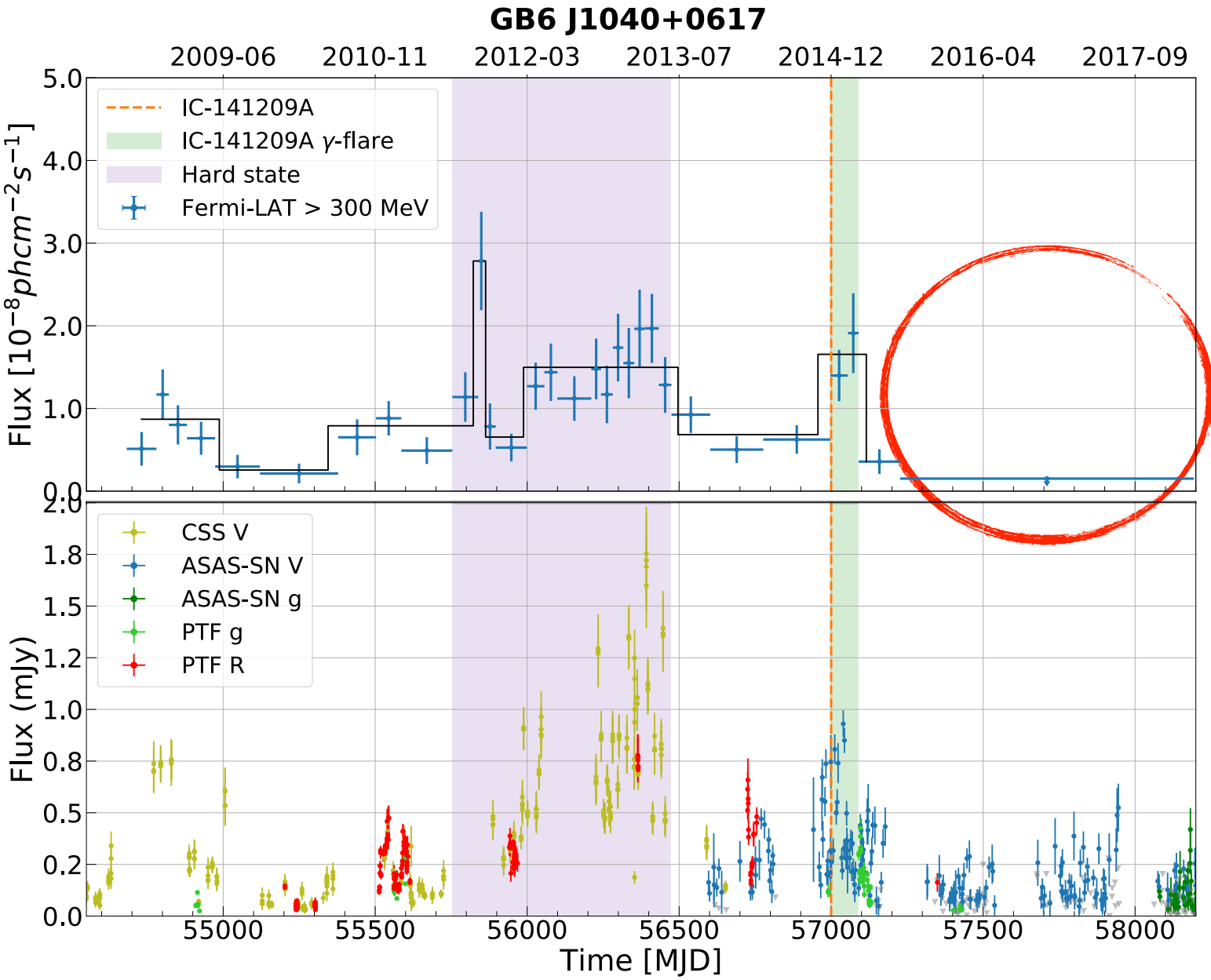

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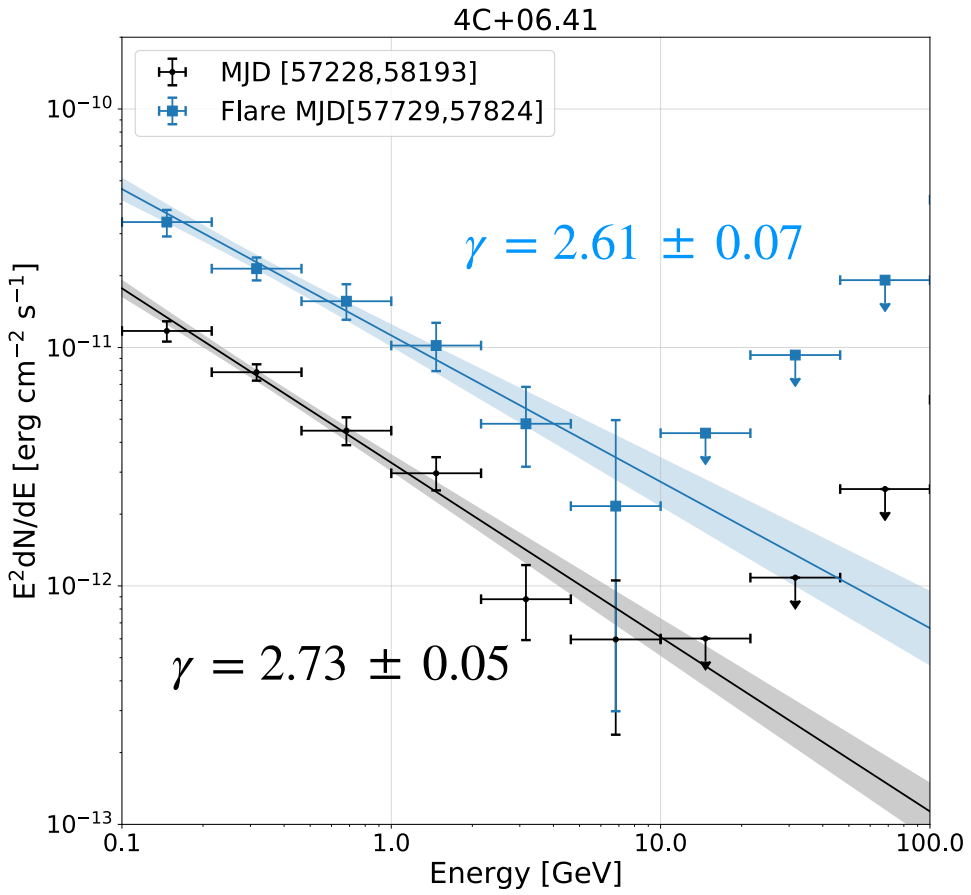
4C+06.41

A new emerging source

- No significant detection before MJD 57228
- Bright flaring state lasting 95 days



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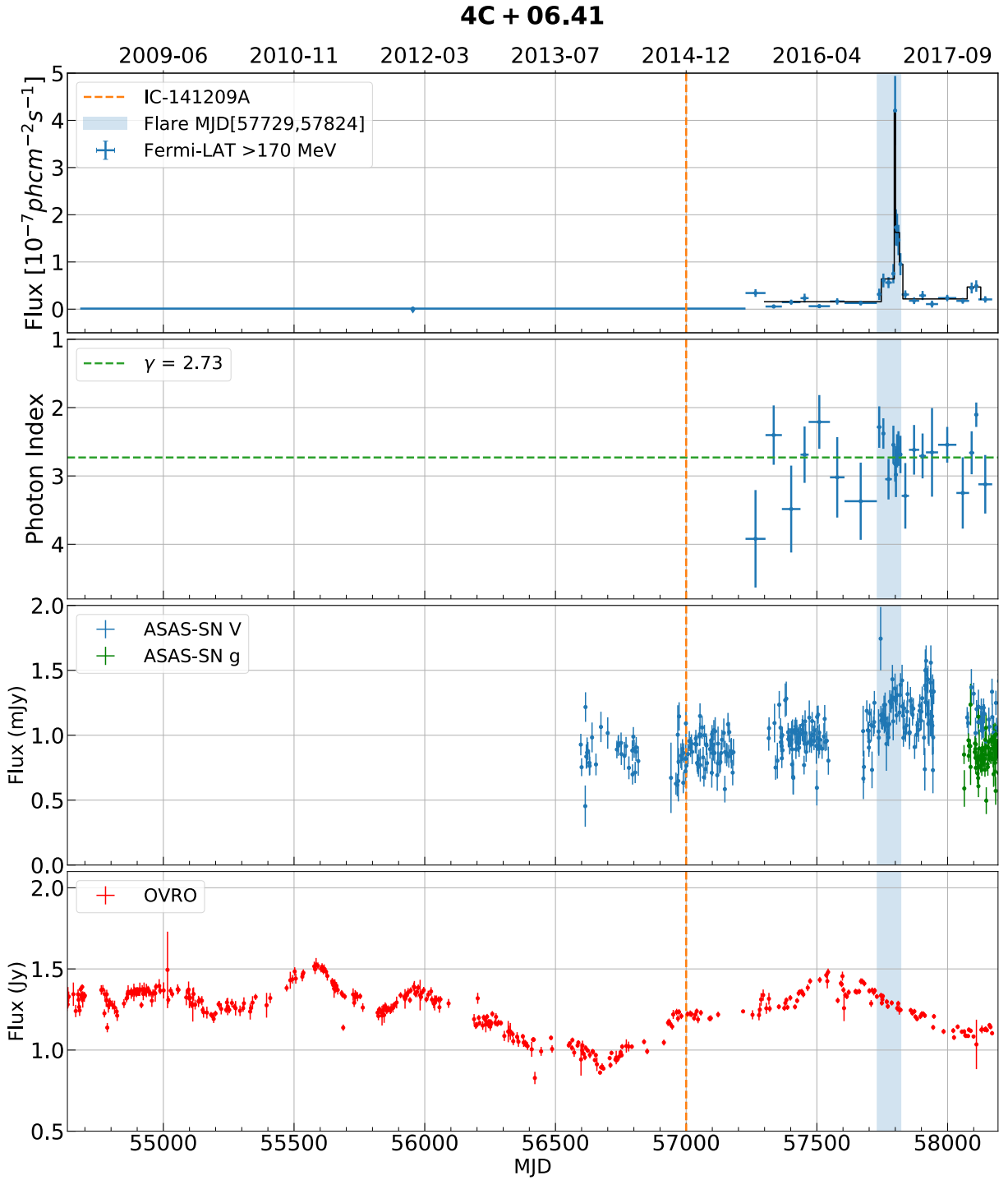

Chance coincidence

IC-141209A

- We considered N_s = 2257 sources with monthly light curves
- Among all lightcurve bins, 9.5% show brighter gamma-ray energy flux in 1-100 GeV
- Area of 90% neutrino error circle A_ν = 2.24 deg^2
- Probability of finding unassociated sources is:

$$p = N_s A_\nu / (4\pi) \times 0.095 = 1\,\% \;\rightarrow\; 2.3\sigma$$

- After trials correction for 37 well-reconstructed events in the sample —> p-value = 30%

TXS 0506+056 and GB6 J1040+0617

Summary and take home message

- GB6 J1040+0617 is a plausible candidate for being a gamma-ray counterpart to IC-141209A
- Finding 2 events originating from Fermi blazars is consistent with stacking limits (Aartsen et al. 2017b)
- TXS and GB6 share similar properties:
  - Both BL Lac objects? (Padovani et al. 2019)
  - Similar positive declination —> where IceCube is most sensitive
  - Similar gamma-ray luminosity (assuming z = 0.73 for GB6 J1040+0617)
  - Correlation between gamma-ray, optical activities and HE neutrino observations
- Fermi-LAT sky-survey observations play a leading role in the multi-wavelengths realtime follow-ups
- Multi-wavelength observations are crucial to identify neutrino counterpart candidates

Thank you.

BACKUP

September 22nd, 2017

Most interesting event so far

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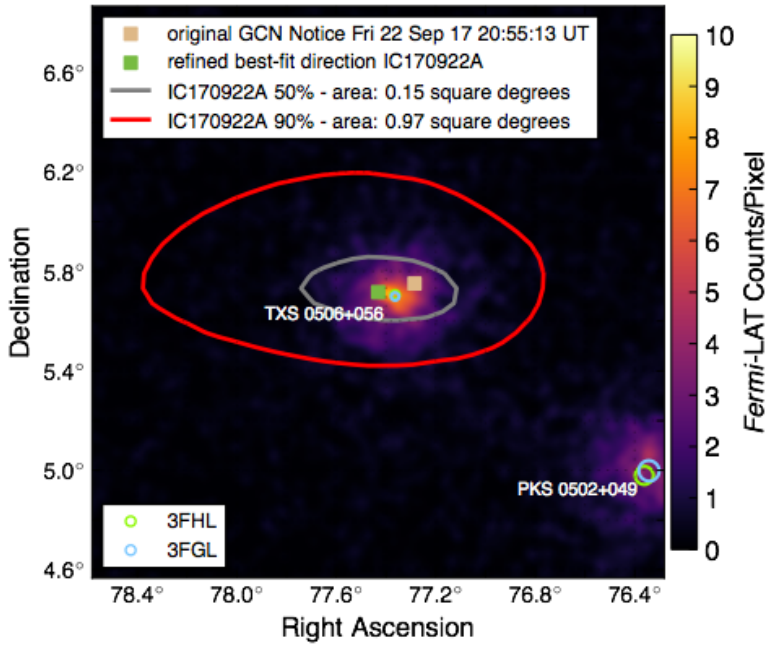

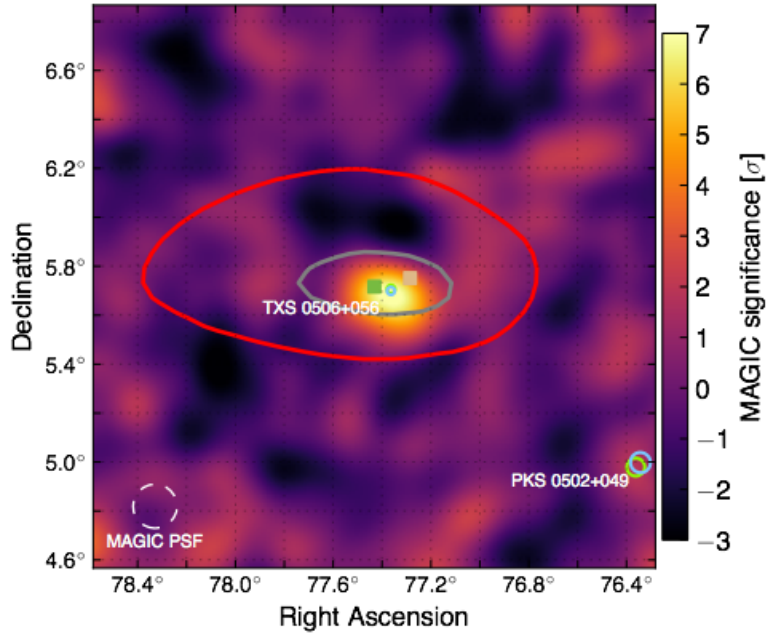

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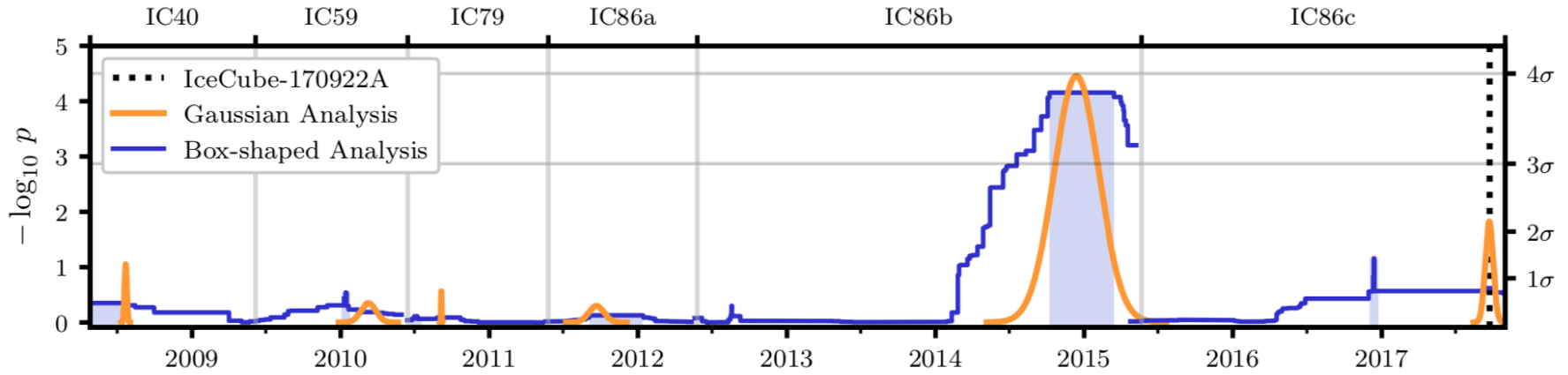
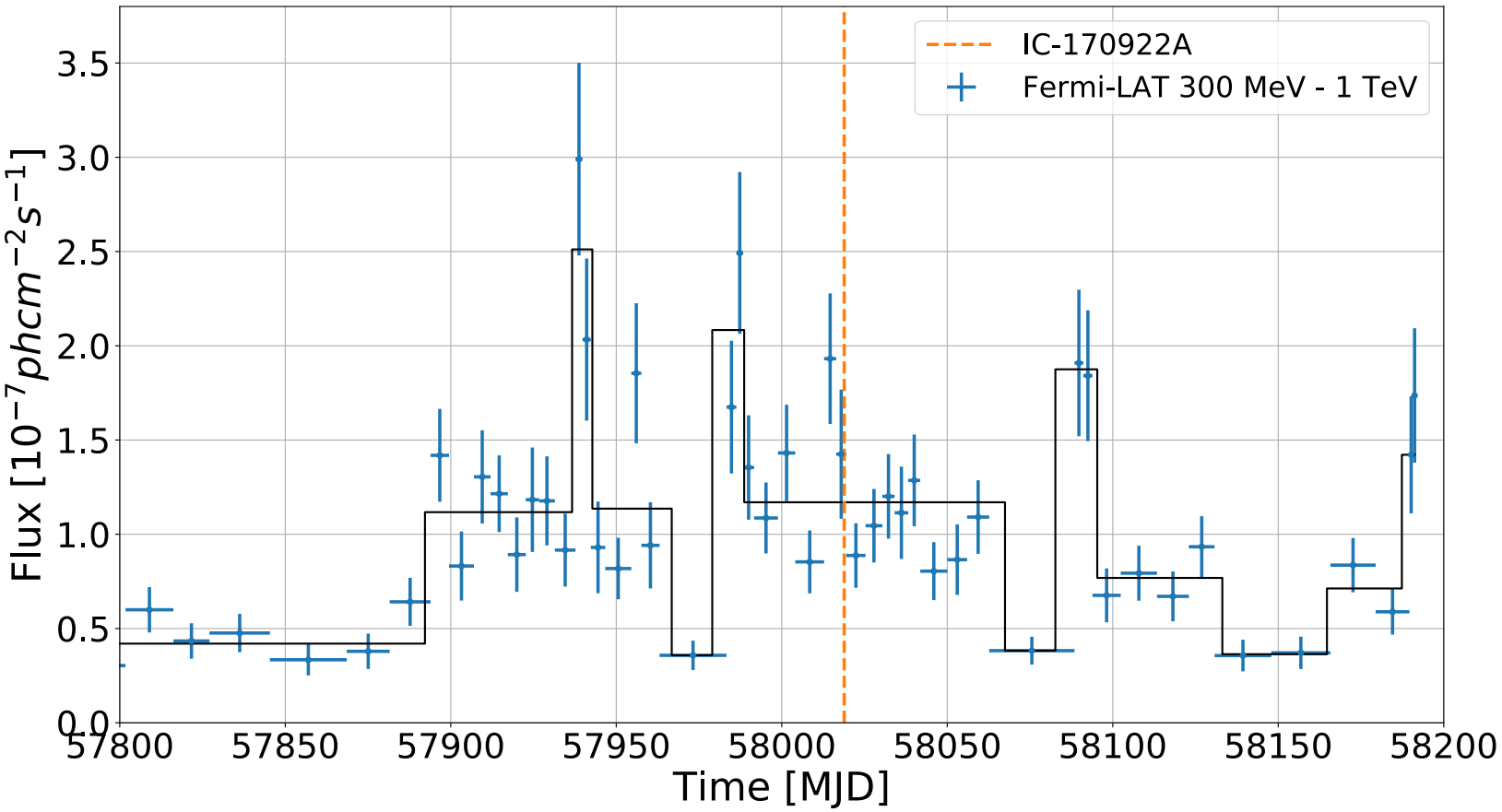
a 3.5σ neutrino excess of 13 ± 5 events



TXS 0506+056

IC-170922A, gamma-ray flare

- Three bright subflares detected in the 2017/18 bright gamma-ray flare
- We find similar spectral shapes compared to the average 9.6 years SED
- Significant structures are found also on a few days timescale

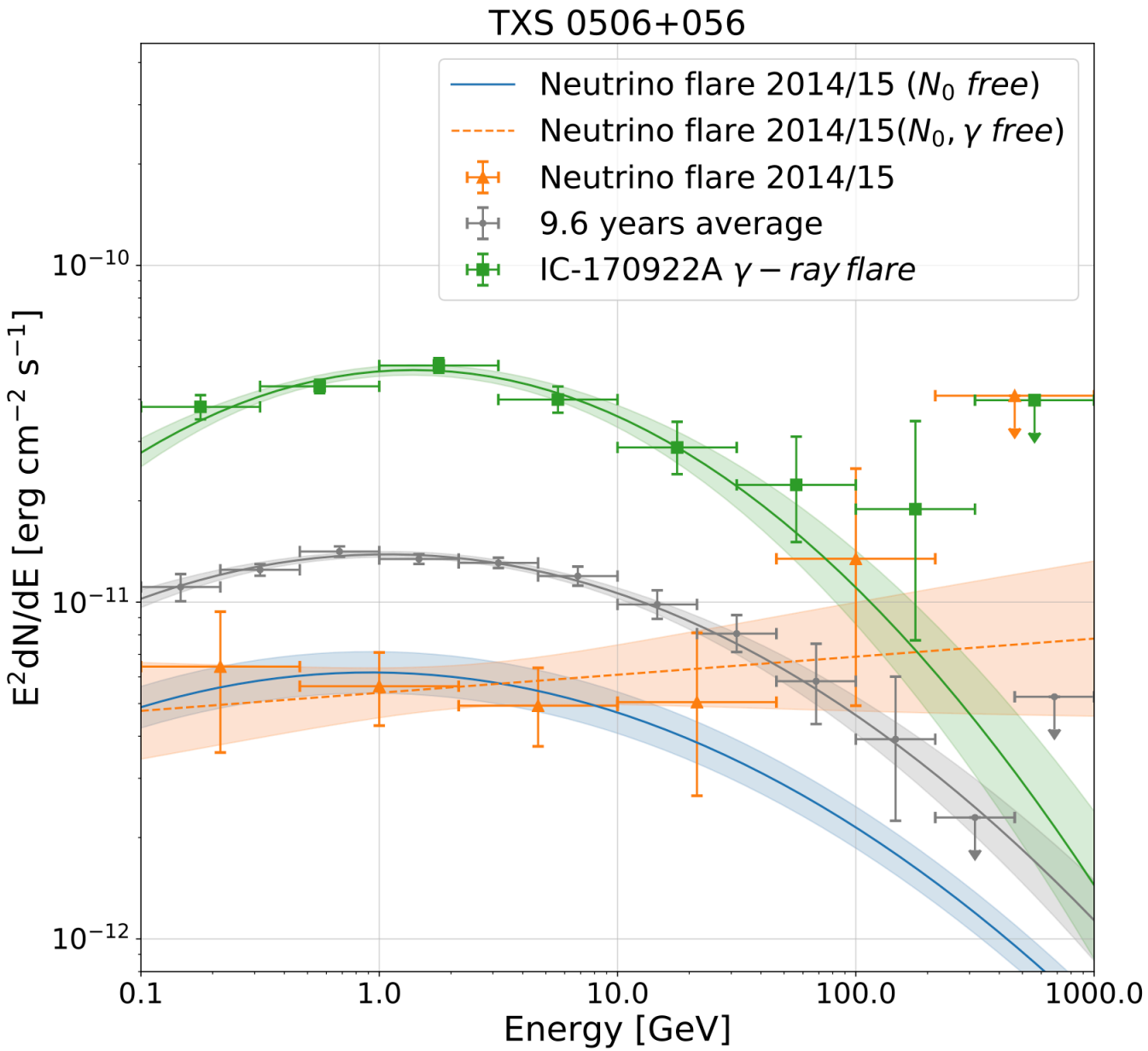


TXS 0506+056

Spectral Analysis

- Likelihood Ratio Test
  - H_0 : spectral shape identical to average
  - H_1 : alternative spectral shape

- $$TS_{SC} = -2(\log\mathcal{L}_0 - \log\mathcal{L}_1)$$



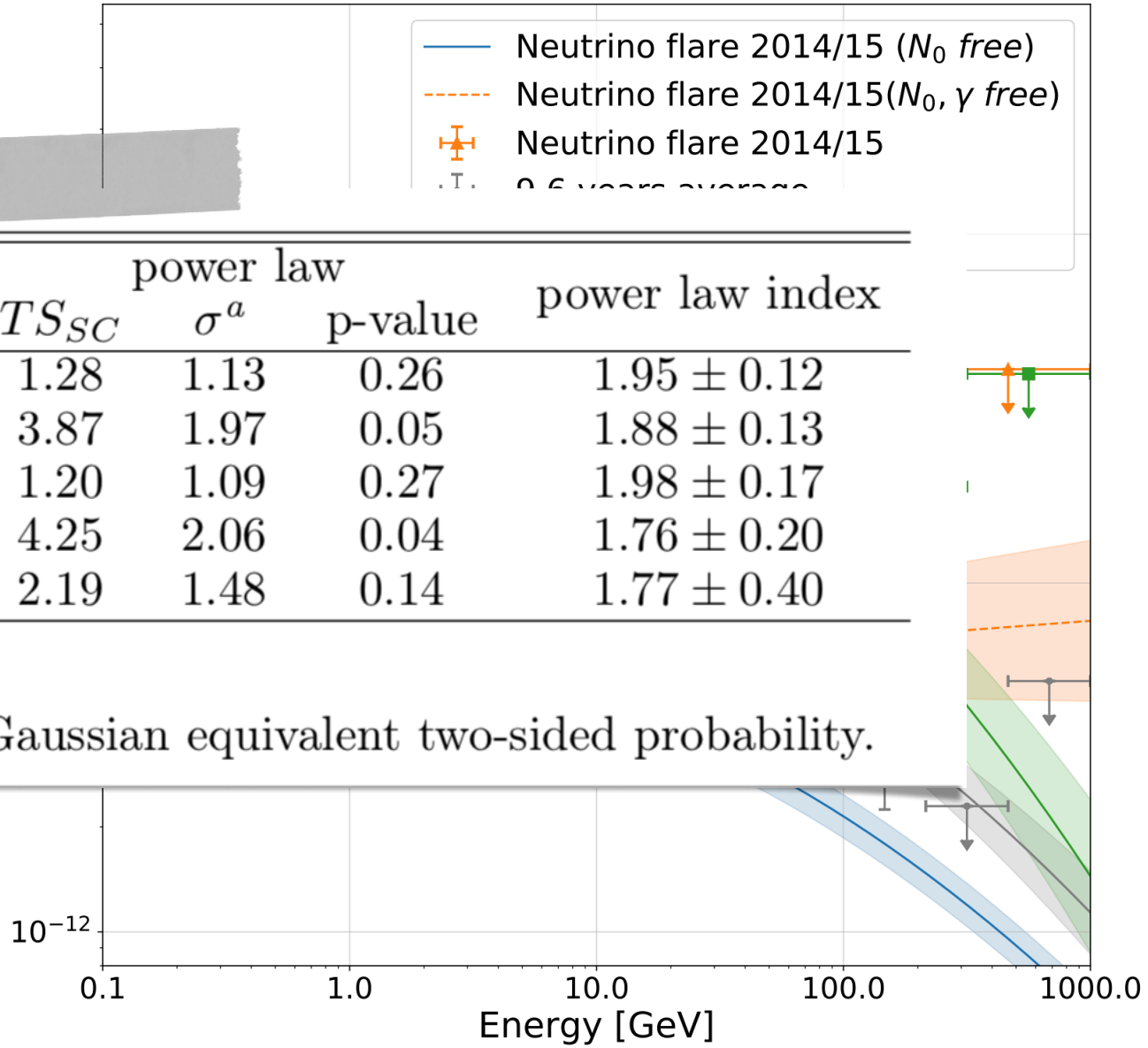
TXS 0506+056

Spectral Analysis

- Likelihood Ratio Test
  - H_0 : s
  - H_1 : a
-

$E_{\min}$ [GeV]	log parabola TS_{SC}	log parabola σ^a	log parabola p-value	power law TS_{SC}	power law σ^a	power law p-value	power law index
0.1	2.49	1.06	0.29	1.28	1.13	0.26	1.95 ± 0.12
0.5	4.13	1.53	0.13	3.87	1.97	0.05	1.88 ± 0.13
1.0	2.33	1.01	0.31	1.20	1.09	0.27	1.98 ± 0.17
2.0	5.12	1.77	0.08	4.25	2.06	0.04	1.76 ± 0.20
10.0	3.64	1.40	0.16	2.19	1.48	0.14	1.77 ± 0.40

$^{(a)}$ Significance in σ assuming a Gaussian equivalent two-sided probability.



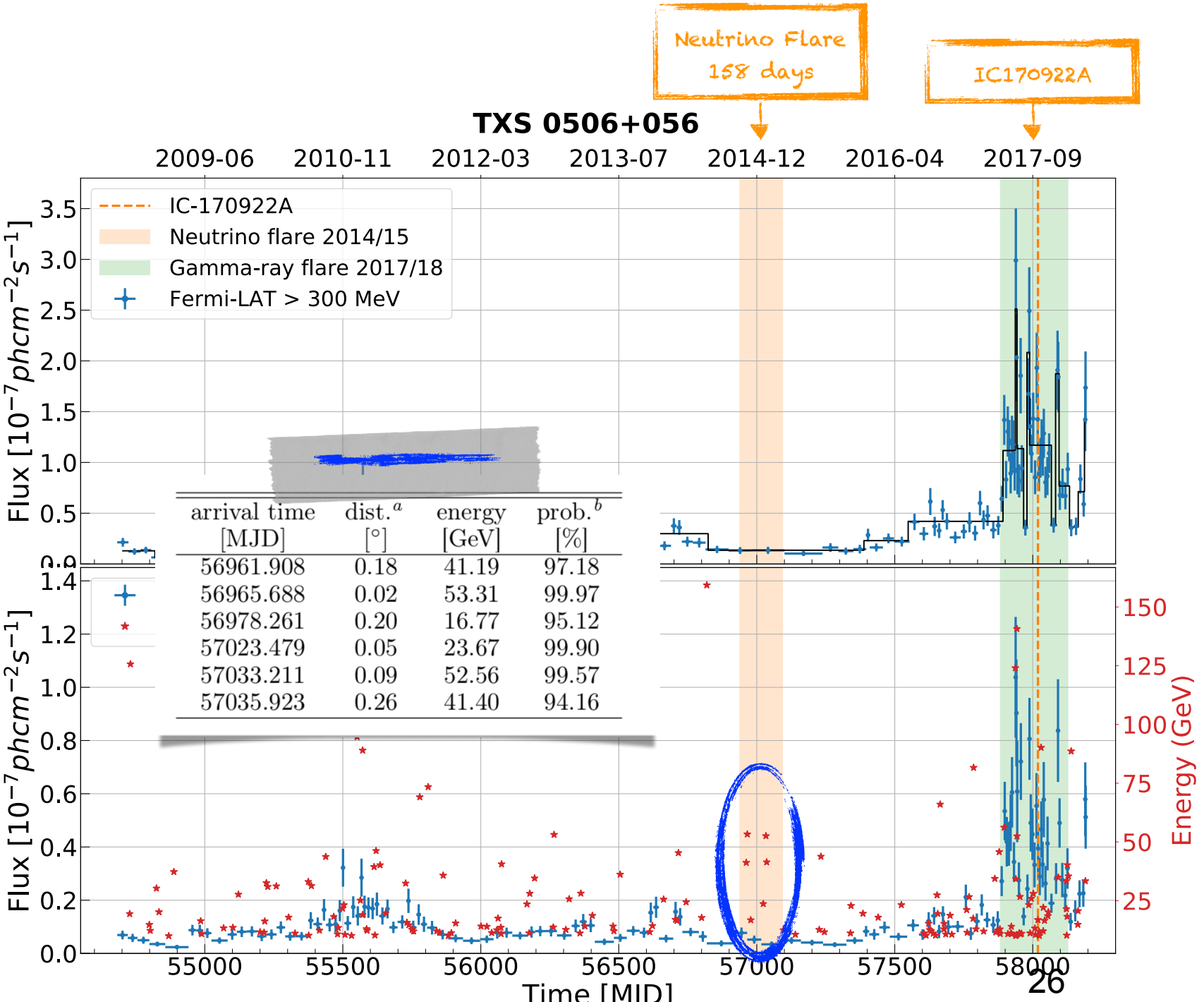
TXS 0506+056

Lightcurve Analysis

- Patterns in the HE photons?
  - 6 photons with E > 10 GeV

Test:

- Spectral shape from 700 quiet days
- Fit normalization in 158days
- Compute number of expected photons
- P-value = 15% -> 1σ

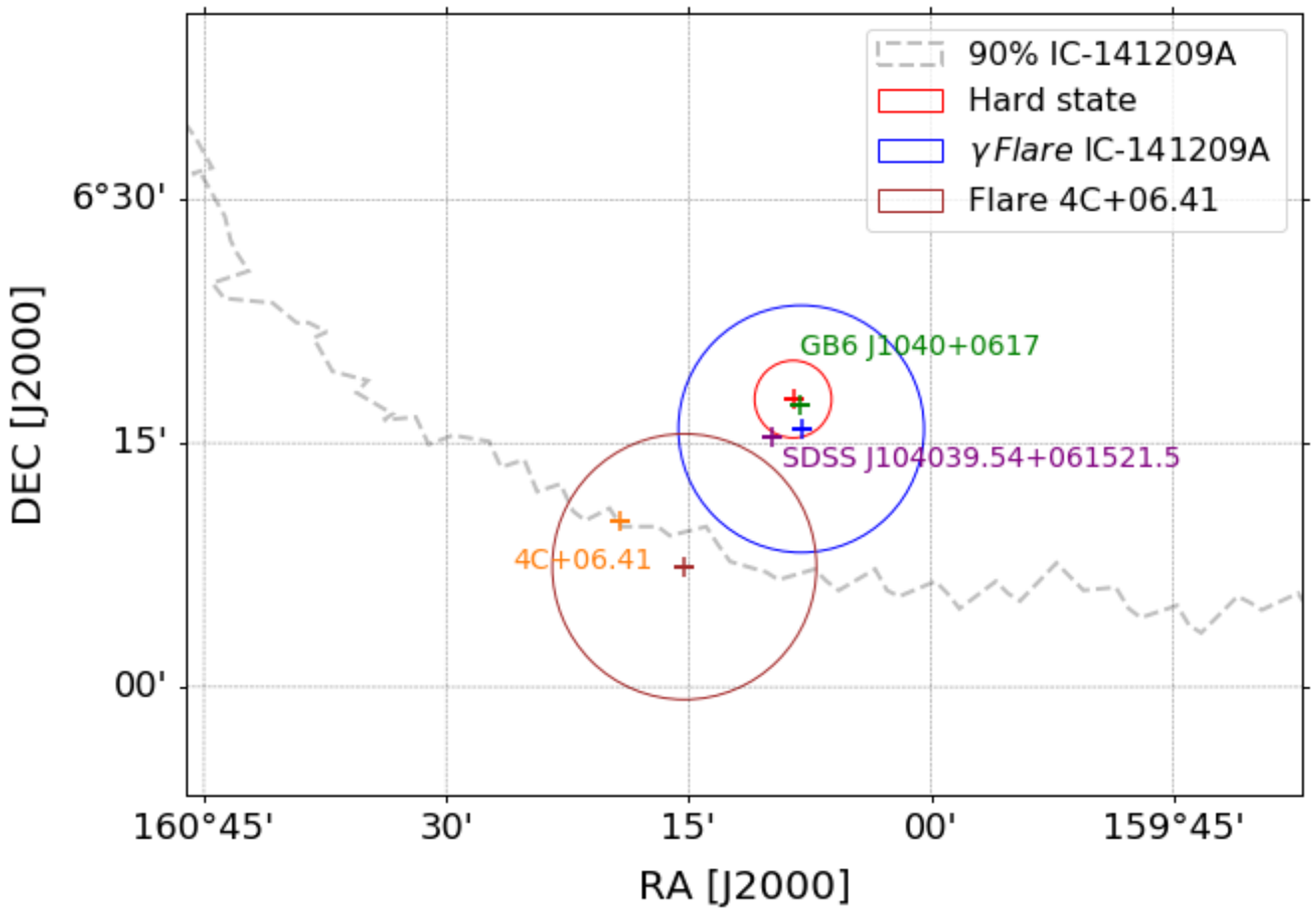


arrival time [MJD]	dist.[a] [°]	energy [GeV]	prob.[b] [%]
56961.908	0.18	41.19	97.18
56965.688	0.02	53.31	99.97
56978.261	0.20	16.77	95.12
57023.479	0.05	23.67	99.90
57033.211	0.09	52.56	99.57
57035.923	0.26	41.40	94.16

Localizing flaring activities

A sanity check

- Consistent with GB6 position:
  - Hard state
  - γ flare coincident with IC-141209A
- Consistent with 4C position:
  - Bright Flare MJD[57729,57824]
- No detection consistent with SDSS



Multi-wavelenght SED

GB6 J1040+0617