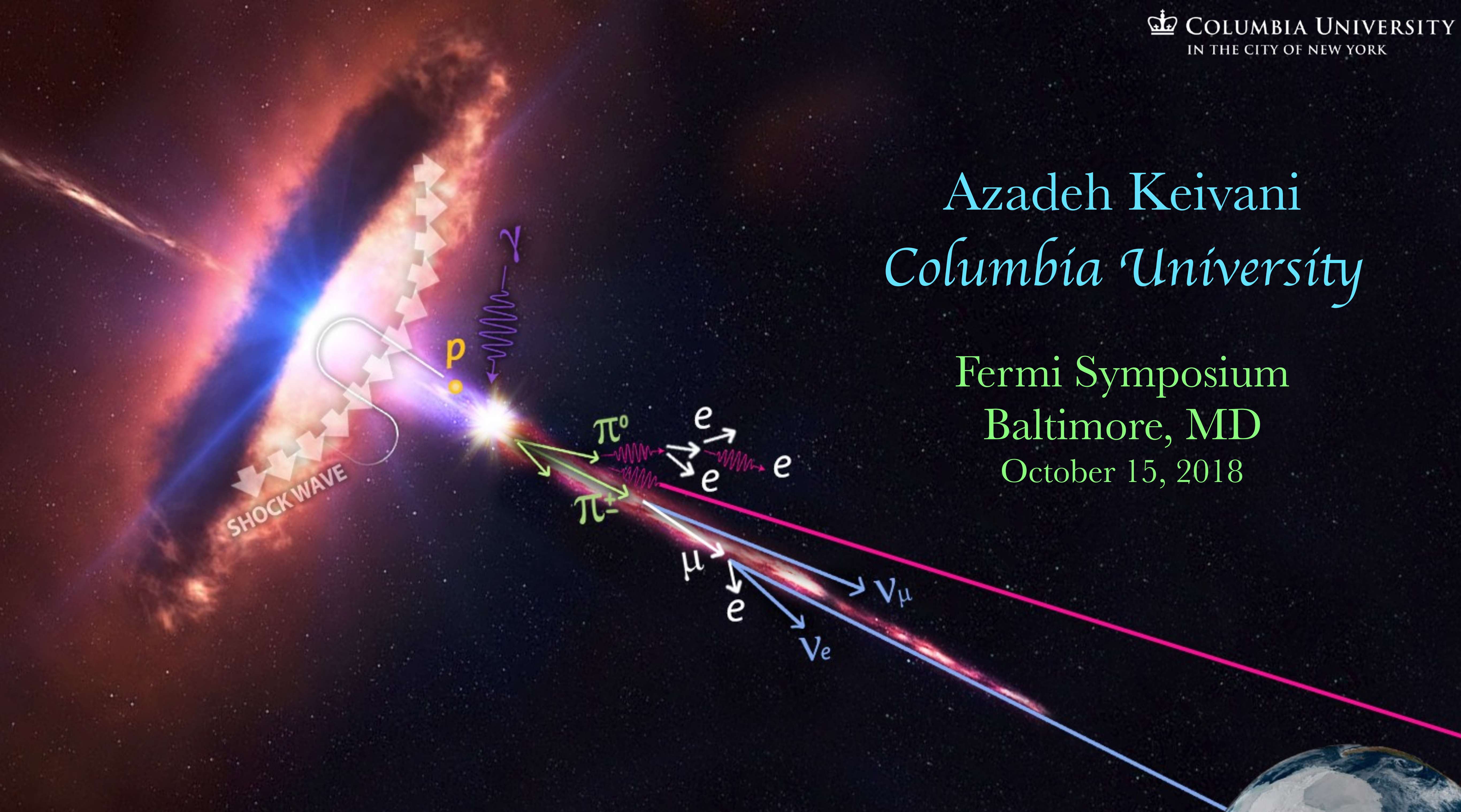
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

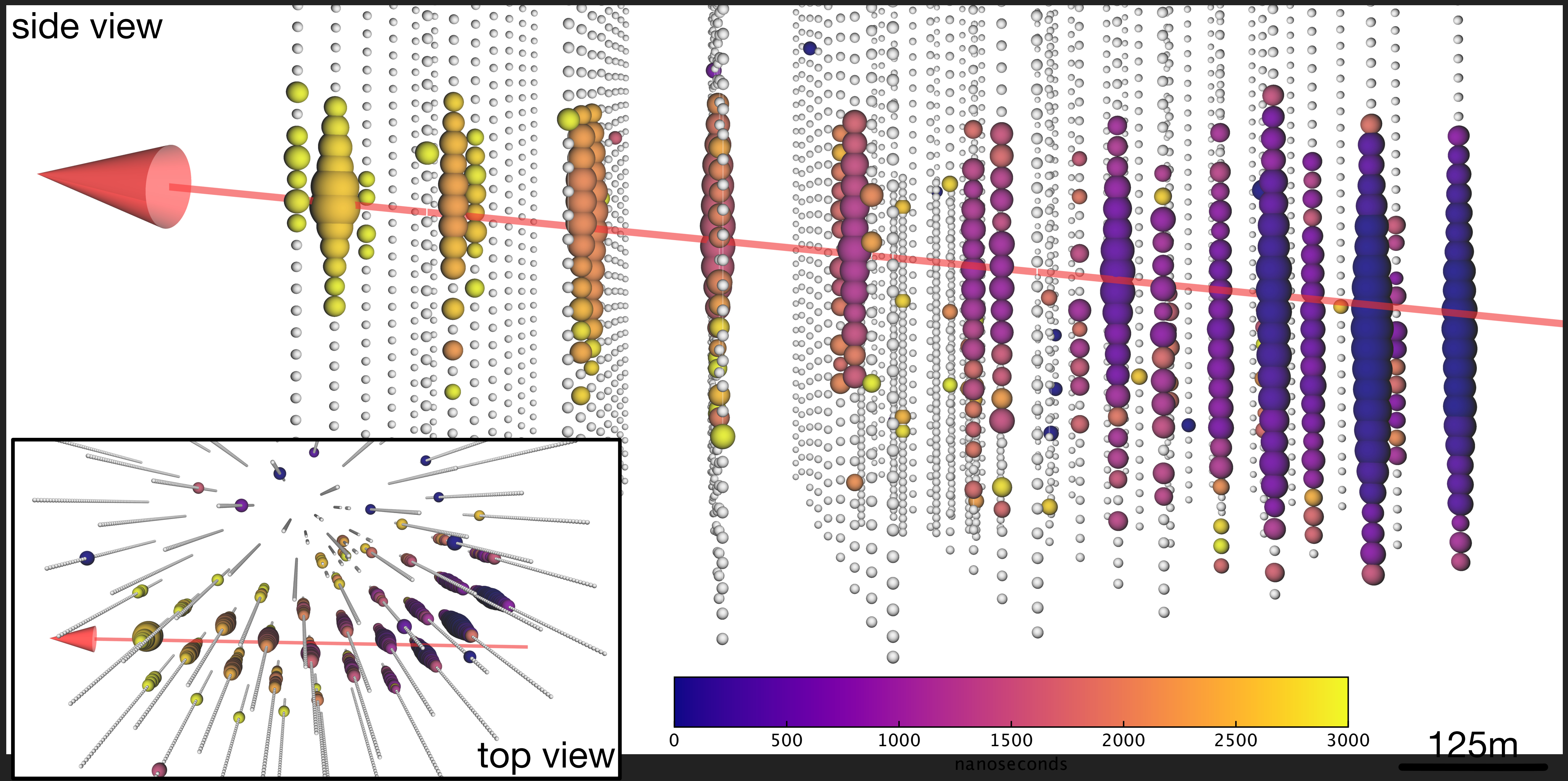


Azadeh Keivani
Columbia University

Fermi Symposium
Baltimore, MD
October 15, 2018

A Multimessenger Picture of Flaring Blazar TXS 0506+056

IceCube-170922A: A High-Energy Neutrino

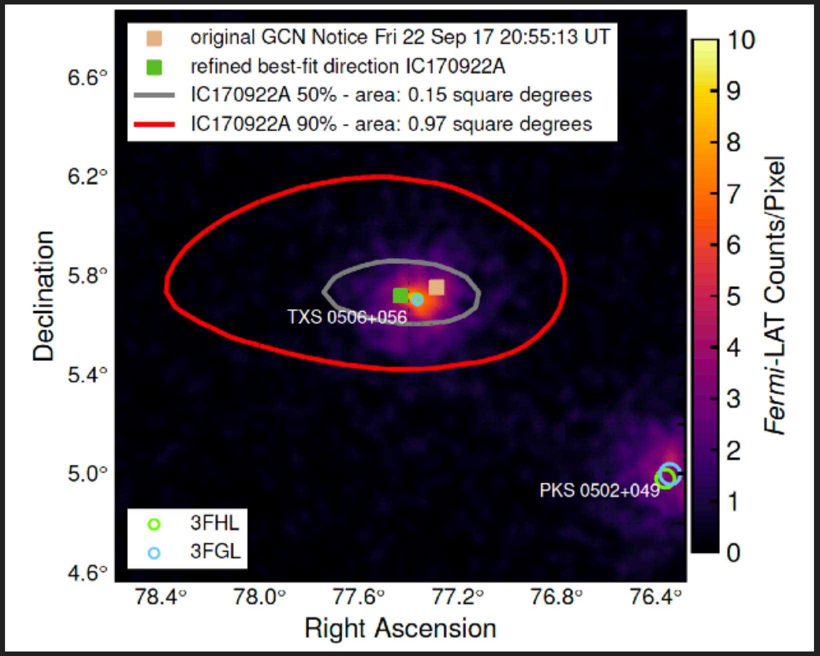


On Sept 22, 2017, IceCube detected a high-energy ν ≅ 290 TeV energy!

IceCube Collaboration, et al., Science 361, eaat1378 (2018)

Fermi LAT was the first telescope to report that TXS 0506+056
was in a flaring state!
An extensive multi-wavelength campaign happened!

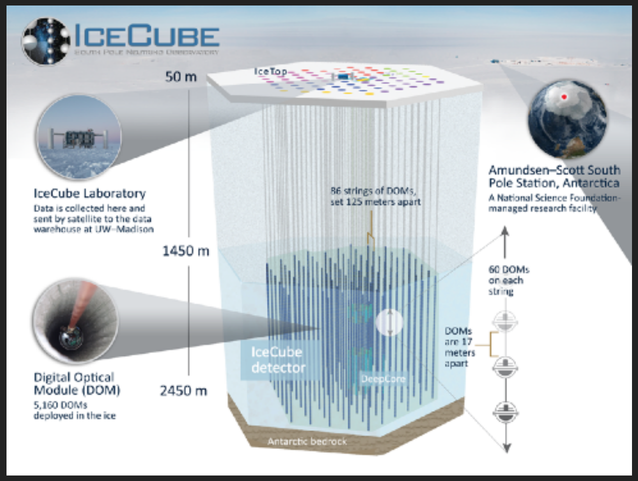
★ See also Anna Franckowiak's talk

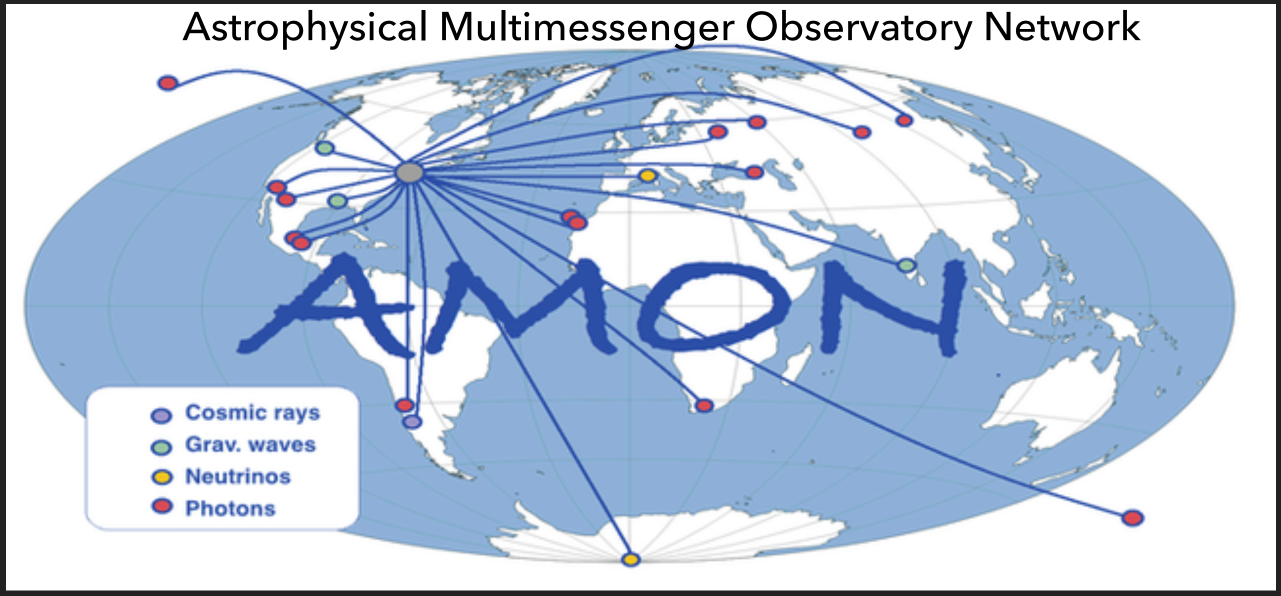


IceCube Realtime Alert System and AMON

★ See also Naoko Kurahashi Neilson's talk

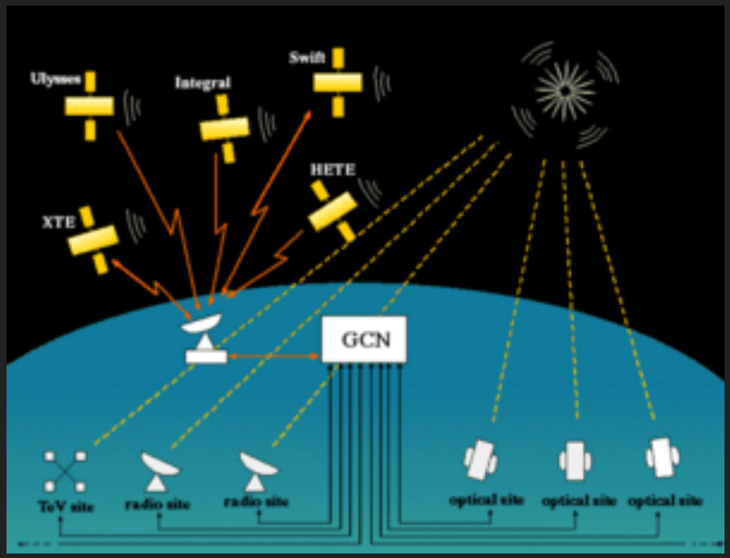
High-energy ν's detected at the South Pole

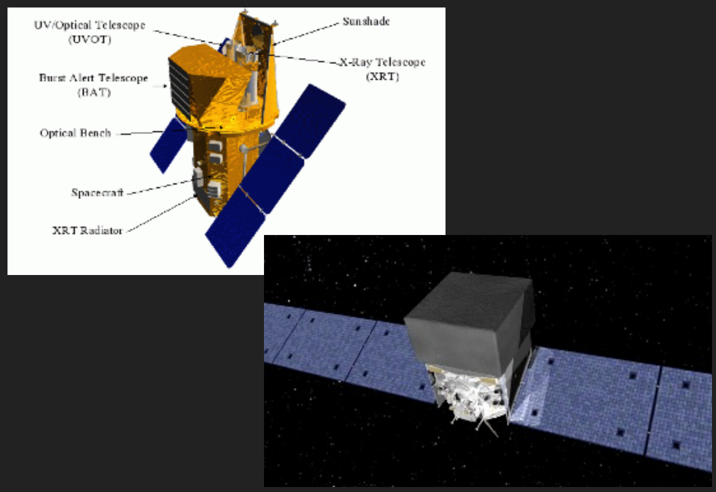




Sent to AMON at Penn State

Sent to GCN





(Automatically) trigger observatories

Multi-Wavelengths Follow-Up Campaigns

Multimessenger campaigns resulted in the first and only 3σ high-energy neutrino source association!

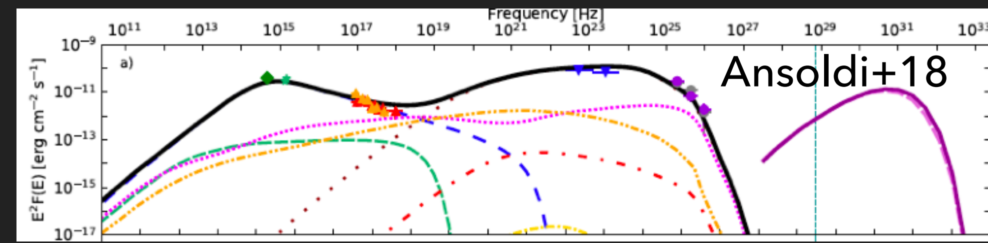
Blazars maybe a source of high-energy neutrinos!

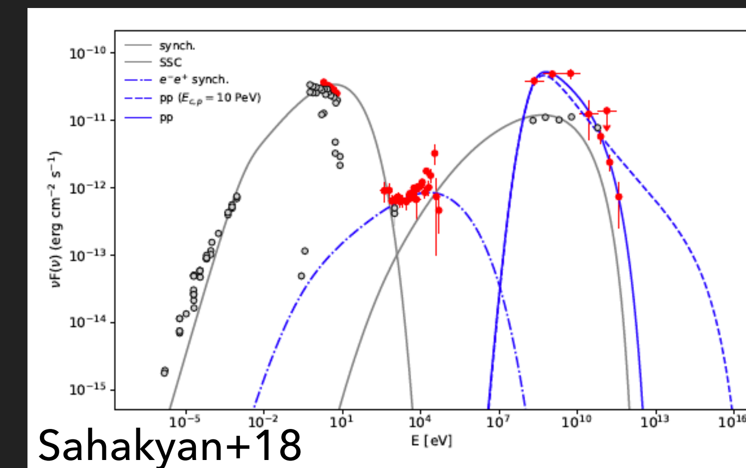
IceCube Collaboration, et al., Science 361, eaat1378 (2018)

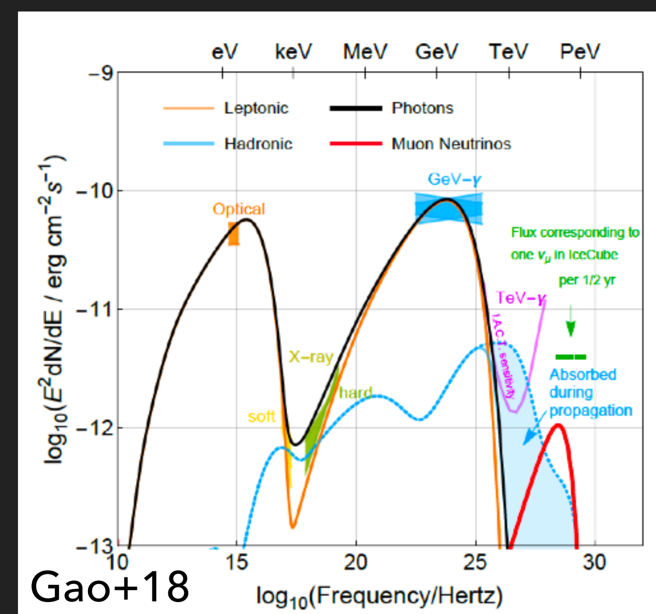
Interpretations of TXS 0506+056: Various Papers

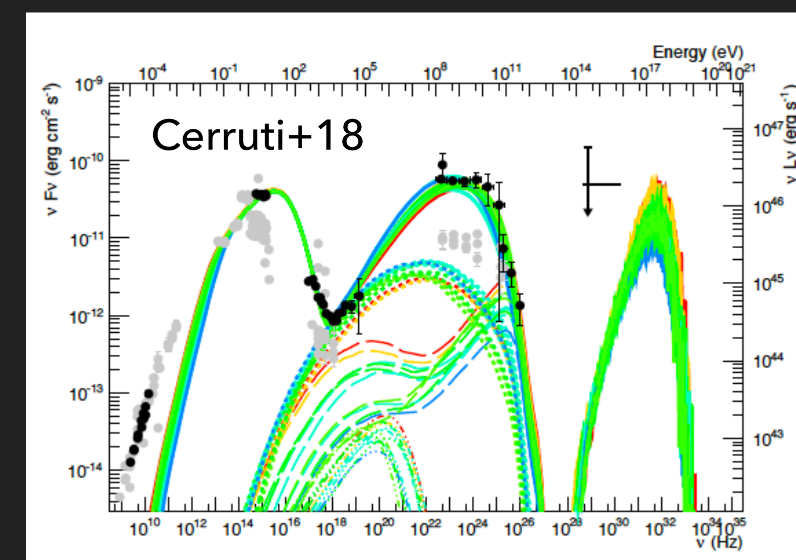
Other papers:

- ★Ansoldi+ (MAGIC Collab.)
- ★Gao+ (1807.04275)
- ★Murase+ (1807.04748)
- ★Cerruti+ (1807.04335)
- ★He+ (1808.04330)
- ★Liu+ (1807.05113)
- ★Sahakyan (1808.05651)
- ★…









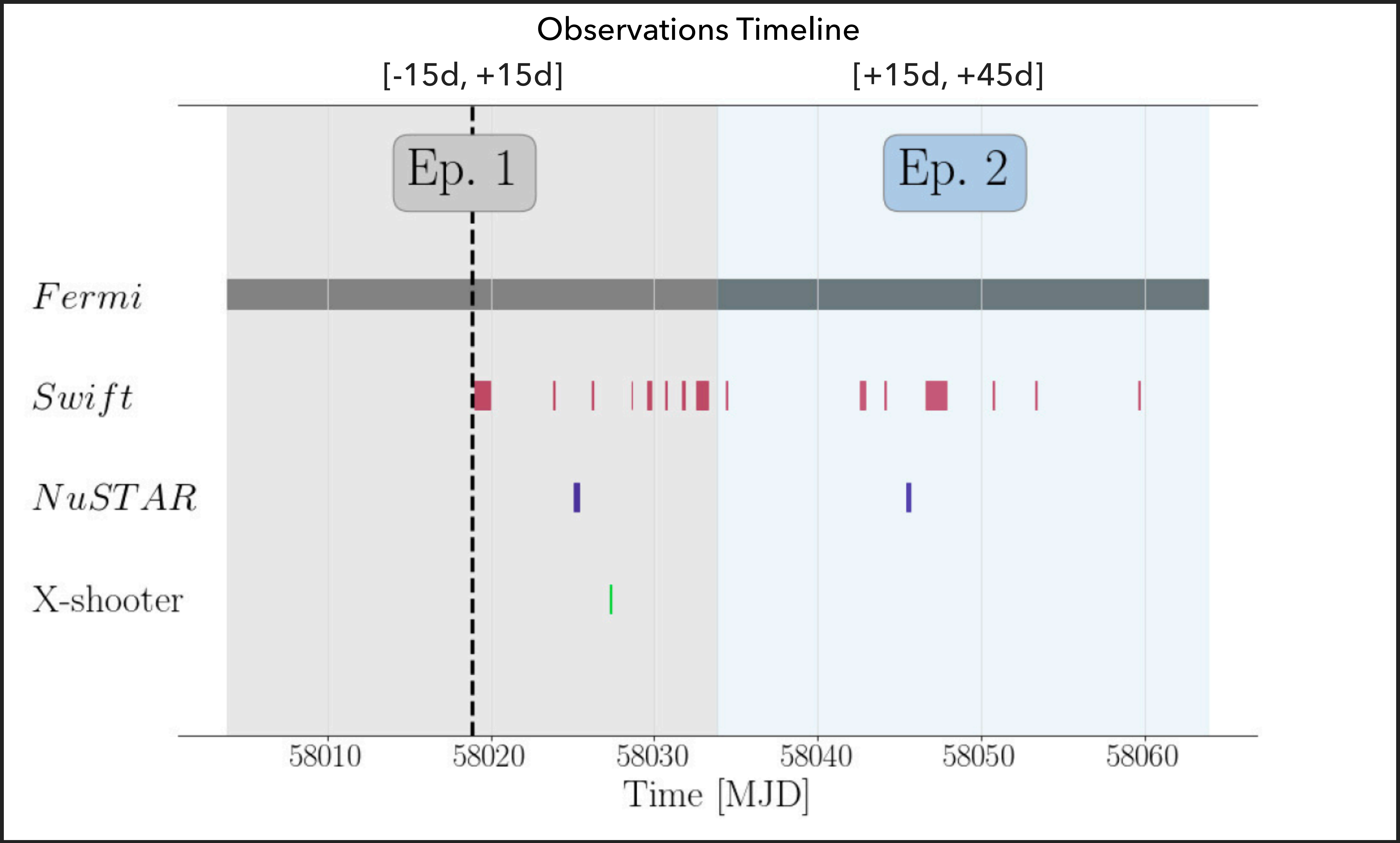
Our paper:

A Multimessenger Picture of the Flaring Blazar TXS 0506+056: Implications for High-Energy Neutrino Emission and Cosmic-Ray Acceleration

AK, Murase, Petropoulou, Fox, Cenko, Chaty, Coleiro, DeLaunay, Dimitrakoudis, Evans, Kennea, Marshall, Mastichiadis, Osborne, Santander, Tohuvavohu, Turley

ApJ 864:84 (16pp), 2018

Time-Dependent Multi-Wavelengths Observations



Fermi LAT (γ-ray), *NuSTAR* (Hard X-ray), *Swift* (Soft X-ray, UV, Optical), X-shooter (Optical)

AK, Murase, Petropoulou, Fox, et al. ApJ 864 (2018)

Spectral Energy Distribution of TXS 0506+056

Observational data used for modeling:

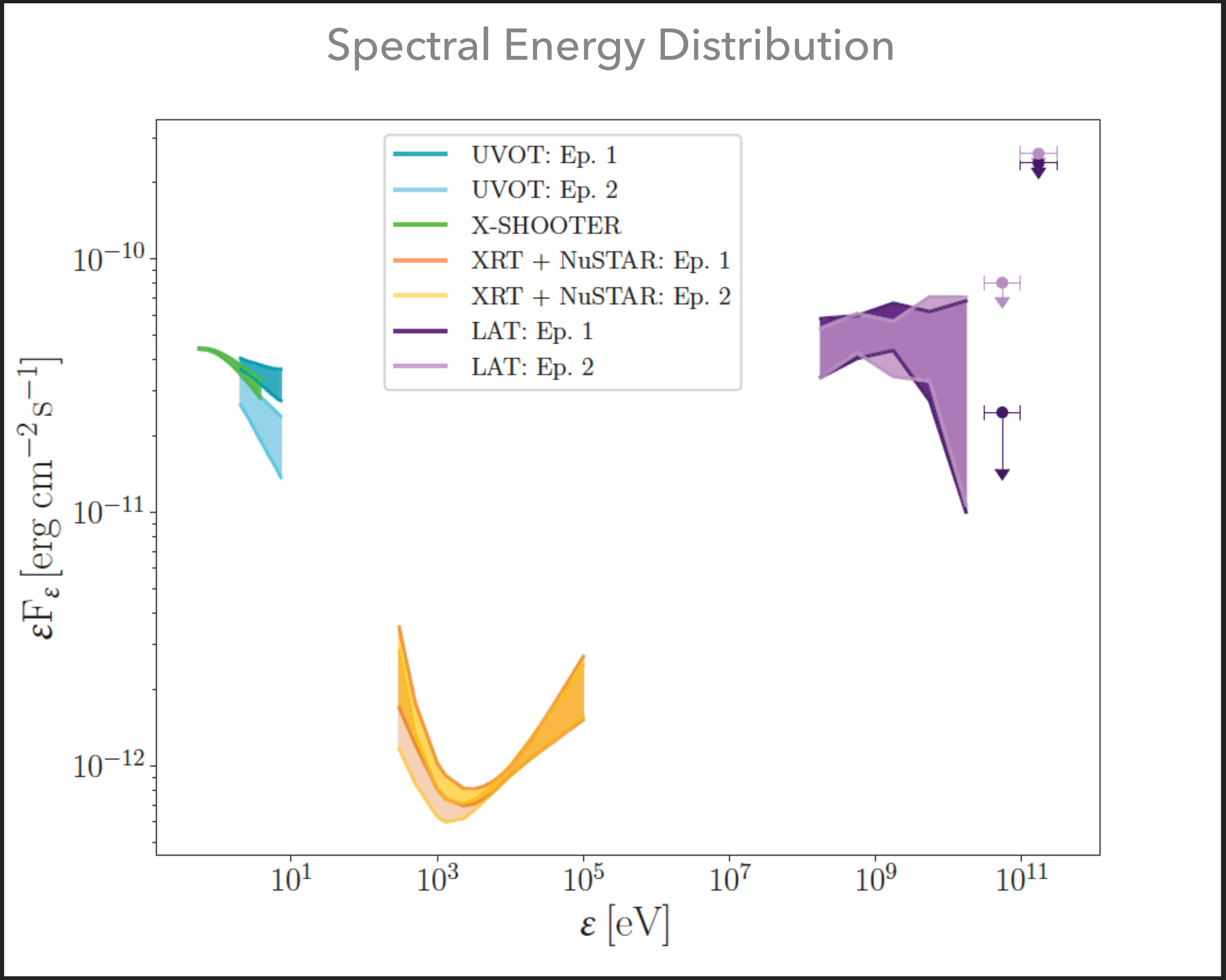
★X-shooter (Optical)

★*Swift* UVOT (Optical and UV)

★*Swift* XRT (Soft X-ray)

★*NuSTAR* (Hard X-ray)

★*Fermi* (γ-ray)

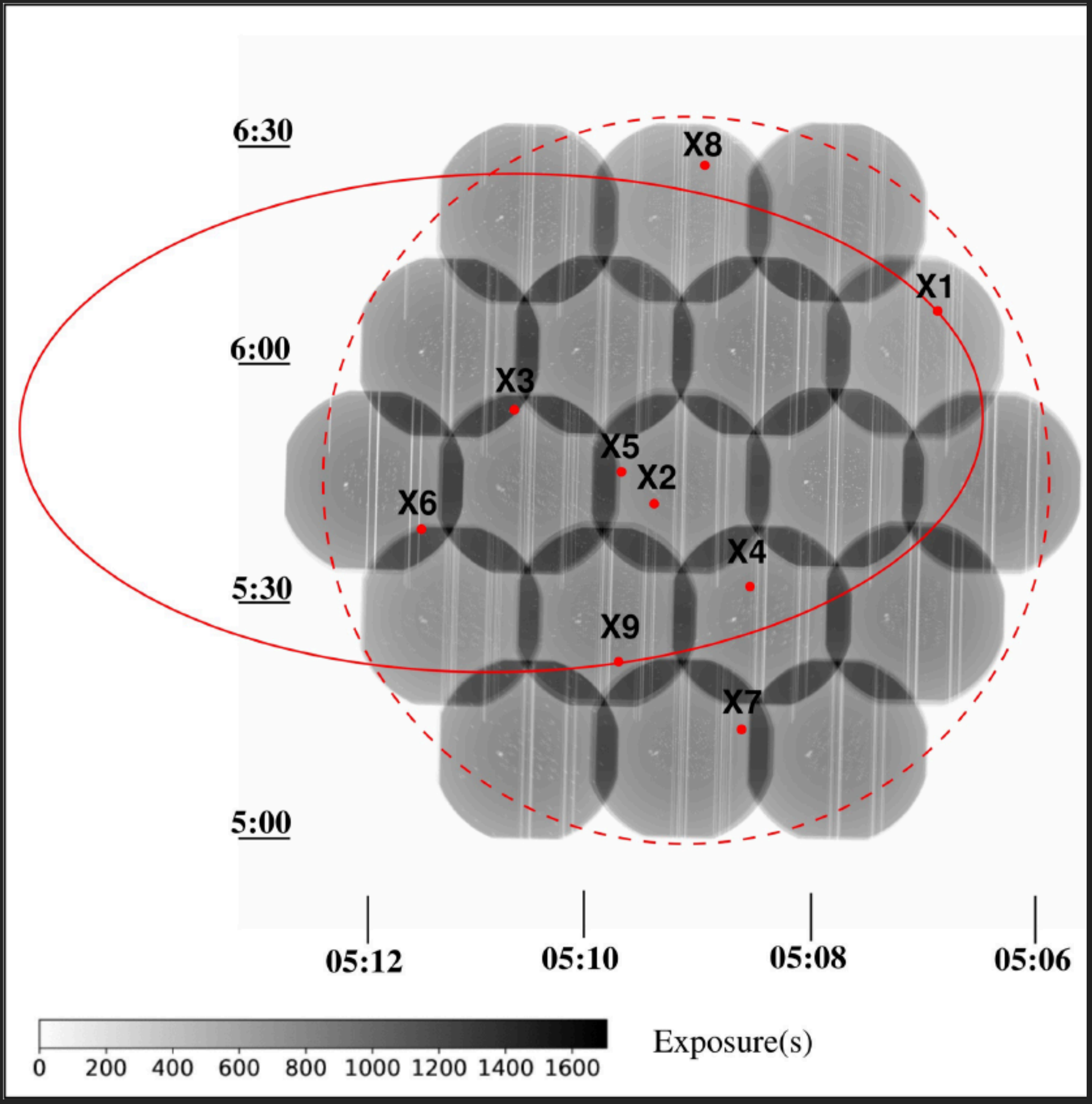


10 orders of magnitude in photon energy (1 eV to >10 GeV)

AK, Murase, Petropoulou, Fox, et al. ApJ 864 (2018)

Swift Observations

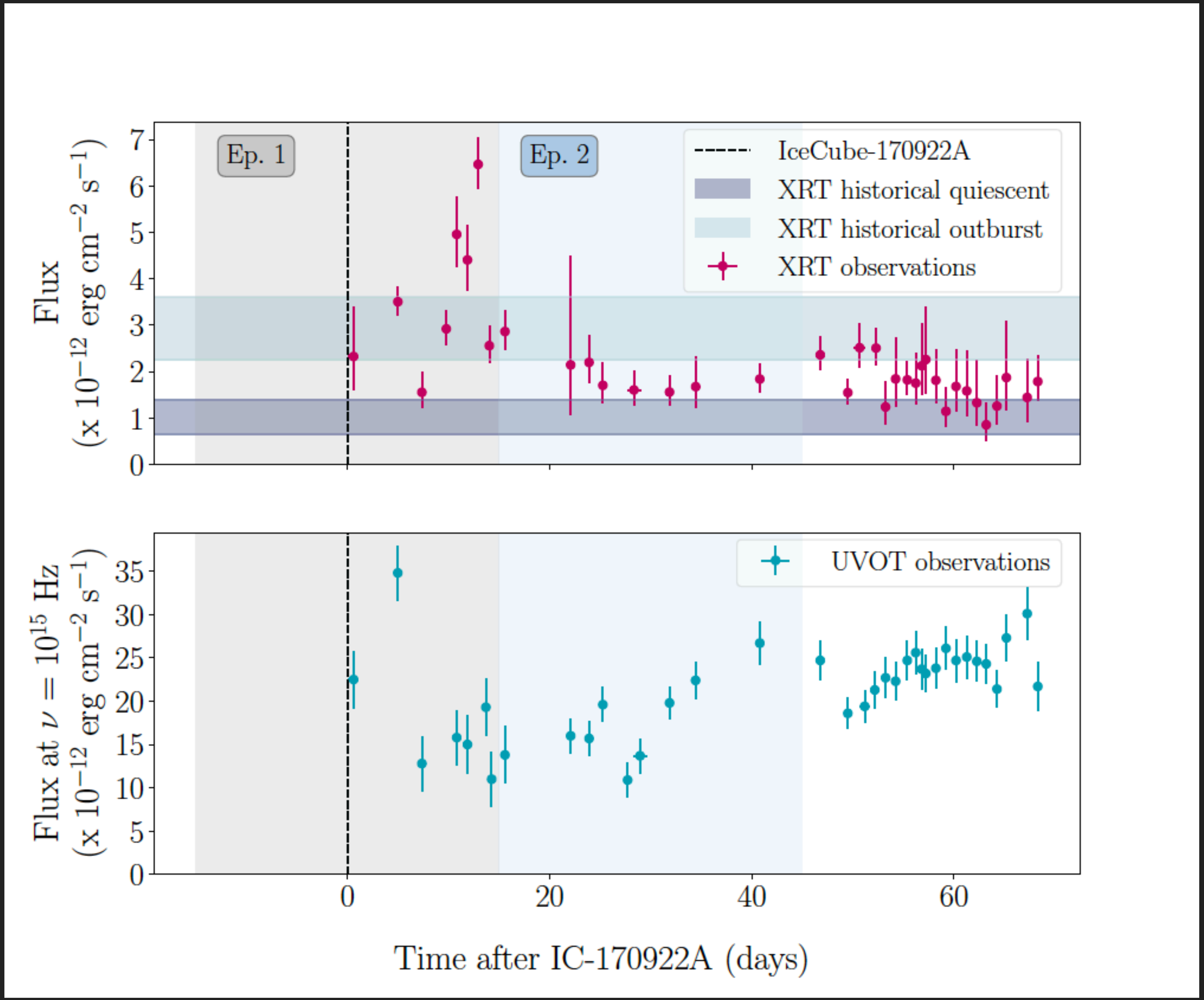
- ★IceCube-170922A triggered Swift in automated fashion via AMON
- ★Rapid-response mosaic-type follow-up observations
- ★19-point tiling: 3.25 hr after the neutrino detection
- ★Spanned 22.5 hr
- ★9 X-ray sources
- ★X2: TXS 0506+056 (4.6′ away)
- ★Energy range: 0.3-10 keV
- ★Following the Fermi report of TXS 0506+056 in a GeV-flaring state:
  - ★Swift monitoring campaign started



Swift Flux

- ⭐Following the *Fermi* report on the GeV-flaring state of the blazar, *Swift* started a monitoring campaign
- ⭐36 more epochs until the end of Nov 2017 (~54 ks)

- ⭐Observation in the 0.3-10 keV
- ⭐$N_H = 1.11 \times 10^{21}$ cm^{-2}
- ⭐Horizontal bands: XRT historical data
- ⭐Two epochs: [-15d, +15d] and [+15d, +45d]



AK, P.A.Evans, et al., GCN Circular 21930 (2017)

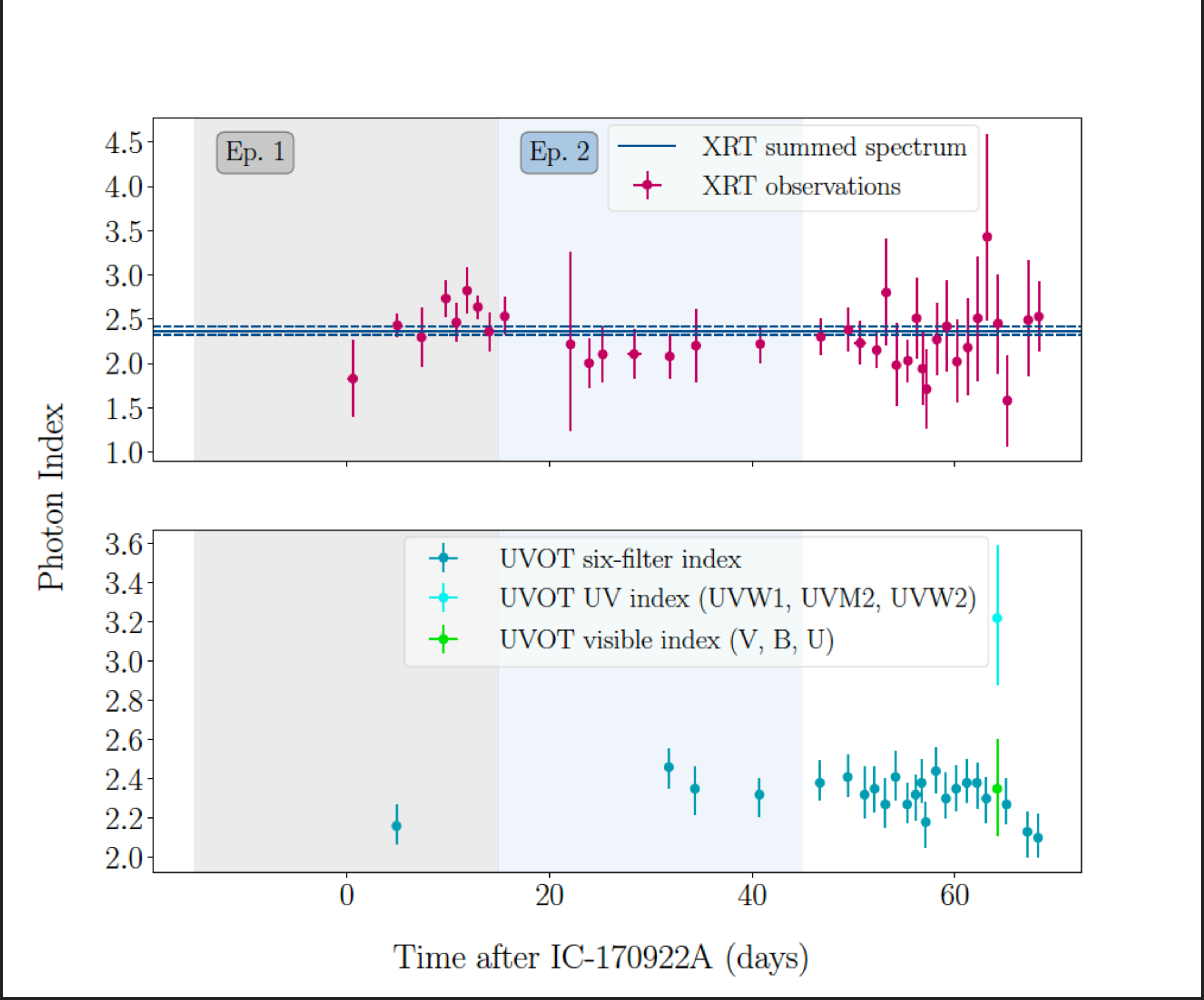
P.A.Evans, AK, et al., ATel 10792 (2017)

AK, Murase, Petropoulou, Fox, et al. ApJ 864 (2018)

Swift Spectral Variability

- ★Solid horizontal: photon index of the stacked X-ray spectrum over the 2 epochs
- ★Dashed lines: uncertainties
- ★$\alpha_{XRT} = 2.37 \pm 0.05$

- ★UVOT photon index obtained from a power-law fit to the energy flux spectrum



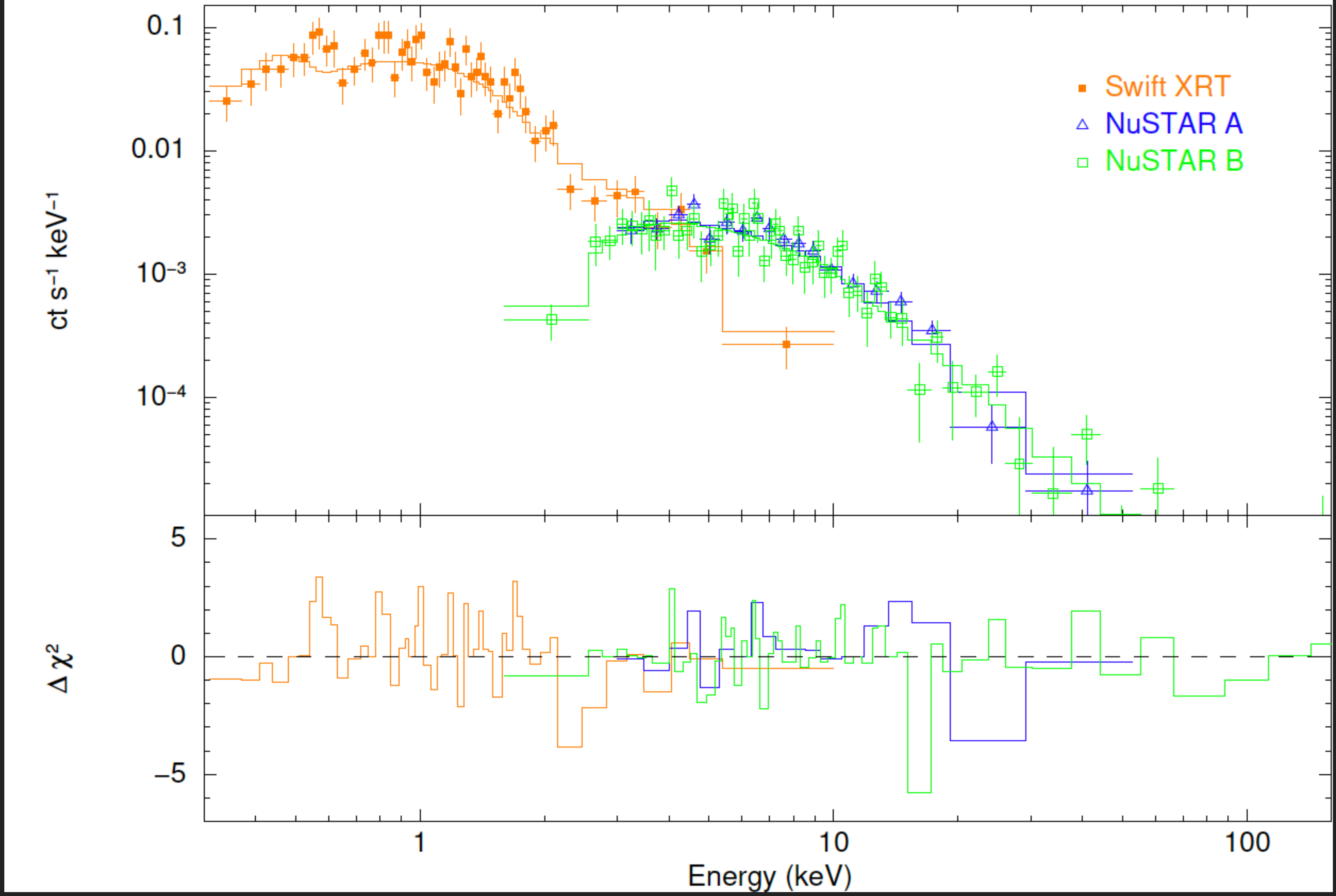
AK, P.A.Evans, et al., GCN Circular 21930 (2017)

P.A.Evans, AK, et al., ATel 10792 (2017)

AK, Murase, Petropoulou, Fox, et al. ApJ 864 (2018)

NuSTAR: Hard X-ray Data

- Requested *NuSTAR* observations to complete X-ray band
- Two observations: Sept 29 and Oct 19
- Energy: 3.0-100 keV
- Overal exposure ~44 ks
- Simultaneously fit XRT and *NuSTAR*
- Best fit photon indices:
  $\alpha_{XRT} = 2.37 \pm 0.05$
  $\alpha_{NuSTAR} = 1.69 \pm 0.12$



D,B. Fox, et al., ATel 10845 (2017)

IceCube Collaboration, et al., Science 361, eaat1378 (2018)

Fermi γ-ray Data

Fermi LAT photons:

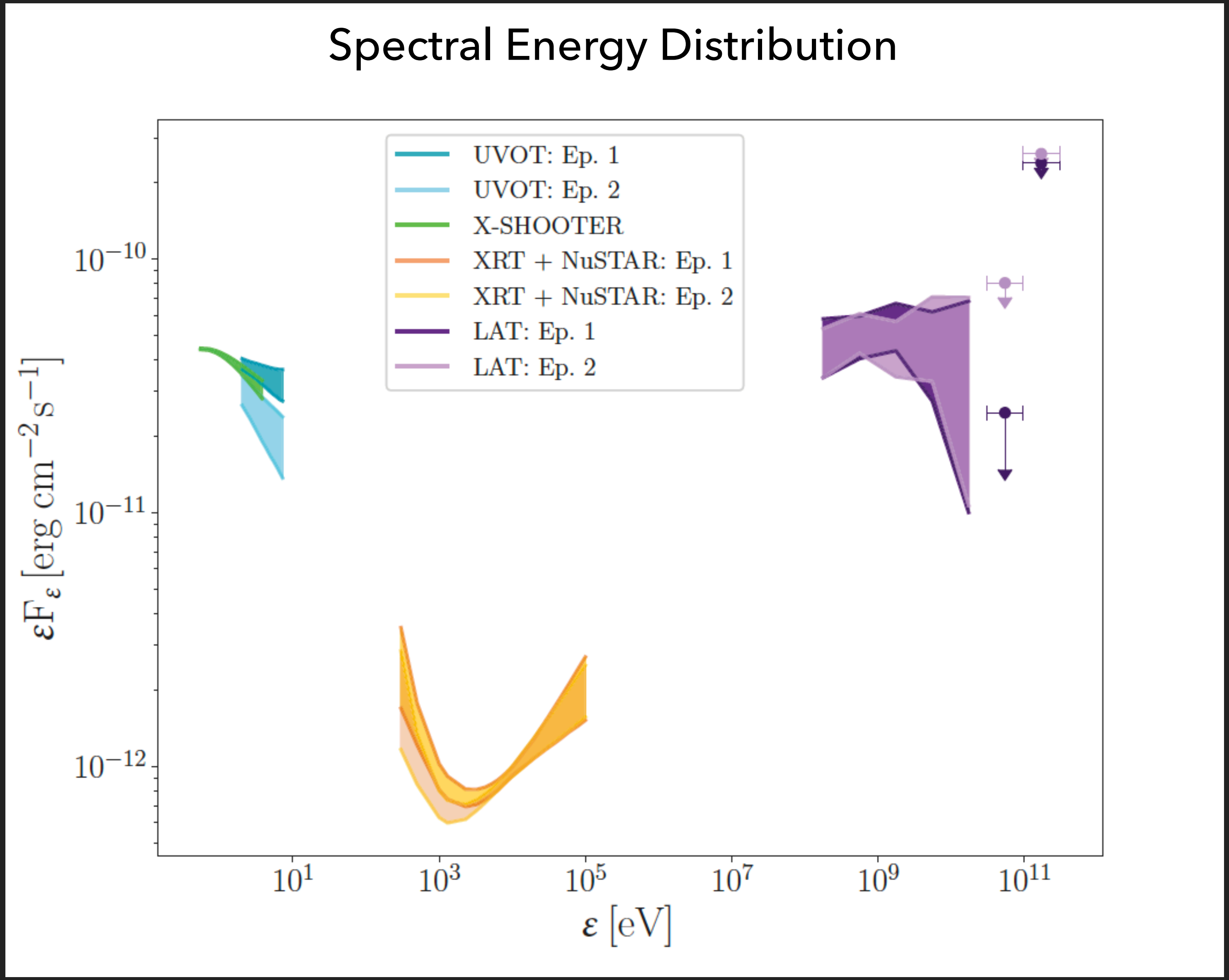
- ★100 MeV < E < 300 GeV
- ★15° from TXS 0506+056
- ★Zenith<90°

Sources in 3FGL:

- ★15° from TXS 0506+056
- ★Spectral parameters fixed to their catalog values, unless within 3°

Spectral fit was performed with a binned likelihood method

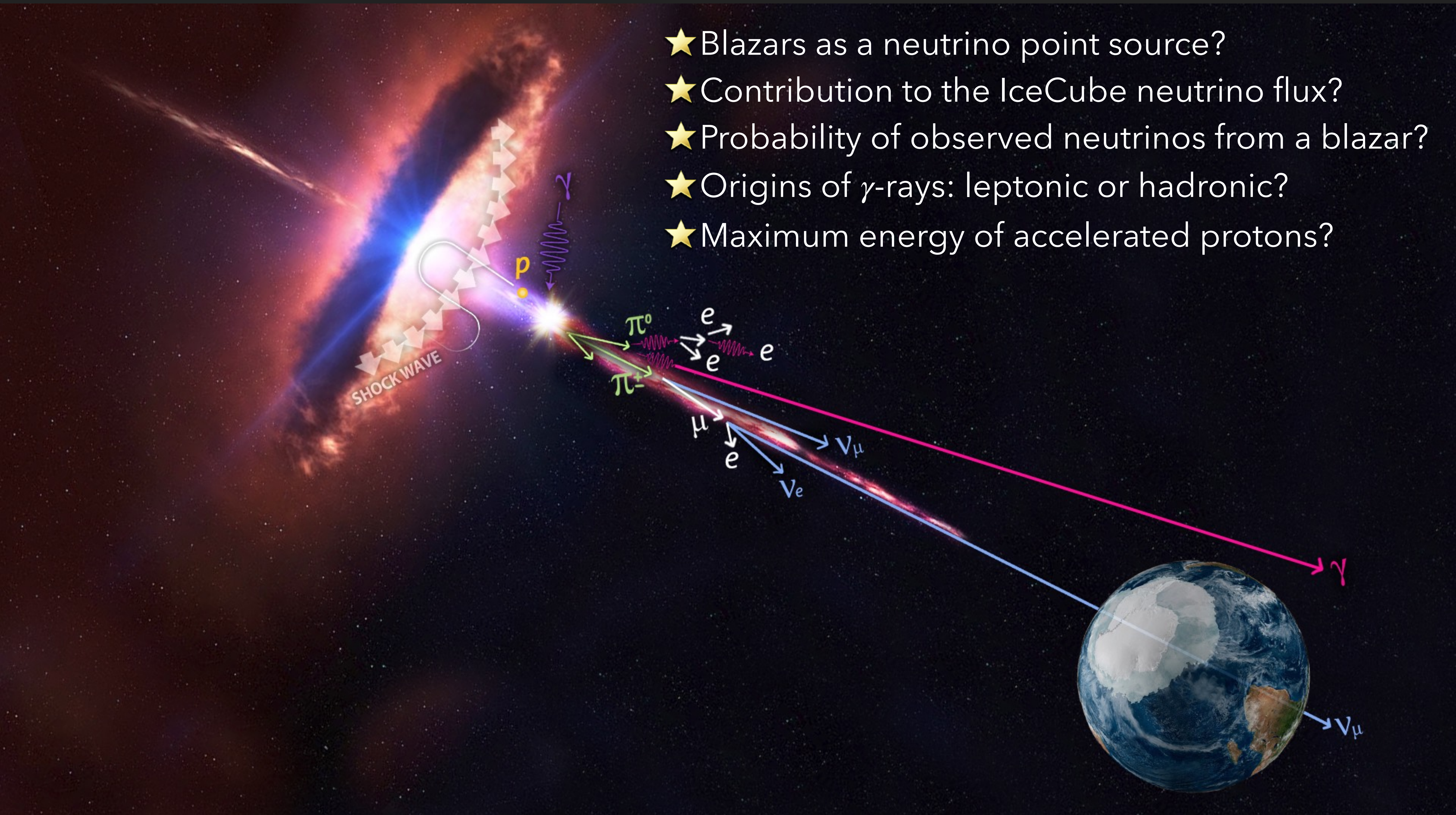
- ★$\alpha_{LAT} = 2.05 \pm 0.05$



IceCube Collaboration, et al., Science 361, eaat1378 (2018)

Big Questions on Blazars: ν's and γ-rays

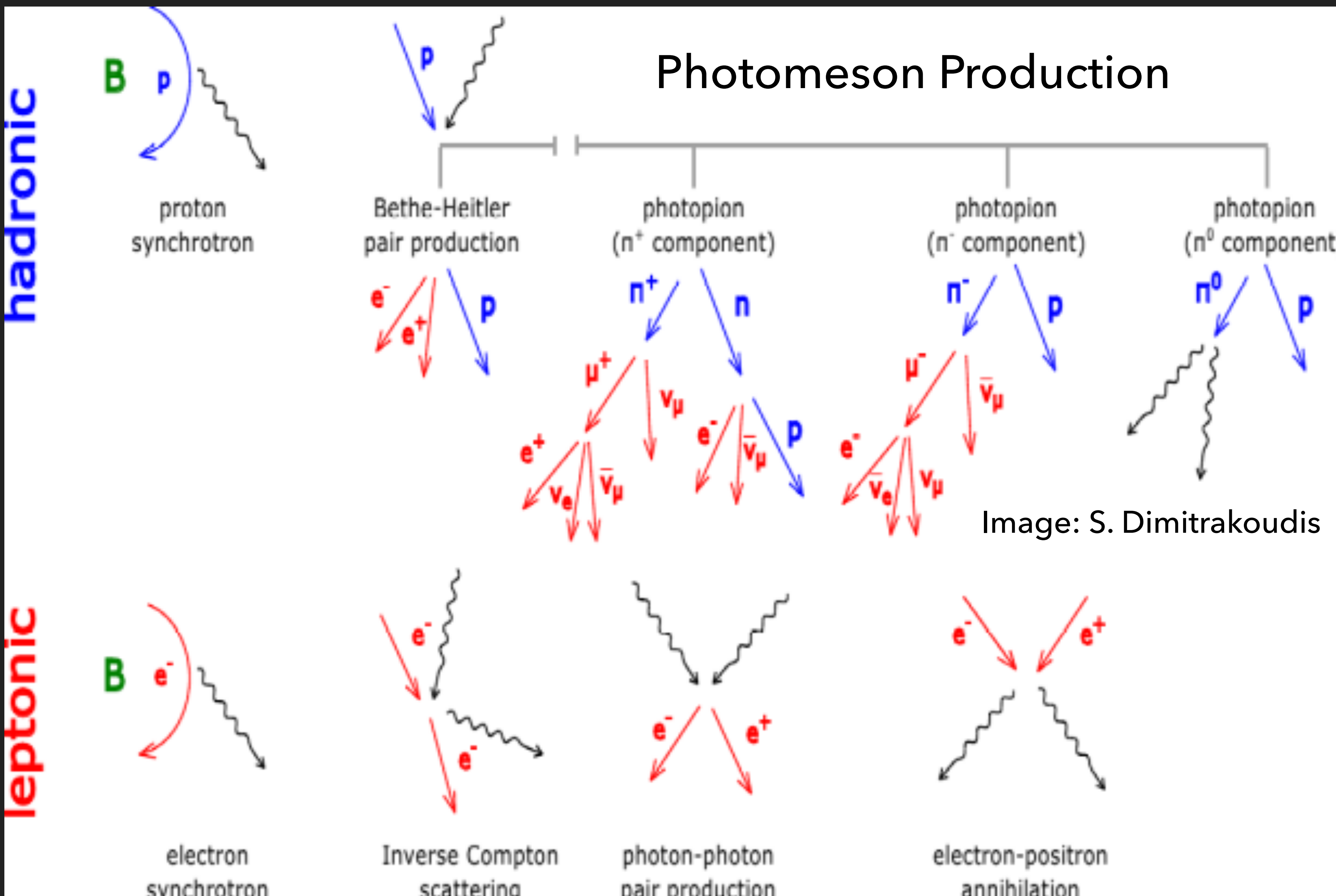
- ★ Blazars as a neutrino point source?
- ★ Contribution to the IceCube neutrino flux?
- ★ Probability of observed neutrinos from a blazar?
- ★ Origins of γ-rays: leptonic or hadronic?
- ★ Maximum energy of accelerated protons?



★ See also Maria Petropoulou's talk

ν and γ Production in Blazars

Leptonic and (Lepto)hadronic Scenarios



PeV-EeV ν's via photomeson production process

Target photons:

- ⭐Intra-jet
- ⭐External radiation fields

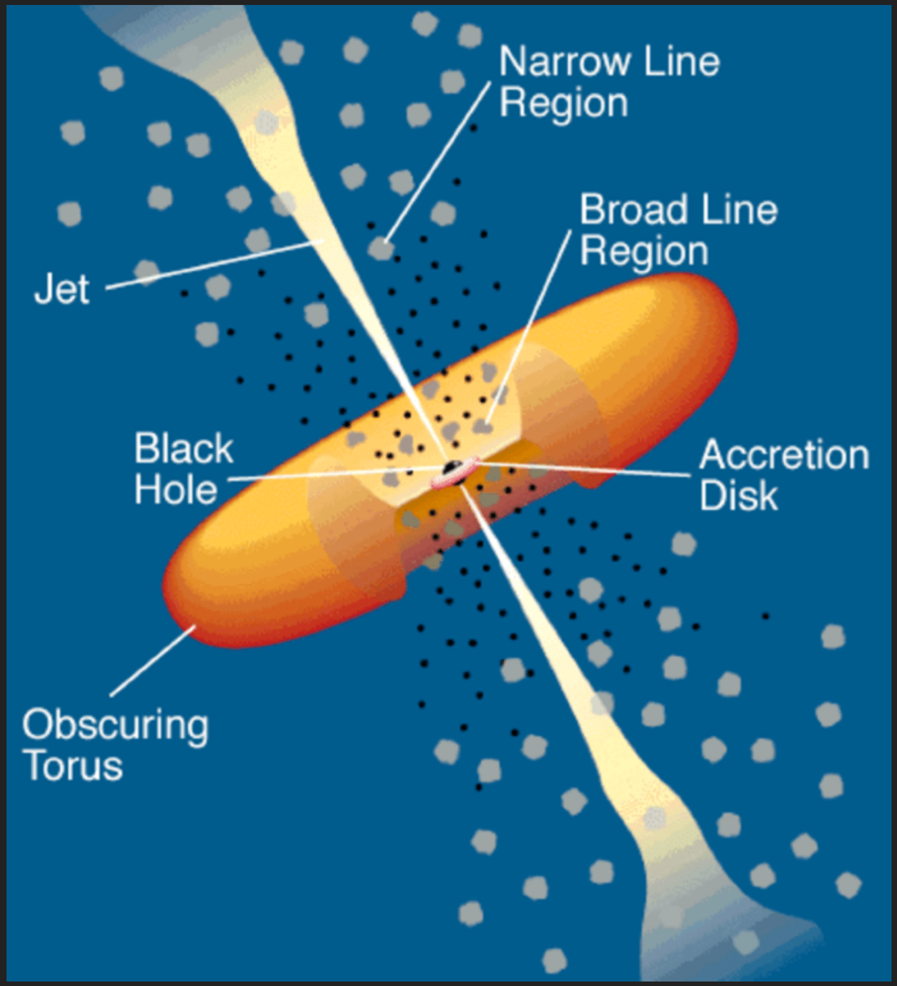
Leptonic:

- ⭐Synchrotron self-Compton
- ⭐External inverse-Compton

Leptonic vs Leptohadronic Models

Leptonic Models:

- ★Synchrotron emission
- ★Inverse Compton scattering
- ★Pair production
- ★Pair annihilation



Leptohadronic Models:

- ★Synchrotron emission
- ★Inverse Compton scattering
- ★Pair production
- ★Pair annihilation
- ★Photomeson production
- ★Photopair production

ν and γ-ray Luminosities

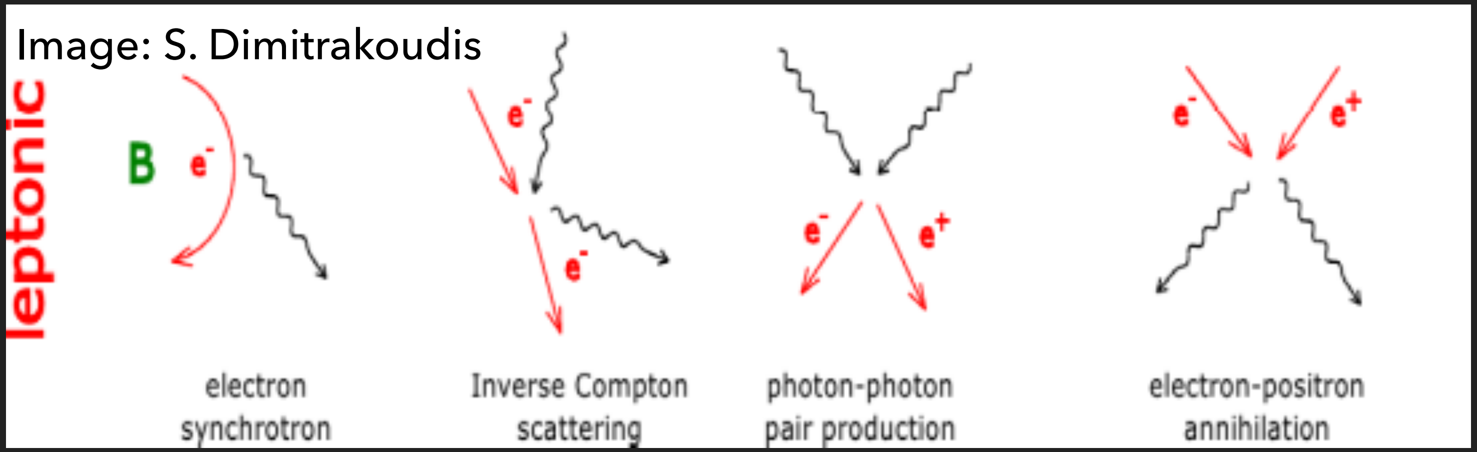
Electromagnetic cascades redistribute energy from high energies (e.g. PeV) to lower energies (e.g. keV-MeV):

Cascade effects

$L_\nu \cong L_\gamma$

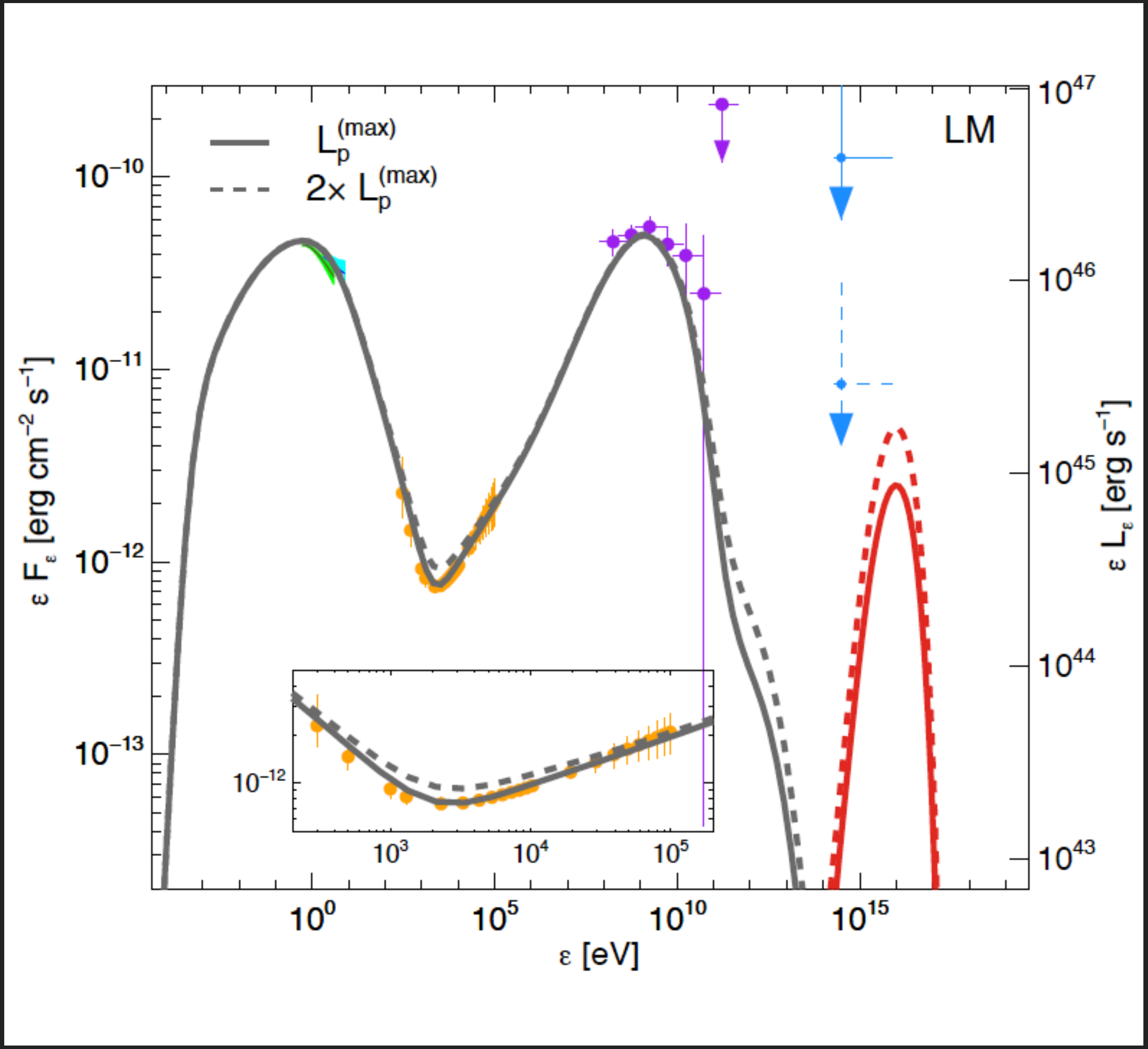
Data do not always allow for solutions with $L_\nu \cong L_\gamma$

If $L_\nu \ll L_\gamma$: leptonic origin of γ-rays



Modeling of the TXS 0506+056 Flare

- *Swift*-UVOT + X-shooter show that $\nu_{pk} < 3 \times 10^{14}$ Hz (ISP)
- External inverse-Compton explains γ-rays
- Hadronic cascade should not exceed X-ray data
- Upper limits on proton and therefore ν flux



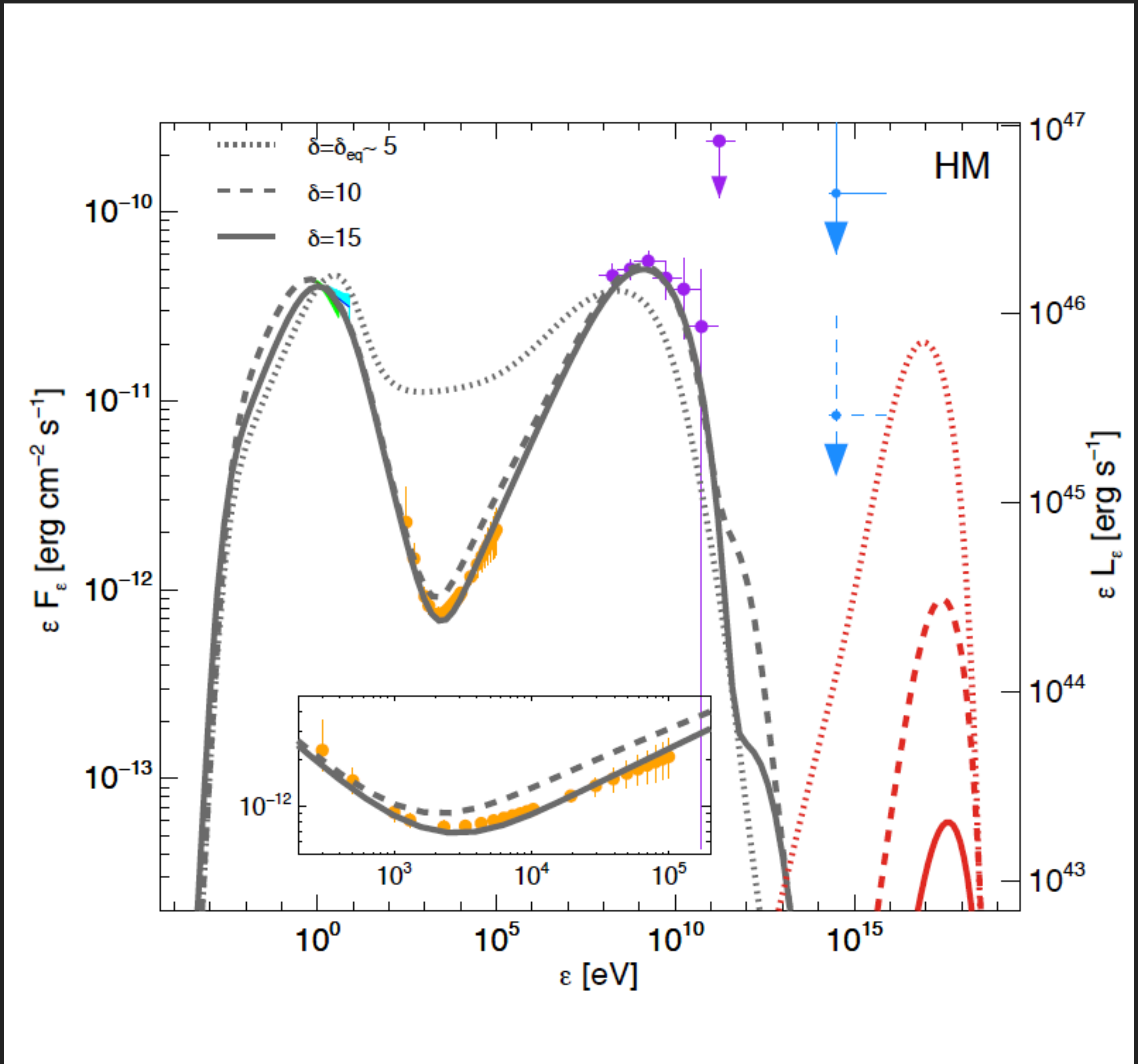
Single-zone picture:
Leptonic scenario with a radiatively-subdominant hadronic component!

- $F_\nu < 2 \times 10^{-12}$ erg cm^{-2} s^{-1}
- $L_p/L_e > 300$
- $E_{p,\,max} < 0.3$ EeV

Modeling of the TXS 0506+056 Flare

Leptohadronic model

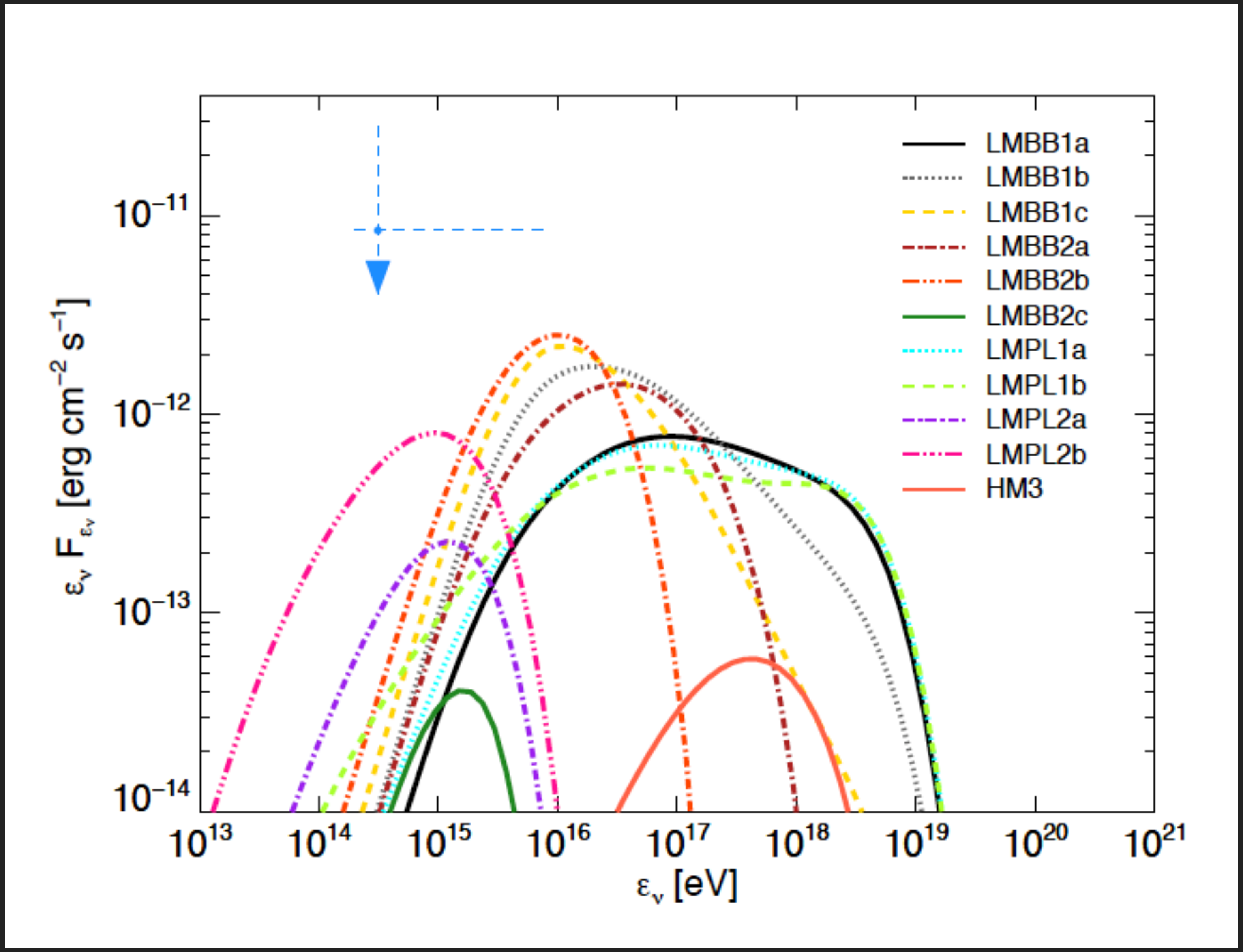
- ★ Model with γ-rays from pion-induced cascade is ruled out ($L_\nu \sim L_\gamma$)
- ★ Model with γ-rays from proton synchrotron leads to EeV neutrinos with very low luminosities



IceCube-170922A can not be explained with the leptohadronic scenario

Modeling of the TXS 0506+056 Flare

- ★ Upper limits on the all-flavor neutrino fluxes for our modeling of the SED:
  - ★ Several parameters
  - ★ Leptonic and Hadronic Models



~1-2% probability to see 1 neutrino event in half a year!

	$\int F_{\varepsilon_\nu}^{(\max)} d\varepsilon_\nu$ [erg cm^{-2} s^{-1}]		$\mathcal{N}_\nu$
	100 TeV–1 PeV	100 TeV–10 PeV	⩽10 PeV
LMBB1a	1.6×10^{-14}	4.5×10^{-13}	1×10^{-3}
LMBB1b	5.2×10^{-14}	1.7×10^{-12}	4×10^{-3}
LMBB1c	9.1×10^{-14}	2.7×10^{-12}	6×10^{-3}
LMBB2a	4.5×10^{-14}	1.1×10^{-12}	3×10^{-3}
LMBB2b	1.8×10^{-13}	3.6×10^{-12}	8×10^{-3}
LMBB2c	2.5×10^{-14}	7.3×10^{-14}	2×10^{-4}
LMPL1a	3.1×10^{-14}	5.2×10^{-13}	1×10^{-3}
LMPL1b	9×10^{-14}	6.3×10^{-13}	1×10^{-3}
LMPL2a	2.5×10^{-13}	5.2×10^{-13}	5×10^{-3}
LMPL2b	1.2×10^{-12}	2×10^{-12}	1×10^{-2}
HM3	1.6×10^{-16}	2×10^{-15}	4×10^{-6}

Importance of *Fermi* in Blazar Neutrino

- ★ *Fermi* LAT has so far observed and monitored many blazars!
- ★ This has been extremely helpful in studies related to high-energy neutrino and ultra-high energy cosmic ray sources
- ★ Monitoring the γ-ray sky is crucial for revealing the sources of neutrinos and cosmic rays and for understanding the nature of these phenomena
- ★ *Fermi* γ-ray data also play a crucial role in other multi-messenger searches including:
    - ★ Archival joint searches (e.g. Turley et al. 2018)
    - ★ Future joint gravitational waves and high-energy neutrinos (e.g. ApJ 850, L35, 2017)

★ See also Colin Turley's talk

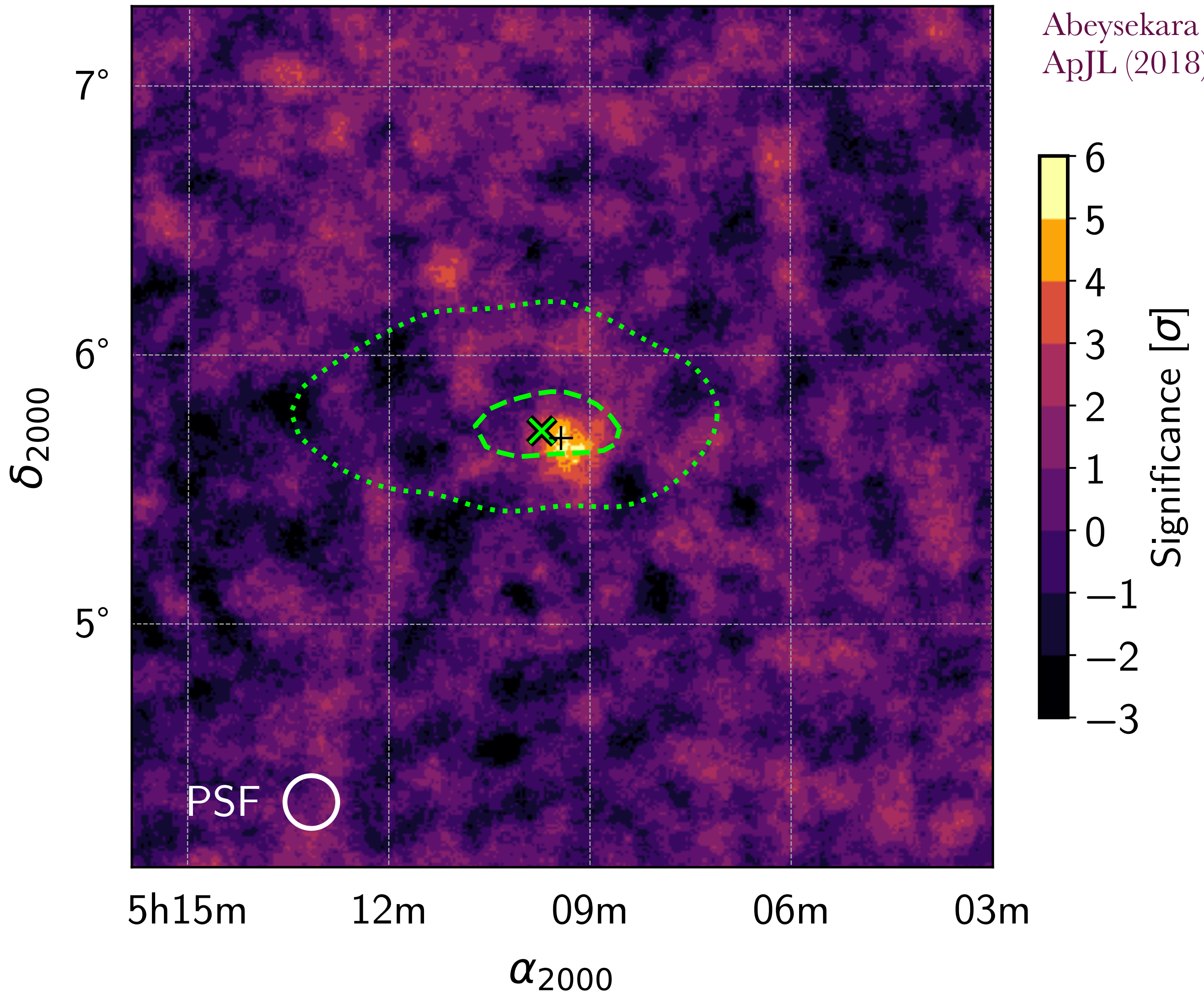
VERITAS Observations of TXS 0506+056

Presenting a short review on VERITAS VHE γ-ray SED

on behalf of

Reshmi Mukherjee, Marcos Santander, and Brian Humensky

VERITAS observations of TXS 0506+056

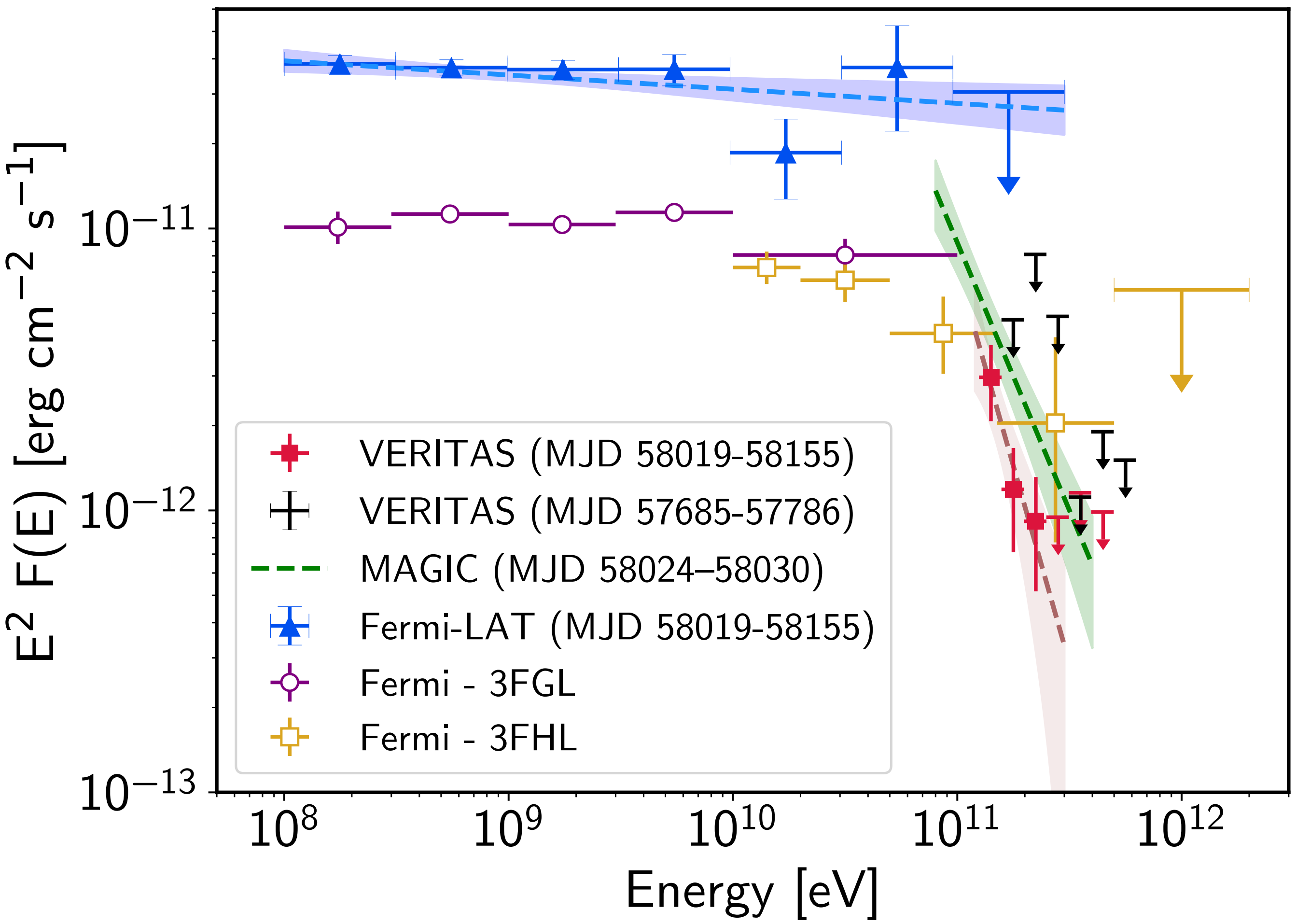


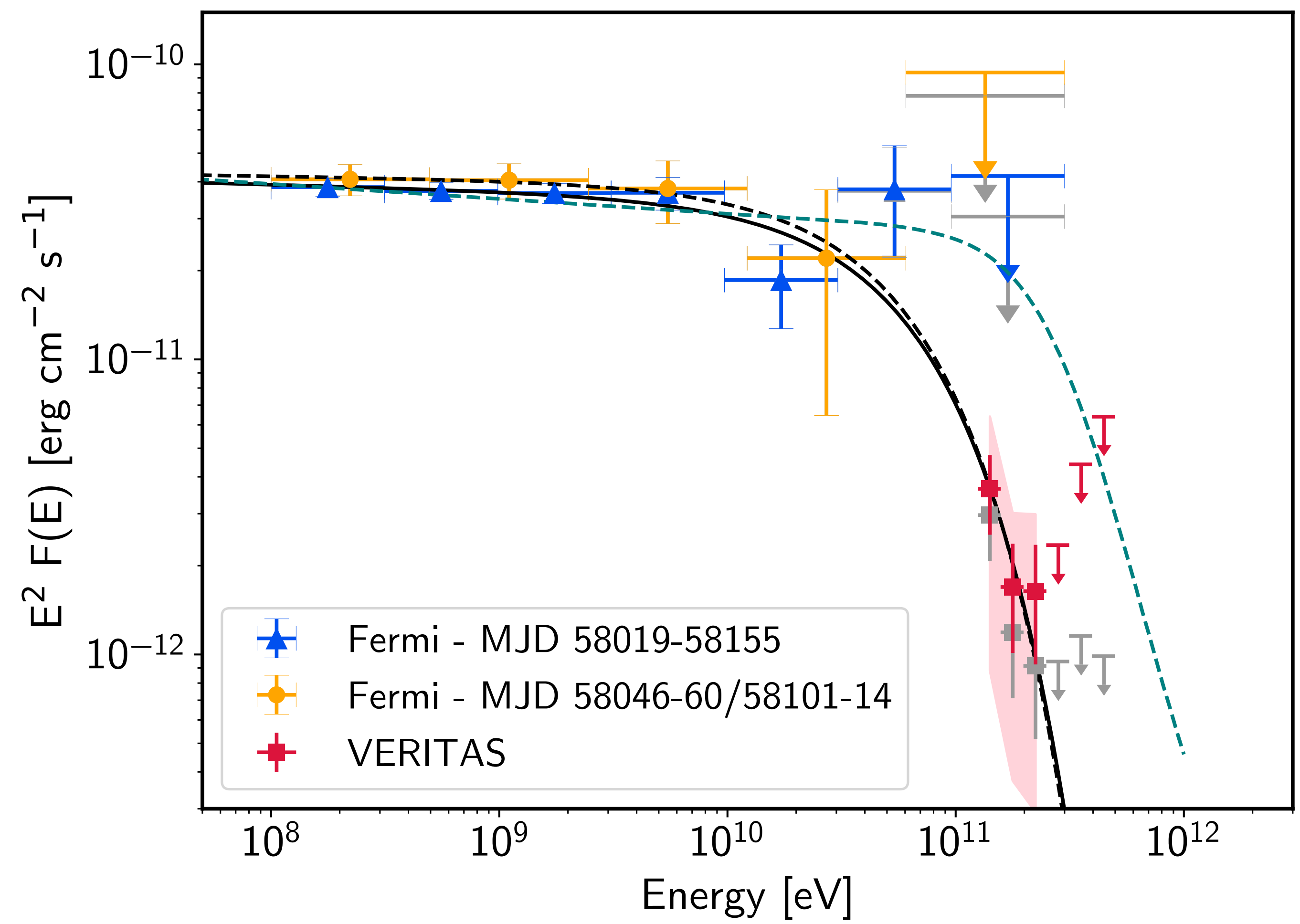
Abeysekara et al.
ApJL (2018). arXiv/1807.04607

- Observations taken between Sept 2017 and Feb 2018. **35 hrs of quality** selected data.
- **5.8σ** at source location. Flux of 1.6% of the Crab nebula above 110 GeV.
- Photon excess centroid is consistent with the radio location of TXS 0506+056.

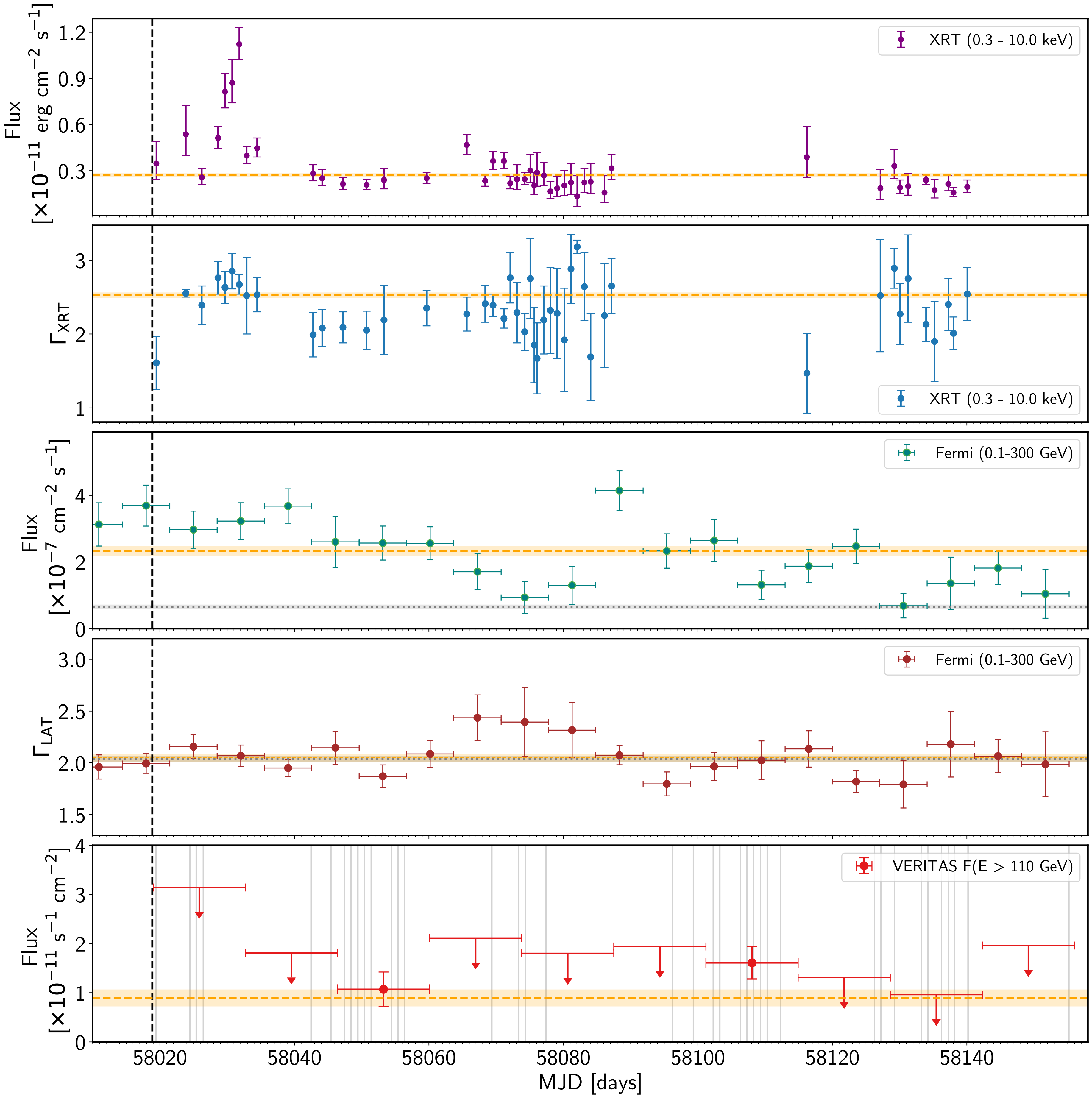
Gamma-ray SED of TXS 0506+056

ApJL (2018). arXiv/1807.04607 **VERITAS**





- Best power-law fit in the 110-300 GeV yields **$\Gamma = 4.8 \pm 1.3$.**
- Spectrum softening not consistent with EBL absorption alone of VHE gamma-ray flux.
- Flux level compatible with archival Fermi observations of the source.
- Break in the particle population? Self-absorption? Multiple zones with leptonic+hadronic emission?



Multiwavelength light curve of TXS 0506+056 (09/17 - 02/18)

- Flux variability in X-rays and GeV gamma rays. No clear correlation across energy bands.
- VERITAS VHE flux consistent with a steady flux (sensitivity limited)

Summary

★Multi-wavelength data during the flare is crucial to constrain emission models.

★SED modeling of blazers shows that data do not always allow for $L_\nu \cong L_\gamma$ and this is almost always ruled out.

★A leptonic model (with a radiatively subdominant hadronic component) can explain a high-energy neutrino from TXS 0506+056 with 1-2% probability of detecting it in realtime.

★Alternative models (e.g. multi-zone) might be needed to explain IceCube-170922A and TXS 0506+056.

★Regular X-ray and γ-ray monitoring of blazars is required.

★*Fermi* plays a significant role in multi-messenger studies, including the blazer observations.

Thank you!