Multi-messenger interpretation of neutrinos from TXS 0506+056

A mini review

https://multimessenger.desy.de/

Winter, Walter
DESY, Zeuthen, Germany

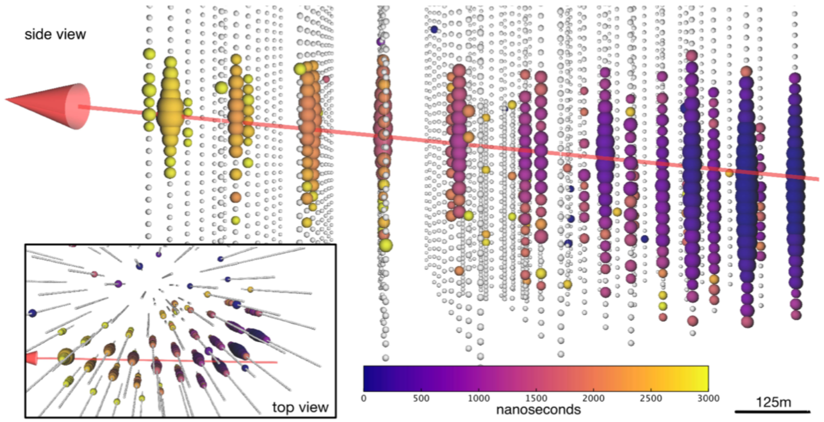
ICRC 2019
University of Madison, Wisconsin, USA
July 25, 2019

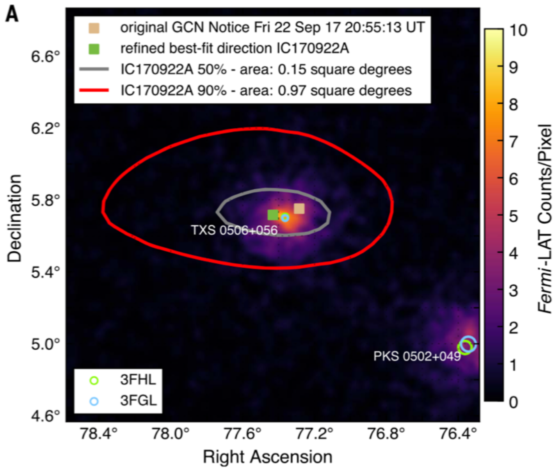
Thanks to Anatoli Fedynitch, Shan Gao, Andrea Palladino, Martin Pohl, and Xavier Rodrigues for collaborations on the subject, and the participants of the PAX 2019 workshop for useful discussions.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Neutrinos from the AGN blazar TXS 0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



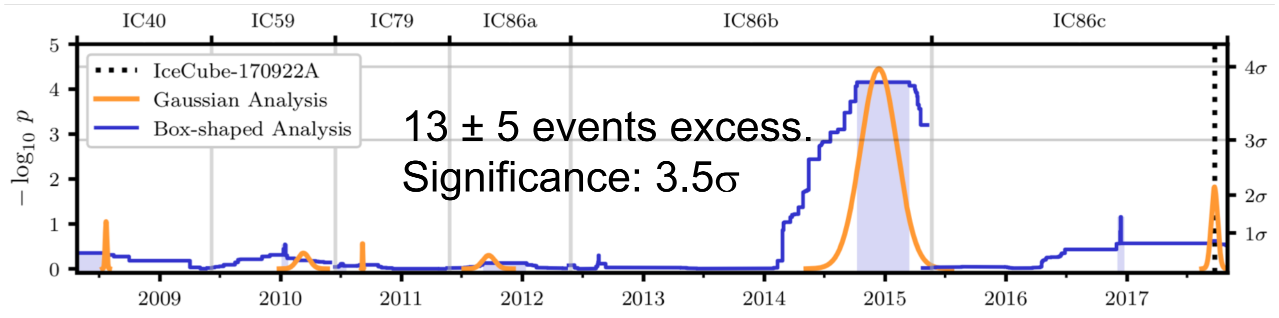


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

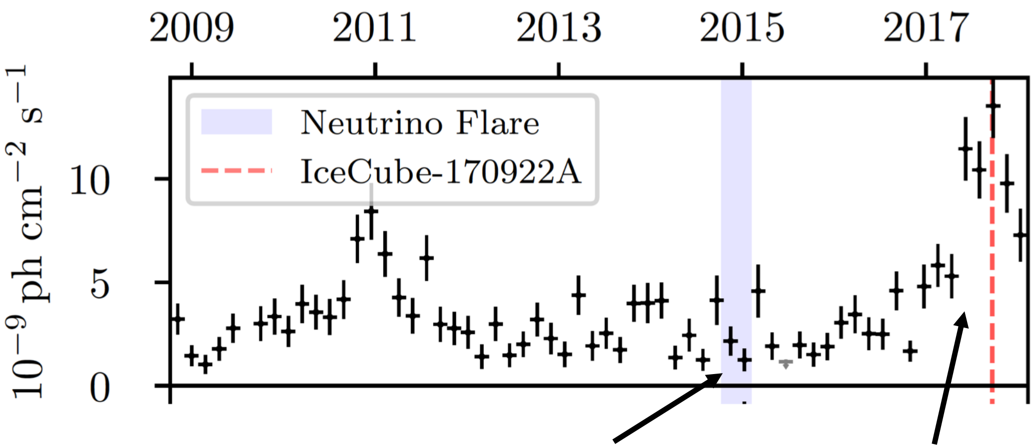
Science 361 (2018) no. 6398, eaat1378

2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



At 2014-15 neutrino flare

The 2017 flare

Number of expected neutrinos from a theoretical model?

Sept. 22, 2017:
One neutrino observed

Event rate – flux translation depends on effective area (effective area for alert system lower!)

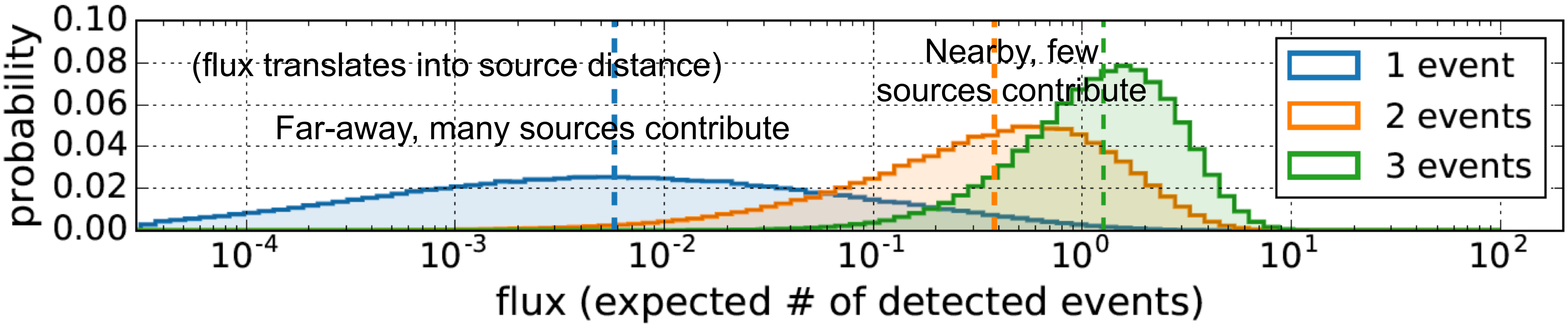
Good reasons to expect that the *predicted* model neutrino flux should be significantly lower:

- **Eddington bias:**
  Trial factor for numerous faint sources (here 10^4 equal-lumi BL Lacs z-distributed within z<4, 10 events total)

2014-2015:
13 ± 5 neutrinos observed

Relatively high number, Gaussian statistics
→ Model prediction of similar order needed

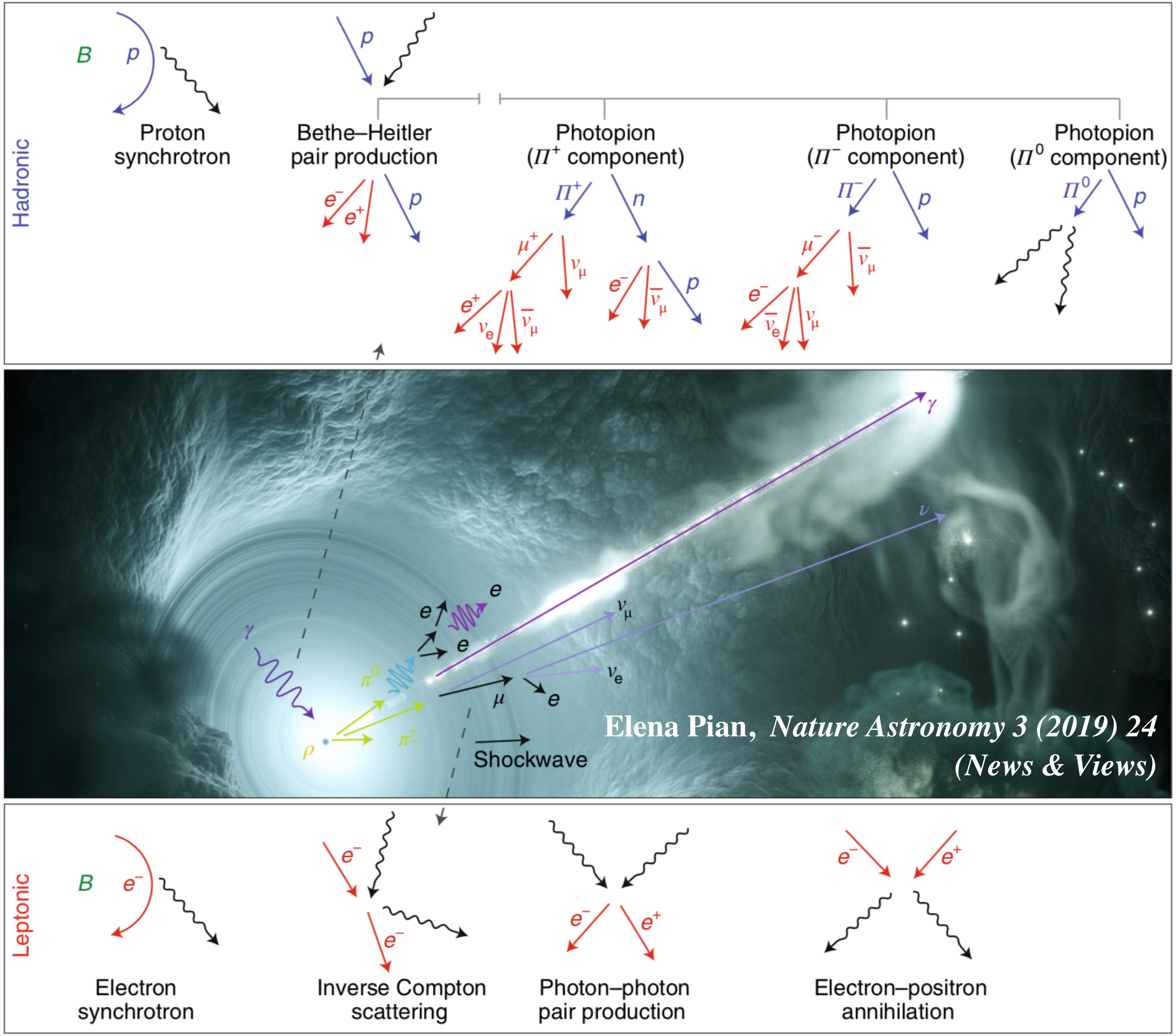
However: This number (background extraction!) may depend on the assumed spectral shape



Strotjohann, Kowalski, Frankowiack, A&A 622 (2019) L9;
see also Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41 and talk by Rodrigues feat. Fedynitch

Methods

- Solve a coupled PDE system for all involved species (e^+, e^-, p, γ, ...)
- Include relevant processes ⟶
- Neutrino production rate ~ Proton density x Radiation density
- Proton density ~ Proton injection (baryonic loading!) x confinement time
- Radiation density given by source luminosity, geometry and size (R', Γ, L_γ, ...)
- Systematic scan over source parameters (including injection spectral properties)
- Millions of model computations

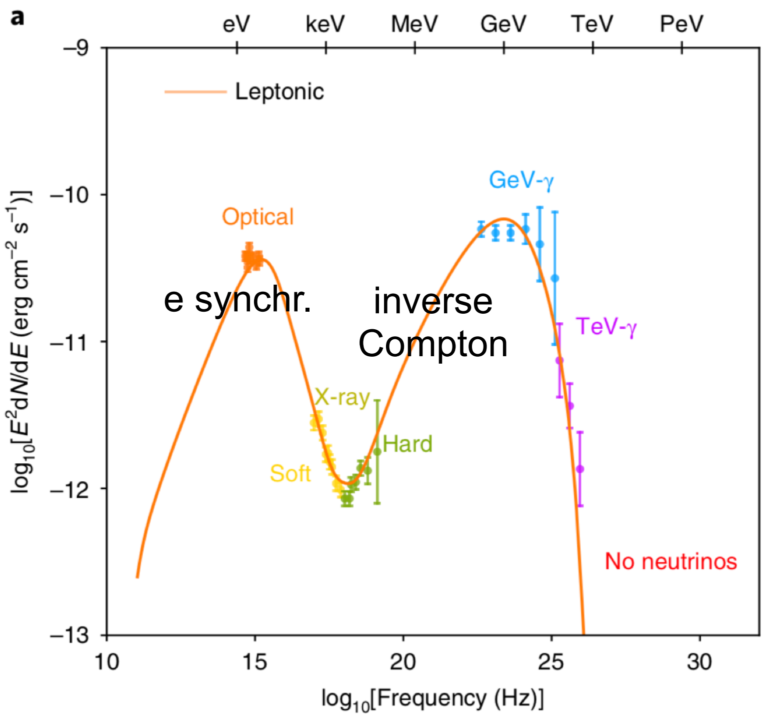


One zone model results (2017 flare)

One spherical radiation zone
Fewest assumptions

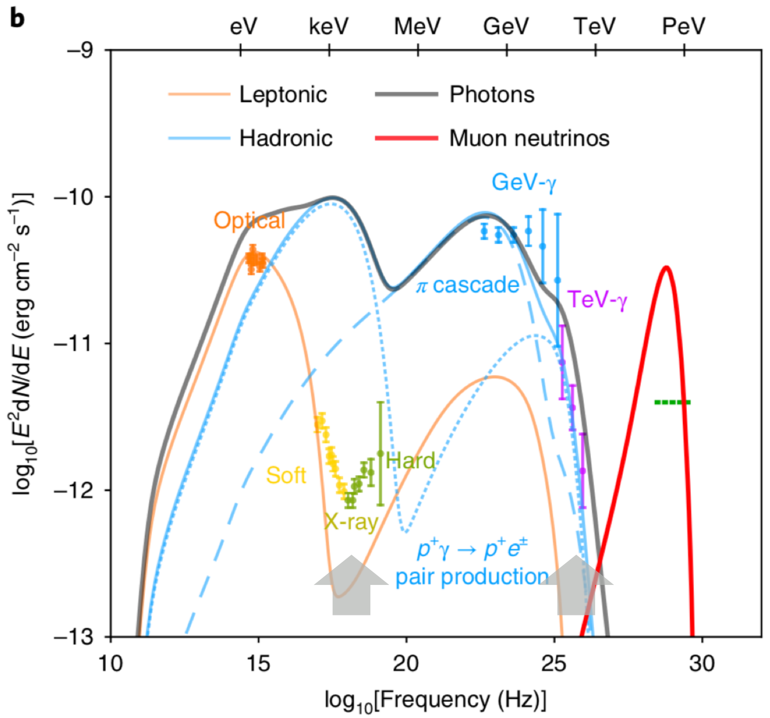
R’

Leptonic models



- No neutrinos

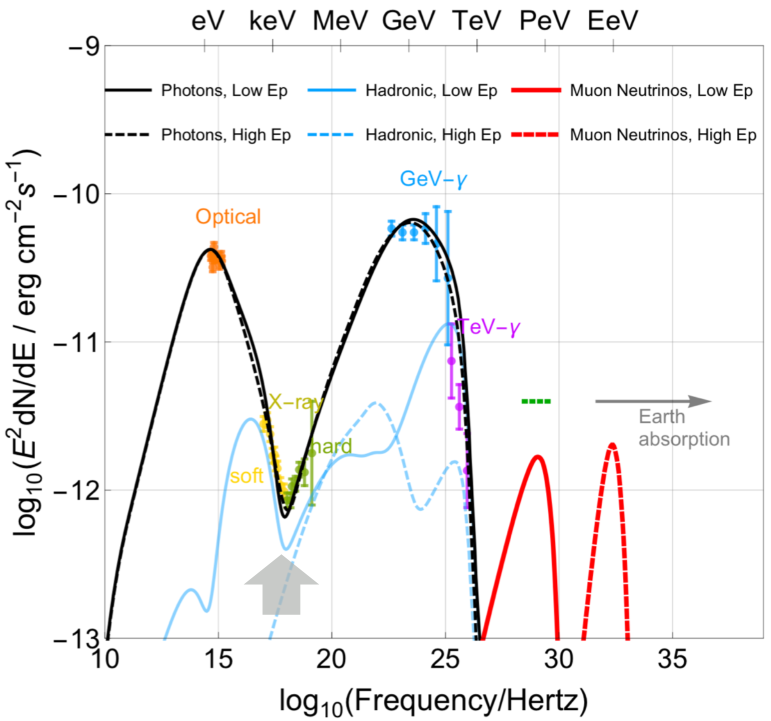
Hadronic (π cascade) models



- Violate X-ray data

X-ray (and TeV γ-ray) data
indicative for hadronic origin

Hybrid or p synchrotron models

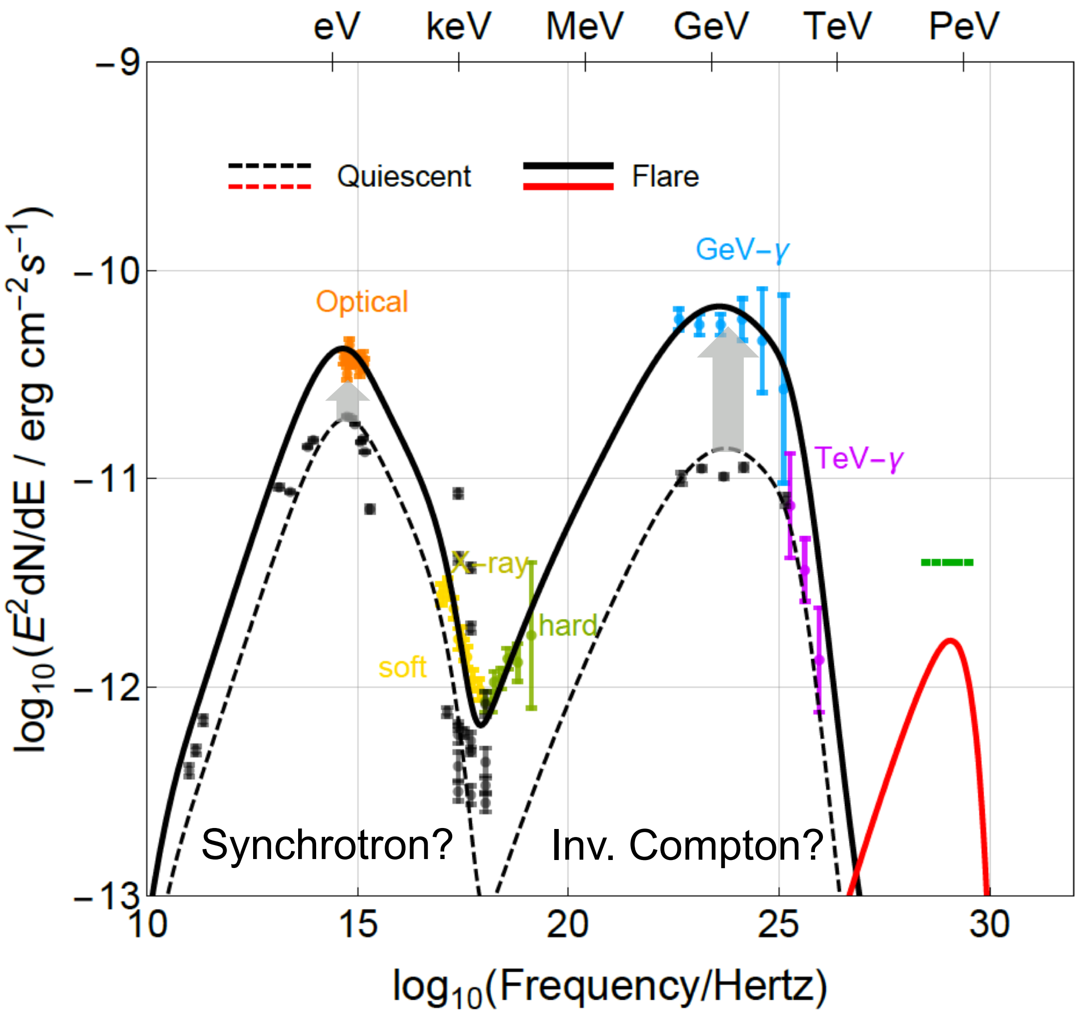


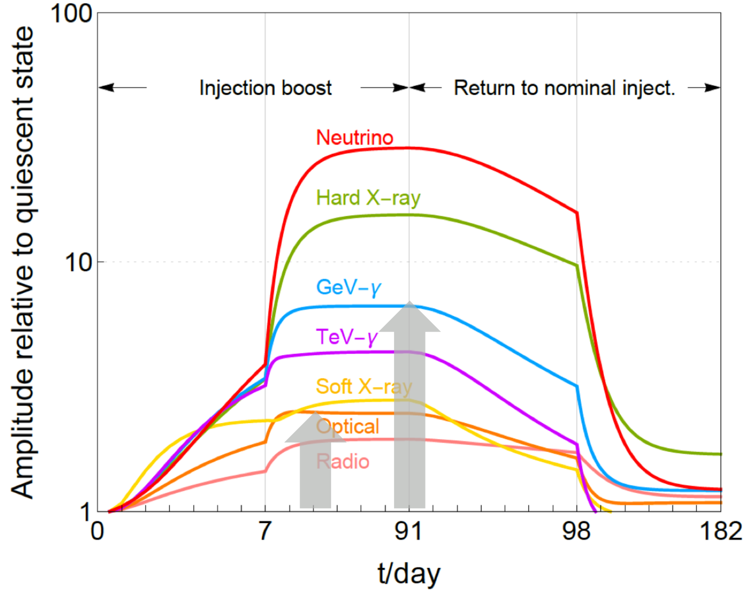
- Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy

Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88;*
see also Cerutti et al, 2018; Sahakyan, 2018; Gokus et at, 2018; Keivani et al, 2018

What do we learn from the time-dependence?

Example: One zone model. Blob size unchanged





L: injection luminosity

Neutrinos: ~ L_p L_e.
Need to ramp up product at least by factor of ten (from flare duty cycle, otherwise neutrino flux in quiescent period comparable)

Homework:
How would second hump scale for other models? (e.g. proton inverse Compton, pion peak, ...)

Time-response:

- Synchrotron with L_e
- Inverse Compton with ~ L_e^2

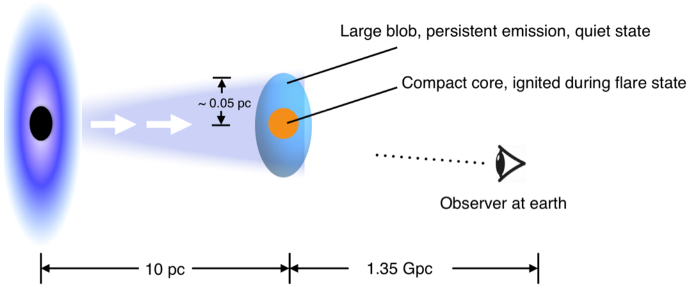
Supports argument that conventional SSC model dominates!

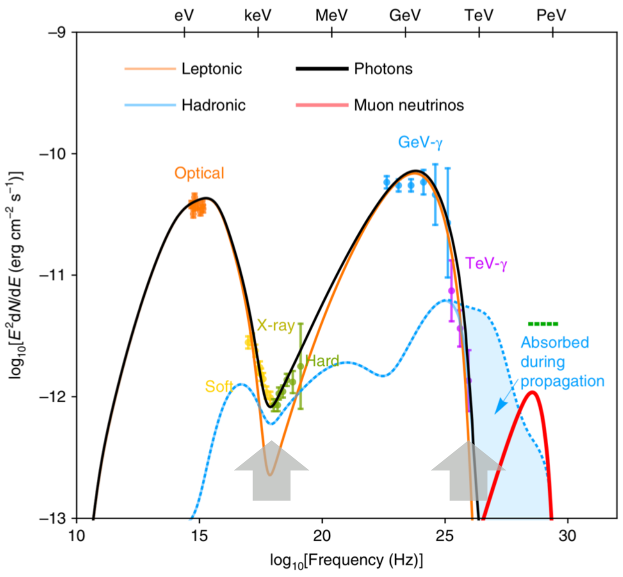
Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88* (from Suppl. Materials); see also Mastichiadis, Petropoulou, Dimitrakoudis, 2013 + others

More freedom through more sophisticated sources geometries

... to satisfy energetics problem. At the expense of more parameters.

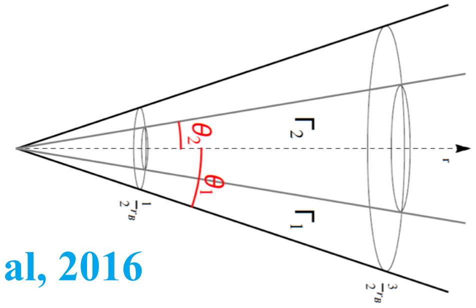
Formation of a compact core



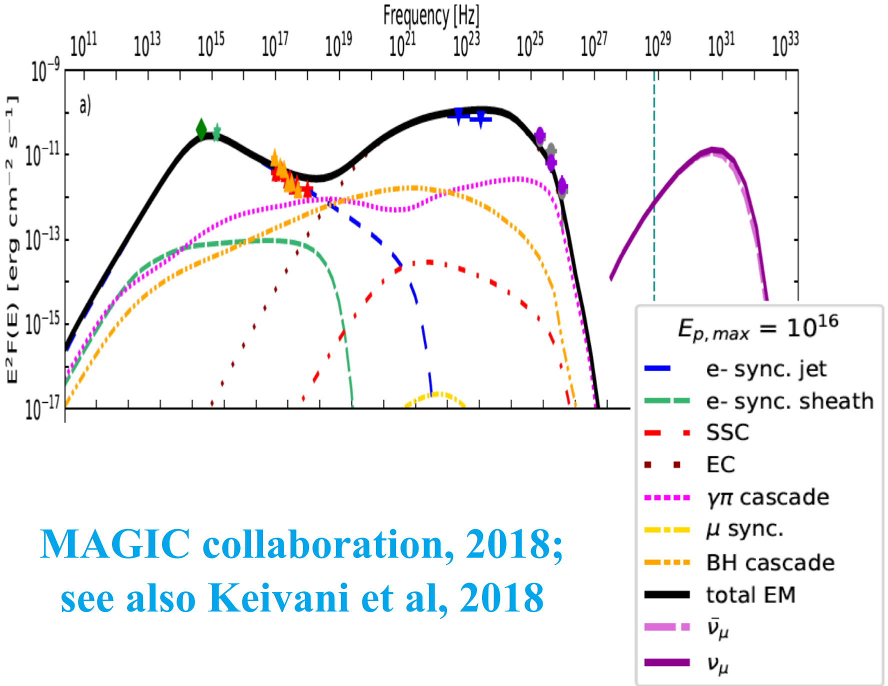


Gao et al, *Nature Astronomy 3 (2019) 88*

External radiation fields

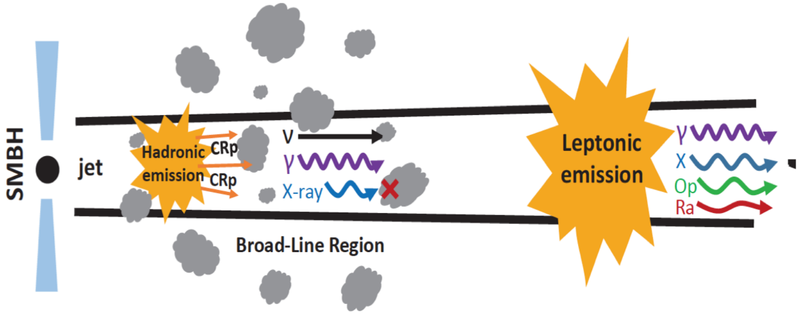


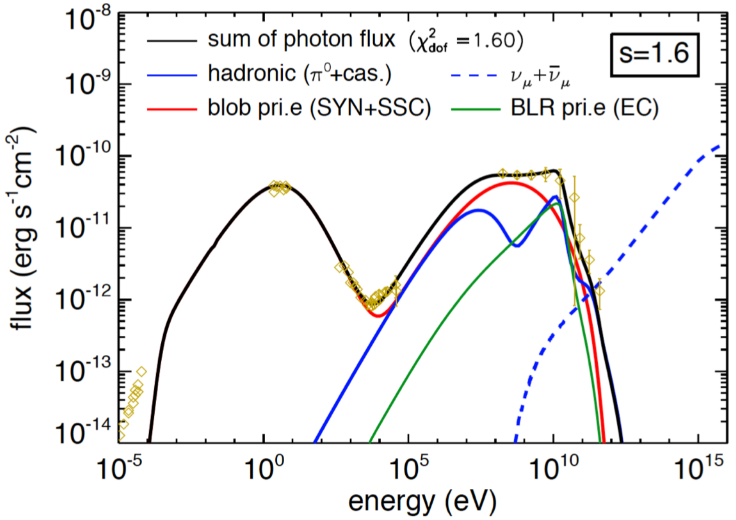
Sikora et al, 2016



MAGIC collaboration, 2018; see also Keivani et al, 2018

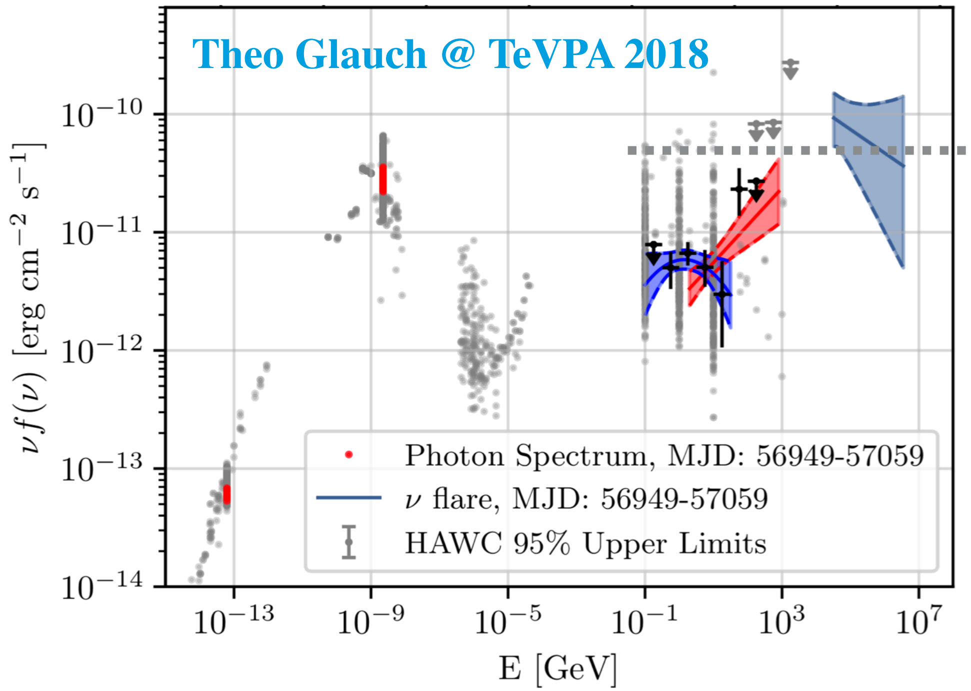
Jet-cloud interactions





Liu et et al, 2018

The historical (2014-15) neutrino flare of TXS 0506+056



- Electromagnetic data during neutrino flare sparse (colored)
- Hardening in gamma-rays? (red shaded region)

Padovani et al, 2018; Garrappa et al, arXiv:1901.10806

Theoretical challenge: Where did all the energy go to?

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & \Rightarrow \nu \\ p + \pi^0 & \Rightarrow \gamma \end{cases}$$

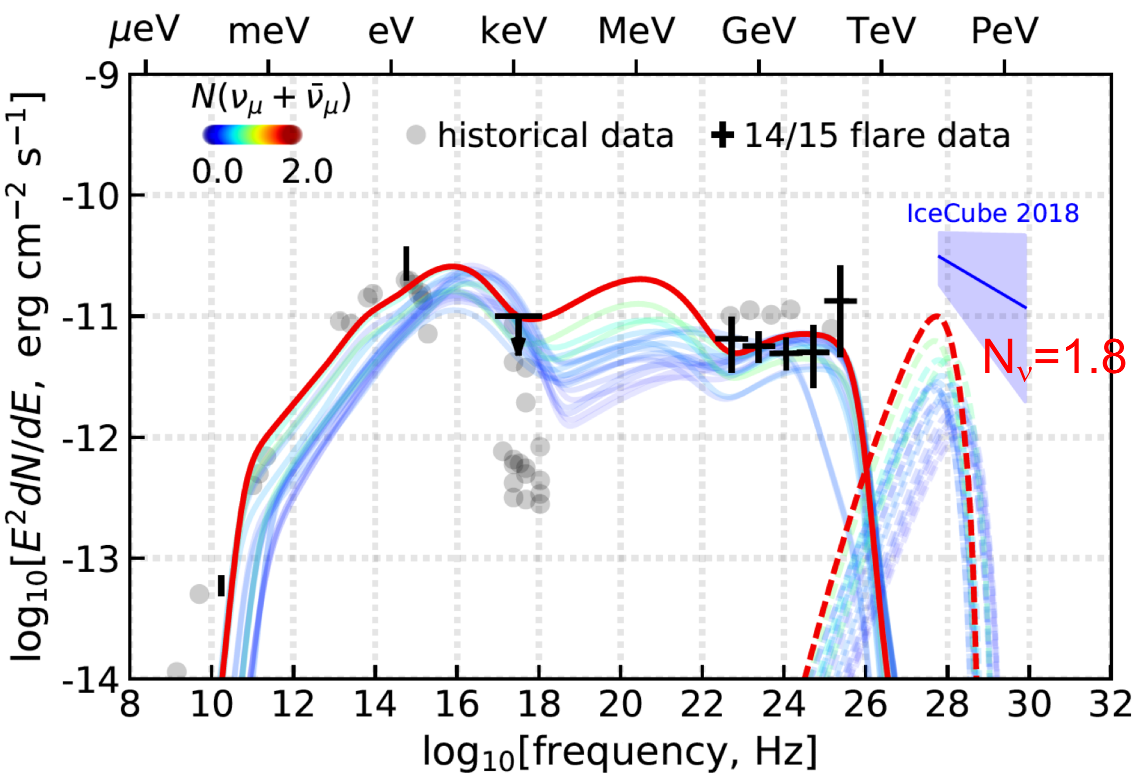
Comparable amounts of energy

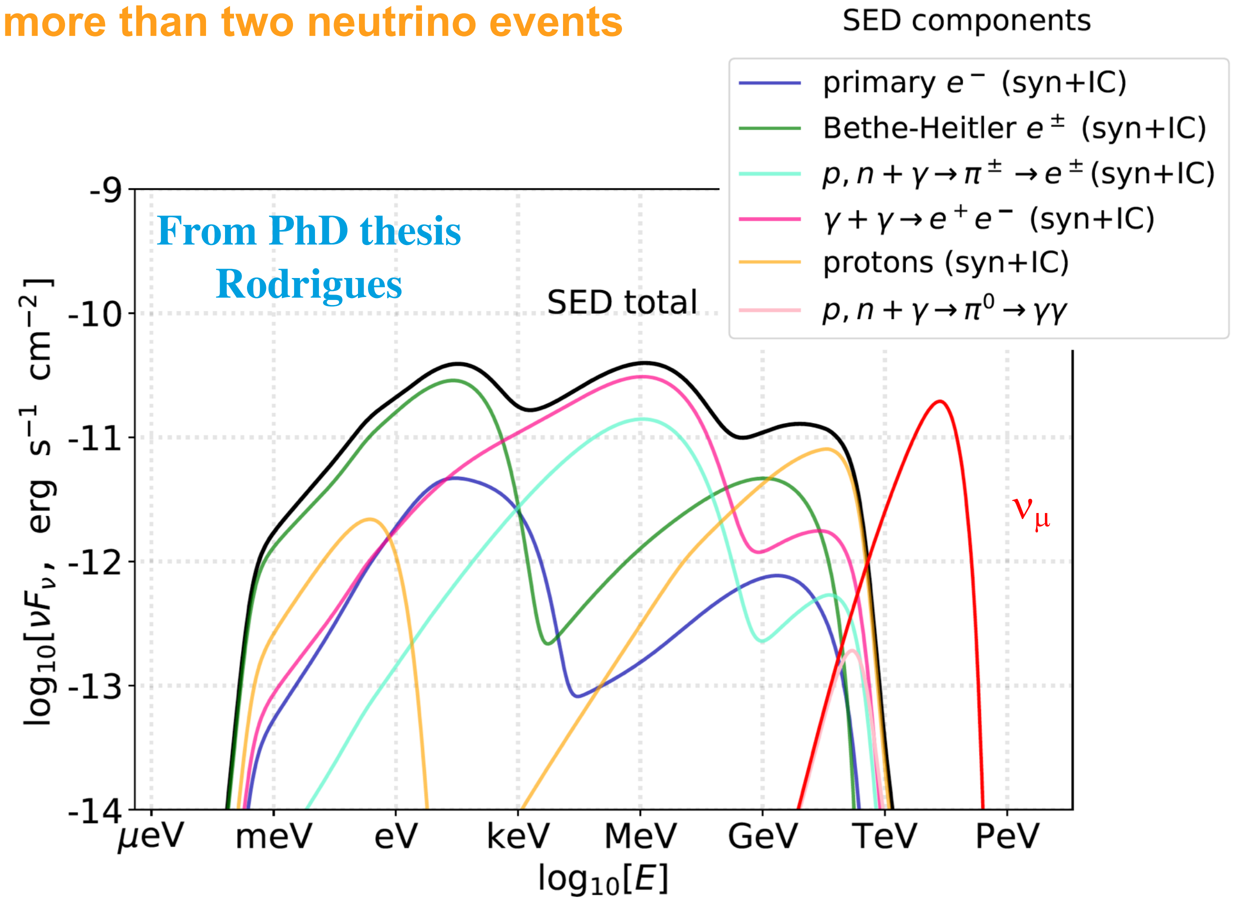
Options for hiding the gamma-rays (+electrons):

- **Reprocessed** and "parked" in E ranges without data during flare? (e.g. MeV range, sub-eV range)
  - → Can this be accommodated in a self-consistent model (next slide)? Fine-tuned during flare?
  - → Requires monitoring in all wavelength bands
- Leave source + **dumped** into the **background light**?
  - → Implies low radiation density to have gamma-rays escape
  - → Difficult to accommodate energetics if sole solution (low neutrino production efficiency!)
- **Absorbed or scattered** in some **opaque region**, e.g. dust/gas/radiation?
  - → Requires additional model ingredients
    see e.g. Wang et al, 2018; Murase et al, 2018

One zone description of spectral energy distribution

.... can describe SED (with significant excess of L_{edd}), but no more than two neutrino events





Energy deposited in MeV range and absorbed in EBL
(here about 80% absorbed, 20% re-processed for E_γ > TeV)

Primary electron processes (synchrotron and inverse Compton) dominate *nowhere* in this model!

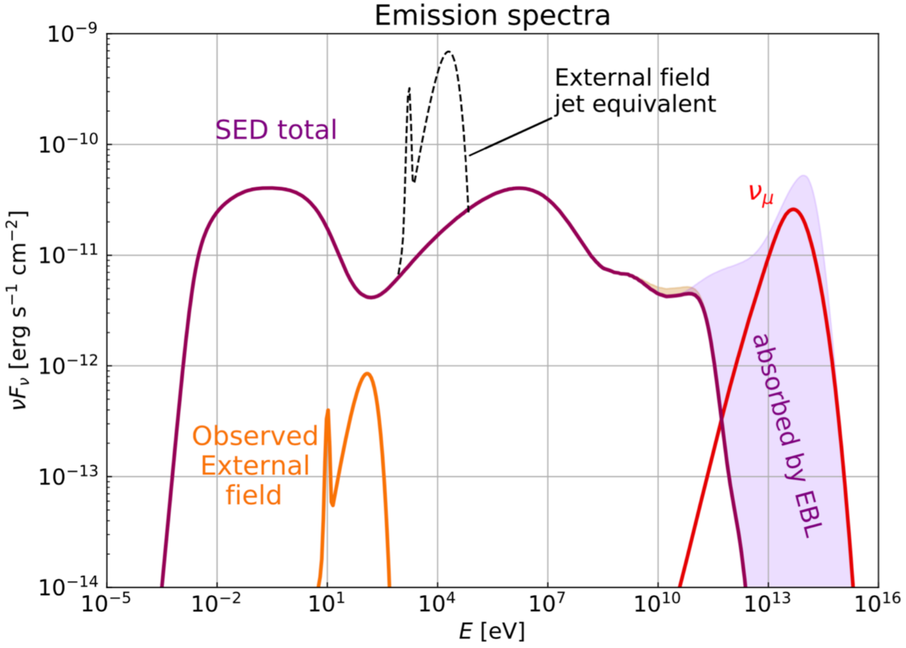
From: Rodrigues, Gao, Fedynitch, Palladino, Winter, ApJL 874 (2019) L29; see also Halzen, et al, arXiv:1811.07439

External radiation field example

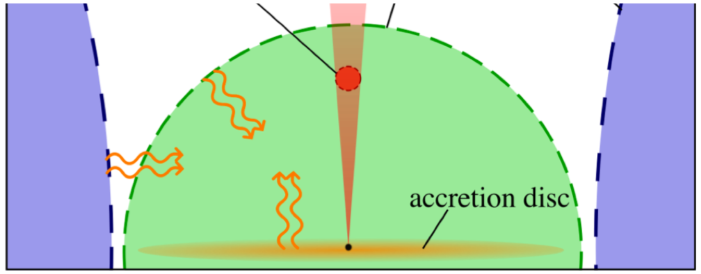
Can yield up to about five neutrino events during neutrino flare

- TXS 0506+056 may be actually an FSRQ
  Padovani et al, MNRAS 484 (2019) L104

- These can be relevant in the jet frame. Example:

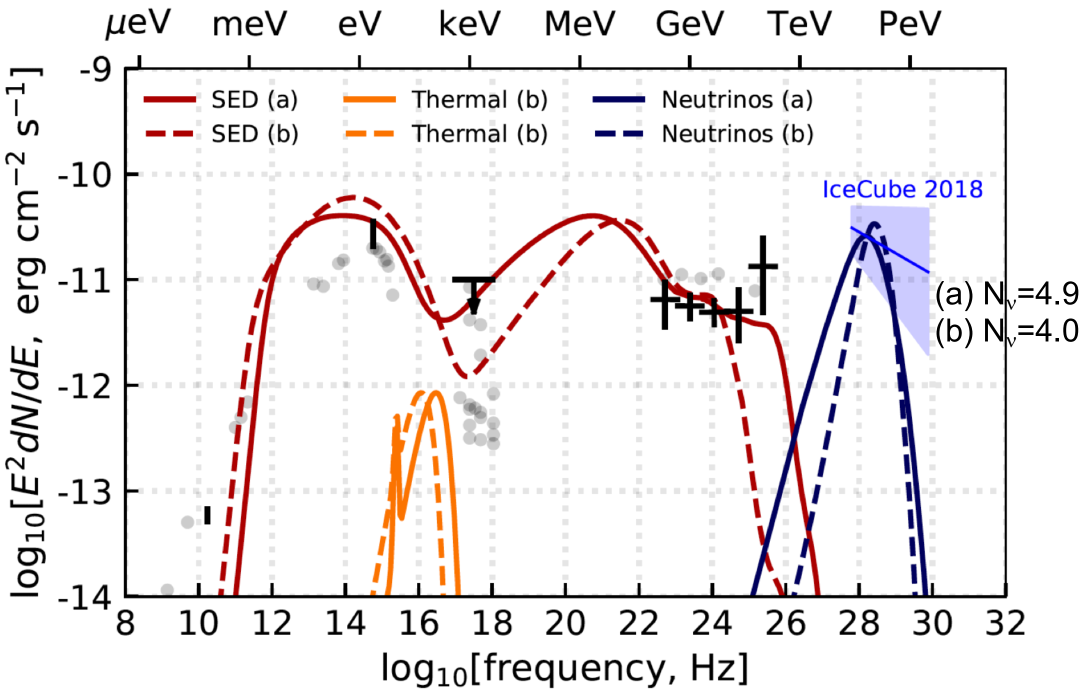


Courtesy X. Rodrigues



Rodrigues et al, ApJ 854 (2018) 54; see talk Rodrigues feat. Fedynitch

- Results for TXS 0506+056:



- May be consistent with IceCube result if different spectral shape is assumed

Rodrigues, et al, ApJL 874 (2019) L29; see also Reimer et al, 1812.05654

Summary (short)

- X-ray (and VHE gamma-ray) data relevant to detect sub-dominant hadronic contributions
- Simple one-zone models face challenges (L_{edd} or E_ν)
- Time-response of SED during flare is a model indicator
- Historical flare: 13 events very high. Needs (unusual?) sophistication in models to hide the hadronic components

Summary (long)

Interpretation in terms of one-zone models

😀 Simplest possible geometry, few parameters

😀 Describe SED and time response reasonably well (modulo some discussion of UV data)

🧐 Have to accept that either L_{edd} is significantly exceeded or that neutrino energies does not match

🧐 2014-15 neutrino flare: more than two neurino events difficult to accommodate

Interpretation in terms of multi-zone models:

😀 External radiation fields (e.g. disk, sheath) or compact core models promising

😀 Can produce substantially larger neutrino event numbers with reasonable energetics

😀 Some models (compact core, jet-cloud) can produce a spectral hardening in gamma-rays (2014-15 flare)

🧐 Too early for solid conclusions, mostly because of sparseness of data

What did we learn qualitatively from 2017 event?

- Time-response of SED and X-ray data point towards leptonically dominated model
- X-ray/gamma-ray data need to be monitored (indicative for hadronic contribution)
- More such associations are needed for solid conclusions on predicted neutrino event rates

What did we learn qualitatively from 2014-15 flare?

- Description of 13 events requires high radiation density with imprints in the SED which seem to be *in contradiction to observations*
- Up to five events plausible in external radiation field model
- Expected (neutrino) spectral shape very different from IceCube analysis (power law). Consequences?
- Need multi-wavelength monitoring to exclude that signal shows up elsewhere