Neutrinos from blazar modeling

... and the connection to UHECRs

https://multimessenger.desy.de/

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Cosmic Rays and Neutrinos in the Multi-Messenger Era
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Contents

Multi-messenger modeling of AGN blazars

AGN blazar basics

Blazar:
The observer looks into the jet

Estimate for accretion power ~ physical jet power:
Eddington luminosity
$L_{edd} \sim 10^{47}$ erg s^{-1} $M_{BH}/(10^9\ M_{sun})$

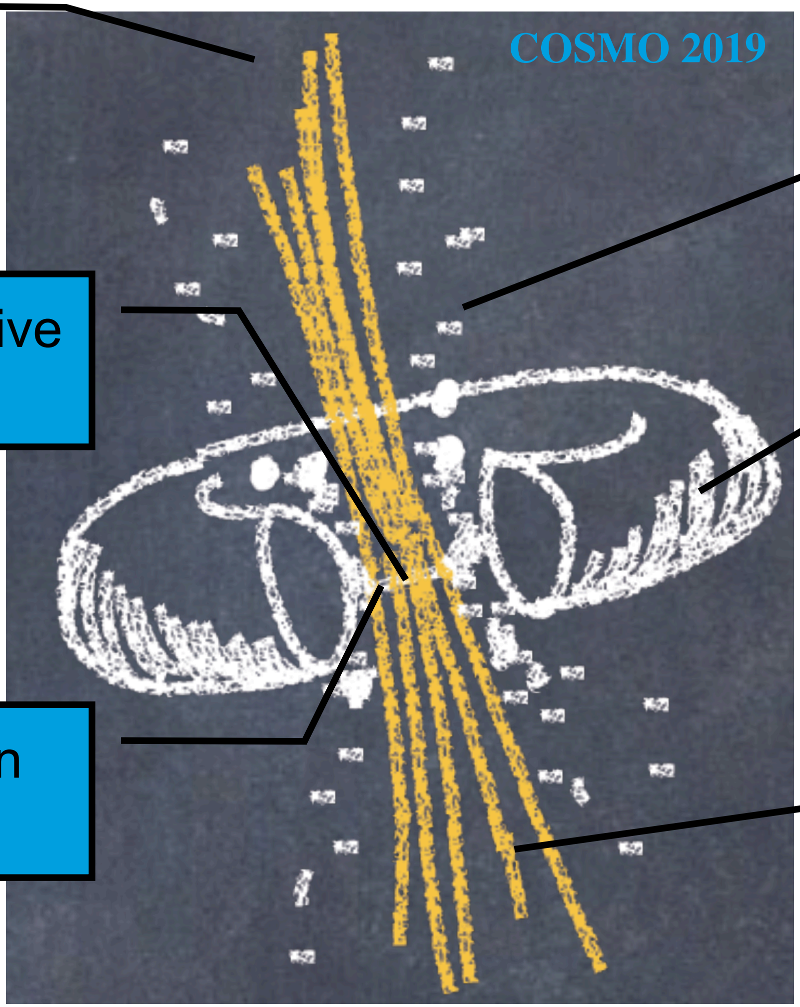
A supermassive black hole

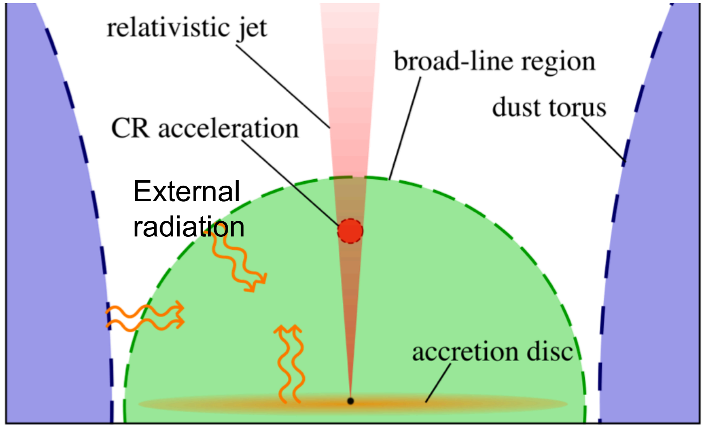
An accretion disk

Clouds (line emissions!)

The dust torus

The jet(s)





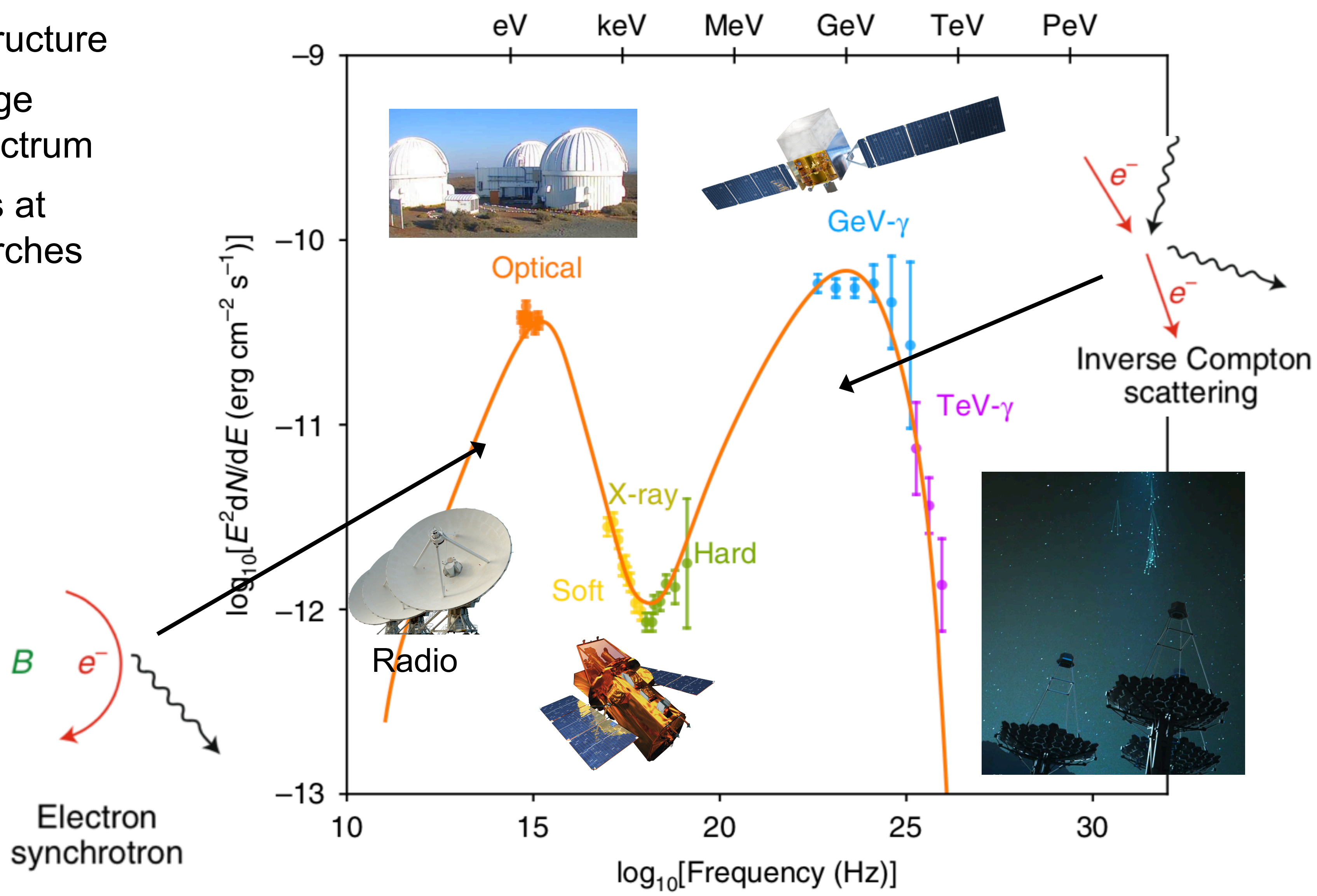
Non-thermal emission toy model (FSRQ)
Rodrigues et al, ApJ 854 (2018) 54; Murase et al, 2014

Two populations:
FSRQs (Flat Spectrum Radio Quasars): higher luminosities and additional spectral features compared to **BL Lacs**

Electromagnetic picture of blazars

- Exhibit a typical two-hump structure
- Measured over extremely large range of electromagnetic spectrum
- Often observation campaigns at similar time, or follow-up searches of neutrinos

- Vanilla explanation:
  SSC – "synchrotron self-Compton model"
  But: **No connection with neutrinos or cosmic rays**



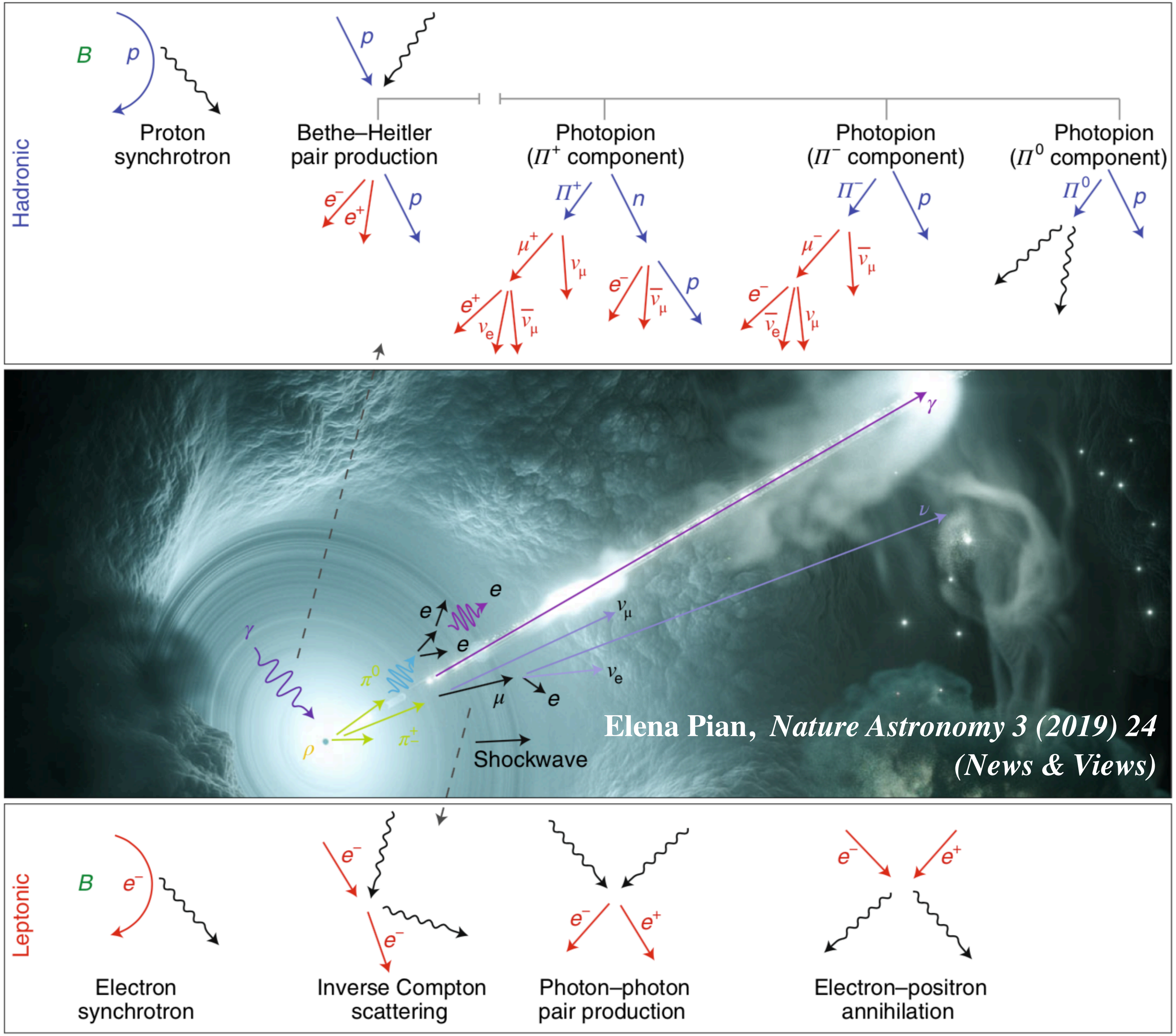
Credits: VLA, ASAS-SN, Swift, Fermi, MAGIC, DESY science comm. lab., Pian 2019, Gao et al, 2019

Hadronic models

- Solve the PDE system for all involved species (e^+, e^-, p, n, γ, ...)
- Include relevant processes ⟶

- Neutrino production rate ~ Proton density x Radiation density
- Proton density ~ Proton injection (compare to L_{edd}?) x confinement time
- Radiation density given by source luminosity, size, geometry (R', Γ, L_γ, ...)

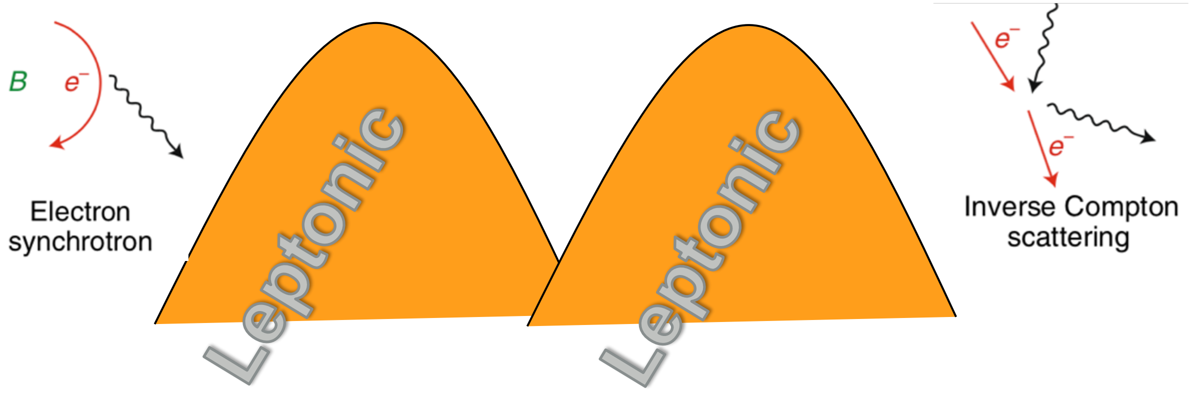
- Systematic scan over source parameters (including injection spectral properties)



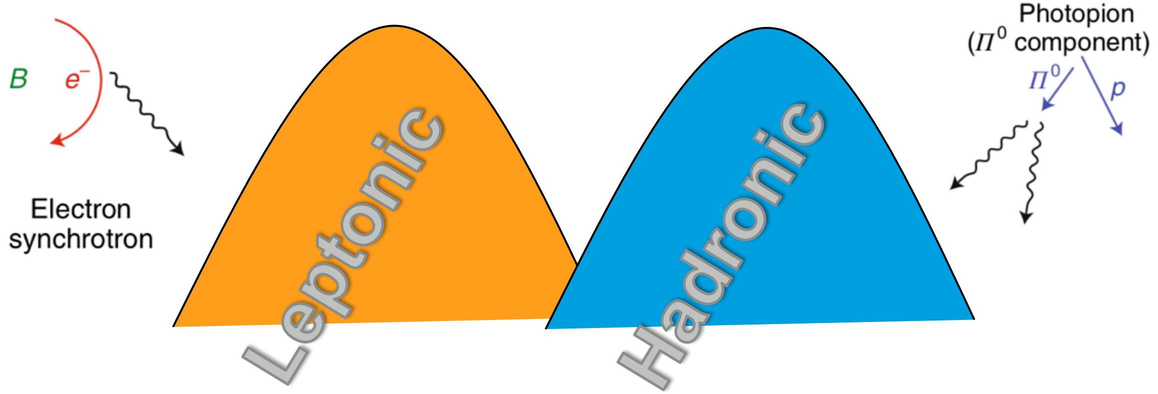
Elena Pian, *Nature Astronomy 3 (2019) 24 (News & Views)*

Typical SED models (qualitatively)

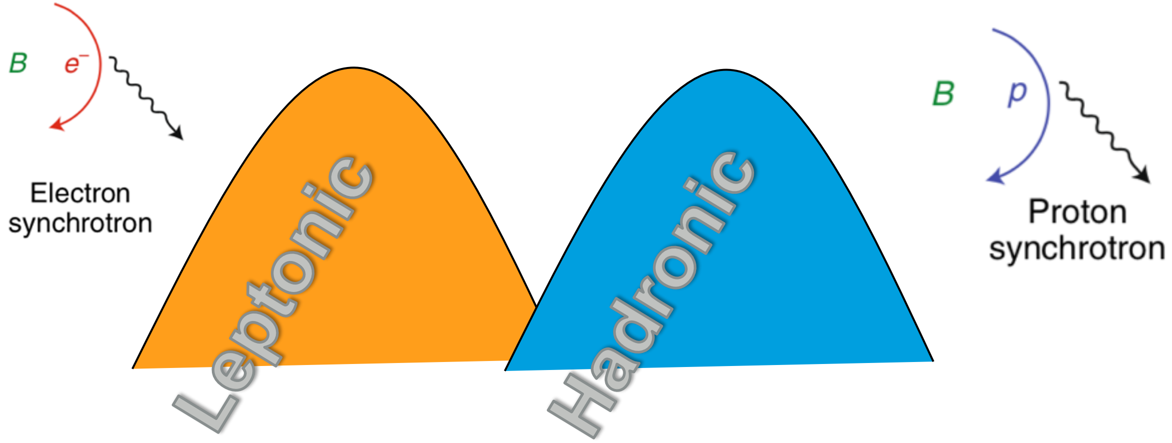
- Synchrotron self-Compton (SSC) or external Compton (EC) models



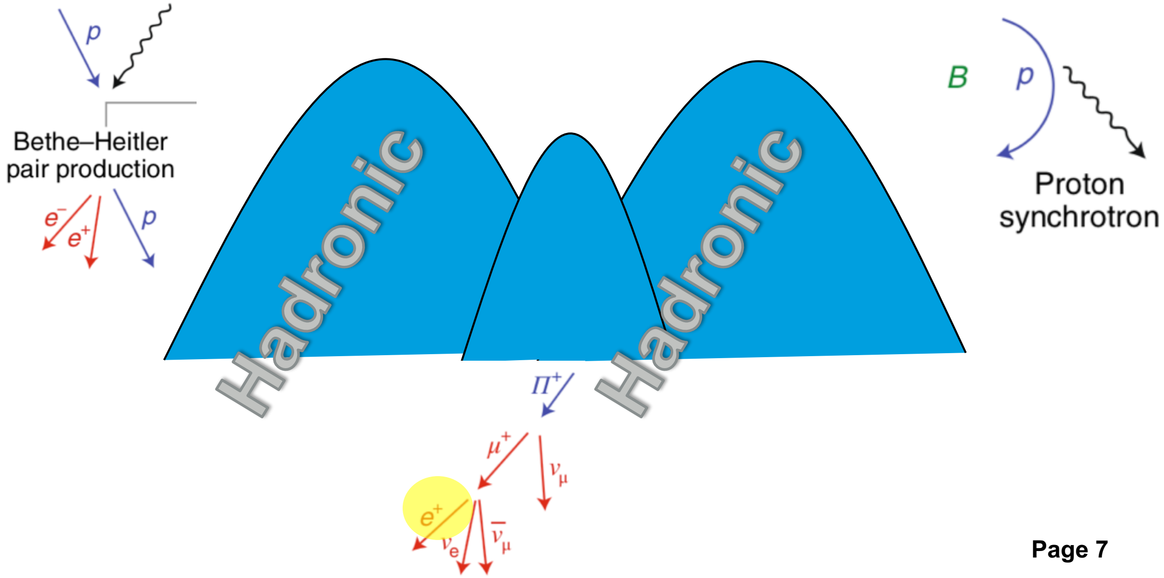
- Pion cascade models



- Proton synchrotron models (require large B')



- More exotic hadronic models, for example:



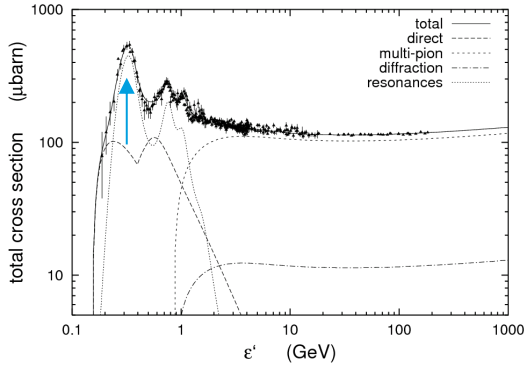
Multiple messengers from photo-pion production

- Neutrino peak determined by maximal cosmic ray energy →

- Interaction with target photons
  (Δ-resonance approximation for C.O.M. energy):

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

E_γ [keV] ~ 0.01 Γ^2/E_ν [PeV]
keV energies interesting!
Watch for X-ray flares!

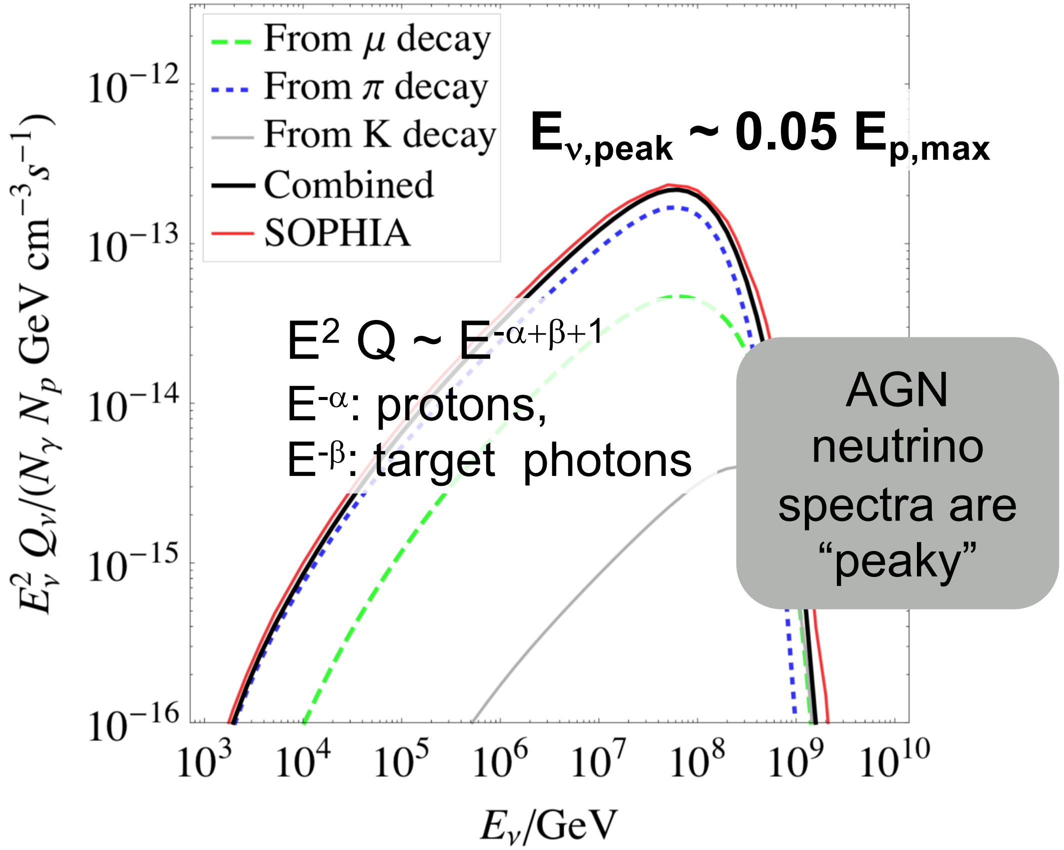


- Photons from pion decay:

$$\pi^0 \rightarrow \gamma + \gamma$$

Injected at $E_{\gamma,peak}$ ~ 0.1 $E_{p,max}$
TeV–PeV energies interesting!
(but: electromagnetic cascade in source, EBL attenuation!)
VHE γ-rays potentially interesting!

AGN prototype neutrino spectrum



From: Hümmer et al, Astrophys. J. 721 (2010) 630

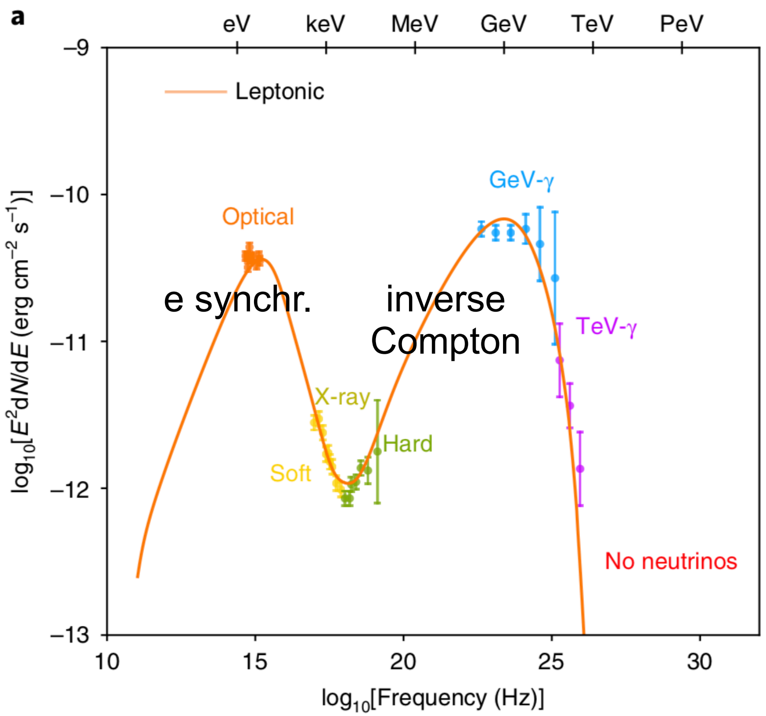
Lessons learned from TXS 0506+056

One zone model results (2017 flare)

One spherical radiation zone
Fewest assumptions

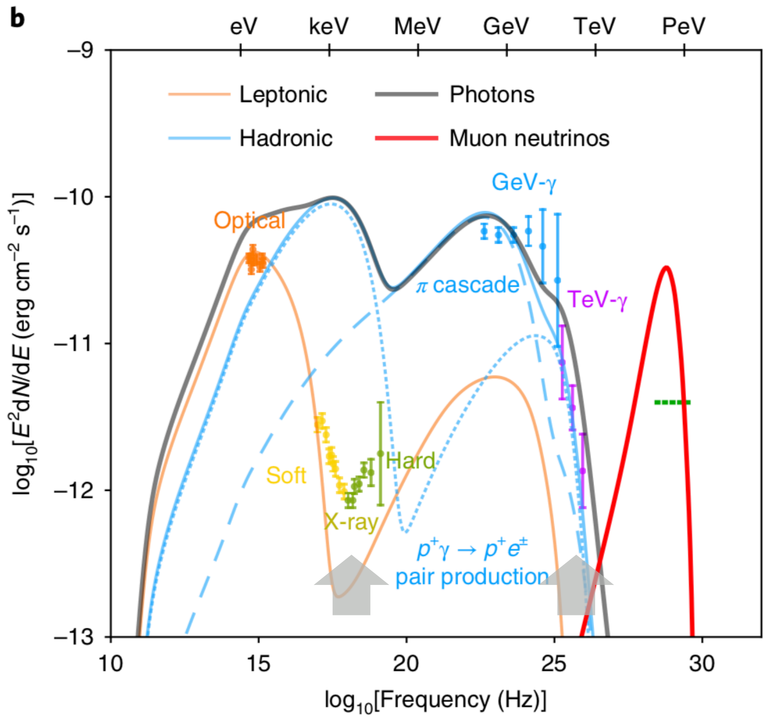
R'

Leptonic models



- No neutrinos

Hadronic (π cascade) models

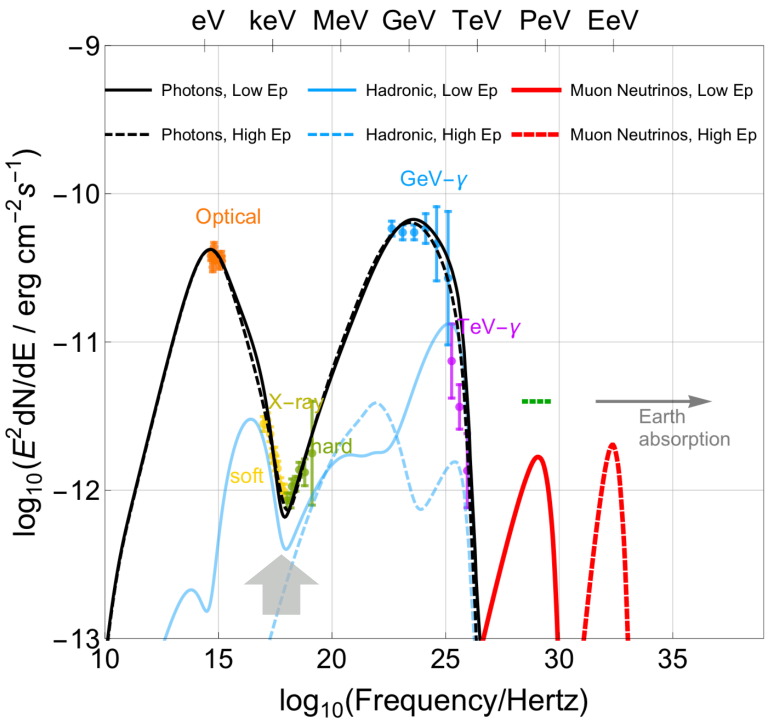


- Violate X-ray data

Hadronic cascade: not only γs from π^0 decays, secondary+BH e^+,e^-!

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

Hybrid or p synchrotron models



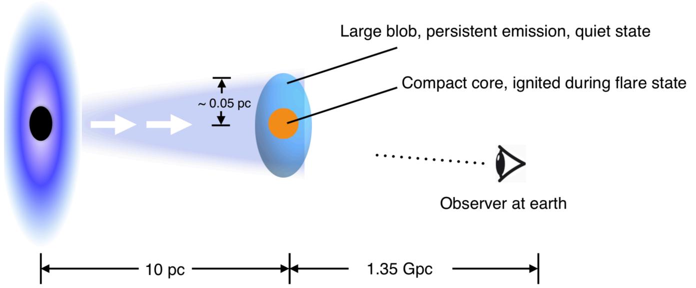
- **Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy**

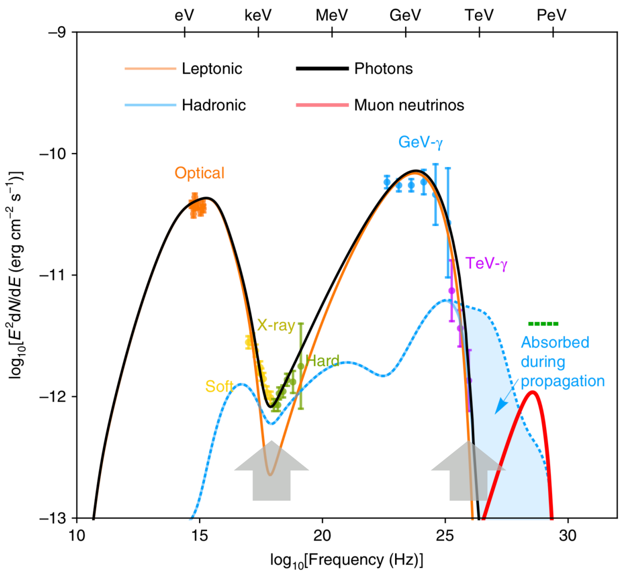
Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88;* see also Cerutti et al, 2018; Sahakyan, 2018; Gokus et at, 2018; Keivani et al, 2018; ...

More freedom through more sophisticated sources geometries

... to solve energetics problem (examples). At the expense of more parameters.

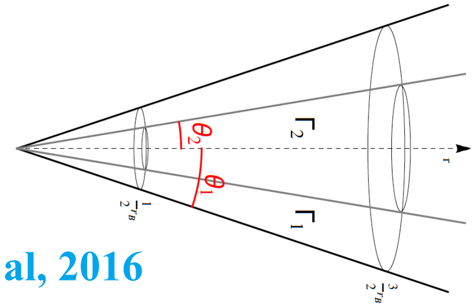
Formation of a compact core



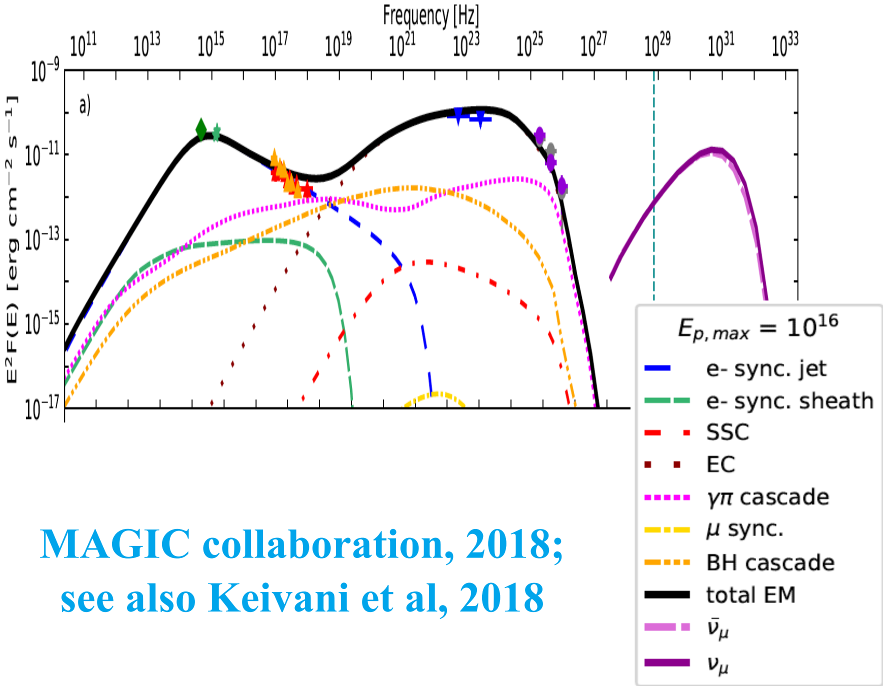


Gao et al, *Nature Astronomy 3 (2019) 88*

External radiation fields

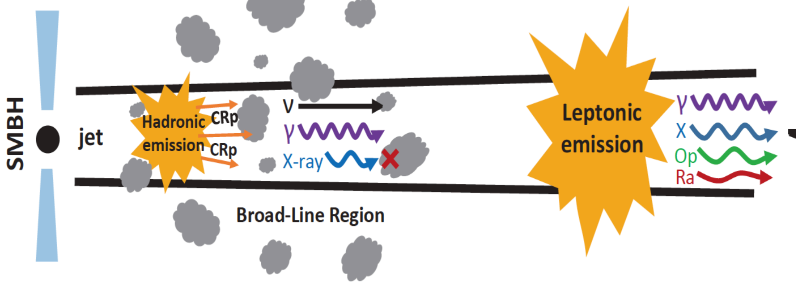


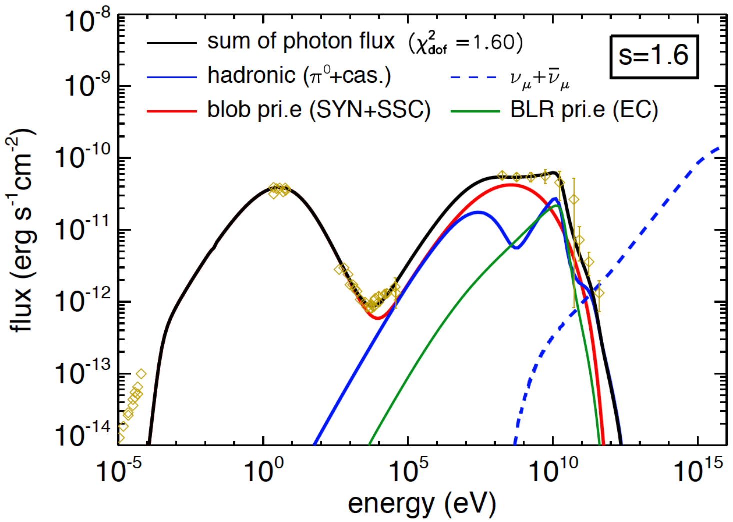
Sikora et al, 2016



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

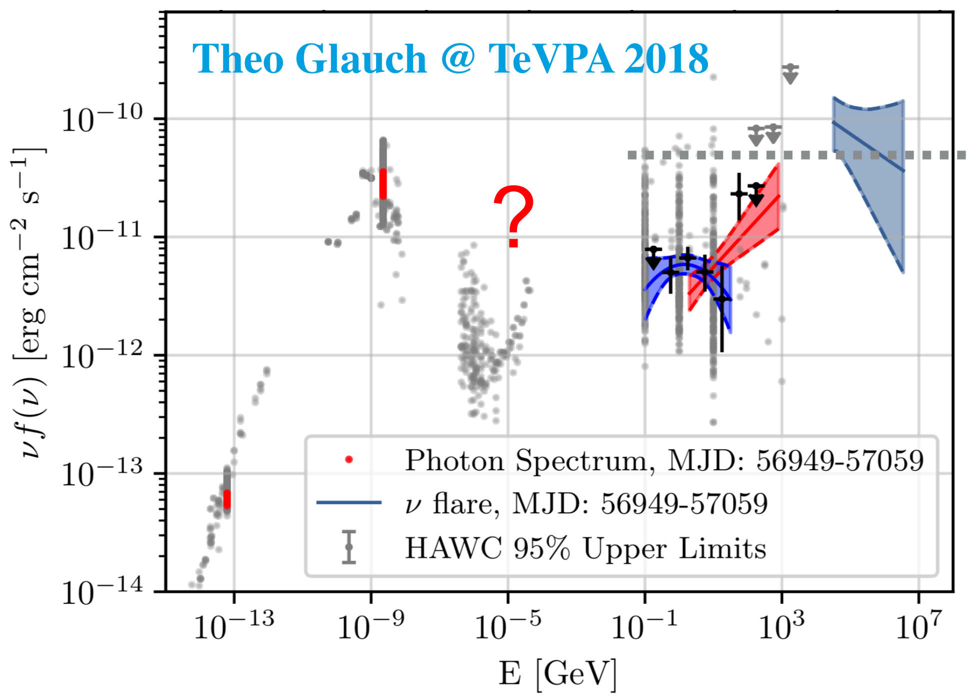
Jet-cloud interactions/ several emission zones





Liu et et al, 2018;
see also Xue et al, 2019;
Zhang et al, 2019

The archival (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: **Energy conservation!**

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

Comparable amounts of energy

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

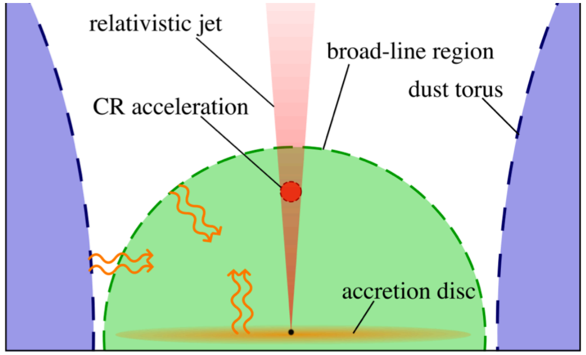
- **Reprocessed** into in E ranges without data during flare? (e.g. MeV range)
  - → Can this be accommodated in a self-consistent model? Exotic SED models?
- Leave source + **dumped** into the **background light**?
  - → Implies low radiation density to have gamma-rays escape
  - → Challenge for energetics (low neutrino production efficiency!)
- **Absorbed or scattered** in some **opaque region**, e.g. dust/gas/radiation? More zones?
  - → Requires additional model ingredients

Wang et al, 2018; Murase et al, 2018; Zhang et al 2019; Xue et al, 2020

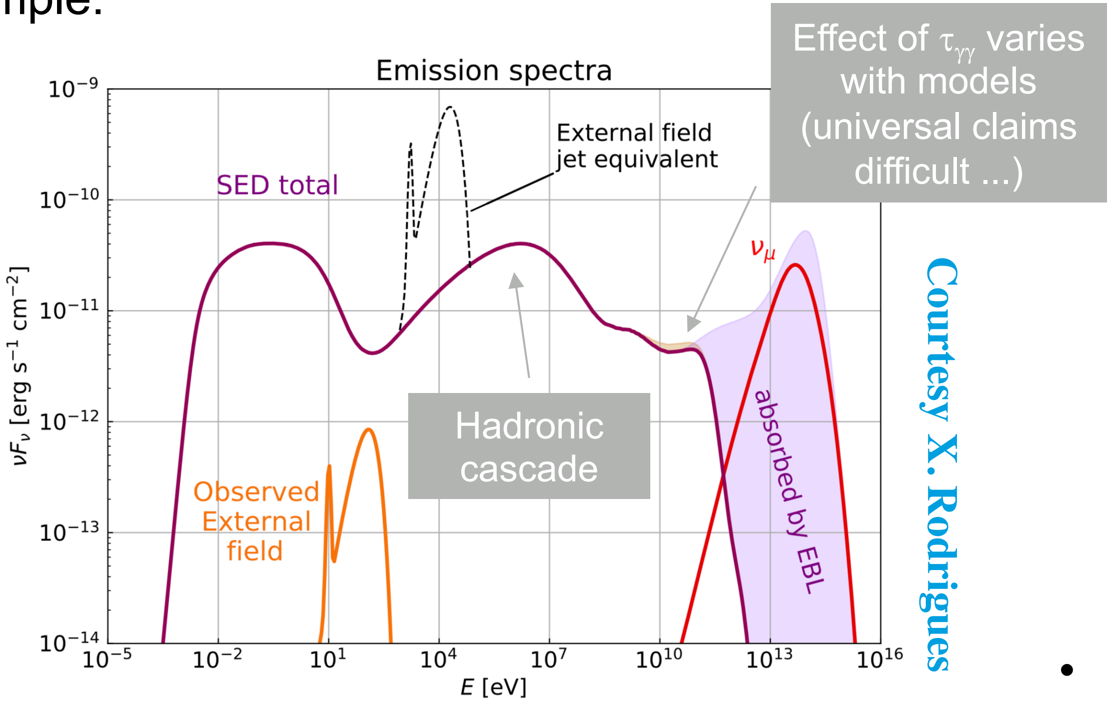
External radiation field example

Can yield up to about five neutrino events during neutrino flare

Rodrigues et al, ApJ 854 (2018) 54

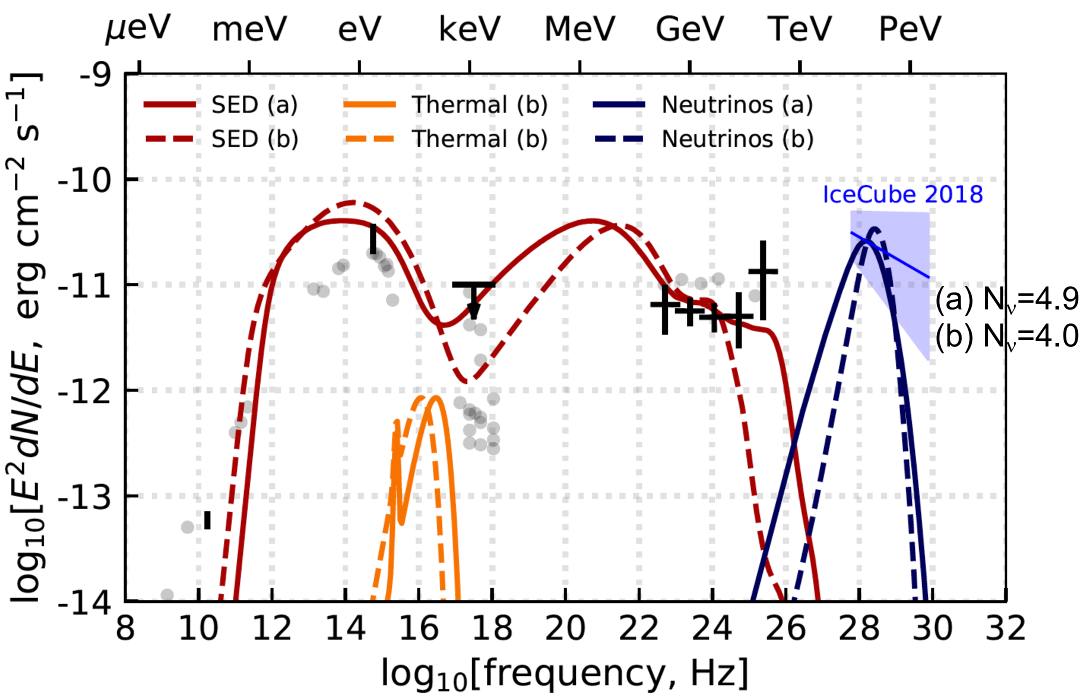


- TXS 0506+056 may be actually an FSRQ
  Padovani et al, MNRAS 484 (2019) L104
- Photons can be back-scattered into the jet frame. Example:



Courtesy X. Rodrigues

- Results for TXS 0506+056:



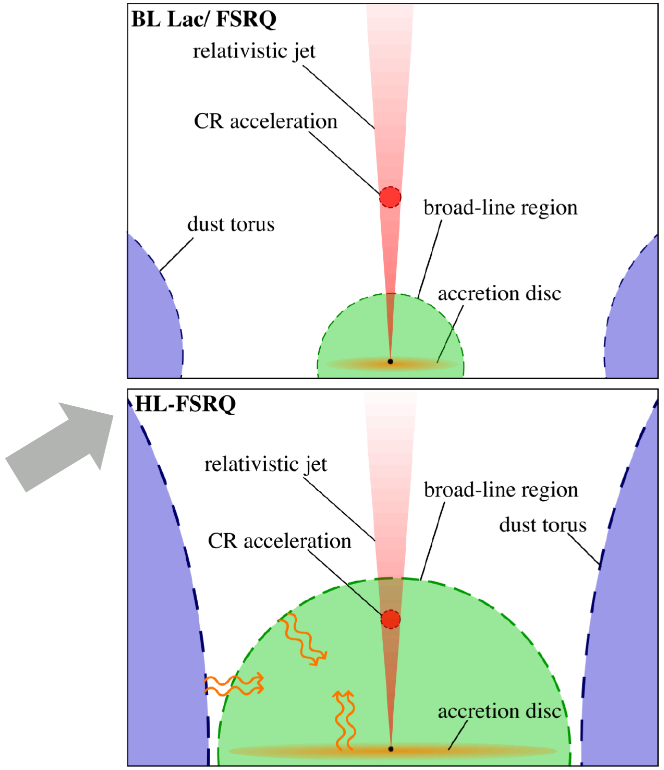
- Maximally five events; may be consistent with IceCube result if different spectral shape is assumed

Rodrigues, et al, ApJL 874 (2019) L29; see also Reimer et al, 1812.05654; Halzen, et al, arXiv:1811.07439; Kun et al, arXiv:2009.09792

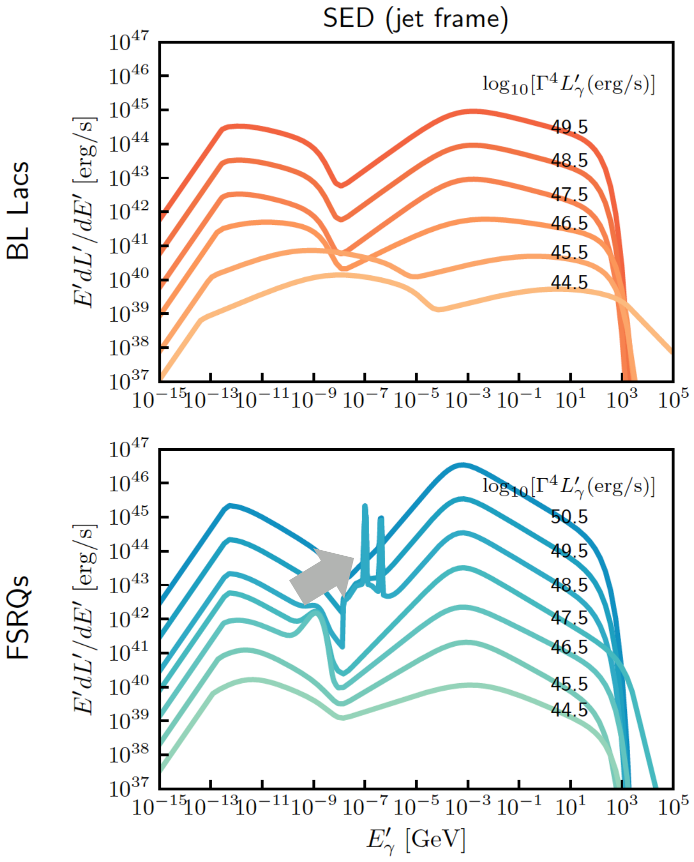
Diffuse neutrinos or UHECRs from AGN jets?

Ingredients: Neutrino production and population models

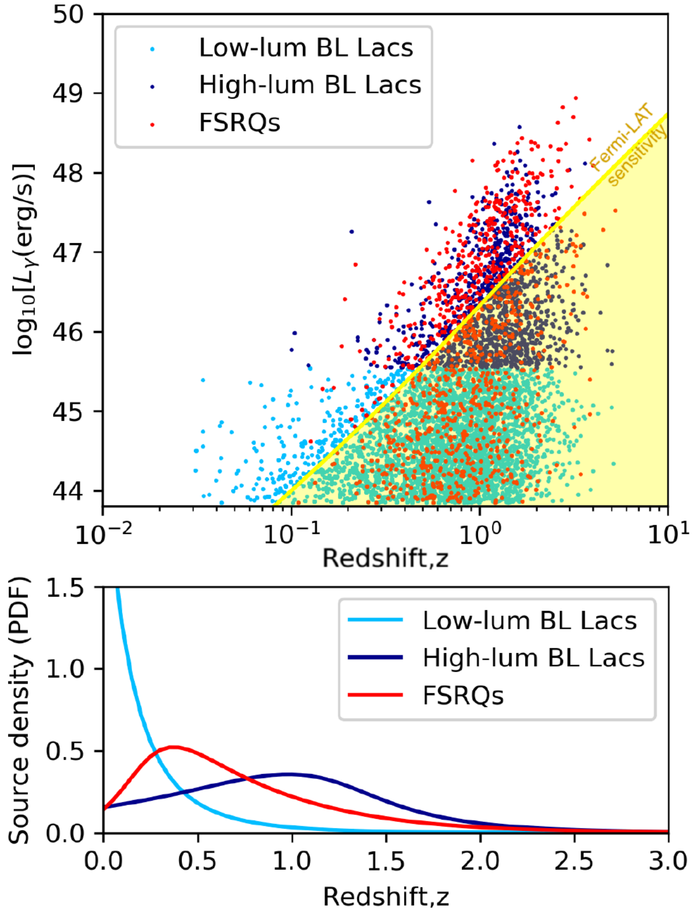
- Geometry determined by disk luminosity:



- SED follows "blazar sequence":



- Population model:
LL-BL Lacs, HL-BL Lacs, FSRQs



Population model by Ajello et al, 2012+2014; sources from Fermi's 3LAC catalogue

- For HL-FSRQs, the blob is exposed to boosted external fields

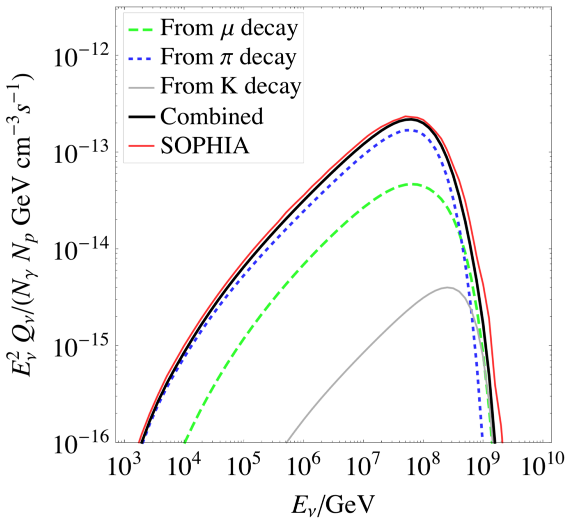
Rodrigues, Fedynitch, Gao, Boncioli, WW, ApJ 854 (2018) 54; Murase, Inoue, Dermer, PRD 90 (2014) 023007; Palladino, Rodrigues, Gao, WW, ApJ 871 (2019) 41; Rodrigues, Heinze, Palladino, van Vliet, WW, arXiv:2003.08392

Describes diffuse γ-ray BG by construction!

Recap: AGN neutrino spectrum ...and two hypotheses

There is no unified (ν, γ-ray, UHECR) one zone model!

$E_{\nu,peak}$ ~ 0.05 $E_{p,max}$



$E_{p,max}$ ~1-10 PeV

Moderately efficient CR acclerators

1) AGN blazars describe neutrino data

$E_{p,max}$ ~ 1-10 EeV

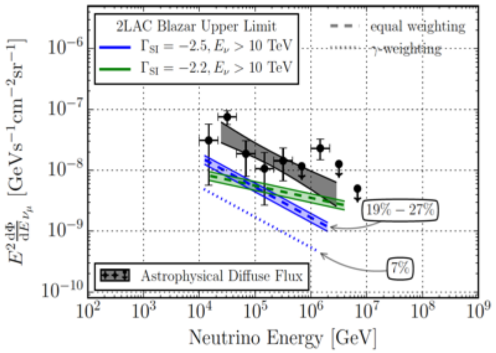
(R_{max} ~ 1-10 EV)

Very efficiency CR accelerators

2) AGN jets describe UHECR data

Postulate that

1. The diffuse neutrino flux is dominated by AGN blazars (such as the extragalactic γ-ray flux!)
2. The blazar stacking limit is obeyed →
   IceCube, Astrophys. J. 835 (2017) 45



3. The baryonic loading evolves over the blazar sequence (depends on L_γ); the one of TXS 0506+056 is in the ballpark of self-consistent SED models

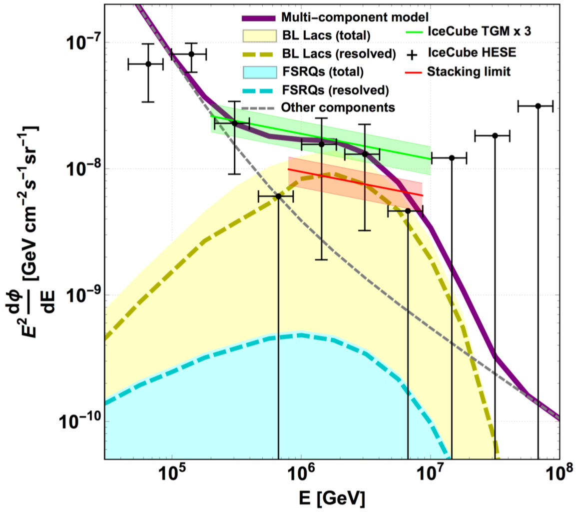
Postulate that:

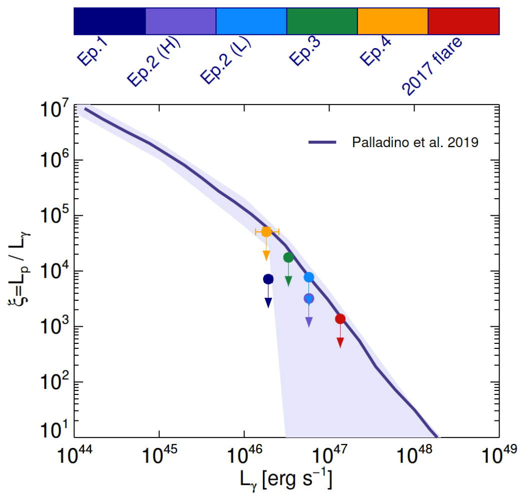
1. AGN jets (can be misaligned!) describe Auger data across the ankle
   (spectrum very well, composition observables roughly)
2. The injection compositon is roughly Galactic
3. Different classes (LL-BL Lacs, HL-BL Lacs, FSRQs) can have a different baryonic loading

Conclusions for different hypotheses

1) AGN blazars describe neutrino data

1. Unresolved BL Lacs must dominate the diffuse neutrino flux
2. The baryonic loading must evolve, as otherwise efficient neutrino emitters (esp. FSRQs) stick out

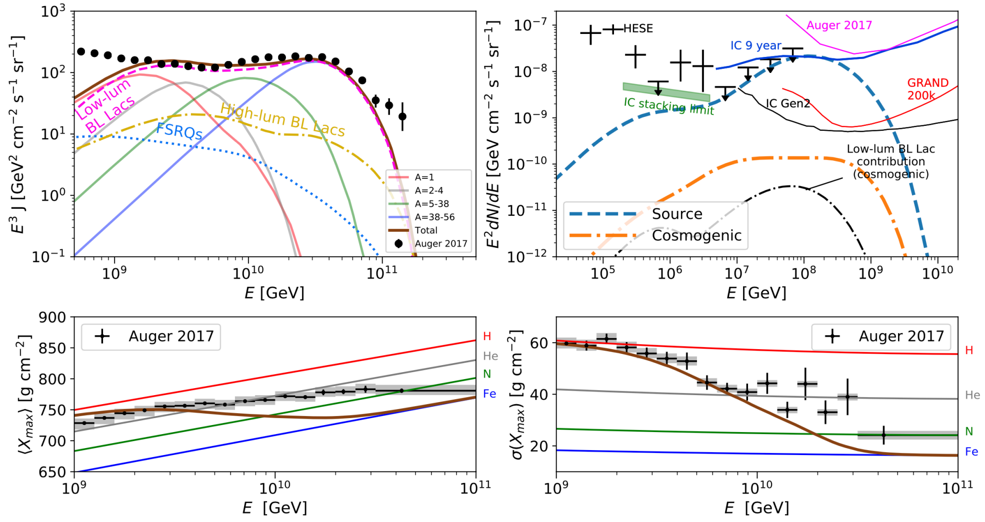




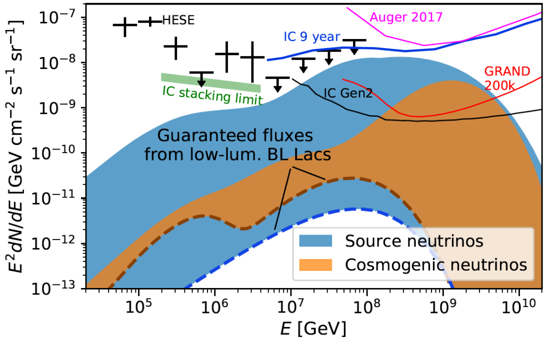
Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41;
Right Fig. from Petropoulou et al, arXiv:1911.04010: same behavior also found in multi-epoch description of TXS 0506+056

2) AGN jets describe UHECR data

1. UHECR description driven by LL-BL Lacs because of
   - Low luminosity → rigidity-dependent max. energy
   - Negative source evolution



2. Neutrinos mostly come from FSRQs, peak at high energies, and may even outshine the cosmogenic flux there



Rodrigues, Heinze, Palladino, van Vliet, WW, arXiv:2003.08392

Do the neutrinos come during (gamma-ray) flares?

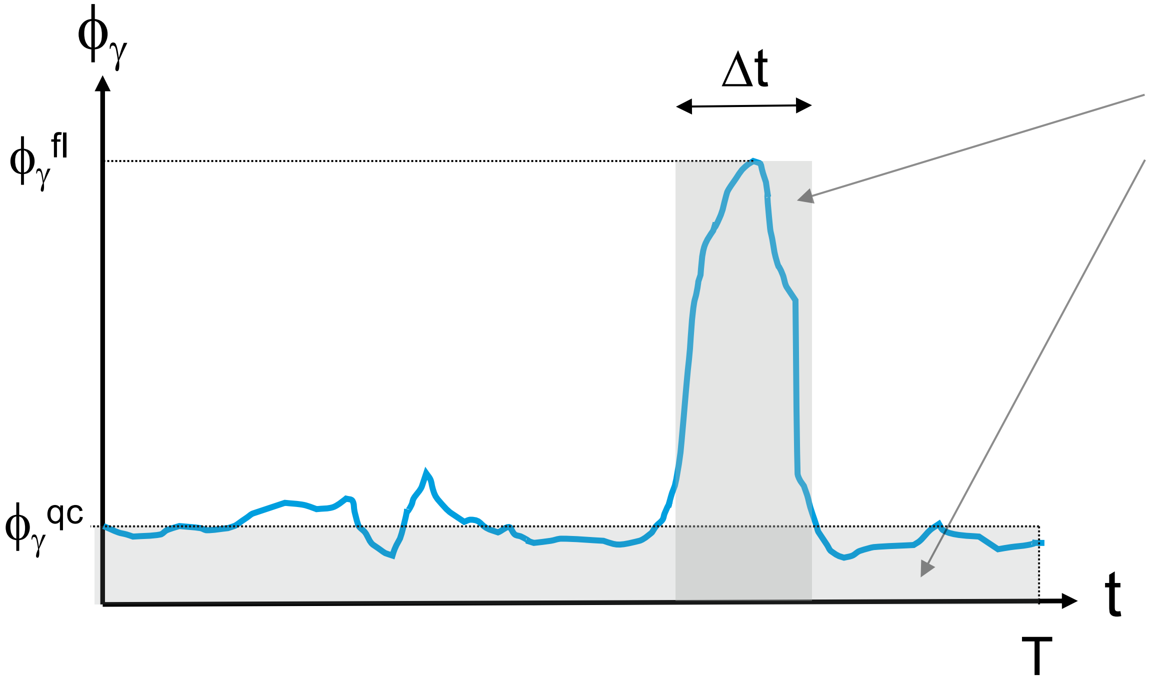
Some theoretical comments

The "flux versus fluence" problem

Is the neutrino emission really expected during a gamma-ray flare or suppression (anti-flare)?

Neutrino observatory

- Long-term monitoring, all sky
- Low statistics, typically (at most) one event
- Sensitive to *fluence* = flux x **time**



Electromagnetic instrument (e.g. γ-ray, X-ray, optical)

- Typically no short-term monitoring, targeted "snapshots"
- High statistics, typically many photons during pointing
- Sensitive to *flux.* Flare = significant increase of flux

Example: Assume flux $\phi_\nu = K\,\phi_\gamma$ Flaring duty cycle (DC) = $\Delta t/T$

Neutrino fluence F – event rate

- Flare: $F_\nu^{fl} = K\,\phi_\gamma^{fl}\,\Delta t = K\,\phi_\gamma^{fl}\,DC\,T$
- Quiescent state: $F_\nu^{qc} = K\,\phi_\gamma^{qc}\,(T-\Delta t) \sim K\,\phi_\gamma^{qc}\,T$ (for DC<<1)

Ratio neutrino fluence flare vs. quiescent state:

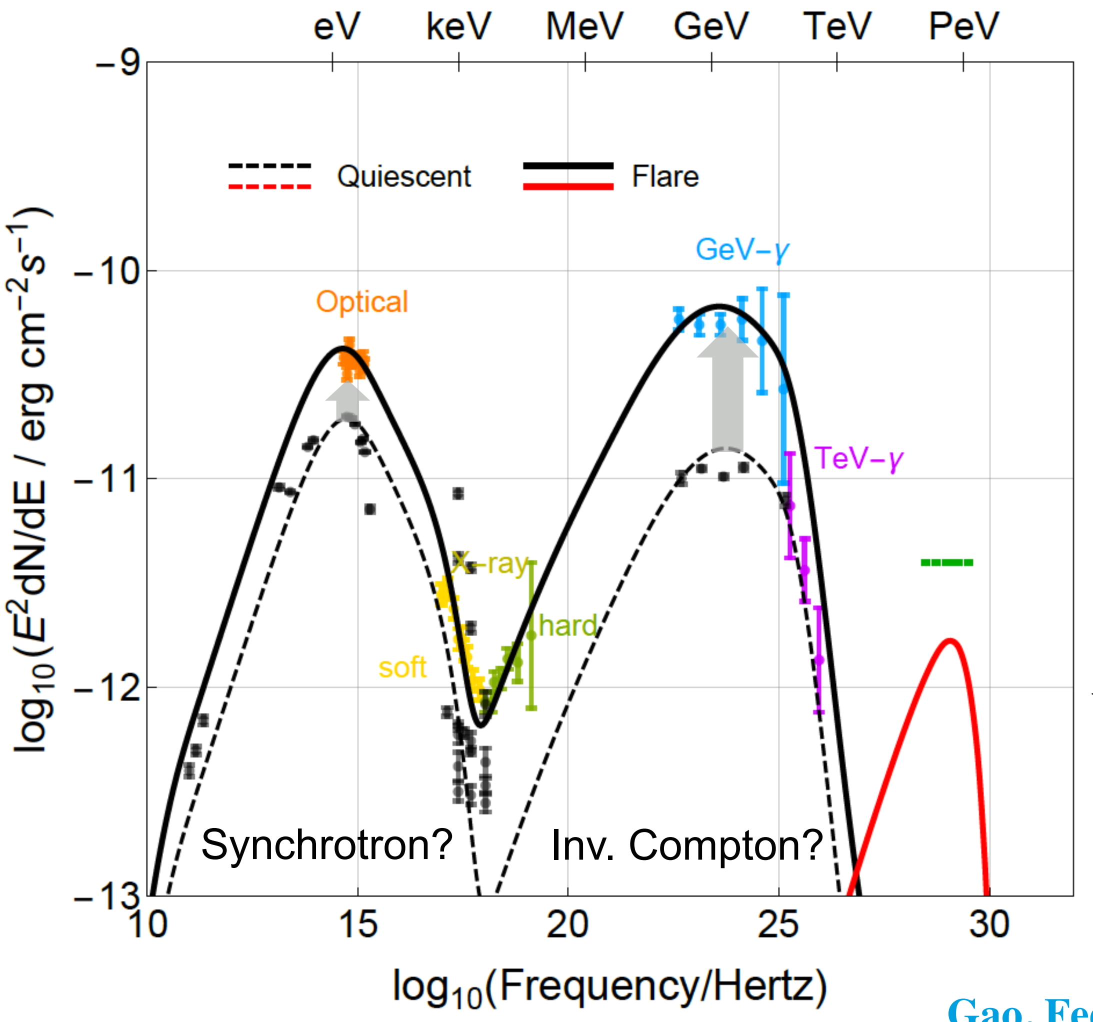
- $F_\nu^{fl}/F_\nu^{qc} = DC\,\phi_\gamma^{fl}/\phi_\gamma^{qc}$ for DC << 1 (rare/short flares)
- $F_\nu^{fl}/F_\nu^{qc} \sim \phi_\gamma^{fl}/\phi_\gamma^{qc}$ for DC closer to 1 (frequent/long flares)

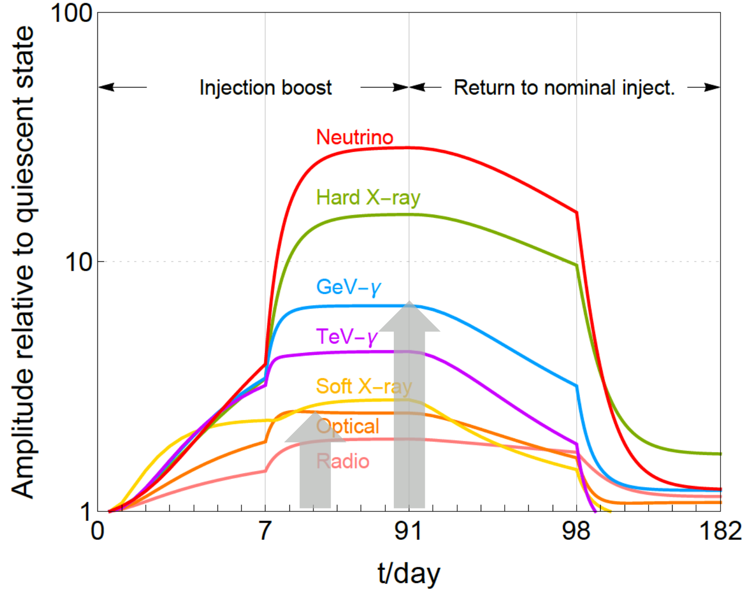
Consequences:

- A priori not clear that neutrino comes during flare (depends on DC!)
- **Short** flaring periods (DC ~ 0) do not matter. Flare fluence relevant!
- Similar argument for $\phi_\nu = K\,\phi_\gamma^{\alpha}$, where $\alpha < 0$ possible (i.e., DC of "anti-flare" or suppression matters)

Flare-response model for TXS 0506+056

Here: One zone model. Blob size unchanged. Example for small duty cycle





← Time-response:
Synchrotron with L_e, inverse Compton with ~ L_e^2
Supports argument that conventional SSC model dominates!

Flare DC small, ~10%, perhaps (?)

Neutrinos: ~ L_p L_e.
(L: injection luminosity)

Need to ramp up product at least by factor of ten to satisfy $F_\nu^{fl}/F_\nu^{qc} > 1$

Here $F_\nu^{fl}/F_\nu^{qc} \sim \phi_\gamma^{fl}/\phi_\gamma^{qc}$ satisfied **by construction**. L_p additional degree of freedom (often ~ L_e)!

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

A test case for a large duty cyle: PKS 1502+106

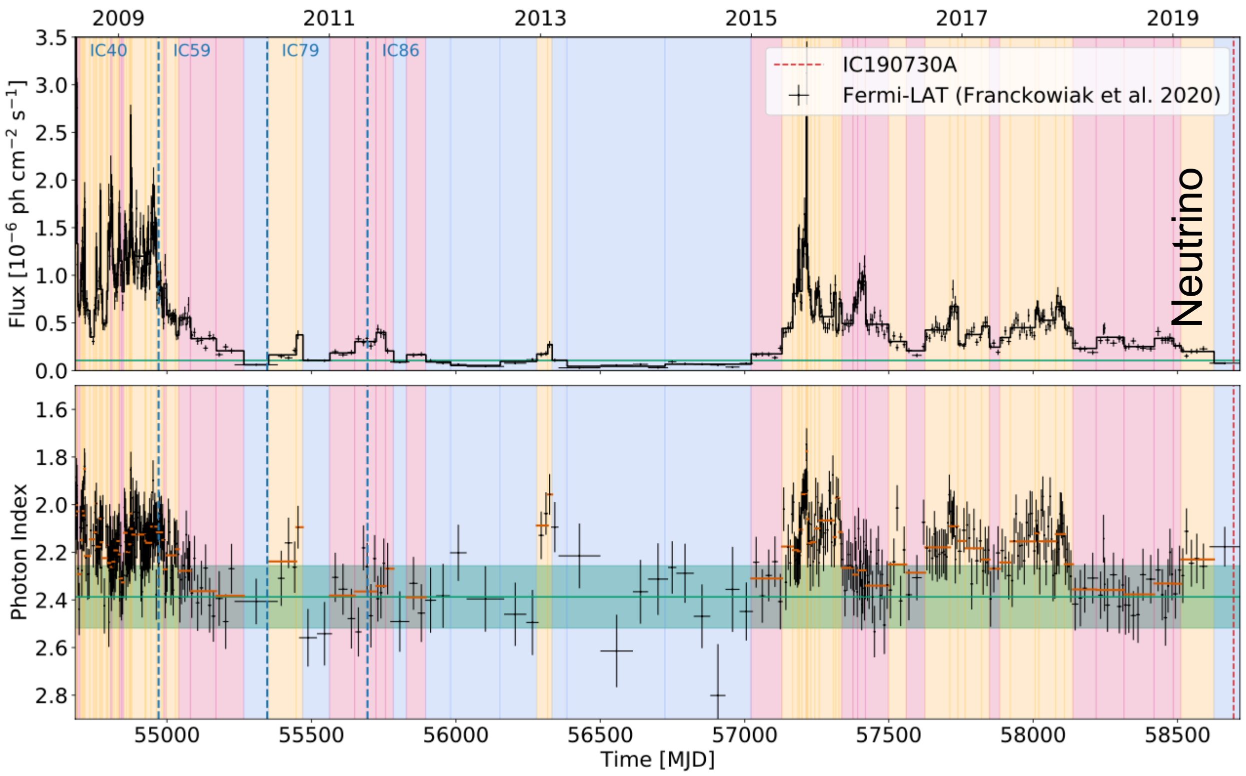
The neutrino came during the quiescent period

Classification scheme:
Three periods

1) γ-ray quiescent (blue)

2) γ-ray hard flare (yellow)

3) γ-ray soft flare (pink)



Would one expect the neutrino during a flare?

From: Rodrigues et al, arXiv:2009.04026; see also Gao et al, Astrophys. J. 843 (2017) 2 for PKS B1424-418

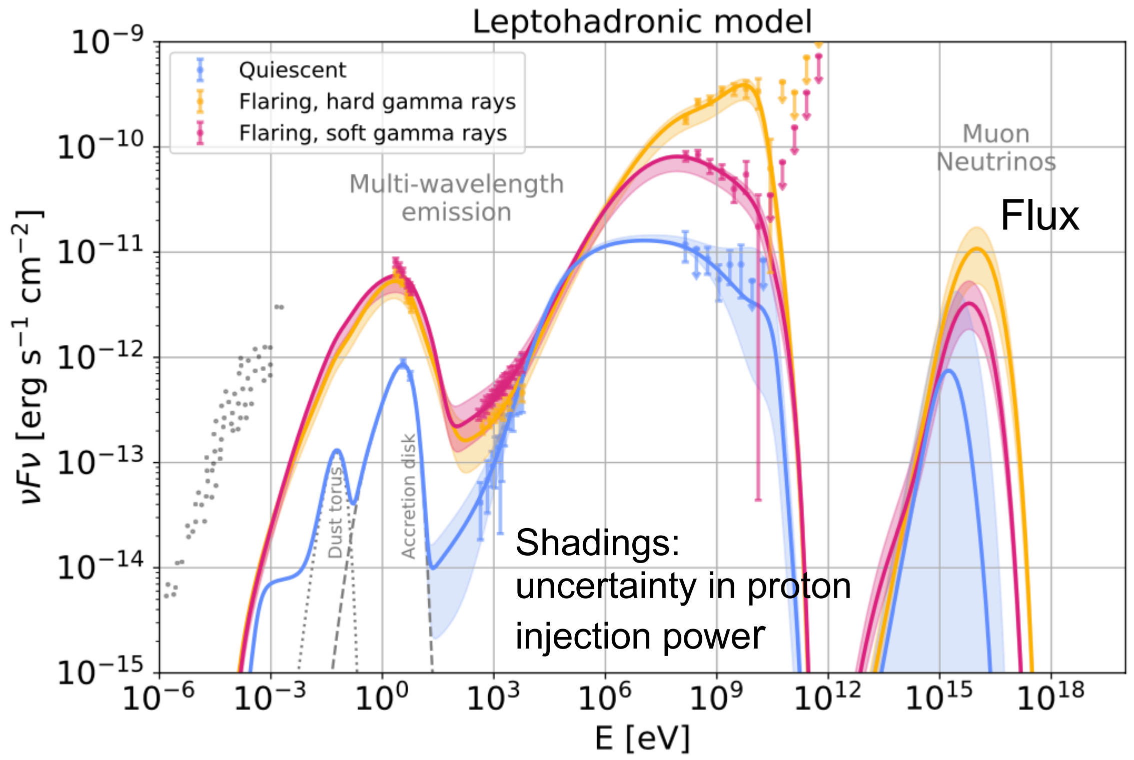
Or are the γ-ray and neutrino fluxes rather anti-correlated?

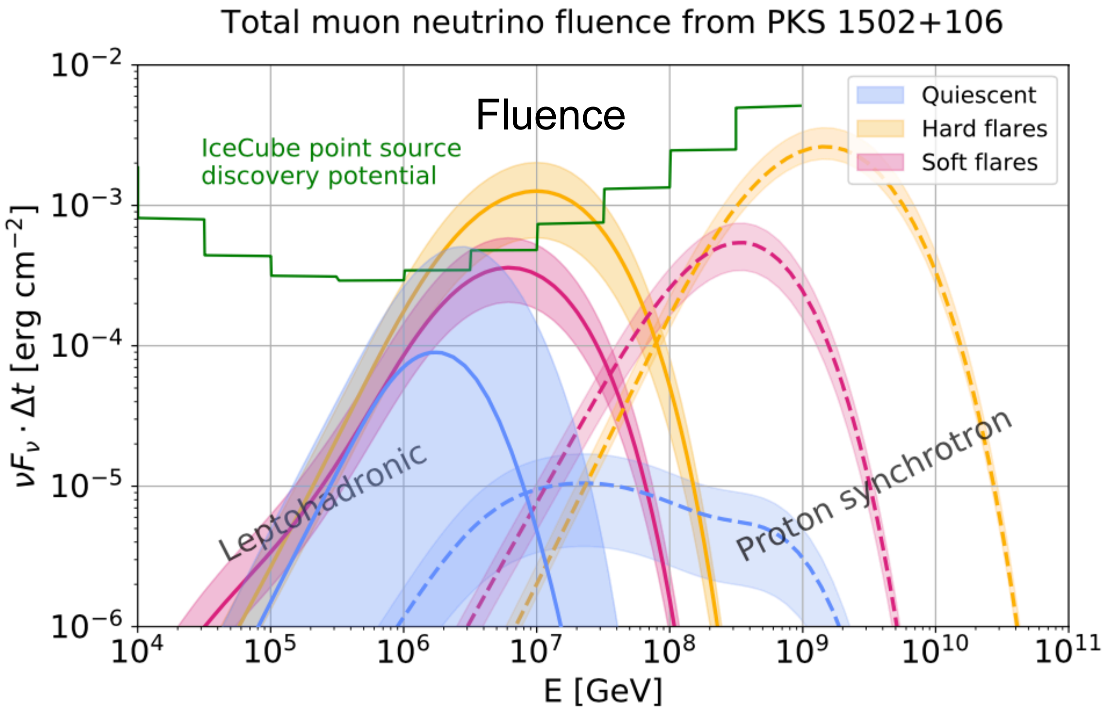
Kun et al, arXiv:2009.09792; see Francis' talk on Tuesday

Test case: PKS 1502+106

Successful SED modeling in all periods for a lepto-hadronic (SSC-dominated) and a proton synchrotron model

- There is a correlation between gamma-ray **flux** and neutrino **fluence** in this case
- The reason is a large flare duty cycle combined with a “coherent multi-wavelength response” during the flares
- Imposes a challenge here: IceCube should also see neutrinos during flaring periods





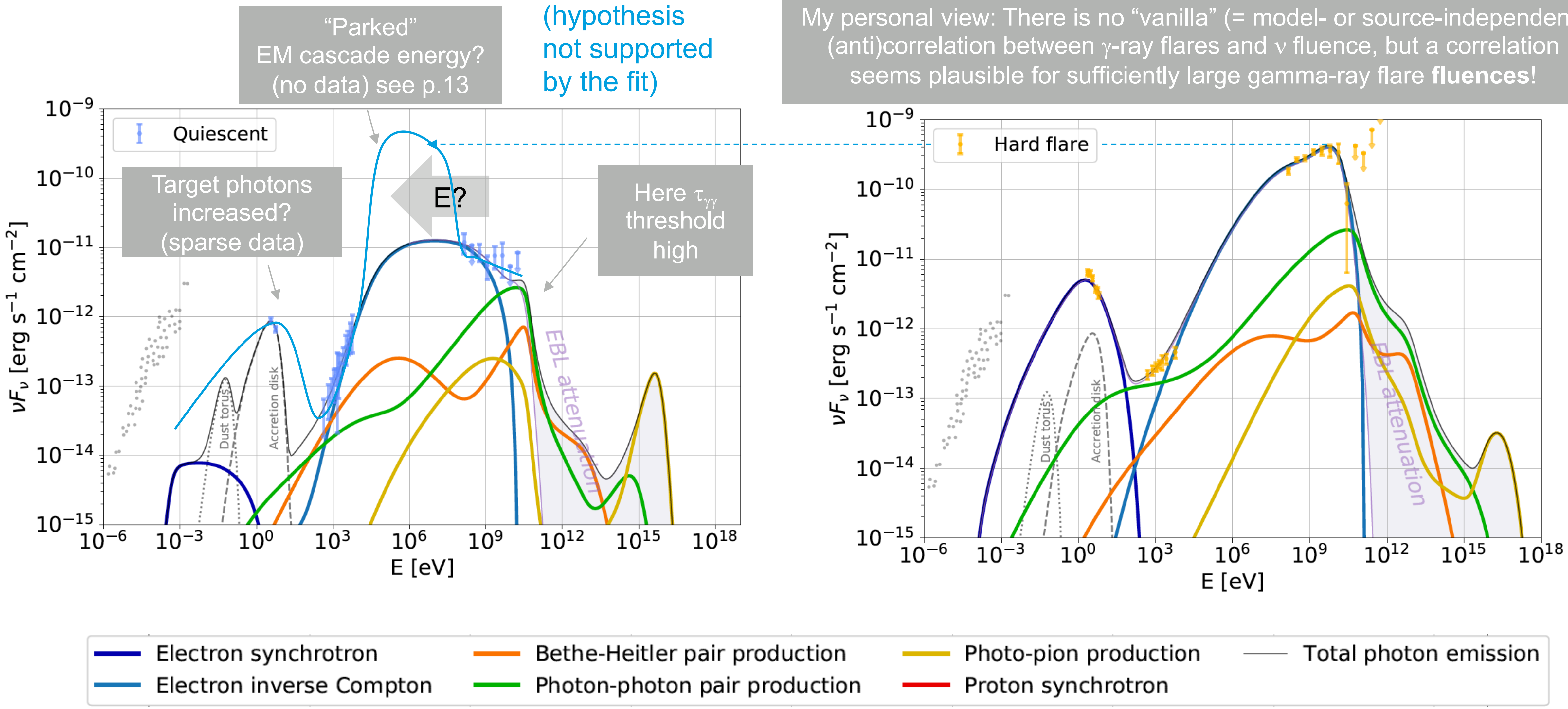
Rodrigues, Garrappa, Gao, Paliya, Franckowiak, Winter, arXiv:2009.04026

See poster
Garrappa et al, ID 91

Are the gamma-ray and neutrino fluxes anti-correlated?

How would a (hypothetical) SED model look like for which the neutrino and gamma-ray fluxes are anti-correlated?

My personal view: There is no "vanilla" (= model- or source-independent) (anti)correlation between γ-ray flares and ν fluence, but a correlation seems plausible for sufficiently large gamma-ray flare **fluences**!



Rodrigues, Garrappa, Gao, Paliya, Franckowiak, Winter, arXiv:2009.04026

Summary

Lessons learned from neutrinos associated with AGN blazars

- SSC-dominated (lepto-hadronic) models plausible for TXS 0506+056, PKS 1502+106, ...
- Hadronic signatures (at least) in X-ray (and VHE γ-ray) ranges – seems to be a quite universal observation (SED low there!)
- Neutrino associations with AGN *flares* (e.g. γ-rays) are source- (e.g. duty cycle) and model-dependent, but plausible for high enough flare *fluences*; can sometimes be implemented (post discovery) by proton injection ramp-up
- Consequence: if a neutrino is associated with a high fluence gamma-ray flare (e.g. by follow-up) the association is plausible; however, that does not mean that the neutrinos always have to come during flares

Diffuse neutrinos or UHECRs from AGN jets?

- If AGN jets power the UHECRs ...

  ... UHECR data can be described across the ankle with different populations of AGNs

  ... the neutrino flux must peak at high (~10^9 GeV) energies

  ... the neutrino flux may (but does not have to) outshine the cosmogenic neutrino flux
- If AGN blazars power the diffuse neutrino flux ...

  ... the baryonic loading must strongly evolve (decrease) over the blazar sequence to avoid the stacking limit

  ... unresolved BL Lacs must dominate the diffuse neutrino flux

There is **no unified (γ-ray, ν, UHECR) AGN jet-only one zone model** because the two options are mutually exclusive (the neutrino spectrum is peaky and follows the maximal primary energy for AGN!)