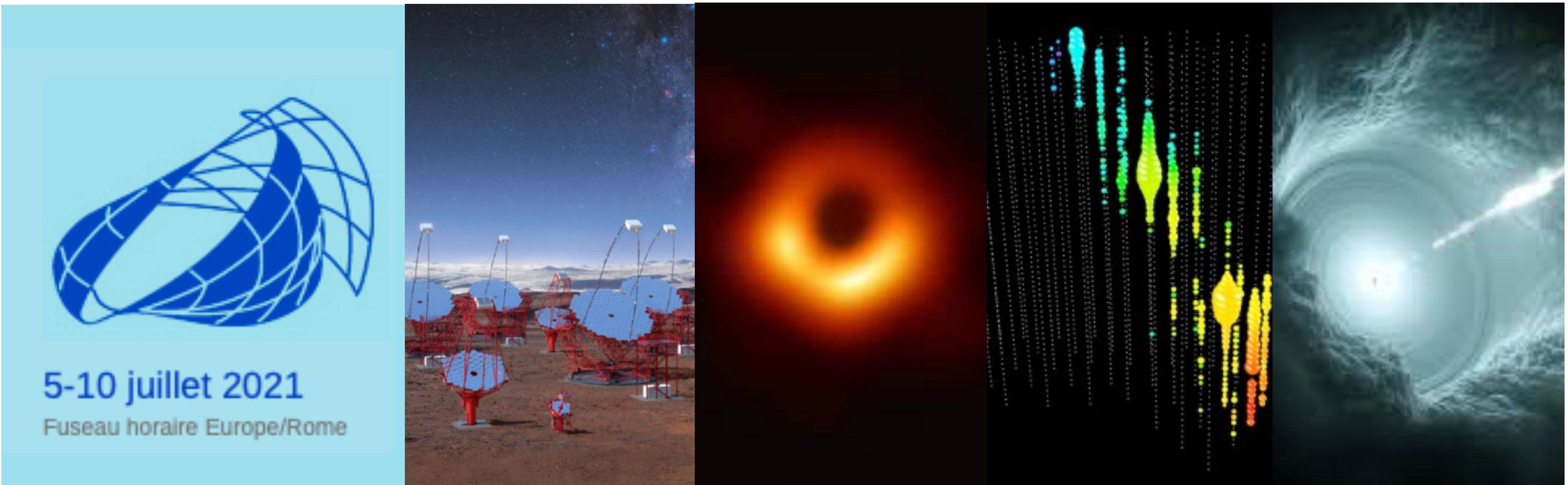


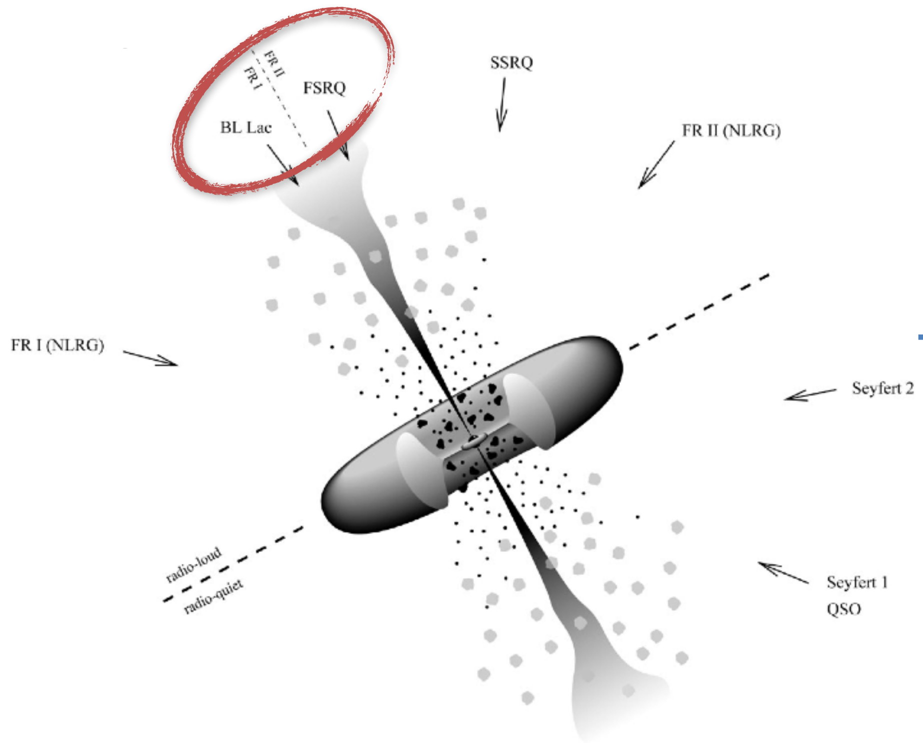
Photons and neutrinos from AGNs

A review on hadronic radiative models

Matteo Cerruti
Université de Paris
Astroparticules et Cosmologie (APC)

XVI Marcel Grossmann Meeting
Virtual
July 7, 2021

BLAZARS



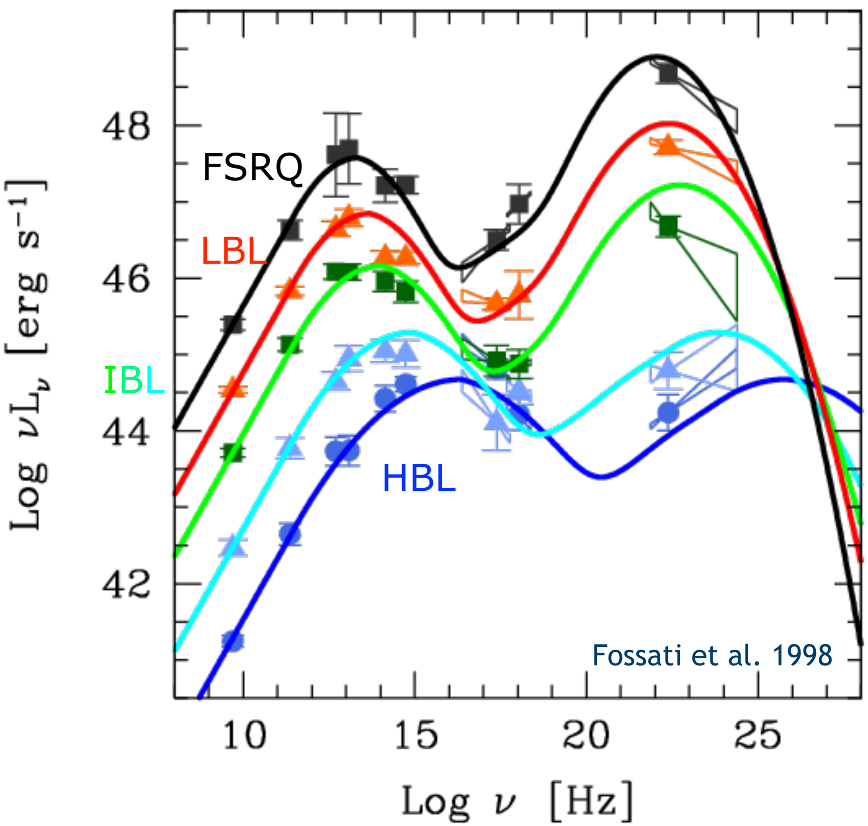
Blazar: radio-loud AGN whose relativistic jet points towards the observer

→ Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)

Flat-spectrum-radio-quasars : optical/UV spectrum with broad emission lines

BL Lacertae objects : featureless optical/UV spectrum

BLAZARS



Spectral energy distributions (SED): two distinct radiative components

FSRQs show a peak in the IR

BL Lacs are classified into:

-IR peak: low-frequency peaked (LBLs)

- optical peak: intermediate (IBLs)

- UV/X peak: high (HBLs)

BLAZARS EMISSION MODELS

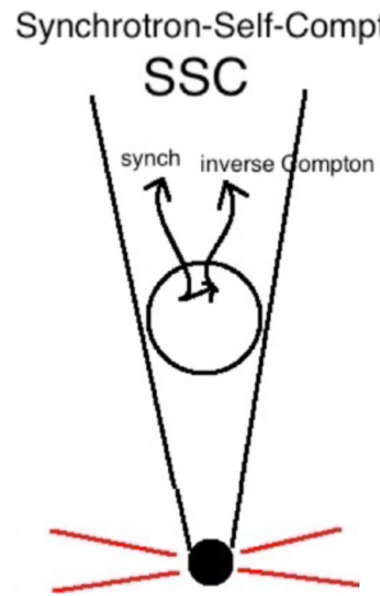
The low-energy SED component is synchrotron emission by electrons

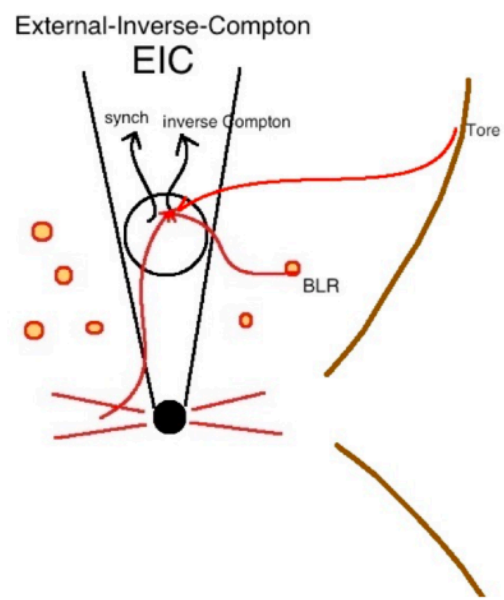
High-energy emission?

Leptonic models: inverse Compton

Same leptons that radiate synchrotron
+ their own synchrotron photons (SSC)
+ external photon fields (EIC)

State-of-the-art models:
HBLs → SSC
LBLs / FSRQs → EIC





BLAZARS HADRONIC EMISSION MODELS

BLAZARS HADRONIC EMISSION MODELS

Why hadronic models if leptonic ones work?

BLAZARS HADRONIC EMISSION MODELS

Why hadronic models if leptonic ones work?

- Natural link with neutrinos and cosmic rays:
AGNs are candidates for (UHE)CR acceleration

BLAZARS HADRONIC EMISSION MODELS

Why hadronic models if leptonic ones work?

- Natural link with neutrinos and cosmic rays:
AGNs are candidates for (UHE)CR acceleration

- Leptonic models don't always work well:
Orphan flares!

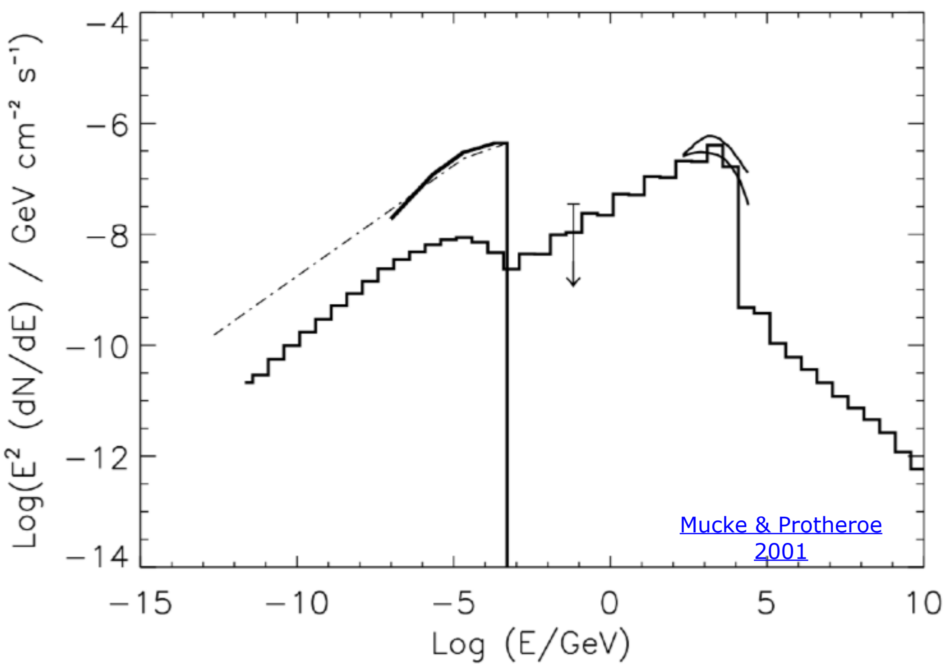
Matteo Cerruti
Université de Paris

BLAZARS HADRONIC EMISSION MODELS

Simplest hadronic model:

The high-energy component is proton synchrotron radiation

(Mannheim 1993, Aharonian 2000, Mucke & Protheroe 2001)



Mucke & Protheroe 2001

BLAZARS HADRONIC EMISSION MODELS

Proton-photon interactions complicate the modeling

Photo-meson

$$p + \gamma = n^0\pi^0 + n^+\pi^+ + n^-\pi^- + \ldots$$

$$\pi^0 \rightarrow 2\,\gamma \qquad \pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

Bethe-Heitler pair production

$$p + \gamma = p' + e^+ + e^-$$

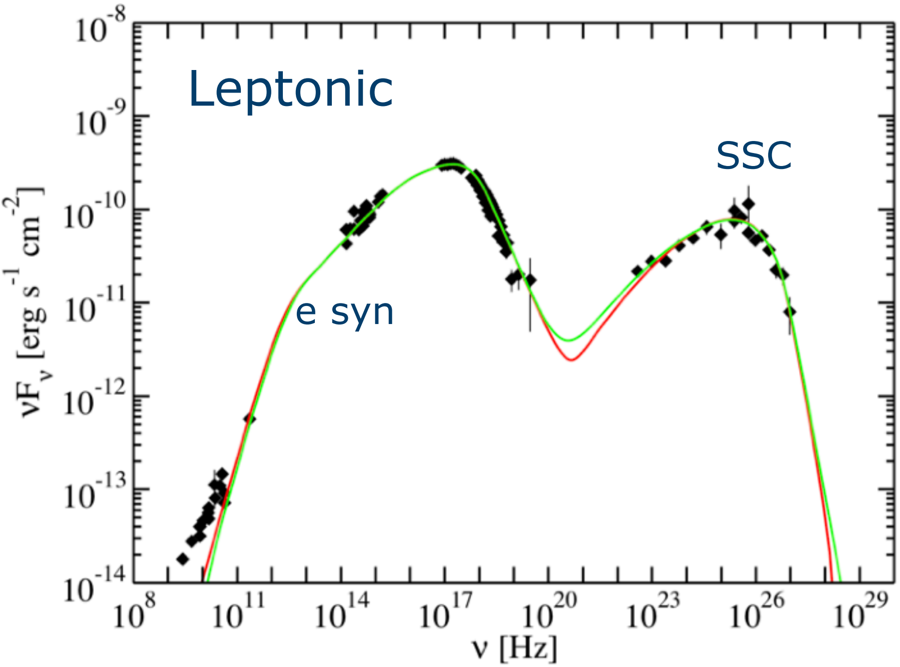
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

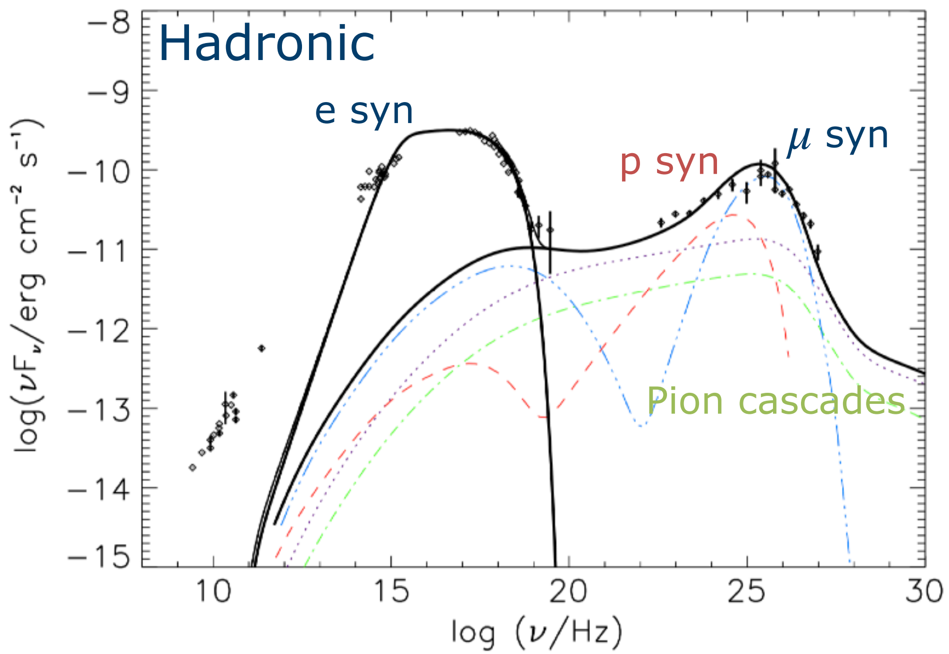
Synchrotron emission by muons can be important

BLAZARS HADRONIC EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011





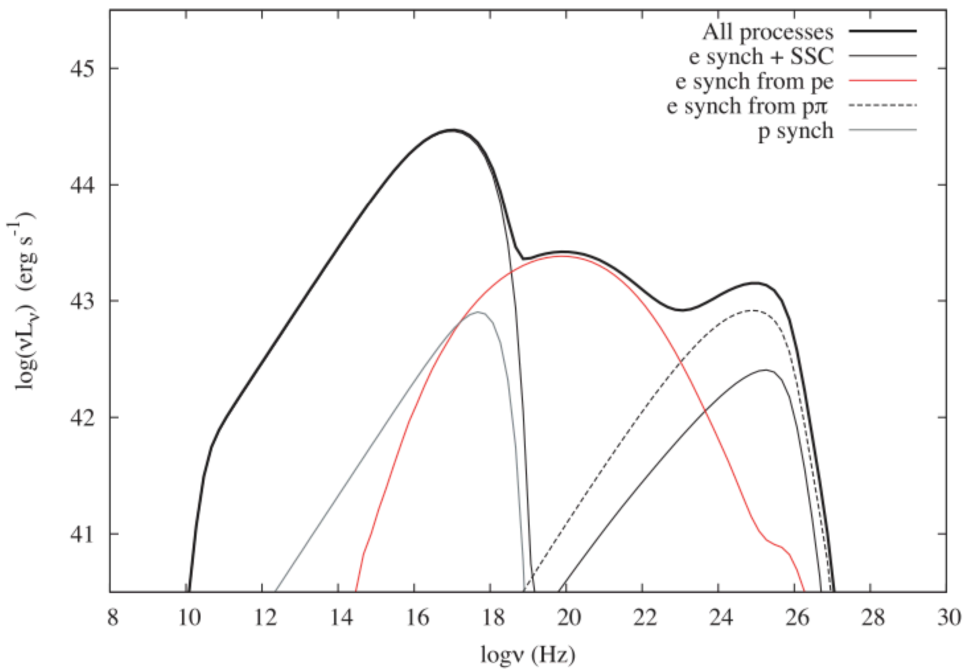
Abdo et al. 2011

BLAZARS HADRONIC EMISSION MODELS

Why is Bethe-Heitler important?

Injection of pairs at lower energy (compared to photo-meson)

Can dominate the X-ray band and fill the SED valley



[Petropoulou and Mastichiadis 2015]

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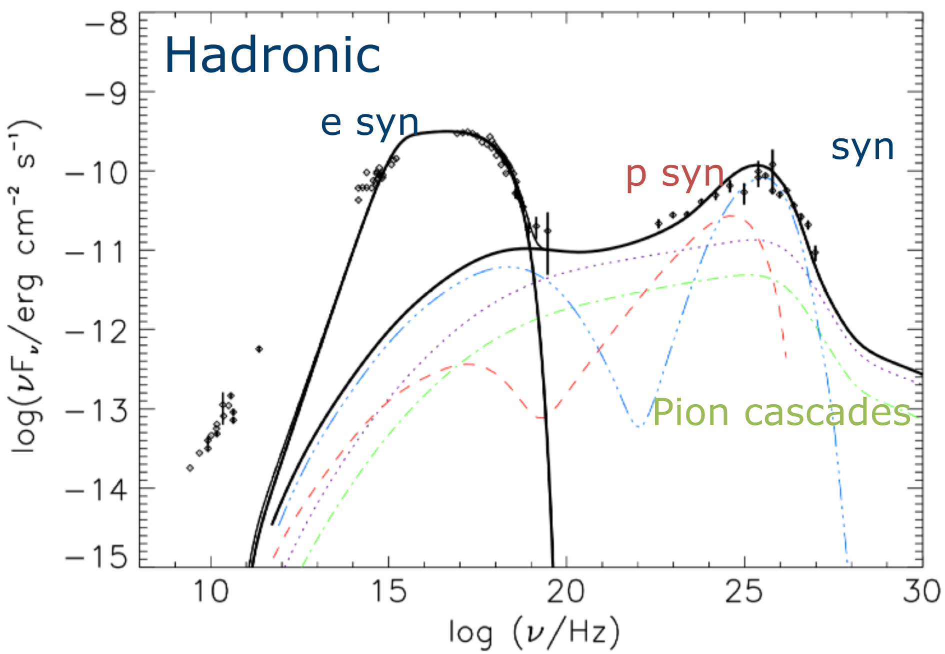
Why are muons important?

In some parts of the parameter space we can have a steady state muon population that can radiate in the TeV band



[Abdo et al. 2011]

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BLAZARS HADRONIC EMISSION MODELS

Proton-proton interactions

- Can also pion produce and lead to photon and neutrino emission (widely used in Galactic sources, like SNR)

- The required density of target protons is much higher than the one usually assumed in blazar jets

-> can become an important process only in very small and dense emitting regions;

-> an interesting scenario are the jet-obstacles interactions

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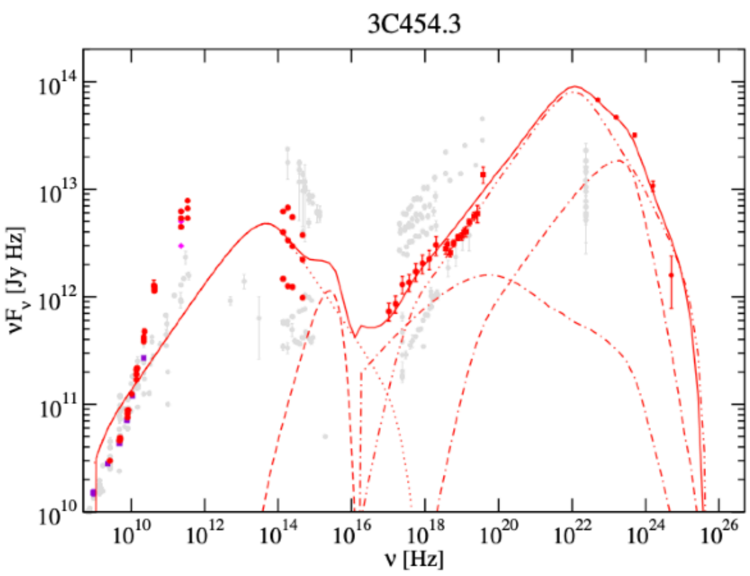
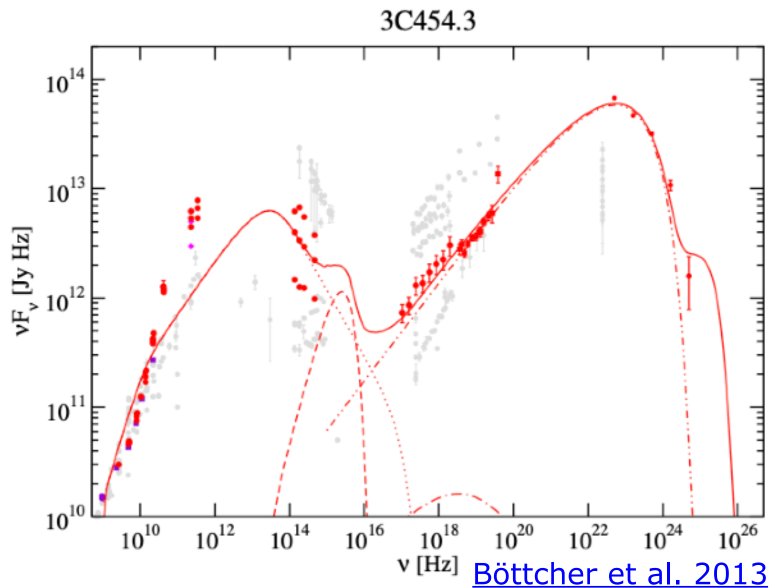
BLAZARS HADRONIC EMISSION MODELS

FSRQ modeling

Leptonic (EIC)



Hadronic (proton synchrotron)



Böttcher et al. 2013

$$L_{jet} = 10^{47-49} erg/s$$

Hadronic models fit the SED but require super-Eddington luminosities (sometimes by orders of magnitudes -> *always check energetics of hadronic models)*

Matteo Cerruti

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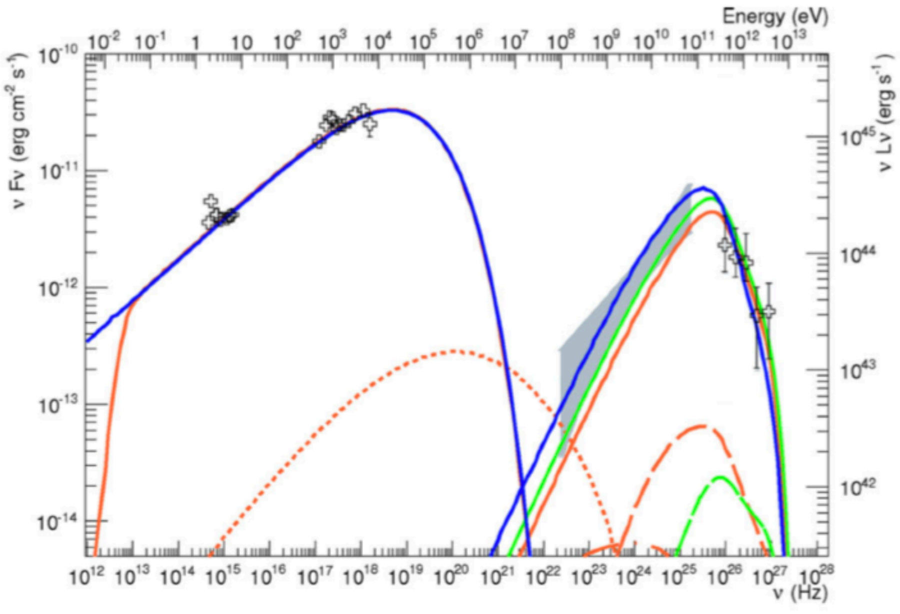
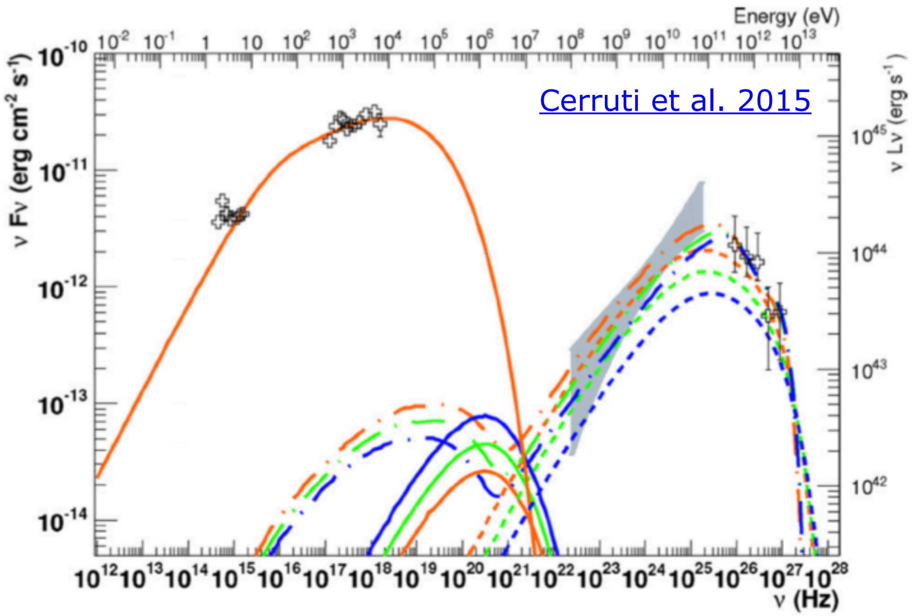
BLAZARS HADRONIC EMISSION MODELS

Extreme blazars (peak > 1 keV)

Leptonic modeling faces difficulties (high Doppler factor / high minimum energy of the particle distribution)

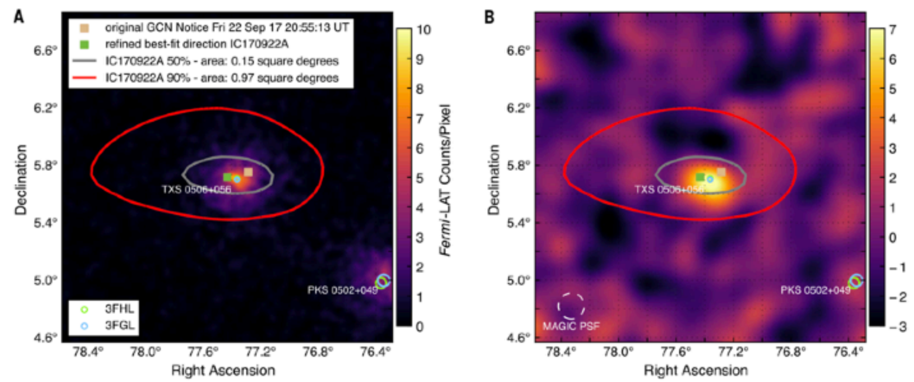
Hadronic modeling perfectly suited for them

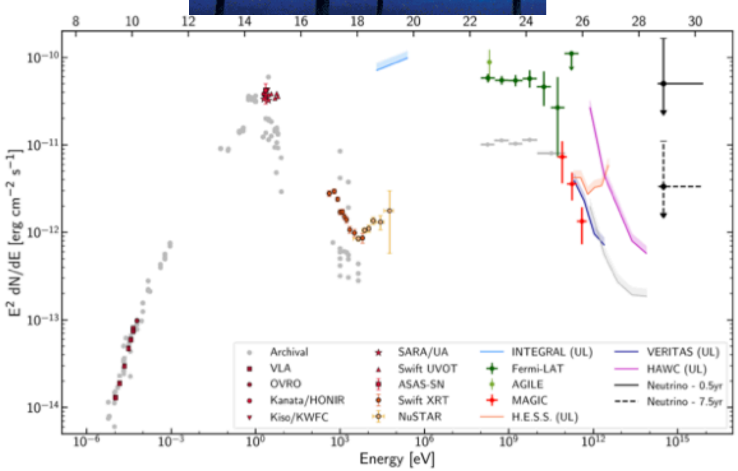


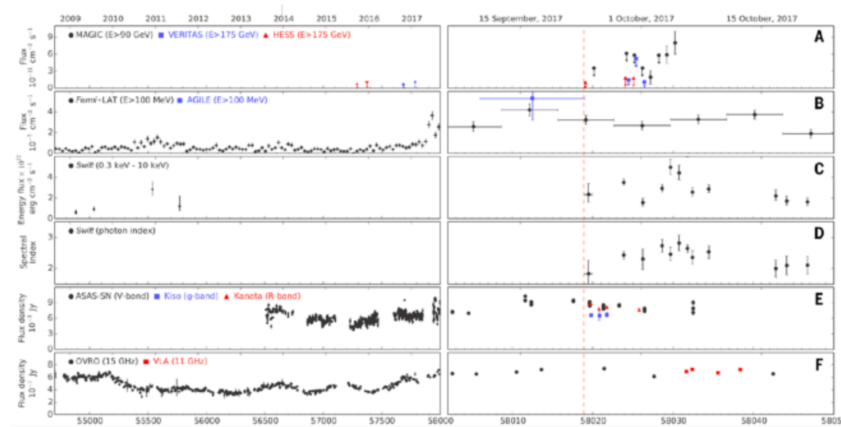


IceCube-170922A / TXS 0506+056

Most significant association (3σ)
of a high-energy (290 TeV) neutrino with an astrophysical source







[IceCube, Fermi, MAGIC et al. 2018](#)

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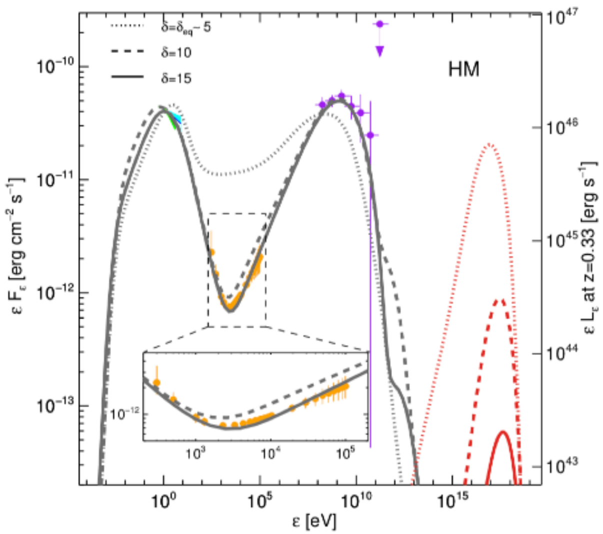
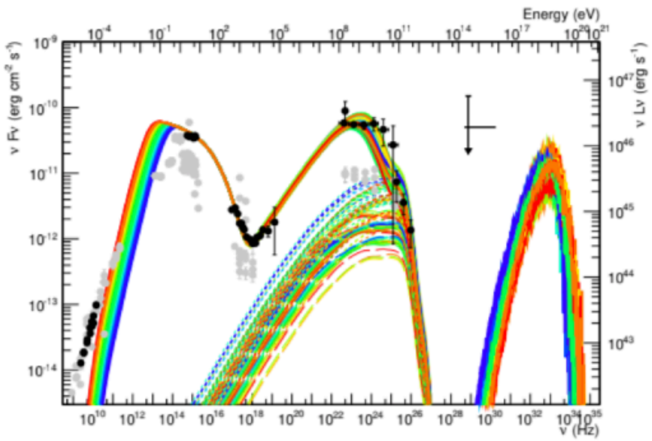
TXS 0506+056: THE 2017 FLARE



Keivani et al. 2018

$\nu \simeq 10^{-5}\ yr^{-1}$

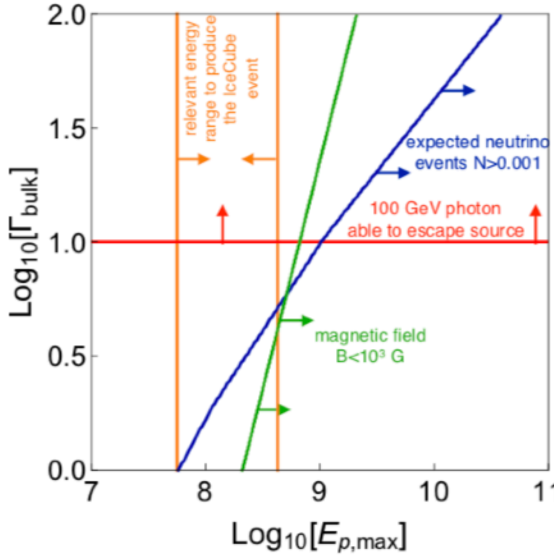


(a) Proton synchrotron modeling of TXS 0506+056

Cerruti et al. 2019

$\nu = 10^{-5} - 10^{-3}\ yr^{-1}$

Proton synchrotron solutions exist,
but the expected neutrino rate is very low



Gao et al. 2018

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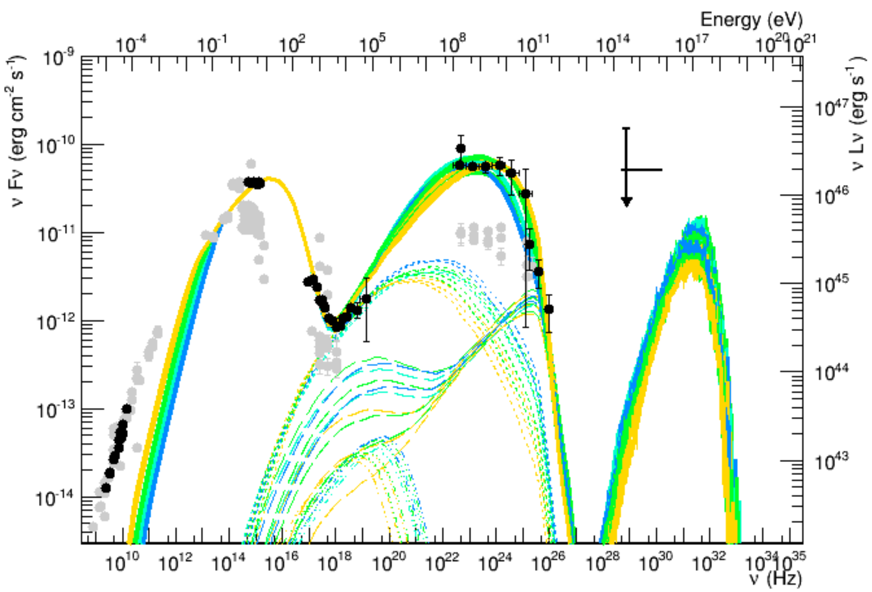
TXS 0506+056: THE 2017 FLARE

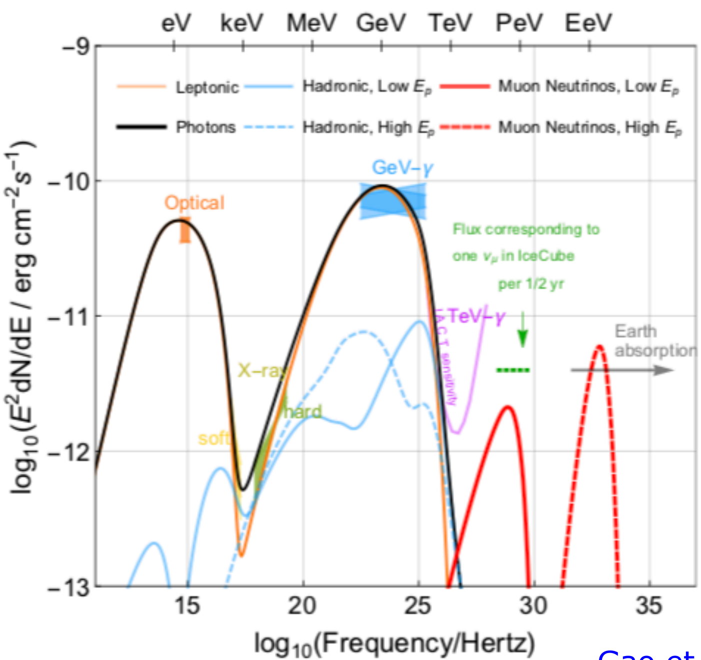
Lepto-hadronic solutions



[Cerruti et al. 2019]

$L_{jet} = (9 - 60) \times 10^{47} erg/s$

$\nu = 0.01 - 0.06\ yr^{-1}$



[Gao et al. 2018]

$L_{jet} \simeq \times 10^{50} erg/s$

$\nu = 0.3\ yr^{-1}$

They can work: neutrino rates of the order of 0.1 / yr

But rather high energetic requirement : $L_{jet} \gg L_{Edd} \simeq \times 10^{46-47}\ erg/s$

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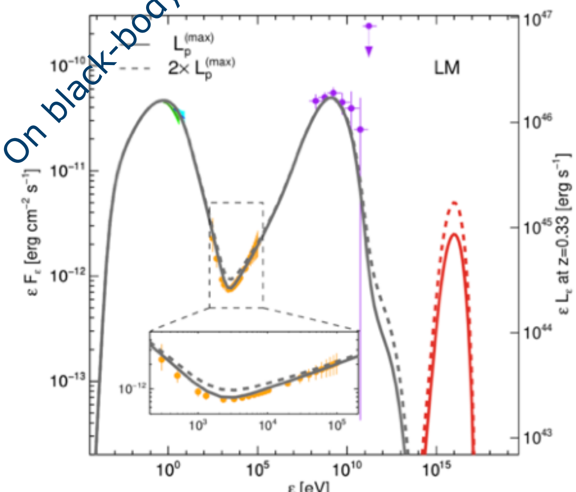
TXS 0506+056: THE 2017 FLARE

Proton-photon interaction on external photon fields

On black-body

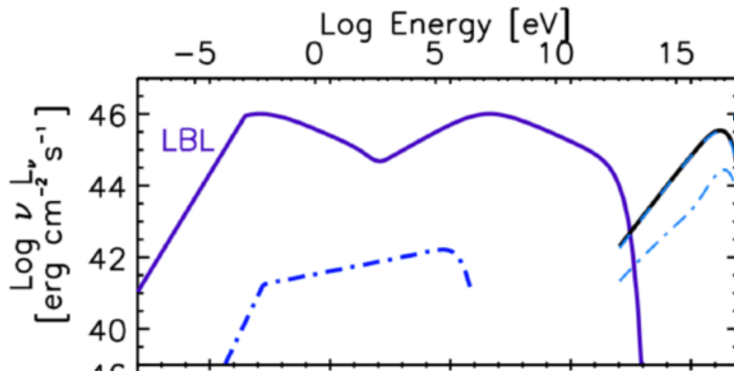


[Keivani et al. 2018](#)

$L_{jet} = (4 - 150) \times 10^{45} erg/s$

$\nu_{max} = 0.02\ yr^{-1}$

On RIAF

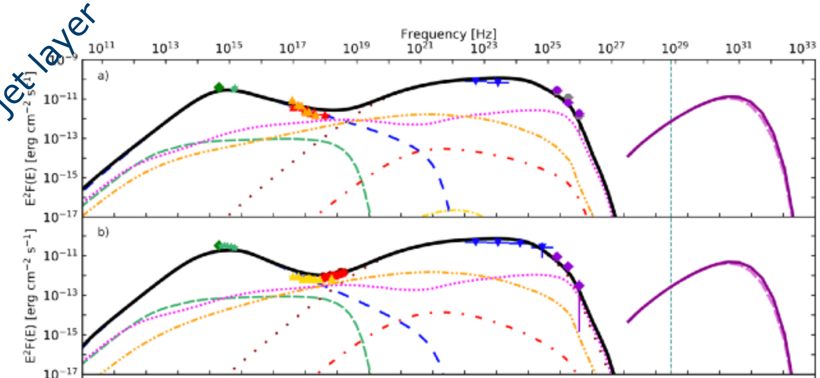


[Righi et al. 2019](#)

$L_{jet} = 6.3 \times 10^{45} erg/s$

$\nu = 0.14\ yr^{-1}$

On jet layer



[Ansoldi et al. 2018](#)

$L_{jet} = (3 - 8) \times 10^{45} erg/s$

$\nu = 0.12 - 0.34\ yr^{-1}$

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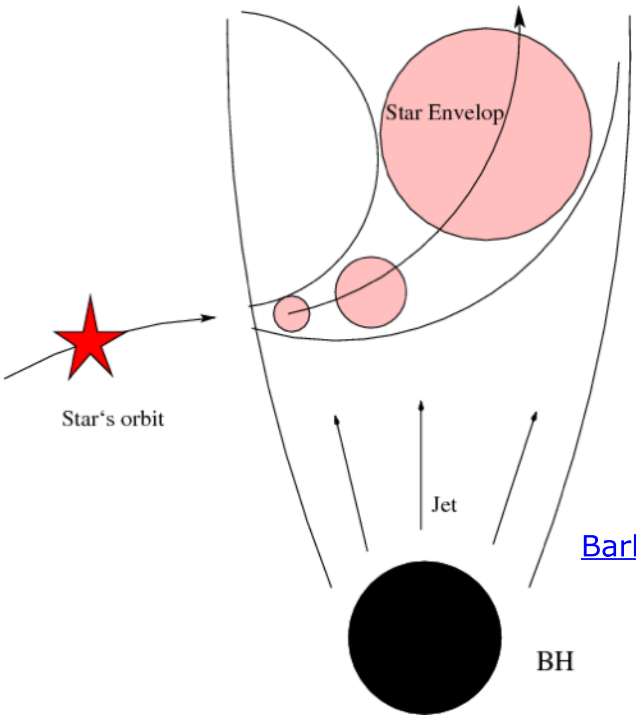
TXS 0506+056: THE 2017 FLARE

$$p + p = n^0\pi^0 + n^+\pi^+ + n^-\pi^-$$

Alternative hadronic scenario

Jet - cloud interaction



Barkov et al. 2012

TXS 0506+056: THE 2017 FLARE

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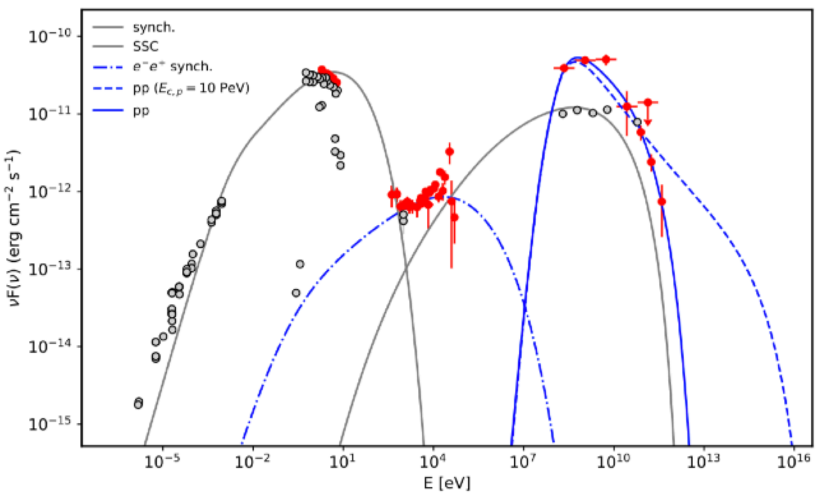
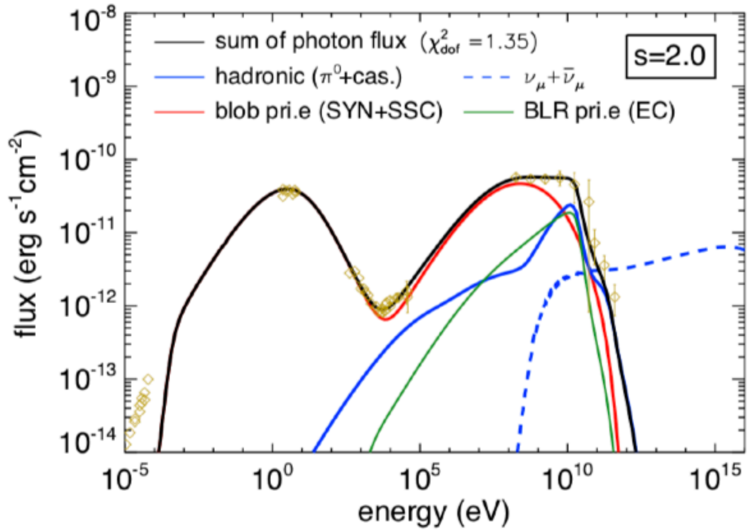


Sahakyan 2018

$L_{jet} = 1 \times 10^{48} erg/s$

$\nu = 0.13 - 0.46\ yr^{-1}$



$L_{jet} = (0.8 - 5) \times 10^{46} erg/s$ Liu et al. 2019

$\nu = 0.26\ yr^{-1}$

see as well Wang et al. 2018

TXS 0506+056: THE 2017 FLARE

TXS 0506+056: THE 2017 FLARE

What did we learn on blazars?

TXS 0506+056: THE 2017 FLARE

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- Simple one-zone models can be enough, at the expenses of a high proton luminosity, and only if the acceleration efficiency is low

TXS 0506+056: THE 2017 FLARE

What did we learn on blazars?

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- The favored scenario is a leptonic electromagnetic emission, with subdominant hadronic component

- Simple one-zone models can be enough, at the expenses of a high proton luminosity, and only if the acceleration efficiency is low

- External fields as photon target can help on this aspect

COSMIC RAYS FROM TXS 0506+056

Can AGNs accelerate (UHE)CRs?

- From Cerruti et al. 2019, $E_{p,max} = (2-7) \times 10^{18} eV$

- From Ansoldi et al. 2018, $E_{p,max} = 2 \times 10^{15} - 2 \times 10^{19} eV$

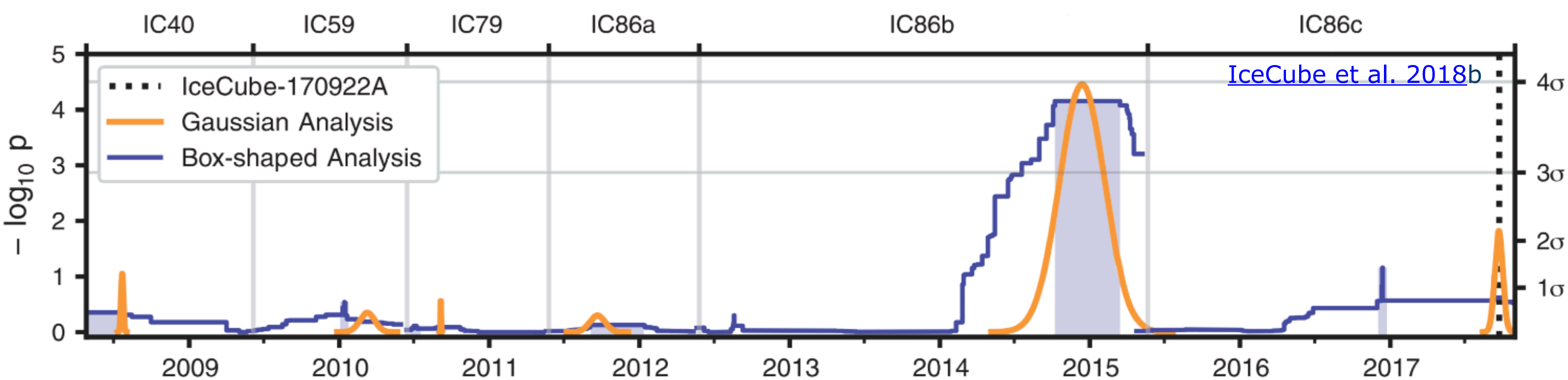
- From Keivani et al. 2018, “assuming the IceCube-170922A association holds, TXS 0506+056 is not a significant UHECR accelerator”

- From Gao et al. 2018, “The scenario [of UHECR in the source] is not acceptable”

TXS0506+056 not really an UHECR accelerator!

IceCube-170922A / TXS 0506+056

Detection of a second neutrino flare in 2014-2015
(without a gamma-ray counterpart)

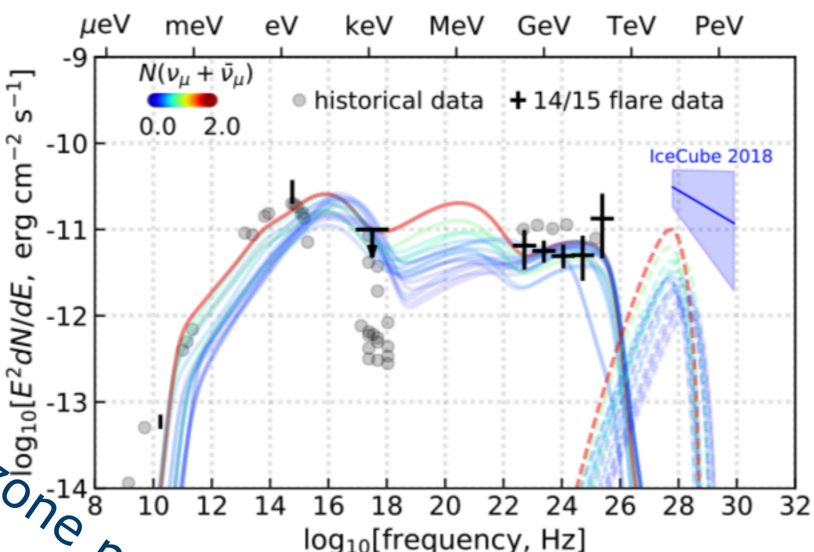


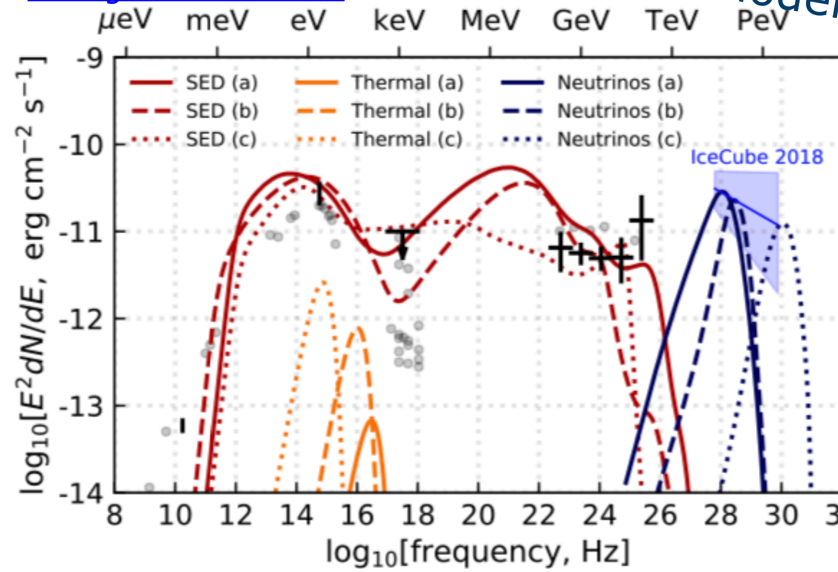
3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event

TXS 0506+056 : THE 2014 ν FLARE

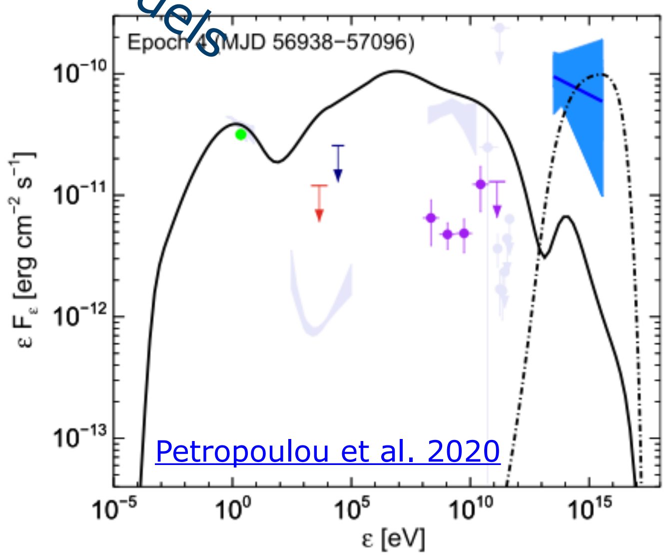
External field models

[Rodrigues et al. 2019](#)

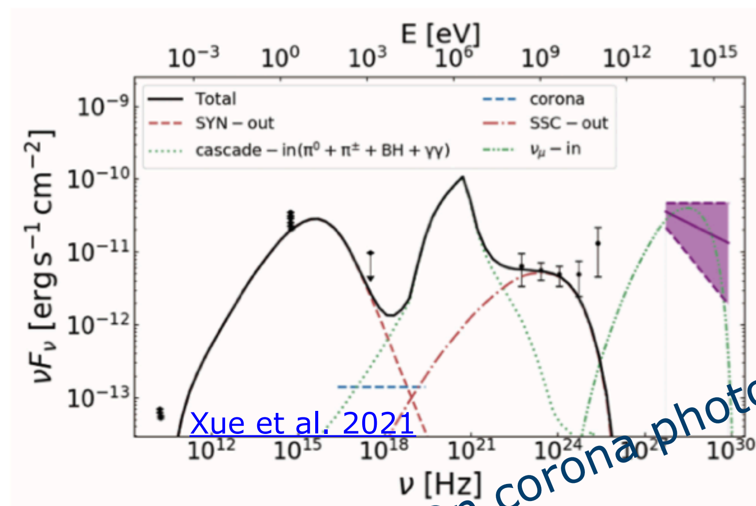




1-zone models



[Petropoulou et al. 2020](#)

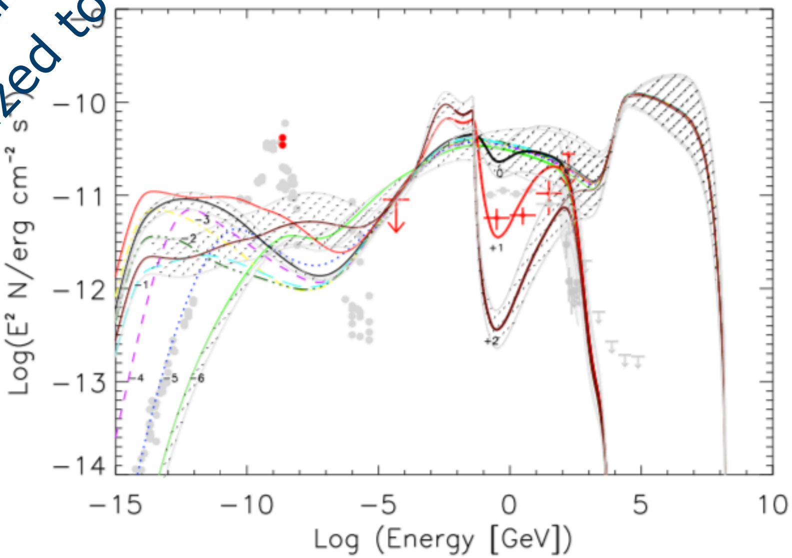


[Xue et al. 2021](#)

On corona photons

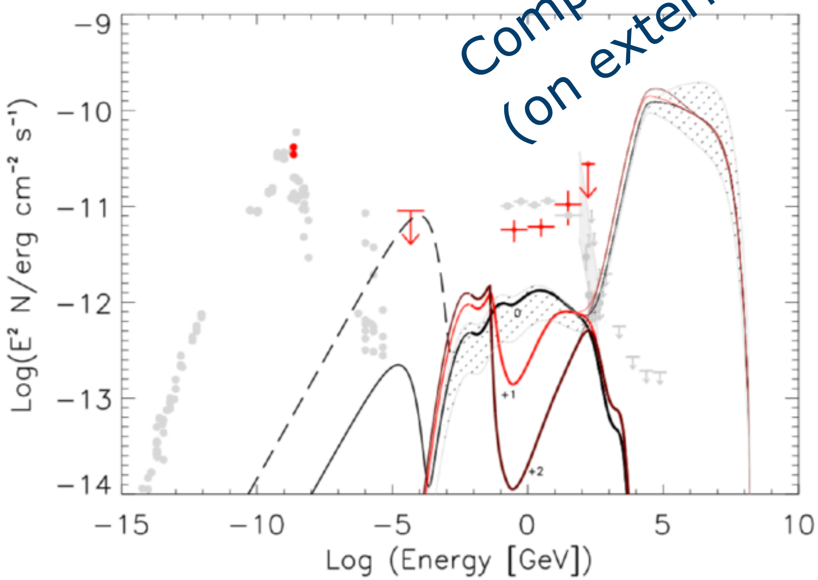
TXS 0506+056 : THE 2014 ν FLARE

Synchrotron cascades
(normalized to get right ν)



[Reimer et al. 2019](#)

Compton cascades
(on external field!)



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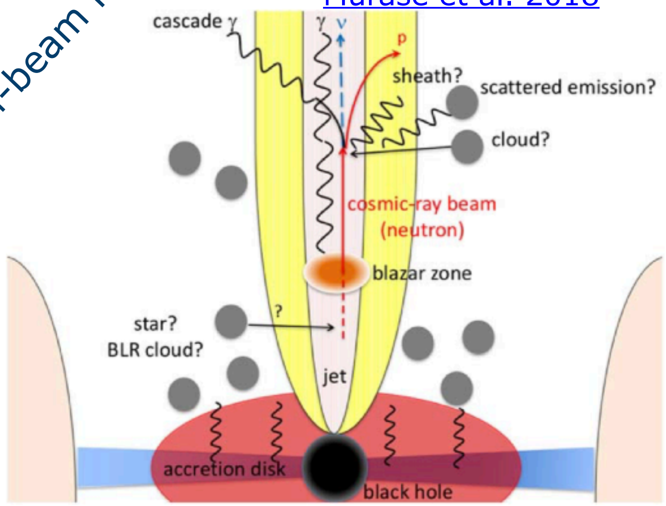
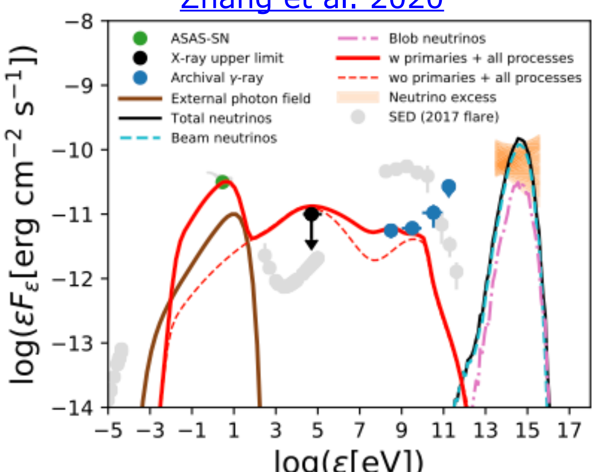
TXS 0506+056 : THE 2014 ν FLARE

The neutron-beam model

Murase et al. 2018



Zhang et al. 2020



Two-zone model:

- neutrons escape the blazar zone

- proton-photon interaction with external fields at larger scales in the jet

- secondary pairs are isotropized in the larger-scale jet

TXS 0506+056 : THE 2014 ν FLARE

- Single zone models are disfavored : very difficult to get no photons with the neutrino flare
(although there may be some room in the MeV band)

- A simple solution could be a two-zone models:
  the ν and the γ-ray emitting region are not the same one.

CONCLUSIONS

Developed as an alternative to leptonic models, hadronic models can describe blazar SEDs and provide natural link with **neutrino astronomy** and **cosmic rays physics**

The first (evidence of) neutrino emission from a blazar seems to support **hybrid scenarios**, with sub-dominant hadronic cascades

The 2014-15 neutrino flare of TXS 0506+056 seems to support multi-zone scenarios with neutrino emitting region opaque to gamma-rays

OPEN QUESTIONS

Why is TXS 0506+056 the first neutrino AGN candidate?

Can we get a consistent picture for both 2014/15 and 2017 flares from TXS 0506+056?

Are there leptonic blazars and hadronic blazars?

Are there leptonic flares and hadronic flares?

Matteo Cerruti

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