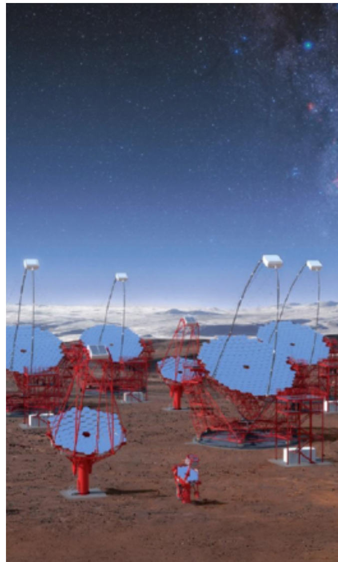
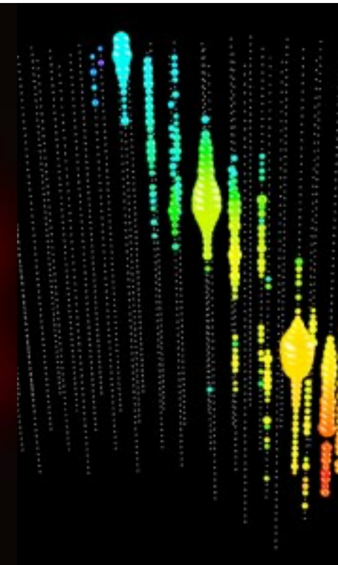
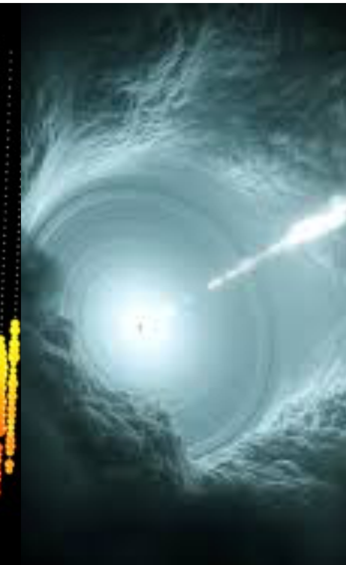


AGN Multimessenger Modeling

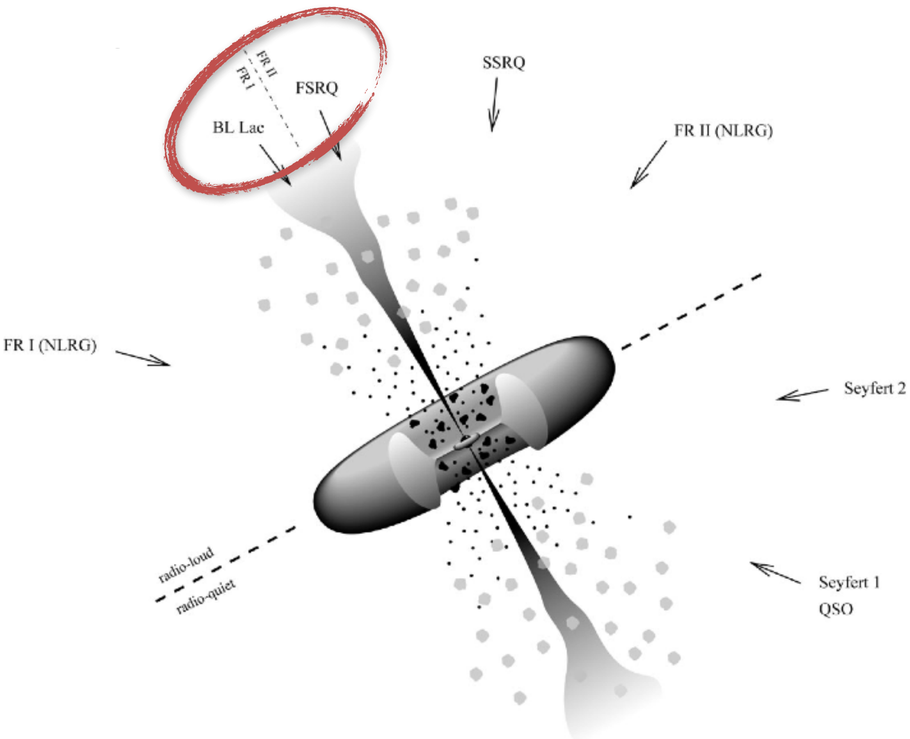
Matteo Cerruti

Université Paris Cité
Astroparticule et Cosmologie (APC)

Astroparticle Symposium 2025

Paris
Nov 17, 2025

BLAZARS



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

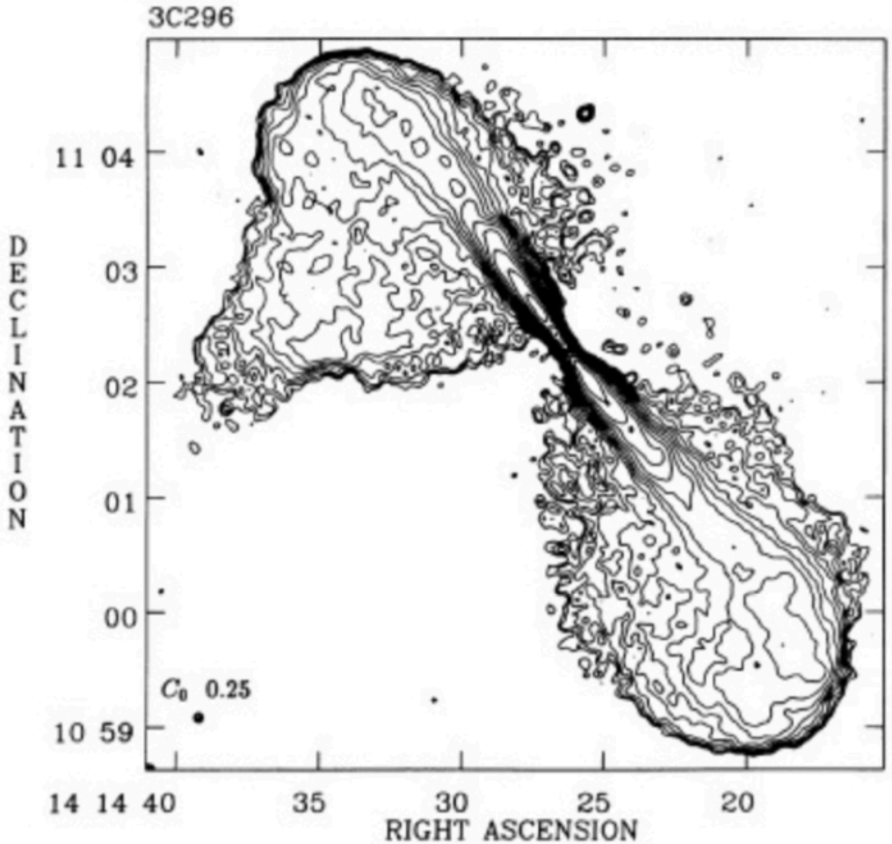
→ Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)

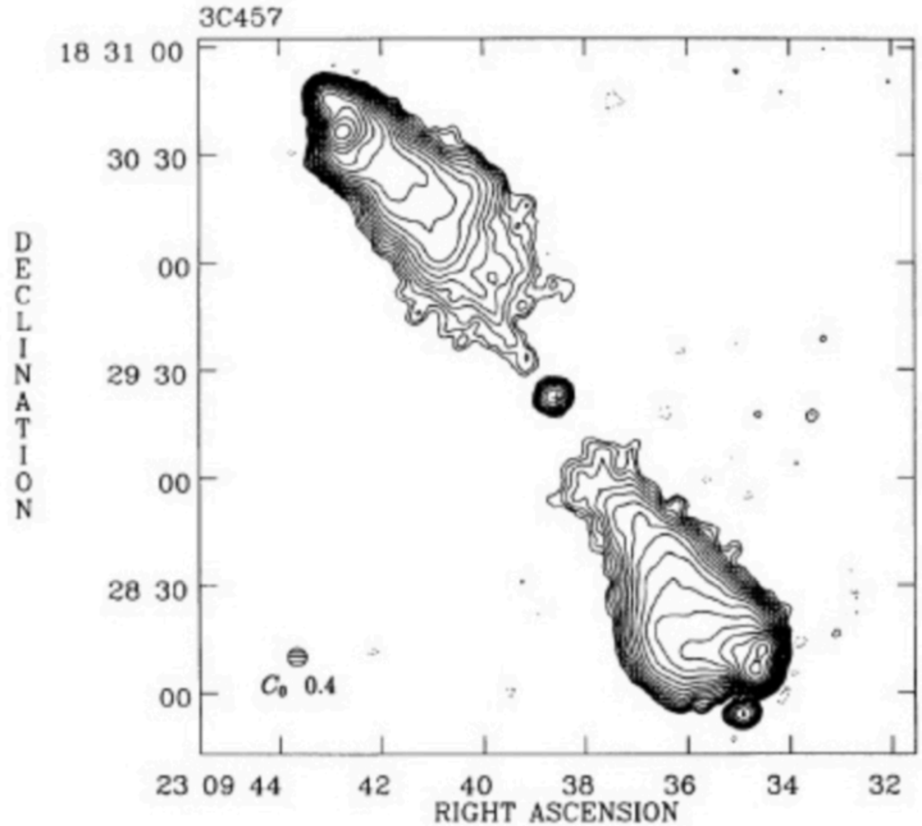
Flat-spectrum-radio-quasars : optical/UV spectrum with broad emission lines

BL Lacertae objects : featureless optical/UV spectrum

BLAZARS

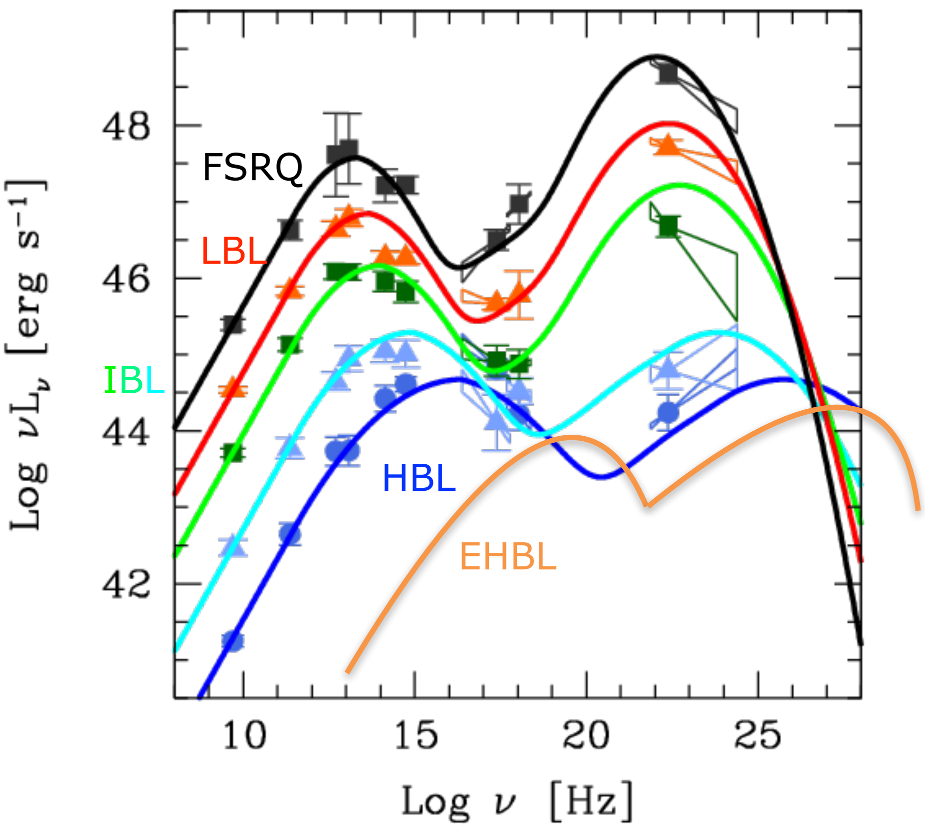
Radio-loud dichotomy: Fanaroff-Riley I and FRII





[Leahy & Perley 1991]

BLAZAR SPECTRAL ENERGY DISTRIBUTIONS



[Fossati et al. 1998](#)

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)

- >X-ray peak: extreme-HBLs (EHBLs)

BLAZARS EMISSION MODELS

The low-energy SED component is synchrotron emission by electrons

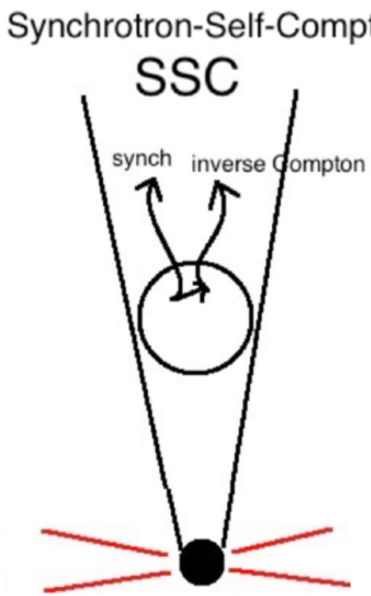
High-energy emission?

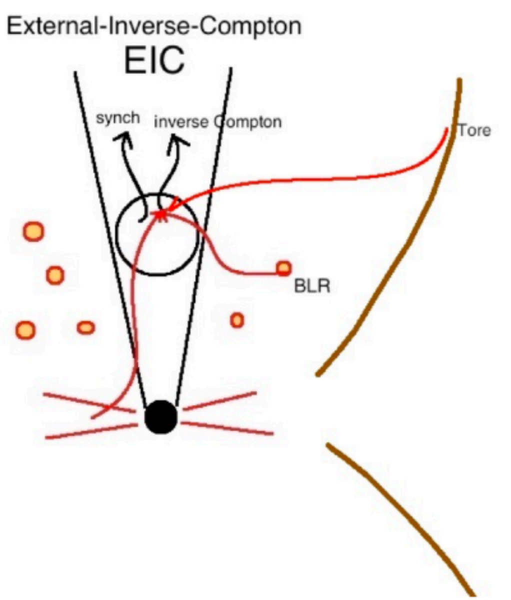
Leptonic models: inverse Compton

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

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

Hadronic models: proton synchrotron
secondaries from p-gamma interactions





Matteo Cerruti

BLAZARS EMISSION MODELS

What did a ~2010 TeV blazar paper look like?

Example: ‘A multiwavelength view of the flaring state of PKS 2155-304 in 2006’ by H.E.S.S., 2012

Very detailed leptonic modeling, and hadrons only quickly mentioned to justify why we do not investigated them

‘However, detailed time-dependent modelling with hadrons is difficult to achieve due to the higher complexity of the hadronic interactions and the large number of free parameters in those models. Moreover, due to the low efficiency of the hadronic emission processes, such scenarios seem generally less adapted to describe the high-energy emission from blazars (Sikora 2010)’

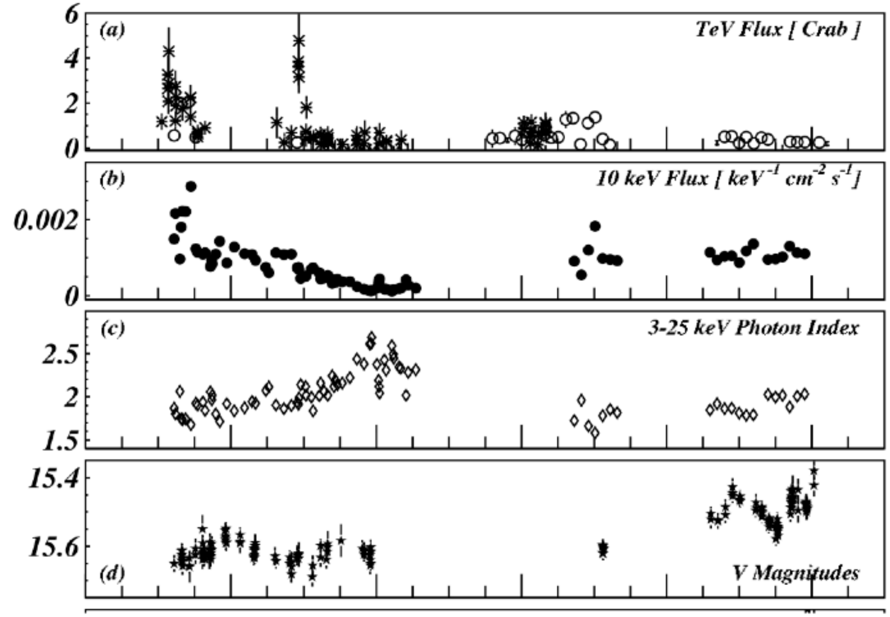
BLAZARS EMISSION MODELS

Why adding hadrons if leptons work??

Leptonic models do not always work. See for example

- extreme blazars (pretty high Doppler factor and/or minimum electron energy)

- orphan flares (leptonic model predicts perfect)



Krawczynski et al. 2004

N.B. none of these 'supports' hadronic models, rather excludes single-zone SSC models.

BLAZARS EMISSION MODELS

Since when do we worry about hadrons in AGN jets?

1) 2013: IceCube detects a diffuse neutrino flux at ~100 TeV, likely extragalactic -> AGNs are among the natural candidates

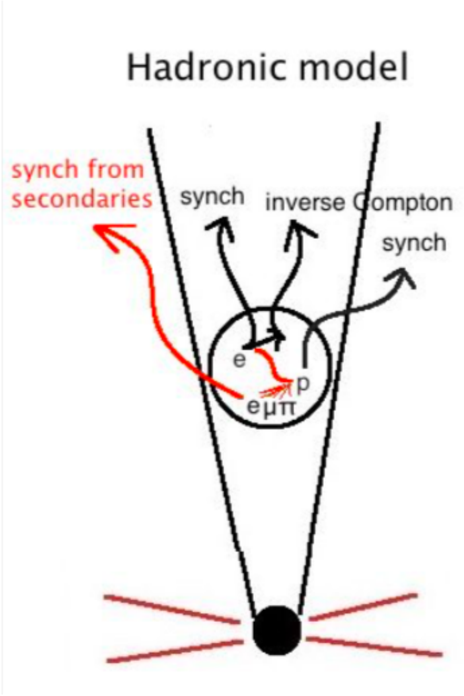
2) 2018: IC + Fermi, 3σ evidence for neutrino emission from a flaring blazar!

3) 2022: IC, 4σ excess from the Seyfert galaxy NGC 1068

BLAZARS EMISSION MODELS

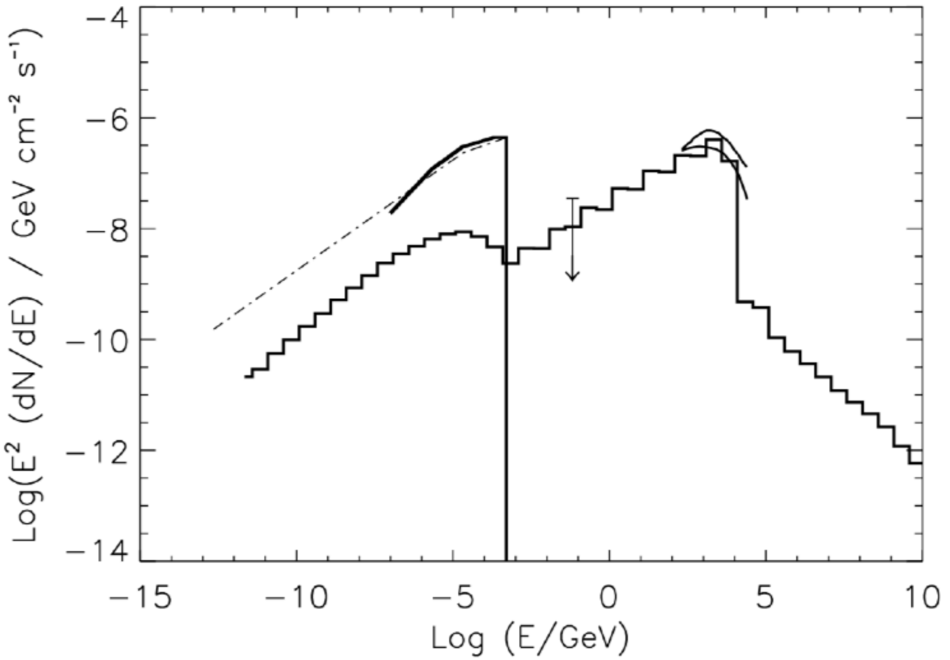
Hadronic models

Simplest hadronic model:



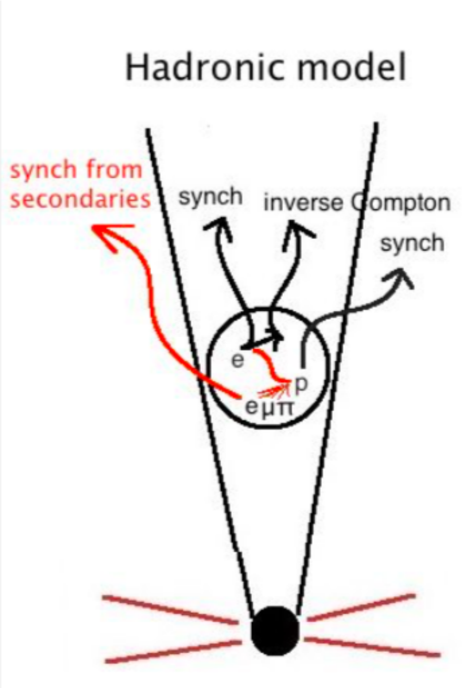
The high-energy component is proton synchrotron radiation

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



Mucke & Protheroe 2001

BLAZARS EMISSION MODELS



Proton-photon interactions complicate the modeling

Photo-meson

$$p + \gamma = p' + \pi^0 \rightarrow p' + 2\gamma$$
$$p + \gamma = n + \pi^+$$
$$p + \gamma = p' + \pi^+ + \pi^-$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

Bethe-Heitler pair production

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

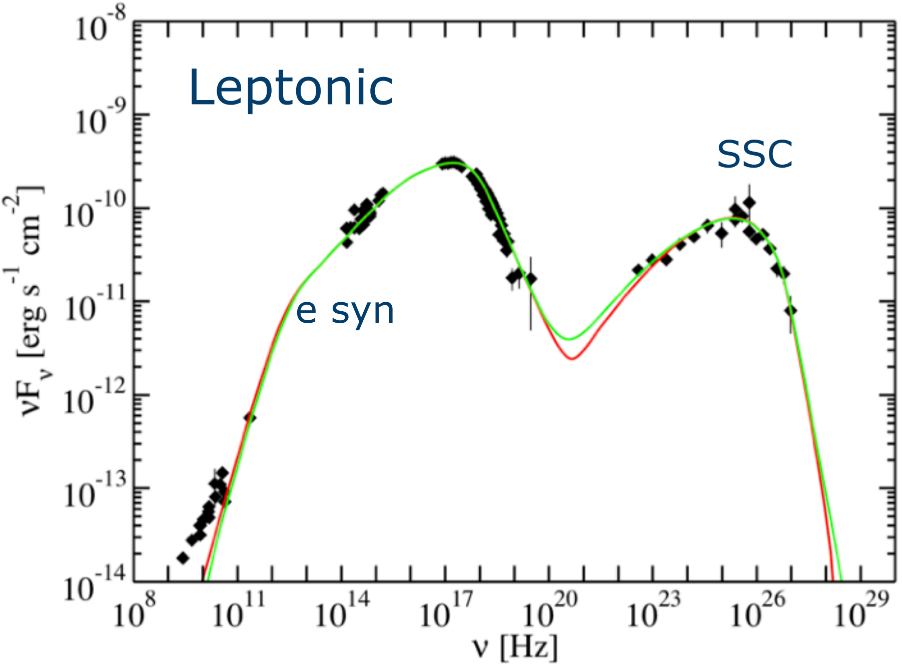
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

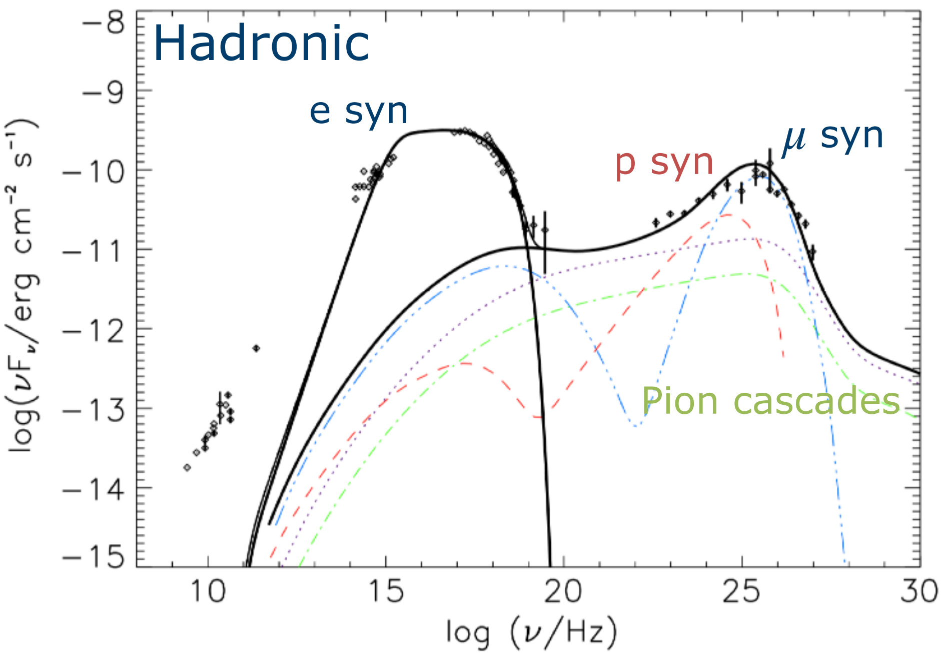
Synchrotron emission by muons can be important

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011





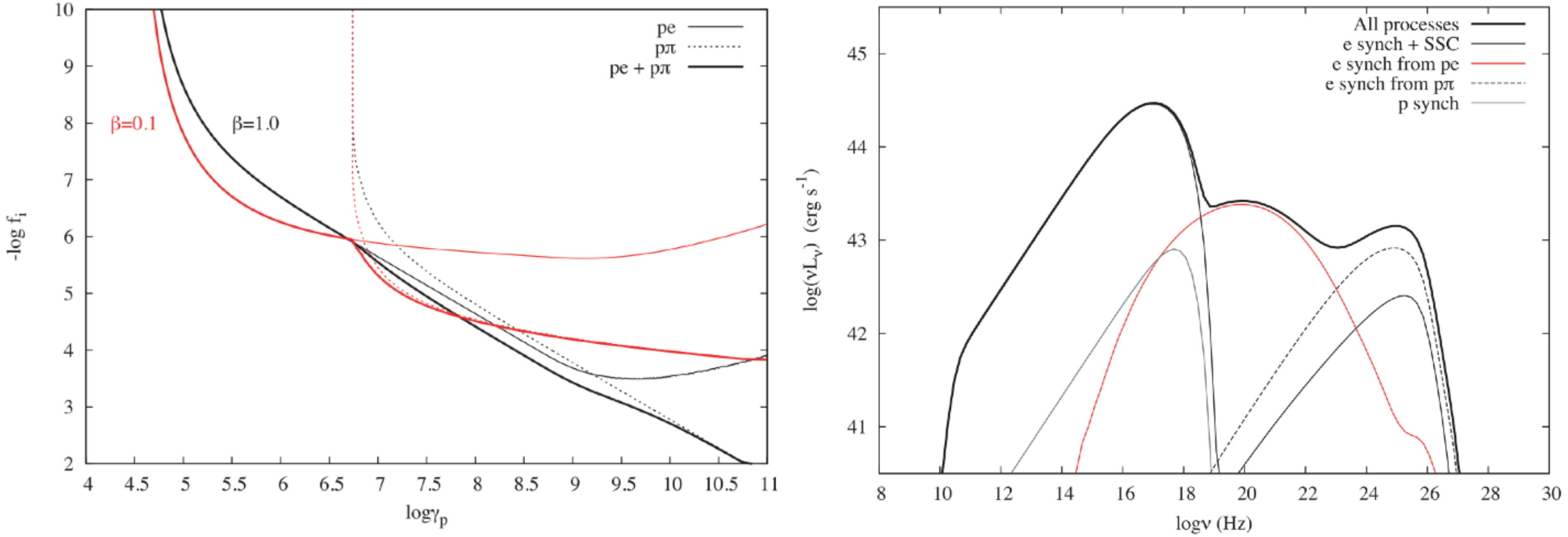
[Abdo et al. 2011]

TXS 0506+056: the 2017 flare

Why is Bethe-Heitler important?

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

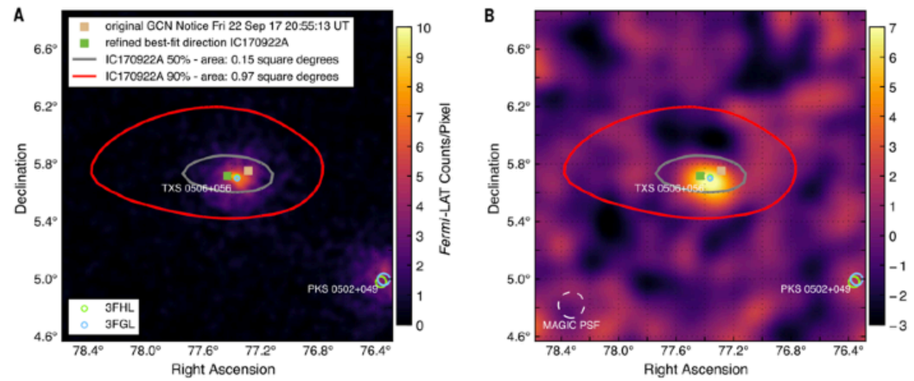
Can dominate the X-ray band and fill the SED valley

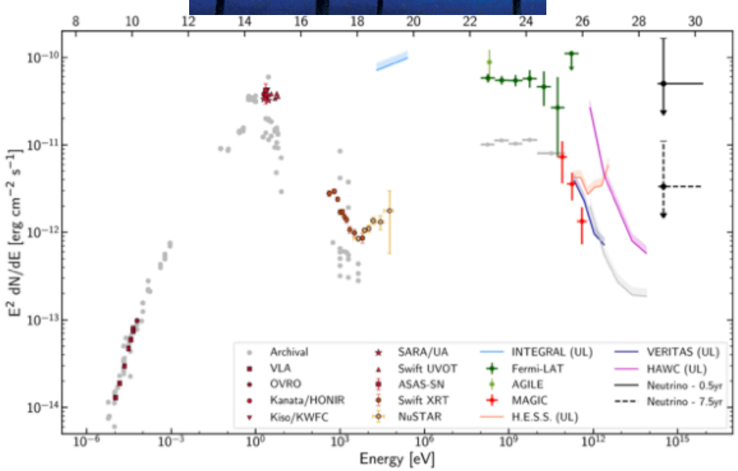


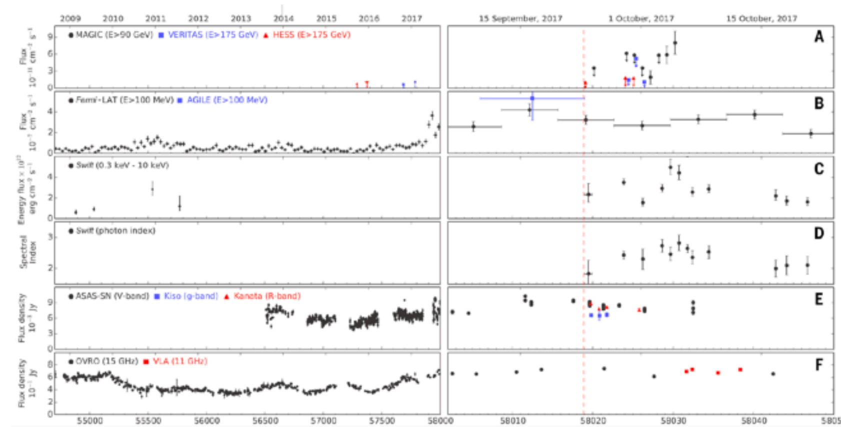
Petropoulou & Mastichiadis 2015

IceCube-170922A / TXS 0506+056

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

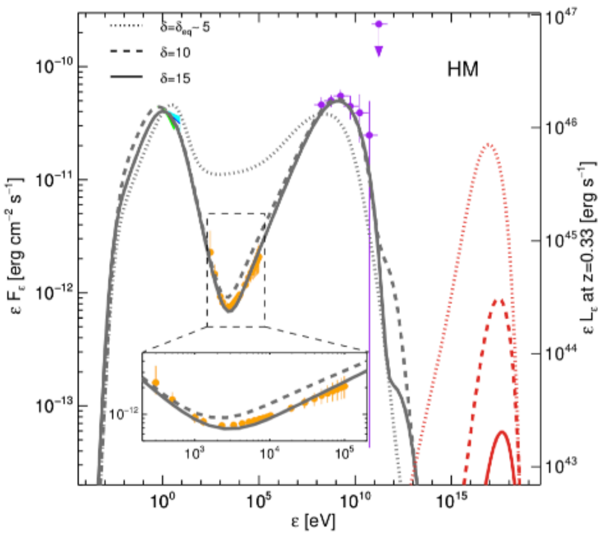


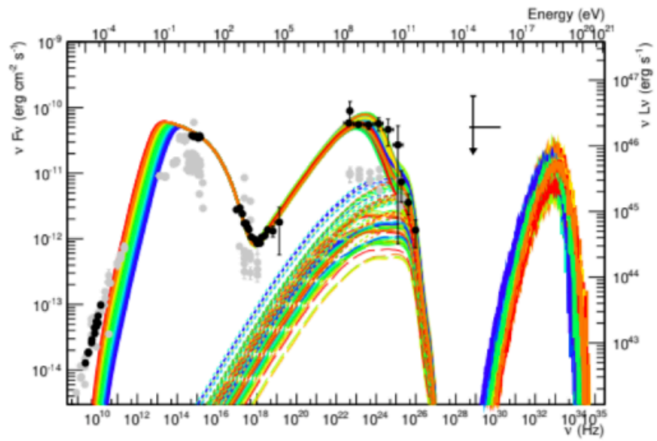




[IceCube, Fermi, MAGIC et al. 2018]

TXS 0506+056: the 2017 flare

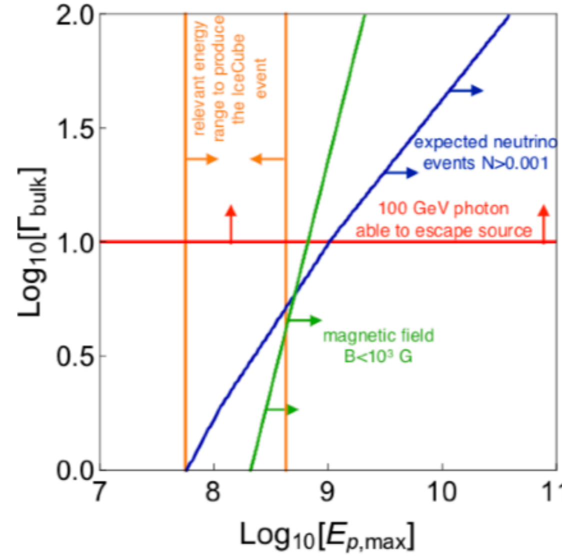




(a) Proton synchrotron modeling of TXS 0506+056

[Cerruti et al. 2019](#)

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



[Keivani et al. 2018](#)

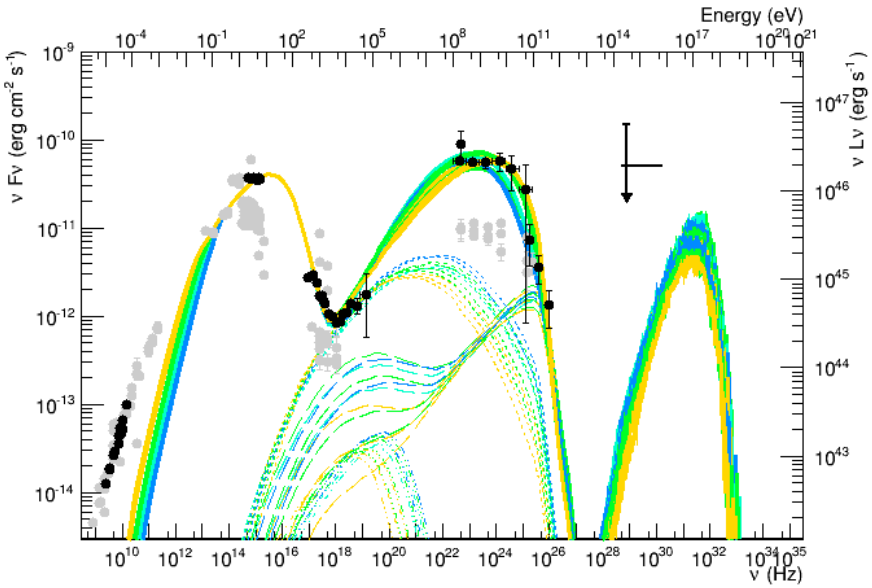
$$\nu \simeq 10^{-5}\ yr^{-1}$$

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

[Gao et al. 2018](#)

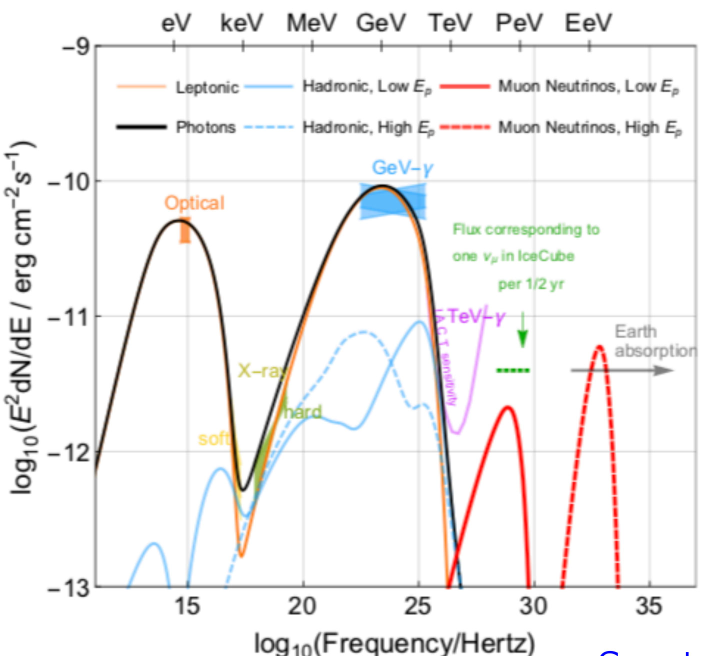
TXS 0506+056: the 2017 flare

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]

$L_{jet} \simeq \times 10^{50} erg/s$
$\nu = 0.3\ yr^{-1}$

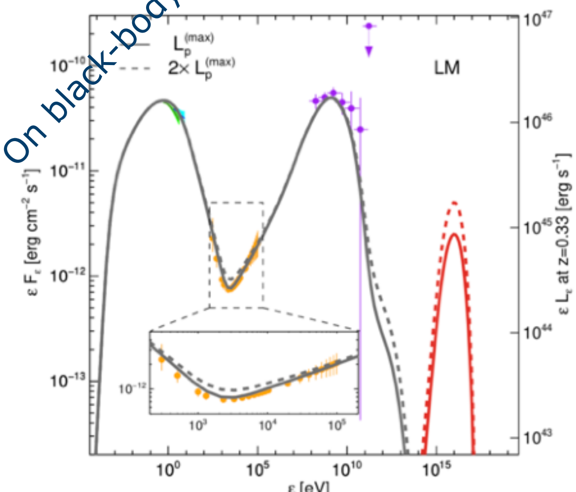
They can work: neutrino rates of the order of 0.1 / yr

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

TXS 0506+056: the 2017 flare

Proton-photon interaction on external photon fields

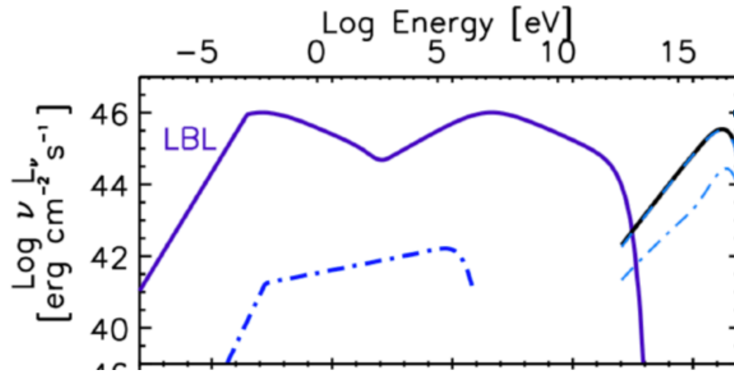
On black-body



Keivani et al. 2018

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

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



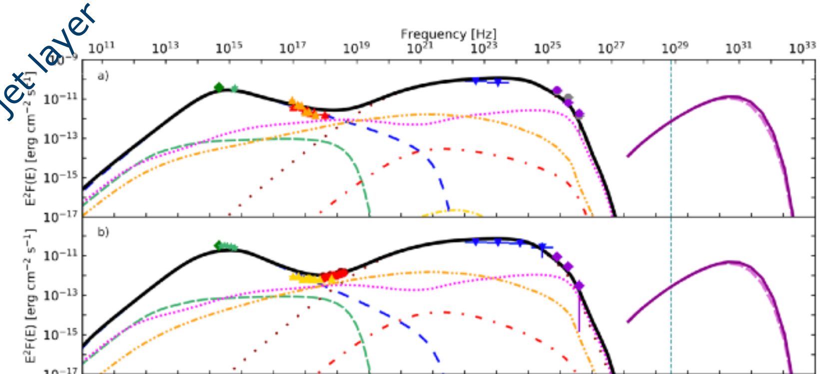
On RIAF

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

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

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

$L_{jet} \gg L_{Edd} \simeq \times 10$ erg/s

TXS 0506+056: the 2017 flare

What did we learn on blazars?

- Pure hadronic solutions are excluded!

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

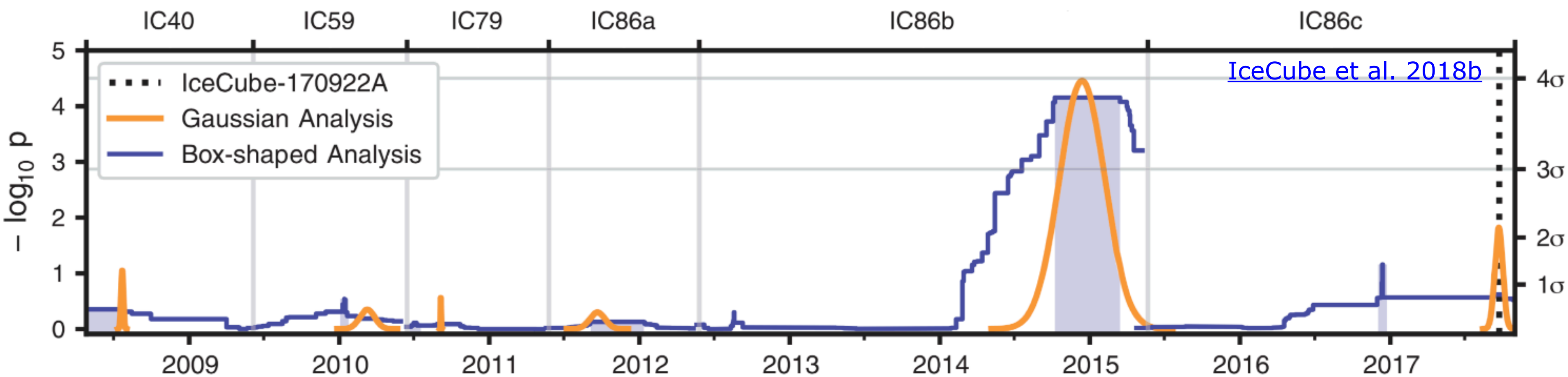
- Simple one-zone models can be enough, at the expenses of a high proton luminosity, and only if the acceleration efficiency is low

- External fields as photon target can help on this aspect

- Maximum proton energy is a free parameter: no UHECR (from this source)

TXS 0506+056: the 2014/15 flare

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

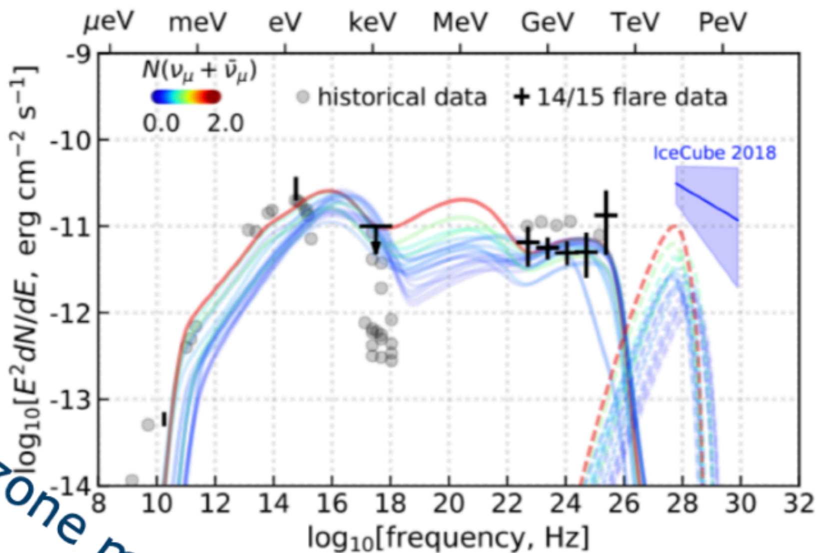


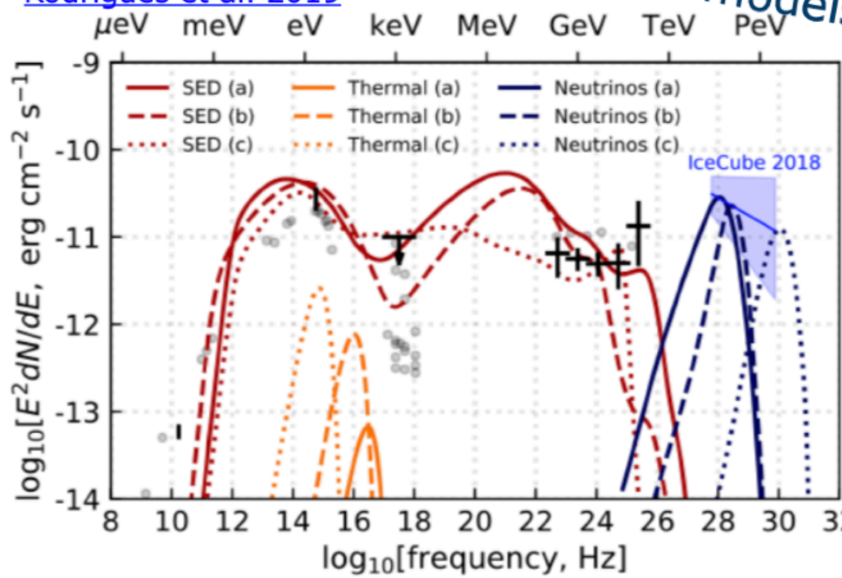
3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event

TXS 0506+056: the 2014/15 flare

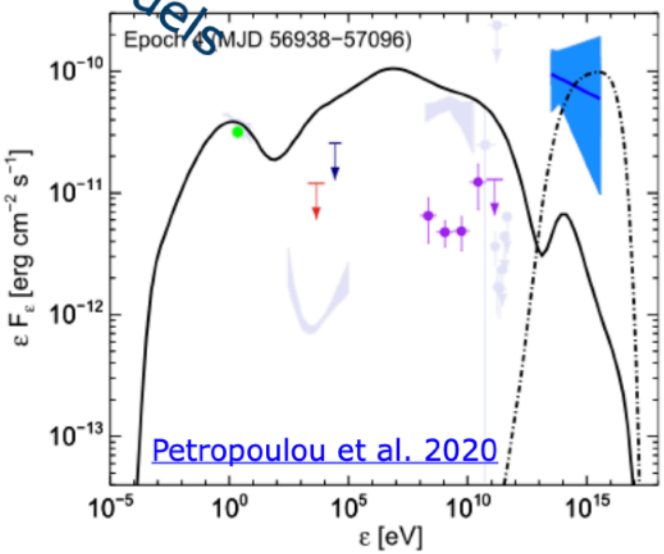
External field models

[Rodrigues et al. 2019](#)

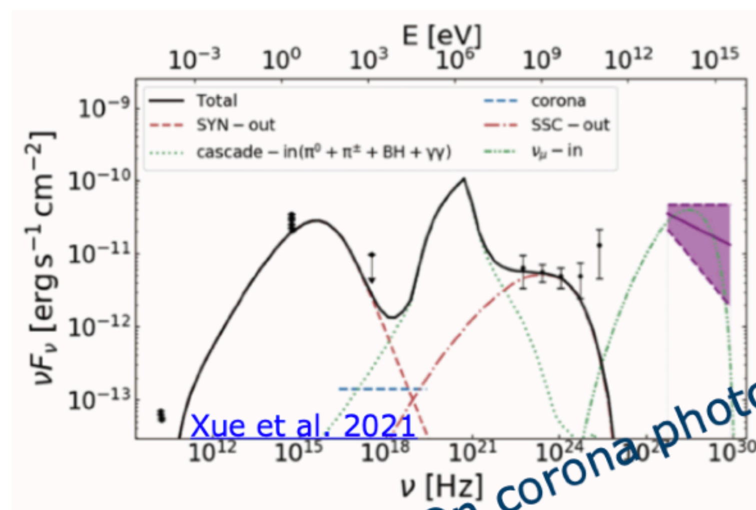




1-zone models



[Petropoulou et al. 2020](#)



[Xue et al. 2021](#)

On corona photons

TXS 0506+056: the 2014/15 flare

What did we learn?

- 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)

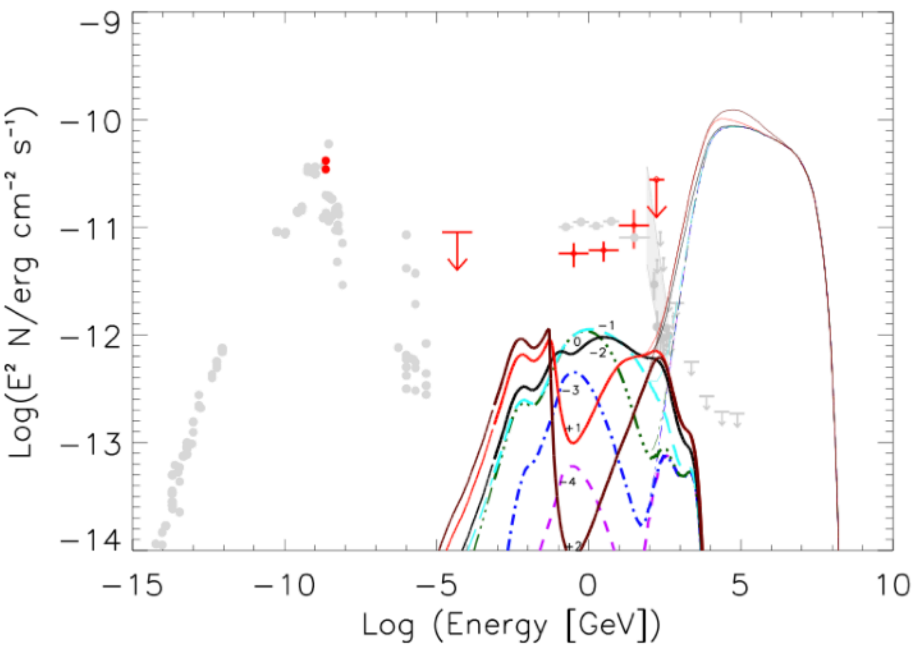
- A possible solution could be a two-zone models:
  the ν and the γ-ray emitting region are not the same

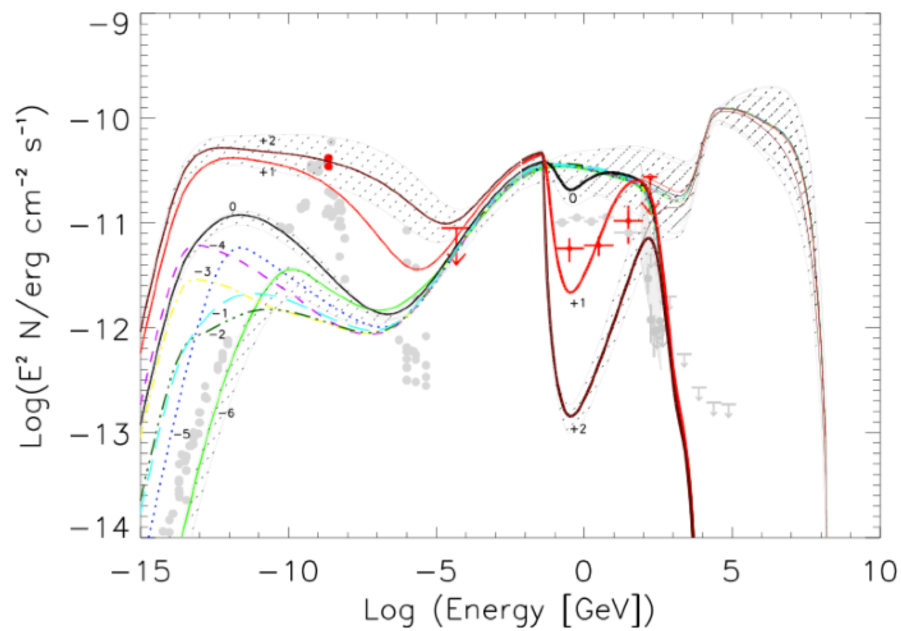
- It is a pity to be blind at MeV energies!

TXS 0506+056: the 2014/15 flare

The exact cascade spectrum varies a lot in the parameter space

inverse-Compton cascade vs synchrotron cascade





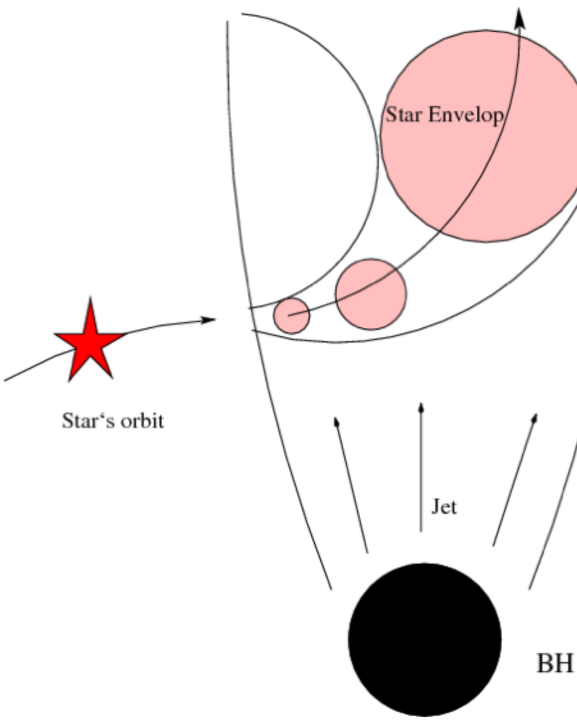
Reimer et al. 2020

ON p-p INTERACTIONS

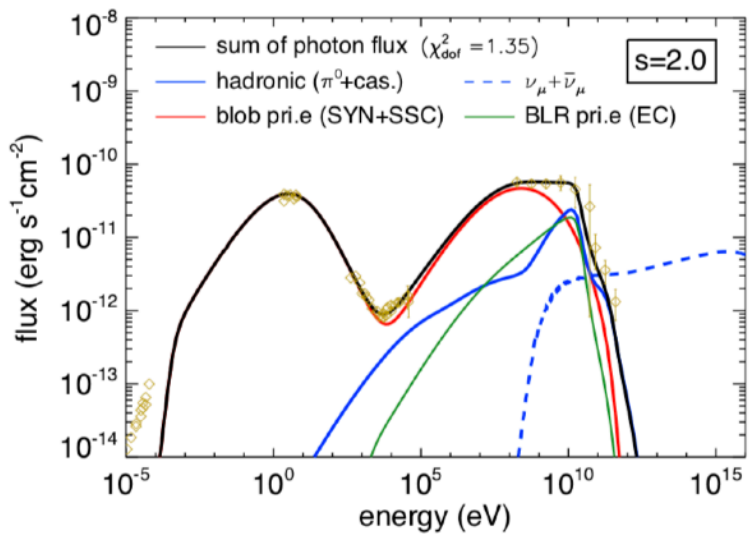
Can p-p interactions be important?

Usually neglected in single zone models

Can become the dominant channel in jets-obstacles models



Barkov et al. 2012



$$L_{jet} = (0.8 - 5) \times 10^{46} erg/s$$

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

Liu et al. 2019

HADRONIC CODE COMPARISON

Comparison of five numerical hadronic codes in the literature:
AM3 (Gao et al. 2017), Athena (Dimitrakoudis et al. 2012),
B13 (Böttcher et al. 2013), LeHa-Paris (Cerruti et al. 2015), LeHaMoc (Stathopoulos et al. 2024)

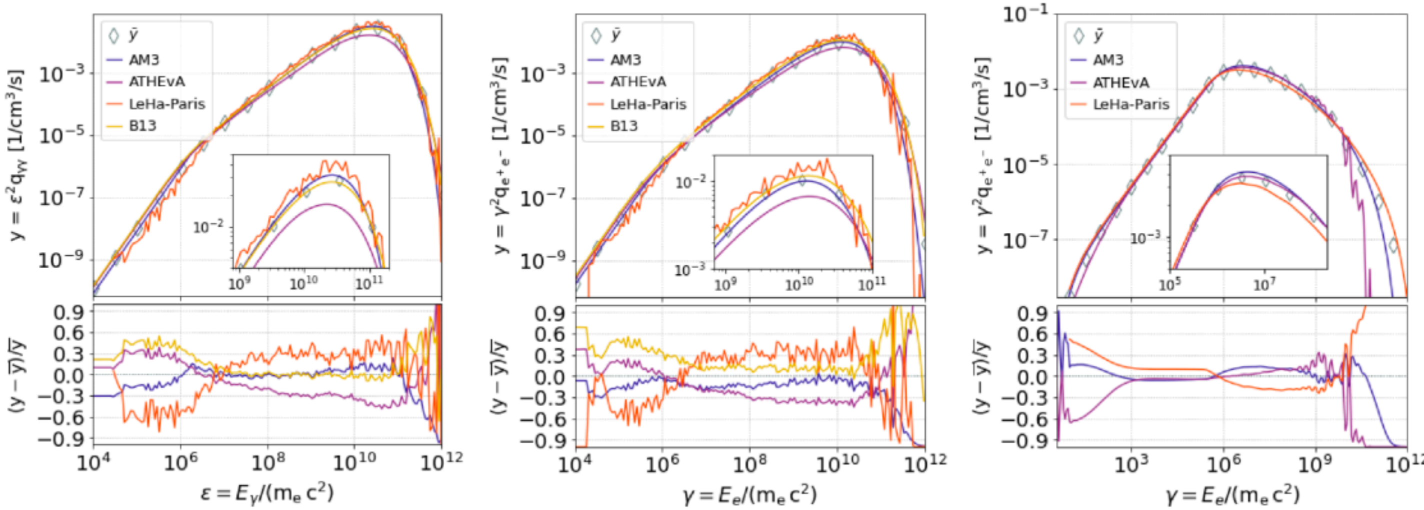
- run tests from simple 'artificial' cases
(Mono-energetic protons on black-body)
to 'realistic' ones
(proton-synchrotron or lepto-hadronic)

- Compute systematic uncertainties from theoretical simulations
- Release all files as benchmark for future developments

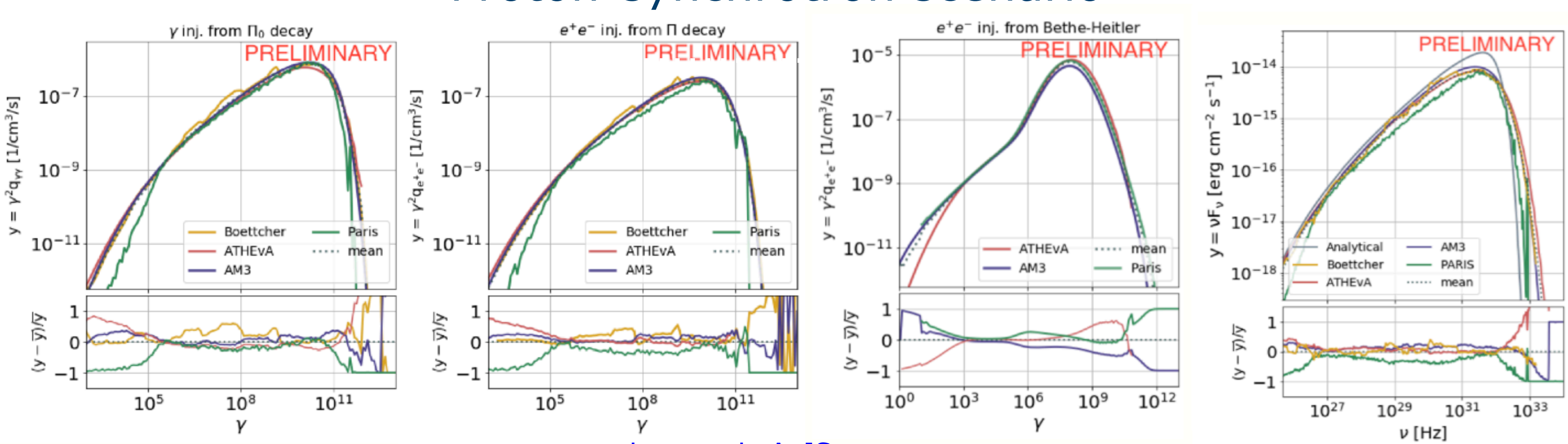
Take home message: spectral shapes are ok; 40% spread in normalization

HADRONIC CODE COMPARISON

Power-law protons on power-law photons



Proton-synchrotron scenario



in press in ApJS

PKS 0735+178

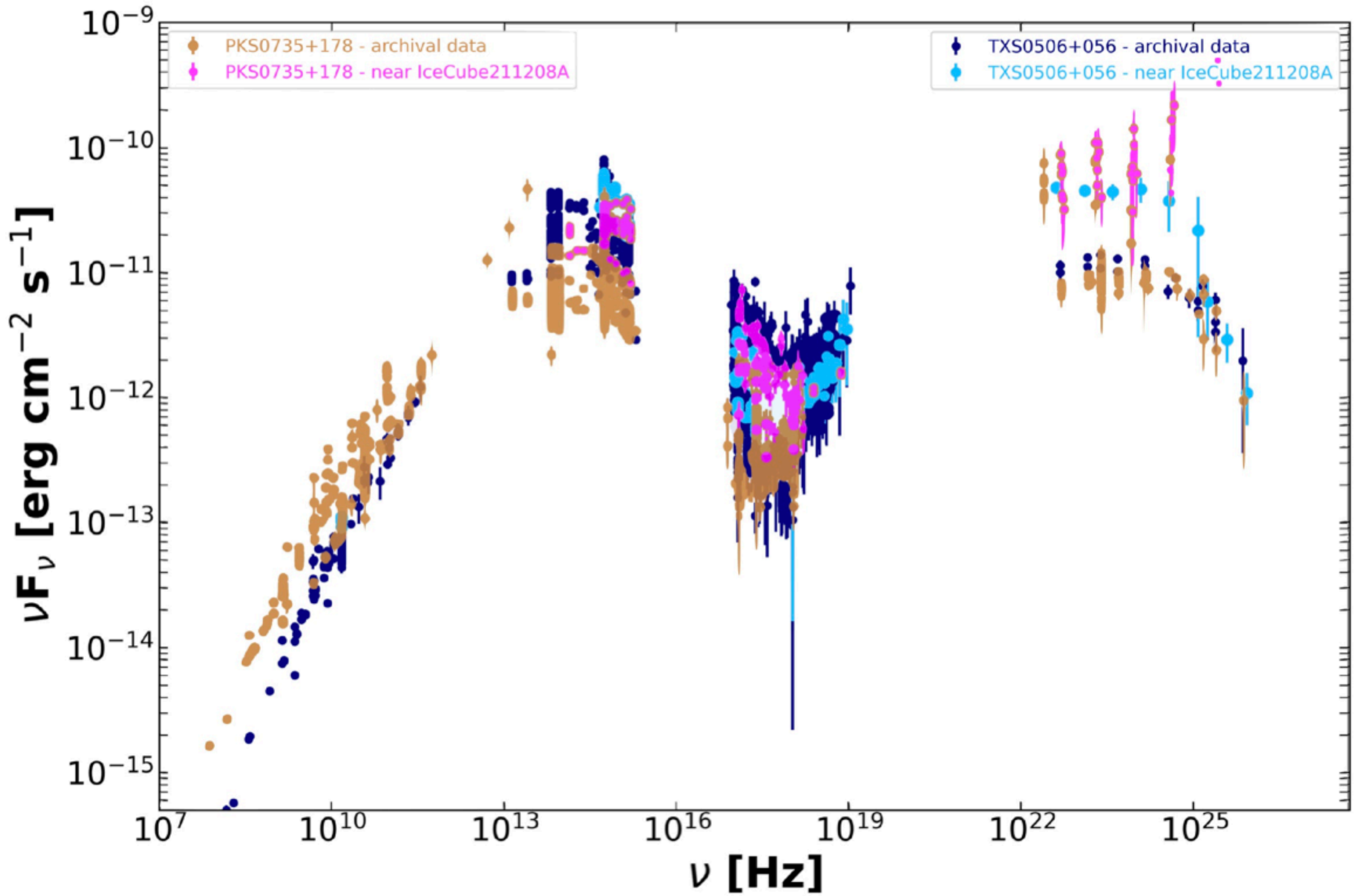
IBL@z=0.65? (>0.42) and IC211208A:

- Neutrino in IC with false alarm rate of 1.2 /yr (GCN)
- LAT source 2.2deg away (slightly beyond the 90% contour)

- Neutrino in Baikal (4h later). Chance coincidence prob. 2.85σ (ATel)
- Neutrino in KM3Net on Dec.15, p-value of 14% (ATel)
- Neutrino in Baksan on Dec.4, p-value of 0.2% (ATel)
- Flaring in Fermi-LAT, optical, X-rays

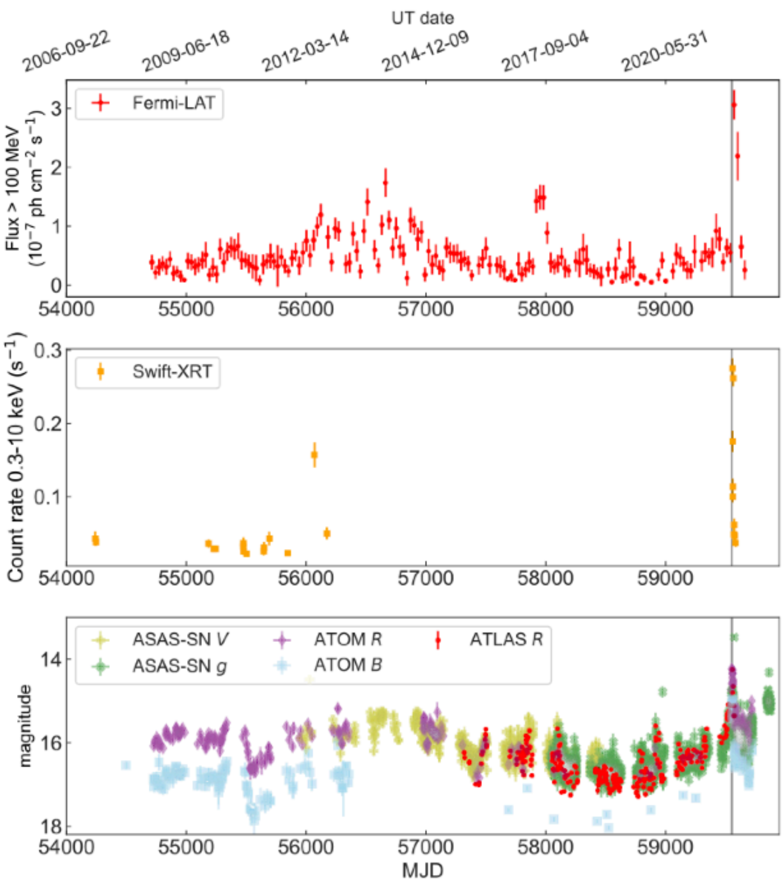
PKS 0735+178

First theory paper by [Sahakyan et al. 2022]

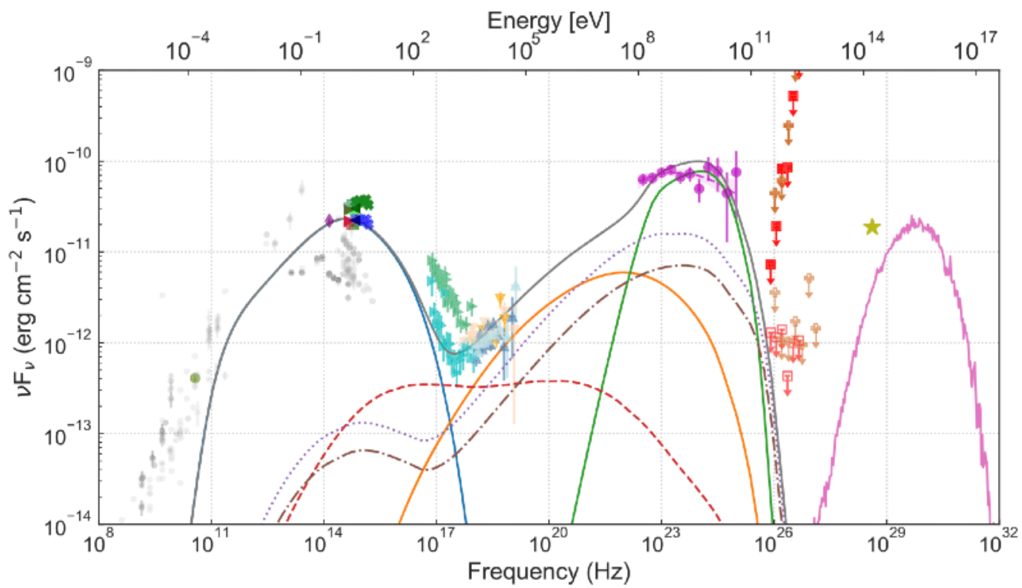


PKS 0735+178

[Acharyya et al. 2023]

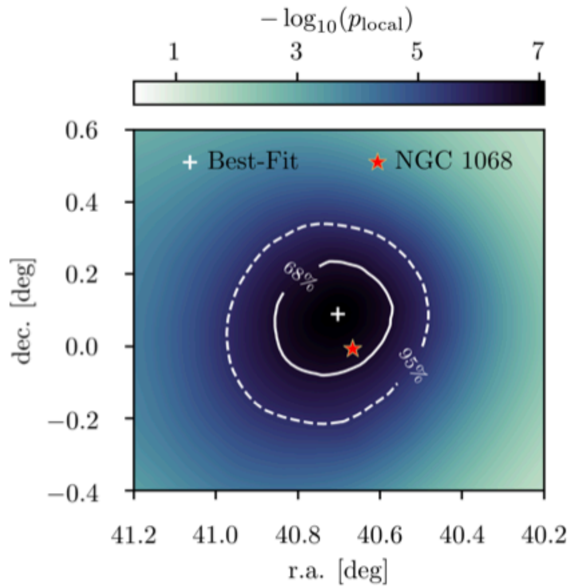


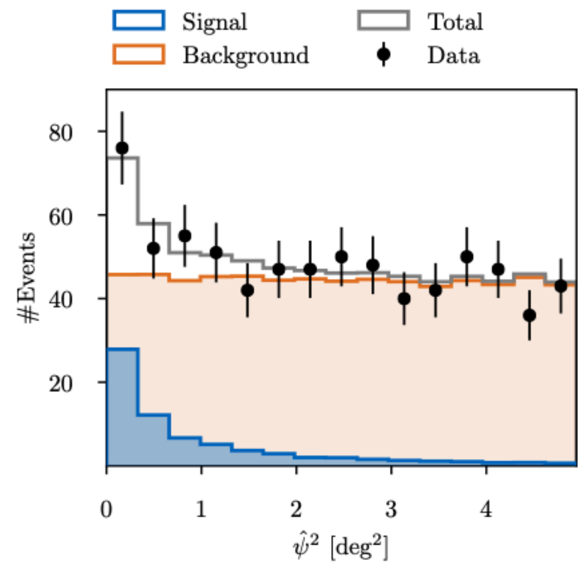
(a)

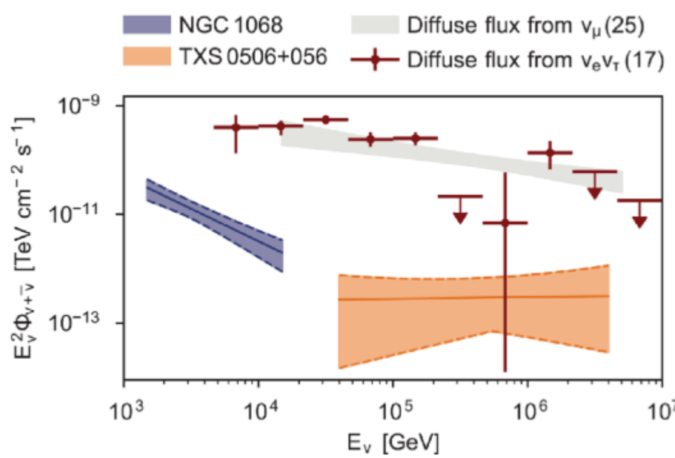


NGC 1068

4σ excess from the Seyfert galaxy NGC 1068





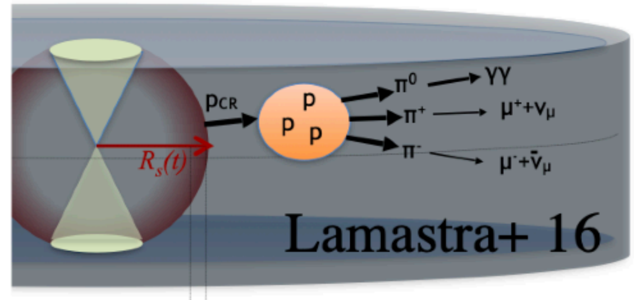


IceCube et al. 2022

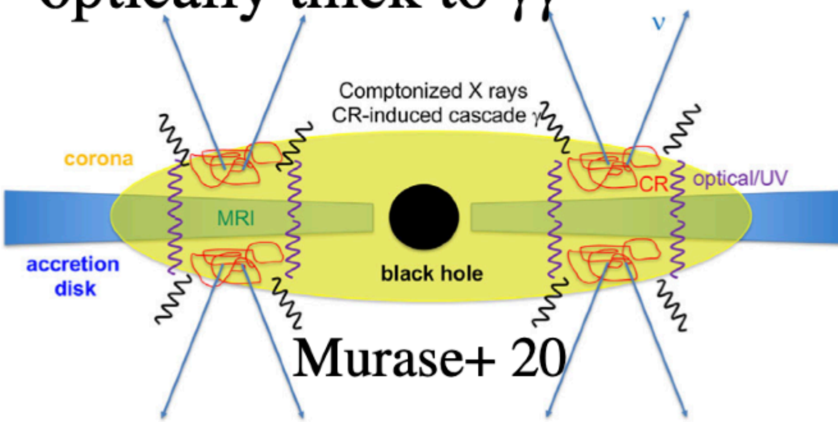
NGC 1068 (AGN) models

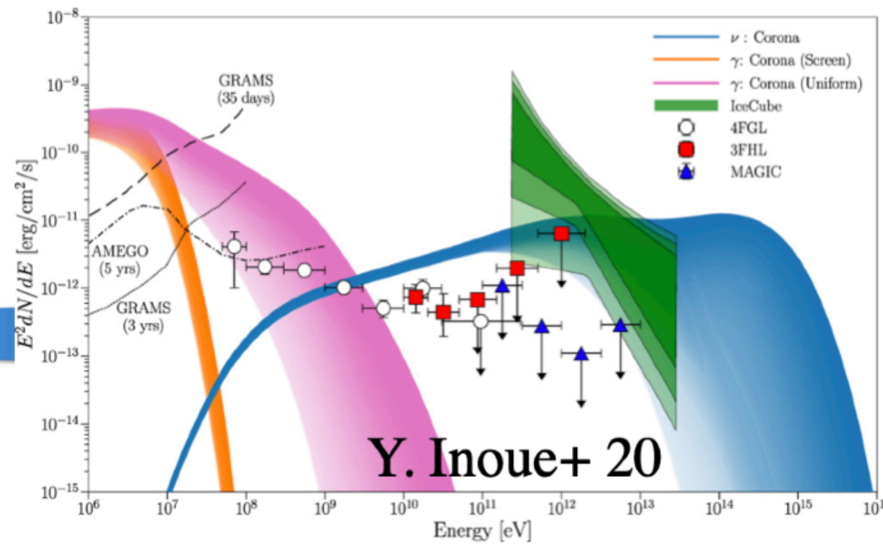
neutrino + gamma from NGC 1068: AGN origin?

AGN wind kpc-scale ext. shock?
-> ruled out by TeV upper limits



hot coronal regions of accretion disks?
pp+pγ in compact regions
optically thick to γγ

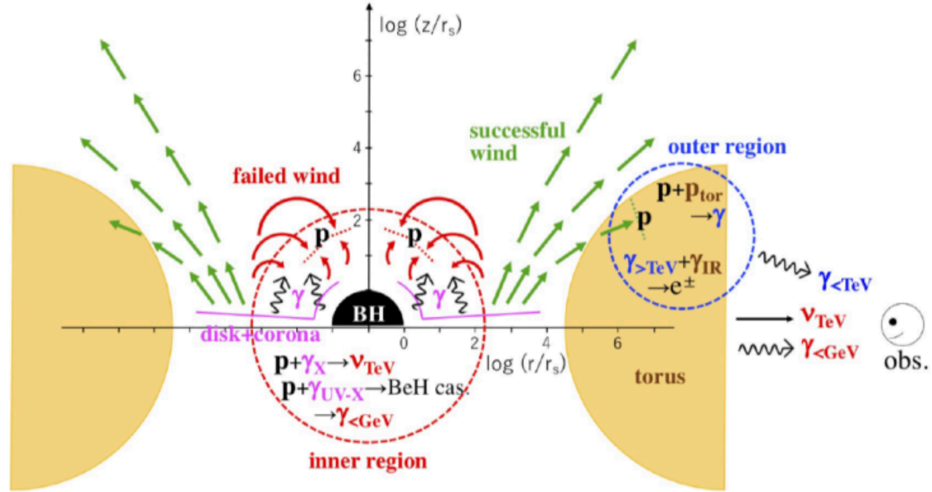


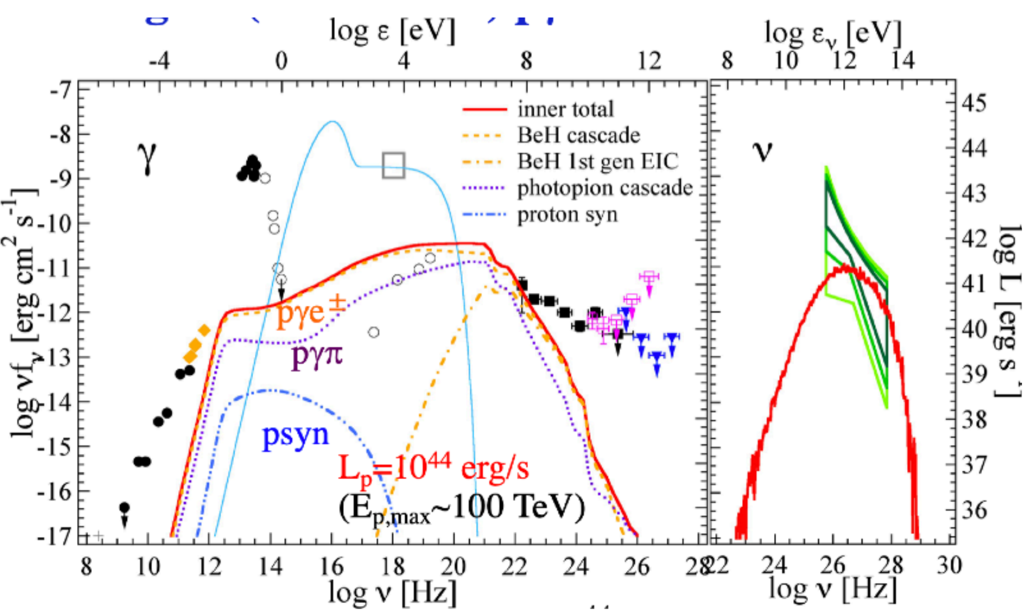


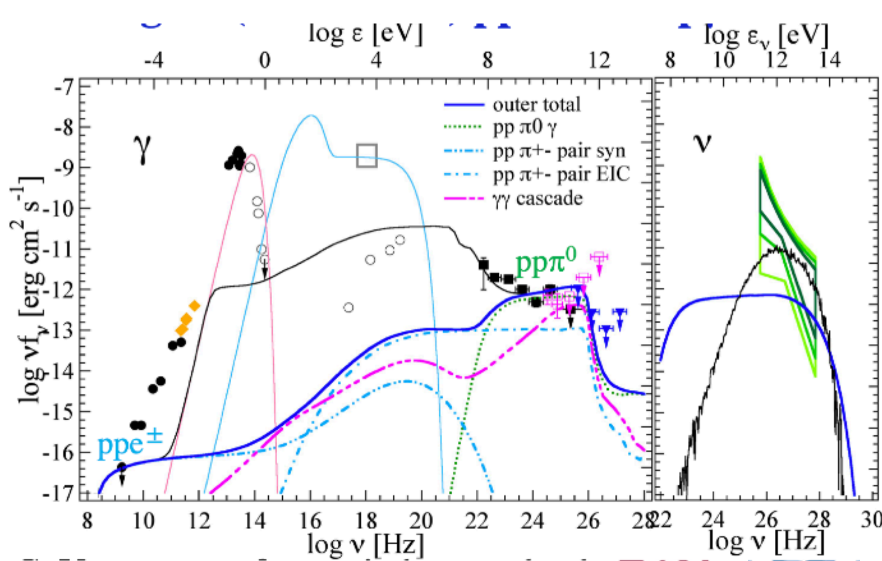
Slides by S. Inoue (Gamma 2022)

NGC 1068 (AGN) models

Inoue S. et al. 2022







CONCLUSIONS

- Blazar hadronic emission models constrained by even a single neutrino (or by absence of neutrinos!).

- ‘Mixed’ lepto-hadronic scenarios favored by TXS 0506+056

- Multi-zone models favored by TXS 0506 2014 neutrino flare
  and by NGC1068 : the neutrino and gamma-ray emitting region must be separated. Can this be generalized to the whole AGN population?

- What happened since TXS 0506+056?
  In Dec. 2021, possible association with PKS 0735+178 (sigma not quantified)
  In Feb. 2023, 220 PeV neutrino in KM3NET but uncertainty in position too large to conclude much. Might be cosmogenic?

Caveats:

- still some uncertainty from numerical implementations
- still over-simplified homogeneous emission models