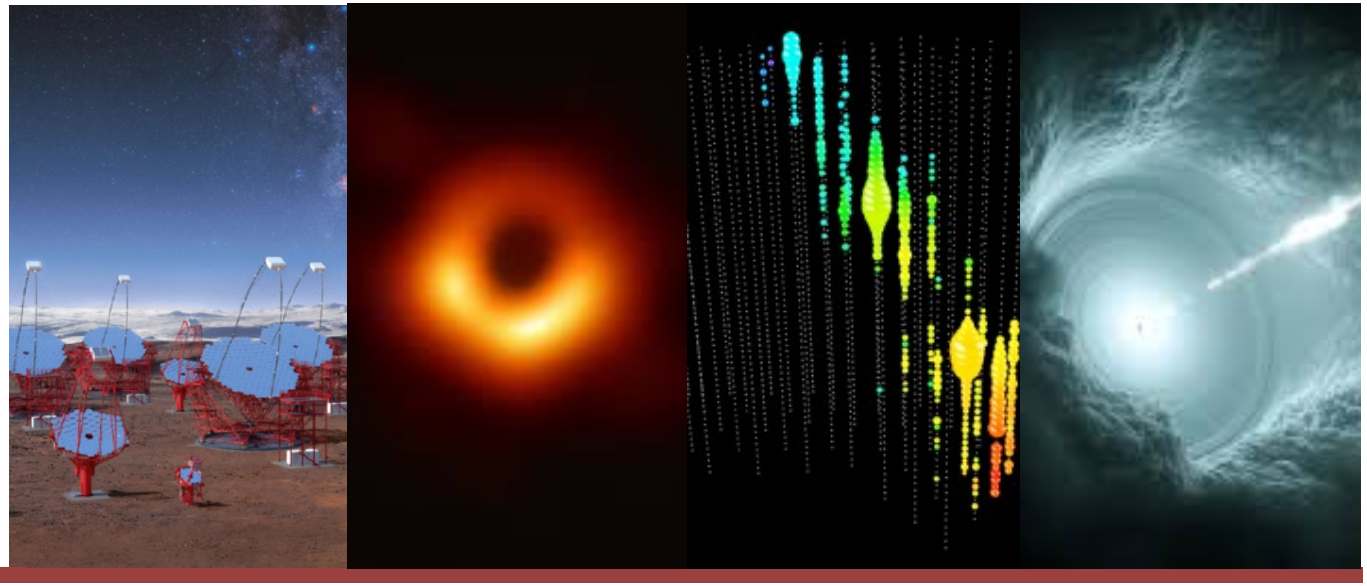


Blazar emission models and implications for multi-messenger observations

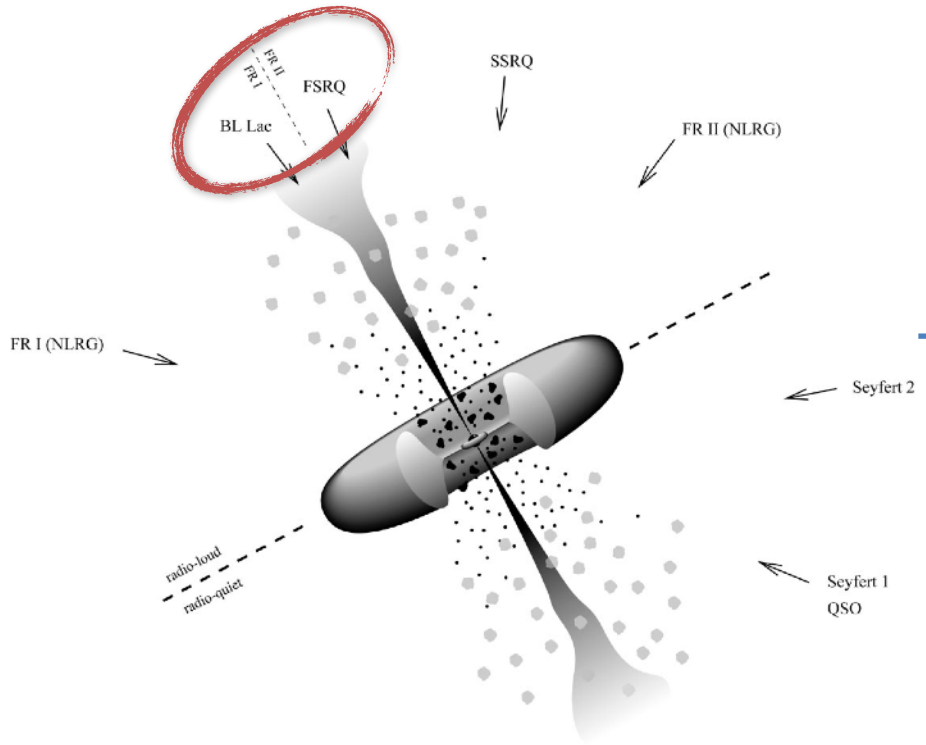
Matteo Cerruti

Université Paris Cité
Astroparticule et Cosmologie (APC)

Neutrinos in the Multi-MSN era

Louvain la Neuve
December 1st, 2022

BLAZARS



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

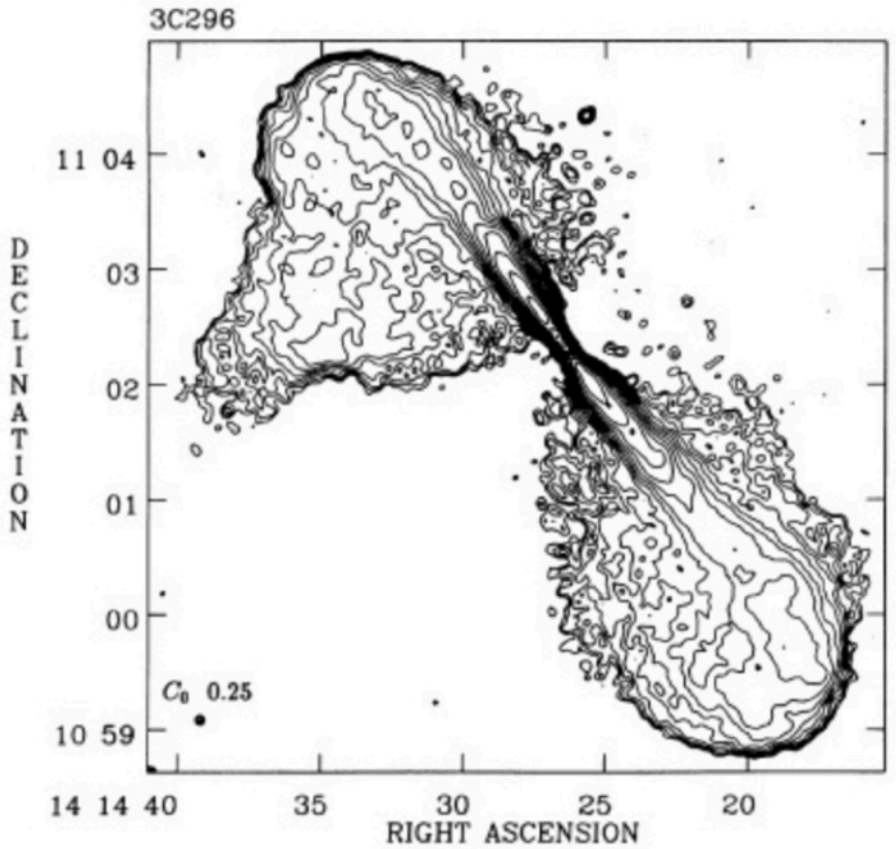
→ Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)

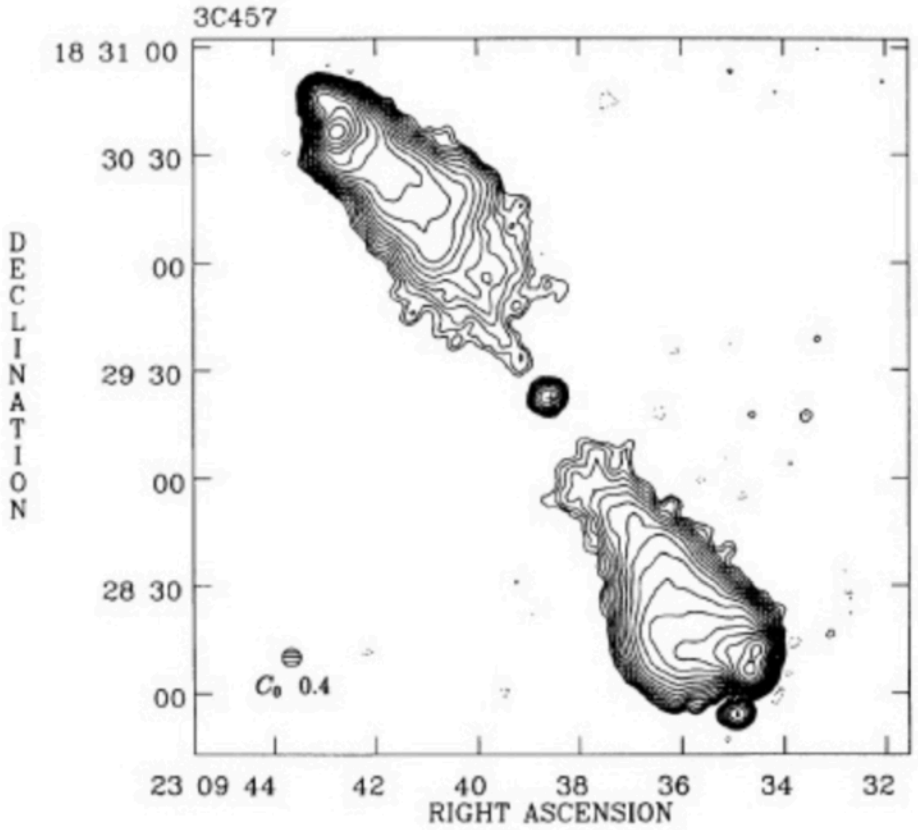
Flat-spectrum-radio-quasars : optical/UV spectrum with broad emission lines

BL Lacertae objects : featureless optical/UV spectrum

BLAZARS

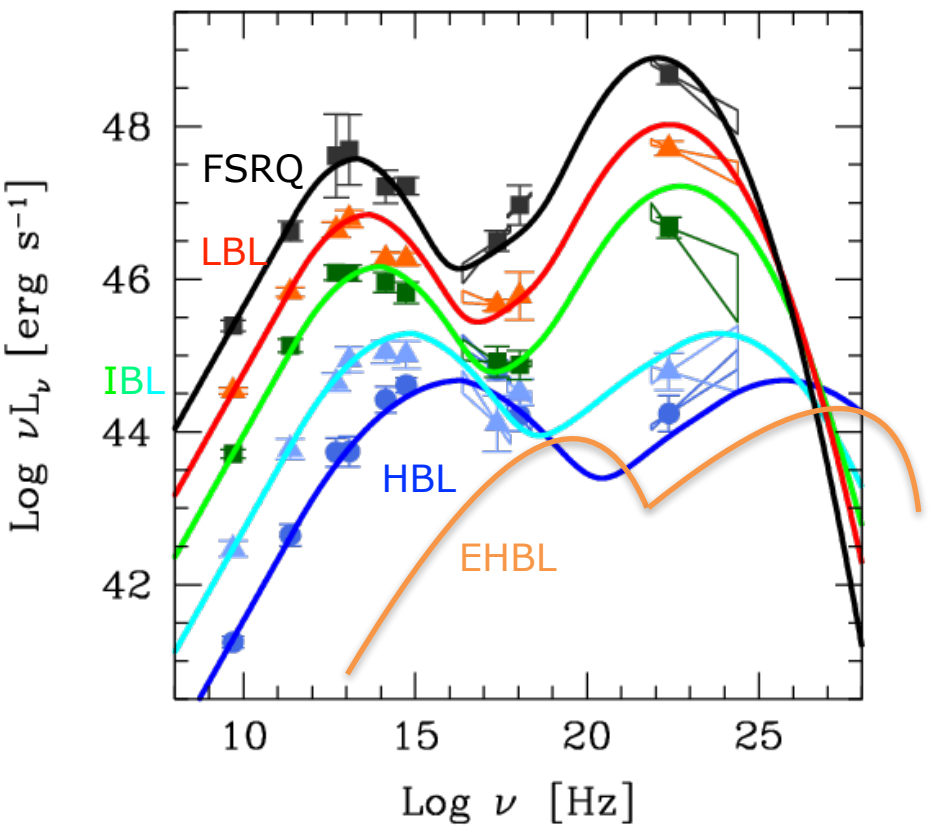
Radio-loud dichotomy: Fanaroff-Riley I and FRII





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

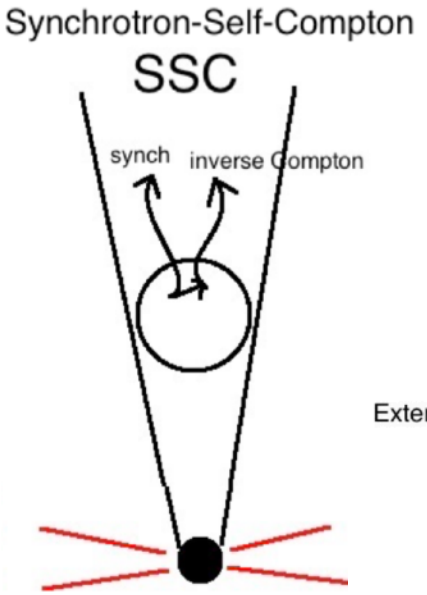
The low-energy SED component is synchrotron emission by electrons

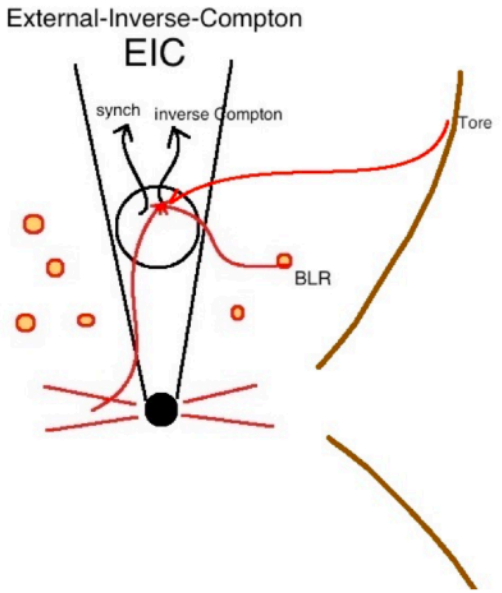
High-energy emission?

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

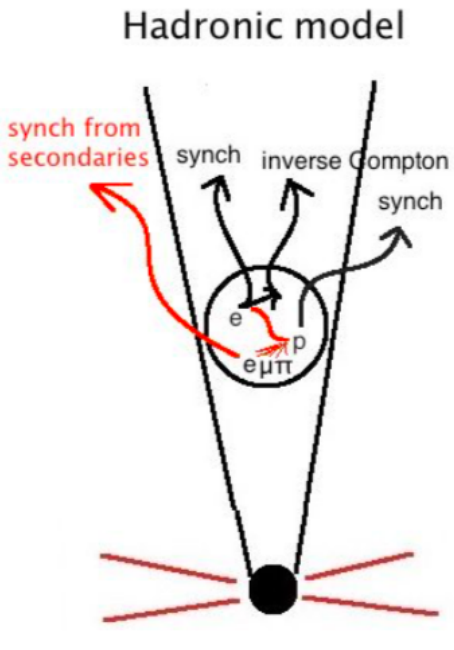




BLAZARS EMISSION MODELS

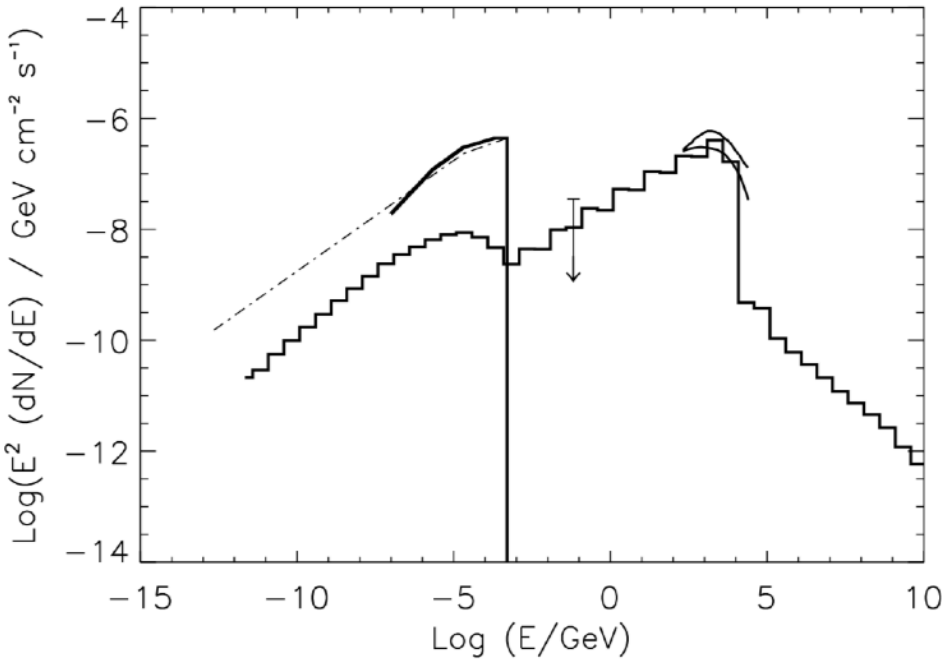
Hadronic models

Simplest hadronic model:



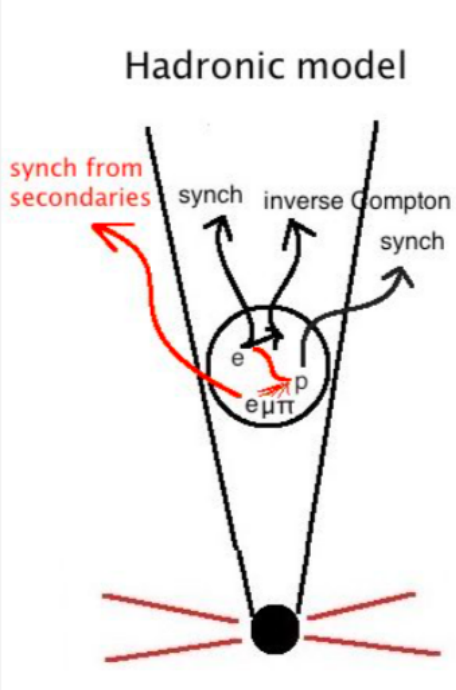
The high-energy component is proton synchrotron radiation

(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

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

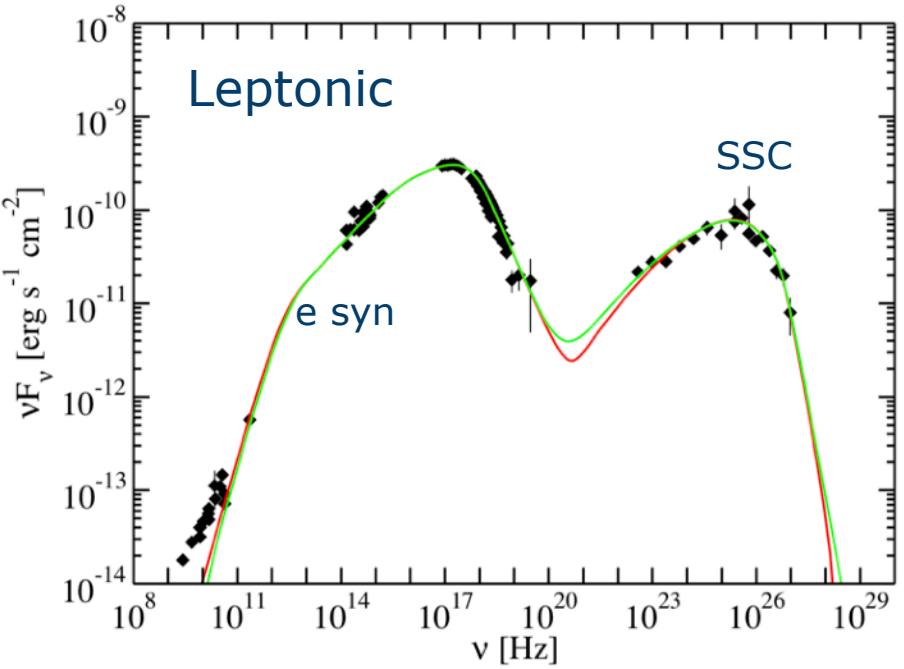
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

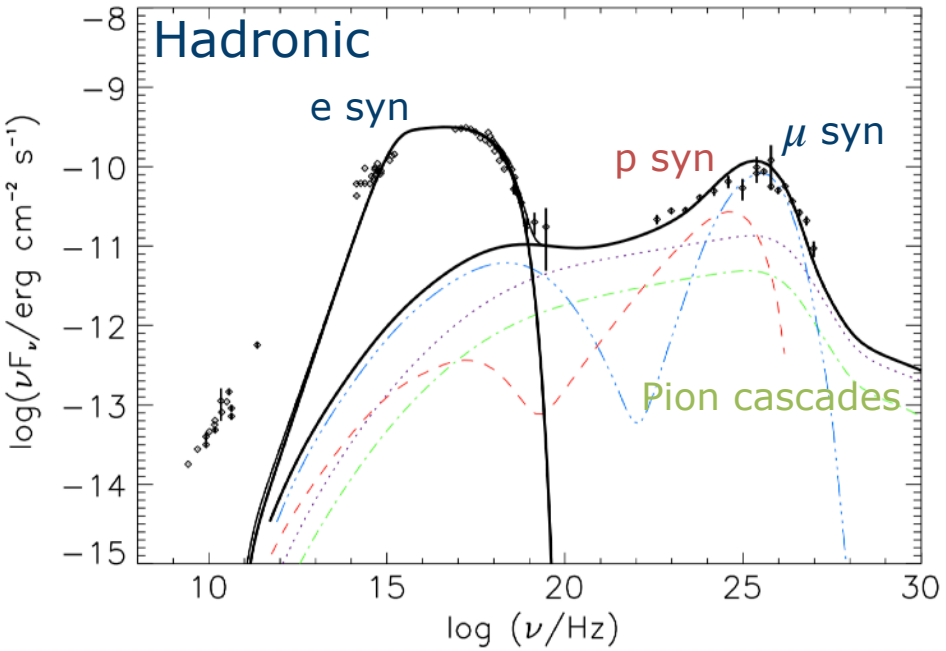
Synchrotron emission by muons can be important

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011

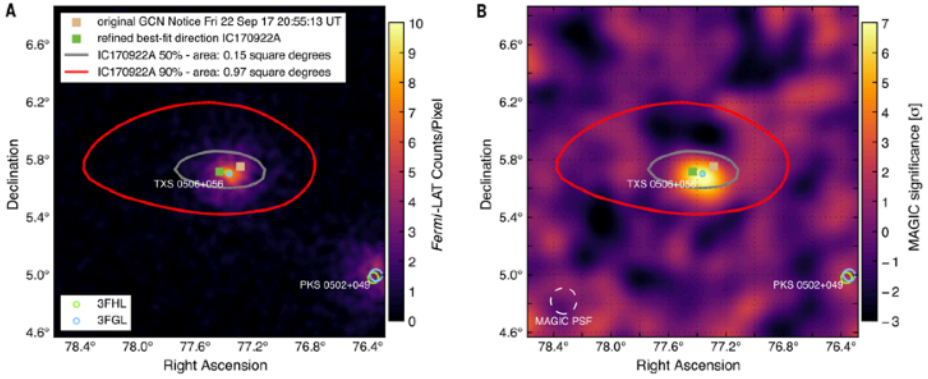


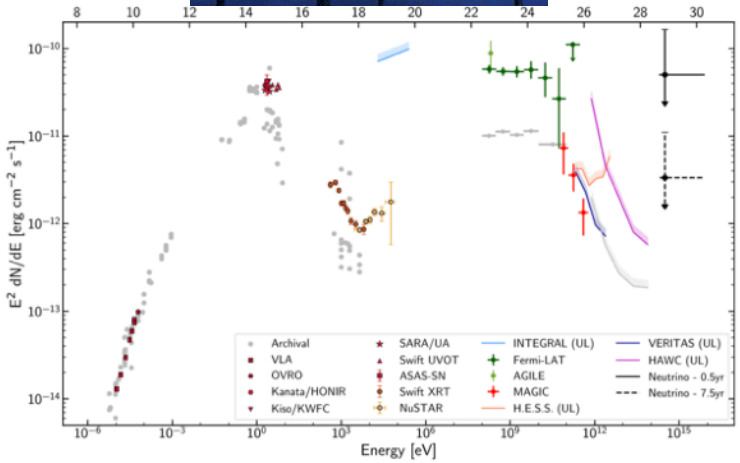


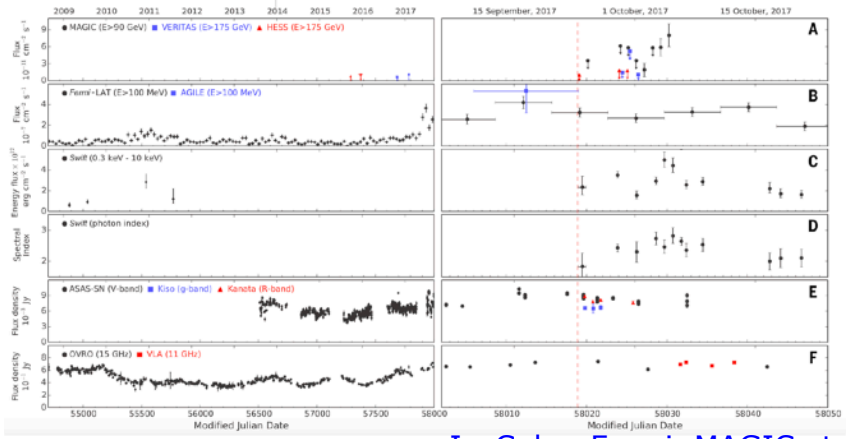
[Abdo et al. 2011]

IceCube-170922A / TXS 0506+056

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

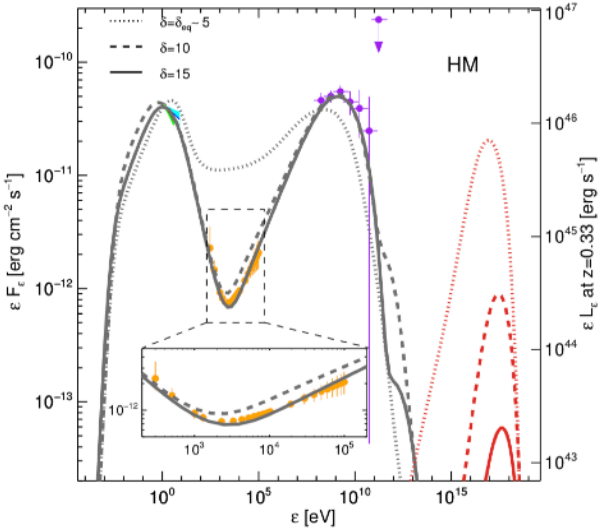






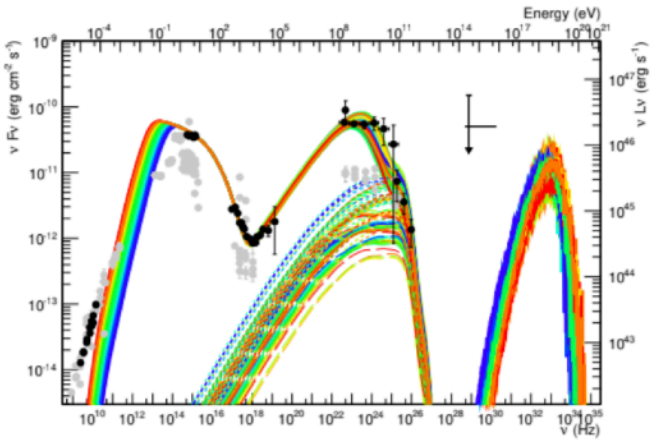
IceCube, Fermi, MAGIC et al. 2018

TXS 0506+056: the 2017 flare



Keivani et al. 2018

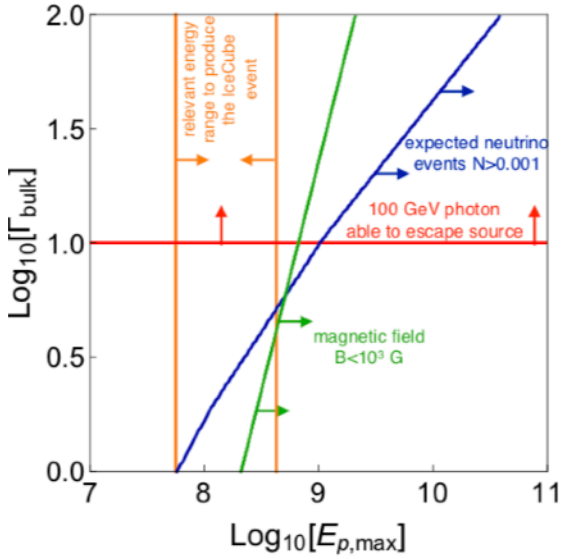
$\nu \simeq 10^{-5}\ yr^{-1}$



(a) Proton synchrotron modeling of TXS 0506+056

Cerruti et al. 2019

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

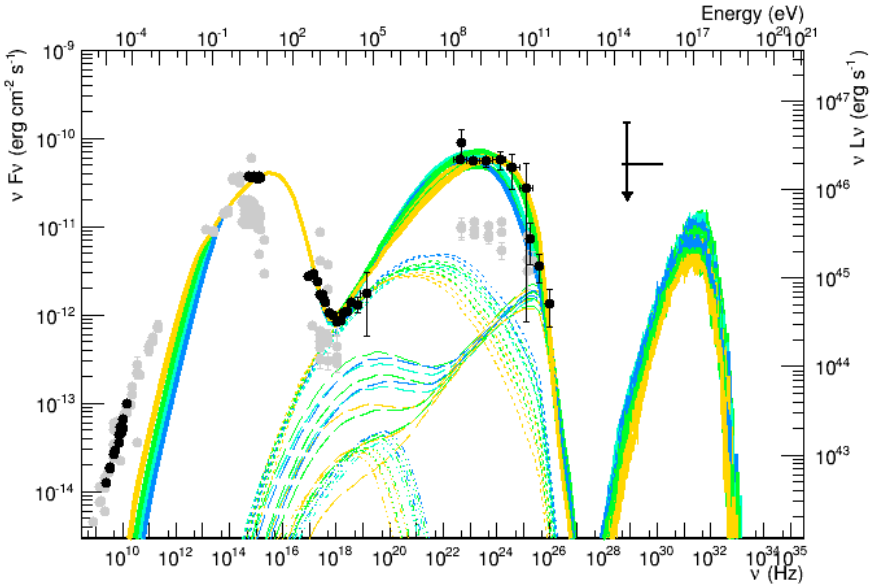


Gao et al. 2018

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

TXS 0506+056: the 2017 flare

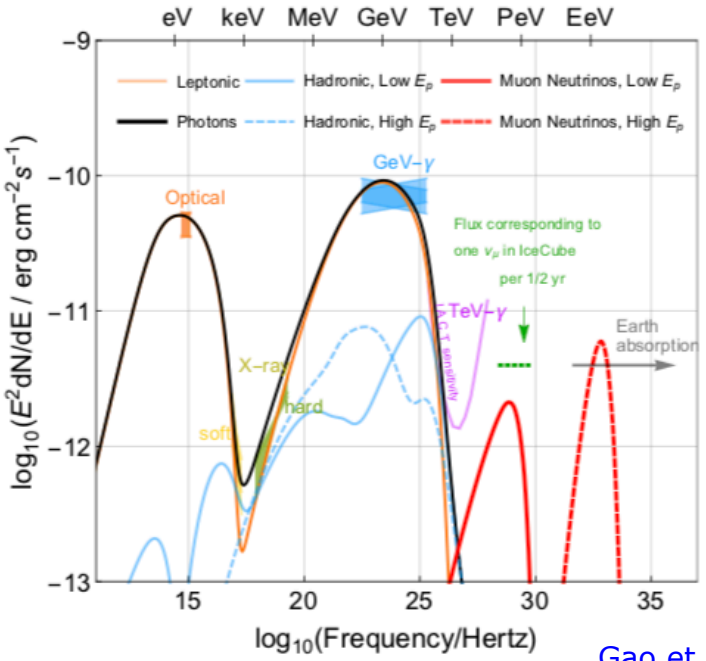
Lepto-hadronic solutions



Cerruti et al. 2019

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

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



Gao et al. 2018

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

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

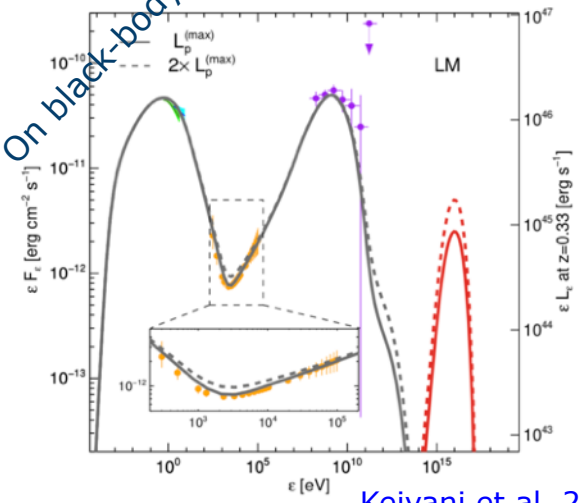
They can work: neutrino rates of the order of 0.1 / yr

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

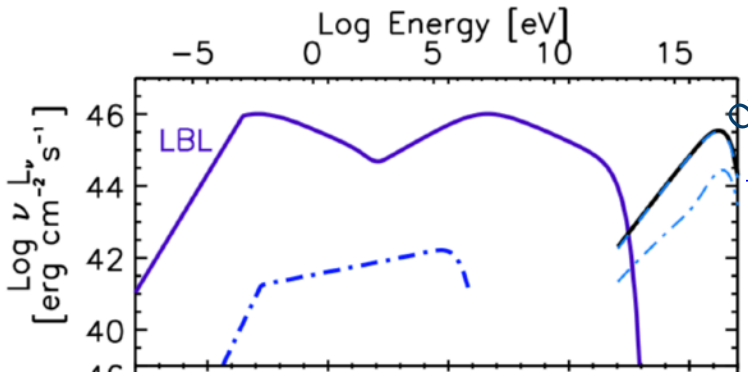


Keivani et al. 2018

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

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

On RIAF

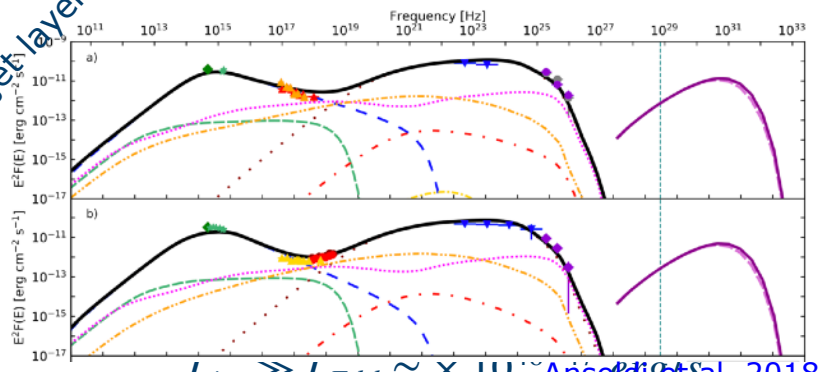


Righi et al. 2019

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

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

On jet layer



Ansoldi et al. 2018

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

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

$L_{jet} \gg L_{Edd} \simeq \times 10^{\cdots}$

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

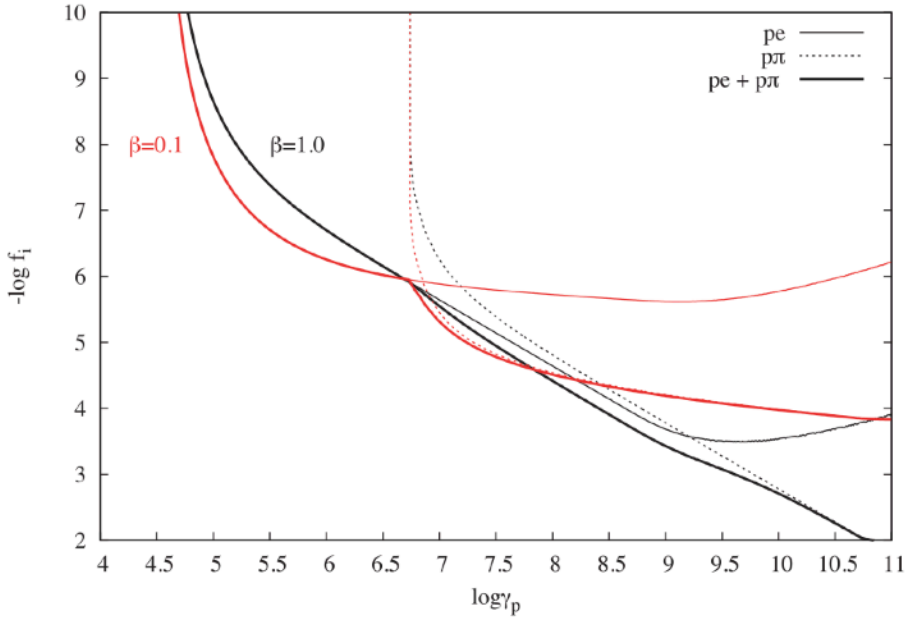
- Maximum proton energy is a free parameter: no UHECR (from this source)

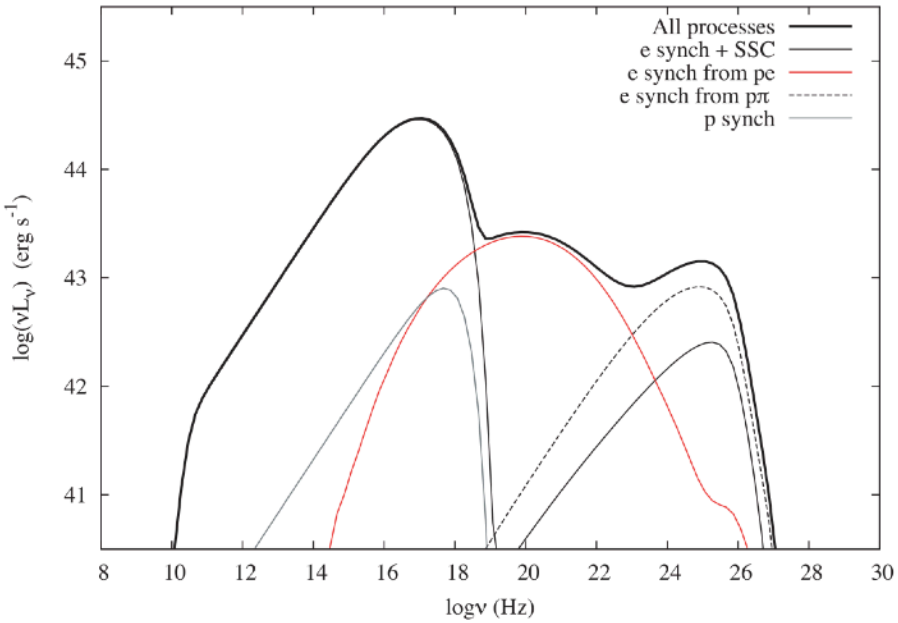
TXS 0506+056: the 2017 flare

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

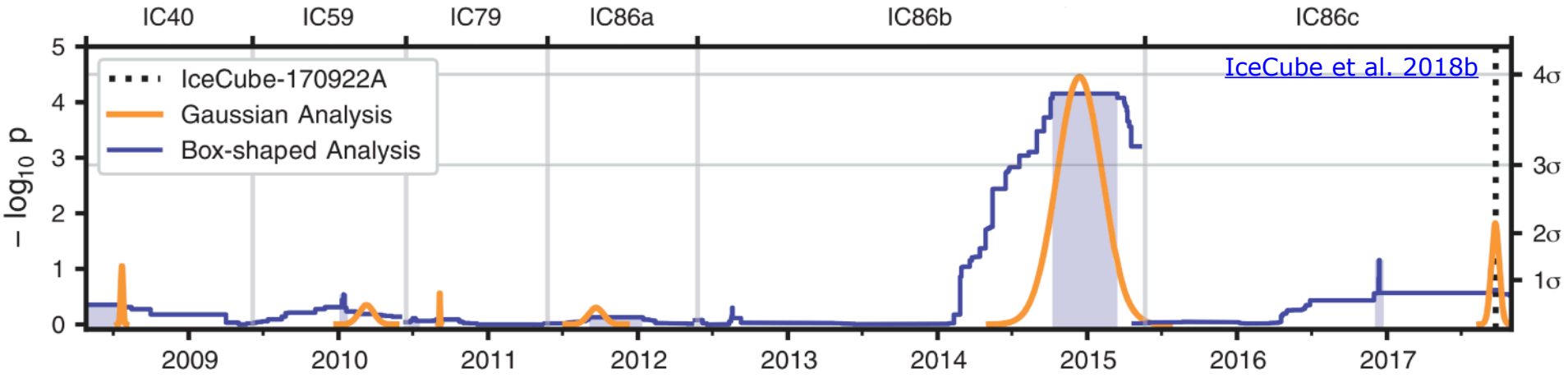




Petropoulou & Mastichiadis 2015

TXS 0506+056: the 2014/15 flare

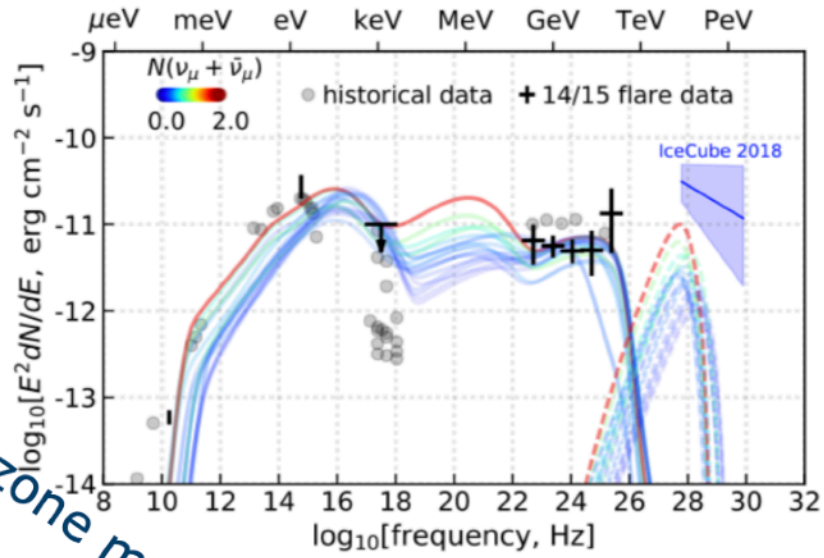
Detection of a second neutrino flare in 2014-2015
(without a gamma-ray counterpart)



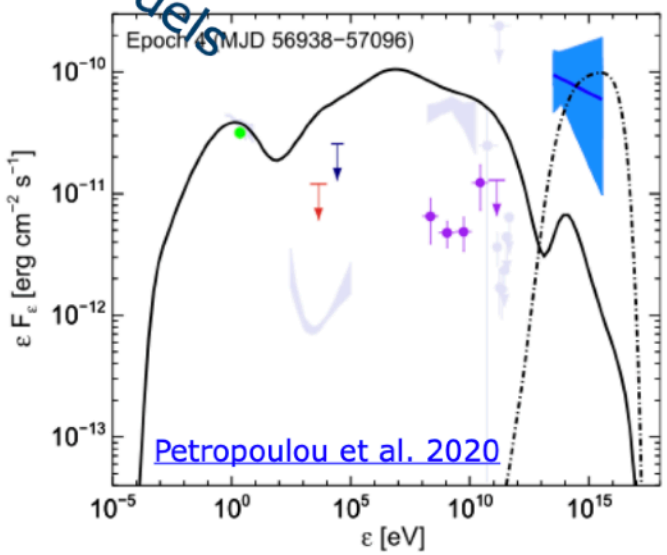
3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event

TXS 0506+056: the 2014/15 flare

External field models

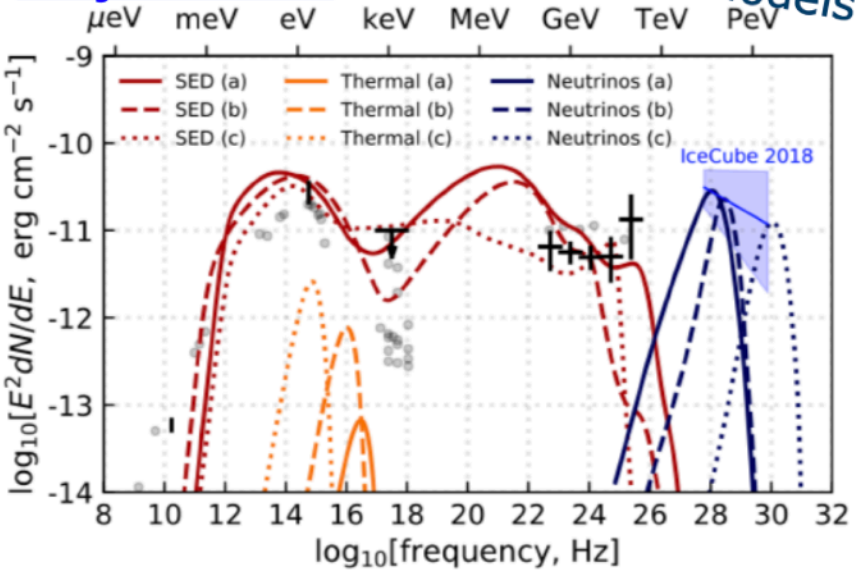


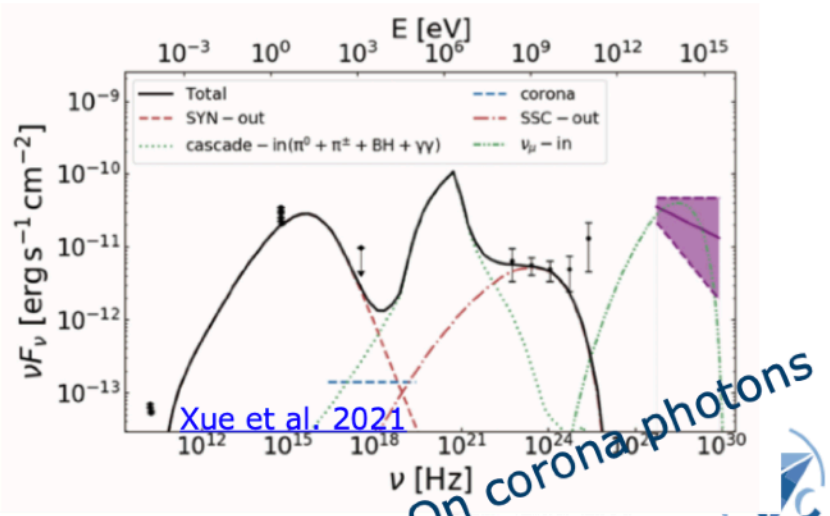
1-zone models



Matteo Cerru

Rodrigues et al. 2019





On corona photons

TXS 0506+056: the 2014/15 flare

What did we learn?

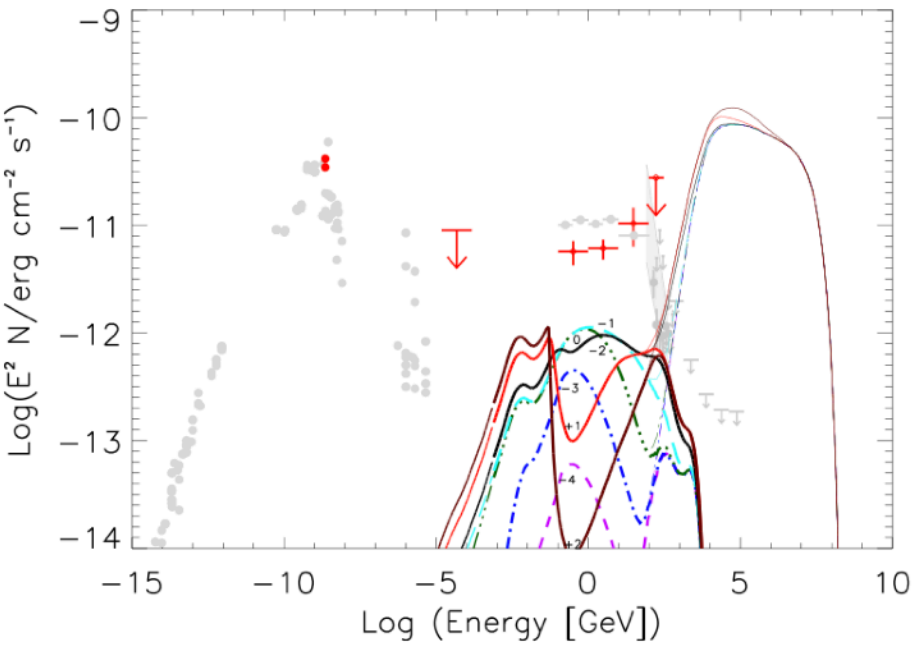
- Single zone models are disfavored : very difficult to get no photons with the neutrino flare
(although there may be some room in the MeV band)

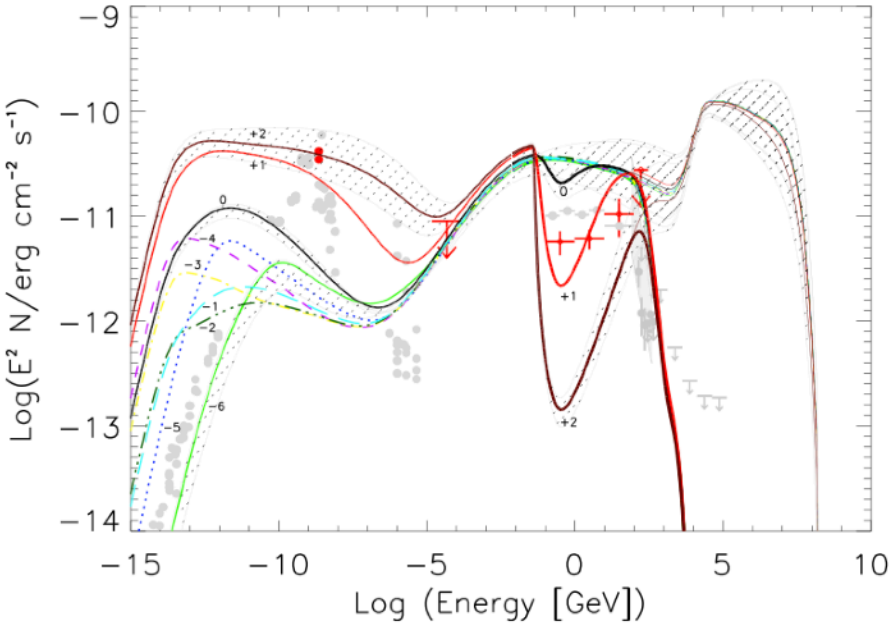
- A possible solution could be a two-zone models:
the ν and the γ-ray emitting region are not the same

TXS 0506+056: the 2014/15 flare

The exact cascade spectrum varies a lot in the parameter space

inverse-Compton cascade vs synchrotron cascade





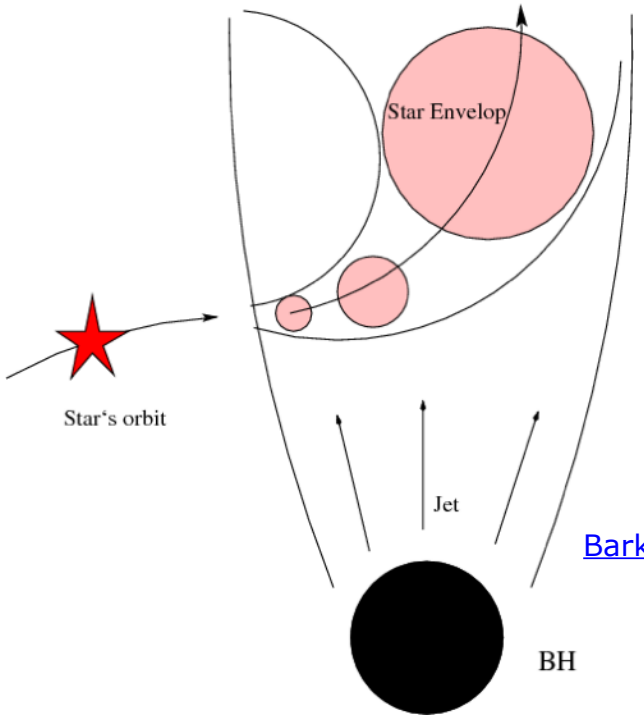
Reimer et al. 2020

ON p-p INTERACTIONS

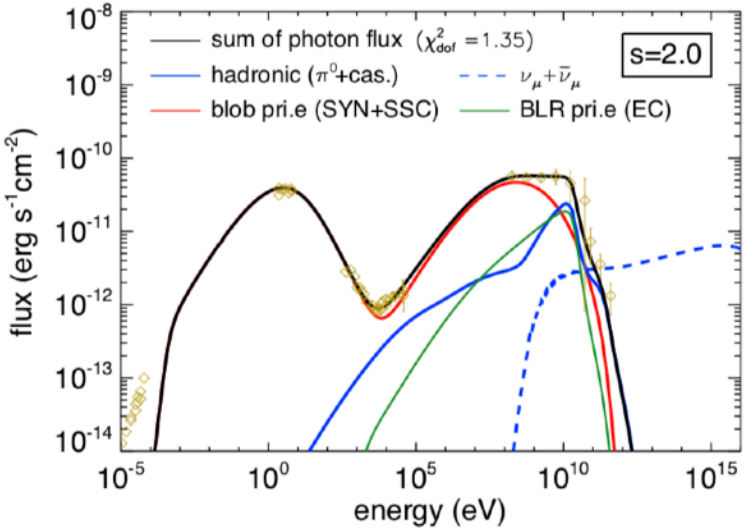
Can p-p interactions be important?

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

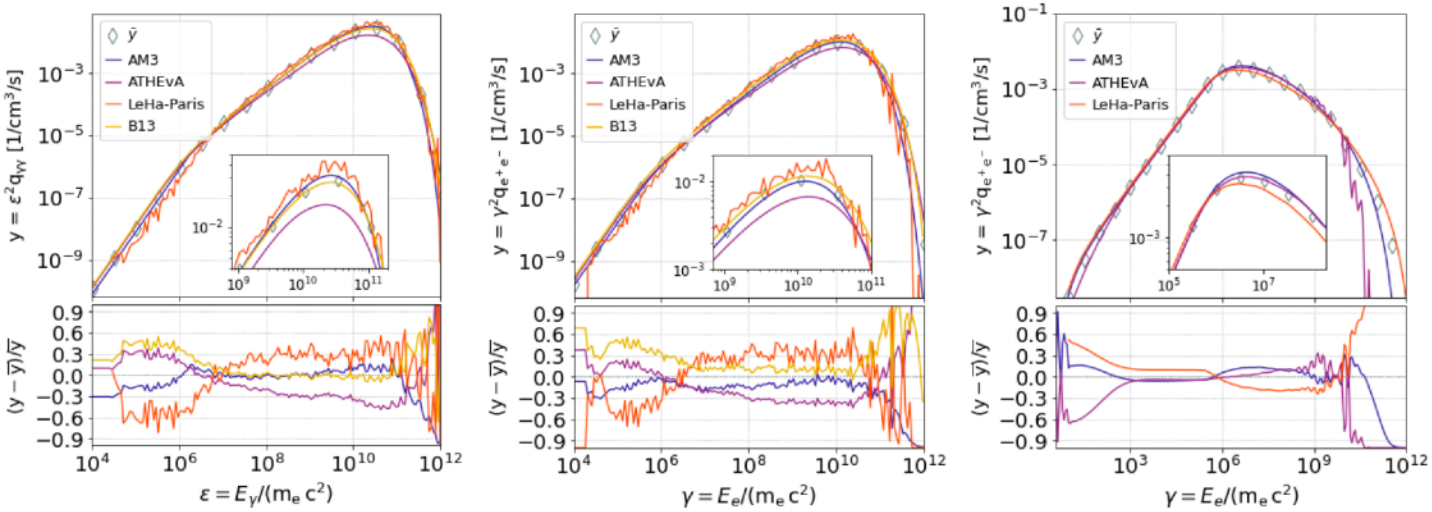
Comparison of four numerical hadronic codes in the literature:
AM3 (Gao et al. 2017), Athena (Dimitrakoudis et al. 2012),
B13 (Böttcher et al. 2013), LeHa-Paris (Cerruti et al. 2015)

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

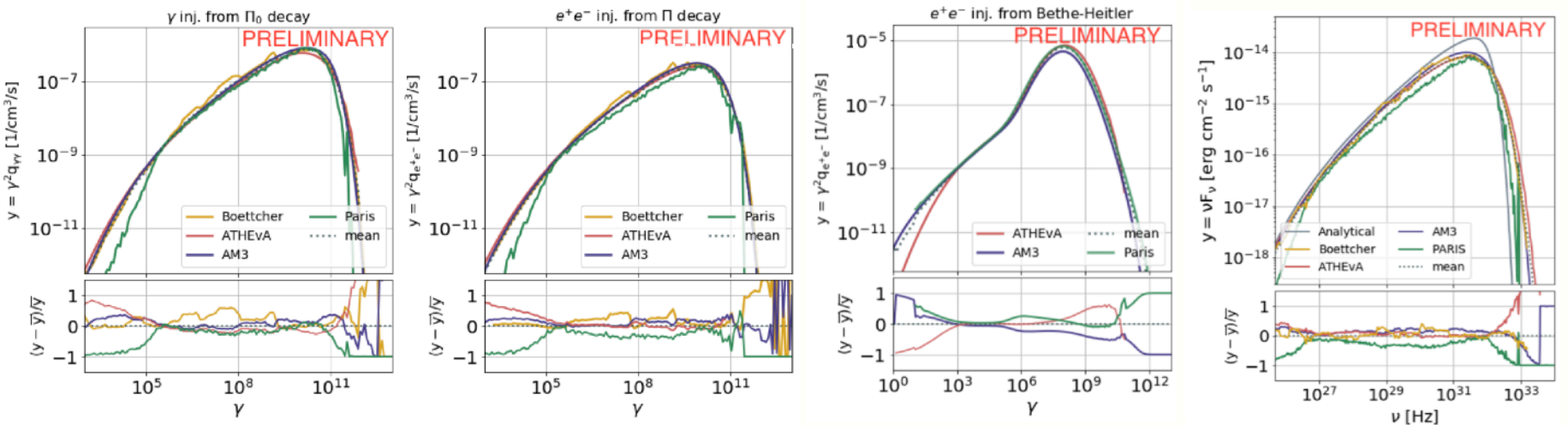
- Compute systematic uncertainties from theoretical simulations
- Release all files as benchmark for future developments

HADRONIC CODE COMPARISON

Power-law protons on power-law photons



Proton-synchrotron scenario

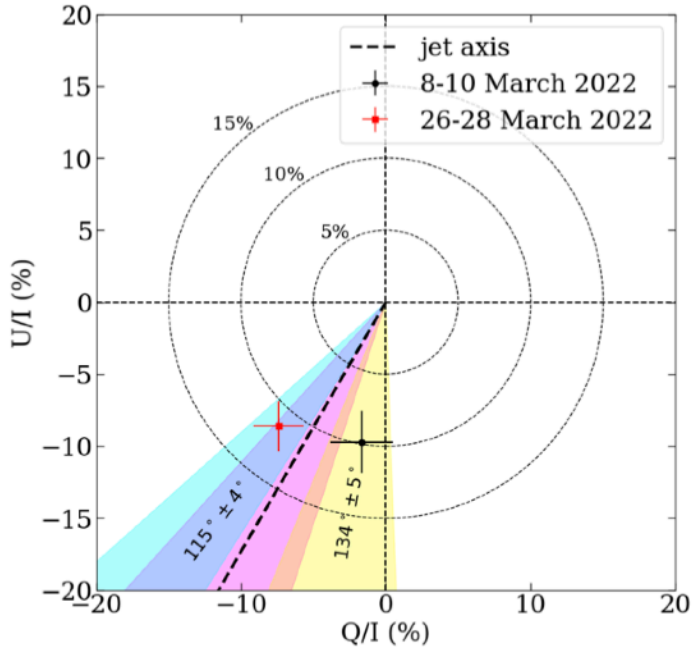


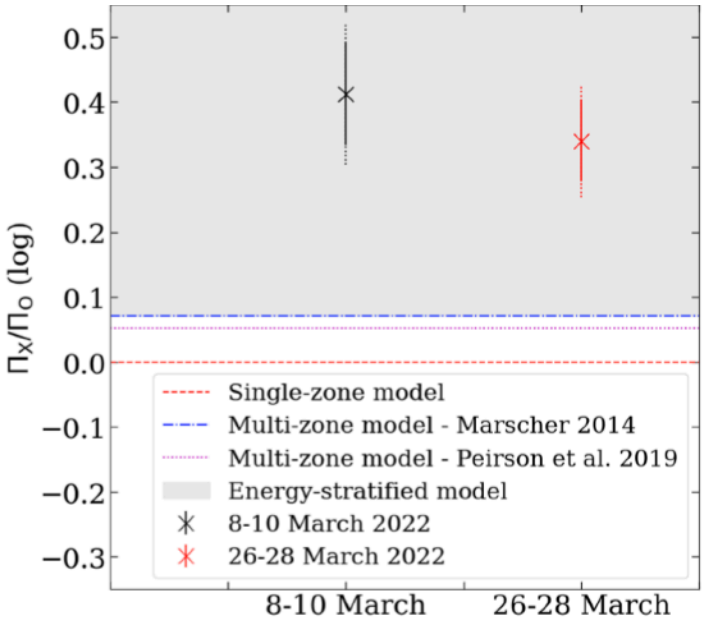
ICRC 2022 proceedings

IXPE RESULTS

X-rays are polarized as expected, but much more than optical!

→ stratified emitting region with high energy particles closer to the acceleration site





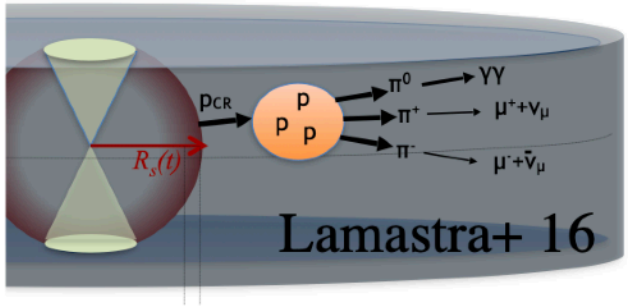
Is this the end of homogeneous single-zone models?

Liodakis et al. 2022

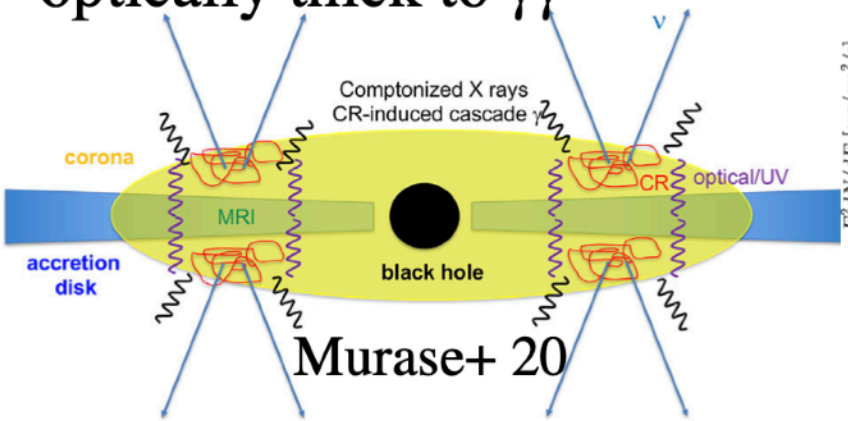
NGC 1068 (AGN) models

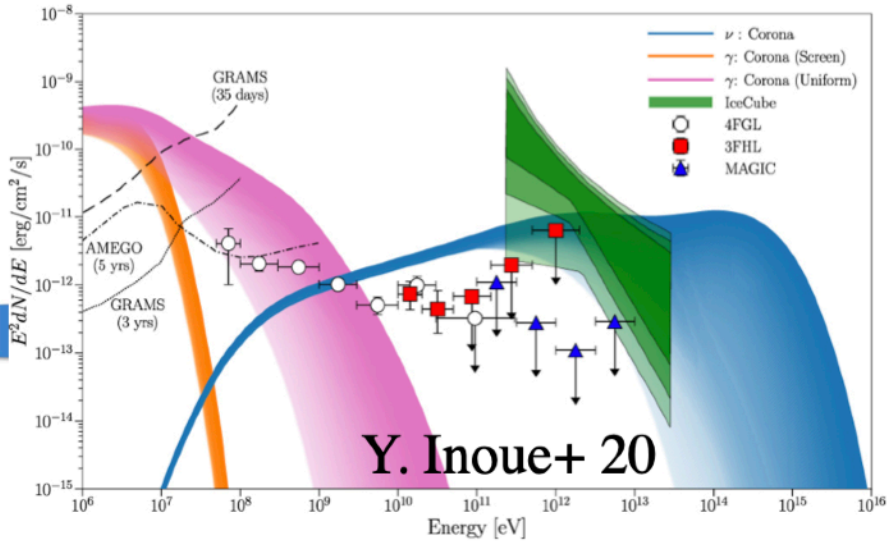
neutrino + gamma from NGC 1068: AGN origin?

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

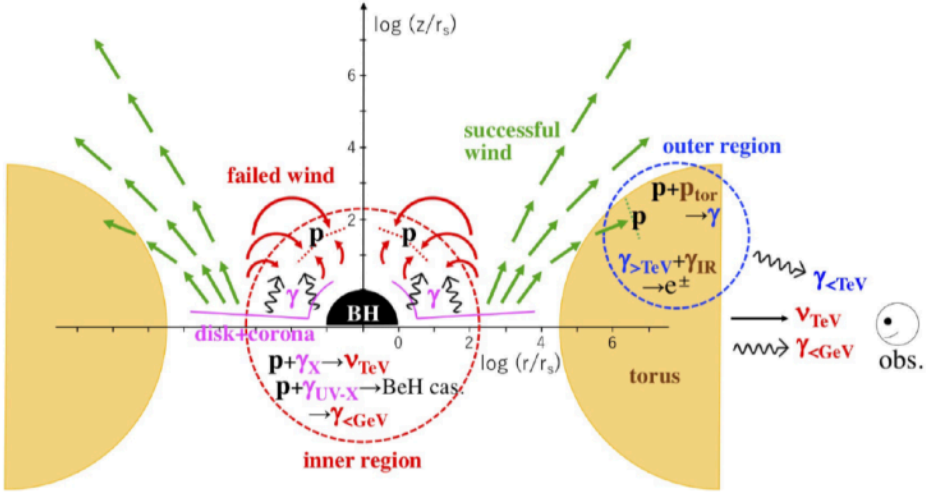


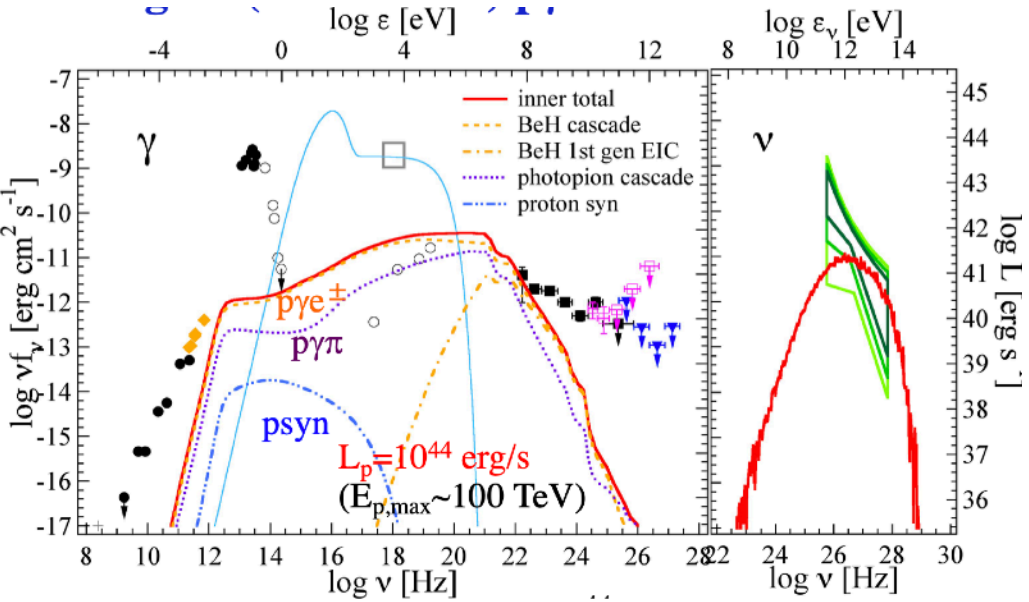


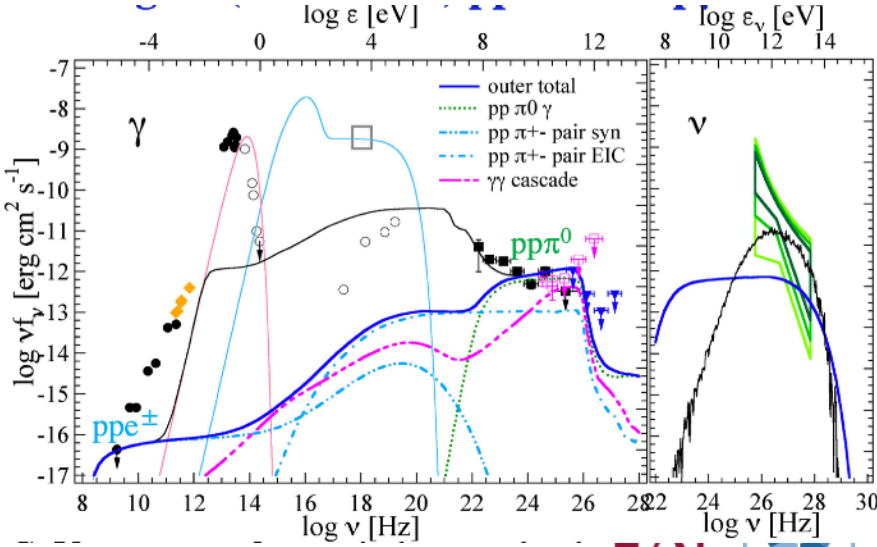
Slides by S. Inoue (Gamma 2022), submitted, see arXiv

NGC 1068 (AGN) models

Slides by S. Inoue (Gamma 2022), submitted, see arXiv







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

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