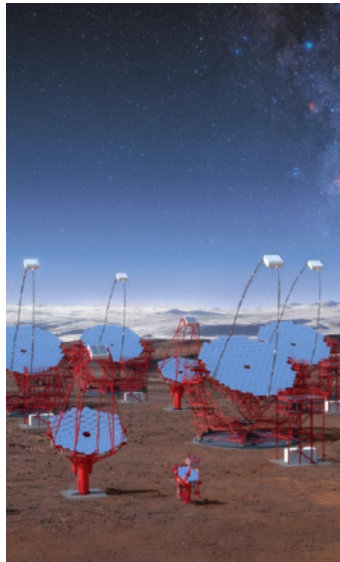

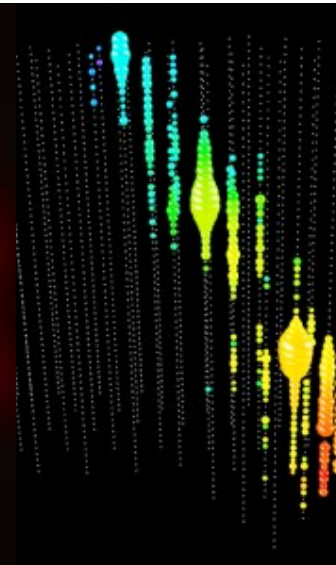
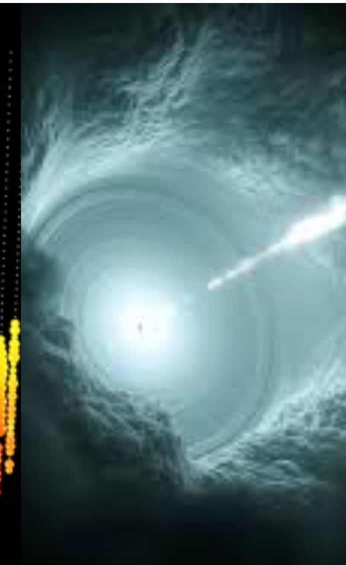

Blazar hadronic models

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Astroparticule et Cosmologie (APC)

Sexten MMSN schol

Sexten
July 1, 2025

BLAZARS EMISSION MODELS

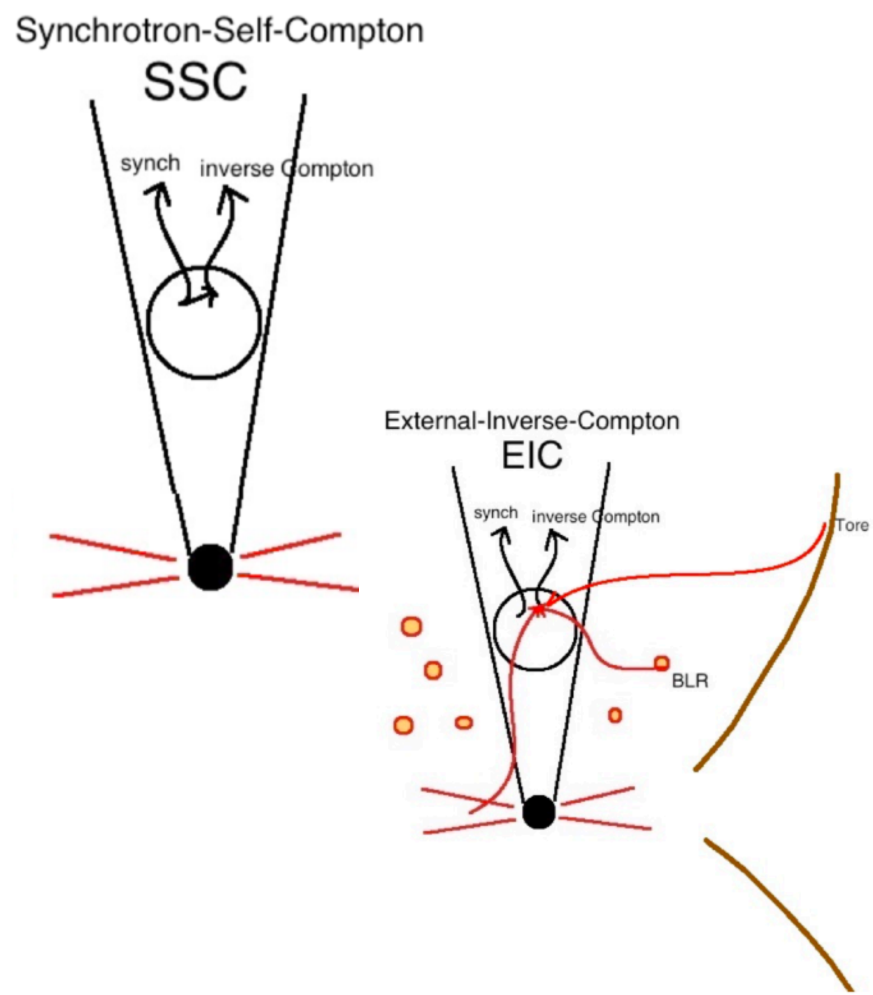
The low-energy SED component is synchrotron emission by electrons

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



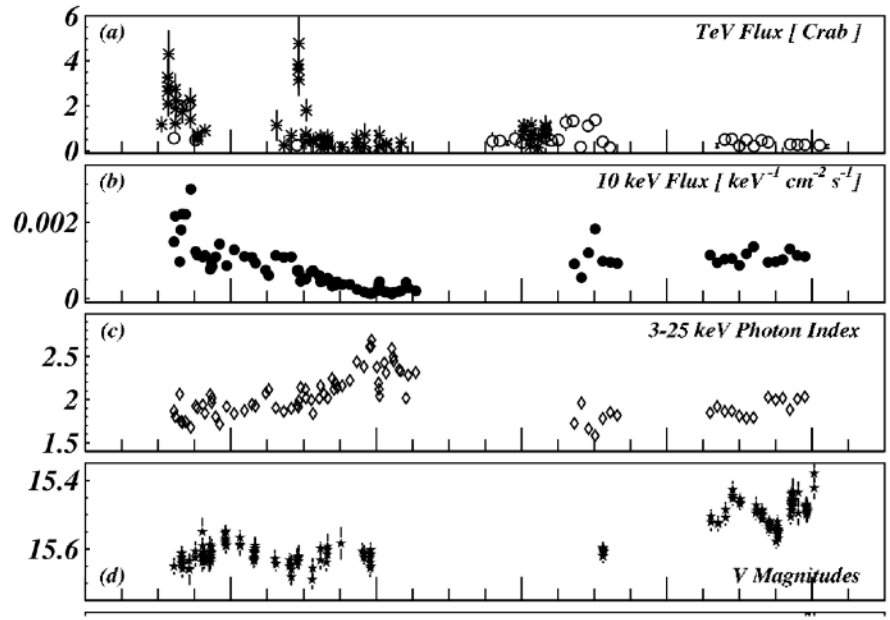
BLAZARS EMISSION MODELS

Why adding hadrons if leptons work??

1) 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)



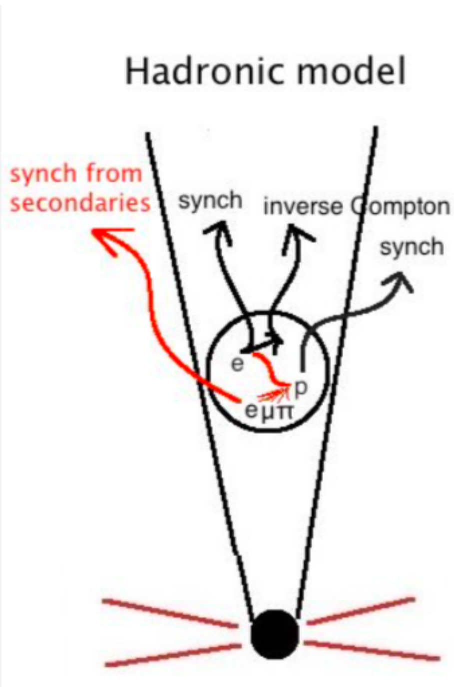
Krawczynski et al. 2004

2) Natural link with cosmic-rays and neutrinos

BLAZARS EMISSION MODELS

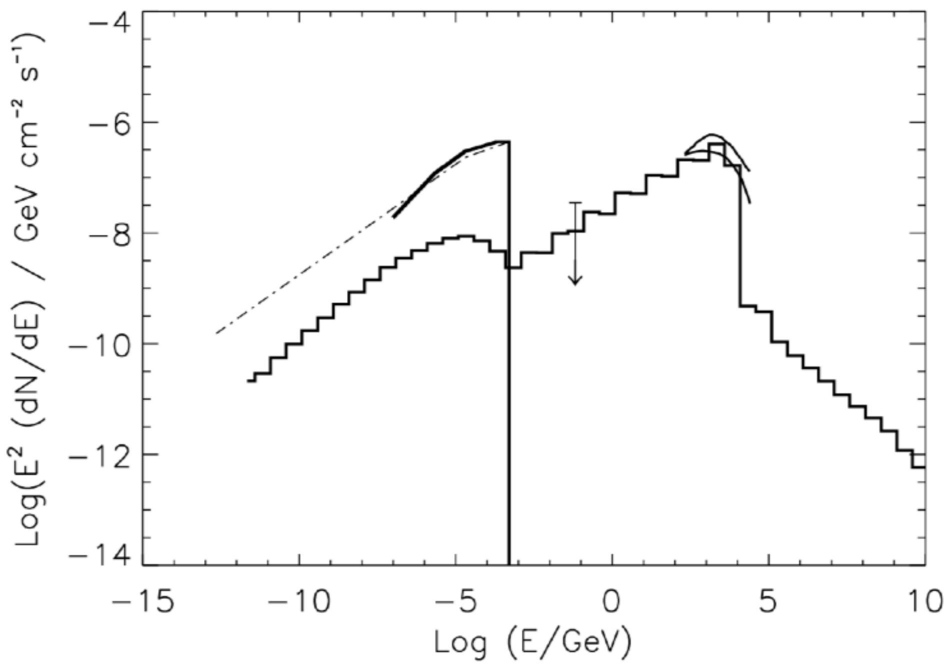
Hadronic models

Simplest hadronic model:



The high-energy component is proton synchrotron radiation

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



[Mucke & Protheroe 2001]()

HADRONIC INTERACTIONS

Proton-photon interactions complicate the modeling: Pion production

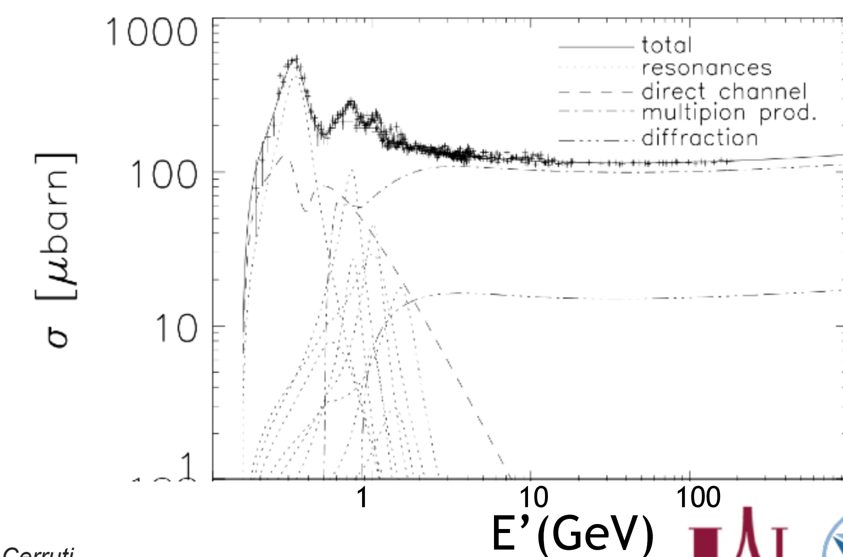
$$p + \gamma = p' + \pi^0 \rightarrow p' + 2\gamma$$
$$p + \gamma = n + \pi^+$$
$$p + \gamma = p' + \pi^+ + \pi^-$$

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

The only relevant radiative processes are from leptons!

Pair cascades from neutral pion decay and charged pion decay

In some cases, muon synchrotron can be important



HADRONIC INTERACTIONS

(The same thing holds for proton-proton interactions.
In jets the p-p is not important)

HADRONIC INTERACTIONS

Bethe-Heitler pair production is the direct production of a pair in proton-photon interactions

$$p + \gamma \rightarrow p + e^- + e^+$$

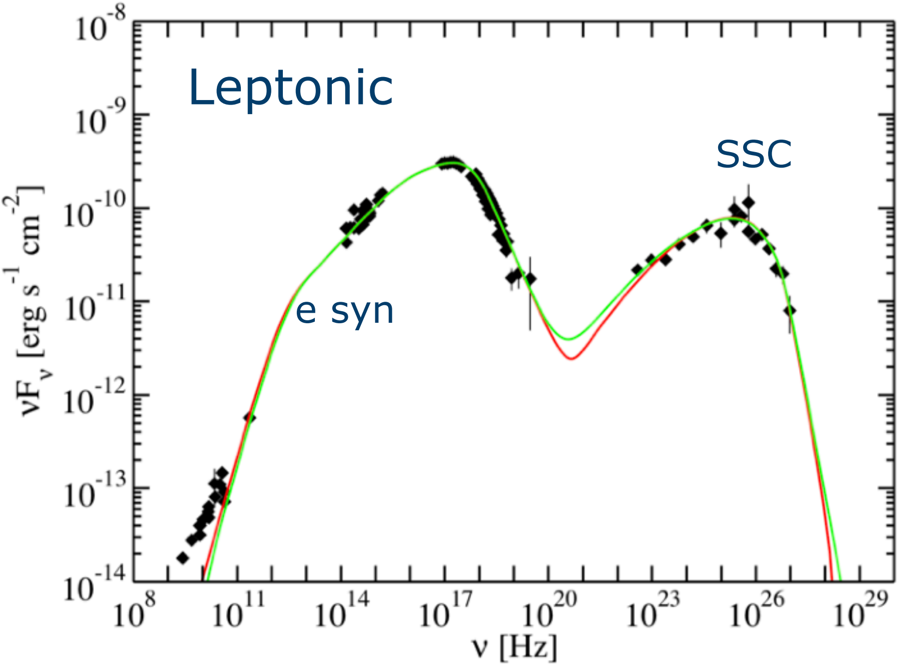
It is a process that competes with photo-meson
(But without producing neutrinos!)

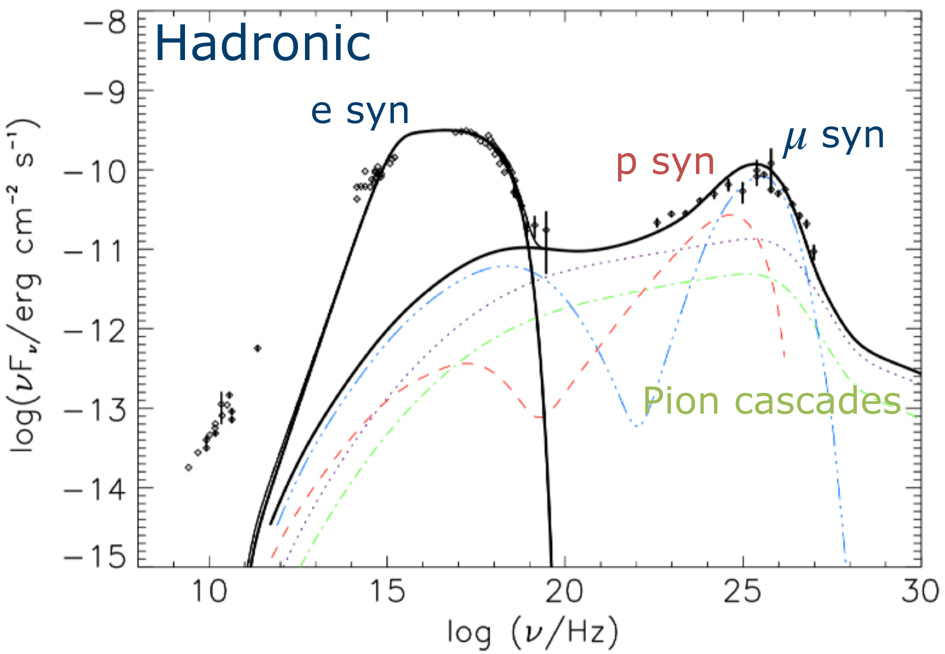
Different thresholds and different cross sections:
The ratio between photo-meson and BH depends on the spectrum of protons and photons

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011





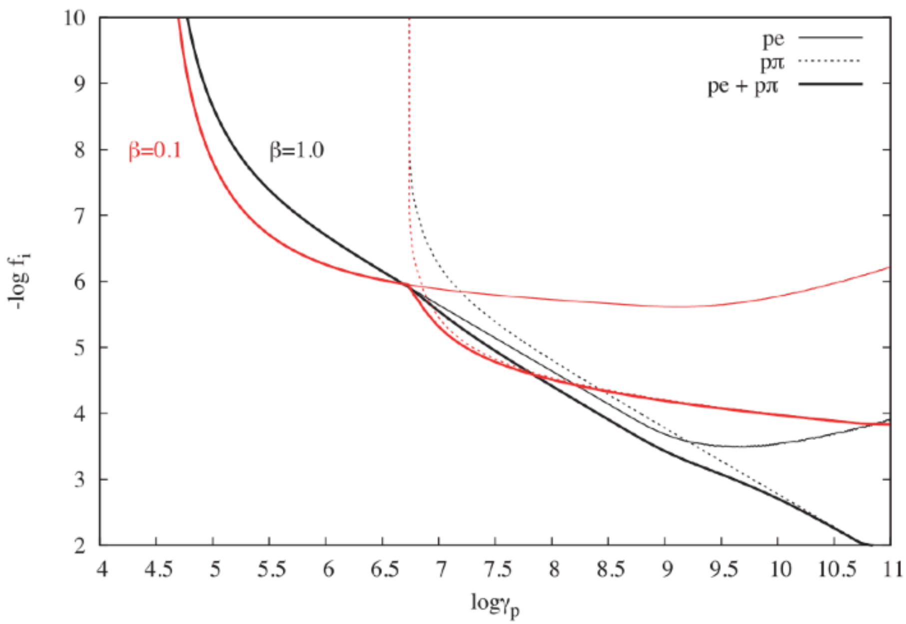
Abdo et al. 2011

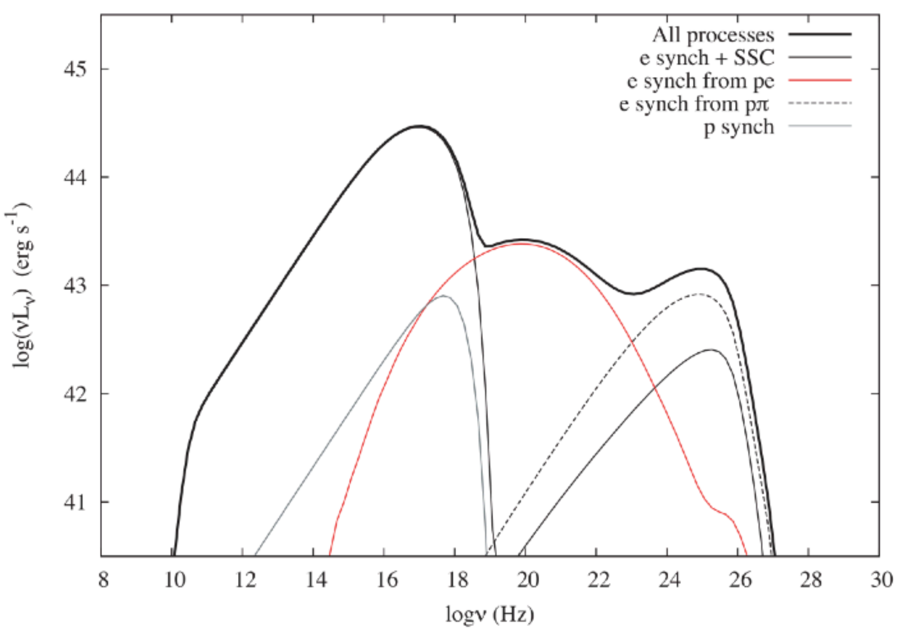
BLAZARS EMISSION MODELS

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

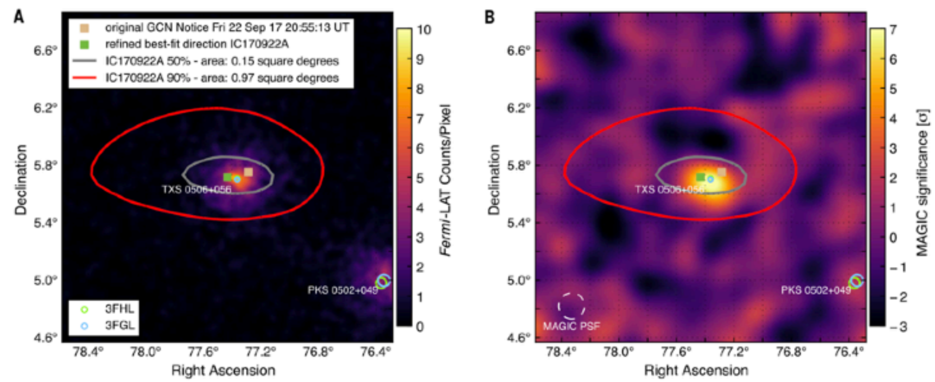


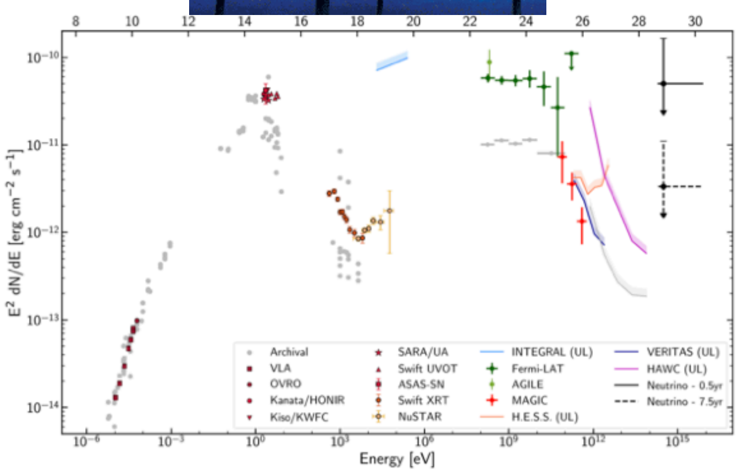


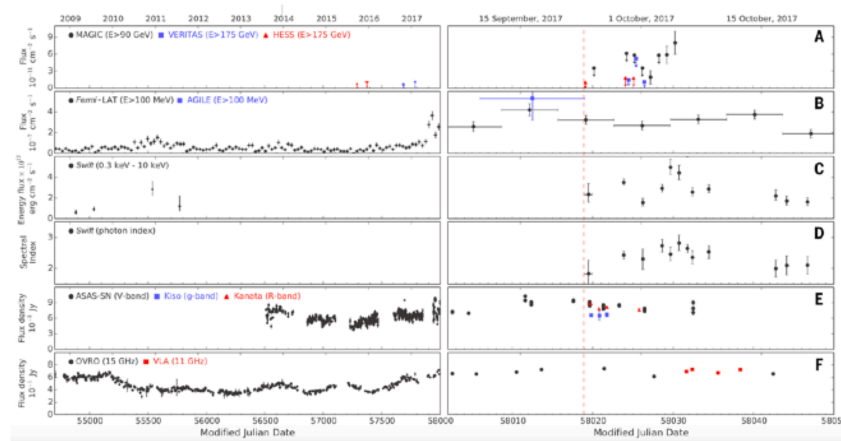
Petropoulou & Mastichiadis 2015

IceCube-170922A / TXS 0506+056

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

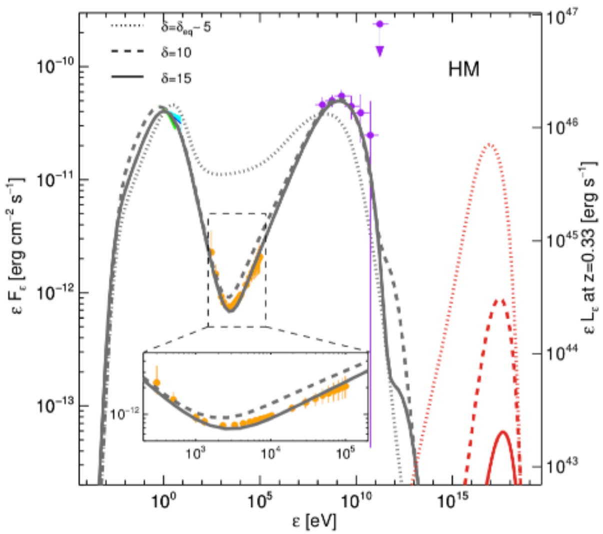






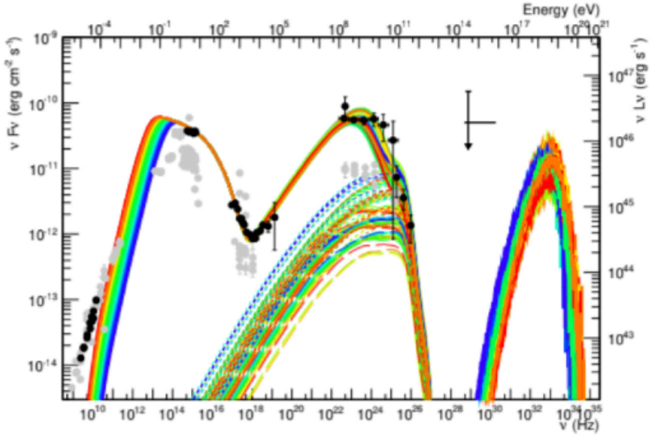
[IceCube, Fermi, MAGIC et al. 2018]()

TXS 0506+056: the 2017 flare



Keivani et al. 2018

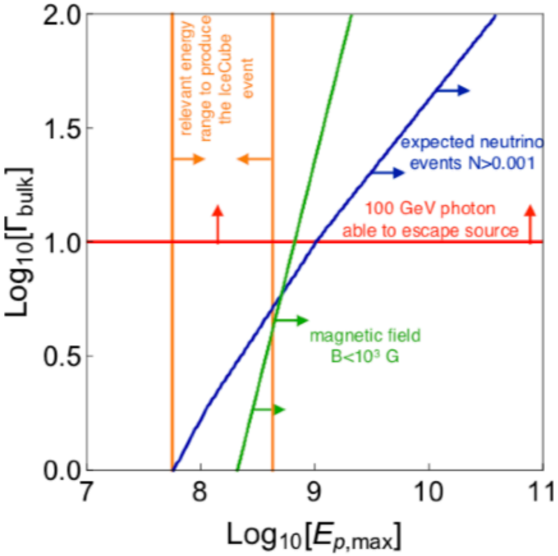
$\nu \simeq 10^{-5}\ yr^{-1}$



(a) Proton synchrotron modeling of TXS 0506+056

Cerruti et al. 2019

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

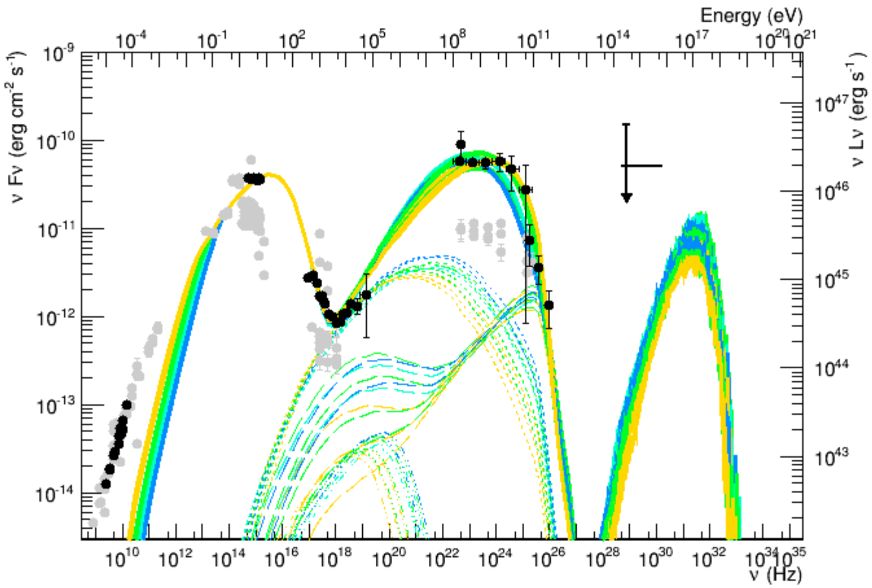


Gao et al. 2018

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

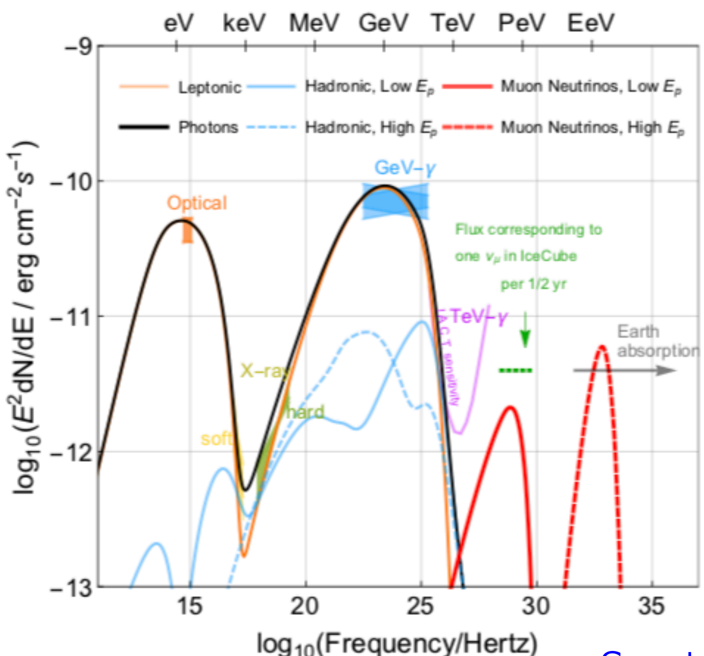
TXS 0506+056: the 2017 flare

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

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

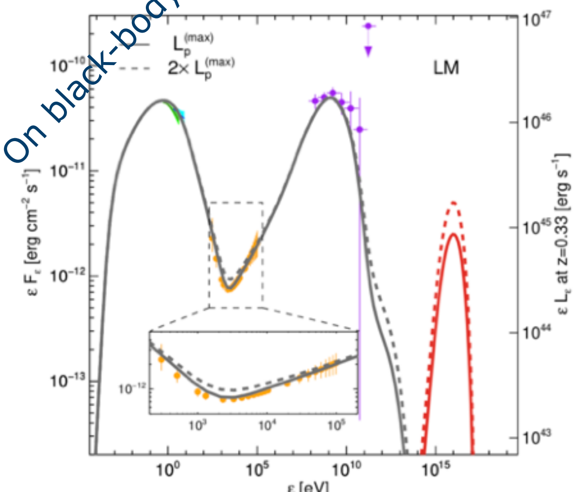
They can work: neutrino rates of the order of 0.1 / yr

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

TXS 0506+056: the 2017 flare

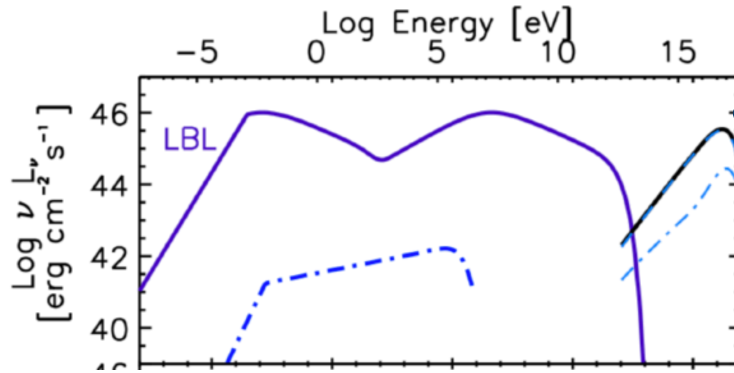
Proton-photon interaction on external photon fields

On black-body



Keivani et al. 2018

$$L_{jet} = (4 - 150) \times 10^{45} erg/s$$
$$\nu_{max} = 0.02\ yr^{-1}$$

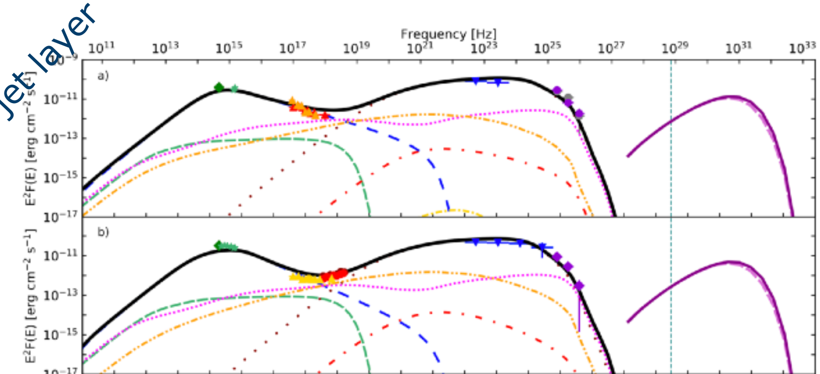


On RIAF

Righi et al. 2019

$$L_{jet} = 6.3 \times 10^{45} erg/s$$
$$\nu = 0.14\ yr^{-1}$$

On jet layer



$$L_{jet} = (3 - 8) \times 10^{45} erg/s$$
$$\nu = 0.12 - 0.34\ yr^{-1}$$

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

Ansoldi et al. 2018

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

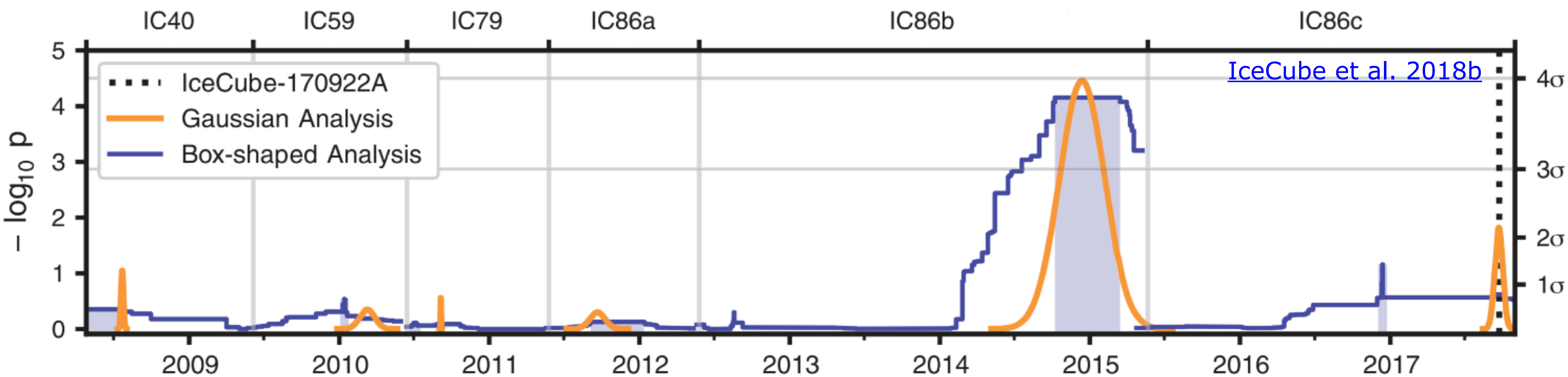
- Simple one-zone models can be enough, at the expenses of a high proton luminosity, and only if the acceleration efficiency is low

- 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)

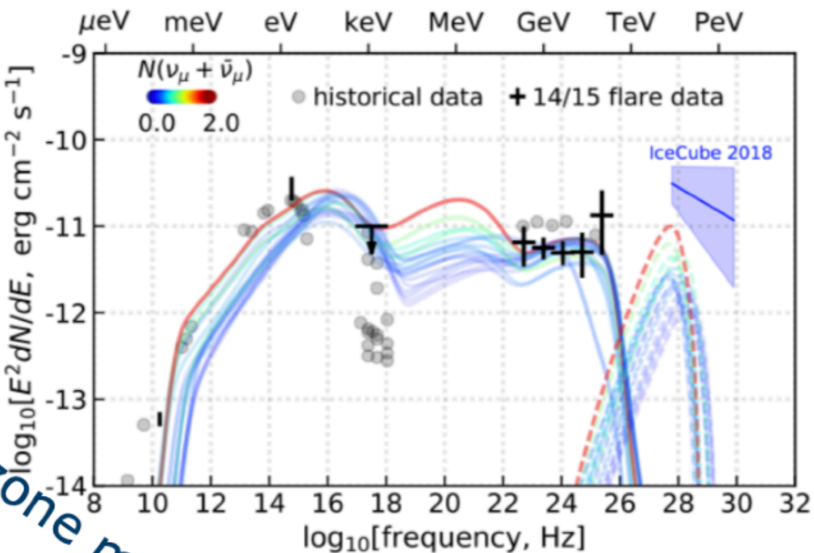


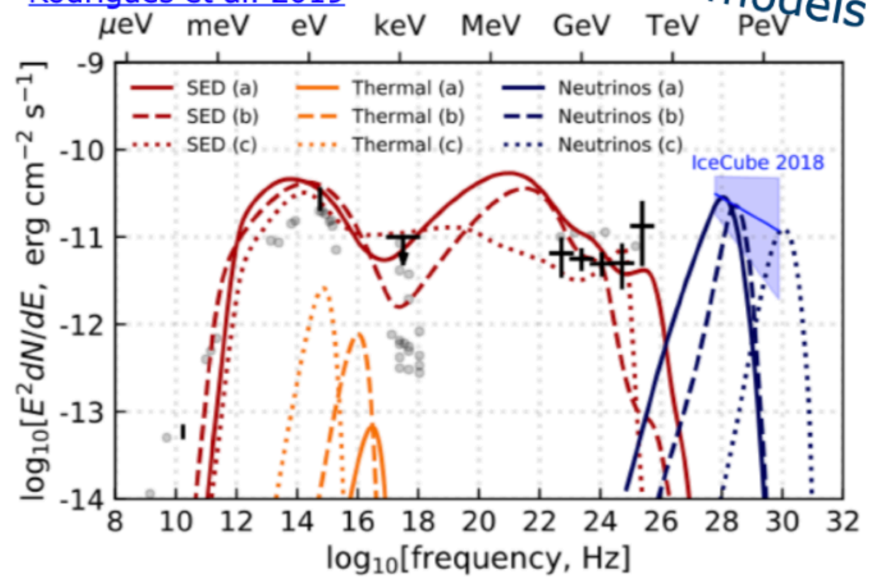
3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event

TXS 0506+056: the 2014/15 flare

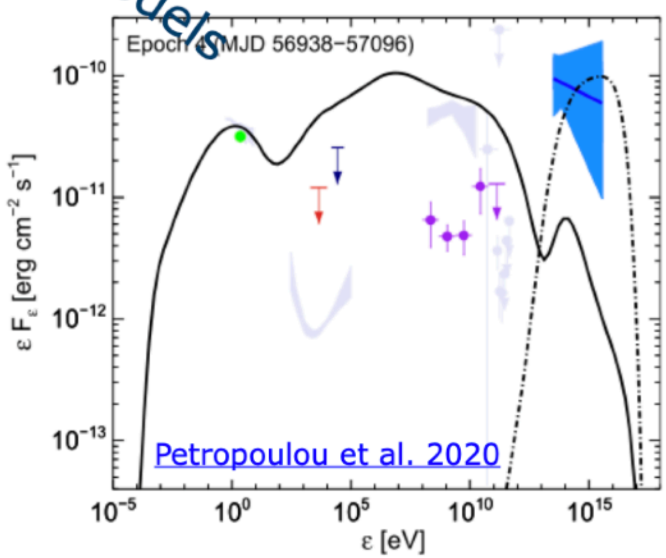
External field models

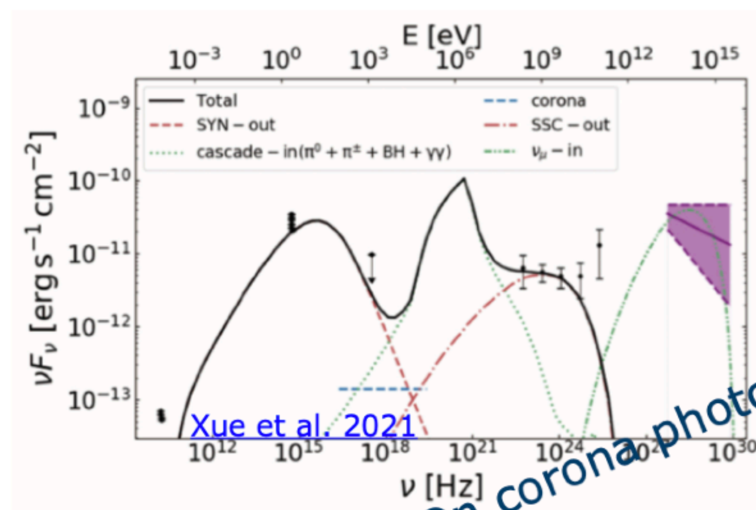
Rodrigues et al. 2019





1-zone models





On corona photons

TXS 0506+056: the 2014/15 flare

What did we learn?

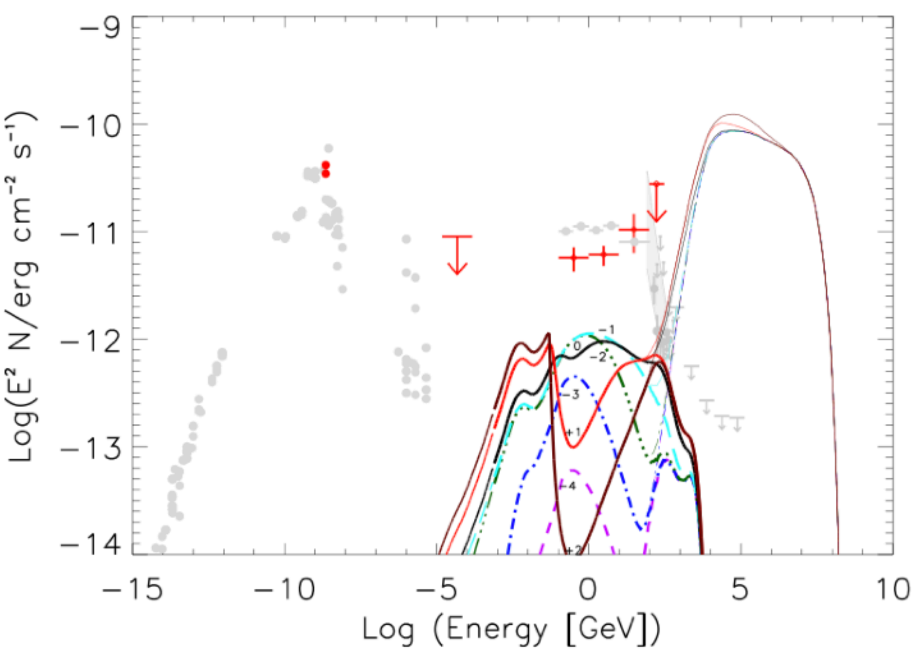
- Single zone models are disfavored : very difficult to get no photons with the neutrino flare
(although there may be some room in the MeV band)

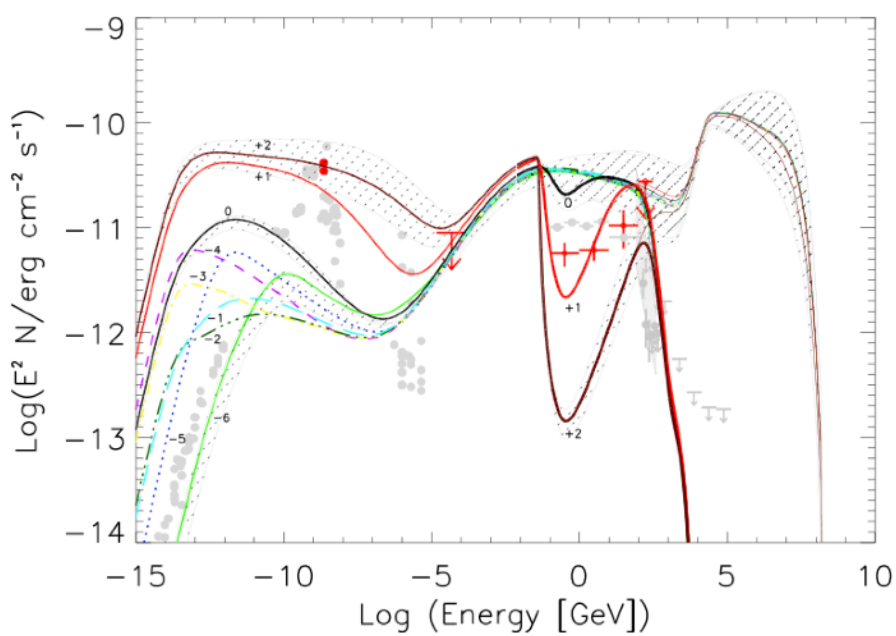
- A possible solution could be a two-zone models:
the ν and the γ-ray emitting region are not the same

TXS 0506+056: the 2014/15 flare

The exact cascade spectrum varies a lot in the parameter space

inverse-Compton cascade vs synchrotron cascade





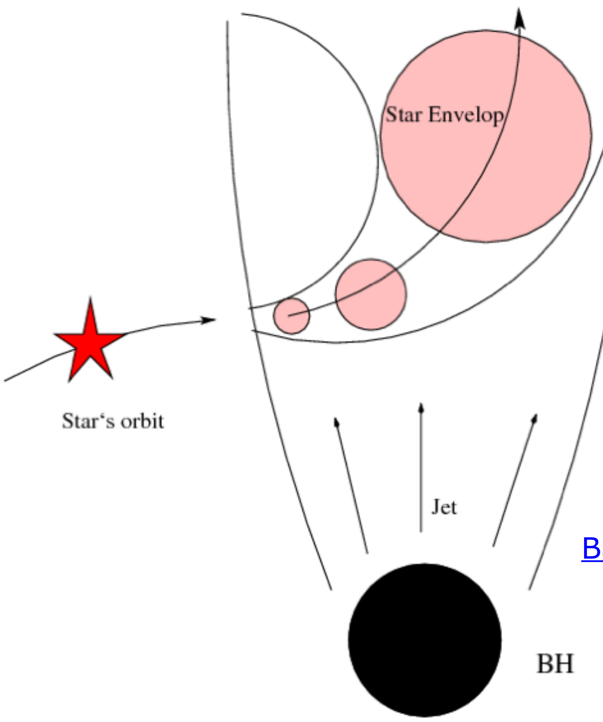
Reimer et al. 2020

ON p-p INTERACTIONS

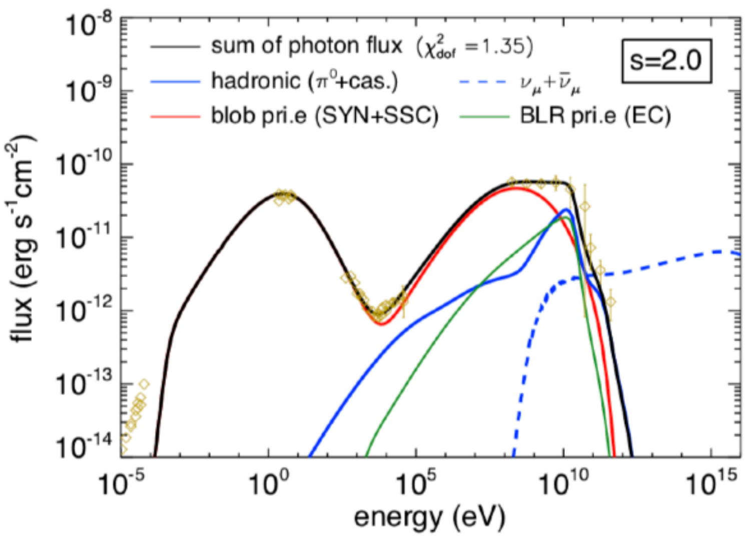
Can p-p interactions be important?

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 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)

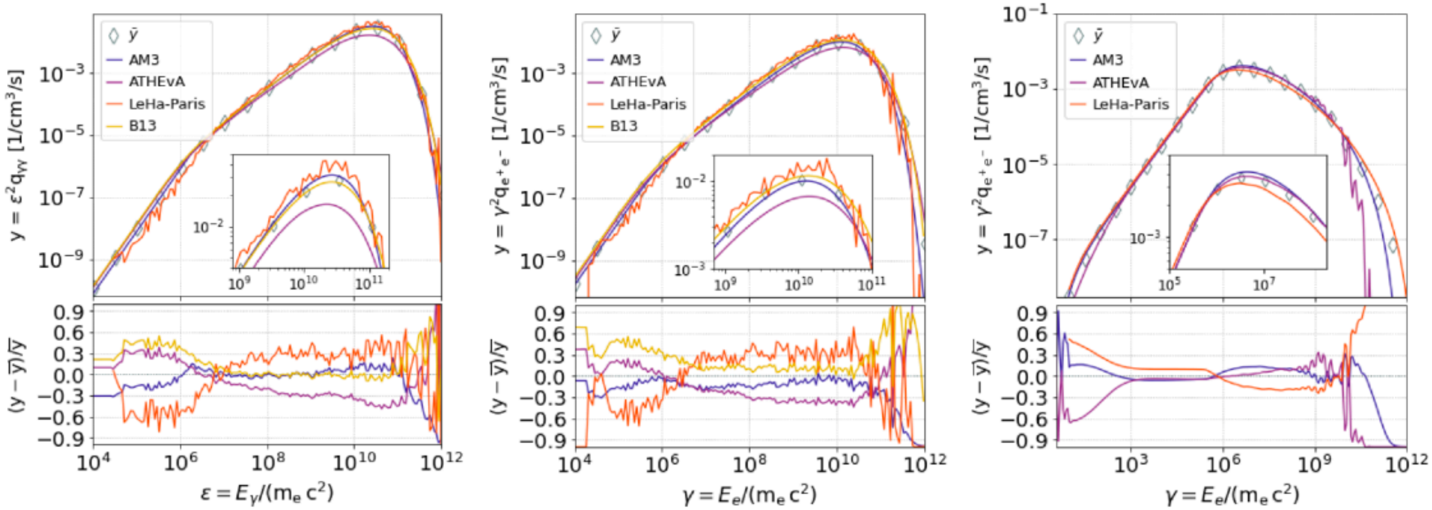
- run tests from simple 'artificial' cases
(Mono-energetic protons on black-body)
to 'realistic' ones
(proton-synchrotron or lepto-hadronic)

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

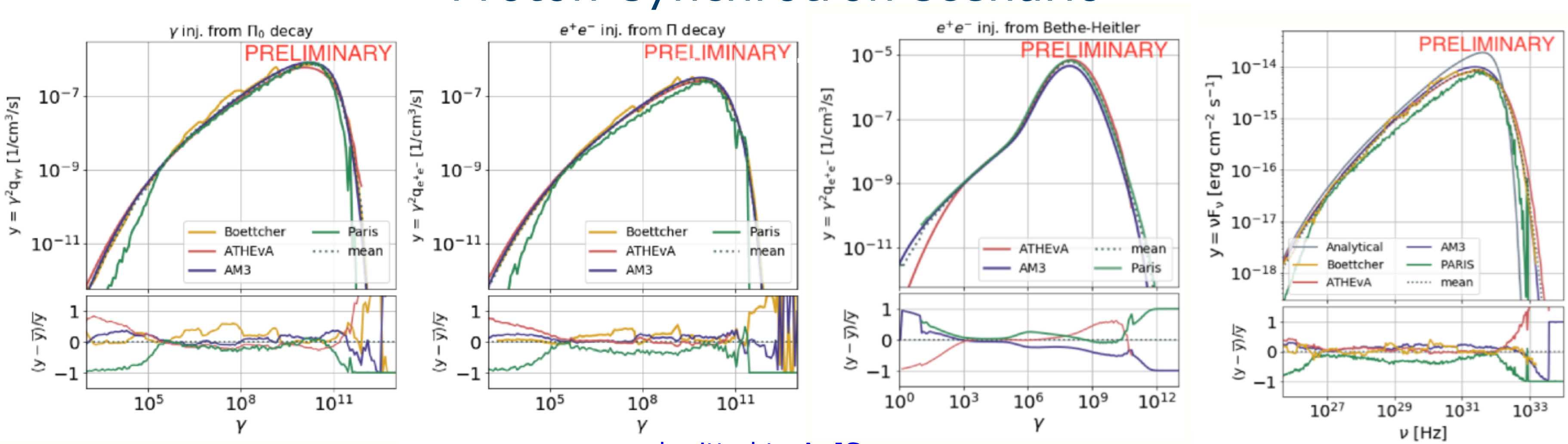
Take home message: spectral shapes are ok; 40% spread in normalization

HADRONIC CODE COMPARISON

Power-law protons on power-law photons



Proton-synchrotron scenario



[submitted to ApJS]

PKS 0735+178

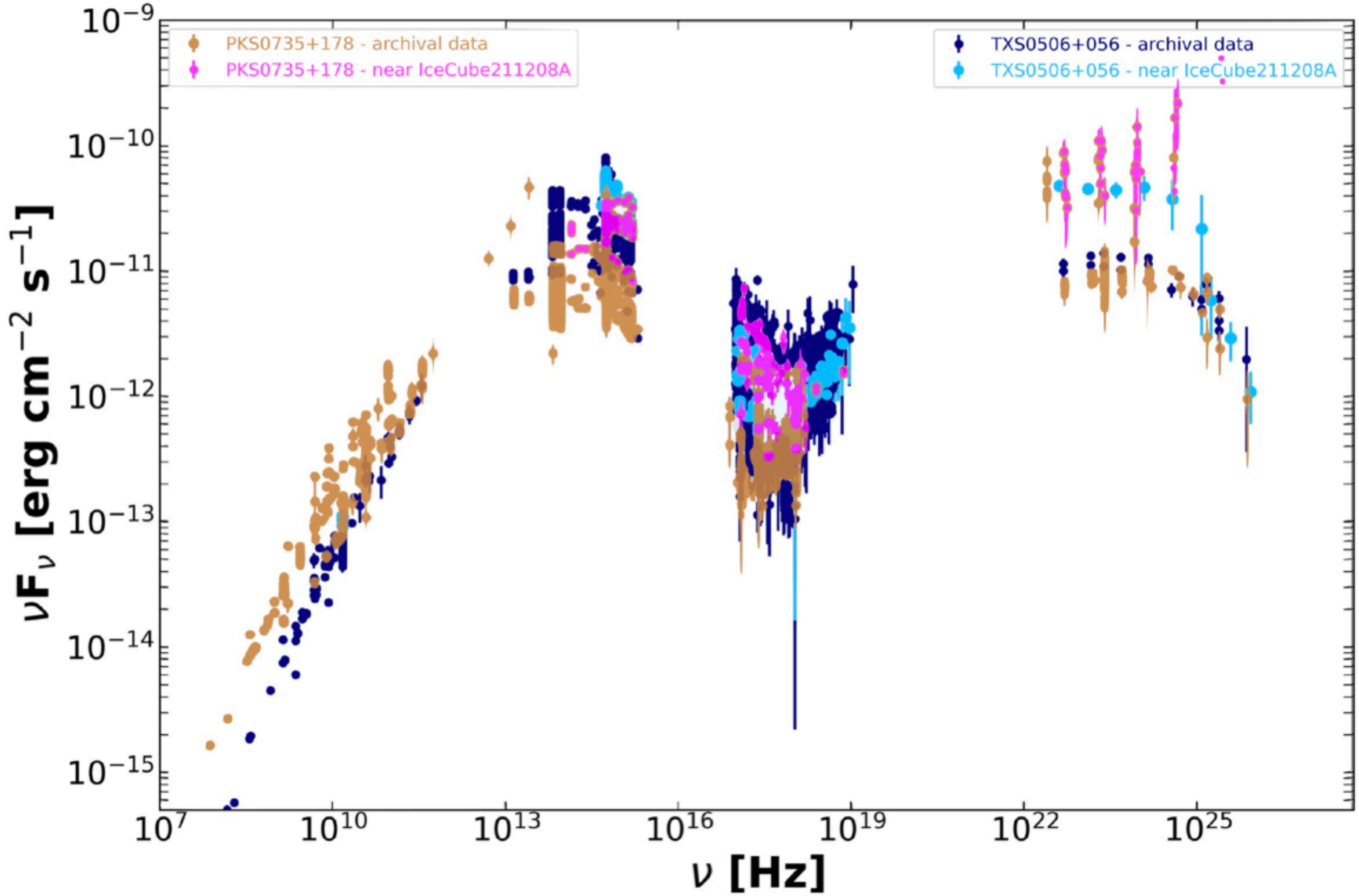
IBL@z=0.65? (>0.42) and IC211208A:

- 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

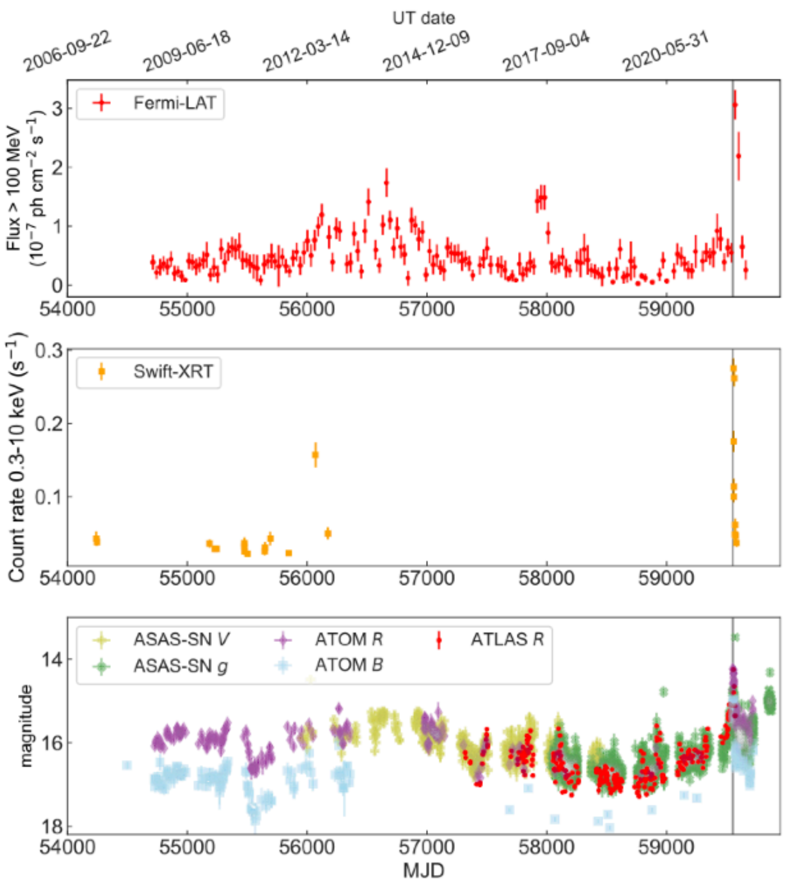
PKS 0735+178

First theory paper by [Sahakyan et al. 2022]

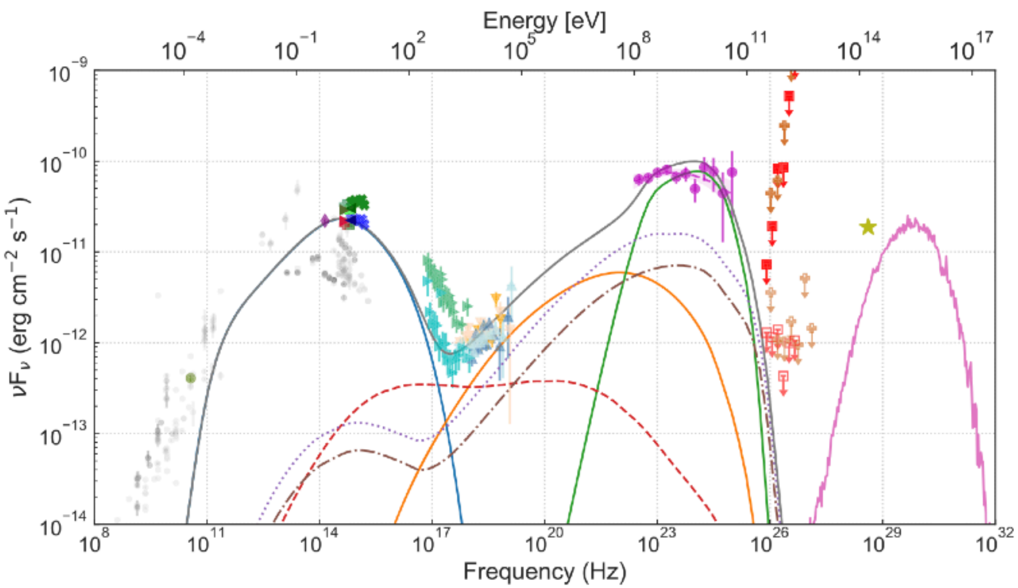


PKS 0735+178

Acharyya et al. 2023



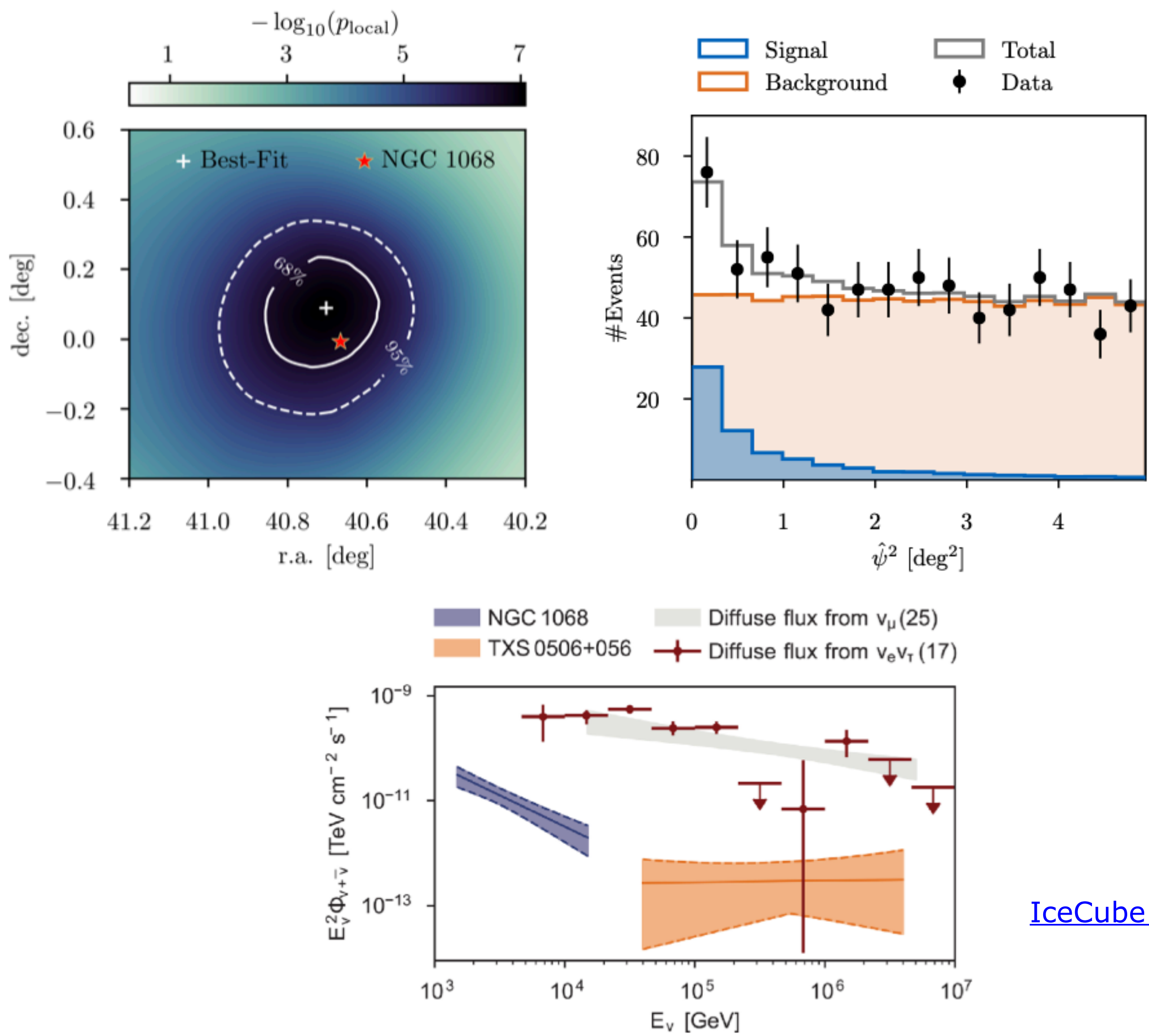
(a)



Matteo Cerruti

NGC 1068

4σ excess from the Seyfert galaxy NGC 1068

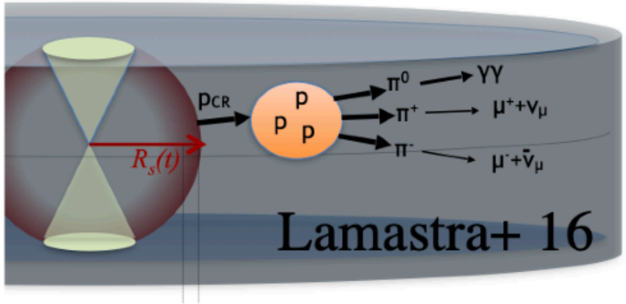


IceCube et al. 2022

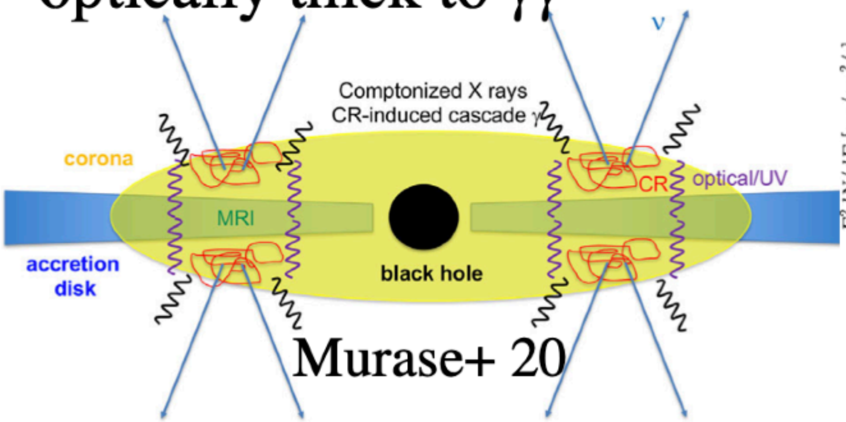
NGC 1068 (AGN) models

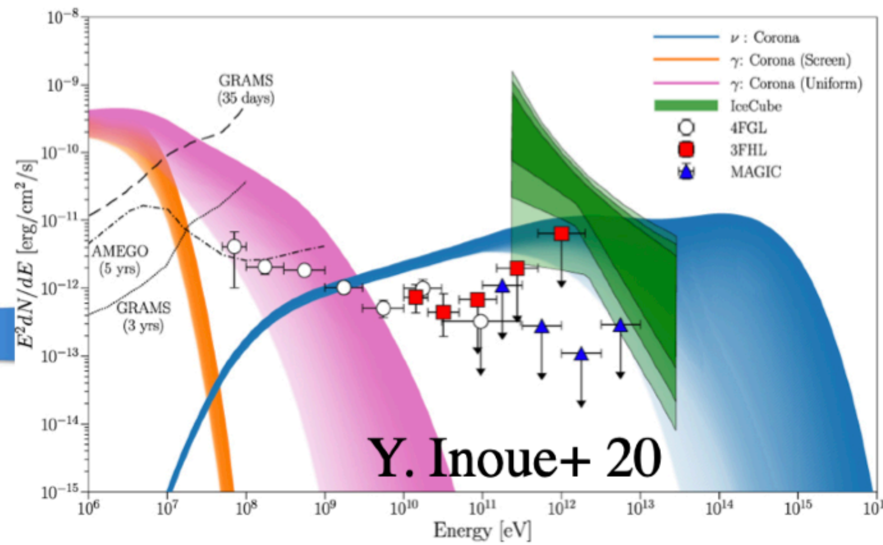
neutrino + gamma from NGC 1068: AGN origin?

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

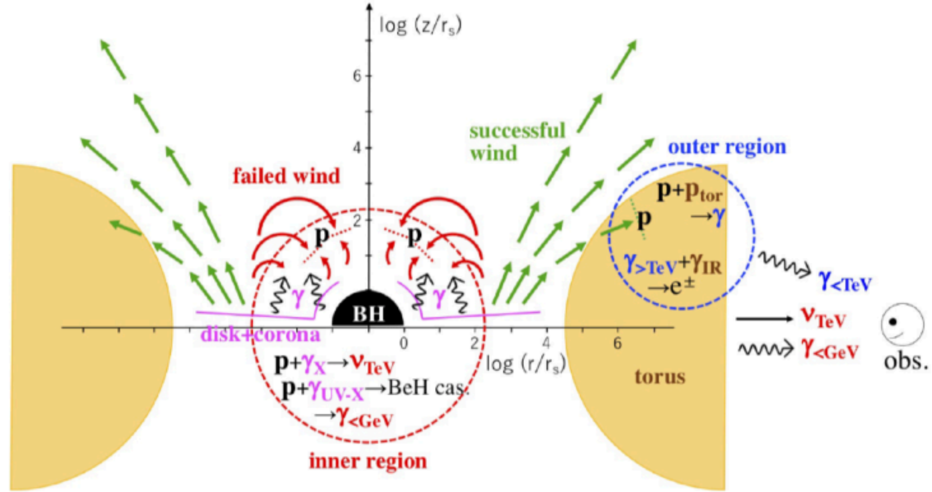


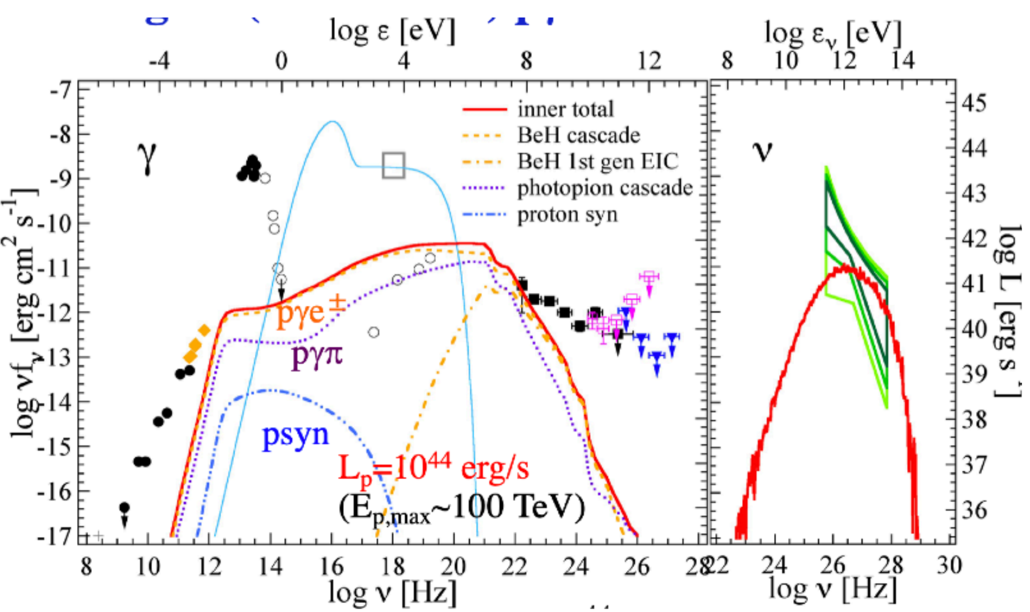


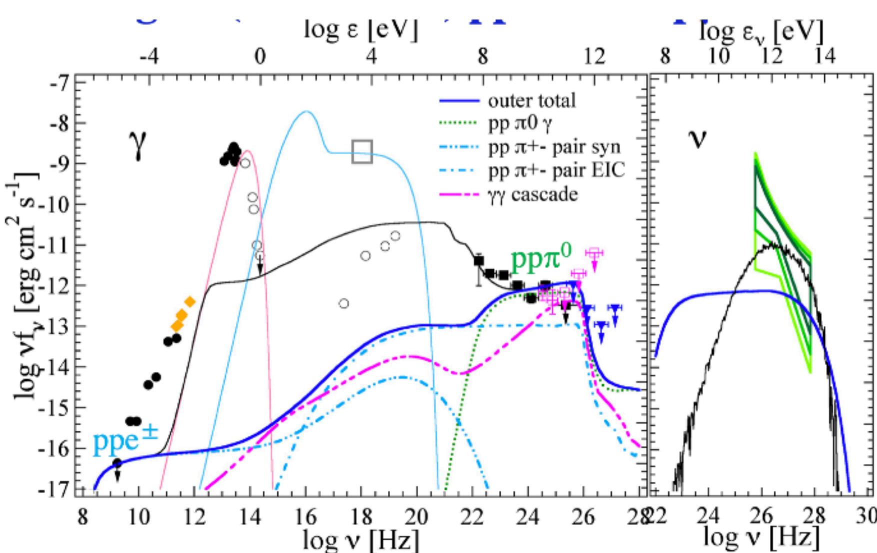
[Slides by S. Inoue (Gamma 2022), submitted, see arXiv]

NGC 1068 (AGN) models

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







WHICH CODES?

Open-source full lepto-hadronic codes:

AM3

LehaMoc

IF YOU LIKE RADIATIVE CODES…

New series of technical workshops focused on numerical multi-messenger modeling:

Three-days meetings in February, with co-working time

- Bochum 2023
- Paris 2024
- Berlin 2025
- **Athens 2026!**

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