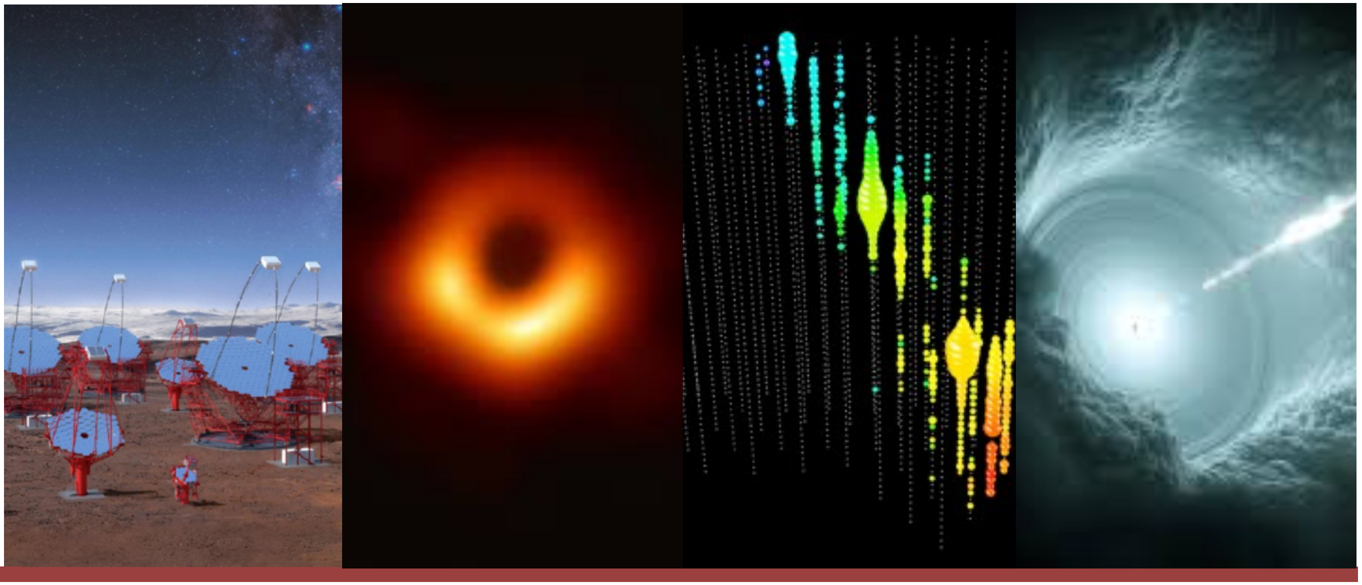


Searching for counterparts of high-energy neutrinos (from a theory PoV)

Matteo Cerruti

Université Paris Cité
Astroparticule et Cosmologie (APC)

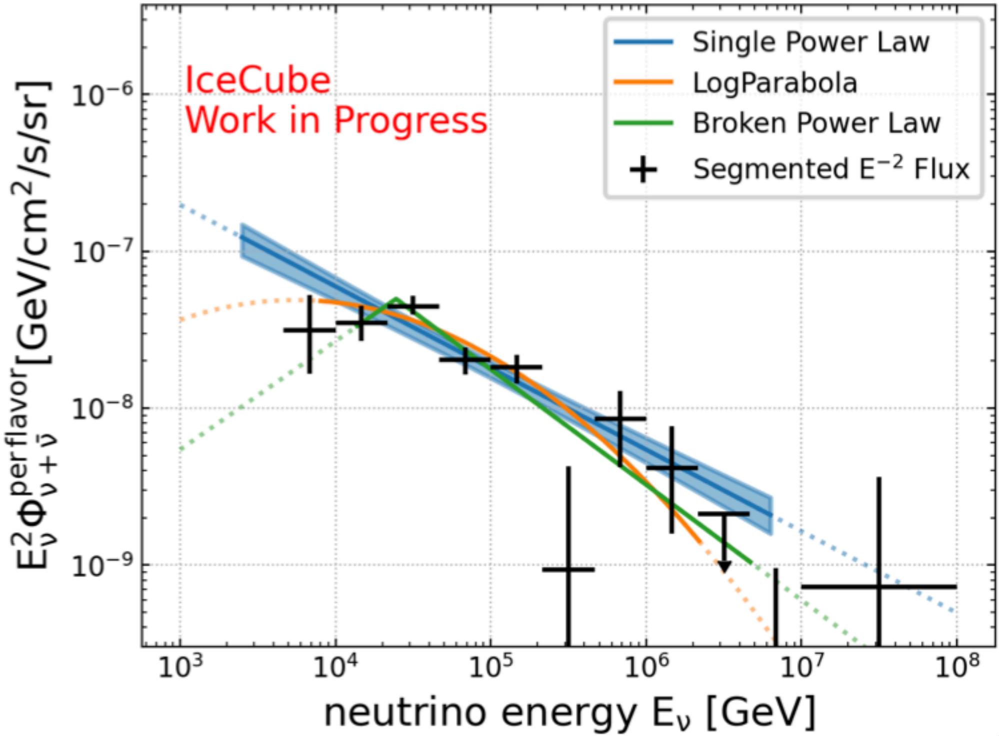
PNHE Theory Days

Paris
November 6, 2024

Diffuse High-Energy Neutrino Flux

First announced by IceCube in 2013

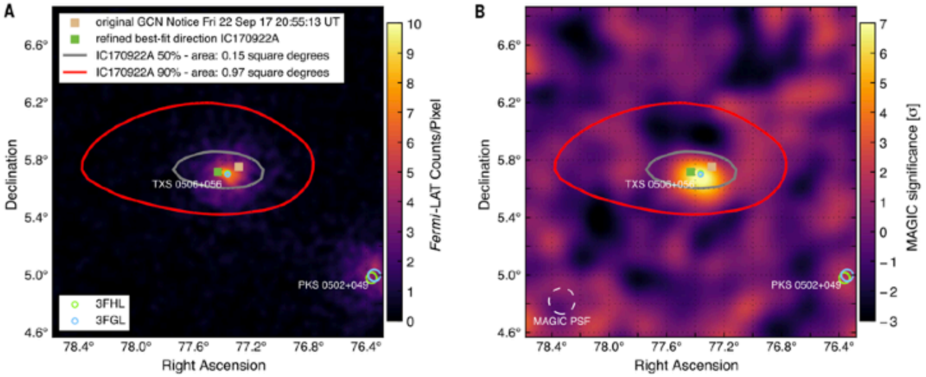
Spectrum consistent with a power law (here latest plot from ICRC 23)

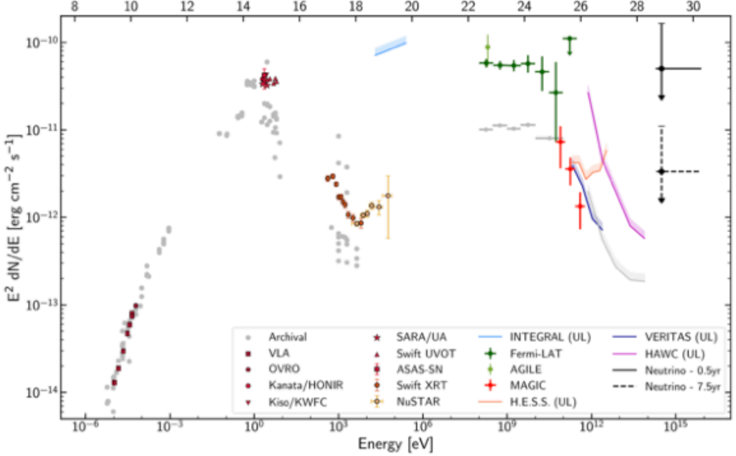


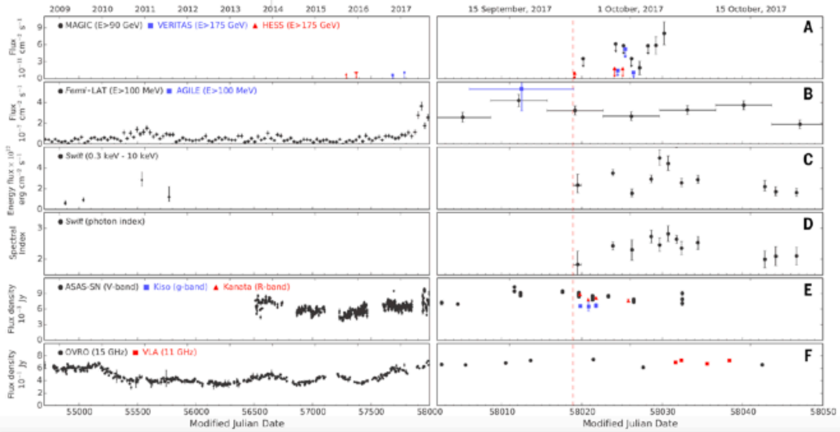
IceCube, Fermi, MAGIC et al. 2018

IceCube-170922A / TXS 0506+056

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



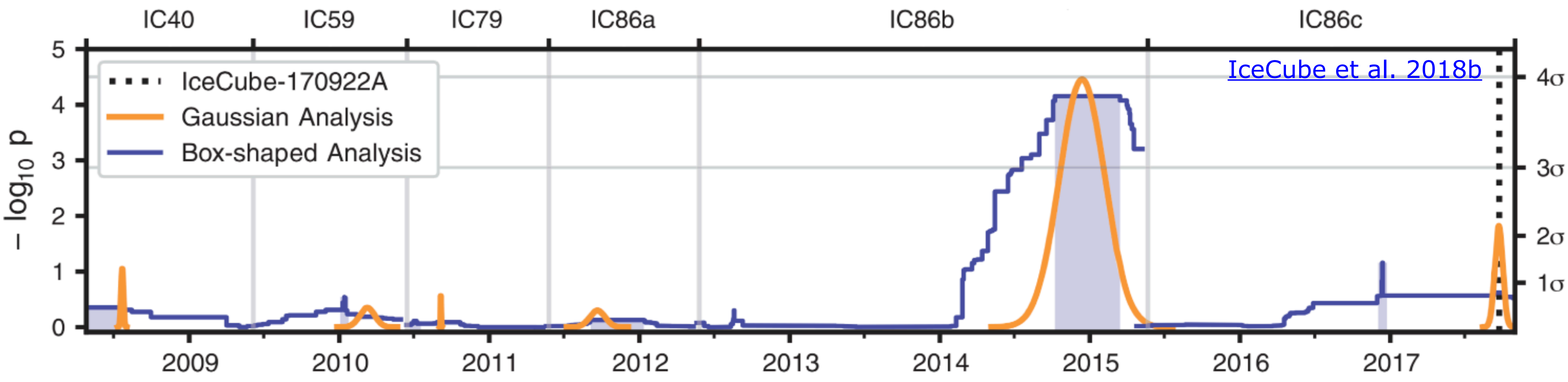




IceCube, Fermi, MAGIC et al. 2018

TXS 0506+056: the 2014/15 flare

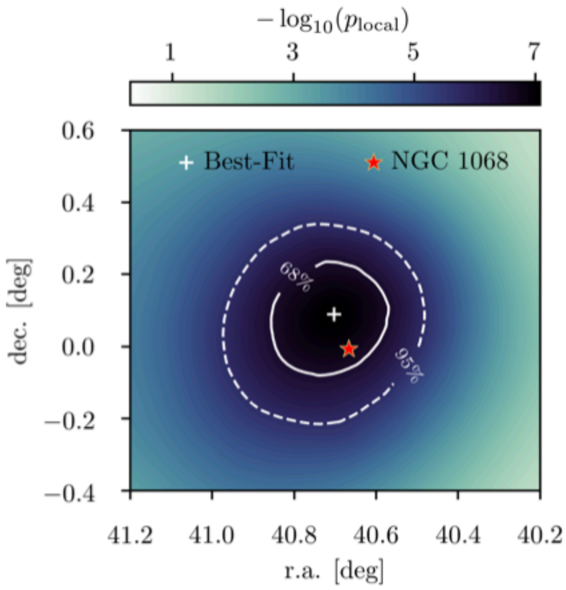
Detection of a second neutrino flare in 2014-2015
(without a gamma-ray counterpart)

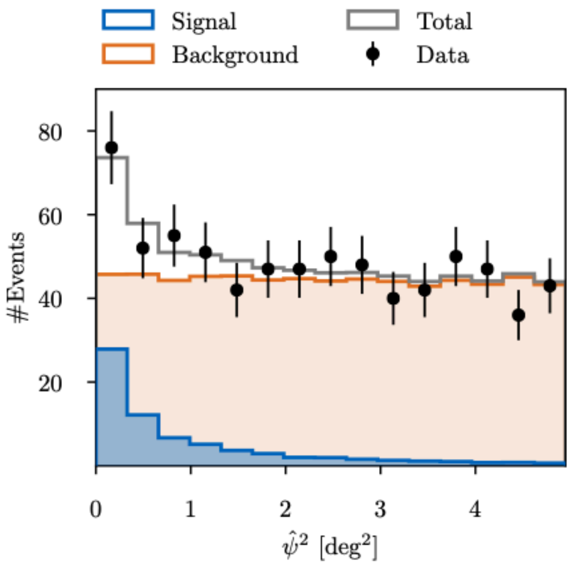


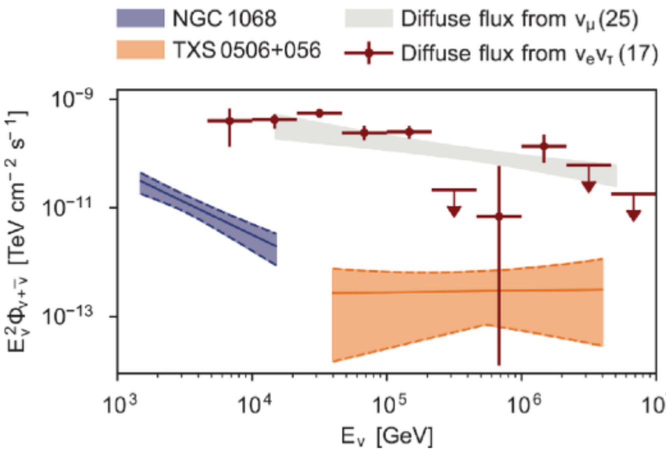
3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event

NGC 1068

4σ excess from the Seyfert galaxy NGC 1068

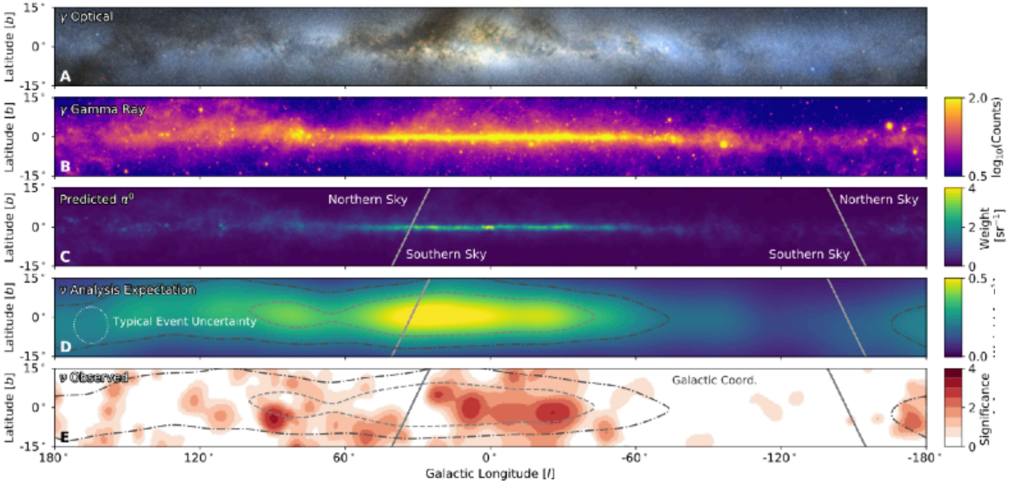


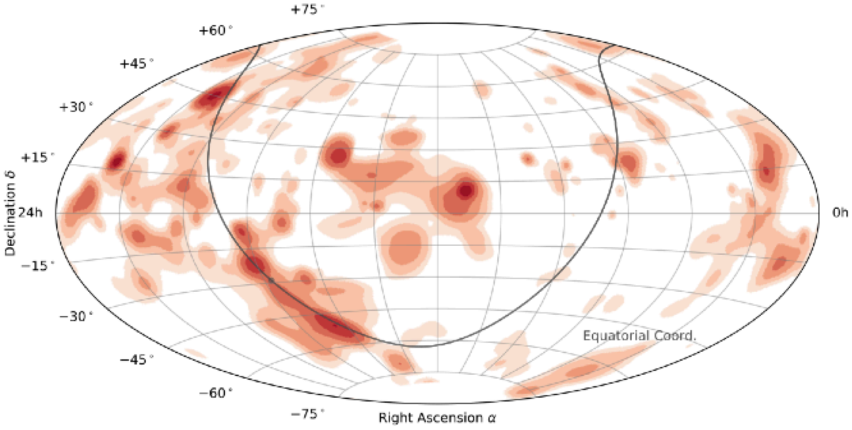




MILKY WAY

4.5σ excess from the Galactic plane



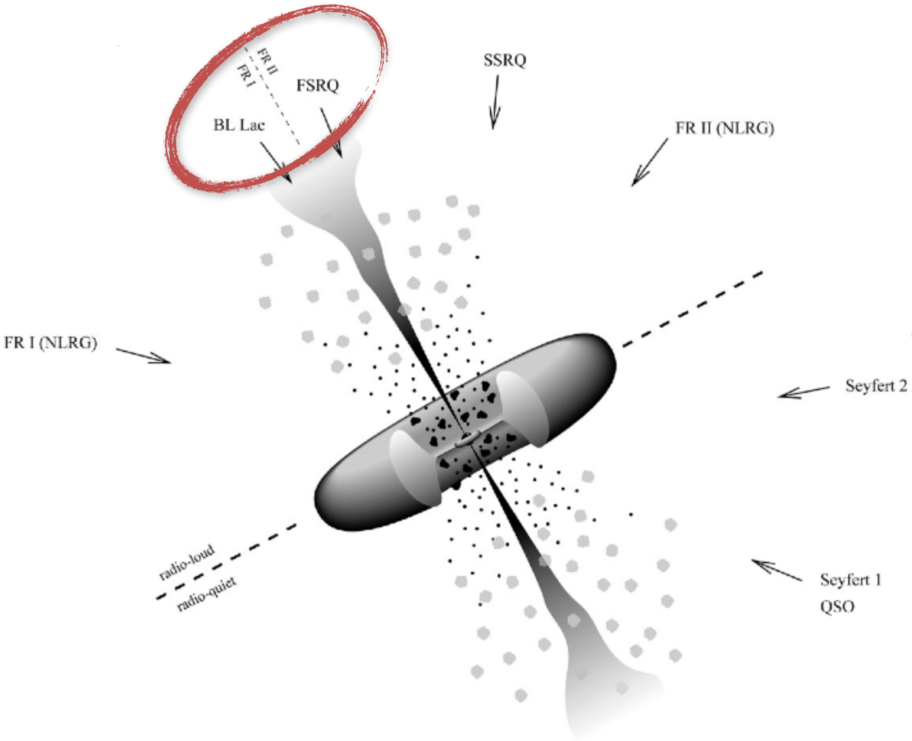


Consistent with diffuse emission from cosmic ray population (p + p):

Neutral pions produce the LAT diffuse

Charged pions produce the neutrino diffuse

BLAZARS



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

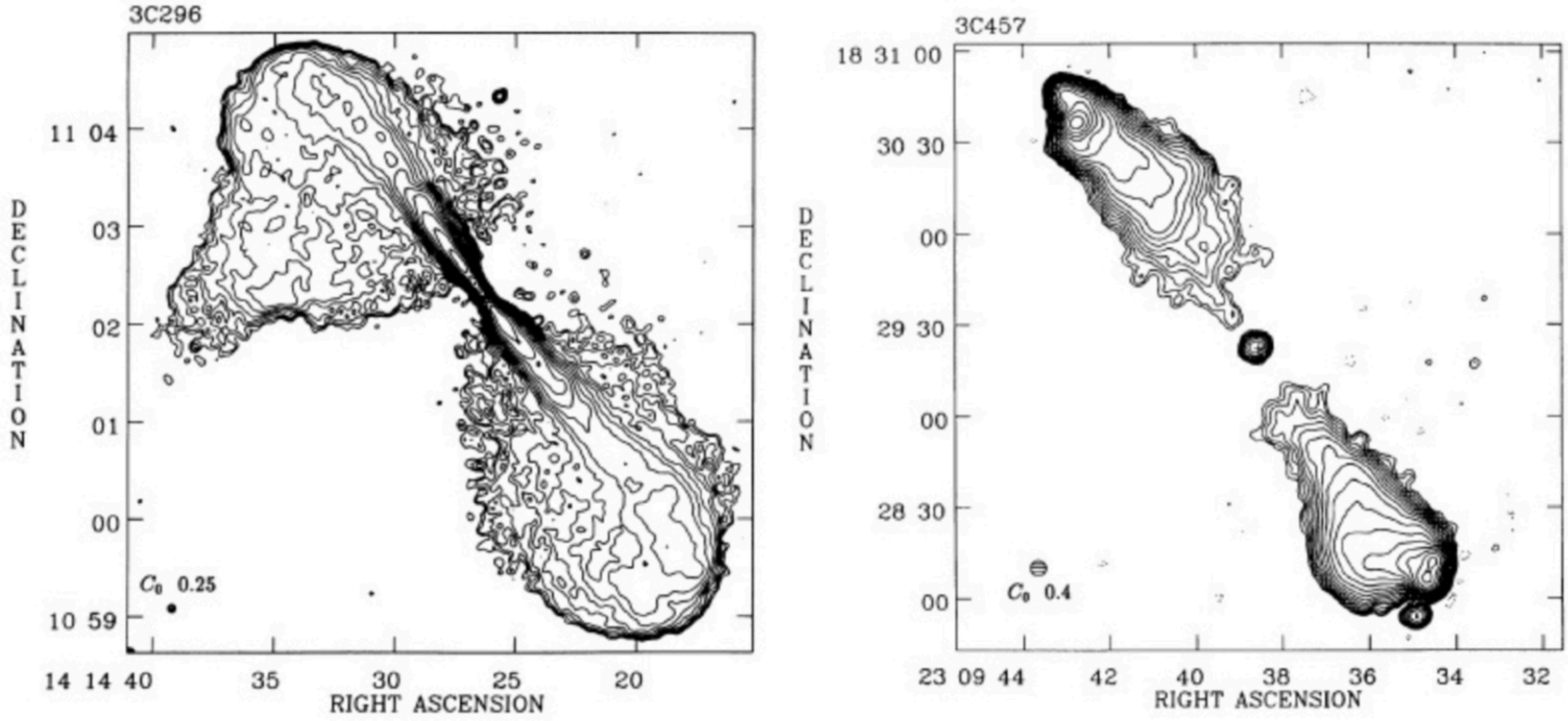
→ Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)

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

BL Lacertae objects : featureless optical/UV spectrum

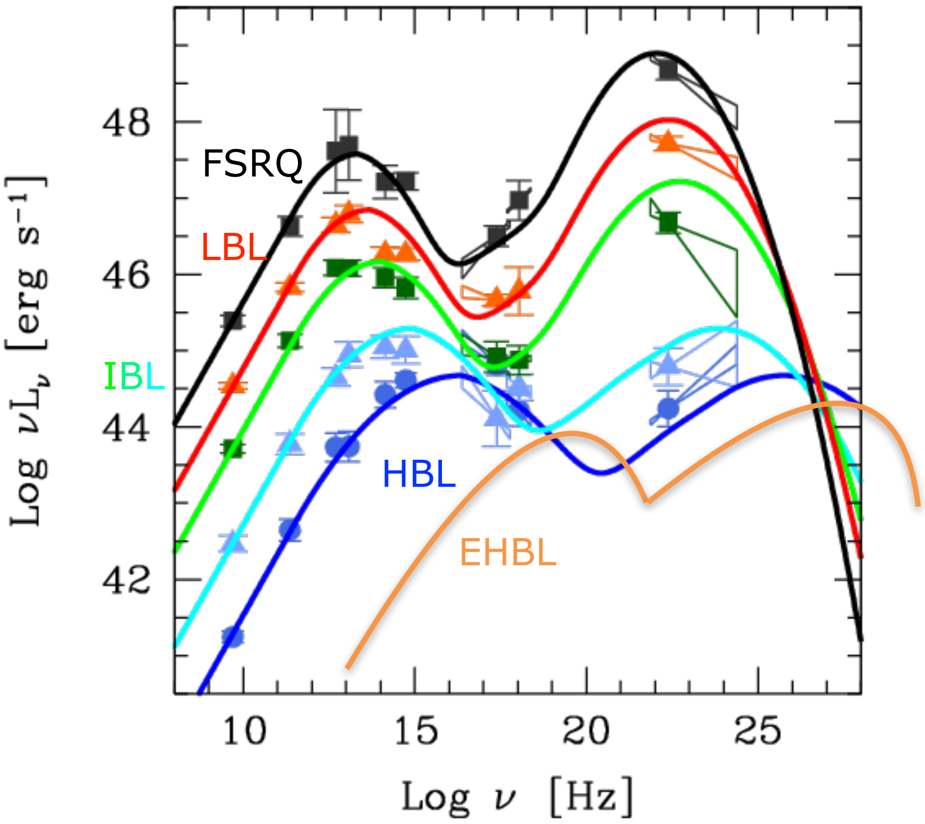
BLAZARS

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)

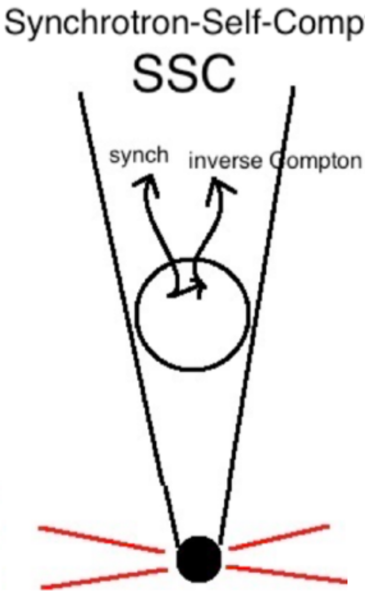
- UV/X peak: high (HBLs)

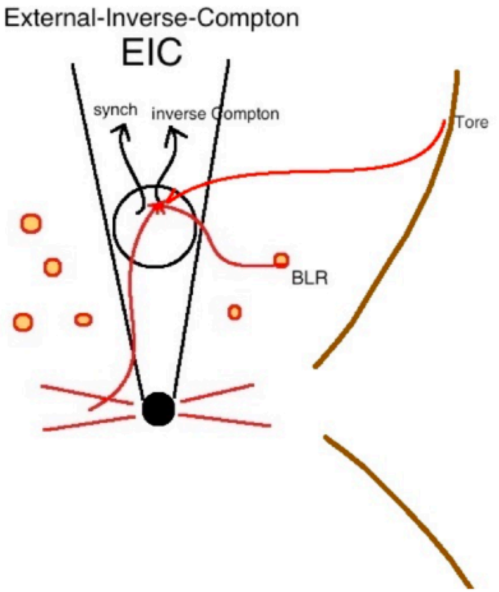
- >X-ray peak: extreme-HBLs (EHBLs)

BLAZARS EMISSION MODELS

The low-energy SED component is synchrotron emission by electrons

High-energy emission?





Leptonic models: inverse Compton

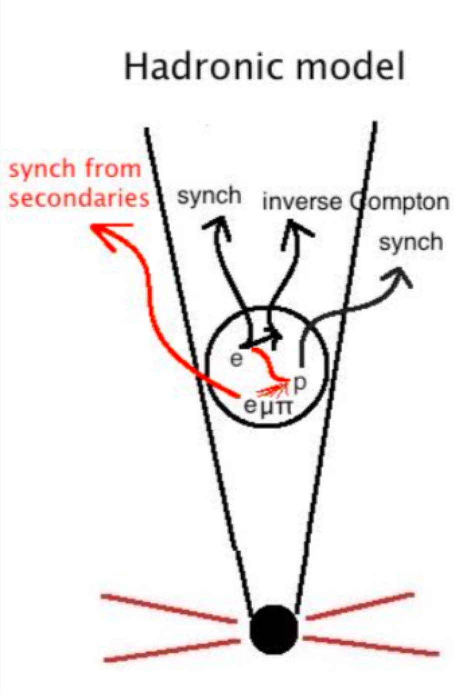
Same leptons that radiate synchrotron
+ their own synchrotron photons (SSC)
+ external photon fields (EIC)

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

BLAZARS EMISSION MODELS

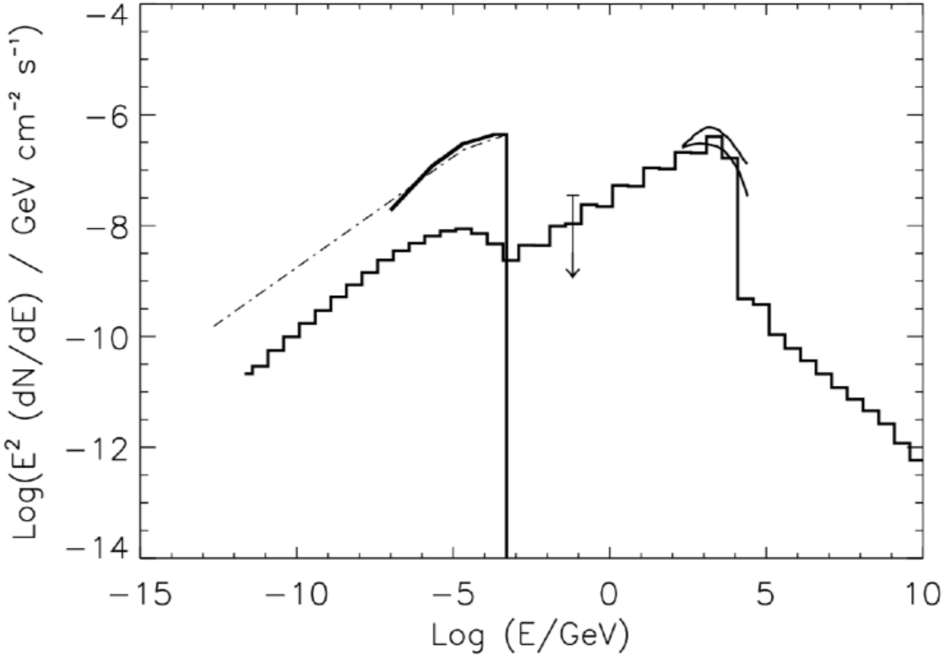
Hadronic models

Simplest hadronic model:



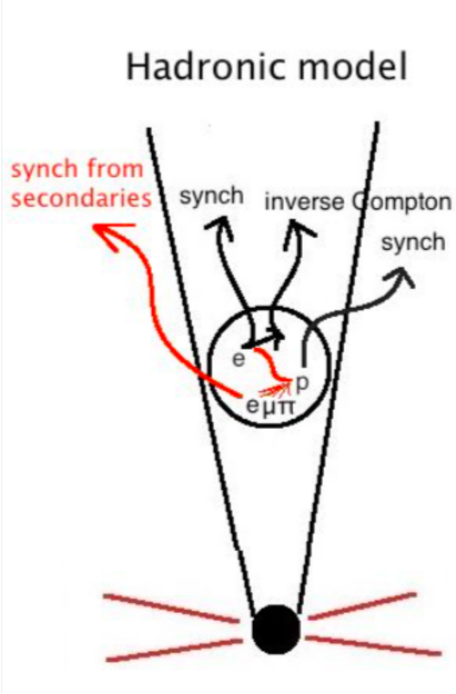
The high-energy component is proton synchrotron radiation

(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

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

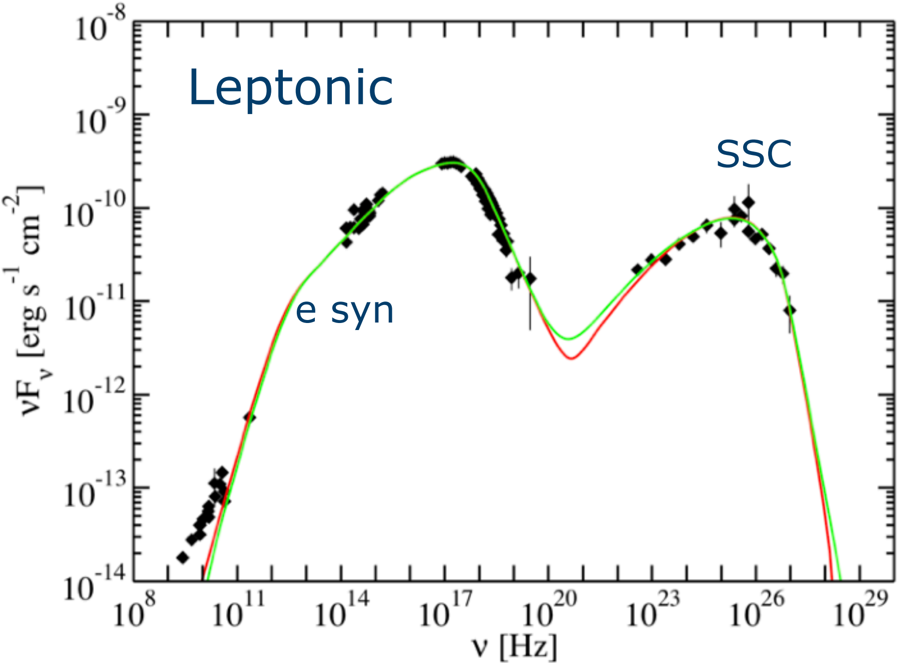
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

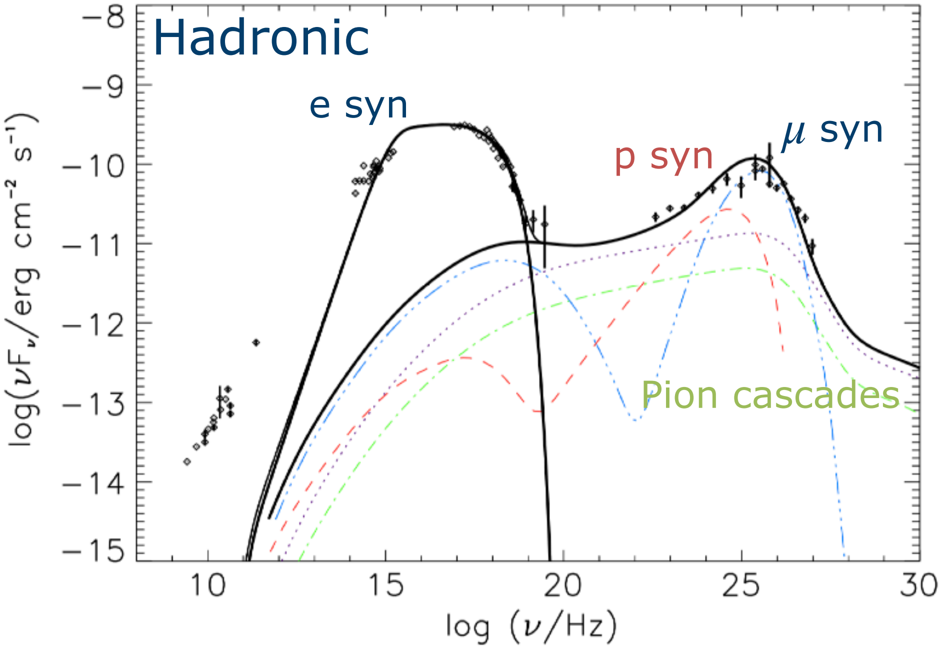
Synchrotron emission by muons can be important

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011





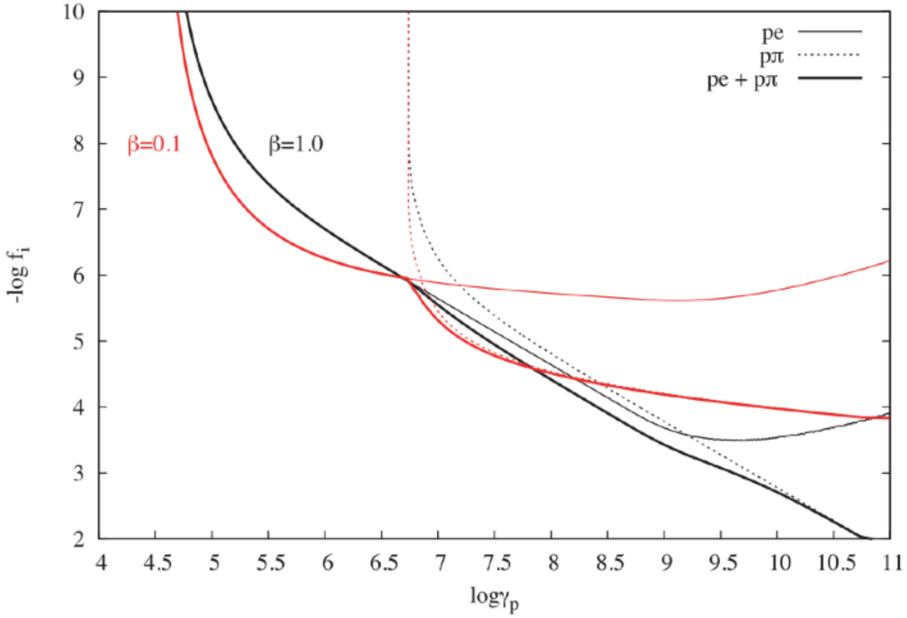
Abdo et al. 2011

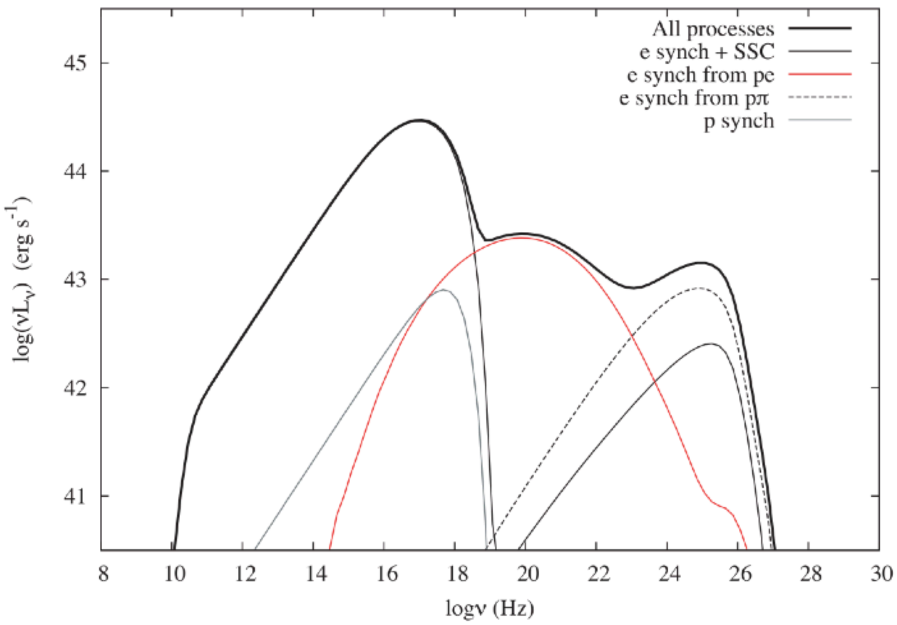
BLAZARS EMISSION MODELS

Why is Bethe-Heitler important?

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

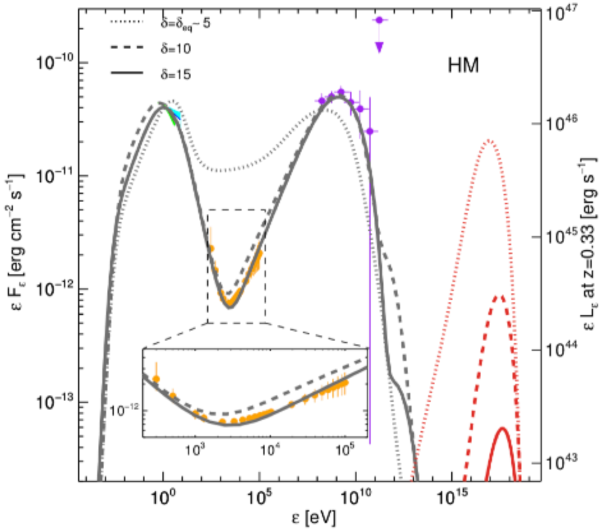
Can dominate the X-ray band and fill the SED valley





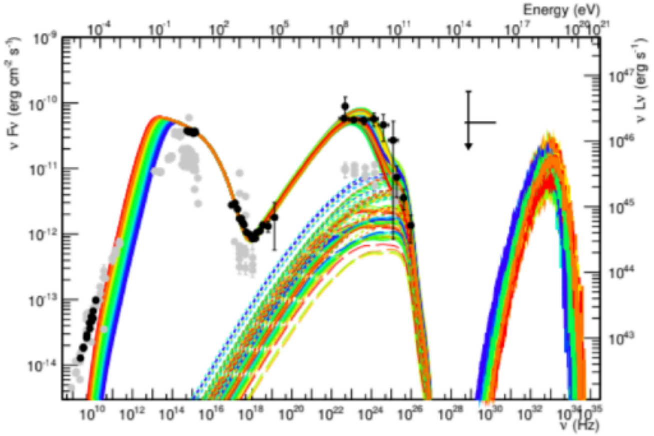
Petropoulou & Mastichiadis 2015

TXS 0506+056: the 2017 flare



[Keivani et al. 2018](#)

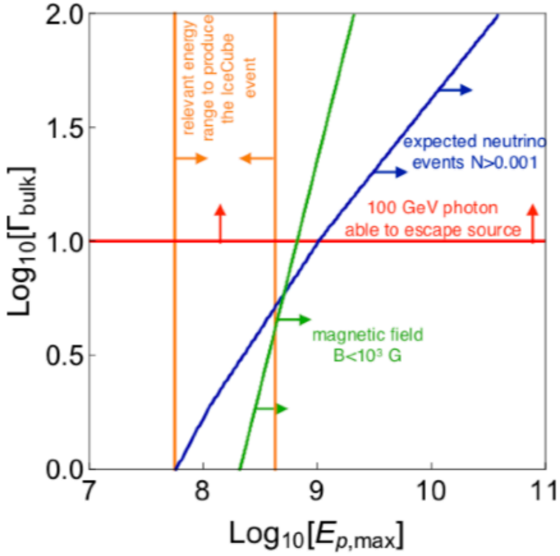
$\nu \simeq 10^{-5}\ yr^{-1}$



(a) Proton synchrotron modeling of TXS 0506+056

[Cerruti et al. 2019](#)

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

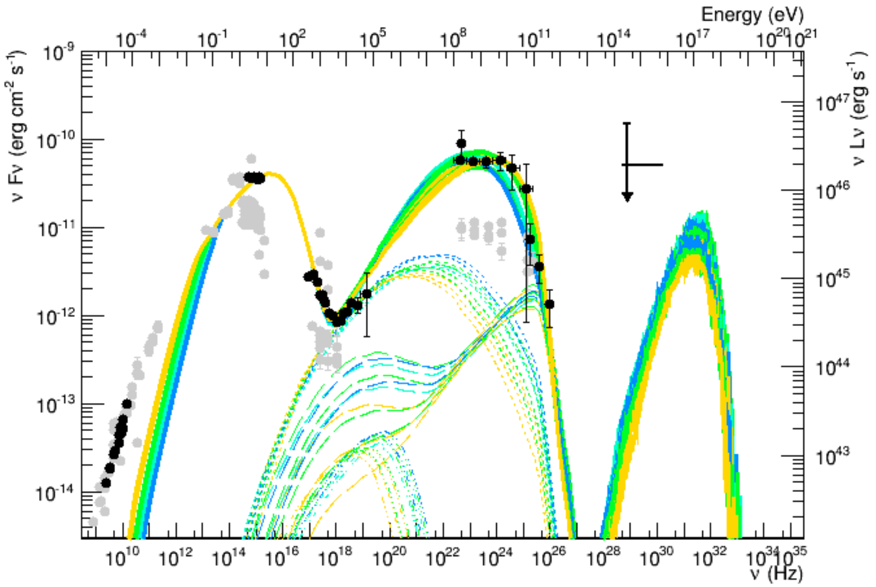


[Gao et al. 2018](#)

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

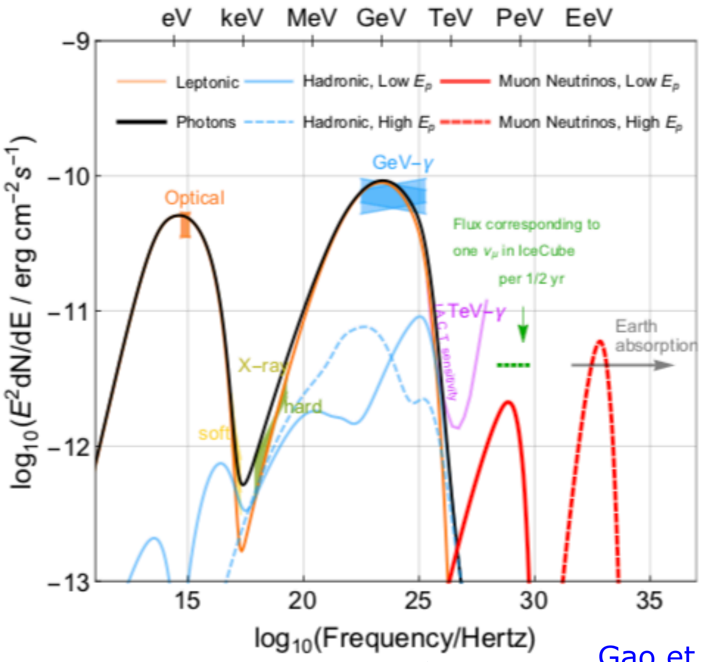
TXS 0506+056: the 2017 flare

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

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

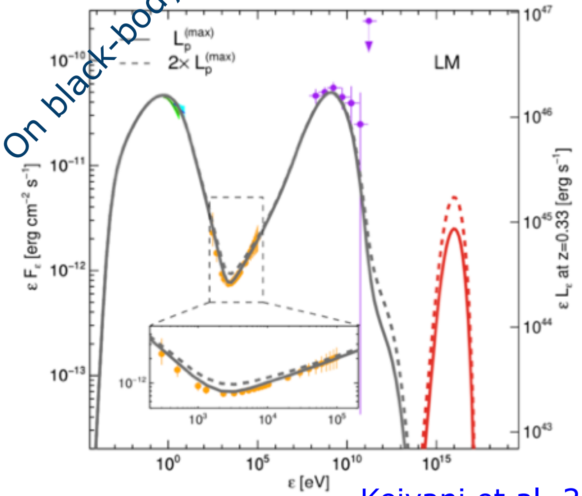
They can work: neutrino rates of the order of 0.1 / yr

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

TXS 0506+056: the 2017 flare

Proton-photon interaction on external photon fields

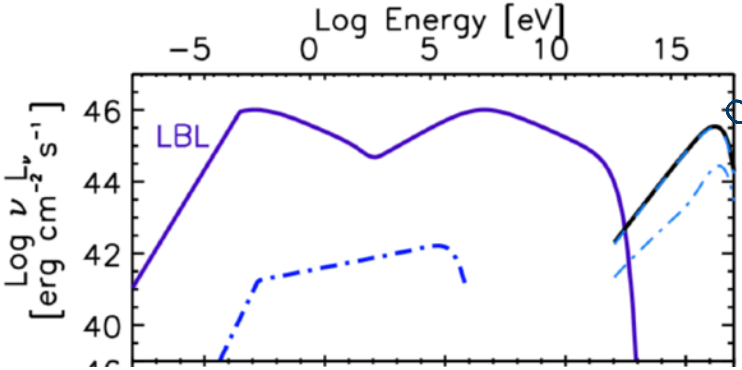
On black-body



Keivani et al. 2018

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

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



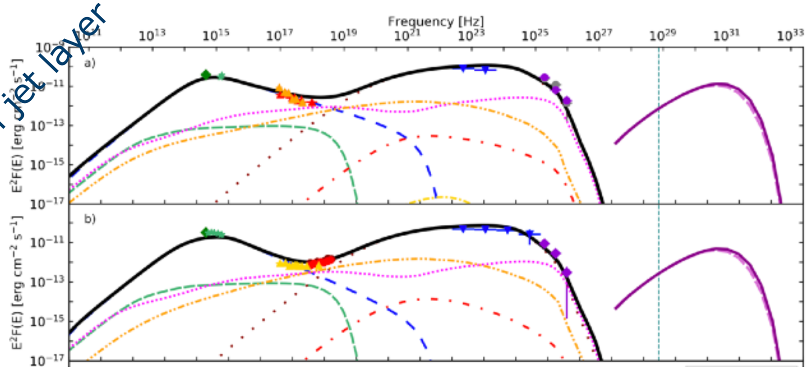
On RIAF

Righi et al. 2019

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

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

On jet layer



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

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

Ansoldi et al. 2018

TXS 0506+056: the 2017 flare

What did we learn on blazars?

- Pure hadronic solutions are excluded!

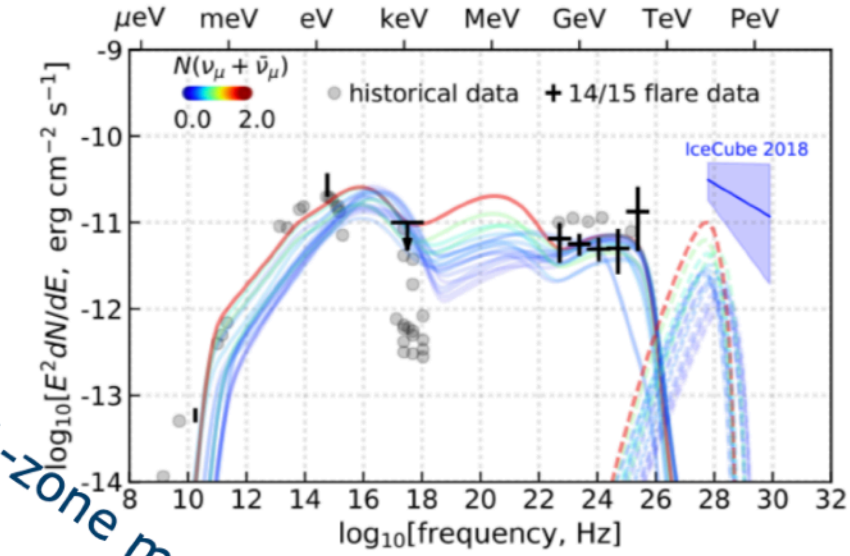
- The favored scenario is a leptonic electromagnetic emission, with subdominant hadronic component

- 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)

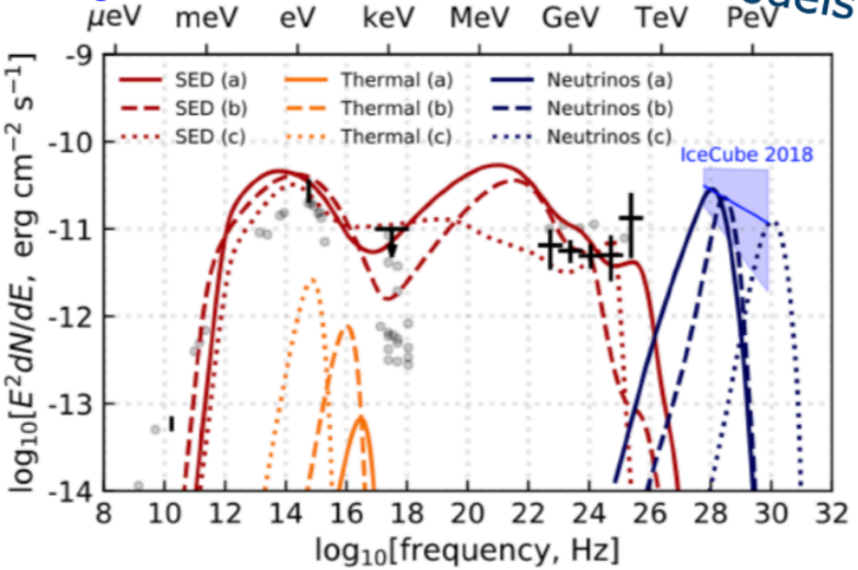
TXS 0506+056: the 2014/15 flare

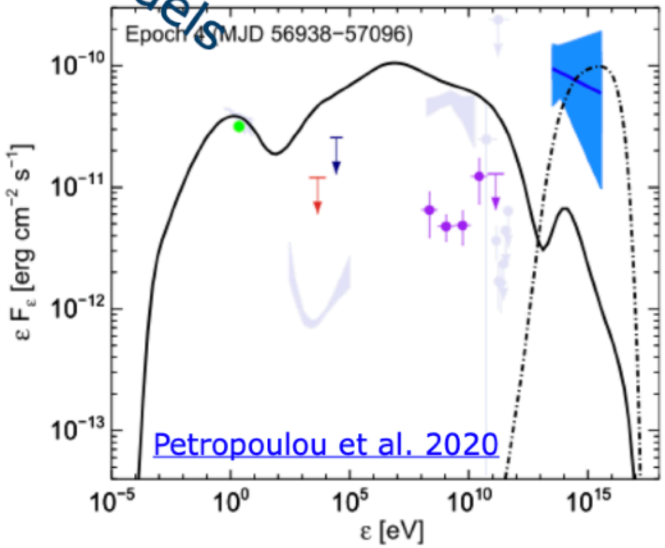


1-zone models

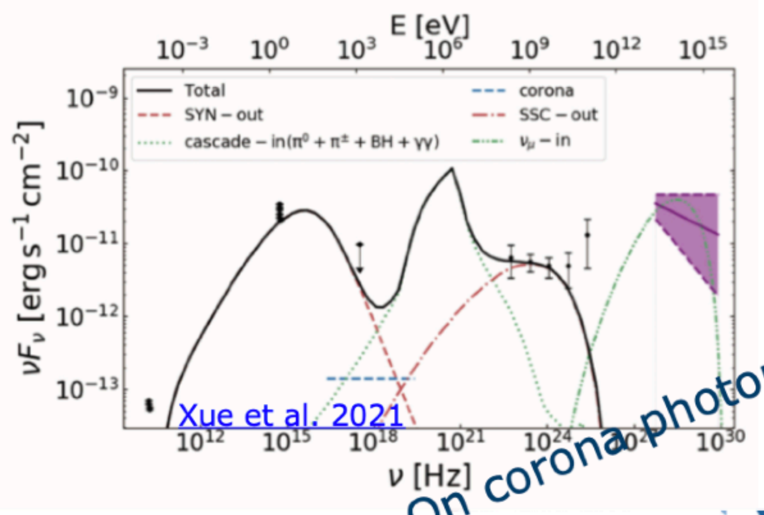
External field models

Rodrigues et al. 2019





Petropoulou et al. 2020



Xue et al. 2021

On corona photons

TXS 0506+056: the 2014/15 flare

What did we learn?

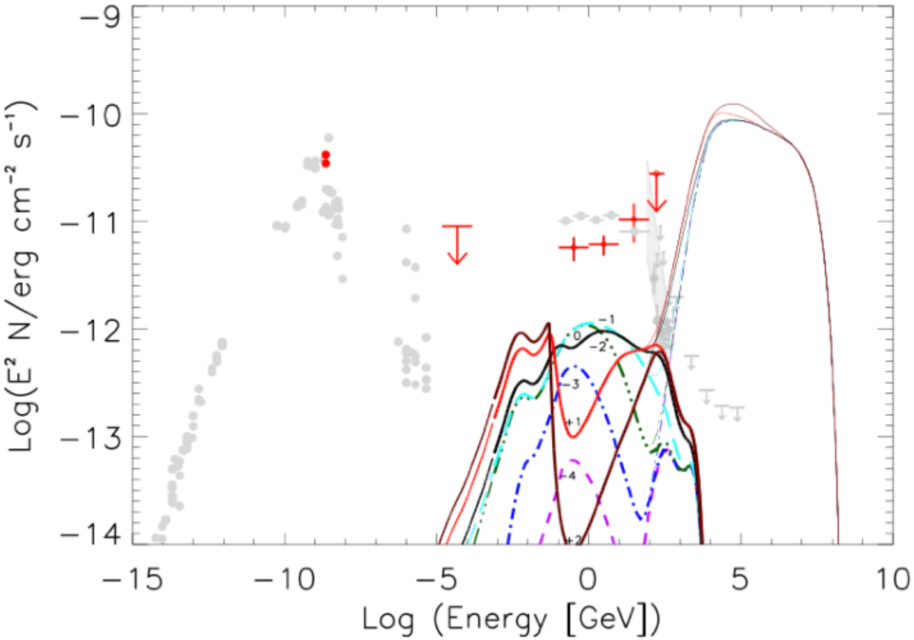
- Single zone models are disfavored : very difficult to get no photons with the neutrino flare
(although there may be some room in the MeV band)

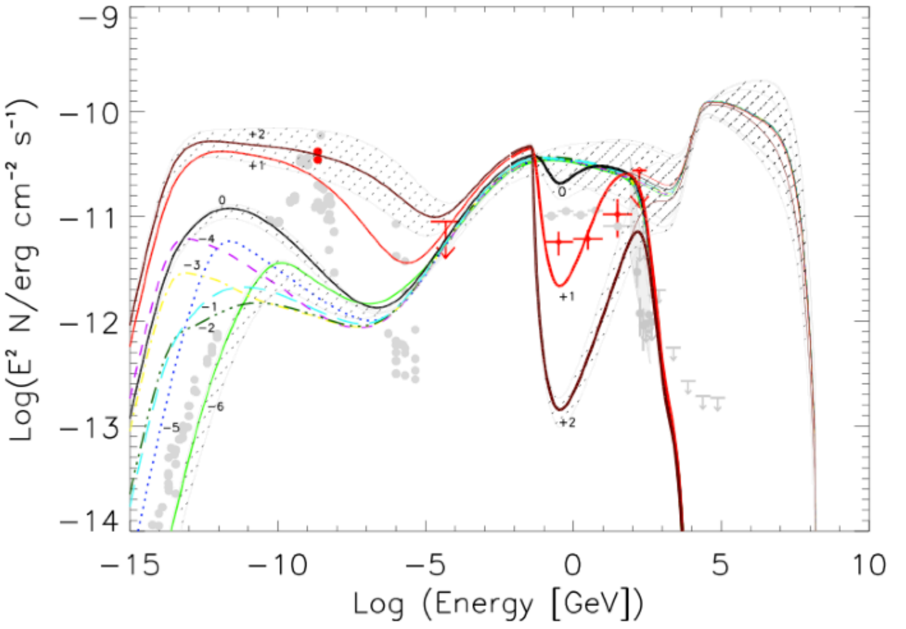
- A possible solution could be a two-zone models:
the ν and the γ-ray emitting region are not the same

TXS 0506+056: the 2014/15 flare

The exact cascade spectrum varies a lot in the parameter space

inverse-Compton cascade vs synchrotron cascade





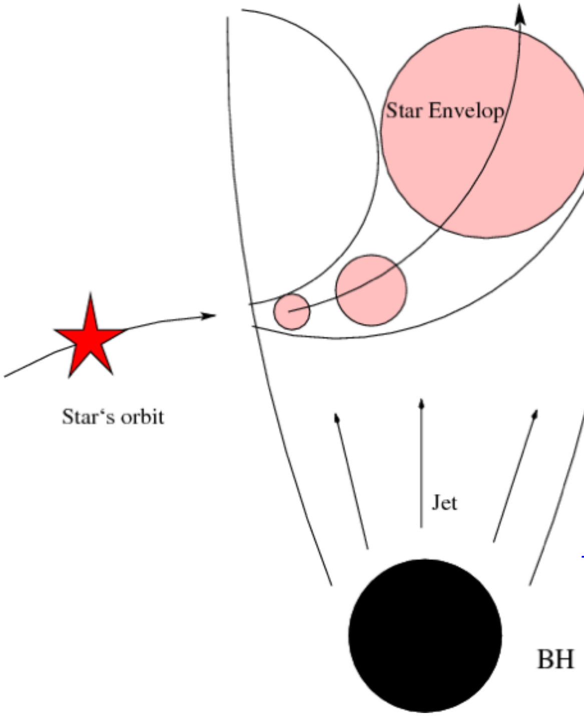
Reimer et al. 2020

ON p-p INTERACTIONS

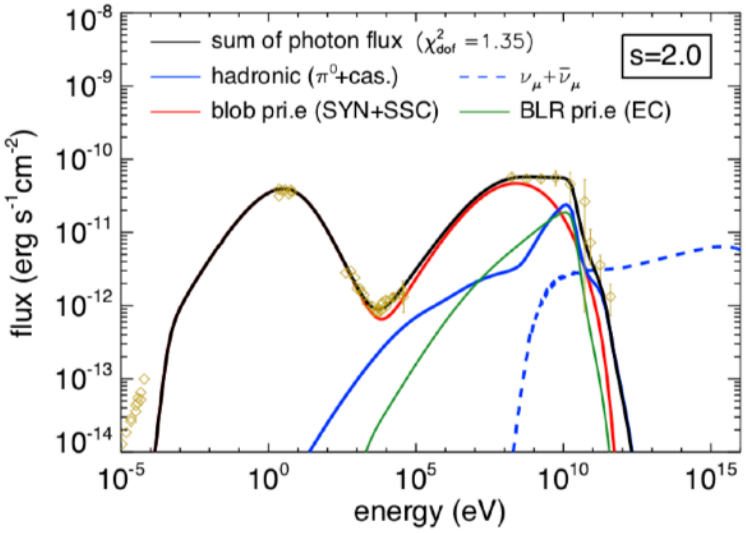
Can p-p interactions be important?

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

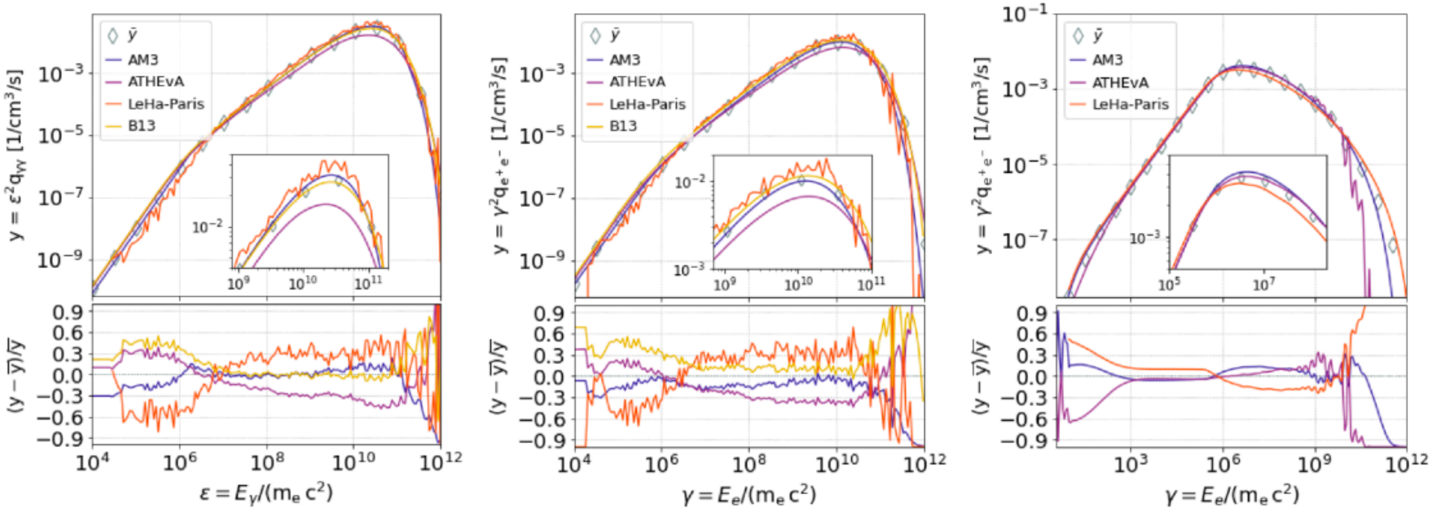
Comparison of five numerical hadronic codes in the literature:
AM3 (Gao et al. 2017), Athena (Dimitrakoudis et al. 2012),
B13 (Böttcher et al. 2013), LeHa-Paris (Cerruti et al. 2015)
LeHaMoC(Stathopoulos et al. 2023)

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

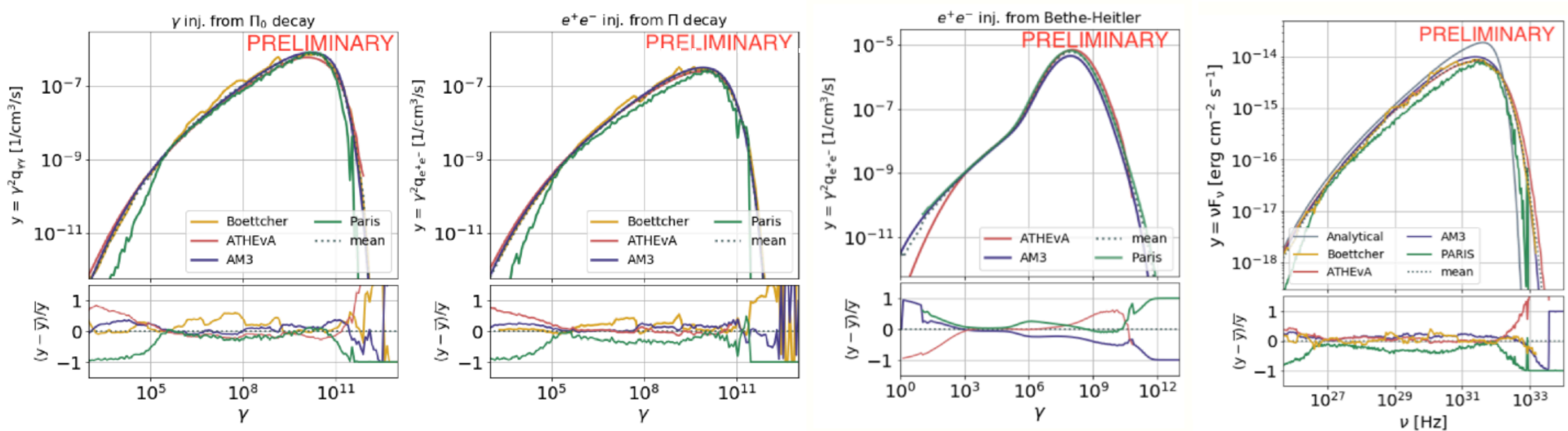
- Compute systematic uncertainties from theoretical simulations
- Release all files as benchmark for future developments

HADRONIC CODE COMPARISON

Power-law protons on power-law photons



Proton-synchrotron scenario



ICRC 2022 proceedings

PKS 0735+178

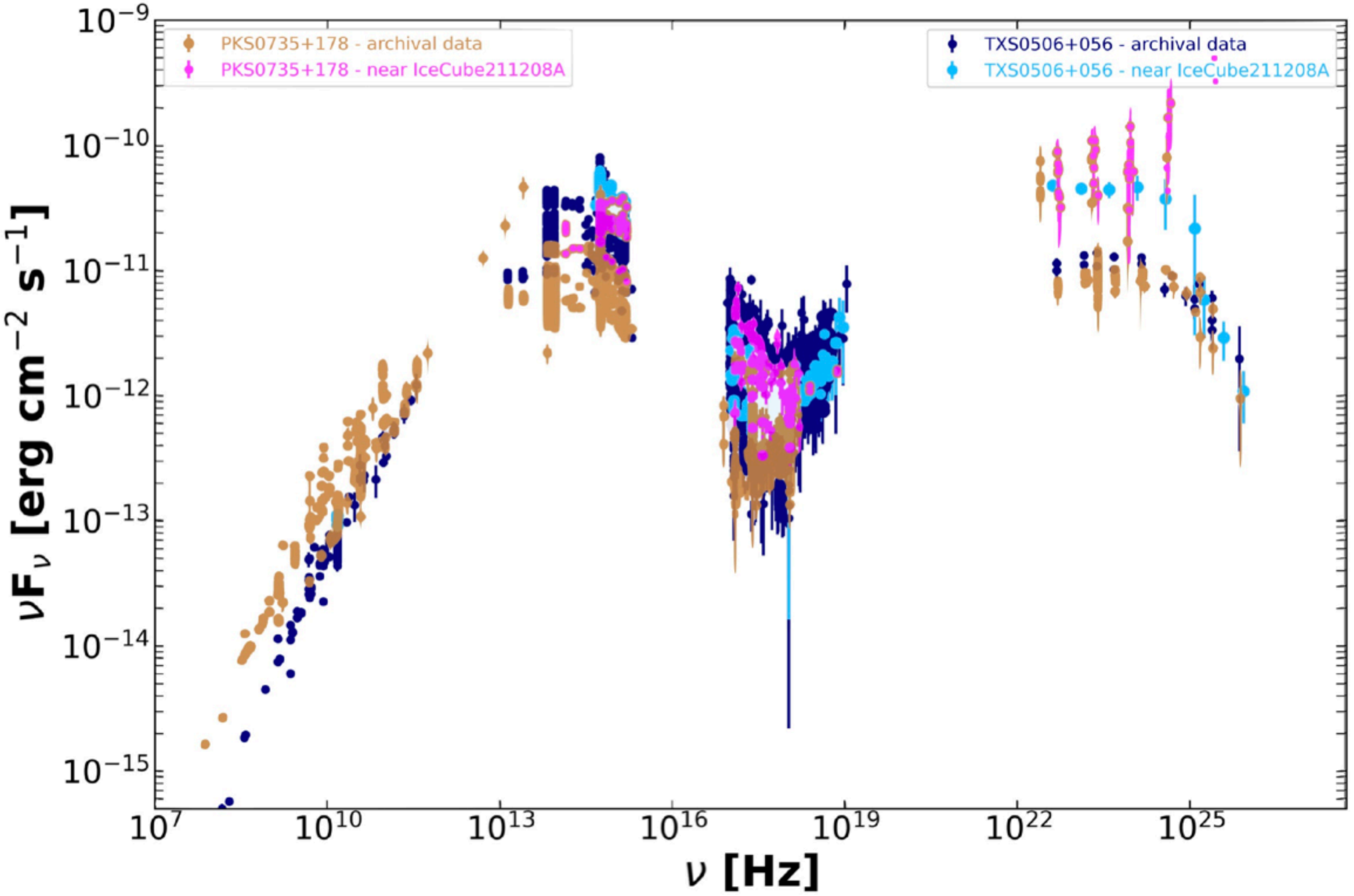
IBL@z=0.65? (>0.42) and IC211208A:

- 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

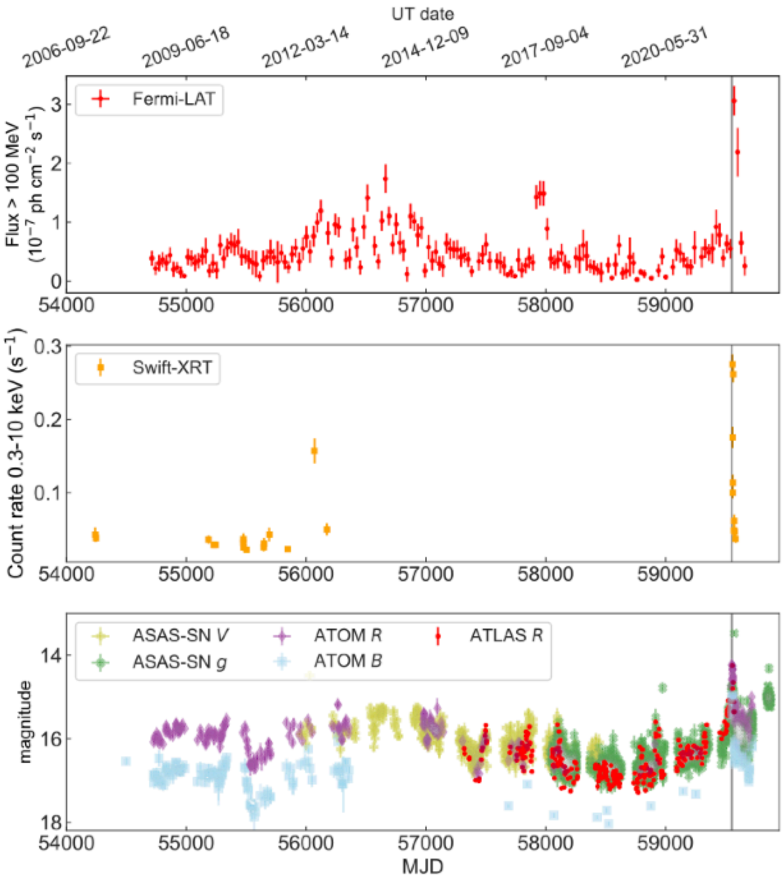
PKS 0735+178

Sahakyan et al. 2022

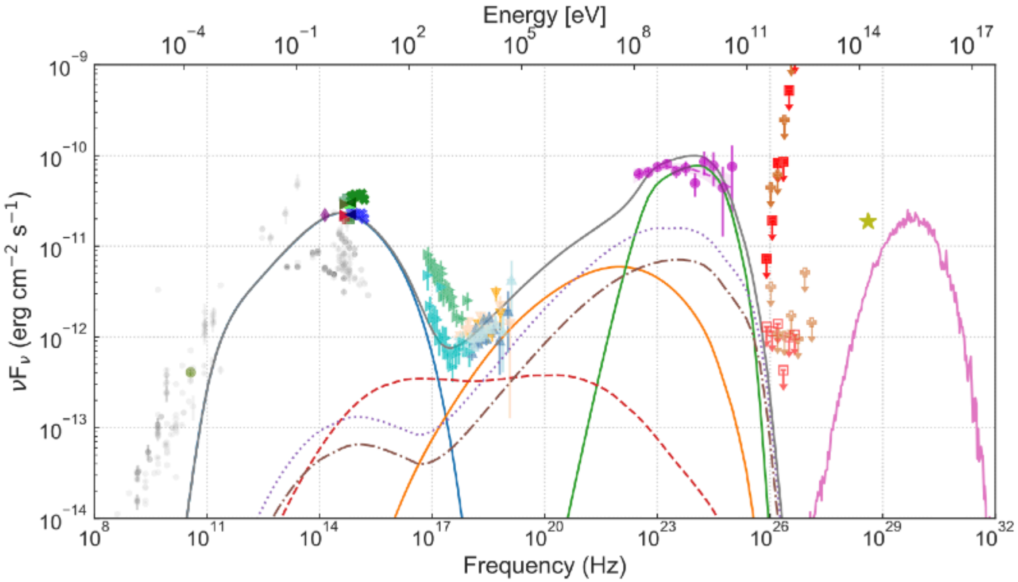


PKS 0735+178

[Acharyya et al. 2023](#)



(a)



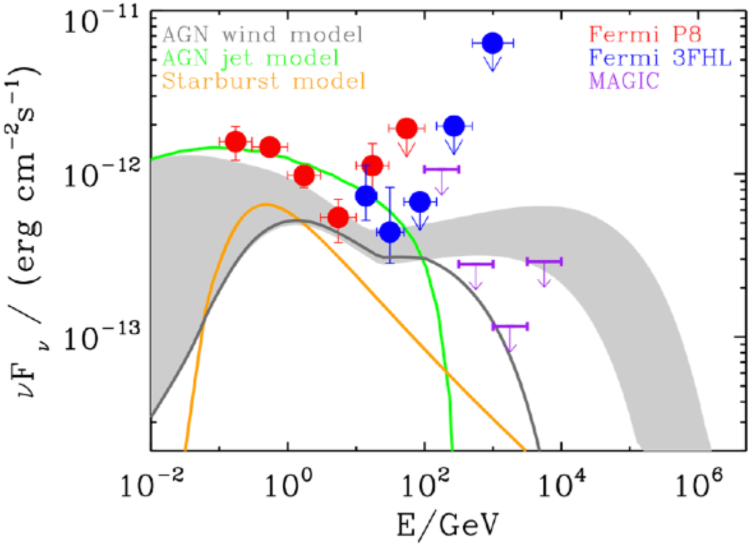
NGC 1068 (AGN) models

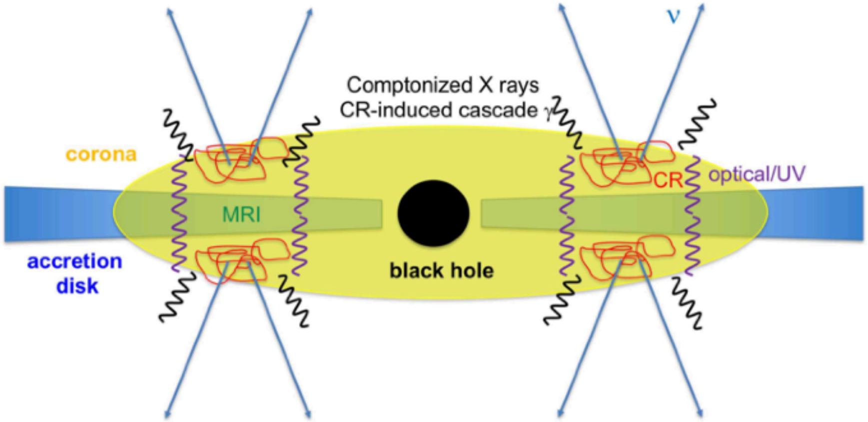
Radio-quiet AGN + starburst component

GeV emission but only upper limits in the TeV band

Opacity issue: the gamma-ray emission has to be compact enough to provide opacity to TeV photons -> from AGN

Hot coronal region?





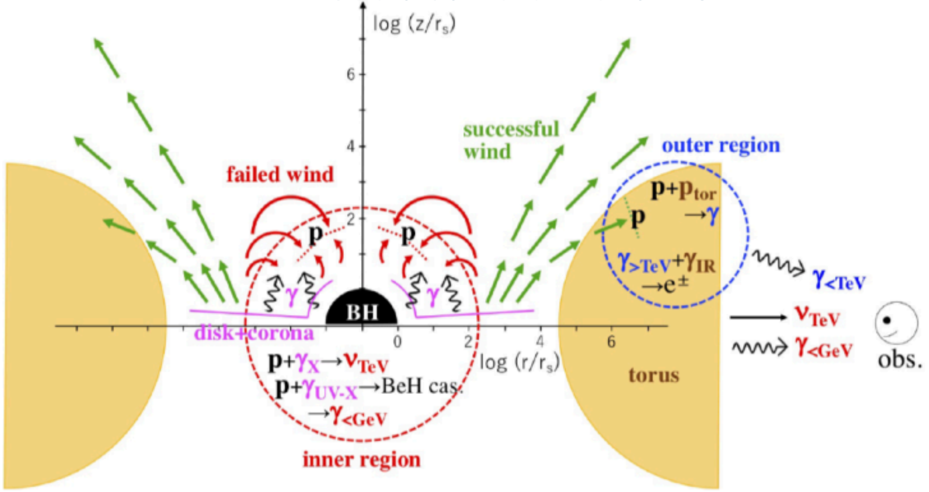
NGC 1068 (AGN) models

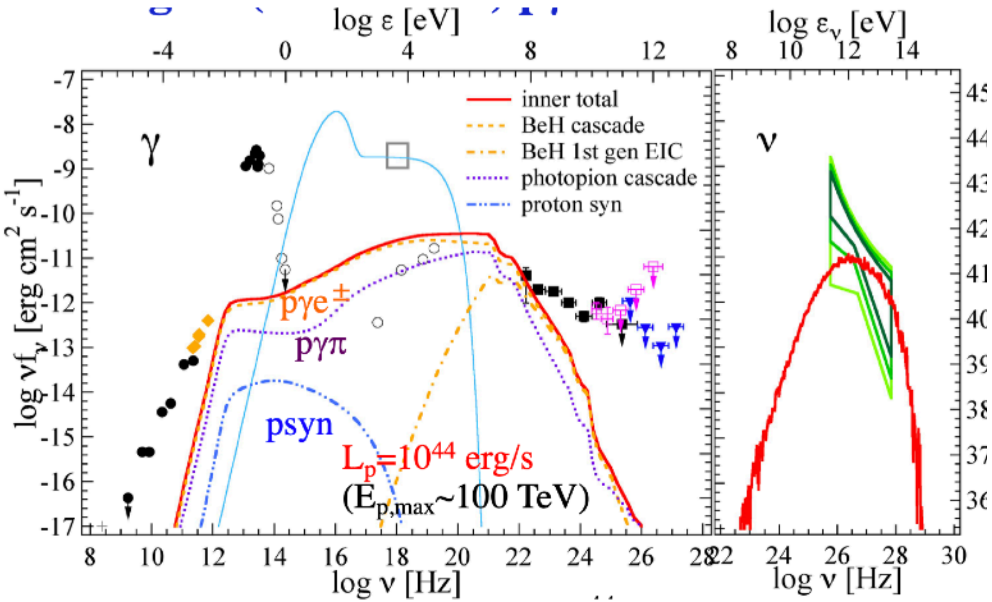
Inoue et al. 22
See also Peretti et al.23

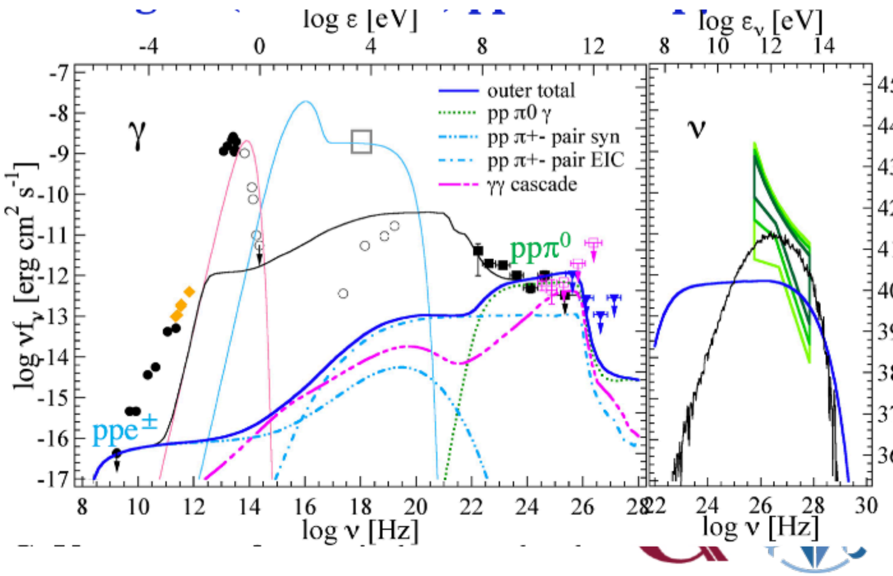
Disc winds:

Two separate regions to produce neutrinos and gamma-rays.

Cascade computed self-consistently down to the radio







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