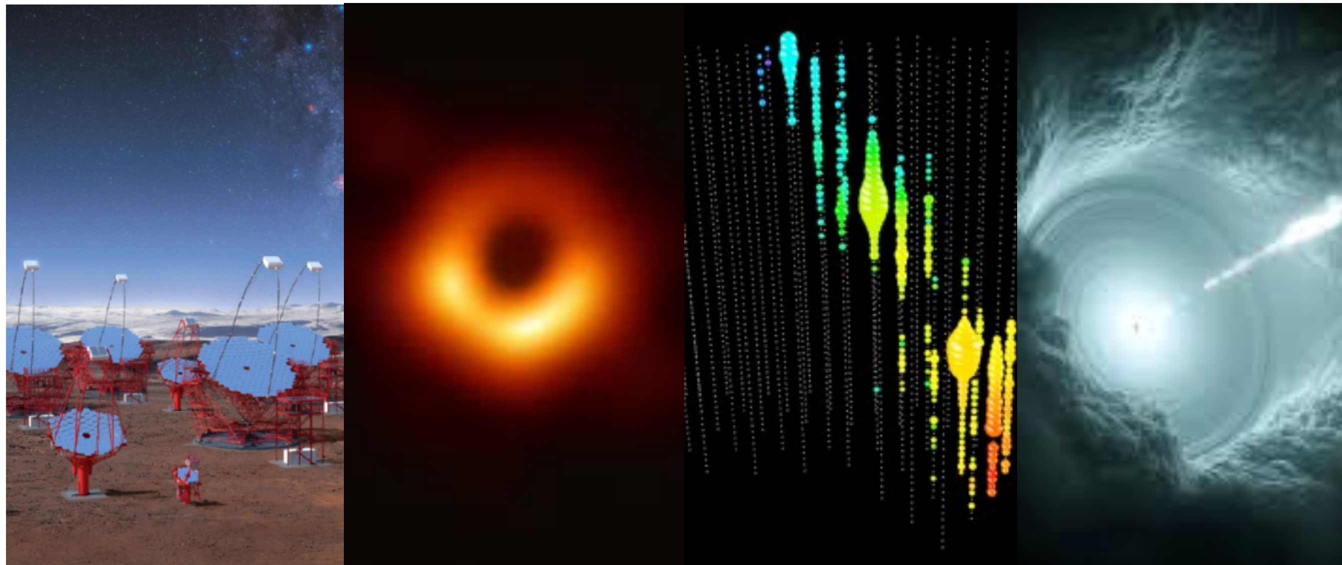


Gamma-rays from supermassive black-hole jets

Matteo Cerruti

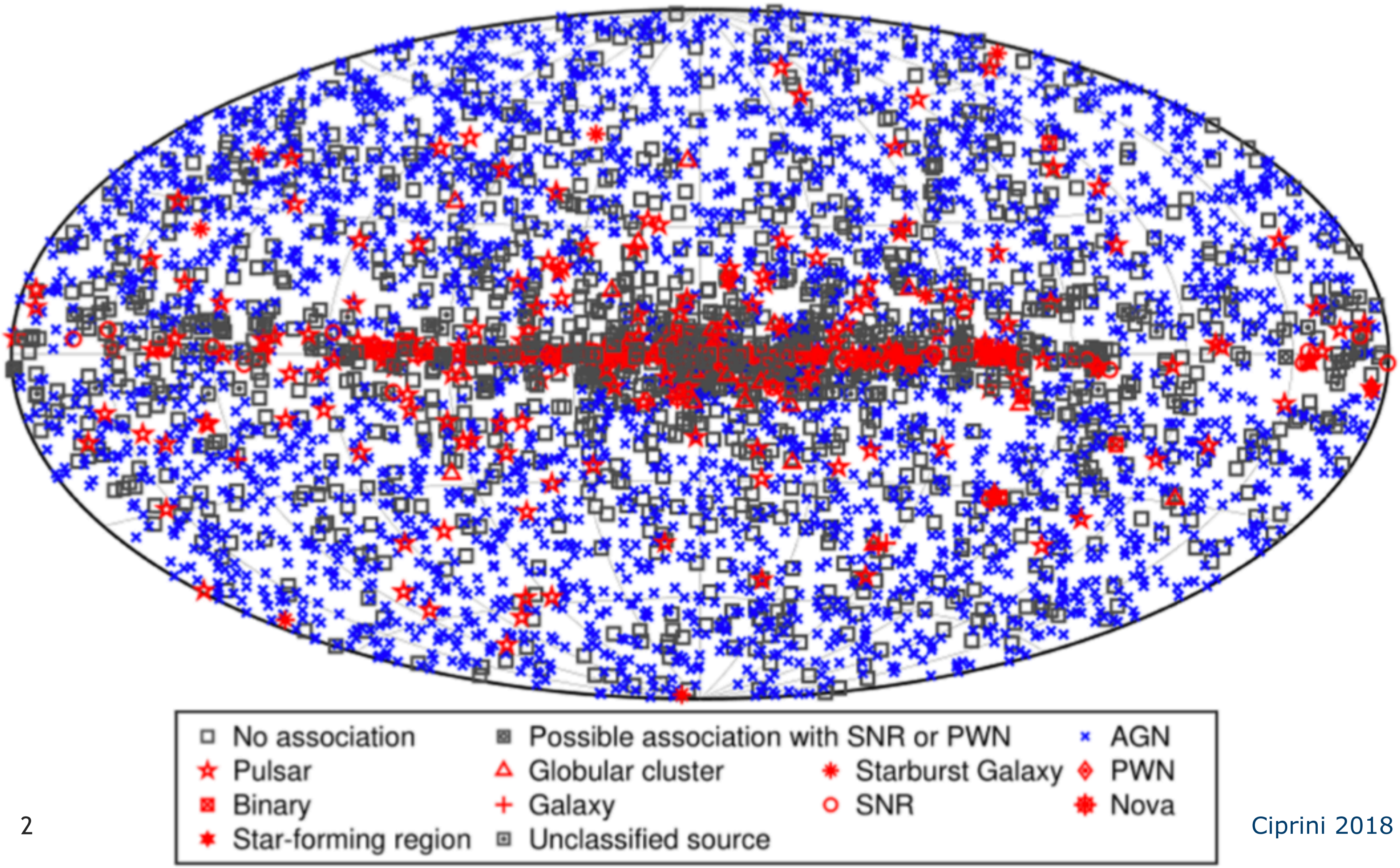
Université Paris Cité

Astroparticule et Cosmologie (APC)

Rencontres de Noirmoutier

Juin 4, 2026

THE GeV EXTRAGALACTIC SKY

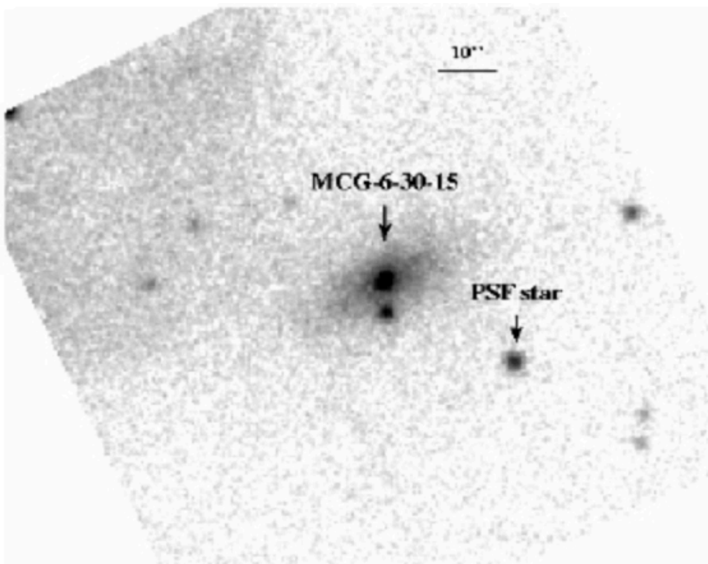


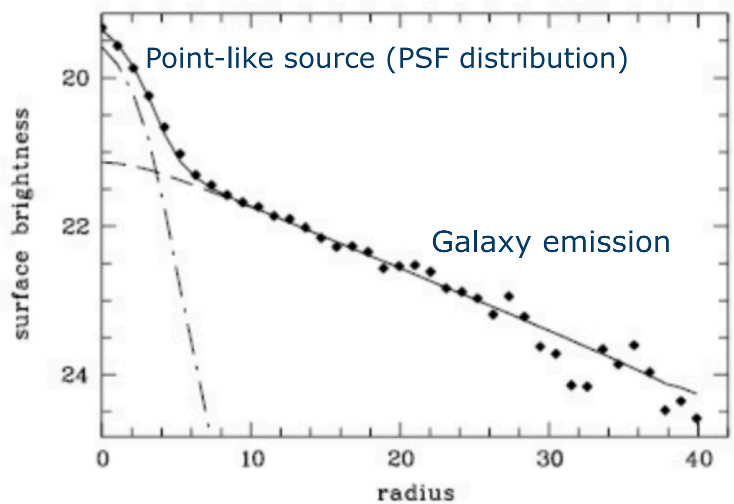
Ciprini 2018

ACTIVE GALACTIC NUCLEI

Point-like source of photons in galaxy center

The brightest ones can outshine the galaxy itself (=quasar)



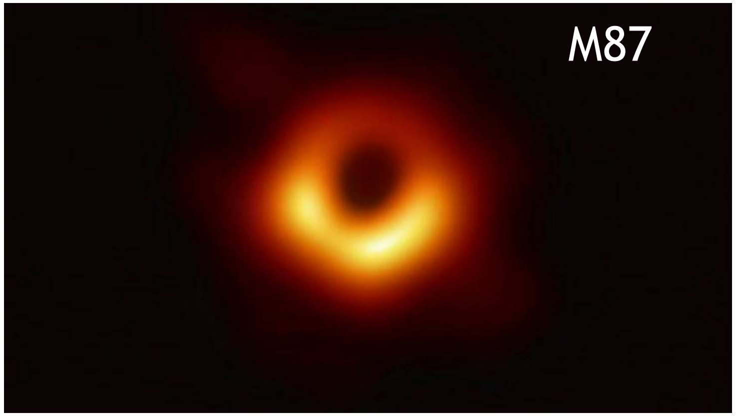


Arevalo et al. 2005

ACTIVE GALACTIC NUCLEI

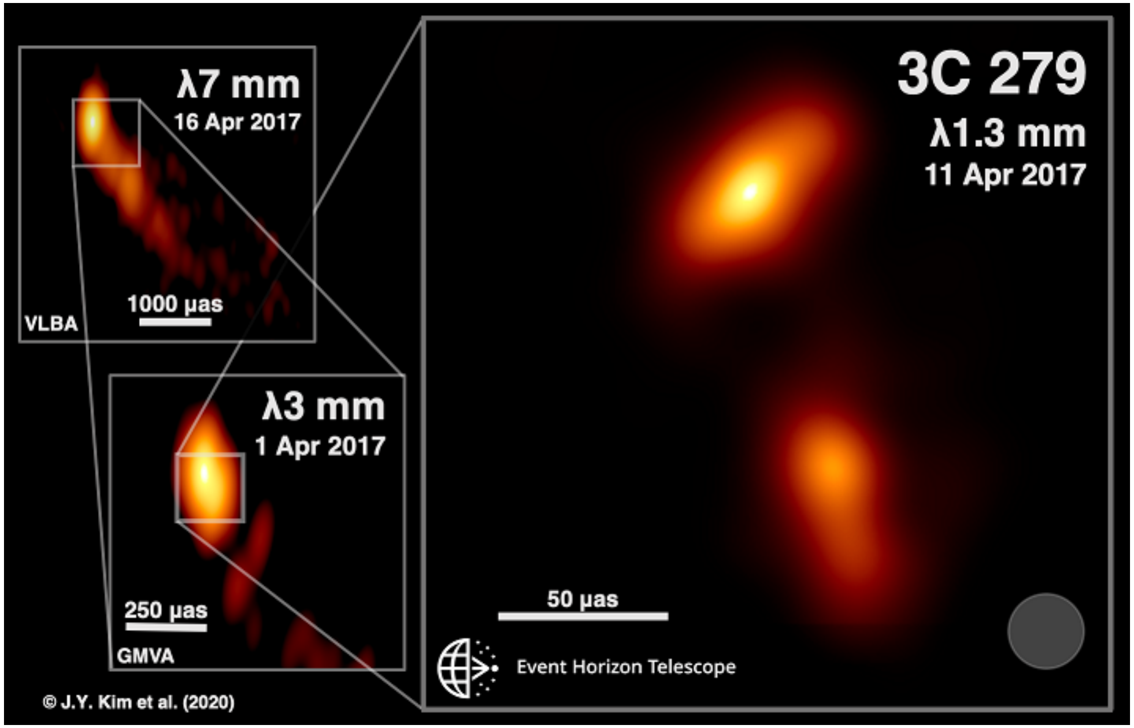
Current understanding

effect of accretion of matter onto a super-massive black hole



Event Horizon Telescope 2019

First image of a black-hole shadow

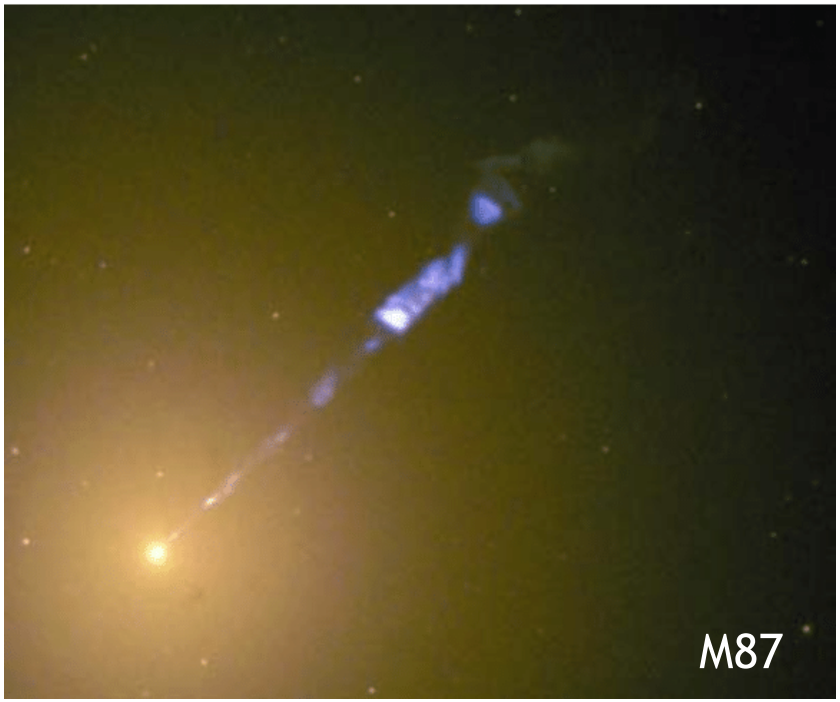


Event Horizon Telescope 2020

Jet launching

ACTIVE GALACTIC NUCLEI

Radio-loud / radio-quiet dichotomy

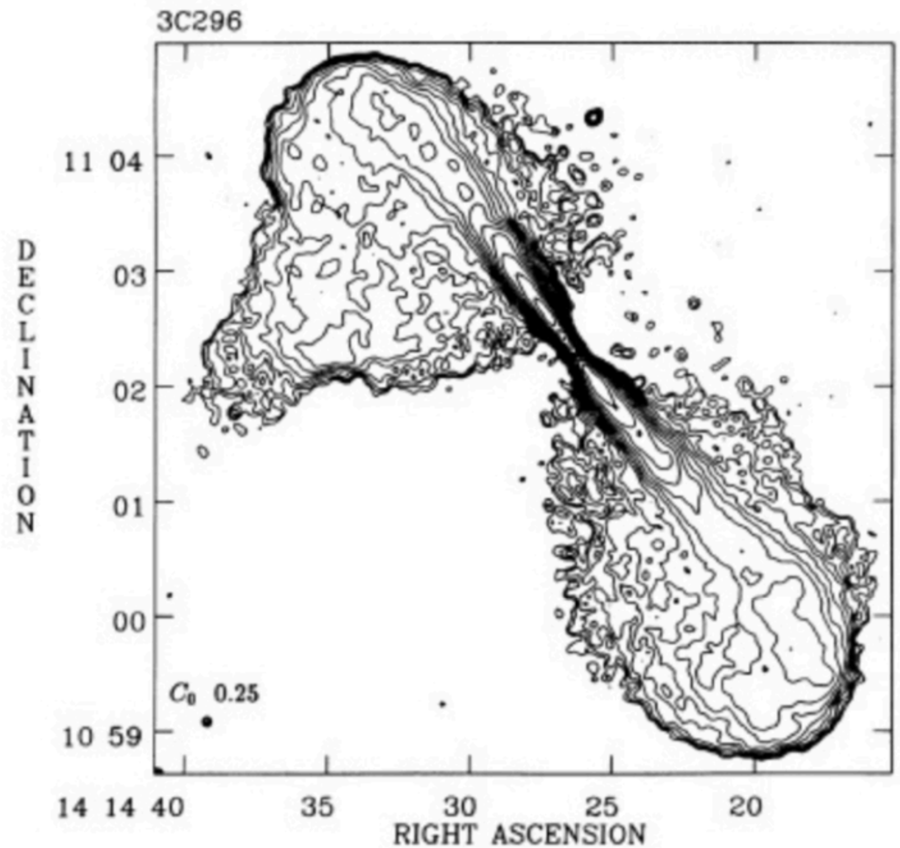


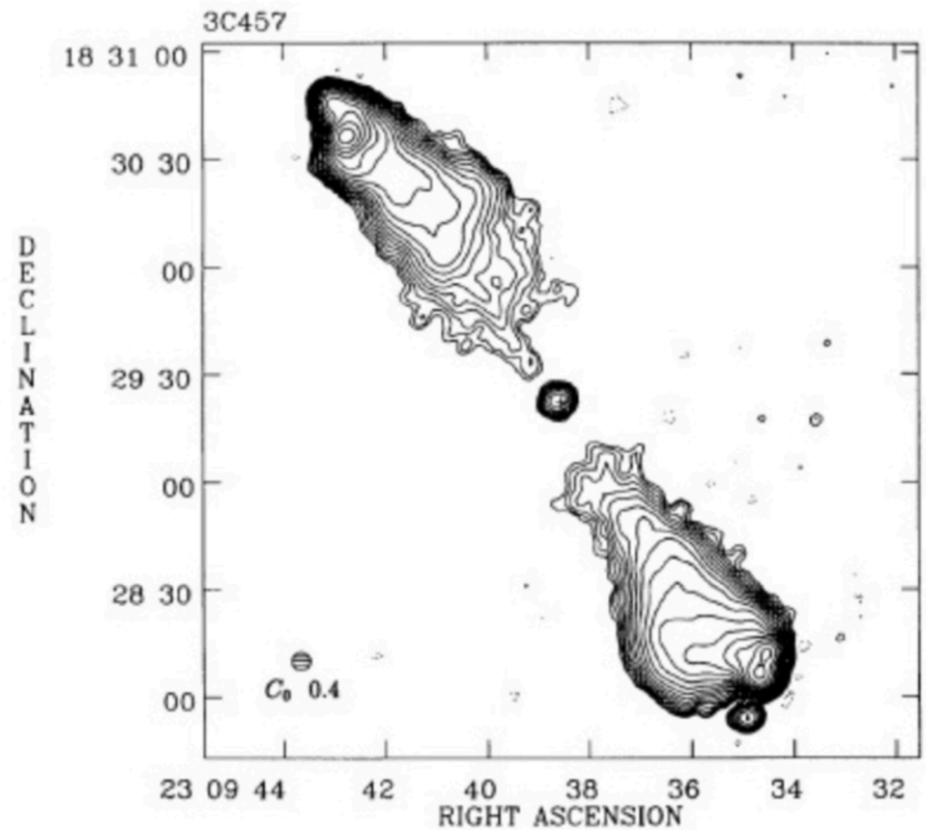
Radio-galaxy
with its relativistic jet

Seyfert galaxy

ACTIVE GALACTIC NUCLEI

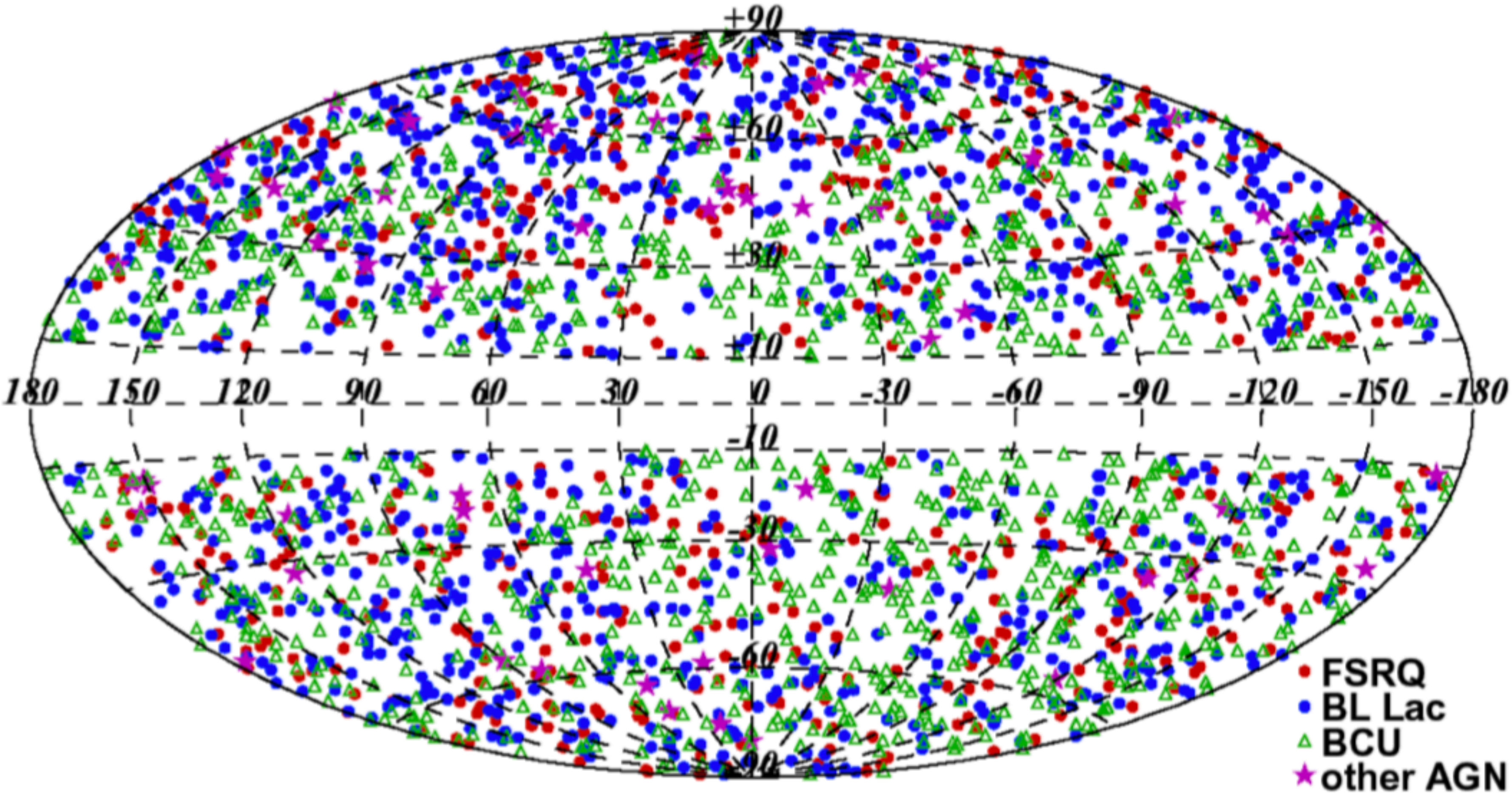
Radio-loud dichotomy: Fanaroff-Riley I and FRII





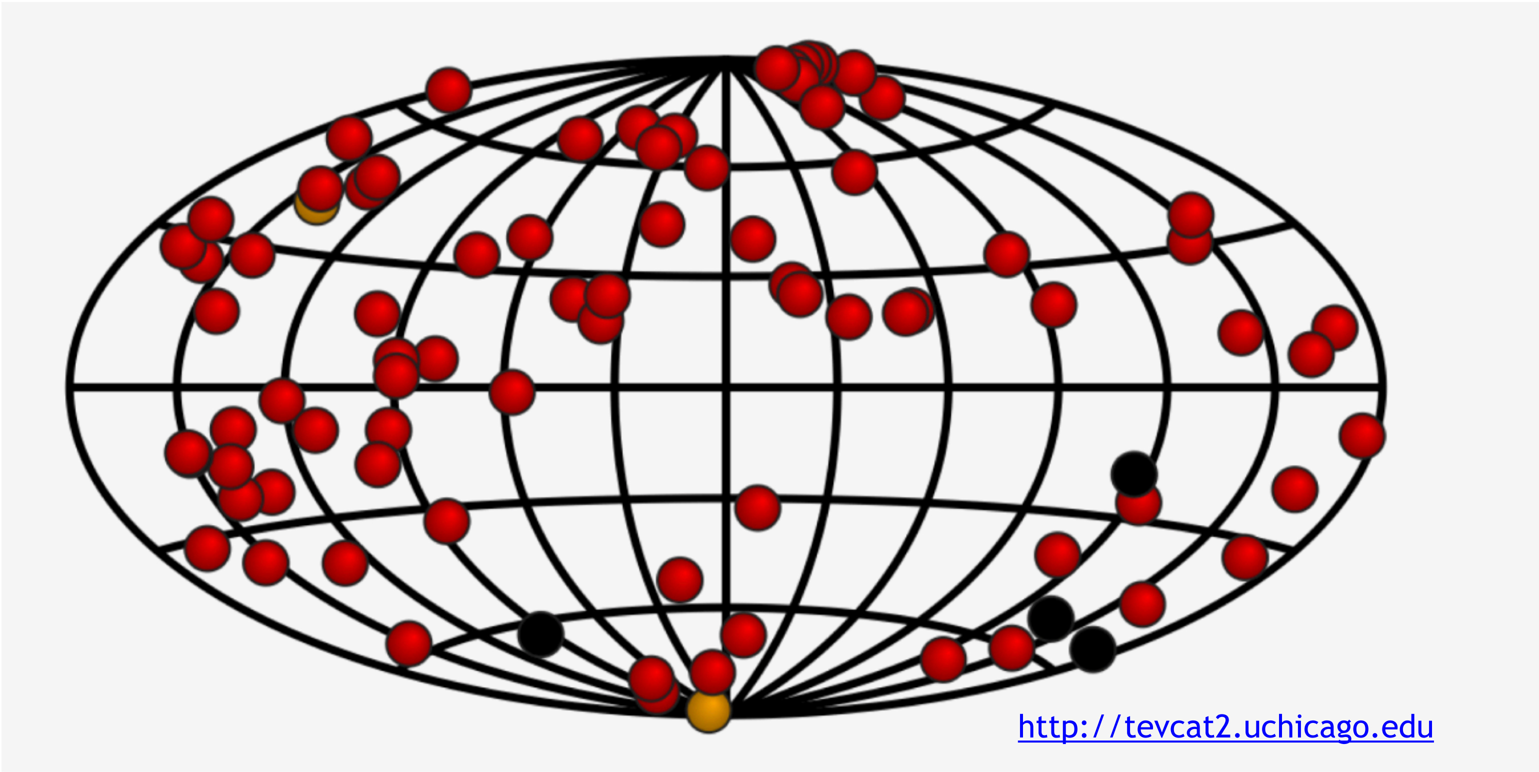
[Leahy & Perley 1991]

THE GeV EXTRAGALACTIC SKY



Ciprini 2018

THE TeV EXTRAGALACTIC SKY



84 extragalactic sources: **3 GRB**

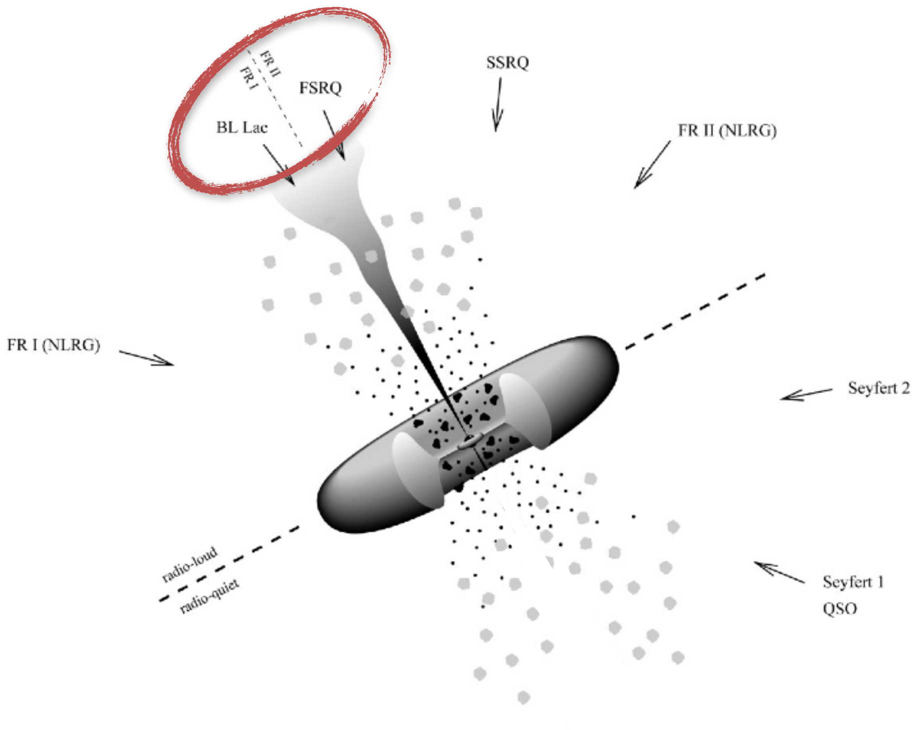
2 starburst galaxies

4 radio galaxies

75 blazars

Ciprini 2018

BLAZARS



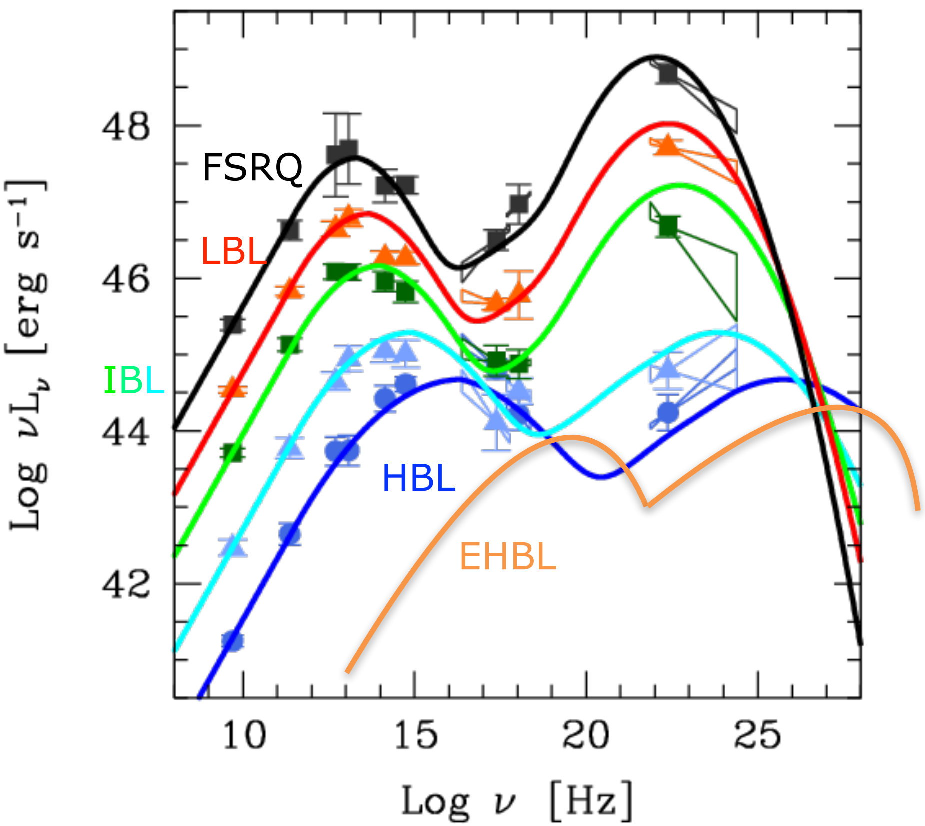
Blazar: radio-loud AGN whose relativistic jet points towards the observer

→ 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

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

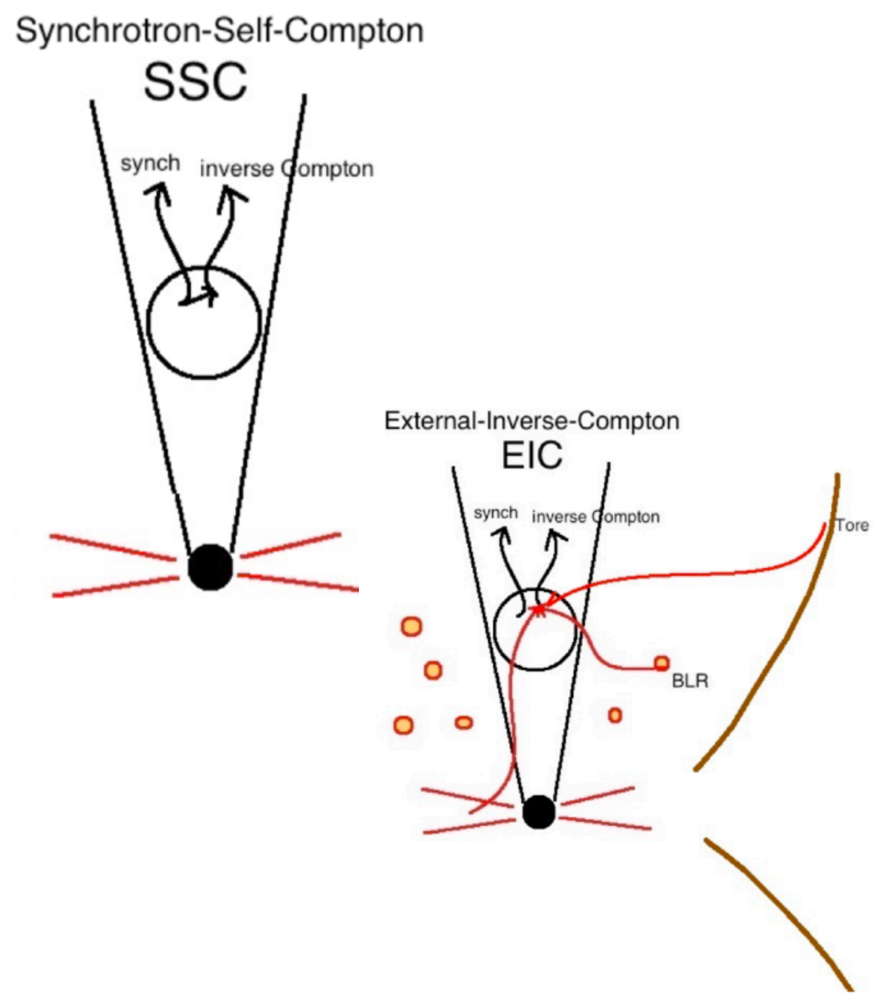
The low-energy SED component is synchrotron emission by electrons

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



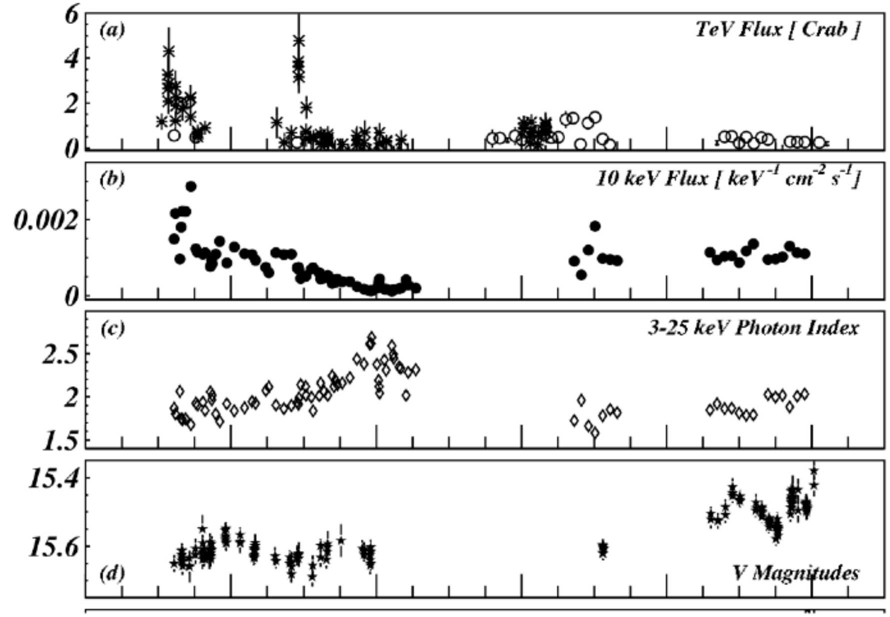
BLAZARS EMISSION MODELS

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)

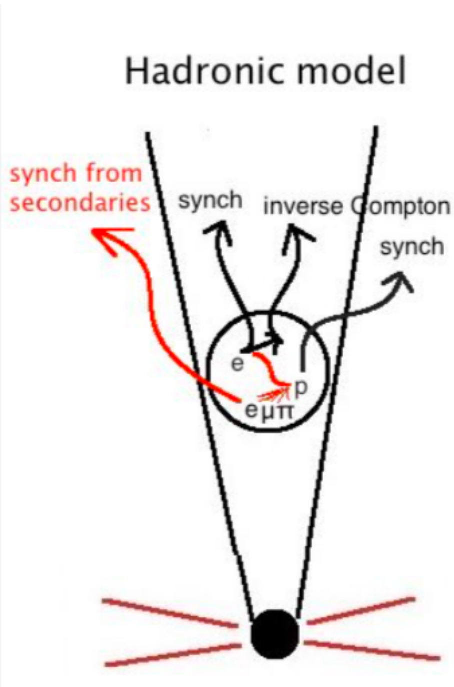
- orphan flares (leptonic model predicts perfect)



Krawczynski et al. 2004

2) Natural link with cosmic-rays and neutrinos

BLAZARS EMISSION MODELS

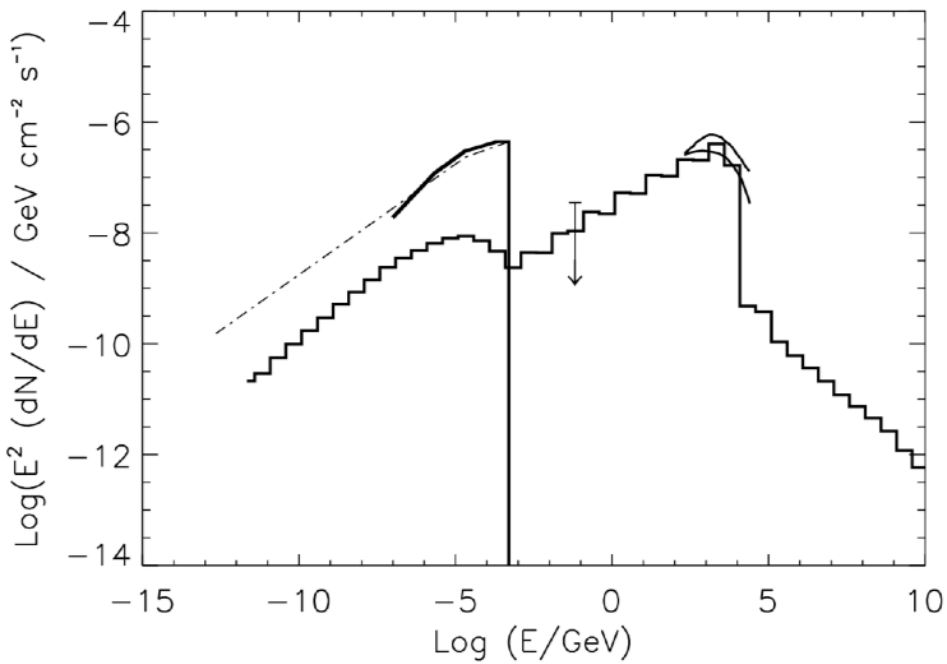


Hadronic models

Simplest hadronic model:

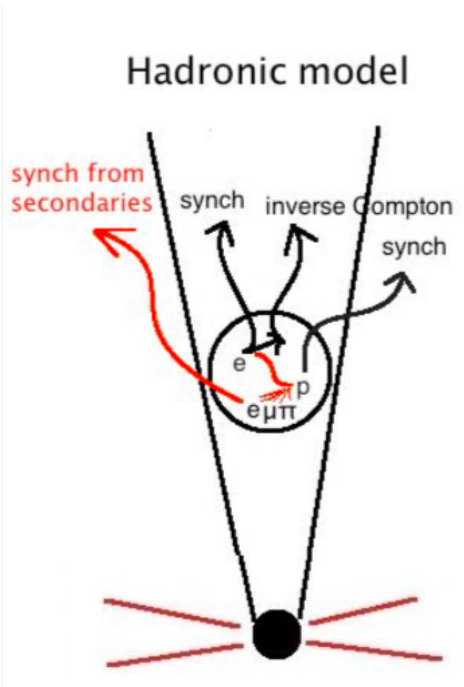
The high-energy component is proton synchrotron radiation

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



Mucke & Protheroe 2001

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

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

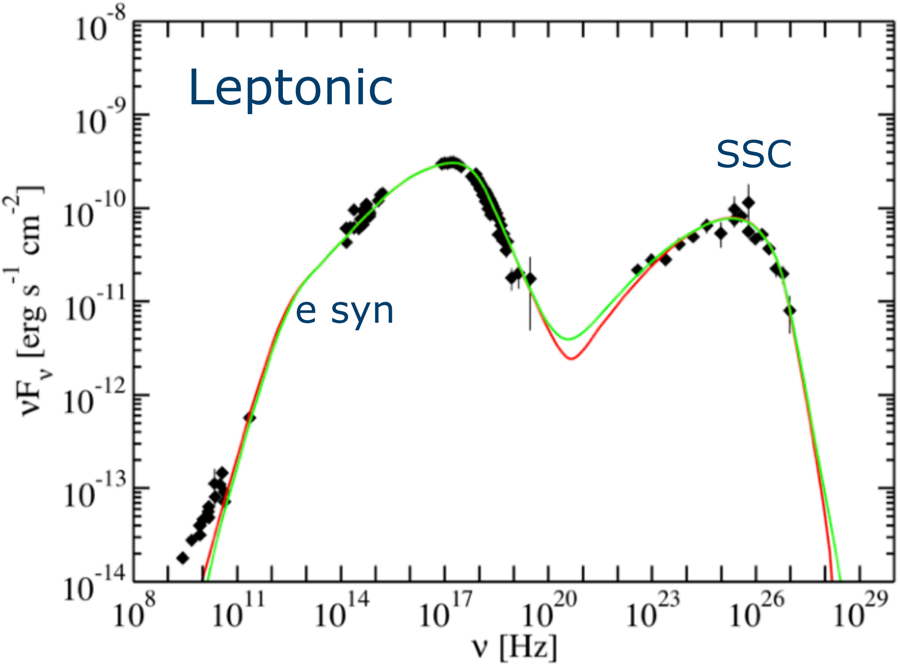
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

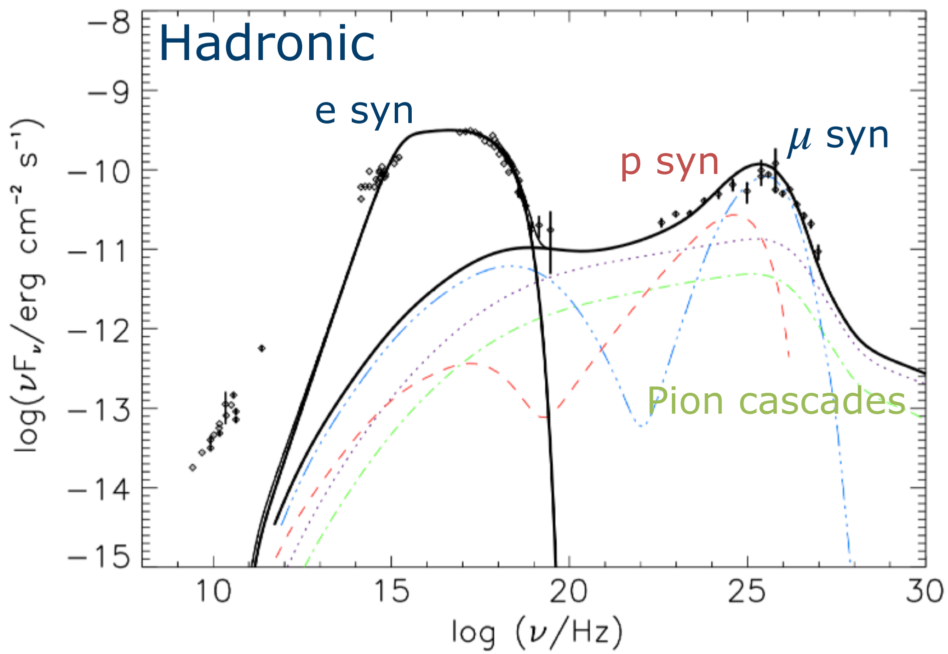
Synchrotron emission by muons can be important

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011





Abdo et al. 2011

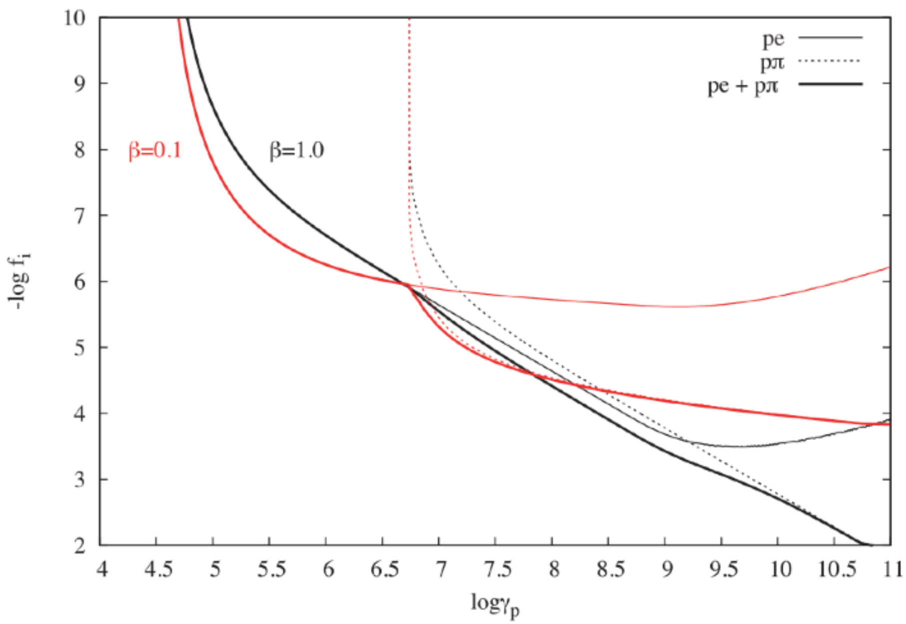
Matteo Cerruti

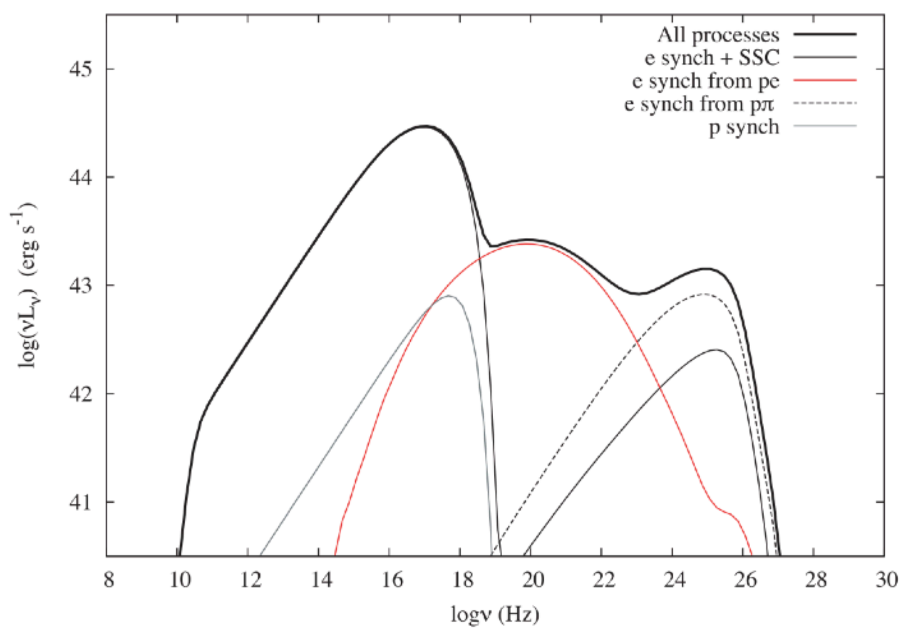
TXS 0506+056: the 2017 flare

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

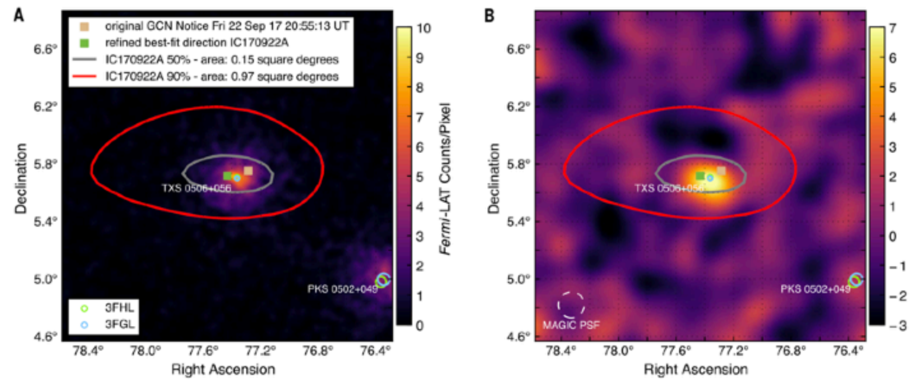


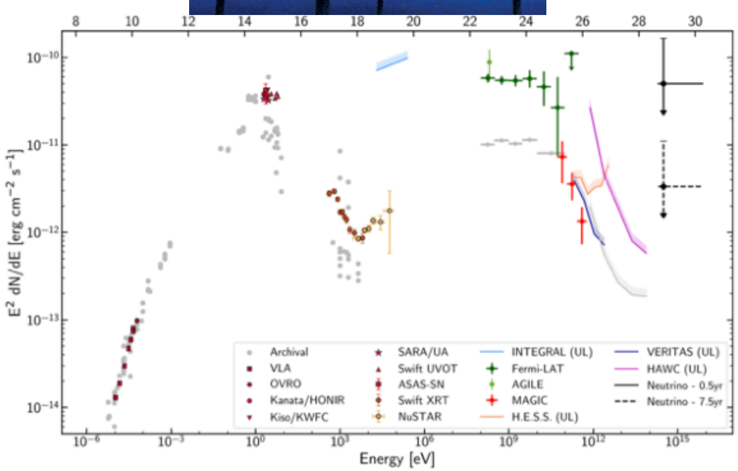


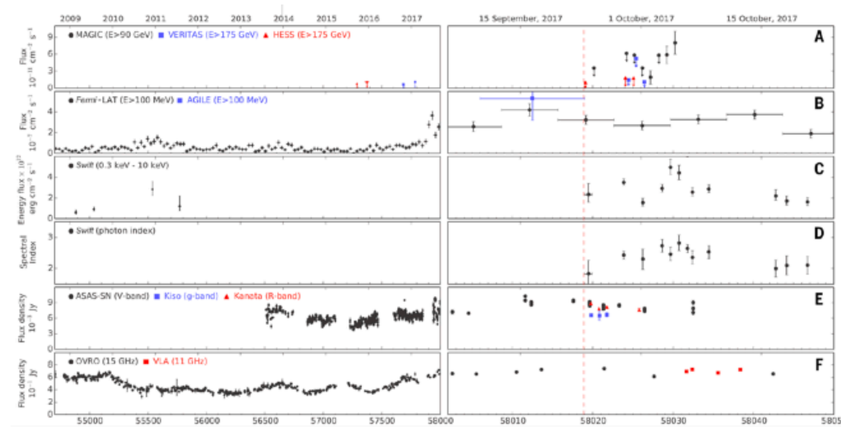
Petropoulou & Mastichiadis 2015

IceCube-170922A / TXS 0506+056

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

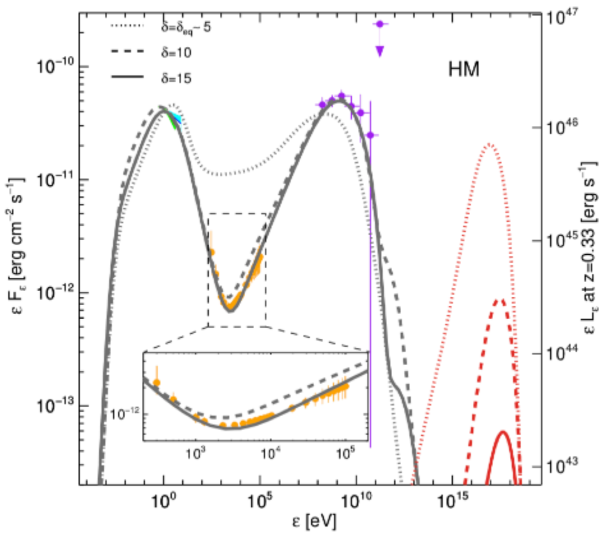


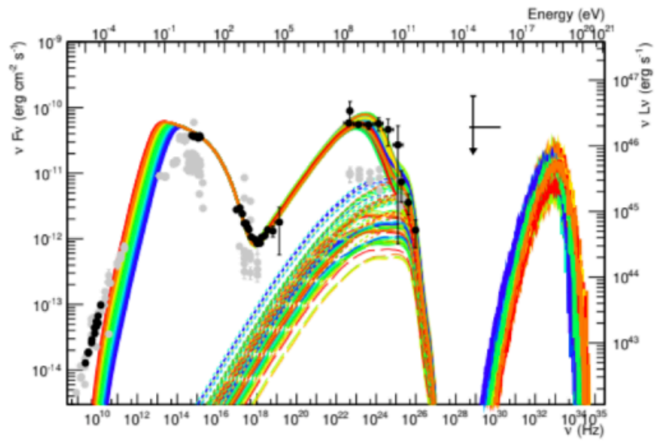




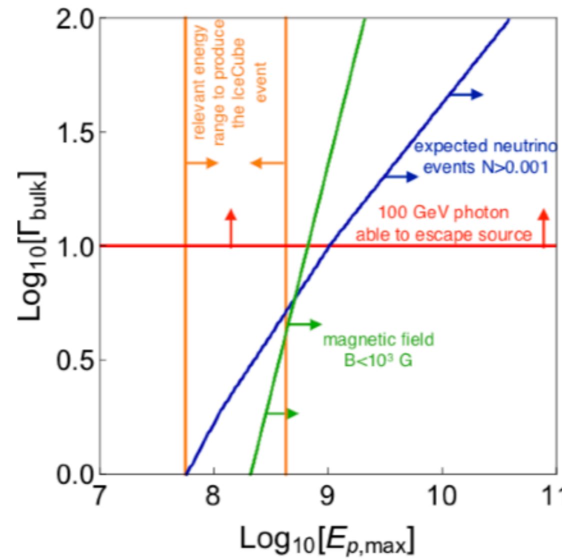
[IceCube, Fermi, MAGIC et al. 2018](#)

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

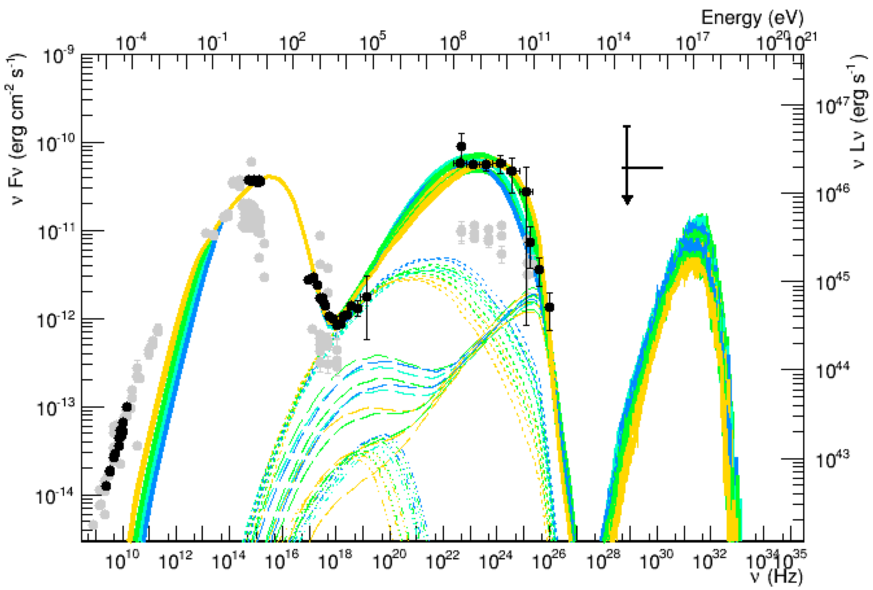
$\nu \simeq 10^{-5}\ yr^{-1}$

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

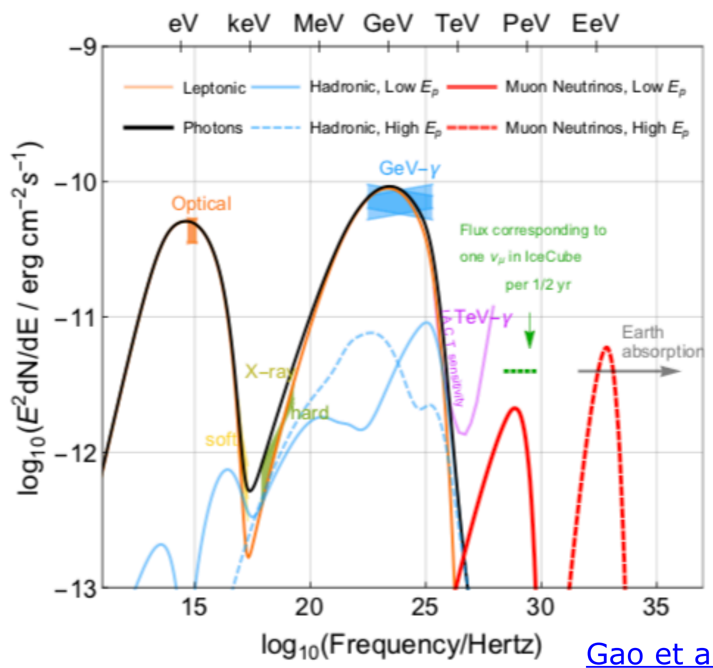
Gao et al. 2018

TXS 0506+056: the 2017 flare

Lepto-hadronic solutions



[Cerruti et al. 2019]



[Gao et al. 2018]

$L_{jet} = (9-60)\times 10^{47} erg/s$
$\nu = 0.01 - 0.06\ yr^{-1}$

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

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

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

Solved if p-γ interactions on external field

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)

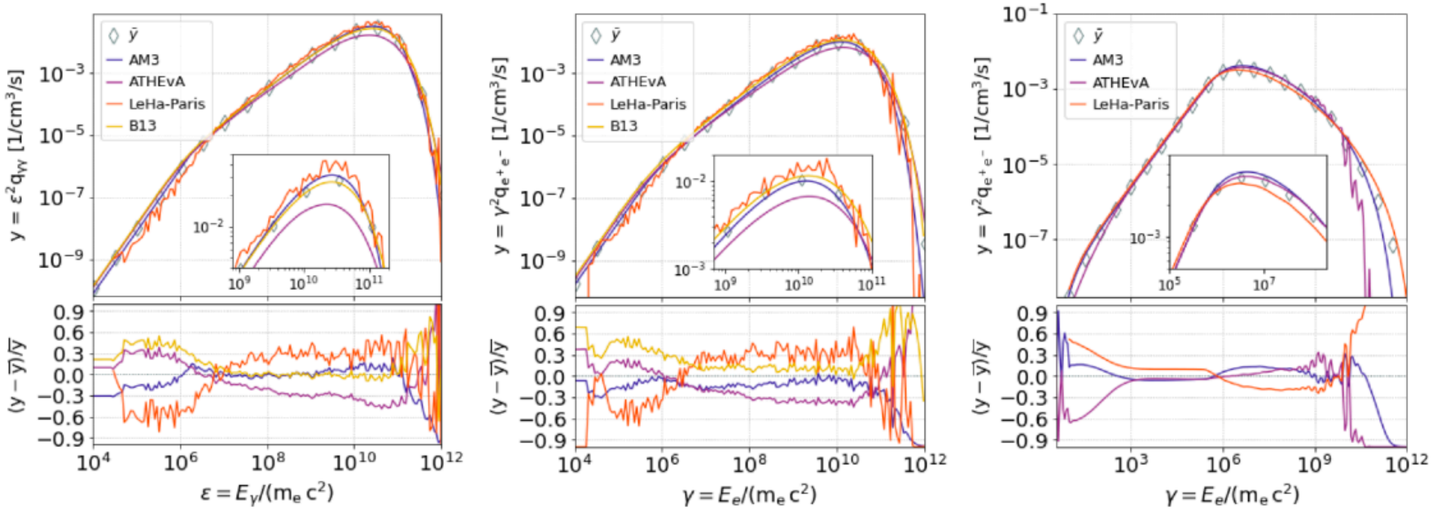
- run tests from simple 'artificial' cases
(Mono-energetic protons on black-body)
to 'realistic' ones
(proton-synchrotron or lepto-hadronic)

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

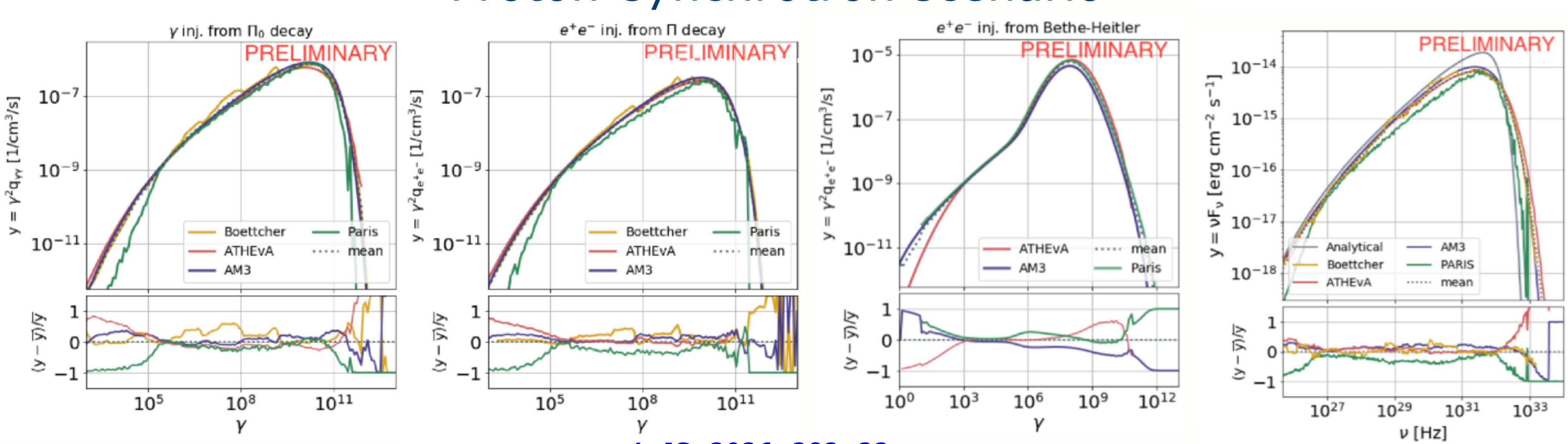
Take home message: spectral shapes are ok; 40% spread in normalization

HADRONIC CODE COMPARISON

Power-law protons on power-law photons



Proton-synchrotron scenario



ApJS, 2026, 282, 22

COMPACT SYMMETRIC OBJECT

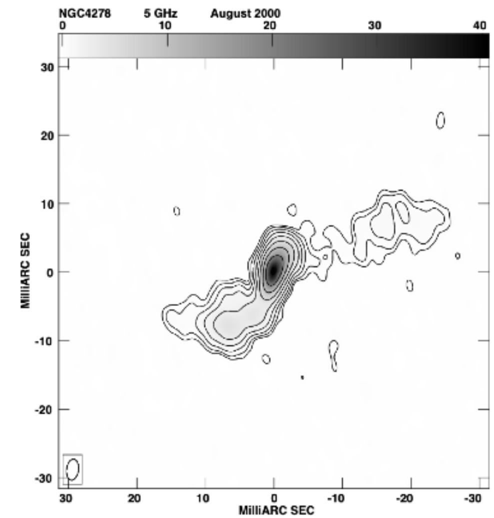
A new class of transient TeV emitters

Like a radio-galaxy, but with much smaller jets (<1 kpc)

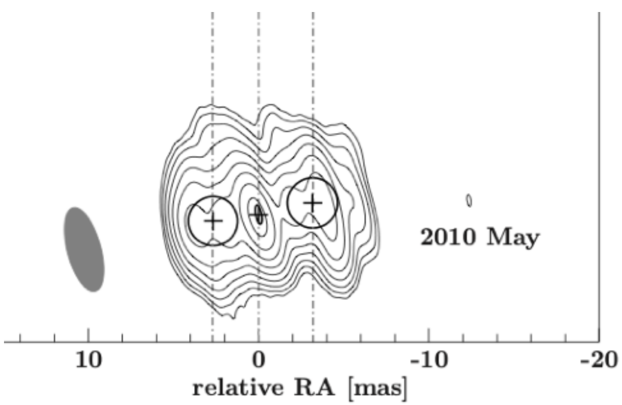
Probably a young, jetted AGNs.

First discovery by LHAASO in 2024: TeV flare from NGC 4278 (Cao et al. 2024, ApJ, 971)

One year ago: HESS discovery of a TeV flare from PMN J1603-4904
(paper in preparation, to be presented at Gamma 2026)



Giovannini et al. 2004



Muller et al. 2014