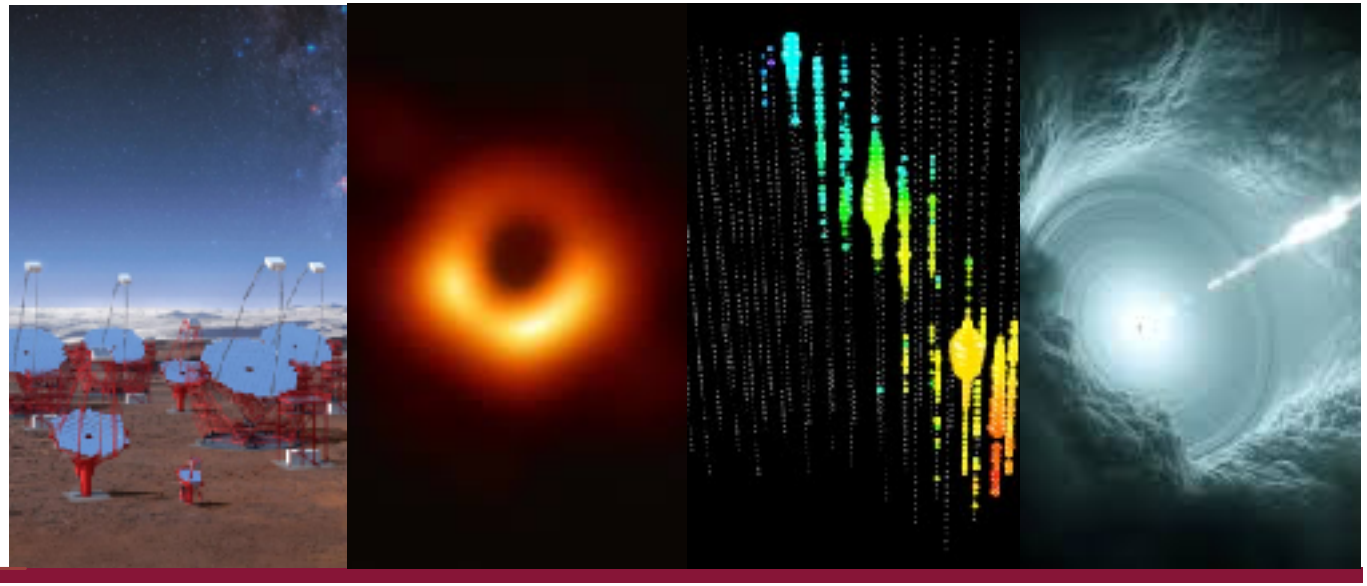


Blazars

Observations and Theory

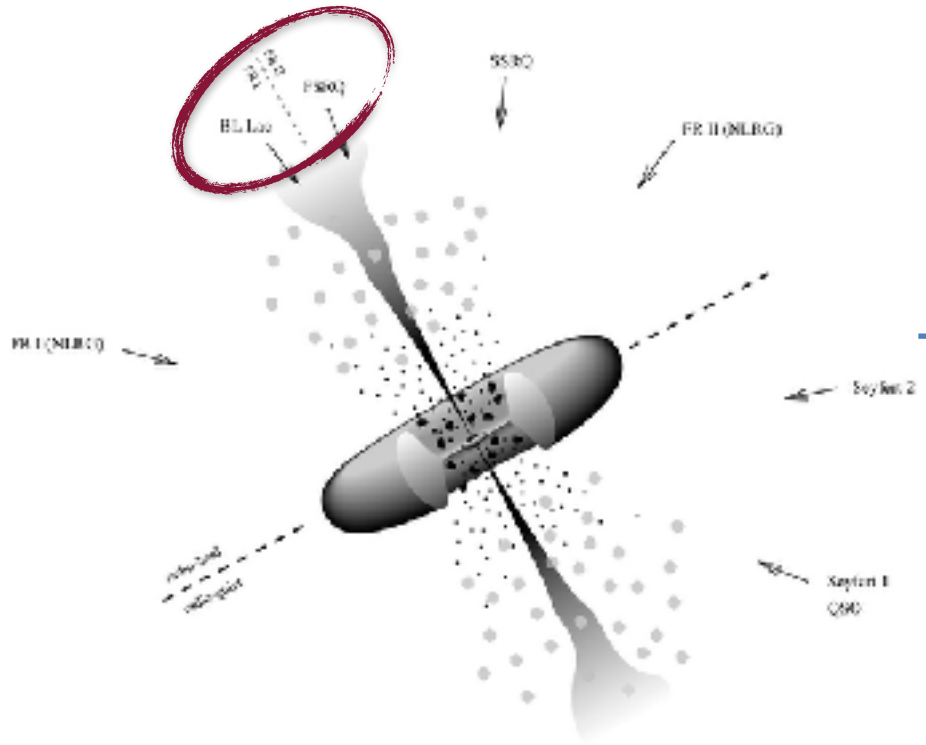
Matteo Cerruti

Université Paris Cité
Astroparticule et Cosmologie (APC)

PNHE DAY 2023

Paris
September 7, 2023

BLAZARS



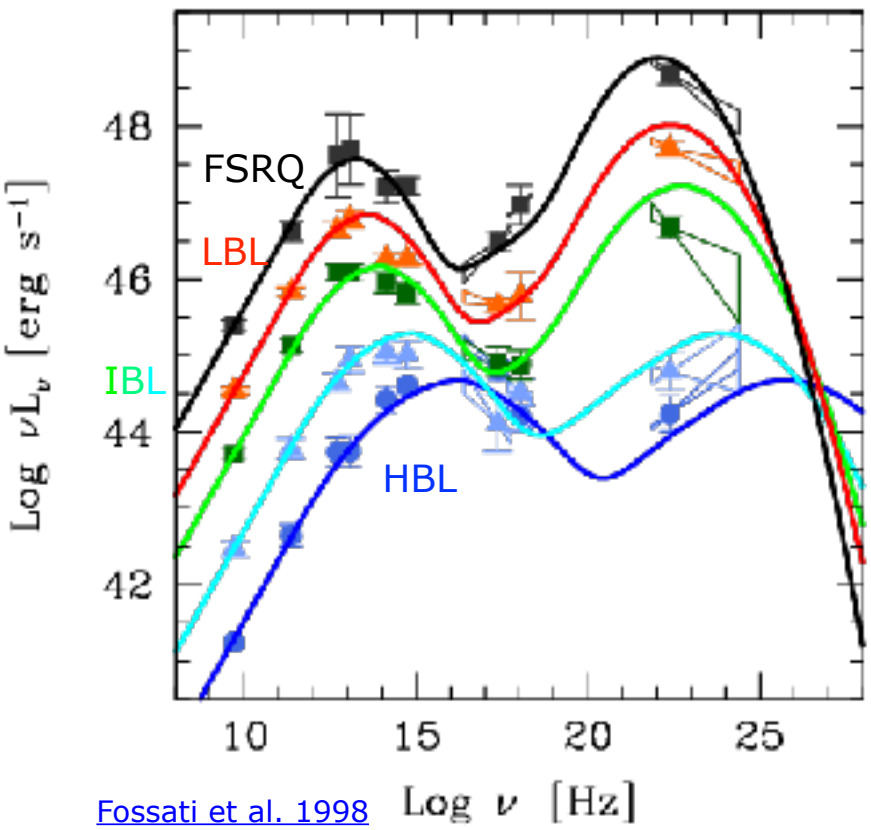
Blazar: radio-loud AGN whose relativistic jet points towards the observer

→ 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

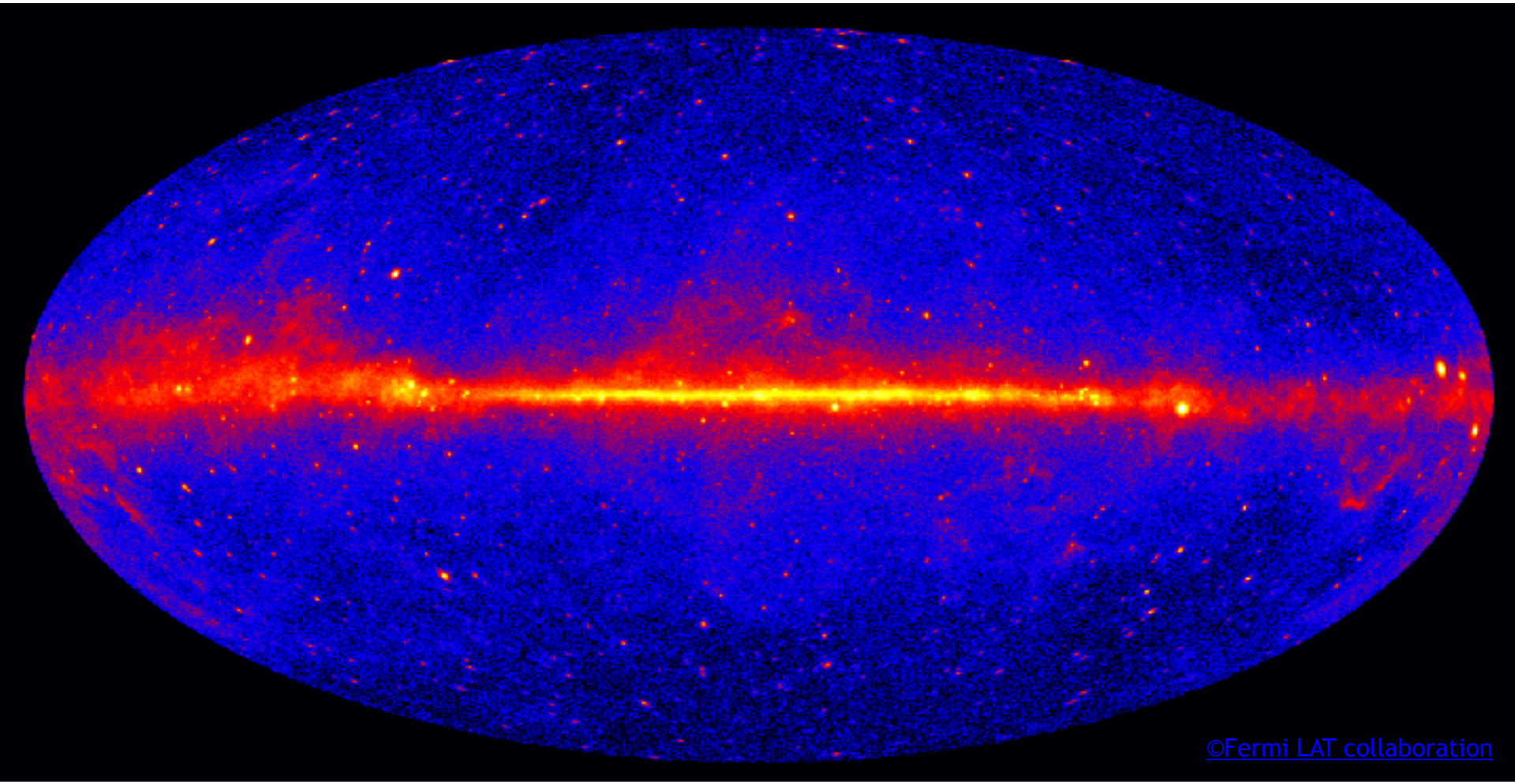
BL Lacs are classified into:

-IR peak: low-frequency peaked (LBLs)

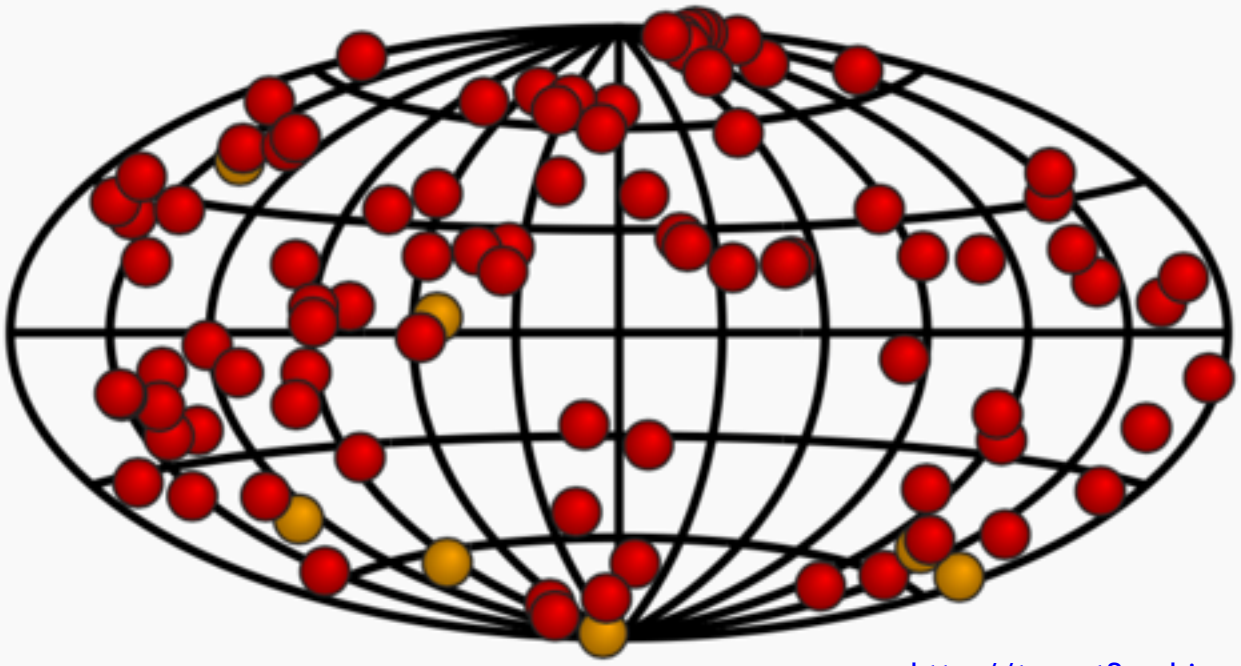
- optical peak: intermediate (IBLs)

- UV/X peak: high (HBLs)

THE GAMMA RAY SKY



THE GAMMA RAY SKY

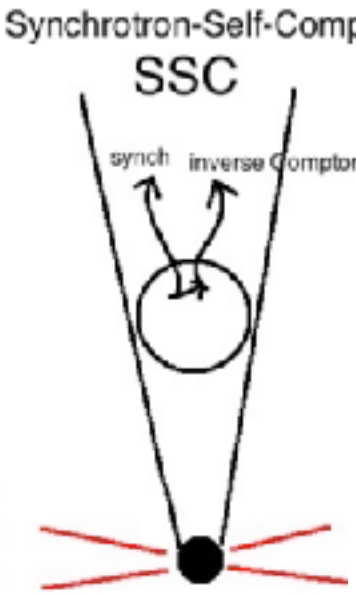


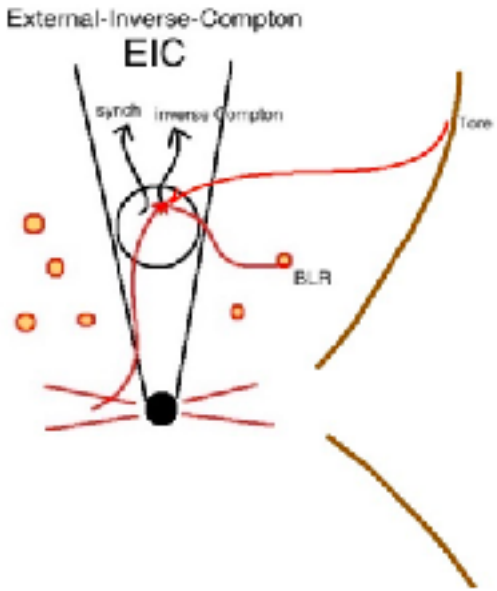
http://tevcat2.uchicago.edu

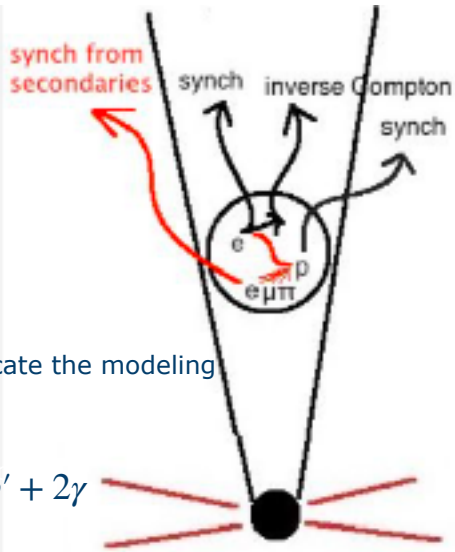
94 extragalactic sources: 5 GRBs
2 starburst galaxies
4 radio galaxies
83 blazars

BLAZARS EMISSION MODELS

Leptonic vs Hadronic







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

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

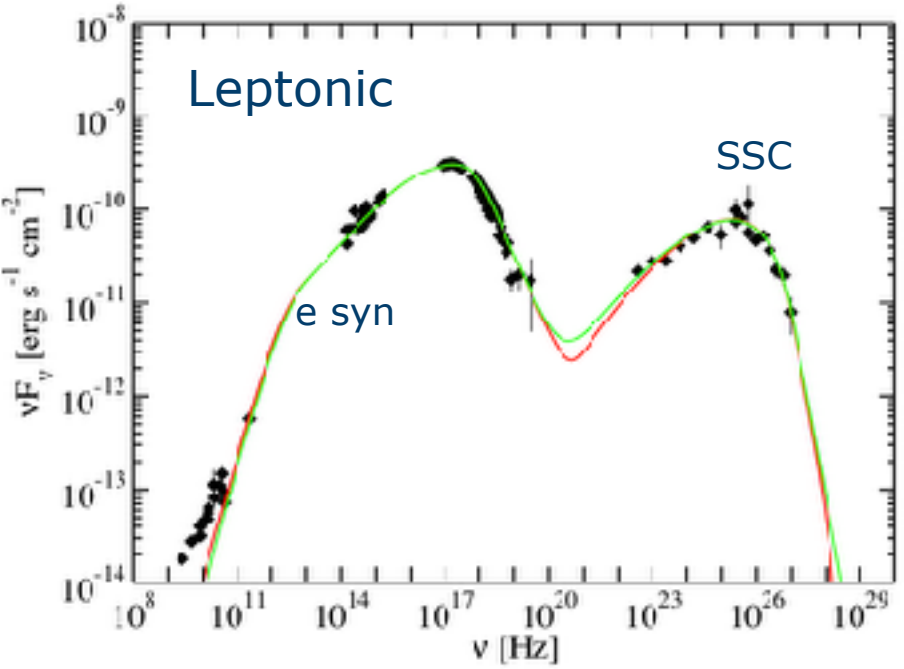
Injection of secondary leptons in the emitting region,
triggering synchrotron supported pair-cascades

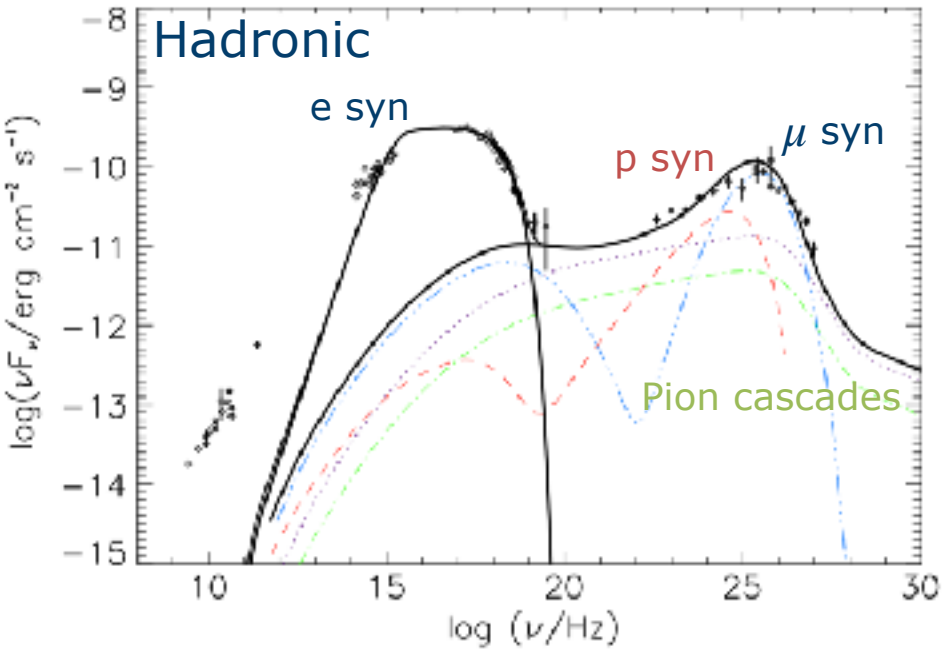
Synchrotron emission by muons can be important

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011





State-of-the-art models:

HBLs → SSC

LBLs / FSRQs → EIC

Abdo et al. 2011

WHY BLAZARS?

Relativistic jets from SMBH

Jets physical parameters (Lorentz factor, magnetic field)

Dissipation region identification

AGN unified model

AGN/Galaxy feedback

Particle acceleration mechanisms

Properties of the energy distribution (index, max energy)

Leptons or hadrons

Ultra-high-energy cosmic ray accelerators

Blazars as lighthouses

For fundamental physics

Gammay-ray cosmology:

Extragalactic Background light,

Intergalactic Magnetic Fields

Indirect dark matter

Axion-like particles

Quantum Gravity

RECENT TOPICS IN BLAZAR PHYSICS

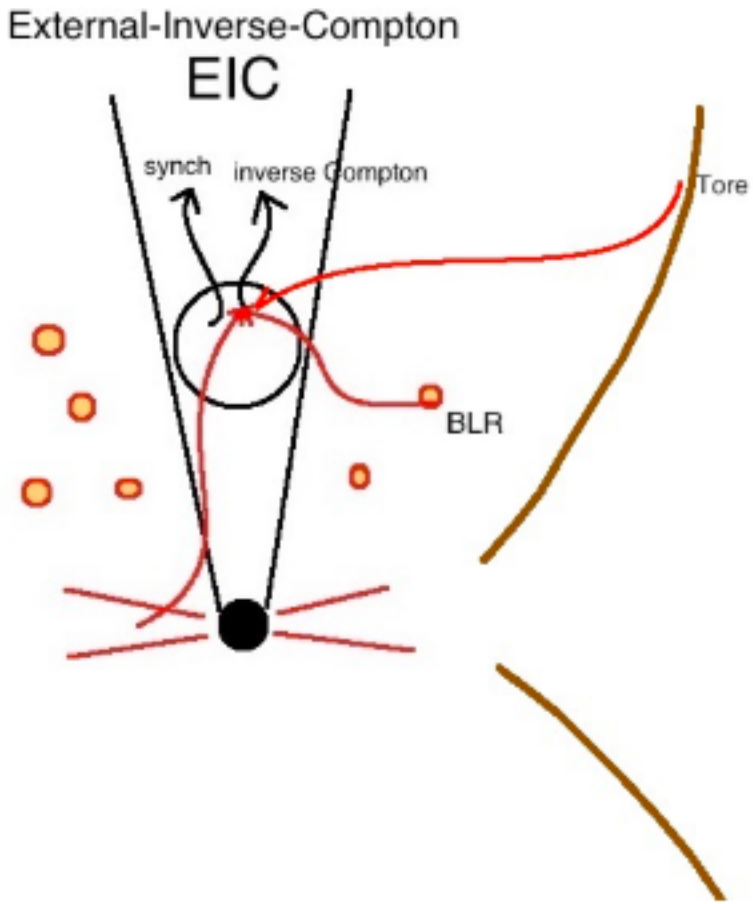
Where are gamma rays produced?

Are blazars **cosmic ray** accelerators?

Are we seeing super-massive black hole **binaries**?

What can **polarization** tell us?

WHERE ARE GAMMA RAYS PRODUCED?



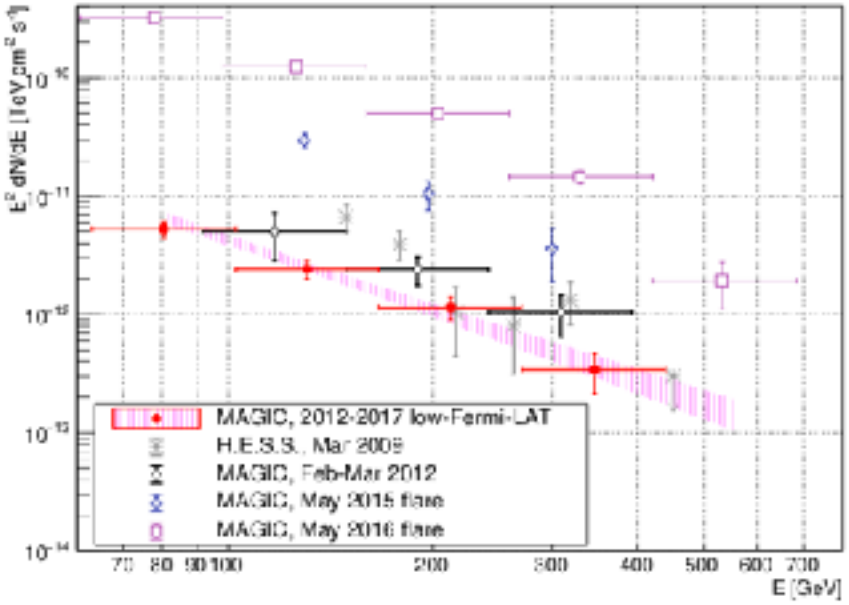
Origin of γ-ray emission:
External-Inverse-Compton

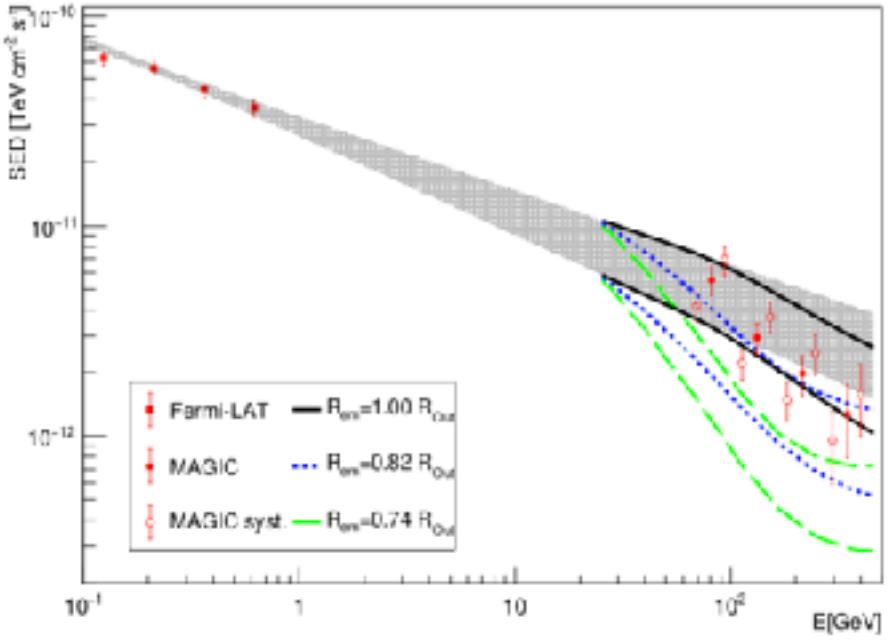
The external field also acts as an absorber via γ-γ pair-production

The detection of γ-ray photons can be used to constrain the (relative) location of the emitting region!

WHERE ARE GAMMA RAYS PRODUCED?

First detection of a VHE FSRQ
in a non-flaring state!

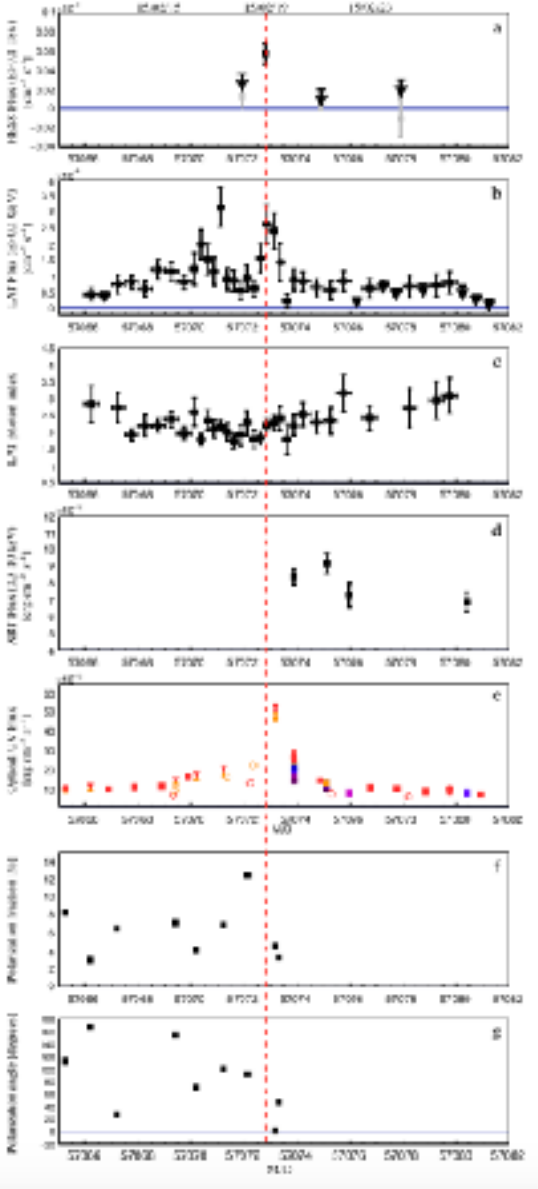




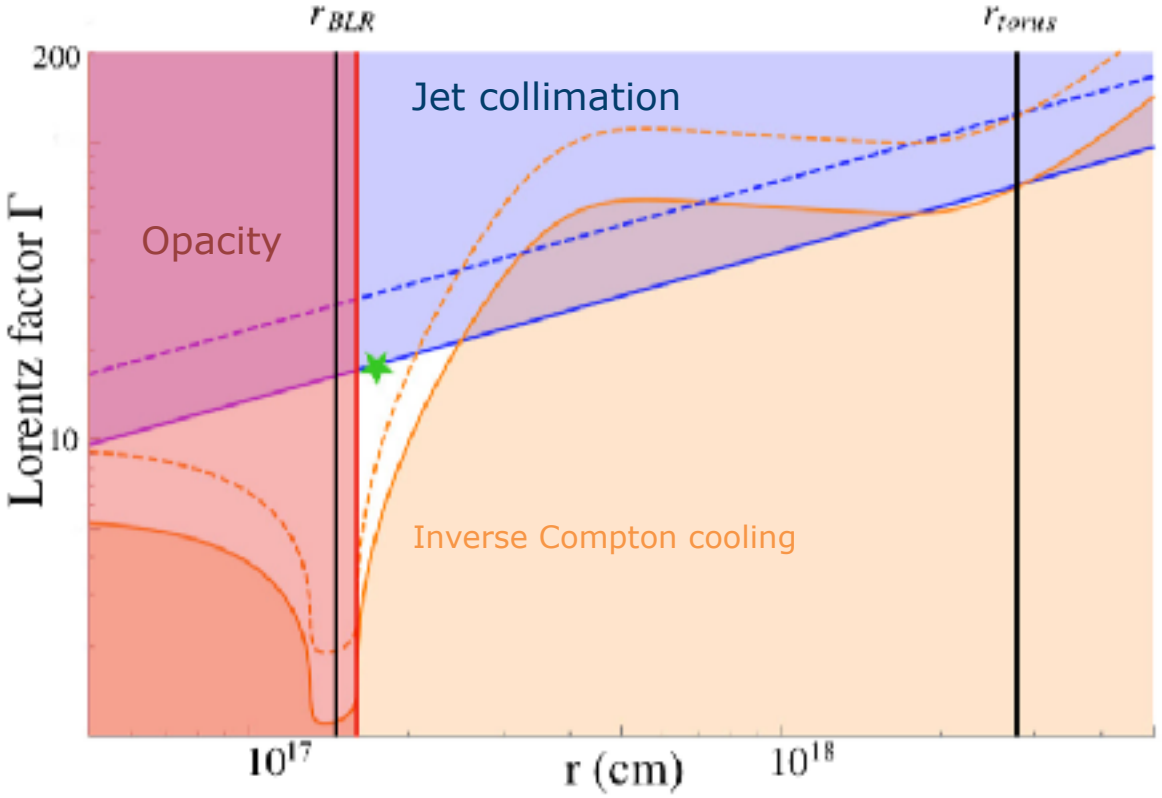
The emitting region HAS to be at
$r \geq r_{BLR}$ even during quiescence

MAGIC Collaboration et al. 2018

WHERE ARE GAMMA RAYS PRODUCED?



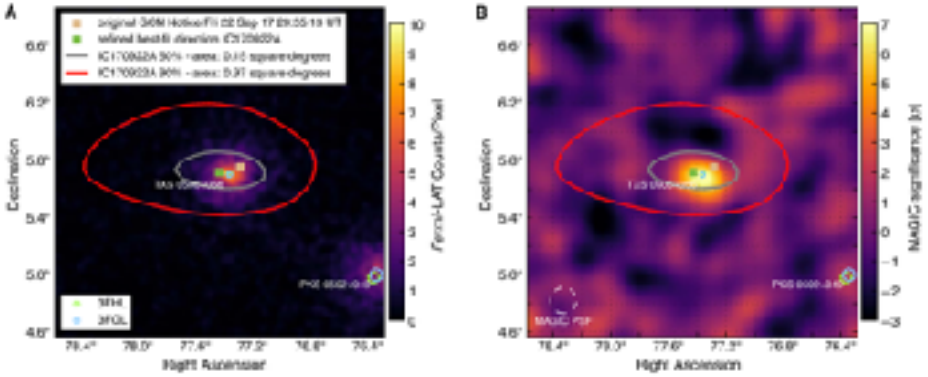
Nearest VHE FSRQ, at z=0.189

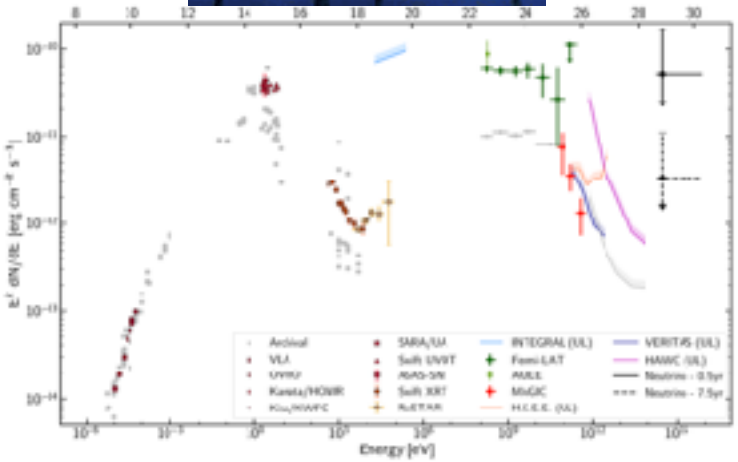


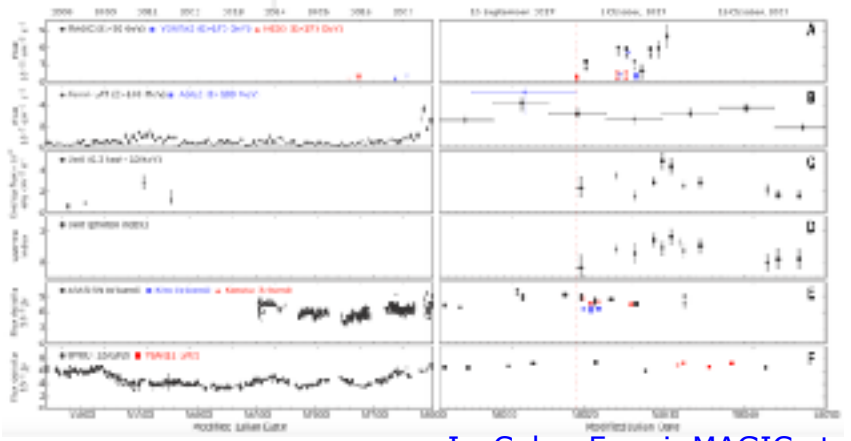
HESS Collaboration et al. 2020

ARE BLAZARS COSMIC RAY ACCELERATORS?

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

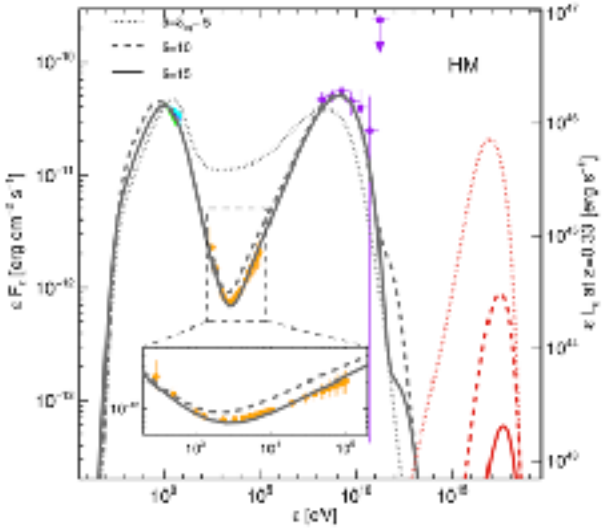






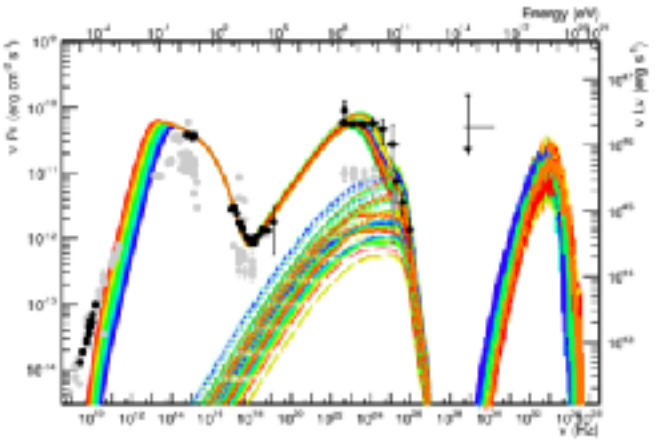
IceCube, Fermi, MAGIC et al. 2018

TXS 0506+056: THE 2017 FLARE



Keivani et al. 2018

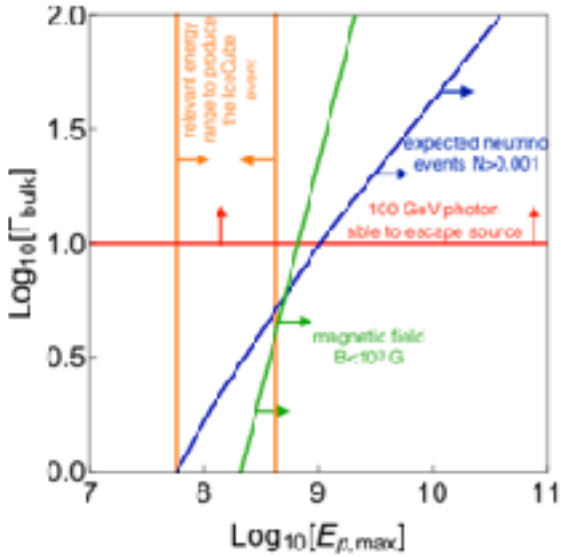
$\nu \simeq 10^{-5}\ yr^{-1}$



(a) Proton synchrotron modeling of TXS 0506+056

Cerruti et al. 2019

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

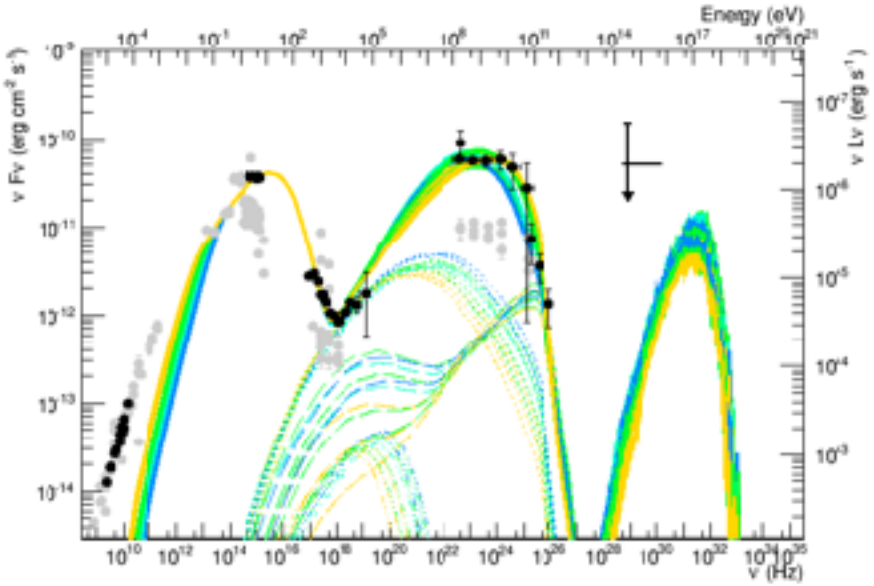


Gao et al. 2018

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

TXS 0506+056: THE 2017 FLARE

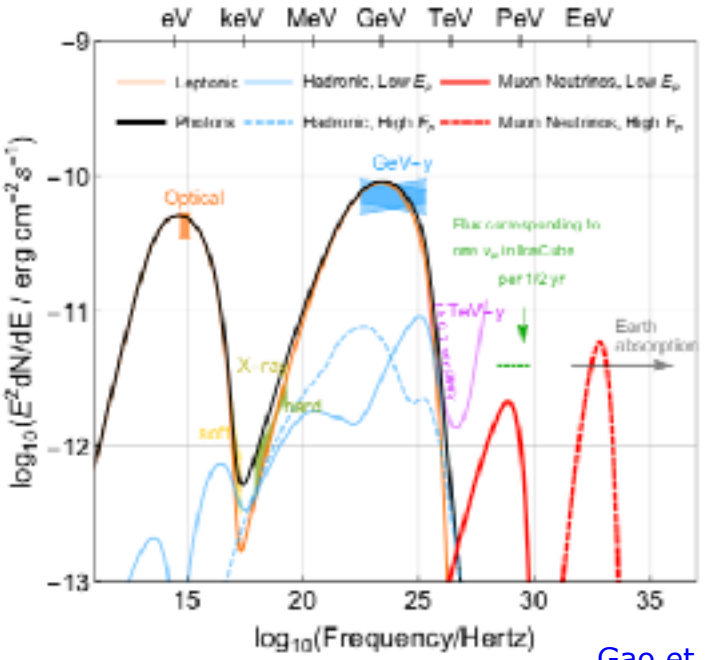
Lepto-hadronic solutions



Cerruti et al. 2019

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

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



Gao et al. 2018

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

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

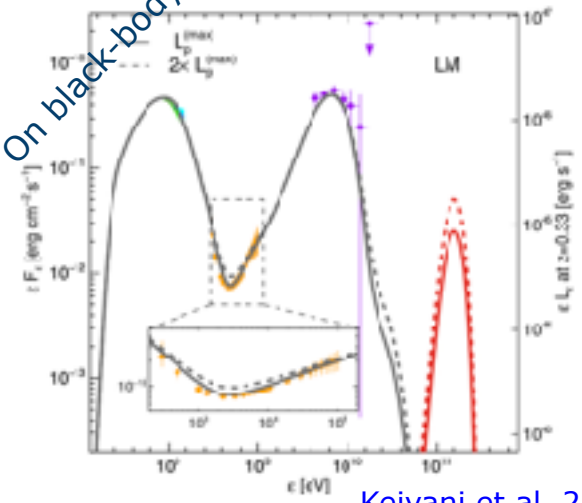
They can work: neutrino rates of the order of 0.1 / yr

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

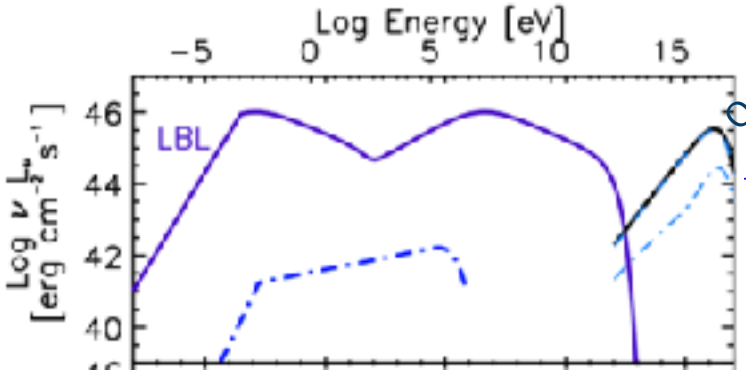


Keivani et al. 2018

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

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

On RIAF

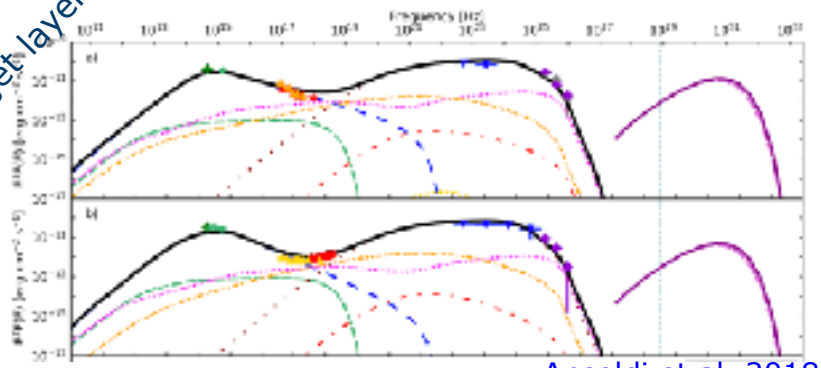


Righi et al. 2019

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

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

On jet layer



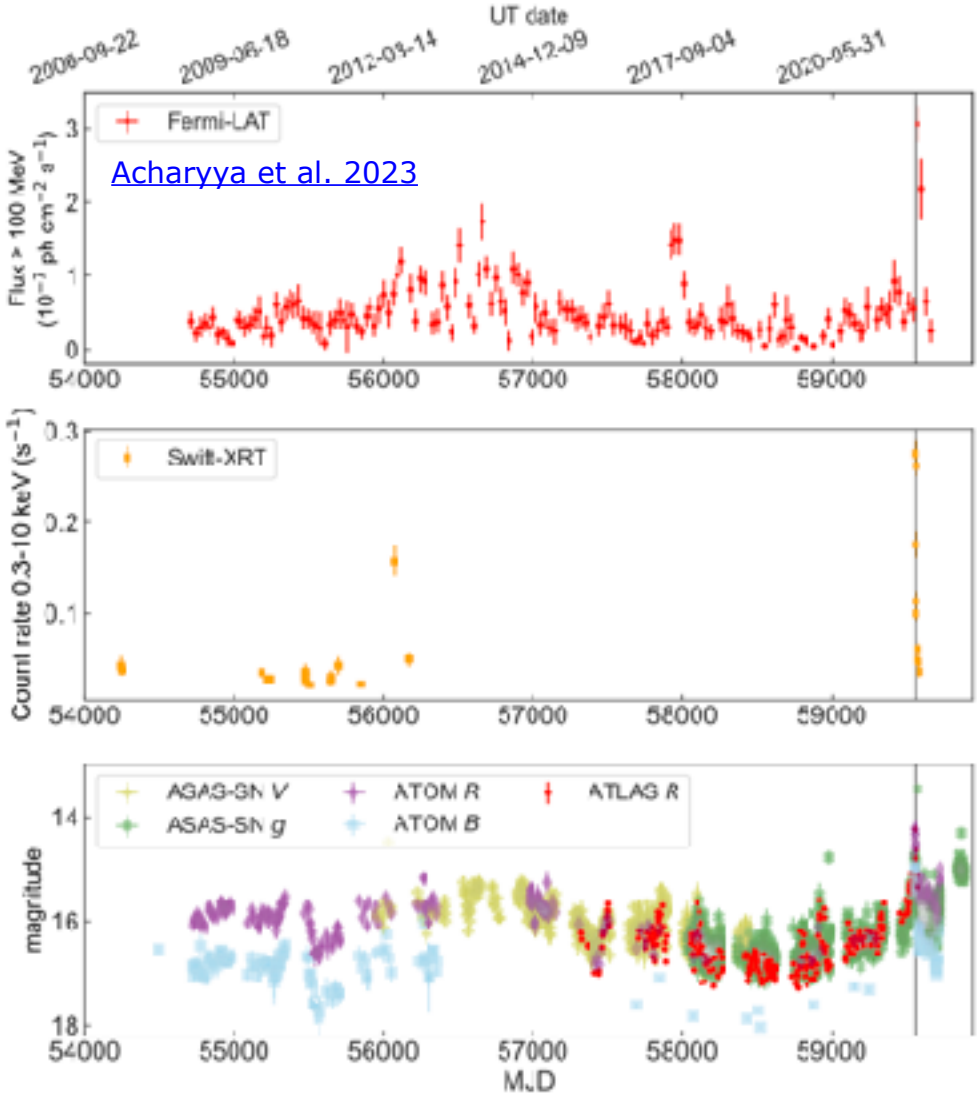
$L_{jet} = (3 - 8) \times 10^{45} erg/s$

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

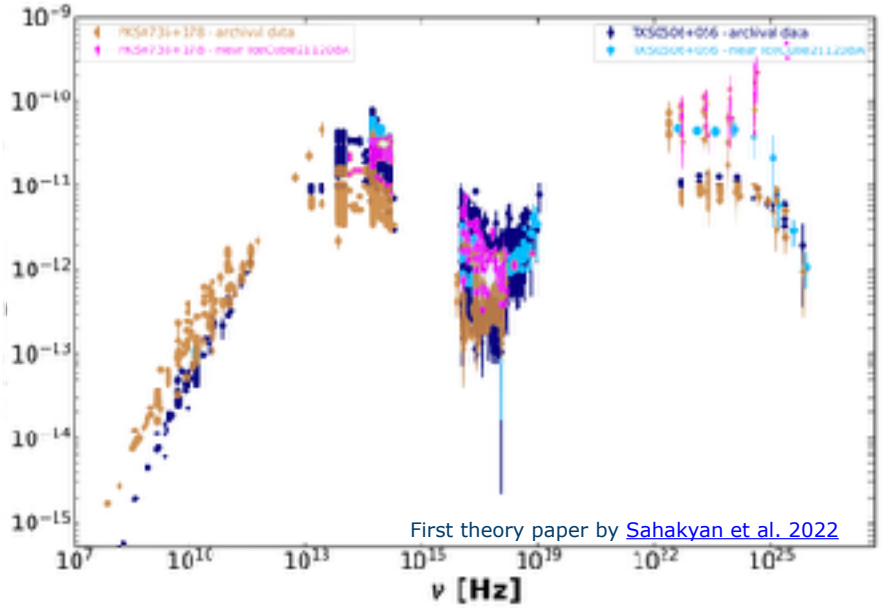
Ansoldi et al. 2018

WHAT HAPPENED SINCE 2017?

FLARE OF PKS 0735+178 / IC211208A



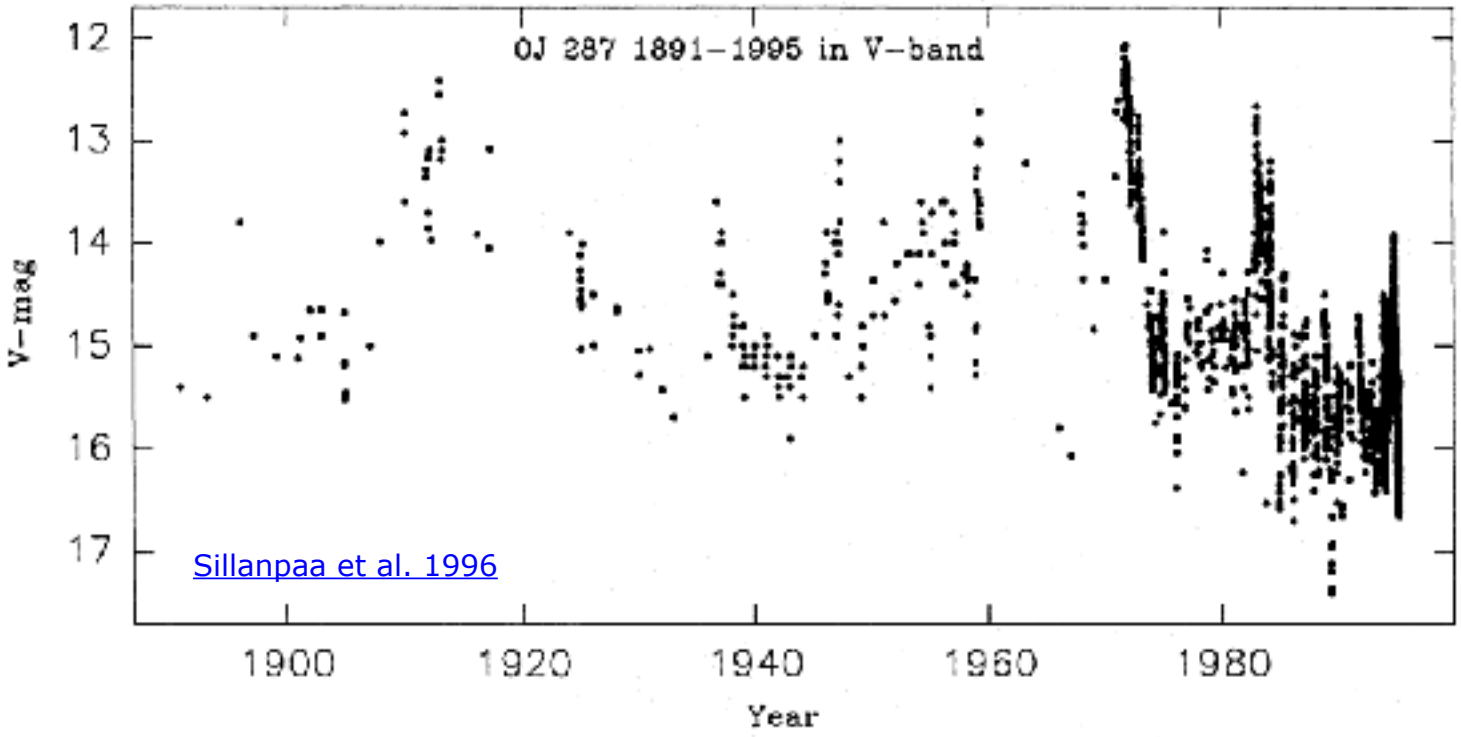
Acharyya et al. 2023



First theory paper by Sahakyan et al. 2022

ARE WE SEEING SMBH BINARIES?

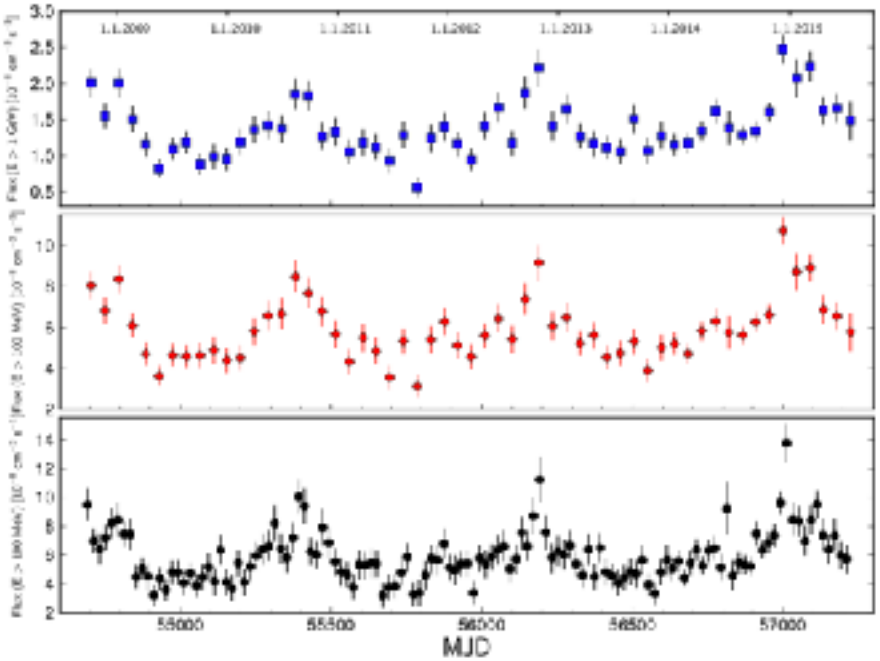
IDENTIFICATION VIA LONG-TERM QUASI-PERIODIC OSCILLATIONS



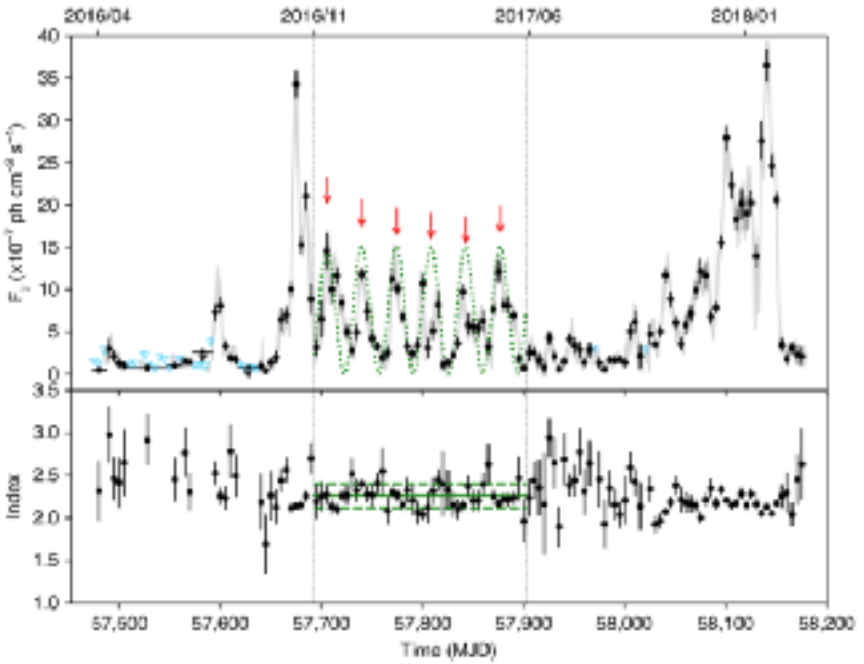
Sillanpaa et al. 1996

ARE WE SEEING SMBH BINARIES?

Periodicity and Quasi-Periodic-Oscillations



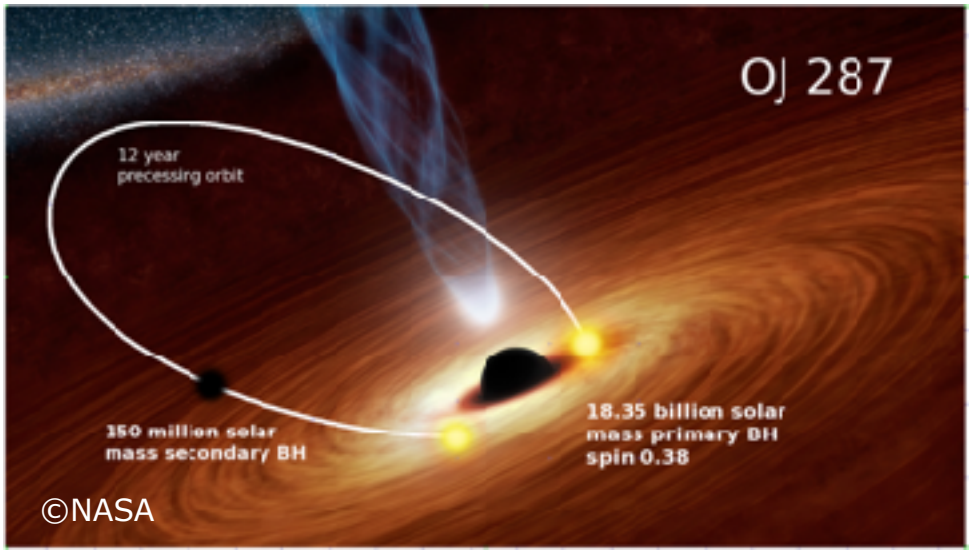
Ackermann et al. 2015



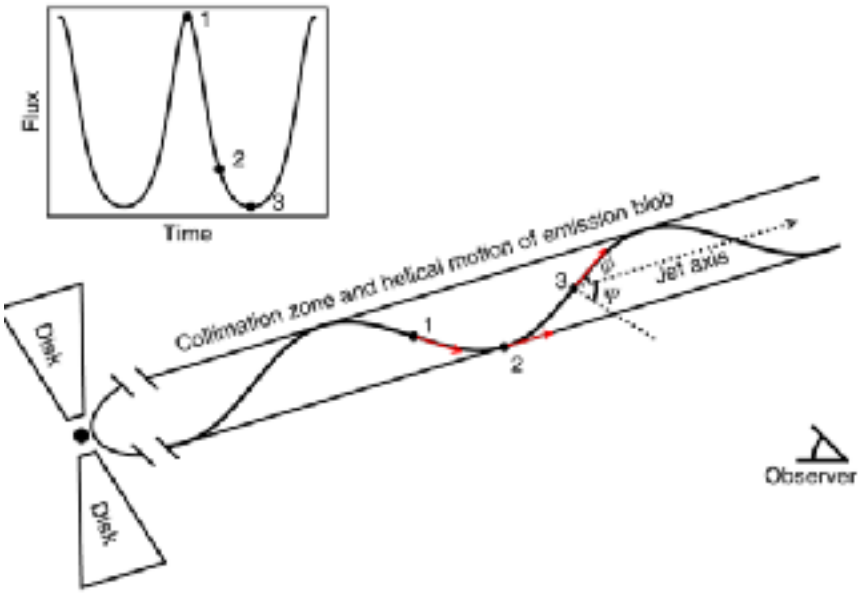
Zhou et al. 2018

ARE WE SEEING SMBH BINARIES?

Super-massive black-hole Binary



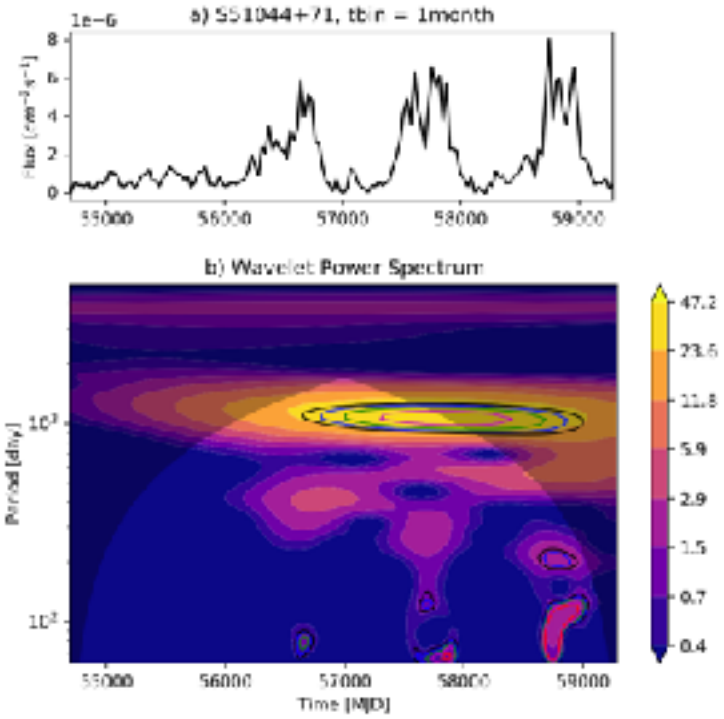
Helical structure of the jet

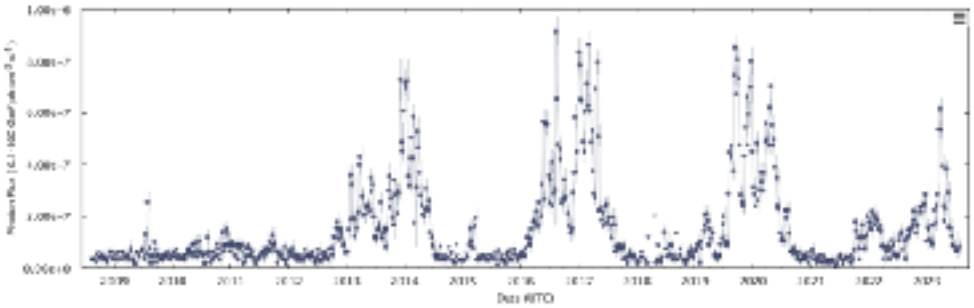


Zhou et al. 2018

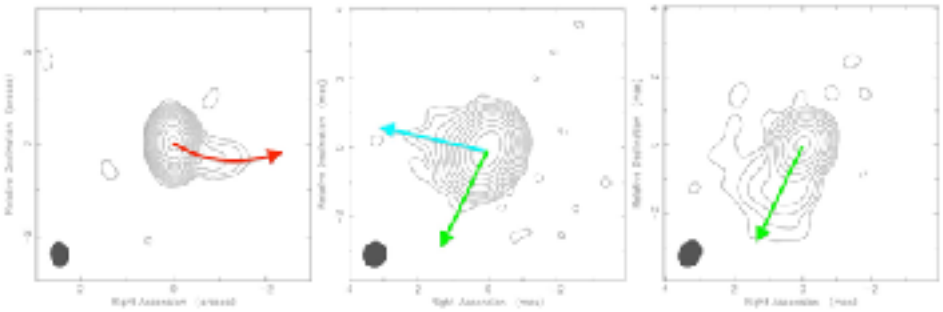
ARE WE SEEING SMBH BINARIES?

Systematic search in LAT data (Ren, H. et al. 2023)
New best candidate is S5 1044+71





Updated light curve from LAT repository

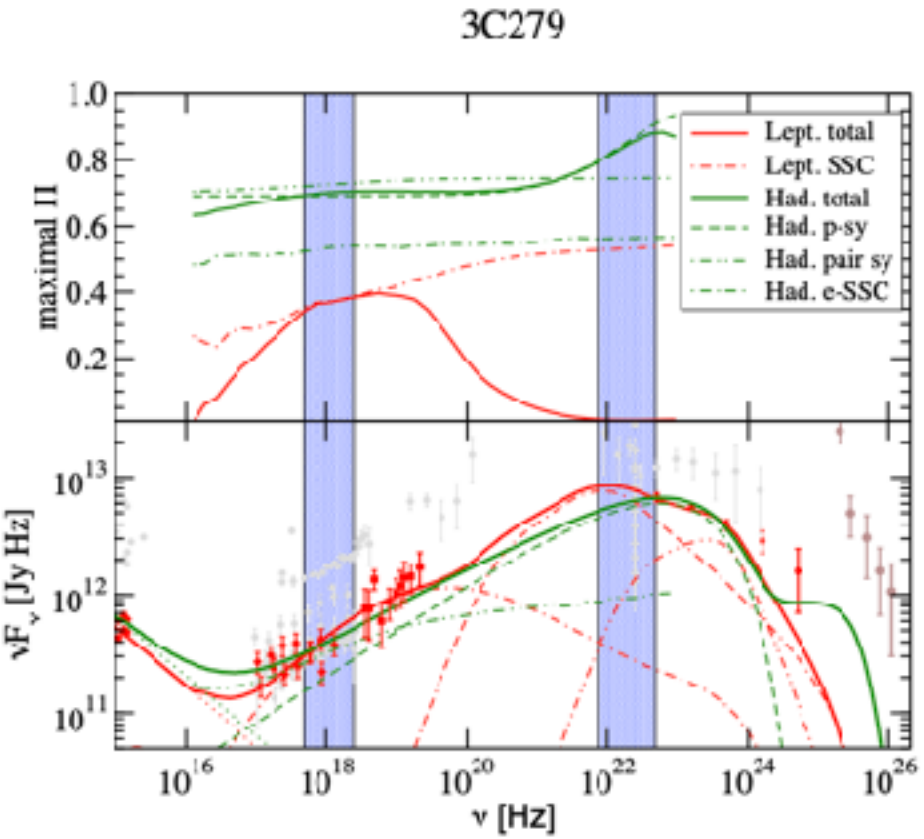


Kun et al. 2023

WHAT IS X-RAY POLARIZATION TELLING US?

X-ray polarization can constrain

- leptonic/hadronic models (in LSP blazars)
- the geometry
- the single zone model



Zhang & Böttcher, 2013

WHAT IS X-RAY POLARIZATION TELLING US?

Results from IXPE

SEE NEXT TALK!

WHY BLAZARS?

What is the particle **acceleration mechanism**?
role of shocks/magnetic reconnection/shear

Are **hadrons** accelerated in black hole jets?
blazars are cosmic rays/neutrino sources

Where are the photons produced?
is the multi-wavelength SED a **single zone**?

How is the jet **launched**?

What is its **structure**?

How it **propagates**?
role of jet/obstacle interactions

What triggers the **variability/flares**?
link accretion/ejection?

What drives the **different blazar SEDs**/peak frequencies?