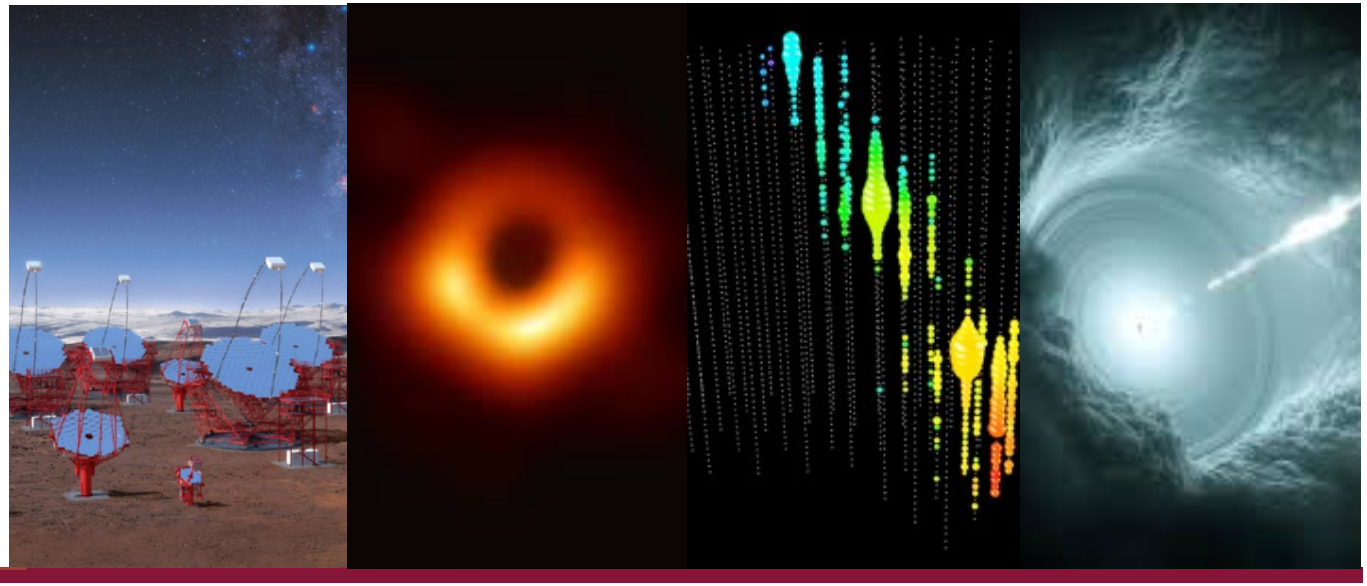


Neutrinos from blazars

five years after the IC 170922A / TXS 0506+056 event

Matteo Cerruti

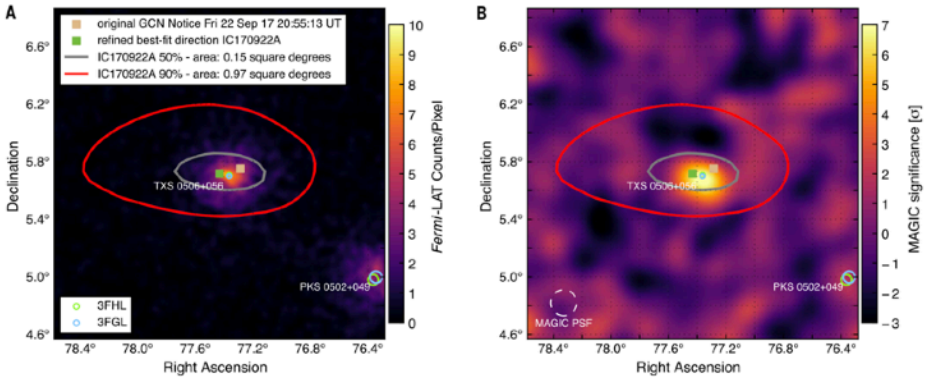
Université Paris Cité
Astroparticule et Cosmologie (APC)

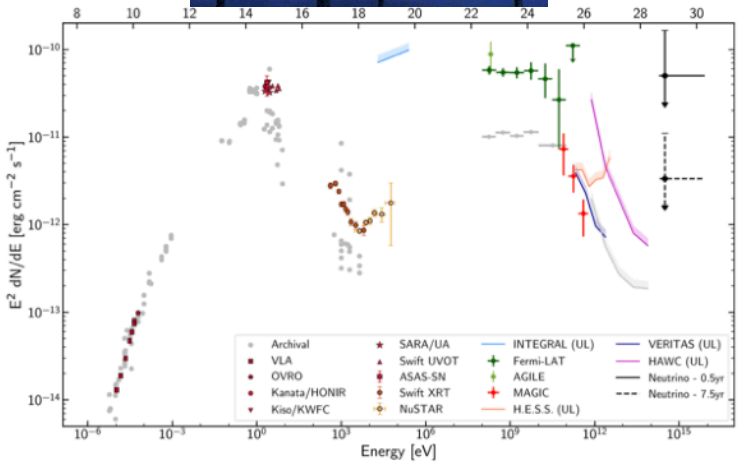
TeVPA 2022

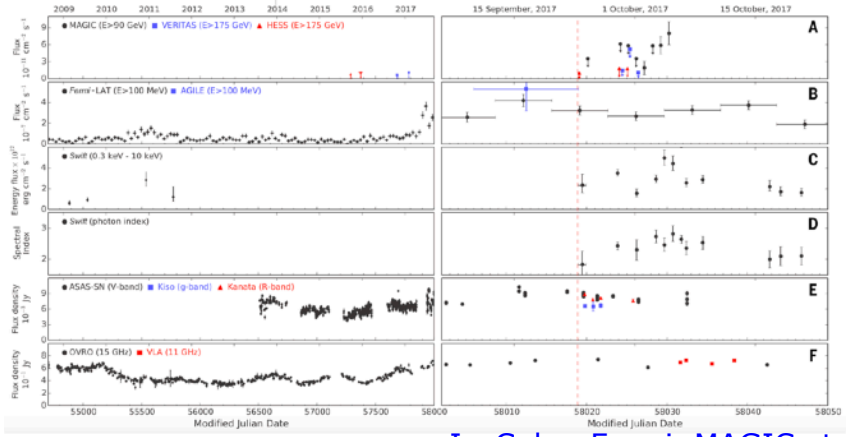
Kingston, ON
August 9, 2022

IceCube-170922A / TXS 0506+056

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

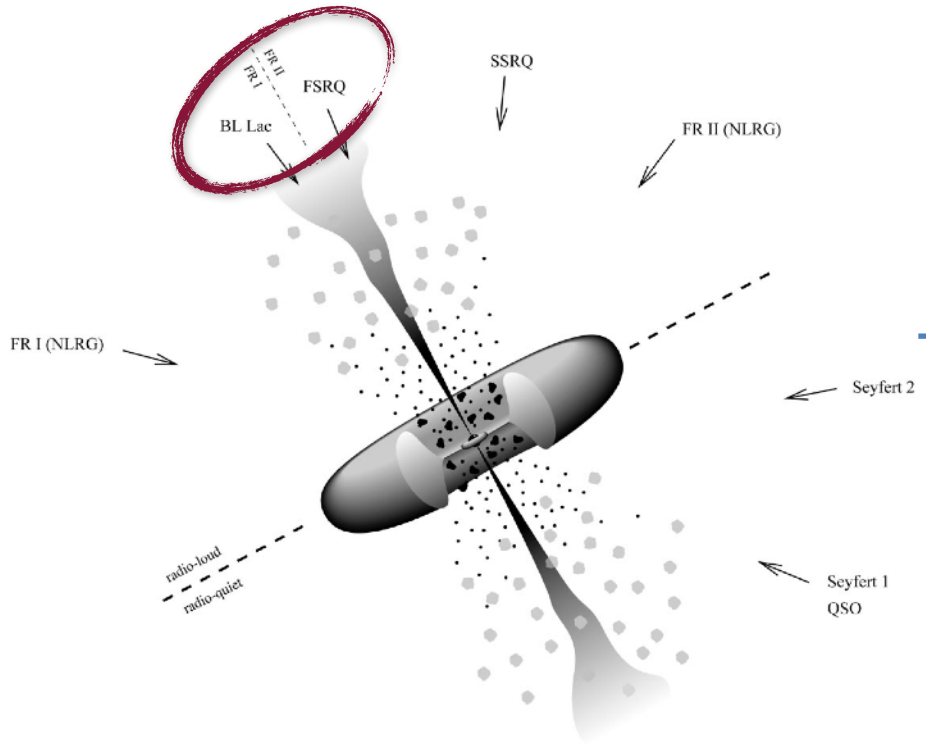






IceCube, Fermi, MAGIC et al. 2018

BLAZARS



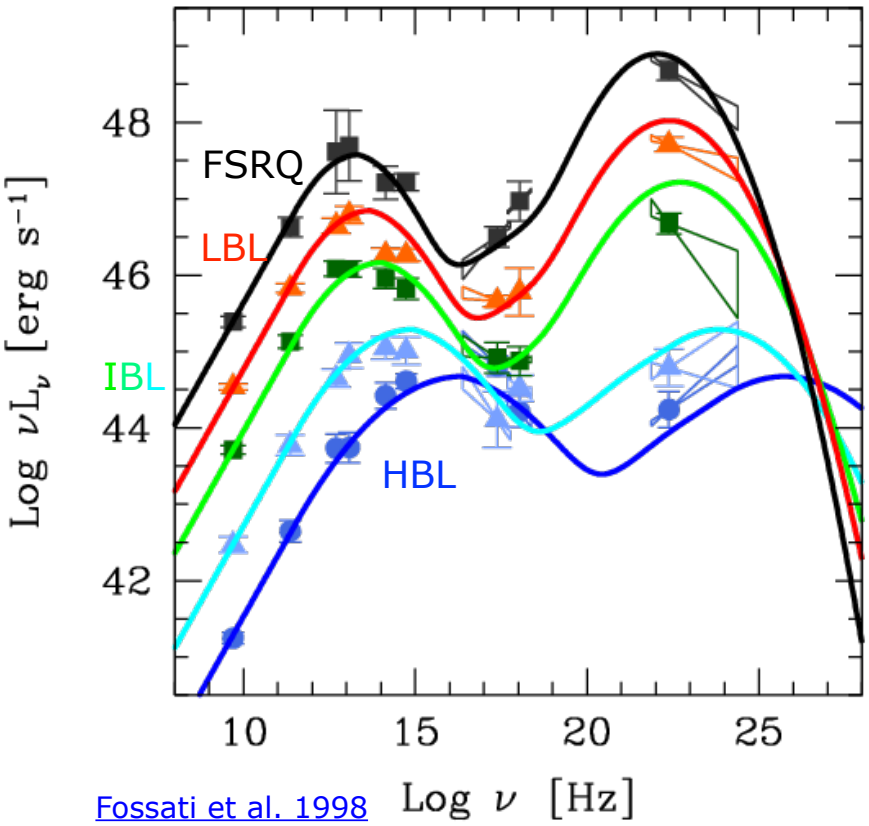
Blazar: radio-loud AGN whose relativistic jet points towards the observer

→ 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)

BLAZARS EMISSION MODELS

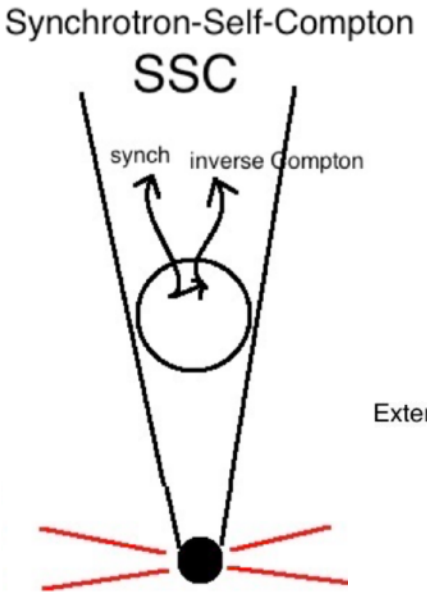
The low-energy SED component is synchrotron emission by electrons

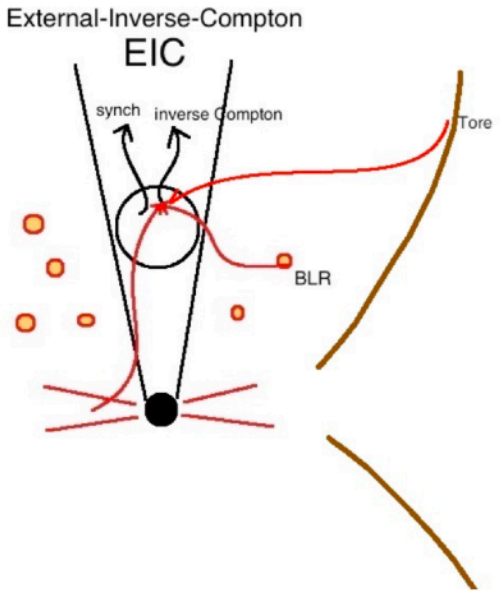
High-energy emission?

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

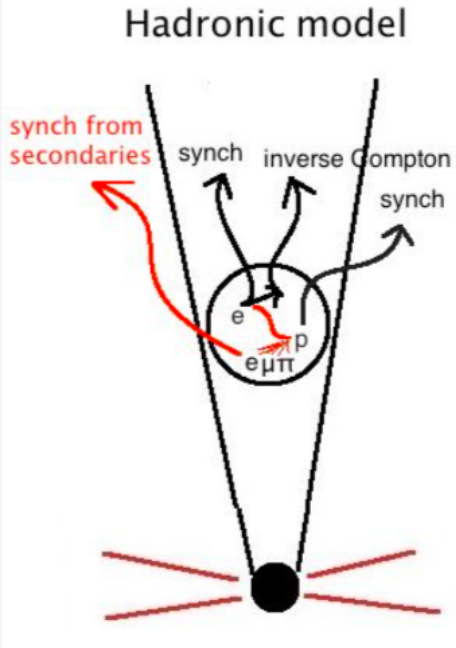




BLAZARS EMISSION MODELS

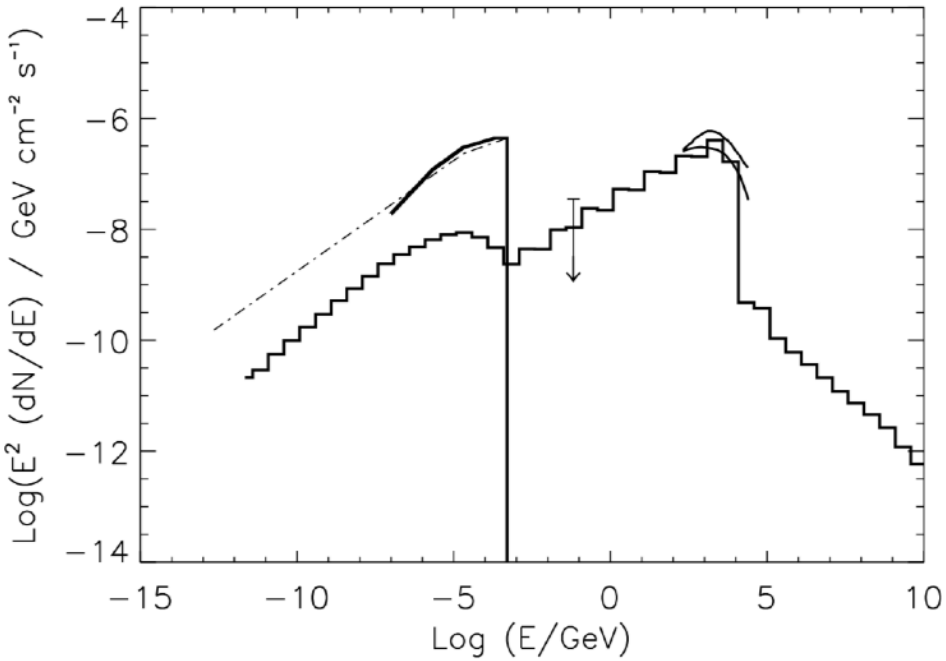
Hadronic models

Simplest hadronic model:



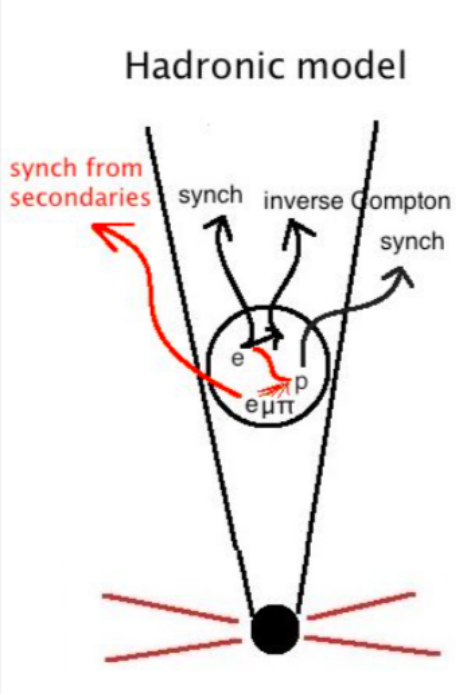
The high-energy component is proton synchrotron radiation

(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

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

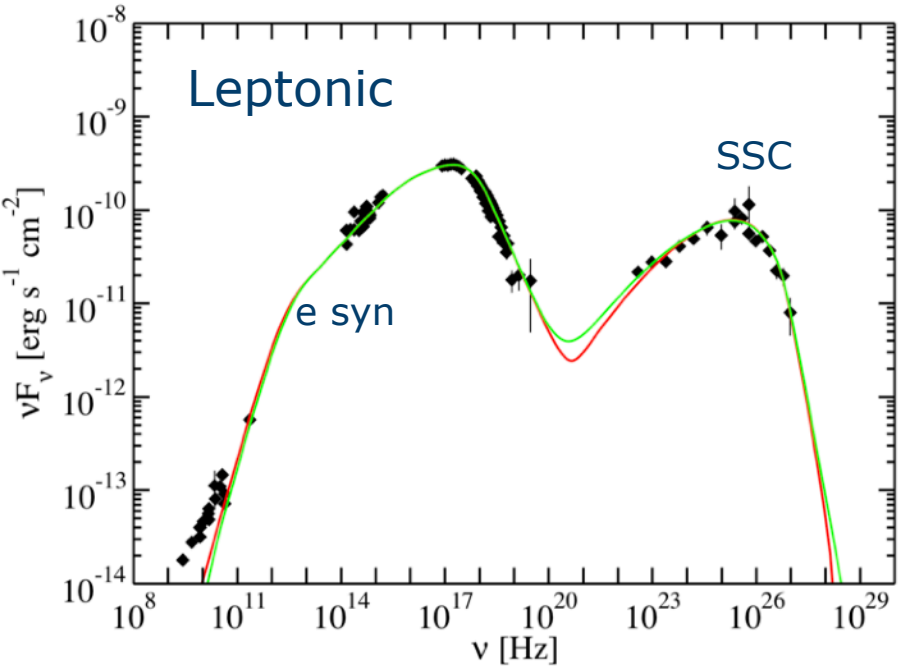
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

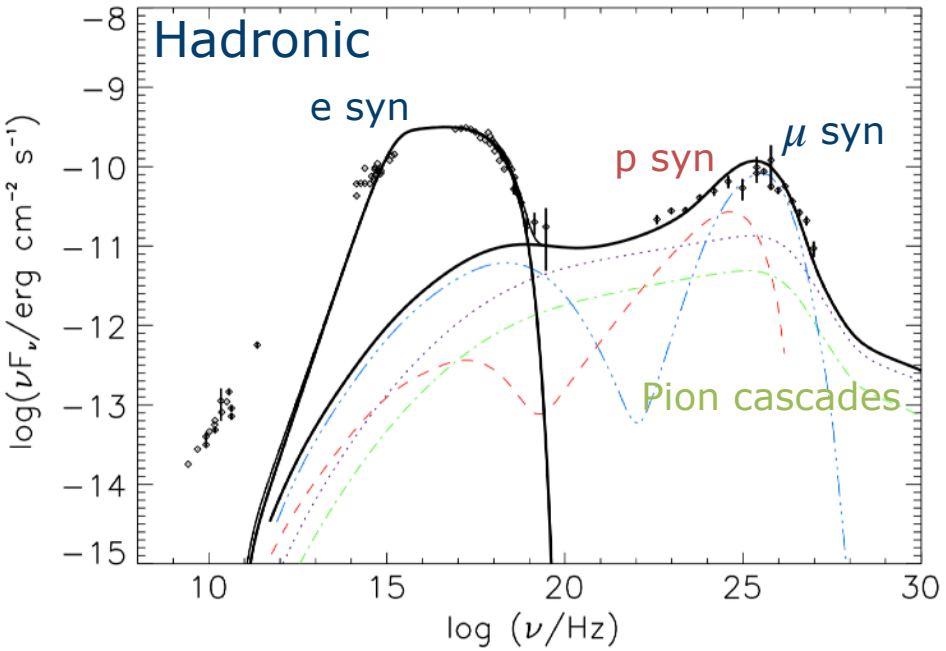
Synchrotron emission by muons can be important

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

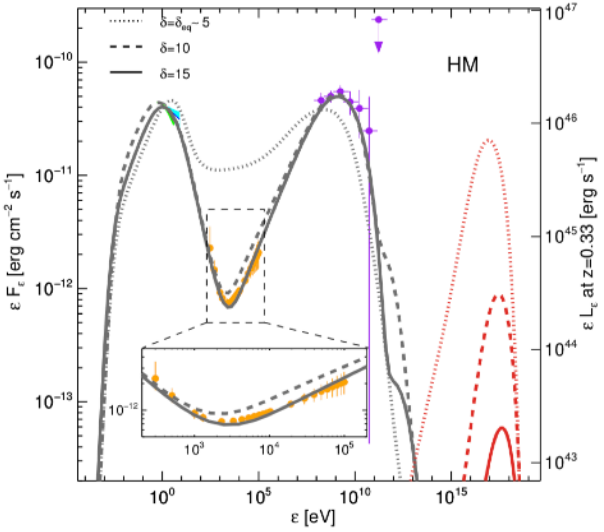
Example for Mrk 421 in 2011





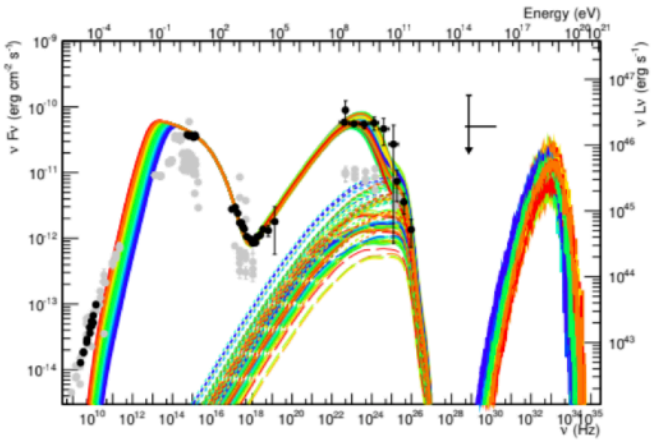
[Abdo et al. 2011]

TXS 0506+056: THE 2017 FLARE



Keivani et al. 2018

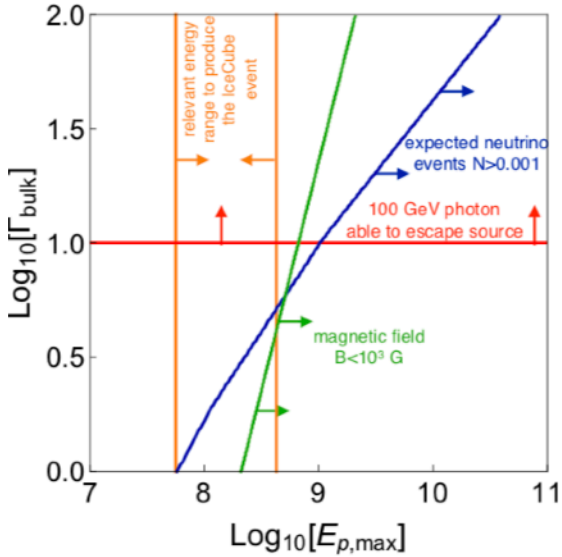
$\nu \simeq 10^{-5}\ yr^{-1}$



(a) Proton synchrotron modeling of TXS 0506+056

Cerruti et al. 2019

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

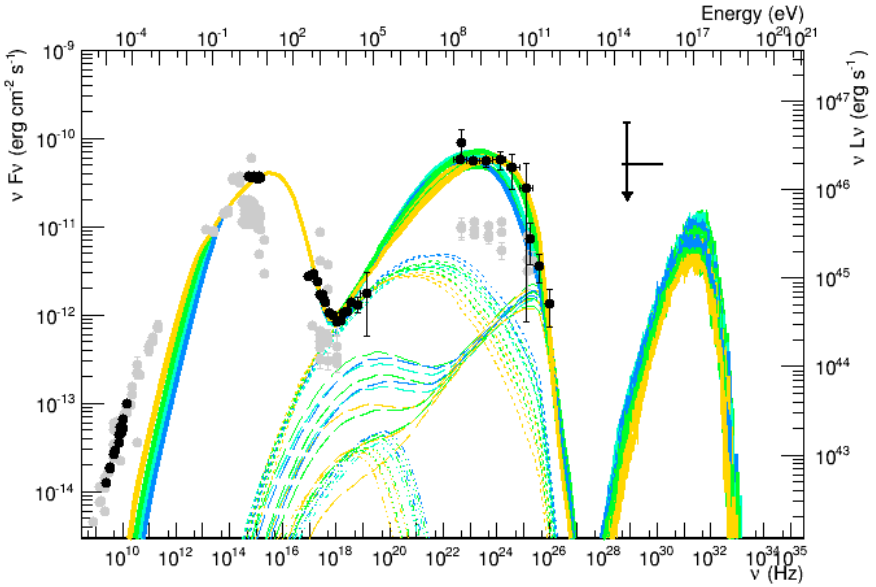


Gao et al. 2018

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

TXS 0506+056: THE 2017 FLARE

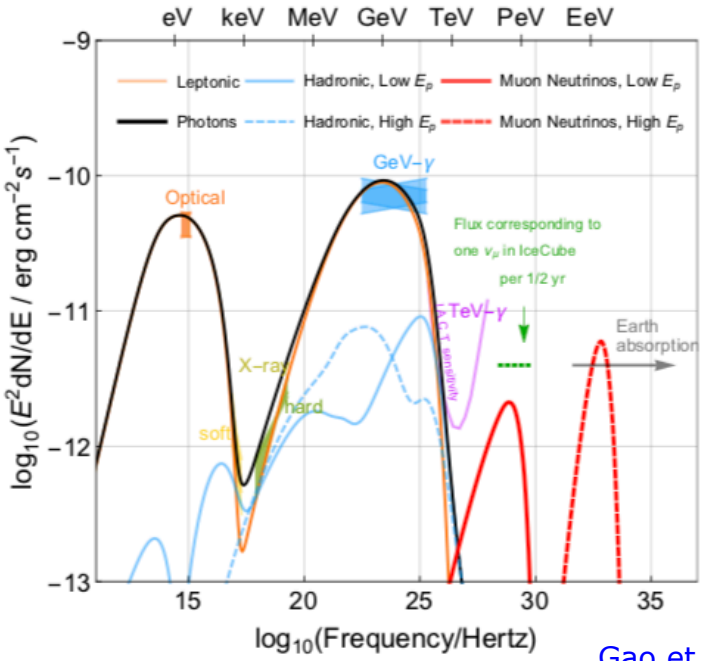
Lepto-hadronic solutions



Cerruti et al. 2019

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

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



Gao et al. 2018

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

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

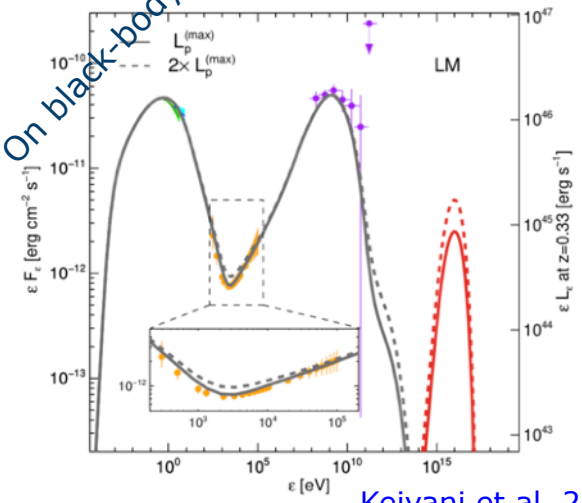
They can work: neutrino rates of the order of 0.1 / yr

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

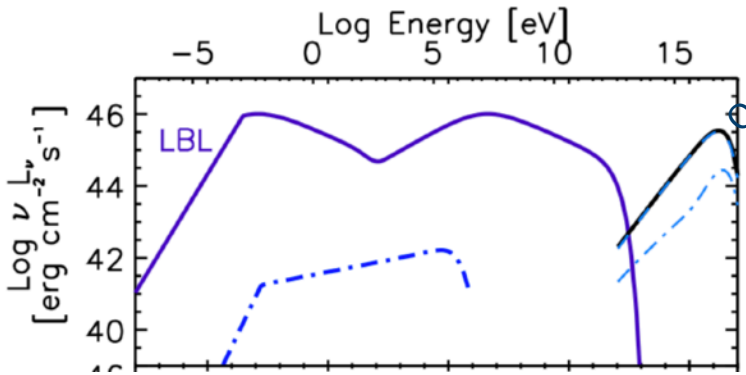
On black-body



Keivani et al. 2018

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

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



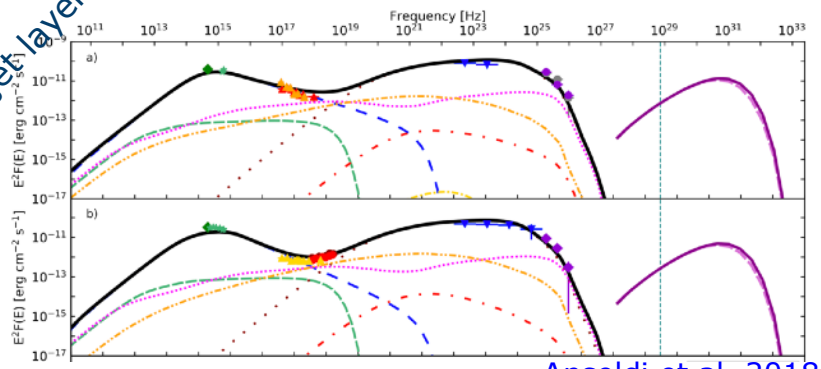
On RIAF

Righi et al. 2019

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

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

On jet layer



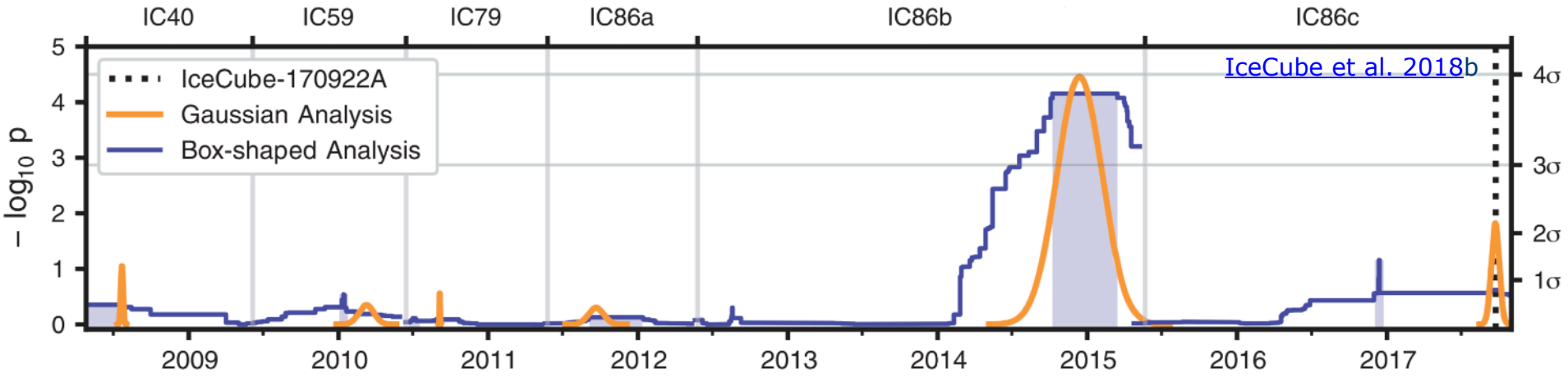
Ansoldi et al. 2018

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

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

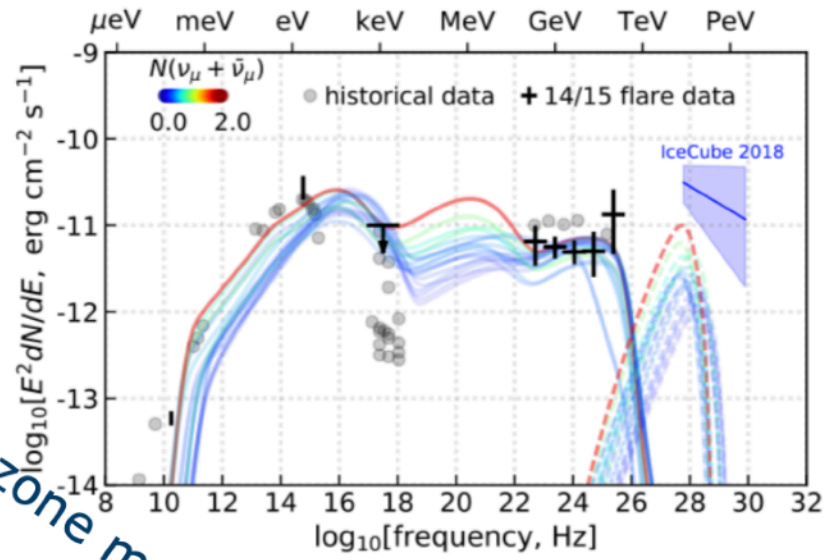
TXS 0506+056: THE 2014/15 ν FLARE

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

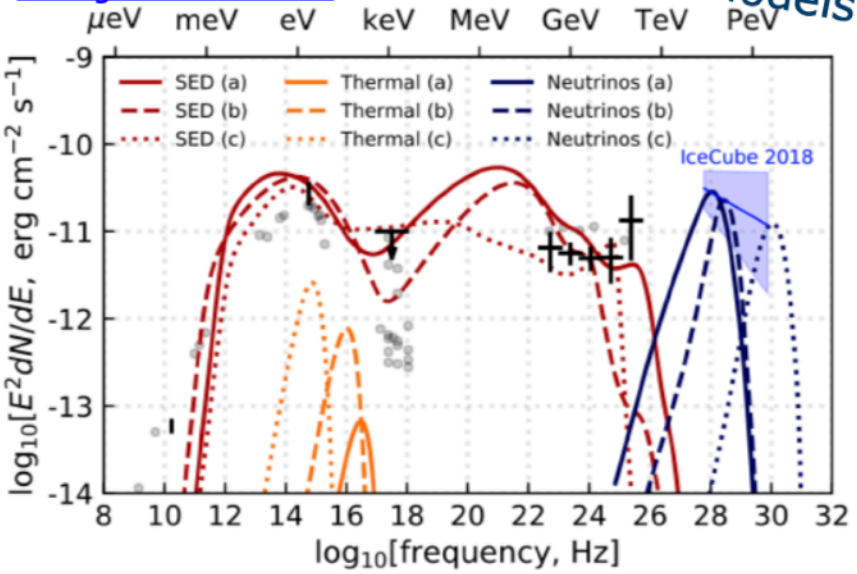
TXS 0506+056: THE 2014/15 ν FLARE

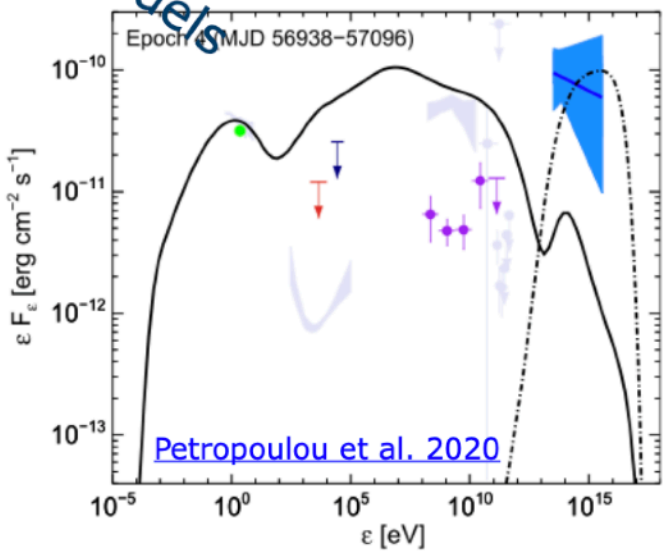


1-zone models

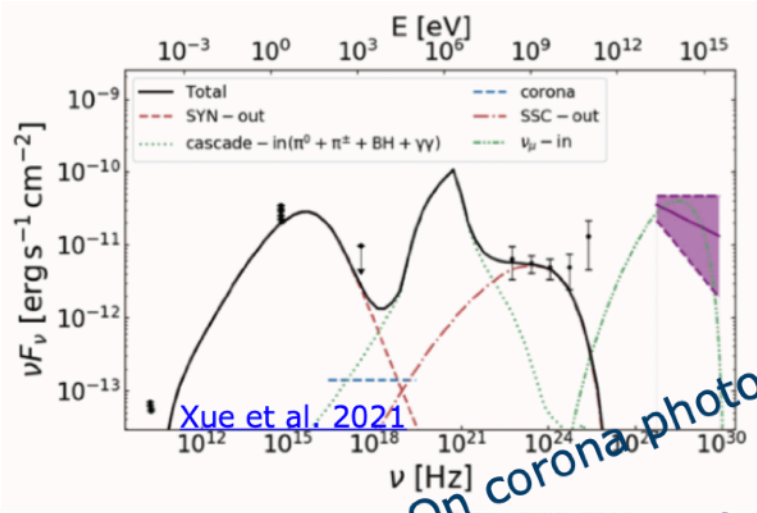
External field models

Rodrigues et al. 2019





Petropoulou et al. 2020



Xue et al. 2021

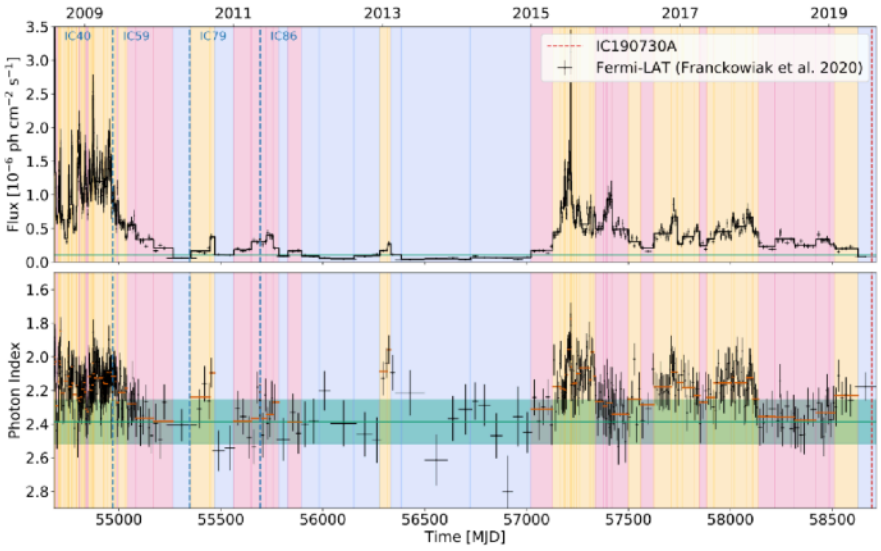
On corona photons

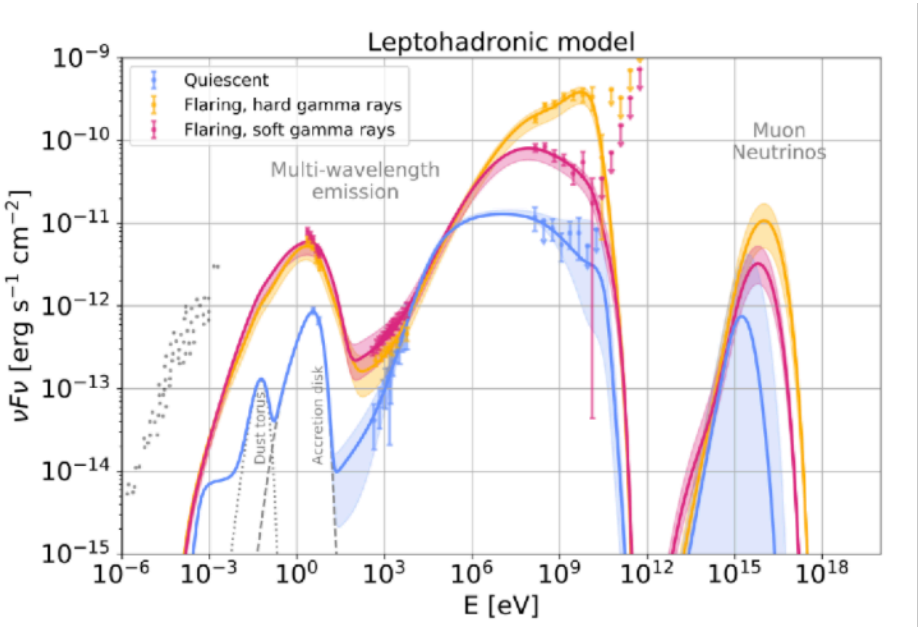
Matteo Cerru

WHAT HAPPENED SINCE THEN?

PKS 1502+106 (FSRQ@z=1.83) and IC190730A:

Spatial association but no flaring activity during the neutrino event



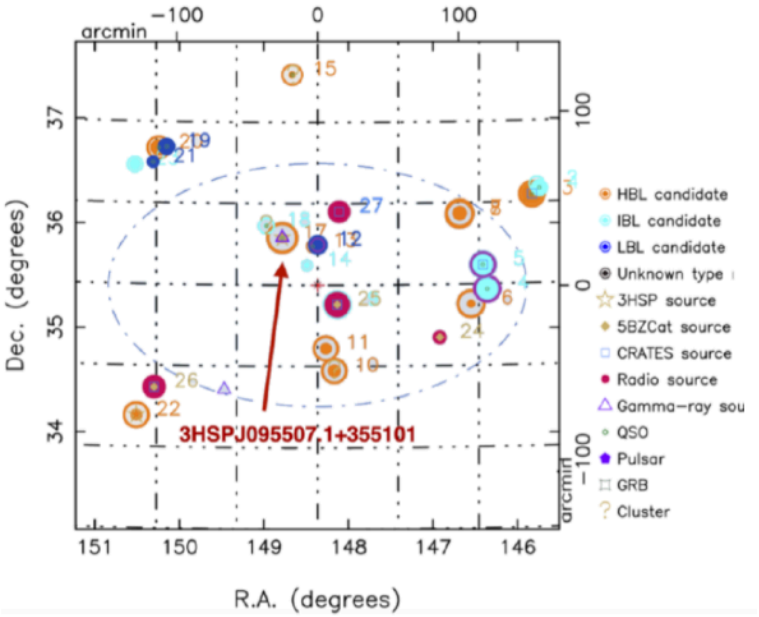


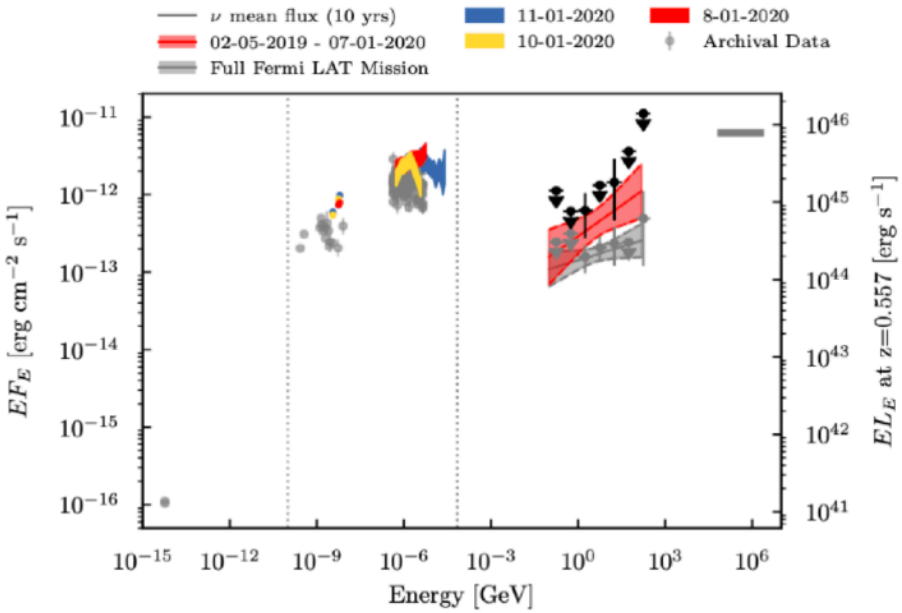
[Rodrigues et al. 2021]

WHAT HAPPENED SINCE THEN?

3HSPJ095507.9+355101 (Extreme HBL @ z=0.56) and IC200107A:

Spatial association (1.7% prob.) but no flaring activity (Fermi hardening?)

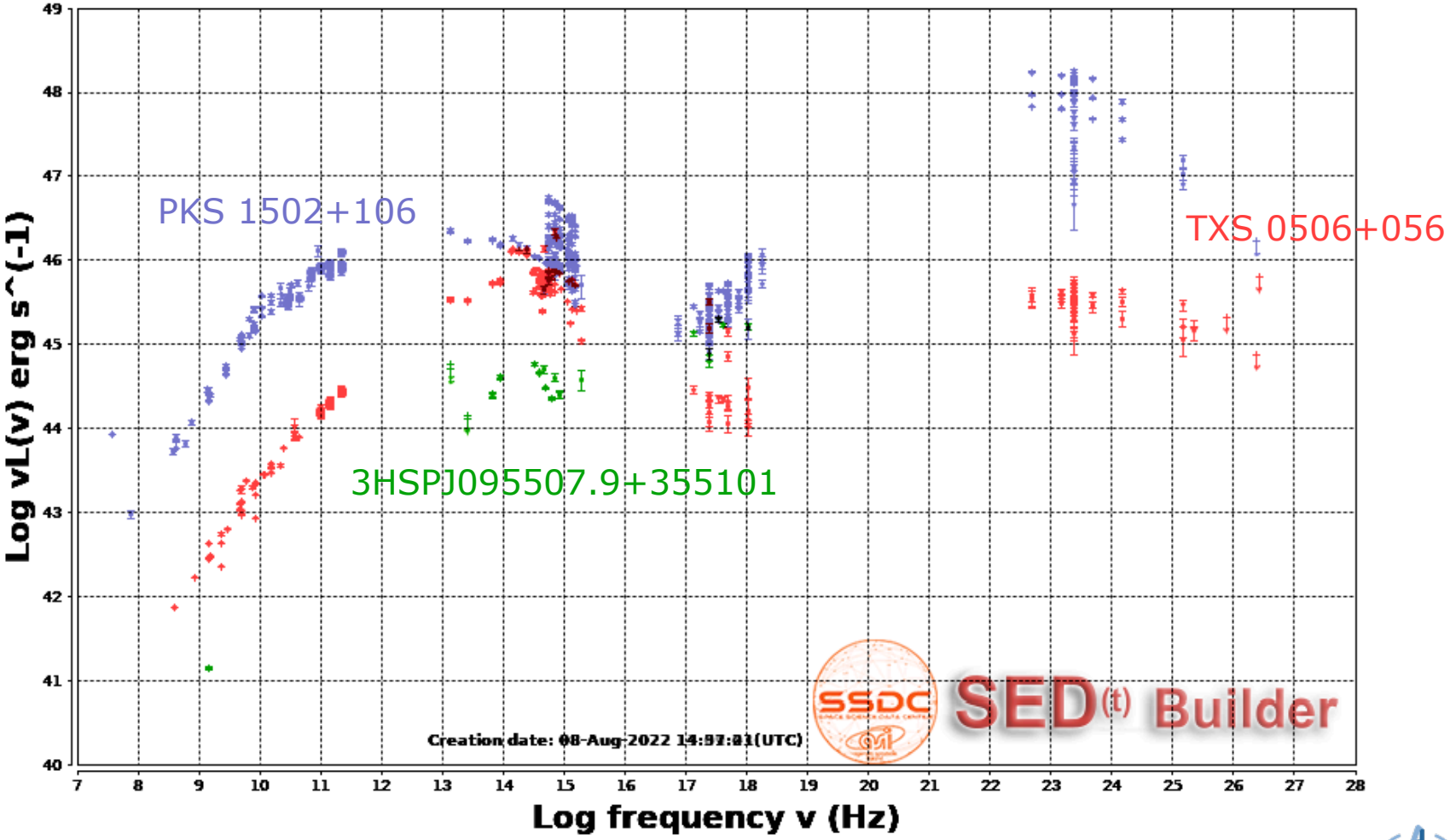




Giommi et al. 2020

WHAT HAPPENED SINCE THEN?

Three very different blazars



PKS 0735+178

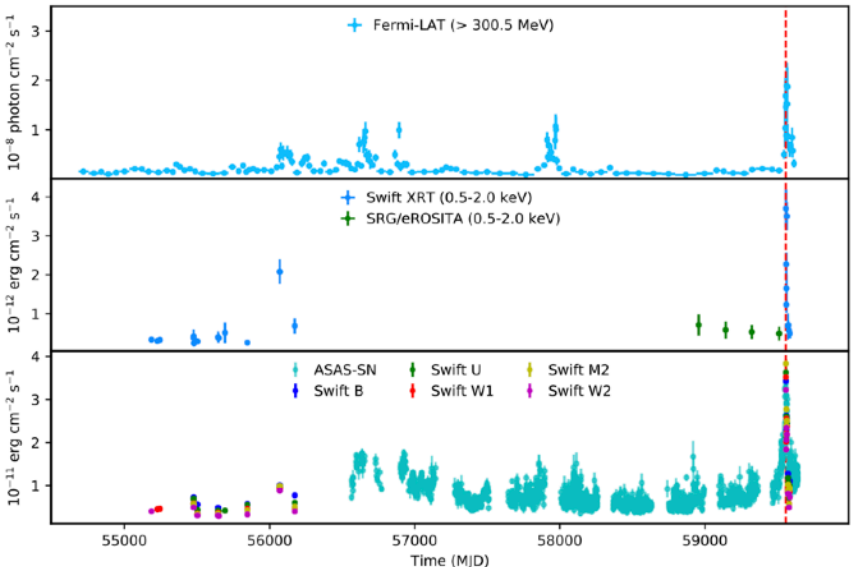
IBL@z=0.65? (>0.42) and IC211208A:

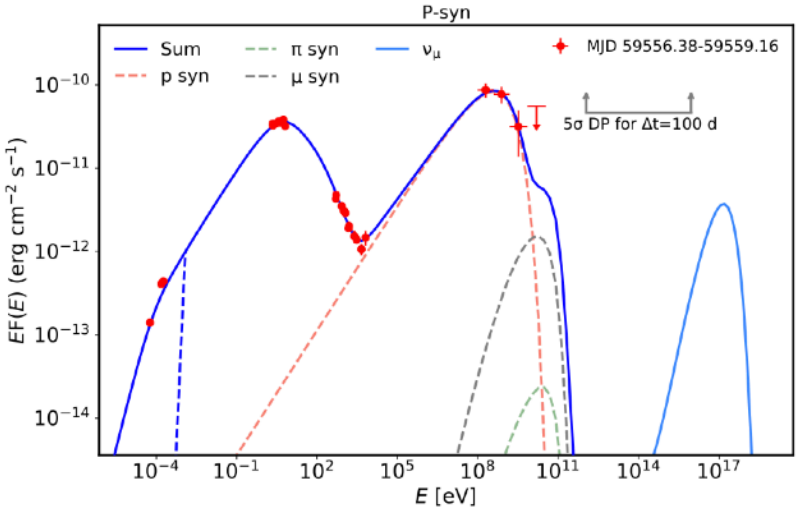
- Neutrino in IC with false alarm rate of 1.2 /yr (GCN)
- LAT source 2.2deg away (slightly beyond the 90% contour)

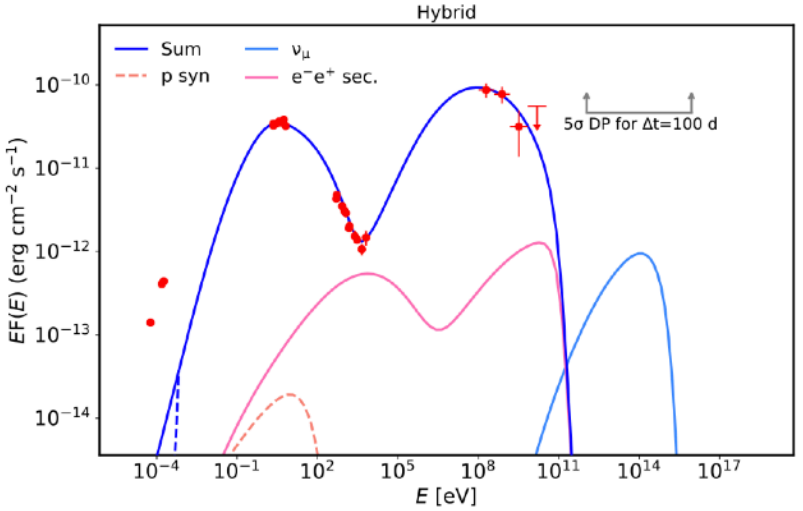
- Neutrino in Baikal (4h later). Chance coincidence prob. 2.85σ (ATel)
- Neutrino in KM3Net on Dec.15, p-value of 14% (ATel)
- Neutrino in Baksan on Dec.4, p-value of 0.2% (ATel)
- Flaring in Fermi-LAT, optical, X-rays

PKS 0735+178

First theory paper by [Sahakyan et al. 2022]

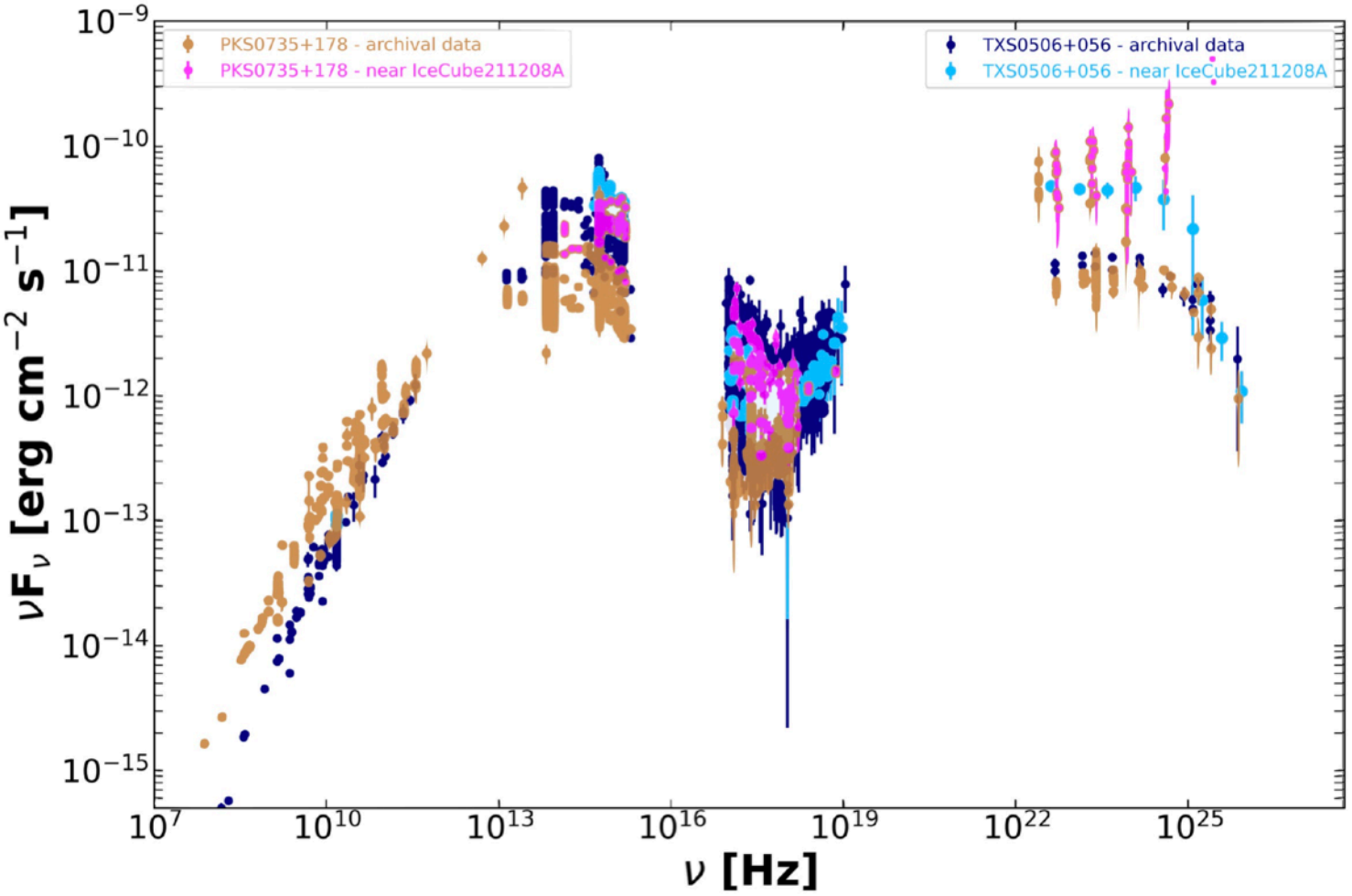






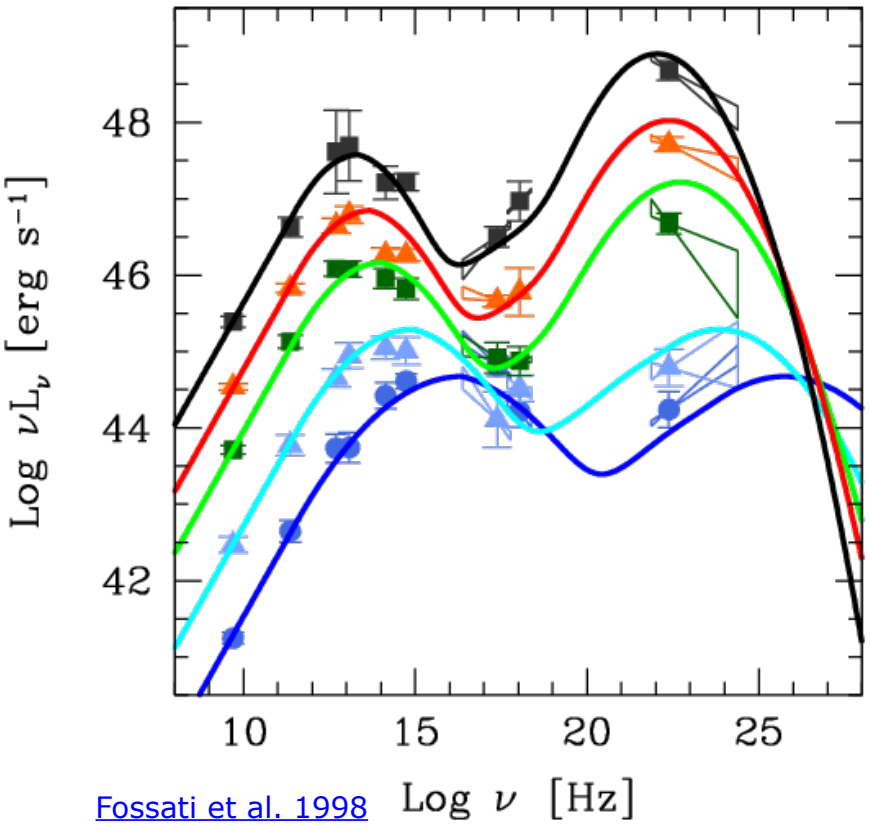
PKS 0735+178

First theory paper by [Sahakyan et al. 2022]

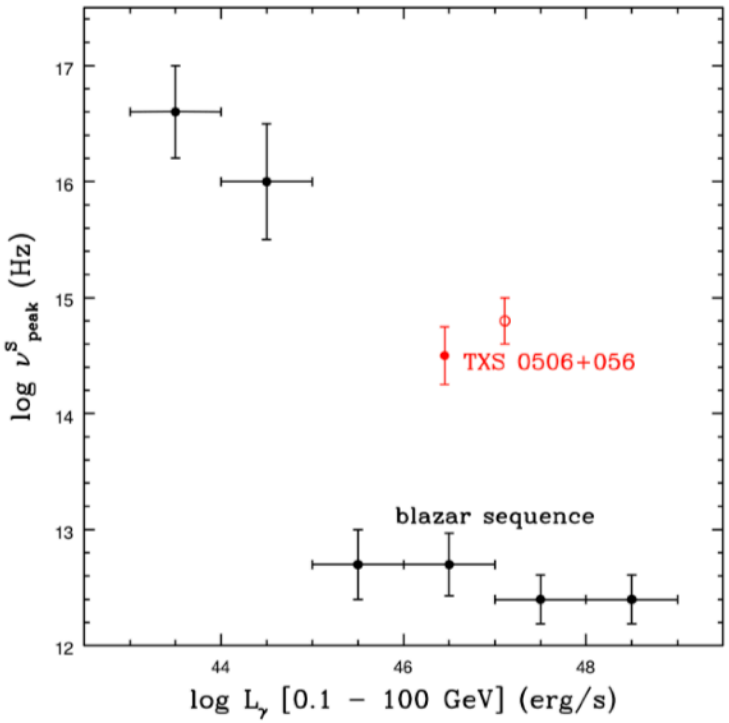


HIGH-LUMINOSITY / HIGH-PEAK BLAZARS

Are we looking at outliers in the blazar population?



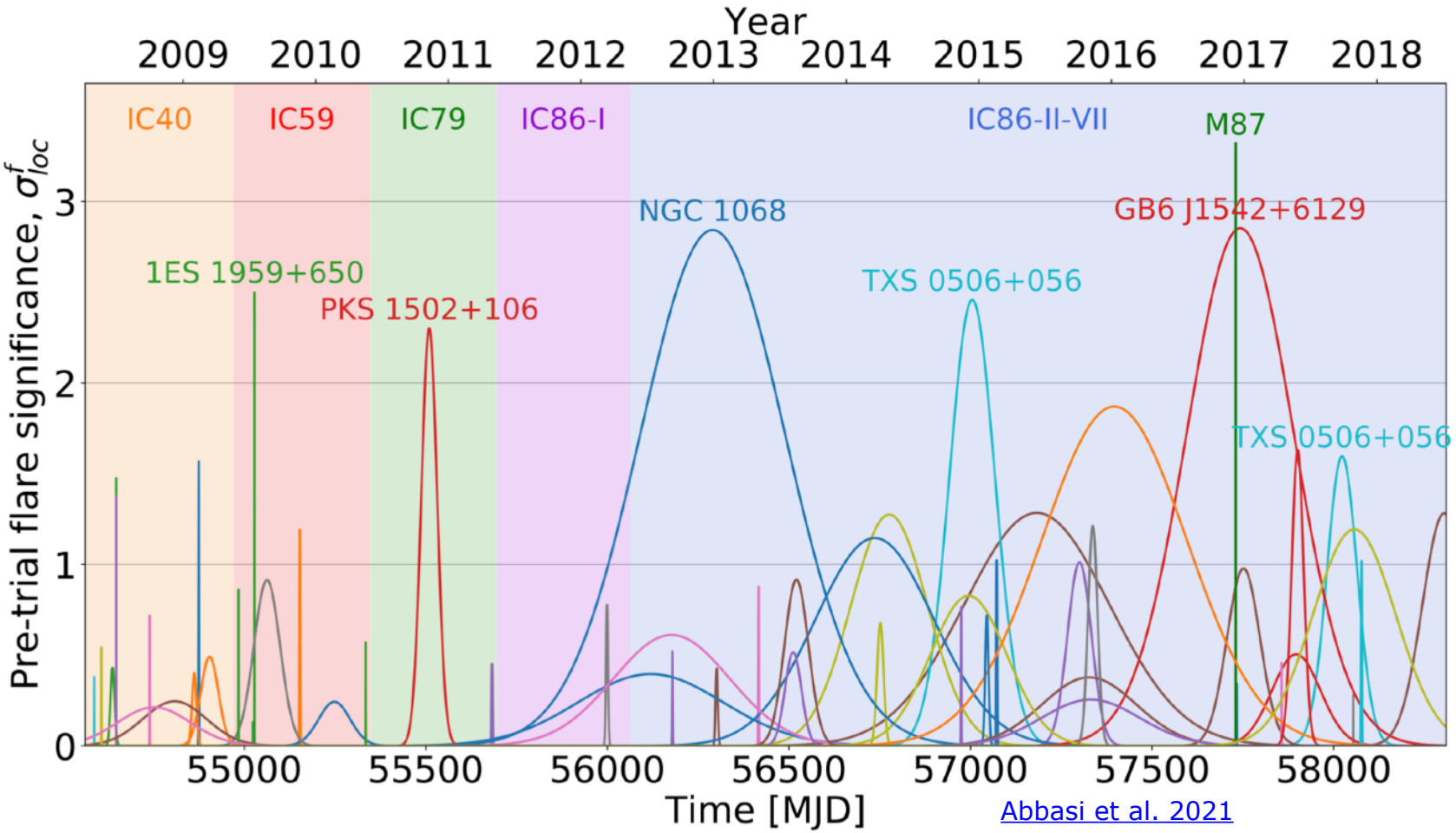
Fossati et al. 1998



Padovani et al. 2018

BLAZAR FLARES

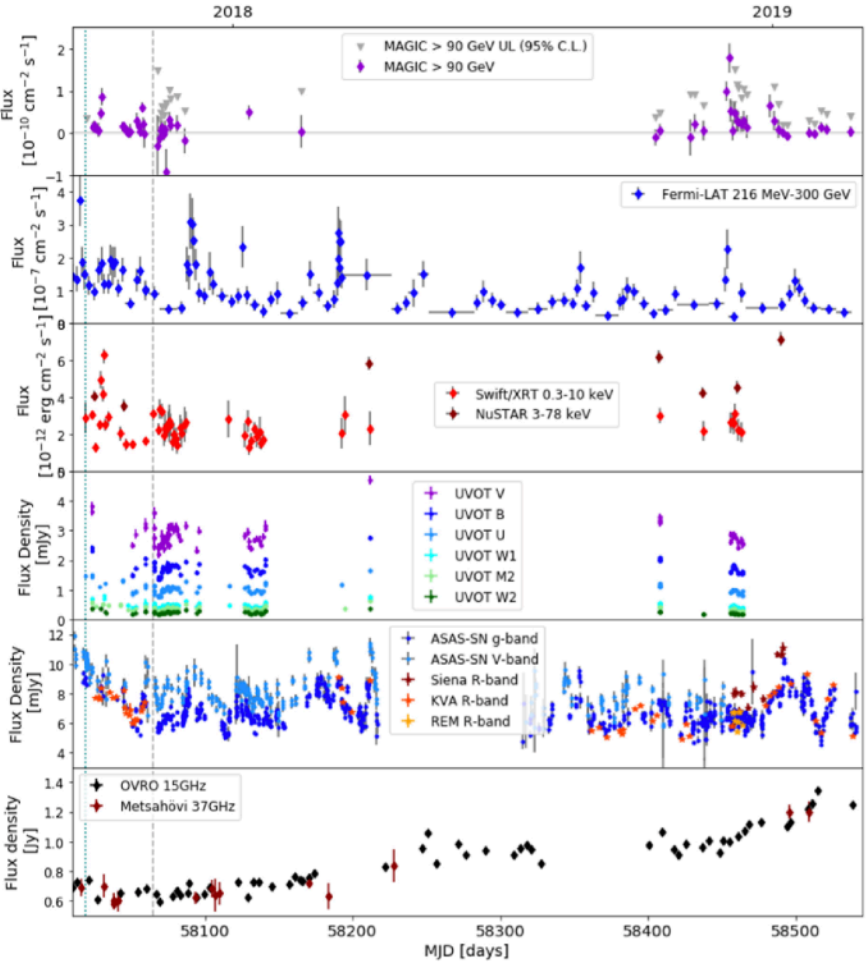
Search for neutrino blazar flares in IC data



Abbasi et al. 2021

TXS 0506+056 AGAIN

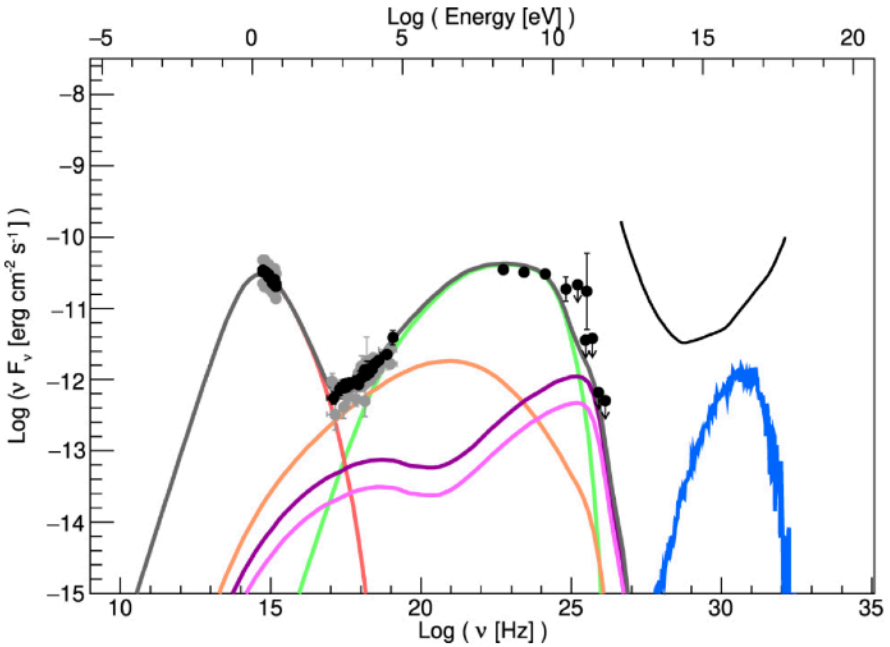
2017-2019 MWL monitoring of TXS 0506+056 after the neutrino event (Acciari et al. 2022)



New VHE flare in December 2018

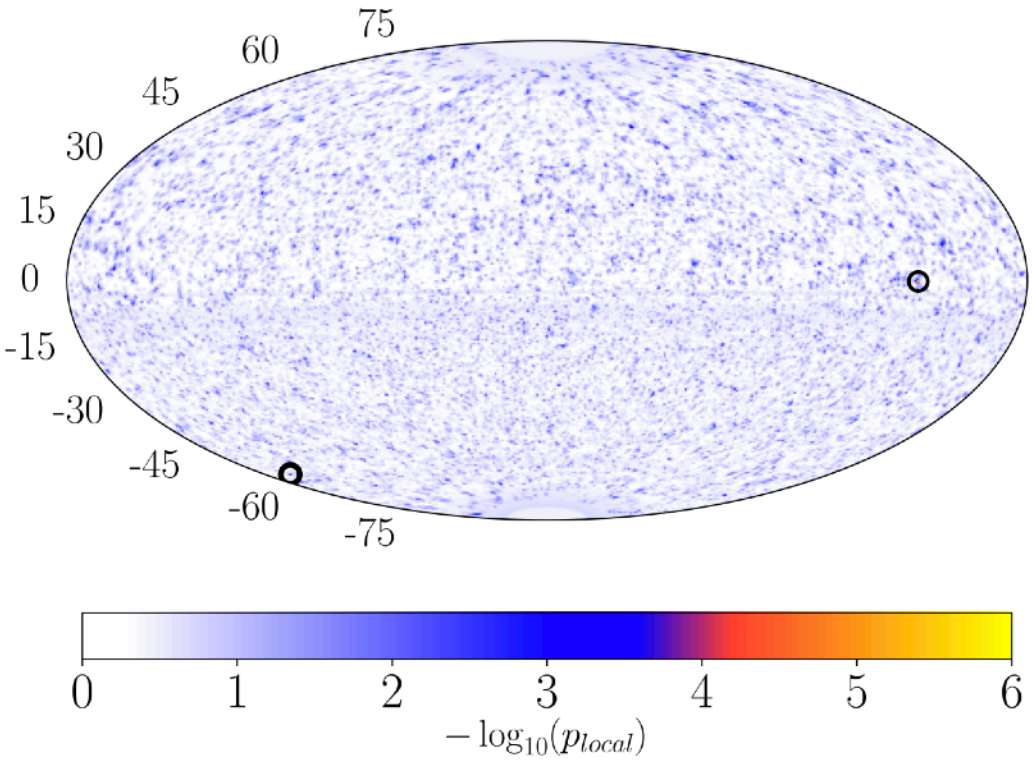
No neutrinos associated with it

Low-state SED much better characterized



ALL-SKY SEARCHES

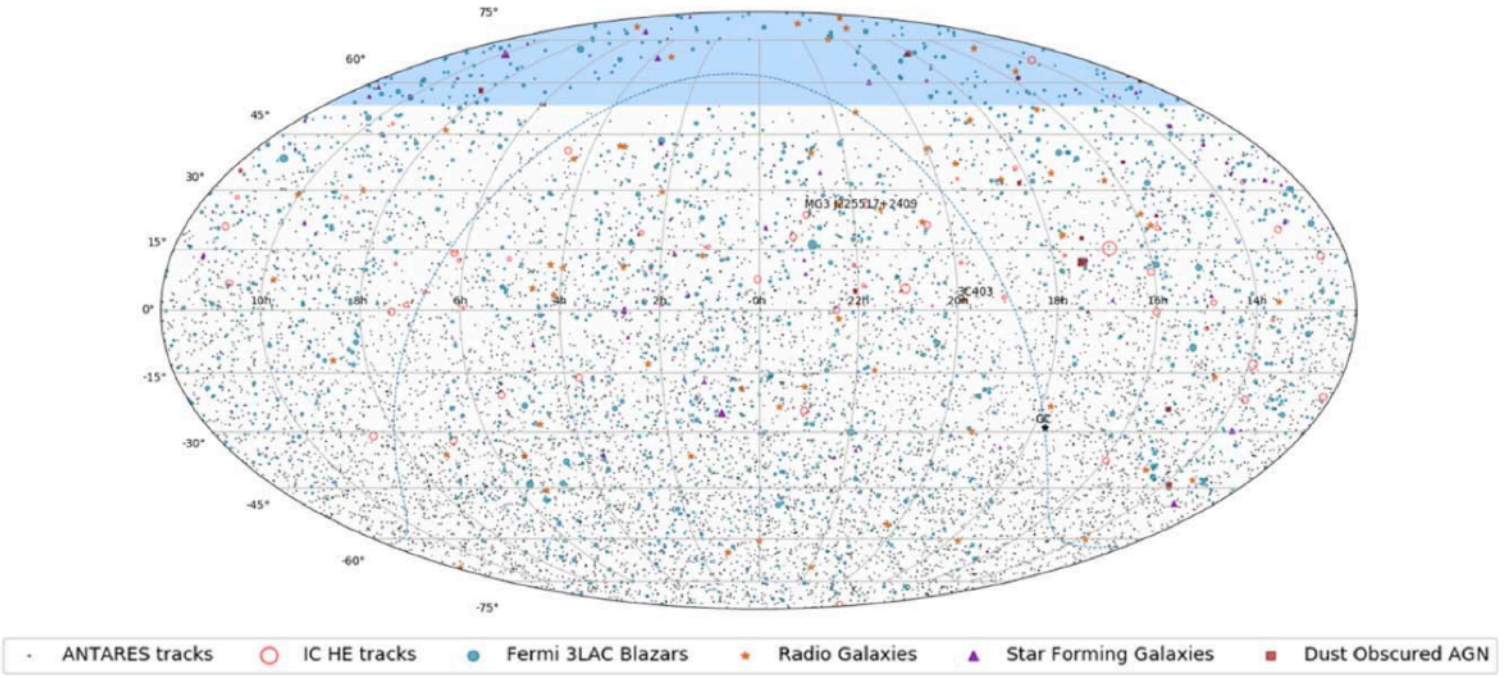
IceCube 10-year paper (Aartsen et al. 2020)



Hottest spot at 2.9 sigma (post-trial) on NGC 1068
TXS 0506+056 stands out at 3.1 sigma pre-trial

ALL-SKY SEARCHES

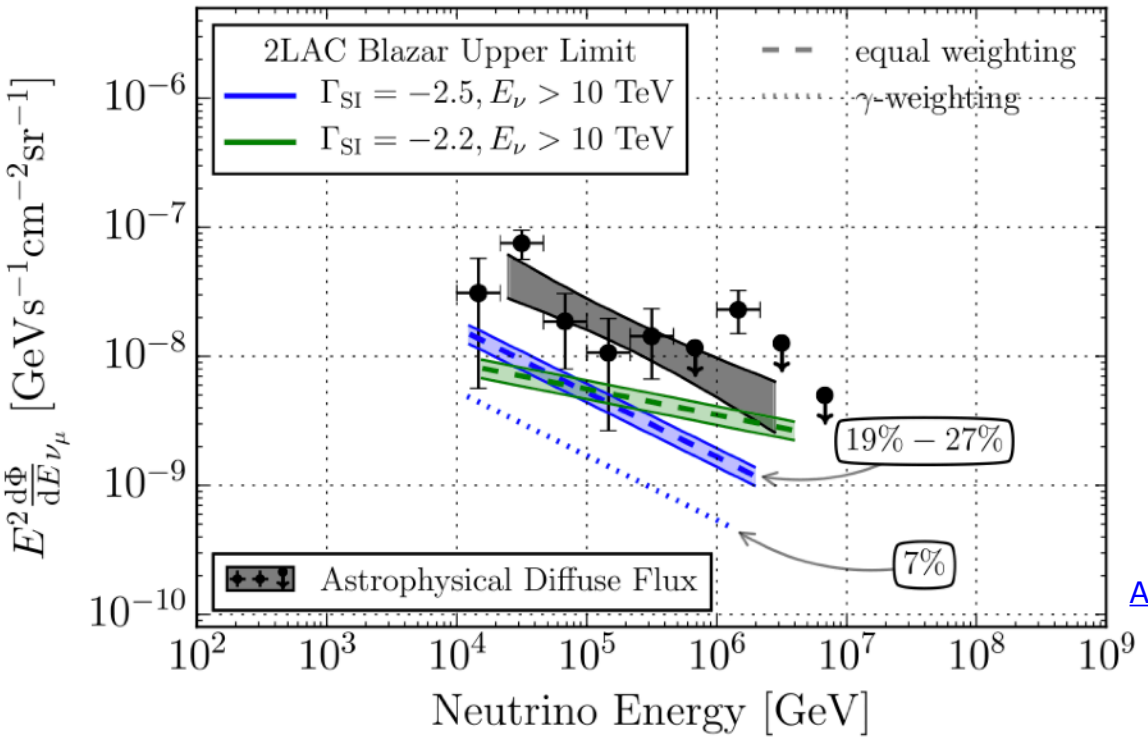
ANTARES 10-year paper (Albert et al. 2021)



Hottest spot at 2.3 sigma on the blazar 3FGLJ2255.1+2411
2.6 sigma when considering information from the IceCube event IC100608A

ALL-SKY SEARCHES

Contribution of Fermi-LAT blazars to the IceCube diffuse neutrino spectrum

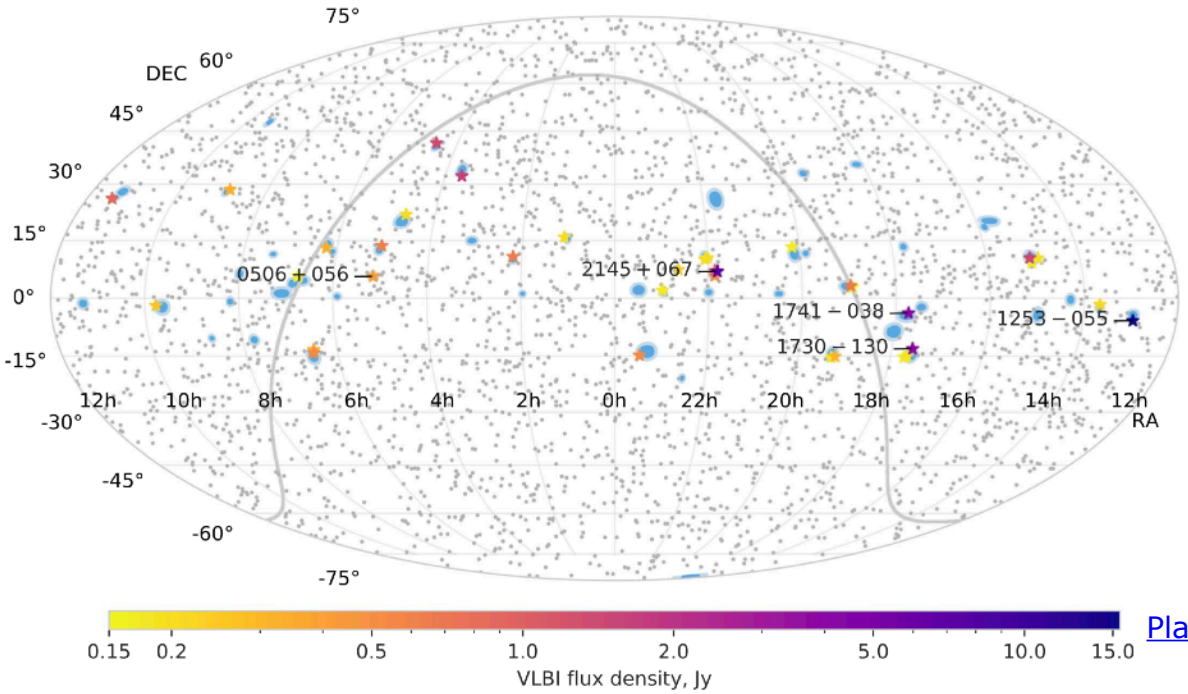


Aartsen et al. 2017

Cannot contribute to more than ~20%

ALL-SKY SEARCHES

Correlation between IceCube neutrinos and the brightest radio-loud AGNs



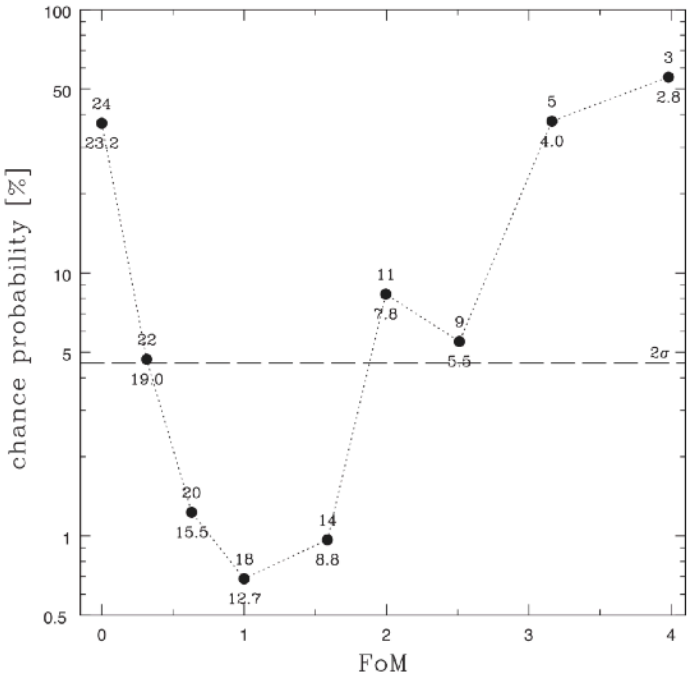
Plavin et al. 2020

Chance probability estimated at 0.2%
But not confirmed by other authors (Zhou et al. 2021)

Nor by IceCube, see yesterday's talk by C. Lagunas-Gualda

ALL-SKY SEARCHES

Correlation between IceCube neutrinos and extreme blazars

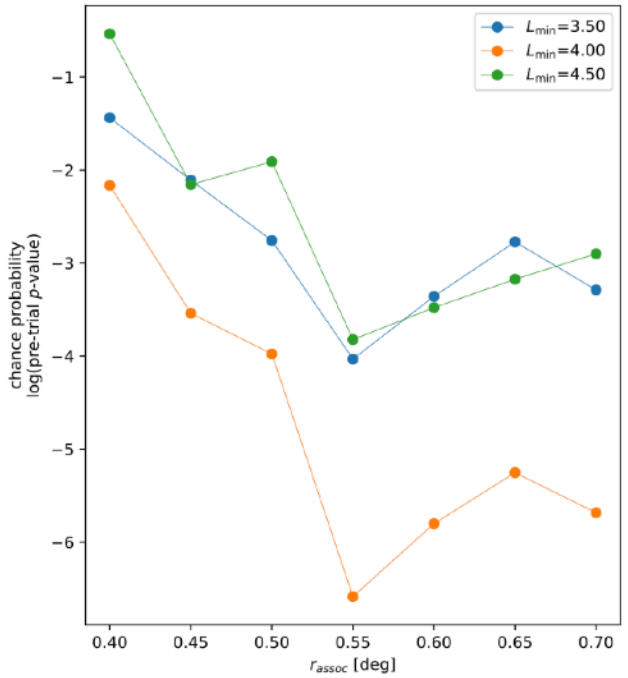


Padovani et al. 2016

Chance probability estimated at ~1%

Correlation with BZCat blazars

(Southern sky only)



Buson et al. 2022 (three weeks ago)

Chance probability minimum at 6e-7!

CONCLUSIONS

- The TXS 0506+056 event of 2017 is still our best evidence for joint photon and neutrino emission from a blazar

- Several new multi-messenger campaigns, but nothing clear: we are still in the hotspot era

- Several claims for significant association from all-sky searches

- Are we learning something on AGNs? Do we have hadronic/ neutrino blazars and leptonic blazars? Are we too much biased by our knowledge of the photon universe?

CONCLUSIONS

Where do we go from here?

- Hard-X-rays / VHE gamma-rays proved to be extremely important to constrain the models

- Huge need for an MeV satellite

- Wait for another neutrino blazar (or not!)