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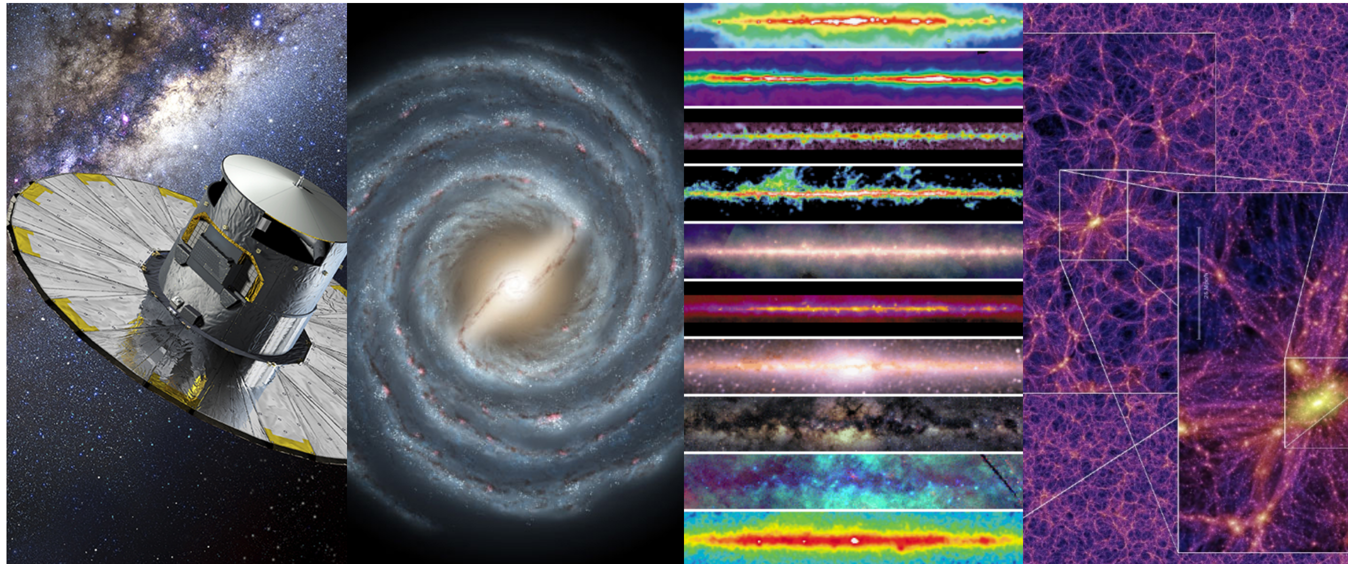


HADRONIC EMISSION MODELS: Gammas & Neutrinos

Matteo Cerruti

"la Caixa" Junior Leader Fellow
Institute of Cosmos Sciences

Universitat de Barcelona

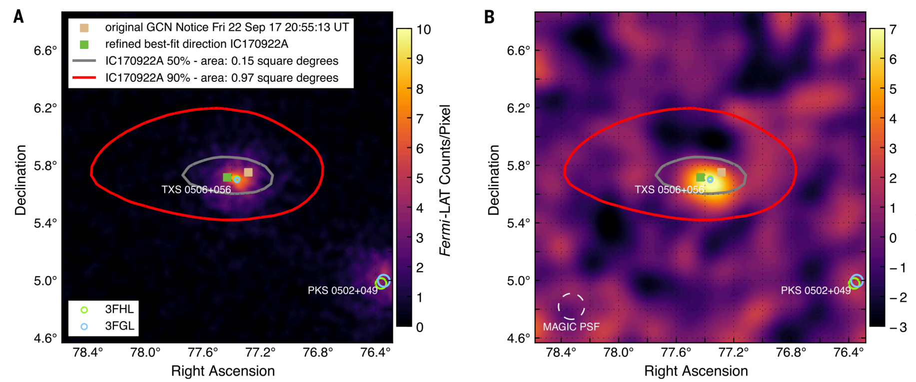
November 29, 2019
Meudon, France

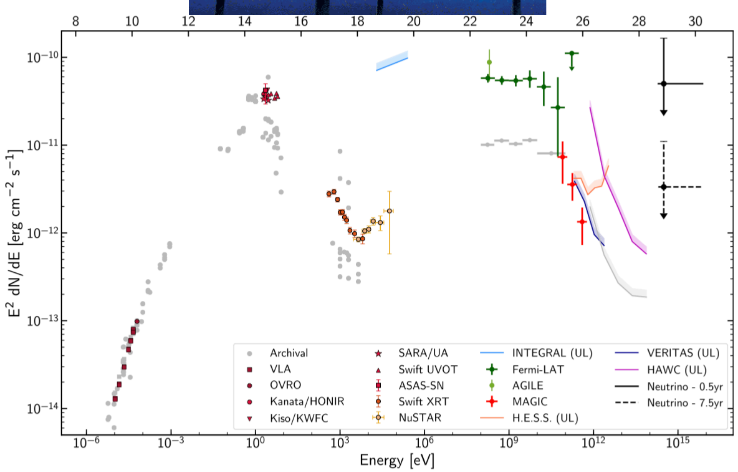
UNIVERSITAT DE BARCELONA

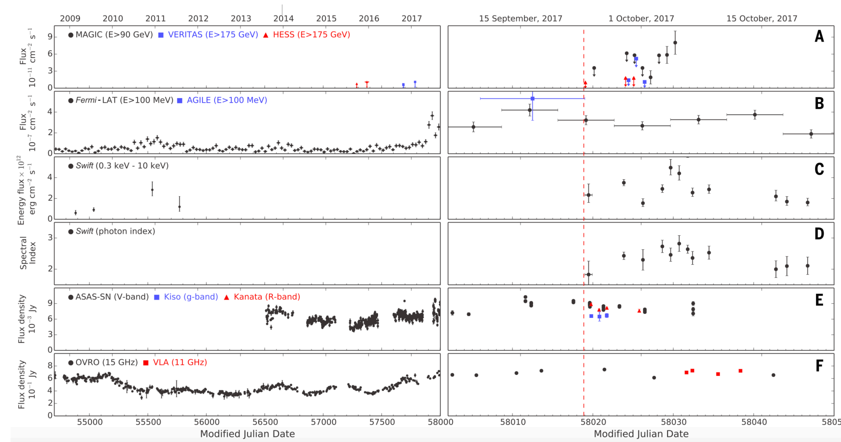
"la Caixa" Foundation

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

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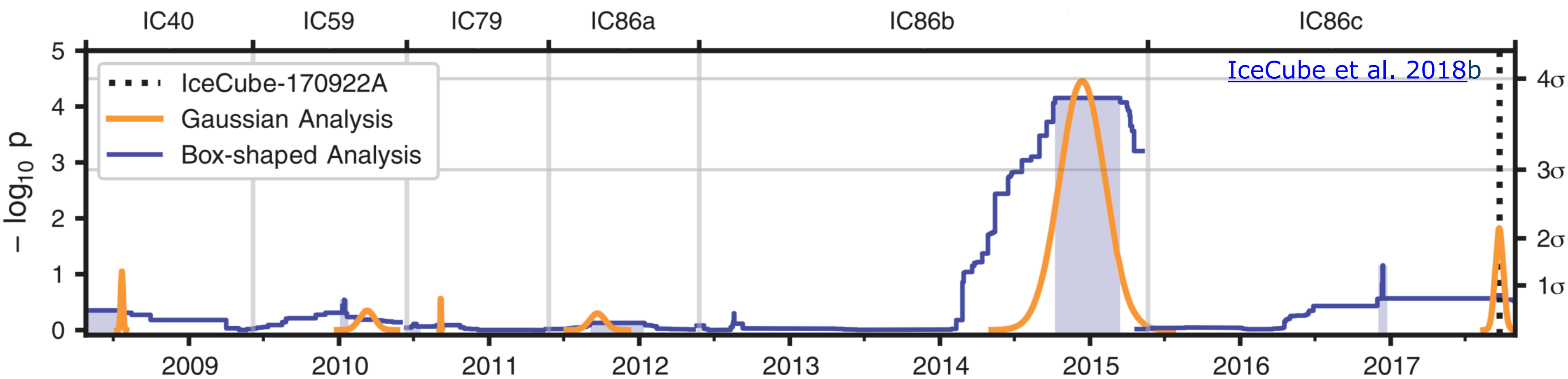
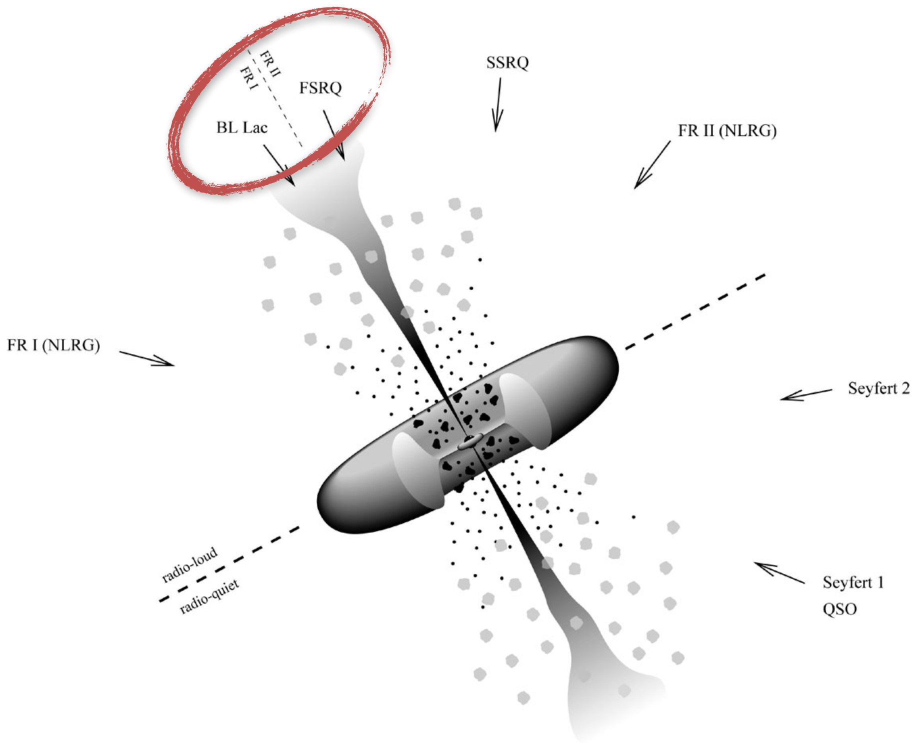
IceCube-170922A / TXS 0506+056

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

Blazars



Blazars: radio-loud Active Galactic Nucleus whose relativistic jet points towards the observer

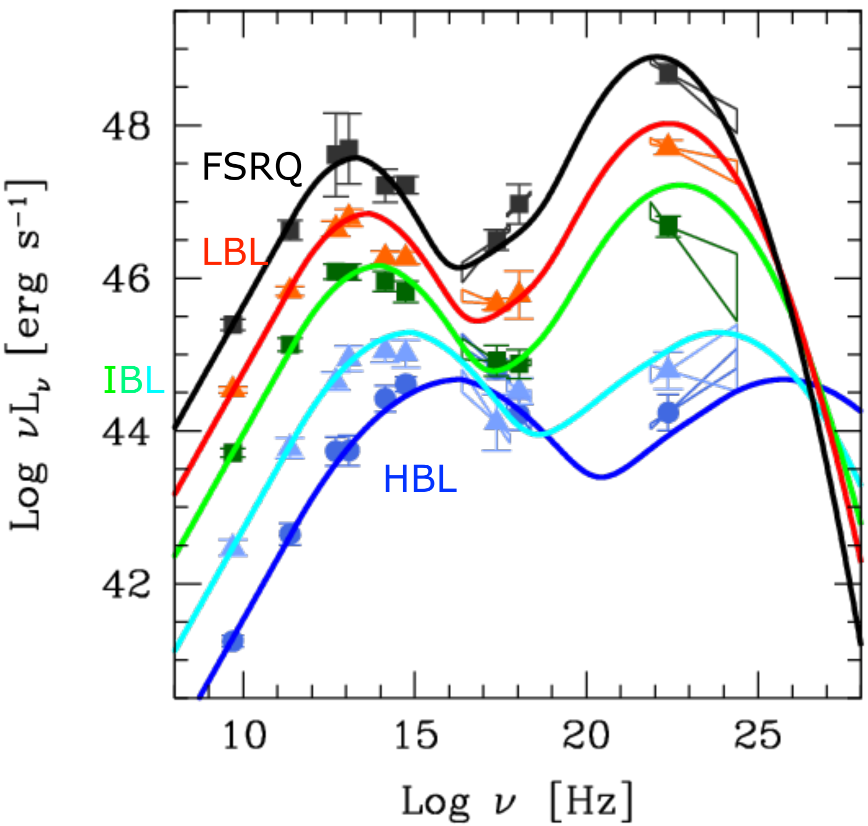
→ emission from the jet outshines all other AGN components (disk, BLR, X-ray corona, …)

→ non-thermal emission from radio-to-gamma-rays, and extreme variability

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

BL Lacertae objects : optical spectrum is featureless (lines $\mathrm{EW} < 5\text{Å}$)

Blazars



Spectral energy distribution (SED): two separate components

FSRQs show a peak in IR

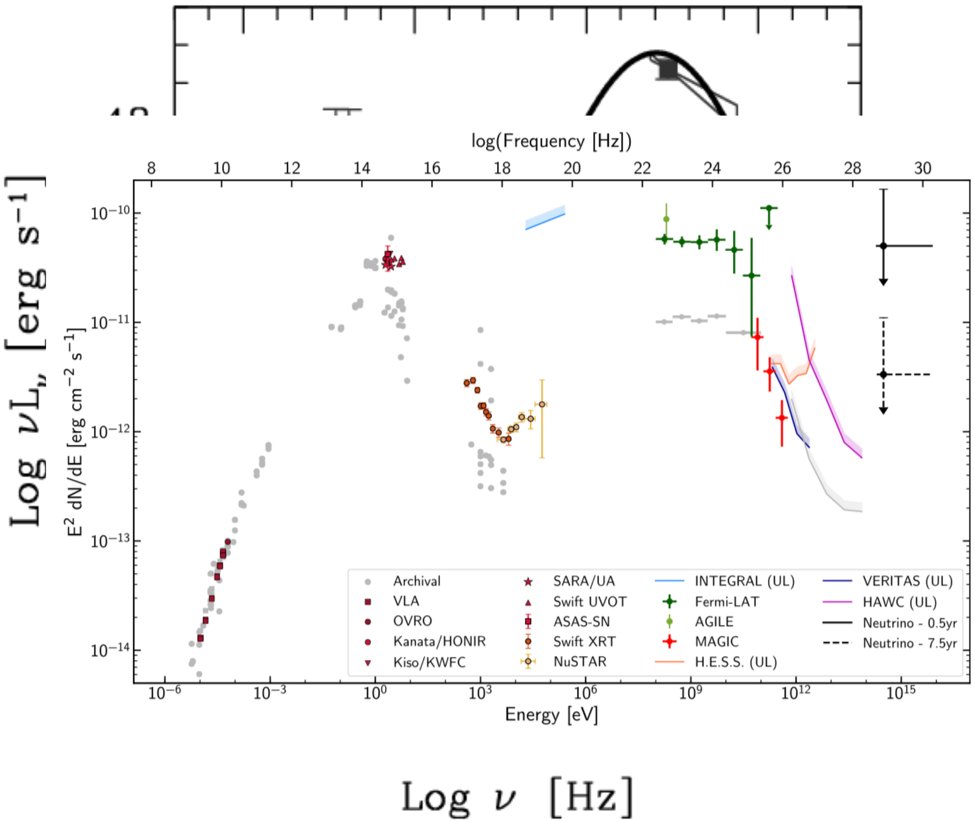
BL Lac objects are classified in:

- peak in IR: low-frequency peaked (LBLs)

- peak in optical: intermediate (IBLs)

- peak in UV / X: high (HBLs)

Blazars



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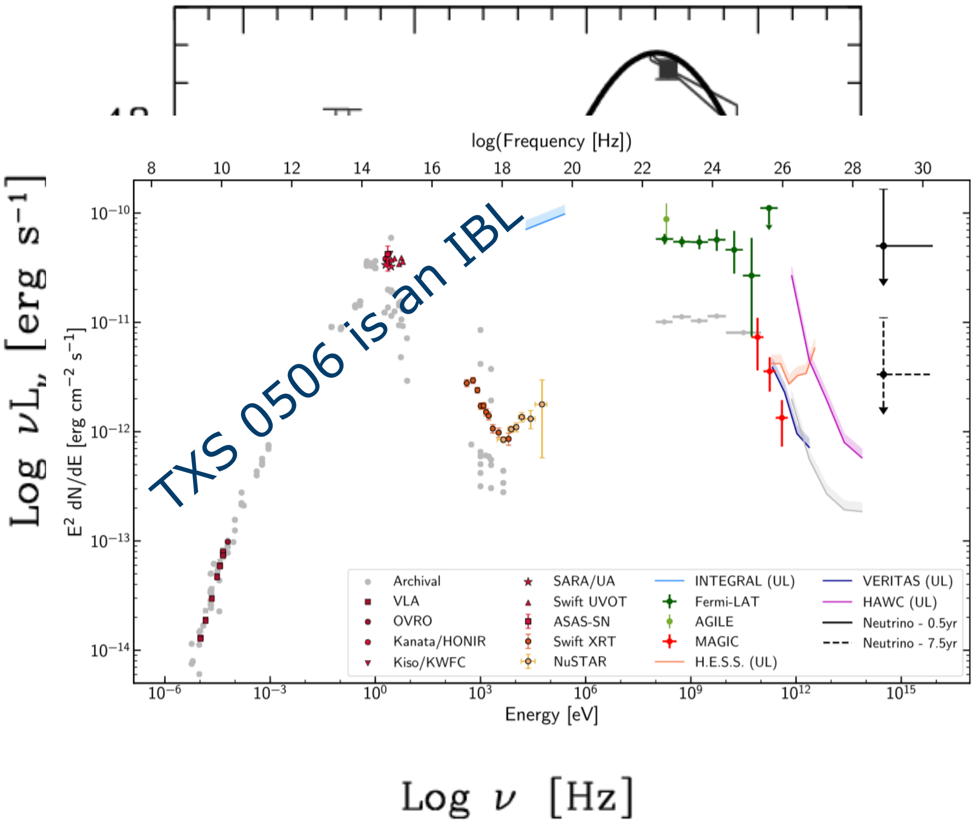

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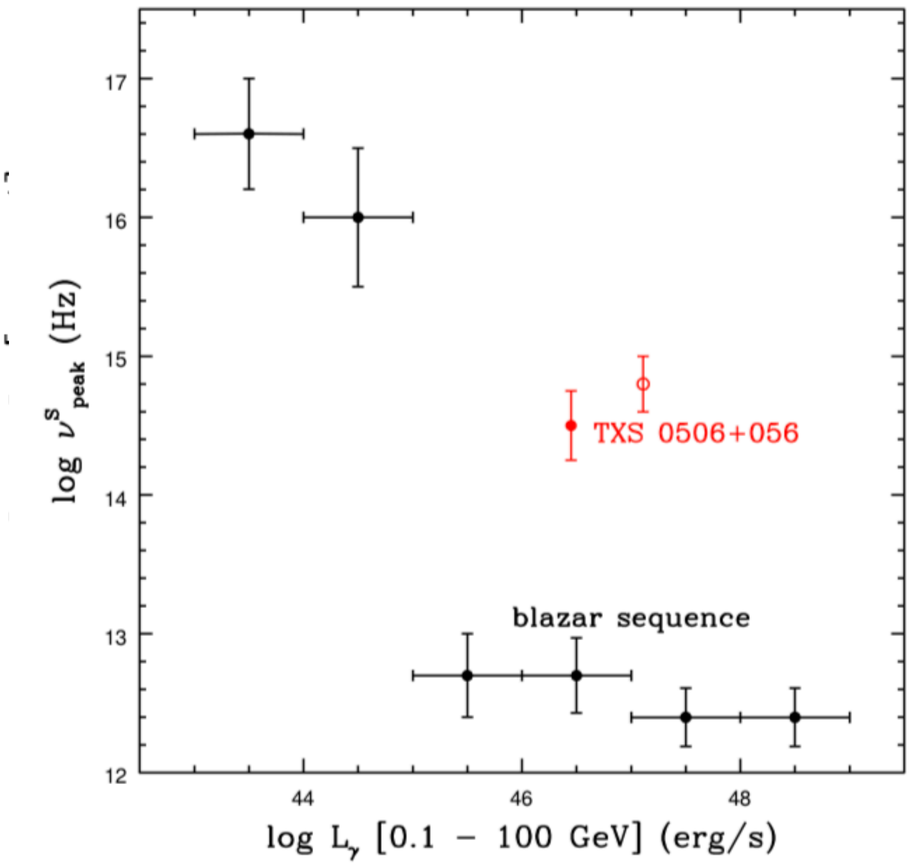

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Blazar emission models

Blazar emission models

Low-energy SED component is synchrotron emission by leptons

High-energy component?

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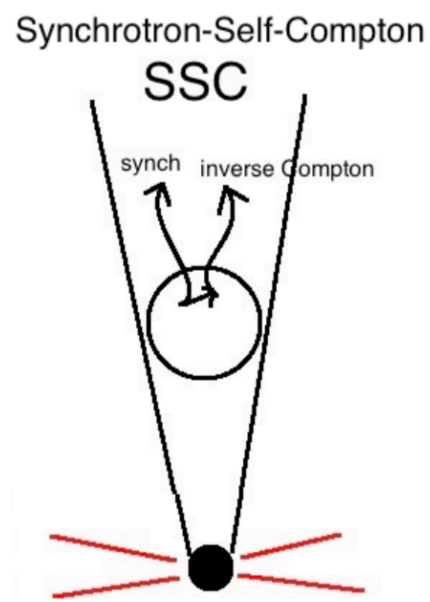

Leptonic models: inverse Compton scattering

Same leptons producing synchrotron
+ their own synchrotron radiation (SSC)

Blazar emission models

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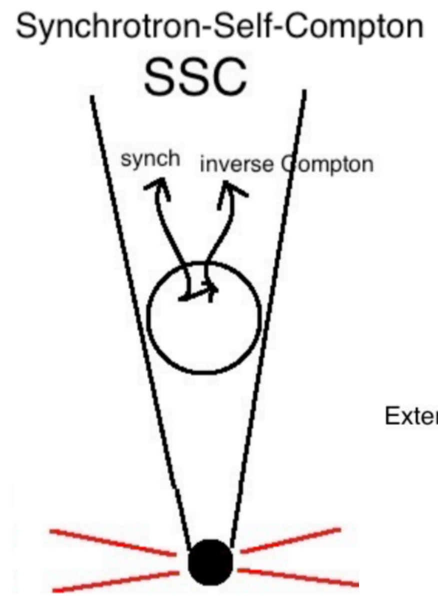
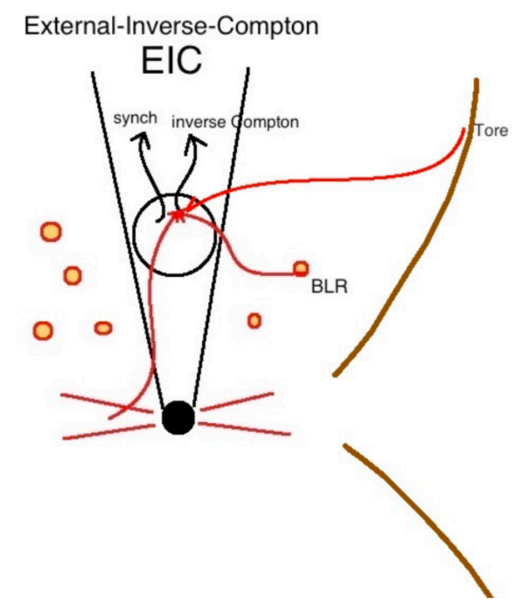
+ their own synchrotron radiation (SSC)
+ an external photon field (EIC)





Blazar emission models

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High-energy component?

Leptonic models: inverse Compton scattering

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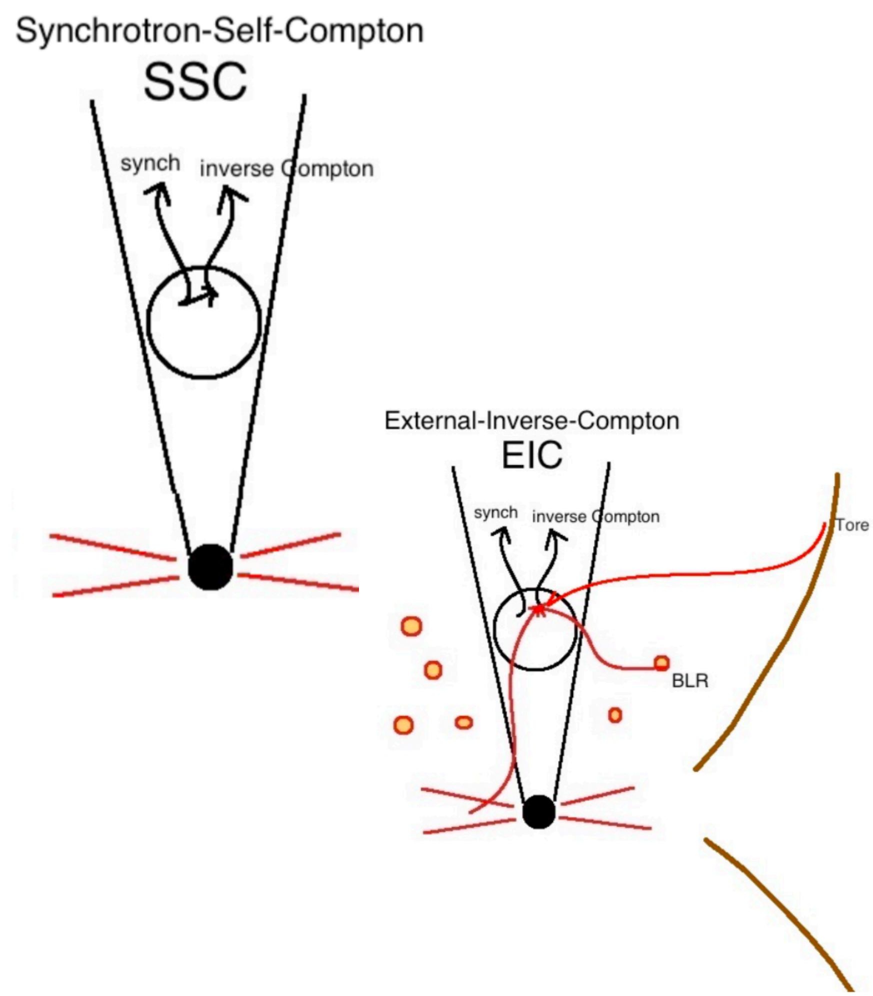
General consensus on the fact that
HBLs → SSC
LBLs / FSRQs → EIC



Blazar hadronic emission models

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Why hadronic models if leptonic ones work?

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- Natural link with neutrinos and cosmic rays:
AGNs are candidates for (UHE)CR acceleration

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Why hadronic models if leptonic ones work?

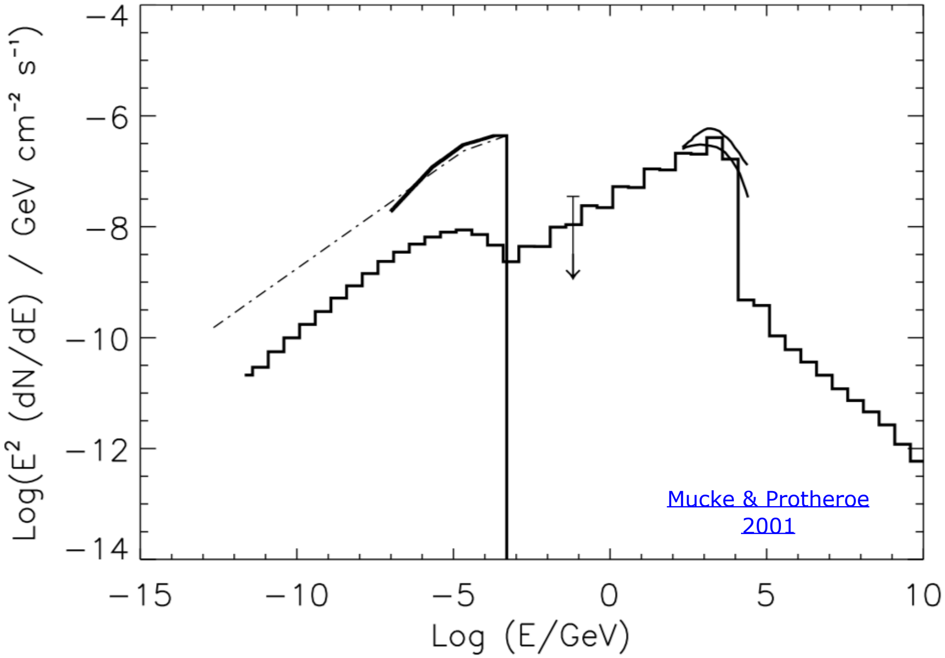
- Natural link with neutrinos and cosmic rays:
AGNs are candidates for (UHE)CR acceleration

- Leptonic models don’t always work well:
Orphan flares!

Blazar hadronic emission models

Simplest hadronic model

The high-energy component is proton synchrotron radiation ([Mannheim 1993](), [Aharonian 2000](), [Mucke & Protheroe 2001]())



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Blazar hadronic emission models

Proton-photon interactions complicate the modeling

Photo-meson

$$p + \gamma = n^0\pi^0 + n^+\pi^+ + n^-\pi^- + \ldots$$

$$2\,\gamma$$

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

Bethe-Heitler pair production

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

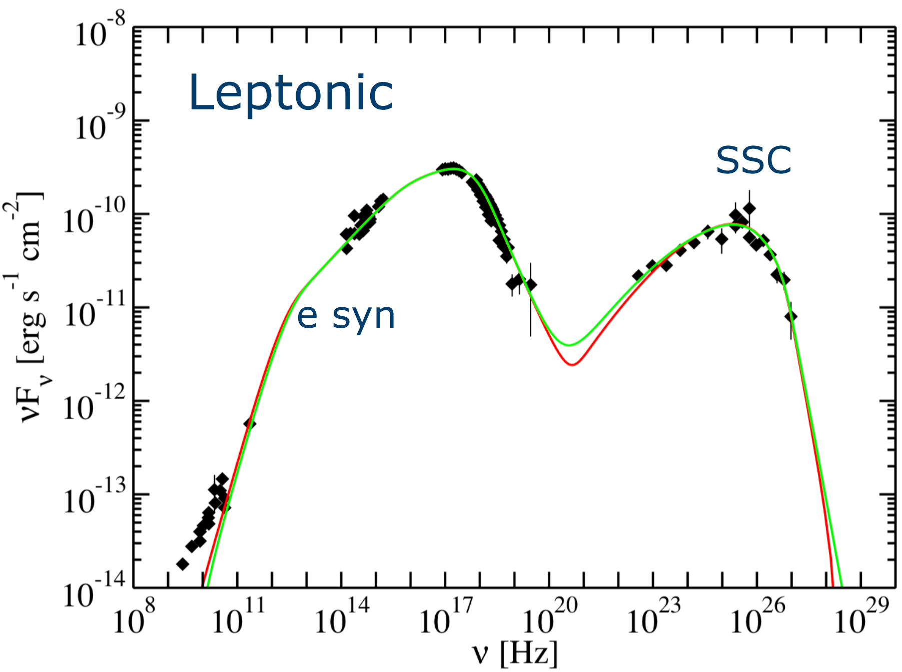
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

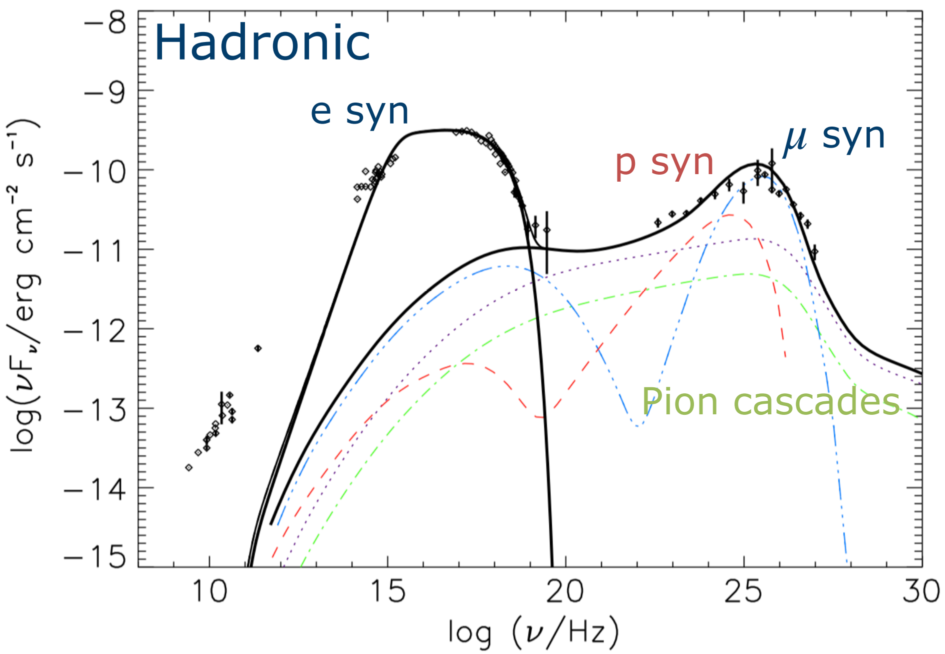
Synchrotron emission by muons can be important

Blazar emission models without ν

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011





Abdo et al. 2011

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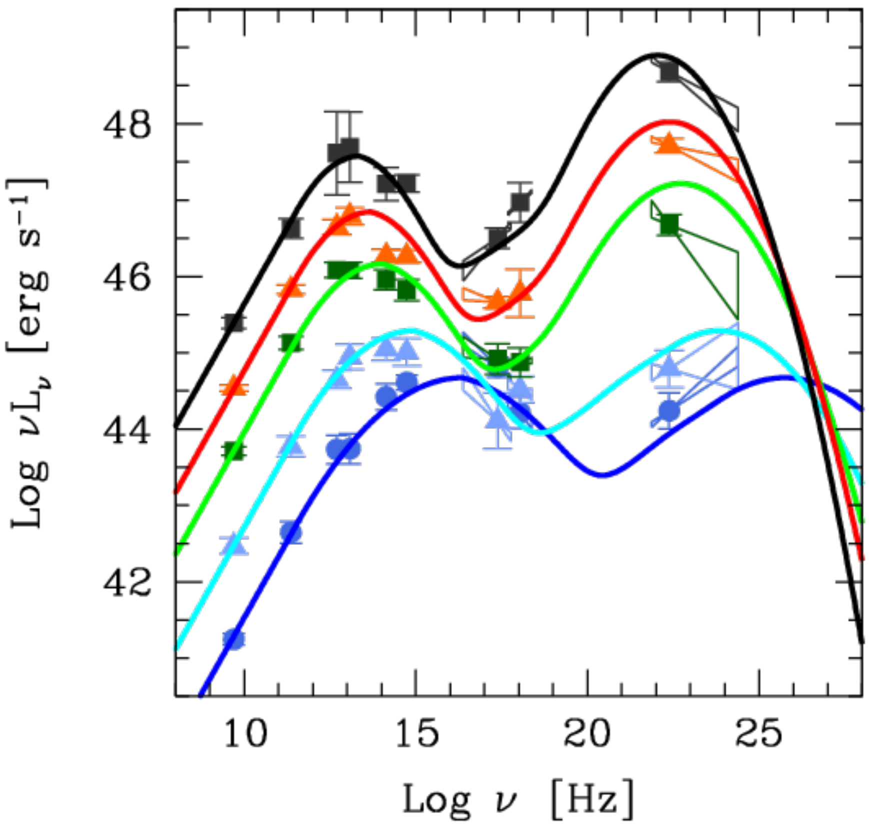
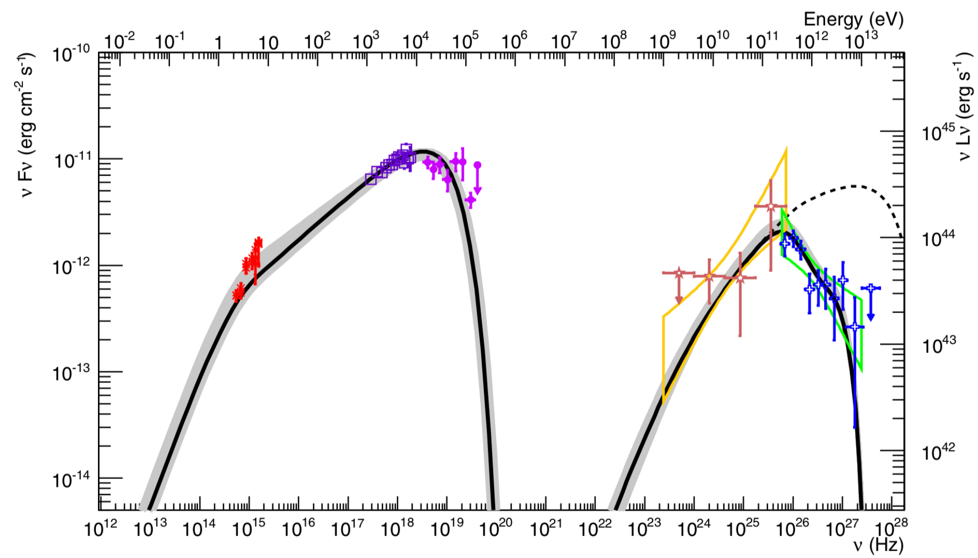
Blazar emission models without ν

Extreme blazars (peak > 1 keV)
Archetype is 1ES0229+200





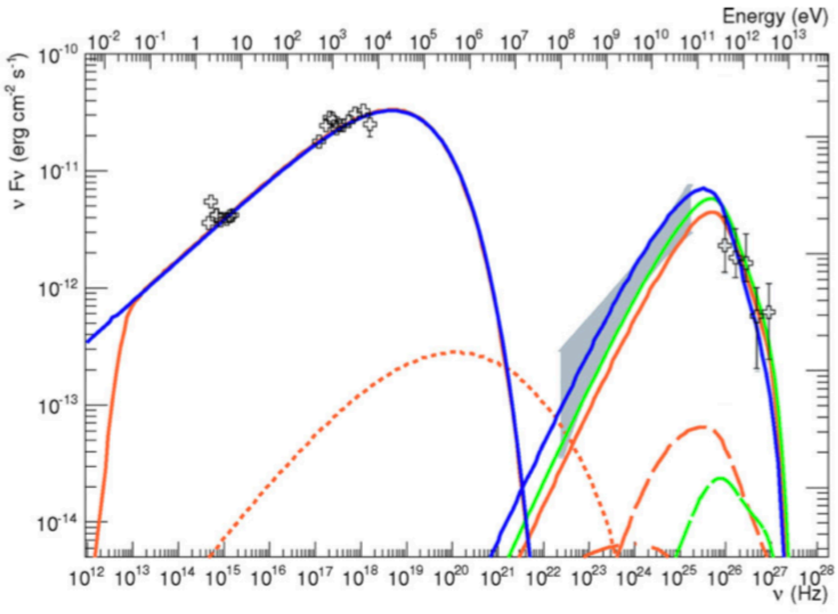
Aliu et al. 2014

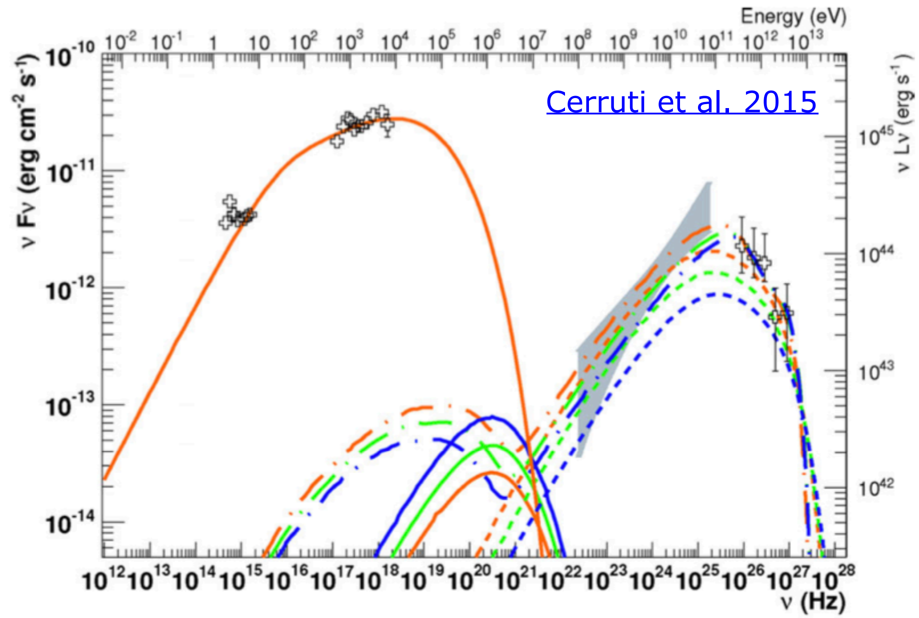
Blazar emission models without ν

Extreme blazars (peak > 1 keV)

Leptonic modeling faces difficulties (high Doppler factor / high minimum energy of the particle distribution)

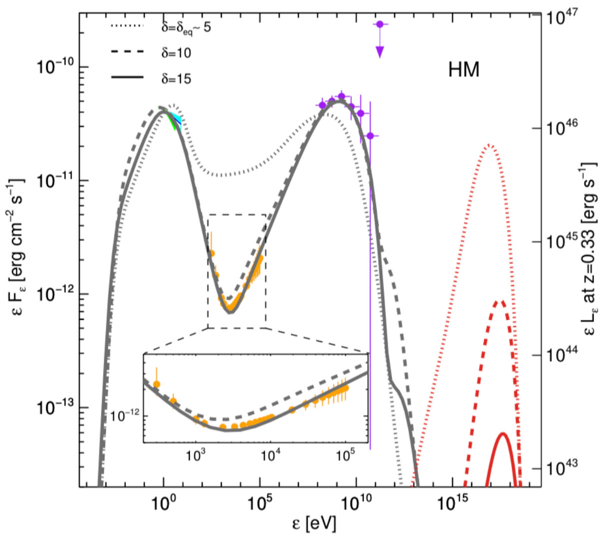
Hadronic modeling perfectly suited for them





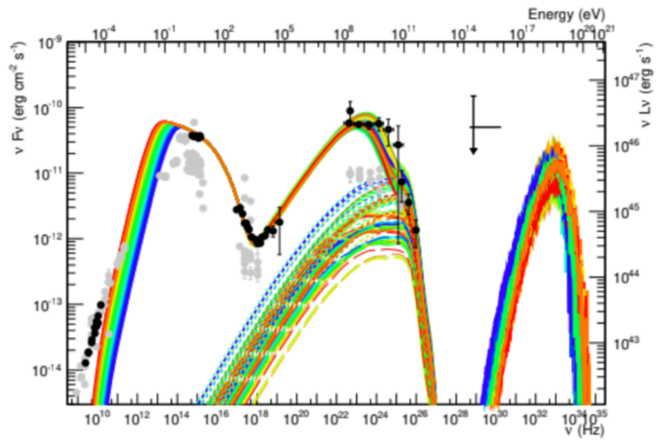
TXS0506+056: the 2017 flare

Proton synchrotron solutions



[Keivani et al. 2018](#)

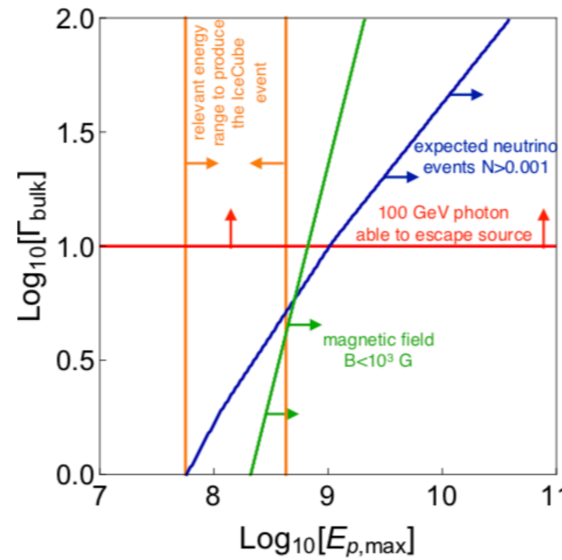
$\nu \simeq 10^{-5}\ yr^{-1}$



(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

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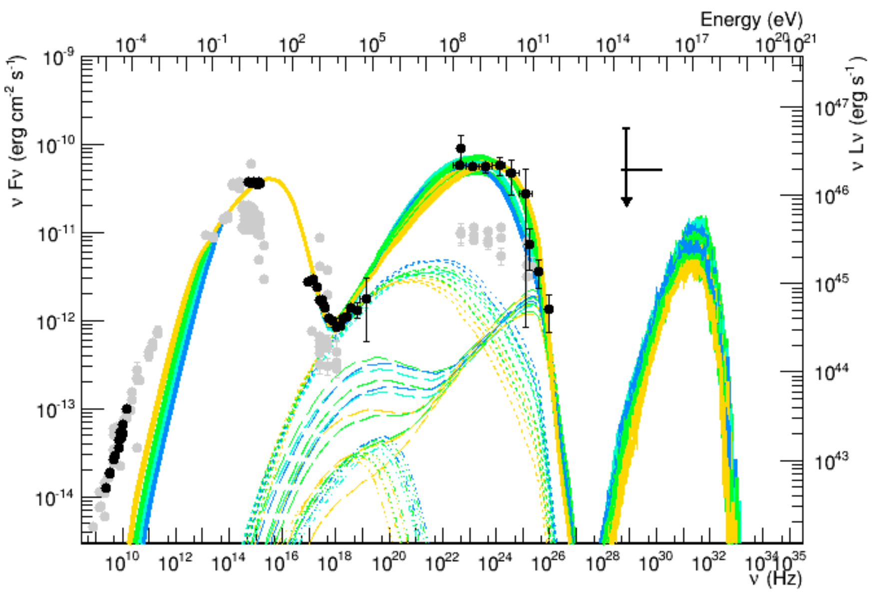
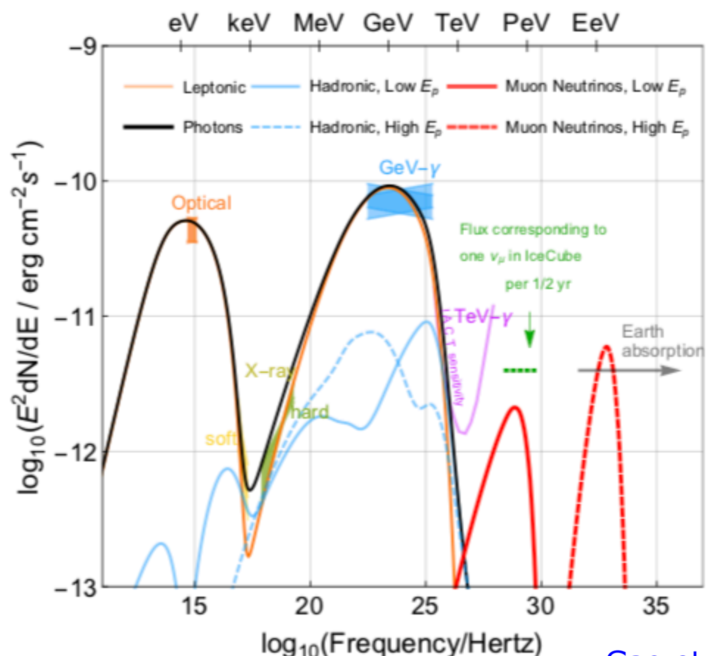
TXS0506+056: the 2017 flare

Lepto-hadronic solutions



[Cerruti et al. 2019](#)



[Gao et al. 2018](#)

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

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

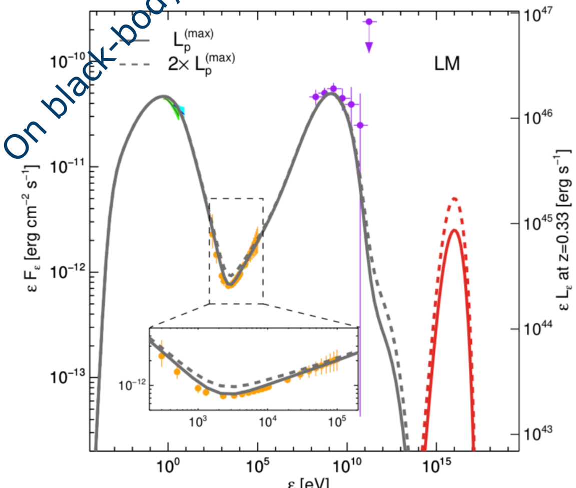
They can work: neutrino rates of the order of 0.1 / yr

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

TXS0506+056: the 2017 flare

Proton-photon interaction on external photon fields

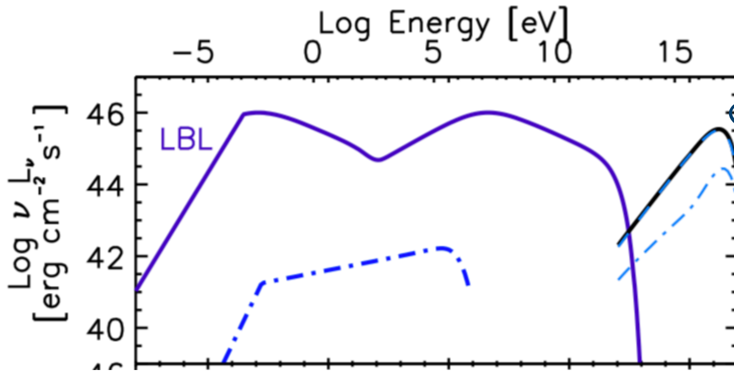
On black-body



Keivani et al. 2018

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

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



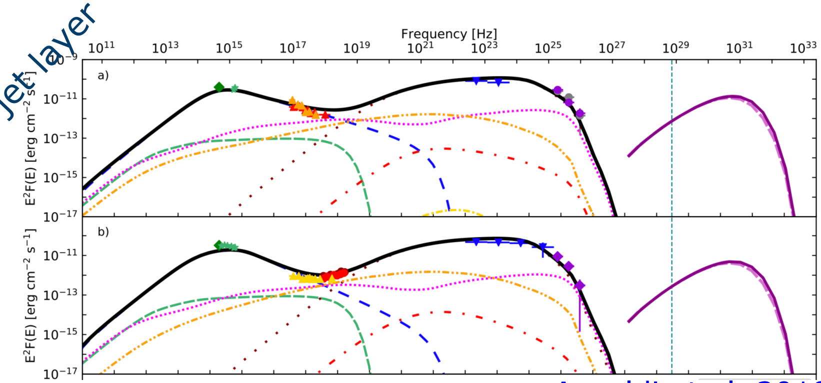
On RIAF

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

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

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

TXS0506+056: the 2017 flare

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What did we learn on blazars?

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- <u>Pure hadronic solutions are excluded!</u>

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- 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

Cosmic Rays from TXS0506+056

Can AGNs accelerate (UHE)CRs?

- From Cerruti et al. 2019, $E_{p,max} = (2-7) \times 10^{18} eV$

- From Ansoldi et al. 2018, $E_{p,max} = 2 \times 10^{15} - 2 \times 10^{19} eV$

- From Keivani et al. 2018, “assuming the IceCube-170922A association holds, TXS 0506+056 is not a significant UHECR accelerator”

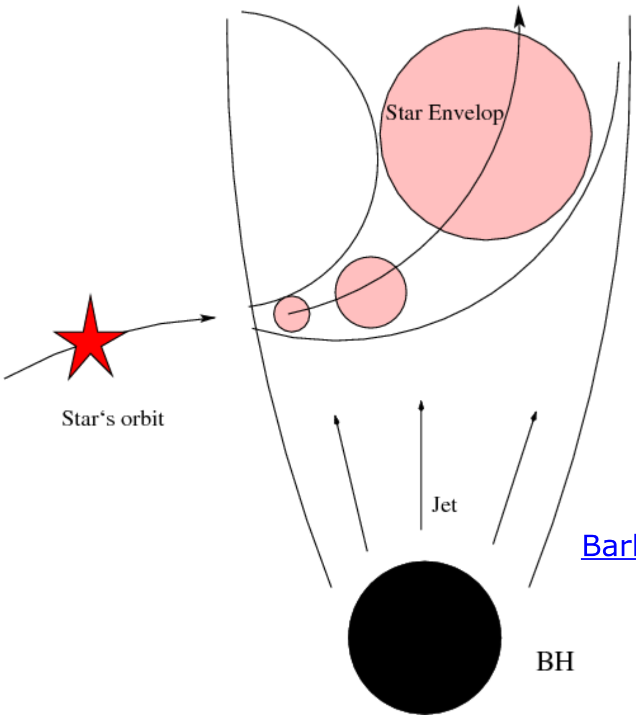
- From Gao et al. 2018, “The scenario [of UHECR in the source] is not acceptable”

TXS0506+056 not really an UHECR accelerator!

TXS0506+056: the 2017 flare

Alternative hadronic scenario

Jet - cloud interaction : $p + p = n^0\pi^0 + n^+\pi^+ + n^-\pi^-$



[Barkov et al. 2012](#)

TXS0506+056: the 2017 flare

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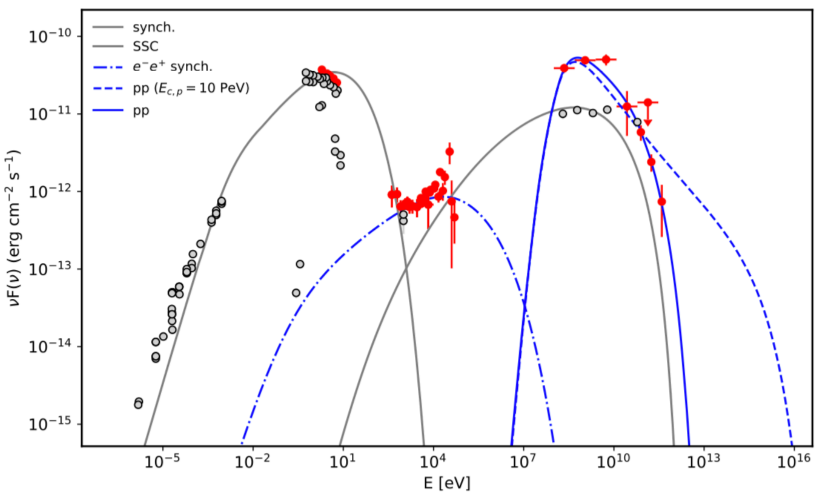
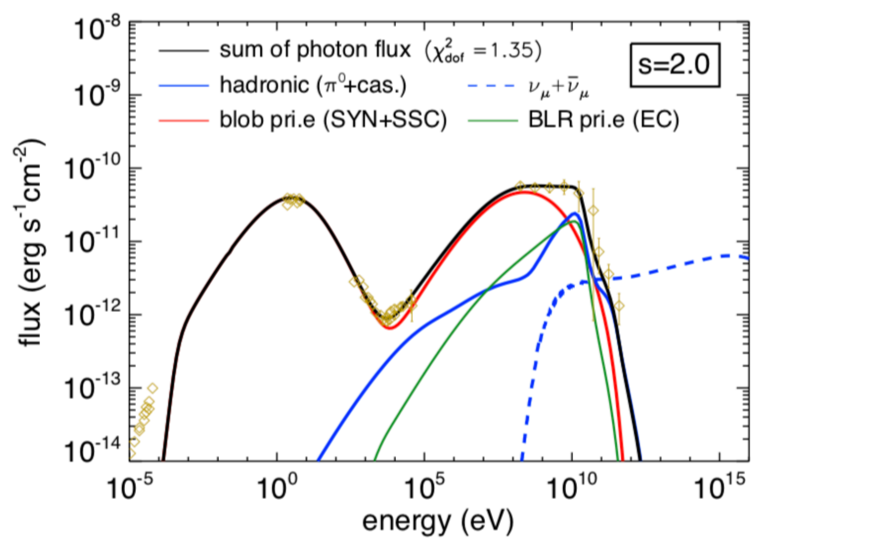


[Sahakyan 2018]

$$L_{jet}=1\times10^{48}erg/s$$
$$\nu=0.13-0.46\ yr^{-1}$$



$$L_{jet}=(0.8-5)\times10^{46}erg/s$$
$$\nu=0.26\ yr^{-1}$$

[Liu et al. 2019]

see as well [Wang et al. 2018]

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IceCube-170922A / TXS 0506+056

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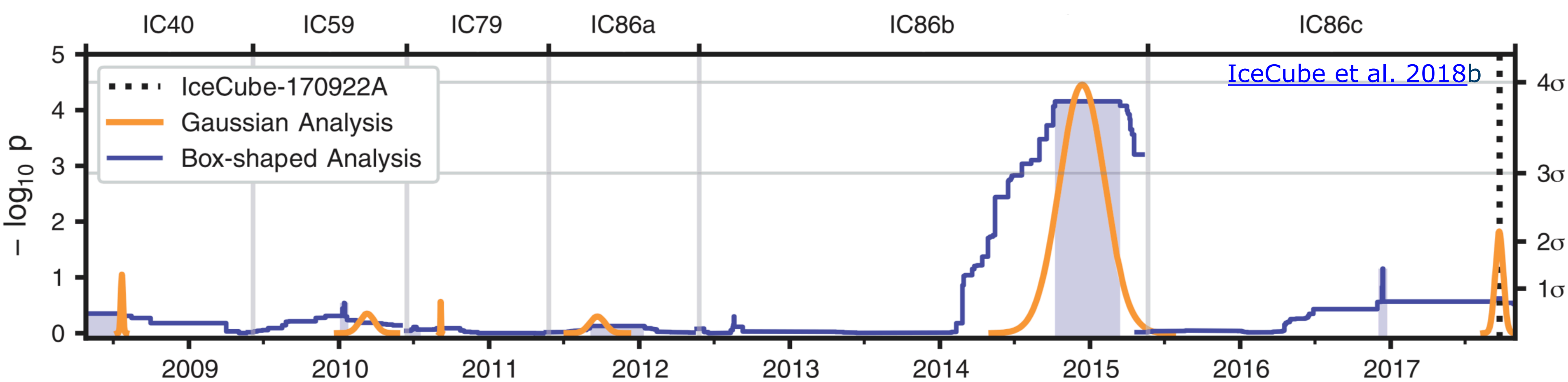

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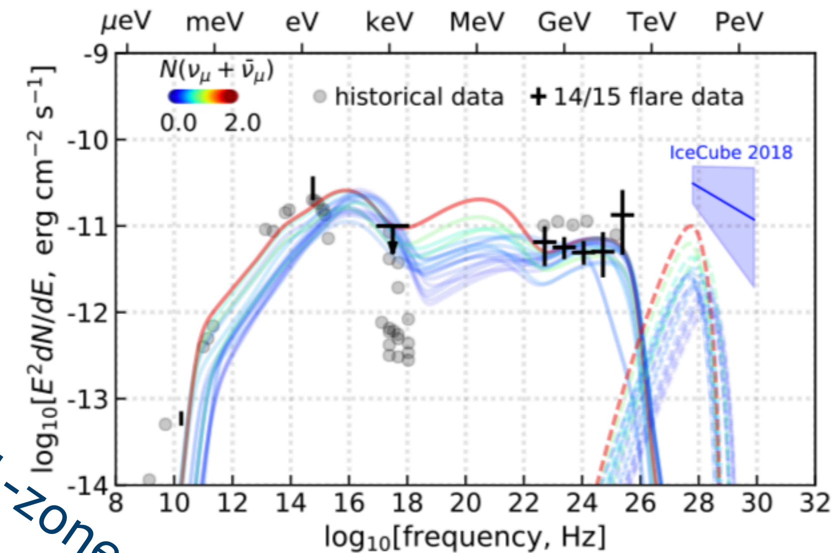
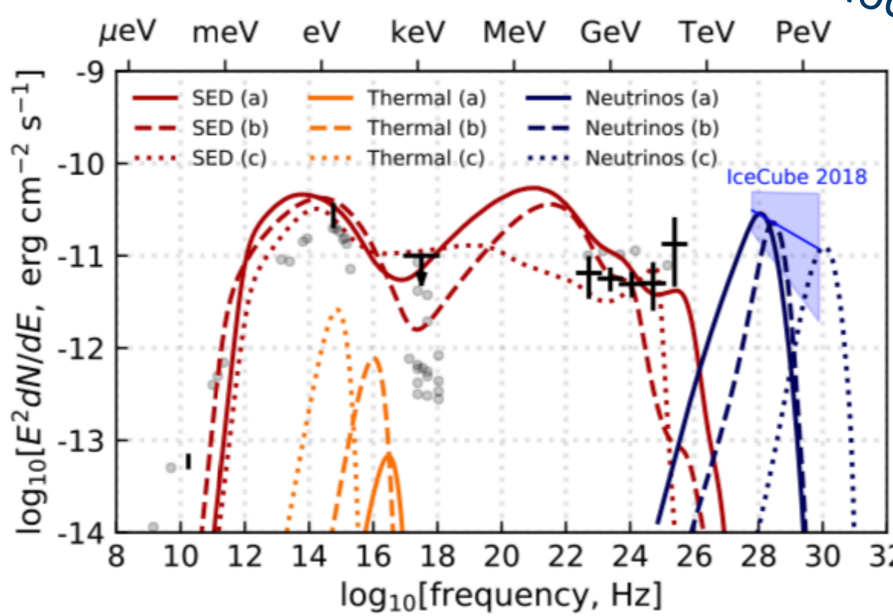
TXS 0506+056 : the 2014 ν flare



1-zone models

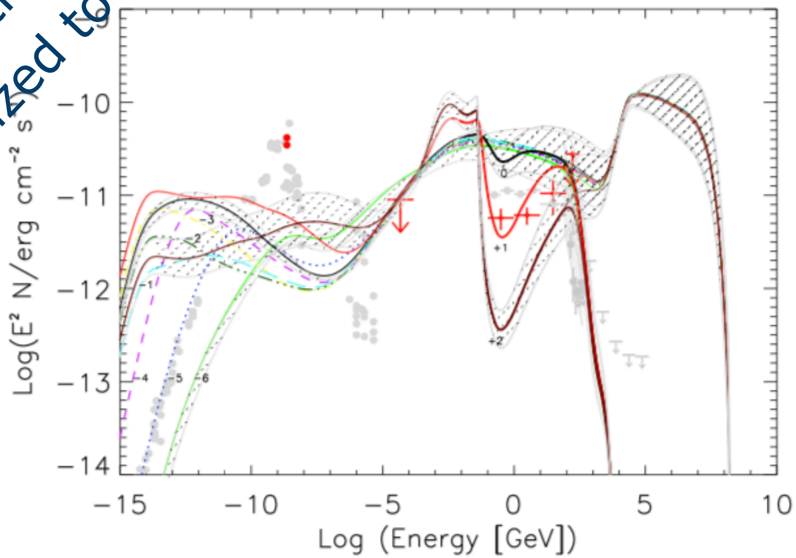
External field model



Rodrigues et al. 2019

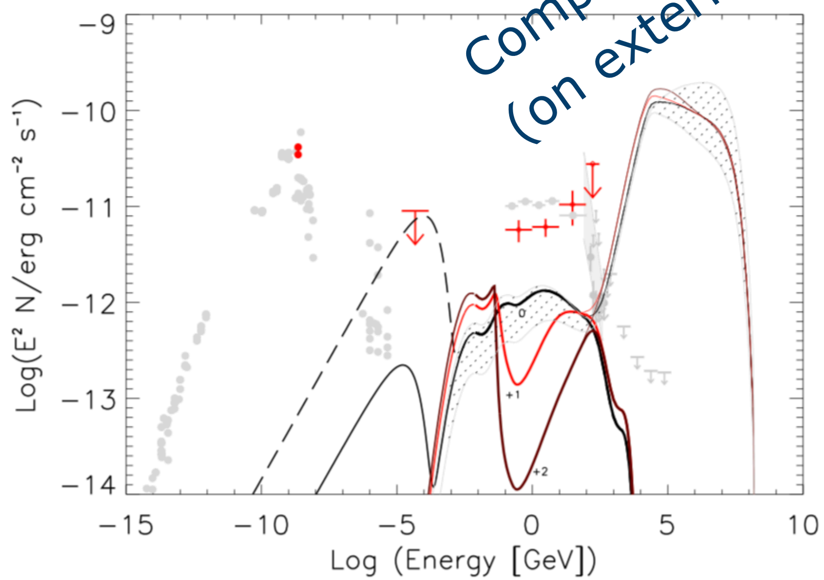
TXS 0506+056 : the 2014 ν flare

Synchrotron cascades (normalized to get right ν)



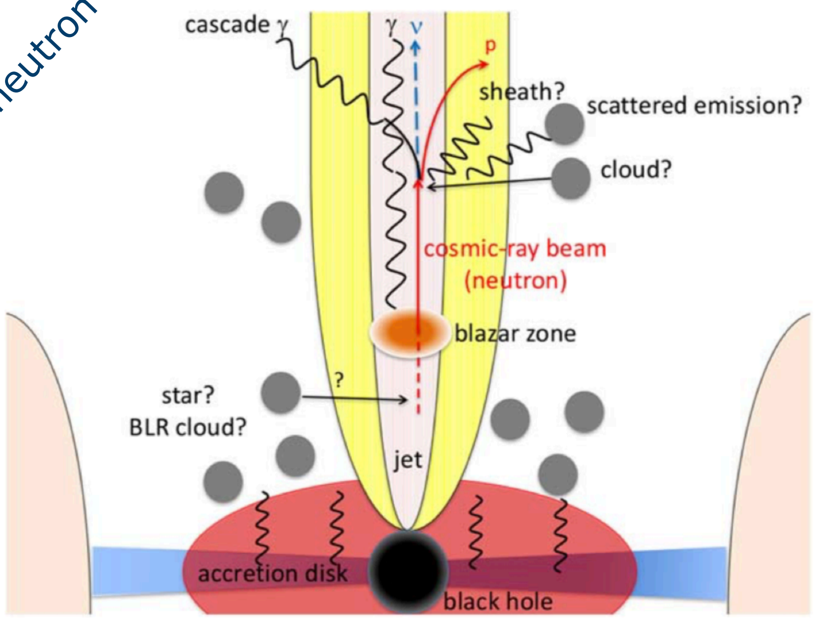
[Reimer et al. 2019](#)

Compton cascades (on external field!)



TXS 0506+056 : the 2014 ν flare

The neutron-beam model



Two-zone model:

- neutrons escape the blazar zone

- proton-photon interaction with external fields at larger scales in the jet

- secondary pairs are isotropized in the larger-scale jet

[Murase et al. 2018]

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TXS 0506+056 : the 2014 ν flare

- 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

Neutrinos from blazars

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Why TXS 0506+056?

Neutrinos from blazars

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- Favorable position in the sky
- Long-term brightening in gamma-rays (not that common)
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- At moderate redshift, it is a luminous gamma-ray AGN

- Are we learning something on AGN populations?
- Do we have hadronic/neutrino blazars and leptonic blazars?
- Does this dichotomy overlap with other blazar classifications?

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Neutrinos from blazars

Neutrinos from blazars

What about the diffuse neutrino emission?

Neutrinos from blazars

What about the diffuse neutrino emission?

- Blazars dominate the diffuse γ background, but should represent less than ~30% of the IceCube background [Aartsen et al. 2017](#)

- Models for the 2017 flare of TXS0506 predict multi-PeV neutrinos which is a characteristic of blazar hadronic models

- Contribution from ν orphan flares as the 2014? [Halzen et al. 2019](#)

Neutrinos from blazars

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Where do we go from here?

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

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Hadronic modeling

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Hadronic modeling

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- Single zone models are starting failing: it is easy to increase in complexity, but at the expenses of an explosion of number of free parameters.

Keep going!

1967: the first X-ray AGN, M 87

1978: the first MeV AGN, 3C 273

1992: the first TeV AGN, Markarian 421

2017: the first neutrino AGN, TXS 0506+056