

# Neutrinos from blazars

(or, a quick review of blazar hadronic models)

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Dark Matter & Neutrinos  
Workshop

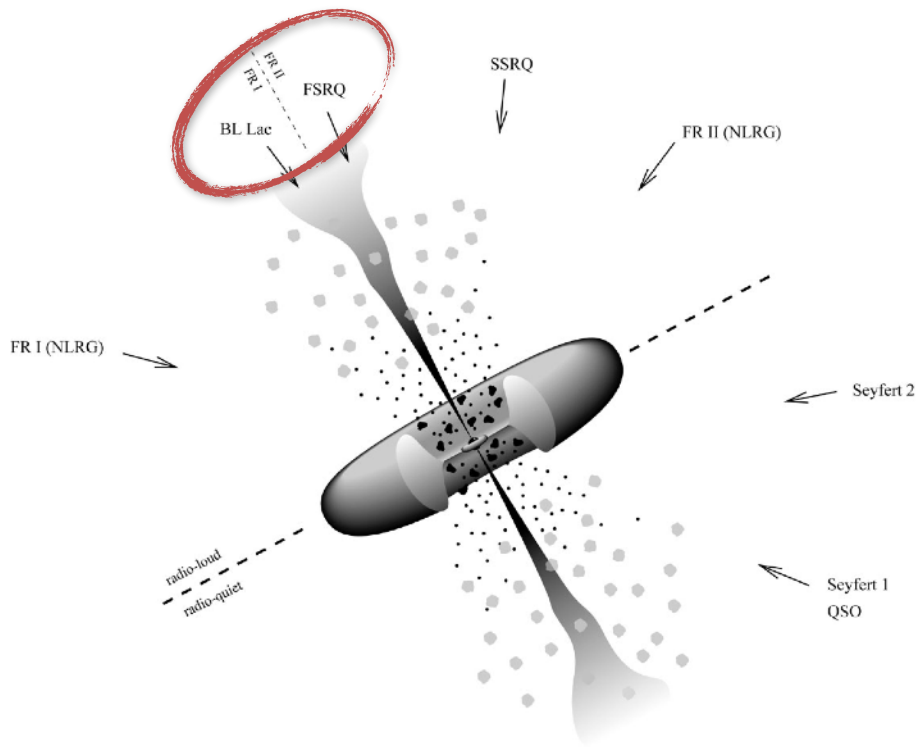
Paris  
May 21, 2025



# BLAZARS

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

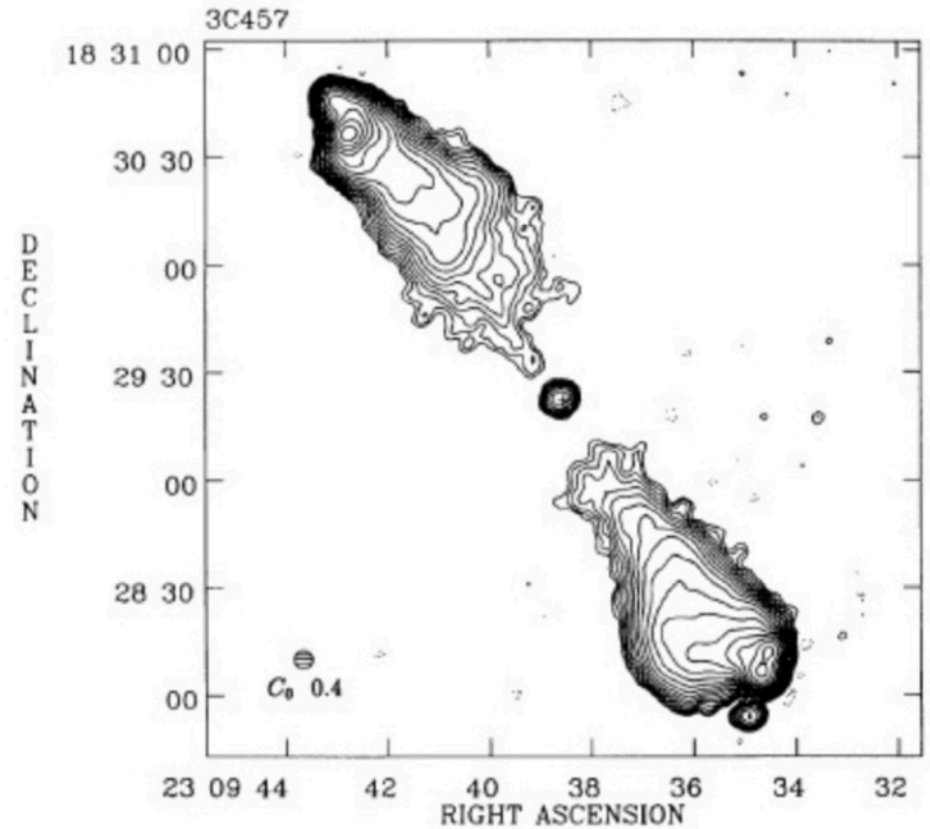
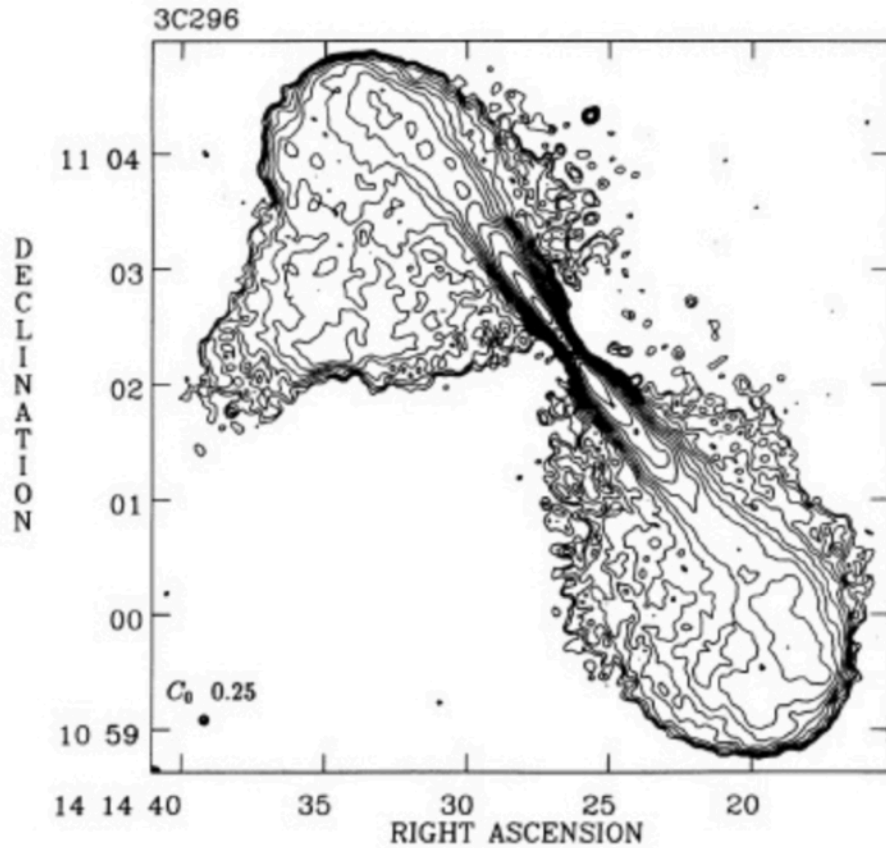
→ Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)



**Flat-spectrum-radio-quasars** : optical/UV spectrum with broad emission lines  
**BL Lacertae objects** : featureless optical/UV spectrum

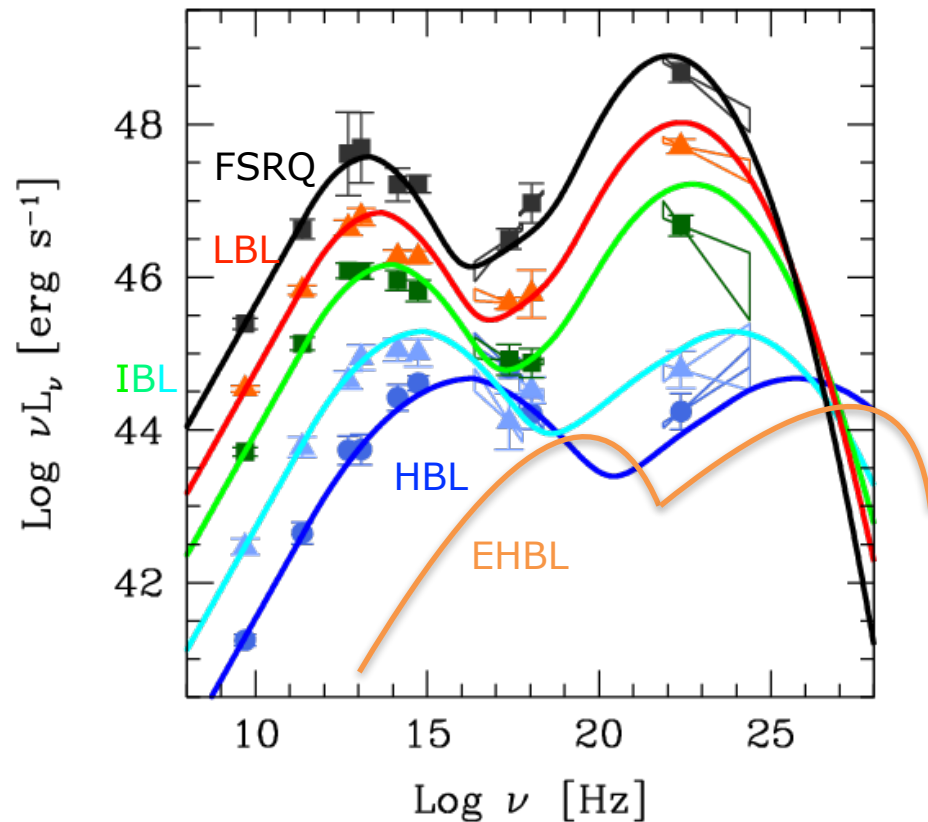
# BLAZARS

## Radio-loud dichotomy: Fanaroff-Riley I and FR II



[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

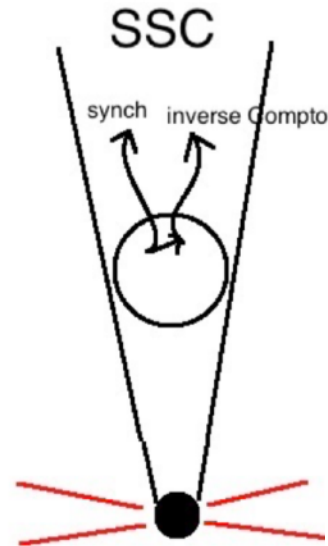
Same leptons that radiate synchrotron  
+ their own synchrotron photons (SSC)  
+ external photon fields (EIC)

State-of-the-art models:

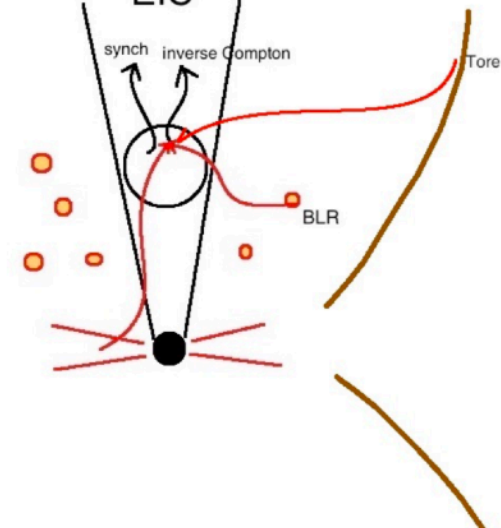
HBLs → SSC

LBLs / FSRQs → EIC

Synchrotron-Self-Compton



External-Inverse-Compton  
EIC



# BLAZARS EMISSION MODELS

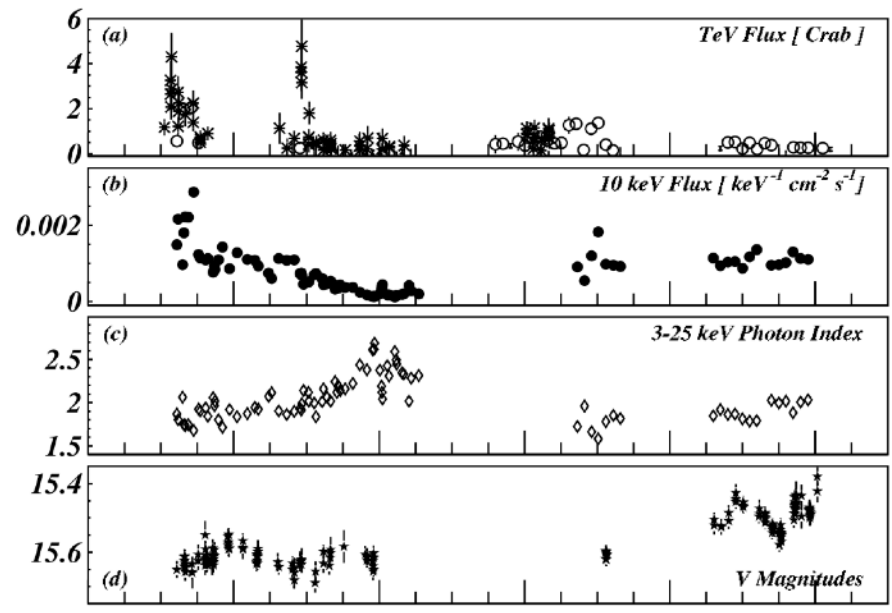
Why adding hadrons if leptons work??

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)

2) Natural link with cosmic-rays and neutrinos

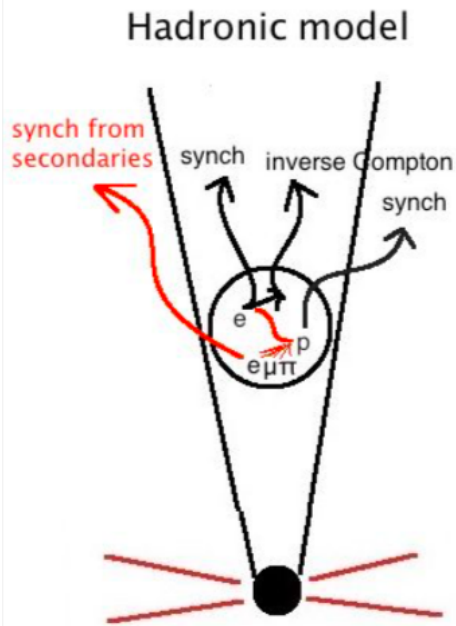


Krawczynski et al. 2004

# BLAZARS EMISSION MODELS

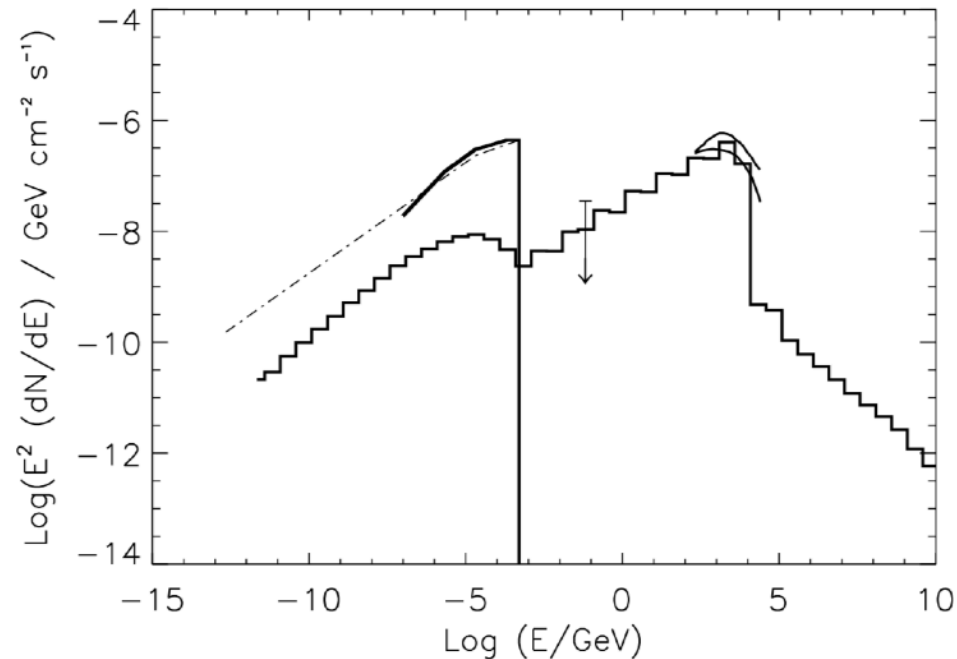
## Hadronic models

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

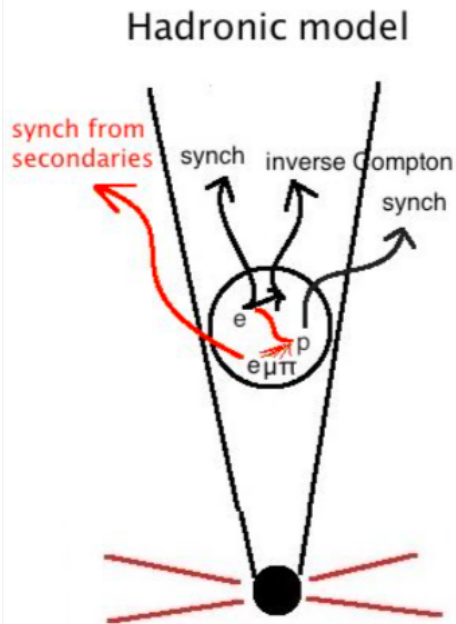


Photo-meson

$$p + \gamma = p' + \pi^0 \rightarrow p' + 2\gamma$$

$$p + \gamma = n + \pi^+$$

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

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

Bethe-Heitler pair production

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

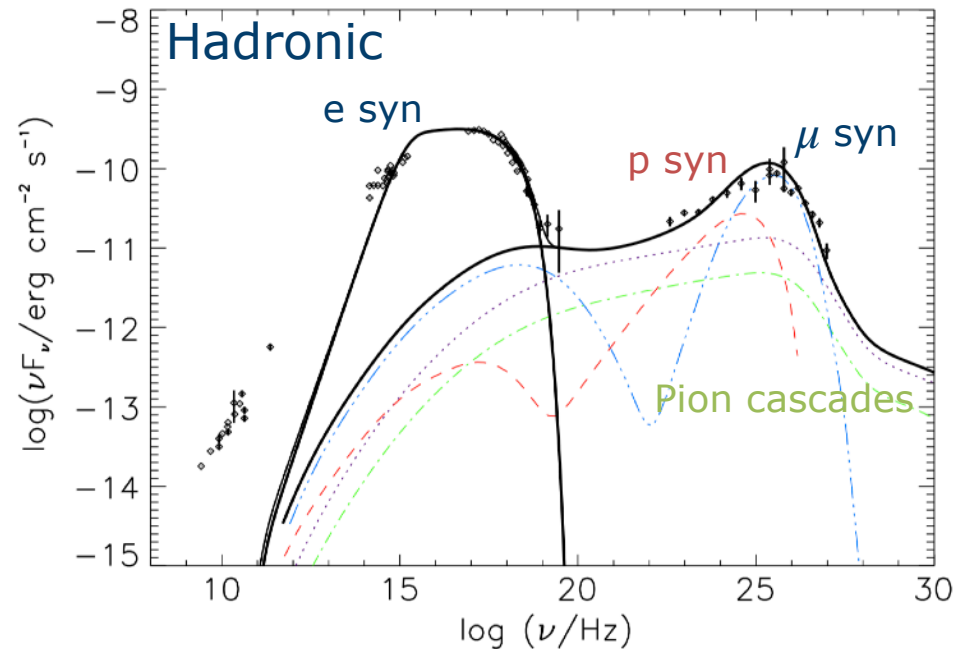
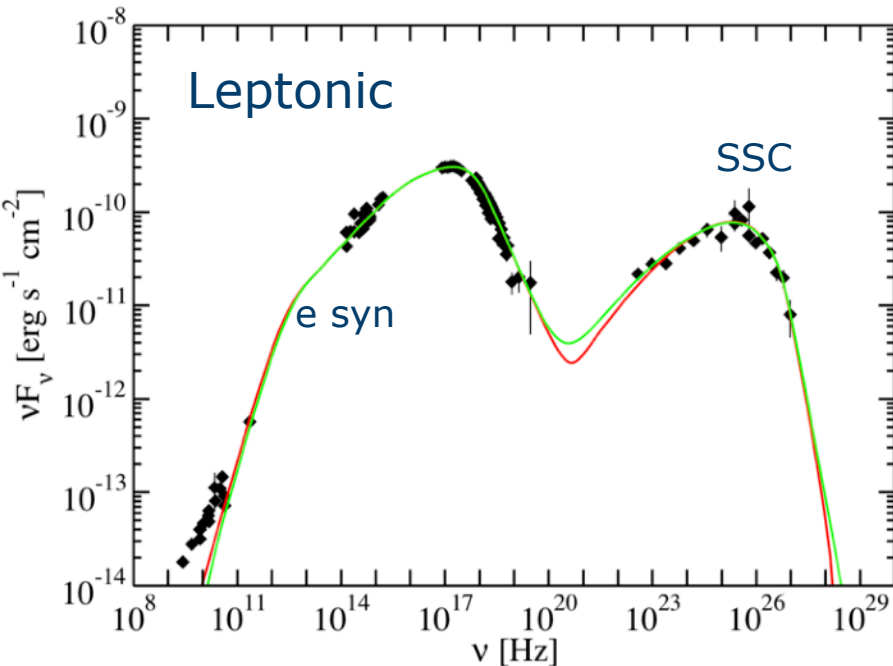
Injection of secondary leptons in the emitting region,  
triggering synchrotron supported **pair-cascades**

Synchrotron emission by **muons** can be important

# BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011



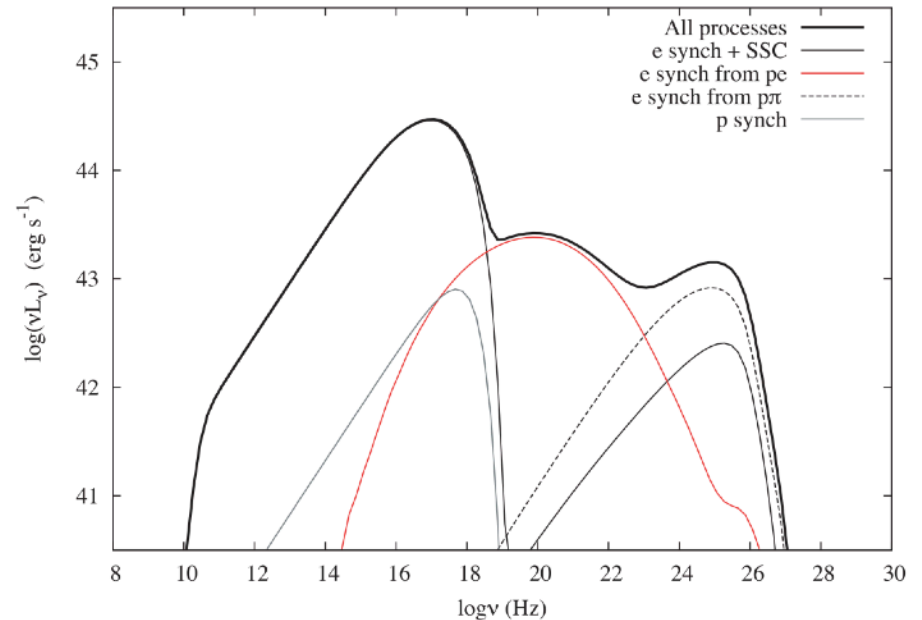
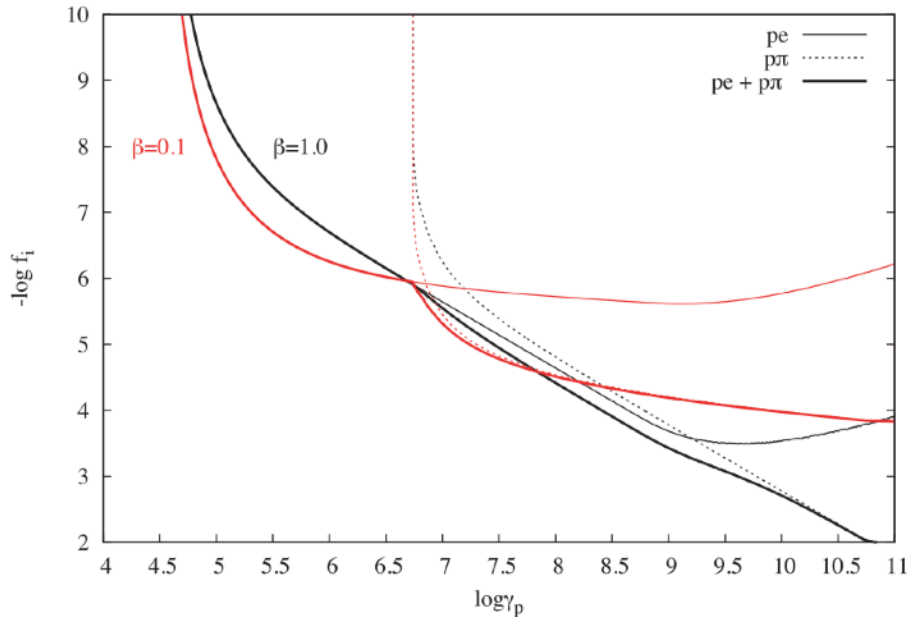
[Abdo et al. 2011](#)

# TXS 0506+056: the 2017 flare

Why is Bethe-Heitler important?

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

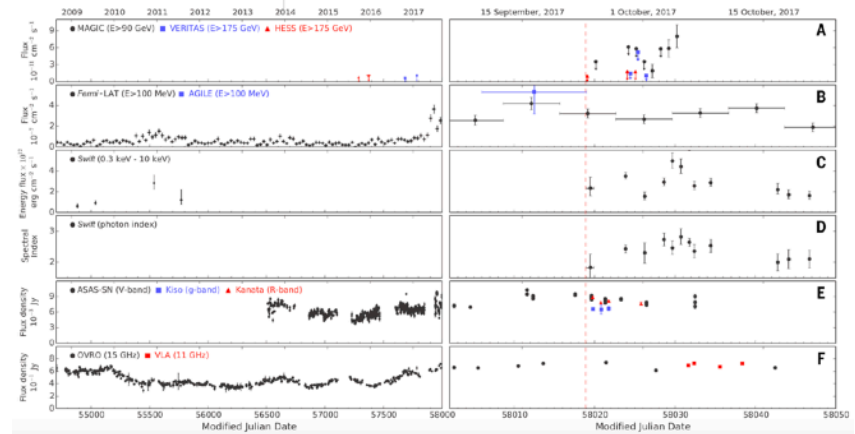
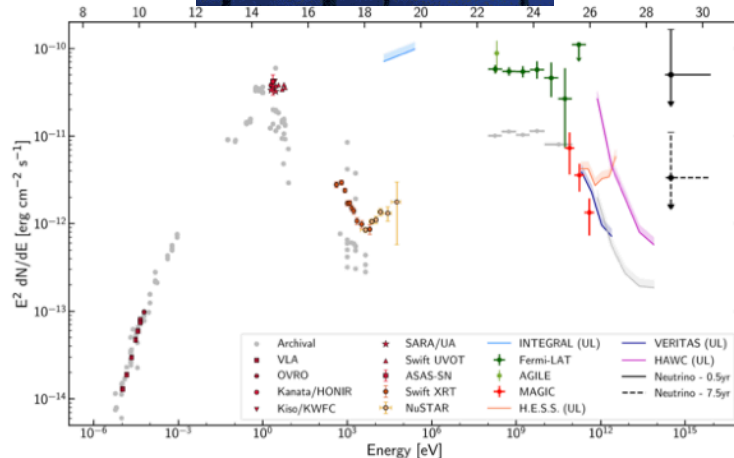
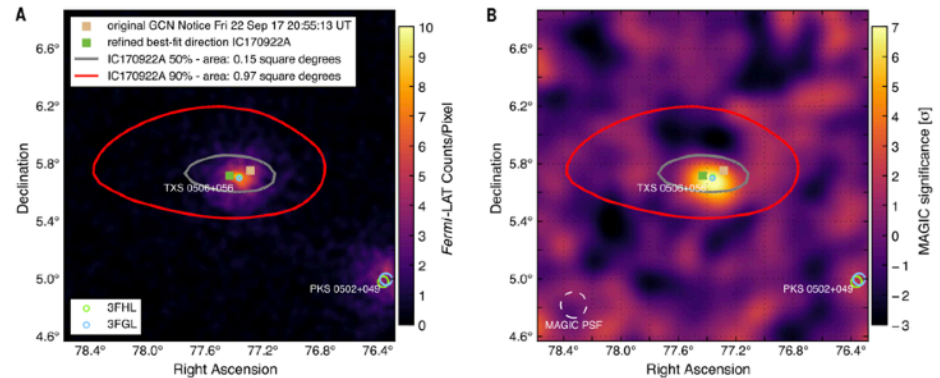
Can dominate the X-ray band and fill the SED valley



[Petropoulou & Mastichiadis 2015](#)

# IceCube-170922A / TXS 0506+056

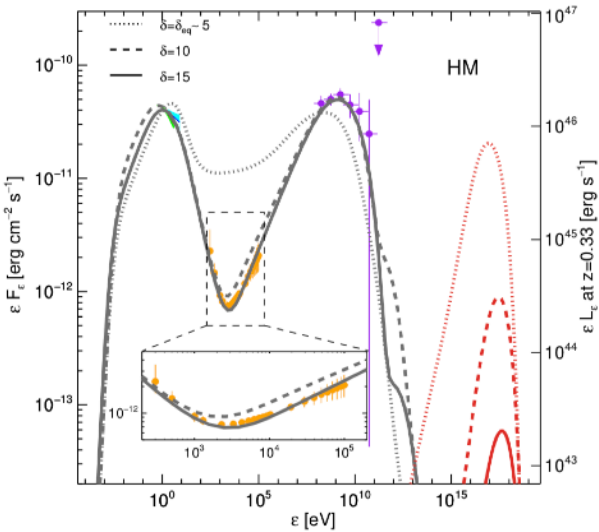
Most significant association ( $3\sigma$ )  
of a high-energy (290 TeV) neutrino with an astrophysical source



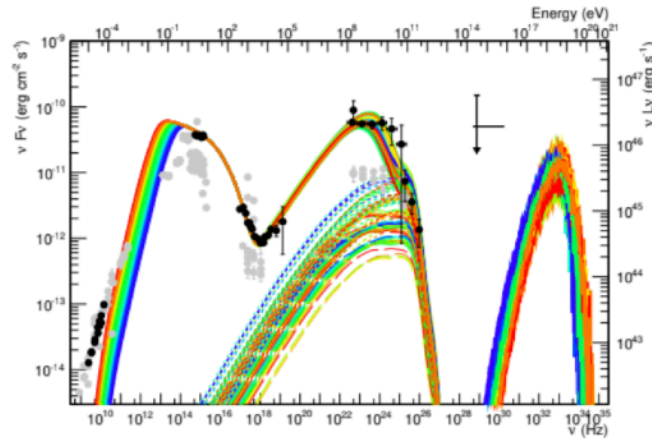
[IceCube, Fermi, MAGIC et al. 2018](#)



# TXS 0506+056: the 2017 flare



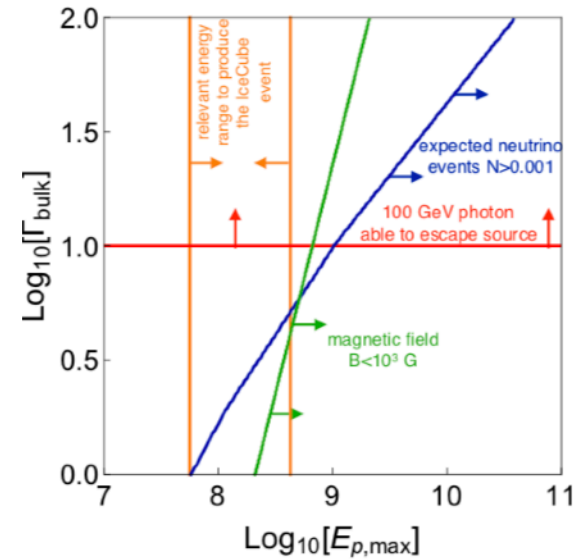
[Keivani et al. 2018](#)  
 $\nu \simeq 10^{-5} \text{ yr}^{-1}$



(a) Proton synchrotron modeling of TXS 0506+056

[Cerruti et al. 2019](#)  
 $\nu = 10^{-5} - 10^{-3} \text{ yr}^{-1}$

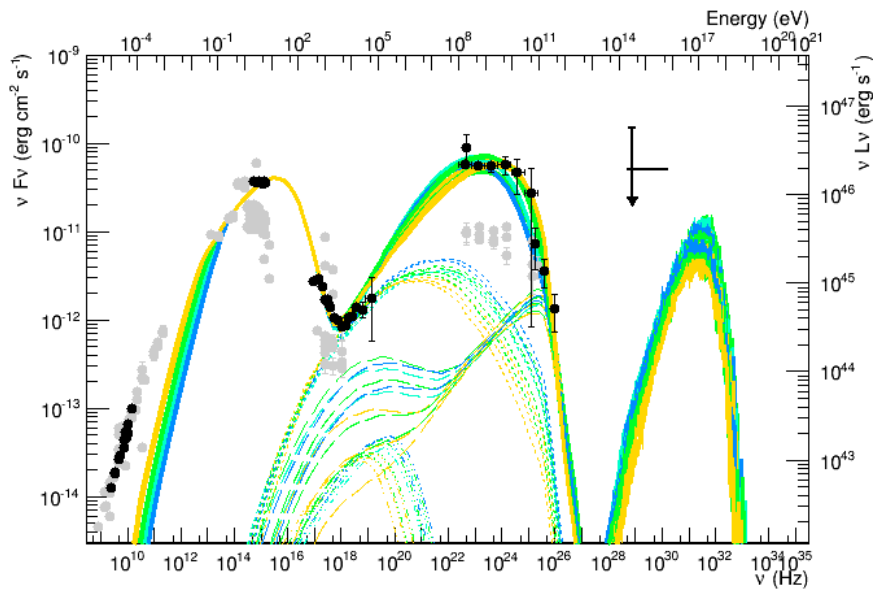
Proton synchrotron solutions exist,  
 but the expected neutrino rate is very low



[Gao et al. 2018](#)

# TXS 0506+056: the 2017 flare

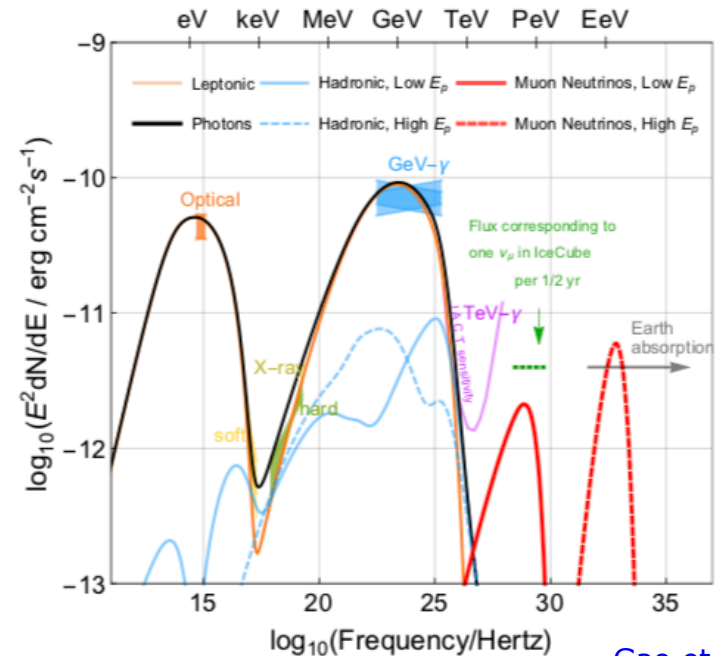
## Lepto-hadronic solutions



[Cerruti et al. 2019](#)

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

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



[Gao et al. 2018](#)

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

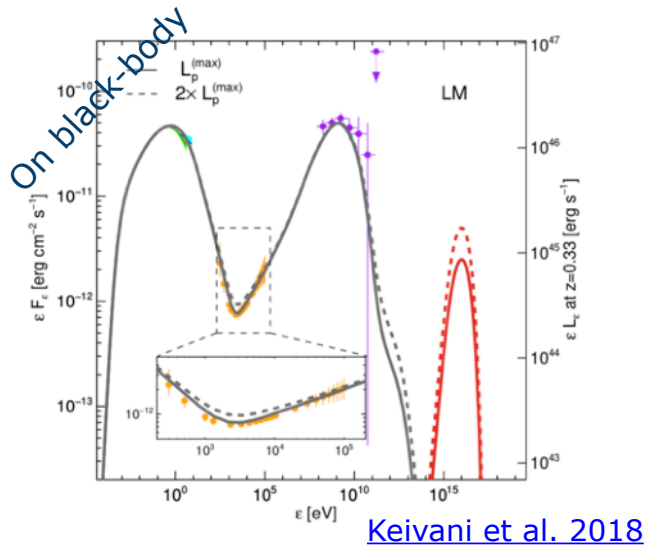
$$\nu = 0.3 \text{ yr}^{-1}$$

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

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

# TXS 0506+056: the 2017 flare

## Proton-photon interaction on external photon fields

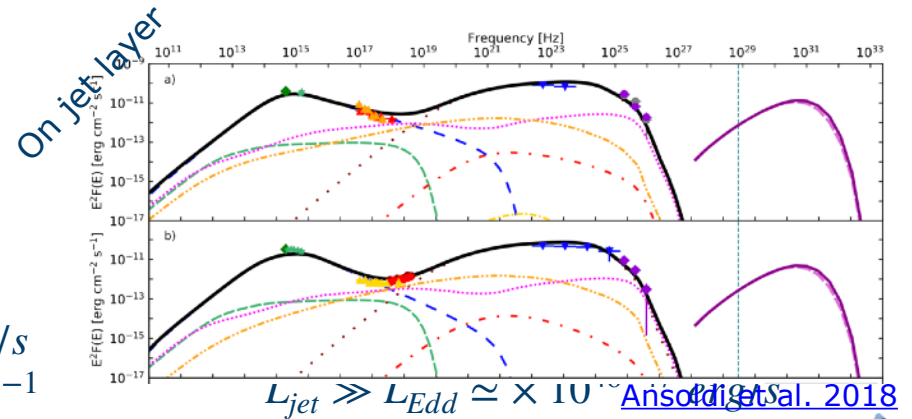
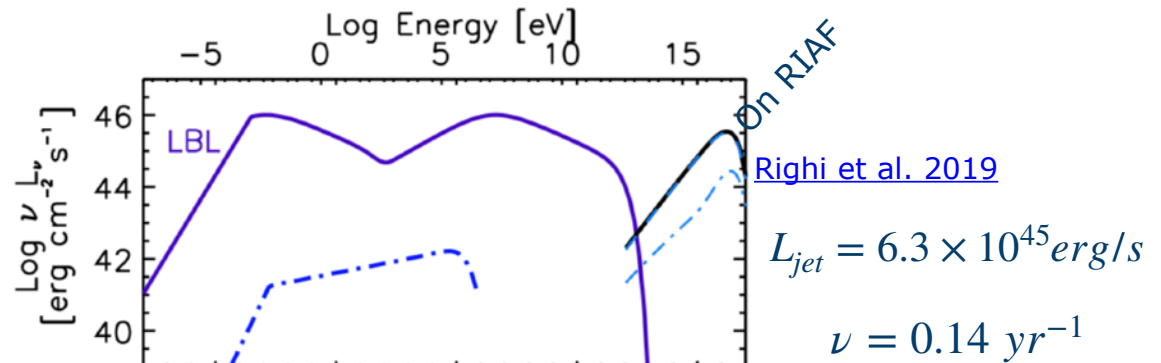


$$L_{jet} = (4 - 150) \times 10^{45} \text{ erg/s}$$

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

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

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



# TXS 0506+056: the 2017 flare

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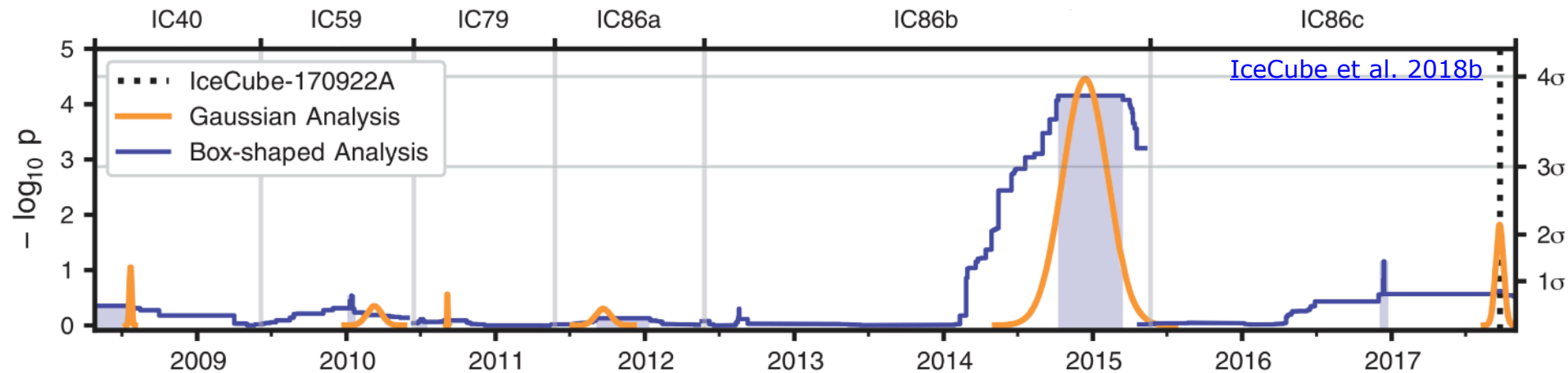
What did we learn on blazars?

- 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

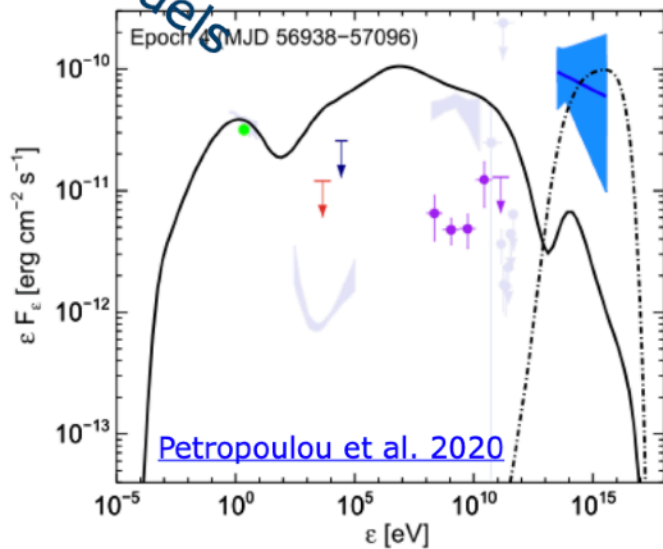
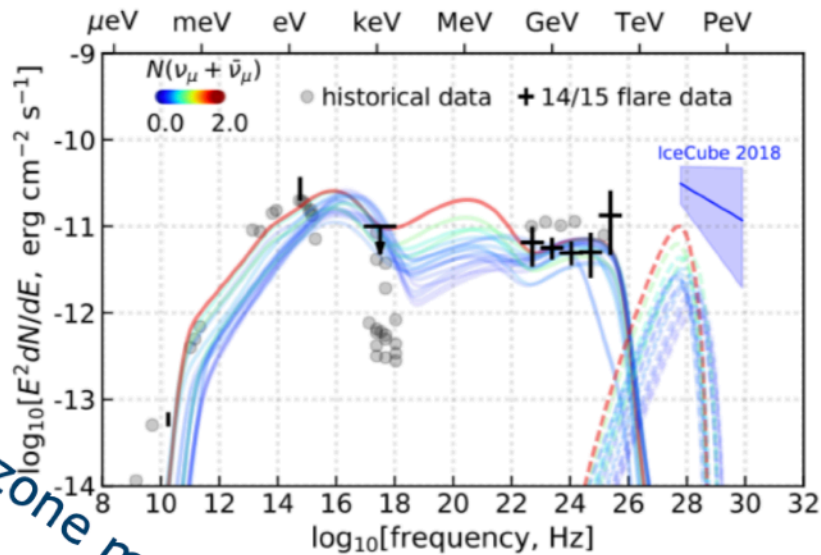
Detection of a second neutrino flare in 2014-2015  
(without a gamma-ray counterpart)



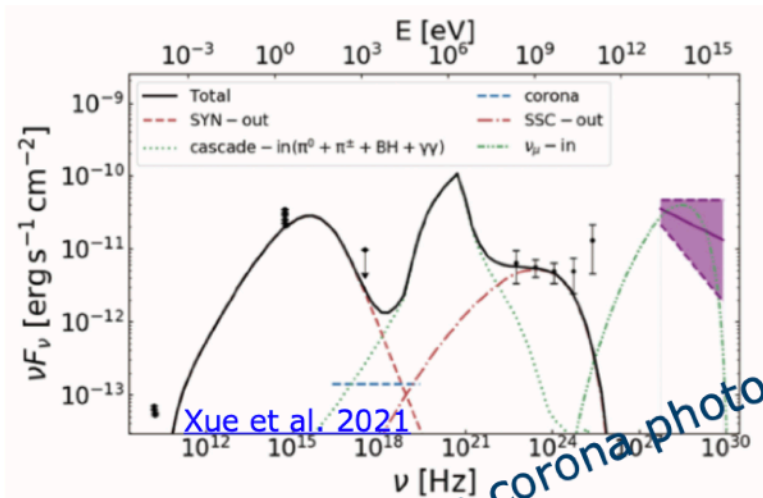
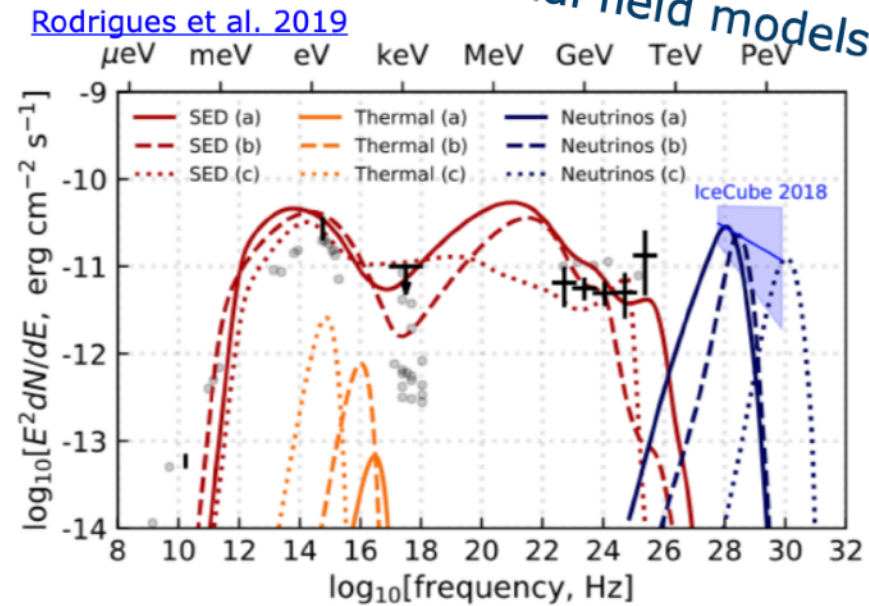
3.5 $\sigma$  evidence for neutrino emission in 2014-2015 independent from the 2017 event

# TXS 0506+056: the 2014/15 flare

1-zone models



External field models



On corona photons

# TXS 0506+056: the 2014/15 flare

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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  $\nu$  and the  $\gamma$ -ray emitting region are not the same

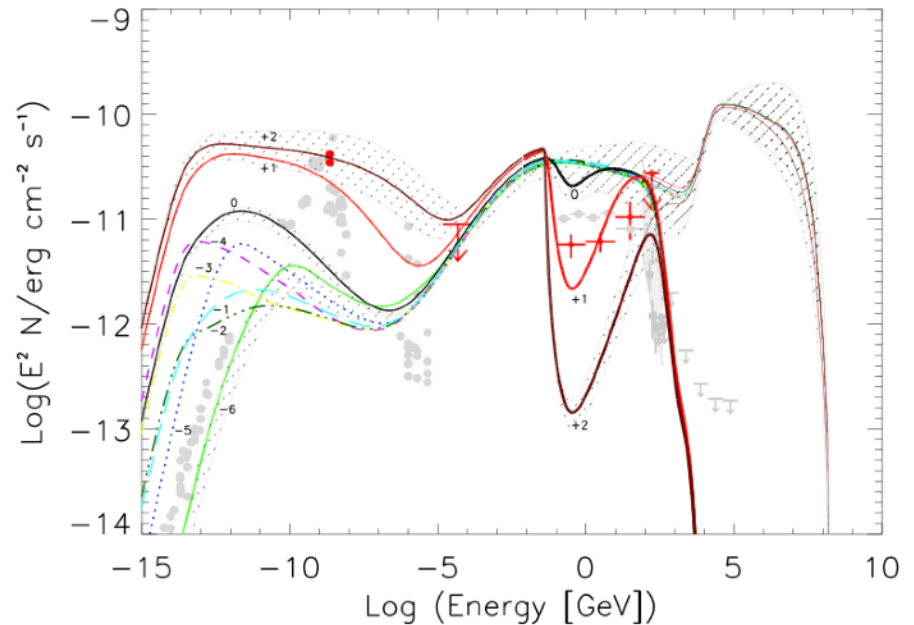
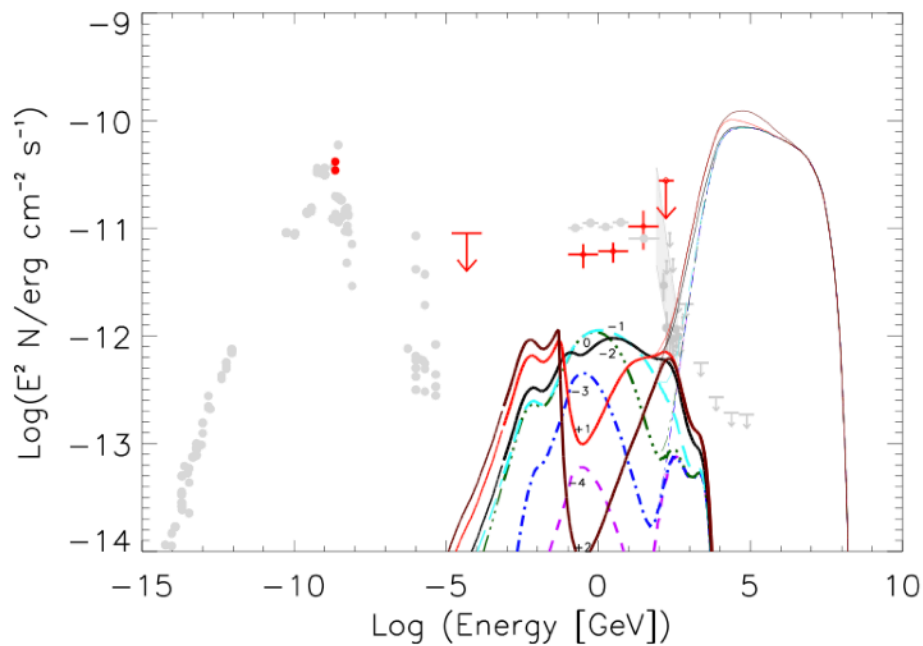
# TXS 0506+056: the 2014/15 flare

The exact cascade spectrum varies a lot in the parameter space

inverse-Compton cascade

vs

synchrotron cascade



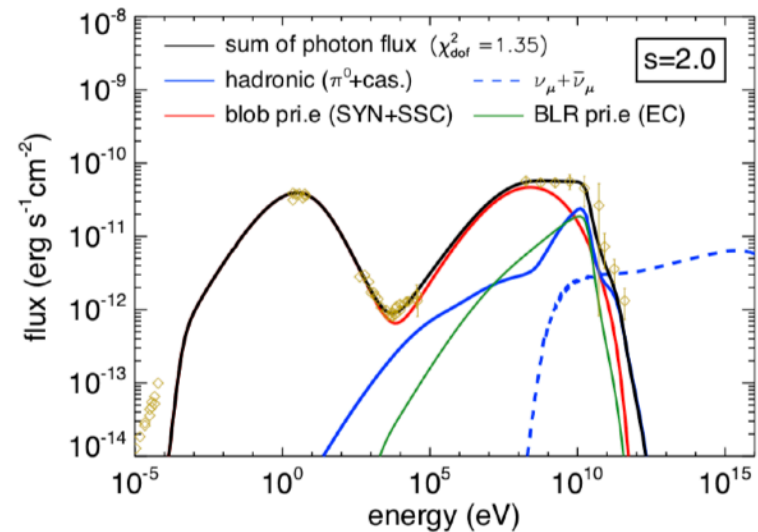
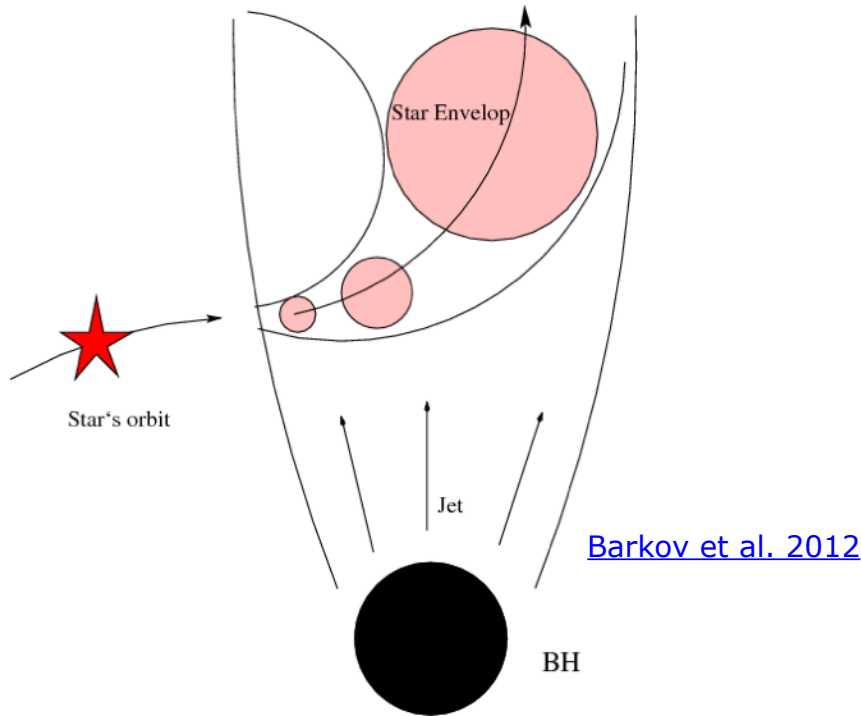
[Reimer et al. 2020](#)

# 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



$$L_{jet} = (0.8 - 5) \times 10^{46} \text{ erg/s}$$

[Liu et al. 2019](#)

$$\nu = 0.26 \text{ yr}^{-1}$$

# HADRONIC CODE COMPARISON

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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](#))

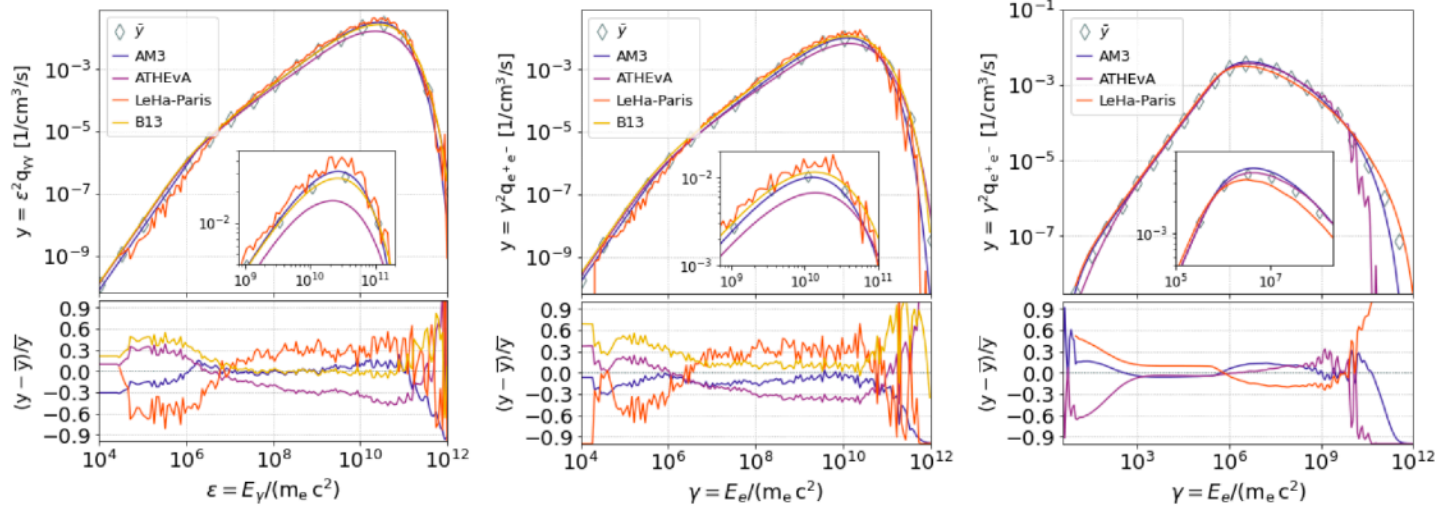
- run tests from simple 'artificial' cases  
(Mono-energetic protons on black-body)  
to 'realistic' ones  
(proton-synchrotron or lepto-hadronic)

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

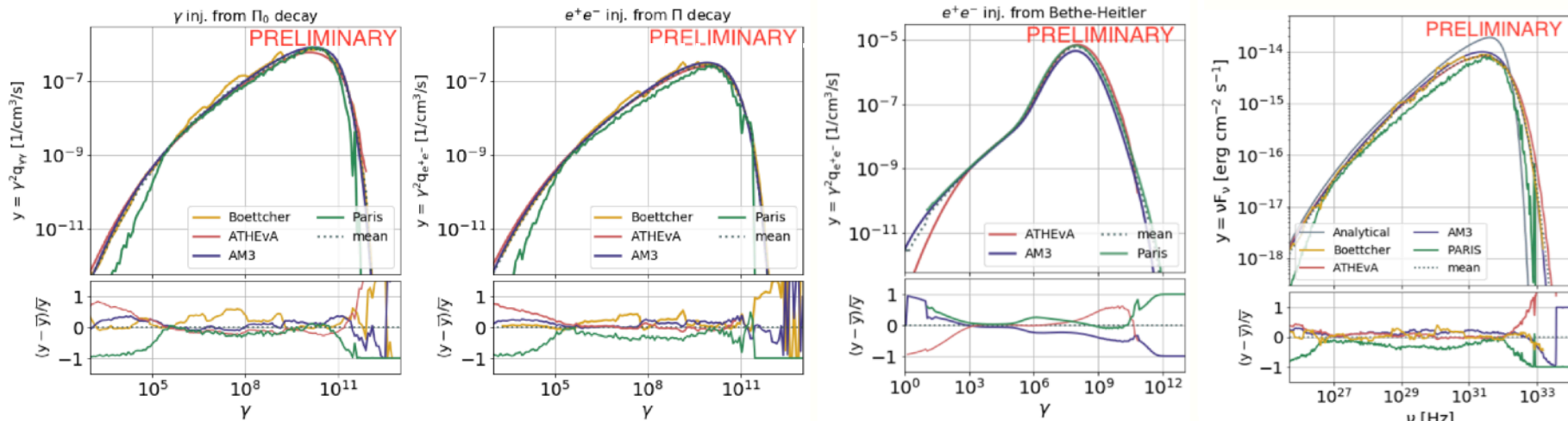
Take home message: spectral shapes are ok; 40% spread in normalization

# HADRONIC CODE COMPARISON

## Power-law protons on power-law photons



## Proton-synchrotron scenario



submitted to ApJS

# PKS 0735+178

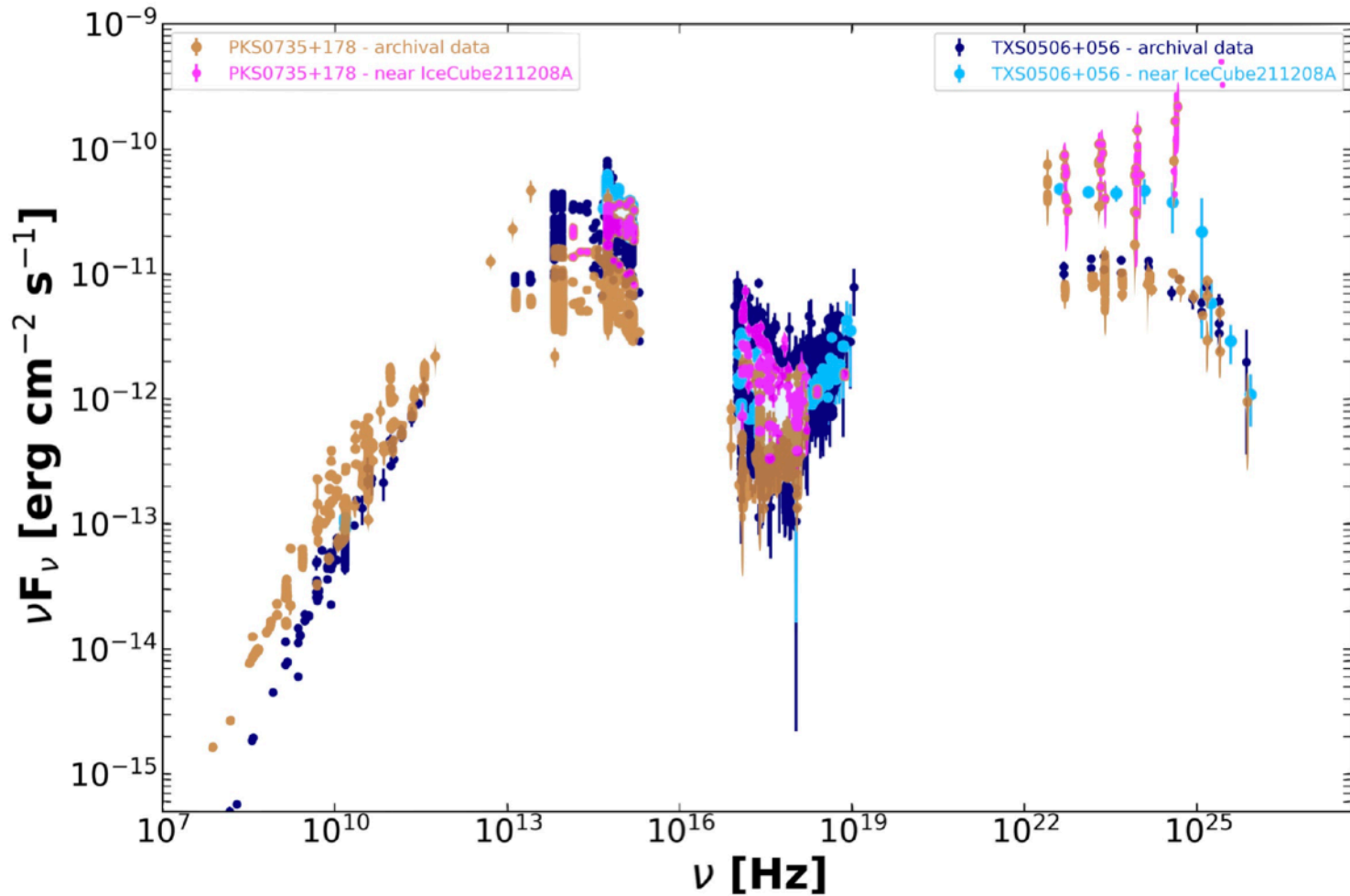
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IBL@z=0.65? (>0.42) and IC211208A:

- 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.  $2.85\sigma$  ([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

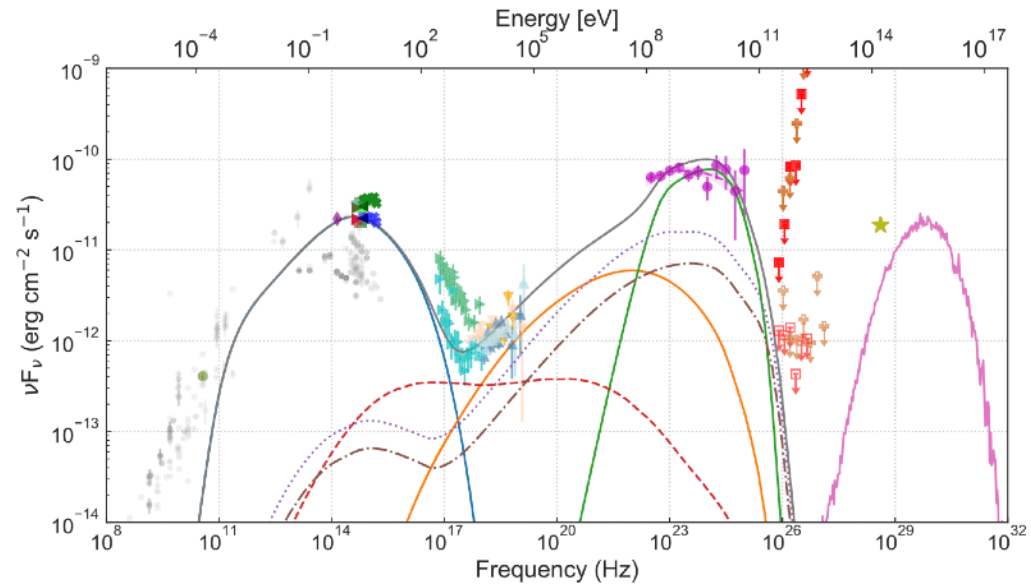
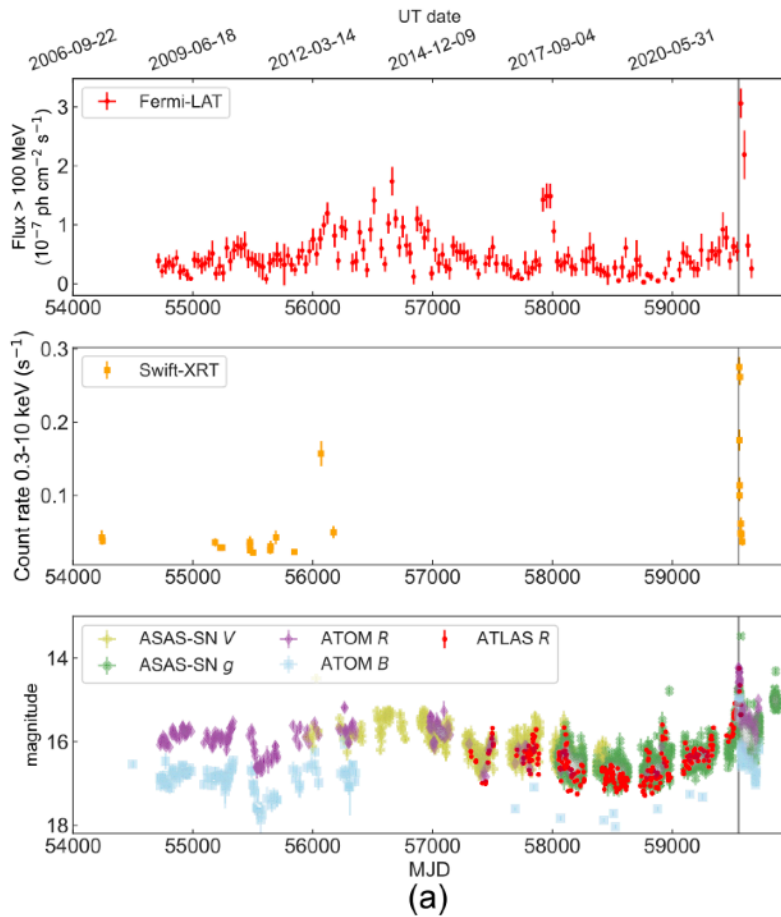
# PKS 0735+178

First theory paper by [Sahakyan et al. 2022](#)



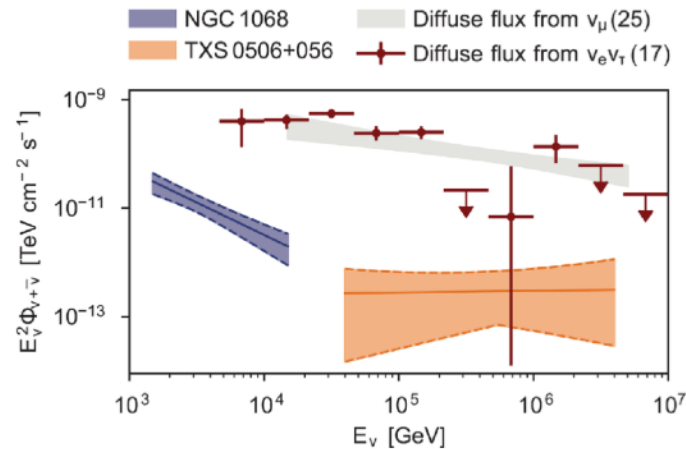
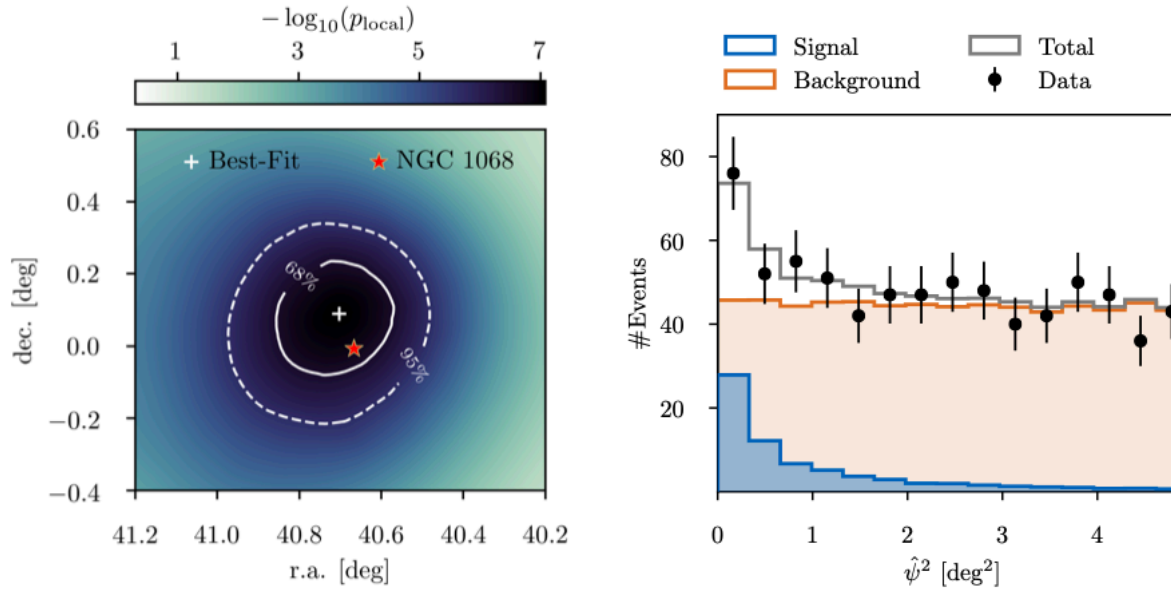
# PKS 0735+178

[Acharyya et al. 2023](#)



# NGC 1068

## 4 $\sigma$ excess from the Seyfert galaxy NGC 1068

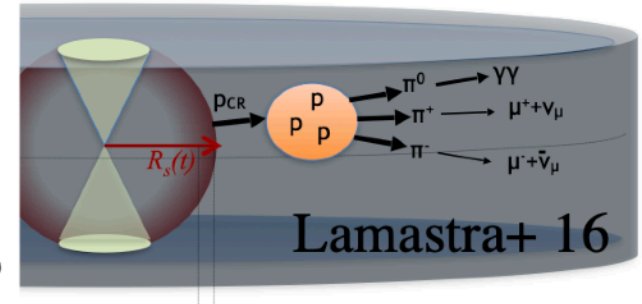


[IceCube et al. 2022](#)

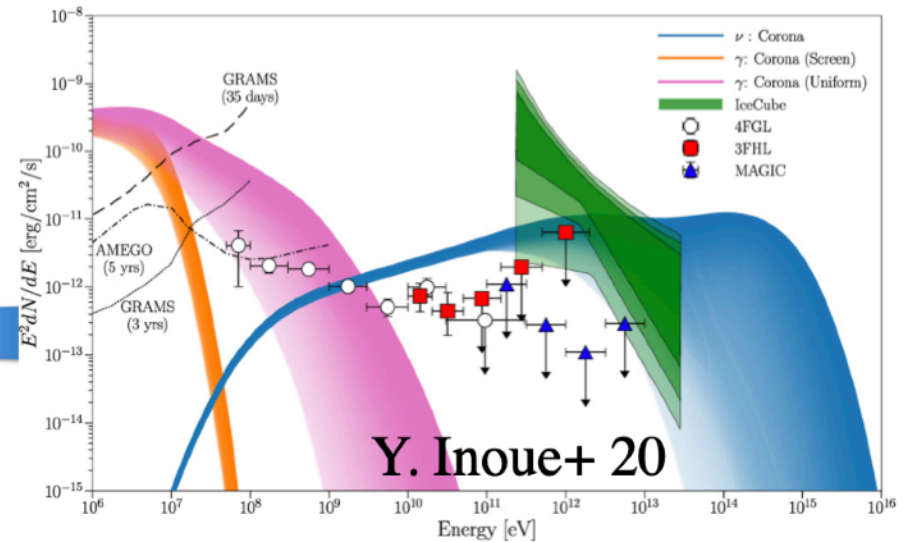
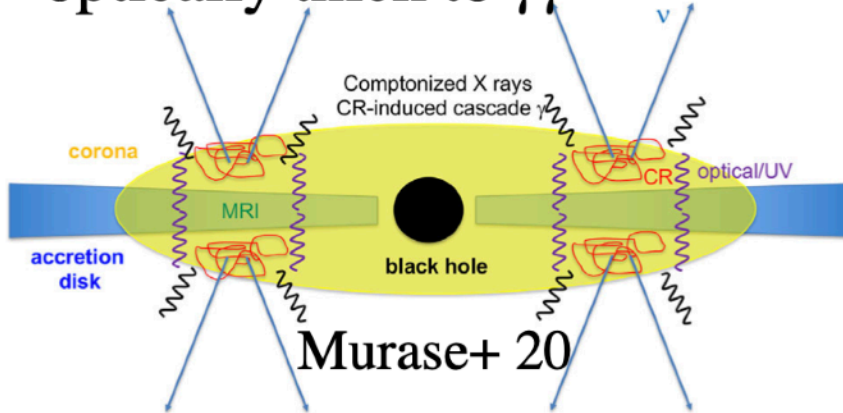
# NGC 1068 (AGN) models

## neutrino + gamma from NGC 1068: AGN origin?

AGN wind kpc-scale ext. shock?  
 -> ruled out by TeV upper limits



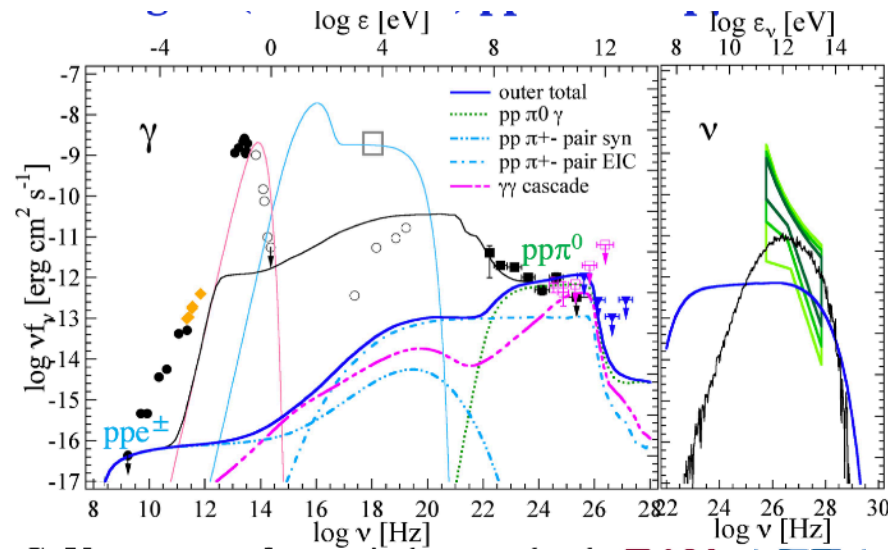
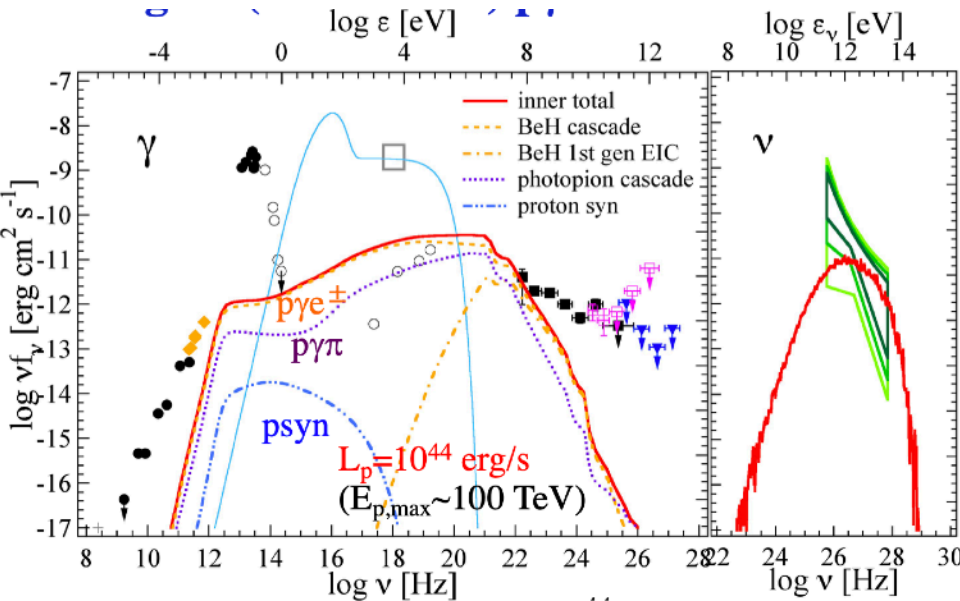
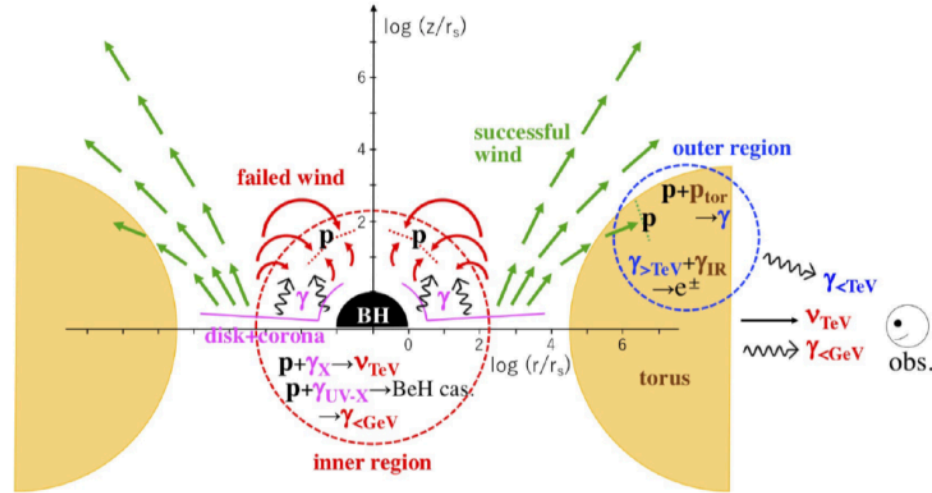
hot coronal regions of accretion disks?  
 pp+py in compact regions  
 optically thick to  $\gamma\gamma$



Slides by S. Inoue (Gamma 2022), submitted, see arXiv

# NGC 1068 (AGN) models

Slides by S. Inoue (Gamma 2022), submitted, see arXiv



# CONCLUSIONS

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- 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