Probing AGN jets with high-energy neutrinos

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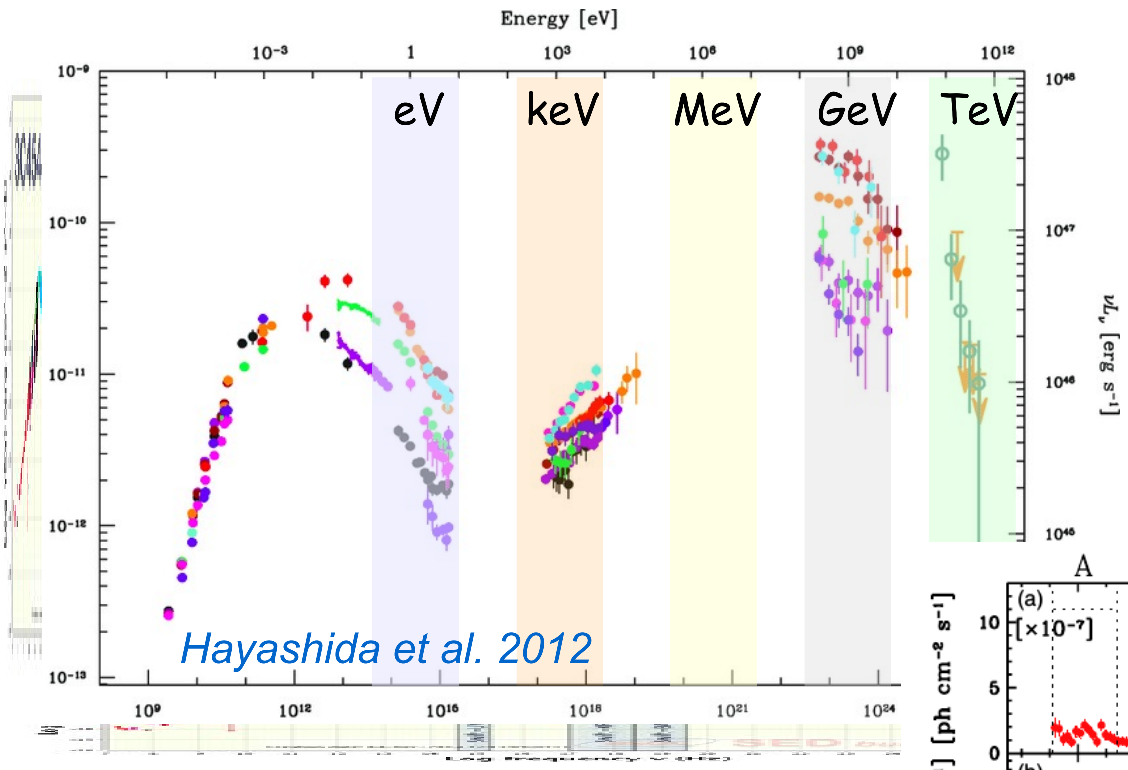
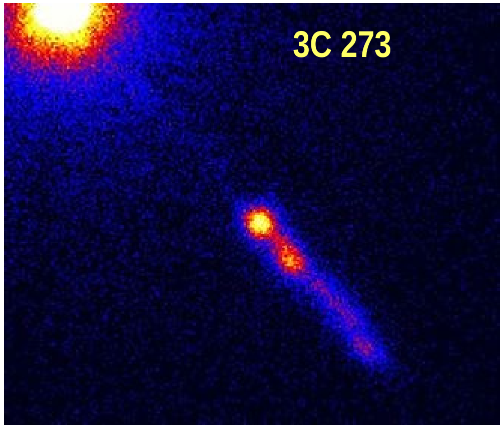
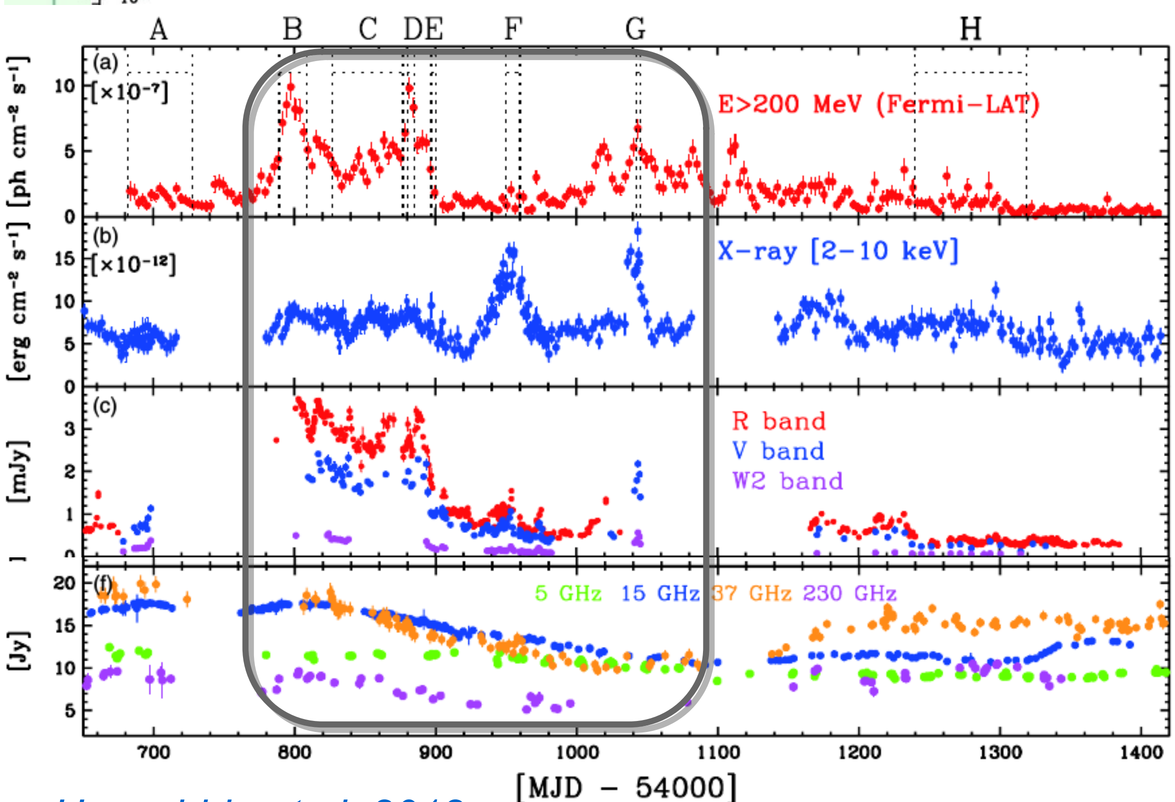
Jet emission





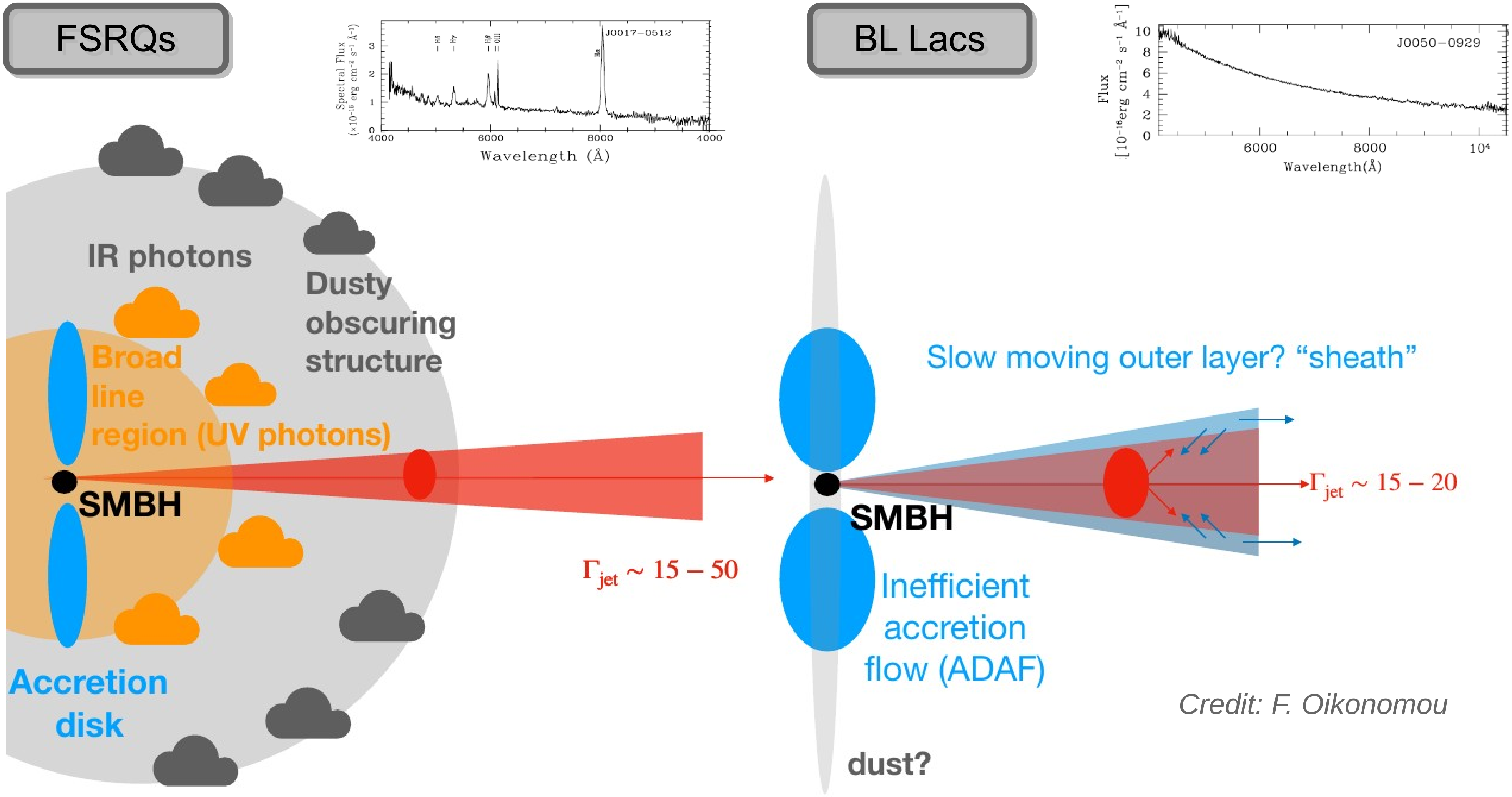
Credit: Chandra X-ray observatory



Hayashida et al. 2012

- Multi-wavelength emission.
- Double-humped photon spectra.
- Flux variability on multiple timescales (min to months).
- Flares across the EM spectrum (not always correlated!)

Blazar classes

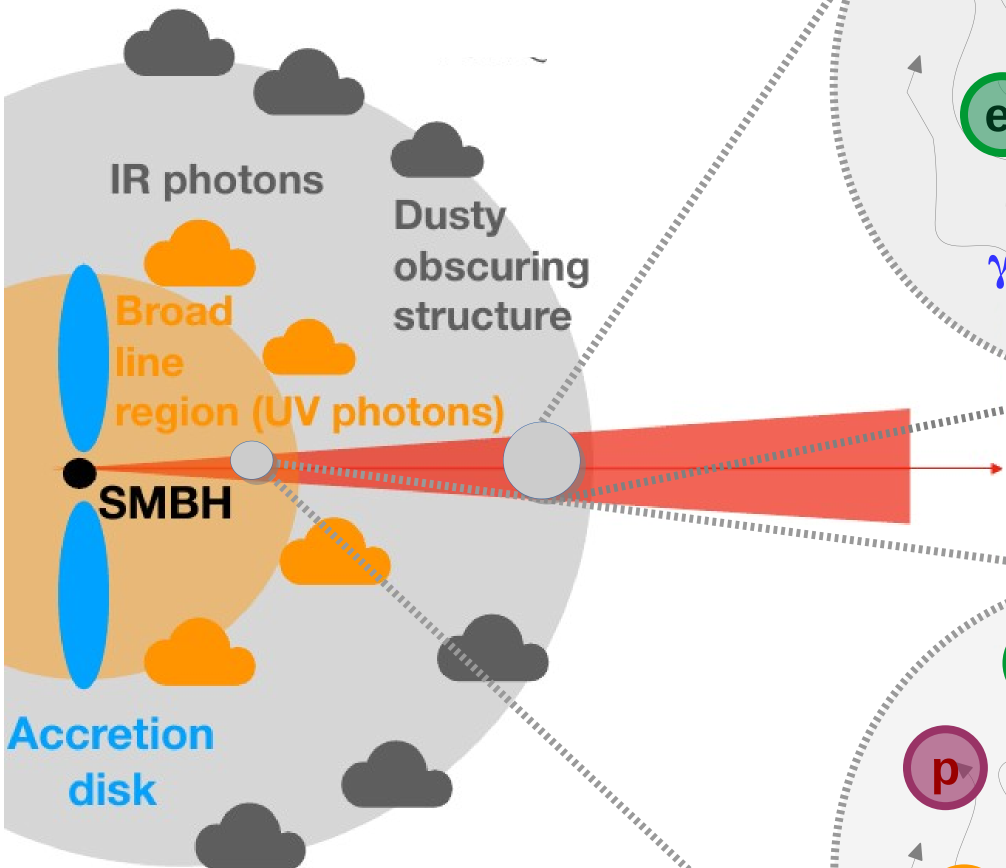


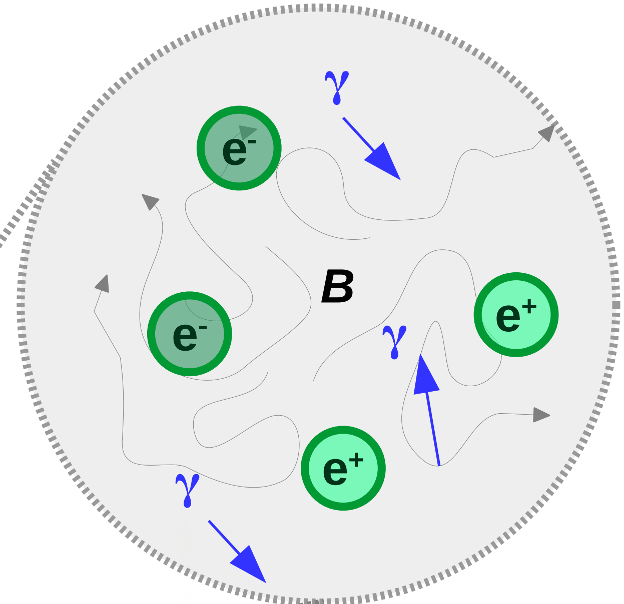
- Broad emission lines in optical spectra
- Radiatively efficient disks
- Accretion at Eddington rates
- High jet power & γ-ray luminosity

- Weak or absent broad emission lines in optical spectra
- Radiatively inefficient disks
- Accretion at sub-Eddington rates
- Low jet power & γ-ray luminosity

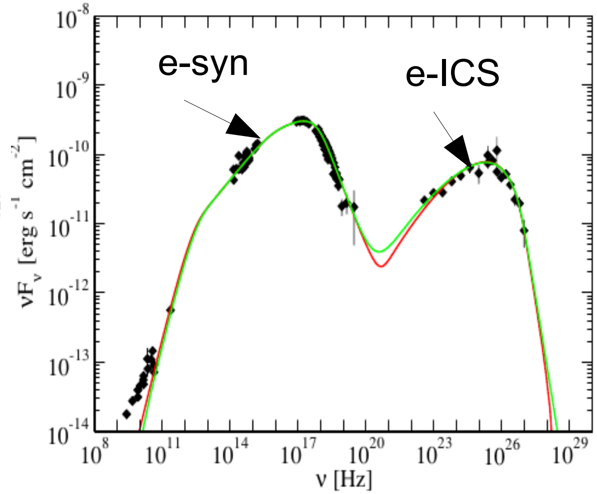
One-zone emission models

e.g., Maraschi et al. 1992; Dermer & Schlickeiser 1993; Sikora et al. 1994; Mastichiadis & Kirk 1995; Bloom & Marscher 1996; Tavecchio et al. 1998; Boettcher & Dermer 1998 +++

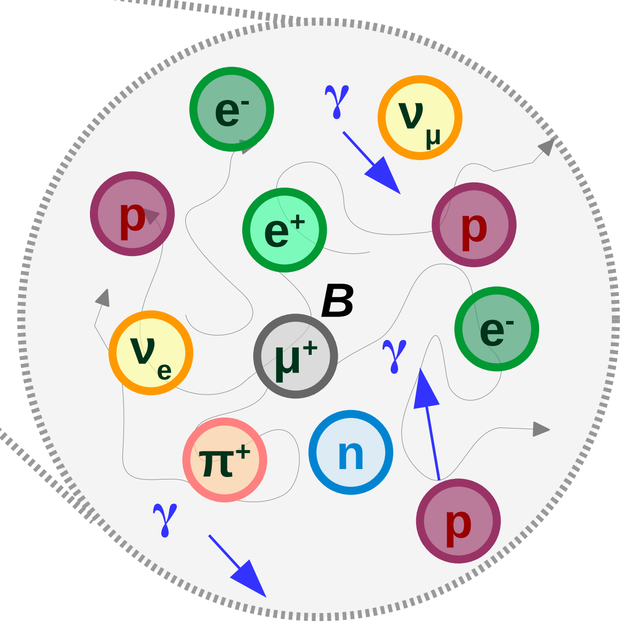




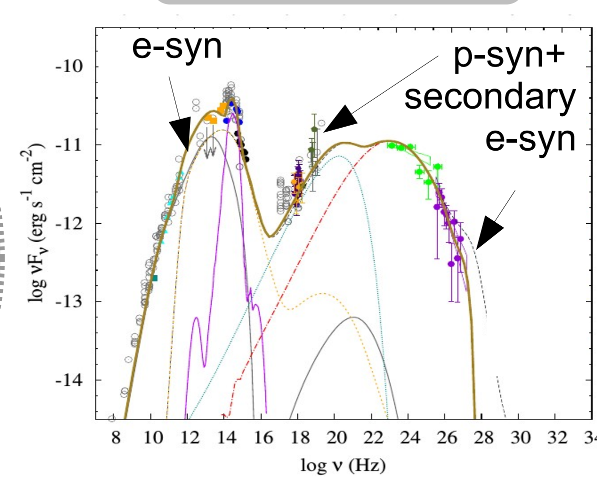
Leptonic



or



Leptohadronic



e.g., Mannheim & Biermann 1992; Mannheim 1993; Aharonian 2000; Muecke & Protheroe 2001; Boettcher et al. 2013; Petropoulou et al. 2015 +++

Open questions

Astro2020 Science White Paper

Multi-Physics of AGN Jets in the Multi-Messenger Era

Thematic Areas: ☑ Multi-Messenger Astronomy and Astrophysics

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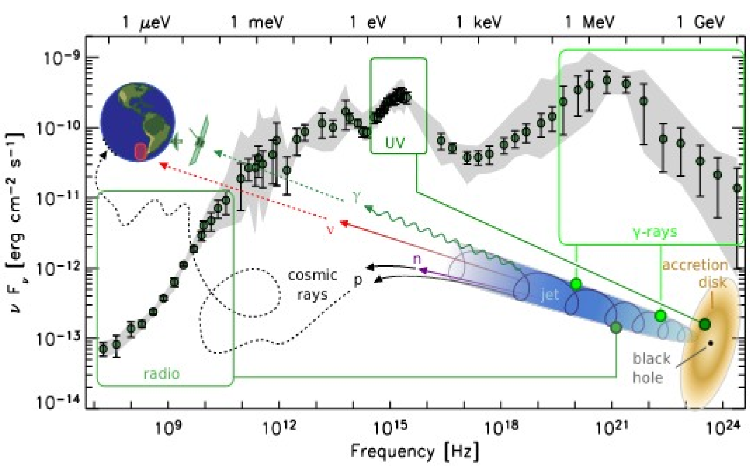
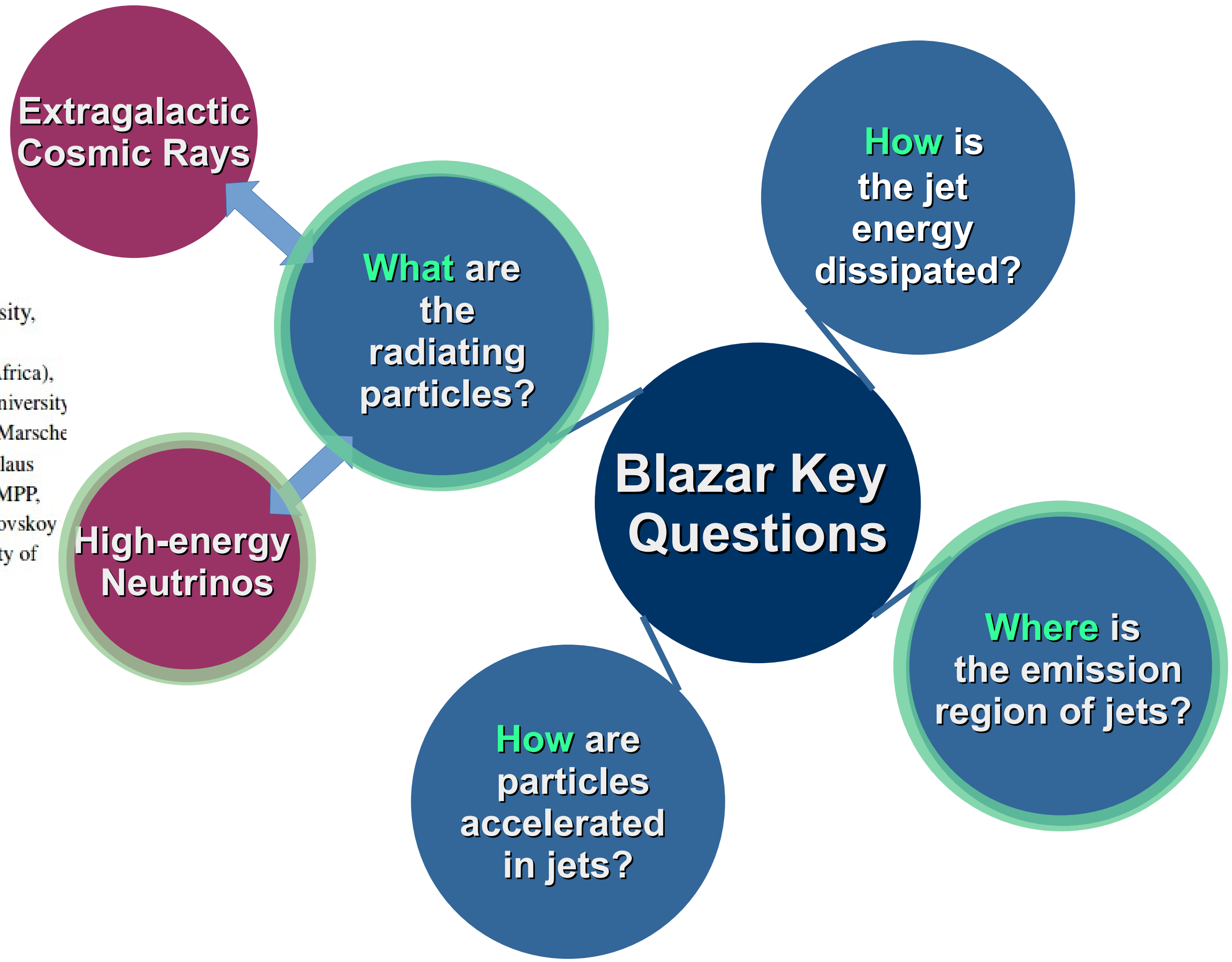




ADS link

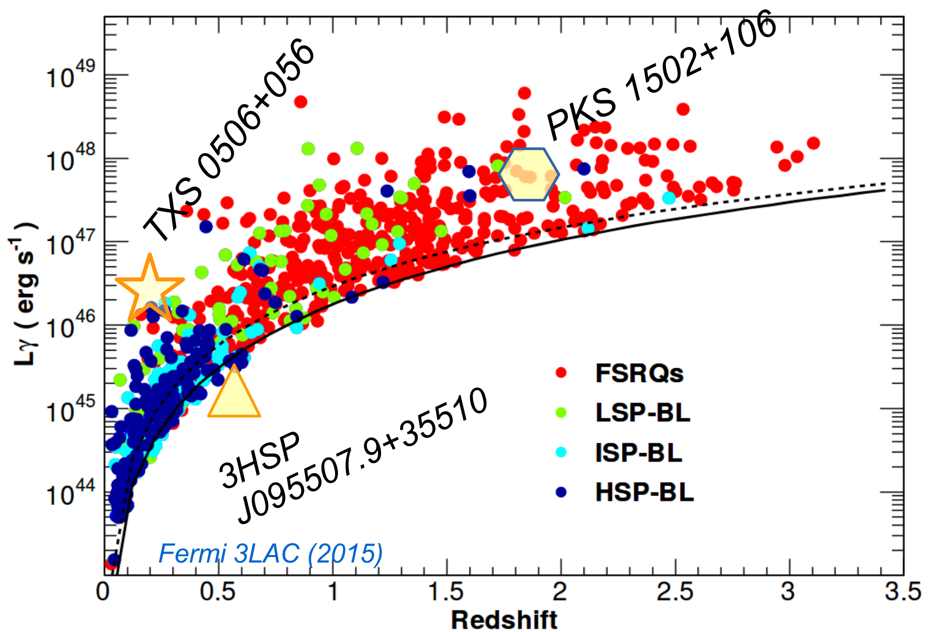
Case studies

- **TXS 0506+056 / IceCube-170922A** *(IceCube Collaboration 2018a)*
  - Masquerading BL Lac with weak BLR emission *(Padovani et al. 2019)*
  - Neutrino detected during a multi-wavelength flare in 2017

- **TXS 0506+056 / 2014-15 Neutrino Excess** *(IceCube Collaboration 2018b)*
  - Neutrino excess detected during a period of low activity in γ-rays

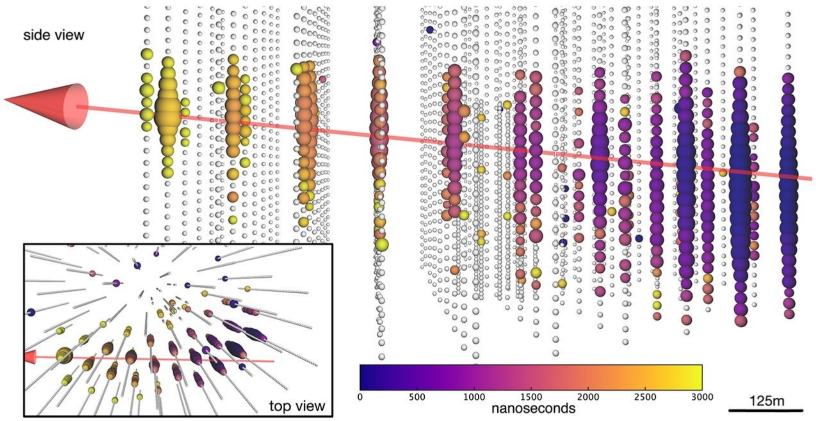
- **PKS 1502+106 / IceCube-190730A** *(Franckowiak+2020)*
  - FSRQ with strong BLR emission
  - Among the 15 brightest sources in the Fourth Fermi-LAT AGN catalog (4LAC)
  - Neutrino detected during period of low activity in γ-rays

- **3HSP J095507.9+35510 / IceCube-200107** *(Giommi+2020; Paliya+2020)*
  - BL Lac without detectable BLR emission and E_{pk} > 1 keV
  - Neutrino detected 1 day prior to a hard X-ray flare in 2020
  - No γ-ray flare detectable at the neutrino detection time

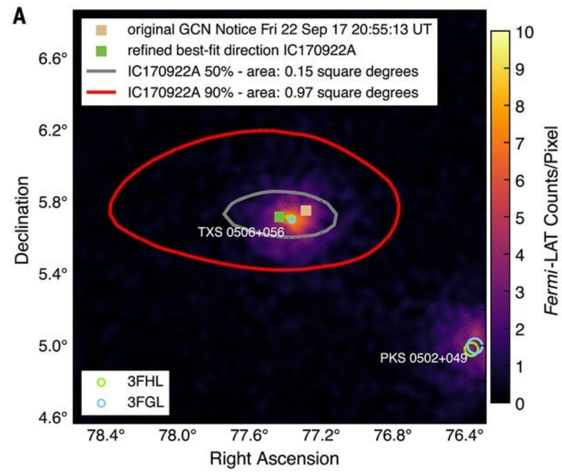


The multi-messenger flare of TXS 0506+056

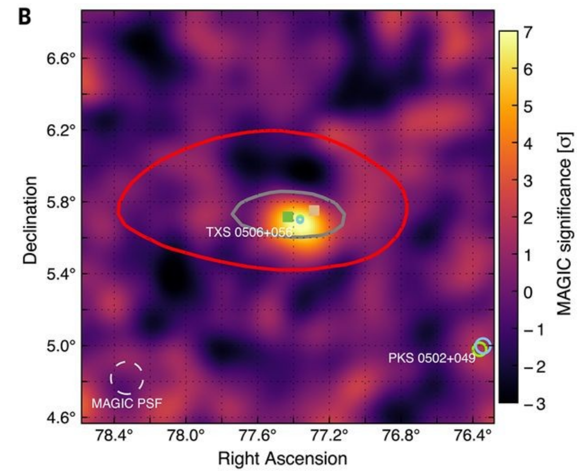
IC-170922A: a 290 TeV neutrino

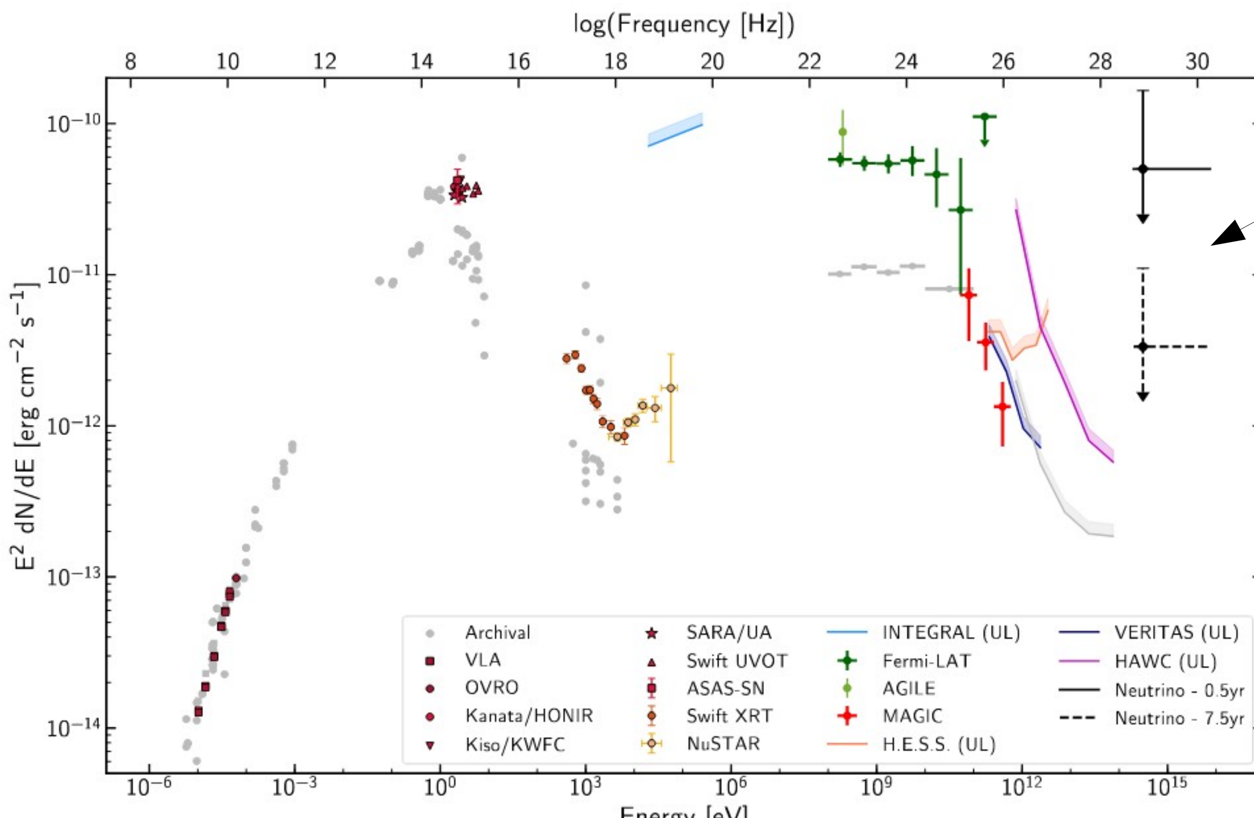


Fermi-LAT



MAGIC

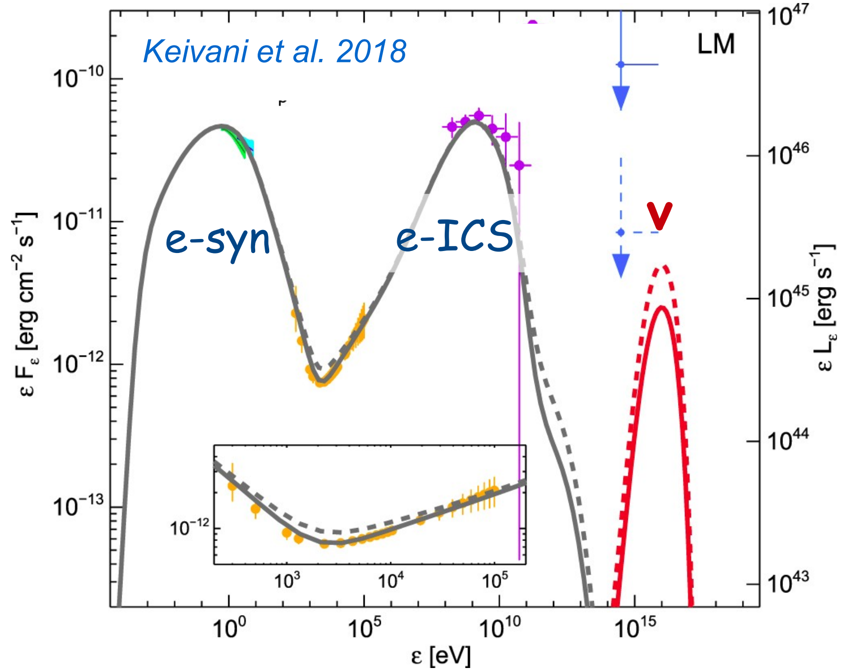


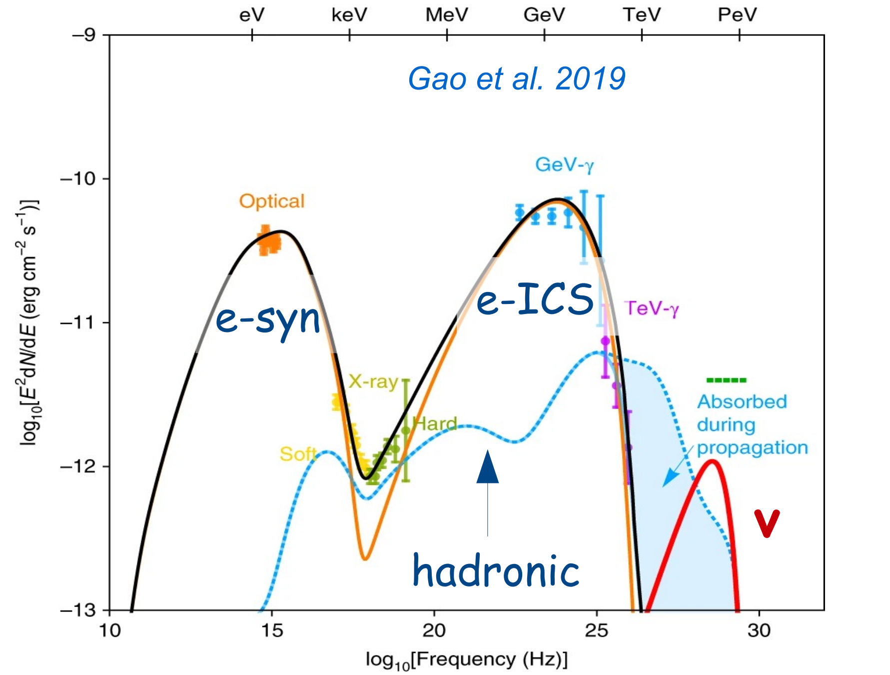


Neutrino flux

IceCube Colloboration et al. 2018a

Modeling results of the 2017 flare

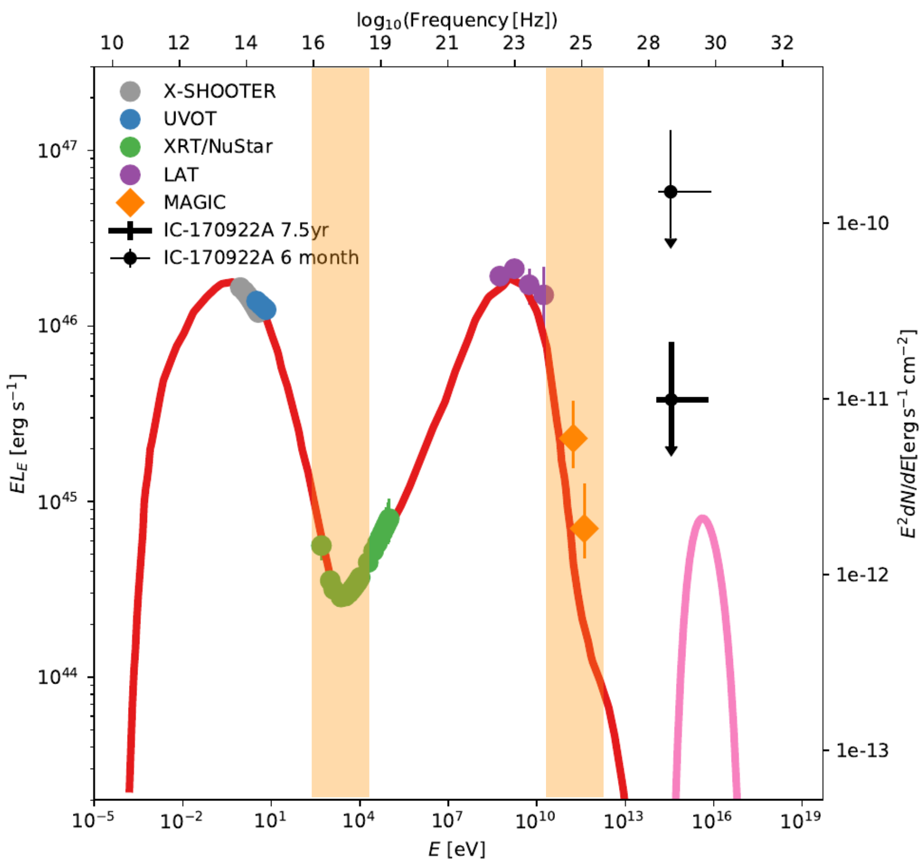


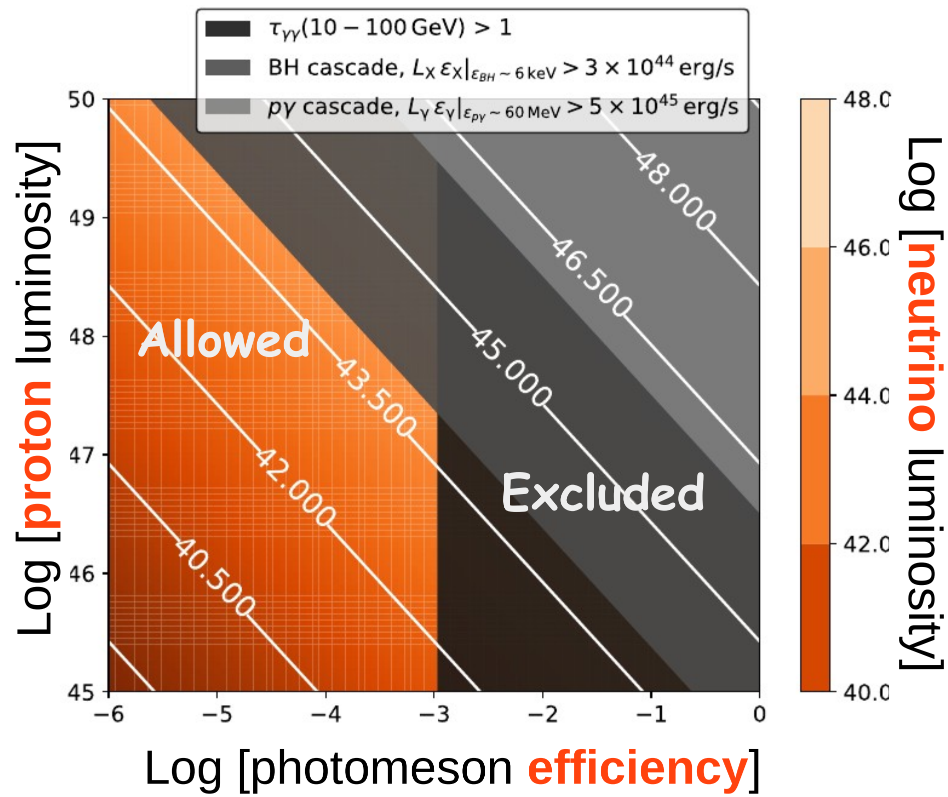


- TXS 0506+056 is unlikely to be an UHECR + PeV neutrino source.
- Modeling of TXS 0506+056/IC-170922A requires a leptonic origin of γ-rays *(Ansoldi et al. 2018, Keivani et al. 2018, Cerruti et al. 2019, Gao et al. 2019)*
- EM emission from the hadronic component is hidden below the leptonic component *(e.g. Keivani et al. 2018, Gao et al. 2019)*
- Number of muon neutrinos per yr < 1, statistically consistent with the detection of 1 event in 0.5 yr *(Strotjohann et al. 2019)*.

Maximum neutrino luminosity in one-zone models

Murase, Oikonomou, MP 2018



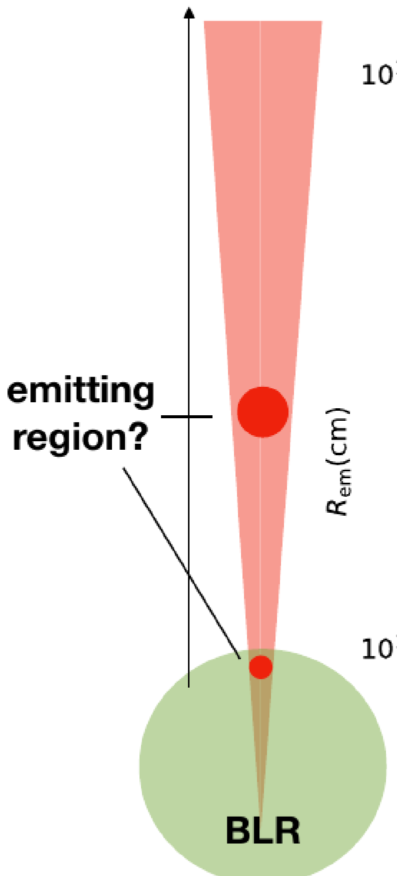


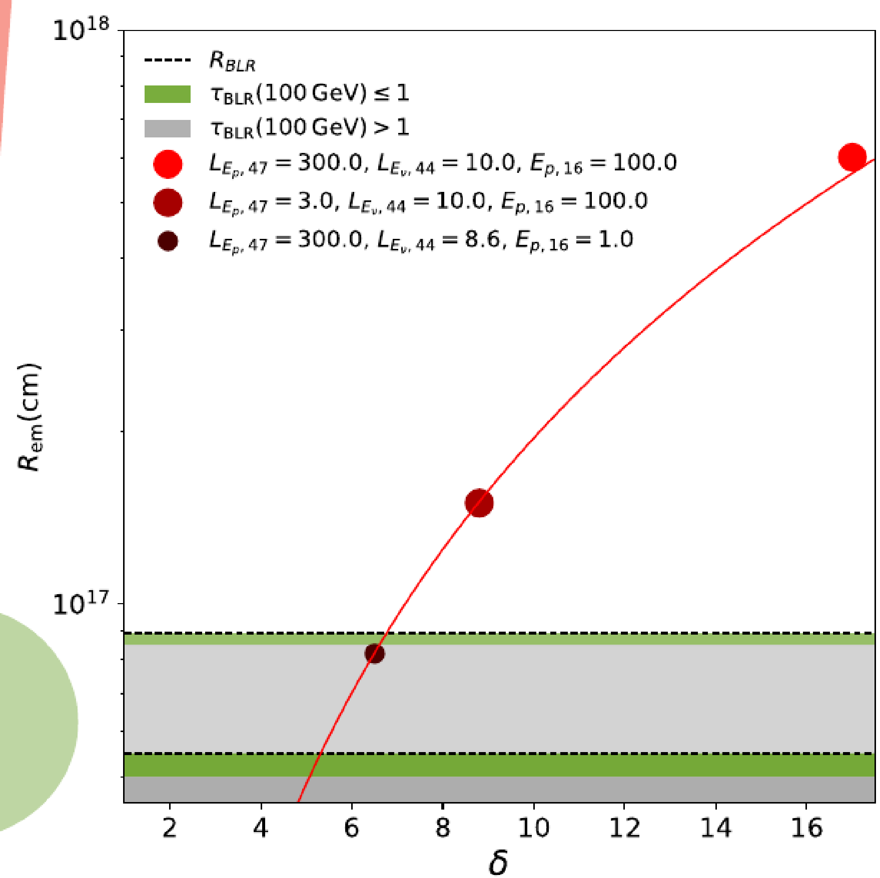
Maximum all-flavor neutrino flux:

$$E_\nu L_{E_\nu} \lesssim 10^{45}\ \mathrm{erg\ s^{-1}}\ \frac{L_{\mathrm{X,lim}}}{3\times10^{44}\ \mathrm{erg\ s^{-1}}}\ \frac{0.1}{f_x}$$

Location of the emitting region of the 2017 flare

TXS 0506+056 is a “masquerading” BL Lac → weak BLR emission (L_{BLR} ~(3-8)x10^{43} erg/s) swamped by the jet emission *(Blandford & Rees 1978, Georganopoulos & Marscher 1998, Giommi & Padovani 2013, Padovani et al. 2019)*

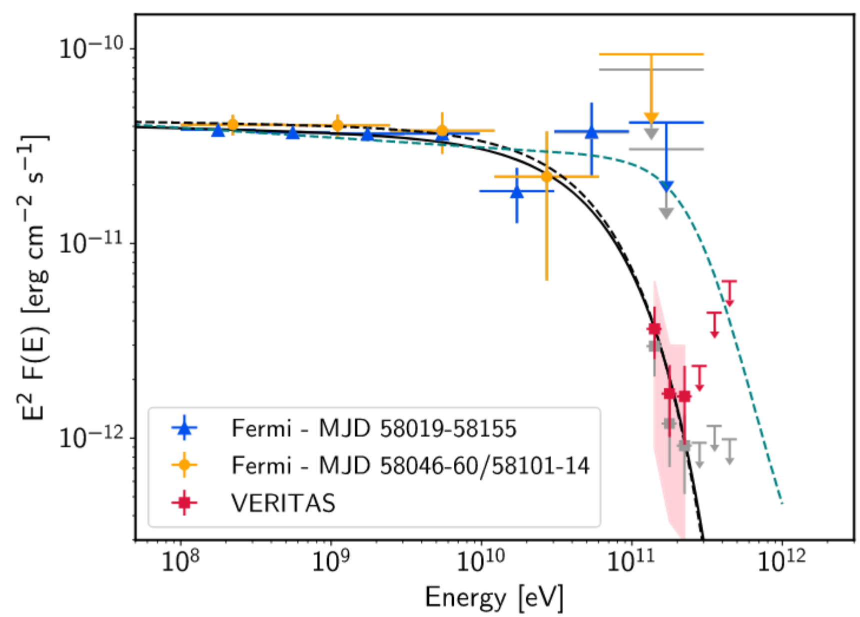




$$E_\nu L_{E_\nu} \lesssim 10^{45}\ \mathrm{erg\ s^{-1}}\ \frac{L_{\mathrm{X,lim}}}{3\times 10^{44}\ \mathrm{erg\ s^{-1}}}\ \frac{0.1}{f_x}$$

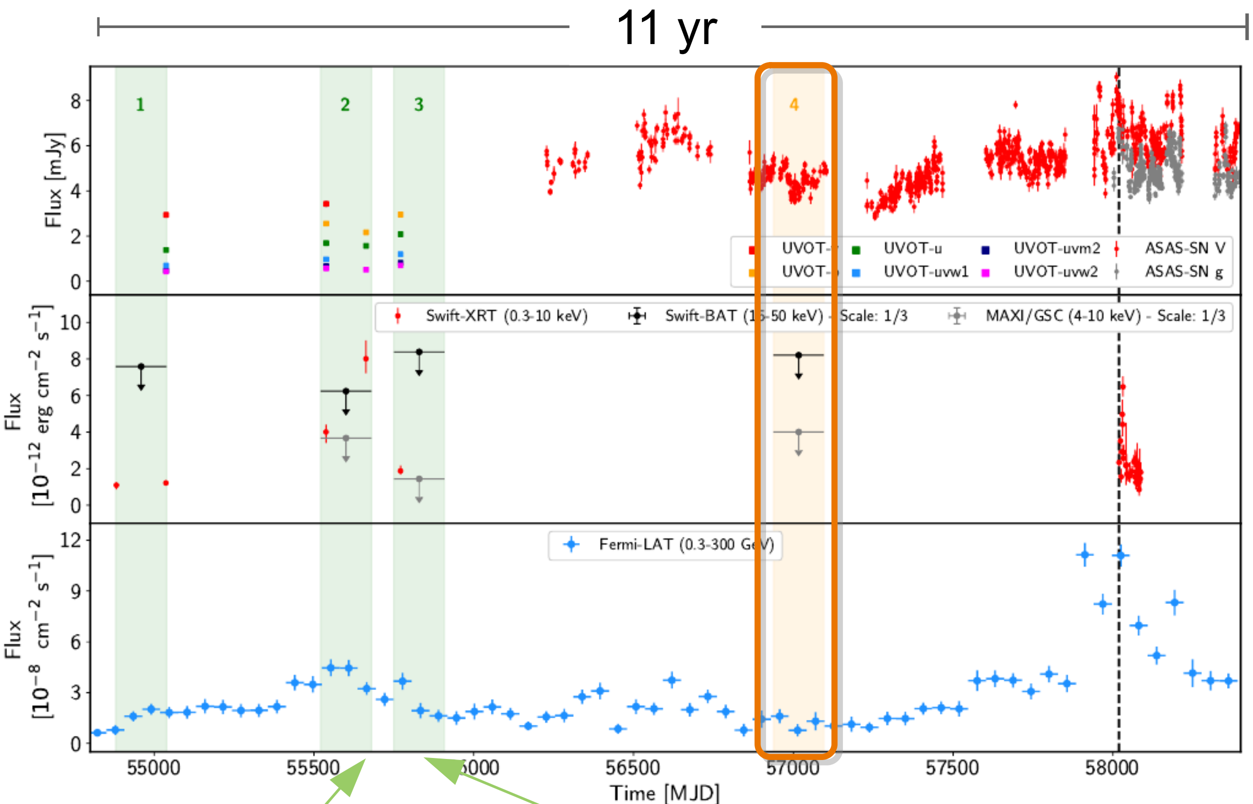
Padovani et al. 2019

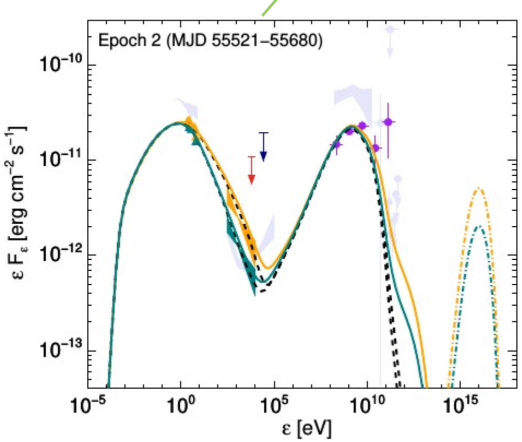
Veritas Collaboration (2018)

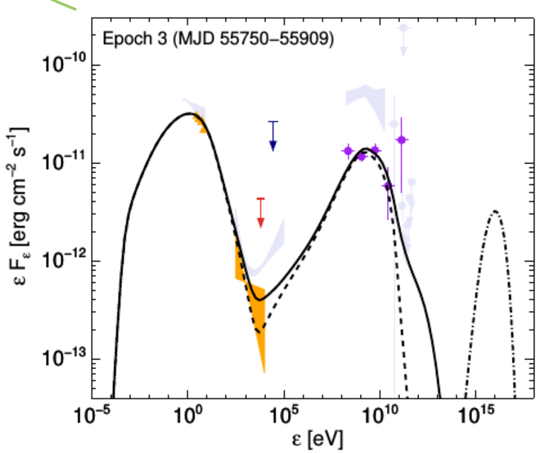


- γγ opacity constraints allow the emitting region to be at the outer edge of the BLR
- Maximum neutrino luminosity independent of the location of emitting region along the jet

Multi-epoch modeling of TXS 0506+056





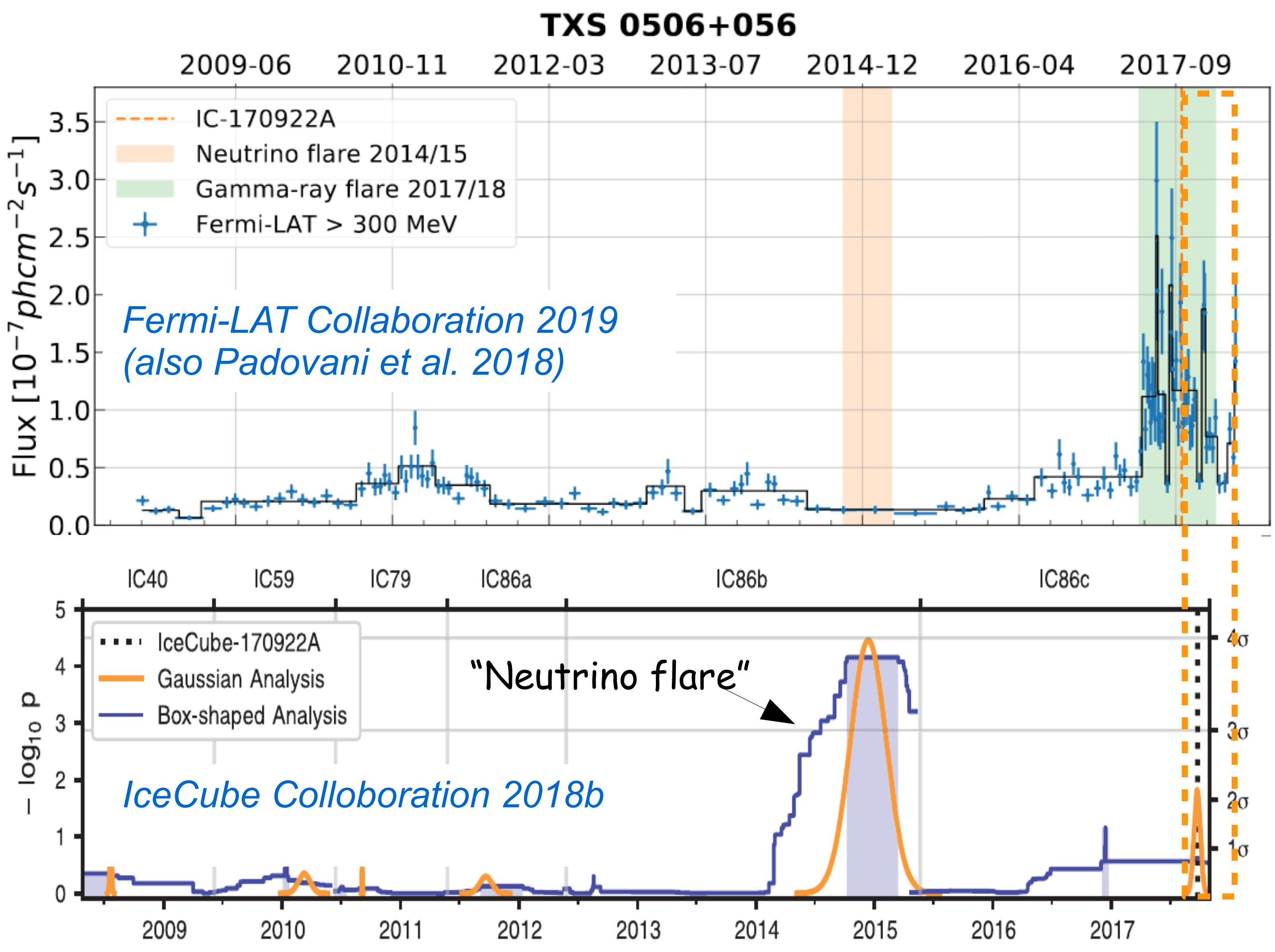


- Multi-epoch obs can be explained by Syn+ICS of electrons with small changes in their energy distribution (e.g. power-law index, electron luminosity)
- Upper limit of $\sim 0.4 - 2$ muon neutrinos in 10 yr of IceCube obs
- IceCube-170922A $\rightarrow$ upper fluctuation from the average neutrino rate ?

Epoch	$F_{\nu+\bar{\nu}}^{(\max)}$ [erg cm^{-2} s^{-1}]	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}$ [yr^{-1}]
1	8.8×10^{-13}	0.04
$2^\dagger$	7.3×10^{-12}	0.2
$2^\ddagger$	3.0×10^{-12}	0.1
3	4.6×10^{-12}	0.2
4	3.3×10^{-12}	0.1
2017	3.6×10^{-12}	0.1

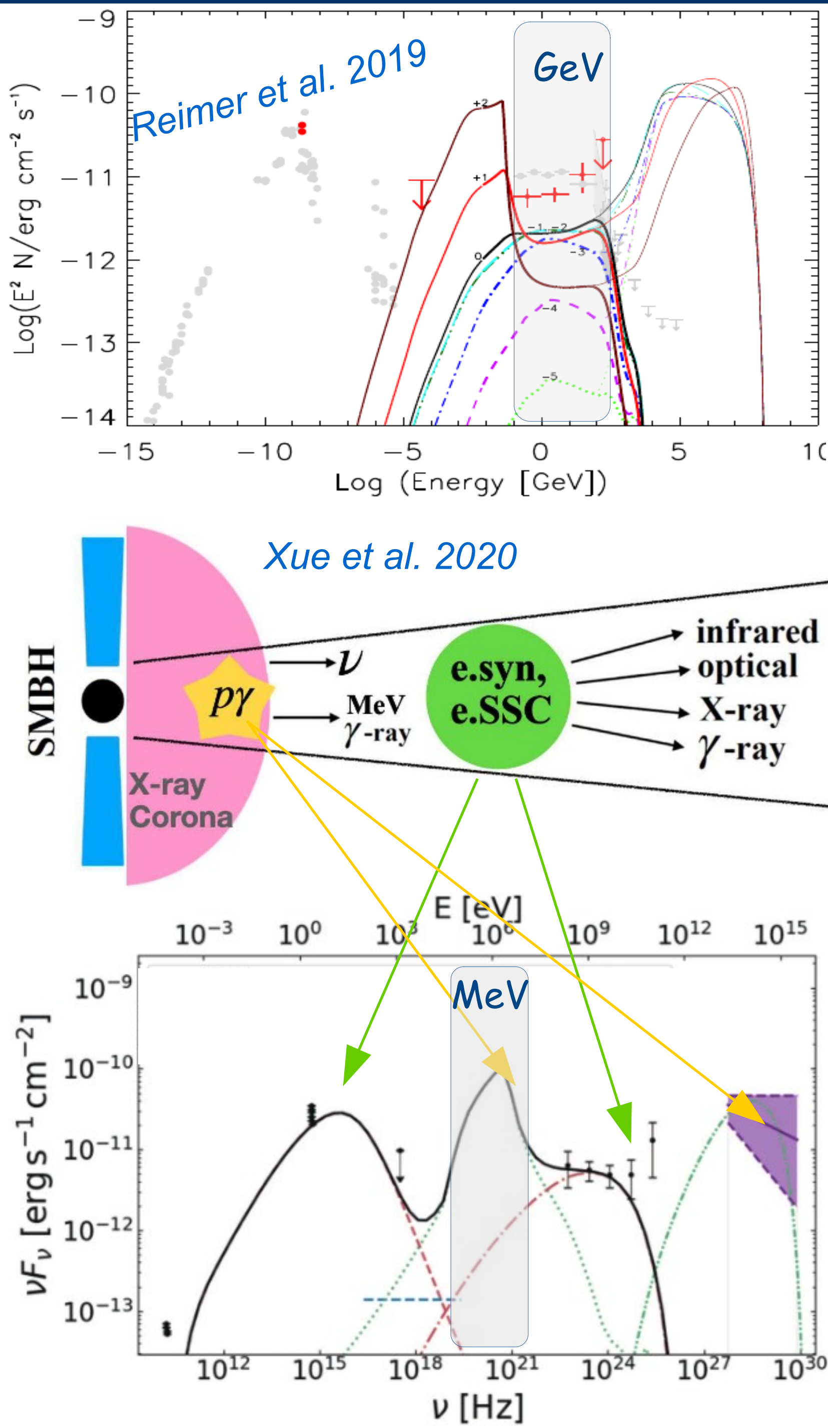
MP, Murase, Oikonomou et al. 2020

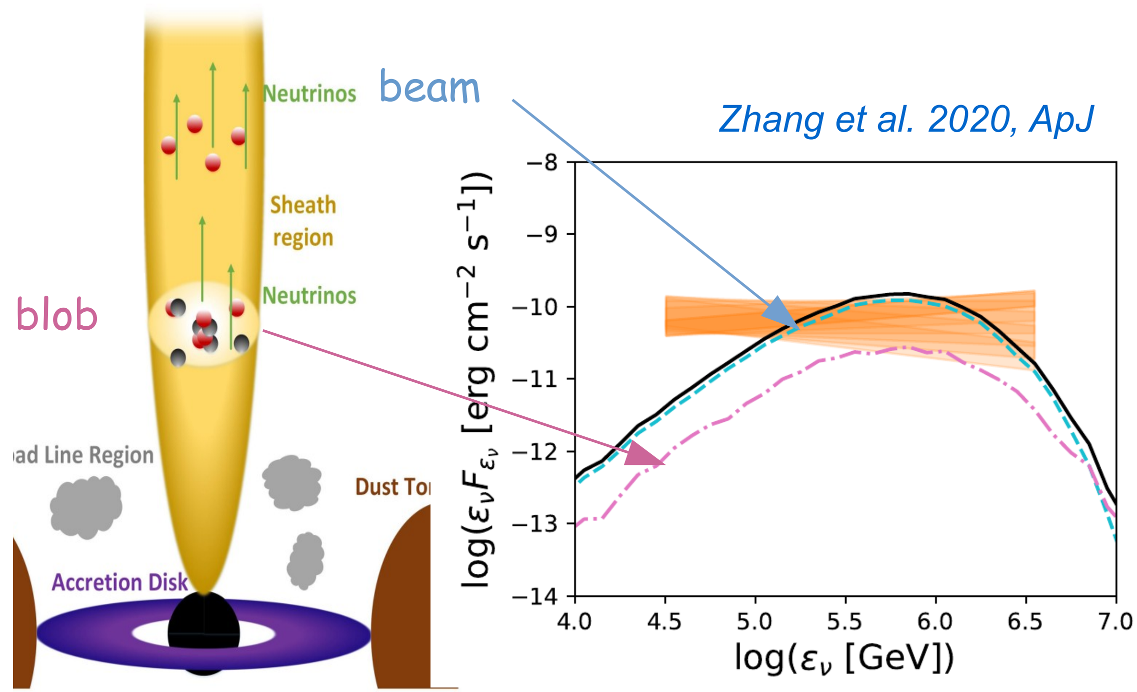
The TXS 0506+056 neutrino excess



- 13 +/- 5 neutrinos above atmospheric background over ~6 months (~3.5 σ)
- Neutrino luminosity (averaged in ~6 months) 4 times larger than average γ-ray luminosity!
- No γ-ray flaring activity in 2014-15. No evidence for flares at other energies either

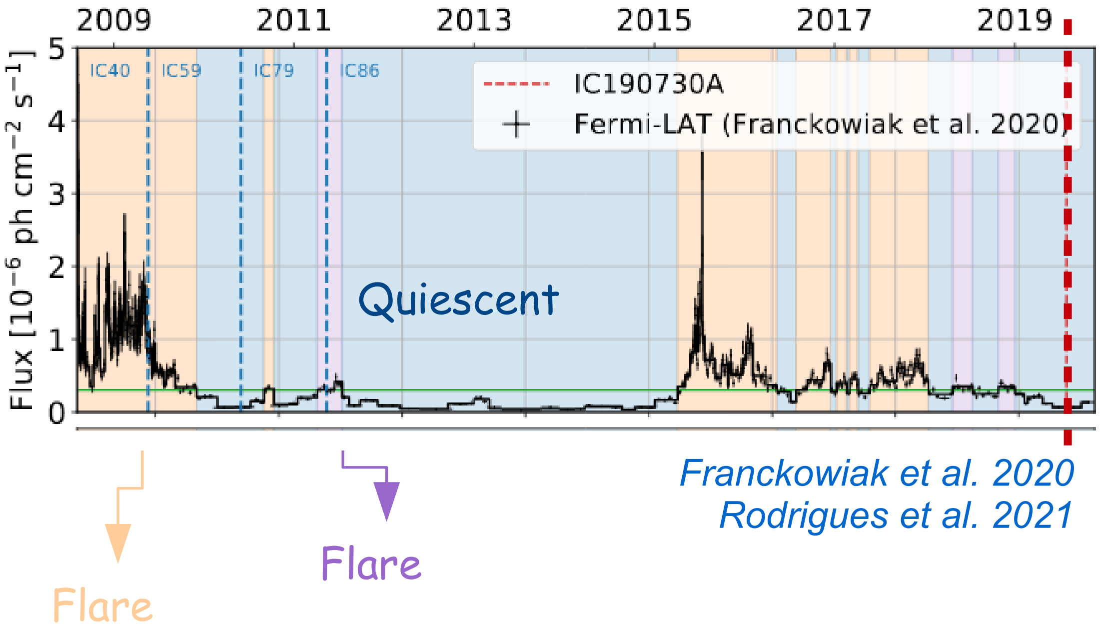
Moving beyond one-zone models …



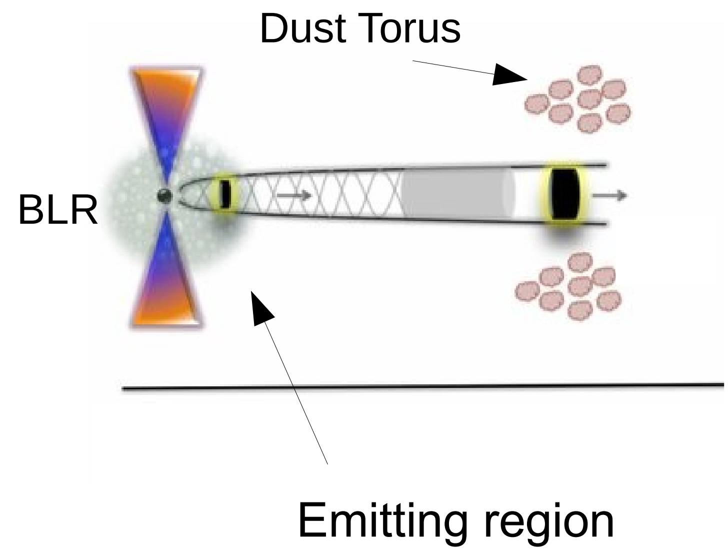


- The blazar observed EM emission is not co-spatial with the neutrino emission.
- Physical conditions in these regions are very different.
- Dense UV or X-ray external photon field is necessary → BUT not directly observed

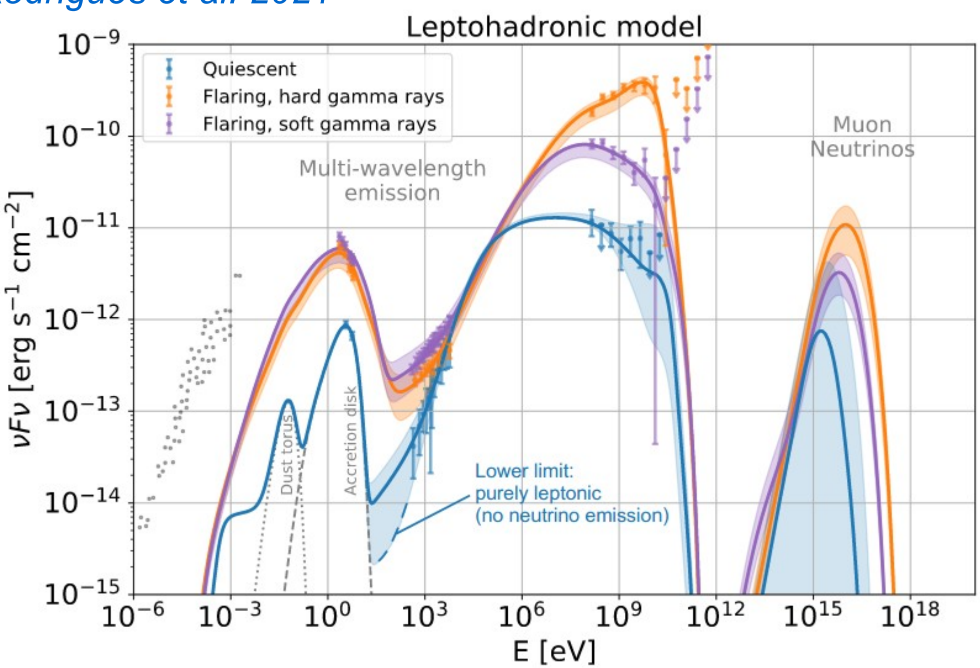
A leptohadronic model of PKS 1502+106



Franckowiak et al. 2020
Rodrigues et al. 2021



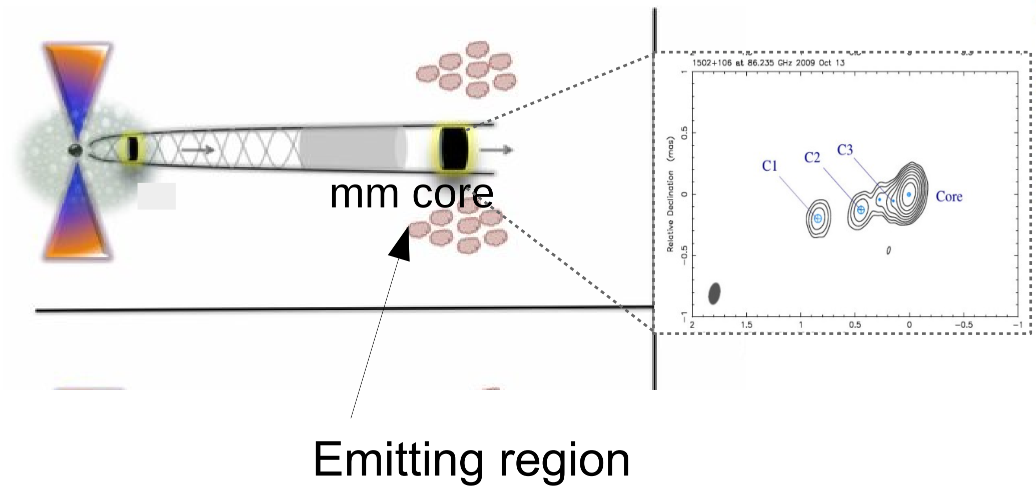
Rodrigues et al. 2021

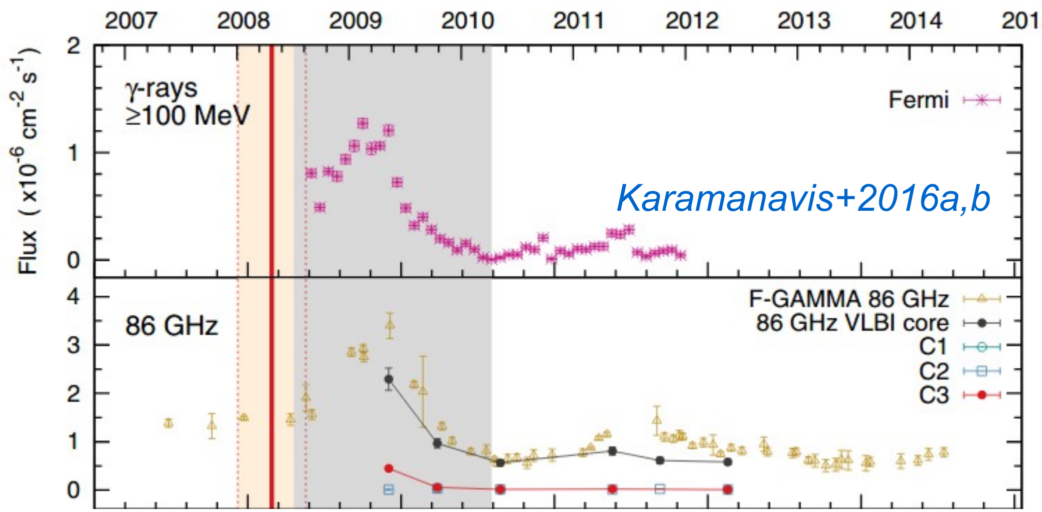


- Flares and “quiescent” emission originate within the BLR
- Leptohadronic model predicts ~ 5-16 muon neutrinos from hard flares and ~1-10 muon neutrinos from quiescent periods in 10 yr (Point Source analysis)
- The 8-yr IceCube Point Source analysis finds zero events *(Aartsen et al. 2019)*

Location of γ-ray flares in PKS 1502+106

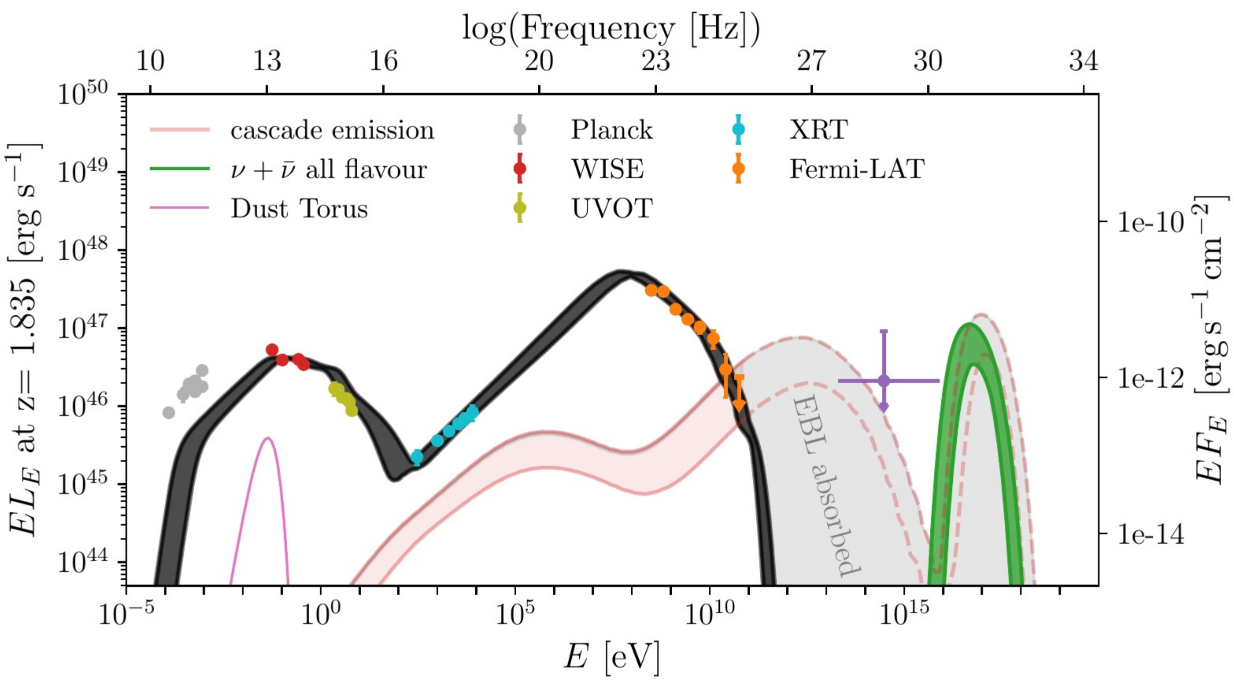
Flares beyond the BLR

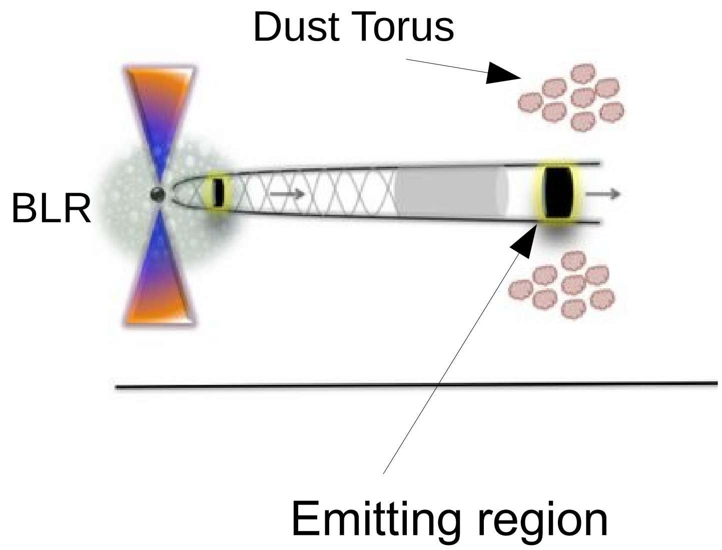




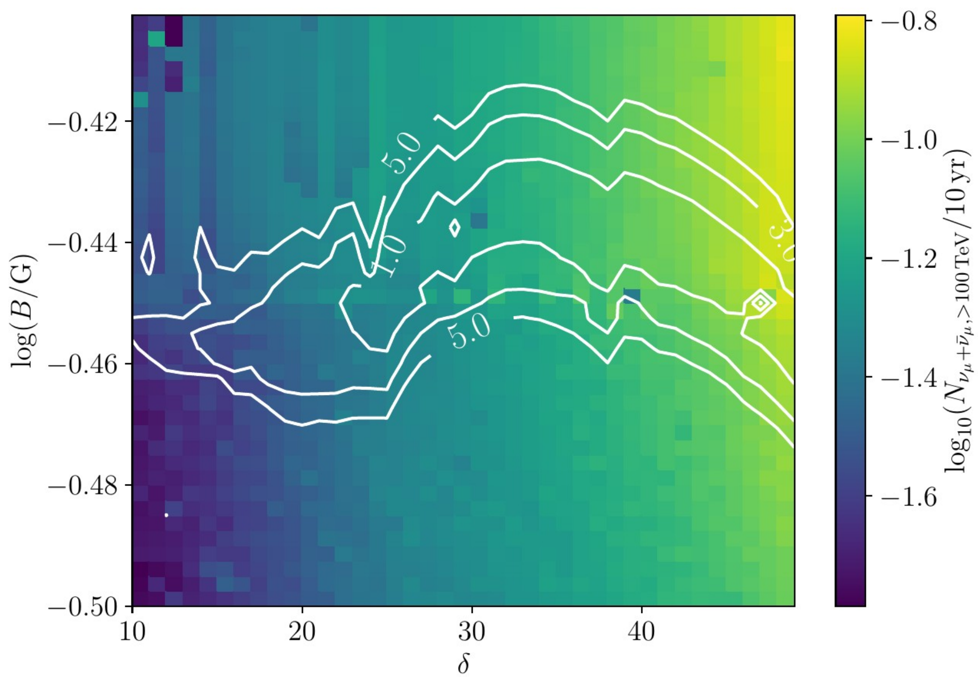
- Evidence for γ-ray flares outside the BLR *(Karamanavis et al. 2016a,b)*
- Time of ejection of knot C3 from core coincides with onset of 2008 γ-ray flare
- Location of γ-ray flaring region outside BLR (~1 – 5 pc)
- Lower neutrino expectation from γ-ray flares than the one found by *Rodrigues et al. 2021* due to de-boosting of BLR photon density

Neutrino production at parsec scales ?



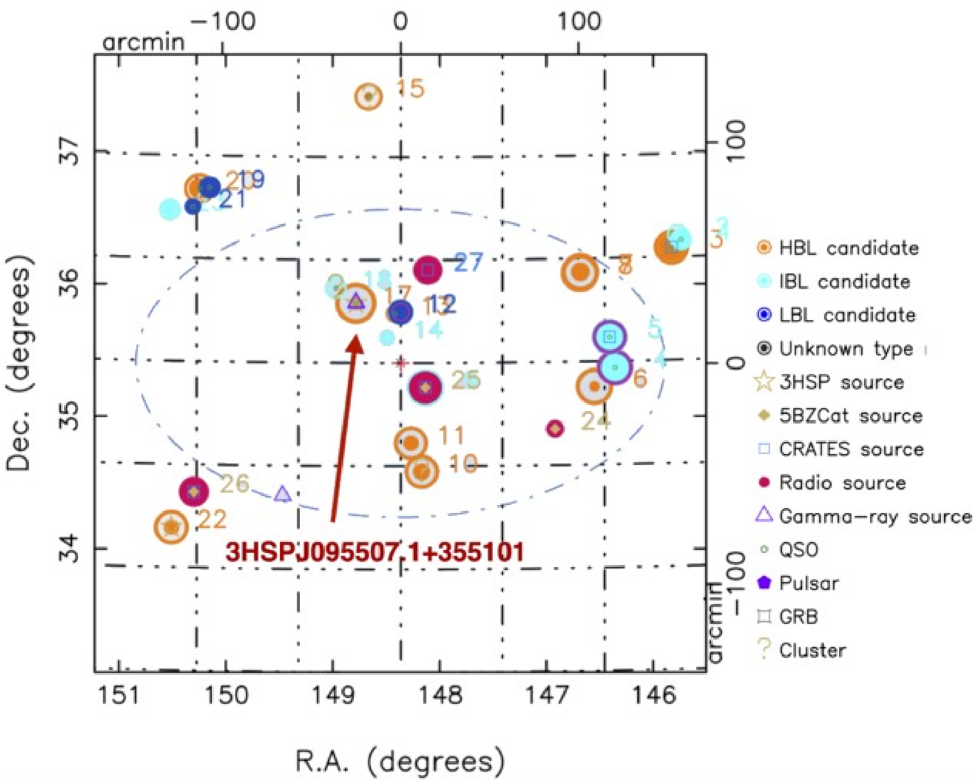


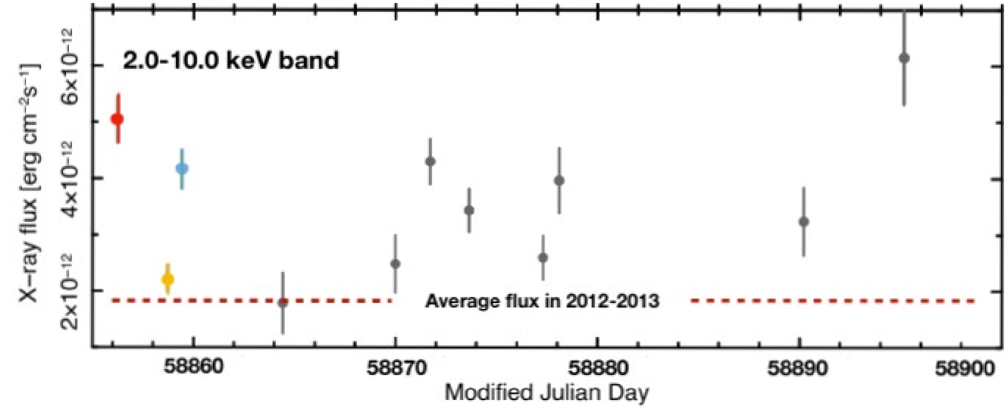
Oikonomou, MP, Murase, submitted



- ~EeV neutrino energies
- Parameter space search performed to find the maximum neutrino contribution
- ~0.1 muon neutrinos in 10 years of IceCube obs→ consistent with 1 neutrino detection
- Similar neutrino predictions as the proton synchrotron model of *Rodrigues et al. 2021* but with lower proton power needed

3HSP J095507.9+35510 / IceCube-200107

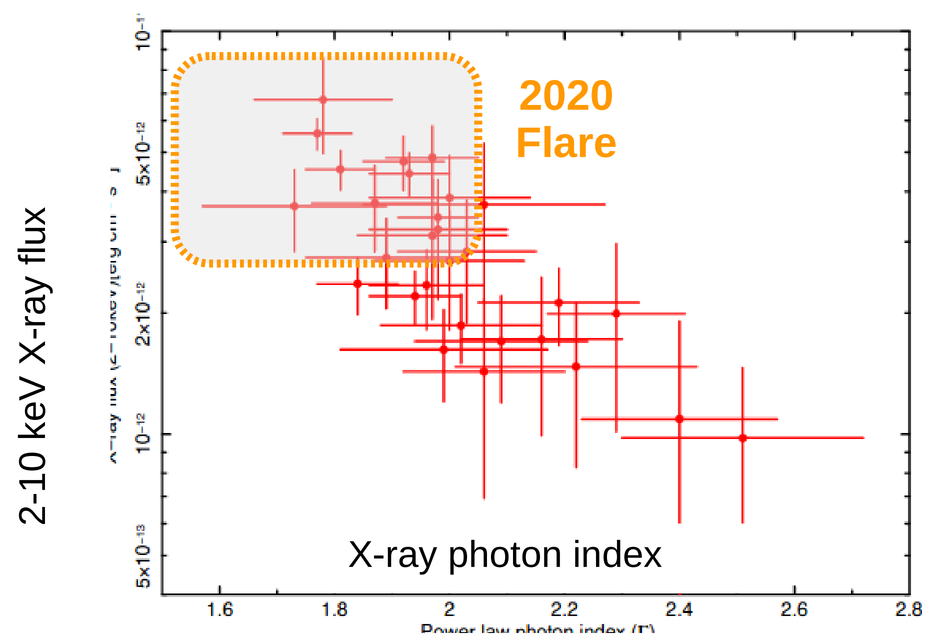




Giommi et al. 2020

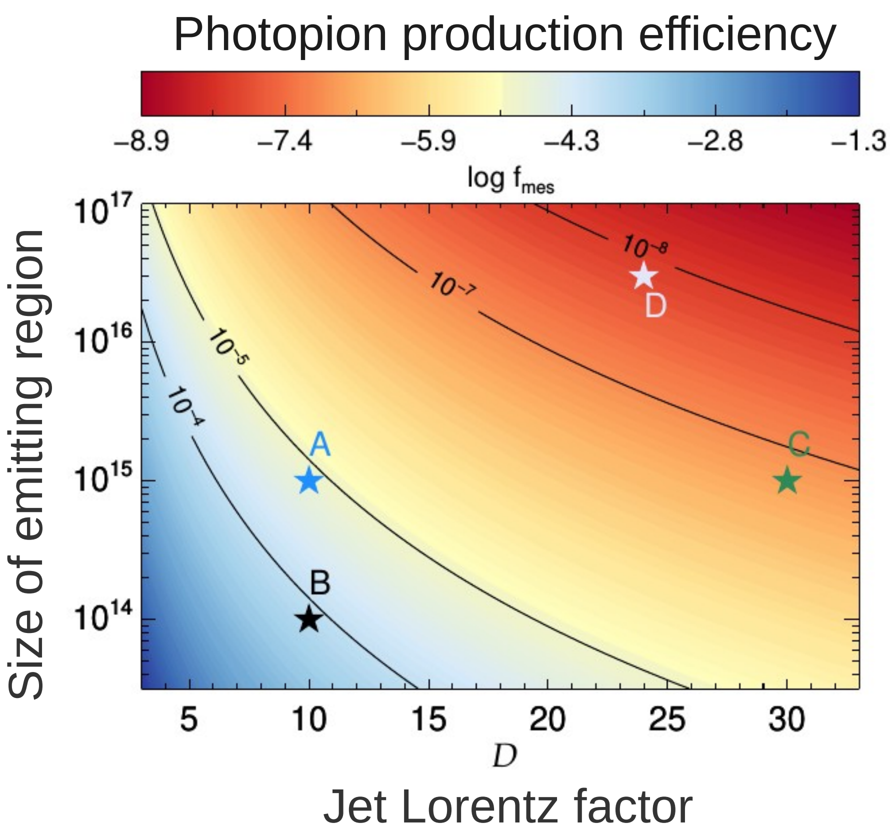
- 3HSP J095507.9+35510 is an extreme blazar at z~0.56 *(Paiano et al. 2020, Paliya et al. 2020)*
- Spatially coincident with IceCube-200107A while undergoing its brightest X-ray flare.
- X-ray flux increased by a factor of ~3 and X-ray spectrum hardened.

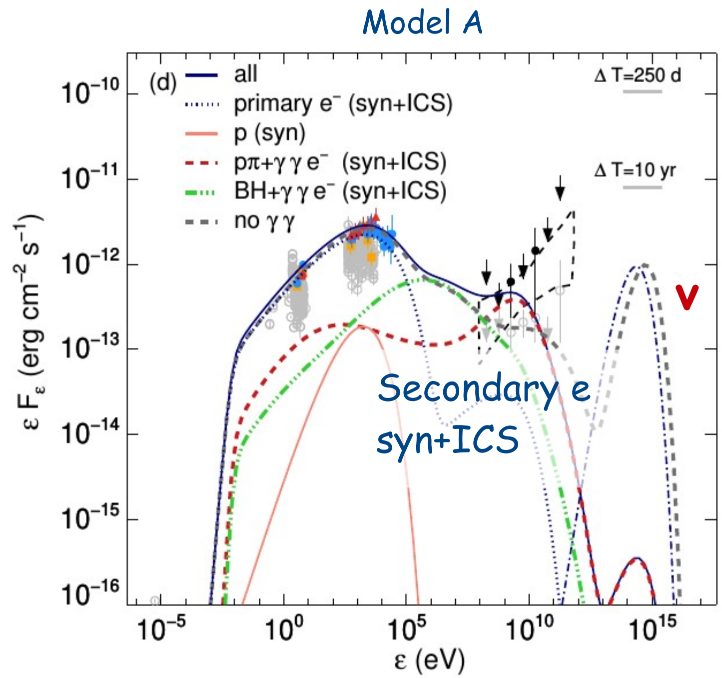
(Giommi et al. 2020, Paliya et al. 2020)

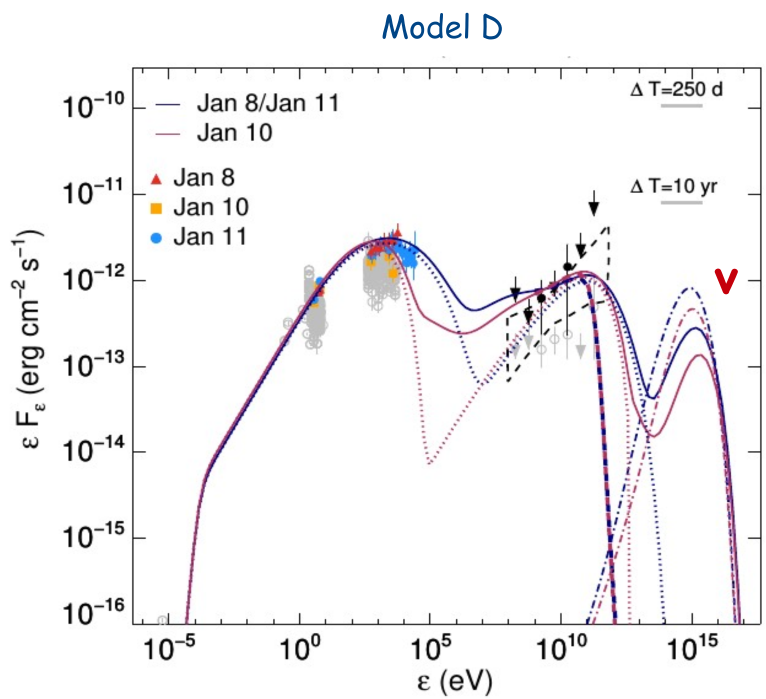


Leptohadronic models of the X-ray flare

MP, Oikonomou, Mastichiadis et al. 2020



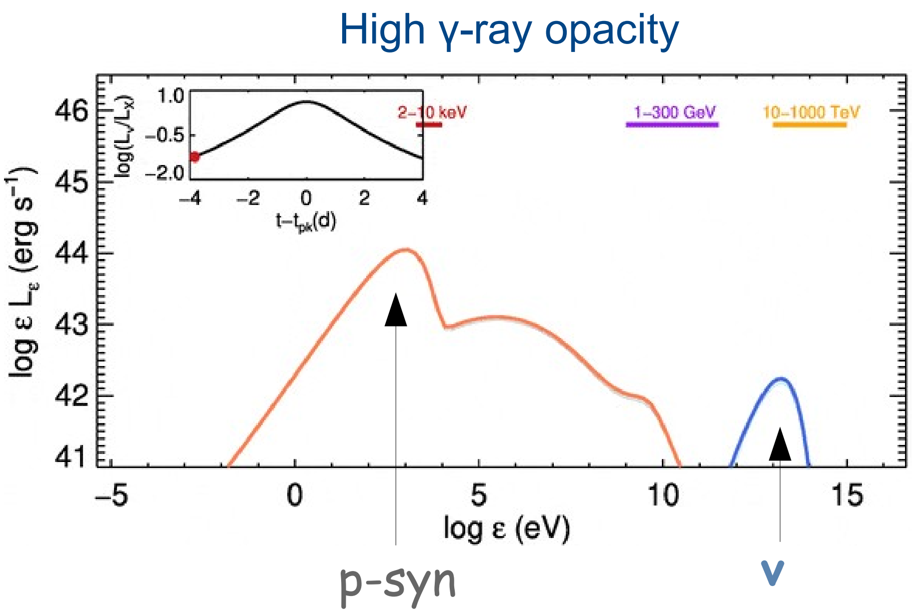


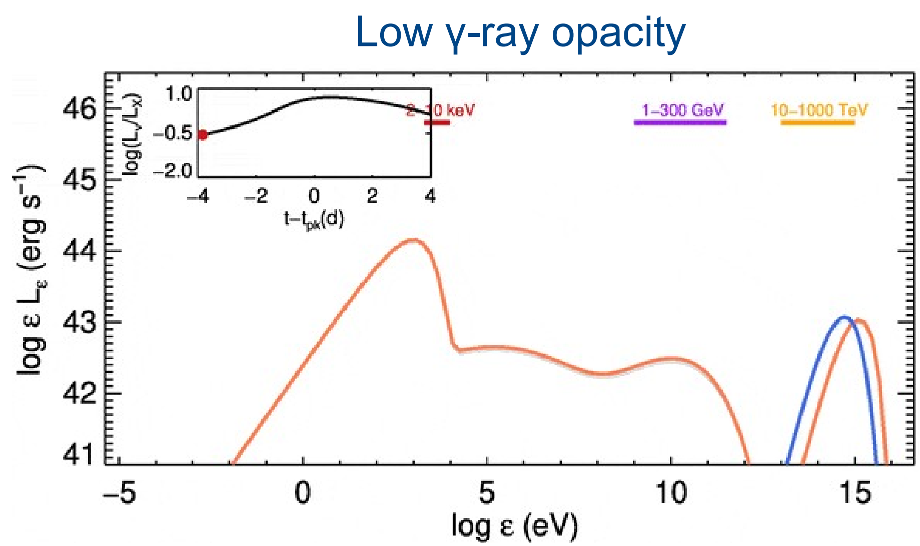


- Predicted number of muon neutrinos during the 3-day X-ray flare << 1
- Ways of increasing neutrino production rate during X-ray flares ?

Hadronic X-ray flares

Mastichiadis & MP 2021

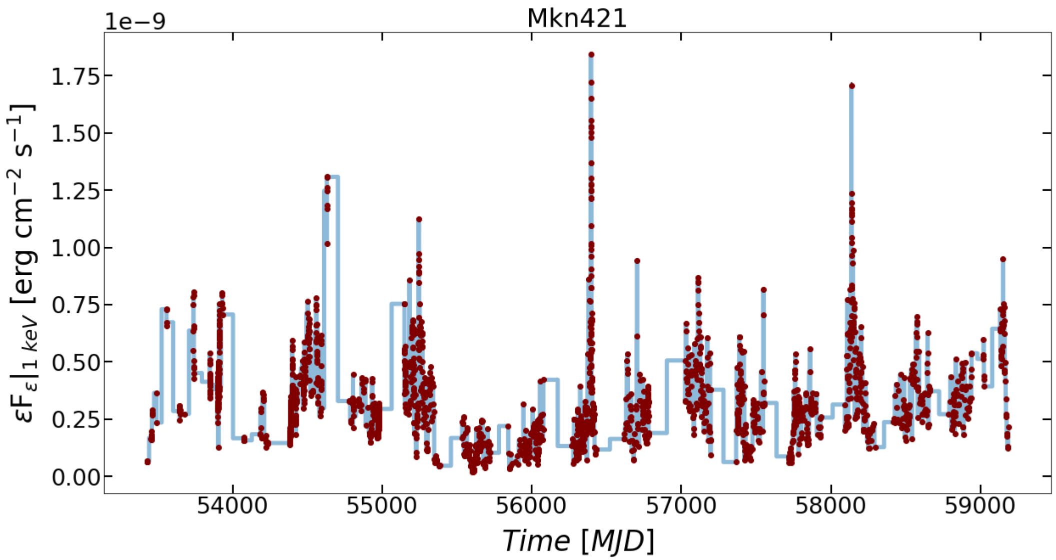




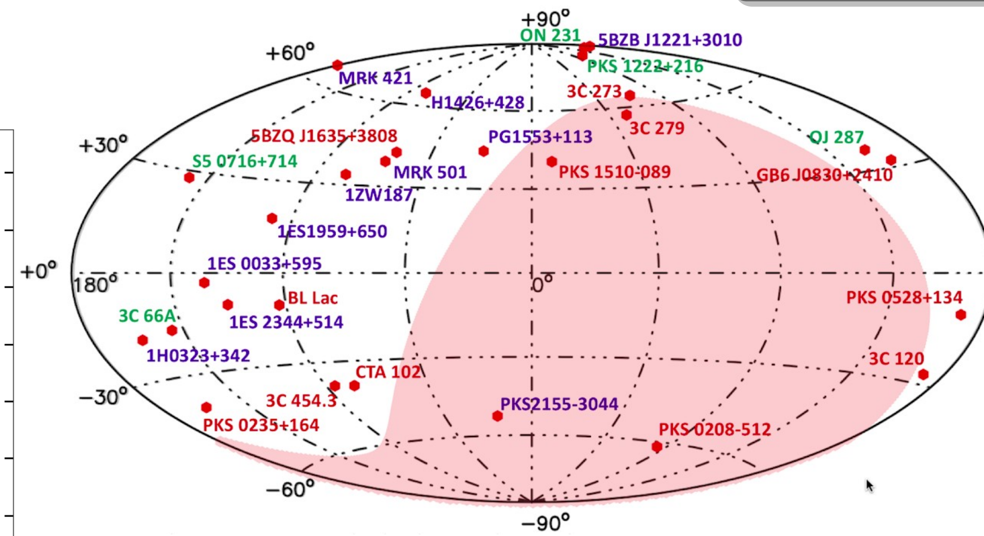
- X-ray flares powered by proton synchrotron radiation
- X-ray photons used as targets for photopion production → non – linear problem
- Neutrino flare with similar duration & flux as X-ray flare
- “γ-ray dark” neutrino flares are possible for strong magnetic fields and small regions

Application to Swift/XRT blazar flares

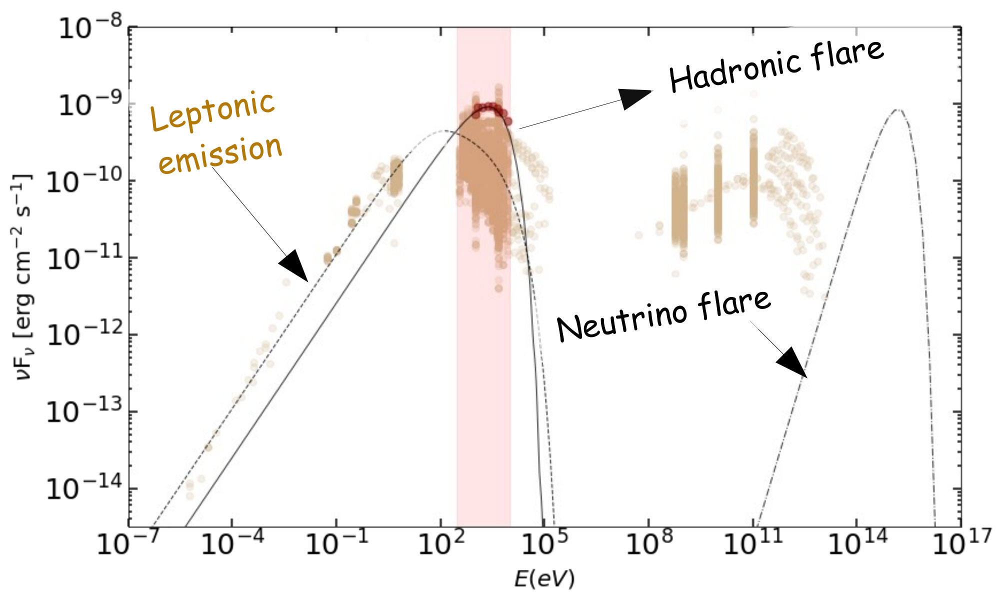
Stathopoulos et al., PoS(ICRC2021)1008
Stathopoulos, MP, Vasilopoulos et al., submitted



Sample



Giommi et al. 2021



Method

- 1keV light curve → identification of flares
- 0.5 – 10 keV fluence → neutrino fluence
- Blazar type → neutrino peak energy
- PS effective area → neutrino rate

Application to Swift/XRT blazar flares

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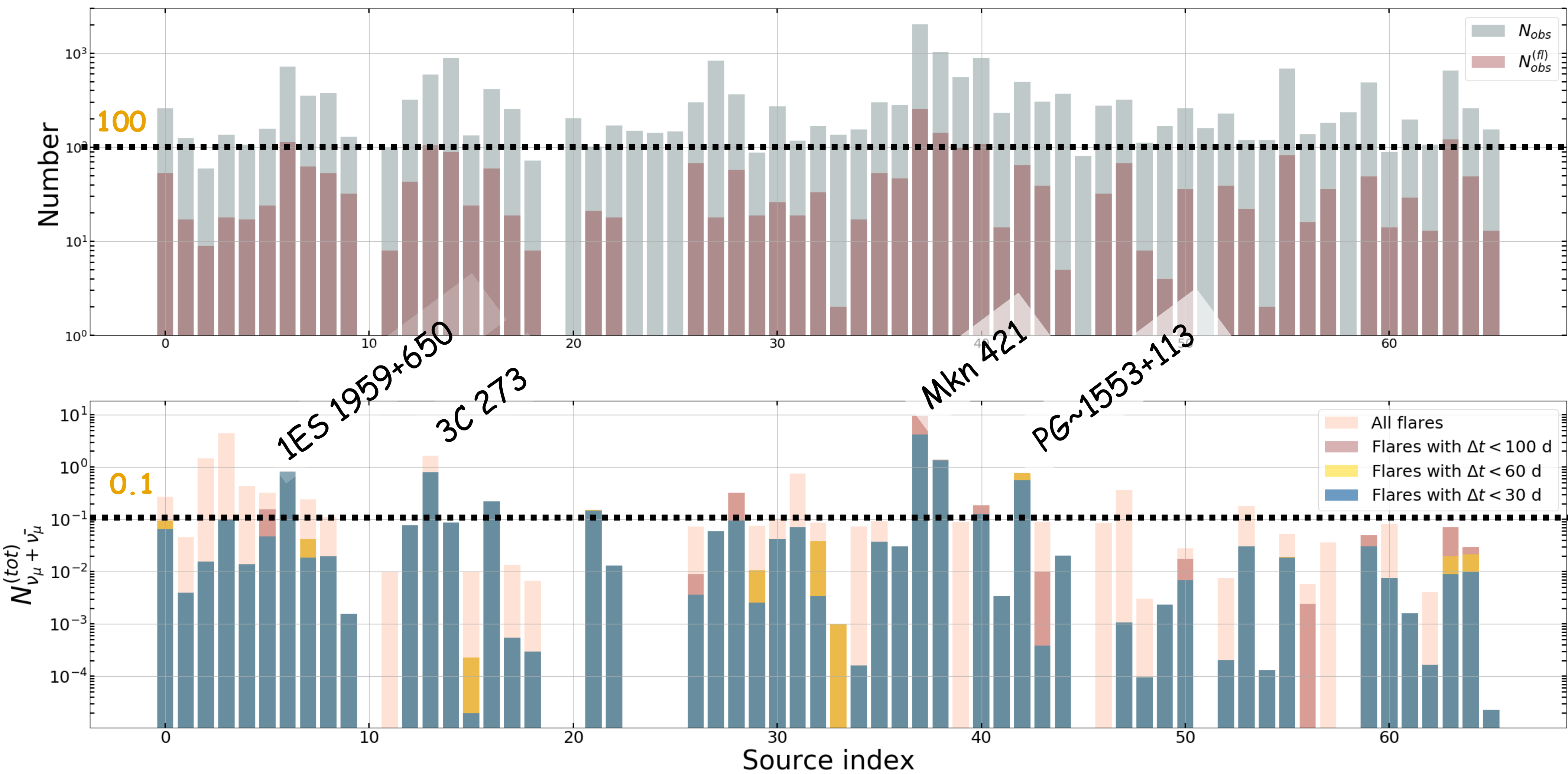

Application to Swift/XRT blazar flares

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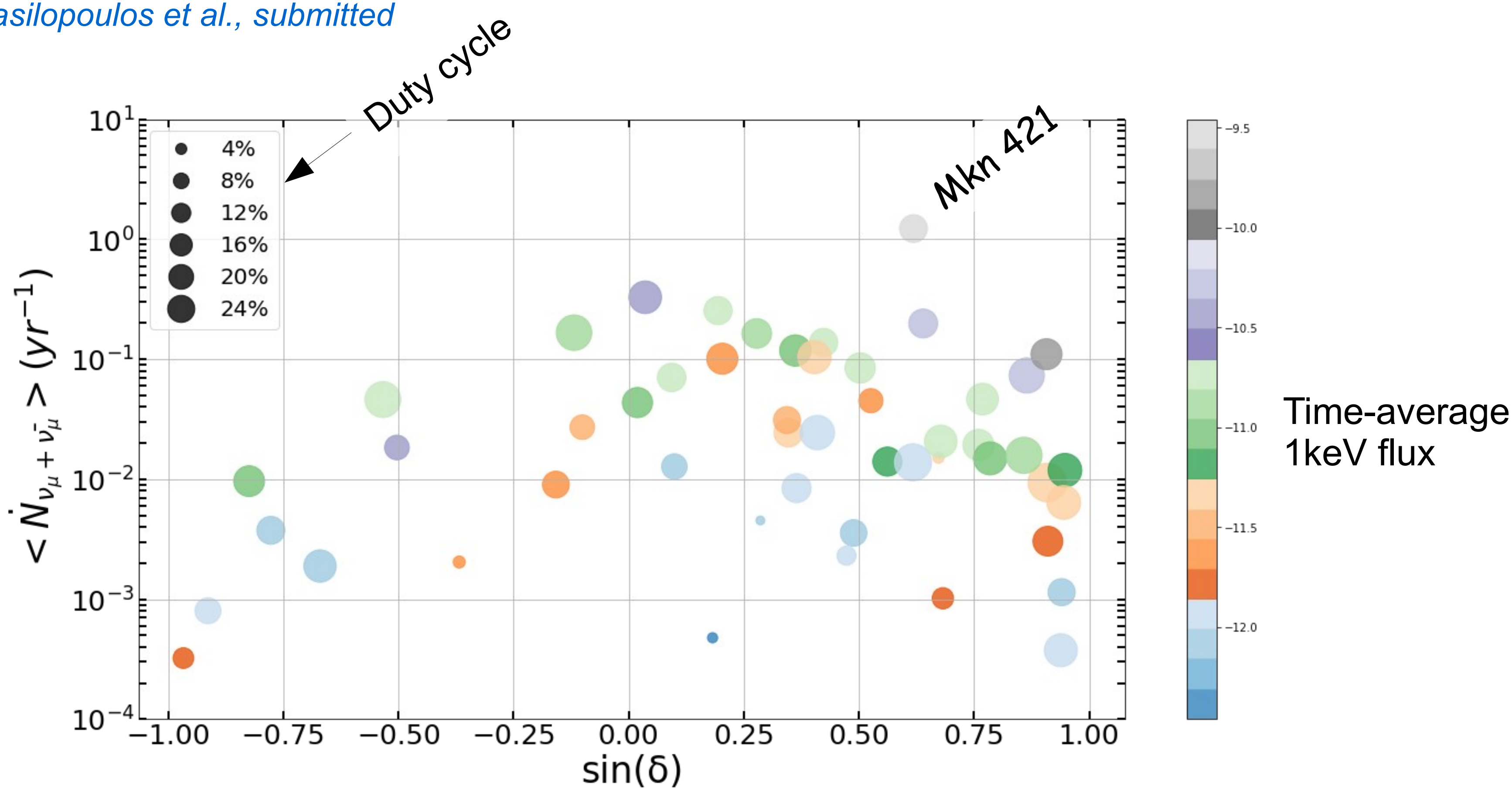

- No correlation between average X-ray flux and duty cycle of flares
- Higher neutrino rates are expected on average from sources with higher X-ray fluxes
- Average neutrino rate depends on source declination

Conclusions and outlook

- Some high-energy neutrinos detected by IceCube are produced in jetted AGN.
- Association of neutrinos with AGN jets does not necessarily mean that the gamma-ray jet emission is of hadronic origin.
- One-zone models for jet emission have an upper bound in the predicted neutrino luminosity, which is set by the in-source cascade emission.
- If the observed neutrino fluence exceeds the gamma-ray fluence, then neutrino and gamma-ray production sites are likely different.
- GeV gamma-ray flares may not be the best probe for neutrinos in contrast to MeV gamma-rays.
- The predicted neutrino rate associated to X-ray flares is also low, but this could be a result of irregular X-ray observations.

Thank you for your attention!

The Blazar Hadronic Code Comparison Project

PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany
37th International Cosmic Ray Conference 12–23 July 2021

The Blazar Hadronic Code Comparison Project

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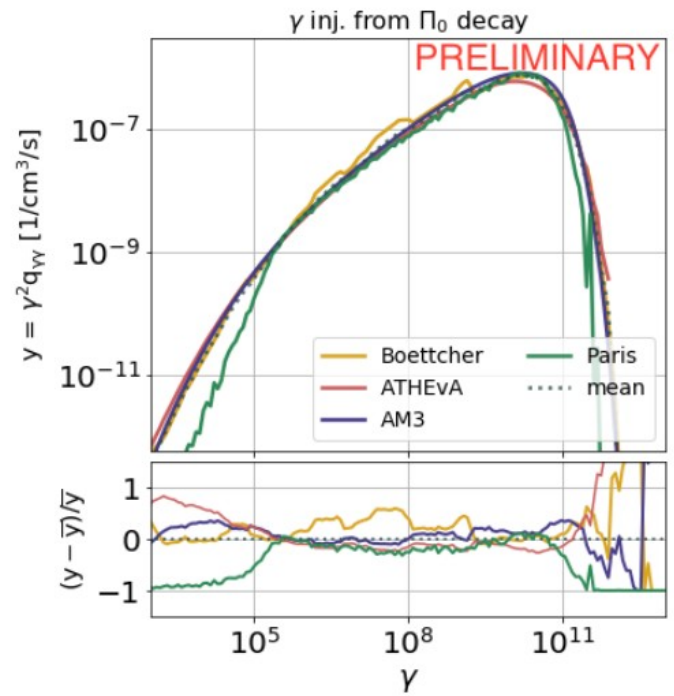
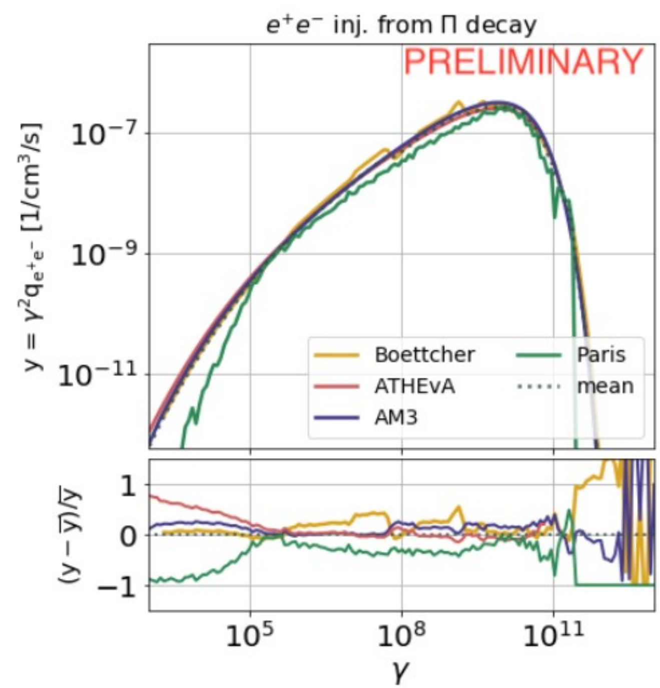
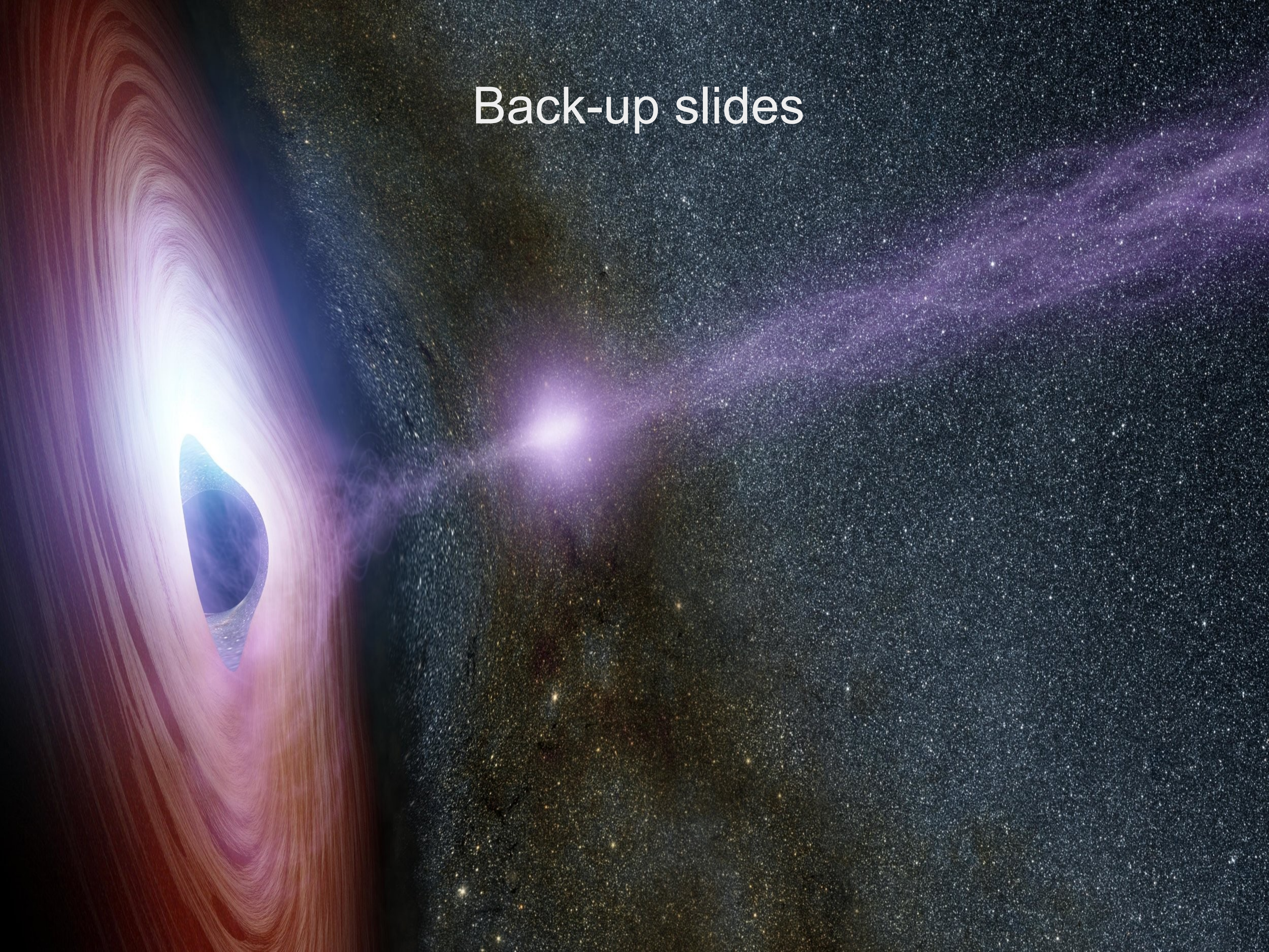




Stay tuned!

https://pos.sissa.it/395/979/

Back-up slides

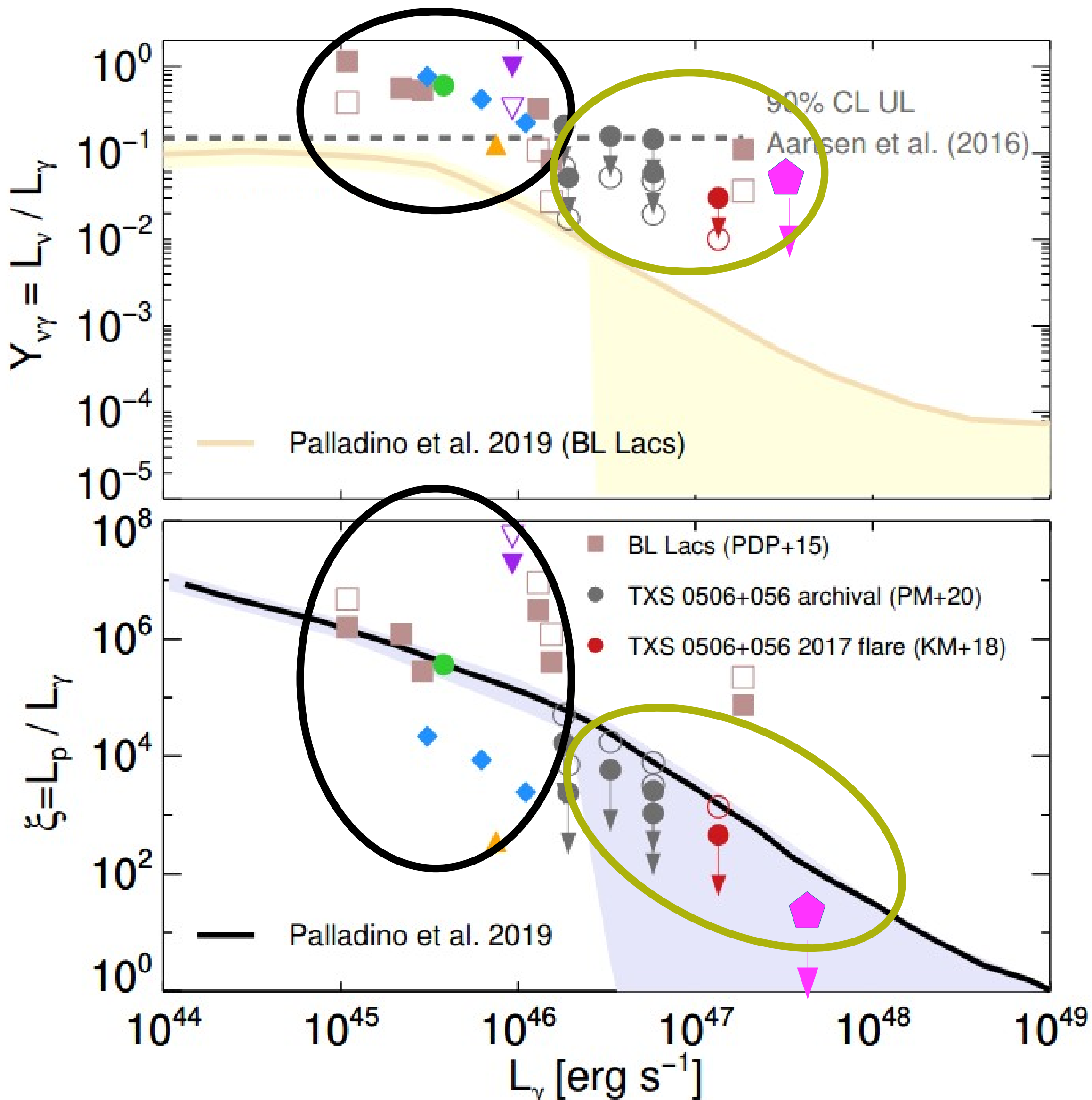


Putting everything together …

Results from ***leptonic** models* (upper limits) and ***cascade** models* (symbols) for γ-ray non-flaring emission for different types of blazars: **PKS 1502+106** (FSRQ,hexagon), **TXS 0506+056** (Masquerading BL Lac; circles), **BL Lacs** (true BL Lacs; squares), and **3HSP J095507.9+35510** (extreme BL Lac; other symbols).

ν to γ-ray luminosity ratio

Baryon loading factor

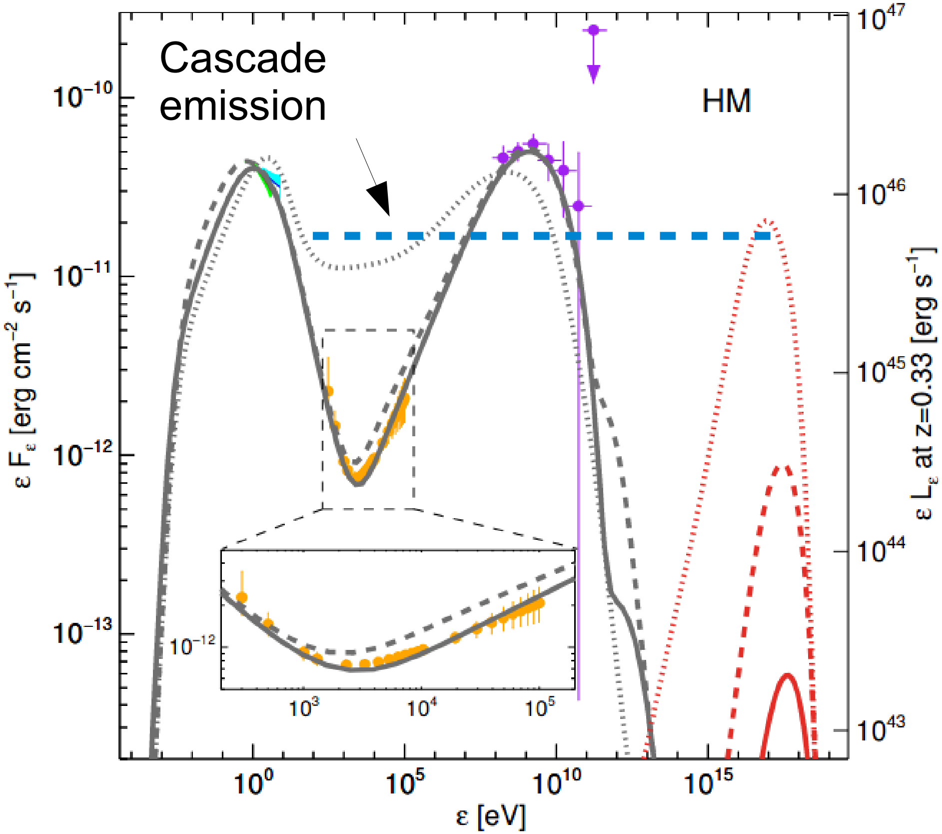


MP, Oikonomou,Mastichiadis+2020

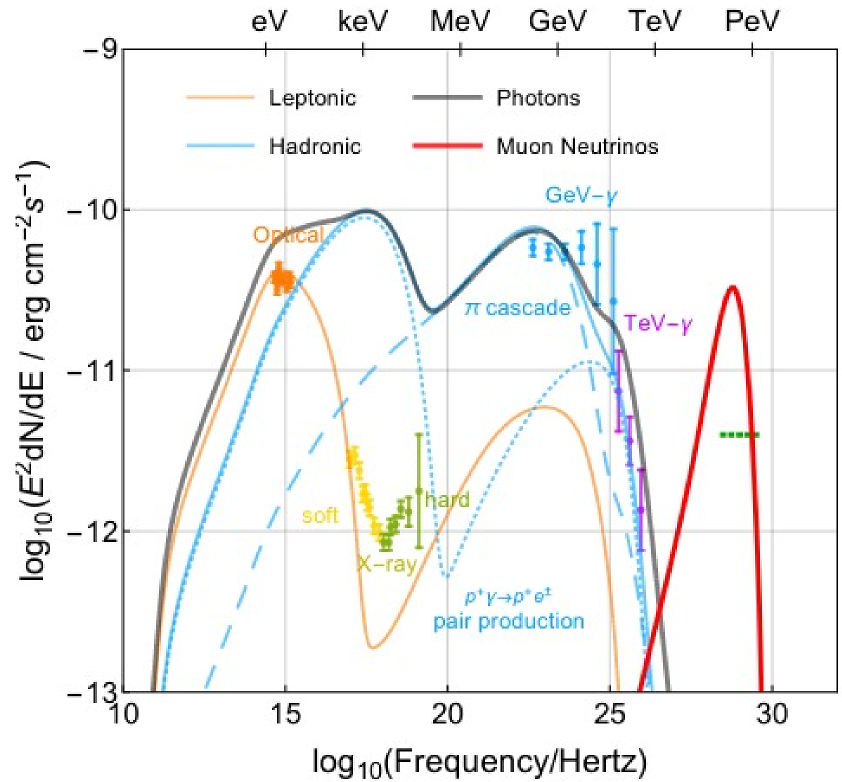
Leptohadronic models of TXS 0506+056

Leptohadronic one-zone models for the 2017 flare are disfavored

Keivani et al. 2018



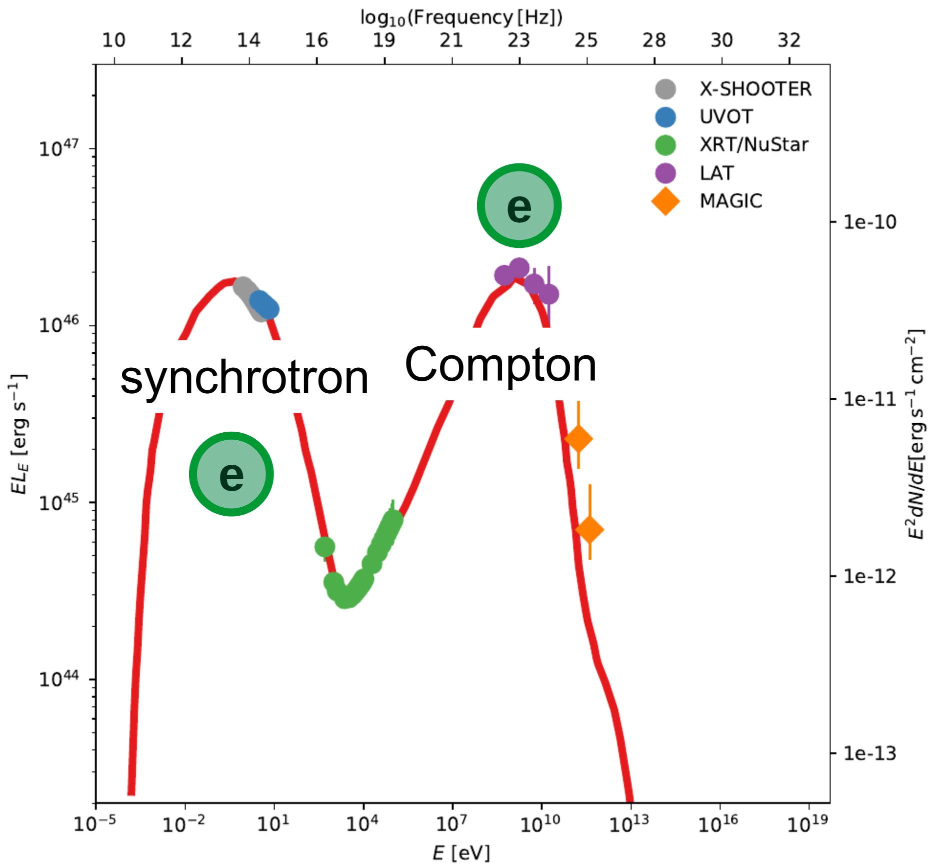
Gao et al. 2019



- Model with γ-rays coming from pion-induced cascade ($L_\gamma - L_\nu$) is ruled out.
- Model with γ-rays from proton synchrotron leads to EeV neutrinos with very low luminosities.
- IC-170922A cannot be explained in this scenario.

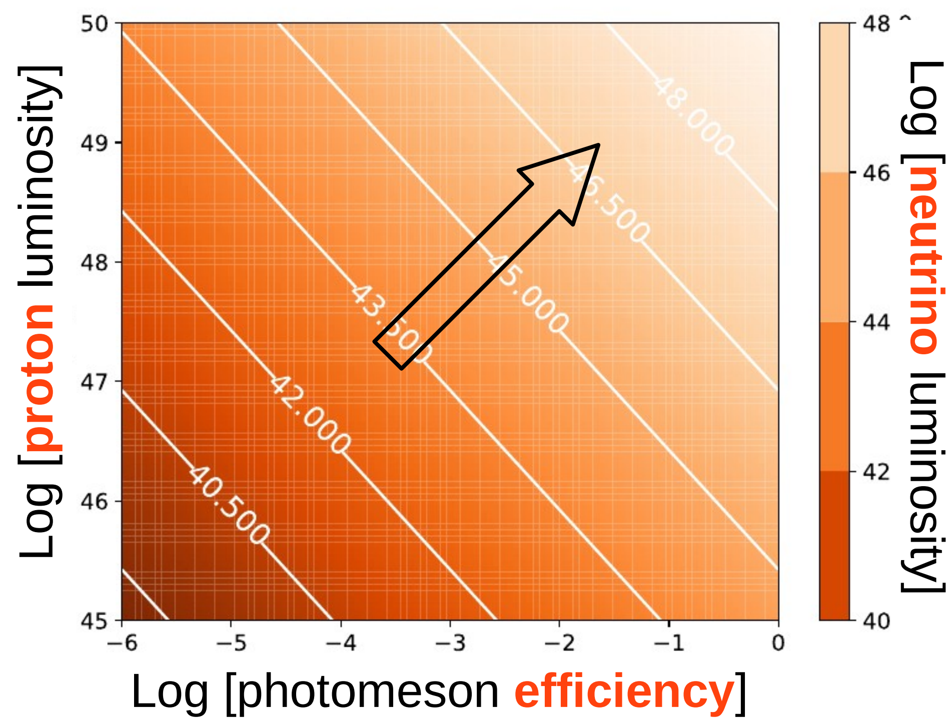
What sets the maximum neutrino flux?

Murase, Oikonomou, MP 2018

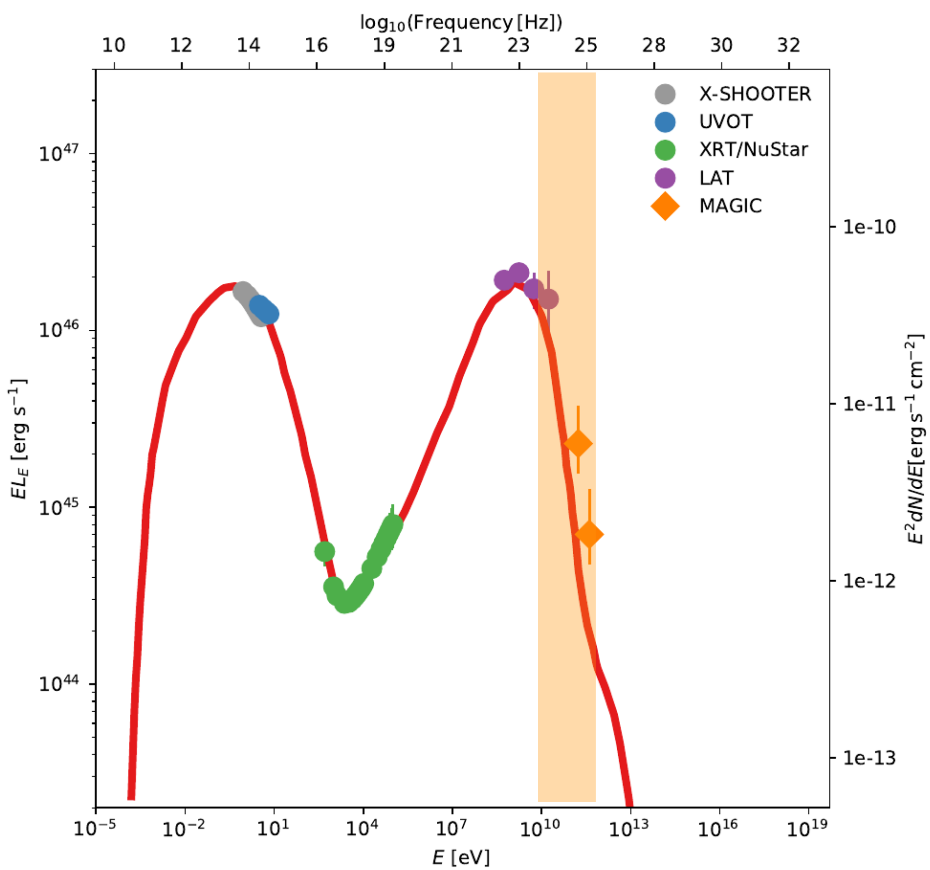


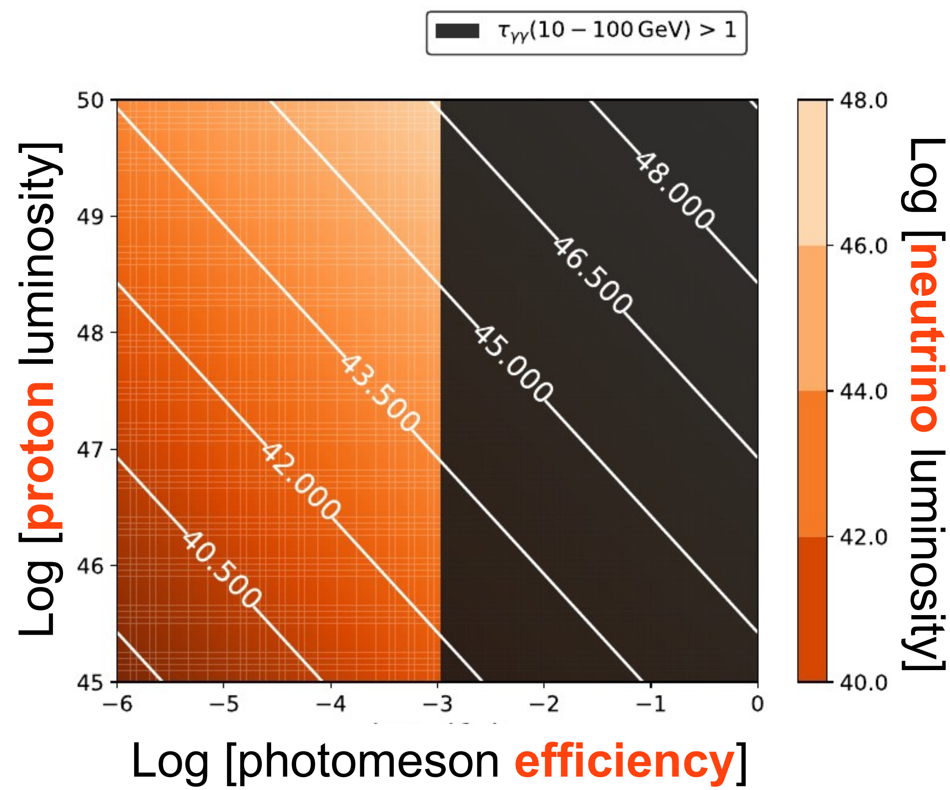
$$\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma}\, \varepsilon_p L_p$$

$* \; \varepsilon_\nu L_\nu^{0.1-1\mathrm{PeV}}$



What sets the maximum neutrino flux?

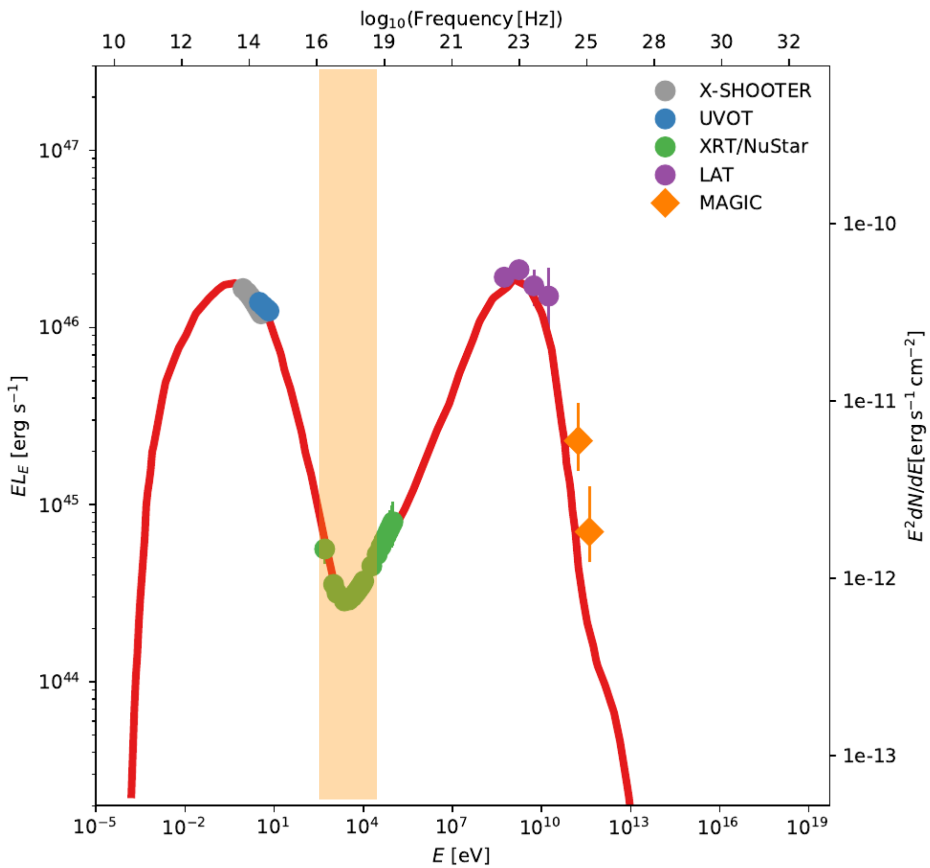


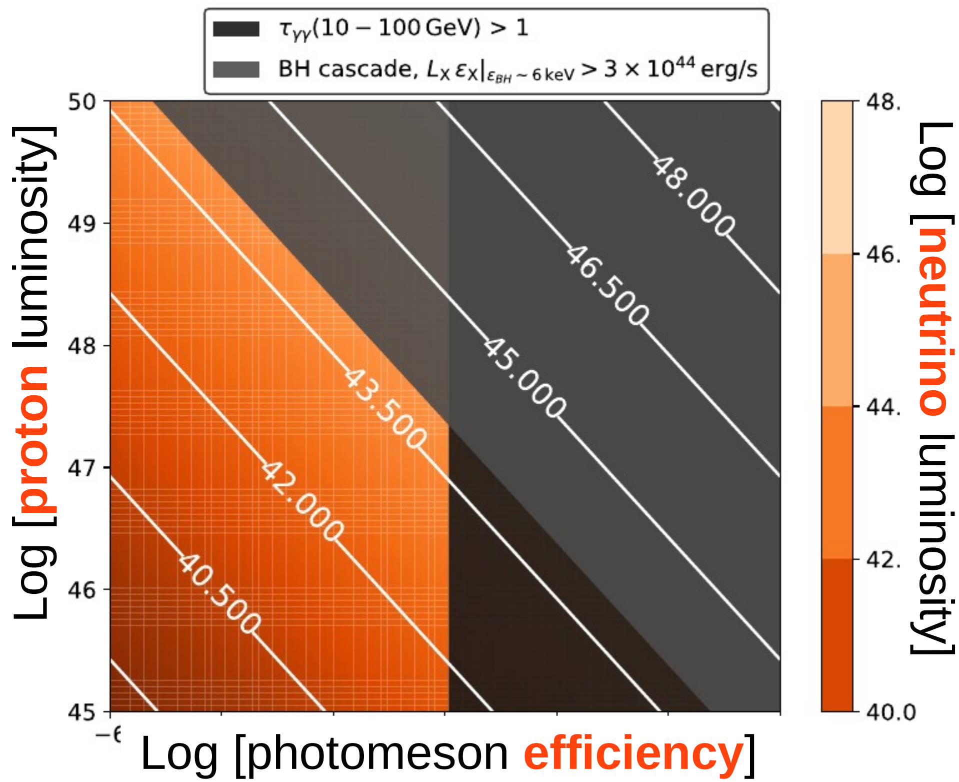


I. Optical depth for absorption of 10-100 GeV γ-rays must be low: $\tau_{\gamma\gamma}(10-100\,\mathrm{GeV}) \lesssim 1$

Note: main source of opacity for PeV γ-rays: co-spatial synchrotron photons

What sets the maximum neutrino flux?



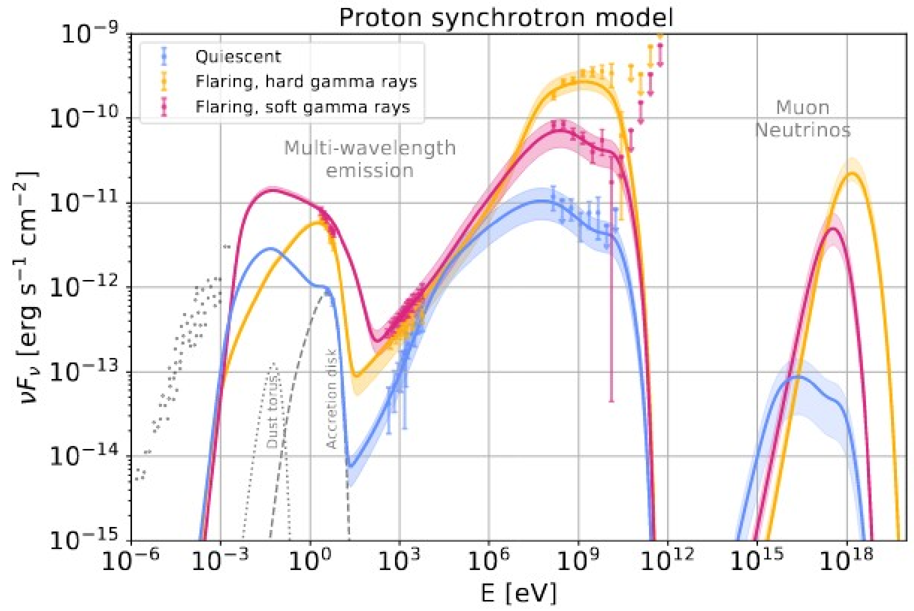


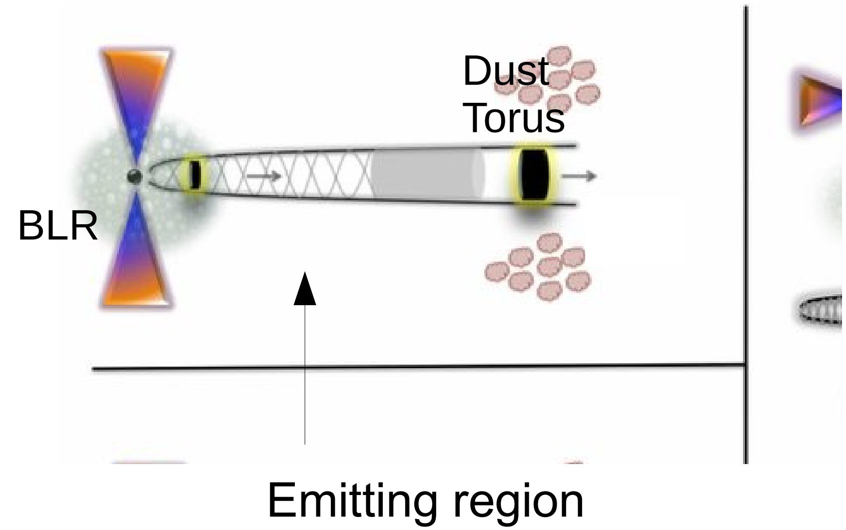
II. Synchrotron emission from Bethe-Heitler pairs must not overshoot X-ray data:

$$\varepsilon_\nu L_{\varepsilon_\nu}^{0.1-1\ \mathrm{PeV}} \sim \varepsilon_\gamma L_{\varepsilon_\gamma}|_{\varepsilon_{\mathrm{syn}}^{\mathrm{BH}}} \sim \frac{1}{4} g[\beta] f_{p\gamma}\, \varepsilon_p L_p \leq 3\times 10^{44}\ \mathrm{erg/s}$$

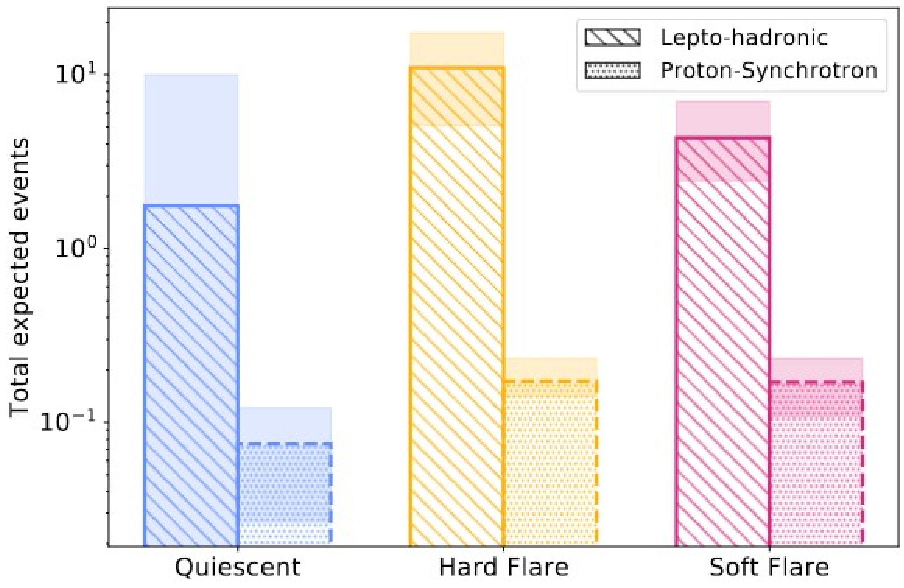
$$\varepsilon_{\mathrm{syn}}^{\mathrm{BH}} \approx 6\ \mathrm{keV} B_{0.5\ \mathrm{G}} (\varepsilon_p/6\ \mathrm{PeV})^2 (20/\delta)$$

A proton-synchrotron model of PKS 1502+106



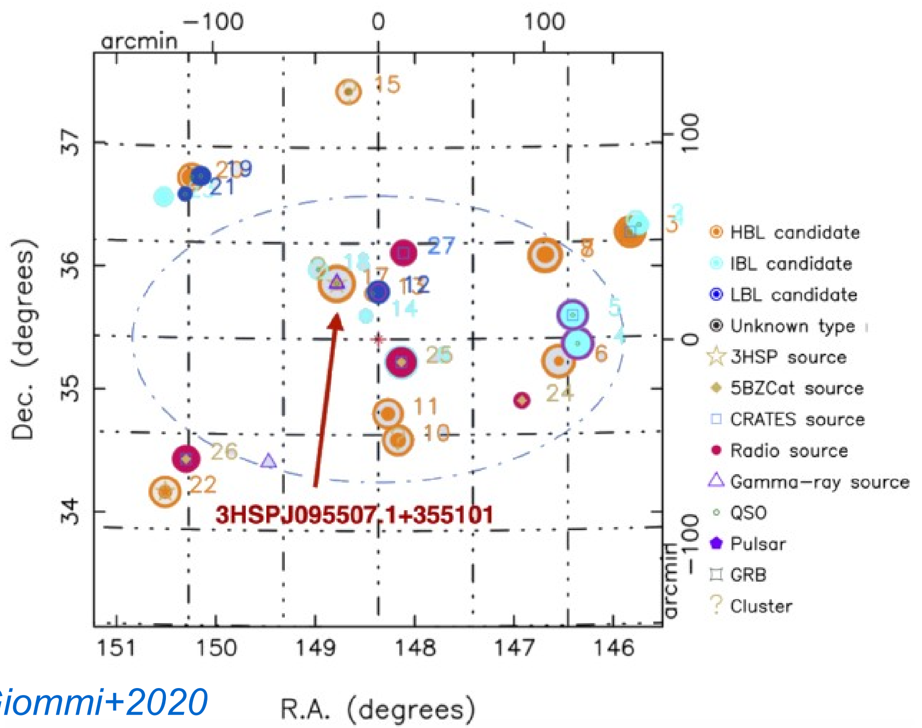


Rodrigues+2021

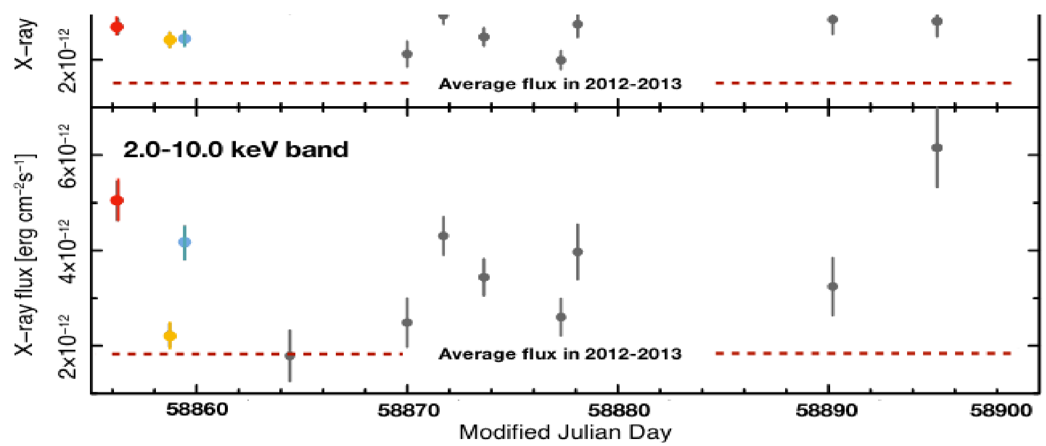


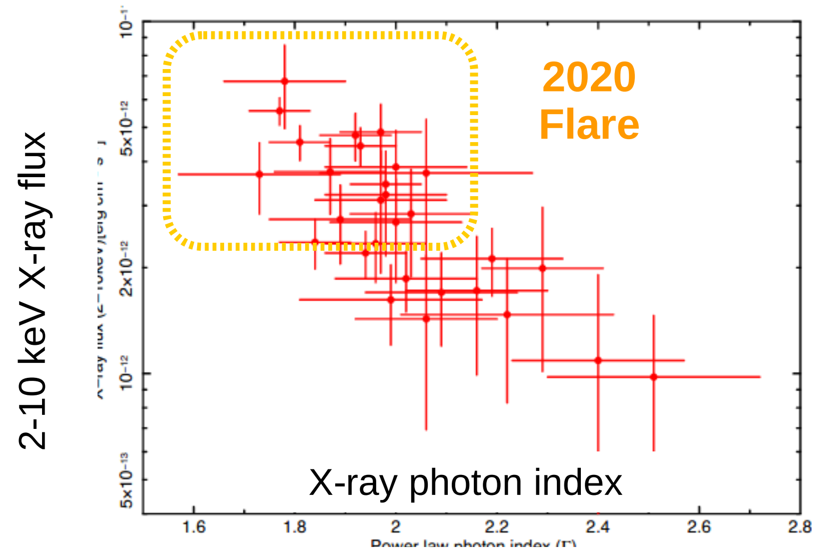
- Proton synchrotron model predicts ~EeV neutrino energies and ~ 0.1 muon neutrinos in 10 yr
- Similar to our pc-scale hybrid leptonic model

3HSP J095507.9+35510 / IceCube-200107



Giommi+2020



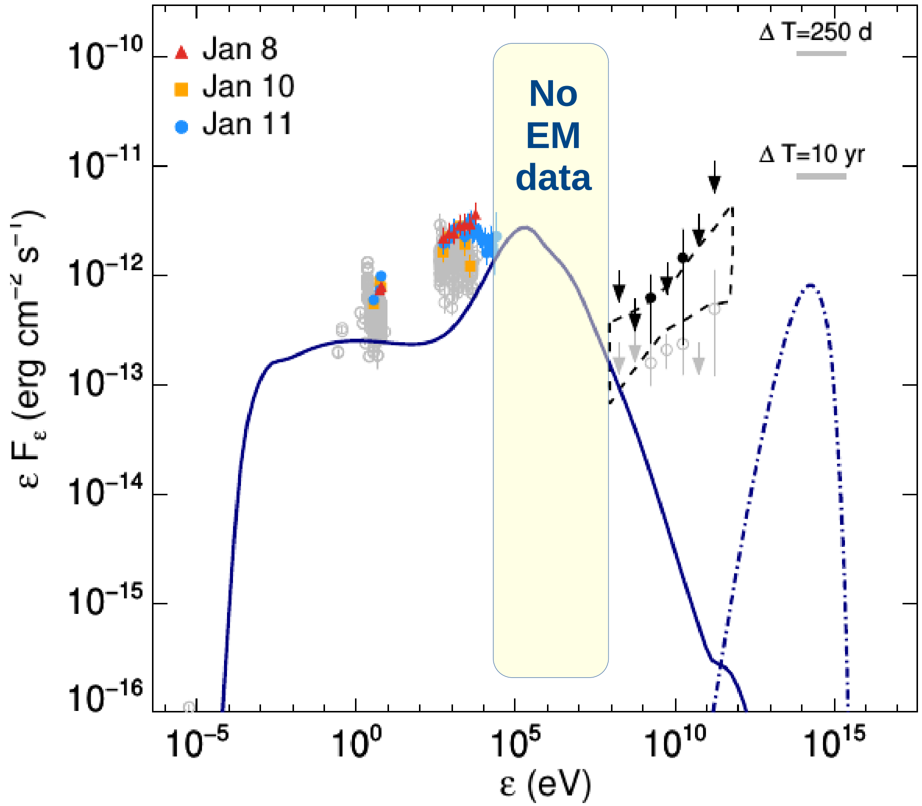


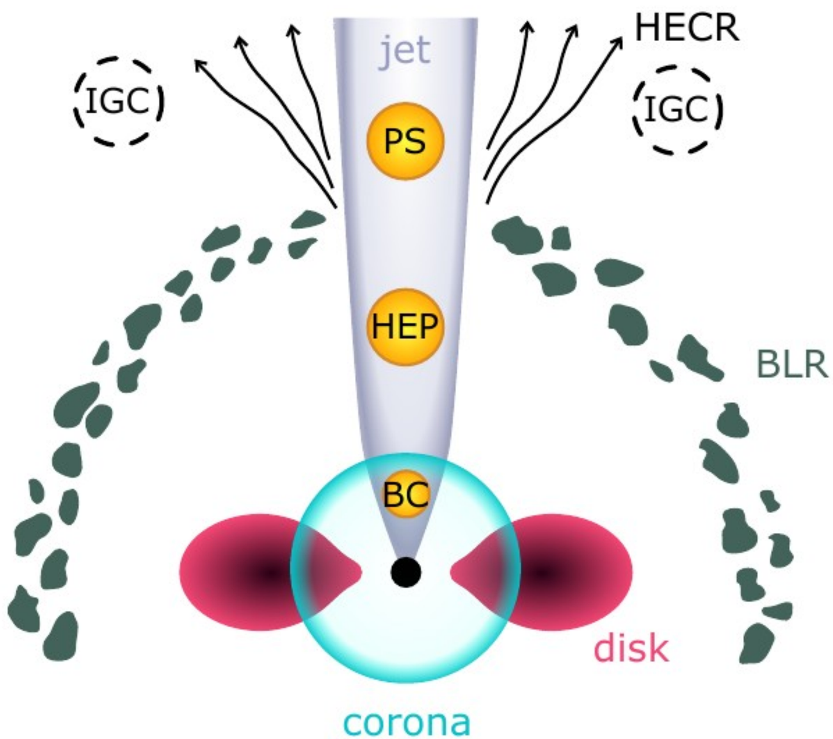
- 3HSP J095507.9+35510 is an HSP blazar at z~0.56 belonging to the extreme subclass.
- Spatially coincident with IceCube-200107A while undergoing its brightest X-ray flare → X-ray flux increased by a factor of ~3 and X-ray spectrum hardened.

Alternative theoretical scenarios (BC)

Blazar Core (BC)

- X-ray coronal field
- Production from inner jet (close to black hole)
- Low jet Lorentz factor ($\Gamma \sim 5$)
- Very strong magnetic field ($B \sim 10^4$ G)
- Size ($R \sim 10^{14}$ cm)





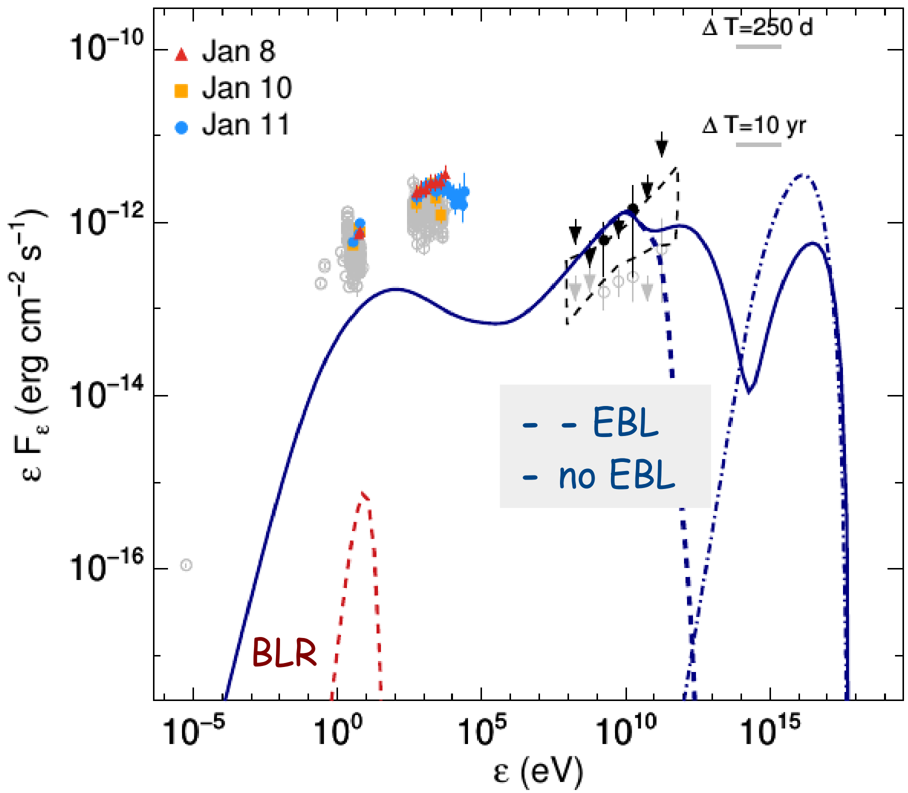
Findings:

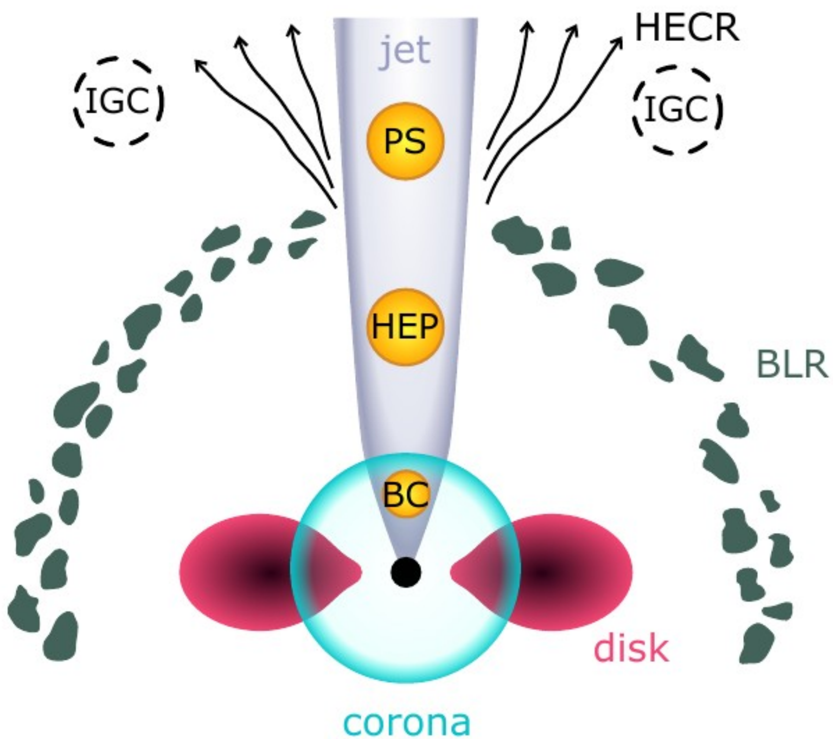
- Applies to transient & persistent emissions
- EM cascade peaks at sub-MeV energies
- Cannot explain optical/UV, X-rays and γ-ray emissions

Alternative theoretical scenarios (HEP)

Hidden External Photons (HEP)

- Weak BLR ? (L_{BLR} < 10^{43} erg/s)
- Production from sub-pc jet
- Typical jet Lorentz factor (Γ~25)
- Weak magnetic field (B~1 G)
- Size (R~2 10^{15} cm)





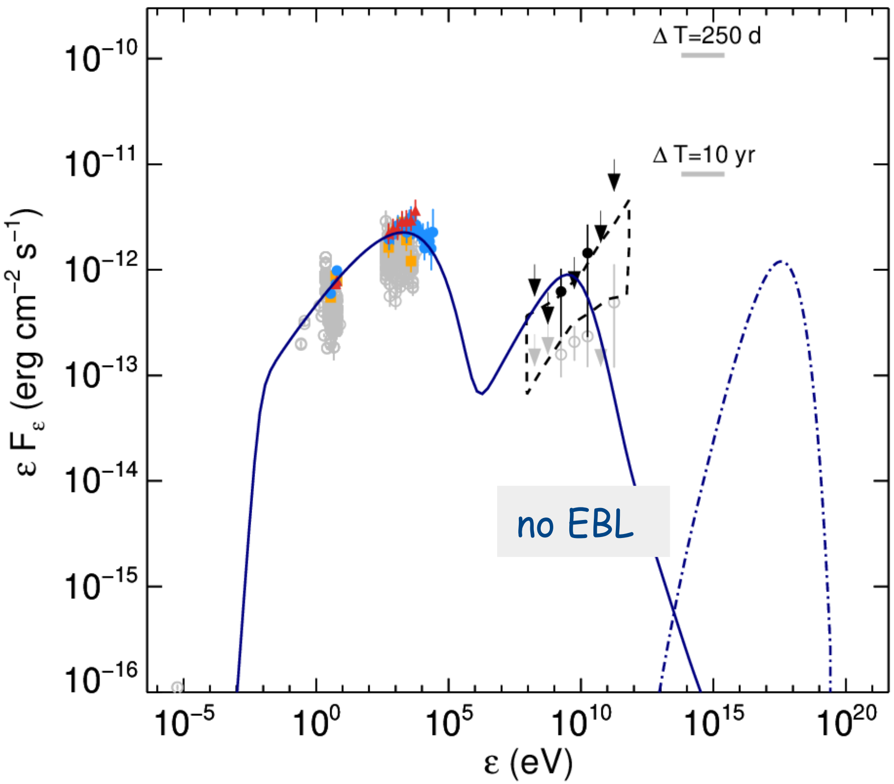
Findings:

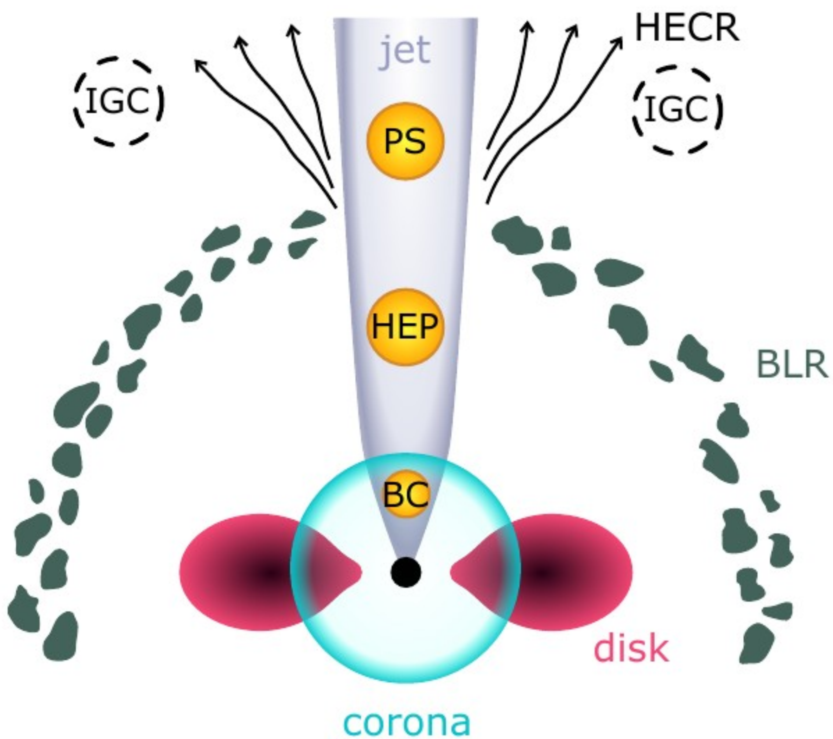
- Applies to transient & persistent emissions
- UV & soft X-rays from the same region or not
- Enhanced neutrino flux by a factor of ~3

Alternative theoretical scenarios (PS)

Proton Synchrotron (PS)

- Ultra-high energy protons in jet ($E_{p,max}$ ~ 10 EeV)
- Production from sub-pc jet
- Typical jet Lorentz factor (Γ~10)
- Strong magnetic field (B~100 G)
- Size (R~10^{15} cm)

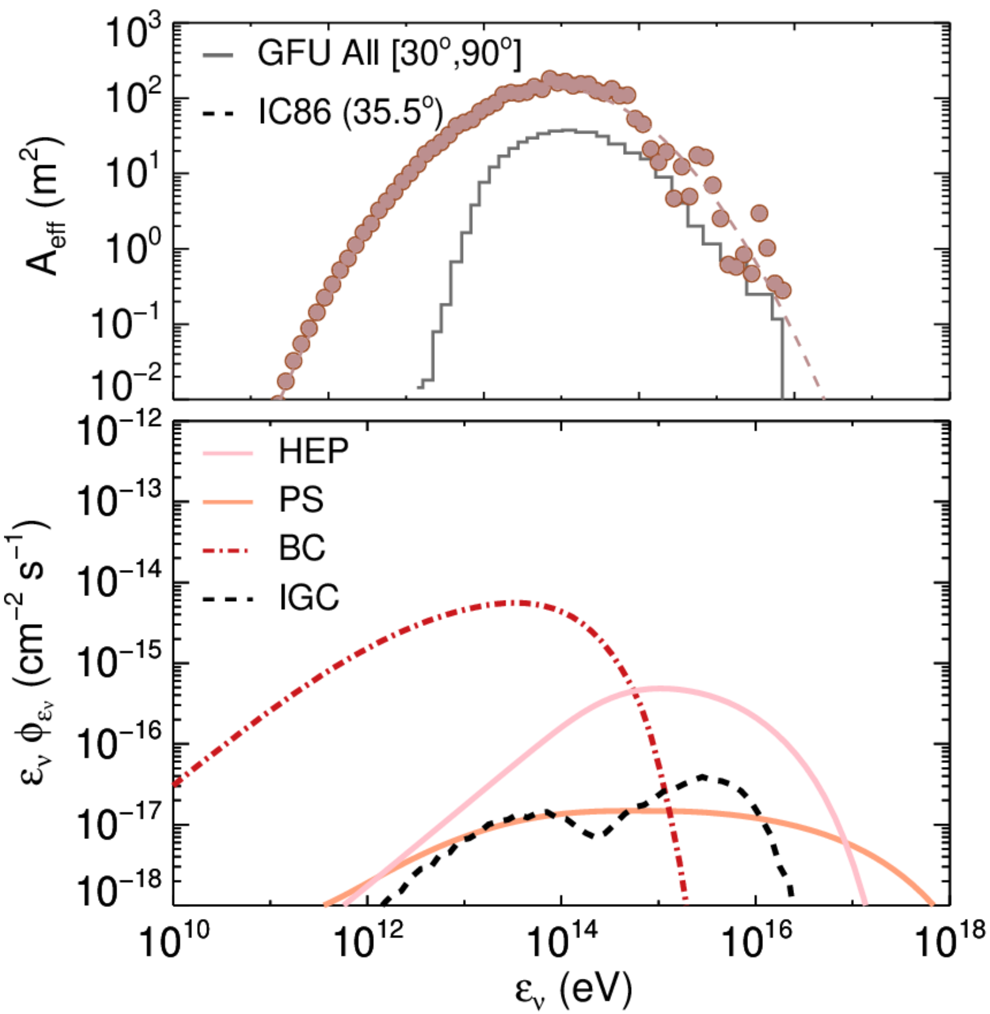


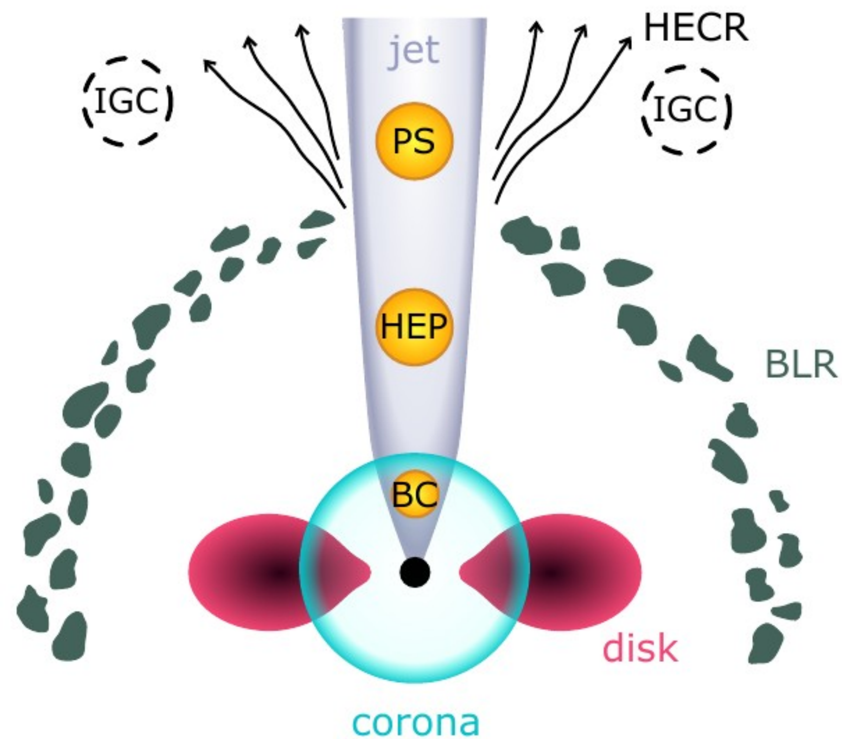


Findings:

- Can explain the transient MW emission
- Neutrino flux peaks at EeV energies
- Neutrino flux similar to leptohadronic models

Alternative theoretical scenarios





Model	State	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}(>100\text{ TeV})$ ($\times 10^{-4}$ yr^{-1}) Alert (PS)	$\mathcal{P}\|_{1\,\nu_\mu \text{ or } \bar{\nu}_\mu}$ (>100 TeV) Alert (PS)
HEP	transient high	50 (190)	0.3 (1)%
PS	transient high	2.1 (7.3)	0.01 (0.05)%
BC	persistent average	33 (370)	3 (30)%
IGC	persistent average	3.6 (10)	0.4 (1)%