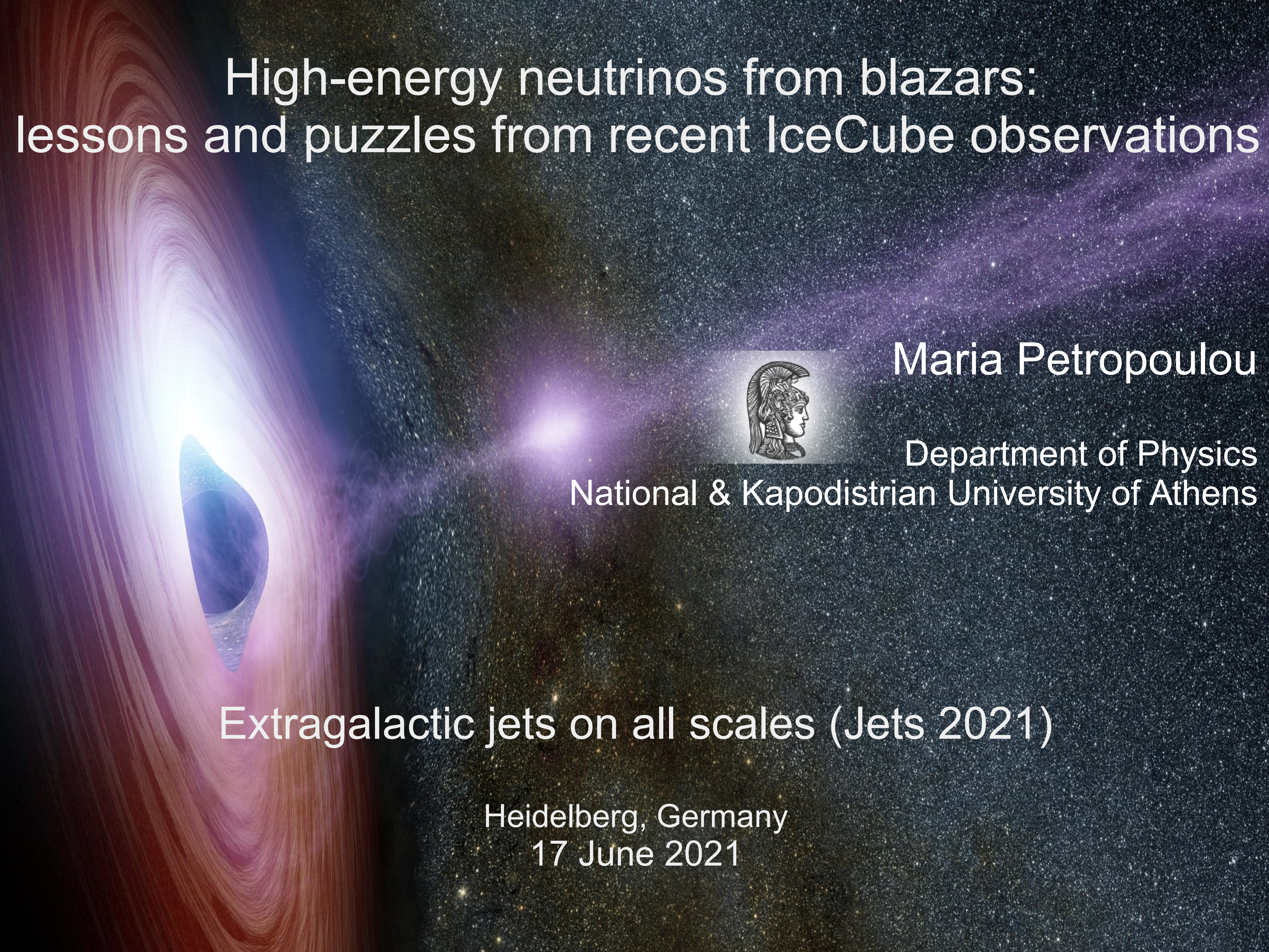


High-energy neutrinos from blazars: lessons and puzzles from recent IceCube observations

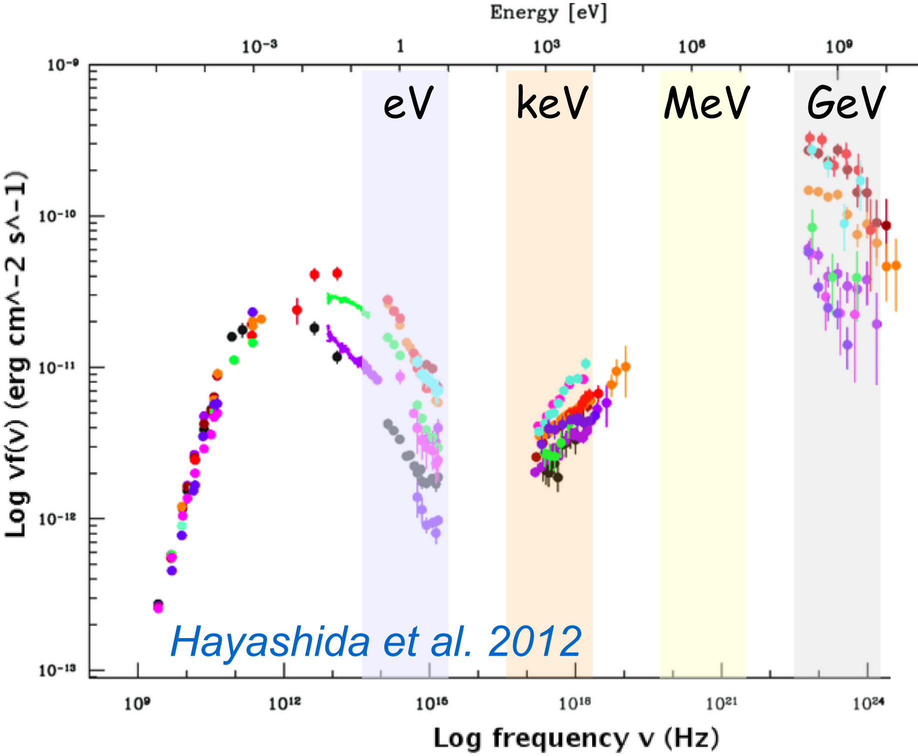
Maria Petropoulou

Department of Physics
National & Kapodistrian University of Athens

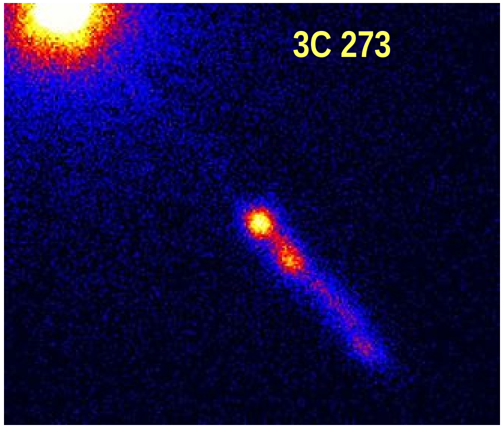
Extragalactic jets on all scales (Jets 2021)

Heidelberg, Germany
17 June 2021

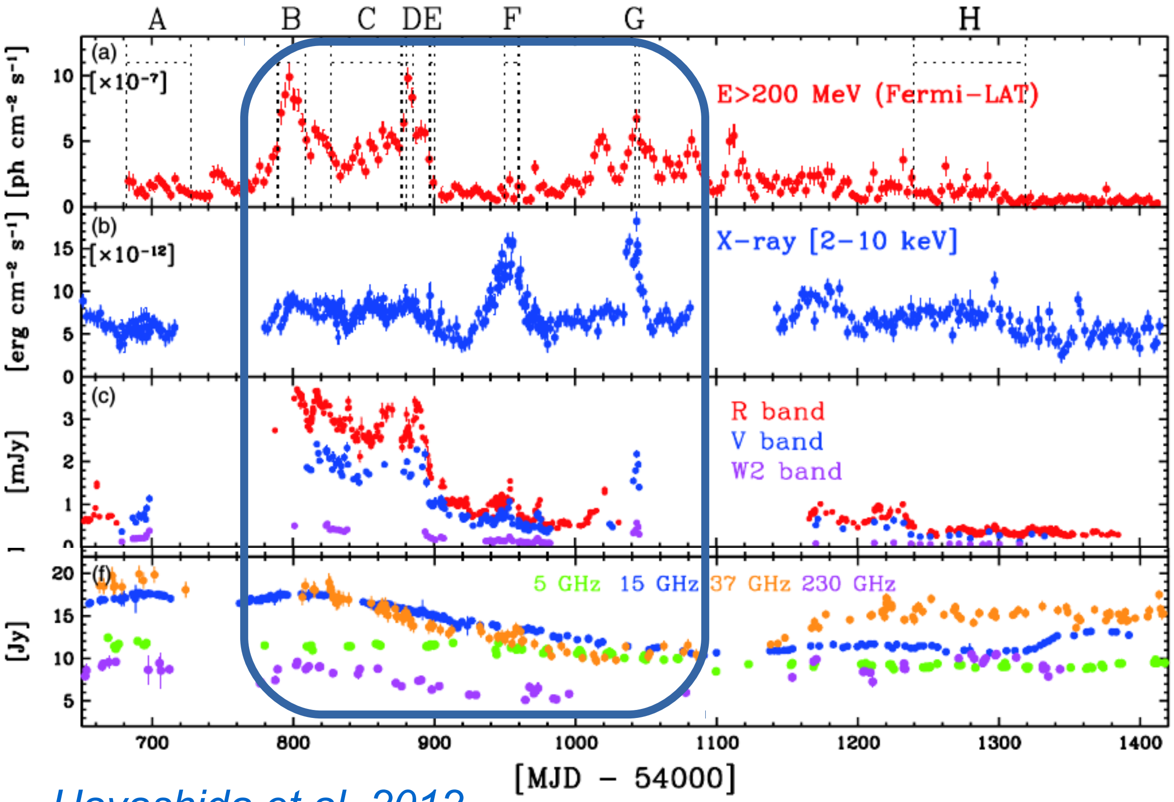
Blazar jet emission



Hayashida et al. 2012



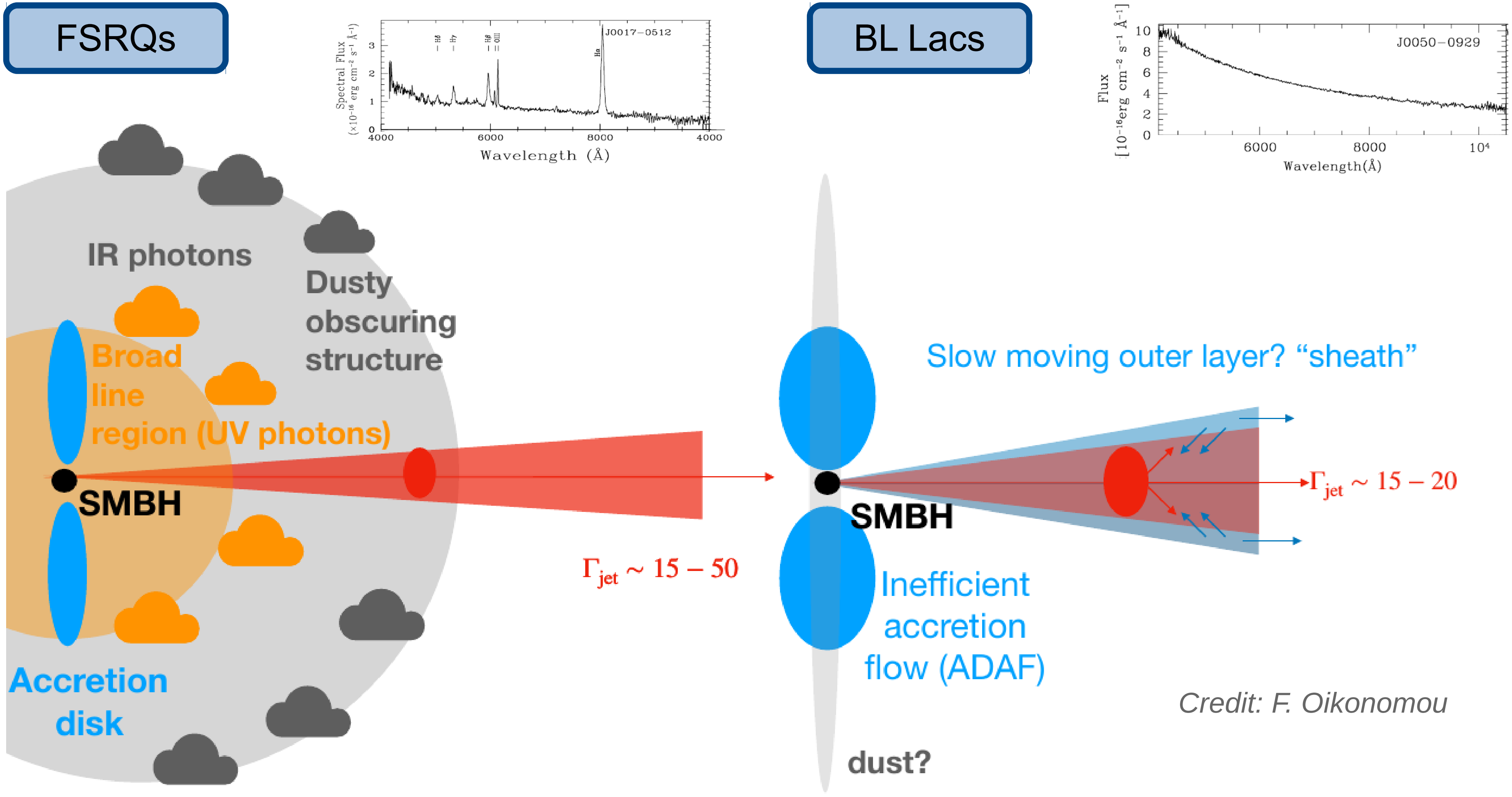
Credit: Chandra X-ray observatory



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

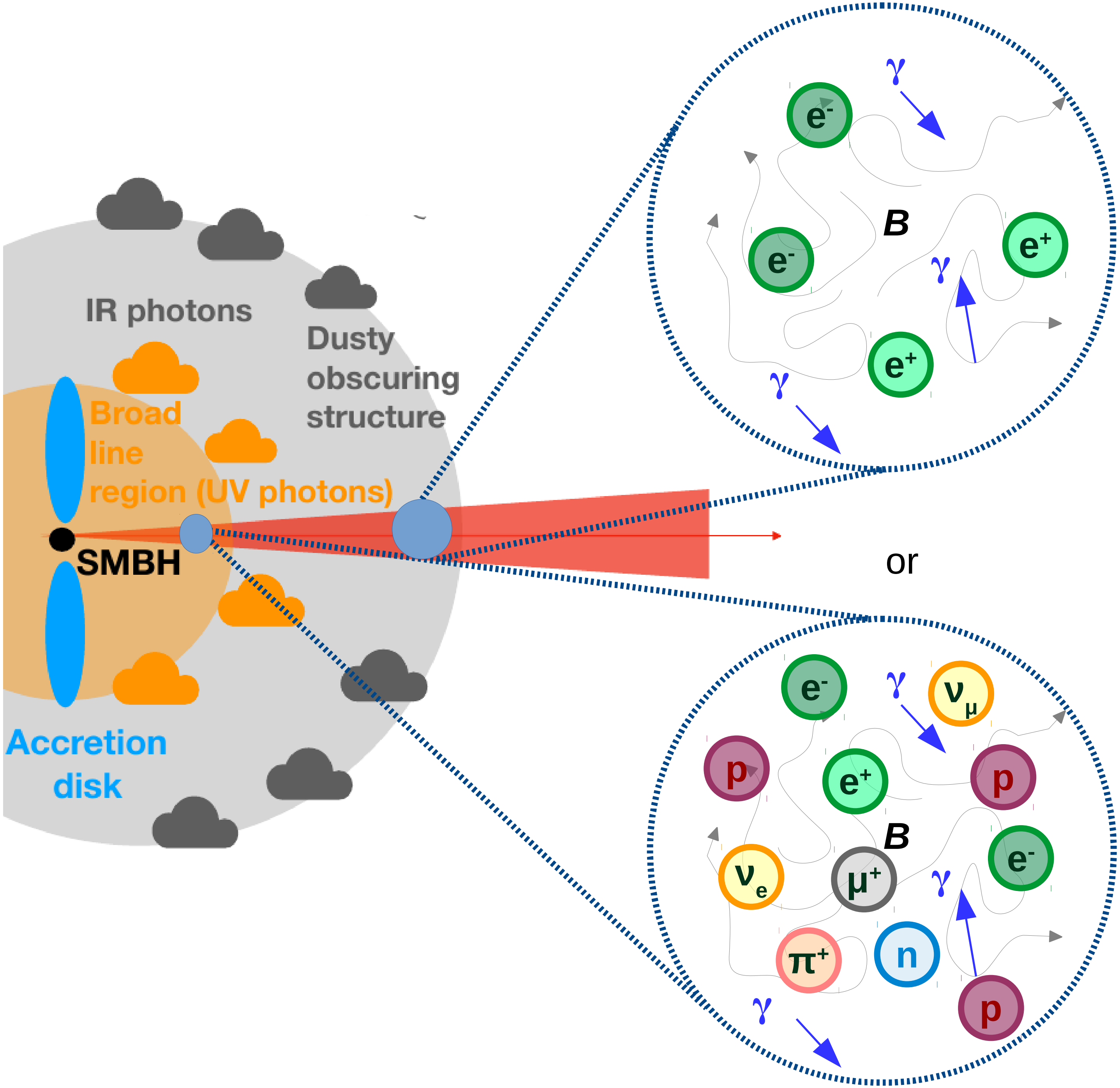


Credit: F. Oikonomou

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

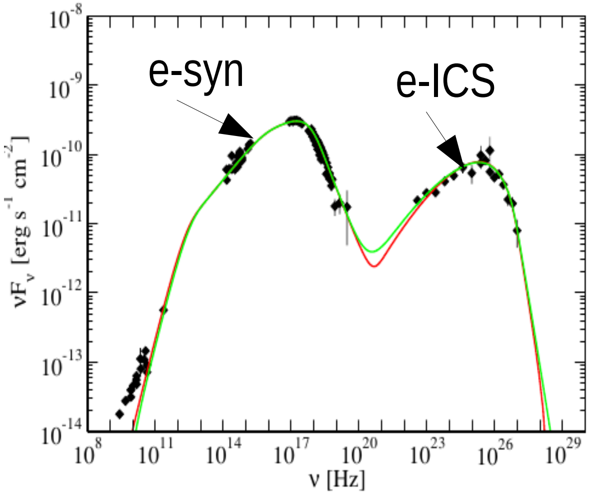
- Weak or absent broad emission lines in optical spectra
- Radiatively inefficient disks
- Accretion at sub-Eddington rates
- Low jet power & γ-ray luminosity

One-zone emission models

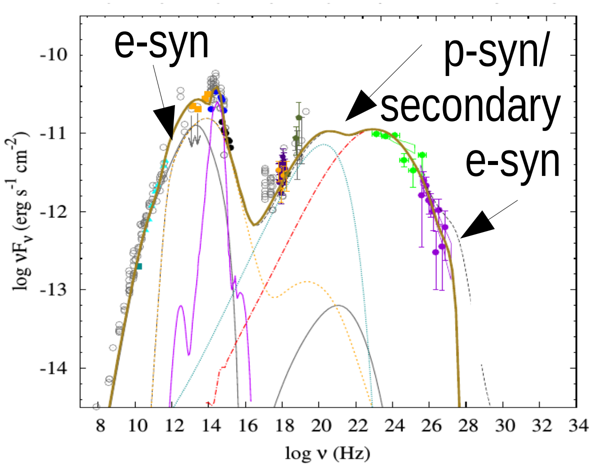


or

Leptonic



Leptohadronic



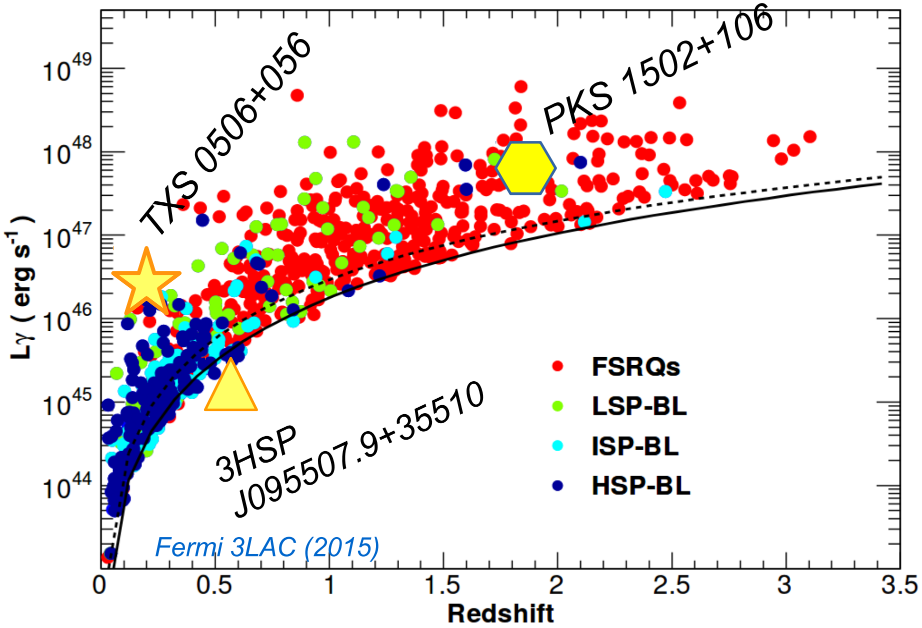
Case studies

- **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

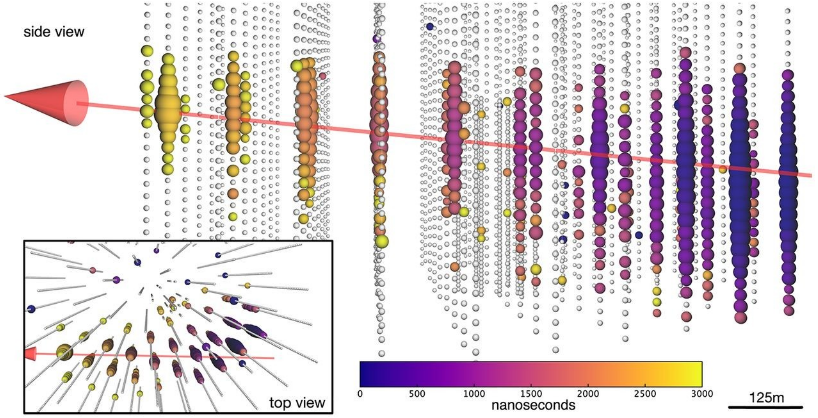
- **PKS 1502+106 / IceCube-190730A** *(Franckowiak+2020)*
  - FSRQ with strong BLR emission
  - Among the 15 brightest sources in the Fourth Fermi-LAT AGN catalog (4LAC)
  - Neutrino detected during period of low activity in γ-rays

- **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



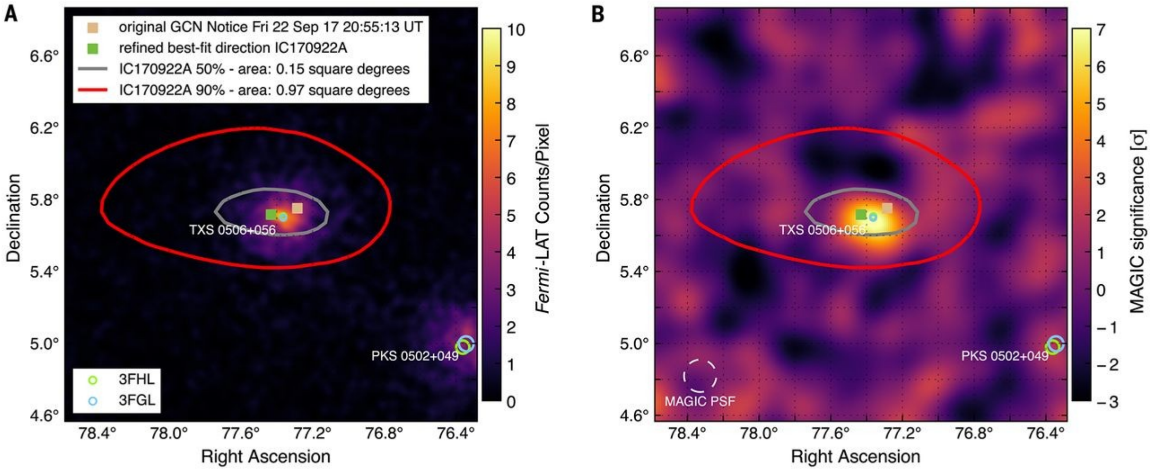
The multi-messenger flare of TXS 0506+056

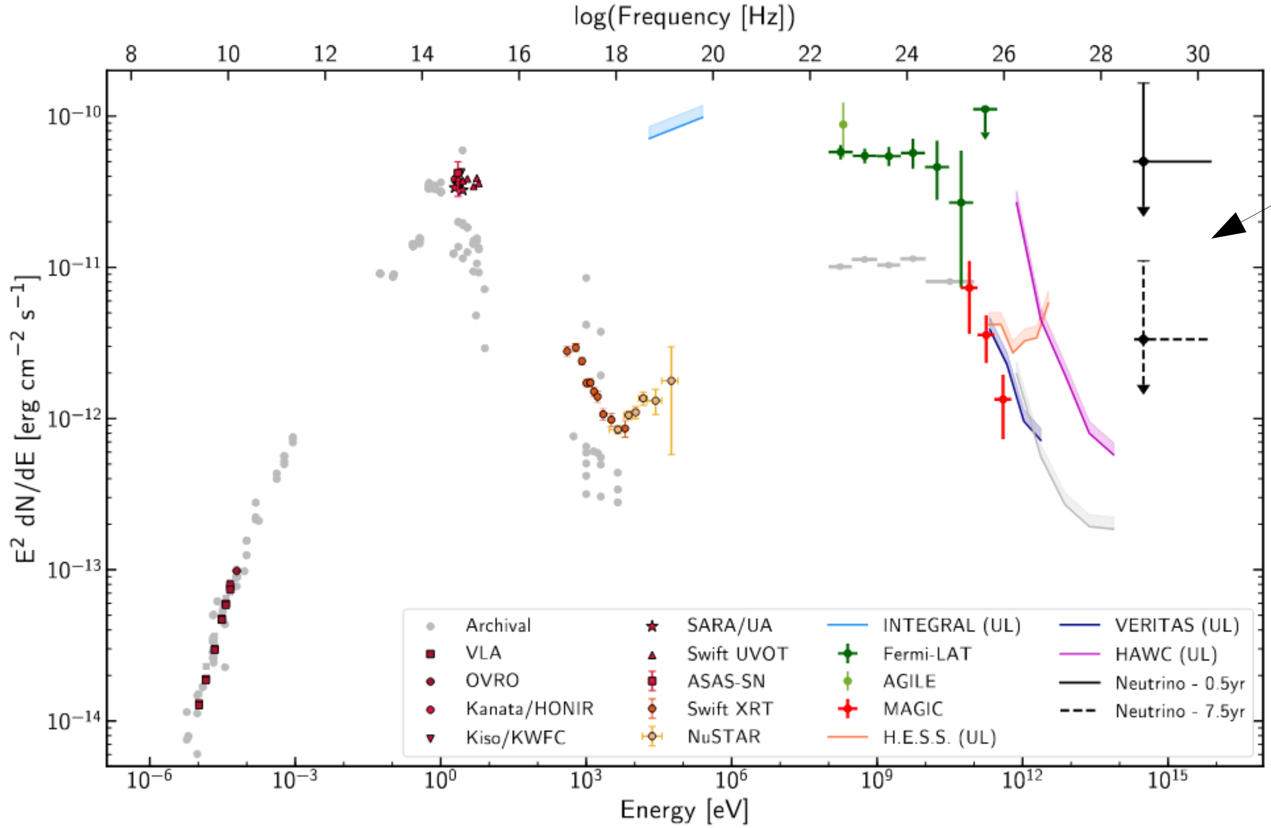
IC-170922A: a 290 TeV neutrino



Fermi-LAT

MAGIC

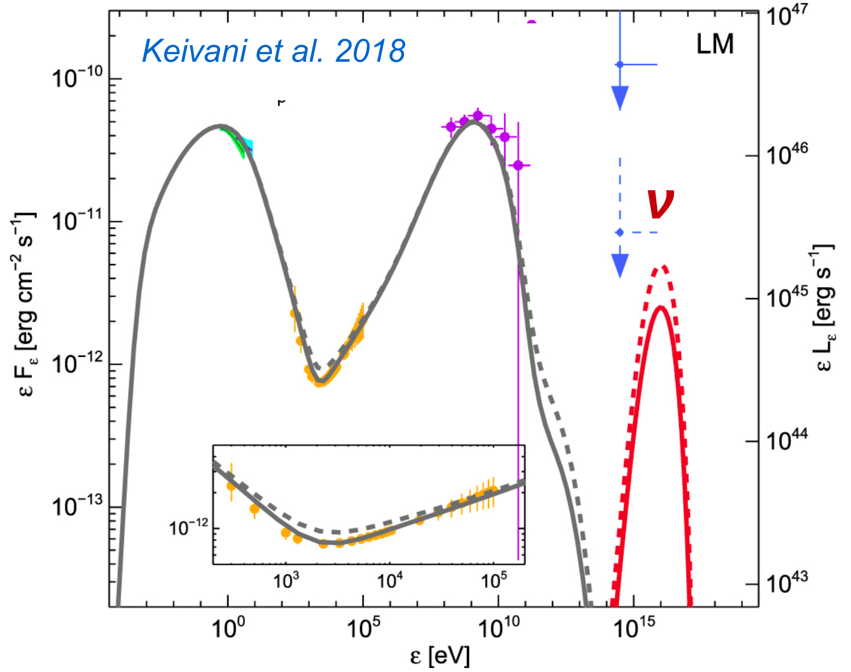


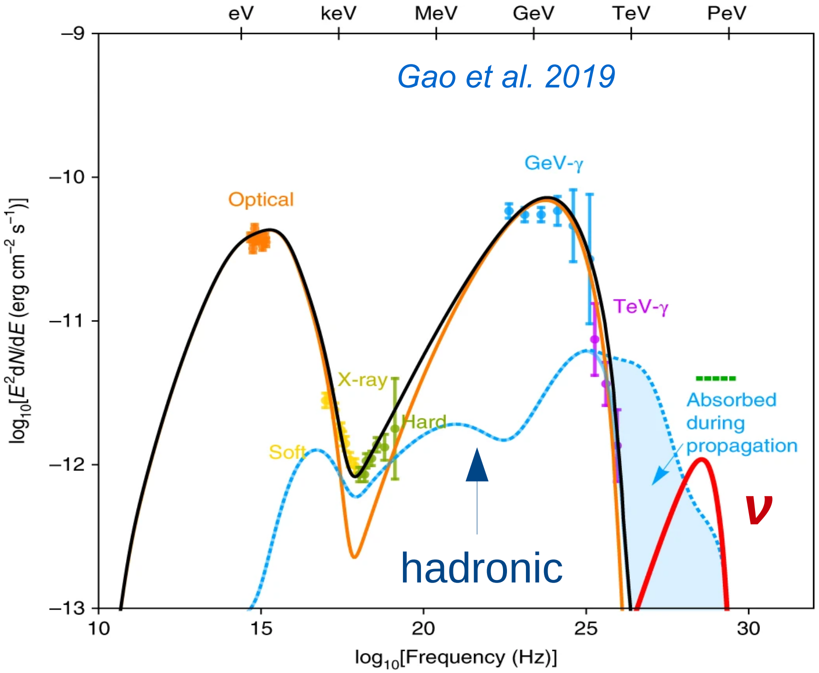


Neutrino flux

IceCube Colloboration et al. 2018a

Modeling results of the 2017 flare





- Maximum proton energies below EeV → TXS 0506+056 is unlikely to be an UHECR + PeV neutrino source.

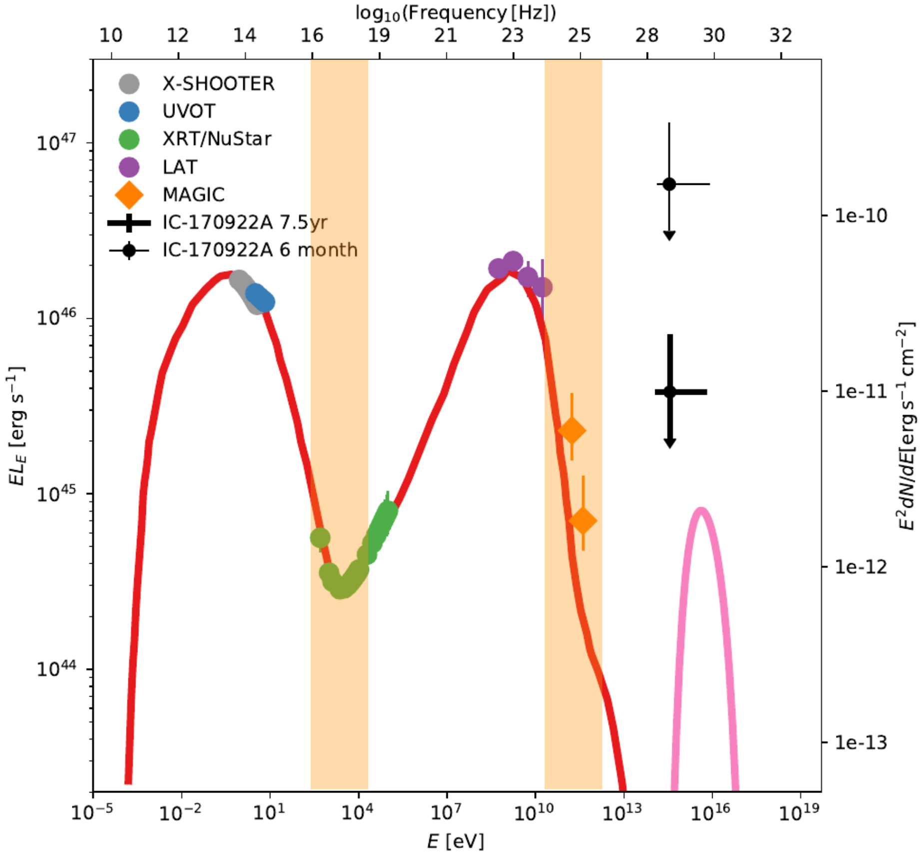
- Modeling of TXS 0506+056/IC-170922A requires a leptonic origin of γ-rays *(Ansoldi et al. 2018, Keivani et al. 2018, Cerruti et al. 2019, Gao et al. 2019)*

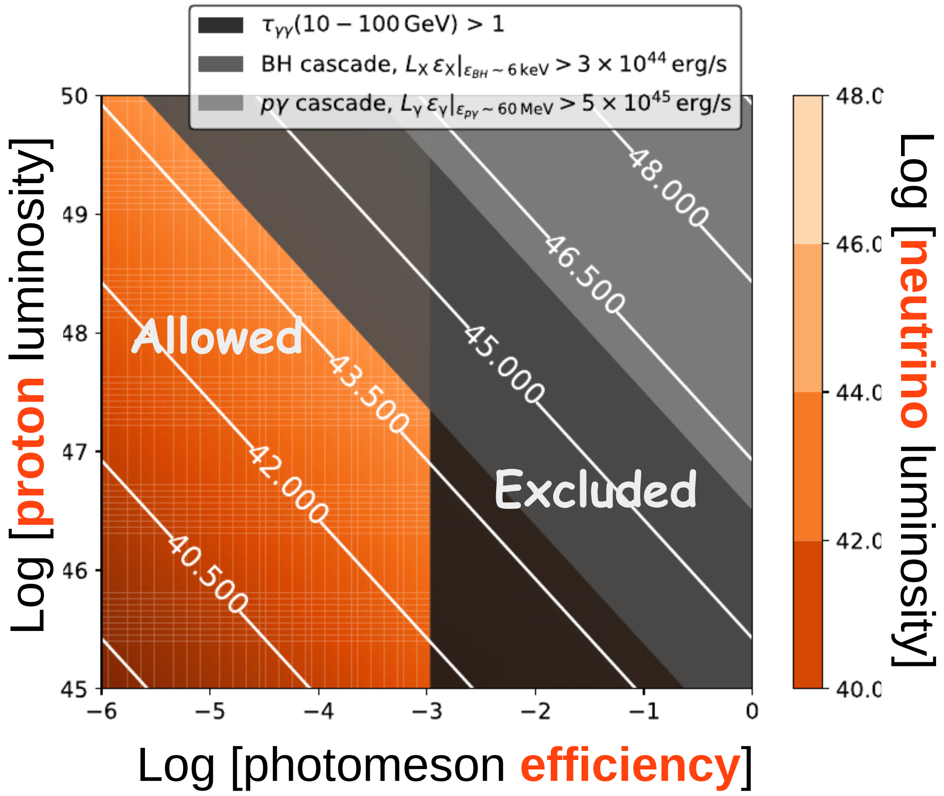
- EM emission from the hadronic component is hidden below the leptonic component *(e.g. Keivani et al. 2018, Gao et al. 2019)*

- Number of muon neutrinos per yr < 1. Still, the predictions are 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



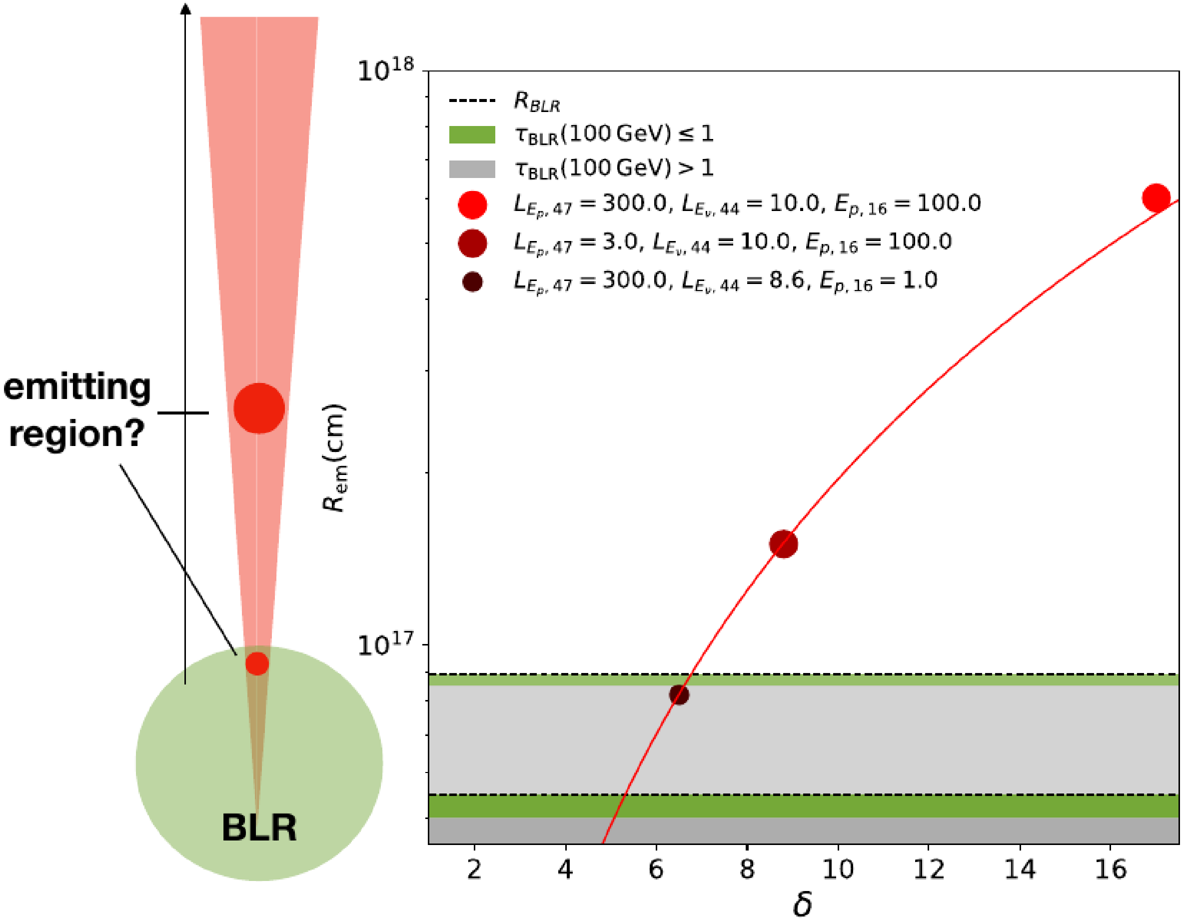


Maximum all-flavor neutrino flux:

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

Location of the emitting region of the 2017 flare

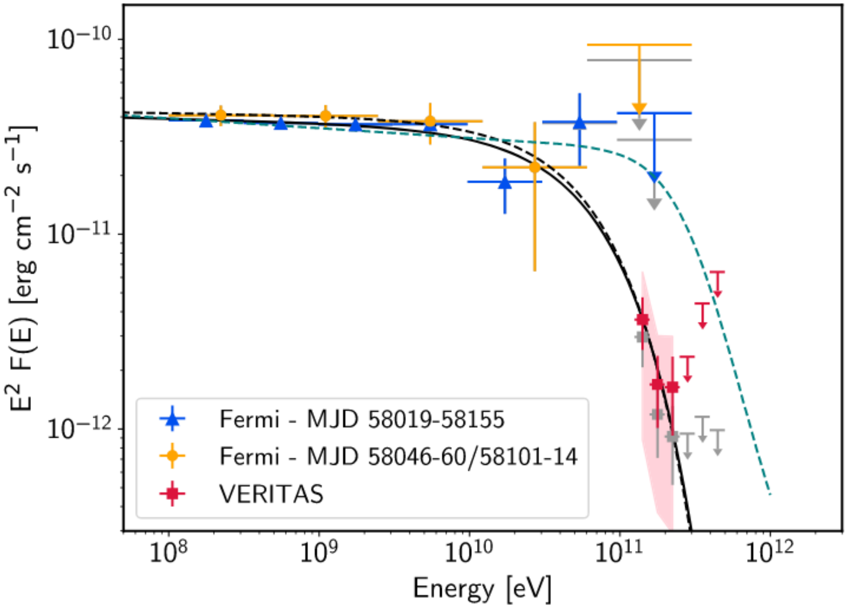
TXS 0506+056 is a “masquerading” BL Lac → weak BLR emission (L_{BLR} ~(3-8)x10^{43} erg/s) swamped by the jet emission *(Blandford & Rees 1978, Georganopoulos & Marscher 1998, Giommi & Padovani 2013, Padovani et al. 2019)*



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

Padovani et al. 2019

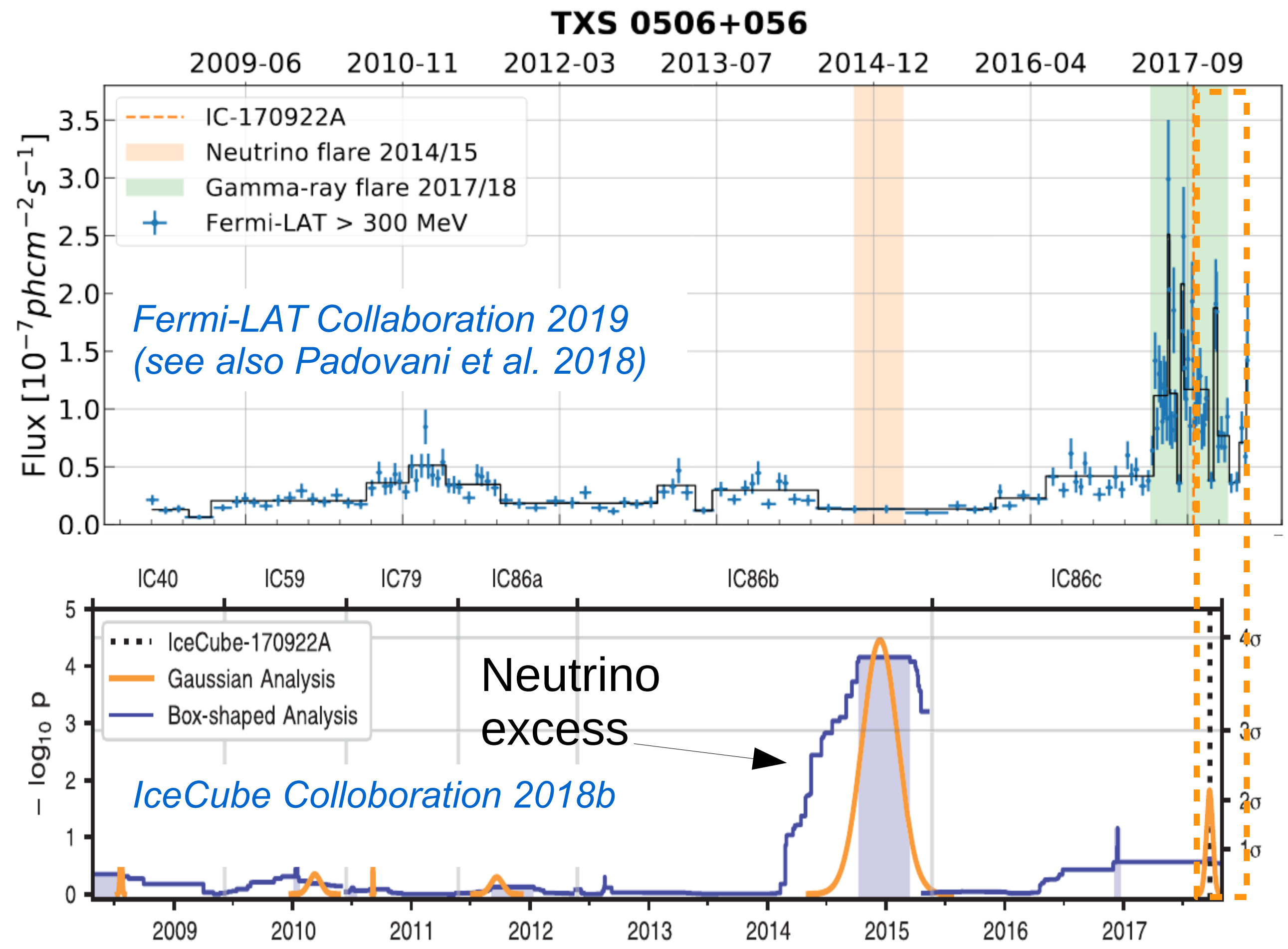
Veritas Collaboration (2018)



- 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

The TXS 0506+056 neutrino excess



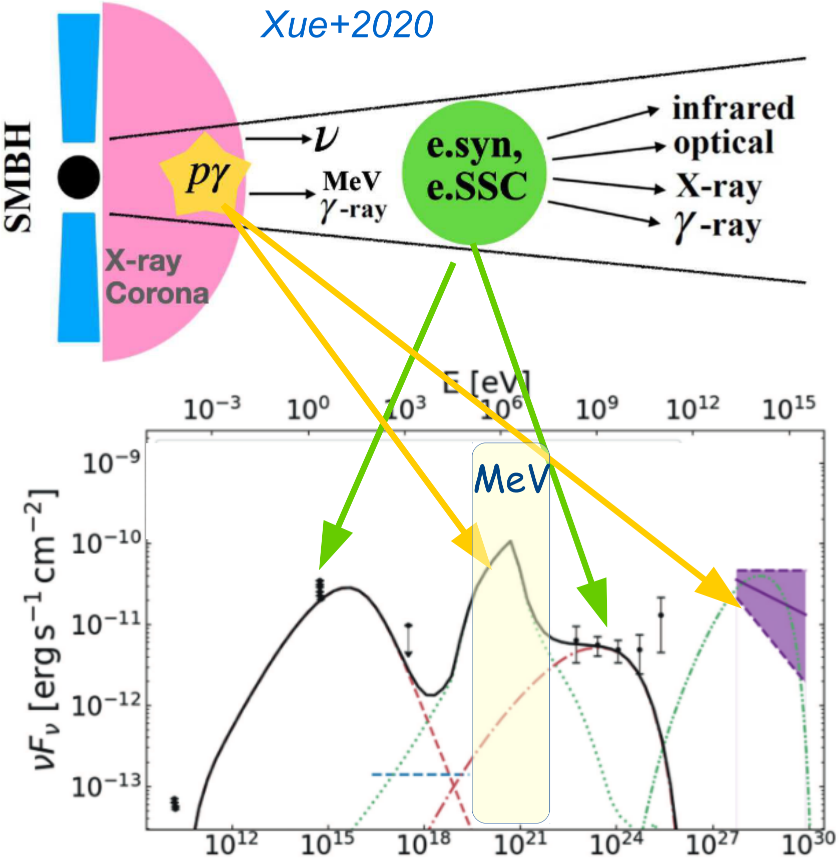
Fermi-LAT Collaboration 2019
(see also Padovani et al. 2018)

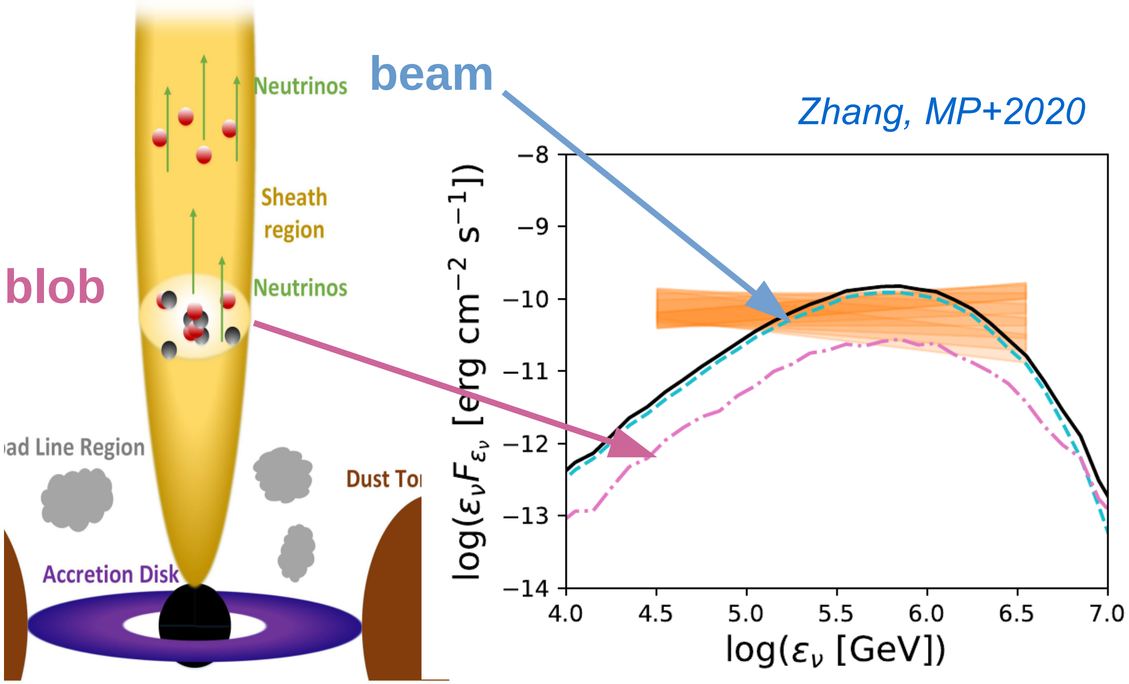
Neutrino excess

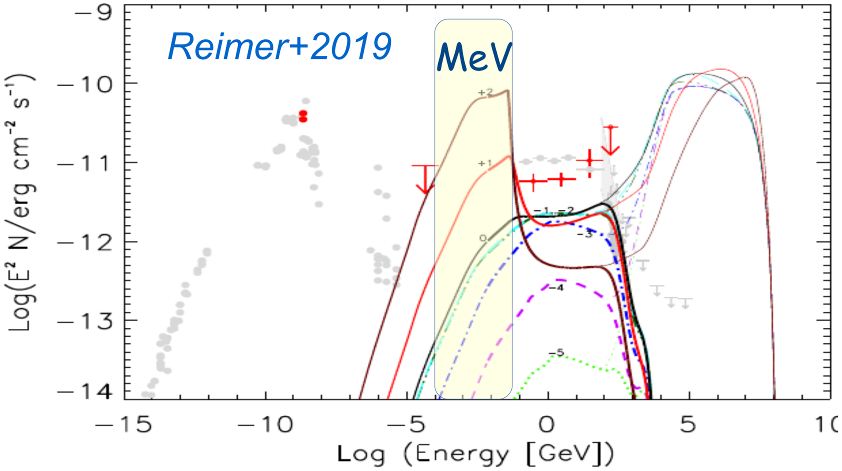
IceCube Colloboration 2018b

- 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 …

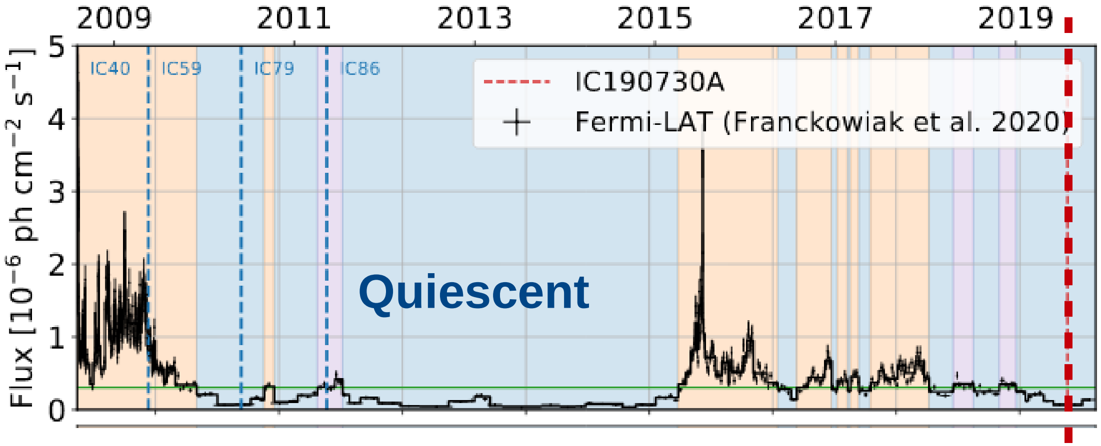






- The blazar observed EM emission is not co-spatial with the neutrino emission.
- Physical conditions in these regions are very different.
- Dense UV or X-ray external photon field is necessary → BUT not directly observed

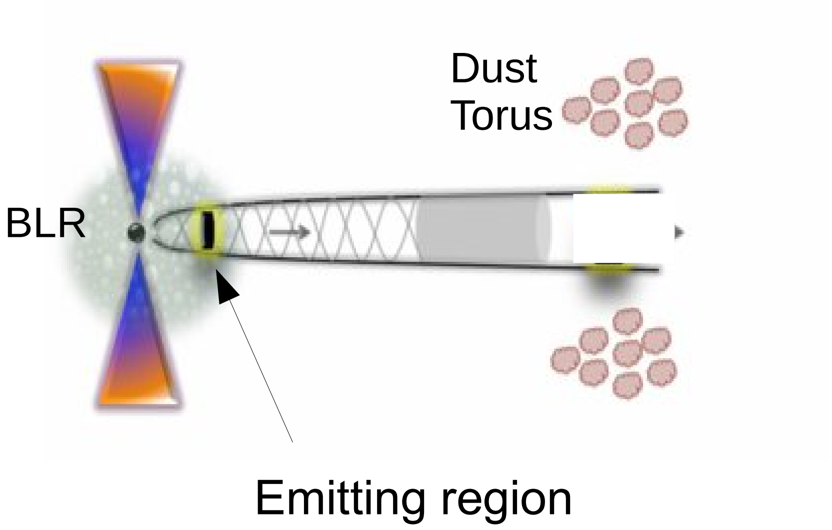
A leptohadronic model of PKS 1502+106



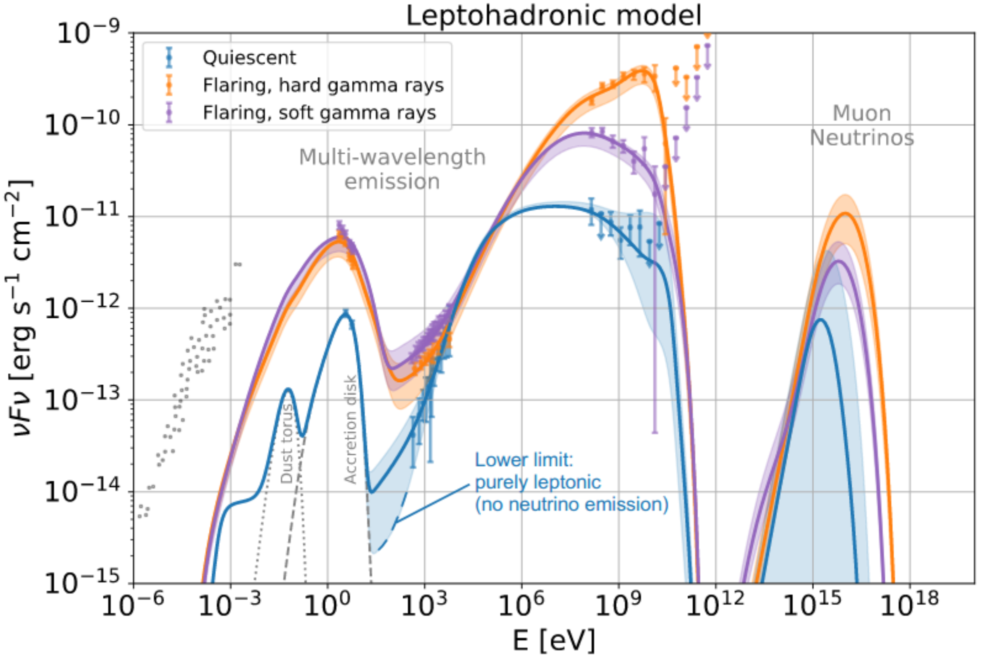
Flare

Flare

Franckowiak+2020, Rodrigues+2021



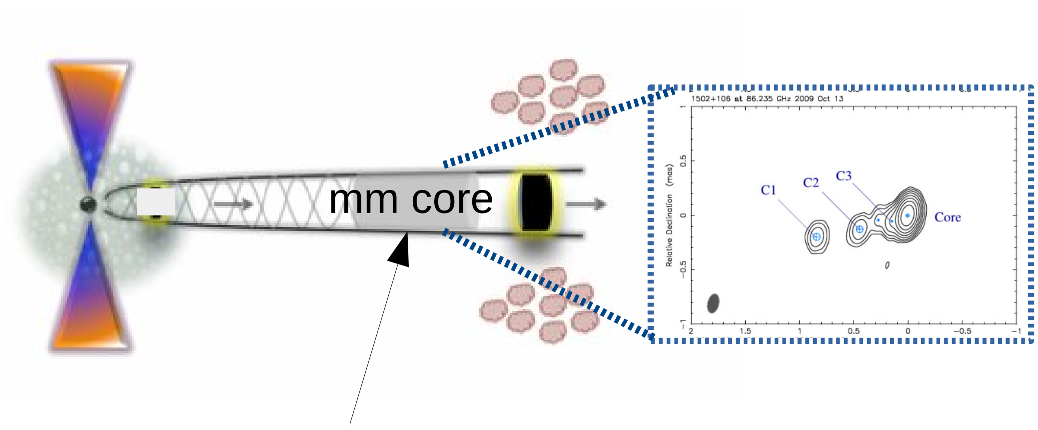
Rodrigues+2021



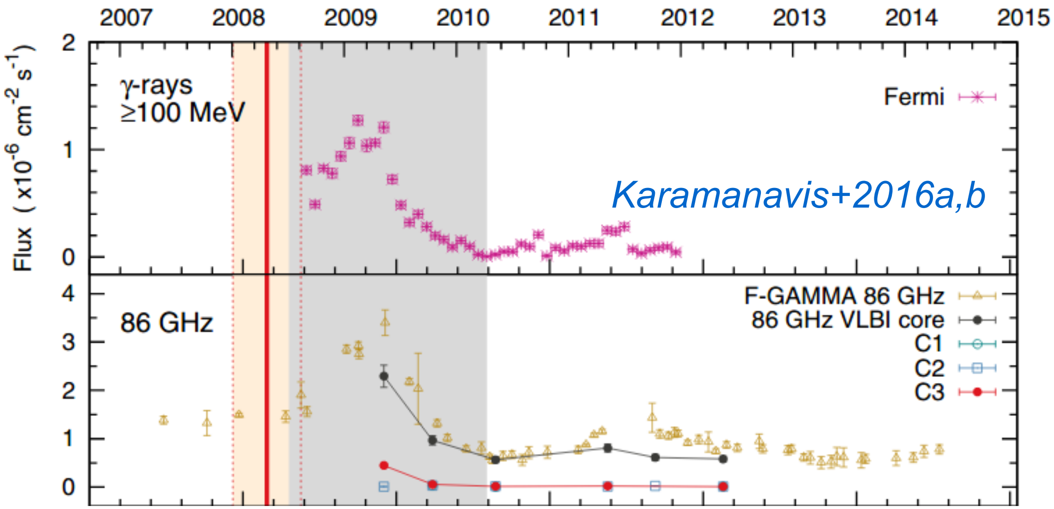
- Flares and “quiescent” emission originate within the BLR
- Leptohadronic model predicts ~ 5-16 muon neutrinos from hard flares and ~1-10 muon neutrinos from quiescent periods in 10 yr (Point Source analysis)
- The 8-yr IceCube Point Source analysis finds zero events *(Aartsen et al. 2019)*

Location of γ-ray flares in PKS 1502+106

Flares beyond the BLR



Emitting region



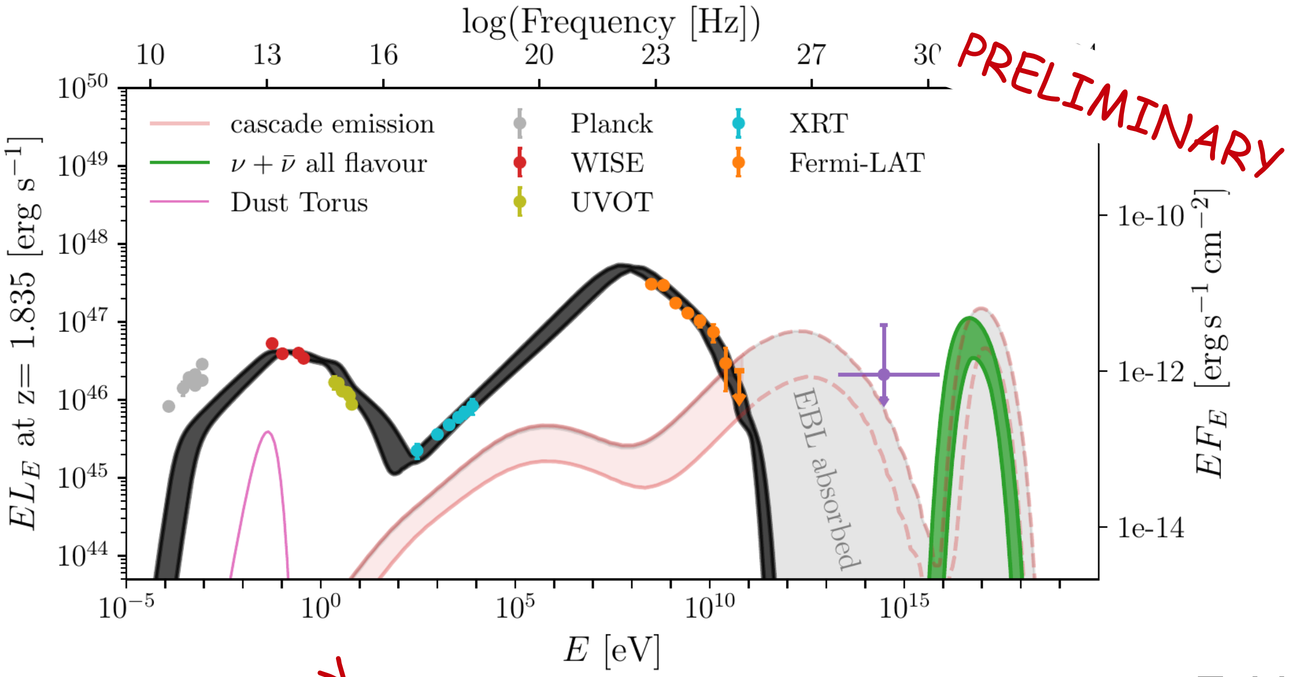
- Evidence for γ-ray flares outside the BLR *(Karamanavis+2016a,b)*

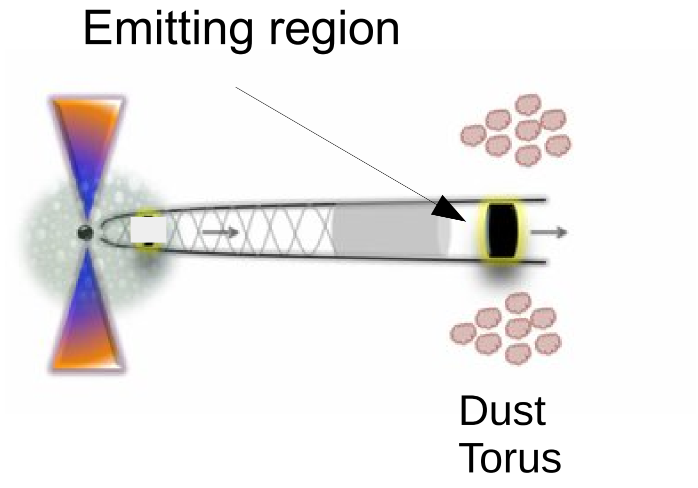
- Time of ejection of knot C3 from core coincides with onset of 2008 γ-ray flare

- Location of γ-ray flaring region outside BLR (~1 – 5 pc)

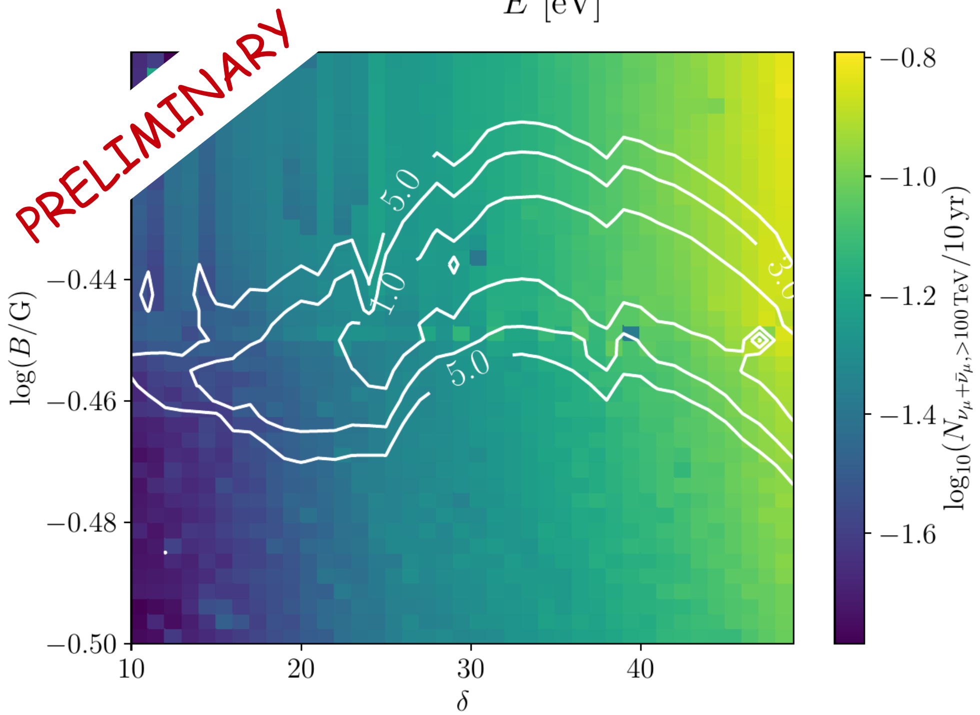
- Lower neutrino expectation from γ-ray flares than the one found by *Rodrigues+2021* due to de-boosting of BLR photon density

Neutrino production at parsec scales ?





Oikonomou, MP, Murase, in prep



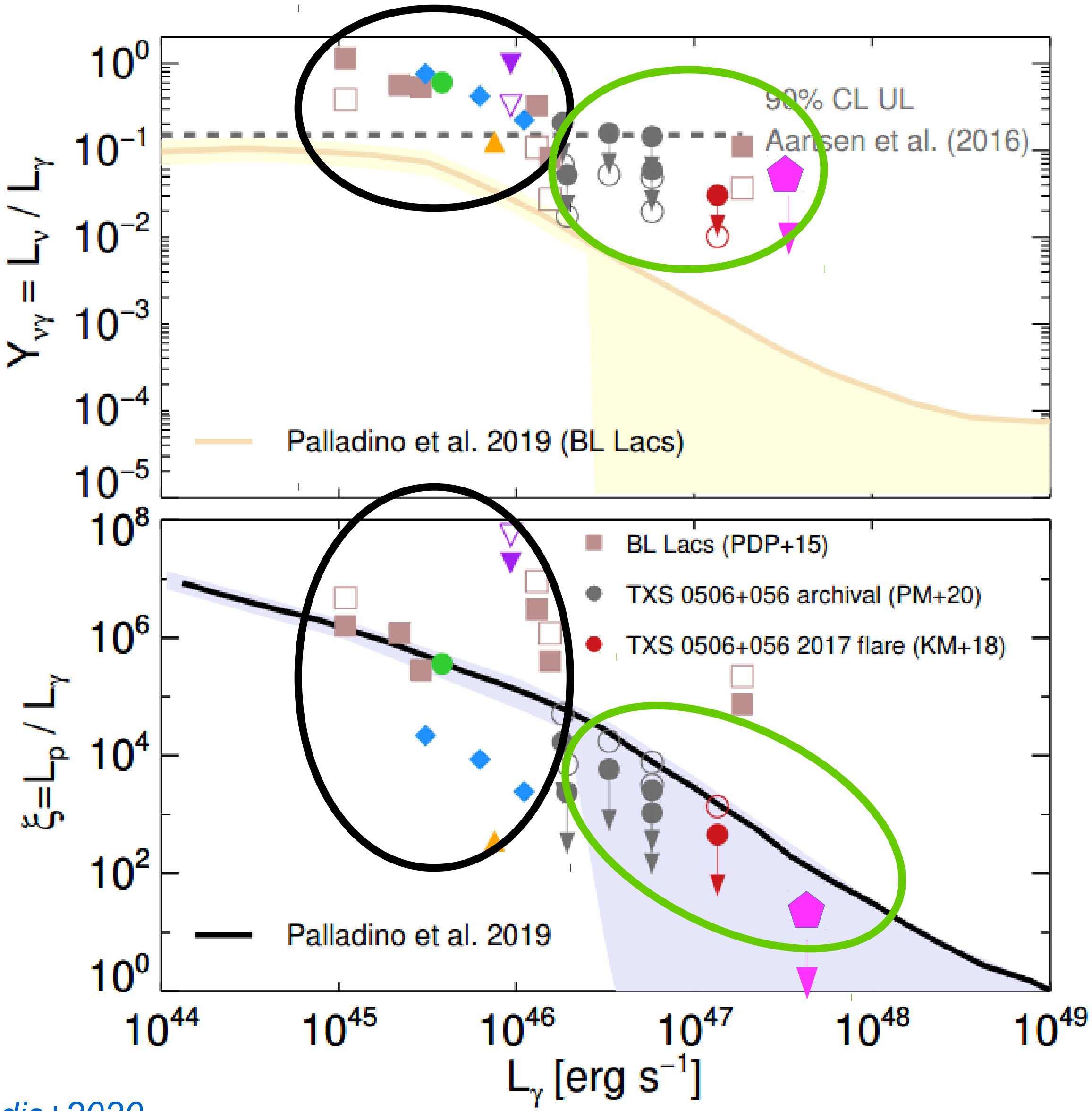
- ~EeV neutrino energies
- Parameter space search performed to find the maximum neutrino contribution
- ~0.1 muon neutrinos in 10 years of IceCube obs → consistent with 1 neutrino detection
- Similar neutrino predictions as the proton synchrotron model of *Rodrigues+2021* but with lower proton power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

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 GeV-γ-ray luminosity ratio

Baryon loading factor



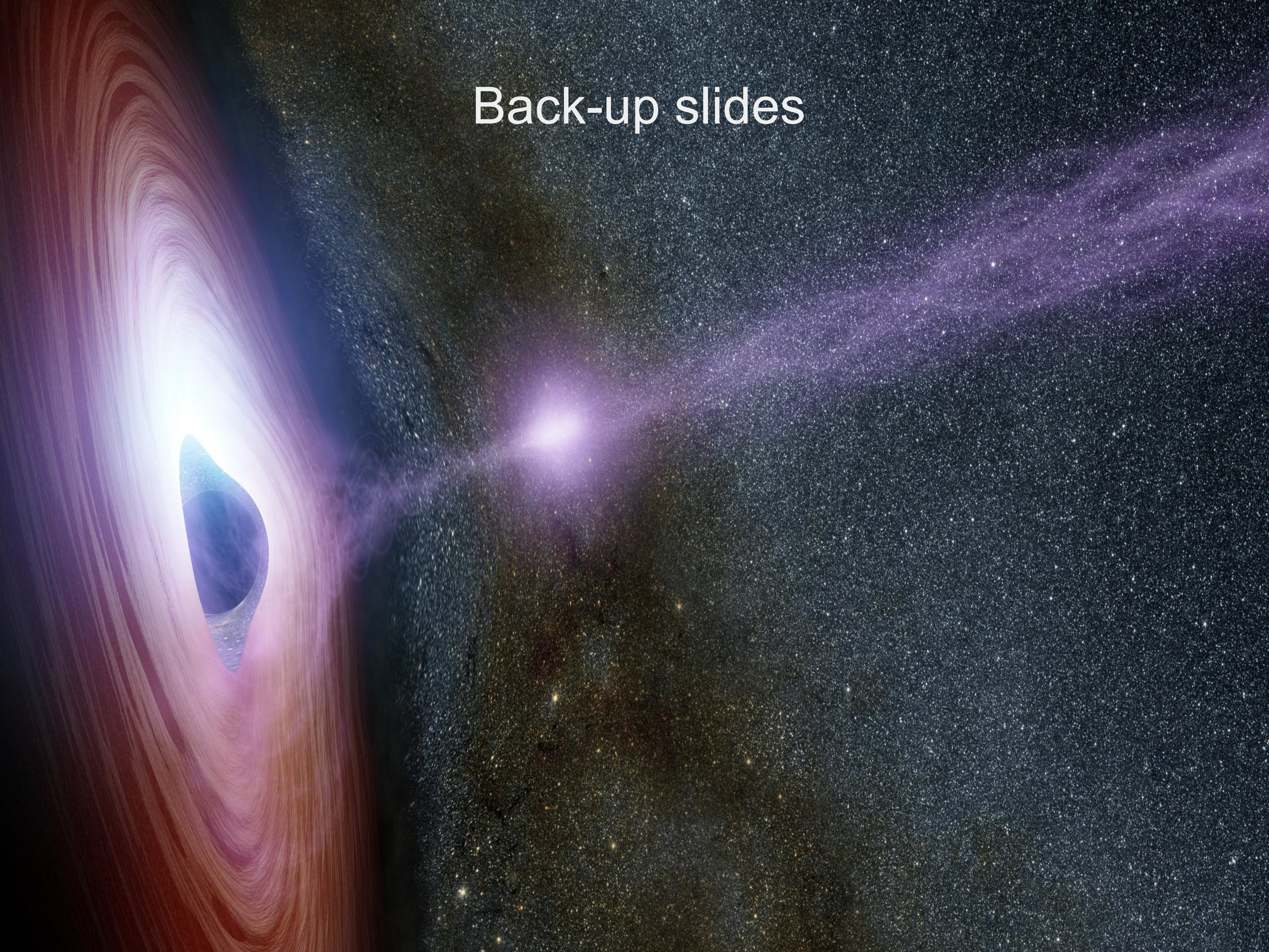
MP, Oikonomou,Mastichiadis+2020

Conclusions

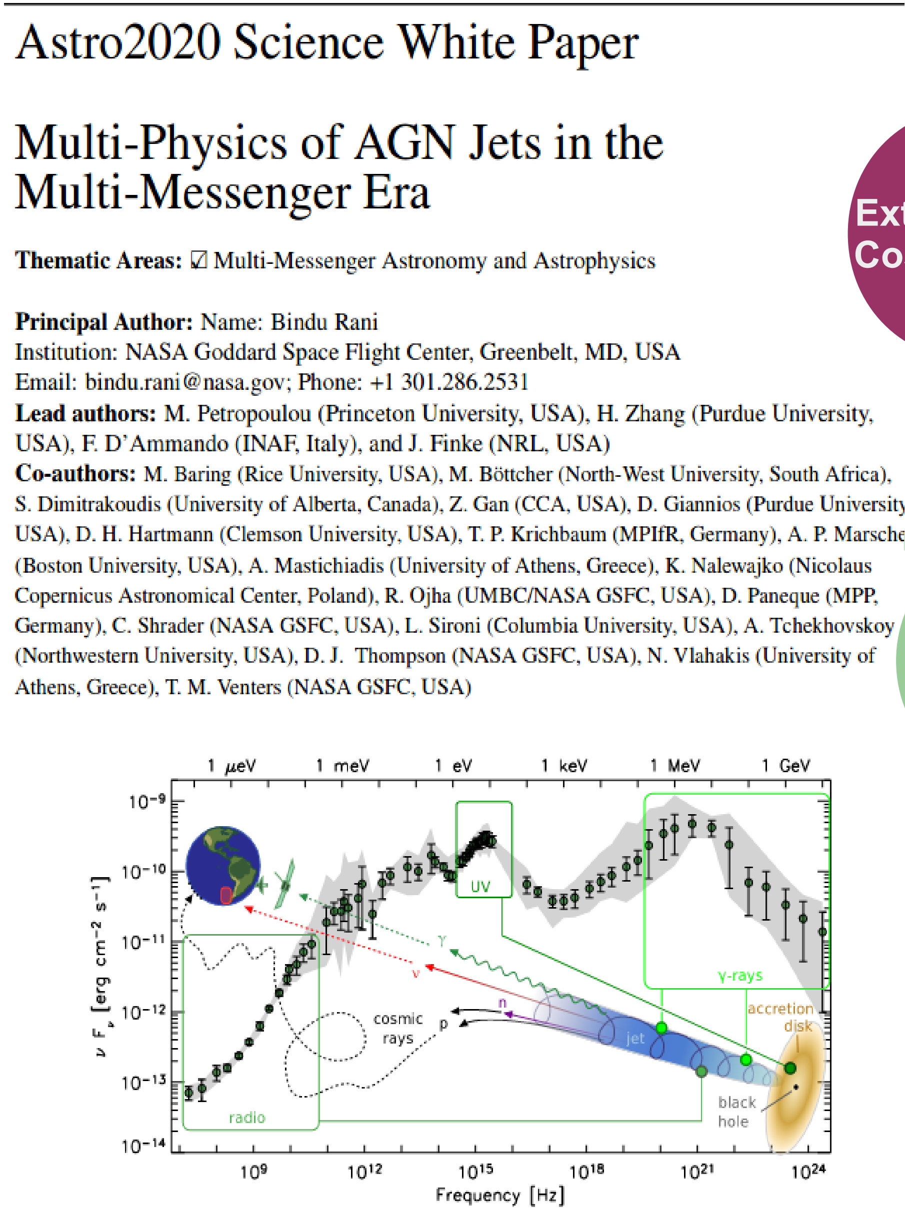
- There are hints that some of the high-energy neutrinos detected by IceCube are produced in blazars.
- Blazar TXS 0506+056 is the first astronomical source to be associated (at 3-3.5σ) with a high-energy neutrino.
- One-zone leptonic models with a radiatively sub-dominant relativistic proton population typically predict < 1 muon neutrinos in 10 yr, which is consistent with the detection of 1 neutrino event in this time window.
- Neutrino emission is accompanied by an equally bright EM cascade emission that typically emerges in the X-ray and MeV gamma-ray bands.
- Exceptional events (e.g. 2014-15 neutrino excess of TXS 0506+056) where the neutrino fluence exceeds the observed X-ray and gamma-ray fluences imply decoupled production sites with very different physical conditions.

Development of physical models for blazar multi-messenger emission coupled with advances in our understanding of jet dissipation and baryon loading mechanisms will help us solve the mystery of astrophysical high-energy neutrinos!

Back-up slides



Open questions



Astro2020 Science White Paper

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

Thematic Areas: ☑ Multi-Messenger Astronomy and Astrophysics

Principal Author: Name: Bindu Rani
Institution: NASA Goddard Space Flight Center, Greenbelt, MD, USA
Email: bindu.rani@nasa.gov; Phone: +1 301.286.2531
Lead authors: M. Petropoulou (Princeton University, USA), H. Zhang (Purdue University, USA), F. D'Ammando (INAF, Italy), and J. Finke (NRL, USA)
Co-authors: M. Baring (Rice University, USA), M. Böttcher (North-West University, South Africa), S. Dimitrakoudis (University of Alberta, Canada), Z. Gan (CCA, USA), D. Giannios (Purdue University USA), D. H. Hartmann (Clemson University, USA), T. P. Krichbaum (MPIfR, Germany), A. P. Marsche (Boston University, USA), A. Mastichiadis (University of Athens, Greece), K. Nalewajko (Nicolaus Copernicus Astronomical Center, Poland), R. Ojha (UMBC/NASA GSFC, USA), D. Paneque (MPP, Germany), C. Shrader (NASA GSFC, USA), L. Sironi (Columbia University, USA), A. Tchekhovskoy (Northwestern University, USA), D. J. Thompson (NASA GSFC, USA), N. Vlahakis (University of Athens, Greece), T. M. Venters (NASA GSFC, USA)

Extragalactic Cosmic Rays

What are the radiating particles?

How is the jet energy dissipated?

High-energy Neutrinos

Blazar Key Questions

Where is the emission region of jets?

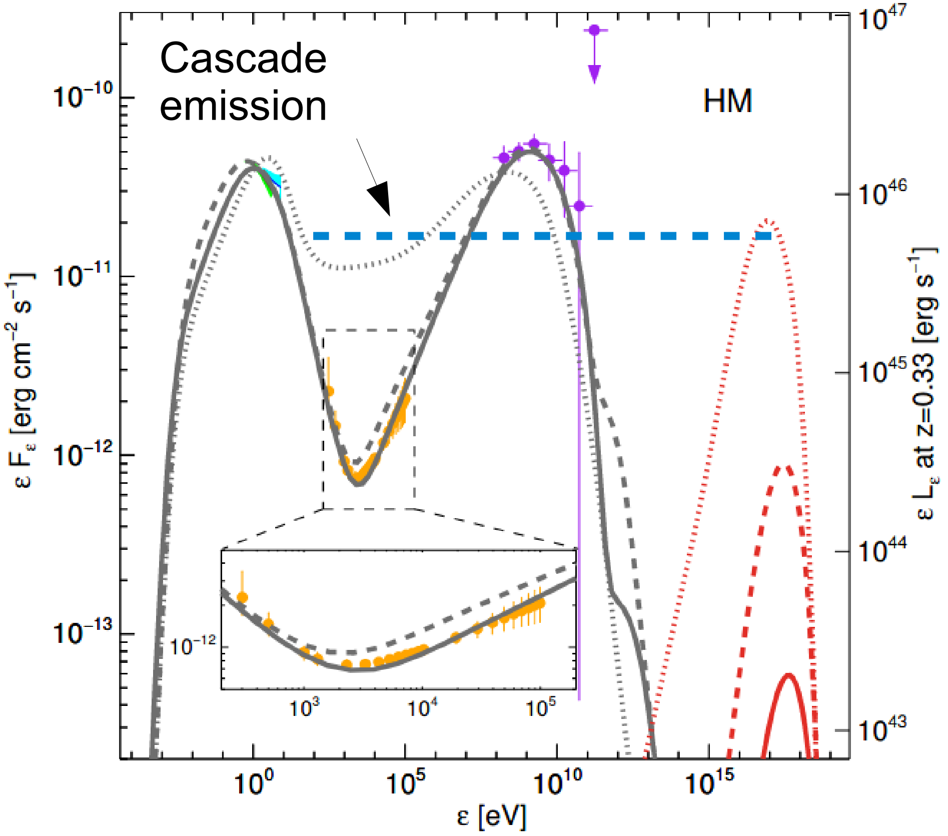
How are particles accelerated in jets?

ADS link

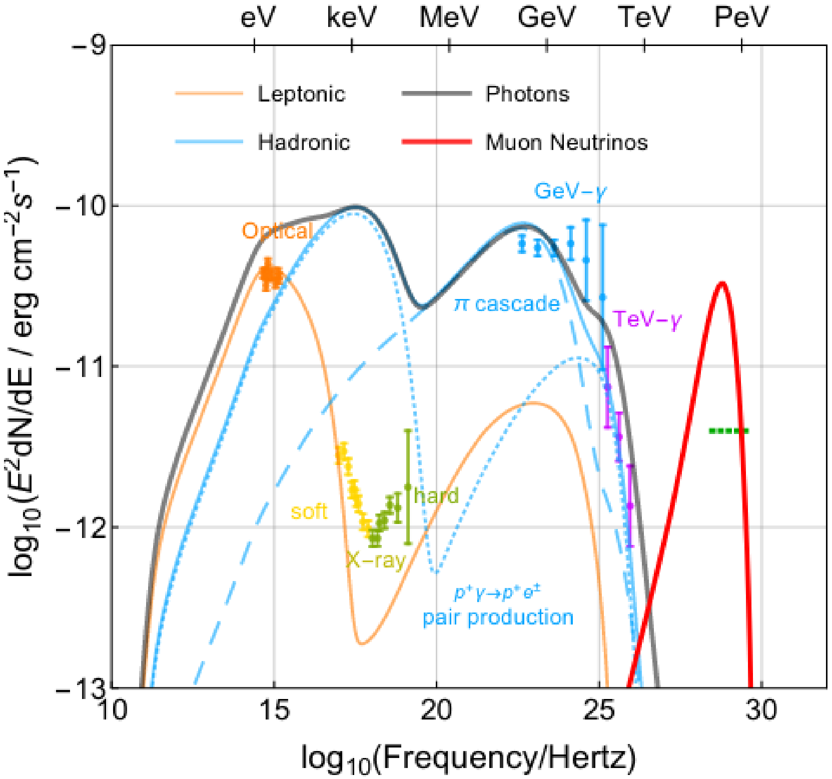
Leptohadronic models of TXS 0506+056

Leptohadronic one-zone models for the 2017 flare are disfavored

Keivani et al. 2018

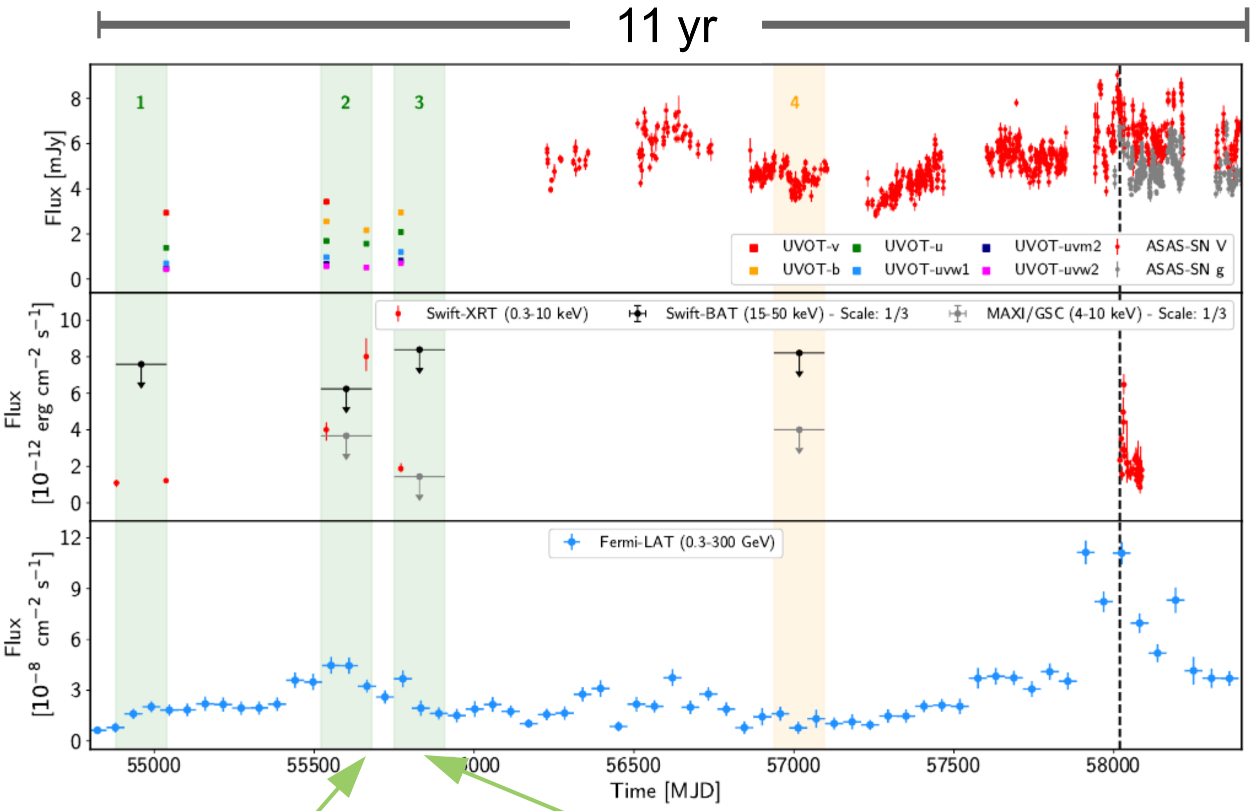


Gao et al. 2019

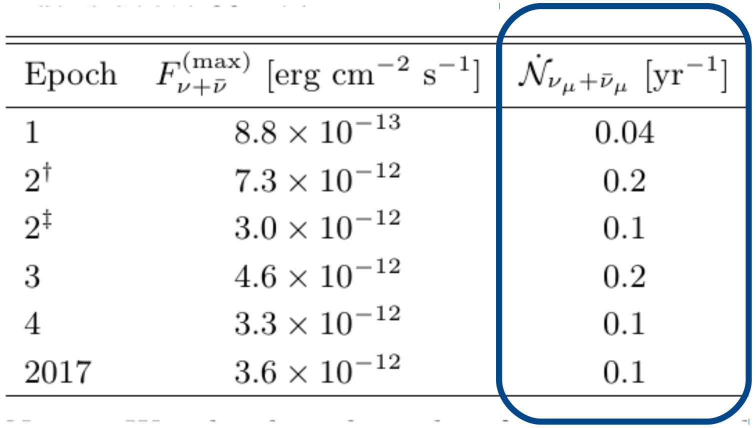


- Model with γ-rays coming from pion-induced cascade ($L_\gamma – L_\nu$) is ruled out.
- Model with γ-rays from proton synchrotron leads to EeV neutrinos with very low luminosities.
- IC-170922A cannot be explained in this scenario.

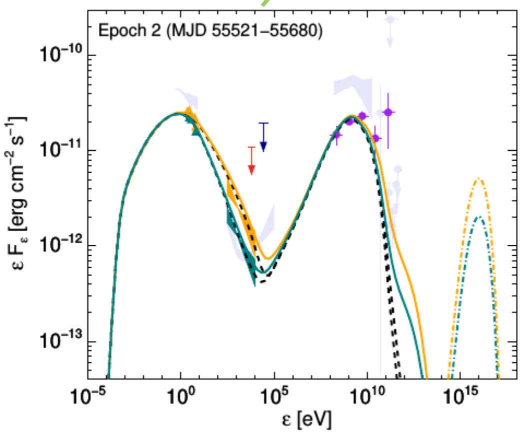
Multi-epoch modeling of TXS 0506+056

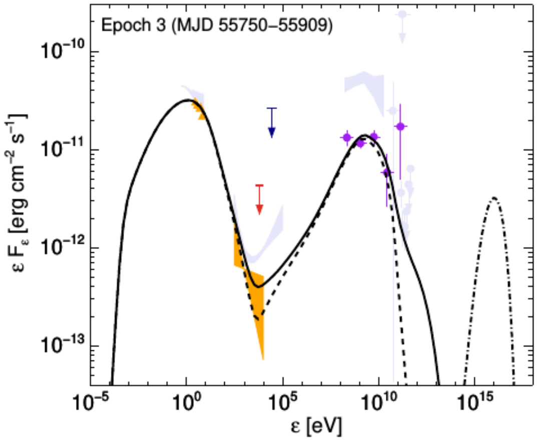


- Multi-epoch obs can be explained by processes of accelerated electrons with small changes in the electron distribution (e.g. power-law index, electron luminosity)
- Upper limit of ∼ 0.4 − 2 muon neutrinos in 10 yr of IceCube obs
- IceCube-170922A → upper fluctuation from the average neutrino rate ?



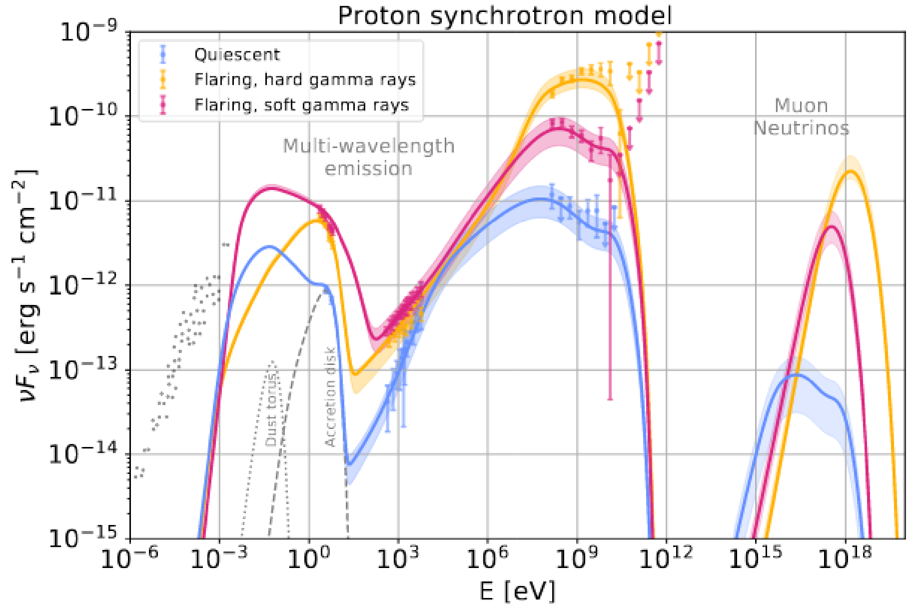
Epoch	$F^{(\max)}_{\nu+\bar{\nu}}$ [erg cm^{-2} s^{-1}]	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}$ [yr^{-1}]
1	8.8×10^{-13}	0.04
$2^\dagger$	7.3×10^{-12}	0.2
$2^\ddagger$	3.0×10^{-12}	0.1
3	4.6×10^{-12}	0.2
4	3.3×10^{-12}	0.1
2017	3.6×10^{-12}	0.1

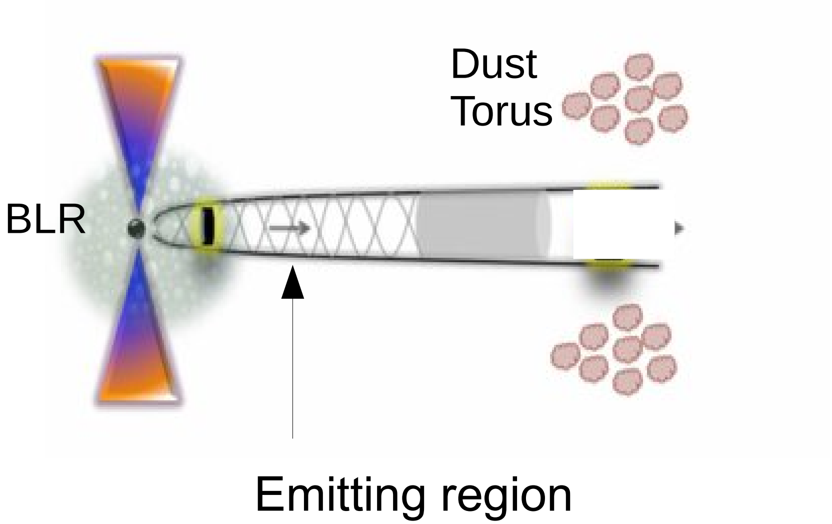




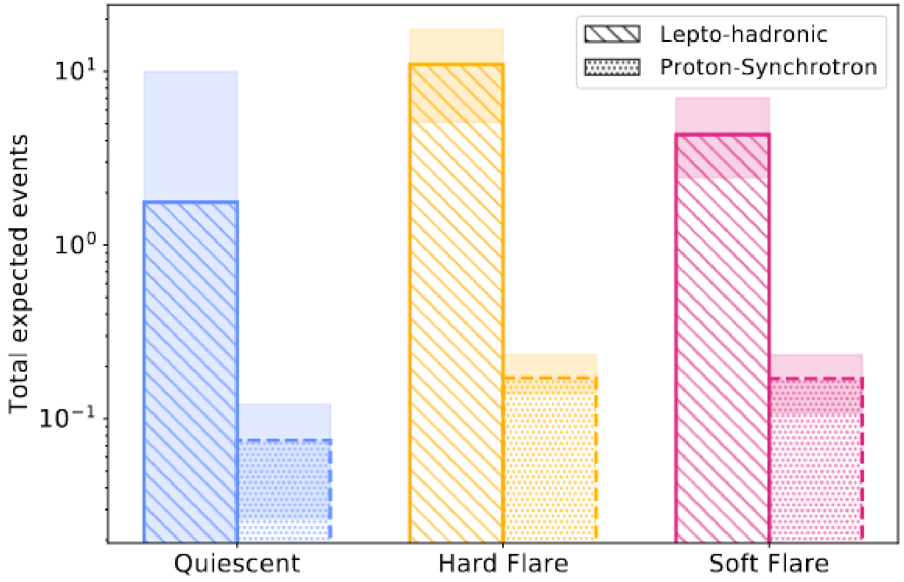
MP, Murase, Oikonomou et al. 2020

A proton-synchrotron model of PKS 1502+106





Rodrigues+2021

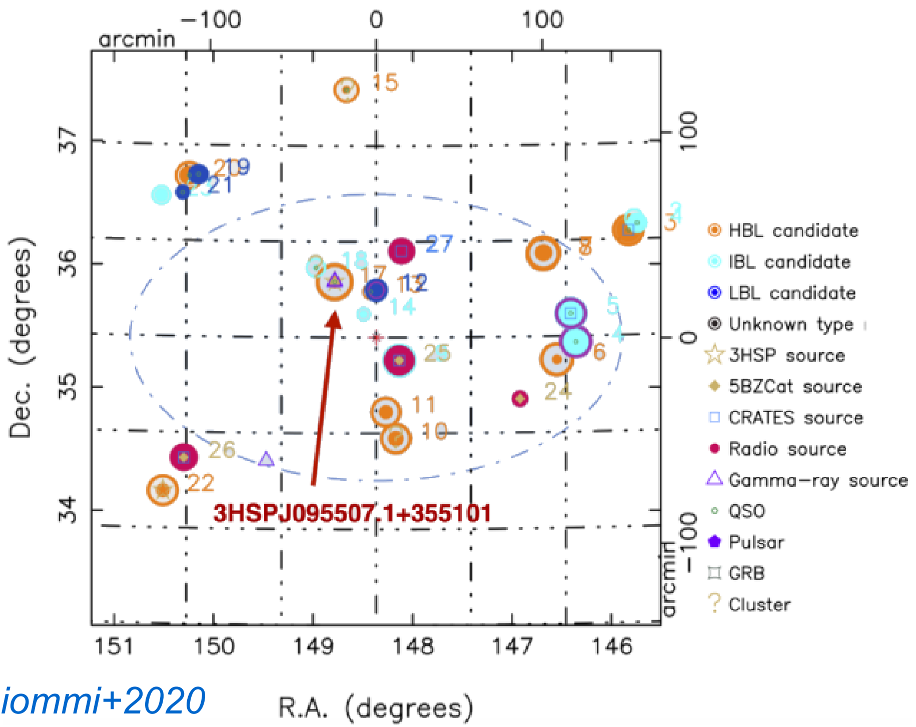


- Proton synchrotron model predicts ~EeV neutrino energies and ~ 0.1 muon neutrinos in 10 yr
- Similar to our pc-scale hybrid leptonic model

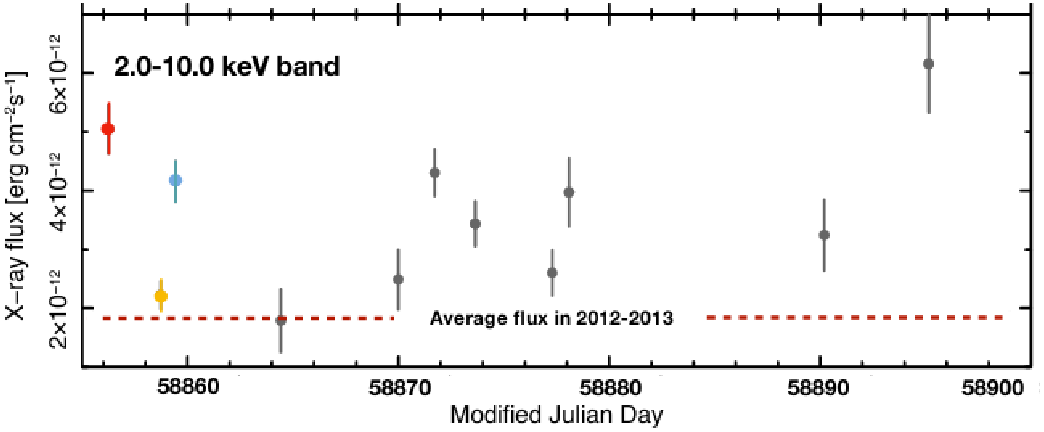
Summary of the 2017 flare modeling results

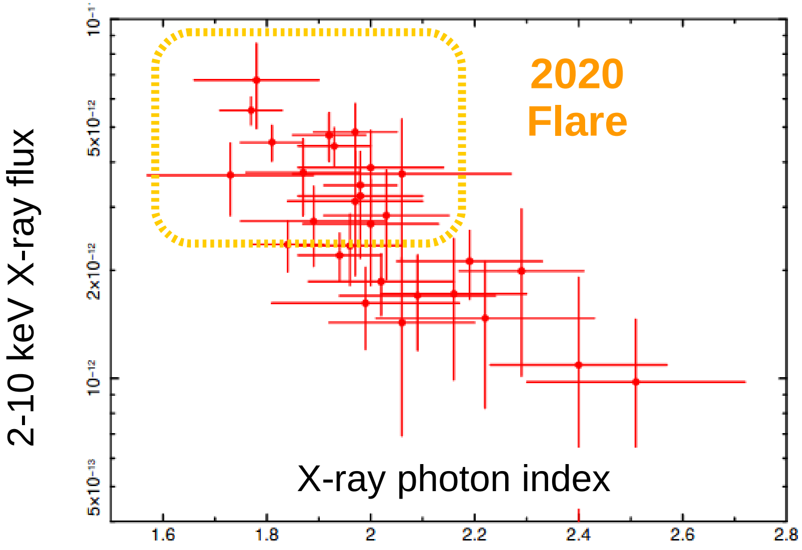
	Origin of γ-rays	**$E_{p,max}$**	**# of ν_μ in 0.5 yr**
Ansoldi et al. 2018	Leptonic – ECS	0.4 EeV	~0.06
Keivani et al. 2018	Leptonic – ECS	~0.04 – 2 EeV	~0.001 – 0.01
Cerruti et al. 2019	Leptonic – SSC	~(0.6-20)x (δ/10) EeV	~0.004 – 0.05
Gao et al. 2019	Leptonic – SSC	4.5 PeV	~0.13

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.

Leptohadronic modeling of the X-ray flare

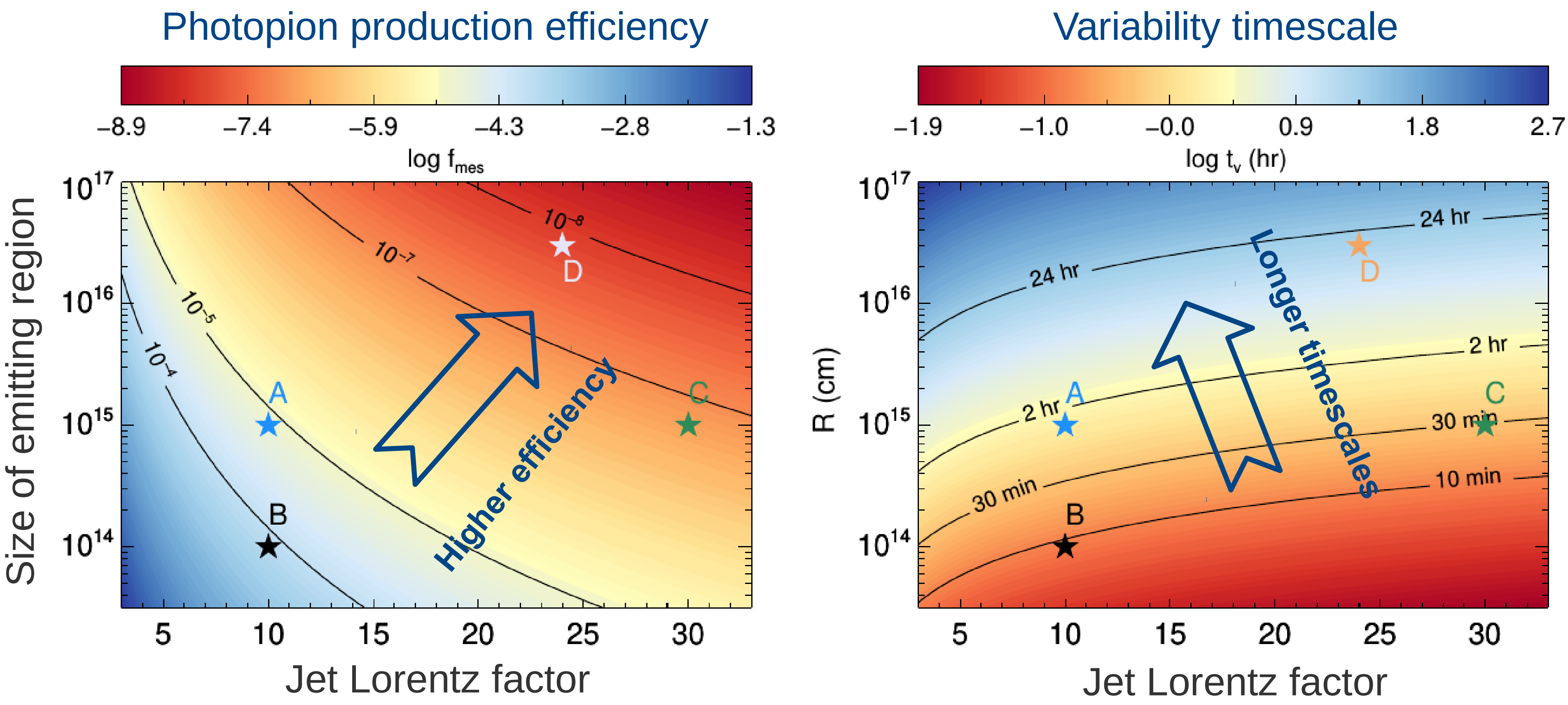
Petropoulou, Oikonomou, Mastichiadis et al. 2020

Proton energy

Jet photon number density

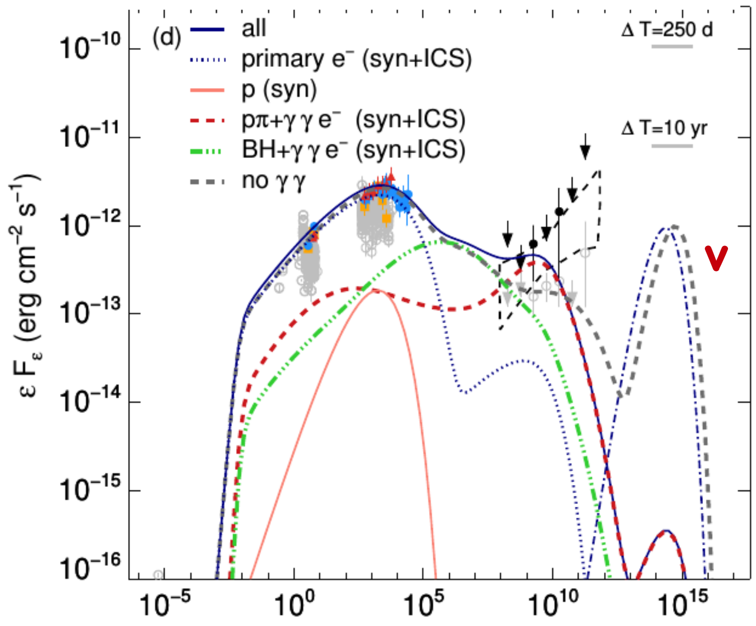
Spectral index

Photopion production efficiency: $f_{p\gamma}(E'_p) \approx \frac{t_{\rm dyn}}{t_{p\gamma}} \simeq \frac{2\kappa_\Delta\sigma_\Delta}{1+\beta}\frac{\Delta\bar{\varepsilon}_\Delta}{\bar{\varepsilon}_\Delta}\frac{3L^s_{\rm rad}}{4\pi r_b\Gamma^2 c E'_s}\left(\frac{E'_p}{E'^b_p}\right)^{\beta-1}$

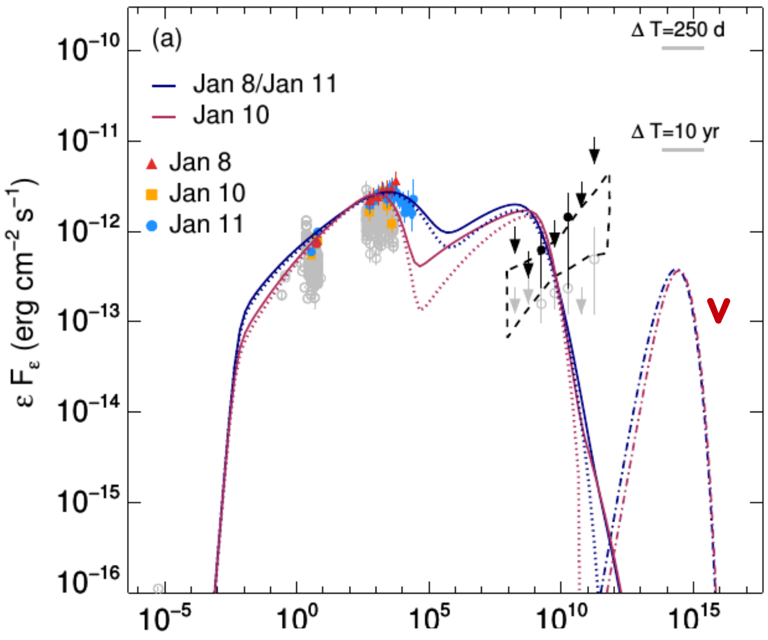


Leptohadronic modeling of the X-ray flare

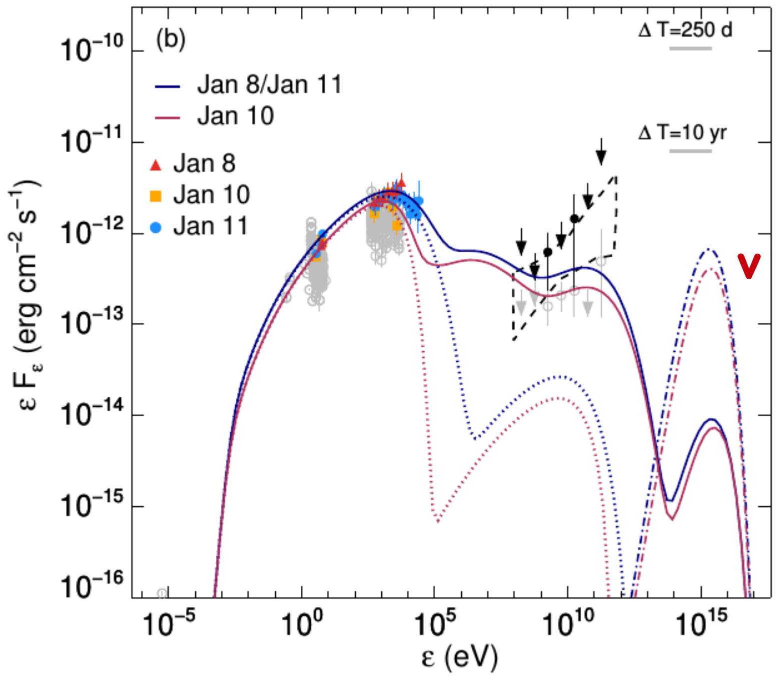
Model A



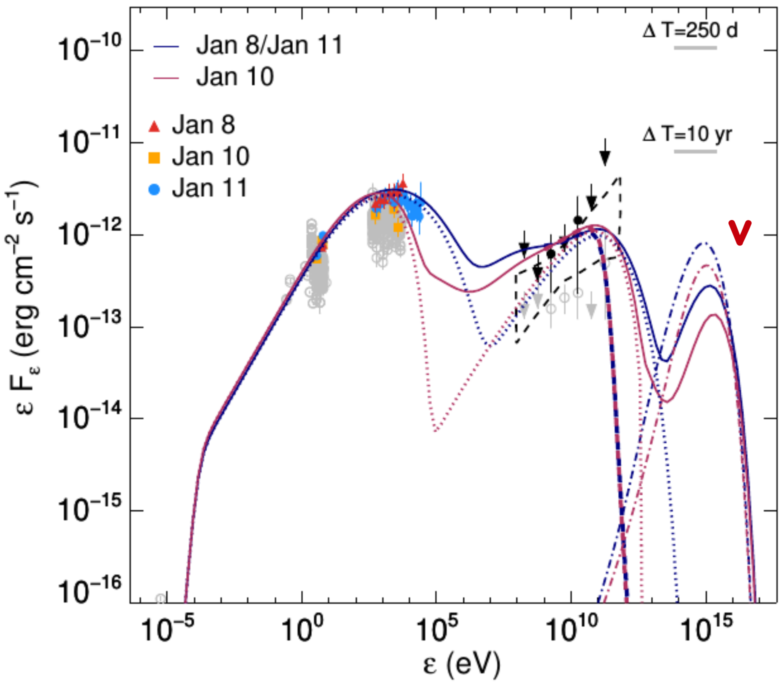
Model B



Model C

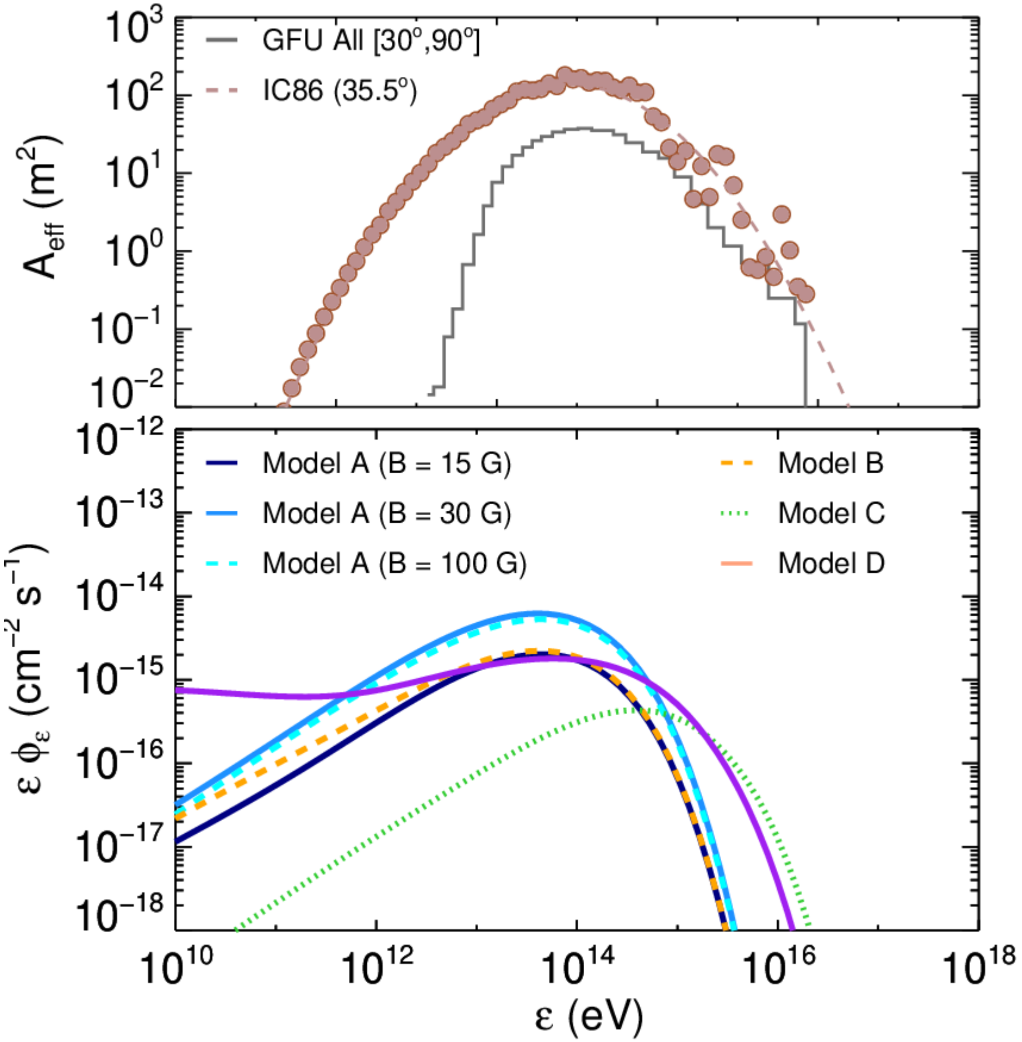


Model D



Neutrino expectation in the leptohadronic model - 1

SED modeling of the X-ray flare



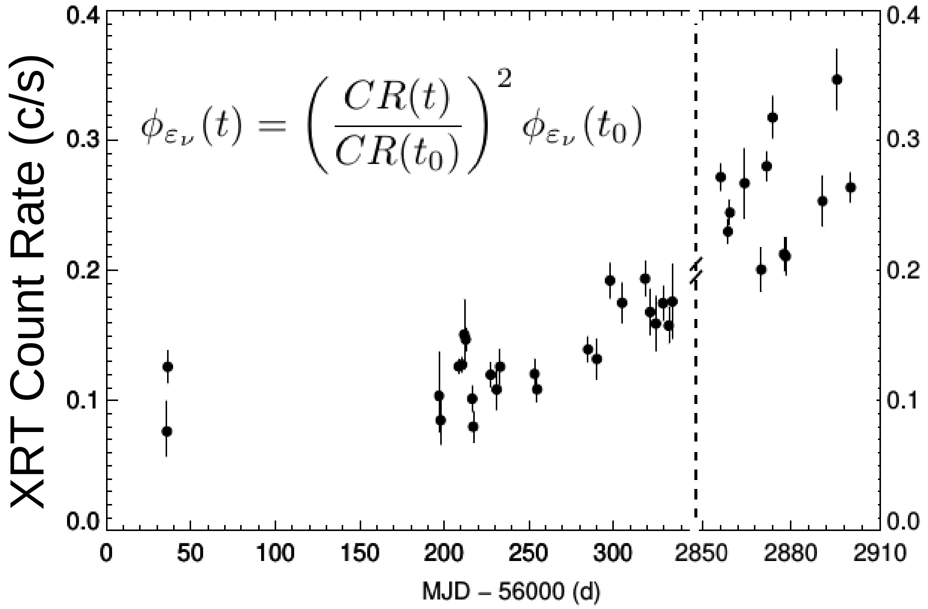
$$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu} = \frac{1}{3}\int_{\varepsilon_{\nu,\rm min}}^{\varepsilon_{\nu,\rm max}} d\varepsilon_\nu\, A_{\rm eff}(\varepsilon_\nu,\delta)\phi_{\varepsilon_\nu}.$$

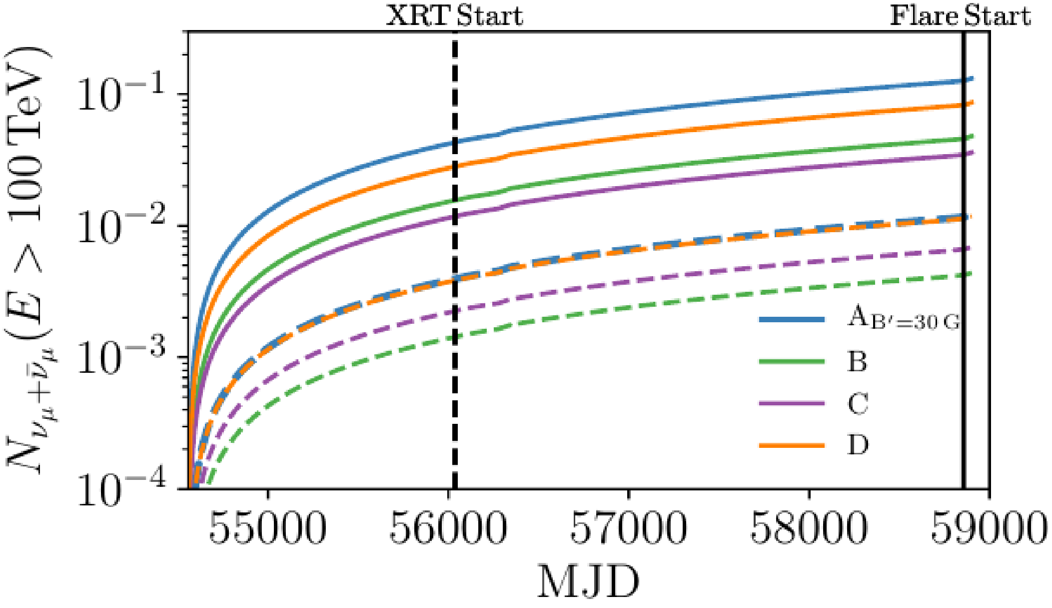
Model	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}(> 100\ \mathrm{TeV})$ $(\times 10^{-4}\ \mathrm{yr}^{-1})$ Alert (Point Source)	$\mathcal{P}\|_{1\,\nu_\mu\ \mathrm{or}\ \bar{\nu}_\mu}(> 100\ \mathrm{TeV})$ Alert (Point Source)
$\mathrm{A}_{(B'=15\mathrm{G})}$	17 (190)	0.02 (0.2) %
$\mathrm{A}_{(B'=30\mathrm{G})}$	50 (540)	0.06 (0.7) %
$\mathrm{A}_{(B'=100\mathrm{G})}$	45 (490)	0.05 (0.6) %
B	18 (200)	0.02 (0.2) %
C	25 (100)	0.03 (0.1) %
D	40 (210)	0.05 (0.3) %

Probability to detect 1 ν_μ during X-ray flare (~44 d) << 1

Neutrino expectation in the leptohadronic model - 2

Full XRT light curve + ν /X-ray correlation



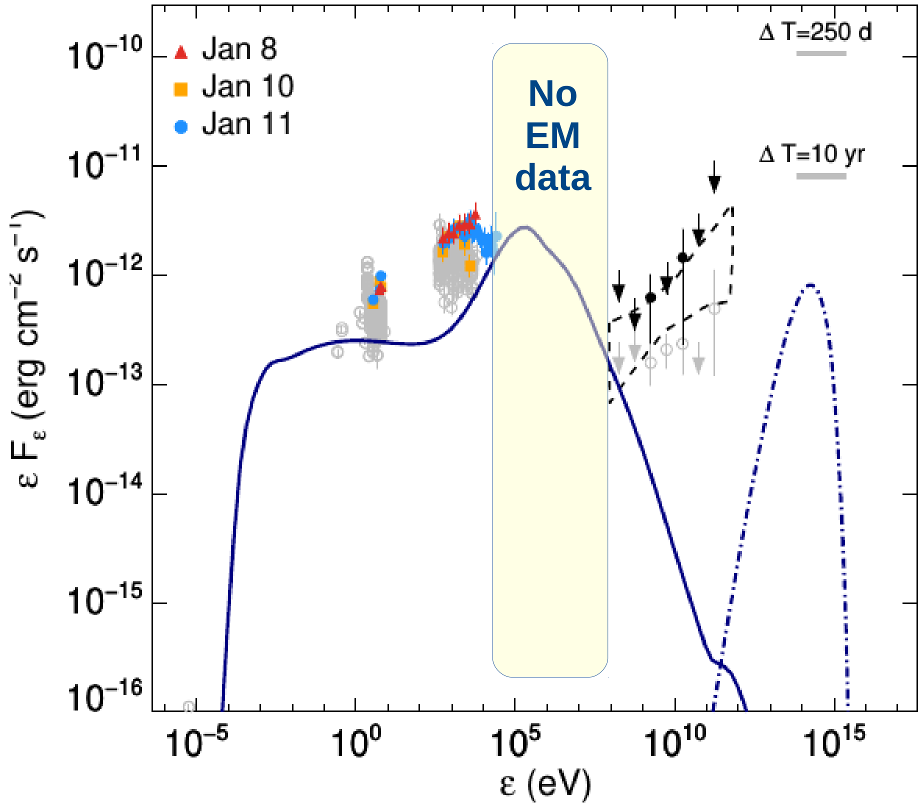


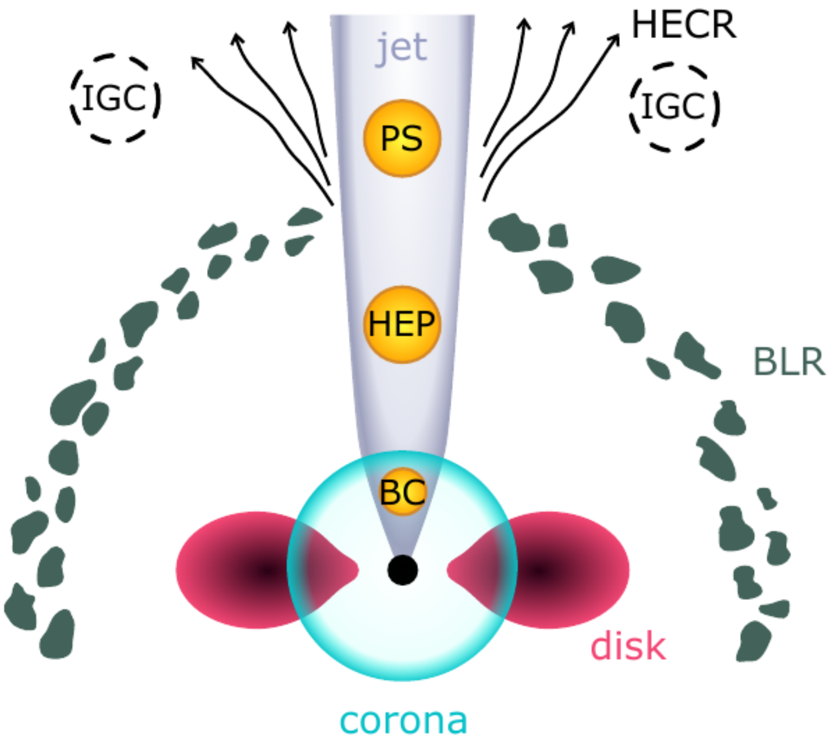
- ~ 0.02 - 0.1 ν_μ within 10 yrs (with Point Source effective area)
- Most optimistic neutrino prediction similar to TXS 0506+056 *(Petropoulou,Murase+2020)*

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)





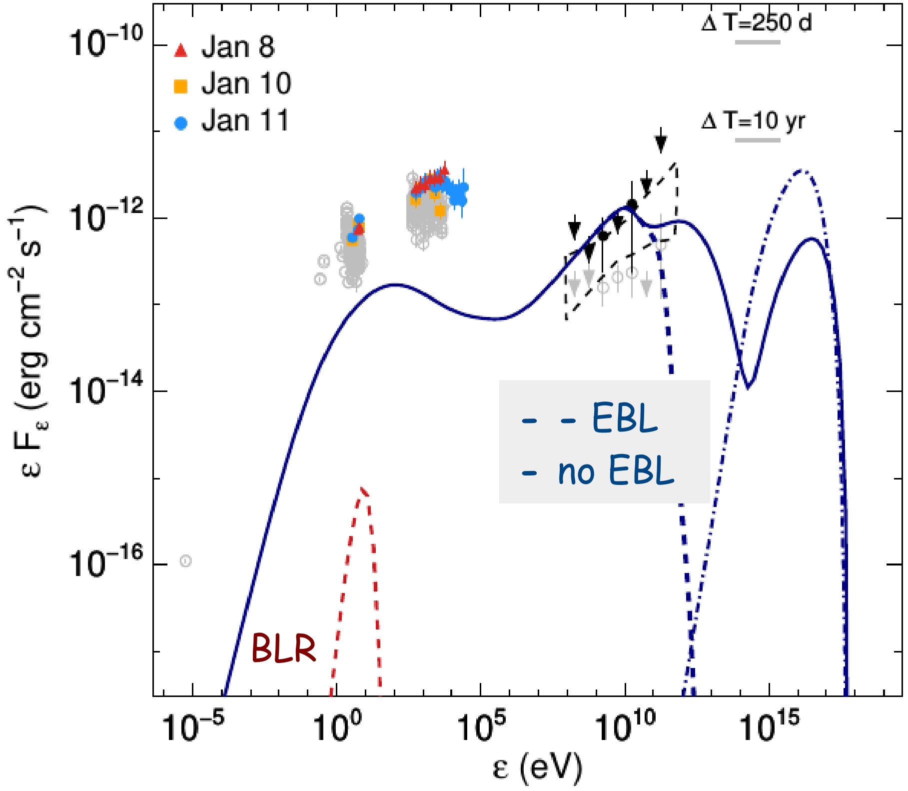
Findings:

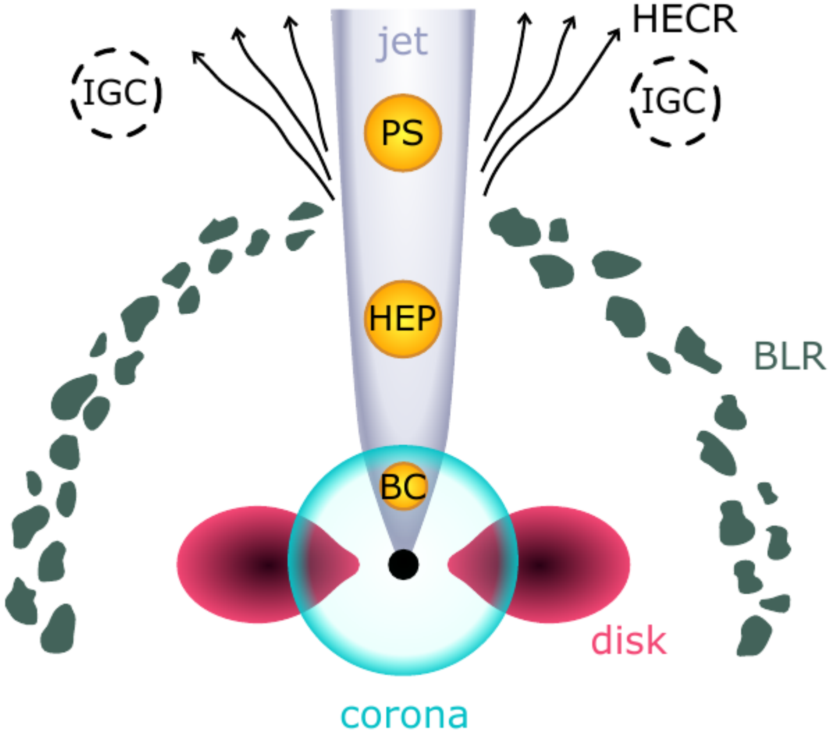
- Applies to transient & persistent emissions
- EM cascade peaks at sub-MeV energies
- Cannot explain optical/UV, X-rays and γ-ray emissions

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 ($\Gamma \sim 25$)
- Weak magnetic field ($B \sim 1$ G)
- Size ($R \sim 2\ 10^{15}$ cm)





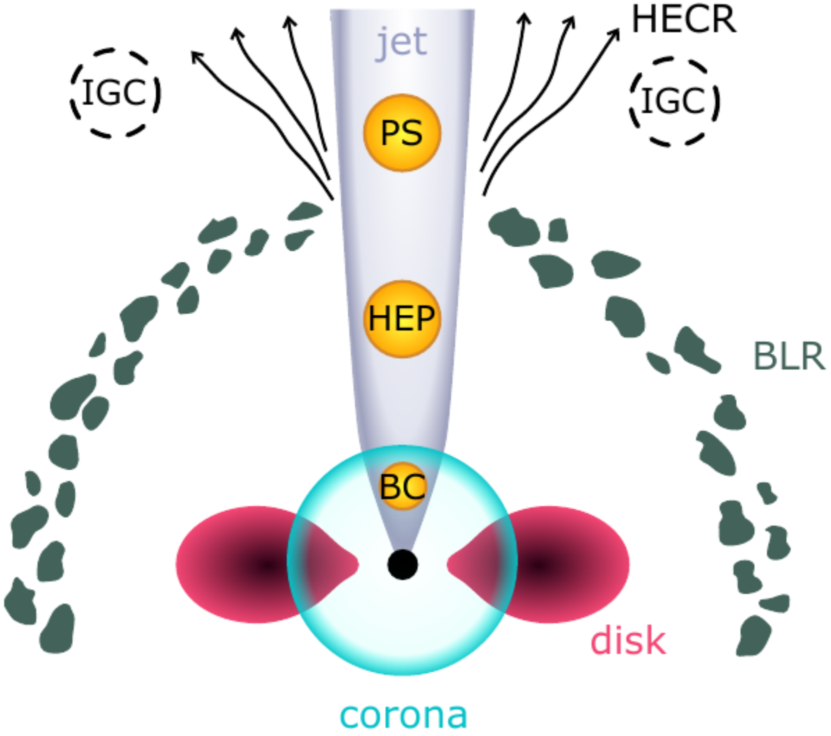
Findings:

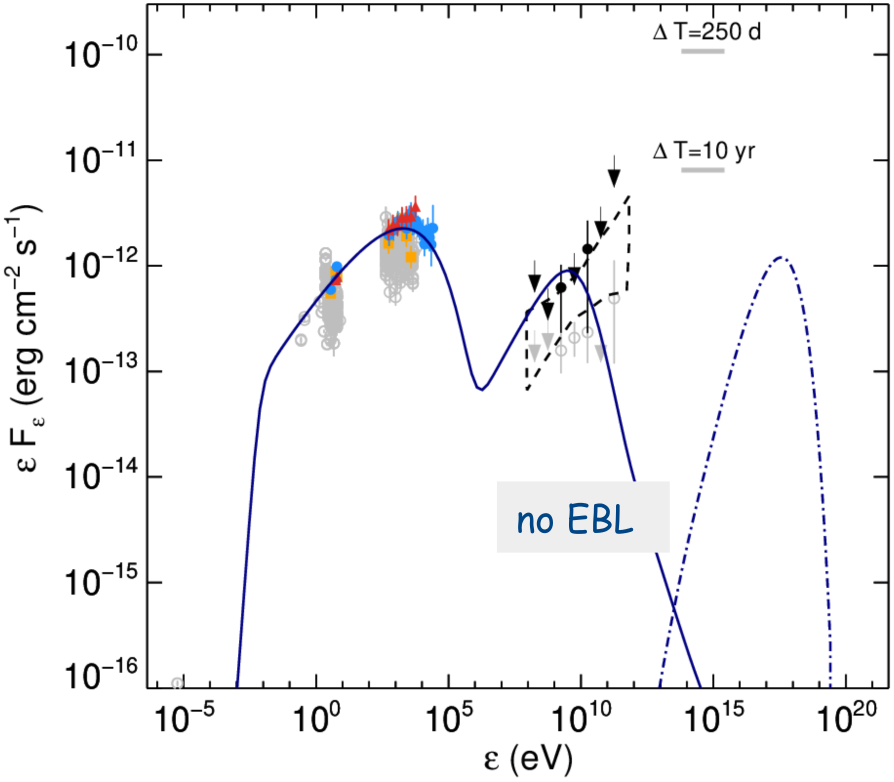
- Applies to transient & persistent emissions
- UV & soft X-rays from the same region or not
- Enhanced neutrino flux by a factor of ~3

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)

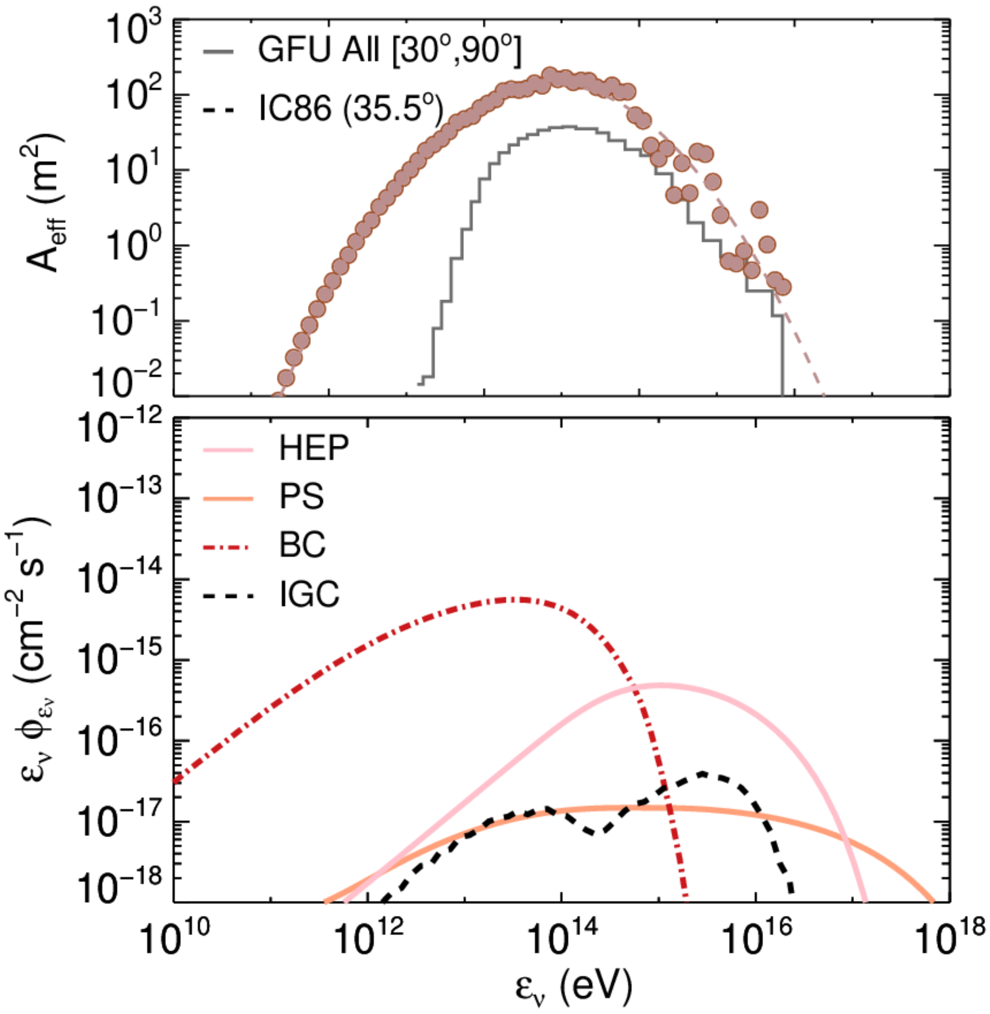


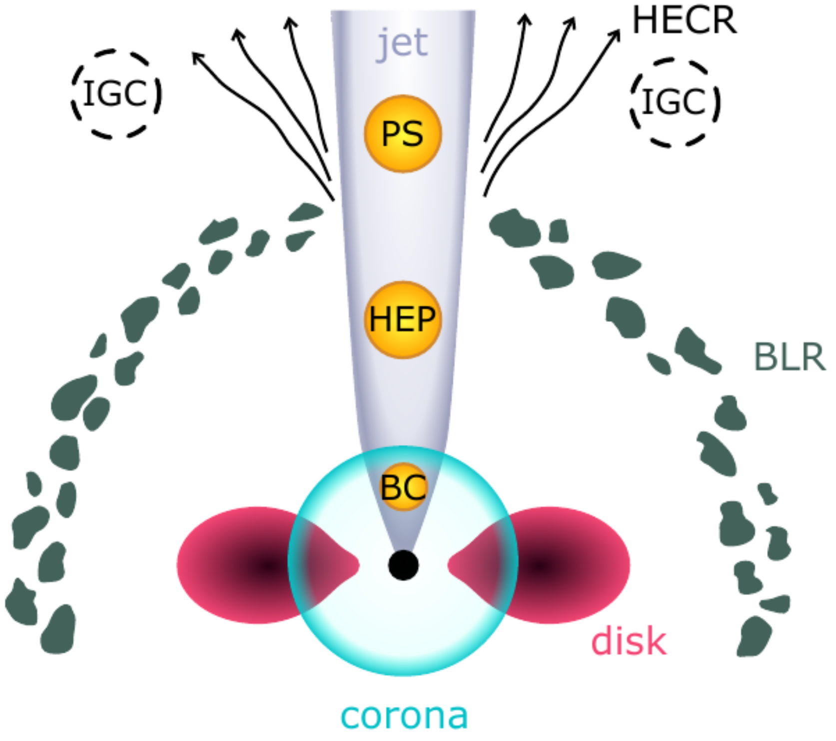


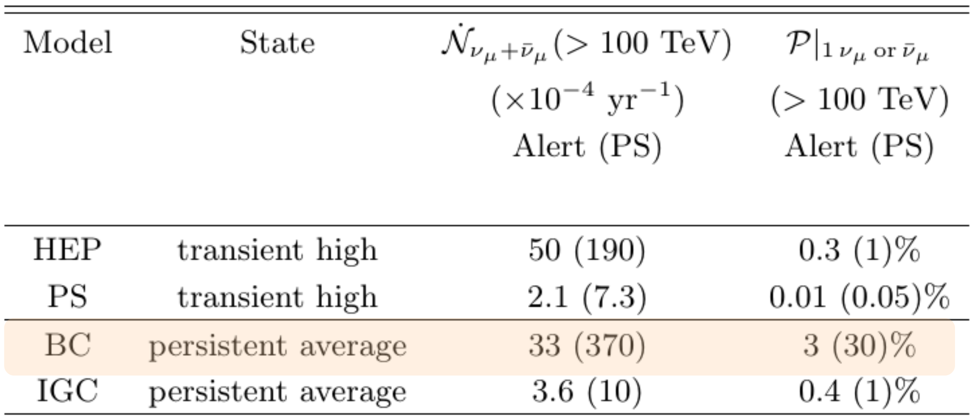
Findings:

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

Alternative theoretical scenarios



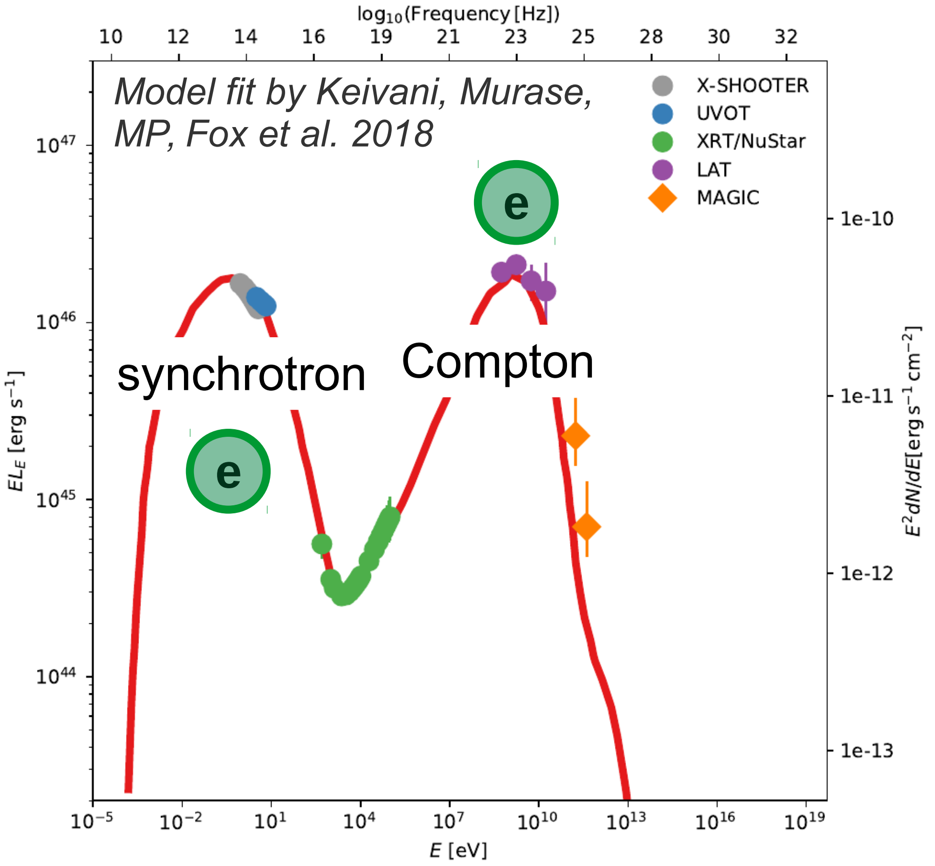




Model	State	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}(>100$ TeV) ($\times 10^{-4}$ yr^{-1}) Alert (PS)	$\mathcal{P}\vert_{1\,\nu_\mu \text{ or } \bar{\nu}_\mu}$ (> 100 TeV) Alert (PS)
HEP	transient high	50 (190)	0.3 (1)%
PS	transient high	2.1 (7.3)	0.01 (0.05)%
BC	persistent average	33 (370)	3 (30)%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

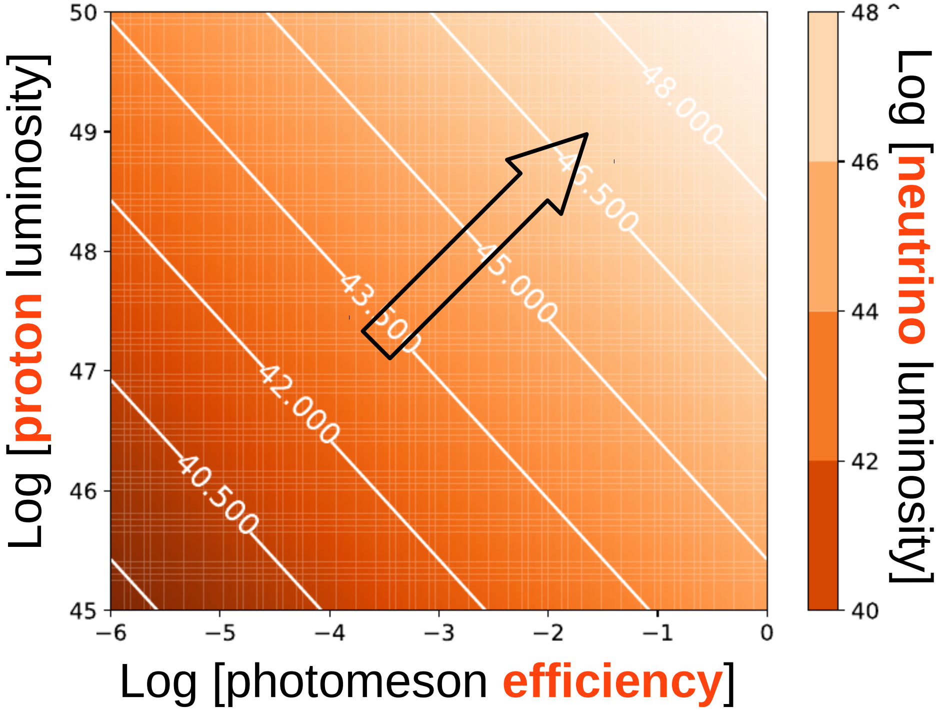
What sets the maximum neutrino flux?

Murase, Oikonomou, MP 2018

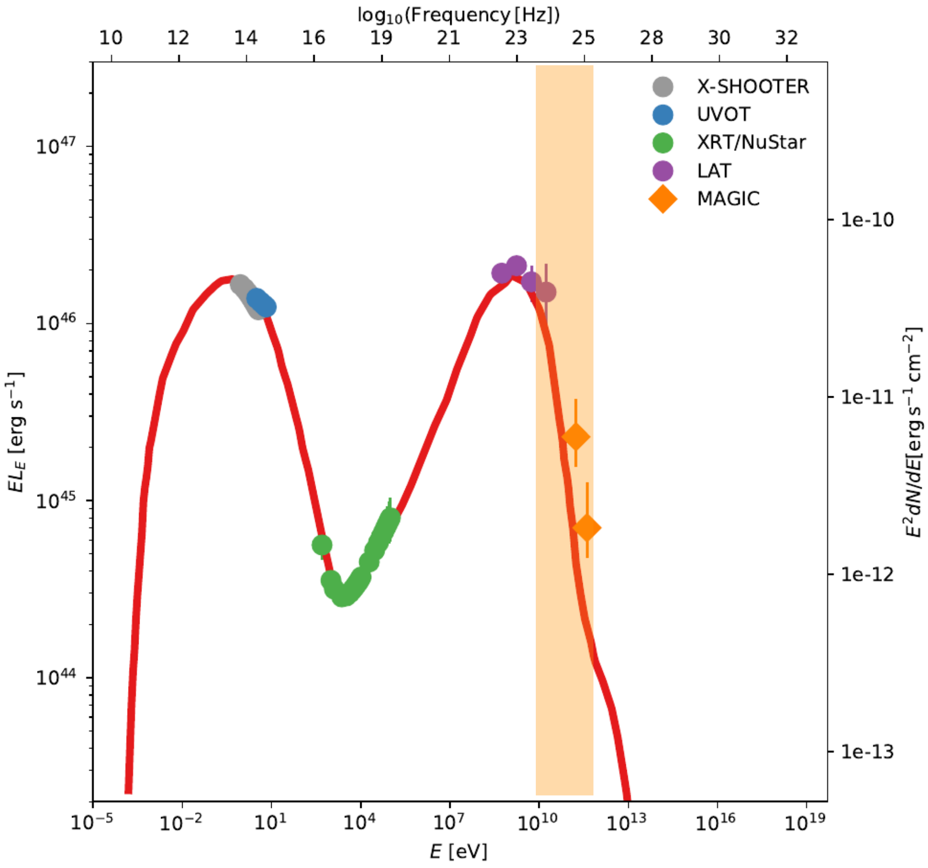

Model fit by Keivani, Murase, MP, Fox et al. 2018

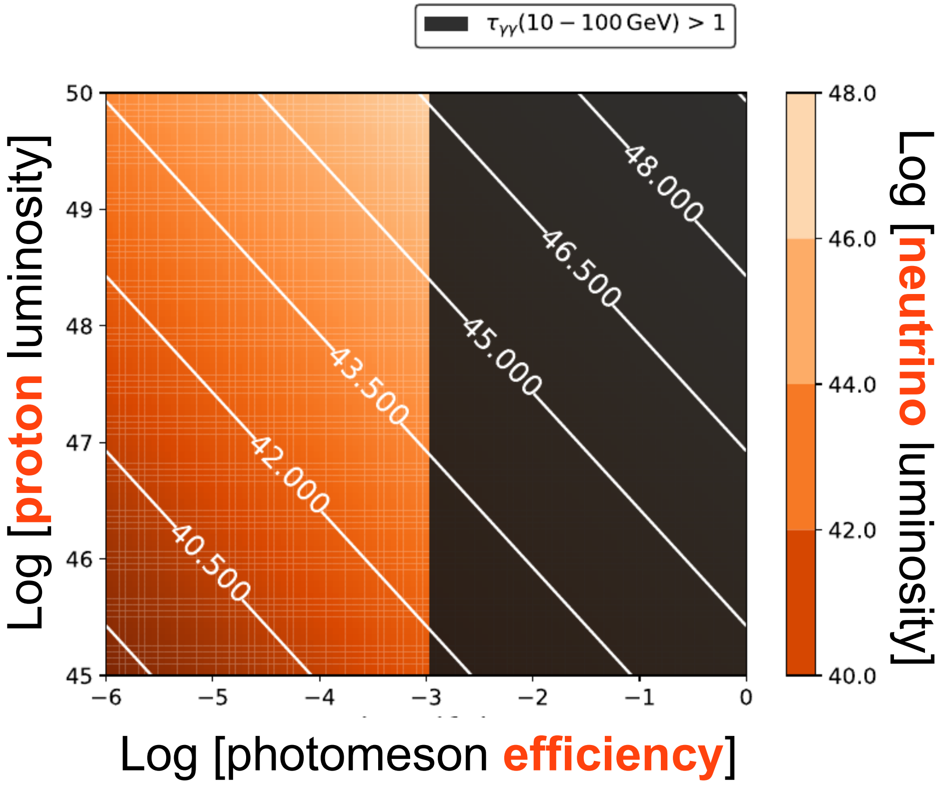
$$\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma}\, \varepsilon_p L_p$$

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



What sets the maximum neutrino flux?

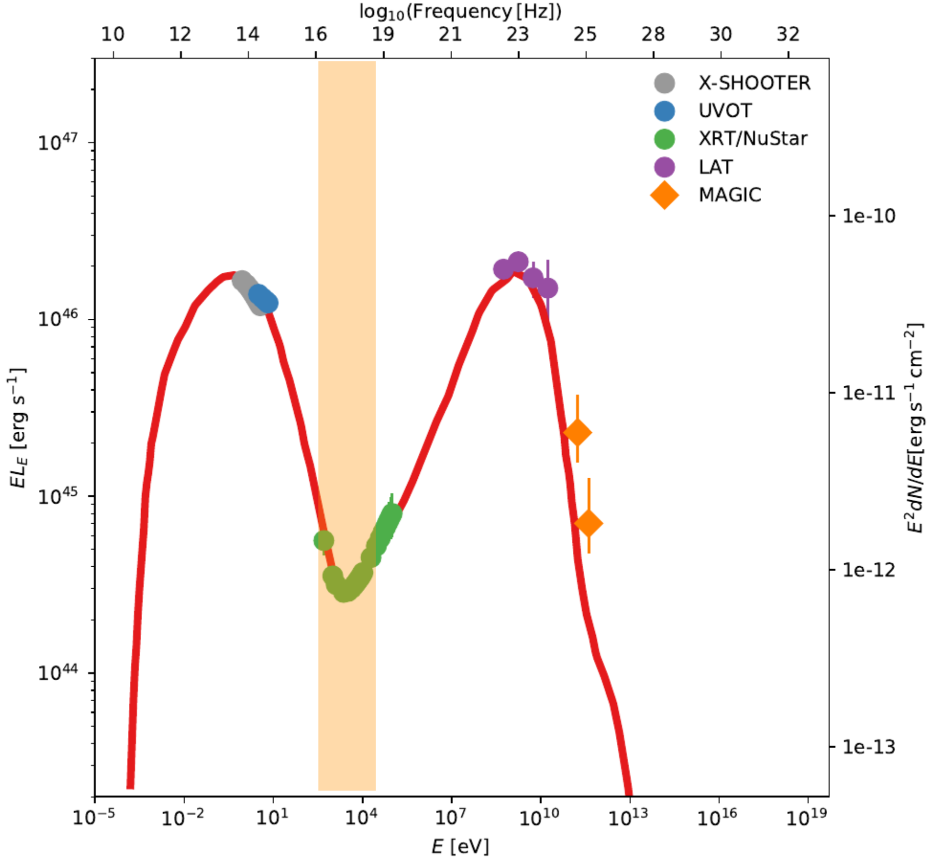


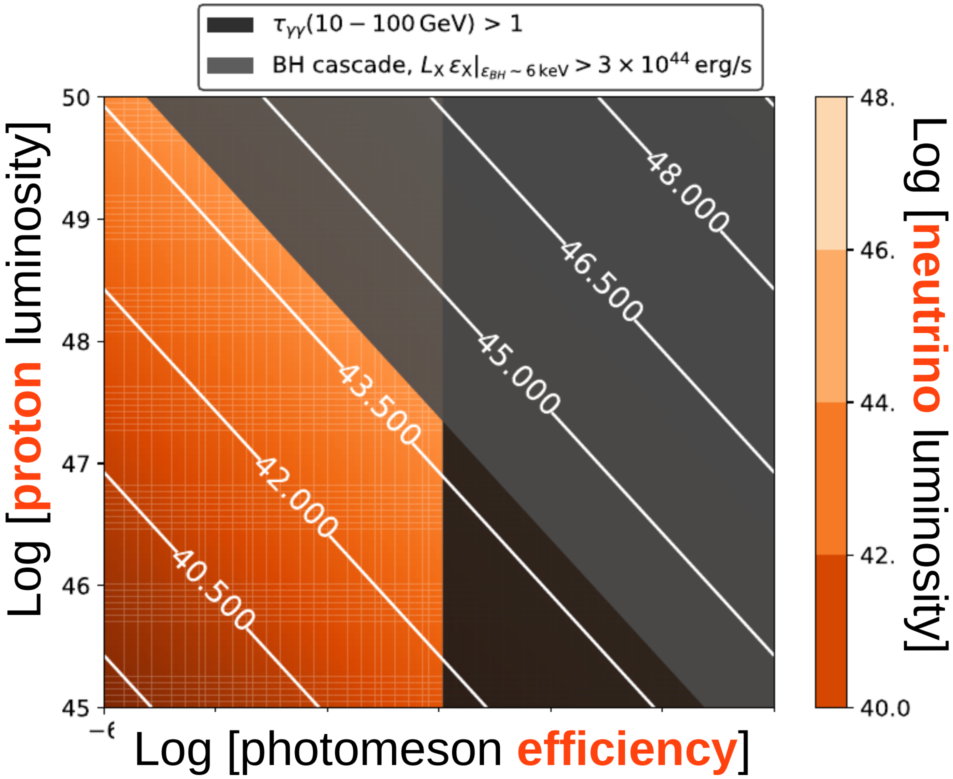


I. Optical depth for absorption of 10-100 GeV γ-rays must be low: $\tau_{\gamma\gamma}(10-100\,\mathrm{GeV}) \lesssim 1$

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

What sets the maximum neutrino flux?



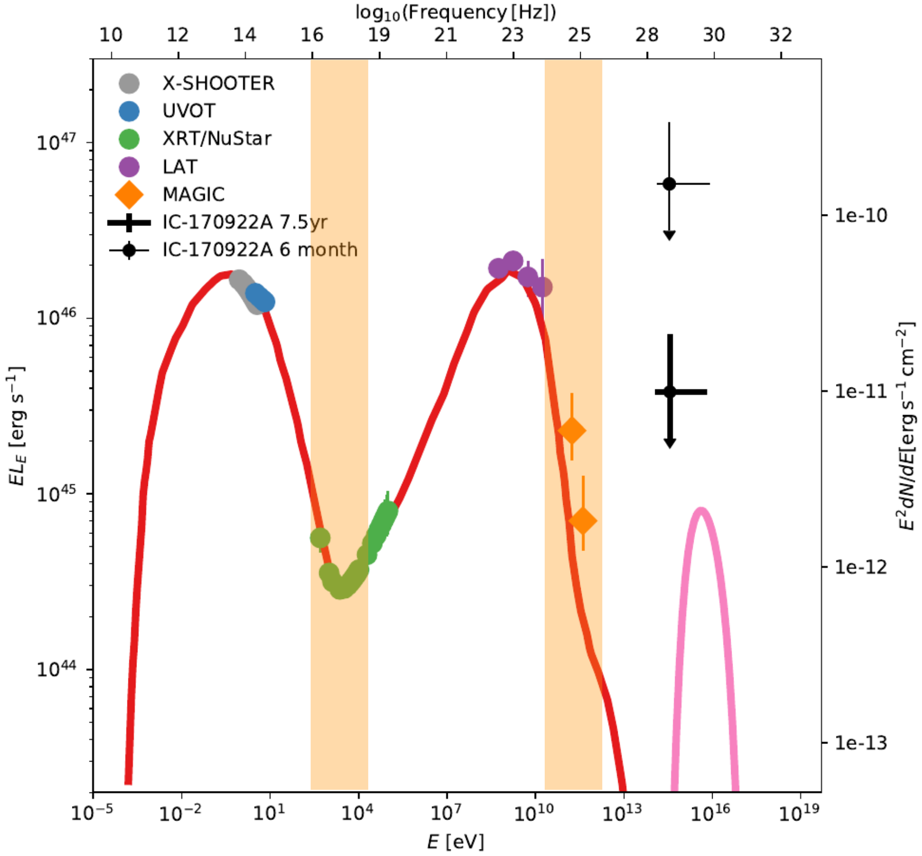


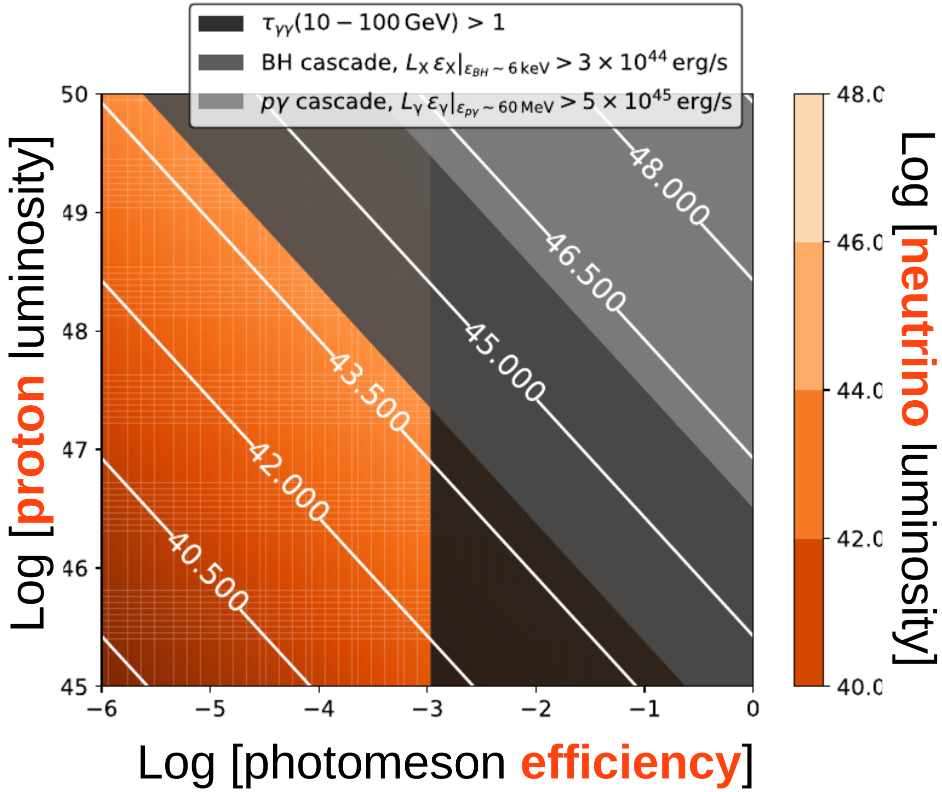
II. Synchrotron emission from Bethe-Heitler pairs must not overshoot X-ray data:

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

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

What sets the maximum neutrino flux?





Maximum all-flavor neutrino flux:

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