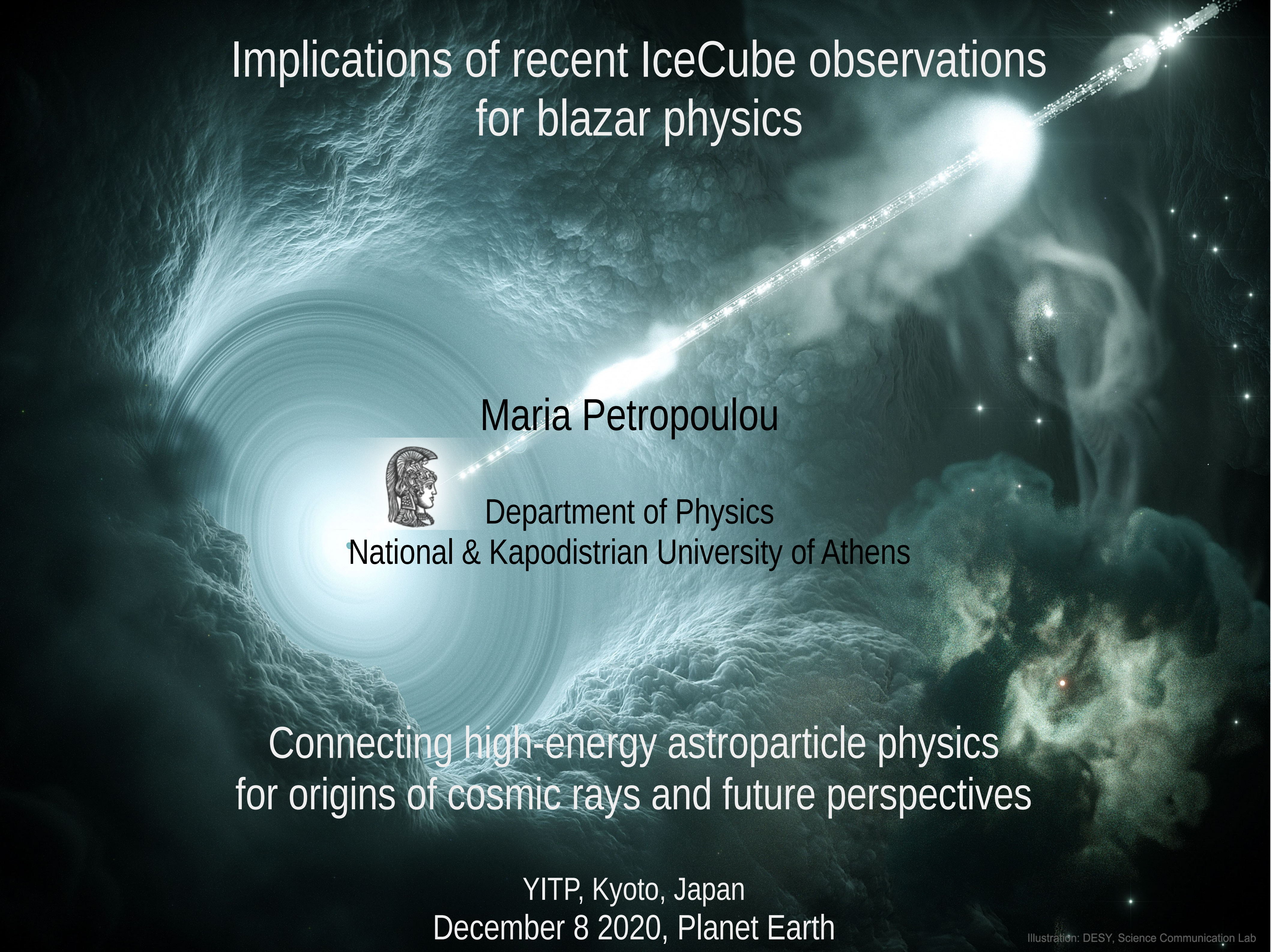

Implications of recent IceCube observations for blazar physics

Maria Petropoulou

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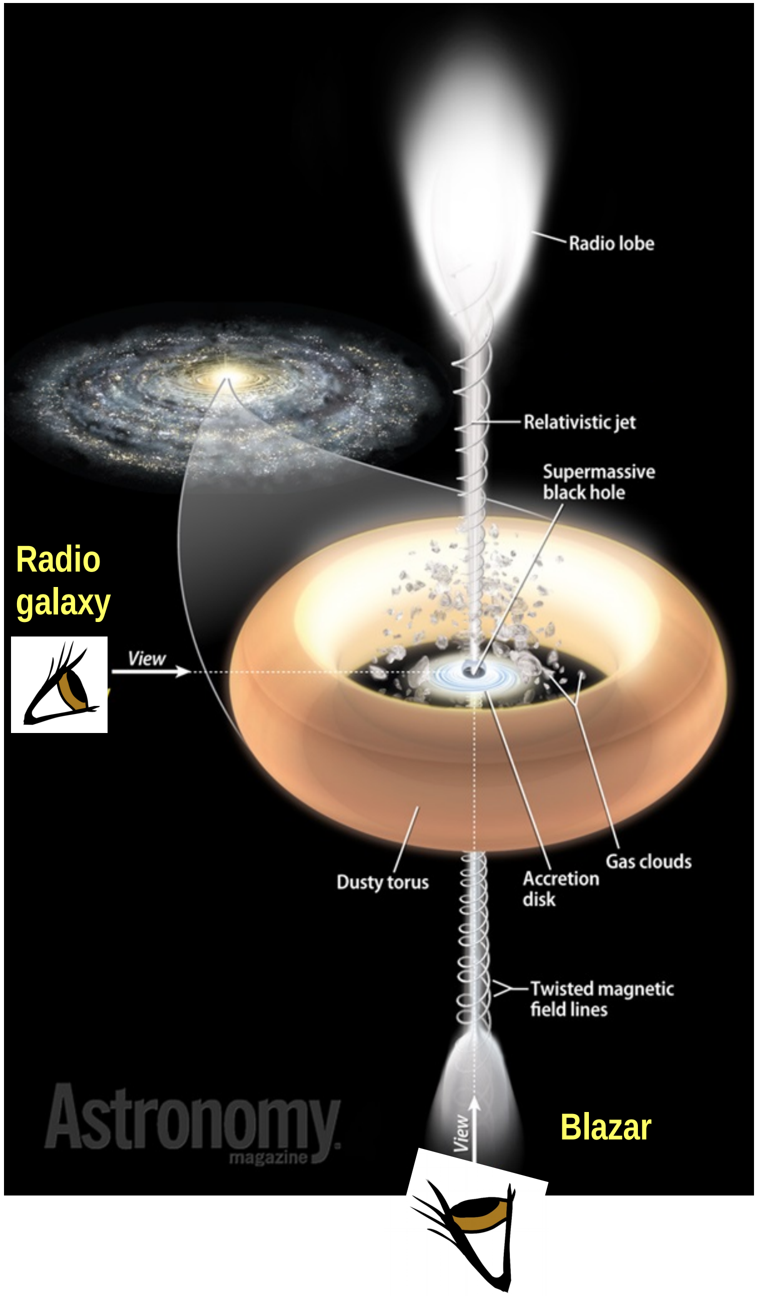
National & Kapodistrian University of Athens

Connecting high-energy astroparticle physics
for origins of cosmic rays and future perspectives

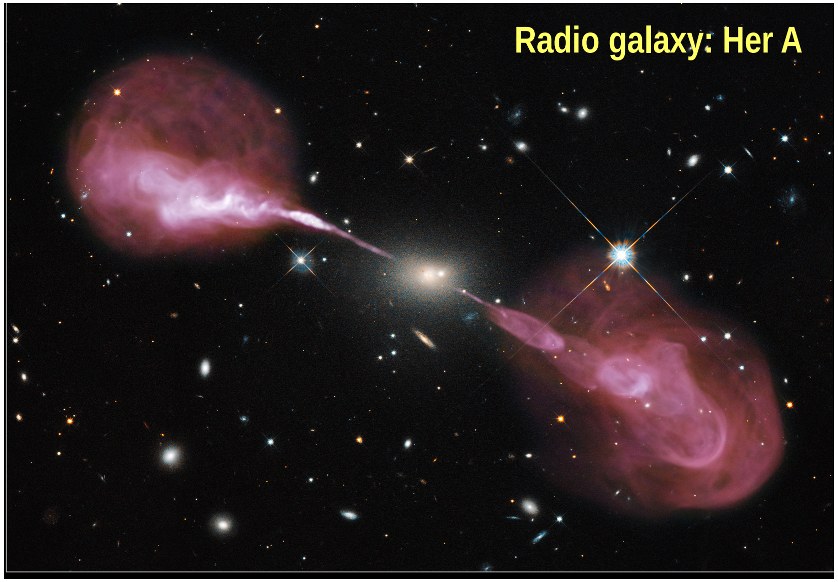
YITP, Kyoto, Japan
December 8 2020, Planet Earth

Illustration: DESY, Science Communication Lab

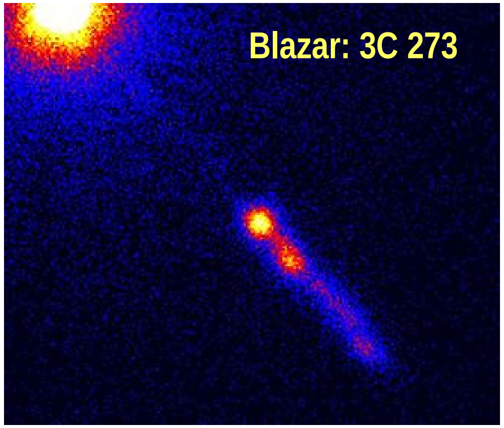
Blazars: AGN with jets viewed face-on



Urry & Padovani 1995



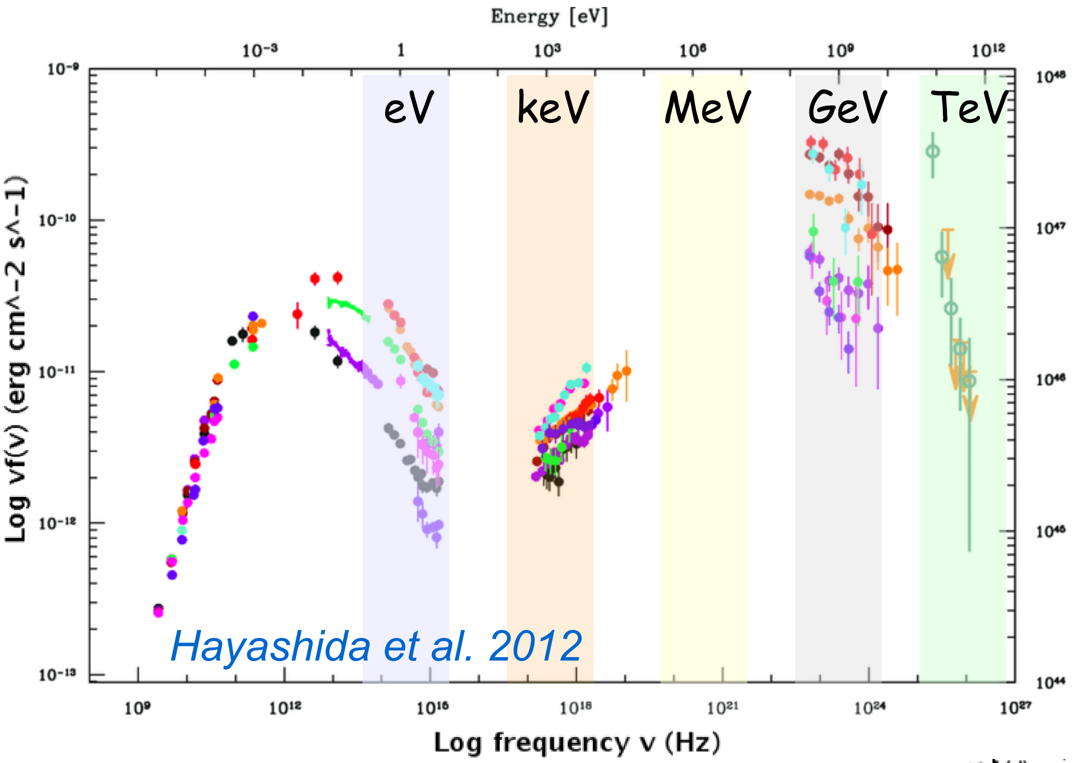
Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)



Credit: Chandra X-ray observatory

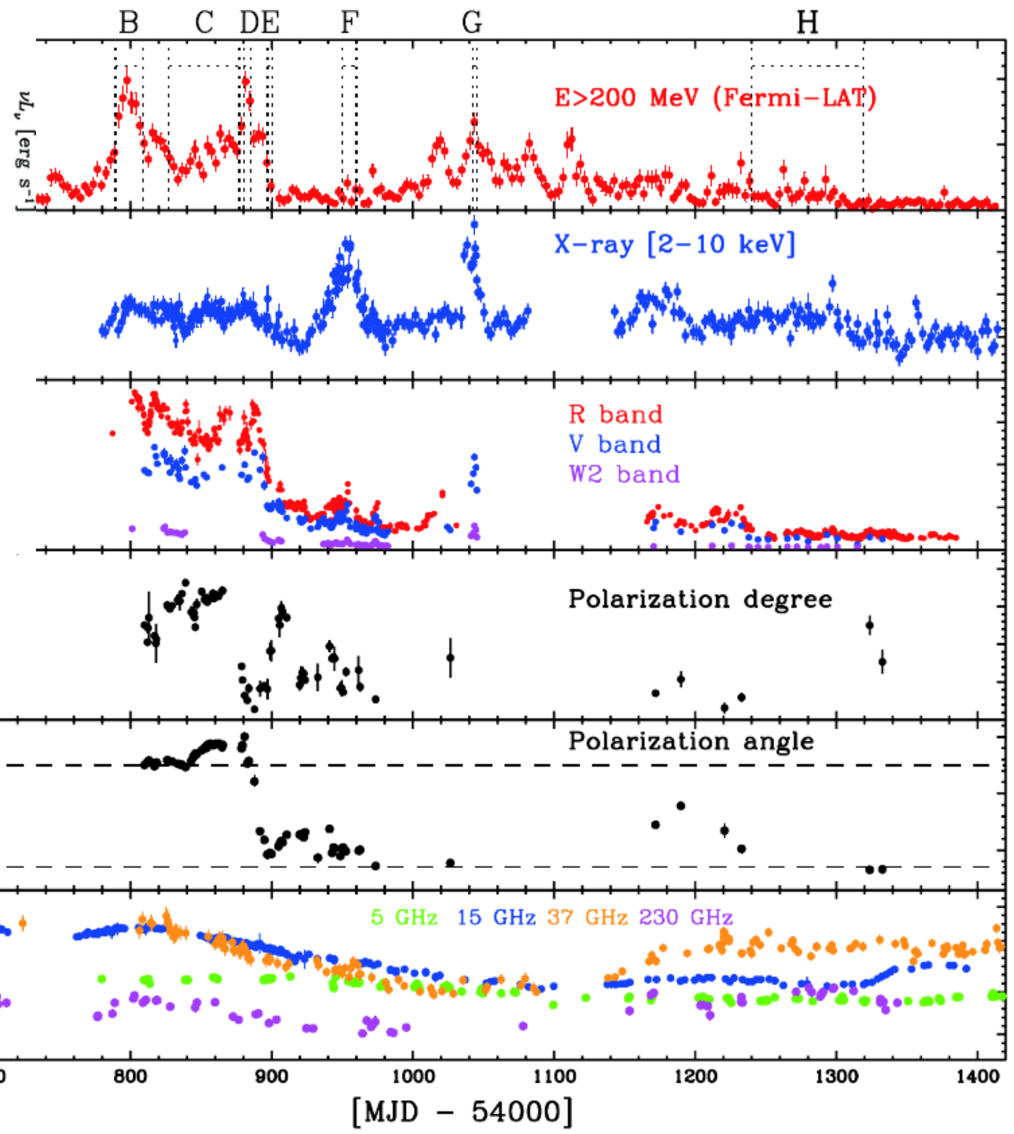
- ~10% of Active Galactic Nuclei (AGN) have relativistic jets.
- Blazars → jetted AGN viewed at small viewing angles.
- Blazar emission dominated by the jet due to Doppler beaming.

Blazar Jets: Multi-wavelength Variable Photon Emitters



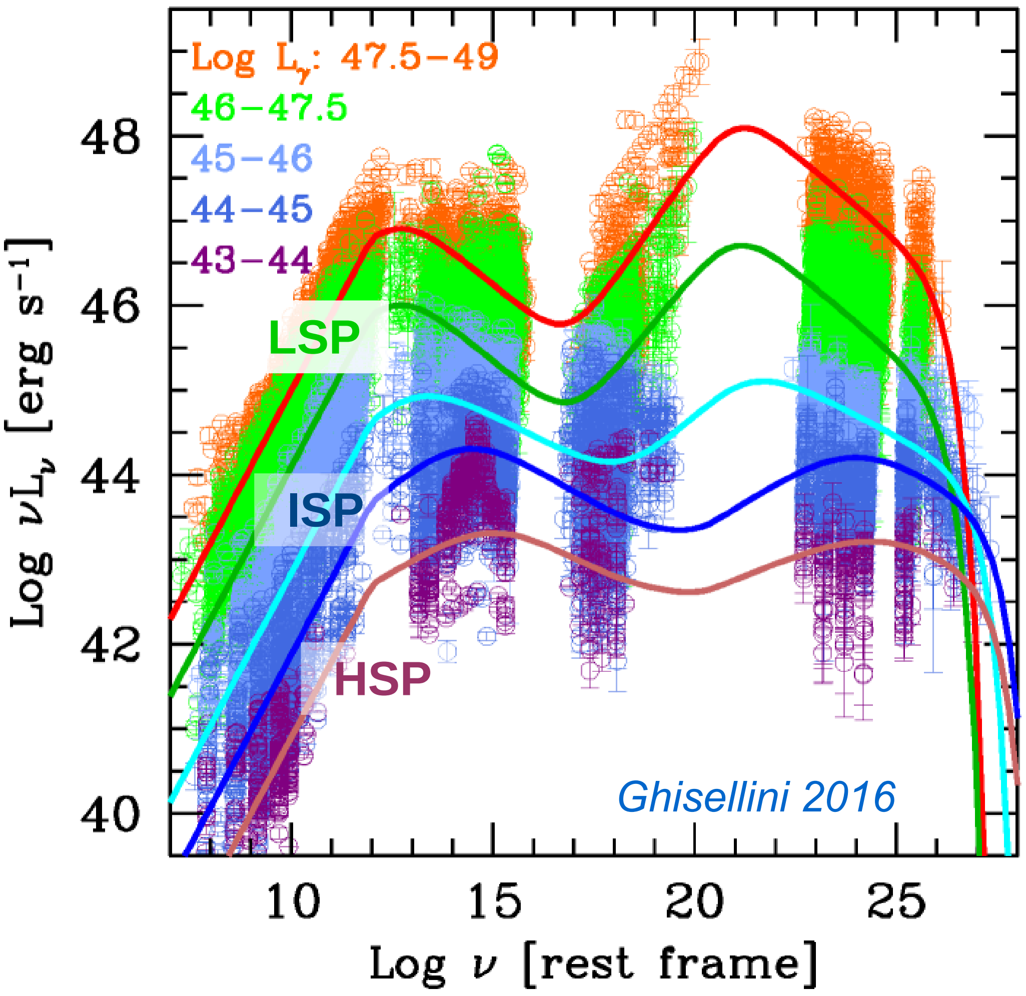
Hayashida et al. 2012

Hayashida et al. 2012



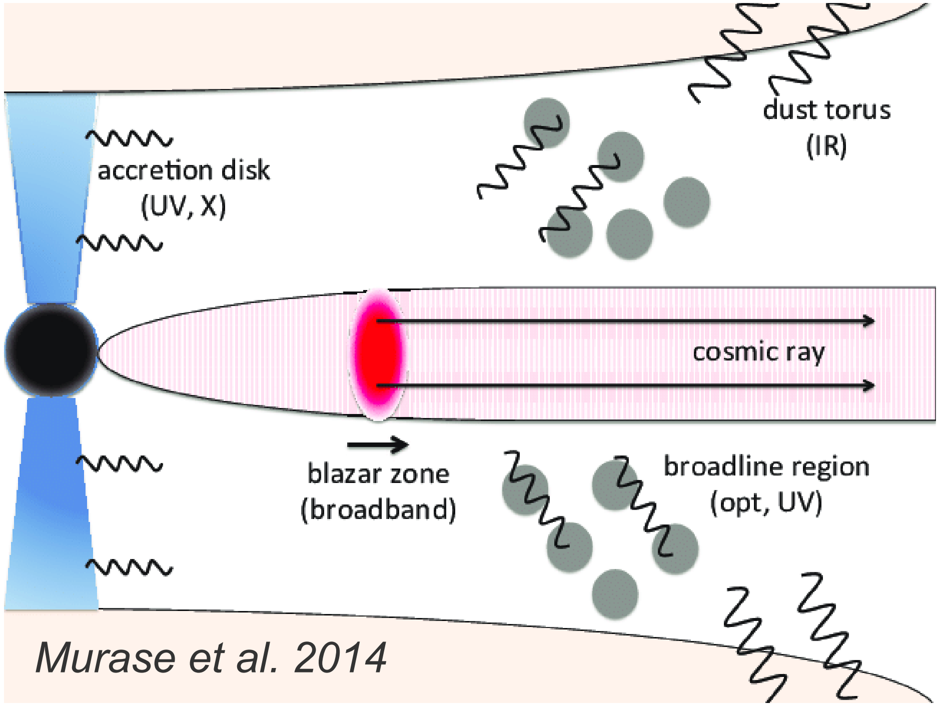
- Multi-wavelength emission.
- Double-humped photon spectra.
- Flux variability on multiple timescales (min to months).
- Flares across the EM spectrum (not always correlated!)

Blazar Spectral Subclasses



Ghisellini 2016

- **HSPs:** $\nu_s > 10^{15}$ Hz – weak or absent external photon fields
- **ISPs:** 10^{14} Hz < vs < 10^{15} Hz – weak external photon fields
- **LSPs:** $\nu_s < 10^{14}$ Hz – strong external photon fields

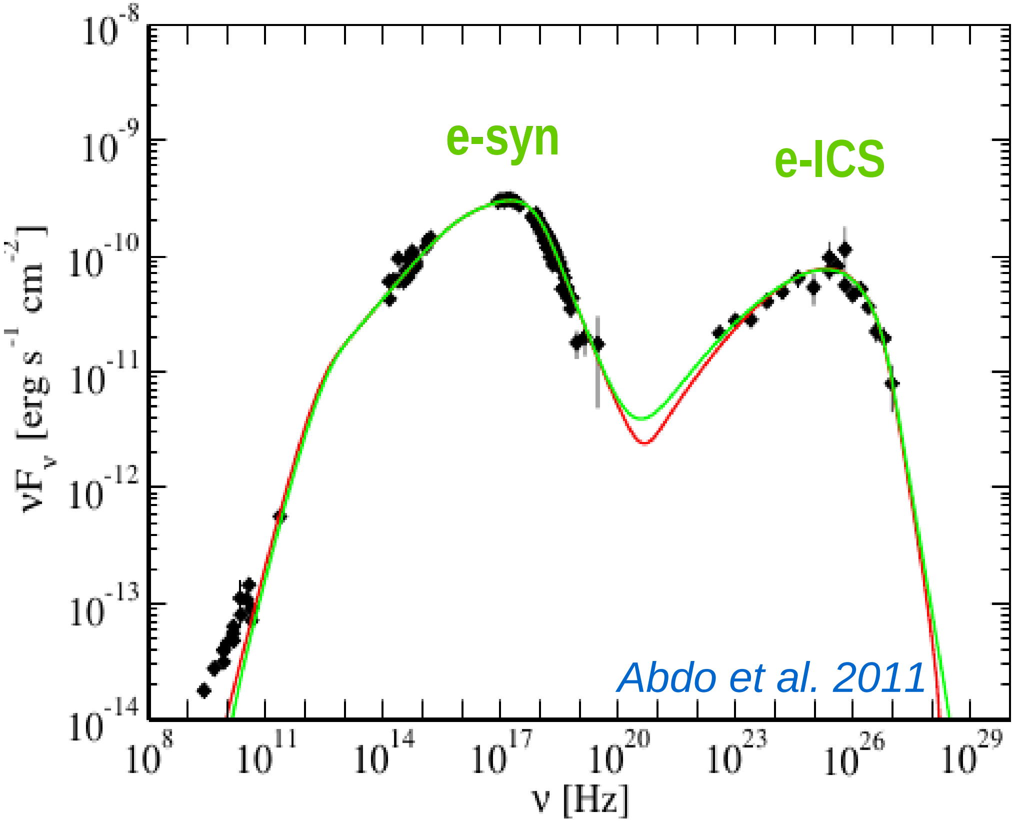


Murase et al. 2014

Blazar Jet Emission Models

Leptonic Models

- **Jet plasma:** relativistic e^+e^- + cold e,p
- **HE emission:** ICS from rel. e^+e^-

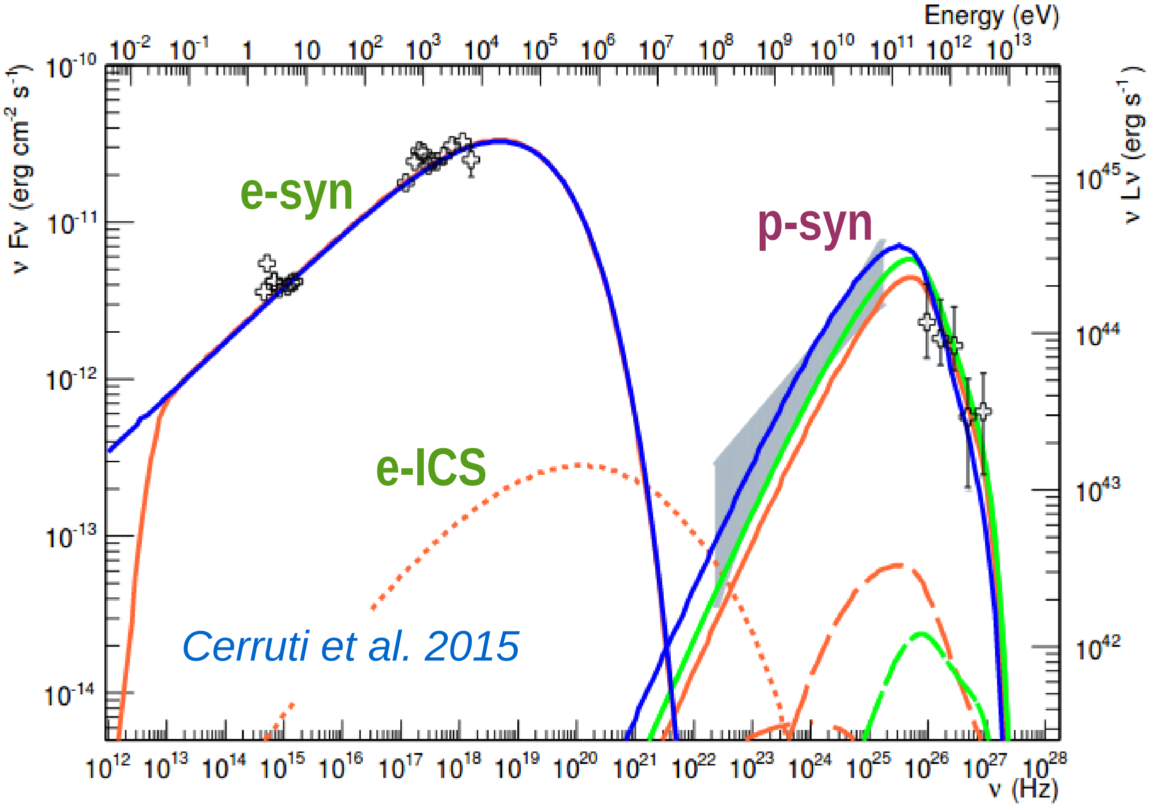


e.g., Maraschi et al. 1992; Dermer et al. 1992; Dermer & Schlickeiser 1993; Sikora et al. 1994; Mastichiadis & Kirk 1995; Bloom & Marscher 1996; Mastichiadis & Kirk 1997; Tavecchio et al. 1998; Boettcher & Dermer 1998; Cerruti et al. 2012 …

Blazar Jet Emission Models

Hadronic Synchrotron Models

- **Jet plasma:** relativistic e^+e^- p + cold e,p
- **HE emission:** SYN from rel. p

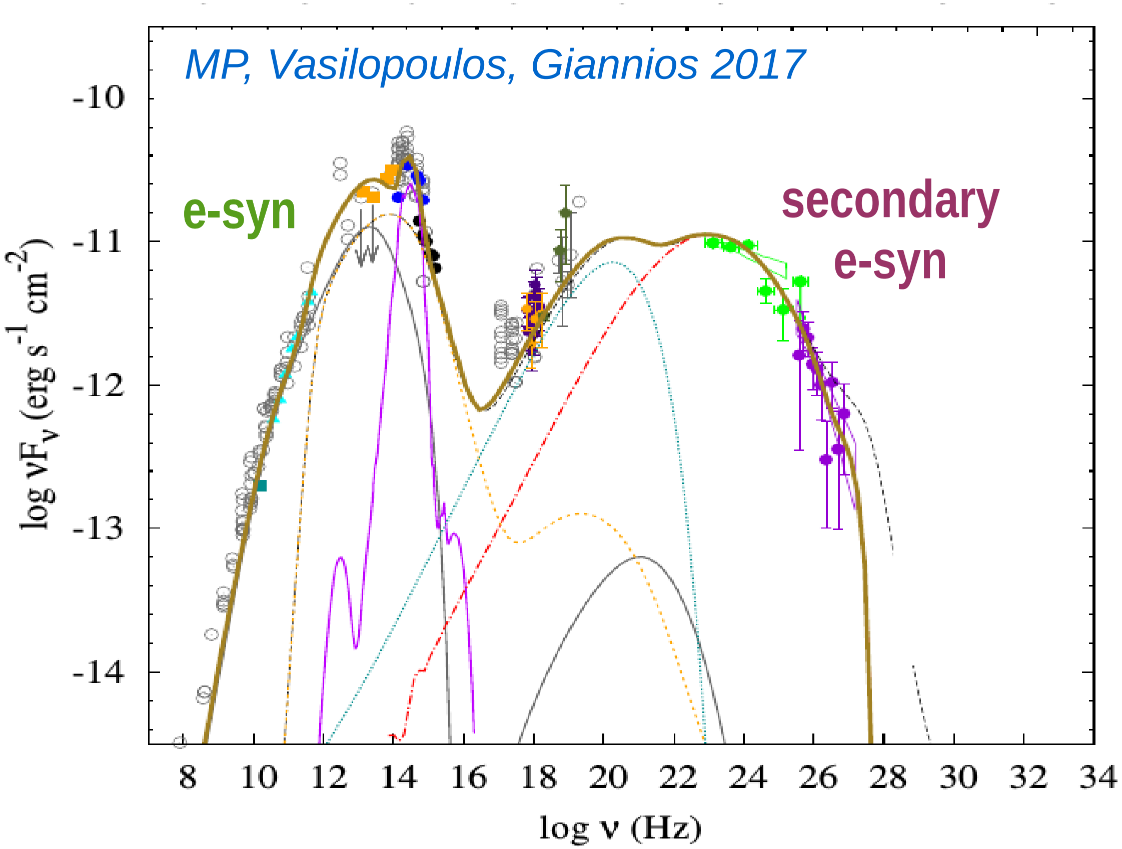


e.g., Mannheim & Biermann 1992; Aharonian 2000; Muecke & Protheroe 2001; Muecke et al. 2003, Boettcher et al. 2013; Cerruti et al. 2015, Petropoulou & Dimitrakoudis 2015; …

Blazar Jet Emission Models

Hadronic Cascade Models

- **Jet plasma:** relativistic e^+e^-p + cold e,p
- **HE emission:** ICS/SYN from secondary e^+e^-



MP, Vasilopoulos, Giannios 2017

e.g., Mannheim et al. 1991; Mannheim 1993; Sahu et al. 2013; Petropoulou & Mastichiadis 2012; Petropoulou et al. 2015; Petropoulou et al. 2017; …

Blazar Jet Emission: A Challenging Problem

All models describe equally well the photon spectra.

1) Many free parameters for each zone (13 – 20)

2) Non-contemporaneous multi-wavelength data besides exceptional periods (e.g. flares)

3) Not full coverage of the electromagnetic spectrum

How can we tell which scenario is true?

1) High-energy neutrino observations

2) Multi-frequency temporal information

3) MeV monitoring observations (flux & polarization)

Case studies

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

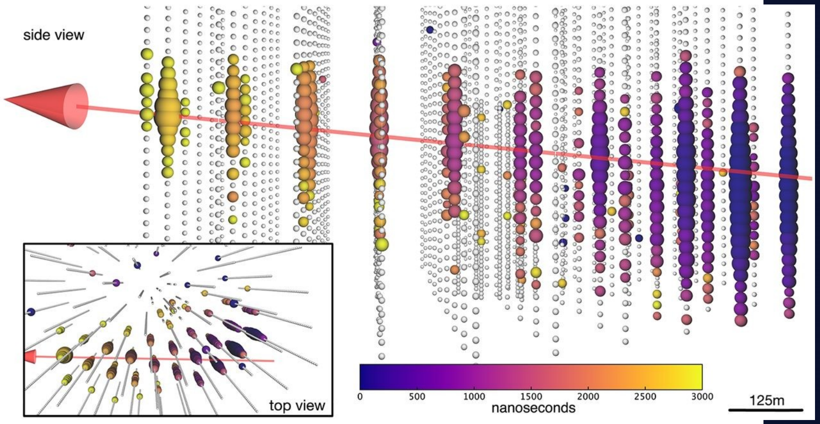
- **TXS 0506+056 / 2014-15 Neutrino Excess** ***(IceCube Collaboration 2018b)***
  - Neutrino excess detected during a period of low activity in γ-rays

- **3HSP J095507.9+35510 / IceCube-200107** ***(Giommi + 2020; Paliya + 2020)***
  - Extreme HSP blazar without detectable BLR emission
  - Neutrino detected 1 day prior to a hard X-ray flare in 2020

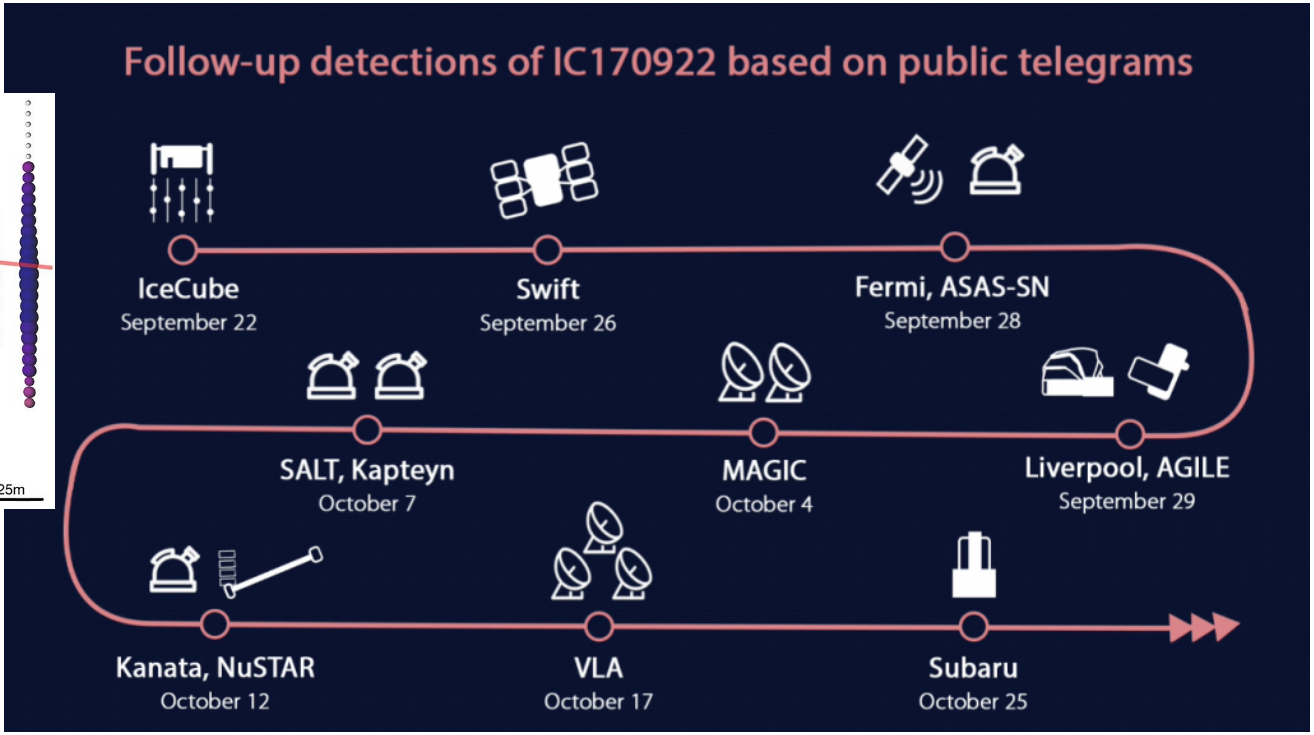
- **PKS 1502+106 / IceCube-190730A** ***(Franckowiak+2020)***
  - LSP blazar with strong BLR emission
  - Among the 15 brightest sources in the Fourth Fermi-LAT AGN catalog (4LAC)
  - Neutrino detected during period of low activity in γ-rays

The multi-messenger flare of TXS 0506+056

IC-170922A: a 290 TeV neutrino



IceCube Colloboration et al. 2018a



Follow-up detections of IC170922 based on public telegrams

IceCube September 22

Swift September 26

Fermi, ASAS-SN September 28

Liverpool, AGILE September 29

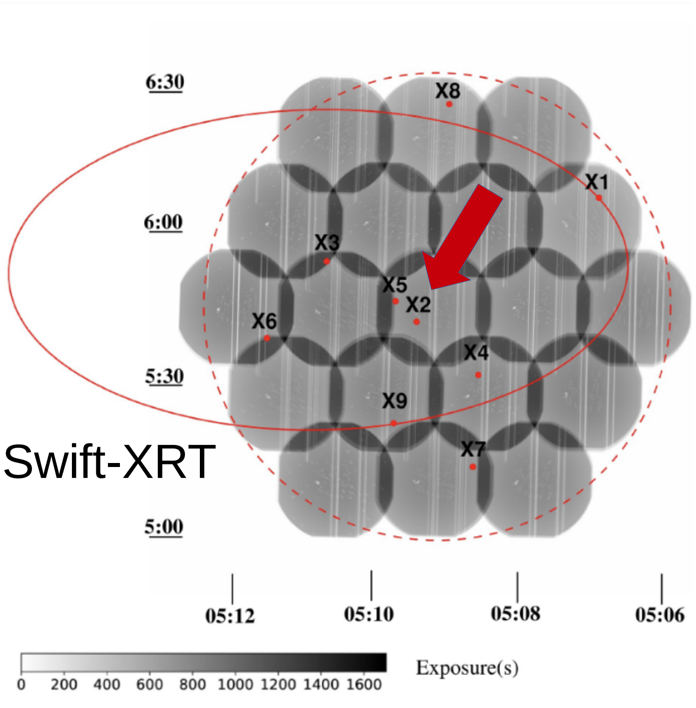
MAGIC October 4

SALT, Kapteyn October 7

Kanata, NuSTAR October 12

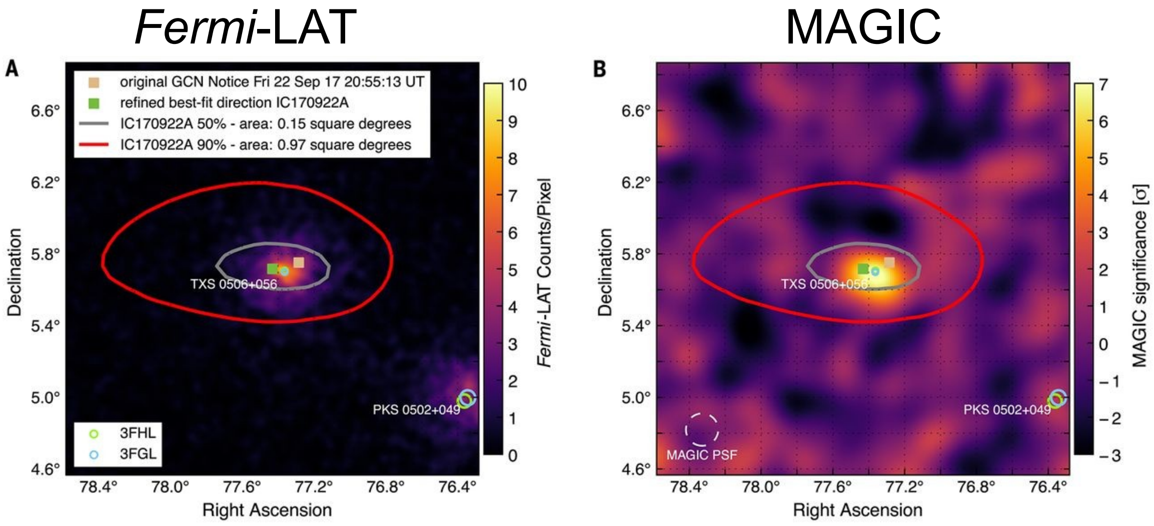
VLA October 17

Subaru October 25



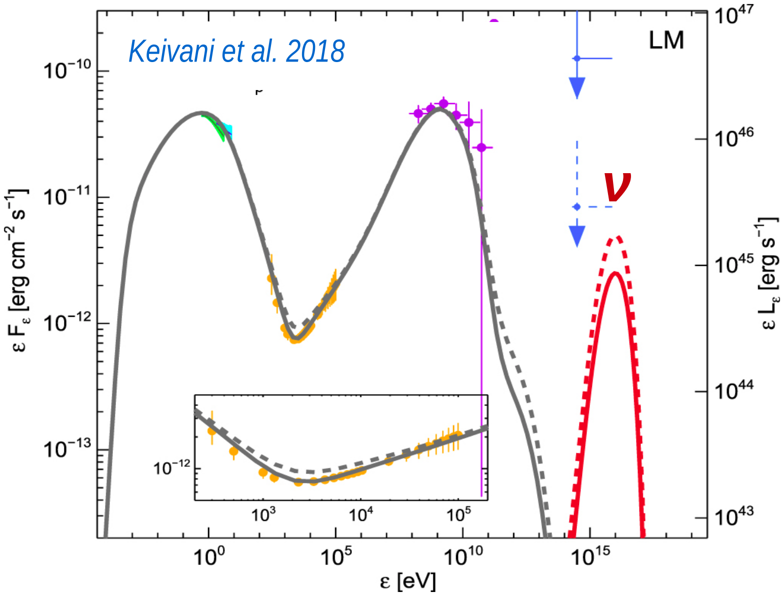
Swift-XRT

Keivani, Murase, MP, Fox et al. 2018

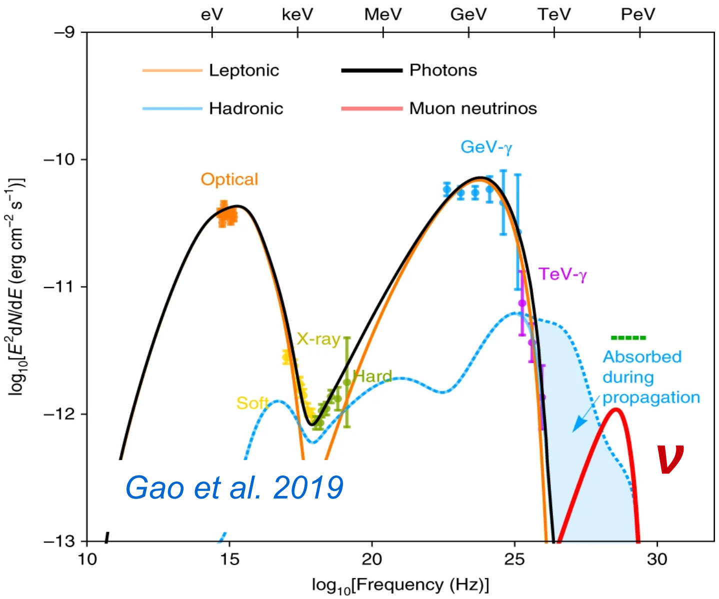


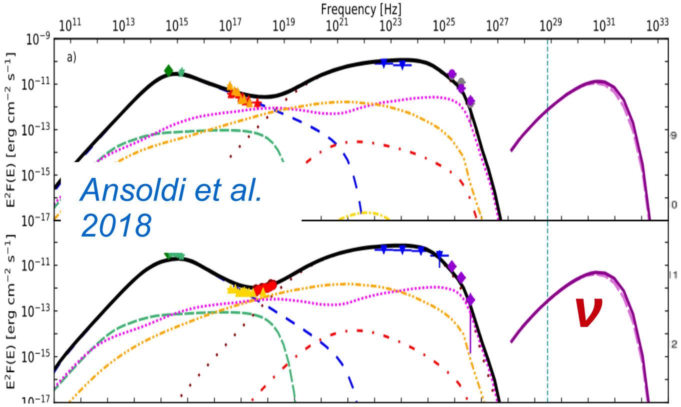
IceCube Colloboration et al. 2018a

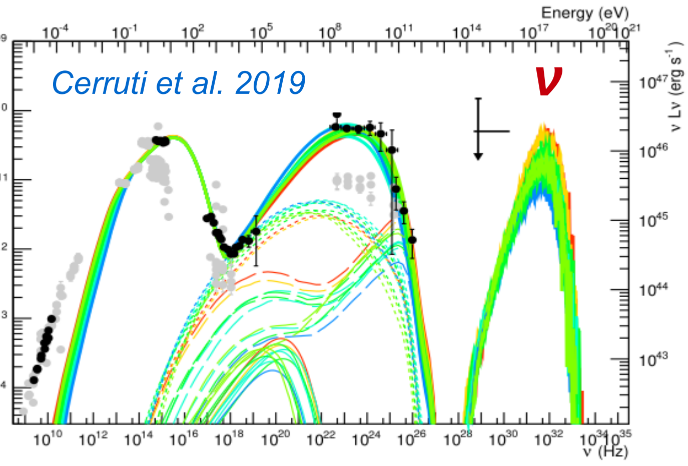
Implications from the 2017 Flare Modeling



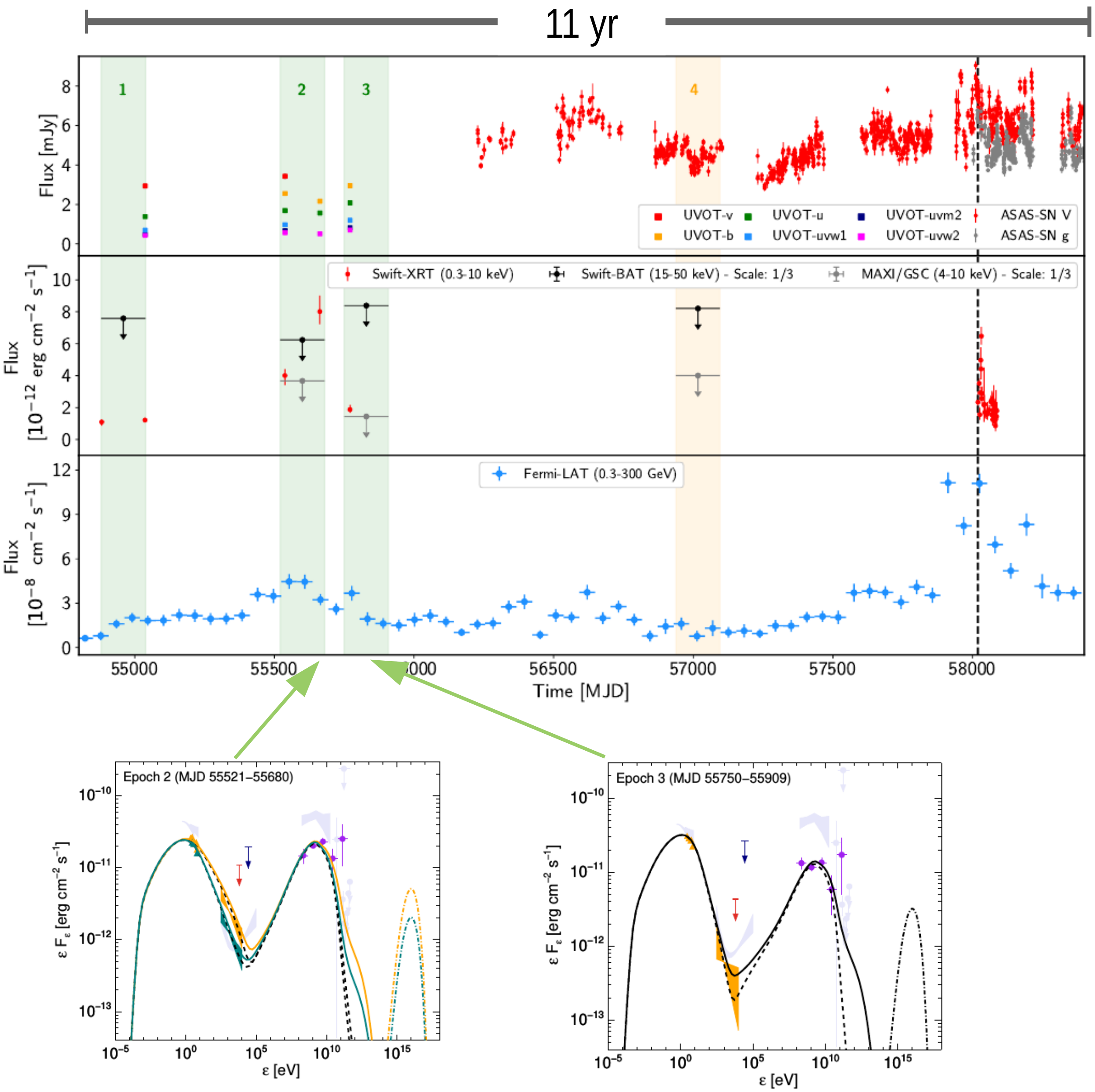
- Past studies of neutrinos from blazars predicted hadronic γ-rays. **BUT** modeling of TXS 0506+056/IC-170922A requires a **leptonic** origin of γ-rays.
- Maximum proton energies below EeV → TXS 0506+056 is **unlikely** to be an UHECR + PeV neutrino source.
- Number of muon neutrinos per yr < 1. Still, the predictions are **statistically consistent** with the detection of 1 event in 0.5 yr *(e.g. Strotjohann et al. 2019).*





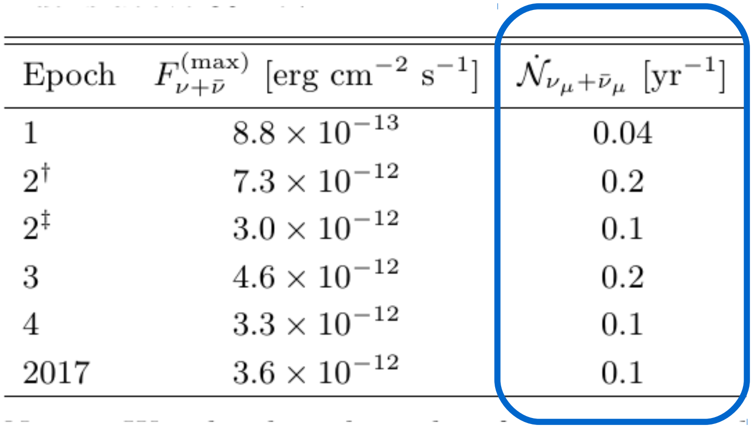


Implications from Multi-Epoch Modeling



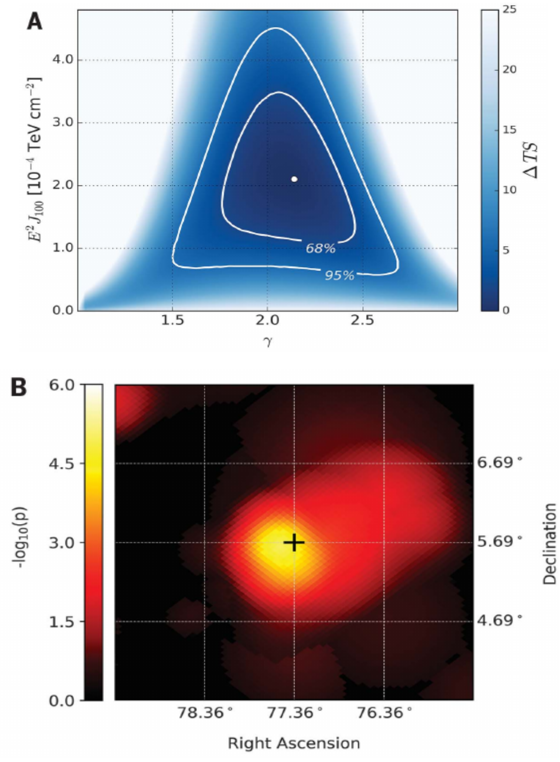
Petropoulou, Murase+2020

- **Leptonic** origin of γ-rays for all epochs studied.
- Upper limit of **∼ 0.4 − 2** on the muon neutrino number in **10 years** of IceCube observations.
- Consistent with the IceCube-170922A detection, which can be explained as an upper fluctuation from the average neutrino rate expected from the source.

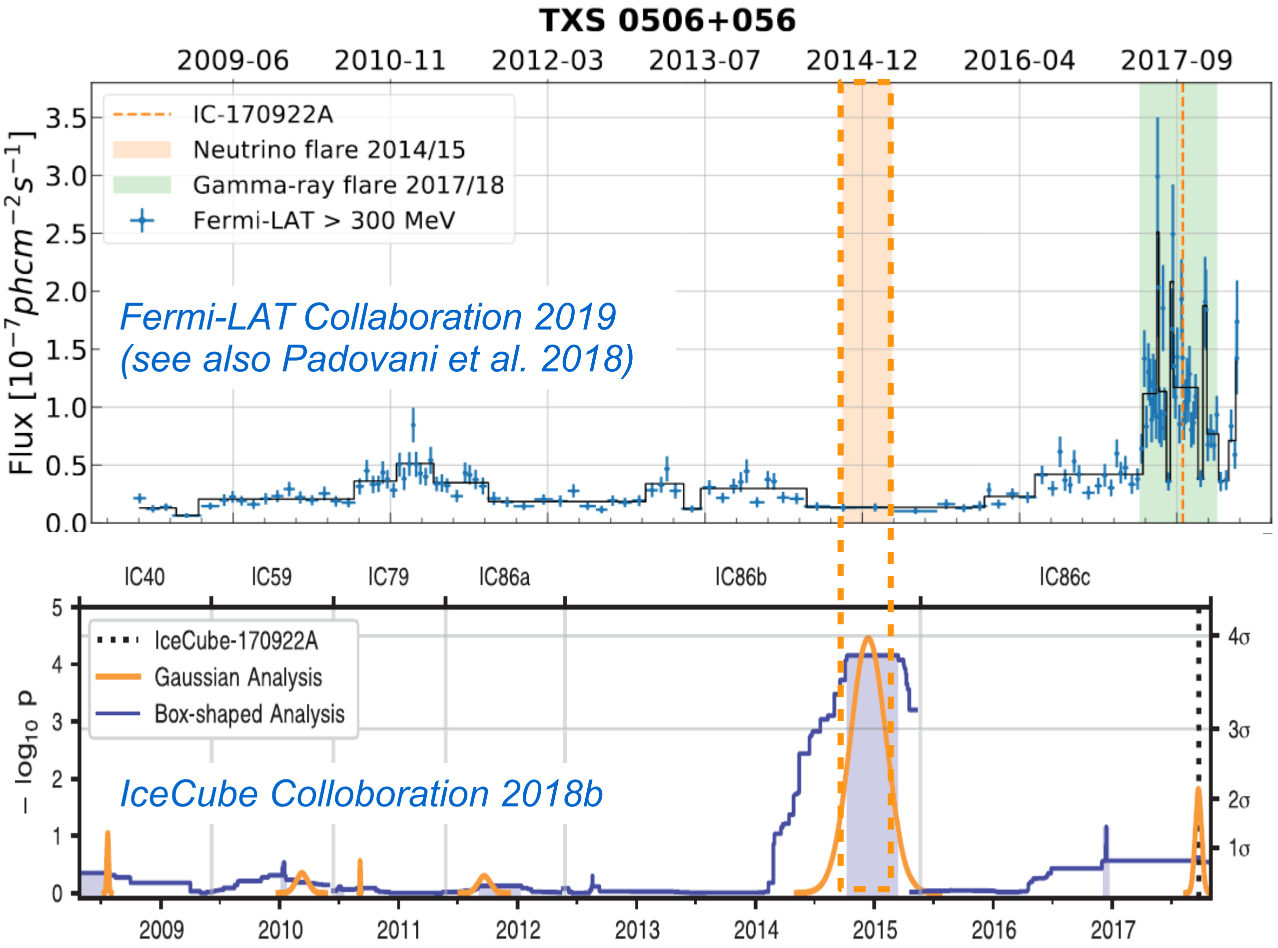


Epoch	$F^{(\rm max)}_{\nu+\bar{\nu}}$ [erg cm^{-2} s^{-1}]	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}$ [yr^{-1}]
1	8.8×10^{-13}	0.04
$2^{\dagger}$	7.3×10^{-12}	0.2
$2^{\ddagger}$	3.0×10^{-12}	0.1
3	4.6×10^{-12}	0.2
4	3.3×10^{-12}	0.1
2017	3.6×10^{-12}	0.1

The Neutrino Excess from TXS 0506+056



IceCube Colloboration 2018b

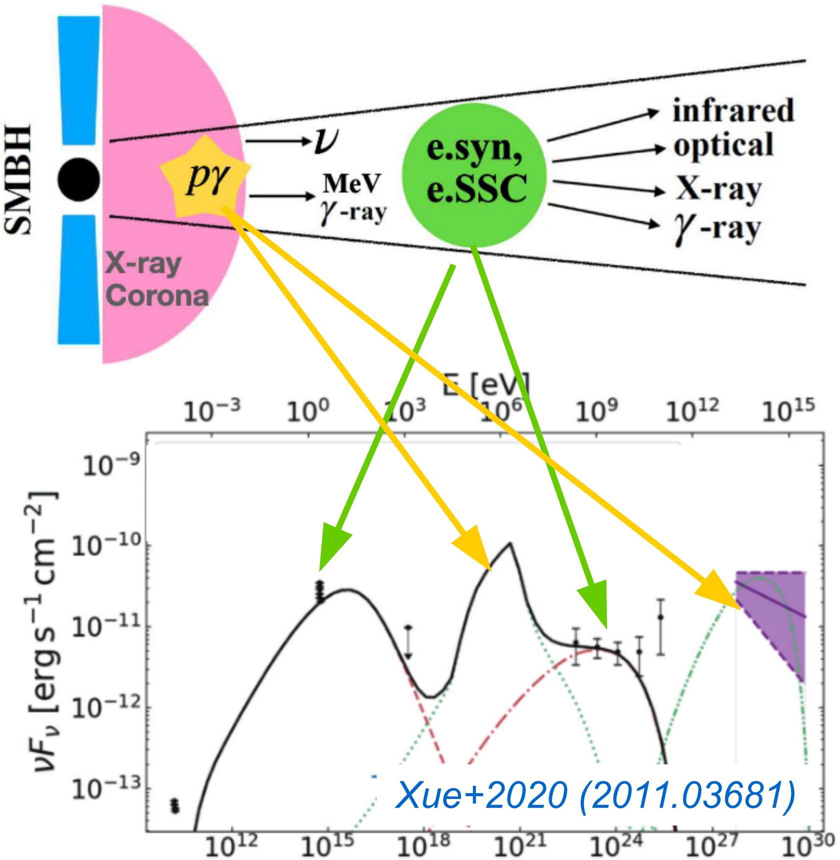


Fermi-LAT Collaboration 2019
(see also Padovani et al. 2018)

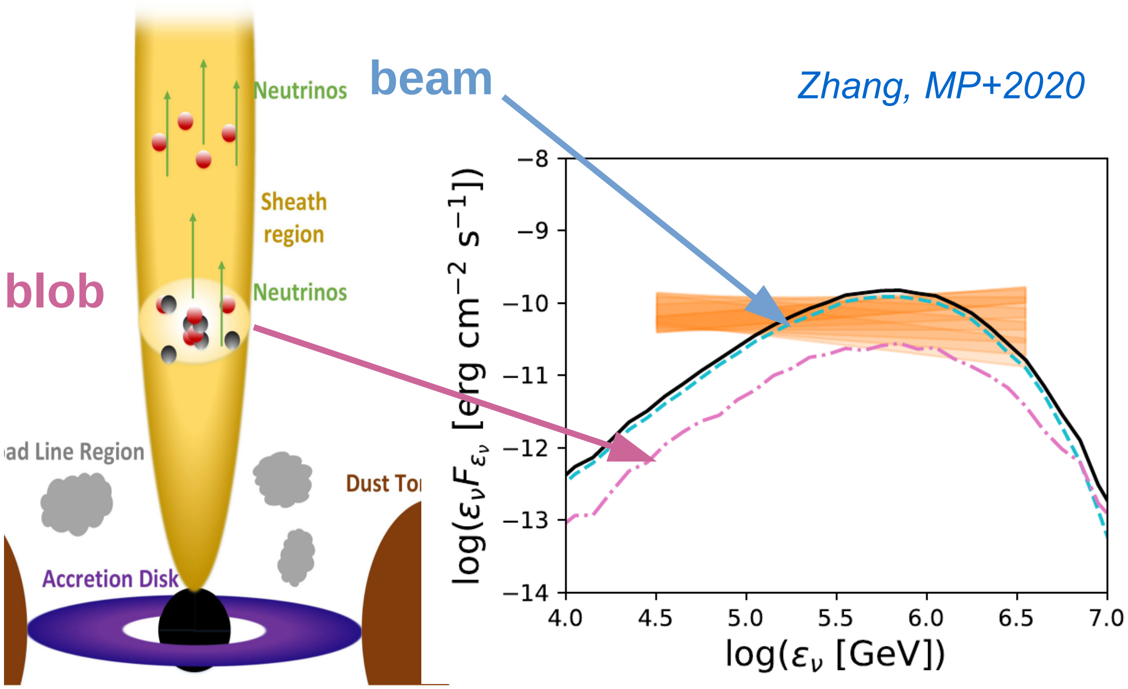
IceCube Colloboration 2018b

- 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.

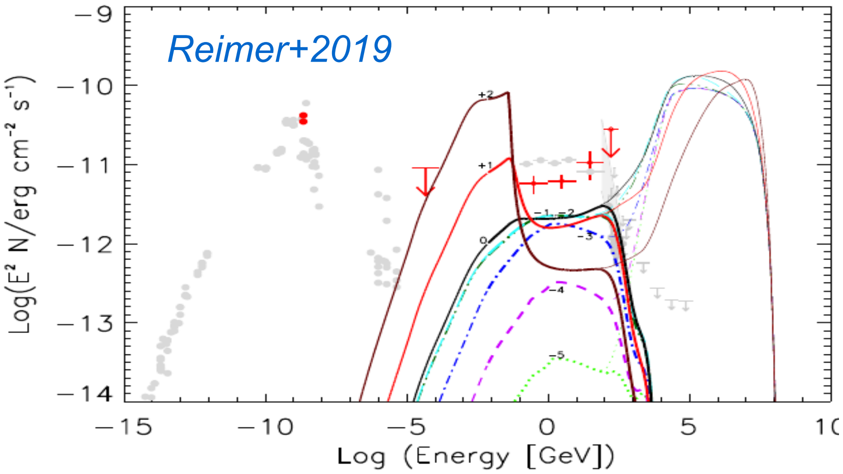
Moving Beyond One-zone Scenarios …



Xue+2020 (2011.03681)



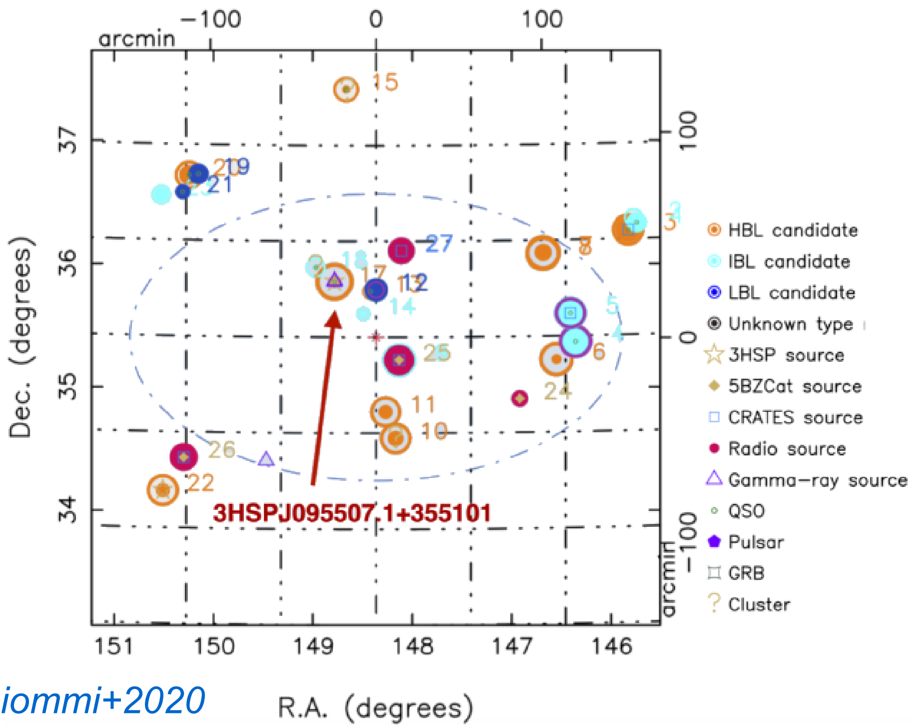
Zhang, MP+2020



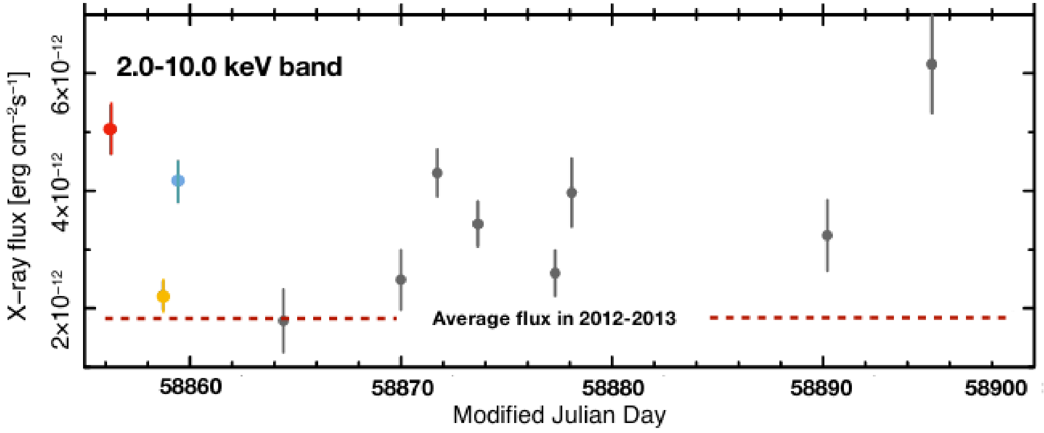
Reimer+2019

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

3HSP J095507.9+35510 / IceCube-200107

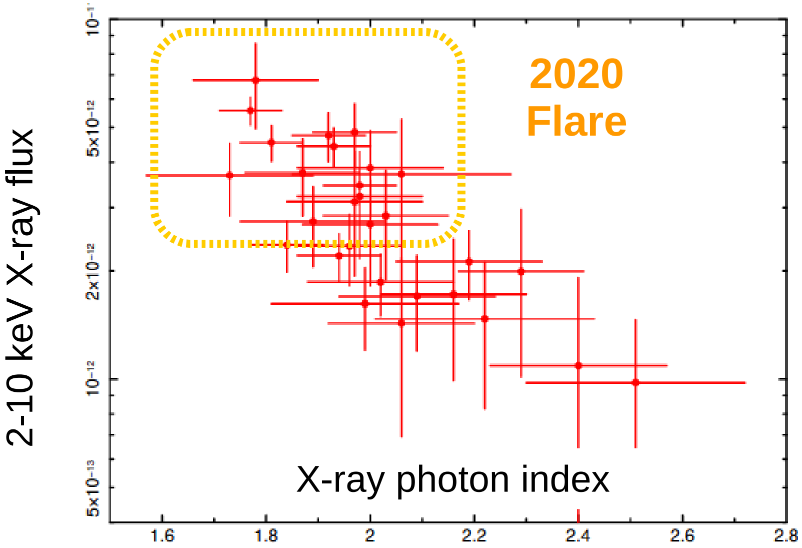


Giommi+2020



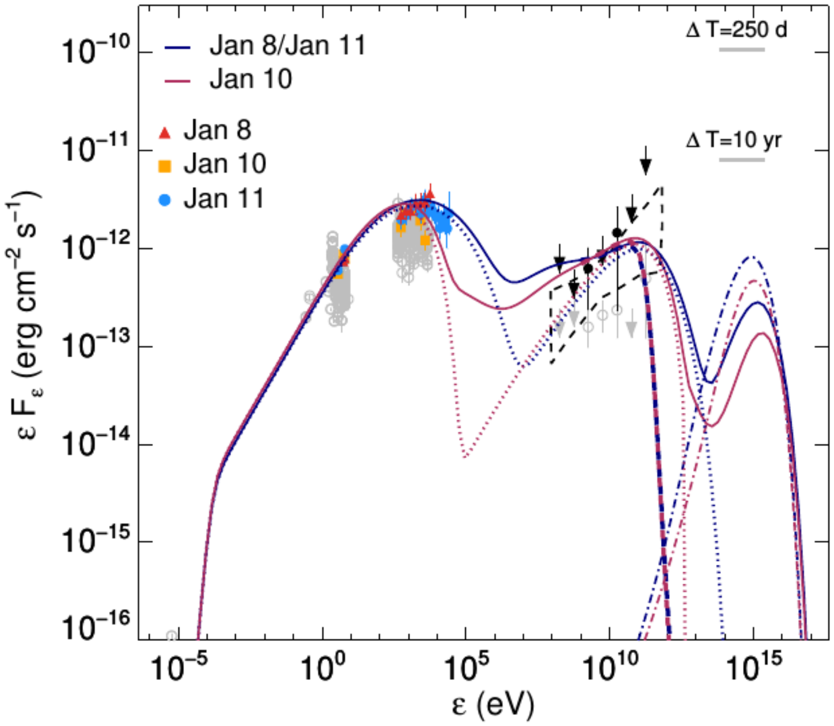
- 3HSP J095507.9+35510 is an HSP blazar at z~0.56 belonging to the extreme subclass.

- 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.



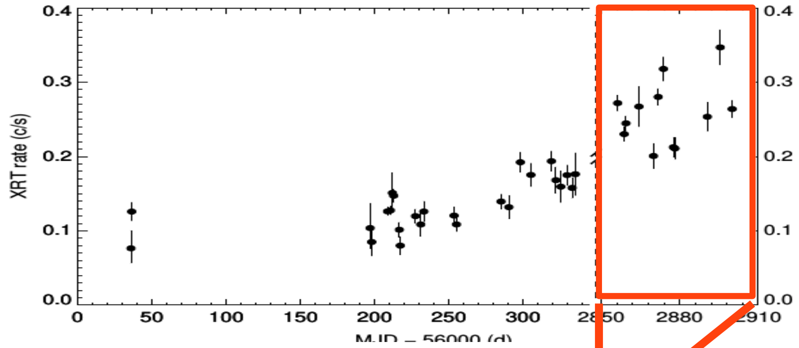
X-ray Flaring vs. Non-Flaring State

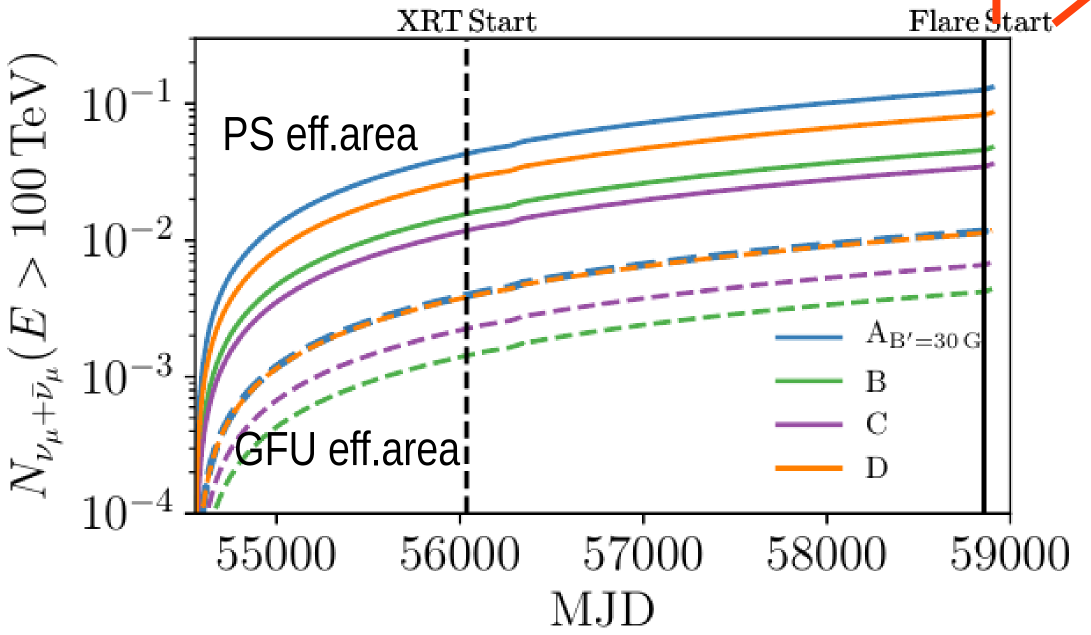
3-day X-ray flare



MP, Oikonomou+2020

10 yr X-ray emission



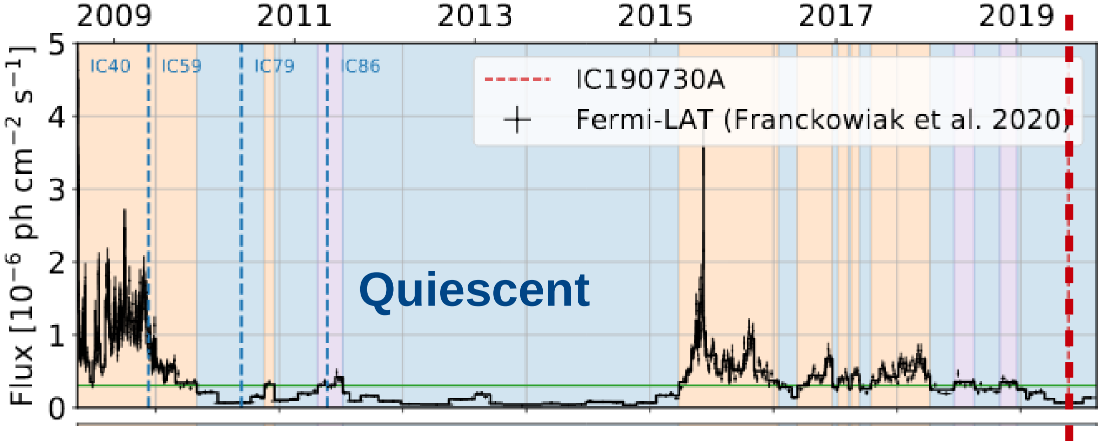


- Gamma-rays from **hadronic cascade** emission → **$L_\nu \sim (L_X)^2$**

- Predicted number of muon neutrinos during **high X-ray flux state << 1**.

- **~0.1** muon neutrinos in **10 yr** → comparable to the expectation from multi-epoch modeling of TXS 0506+056.

PKS 1502+106 / IceCube-190730A

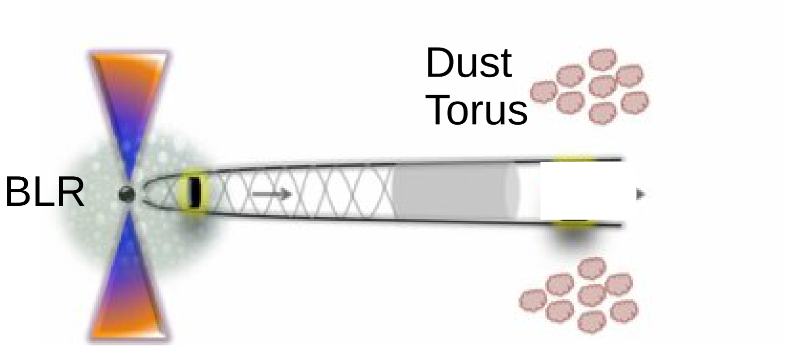


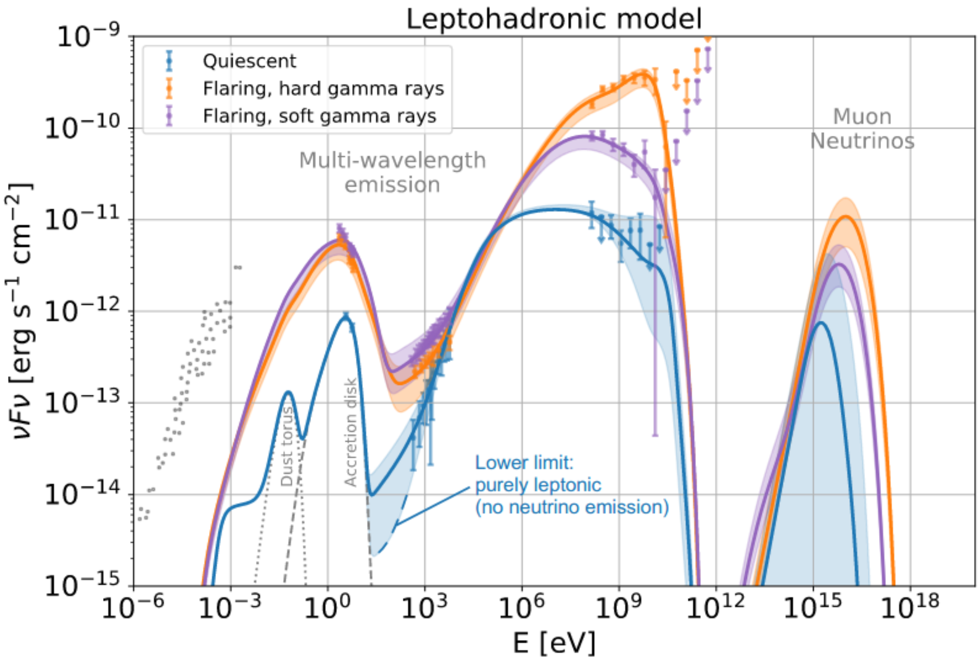
Flare

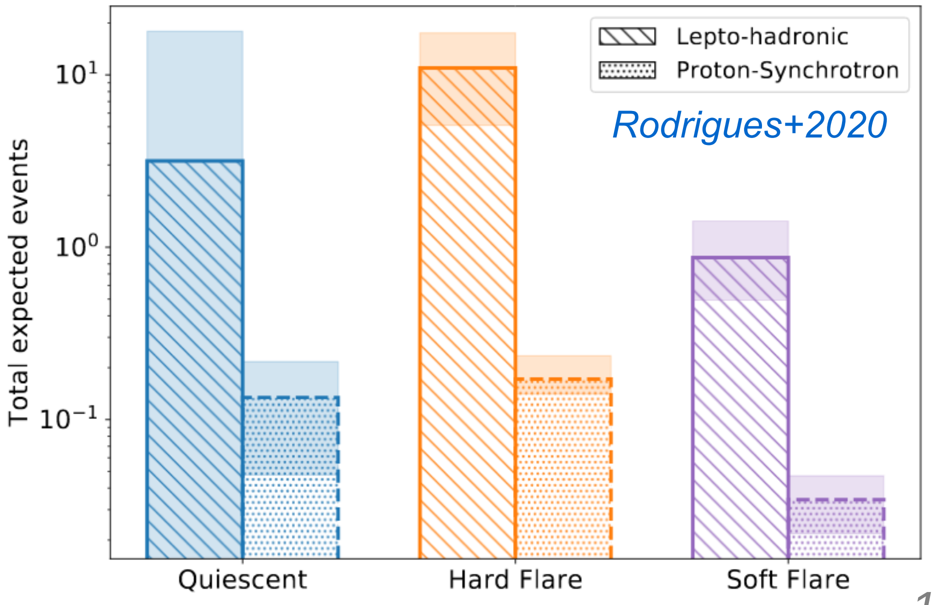
Flare

Franckowiak+2020, Rodrigues+2020

- PKS 1502+106 is an LSP at z~1.84.
- Spatially coincident with IceCube190703A. Blazar observed in a low-flux state.



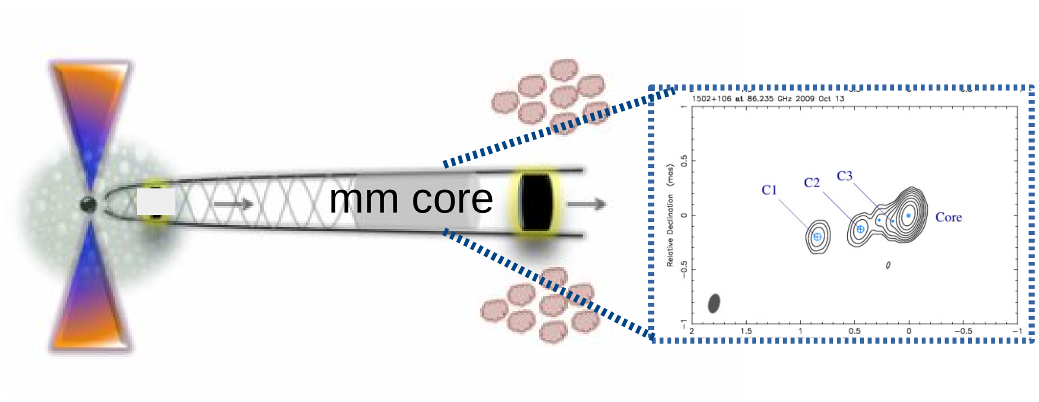


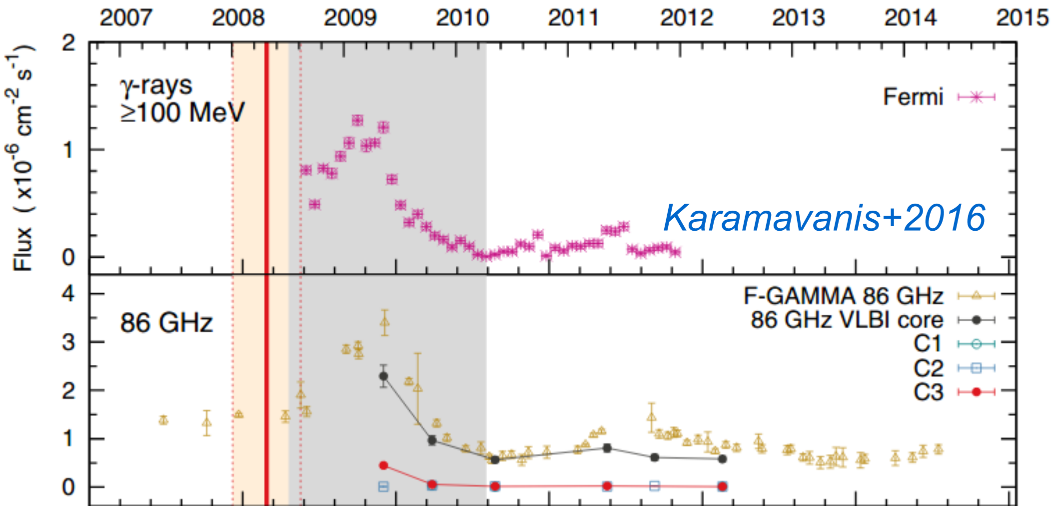


Rodrigues+2020

Location of γ-ray flares

Flares beyond the BLR

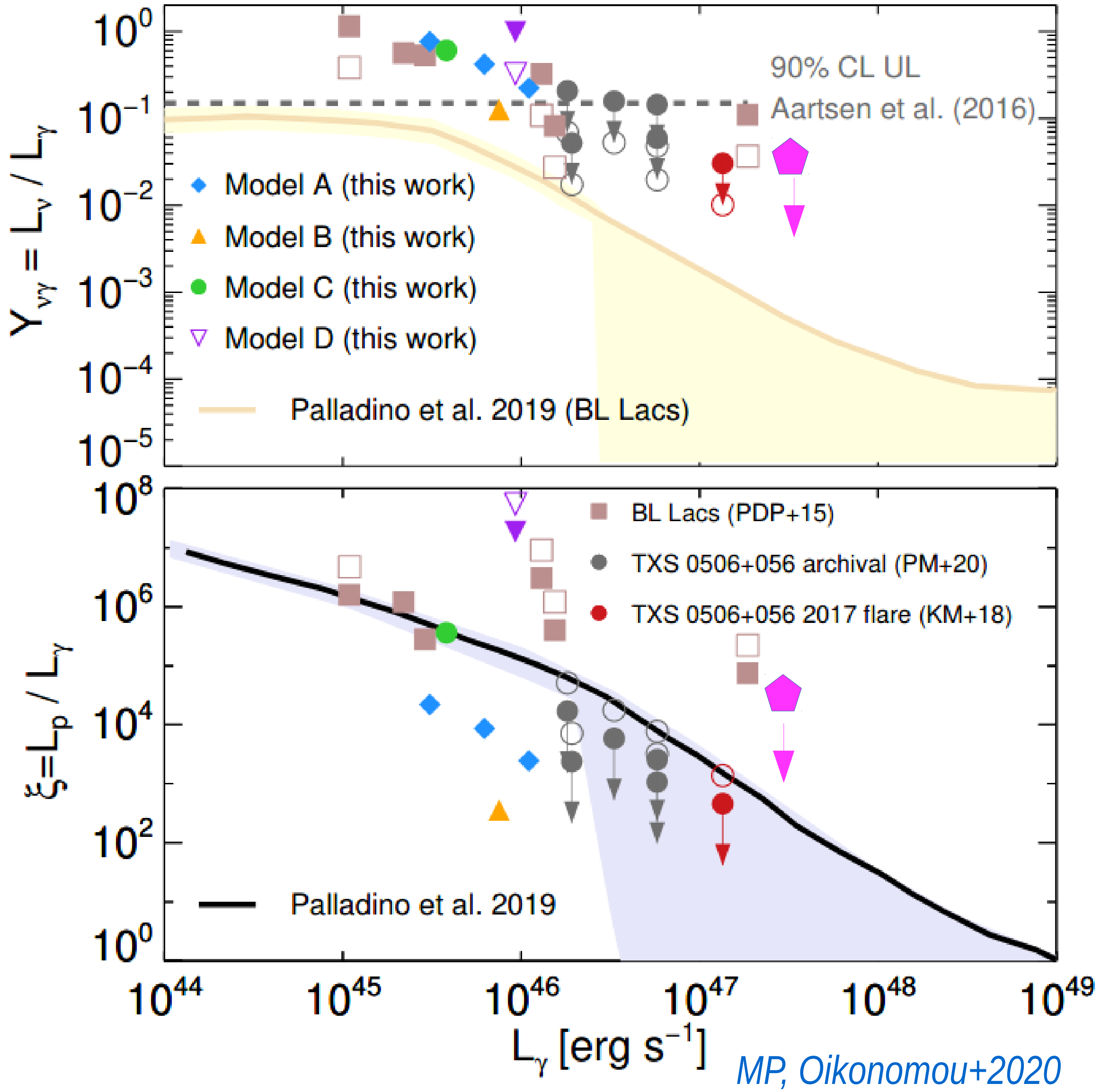




- Time of ejection of knot C3 from core coincides with onset of 2008 γ-ray flare.
- Location of γ-ray flaring region @ 1 – 5 pc!
- Lower neutrino expectation from γ-ray flares.
- **Neutrino emission likely dominated by quiescent states** → Consistent with the detection of 1 event from PKS 1502+106

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** (LSP; hexagon), **TXS 0506+056** (ISP; circles), **BL Lacs** (HSPs; squares), and **3HSP J095507.9+35510** (extreme HSP; other symbols).

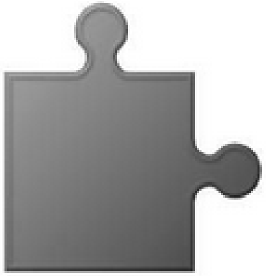


MP, Oikonomou+2020

- The ν-to-γ luminosity ratio decreases in more γ-ray luminous blazars. **Why??**
- The baryon loading factor ξ strongly depends on the source conditions (e.g., Doppler factor, size, magnetic field).
- The baryon loading factor >> 1. **How ??**

What have we learned so far ?

γ-rays may have a leptonic origin, while hadronic processes have sub-dominant contributions to X-rays (e.g., TXS 0506+056, PKS 1502+106).
Still, hadronic emission can dominate in γ-rays in extreme HSPs.



Neutrino production during quiescent periods of EM blazar emission may be responsible for the detection of 1 neutrino.

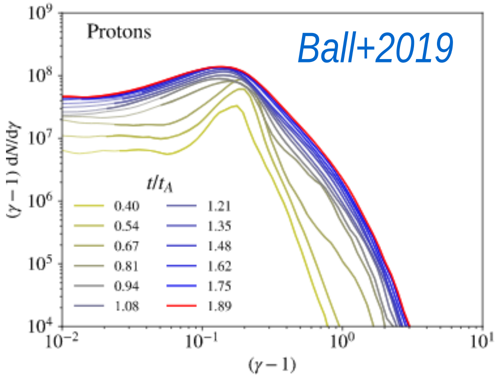
While neutrino production is enhanced during flares, a high duty cycle of flares and/or long-duration flares are still needed to explain the detection of 1 neutrino (not always true).

Likely more than 1 neutrino production sites in blazar jets:

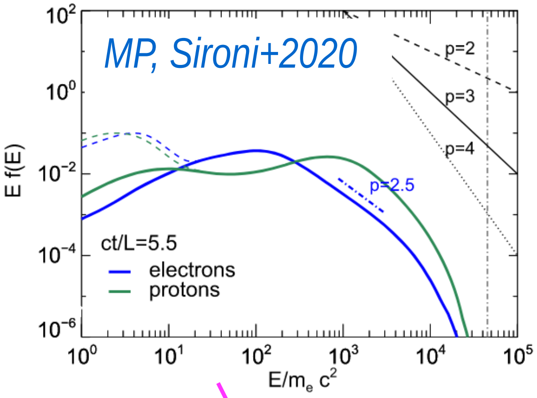
- an optically thick to pγ interactions that is dark in GeV γ-rays but bright in MeV γ-rays → likely in the inner jet close to black hole and transient.
- an optically thin where the broadband EM emission comes from → likely in (sub-)pc scale jet and persistent.

Looking into the future: theoretical perspective

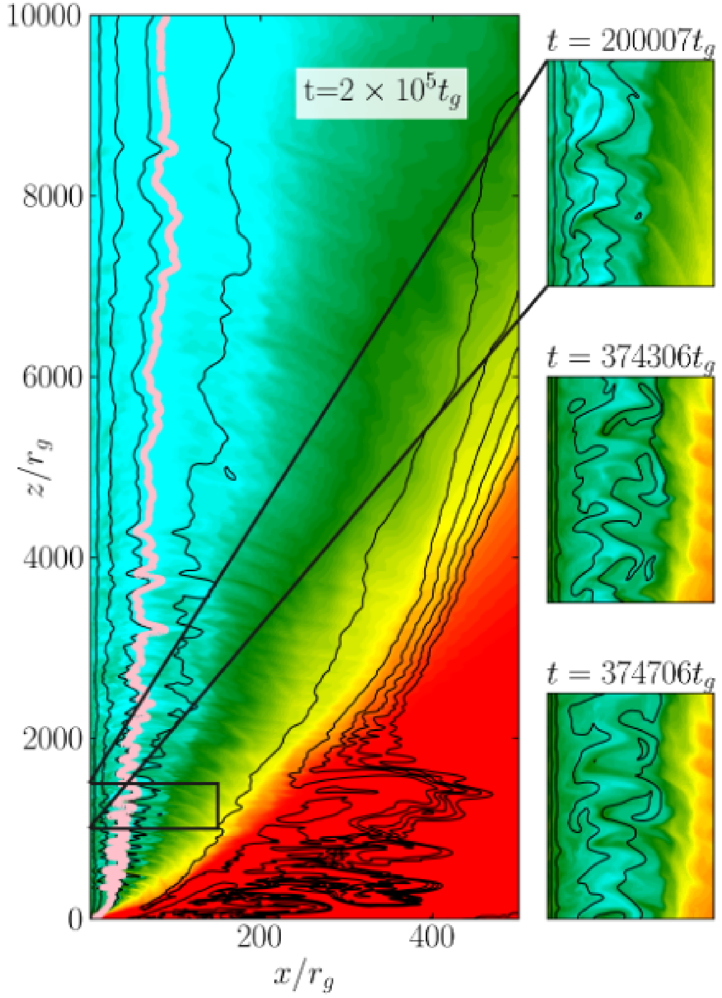
- Connect **plasma physics** (particle acceleration) with **magnetized fluid physics** (jet dynamics and acceleration) with **radiation physics** to create a physical model for multi-messenger emission in jets.



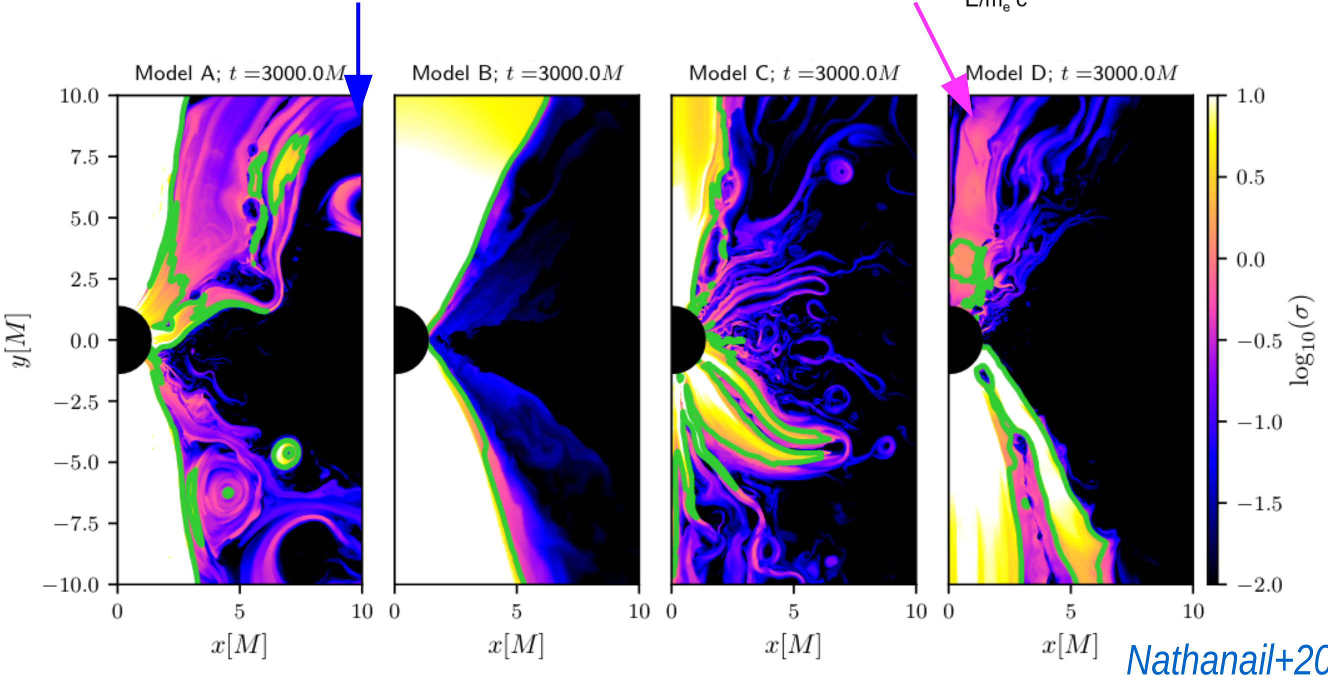
Ball+2019



MP, Sironi+2020



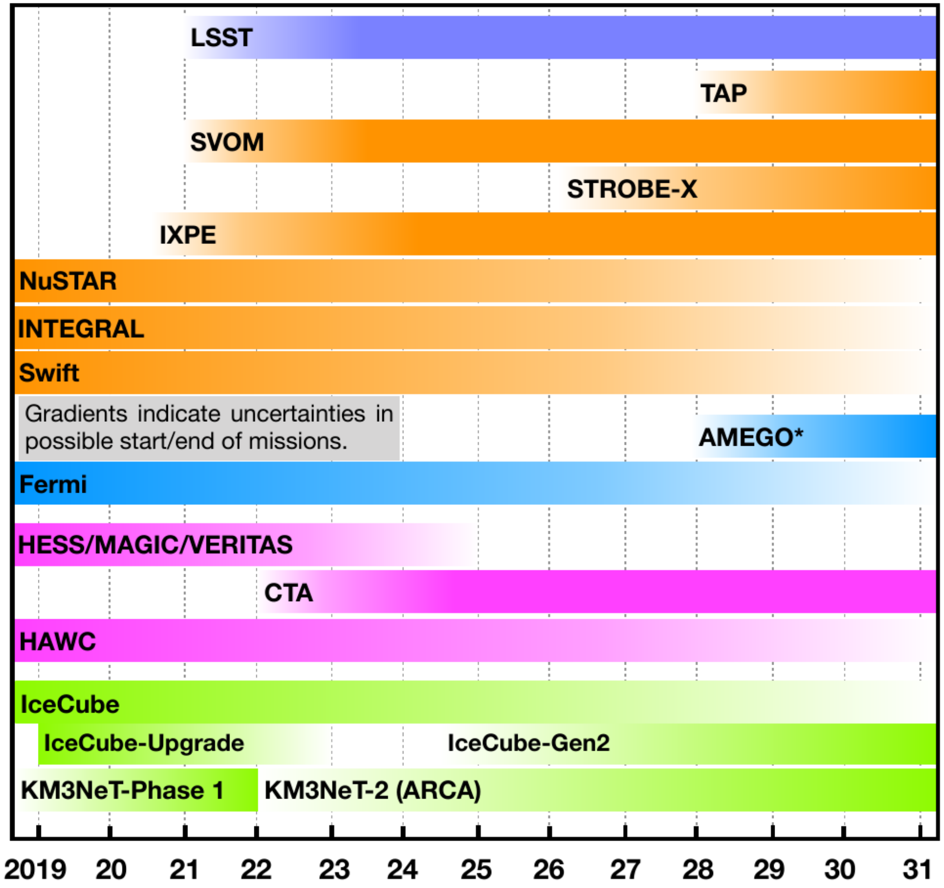
Chatterjee+2020



Nathanail+2020

Looking into the future: observational perspective

- **X-ray monitoring** of blazars with **polarization capabilities** → (i) determine X-ray flare duty cycle (ii) differentiate between Compton and synchrotron scenarios for the γ-ray emission.
- **Sensitive MeV monitoring** of the sky with **polarization capabilities** → (i) fill in the "gap" between the 2 components of the blazar SED (ii) discover neutrino sources that are otherwise "dark" in γ-rays.
- **Sensitive VHE γ-ray observatories** → search for hadronic spectral signatures
- **Next generation neutrino detectors** → (i) increase of neutrino statistics (ii) provide almost uniform coverage of the Sky in neutrinos
- *Synergy of multi-messenger observatories in the time domain is a MUST!*

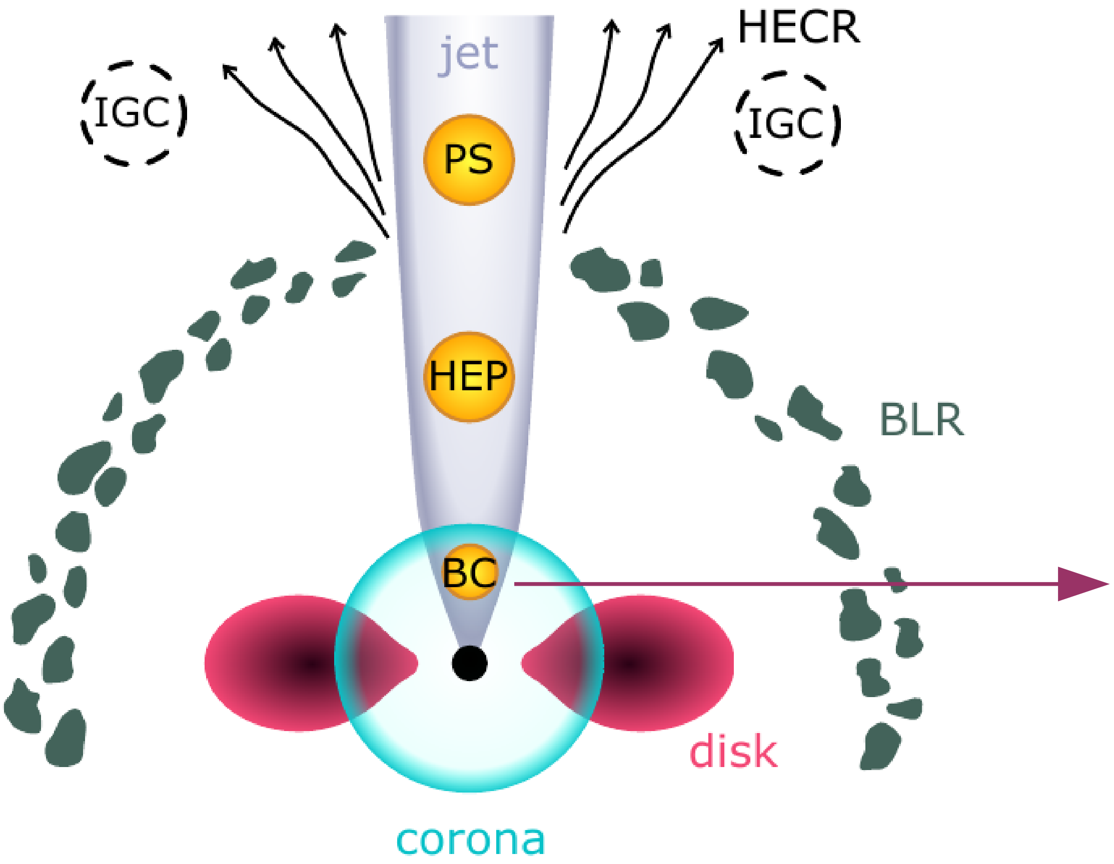


Buson et al. 2019 for Astro2020 (arXiv:1903.04447)

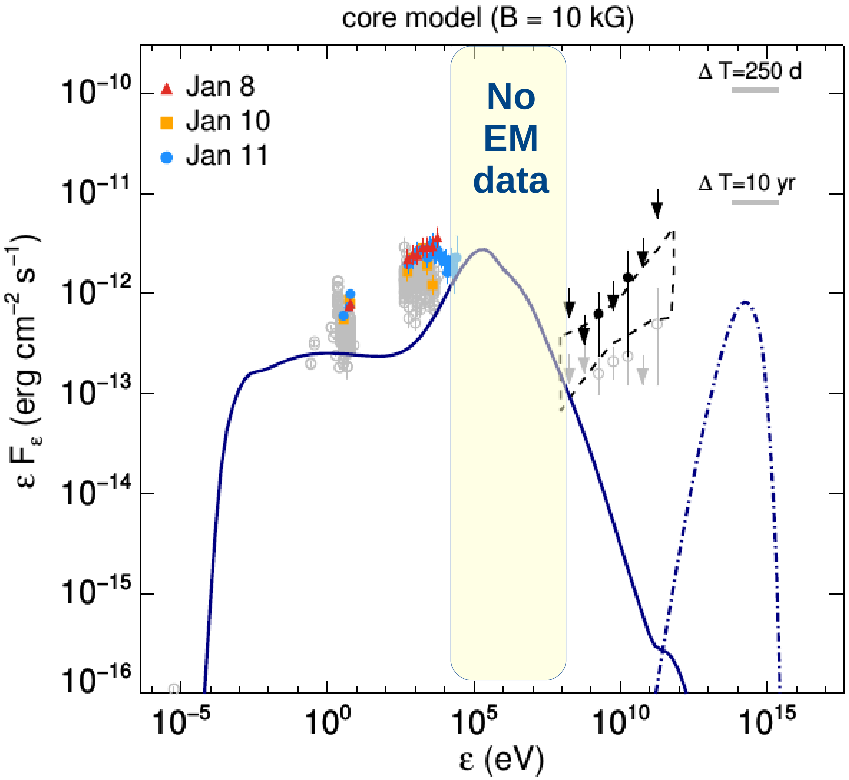
Thank you

Back-up slides

Exploring Alternative Scenarios



MP, Oikonomou+2020

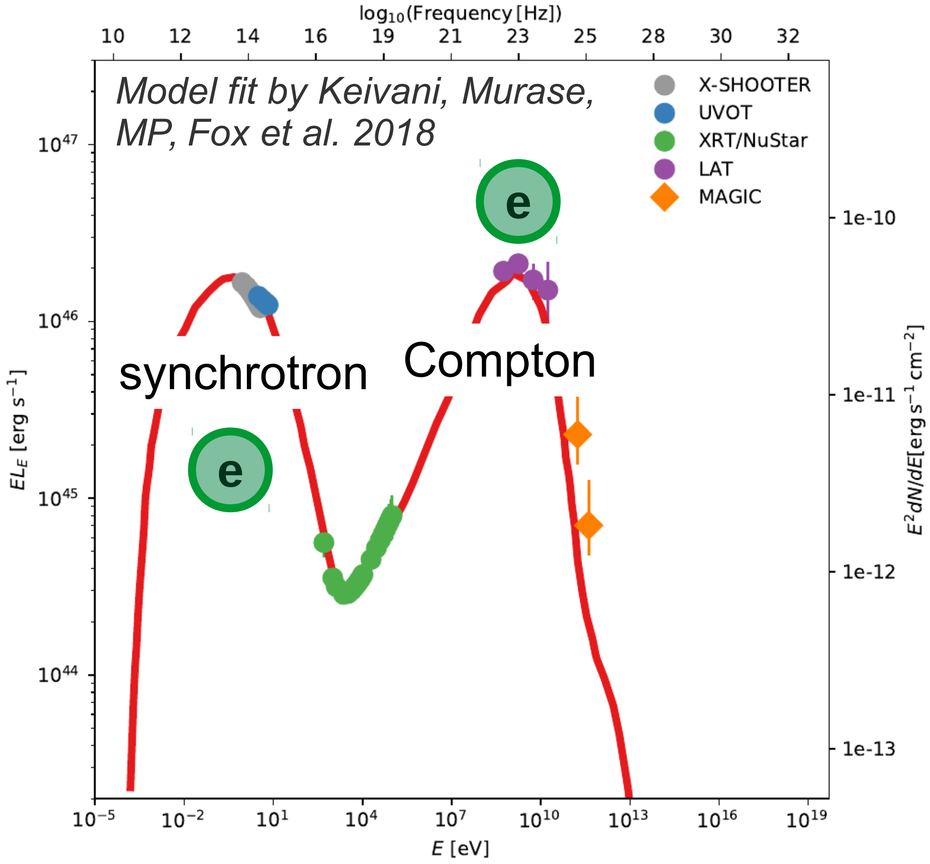


Model	State	$\dot{N}_{\nu_\mu+\bar{\nu}_\mu}(>100\ \text{TeV})$ $(\times10^{-4}\ \text{yr}^{-1})$ Alert (PS)
HEP	transient high	50 (190)
PS	transient high	2.1 (7.3)
BC	persistent average	33 (370)
IGC	persistent average	3.6 (10)

- ***Blazar Core (BC):*** compact region of jet embedded in a dense X-ray coronal field – Persistent emission
- ***Hidden External Photons (HEP):*** region lying within a weak BLR emission (not detectable) – Transient emission
- ***Proton Synchrotron (PS):*** UHECR protons – Transient emission

What sets the maximum neutrino flux?

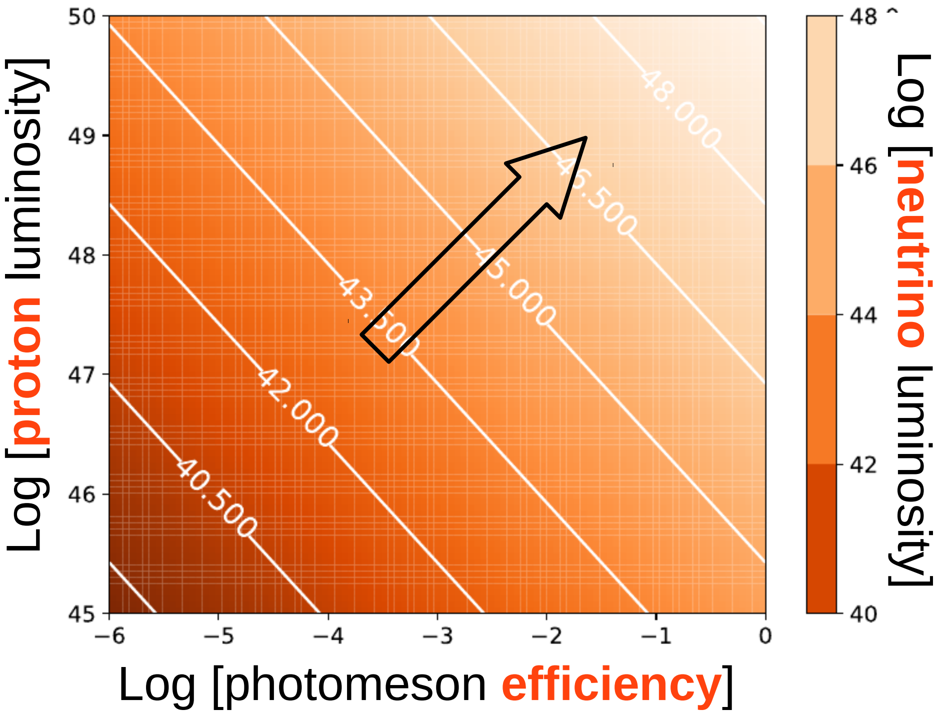
Murase, Oikonomou, MP 2018



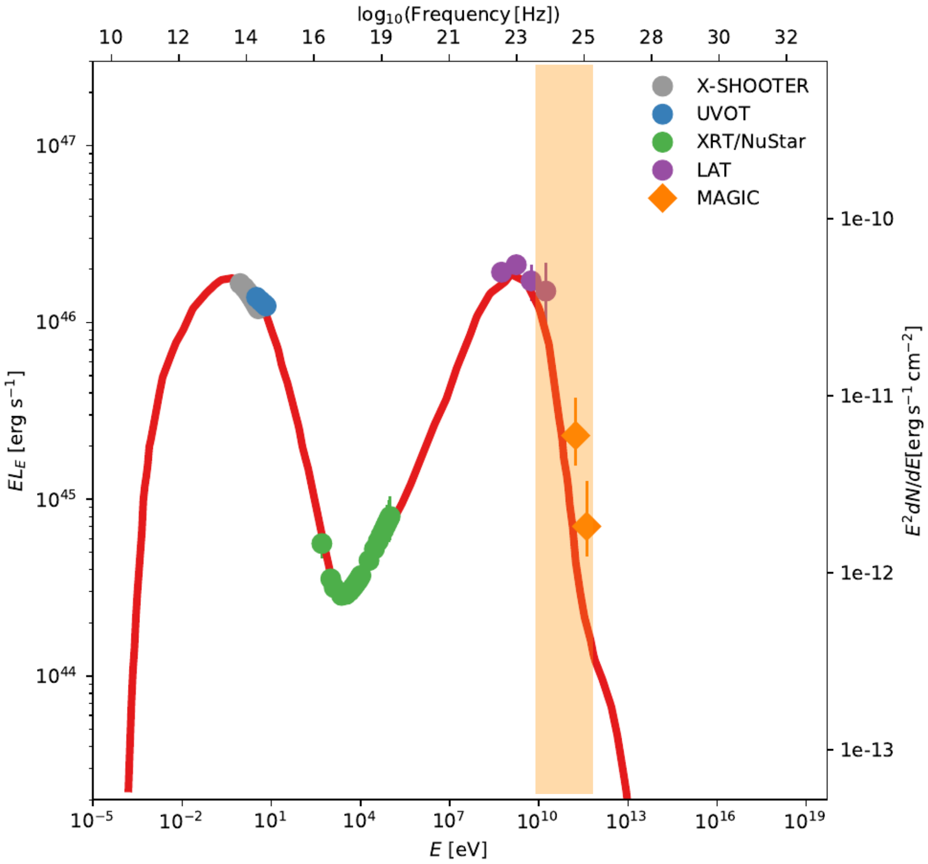
Model fit by Keivani, Murase, MP, Fox et al. 2018

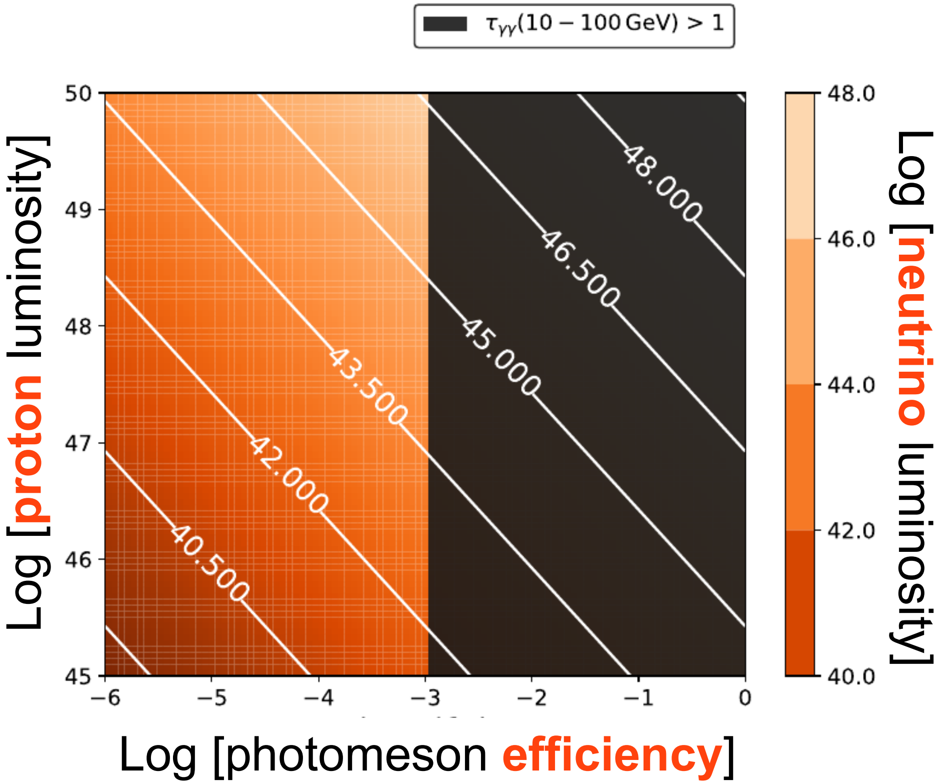
$$\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma}\, \varepsilon_p L_p$$

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



What sets the maximum neutrino flux?

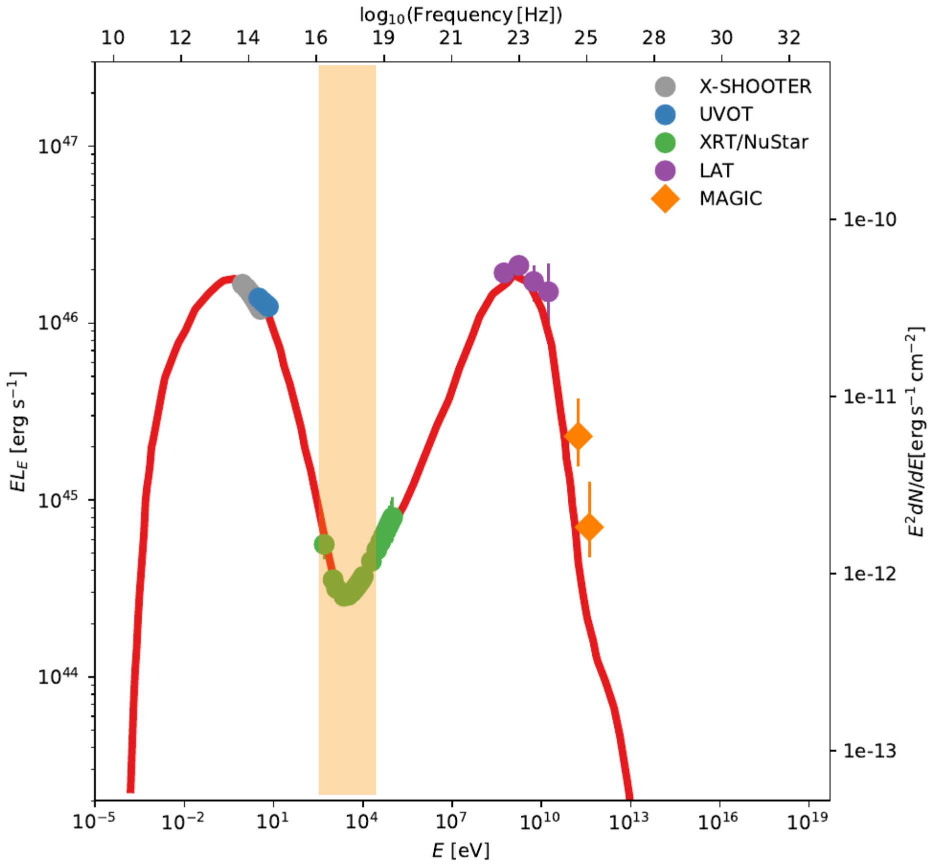


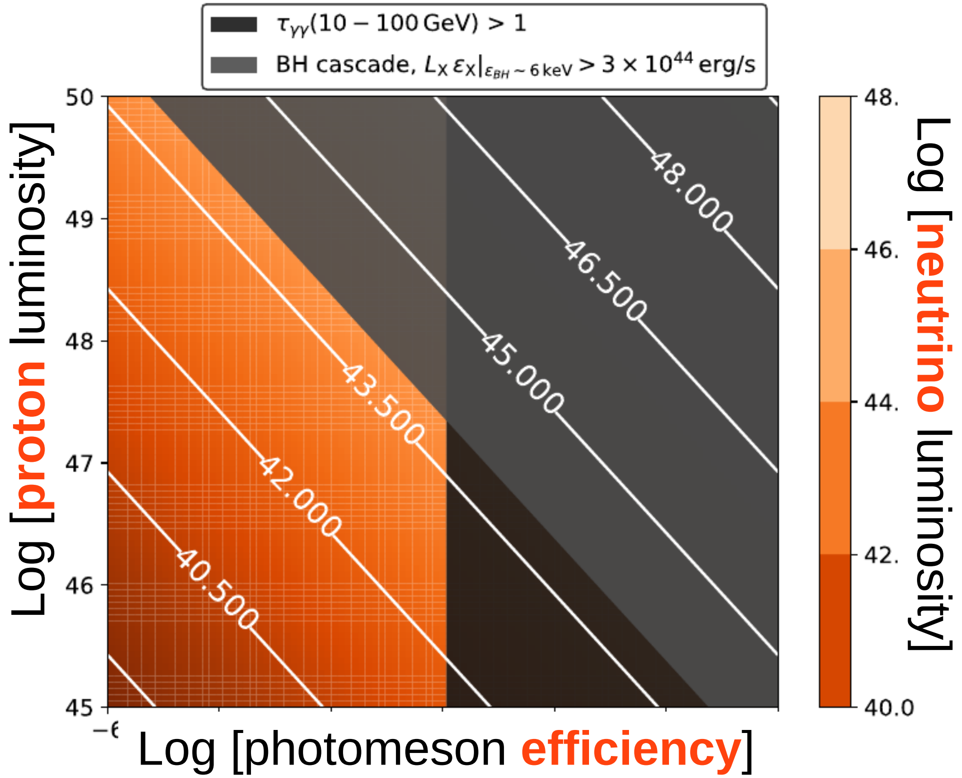


I. Optical depth for absorption of 10-100 GeV γ-rays must be low: $\tau_{\gamma\gamma}(10-100\,\mathrm{GeV}) \lesssim 1$

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

What sets the maximum neutrino flux?



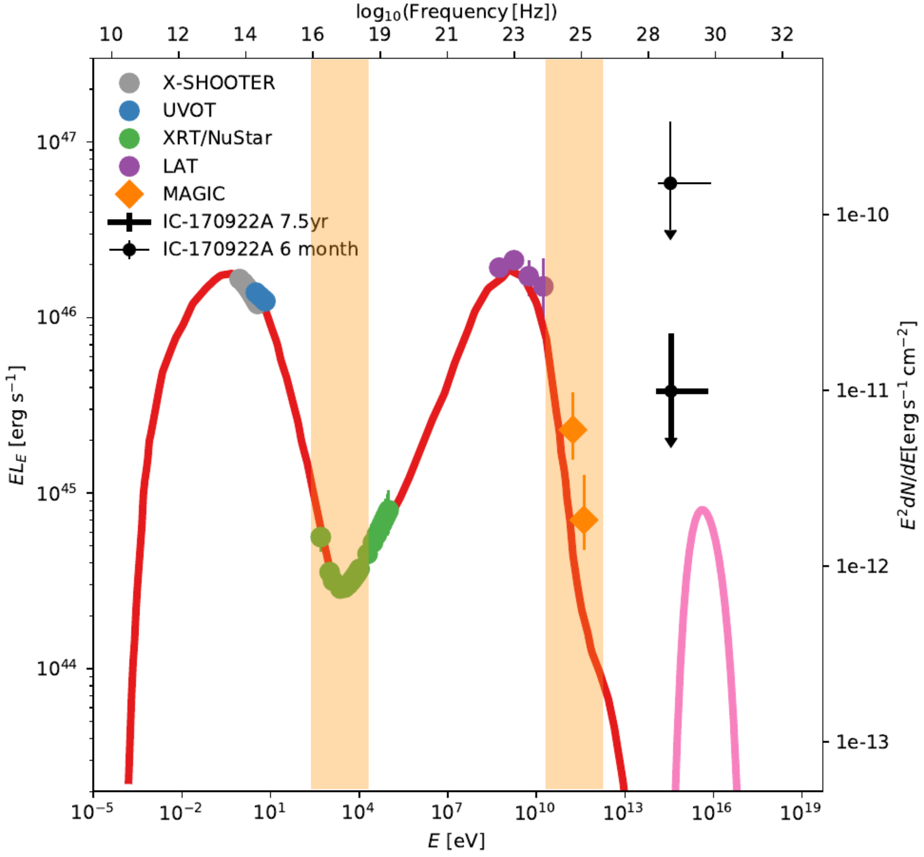


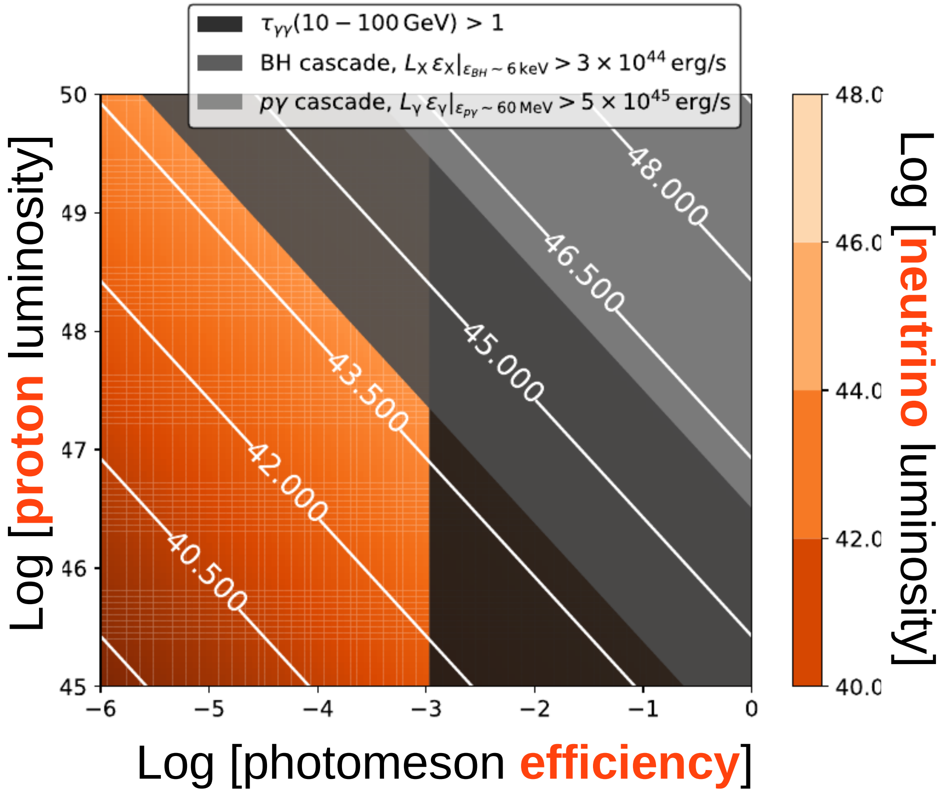
II. Synchrotron emission from Bethe-Heitler pairs must not overshoot X-ray data:

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

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

What sets the maximum neutrino flux?





Maximum all-flavor neutrino flux:

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