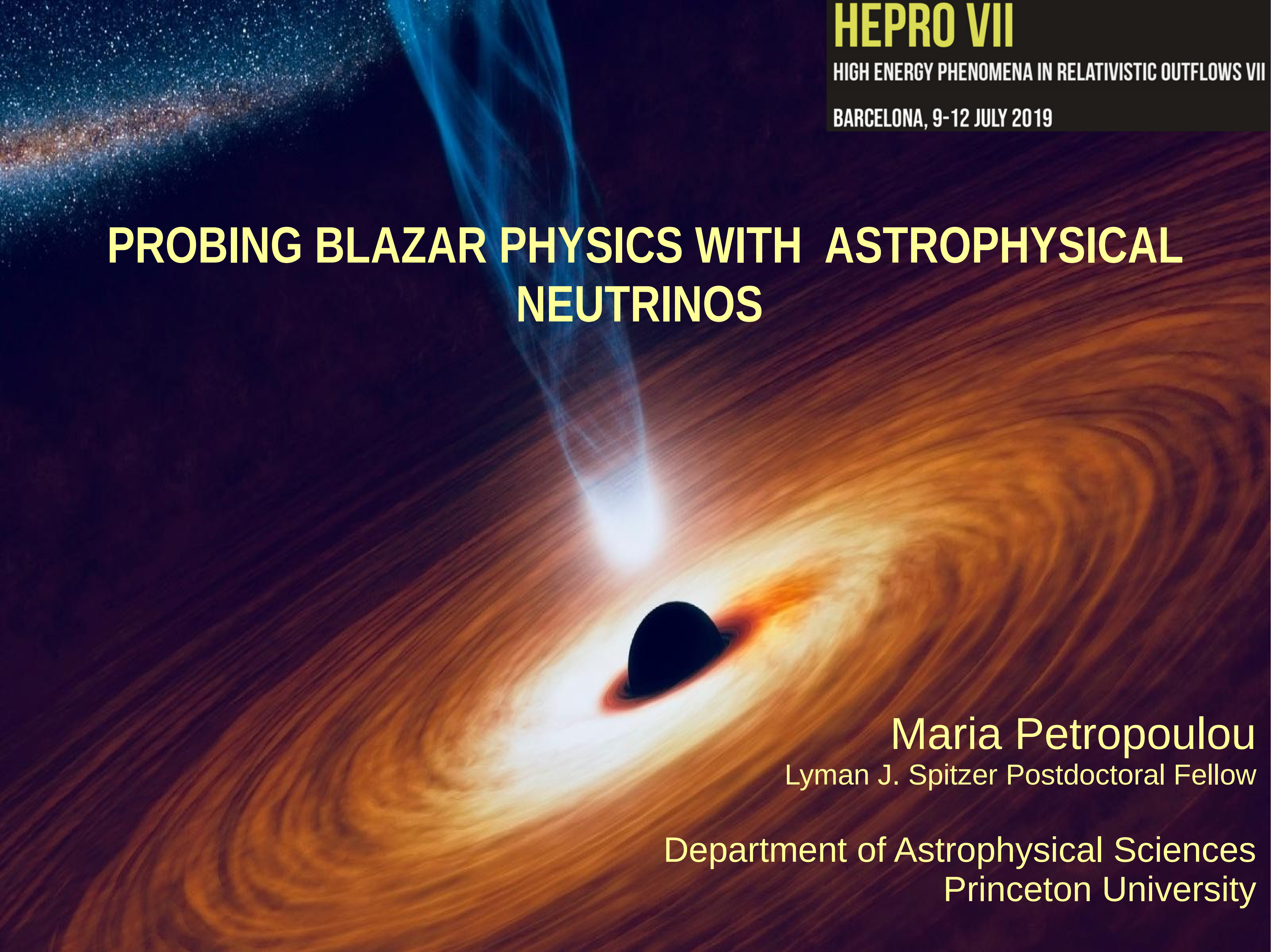


HEPRO VII
HIGH ENERGY PHENOMENA IN RELATIVISTIC OUTFLOWS VII
BARCELONA, 9-12 JULY 2019

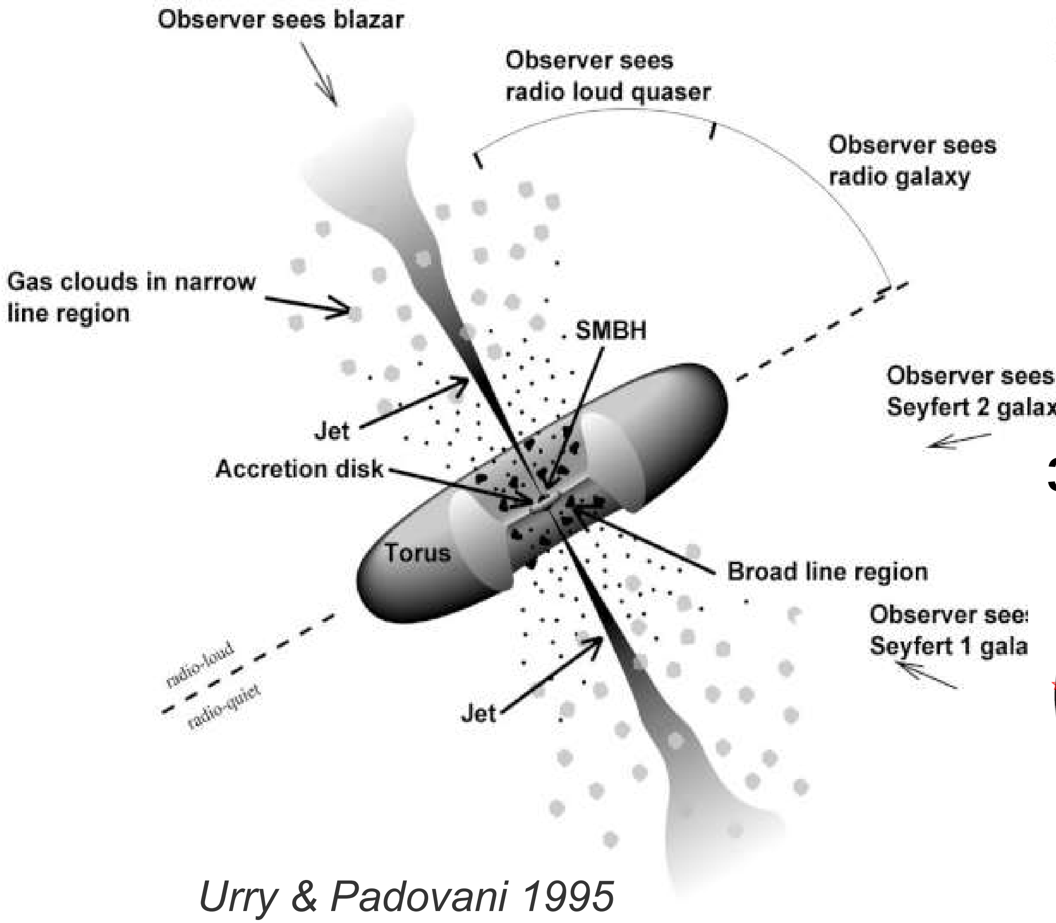
PROBING BLAZAR PHYSICS WITH ASTROPHYSICAL NEUTRINOS

Maria Petropoulou
Lyman J. Spitzer Postdoctoral Fellow

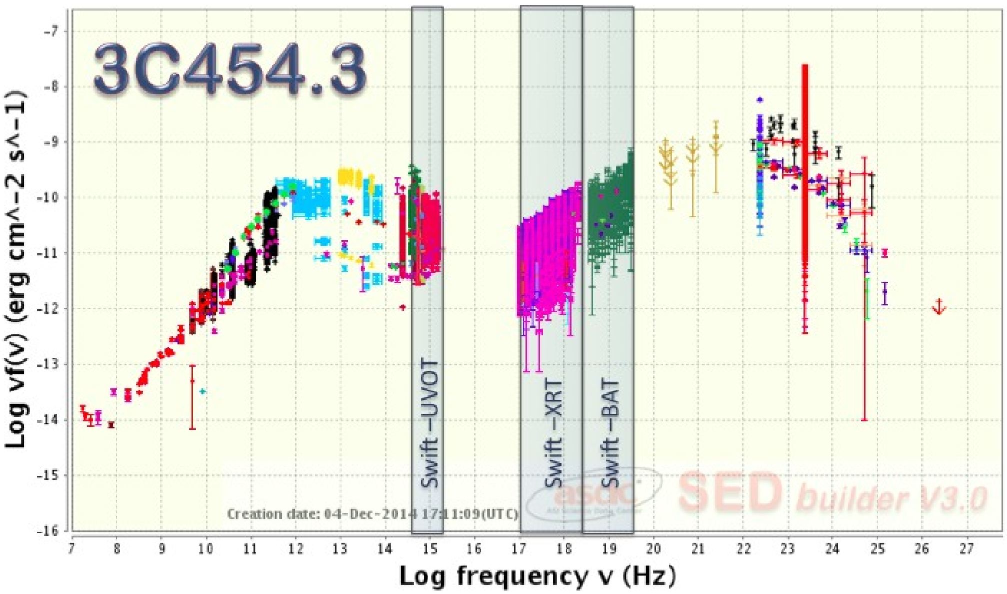
Department of Astrophysical Sciences
Princeton University

Blazars: AGN with jets viewed face-on

Many talks at the Session:
Relativistic outflows from extragalactic sources



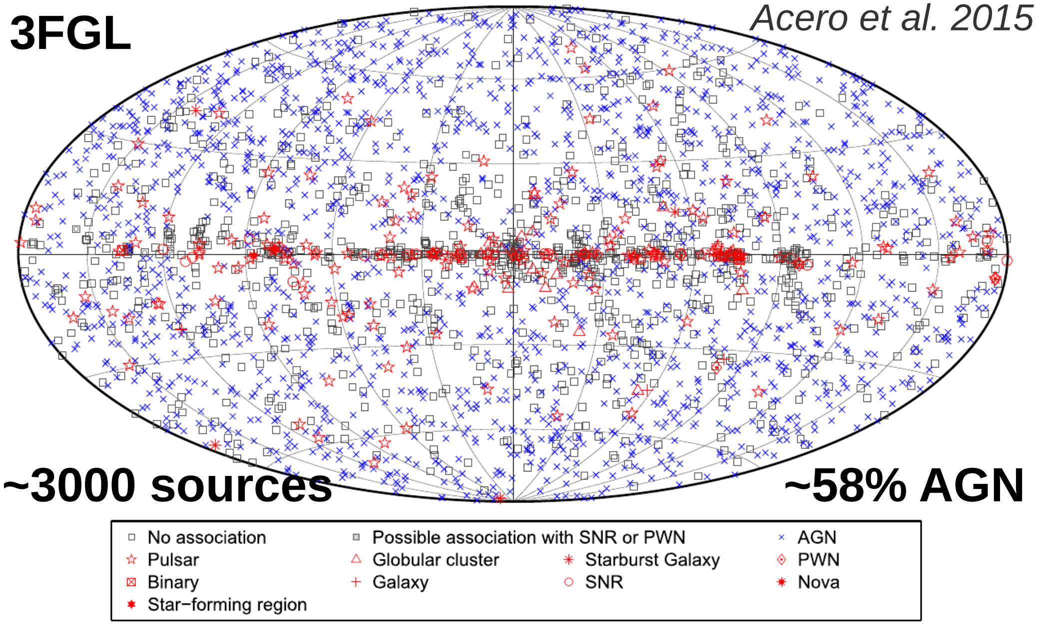
Urry & Padovani 1995



Giommi 2015, JHEA (https://tools.asdc.asi.it/SED/)

3FGL

Acero et al. 2015



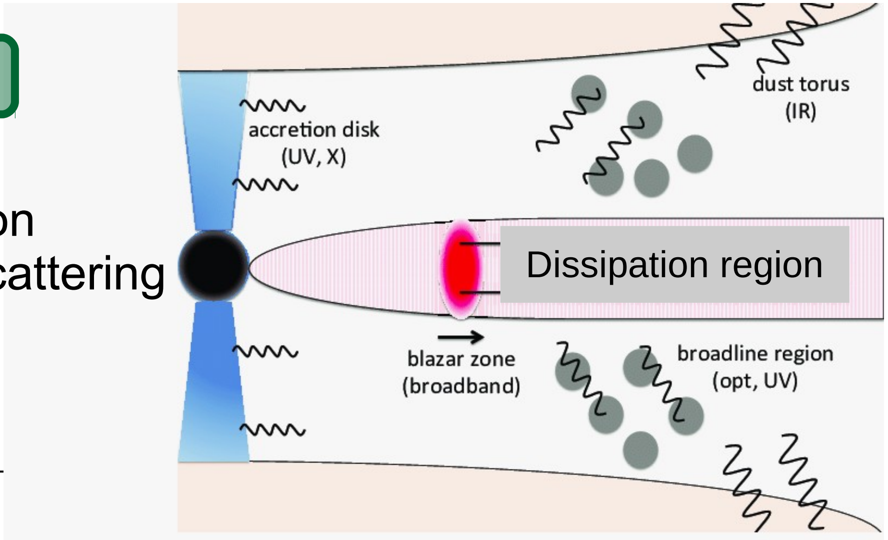
~3000 sources

~58% AGN

Origin of γ-rays: leptonic or hadronic ?

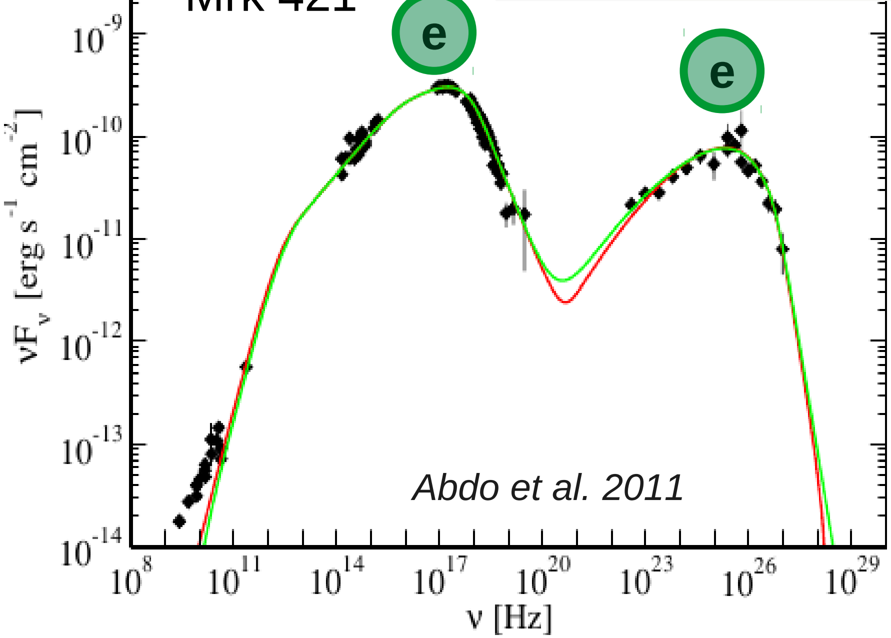
Leptonic models

- Synchrotron radiation
- Inverse Compton scattering
- Pair production



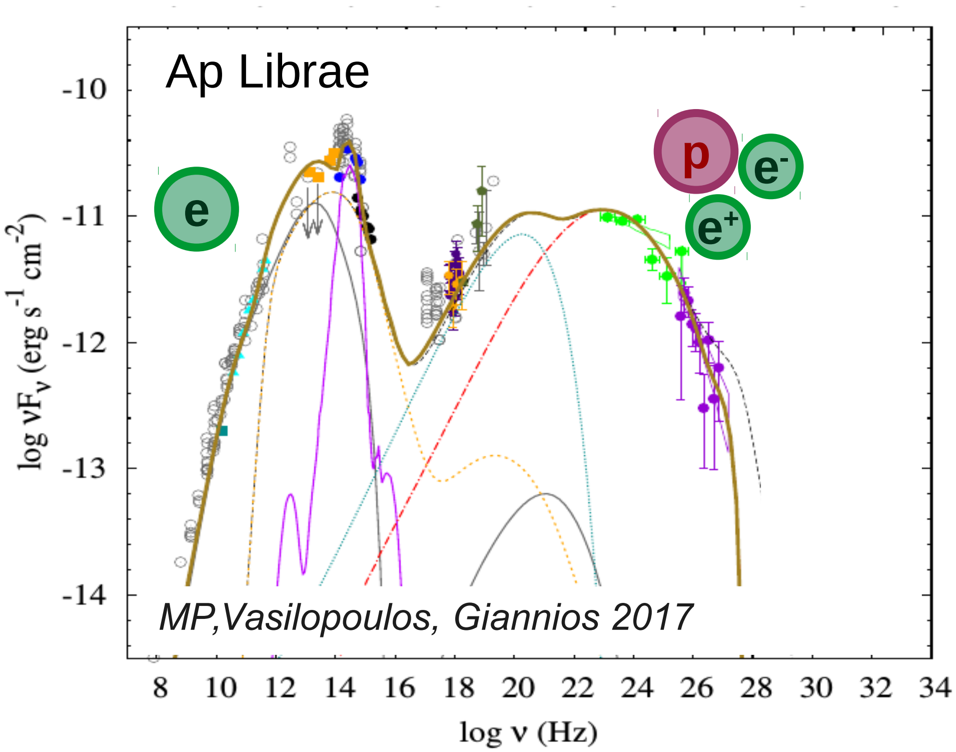
Hadronic models

- Synchrotron radiation
- Inverse Compton scattering
- Pair production
- Photo-meson production
- Photo-pair (Bethe-Heitler) production
- Hadro-nuclear collisions



Abdo et al. 2011

Early studies: *Mannheim & Biermann 1992; Sikora+1994; Dermer & Schlickeiser 1994; Mastichiadis & Kirk 1995; Bloom & Marscher 1996; Rieger +1998; Aharonian 2000, Atoyan & Dermer 2001; Muecke+2003*



MP,Vasilopoulos, Giannios 2017

Status of the field prior to 2017

- Both models describe equally well the photon spectra.

- **Leptonic** models:

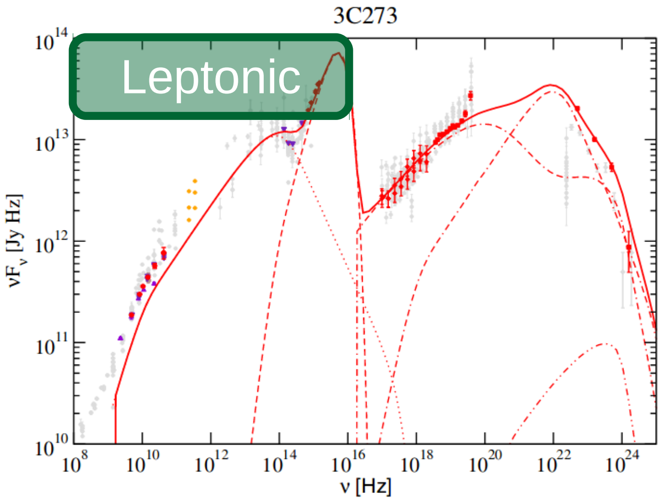
a) Work for both FSRQs and BL Lacs.
b) Jet power L_j~ **10^{44} – 10^{46} erg/s** for BL Lacs, ~**10^{46} – 10^{48} erg/s** for FSRQs
c) Particle-dominated emitting regions in BL Lacs.
d) No neutrinos.

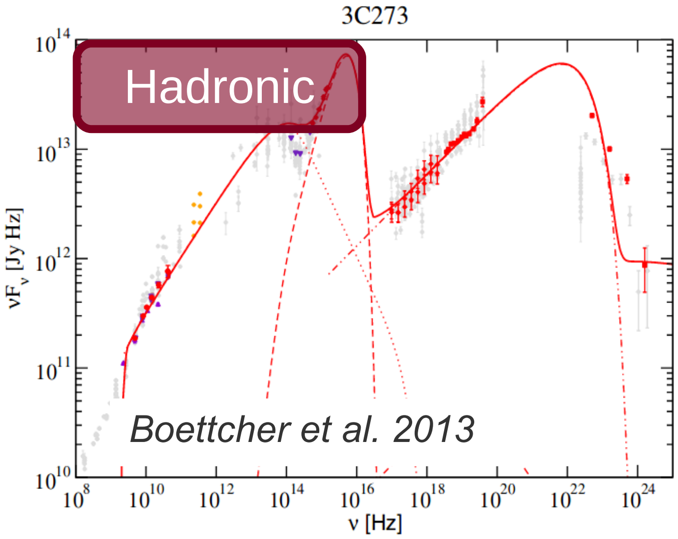
- **Proton-synchrotron hadronic** models:

a) Work for both FSRQs and BL Lacs
b) High jet power L_j~ **10^{47} – 10^{48} erg/s** for FSRQs, but **lower for BL Lacs**
c) High proton energies, e.g. **E_{pmax} ~ 10 EeV** (for BL Lacs)
d) Strong magnetic fields, e.g. **B ~1-100 G**
e) **~ EeV** neutrinos

- **Photo-pion hadronic** models:

a) Work for BL Lacs, but unlikely for FSRQs
b) High jet power **L_j~ 10^{47} – 10^{48} erg/s**
c) Moderate proton energies e.g. **E_{pmax} ~ 10 PeV**
d) Moderate magnetic fields, e.g. **B ~ 0.1-1 G**
e) **~ PeV** neutrinos

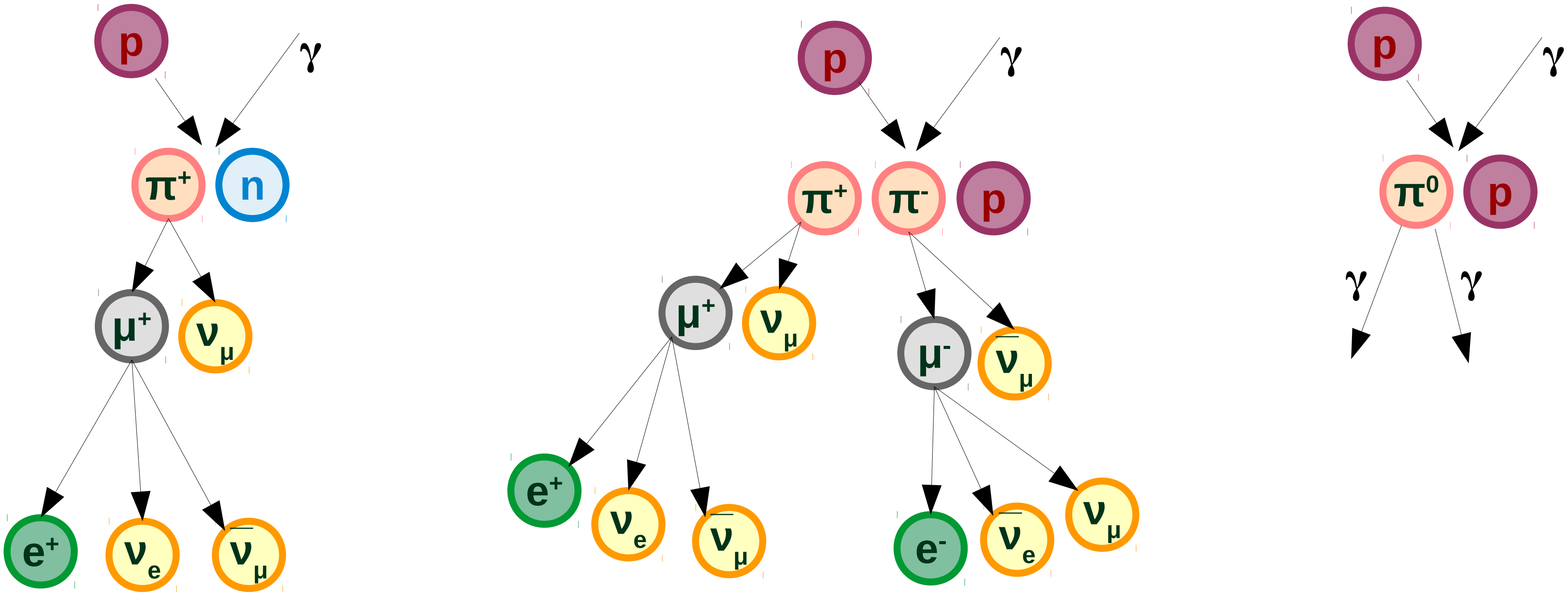




Boettcher et al. 2013

***Modeling studies**: Ghisellini et al. 2010; Boettcher et al. 2013; Dimitrakoudis, MP, Mastichiadis 2014; MP 2014; MP**,** Dimitrikoudis et al. 2015; Cerruti et al. 2015; Diltz, Boettcher & Fossati 2015; MP & Dermer 2016; Gao, Winter & Pohl 2017; MP, Nalewajko et al. 2017; Cerruti et al. 2017 +++*

Neutrinos: the smoking gun of hadrons



All-flavor ν luminosity: $\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma} \boxed{\varepsilon_p L_p}$ Proton power

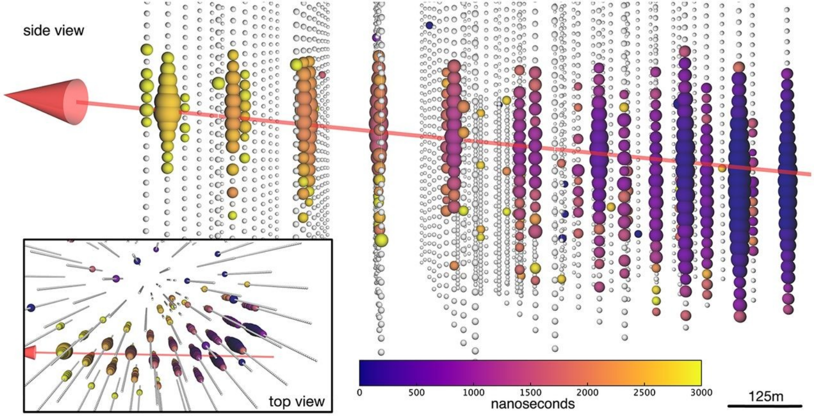
Target photons

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

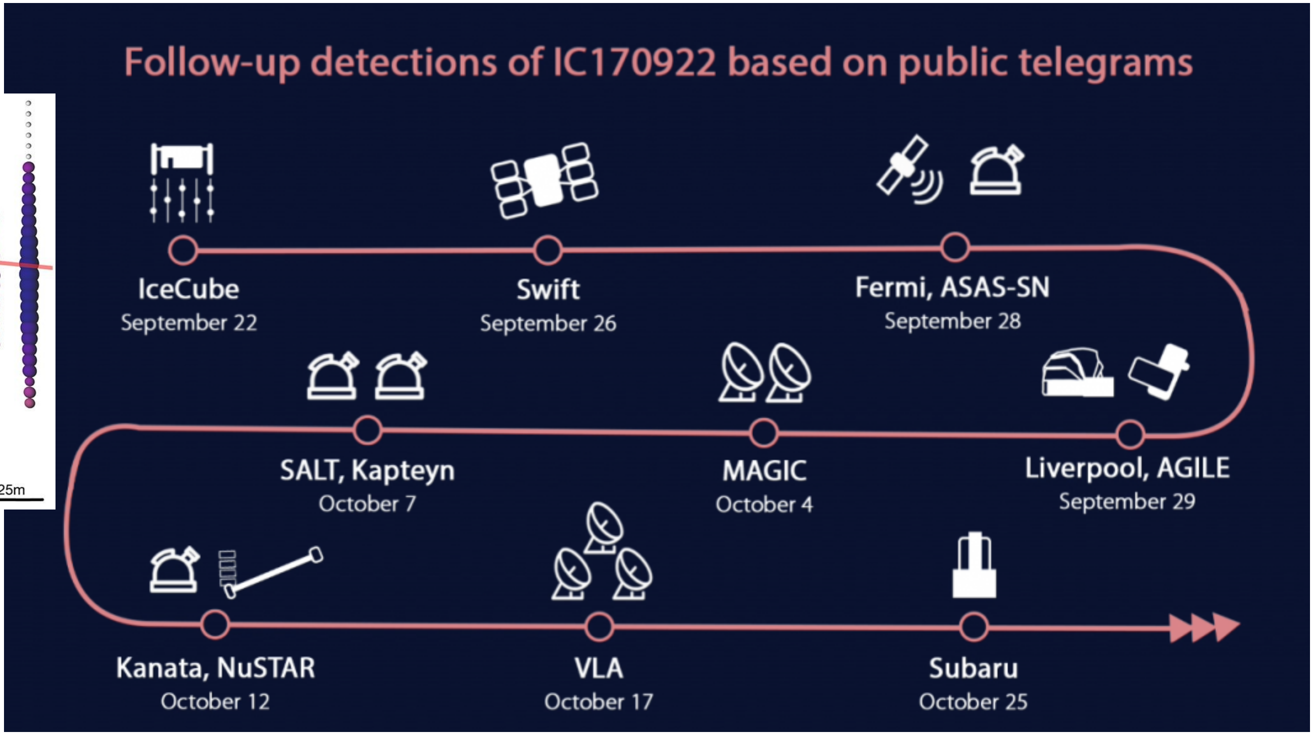
Typical neutrino energy: $E'^b_\nu \approx 0.05 E'^b_p \simeq 80\ \mathrm{PeV}\ \Gamma_1^2 (E'_s/10\ \mathrm{eV})^{-1}$

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

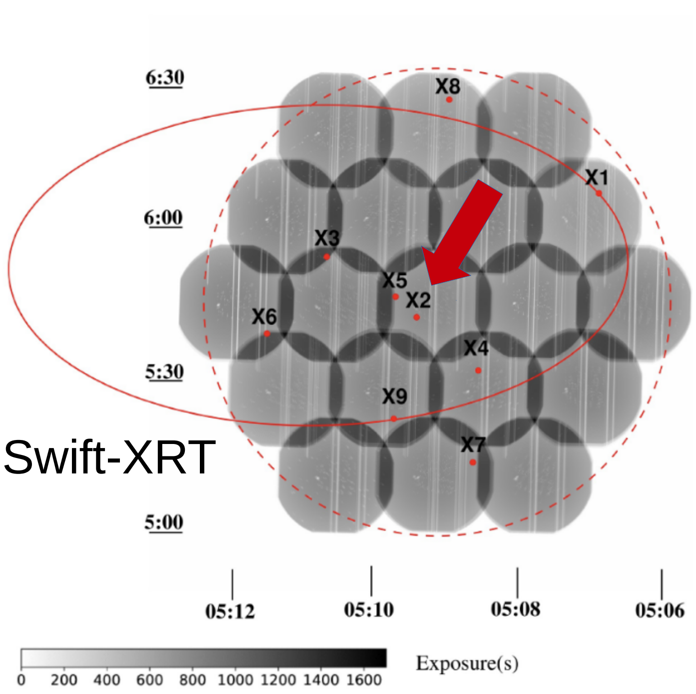
MAGIC
October 4

SALT, Kapteyn
October 7

Kanata, NuSTAR
October 12

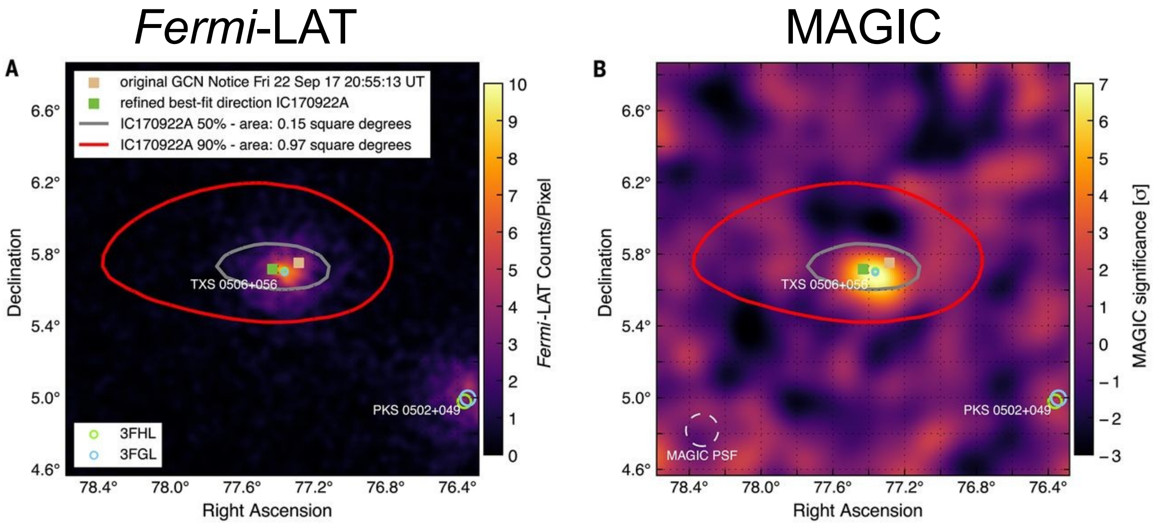
VLA
October 17

Subaru
October 25



Swift-XRT

Keivani, Murase, MP, Fox et al. 2018

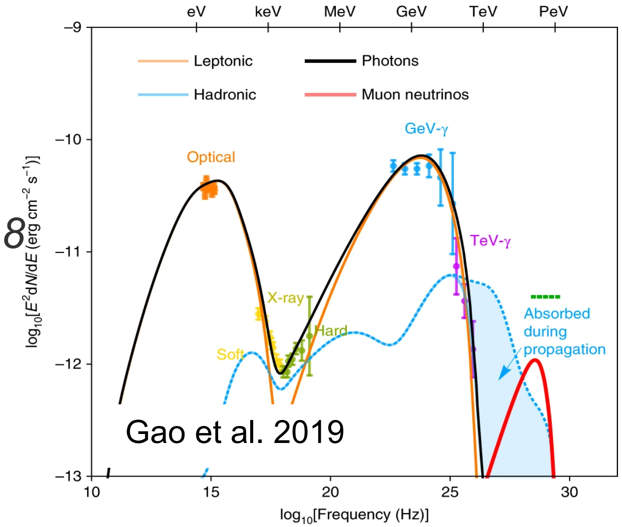


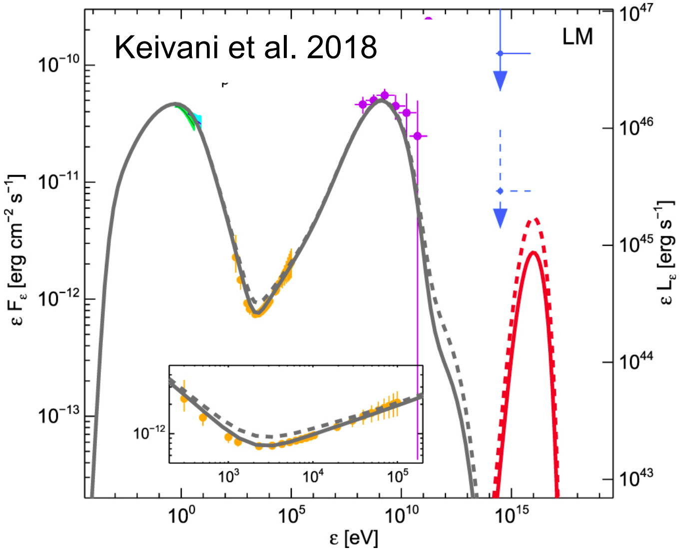
IceCube Colloboration et al. 2018a

Models for the 2017 multi-messenger flare

Photo-hadronic

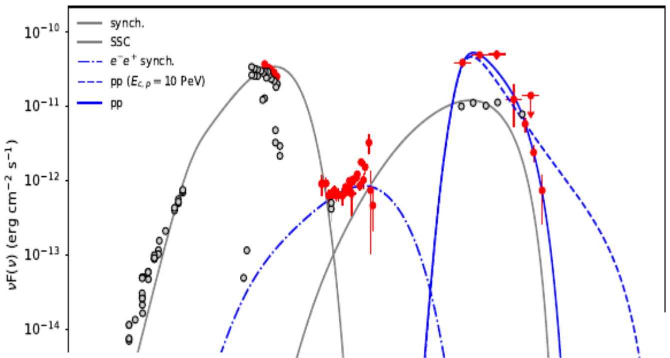
- *Ansoldi et al. 2018 for MAGIC*
- *Keivani,Murase, MP, Fox et al. 2018*
- *Murase, Oikonomou, MP 2018*
- *Cerruti et al. 2019*
- *Gao et al. 2019*
- *…*

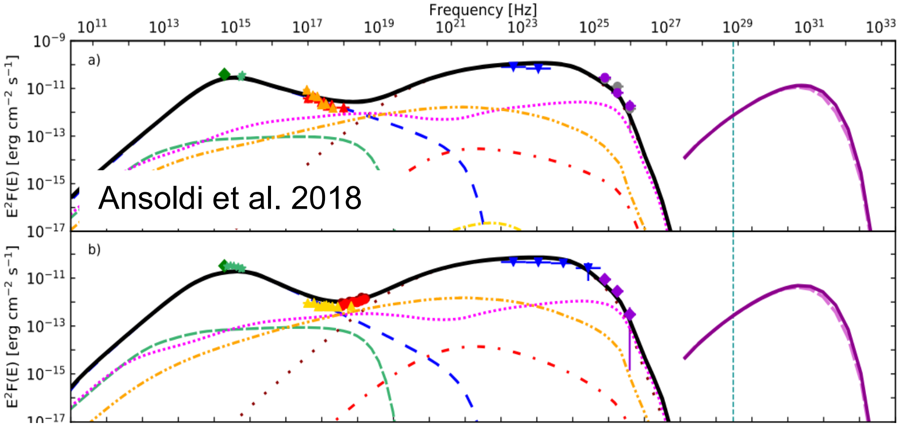


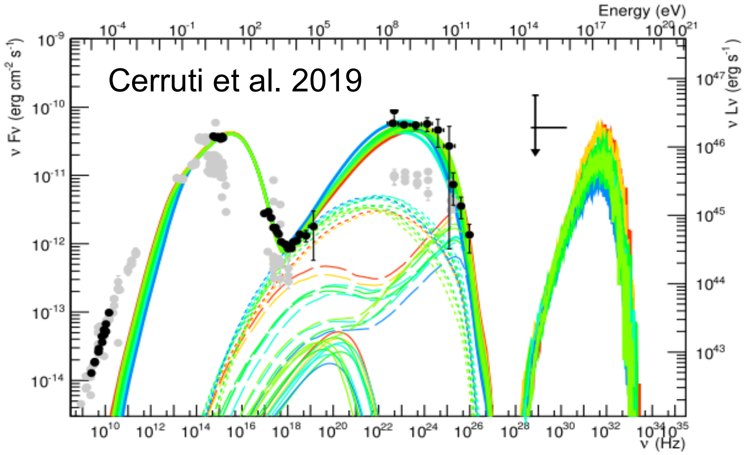


Hadro-nuclear

- *Sahakyan 2018*
- *Murase, Oikonomou, MP 2018*
- *Liu et al. 2019*
- *…*







Summary of results for the 2017 flare

	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

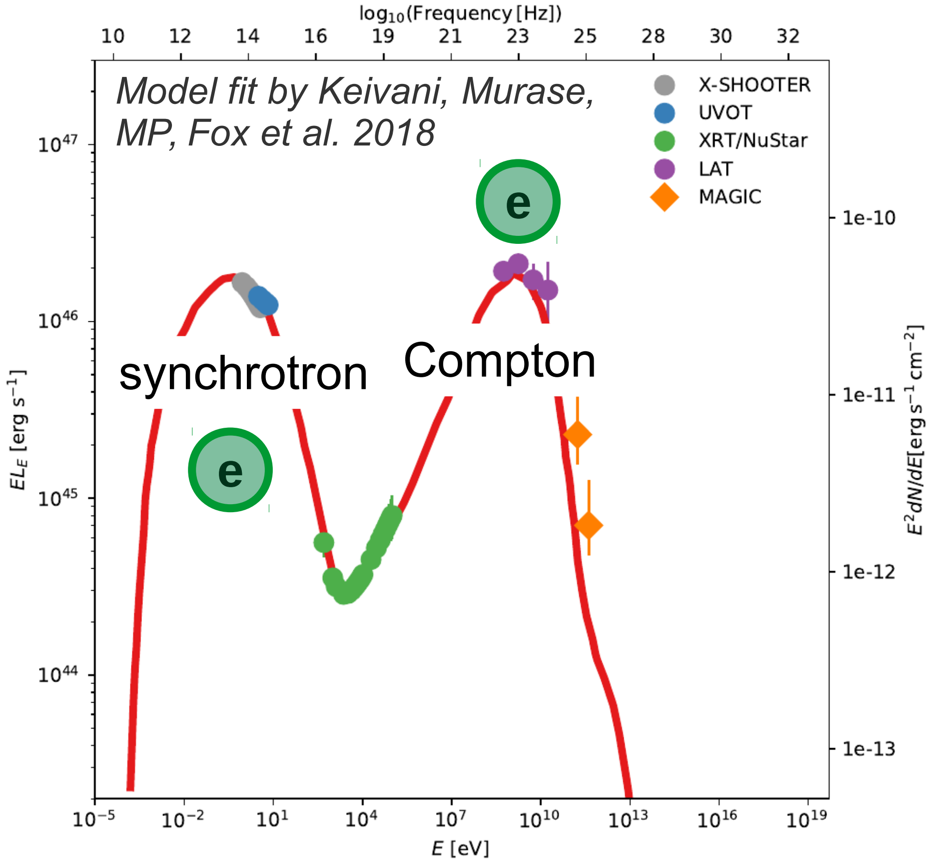
- Past studies of neutrinos from blazars predicted hadronic γ-rays. Modeling of TXS 0506+056/IC-170922A requires a **leptonic** origin of γ-rays.

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

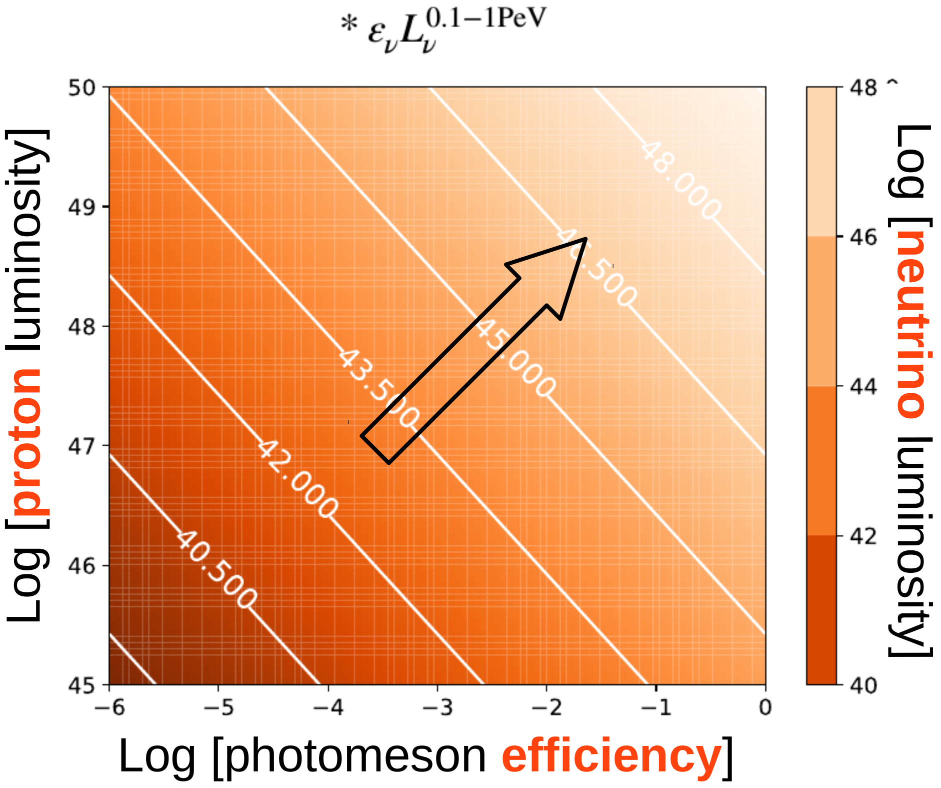
- Number of muon neutrinos per yr < 1. Still, the predictions are **statistically consistent** with the detection of 1 event in 0.5 yr *(e.g. Strotjohann et al. 2019)*.

What sets the maximum neutrino flux?

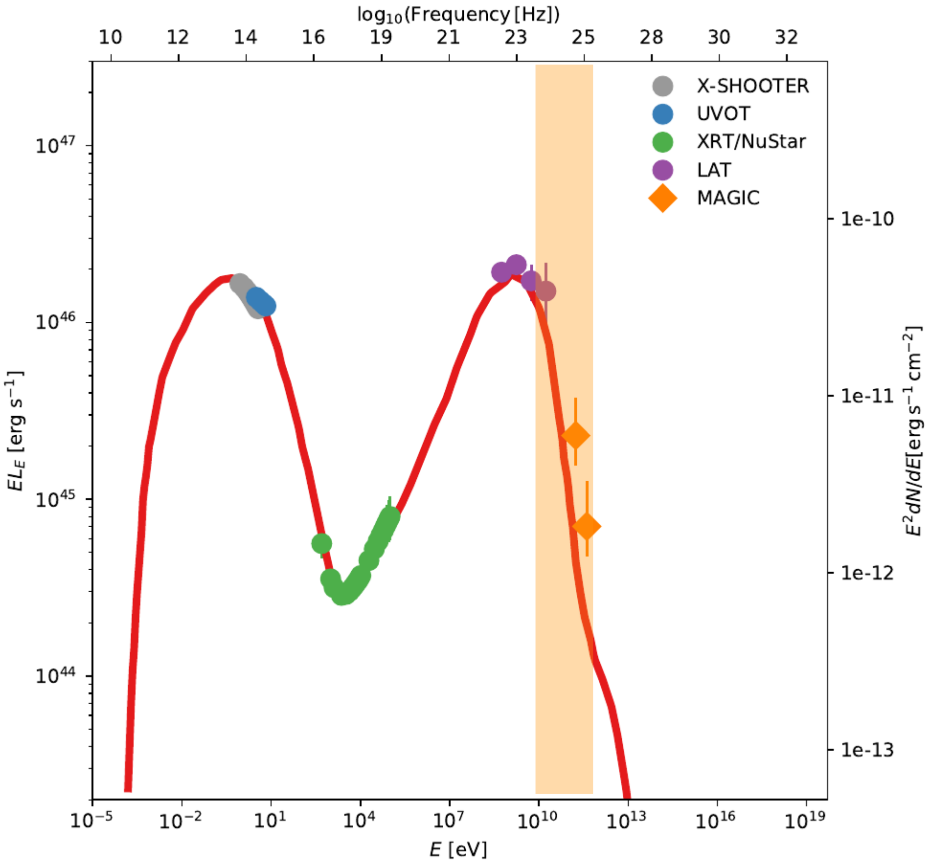
Murase, Oikonomou, MP 2018

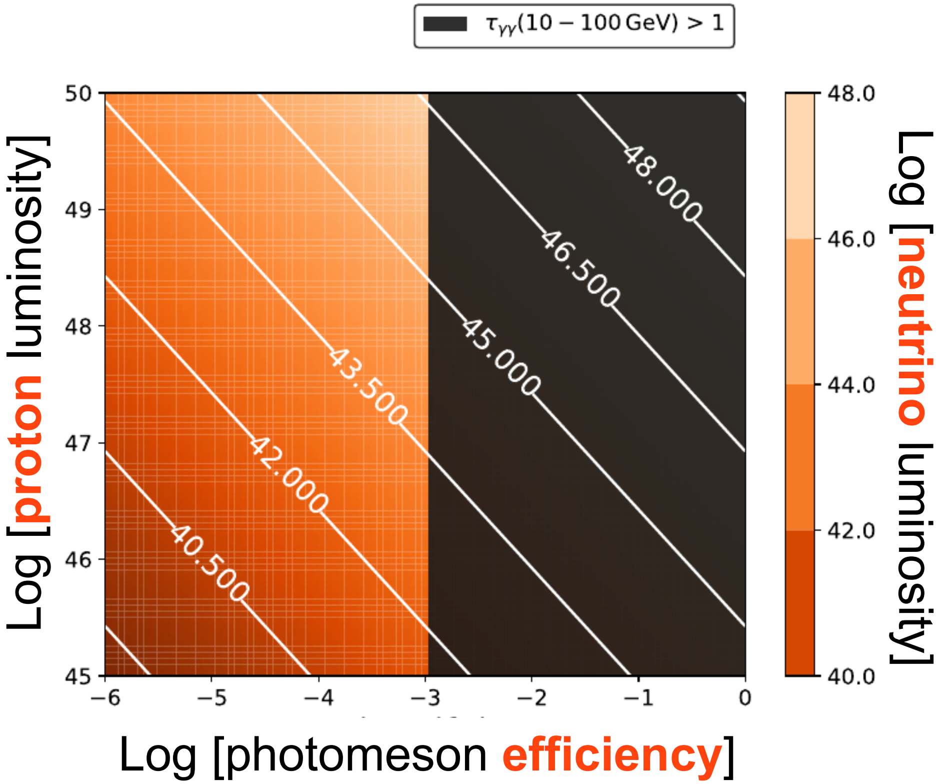


Model fit by Keivani, Murase, MP, Fox et al. 2018



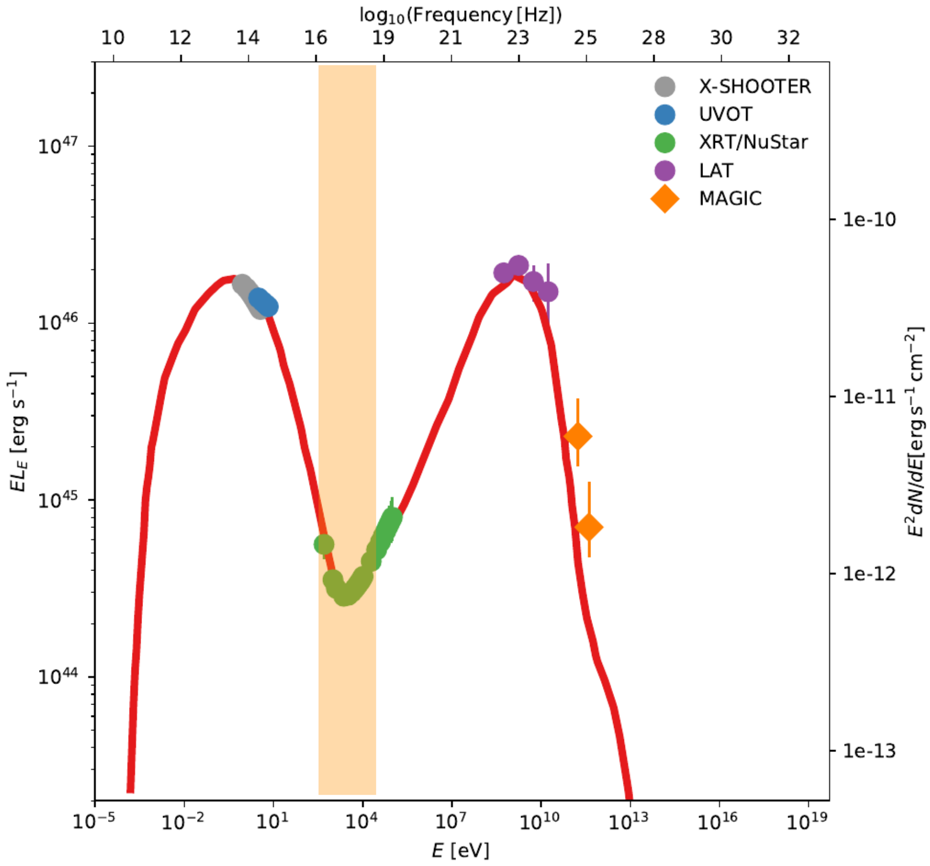
What sets the maximum neutrino flux?

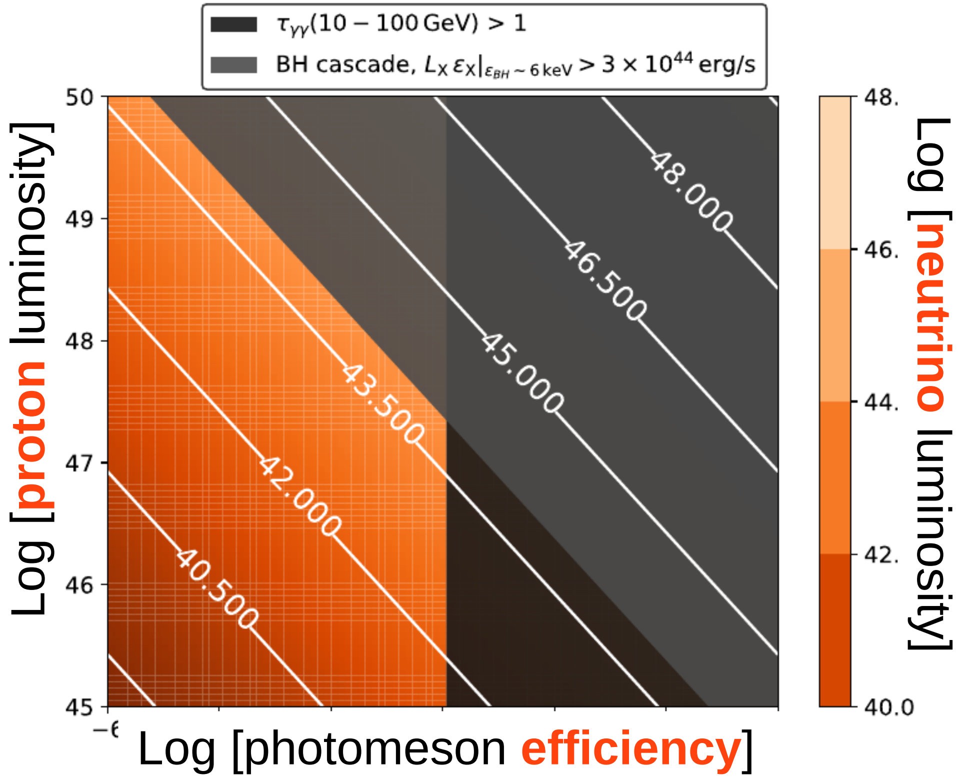




I. Optical depth for absorption of 10-100 GeV γ-rays must be low: $\tau_{\gamma\gamma}(10-100\,\mathrm{GeV}) \lesssim 1$

What sets the maximum neutrino flux?



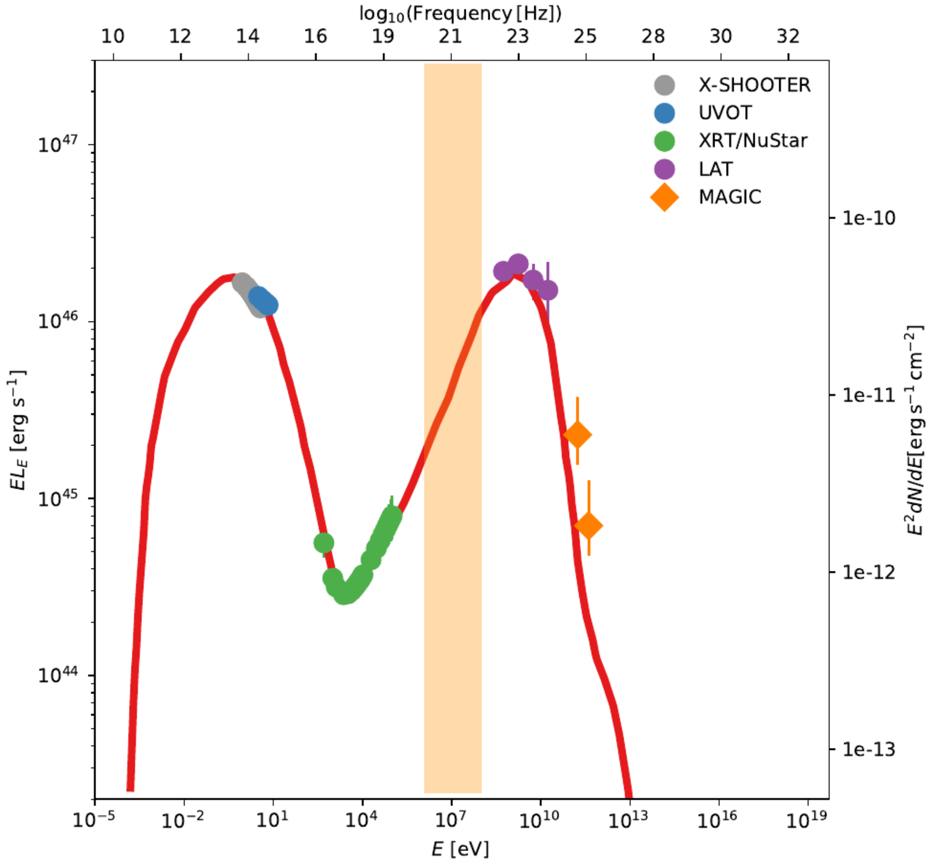


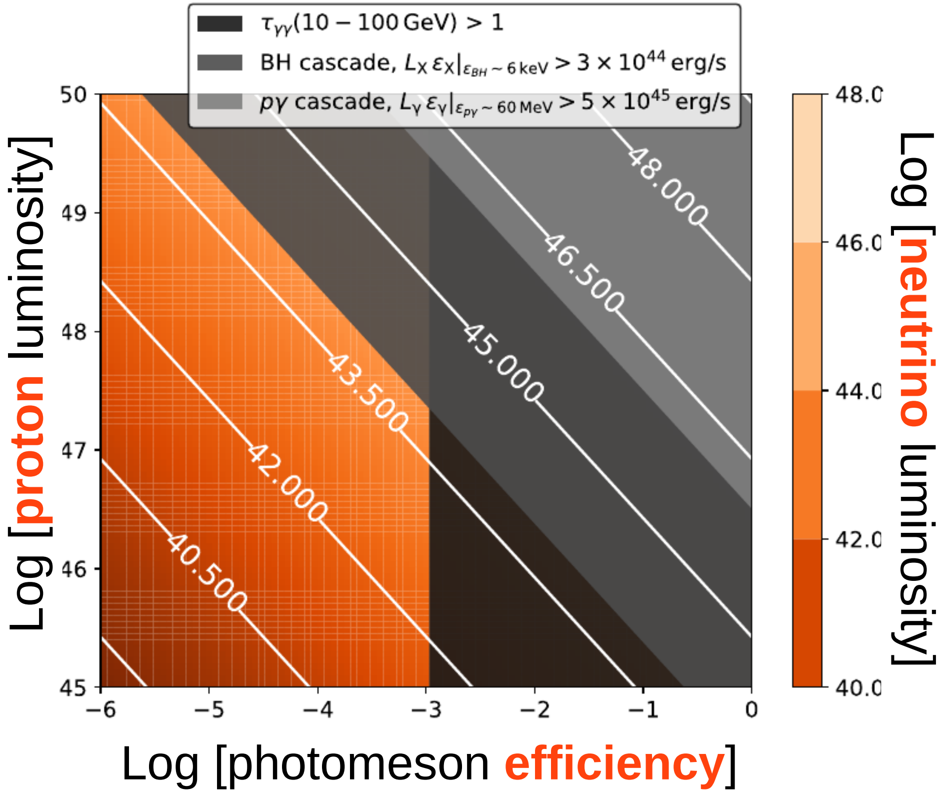
II. Synchrotron emission from Bethe-Heitler pairs must not overshoot X-ray data:

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

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

What sets the maximum neutrino flux?



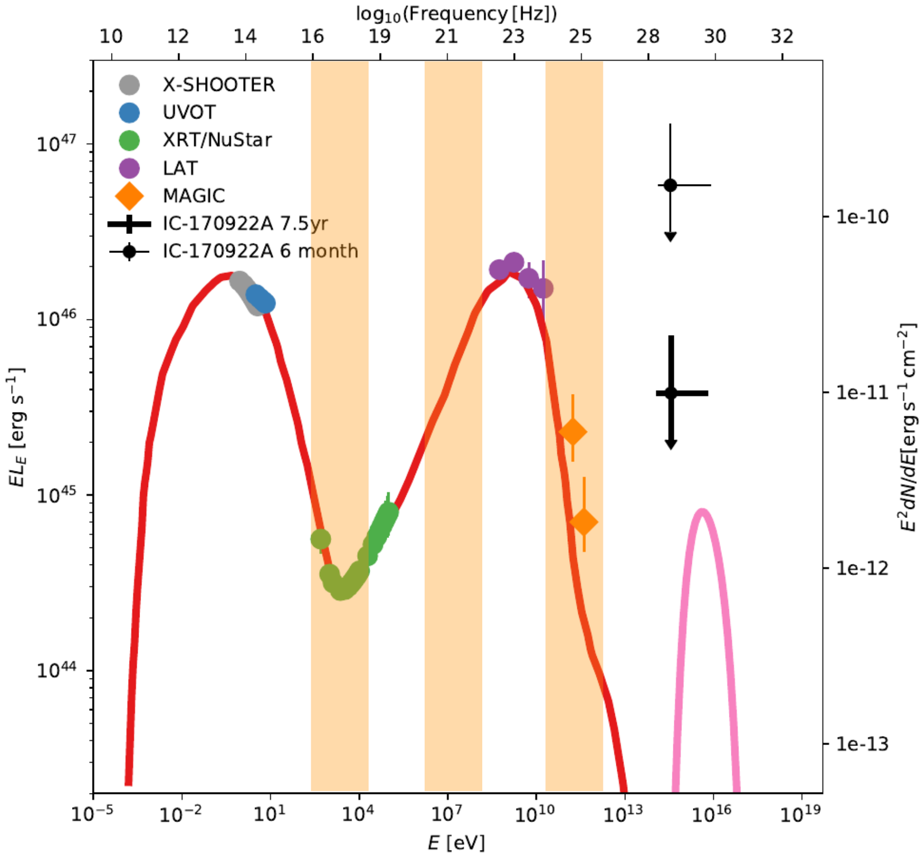


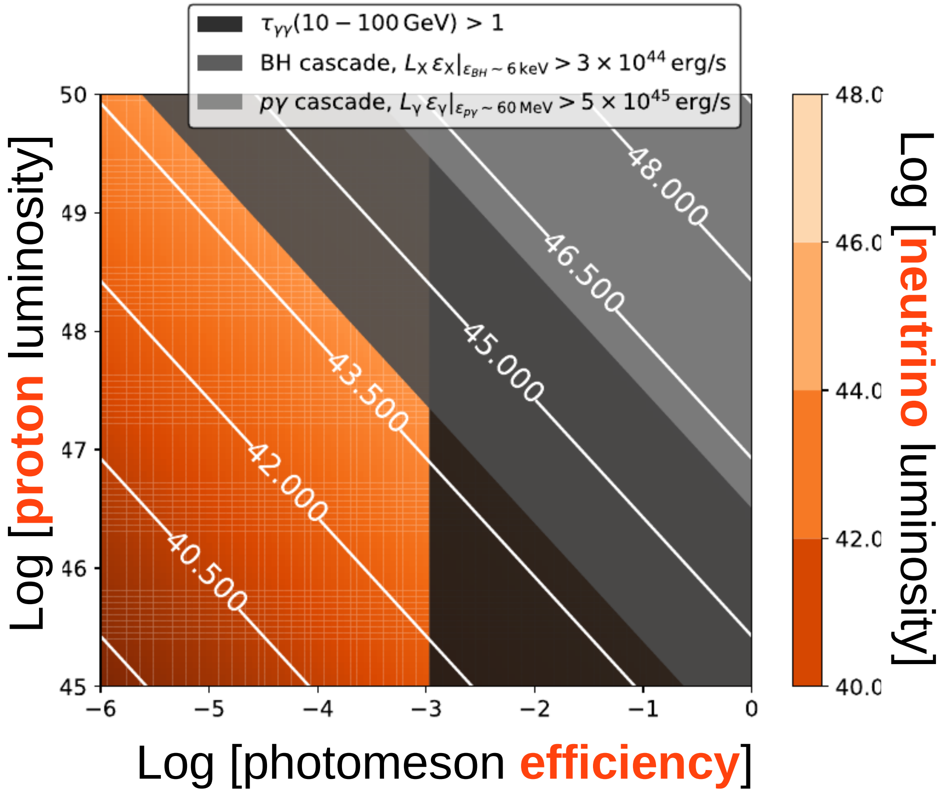
III. Synchrotron emission from photo-meson pairs produces ~MeV emission:

$$\varepsilon_\gamma L_{\varepsilon_\gamma}|_{\varepsilon_{\rm syn}^{p\gamma}} \sim \frac{5}{12}\varepsilon_\nu L_{\varepsilon_\nu} \sim \frac{1}{4}\frac{5}{8} f_{p\gamma}\,\varepsilon_p L_p \le 5\times 10^{45}\ \mathrm{erg/s}$$

$$\varepsilon_{\rm syn}^{p\gamma} \approx 60\ \mathrm{MeV} B_{0.5\ \mathrm{G}}(\varepsilon_p/6\ \mathrm{PeV})^2(20/\delta)$$

What sets the maximum neutrino flux?

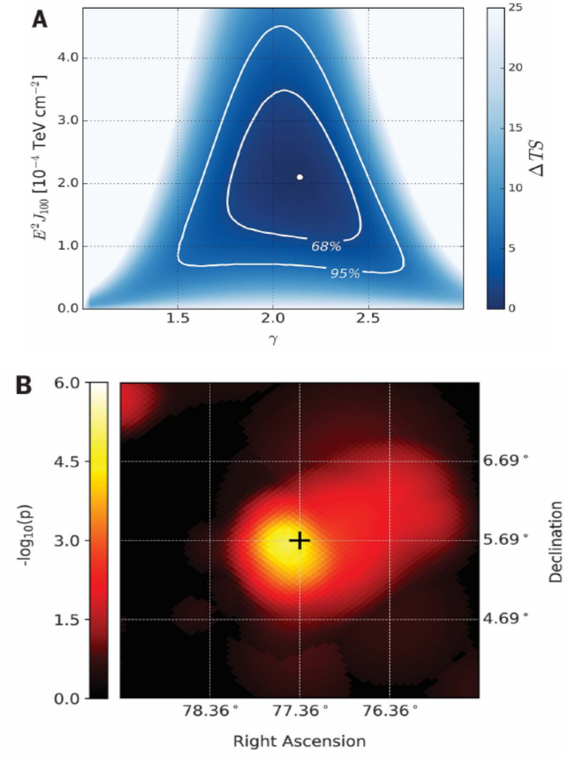




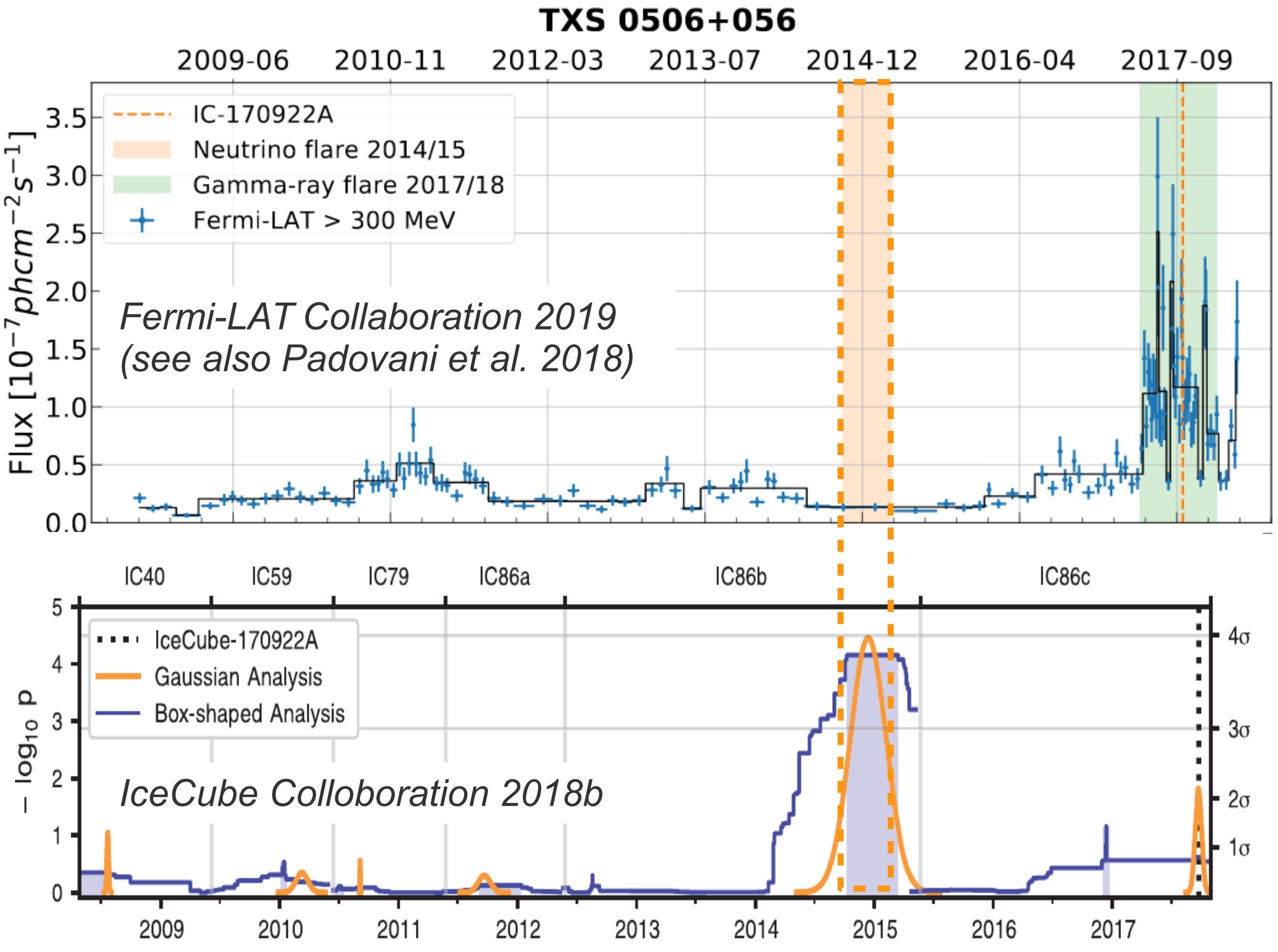
Maximum all-flavor neutrino flux:

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

Are there more neutrinos from TXS 0506+056?



IceCube Colloboration 2018b



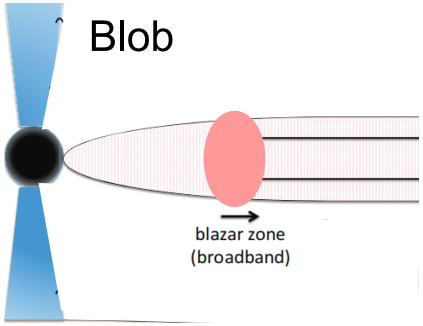
Fermi-LAT Collaboration 2019 (see also Padovani et al. 2018)

IceCube Colloboration 2018b

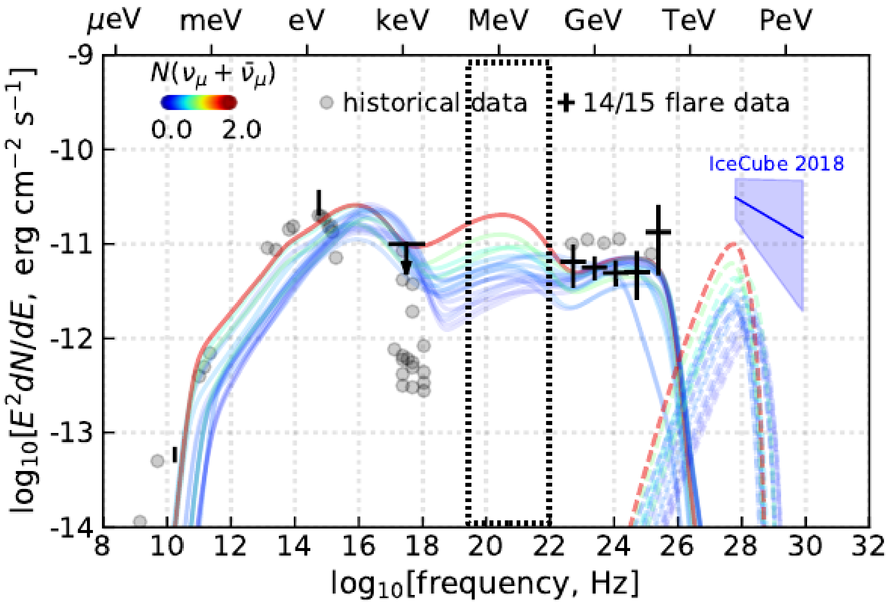
- 13 +/- 5 neutrinos above atmospheric background over ~6 months (~3.5 σ)
- Neutrino luminosity (averaged in ~6 months) **4 times larger** than average γ-ray luminosity!
- **No γ-ray** flaring activity in 2014-15. No evidence for flares at other energies either.

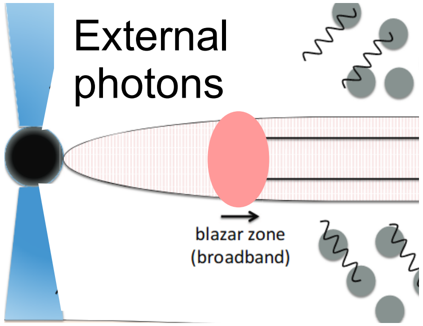
A challenge for one - zone models

Rodrigues et al. 2018

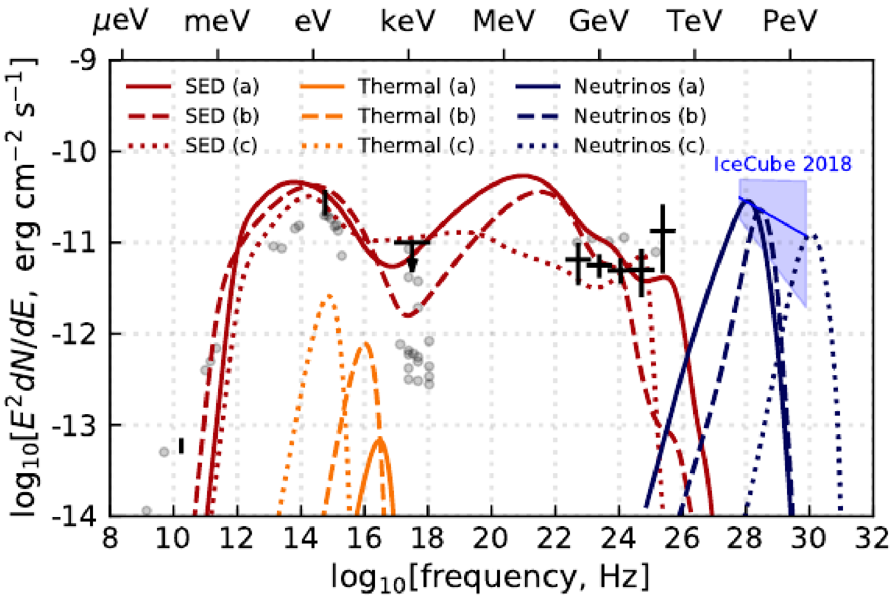


- **< 1.8 events**
- MeV band unconstrained!
- X-ray flux close to UL



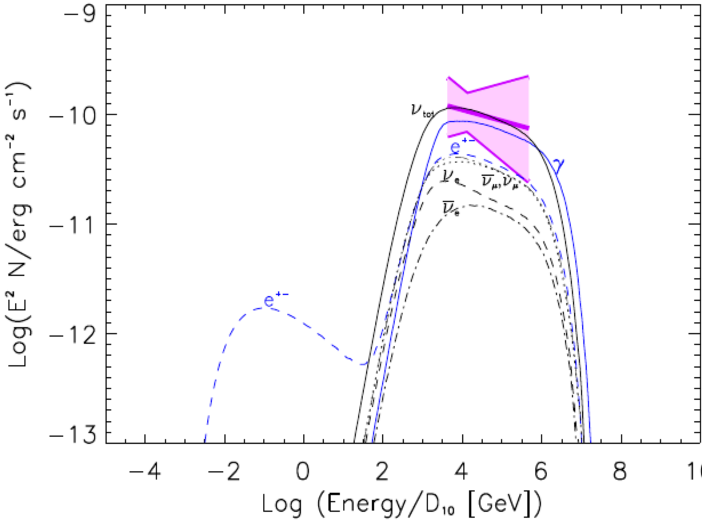


- **< 4.8 events**
- Attenuation > 10 GeV
- X-ray flux close to UL

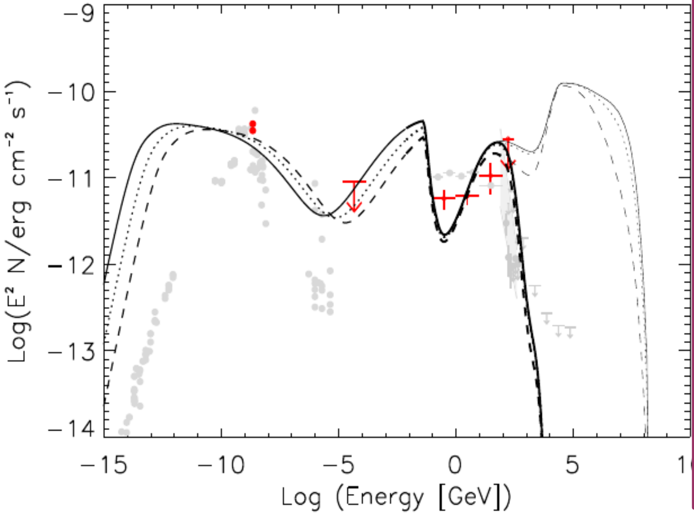


Minimal requirements for the 2014-15 neutrinos

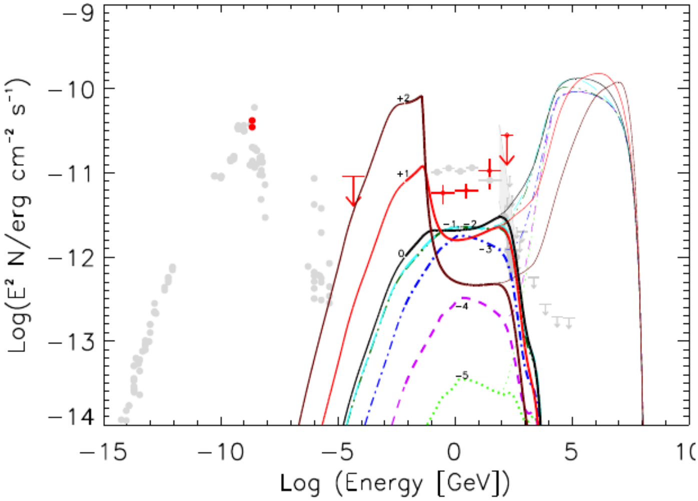
Reimer, Boettcher & Buson 2018



Neutrinos, pairs, γ rays



Synchrotron cascade



Compton-cascade

- *Goal:* find the required target photon field to explain neutrino "excess"
- Synchrotron-& Compton-supported **linear** cascades
- Stationary **X-ray photon field** as target for photo-meson interactions
- **No correlation** between TeV/PeV neutrinos with GeV γ rays
- The blazar EM emission is **not co-spatially** produced with the neutrinos

See also talk by M. Boettcher

The neutral beam model

A 3-step process

I. Photo-disintegration + Bethe Heitler processes of nuclei in blob → production of pairs, γ-rays neutrinos & neutrons

II. Photo-meson interactions of escaping neutrons with external photons → production of pairs, γ-rays, neutrinos

III. Isotropization of pairs in weak B-field of large-scale jet → suppression of cascade emission

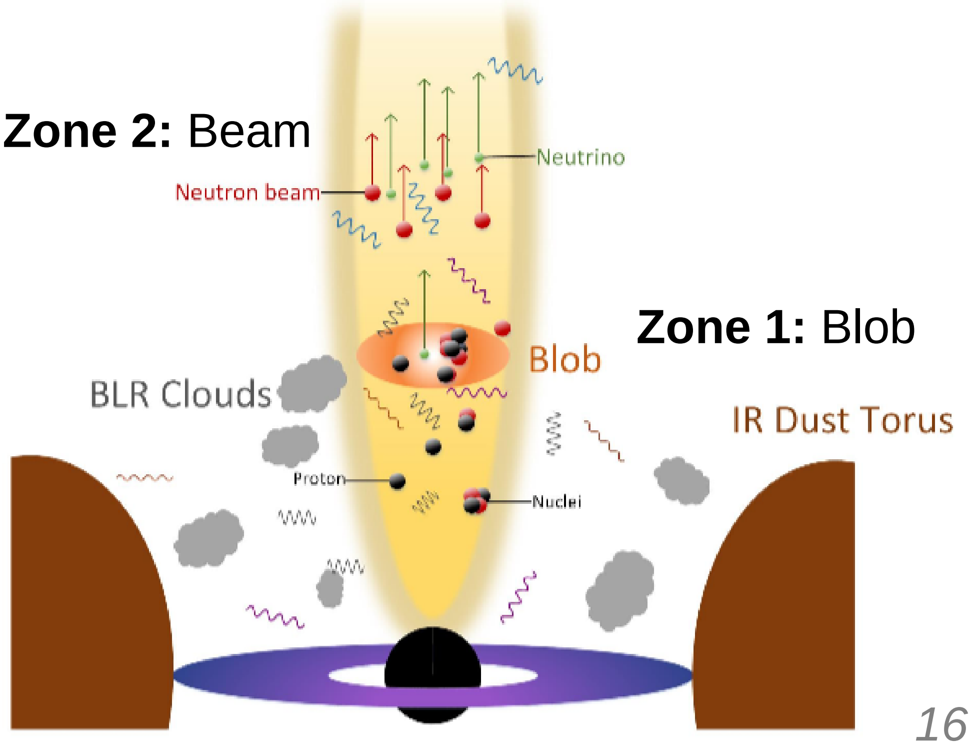
Atoyan & Dermer 2003; Dermer et al. 2012, 2014; Murase, Oikonomou, MP 2018

Model parameters

I. Blob: radius,magnetic field, Lorentz factor

II. Cosmic rays: composition, luminosity, maximum energy, power-law index

III. **External radiation fields:** energy density, spectrum, luminosity



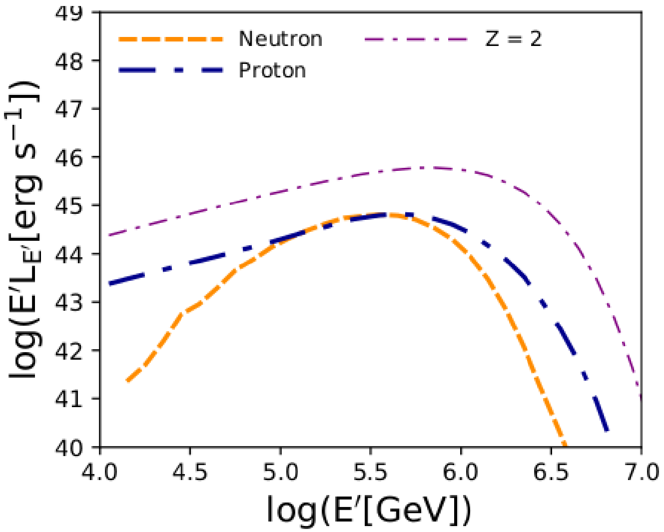
Zone 2: Beam

Zone 1: Blob

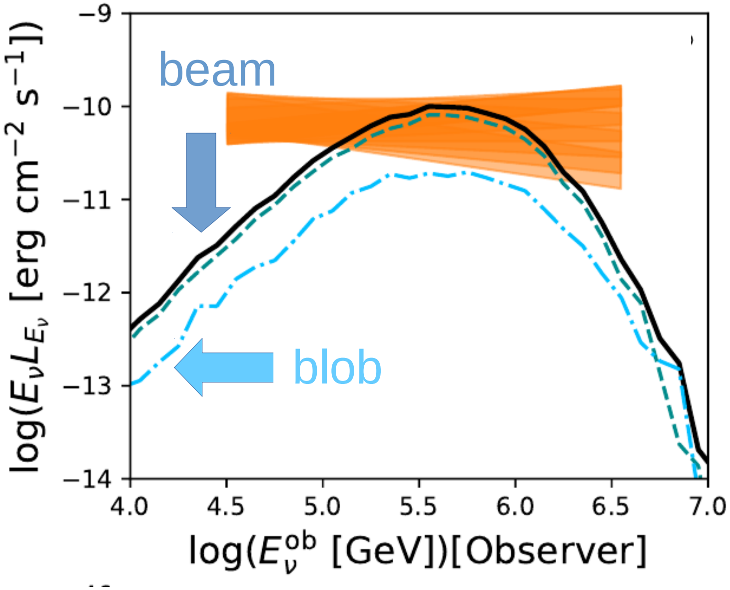
Preliminary results from the neutral beam model

Zhang, MP, Murase, Oikonomou, in prep.

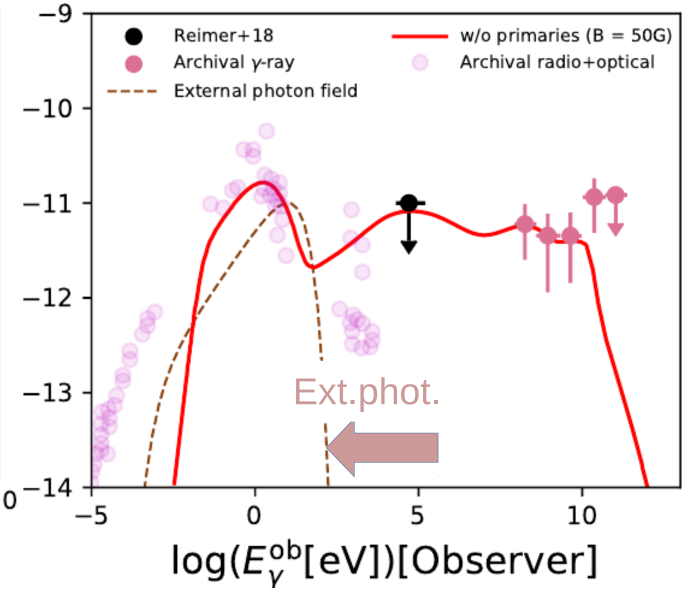
Nuclei



Neutrinos



Photons



- Light composition of nuclei (proton & He)
- Neutrinos produced by the beam and in the blob
- Stationary **high-density (UV) photon field** as target for photo-meson/photo-disintegration
- **Compact blob** (~10^{15} cm) with **strong** (~30-50 G) magnetic fields
- Attenuation of γ-rays **> 100 GeV** in blob

Conclusions

- TXS 0506+056 is the first source to be ever associated with a high-energy neutrino (at ~3σ).

- More high-energy neutrinos (~13) were discovered from the direction of TXS 0506+056 in 2014-15 (neutrino “excess” at ~3.5σ).

- The 2017 multi-messenger flare of TXS 0506+056 can be explained by one-zone leptonic models with a radiatively sub-dominant hadronic component.

- The neutrino luminosity from TXS 0506+056 is bound by X-ray data ($<10^{45}$ erg/s) in one-zone models of the 2017 flare.

- The 2014-15 neutrino “excess” & EM radiation cannot be explained by one-zone models → need for more complex models (e.g., multi-zone models).

- The predictions of the neutral beam model for the 2014-15 neutrino “excess” are consistent with the data, if
  - the dissipation region is compact and strongly magnetized
  - Stationary external photon field (~UV)
  - Proton-Helium composition

Open questions

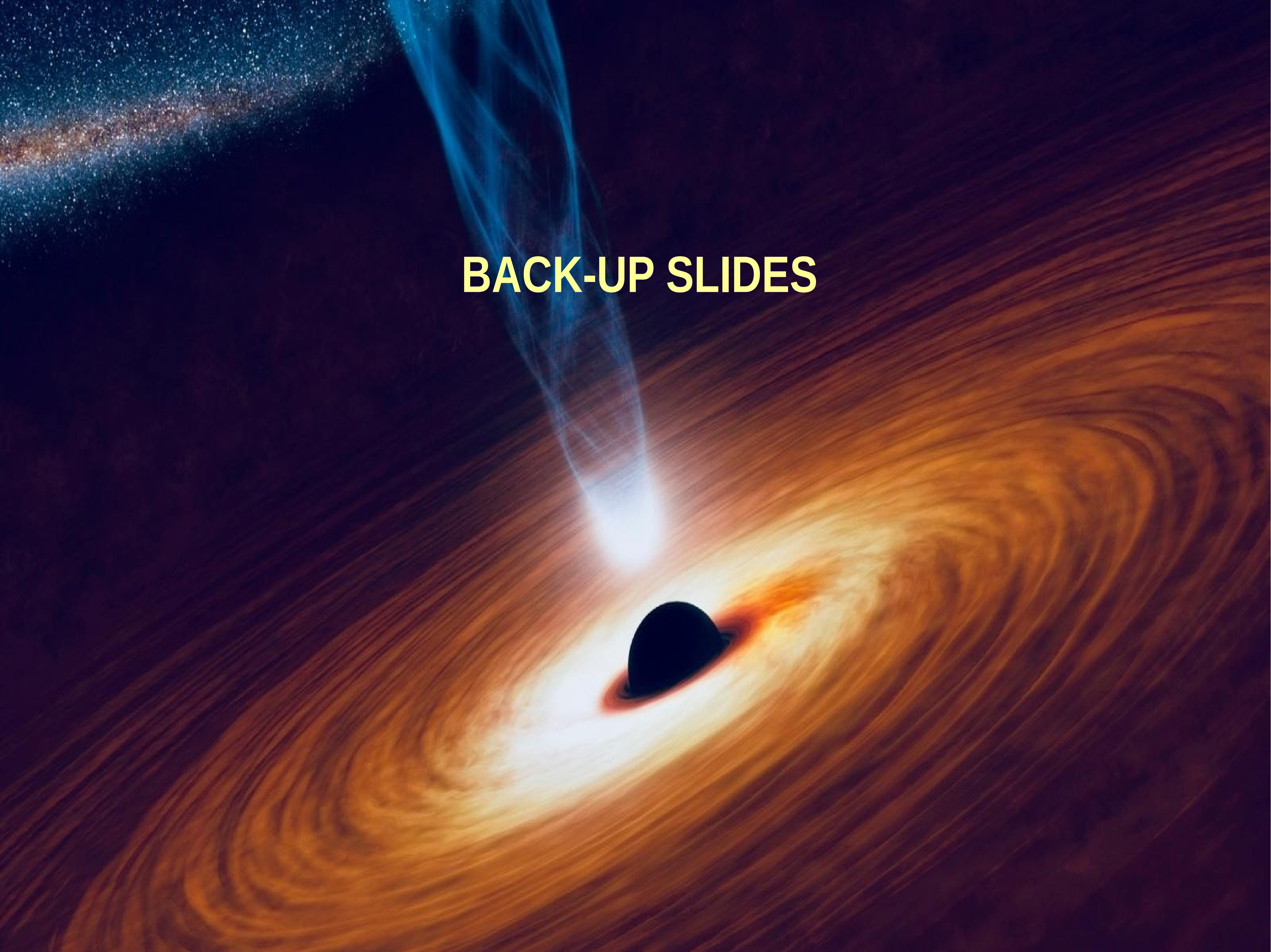
- Is there a consistent physical picture for the multi-messenger emission of TXS 0506+056 for 2014-15 and 2017?

- What is the best observing strategy to search for neutrino point sources, if GeV γ rays flares are not correlated with periods of high TeV/PeV neutrino flux?
- Which wavelength is the best probe for the neutrino emission of blazars?

- What do we learn about the blazar population?
- Do we have leptonic and hadronic flares? How?

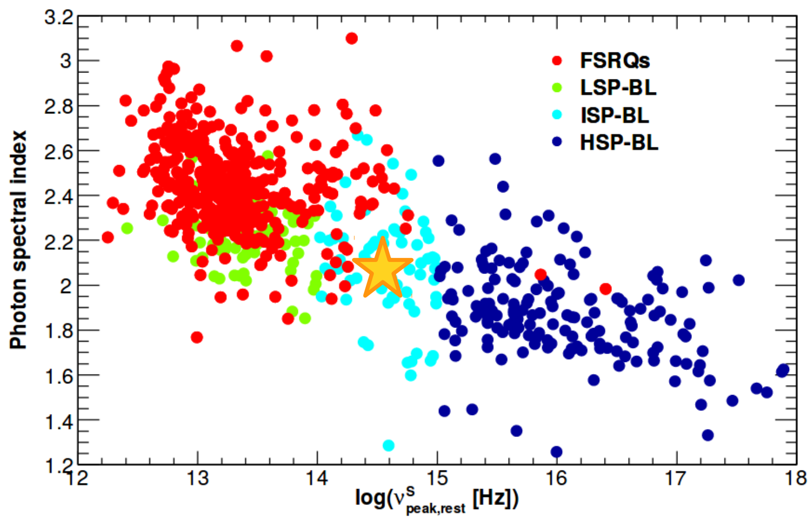
- What will are the implications for the origin of neutrinos, if the association with TXS 0506+056 weakens over the years?

THANK YOU

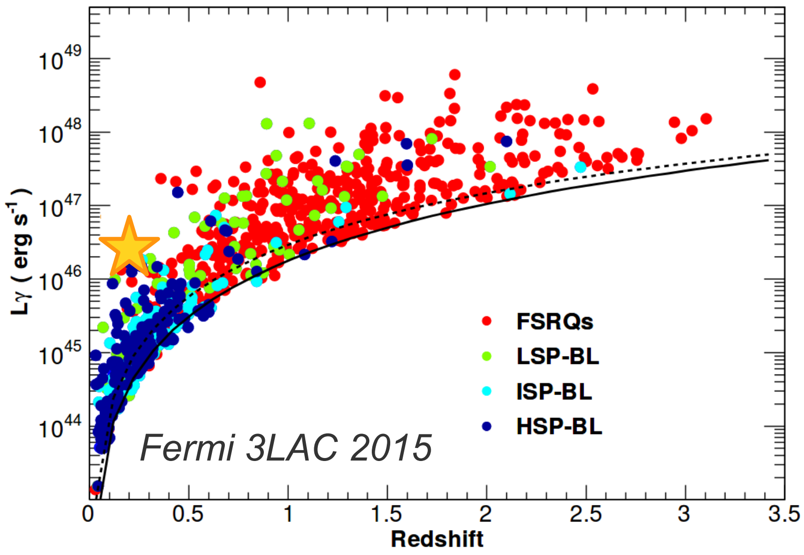


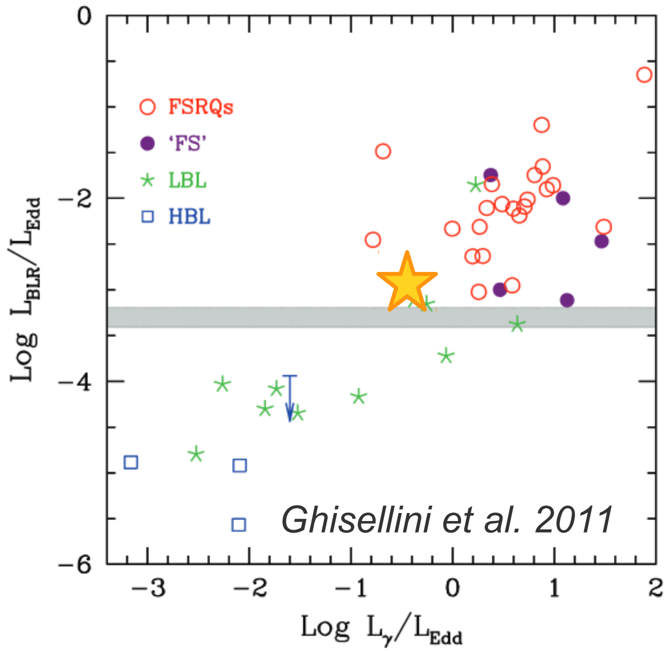
BACK-UP SLIDES

Fact sheet of TXS 0506+056



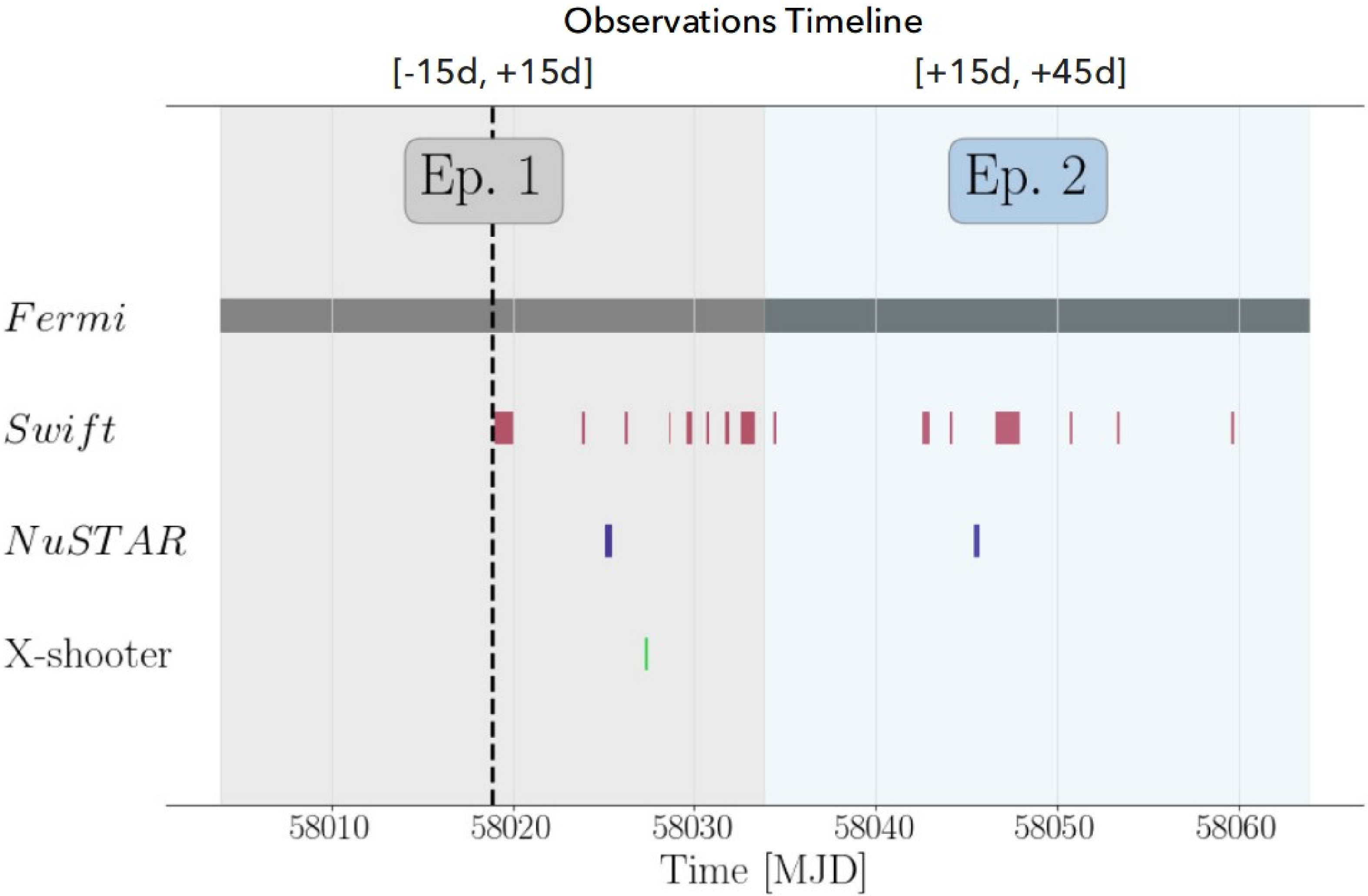
- Redshift z=0.336(5) *(Ajello et al. 2014; Paiano et al. 2018)*
- Among ~4.5% of 3LAC blazars with highest energy flux *(Fermi-LAT Collaboration 2015; 2019)*
- Among the brightest radio sources (~0.3 %) *(Padovani et al. 2018)*
- ISP BL Lac, if classified with line width *(Stickel et al. 1991; Stocke et al. 1991)* or γ-ray properties *(3LAC)*
- “Masquerading” BL Lac → with BLR whose emission is swamped by the jet *(Padovani et al. 2007; Padovani, Oikonomou, MP et al. 2019)*





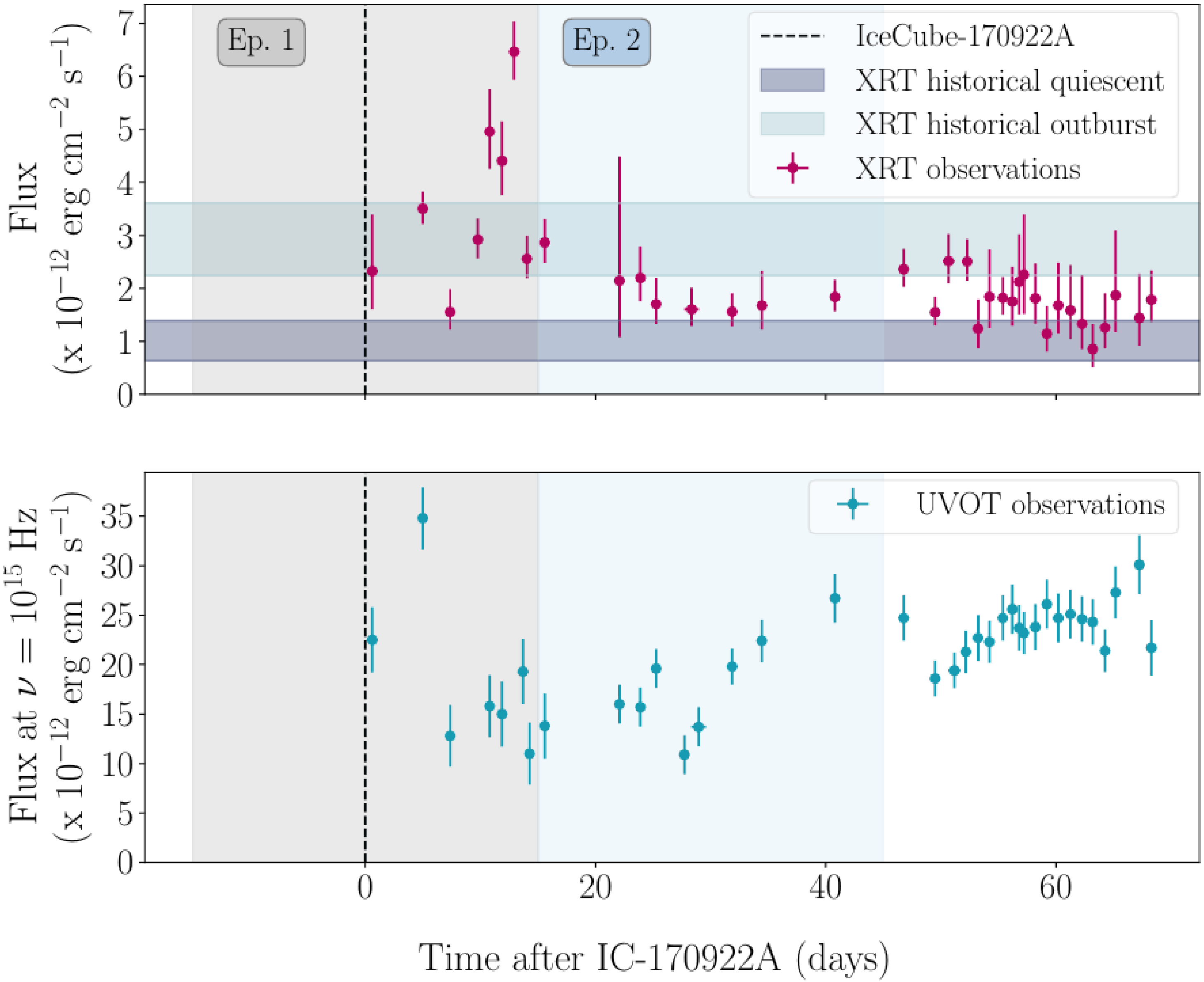
Multi-wavelength observations

*Keivani,Murase, MP, **,** Fox et al. 2018*



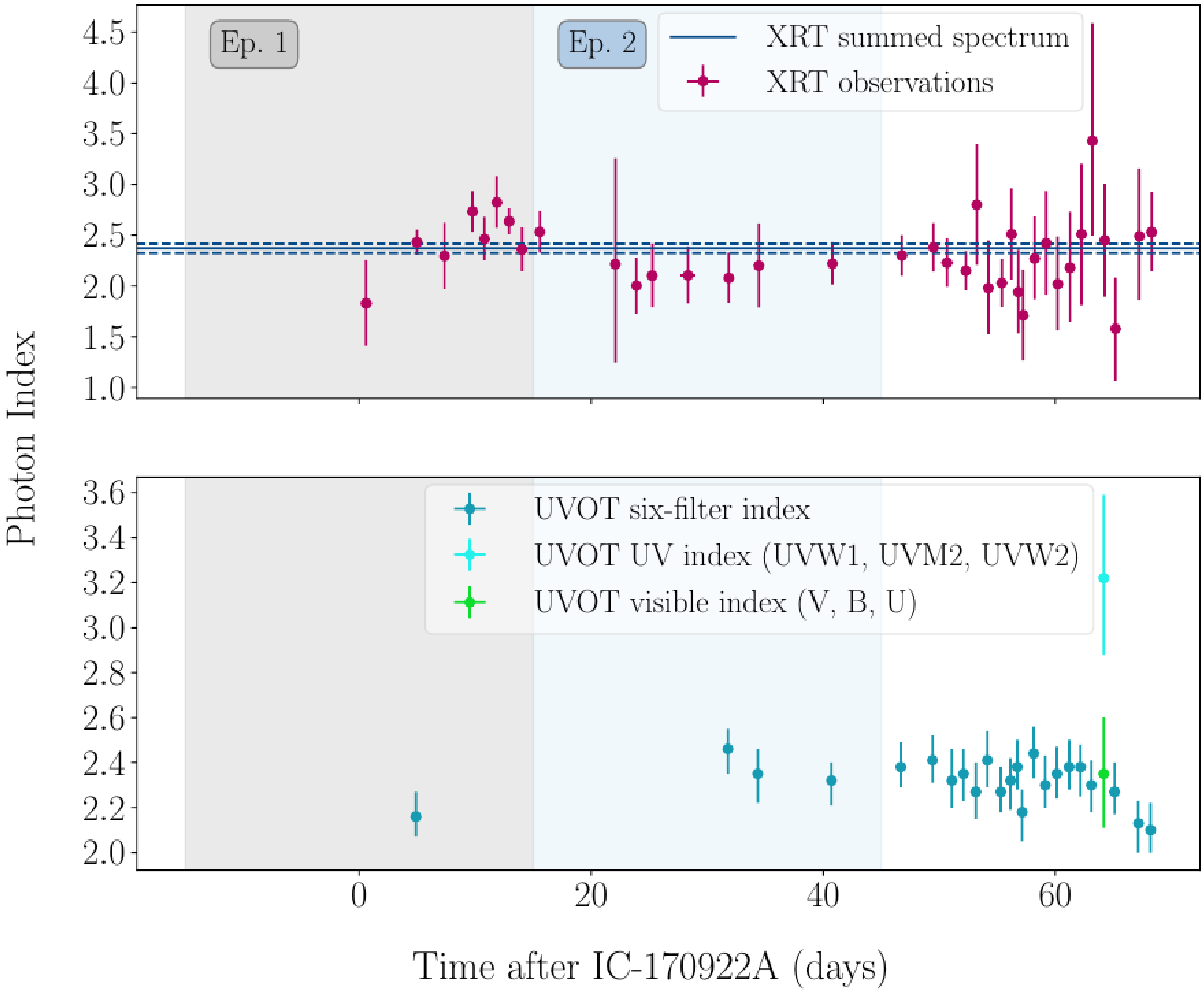
Swift flux variability

Keivani,Murase, MP, Fox et al. 2018

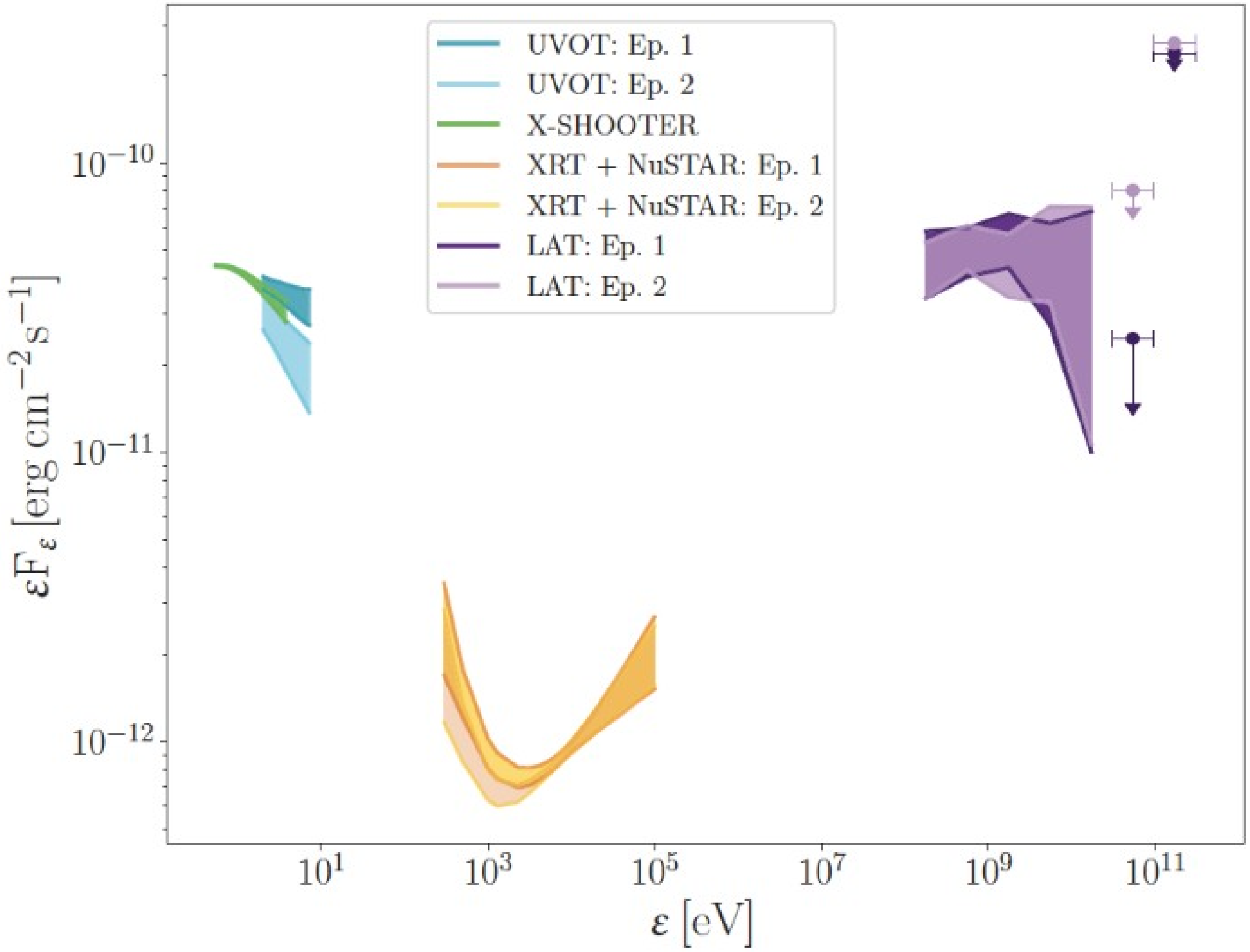


Swift spectral variability

Keivani,Murase, MP, Fox et al. 2018

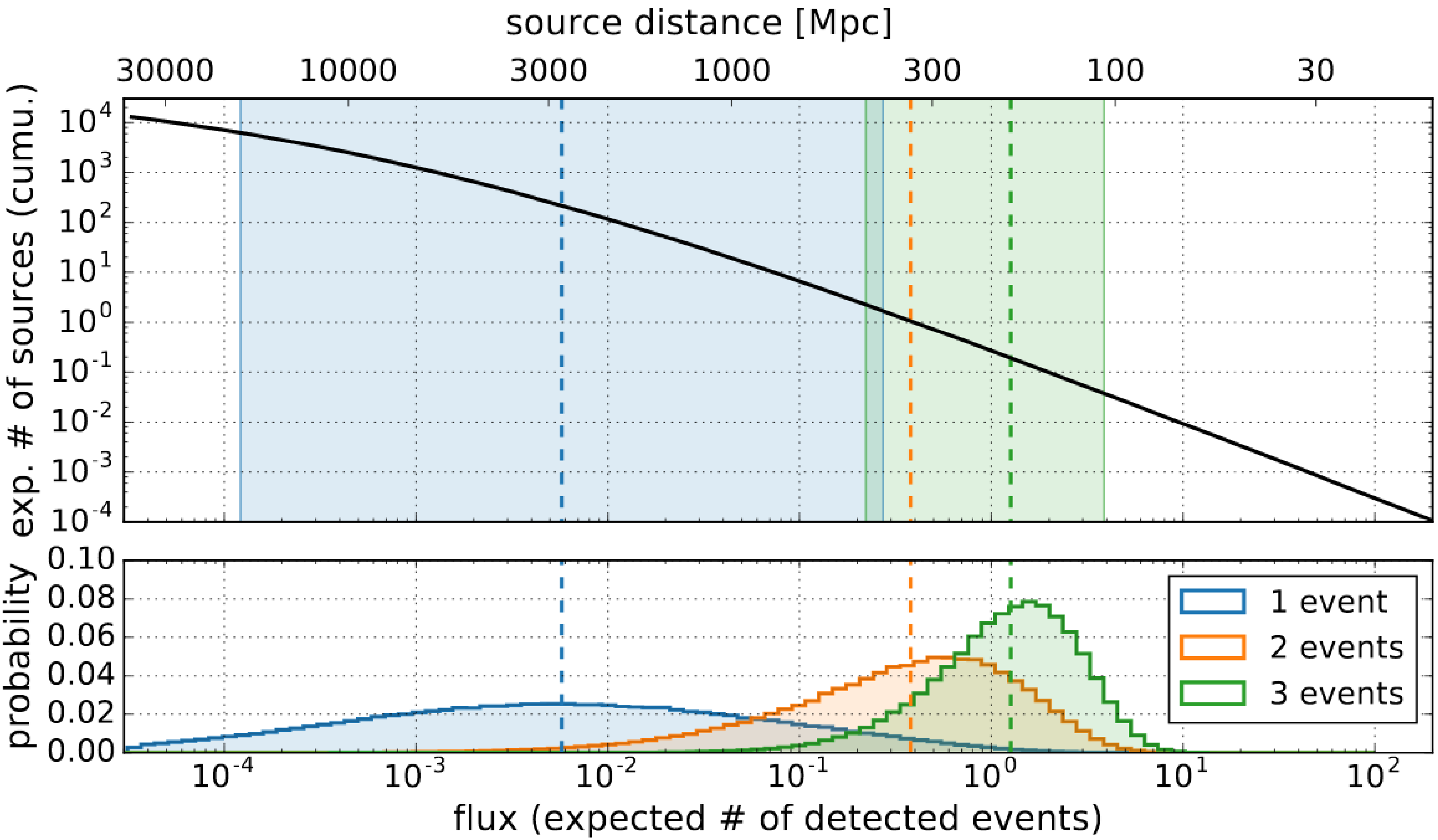


Multi-wavelength spectrum



Eddington bias for neutrino sources

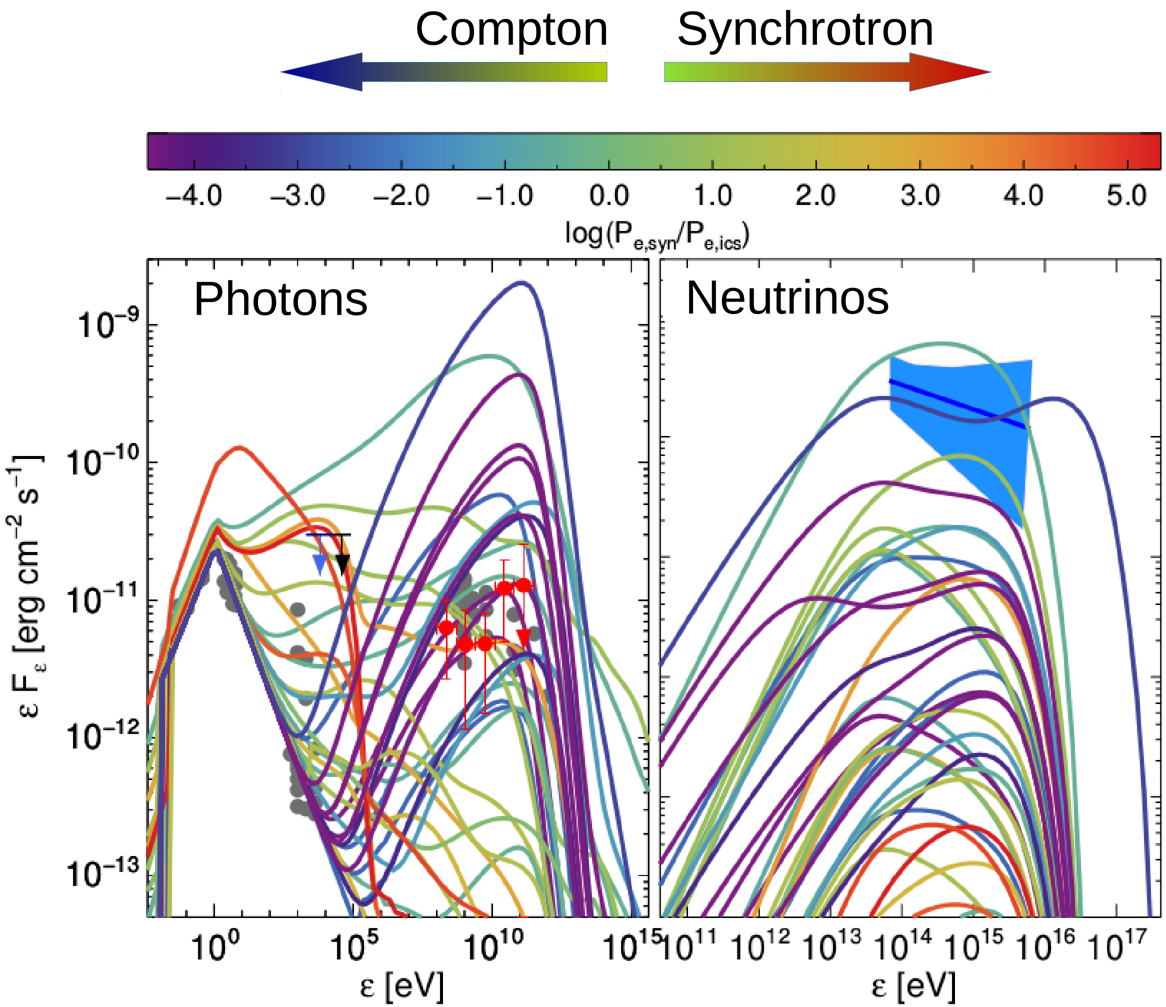
Strotjohann et al. 2019

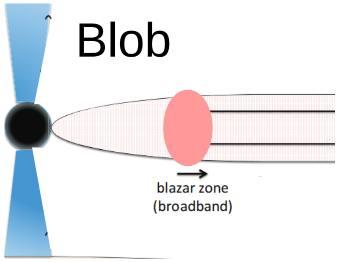


- More likely to detect 1 neutrino from sources with median flux << 1
- Bright rare sources are more likely to be detected with >1 events
- The size of bias depends on: source evolution & luminosity function

A challenge for one - zone models

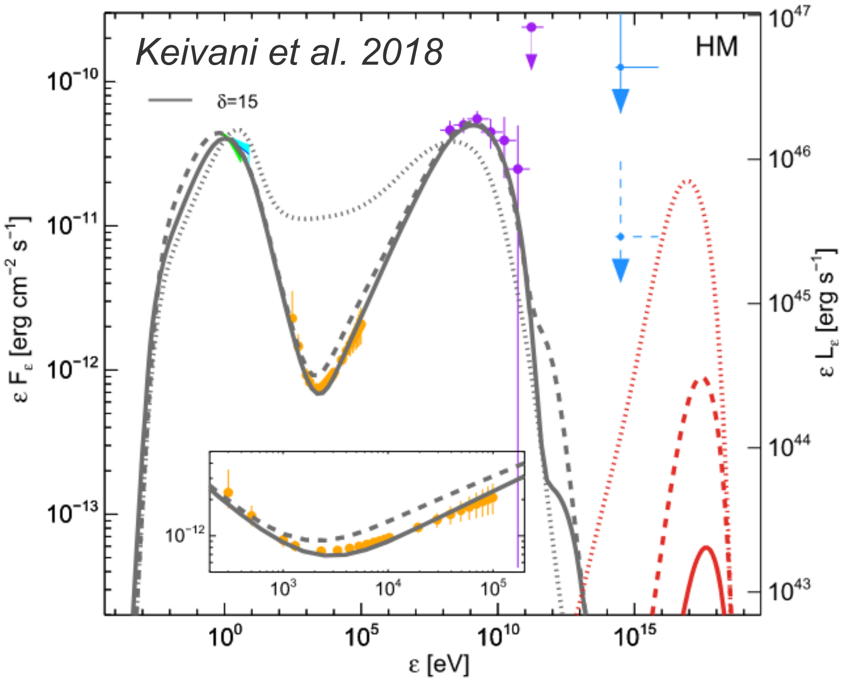
MP, Murase et al., in prep.

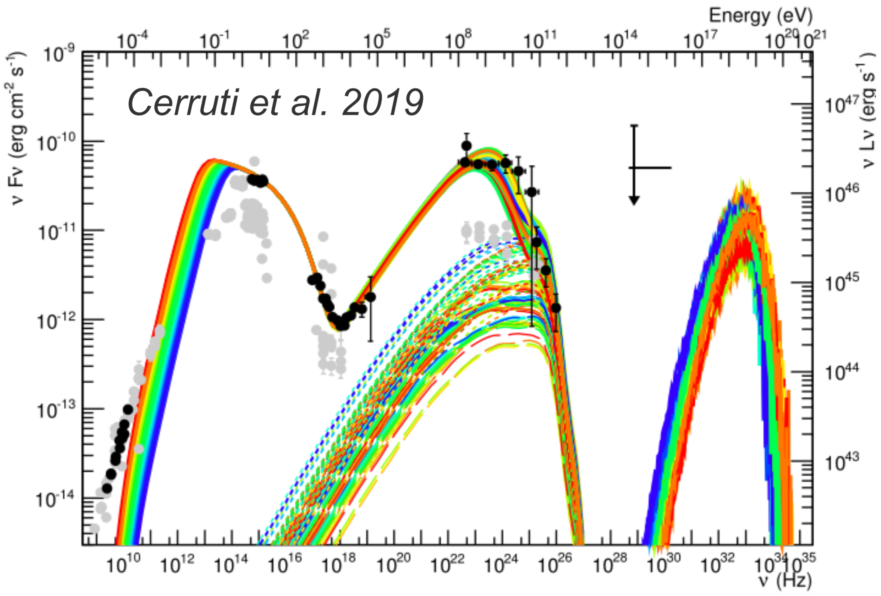


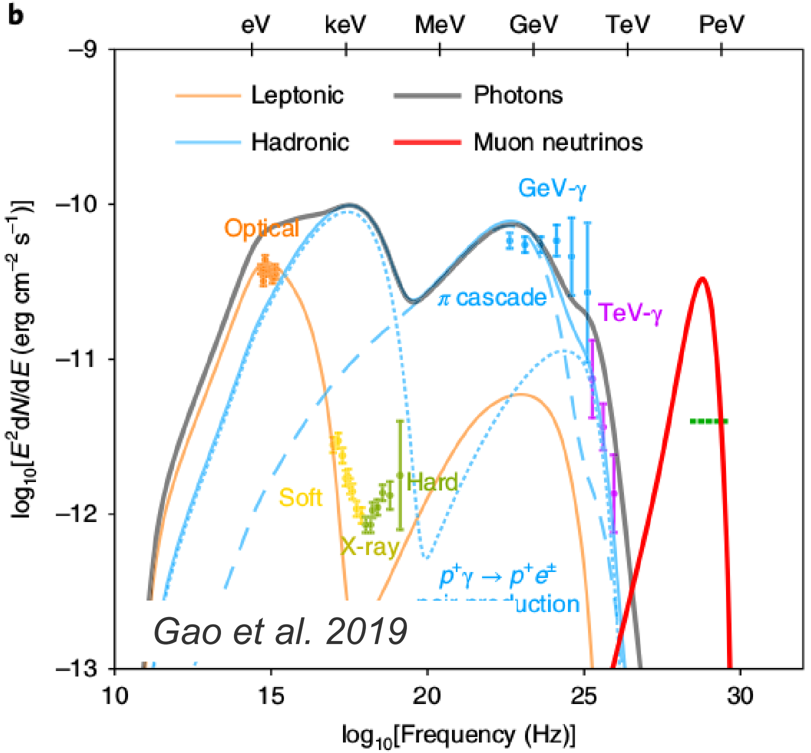


- Wide parameter search
- Linear & non-linear cascades
- Synchrotron & Compton supported cascades
- **No model consistent** with $L_\nu > L_\gamma$ and EM data.

Lepto-hadronic models for the 2017 flare



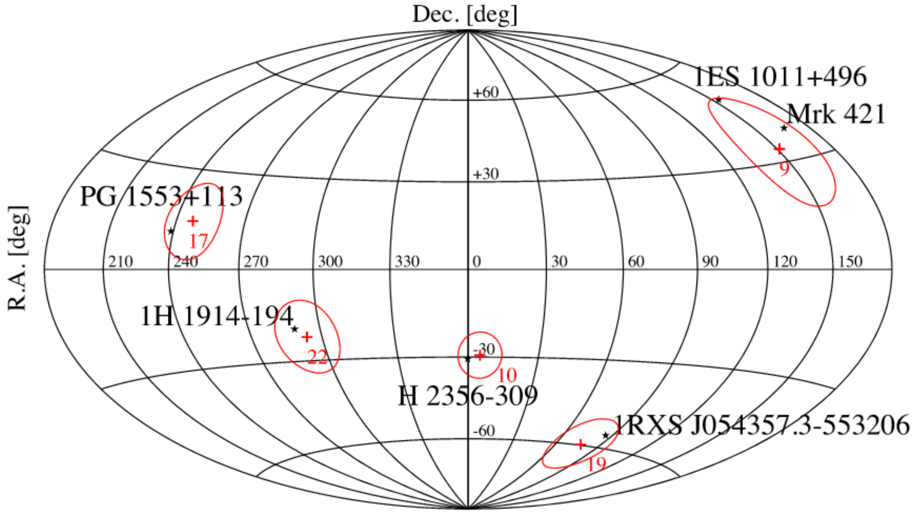




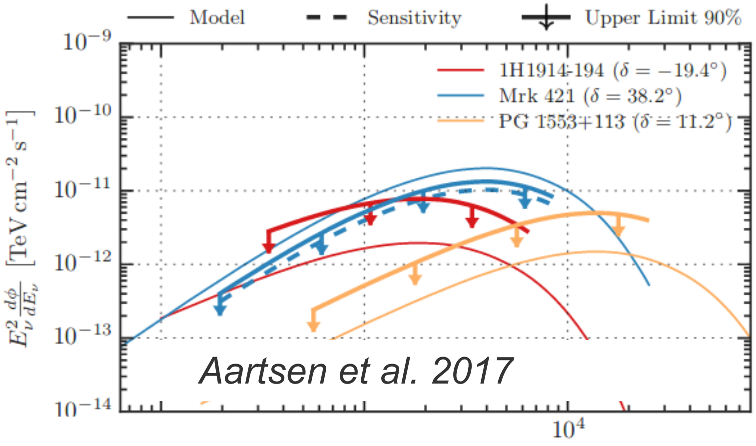
- Lepto-hadronic SED models for TXS 0506+056/IC-170922A are excluded.
- EeV neutrinos are predicted.
- Low neutrino flux, unless cascade emission overshoots X-rays.

Status of the field prior to 2017 - neutrinos

Padovani & Resconi 2014; MP et al. 2015

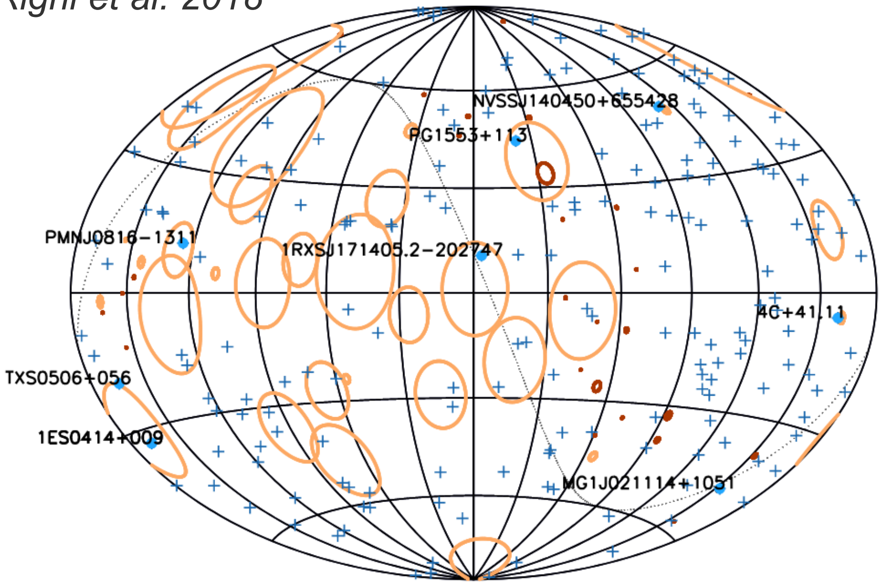


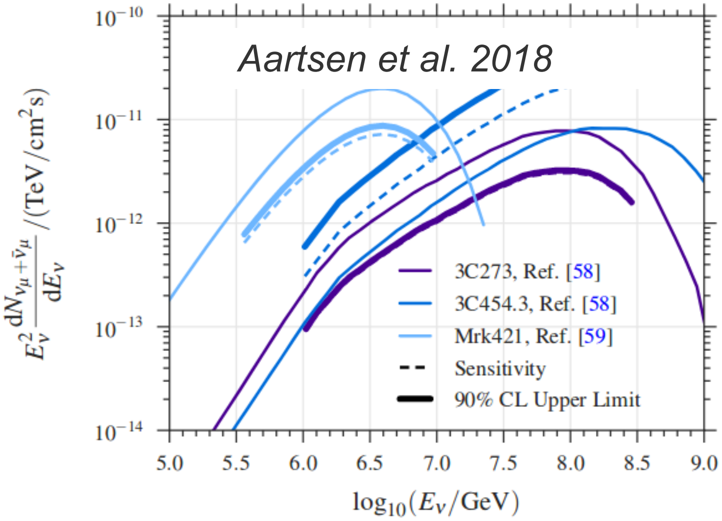
- BL Lacs as probable counterparts of high-energy neutrinos *(Padovani & Resconi 2014, 2016; Righi et al. 2017; 2018)*
- IceCube constrains most optimistic models of constant neutrino emission *(e.g. Aartsen et al. 2017; 2018)*



Aartsen et al. 2017

Righi et al. 2018

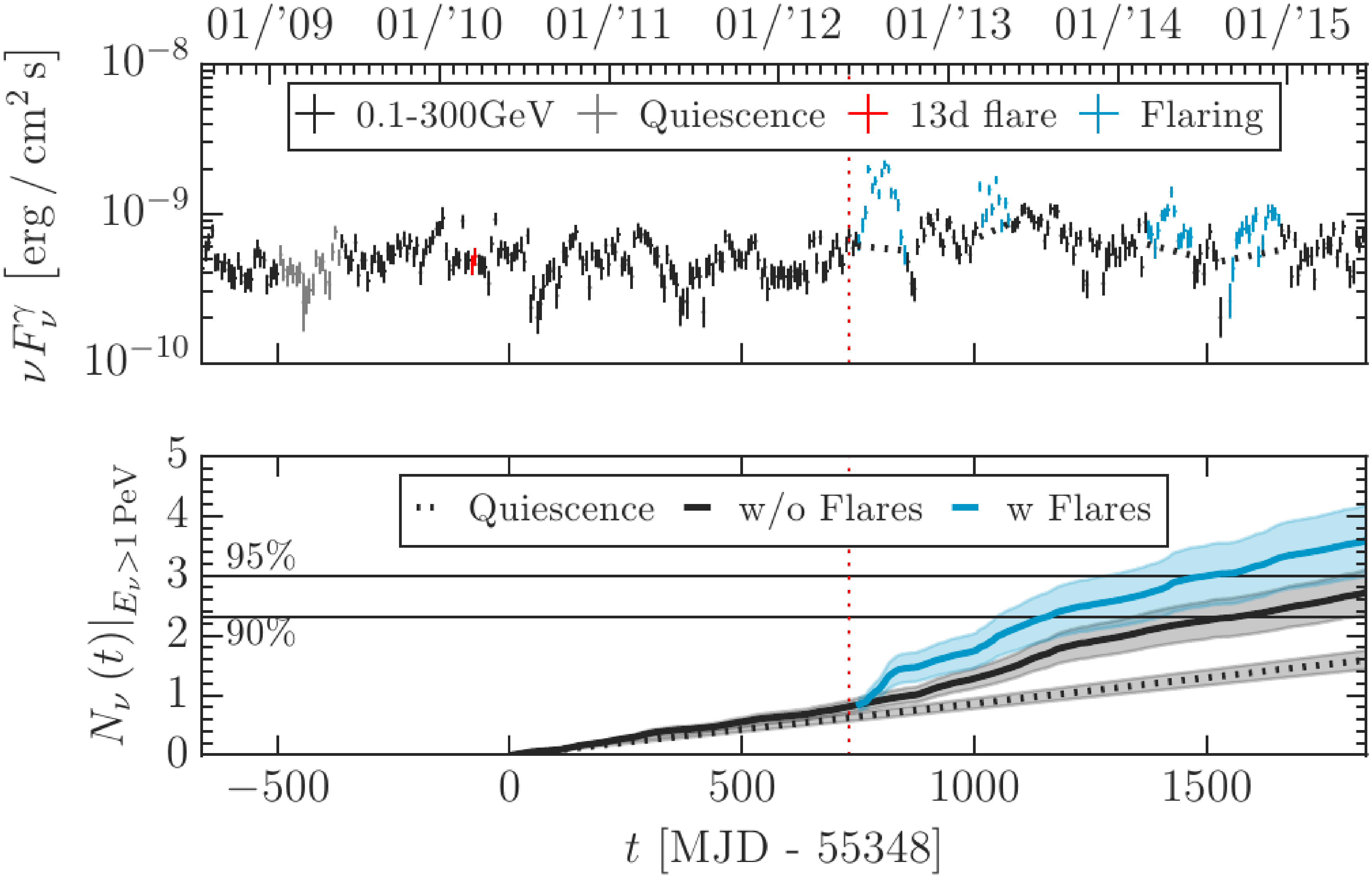




Aartsen et al. 2018

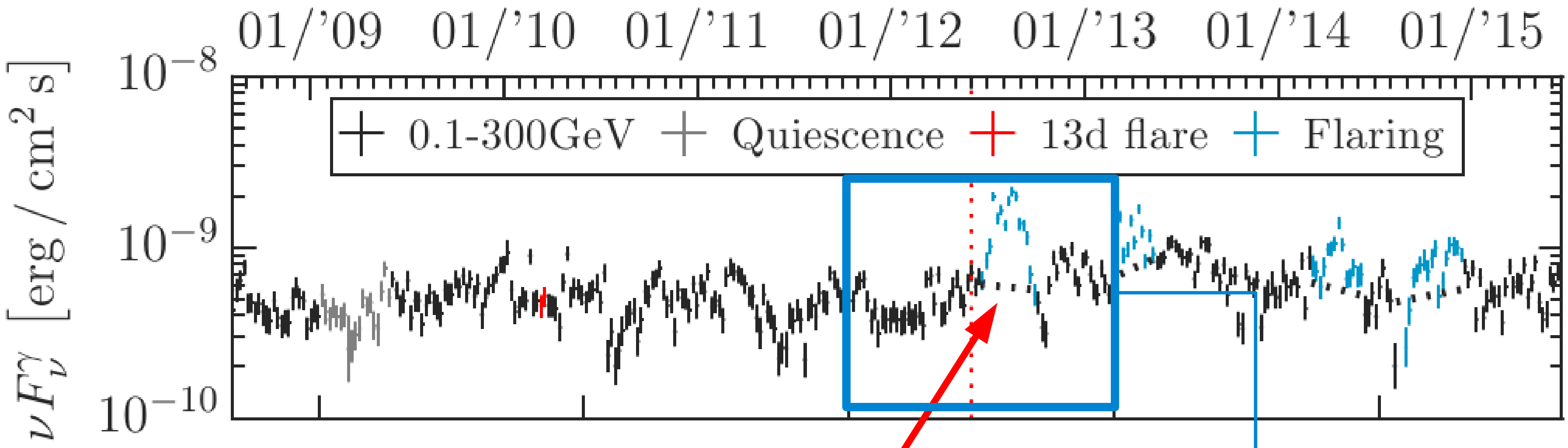
Blazar flares & neutrino prediction for Mkr 421

MP, Coenders & Dimitrakoudis, 2016



ν-γ correlation

Blazar flares & neutrino prediction for Mkr 421



Major GeV flares

No.	T (days)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}$(%)
Flares 1a+1b	105	0.61 ± 0.16	46 ± 8
Flare 2	70	0.32 ± 0.07	27 ± 5
Flare 3	98	0.26 ± 0.05	23 ± 4
Flares 4a+4b	112	0.26 ± 0.05	23 ± 4
∑ Flares	385	1.46 ± 0.32	77 ± 7

Without major GeV flares

Season	T (days)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}$(%)[†]
06/2010-05/2011	364	0.43 ± 0.06	34 ± 4
06/2011-05/2012	364	0.38 ± 0.05	32 ± 3
06/2012-05/2013	371	0.71 ± 0.11	51 ± 5
06/2013-05/2014	364	0.70 ± 0.11	50 ± 5
06/2014-05/2015	350	0.47 ± 0.06	38 ± 4
∑ w/o Flares	1834[a]	2.73 ± 0.38	94 ± 2
∑ w Flares	1834	3.59 ± 0.60	97 ± 2

* Similar probability for detecting at least 1 neutrino from the 2012 flare alone OR the whole IC Season 3

* Still <50%

Fraction of neutrinos produced during flares - (1)

Murase, Oikonomou, MP 2018

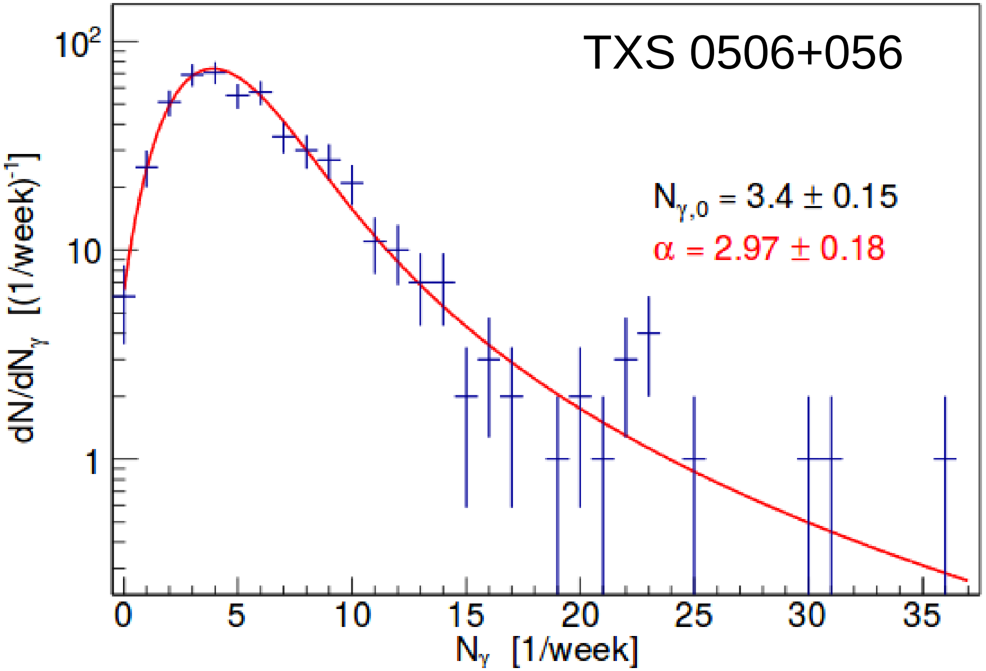
- Model-predicted scaling *(e.g., Murase et al. 2015, Tavecchio et al. 2015, MP et al. 2016):*

$$L_\nu \propto L_\gamma^\gamma \text{ with } \gamma \sim 1.5 - 2$$

- Neutrino luminosity distribution:

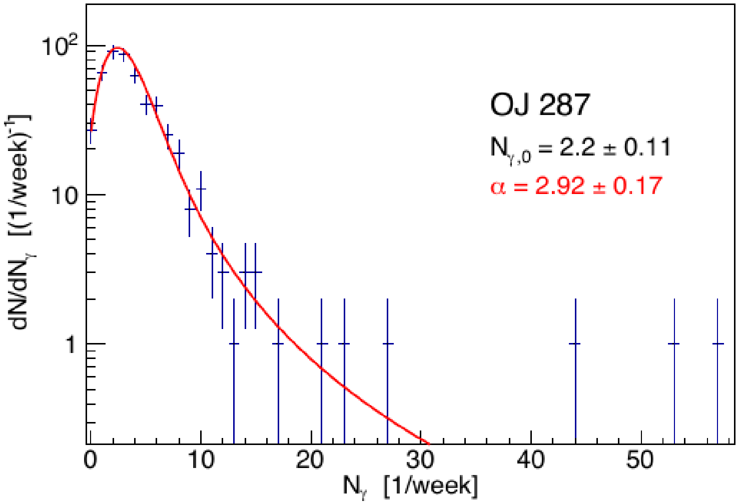
$$L_\nu^2 \frac{dN}{dL_\nu} \propto L_\nu^{1-\frac{\alpha-1}{\gamma}}$$

- Flares dominate neutrino output, if α < 3



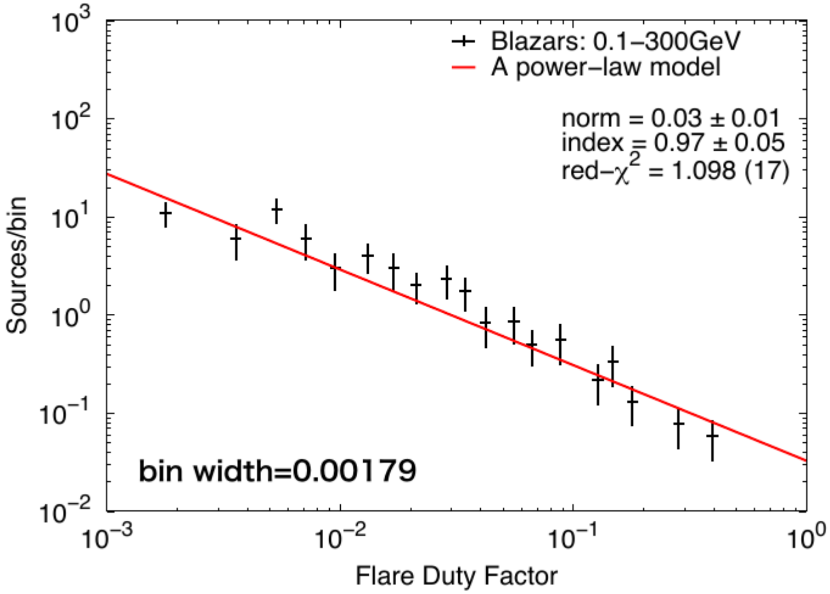
FAVA sample of 6 blazars

- Duty factor (>5σ): ~ 0.3-10 %
- Fraction of flare energy release: ~10%
- Luminosity distribution: $dN/dL_\gamma \propto L_\gamma^{-\alpha}$ (α~2-4)



Fraction of neutrinos produced during flares - (2)

Yoshida, MP, Oikonomou, Vasilopoulos, Urry, Murase, in prep.



Fermi-LAT sample of 124 blazars

- Duty factor (>6σ): power-law with index *-1* (~0.3-10 %)
- Fraction of flare energy release: power-law with index *-1* (~1-60 %)