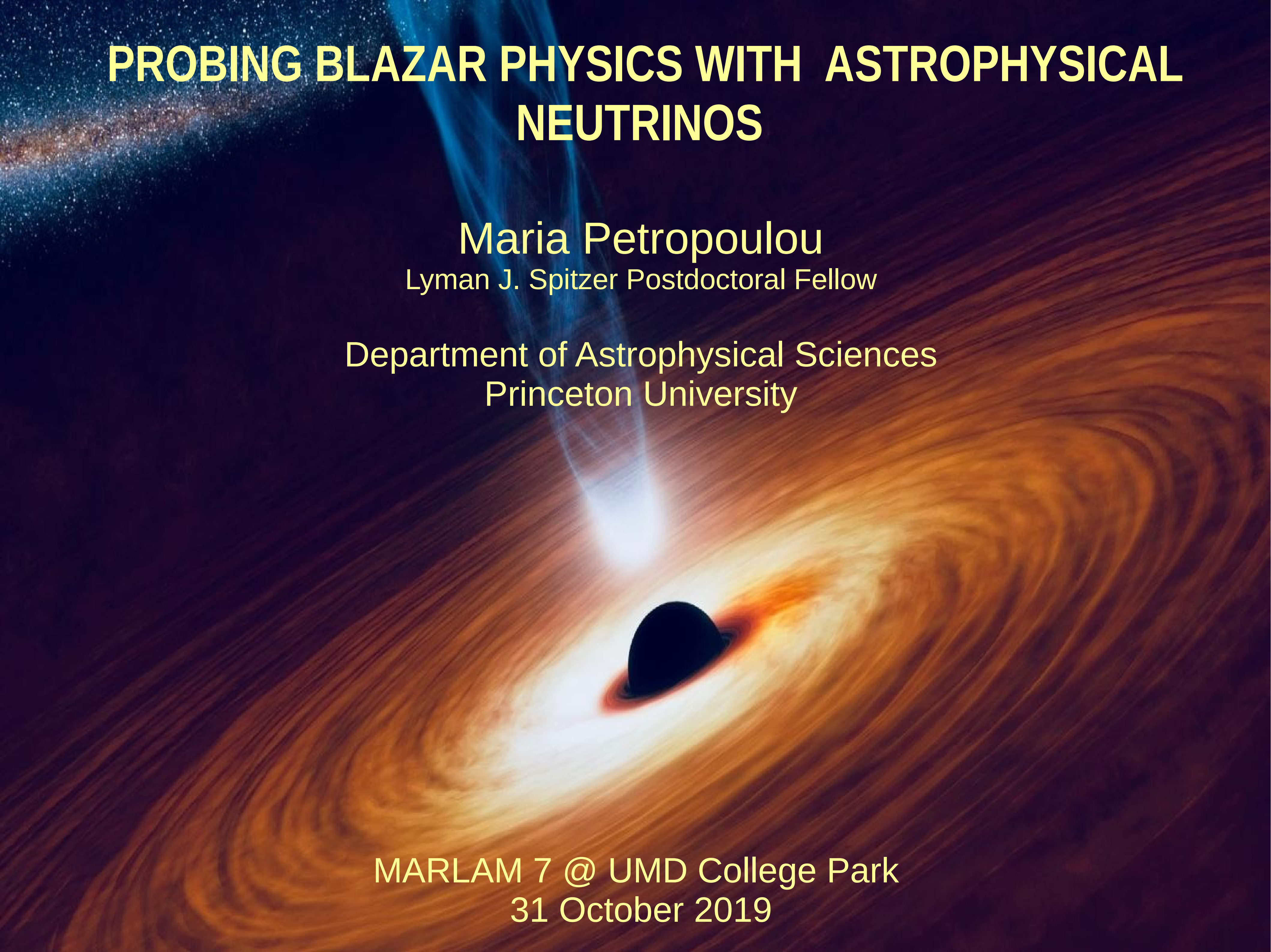

PROBING BLAZAR PHYSICS WITH ASTROPHYSICAL NEUTRINOS

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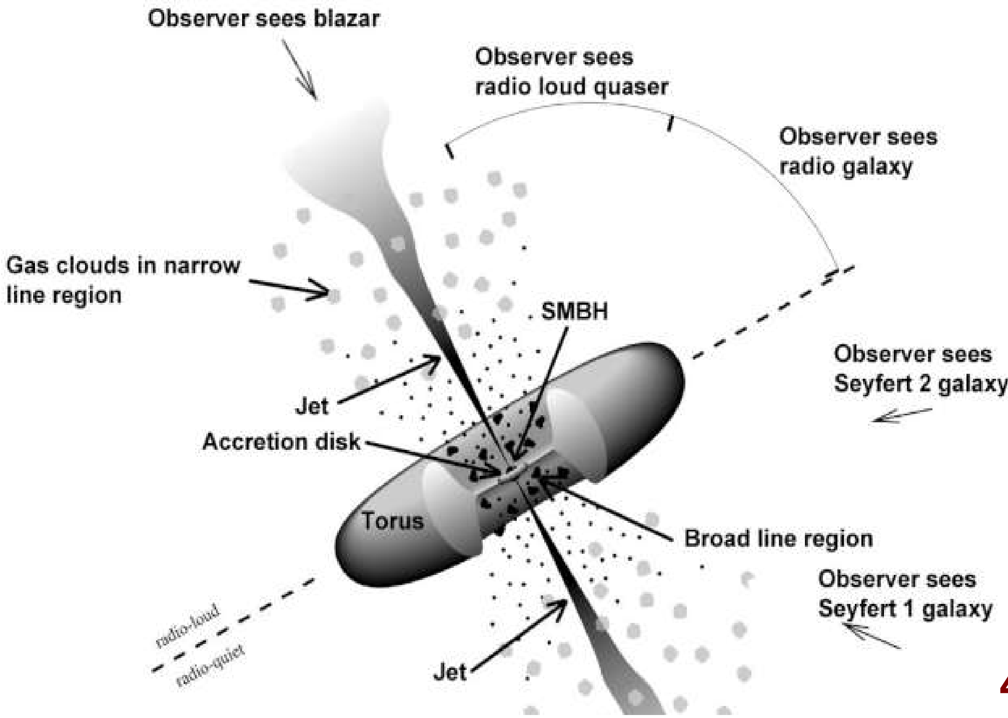
Department of Astrophysical Sciences

Princeton University

MARLAM 7 @ UMD College Park

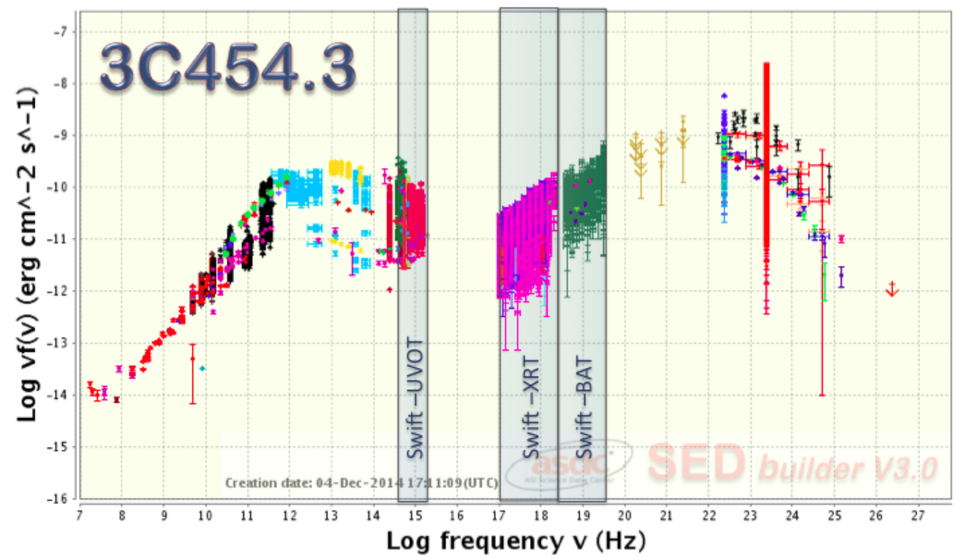
31 October 2019

Blazars: AGN with jets viewed face-on

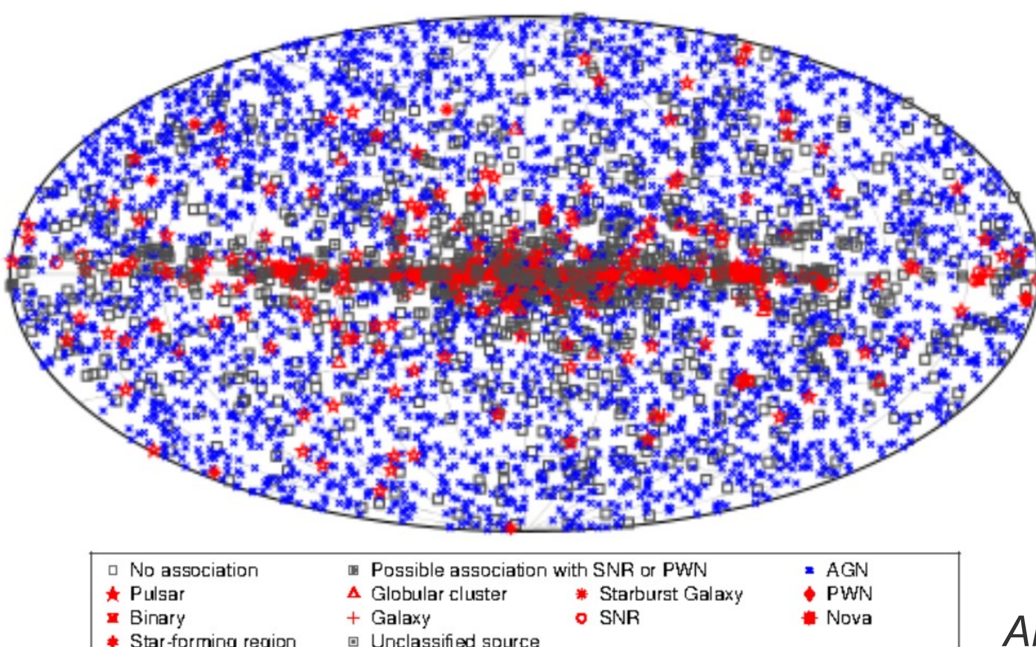


Urry & Padovani 1995

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



4FGL



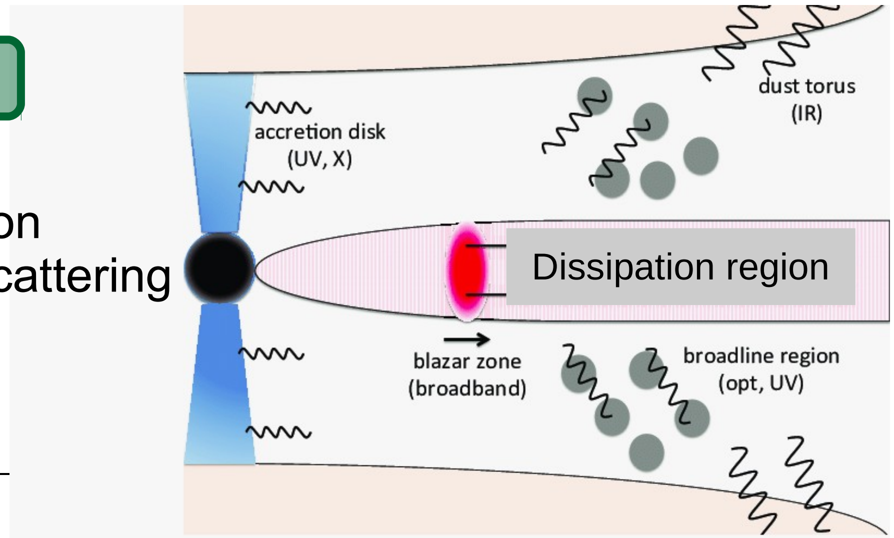
- 8yr science data
- ~5000 sources
- ~60% blazars

Abdollahi et al. 2019

Origin of γ-rays: leptonic or hadronic ?

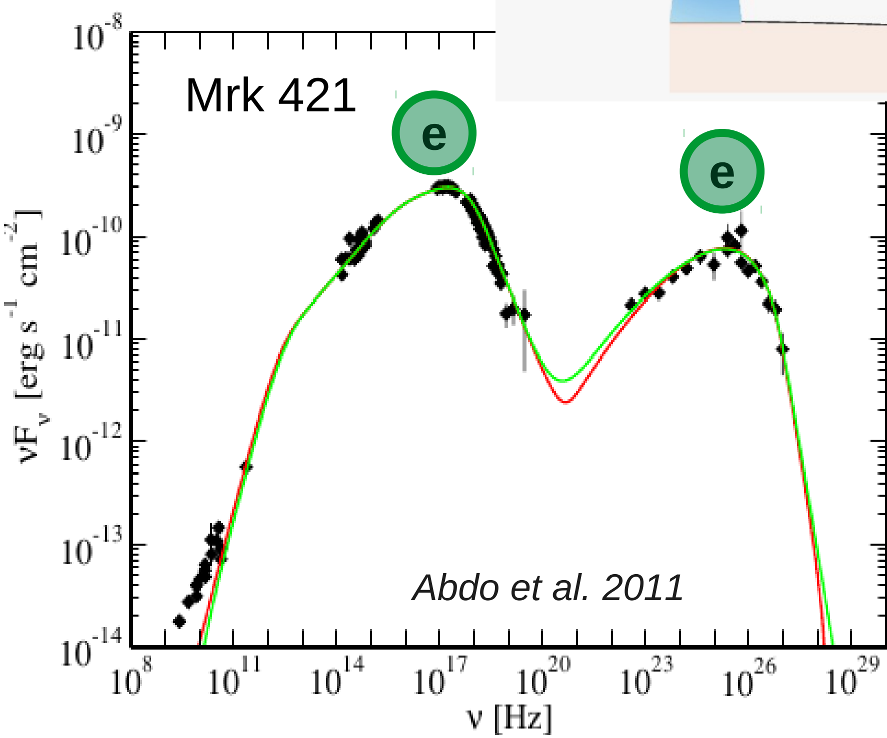
Leptonic models

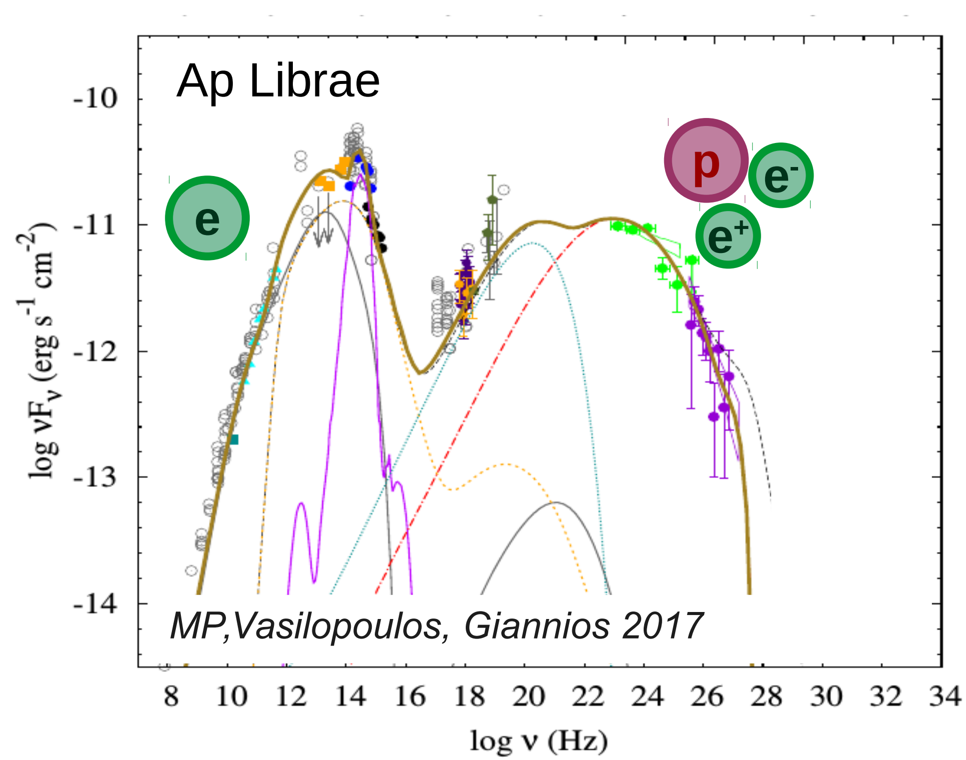
- Synchrotron radiation
- Inverse Compton scattering
- Pair production



Hadronic models

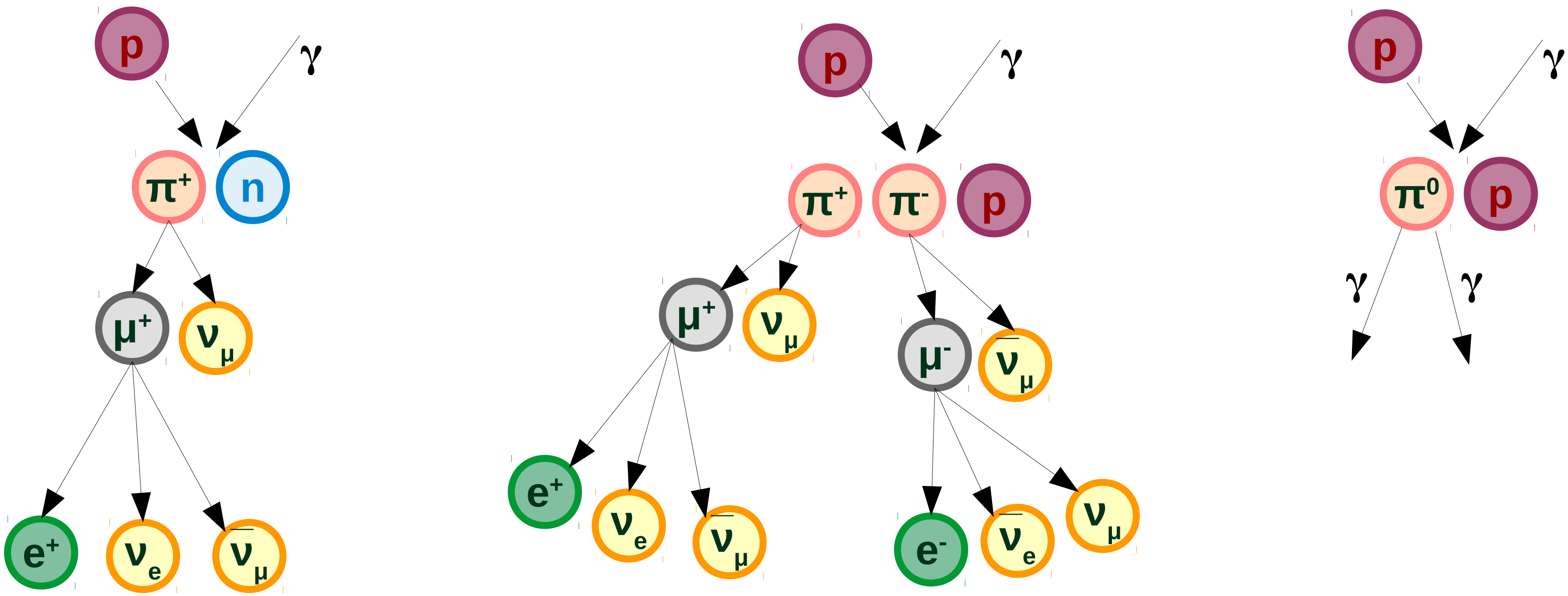
- Synchrotron radiation
- Inverse Compton scattering
- Pair production
- Photo-meson production
- Photo-pair (Bethe-Heitler) production
- Hadro-nuclear collisions





***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*

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

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

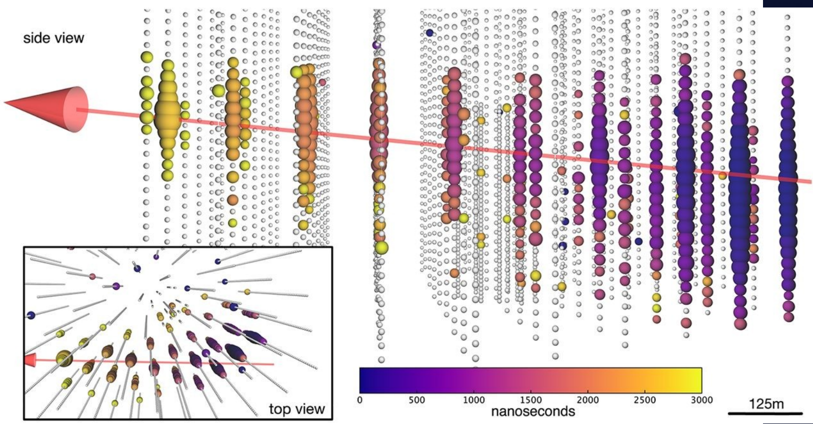
Target photons

Proton Energy

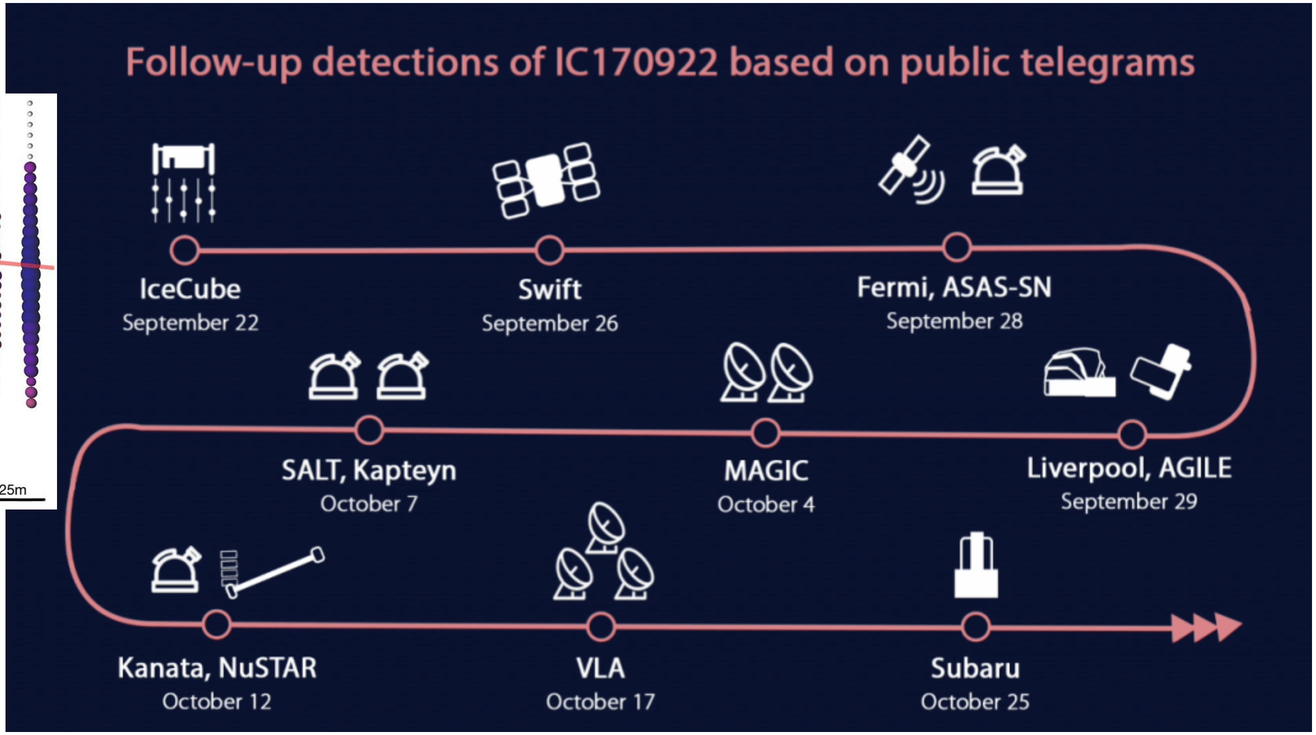
Typical neutrino energy: $E'^b_\nu \approx 0.05 E'^b_p \simeq 80~\mathrm{PeV}~\Gamma_1^2 (E'_s/10~\mathrm{eV})^{-1}$

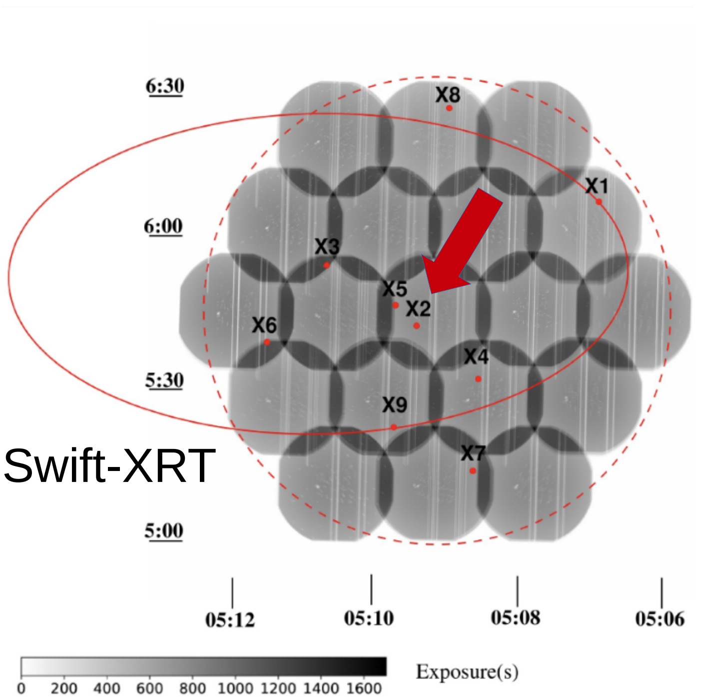
The multi-messenger flare of TXS 0506+056

IC-170922A: a 290 TeV neutrino



IceCube Colloboration et al. 2018a

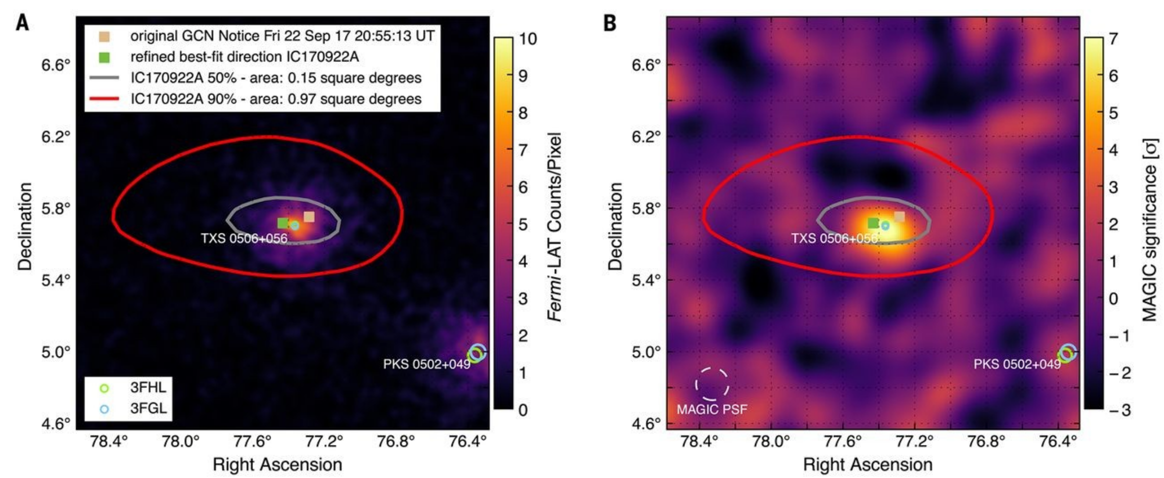




Swift-XRT

Keivani, Murase, MP, Fox et al. 2018

Fermi-LAT　　MAGIC

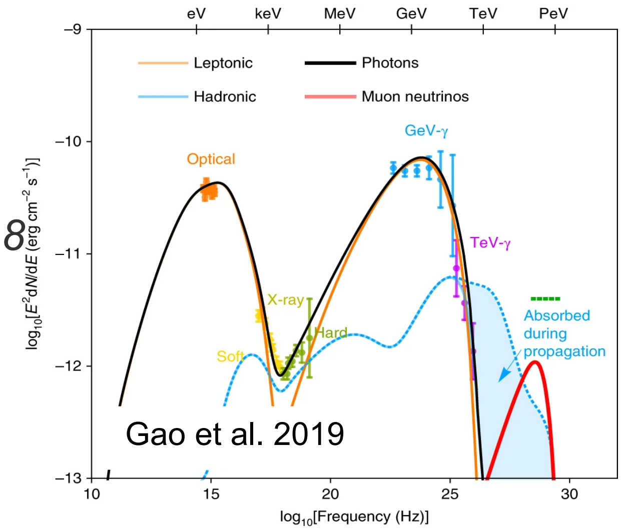


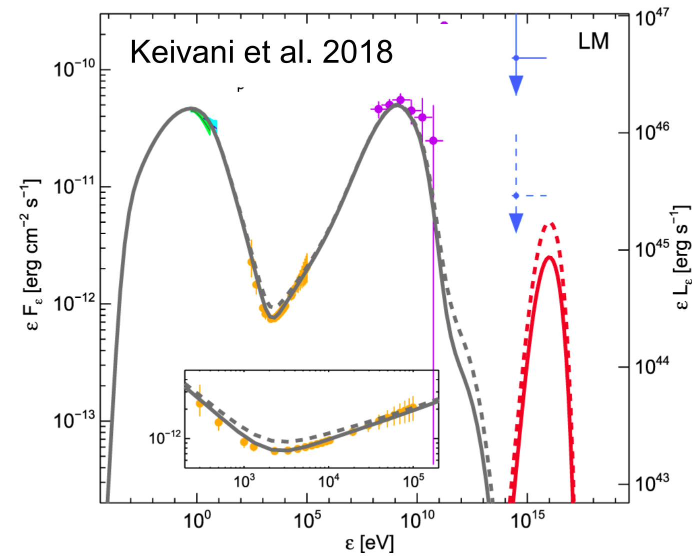
IceCube Colloboration et al. 2018a

Models for the 2017 multi-messenger flare

Photo-hadronic

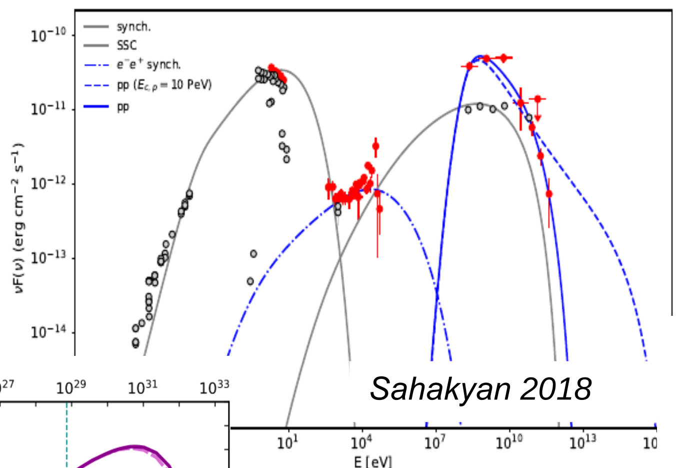
- *Ansoldi et al. 2018 for MAGIC*
- *Keivani,Murase, MP, Fox et al. 2018*
- *Murase, Oikonomou, MP 2018*
- *Cerruti et al. 2019*
- *Gao et al. 2019*
- *…*

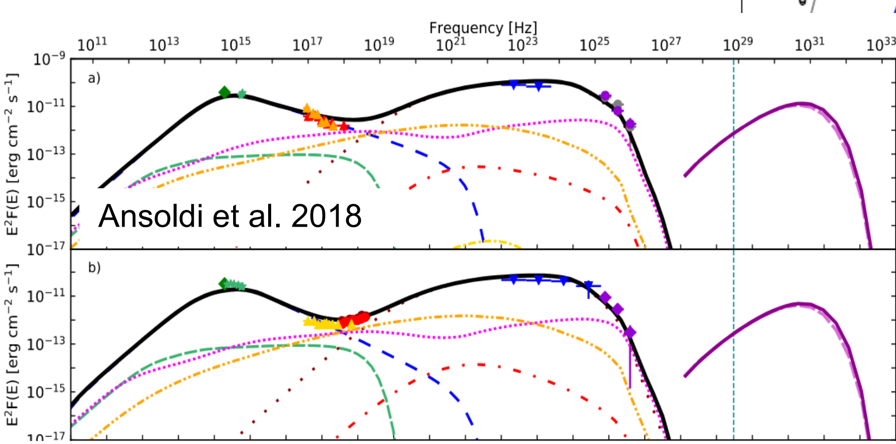


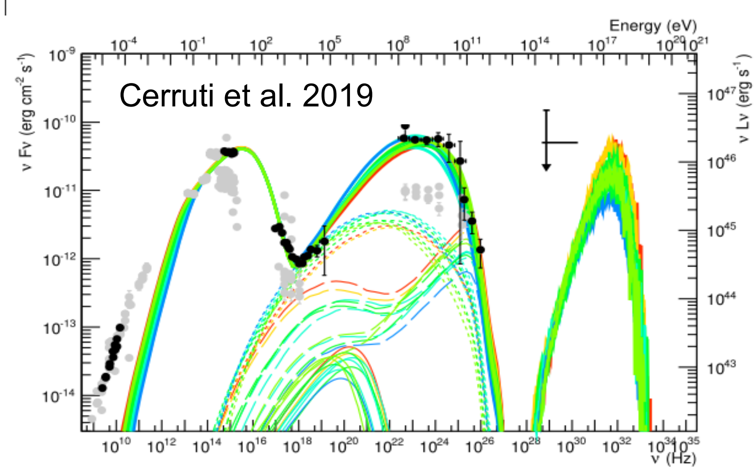


Hadro-nuclear

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







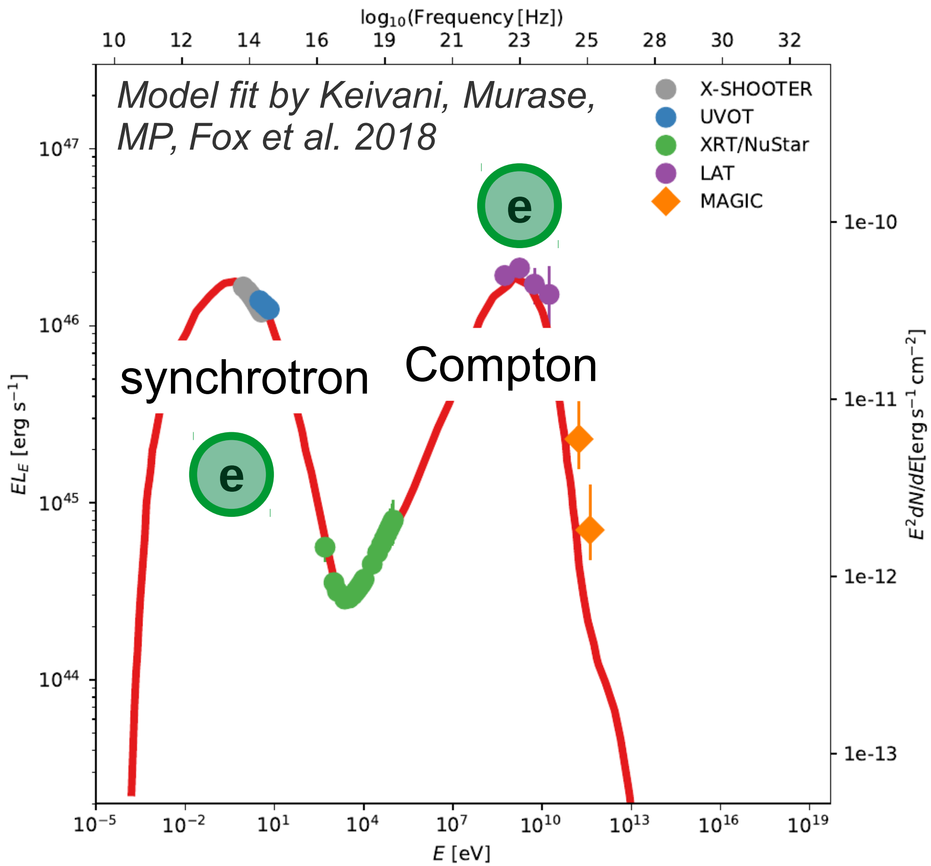
Summary of results for the 2017 flare

	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)*.

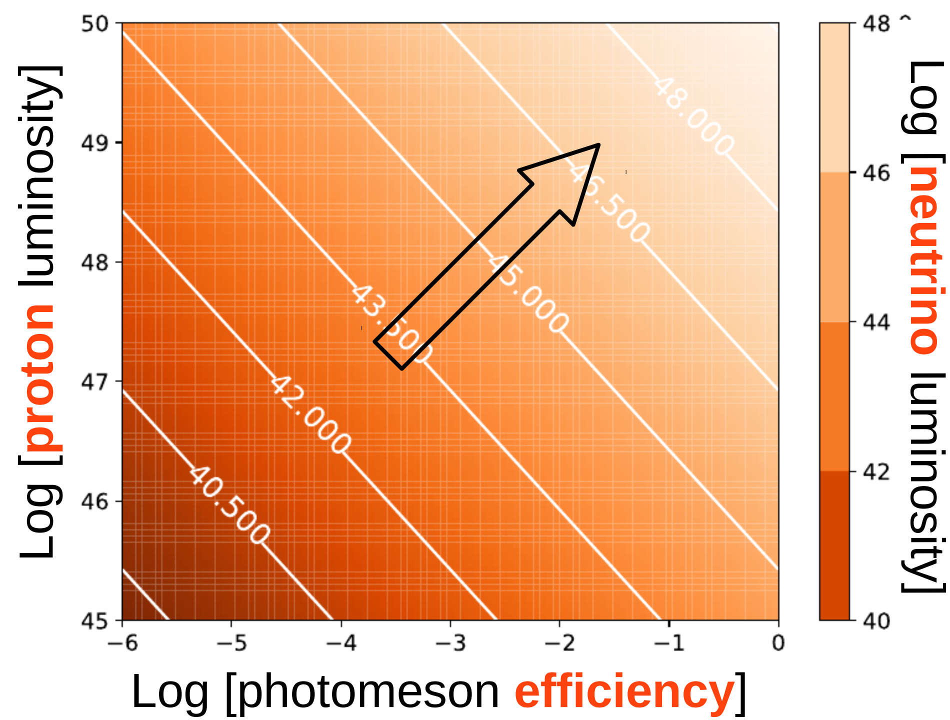
What sets the maximum neutrino flux?

Murase, Oikonomou, MP 2018

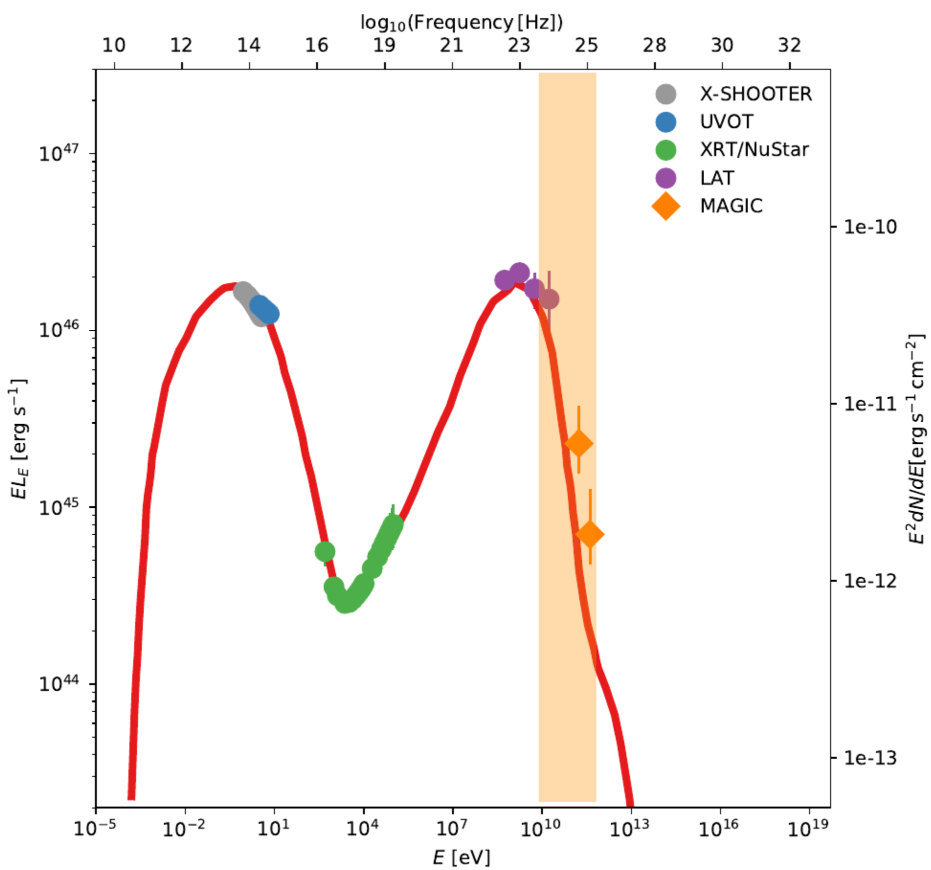


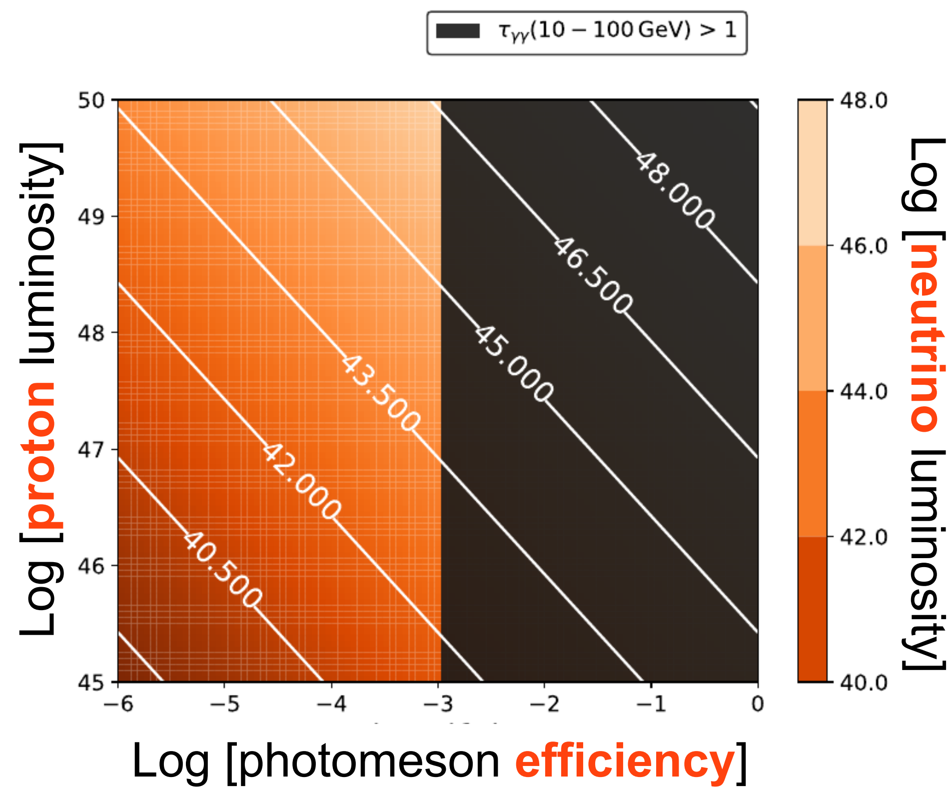
$$\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma}\, \varepsilon_p L_p$$

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



What sets the maximum neutrino flux?

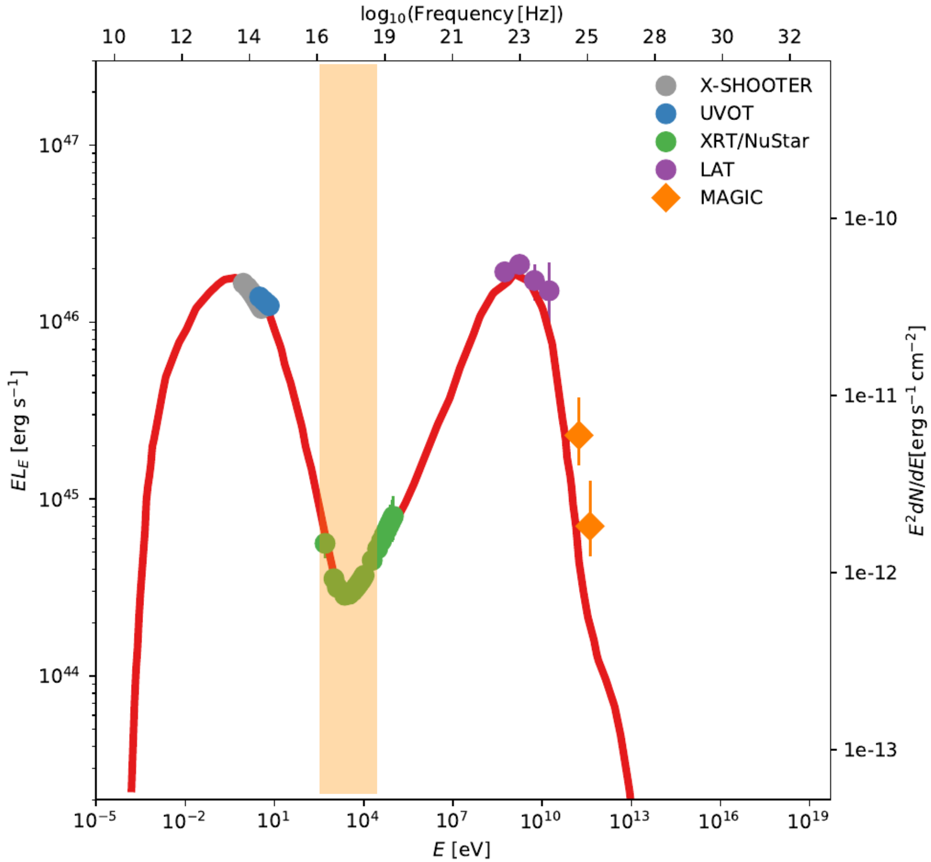


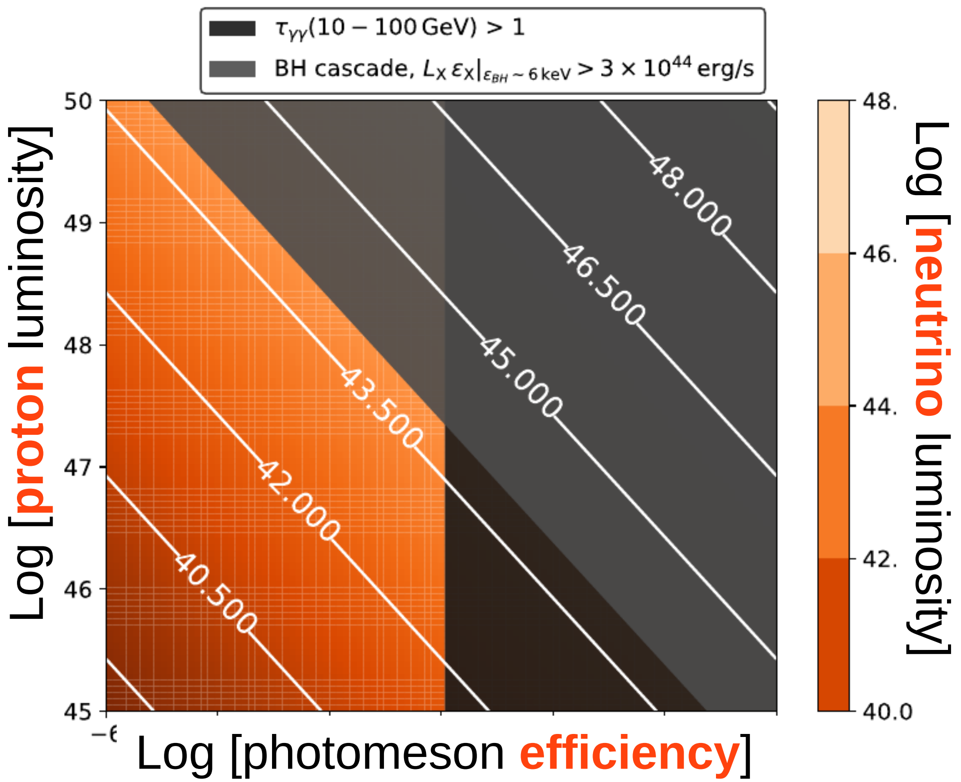


I. Optical depth for absorption of 10-100 GeV γ-rays must be low: $\tau_{\gamma\gamma}(10 - 100\,\mathrm{GeV}) \lesssim 1$

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

What sets the maximum neutrino flux?



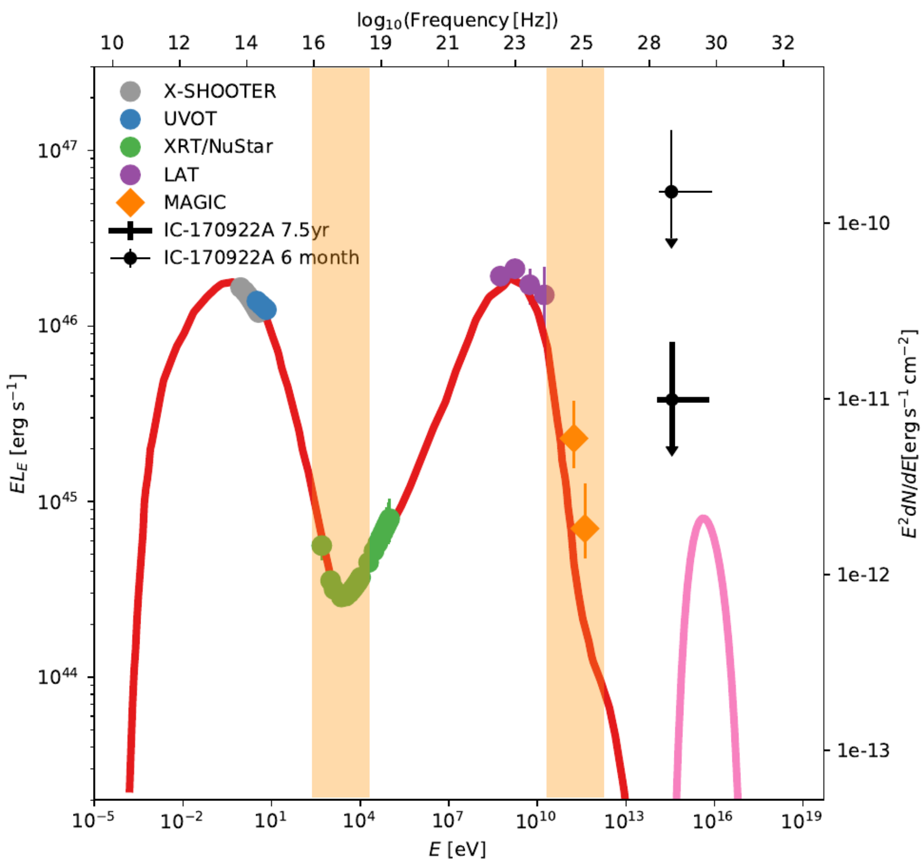


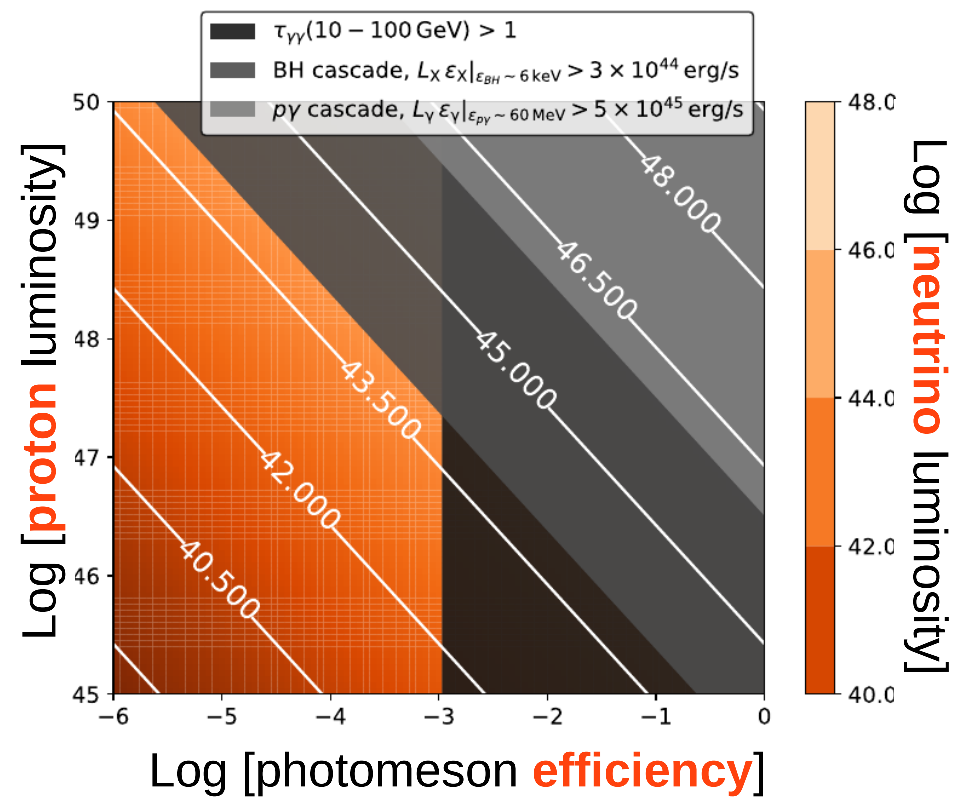
II. Synchrotron emission from Bethe-Heitler pairs must not overshoot X-ray data:

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

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

What sets the maximum neutrino flux?

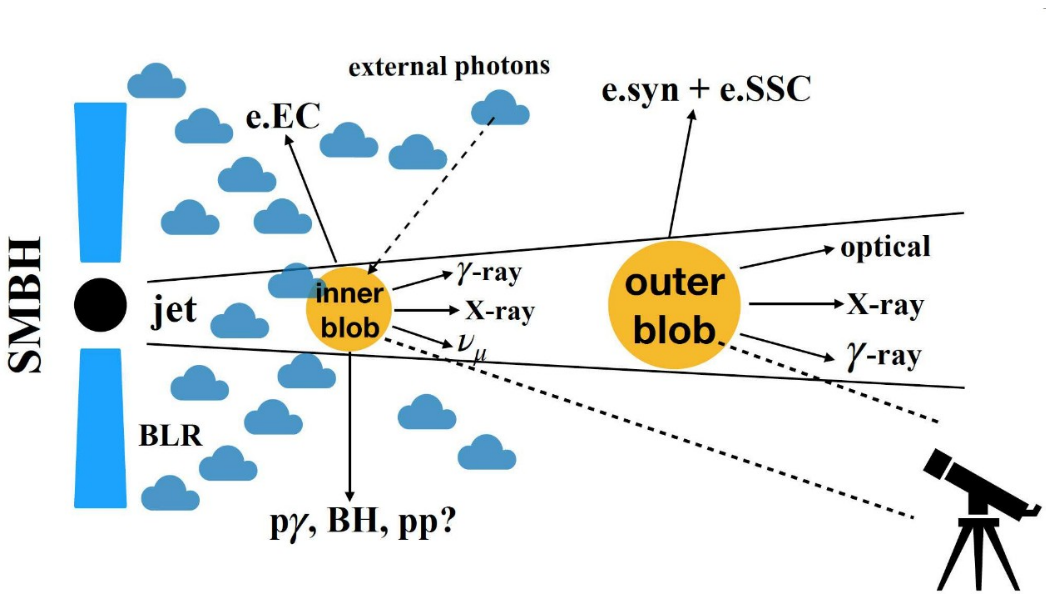


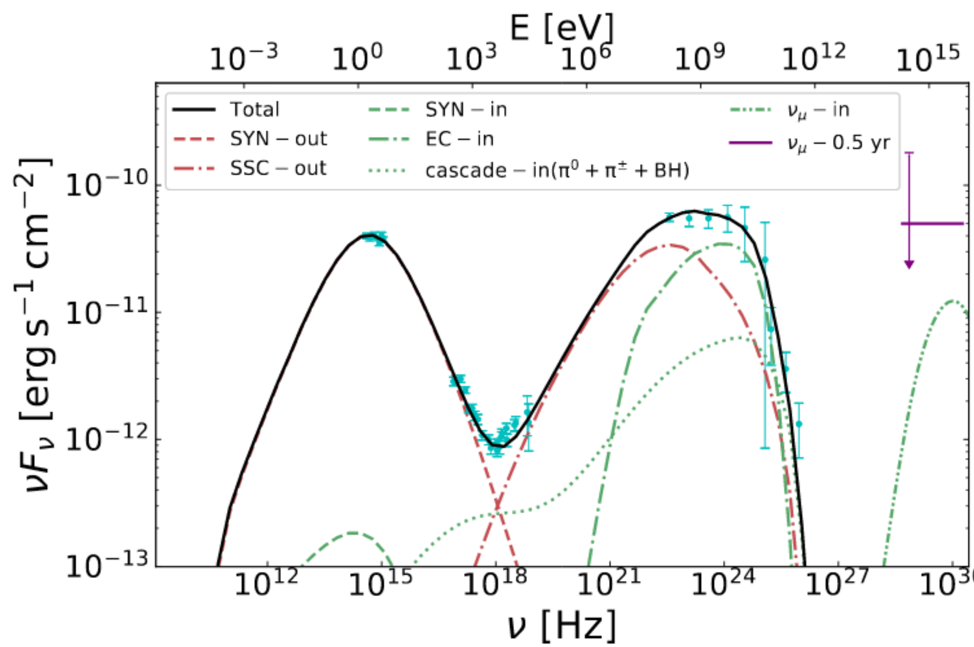


Maximum all-flavor neutrino flux: $$E_\nu L_{E_\nu} \lesssim 10^{45}\ \mathrm{erg\ s^{-1}}\ \frac{L_{\mathrm{X,lim}}}{3\times10^{44}\ \mathrm{erg\ s^{-1}}}\frac{0.1}{f_x}$$

A two-zone model for the 2017 flare

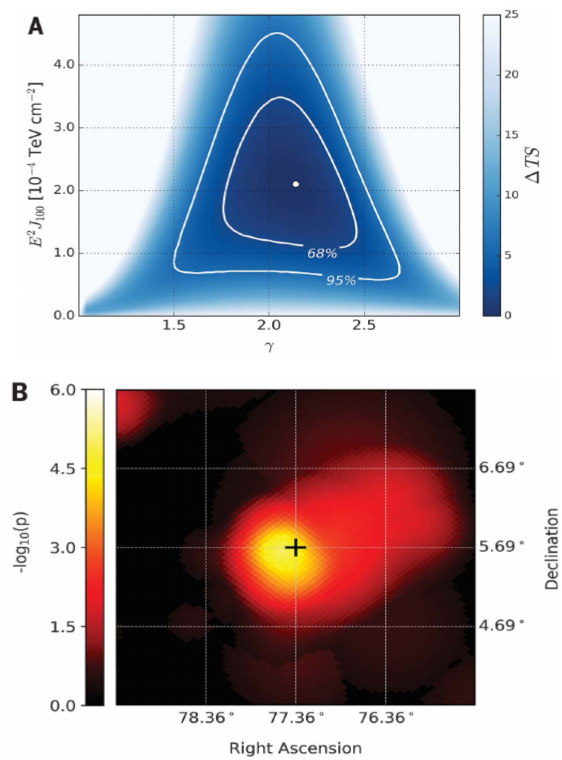
Xue, Liu, MP et al. 2019 (arXiV:1908.10190)



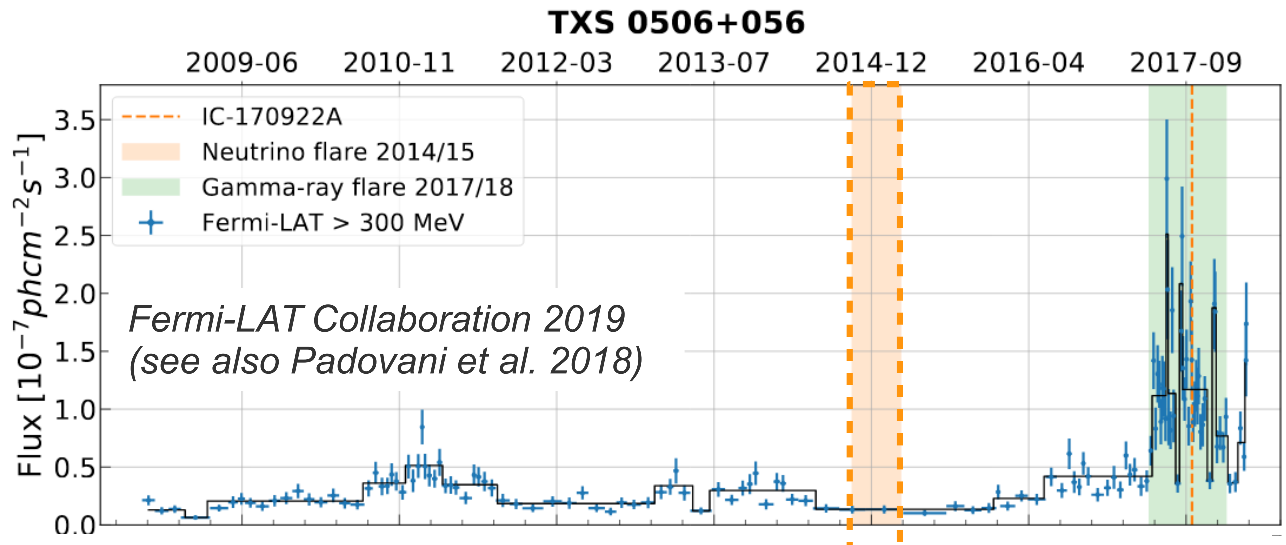


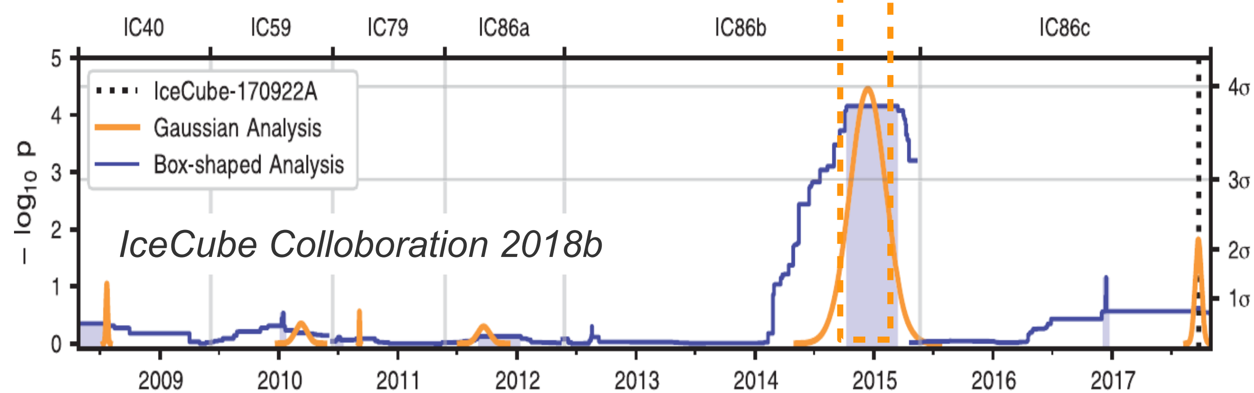
- Two zones with different conditions.
- Suppression of cascade emission in inner blob because of reduced γγ opacity.
- Prediction of **~10 times** higher neutrino flux than single-zone models.
- **Many free** parameters → model degeneracies.

Are there more neutrinos from TXS 0506+056?



IceCube Colloboration 2018b

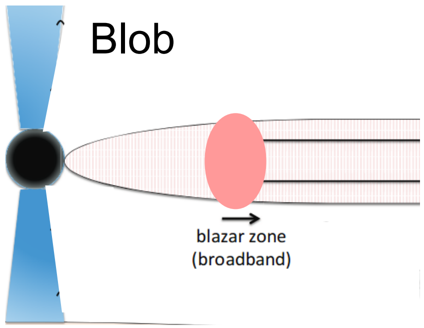


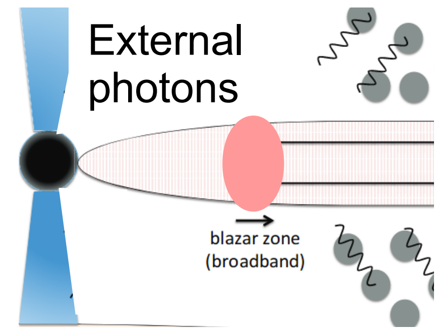


- 13 +/- 5 neutrinos above atmospheric background over ~6 months (~3.5 σ)
- Neutrino luminosity (averaged in ~6 months) **4 times larger** than average γ-ray luminosity!
- **No γ-ray** flaring activity in 2014-15. No evidence for flares at other energies either.

A challenge for one - zone models

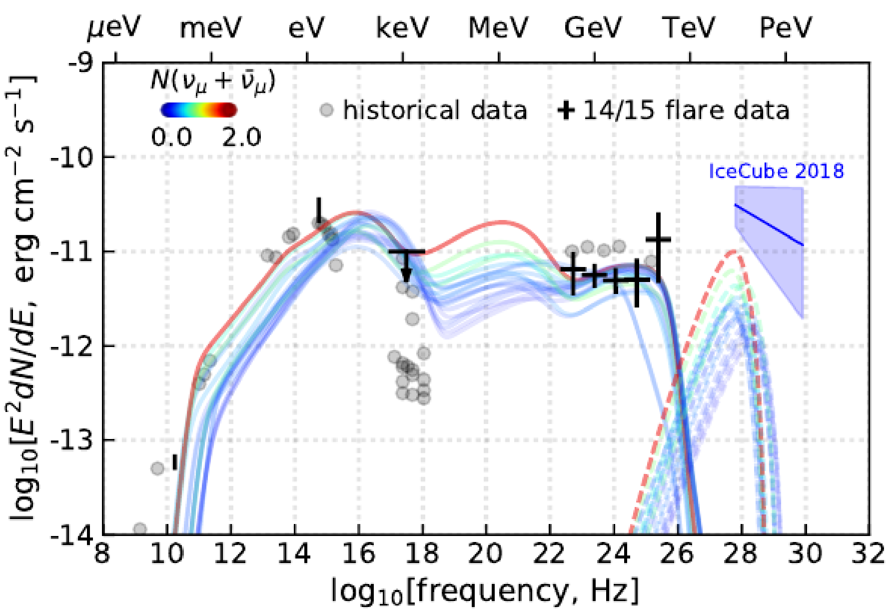
Rodrigues et al. 2018

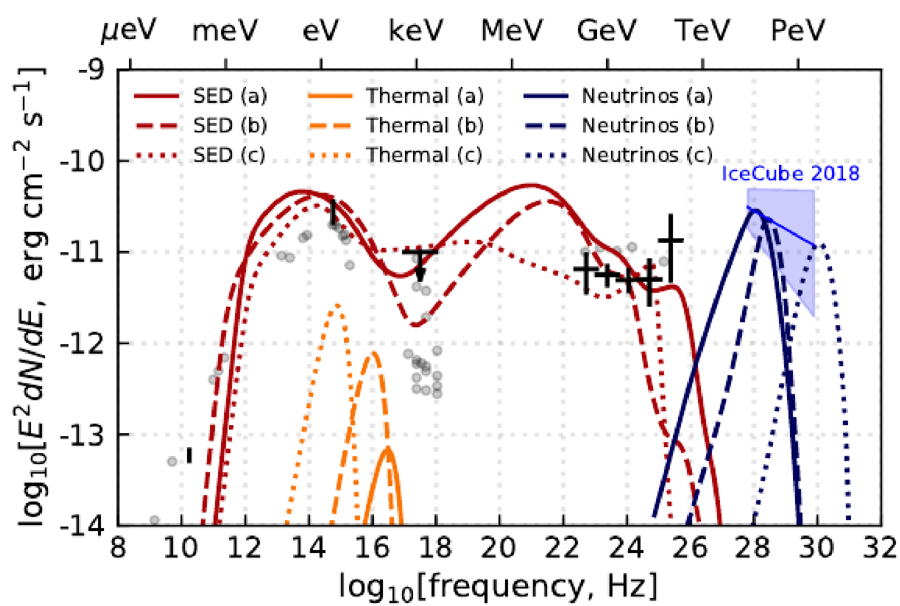




- **< 1.8 events**
- MeV band unconstrained!
- X-ray flux close to UL

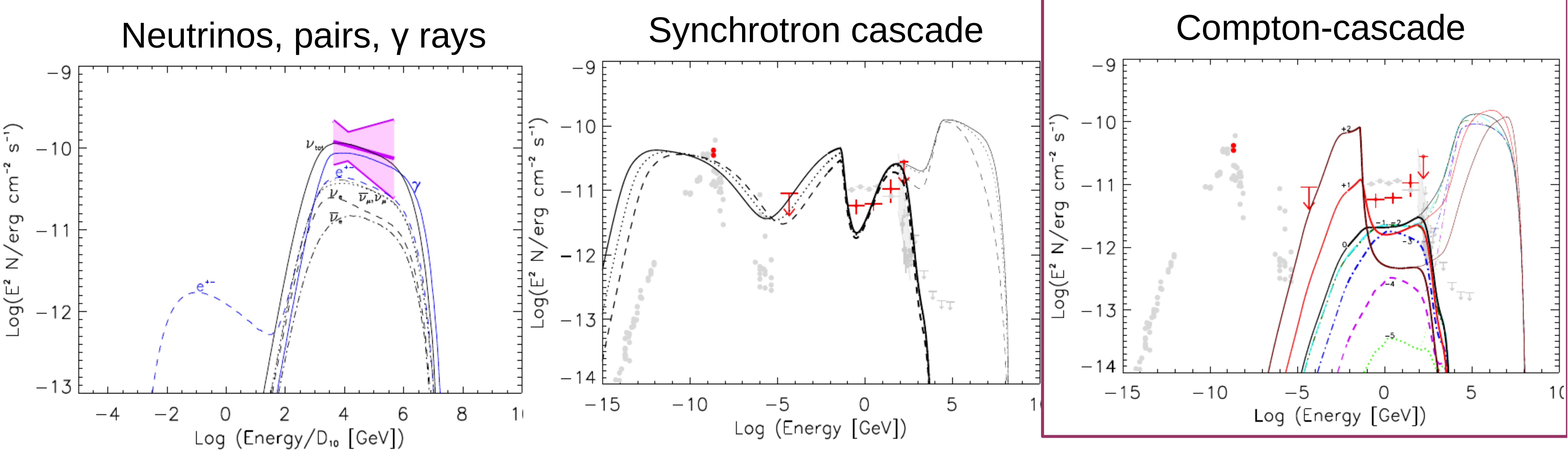
- **< 4.8 events**
- Attenuation > 10 GeV
- X-ray flux close to UL





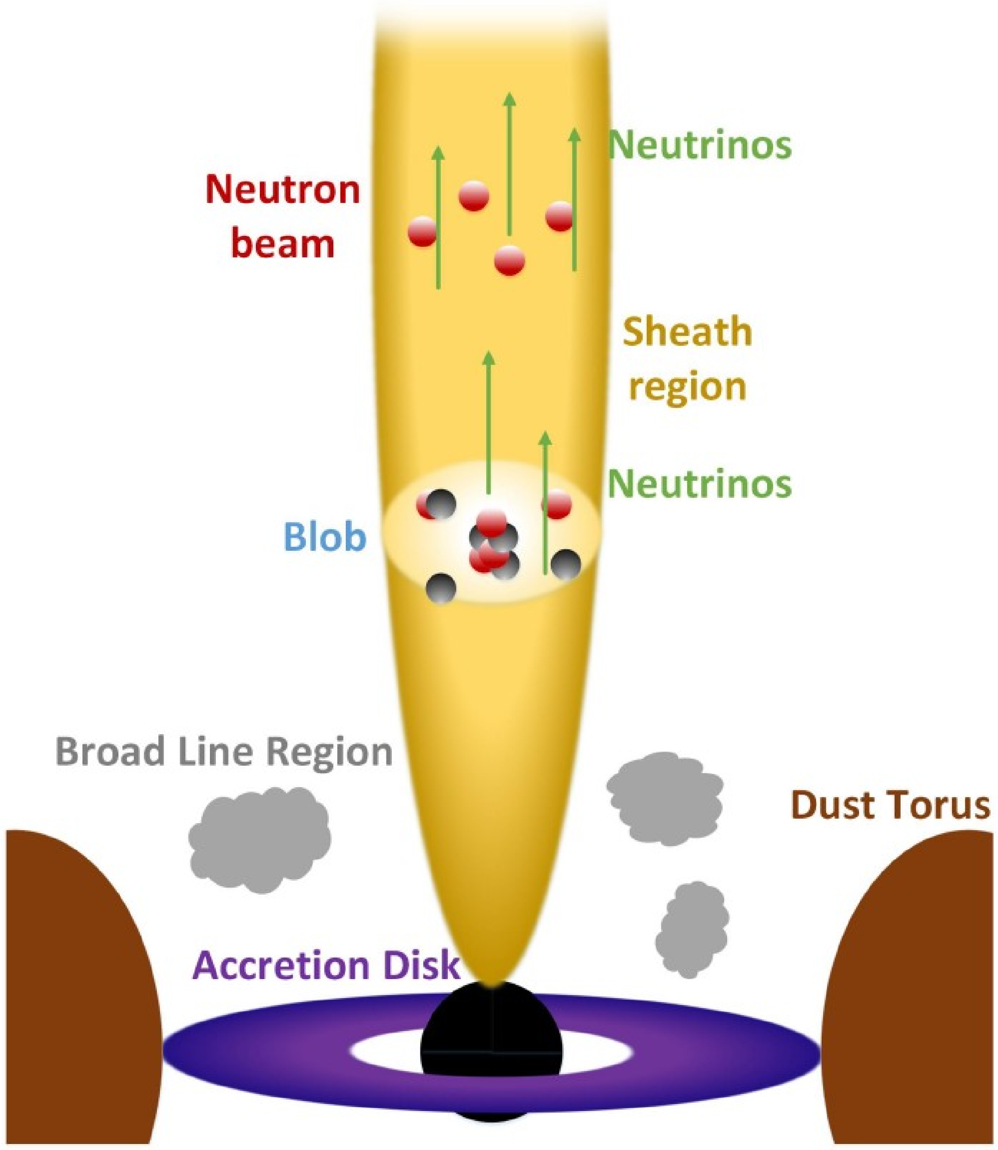
Minimal requirements for the 2014-15 neutrinos

Reimer, Boettcher & Buson 2019



- **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

The neutral beam model



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

A two-zone model

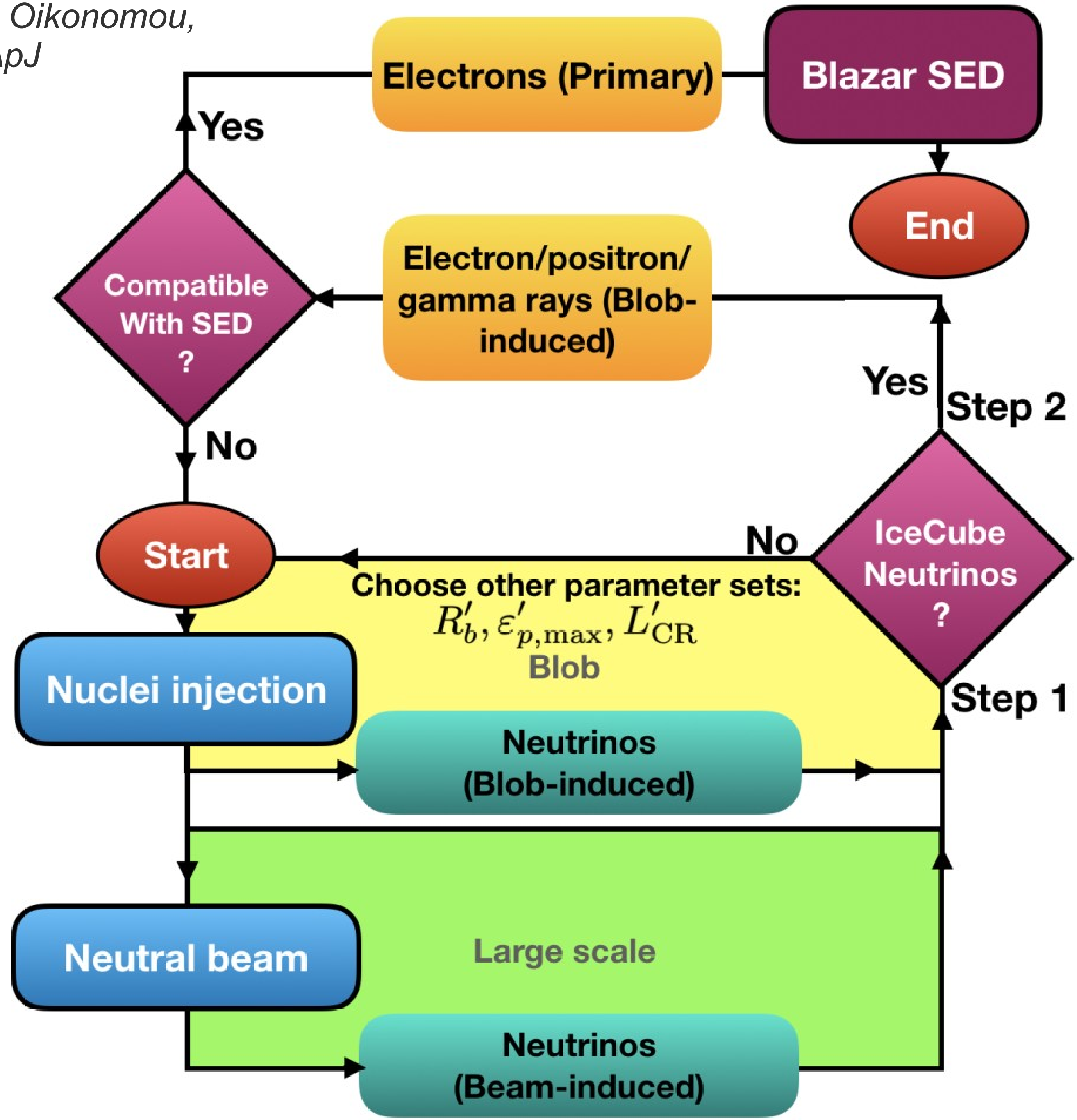
- **Blob:** Photo-disintegration + Photo-meson+Bethe Heitler processes of nuclei → pairs, γ-rays neutrinos & neutrons
- **Beam:** Photo-meson interactions of neutrons with external photons → pairs, γ-rays, neutrinos

Model parameters

- **Blob:** radius,magnetic field, Lorentz factor
- **Cosmic rays:** composition, luminosity, maximum energy, power-law index
- **External radiation fields:** energy density, spectrum, luminosity

Methodology

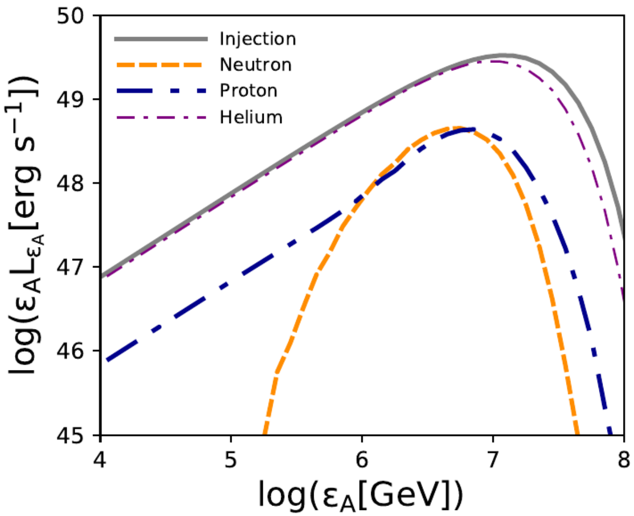
Zhang, MP, Murase, Oikonomou, 2019, submitted in ApJ



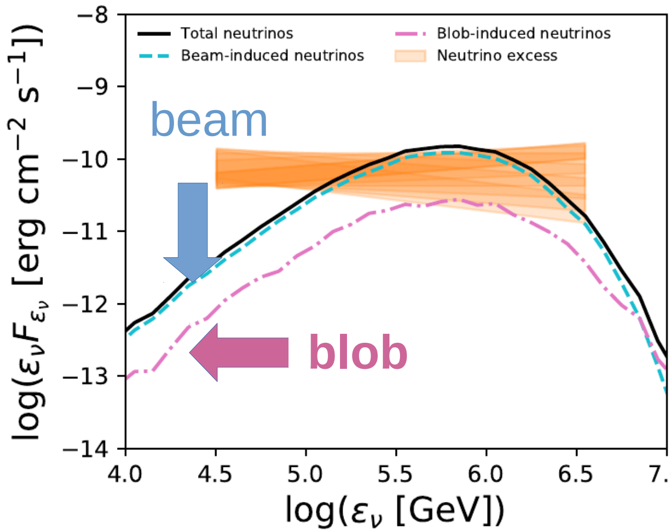
The 2014-15 neutrino excess

Zhang, MP, Murase, Oikonomou, 2019, submitted in ApJ

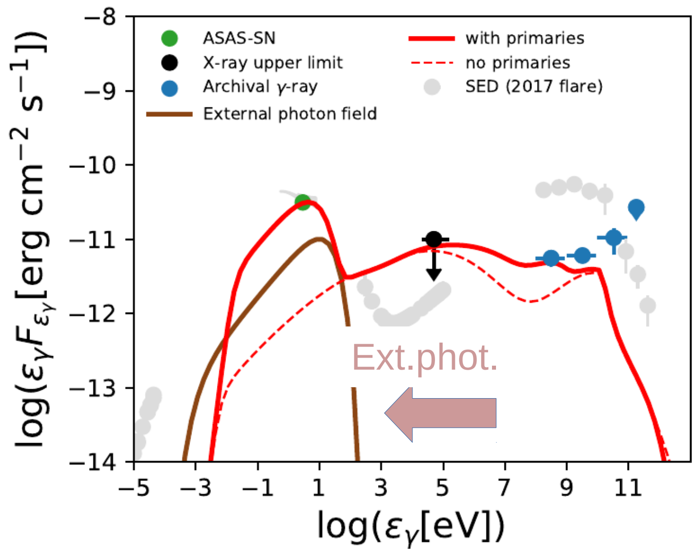
Nuclei



Neutrinos



Photons

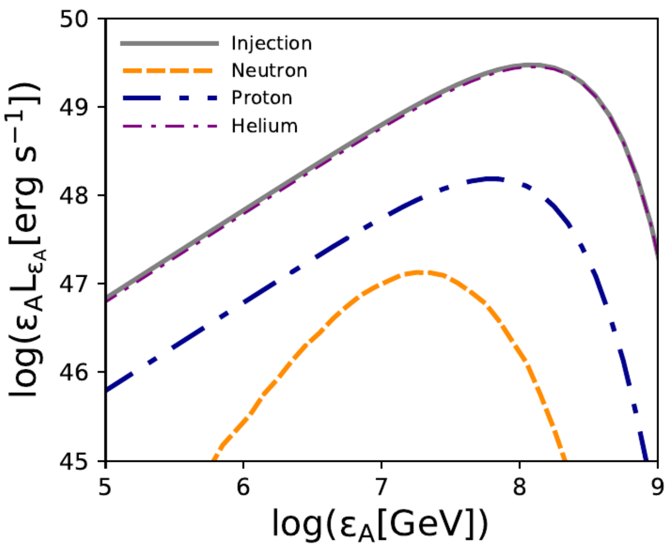


- Light composition of nuclei (proton & He).
- Neutrino flux dominated by the **beam**.
- Stationary **(UV) photon field** with **high energy density** as target for photo-meson/photo-disintegrations.
- **Compact blob** (~10^{15} - 10^{16} cm) with **strong** (~80 G) magnetic fields.
- Attenuation of γ-rays **> 100 GeV** in blob.

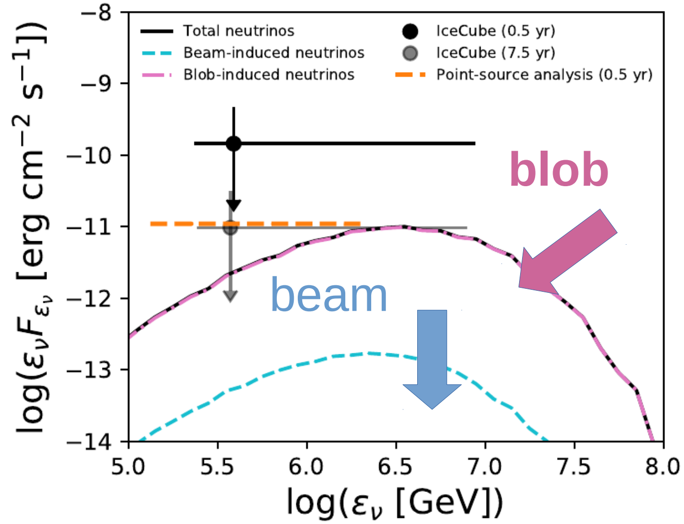
The 2017 flare

Zhang, MP, Murase, Oikonomou, 2019, submitted in ApJ

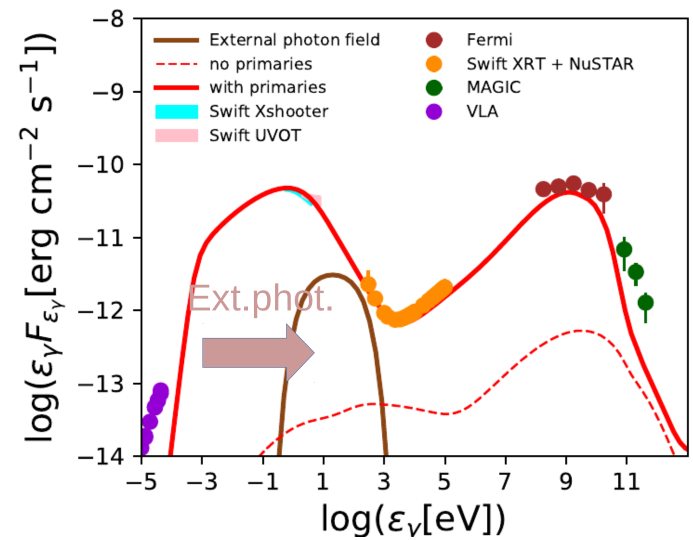
Nuclei



Neutrinos



Photons

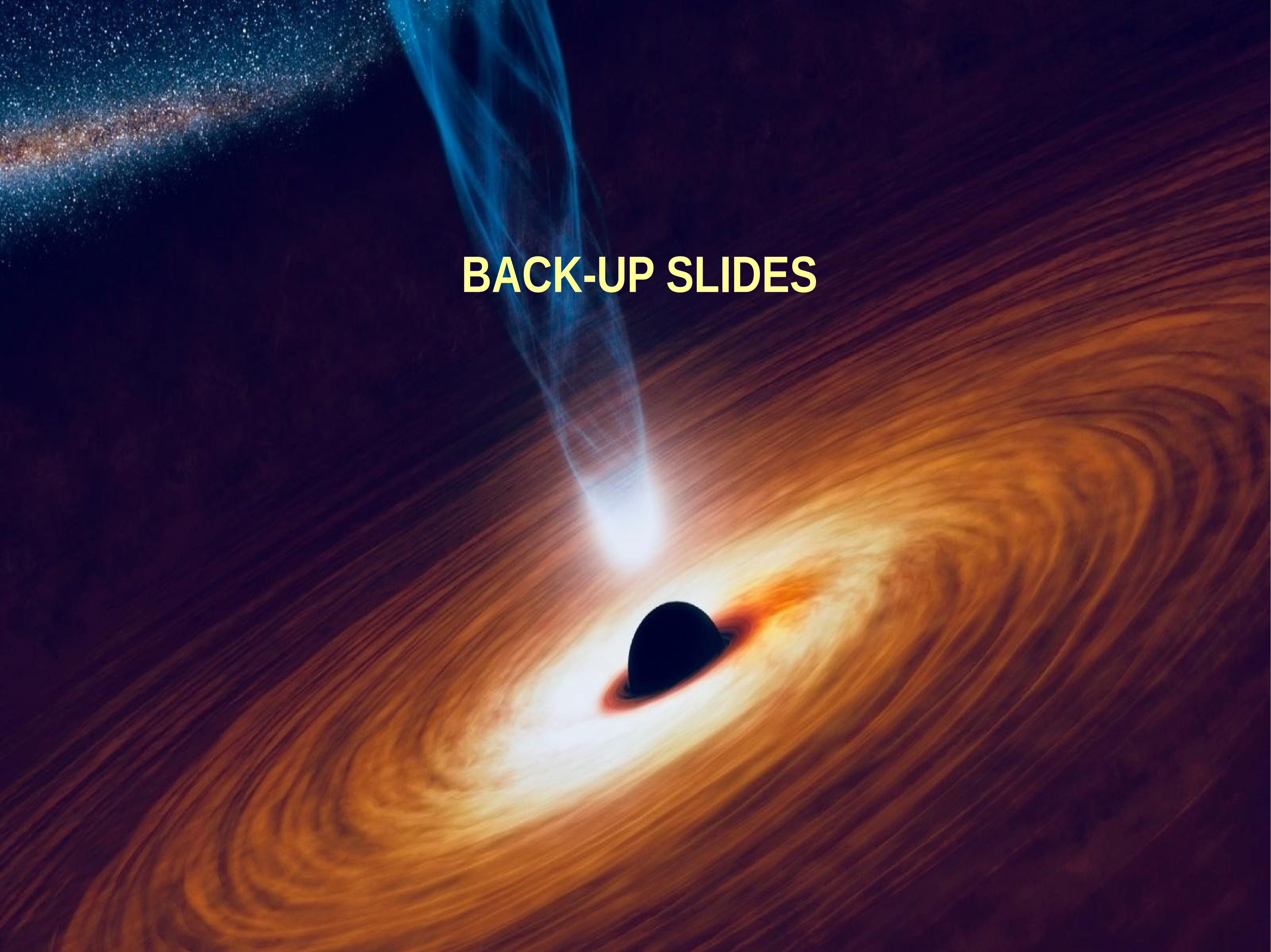


- Light composition of nuclei (proton & He).
- Neutrino flux dominated by the **blob.**
- Stationary **(UV) photon field** with **low energy density** (<1 erg/cm^3) as target for photo-meson/photo-disintegrations.
- **Extended blob** (~10^{17} cm) with weak (<1 G) magnetic fields.
- Attenuation of γ-rays **> 100 GeV** in blob.

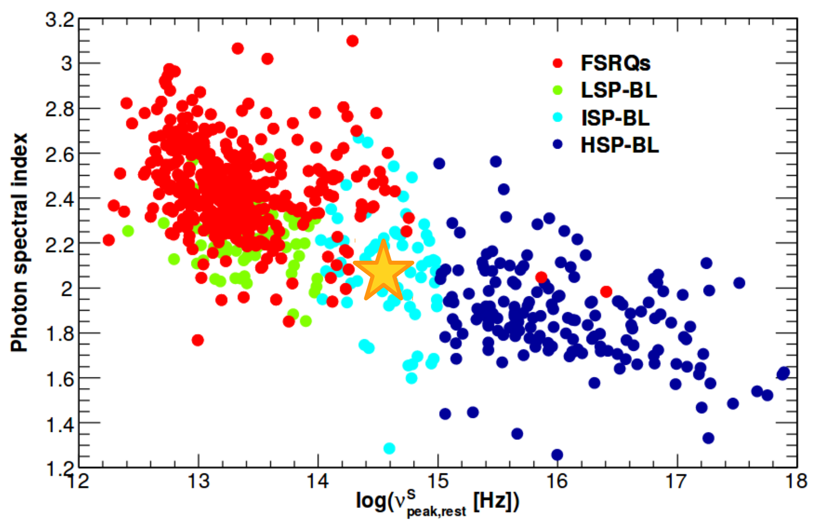
Conclusions

- 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.
- Two-zone models can relax the cascade constraints, leading to higher neutrino luminosities than single zone models (by factor of ~10).
- 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 **neutral beam model** provides a physically plausible scenario for the 2014-15 and 2017 neutrino detections and requires that:
  - the CR composition is light (He:P = 5:1)
  - there is a luminous (~10^{46} erg/s) external photon field, variable on year-long scales.
  - the blob properties vary on year-long scales.

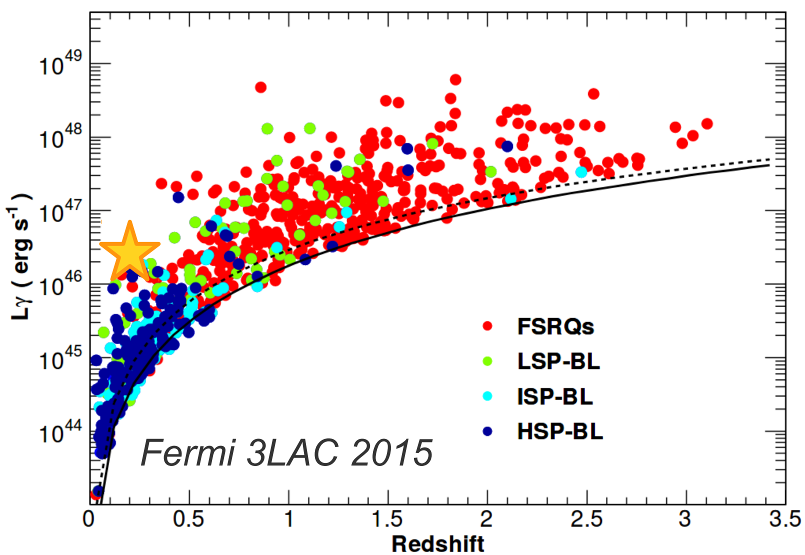
Thank you!

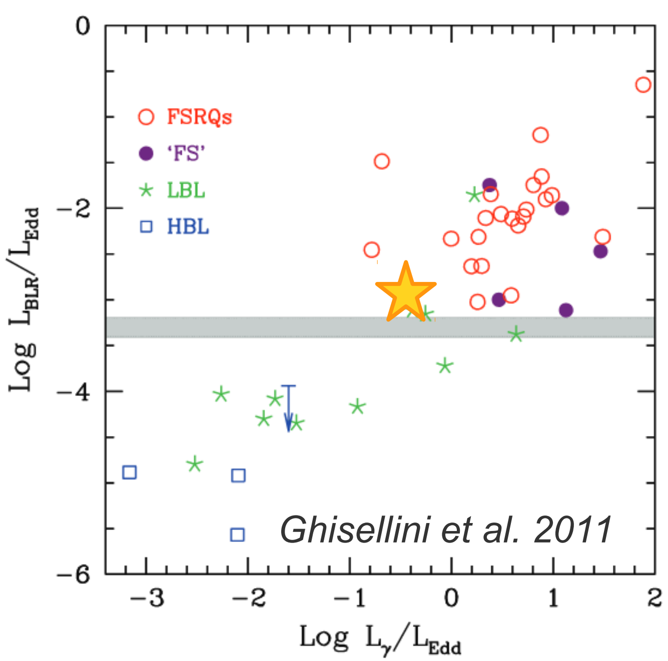

BACK-UP SLIDES

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)*





Status of the field prior to 2017

- Both models describe equally well the photon spectra.

- **Leptonic** models:

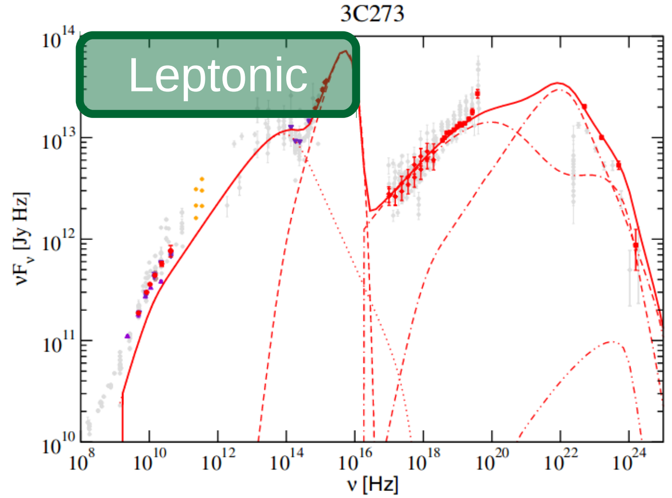
a) Work for both FSRQs and BL Lacs.
b) Jet power **L_j~ 10^{44} – 10^{46} erg/s** for BL Lacs, ~**10^{46} – 10^{48} erg/s** for FSRQs
c) Particle-dominated emitting regions in BL Lacs.
d) No neutrinos.

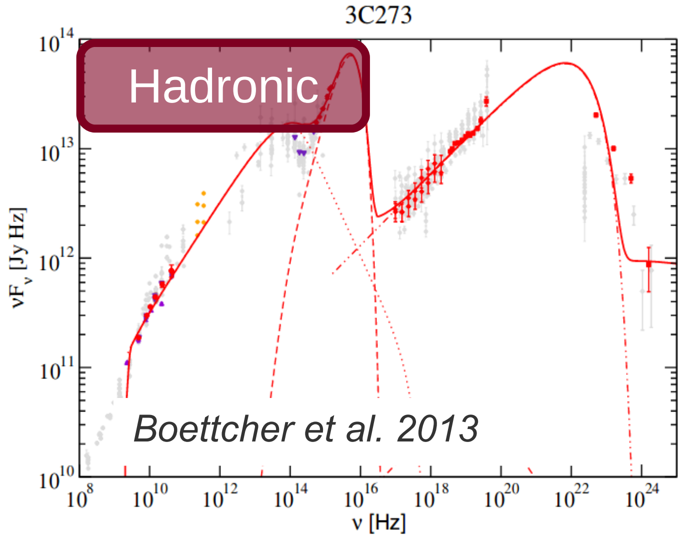
- **Proton-synchrotron hadronic** models:

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:

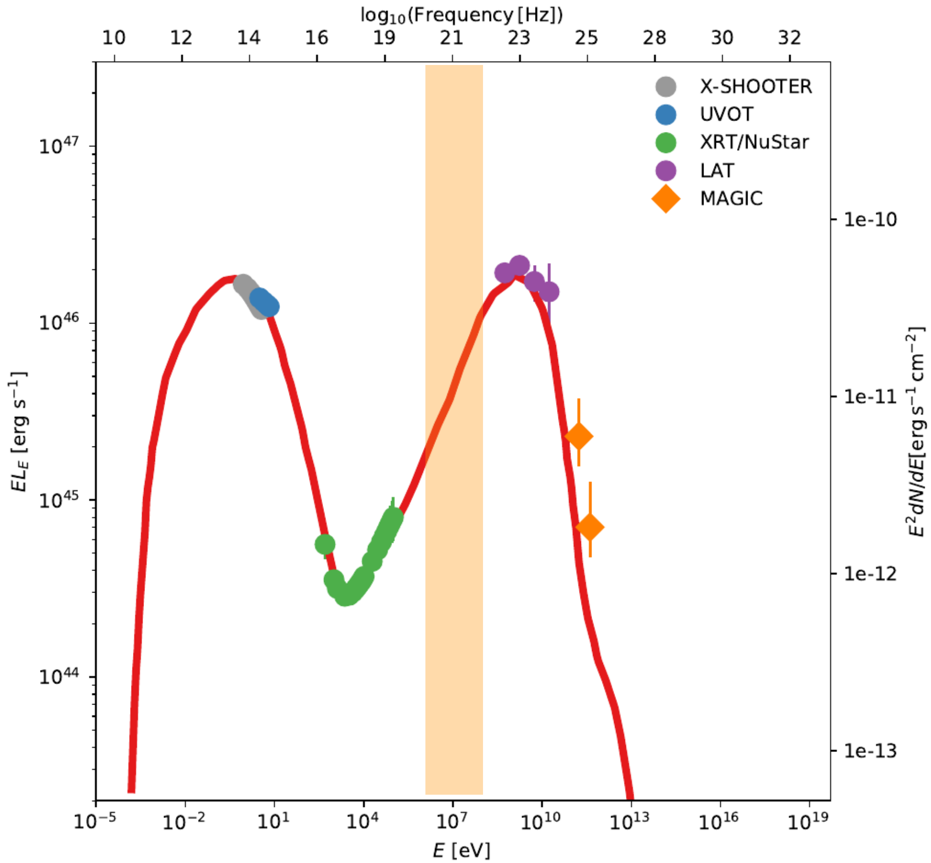
a) Work for BL Lacs, but unlikely for FSRQs
b) High jet power **L_j~ 10^{47} – 10^{48} erg/s**
c) Moderate proton energies e.g. **E_{pmax} ~ 10 PeV**
d) Moderate magnetic fields, e.g. **B ~ 0.1-1 G**
e) **~ PeV** neutrinos

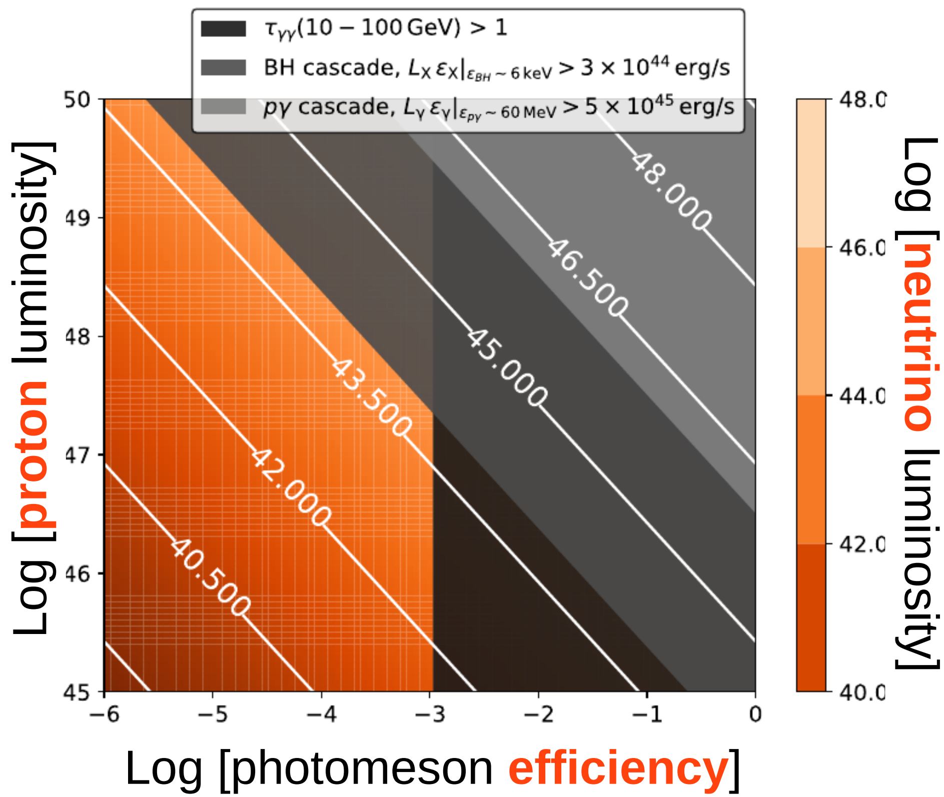




***Modeling studies**: Ghisellini et al. 2010; Boettcher et al. 2013; Dimitrakoudis, MP, Mastichiadis 2014; MP 2014; MP, Dimitrikoudis et al. 2015; Cerruti et al. 2015; Diltz, Boettcher & Fossati 2015; MP & Dermer 2016; Gao, Winter & Pohl 2017; MP, Nalewajko et al. 2017; Cerruti et al. 2017 +++*

What sets the maximum neutrino flux?





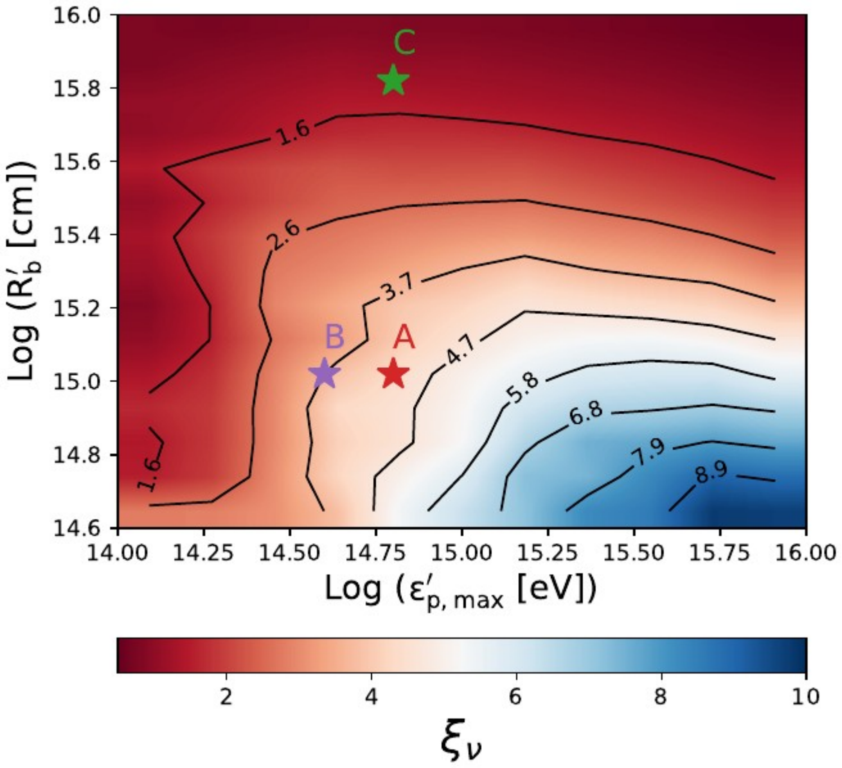
III. Synchrotron emission from photo-meson pairs produces ~MeV emission:

$$\varepsilon_\gamma L_{\varepsilon_\gamma}|_{\varepsilon_{\rm syn}^{\rm p\gamma}} \sim \frac{5}{12}\varepsilon_\nu L_{\varepsilon_\nu} \sim \frac{1}{4}\frac{5}{8} f_{p\gamma}\,\varepsilon_p L_p \le 5\times10^{45}\ \mathrm{erg/s}$$

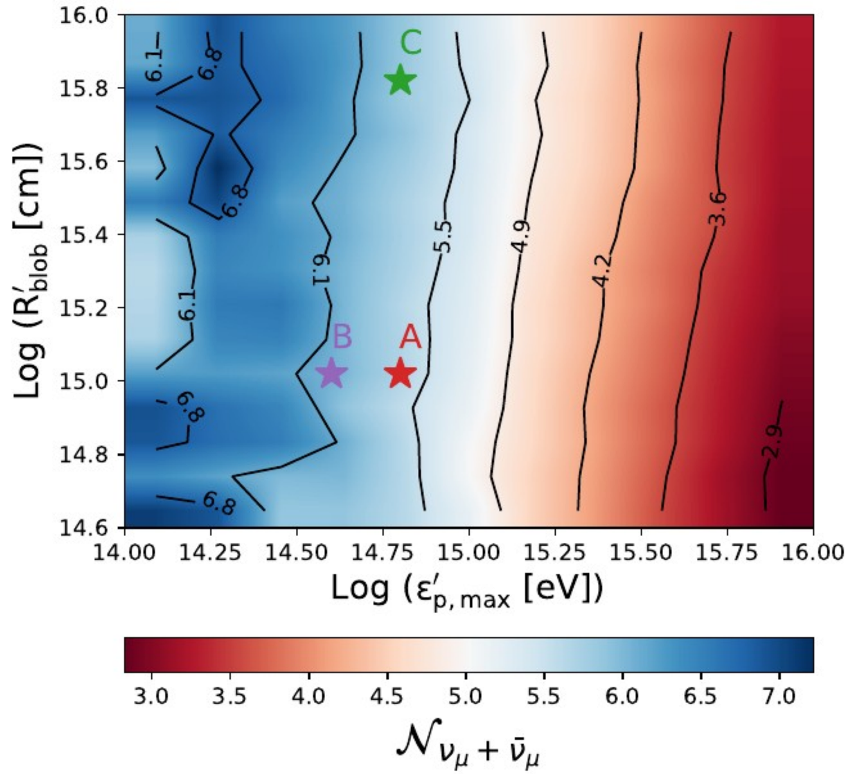
$$\varepsilon_{\rm syn}^{\rm p\gamma} \approx 60\ \mathrm{MeV} B_{0.5\ \mathrm{G}}(\varepsilon_p/6\ \mathrm{PeV})^2(20/\delta)$$

Neutral beam model: parameter scan - 1

Ratio of beam-to-blob neutrino flux

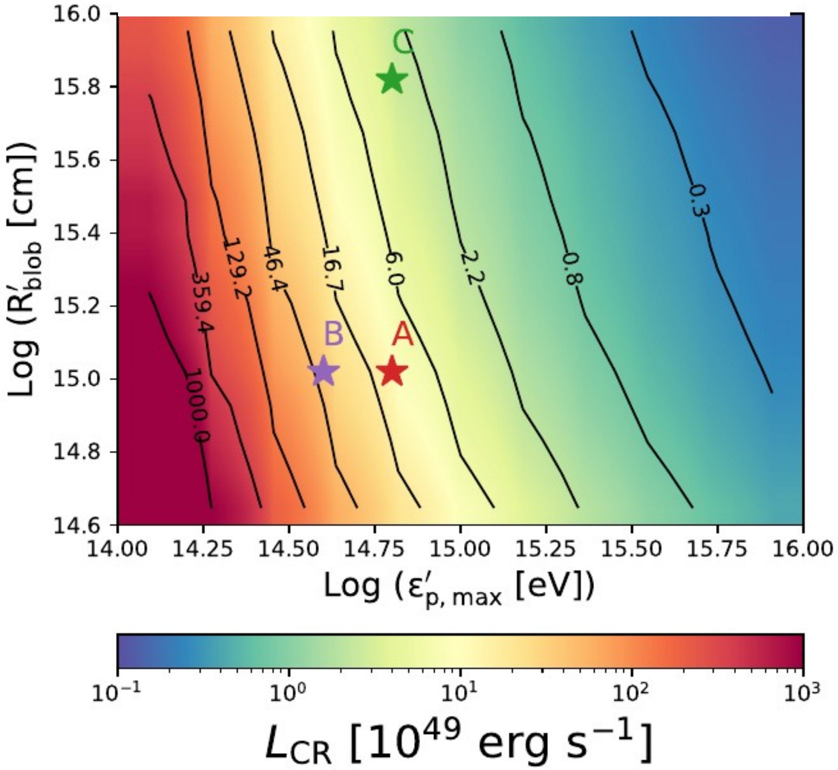


Number of muon neutrinos in 0.5 yr

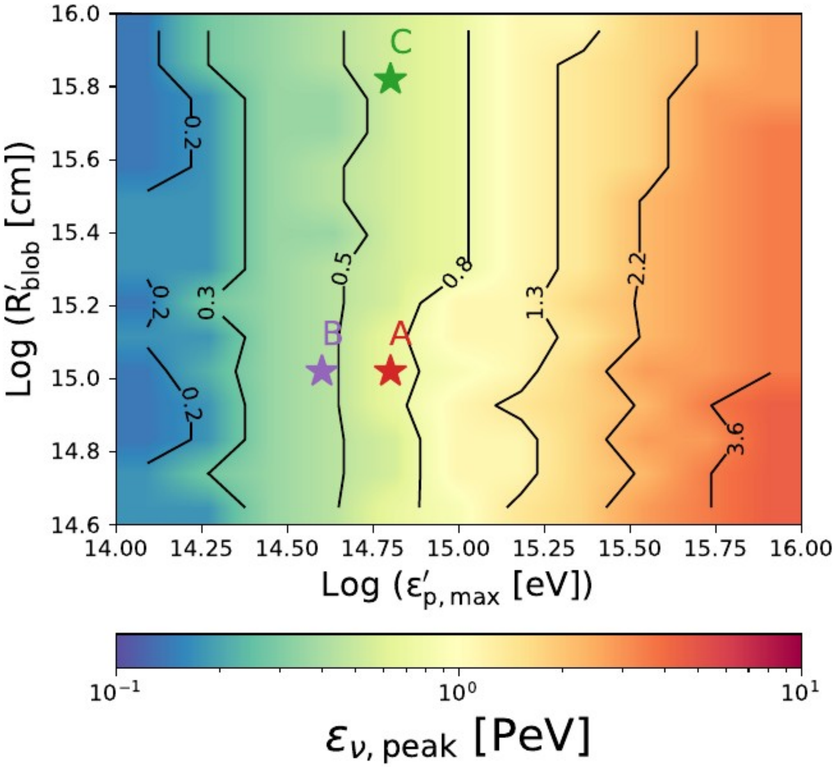


Neutral beam model: parameter scan - 2

Observed isotropic-equivalent CR luminosity

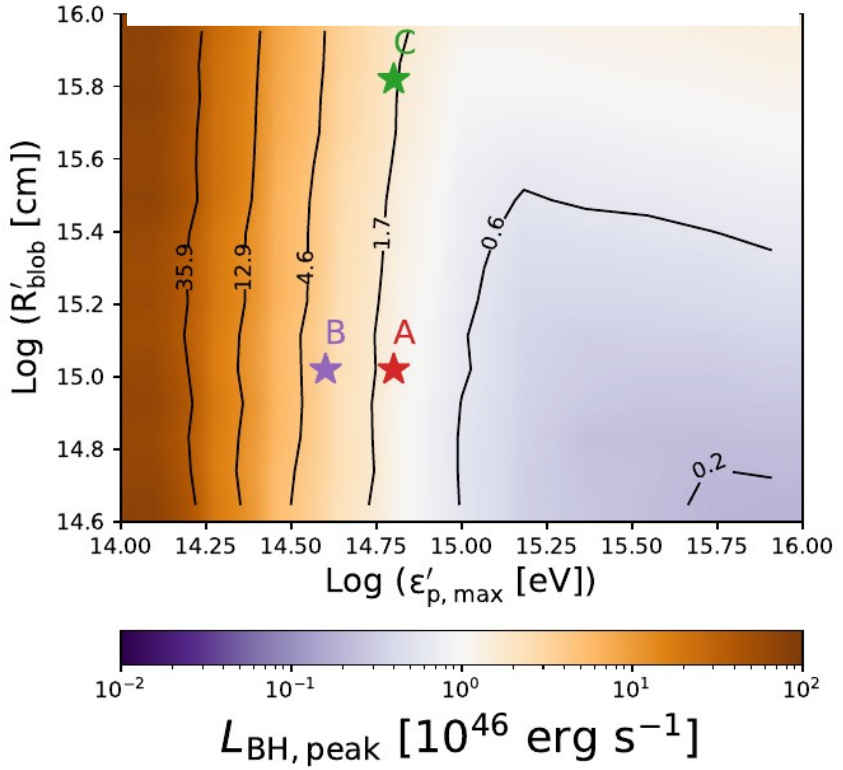


Observed peak neutrino energy

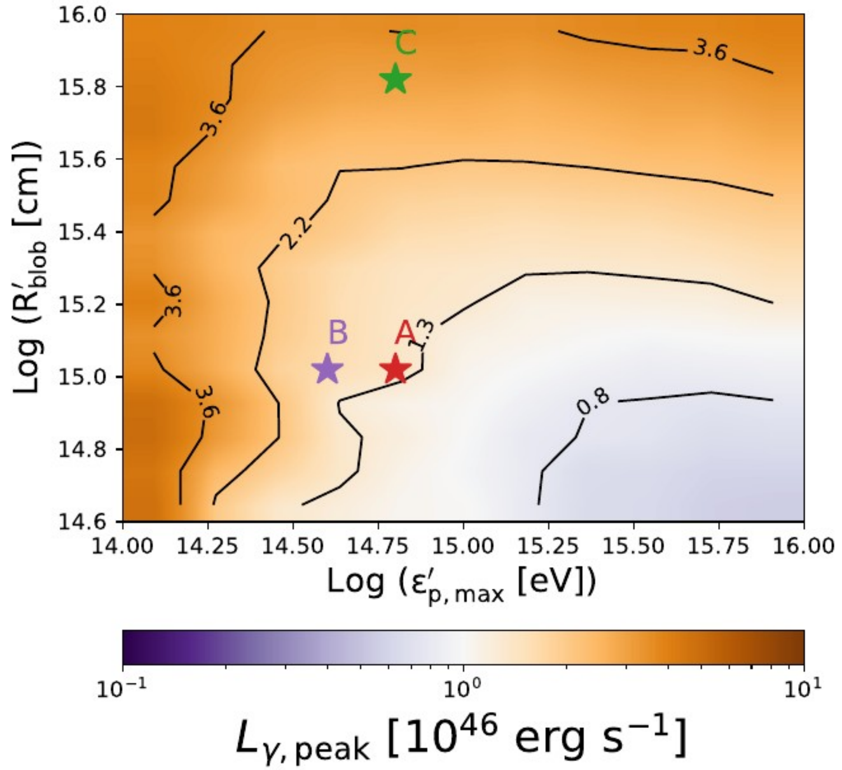


Neutral beam model: parameter scan - 3

Observed isotropic-equivalent
BH pair injection luminosity

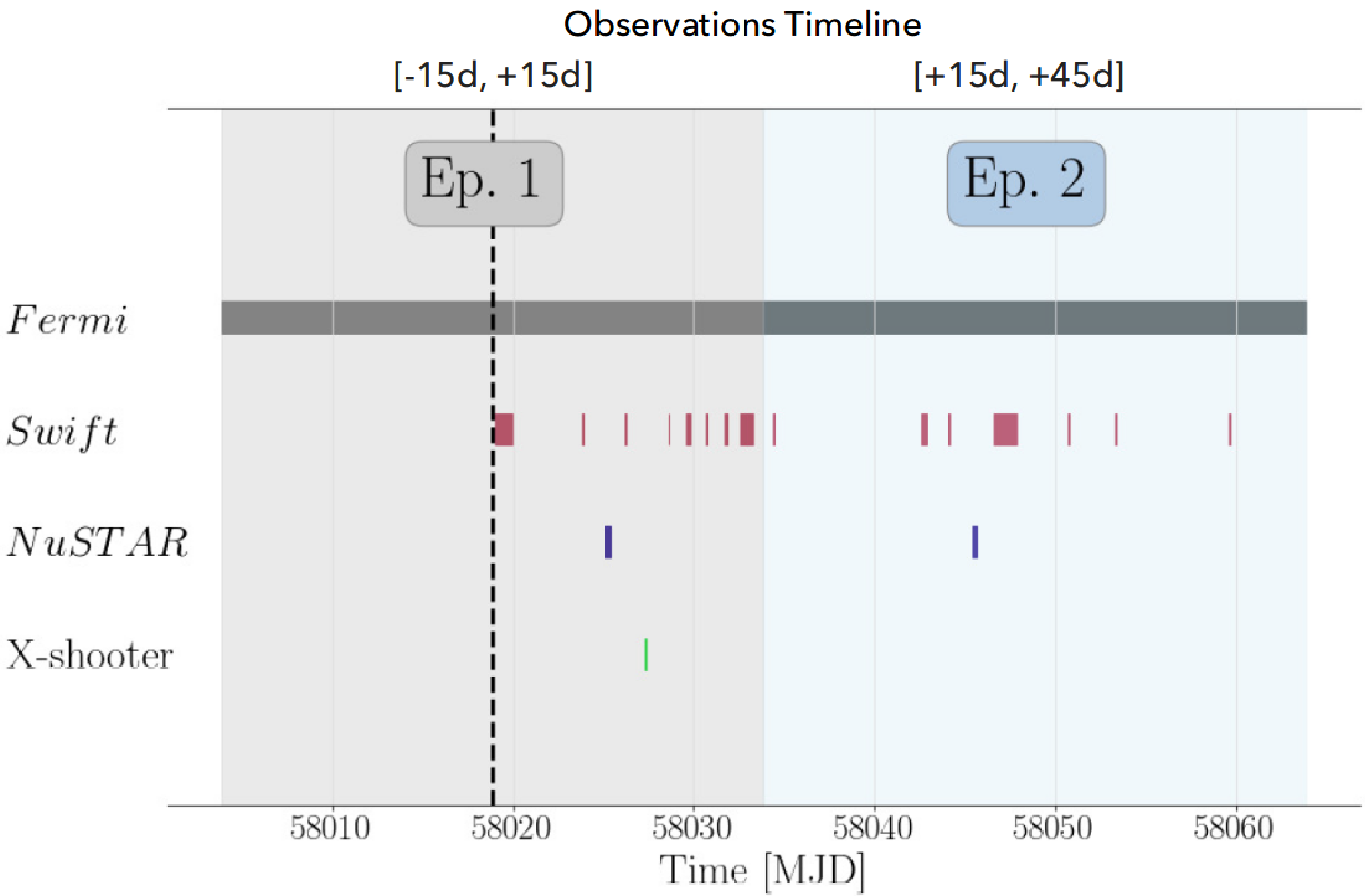


Observed isotropic-equivalent
γ-ray injection luminosity



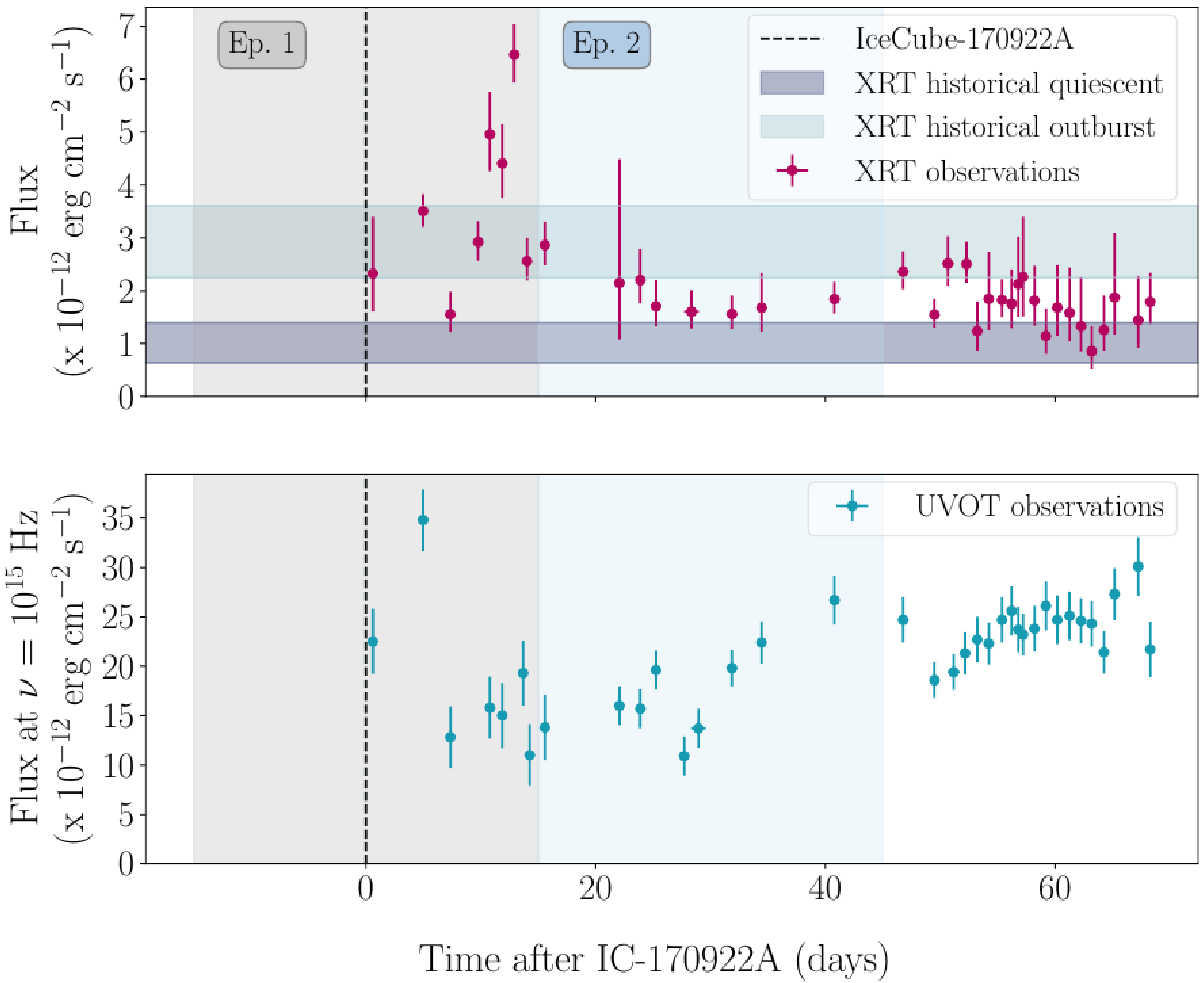
Multi-wavelength observations

Keivani,Murase, MP, Fox et al. 2018



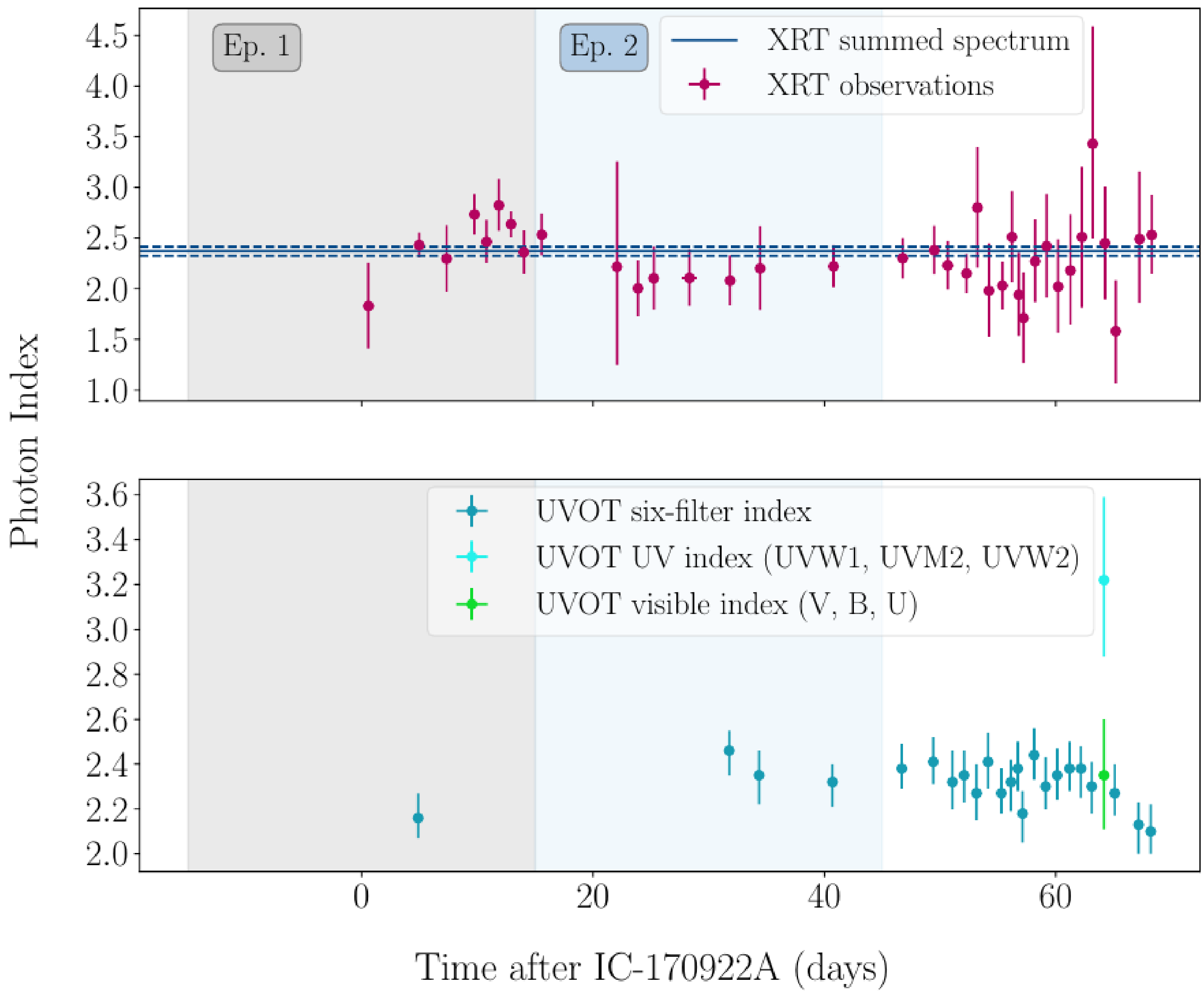
Swift flux variability

Keivani,Murase, MP, Fox et al. 2018

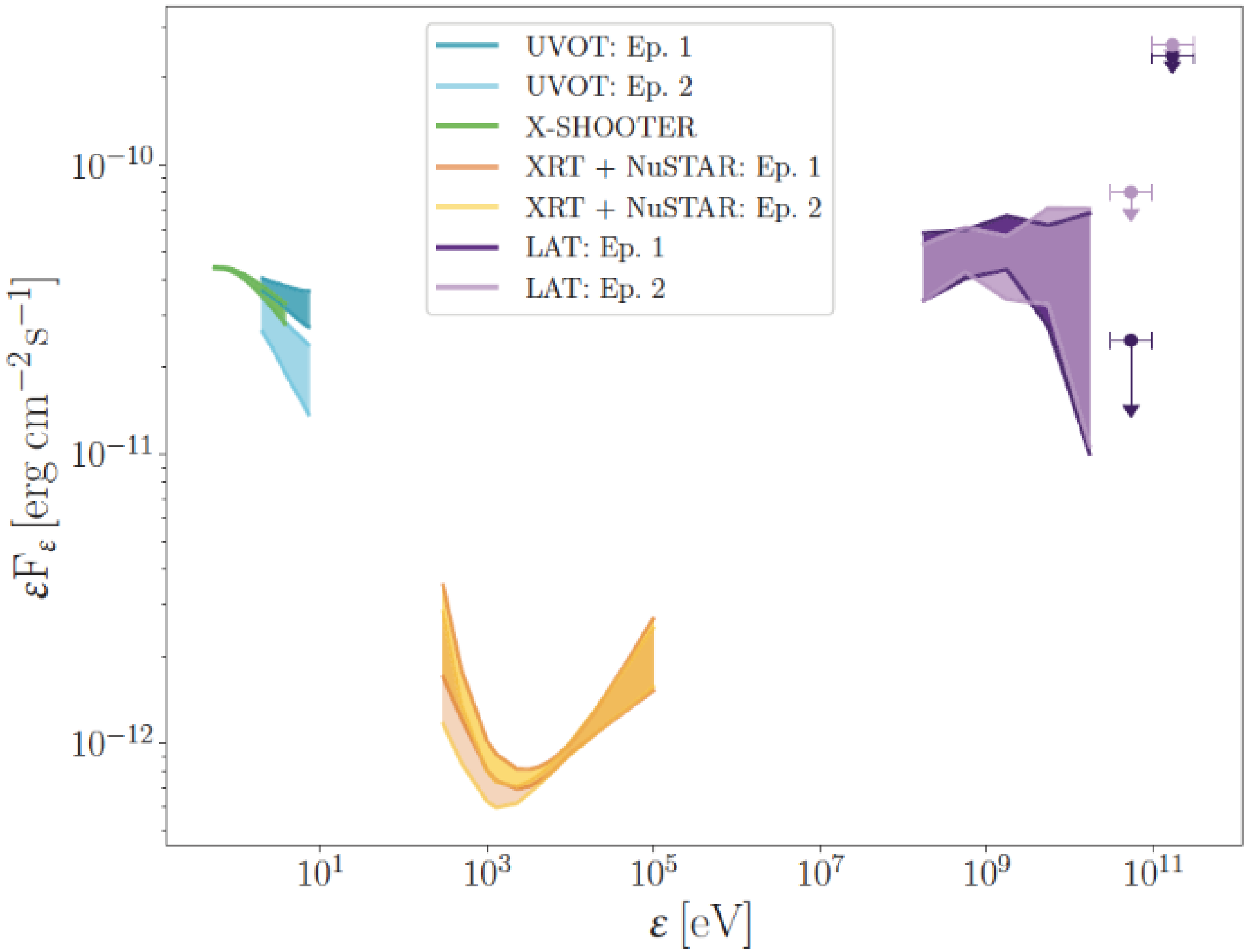


Swift spectral variability

Keivani,Murase, MP, Fox et al. 2018

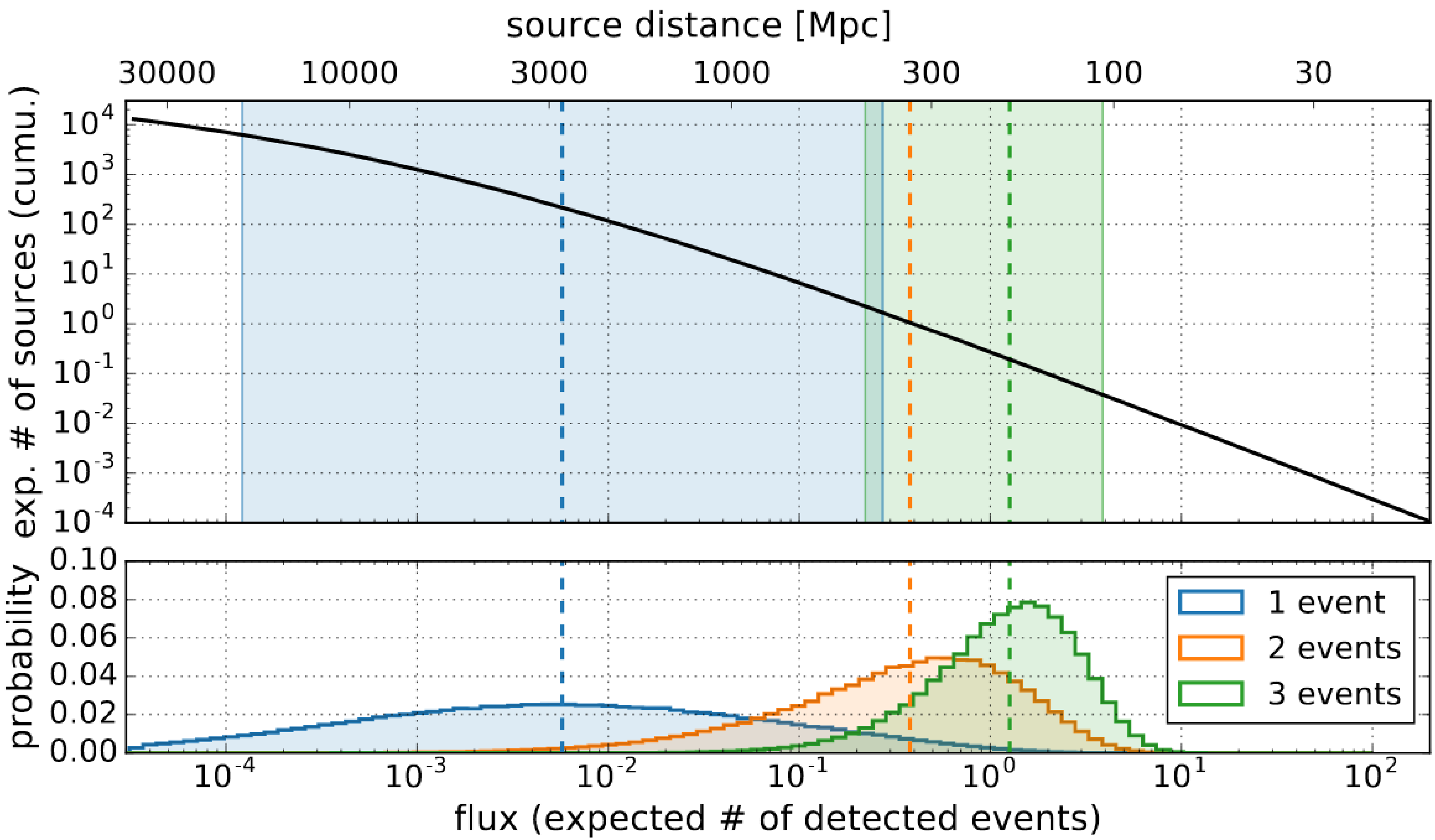


Multi-wavelength spectrum



Eddington bias for neutrino sources

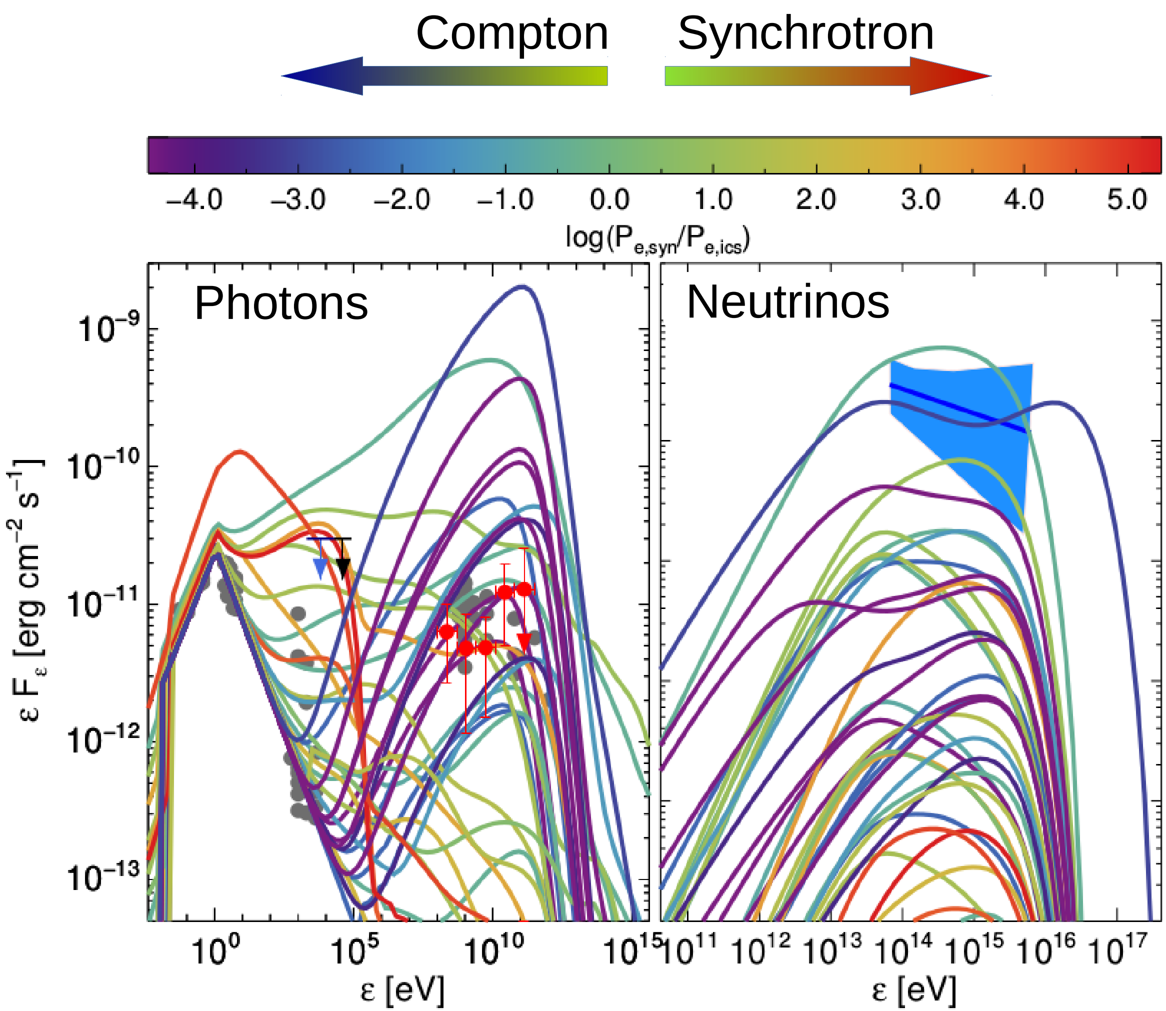
Strotjohann et al. 2019

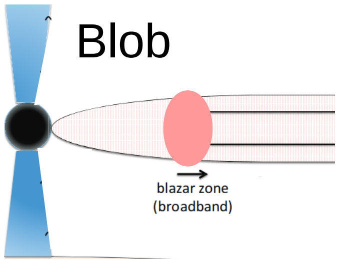


- More likely to detect 1 neutrino from sources with median flux << 1
- Bright rare sources are more likely to be detected with >1 events
- The size of bias depends on: source evolution & luminosity function

A challenge for one - zone models

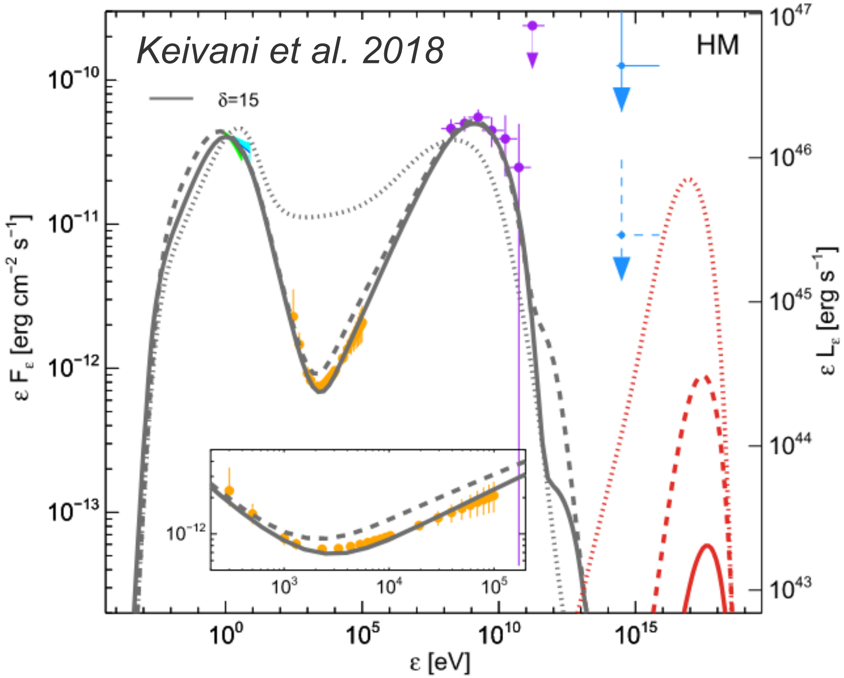
MP, Murase et al., in prep.

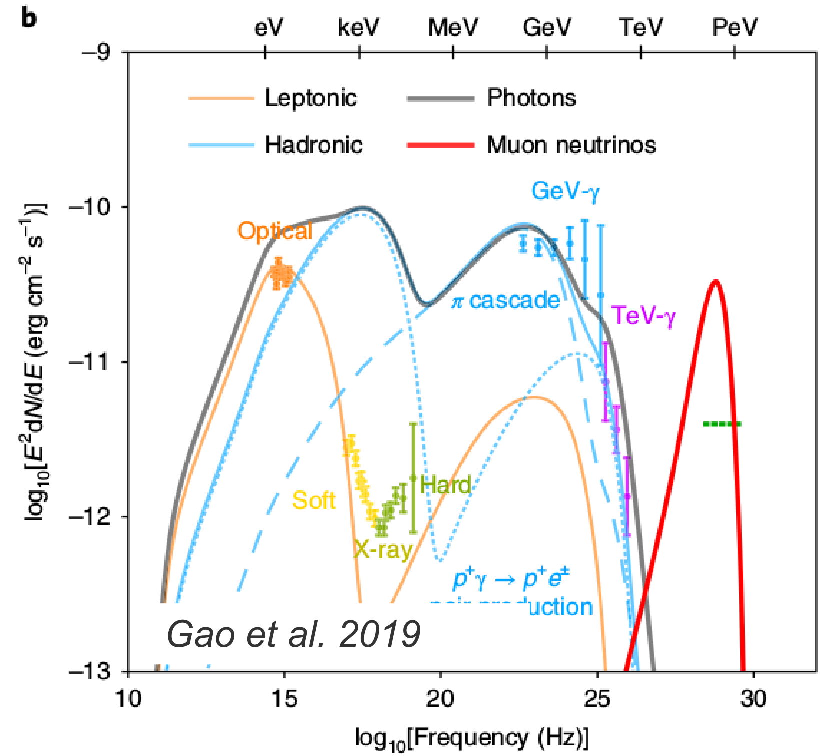


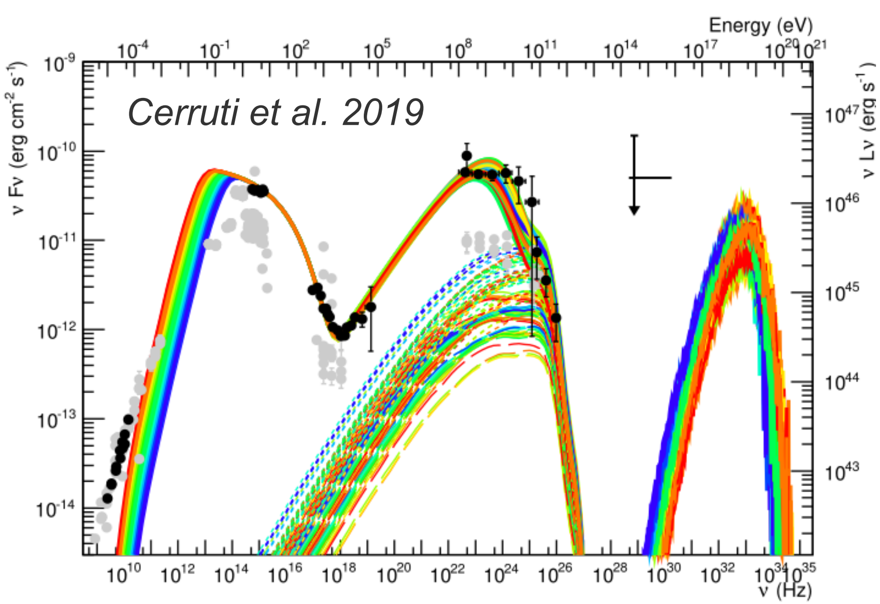


- Wide parameter search
- Linear & non-linear cascades
- Synchrotron & Compton supported cascades
- **No model consistent** with $L_\nu > L_\gamma$ and EM data.

Lepto-hadronic models for the 2017 flare



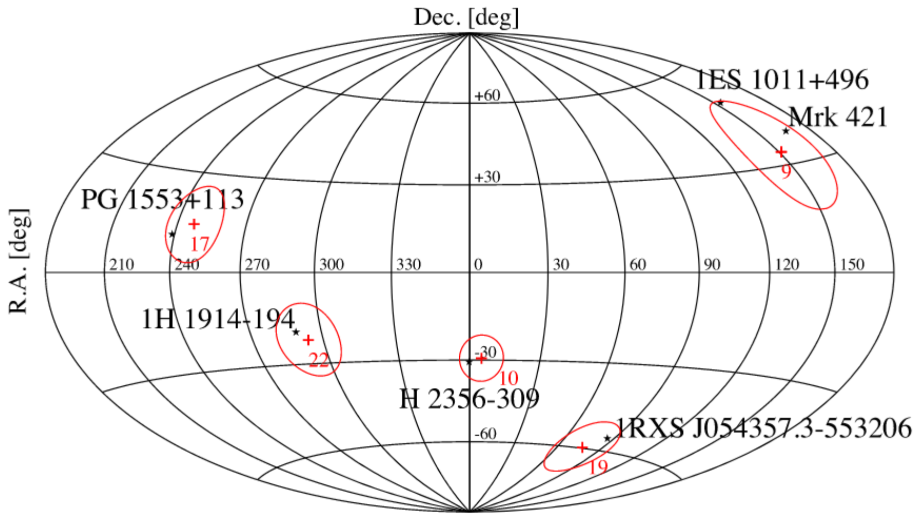




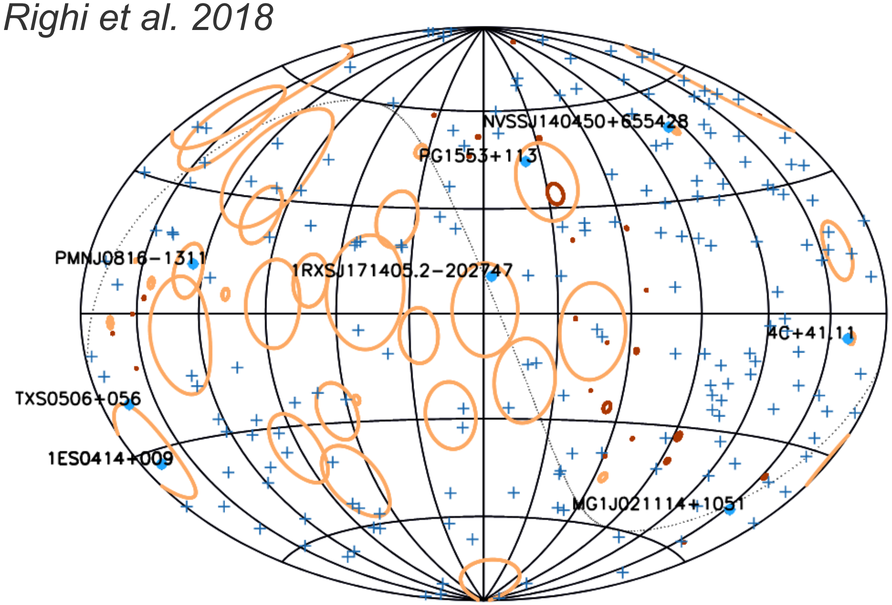
- Lepto-hadronic SED models for TXS 0506+056/IC-170922A are excluded.
- EeV neutrinos are predicted.
- Low neutrino flux, unless cascade emission overshoots X-rays.

Status of the field prior to 2017 - neutrinos

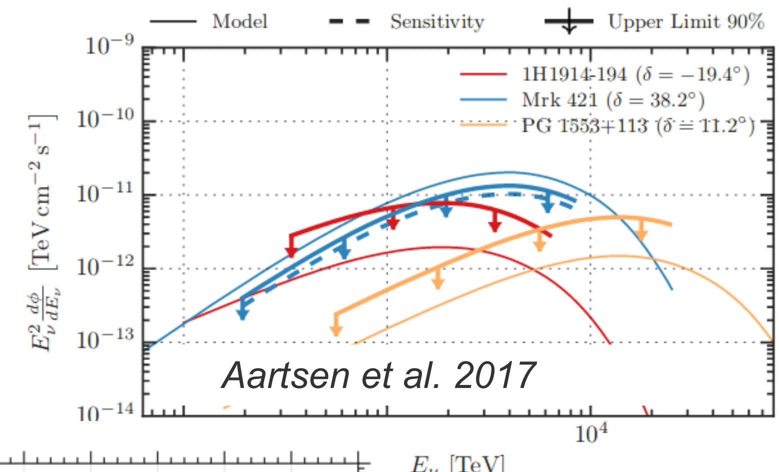
Padovani & Resconi 2014; MP et al. 2015

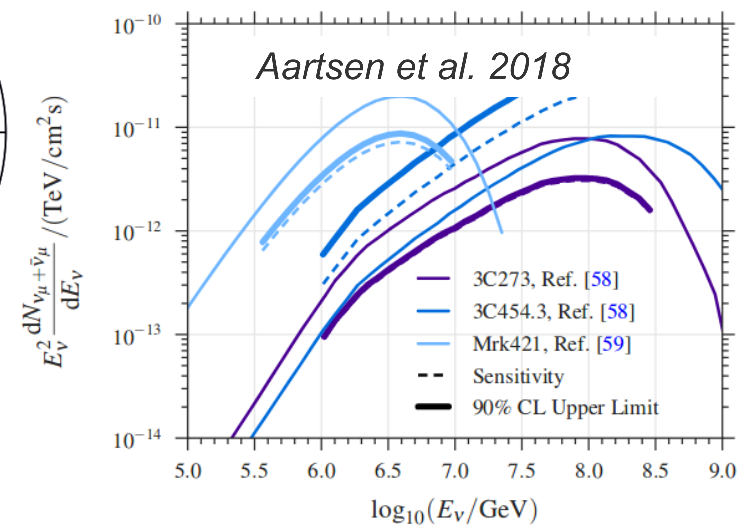


Righi et al. 2018



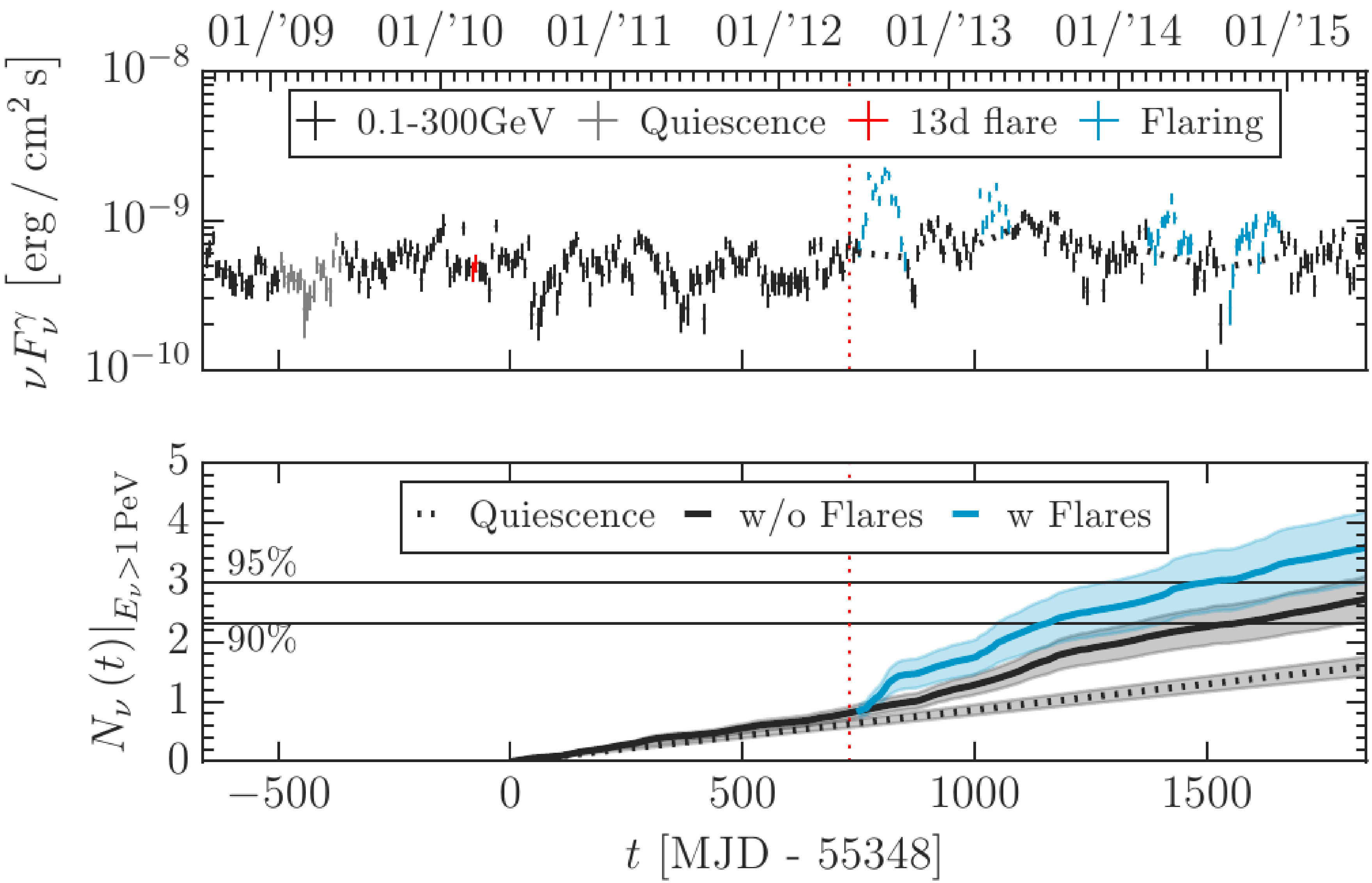
- BL Lacs as probable counterparts of high-energy neutrinos *(Padovani & Resconi 2014, 2016; Righi et al. 2017; 2018)*
- IceCube constrains most optimistic models of constant neutrino emission *(e.g. Aartsen et al. 2017; 2018)*





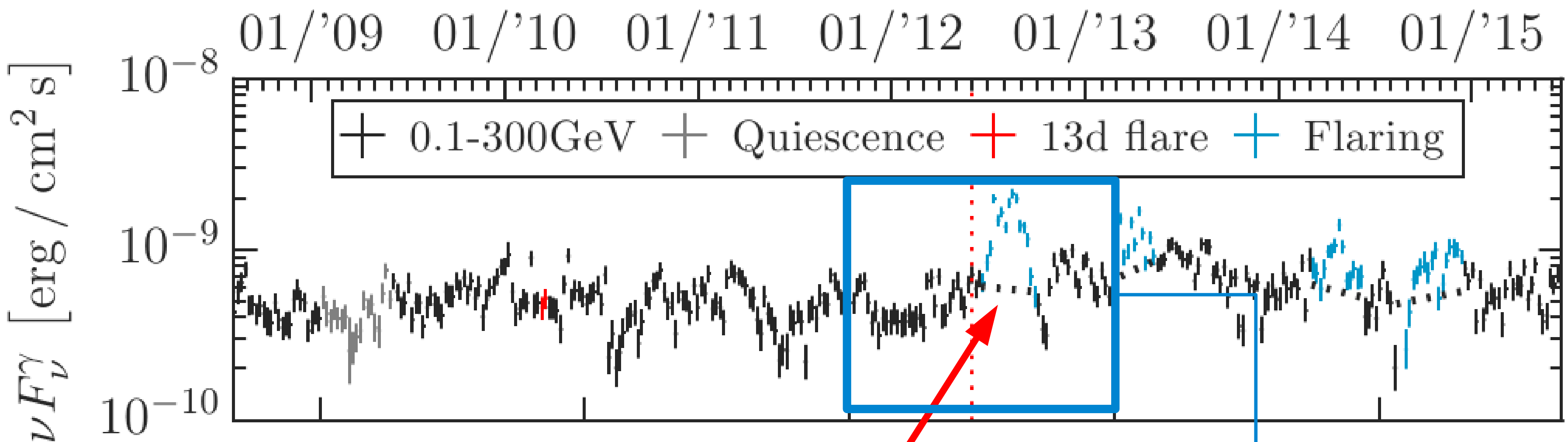
Blazar flares & neutrino prediction for Mkr 421

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)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}(\%)^\dagger$
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

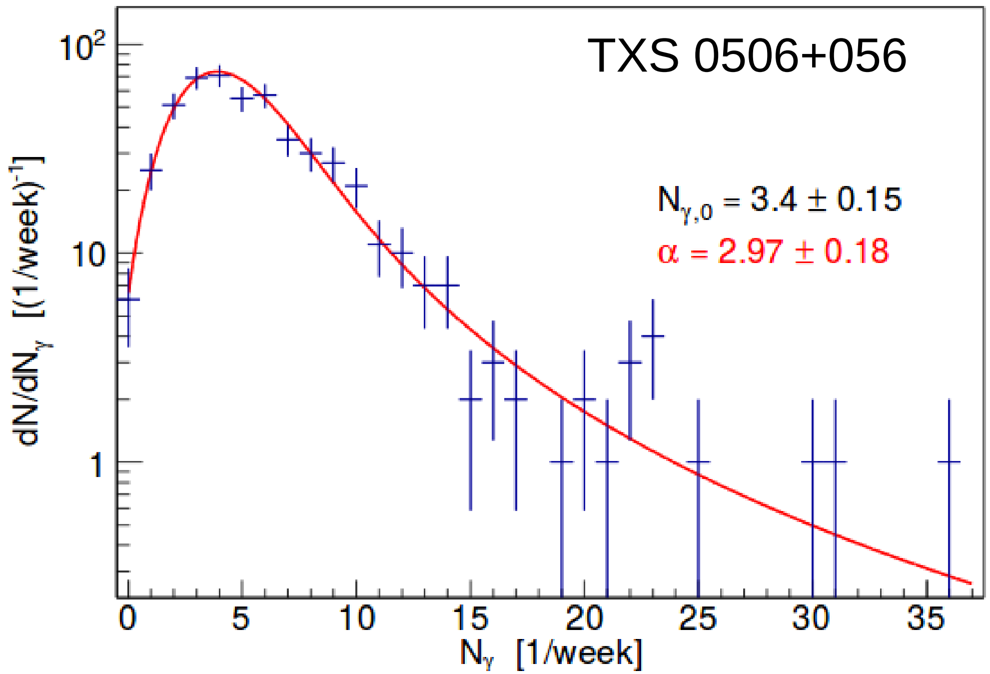
- Model-predicted scaling *(e.g., Murase et al. 2015, Tavecchio et al. 2015, MP et al. 2016):*

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

- Neutrino luminosity distribution:

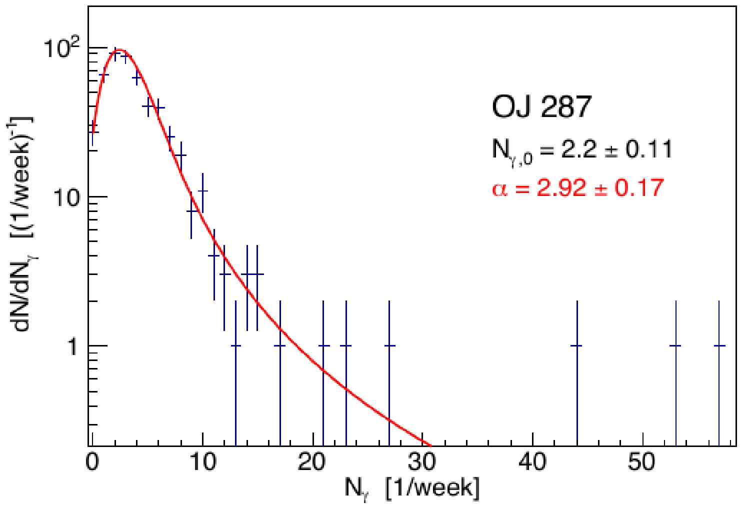
$$L_\nu^2 \frac{dN}{dL_\nu} \propto L_\nu^{1-\frac{\alpha-1}{\gamma}}$$

- Flares dominate neutrino output, if α < 3



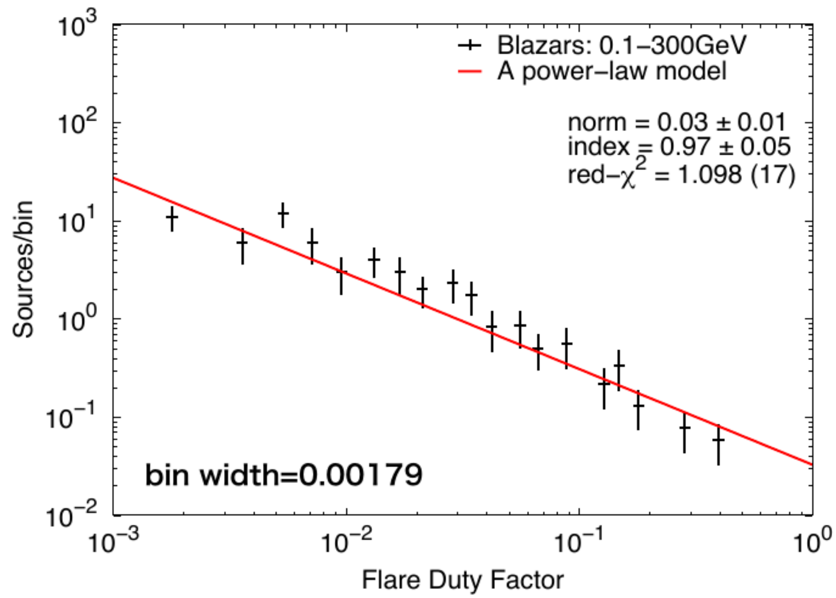
FAVA sample of 6 blazars

- 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 %)