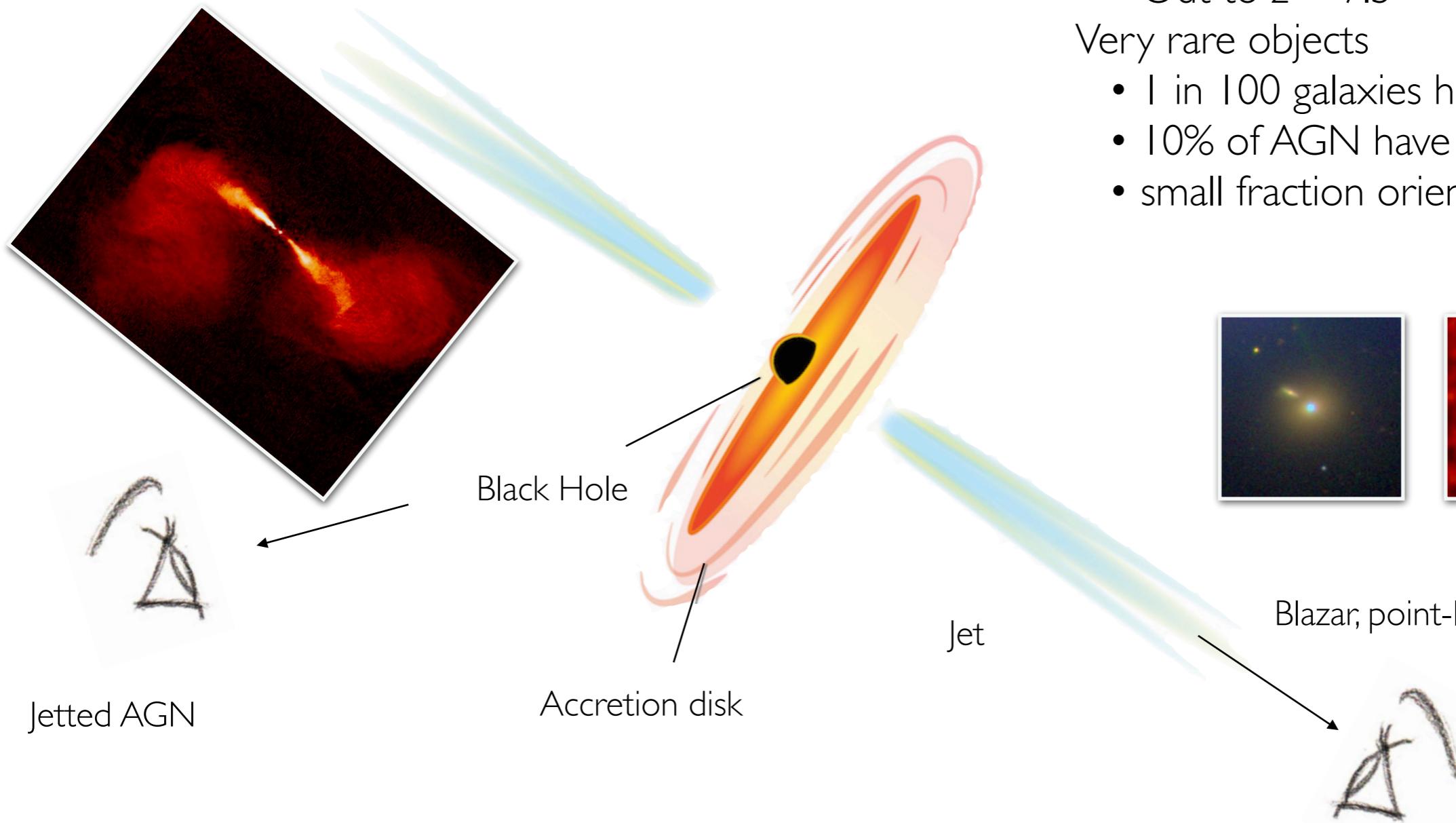




High energy neutrino emission from blazars

Blazars: Extreme and rare sources

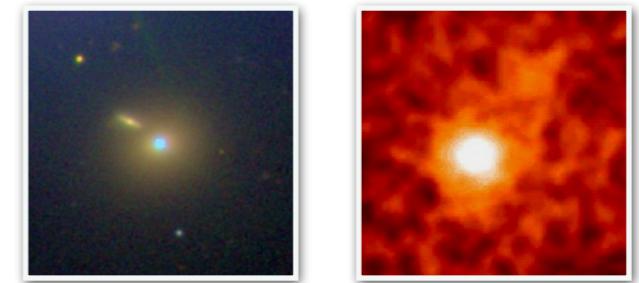


Brightest persistent sources in the sky

- Up to 10^{48} erg/s
- Out to $z \sim 7.5$

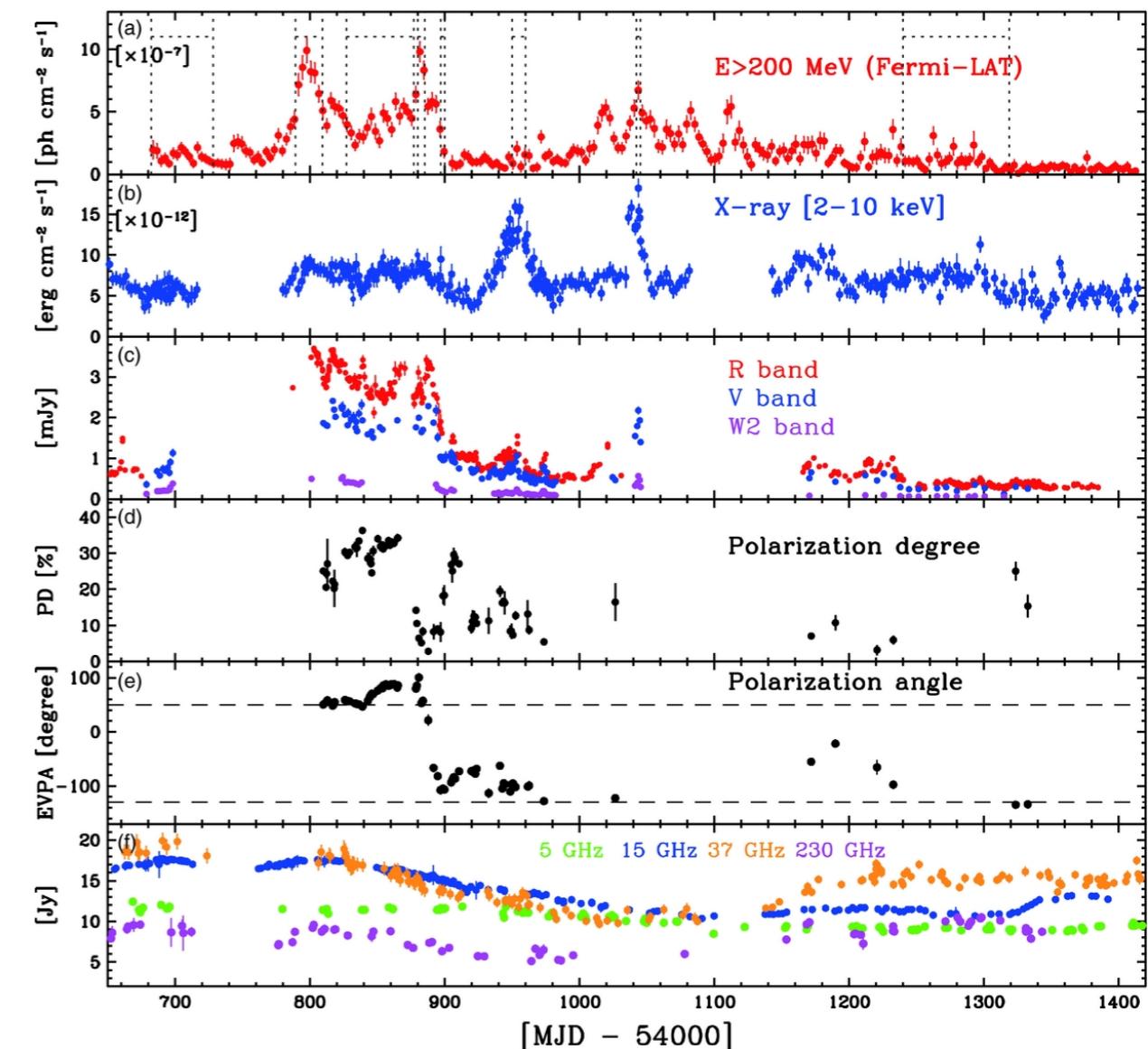
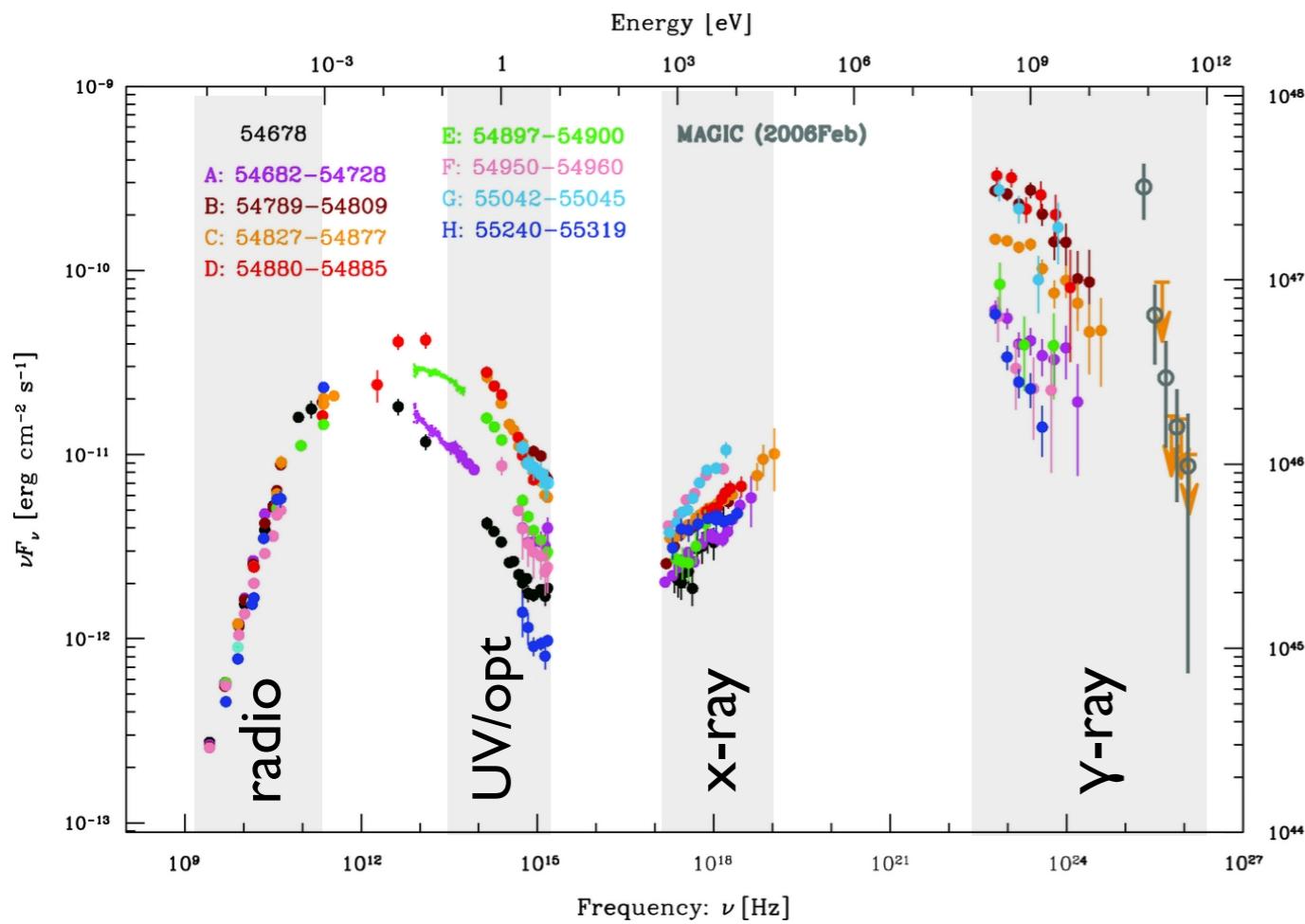
Very rare objects

- 1 in 100 galaxies hosts an AGN
- 10% of AGN have a jet
- small fraction oriented towards us



Likely high energy accelerators

3C 279, Hayashida et al 2012

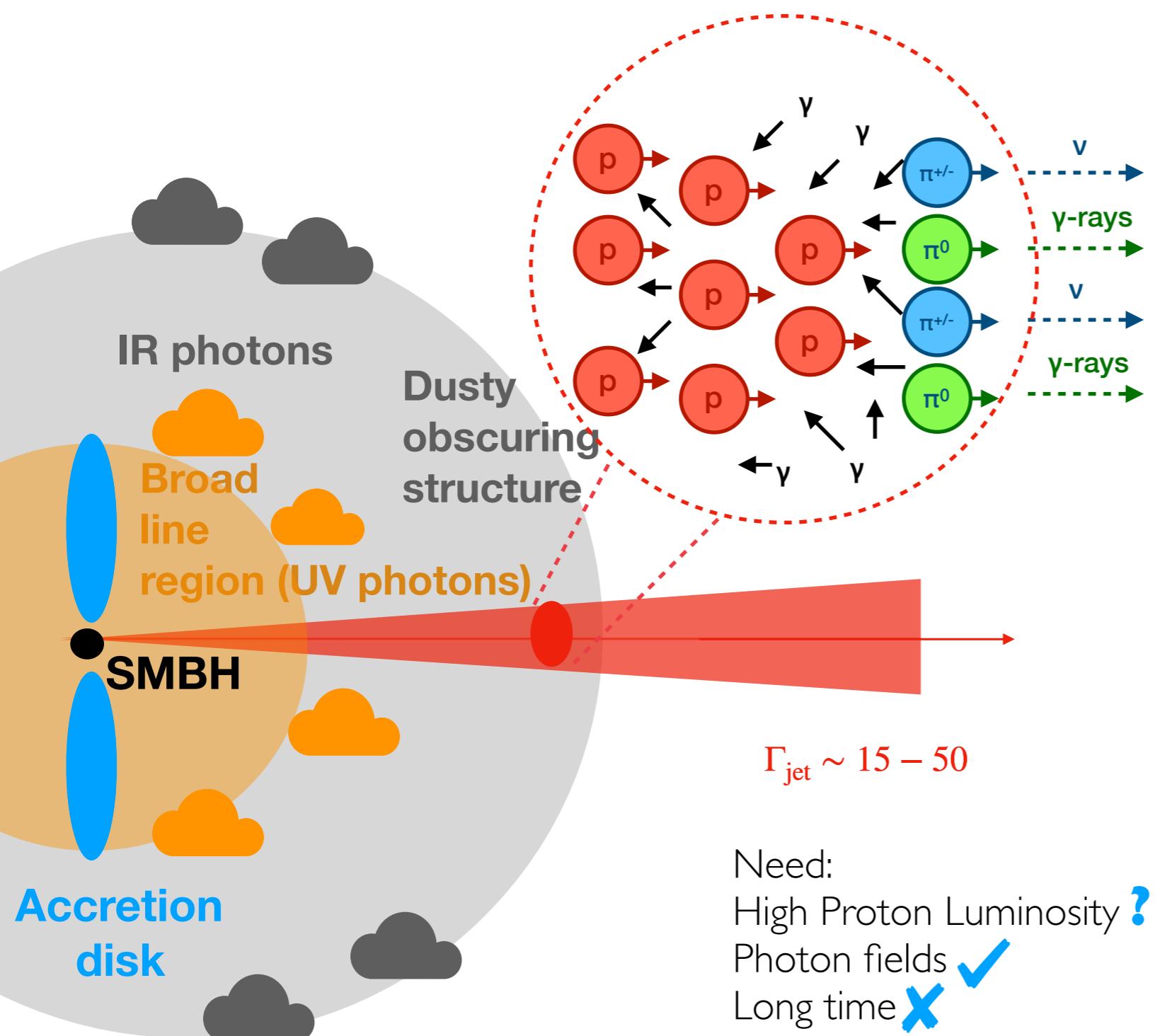


For characteristic values of B , R , and δ :

$$E_{\text{CR,max}} \sim \left(\frac{Z}{1}\right) \left(\frac{\eta}{1}\right) \left(\frac{B}{0.35 \text{ G}}\right) \left(\frac{R'}{10^{16} \text{ cm}}\right) \left(\frac{\Gamma}{25}\right) \sim Z \cdot 5 \times 10^{19} \text{ eV}$$

Neutrino production in blazars

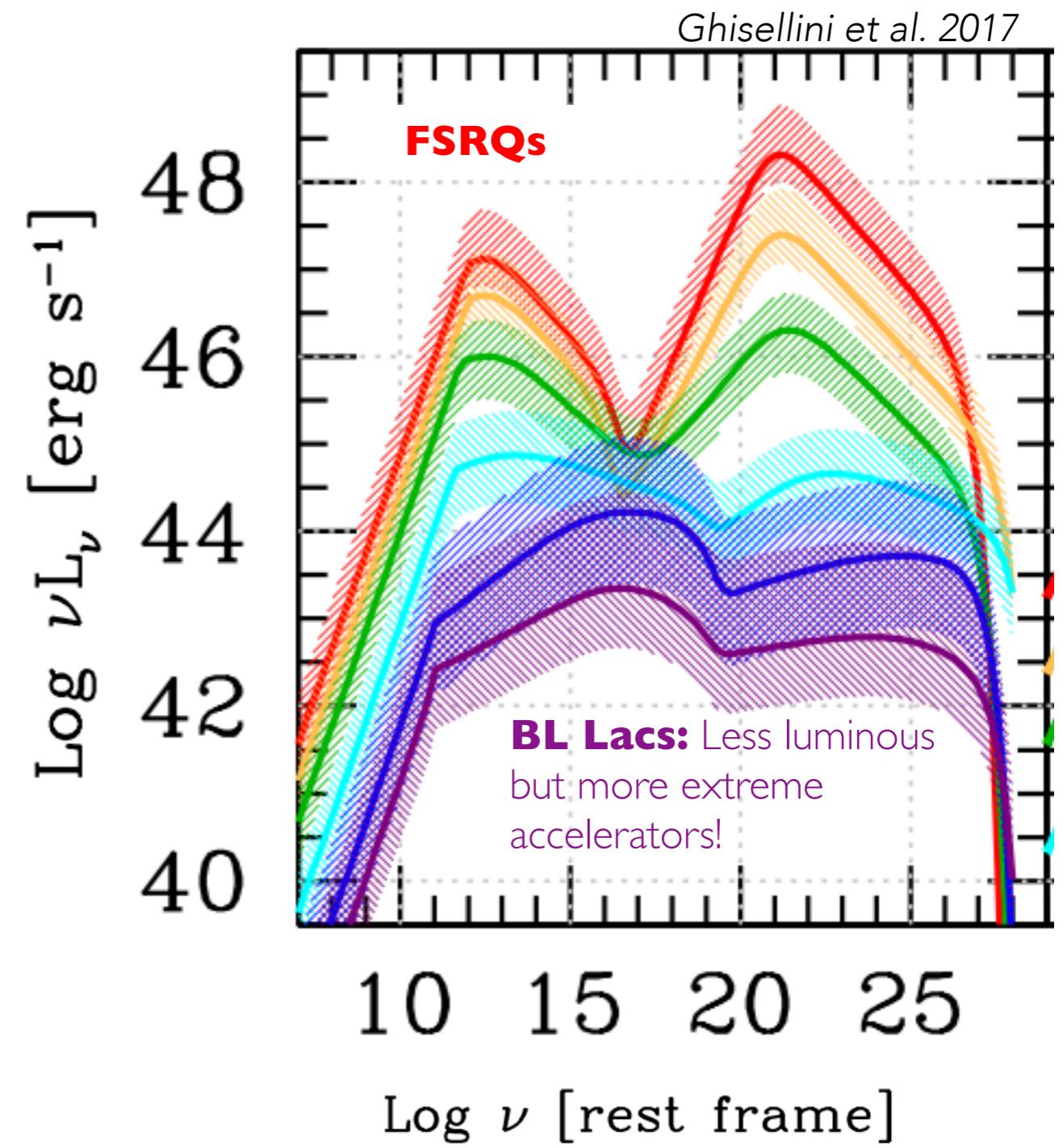
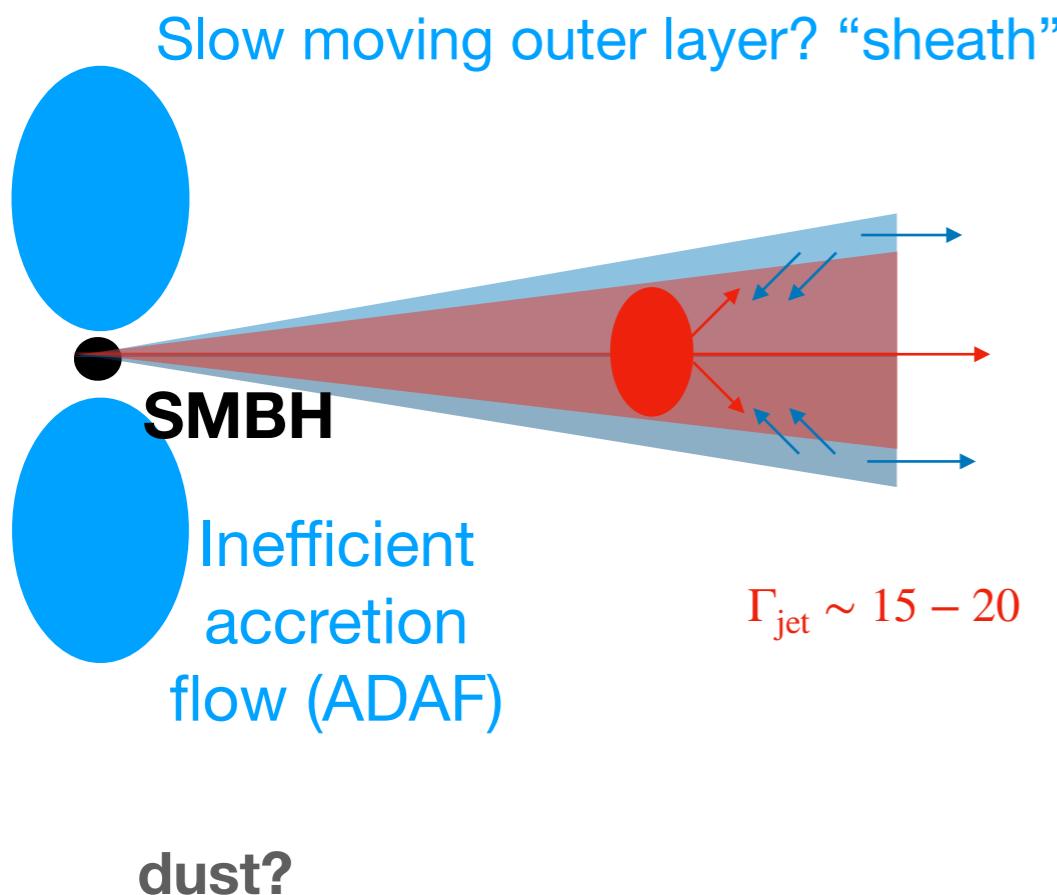
e.g. Mannheim 1991, 1993, Mücke 2001, 2003, Atoyan, Dermer 2001, Neronov, Semikoz 2002, Dermer et al 2006, Kachelriess et al 2009, Neronov et al 2009, Böttcher 2013, Dermer; Cerruti 2013, Cerruti et al 2013, Tchernin et al 2013, Murase et al. 2012, 2014, Dermer et al 2014, Tavecchio et al 2014, 2015, Petropoulou et al 2014, 2015a,b, 2016, Gao et al 2017, Rodrigues et al 2017, 2020 Palladino et al. 2019, Righi et al 2020....



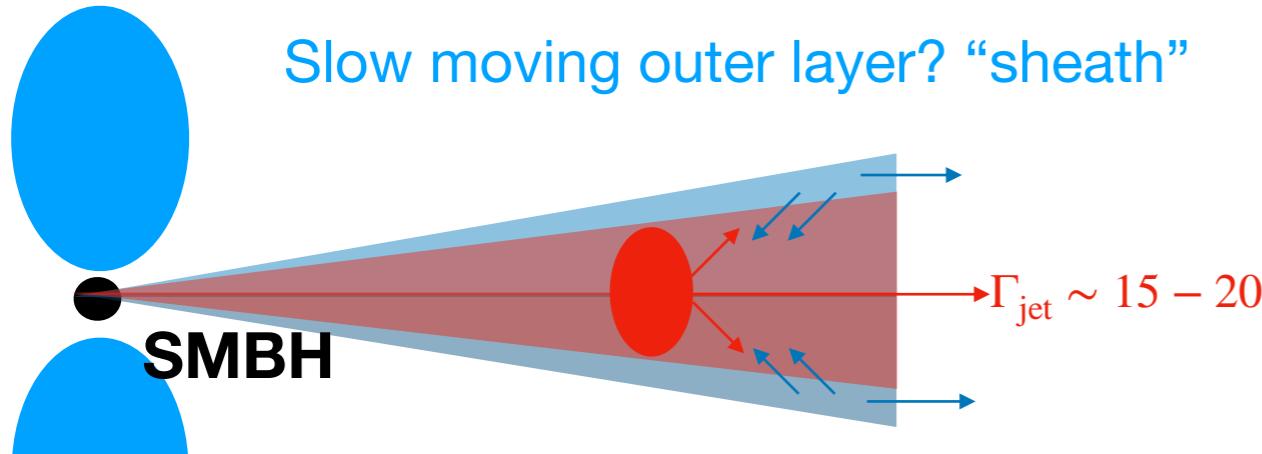
Need:
High Proton Luminosity ?
Photon fields ✓
Long time ✗

In BL Lacs: Internal radiation, sheath or ADAF

BL Lac objects



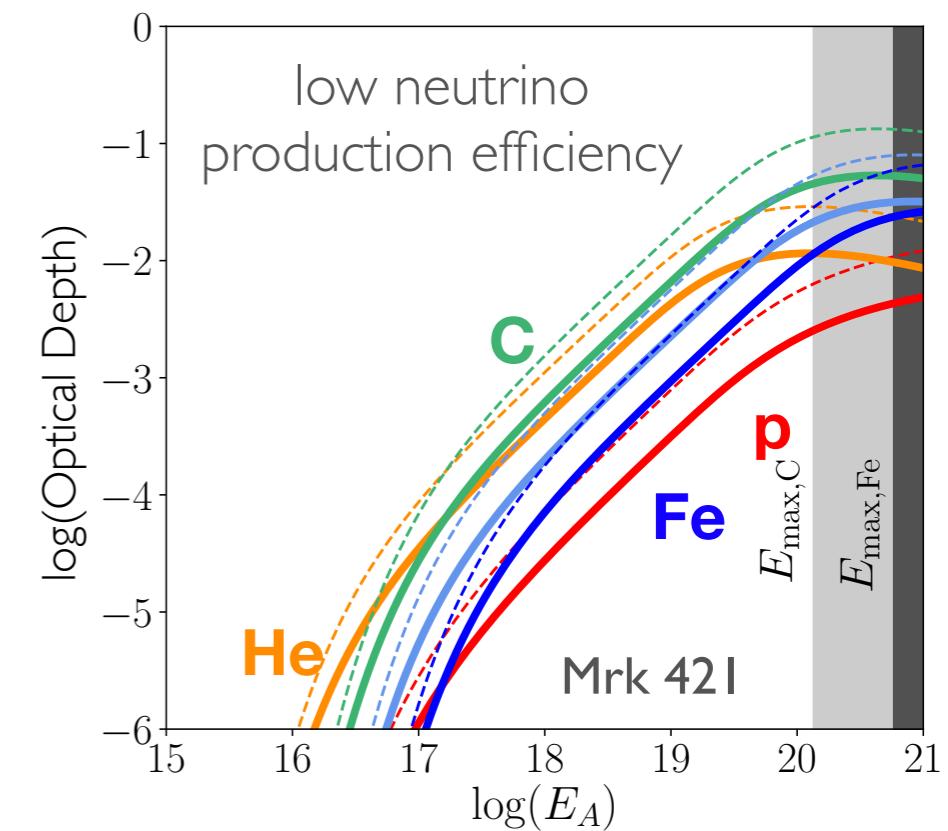
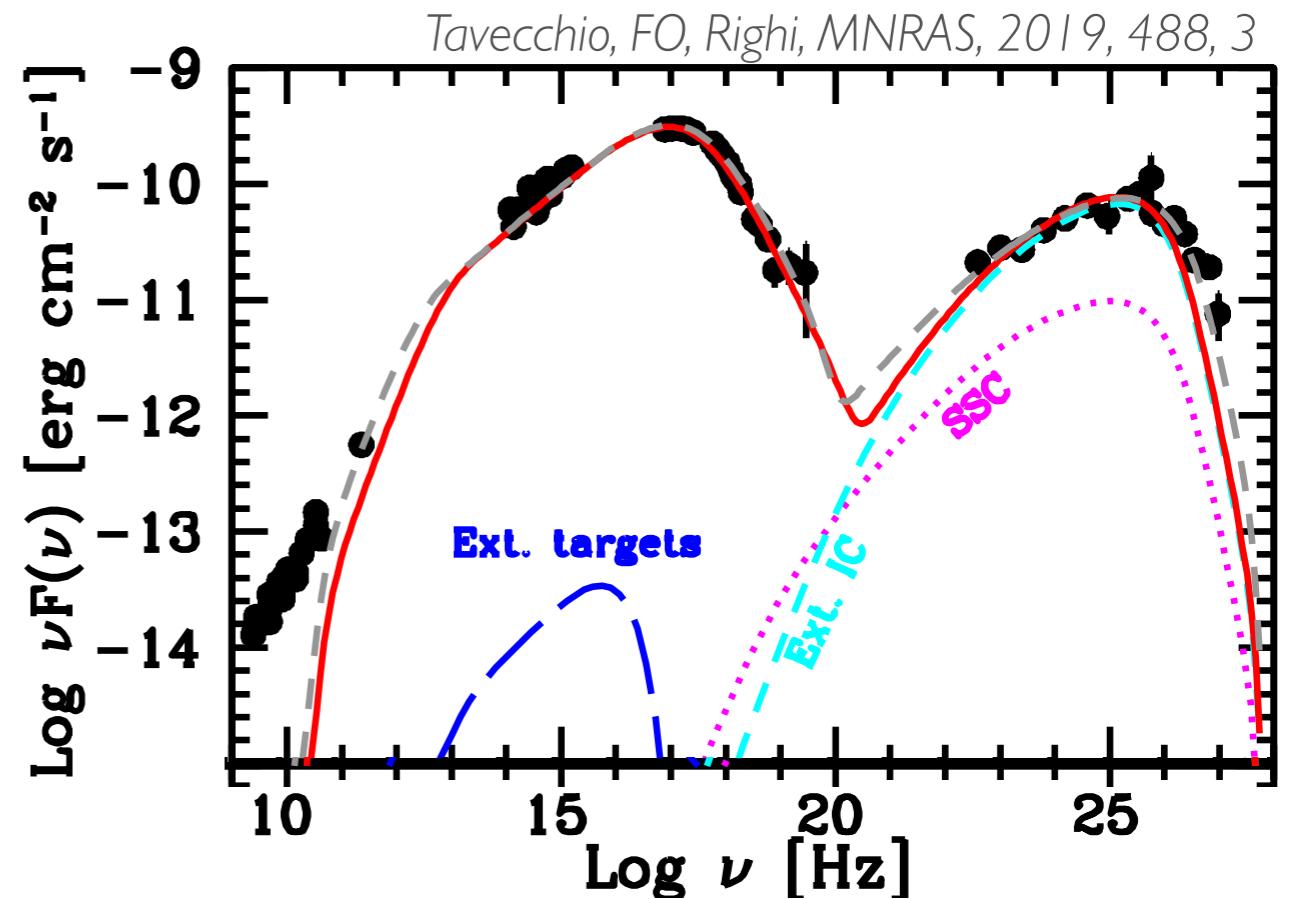
BL Lac objects



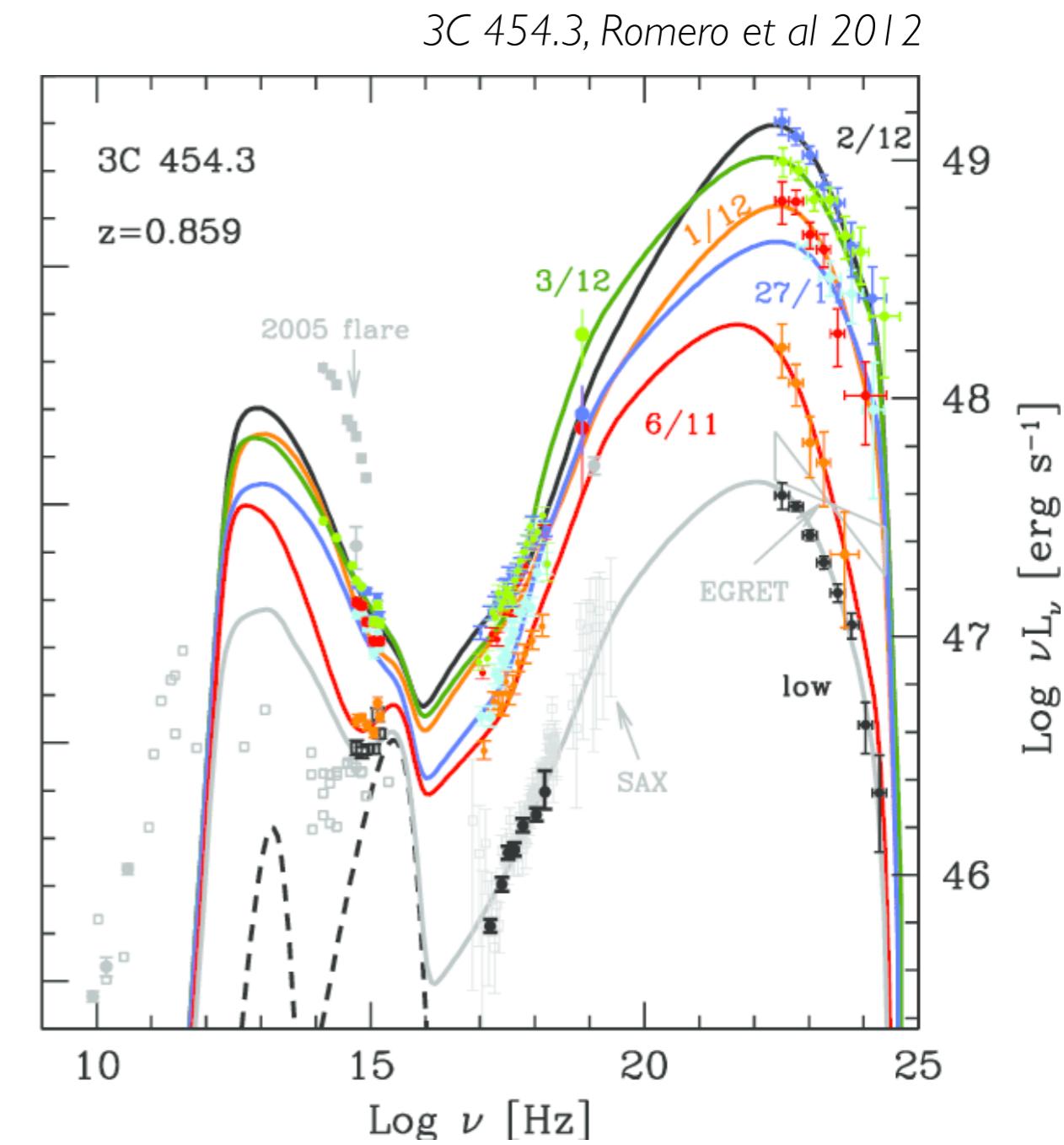
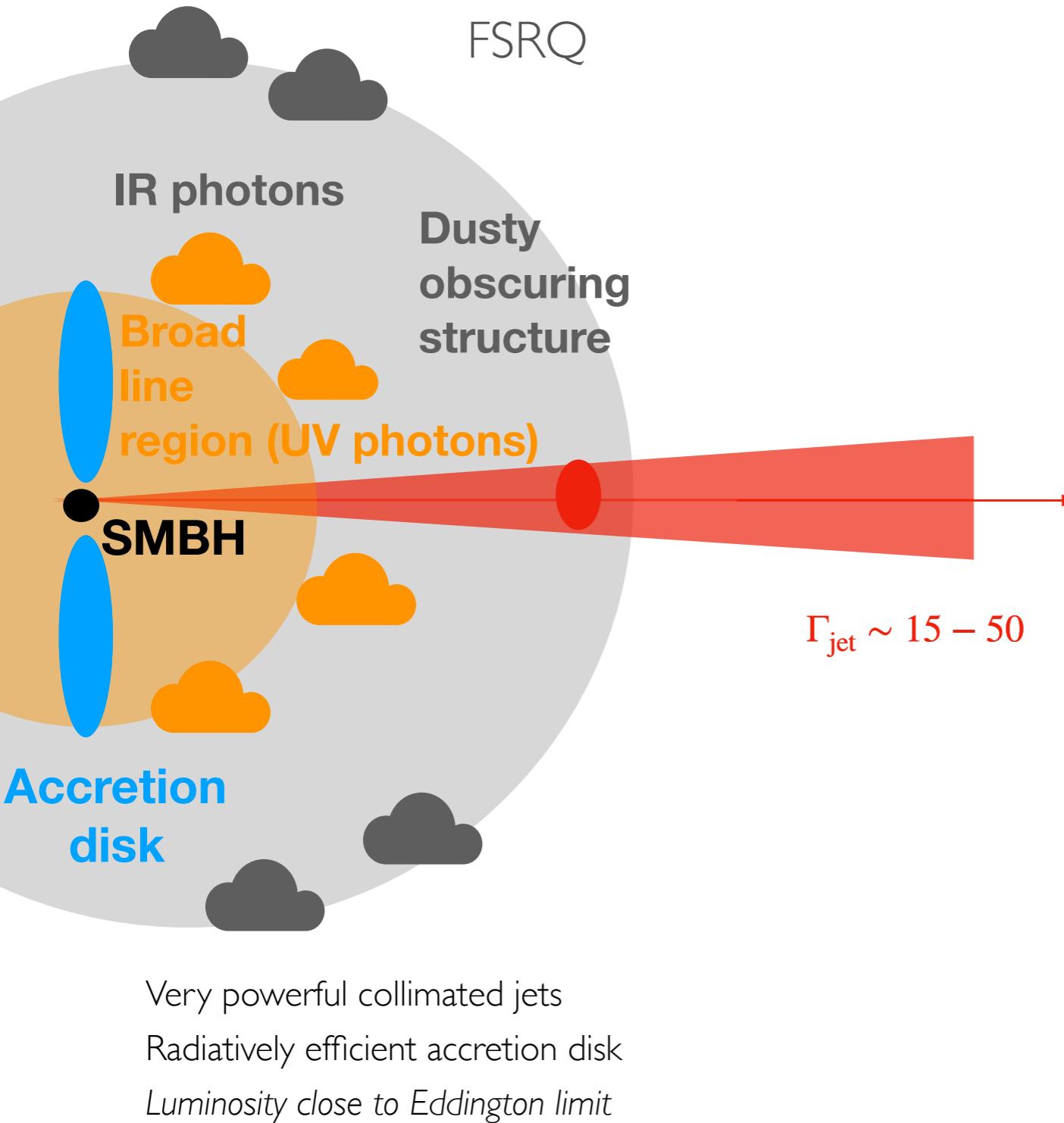
Inefficient
accretion
flow (ADAF)

dust?

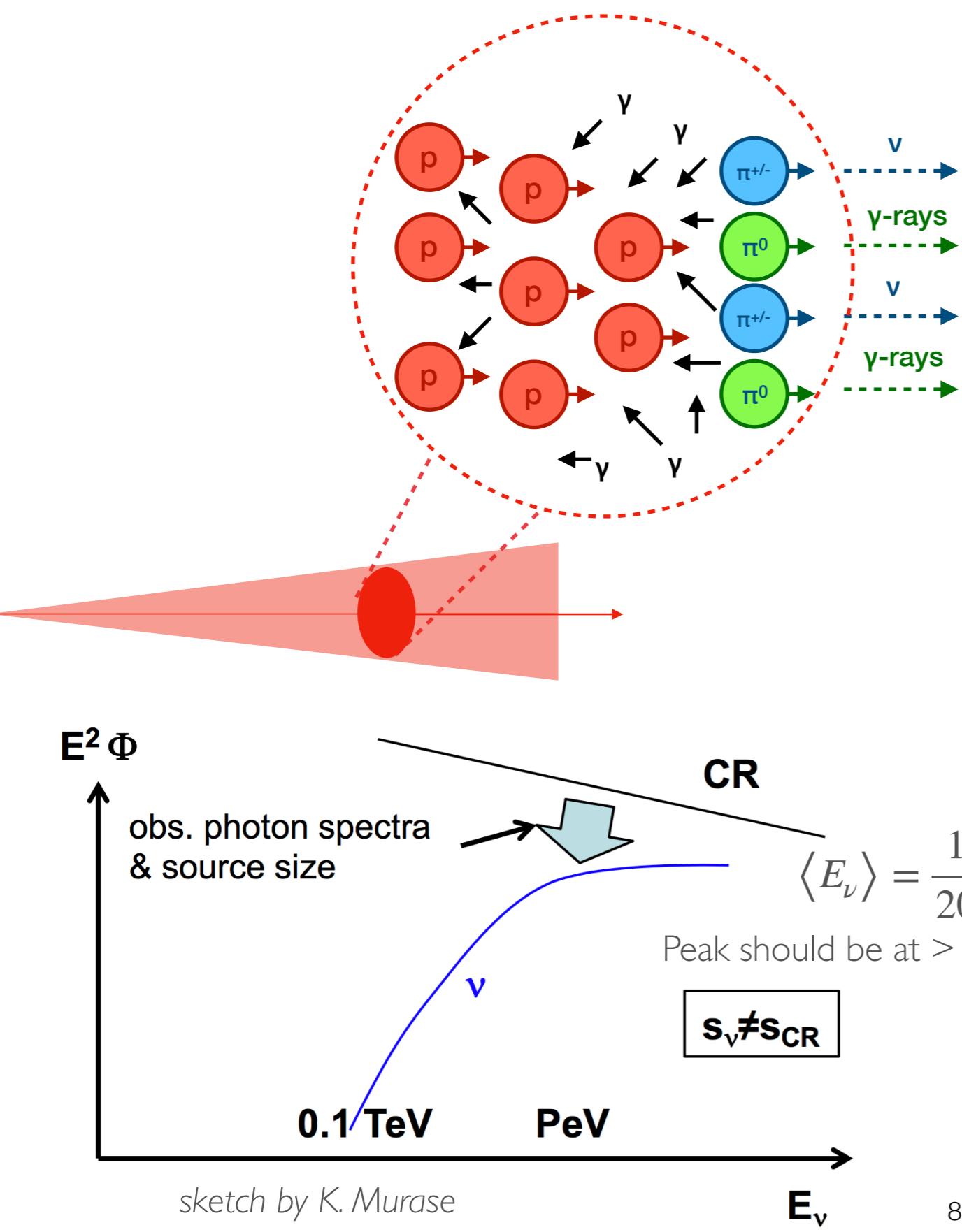
- Less powerful jets (plumes at large distances)
- Radiatively inefficient accretion flow
- Lower Eddington ratio



Flat Spectrum Radio Quasars

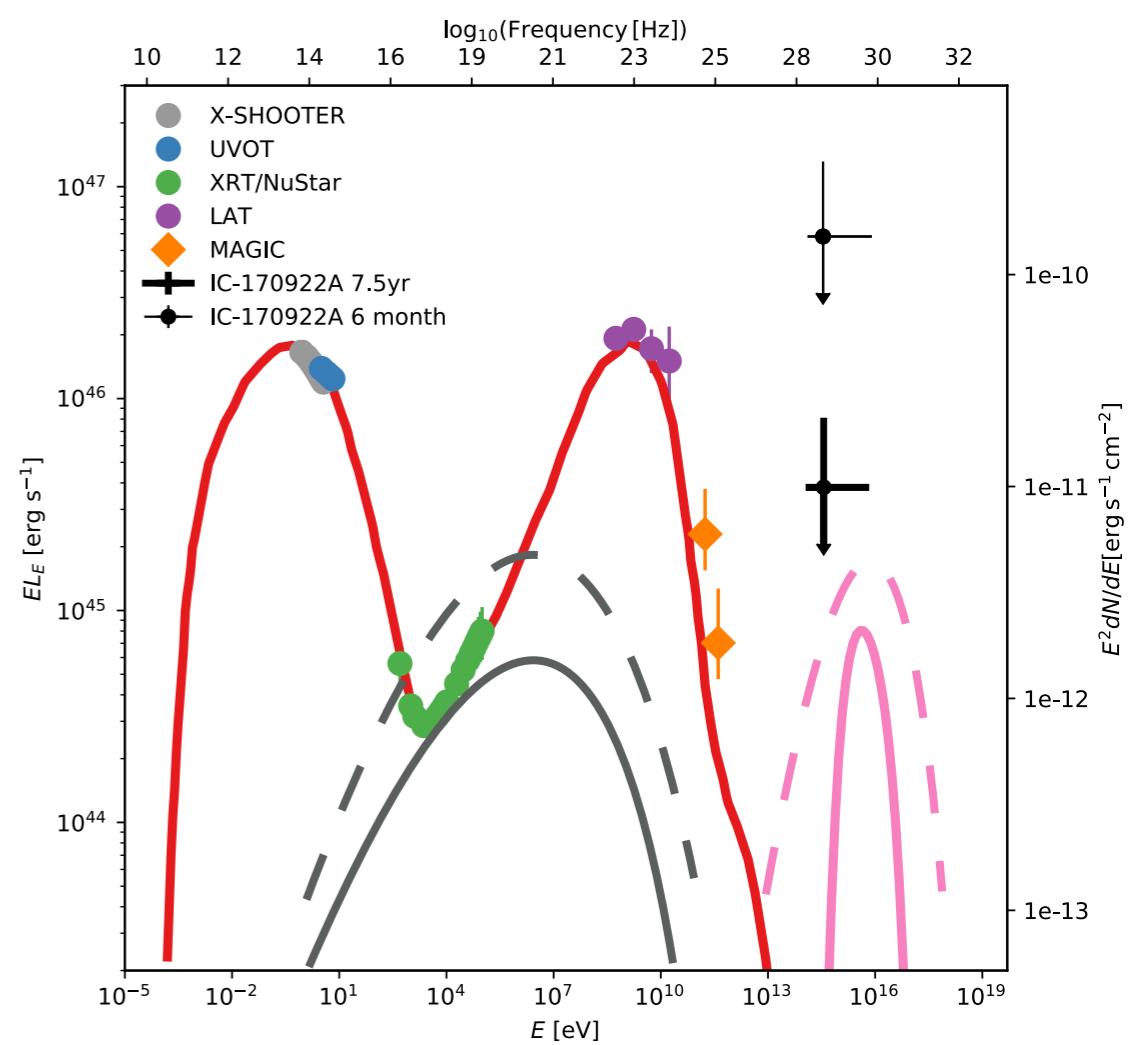


Neutrino production in blazars



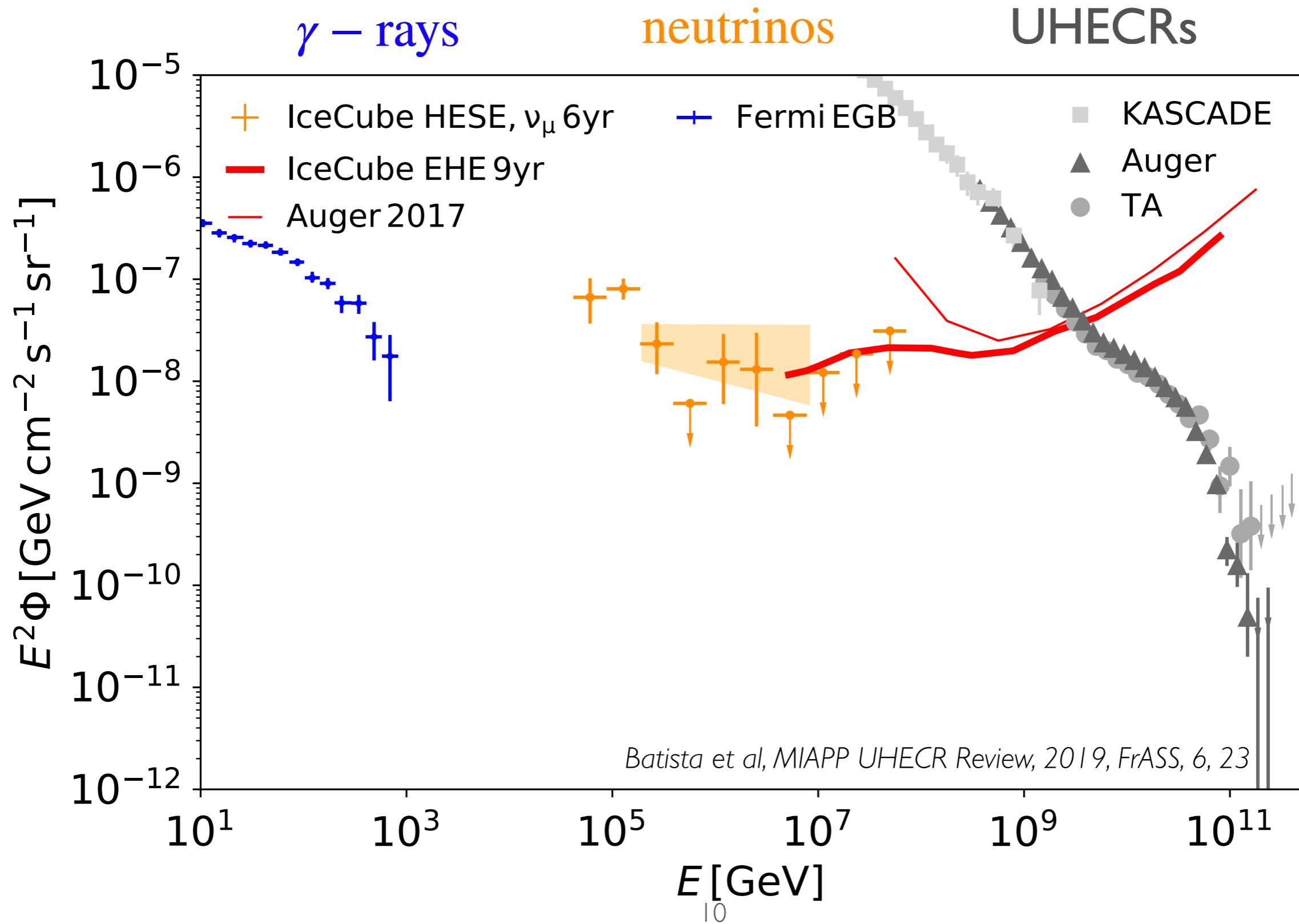
Of proton energy lost:
 3/8ths → neutrinos
 5/8ths → photons (gamma-rays/X-rays)

The spectral energy distribution gives an upper limit to the neutrino luminosity

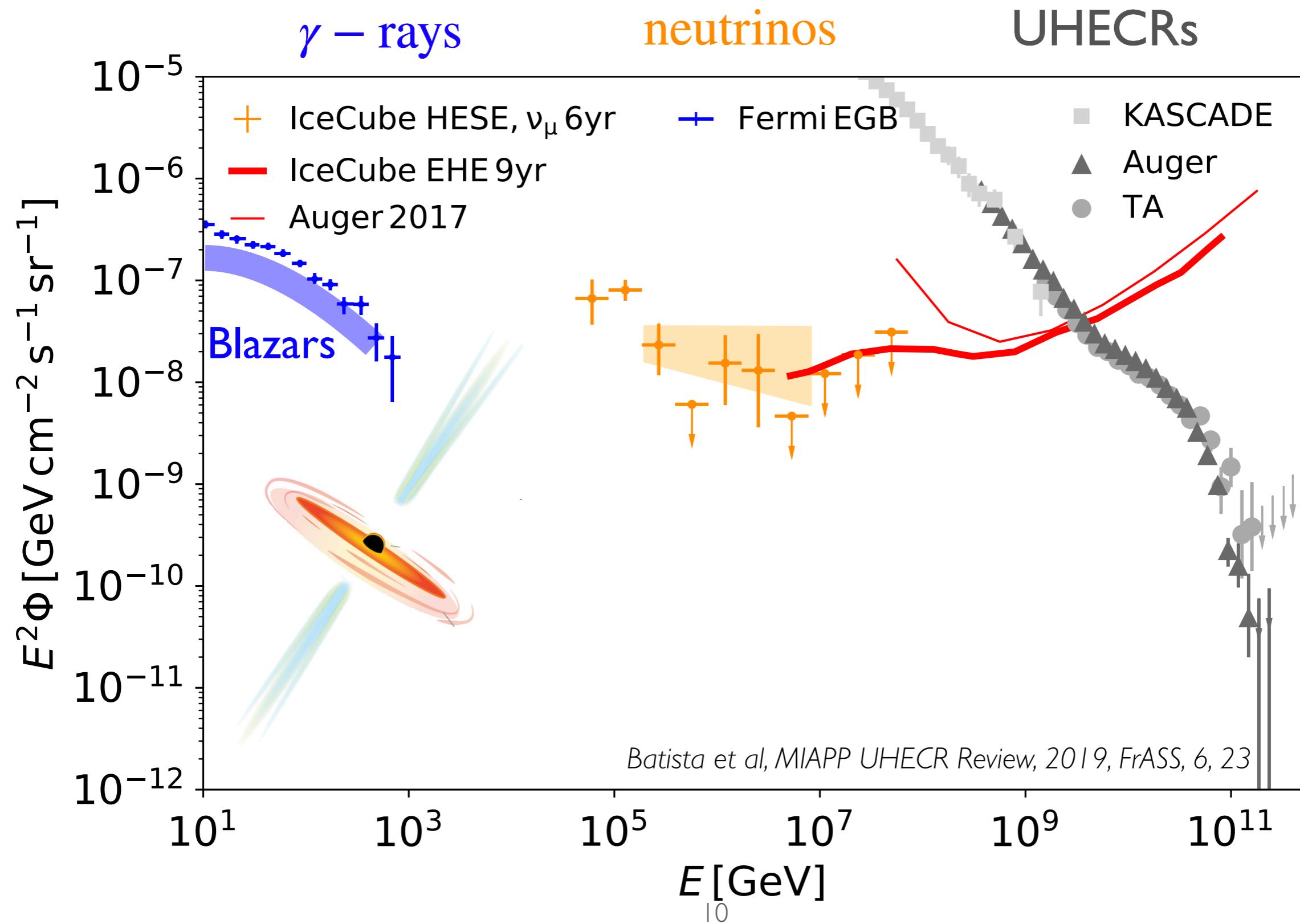


- Diffuse limits
- Flares
- Recent IceCube Alerts

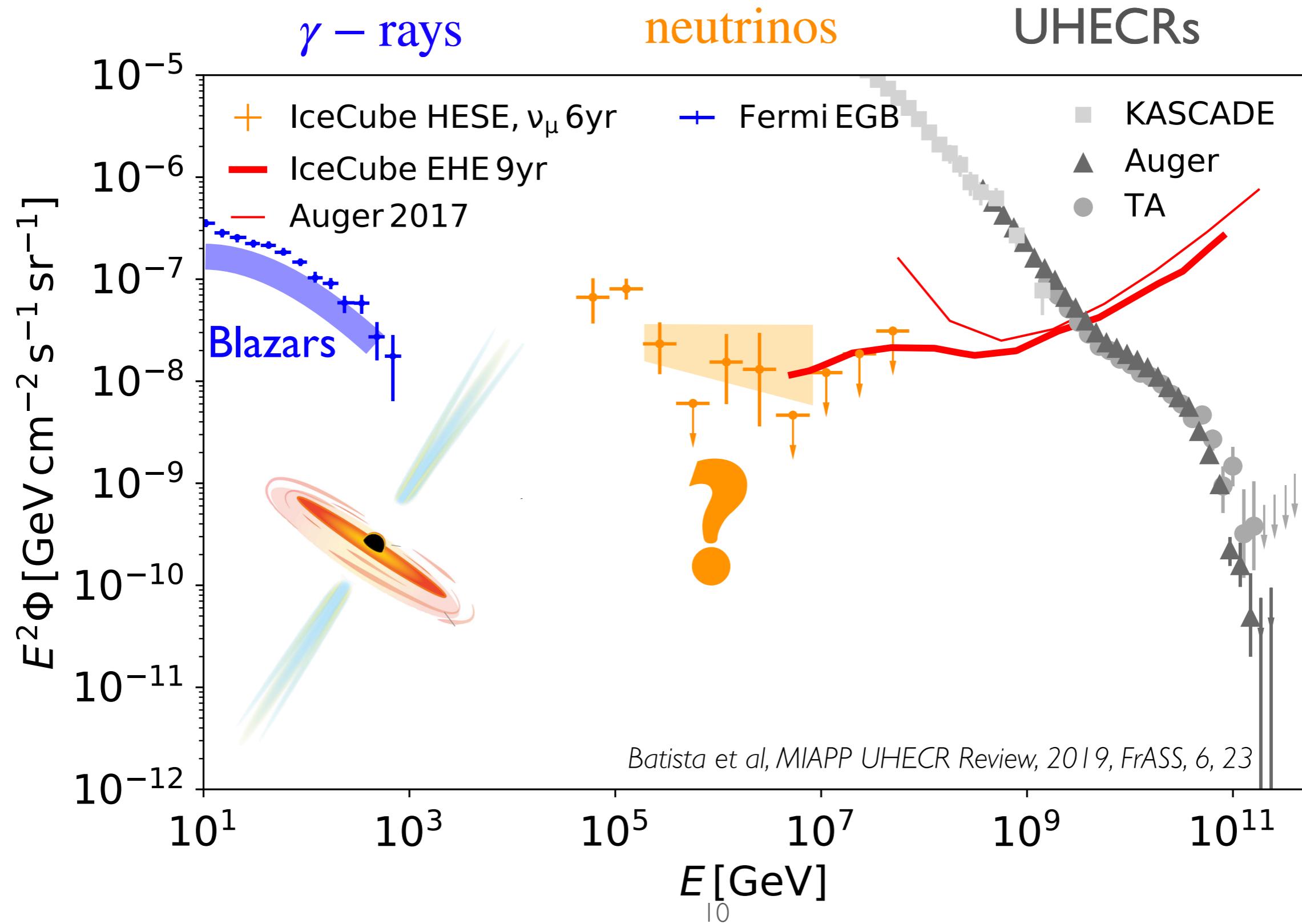
Constraints on the contribution of blazars to the diffuse neutrino flux



Constraints on the contribution of blazars to the diffuse neutrino flux

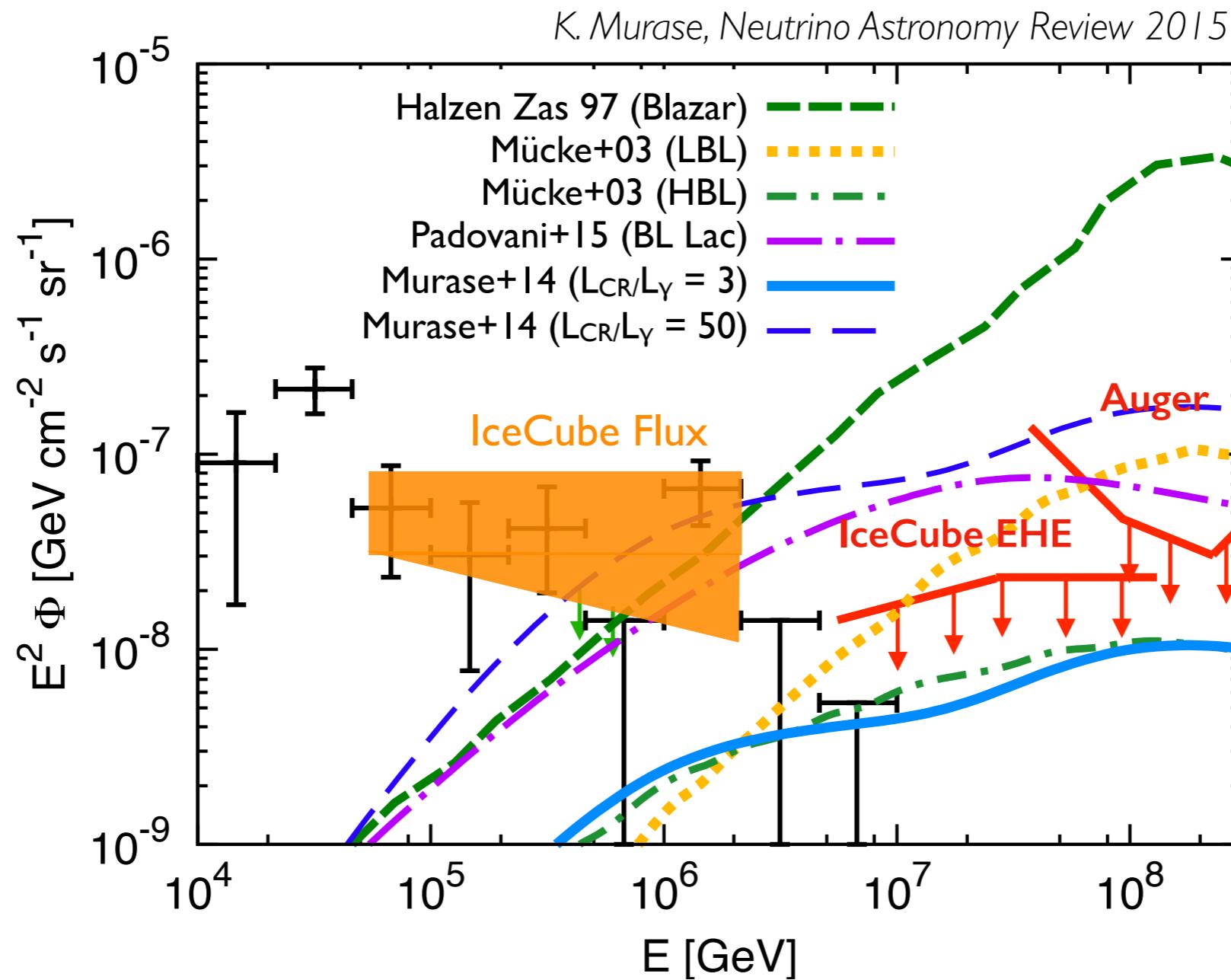


Constraints on the contribution of blazars to the diffuse neutrino flux



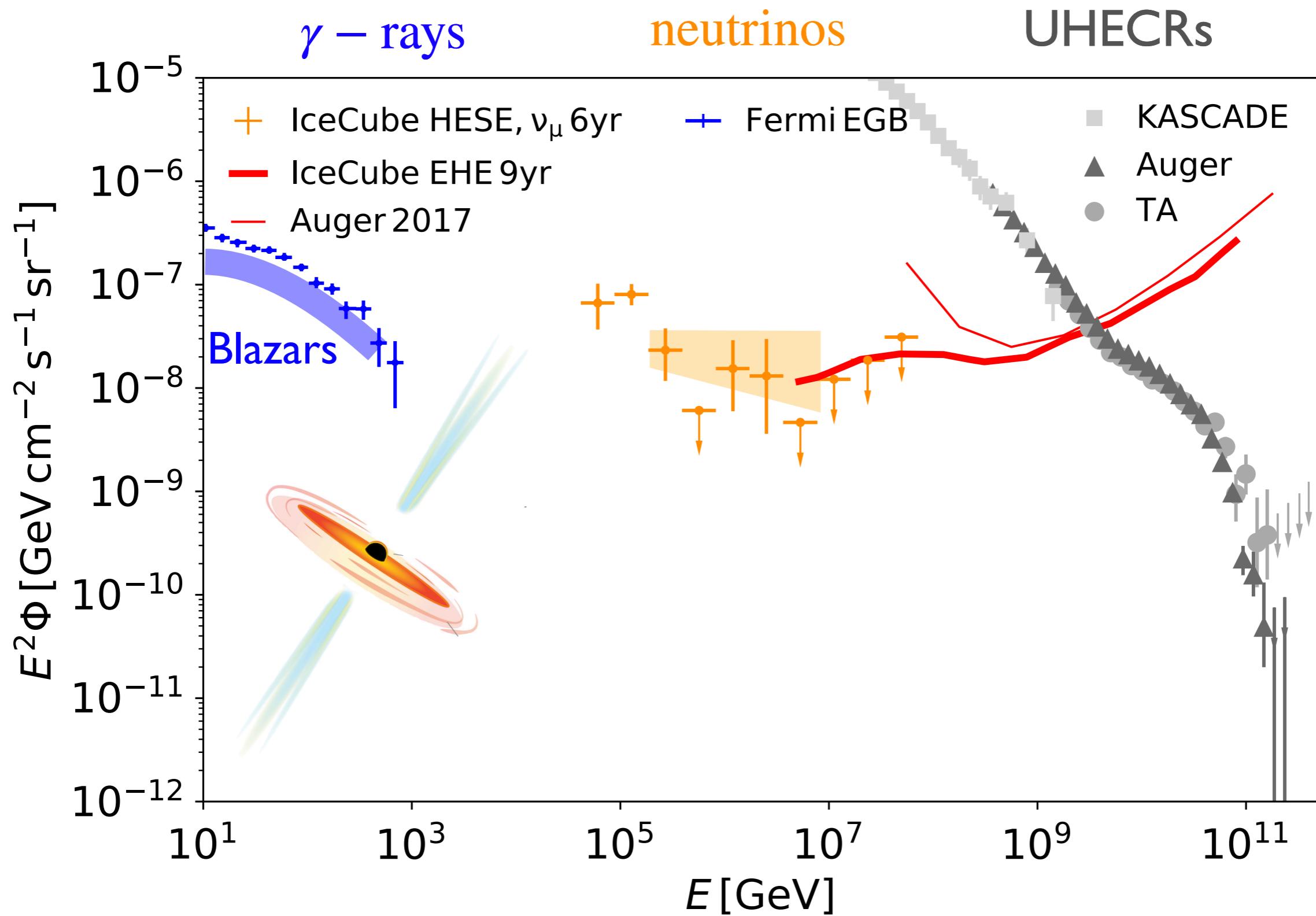
Constraints on the contribution of blazars to the diffuse neutrino flux

see also IceCube EHE PRL 2016, PRD 2018



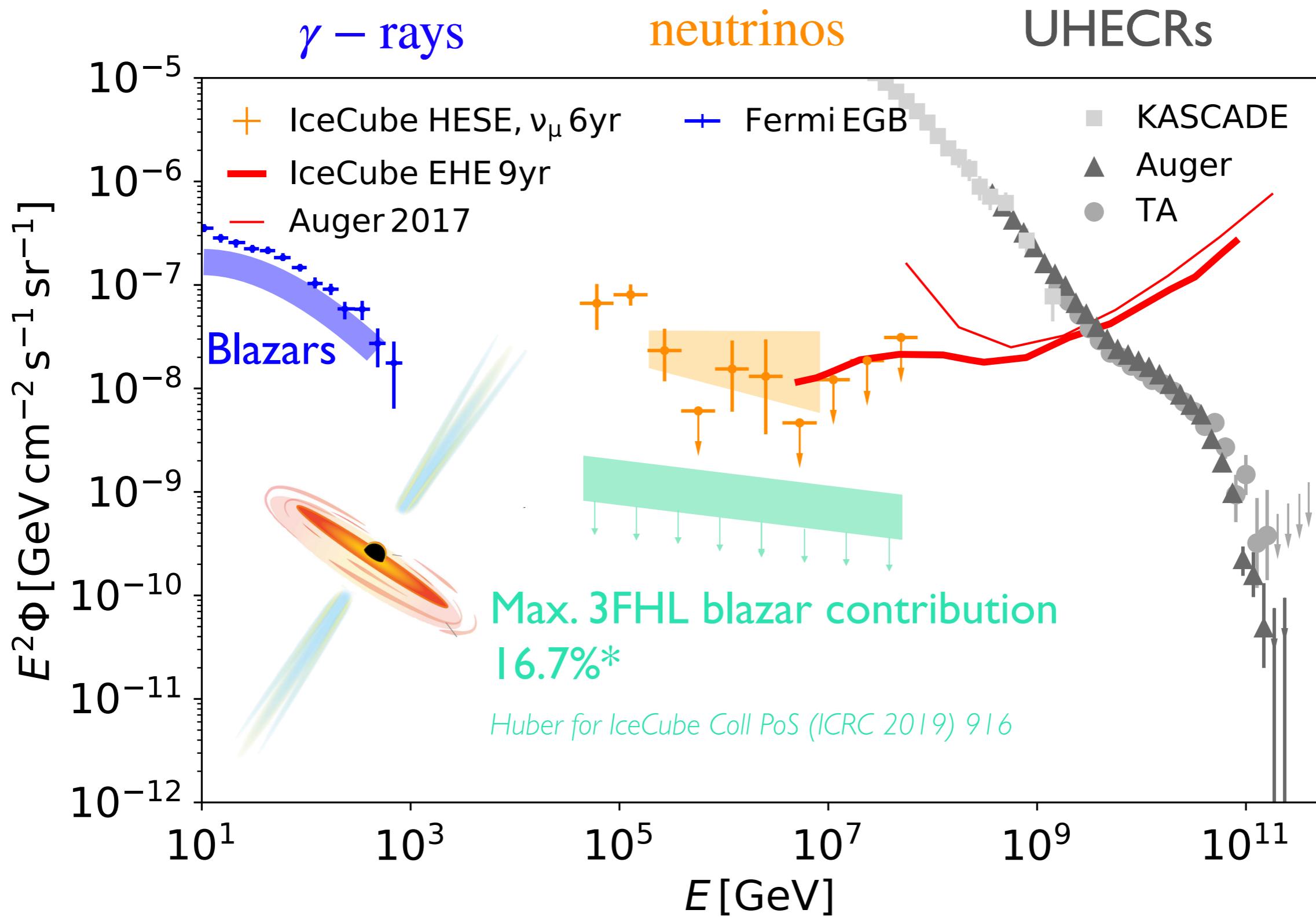
Blazar proton content is (on average) low!

Constraints on the contribution of blazars to the diffuse neutrino flux: Stacking

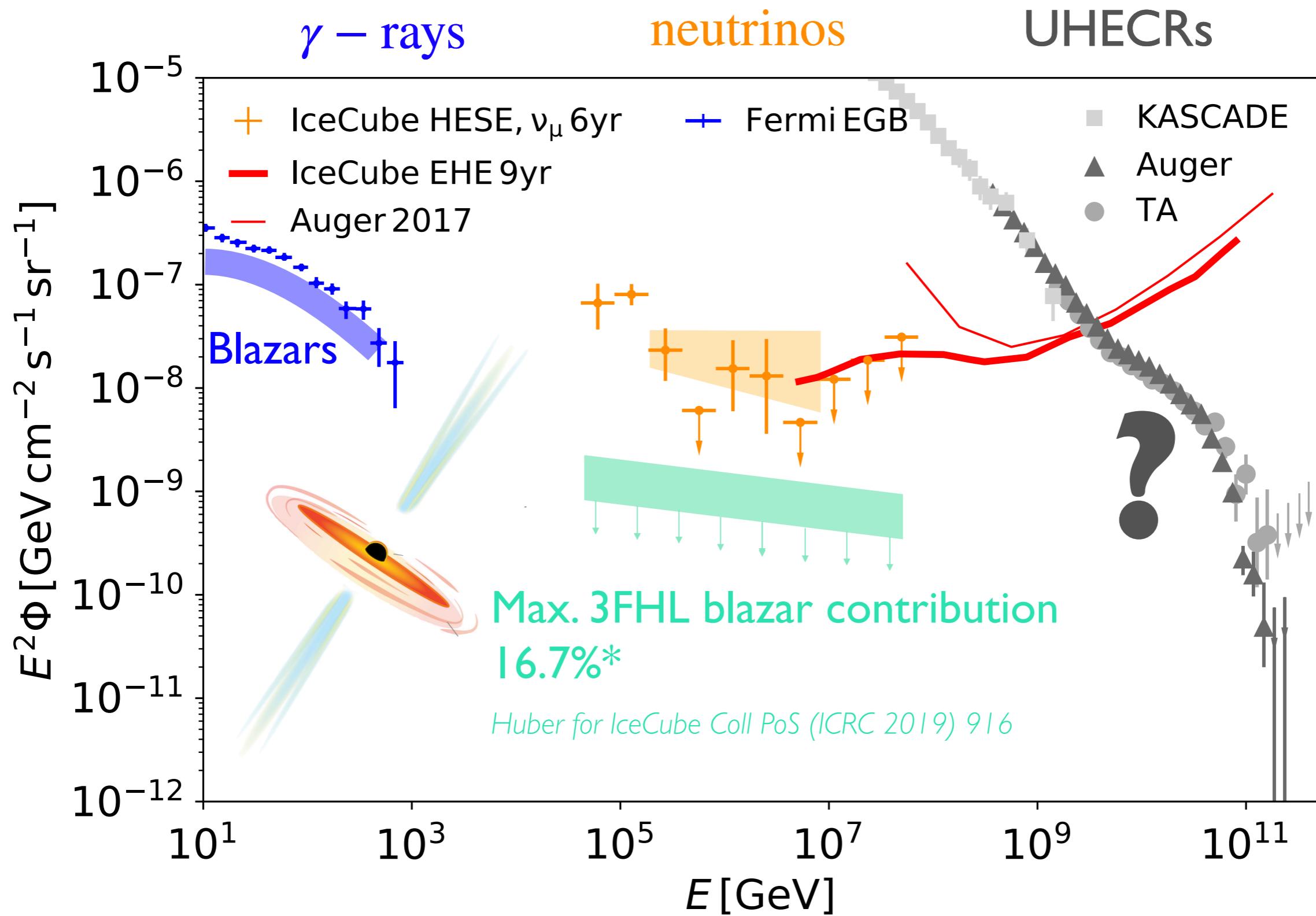


* limits apply to infrared selected blazars as well, $\lesssim 27\%$ with ¹² spectral templates: *IceCube Coll PoS (ICRC2017) 994*

Constraints on the contribution of blazars to the diffuse neutrino flux: Stacking



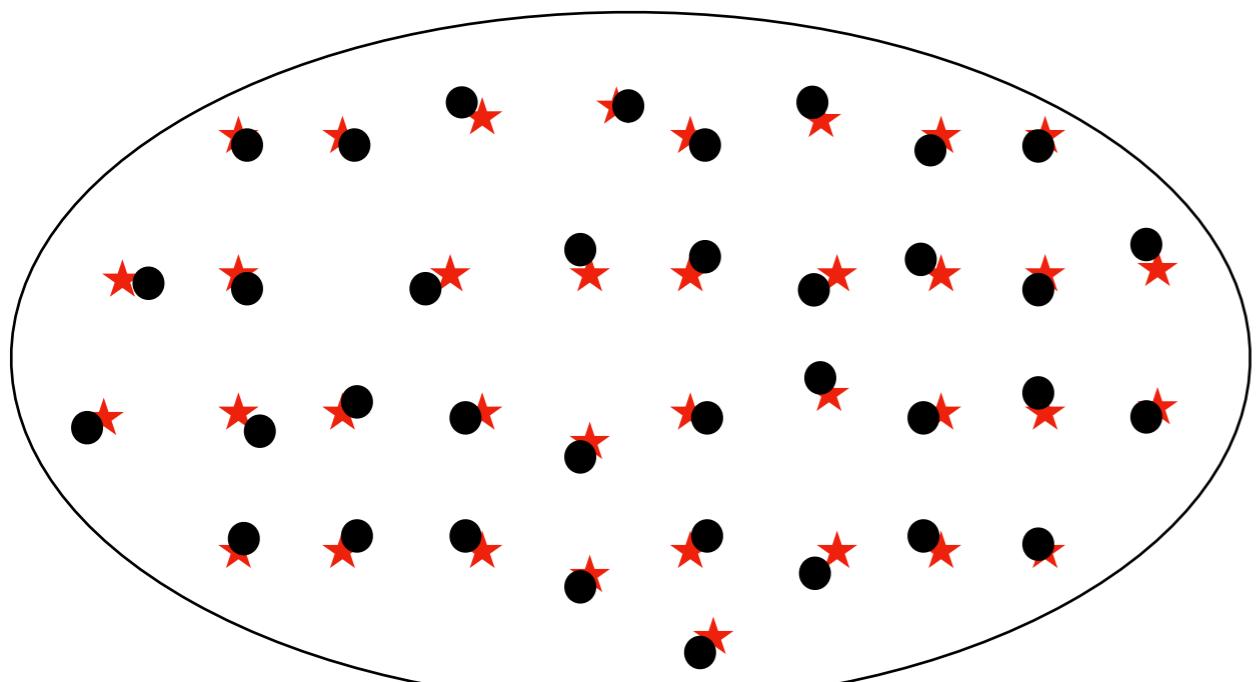
Constraints on the contribution of blazars to the diffuse neutrino flux: Stacking



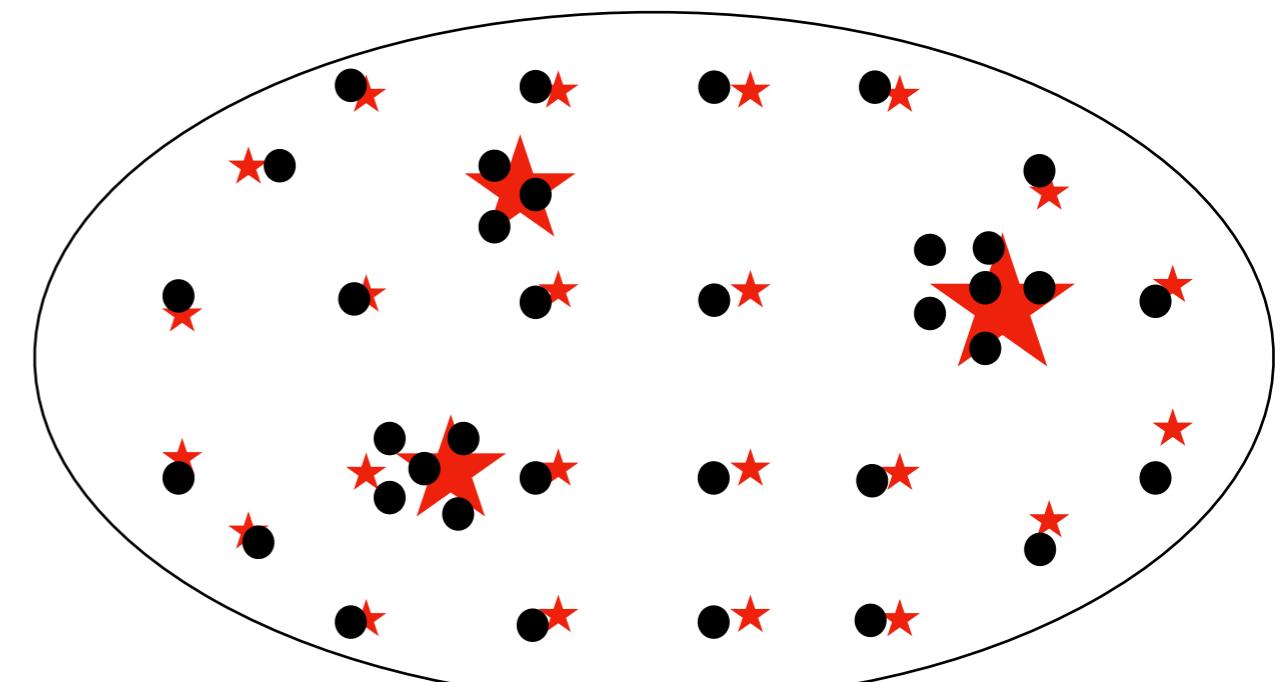
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

Lipari 2008,
Ahlers & Halzen 2014,
Murase & Waxman 2016,
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan et al 2019,
Capel, Mortlock, Finley 2020,
Palladino, Van Vliet et al 2020

Large number of sources



Nearby or very luminous source

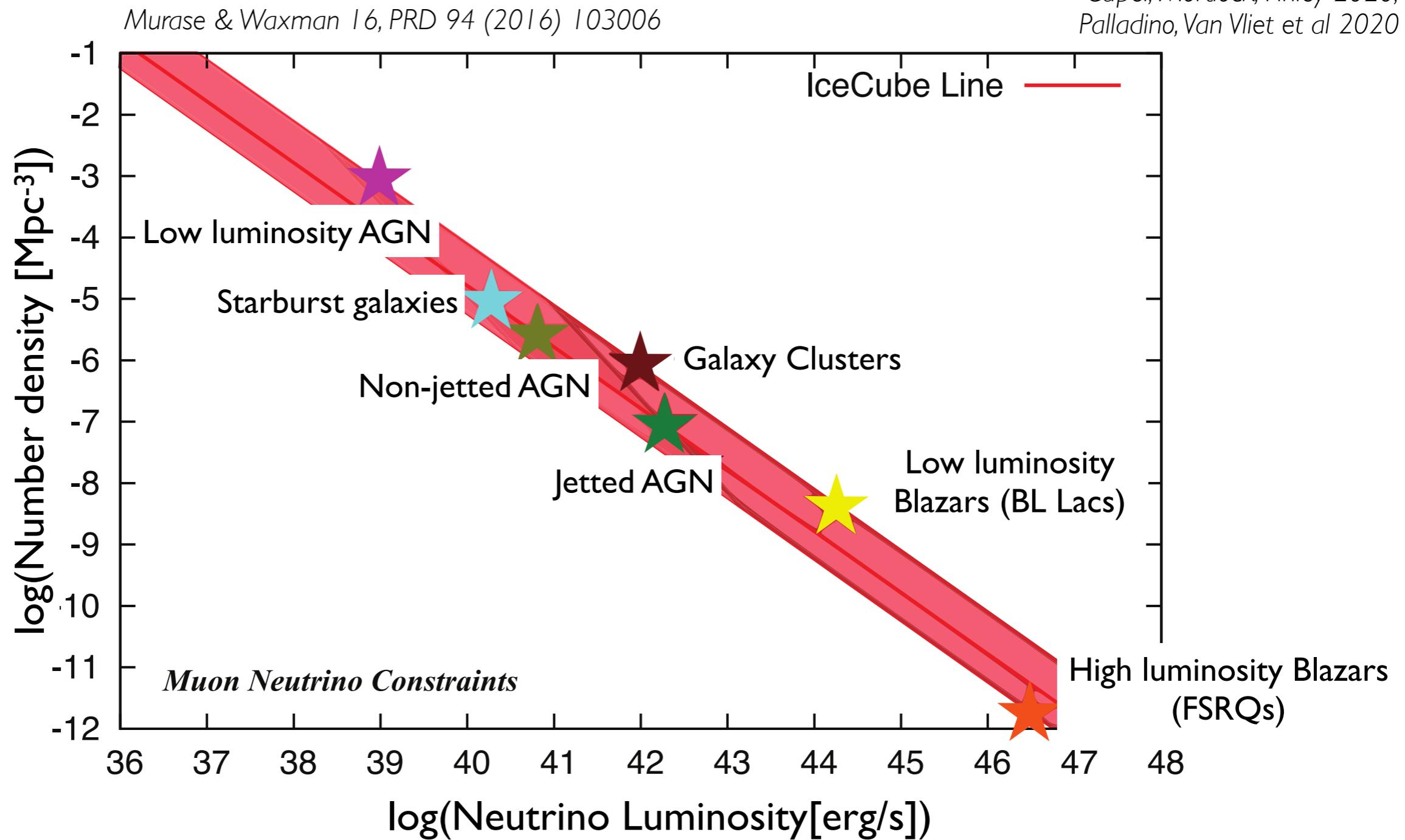


Sources - Neutrinos

No significant clustering in the IceCube data → Low density (nearest source far) or low luminosity

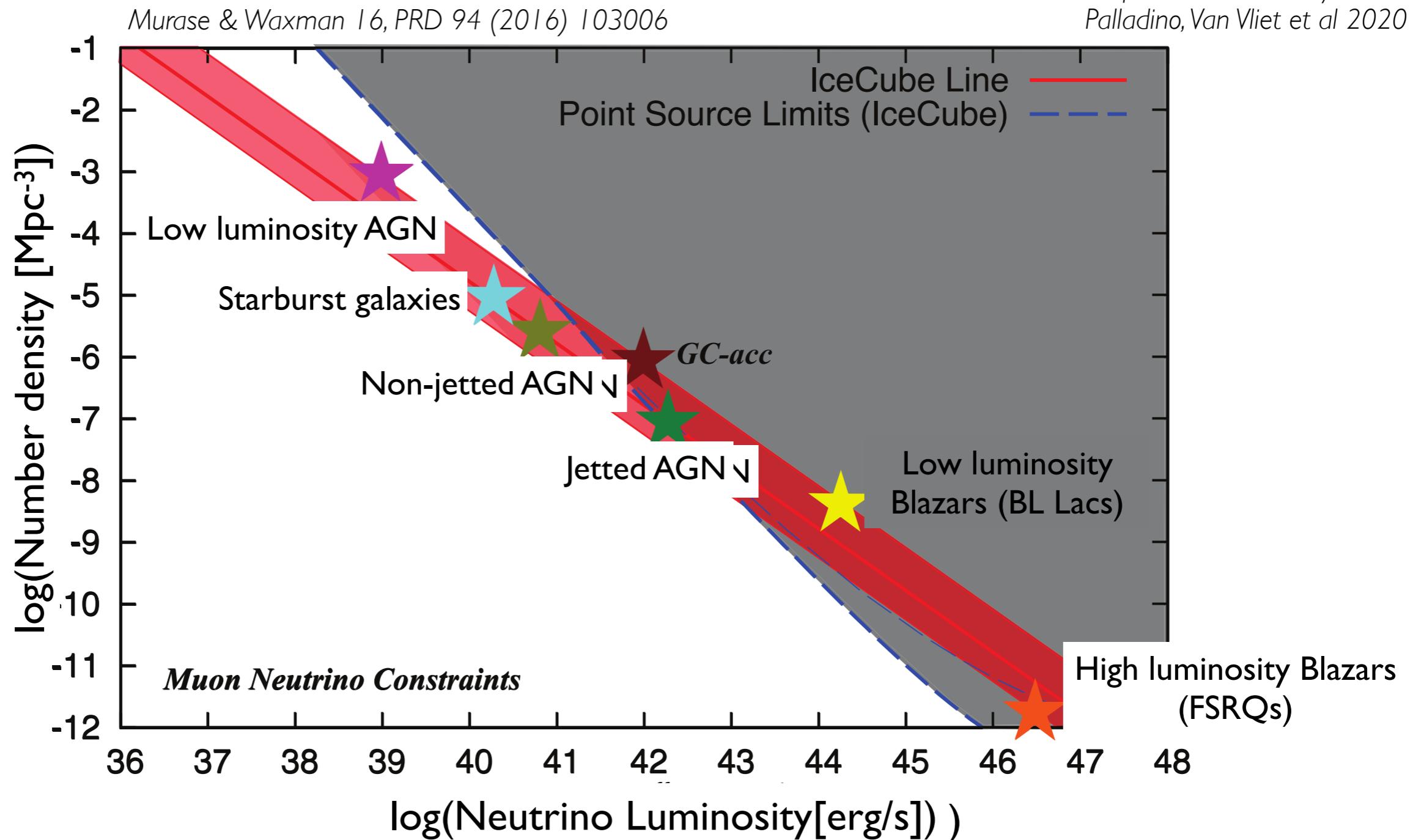
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

Lipari 2008,
Ahlers & Halzen 2014,
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan et al 2019,
Capel, Mortlock, Finley 2020,
Palladino, Van Vliet et al 2020



Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

Lipari 2008,
Ahlers & Halzen 2014,
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan et al 2019,
Capel, Mortlock, Finley 2020,
Palladino, Van Vliet et al 2020

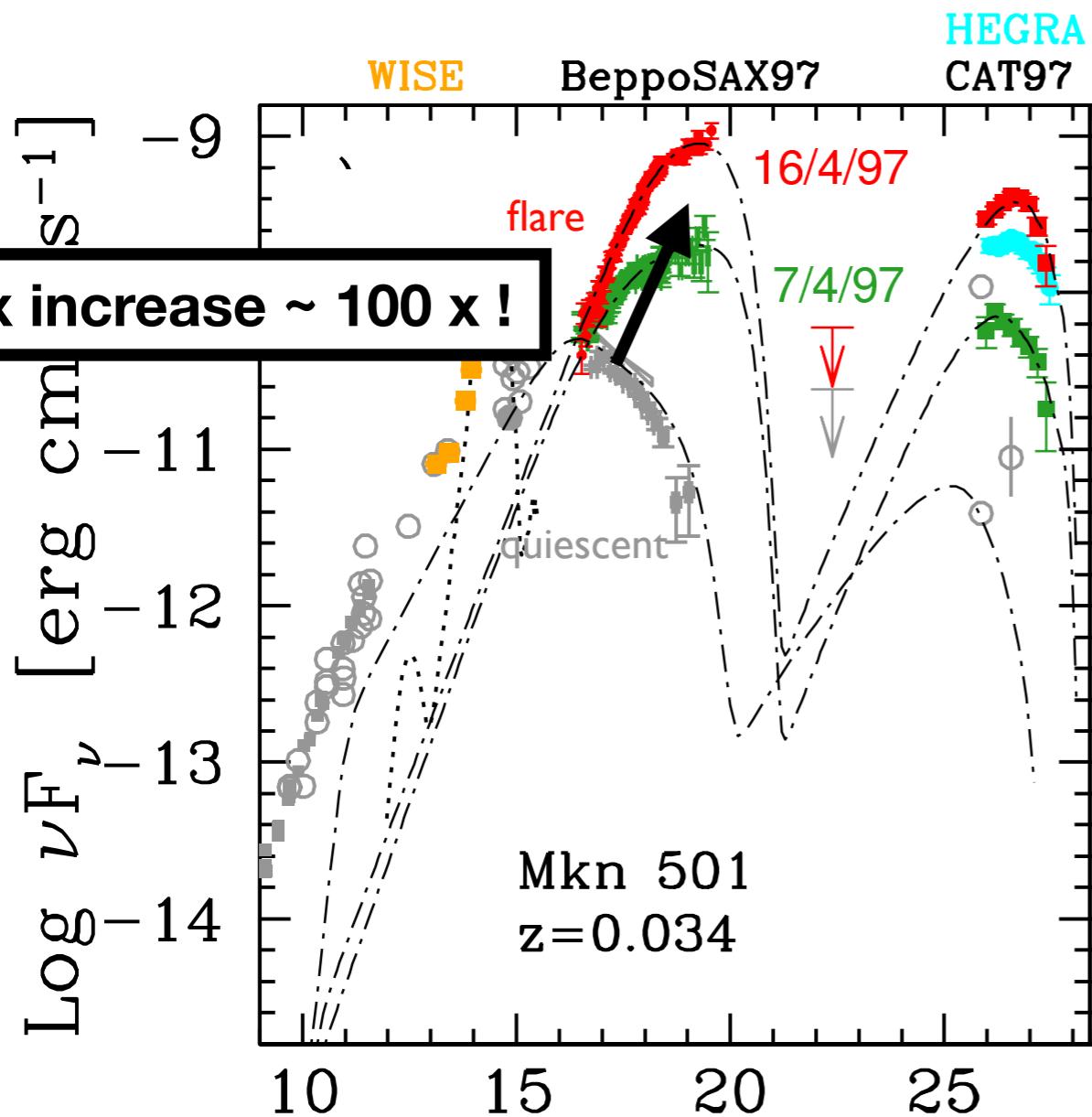


other diagnostics: cross-correlations (Padovani et al 2016, Palladino 2017, Giommi et al, 2020, Plavin et al 2020)

autocorrelations (IceCube Coll 2015, 17, Ando et al 2017, Dekker & Ando 2019), EHE Limits (IceCube Coll 2016, 17)...

- Diffuse limits
- **Flares**
- Recent IceCube Alerts

Blazar flares: Interesting as neutrino point sources



Generally $L_\nu \sim L_{\text{proton}} \times L_{\text{target photon}}$

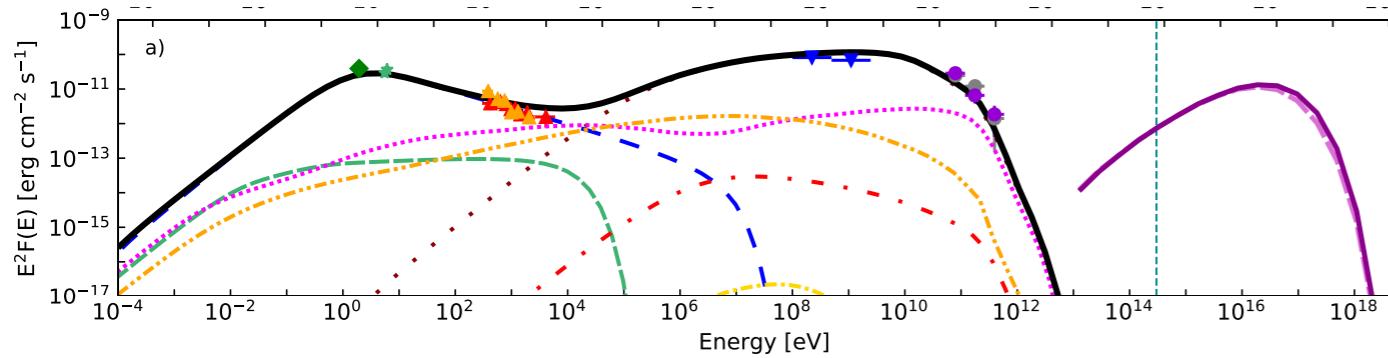
During flares, $L_\nu \propto L_{\text{target photon}}^2$ (BL Lac)

$L_\nu \propto L_{\text{target photon}}^{1.5}$ (FSRQ)

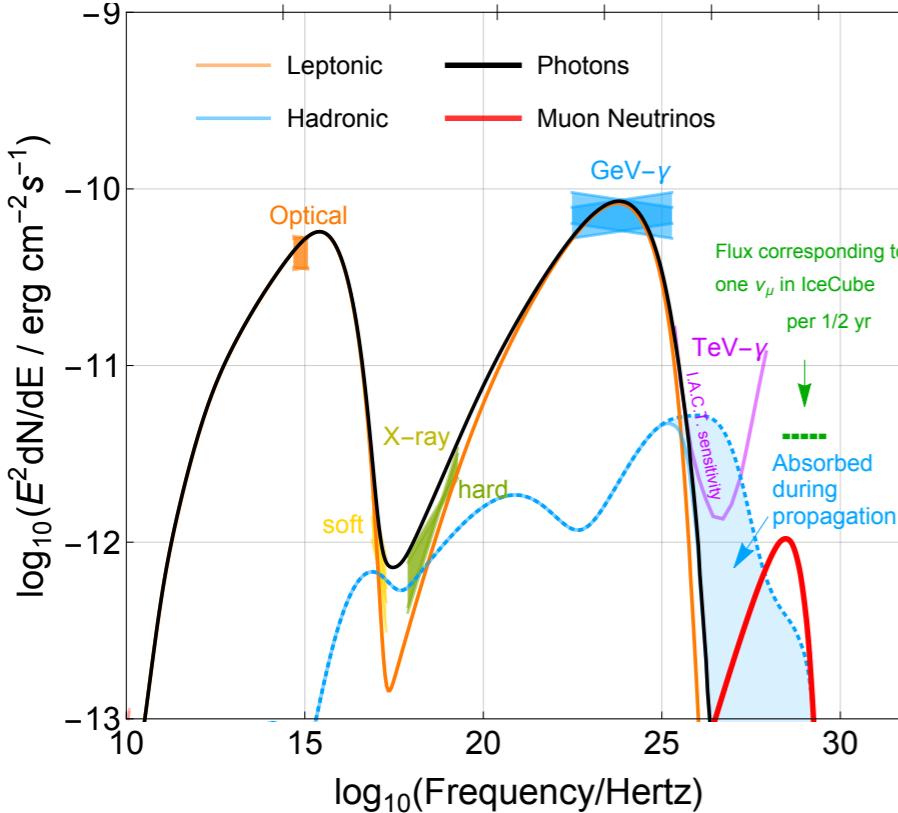
Image from Biteau, Prandini, Costamante + Nat.Astr 4, 124–131(2020)

TXS 0506+056 + IC170922A

MAGIC Coll 2018, ApJ, 863, L10

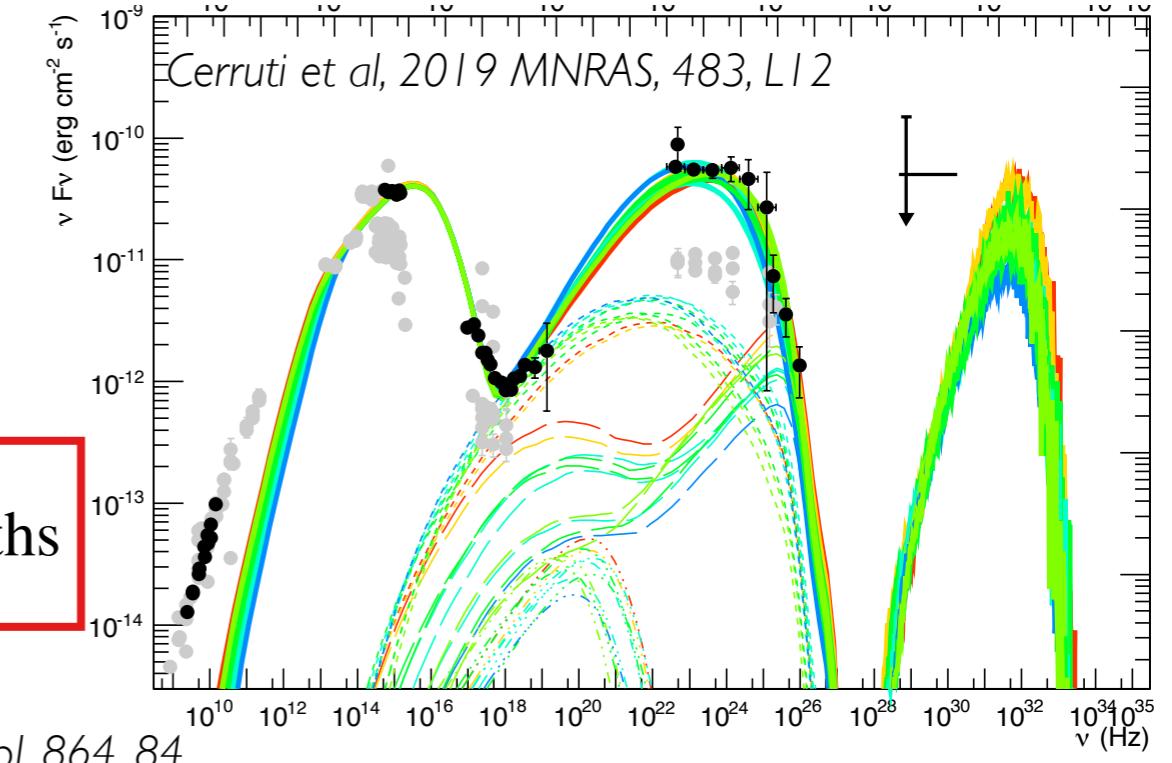


Gao et al, 2019, Nat. Astron., 3, 88

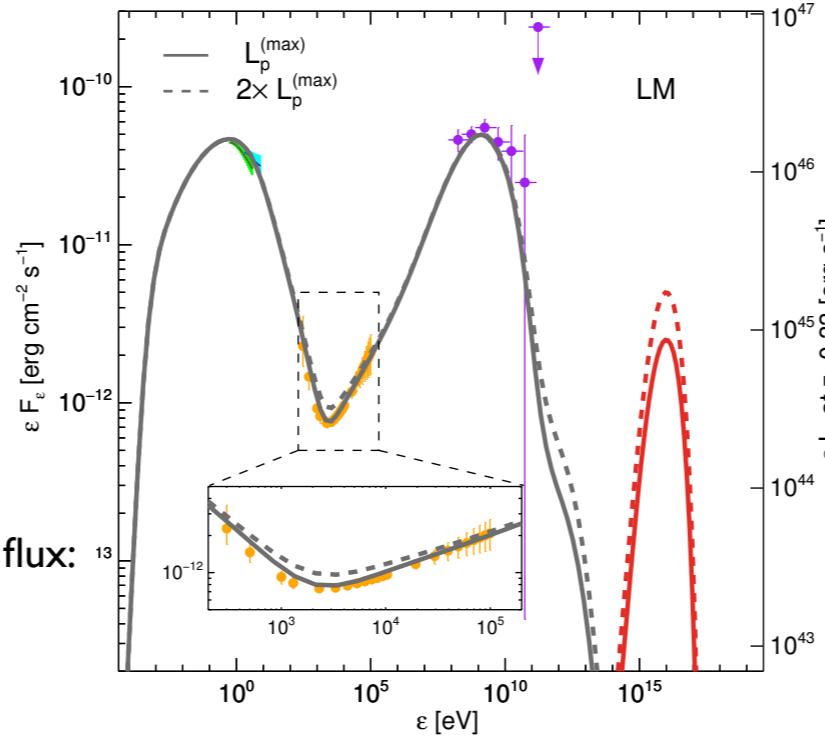


$$N_{\nu_\mu} \lesssim 0.01/6 \text{ months}$$

Cerruti et al, 2019 MNRAS, 483, L12



Keivani et al. 2018, ApJ, 864, 84



Statistically consistent with the detection of one event
(e.g. Strotjohann et al 2019)

A misclassified FSRQ
(Padovani, FO, Petropoulou et al 2019)

Still requires **atypically large proton luminosity or photon fields** even with Eddington bias

Other more exotic options find increased neutrino flux:

hadro-nuclear interactions: Liu et al, PRD 2019

stellar disruption: Wang, Liu et al, arXiv:1809.00601

multiple zones: Xue, et al (inc FO) et al, ApJ 2019

neutron beam: Zhang, Petropoulou, Murase, FO, ApJ 2019

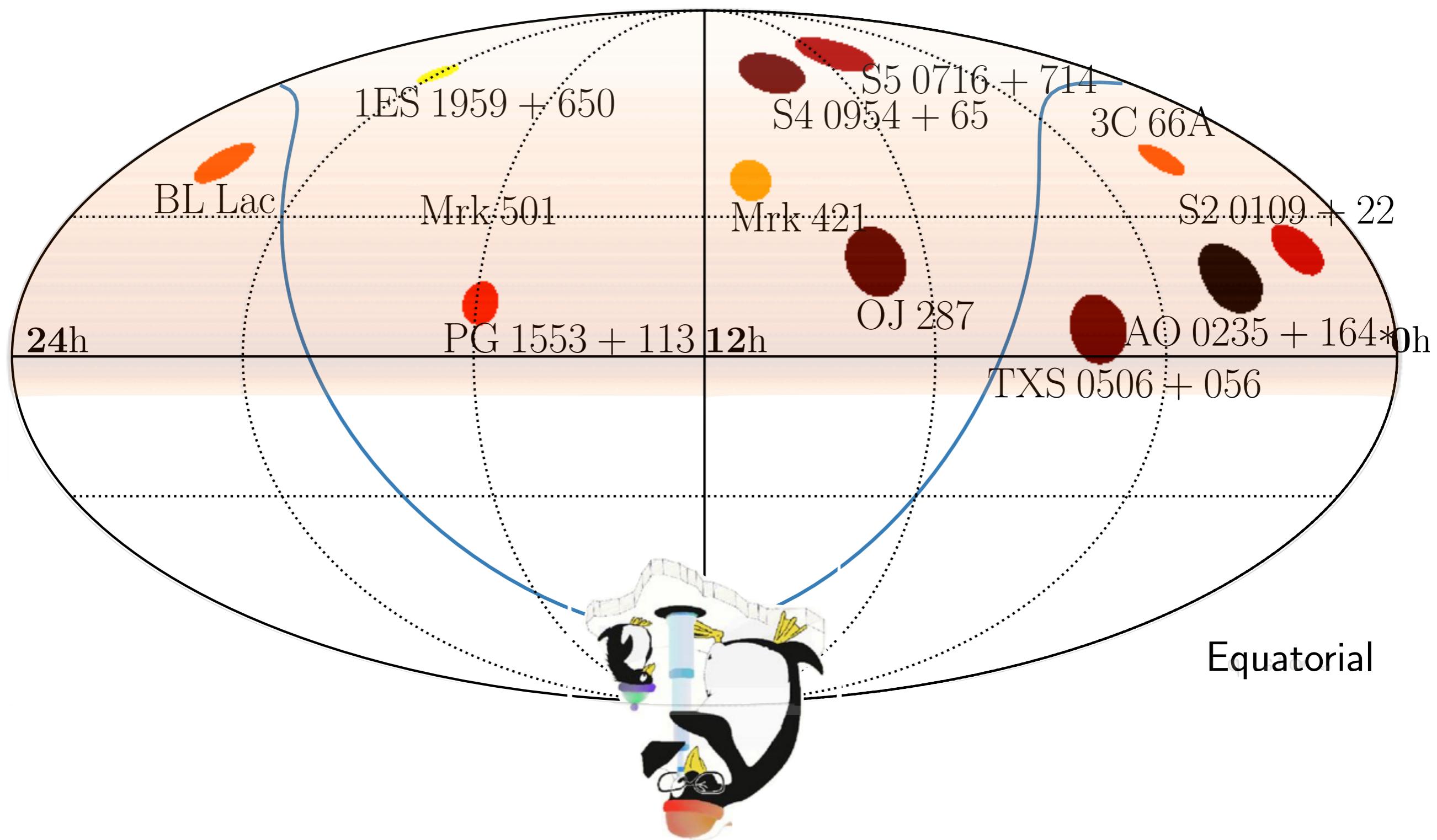
curved/double jet: Britzen, Fendt, Böttcher et al, A&A 2019

Inefficient accretion flow: Righi et al, MNRAS 483, L127 **and more...!**

2014 flare: Reimer+19, Reimer+19, Petropoulou+19...

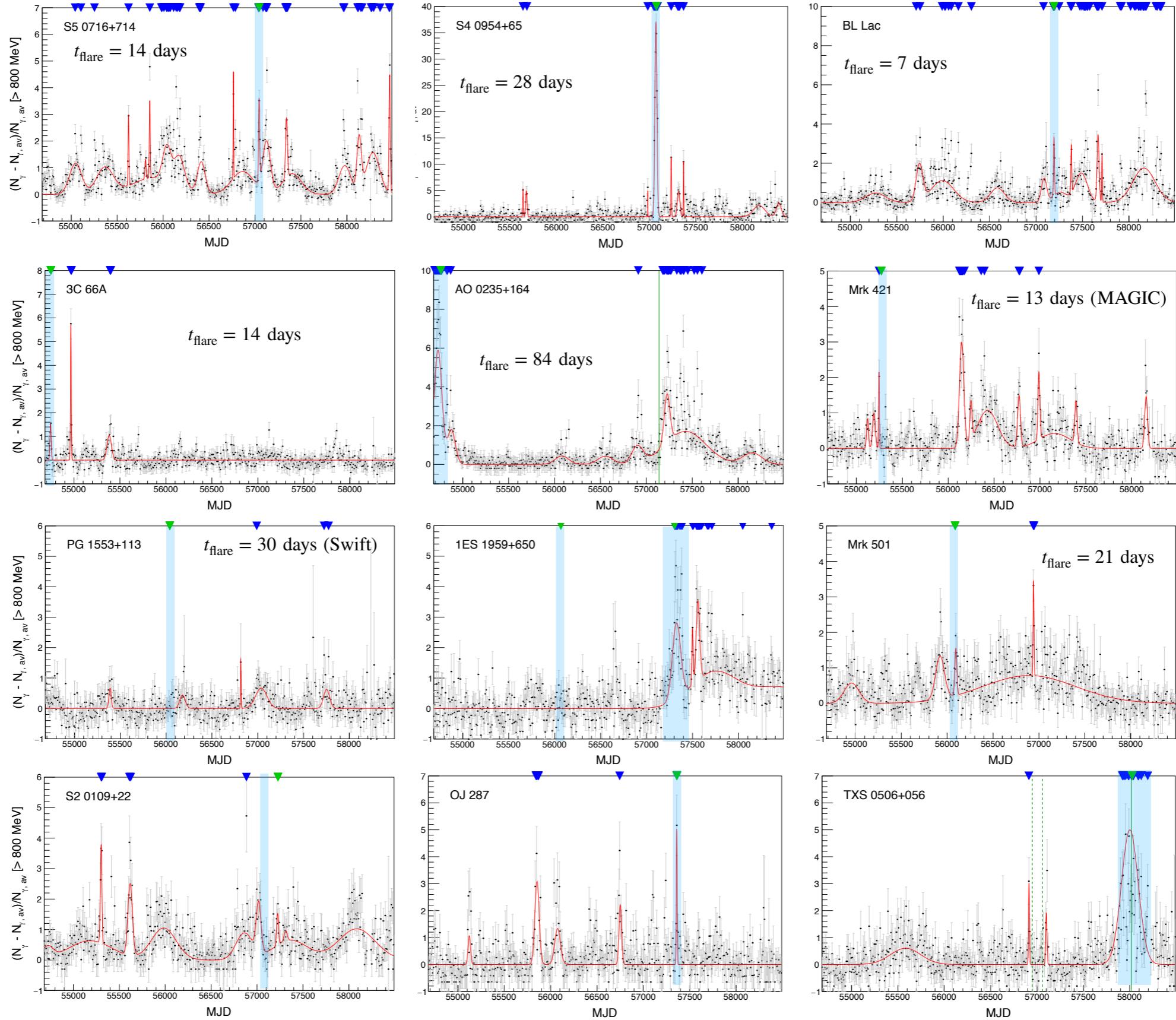
High-energy neutrinos from other blazar flares?

FO, Murase, Padovani, Resconi, Mészáros, MNRAS, 23, 2019



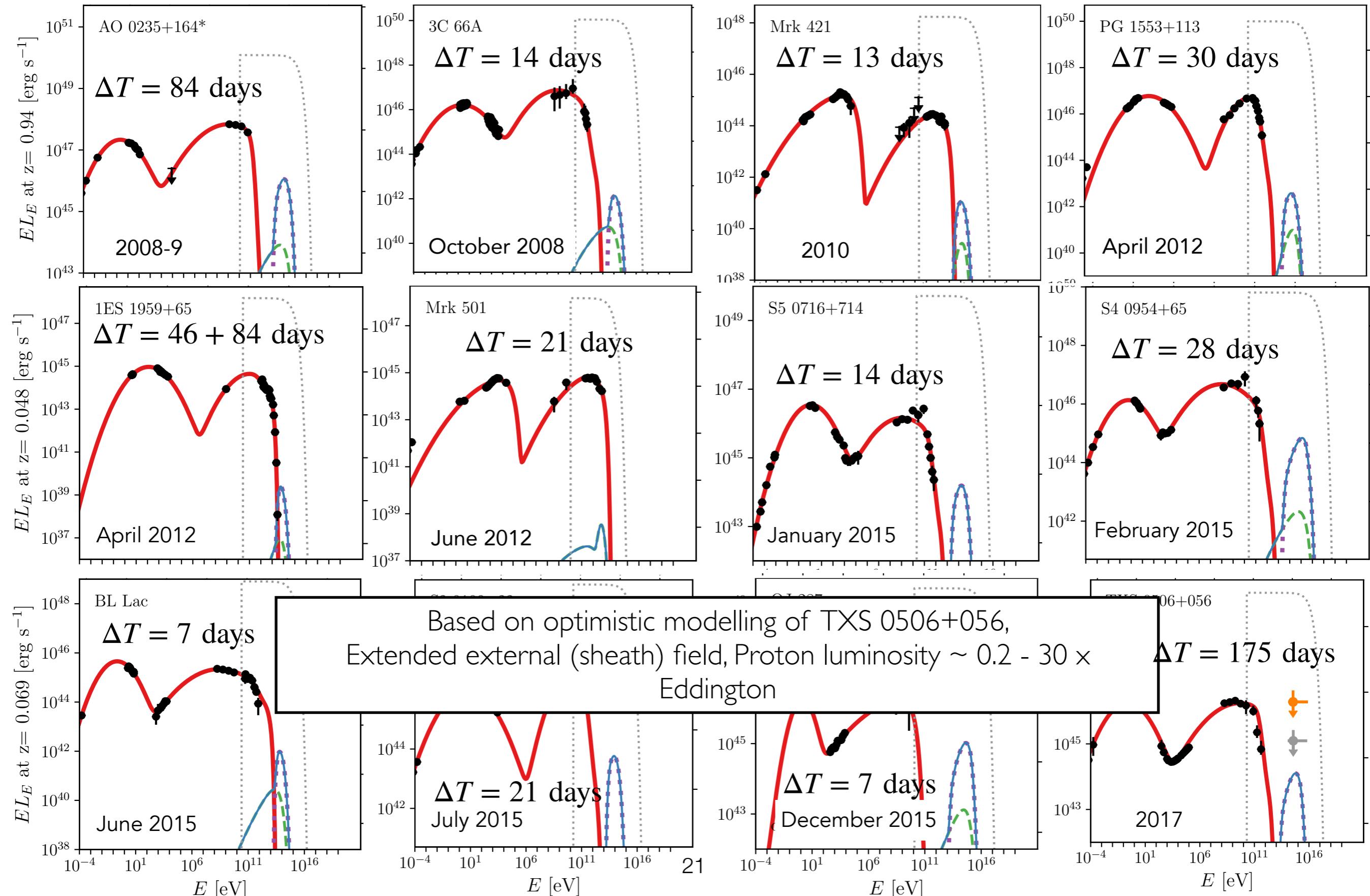
FAVA light curves

FO, Murase, Padovani, Resconi, Mészáros, MNRAS, 23, 2019

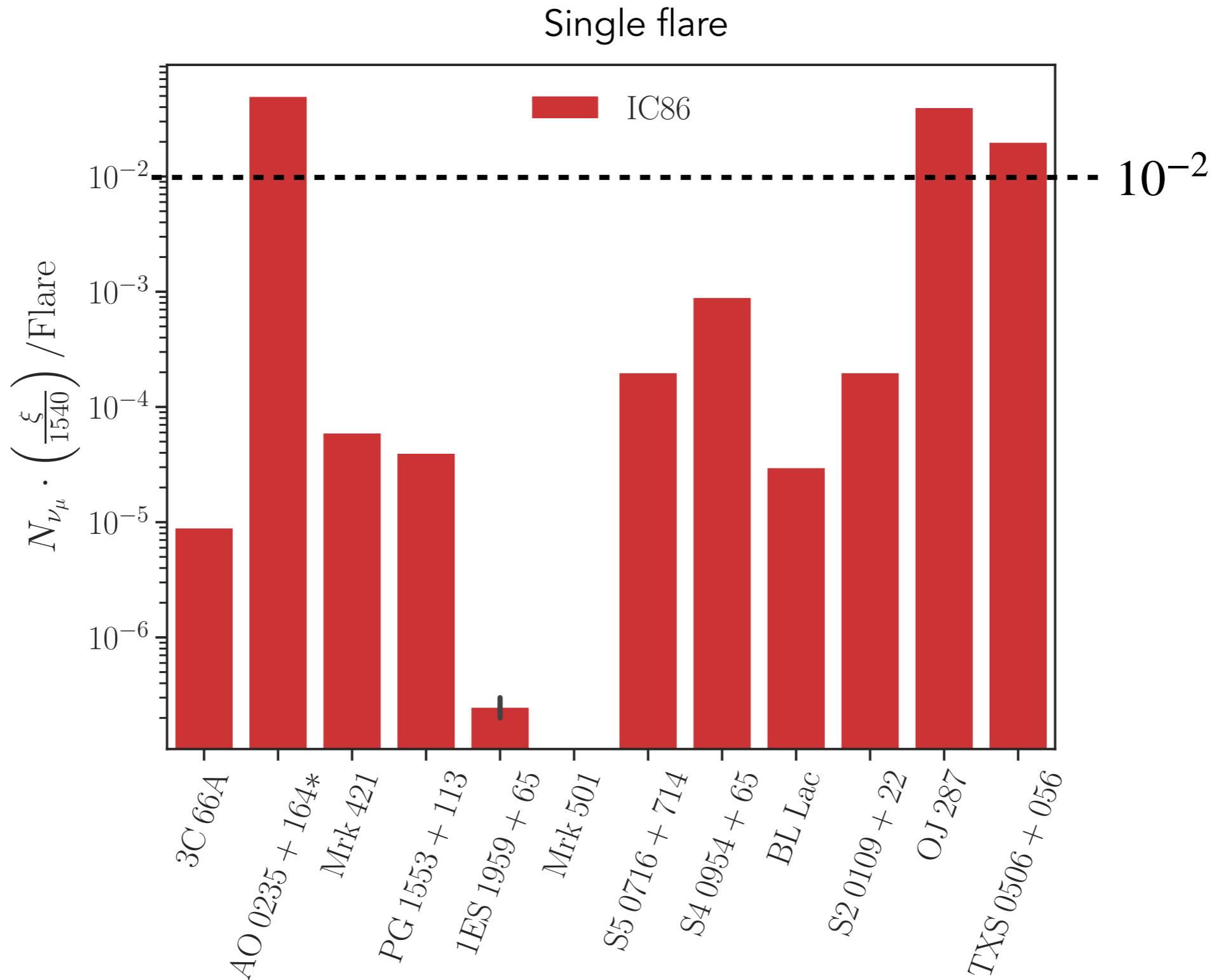


Optimistic scenario based on 2017 flare of TXS 0506+056

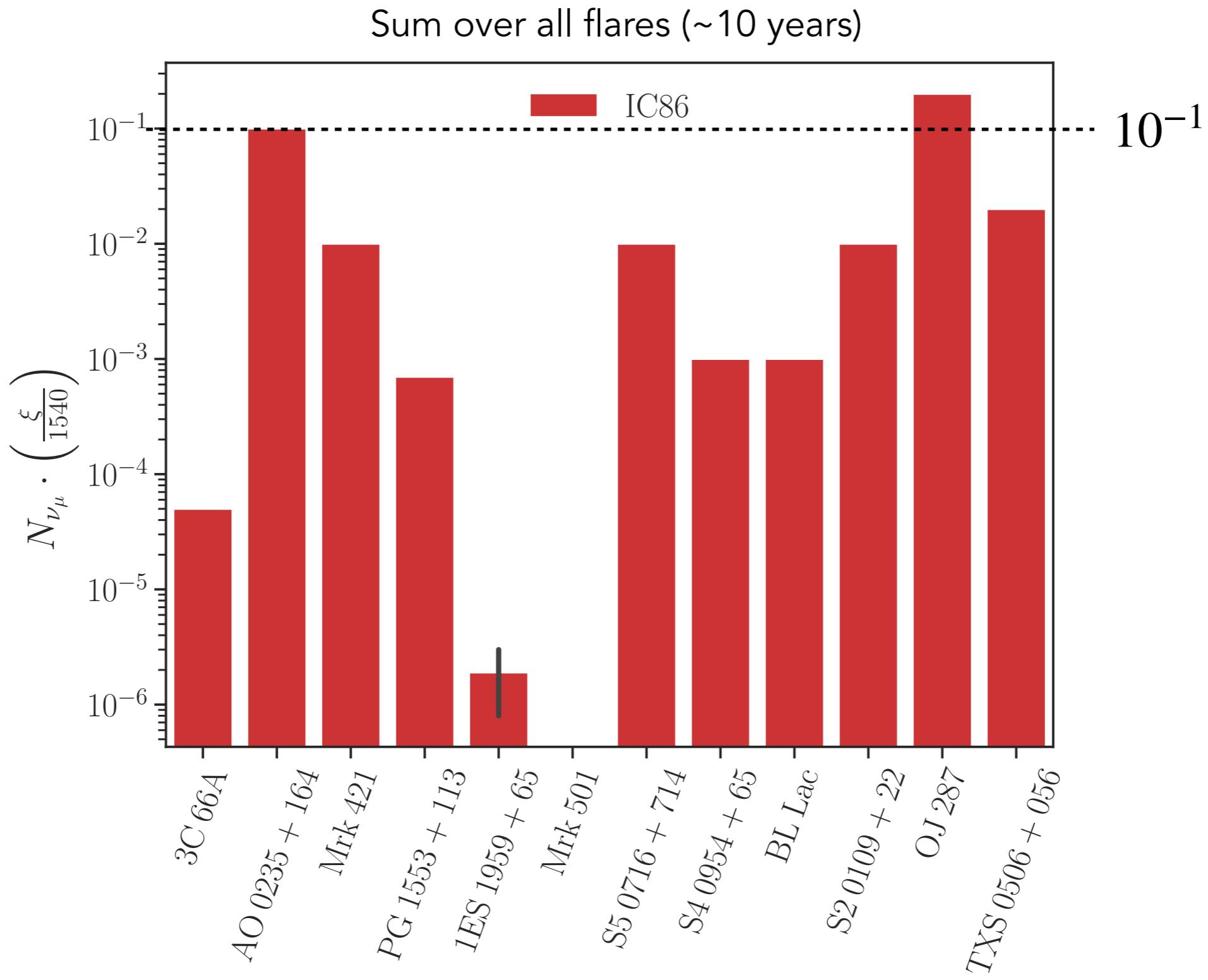
FO, Murase, Padovani, Resconi, Mészáros, MNRAS, 23, 2019



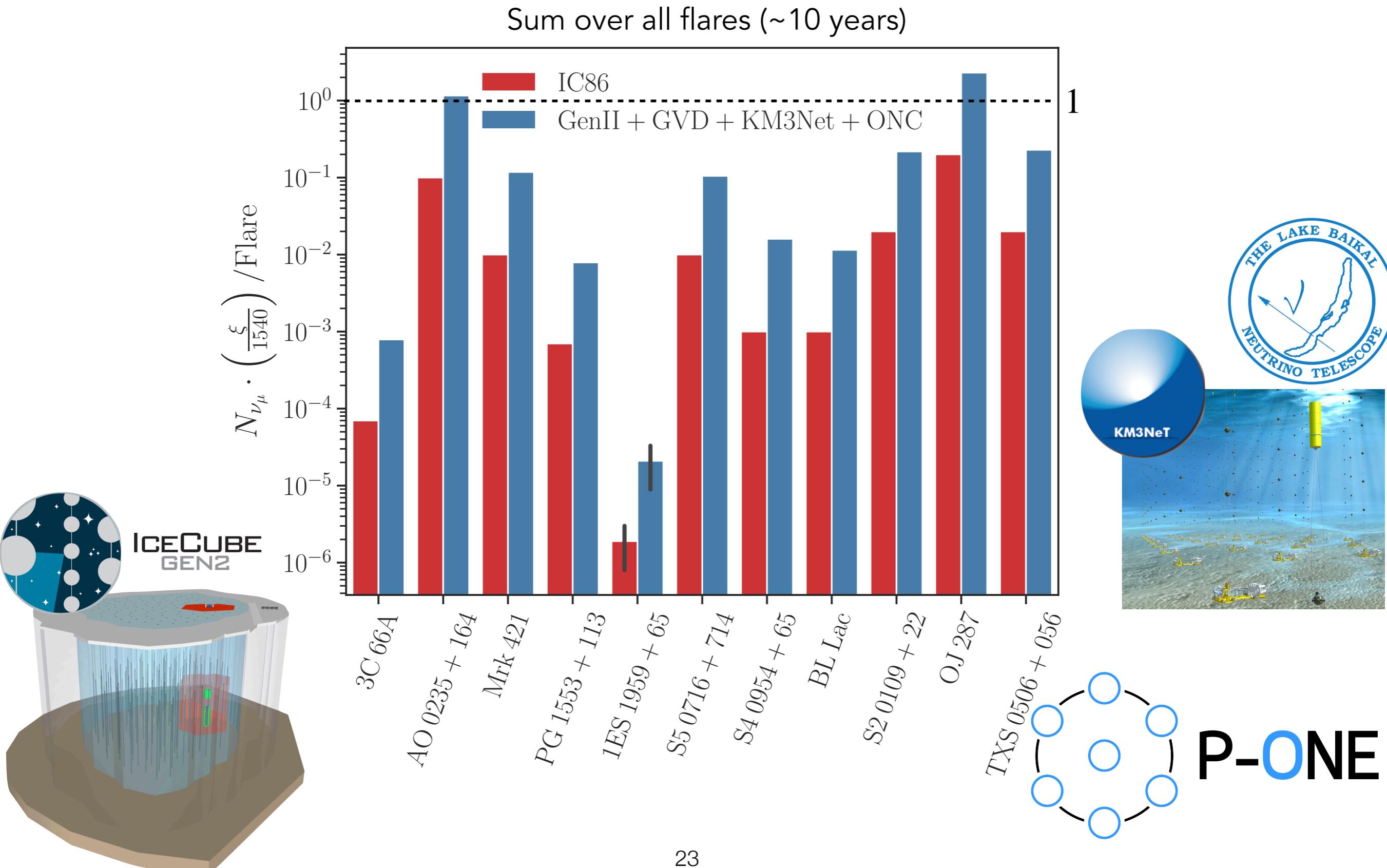
Expected neutrino signal in optimistic case



Expected neutrino signal in optimistic case



Expected neutrino signal with next generation detectors



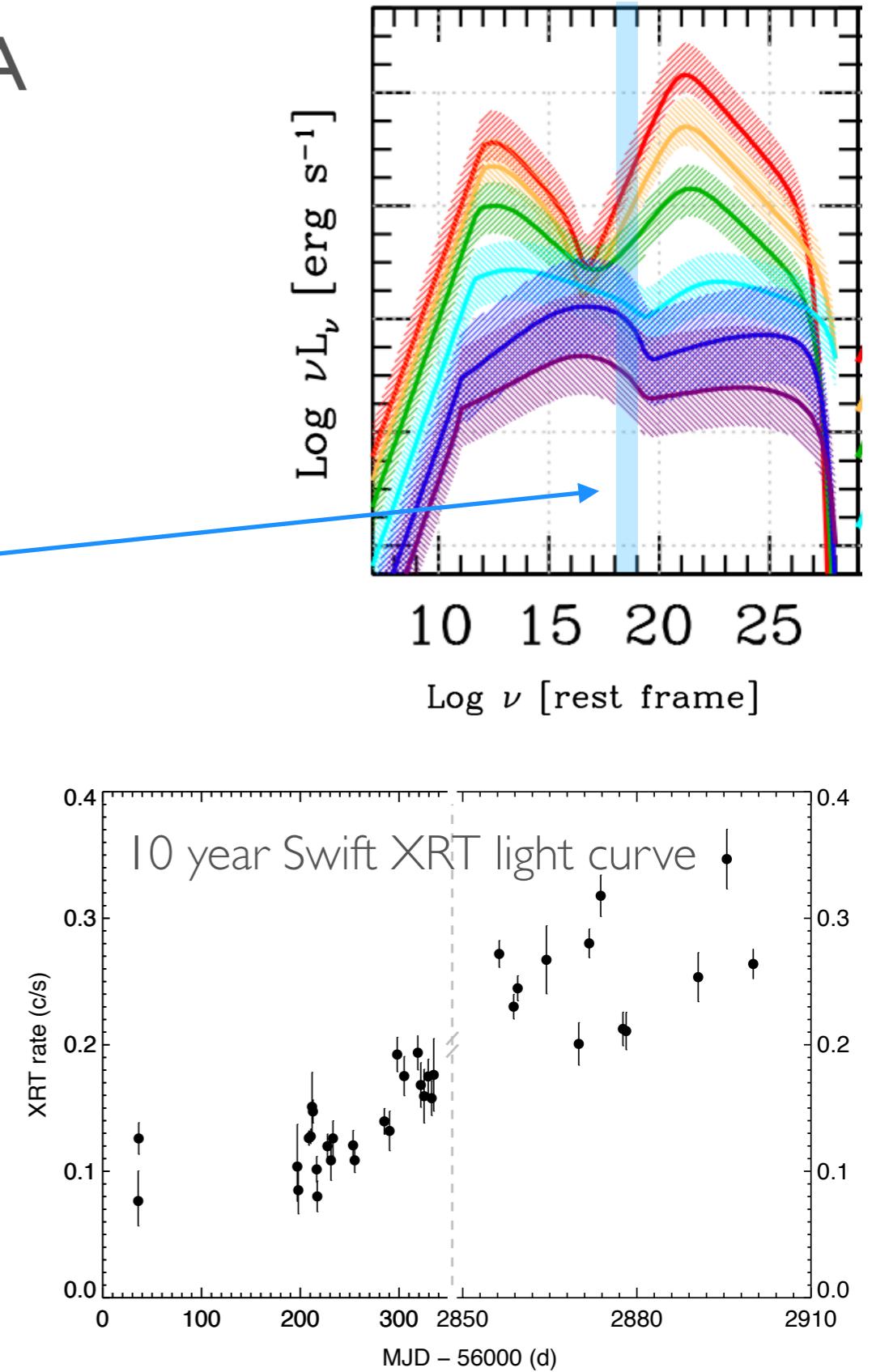
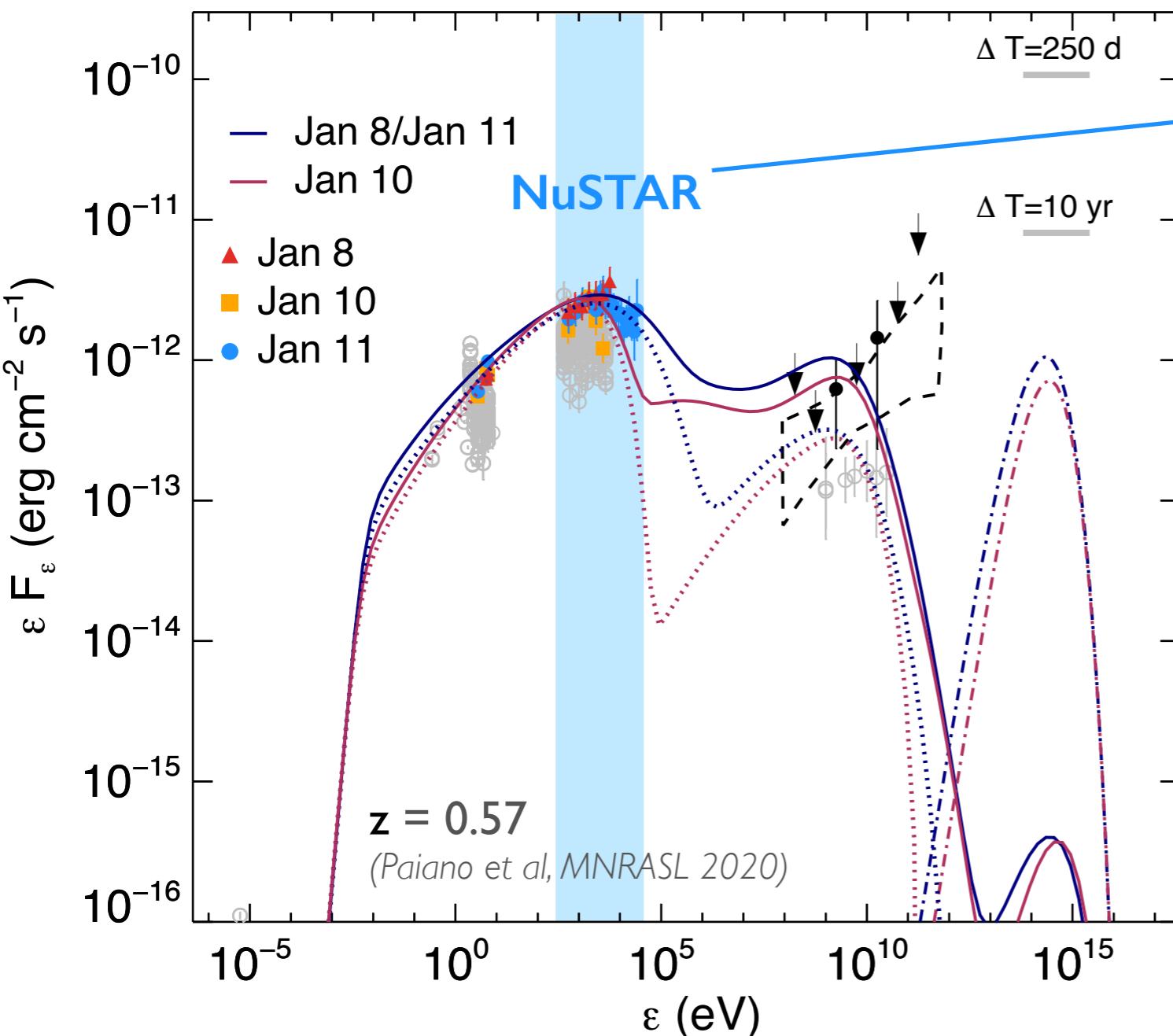
- Diffuse limits
- Flares
- **Recent IceCube Alerts**

3HSP J095507.9+355101 - IC 200107A

Giommi, Padovani, FO, Glauch, Paiano, Resconi, A&A Letters (arXiv:2003.06405)
 [see also Paliya, Böttcher et al. ApJ, arXiv:2003.06012]

Extreme HSP with luminosity similar to TXS 0506+056
 coincident with ~ 0.3 PeV track

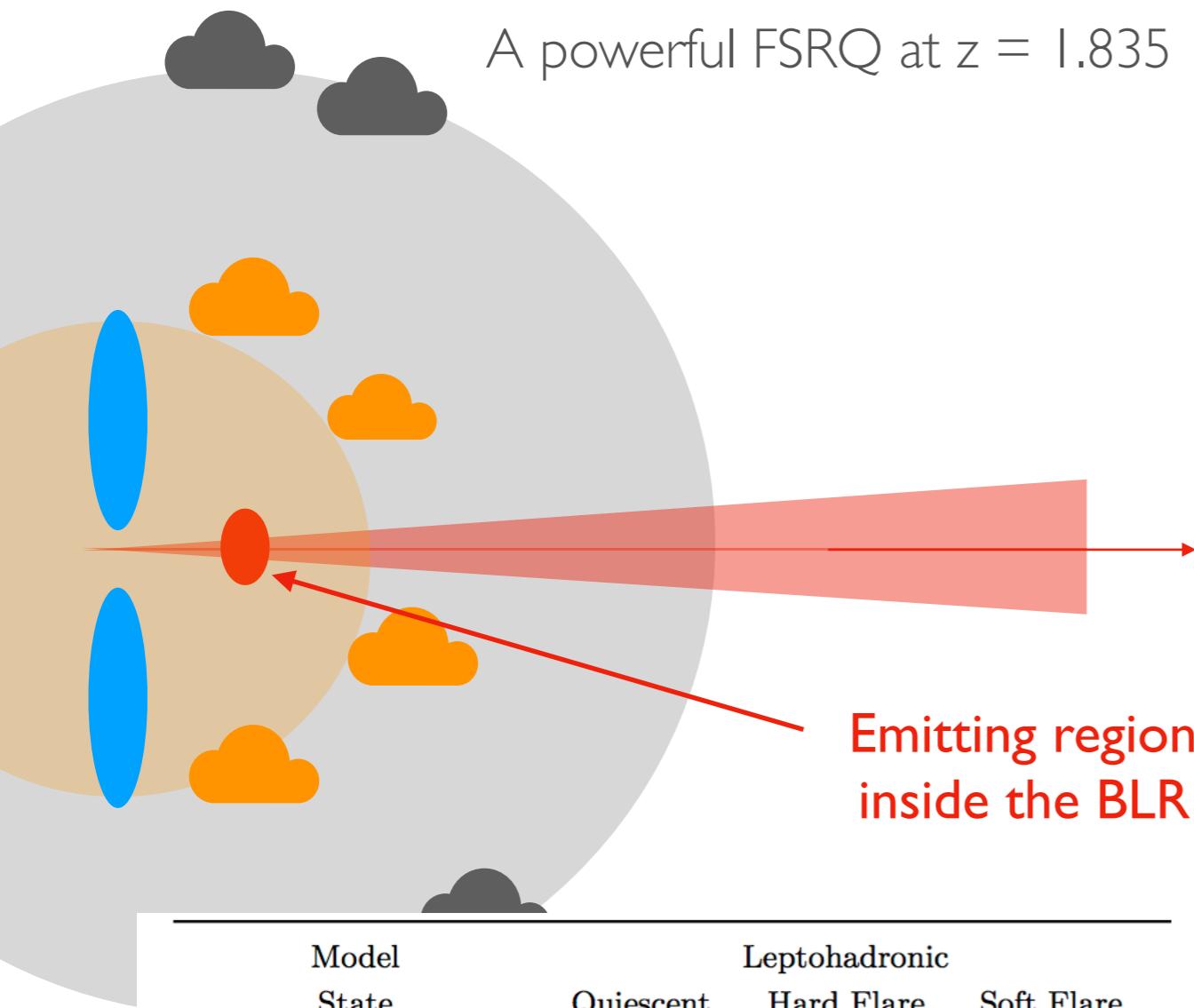
Petropoulou, FO et al, ApJ, 889 (2020) arXiv:2005.07218



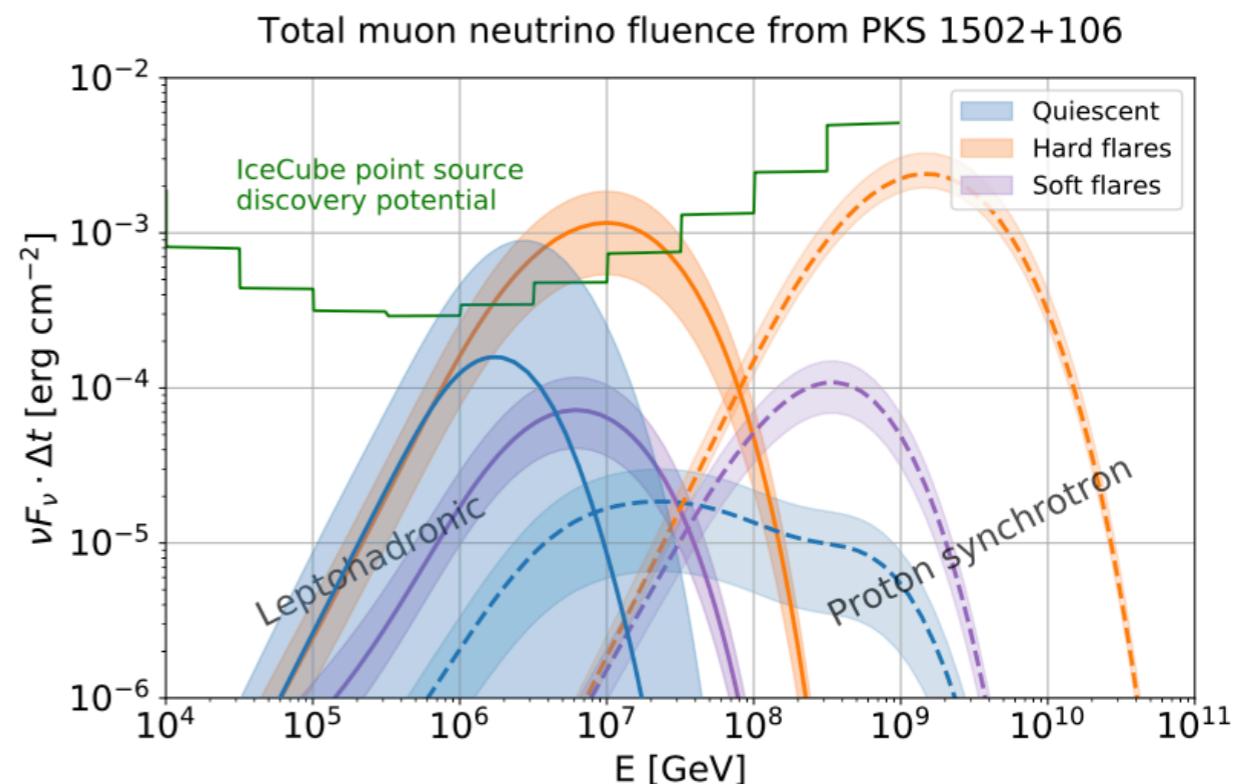
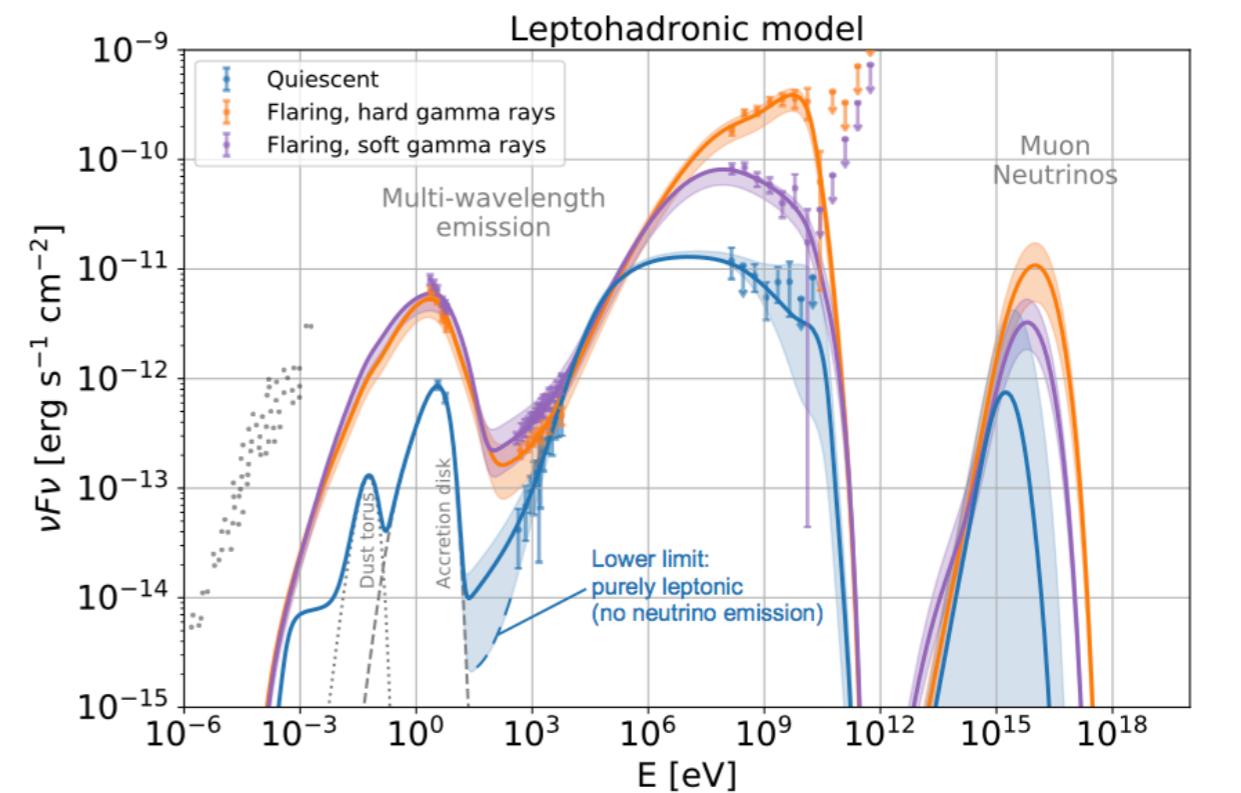
$N_{\nu_\mu} \lesssim 0.1/10$ years (IC Point Source)
 $\lesssim 0.01/10$ years (IceCube GFU)

PKS 1502+106 - IC 190730A

Franckowiak et al. 2020, *ApJ* 893(2):162
 Rodrigues, Garrappa et al, arXiv: 2009.04026v1



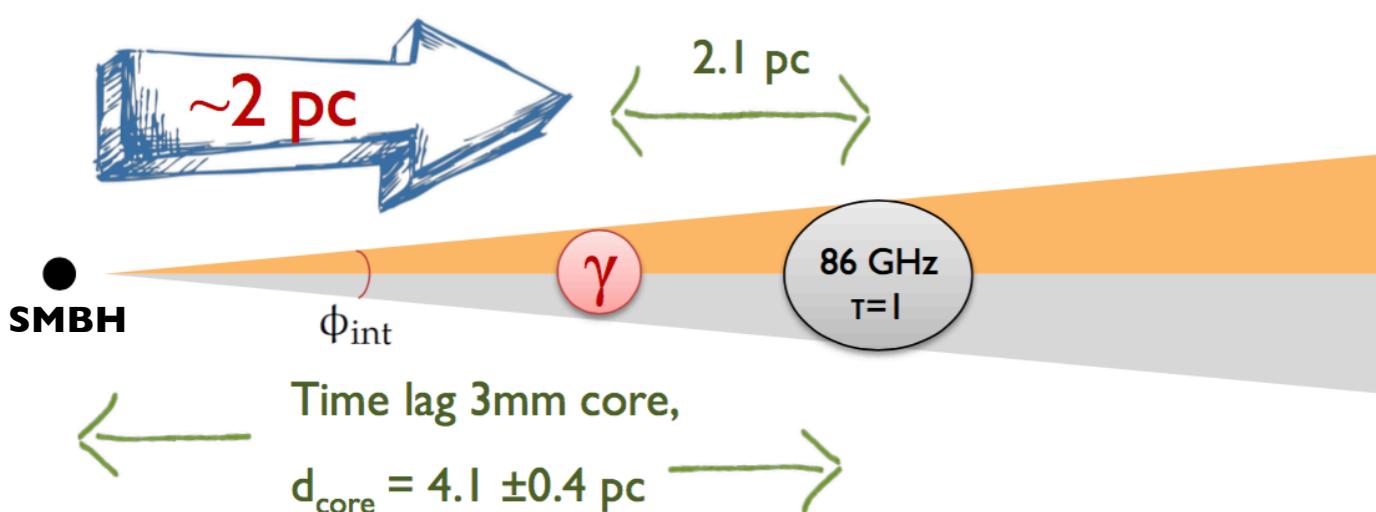
But this is a monitored source and IC Point Source data show no archival events -IC 8yr PS limits



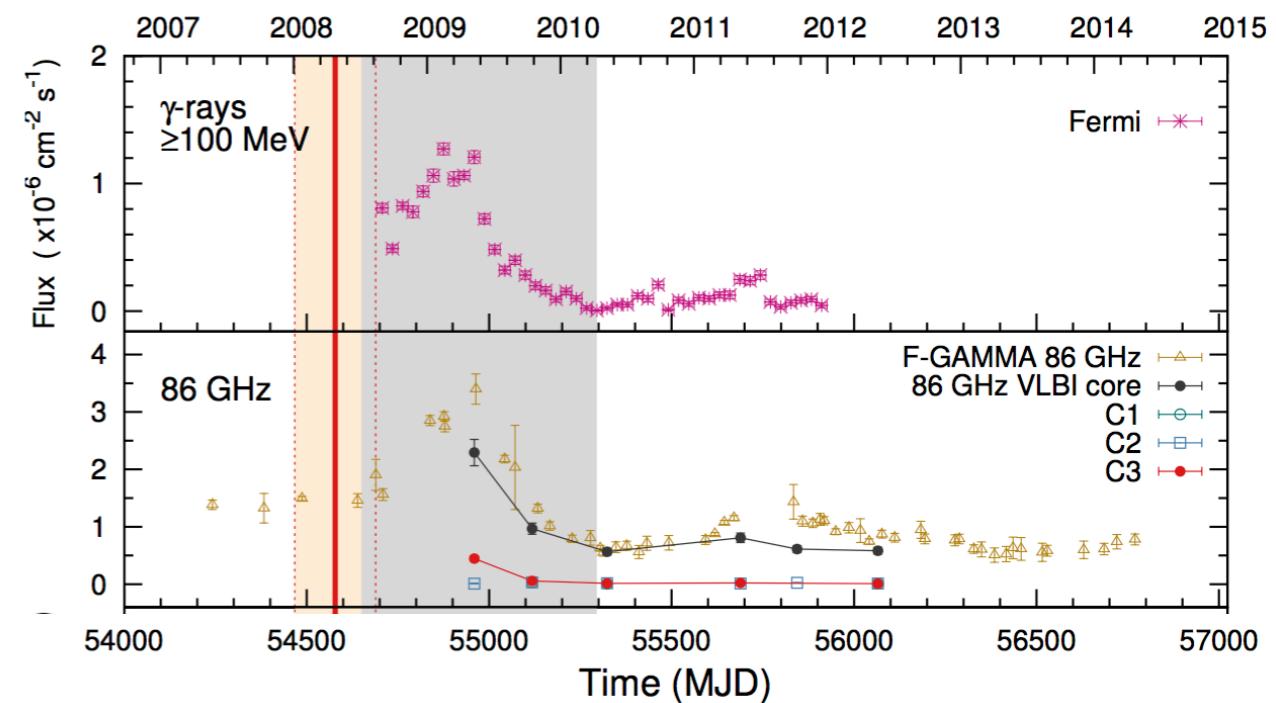
see also Kun, Bartos et al arXiv:2009.09792

The location of the emitting region in PKS 1502+106

A VLBA monitored source
(F-GAMMA, MOJAVE...)



Karamanavis et al 2016



Gamma-rays at $\sim 2 \text{ pc}$ during 2008 flare (Furhmann et al 2014, Max-Moerbeck, Hovatta et al, MNRAS, 2014, Karamanavis et al 2015, 2016)

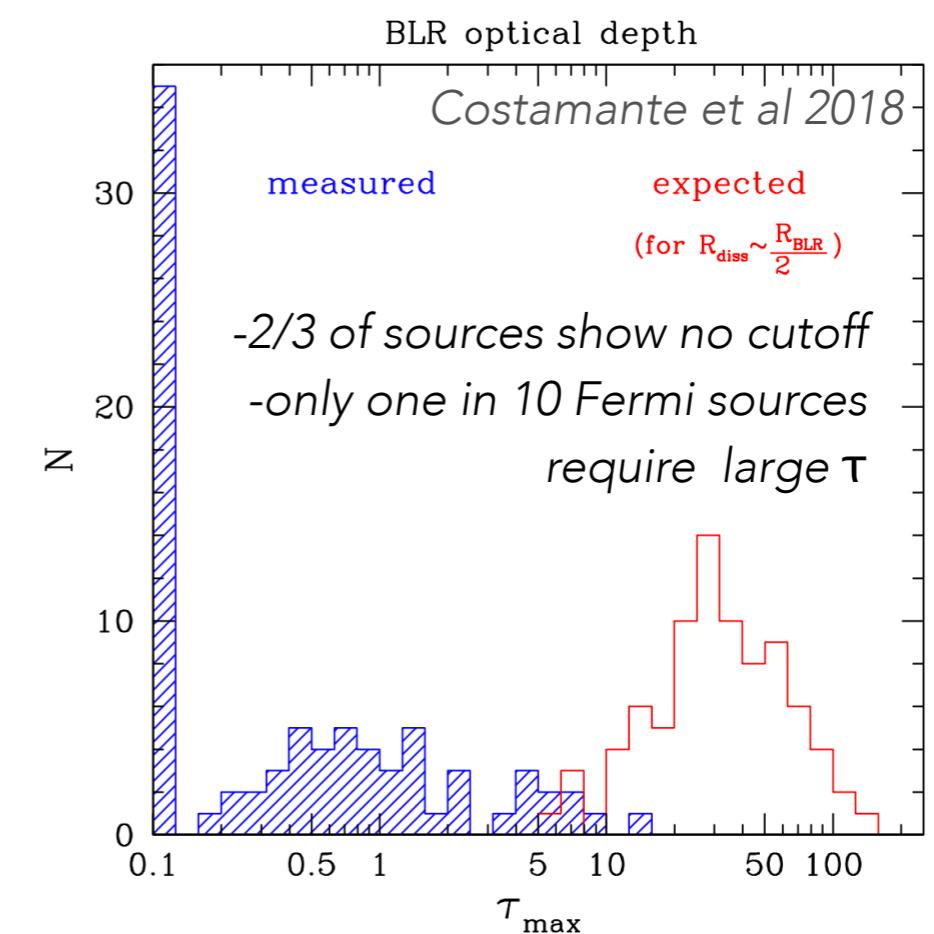
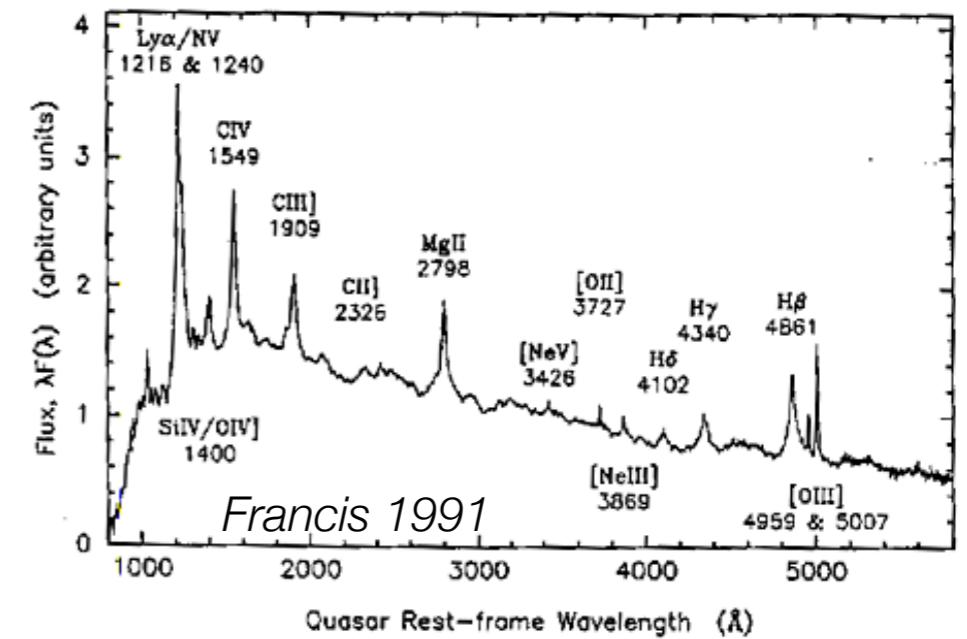
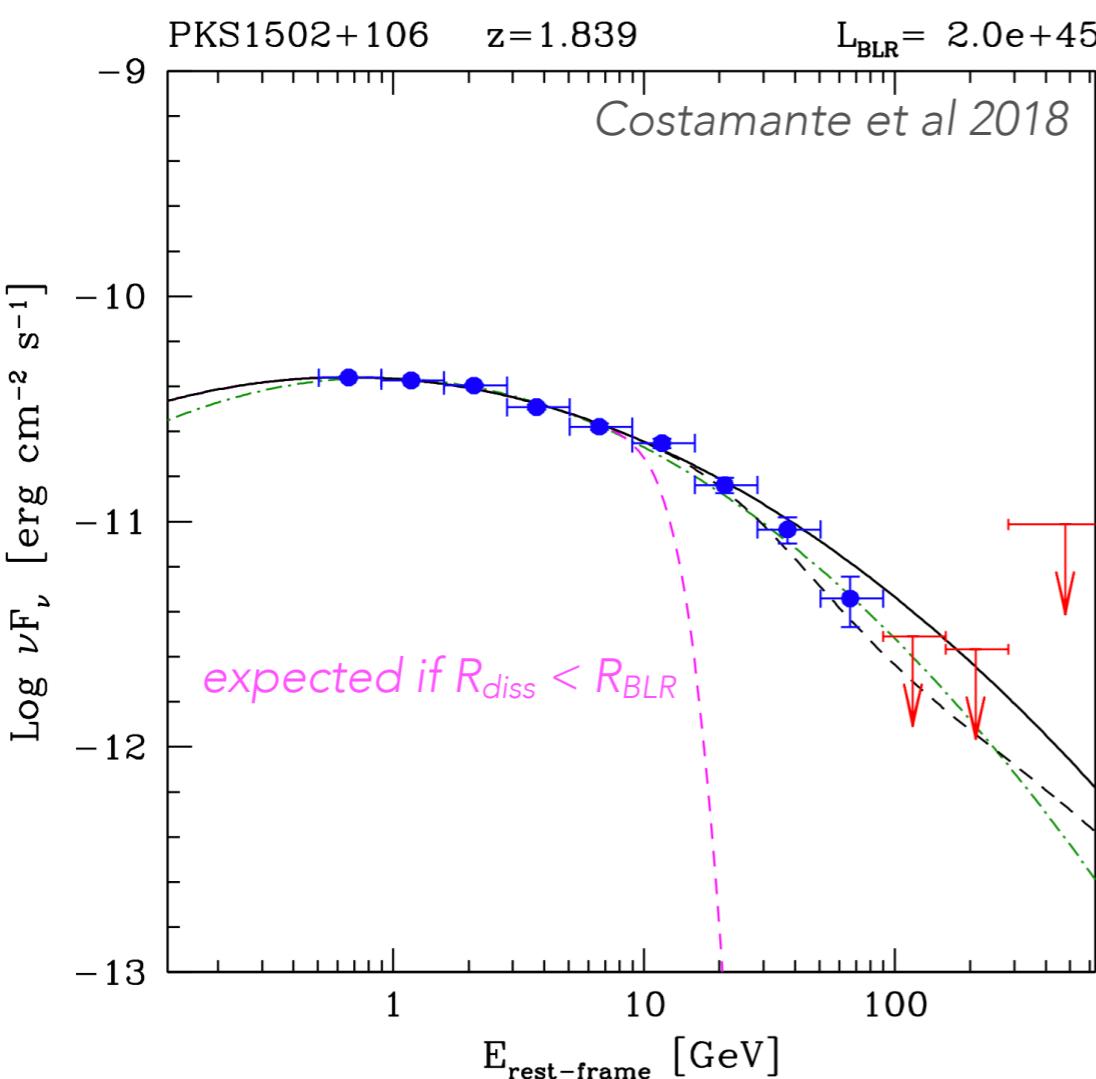
Optical and gamma rays $\sim 1.2 \text{ pc}$ from jet-base 10 year analysis (Shao et al. 2019 ApJ)

The location of the emitting region in FSRQs

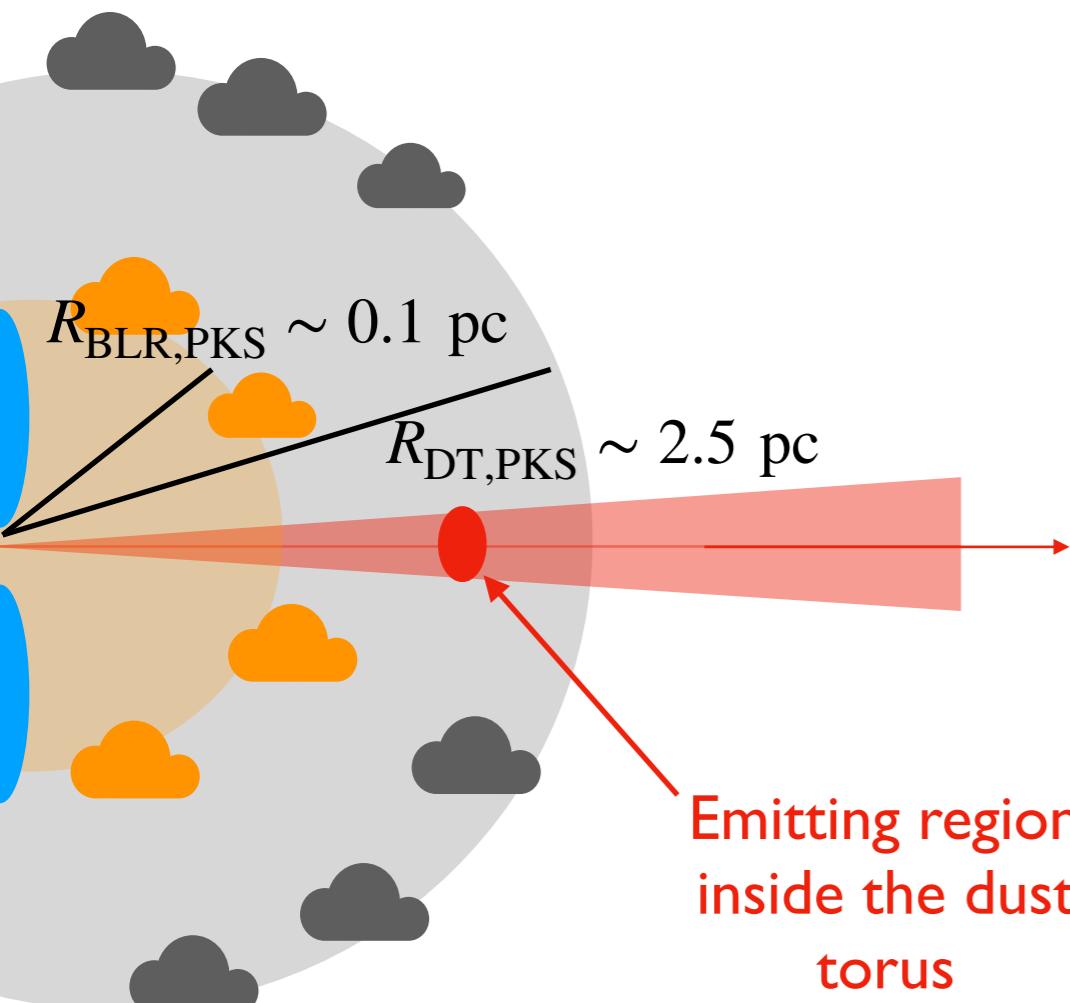
Abdo et al. 2010,
 Costamante et al 2010, 2018,
 see also Plavin, Kovalev, Petrov, 2018

A break is expected if $R_{\text{diss}} < R_{\text{BLR}}$

$$E_{\gamma, \text{br}} \approx \frac{20 \text{ GeV}}{(1+z)} \frac{10.2 \text{ eV}}{\epsilon_\gamma}$$

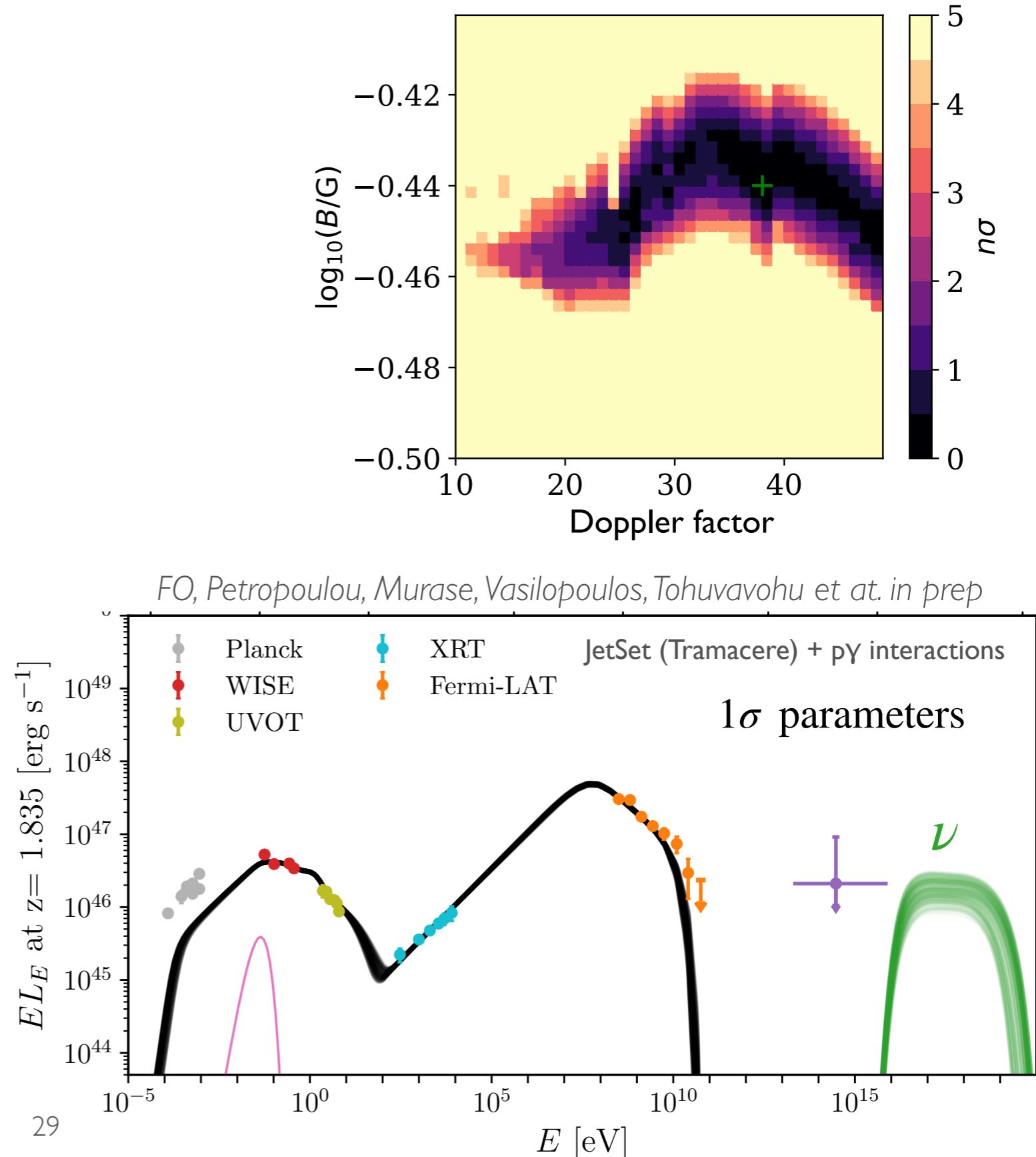


PKS 1502+106: Neutrino production in the dust torus



From quiescent SED:

$N_{\nu_\mu}(E > 100 \text{ TeV})/10 \text{ years} \sim 0.01 \text{ GFU}$
 $\sim 0.1 \text{ IC Point Source}$
 with $L_{\text{CR}} \sim L_{\gamma}$



Summary

Blazars: Natural candidates for HE/UHE acceleration

Not the sources of IceCube neutrinos/may be dominant at higher energies

Some bright blazars are very interesting point sources for next generation neutrino detectors

Very precise astronomical measurements needed for modelling!

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

