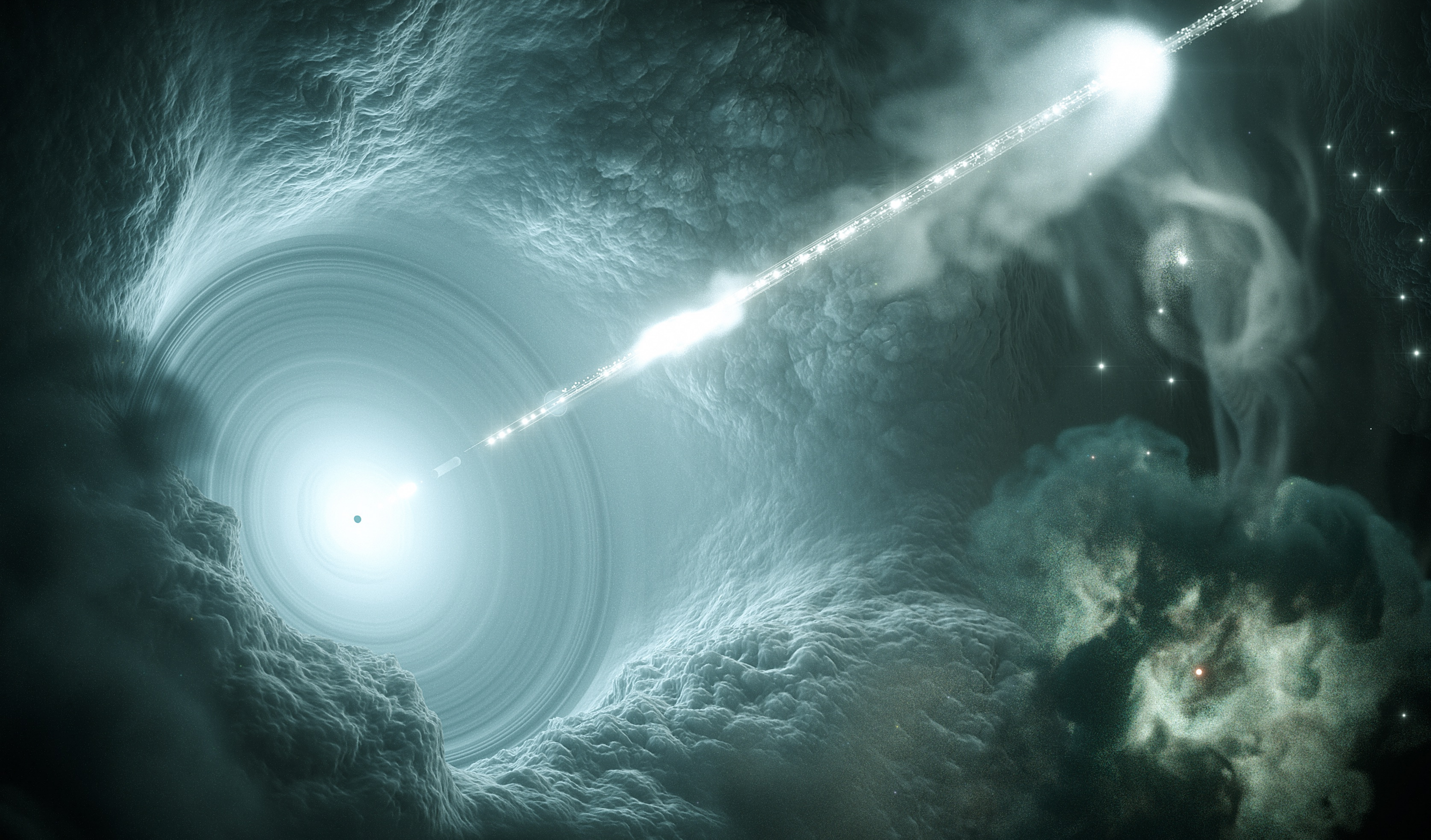


Blazars: High-energy neutrino emission and their multi-messenger role

Foteini Oikonomou

NTNU
Norwegian University of
Science and Technology

7 Dec 2020
Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives

Blazars as an orientation

Brightest persistent sources in the sky:

- Up to 10^{48} erg/s
- Out to z ~ 7.5

Very rare objects:

- 1 in 100 galaxies hosts an AGN
- 10% of AGN have a jet

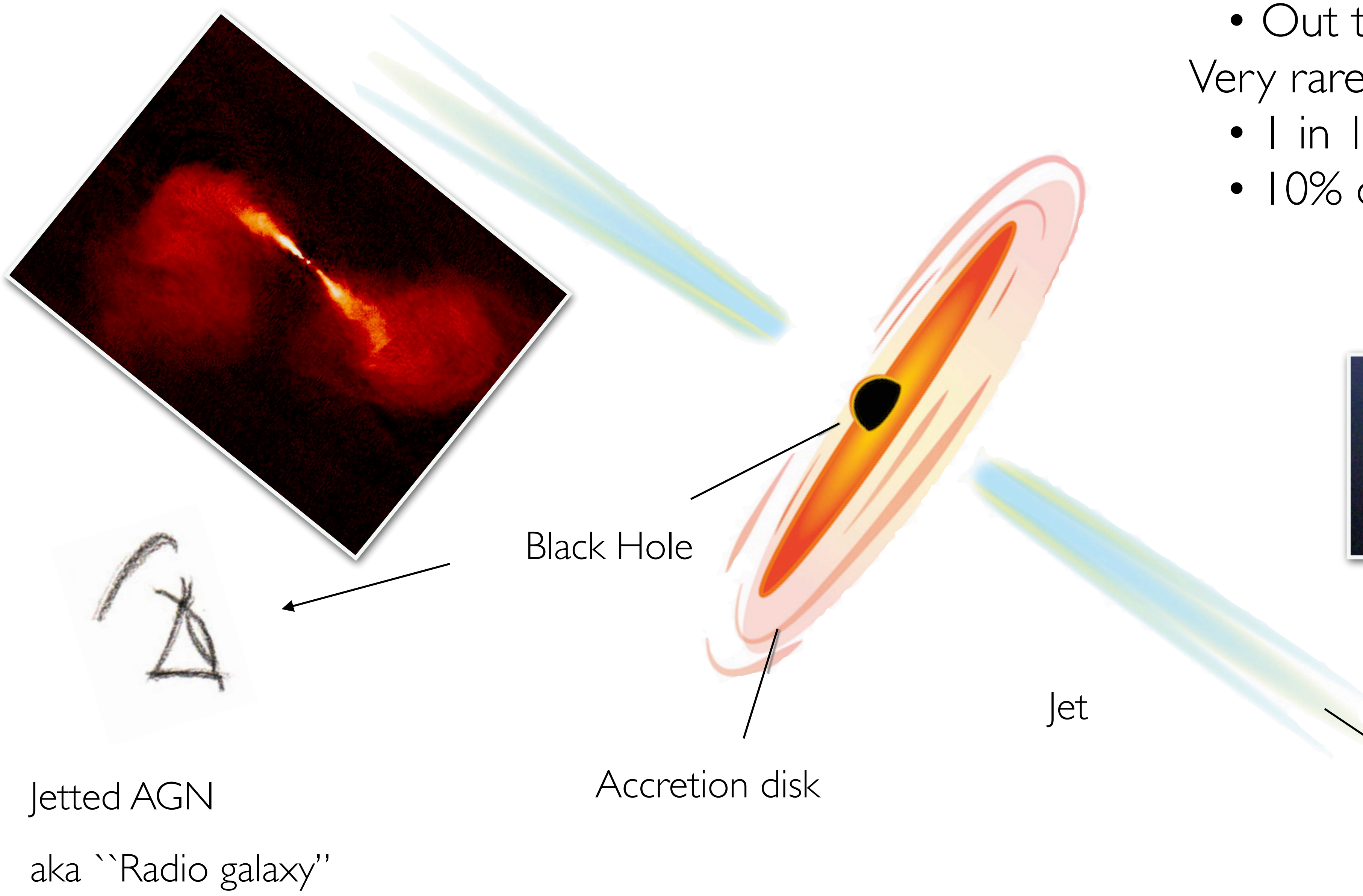
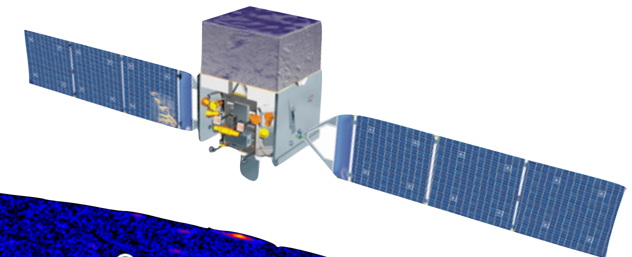


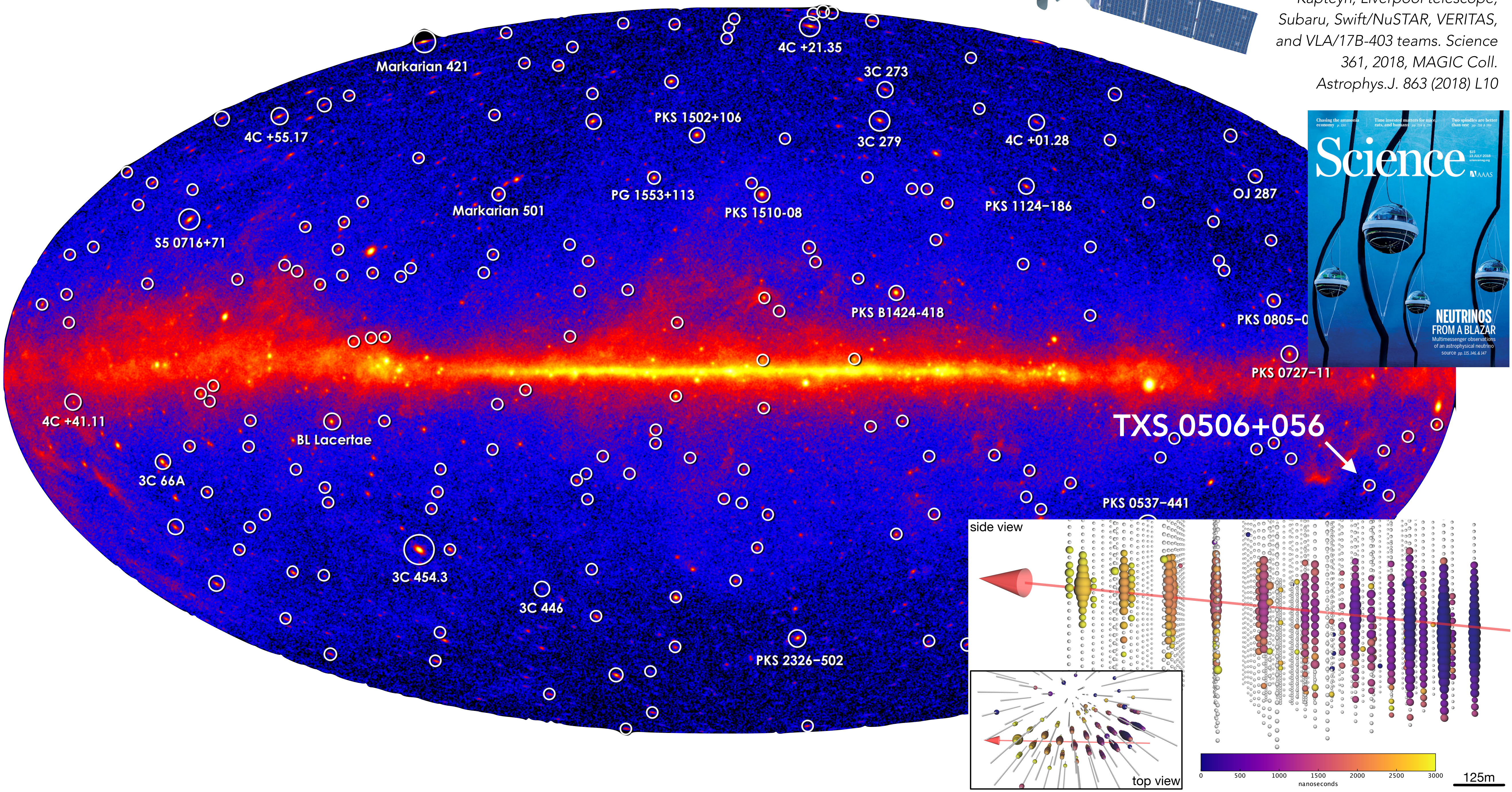
Image Credit: Sophia Dagnello, NRAO/AUI/NSF, SDSS, EGRET, VLBA

Blazars Dominate the Extragalactic γ-ray sky

Fermi 5-yr blazars

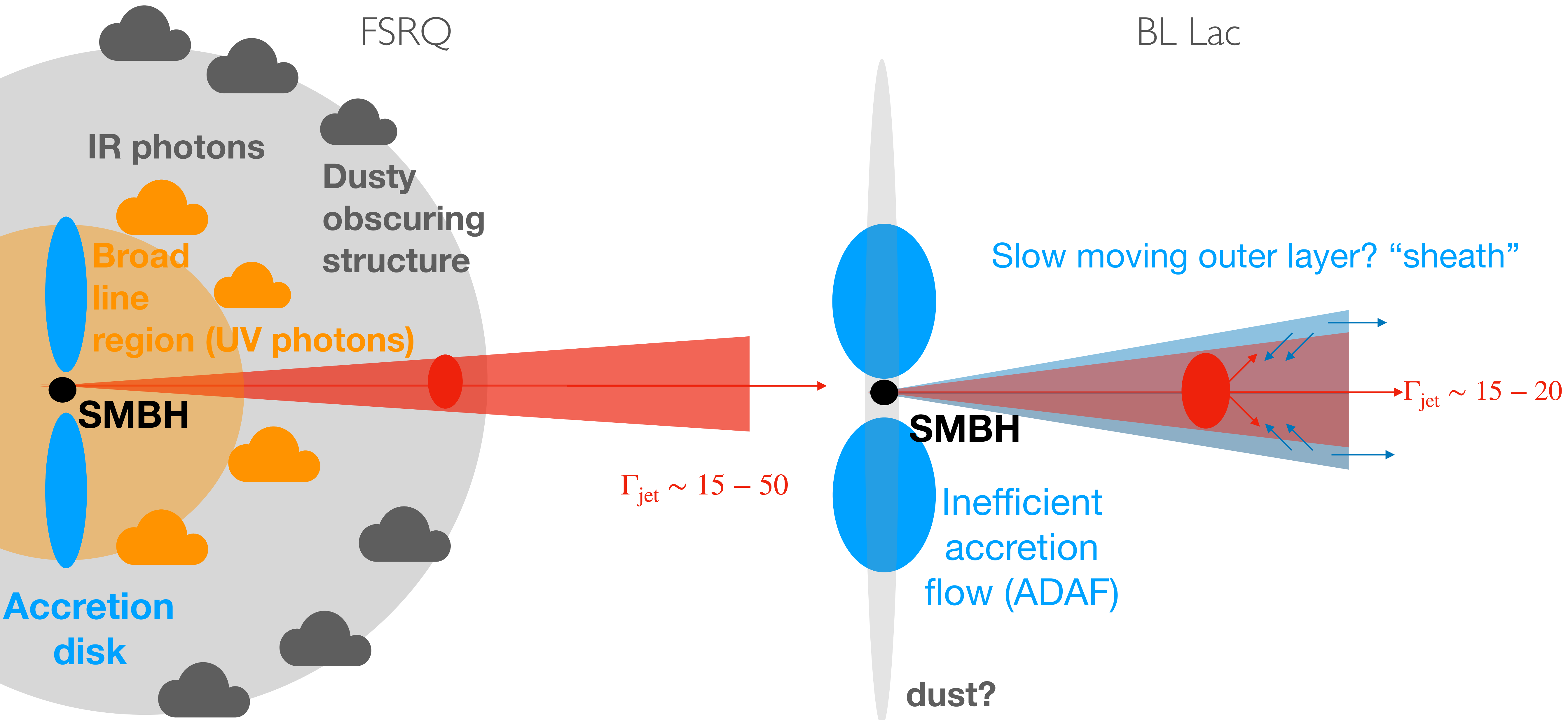


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. Science 361, 2018, MAGIC Coll. Astrophys.J. 863 (2018) L10



>90% of extragalactic Fermi sources

BL Lac objects vs Flat Spectrum Radio Quasars



Very powerful collimated jets

Radiatively efficient accretion disk

Luminosity close to Eddington limit

Less powerful jets (plumes at large distances)

Radiatively inefficient accretion flow

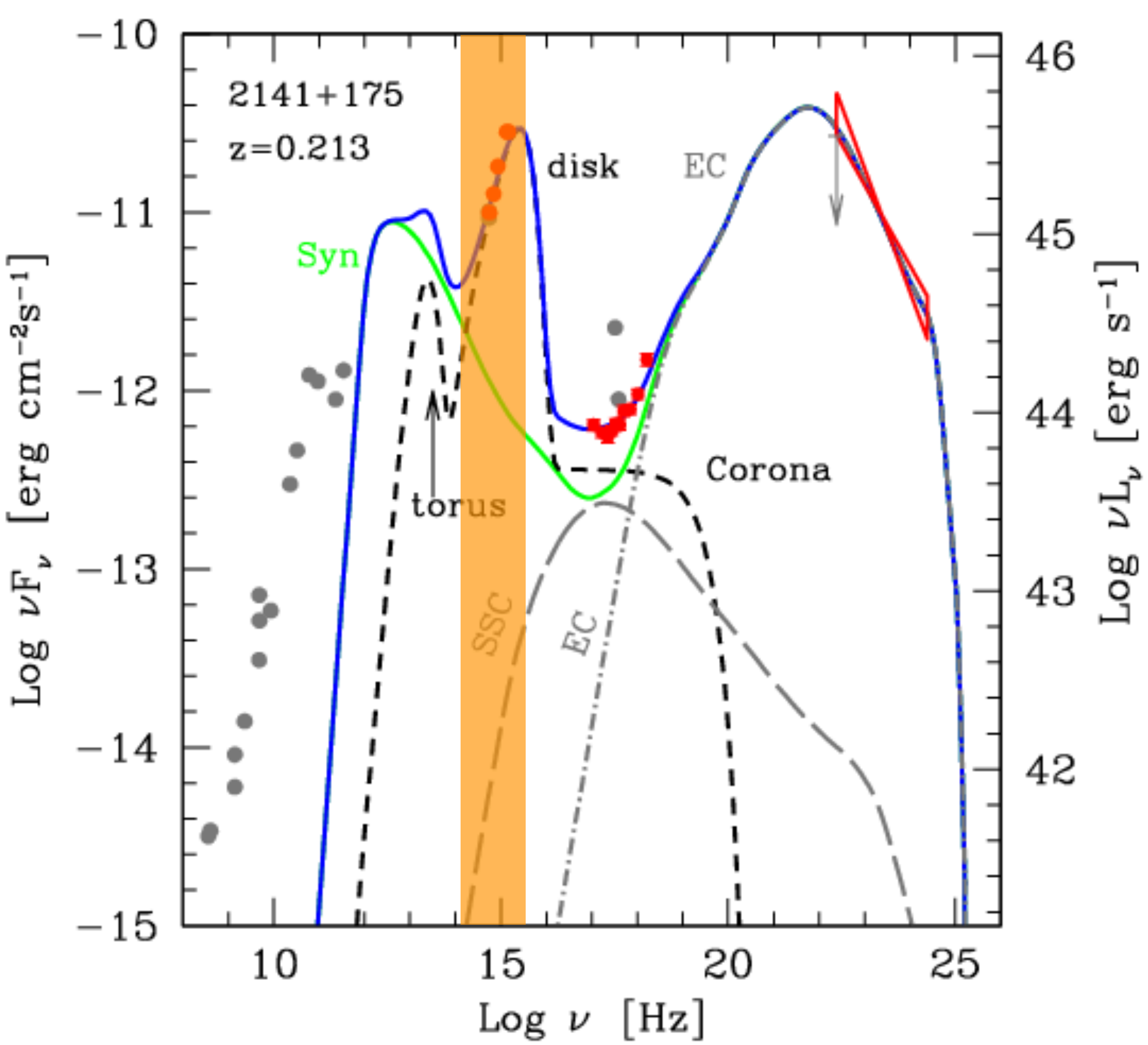
Lower Eddington ratio

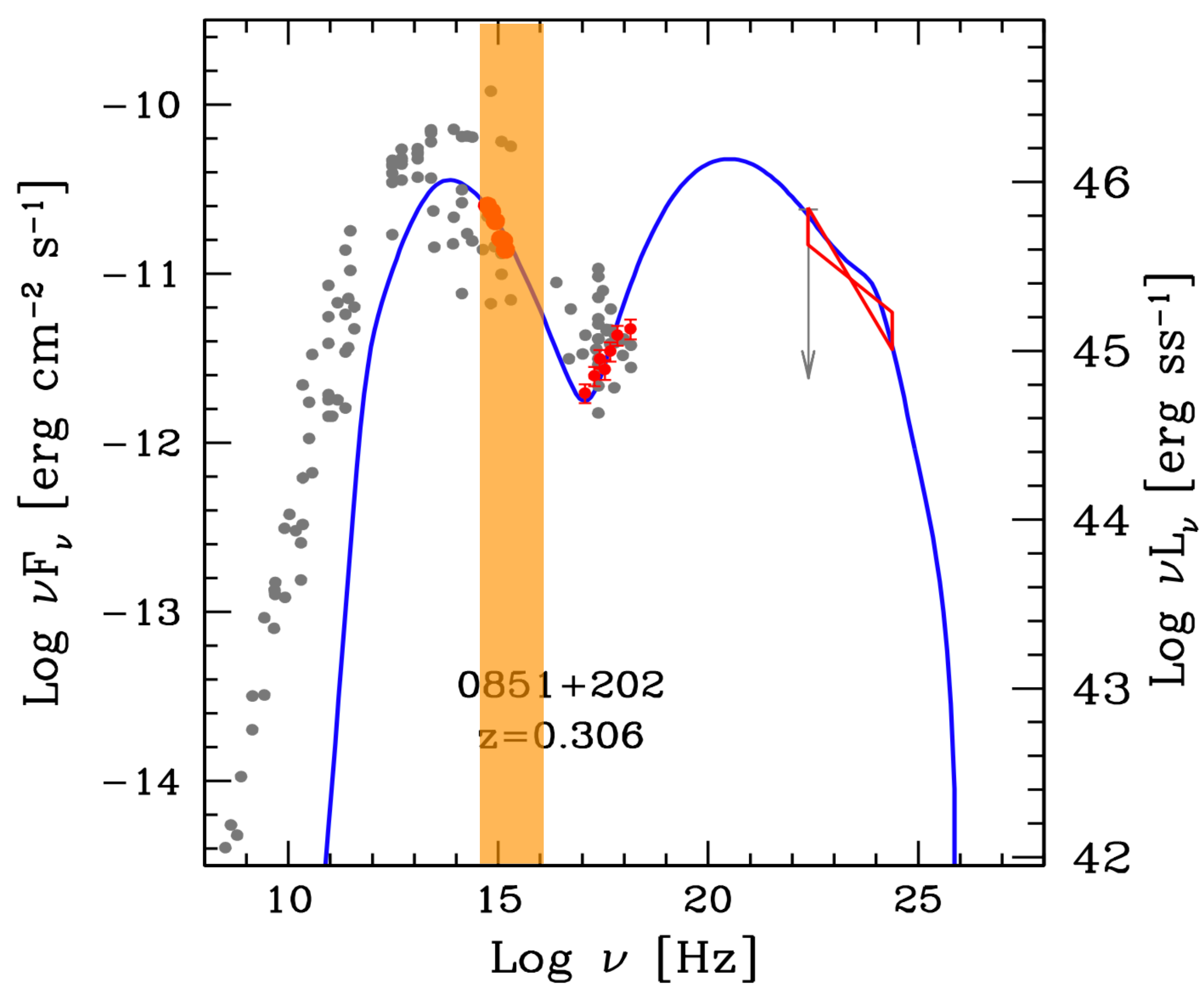
Blazar Classes: BL Lac Objects and Flat Spectrum Radio Quasars

FSRQ

BL Lac

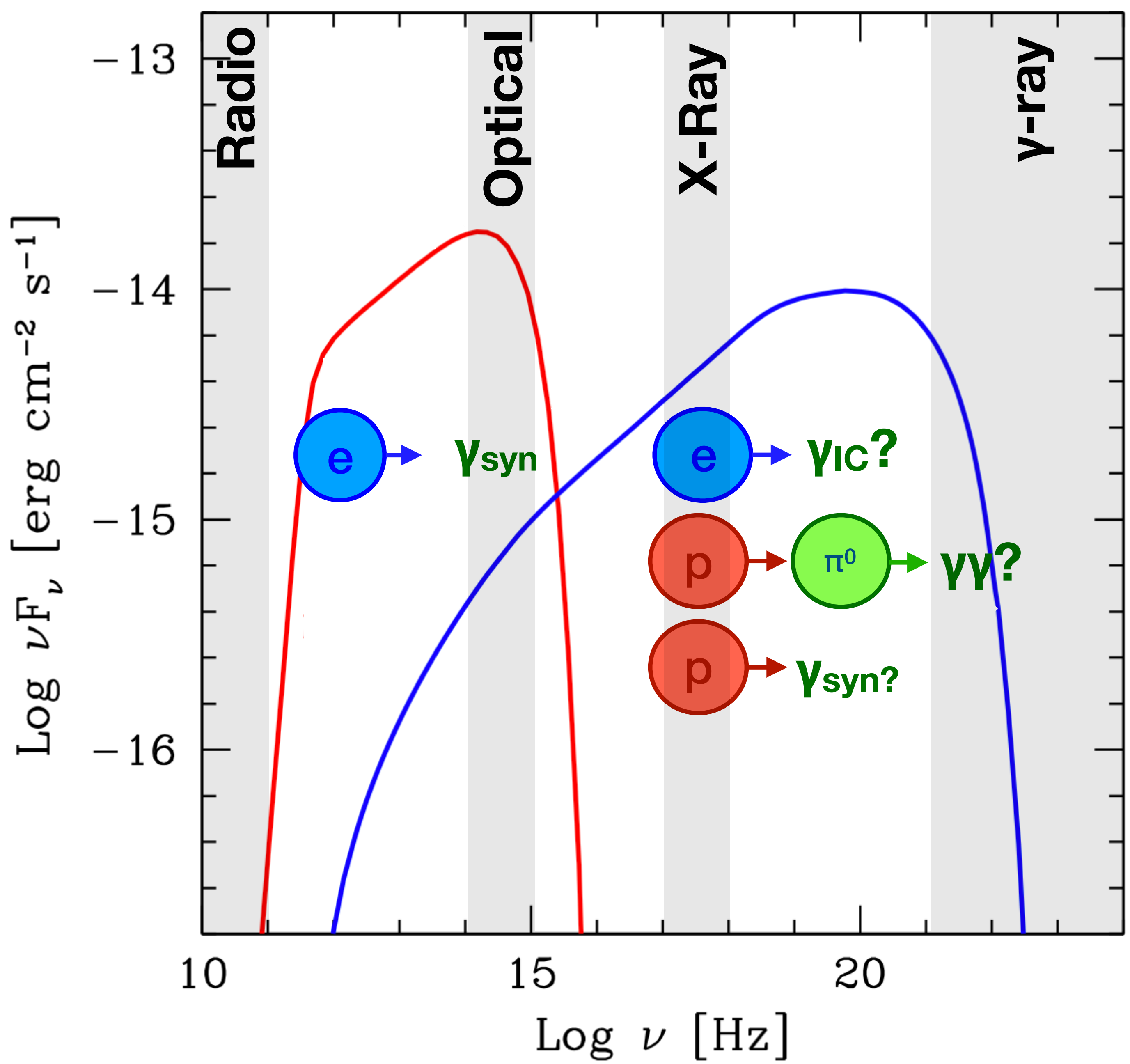
Optical/UV light





plots by Ghisellini 2009

Origin of multi-wavelength non-thermal blazar emission



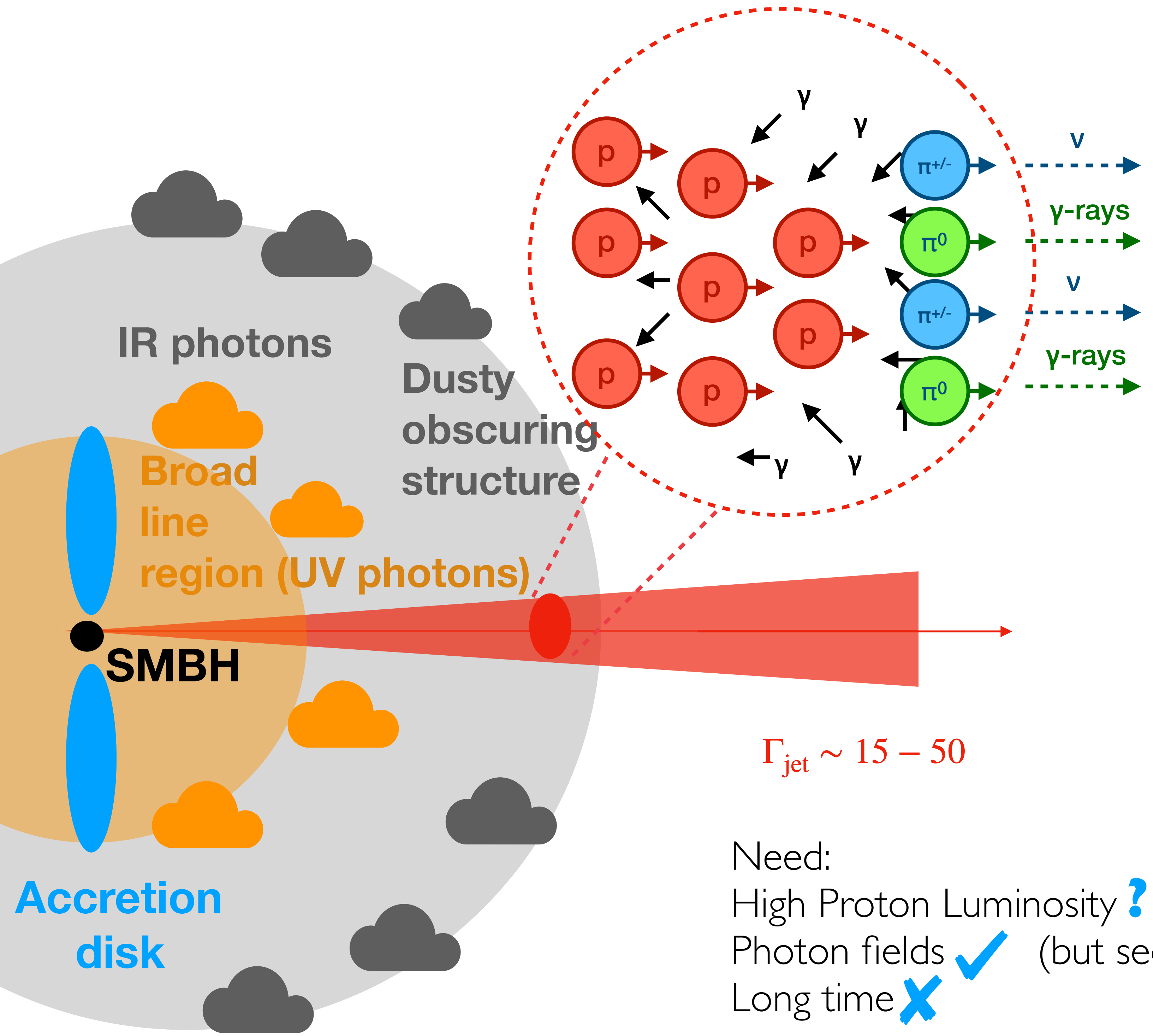
For characteristic values of B, R, and delta, we end up with E_{max} in the ~UHE ball park, if efficient acceleration.

From Hillas condition:

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

Neutrino production in blazars

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

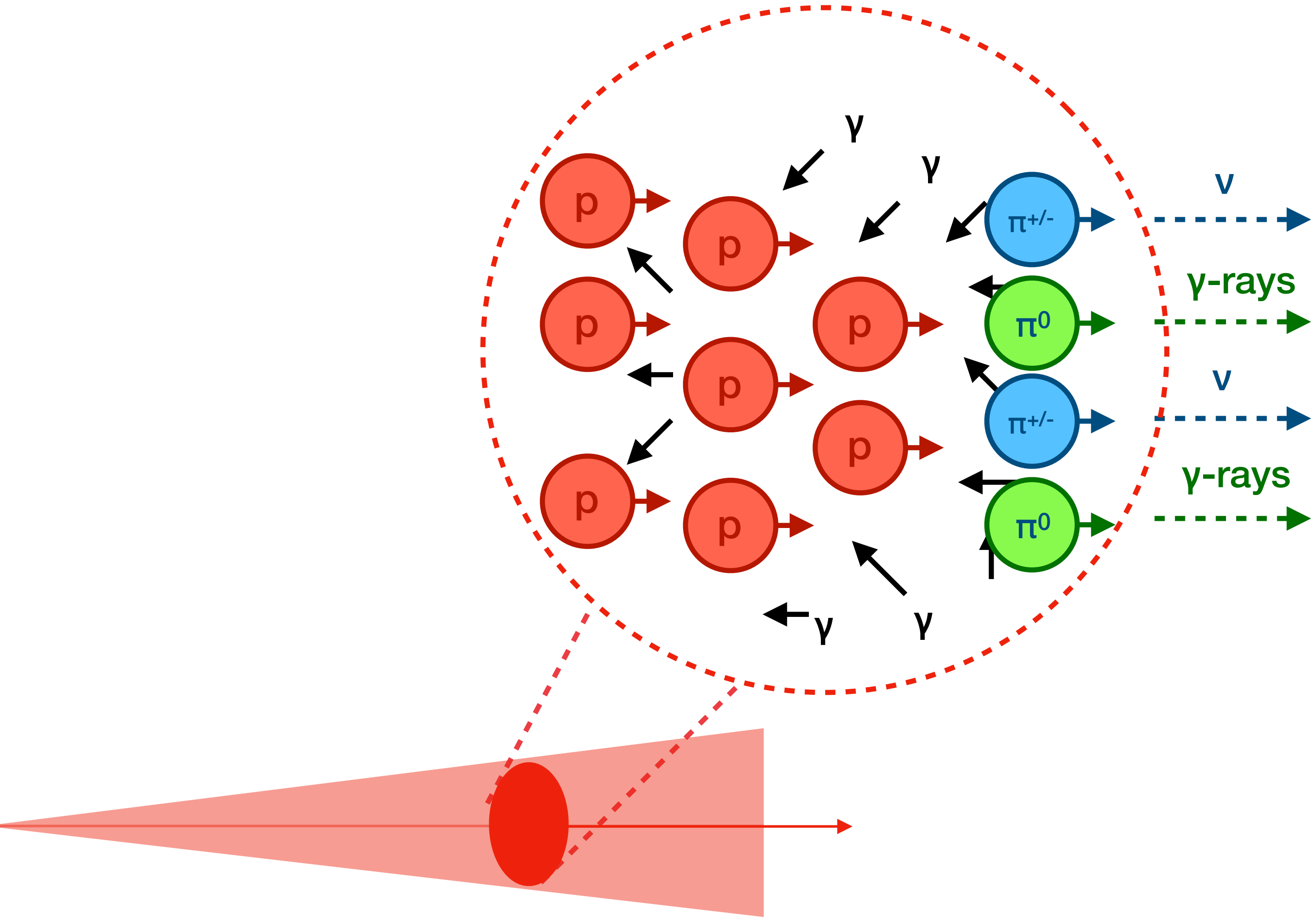


$\Gamma_{jet} \sim 15 - 50$

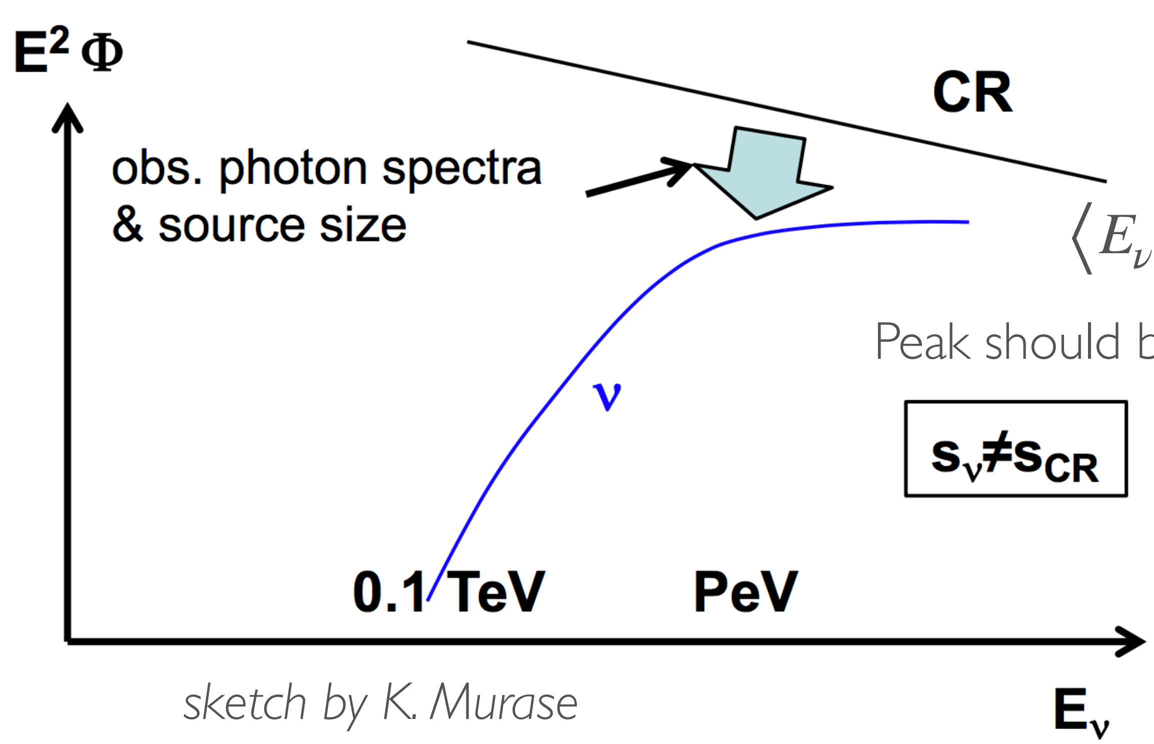
Need:
High Proton Luminosity ?
Photon fields ✓ (but see Costamante 2018, emission beyond the BLR)
Long time ✗

In BL Lacs: Internal radiation, sheath or ADAF

Neutrino production in blazars



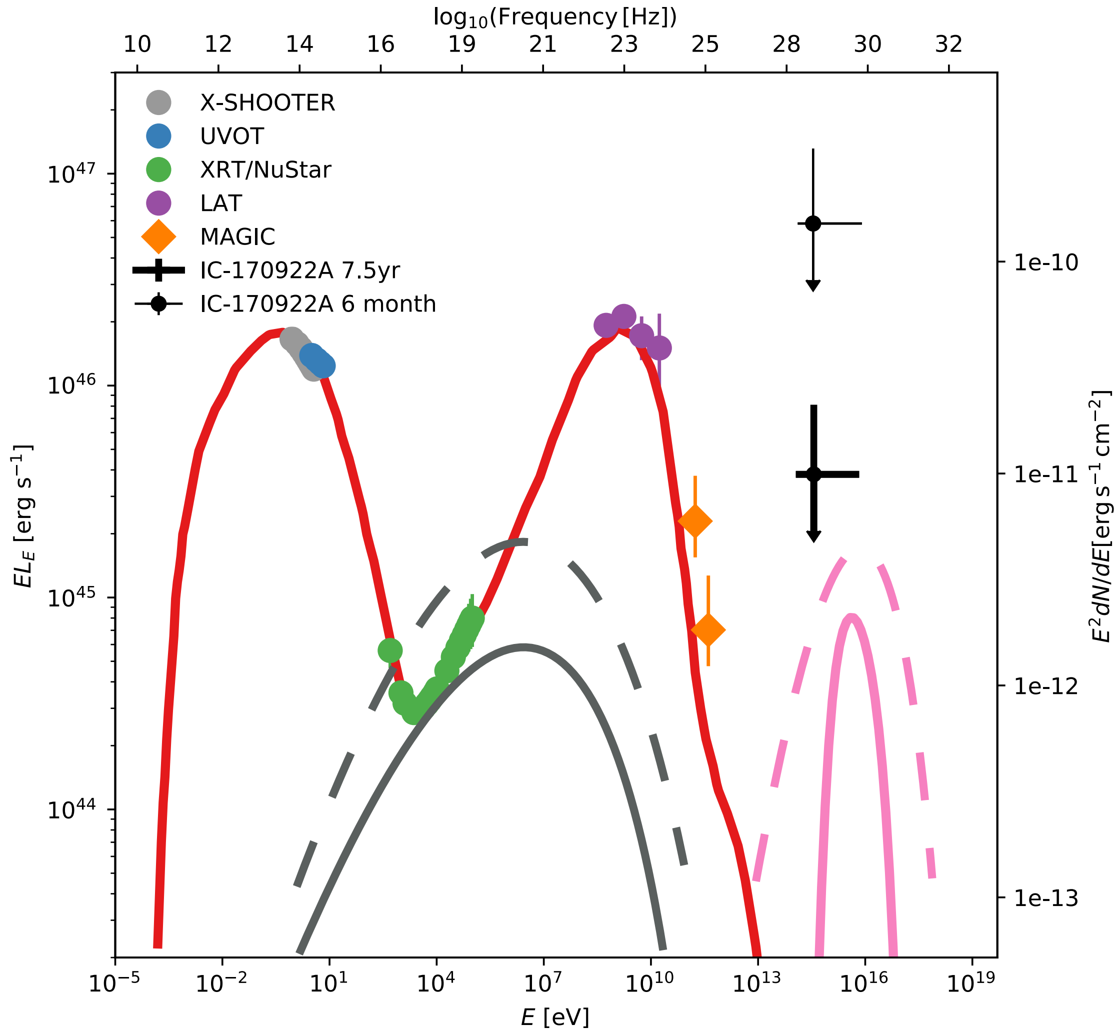
Of proton energy lost:
3/8ths → neutrinos
5/8ths → photons (gamma-rays/X-rays)



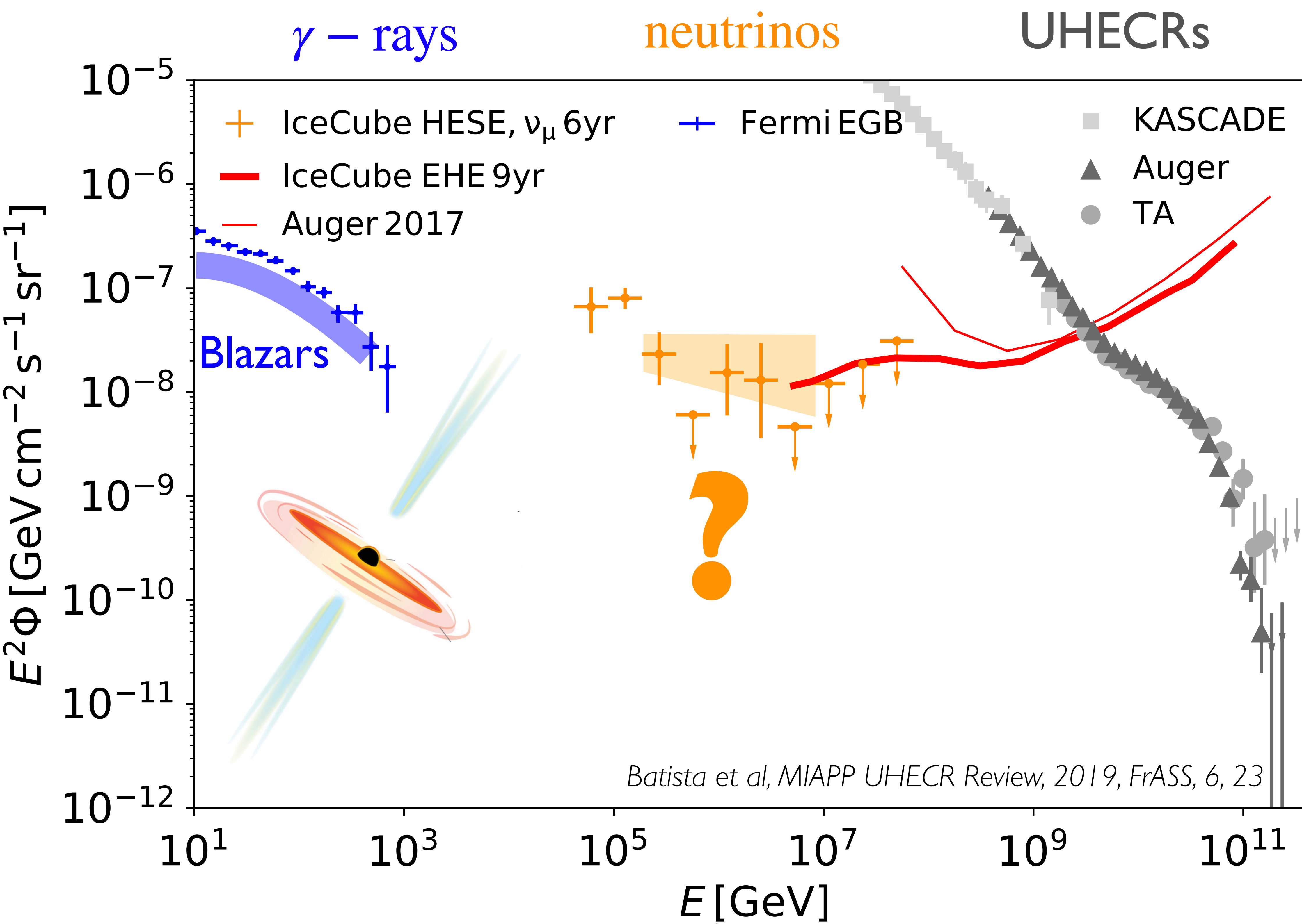
$$\langle E_\nu \rangle = \frac{1}{20} E_p$$

Peak should be at > PeV !

sketch by K. Murase

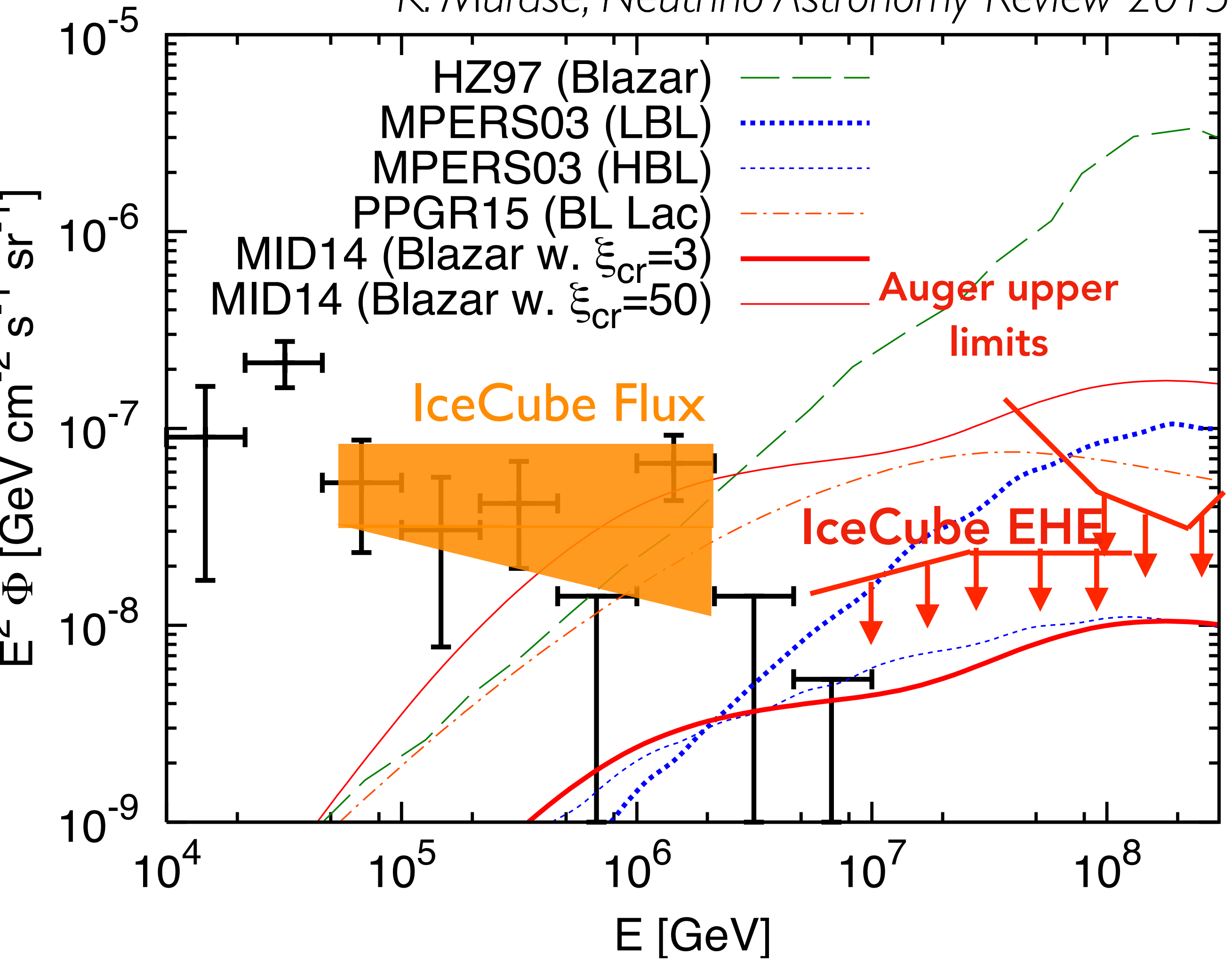


Constraints on the contribution of blazars to the diffuse neutrino flux

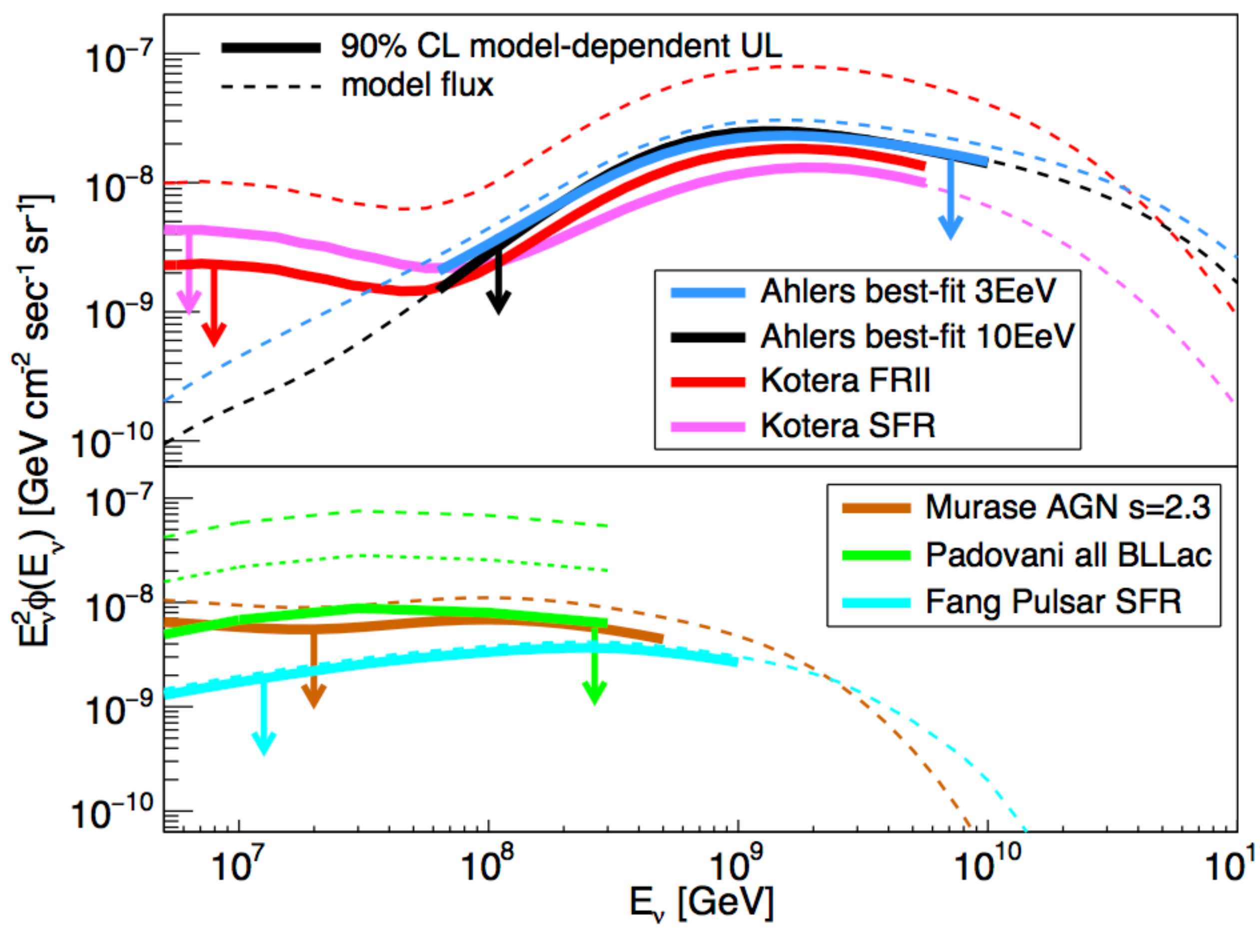


Constraints on the contribution of blazars to the diffuse neutrino flux

K. Murase, Neutrino Astronomy Review 2015

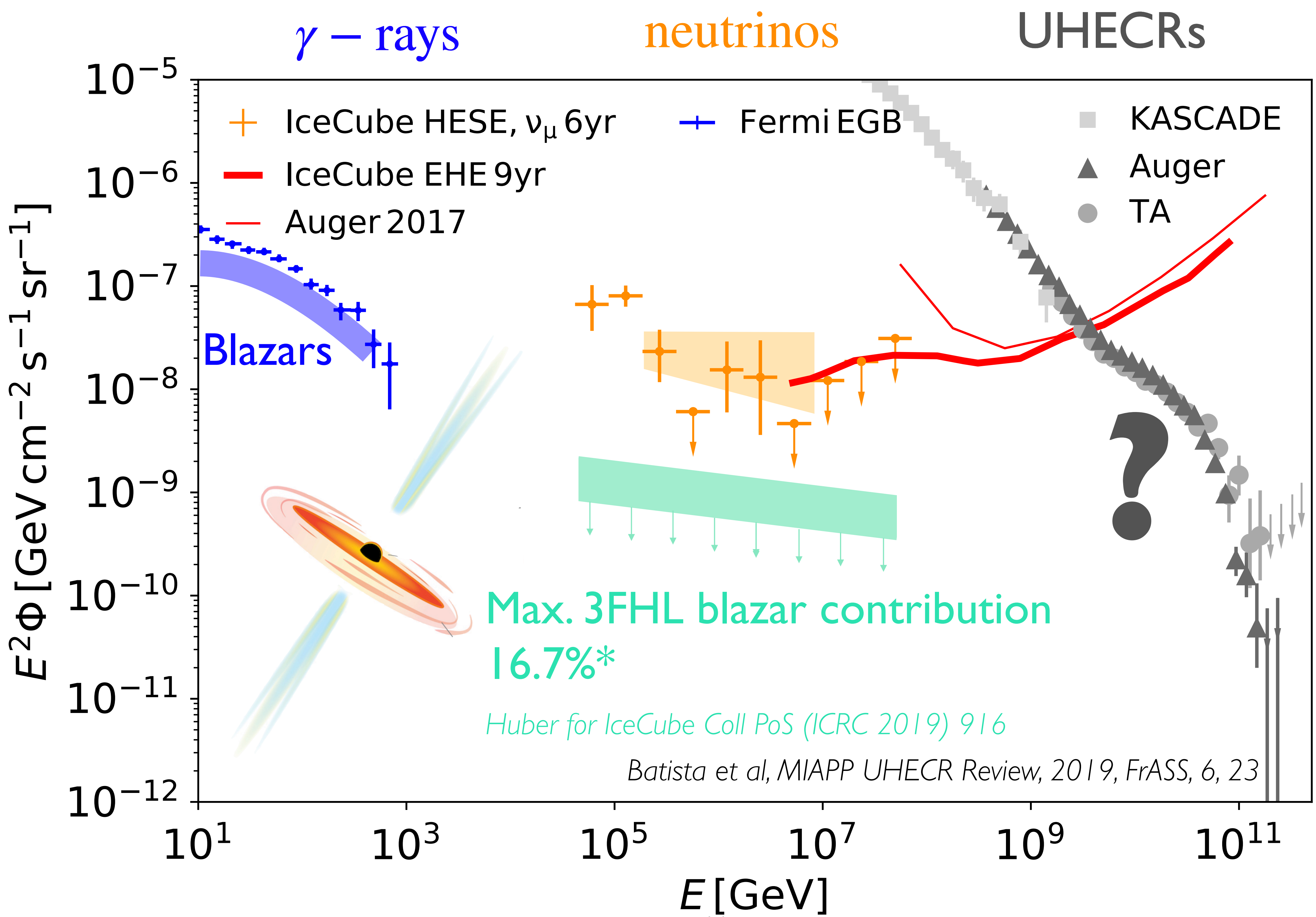


IceCube EHE PRL 2016, see also PRD 2018



Blazar proton content must be low!

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

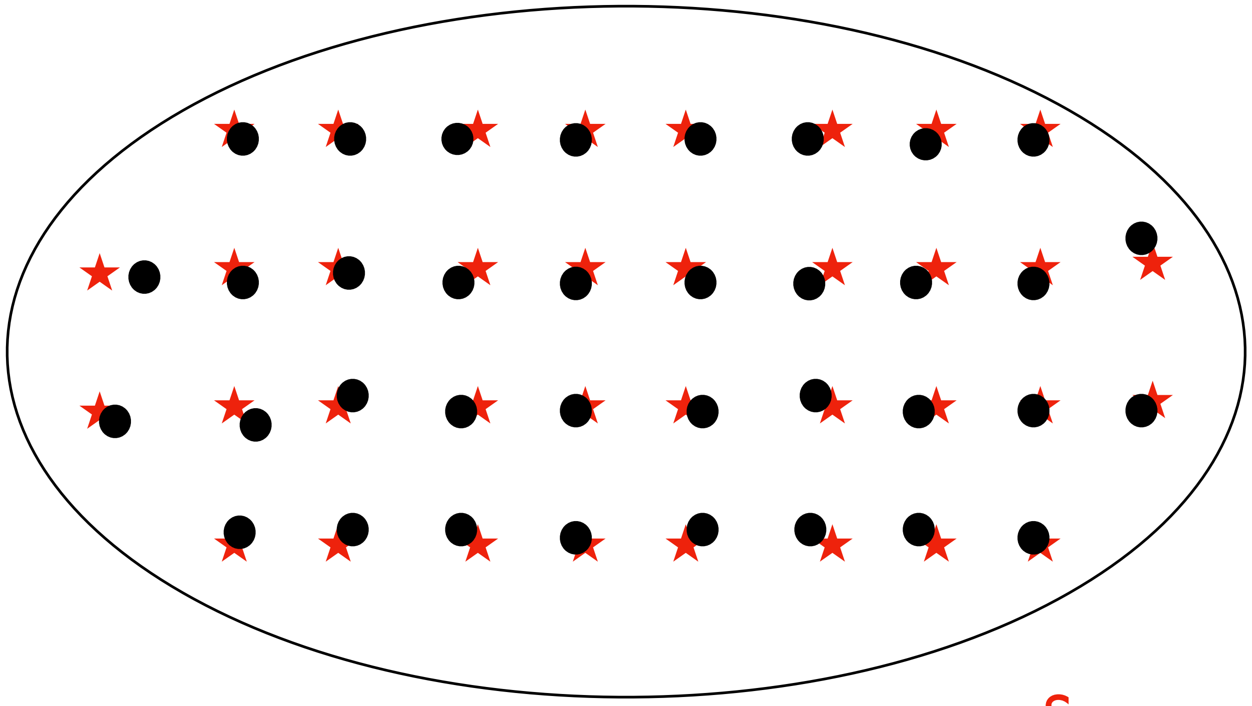


* ≤27% with spectral templates: *IceCube Coll PoS (ICRC2017) 994*

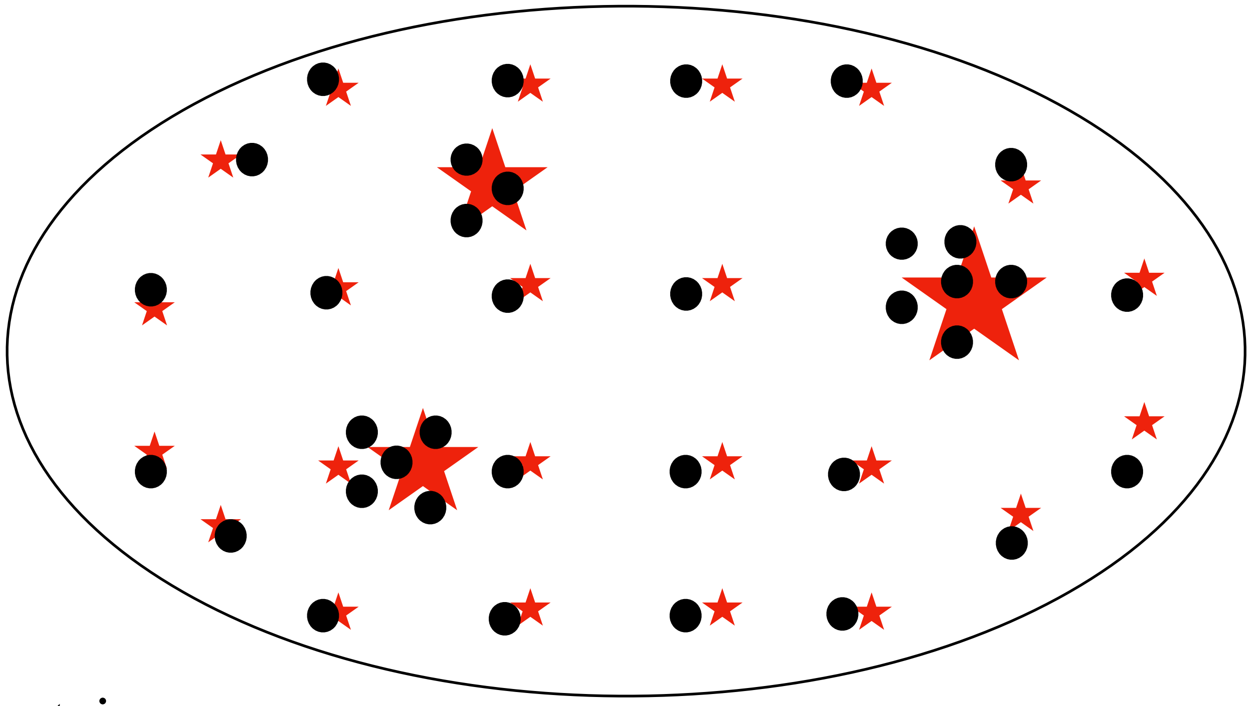
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

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



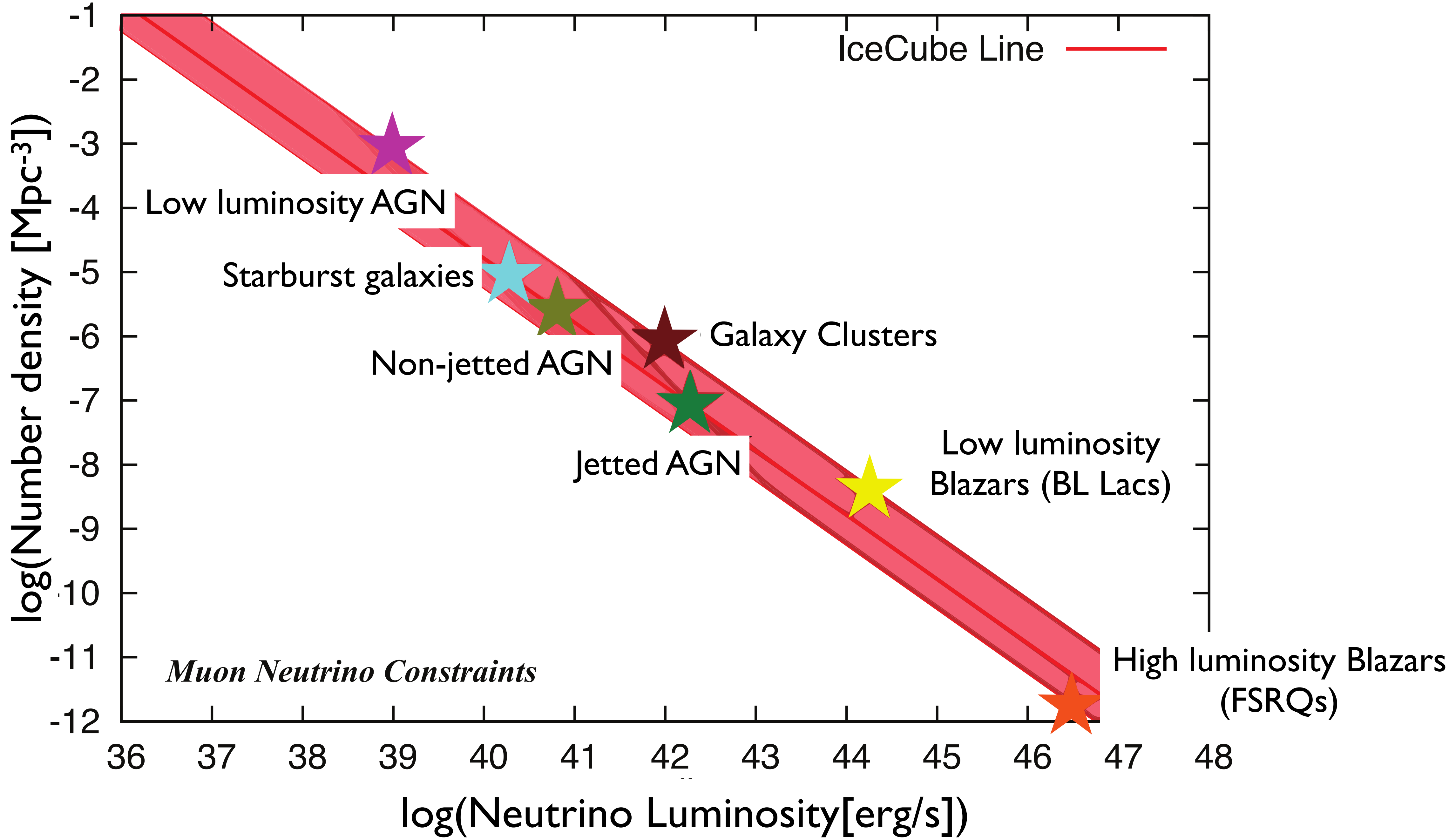
Sources - Neutrinos

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

Murase & Waxman 16, PRD 94 (2016) 103006

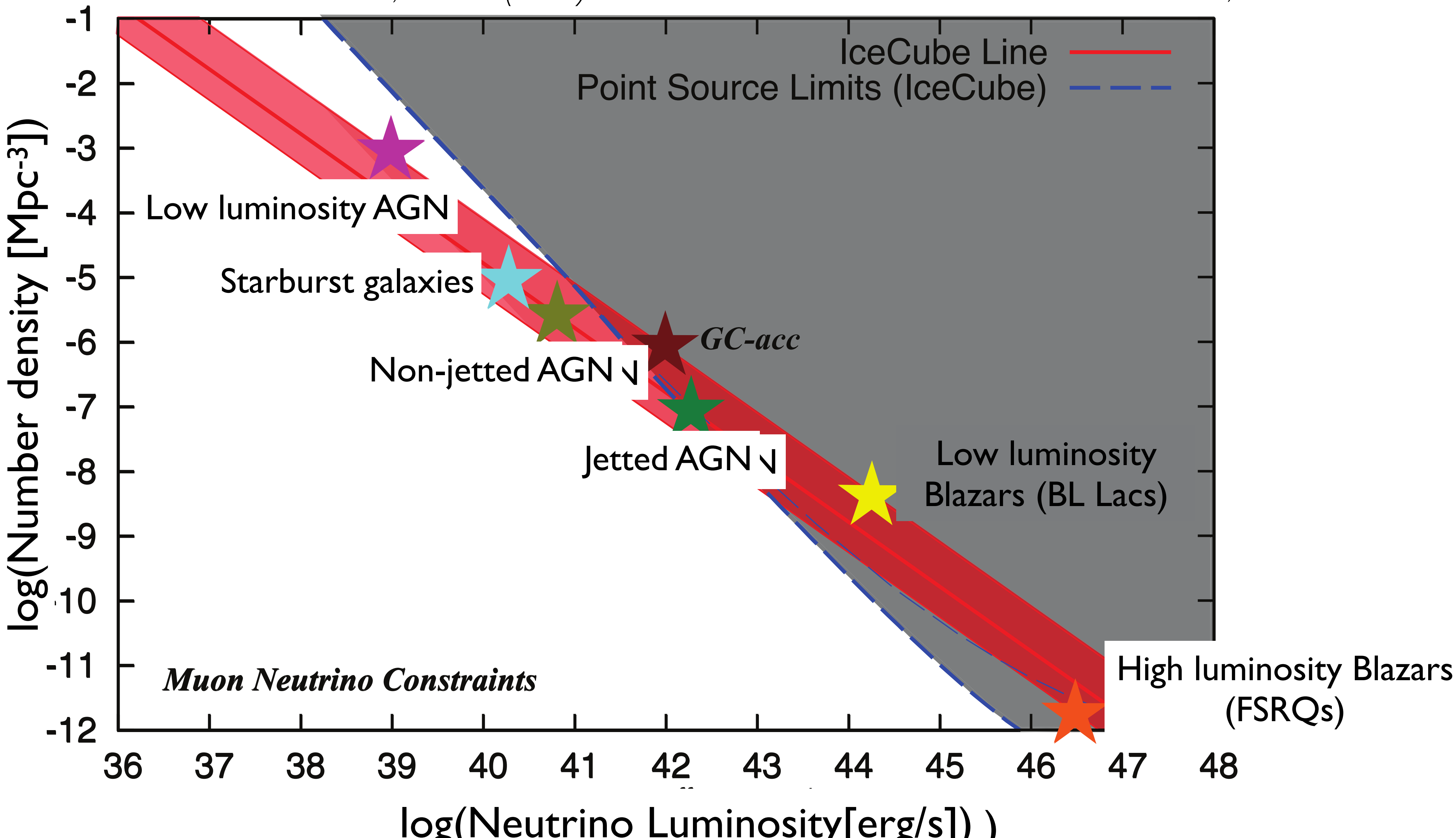


* clustering limits are sensitive up to ~100 TeV

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

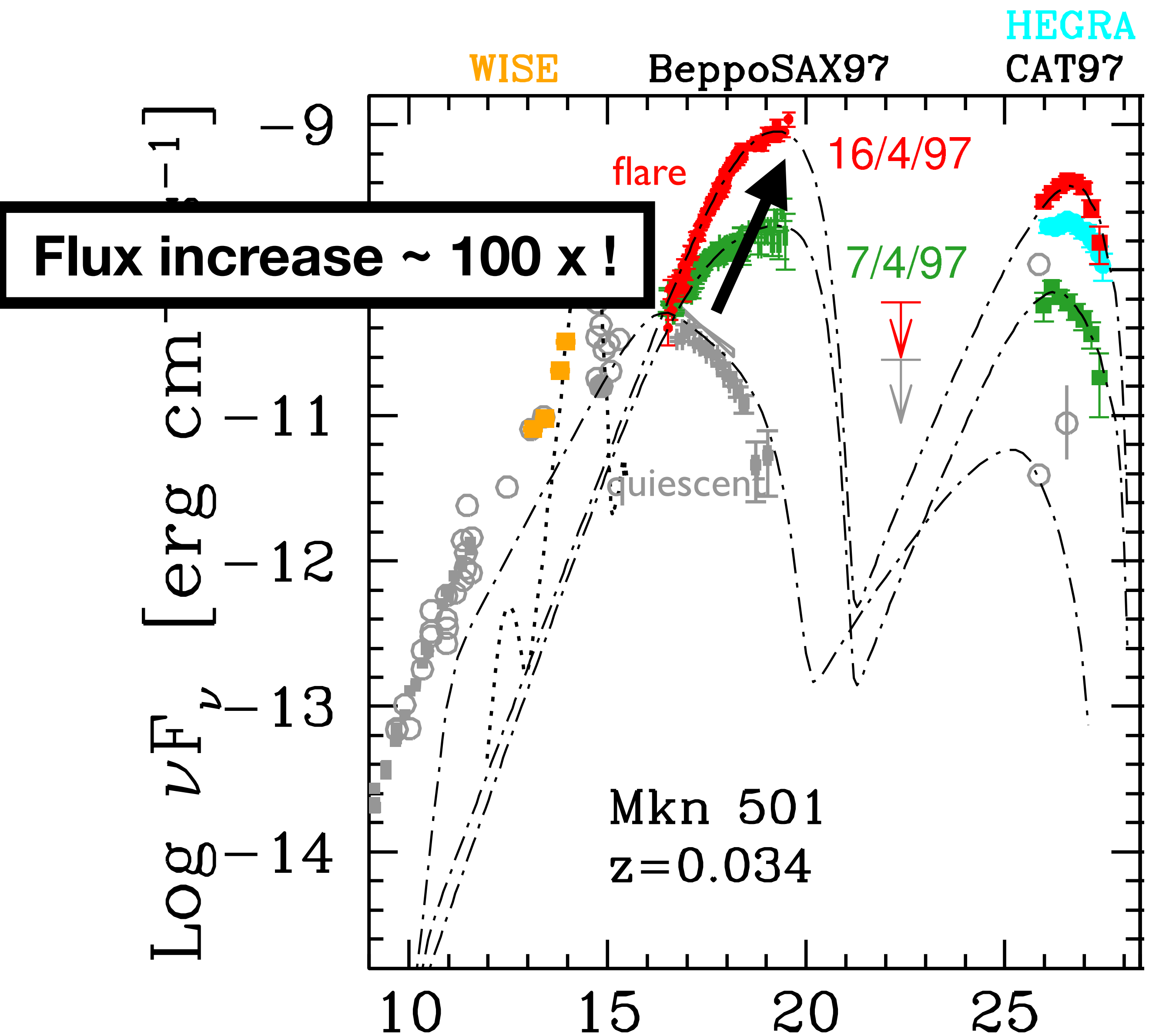
Murase & Waxman 16, PRD 94 (2016) 103006



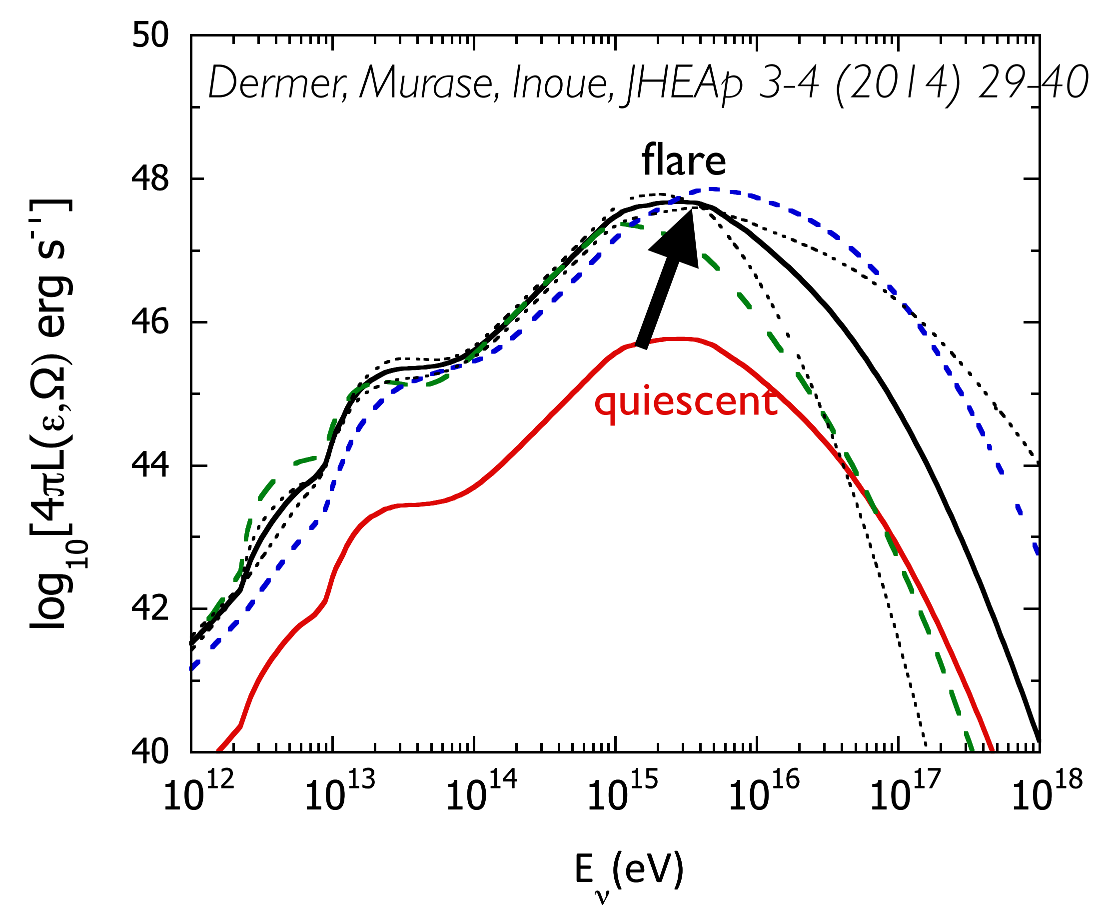
other diagnostics: cross-correlations (Padovani et al 2016, Palladino 2017, Giommi et al, 2020, Plavin et al 2020)
autocorrelations (IceCube Coll 2015,17, Ando et al 2017, Dekker & Ando 2019), EHE Limits (IceCube Coll 2016,17)…

Blazar flares: Interesting as neutrino point sources

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



Model neutrino spectrum of bright FSRQ (3C 279)



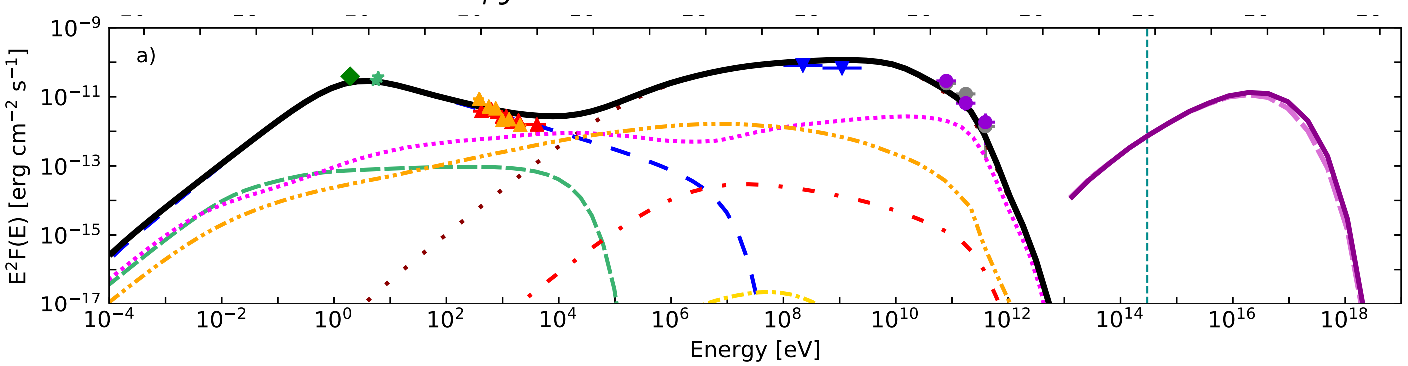
During flares, $L_\nu \propto L^2_{\text{target photon}}$ (BL Lac)

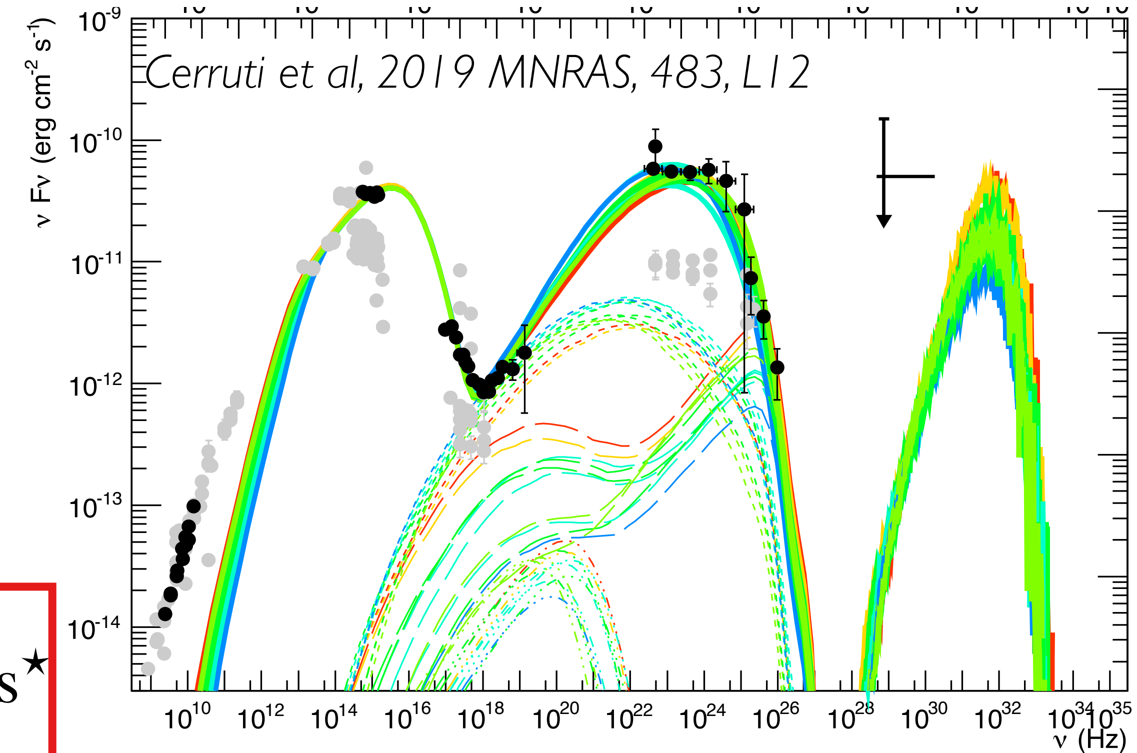
Generally $L_\nu \sim L_{\text{proton}} \times L_{\text{target photon}}$

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

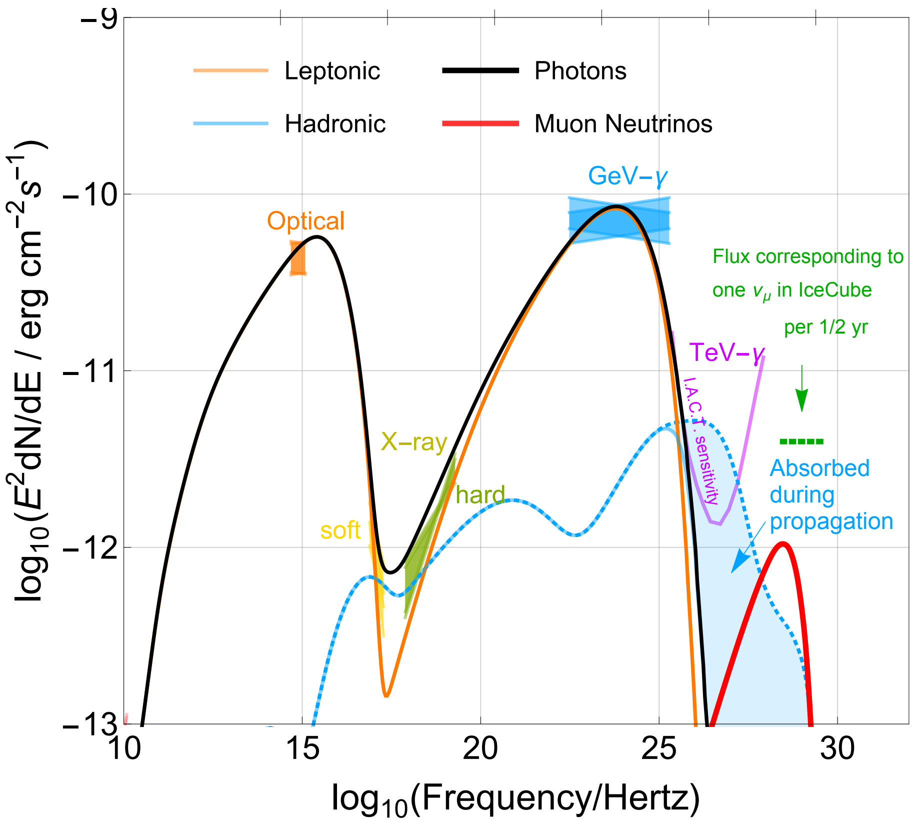
TXS 0506+056 + IC170922A

MAGIC Coll 2018, ApJ, 863, L10



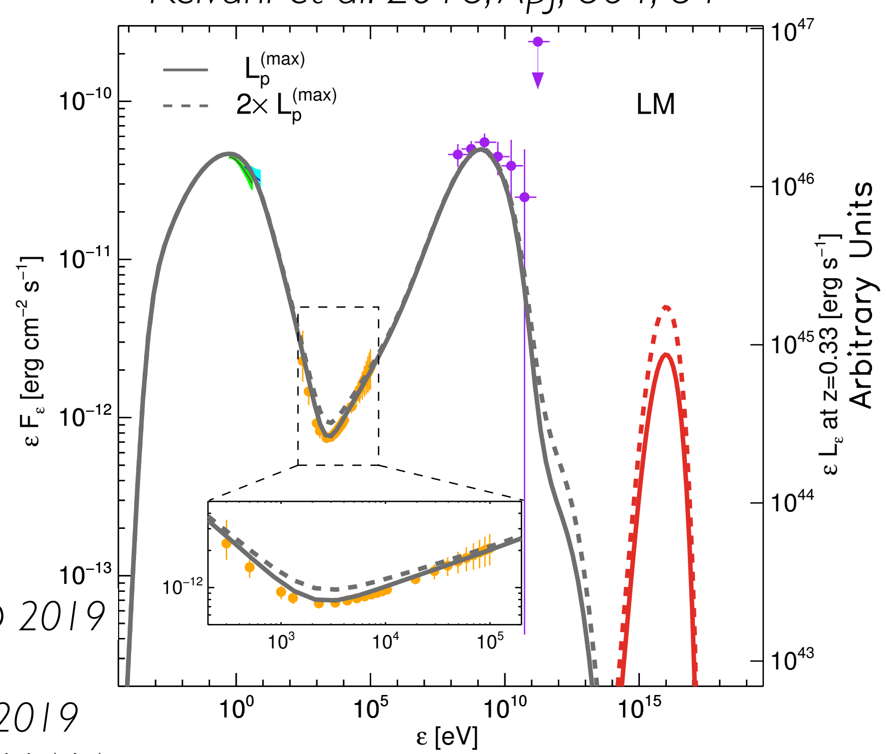


Gao et al, 2019, Nat. Astron., 3, 88

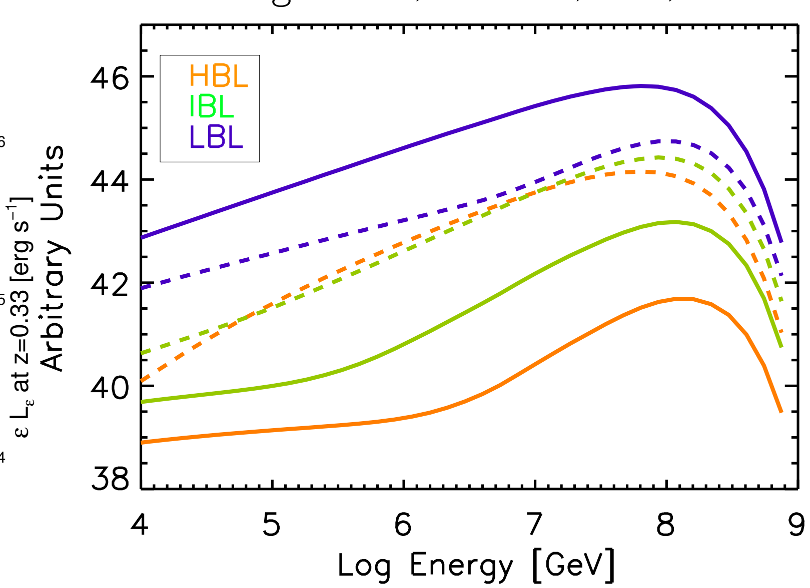


$$N_{\nu_\mu} \lesssim 0.01/6\text{ months}^\star$$

Keivani et al. 2018, ApJ, 864, 84



Righi et al, MNRAS, 483, L127



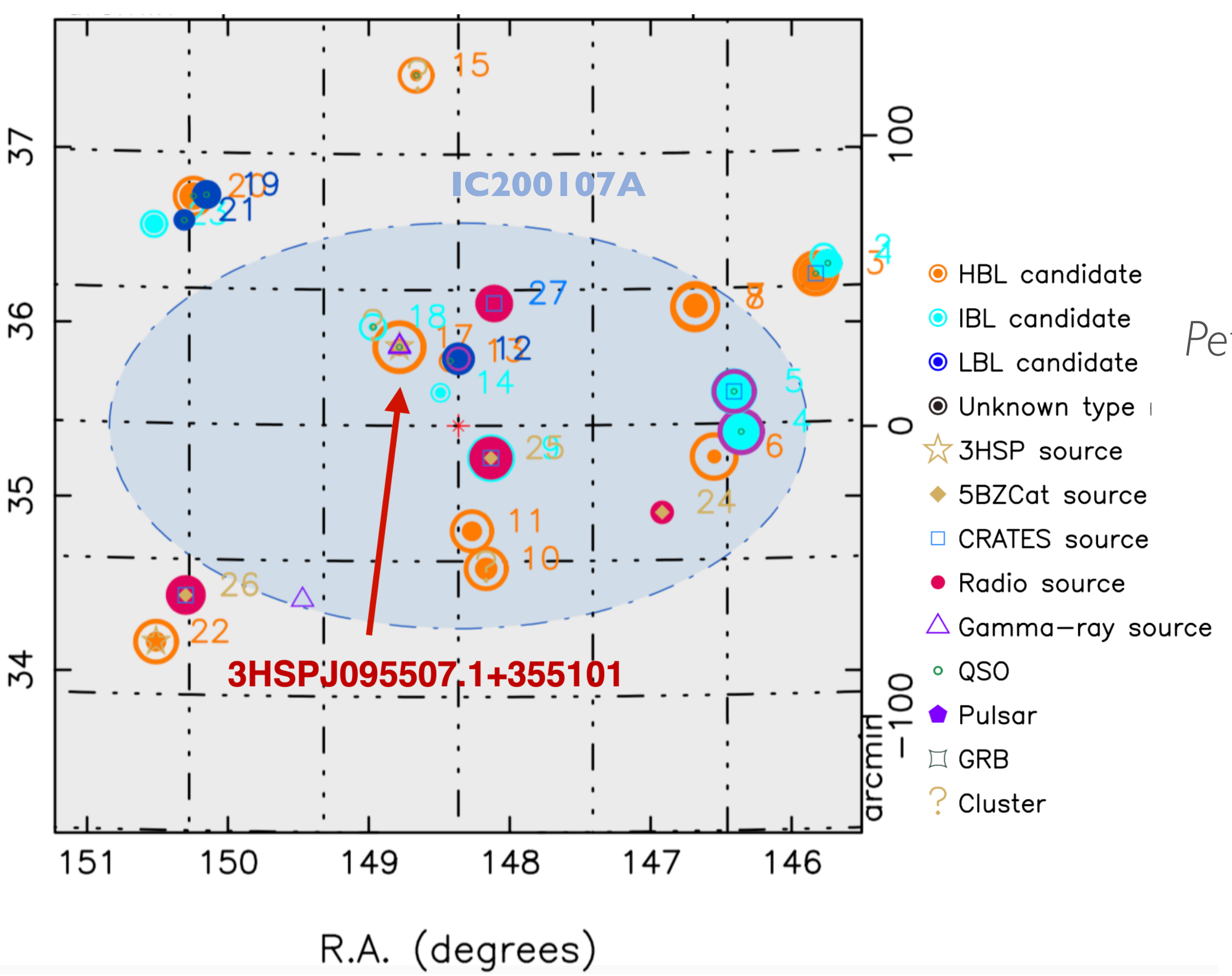
Other more exotic options find increased neutrino flux:
hadro-nuclear interactions: *Liu, Wang, Xue, Taylor et al, PRD 2019*
stellar disruption: *Wang, Liu et al, arXiv:1809.00601*
multiple zones: *Xue, Liu, Petropoulou, Oikonomou et al. ApJ 2019*
neutron beam: *Zhang, Petropoulou, Murase, FO, arXiv:1910.11464*
curved/double jet: *Britzen, Fendt, Böttcher et al, A&A 2019*

See Maria's talk tomorrow!

*(*ok due to population bias, Strotjohann et al 2019)*

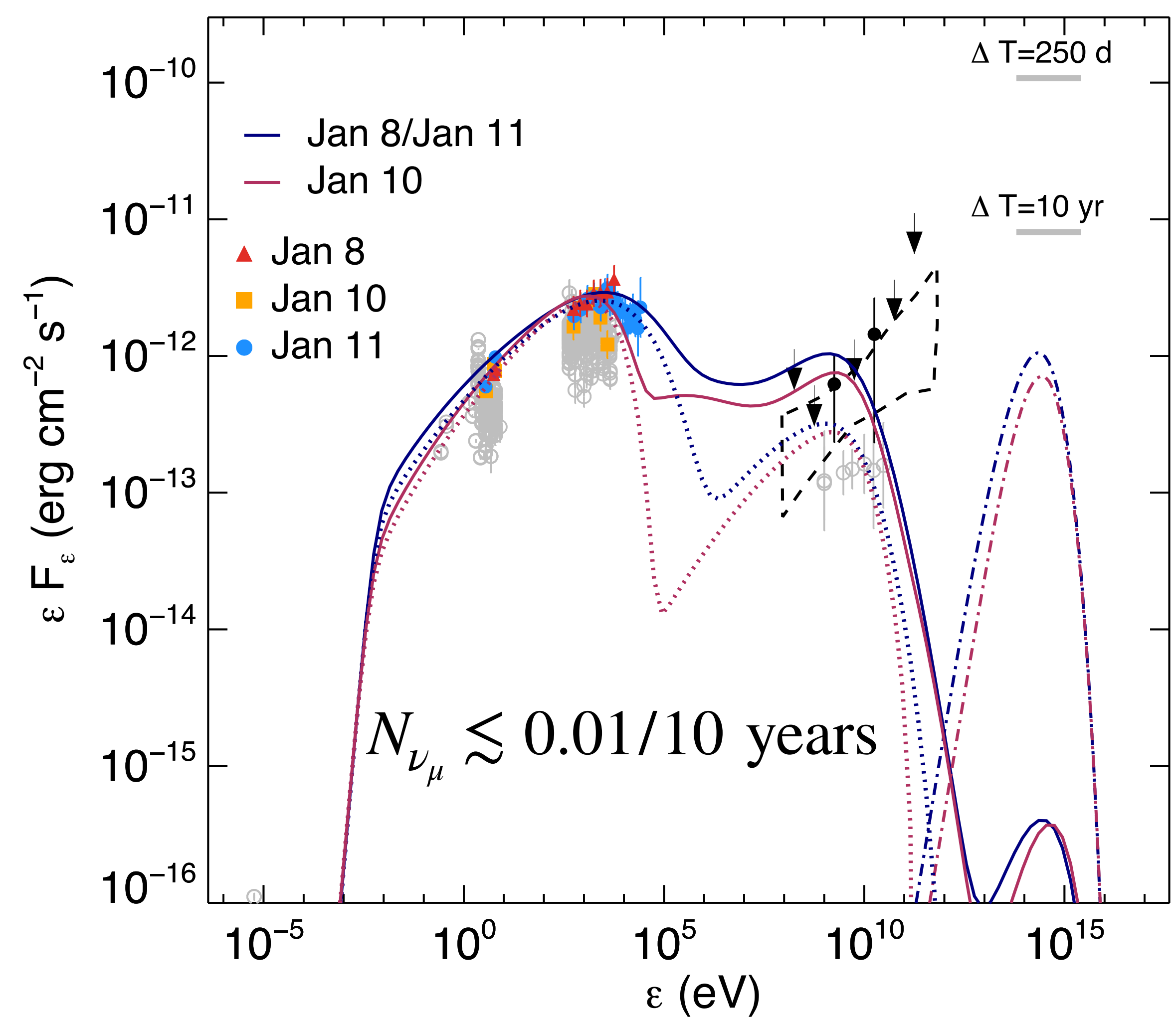
3HSP J095507.9+355101 - IC 200107A

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 0.33+2.23-0.27 PeV track
Redshift = 0.57 *(Paiano et al, MNRASL 2020)*

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

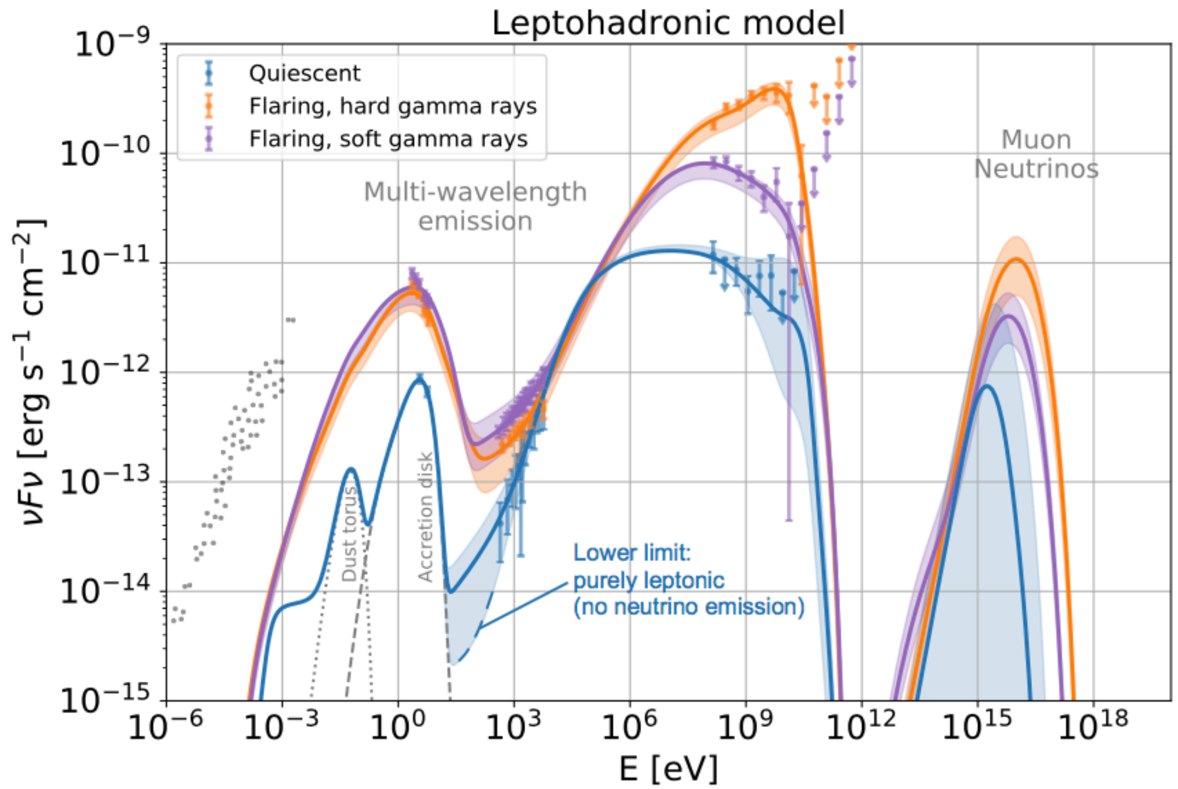


Poisson probability to detect 1 muon neutrino with E > 100 TeV ~ 1%
Eddington Bias: ``Lucky source'' if ensemble of sources with summed expectation ≳1 event

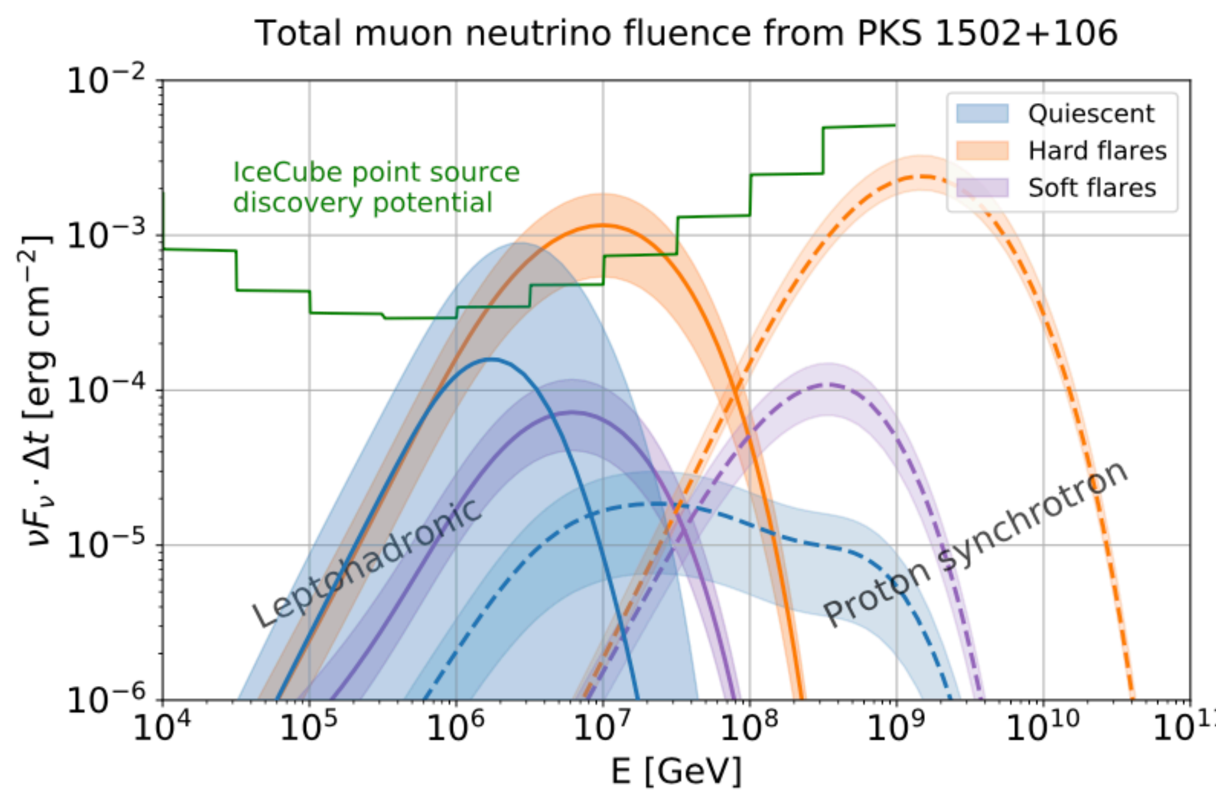
PKS 1506+102 - IC 190730A

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

A powerful FSRQ at z = 1.835
~2σ association significance (a posteriori)
Possible that it produces $\sim 0.5 N_{\nu_\mu}$/year



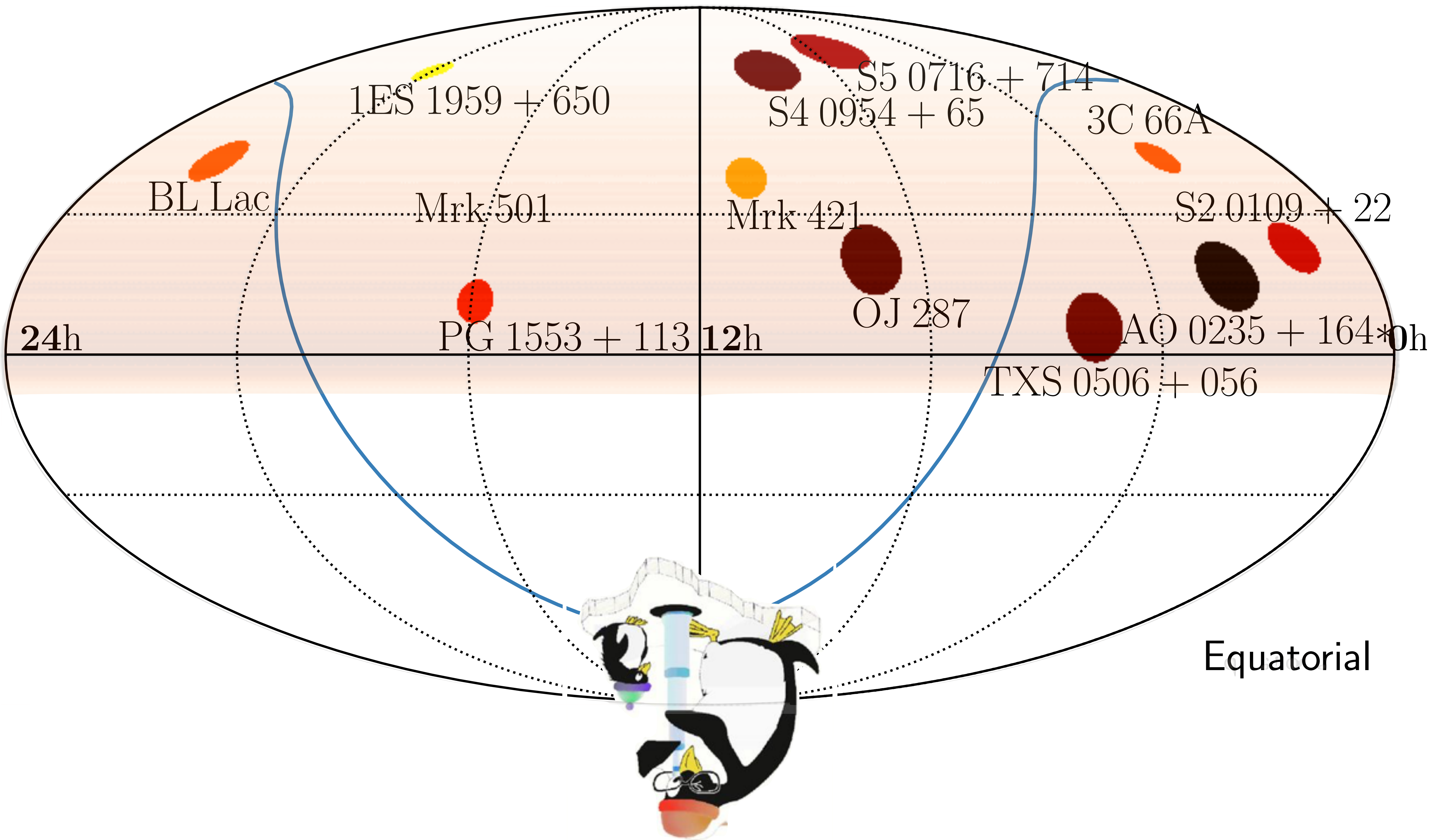
But..
Has to be a special case as otherwise diffuse limits v. severe for FSRQs



see also Kun, Bartos et al arXiv:2009.09792

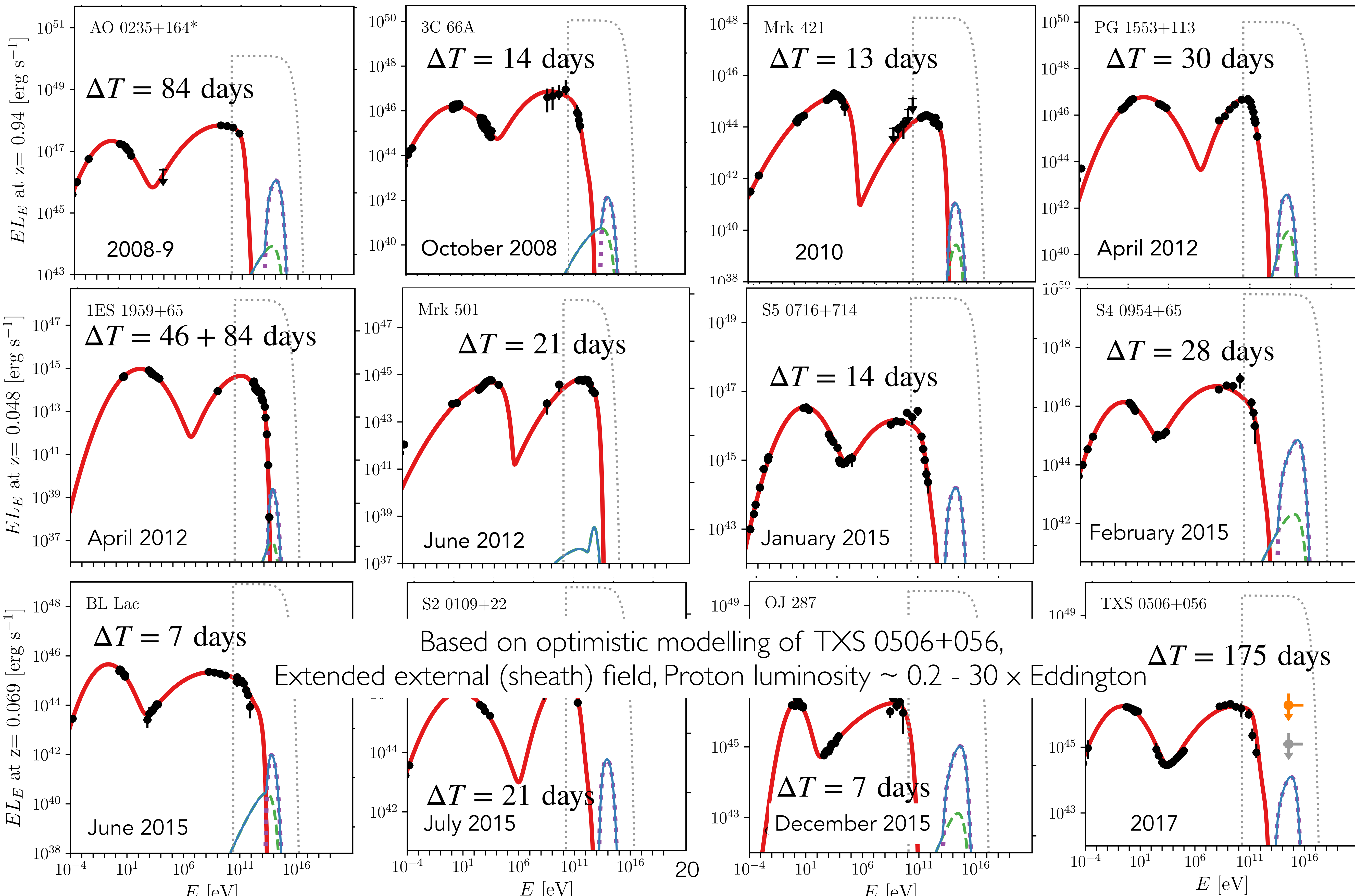
High-energy neutrinos from other blazar flares?

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



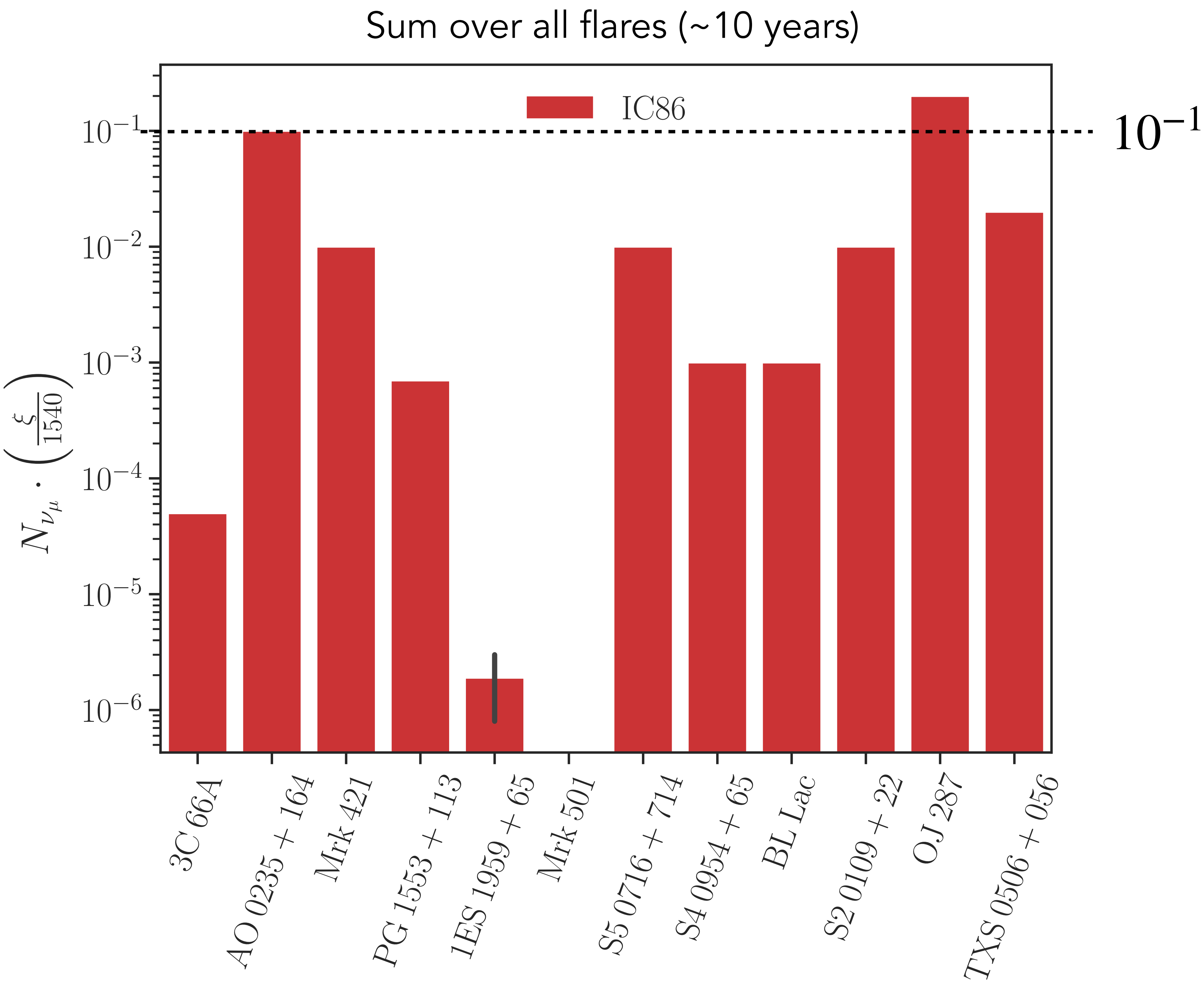
Optimistic scenario based on 2017 flare of TXS 0506+056

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

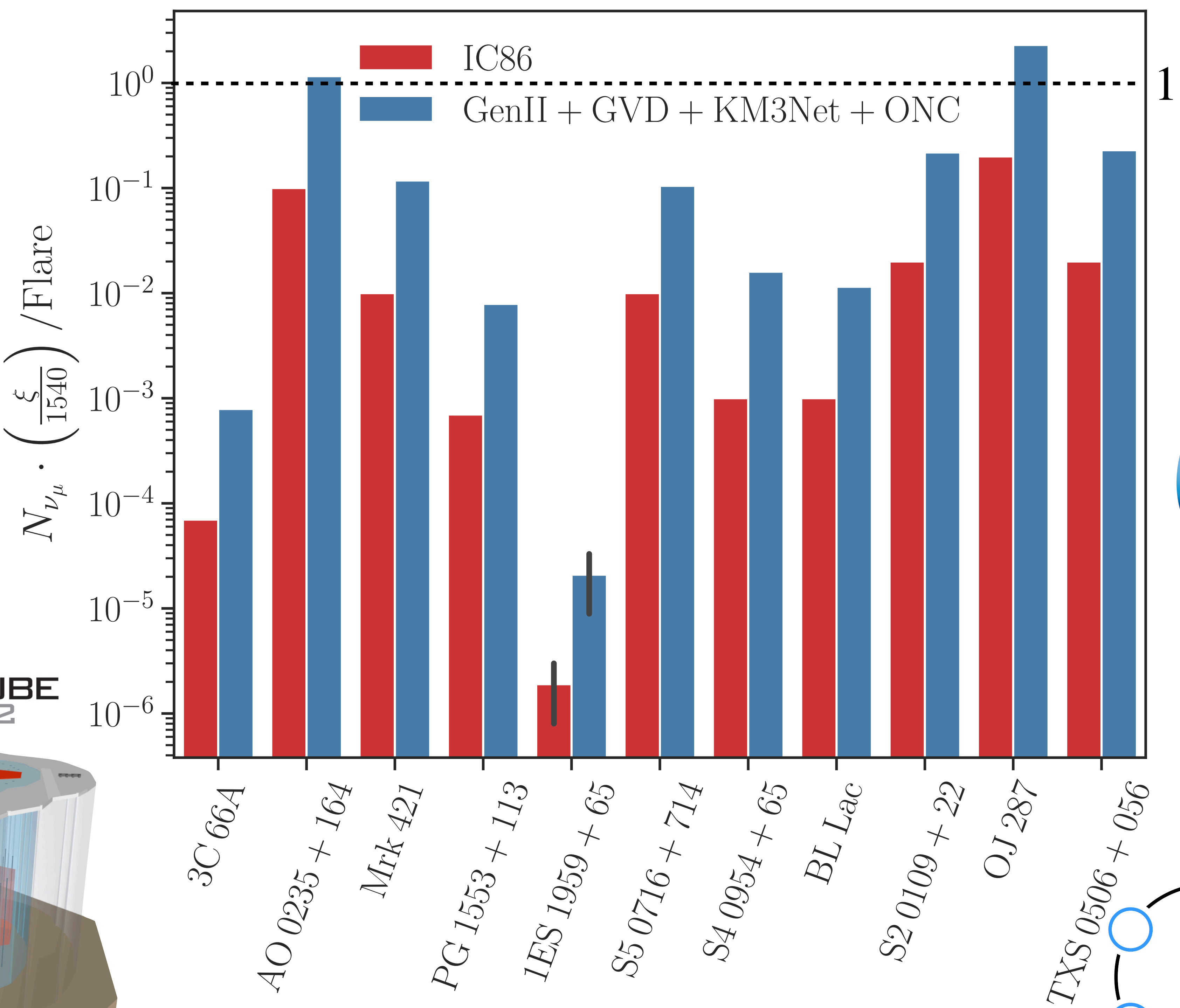


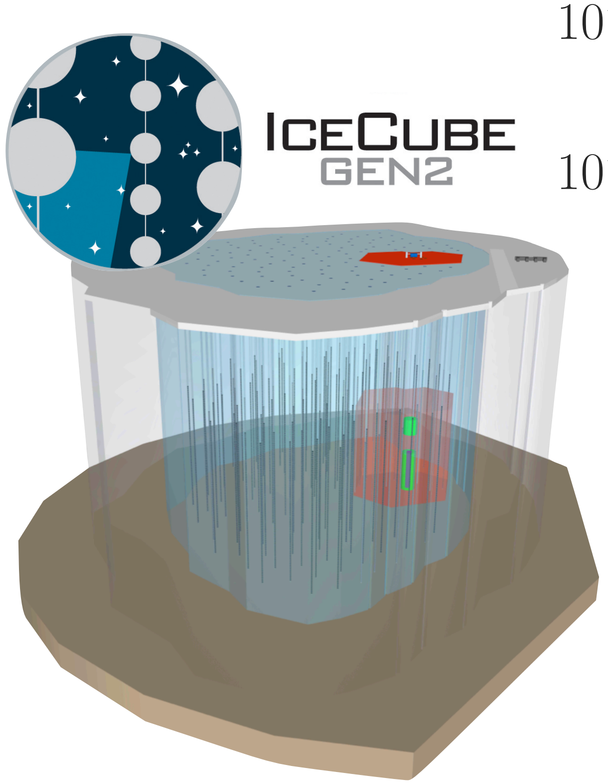
Based on optimistic modelling of TXS 0506+056,
Extended external (sheath) field, Proton luminosity ~ 0.2 - 30 × Eddington

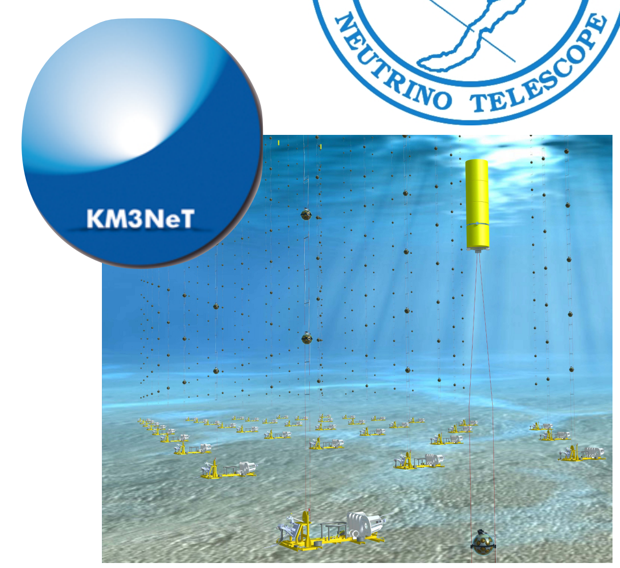
Expected neutrino signal in optimistic case



Expected neutrino signal with next generation detectors

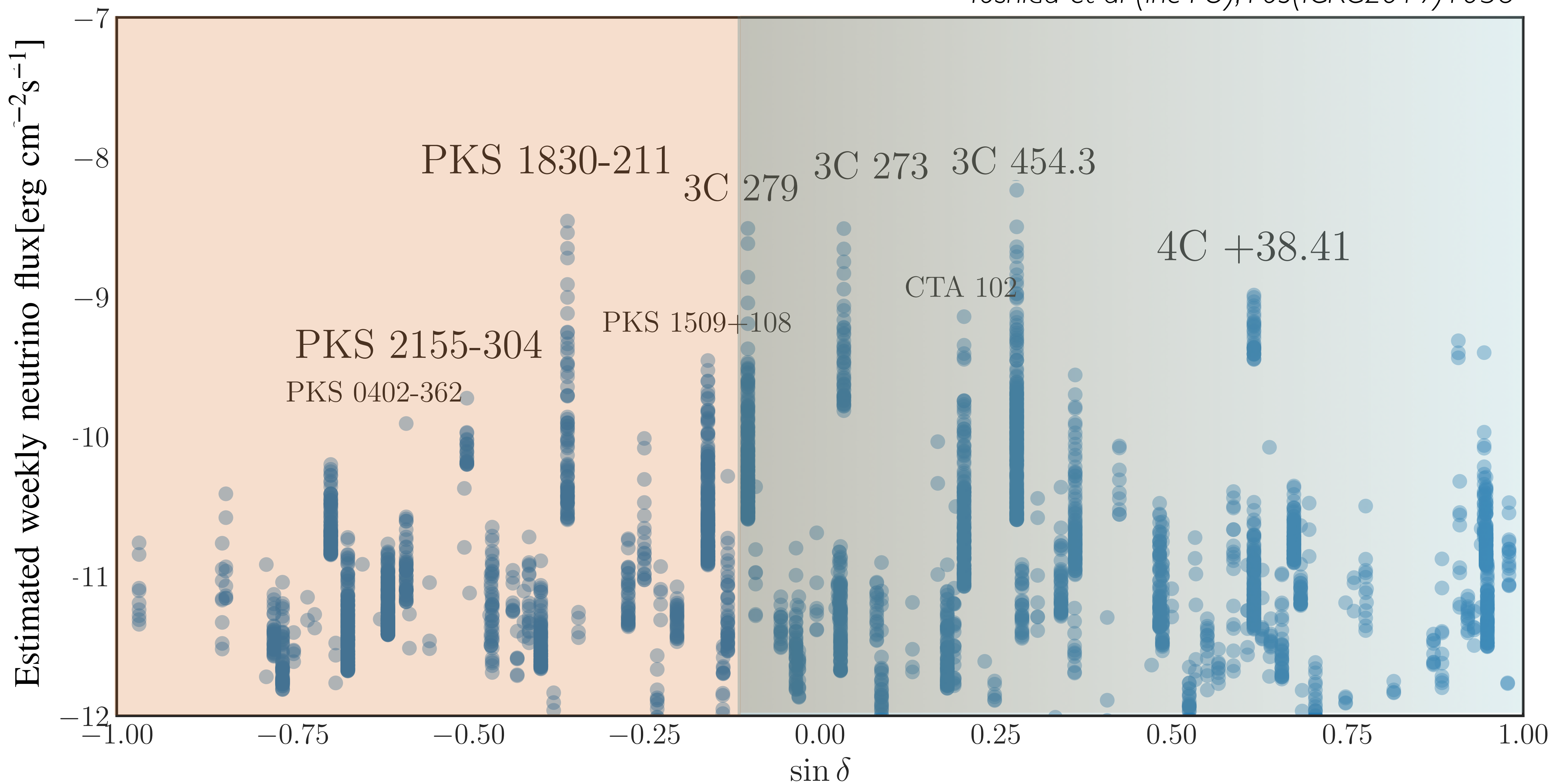


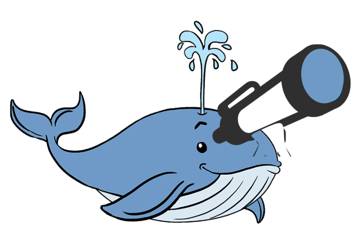




Fermi monitored blazars: neutrino flux expectations

Yoshida et al (inc FO), PoS(ICRC2019)1038

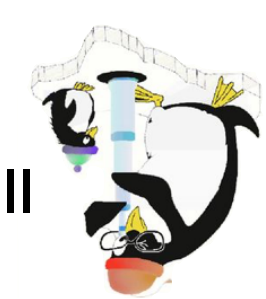




KM3NeT/GVD/P-One

$$\varepsilon_{\nu_\mu} F^{\rm fl}_{\varepsilon_{\nu_\mu}} = \varepsilon F^{\rm qui}_{\varepsilon,{\rm XRT}} \left(\frac{F^{\rm fl}_{\rm LAT}}{F^{\rm qui}_{\rm LAT}} \right)^{1.5}$$

IceCube/GenII



Summary

- Blazars not main sources of IceCube neutrinos
- May be dominant at higher energies
- Promising point sources for next generation detectors if high proton content
- Strong dependence of neutrino expectation on physical parameters (baryon loading, doppler factor, magnetic field strength, external photon field energy density)
- To identify the brightest neutrino flares v. precise astronomical measurements needed