NEUTRINOS AND BLAZARS

ICRC2021

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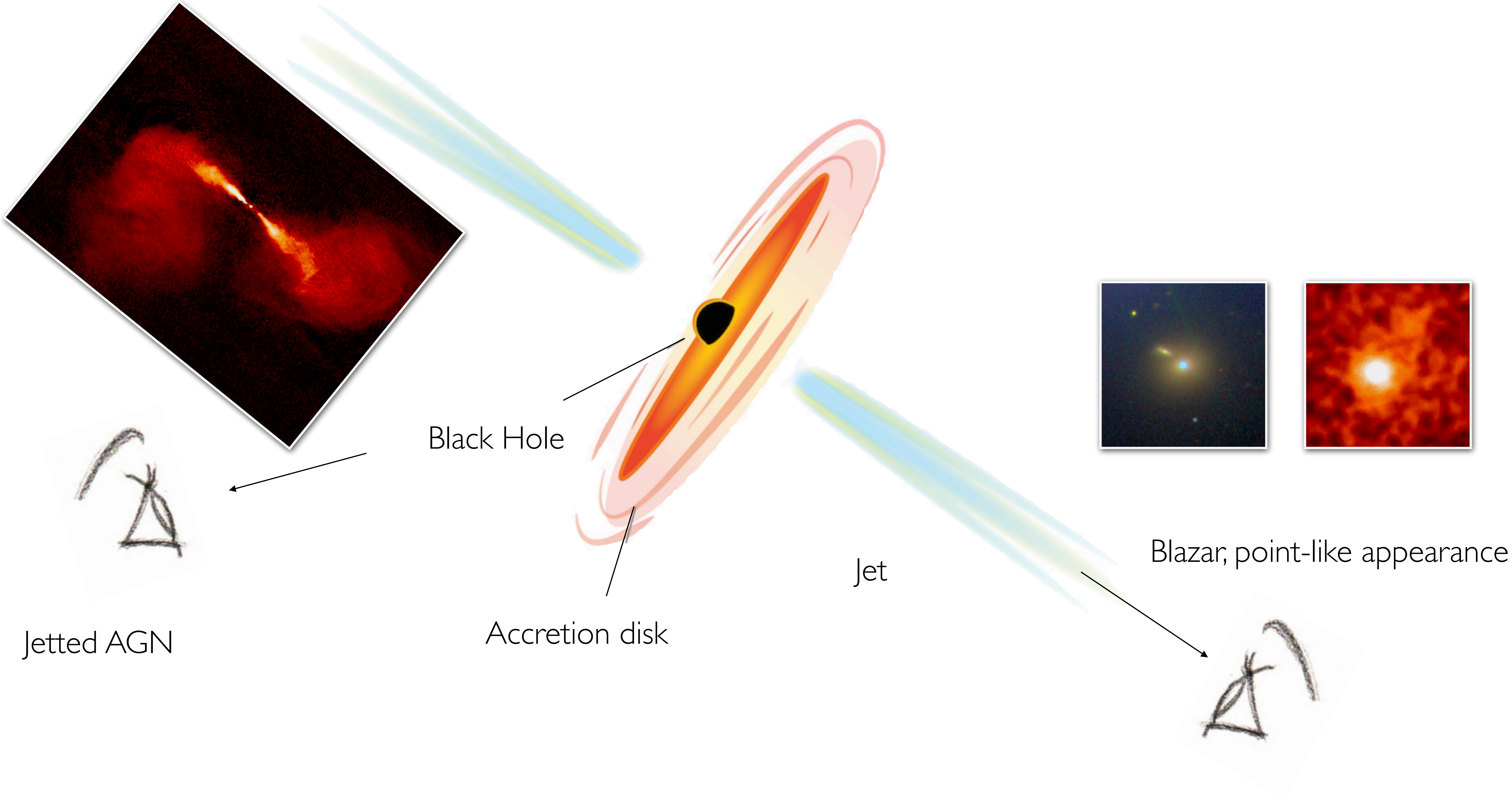
Blazars: Extreme and rare sources



Very rare objects

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

Apparent power up to 10^{49} erg/s cf.

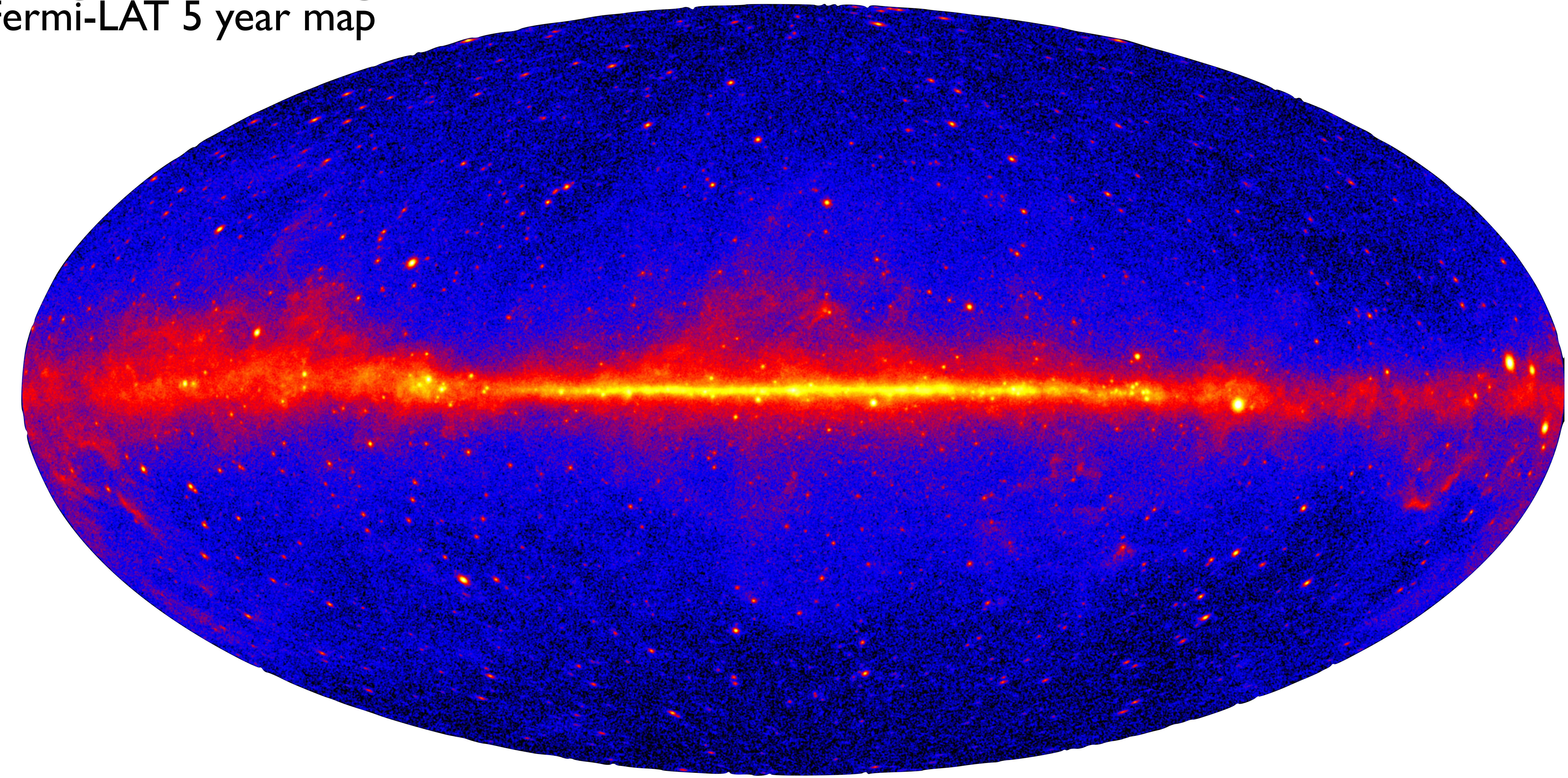
Object	Power [erg/s]
Milky Way	10^{42}
gamma-ray burst	10^{50-52}
jetted TDE (on-axis)	$\lesssim 10^{48}$
starburst galaxy (gamma rays/far infrared)	$10^{41/43}$
galaxy cluster (X-rays)	10^{45}
jetted AGN (γ-rays)	10^{43}

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

O(100) contributions at this ICRC! discussion sessions #25, #48, UHECR acceleration, neutrino emission, Lorentz Invariance Violation searches, intergalactic magnetic field studies, variability, monitoring…

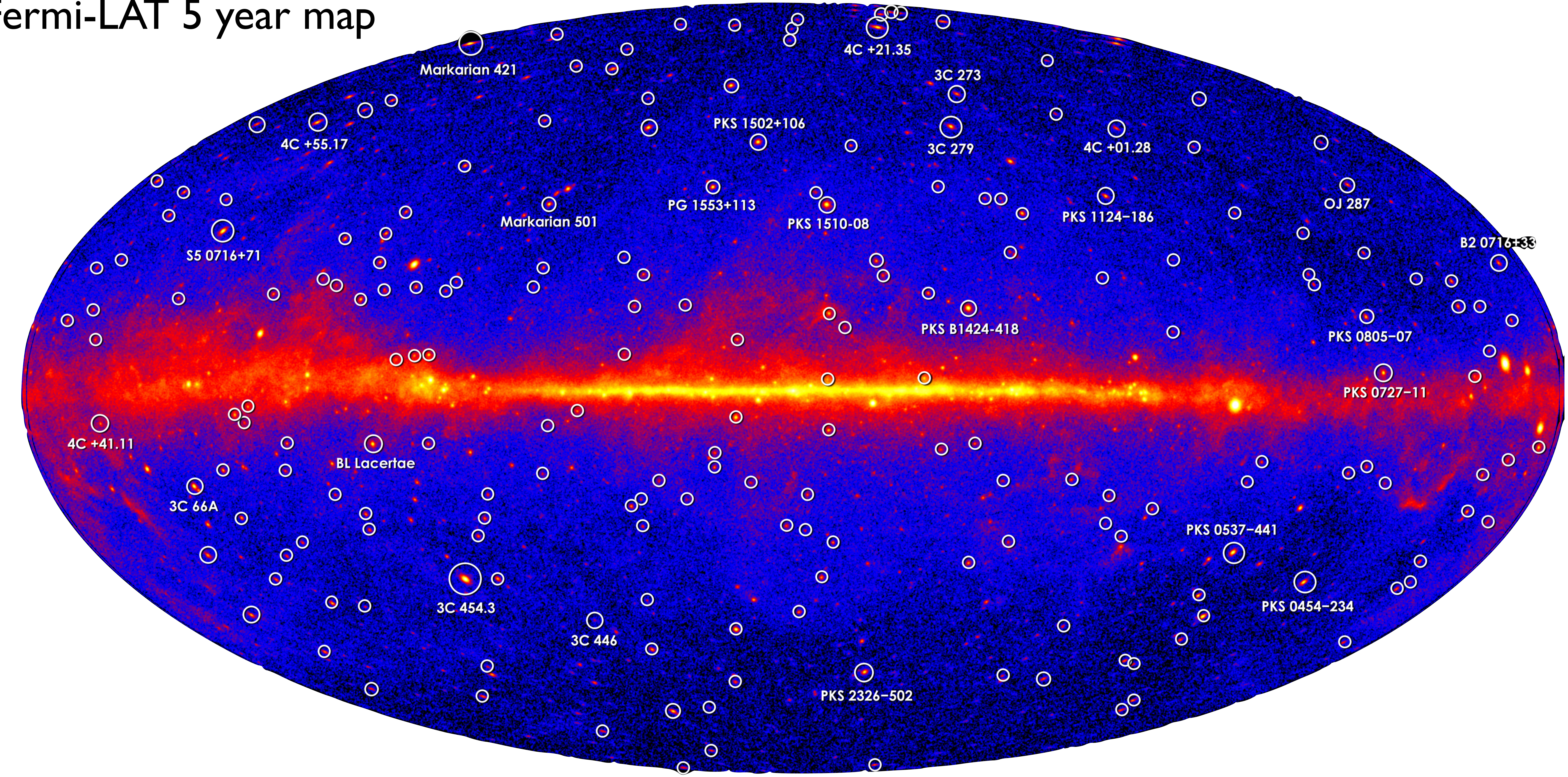
High–energy accelerators

Fermi-LAT 5 year map

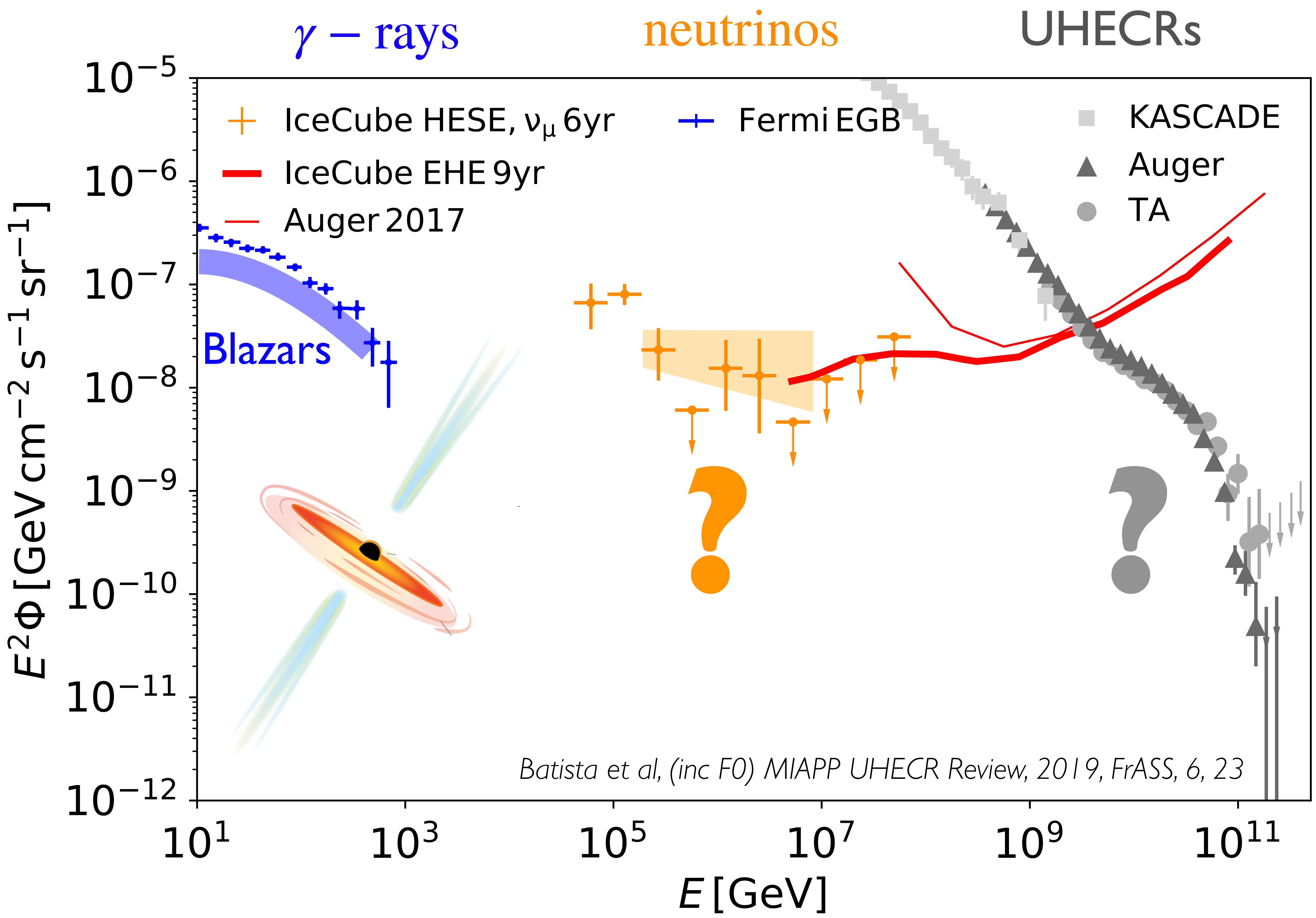


High–energy accelerators

Fermi-LAT 5 year map

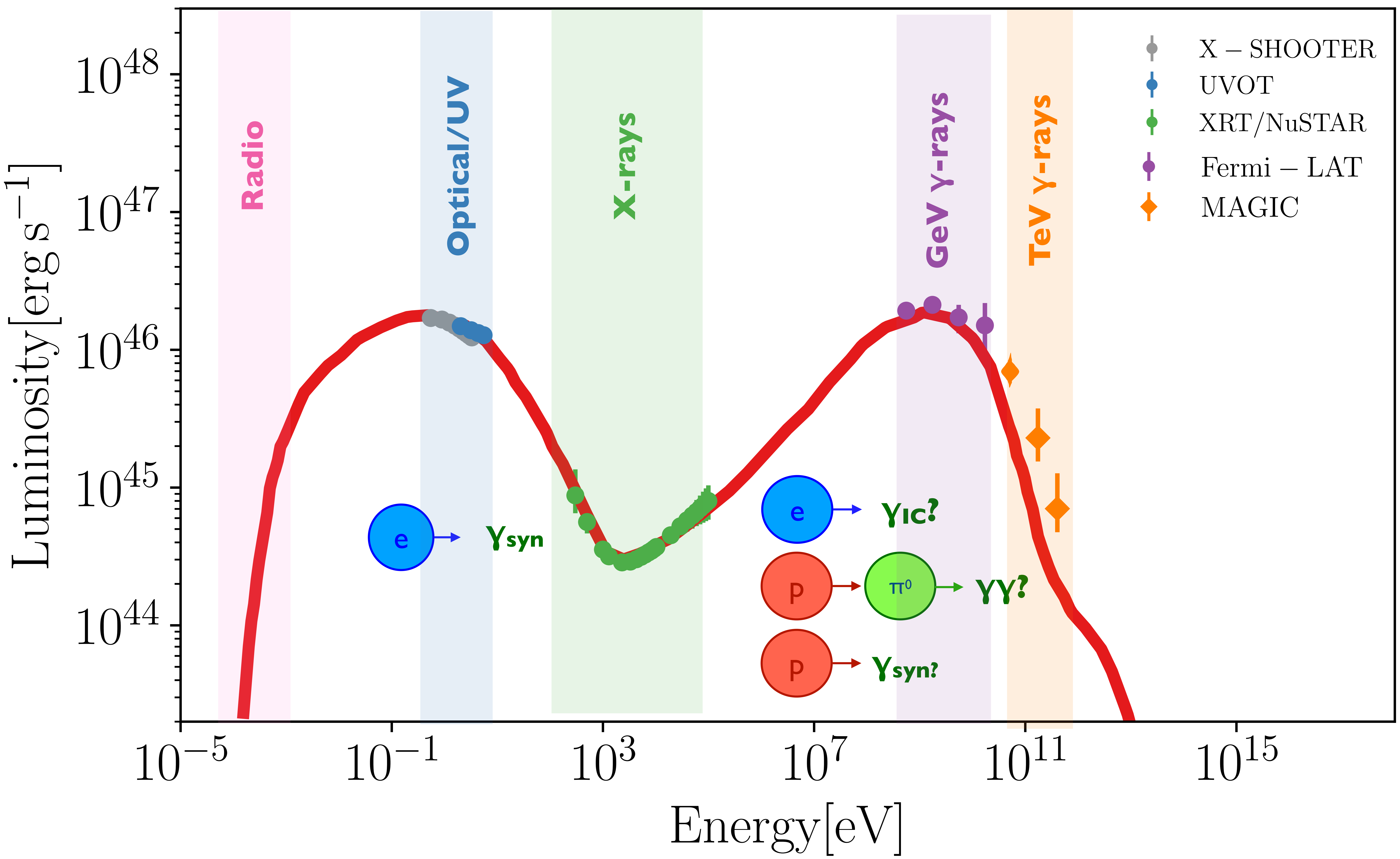


Blazars dominate the γ-ray sky



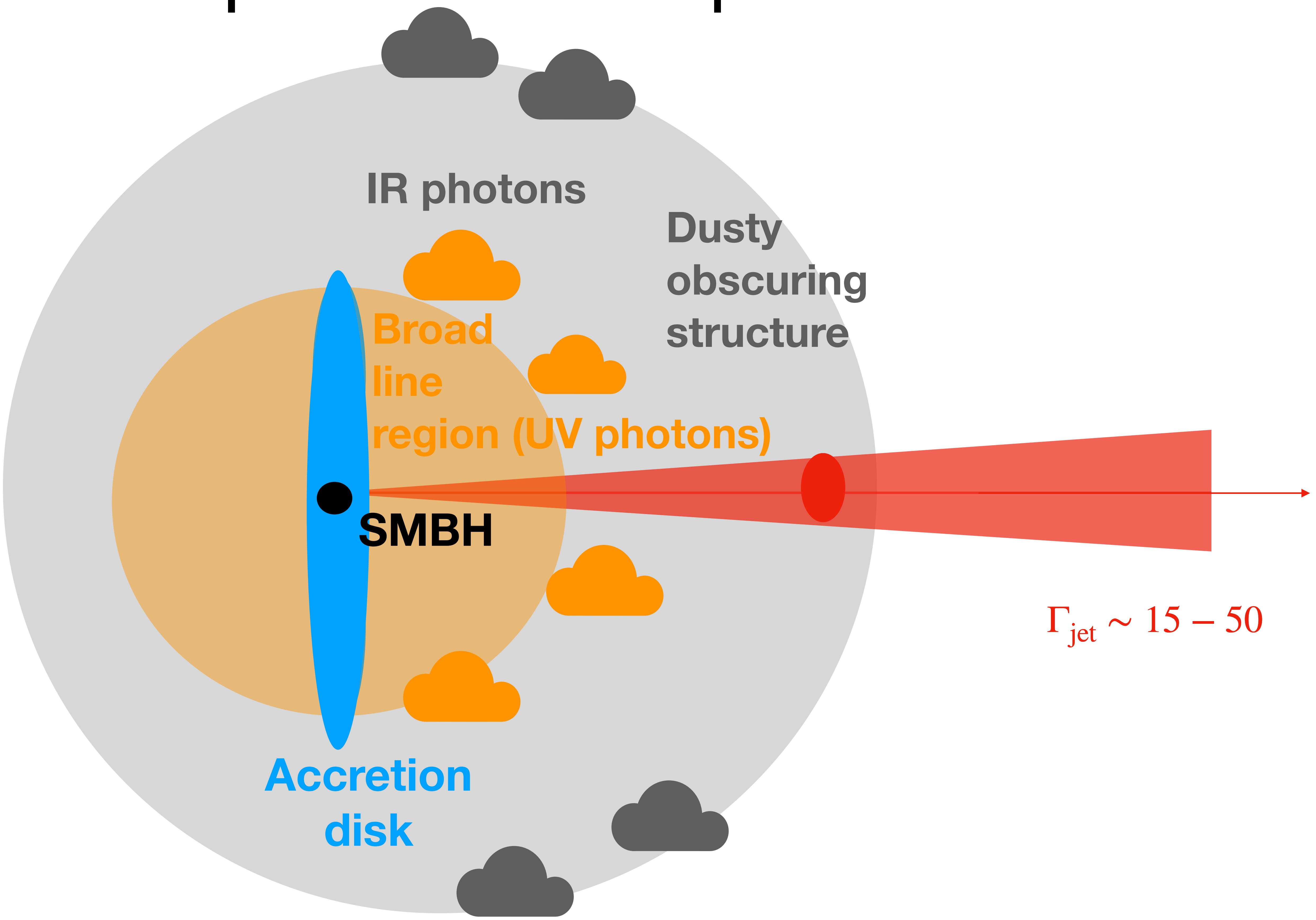
Blazar emission models

Observations of TXS 0506+056 in 2017 and model SED
from Keivani et al ApJ 864 (2018) and MAGIC Coll. ApJ 863 (2018)



Blazar spectral subclasses

Flat spectrum radio quasars



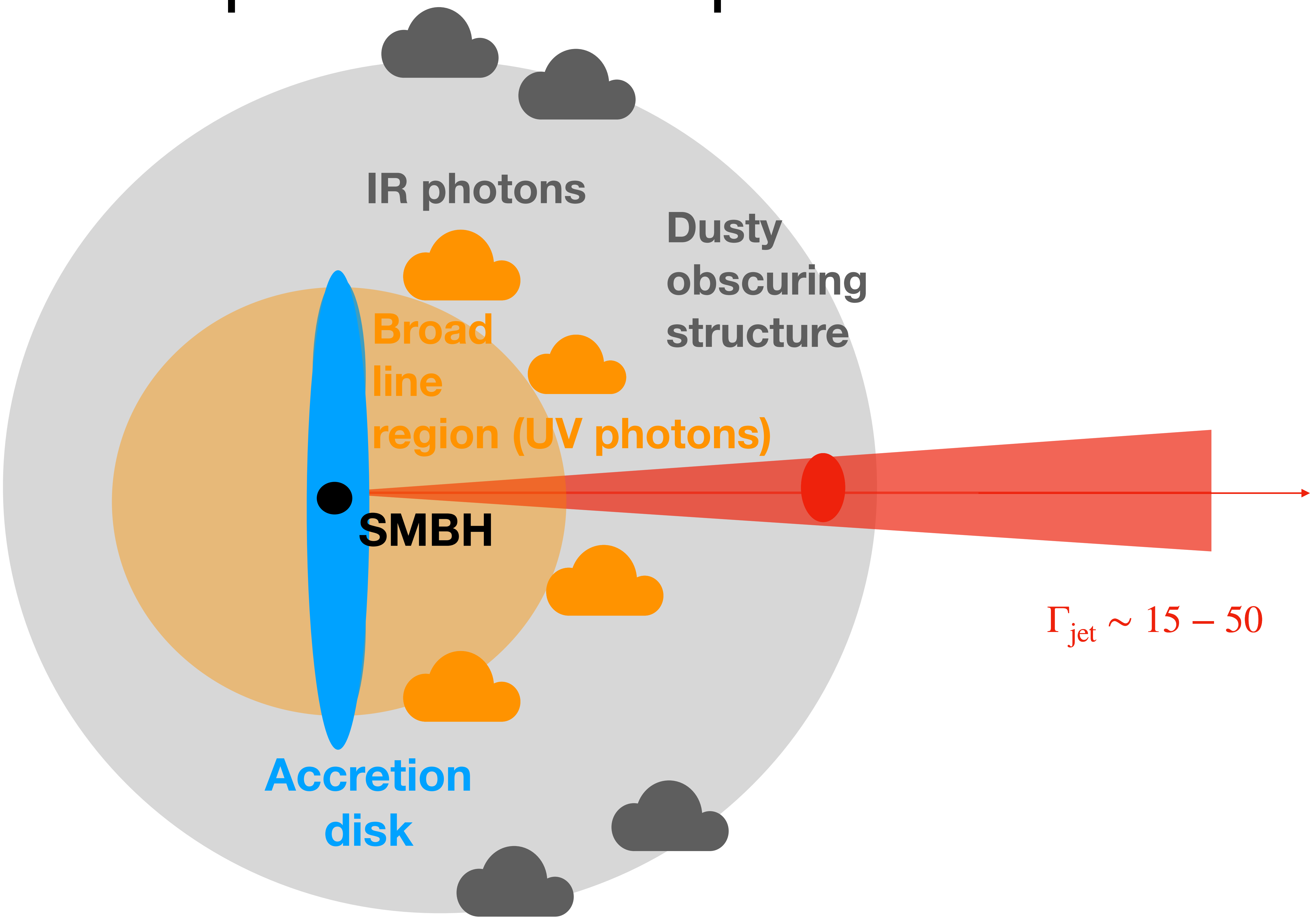
Very powerful collimated jets

Radiatively efficient accretion disk

Luminosity close to Eddington limit

Blazar spectral subclasses

Flat spectrum radio quasars



Very powerful collimated jets

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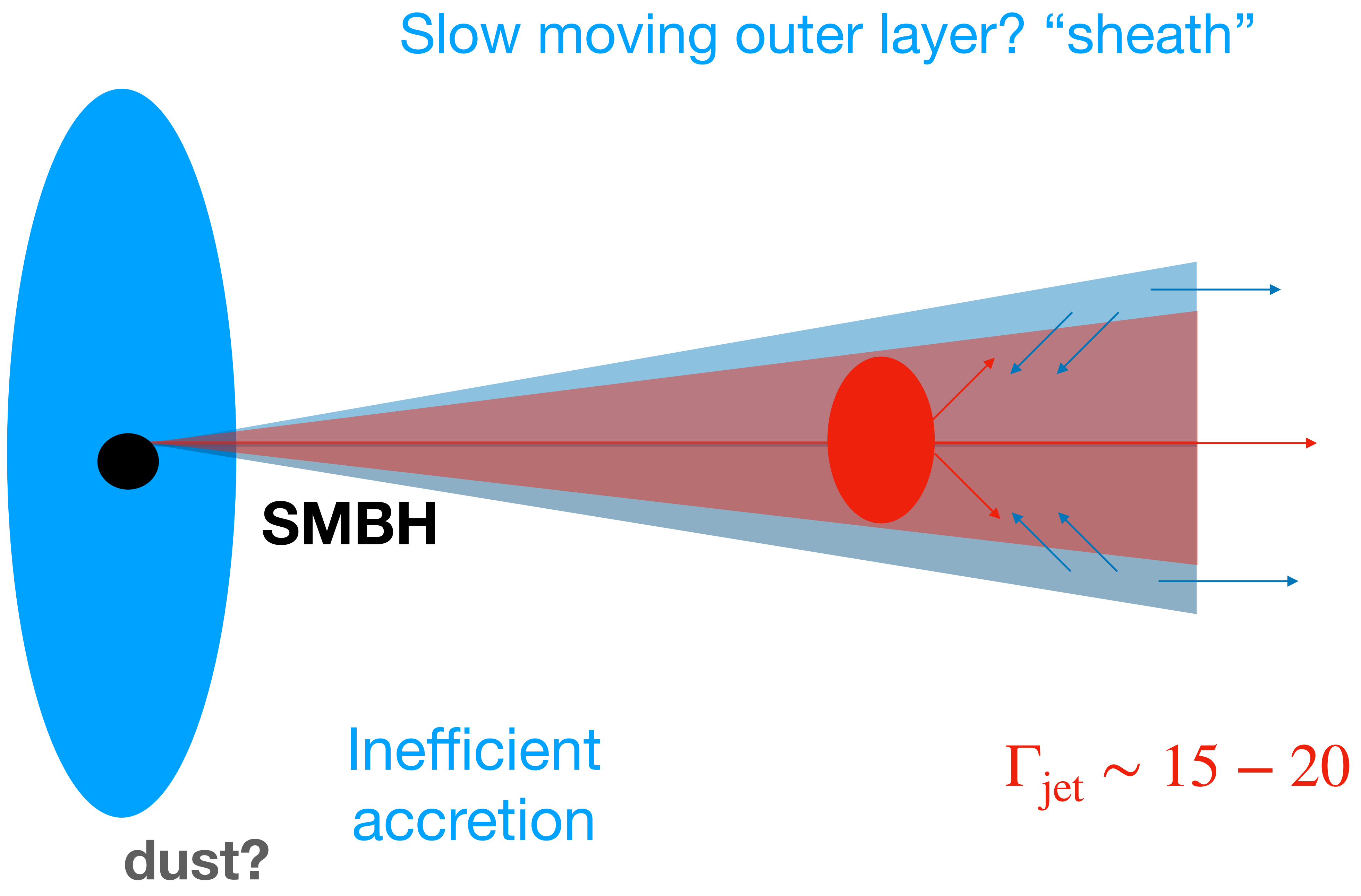
BL Lac Objects

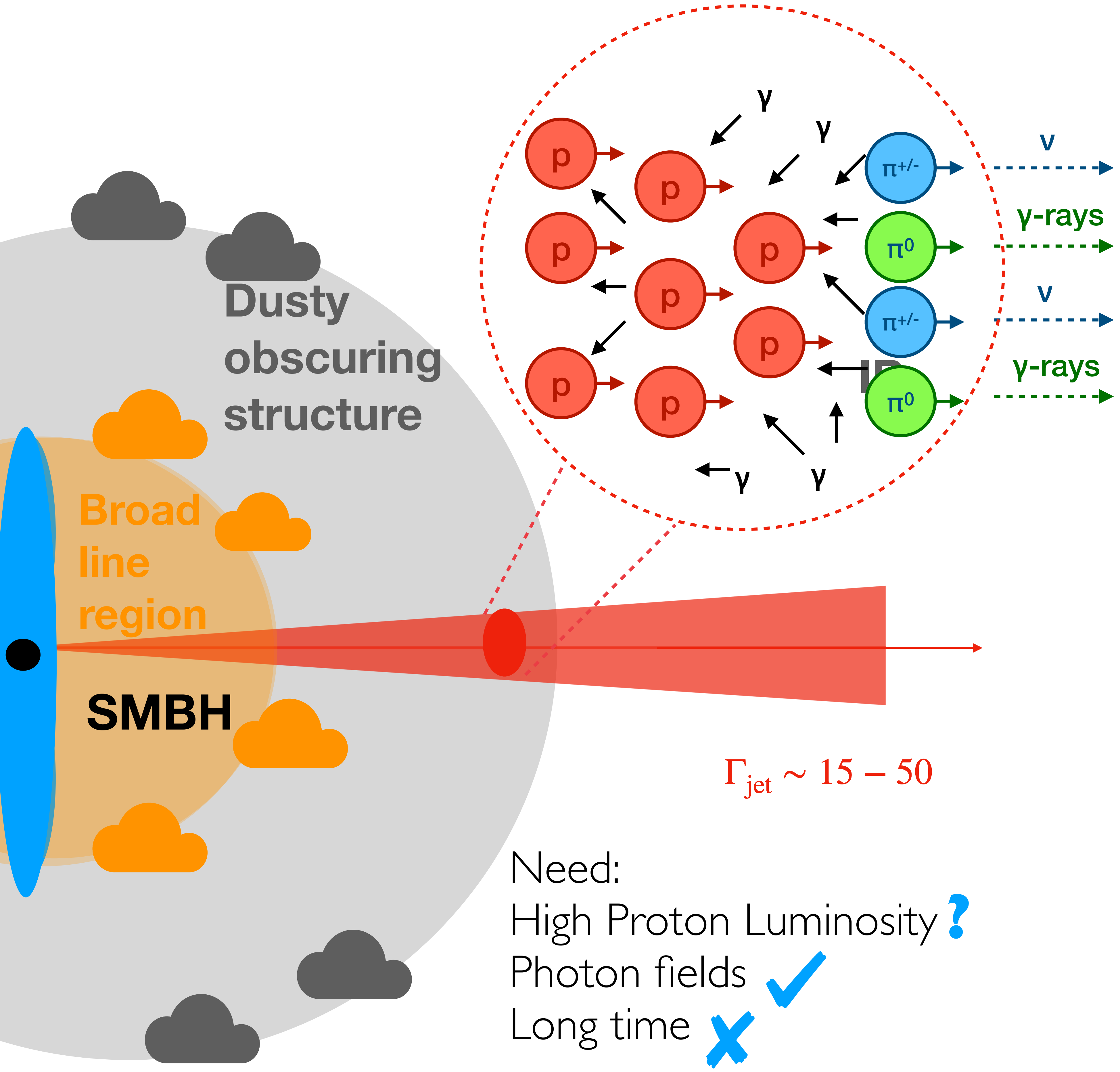


Less collimated jets

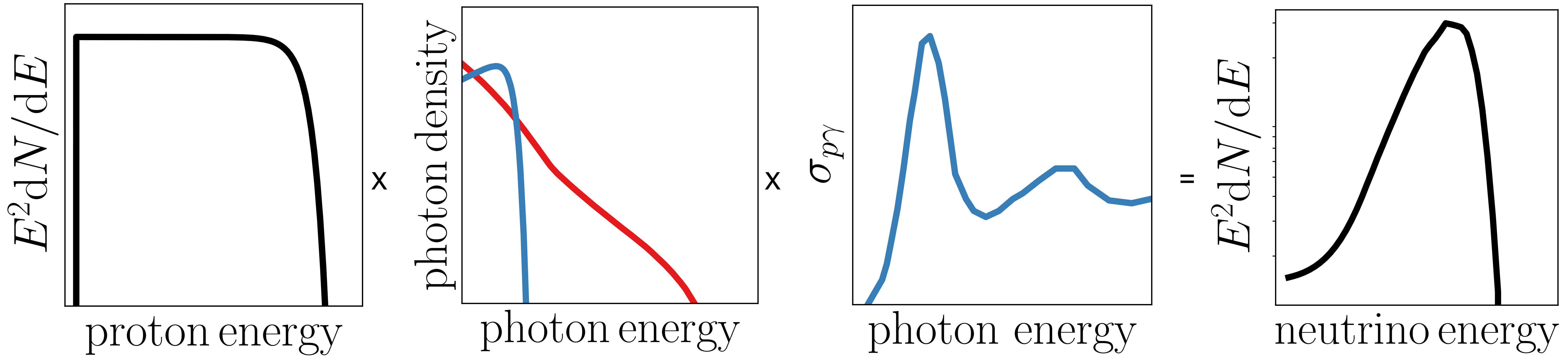
Radiatively inefficient accretion disk

Neutrino production in blazars

this ICRC: Xue #31, Fiorillo #65, Schroller, #166, Das, #425, Cerruti #905, Stathopoulos #991, Rodrigues -Ramirez #1317, Mbarek #1325
Rodrigues #1321, #1330



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



$$E_{\mathrm{BLR}} = 10.2\ \mathrm{eV}$$

$$E_{\mathrm{dust\ torus}} = 0.1\ \mathrm{eV}$$

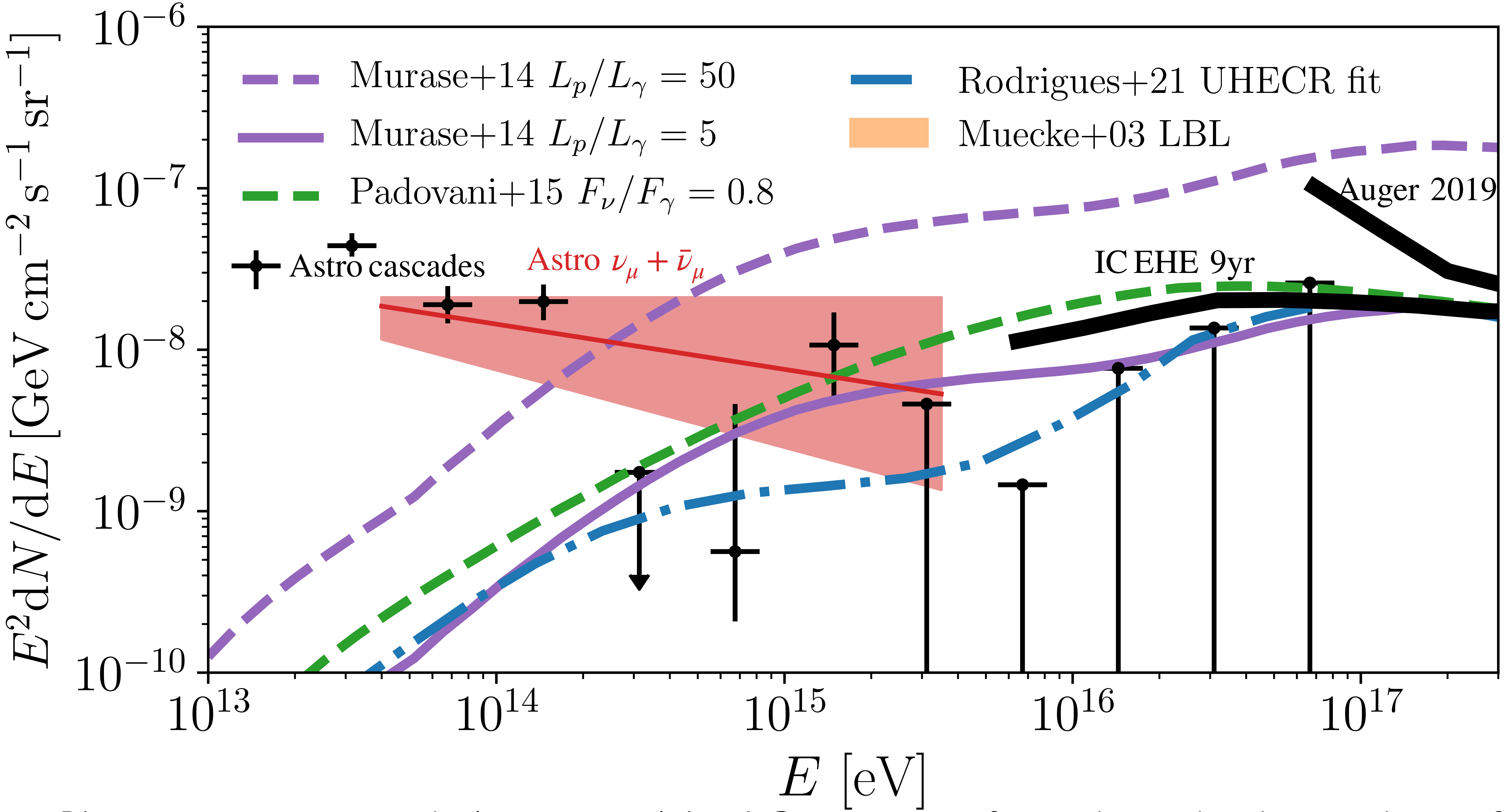
Neutrino typical energy:

$$E_{\nu,\mathrm{BLR}} = \frac{80\ \mathrm{PeV}}{(1+z)^2}\left(\frac{\delta}{10}\right)^2 \frac{10\ \mathrm{eV}}{E_\gamma}$$

$$E_{\nu,\mathrm{IR}} = \frac{8\ \mathrm{EeV}}{(1+z)^2}\left(\frac{\delta}{10}\right)^2 \frac{0.1\ \mathrm{eV}}{E_\gamma}$$

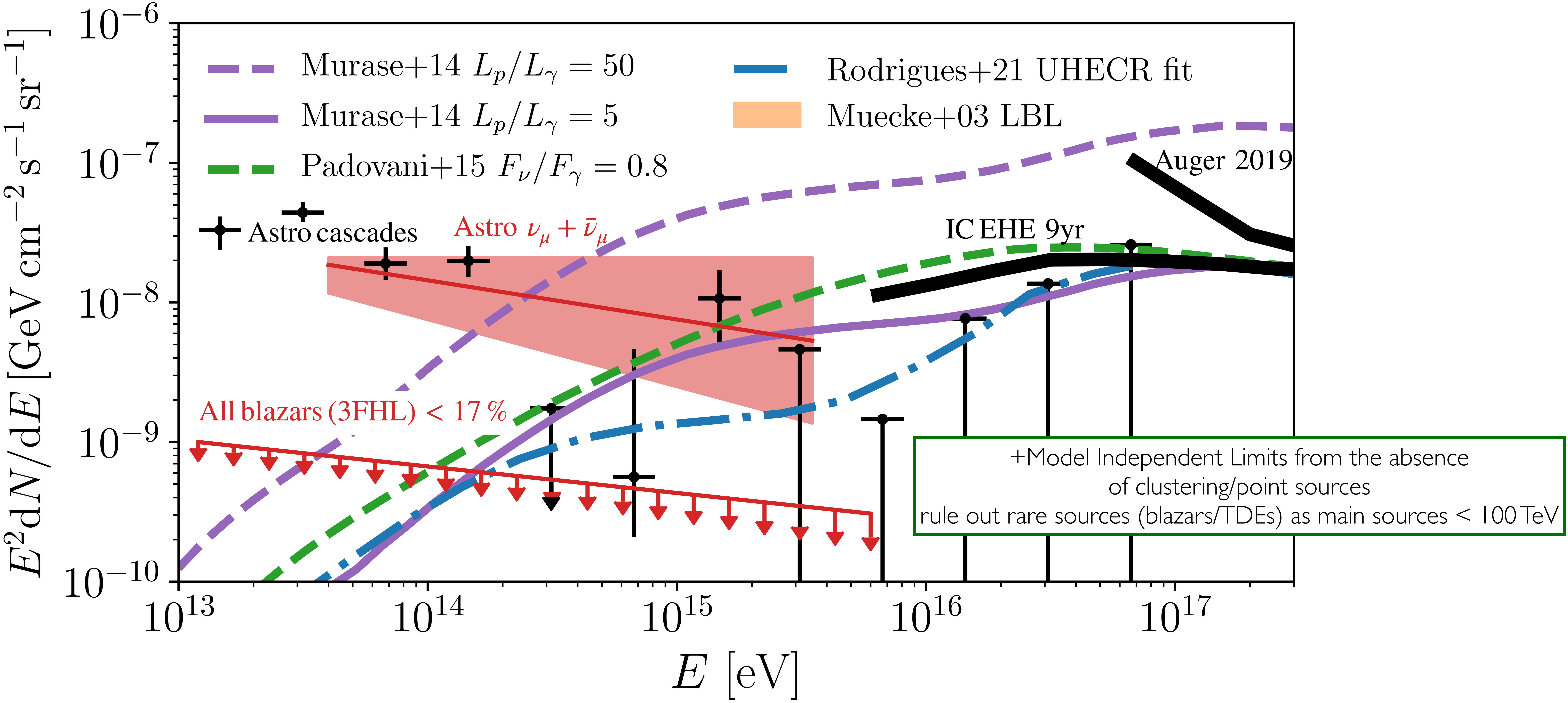
e.g. Mannheim 1991, 1993, Halzen & Zas 1997, Mücke 2001, 2003, Atoyan & Dermer 2001, 2004, Neronov, Semikoz 2002, Dermer et al 2006, Kachelriess et al 2009, Neronov et al 2009, Böttcher 2013, Dermer, Cerruti 2013, Cerruti et al 2013, Tchernin et al 2013, Murase et al. 2012, 2014, Dermer et al 2014, Tavecchio et al 2014, 2015, Petropoulou et al 2014, 2015, 2016, Jacobsen 2015, Padovani 2015, Gao et al 2017, Rodrigues et al 2017, 2020, Palladino et al. 2019, Righi et al 2020, Rodrigues et al 2021

The contribution of blazars to the diffuse neutrino flux



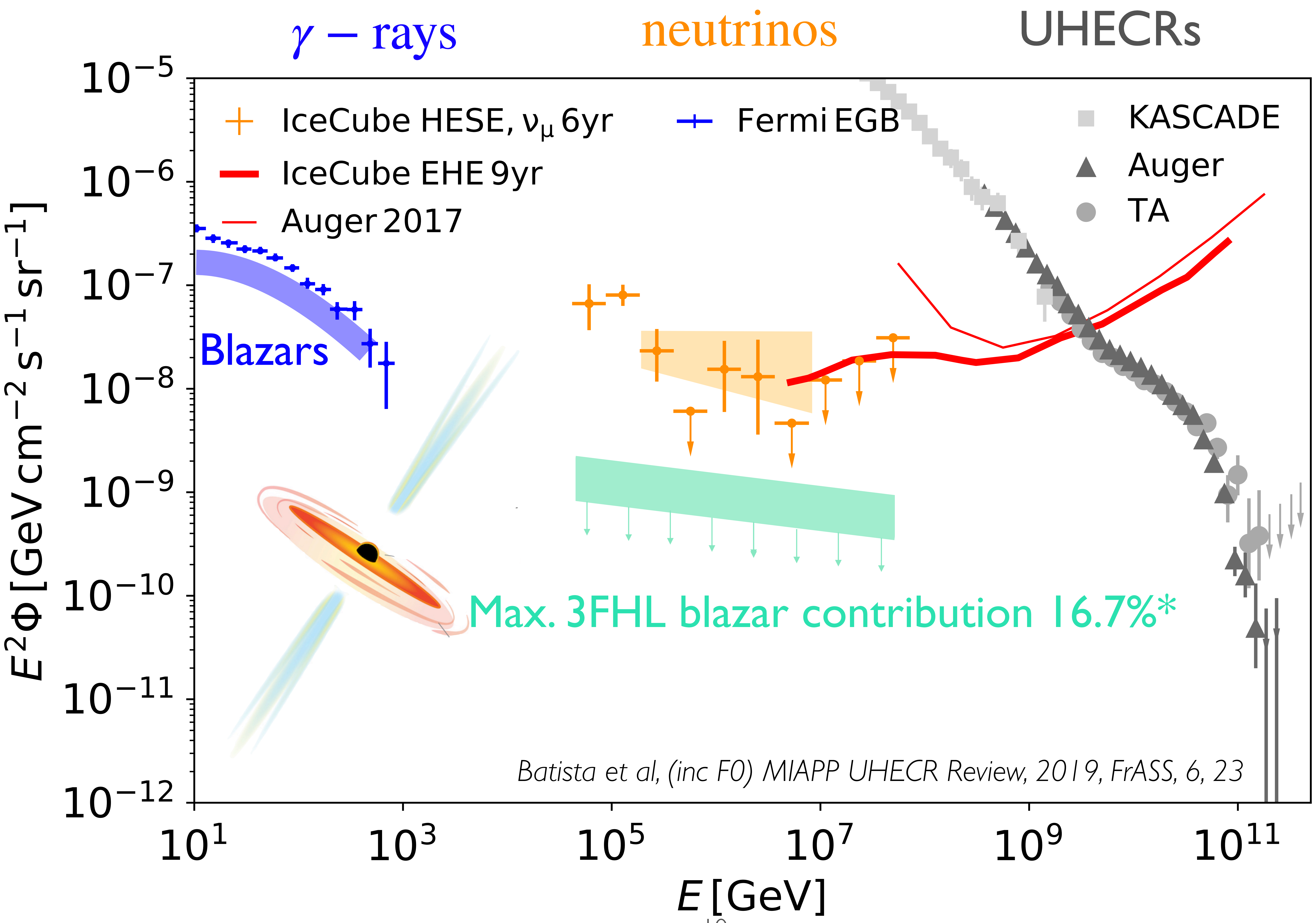
Blazar proton content is (on average) low! Gamma-rays from photopion interactions <few %

The contribution of blazars to the diffuse neutrino flux

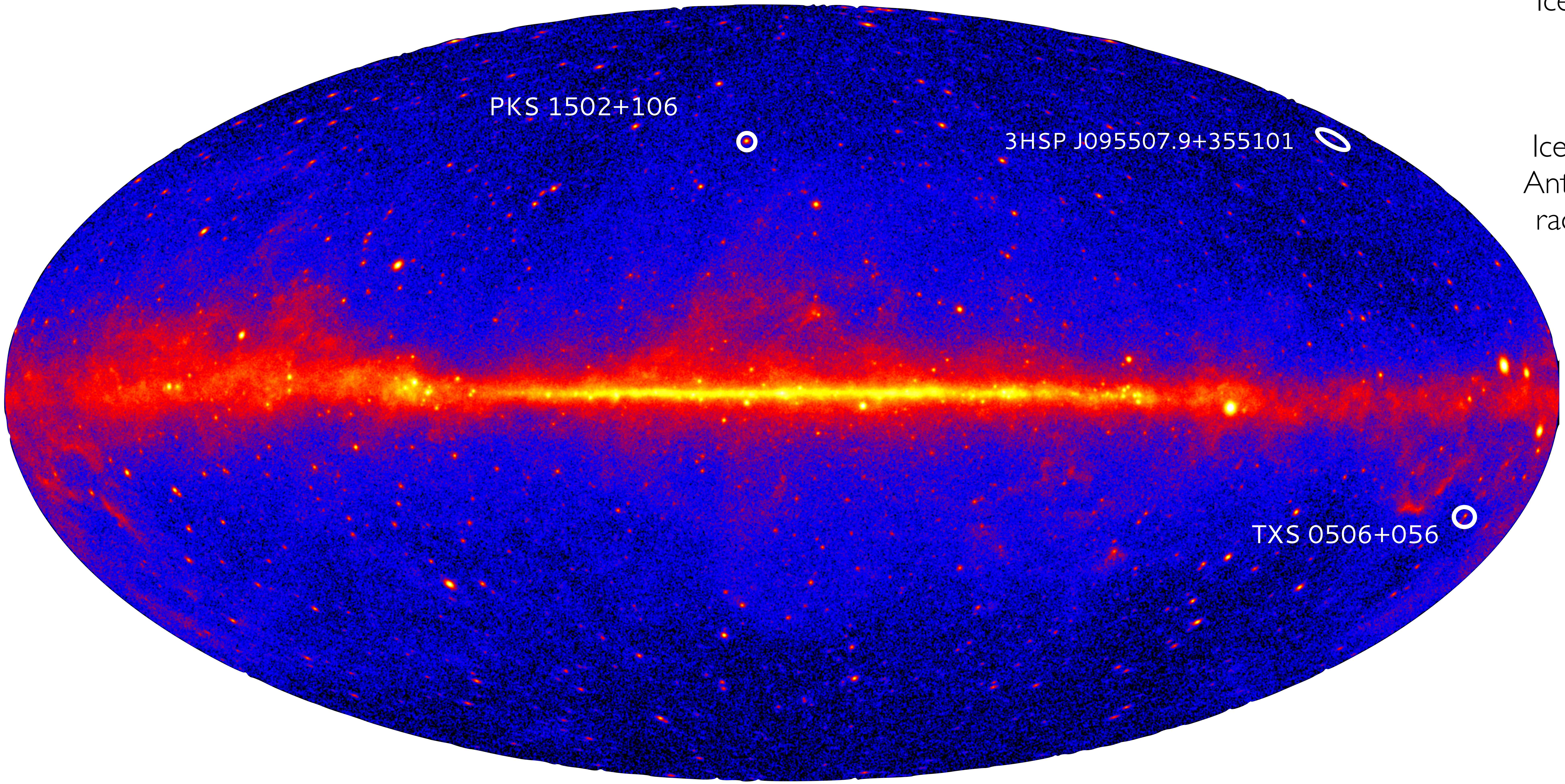


Huber for IceCube Coll PoS (ICRC 2019) 916. Limits also apply to infrared selected blazars, ≲27% with spectral templates: IceCube Coll PoS (ICRC2017) 994
see also (Plavin #1015) >25% VLBI blazars, but <6% (Desai #469) from MOJAVE blazars<30% equal weights (13.8% x-ray weights) VLBI blazars Zhou et al 2021 PRD

The contribution of blazars to the diffuse neutrino flux



Blazars coincident with high-energy neutrinos



Several dozen associations so far:

IceCube sends public alerts since 2016
Fermi-LAT follow up: 6 blazars in 23 follow-ups (S. Garrappa #812)
Telamon (M. Sadler #1320)
IceCube flares - X-rays (Sharma #299)
Antares flares - radio (Illuminati #1137)
radio blazars + Antares (Aublin #1240
IACTs: (Satalecka #907)

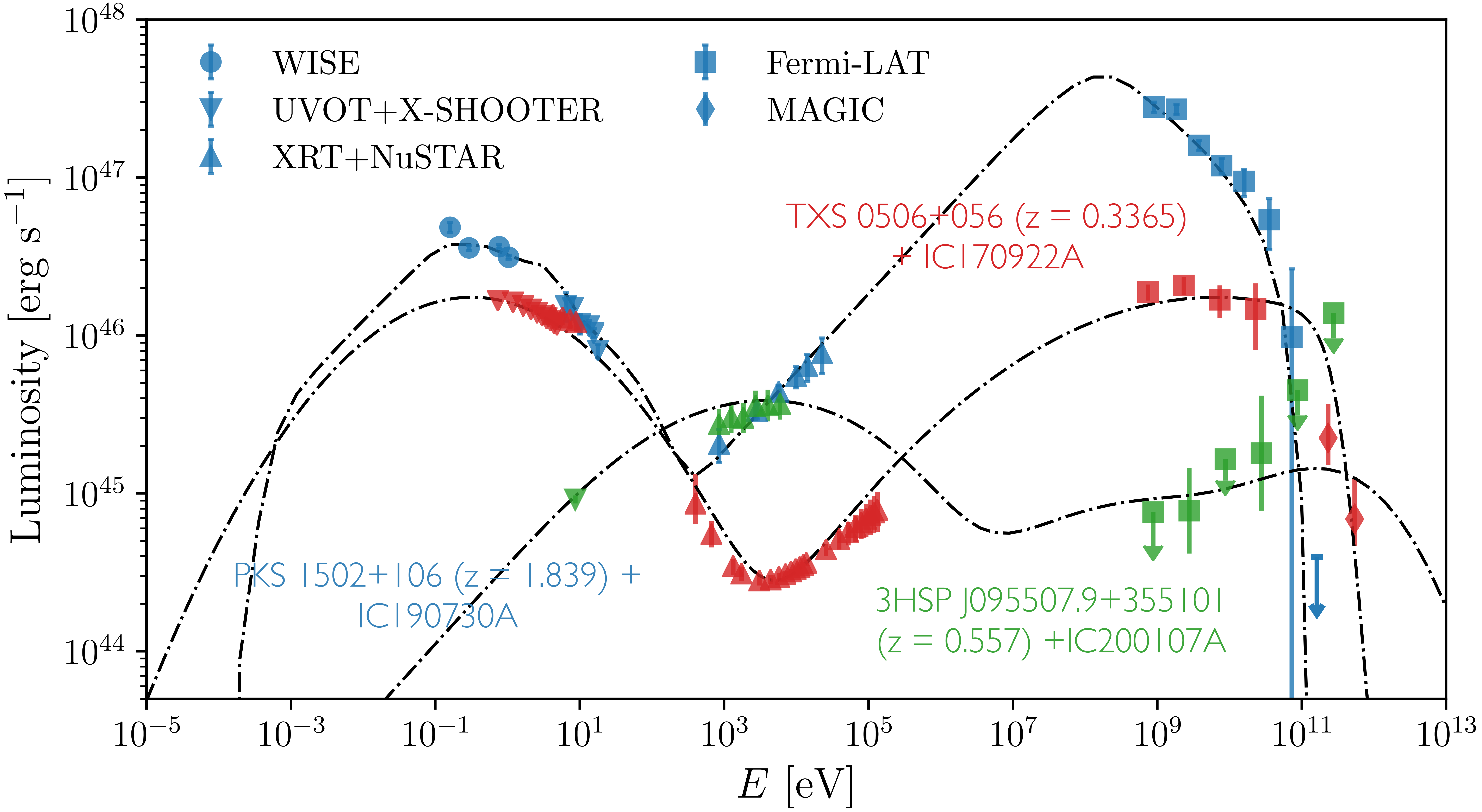
4FGL J0658.6+0636+IC201114A: (de Menezes #296, Rosales de Leon #308)

3.3σ IceCube Coll 10yr Point-Source Analysis (3 blazars)
Franckowiak et al ApJ 893 (2020)
Giommi et al MNRAS 497 (2020)
Hovatta et al A&A 650 (2021)
Plavin et al ApJ 908 (2021)

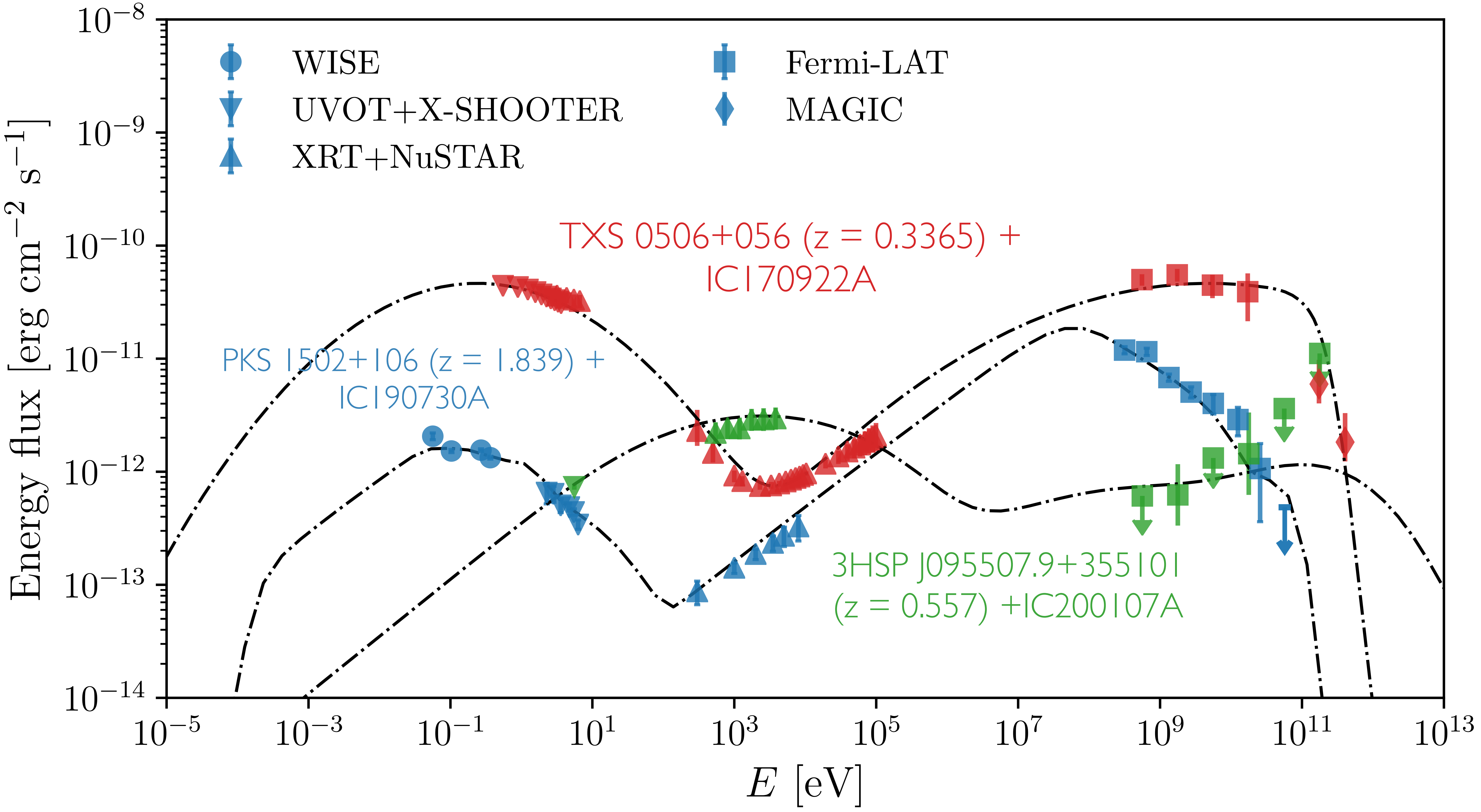
Evaluating the significance of coincidences: Capel #1346

 PKS B1424-418+IC35 Kadler, Nat Phys 12 (2016), Gao, Pohl, Winter, ApJ 843 (2017)

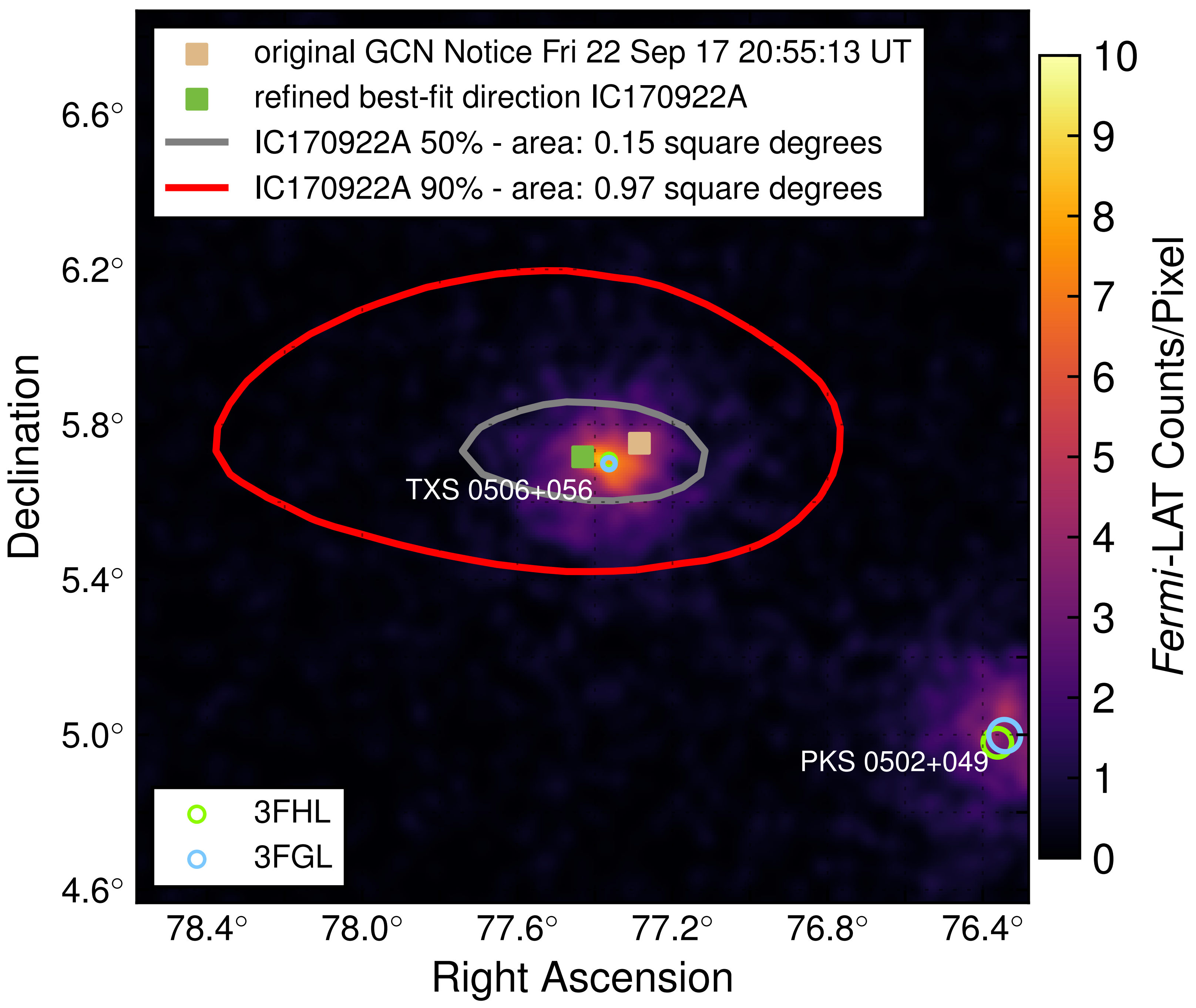
Blazars coincident with high−energy neutrinos



Blazars coincident with high–energy neutrinos



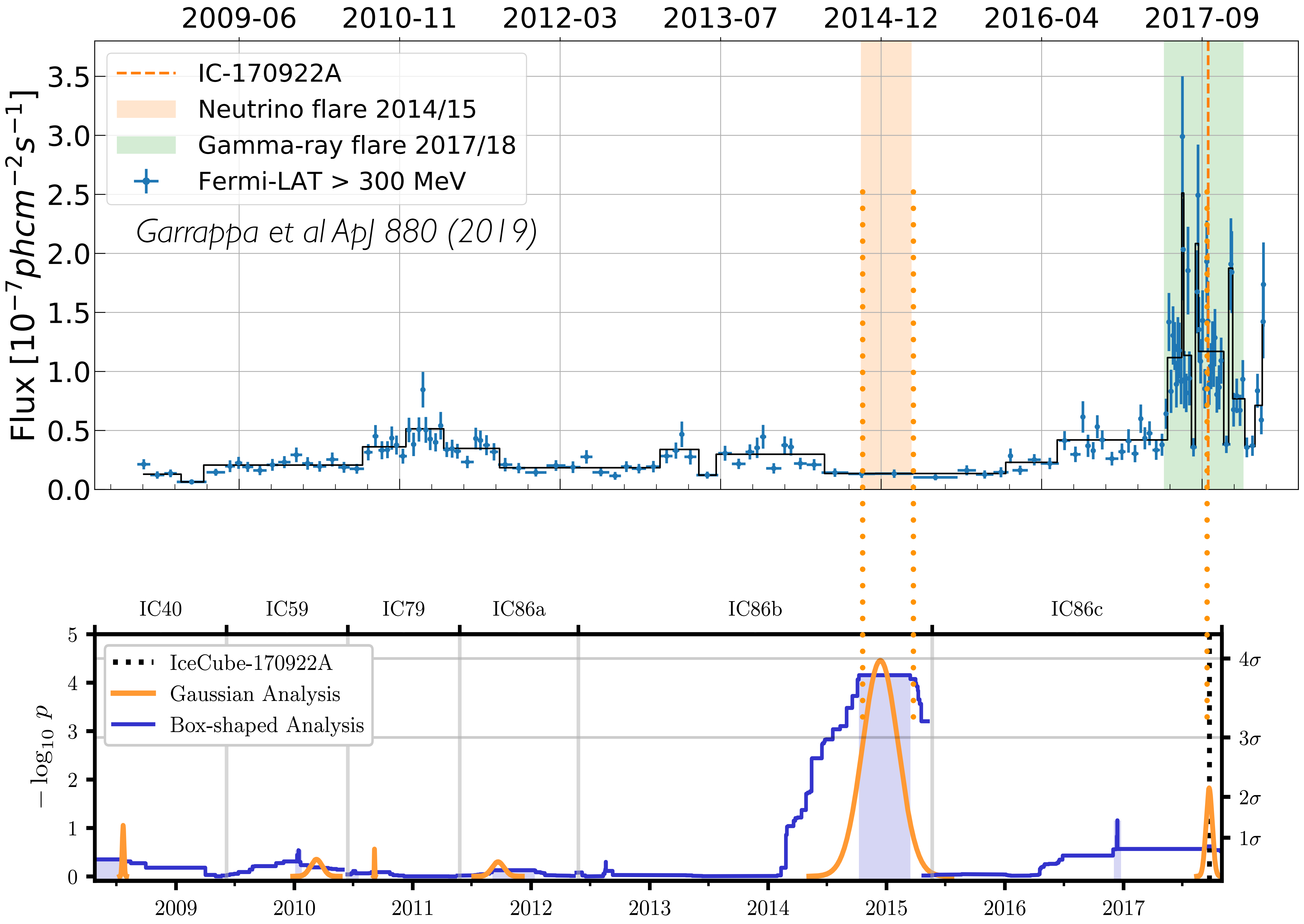
TXS 0506+056 + IC170922A



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

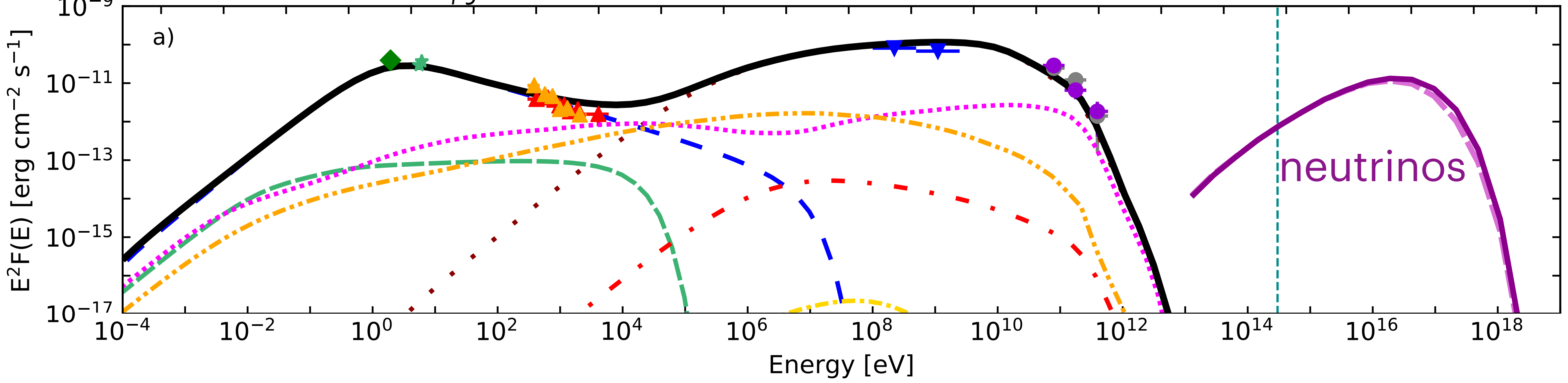
IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018)



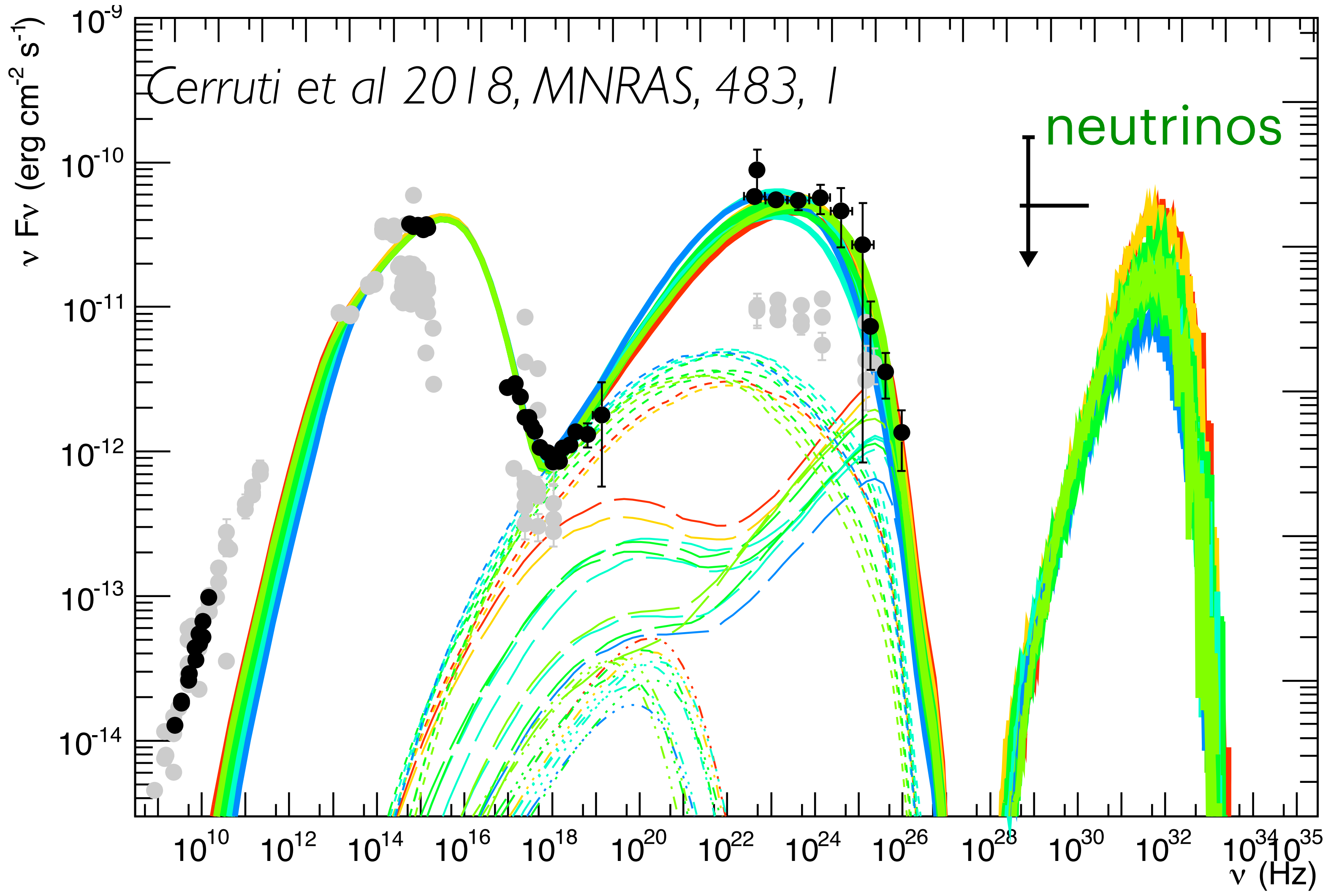
290 TeV muon neutrino coincident with bright flare of TXS 0506+056 (3σ)
signalness of neutrino 56.5%
13±5 more neutrinos from direction of TXS 0506+056 seen in 2014-15 (3.5σ)

TXS 0506+056 + IC170922A

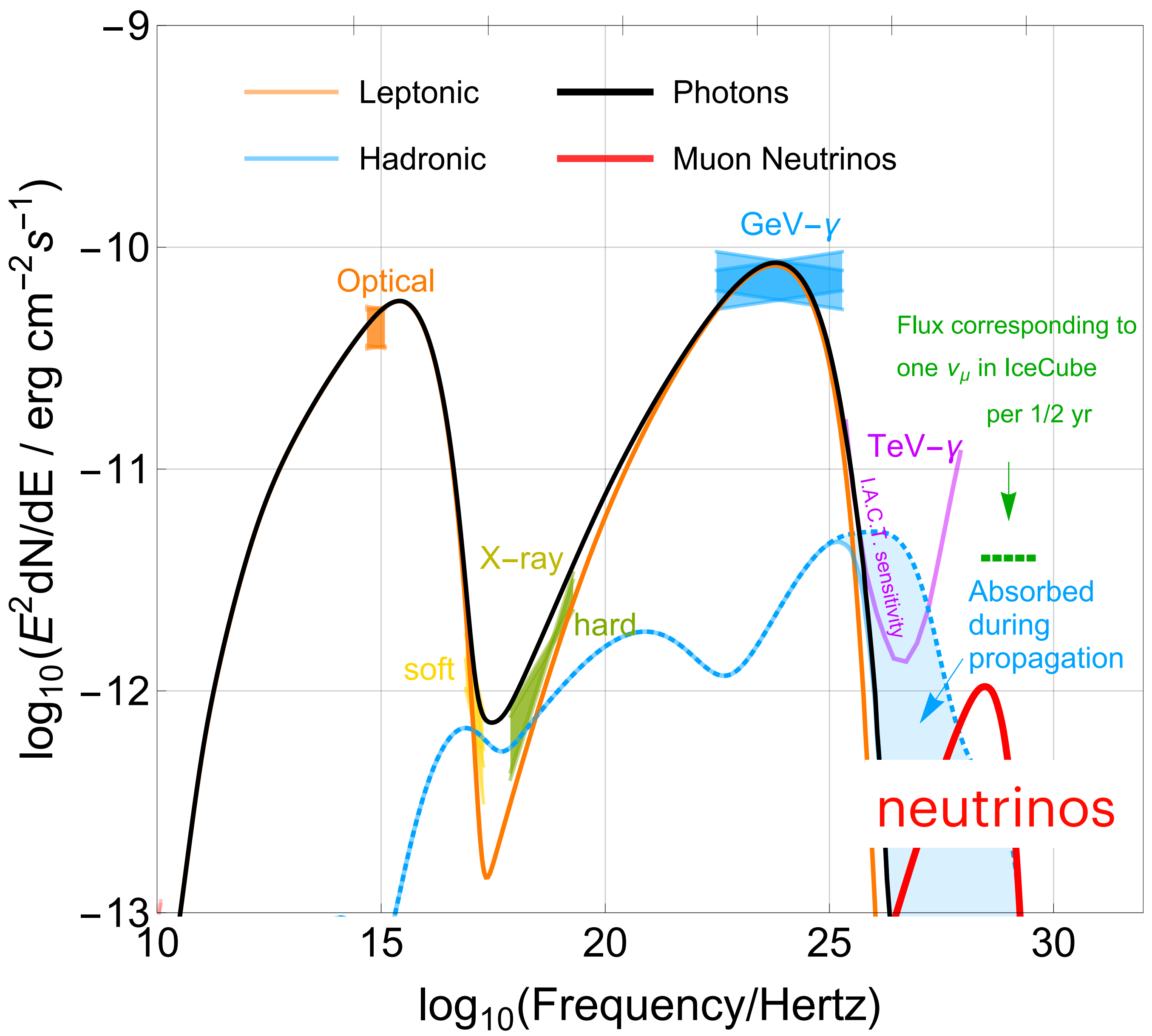
MAGIC Coll 2018, ApJ, 863, L10



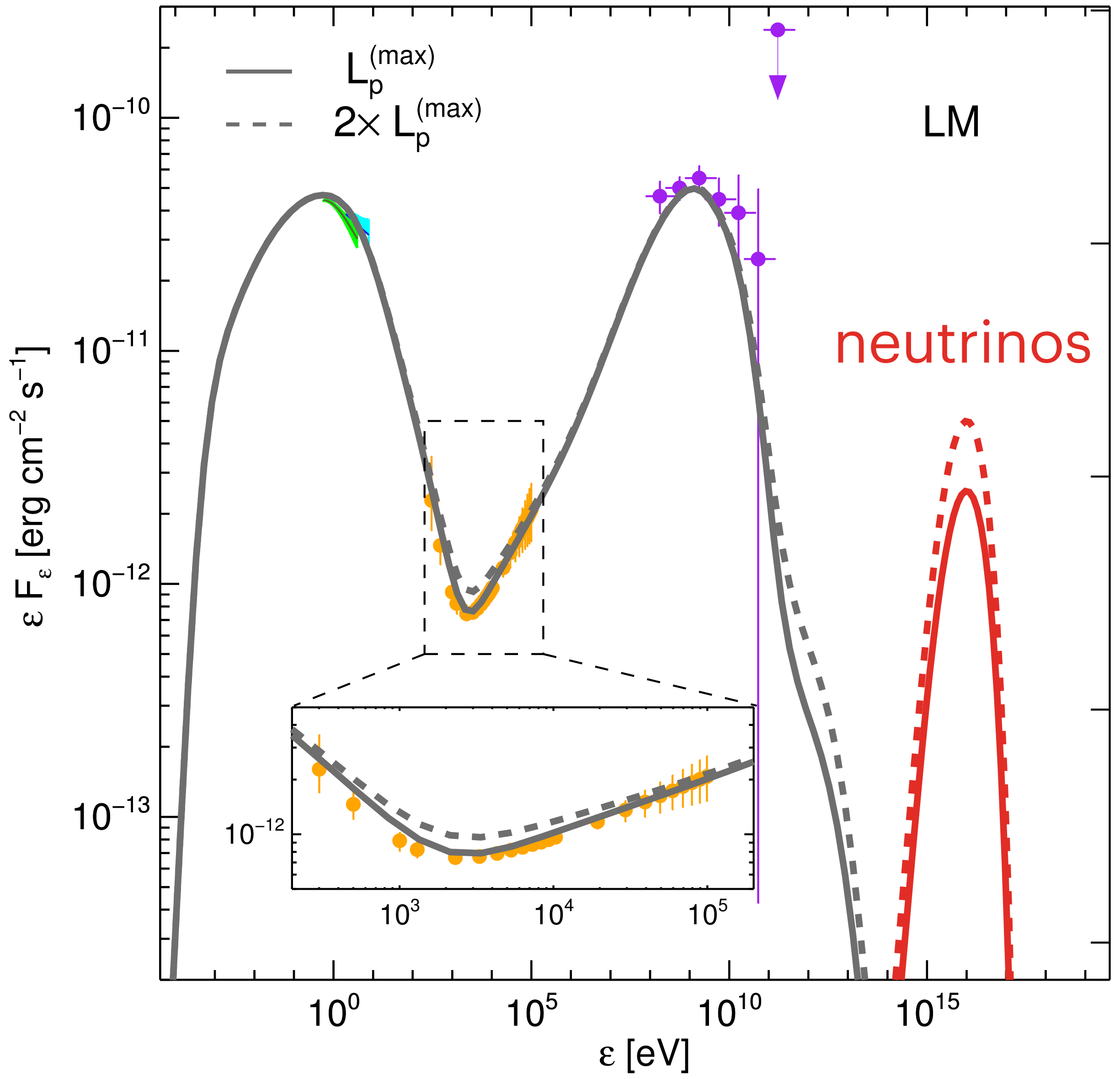
$N_{\nu_\mu} \lesssim 0.05/6$ months



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



Keivani et al. 2018, ApJ, 864, 84



Other more exotic options find increased neutrino flux:
hadro-nuclear interactions: *Liu+19*
stellar disruption: *Wang+19*
multiple zones: *Xue+(inc FO)19*
neutron beam: *Zhang+(inc FO)19*
curved/double jet: *Britzen+19, Ros+19*
inefficient accretion flow: *Righi+19*
2014 flare: Reimer+19, Rodrigues+19, Halzen+19, Petropoulou+20,
and more…!

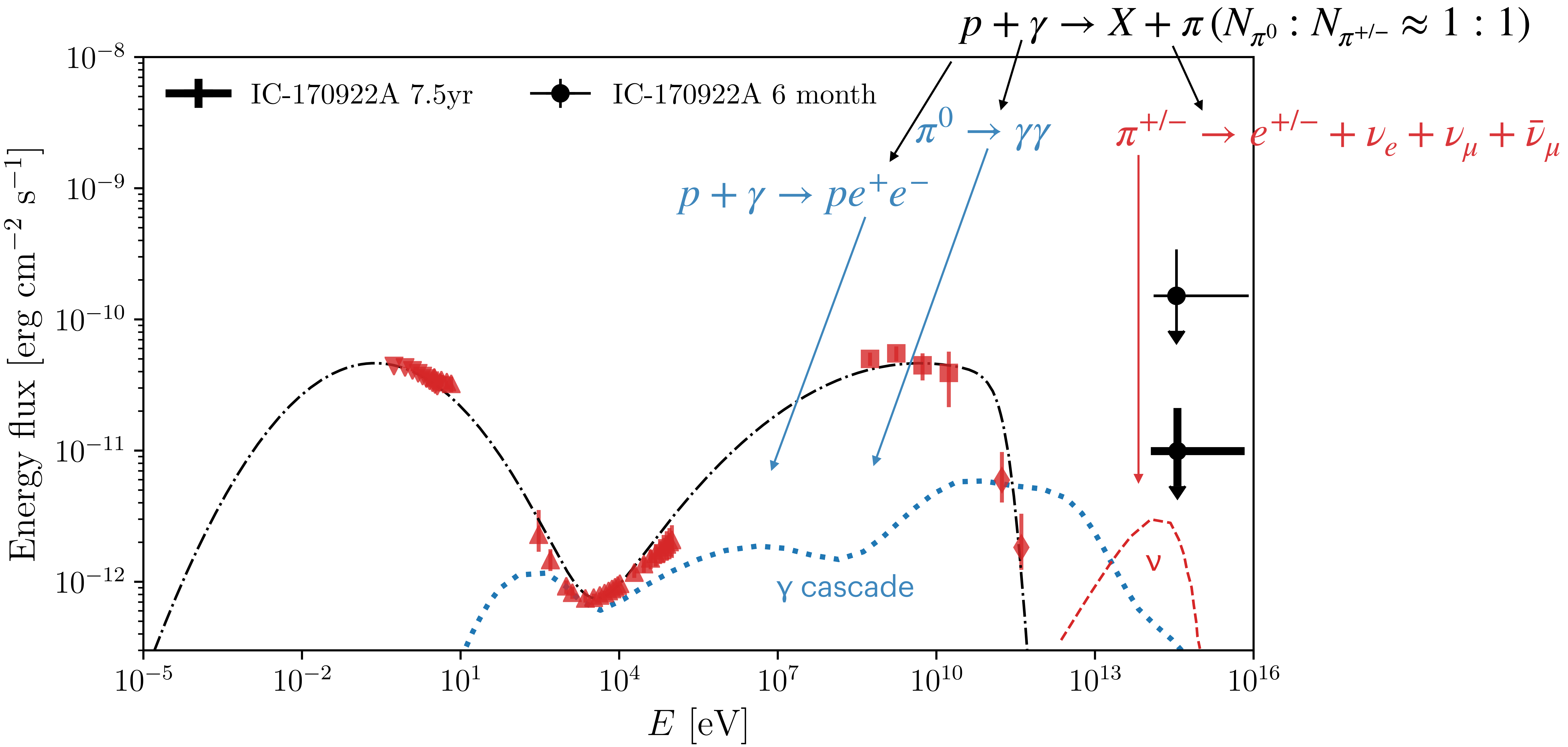
Statistically consistent with the detection of one event
IceCube et al 2018, Strotjohann et al A&A 622(2019)

A misclassified FSRQ
Padovani, FO, Petropoulou et al MNRAS 484 (2019)

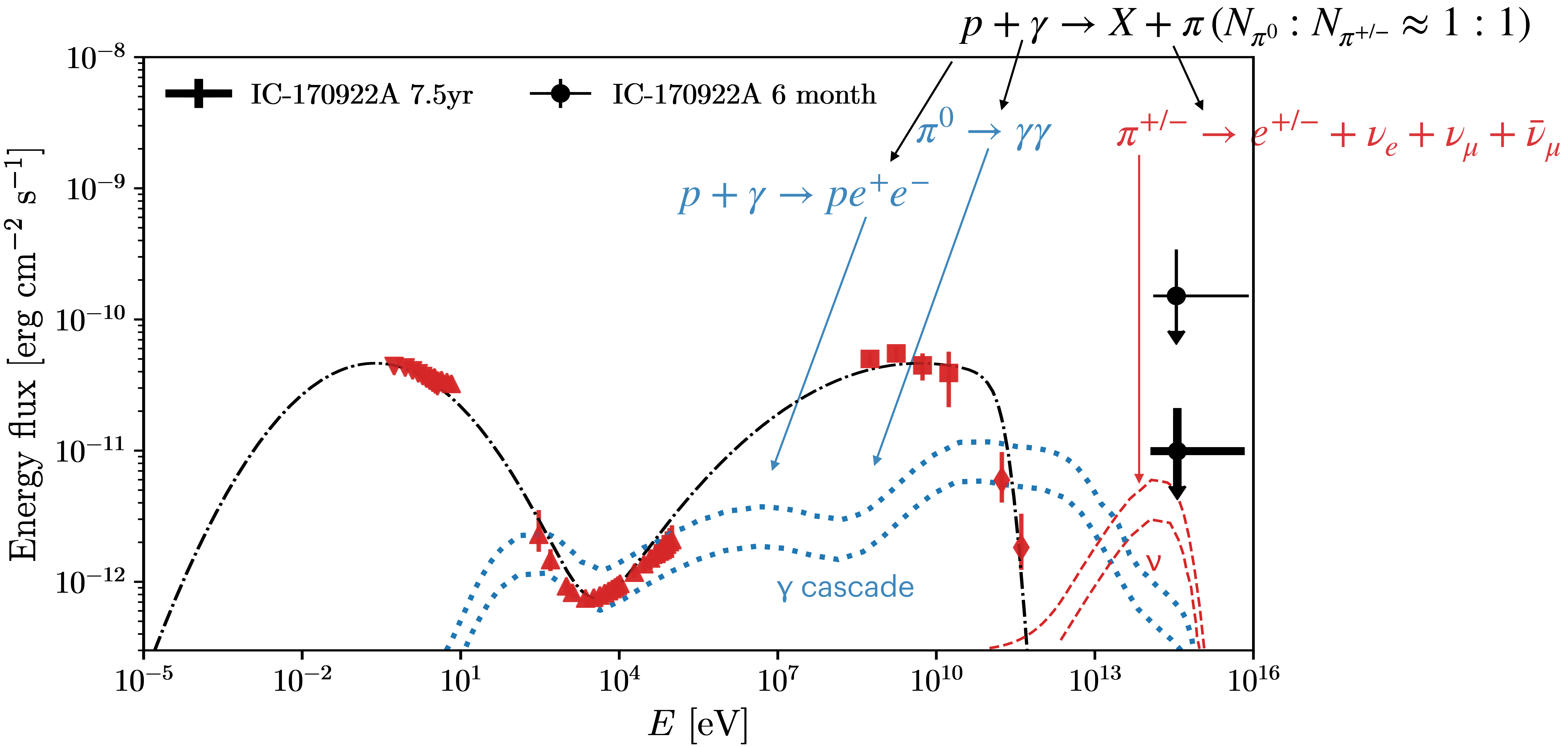
Requires **atypically large proton luminosity and photon fields** ***to have produced 0.05 neutrinos/6 months***

TXS 0506+056 + IC170922A

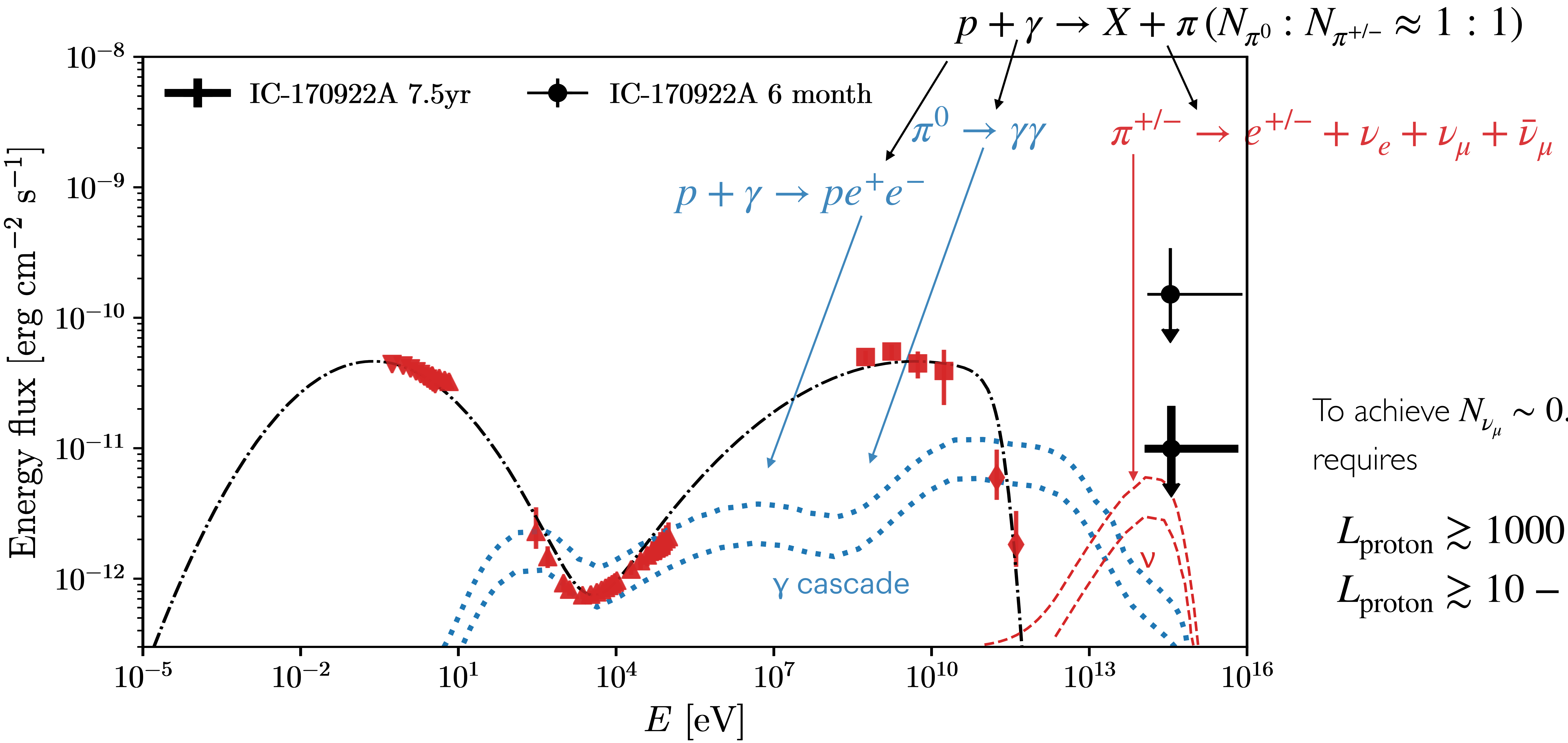
Modelling implications



TXS 0506+056 + IC170922A



TXS 0506+056 + IC170922A



To achieve $N_{\nu_\mu} \sim 0.05/6$ months requires

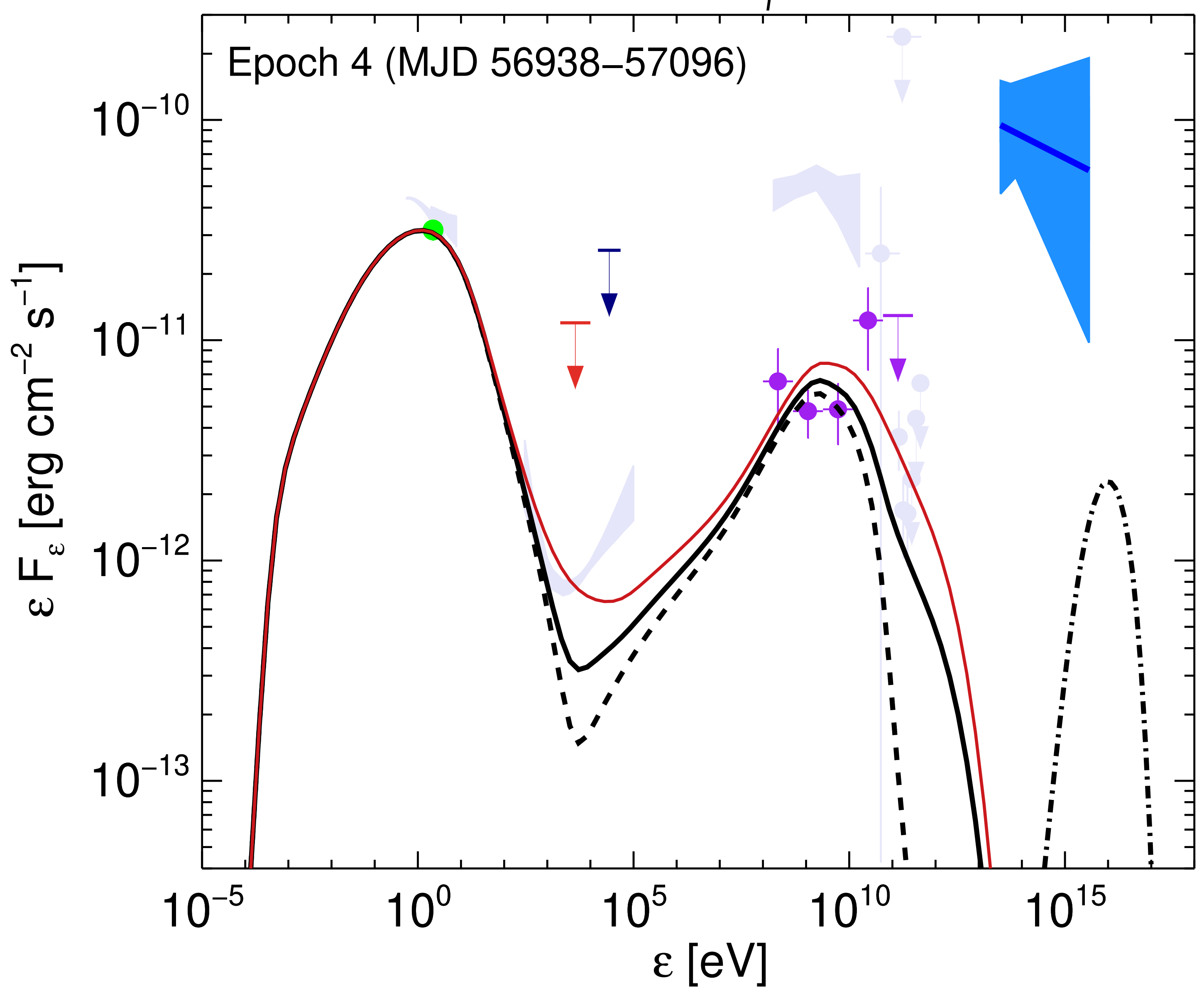
$$L_{\rm proton} \gtrsim 1000 \; L_\gamma$$
$$L_{\rm proton} \gtrsim 10 - 100 \; L_{\rm Eddington}$$

TXS 0506+056 2014–15 neutrino flare

Rodrigues, Gao, Fedynitch, Palladino, Winter, ApJL 871 (2019)
Reimer, Böttcher, Buson, ApJ 889 (2019)
Zhang, Petropoulou, Murase, FO, ApJ 889 (2020)
Xue et al (inc FO), ApJ 886 (2020)
Petropoulou et al ApJ 891 (2020)

Model constrained by other epochs

Petropoulou et al 2020

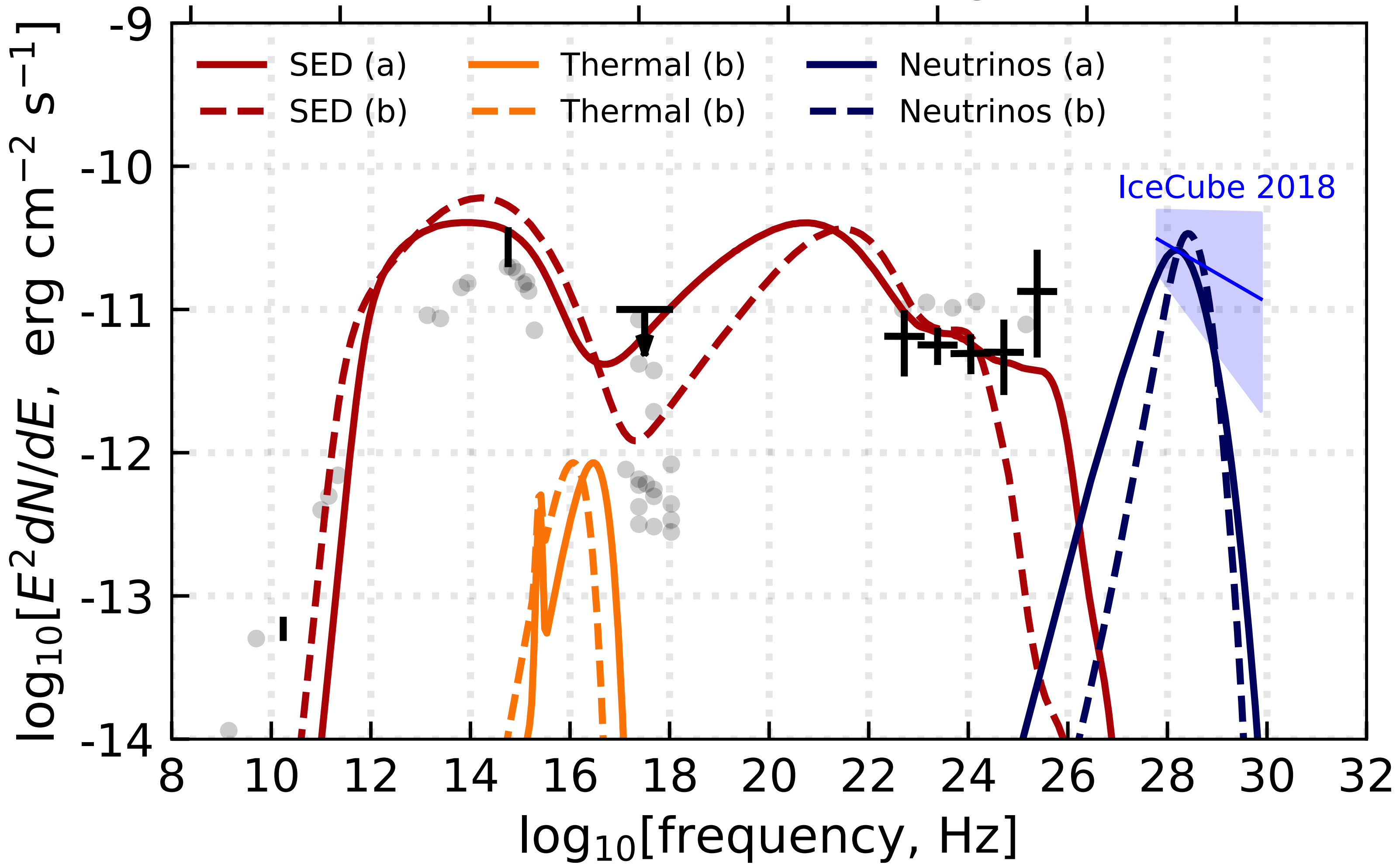


$N_{\nu_\mu} \leq 0.05/6$ months

$L_{\rm proton} \sim 10\, L_{\rm Eddington}$

Model unconstrained by other epochs

Rodrigues et al 2019

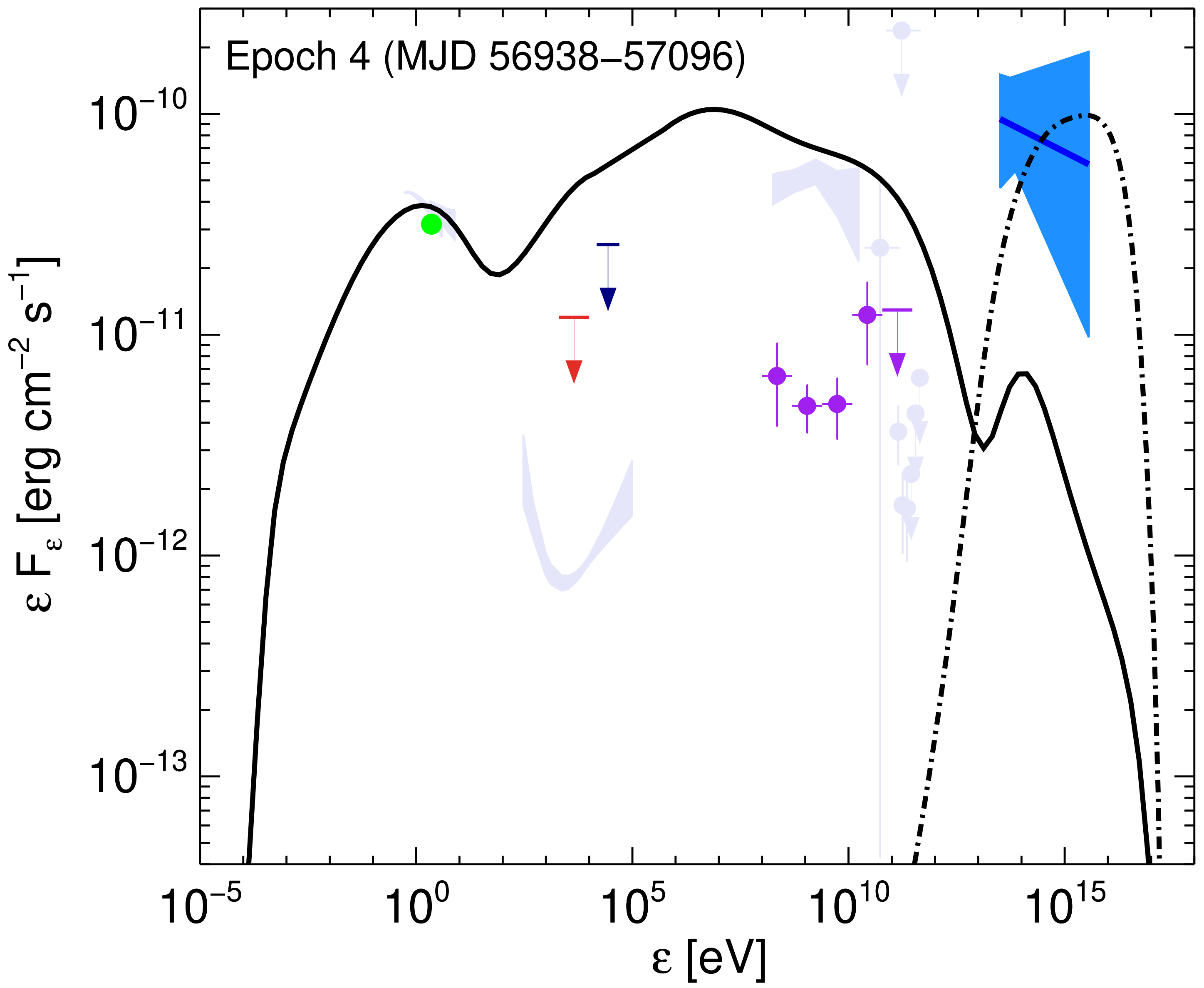


$N_{\nu_\mu} \leq 4.9/6$ months

$L_{\rm proton} \sim 100\, L_{\rm Eddington}$

Overshoots SED

Petropoulou et al 2020



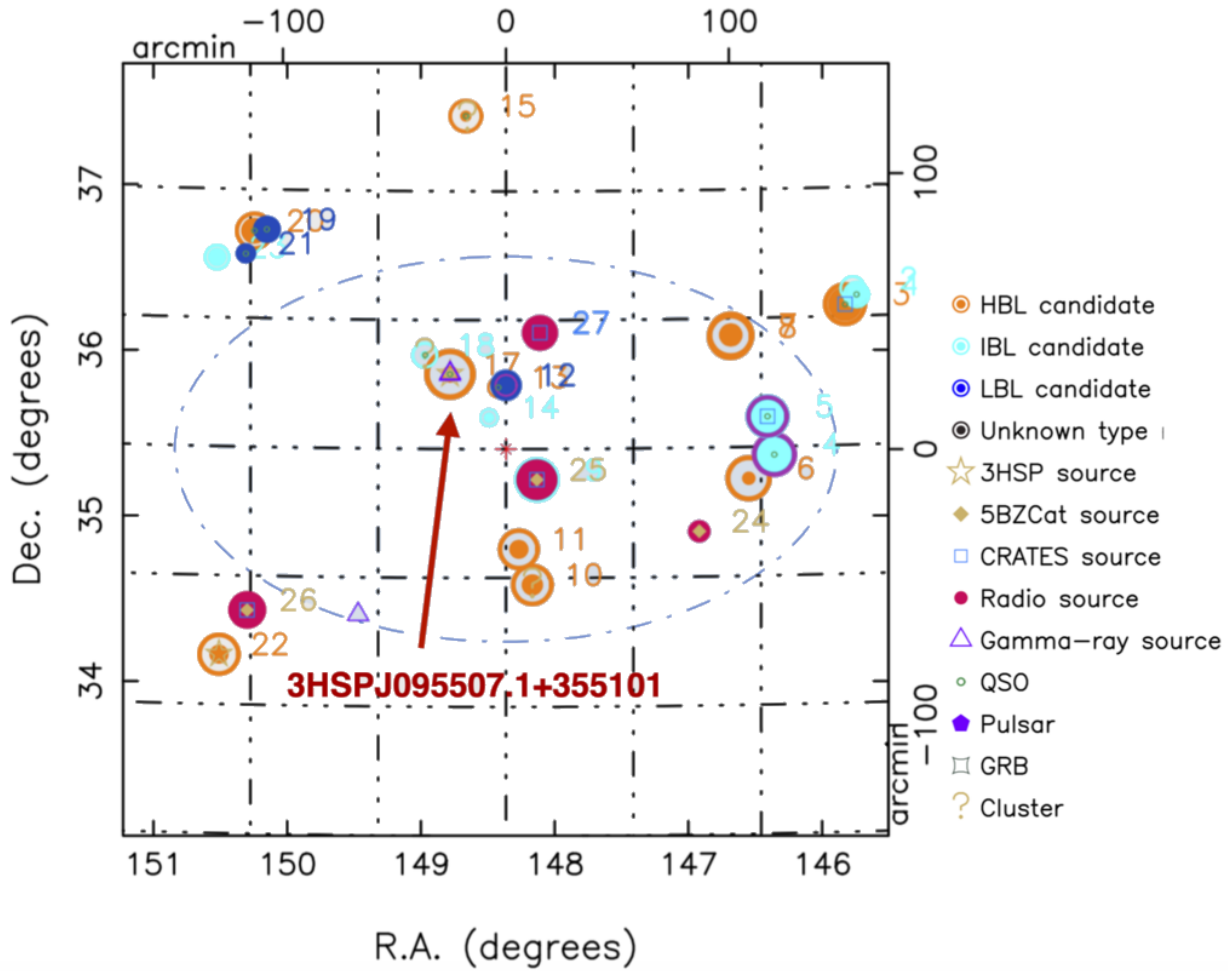
$N_{\nu_\mu} = 13.2/6$ months

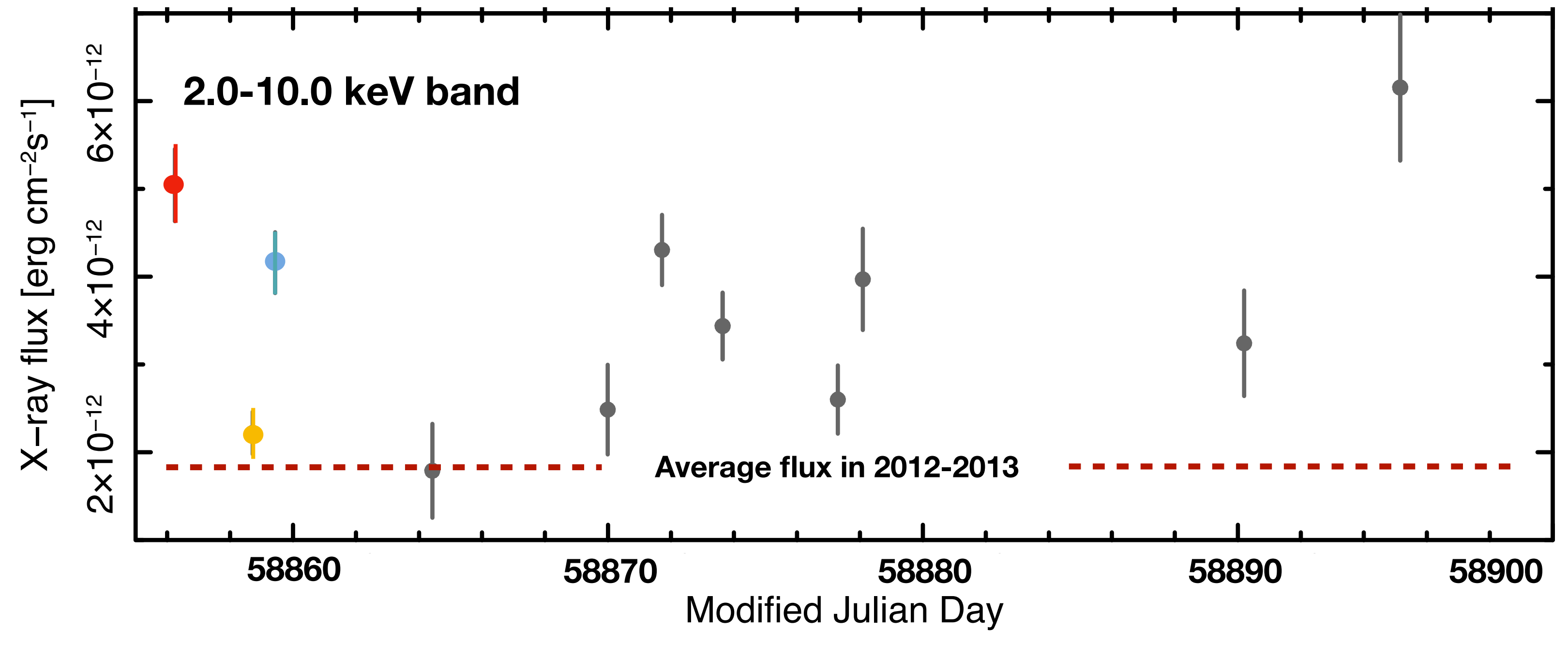
$L_{\rm proton} \sim 1000\, L_{\rm Eddington}$

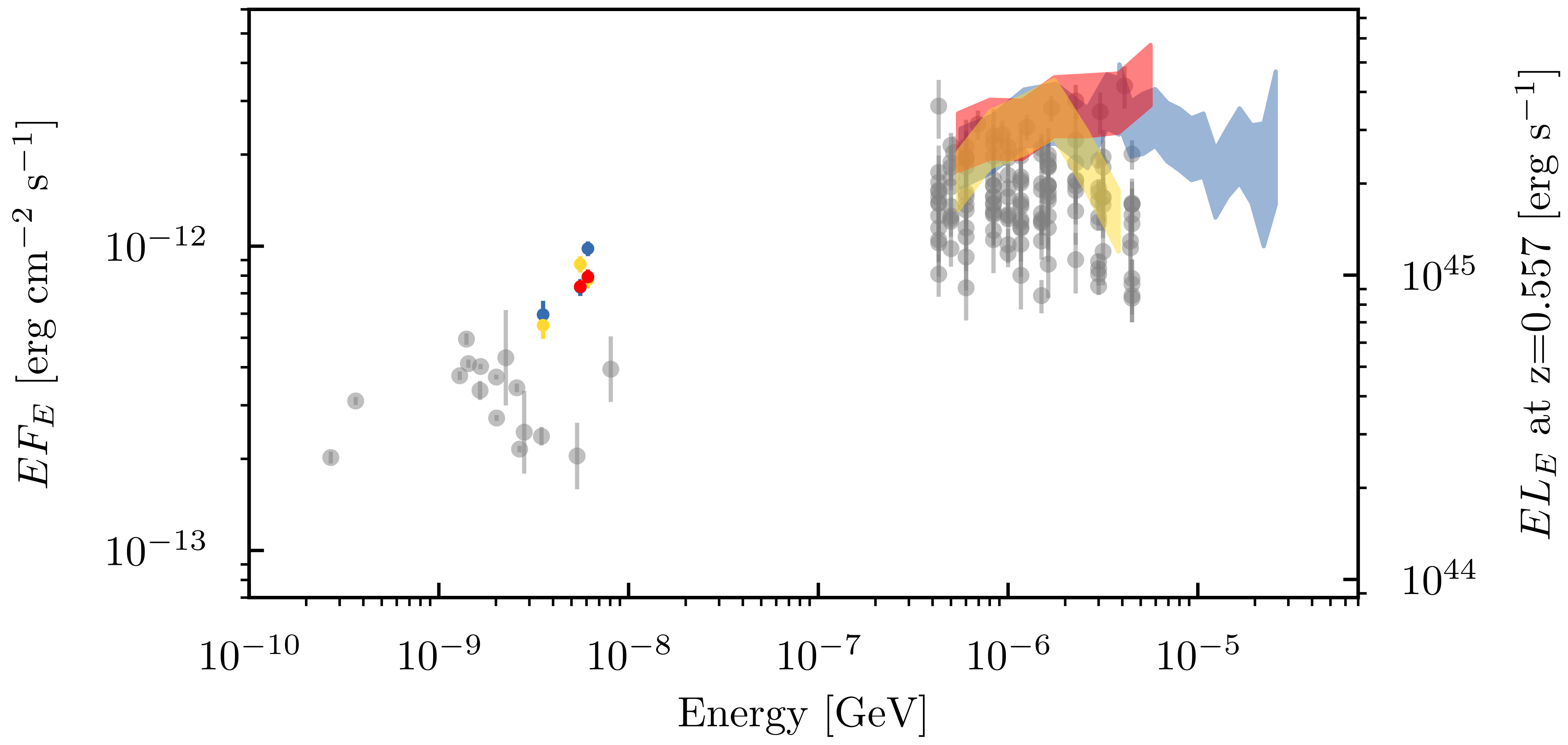
3HSP J095507.9+355101 + IC 200107A

An extreme blazar at z = 0.557 coincident with a 300 TeV neutrino

Giommi, Padovani, FO, Glauch, Paiano, Resconi, A&A 640 (2020)
Paliya et al. ApJ 893 (2020)



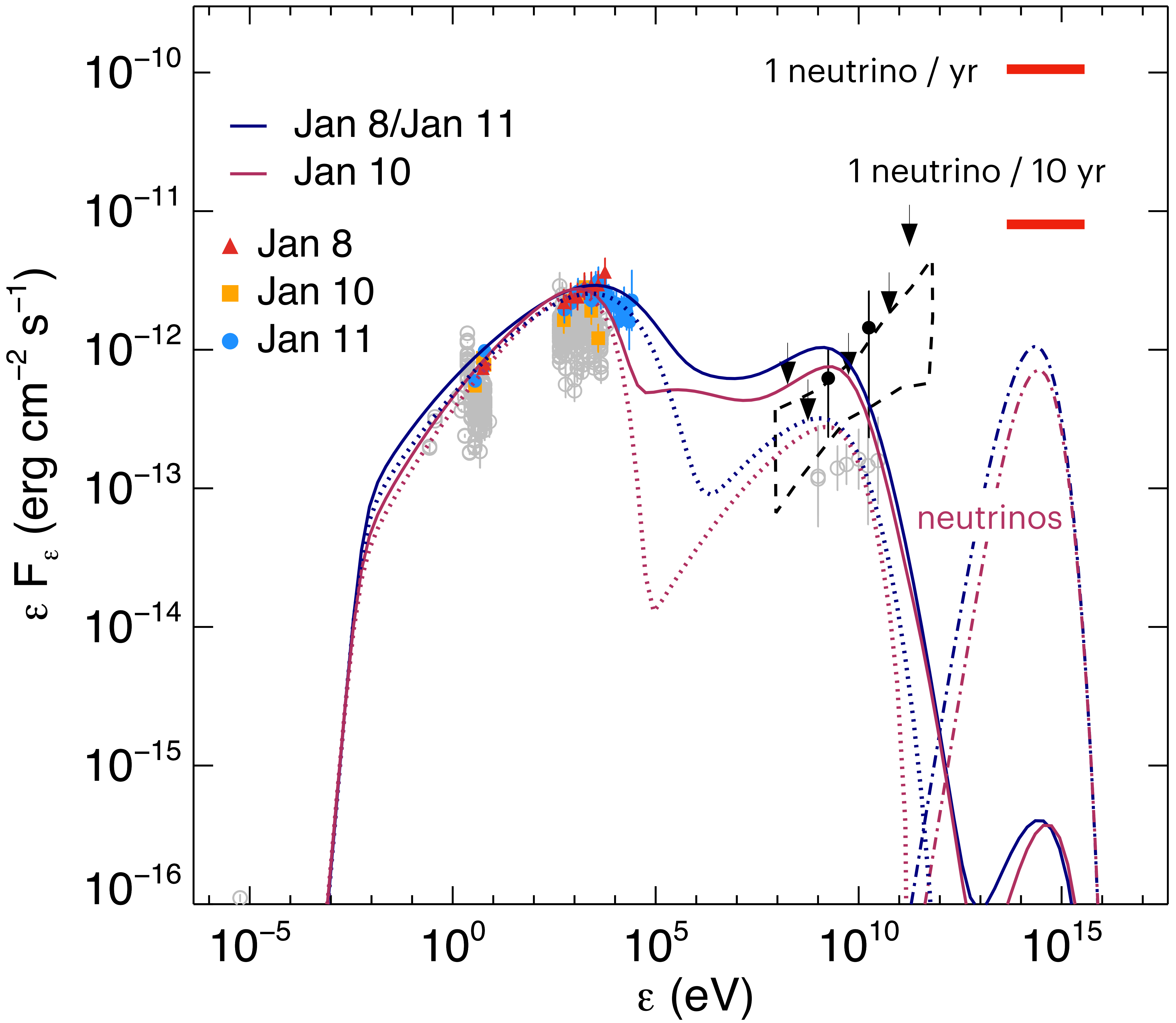




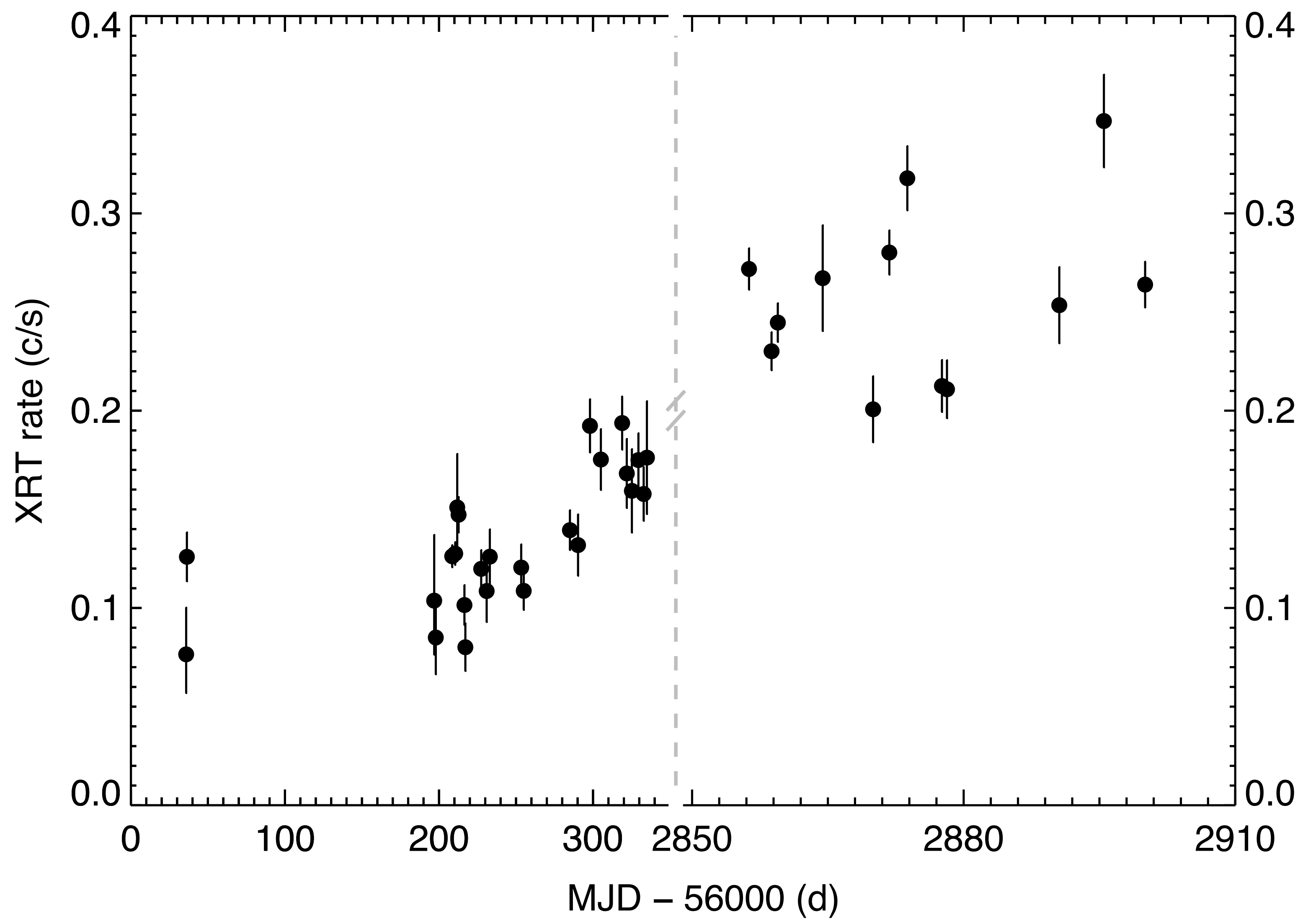
3HSP J095507.9+355101 + IC 200107A

An extreme blazar at z = 0.557 coincident with a 300 TeV neutrino

Petropoulou, FO, Mastichiadis et al, ApJ, 889 (2020)



10year Swift-XRT Light curve



Neutrino production in interactions with jet photons

Scaling the neutrino flux with the X-ray flux of the source we obtained:

$$N_{\nu_\mu}(E > 100\ \mathrm{TeV}) \lesssim 0.1/10\ \mathrm{years}\ \mathrm{(IC\ Point\ Source)}$$
$$\lesssim 0.01/10\ \mathrm{years}\ \mathrm{(IceCube\ GFU)}$$

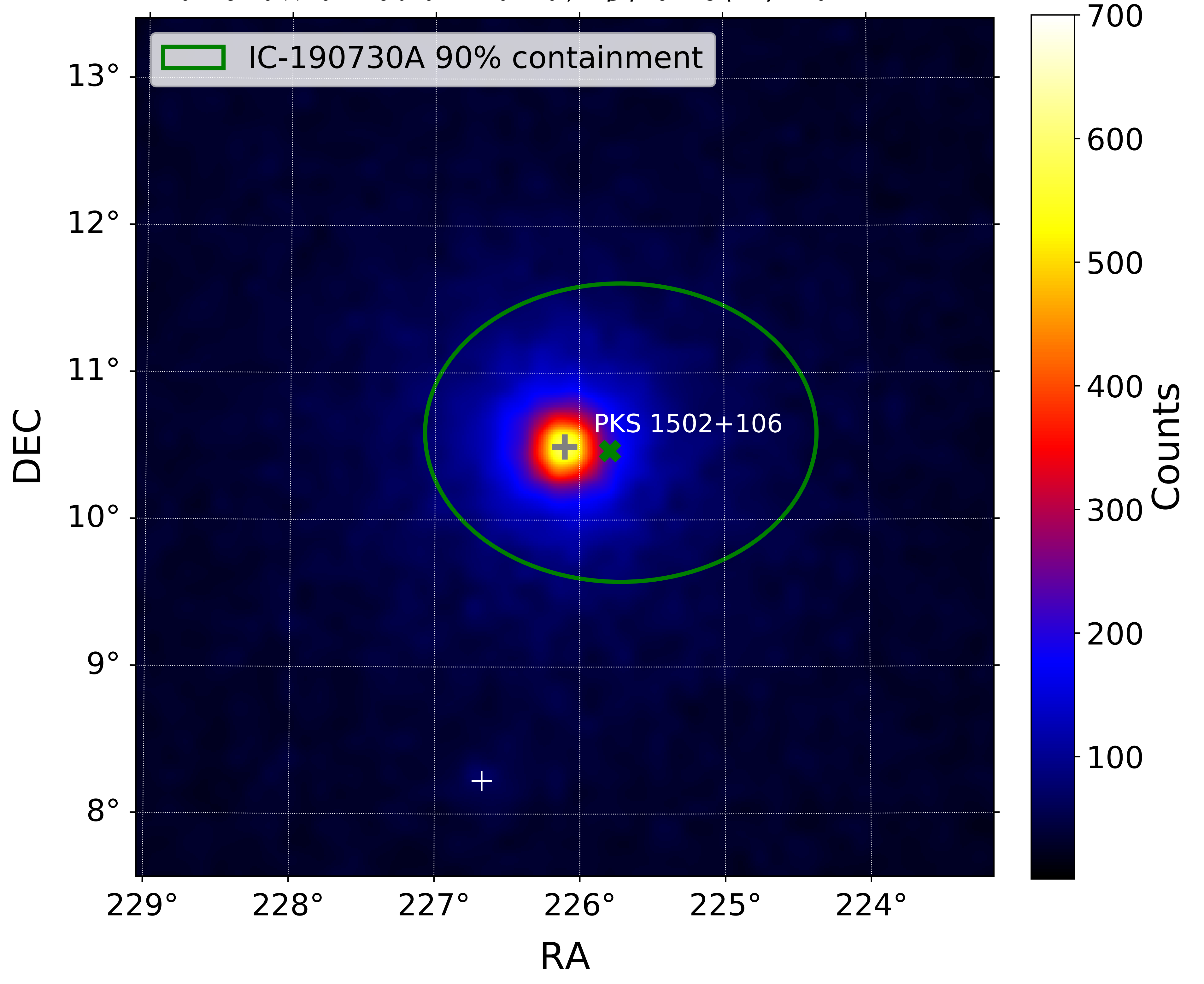
$$L_p \gtrsim 360$$

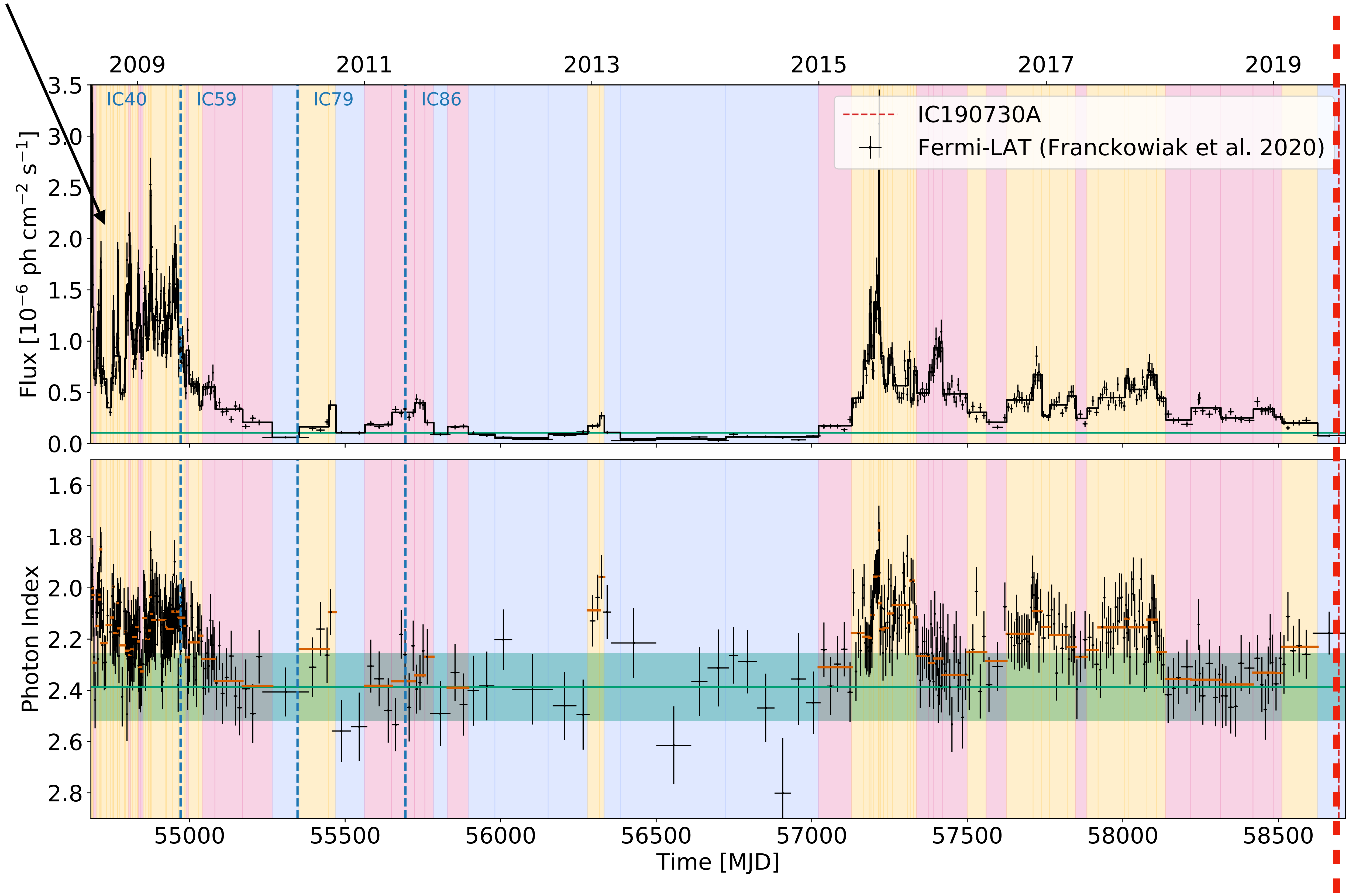
PKS 1502+106 + IC190730A

A powerful flat spectrum radio quasar at z = 1.835 coincident with a 300 TeV neutrino

Second brightest extragalactic gamma-ray source

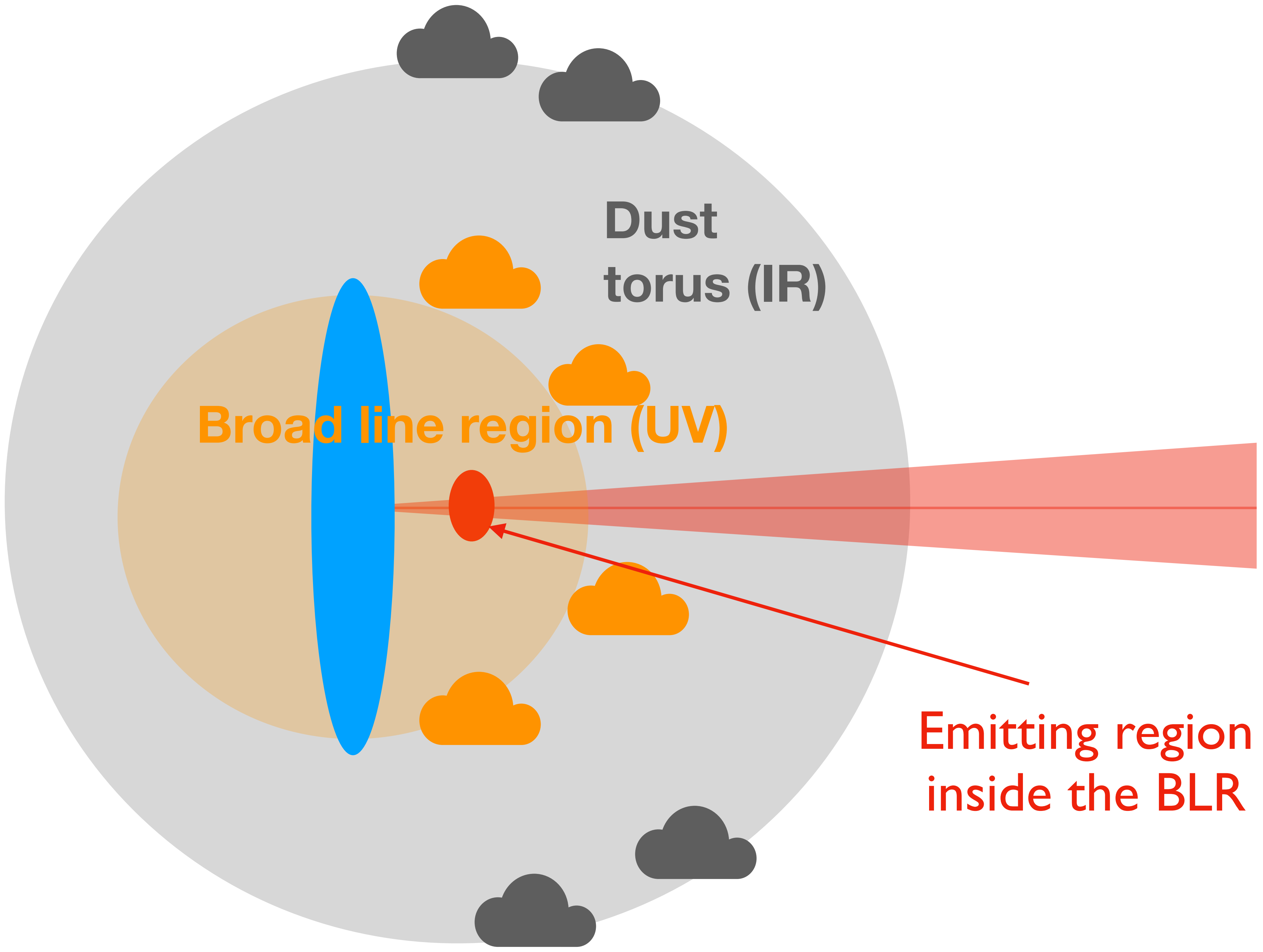
Franckowiak et al. 2020, ApJ 893(2):162



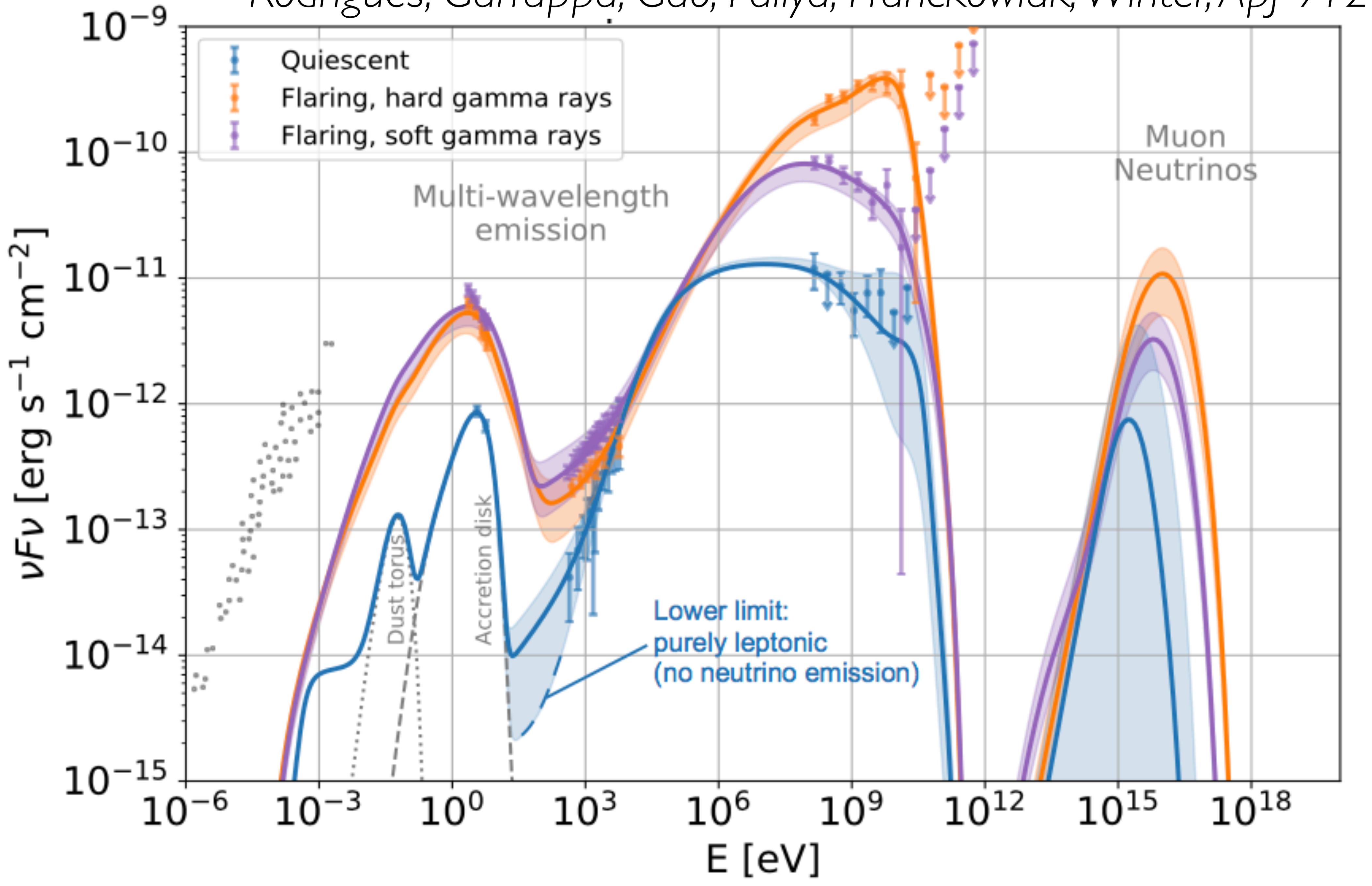


Rodrigues, Garrappa, Gao, Paliya, Franckowiak, Winter, ApJ 912 (2021)

PKS 1502+106 + IC190730A



Rodrigues, Garrappa, Gao, Paliya, Franckowiak, Winter, ApJ 912 (2021)



$$L_p \sim 500 \sim 10 L_{\mathrm{Edd}}$$

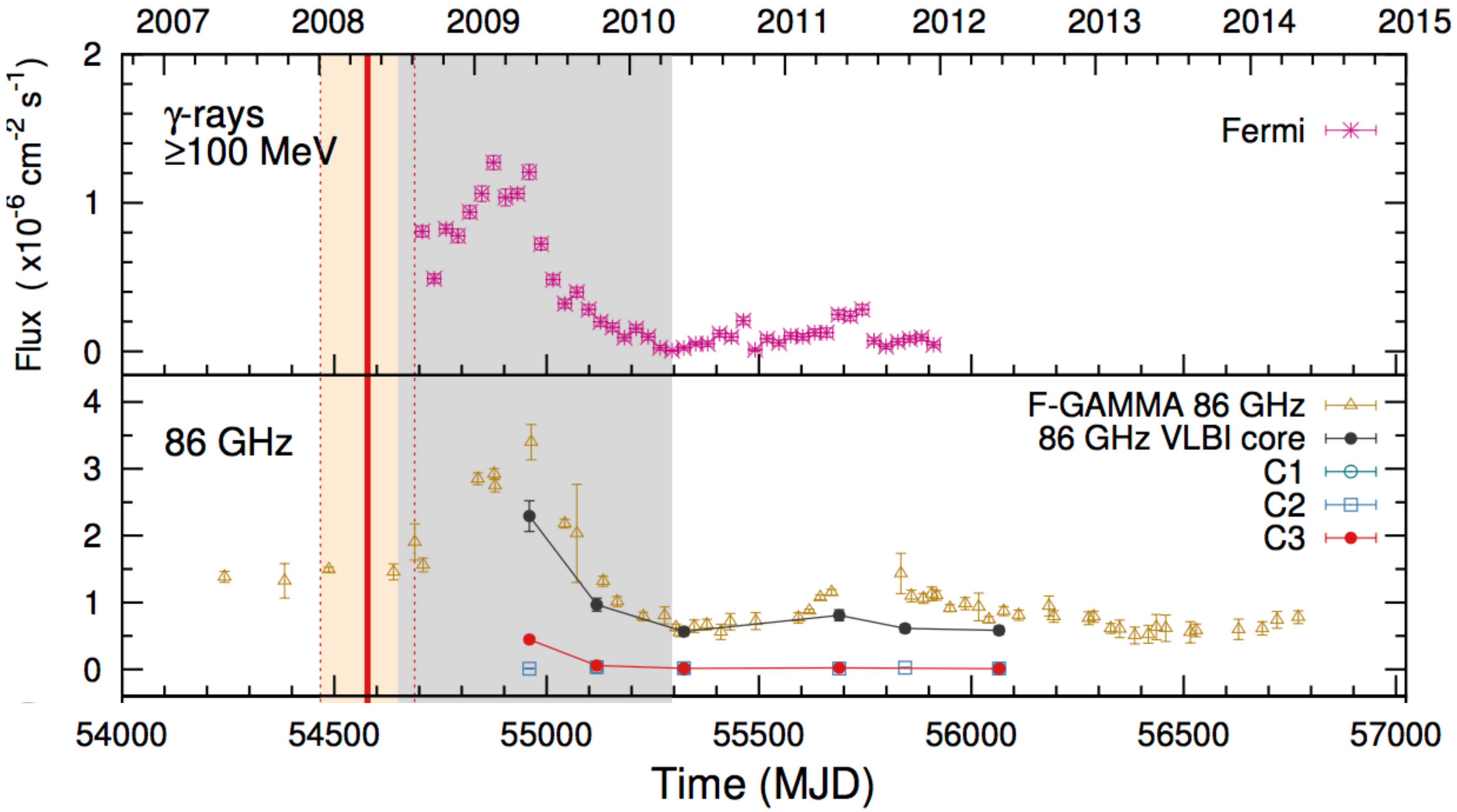
Model		Leptohadronic	
State	Quiescent	Hard Flare	Soft Flare
N_{events} per year	$0.47^{+2.19}_{-0.47}$	$3.19^{+1.90}_{-1.71}$	$1.27^{+0.8}_{-0.55}$
N_{events} (total)	$1.77^{+8.23}_{-1.77}$	$10.94^{+6.56}_{-5.84}$	$4.32^{+2.71}_{-1.87}$

see also Kun et al 2021 ApJL 911 (2021)
Britzen et al MNRAS 501 (2021)

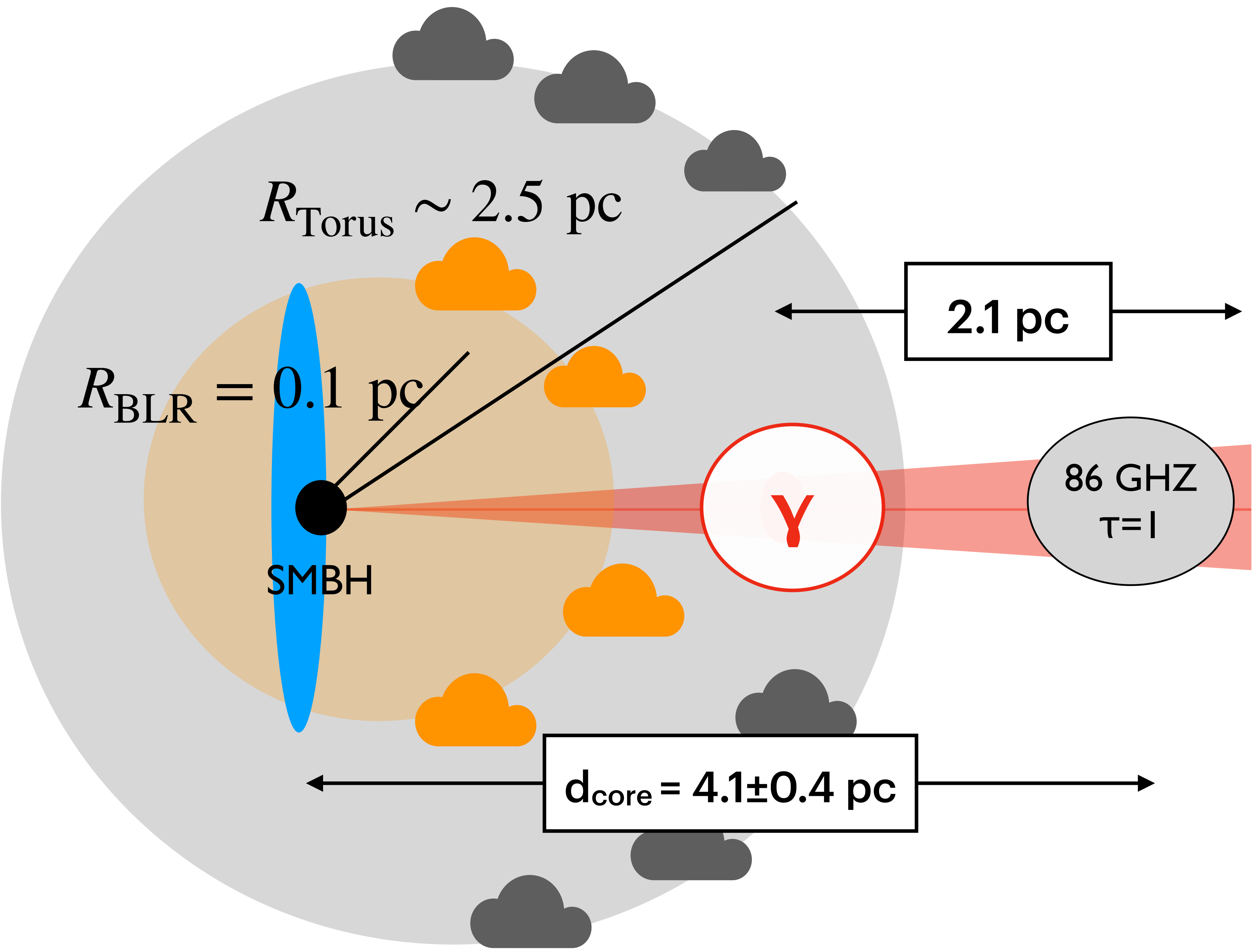
No archival events, see *8yr Point Source Limits, Aartsen et al EPJC 79 (2019)*

Location of the γ-ray emitting region of PKS 1502+106

A radio monitored source (GMVA, F-GAMMA, OVRO…)



Karamanavis et al A&A 586 (2016)
Karamanavis et al A&A 590 (2016)



Gamma-rays at ~ 2pc during 2008 flare
Fuhrmann et al MNRAS 441 (2014)
Max-Moerbeck et al MNRAS 445 (2014)
Karamanavis et al A&A 590 (2016)

Optical and gamma rays ~ 1.2 pc from jet-base
10 year analysis *Shao et al. ApJ 884 (2019)*

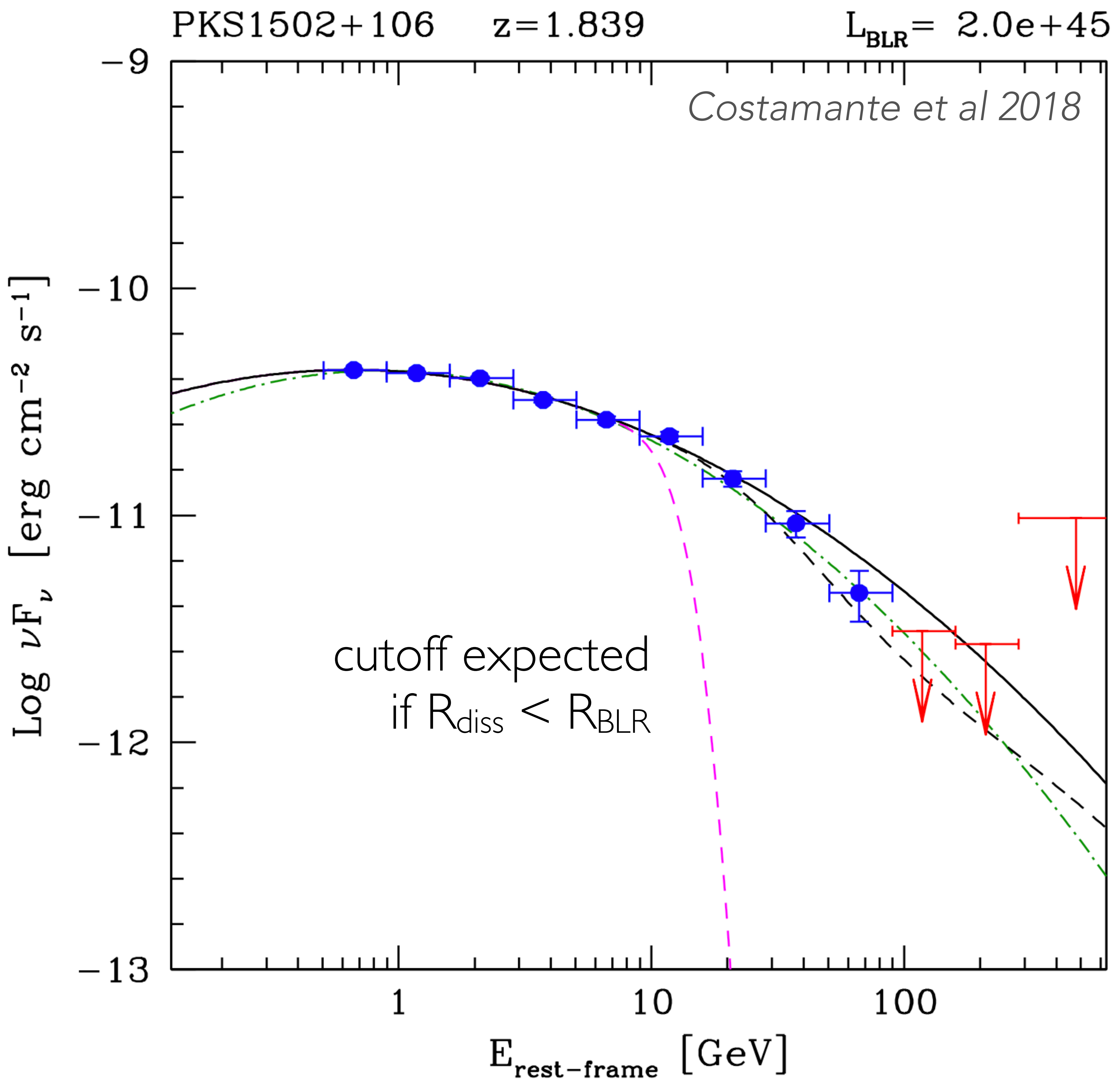
The location of the blazar γ-ray emitting region

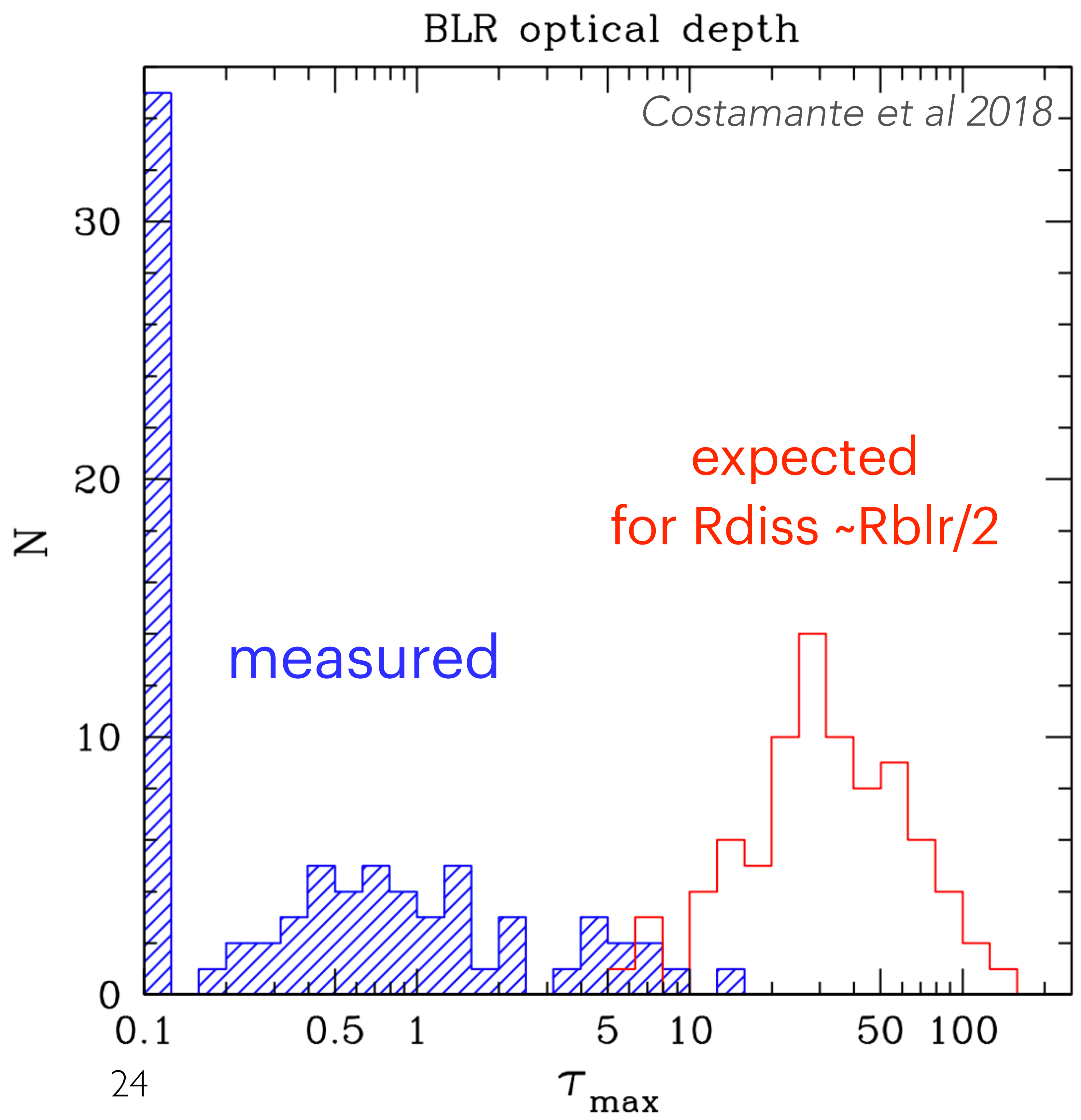
Beyond the BLR for the majority of FSRQs

e.g. *Abdo et al ApJ 716 (2010), Costamante et al MNRAS 477 (2018), Meyer et al ApJ 877 (2019) Acharyya et al MNRAS 500 (2021)*

20 GeV photons are produced by electrons in the KN regime if interacting with 10 eV BLR photons

A spectral break is expected if $R_{diss} < R_{BLR}$, at energy $E_{\gamma,\mathrm{br}} \approx \frac{20\ \mathrm{GeV}}{(1+z)} \frac{10.2\ \mathrm{eV}}{\varepsilon_\gamma}$

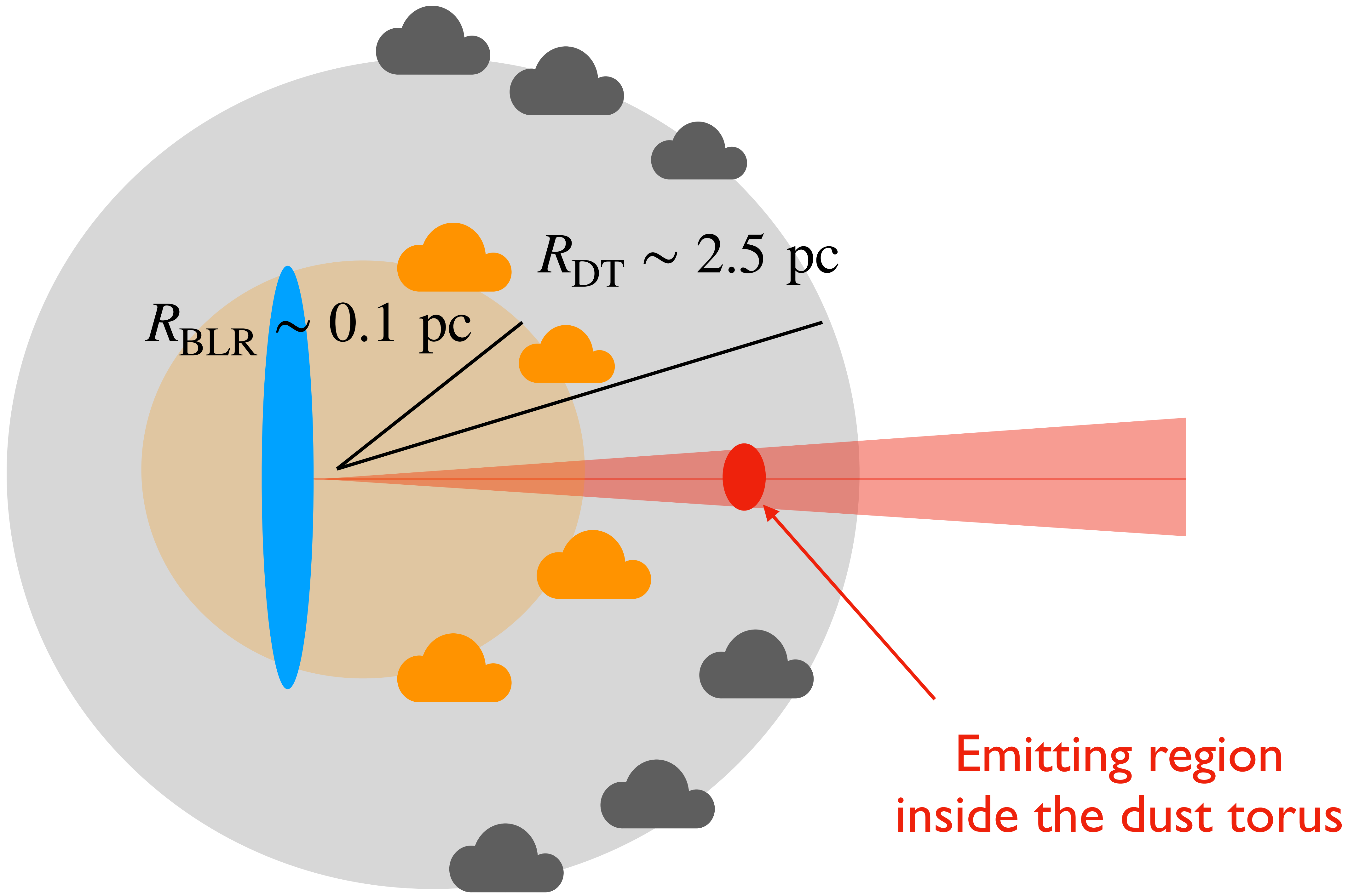


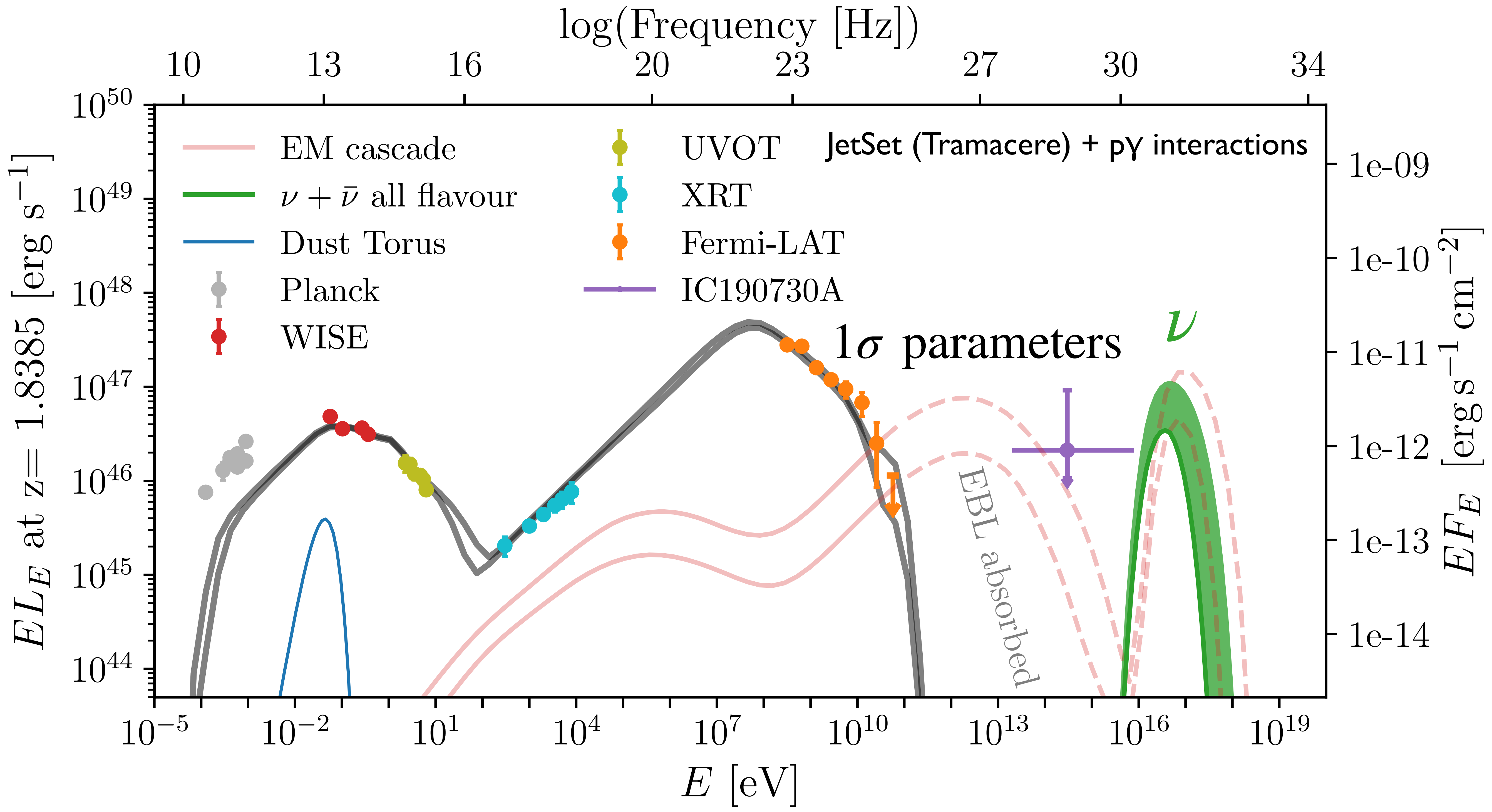


- -2/3rds of 106 sources show no cutoff
- -only one in 10 Fermi sources require large τ
- -the same conclusion was reached by studying well sampled flare spectra

PKS 1502+106

FO, Petropoulou, Murase, Tohuvavohu, Vasilopoulos, Buson, Santander, to be submitted

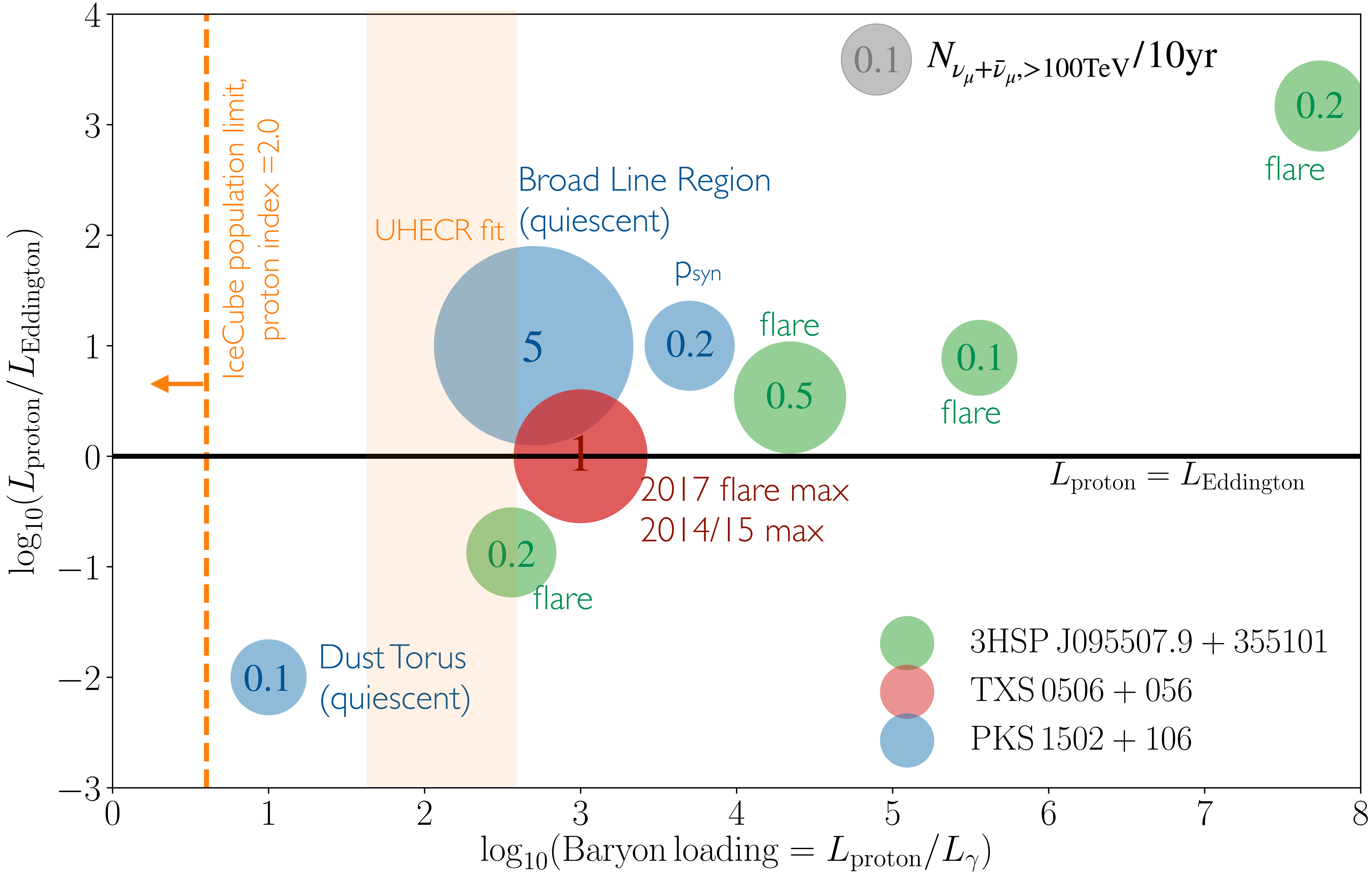




$$N_{\nu_\mu}(E > 100 \text{ TeV})/10 \text{ yr} \lesssim 0.1 \text{ (GFU)}$$

$$L_{\text{proton}} \sim 10\, L_\gamma \sim 0.01\, L_{\text{Edd}}$$

Proton luminosity (model requirements)



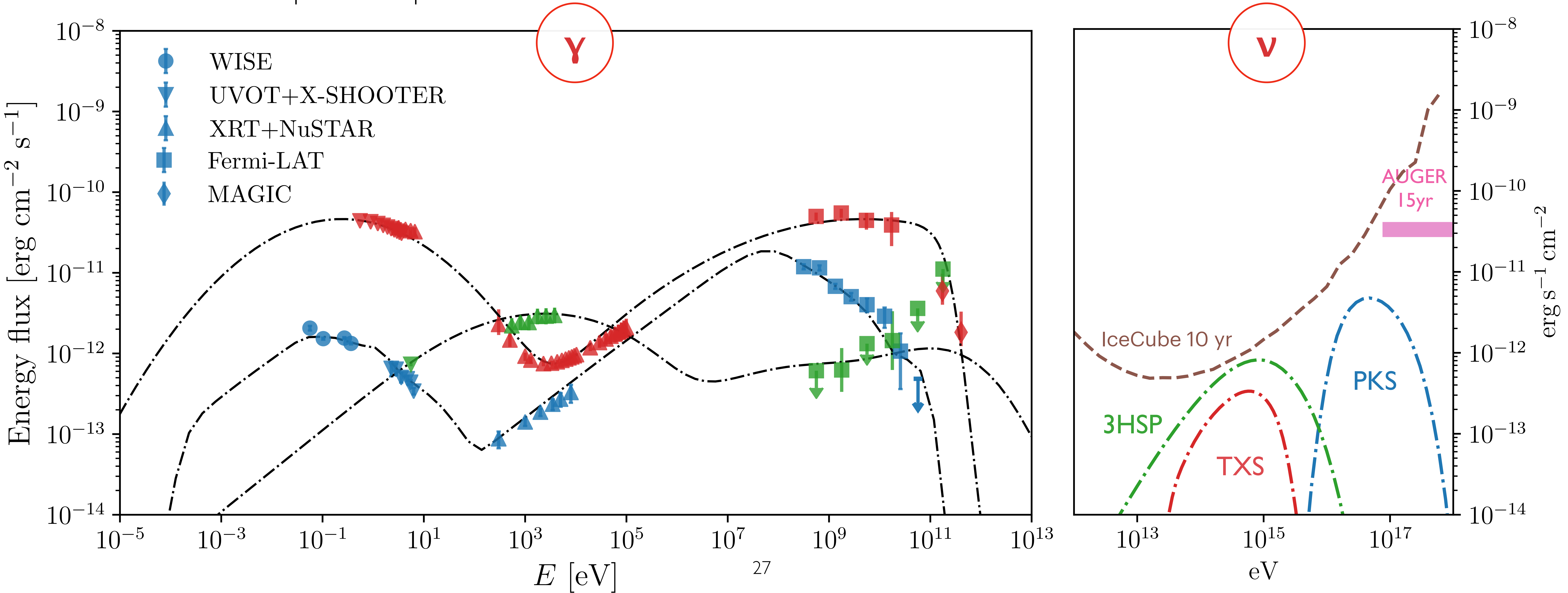
Model results from
Petropoulou et al, ApJ 891 (2020)
Petropoulou, FO et al, ApJ 886 (2020)
Rodrigues et al 2021, ApJ 912 (2021)
FO, Petropoulou et al, to be submitted
IceCube Extremely High Energy Analysis, Aartsen et al, PRL 117 (2017)
Murase et al. 2014 PRD 90 (2014)
Rodrigues et al, 2021, PRL 126 (2021)

The baryon loading factor is ≫ 1 and larger than the Eddington luminosity

How??

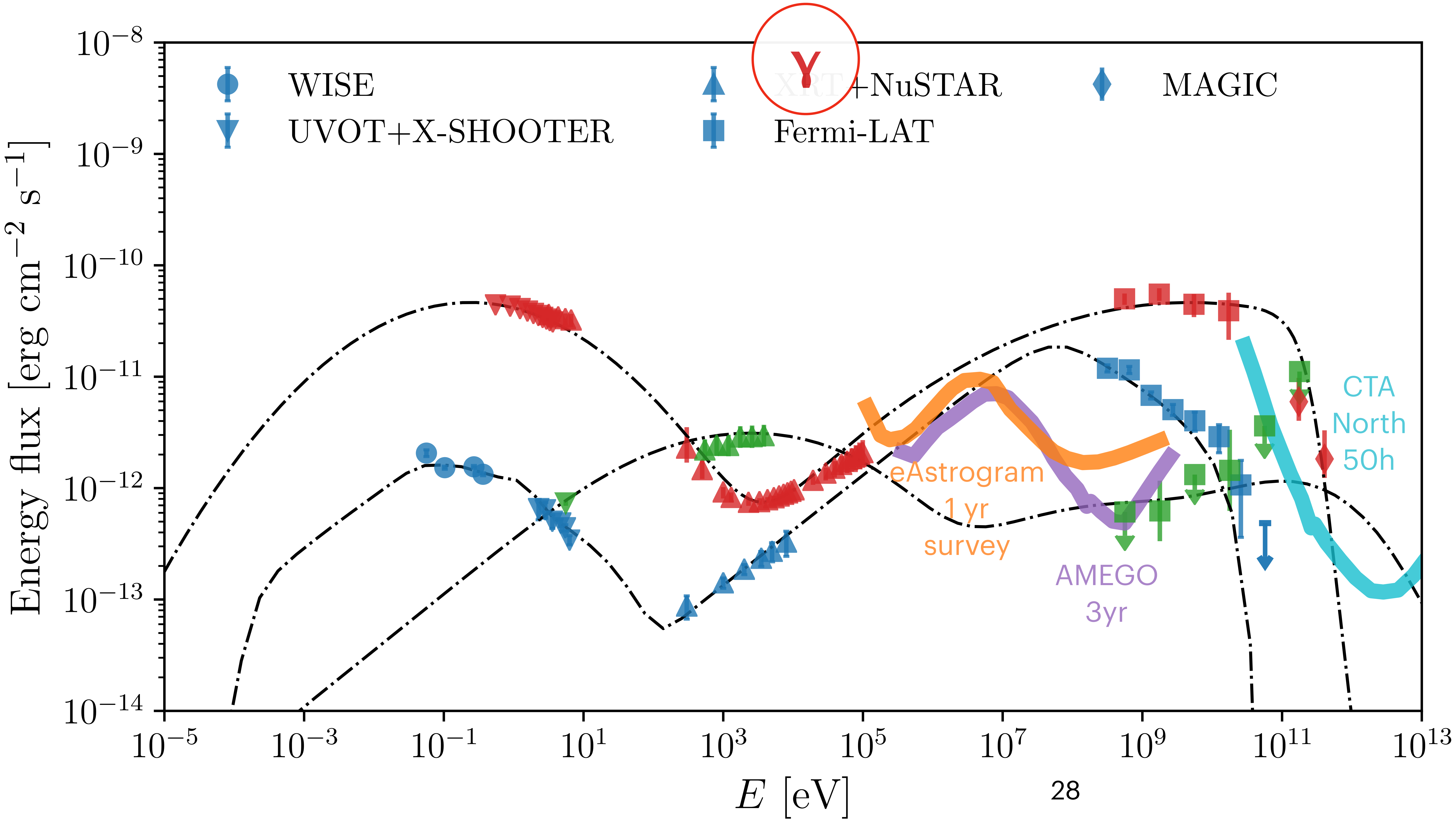
Modelling result summary

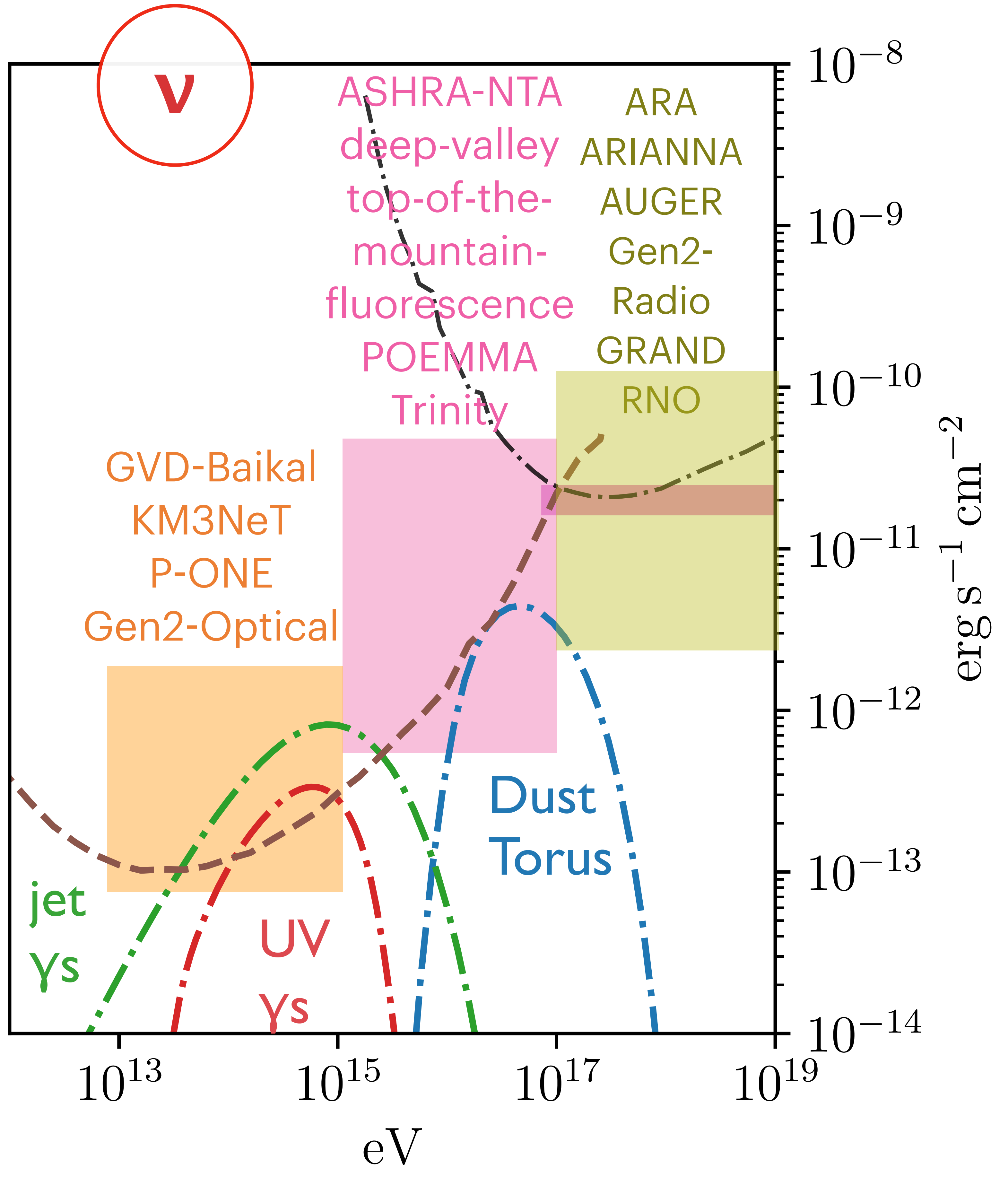
- Models consistent (statistically) with the detection of the neutrinos
- but require extreme parameters atypical of the blazar population
- The most powerful sources are consistent with producing ~ 0.1-1 neutrino/10 yrs in IceCube, peak possibly at >10 PeV with more modest proton requirements



Future prospects

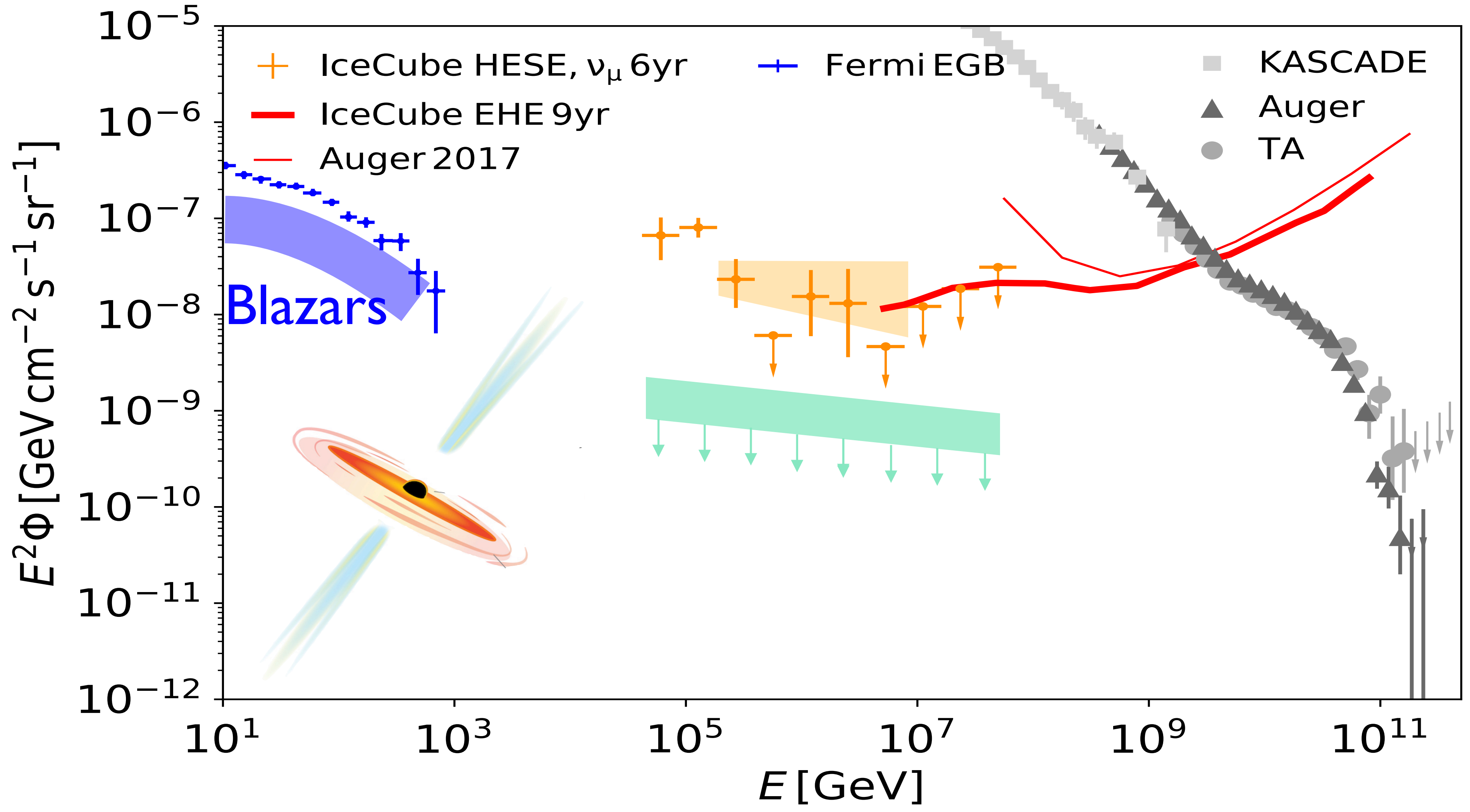
- Monitoring and new instruments will be crucial for assessing future associations
- Theoretical modelling efforts also ramped up (see Cerutti #905)



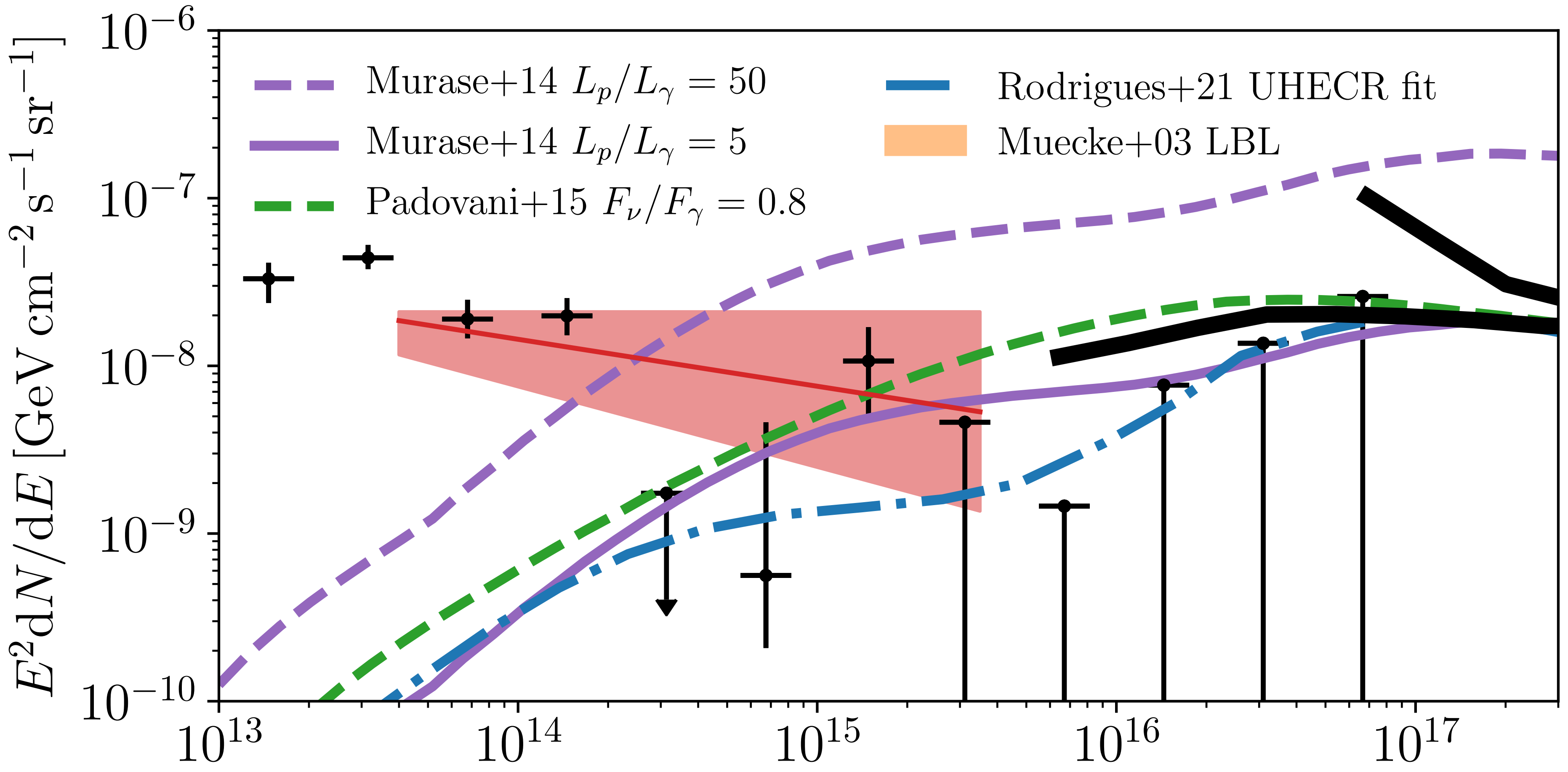


Summary

Blazars constrained by IceCube as sources of < 100 TeV neutrinos



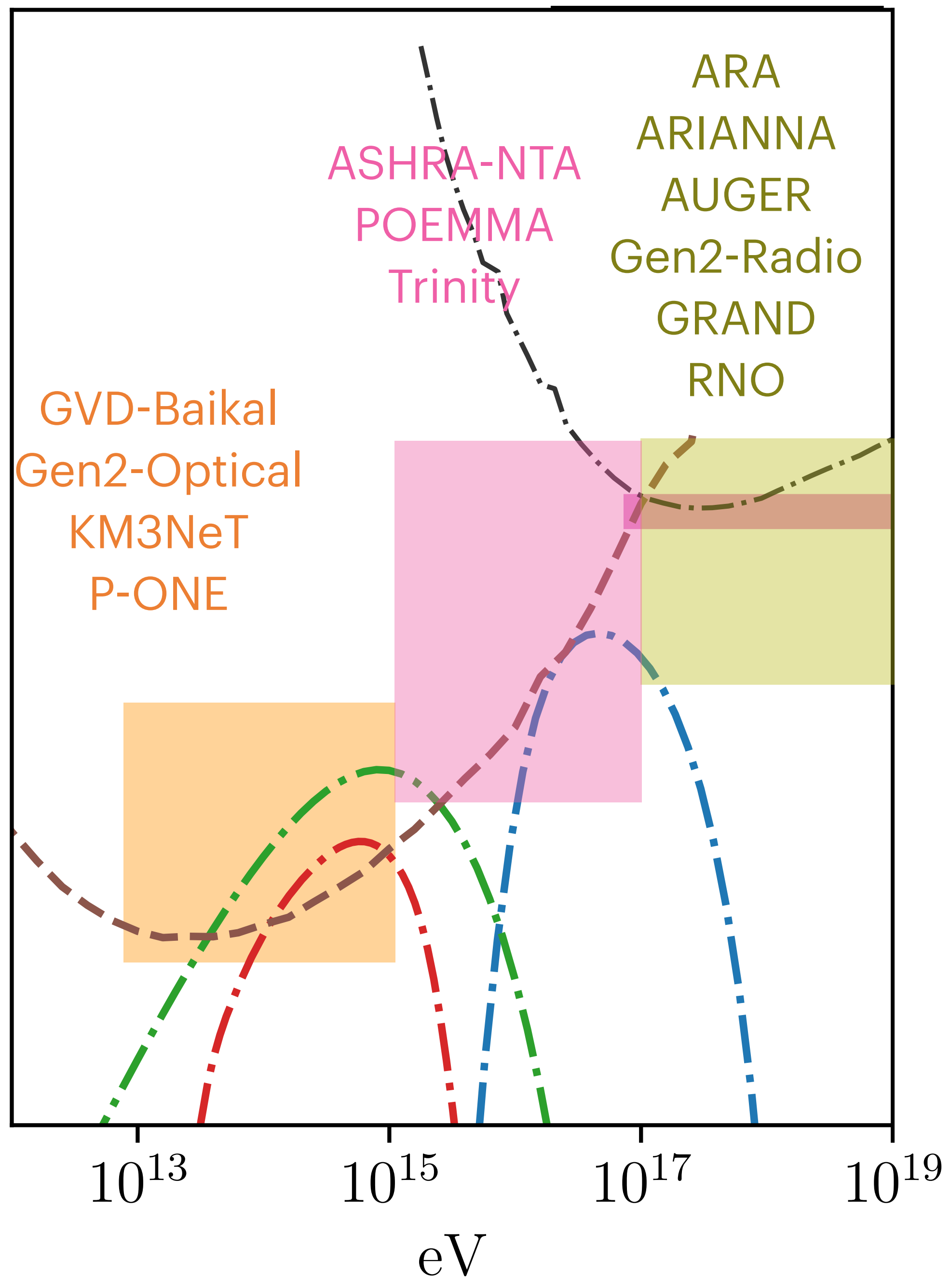
The proton content of the population is relatively low

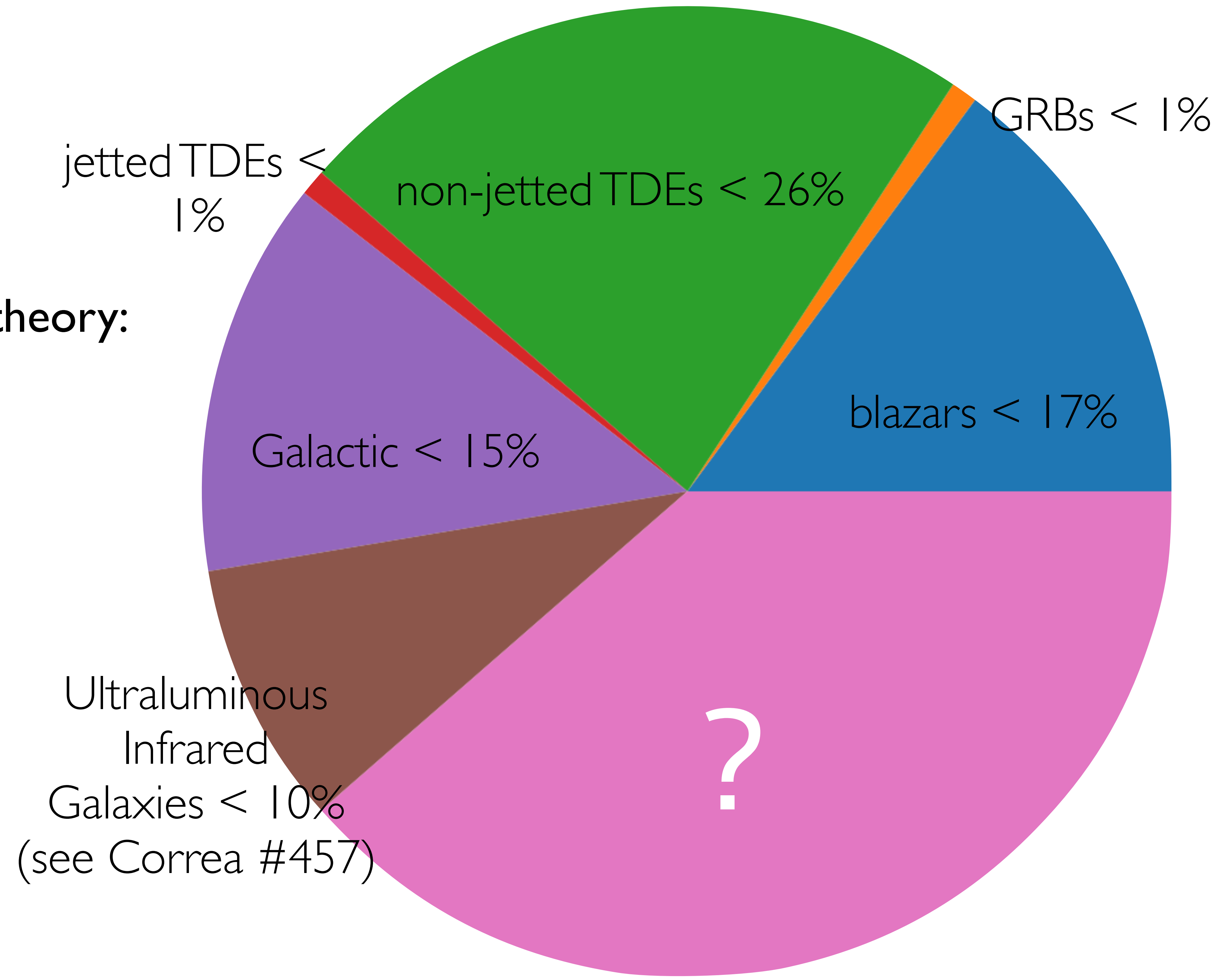


ν-telescopes +monitoring + theory:

-scrutinise individual multimessenger sources

-KM3NeT + GVD Baikal currently being deployed





based on stacking limits from IceCube,
see Bartos et al arXiv:2105.03792 for a different approach