High-energy emission from blazars

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15 July 2020 - Virtual Seminar on Multimessenger Astronomy

NTNU
Norwegian University of Science and Technology

Active Galactic Nuclei (AGN)

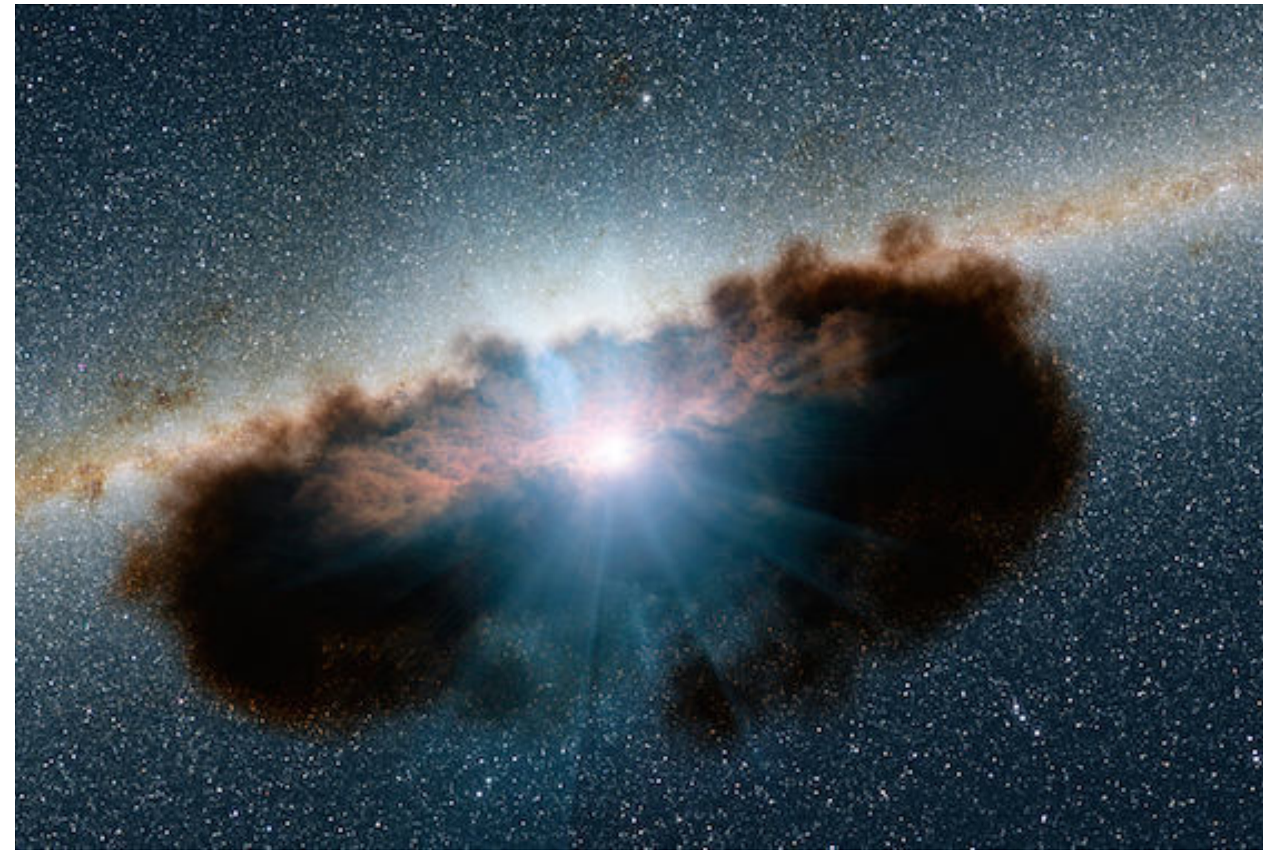
Most powerful ``steady'' sources in the Universe ($L \geq 10^{47}$ erg/s) > 1000 bright Galaxies!

They host a SMBH (10^{6}-10^{10} M_{sun}). ``Active'' as emission >> stars in the galaxy - accretion on to SMBH

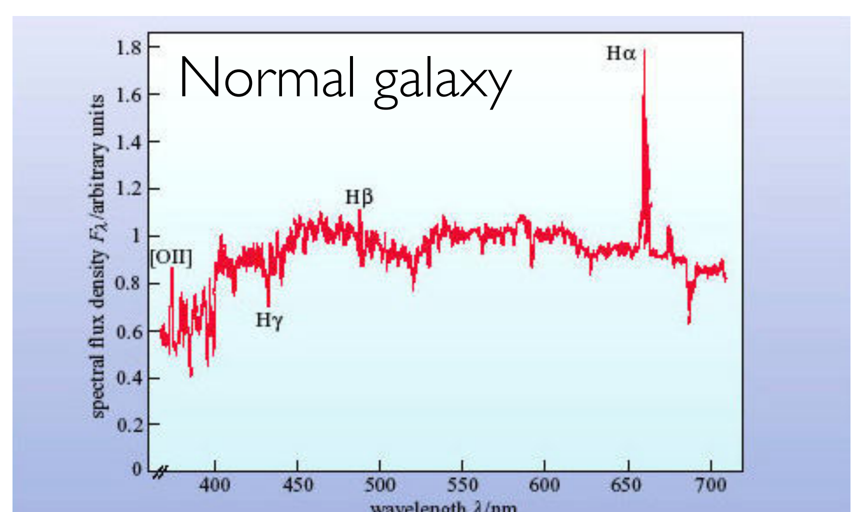
Visible to large redshifts (z > 7.5) - peak z~2 (depends on type)

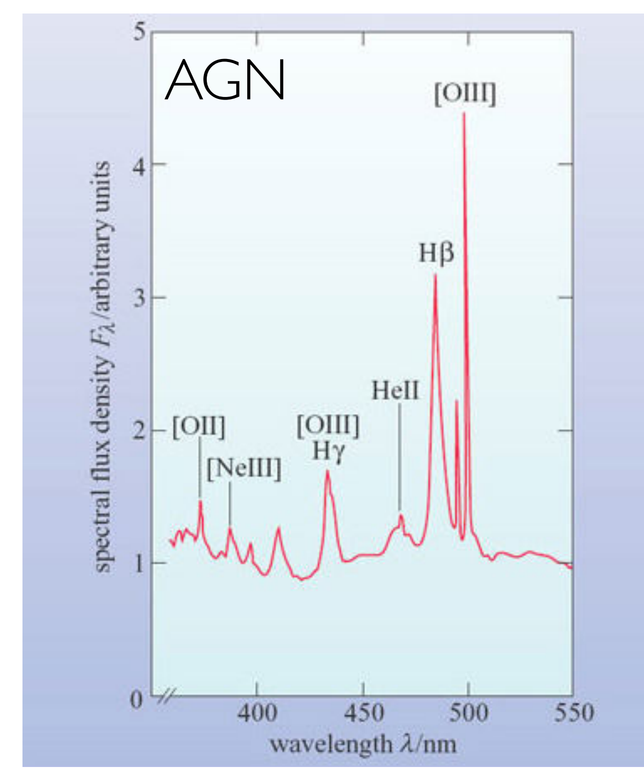
1% of galaxies active

Broad emission lines reveal rapid bulk rotation



Artist's impression of non-jetted AGN shrouded in dust [NASA/JPL]





[Spectra from: https://www.open.edu/openlearn/science-maths-technology/introduction-active-galaxies/content-section-2.2.2]

The engine

An efficient way to produce the power required, is through accretion onto a black-hole. As much as 10% of the rest mass energy in-falling into a black hole is converted into radiation

$$L_{\rm disk} = 0.1\dot{M}c^2 = 10^{46}\ {\rm erg/s}$$

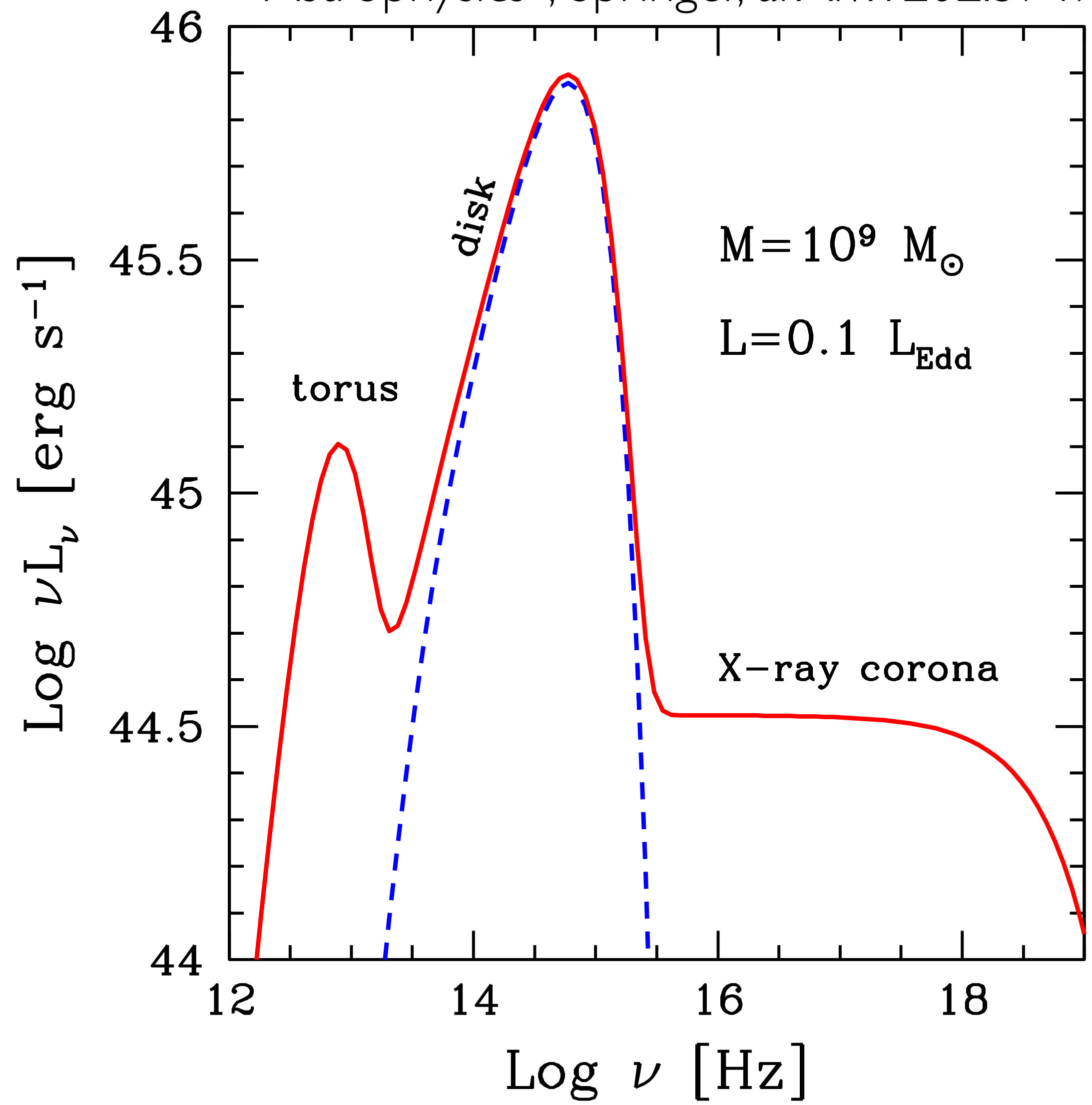
In solar masses per year, the requirement is

$$\dot{M} = \frac{L_{\rm disk}}{0.1c^2} = 1.75\frac{L_{\rm disk}}{10^{46}\ {\rm erg/s}} M_{\rm Sun}\ {\rm yr}^{-1}$$

This should be "easy" to supply. A typical galaxy might have gas mass,

$$M_{\rm gas} \sim 10^{10} M_{\rm Sun}$$

Ghisellini, 2012, "Radiative Processes in Astrophysics", Springer, arXiv:1202.5949



*1 erg ~ 1 TeV, $L_{\rm Sun}$ = 3.85 x 10^{33} erg/s

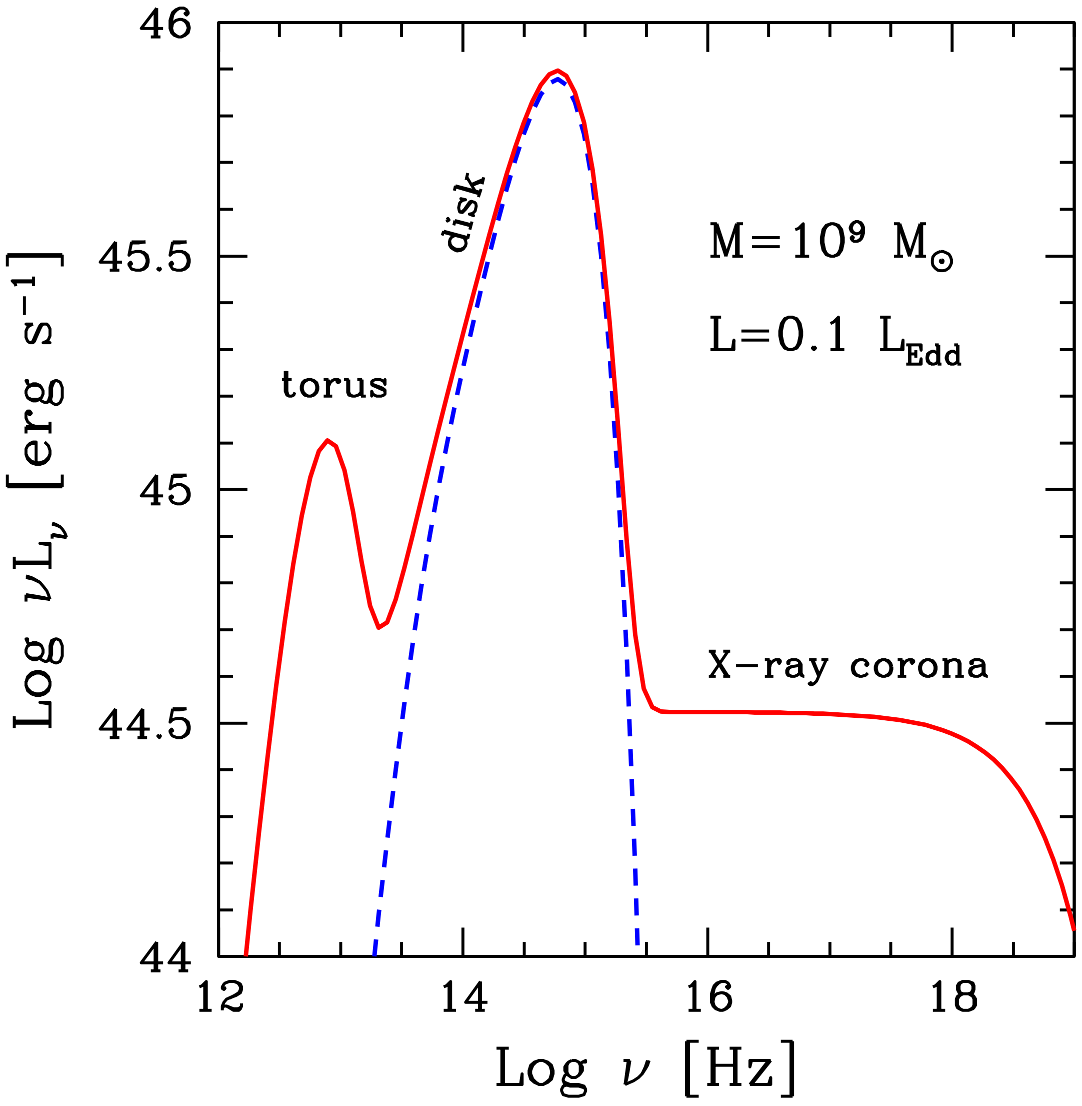
The engine

But to provide 10^{46} erg/s, we need a SMBH due to the Eddington limit!

$$L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma_{\rm T}} = 10^{38} {\rm erg/s} \left(\frac{M}{M_{\rm Sun}} \right)$$

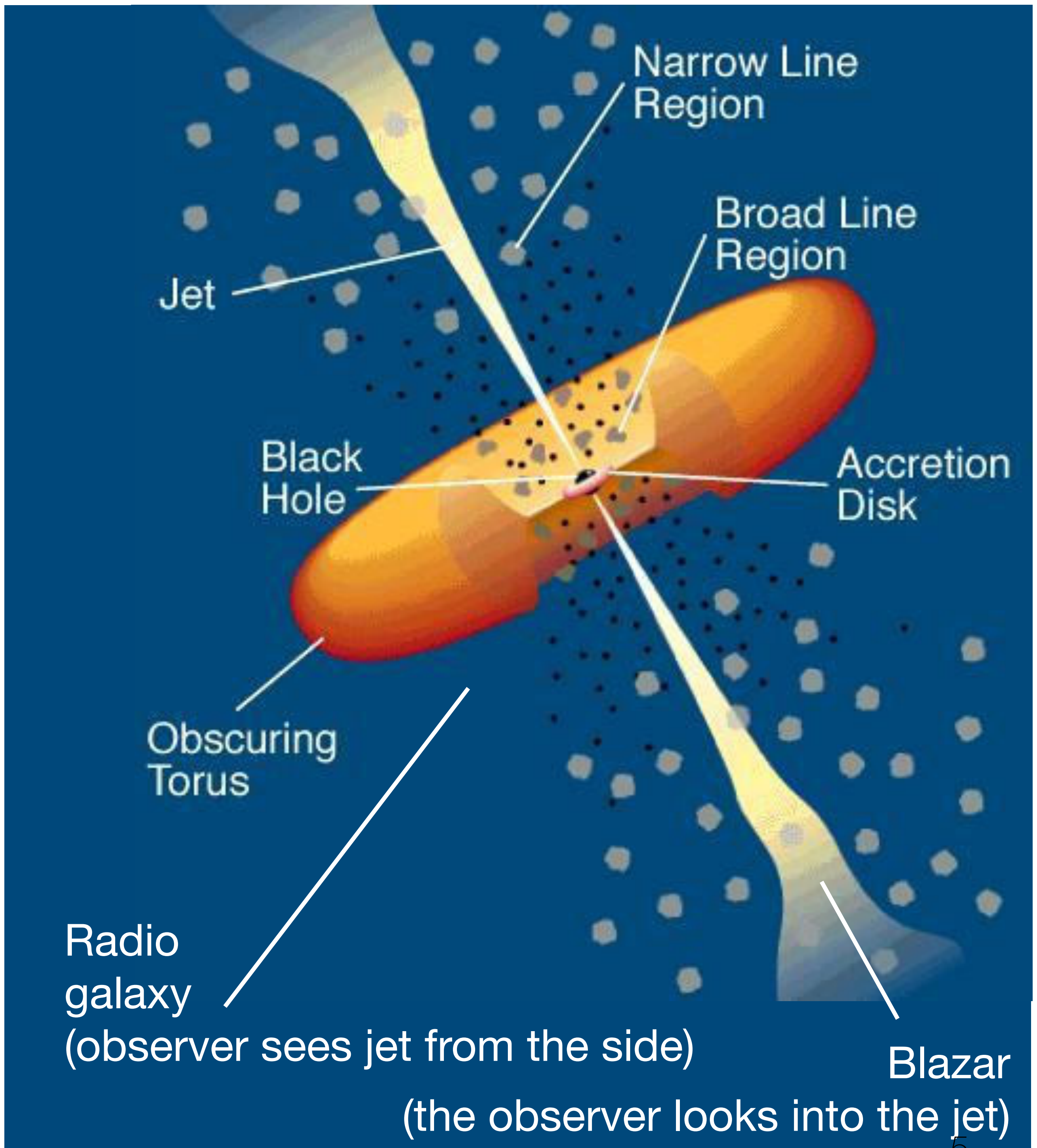
I.e. we need,

$$M \geq 10^8 M_{\rm Sun} \left(\frac{L_{\rm disk}}{10^{46}\ {\rm erg/s}} \right)$$



AGN unification

see Urry & Padovani 1995



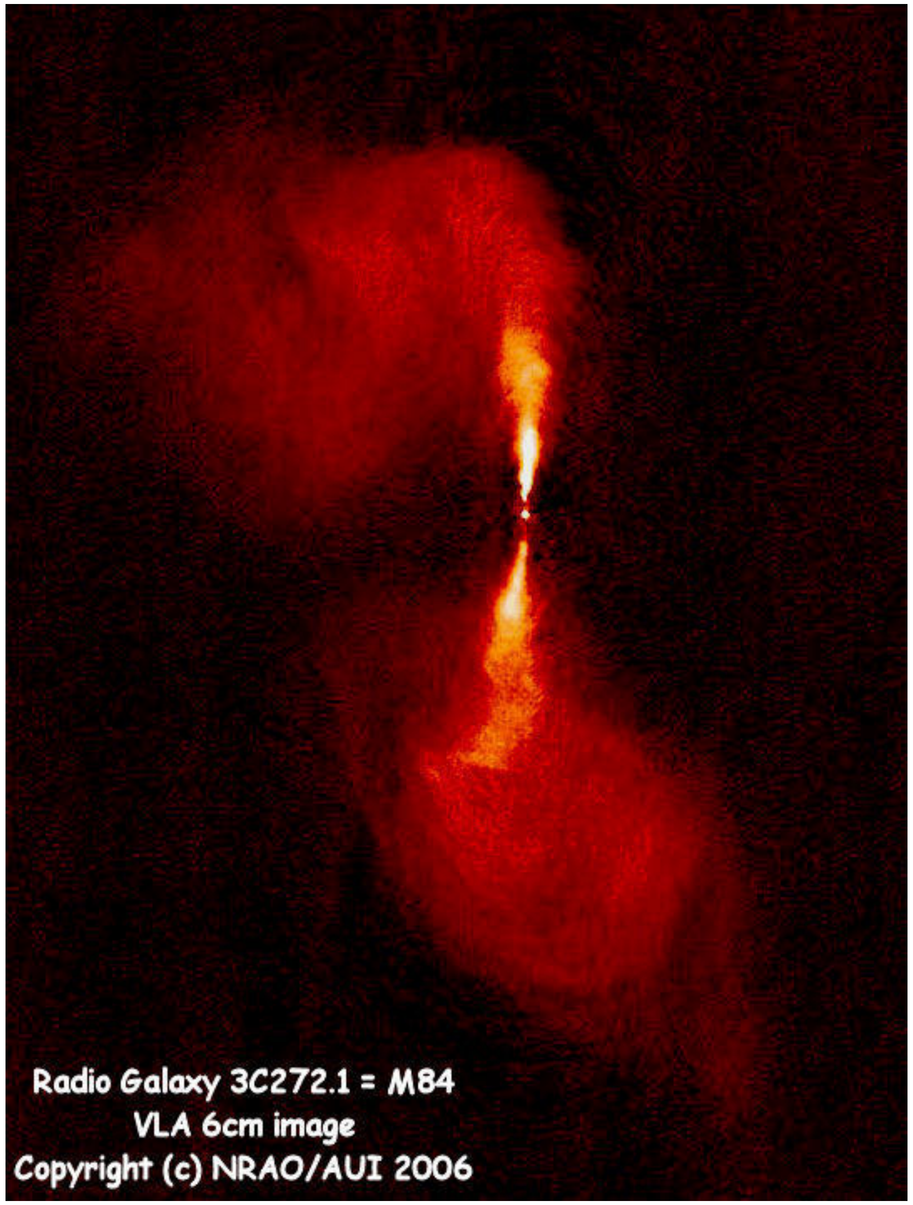
The majority of AGN classes can be explained by three parameters:

- Orientation
- Presence of jet or not (10% have it)
- Radiative efficiency

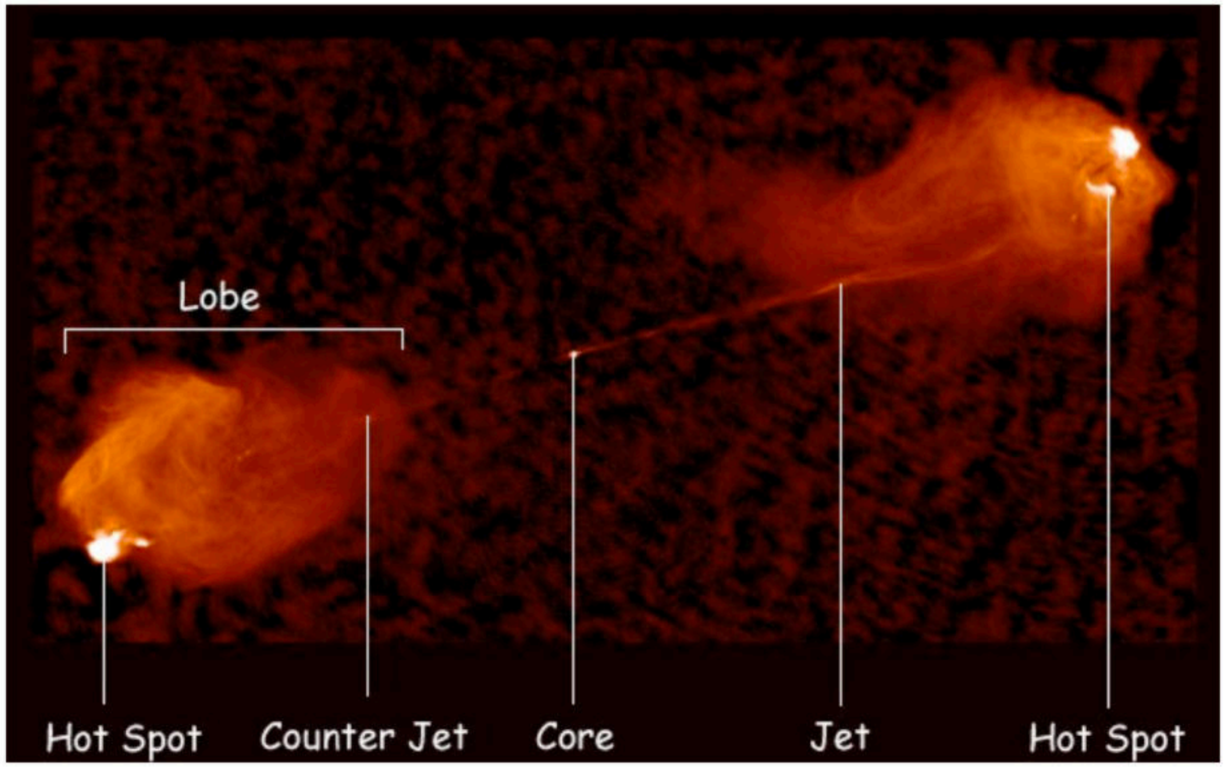
	Face on	Side-view
Jetted (radio-loud)	Blazars (BL Lac/ FSRQ)	Radio-Galaxies (FRI/II)
Non-jetted (radio-quiet)	Seyfert I	Seyfert II

10% of AGN have jets

FRI



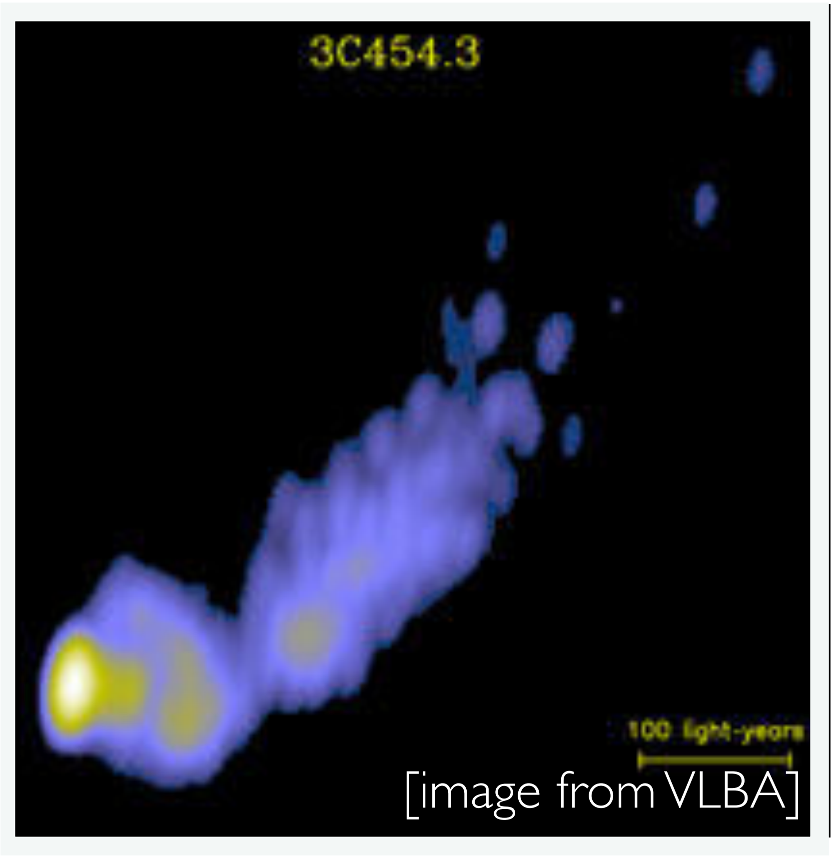
FRII



Radio galaxy Cygnus A Image credits: NRAO/AUI,A. Bridle

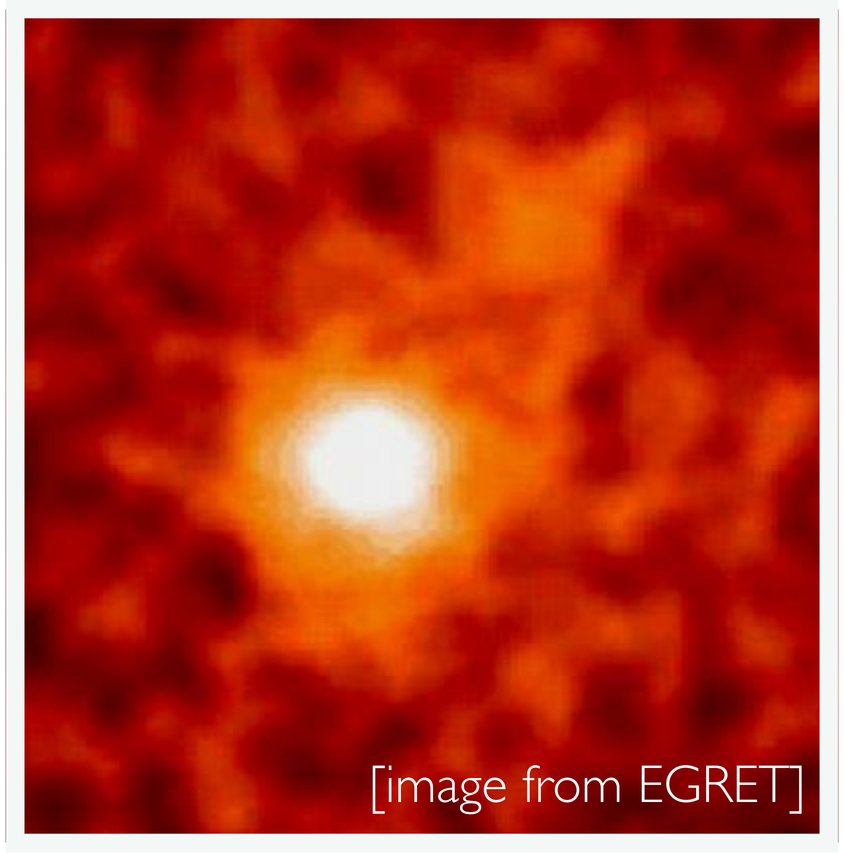
Blazars: star-like appearance

Radio



Optical

γ-rays



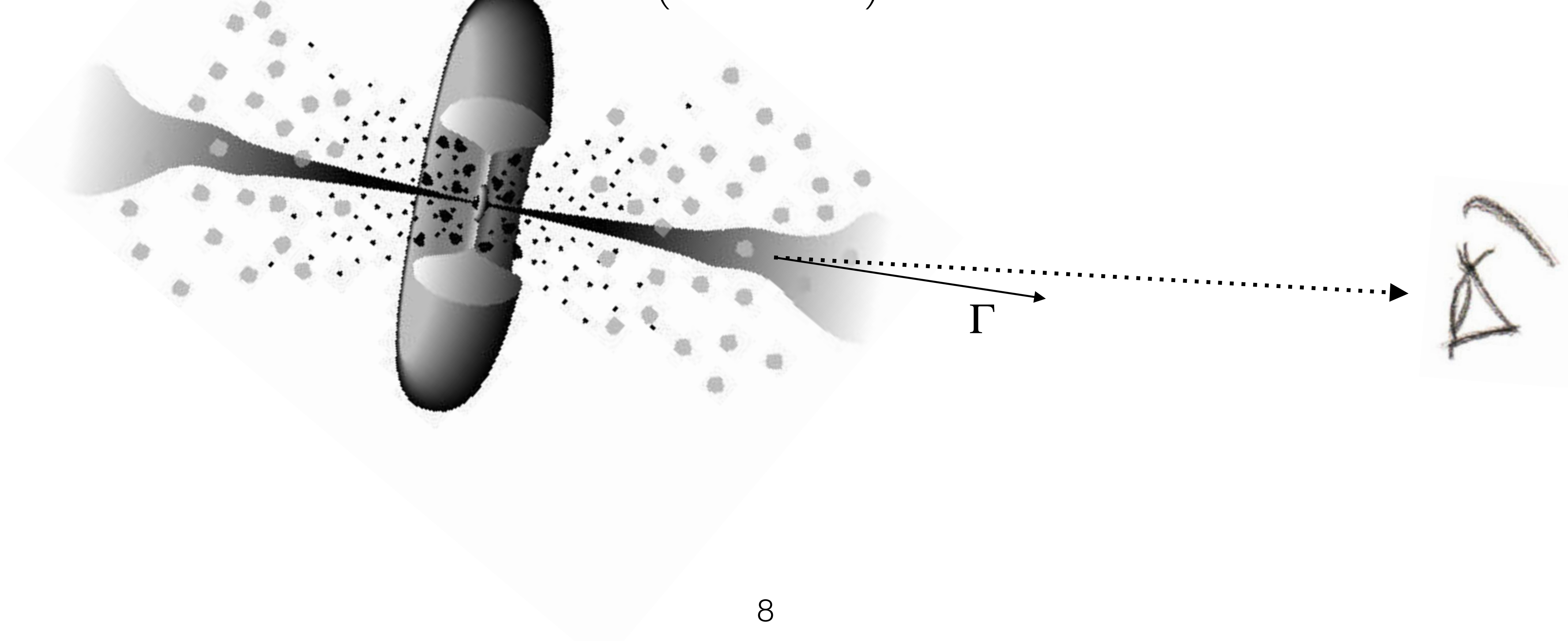
No spectacular jets…but wealth of information from timing/variability and spectra!

Relativistic beaming

Usual relativity (rulers and clocks)

$$\Delta x = \frac{\Delta x'}{\Gamma} \qquad \Delta t = \Delta t' \, \Gamma \qquad \Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Not so for photons!
(Terrel 1959)



Relativistic beaming

If the emitting region is moving relativistically, observed features appear boosted:

Doppler factor, $\delta = \dfrac{1}{\Gamma(1-\beta\cos\theta)}$

$\left(\dfrac{1}{\Gamma}\right.$: Usual special relativity term, $\dfrac{1}{(1-\beta\cos\theta)}$: Usual Doppler effect.$\left.\right)$

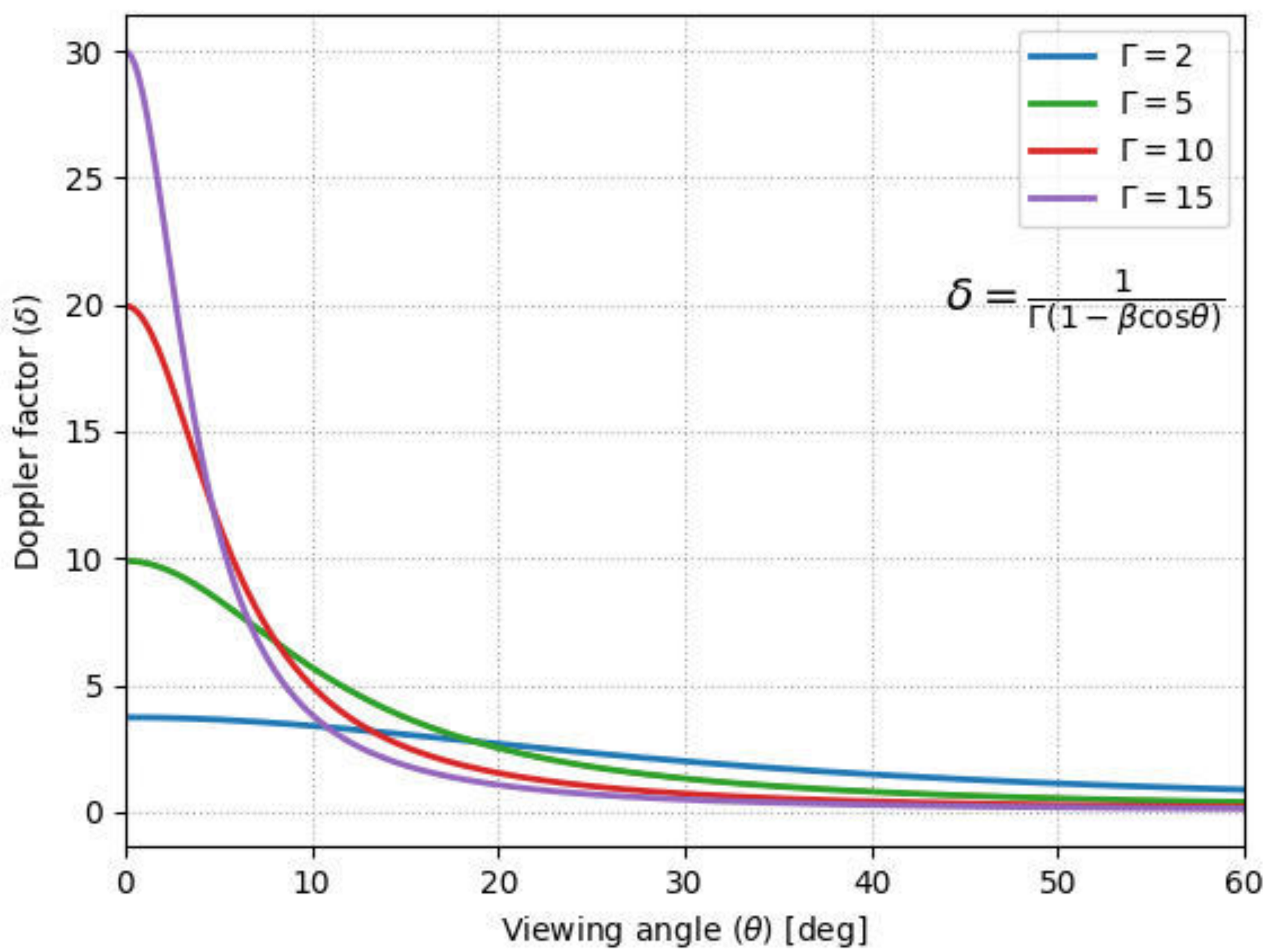
$\Delta t = \Delta t'/\delta$ (shortening of timescales)

$\Delta x = \Delta x'\ \delta$

$\nu = \delta\nu',\ E = \delta E'$ (blueshift)

$L_{\rm obs} = \delta^4 L'$

(dashes denote rest-frame quantities)



Special cases:

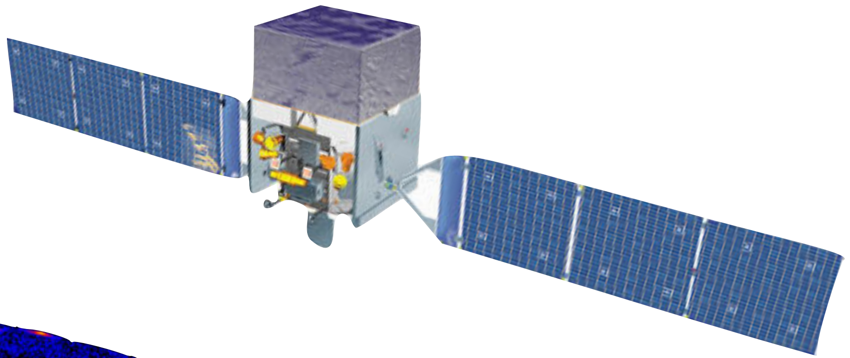
$$\delta_{\rm max} = \delta(0^\circ) = \frac{1}{\Gamma(1-\beta)} = \Gamma(1+\beta) \sim 2\Gamma$$

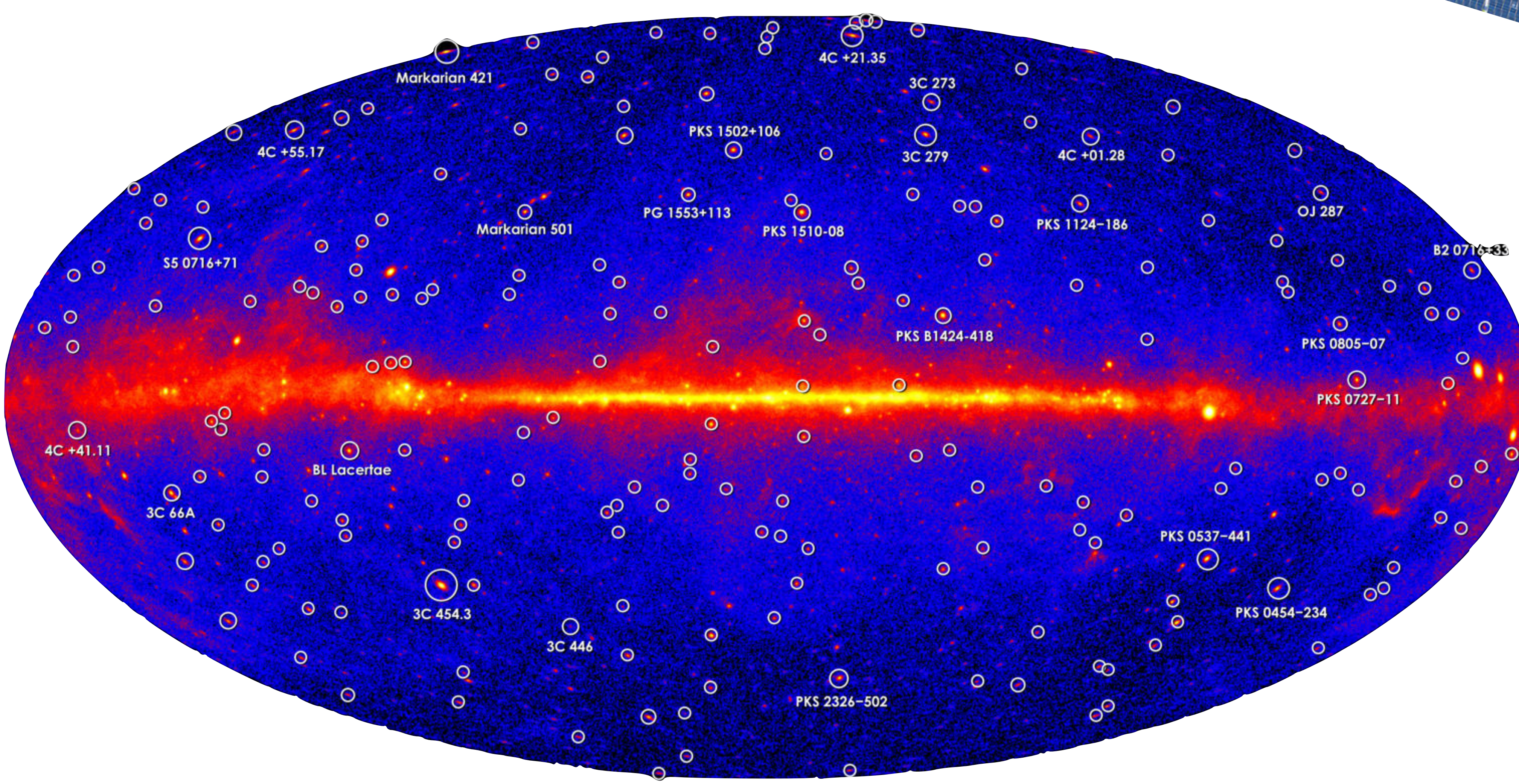
$\delta_{\rm min} = \delta(90^\circ) = 1/\Gamma$ – recover special relativity

$\theta = 1/\Gamma, \cos\theta \approx 1 - \dfrac{\theta^2}{2} \approx \beta,\ \delta = \Gamma$ – opposite of special relativity!

Blazars Dominate the Extragalactic γ-ray sky

Fermi 5-yr blazars

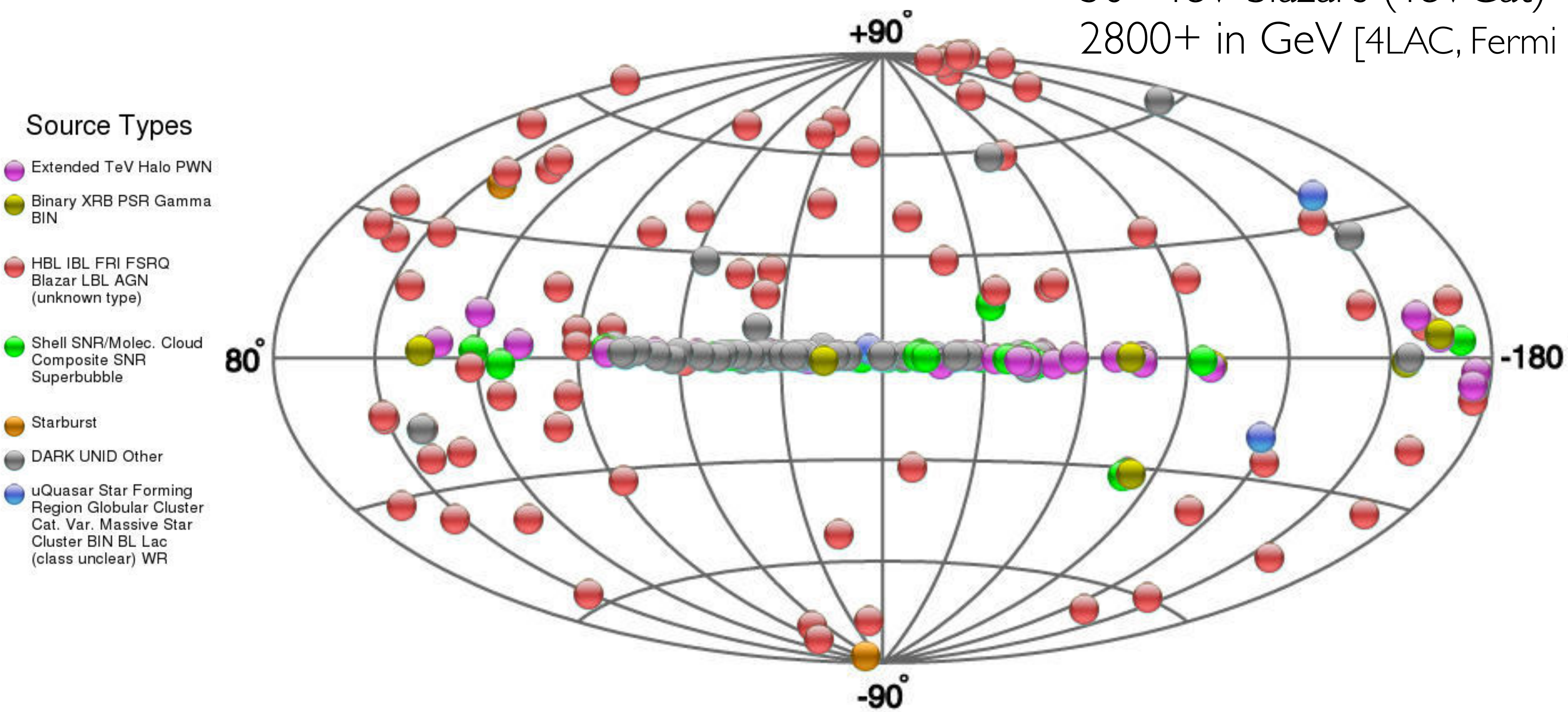




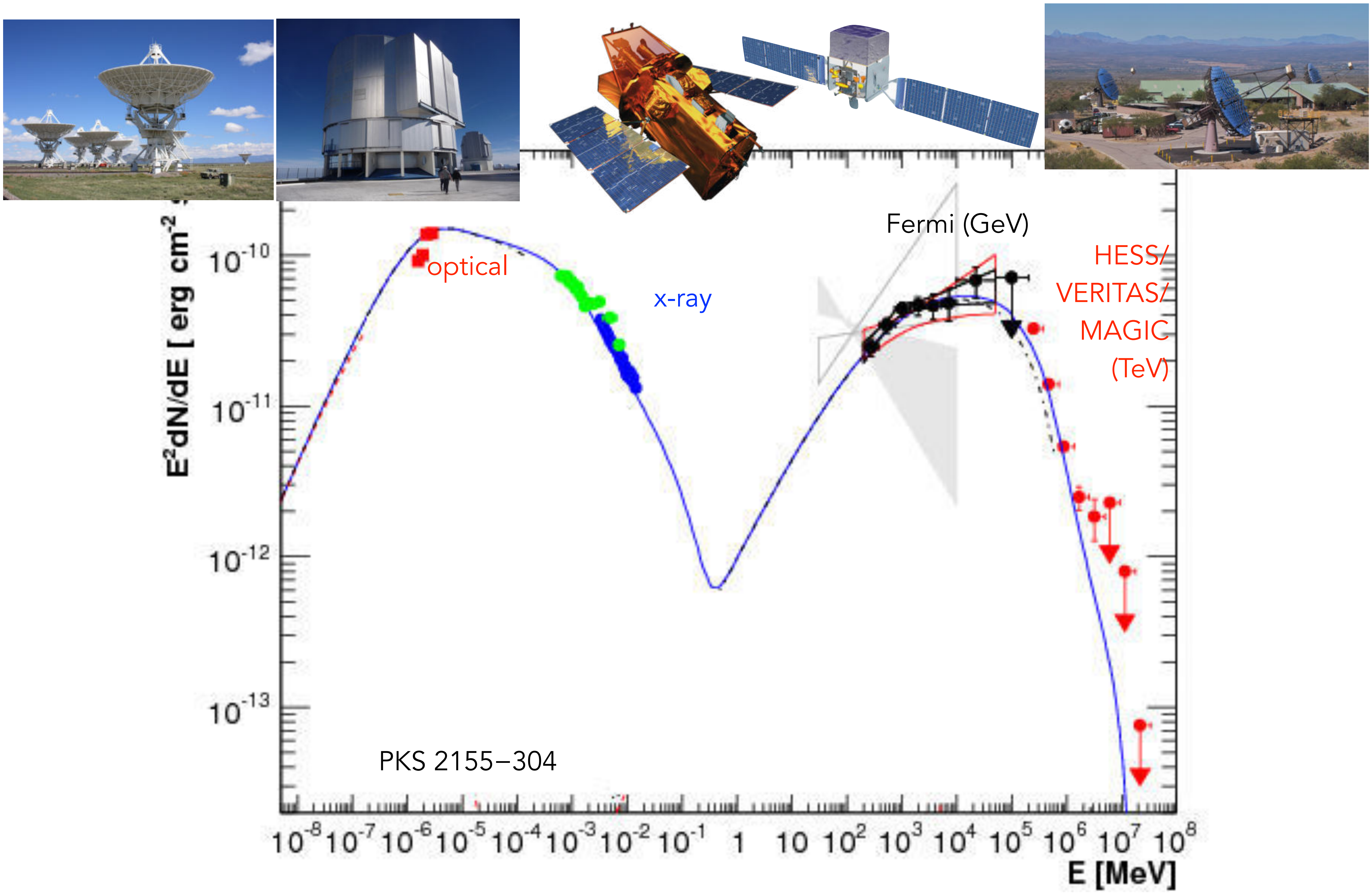
>90% of extragalactic Fermi sources (see also TeVCaT)

Blazars Dominate the Extragalactic γ-ray sky

50+ TeV blazars (TeVCat)
2800+ in GeV [4LAC, Fermi Coll 2019]



Blazar Spectral Energy Distribution

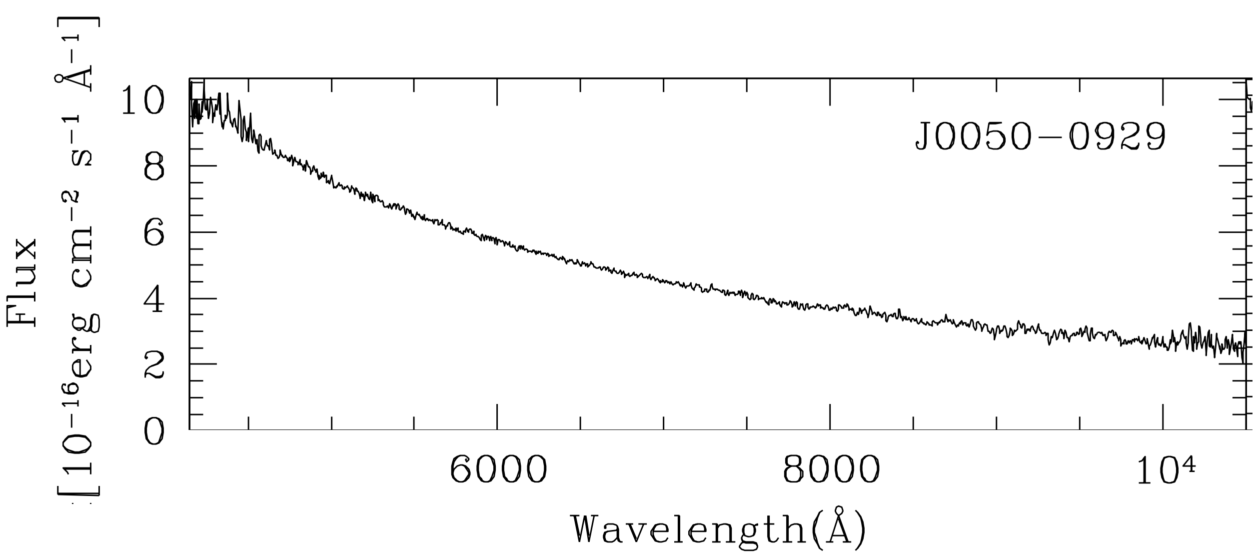


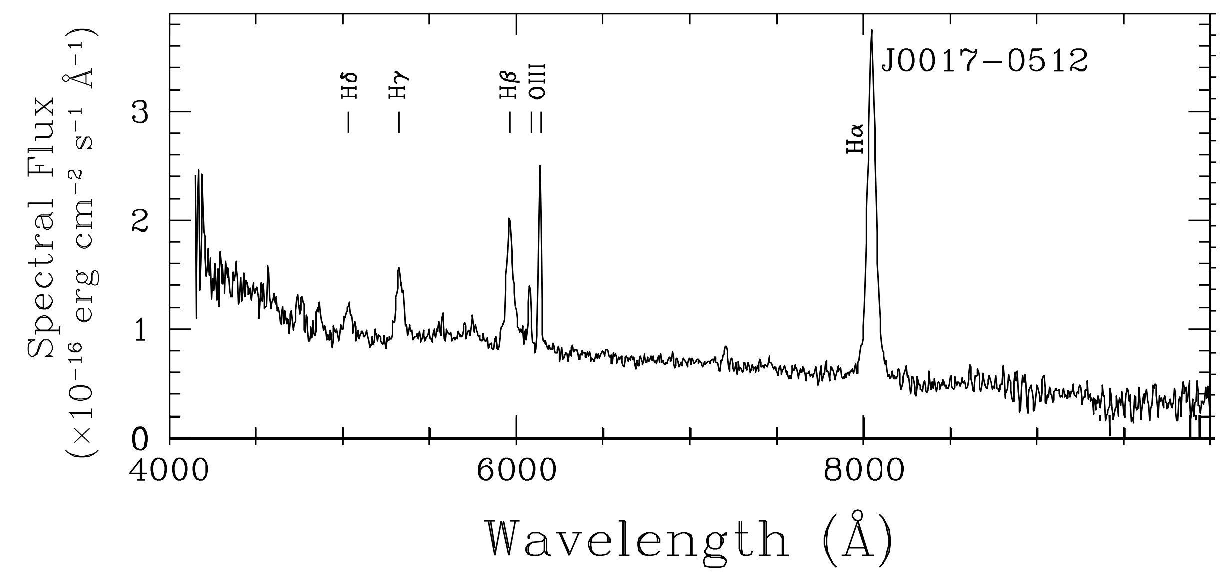
Extremely variable!

Blazar Classes: BL Lac Objects and Flat Spectrum Radio Quasars

BL Lac

FSRQ





	BL Lacs	FSRQs
accretion	inefficient	efficient
EW	< 5 Å	> 5 Å
L/L_{Edd}	$\lesssim 0.01$	$\gtrsim 0.01$
ν^S_{peak}	any	$\lesssim 10^{14}$ Hz

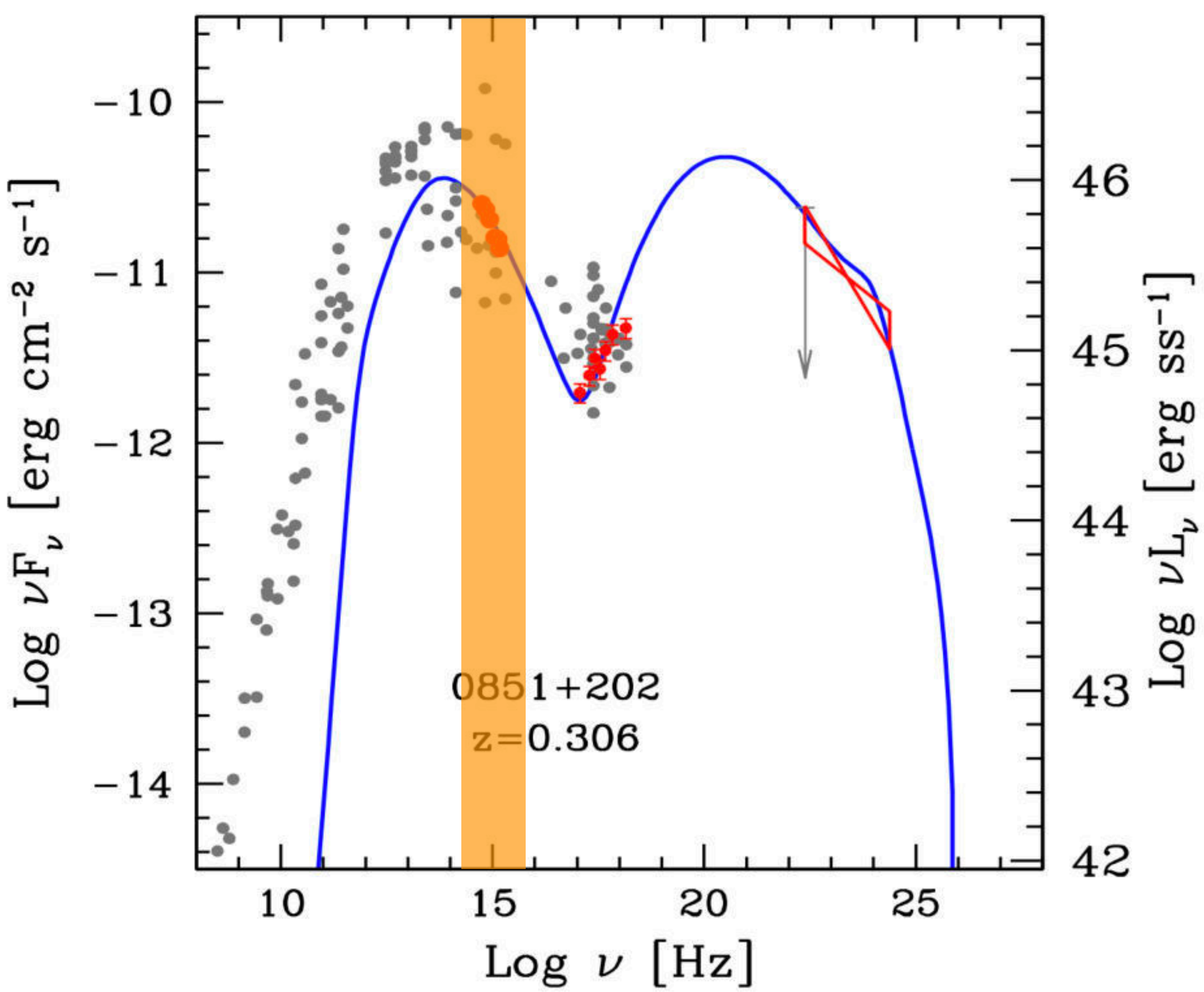
Blazar Classes: BL Lac Objects and Flat Spectrum Radio Quasars

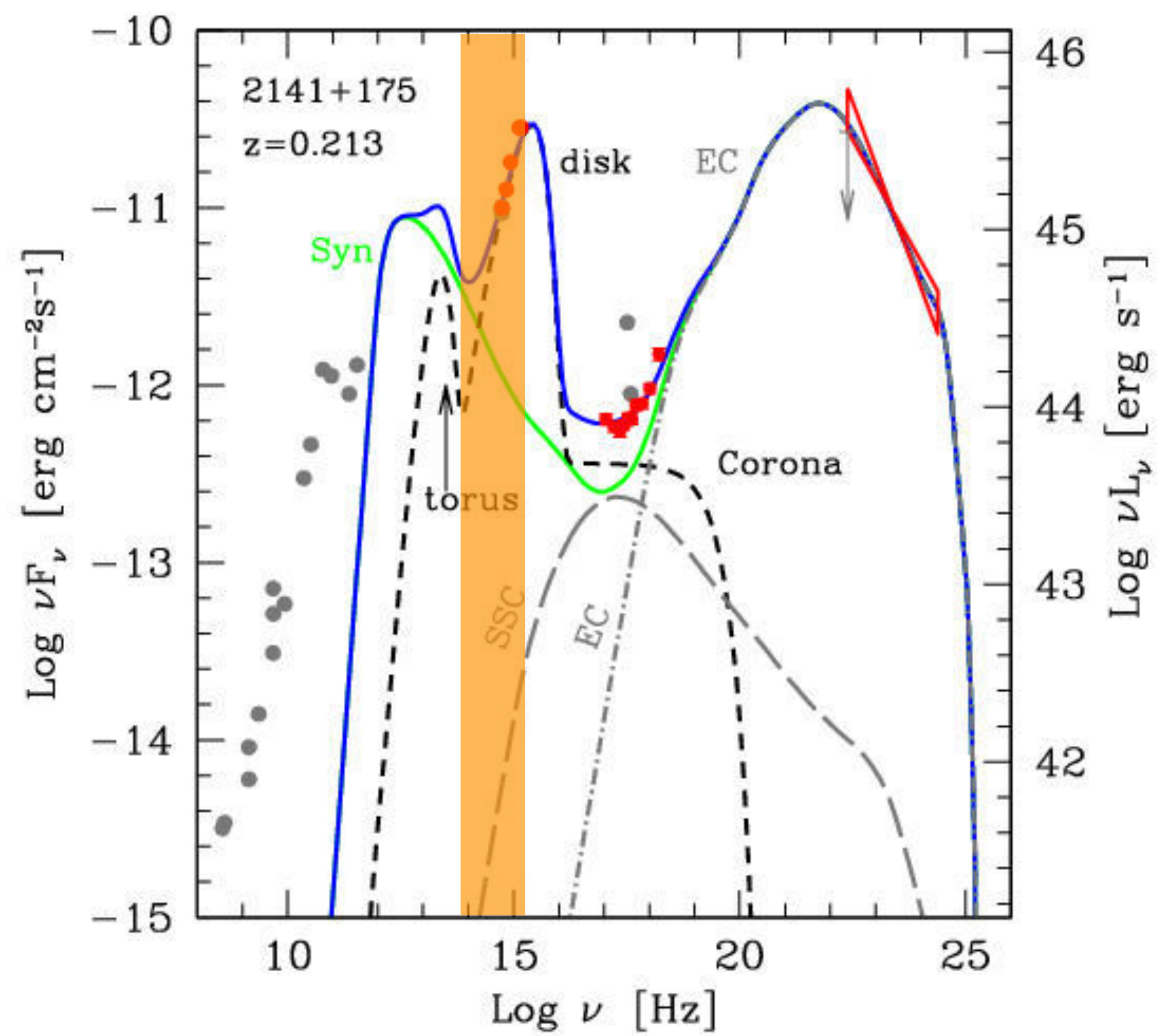
BL Lac

FSRQ

Optical light

Ghisellini 2009

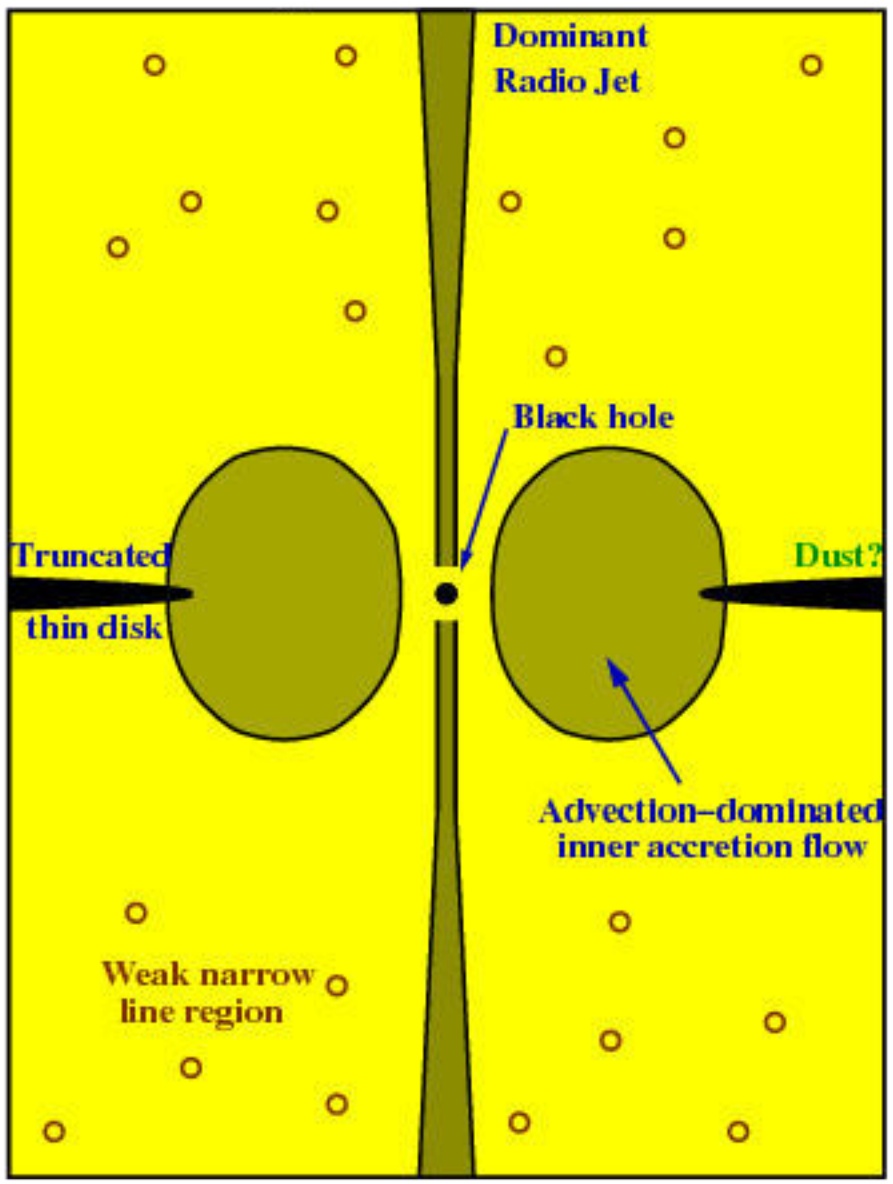




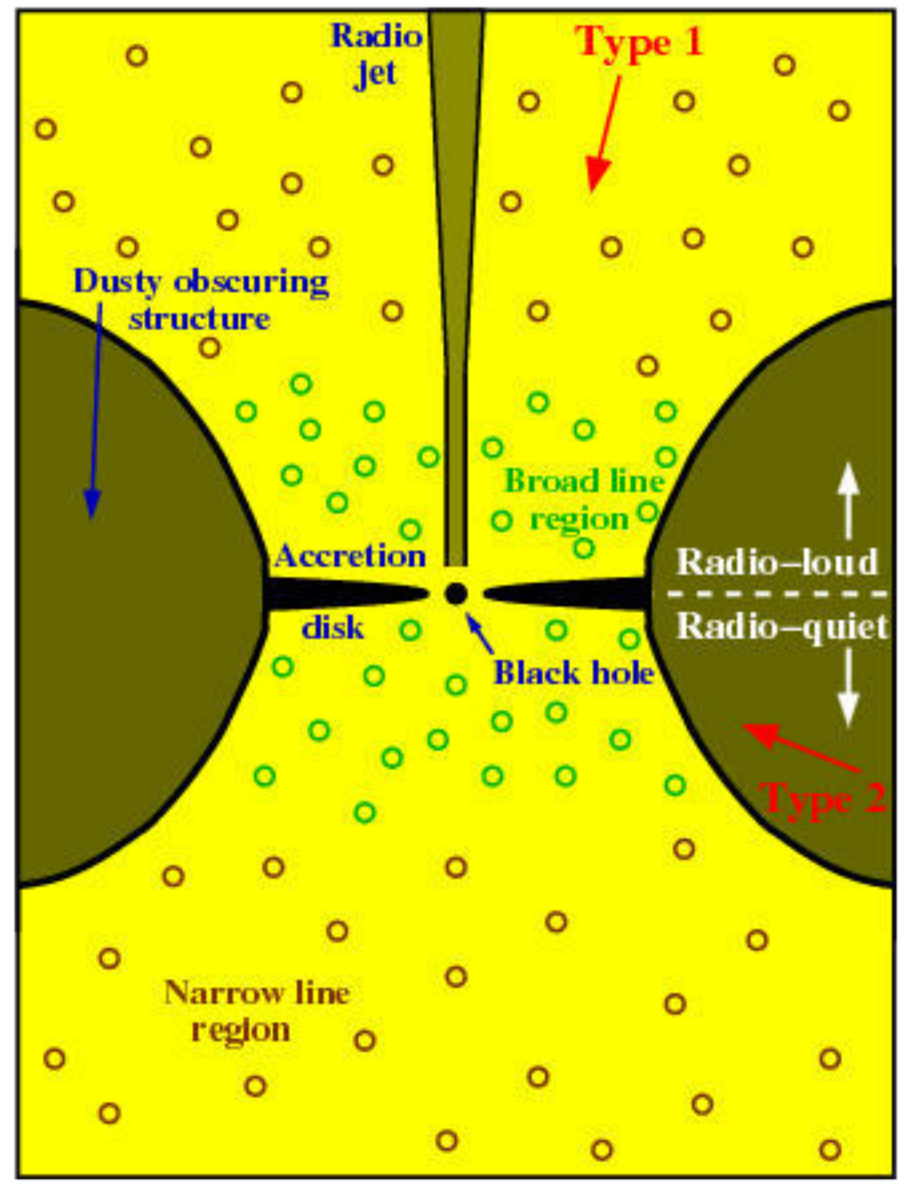
Blazar Classes: BL Lac Objects and Flat Spectrum Radio Quasars

Heckman & Best 2014

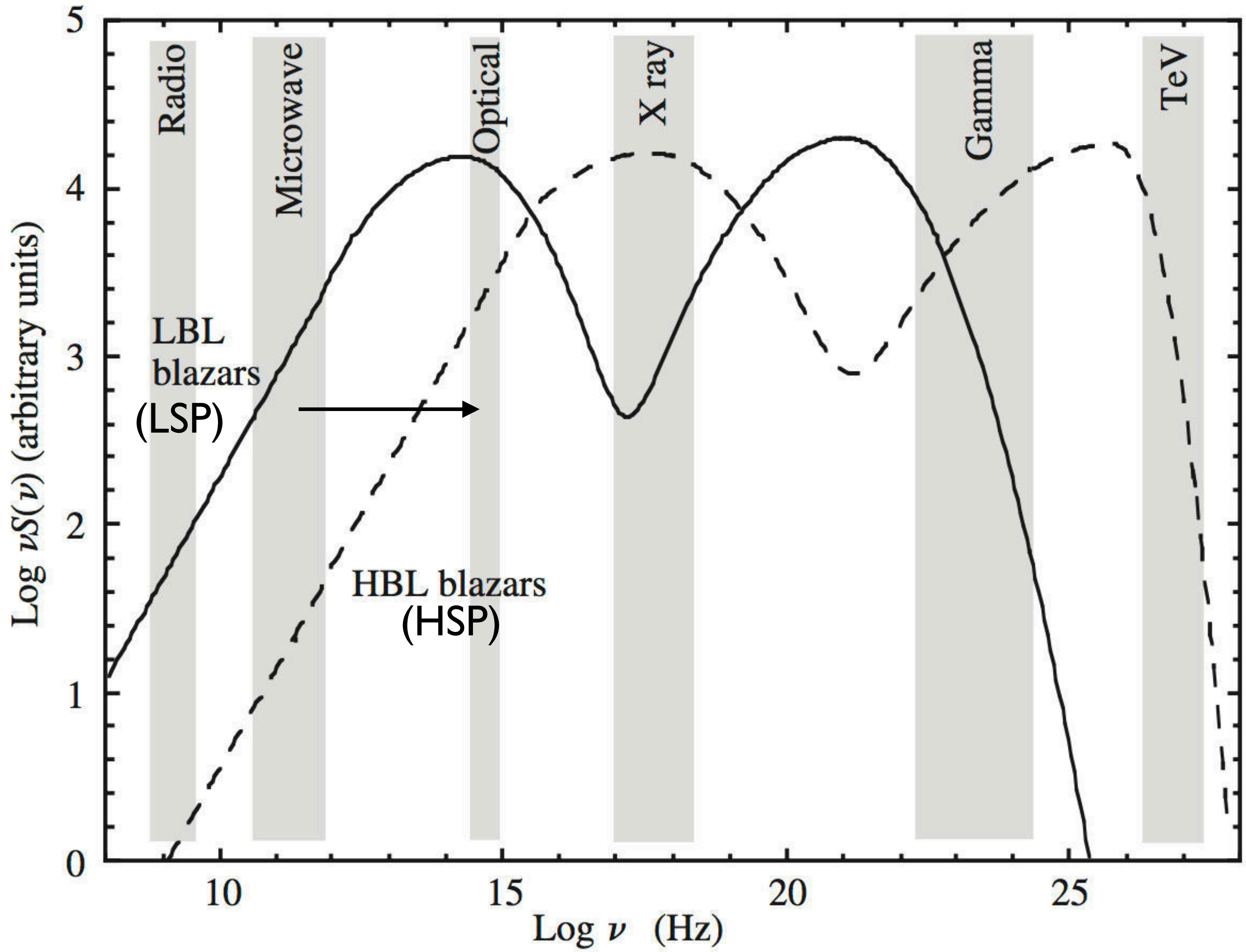
BL Lac/FRI



FSRQ/FRII



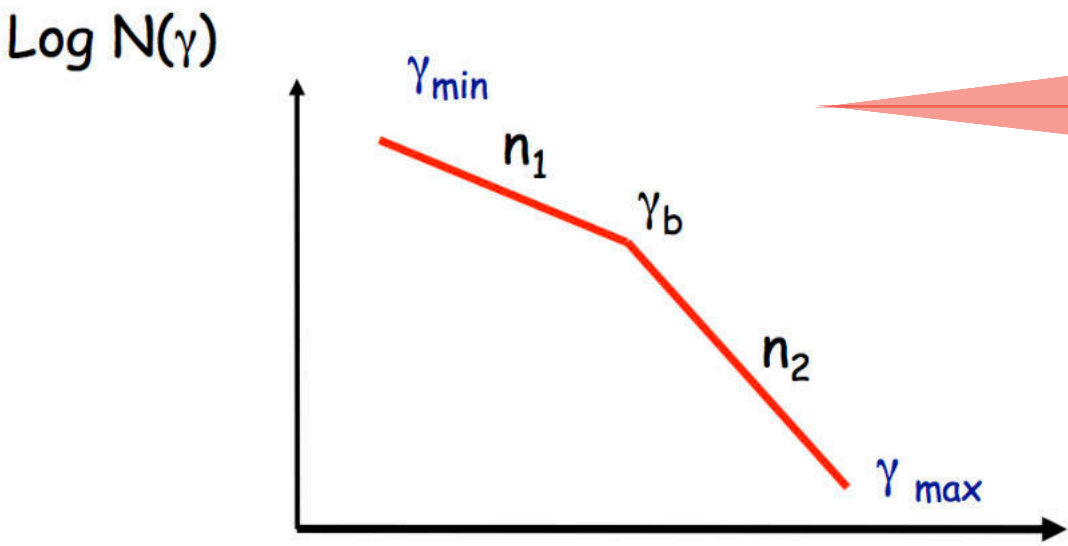
Classification of BL Lac objects

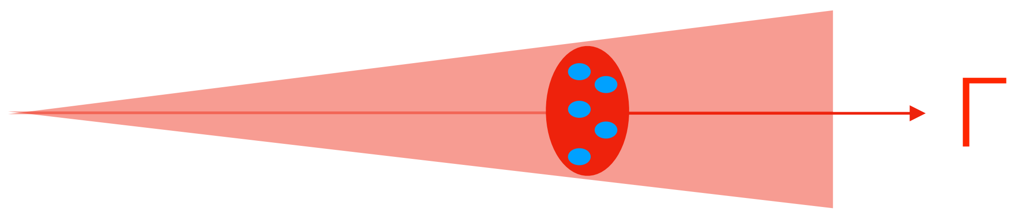


H. Bradt "Astrophysics processes" 2008, originally from P. Giommi et al., A&A 445, 843 (2006)

Emission from BL Lac Objects

see e.g. Tavecchio, Maraschi & Ghisellini 1998



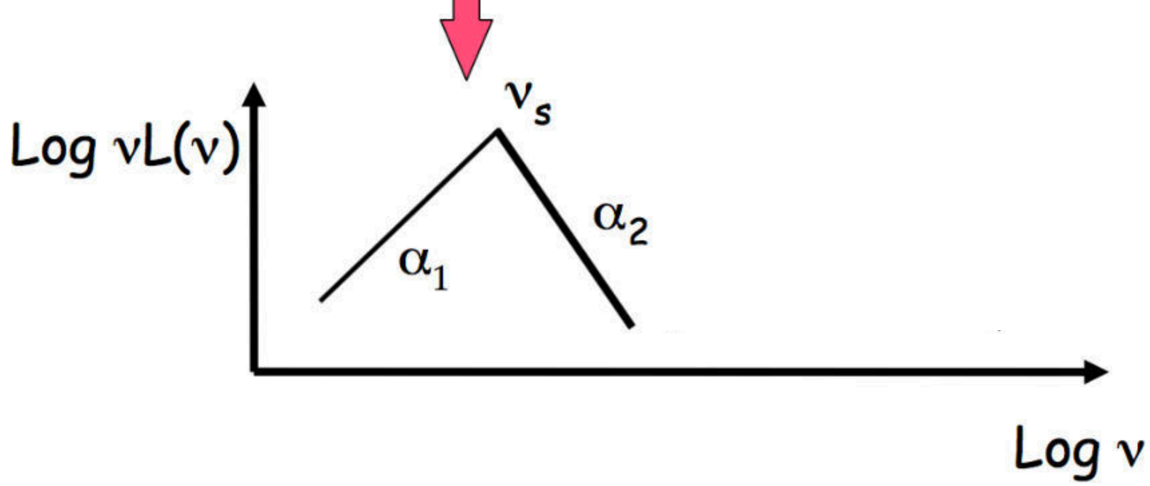


Relativistic electrons in a "blob"

$$\nu_s = 3 \times 10^6 B \gamma_B^2 \delta$$

$$\alpha_1 = \frac{n_1 - 1}{2}$$

Synchrotron



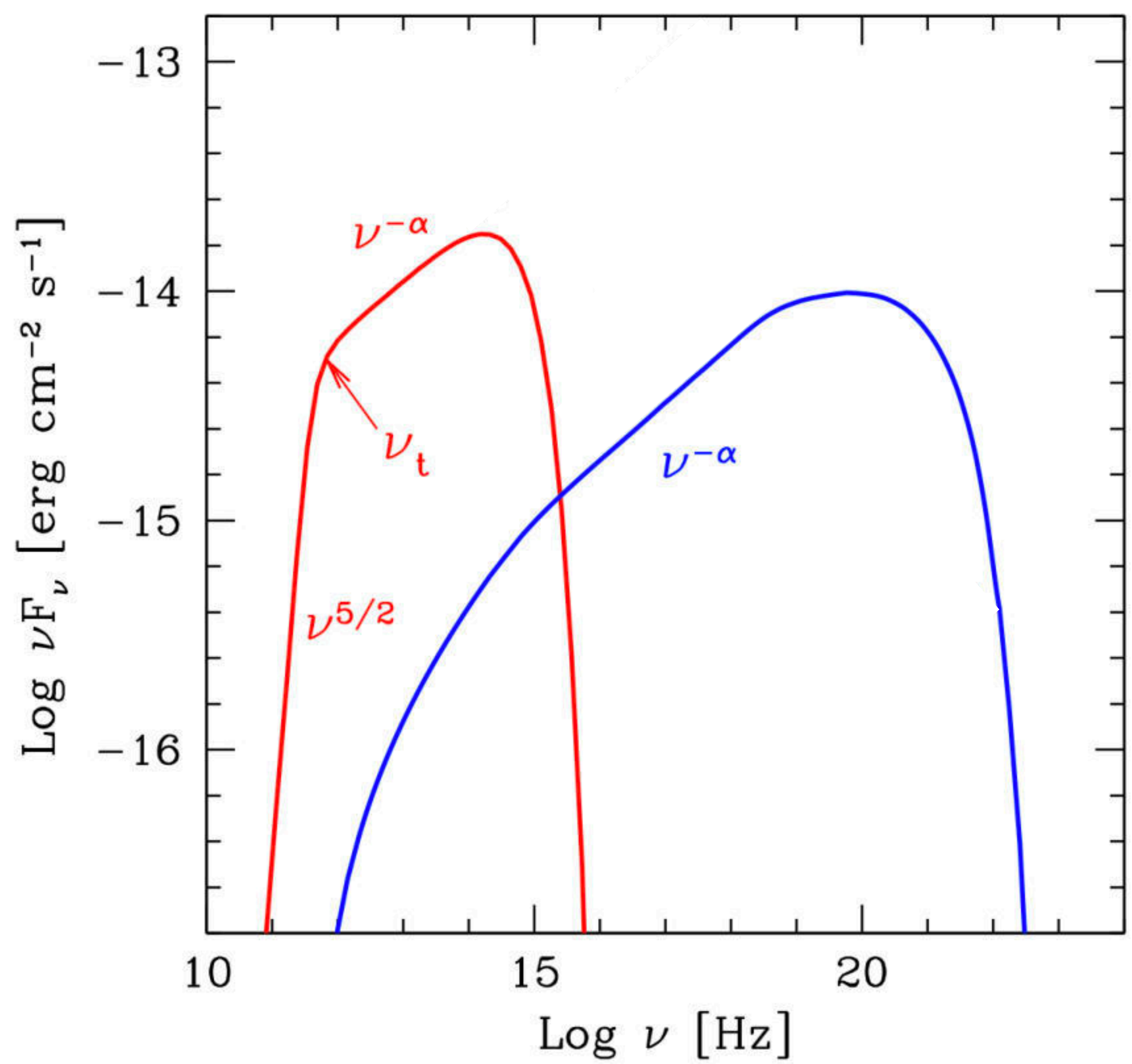


Image credit: L. Costamante 2011, H. Bradt "Astrophysical processes" 2008

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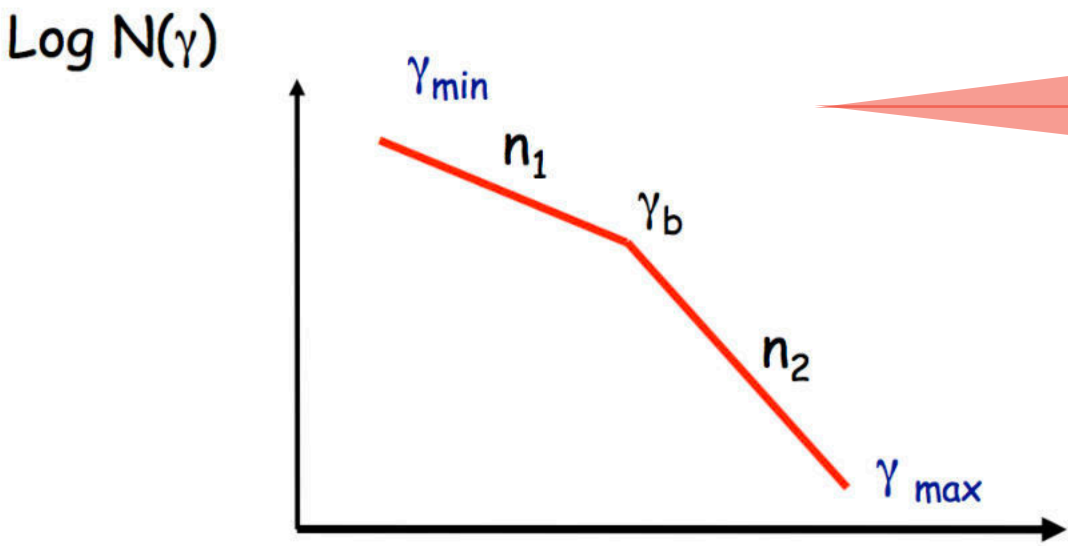

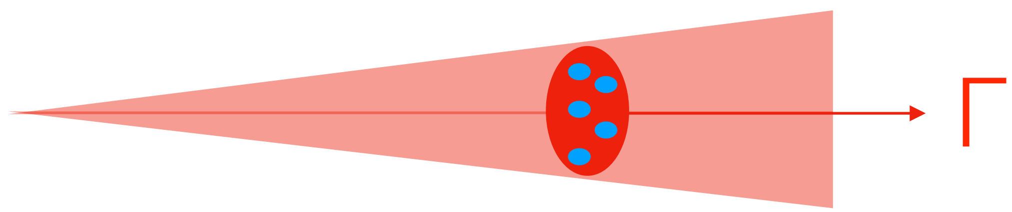

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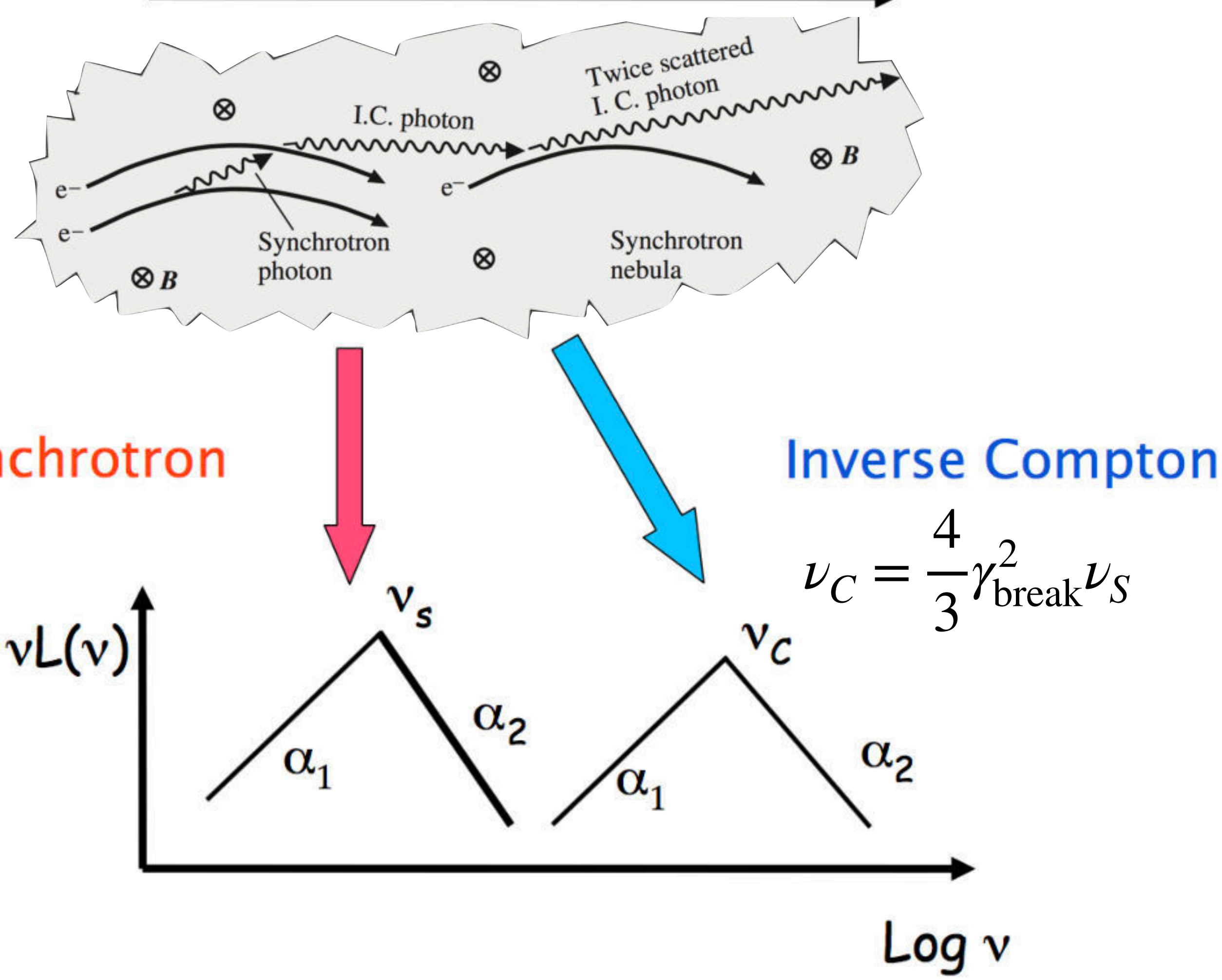


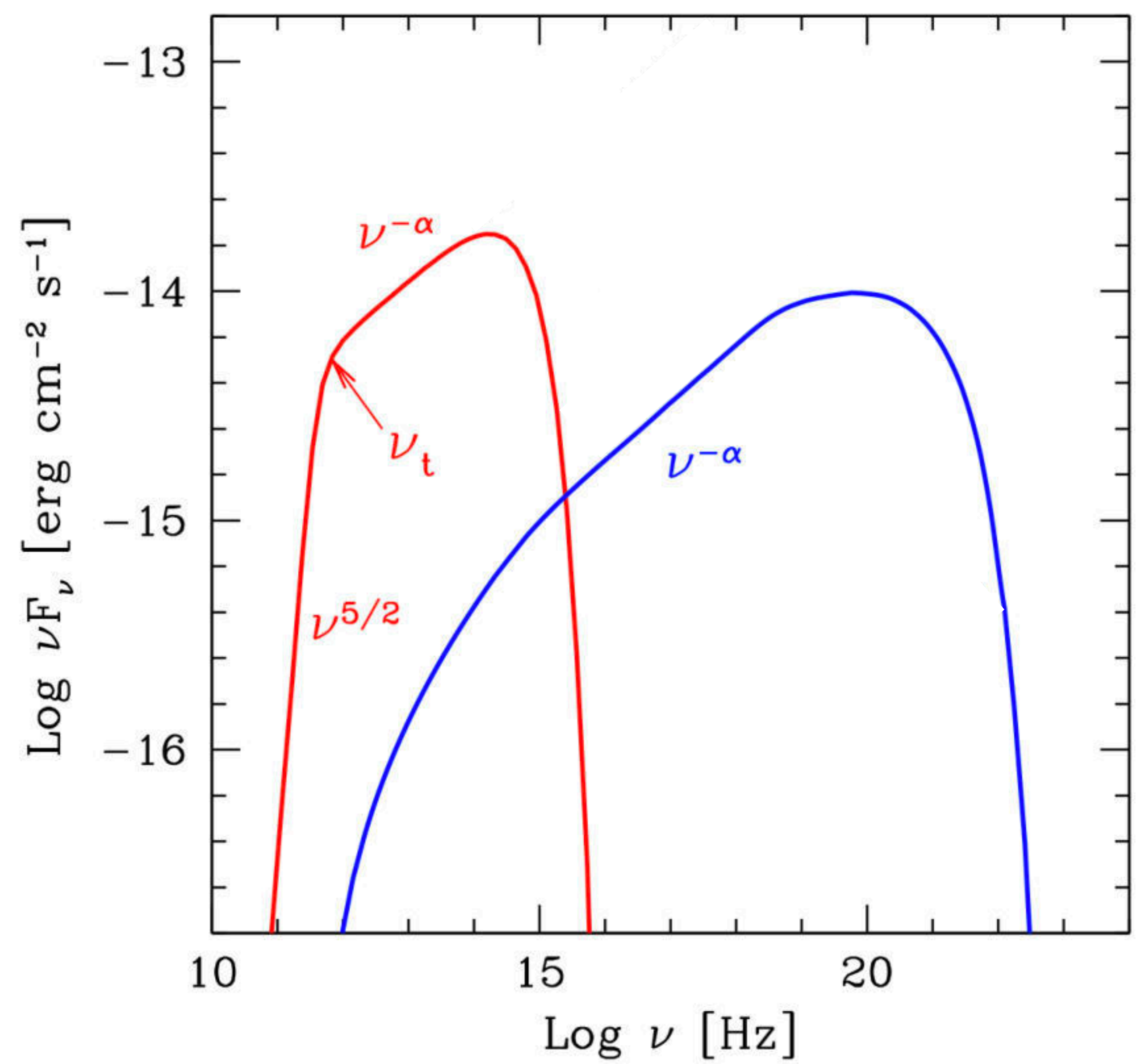
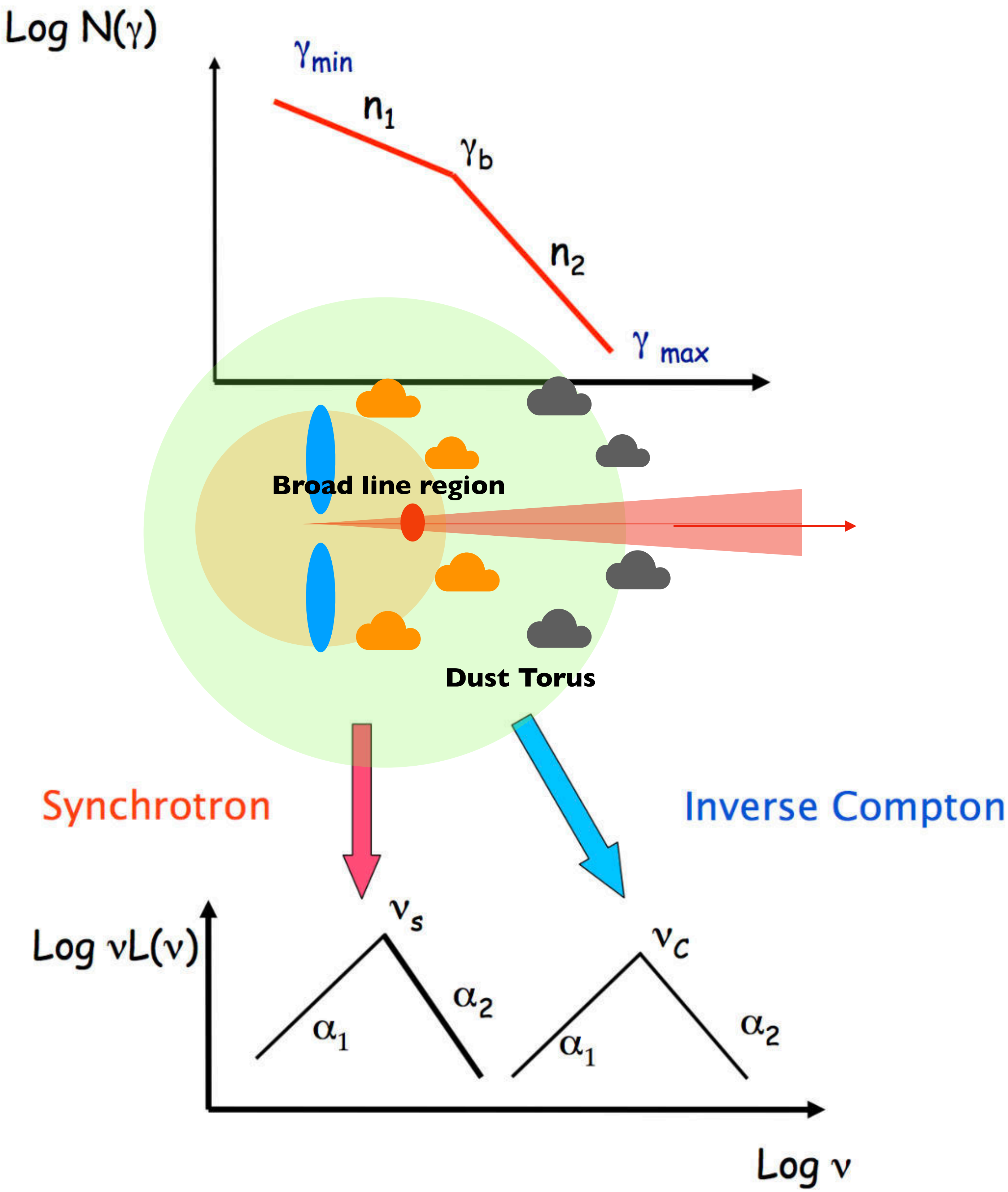


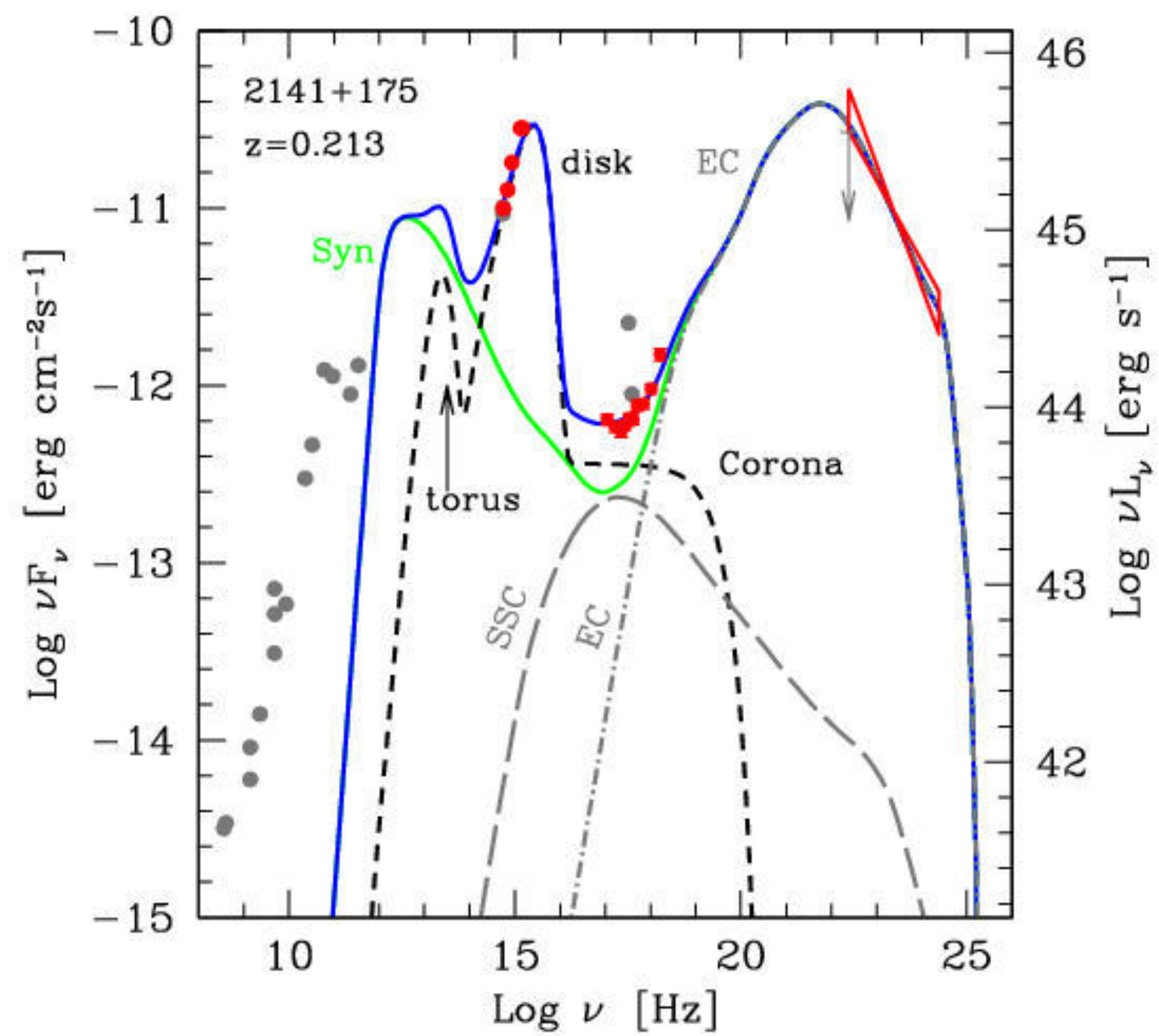
Image credit: L. Costamante 2011, H. Bradt "Astrophysical processes" 2008

In this synchrotron + synchrotron self Compton (SSC) model, we can in principle determine the magnetic field strength, doppler factor, γ_b, n_1, n_2, electron density, size of emitting region from observed quantities (see back-up)

Emission from Flat Spectrum Radio Quasars

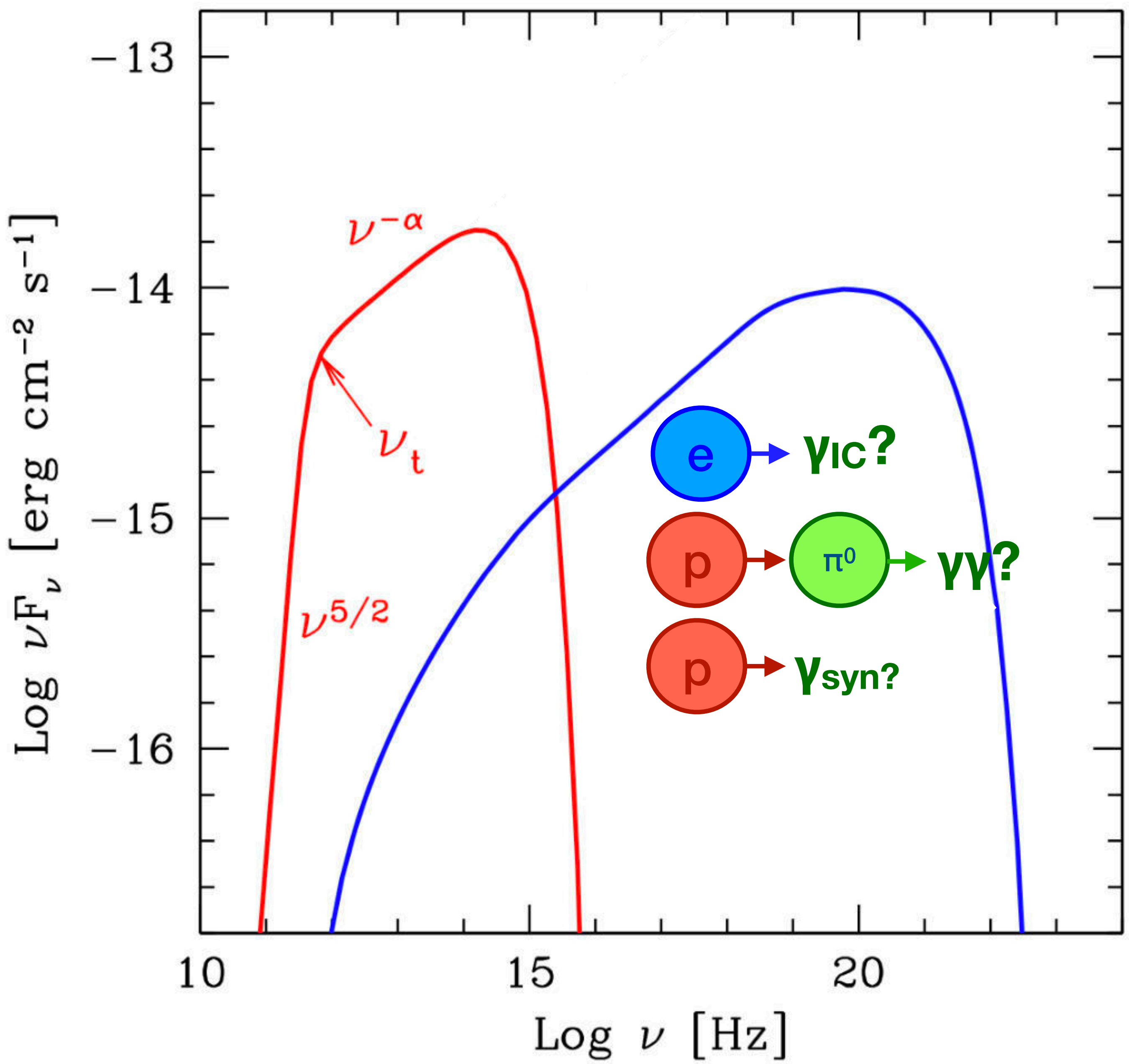


Ghisellini 2009



Enter the protons

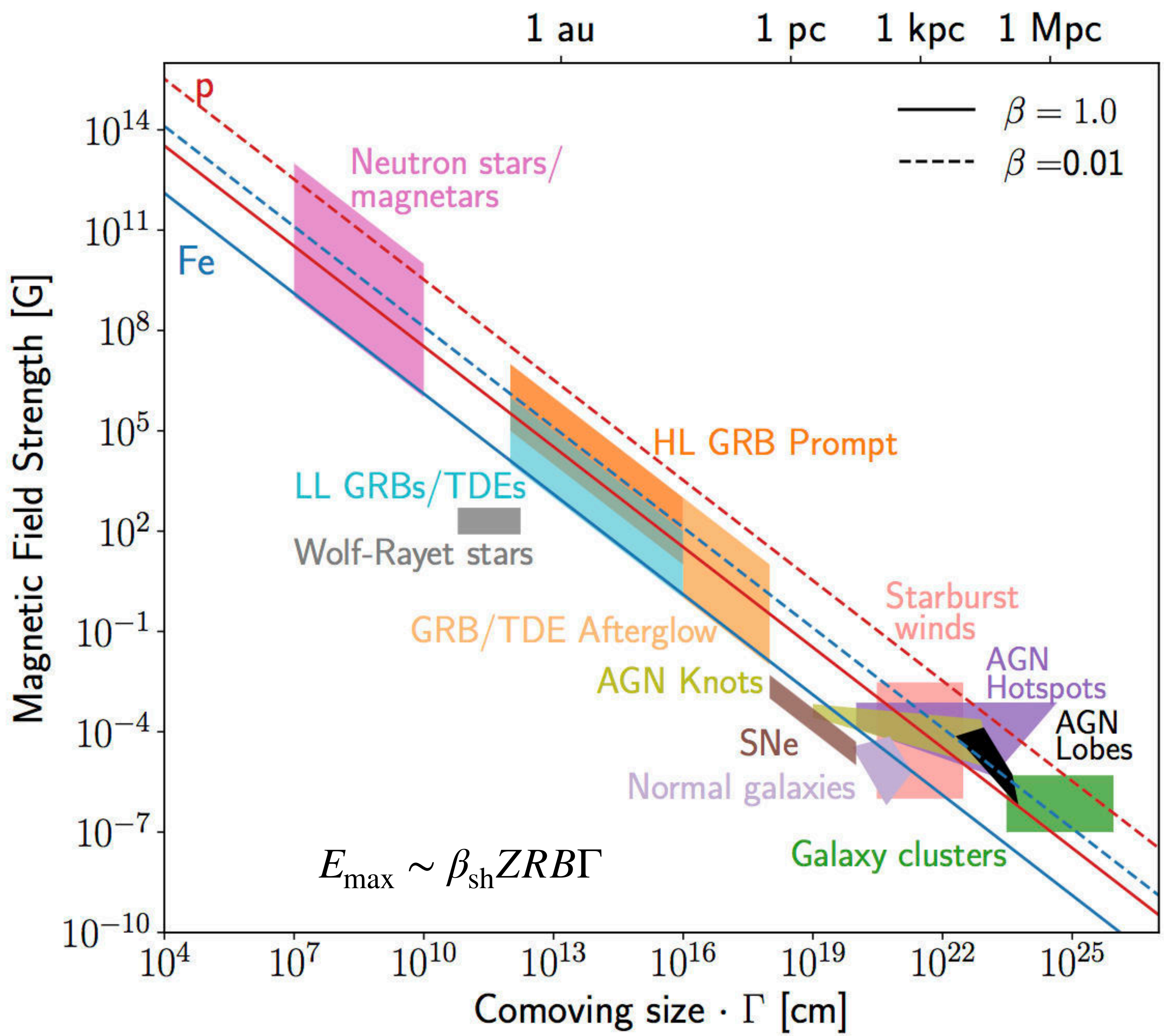
For theory of UHECR acceleration in AGN jets see,
e.g. Bell et al, MNRAS, 473, 2364
Matthews et al, MNRAS, 482, 4303,
Rieger et al, Galaxies (2019), 7(3)
Caprioli, ApJL (2015), 811(2)
Mbarek & Caprioli, ApJ (2019), 886(1)

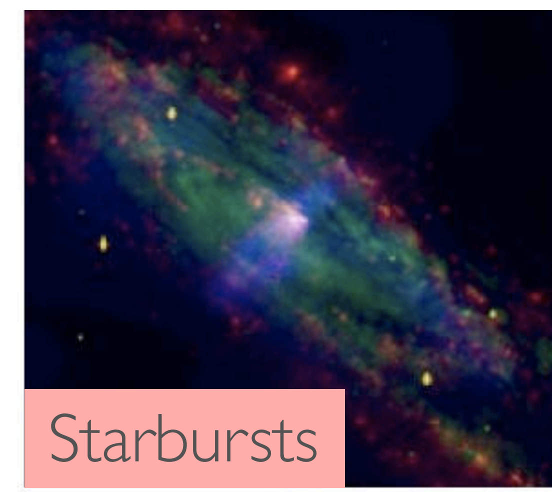


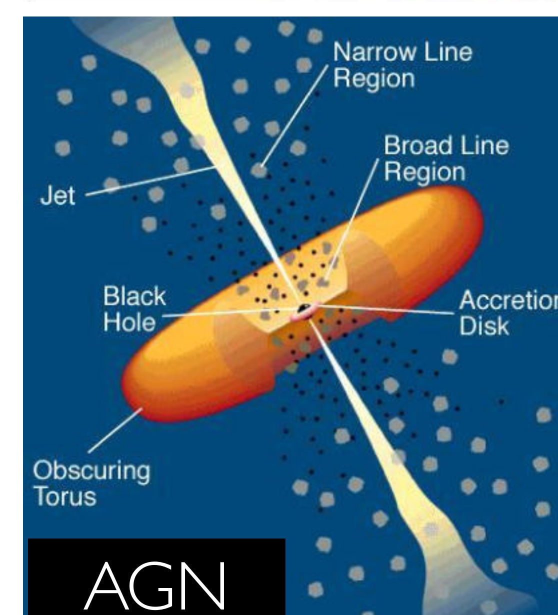
For characteristic values of B, R, and delta , we end up with E_{max} in the UHECR ball park,

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

Hillas criterion



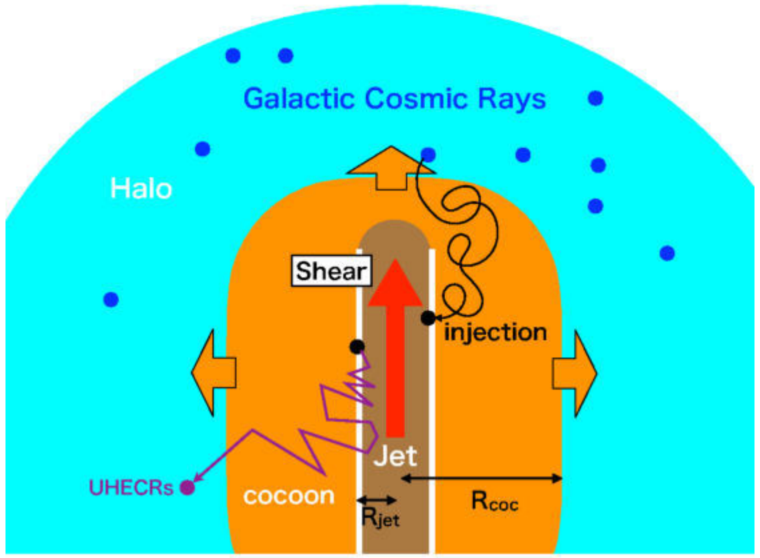




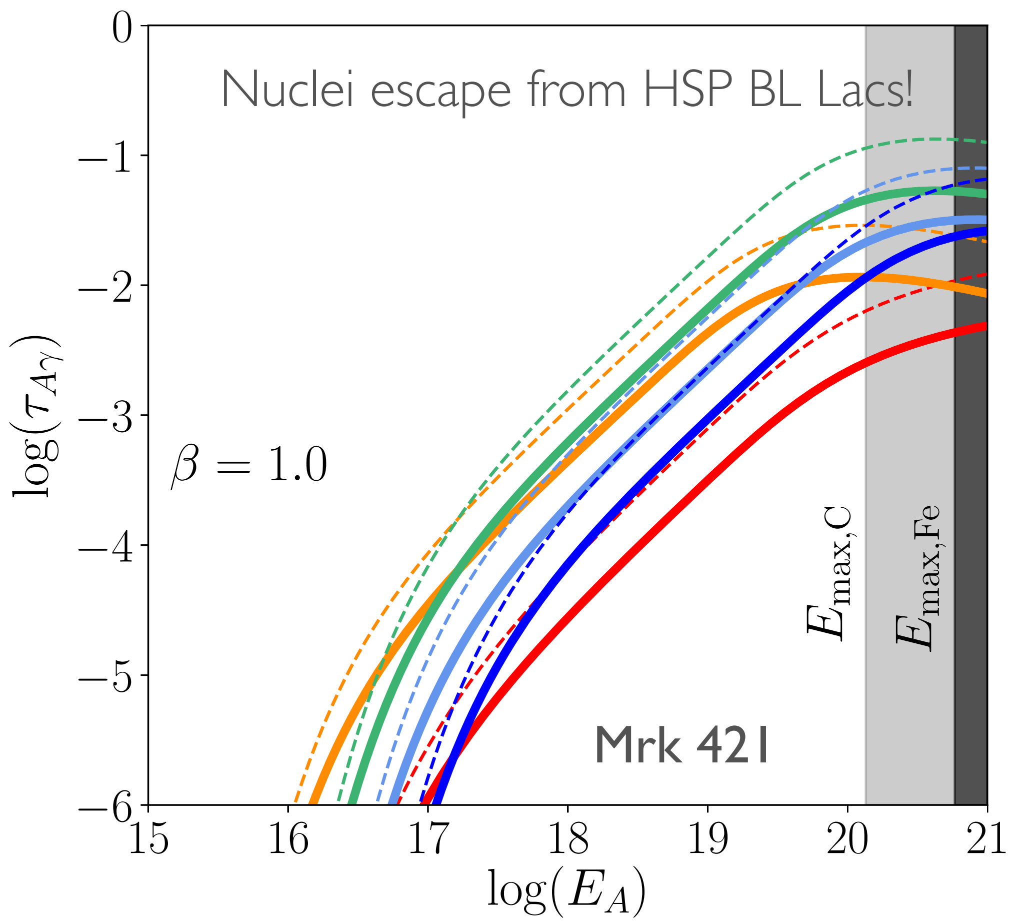
FO for MIAPP UHECR Review, 2019, FrASS, 6, 23

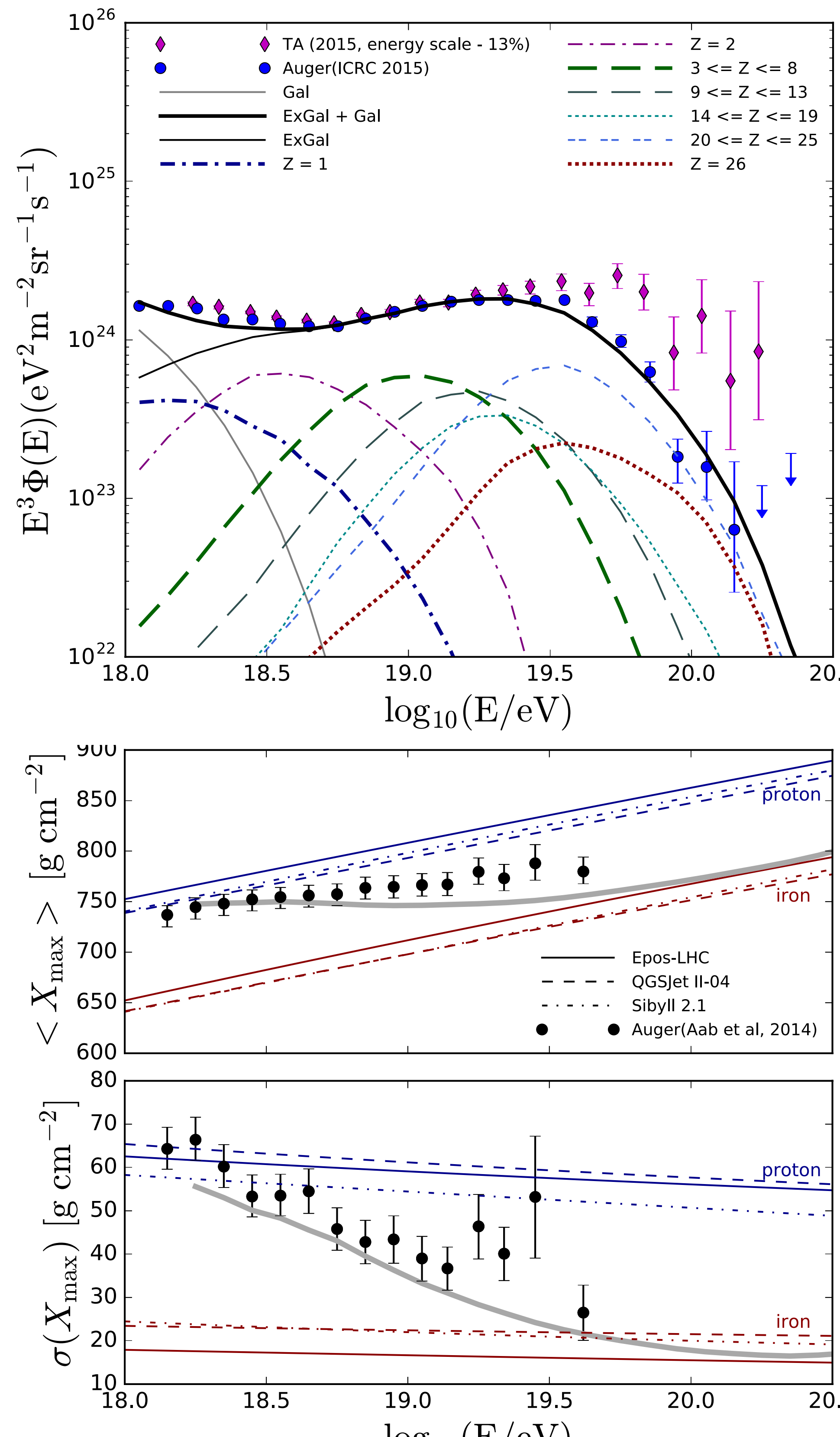
Galactic UHECRs reaccelerated by AGN Jets can fit the UHECR spectrum and composition

Kimura, Murase, Zhang , PRD 97, 023026, 2018
[see also Rodrigues, Heinze, Palladino arXiv:2003.08392]



Tavecchio, FO, Righi, MNRAS, 2019, 488, 3

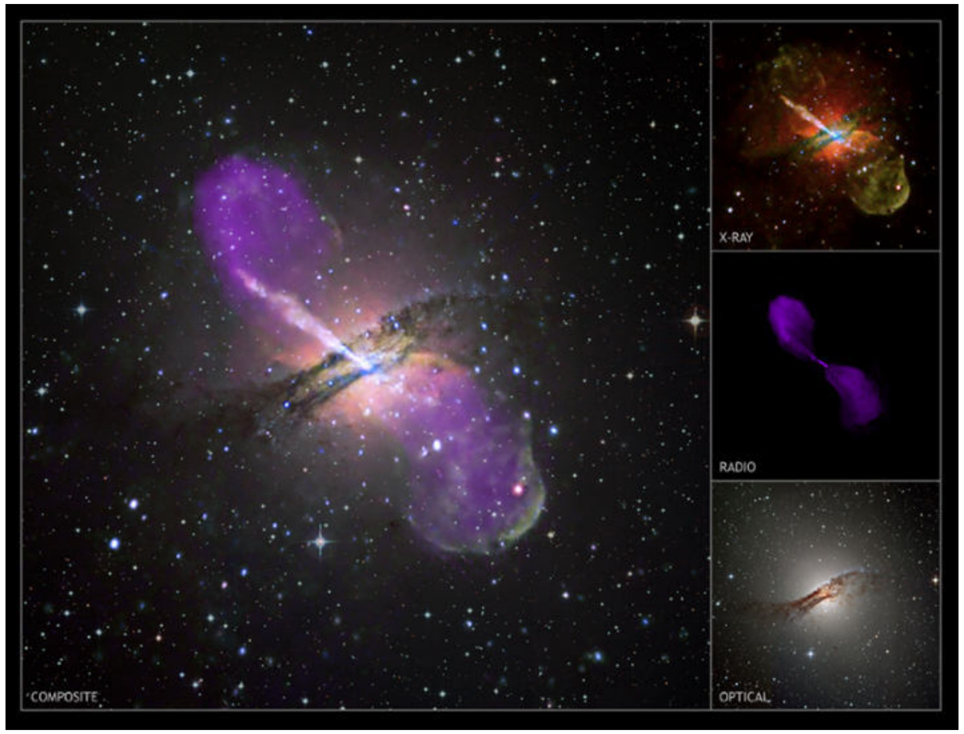


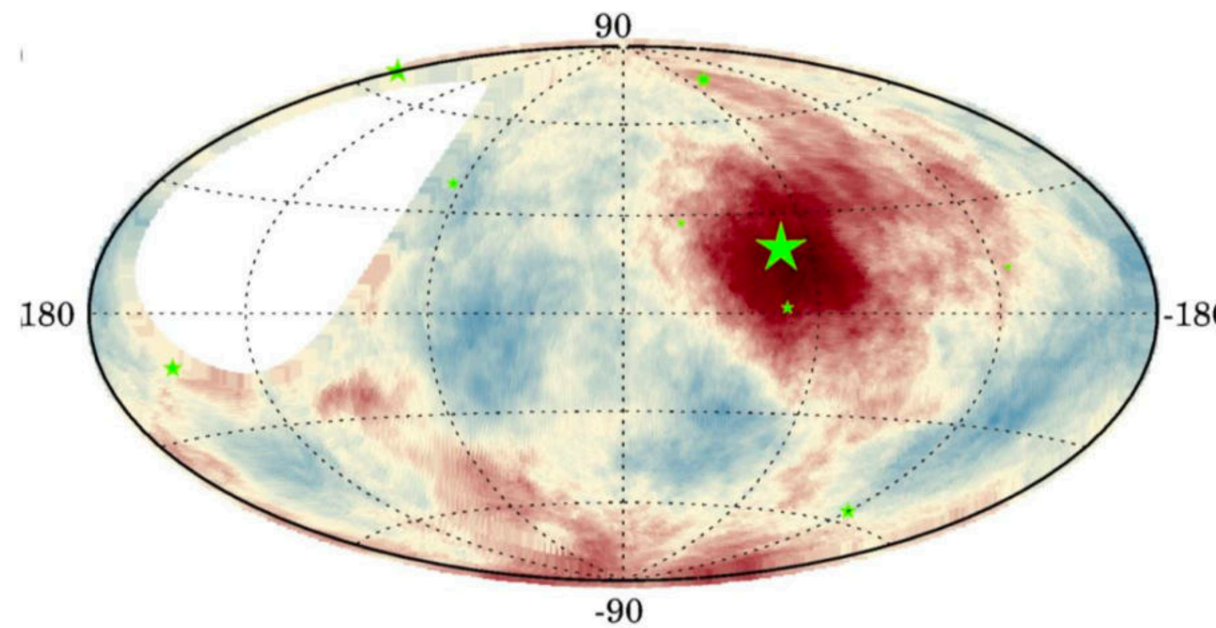


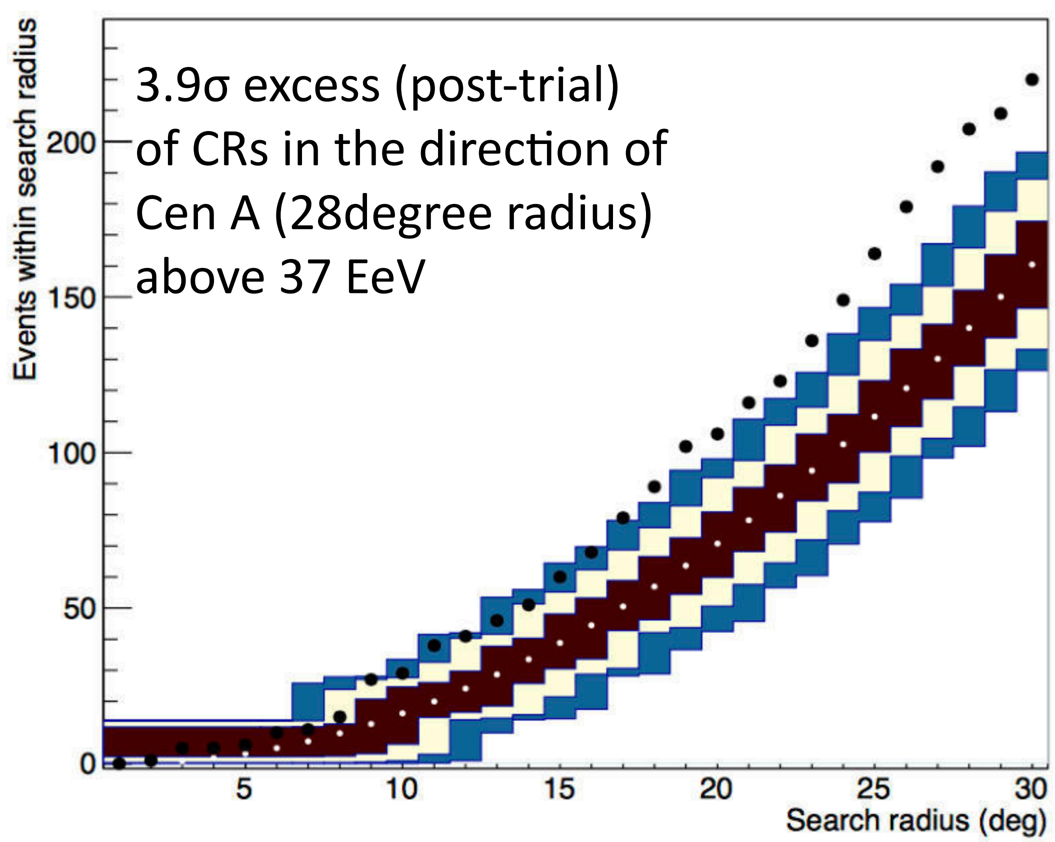
Clues from UHECR arrival directions

Auger Coll, ApJL, 853, L29, 2018

Caccianiga, L. on behalf of Auger, PoS, ICRC2019, 206



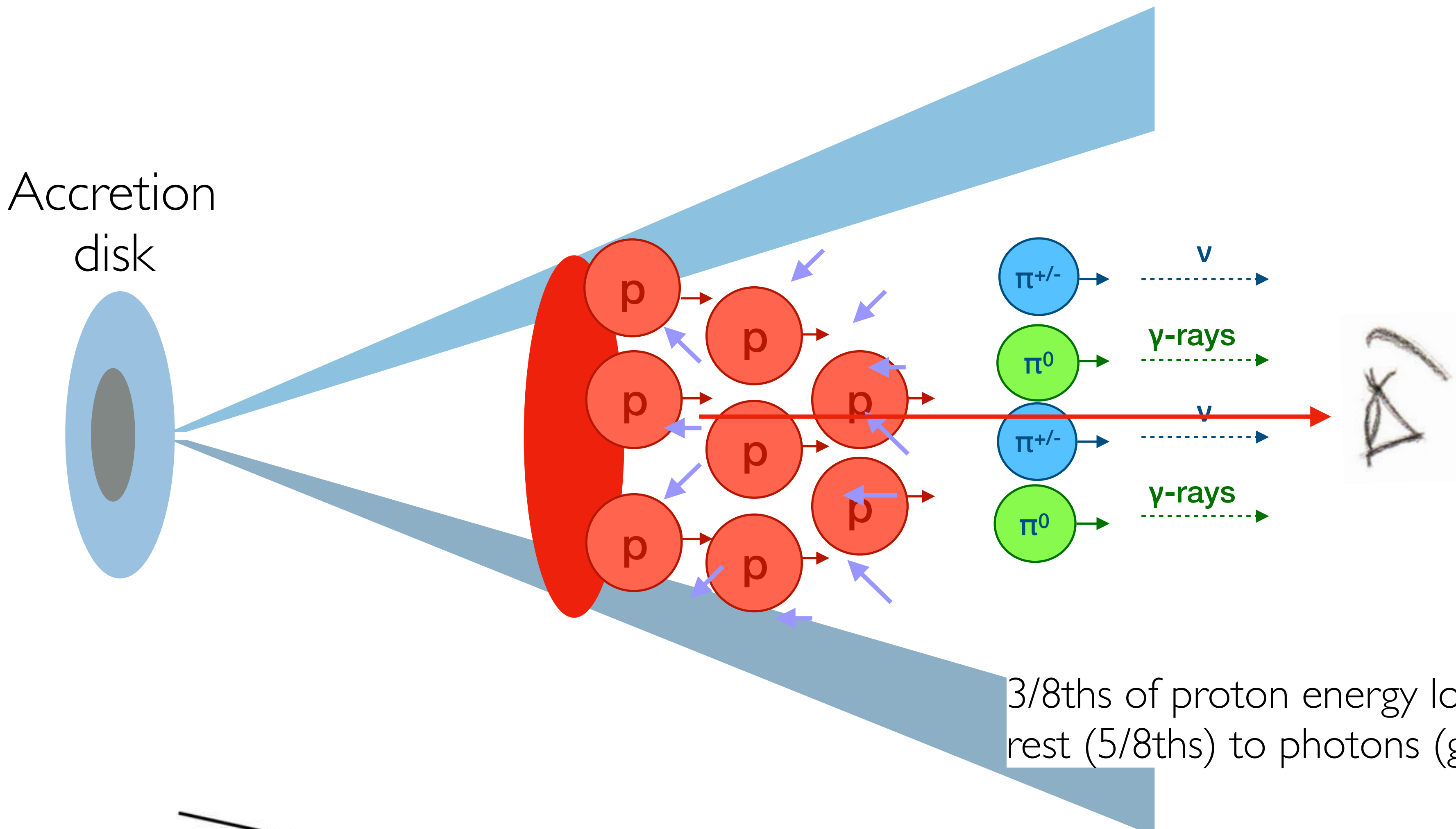




3.1σ excess (post-trial)
of CRs in the direction of 33
3FHL AGN (Cen A, Fornax A, M87, Mrk 421…),
14 degree smearing angle
above 39 EeV - but less significant than
starbursts and large-scale structure

*1 EeV = 10^{18} eV

Neutrino production in blazars



3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

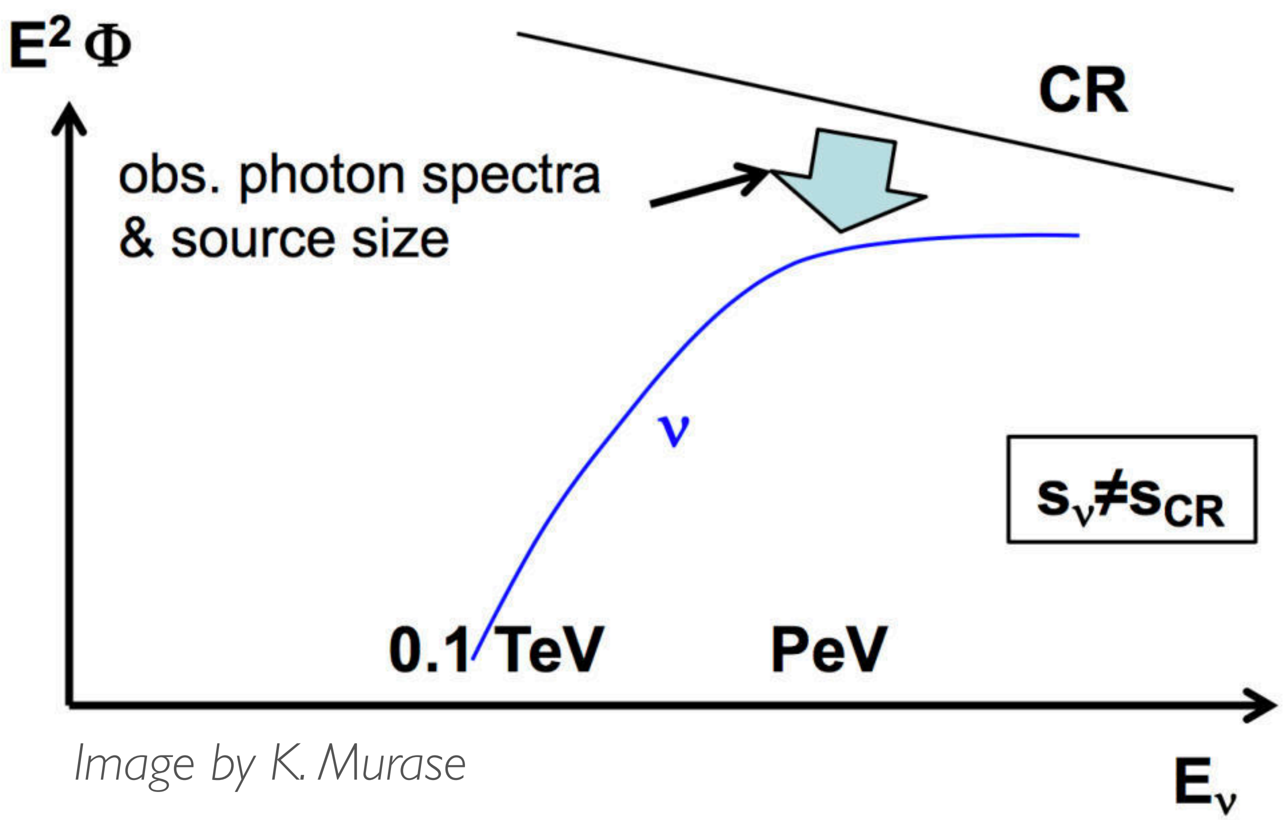


Image by K. Murase

$$p + \gamma \rightarrow n + \pi^+ \rightarrow n + \mu^+ \nu_\mu \rightarrow n + e^+ + \nu_e + \bar{\nu}_e + \nu_\mu$$

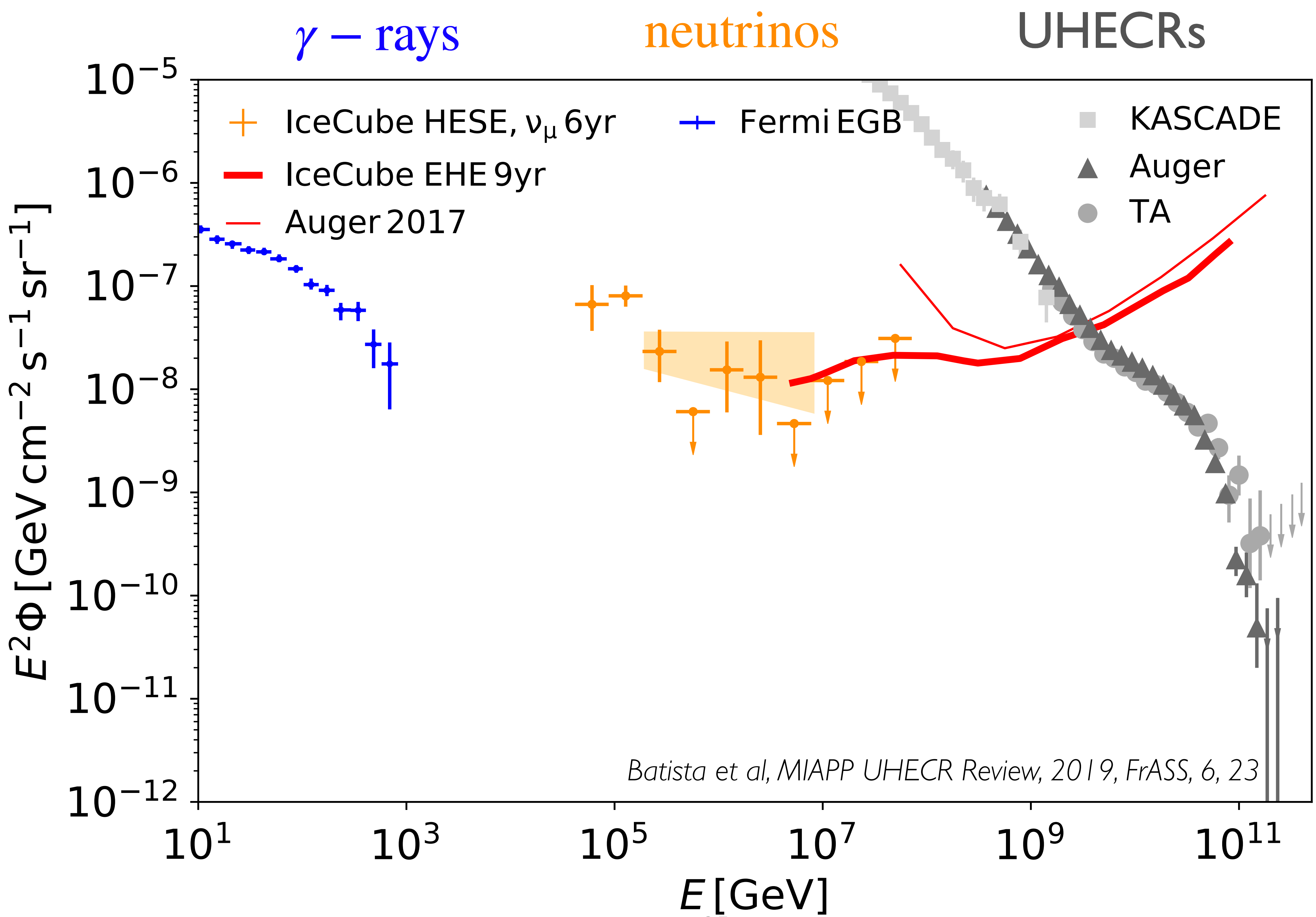
$$p + \gamma \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma$$

$$p_{\mathrm{PeV}} + \gamma \rightarrow p + e^+ + e^- \rightarrow \text{cascade that peaks in keV band}$$

$$\langle E_\nu \rangle = \frac{1}{20} E_p \qquad \langle E_\gamma \rangle = \frac{1}{10} E_p$$

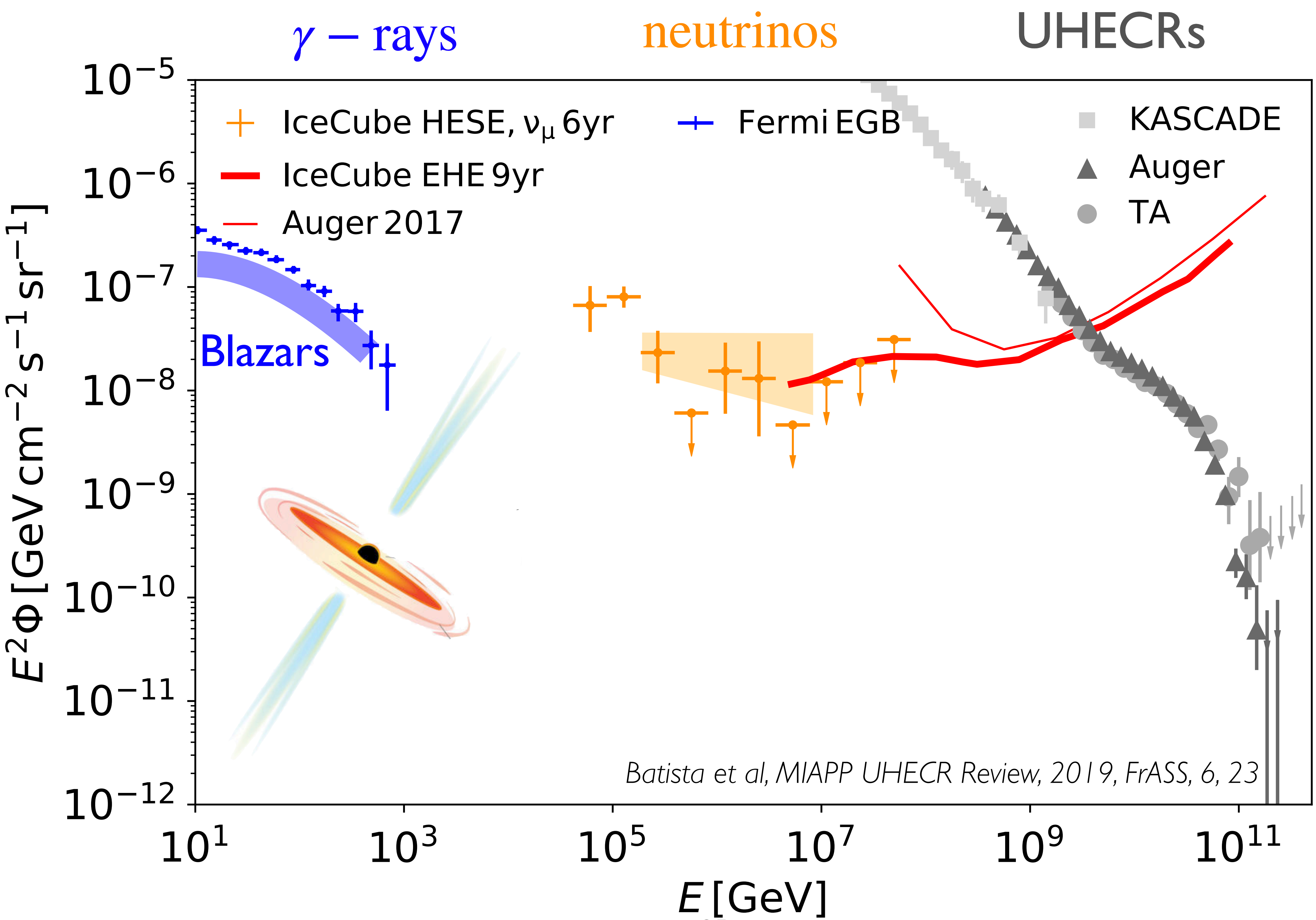
Easy for blazars to produce 20 PeV protons

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



* ≲27% with spectral templates Huber, Krings for IceCube Coll PoS (ICRC2017) 994

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



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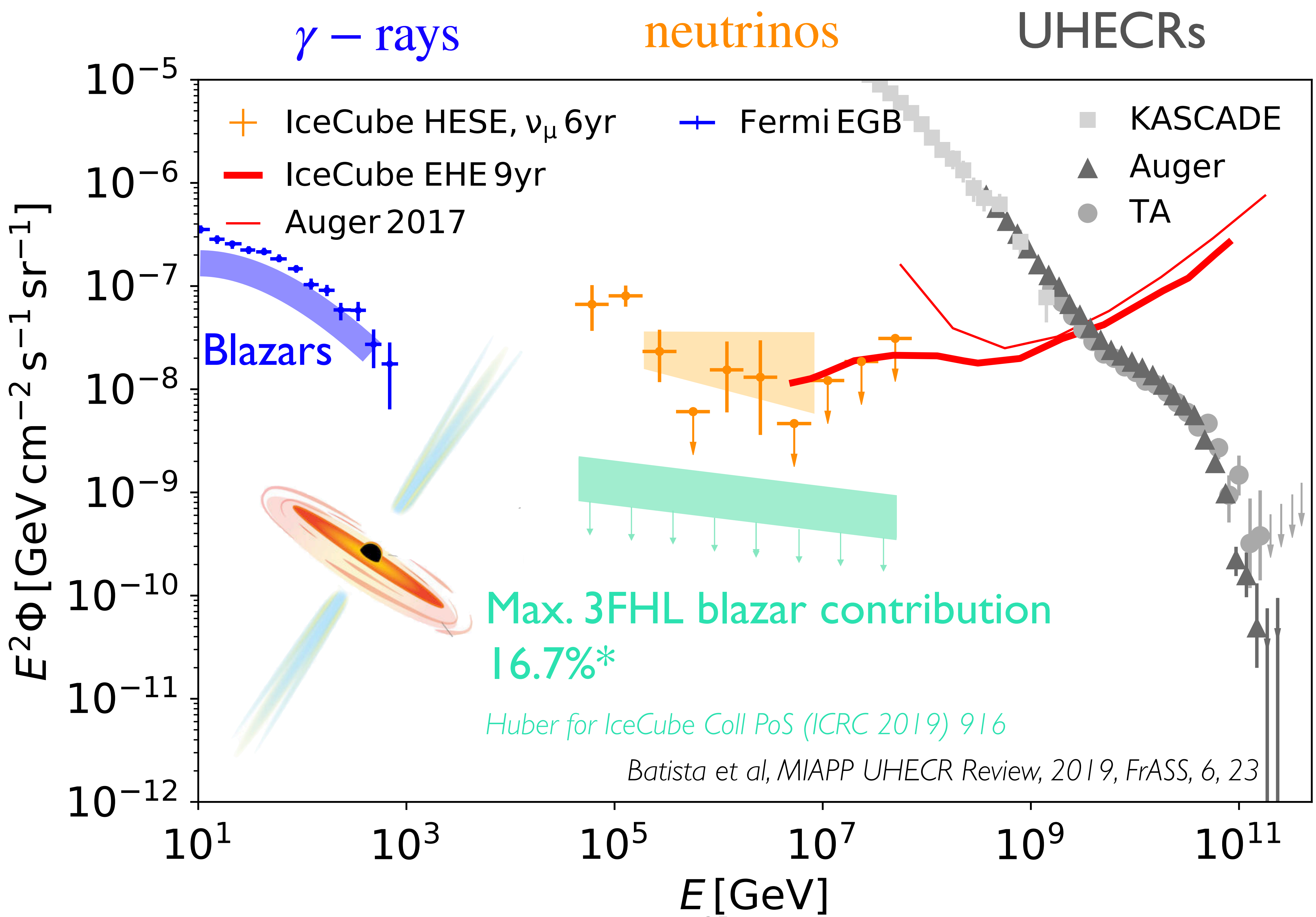

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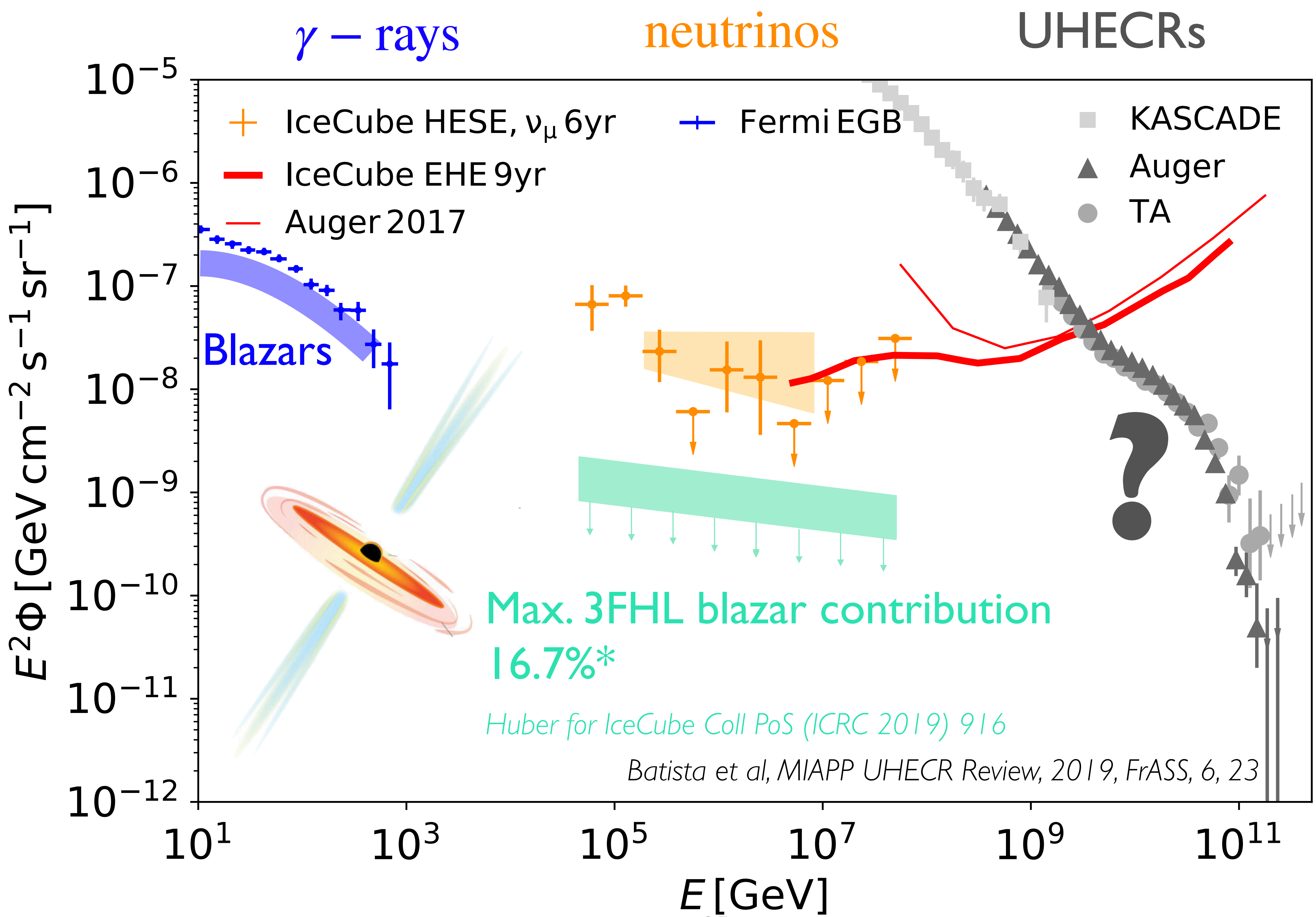

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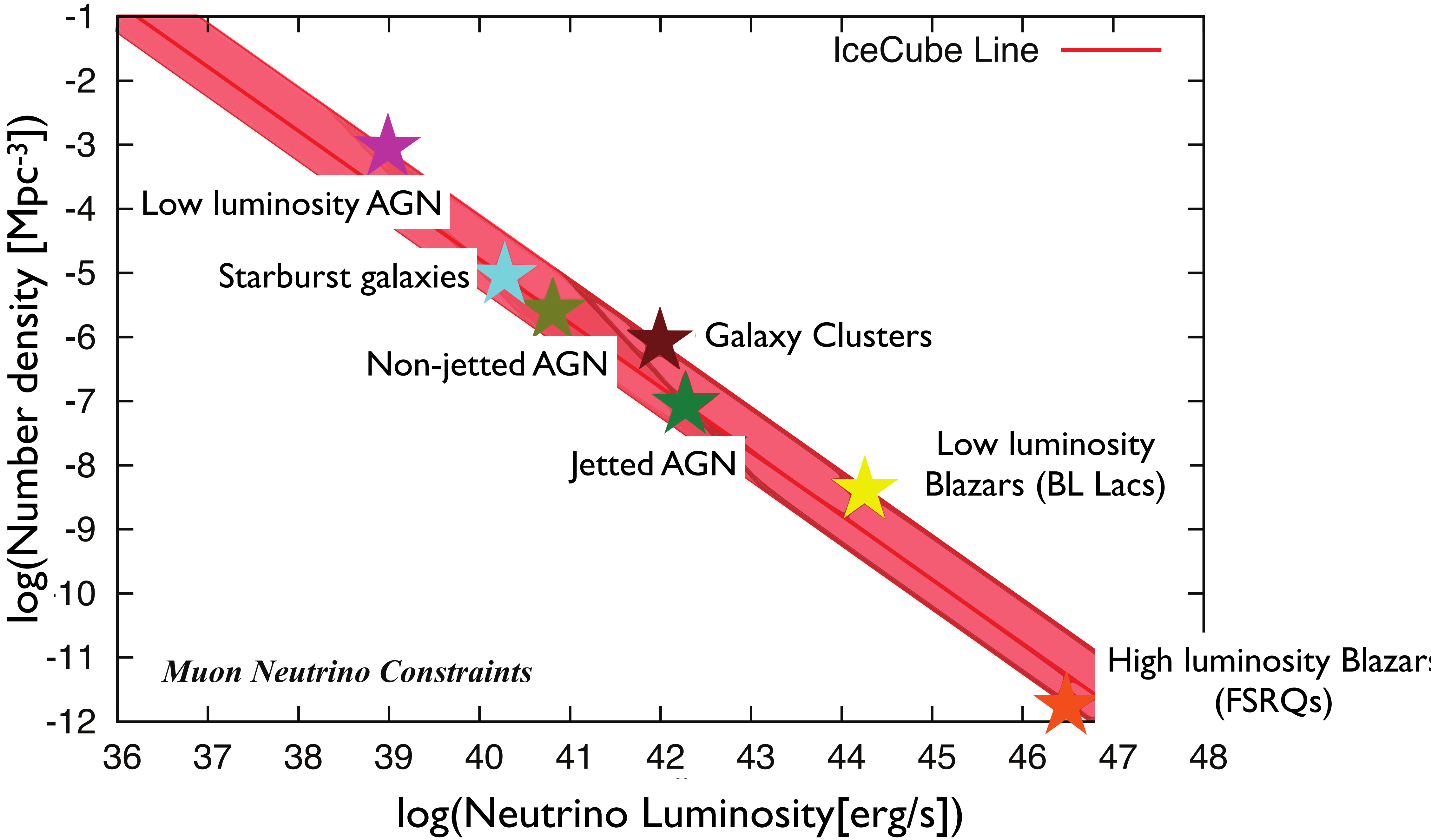
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

see also Lipari PRD78(2008)083011
Ahlers & Halzen PRD90(2014)043005
Kowalski 2014,
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan et al 2019,
Capel, Mortlock, Finley 2020

Murase & Waxman 16, PRD 94 (2016) 103006



* clustering limits are sensitive up to ~100 TeV

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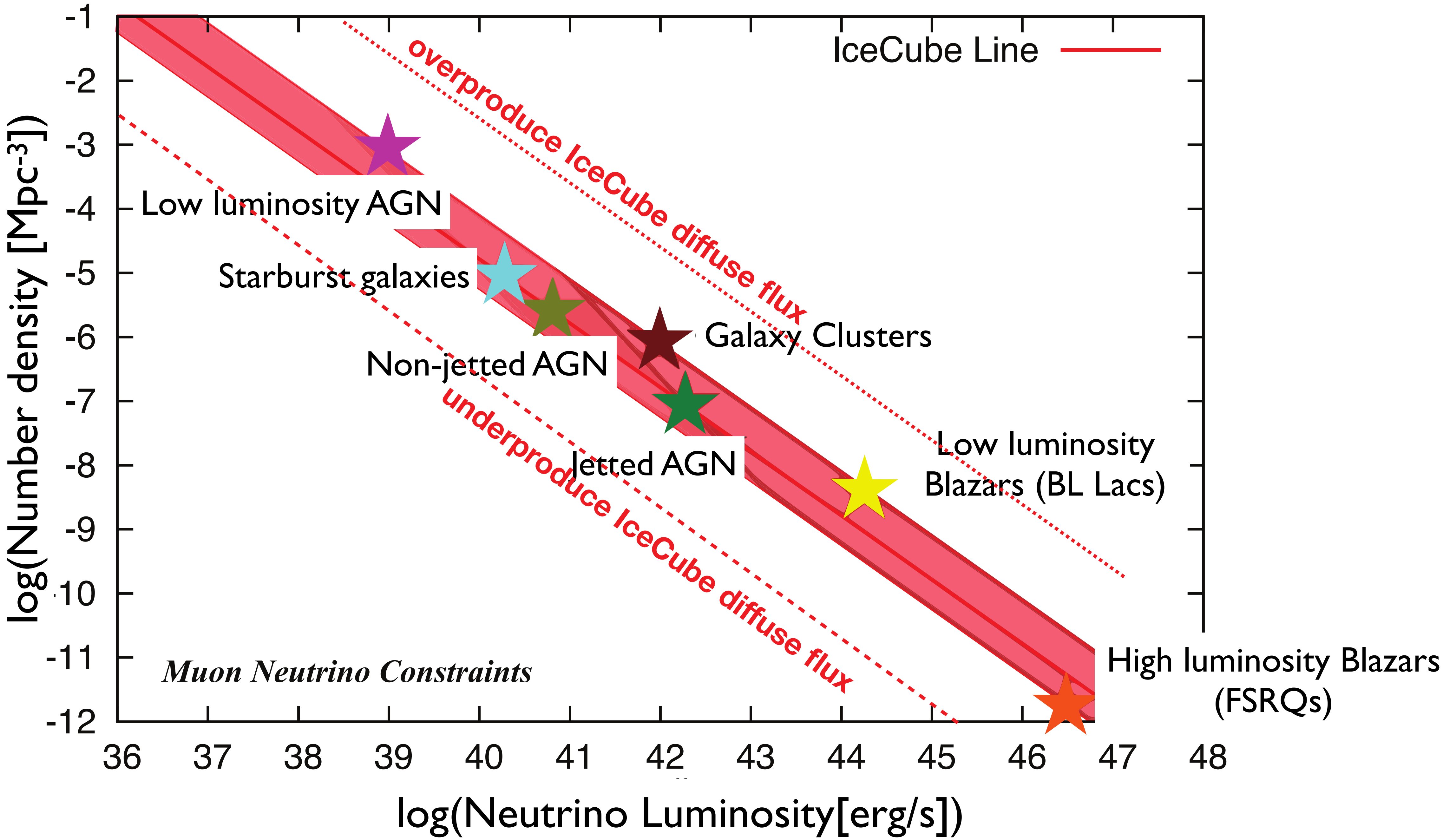

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Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

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Ahlers & Halzen PRD90(2014)043005
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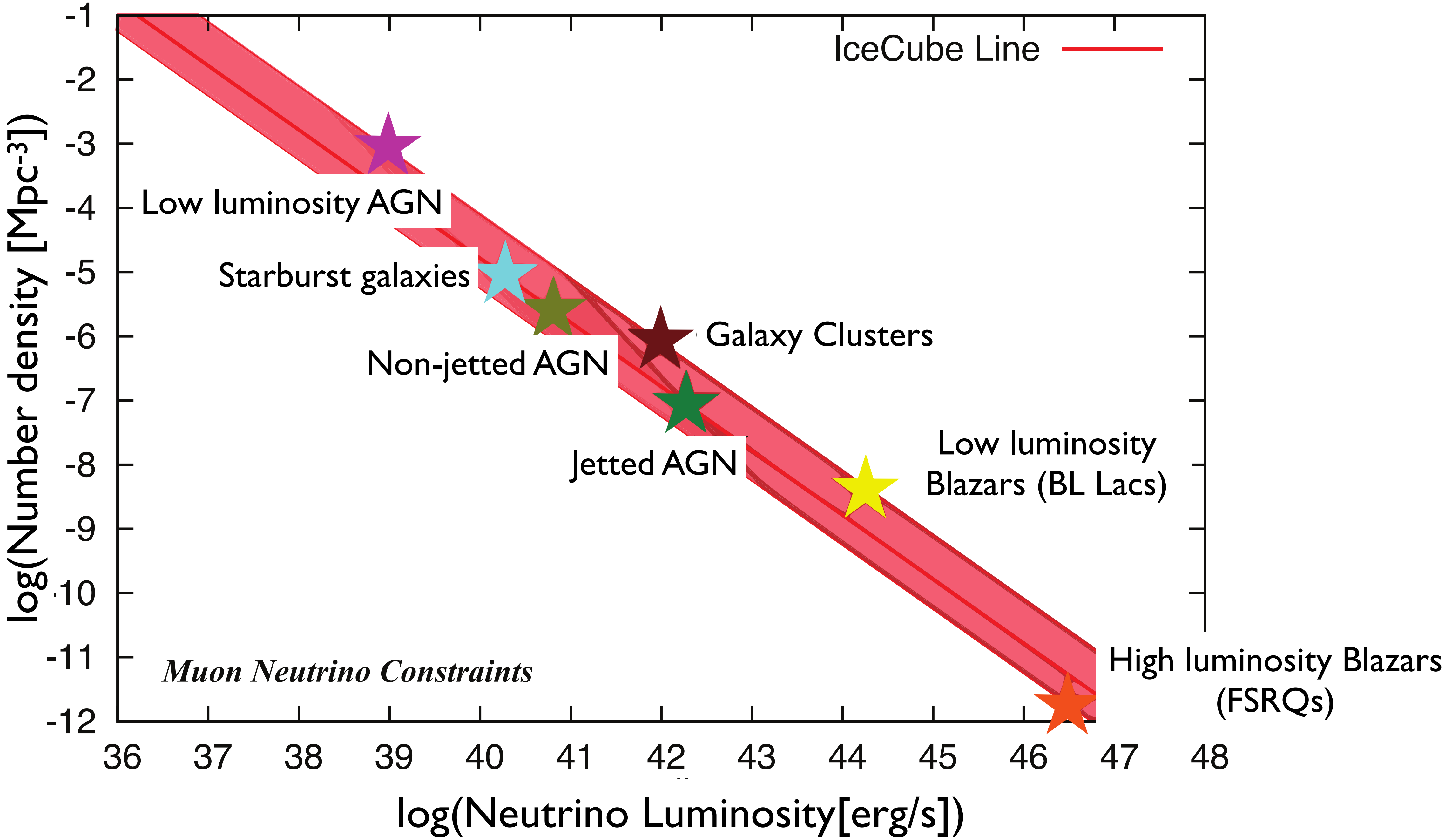
Capel, Mortlock, Finley 2020

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

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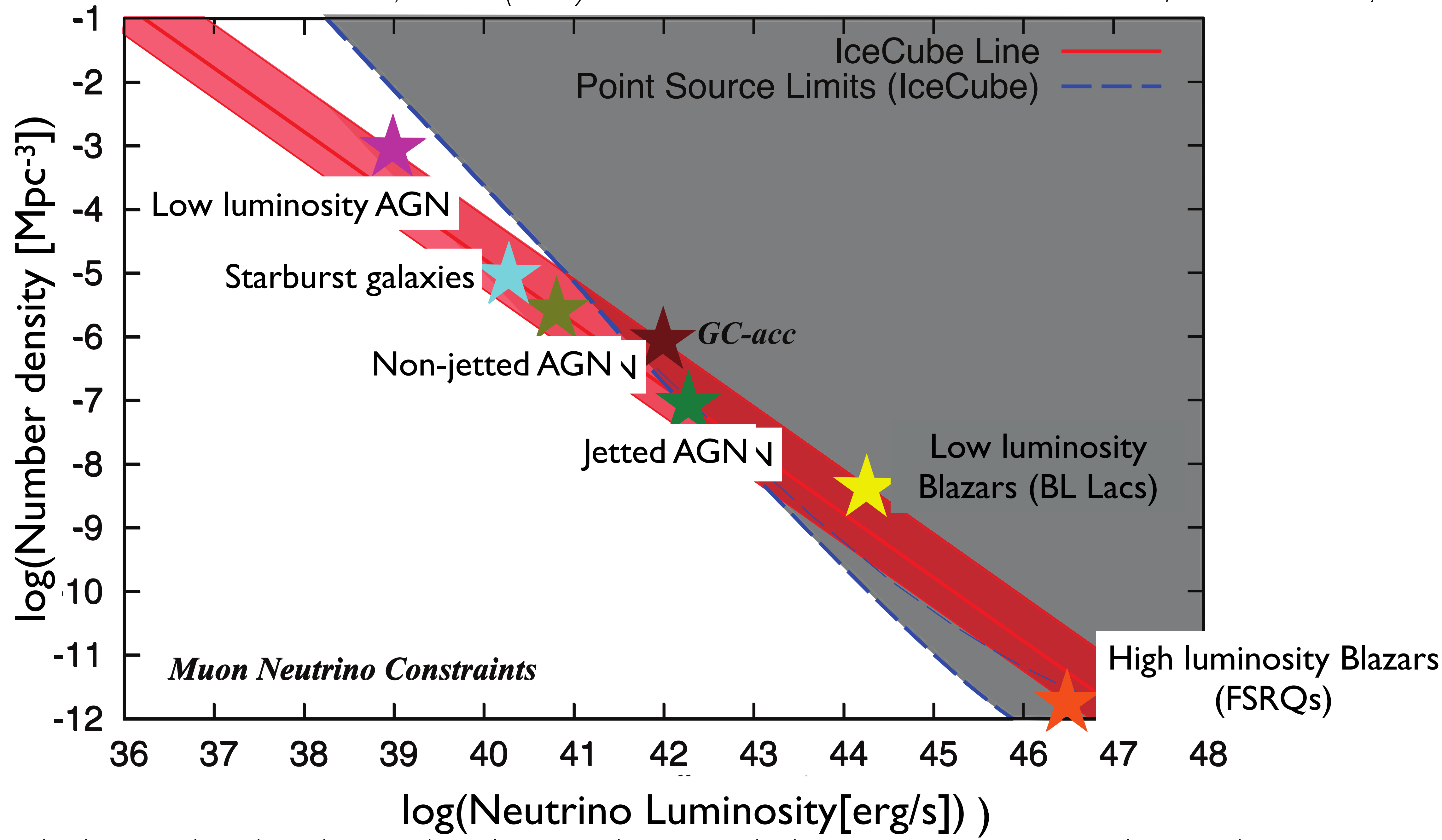

Absence of multiplets implies that the number density is low enough that no source exists at distance low enough to produce a multiplet

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

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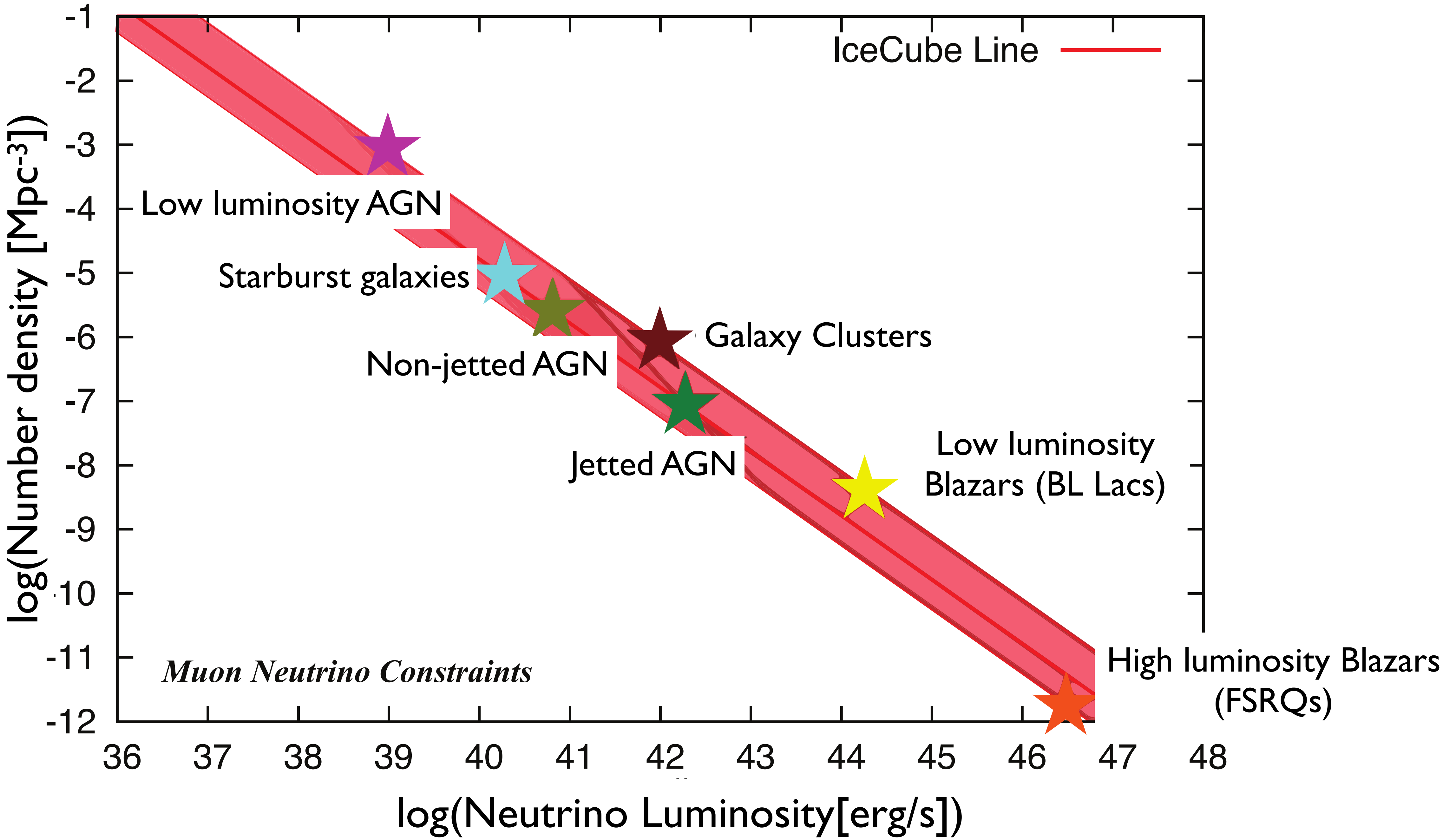

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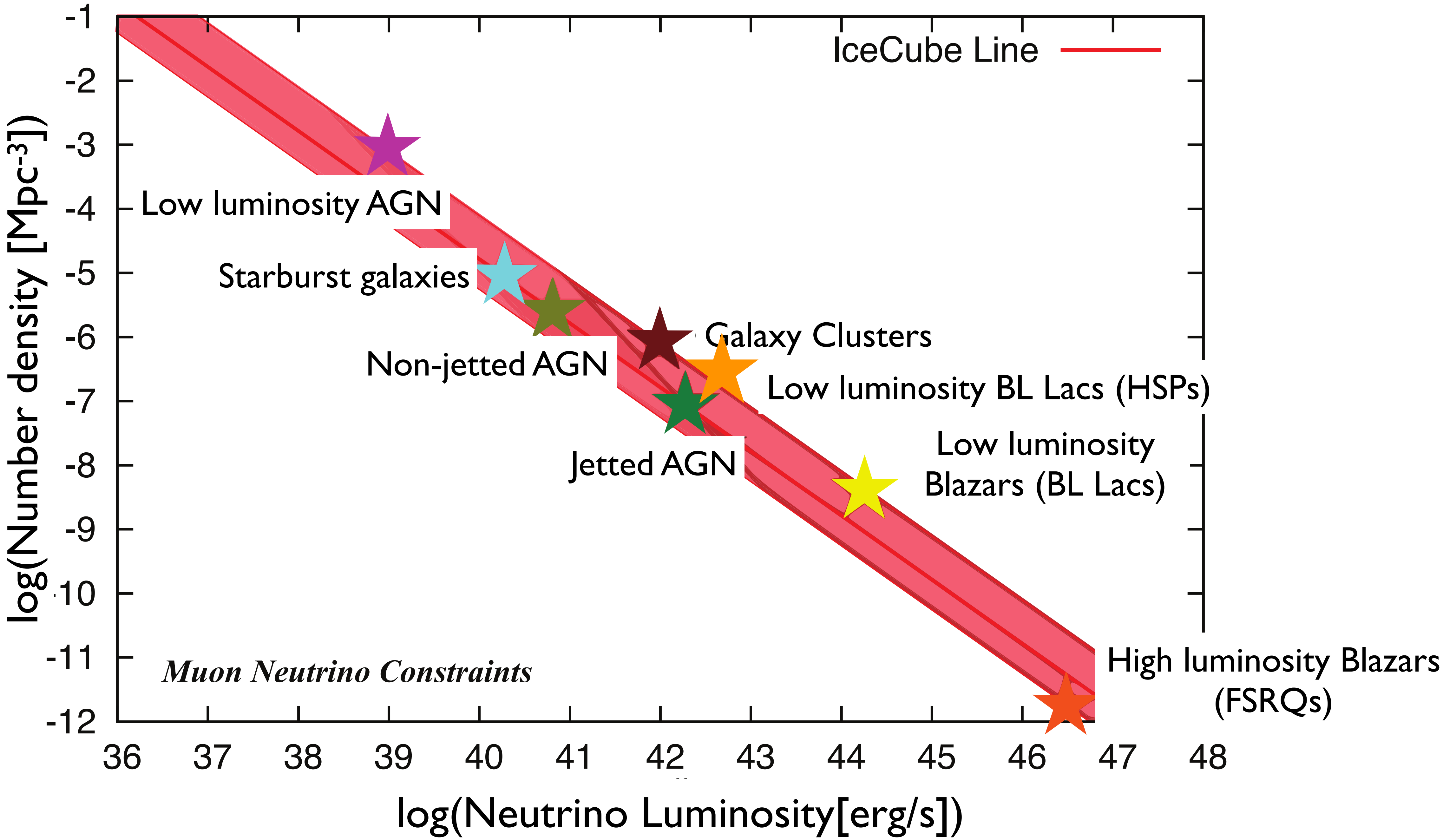

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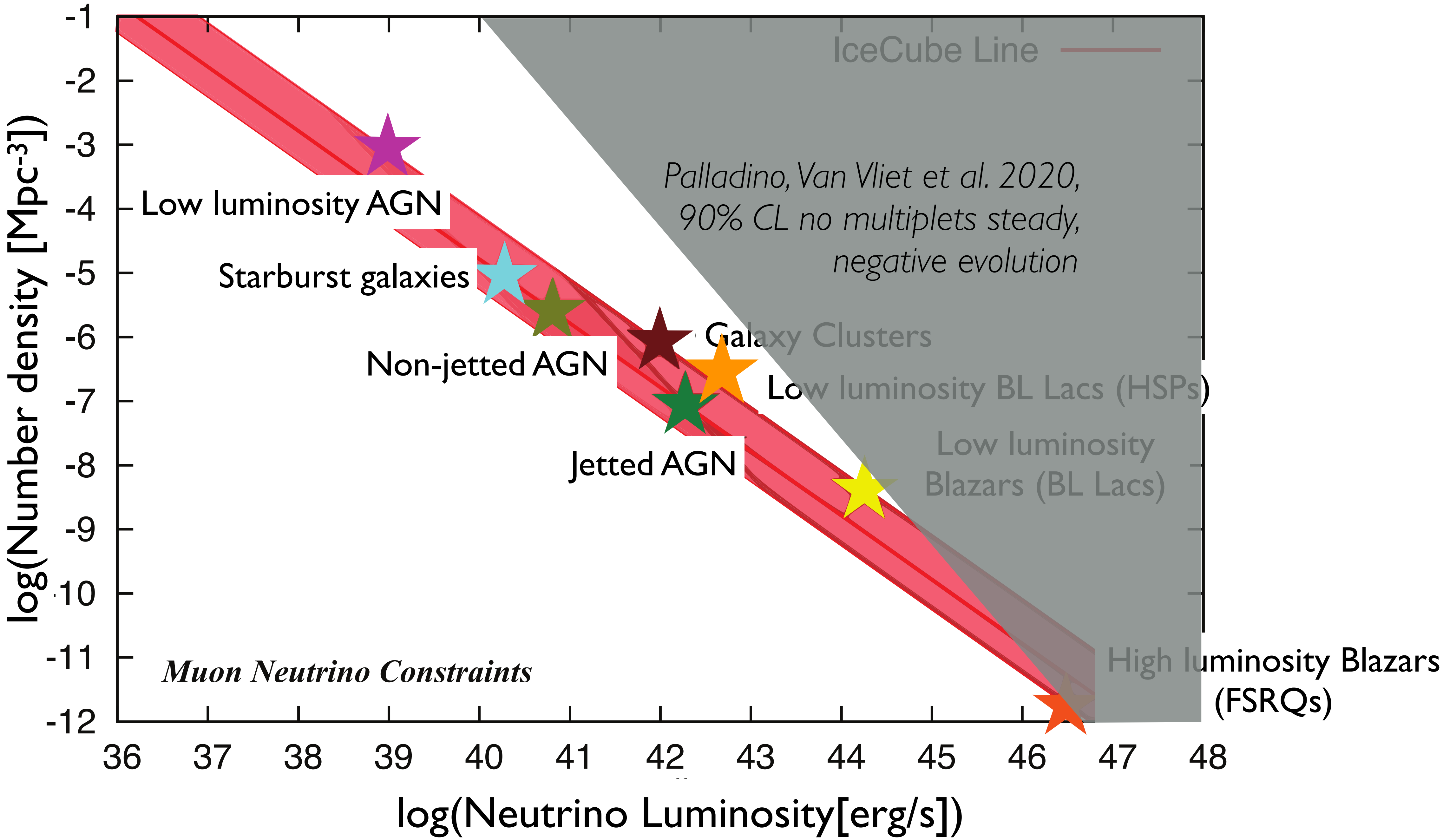

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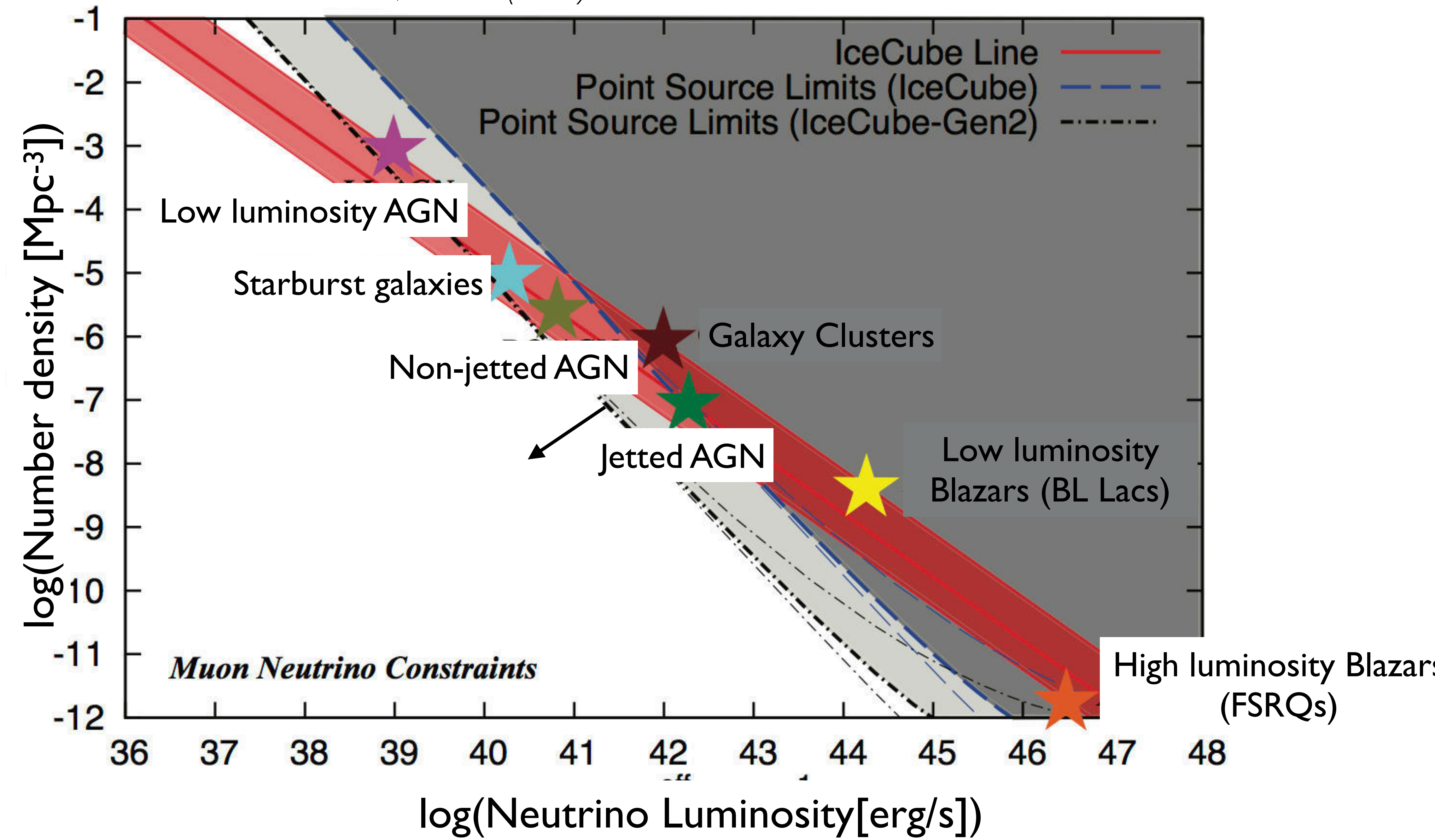

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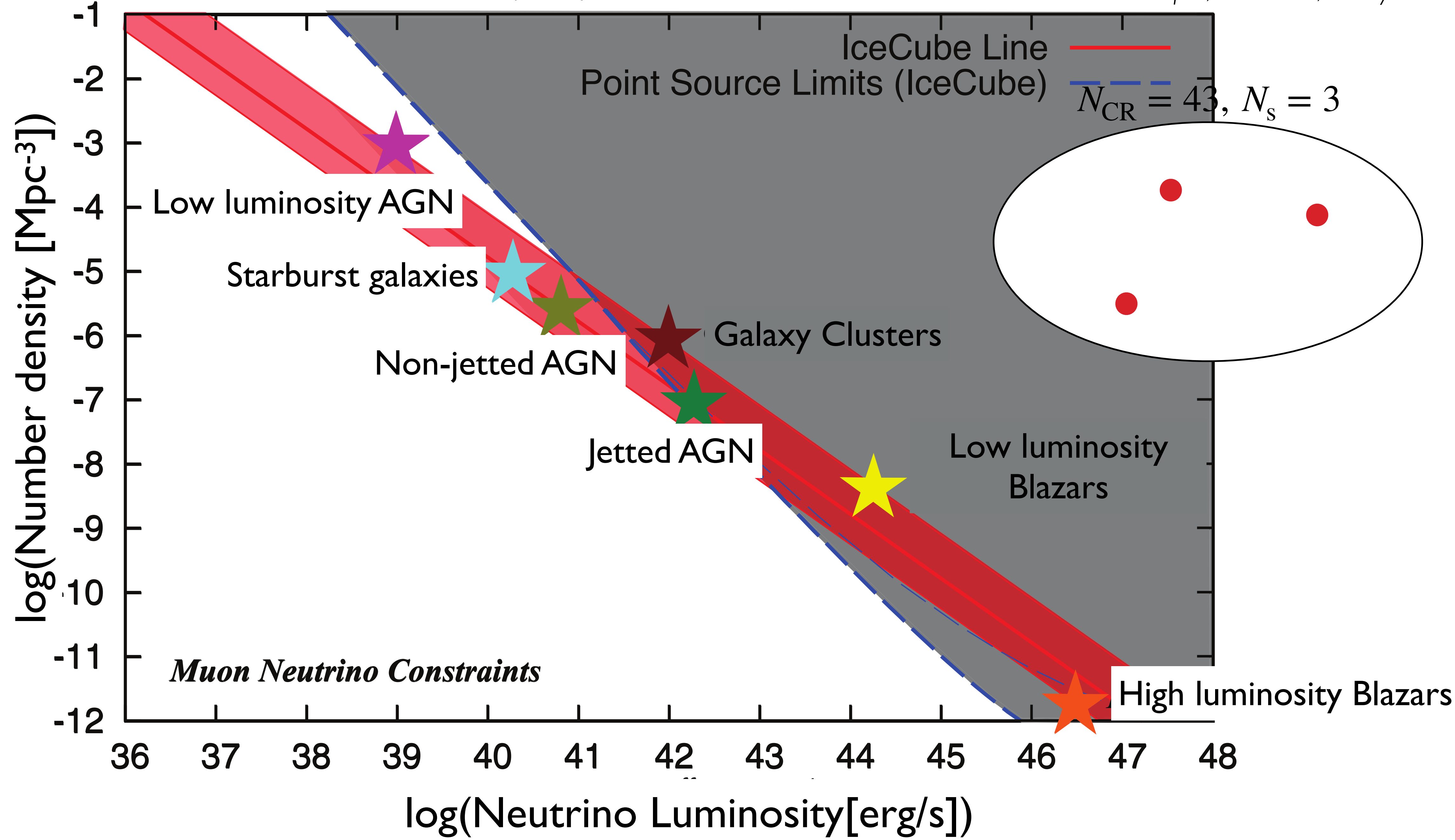

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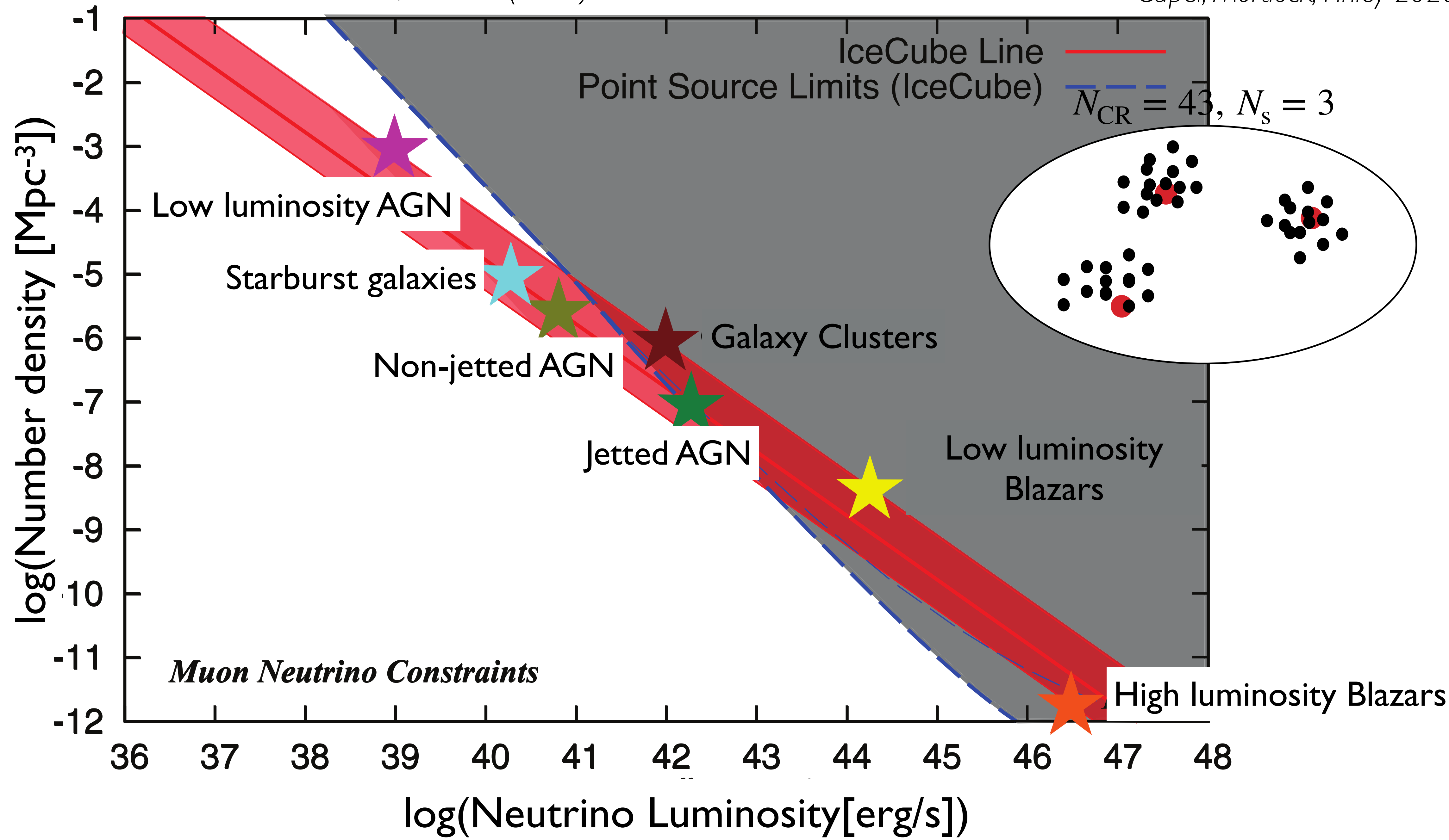

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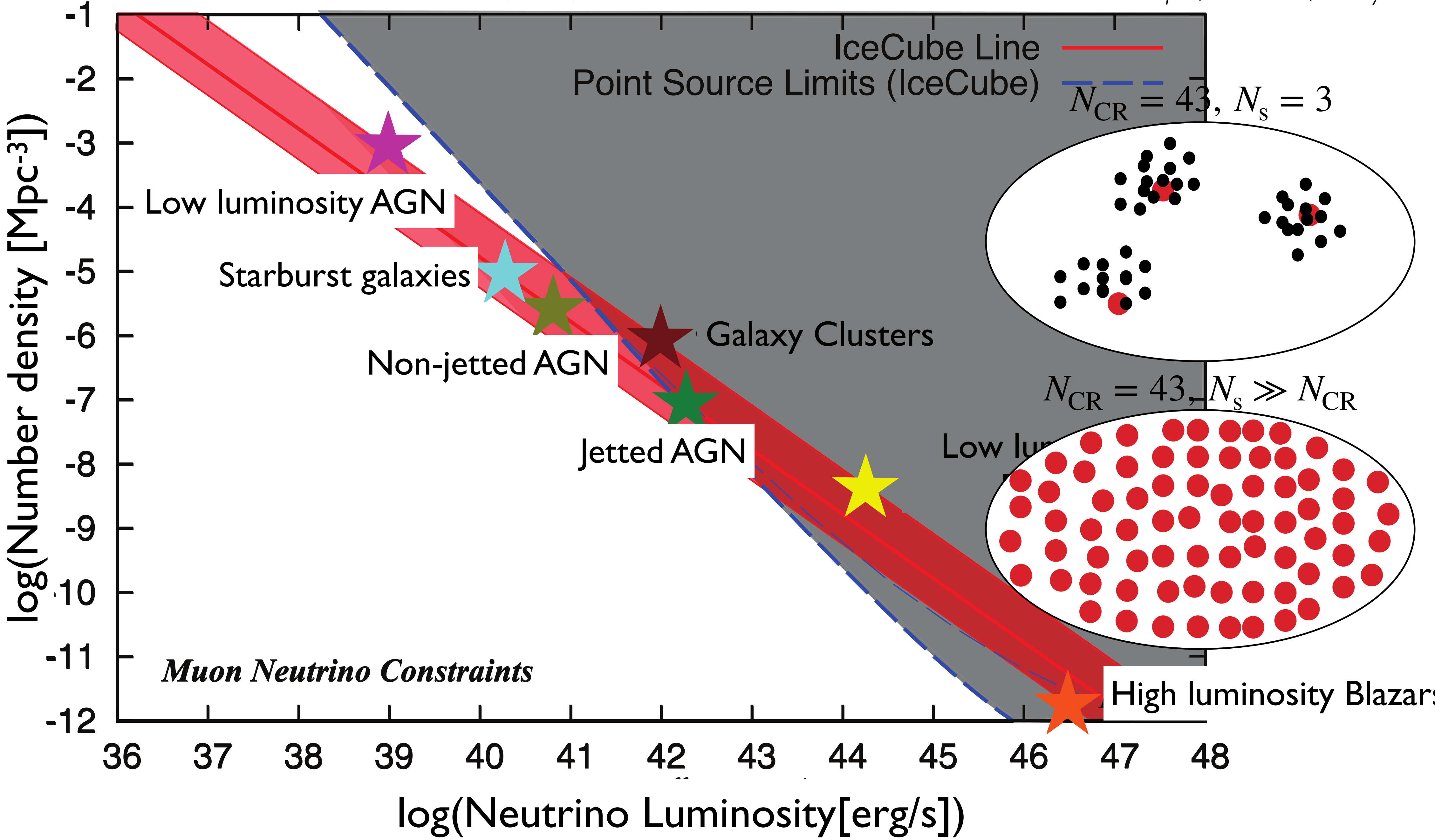

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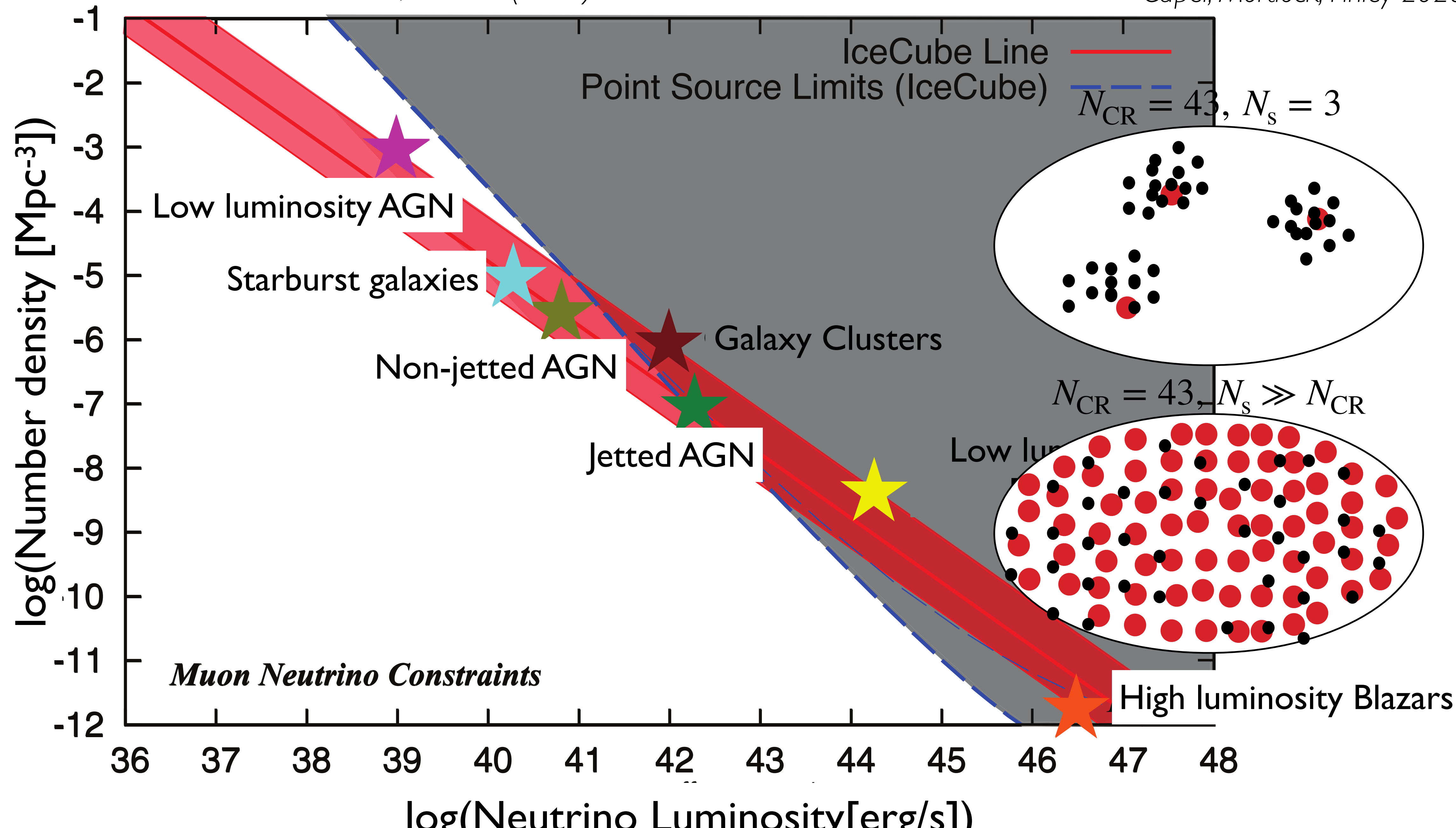

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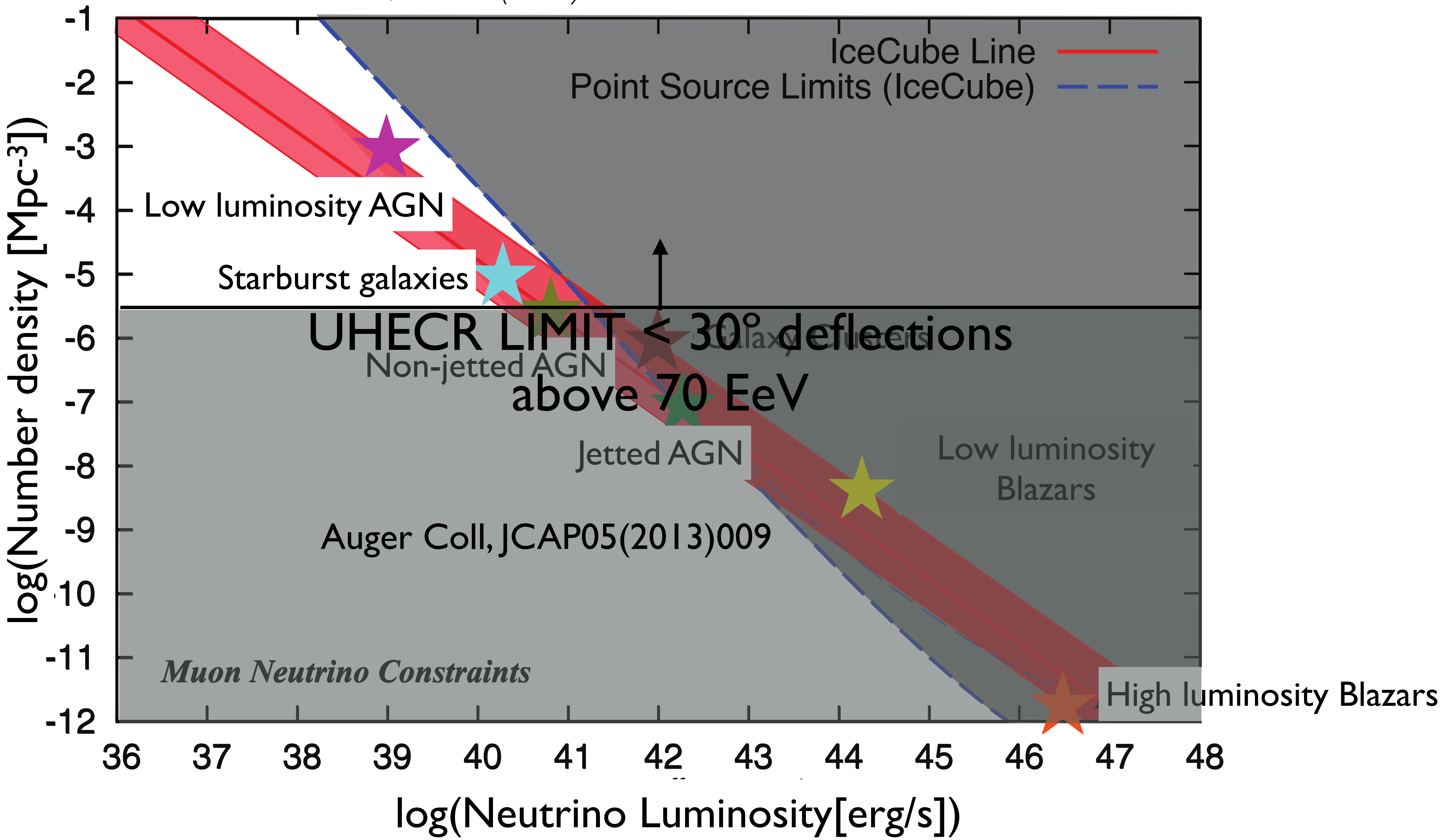
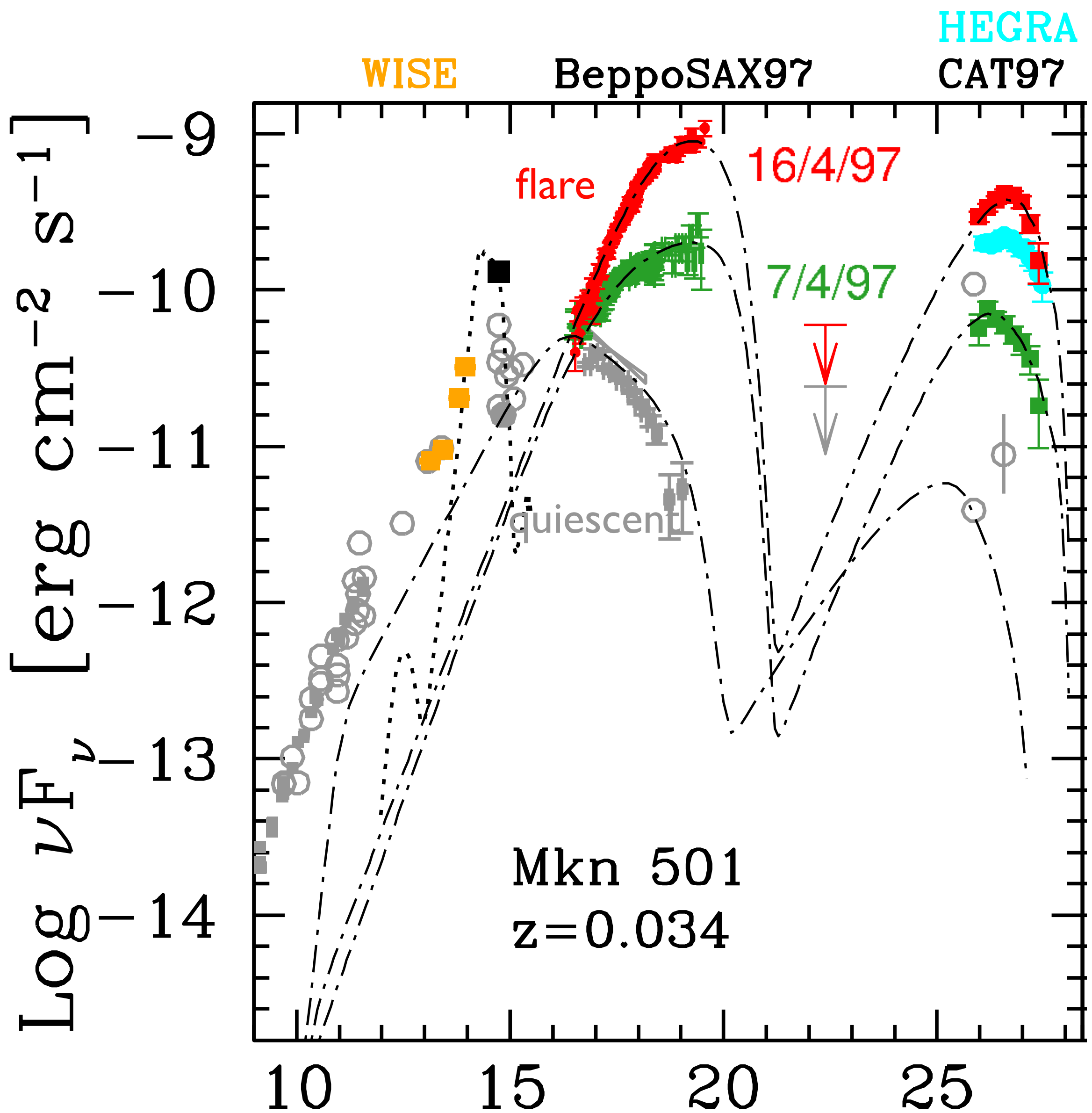


For joint UHECR-neutrino analyses see also ANTARES, IceCube, Auger, Telescope Array 2019 PoS(ICRC2019)1177, Resconi et al. MNRAS 468,1 2017

Blazar flares: Interesting as neutrino point sources



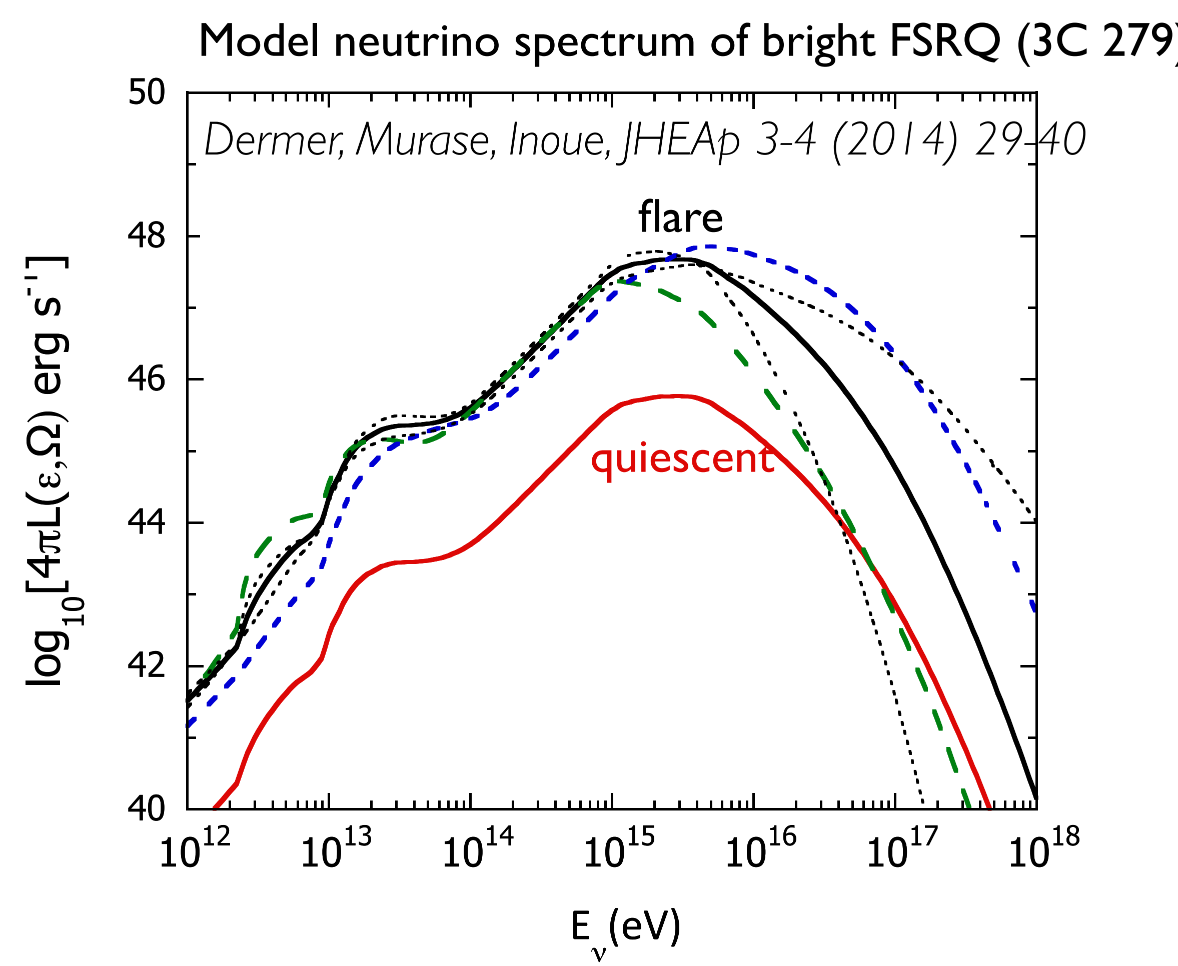
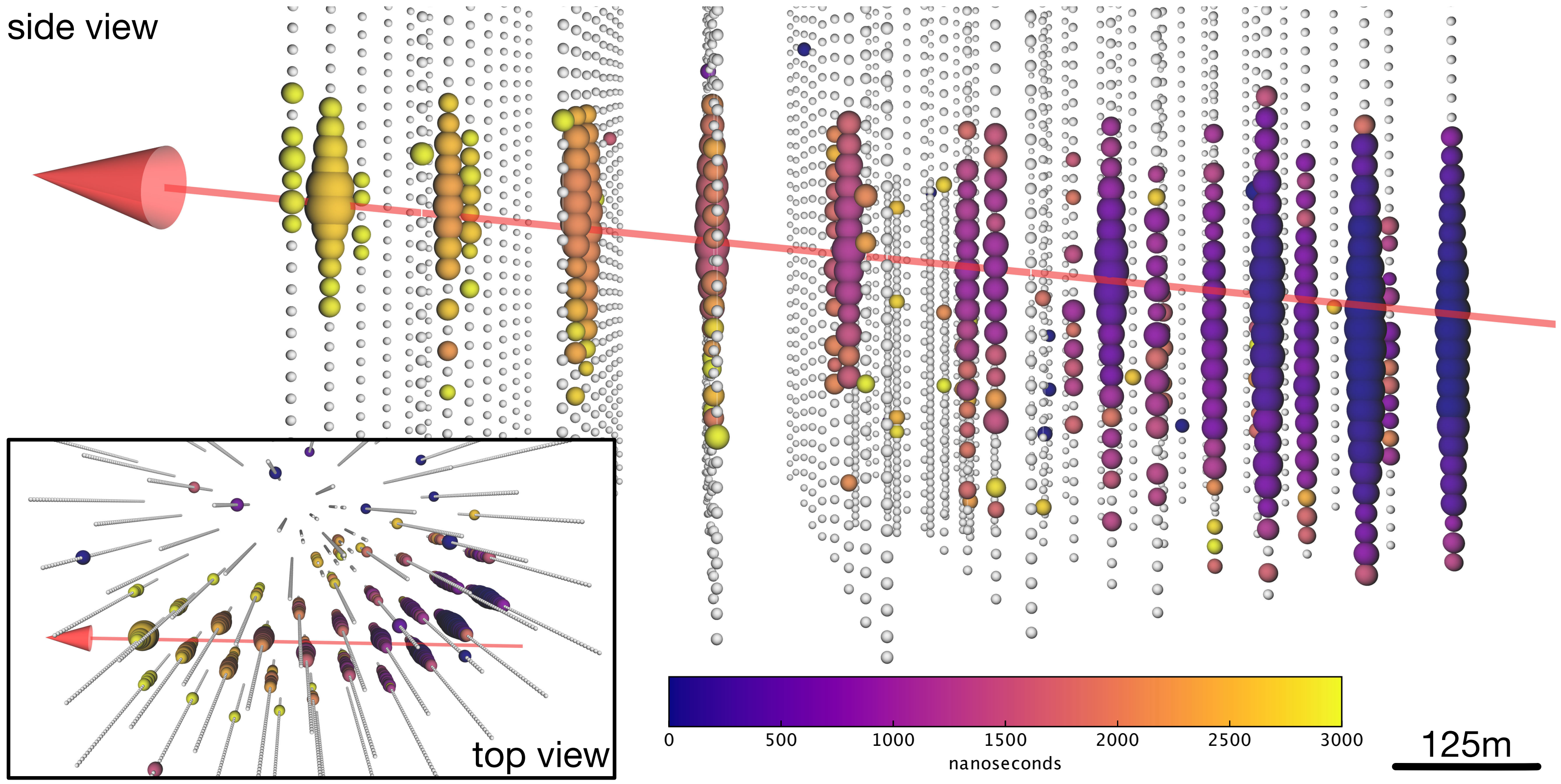


Image from Biteau, Prandini, Costamante+ Nat. Astr 4, 124–131(2020)

TXS 0506+056 IC170922A

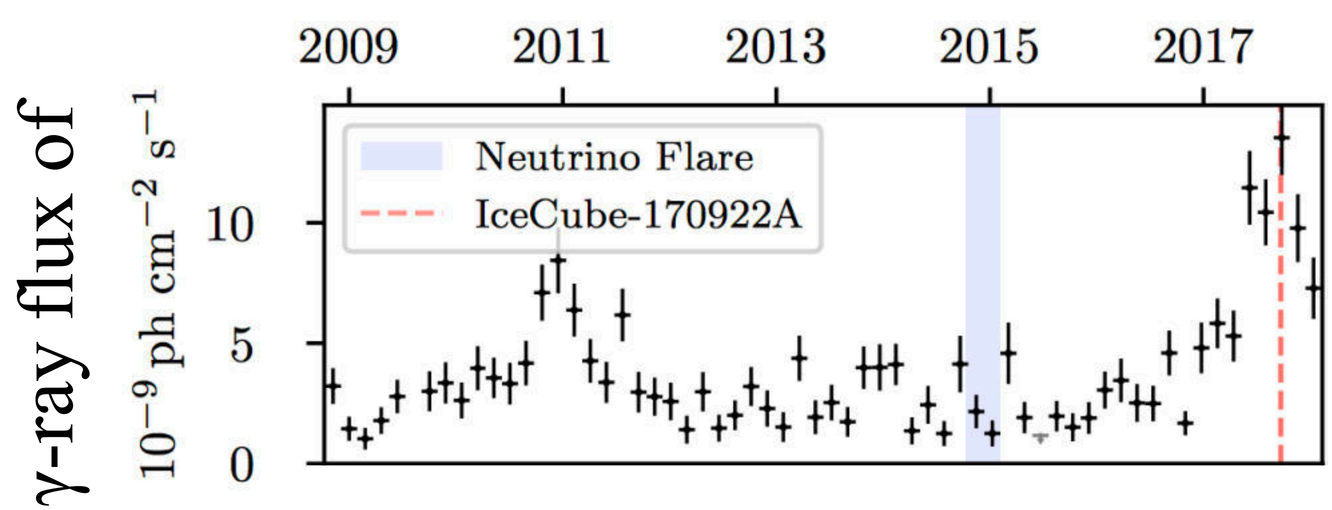
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. Science 361, 2018, MAGIC Coll. Astrophys.J. 863 (2018) L10



Background fluctuation?
Chance probability ~0.3%

IceCube archival search: 13±5 more neutrinos found in 2014-15

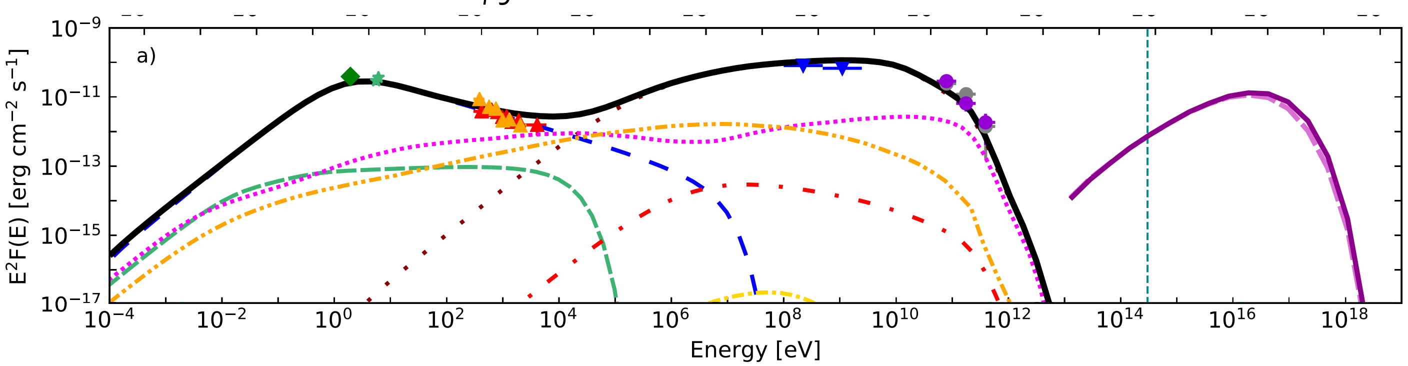
Background fluctuation? Chance probability 0.05%

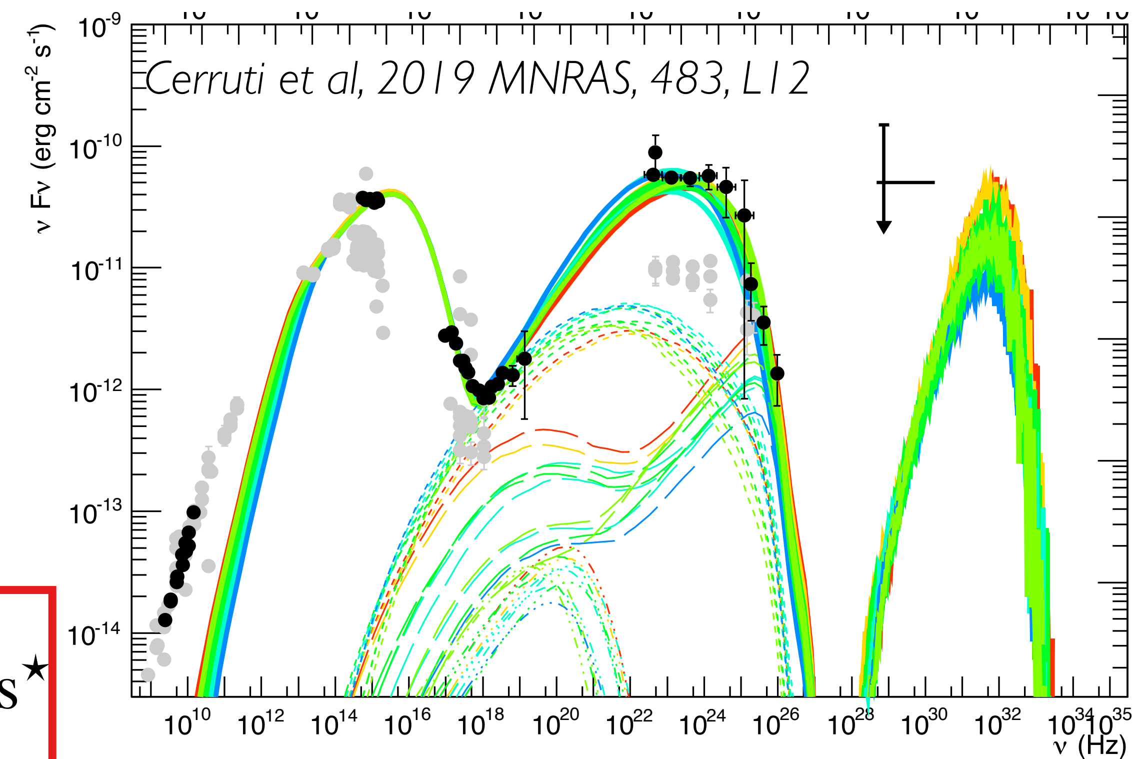


Padovani, Giommi, Resconi, Glauch, Arsioli, Sahakyan, Huber, MNRAS. 480 (2018) 1

Neutrino production in TXS 0506+056 in 2017

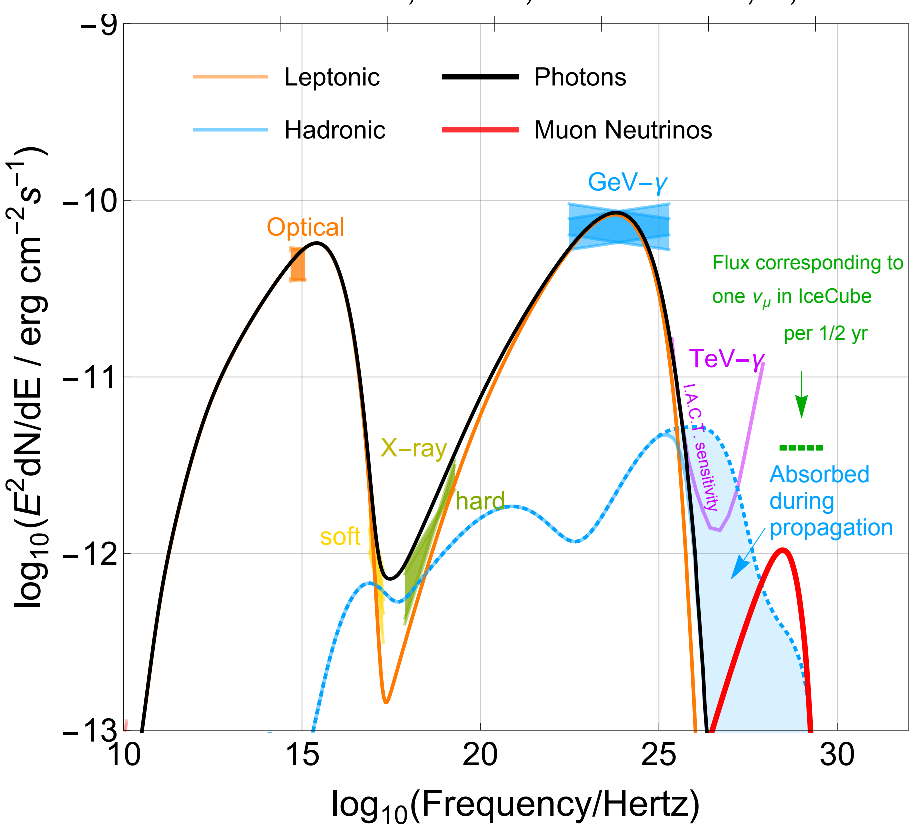
MAGIC Coll 2018, ApJ, 863, L10





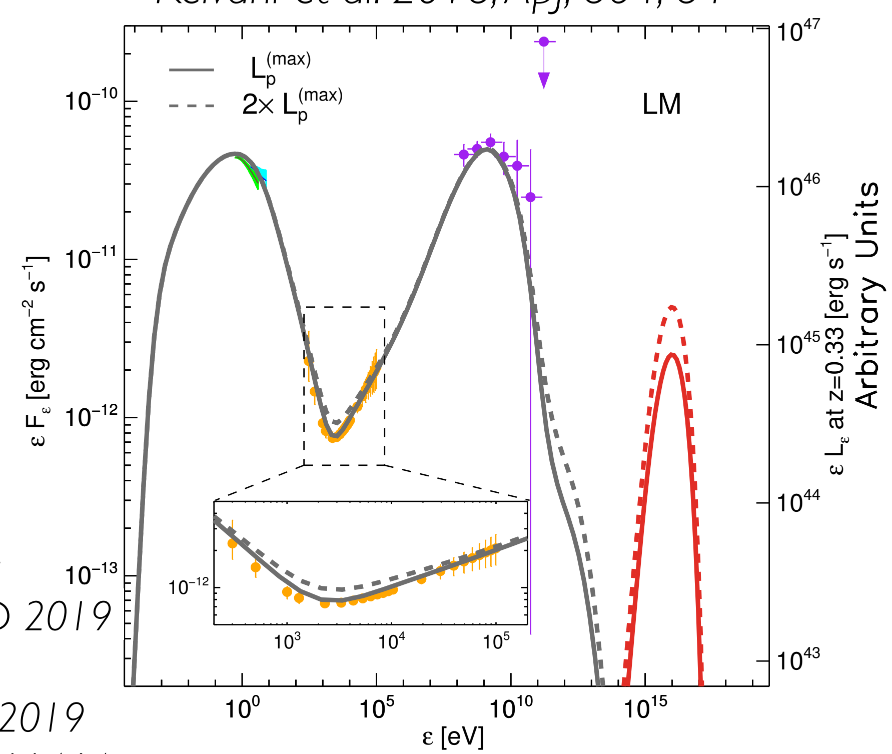
Cerruti et al, 2019 MNRAS, 483, L12

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

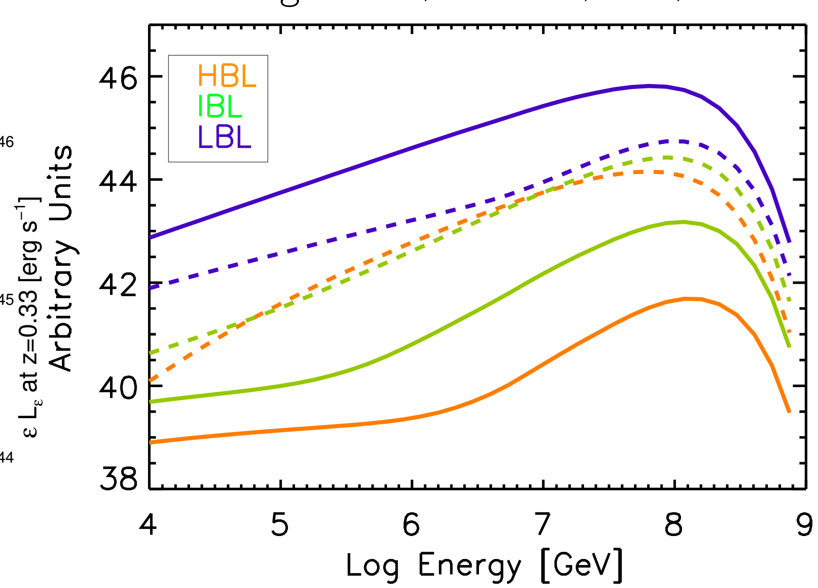


$N_{\nu_\mu} \lesssim 0.01/6$ months*

Keivani et al. 2018, ApJ, 864, 84



Righi et al, MNRAS, 483, L127

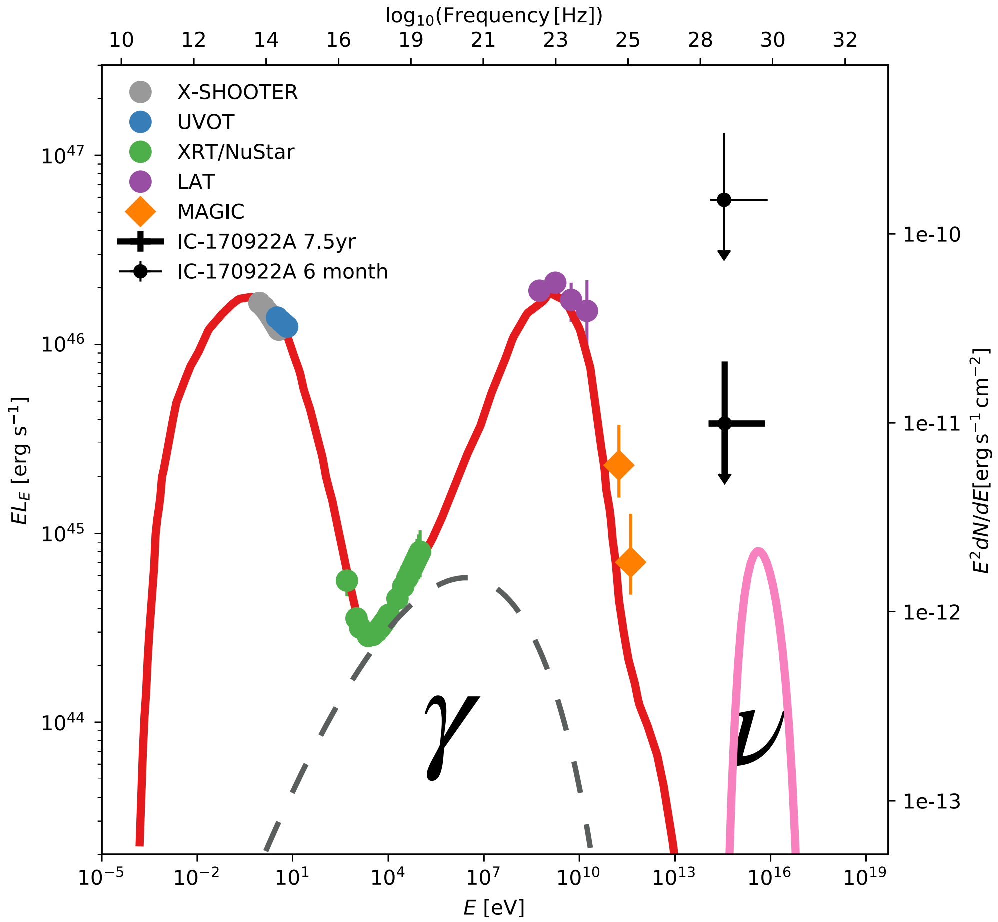


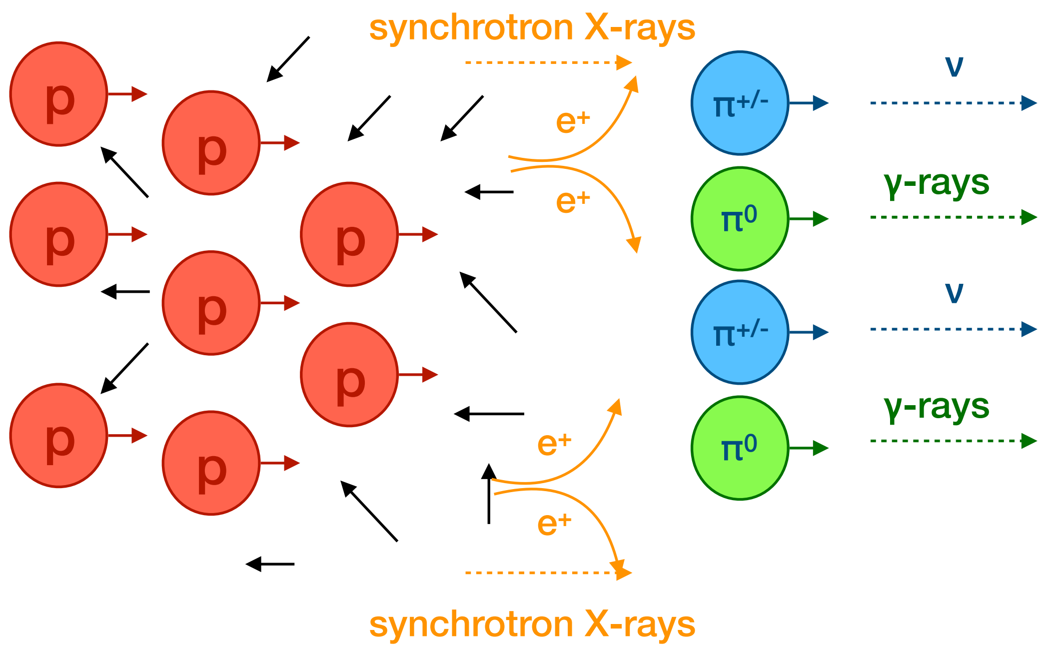
Other more exotic options find increased neutrino flux:
hadro-nuclear interactions: *Liu, Wang, Xue, Taylor et al, PRD 2019*
stellar disruption: *Wang, Liu et al, arXiv:1809.00601*
multiple zones: *Xue, Liu, Petropoulou, Oikonomou et al. ApJ 2019*
neutron beam: *Zhang, Petropoulou, Murase, FO, arXiv:1910.11464*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

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

Neutrino production in TXS 0506+056 in 2017

$p_{\mathrm{PeV}} + \gamma \rightarrow p + e^{+} + e^{-} \rightarrow$ cascade that peaks in keV band





3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

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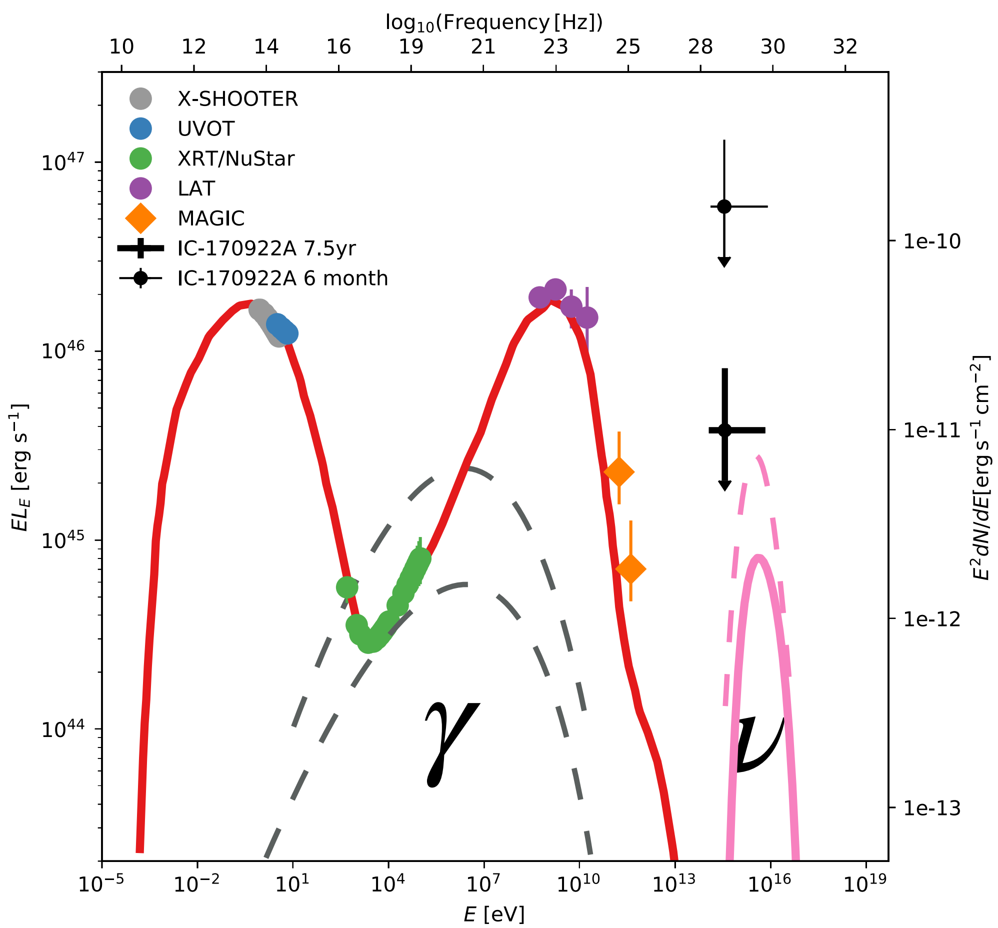

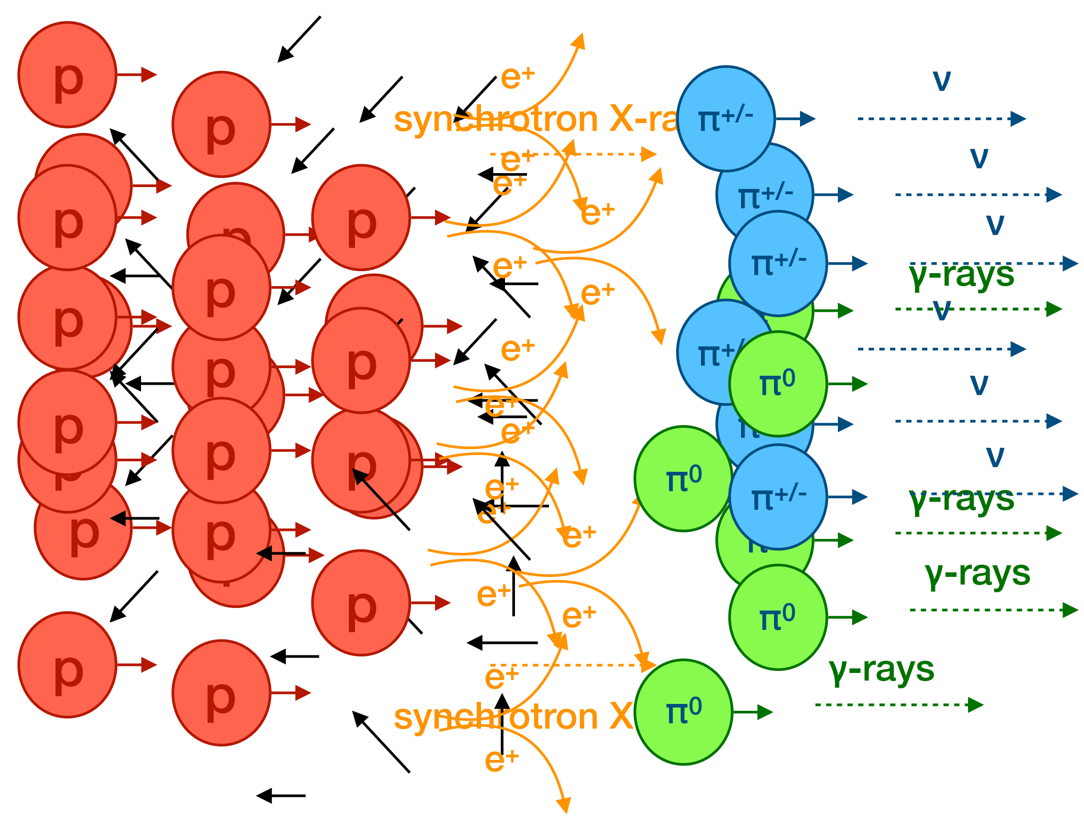

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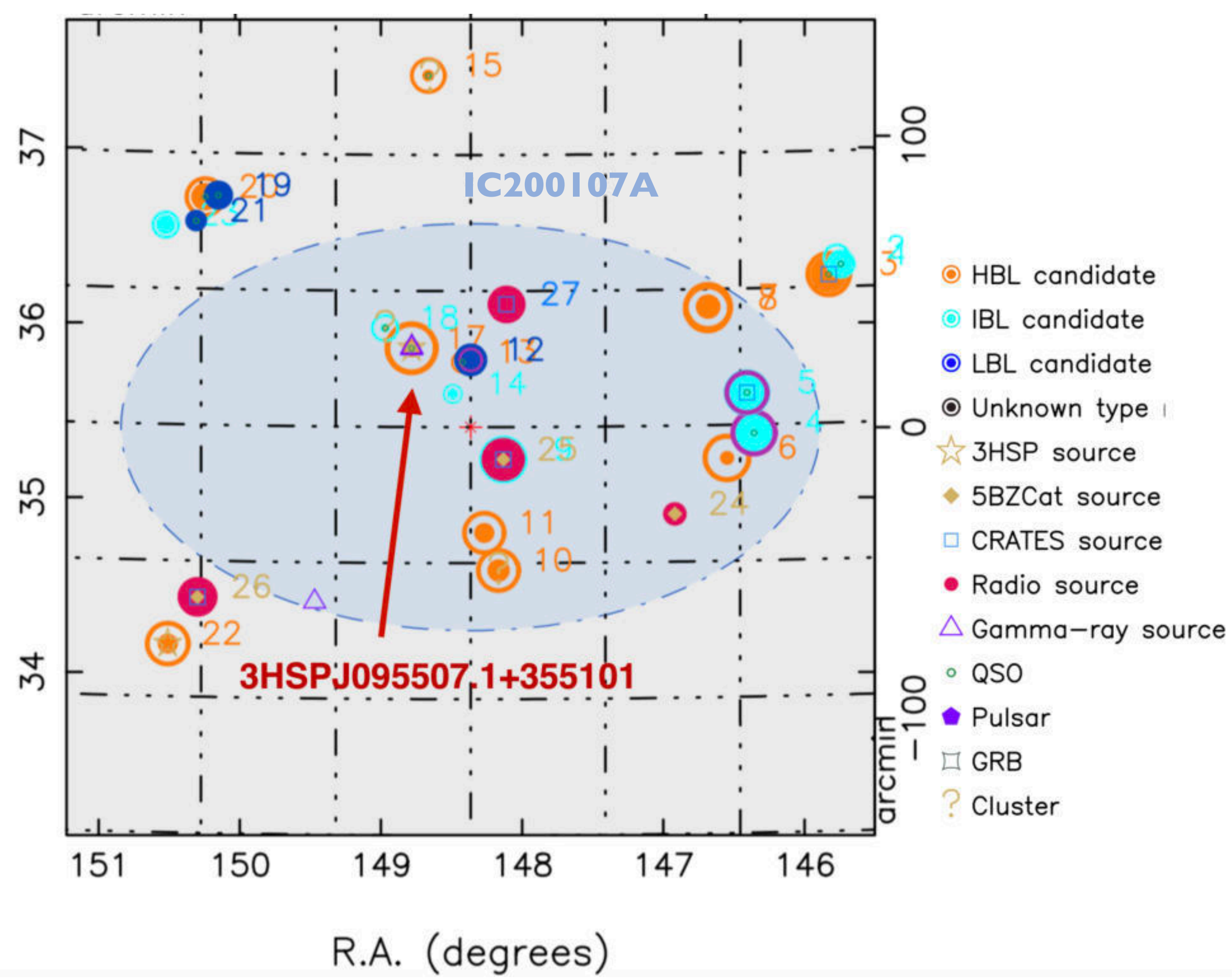
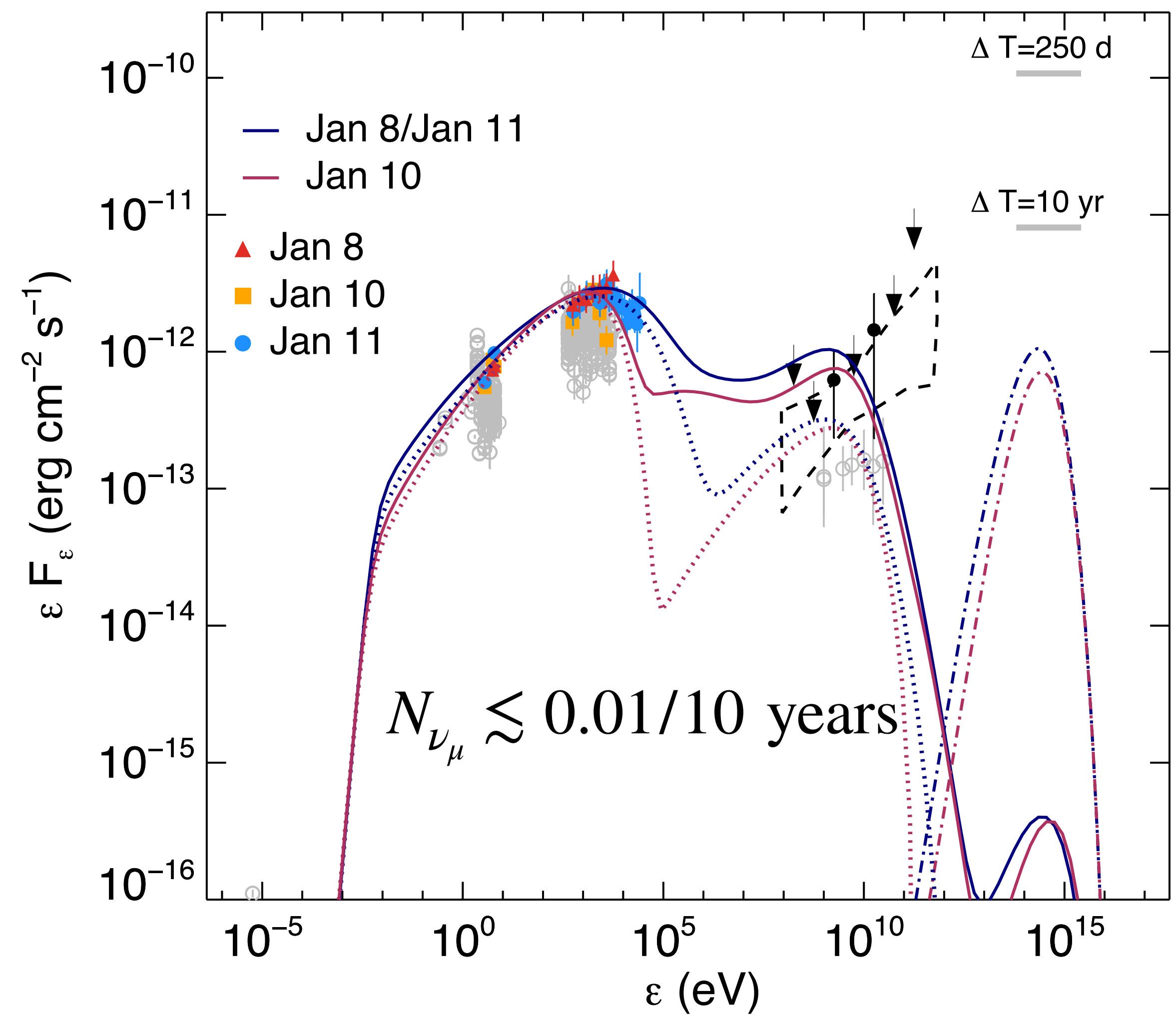
3HSP J095507.9+355101 - IC 200107A

Giommi, Padovani, FO, Glauch, Paiano, Resconi, A&A Letters (arXiv:2003.06405)
[see also Paliya, Böttcher+20 arXiv:2003.06012]



Petropoulou, FO, Mastichiadis et al, to appear in ApJ, arXiv:2005.07218

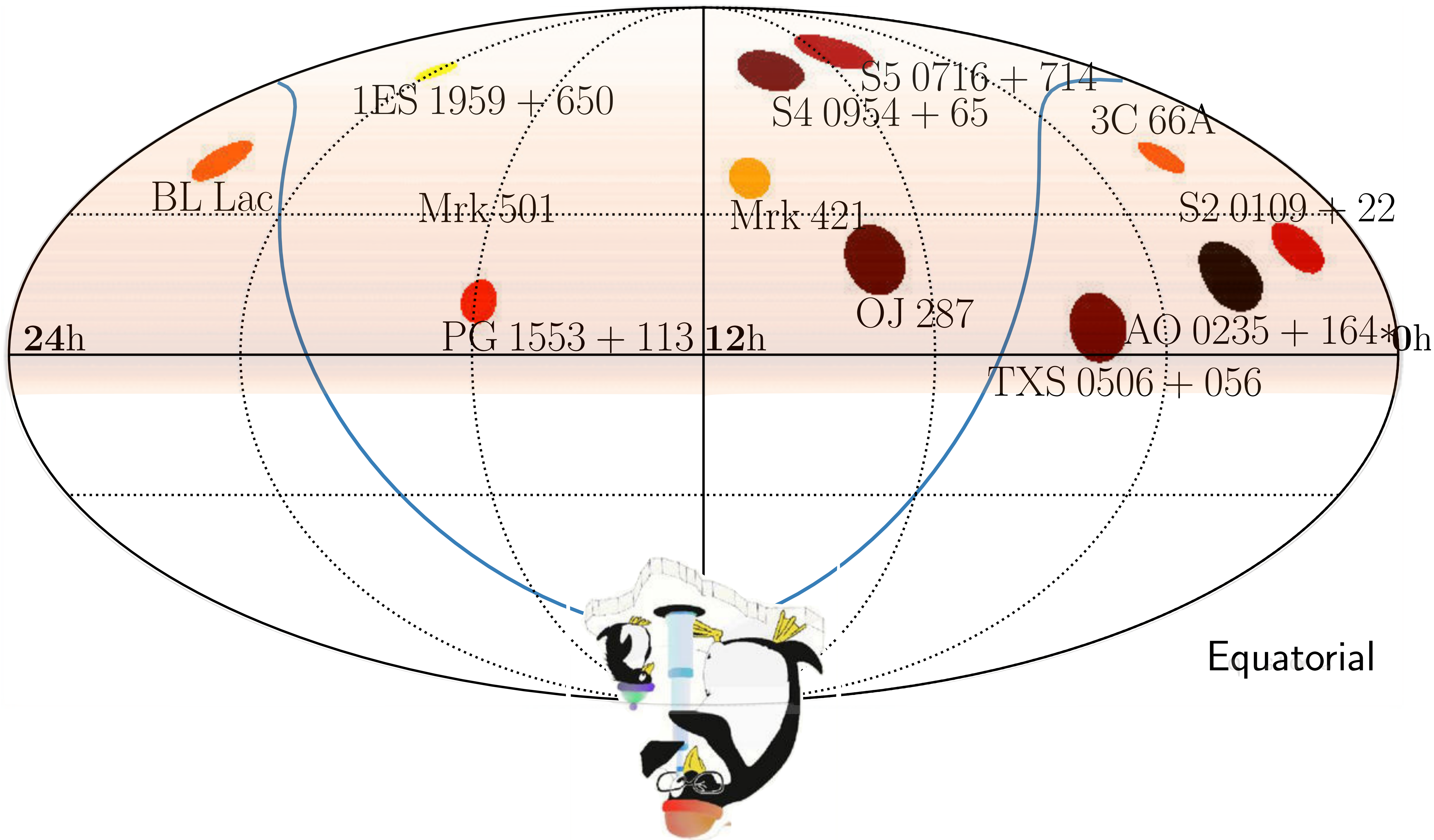


Extreme HSP with luminosity similar to TXS 0506+056 coincident with 0.33+2.23-0.27 PeV track
Redshift = 0.57 *(Paiano et al, MNRASL 2020)*

See also Giommi, Glauch, Padovani, Resconi, Turcati, Chang MNRAS 2020 who find a 3.23σ excess of IceCube tracks in the direction of HSP/ISP blazars

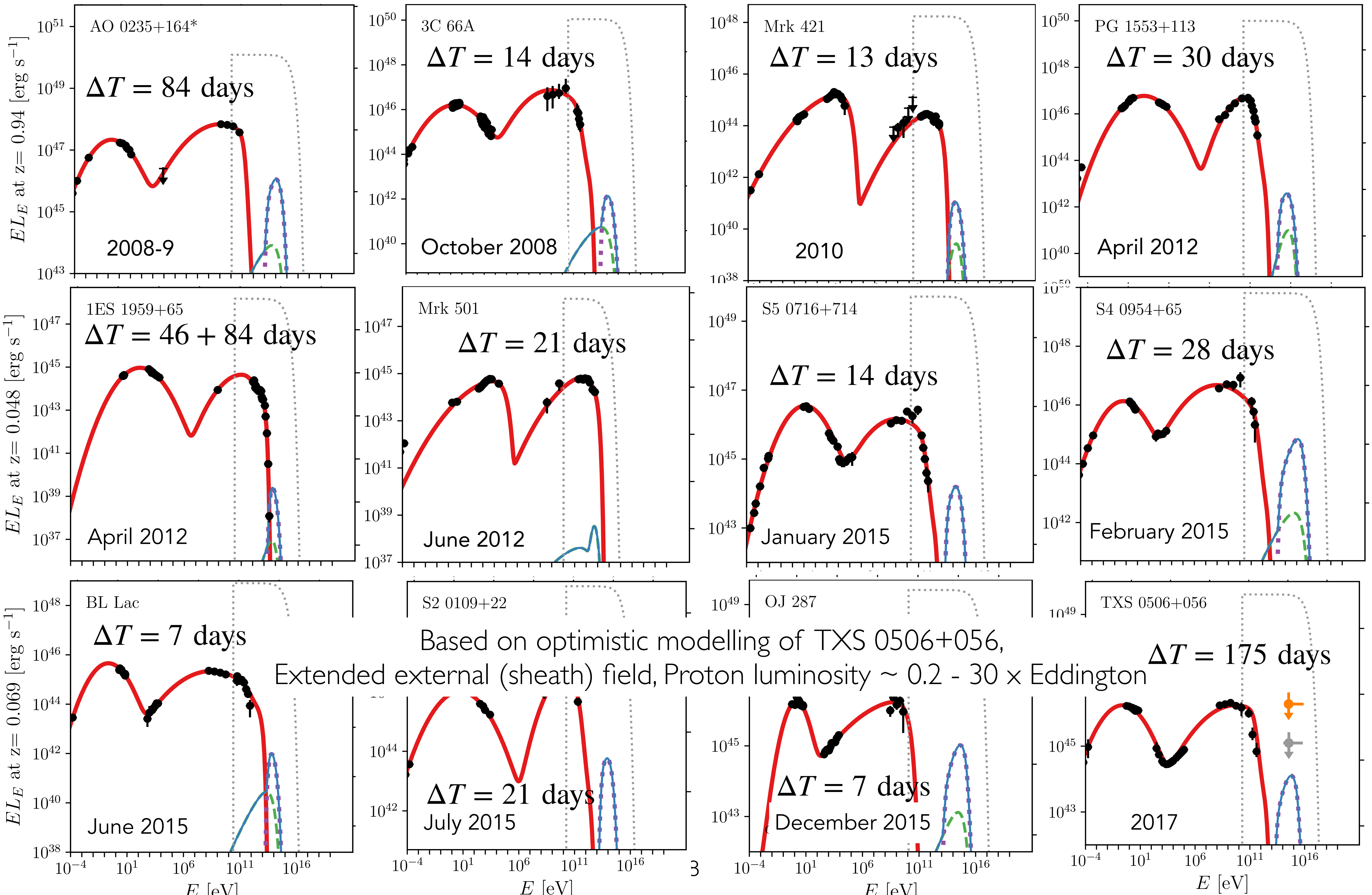
High-energy neutrinos from other blazar flares?

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



Optimistic scenario based on 2017 flare of TXS 0506+056

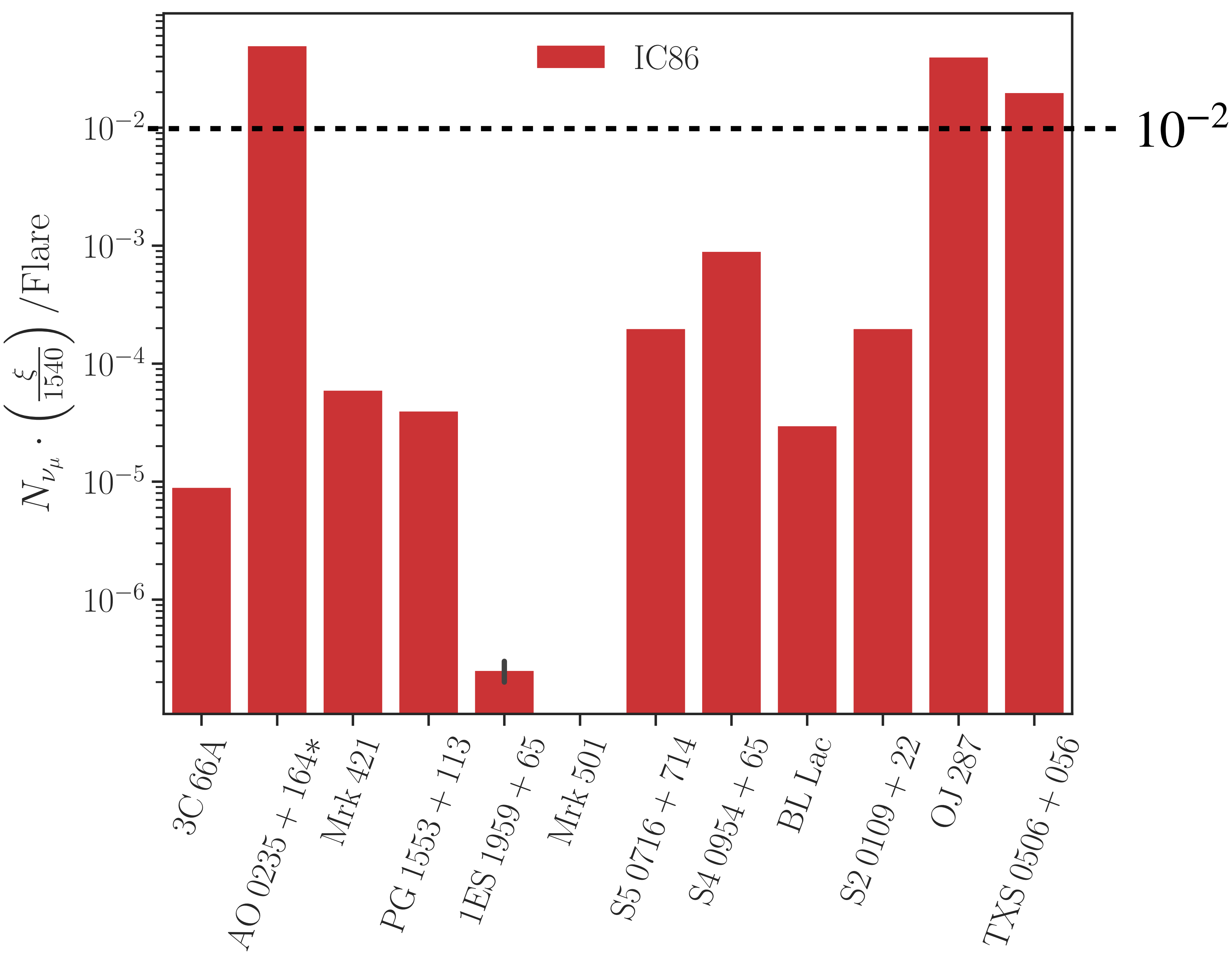
FO, Murase, Padovani, Resconi, Mészáros, MNRAS, 23, 2019



Based on optimistic modelling of TXS 0506+056,

Extended external (sheath) field, Proton luminosity ~ 0.2 - 30 × Eddington

Expected neutrino signal in optimistic case



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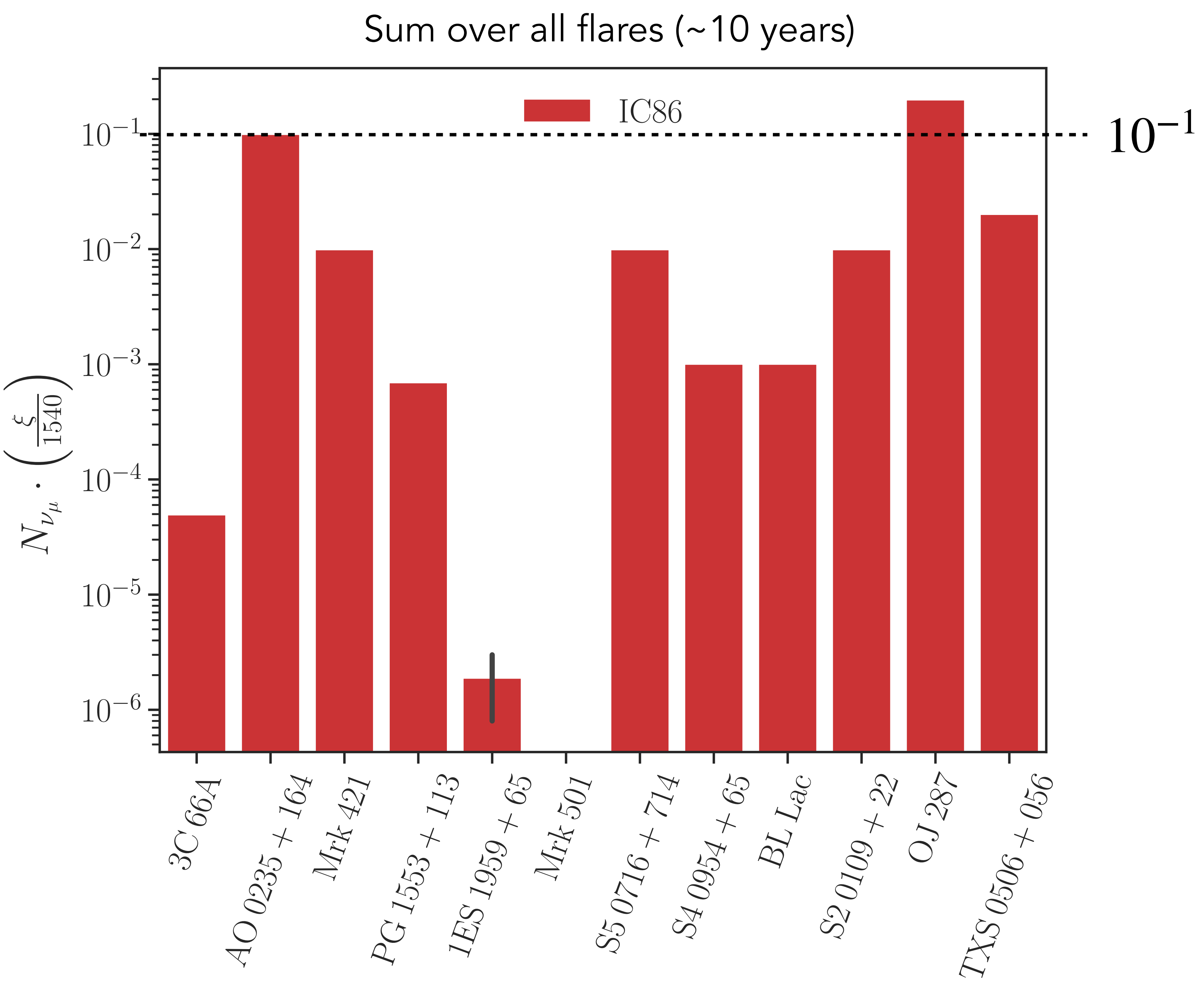
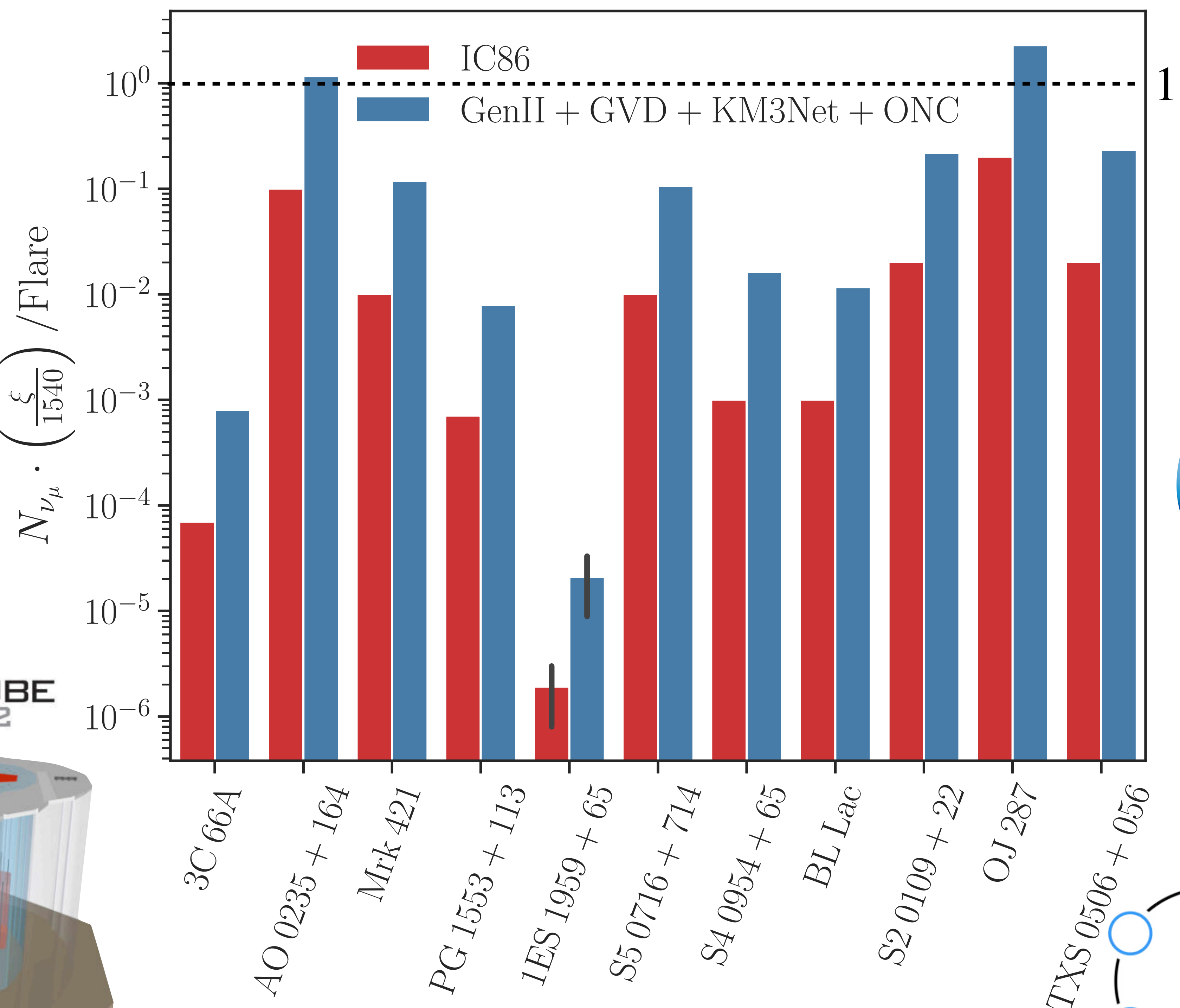
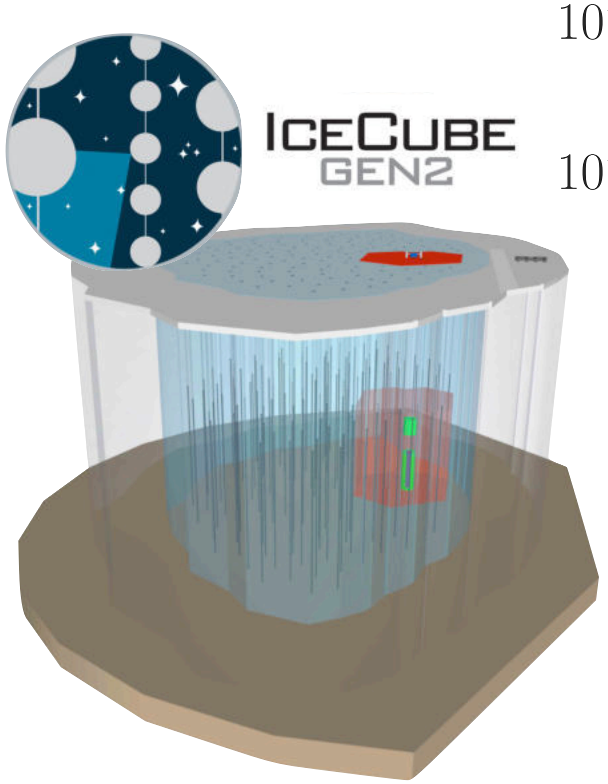
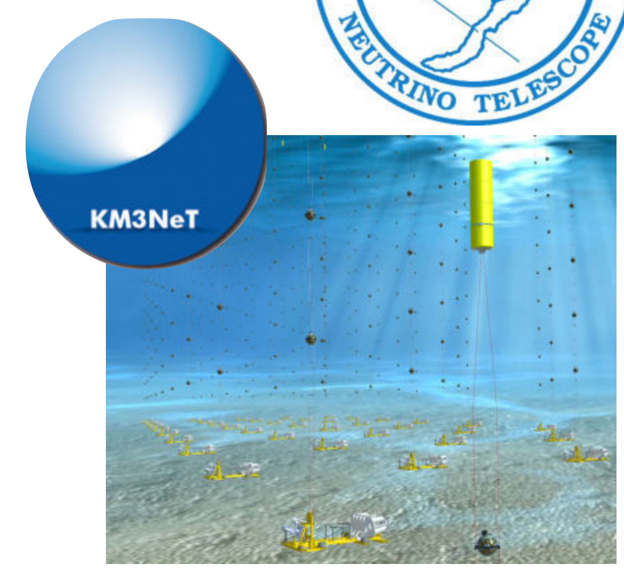


Expected neutrino signal with next generation detectors







Outlook

Blazars are fantastic objects

- future multi-wavelength observations will reveal more details of the physical conditions
- …and about their multi-messenger role