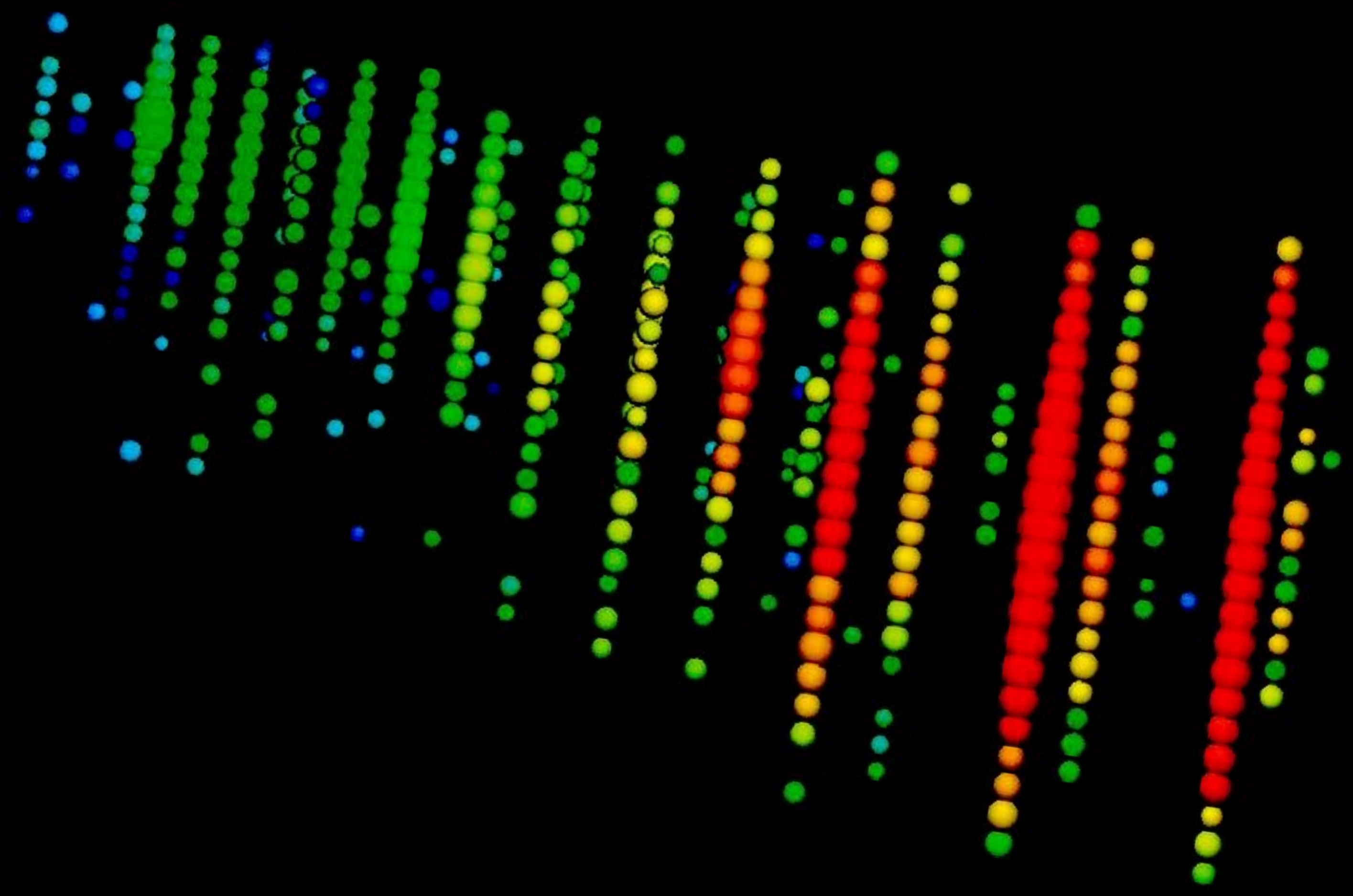


Multimessenger Astroparticle Physics

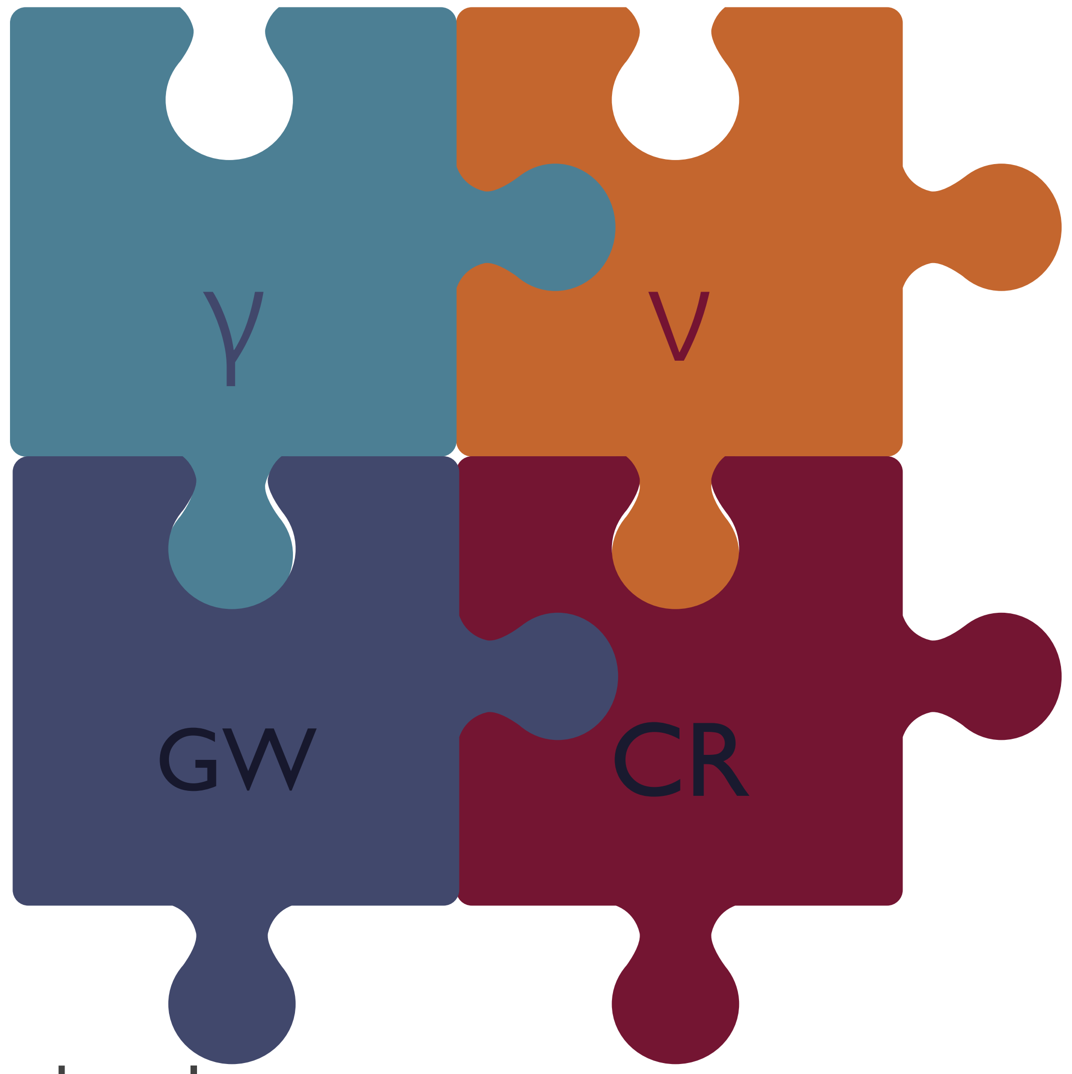
ISCRA 2024

NTNU
Norwegian University of
Science and Technology

Foteini Oikonomou

July 23rd 2024

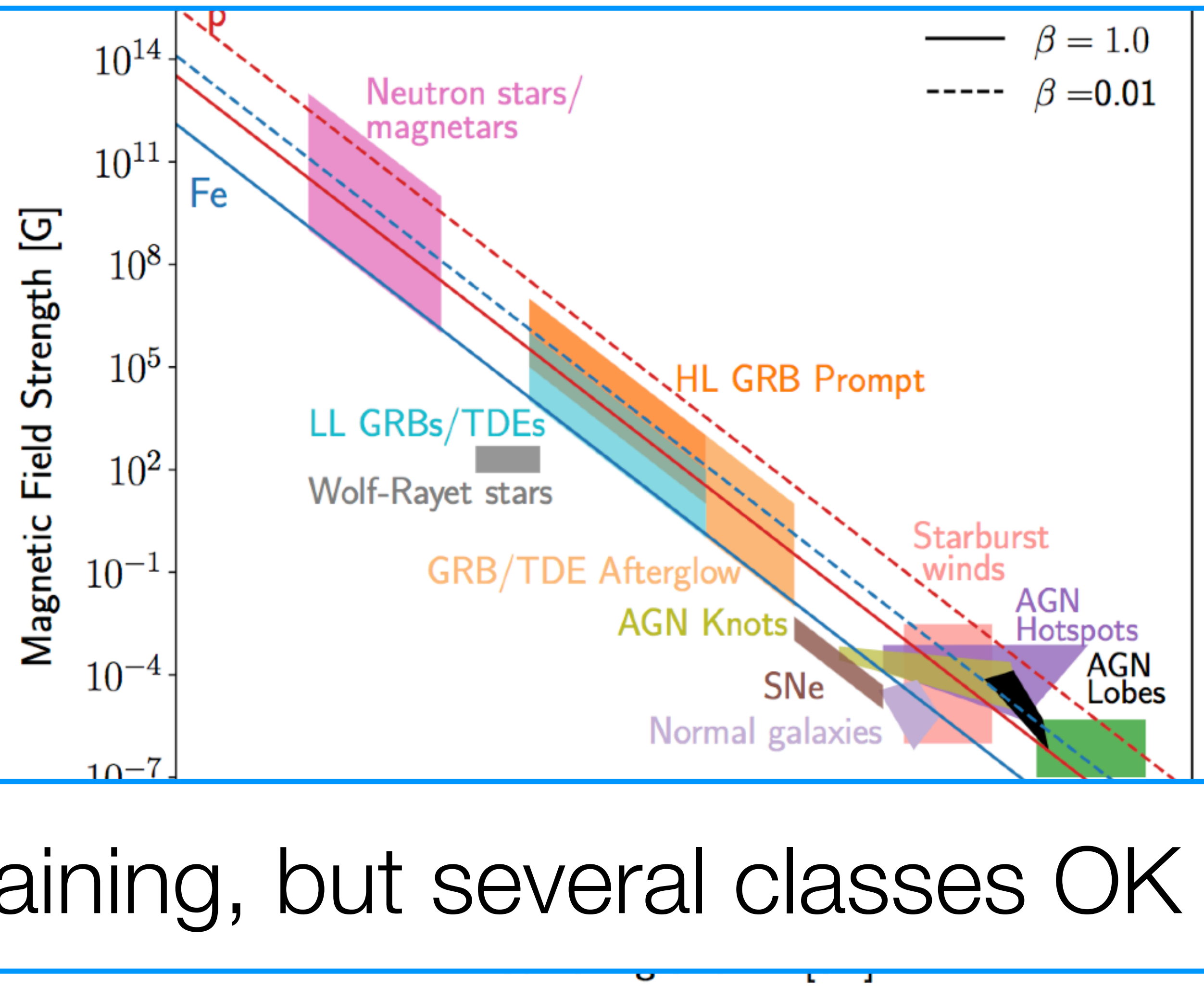
Lecture plan



- Focus on: UHECRs, neutrinos and EM counterparts
- **Monday**: Generic source properties (Requirements for astrophysical accelerators of high-energy cosmic rays/high-energy neutrinos)
- **Tuesday/Wednesday:** Overview of candidate multimessenger sources
  - **Tuesday:** Jetted Active Galactic Nuclei
  - **Wednesday:** Non-jetted AGN/Starburst Galaxies/Gamma-ray bursts/Pulsars/Tidal Disruption Events

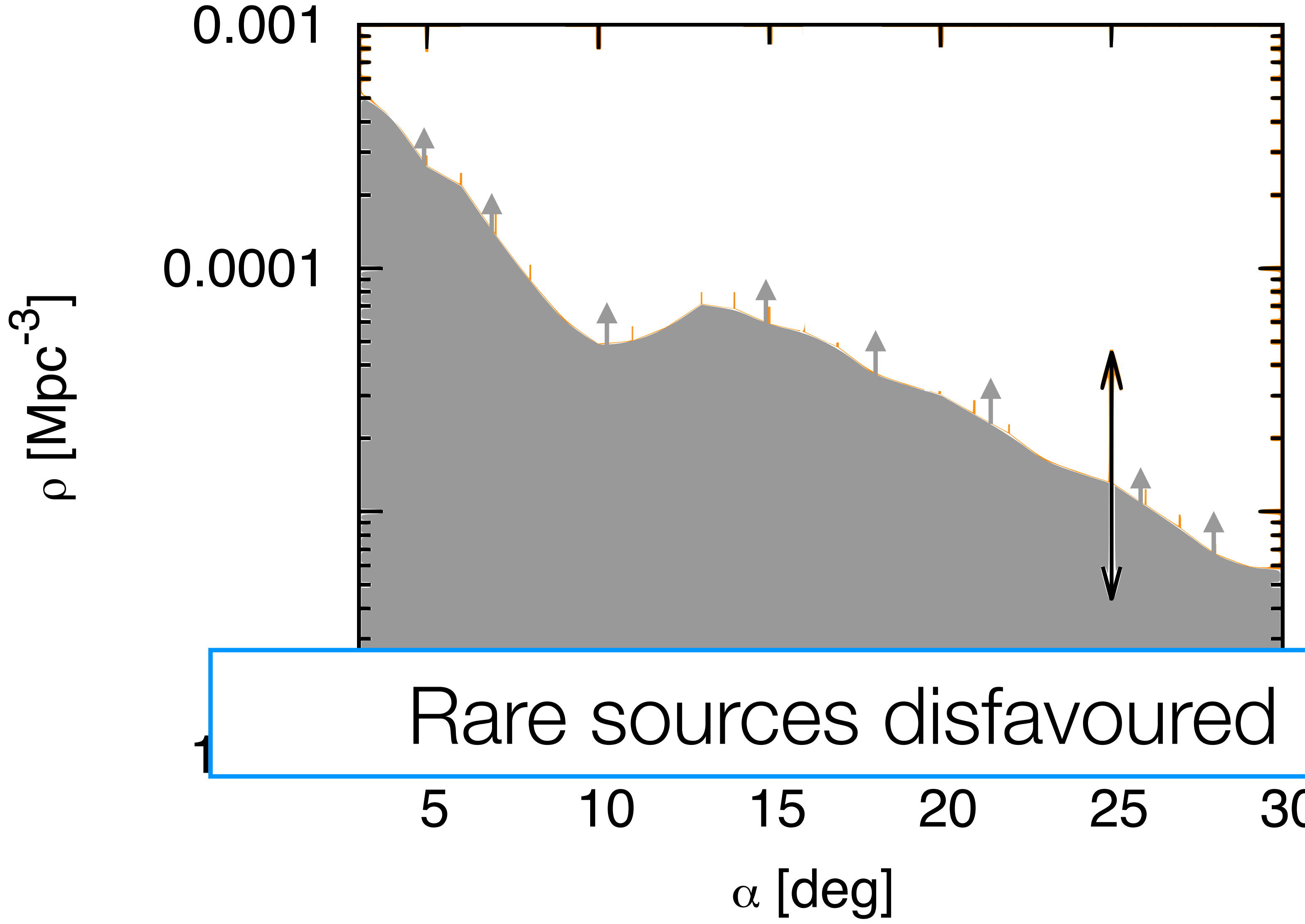
Recap of Monday's lecture

UHECR Maximum Energy



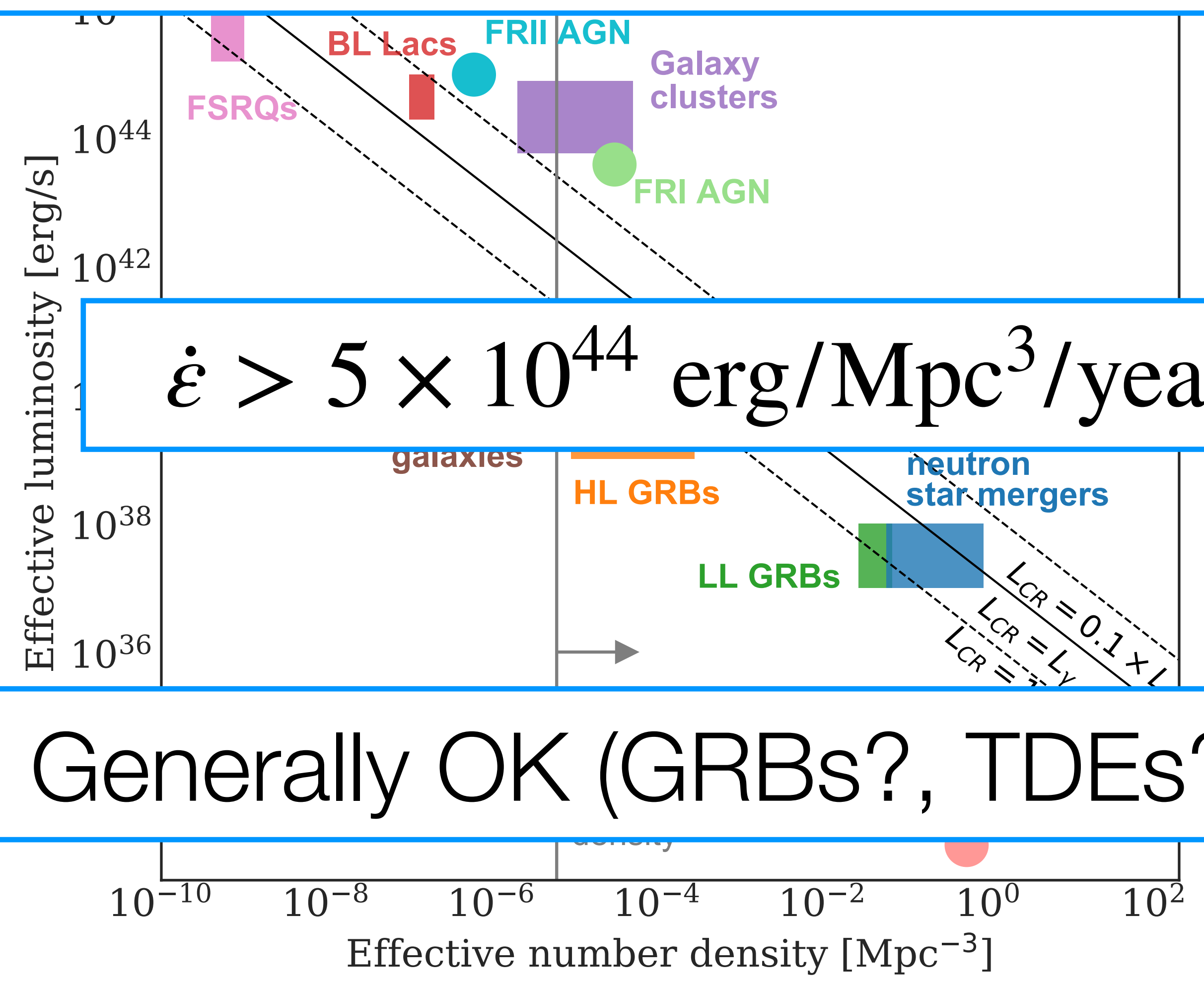
constraining, but several classes OK for nuclei

UHECR number density



Rare sources disfavoured

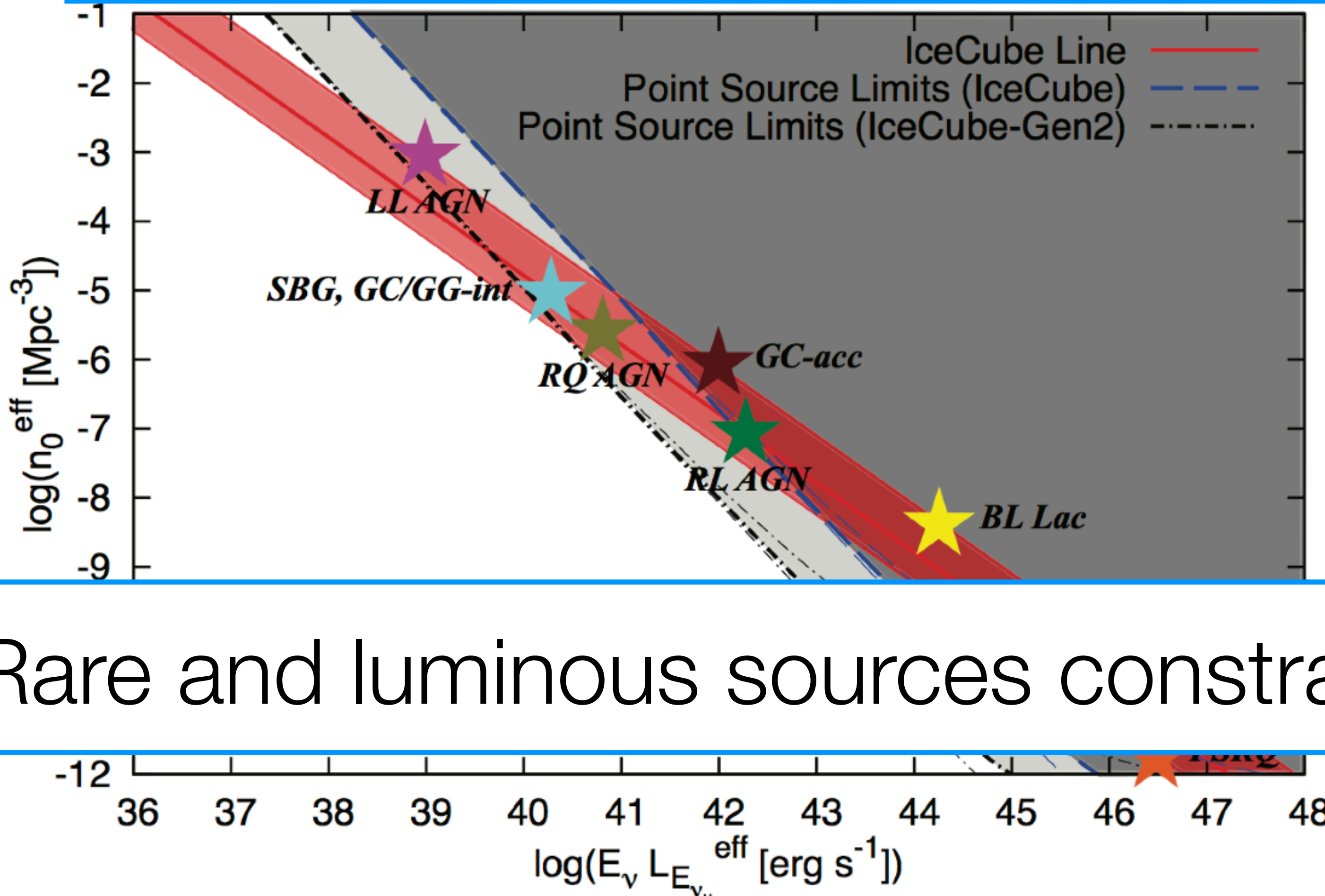
UHECR Emissivity



$$\dot{\epsilon} > 5 \times 10^{44}\ \mathrm{erg/Mpc^3/year}$$

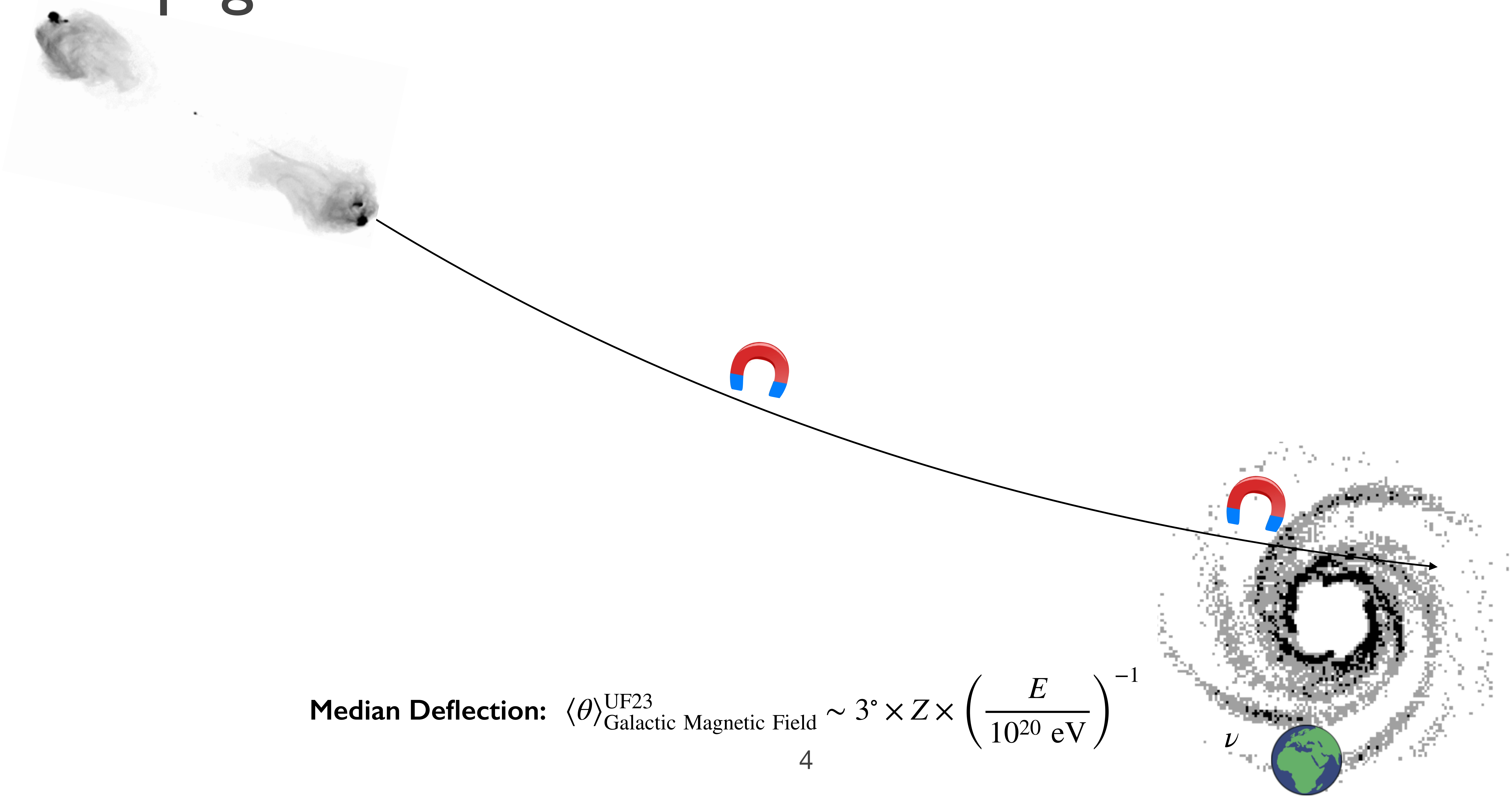
Generally OK (GRBs?, TDEs?)

Neutrino clustering constraints



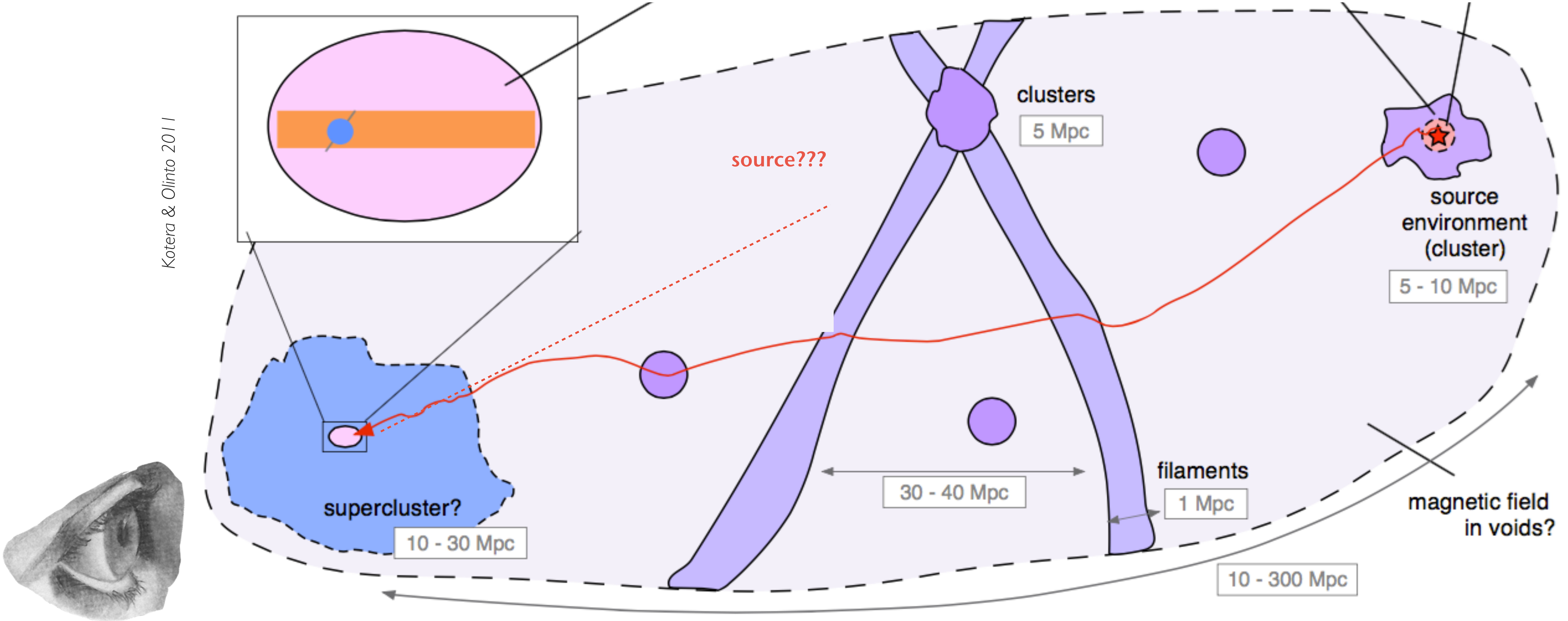
Rare and luminous sources constrained

Propagation of UHECRs



Median Deflection: $\langle\theta\rangle^{\mathrm{UF23}}_{\mathrm{Galactic\ Magnetic\ Field}} \sim 3^{\circ} \times Z \times \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1}$

Magnetic fields in the Universe

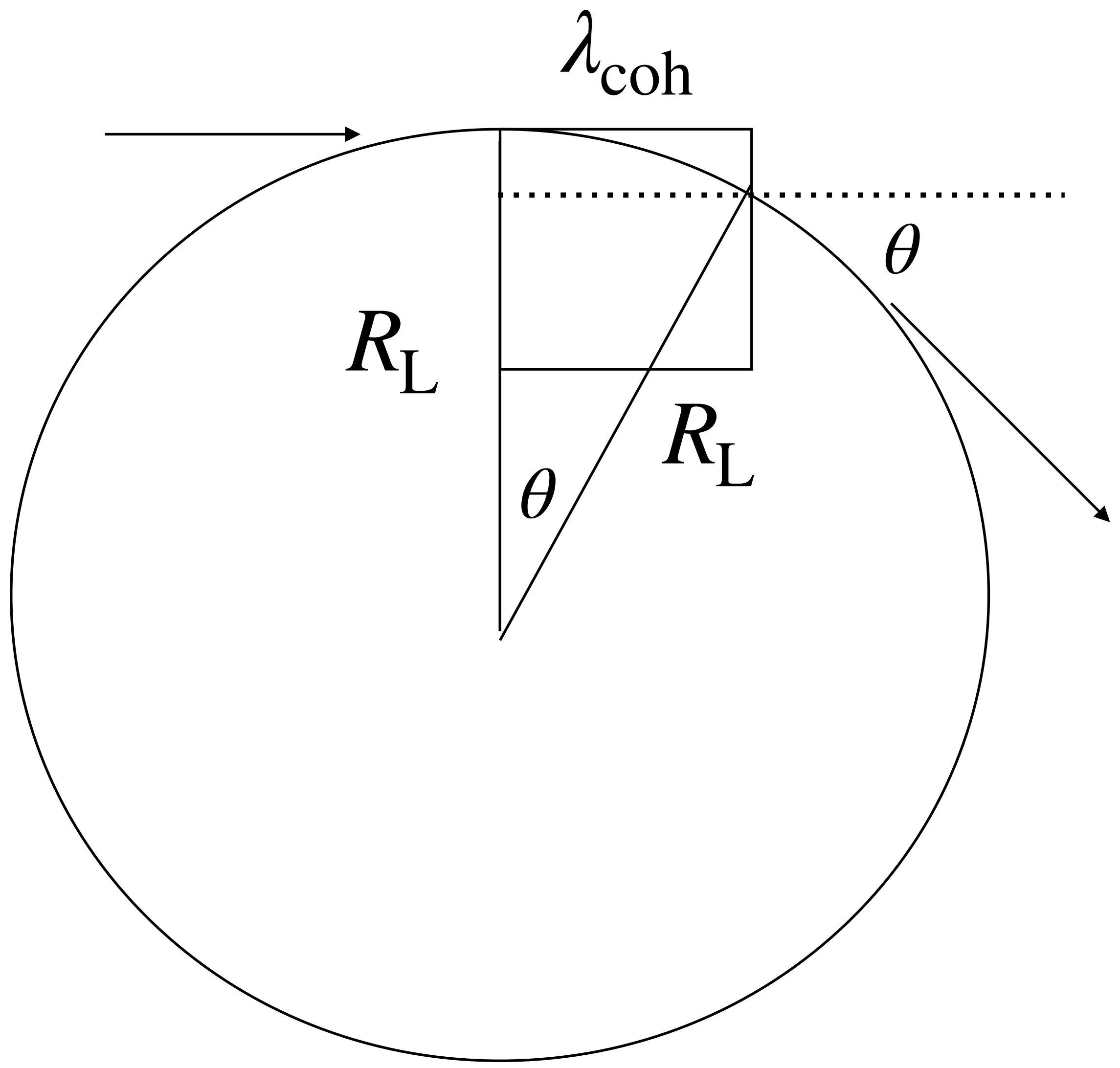


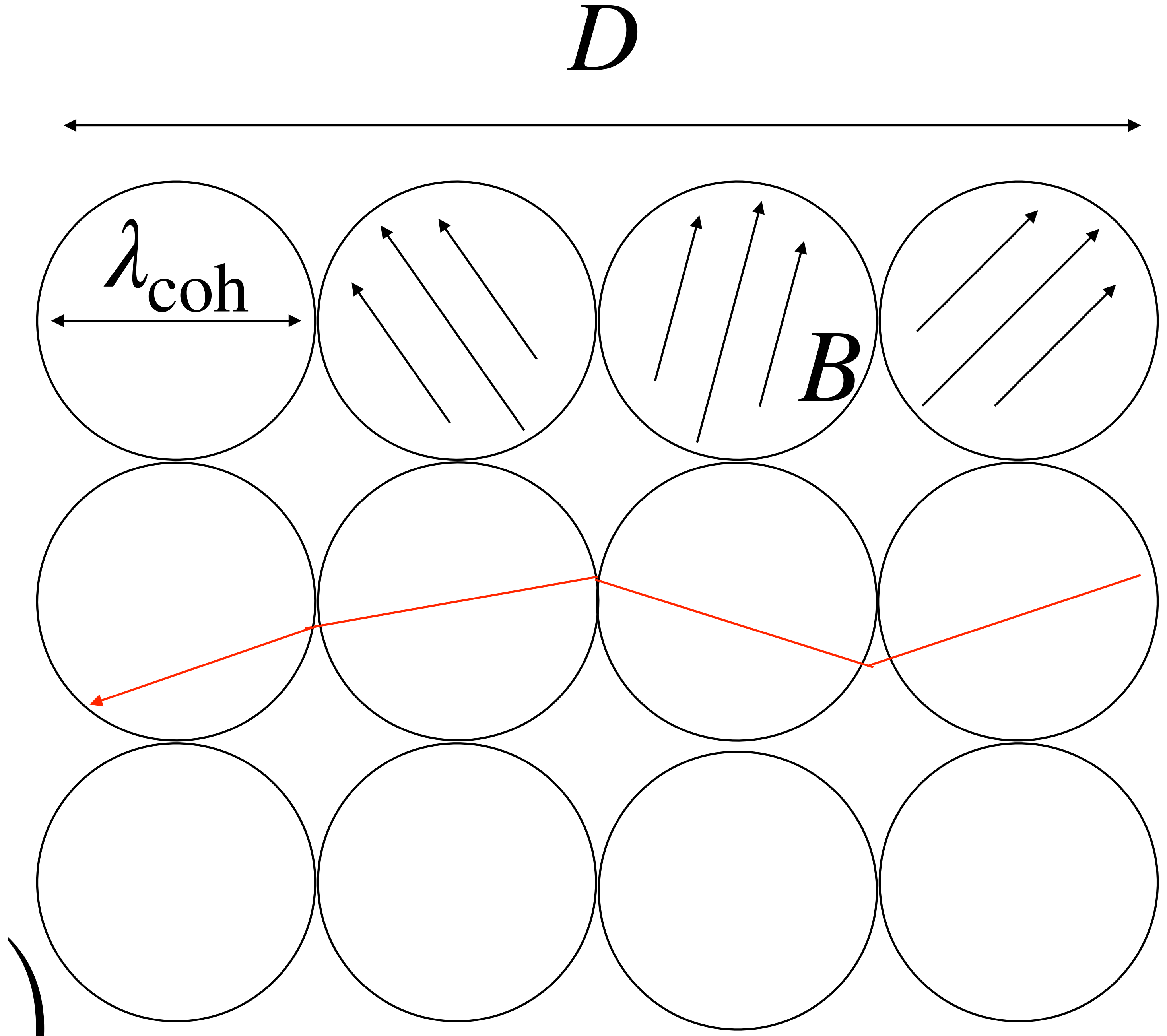
Kotera & Olinto 2011

Deflections: Quasi rectilinear regime

$R_{\text{Larmor}} \gg \lambda_{\text{coh}}$

$$\frac{\lambda_{\text{coh}}}{R_{\text{Larmor}}} = \sin\theta \approx \delta\theta_{\text{cell}}$$





$$\left\langle \Delta\theta^2_{\text{tot}} \right\rangle \approx N \cdot \left\langle \delta\theta^2_{\text{cell}} \right\rangle, \quad \left[N = \frac{D}{\lambda} \right]$$

$$\Delta\theta_{\text{tot}} \approx 1^\circ \cdot Z \cdot \left(\frac{D}{100\,\text{Mpc}} \right)^{1/2} \left(\frac{E}{10^{20}\,\text{eV}} \right)^{-1} \left(\frac{\lambda_{\text{coh}}}{1\,\text{Mpc}} \right)^{1/2} \left(\frac{B}{0.1\,\text{nG}} \right)$$

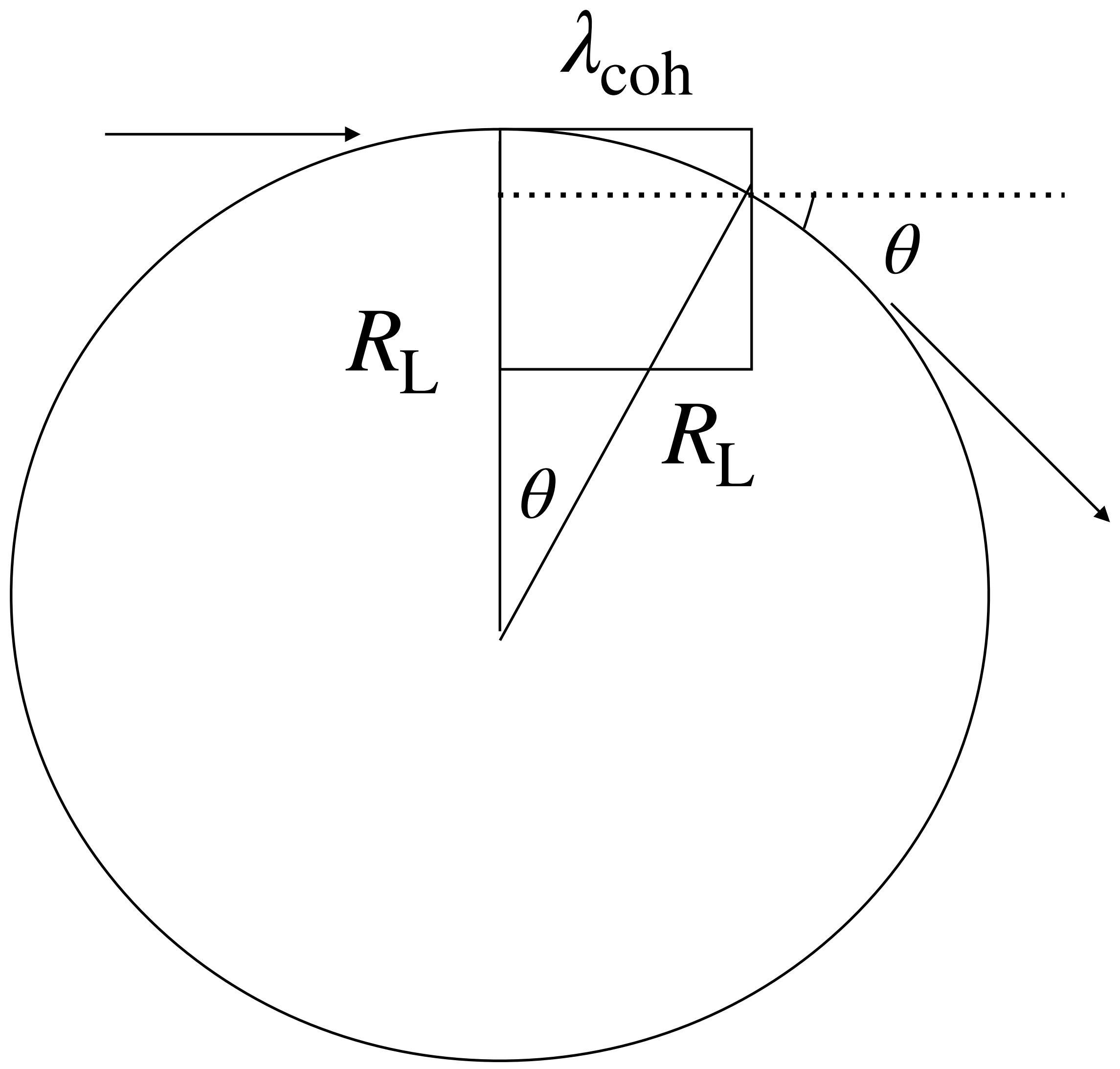
$$\Delta\theta_{\text{tot}}(\text{H}, 10^{20}\,\text{eV}, 100\,\text{Mpc}) \sim 1^\circ$$

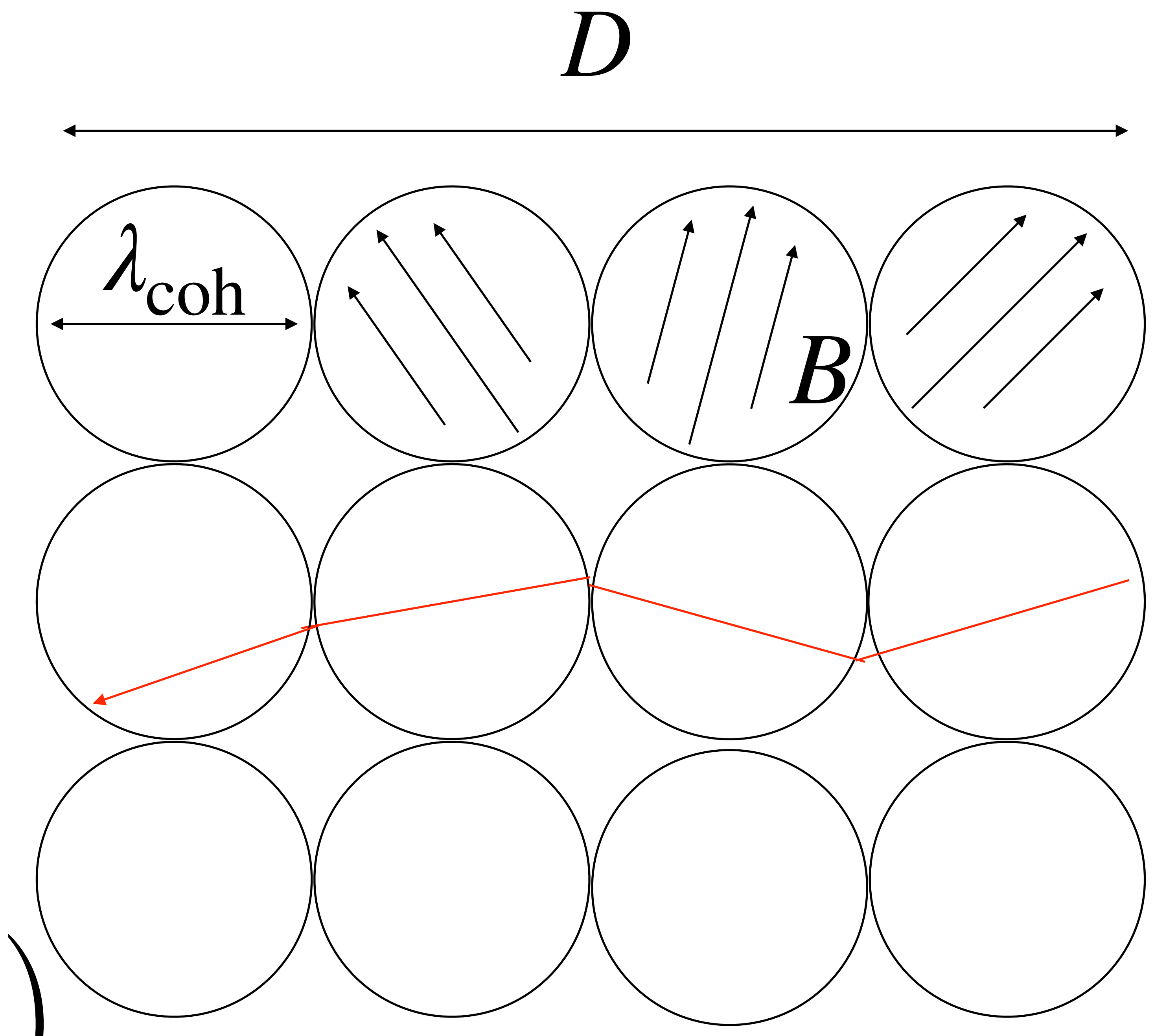
$$\Delta\theta_{\text{tot}}(\text{Fe}, 10^{20}\,\text{eV}, 100\,\text{Mpc}) \sim 26^\circ$$

Deflections: Quasi rectilinear regime

$$R_{\rm Larmor} \gg \lambda_{\rm coh}$$

$$\frac{\lambda_{\rm coh}}{R_{\rm Larmor}} = \sin\theta \approx \delta\theta_{\rm cell}$$





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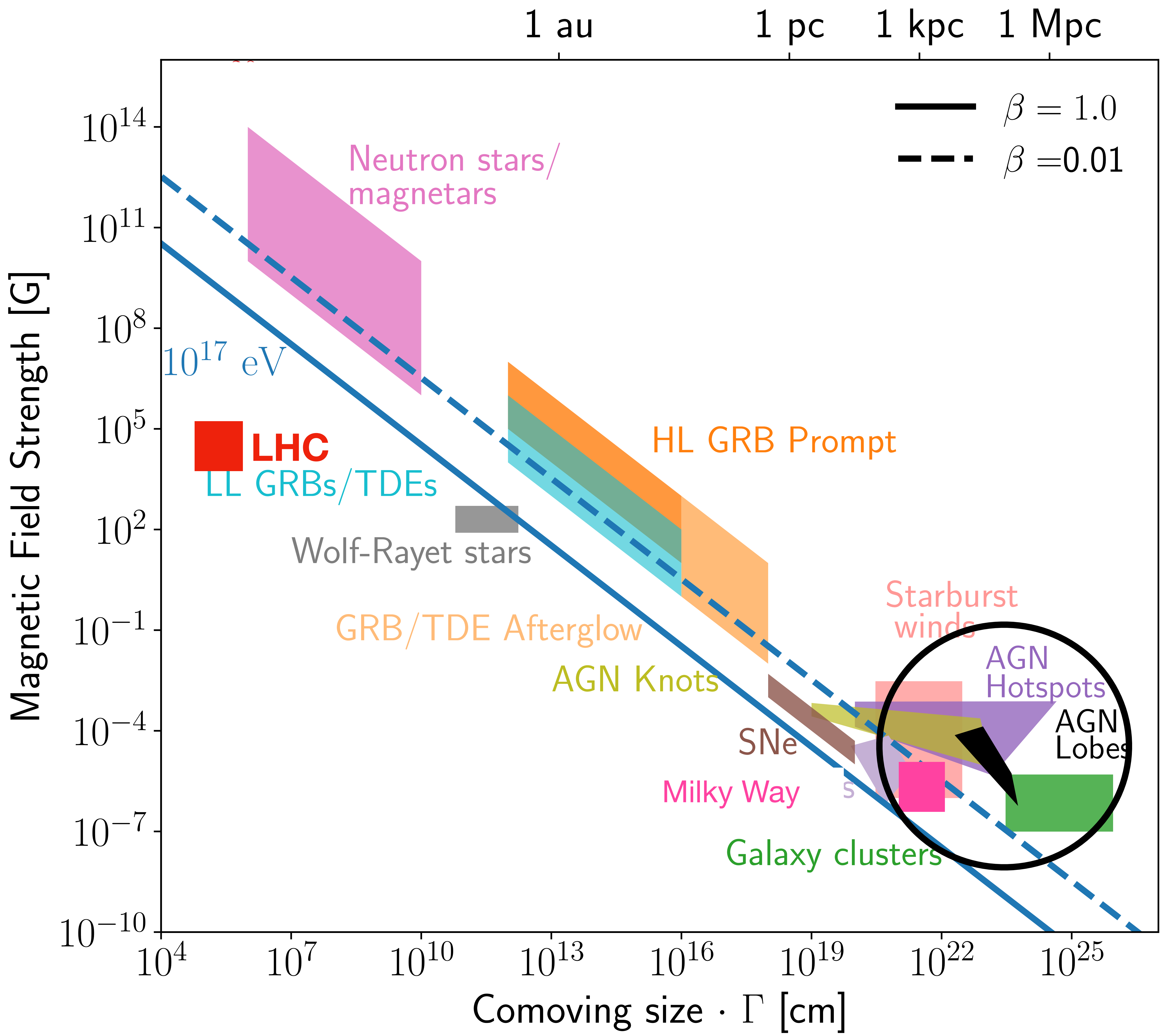
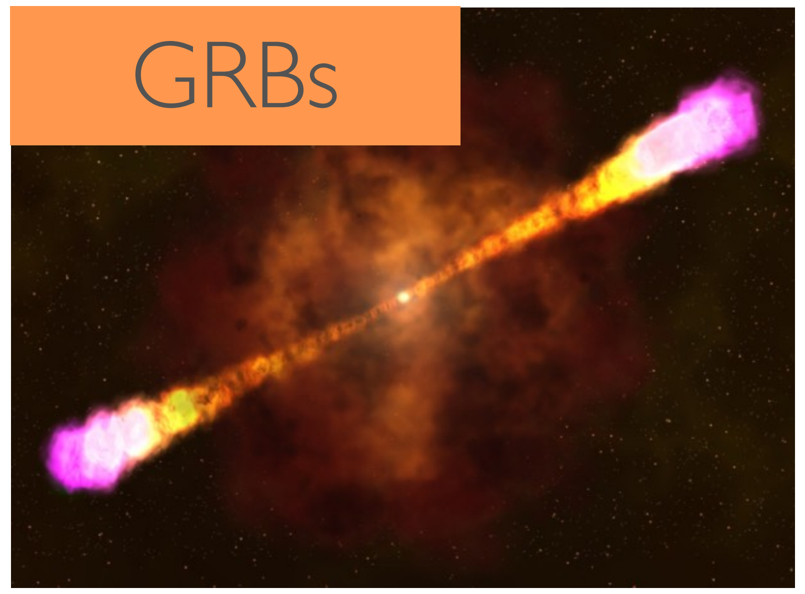
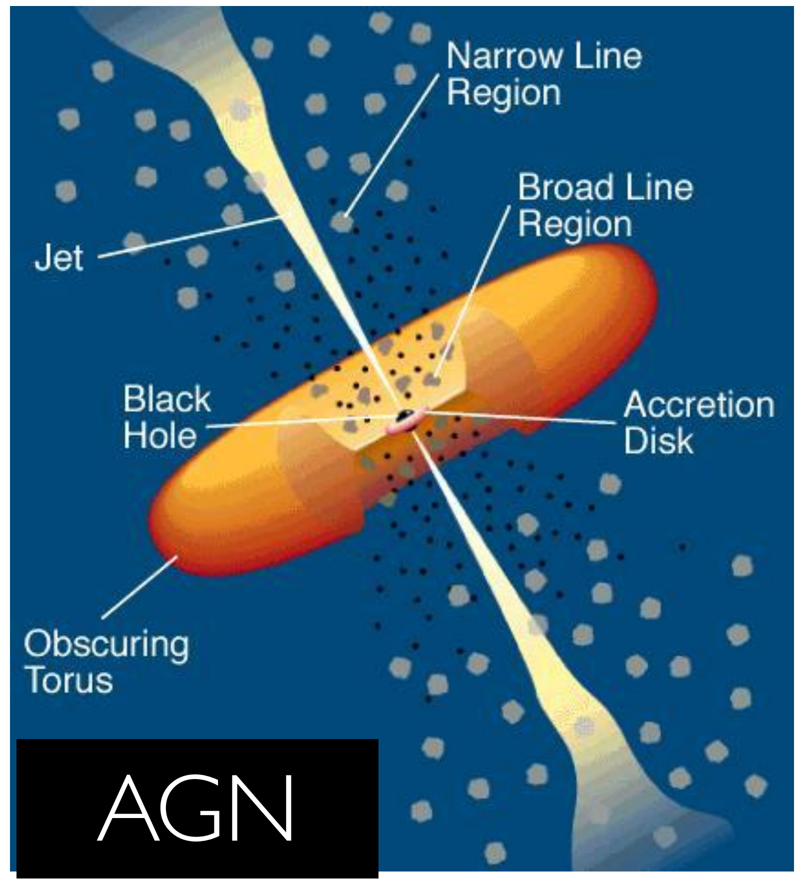
$$\tau_{\rm delay} \approx D\frac{\Delta\theta^2}{2c} \approx 1.5 \times 10^3\ {\rm yr} \cdot Z^2 \cdot \left(\frac{D}{100\,{\rm Mpc}}\right)^2 \left(\frac{E}{10^{20}\,{\rm eV}}\right)^{-2} \left(\frac{\lambda_{\rm coh}}{1\,{\rm Mpc}}\right) \left(\frac{B}{0.1\,{\rm nG}}\right)^2$$

Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)







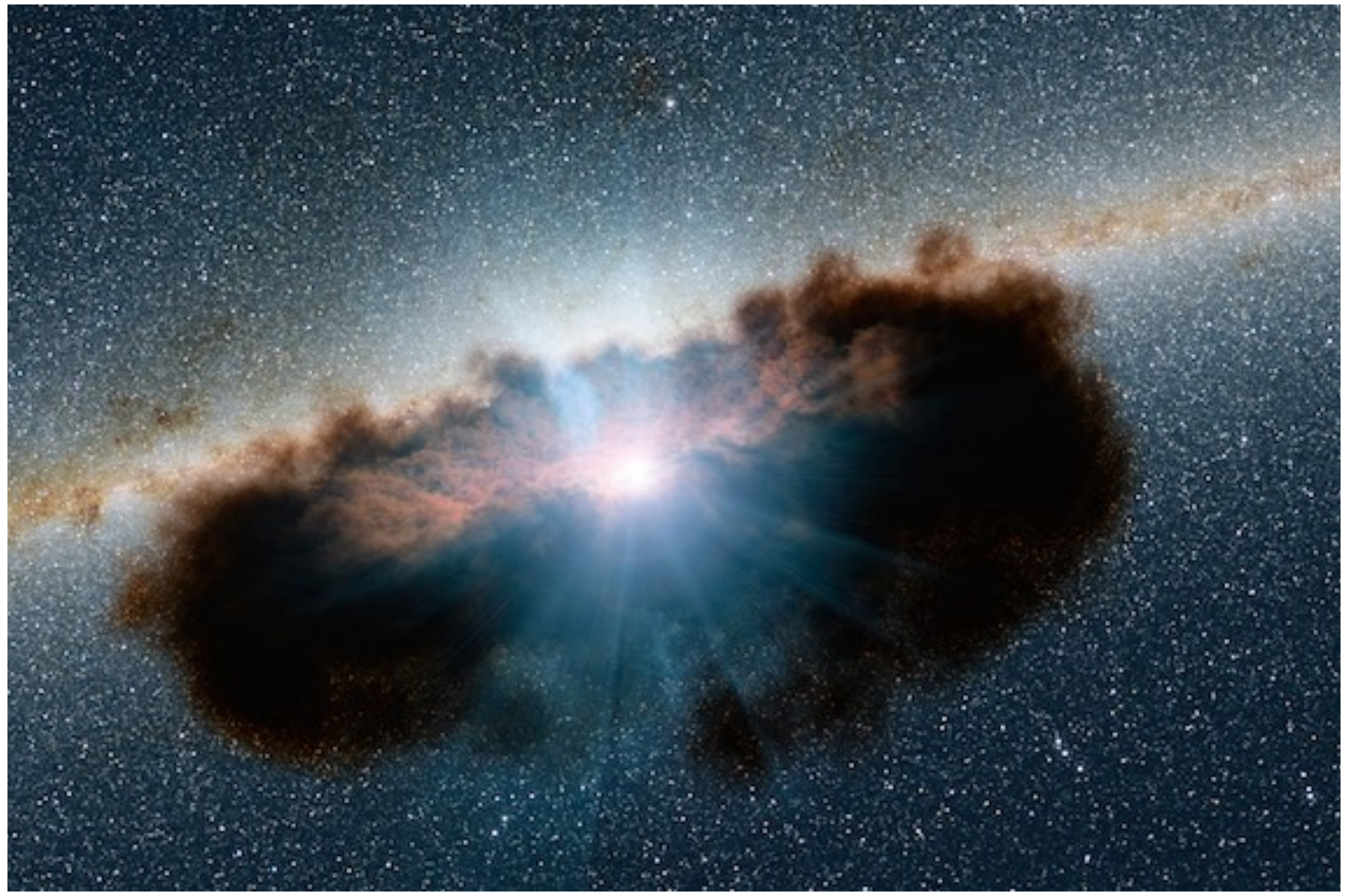
Active Galactic Nuclei

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

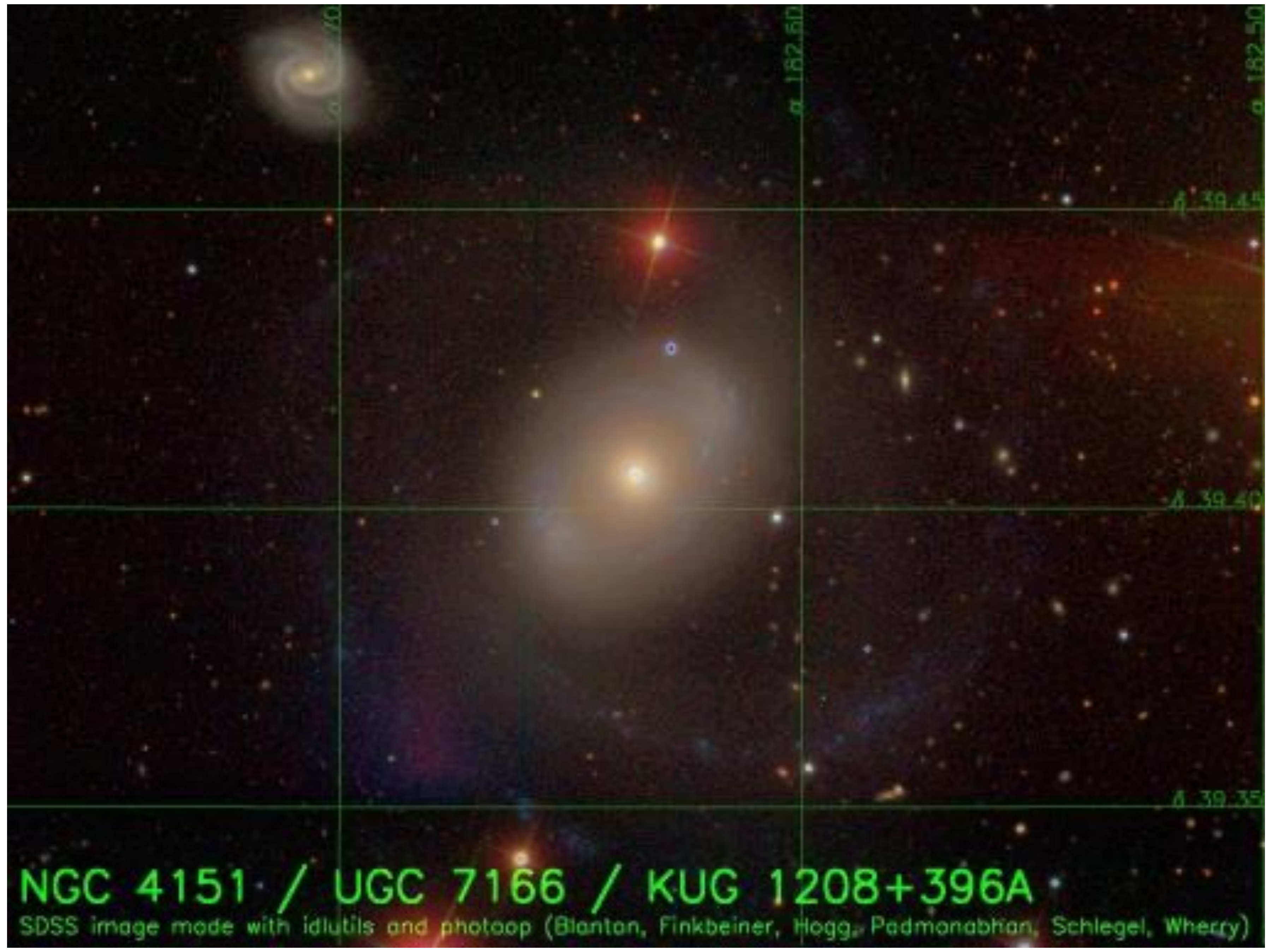
They host a super-massive black hole (SMBH) (10^{6}-10^{10} M_{sun}). ``Active'' as emission >> stars in the galaxy - accretion on to SMBH

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

1% of galaxies active



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



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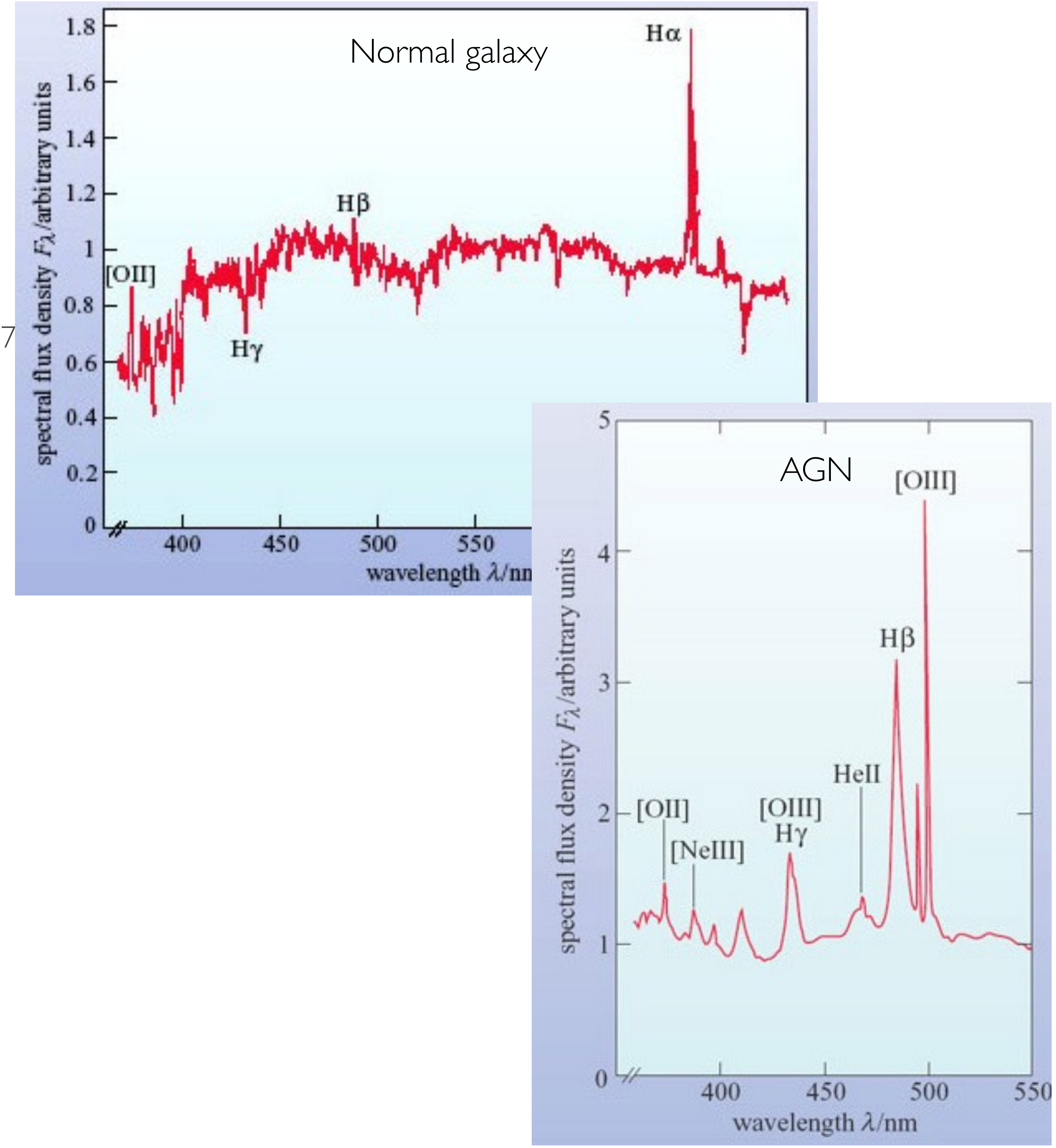
1% of galaxies active

Broad emission lines reveal rapid bulk rotation



[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

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

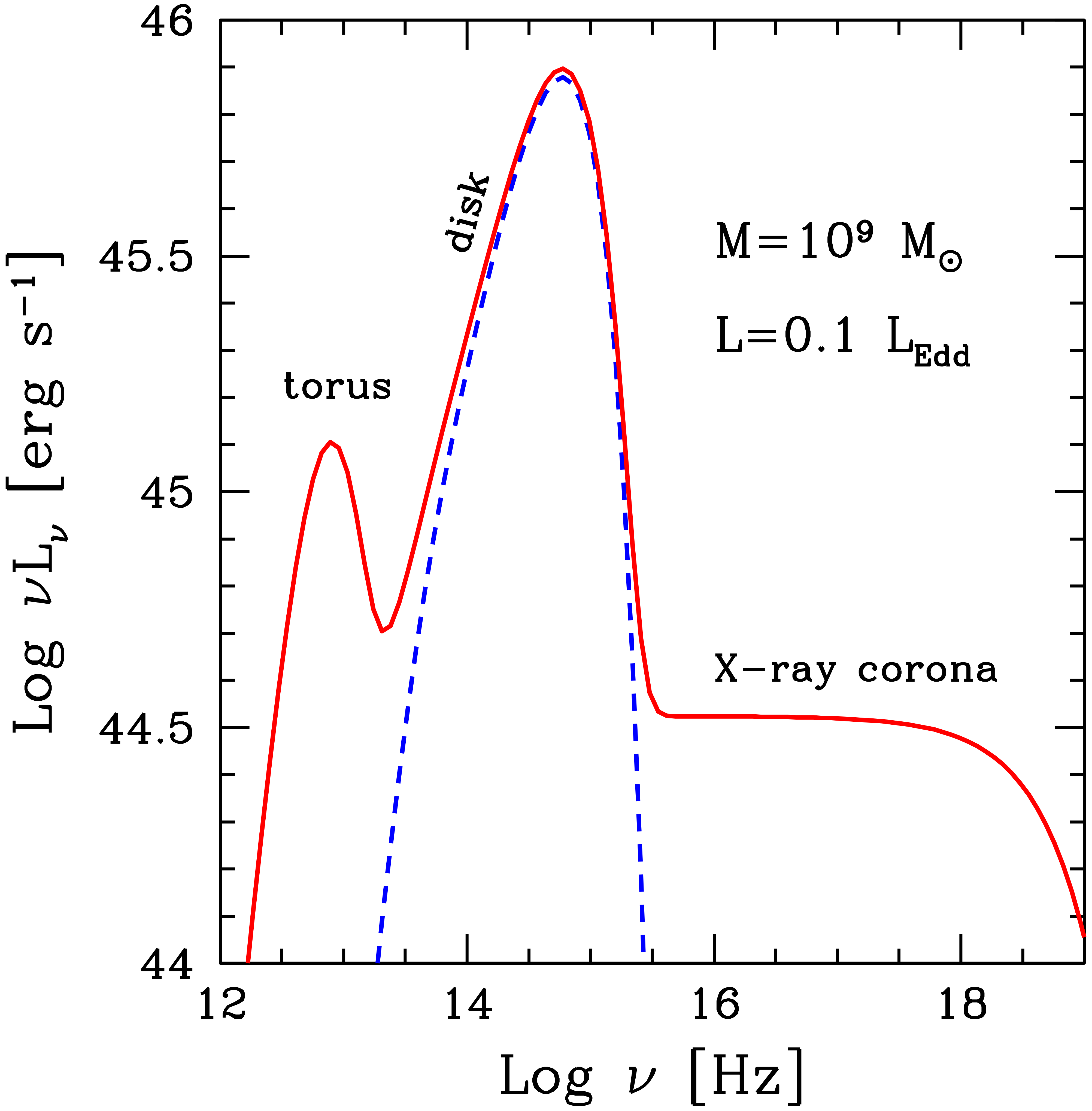
In solar masses per year, the requirement is

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

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

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

G. Ghisellini, Radiative Processes in HE Astrophysics (2012)



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

The engine

For an AGN with disk luminosity

$$L_{\text{disk}} = 10^{46}\ \text{erg/s}$$

and time variability

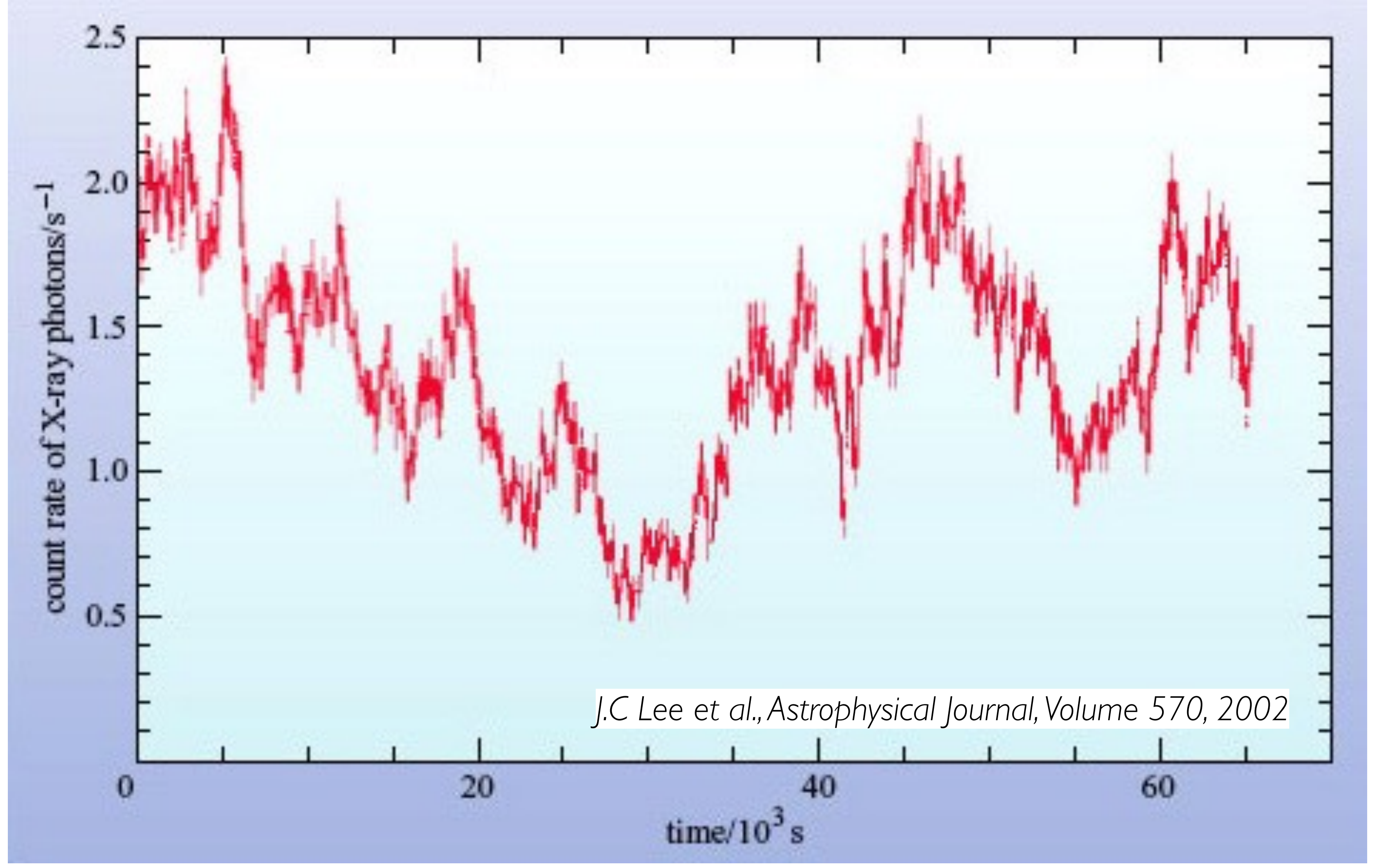
$\Delta t = 10^4$ s, causality dictates $R \sim c\Delta t = 0.01\ \text{pc} = 20\ \text{AU}$

We need a supermassive black hole due to the Eddington limit!

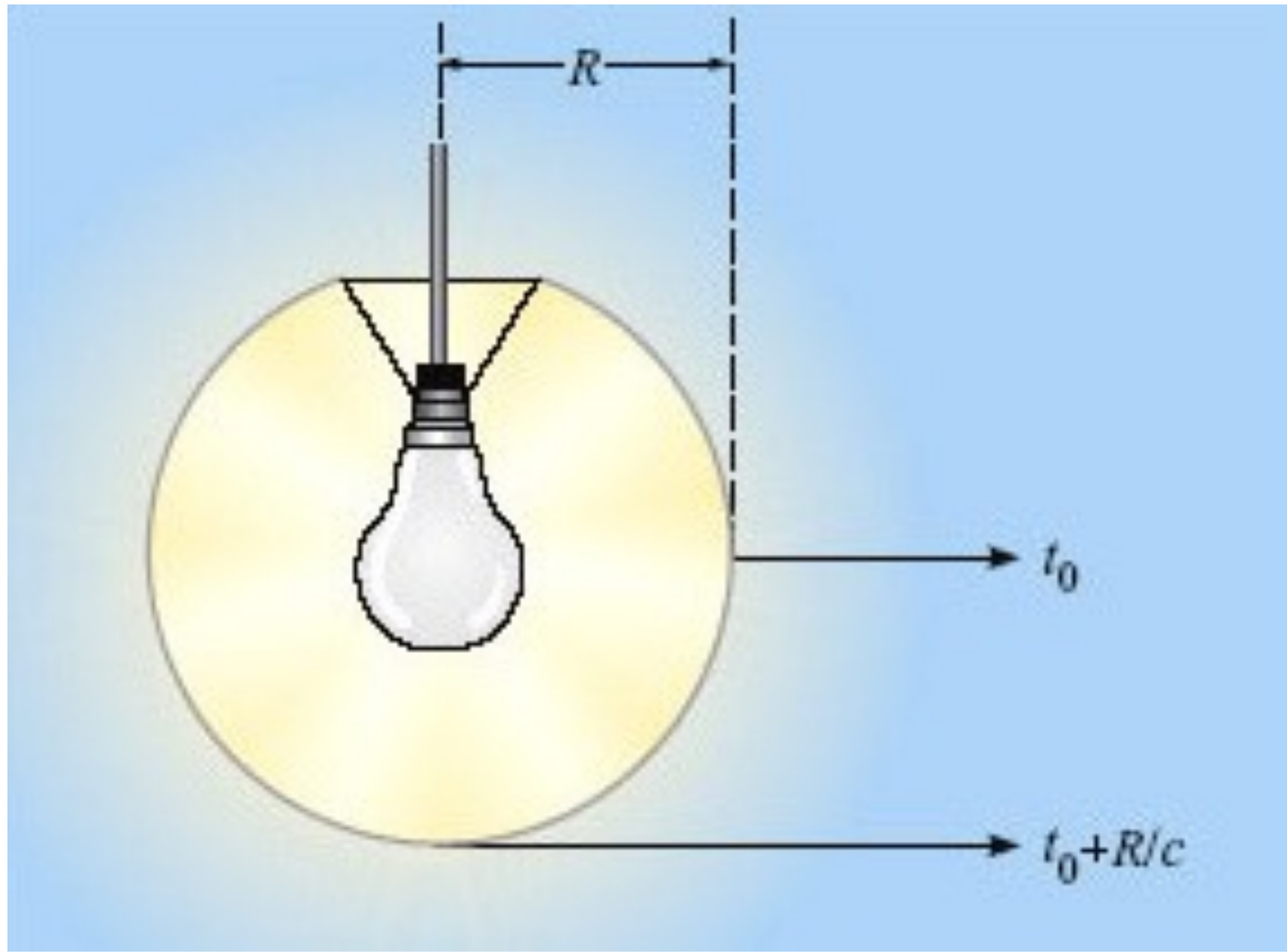
$$L_{\text{Edd}} = \frac{4\pi G M m_p c}{\sigma_{\text{T}}} = 10^{38}\text{erg/s}\left(\frac{M}{M_{\text{Sun}}}\right)$$

I.e. we need,

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



J.C Lee et al., Astrophysical Journal, Volume 570, 2002



AGN Zoo

P. Padovani et al 2017: AGN: What's in a name?

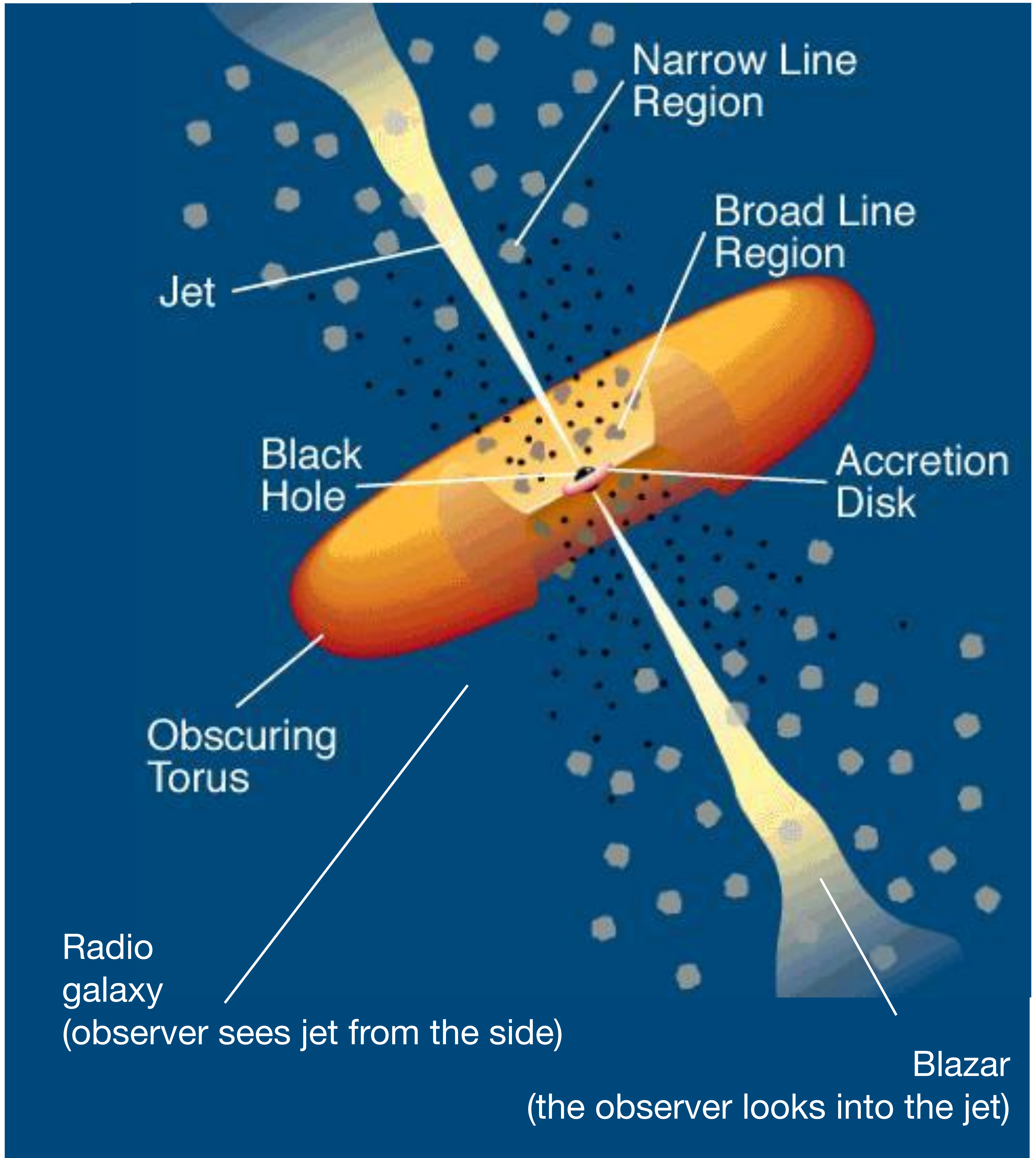
Class/Acronym	Meaning	Main properties/reference
Quasar	Quasi-stellar radio source (originally)	Radio detection no longer required
Sey1	Seyfert 1	FWHM $\gtrsim 1,000$ km s^{-1}
Sey2	Seyfert 2	FWHM $\lesssim 1,000$ km s^{-1}
QSO	Quasi-stellar object	Quasar-like, non-radio source
QSO2	Quasi-stellar object 2	High power Sey2
RQ AGN	Radio-quiet AGN	see ref. 1
RL AGN	Radio-loud AGN	see ref. 1
Jetted AGN		with strong relativistic jets; see ref. 1
Non-jetted AGN		without strong relativistic jets; see ref. 1
Type 1		Sey1 and quasars
Type 2		Sey2 and QSO2
FR I	Fanaroff-Riley class I radio source	radio core-brightened (ref. 2)
FR II	Fanaroff-Riley class II radio source	radio edge-brightened (ref. 2)
BL Lac	BL Lacertae object	see ref. 3
Blazar	BL Lac and quasar	BL Lacs and FSRQs
BAL	Broad absorption line (quasar)	ref. 4
BLO	Broad-line object	FWHM $\gtrsim 1,000$ km s^{-1}
BLAGN	Broad-line AGN	FWHM $\gtrsim 1,000$ km s^{-1}
BLRG	Broad-line radio galaxy	RL Sey1
CDQ	Core-dominated quasar	RL AGN, $f_{\rm core} \geq f_{\rm ext}$ (same as FSRQ)
CSS	Compact steep spectrum radio source	core dominated, $\alpha_{\rm r} > 0.5$
CT	Compton-thick	$N_{\rm H} \geq 1.5 \times 10^{24}$ cm^{-2}
FR 0	Fanaroff-Riley class 0 radio source	ref. 5
FSRQ	Flat-spectrum radio quasar	RL AGN, $\alpha_{\rm r} \leq 0.5$
GPS	Gigahertz-peaked radio source	see ref. 6
HBL/HSP	High-energy cutoff BL Lac/blazar	$\nu_{\rm synch\ peak} \geq 10^{15}$ Hz (ref. 7)
HEG	High-excitation galaxy	ref. 8
HPQ	High polarization quasar	$P_{\rm opt} \geq 3\%$ (same as FSRQ)
Jet-mode		$L_{\rm kin} \gg L_{\rm rad}$ (same as LERG); see ref. 9
IBL/ISP	Intermediate-energy cutoff BL Lac/blazar	$10^{14} \leq \nu_{\rm synch\ peak} \leq 10^{15}$ Hz (ref. 7)
LINER	Low-ionization nuclear emission-line regions	see ref. 9
LLAGN	Low-luminosity AGN	see ref. 10
LBL/LSP	Low-energy cutoff BL Lac/blazar	$\nu_{\rm synch\ peak} < 10^{14}$ Hz (ref. 7)
LDQ	Lobe-dominated quasar	RL AGN, $f_{\rm core} < f_{\rm ext}$
LEG	Low-excitation galaxy	ref. 8
LPQ	Low polarization quasar	$P_{\rm opt} < 3\%$
NLAGN	Narrow-line AGN	FWHM $\lesssim 1,000$ km s^{-1}
NLRG	Narrow-line radio galaxy	RL Sey2
NLS1	Narrow-line Seyfert 1	ref. 11
OVV	Optically violently variable (quasar)	(same as FSRQ)
Population A		ref. 12
Population B		ref. 12
Radiative-mode		Seyferts and quasars; see ref. 9
RBL	Radio-selected BL Lac	BL Lac selected in the radio band
Sey1.5	Seyfert 1.5	ref. 13
Sey1.8	Seyfert 1.8	ref. 13
Sey1.9	Seyfert 1.9	ref. 13
SSRQ	Steep-spectrum radio quasar	RL AGN, $\alpha_{\rm r} > 0.5$
USS	Ultra-steep spectrum source	RL AGN, $\alpha_{\rm r} > 1.0$
XBL	X-ray-selected BL Lac	BL Lac selected in the X-ray band
XBONG	X-ray bright optically normal galaxy	AGN only in the X-ray band/weak lined

AGN Unification

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

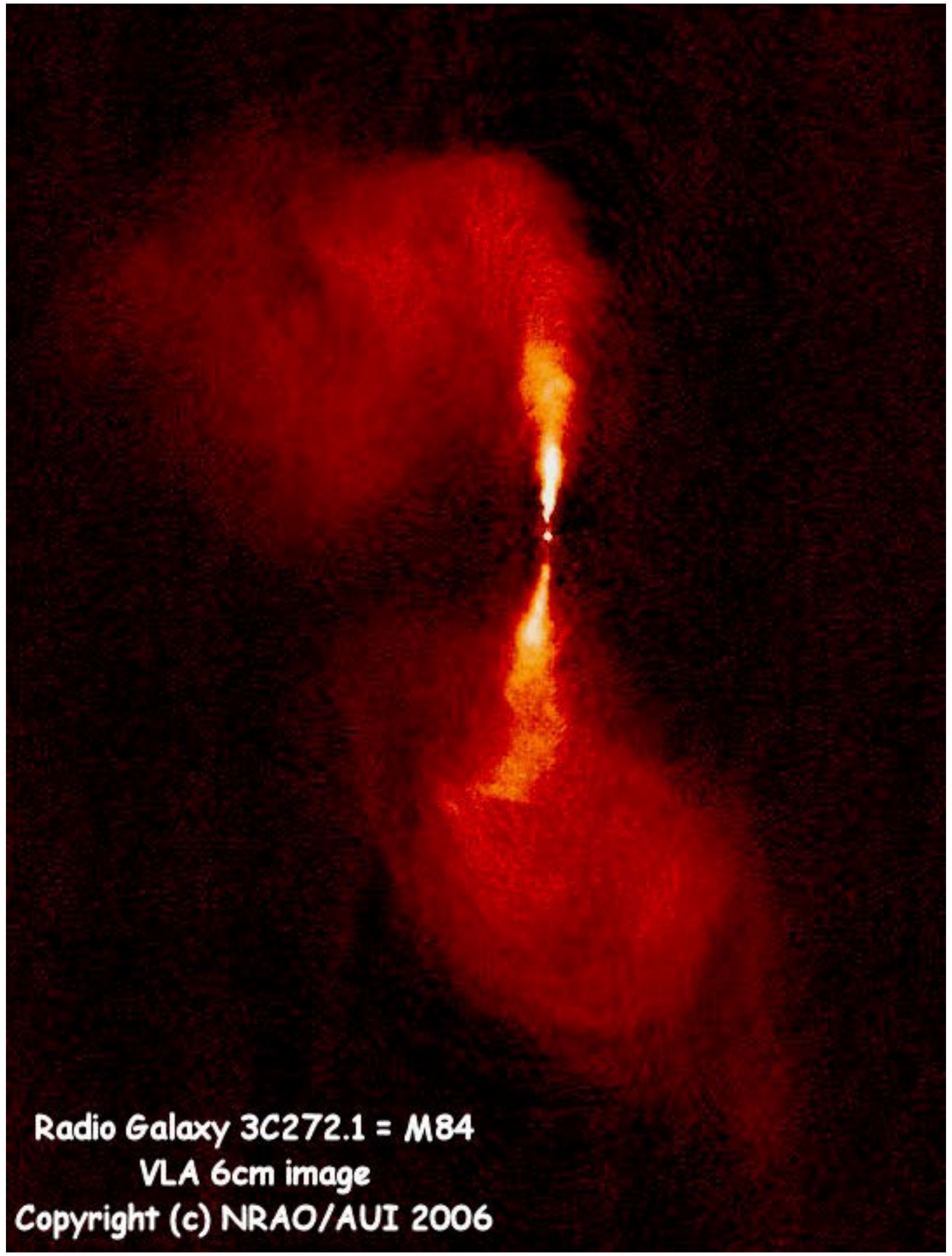


Radio galaxy (observer sees jet from the side)

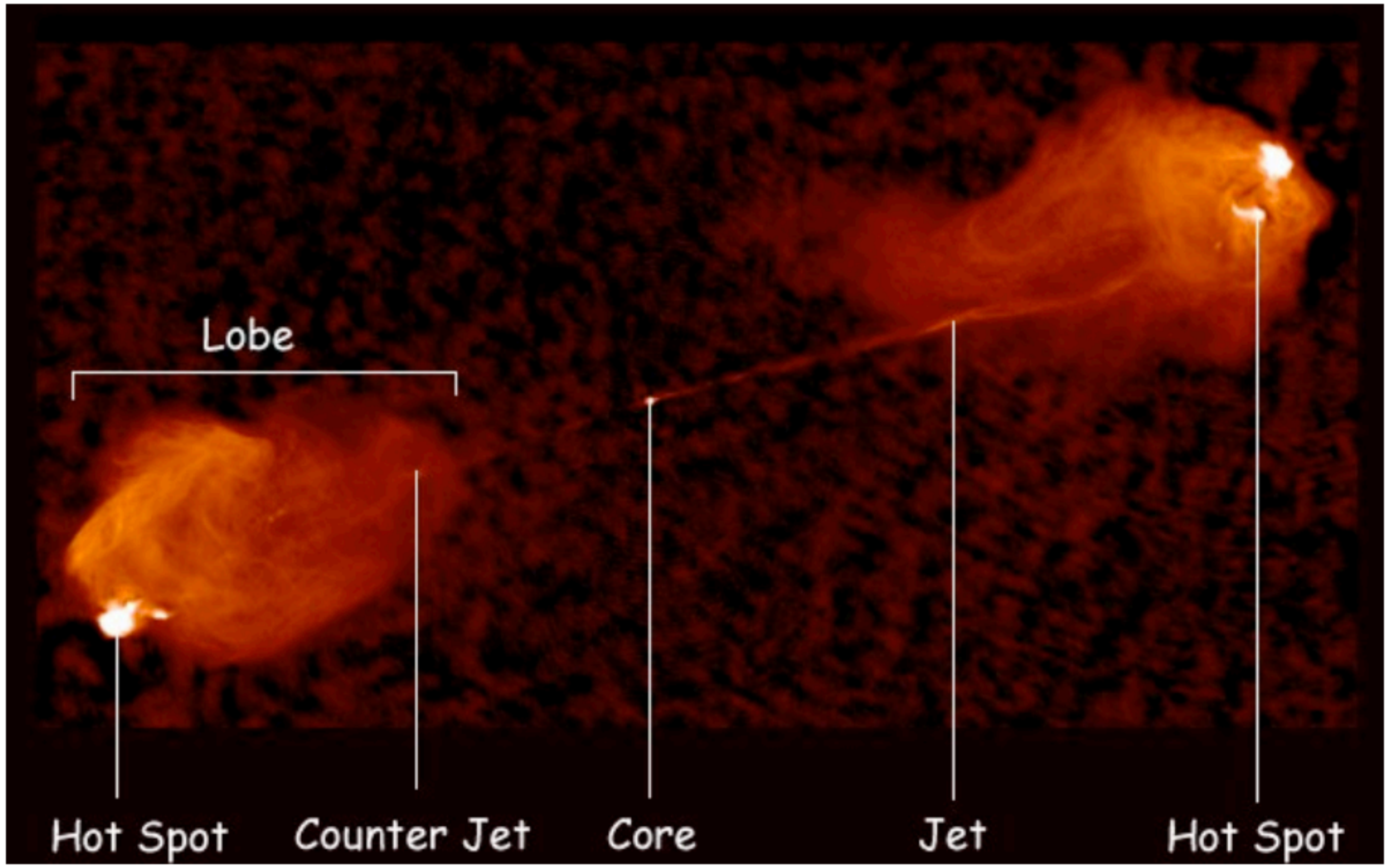
Blazar (the observer looks into the jet)

10% of AGN host jets

FRI



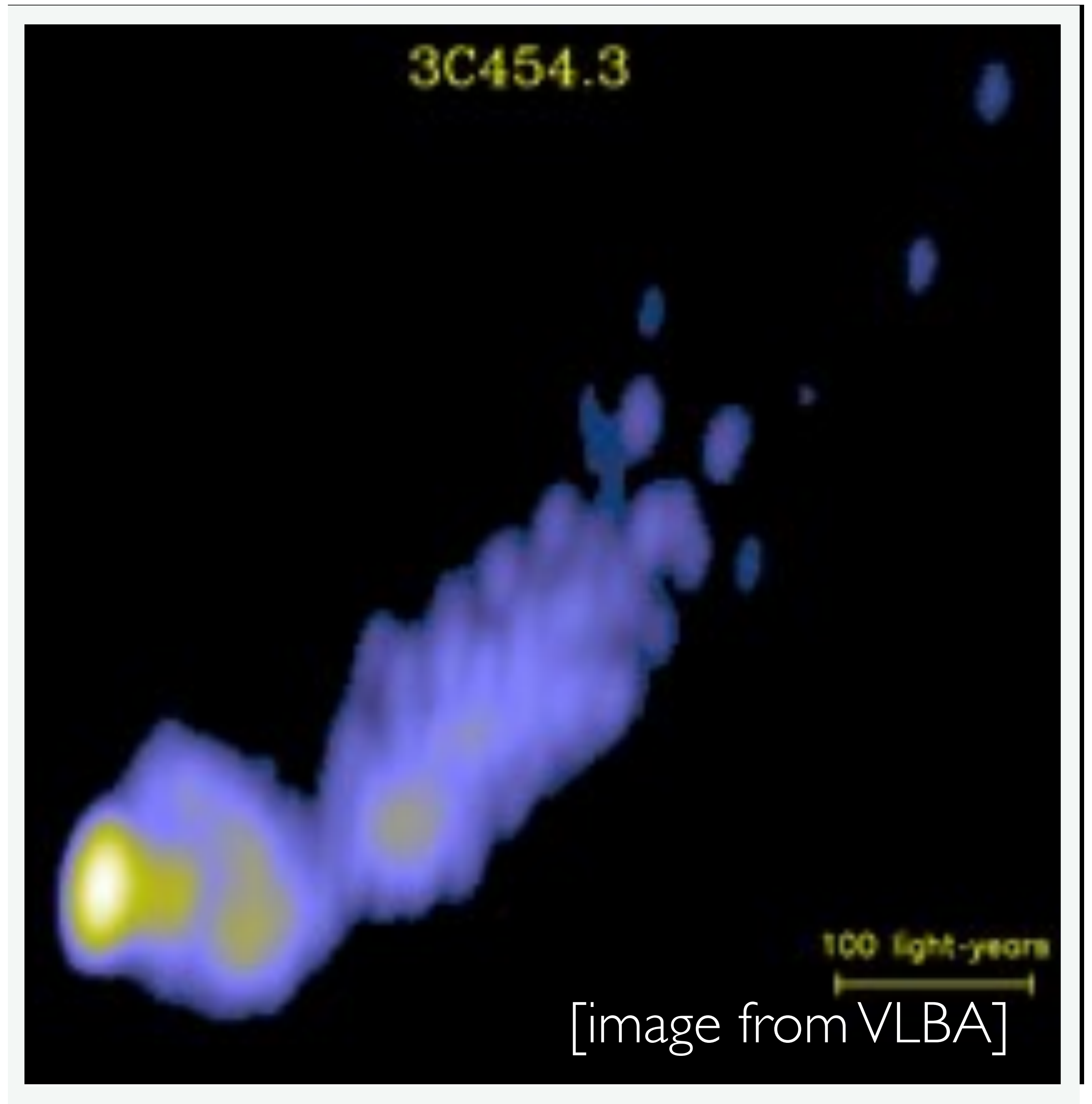
FRII



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

Blazars: Star-like appearance

Radio

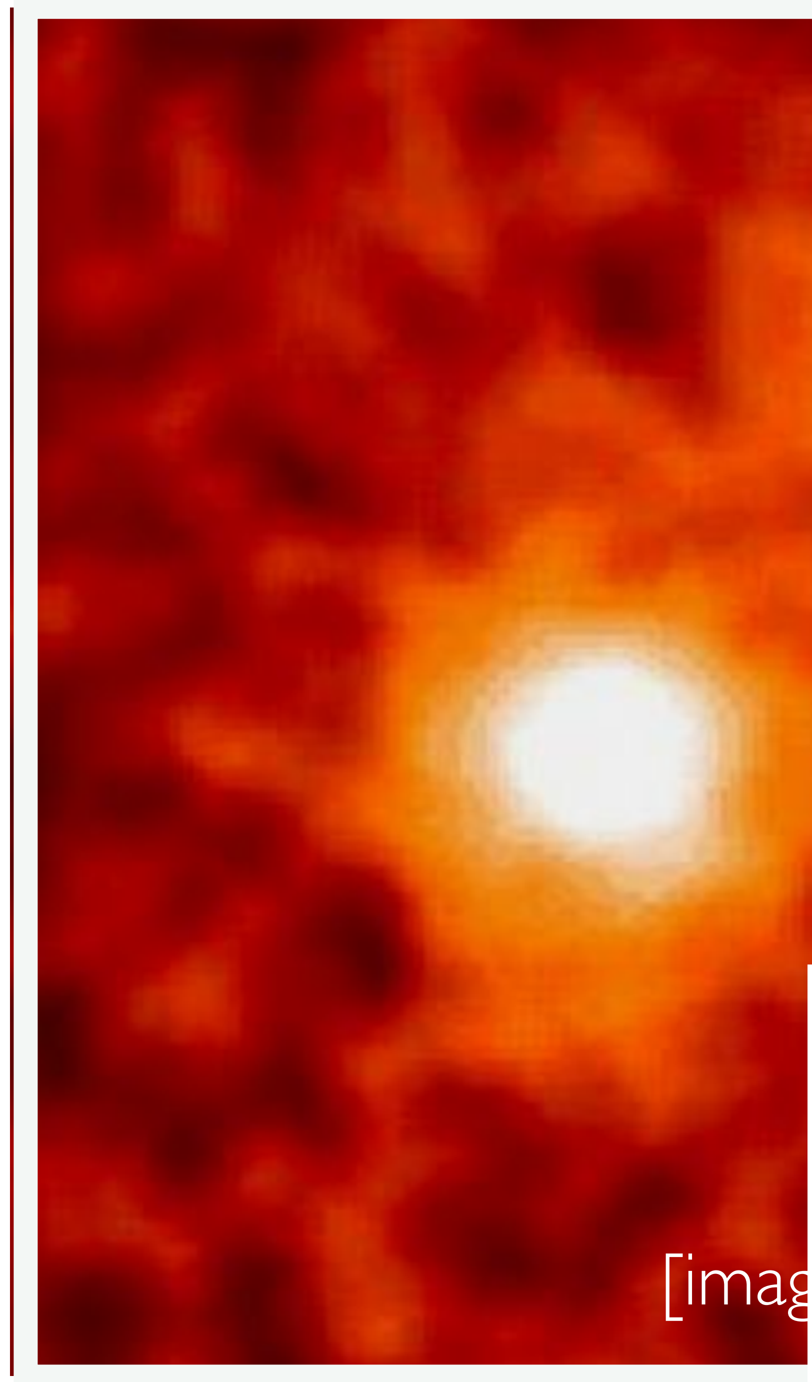


[image from VLBA]

Optical

[image from SDSS]

γ-rays



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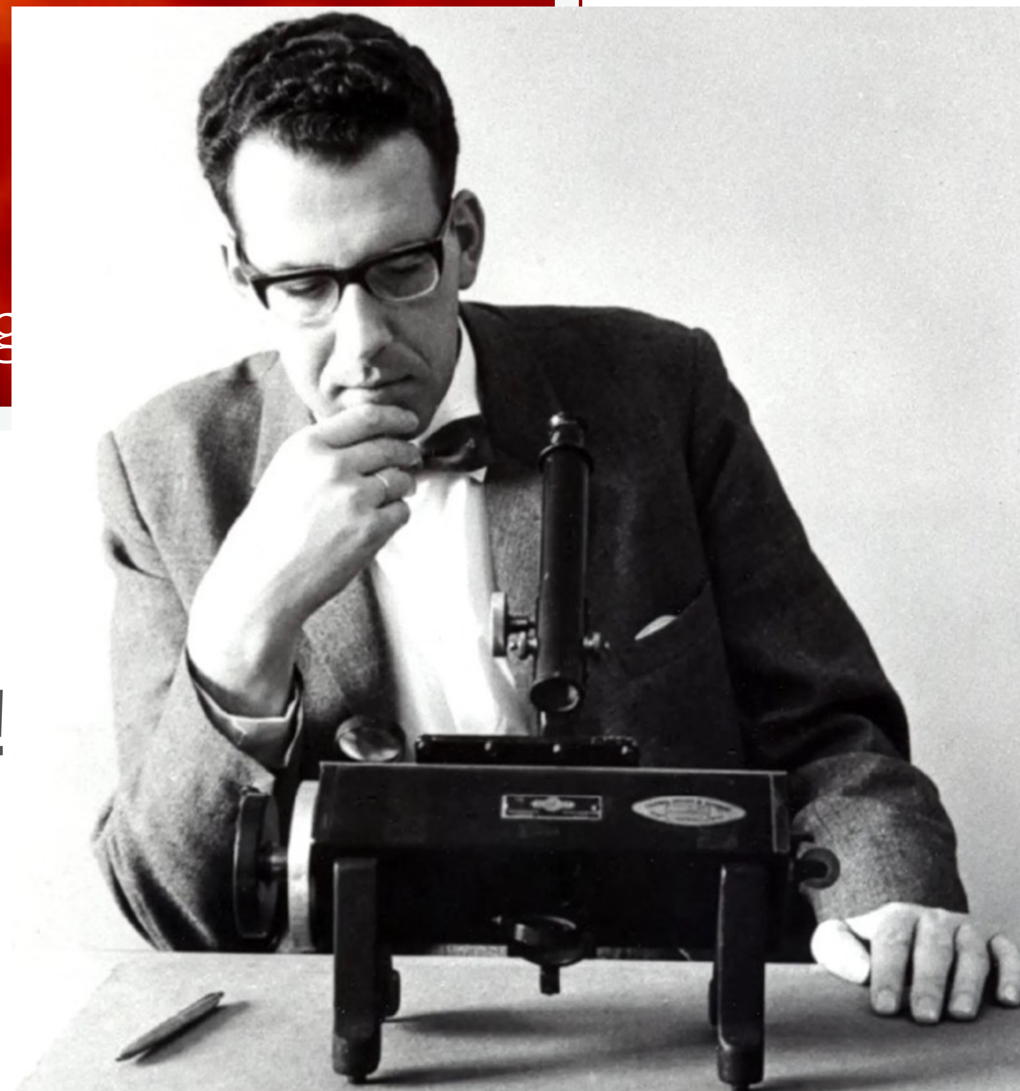


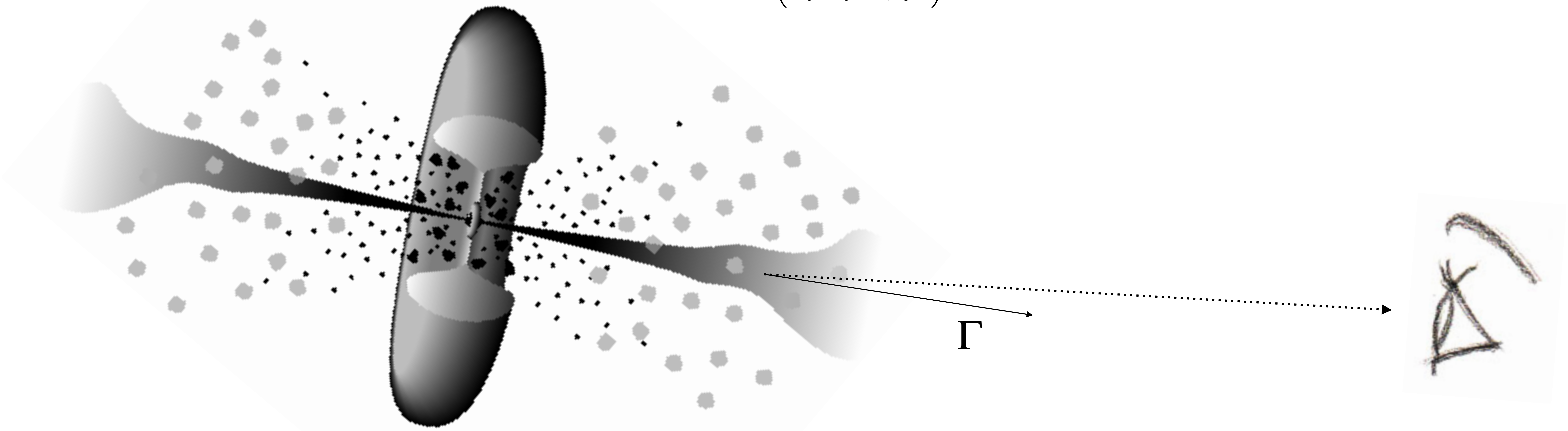
No spectacular jets…but wealth of information from timing/variability and spectra!

Relativistic beaming

Usual relativity (rulers and clocks)

$$\Delta x = \frac{\Delta x'}{\Gamma} \qquad \Delta t = \Delta t' \, \Gamma \qquad \Gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \Gamma = 10 - 50 \text{ in blazars}$$

Not so for photons!
(Terrel 1959)



Relativistic beaming

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

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

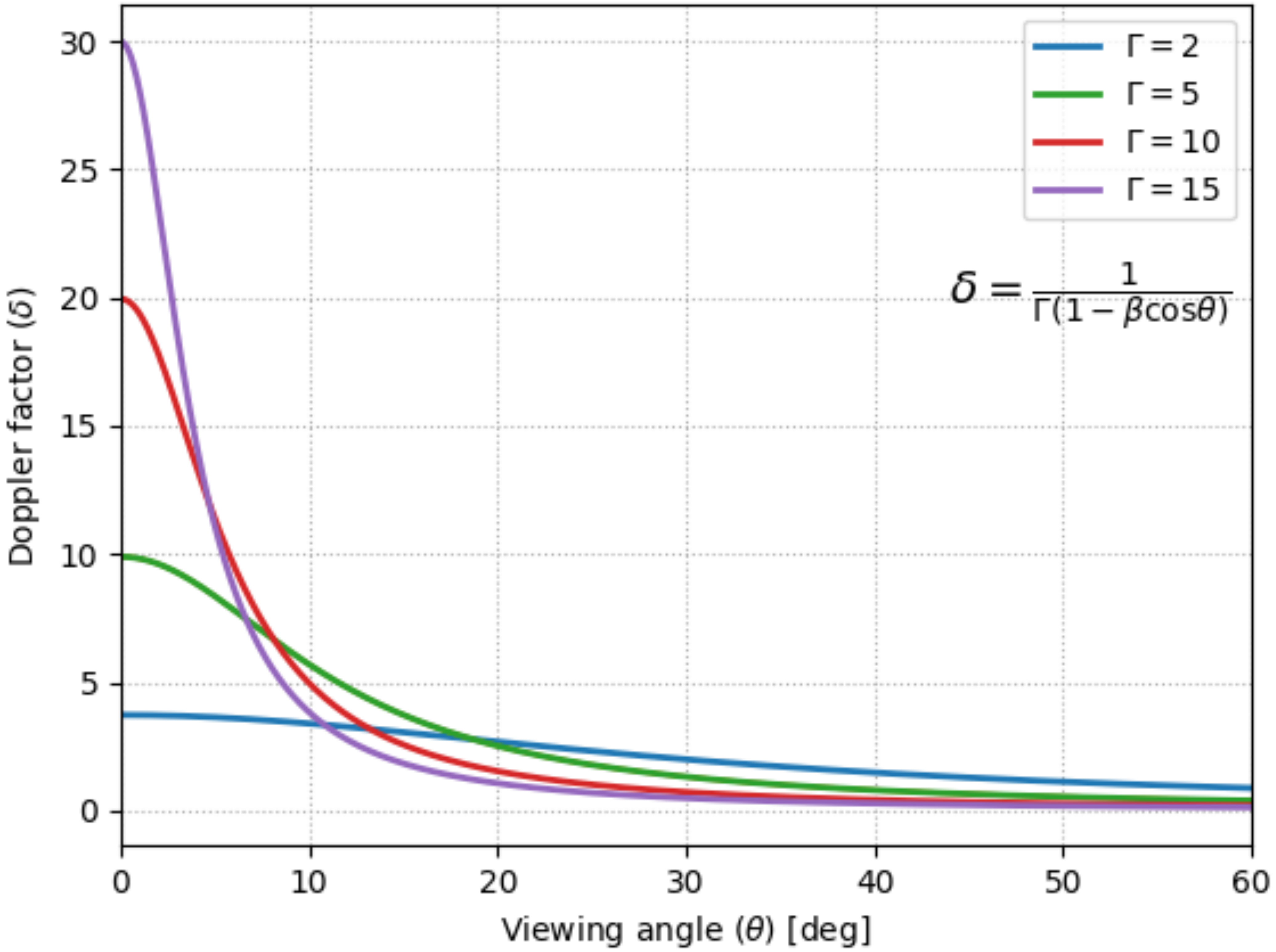
$\Delta t = \Delta t'/\delta$ (shortening of timescales)

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

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

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

(dashes denote rest-frame quantities)



Special cases:

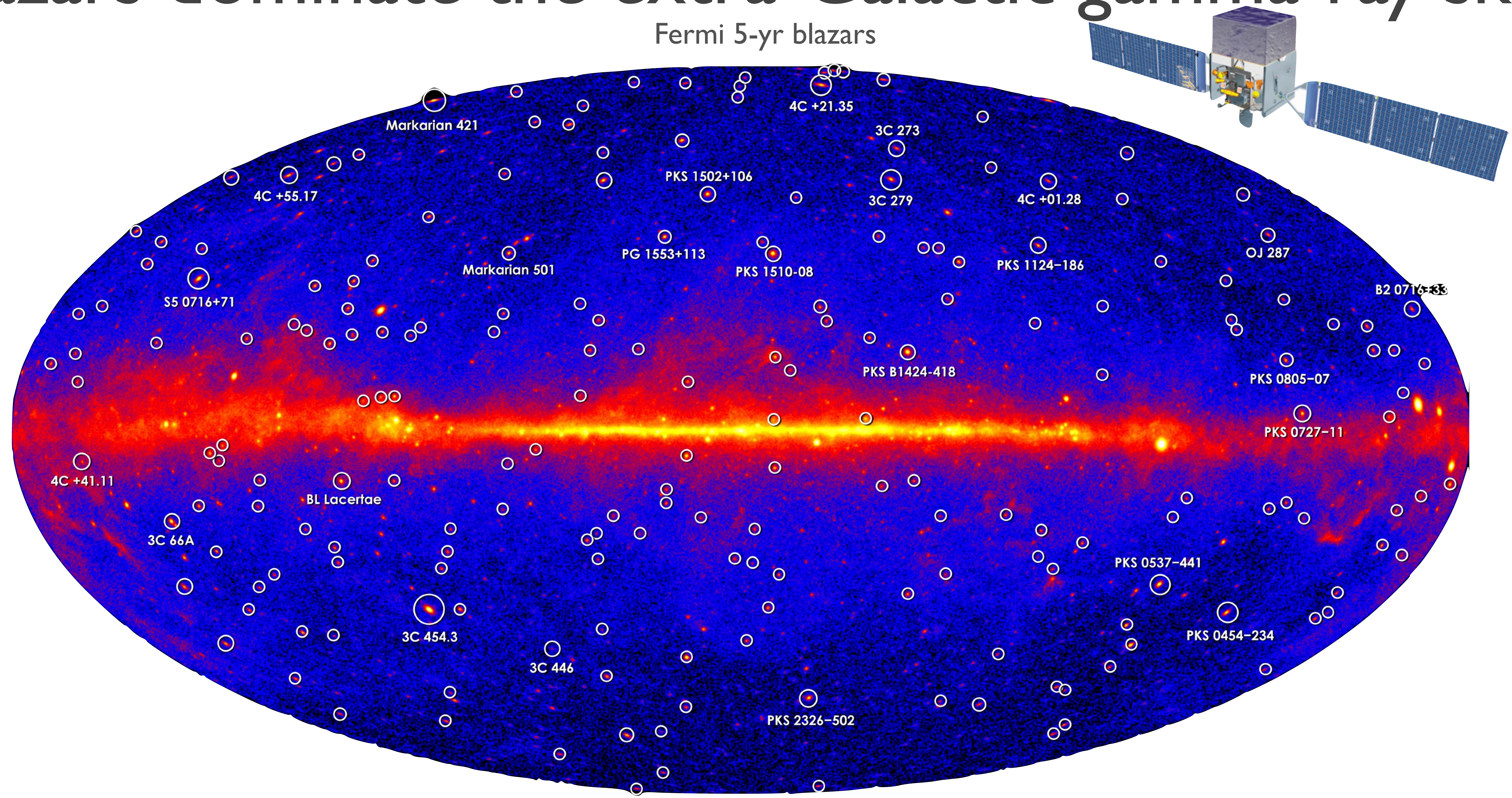
$\delta_{\max} = \delta(0°) = \dfrac{1}{\Gamma(1-\beta)} = \Gamma(1+\beta) \sim 2\Gamma$

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

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

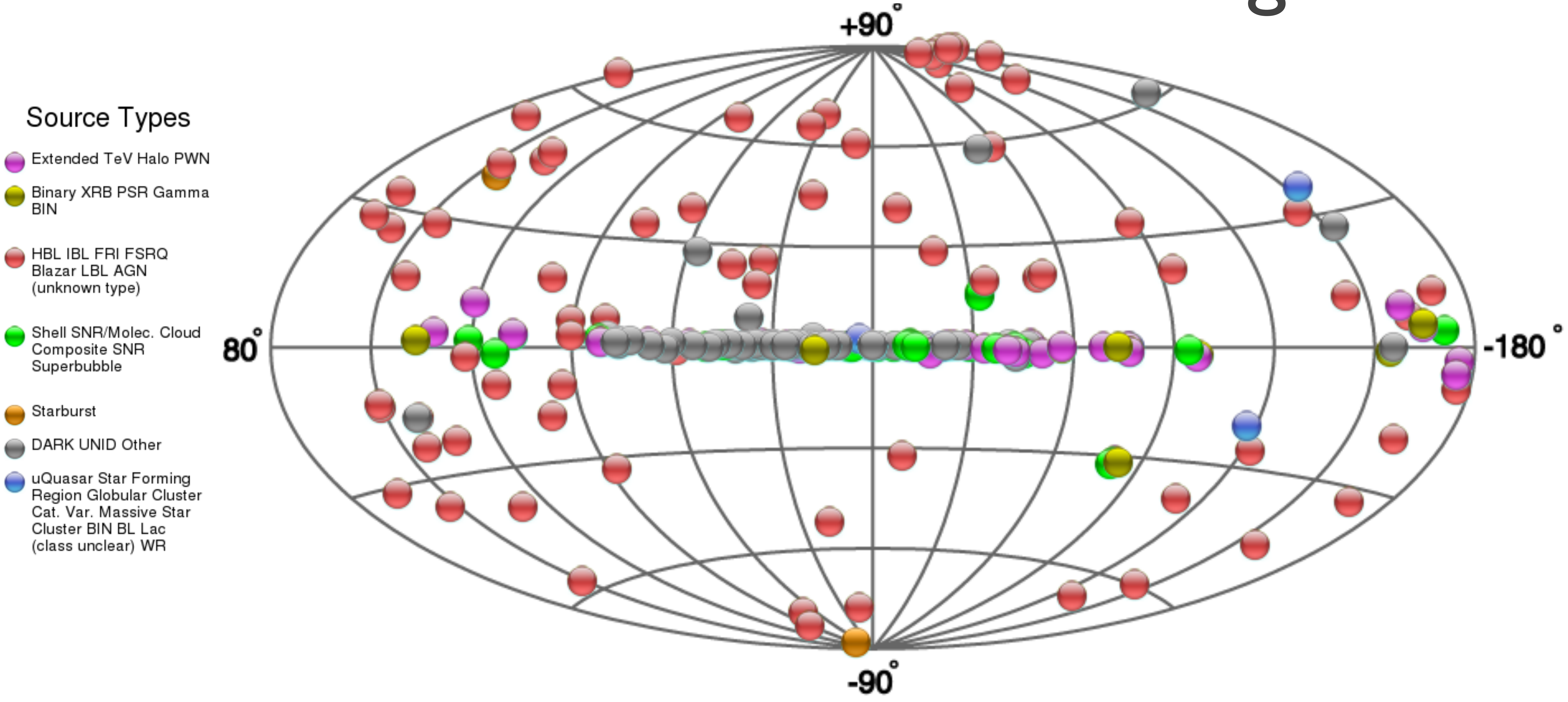
Blazars dominate the extra-Galactic gamma-ray sky

Fermi 5-yr blazars

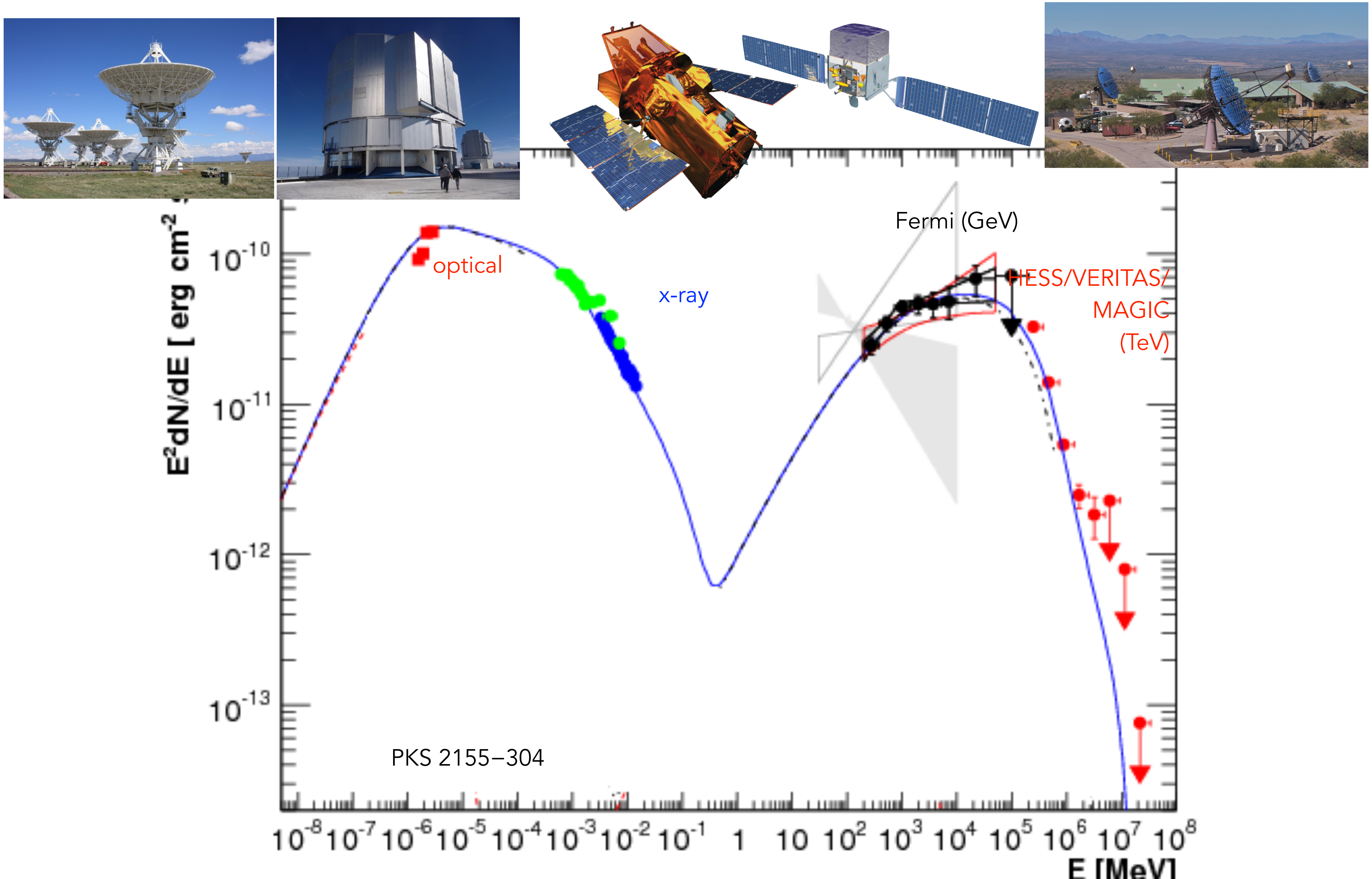


>90% of extragalactic Fermi sources (see also TeVCaT)

Blazars dominate the extra-Galactic gamma-ray sky



Blazar spectral energy distribution

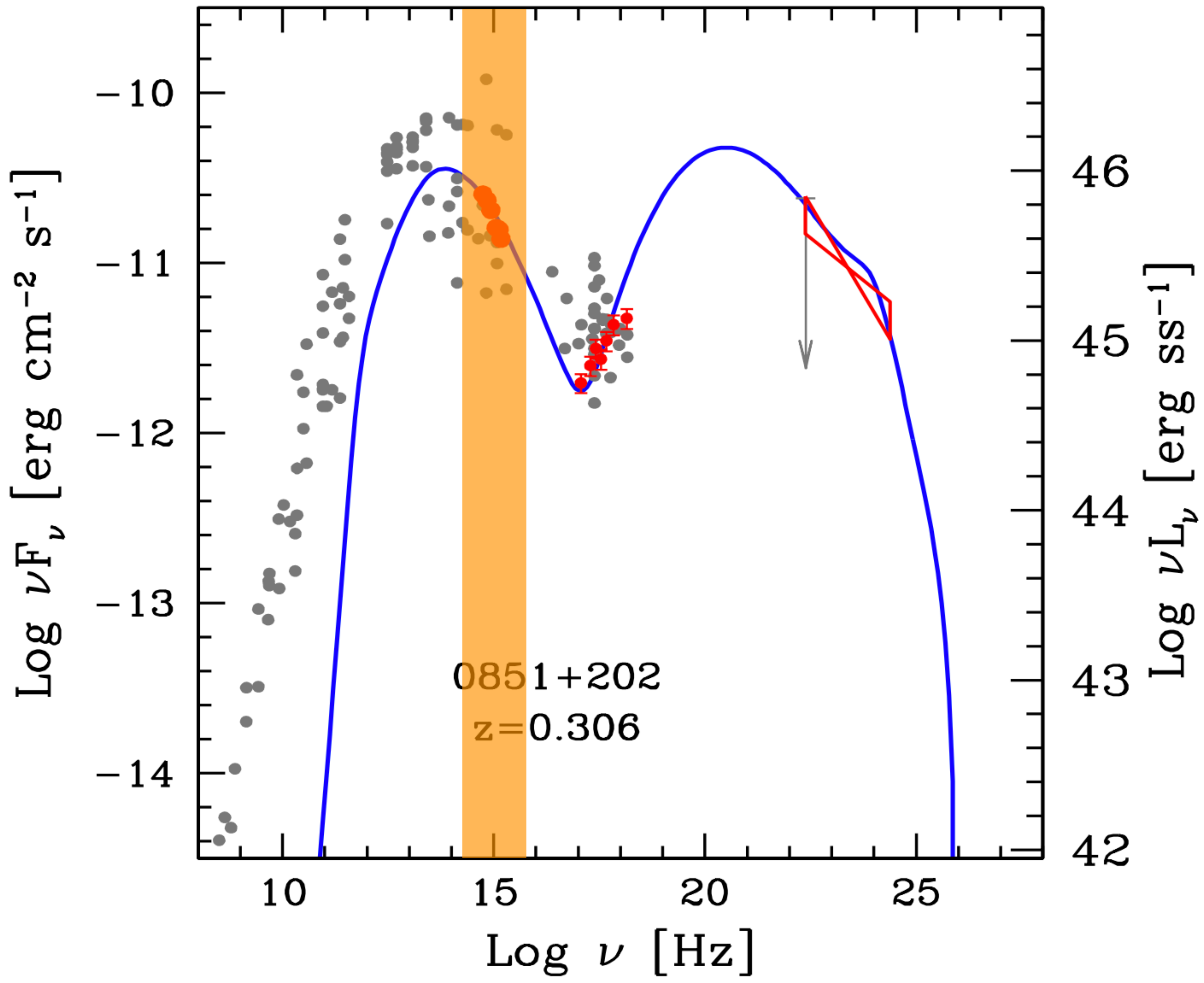


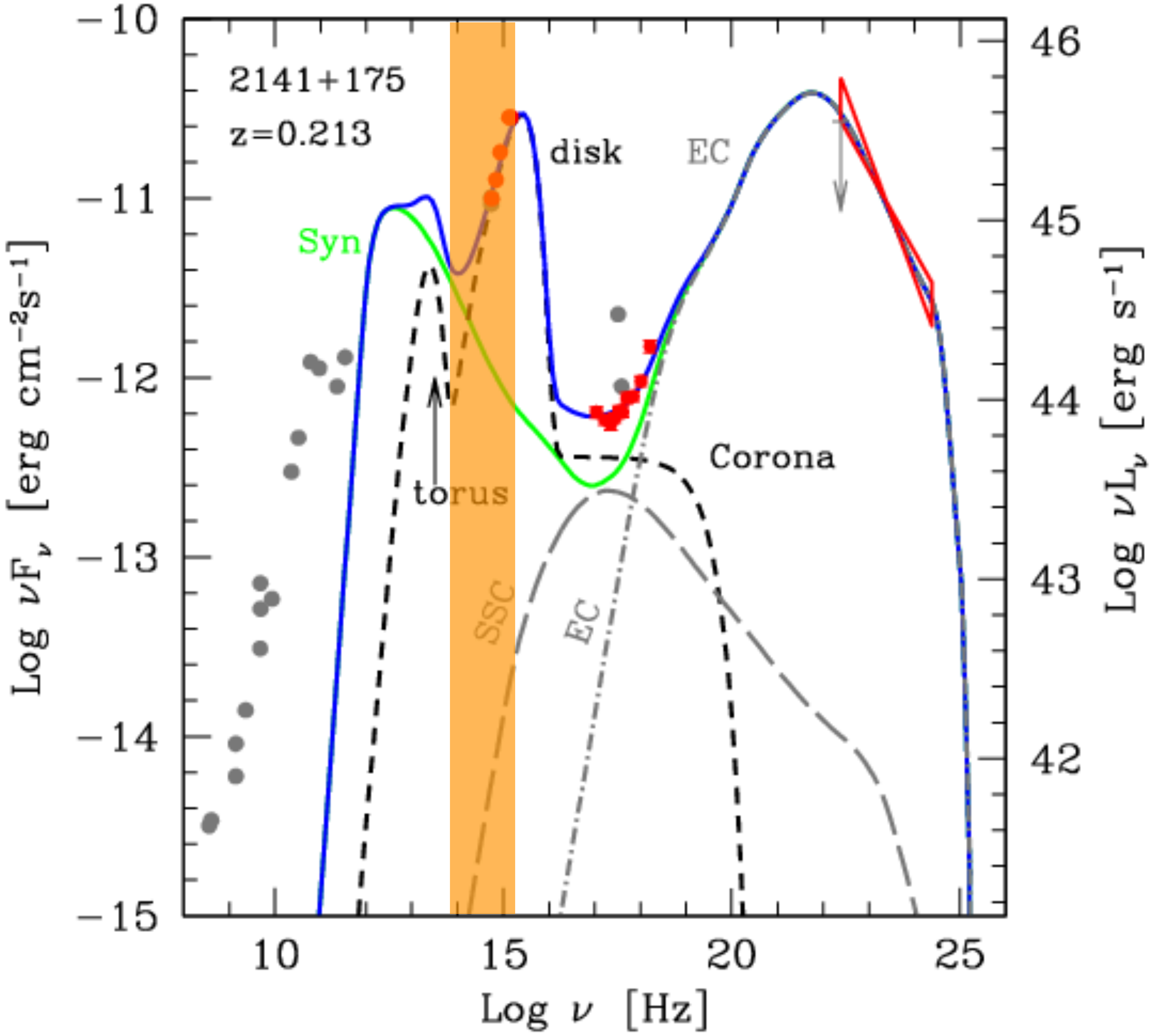
Blazar classes: BL Lac objects and FSRQs

BL Lac Object

Optical light

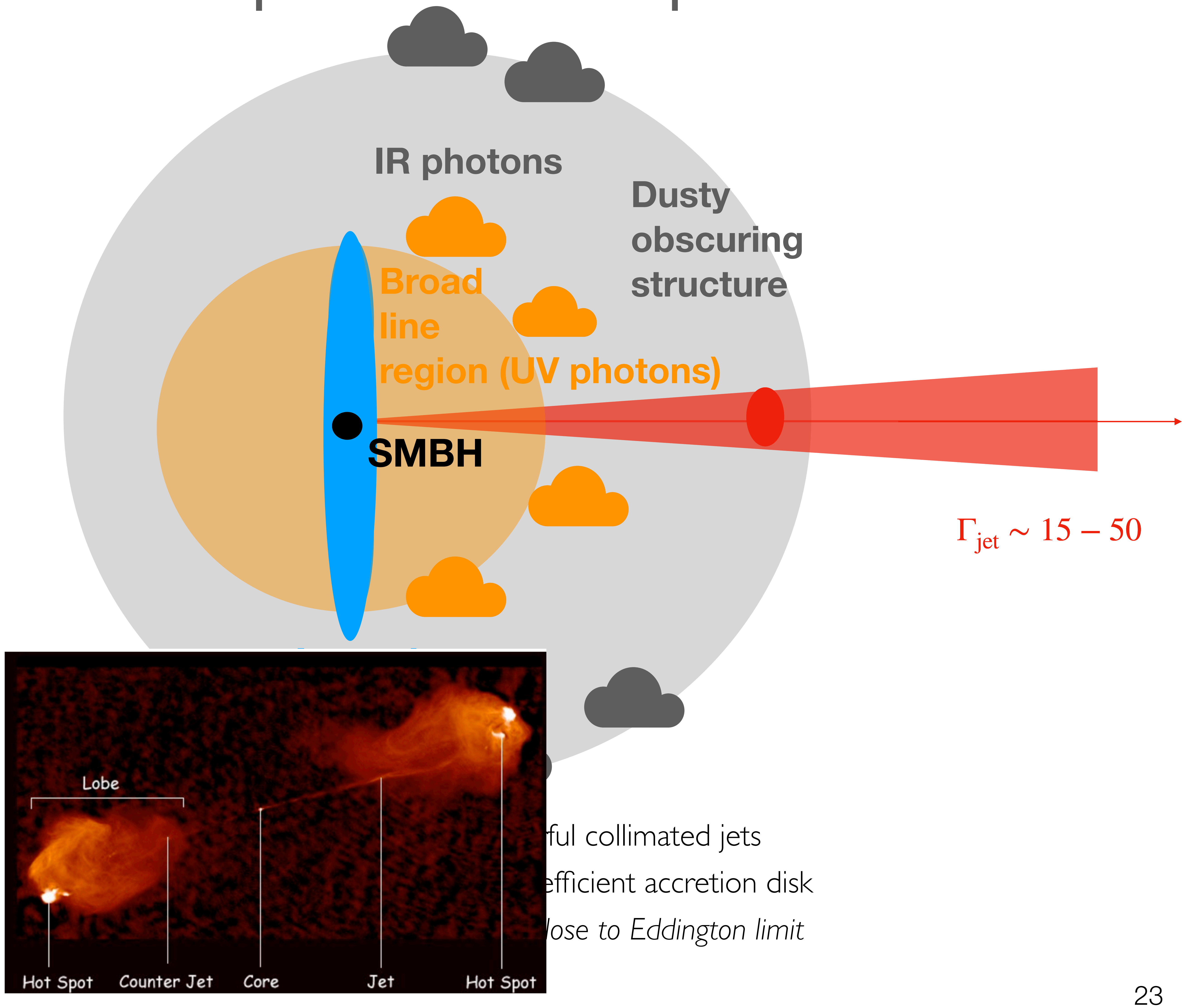
Flat spectrum radio quasar





Blazar subclasses and photon fields

Flat spectrum radio quasars



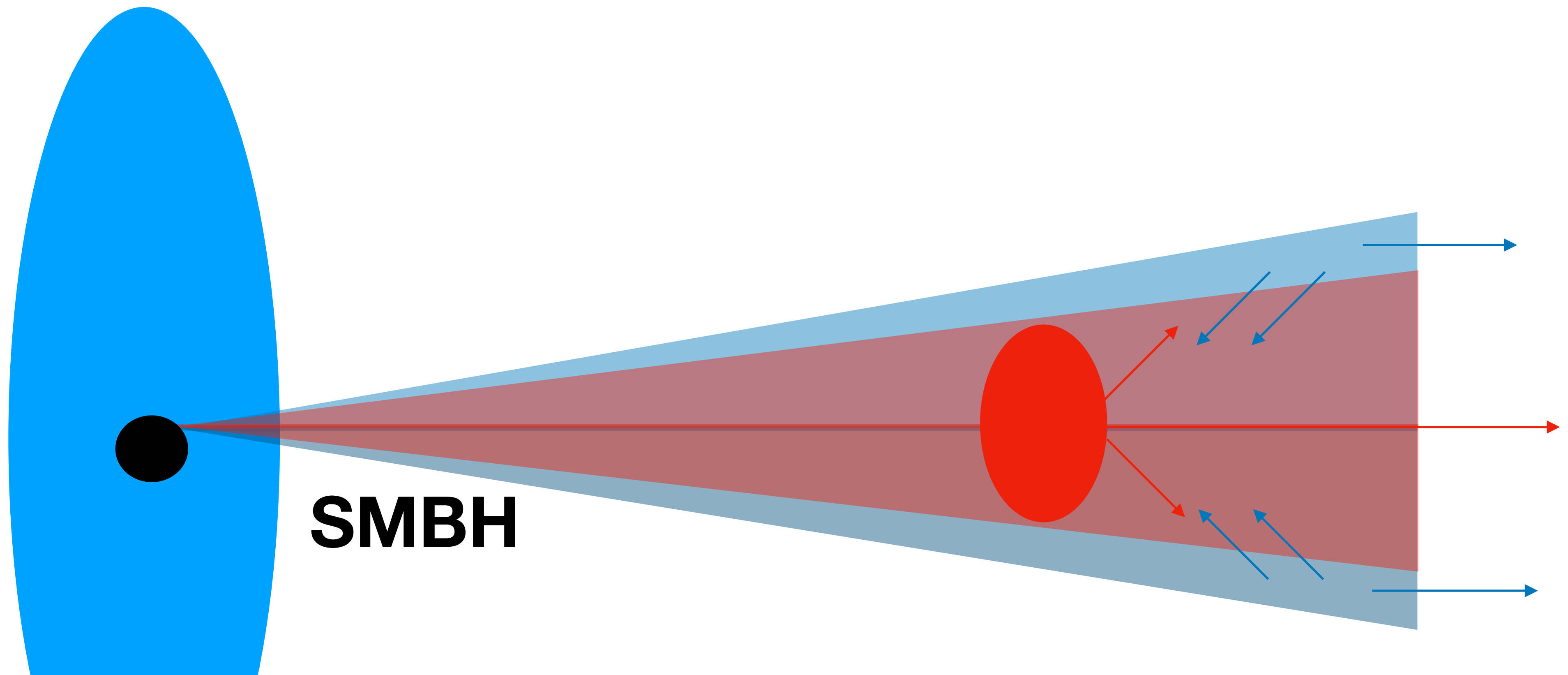
ful collimated jets

efficient accretion disk

lose to Eddington limit

BL Lac Objects

Slow moving outer layer? “sheath”

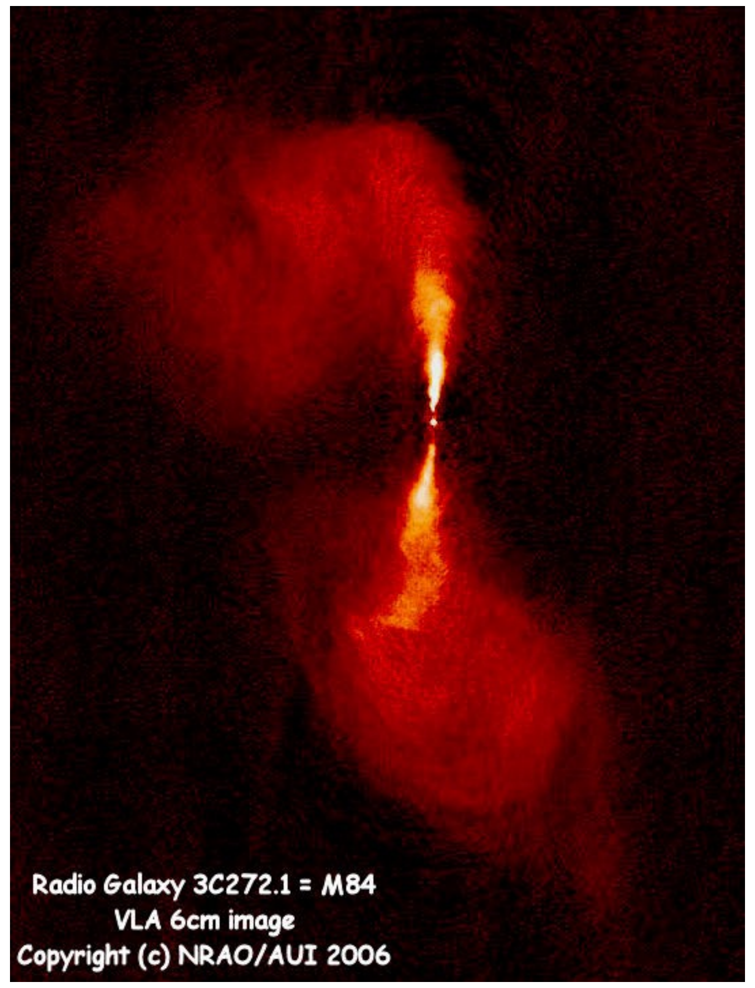


Inefficient accretion

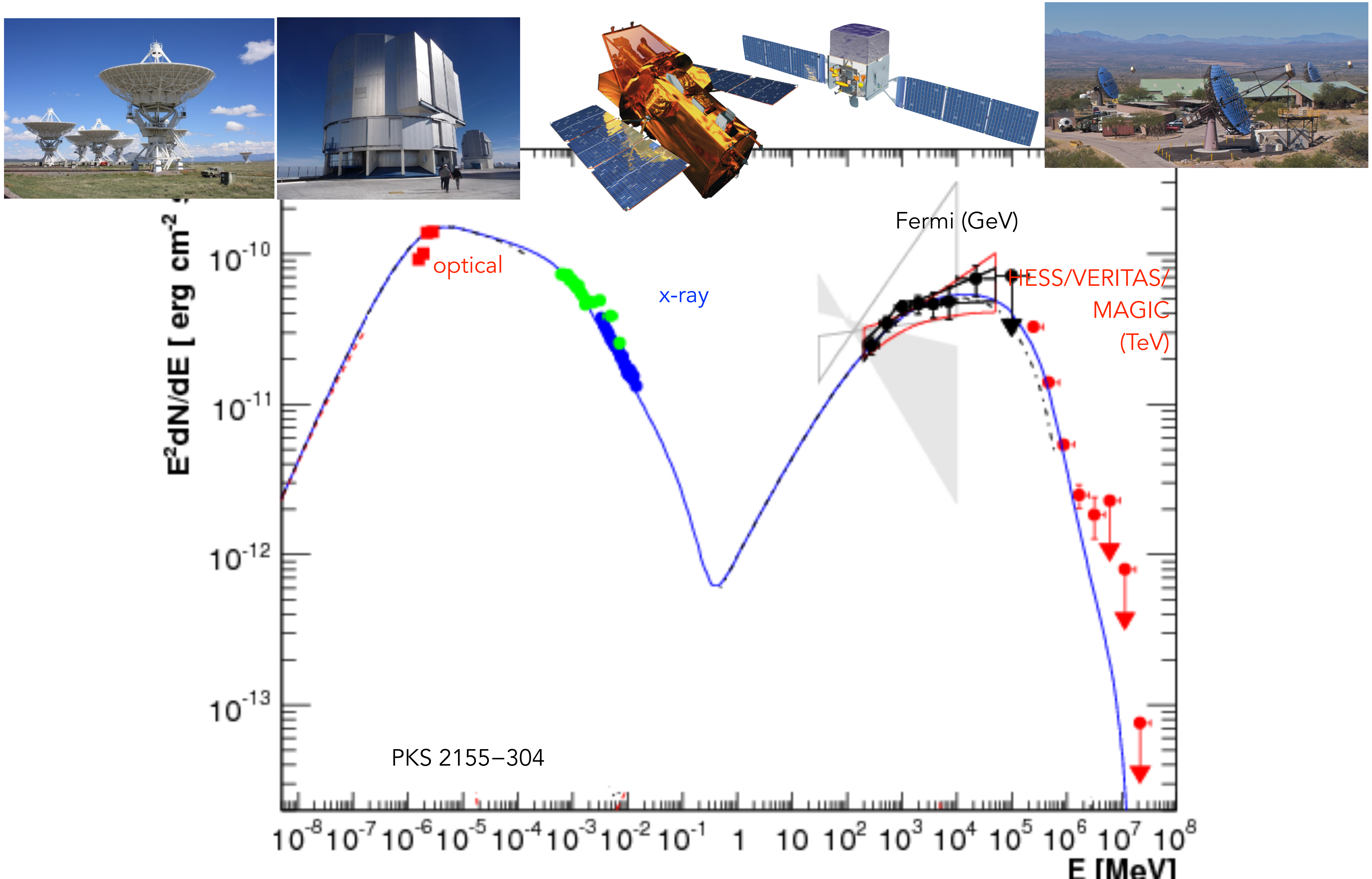
dust?

Less collimated jets

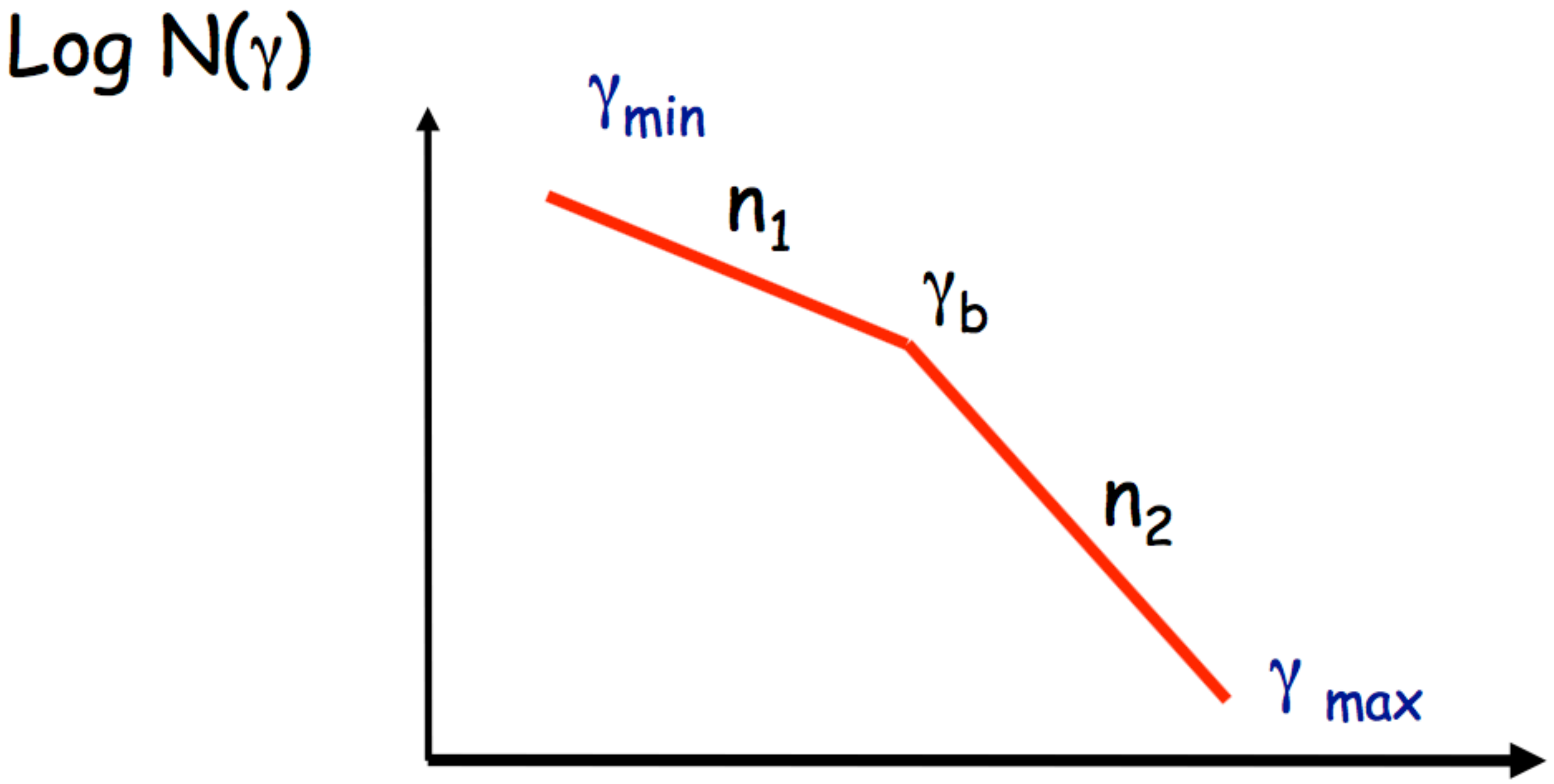
Radiatively inefficient accretion disk

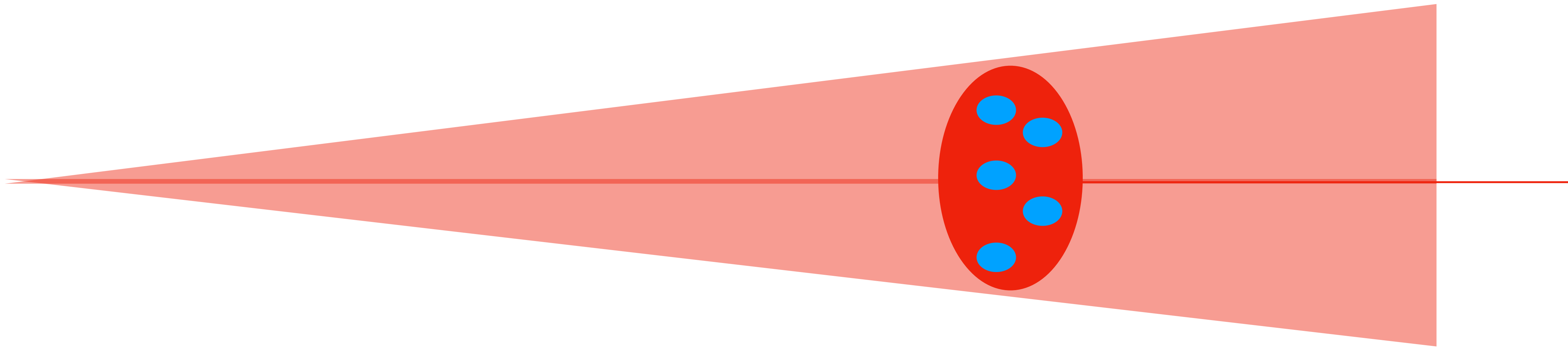


Blazar spectral energy distribution



Emission from BL Lac objects



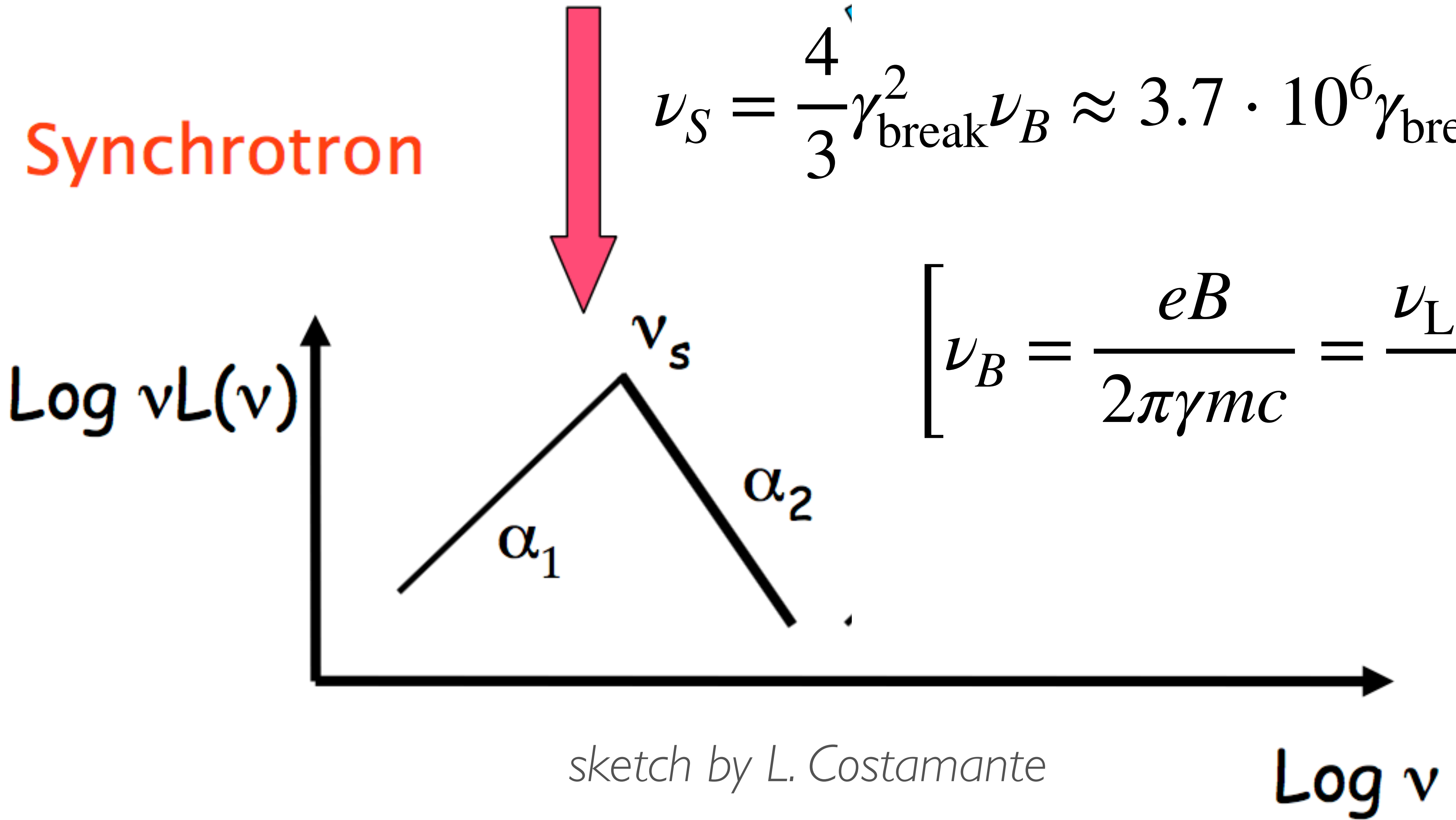


Relativistic electrons in a compact, relativistic region moving at $\beta \sim 1$

Synchrotron

$$\nu_S = \frac{4}{3}\gamma_{\mathrm{break}}^2 \nu_B \approx 3.7 \cdot 10^6 \gamma_{\mathrm{break}} B\delta$$

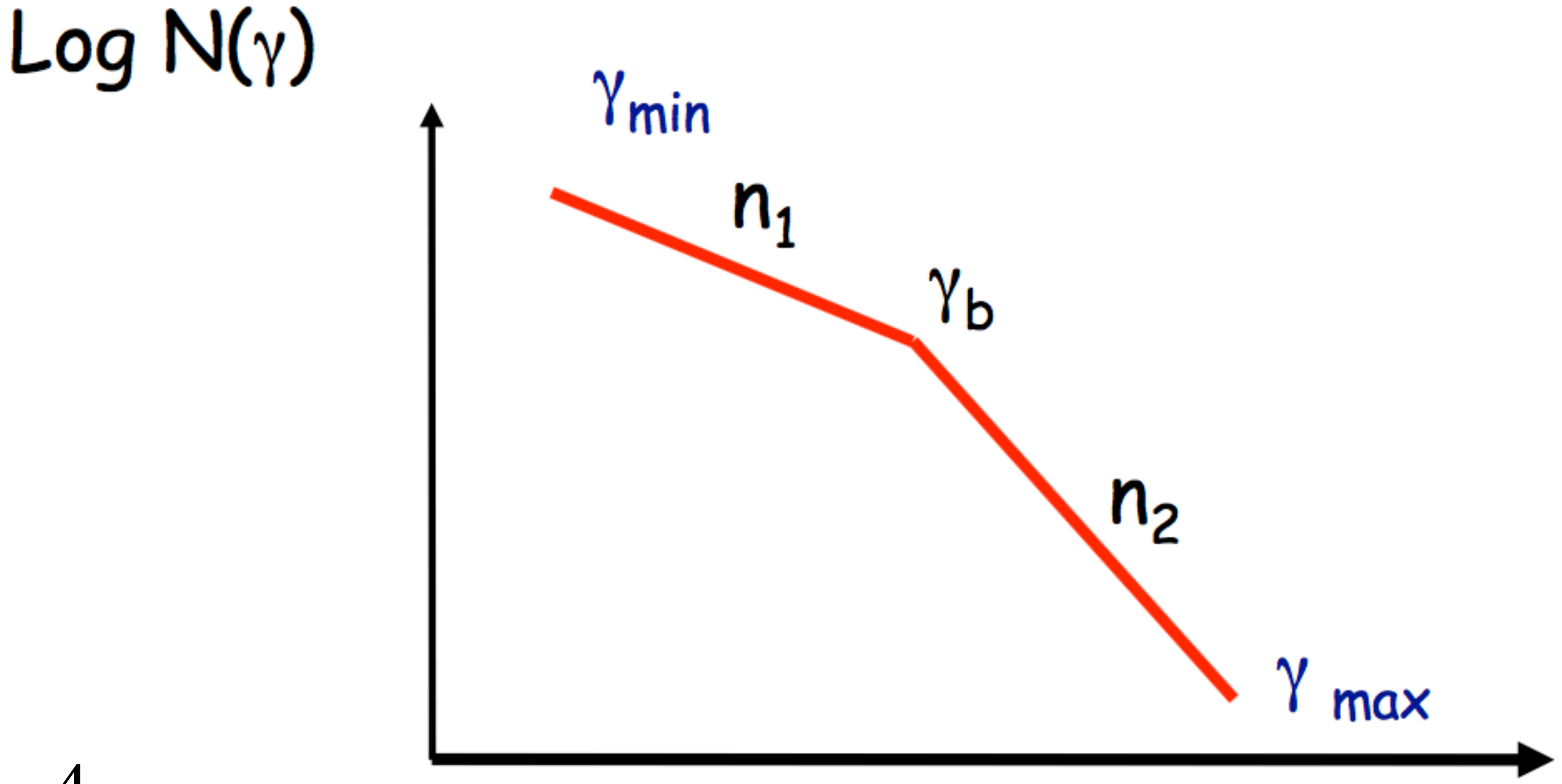
$$\left[\nu_B = \frac{eB}{2\pi\gamma mc} = \frac{\nu_{\mathrm{Larmor}}}{\gamma}\right]$$



Magnetic field strength B, doppler factor δ, electron Lorentz factor γ

sketch by L. Costamante

Emission from BL Lac objects

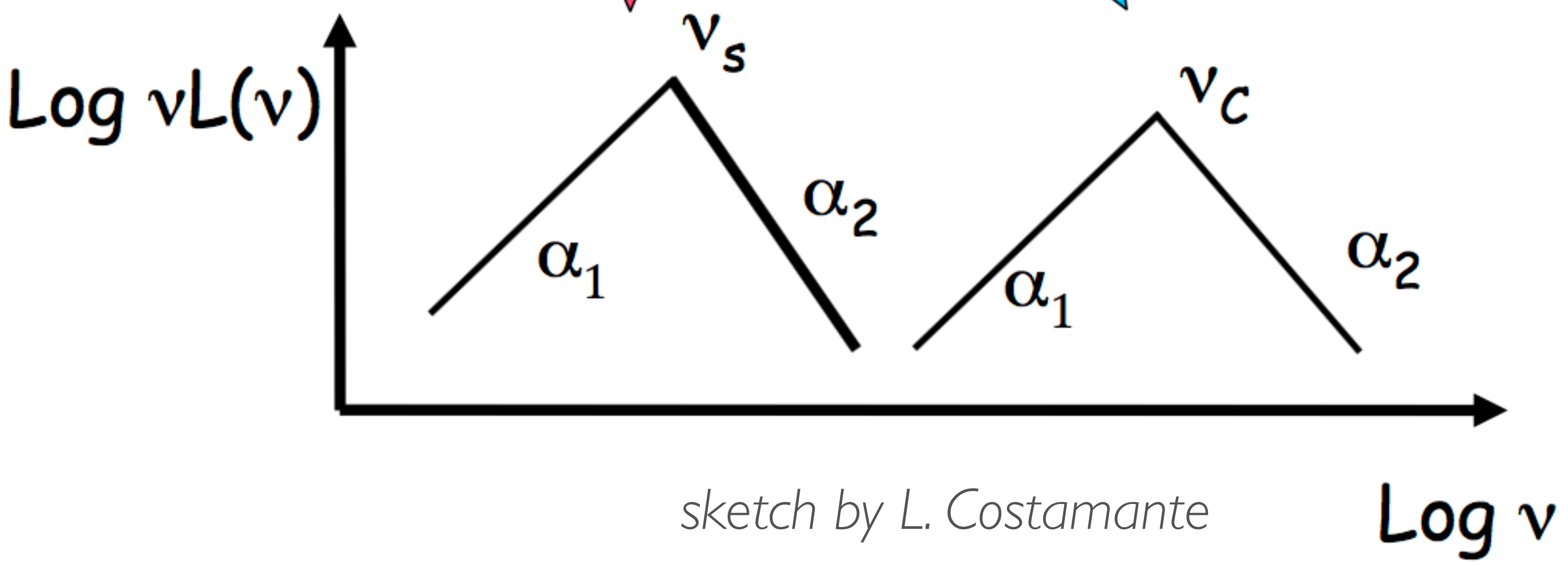


$$\nu_S = \frac{4}{3}\gamma_{\rm break}^2 \nu_B \approx 3.7 \cdot 10^6 \gamma_{\rm break} B\delta$$

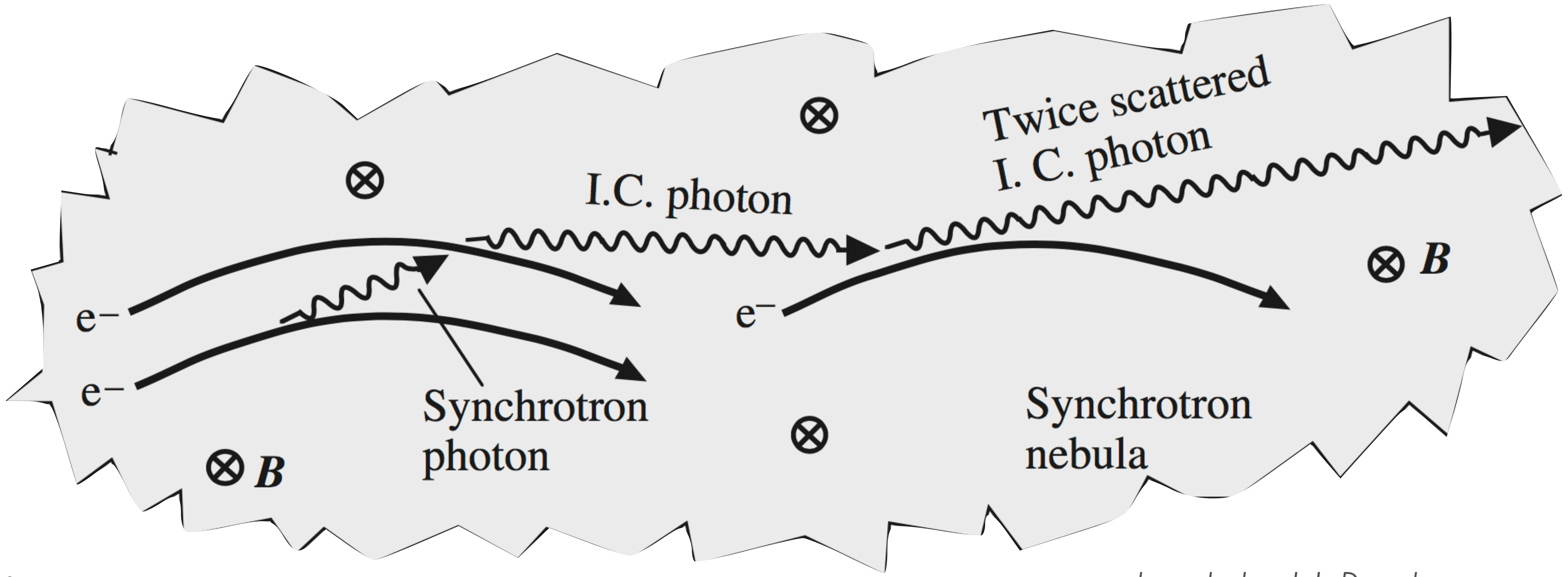
$$\nu_C = \frac{4}{3}\gamma_{\rm b}^2 \nu_S$$

Synchrotron

Inverse Compton



sketch by L. Costamante



sketch by H. Bradt

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

What we can infer from the blazar SED

Low peak very likely synchrotron all from same region (correlated variability)

$$L_s \propto U_B - (1)$$

$$U_B = \frac{B^2}{8\pi} - (2)$$

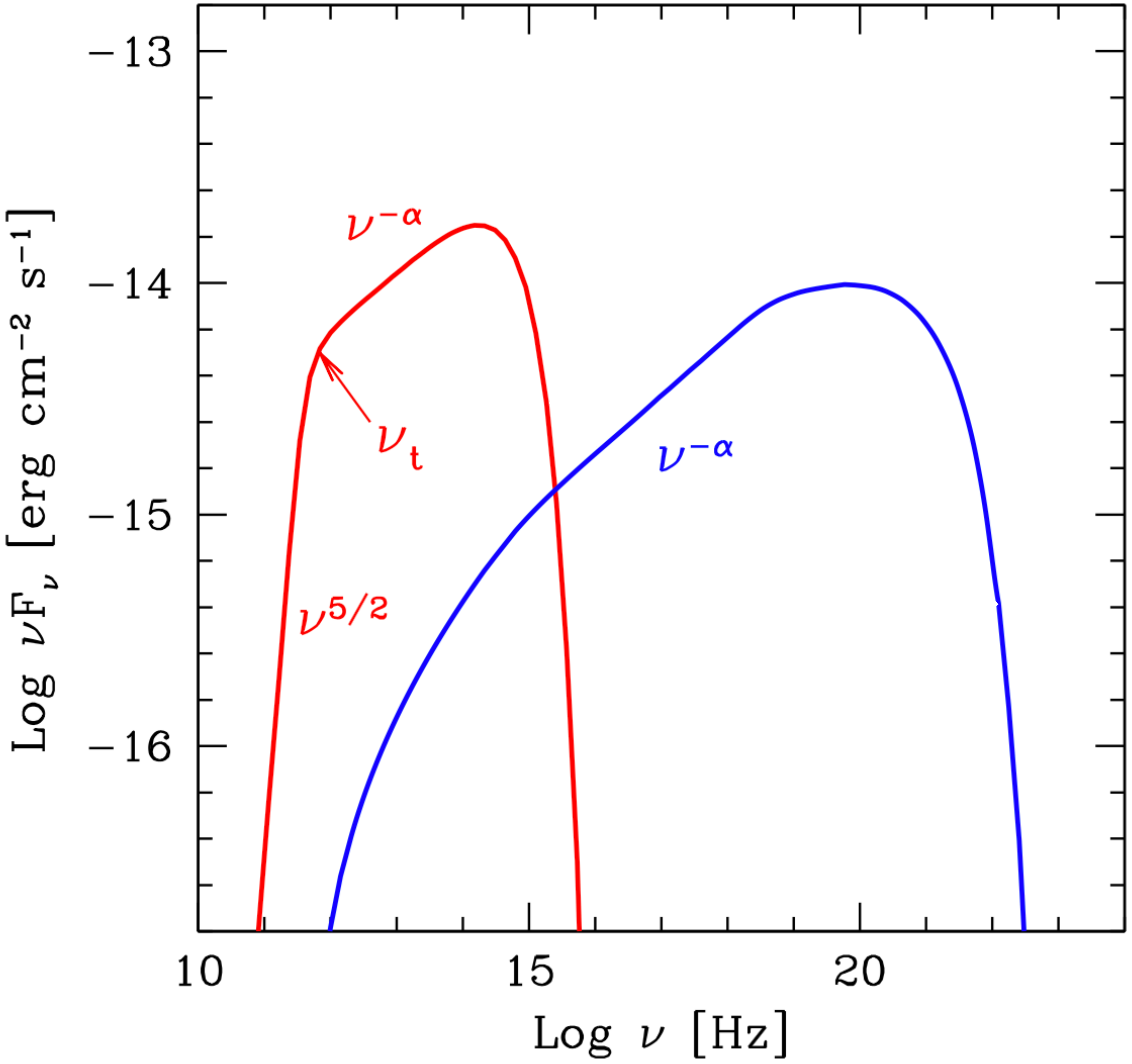
Often correlated variability in high peak, -> Inverse Compton with synchrotron photons

$$L_{\mathrm{IC}} \propto U_{\mathrm{rad}} - (3)$$

$$U_{\mathrm{rad}} = \frac{L_s}{4\pi R^2 \delta^4 c} - (4)$$

$$R = ct_{\mathrm{var}} \frac{\delta}{1+z}$$

G. Ghisellini, Radiative Processes in HE Astrophysics (2012)



What we can infer from the blazar SED

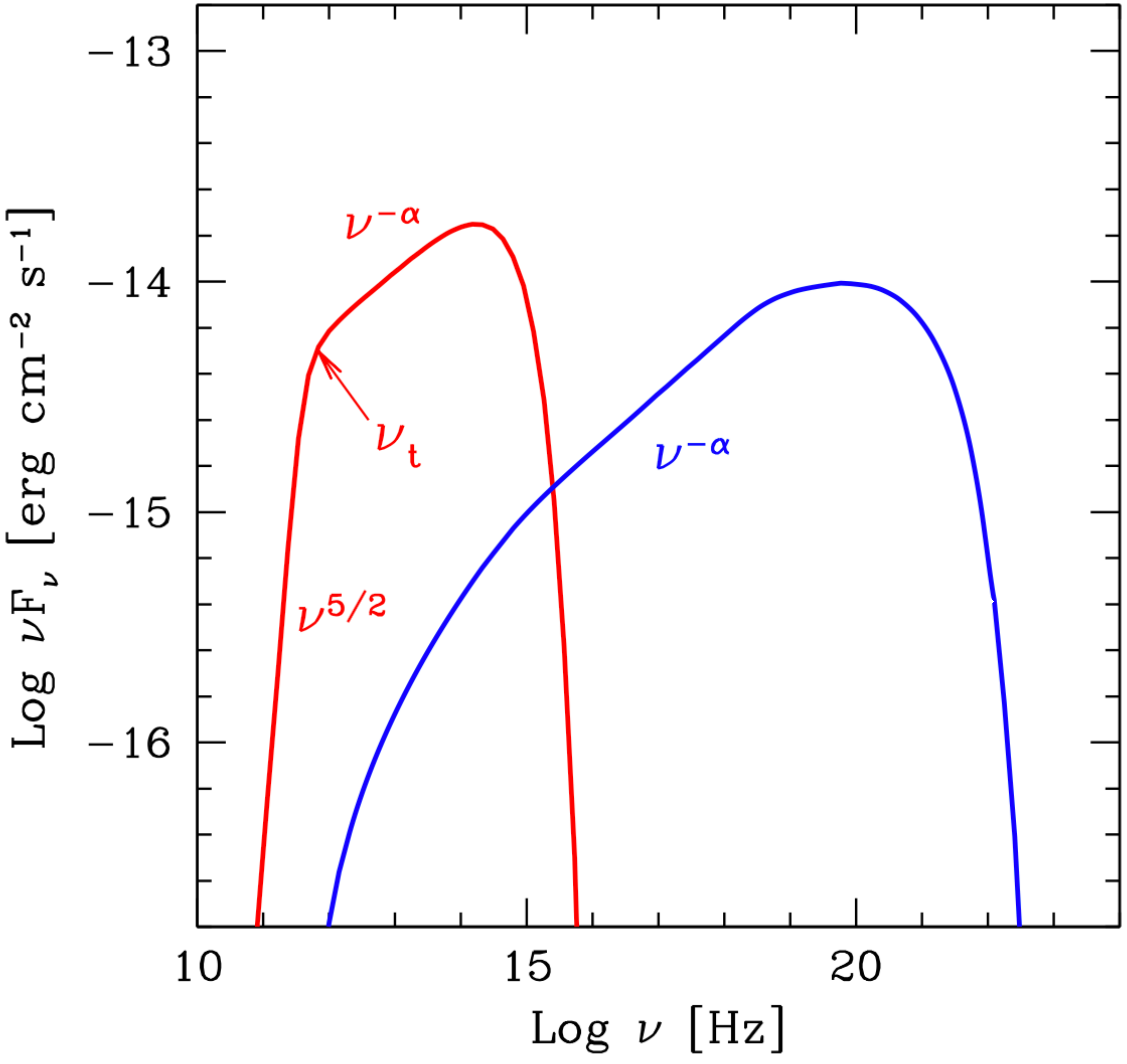
Combining (1), (2) & (3)

$$\frac{L_C}{L_S} = \frac{U_{\rm rad}}{U_B} = \frac{2L_s}{R^2\delta^4 cB^2}$$

Rearranging, we get,

$$B^2\delta^3 = (1+z)\frac{L_s}{ct_{\rm var}}\left(\frac{2}{cL_C}\right)^{1/2} \quad -\ (5)$$

G. Ghisellini, Radiative Processes in HE Astrophysics (2012)



What we can infer from the blazar SED

From the peak frequencies we have,

$$\nu_C = \frac{4}{3}\gamma_{\rm break}^2 \nu_S$$

$$\gamma_{\rm break} = \left(\frac{3\nu_C}{4\nu_S}\right)^{1/2} \quad - (6)$$

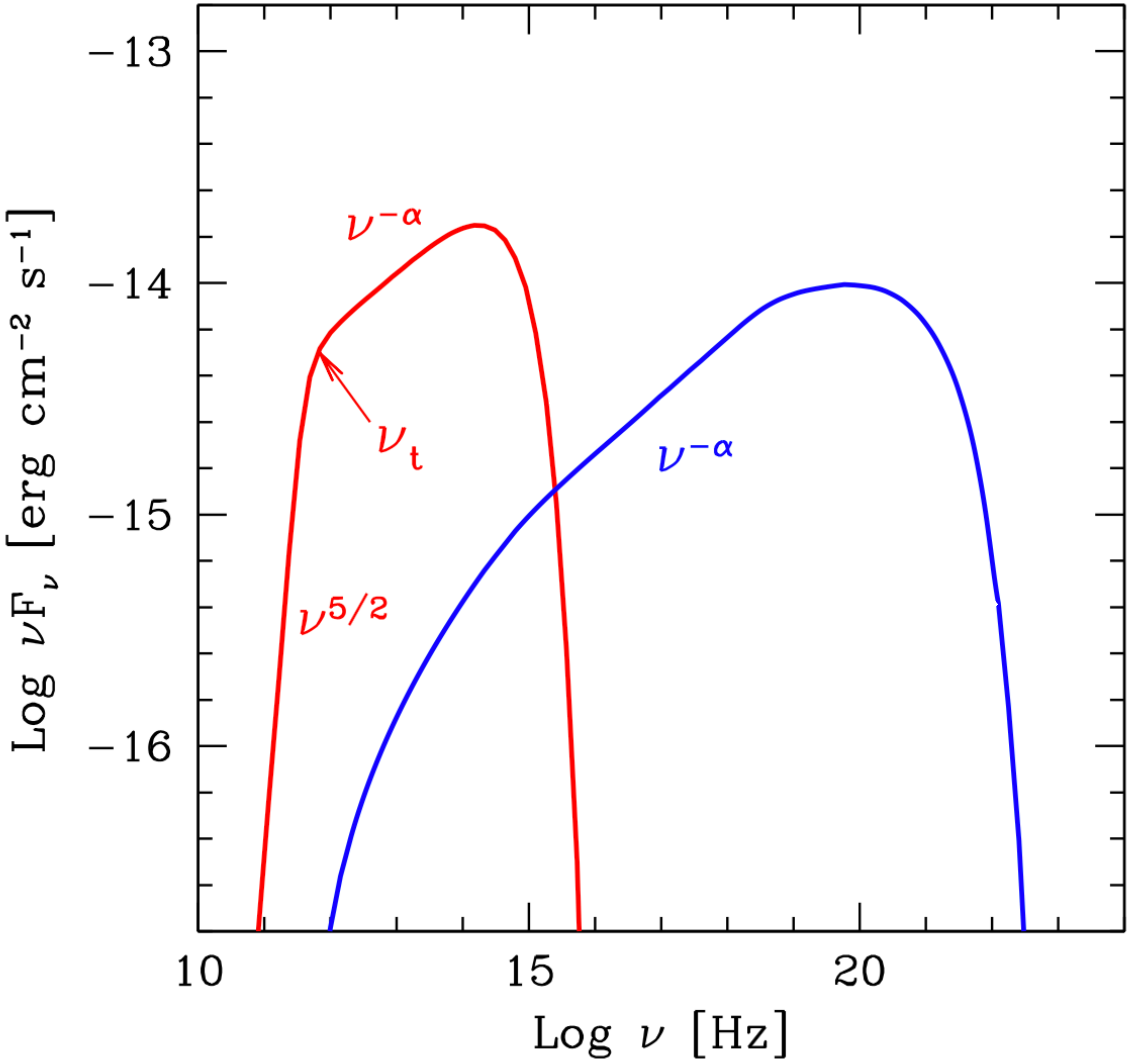
$$\nu_S = \frac{4}{3}\gamma_{\rm break}^2 \nu_B \approx 3.7 \cdot 10^6 \gamma_{\rm break} B \frac{\delta}{1+z}$$

Using (6) we get

$$B \cdot \delta = (1+z)\frac{\nu_S^2}{2.8 \cdot 10^6 \nu_C} \quad - (7)$$

We now have 2 equations (5,7) and 2 unknowns

G. Ghisellini, Radiative Processes in HE Astrophysics (2012)



UHECR acceleration?

For OJ 287:

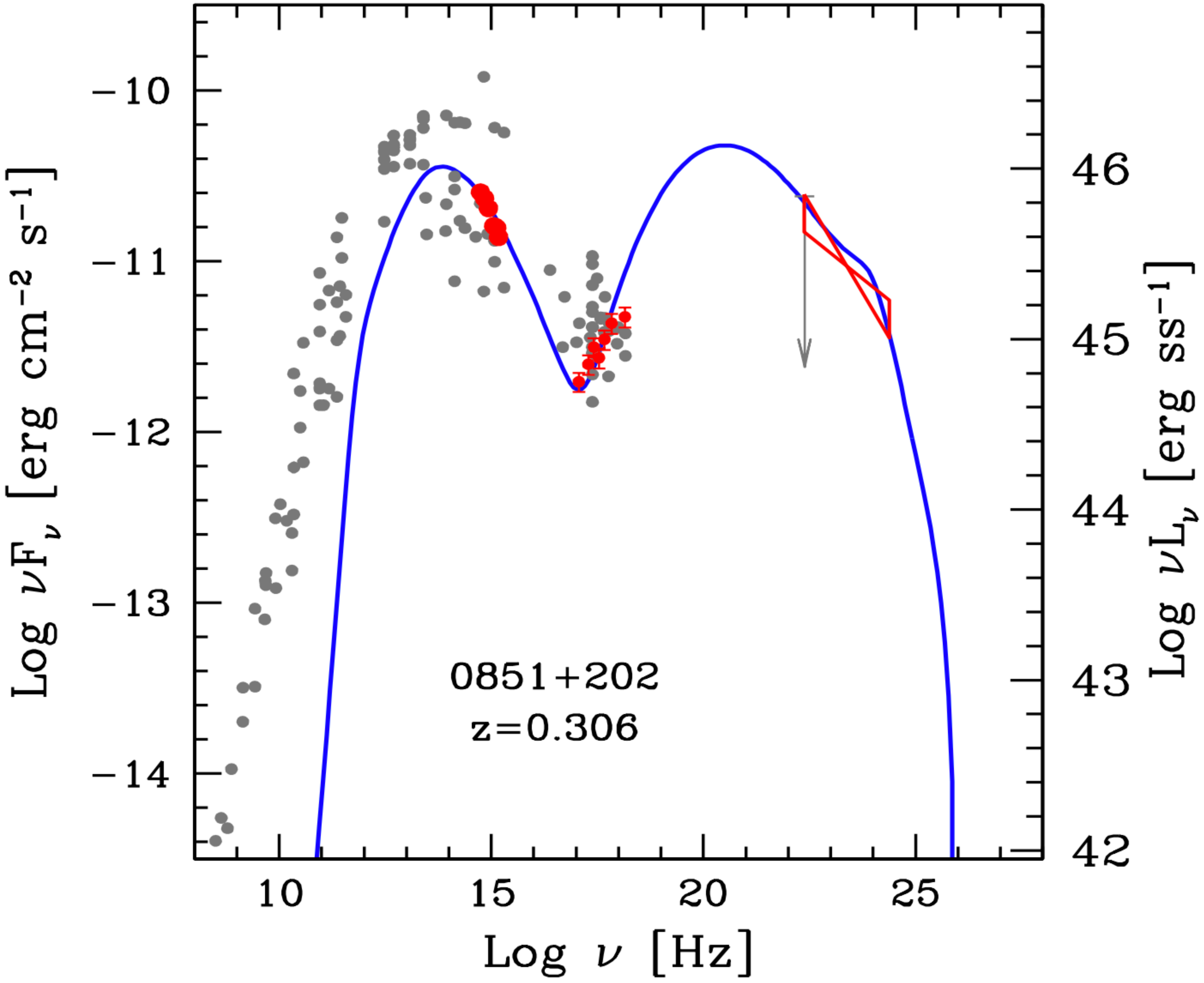
$$t_{\rm var} \sim 10^4 \text{ s}, \nu_{\rm s} \sim 5 \times 10^{13} \text{ Hz}, \nu_{\rm c} \sim 10^{21} \text{ Hz}$$

$$L_C \sim L_S \sim 10^{46} \text{ erg/s}$$

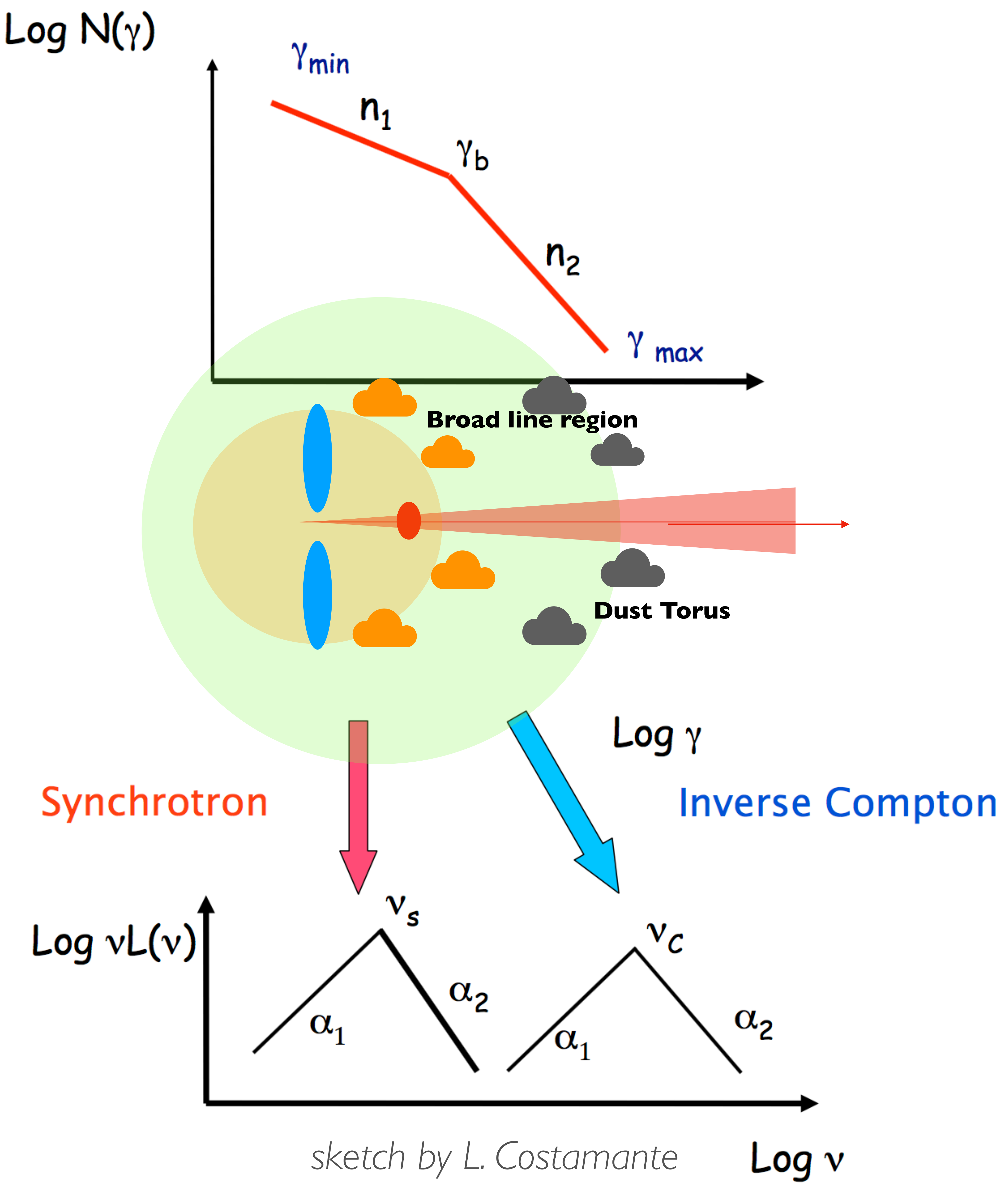
$$\therefore B \approx 0.4\ G, \delta \approx 20$$

$$E_{\rm Hillas} \sim ZeB\Gamma R \sim Z \cdot 4 \times 10^{19} \text{ eV}$$

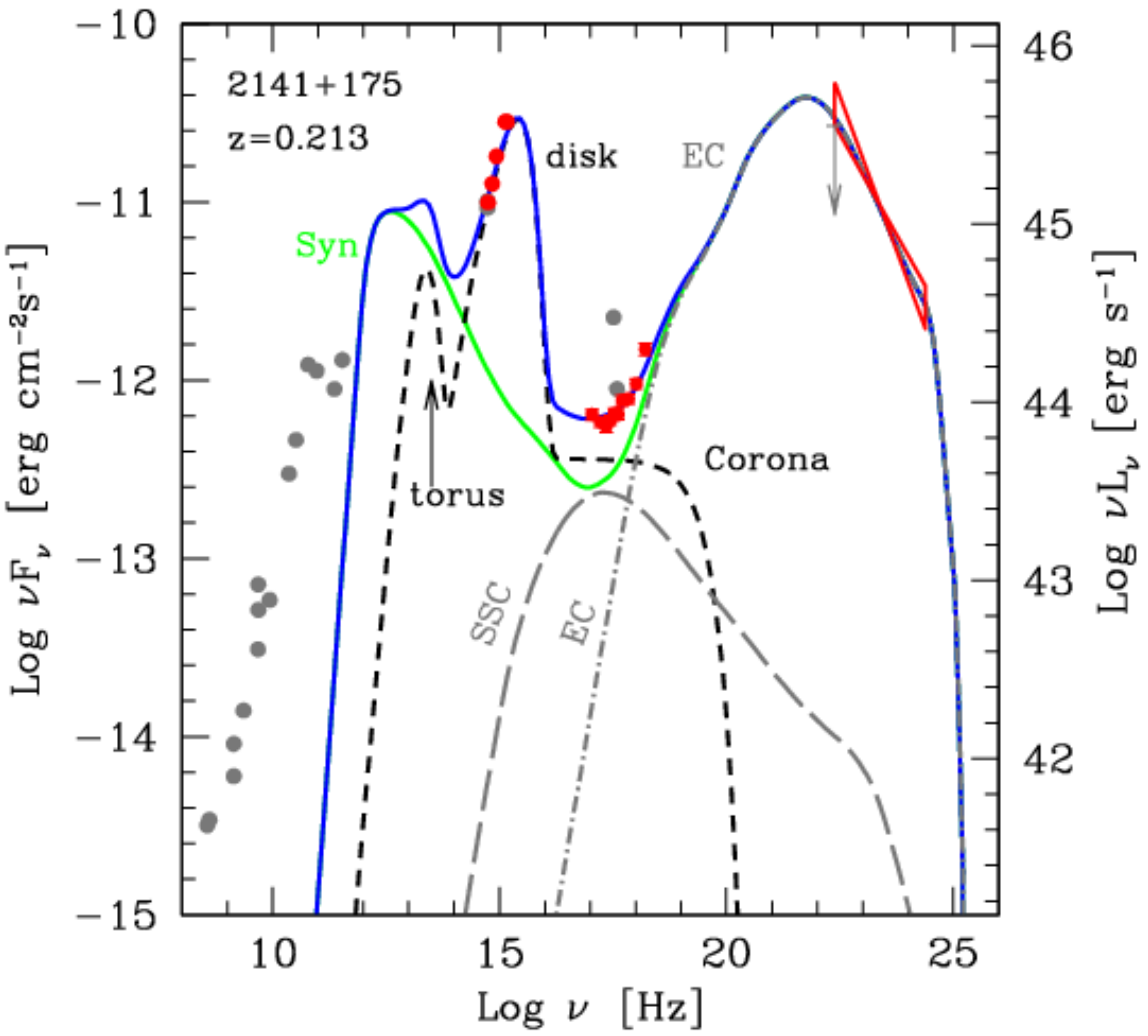
G. Ghisellini, Radiative Processes in HE Astrophysics (2012)



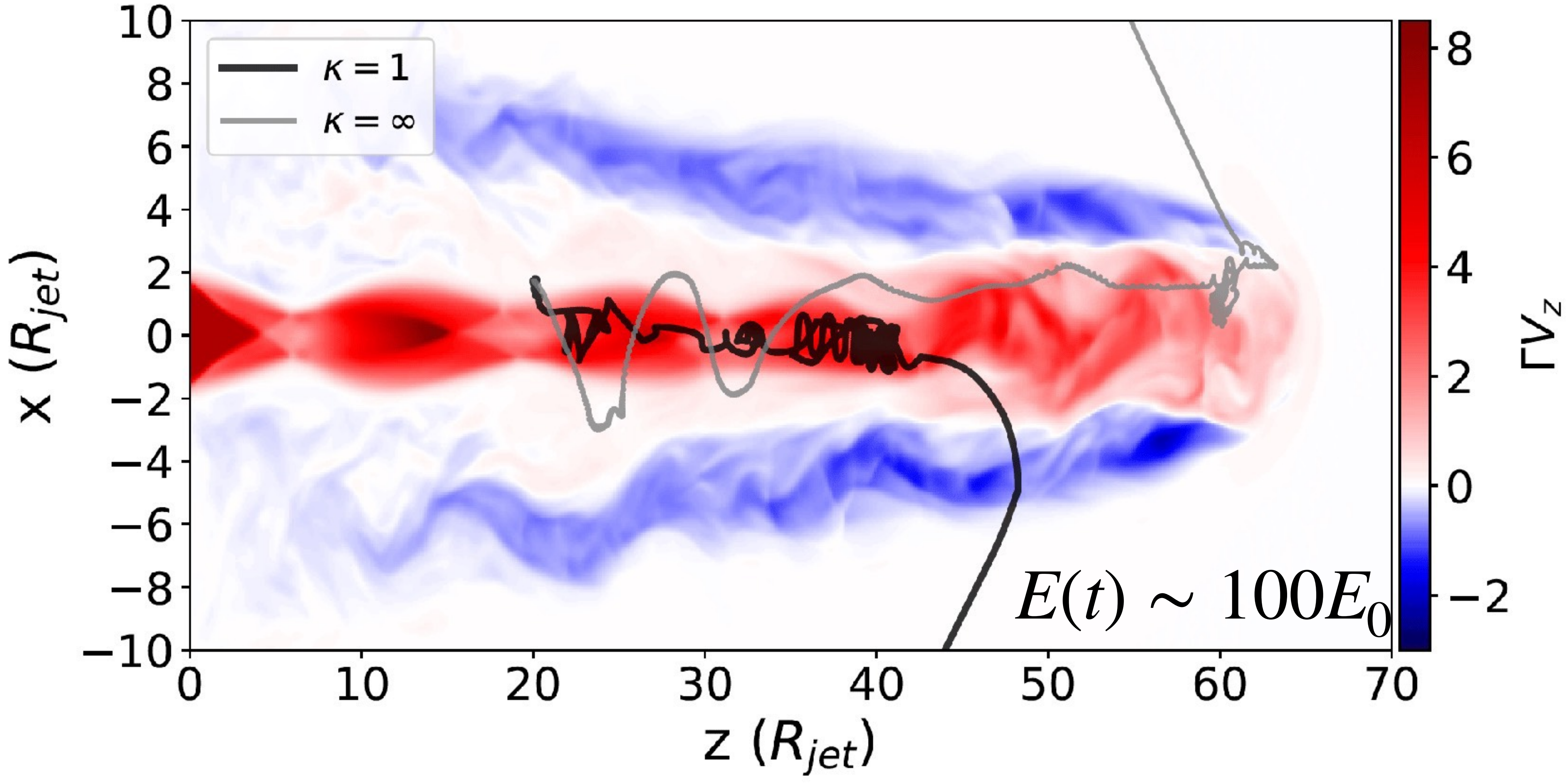
Emission from Flat Spectrum Radio Quasars



sketch by L. Costamante

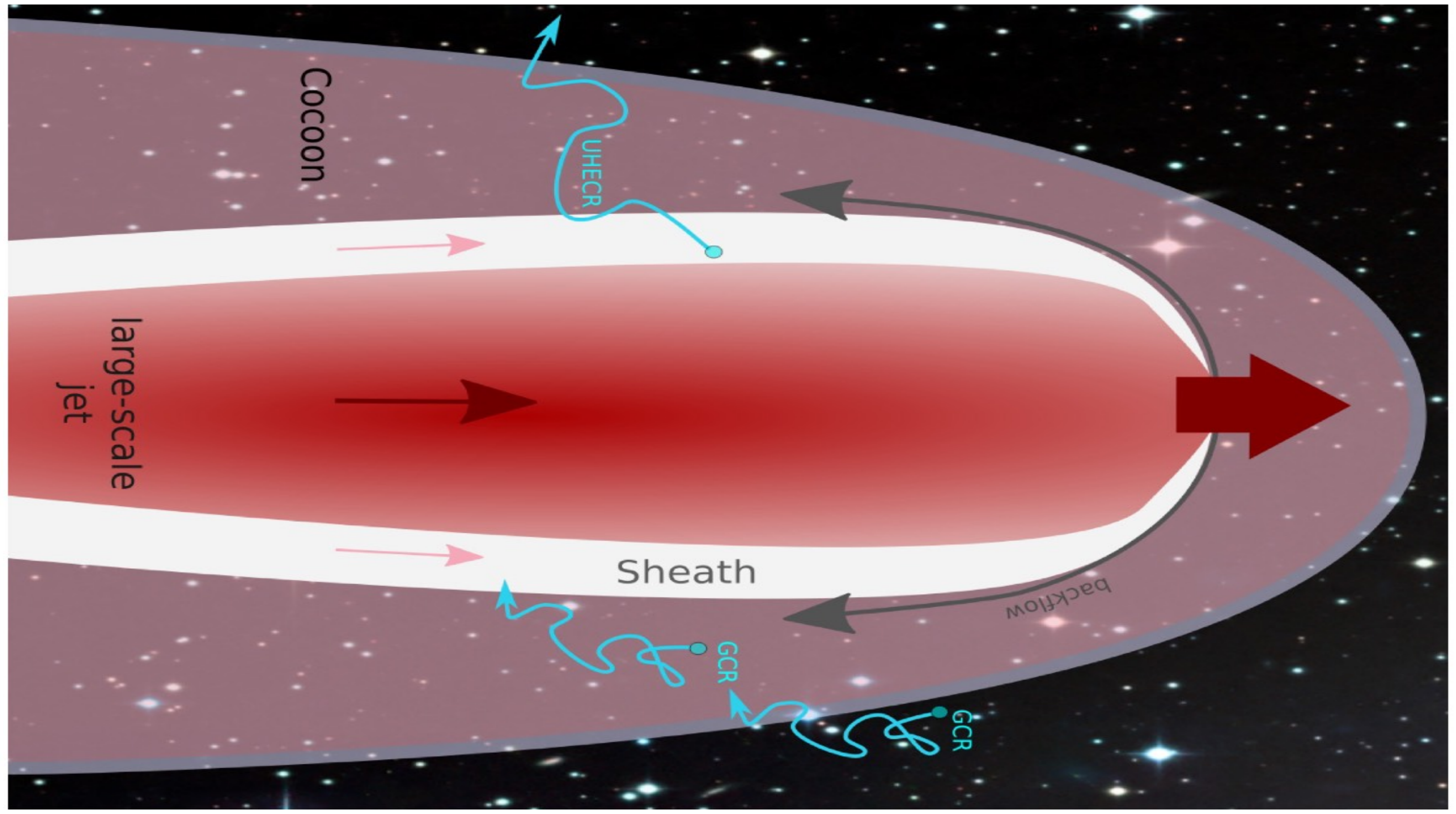


UHECR acceleration: More realistic models

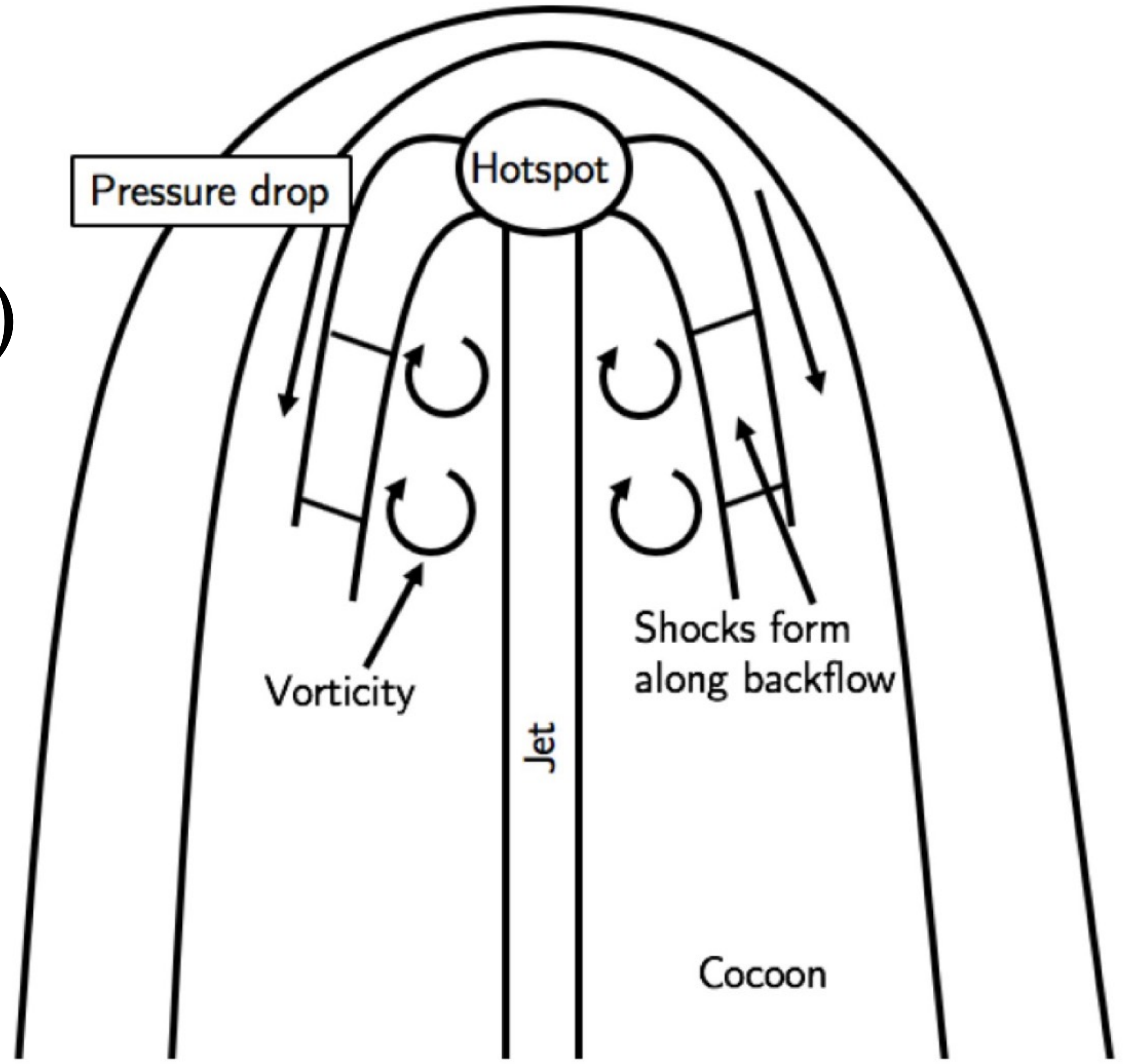


Espresso re-acceleration of Galactic CRs

*****Requires large Γ (FRII jet)**
Mbarek & Caprioli 2021



Re-acceleration of Galactic CRs in multiple shear discontinuities (velocity jumps)
*****Requires a stratified jet (e.g. spine-sheath)**
Rieger 2022



Acceleration in multiple backflow shocks

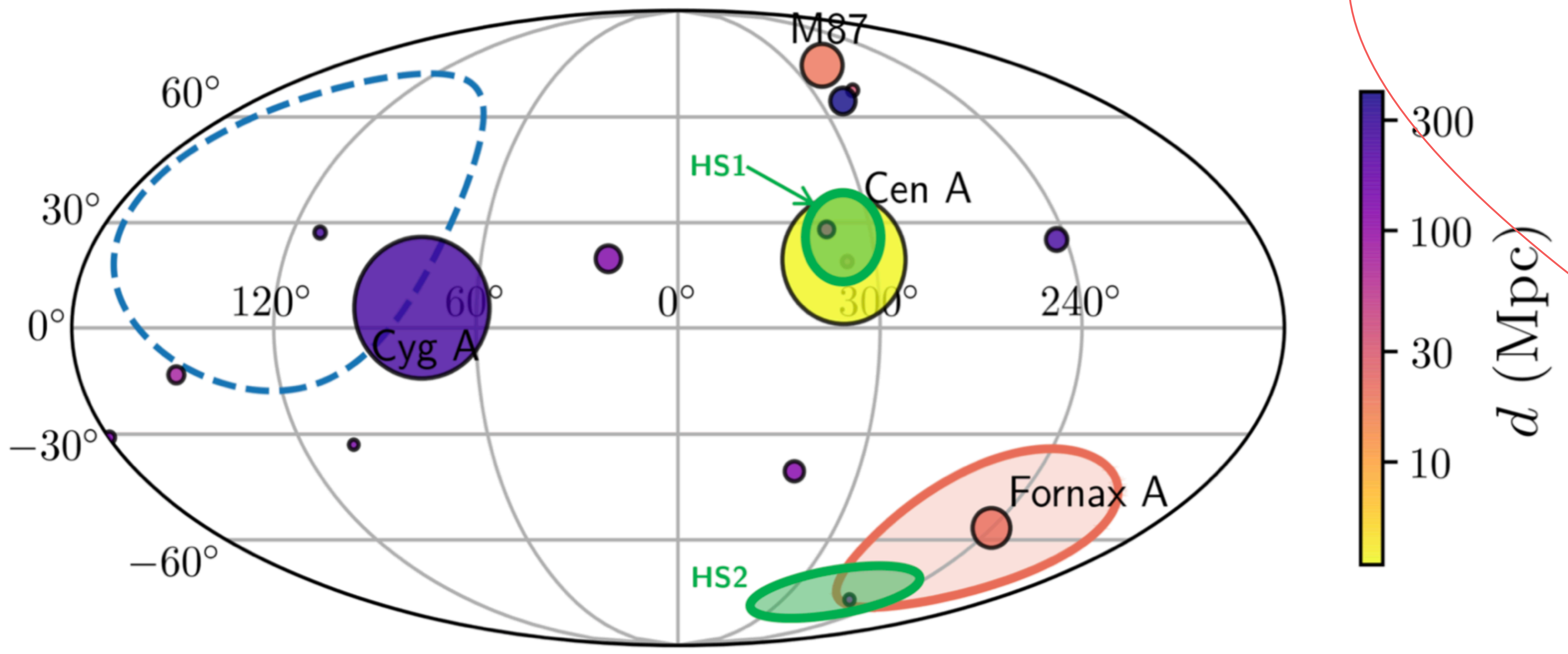
*****Requires FRII jet**
Matthews, Bell et al 2021

A problem: Nearby AGN not powerful enough (today)

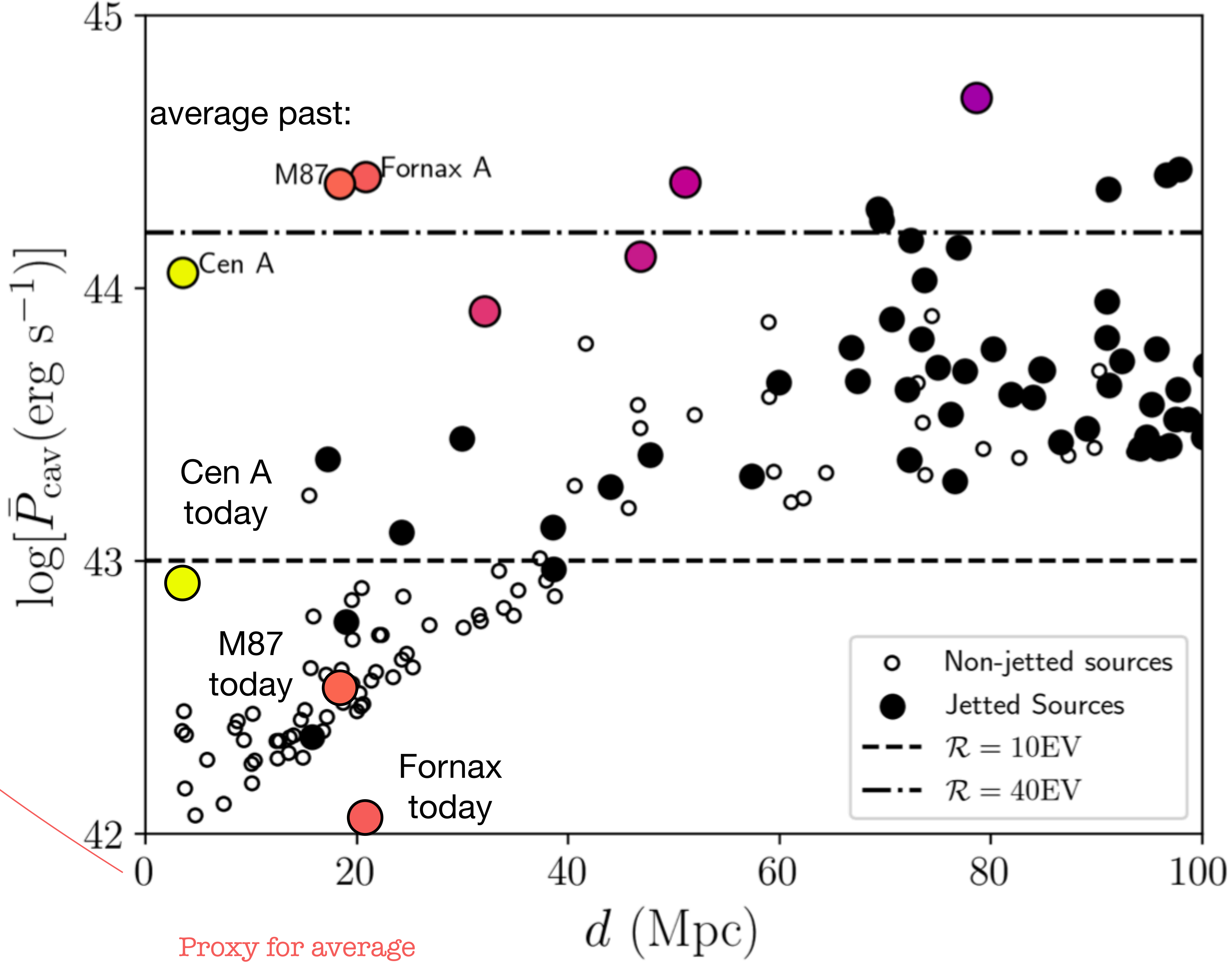
$$L \gtrsim L_B \sim \frac{U_B \cdot \mathrm{Volume}}{t} \sim B^2 R^2 \beta c$$

$$L_{\mathrm{min}} \sim 10^{43}\ \mathrm{erg/s} \cdot \left(\frac{E}{100\ \mathrm{EeV}}\right)^{2} \left(\frac{Z}{10}\right)^{-2} \left(\frac{u}{0.1c}\right)^{-1}$$

Lovelace 1976, Waxman 1995, 2001, Blandford 2000, Lemoine & Waxman 2009, Farrar & Gruzinov 2009

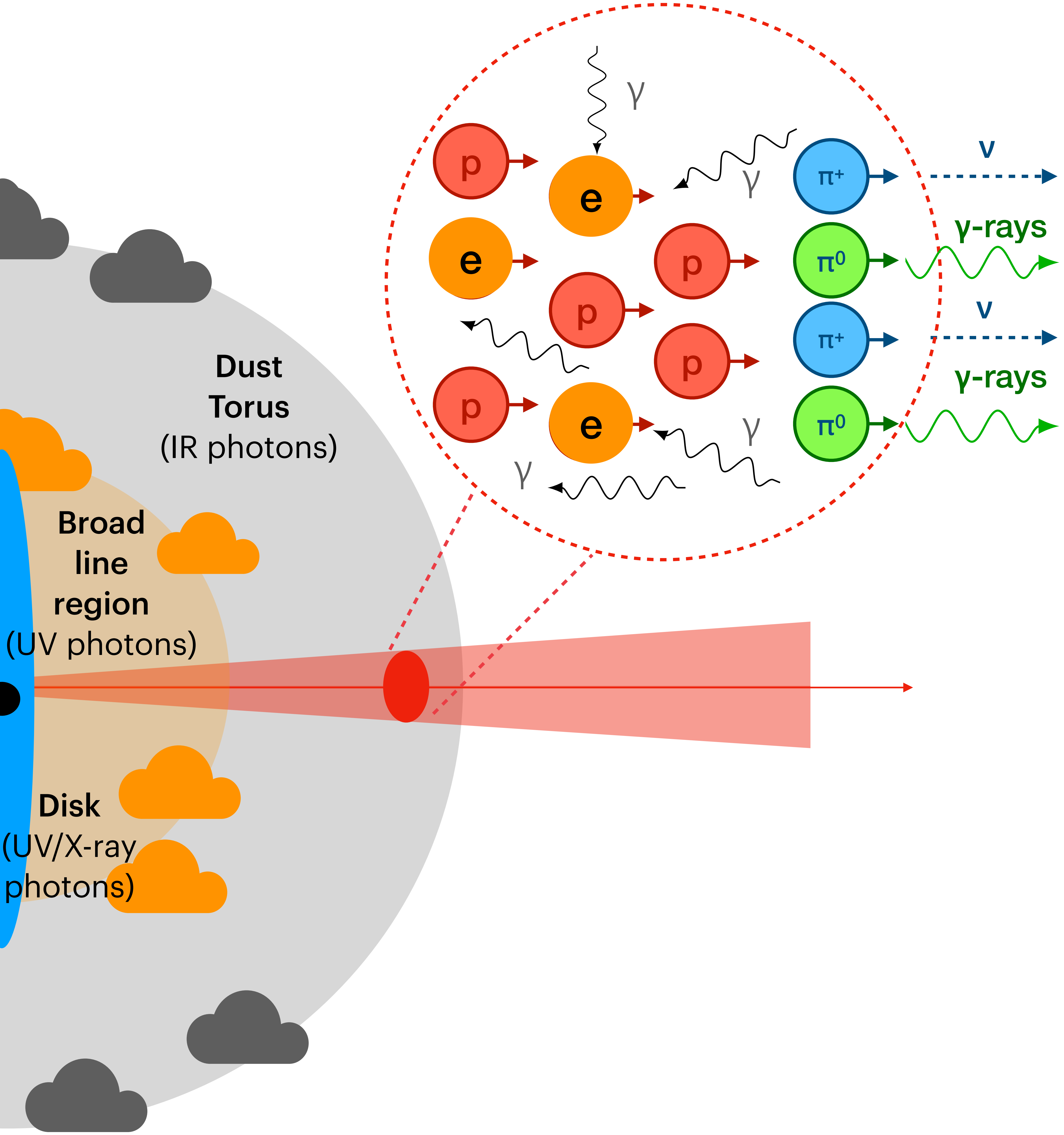


Matthews et al., MNRASL, V479, 1, L76, 2018



Proxy for average kinetic power over the lifetime of the source

Neutrino production in blazars



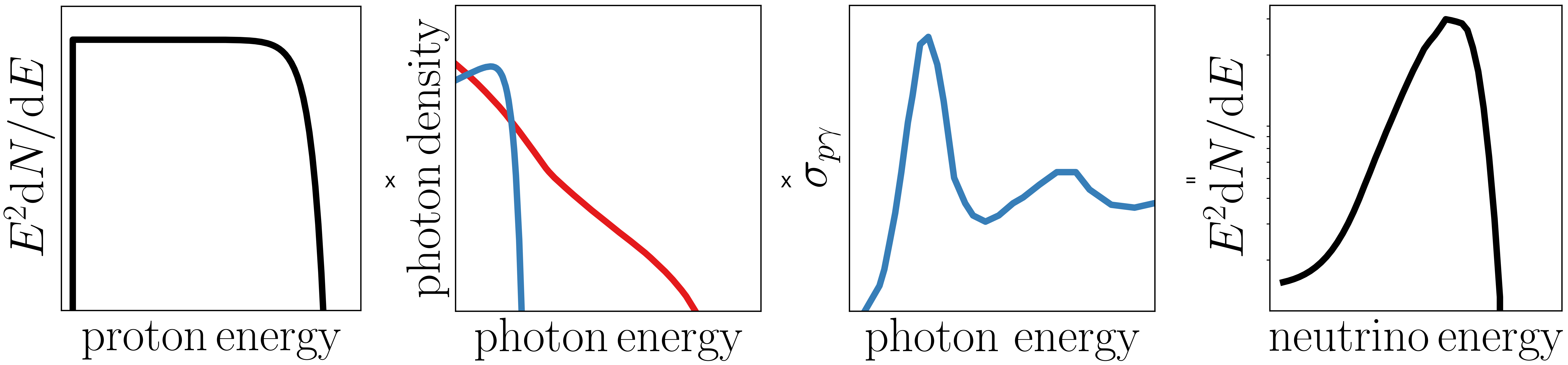
TXS 0506+056 observations:
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. Science 361, 2018,
MAGIC Coll. Astrophys.J. 863 (2018) L10
IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018)

TXS 0506+056 modelling:
MAGIC Coll 2018, ApJ, 863, L10
Gao et al, 2019, Nat. Astron., 3, 88
Keivani et al. 2018, ApJ, 864, 84
Cerruti et al 2018, MNRAS, 483, 1
FO et al 2019, MNRAS, 489, 3

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*
gamma-suppressed states: *Kun+21*
2014 flare: Reimer+19, Rodrigues+19, Halzen+19, Petropoulou+20, and more…!

Neutrino production in blazars :
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, FO et al 2019 , 2021, Righi et al 2020, Rodrigues et al 2021*

Neutrino production in blazars



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

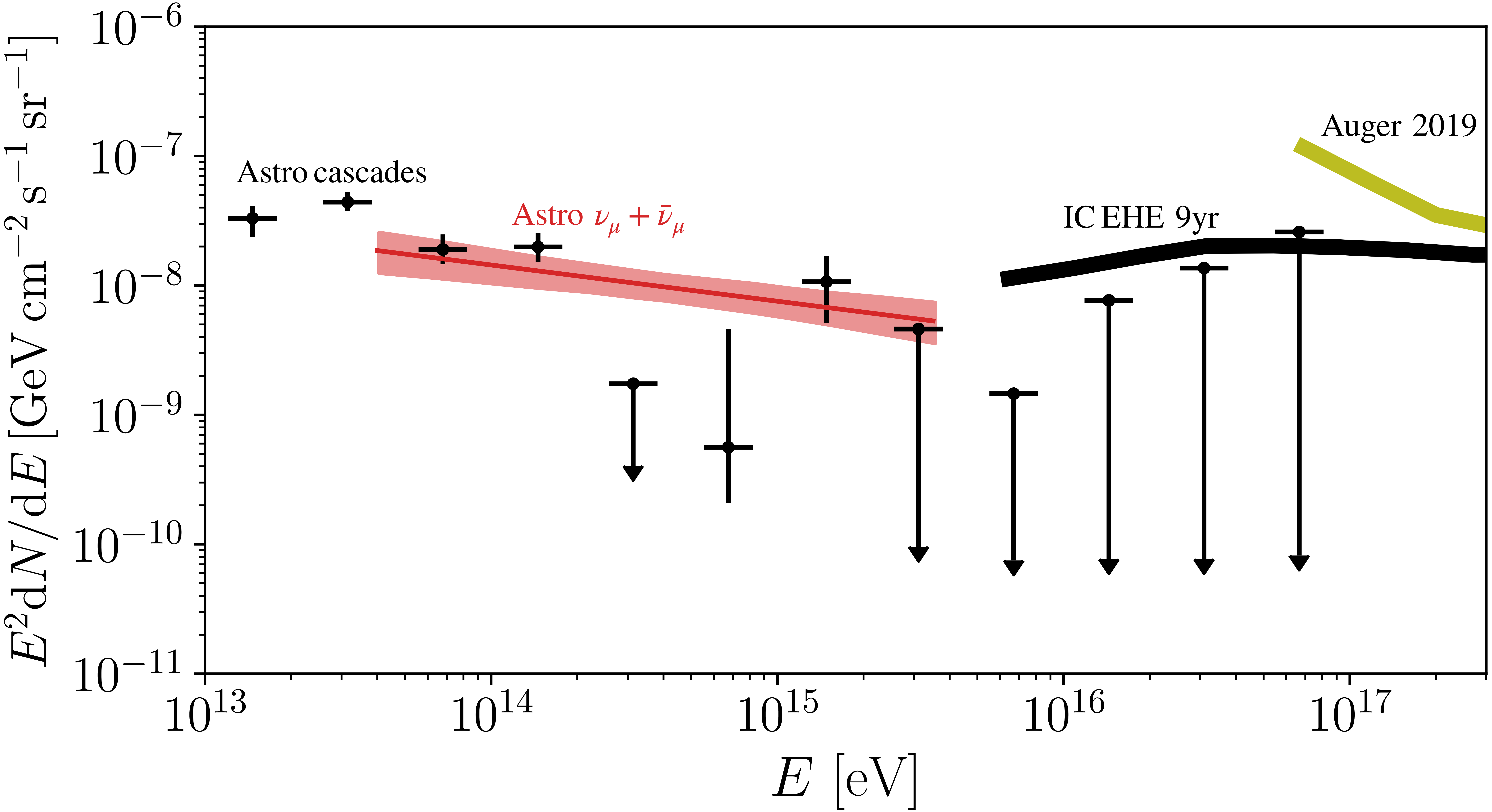
$$E_{\text{dust torus}} = 0.1\ \mathrm{eV}$$

Neutrino typical energy:

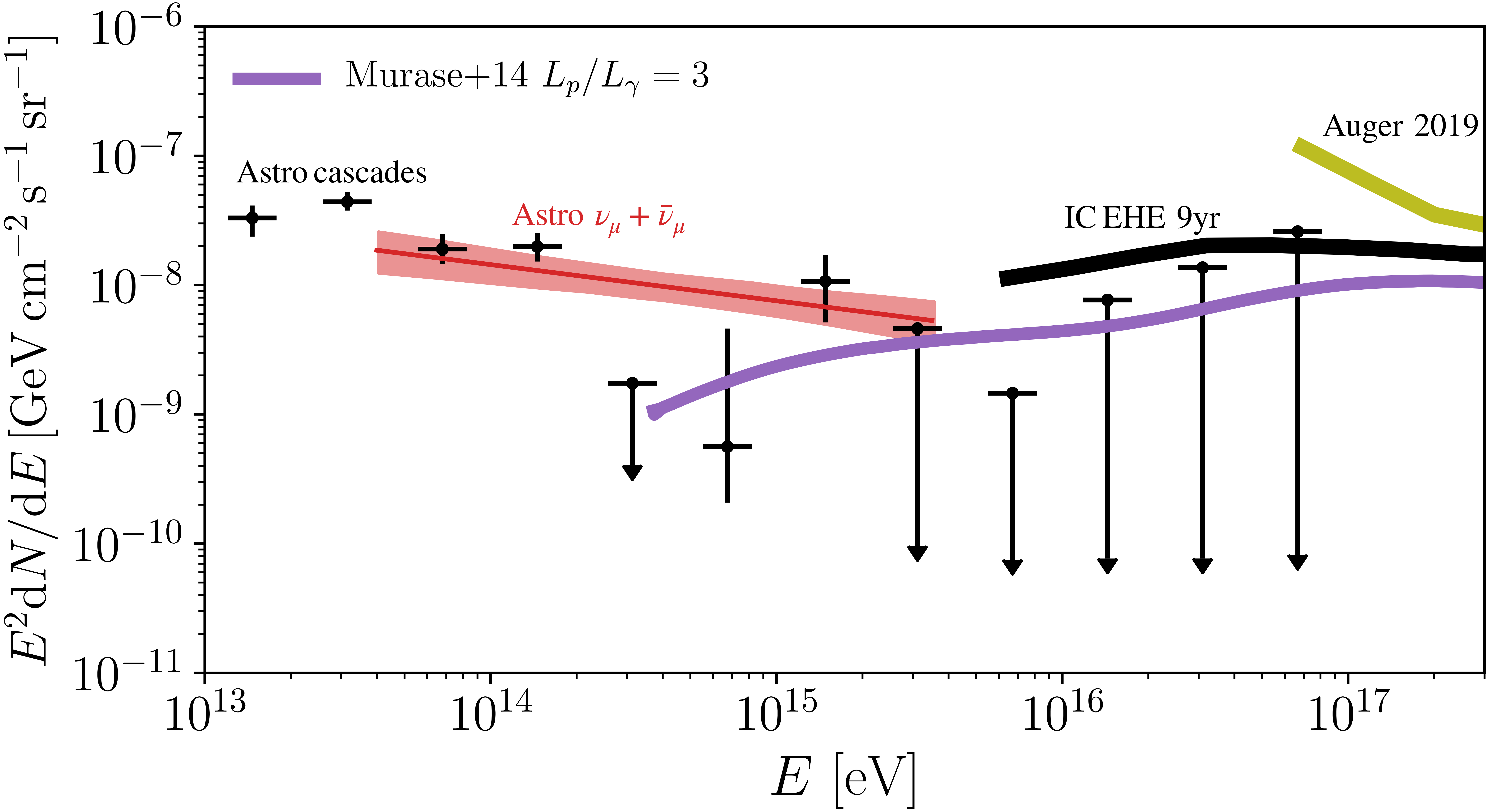
$$E_{\nu,\mathrm{BLR}} = \frac{80\ \mathrm{PeV}}{(1+z)^2} \left(\frac{\delta}{10}\right)^2 \frac{10\ \mathrm{eV}}{E_\gamma}$$

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

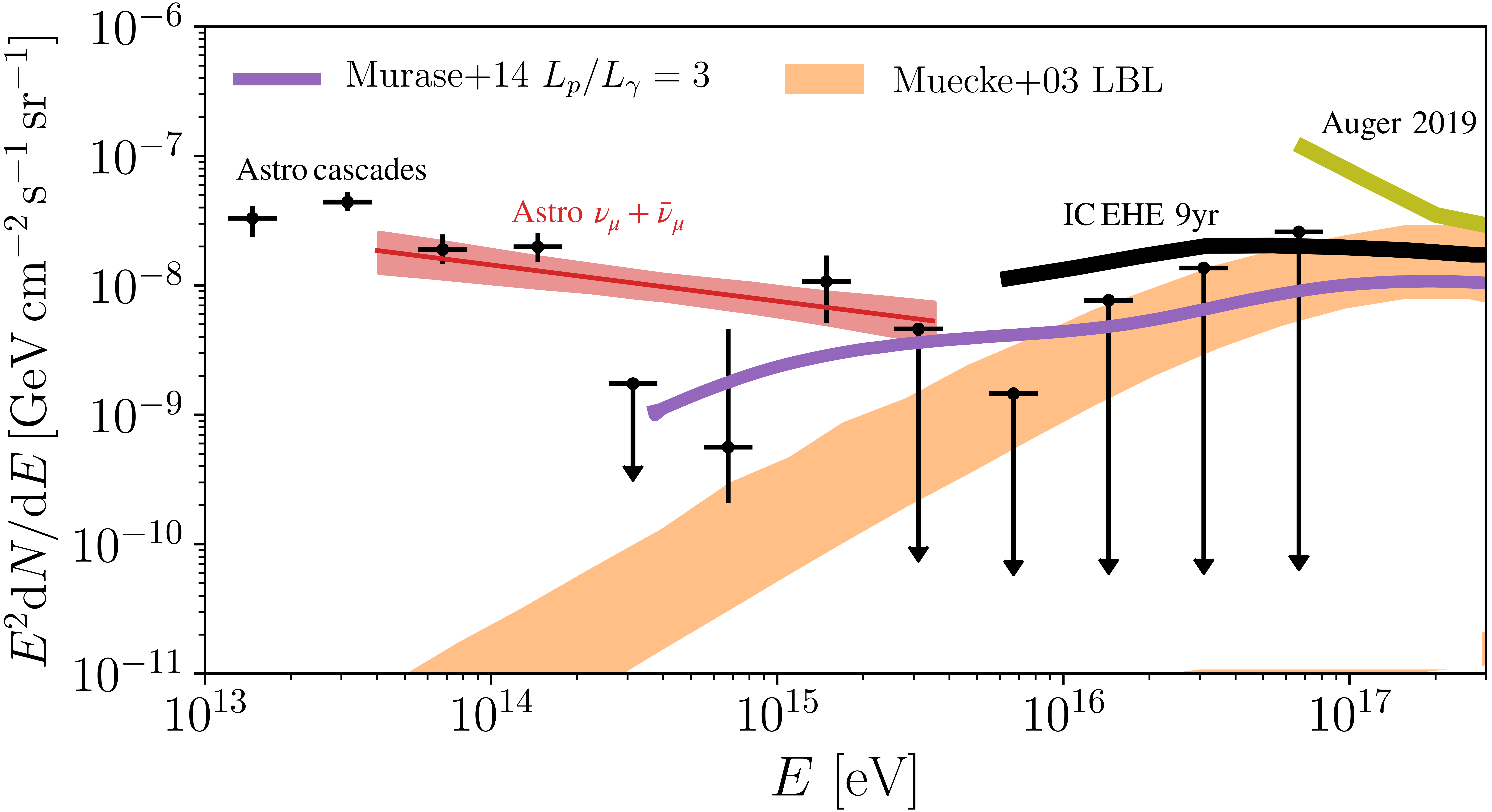
Possible contribution of blazars to the diffuse neutrino flux



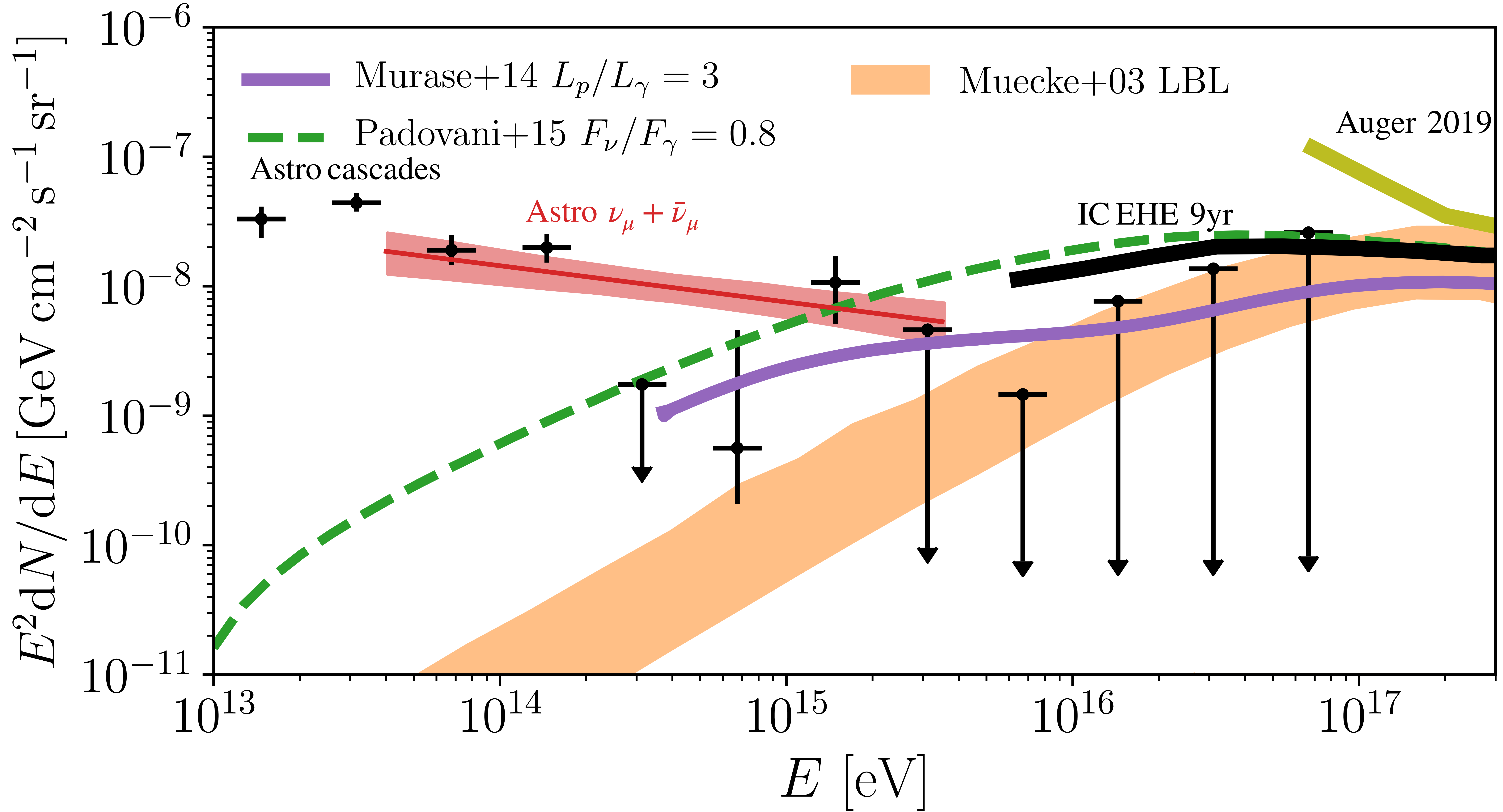
Possible contribution of blazars to the diffuse neutrino flux



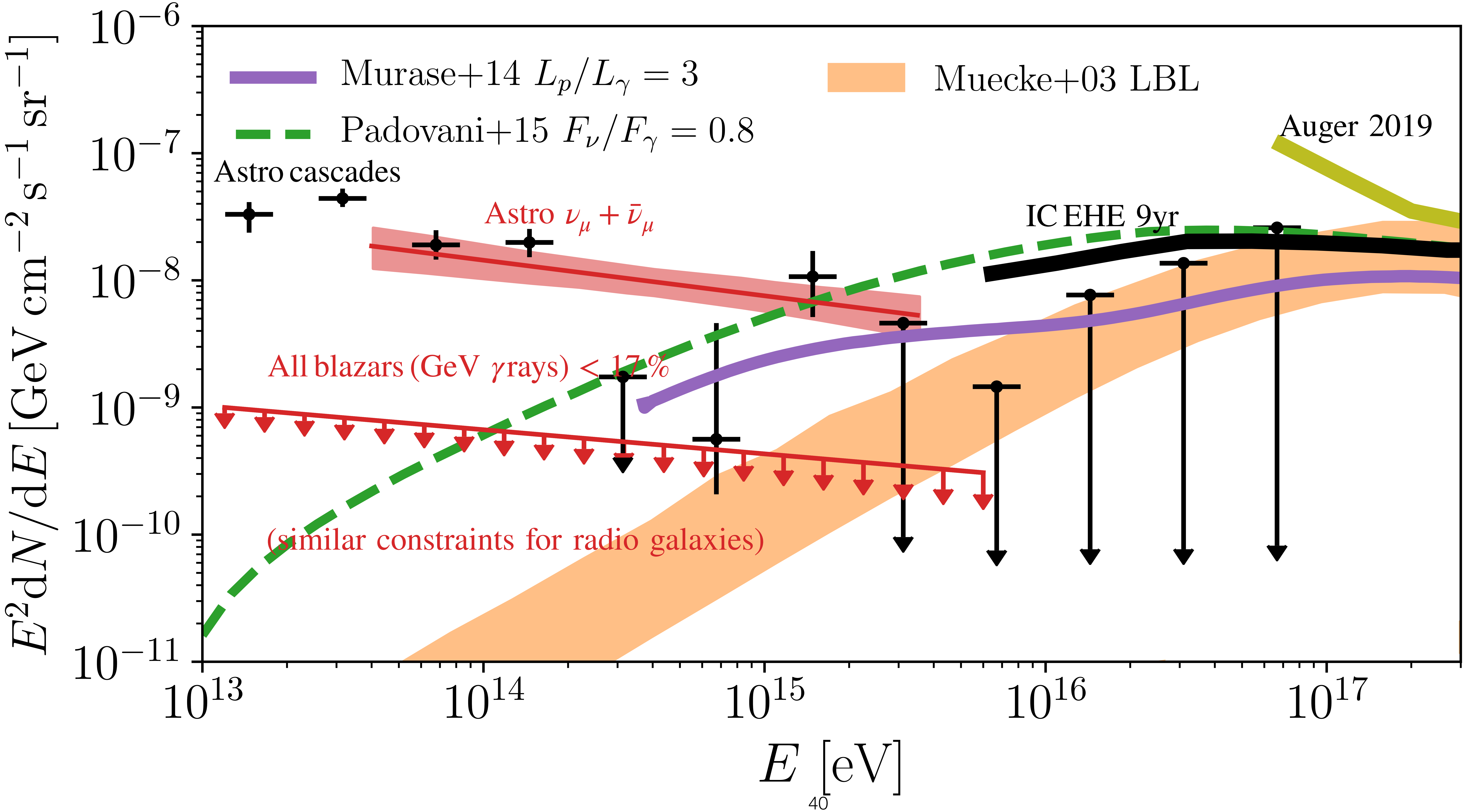
Possible contribution of blazars to the diffuse neutrino flux



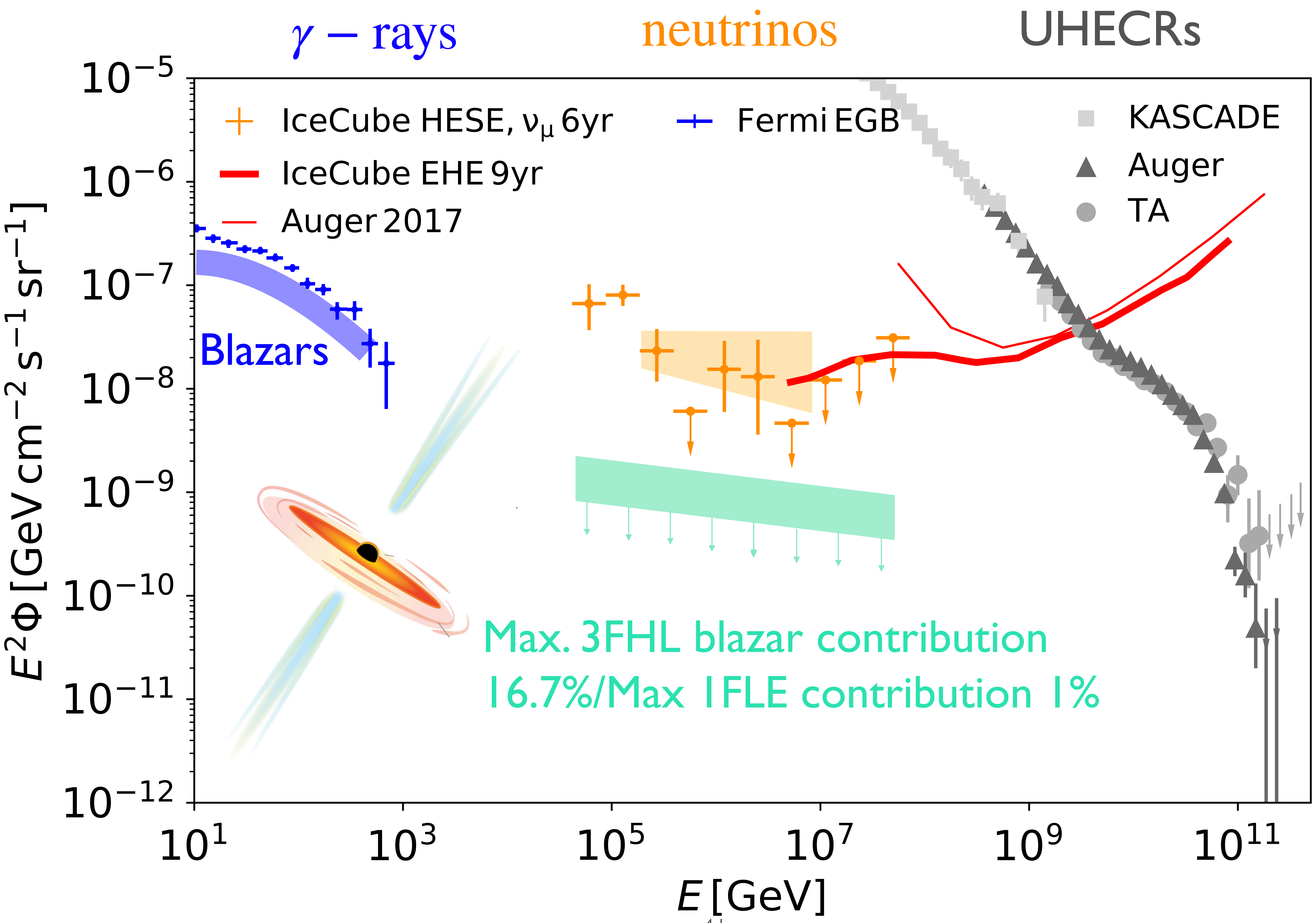
Possible contribution of blazars to the diffuse neutrino flux



Stacking limits from IceCube



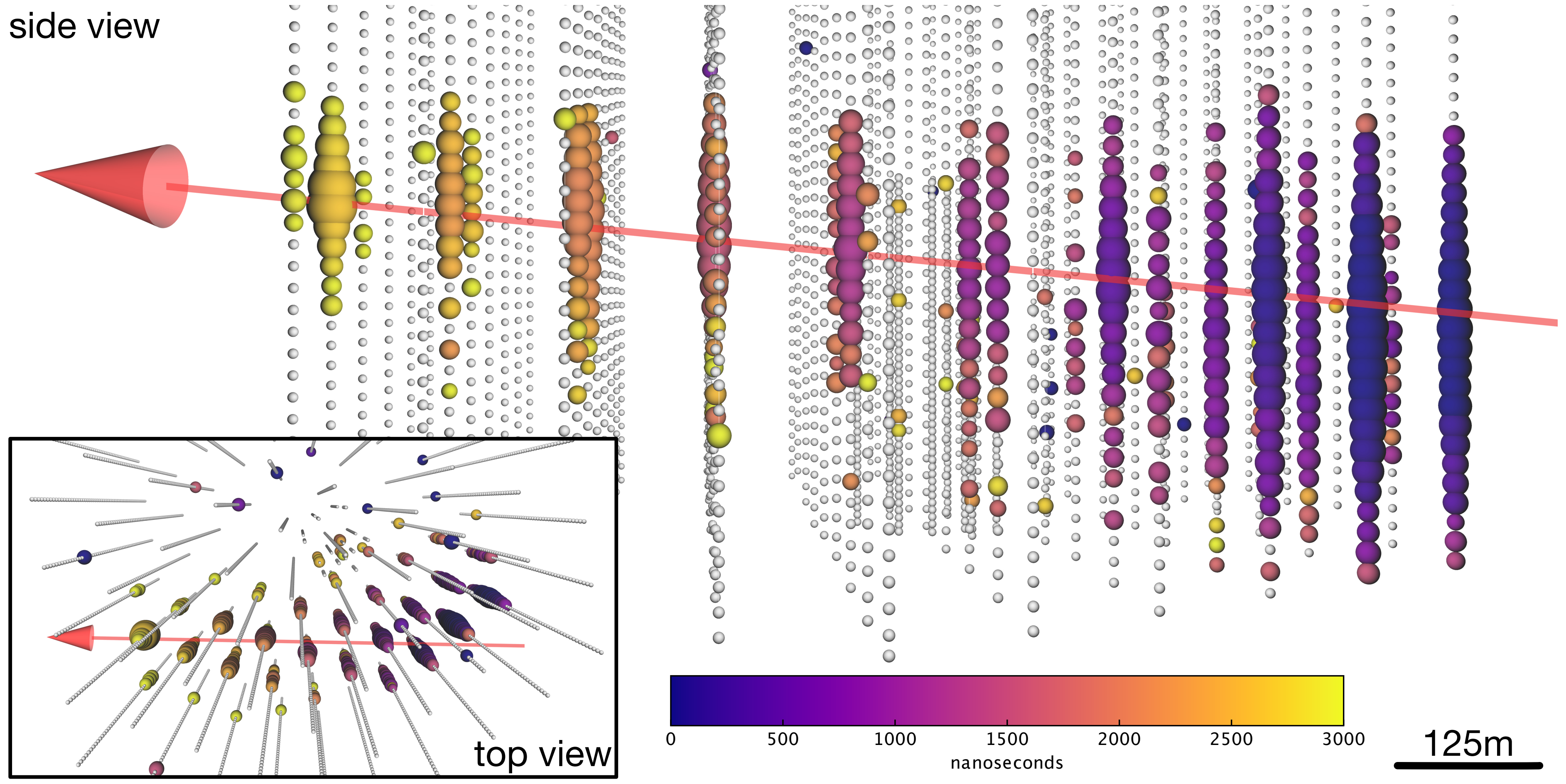
Stacking limits from IceCube



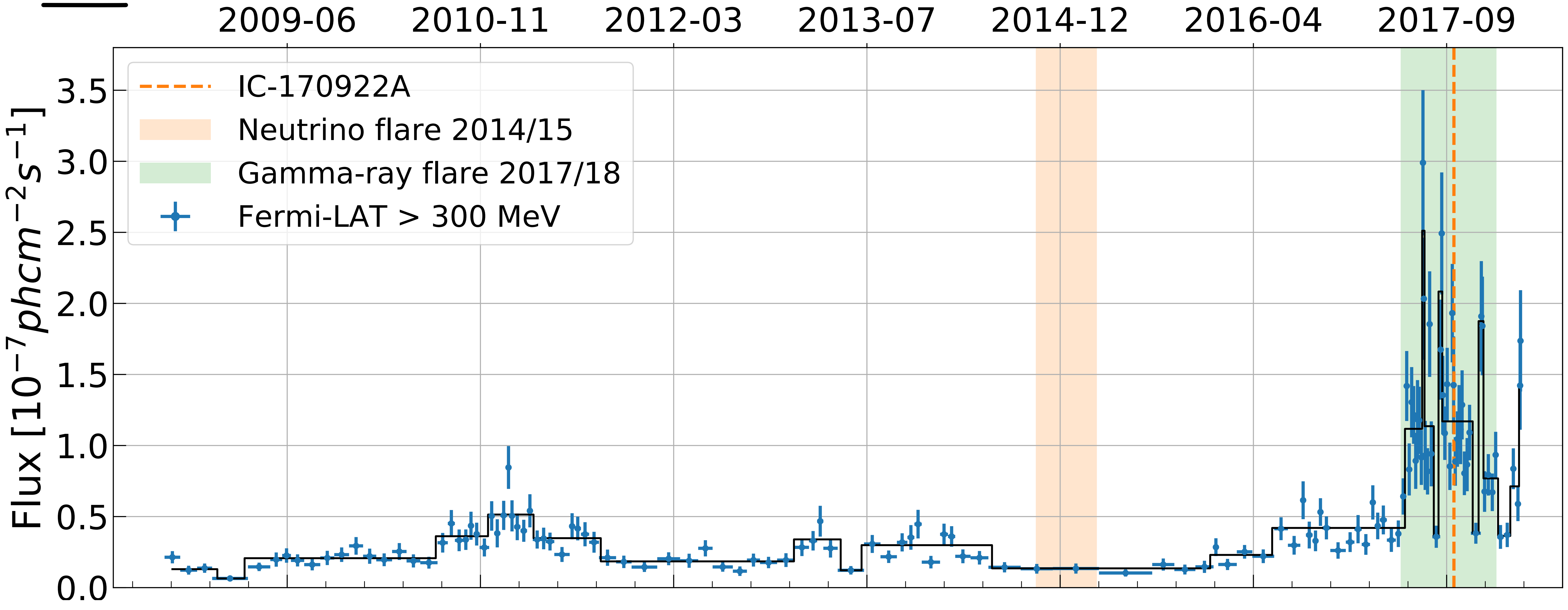
Max. 3FHL blazar contribution 16.7%/Max 1FLE contribution 1%

TXS 0506+056-IC 170922A

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%



Blazar flares: Interesting as neutrino point sources

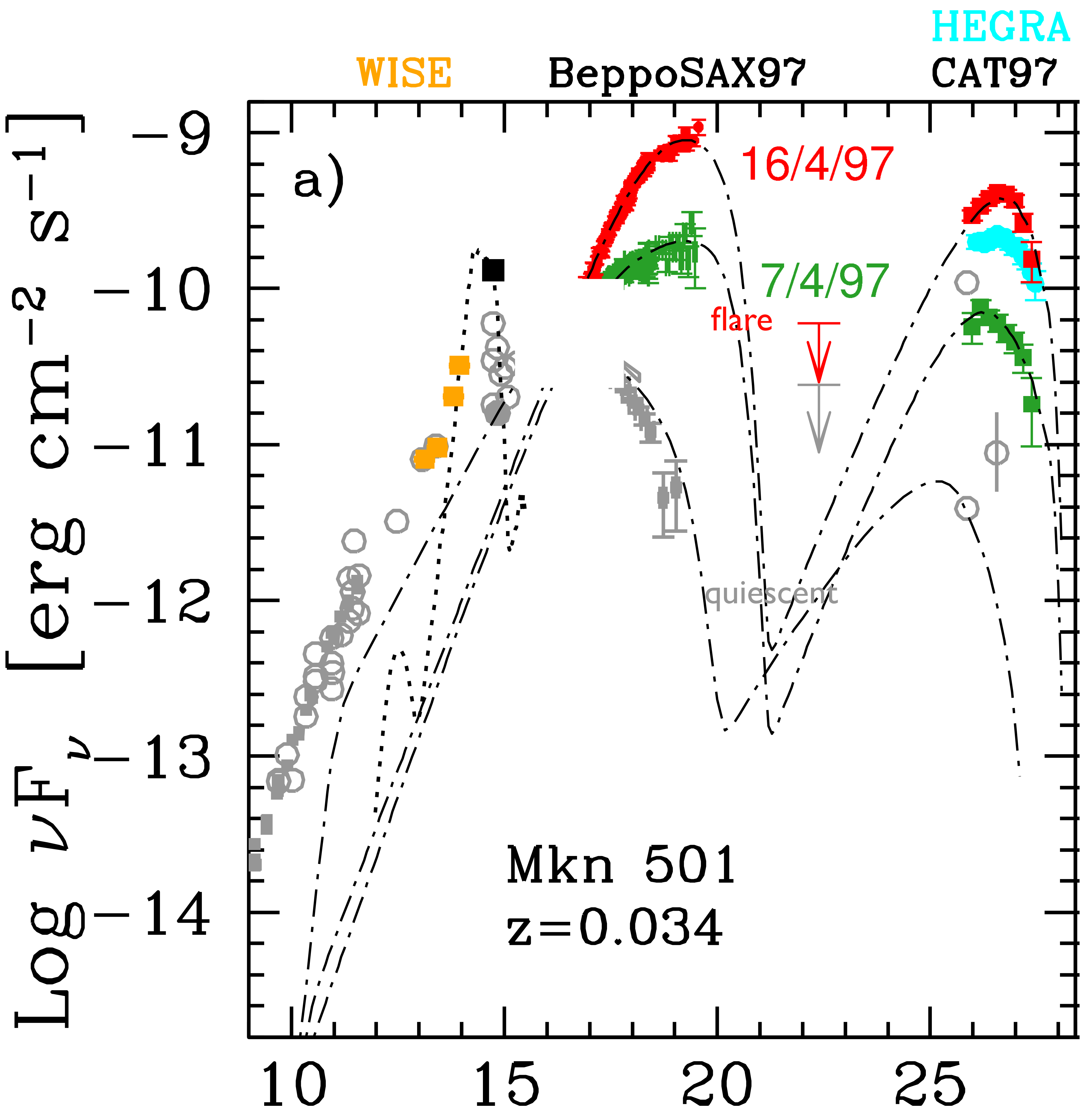
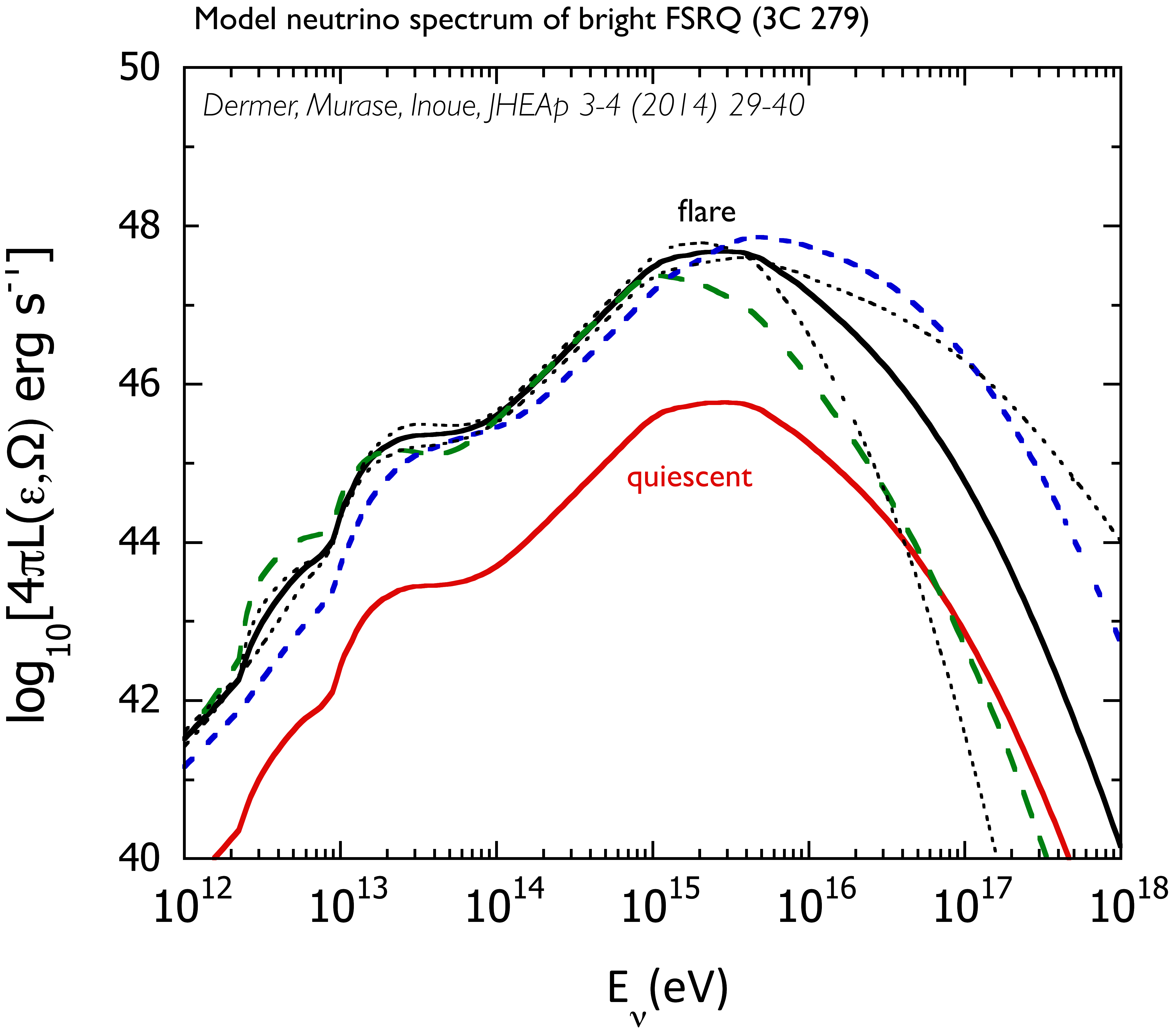
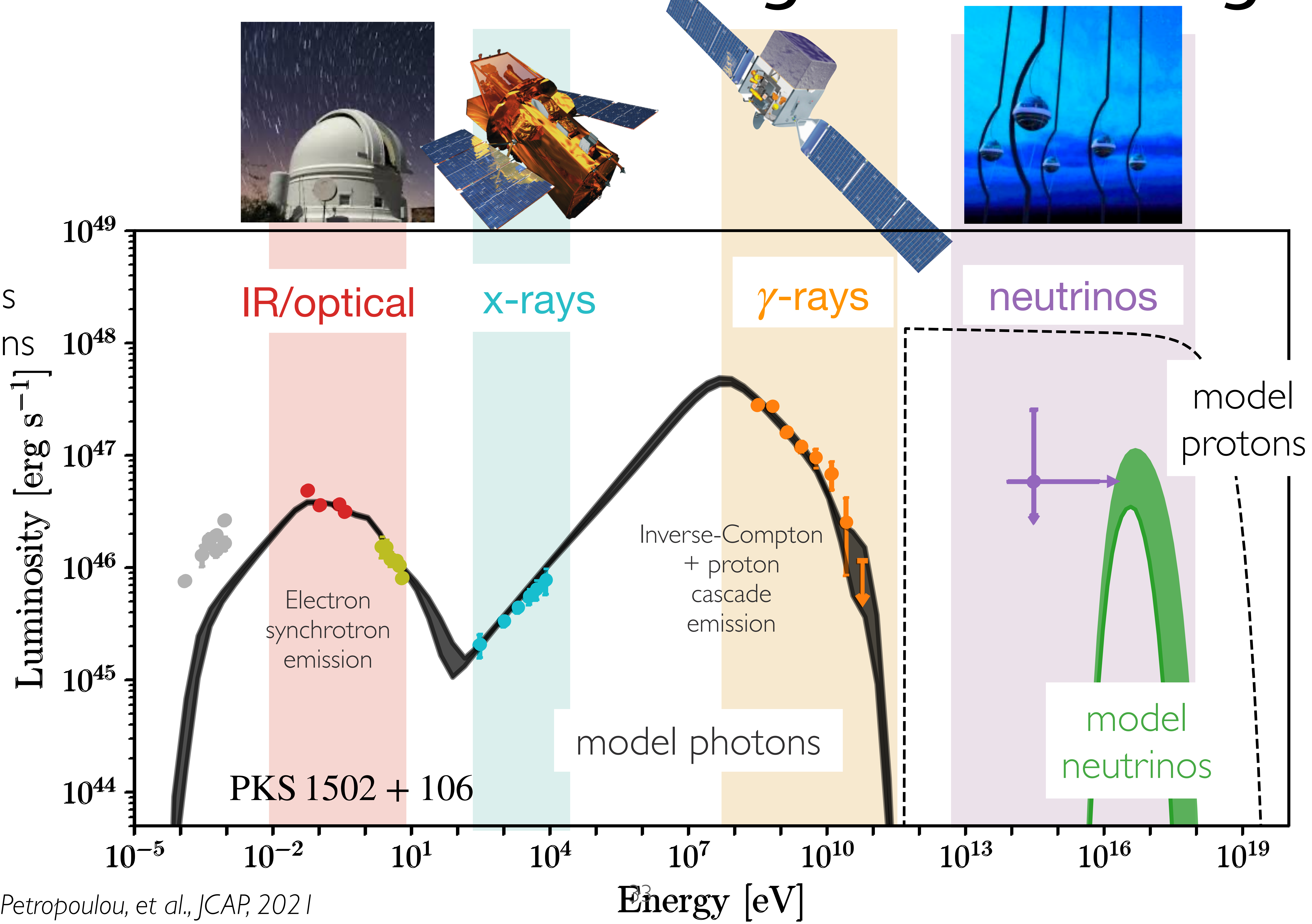


Image from Biteau, Prandini, Costamante+ Nat. Astr 4, 124–131(2020)



The power of multimessenger modelling

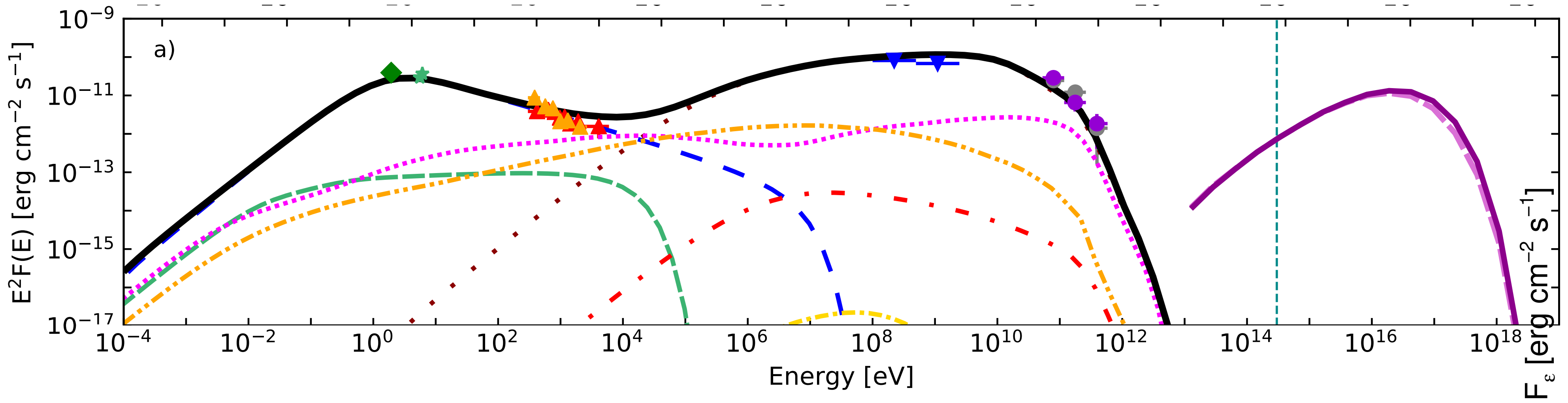
Radiation processes
+ particle interactions



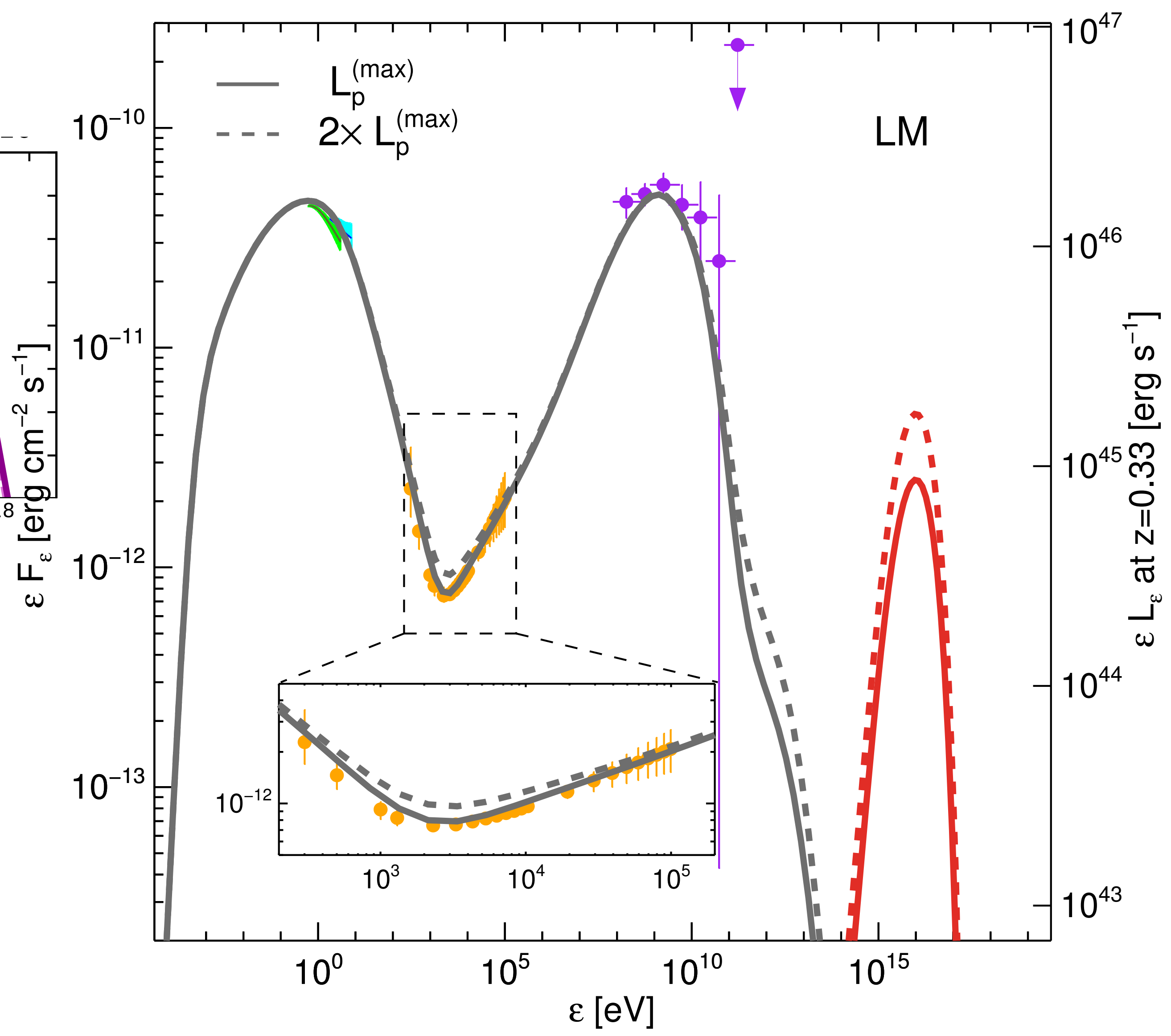
FO, Petropoulou, et al., JCAP, 2021

Neutrino production in TXS 0506+056 in 2017

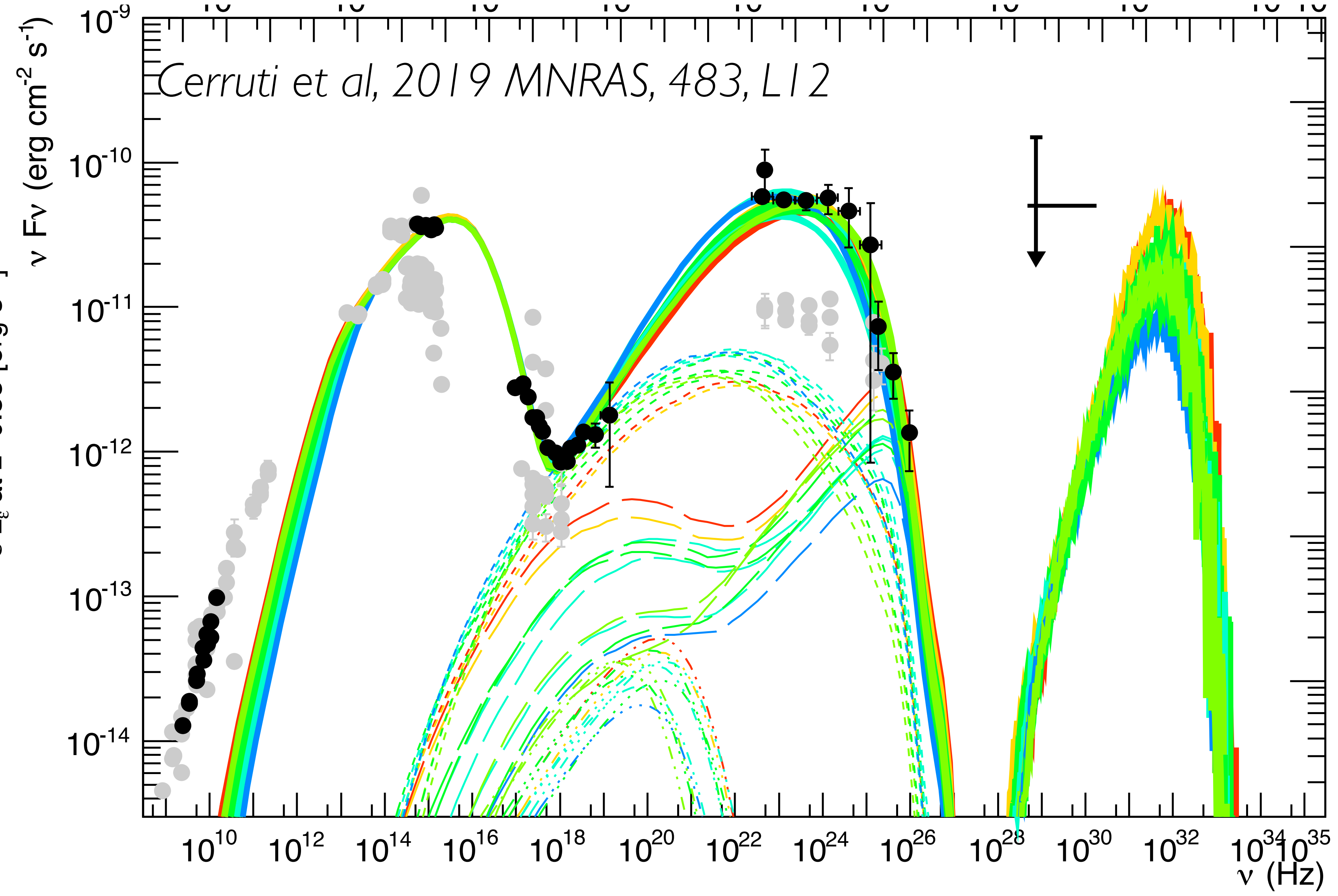
MAGIC Coll 2018, ApJ, 863, L10



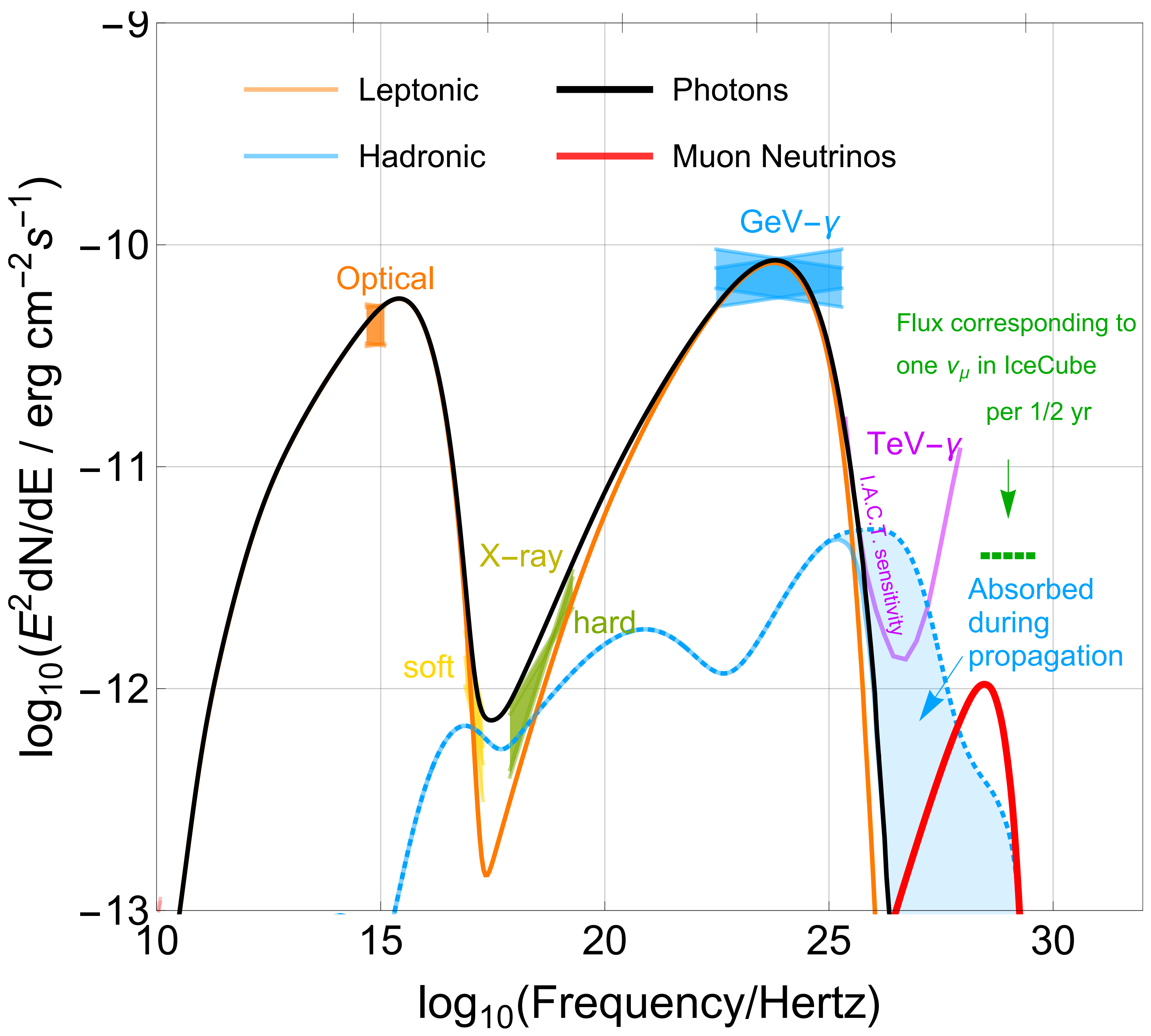
Keivani et al. 2018, ApJ, 864, 84



Cerruti et al, 2019 MNRAS, 483, L12



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



$$\boxed{N_{\nu_\mu} \lesssim 0.05/6\ \text{months}^{\star}}$$

-Ok due to population bias!
(1% chance to see one neutrino from each blazar flare)
-But: What does it take to produce 0.05 neutrinos/6months in this blazar?

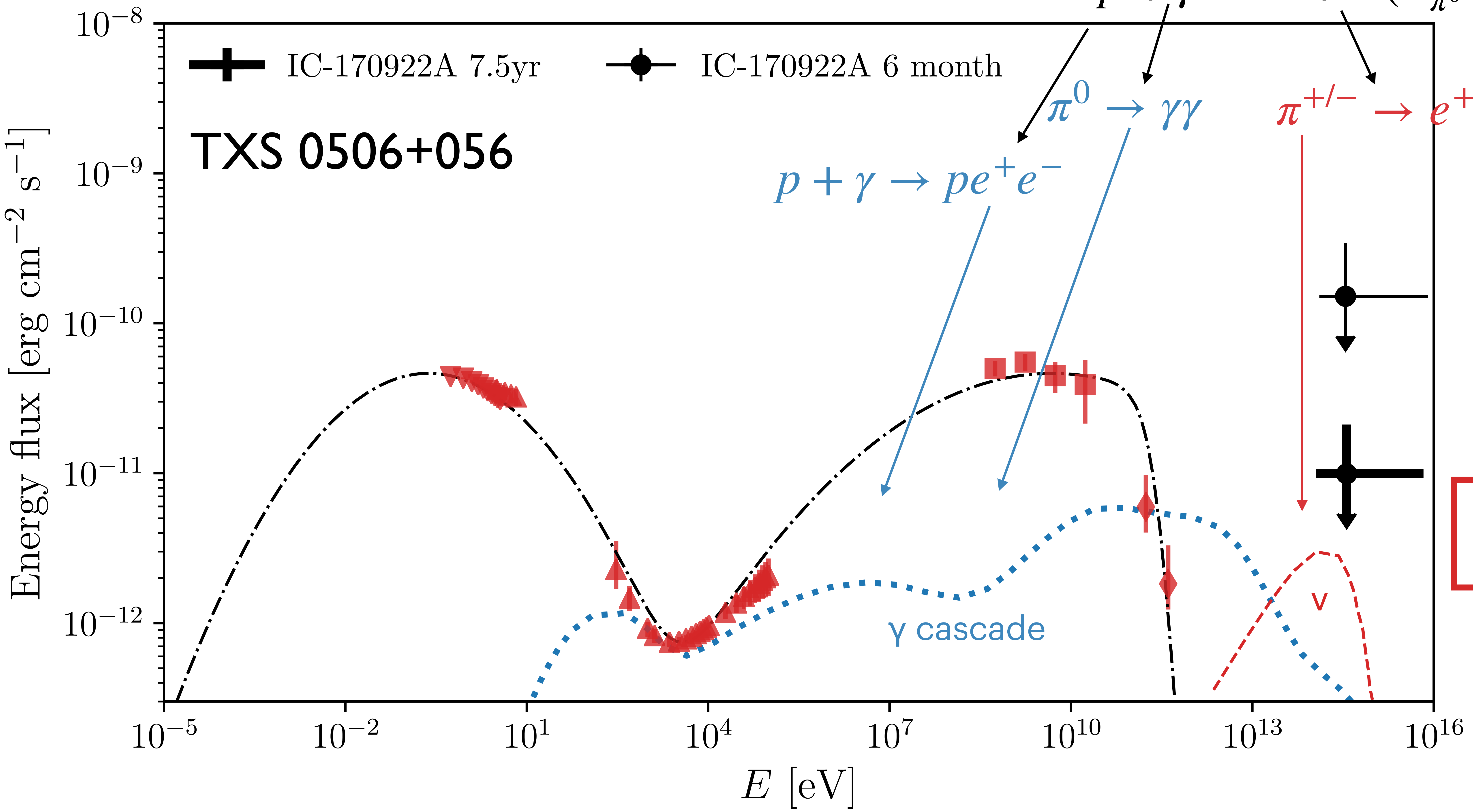
What sets the neutrino flux upper limit?

$p + \gamma \rightarrow X + \pi \, (N_{\pi^0} : N_{\pi^{+/-}} \approx 1 : 1)$

$p + \gamma \rightarrow p e^+ e^-$

$\pi^0 \rightarrow \gamma\gamma$

$\pi^{+/-} \rightarrow e^{+/-} + \nu_e + \nu_\mu + \bar{\nu}_\mu$



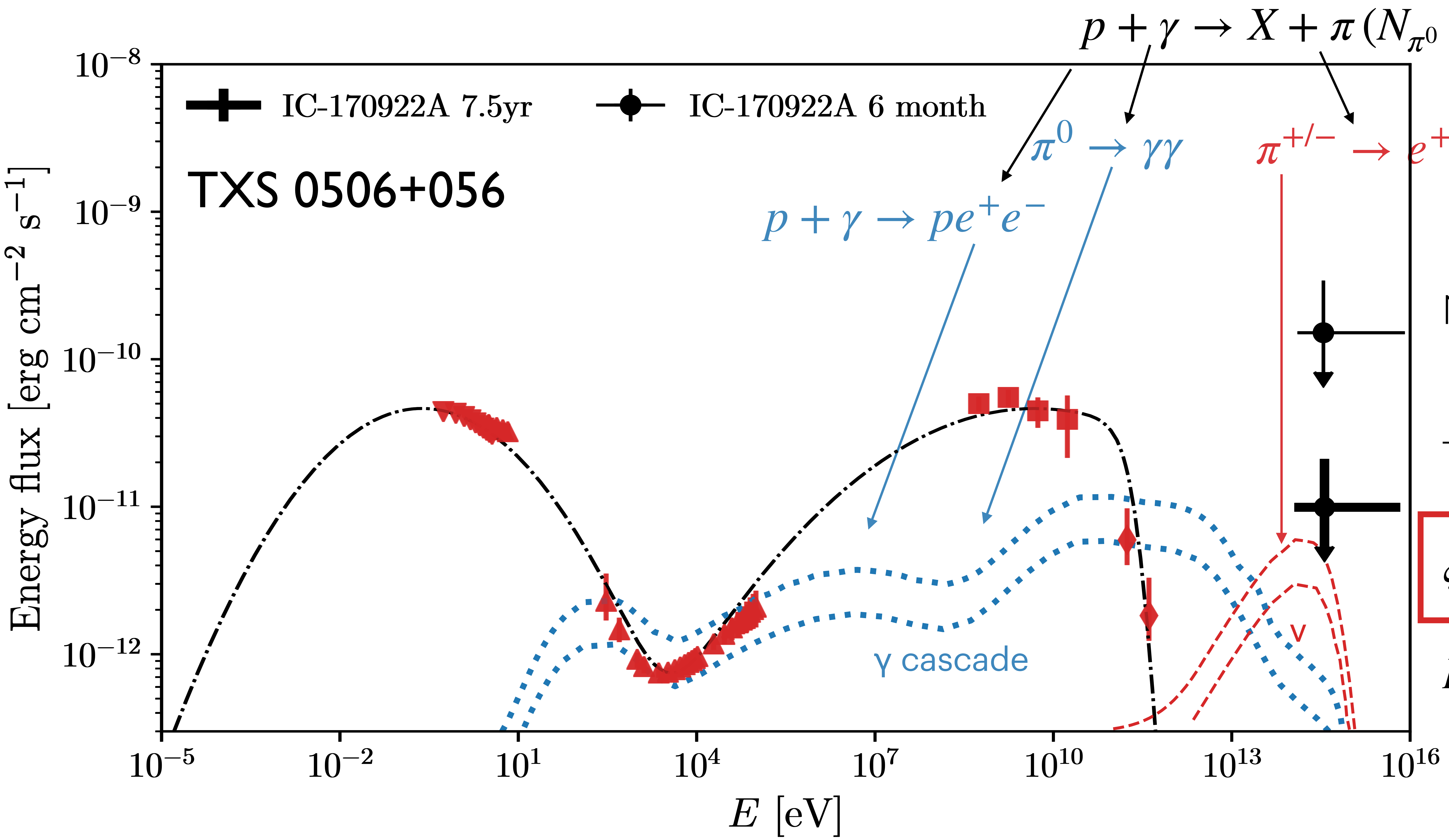
Neutrino luminosity linearly dependent on proton luminosity

To achieve $N_{\nu_\mu}^{>100\ \mathrm{TeV}} \sim 0.05/6$ months

$$\boxed{\xi_{CR} = L_{\mathrm{proton}}/L_\gamma \approx 1000}$$

$L_{\mathrm{proton}} = 10 - 100 L_{\mathrm{Eddington}}$

What sets the neutrino flux upper limit?



$p + \gamma \rightarrow X + \pi \, (N_{\pi^0} : N_{\pi^{+/-}} \approx 1 : 1)$

$p + \gamma \rightarrow p e^+ e^-$

$\pi^0 \rightarrow \gamma\gamma$

$\pi^{+/-} \rightarrow e^{+/-} + \nu_e + \nu_\mu + \bar{\nu}_\mu$

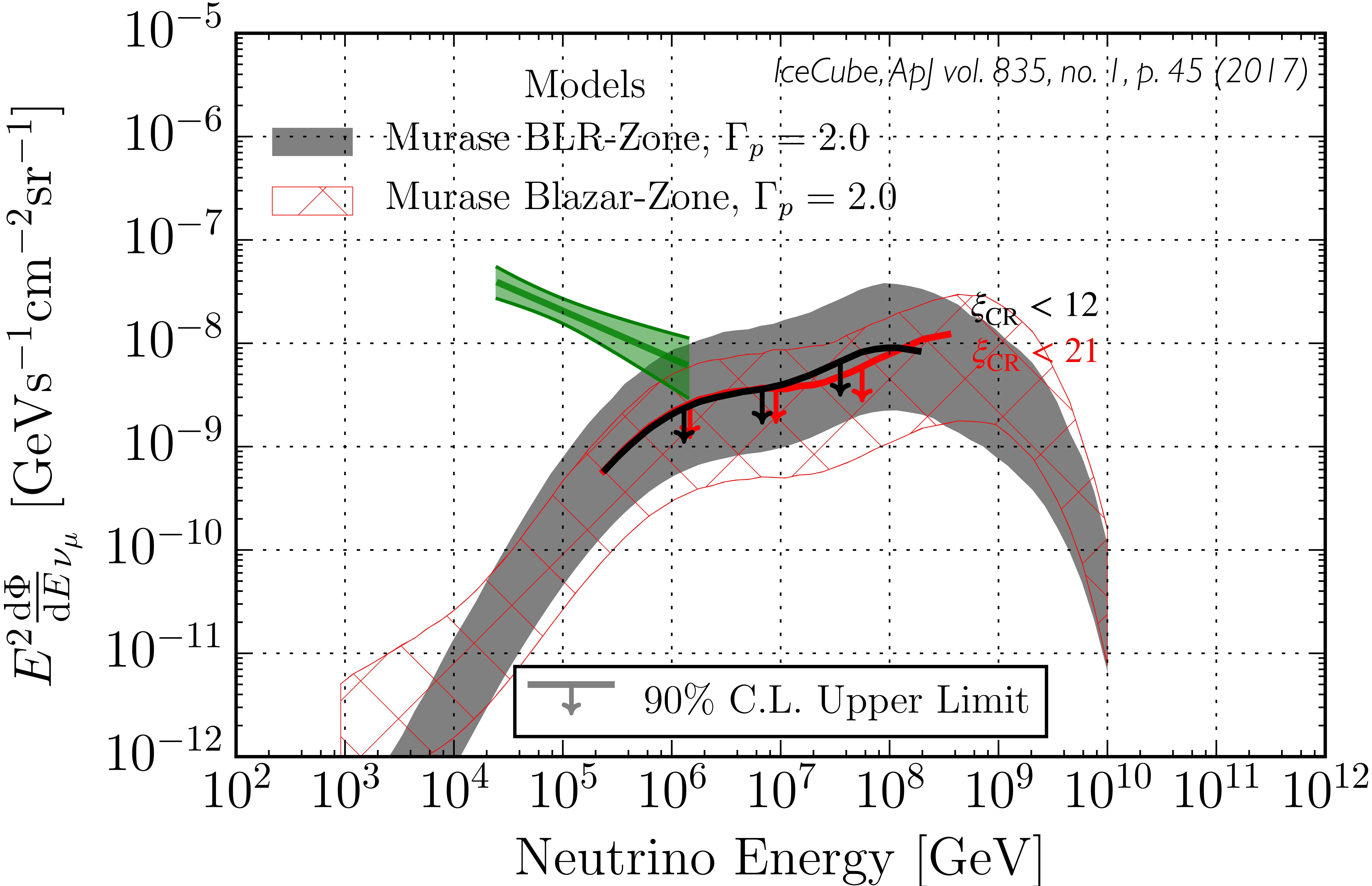
Neutrino luminosity linearly dependent on proton luminosity

To achieve $N_{\nu_\mu}^{>100\text{ TeV}} \sim 0.05/6$ months

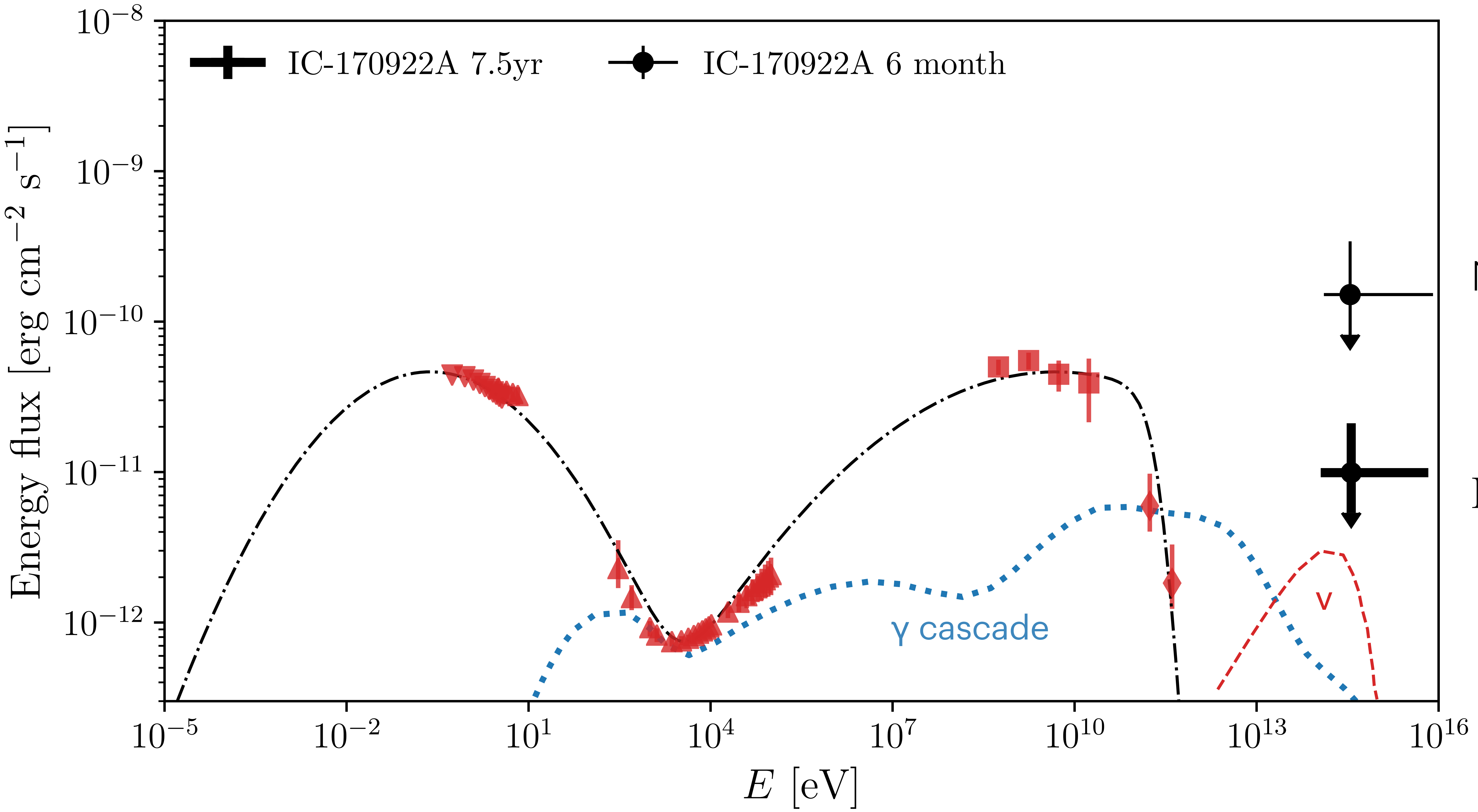
$$\boxed{\xi_{CR} = L_{\text{proton}}/L_\gamma \approx 1000}$$

$L_{\text{proton}} = 10 - 100 L_{\text{Eddington}}$

Population limits from IceCube (and Auger)



Neutrino flux depends on proton luminosity



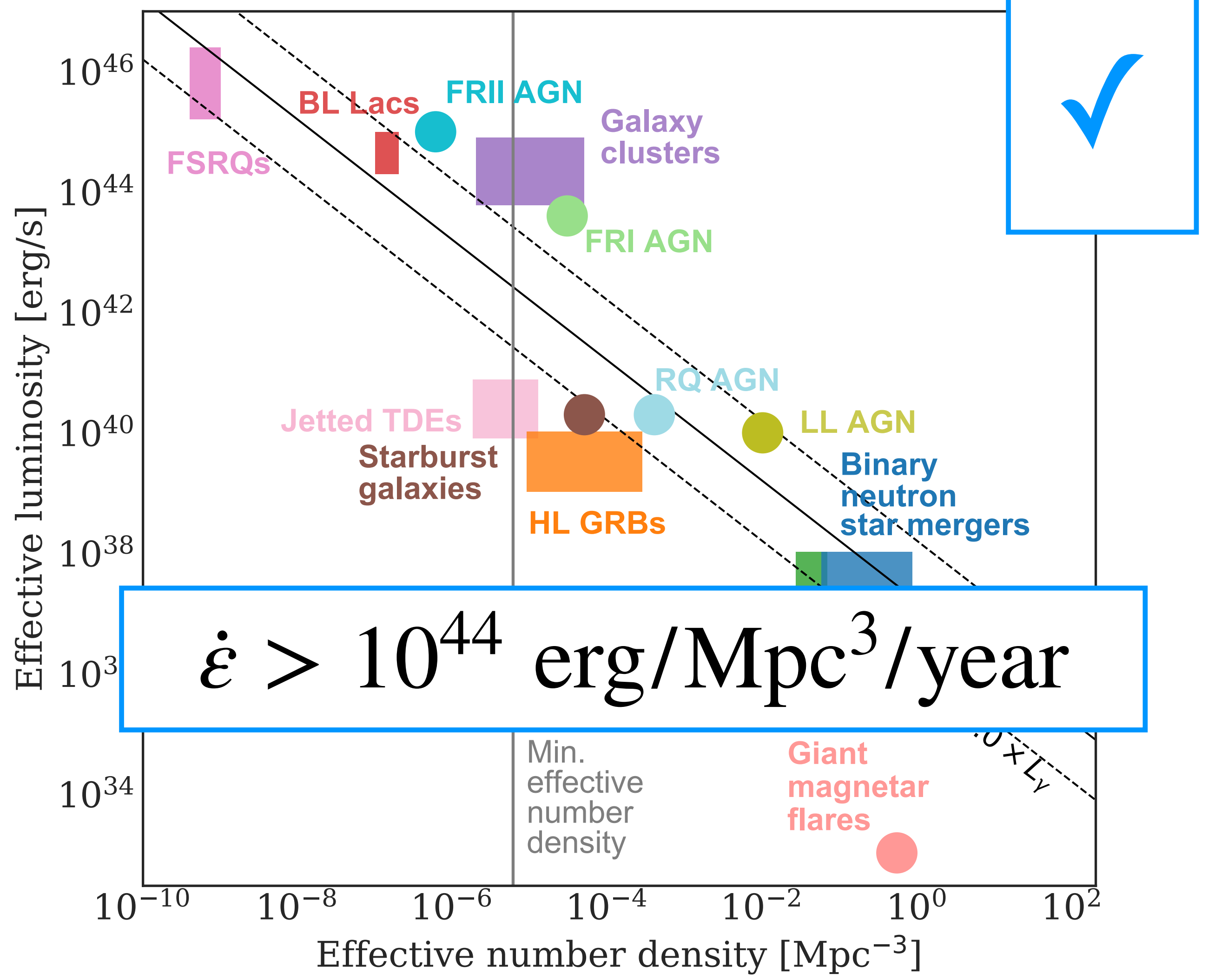
Need Gen2 for "typical" point sources

$N_{\nu_\mu,\mathrm{IceCube}}^{>100\ \mathrm{TeV}} \sim 5 \times 10^{-4}/6$ months

If $\xi_{CR} = 10$

Blazar/radio galaxy contribution to UHECR/neutrino flux?

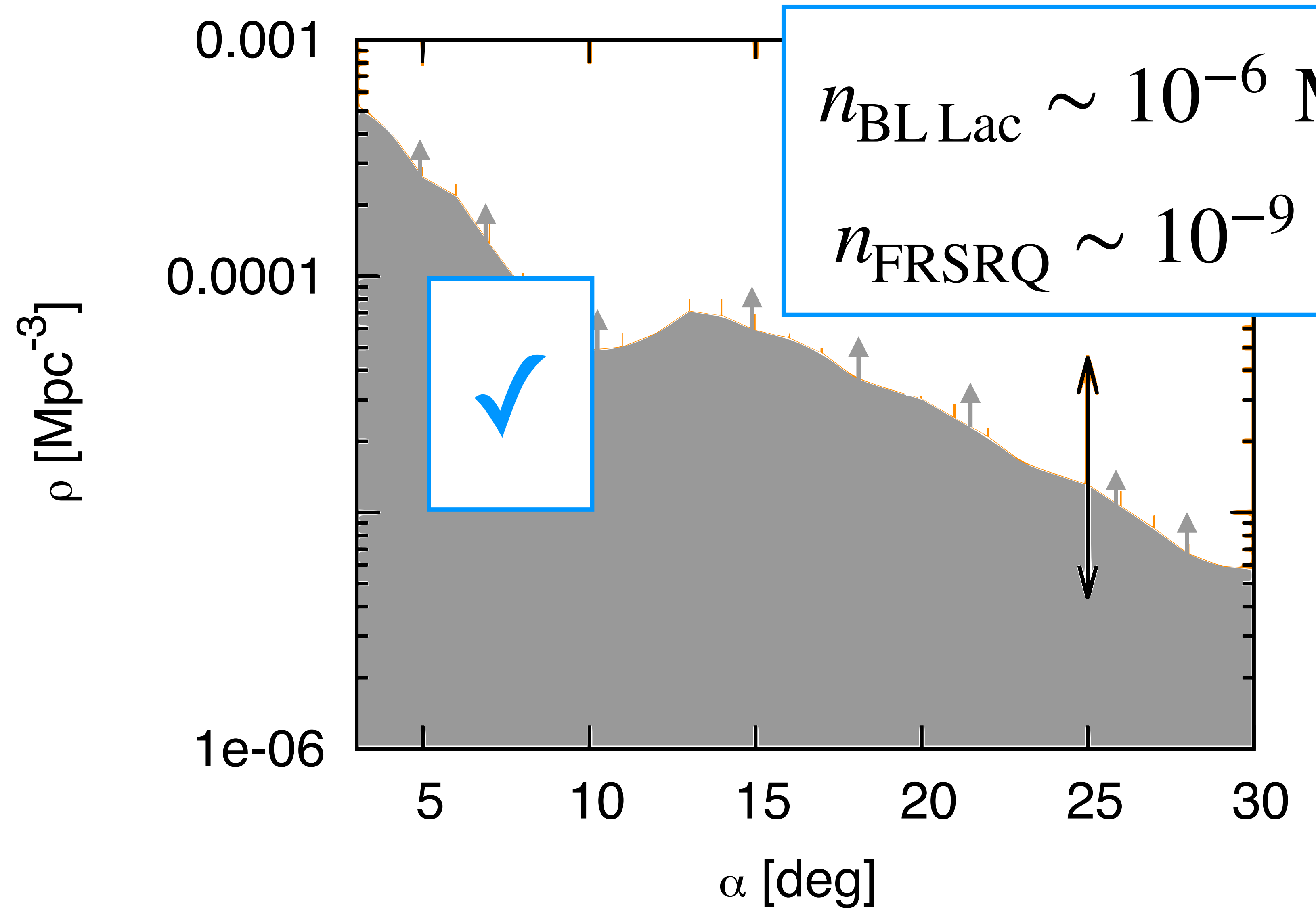
UHECR Emissivity



✓

$$\dot{\varepsilon} > 10^{44}\ \mathrm{erg/Mpc^3/year}$$

UHECR number density

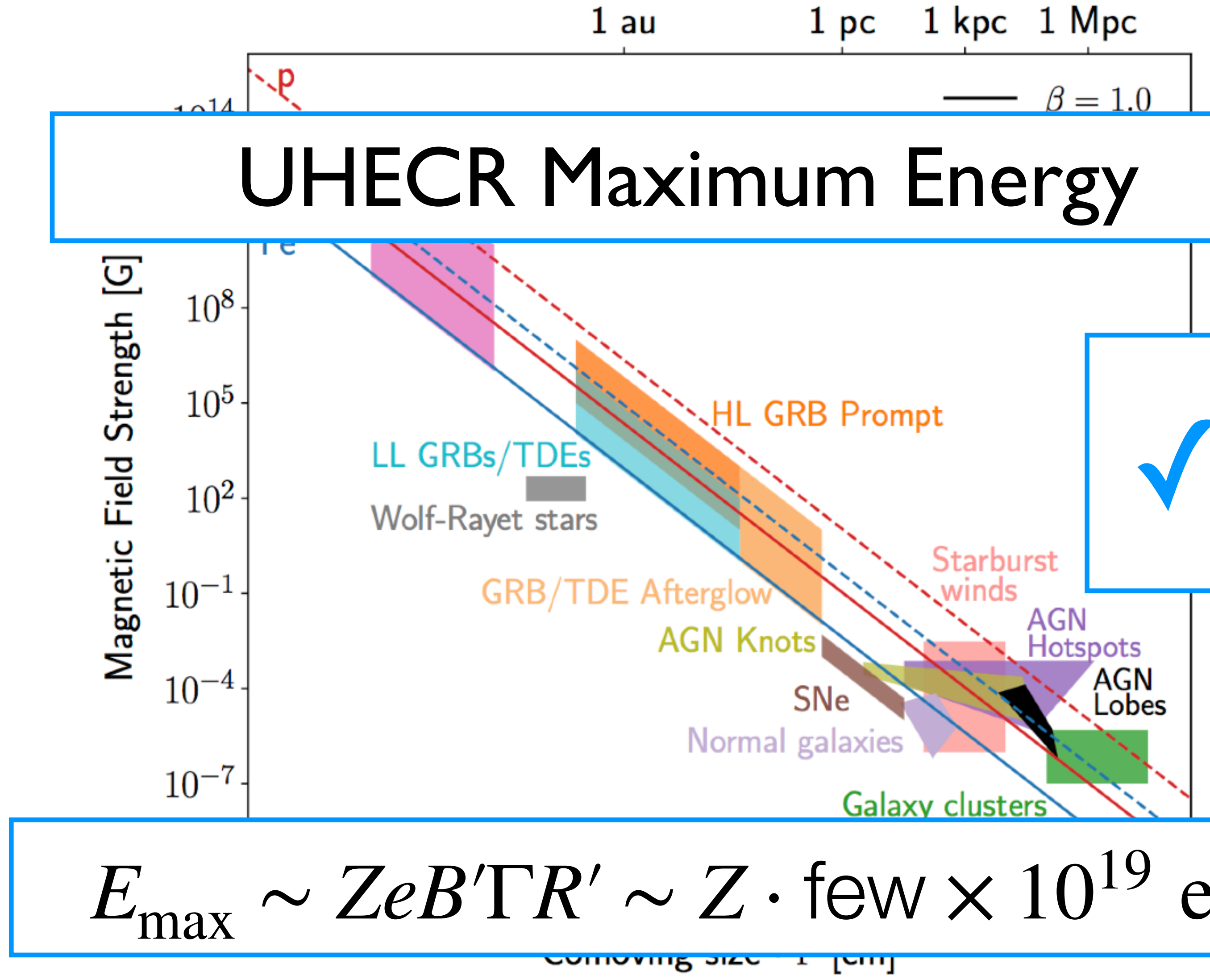


$$n_{\mathrm{BL\,Lac}} \sim 10^{-6}\ \mathrm{Mpc}^3$$

$$n_{\mathrm{FRSRQ}} \sim 10^{-9}\ \mathrm{Mpc}^3$$

✓

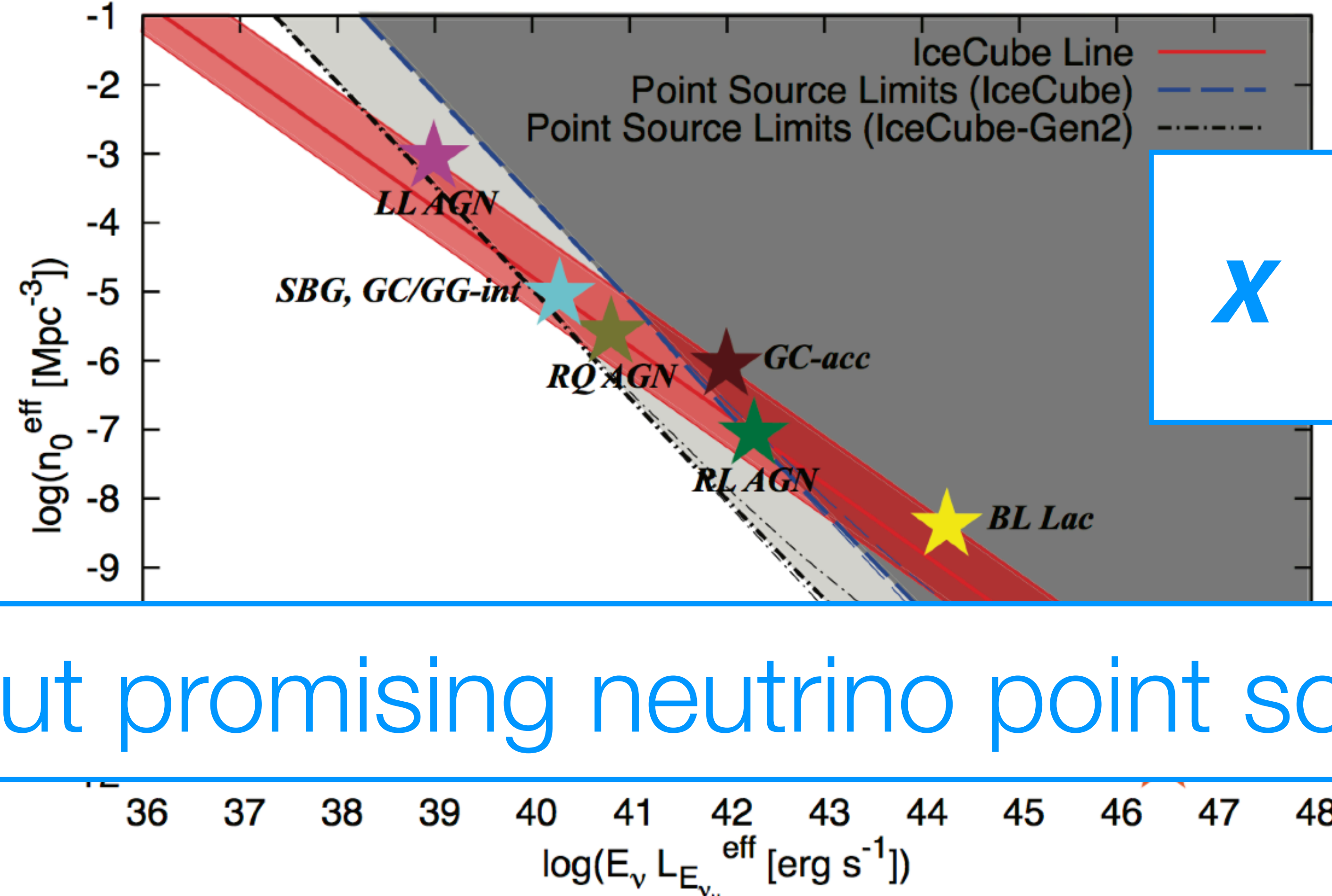
UHECR Maximum Energy



✓

$$E_{\max} \sim ZeB'\Gamma R' \sim Z \cdot \text{few} \times 10^{19}\ \mathrm{eV}$$

Neutrino clustering constraints



x

..but promising neutrino point sources!

Scorecard

	$E_{\rm max}^{\rm UHECR}$		$\dot{\varepsilon}_{\rm UHECR}$	n_ν	Stacking UL
BL Lacs	😀	😞	😀	😞	~20%
FSRQs	😀	😞	😀	😞	~20%
FR I	😀	😀	😀	😀	~20%
FR II	😀	😀	😀	😀	~20%
Non-jetted AGN					
Starburst galaxies					
HL GRBs					
LL GRBs					
TDEs					