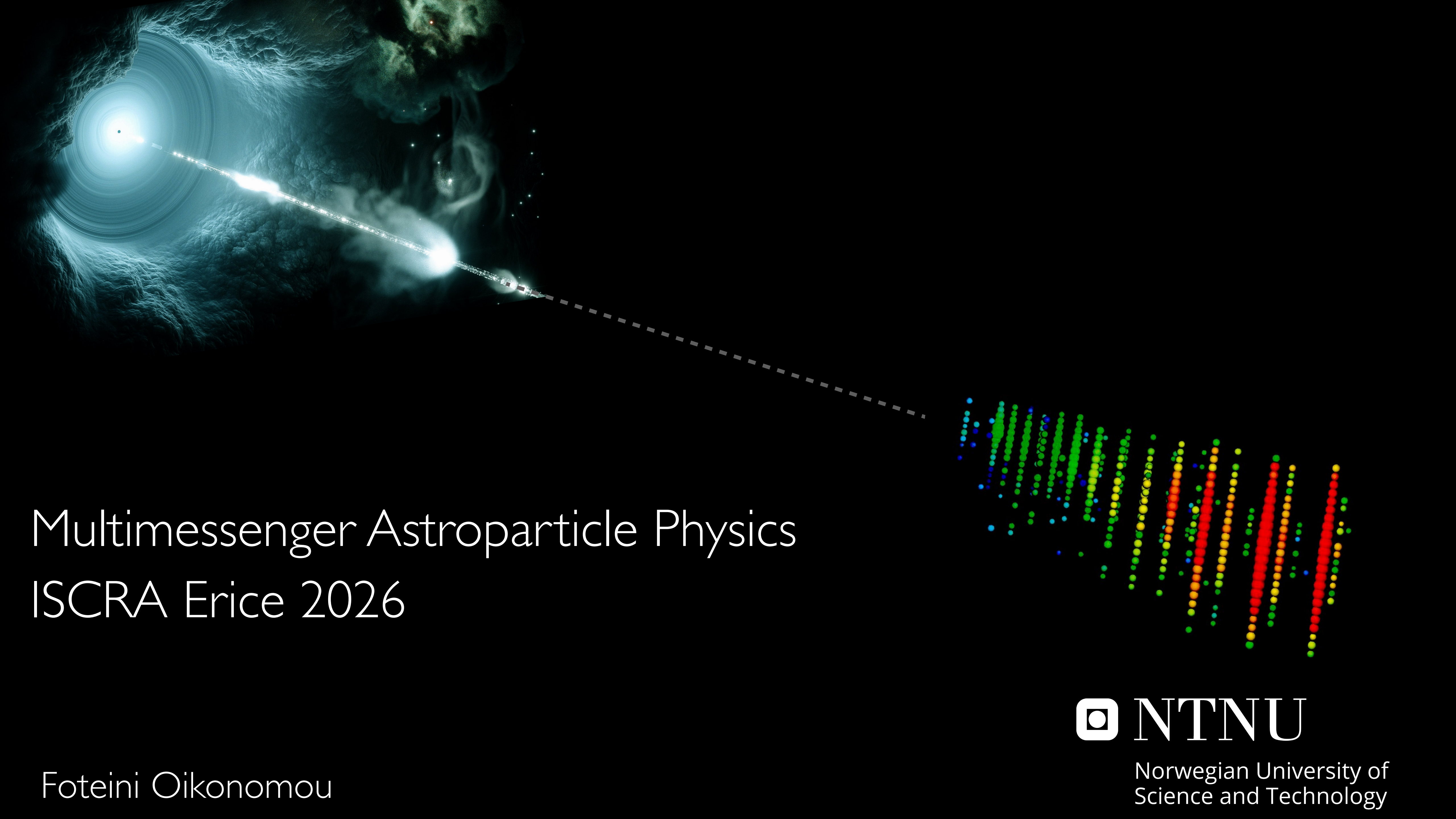




Multimessenger Astroparticle Physics

ISCRA Erice 2026

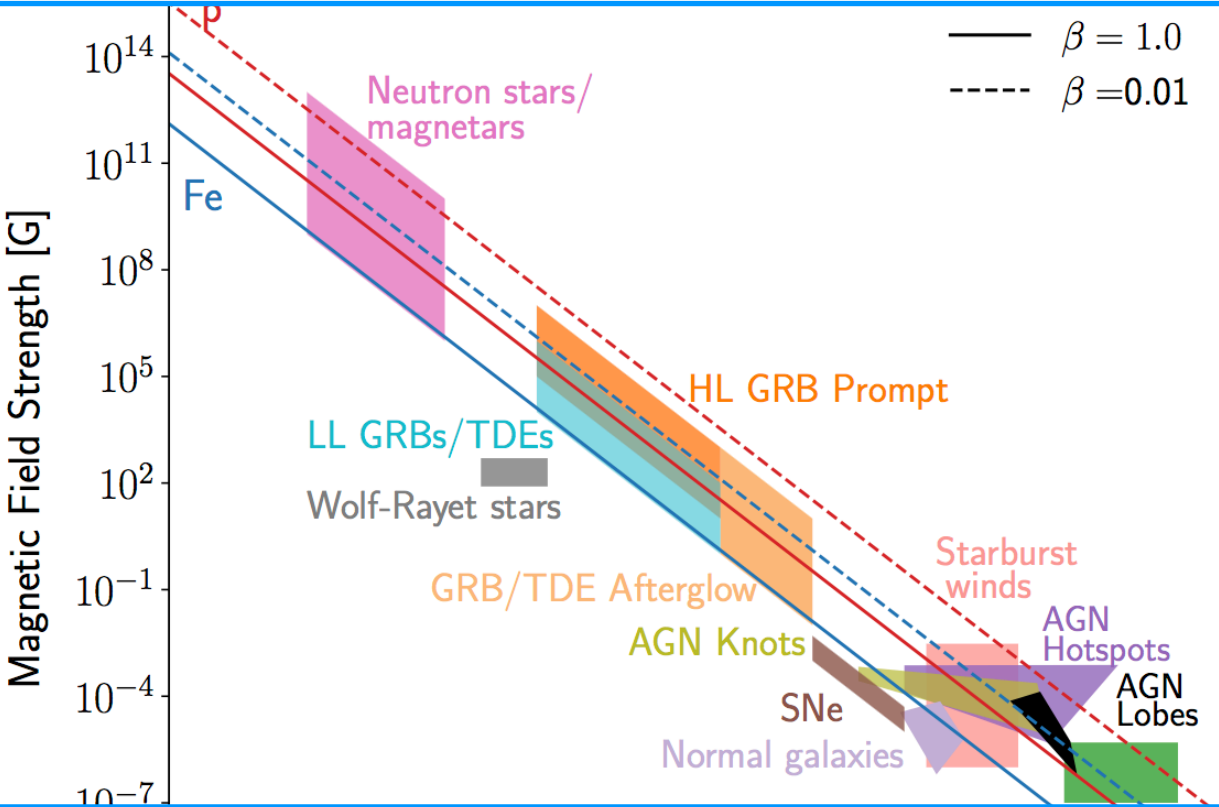
Foteini Oikonomou



Norwegian University of
Science and Technology

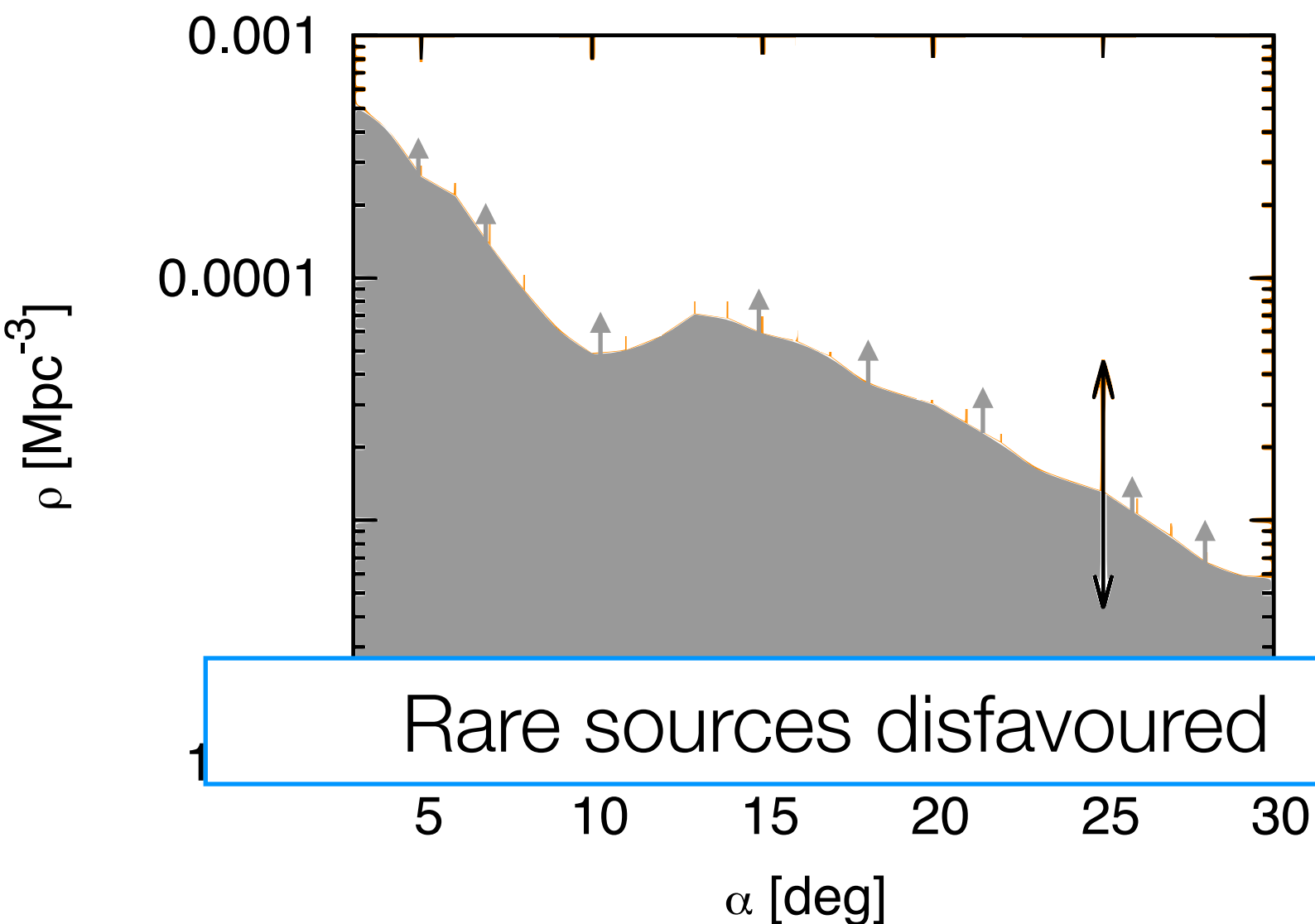
Recap

UHECR Maximum Energy



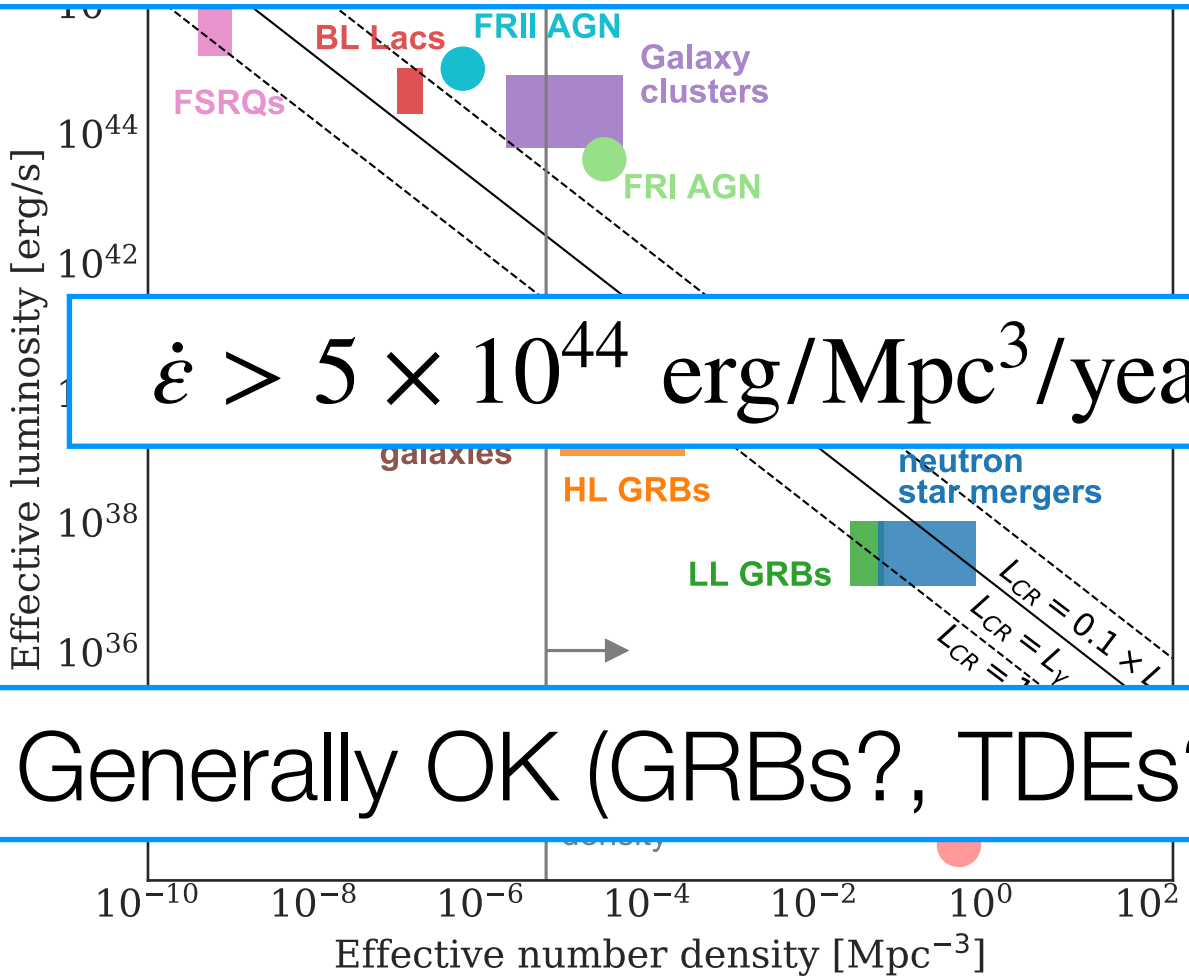
constraining, but several classes OK for nuclei

UHECR number density



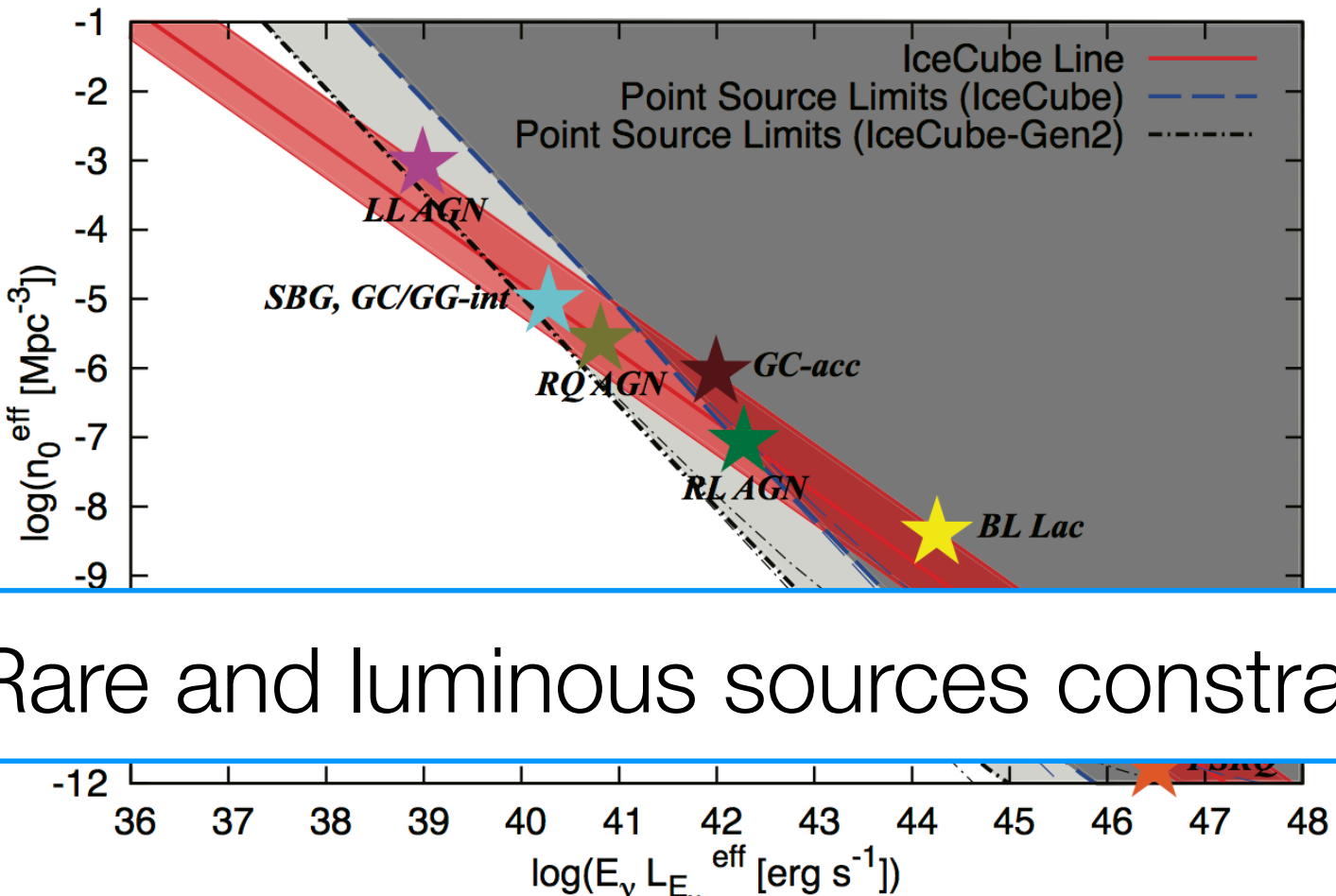
Rare sources disfavoured

UHECR Emissivity



Generally OK (GRBs?, TDEs?)

Neutrino clustering constraints



Rare and luminous sources constrained

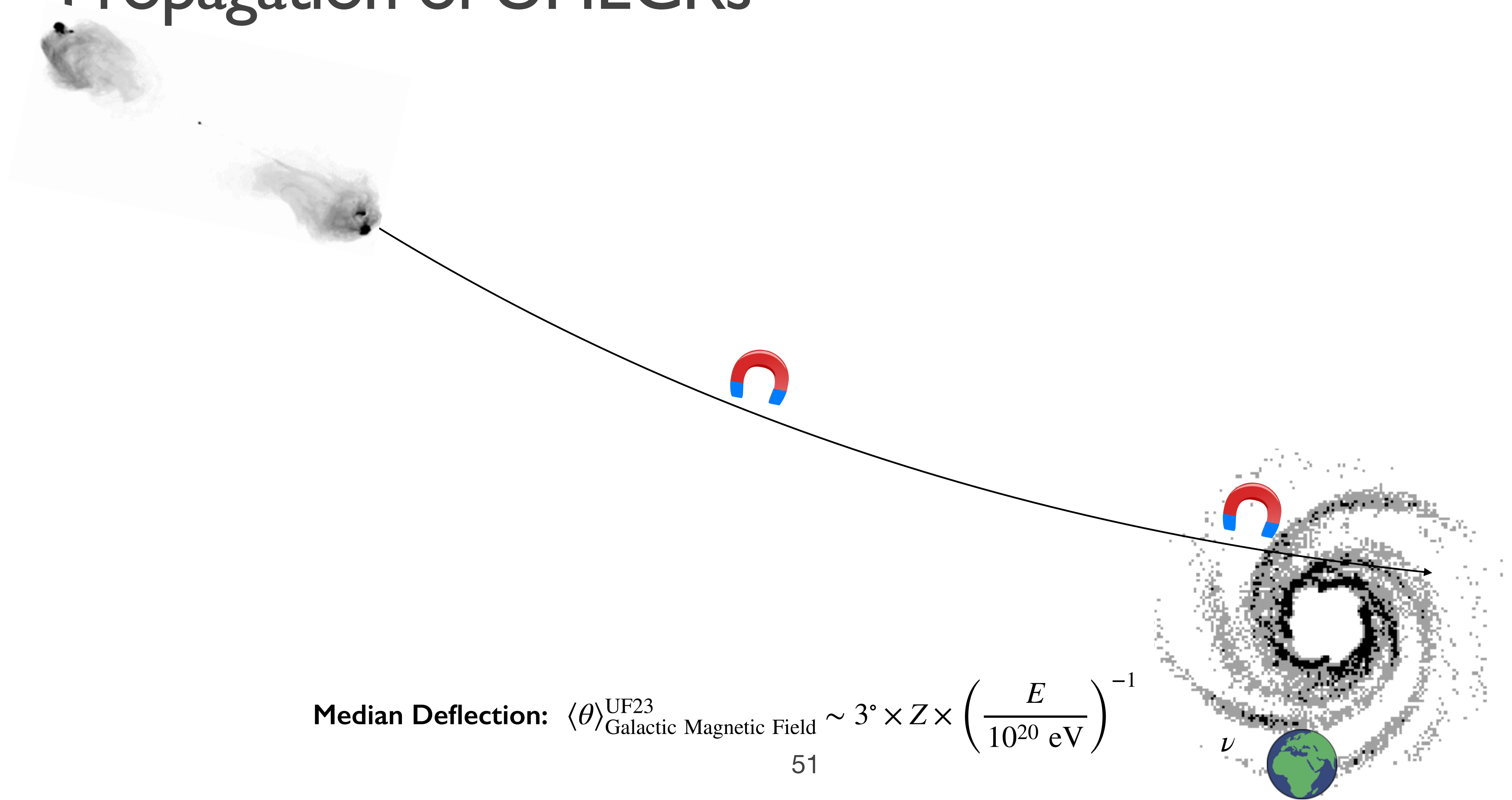
Plan

Today: generic source properties wrap up

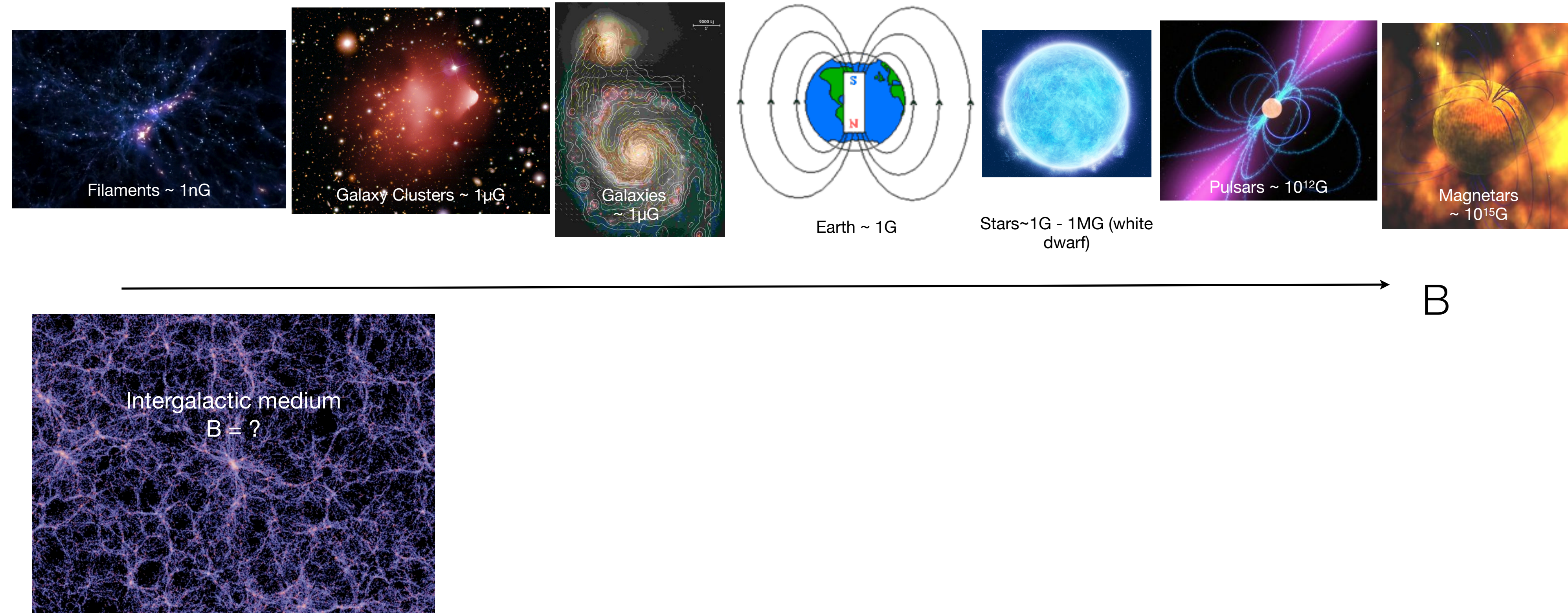
Today: active galactic nuclei (jetted)

Tomorrow: non-jetted agn, starburst galaxies, gamma-ray bursts, tidal-disruption events

Propagation of UHECRs



Magnetic fields in the Universe



No matter to trace fields, only weak upper limits:

$$B < 10^{-9} \text{ G}$$

Lower limits from blazars:

$$B > 10^{-15} \text{ G}$$



Deflections: Quasi rectilinear regime

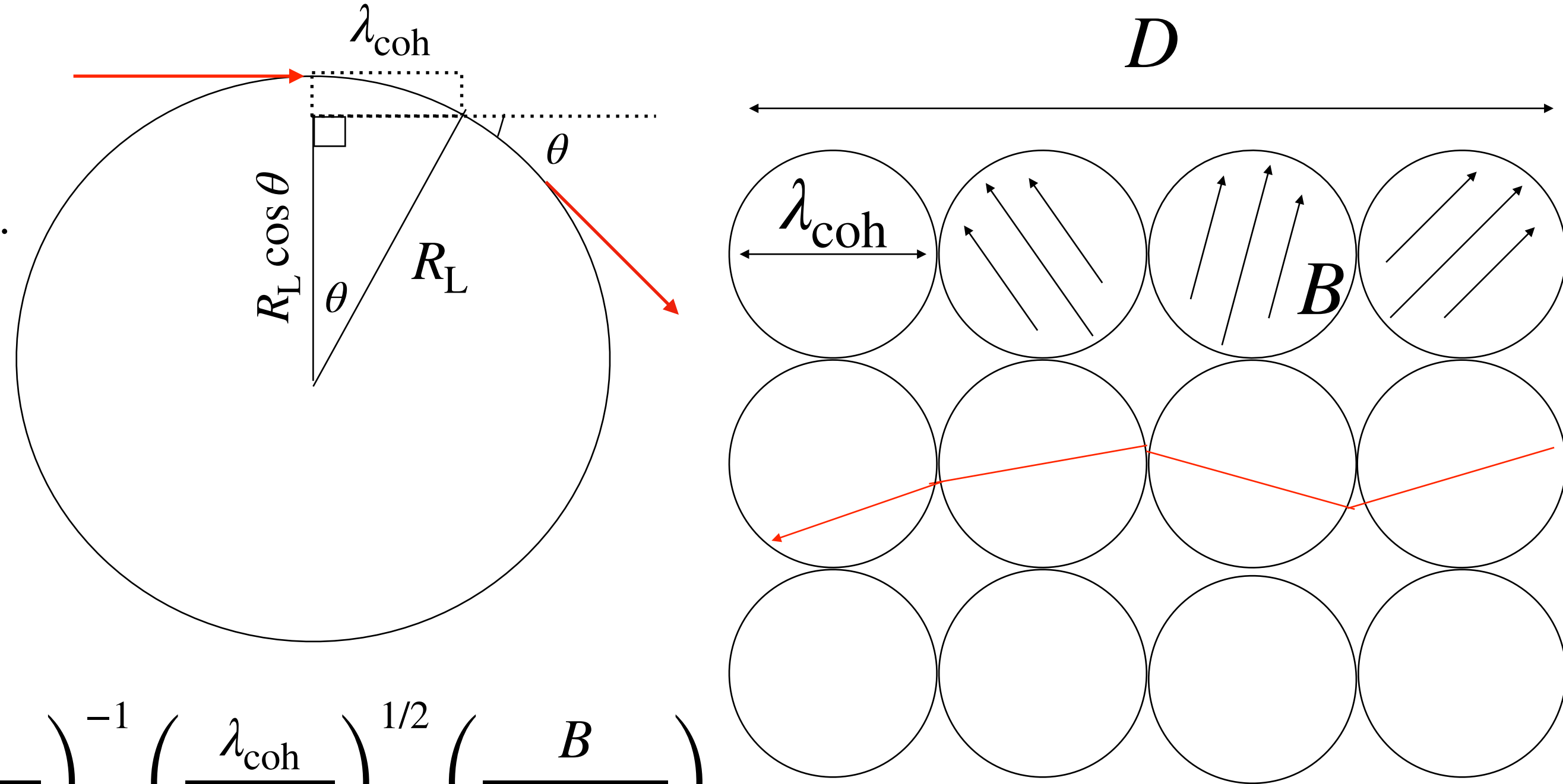
$$R_{\text{Larmor}} \gg \lambda_{\text{coh}}$$

$$R_L \simeq \frac{E}{ZeB} \simeq \frac{110 \text{ Mpc}}{Z} \left(\frac{E}{10^{20} \text{ eV}} \right) \left(\frac{B}{1 \text{ nG}} \right)^{-1}.$$

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

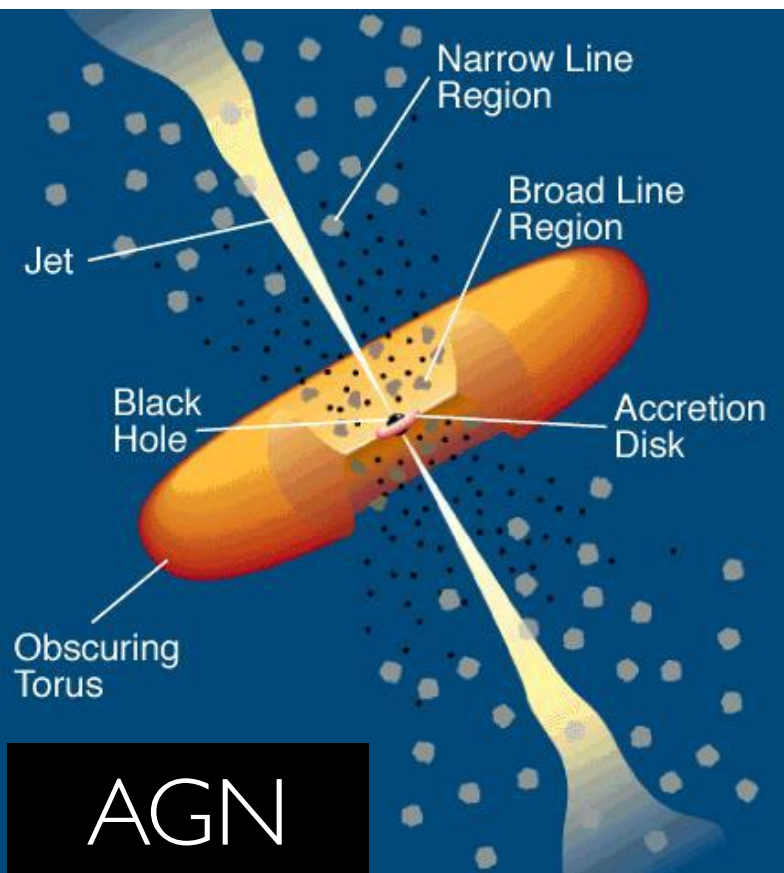
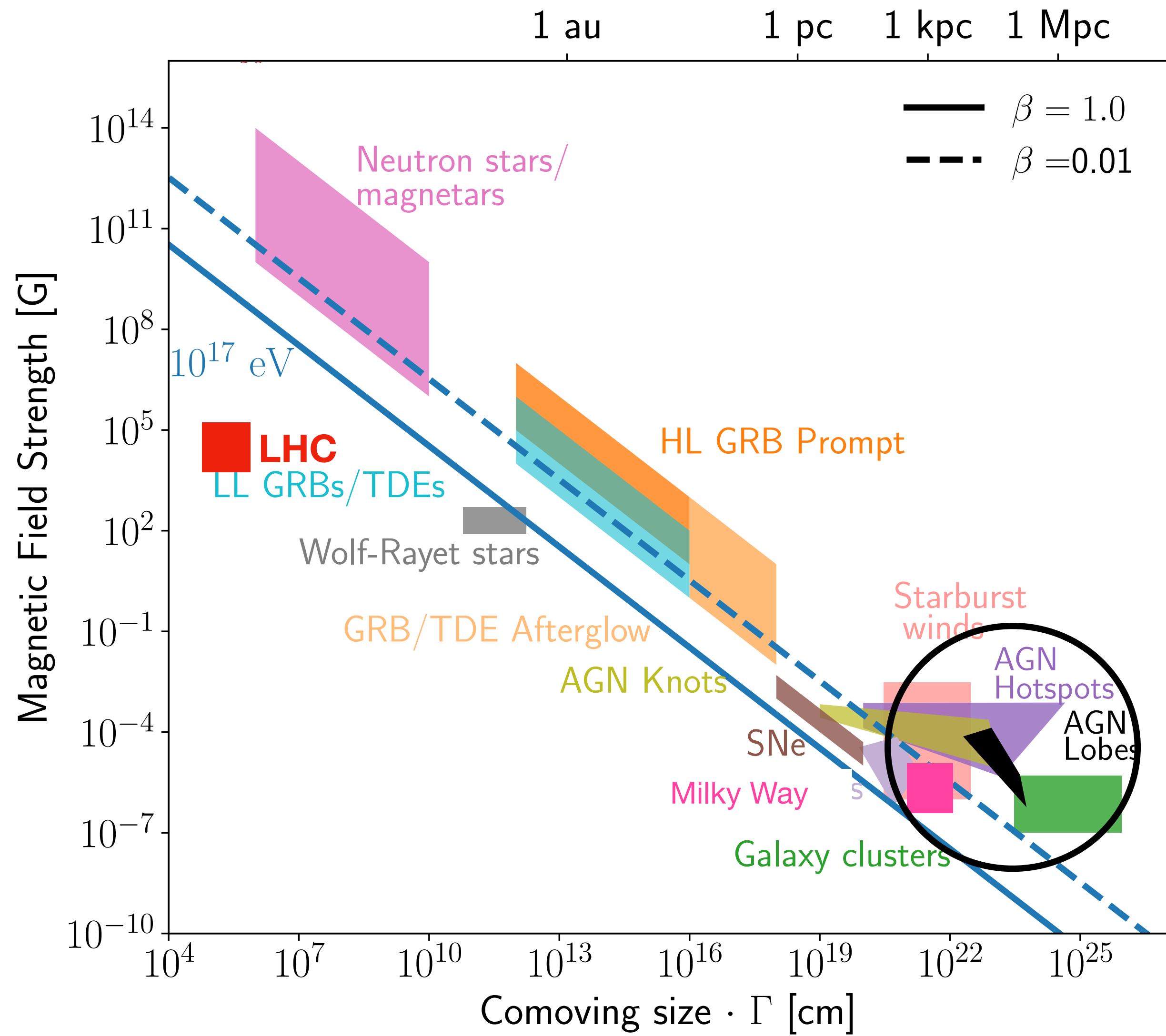
$$\langle \Delta \theta_{\text{tot}}^2 \rangle \approx N \cdot \langle \delta \theta_{\text{cell}}^2 \rangle, \quad \left[N = \frac{D}{\lambda_{\text{coh}}} \right]$$

$$\Delta \theta \simeq 0.1^\circ Z \left(\frac{D}{100 \text{ Mpc}} \right)^{1/2} \left(\frac{E}{10^{20} \text{ eV}} \right)^{-1} \left(\frac{\lambda_{\text{coh}}}{1 \text{ Mpc}} \right)^{1/2} \left(\frac{B}{0.01 \text{ nG}} \right)$$



$$\tau_{\text{delay}} \approx D \frac{\Delta \theta_{\text{tot}}^2}{4c} \approx 10^3 \text{ yr} \cdot Z^2 \cdot \left(\frac{D}{100 \text{ Mpc}} \right)^2 \left(\frac{E}{10^{20} \text{ eV}} \right)^{-2} \left(\frac{\lambda_{\text{coh}}}{1 \text{ Mpc}} \right) \left(\frac{B}{0.1 \text{ nG}} \right)^2$$

Cosmic-ray accelerators that satisfy the confinement



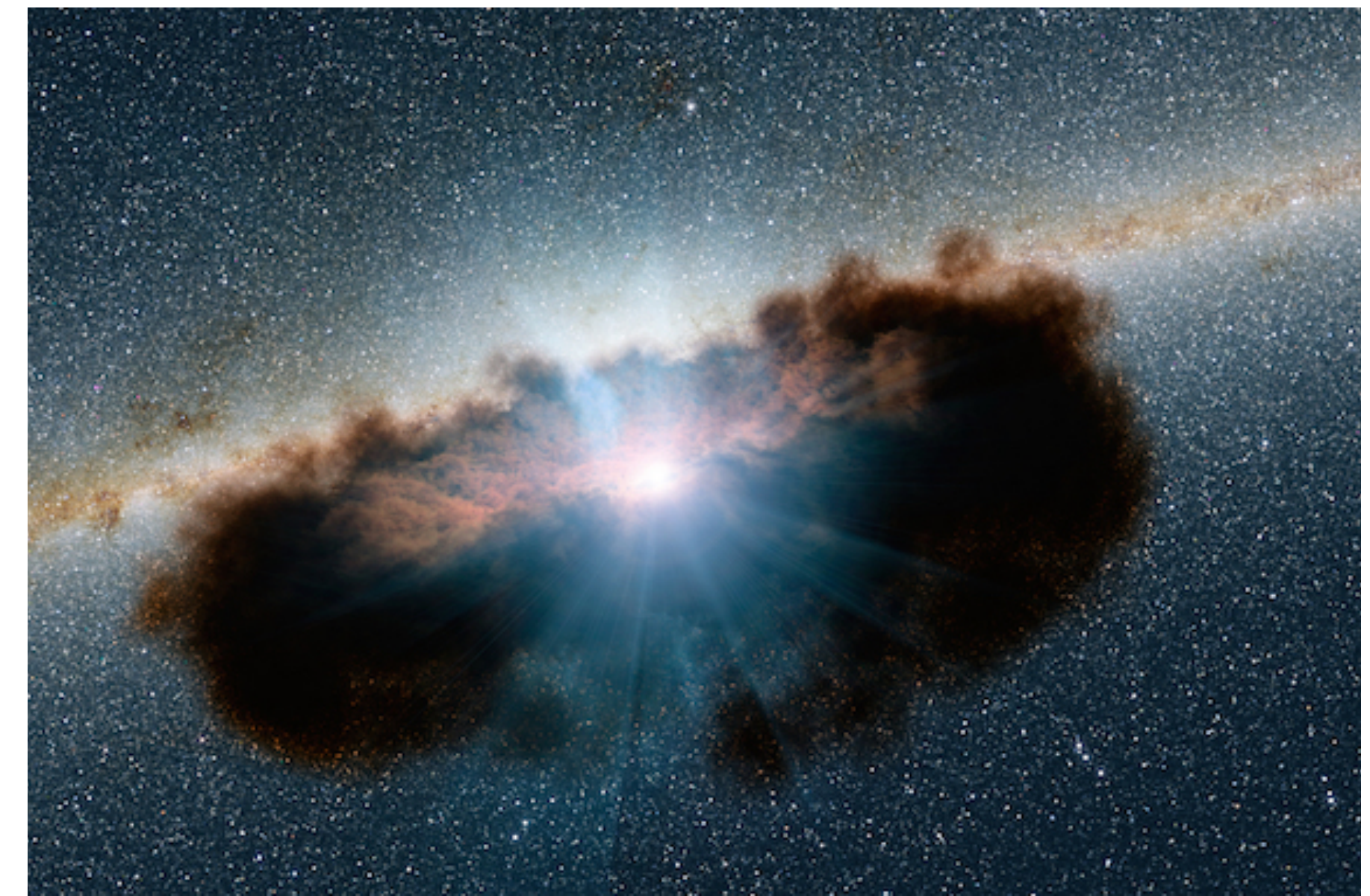
Active Galactic Nuclei

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

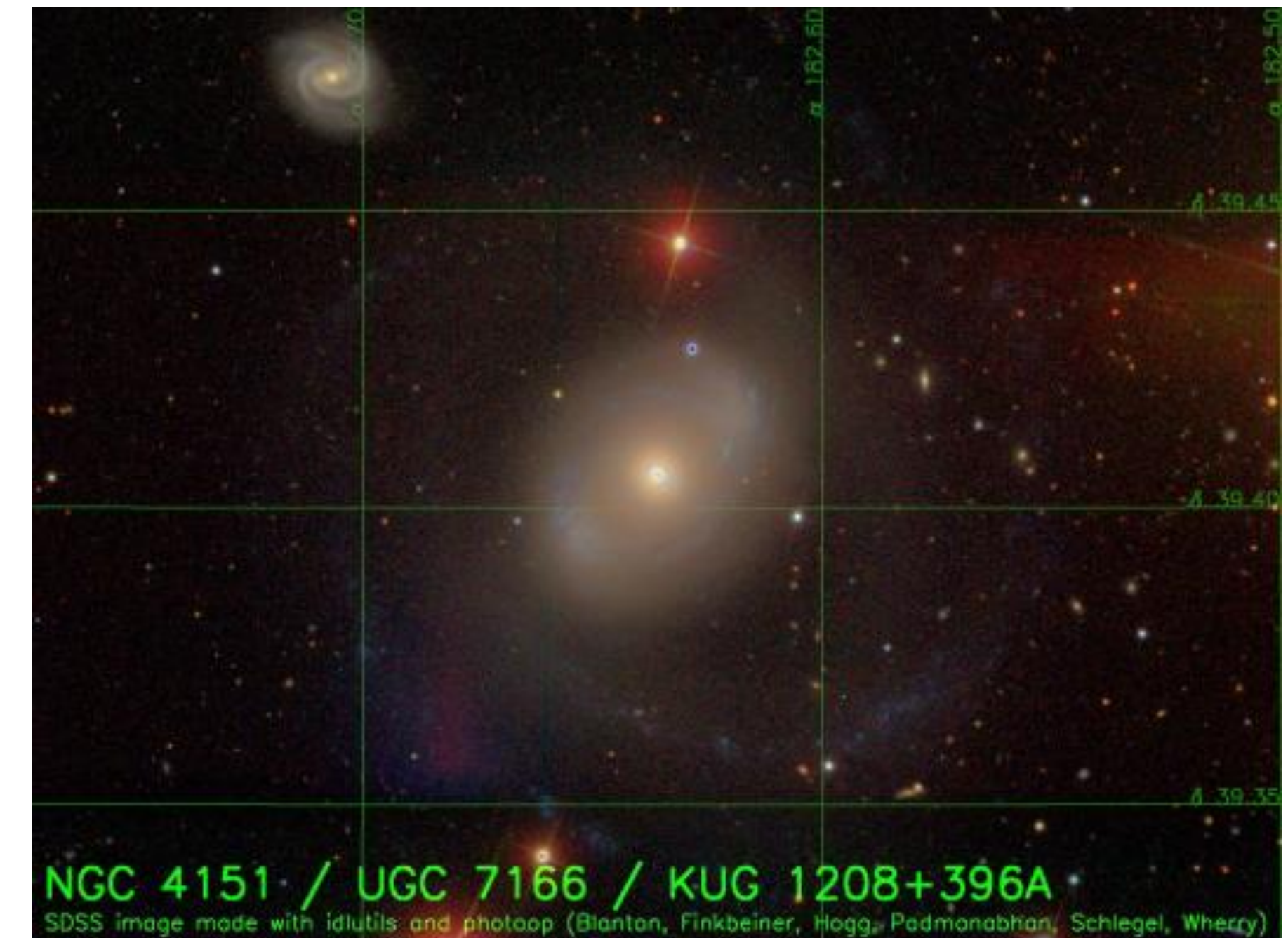
They host a super-massive black hole (SMBH)
(10^6 - $10^{10} M_{\text{sun}}$). “Active” as emission $\gg$ stars in the
galaxy - accretion on to SMBH

Visible to large redshifts ($z > 7.5$) - peak $z \sim 2$ (depends
on type)

1% of galaxies active



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



Active Galactic Nuclei

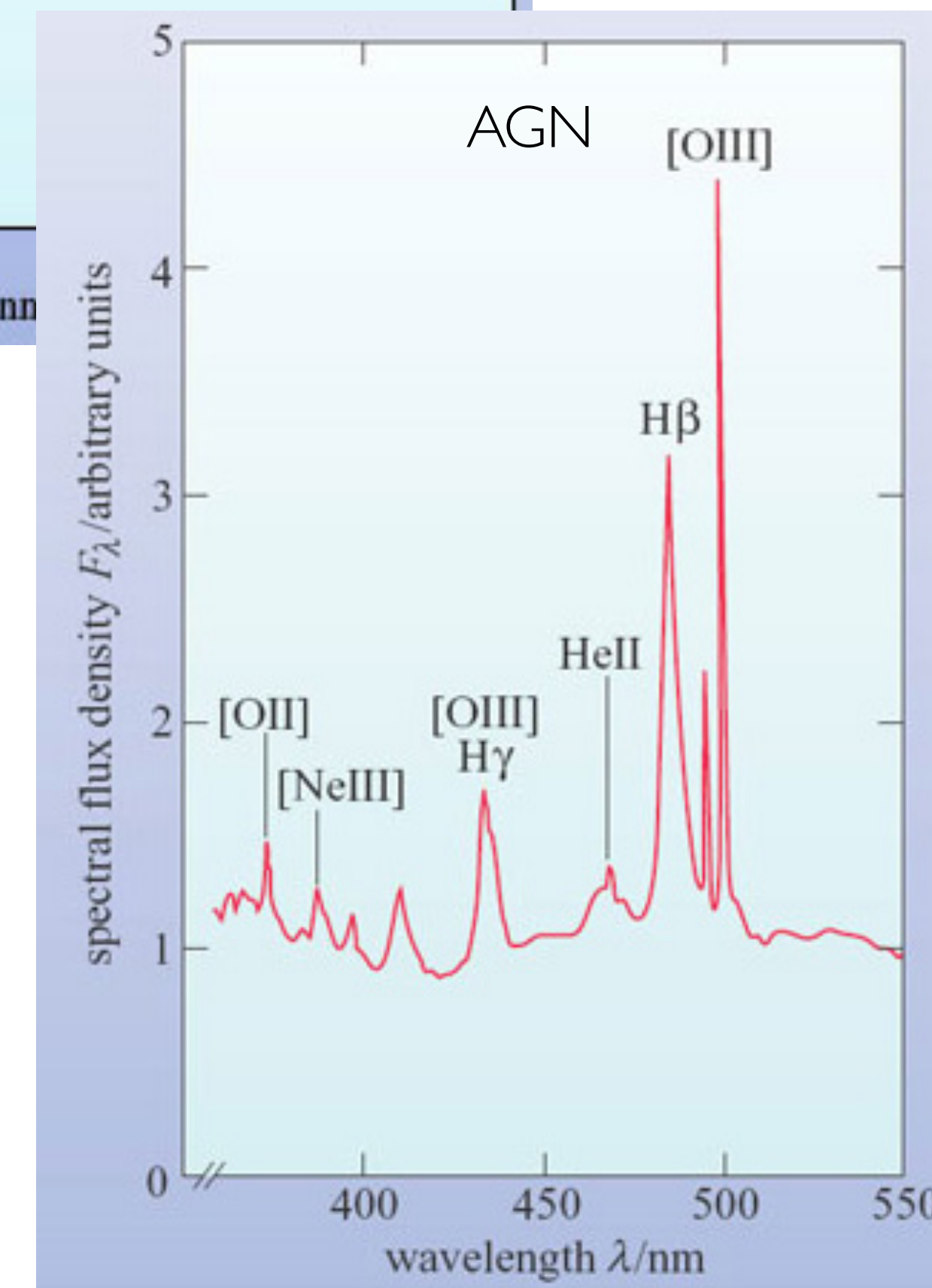
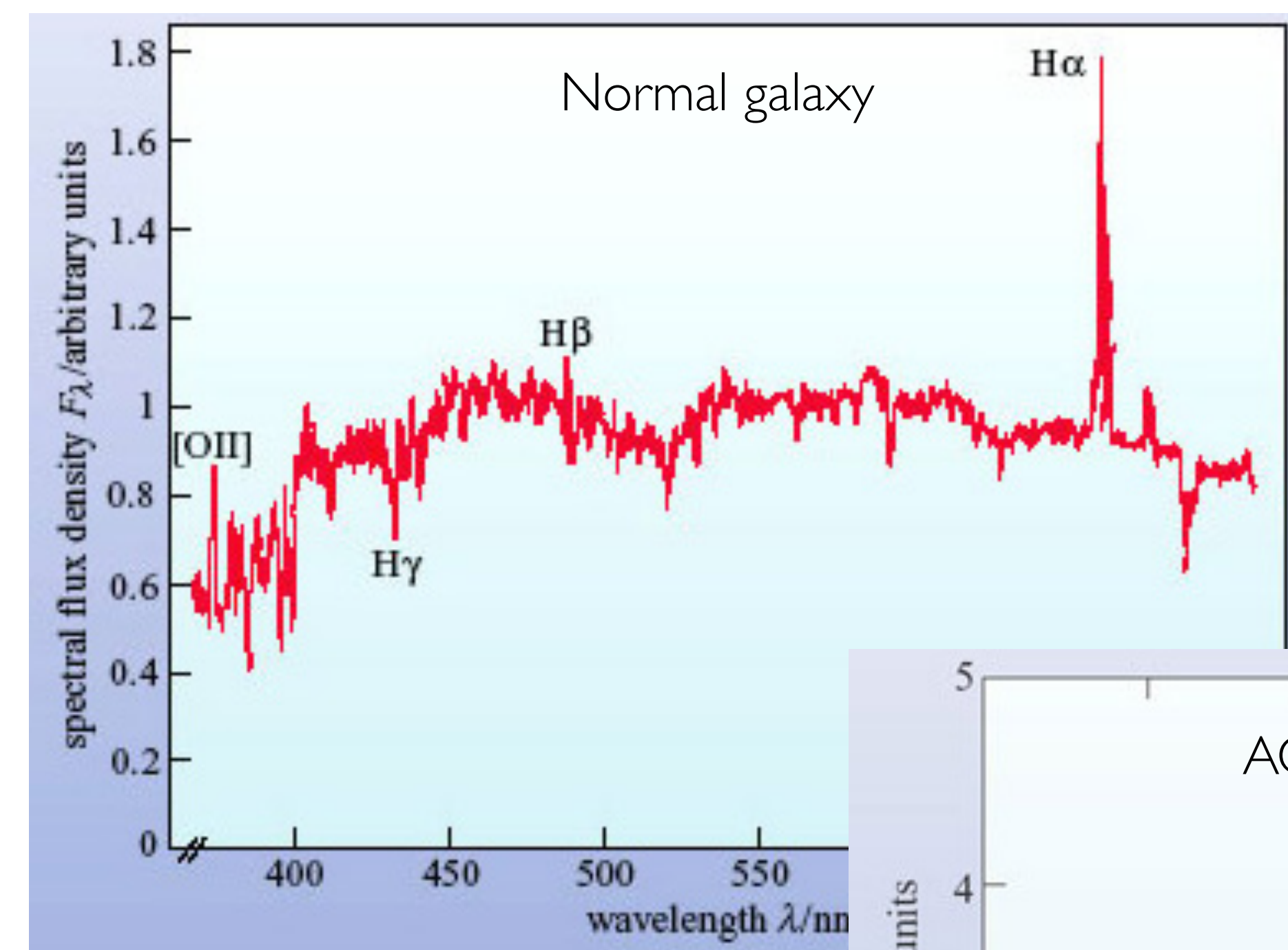
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Visible to large redshifts ($z > 7.5$) - peak $z \sim 2$ (depends on type)

1% of galaxies active

Broad emission lines reveal rapid bulk rotation



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

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

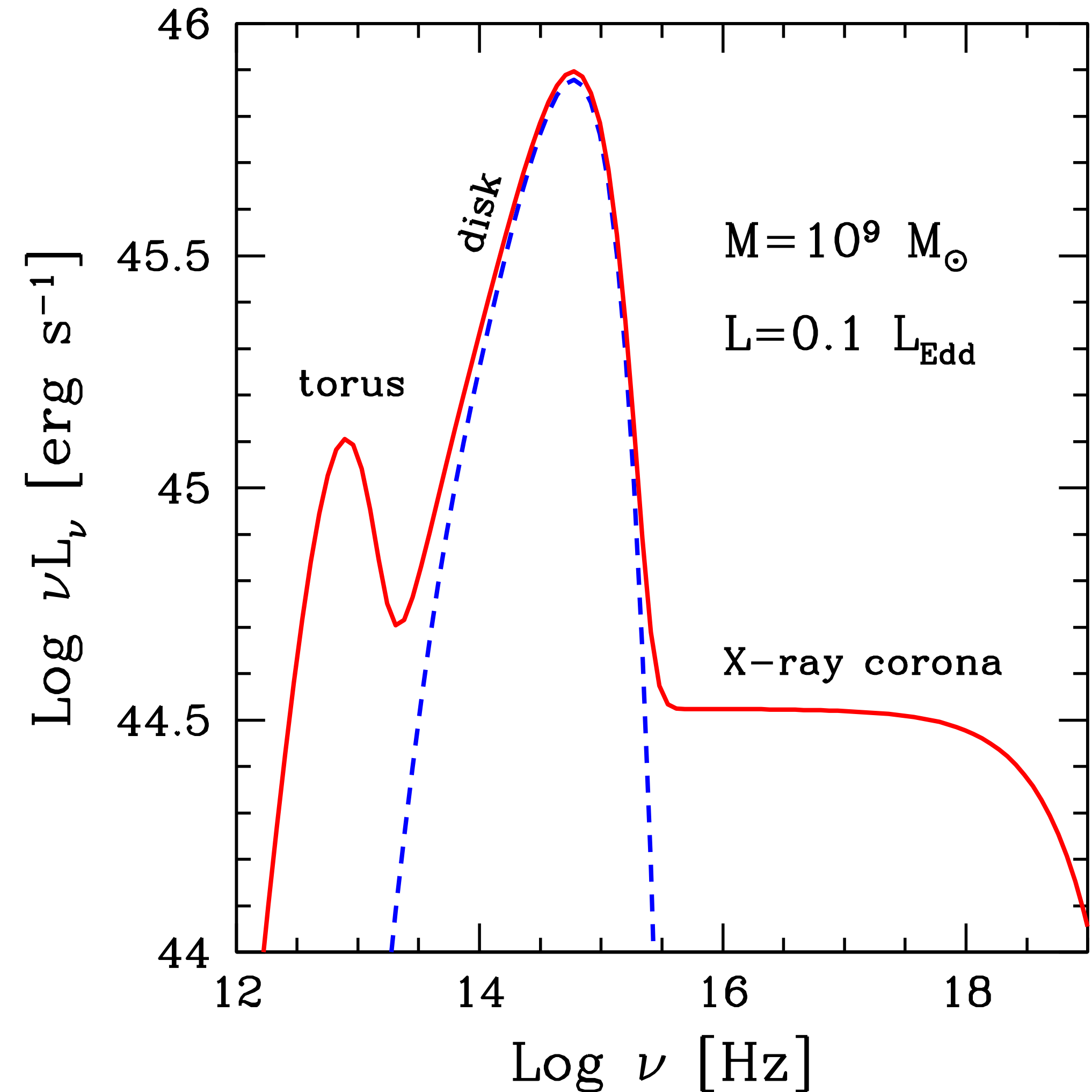
In solar masses per year, the requirement is

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

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

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

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



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

The engine

For an AGN with disk luminosity

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

and time variability

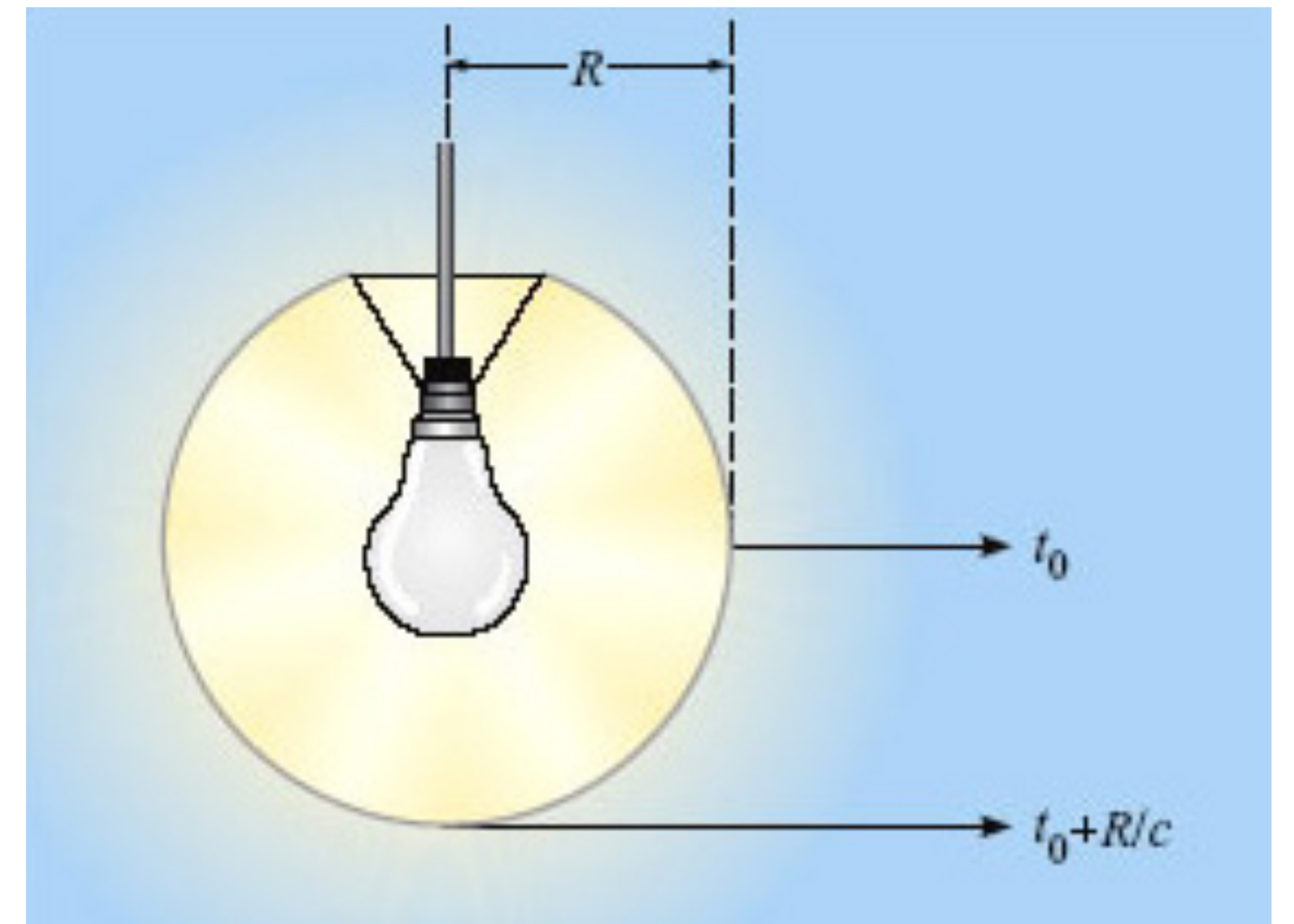
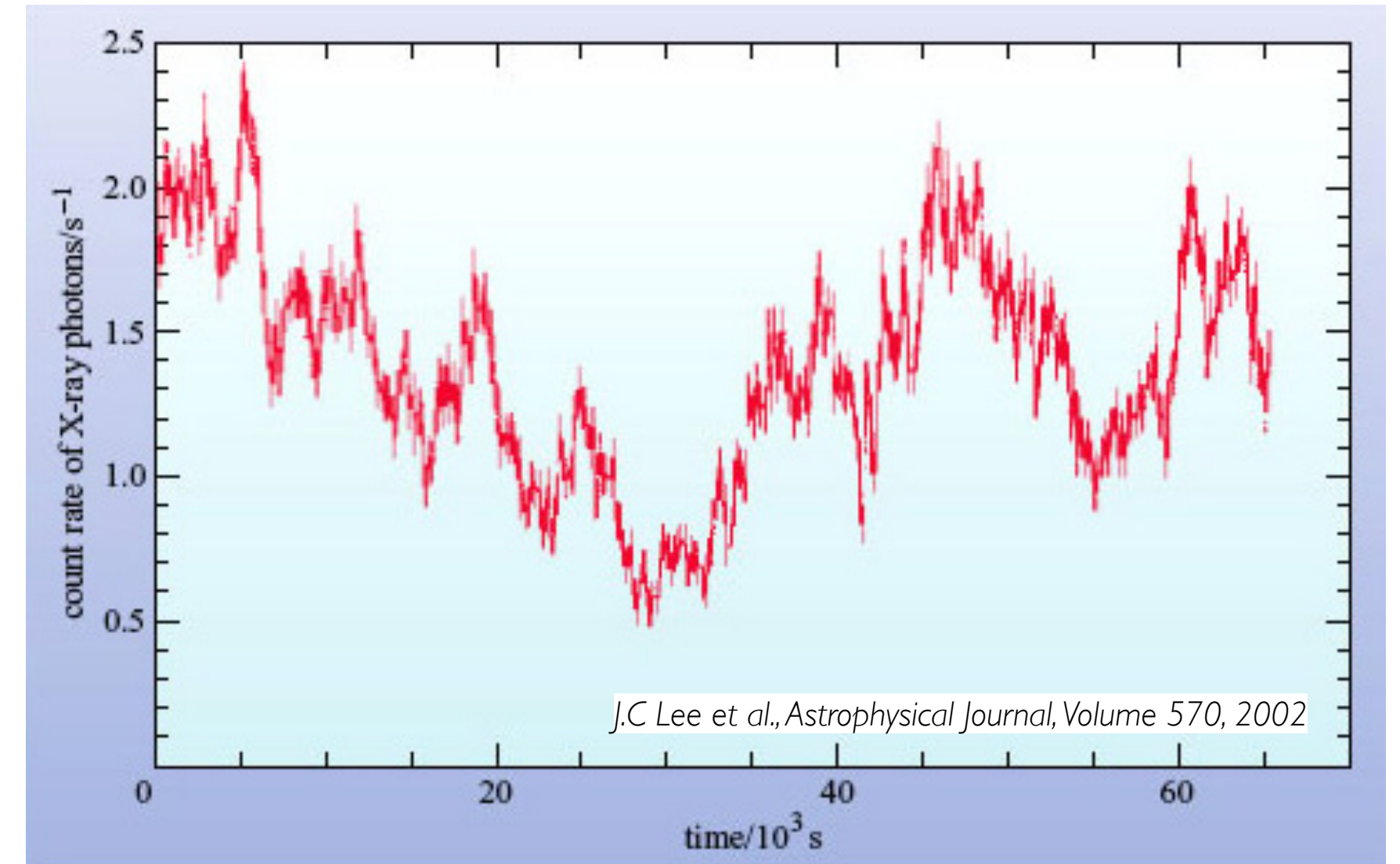
$$\Delta t = 10^4 \text{ s, causality dictates } R \sim c\Delta t = 0.01 \text{ pc} = 20 \text{ AU}$$

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

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

$$\text{i.e. we need, } M \geq 10^8 M_{\text{Sun}} \left(\frac{L_{\text{disk}}}{10^{46} \text{ erg/s}} \right)$$

$$R \sim c\Delta t = 20 \text{ AU} \simeq 10 R_s, \quad R_s = \frac{2GM}{c^2} \simeq 2 \text{ AU} \left(\frac{M}{10^8 M_{\text{Sun}}} \right)$$



AGN Zoo

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

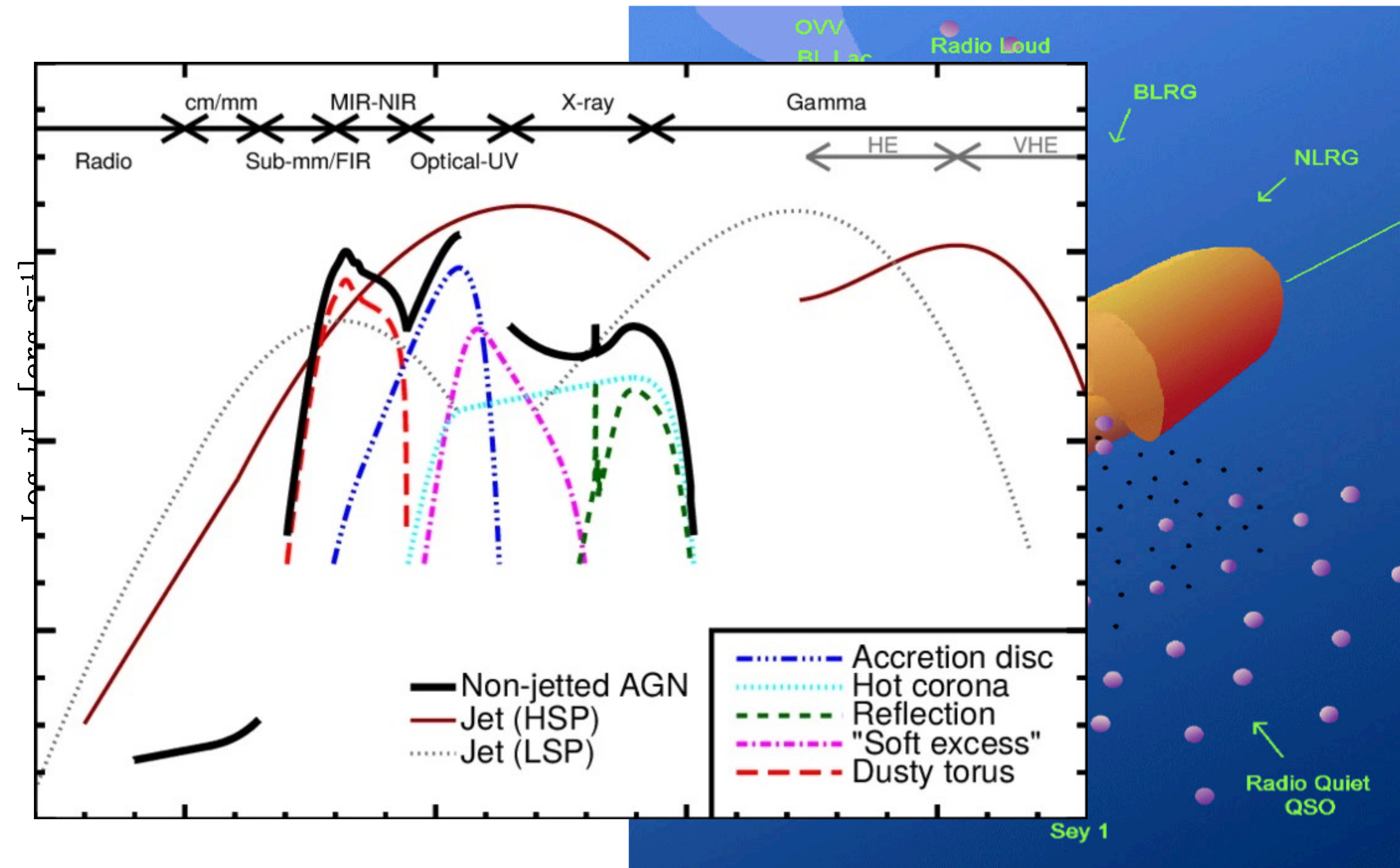
Class/Acronym	Meaning	Main properties/reference
Quasar	Quasi-stellar radio source (originally)	Radio detection no longer required
Sey1	Seyfert 1	$\text{FWHM} \gtrsim 1,000 \text{ km s}^{-1}$
Sey2	Seyfert 2	$\text{FWHM} \lesssim 1,000 \text{ km s}^{-1}$
QSO	Quasi-stellar object	Quasar-like, non-radio 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	$\text{FWHM} \gtrsim 1,000 \text{ km s}^{-1}$
BLAGN	Broad-line AGN	$\text{FWHM} \gtrsim 1,000 \text{ km s}^{-1}$
BLRG	Broad-line radio galaxy	RL Sey1
CDQ	Core-dominated quasar	RL AGN, $f_{\text{core}} \geq f_{\text{ext}}$ (same as FSRQ)
CSS	Compact steep spectrum radio source	core dominated, $\alpha_r > 0.5$
CT	Compton-thick	$N_{\text{H}} \geq 1.5 \times 10^{24} \text{ cm}^{-2}$
FR 0	Fanaroff-Riley class 0 radio source	ref. 5
FSRQ	Flat-spectrum radio quasar	RL AGN, $\alpha_r \leq 0.5$
GPS	Gigahertz-peaked radio source	see ref. 6
HBL/HSP	High-energy cutoff BL Lac/blazar	$\nu_{\text{synch peak}} \geq 10^{15} \text{ Hz}$ (ref. 7)
HEG	High-excitation galaxy	ref. 8
HPQ	High polarization quasar	$P_{\text{opt}} \geq 3\%$ (same as FSRQ)
Jet-mode		$L_{\text{kin}} \gg L_{\text{rad}}$ (same as LERG); see ref. 9
IBL/ISP	Intermediate-energy cutoff BL Lac/blazar	$10^{14} \leq \nu_{\text{synch peak}} \leq 10^{15} \text{ Hz}$ (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	$\nu_{\text{synch peak}} < 10^{14} \text{ Hz}$ (ref. 7)
LDQ	Lobe-dominated quasar	RL AGN, $f_{\text{core}} < f_{\text{ext}}$
LEG	Low-excitation galaxy	ref. 8
LPQ	Low polarization quasar	$P_{\text{opt}} < 3\%$
NLAGN	Narrow-line AGN	$\text{FWHM} \lesssim 1,000 \text{ km s}^{-1}$
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, $\alpha_r > 0.5$
USS	Ultra-steep spectrum source	RL AGN, $\alpha_r > 1.0$
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:

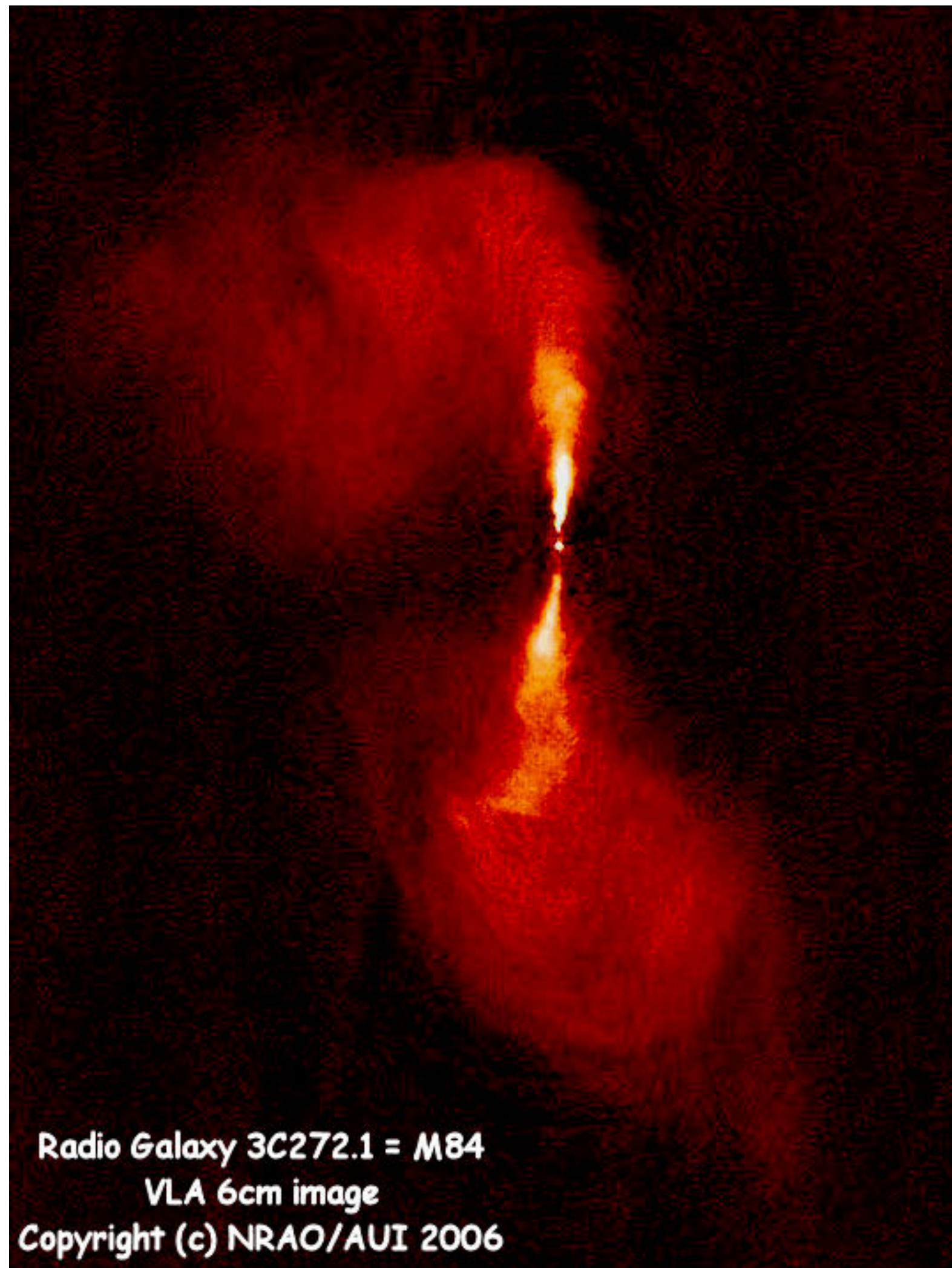
- Orientation
- Presence of jet or not (10% have it)
- Radiative efficiency

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

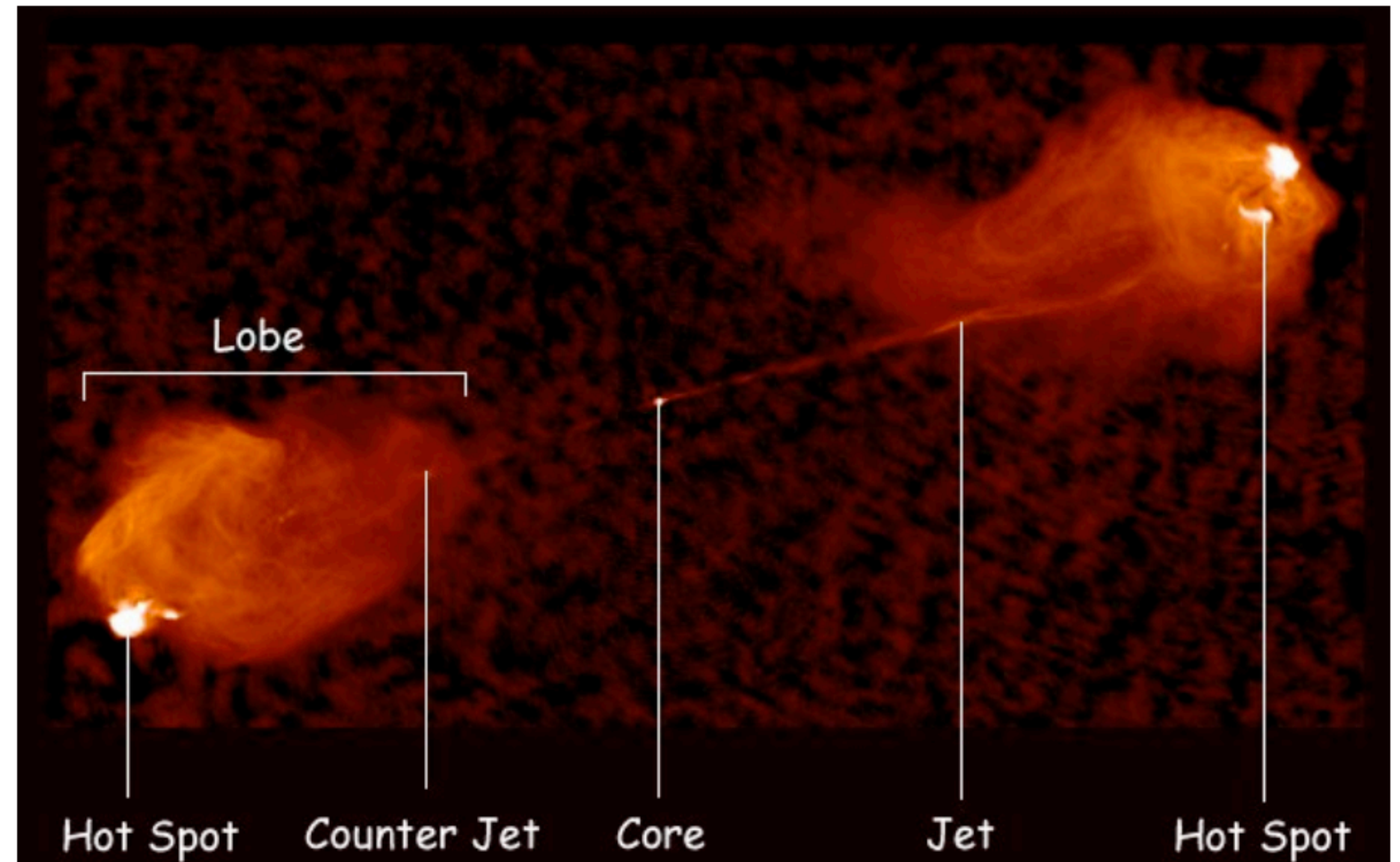


10% of AGN host jets

FRI



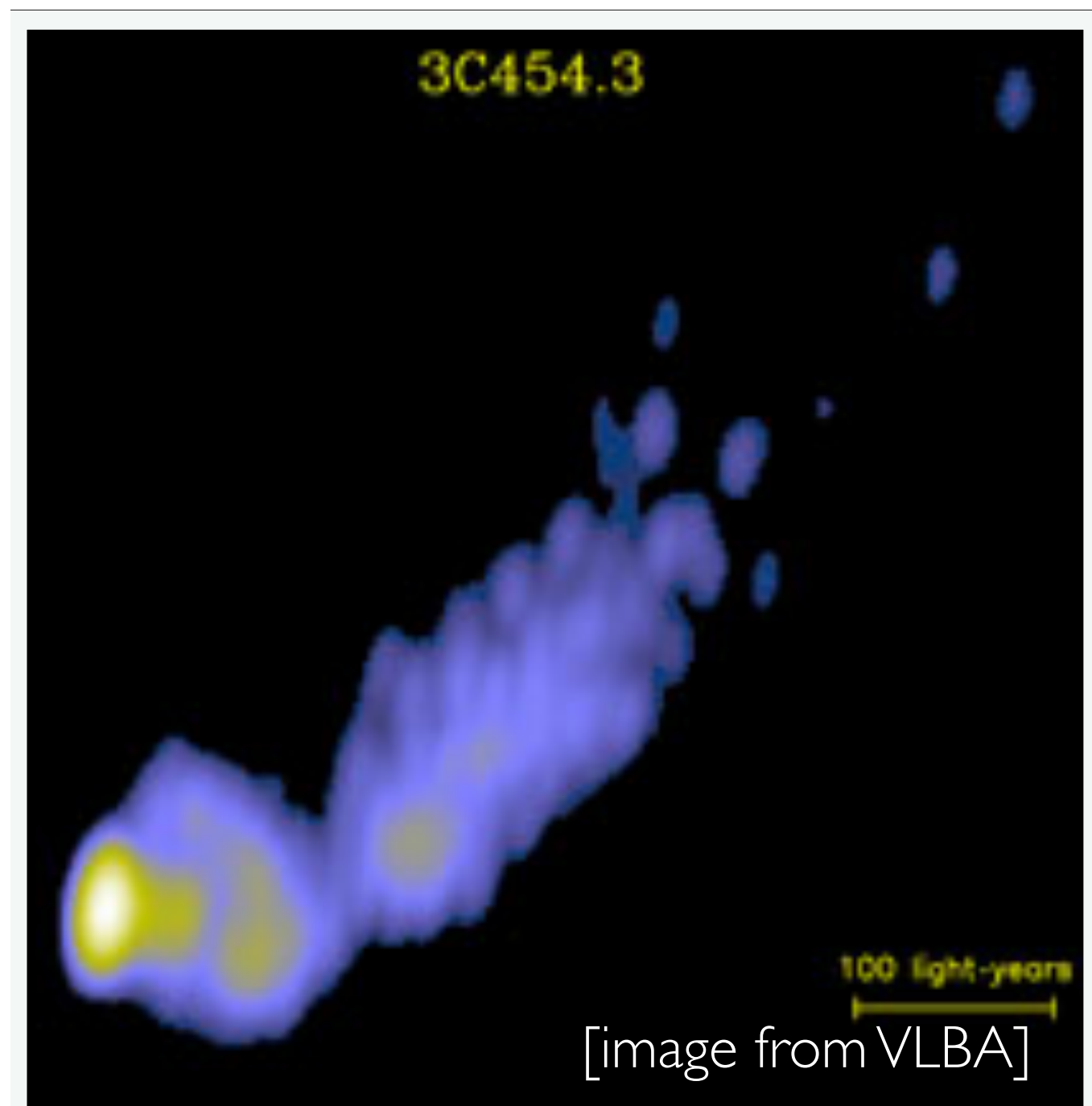
FRII



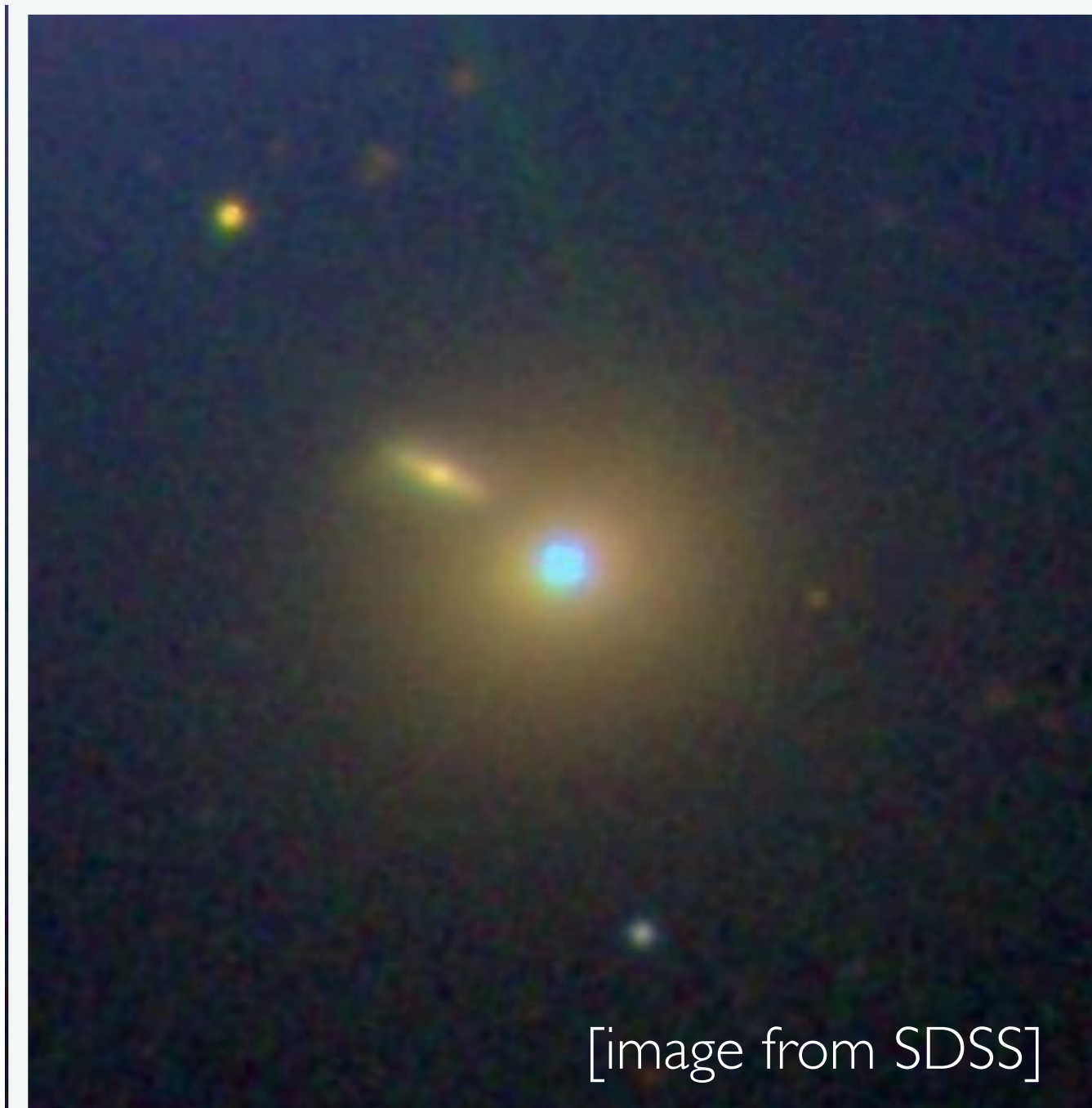
Radio galaxy Cygnus A Image credits: NRAO/AUI, A. Bridle

Blazars: Star-like appearance

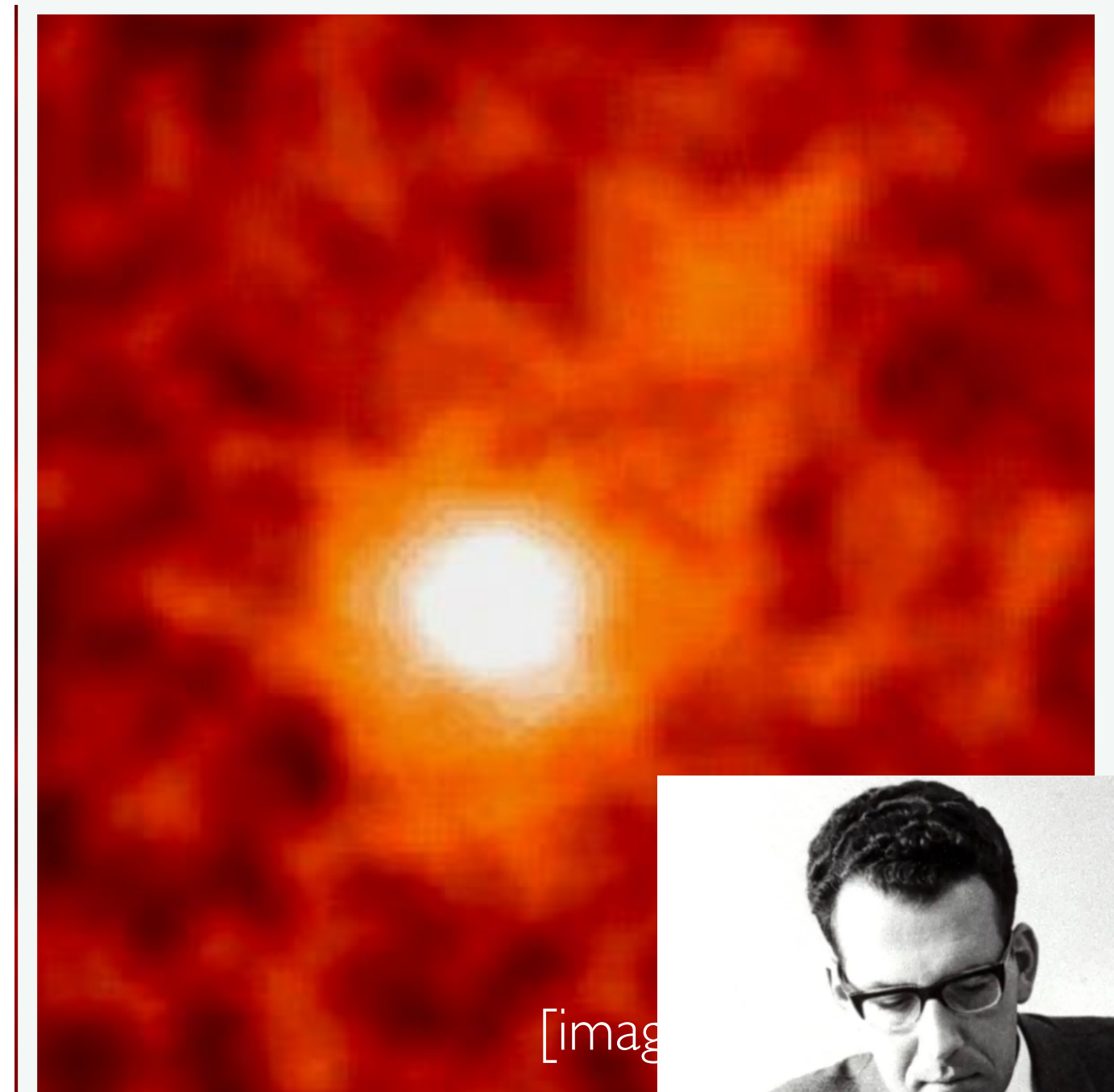
Radio



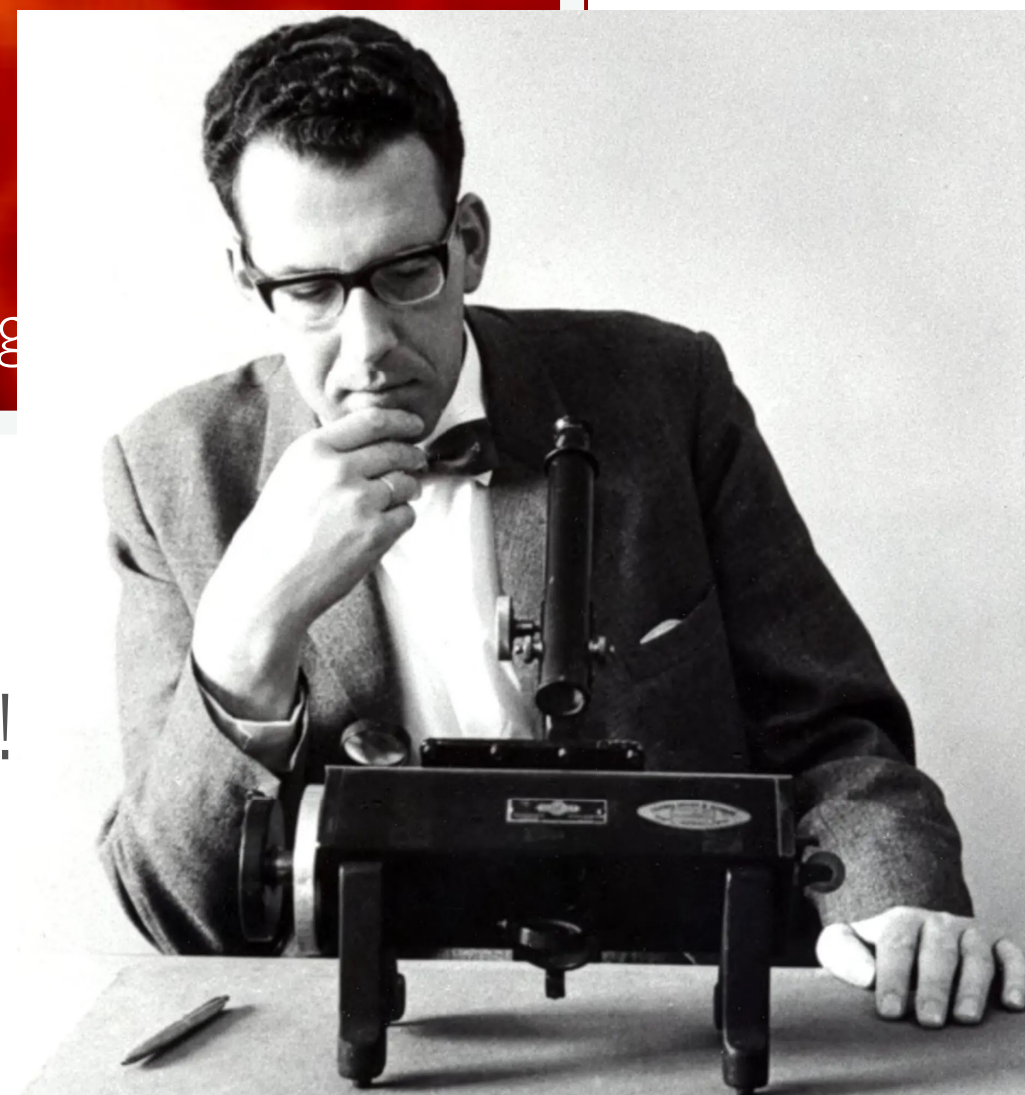
Optical



γ -rays



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



Relativistic beaming

Usual relativity (rulers and clocks)

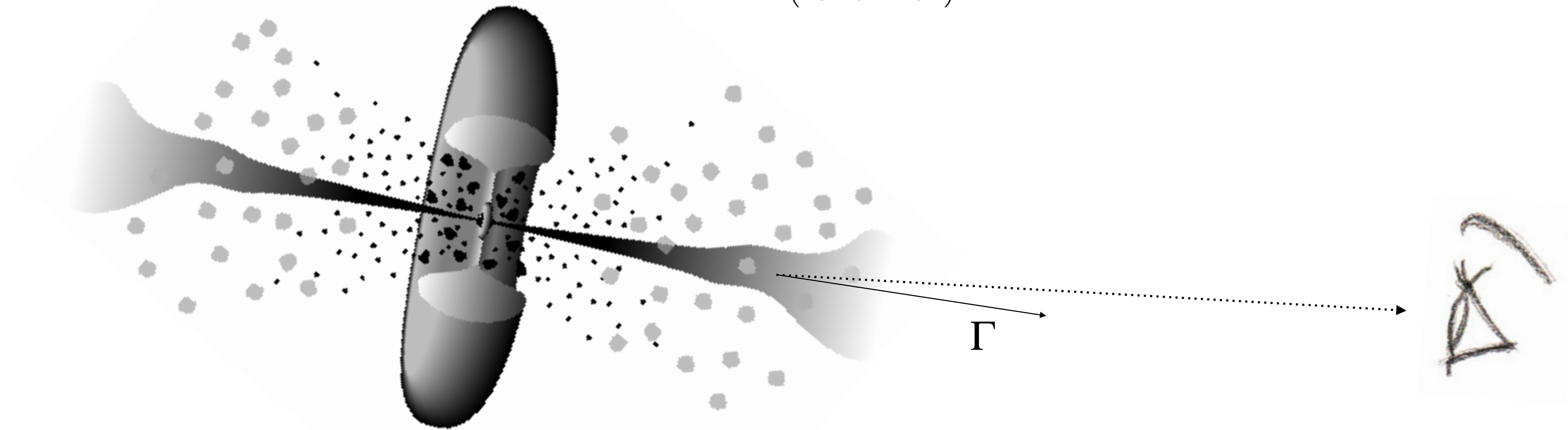
$$\Delta x = \frac{\Delta x'}{\Gamma}$$

$$\Delta t = \Delta t' \Gamma$$

$$\Gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

$\Gamma = 10 - 50$ in blazars

Not so for photons!
(Terrel 1959)



Relativistic beaming

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

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

$$\Delta t = \Delta t' / \delta \quad (\text{shortening of timescales})$$

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

$$\nu = \delta \nu', \quad E = \delta E' \quad (\text{blueshift})$$

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

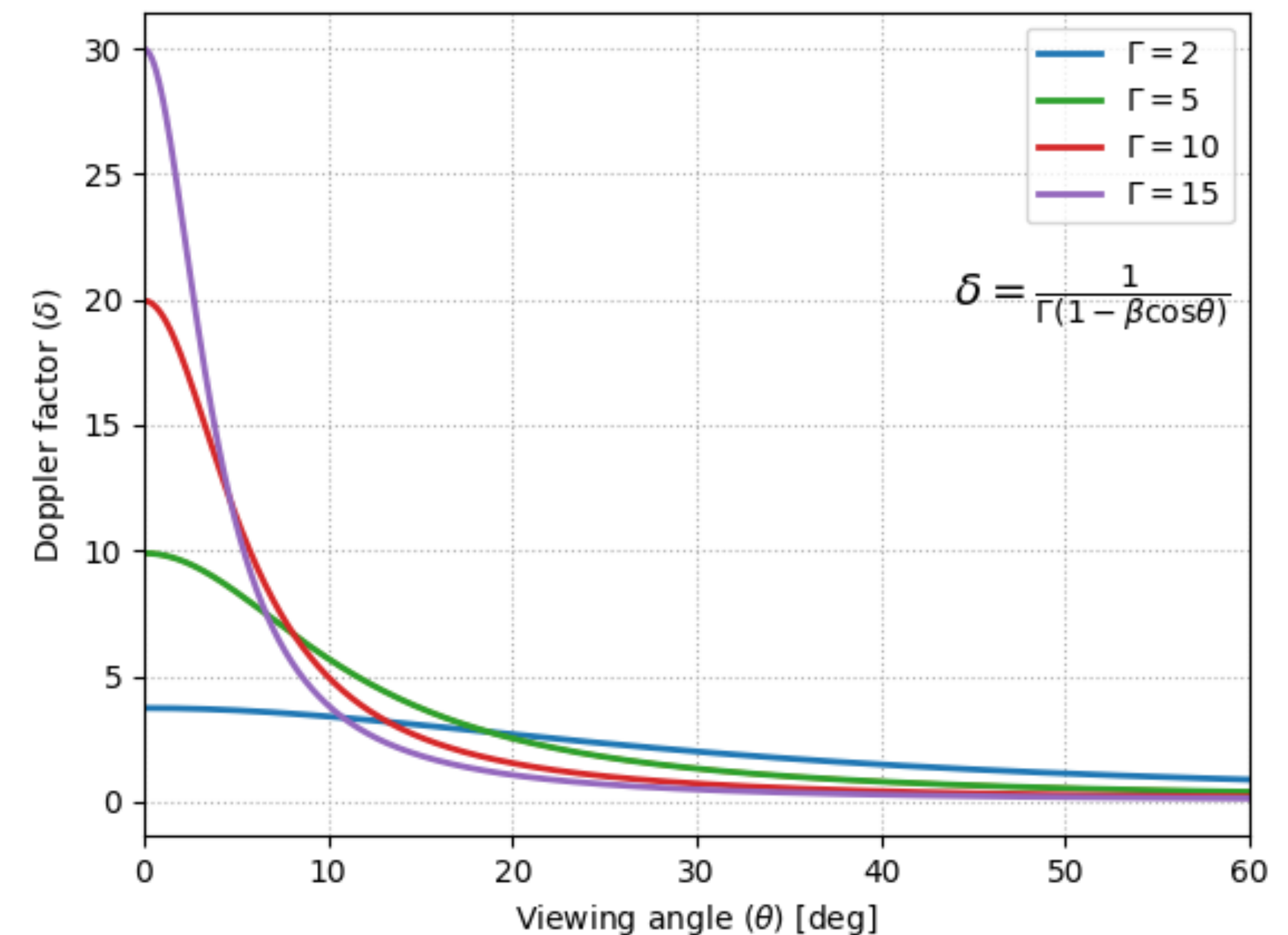
(dashes denote rest-frame quantities)

Special cases:

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

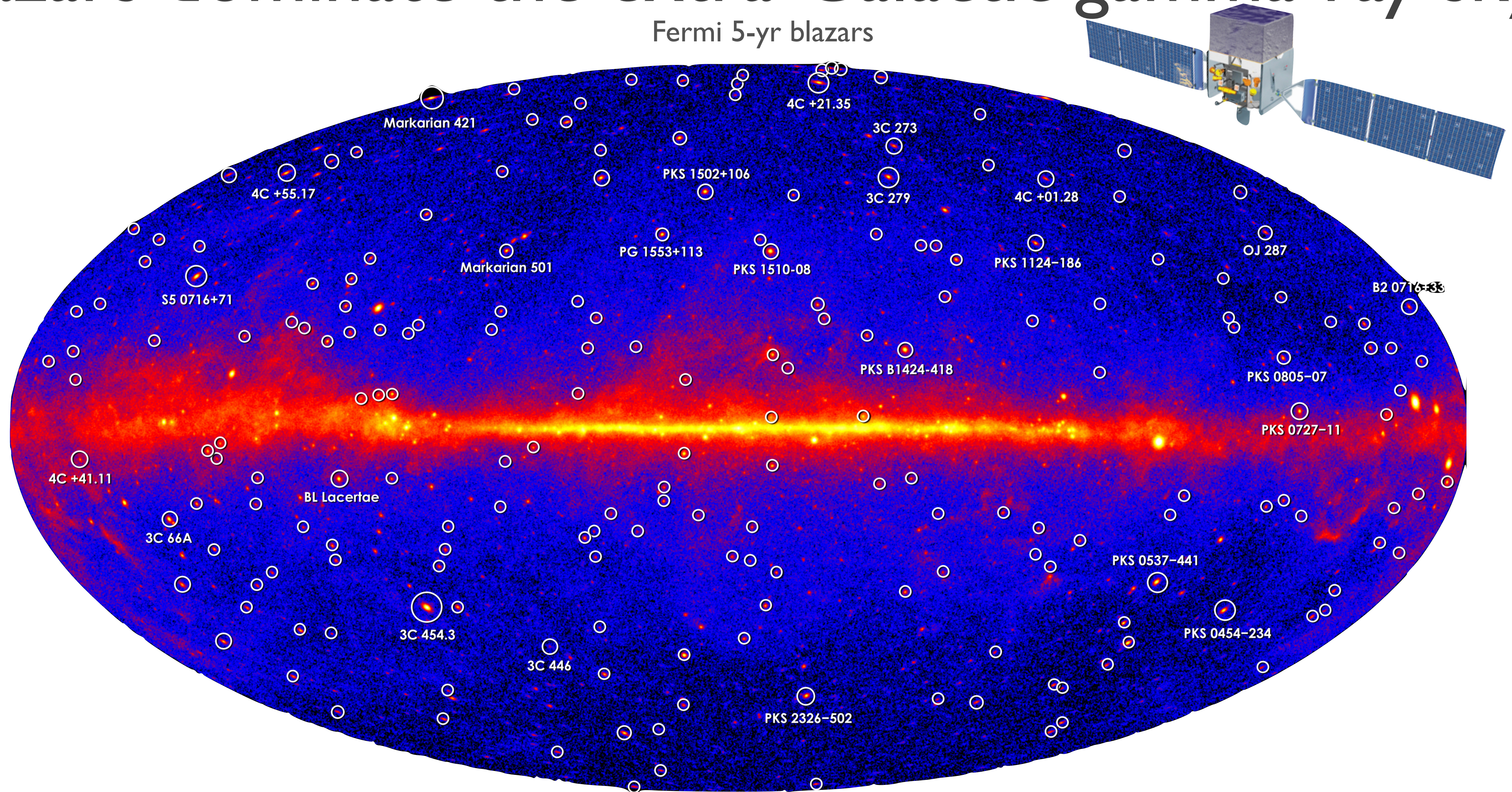
$$\delta_{\text{min}} = \delta(90^\circ) = 1/\Gamma - \text{recover special relativity}$$

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



Blazars dominate the extra-Galactic gamma-ray sky

Fermi 5-yr blazars



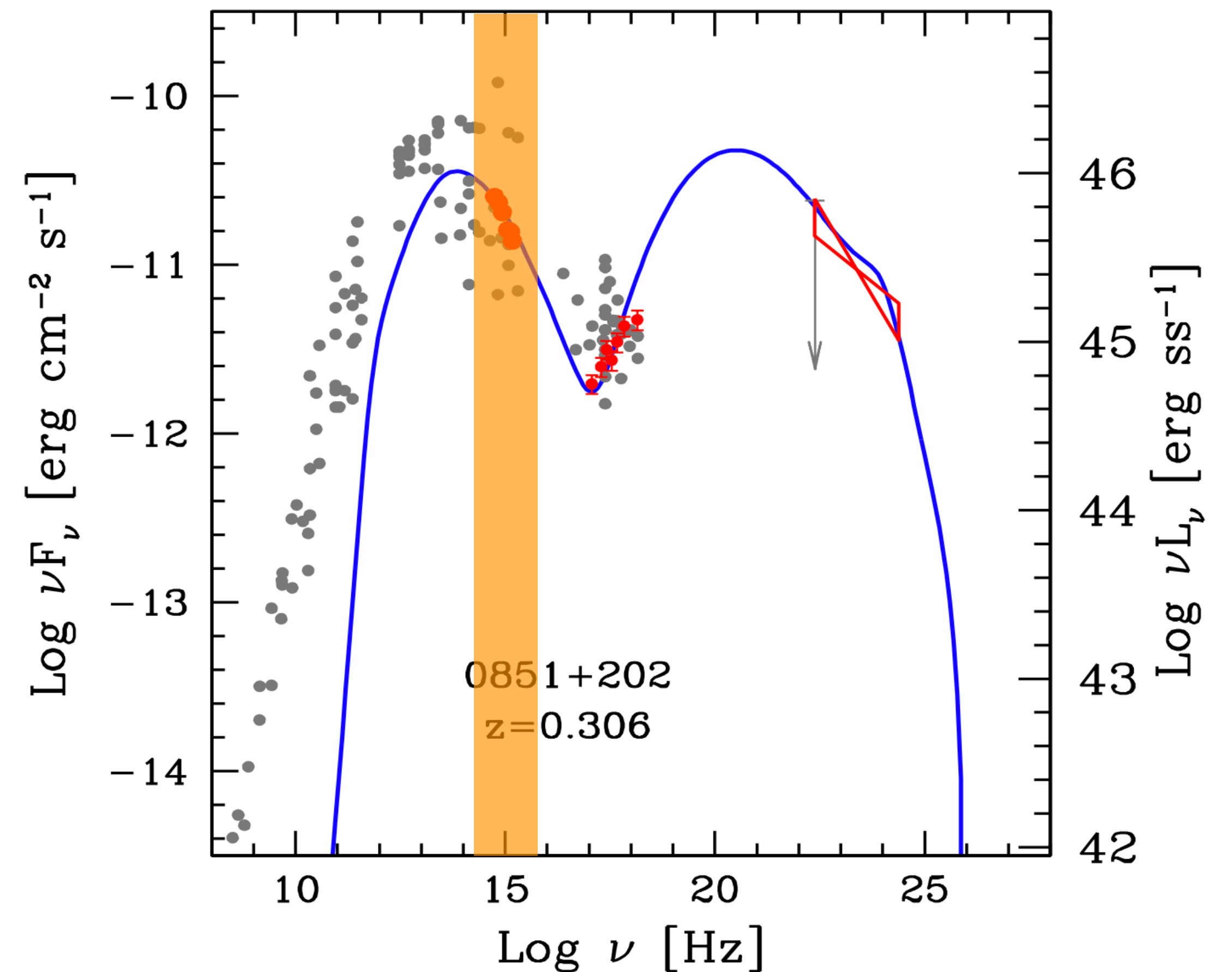
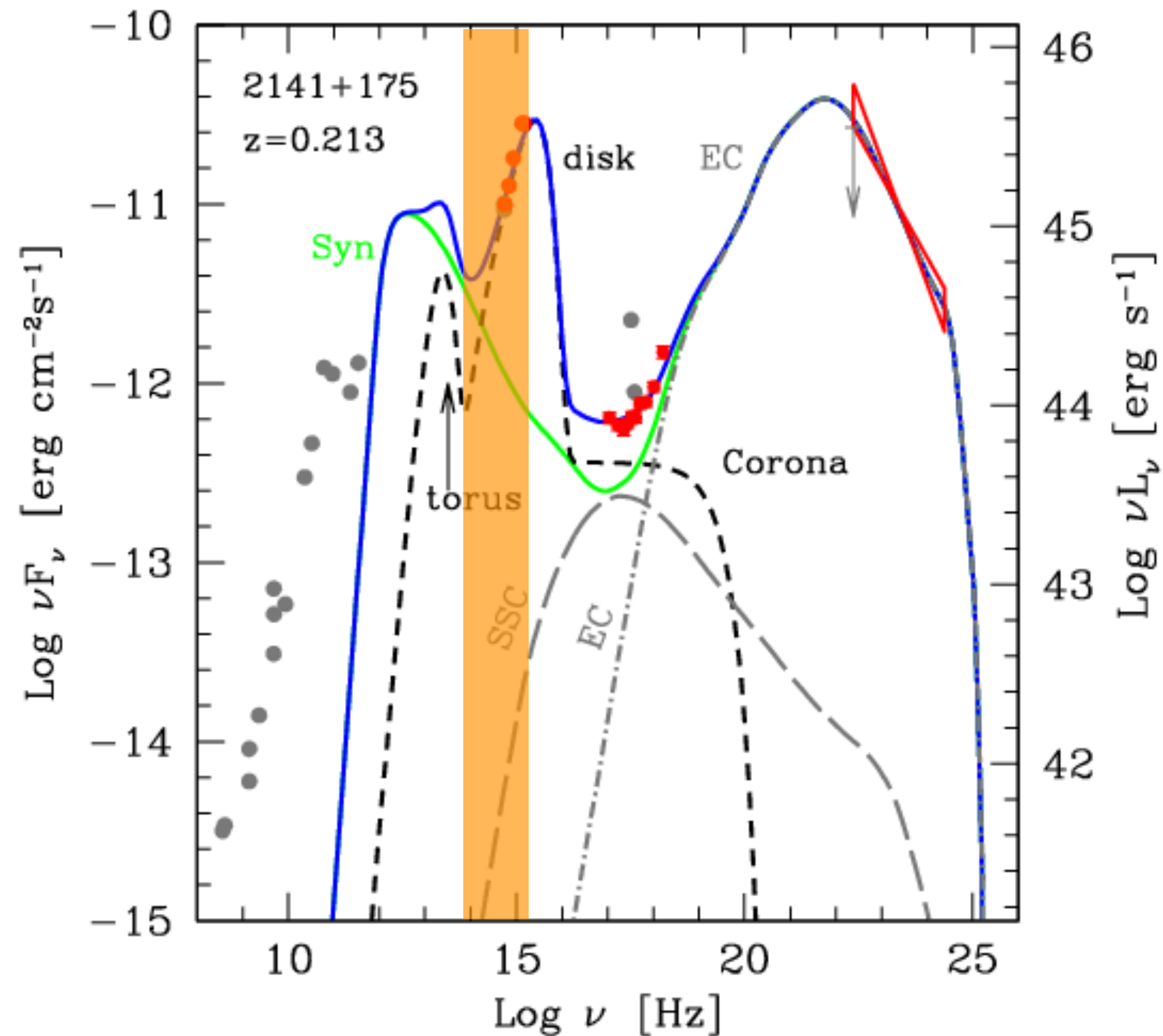
>90% of extragalactic Fermi sources (see also TeVCaT)

Blazar classes: BL Lac objects and FSRQs

Flat spectrum radio quasar

Optical light

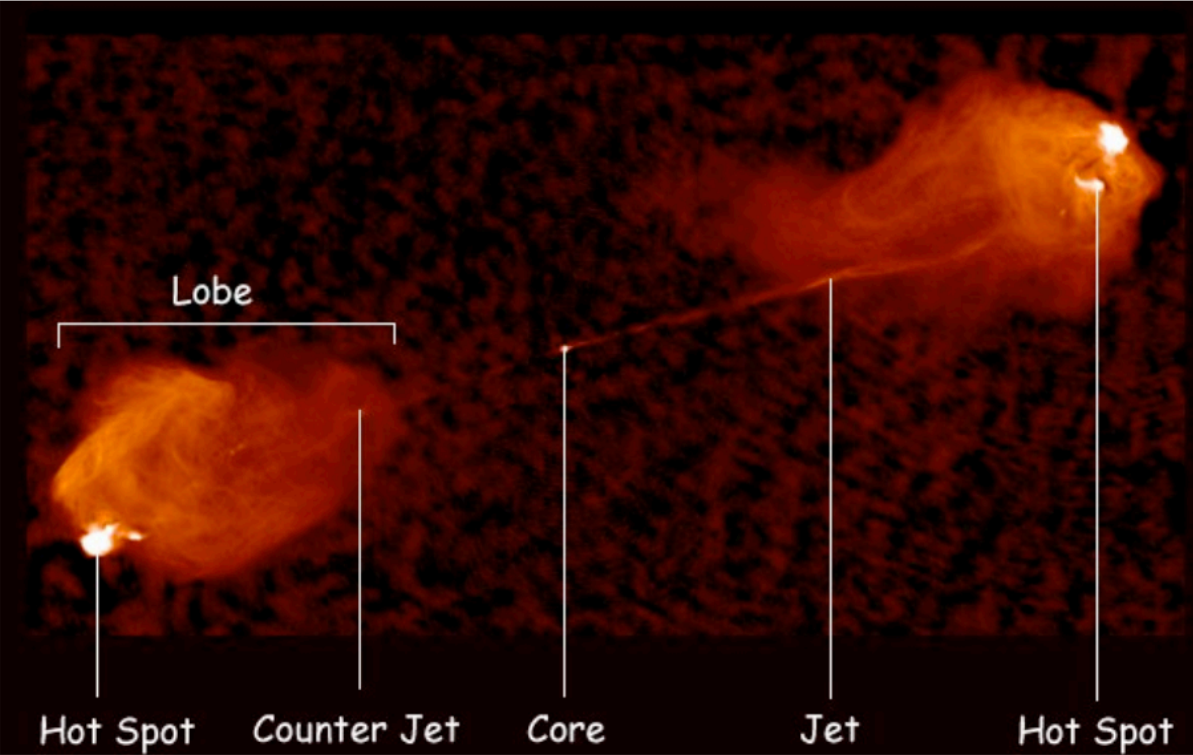
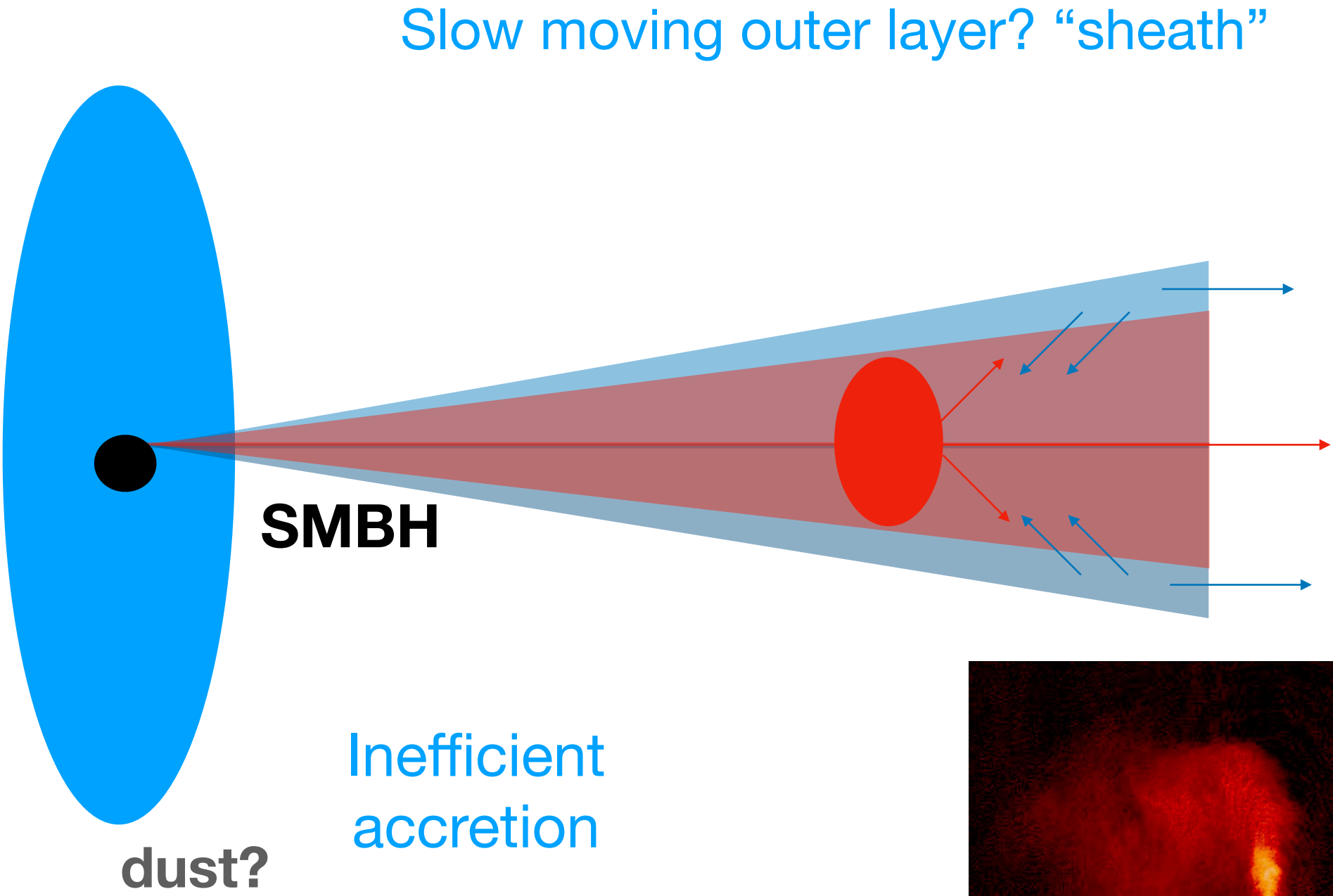
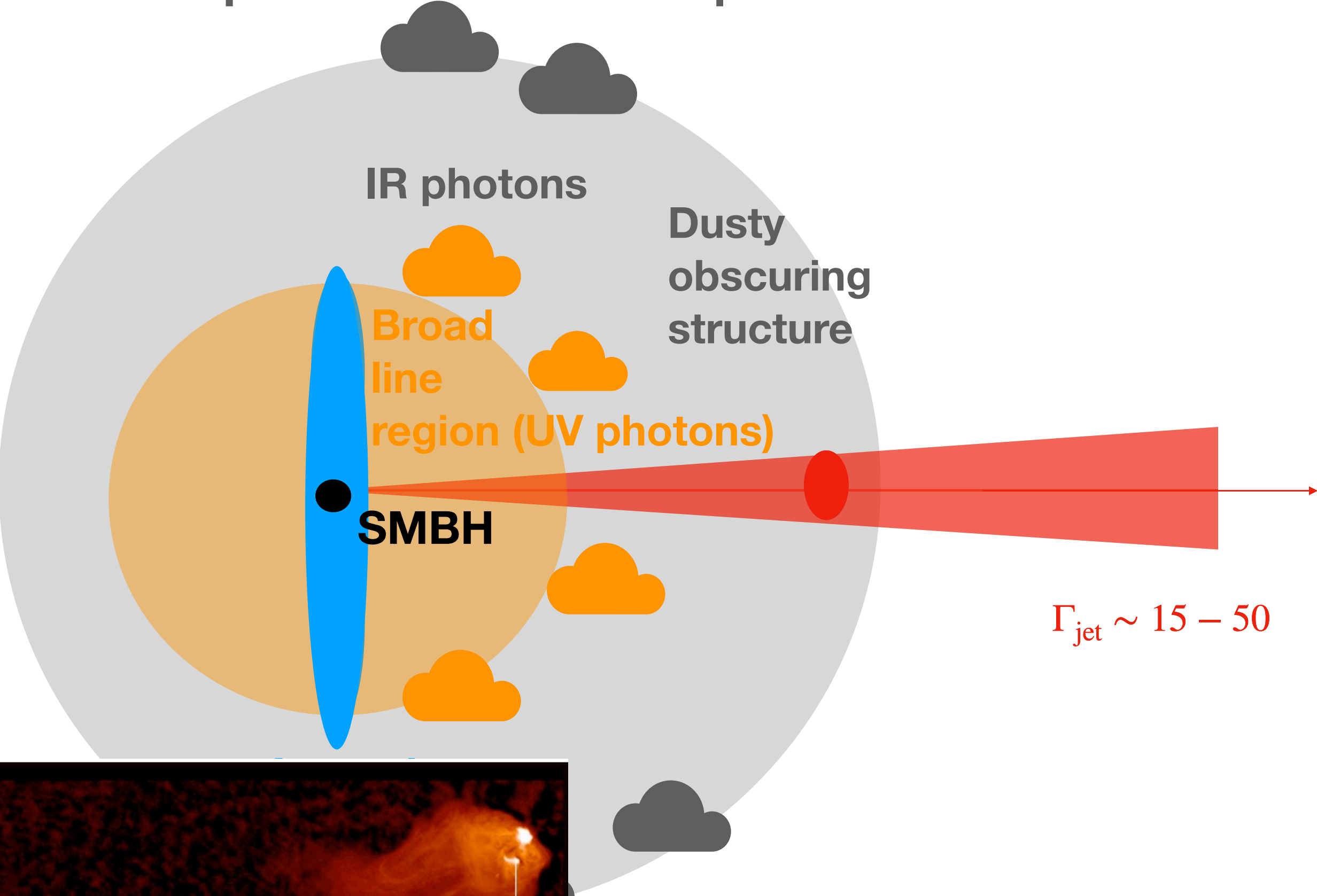
BL Lac Object



Blazar subclasses and photon fields

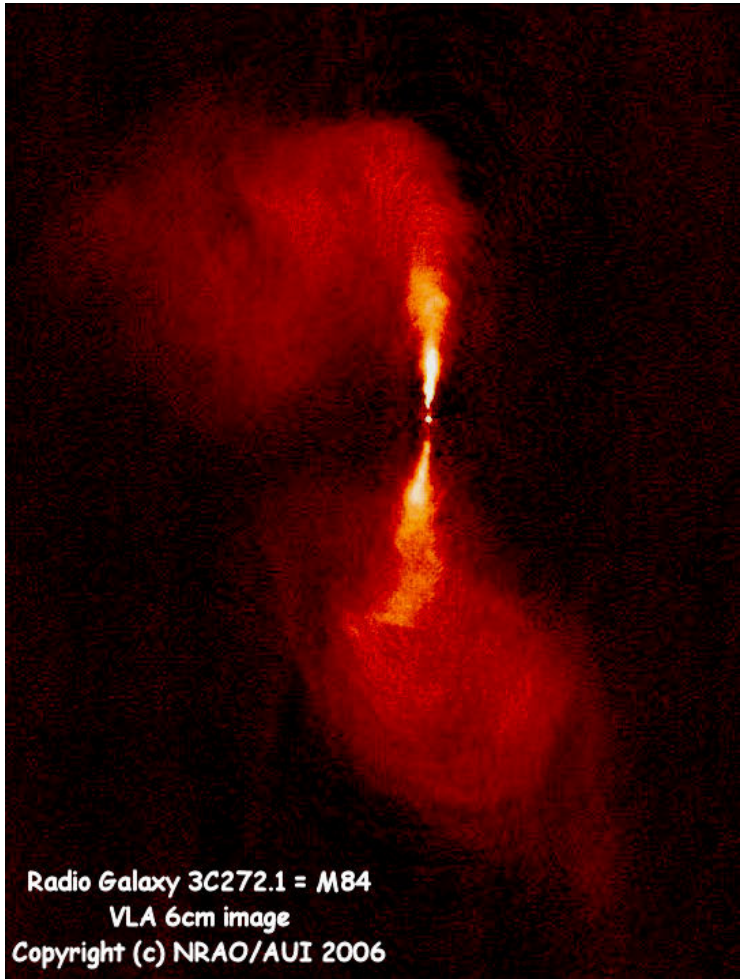
Flat spectrum radio quasars

BL Lac Objects

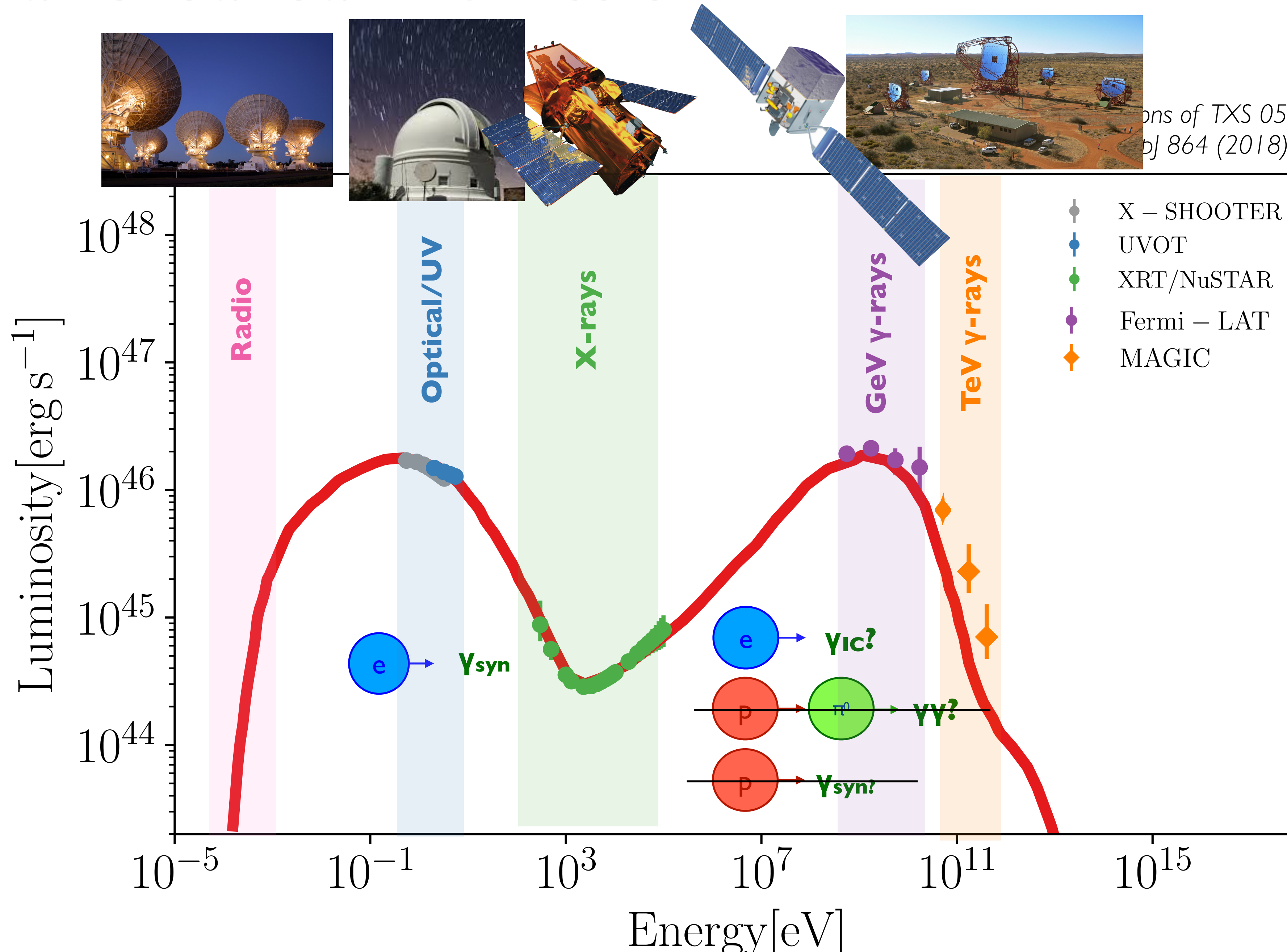


Powerful collimated jets
Efficient accretion disk
Close to Eddington limit

Less collimated jets
Radiatively inefficient accretion disk



Blazar broadband emission



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

What we can infer from the blazar SED

Example OJ 287 (see Ghisel. Ch 9):

ν' – jet frame

ν – observer frame

$\nu = \nu' \delta / (1 + z)$ – frequency

$L = L' \delta^4 / (1 + z)$ – luminosity

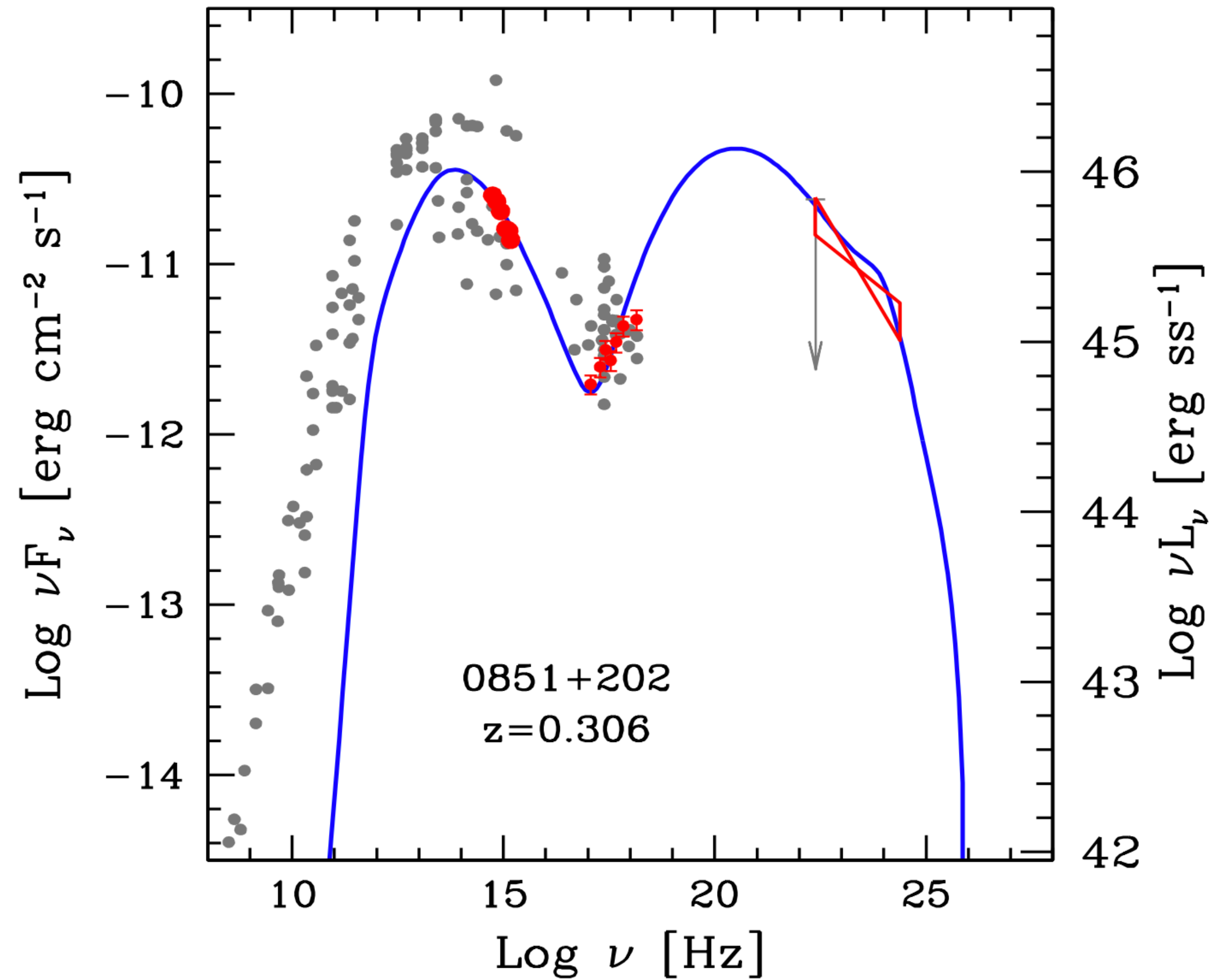
$t = t' / \delta (1 + z)$ – time

see Ghisellini T3.1 pg. 45

Emission radius

$$R \leq ct_{\text{var}} \frac{\delta}{1 + z}$$

Measured



What we can infer from the blazar SED

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

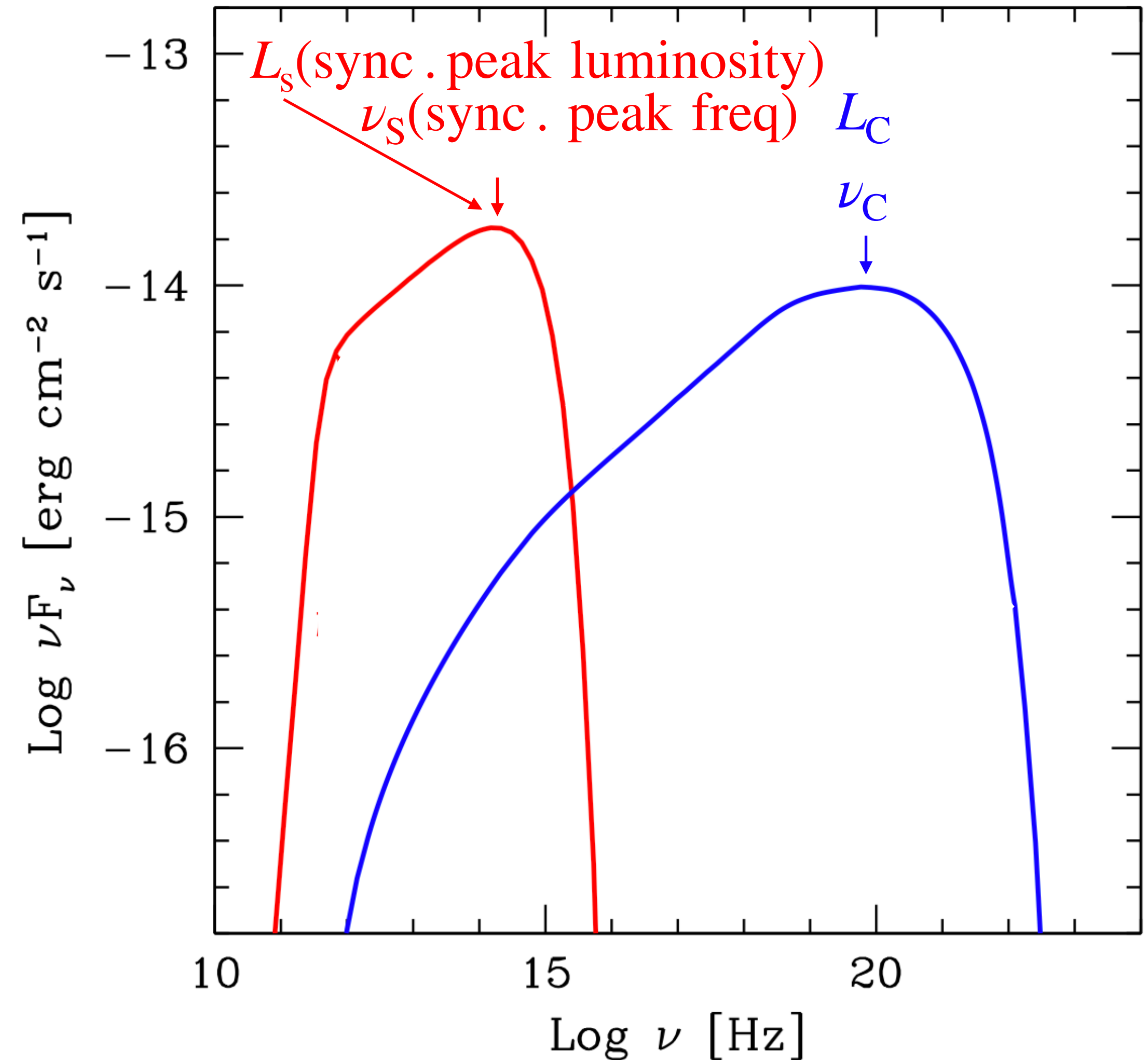
$$L_s \propto U_B - (1)$$

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

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

$$L_C \propto U_{\text{rad}} - (3)$$

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



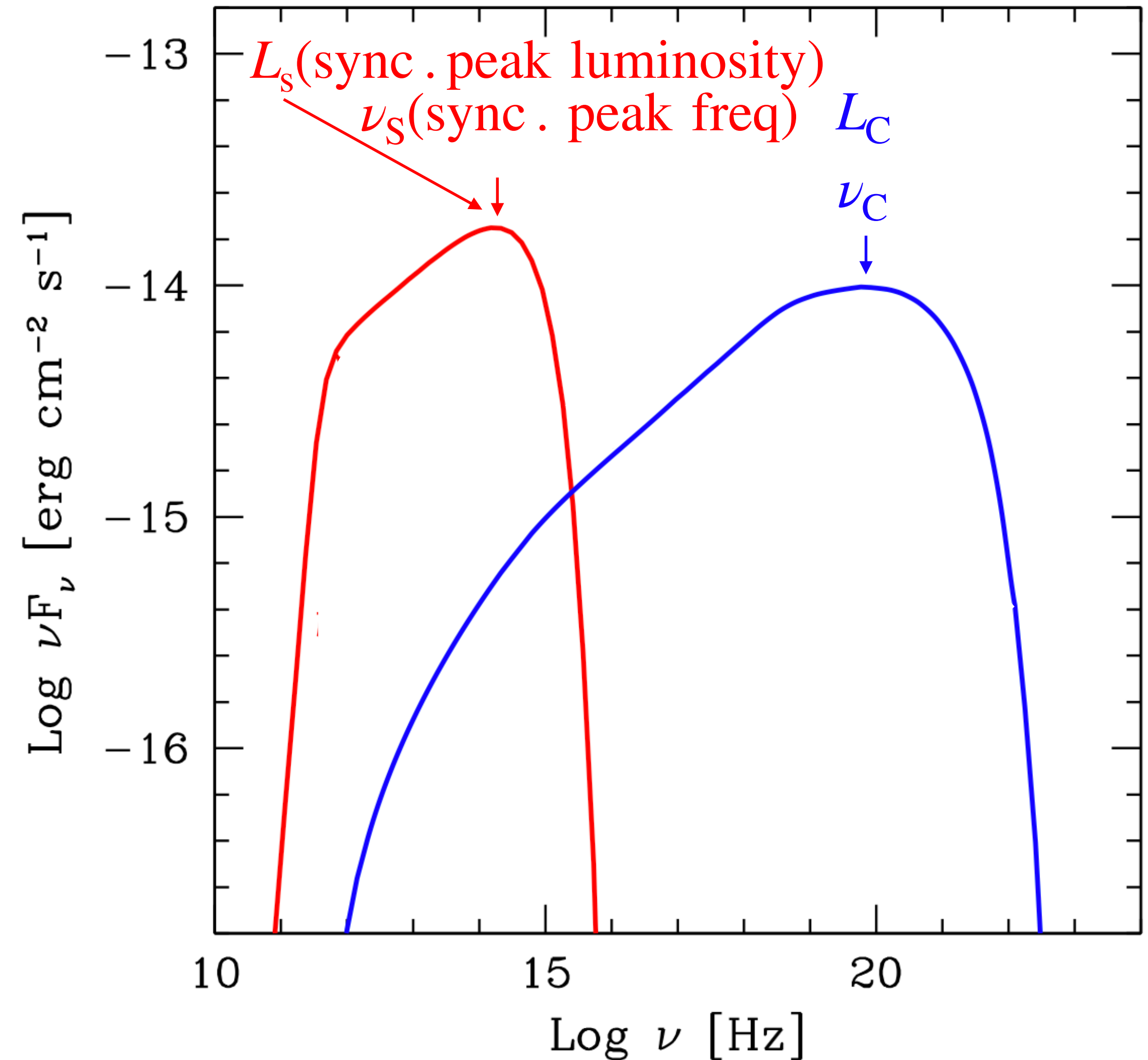
What we can infer from the blazar SED

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

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

Rearranging, we get,

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



What we can infer from the blazar SED

From the peak frequencies we have,

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

γ_{break} – Lorentz factor of emitting elec.

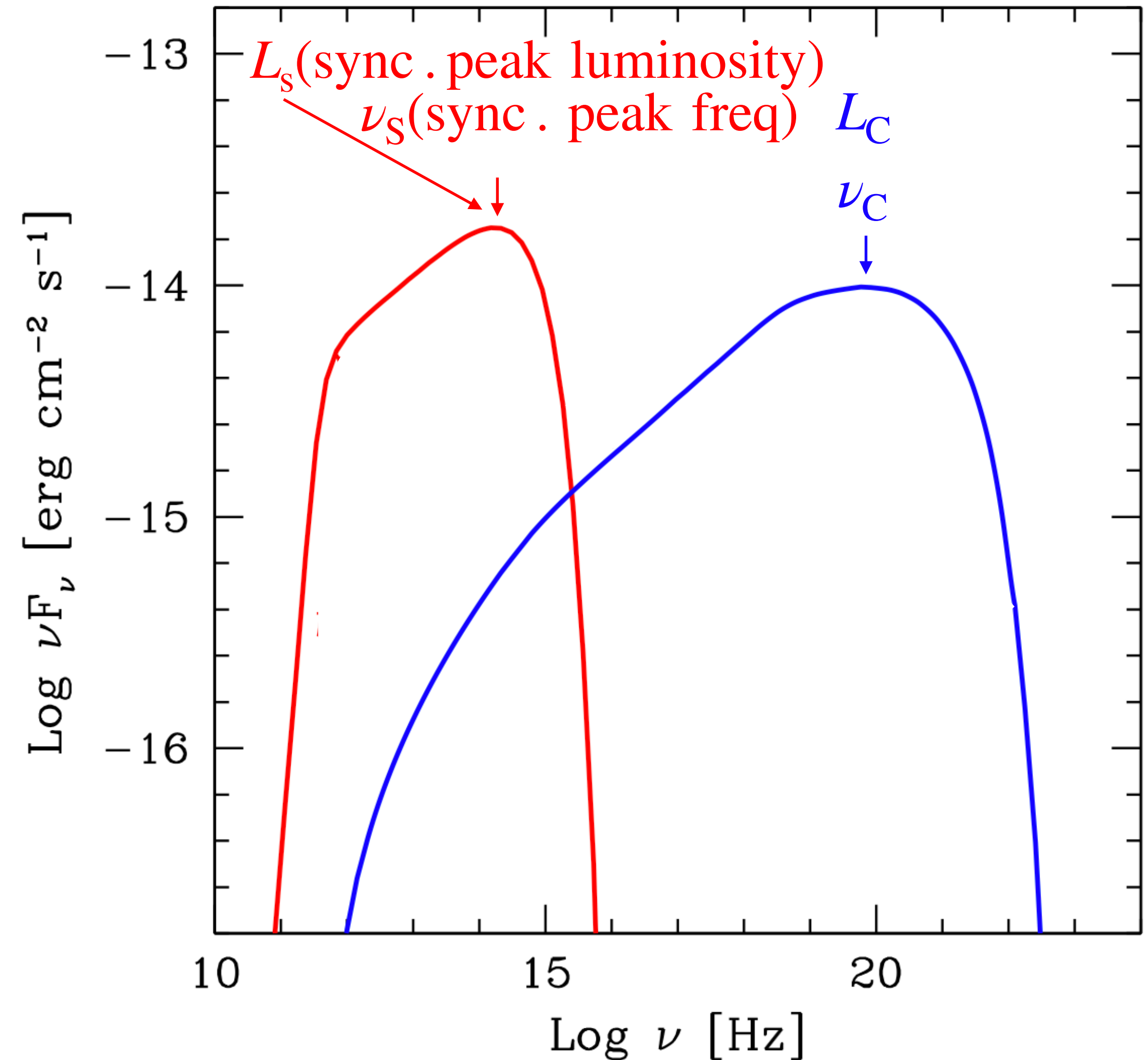
$$\gamma_{\text{break}} = \left(\frac{3\nu_C}{4\nu_S} \right)^{1/2} \quad - (6)$$

$$\nu_S = \frac{4}{3} \frac{eB}{2\pi m_e c} \gamma_{\text{break}}^2 \frac{\delta}{1+z}$$

Using (6) we get

$$B \cdot \delta = (1+z) \frac{3\pi m_e c}{2e} \frac{\nu_S^2}{\nu_C} \quad - (7)$$

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



What we can infer from the blazar SED

For OJ 287:

$$t_{\text{var}} \sim 10^4 \text{ s}, \nu_s \sim 5 \times 10^{13} \text{ Hz}, \nu_c \sim 10^{21} \text{ Hz}$$

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

$$\therefore B \approx 0.4 \text{ G}, \delta \approx 20$$

$$E_{\text{max}} \sim ZeB\Gamma R \sim Z \cdot 4 \times 10^{20} \text{ eV (Hillas criterion)}$$

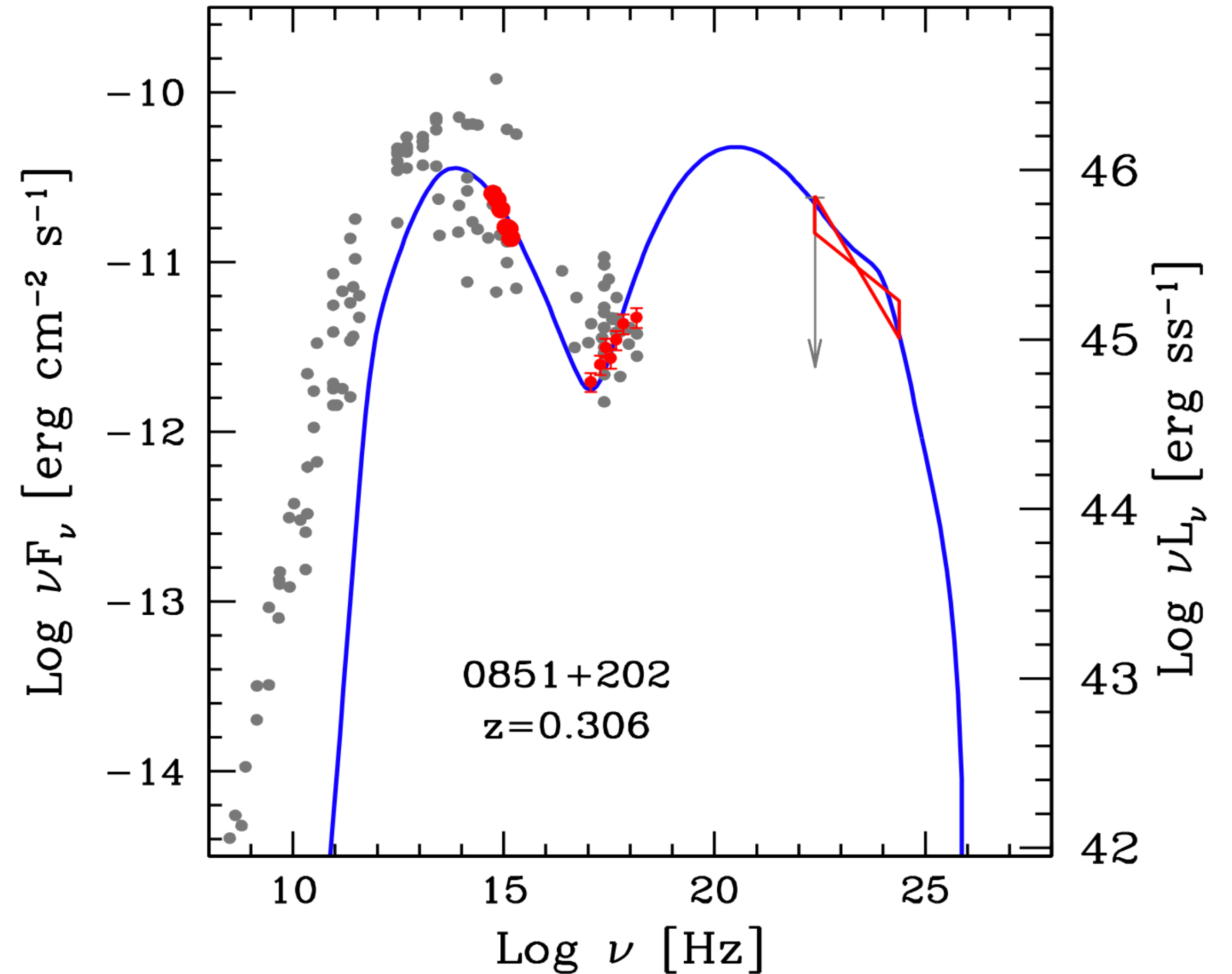
For typically inferred parameters

$$B' \sim 0.1 - 1 \text{ Gauss}$$

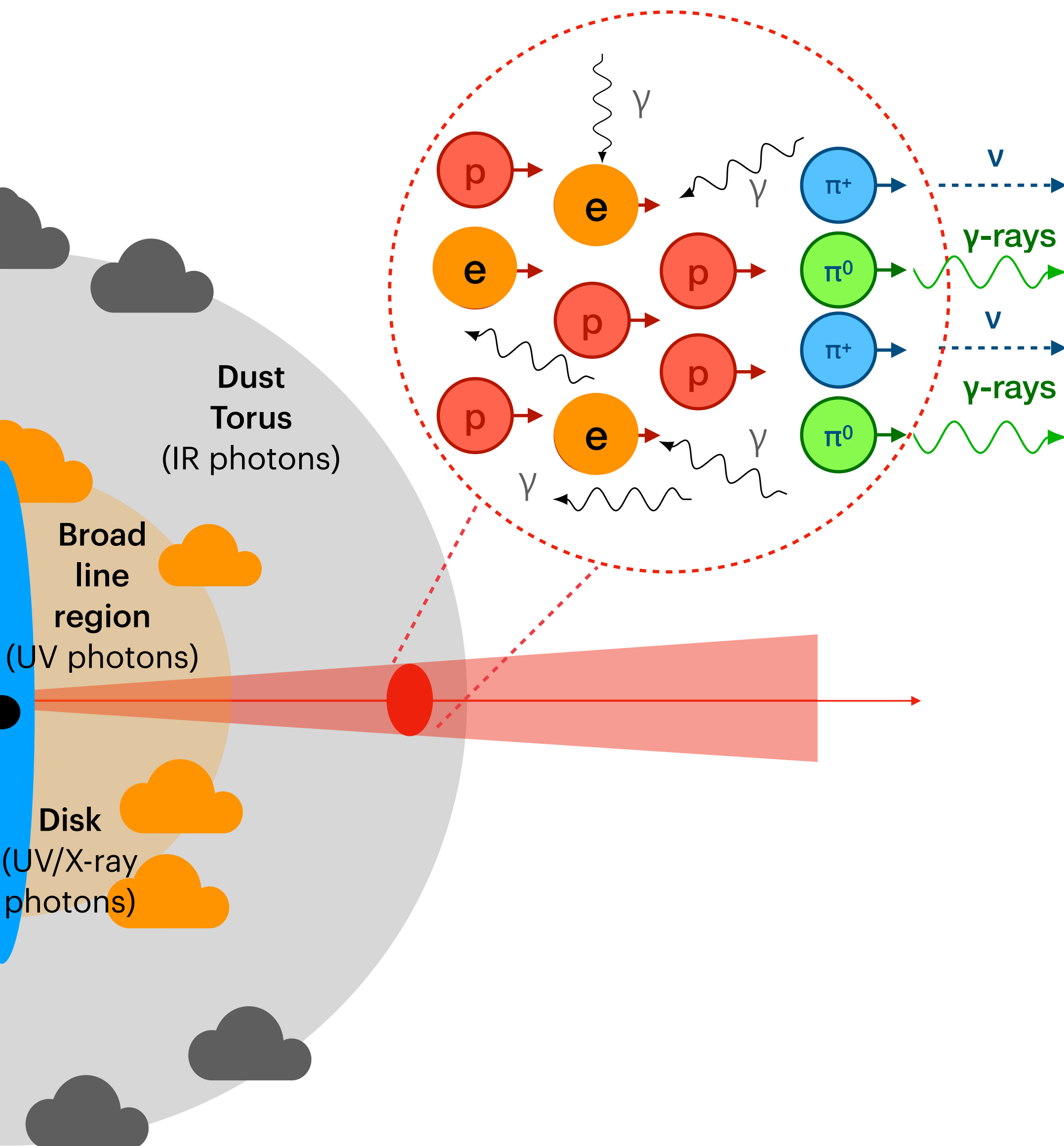
$$\Gamma \sim \delta \sim 10 - 50$$

$$R' \lesssim \delta t_{\text{Var}} c, t_{\text{Var}} \sim \text{day}$$

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



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*

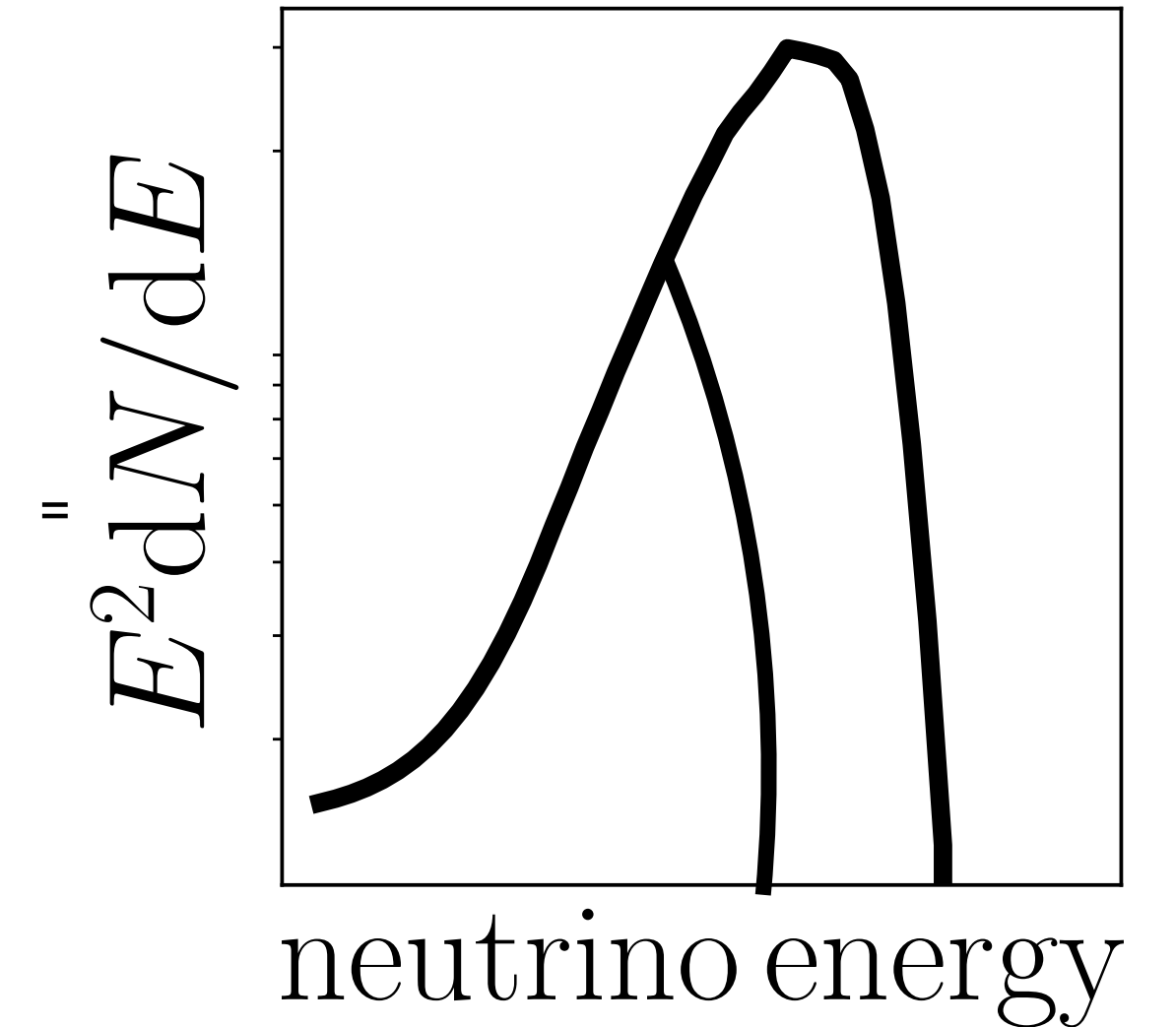
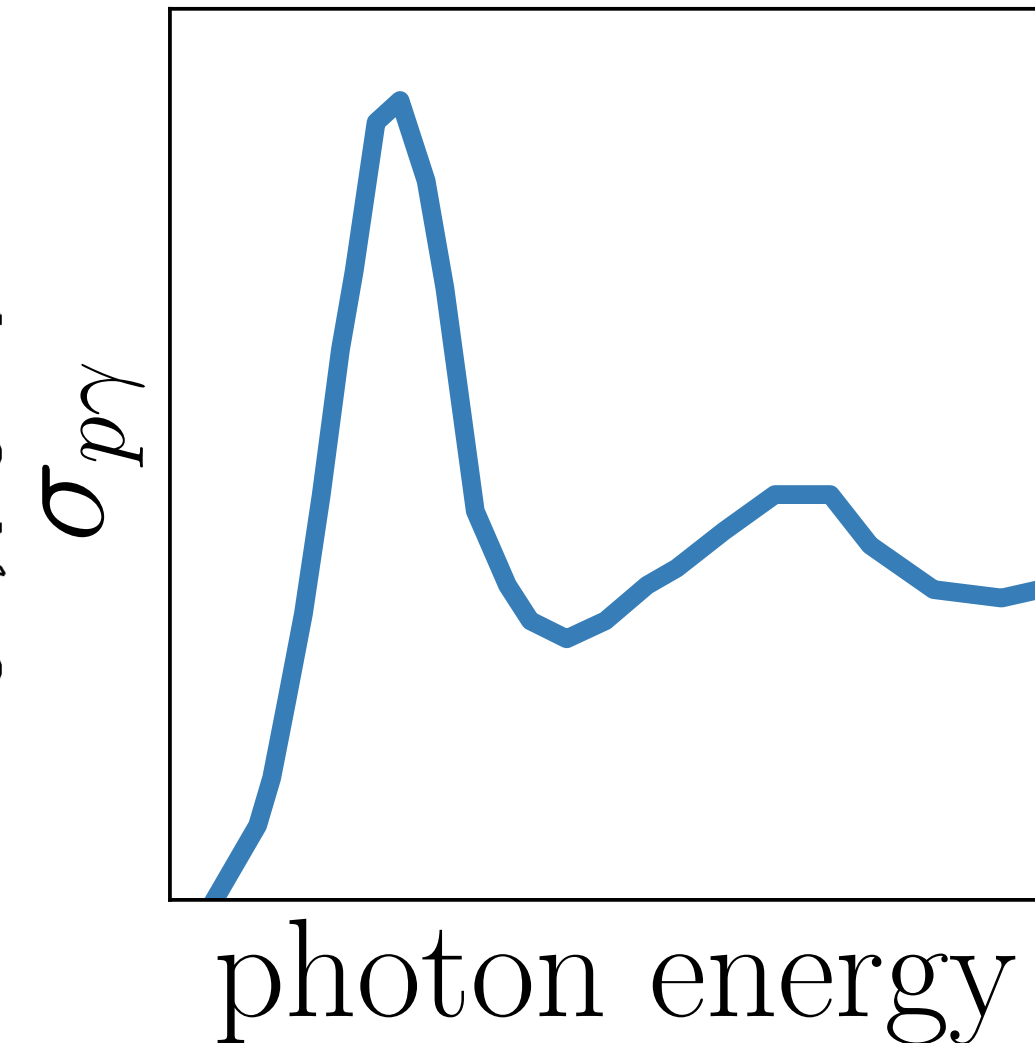
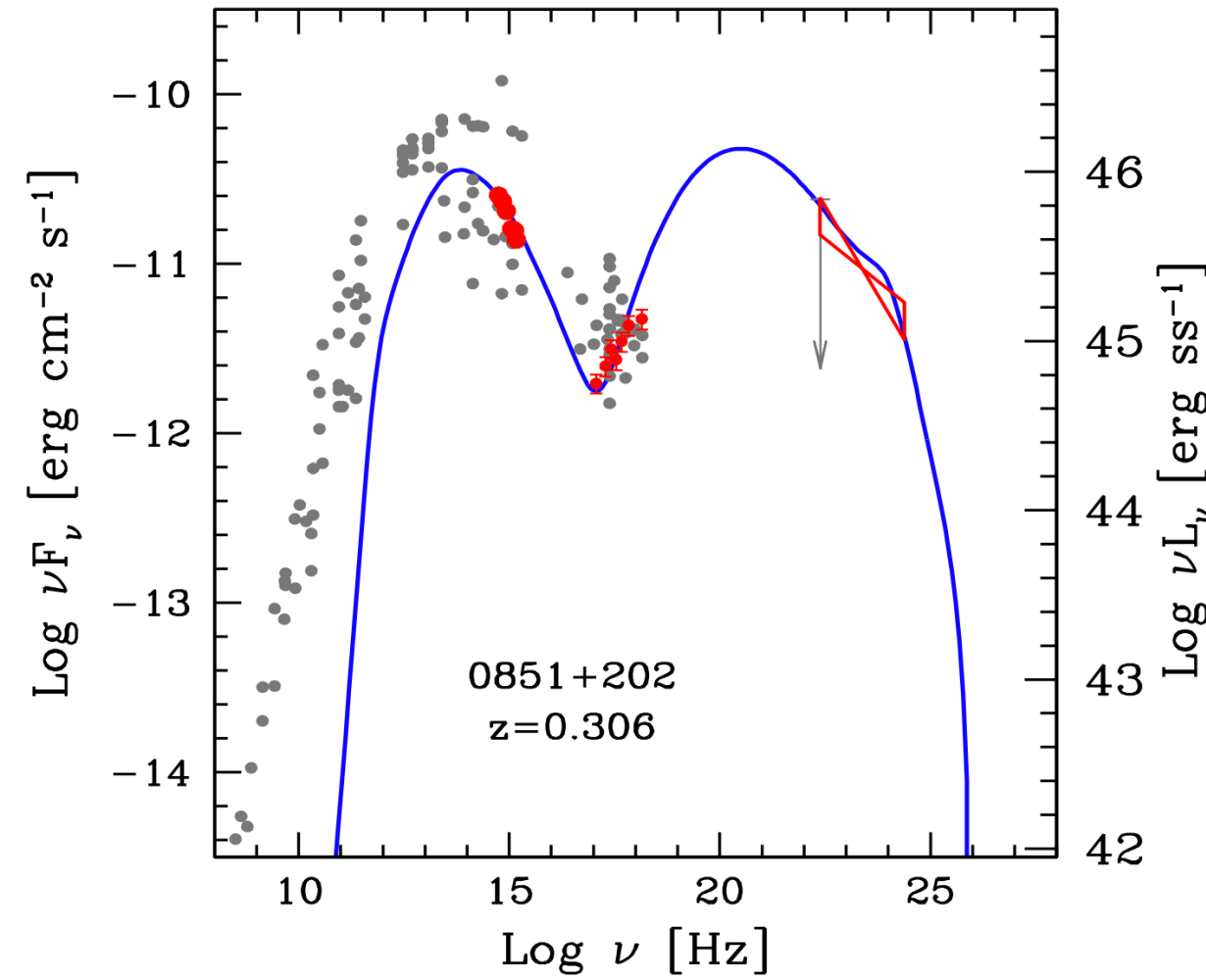
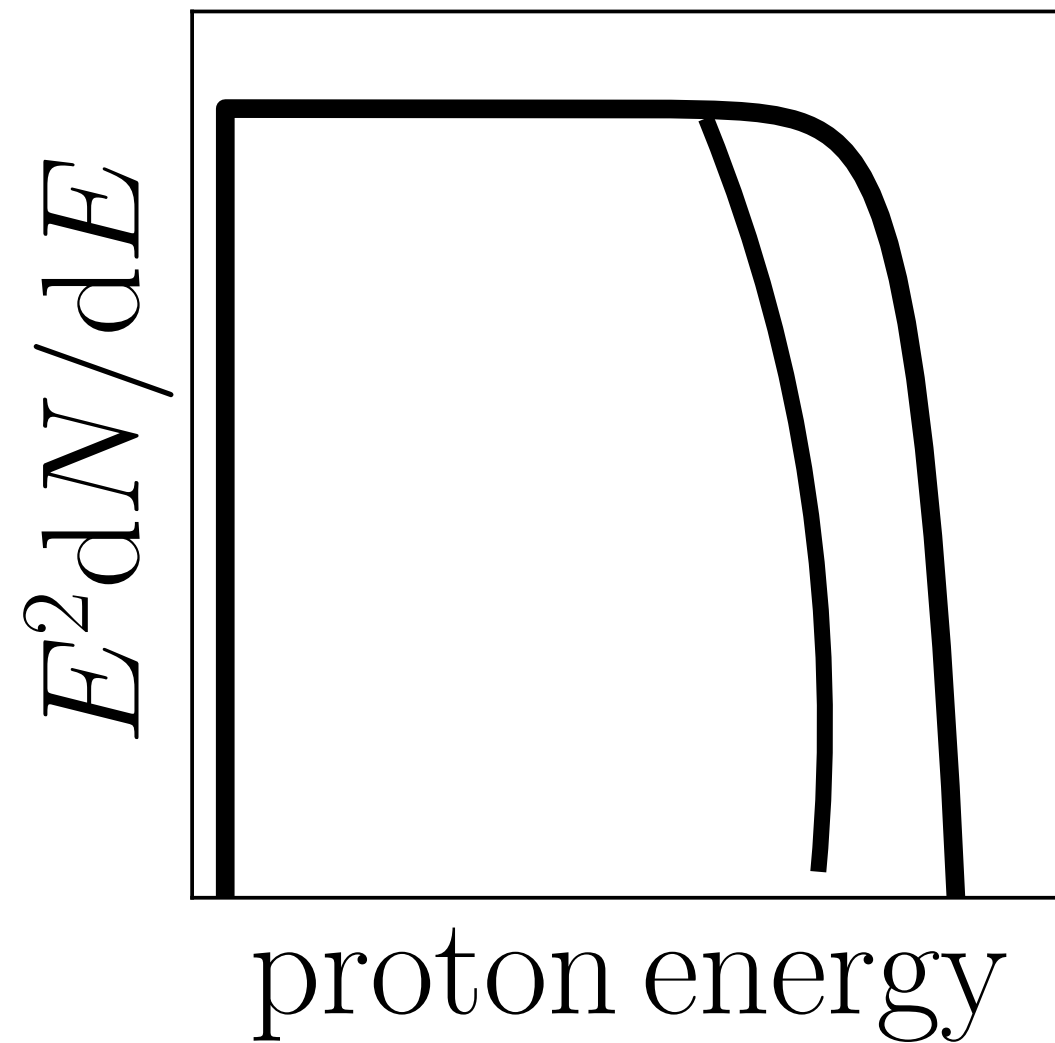
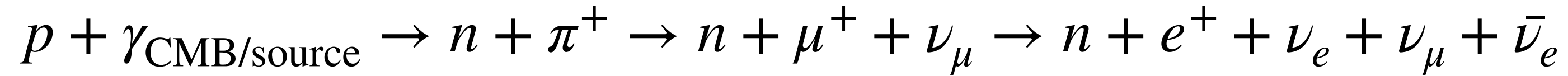
gamma-suppressed states: *Kun+21*

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 (p γ)



$$E_{\text{Broad Line Region(BLR)}} = 10.2 \text{ eV}$$

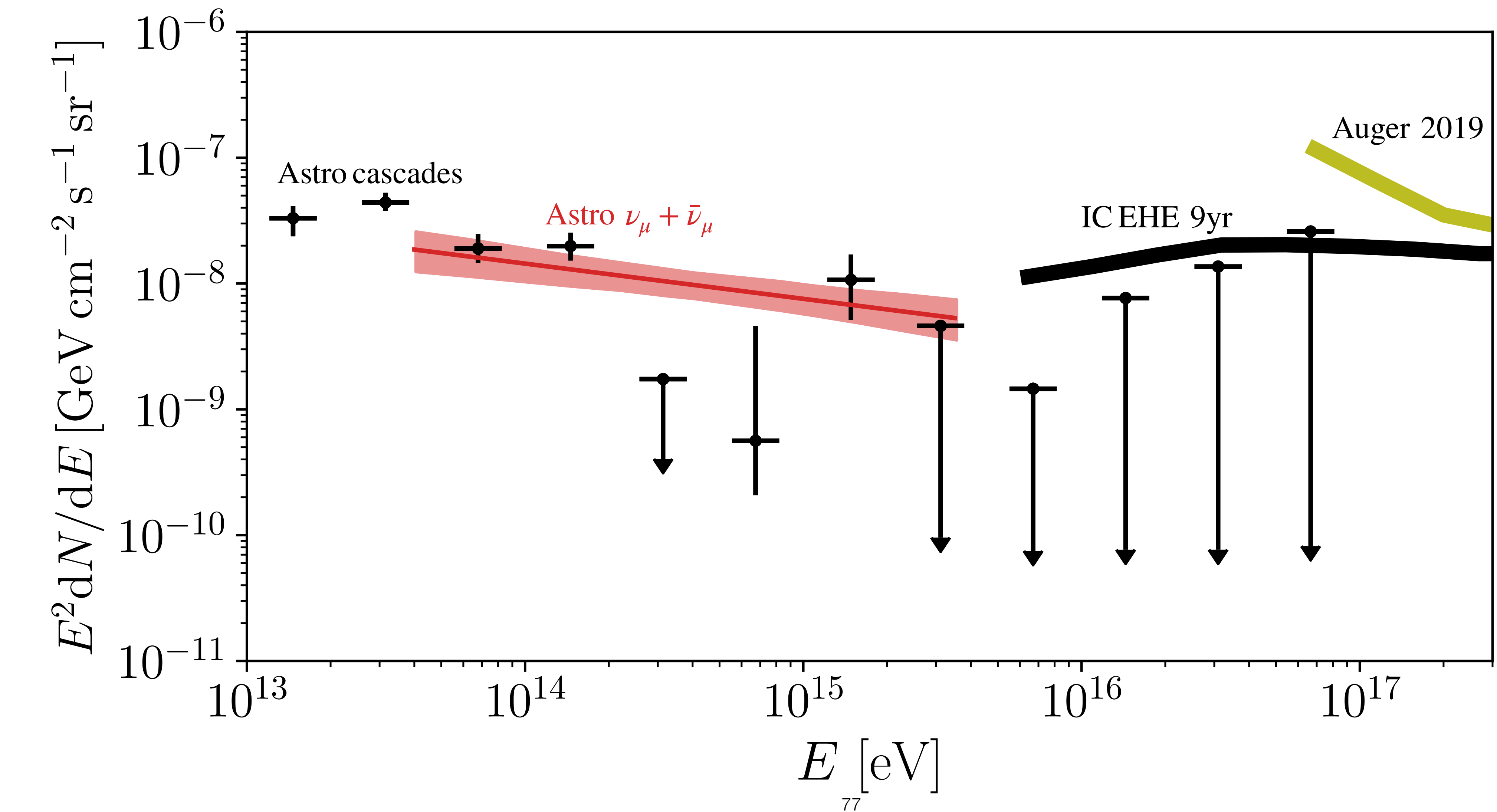
Neutrino typical energy:

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

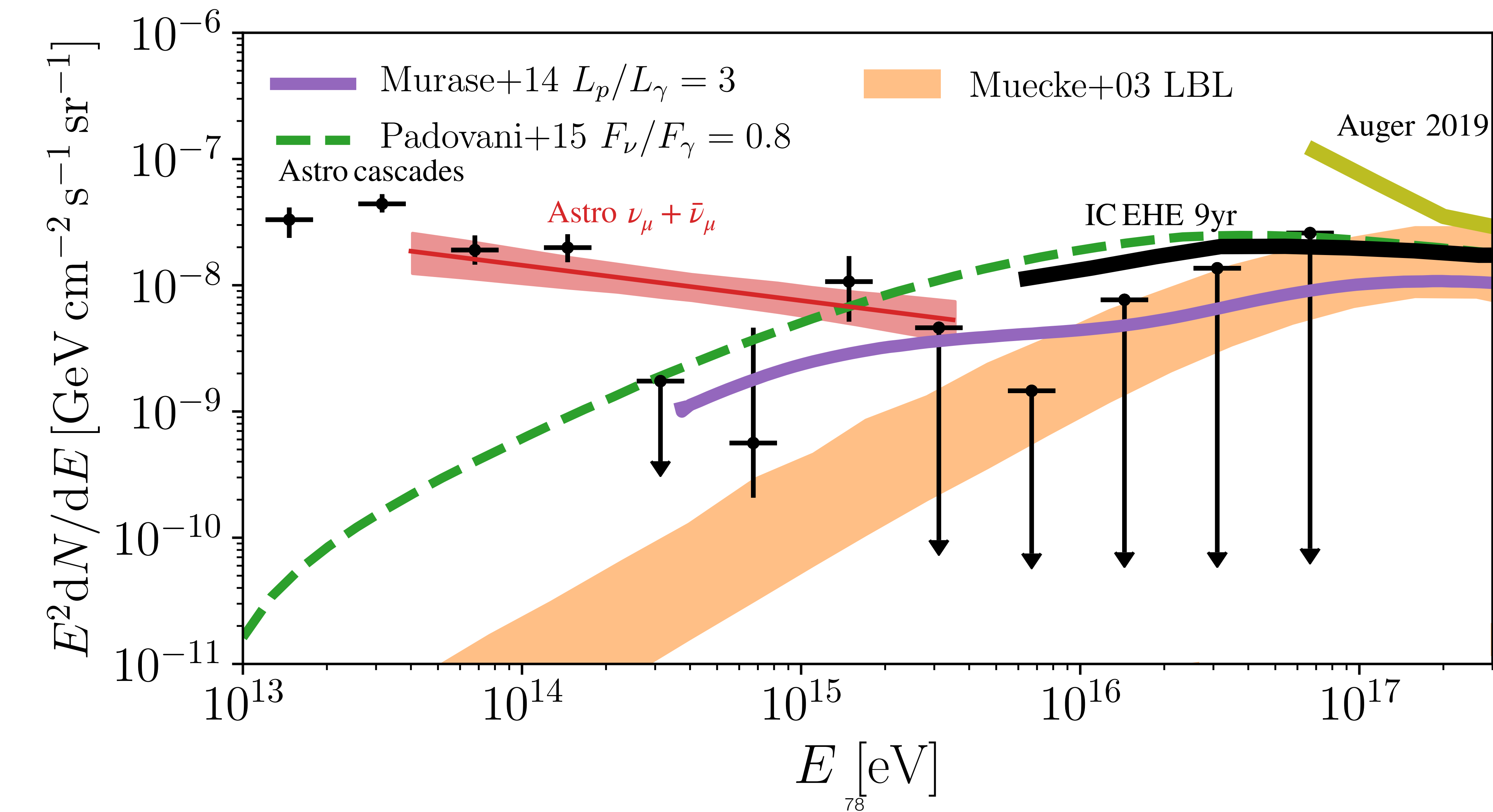
$$E_{\nu, \text{BLR}} = \frac{80 \text{ PeV}}{(1+z)^2} \left(\frac{\delta}{10} \right)^2 \frac{10 \text{ eV}}{E_\gamma}$$

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

Possible contribution of blazars to the diffuse neutrino flux

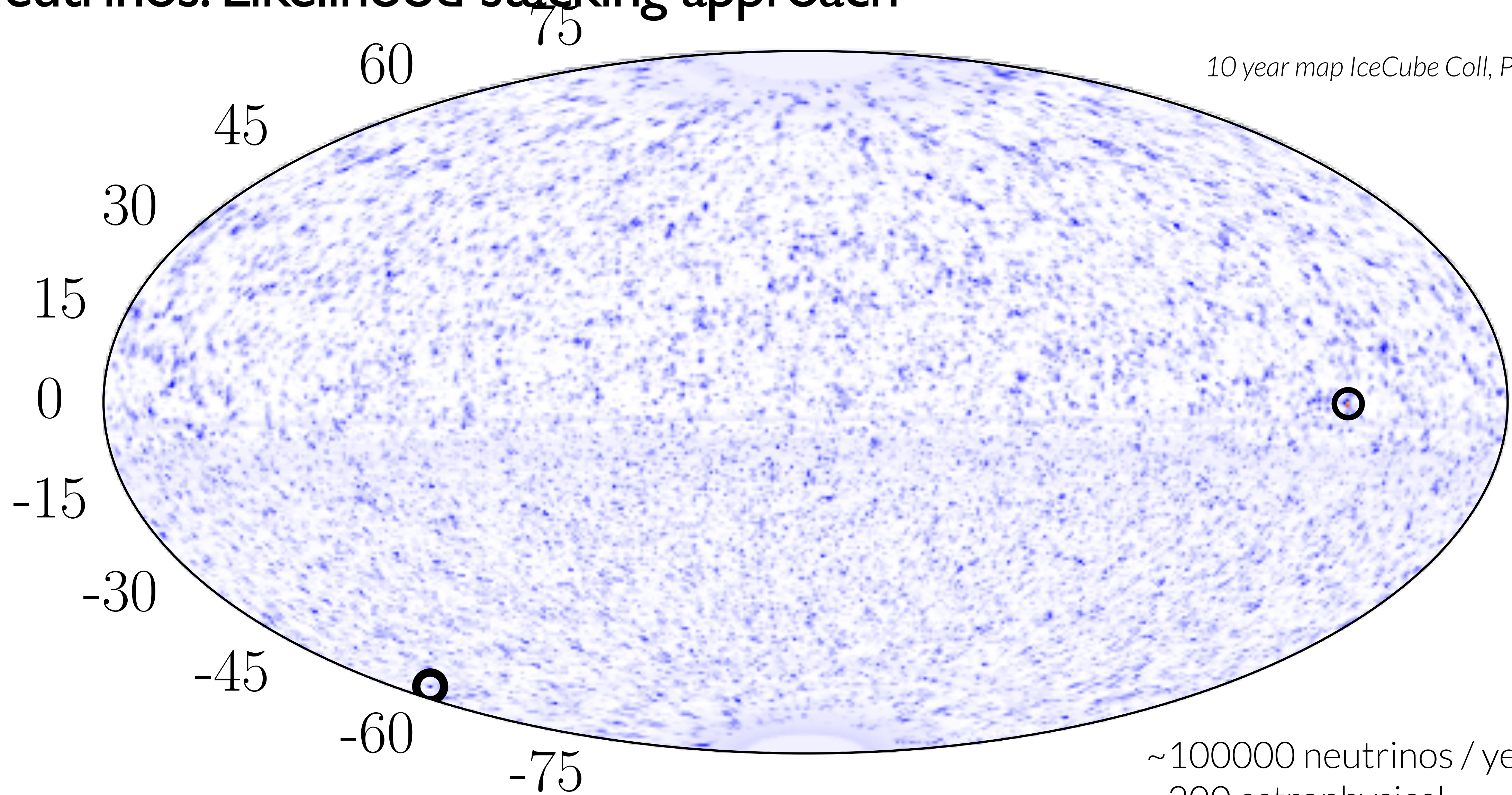


Possible contribution of blazars to the diffuse neutrino flux



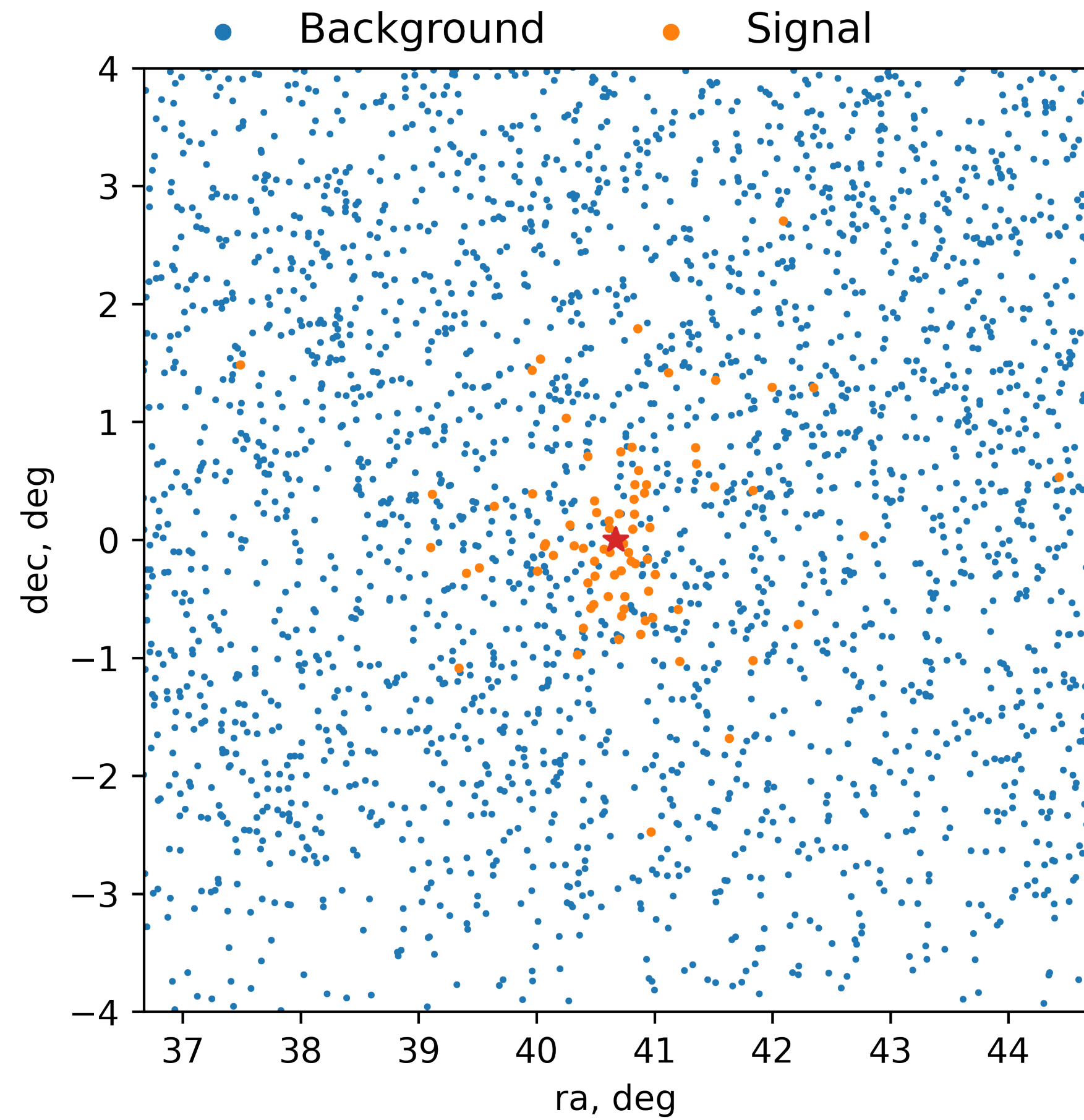
Neutrinos: Likelihood stacking approach

10 year map IceCube Coll, PRL 2020



~100000 neutrinos / year
~200 astrophysical
~30 high energy ($E > 60$ TeV)/year

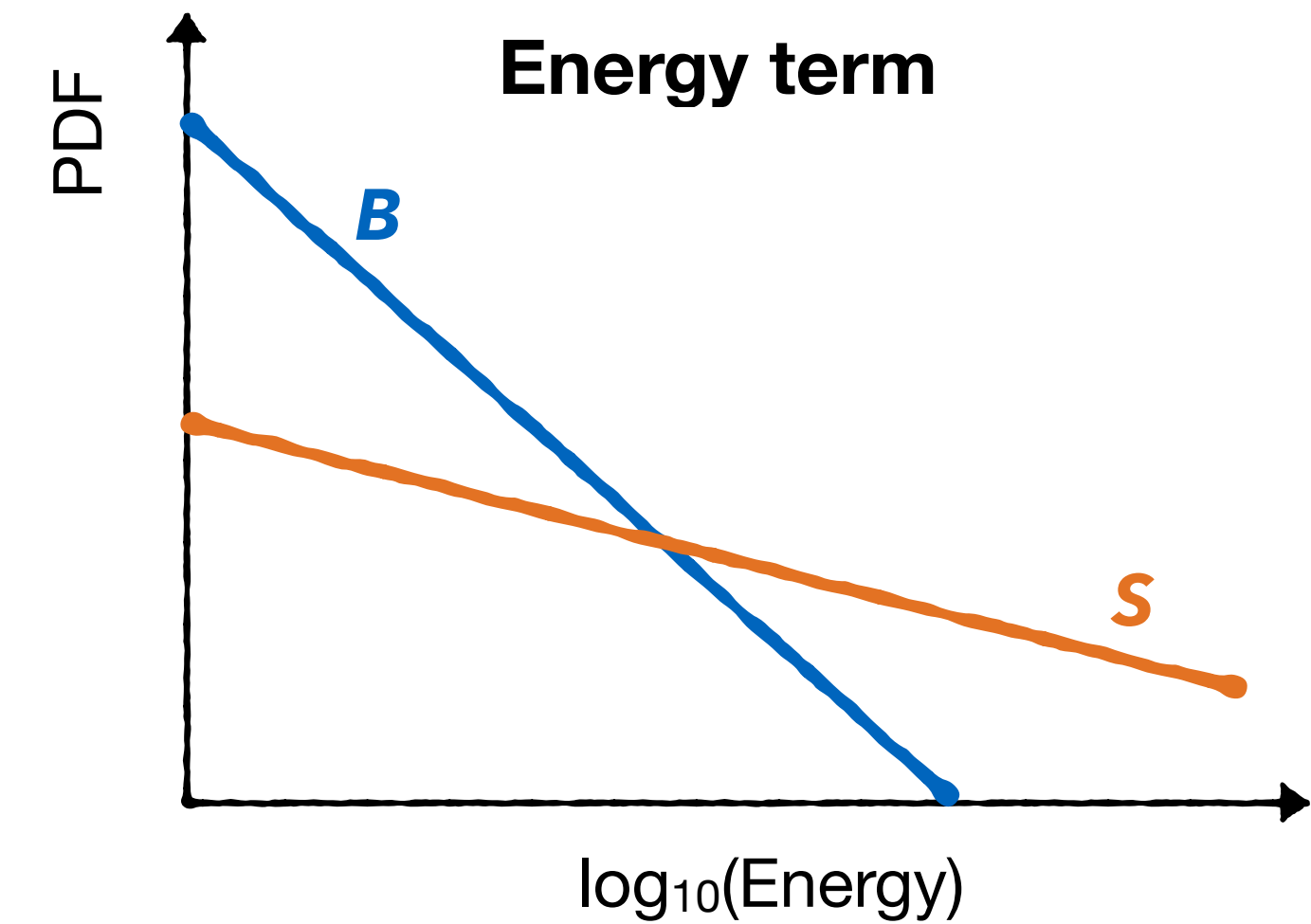
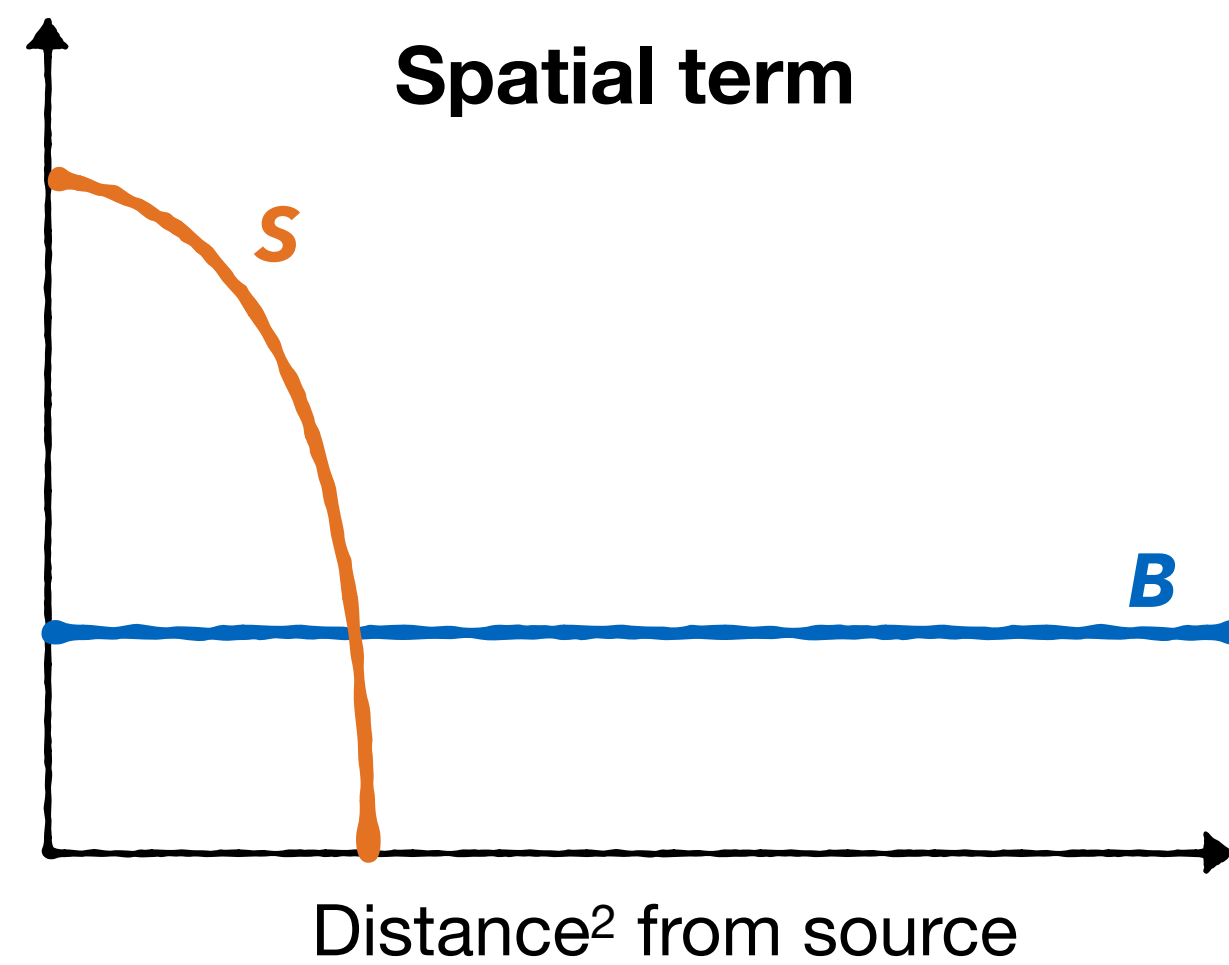
Neutrinos: Likelihood stacking approach



The unbinned likelihood approach:

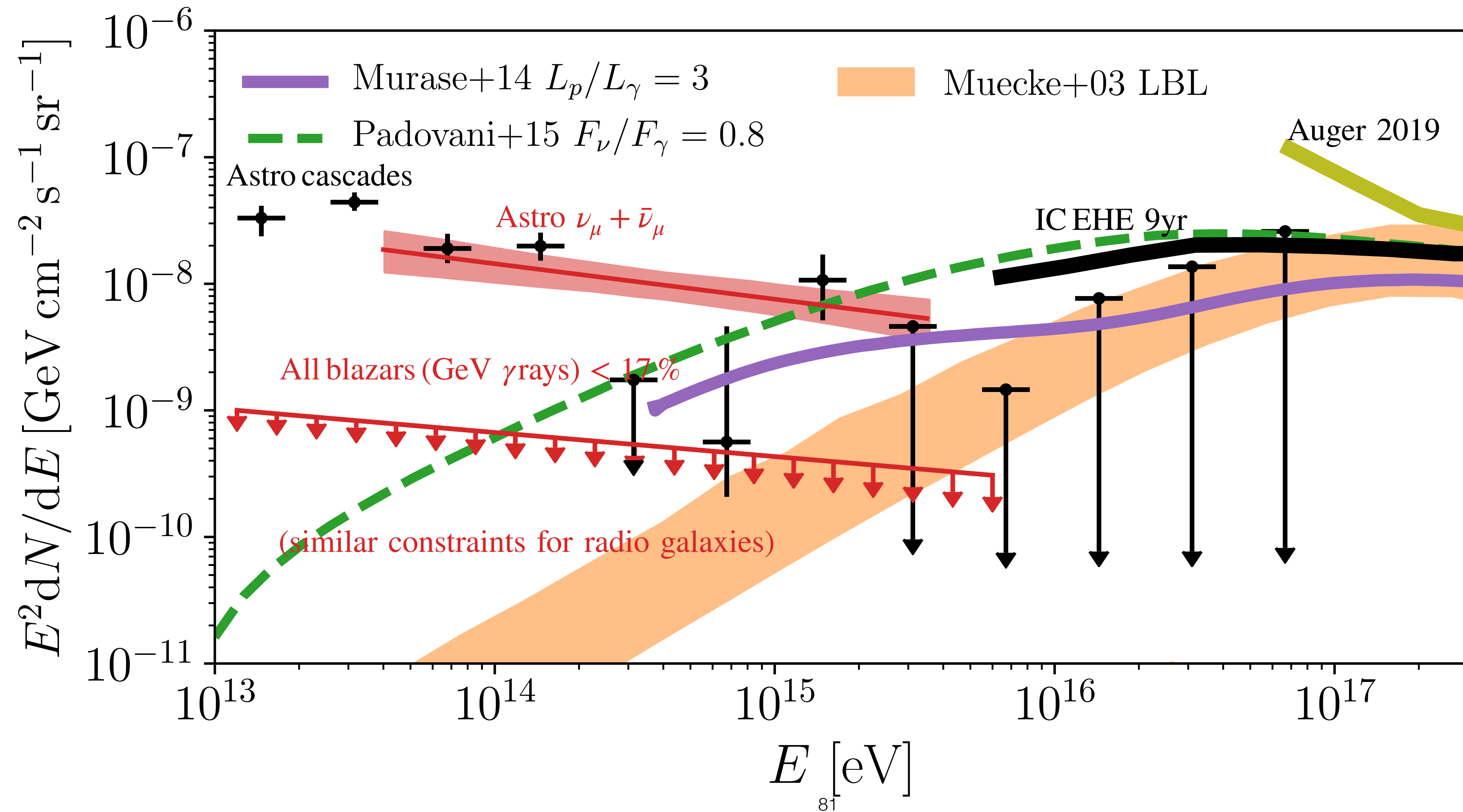
$$\mathcal{L} = \prod_i^N \left[\frac{n_s}{N} \boxed{S_i} + \left(1 - \frac{n_s}{N} \right) \cdot \boxed{B_i} \right]$$

Arrows from the boxed terms S_i and B_i point to the 'Spatial term' and 'Energy term' plots respectively.

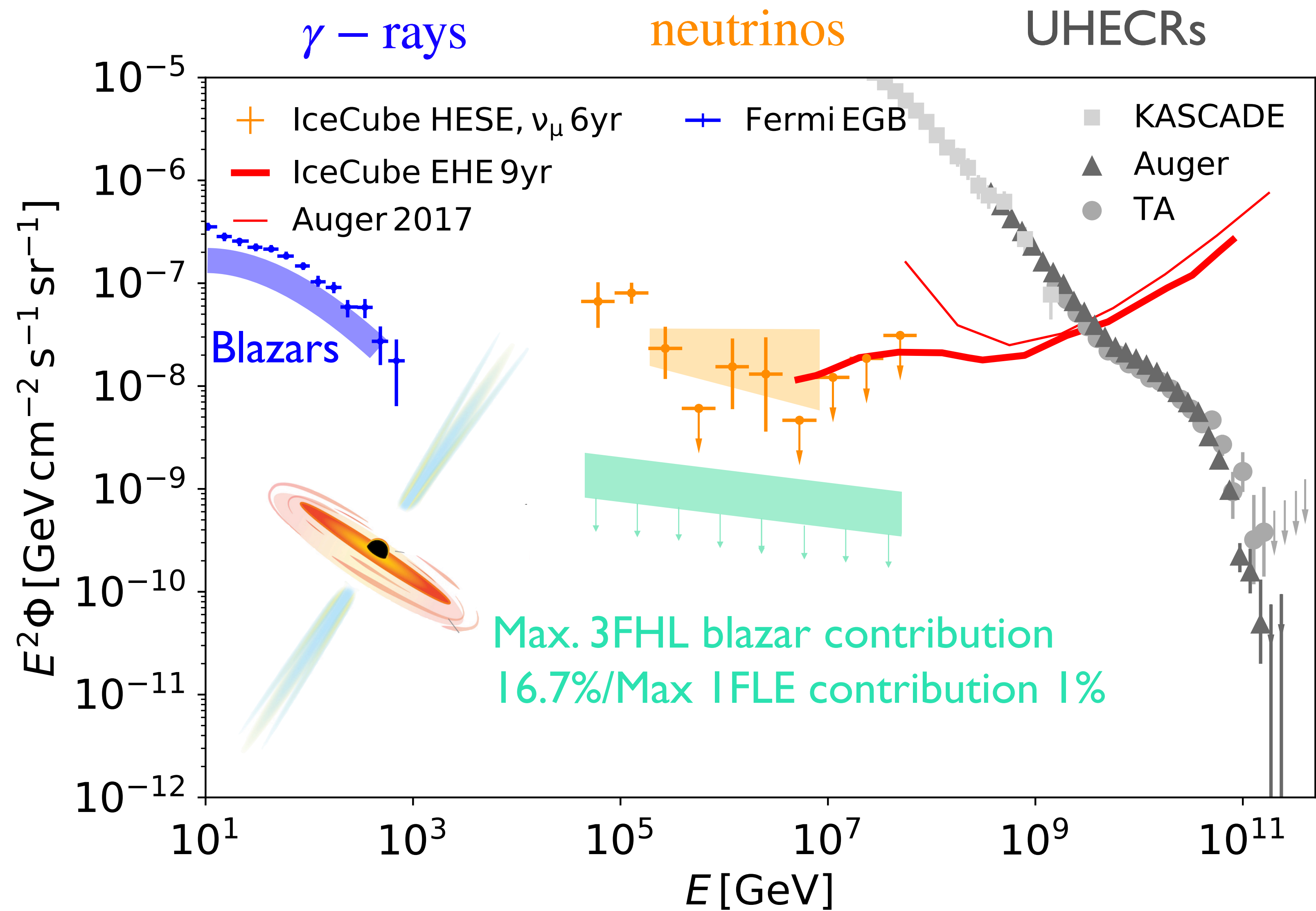


Tomas Kontrimas | TeVPA 2024 | 26th of August, 2024 | Chicago, US

Stacking limits from IceCube

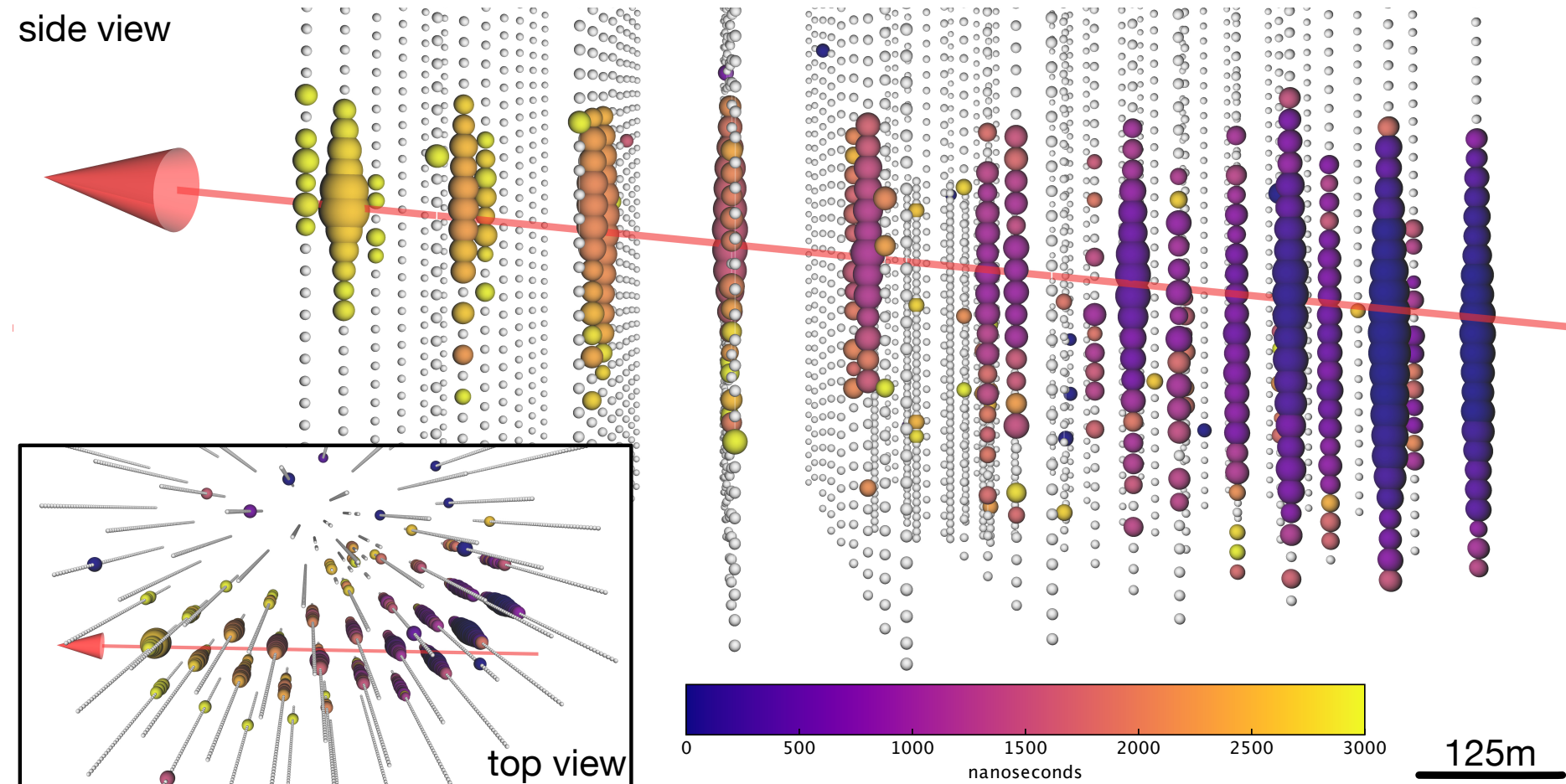


Stacking limits from IceCube

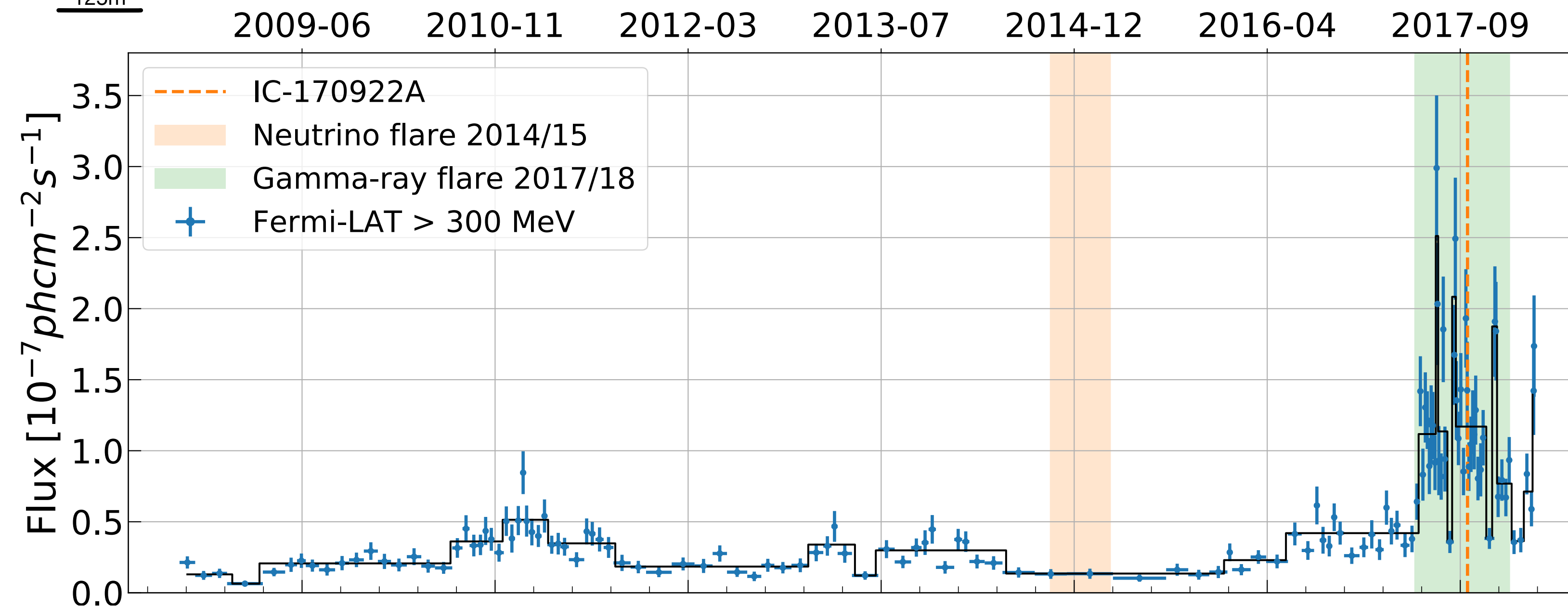


TXS 0506+056-IC 170922A

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN,
HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso,
Kapteyn, Liverpool telescope, Subaru, Swift/
NuSTAR, VERITAS, and VLA/I 7B-403 teams.
Science 361, 2018, MAGIC Coll. *Astrophys.J.*
863 (2018) L10



Background fluctuation? Chance probability $\sim 0.3\%$



Blazar flares: Interesting as neutrino point sources

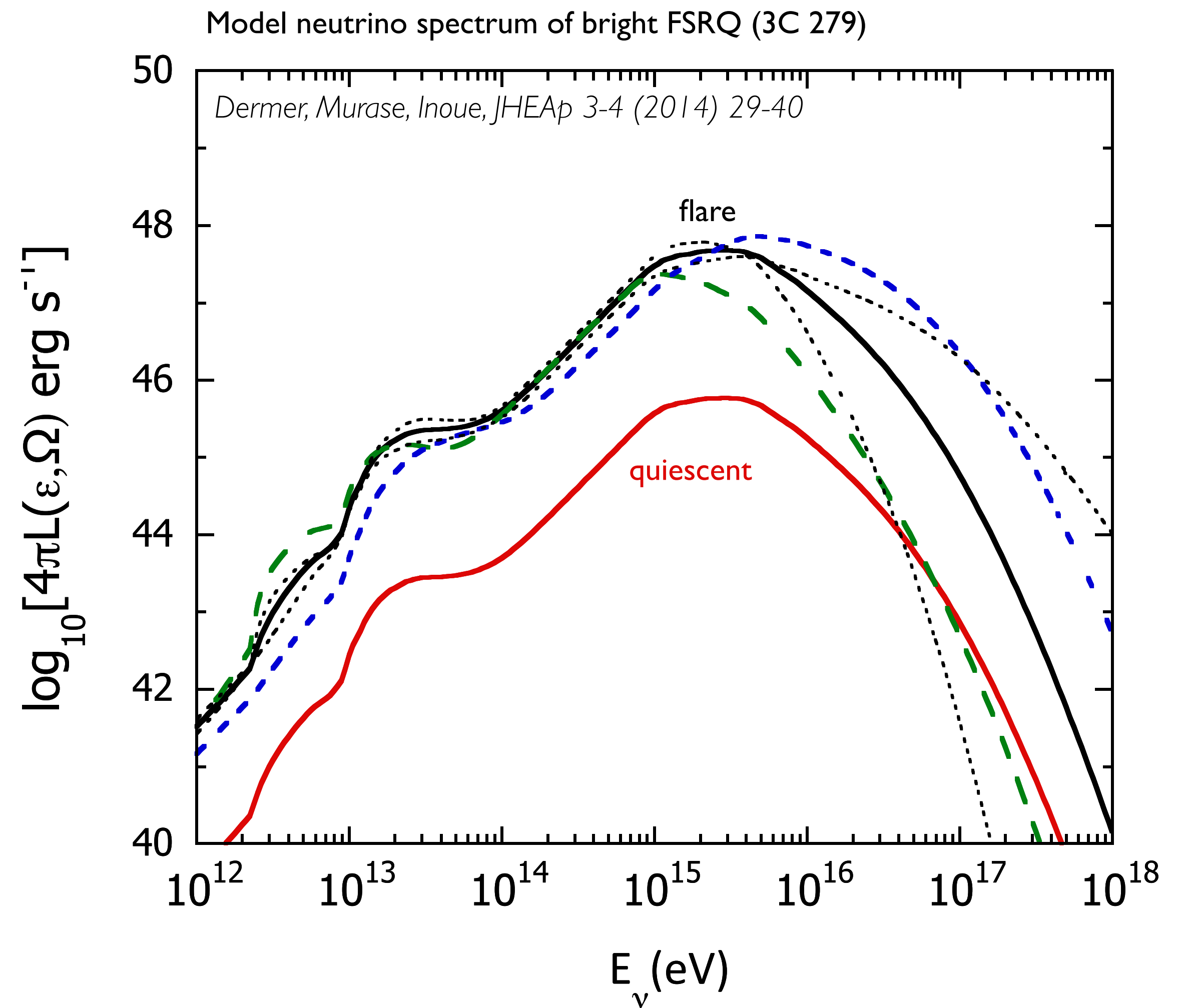
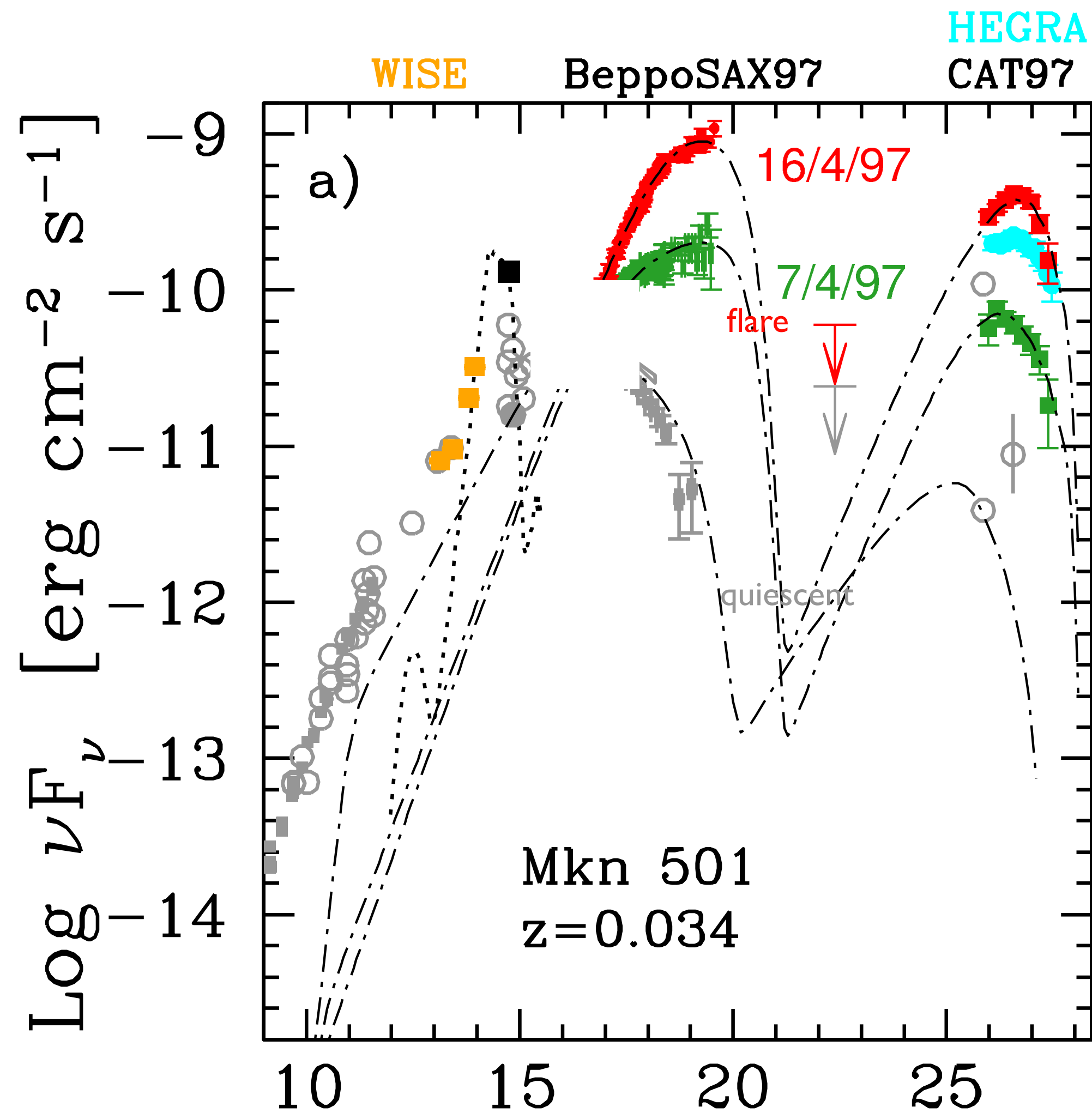
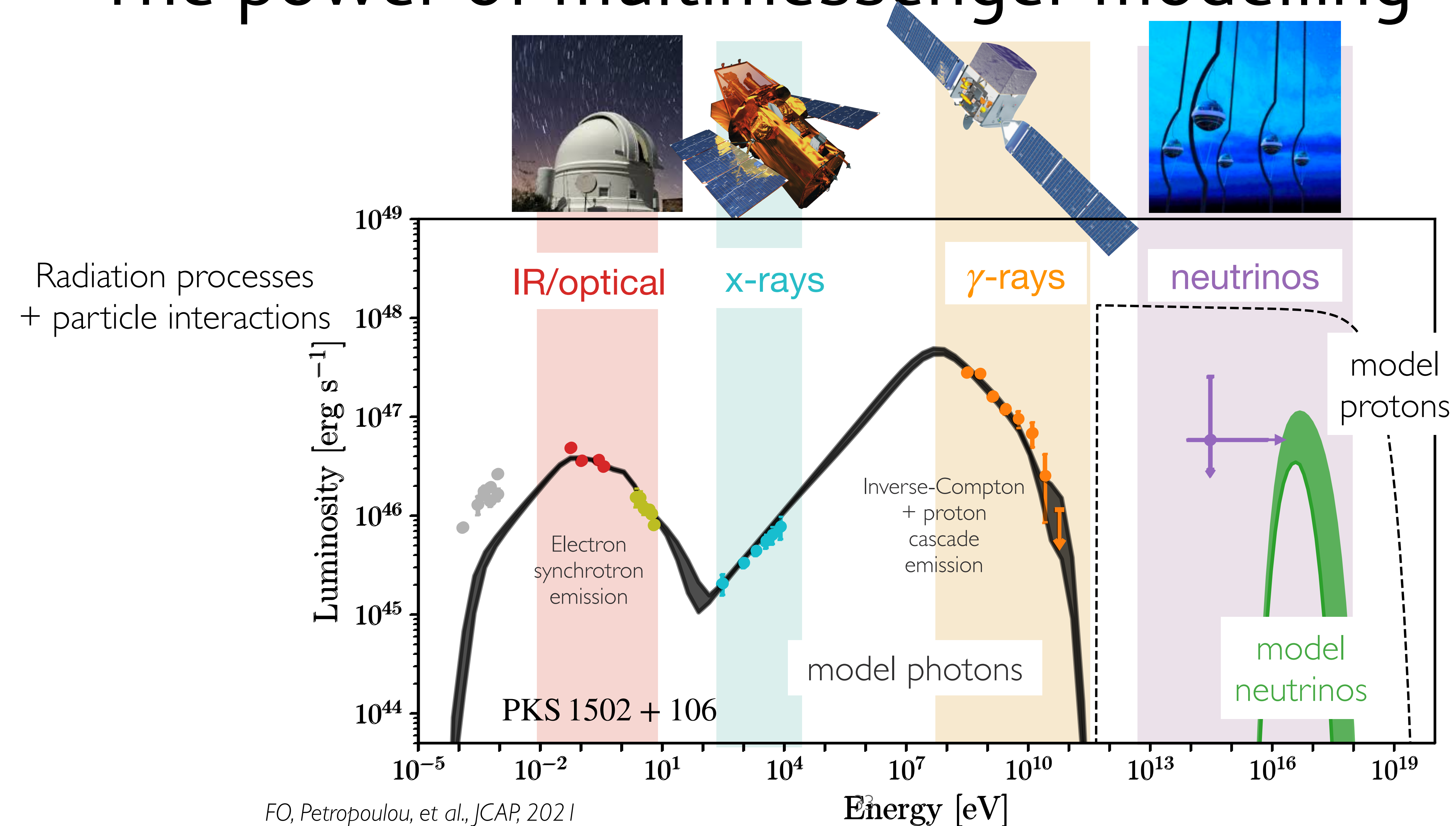


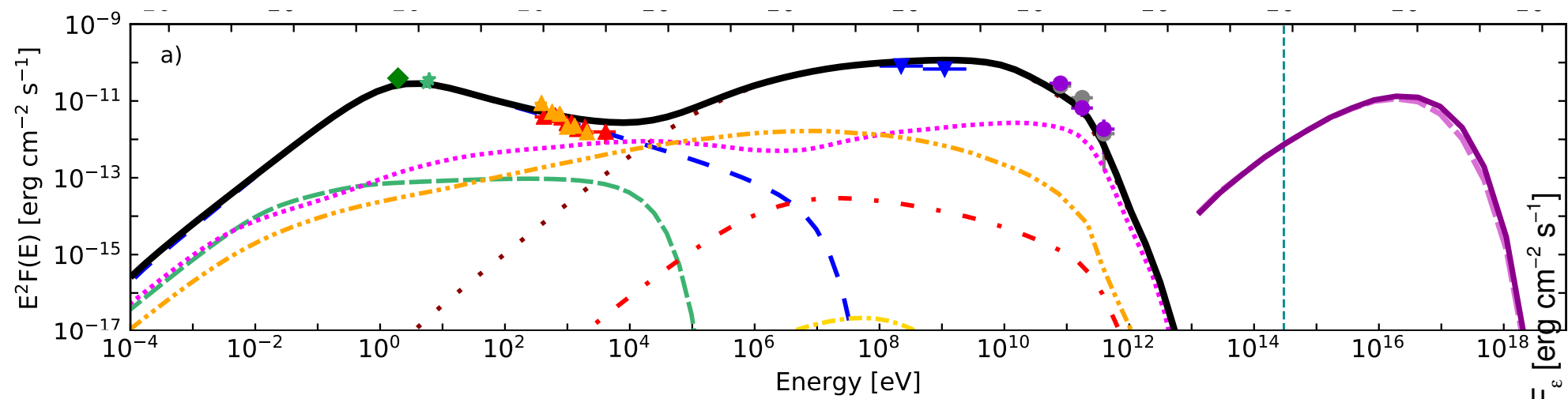
Image from Biteau, Prandini, Costamante+ Nat. Astr 4, 124–131 (2020)

The power of multimessenger modelling

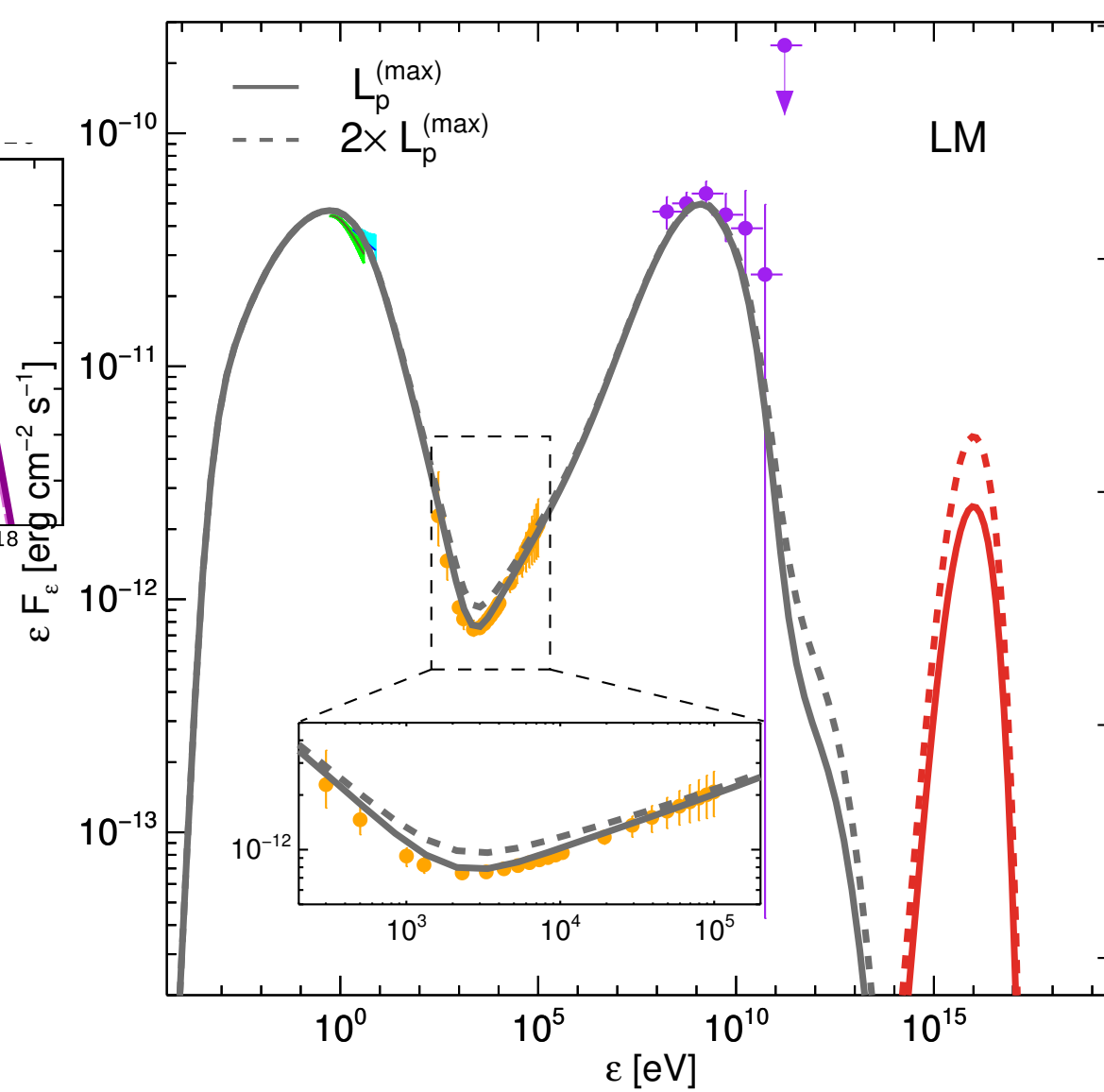


Neutrino production in TXS 0506+056 in 2017

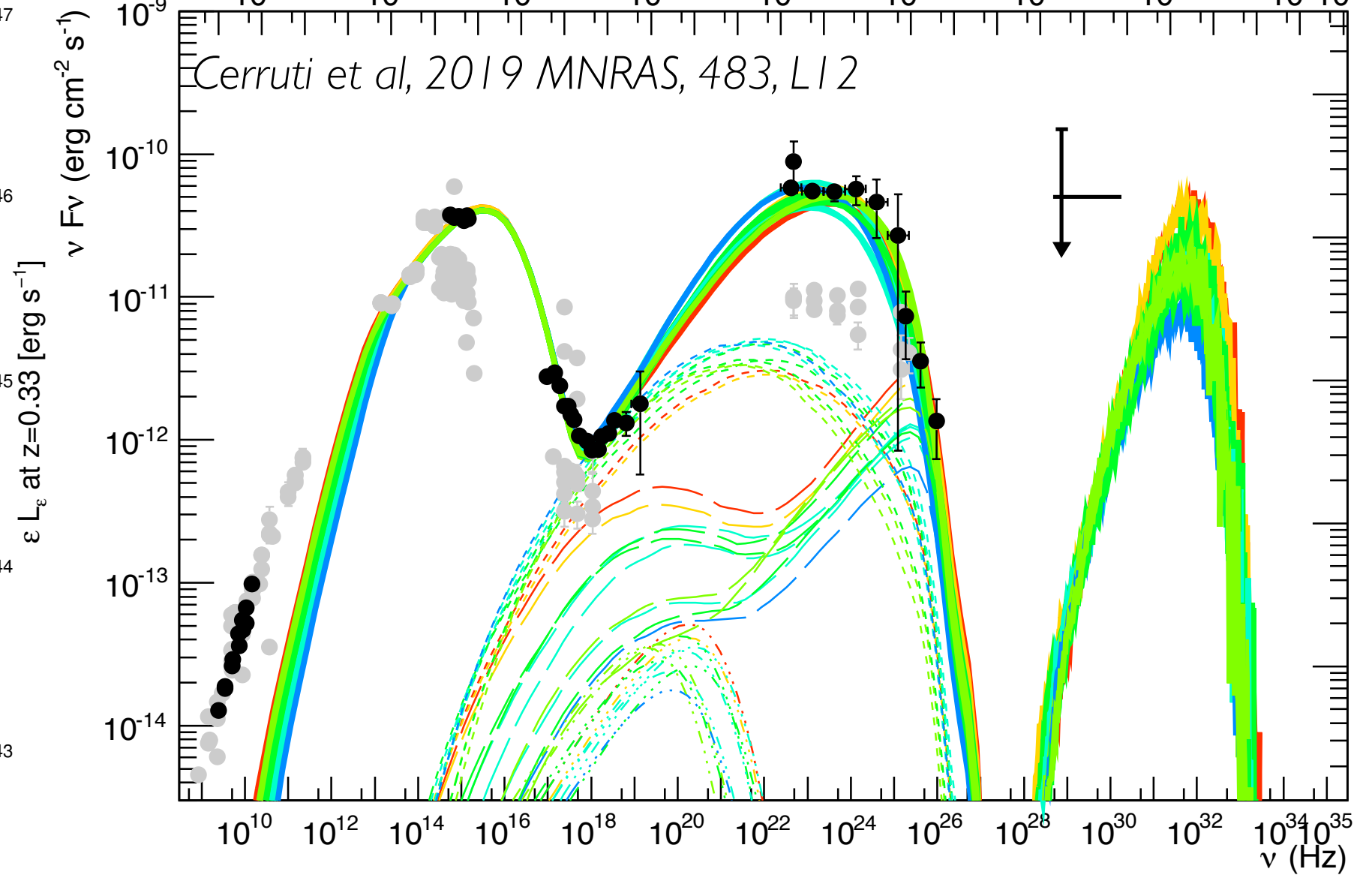
MAGIC Coll 2018, ApJ, 863, L10



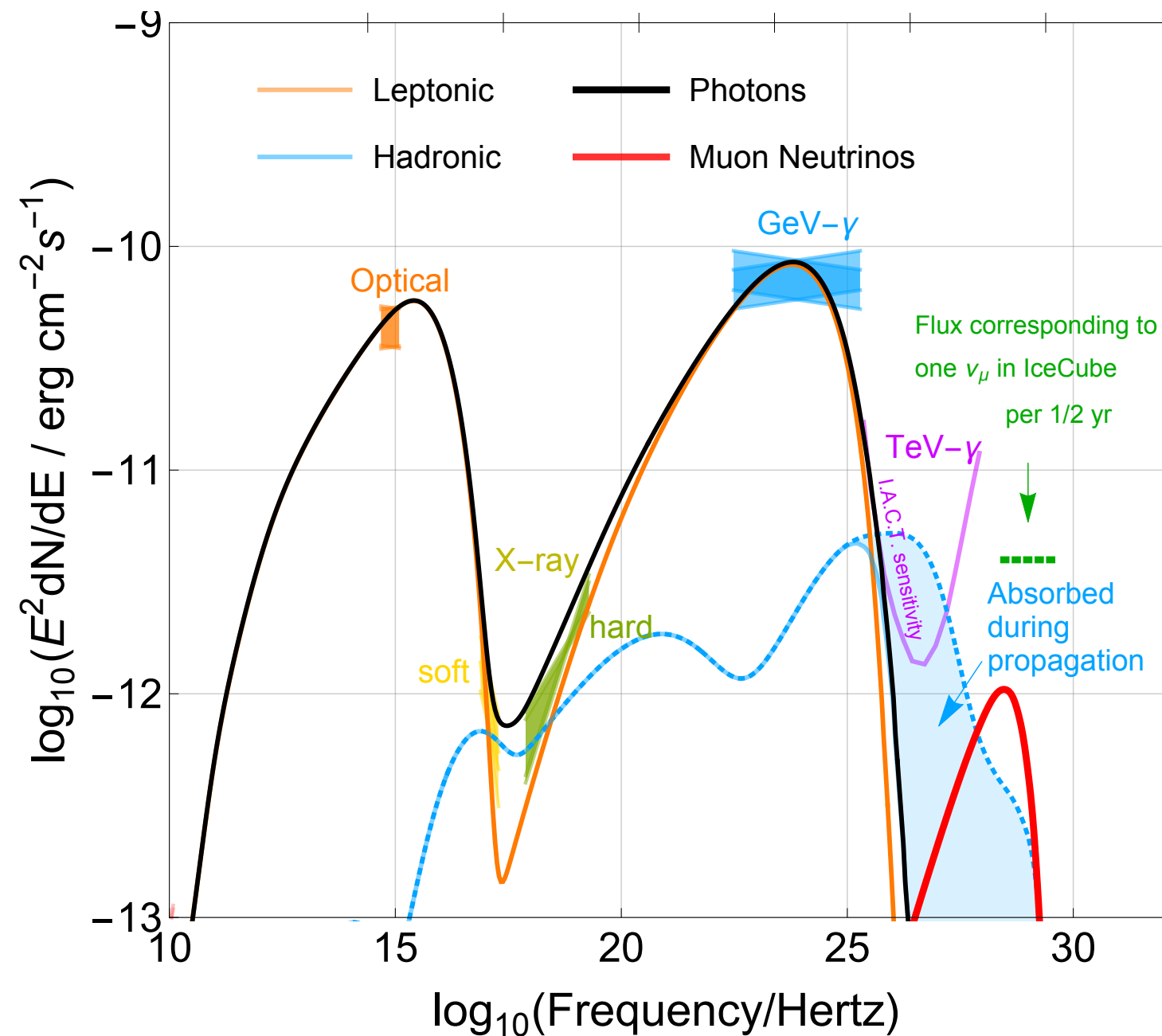
Keivani et al. 2018, ApJ, 864, 84



Cerruti et al, 2019 MNRAS, 483, L12



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



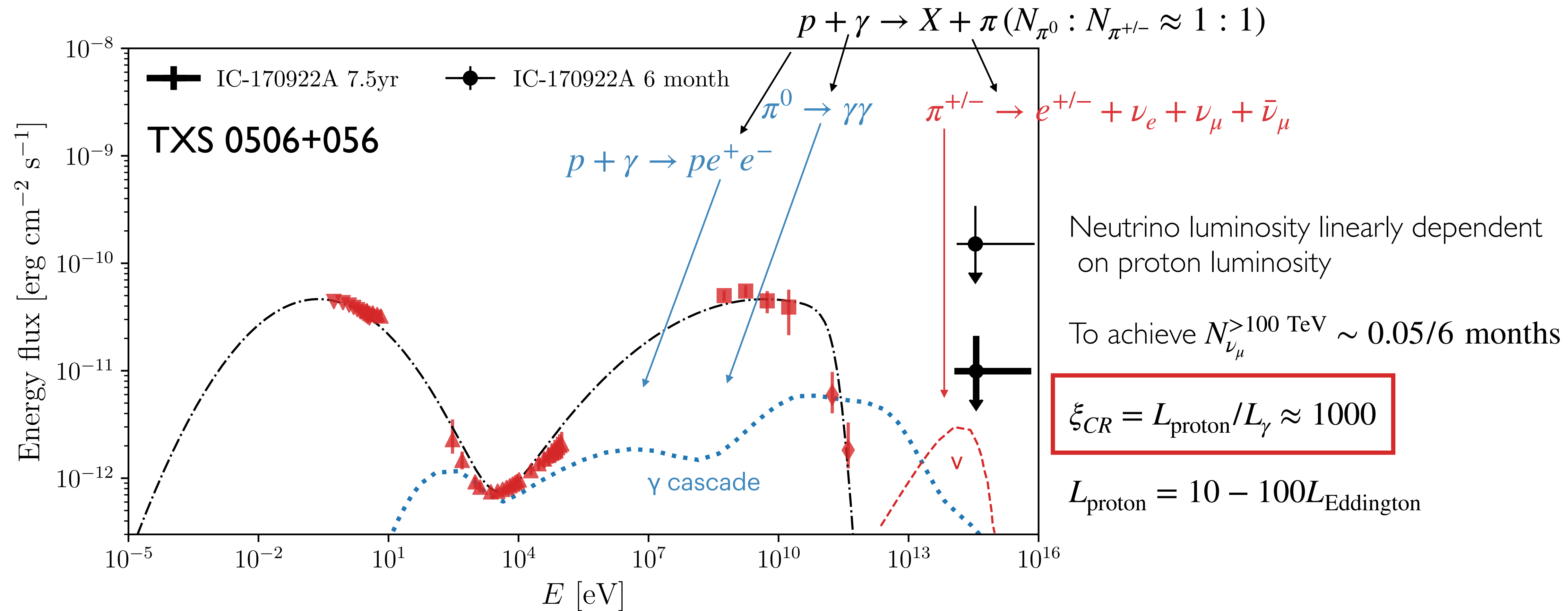
$$N_{\nu_{\mu}} \lesssim 0.05/6 \text{ months}^{\star}$$

-Ok due to population bias!

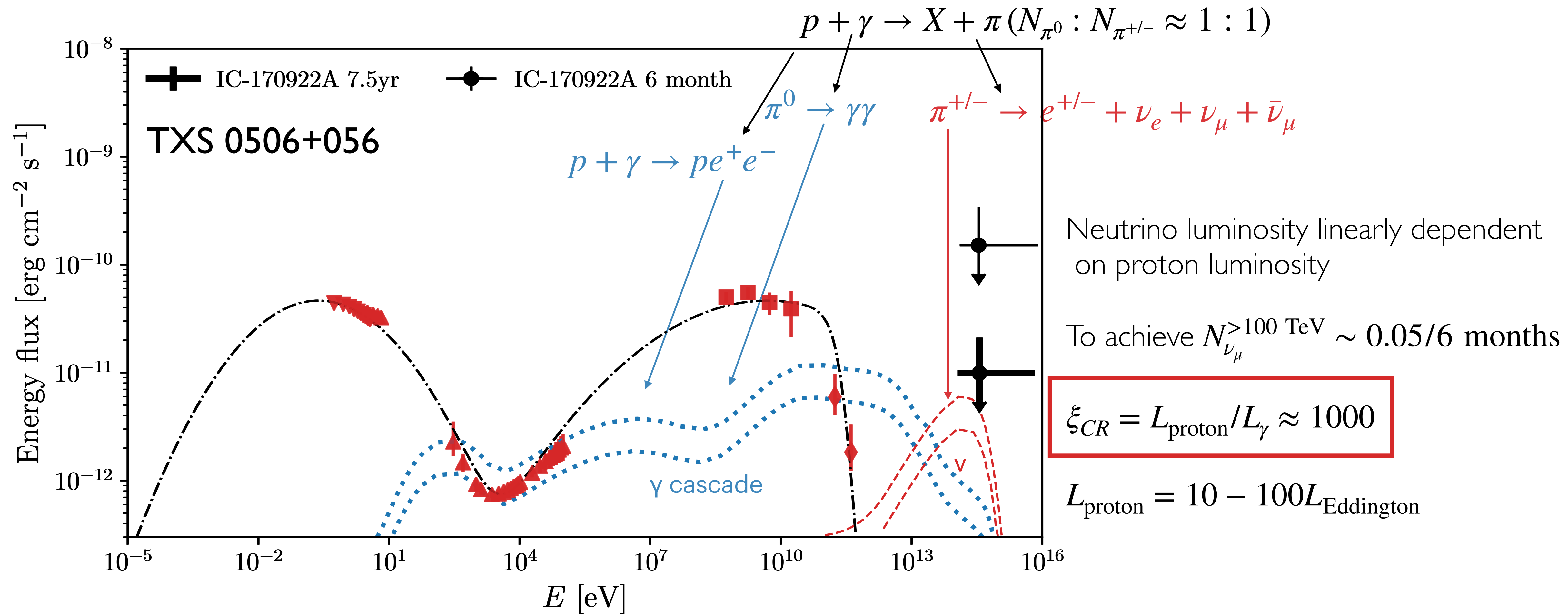
(1% chance to see one neutrino from each blazar flare)

-But: What does it take to produce 0.05 neutrinos/6months in this blazar?

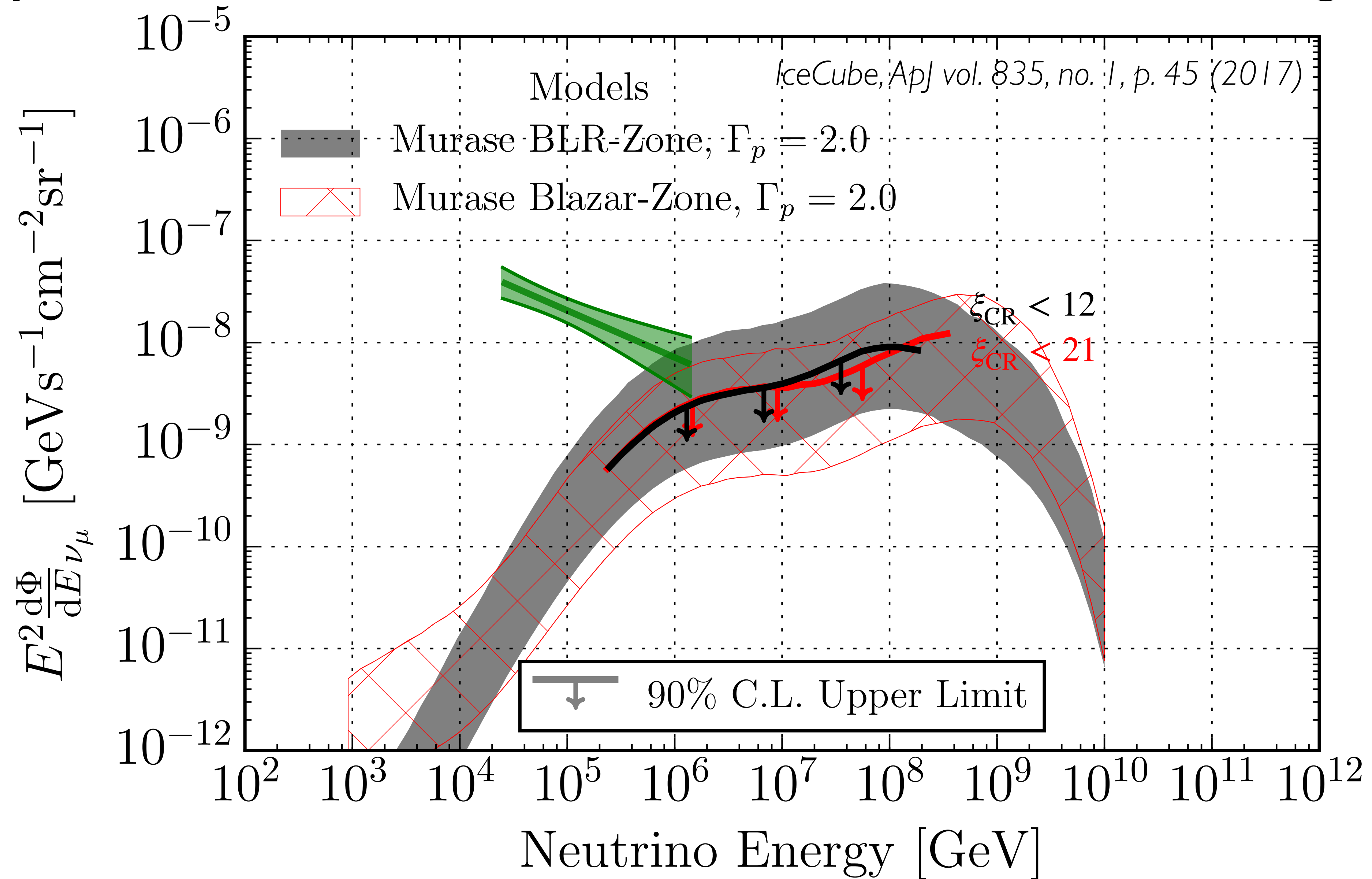
What sets the neutrino flux upper limit?



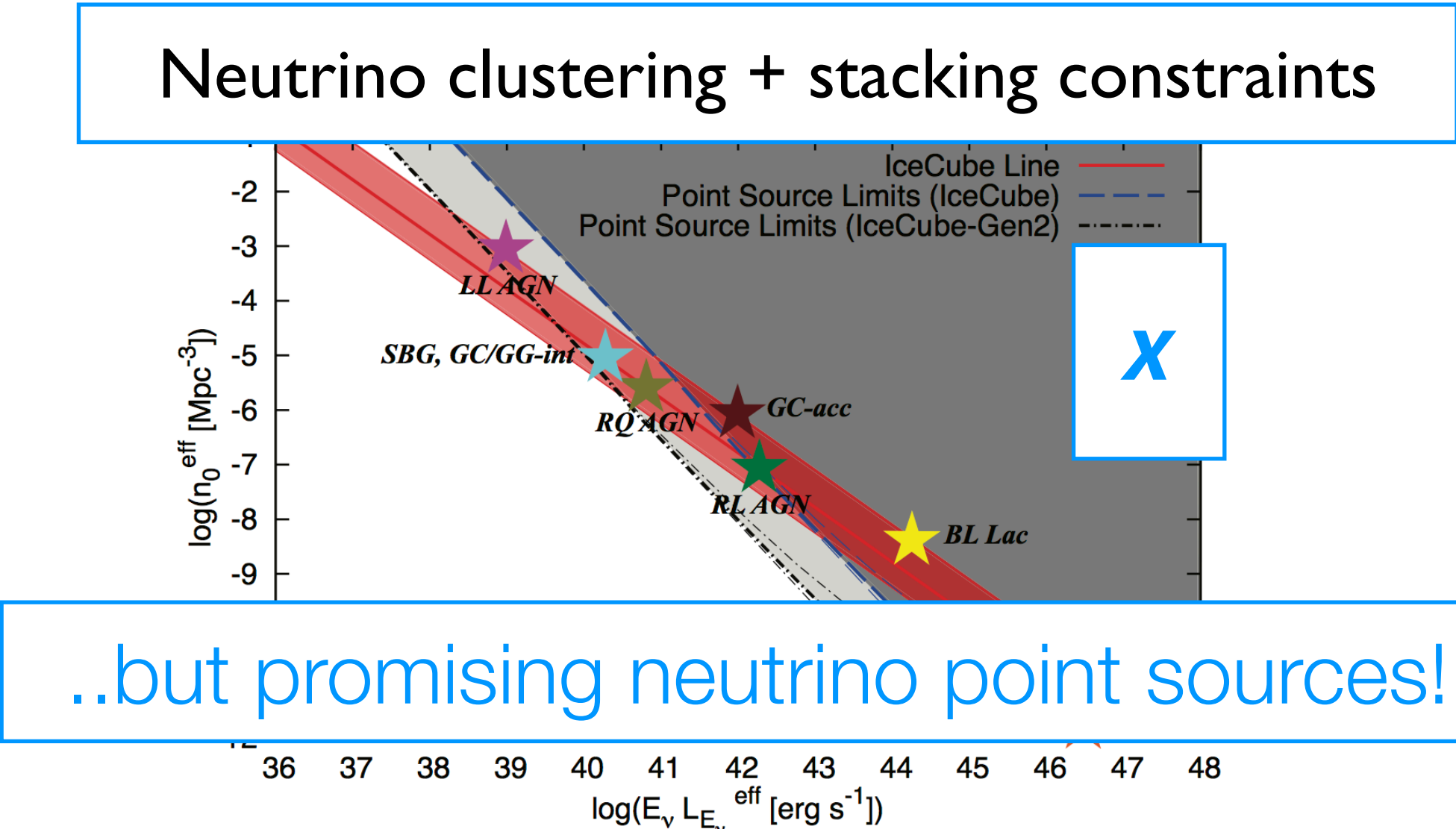
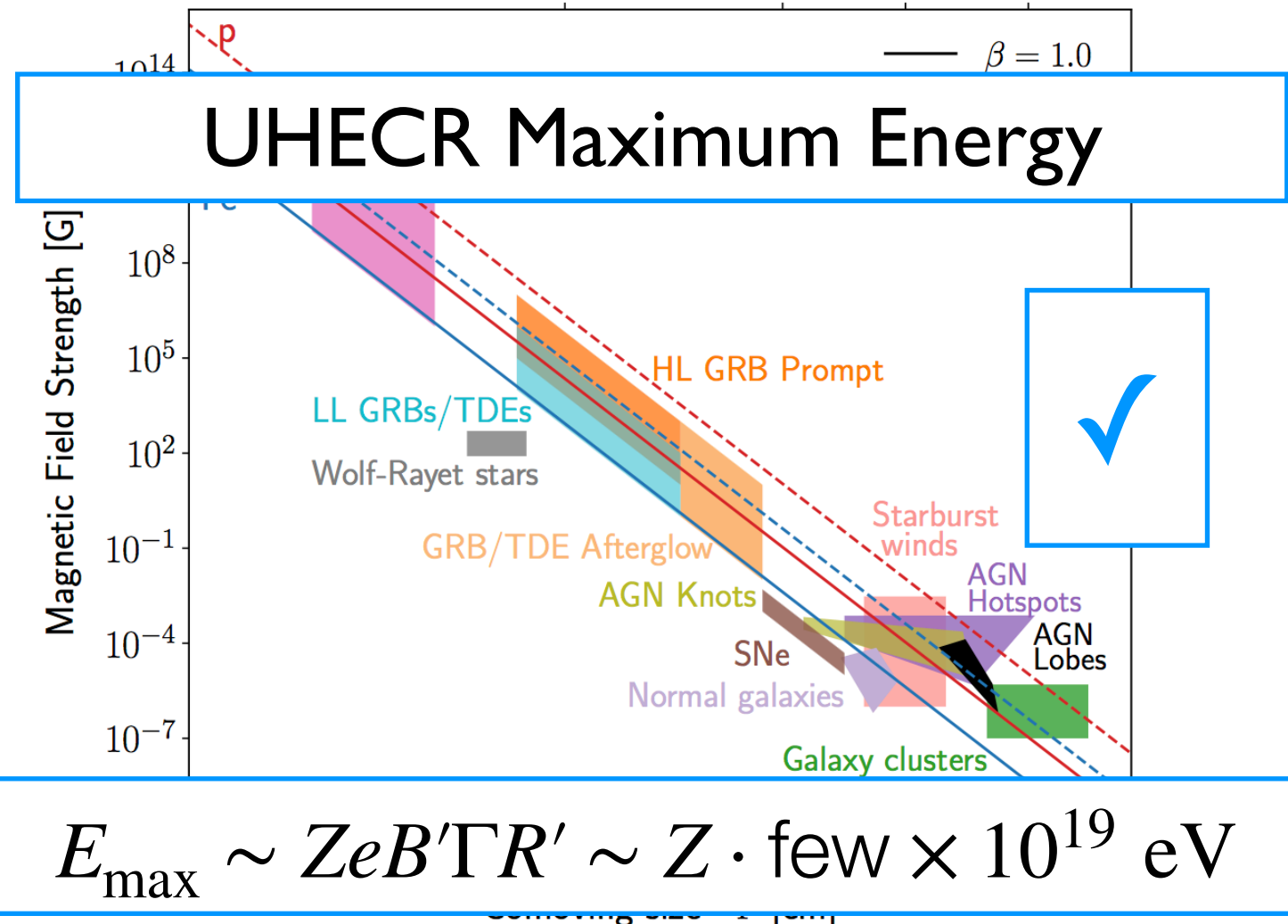
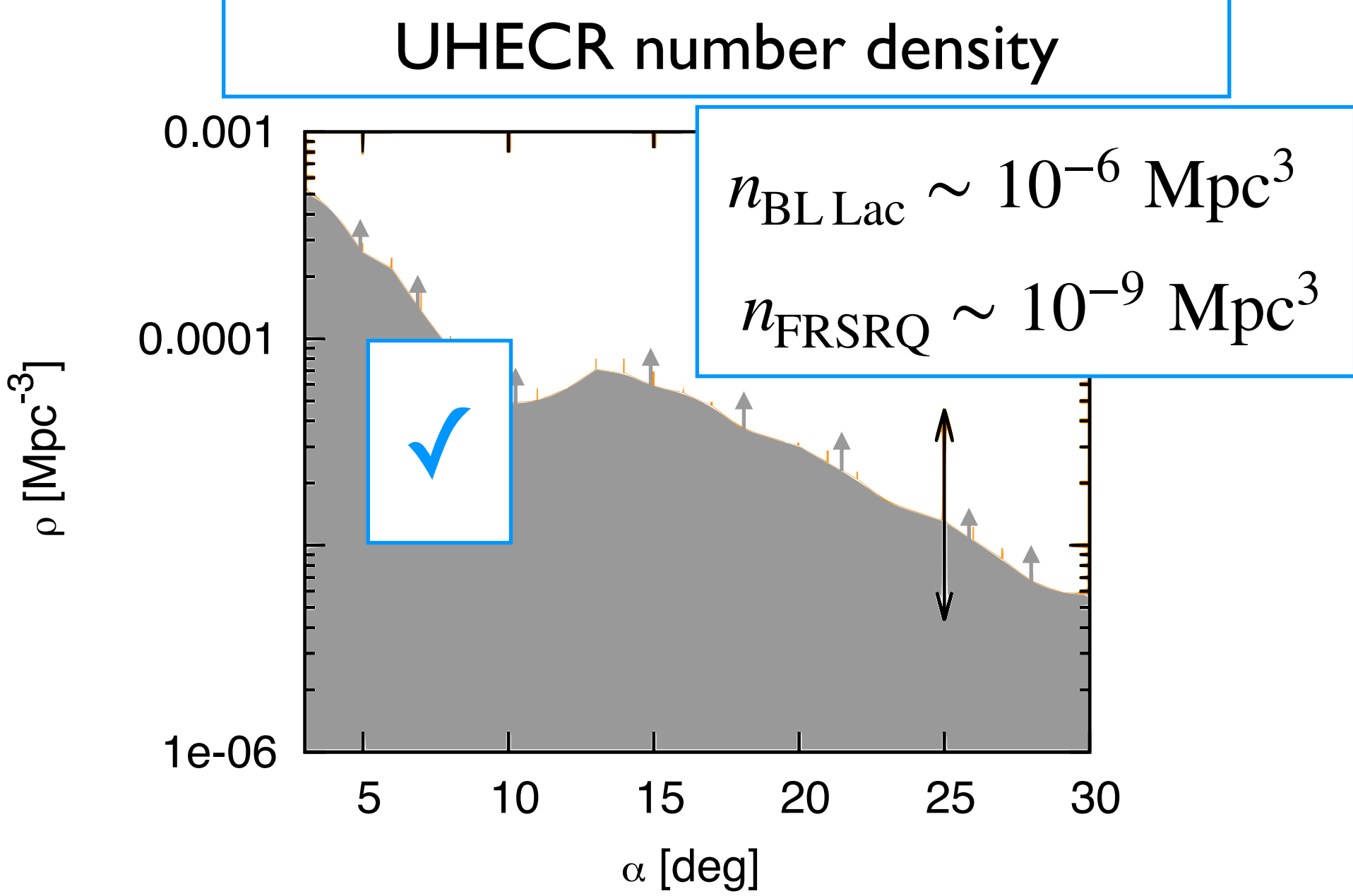
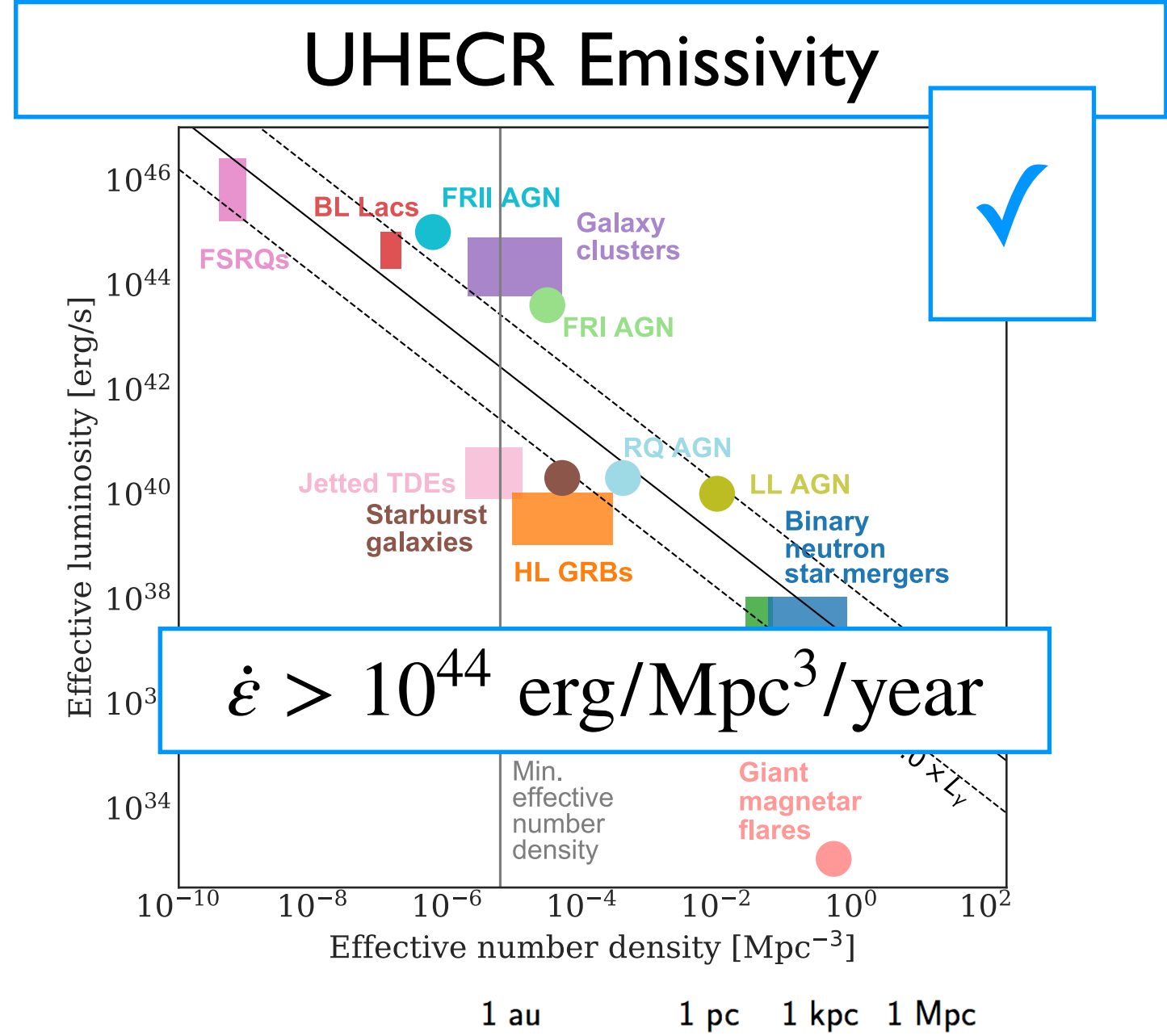
What sets the neutrino flux upper limit?



Population limits from IceCube (and Auger)



Blazar/radio galaxy contribution to UHECR/neutrino flux?



Scorecard

		$E_{\text{max}}^{\text{UHECR}}$	n_{UHECR}	$\dot{\epsilon}_{\text{UHECR}}$	n_{ν}	Stacking UL
Blazars	BL Lacs	😄	😞	😄	😞	~20%
	FSRQs	😄	😞	😄	😞	~20%
Jetted AGN	FR I	😄	😄	😄	😄	~20%
	FR II	😄	😄	😄	😄	~20%
Non-jetted AGN						
Starburst galaxies						
HL GRBs						
LL GRBs						
TDEs						

Tomorrow!



Thank you for your attention!