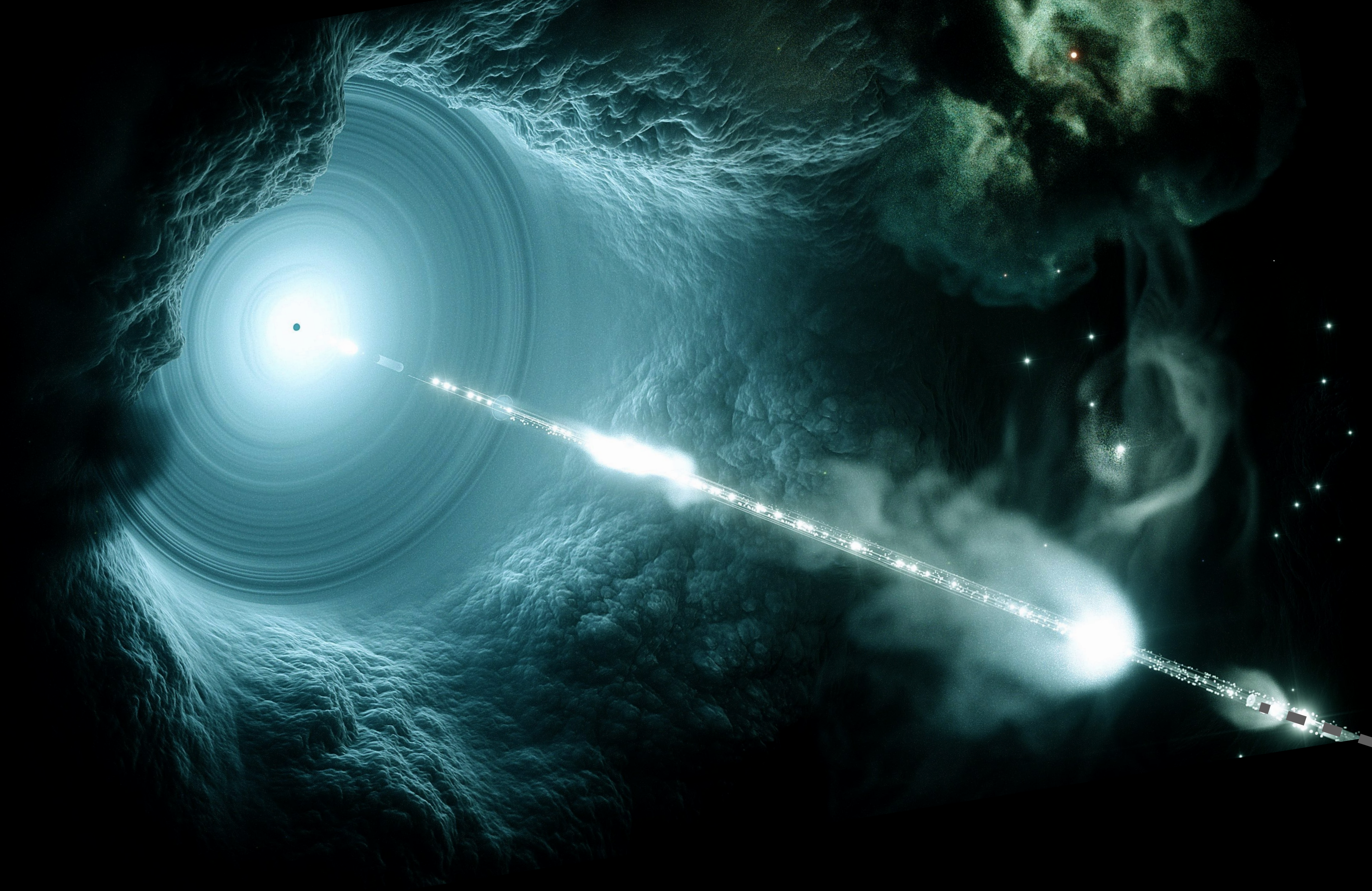
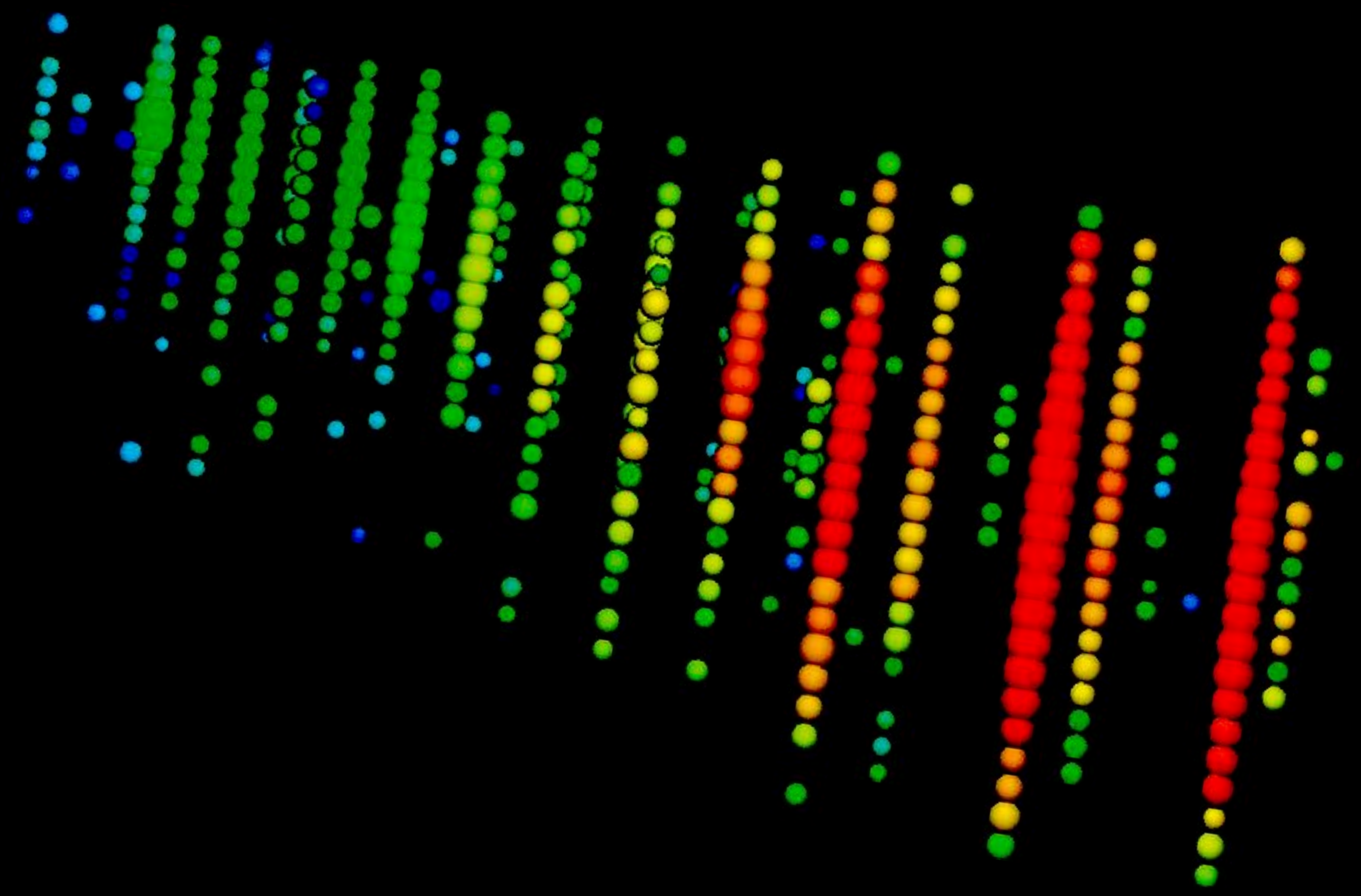




Neutrino Astronomy & Astrophysics

PhD summer school on neutrinos

Here, there & Everywhere

NBI, Copenhagen

Foteini Oikonomou

NTNU
Norwegian University of Science and Technology

July 5th-9th

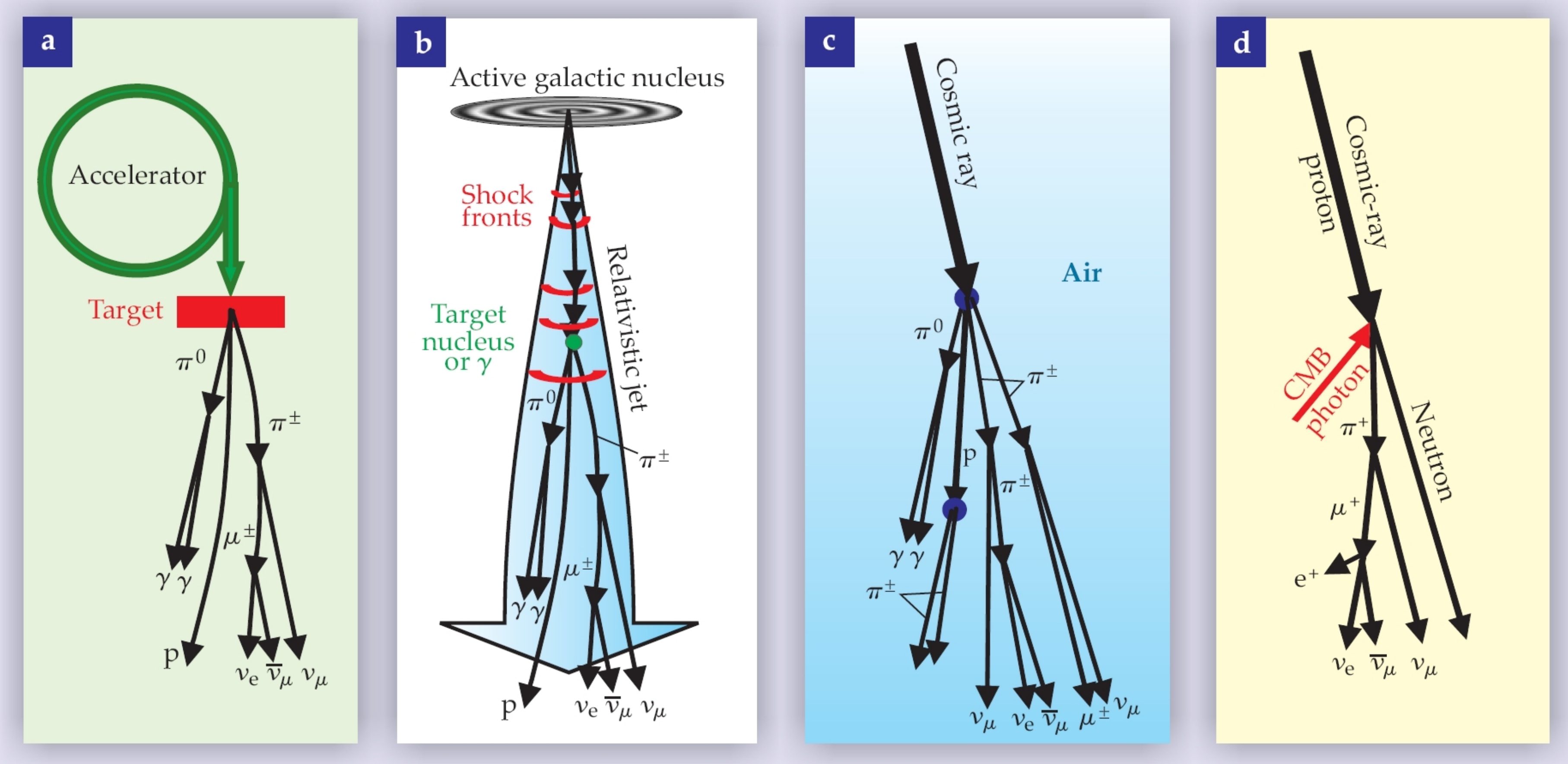
Lecture plan

- Experimental facts and basic theoretical concepts
- Requirements for astrophysical accelerators of high-energy cosmic rays/ high-energy neutrinos (generic source properties)
- Overview of candidate sources (Active Galactic Nuclei/Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events) constraints and prospects

Generic source properties/requirements

- Hillas criterion for acceleration and plausible sources
- Waxman & Bahcall neutrino bound (possible connection to UHECRs)
- Neutrino source energy budget
- Neutrino source number density

UHECR energy losses



Mean free path = 1/ (number density of targets x cross-section)

$$\lambda = 1/n\sigma$$

Relative energy loss per unit time:

$$\left| -\frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}t} \right| = \left\langle \kappa\sigma n_\gamma c \right\rangle, \kappa = \frac{\Delta E}{E} = \text{inelasticity}$$

Energy loss length:

$$\chi_{\text{loss}} = c \cdot \left| \frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}t} \right|^{-1}$$

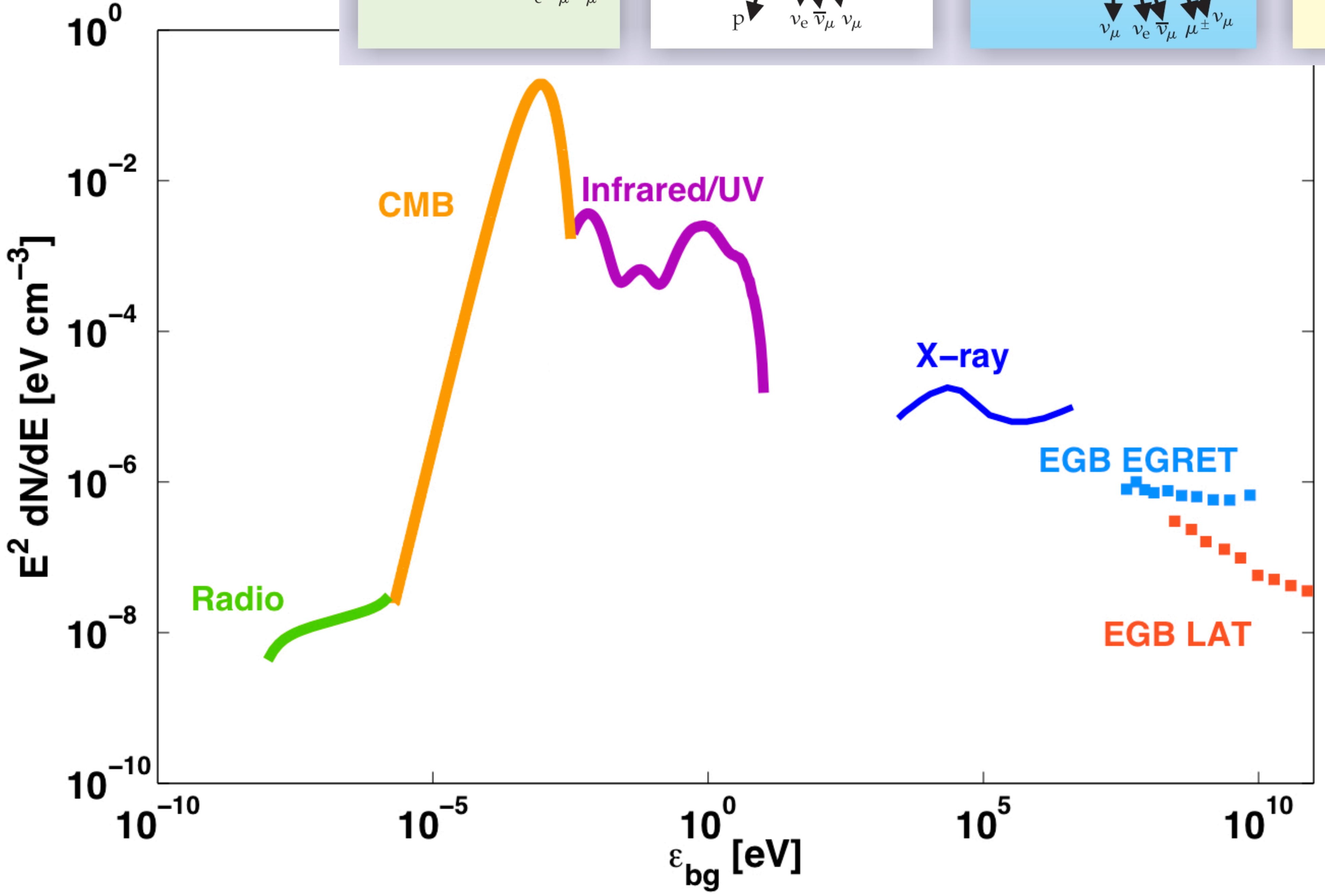


Photo-pair production (Bethe-Heitler process):

$$p + \gamma_{\text{bg}} \rightarrow p + e^+ + e^-$$

$$[\kappa_{p\gamma}^{ee} = 2m_e/m_p \approx 10^{-3}, \sigma_{p\gamma,\text{thresh}}^{ee} \approx 1.2 \cdot 10^{-27}\,\text{cm}^2, n_{\text{CMB}} \approx 411\,\text{cm}^{-3}]$$

$$E_p \gtrsim 10^{19}\,\text{eV} \left(\frac{\varepsilon_\gamma}{6 \times 10^{-4}\,\text{eV}} \right)^{-1}$$

$$\lambda_{p\gamma}^{ee} \sim 1/(n_{\text{CMB}} \cdot \sigma_{p\gamma}^{ee}) \sim 1\,\text{Mpc}$$

$$\chi_{\text{BH,loss}} \sim \lambda_{p\gamma}^{ee}/\kappa \sim 1\text{Gpc}$$

UHECR energy losses
Photo-pion production

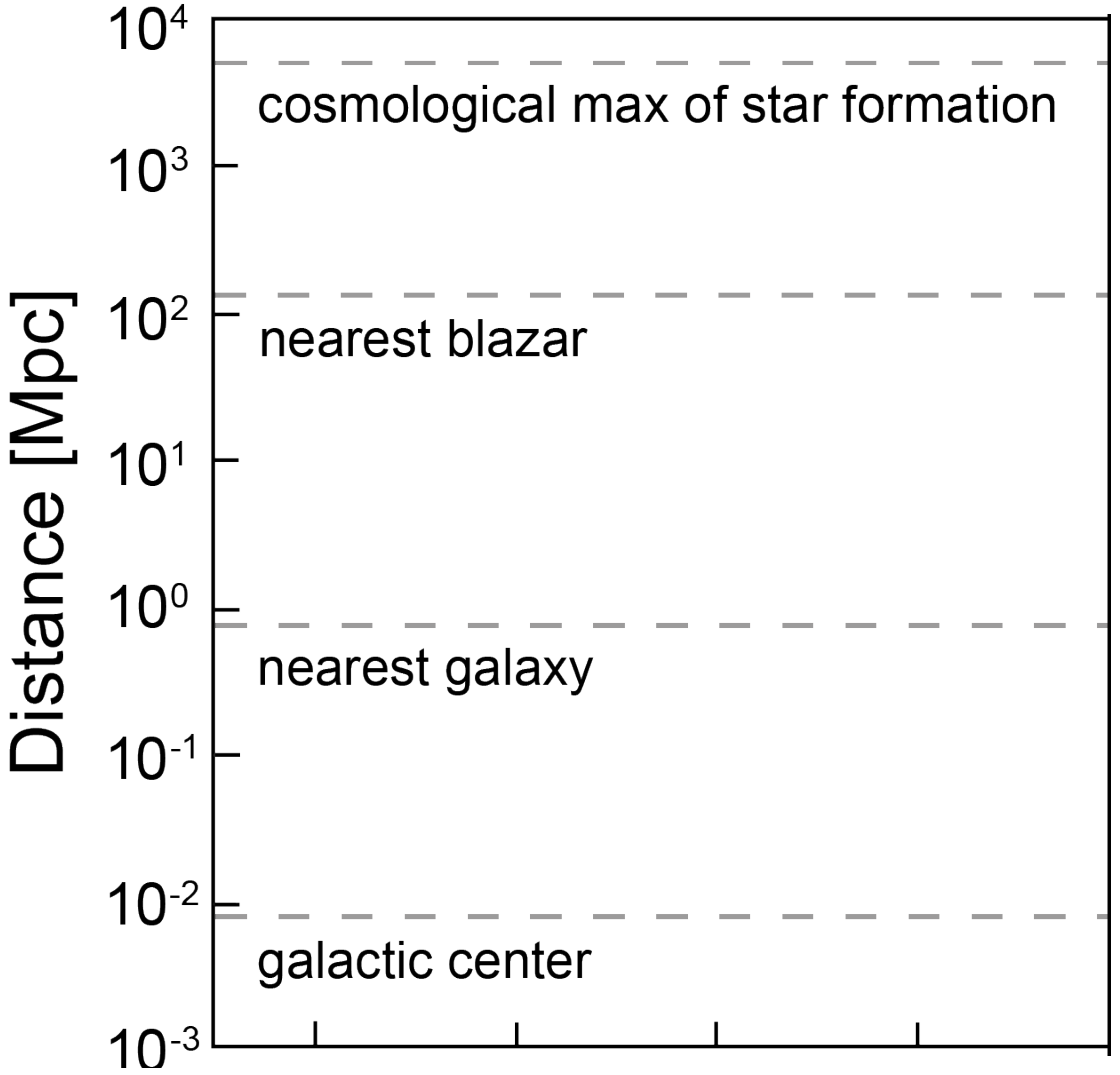
Photo-pion production:

$$p + \gamma_{\rm CMB} \to \Delta^+ \to n/p + \pi^+/\pi^0$$

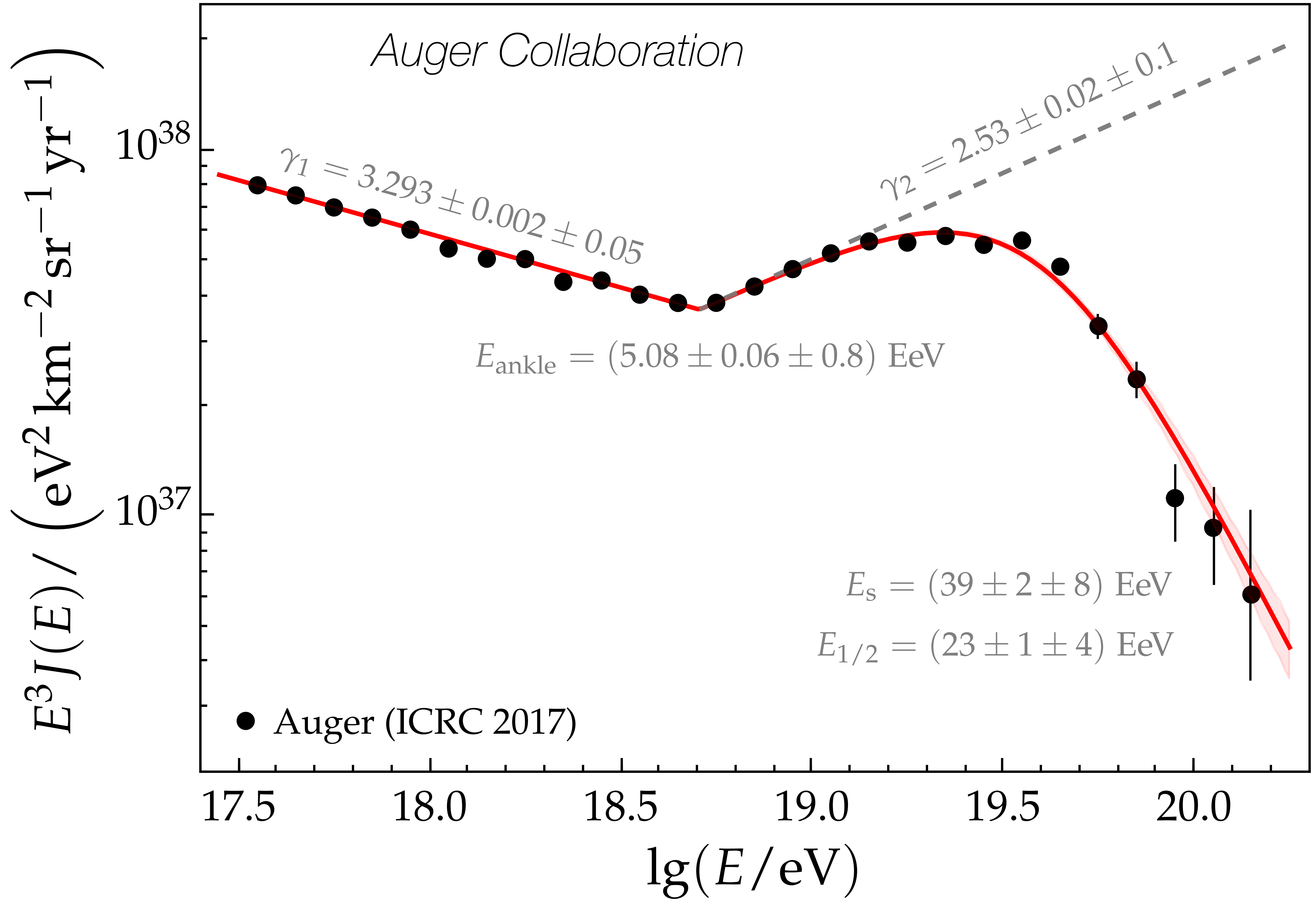
$$E_{\rm p} \gtrsim 10^{20}\,{\rm eV}\left(\frac{\varepsilon_{\gamma,\rm cmb}}{6\cdot 10^{-4}\,{\rm eV}}\right)^{-1}, n_{\rm cmb} \sim 411\,{\rm cm}^{-3}$$

$$\left[\kappa \approx m_\pi/m_p \approx 0.2, \sigma_{p\gamma} \approx 5\cdot 10^{-28}\,{\rm cm}^2\right]$$

$$\lambda_{p\gamma,\rm CMB} = 1/n\sigma \sim 6\,{\rm Mpc},\ \chi_{\rm loss} = \lambda/\kappa \sim 50\,{\rm Mpc}$$



UHECR energy budget



J(E) is the measured number of particles per unit energy, per unit area, per unit time, per unit solid angle

$$J(E) = \frac{\mathrm{d}N}{\mathrm{d}E\mathrm{d}A\mathrm{d}t\mathrm{d}\Omega}$$

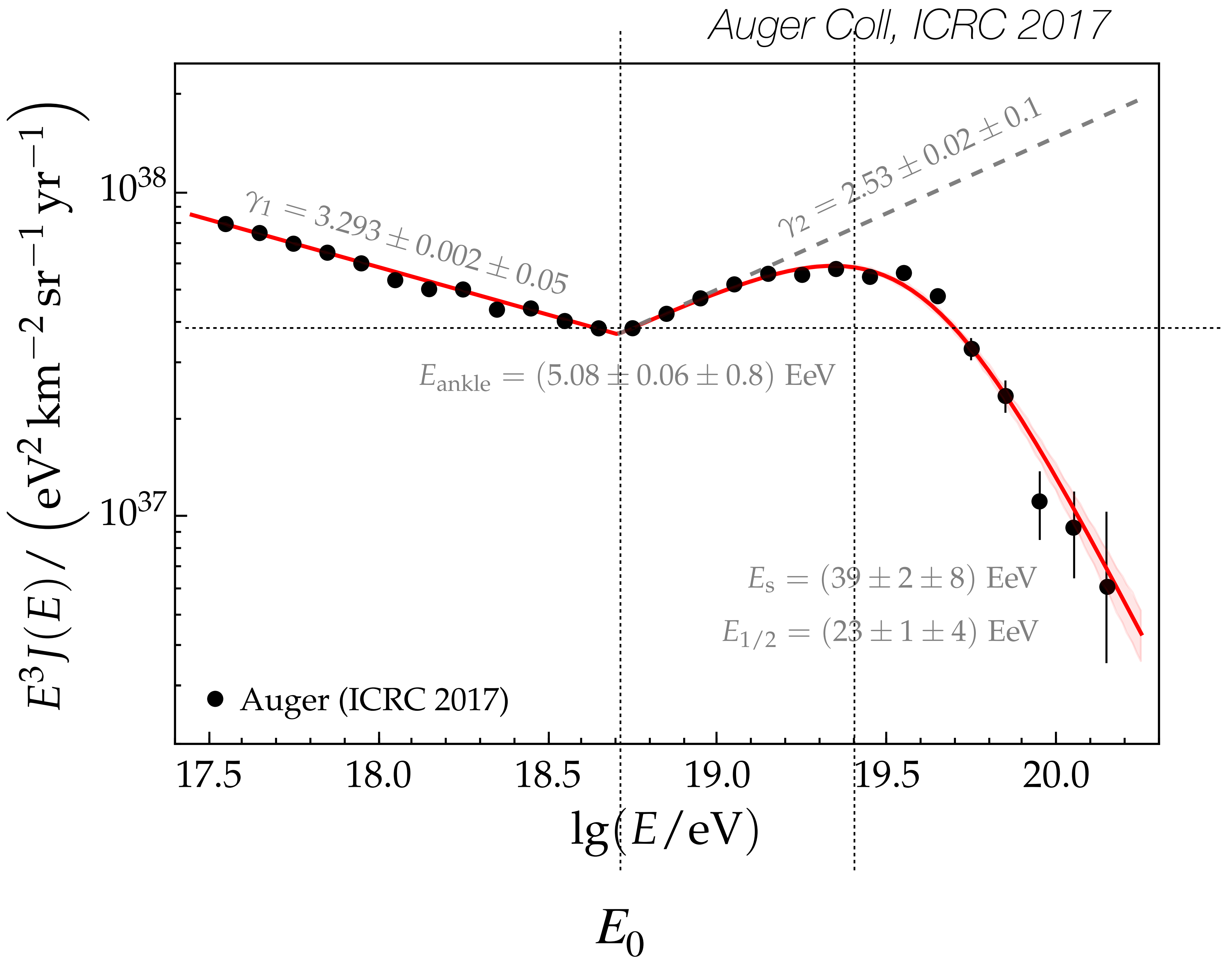
The number density of particles is

$$n(E) = \frac{\mathrm{d}N}{\mathrm{d}E\mathrm{d}^3x} = \frac{\mathrm{d}N}{\mathrm{d}E\ \mathrm{d}l\ \mathrm{d}A} = \frac{\mathrm{d}N}{\mathrm{d}E\ c\mathrm{d}t\ \mathrm{d}A} = \frac{4\pi}{c} J(E)$$

and the energy density is

$$U_E = \int E\ n(E)\ \mathrm{d}E = \frac{4\pi}{c} \int E\ J(E)\ \mathrm{d}E$$

UHECR energy budget



At 5 EeV we measure,

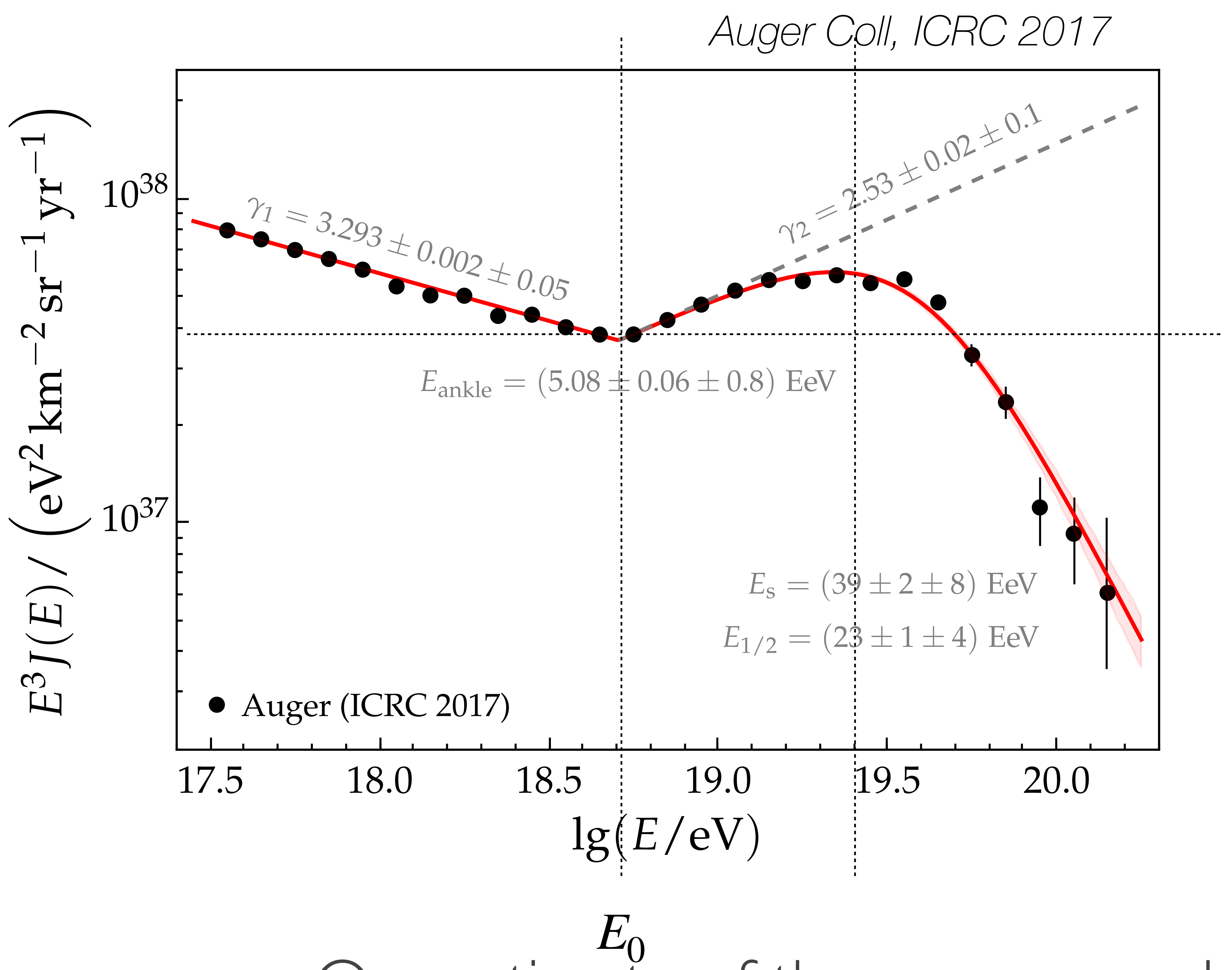
$$E_0^3 \cdot J_0 = 10^{37.3} \text{ eV}^2 \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$$

which corresponds to (for an E^{-2} spectrum),

$$U_{\rm UHECR} \approx \frac{4\pi}{c} E_0^2 J_0 \ln(E_{\rm max}/E_{\rm min}) \sim \frac{4\pi}{c} E_0^2 J_0 \ln(10)$$

$$\approx 10^{-8} \text{ eV cm}^{-3} \quad \approx 6 \times 10^{53} \text{ erg Mpc}^{-3}$$

UHECR energy budget



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$$\approx 10^{-8}\ \mathrm{eV\ cm}^{-3} \quad \approx 6 \times 10^{53}\ \mathrm{erg\ Mpc}^{-3}$$

1 erg ~ 1 TeV!

Our estimate of the energy production rate based on the ***observed*** spectrum:

$$\dot{\varepsilon}_{\mathrm{UHECR}} \approx \frac{U_{\mathrm{UHECR}}}{t_{\mathrm{loss,UHECR}}} = \frac{U_{\mathrm{UHECR}}}{\chi_{\mathrm{loss,UHECR}}/c} = \frac{U_{\mathrm{UHECR}}}{1\ \mathrm{Gpc}/c} \approx 2 \times 10^{44}\ \mathrm{erg\ Mpc}^{-3}\ \mathrm{year}^{-1}$$

Full derivation based on simulated ***intrinsic*** source spectra:

$$\dot{\varepsilon}_{\mathrm{Auger\ combined\ fit}} \approx 5 \times 10^{44}\ \mathrm{erg\ Mpc}^{-3}\ \mathrm{year}^{-1}$$

Waxman-Bahcall bound

- Neutrinos from photo-meson interactions of UHECR protons in sources (AGN/GRBs)
- Optically-thin sources (protons can escape) - otherwise neutrino only sources not UHECR sources
- Fermi-type acceleration

$$E_{\rm CR}^2 {\rm d}N_{\rm CR}/{\rm d}E_{\rm CR} \sim E_{\rm CR}^{-2} \text{ (at the source)}$$

$$\dot{\varepsilon}_{\rm UHECR} \approx 10^{44} \text{ erg Mpc}^{-3} \text{ year}^{-1}$$

- Proton loses fraction, ϵ, of its energy to muon neutrinos

$$E_\nu^2 \Phi_\nu (\text{single flavour})|_{E_\nu = 0.05 E_{cr}} = \frac{c}{4\pi} \epsilon \frac{1}{2} \frac{1}{2} \xi_z t_{\rm H} \dot{\varepsilon}_{\rm UHECR}$$

we called it J before…

$$= 1.5 \times 10^{-8} \epsilon \xi_z \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Hubble time

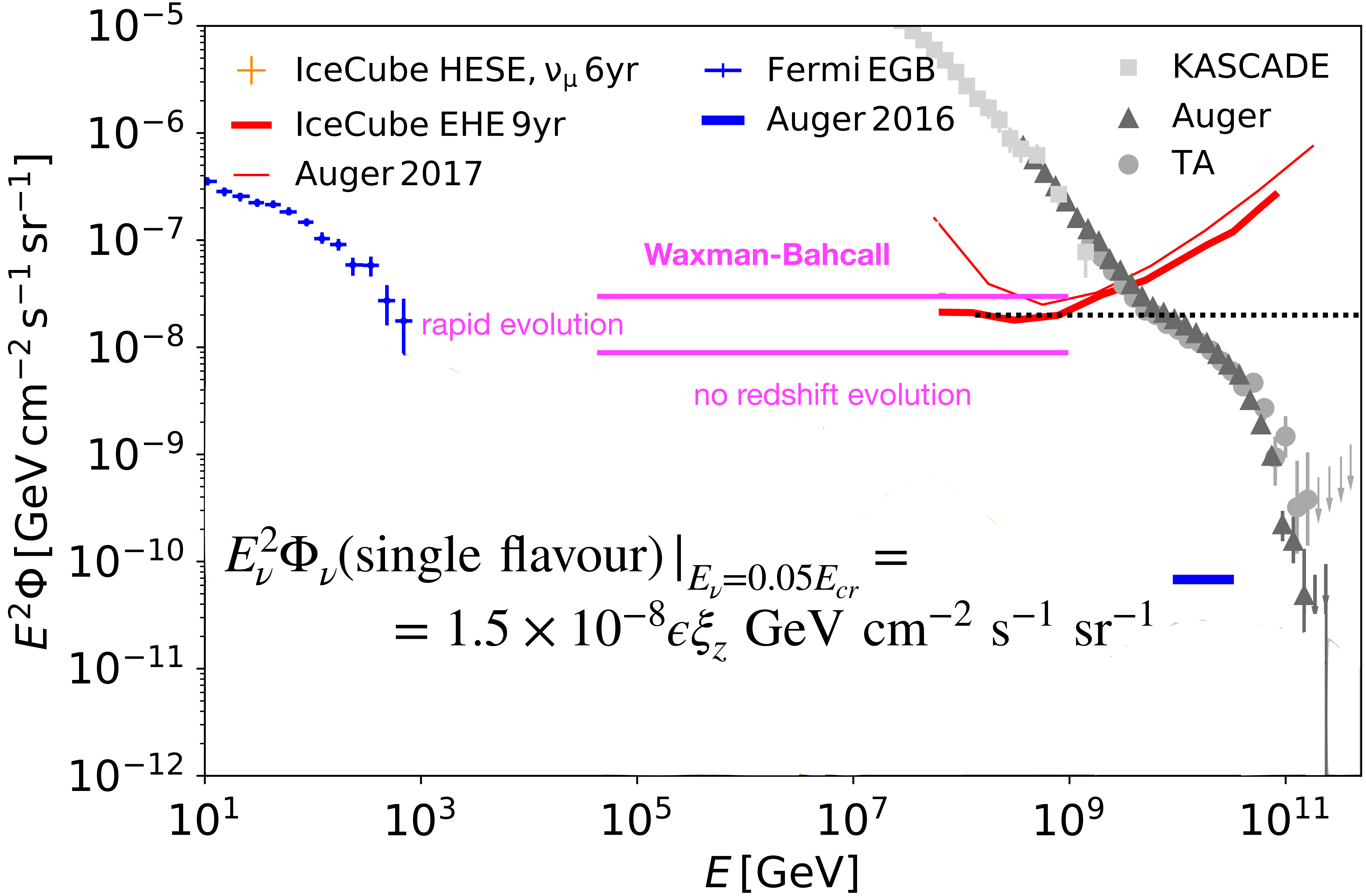
$$p + \gamma_{\rm CMB} \to p + \pi^0 - \text{BR } 50\,\%$$
$$p + \gamma_{\rm CMB} \to n + \pi^+ - \text{BR } 50\,\%$$

$$\xi_z \sim 0.6 \text{ (no evolution)} - 10 \text{ (rapid evolution)}$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e \quad \underbrace{\bar{\nu}_\mu \, \nu_\mu}$$

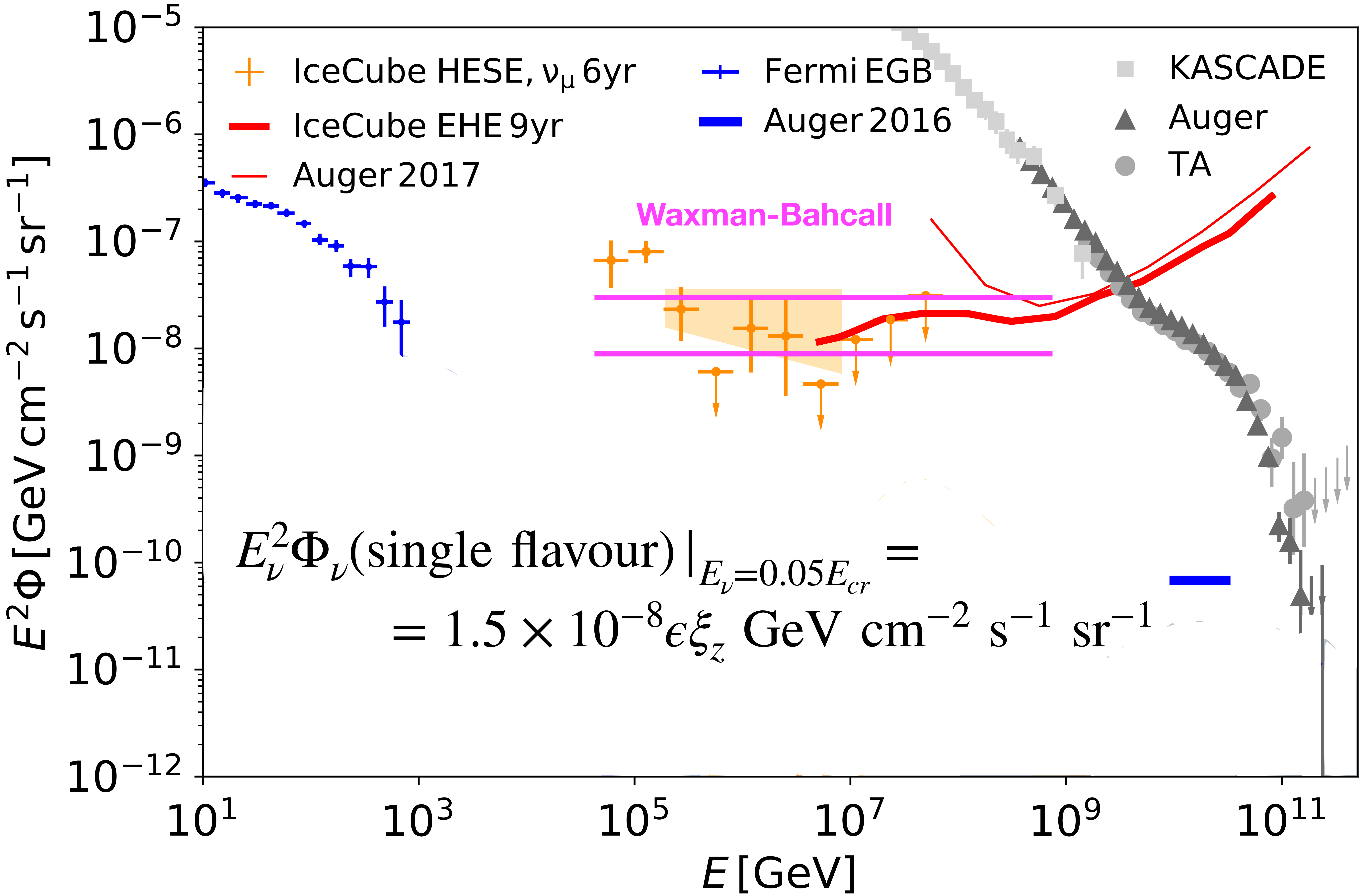
50% of E_{π^+}

Waxman-Bahcall bound



$$E_\nu^2\Phi_\nu(\text{single flavour})\,|_{E_\nu=0.05E_{cr}} = \\ = 1.5\times10^{-8}\epsilon\xi_z\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Waxman-Bahcall bound



$$E_\nu^2 \Phi_\nu (\text{single flavour})|_{E_\nu = 0.05 E_{cr}} =$$

$$= 1.5 \times 10^{-8} \epsilon \xi_z \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Neutrino source number density

The product of luminosity per source, ***L***, and source density, ***n***, corresponds to the total emission per volume and is constrained by the observed diffuse flux of neutrinos

$$\text{luminosity density} \sim L \cdot n$$

The number density gives the volume within which one source must lie is

$$V = \frac{4\pi r^3}{3} \sim \frac{1}{n}$$

Source class	Number density [Mpc^{-3}]
powerful blazars (FSRQ)	10^{-9}
weaker blazars (BL Lac)	10^{-7}
Starburst galaxies	10^{-5}
Galaxy clusters	10^{-5}
Jetted AGN	10^{-4}
Normal galaxies	10^{-2}

Neutrino source number density

- The nearest neutrino source must therefore be at distance

$$r \sim \left(\frac{4\pi n}{3}\right)^{-1/3} \quad - (1) \qquad \text{e.g. } n = 10^{-4}\text{Mpc}^{-3}, \quad r = 10 \text{ Mpc}$$

- The flux expected from an individual source with neutrino luminosity **L** is $f \sim \dfrac{L}{4\pi r^2}$

- Sources below the IceCube point-source flux sensitivity F_{lim} must therefore satisfy

$$r > \left(\frac{L}{4\pi F_{lim}}\right)^{1/2}$$

Source class	Number density [Mpc^{-3}]
powerful blazars (FSRQ)	10^{-9}
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Normal galaxies	10^{-2}

Neutrino source number density

- Sources below the IceCube point source sensitivity must therefore satisfy.

$$r > \left(\frac{L}{4\pi F_{lim}} \right)^{1/2}$$

- which translates to a luminosity dependent upper limit on the number density

$$n \leq \frac{3}{4\pi} \left(\frac{L}{4\pi F_{lim}} \right)^{-3/2}$$

where we used Eq. (1) $r \sim \left(\frac{4\pi n}{3} \right)^{-1/3}$

Source class	Number density [Mpc^{-3}]
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Neutrino source number density

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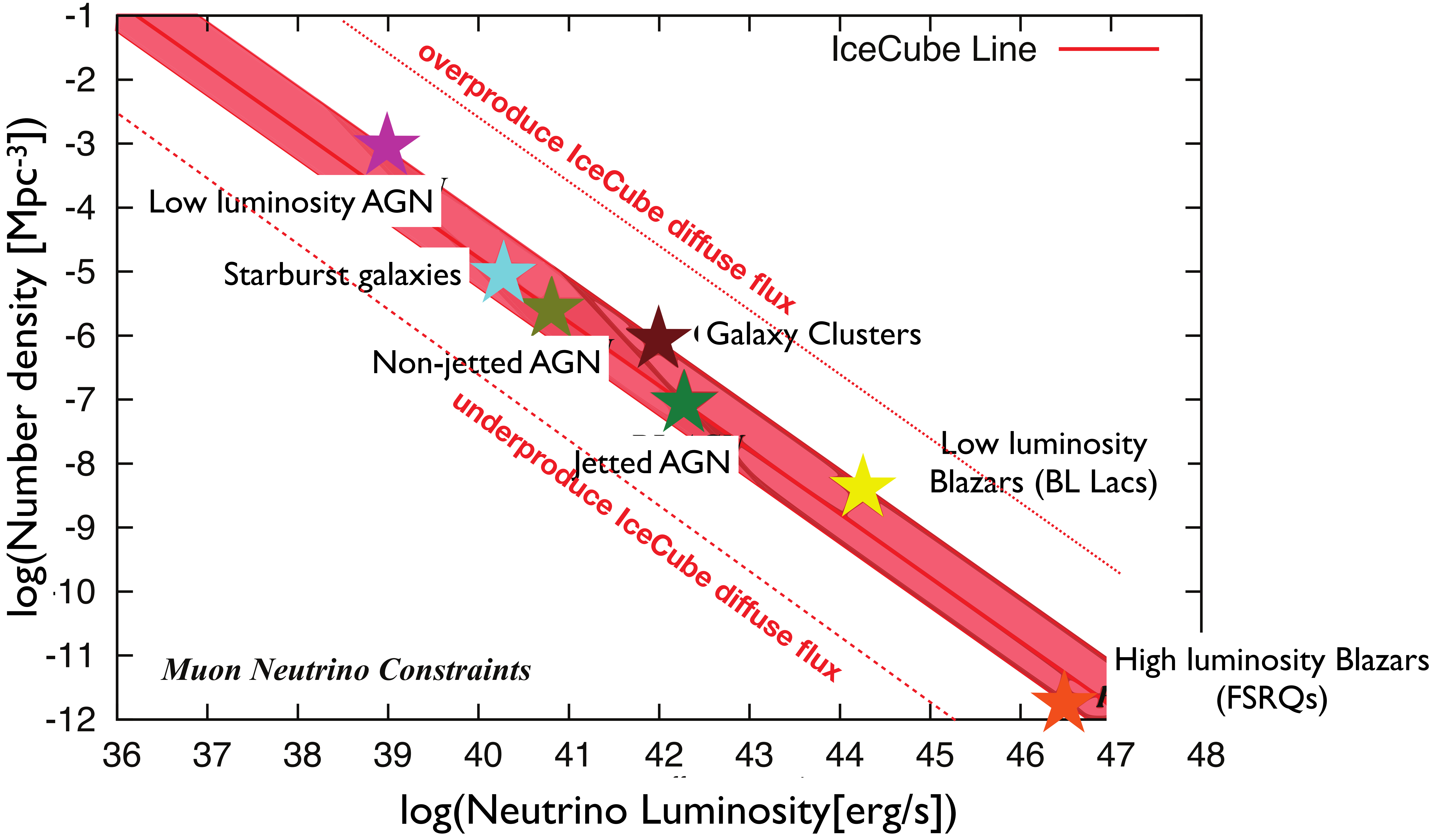
Yuan et al 2019,
Capel, Mortlock, Finley 2020

Murase & Waxman 16, PRD 94 (2016) 103006



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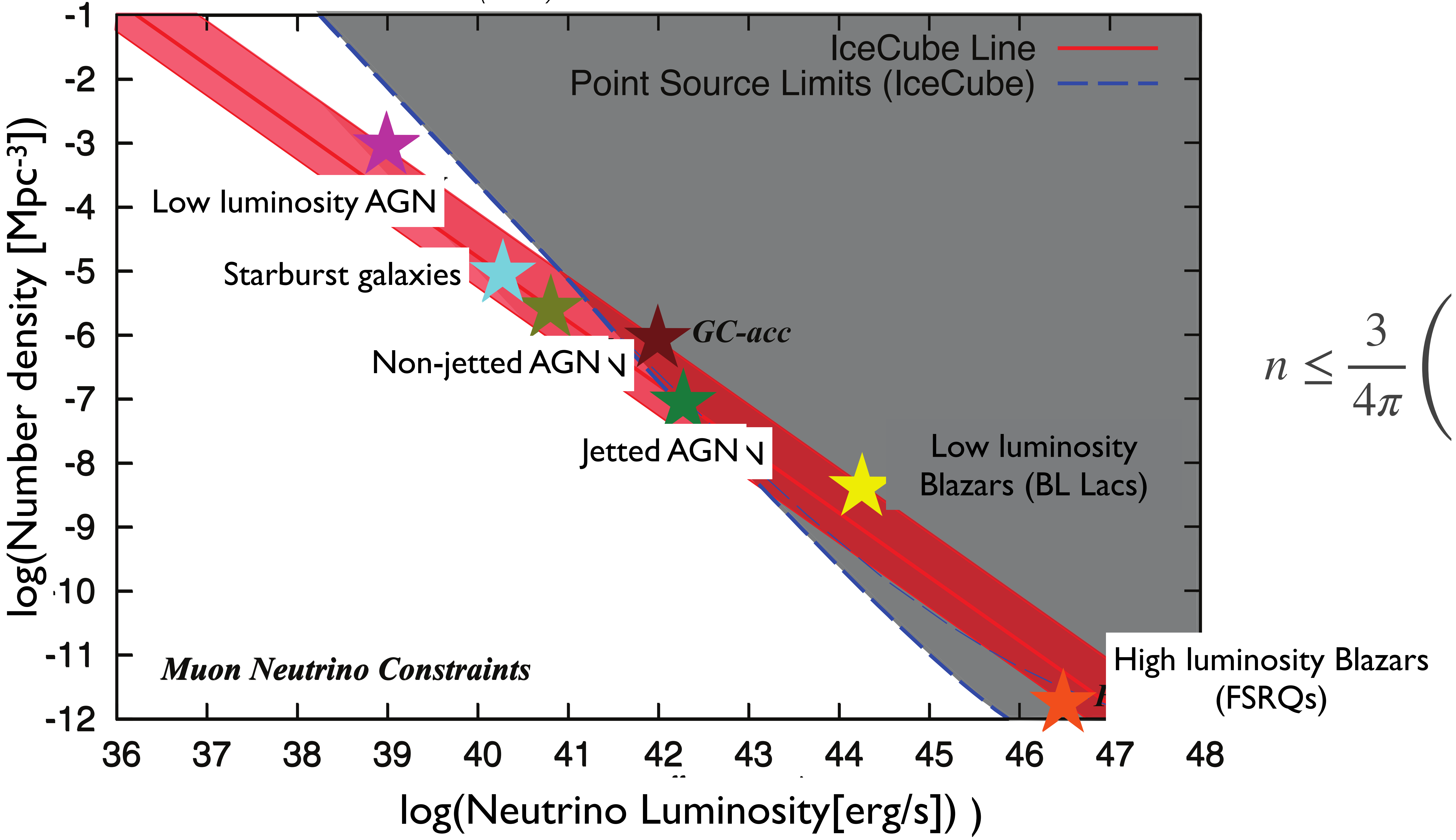

$$n \leq \frac{3}{4\pi}\left(\frac{L}{4\pi F_{lim}}\right)^{-3/2}$$

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

Neutrino source number density

see also Lipari PRD78(2008)083011
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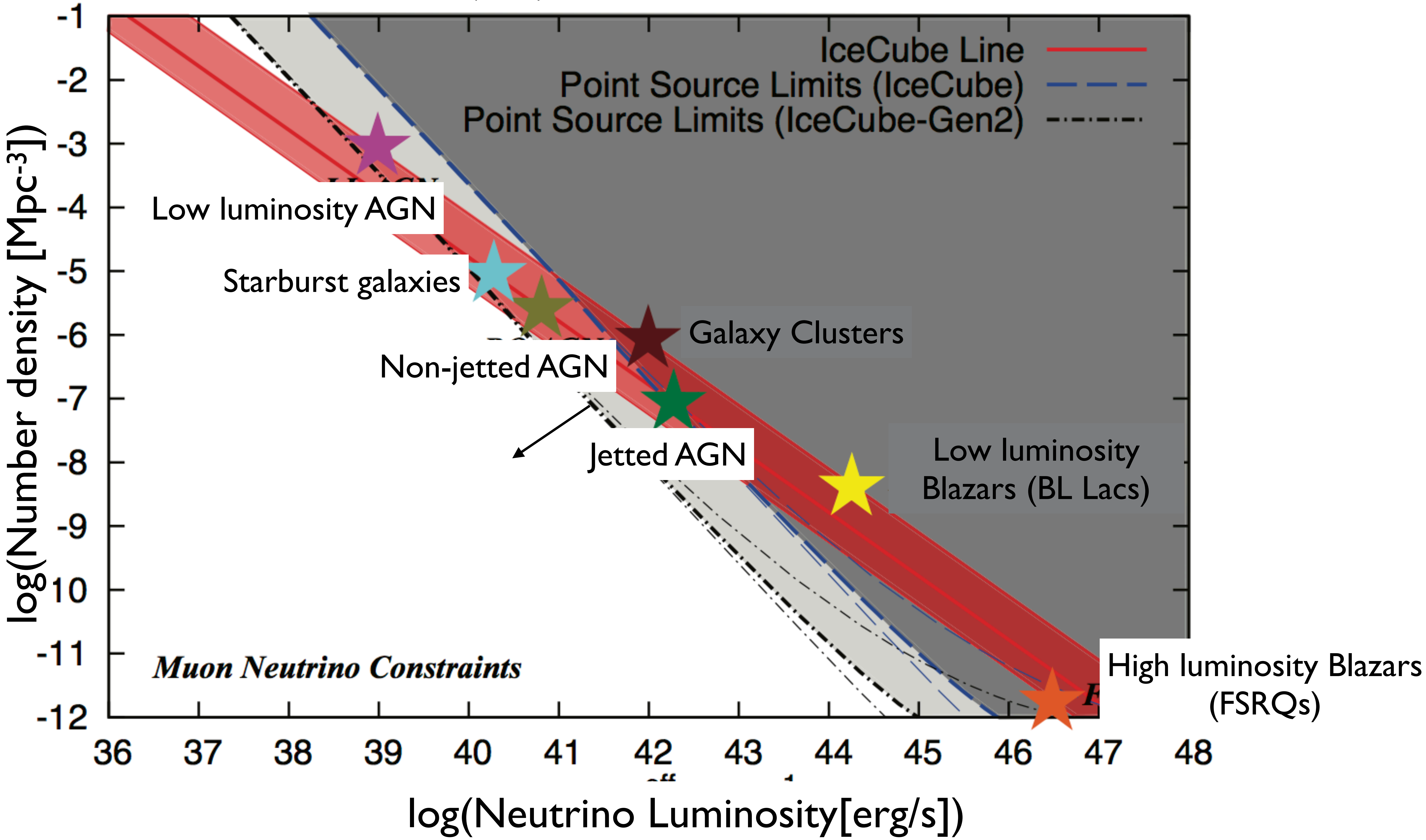


Take home messages

- Neutrino sources must have sufficient energy budget (generally ok)
- IceCube flux at the level predicted by Waxman & Bahcall (common origin of UHECRs and neutrinos or coincidence)
- Neutrino number density constraints disfavour rare and luminous source classes

Lecture plan

- Experimental facts and basic theoretical concepts
- Requirements for astrophysical accelerators of high-energy cosmic rays/ high-energy neutrinos (generic source properties)
- Overview of candidate sources (Active Galactic Nuclei/Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events) constraints and prospects

Active Galactic Nuclei

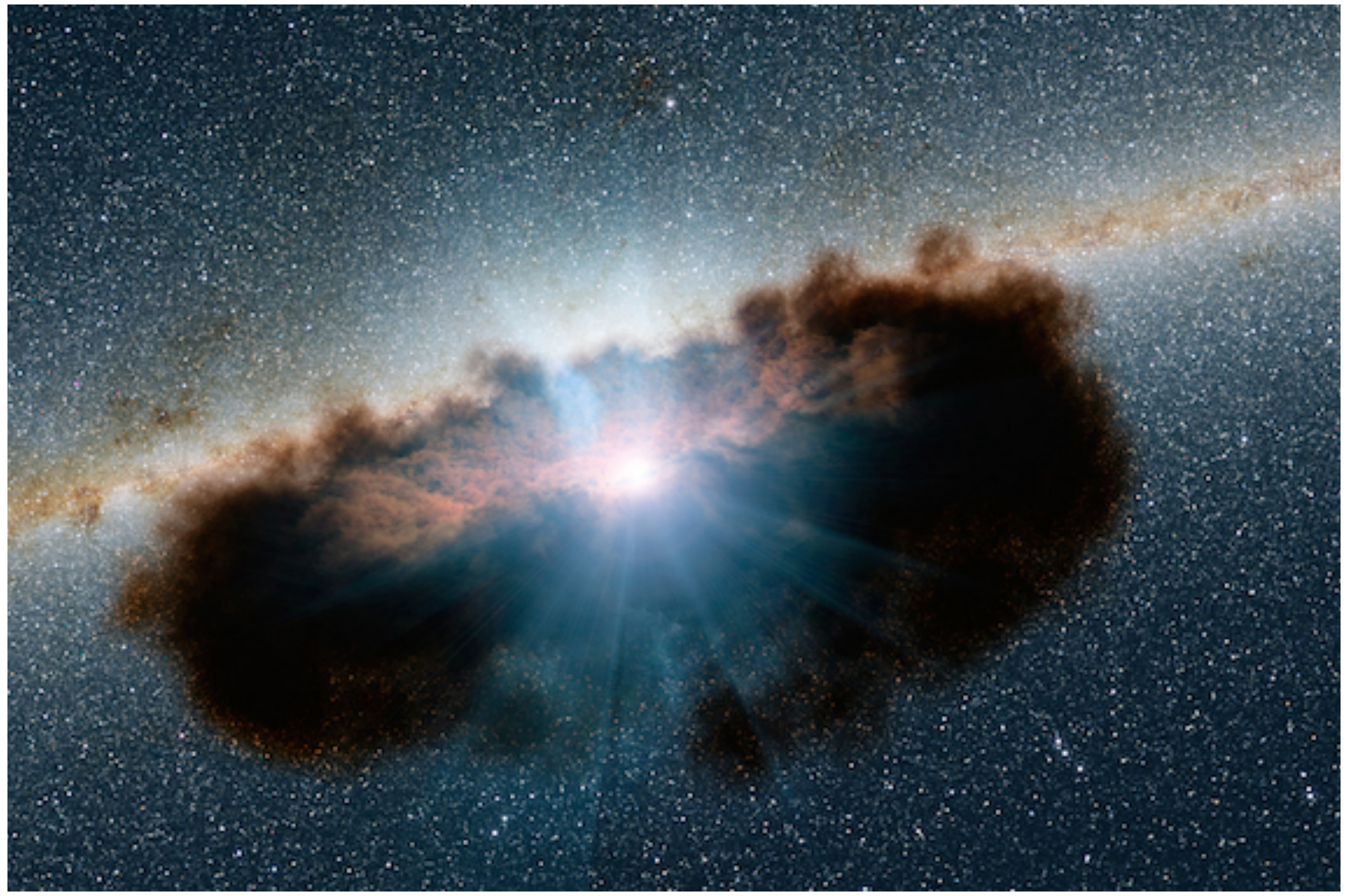
Most powerful ``steady'' sources in the Universe ($L \geq 10^{47}$ erg/s) > 1000 bright Galaxies!

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

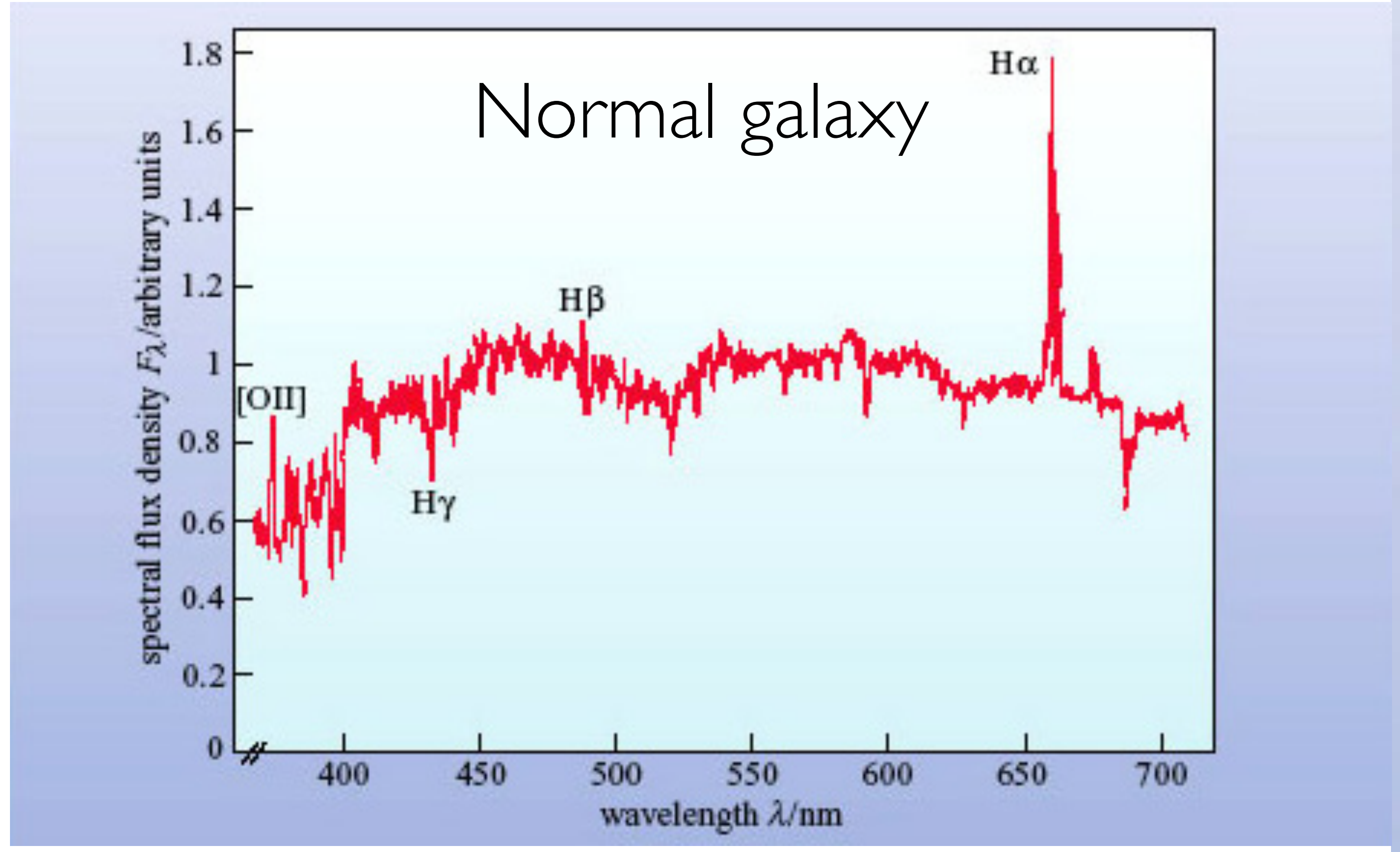
Visible to large redshifts (z > 7.5) - peak z~2 (depends on type)

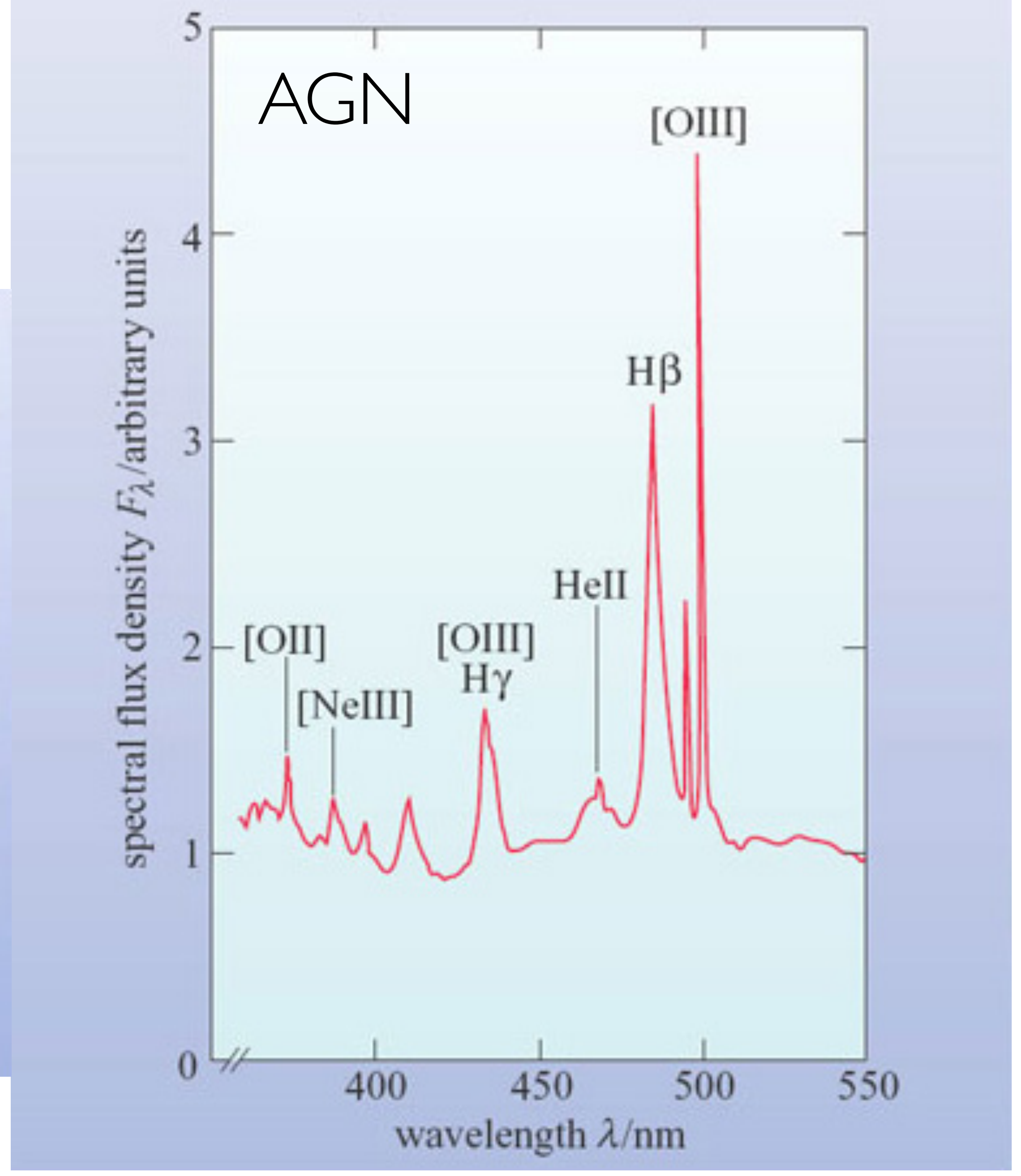
1% of galaxies active

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

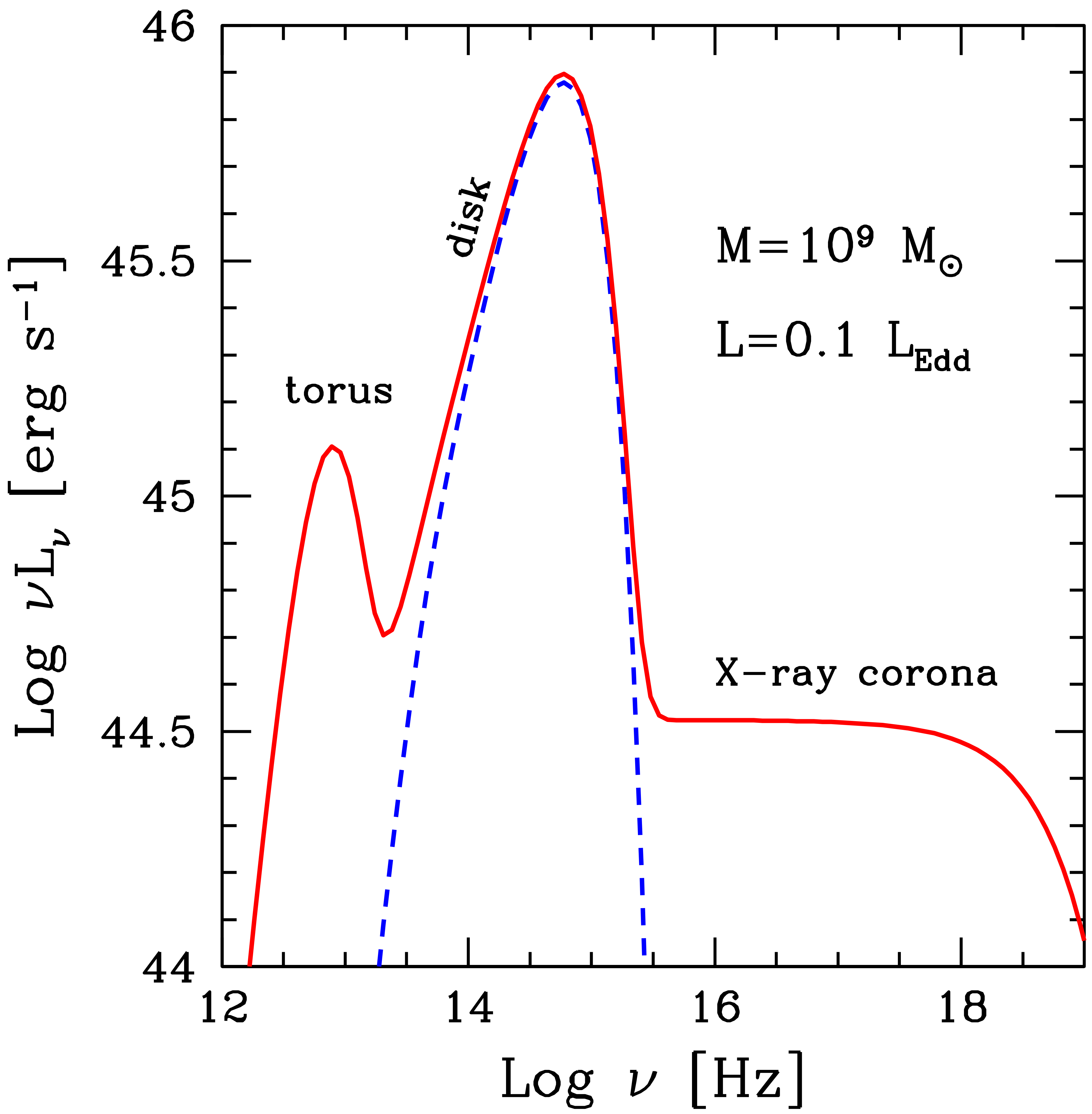
$$L_{\rm disk} = 0.1\dot{M}c^2 = 10^{46}\ {\rm erg/s}$$

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,

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



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

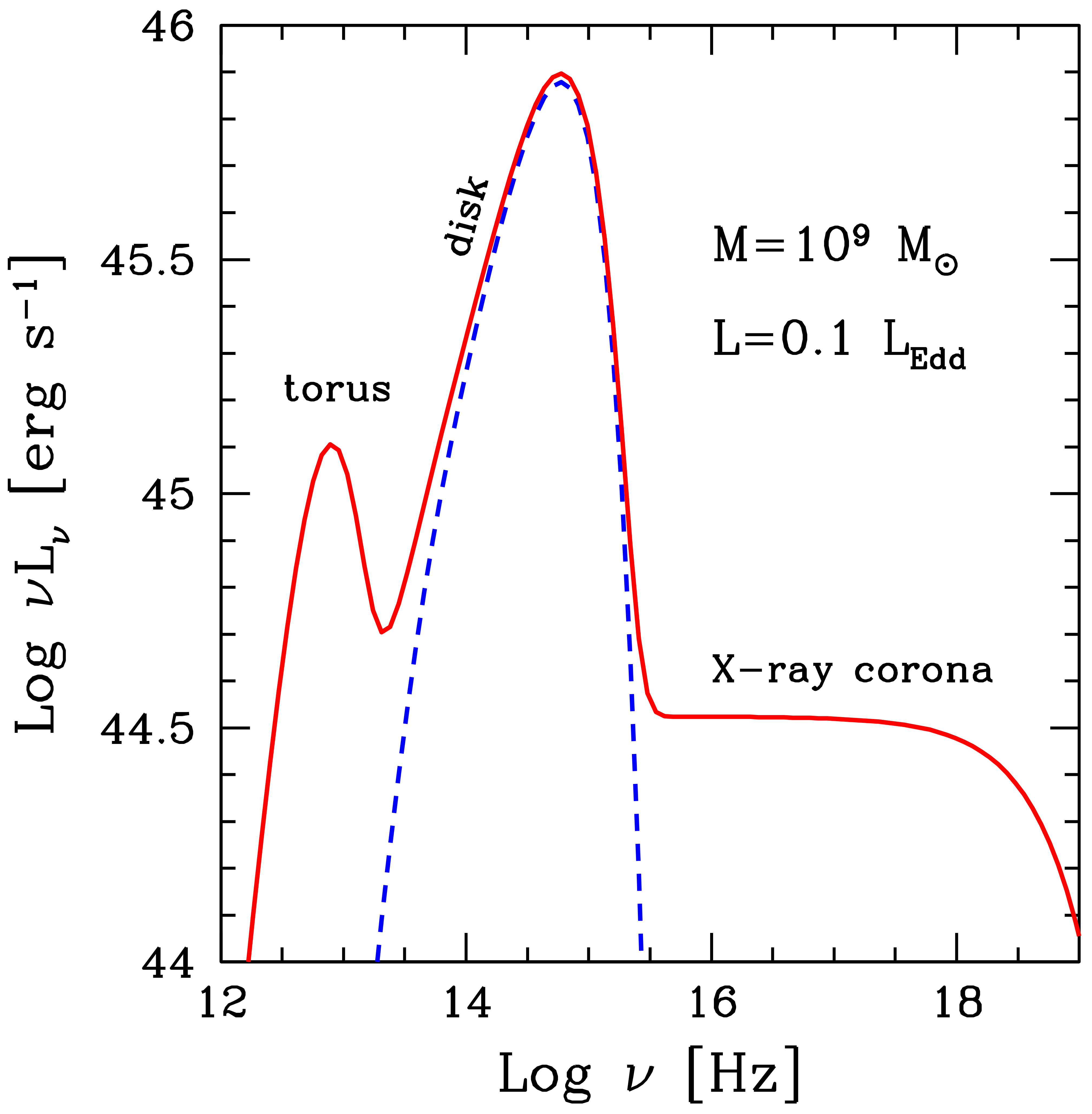
The engine

But to provide 10^{46} erg/s, we need a supermassive black hole 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,

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

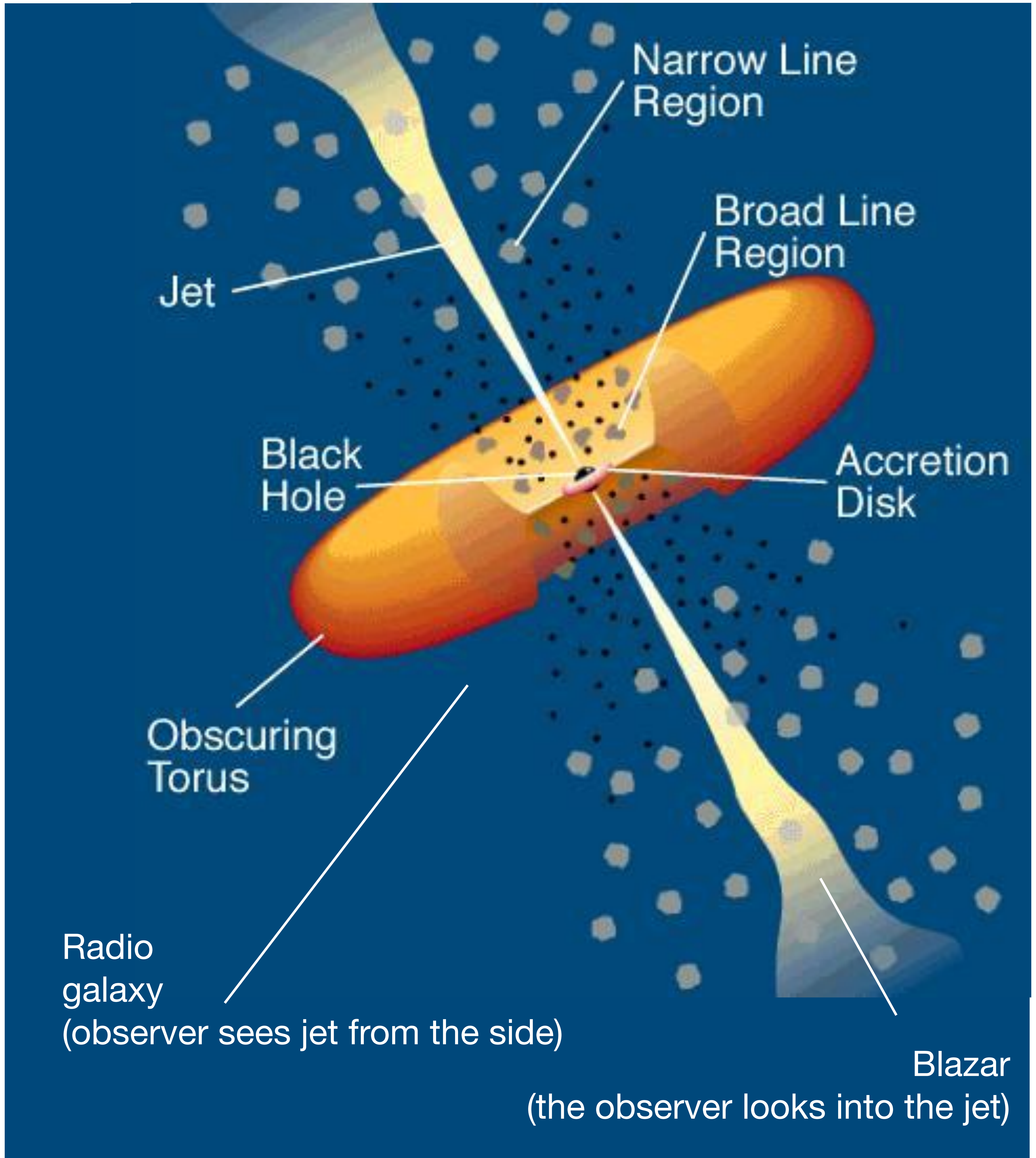


AGN Unification

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

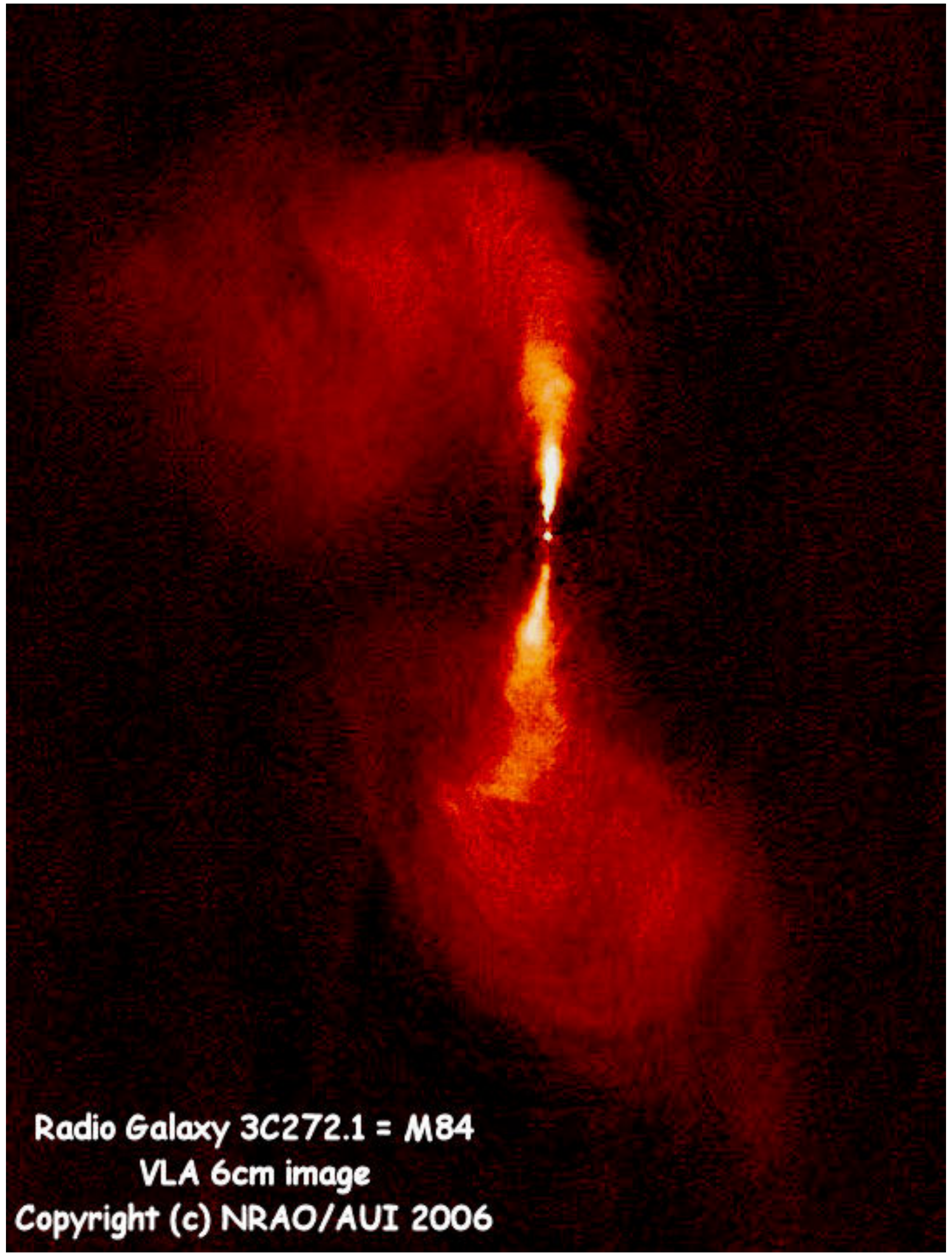
- Orientation
- Presence of jet or not (10% have it)
- Radiative efficiency

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

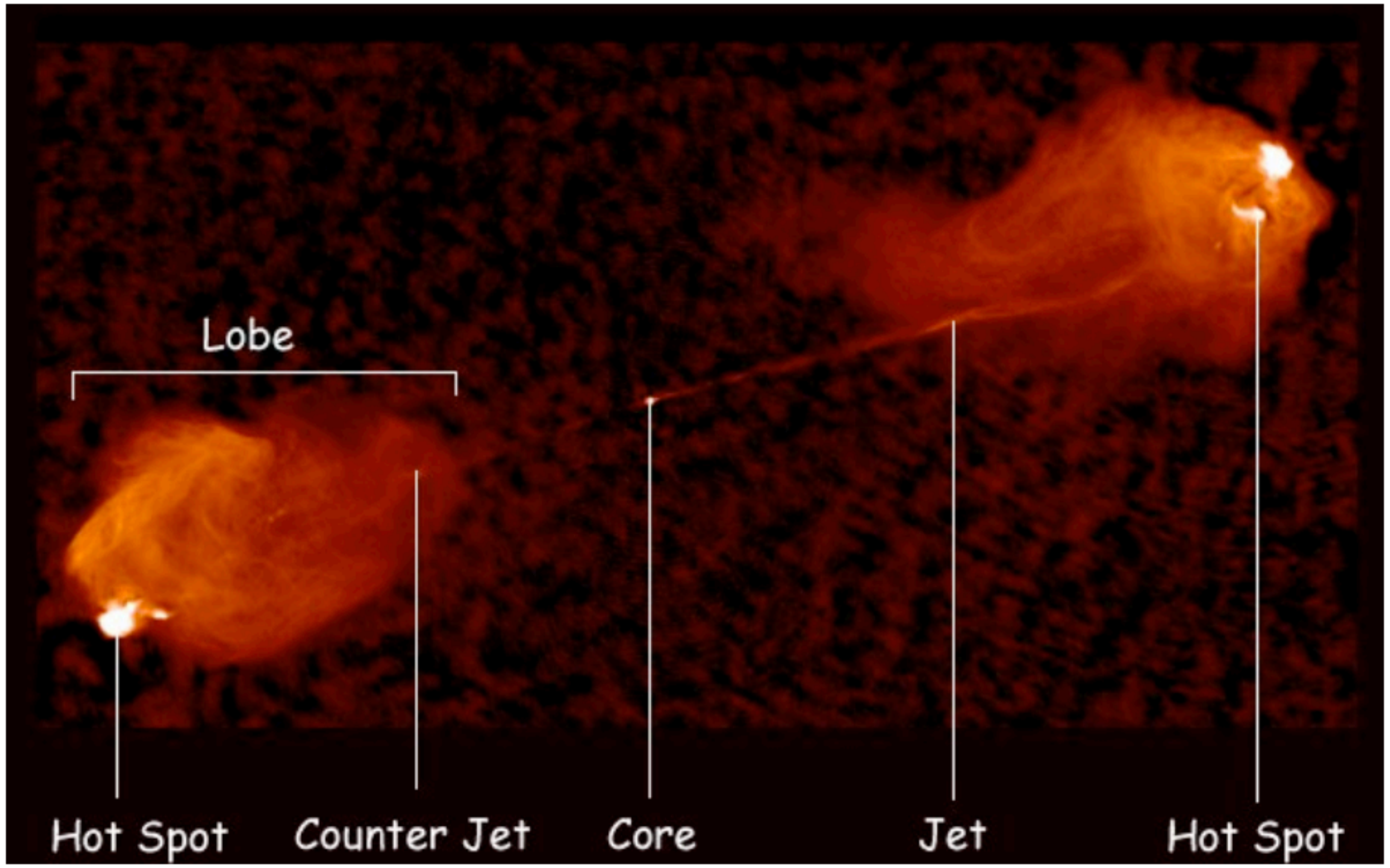


10% of AGN host jets

FRI



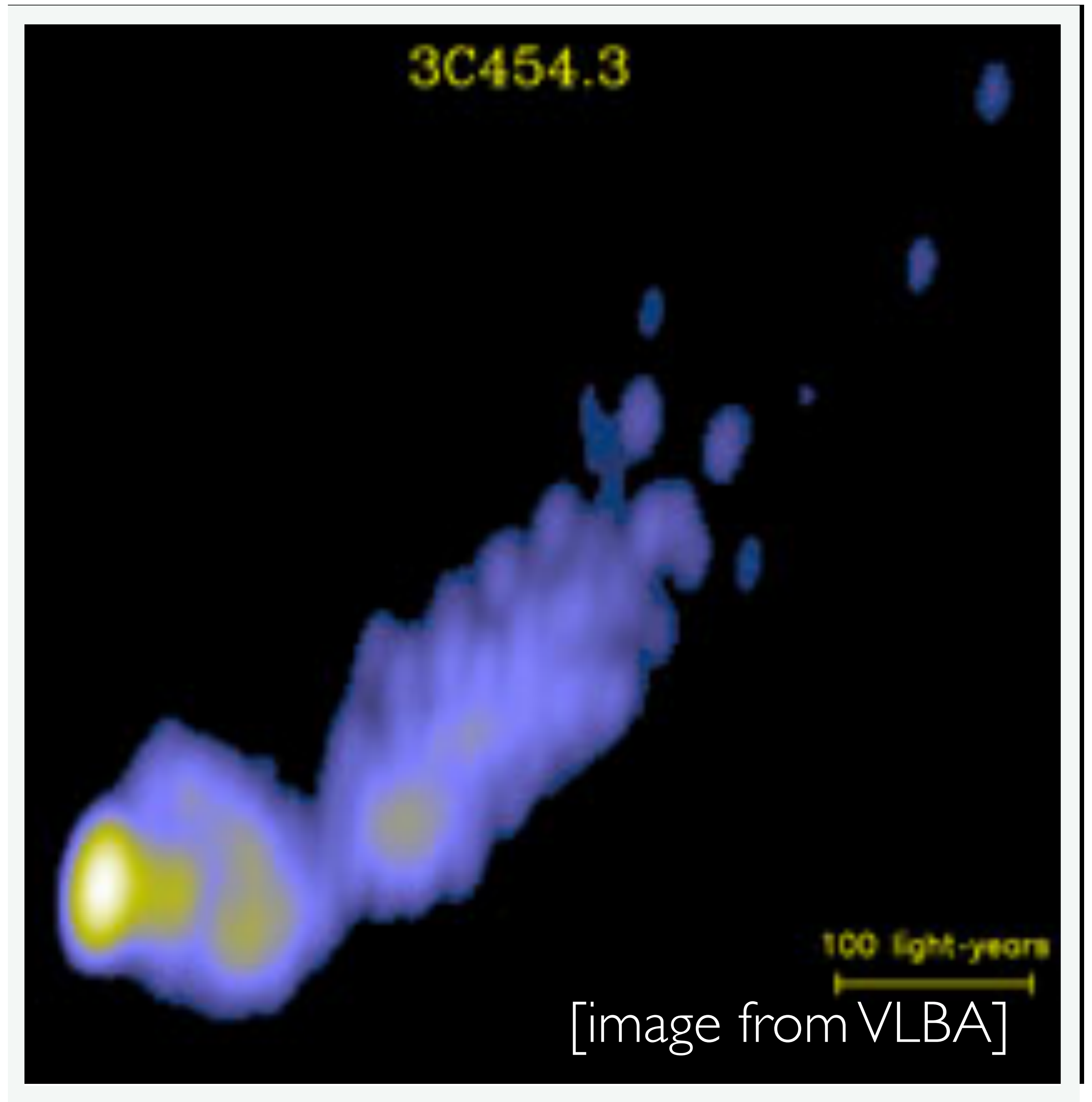
FRII



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

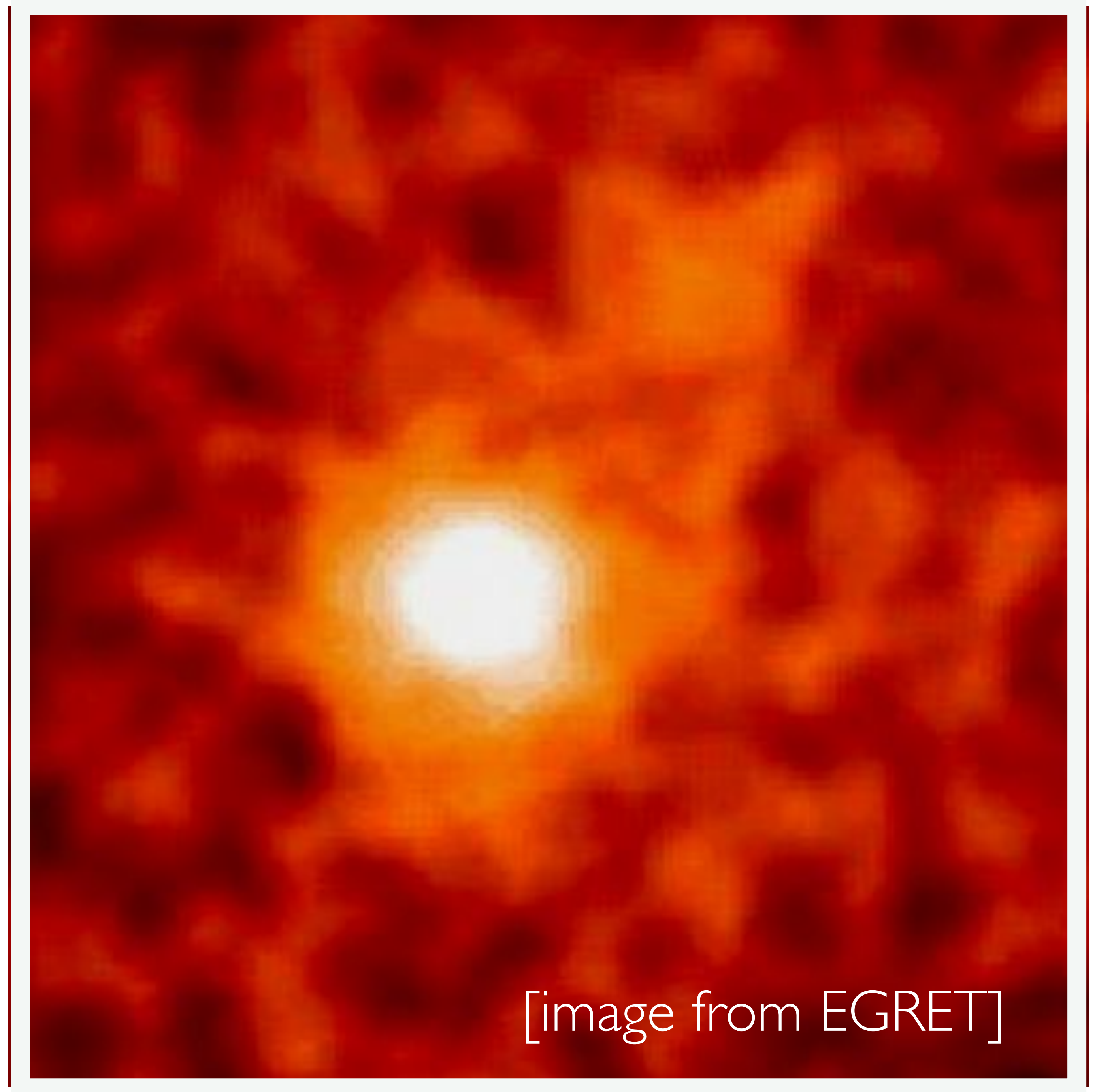
Blazars: Star-like appearance

Radio



Optical

γ-rays



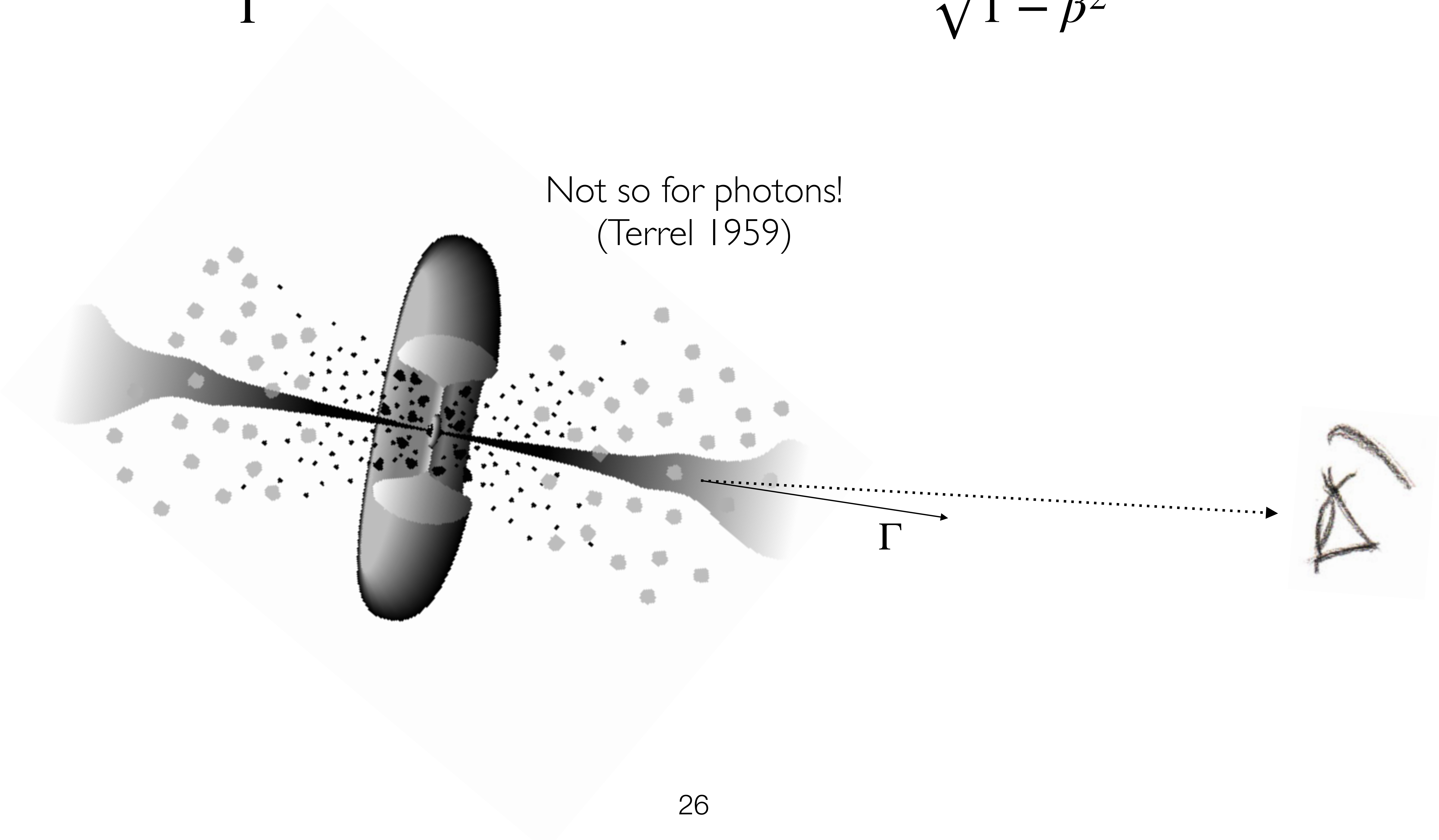
No spectacular jets…but wealth of information from timing/variability and spectra!

Relativistic beaming

Usual relativity (rulers and clocks)

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

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.$\left.\right)$

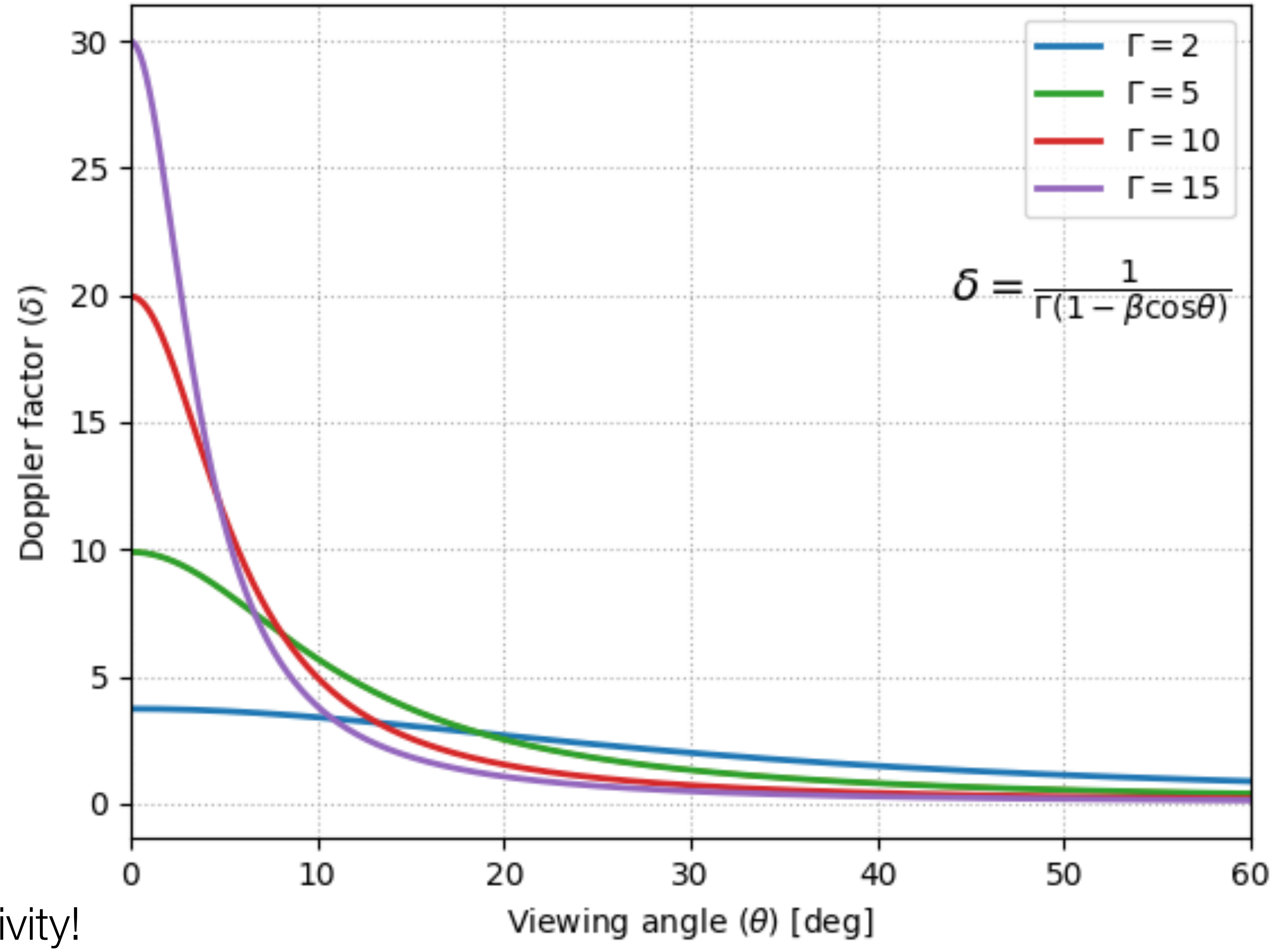
$\Delta t = \Delta t'/\delta$ (shortening of timescales)

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

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

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

(dashes denote rest-frame quantities)



Special cases:

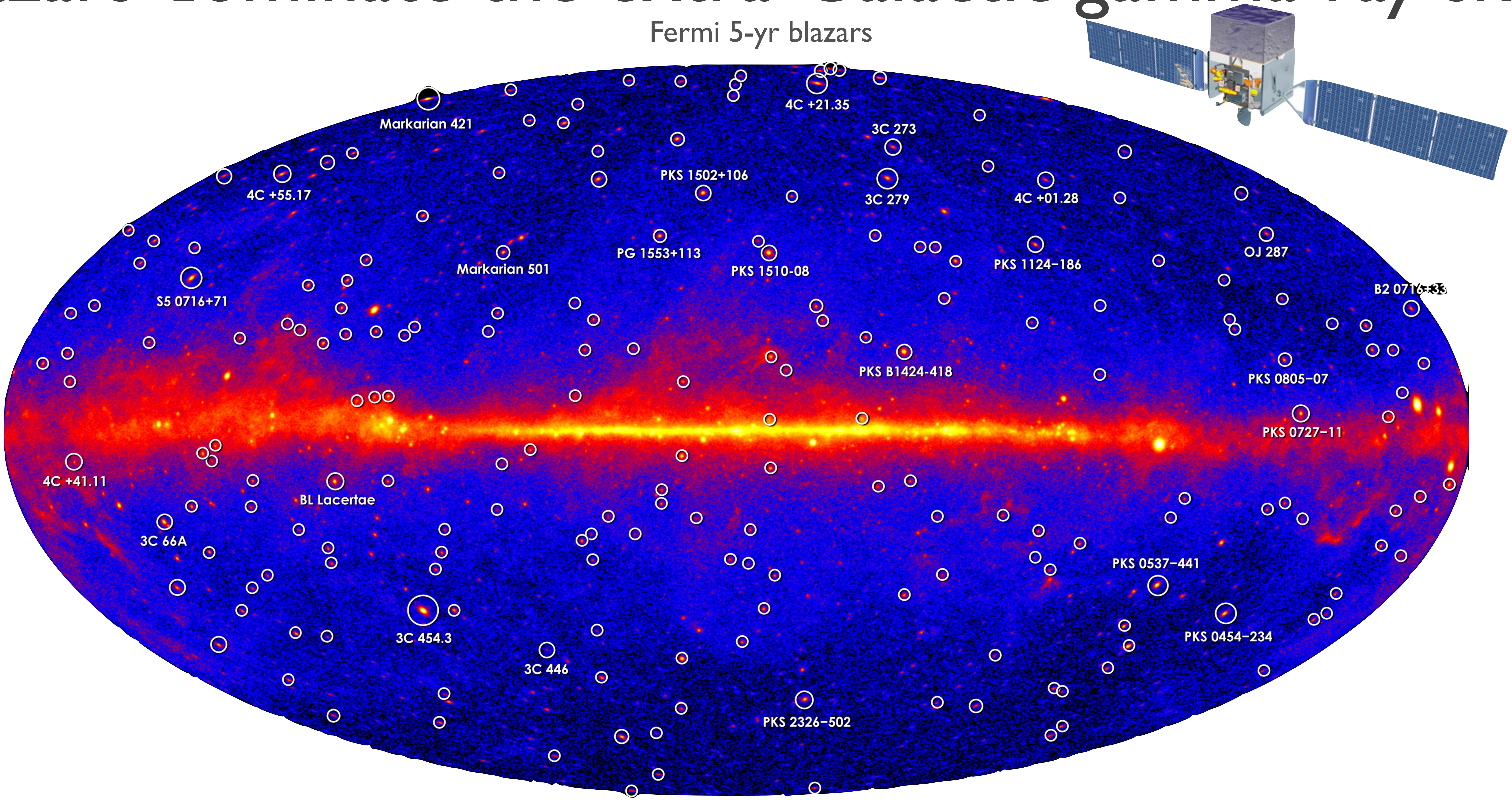
$\delta_{\rm max} = \delta(0^\circ) = \dfrac{1}{\Gamma(1-\beta)} = \Gamma(1+\beta) \sim 2\Gamma$

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

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

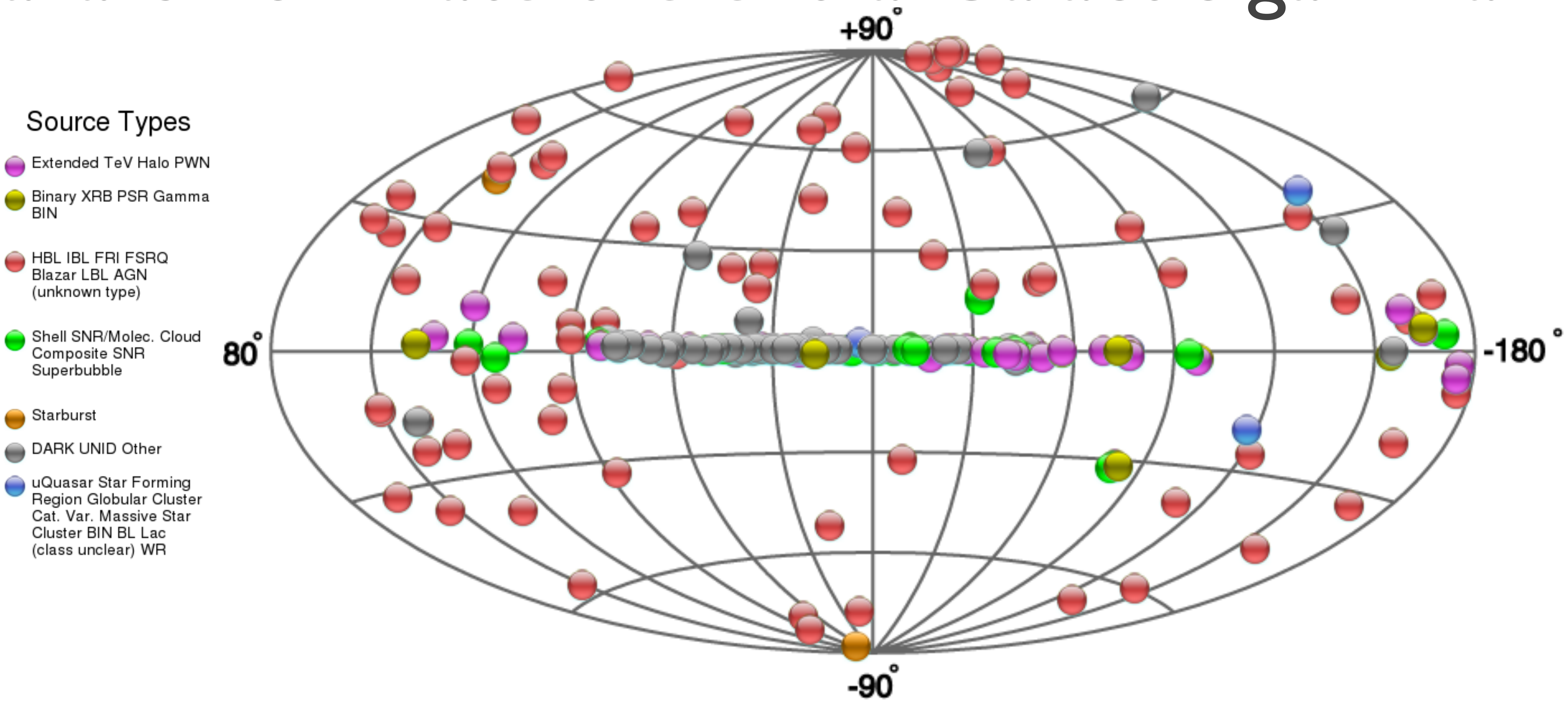
Blazars dominate the extra-Galactic gamma-ray sky

Fermi 5-yr blazars

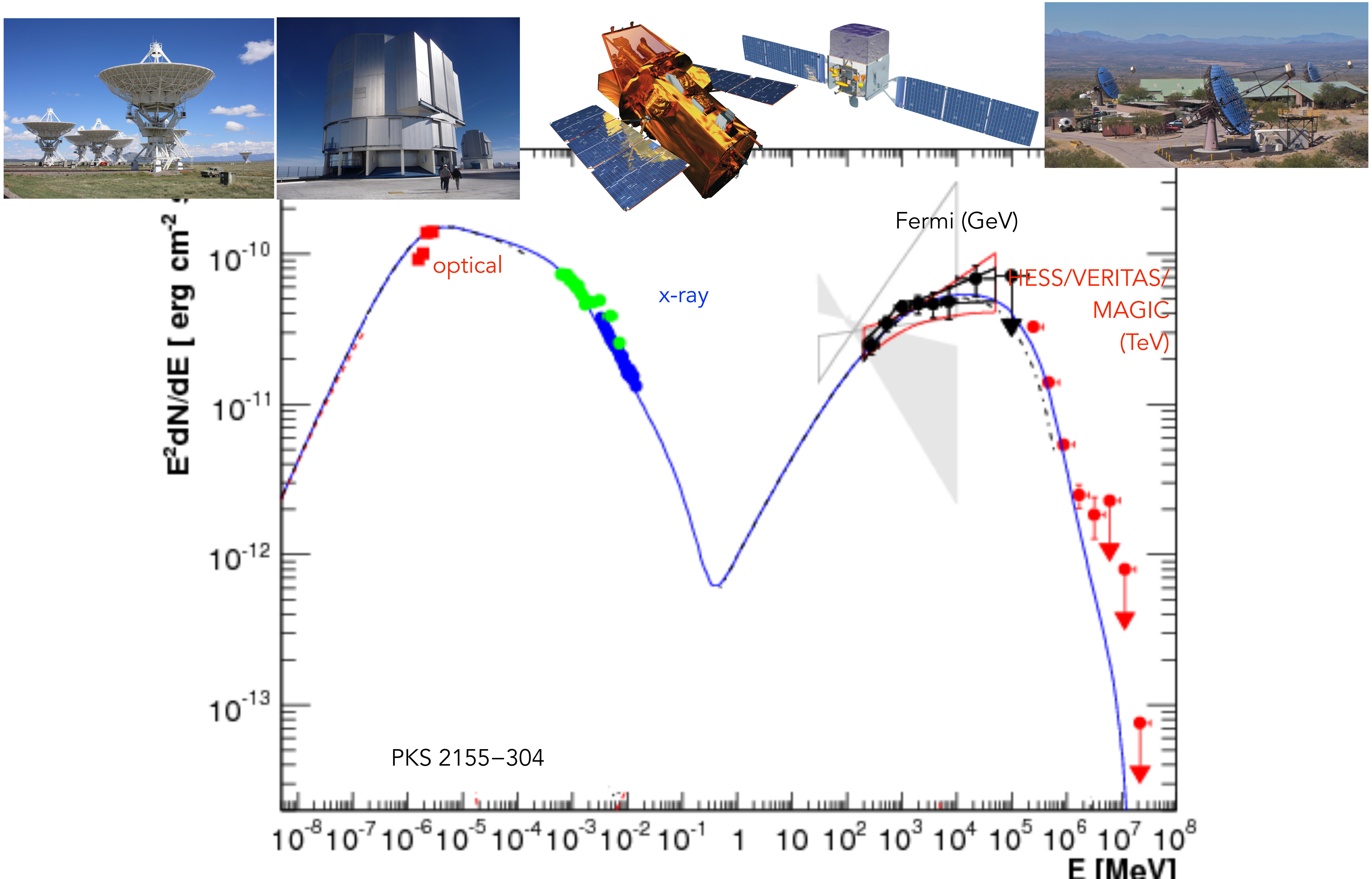


>90% of extragalactic Fermi sources (see also TeVCaT)

Blazars dominate the extra-Galactic gamma-ray sky



Blazar spectral energy distribution

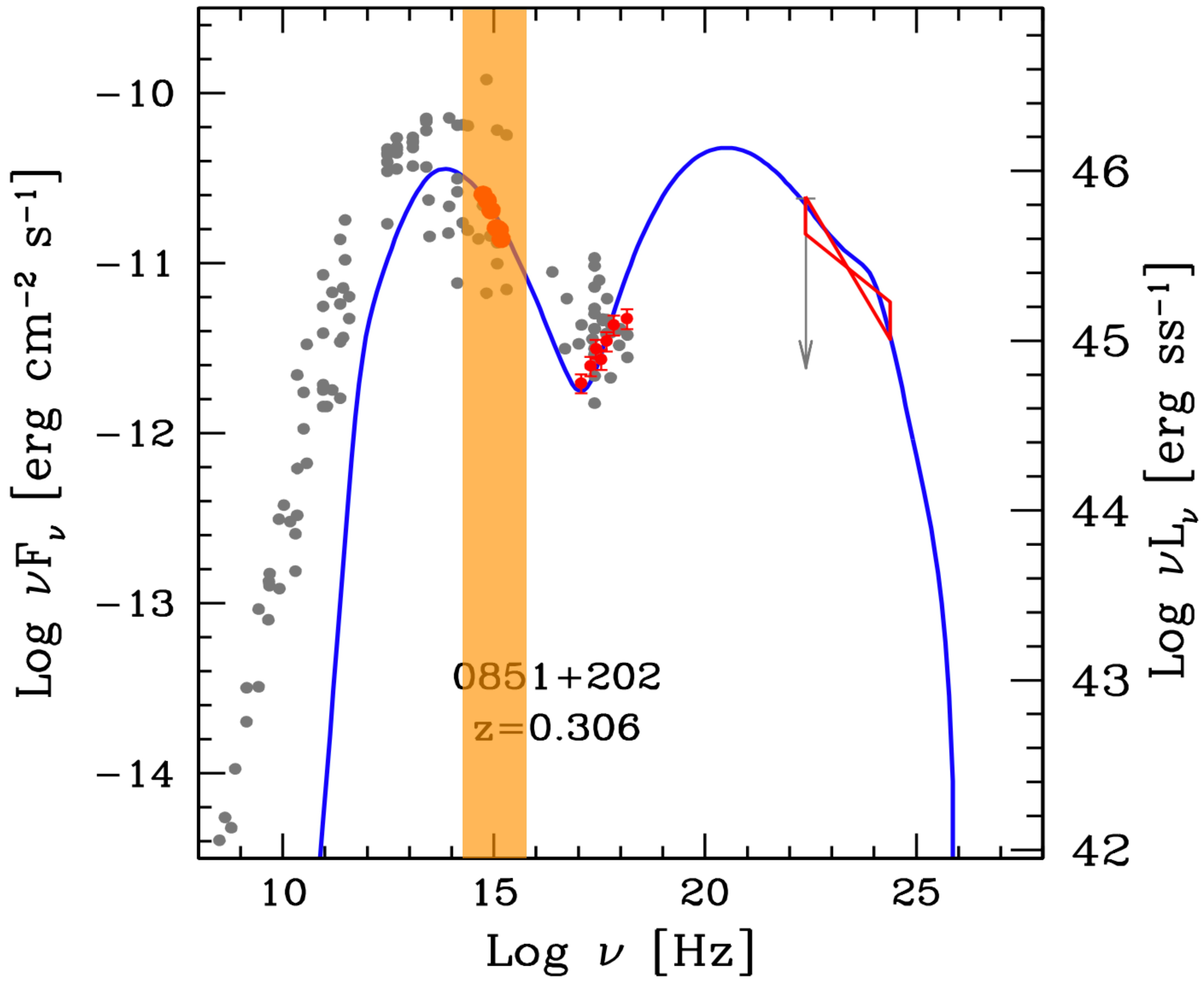


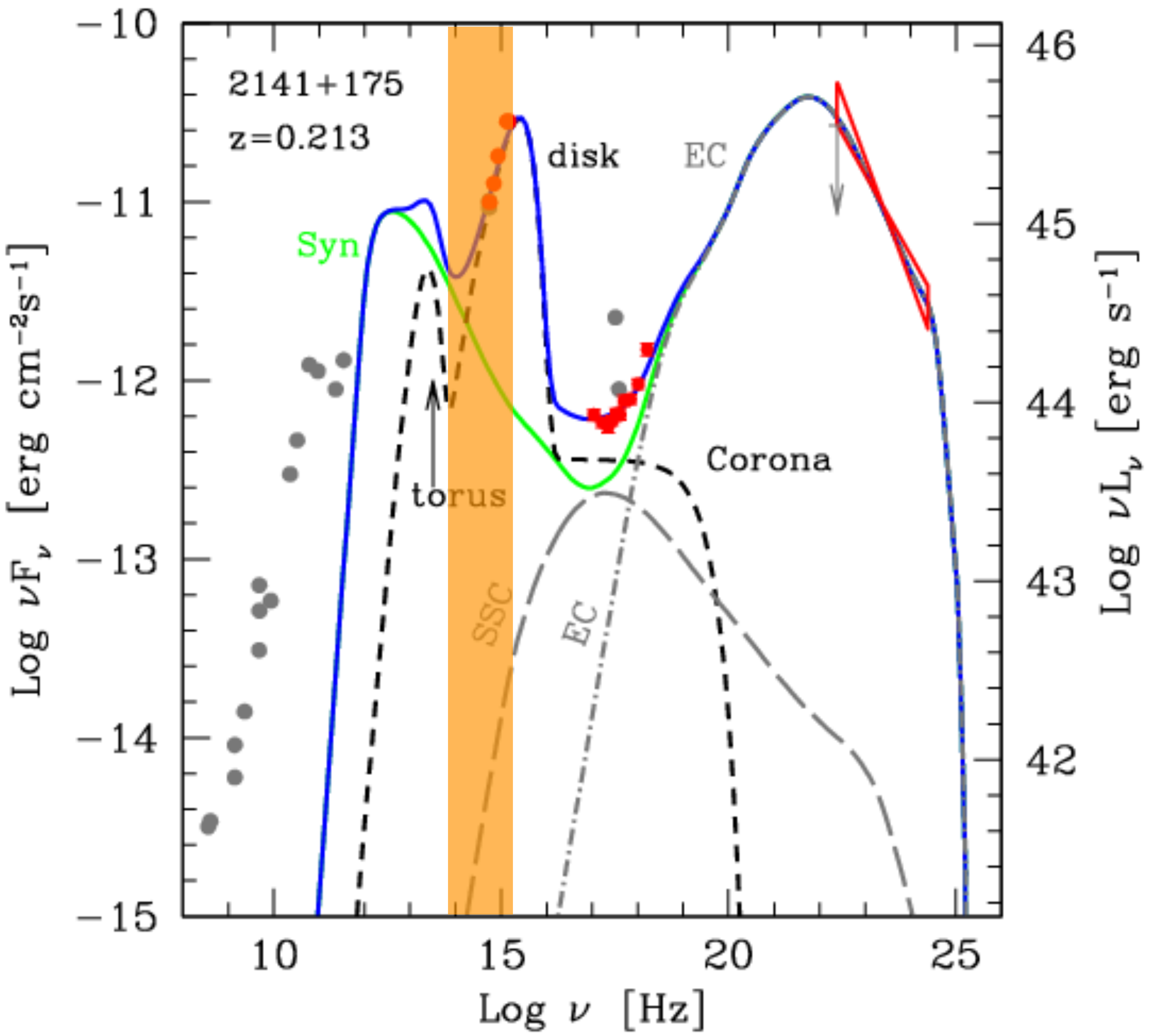
Blazar classes: BL Lac objects and FSRQs

BL Lac Object

Optical light

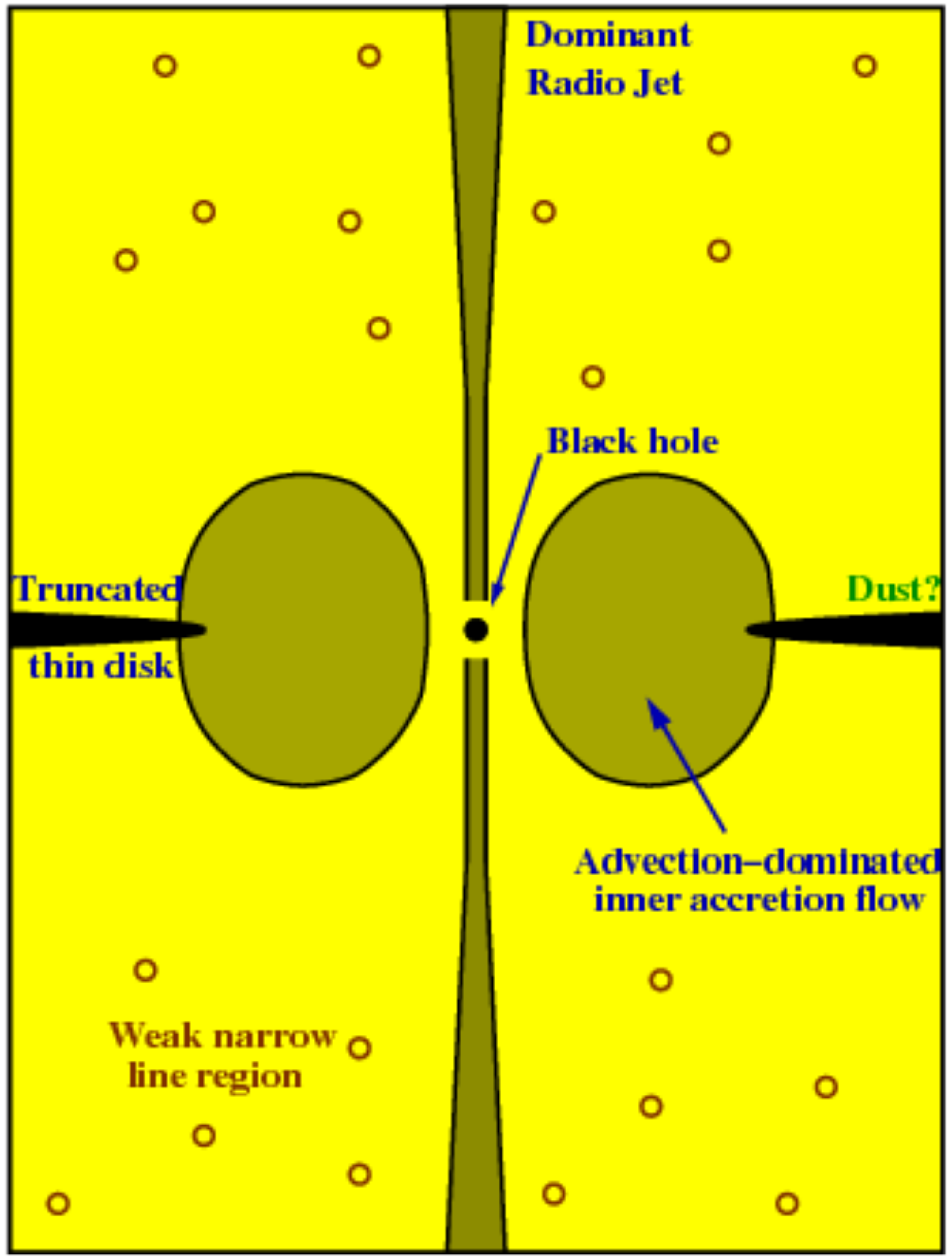
Flat spectrum radio quasar



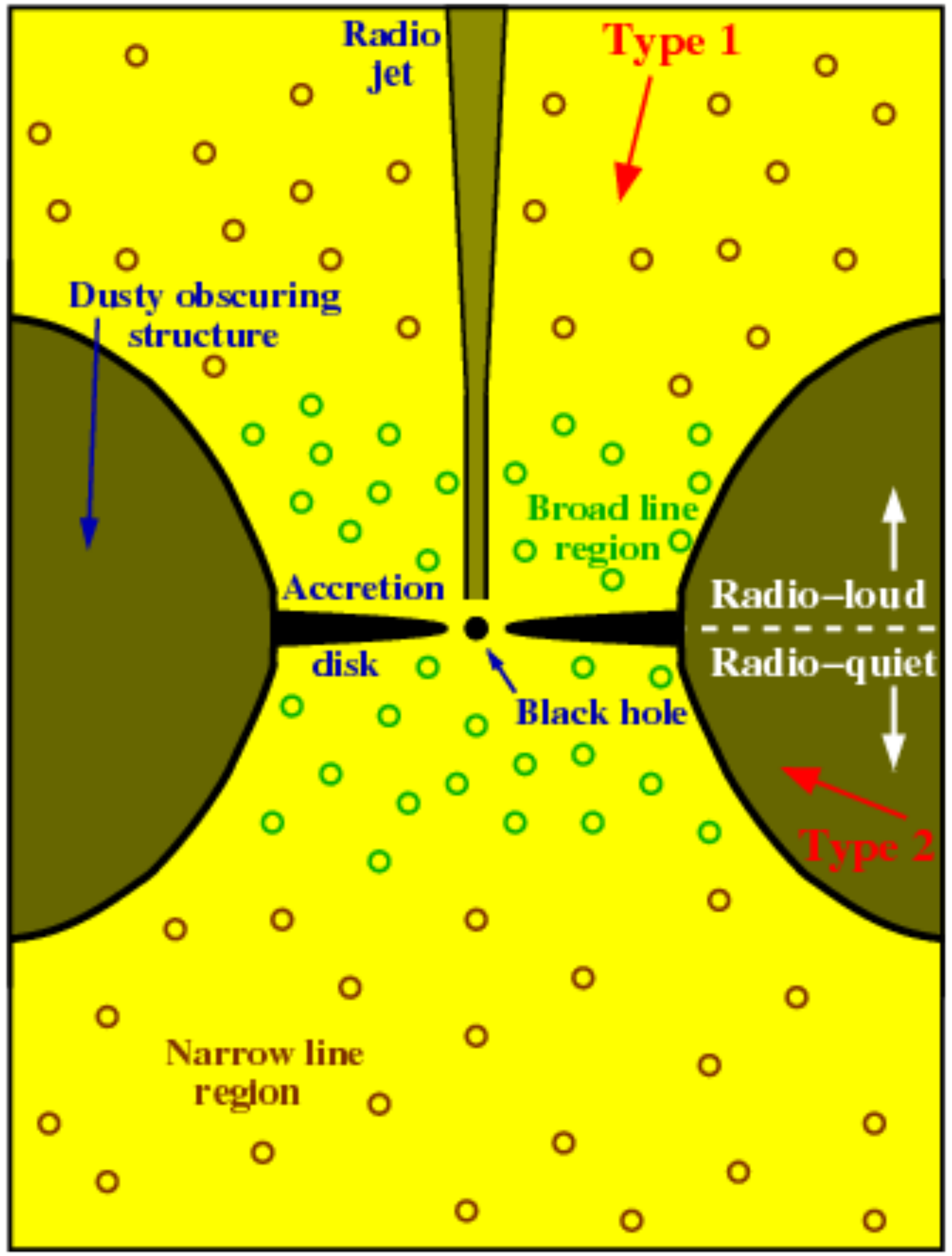


Blazar classes: BL Lac objects and FSRQs

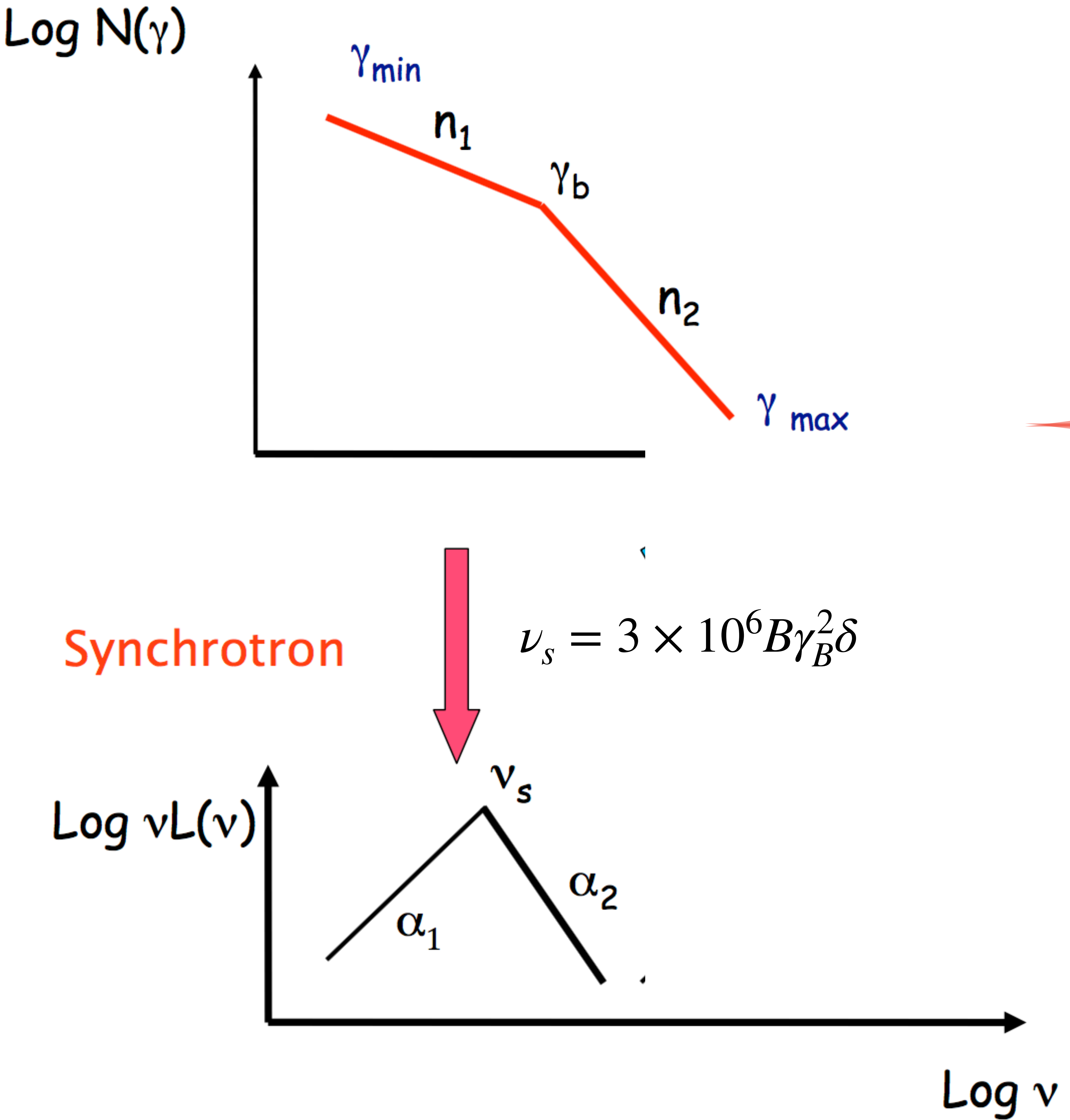
BL Lac Object



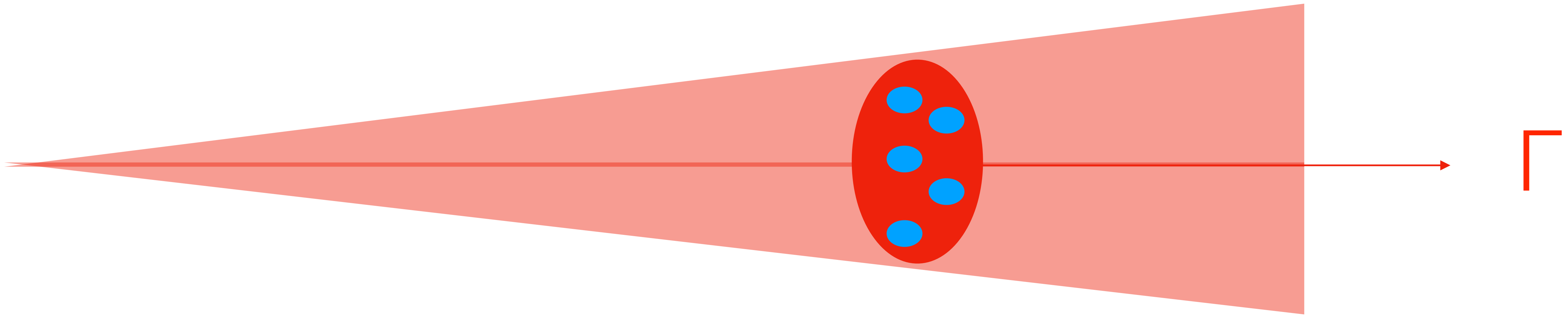
Flat spectrum radio quasar



Emission from BL Lac objects



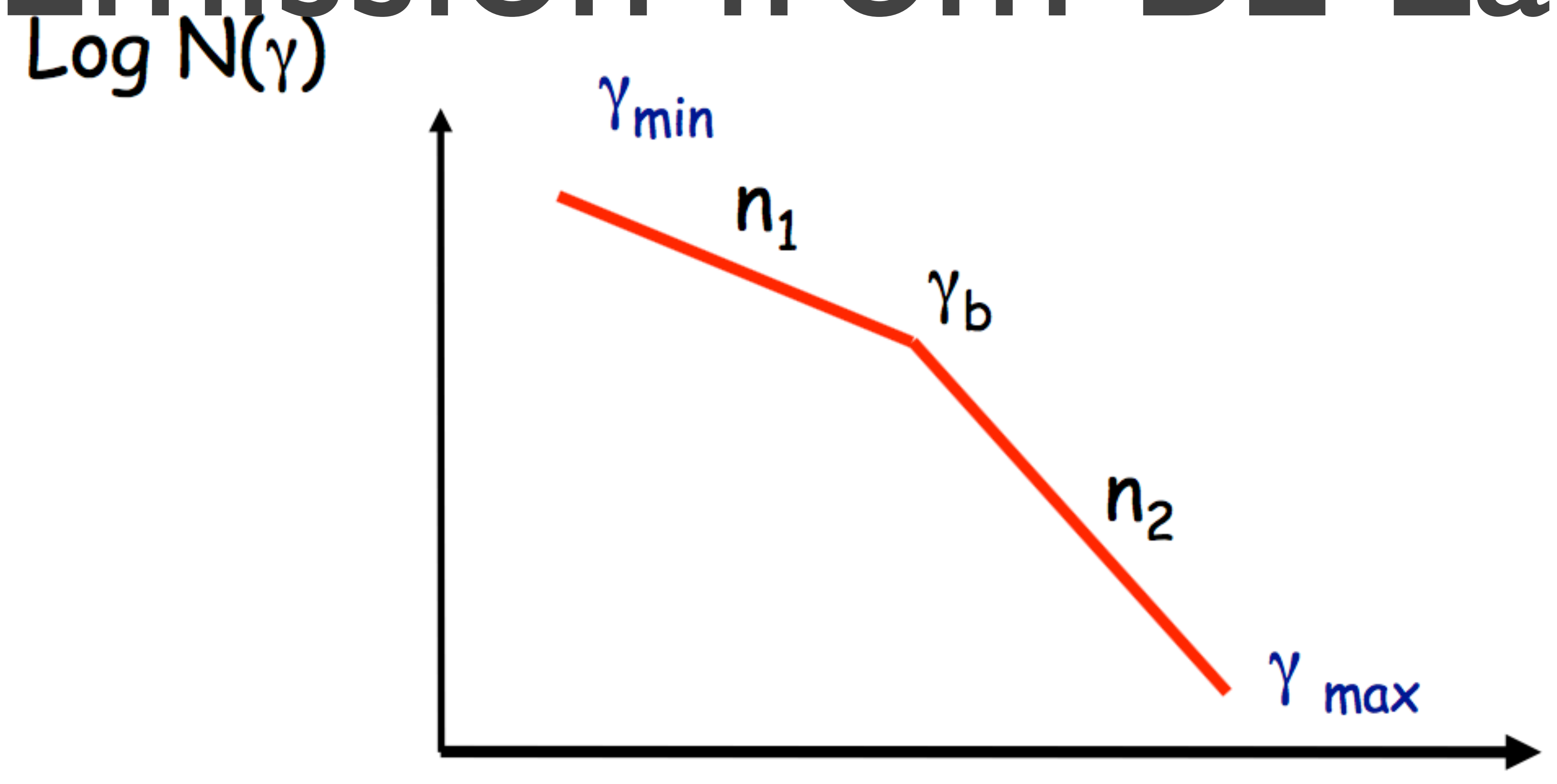
$$\nu_s = 3 \times 10^6 B \gamma_B^2 \delta$$

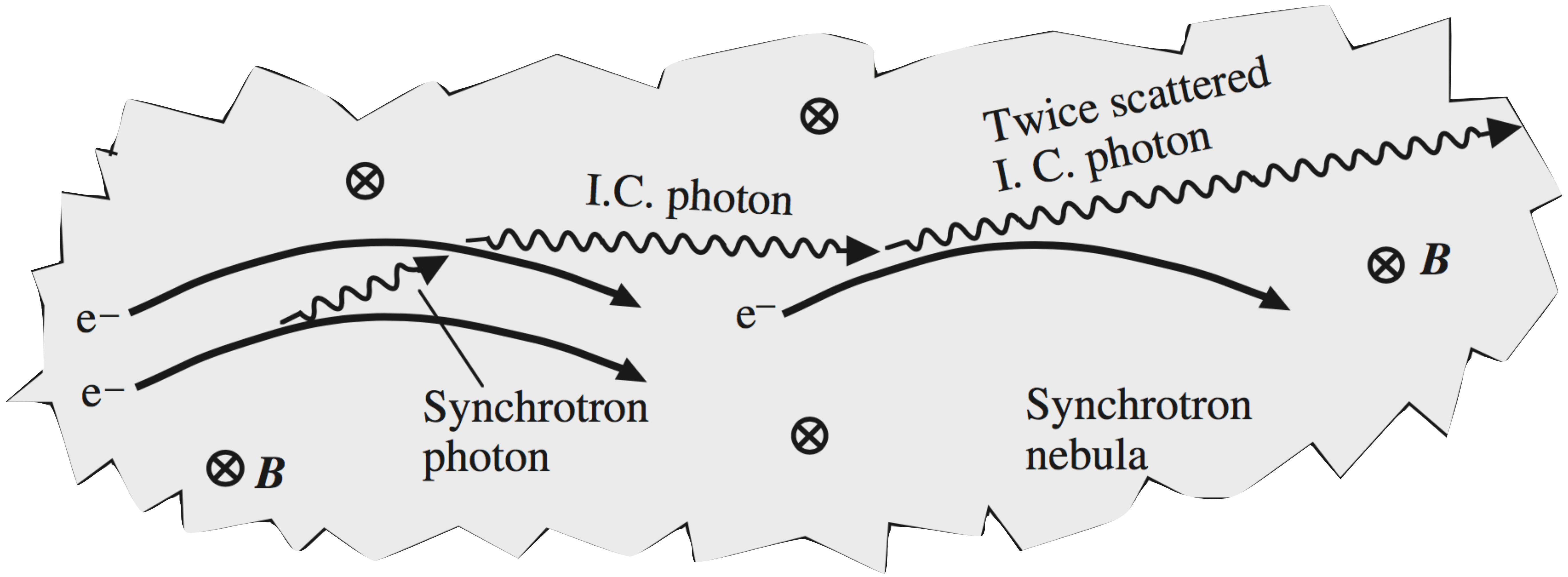


Relativistic electrons in a compact, relativistic region moving

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

Emission from BL Lac objects



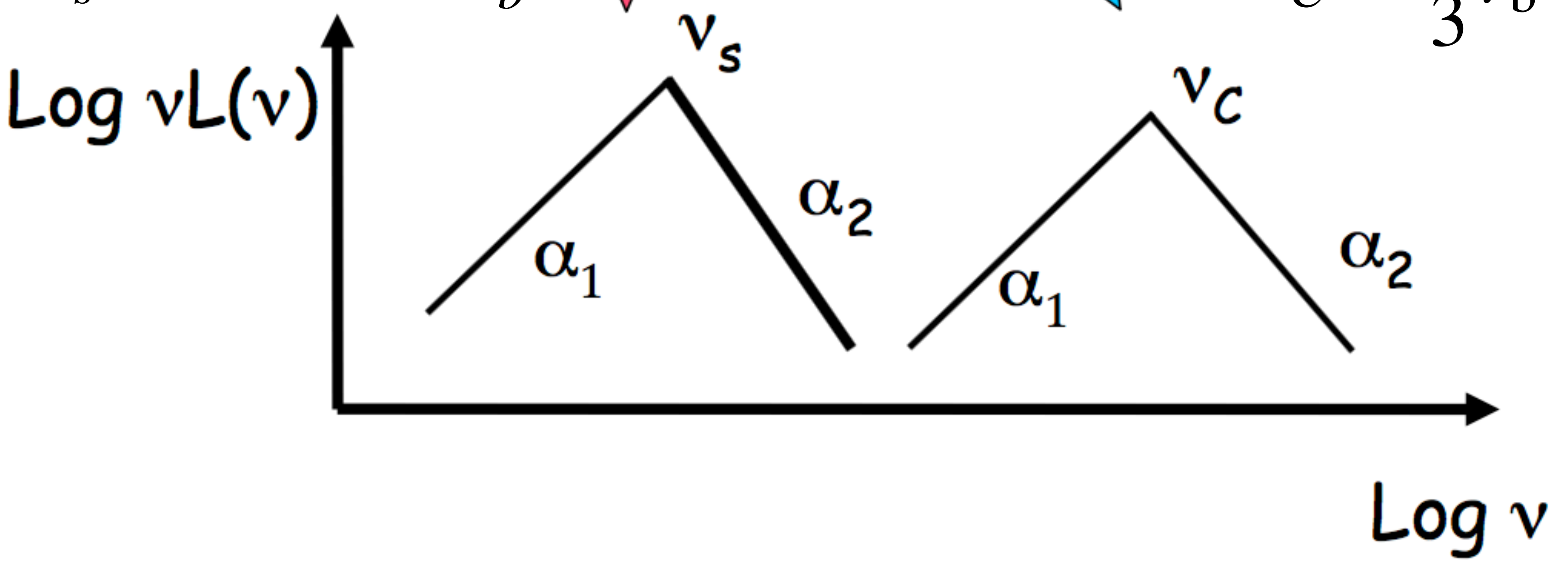


Synchrotron

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

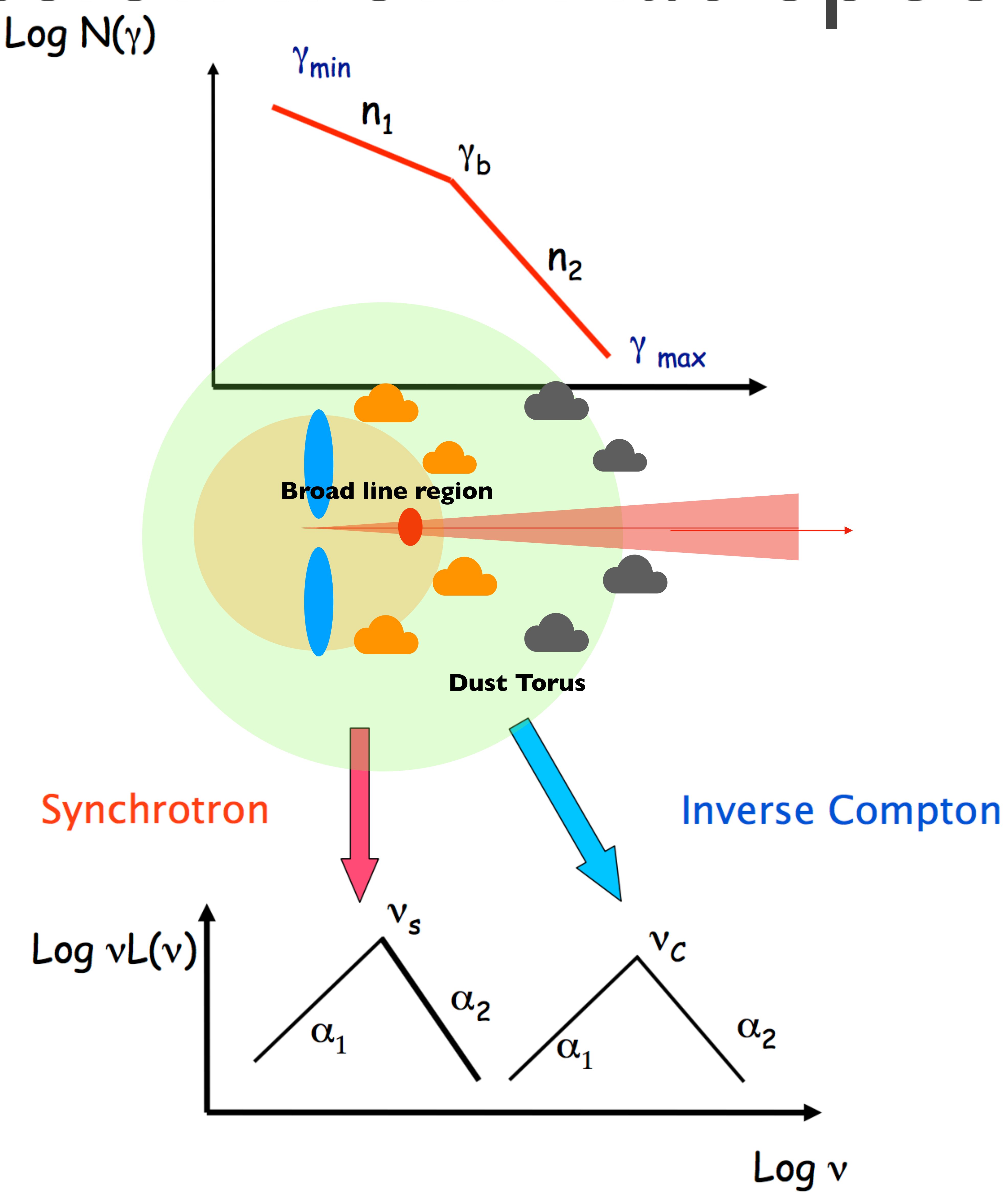
Inverse Compton

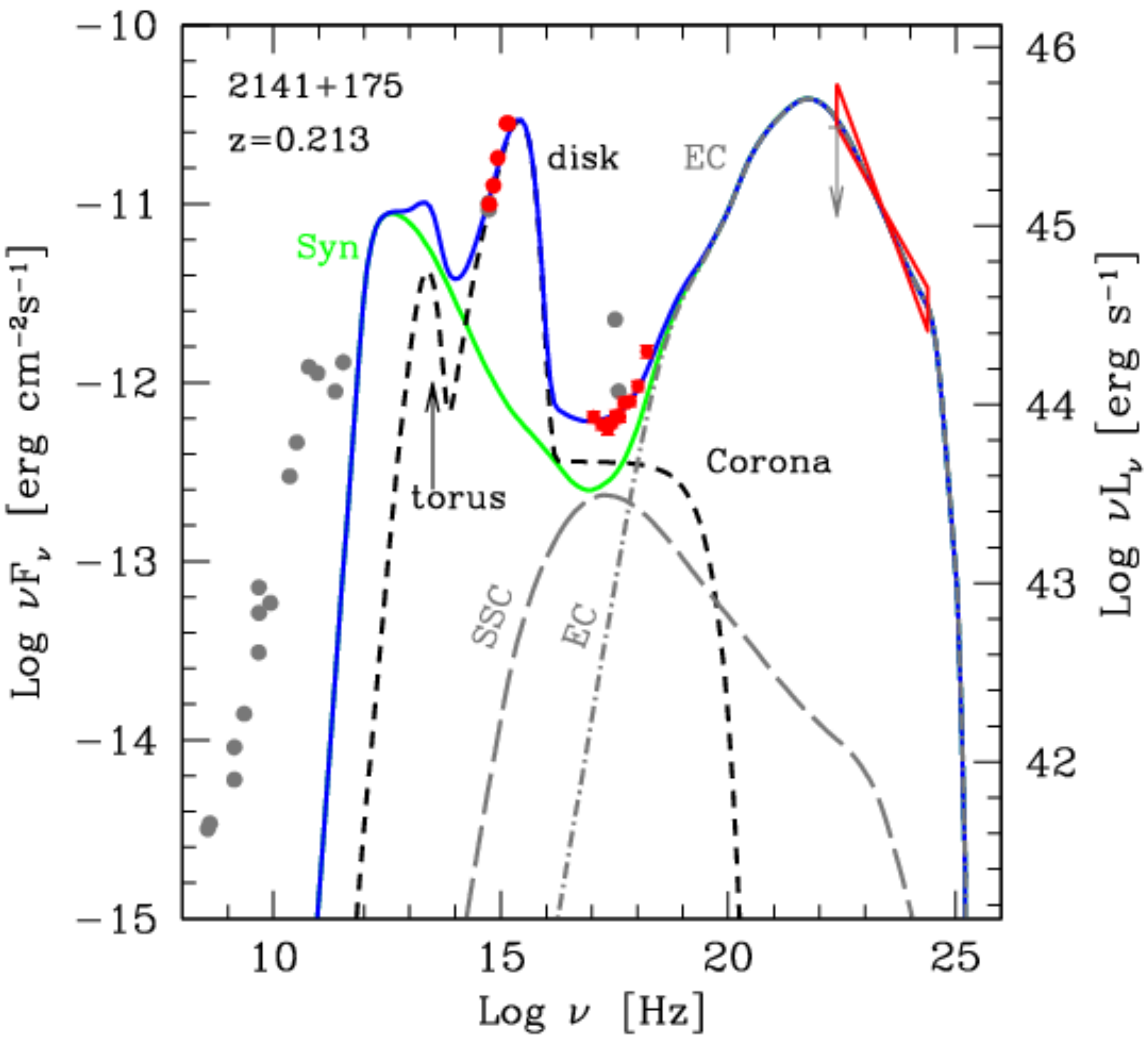
$$\nu_C = \frac{4}{3} \gamma_b^2 \nu_S$$



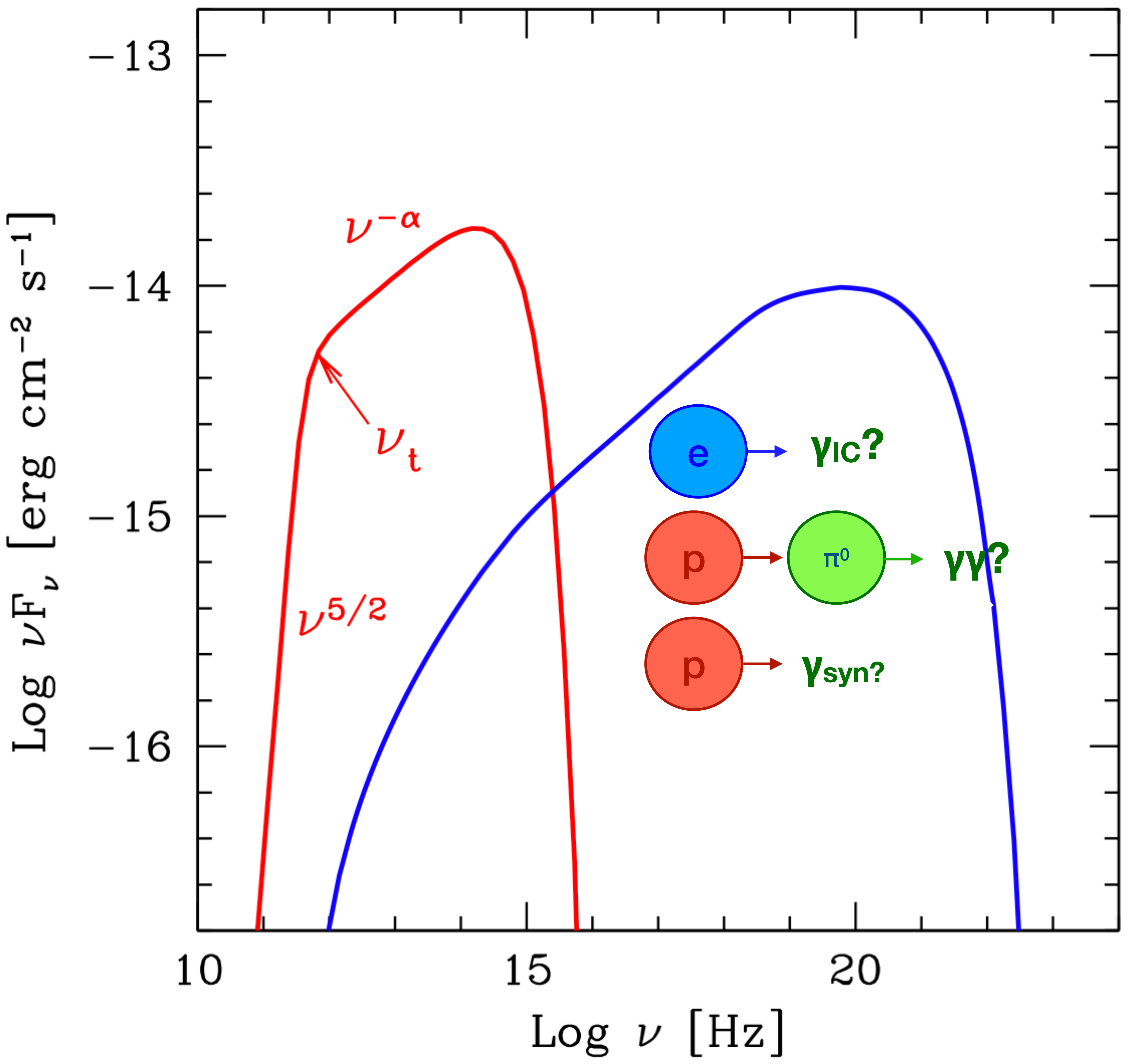
In this synchrotron + synchrotron self Compton (SSC) model, we can in principle determine the magnetic field strength, doppler factor, γ_b, n_1, n_2, electron density, size of emitting region from observed quantities (see back-up)

Emission from Flat Spectrum Radio Quasars





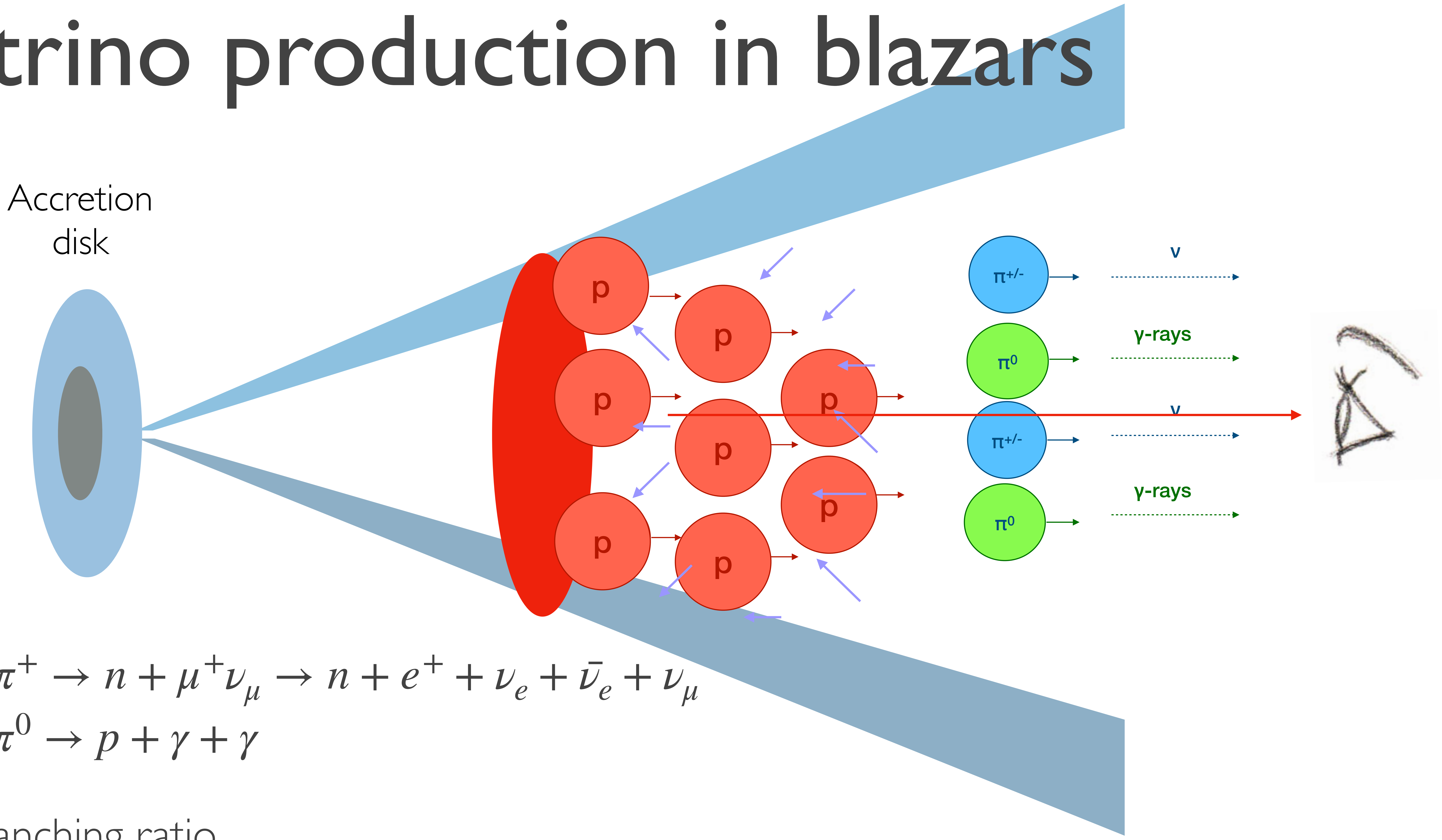
Enter the protons



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

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

Neutrino production in blazars



$$p + \gamma \rightarrow n + \pi^+ \rightarrow n + \mu^+ \nu_\mu \rightarrow n + e^+ + \nu_e + \bar{\nu_e} + \nu_\mu$$
$$p + \gamma \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma$$

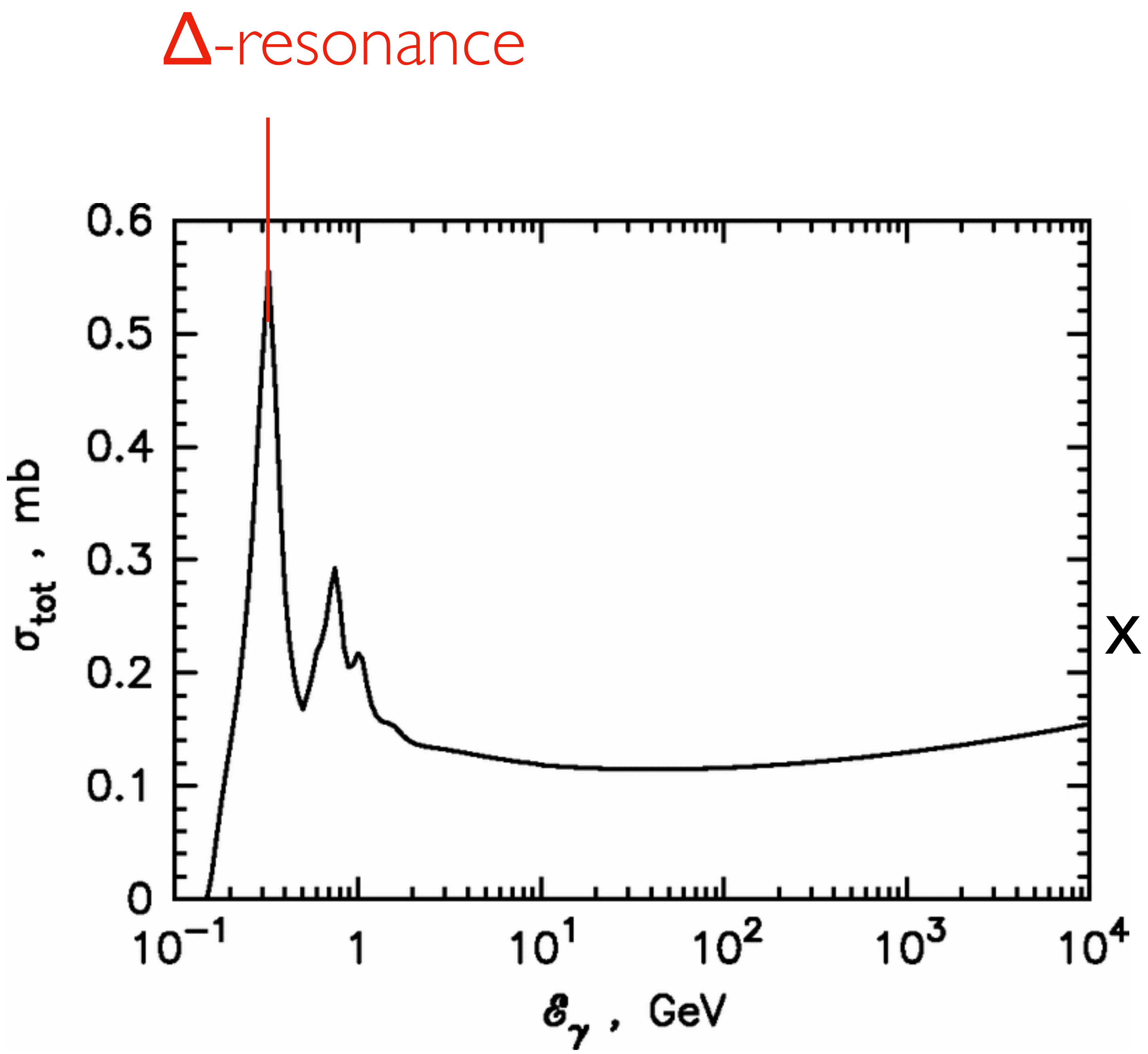
Averaged branching ratio,

$$R_\pi = \frac{\Gamma(\rightarrow \pi^{+/-})}{\Gamma(\rightarrow \pi^0)} \sim 1$$

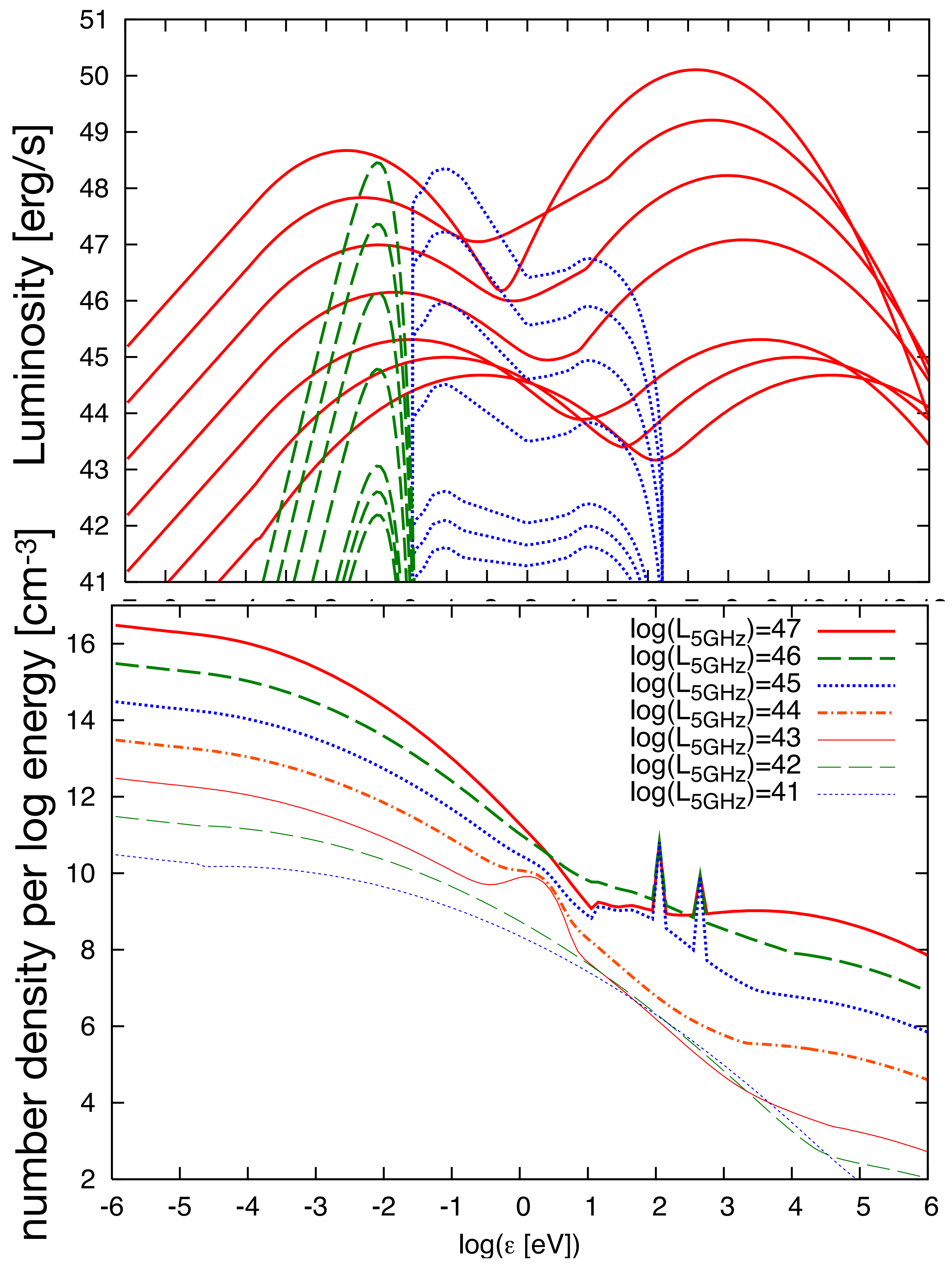
$$E_\nu^2 \frac{dN}{dE_\nu} = \frac{3}{2}\frac{1}{2} E_\gamma^2 \frac{dN}{dE_\gamma} |_{E_\gamma = 2E_\nu}$$ $\longrightarrow$ Upper limit to the neutrino flux

Neutrino production in blazars (photo-pion interactions)

Neutrino production efficiency ~ cross-section x target number density



x



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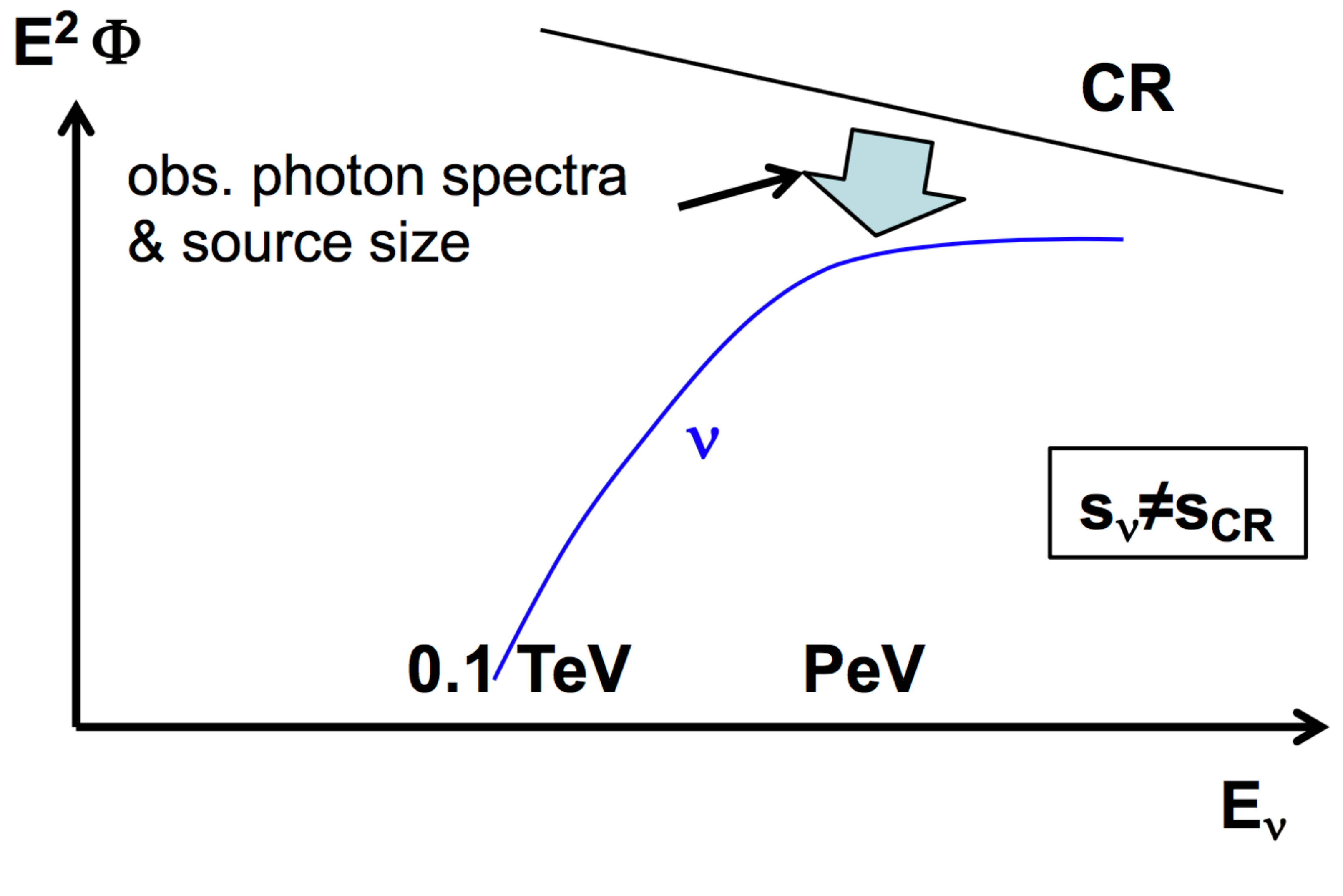
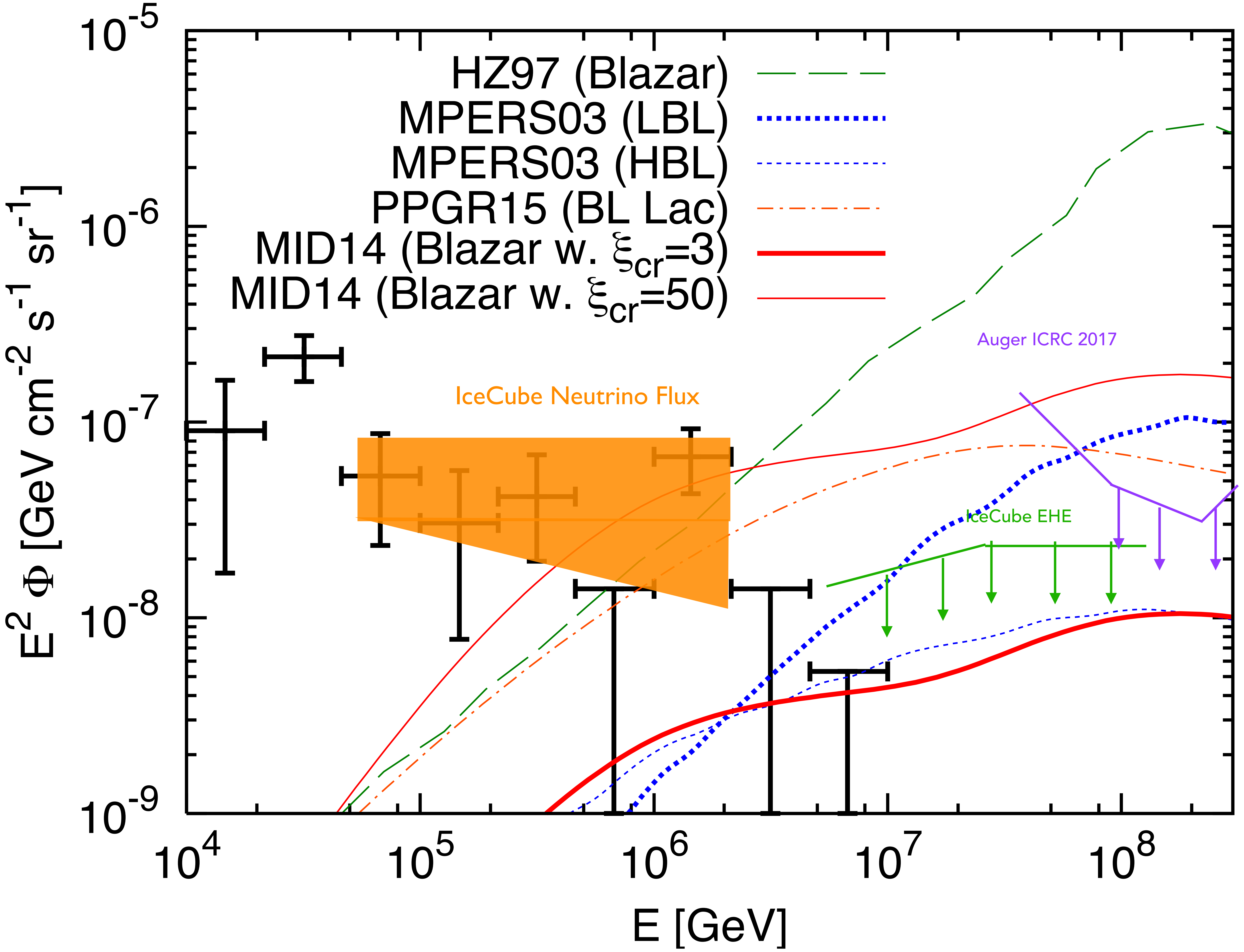
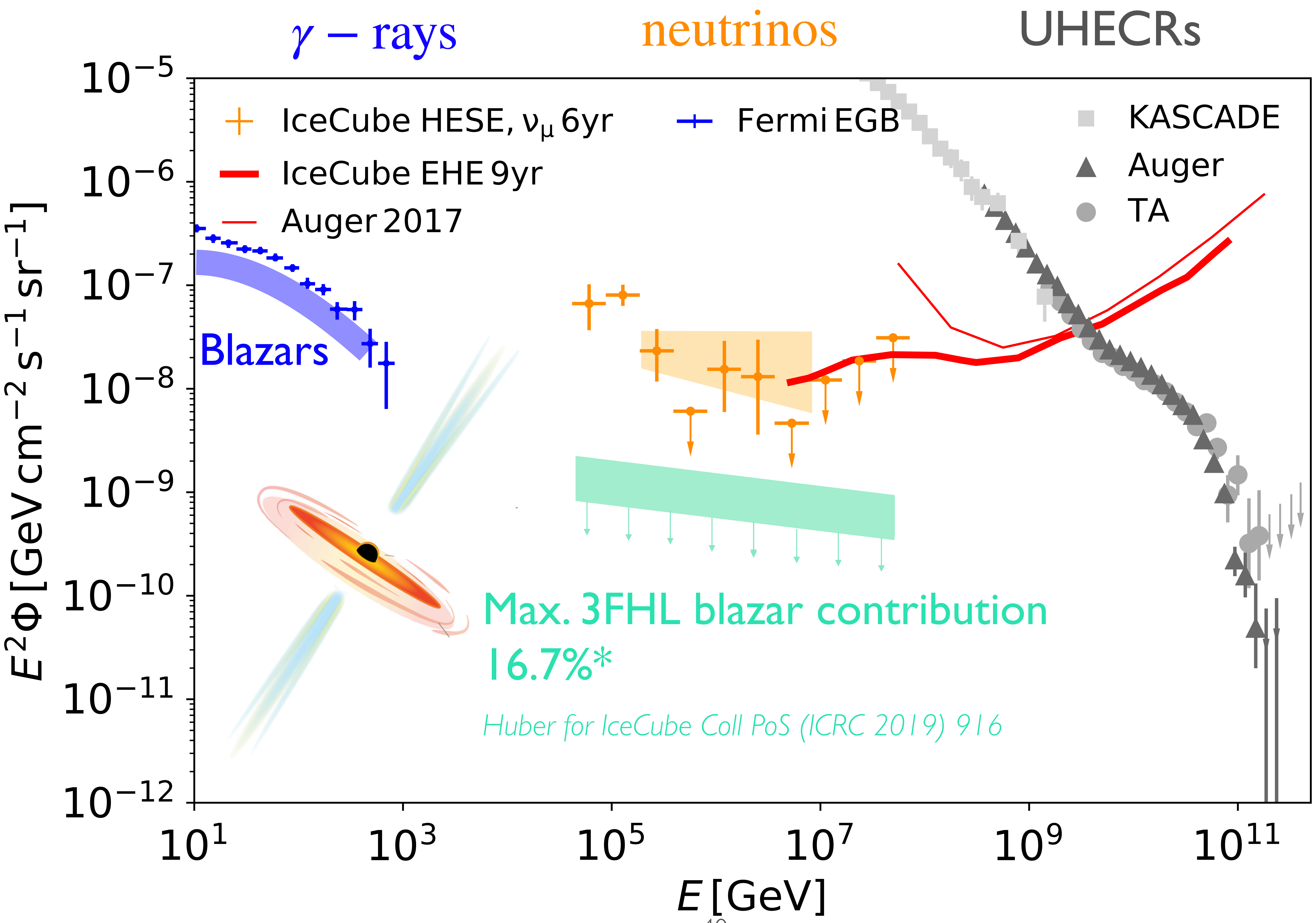


Possible contribution of blazars to the diffuse neutrino flux

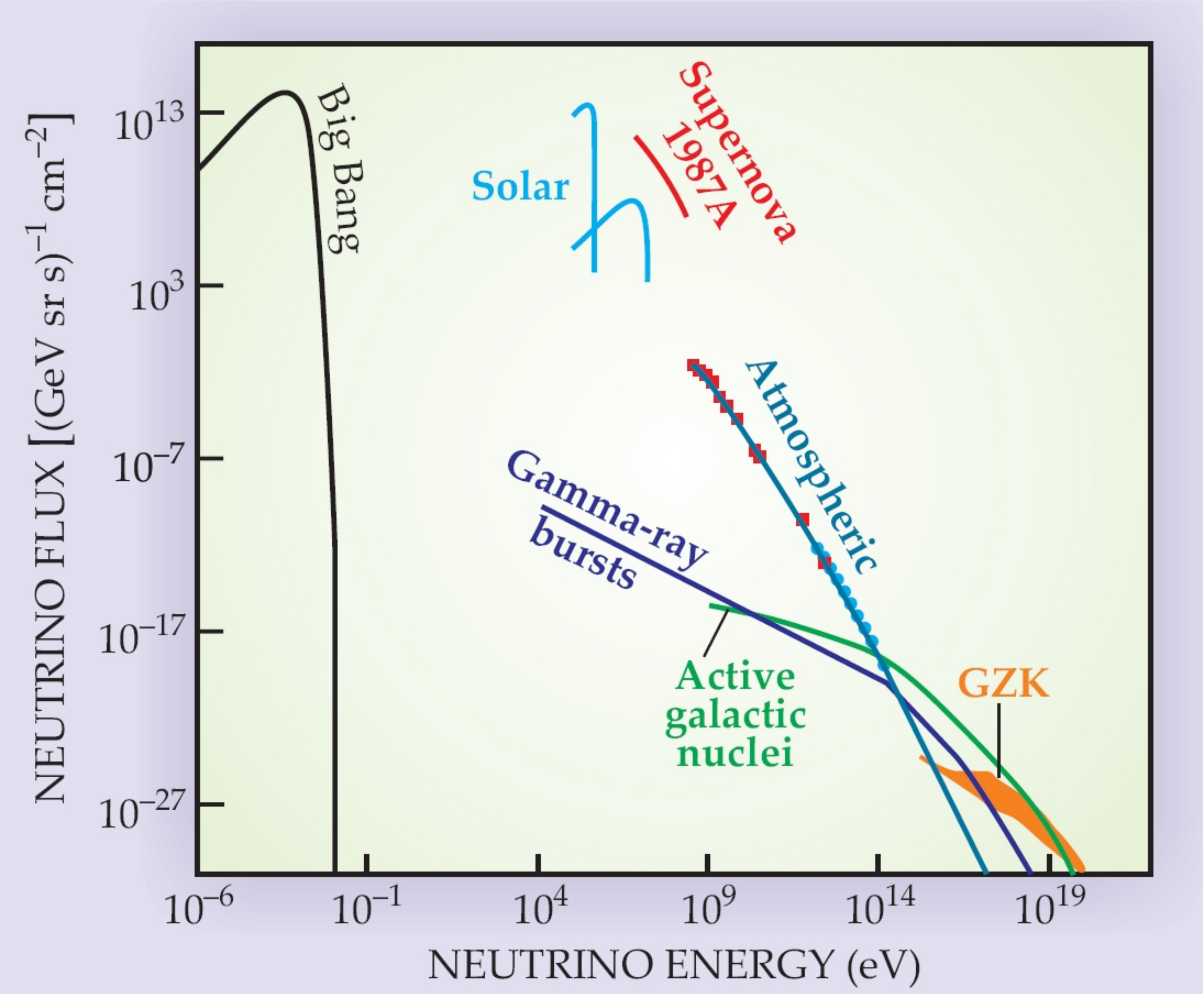


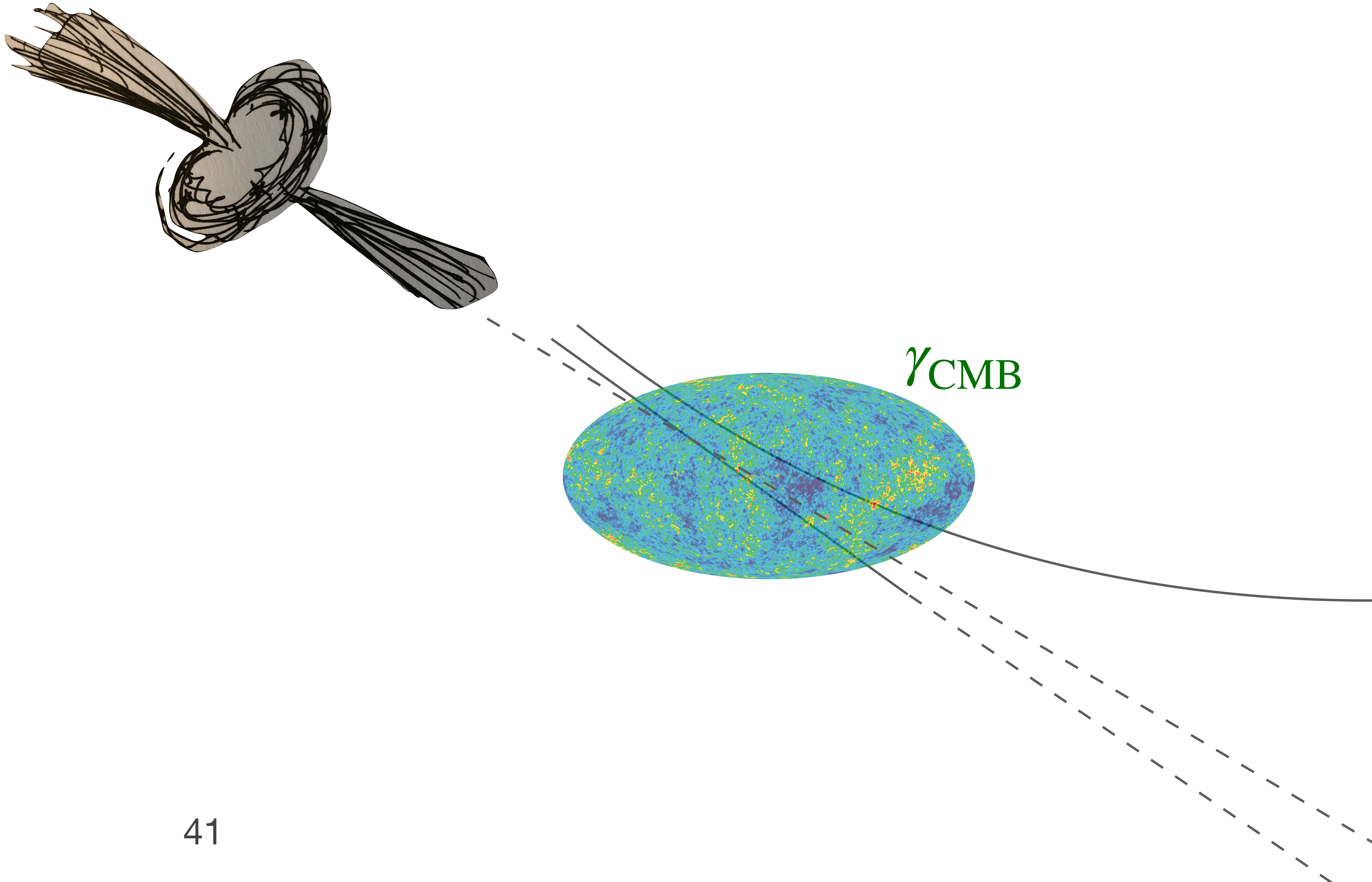
Constraints on the contribution of blazars to the diffuse neutrino flux: Stacking



Ultra-high energy neutrinos

How to detect them?

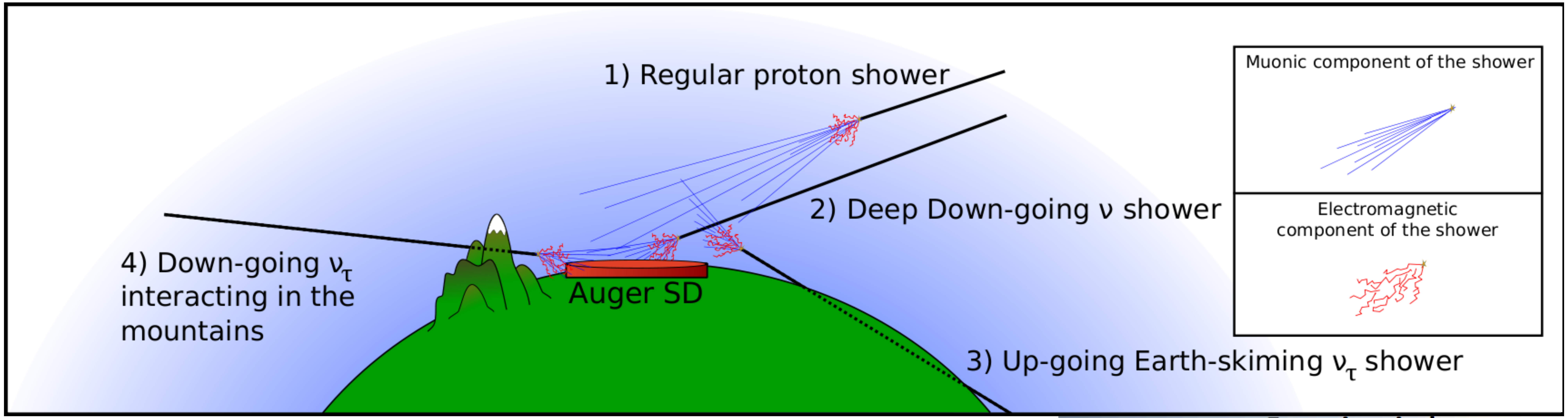


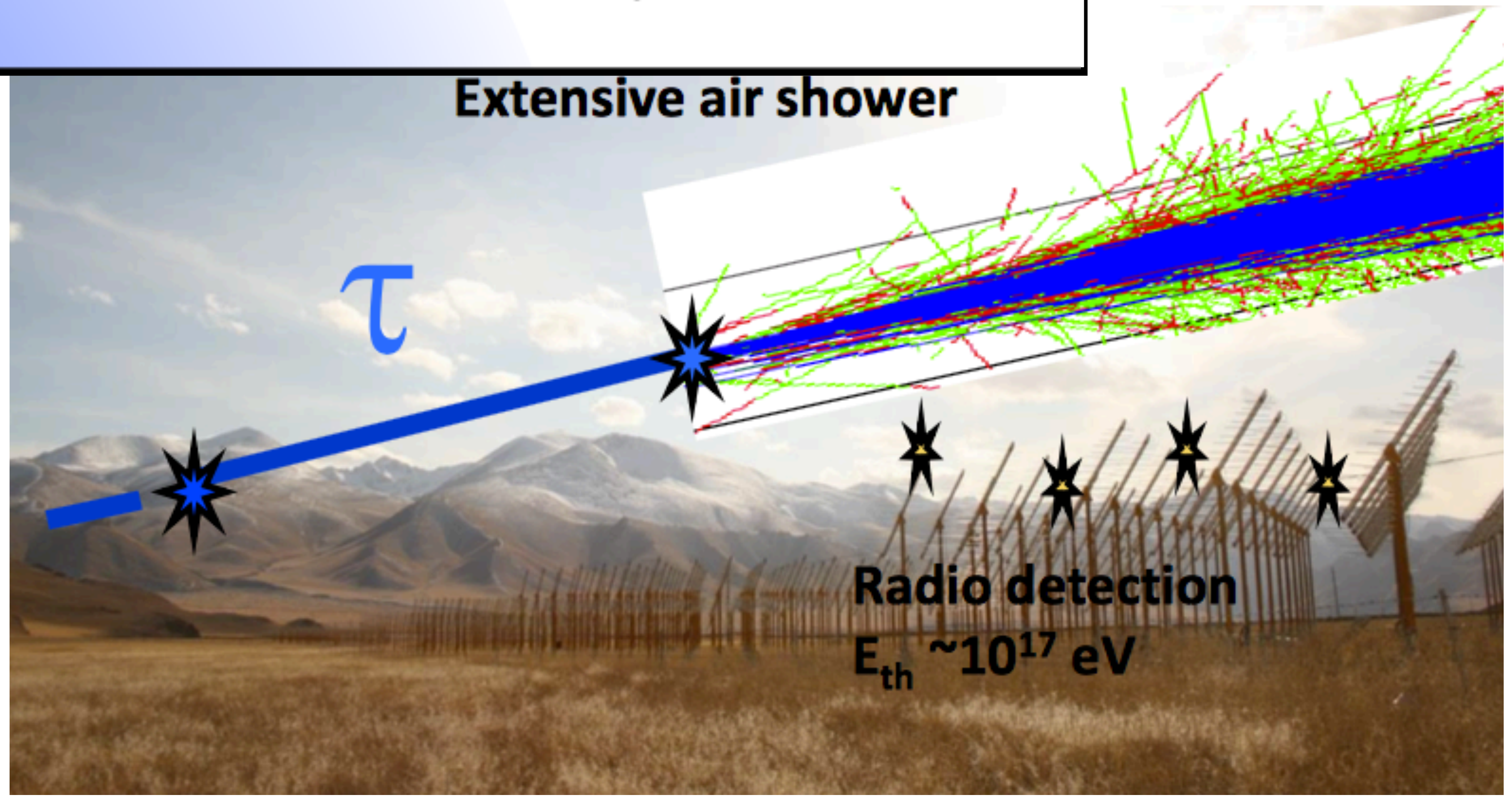


Back-up

Ultra-high energy neutrinos

How to detect them? Extensive-air showers



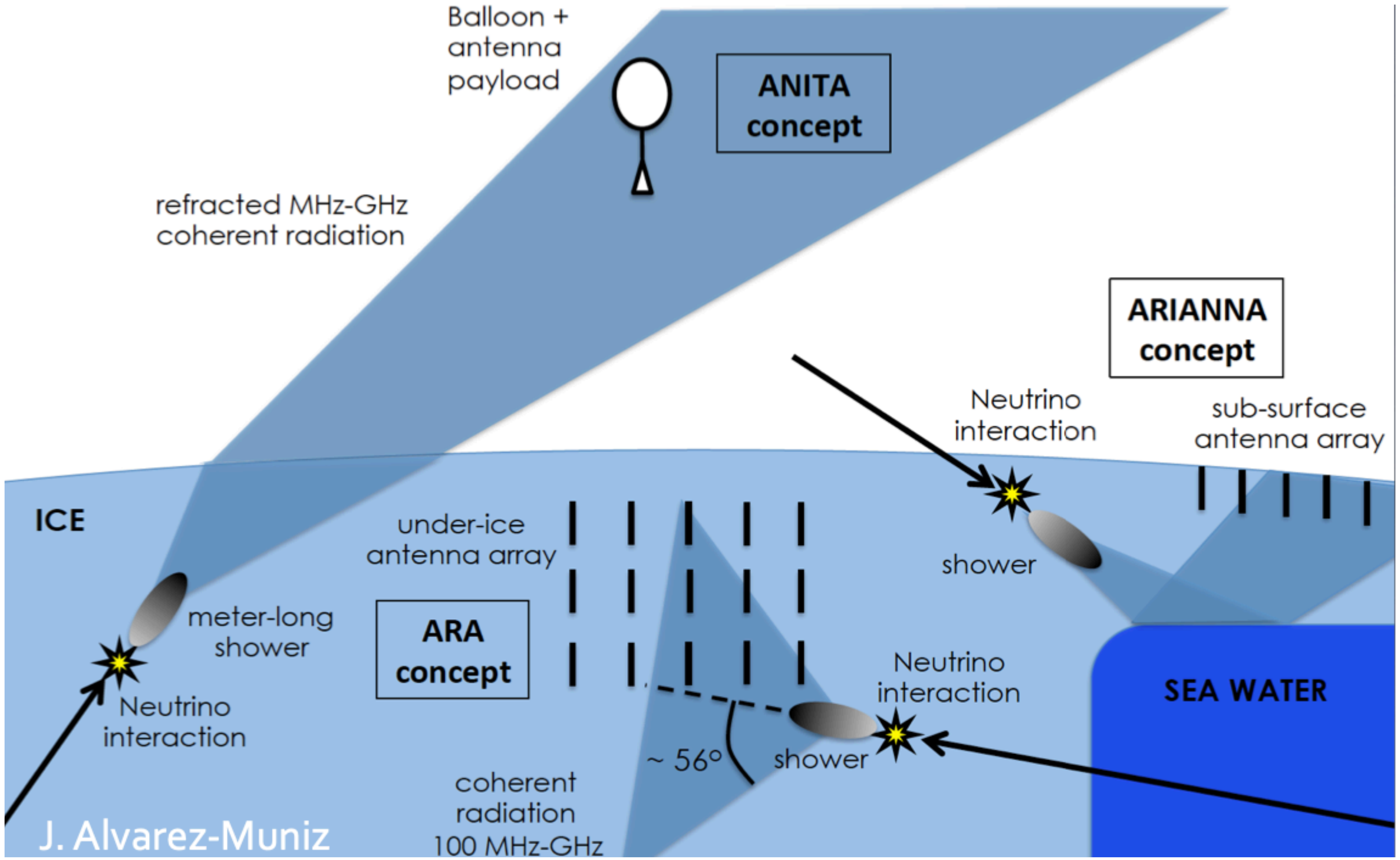


Pierre Auger Observatory ~ 3000 km²

Planned detectors with up to 200,000 km² effective area (GRAND, GCOS…)

Ultra-high energy neutrinos

How to detect them? Askaryan radiation



many more ongoing efforts (Greenland Neutrino Observatory, IceCube Gen-II radio, PUEO…)

Eddington luminosity reminder

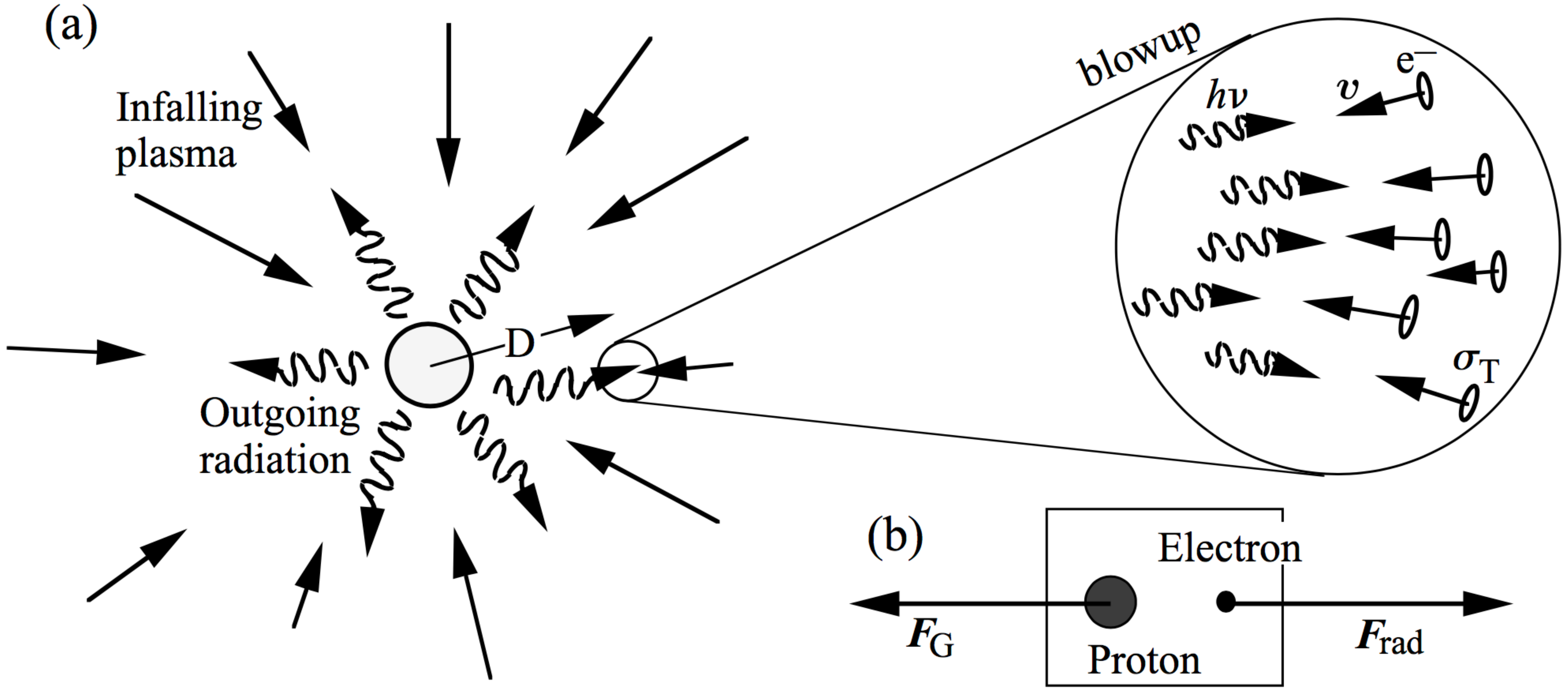


Image from H. Bradt "Astrophysical processes" 2008

Outward radiative force = Inward self-gravity

$$F_{rad} = \frac{L\sigma_T}{4\pi r^2 c}^{*} \qquad F_{Grav} = \frac{GMm_p}{r^2}$$

$\frac{L}{4\pi r^2 c}$ is the radiation pressure since we have here, momentum per second which is a force and force per unit area.

$$L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} = 30{,}000\left(\frac{M}{M_{Sun}}\right)L_{Sun}$$

What we can infer from the blazar SED

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

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

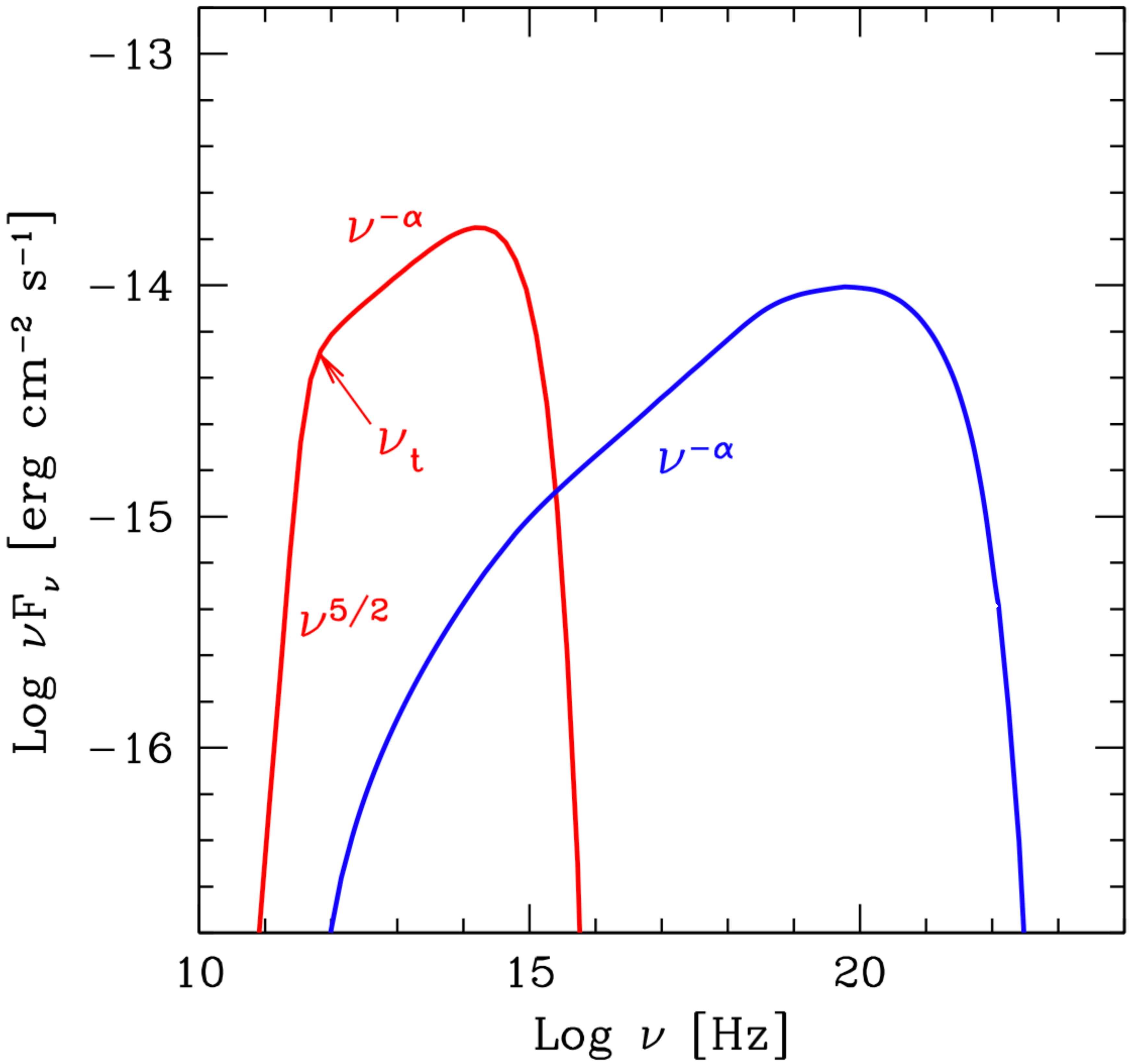
$$U_B = \frac{B^2}{8\pi} - (2)$$

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

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

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

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



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What we can infer from the blazar SED

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

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

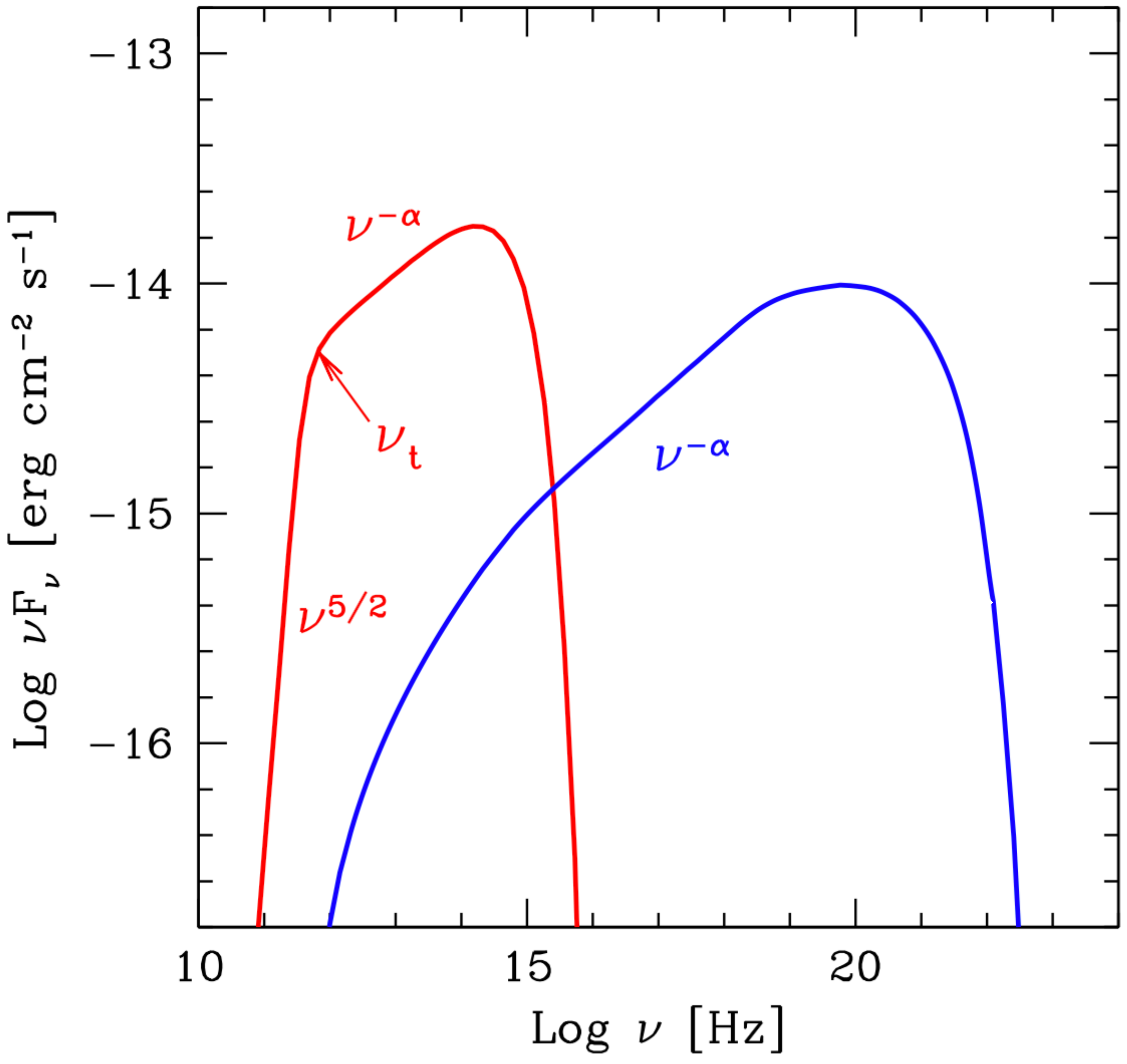
Rearranging, we get,

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

From the peak frequencies we have,

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

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



What we can infer from the blazar SED

From the peak frequencies we have,

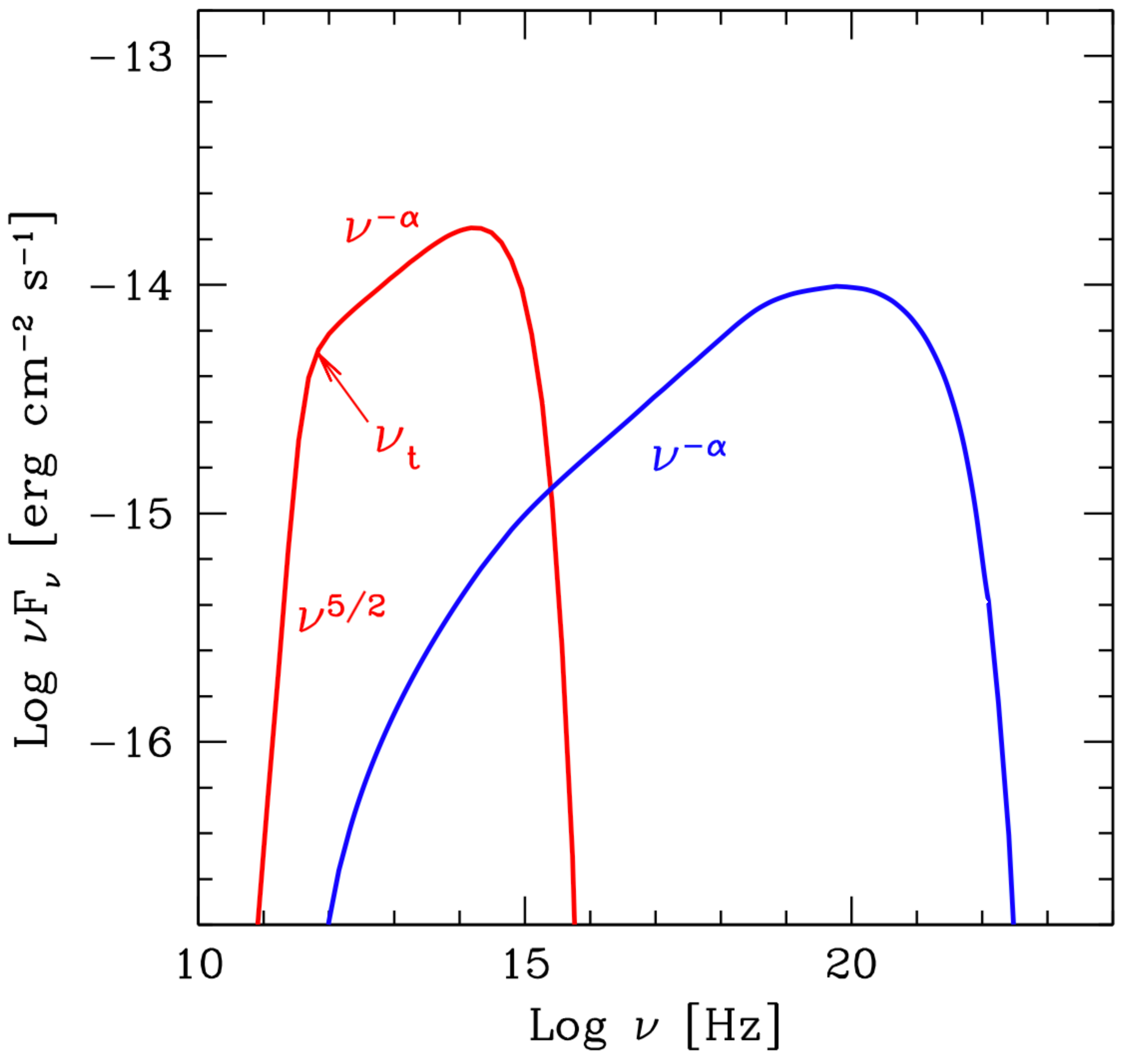
$$\nu_C = \frac{4}{3}\gamma_{\rm break}^2 \nu_S$$

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

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

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