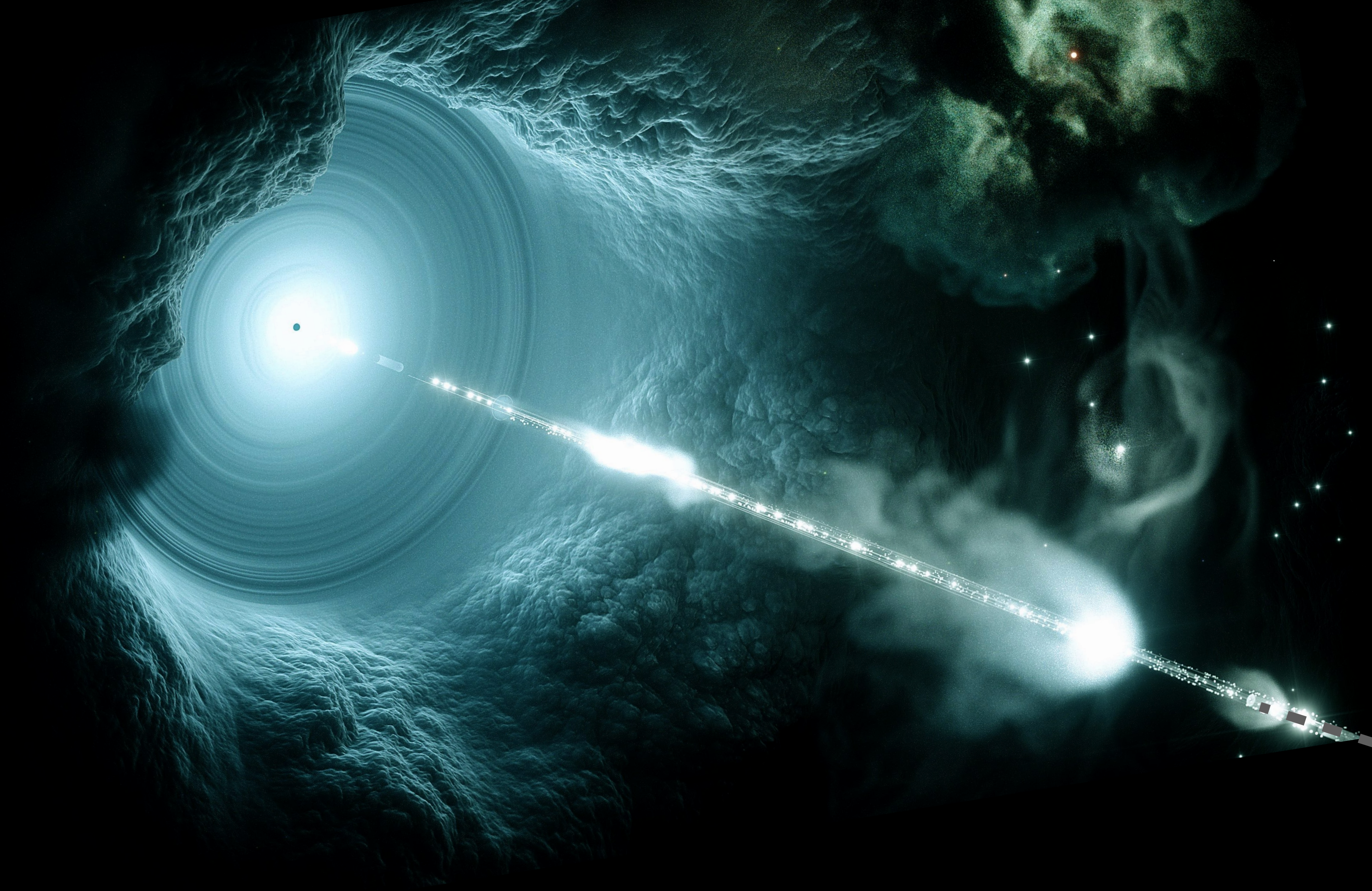
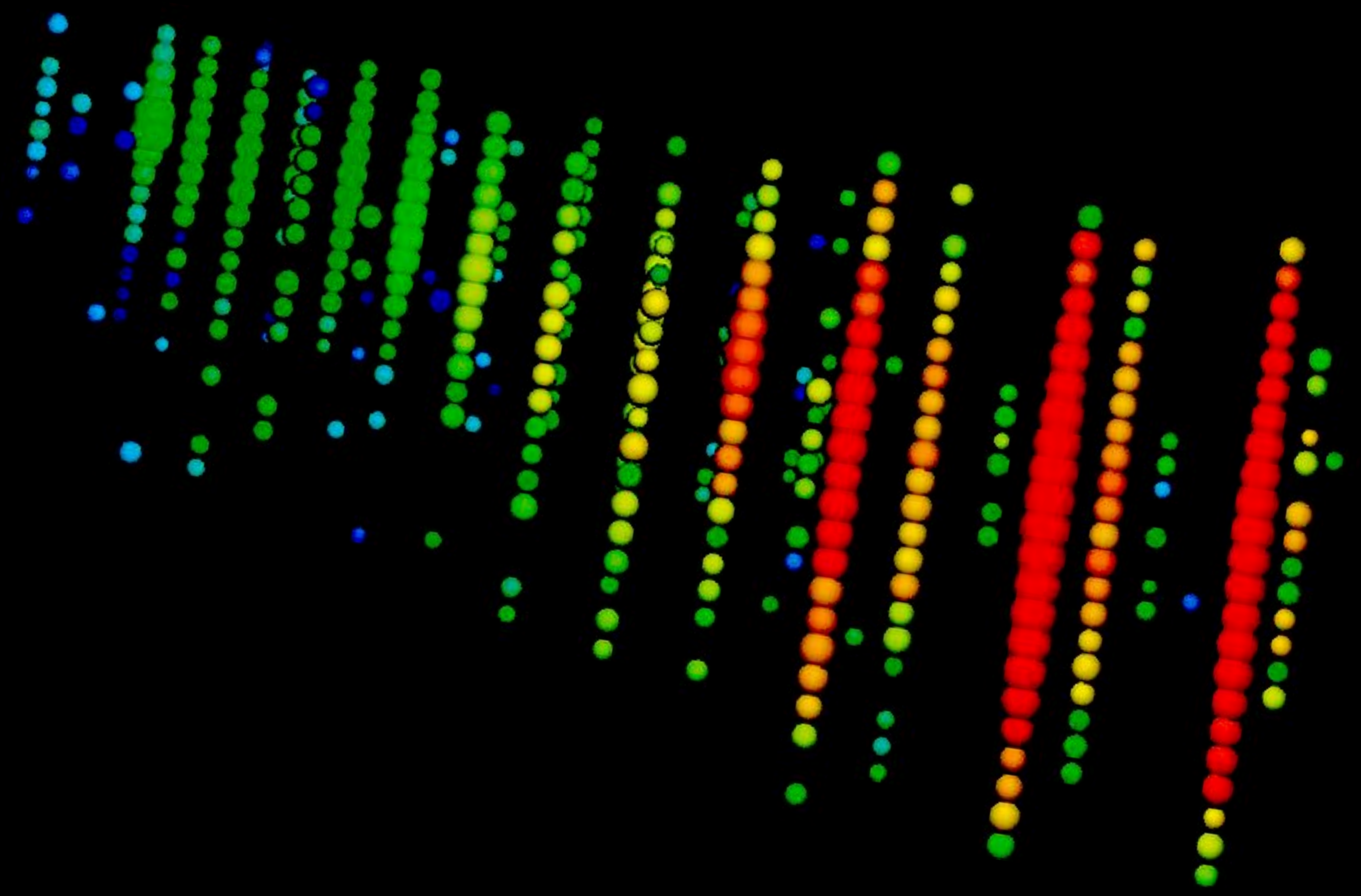


Multimessenger Astroparticle Physics



Exploring the Dark Universe from Particles
to Galaxies - ISAPP

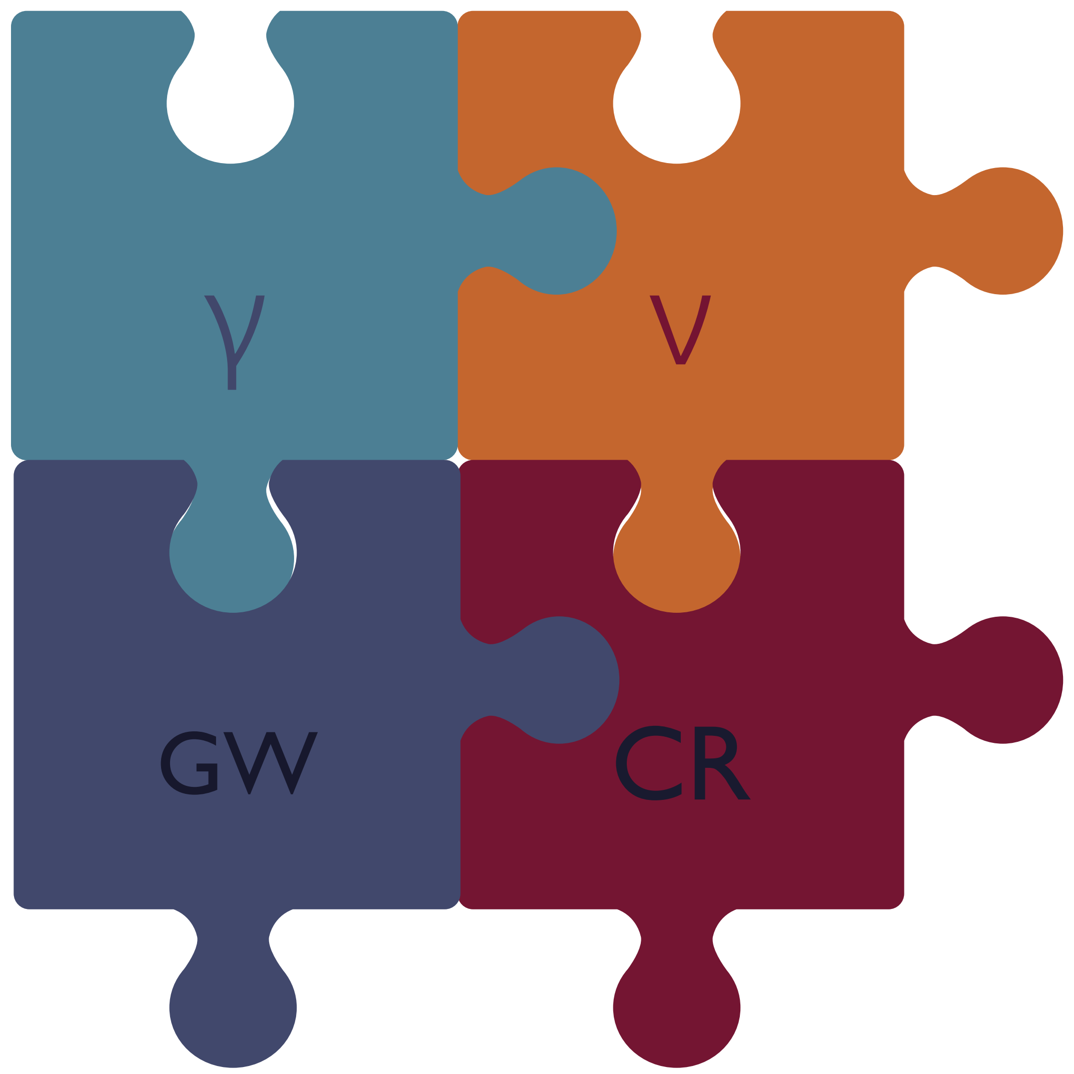
Foteini Oikonomou

Nov 16th and 17th

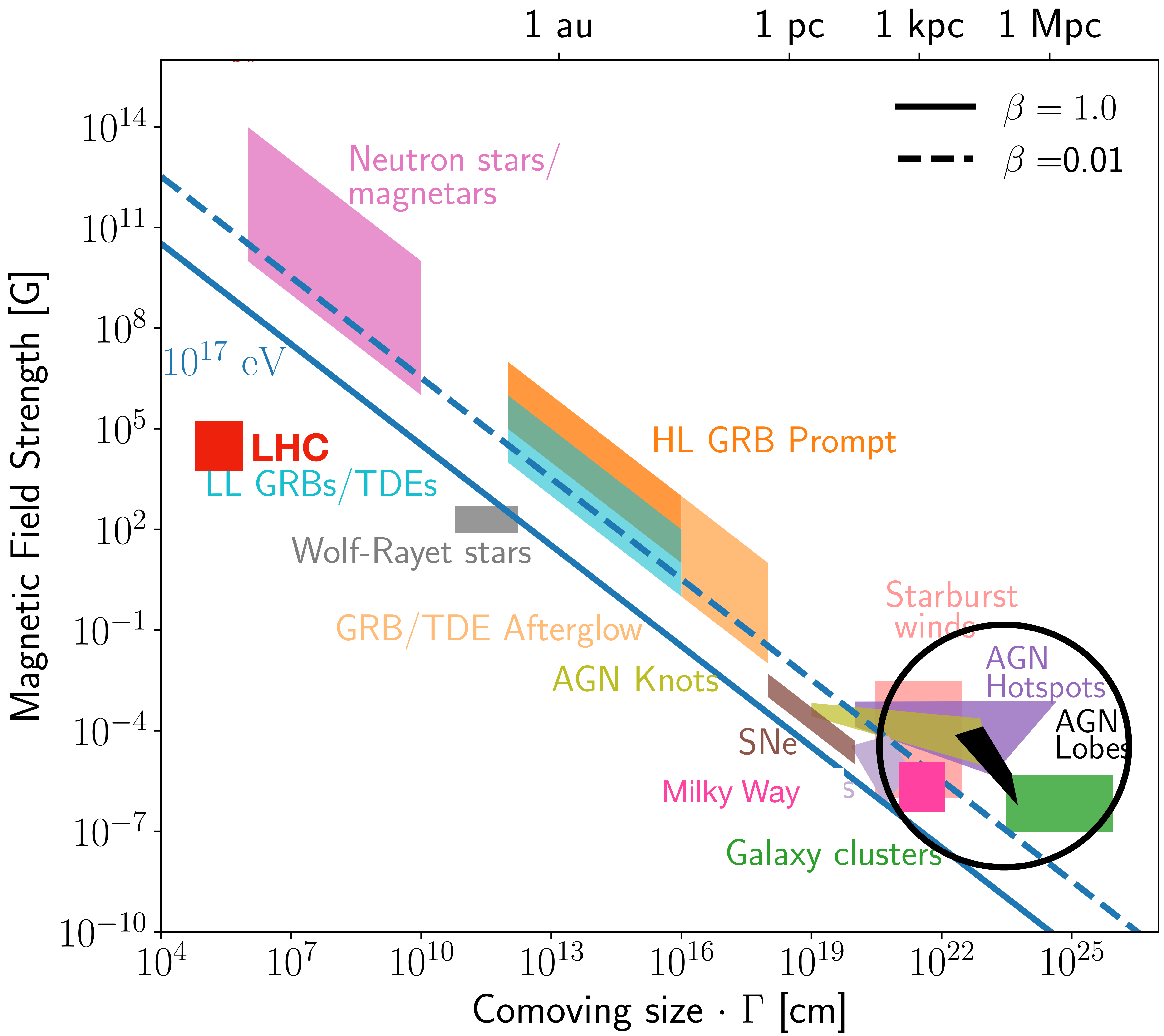
NTNU
Norwegian University of
Science and Technology

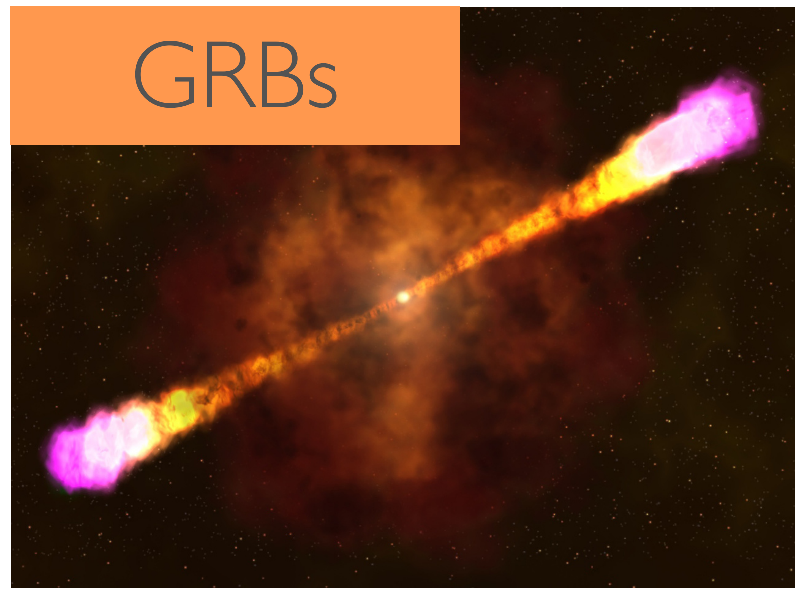
Lecture plan

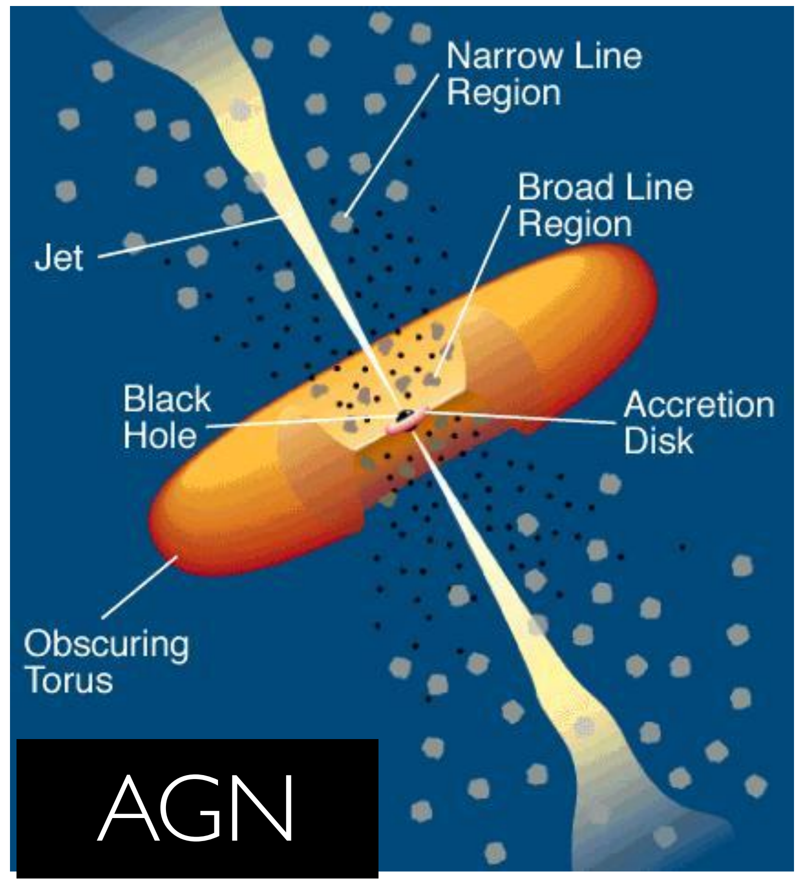
- Observations and basic theoretical concepts
- Generic source properties
- Requirements for astrophysical accelerators of UHECRs/HE neutrinos
- Candidate astrophysical sources (Active Galactic Nuclei/Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events)



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







Active Galactic Nuclei

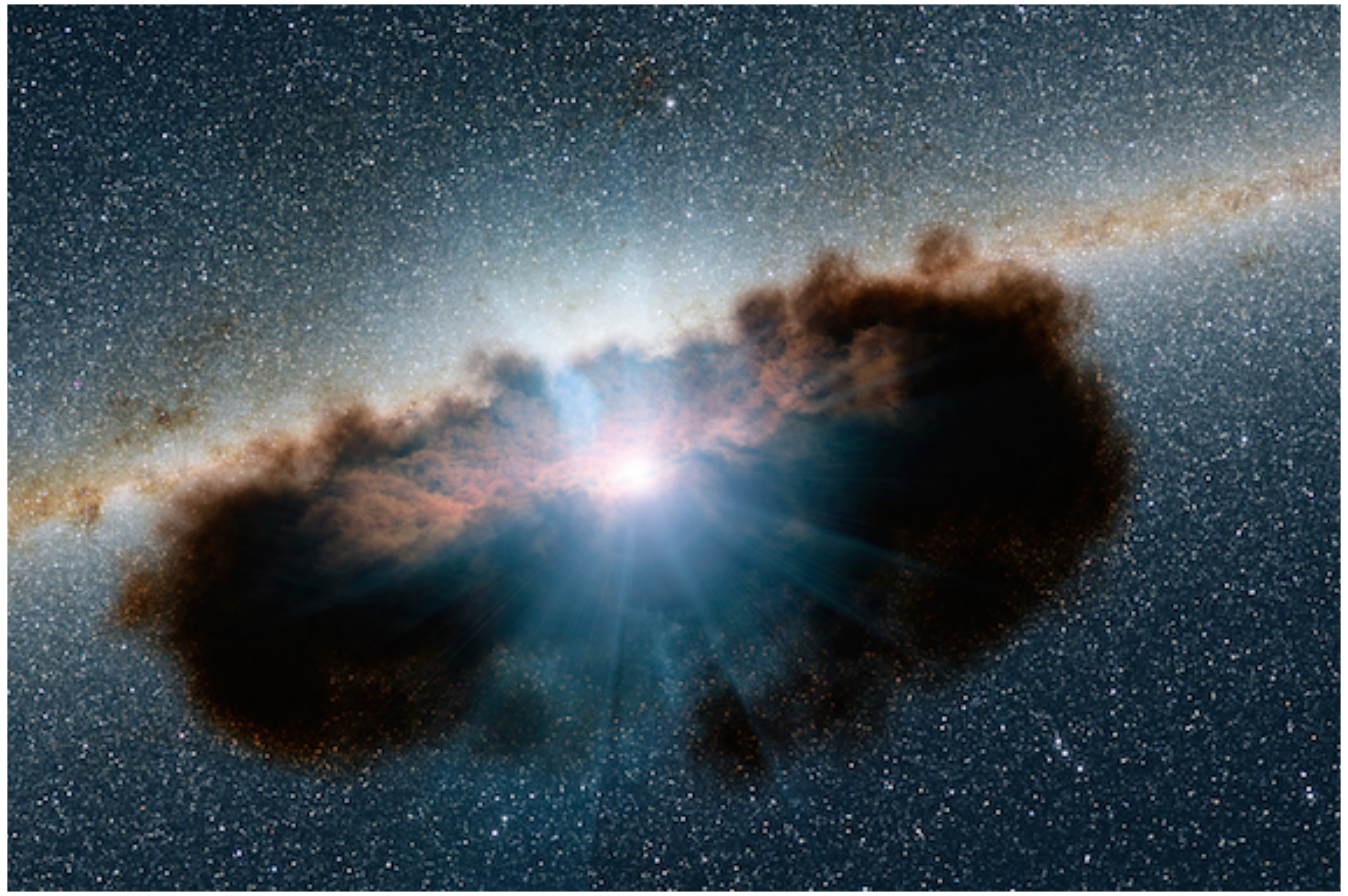
Most powerful ``steady'' sources in the Universe ($L \geq 10^{47}$ erg/s) > 1000 bright Galaxies!

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

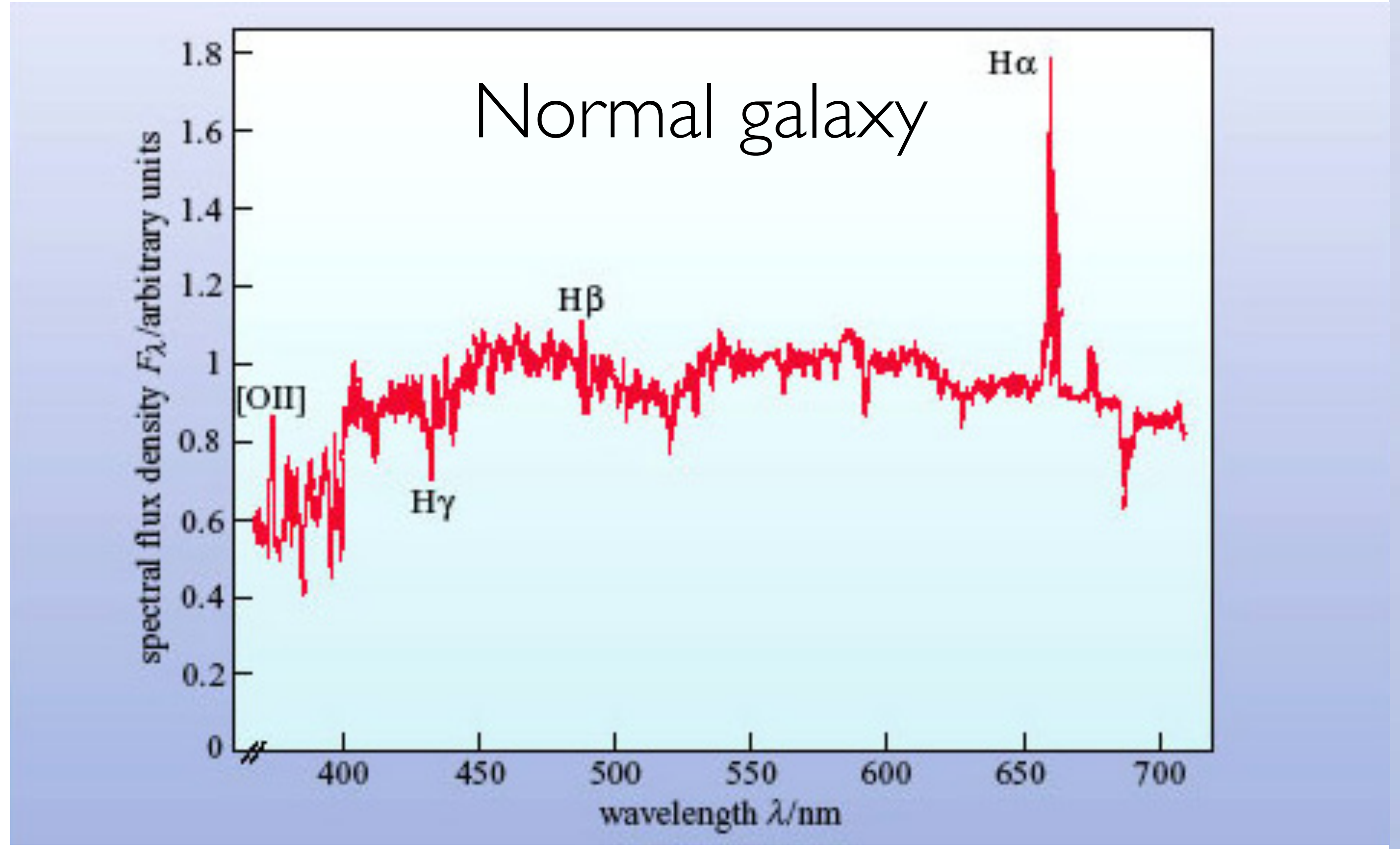
Visible to large redshifts (z > 7.5) - peak z~2 (depends on type)

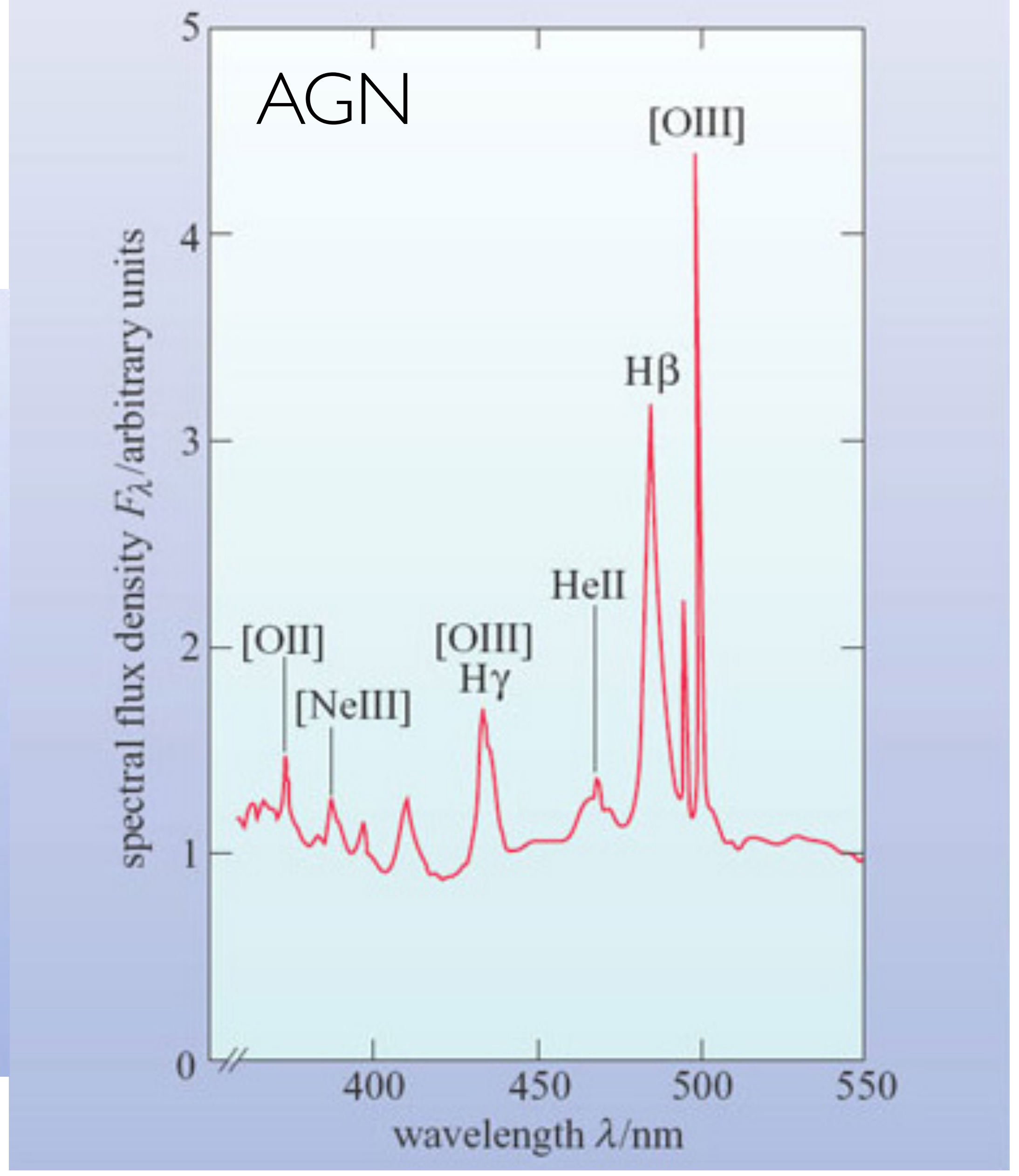
1% of galaxies active

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

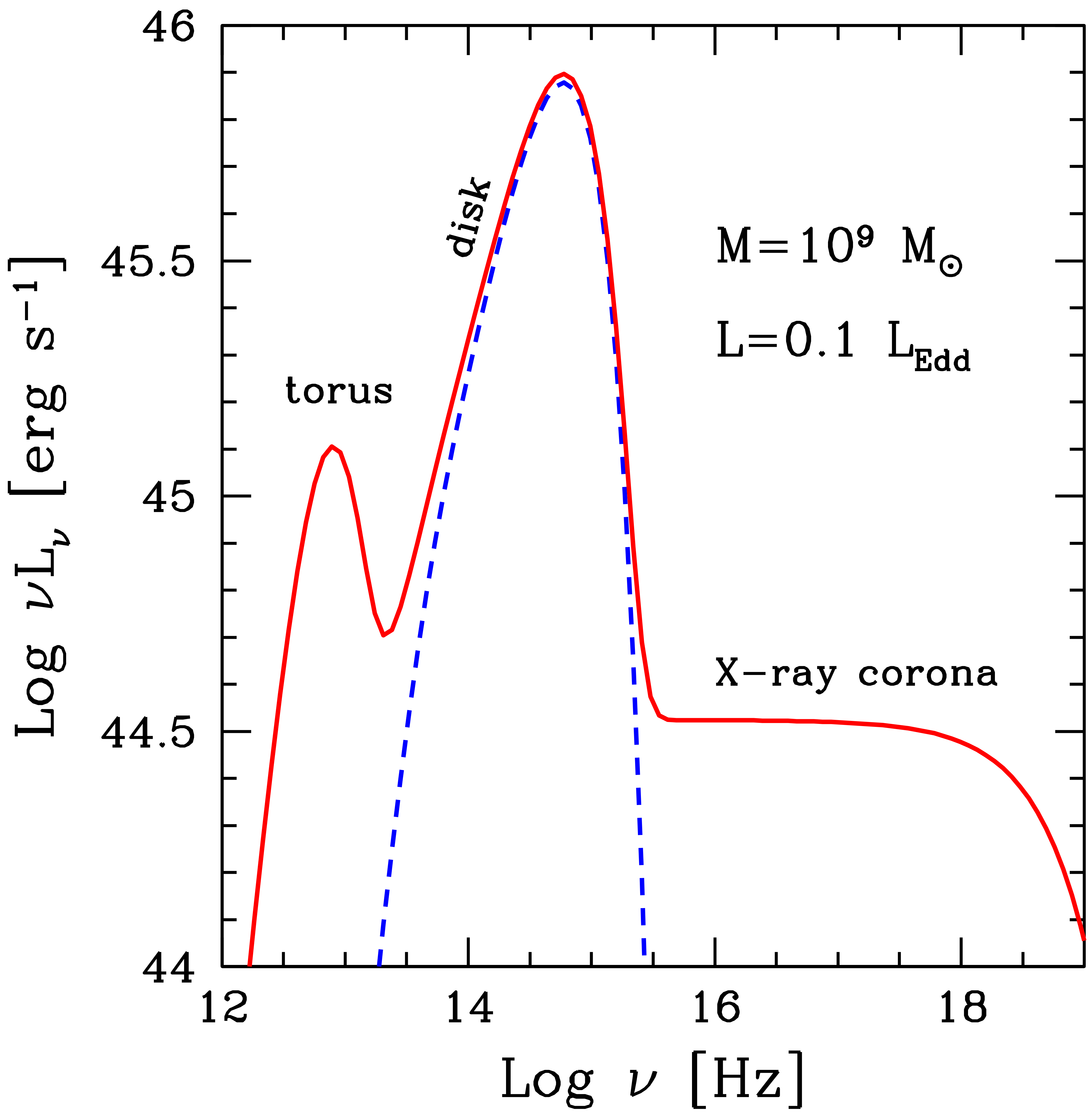
$$L_{\rm disk} = 0.1\dot{M}c^2 = 10^{46}\ \mathrm{erg/s}$$

In solar masses per year, the requirement is

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

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, $L_{\rm Sun}$ = 3.85 × 10^{33} erg/s

The engine

For an AGN with disk luminosity

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

and time variability

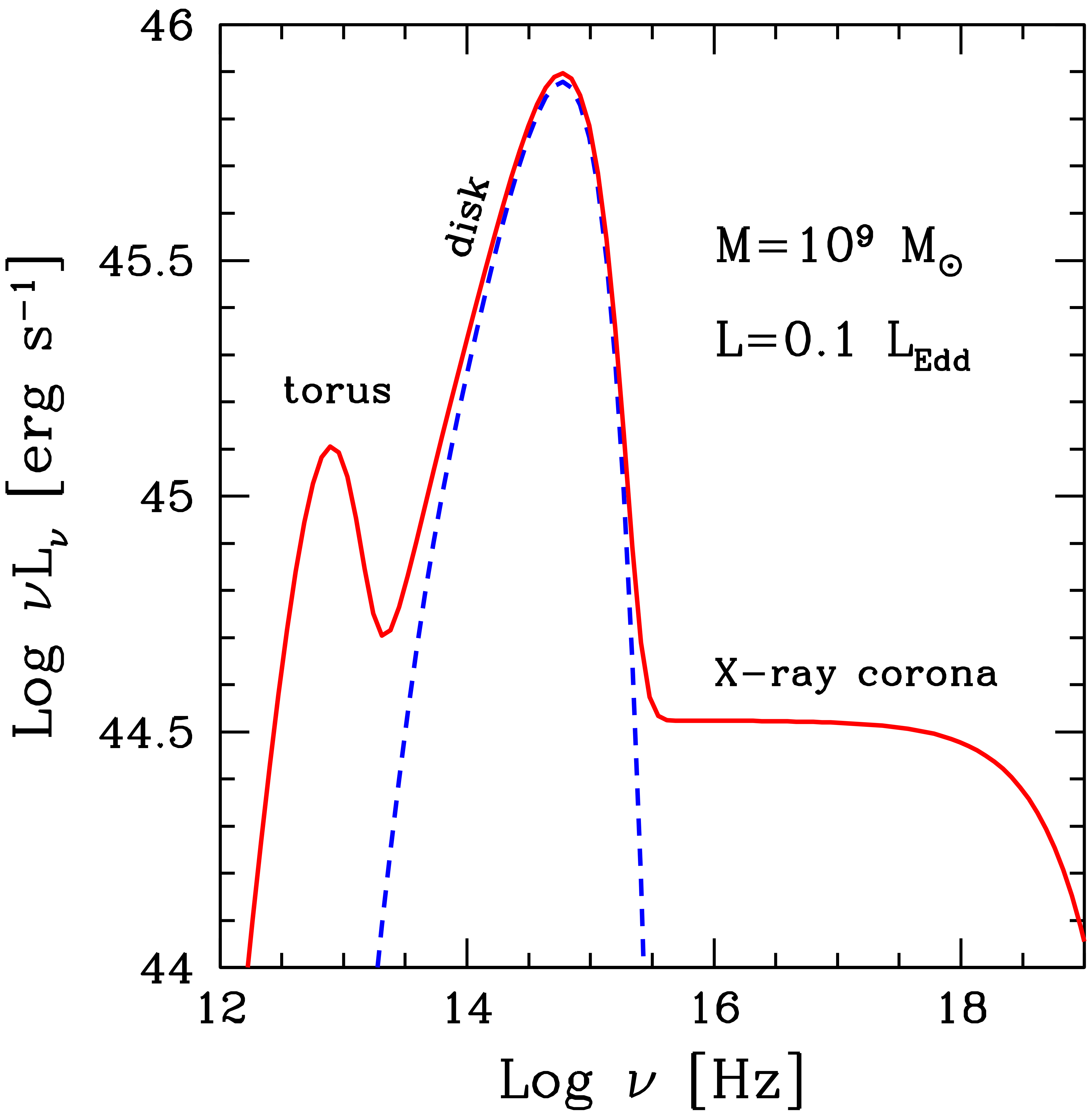
$\Delta t = 10^4\ {\rm s}$, causality dictates $R \sim c\Delta t = 0.01\ {\rm pc} = 20\ {\rm AU}$

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,

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

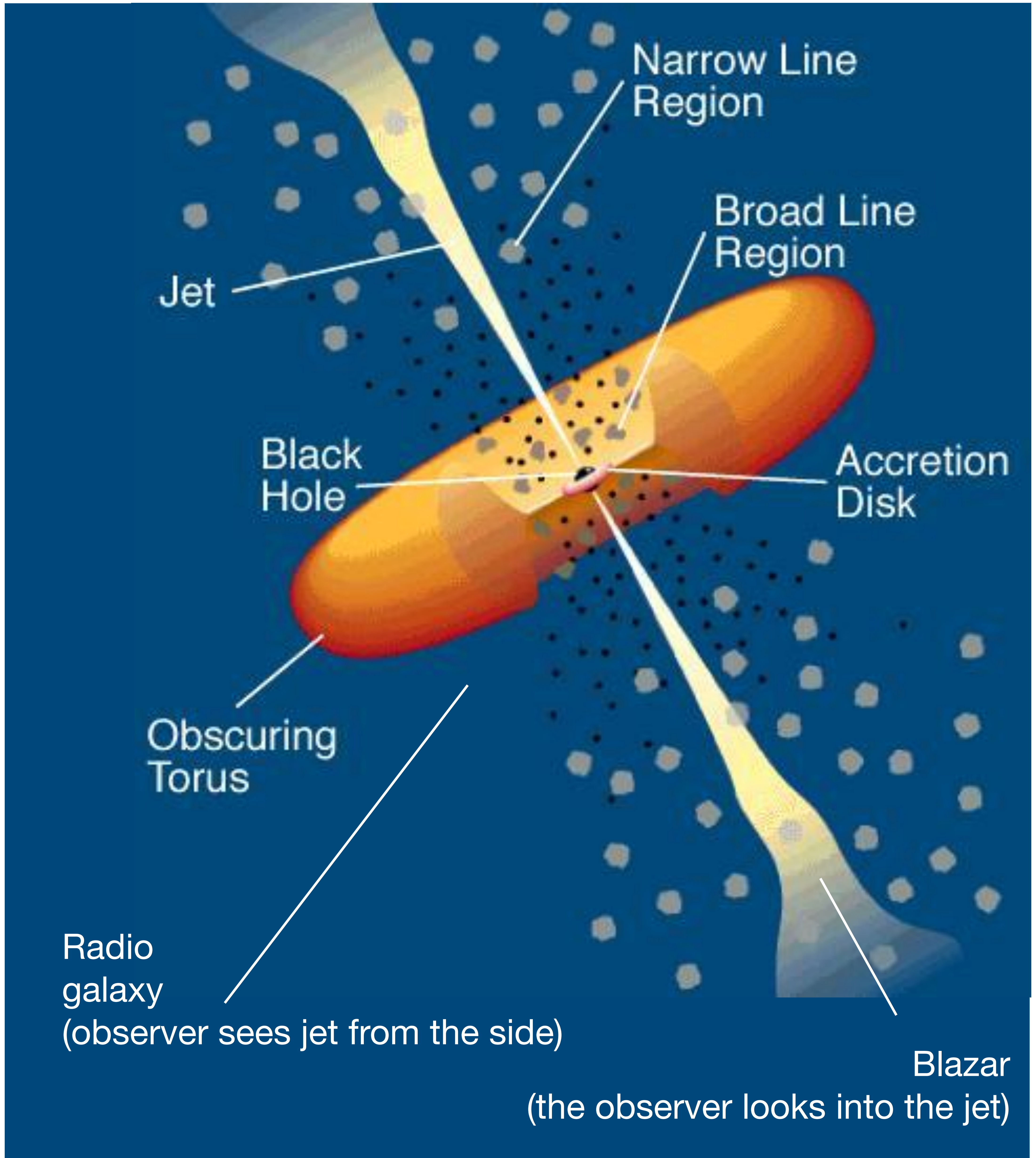


AGN Unification

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

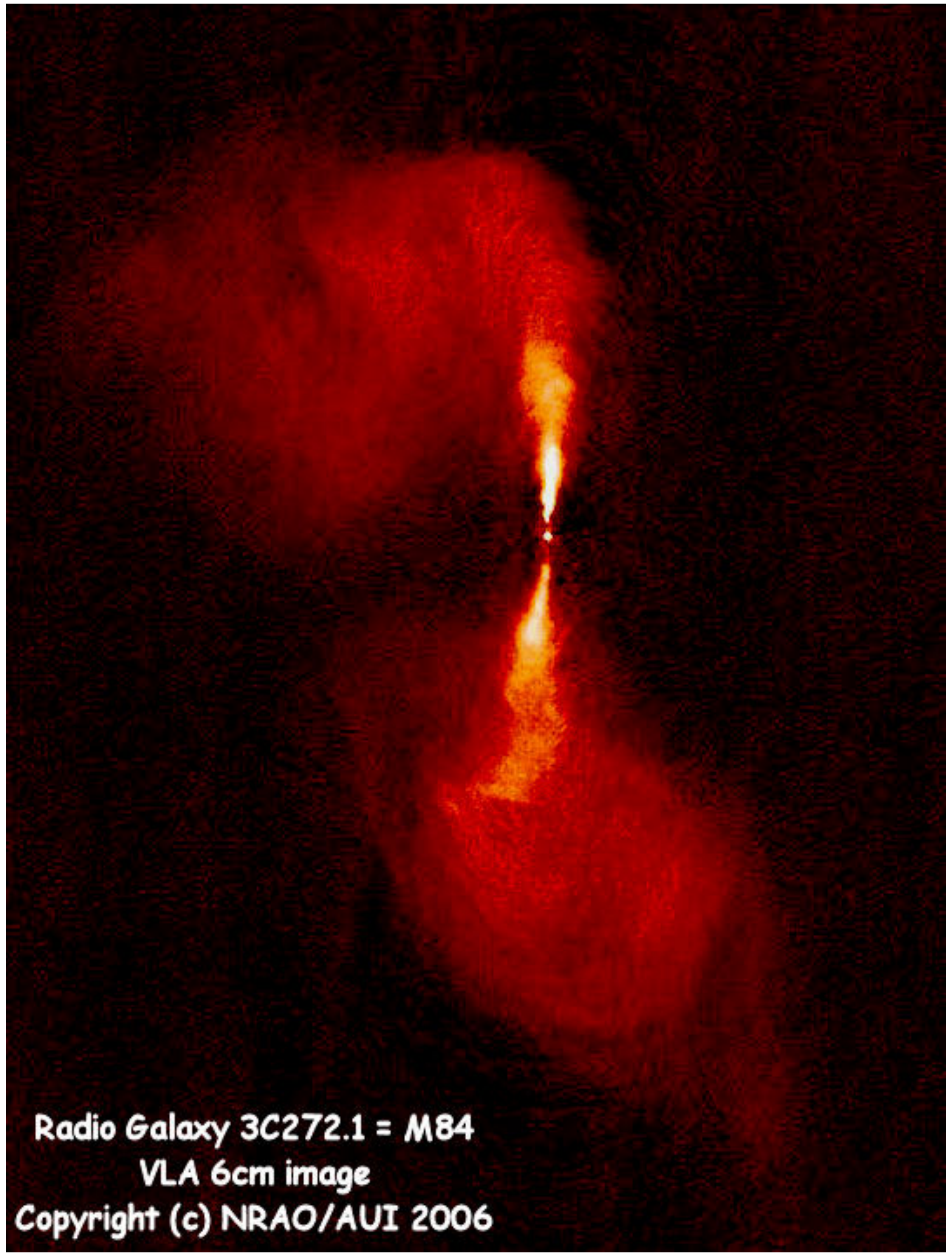
- Orientation
- Presence of jet or not (10% have it)
- Radiative efficiency

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

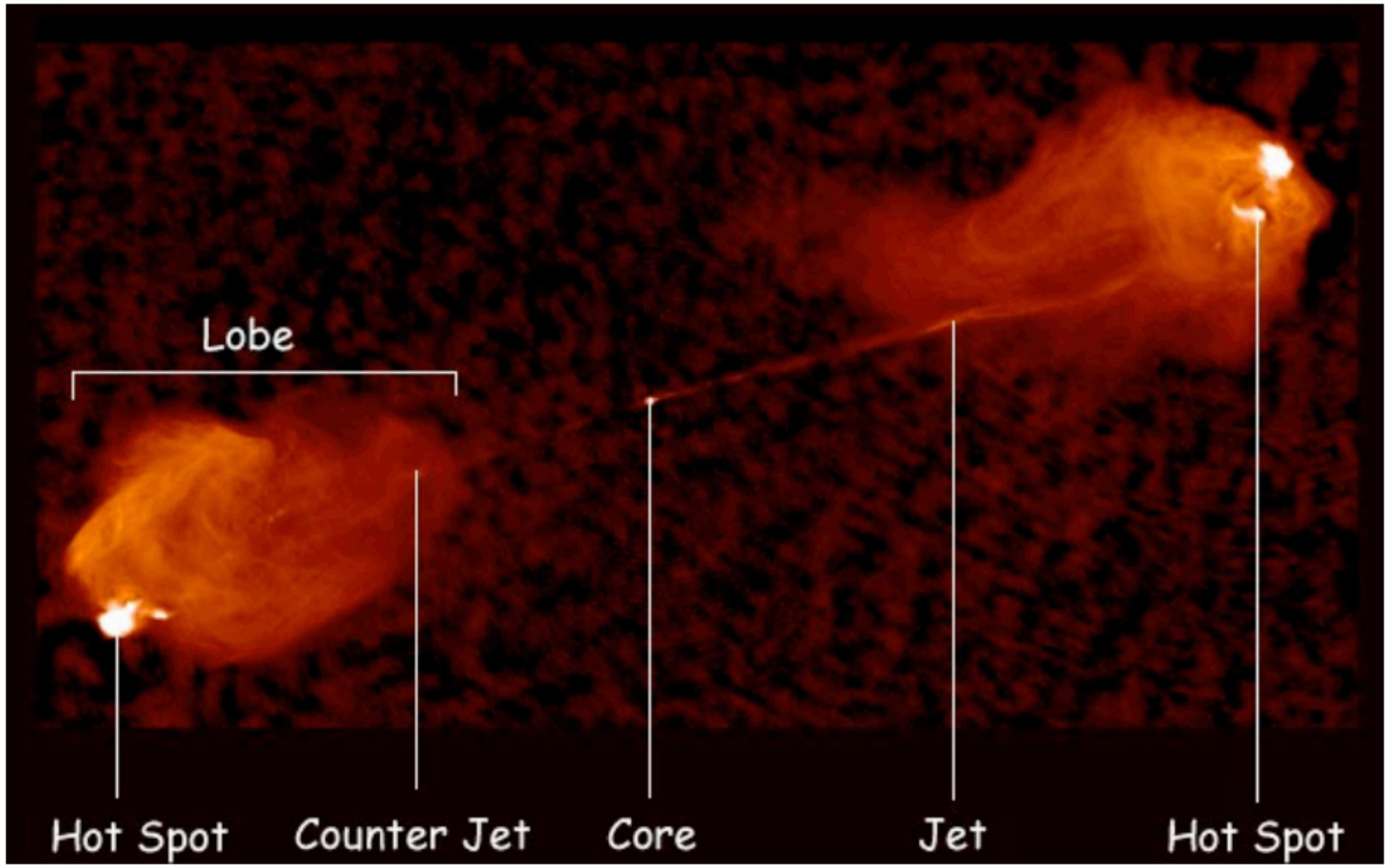


10% of AGN host jets

FRI



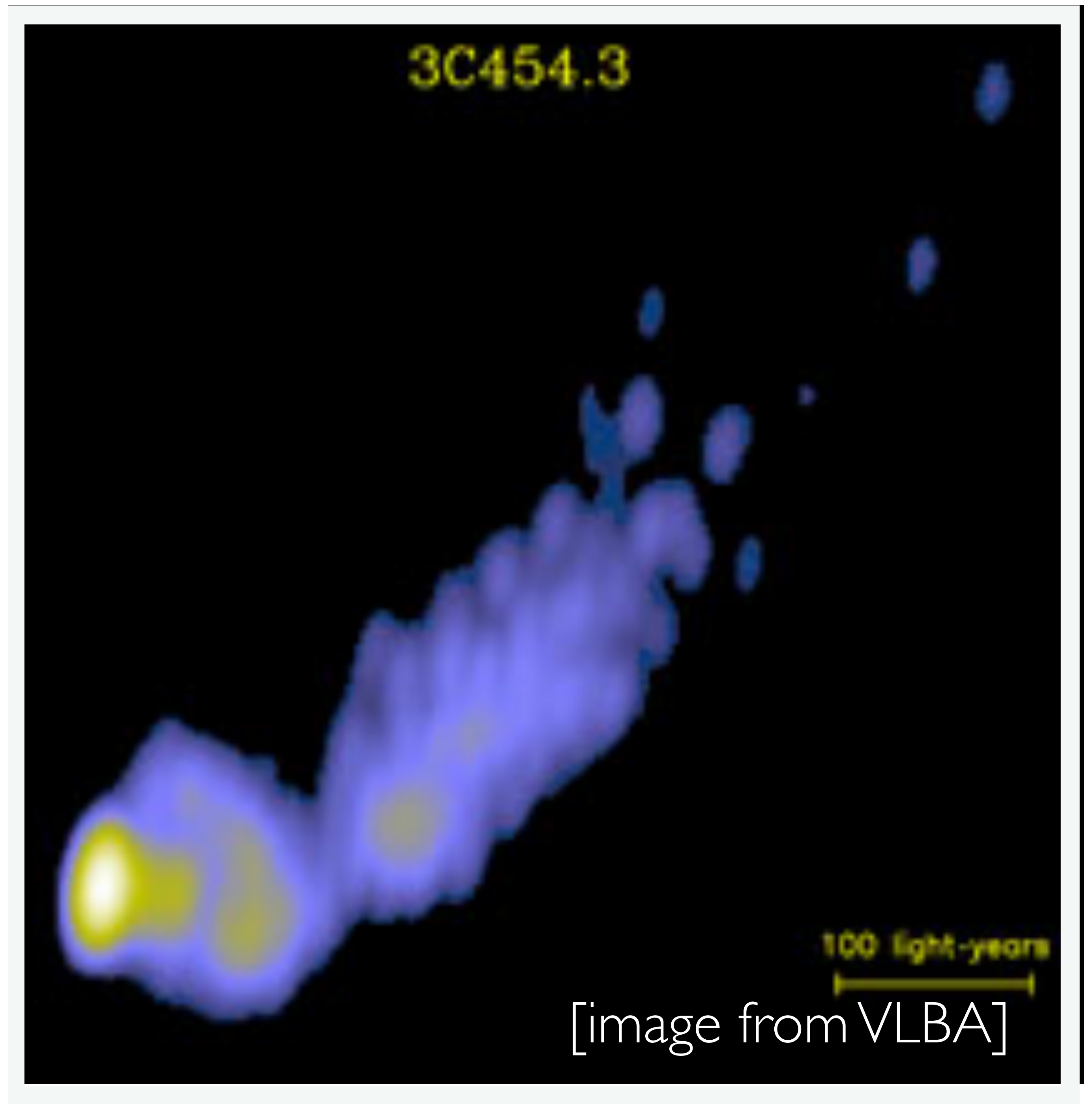
FRII



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

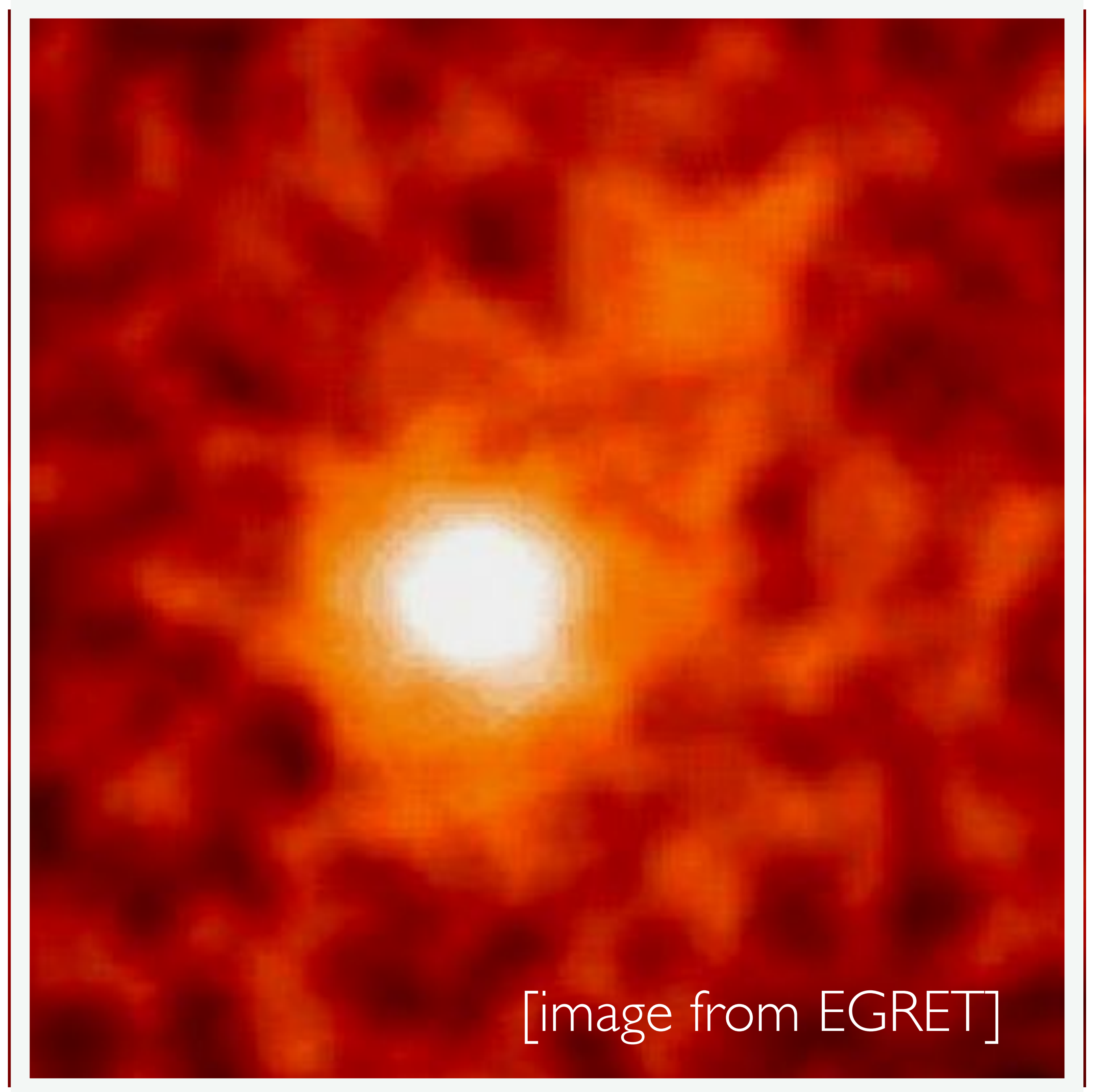
Blazars: Star-like appearance

Radio



Optical

γ-rays



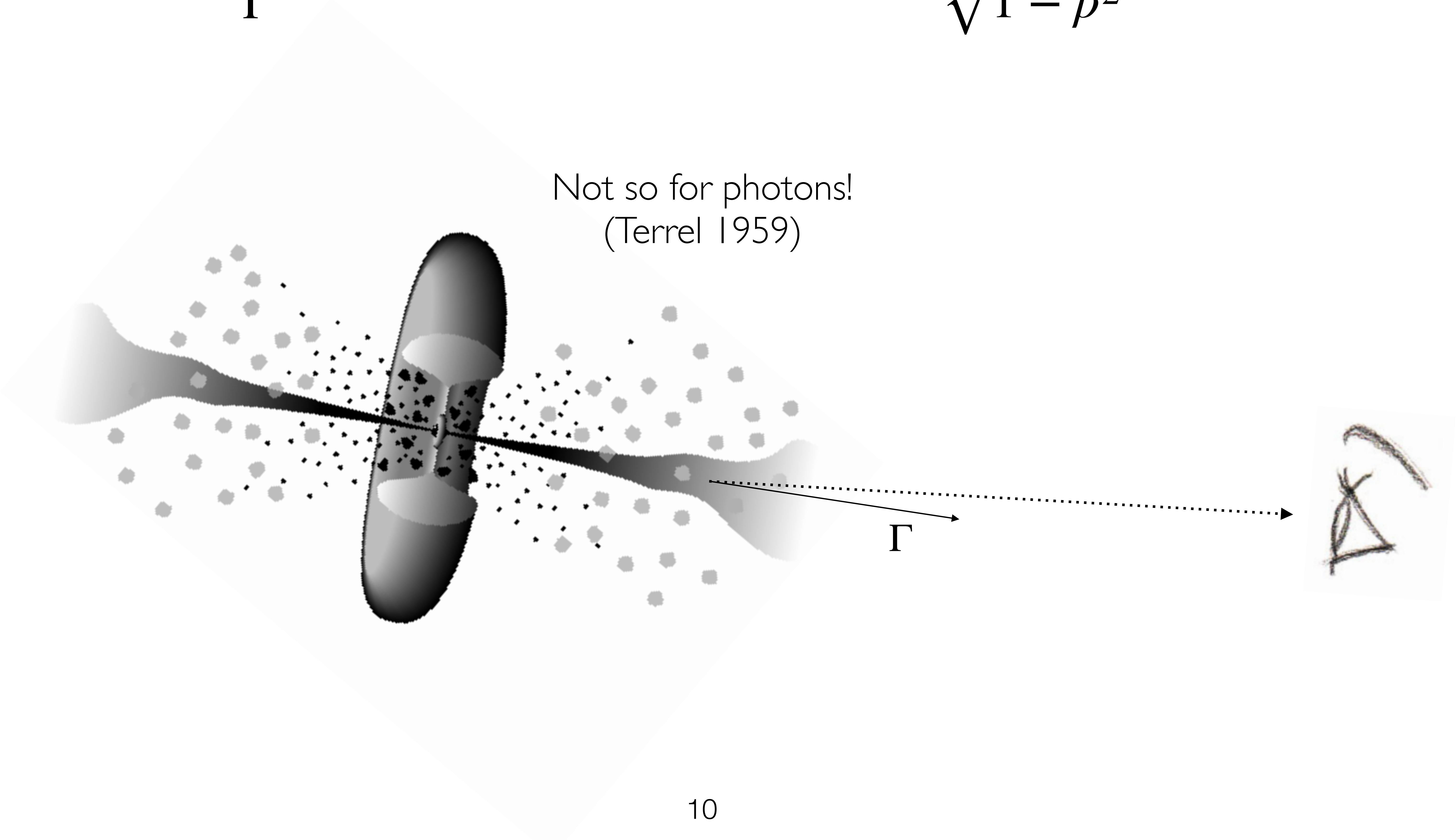
No spectacular jets…but wealth of information from timing/variability and spectra!

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

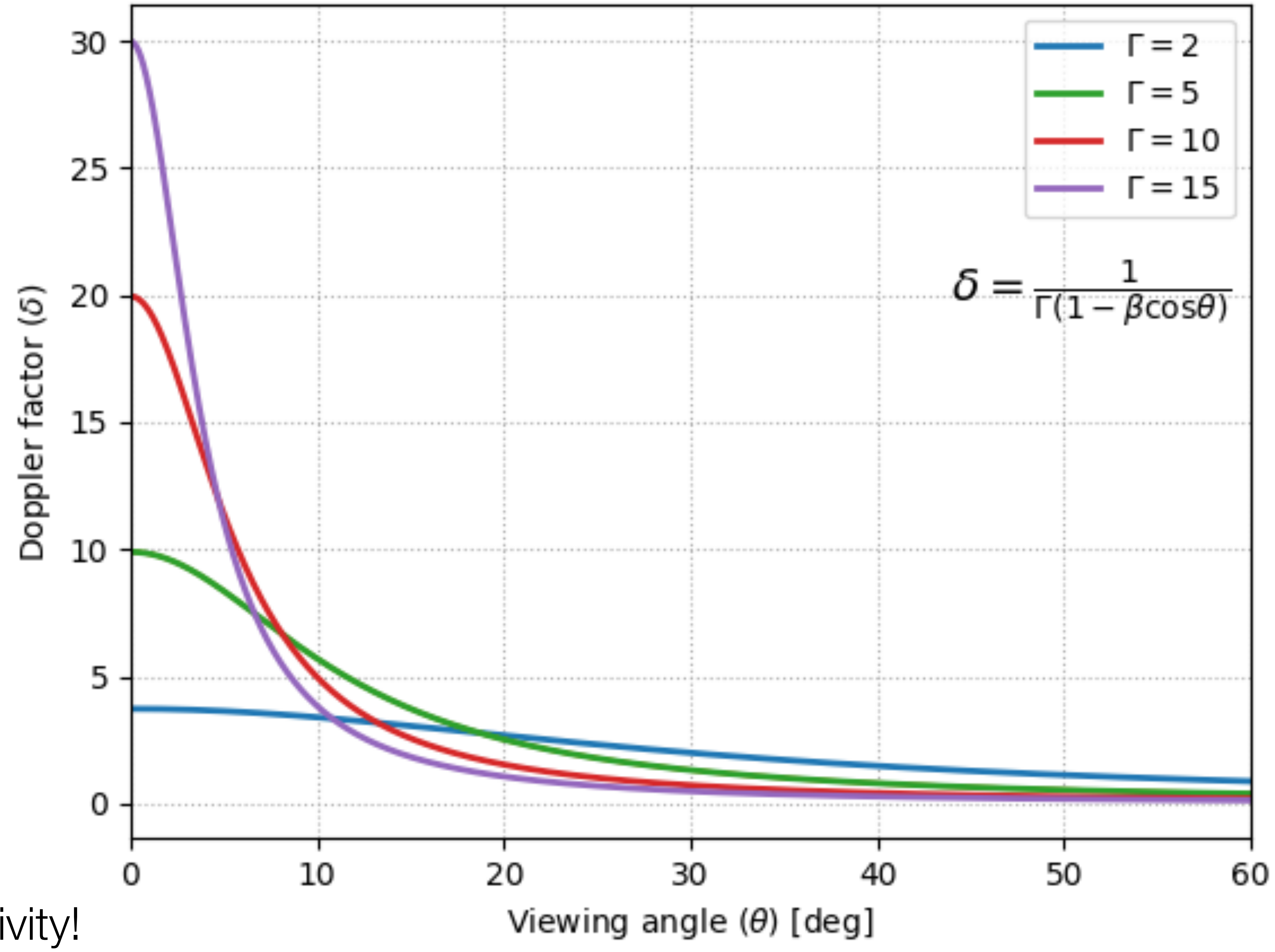
$\Delta t = \Delta t'/\delta$ (shortening of timescales)

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

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

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

(dashes denote rest-frame quantities)



Special cases:

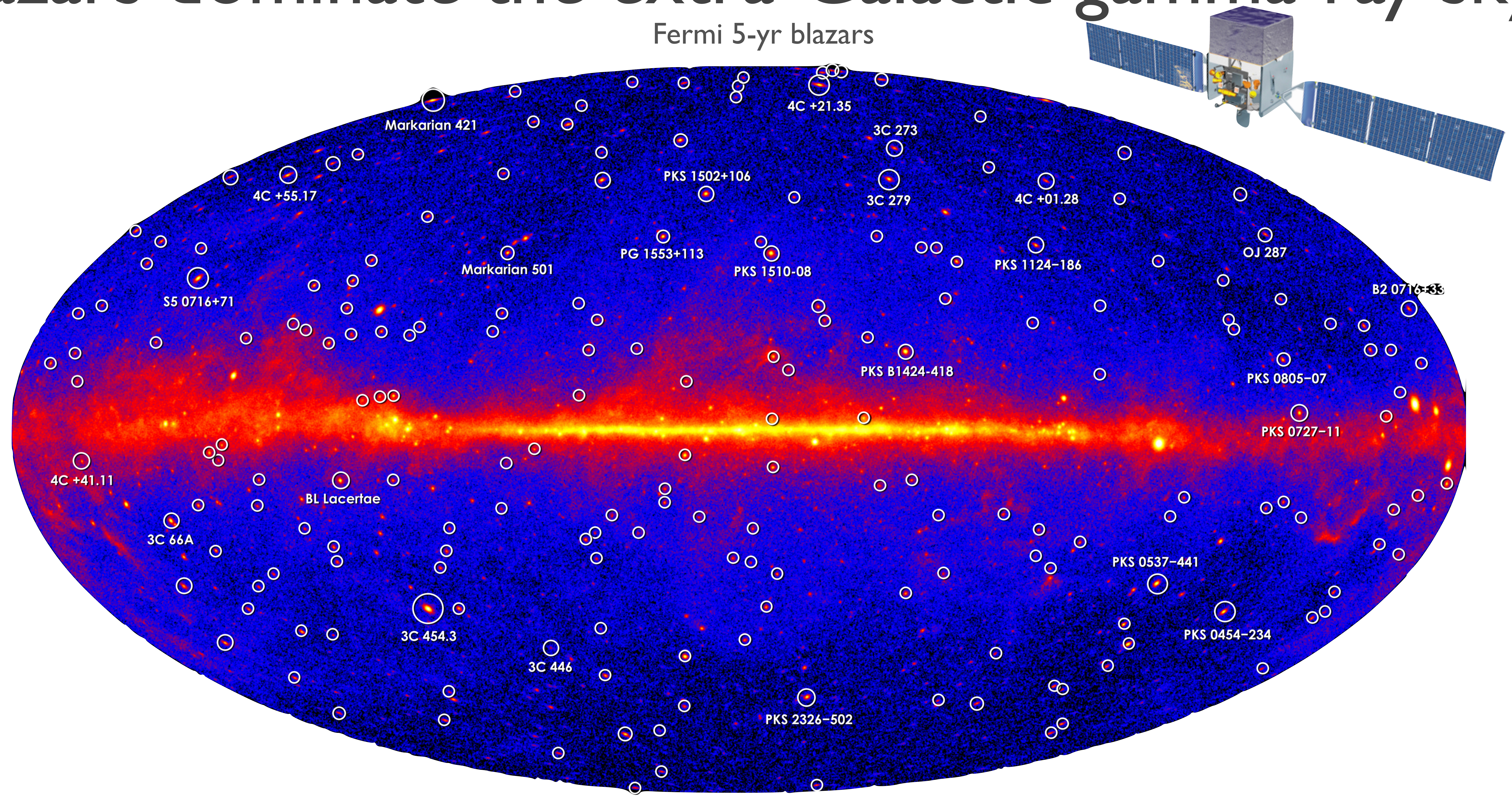
$\delta_{\rm max} = \delta(0^\circ) = \dfrac{1}{\Gamma(1-\beta)} = \Gamma(1+\beta) \sim 2\Gamma$

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

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

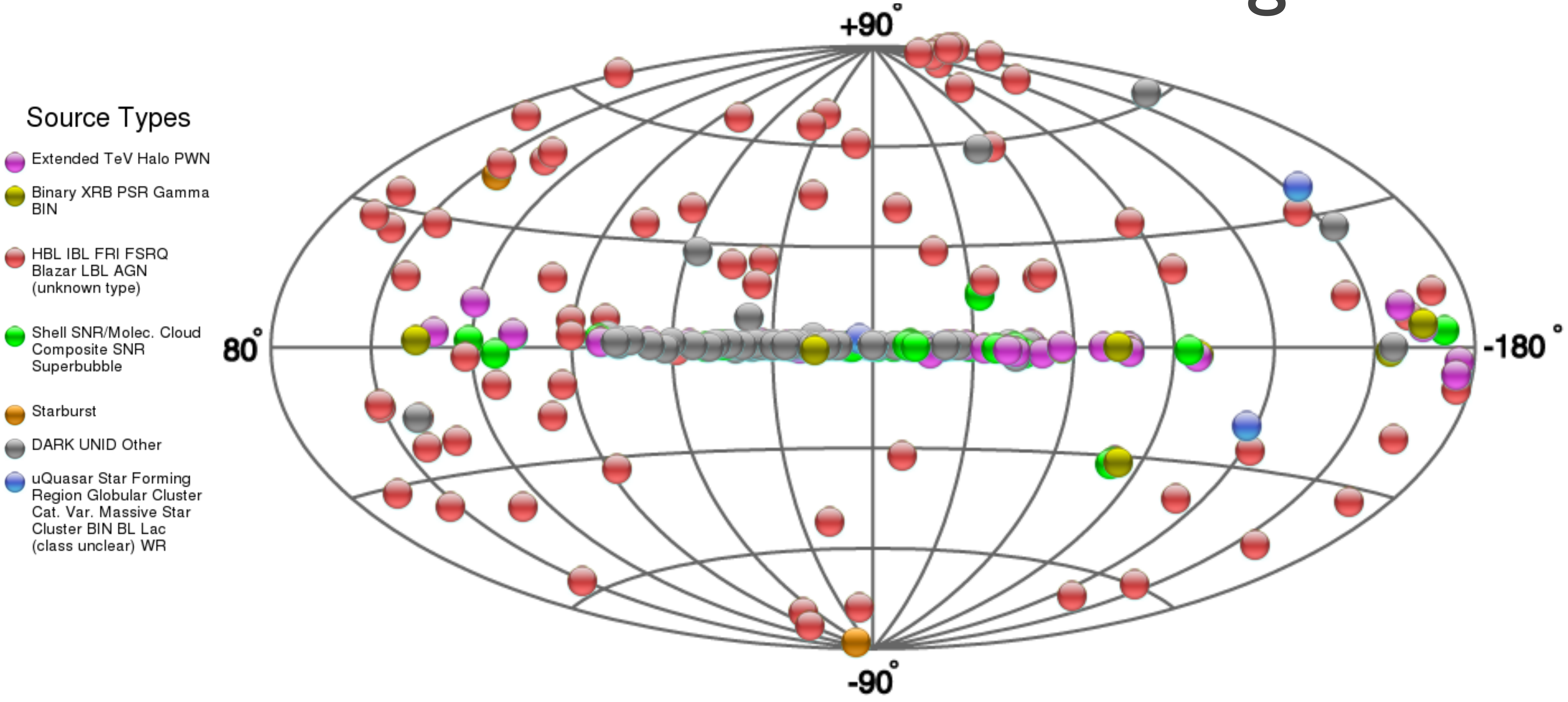
Blazars dominate the extra-Galactic gamma-ray sky

Fermi 5-yr blazars

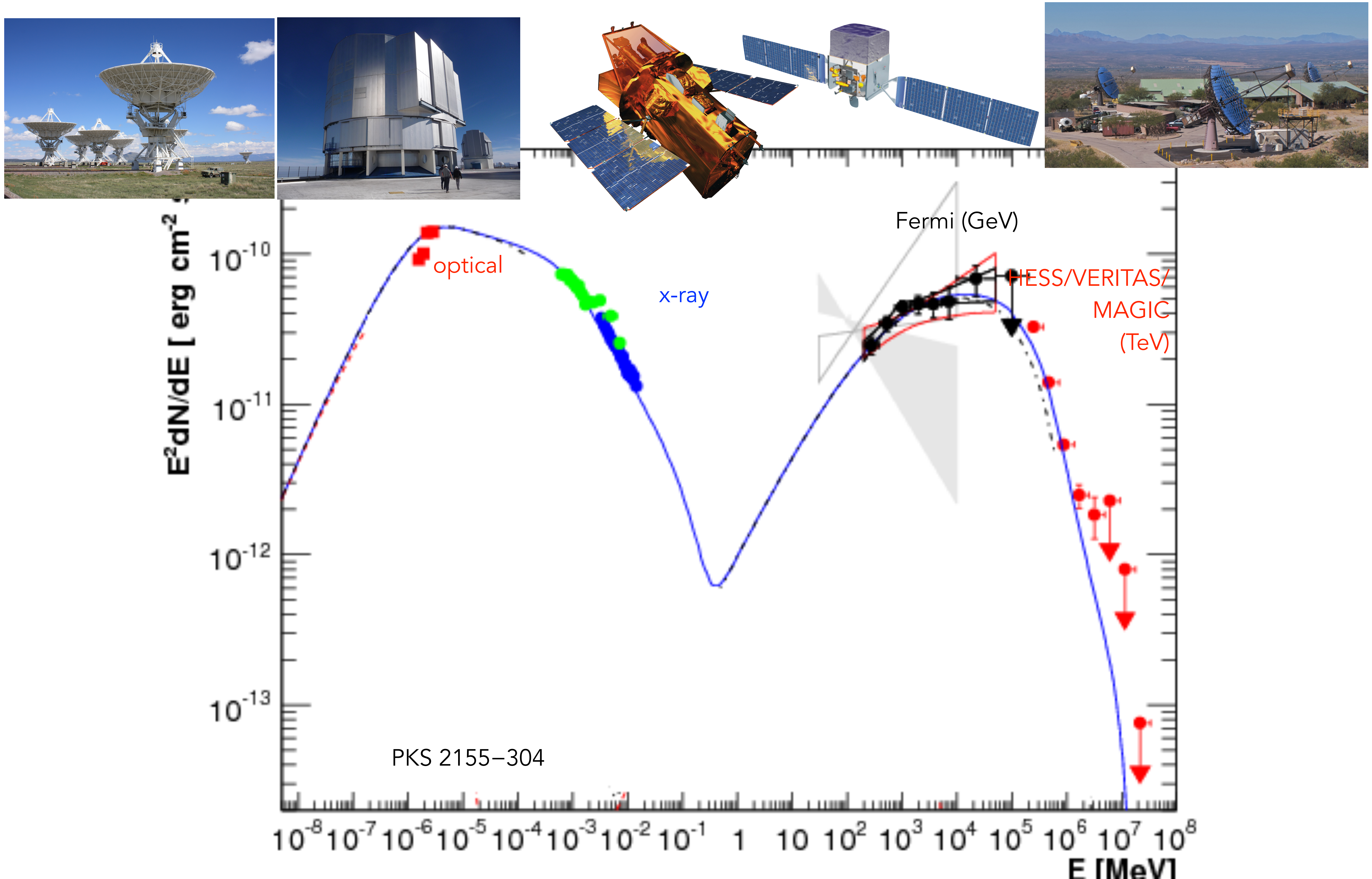


>90% of extragalactic Fermi sources (see also TeVCaT)

Blazars dominate the extra-Galactic gamma-ray sky



Blazar spectral energy distribution

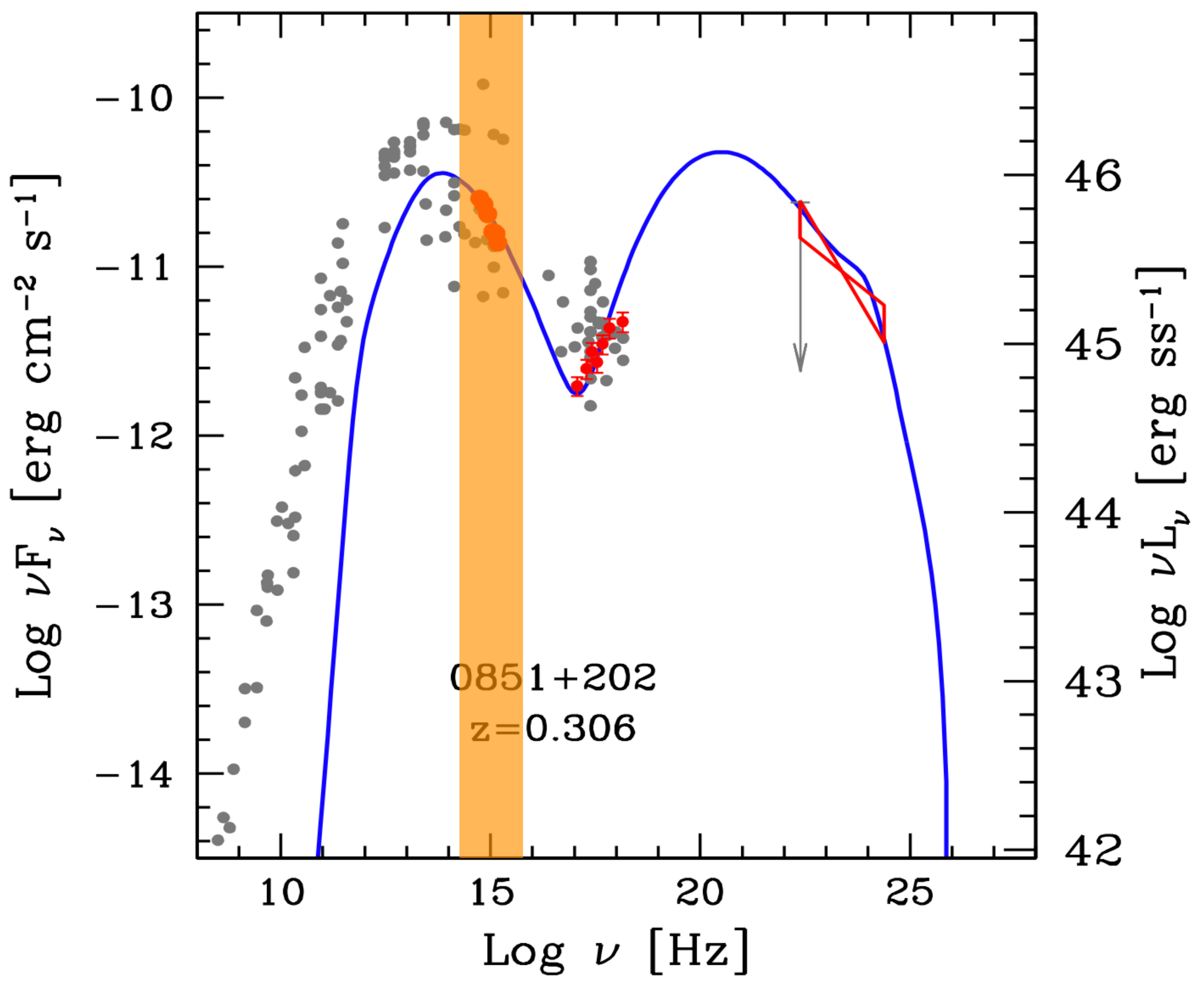


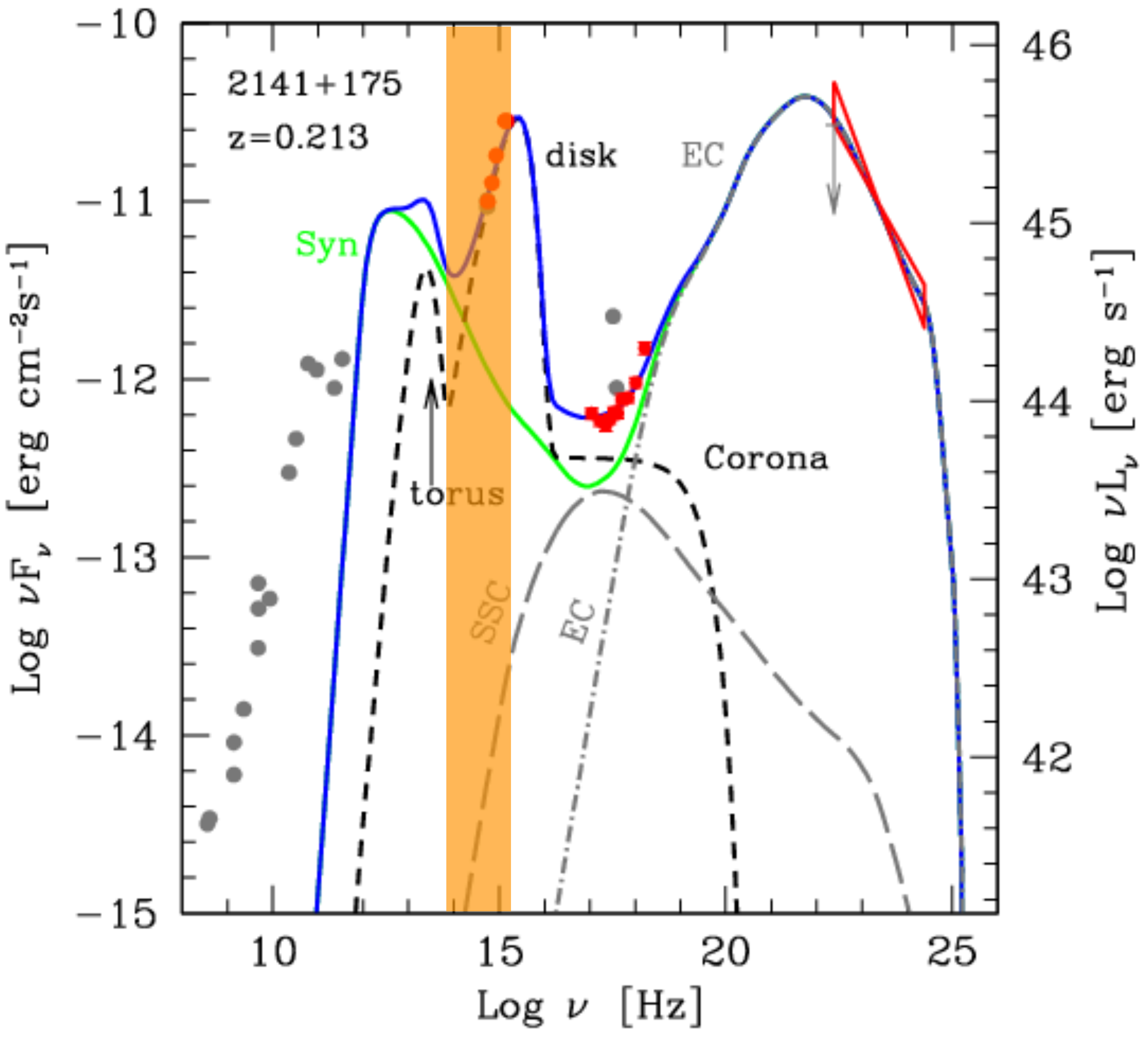
Blazar classes: BL Lac objects and FSRQs

BL Lac Object

Optical light

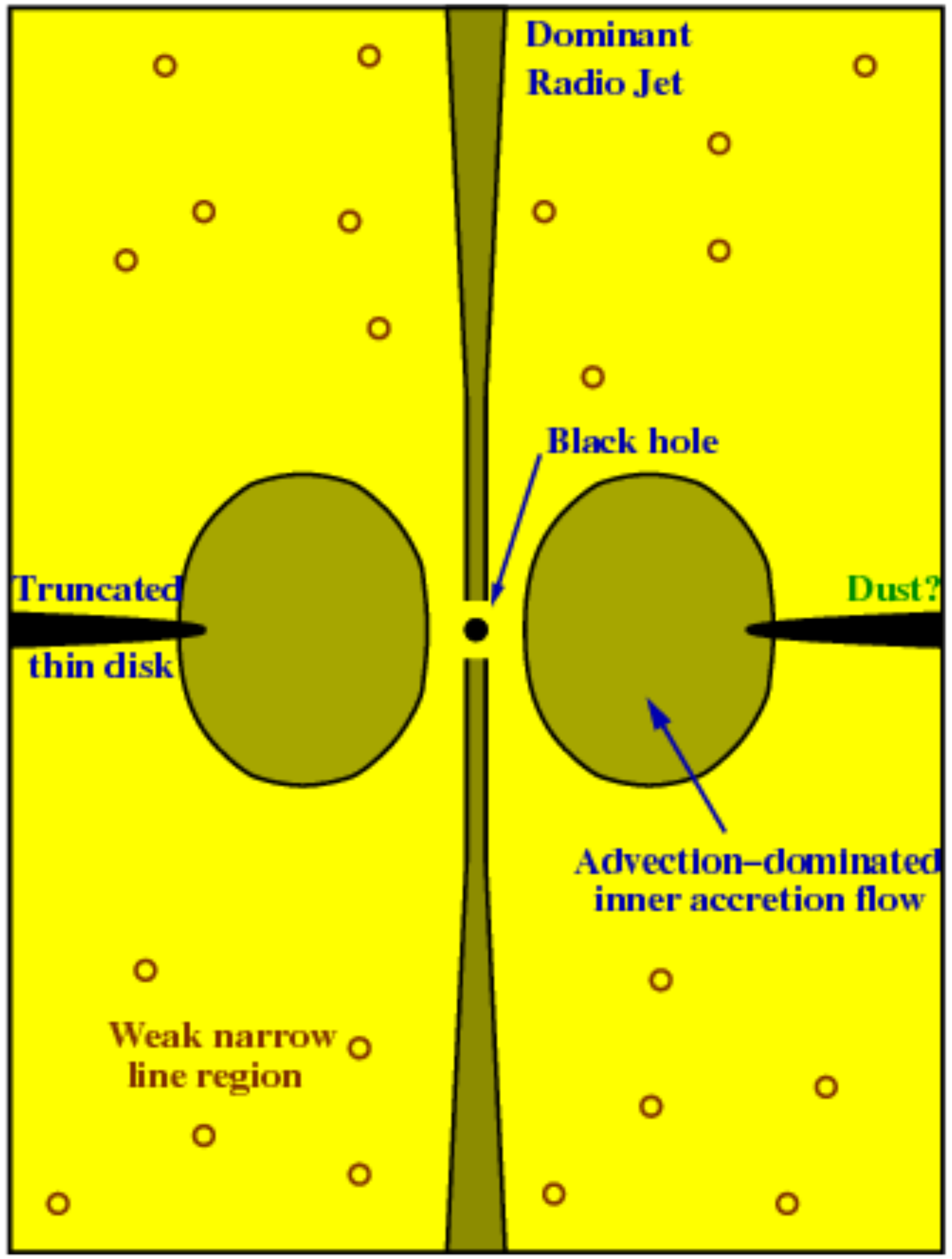
Flat spectrum radio quasar



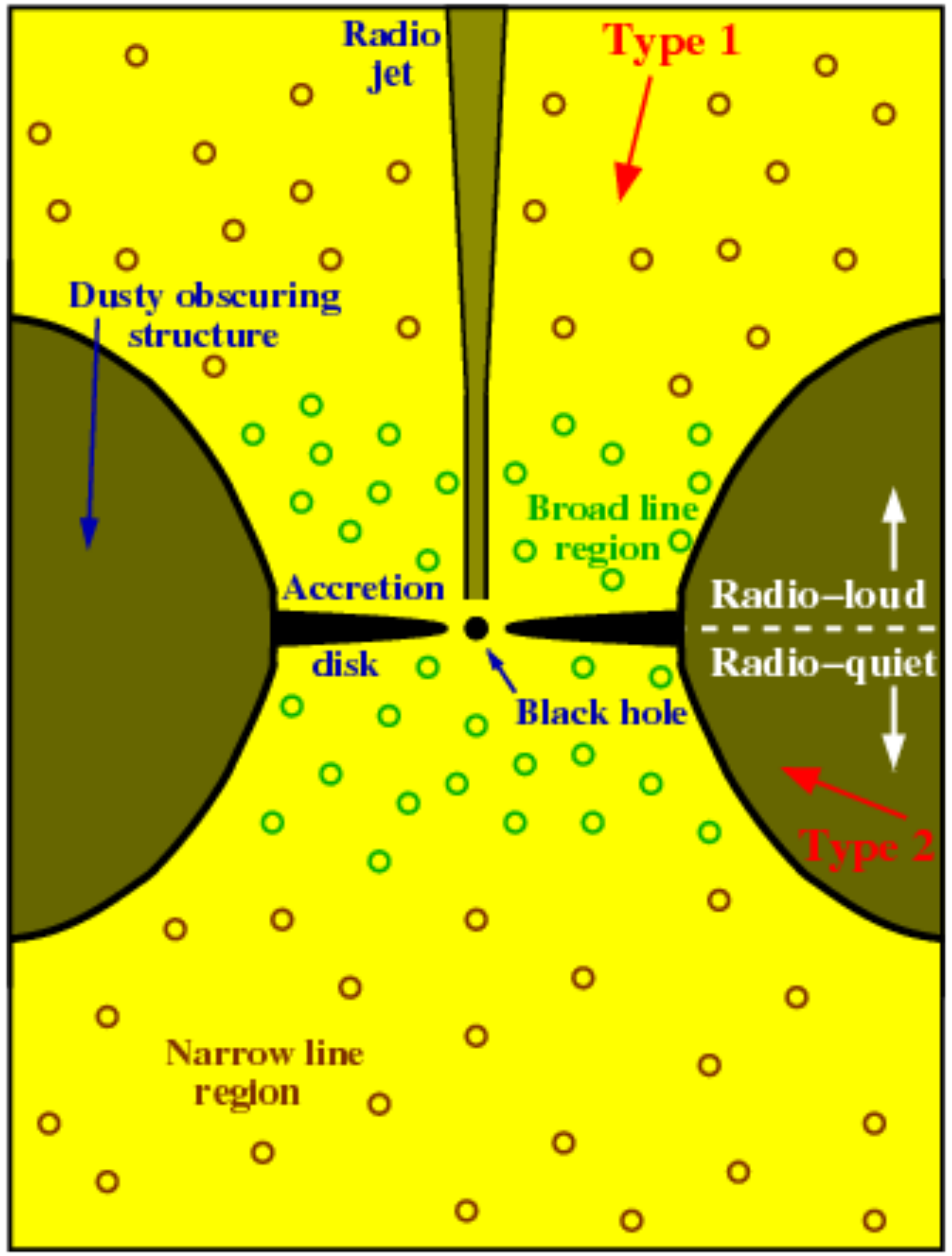


Blazar classes: BL Lac objects and FSRQs

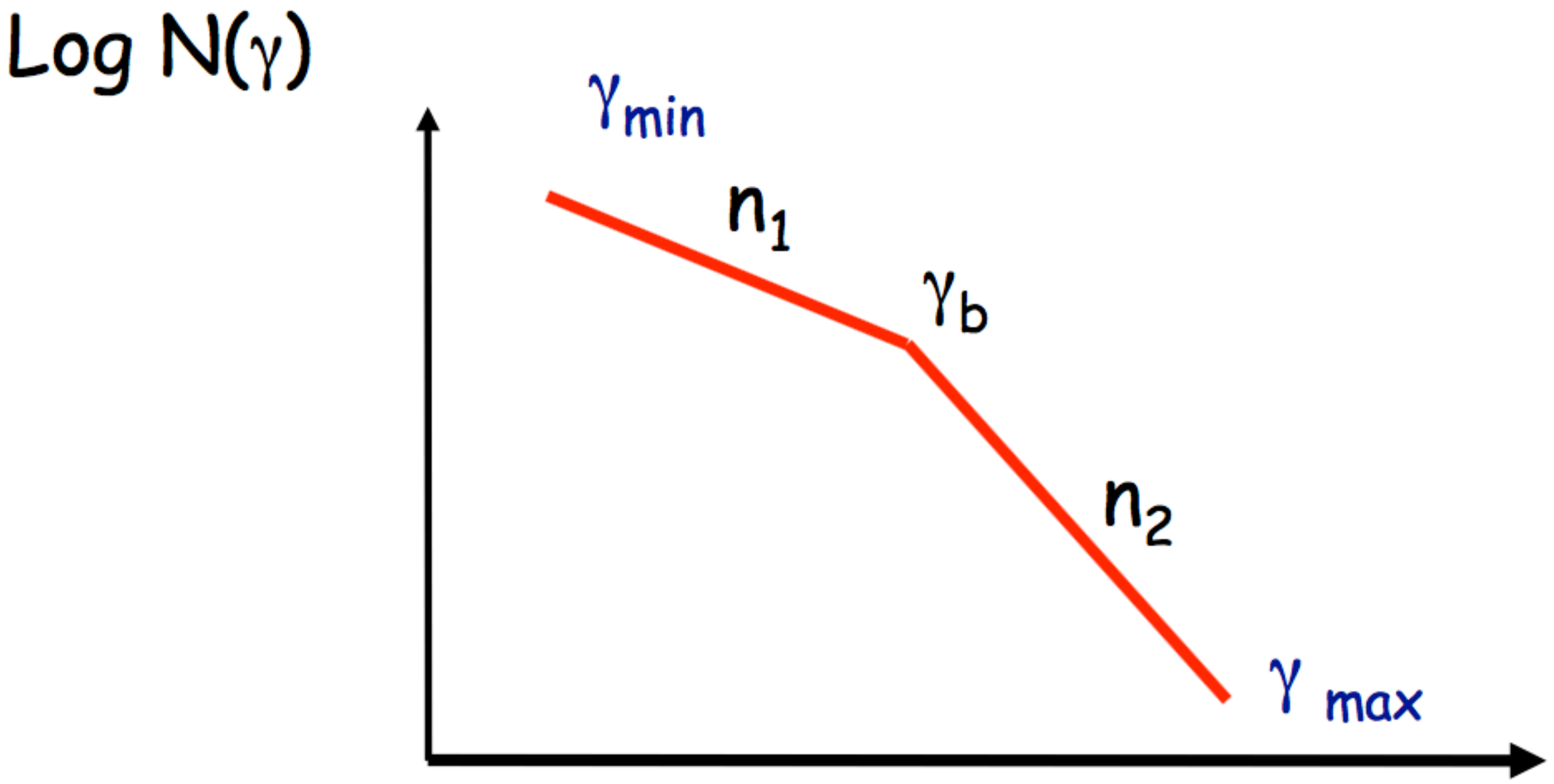
BL Lac Object



Flat spectrum radio quasar



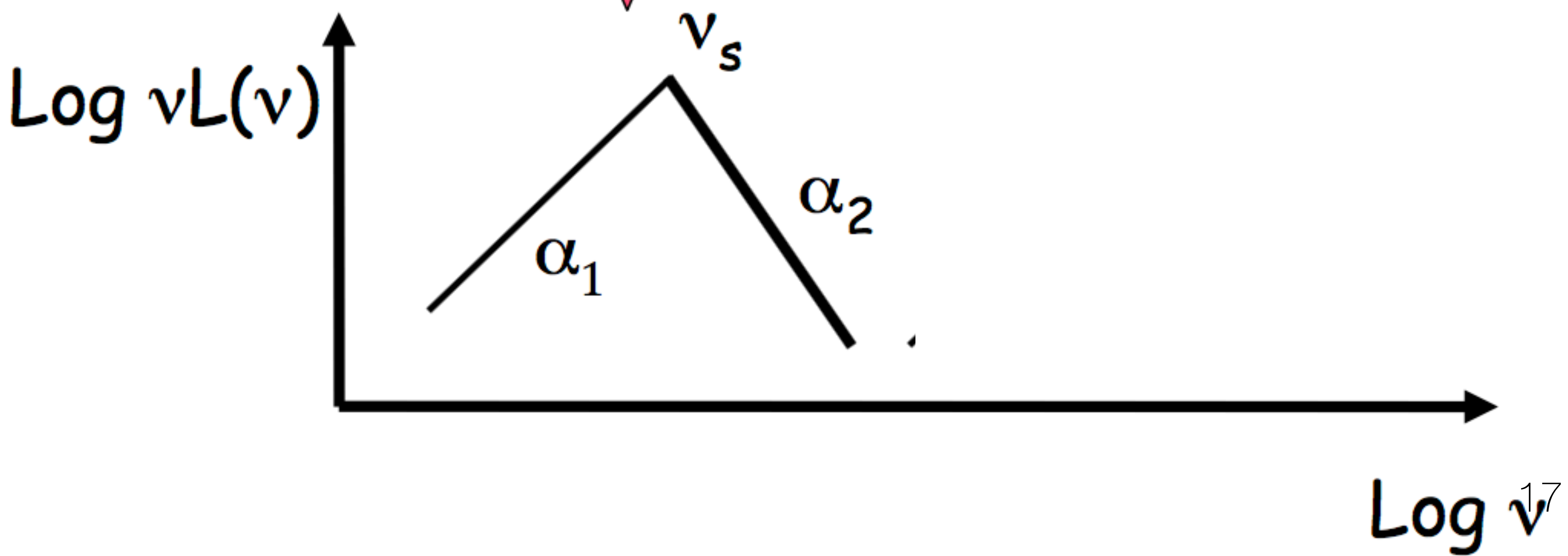
Emission from BL Lac objects

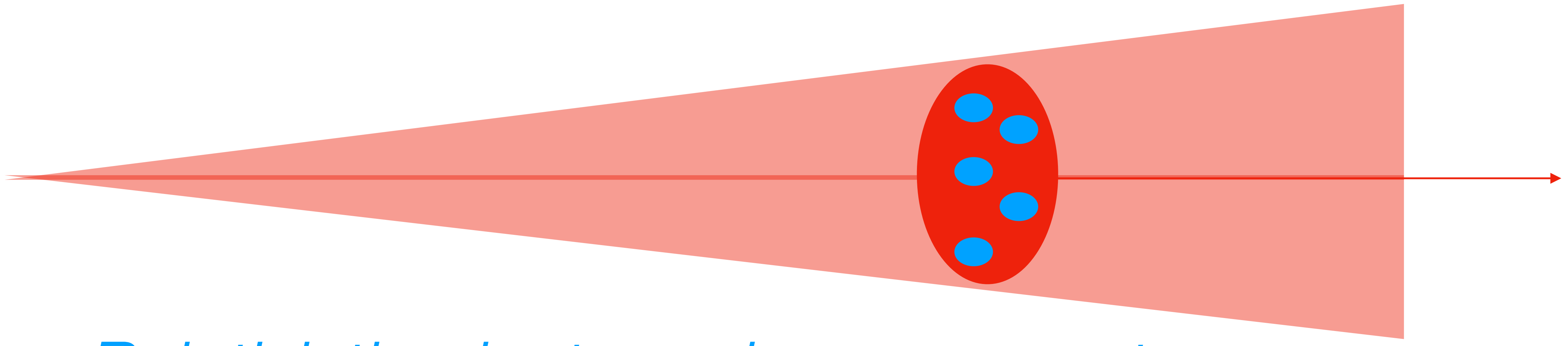


Synchrotron

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

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

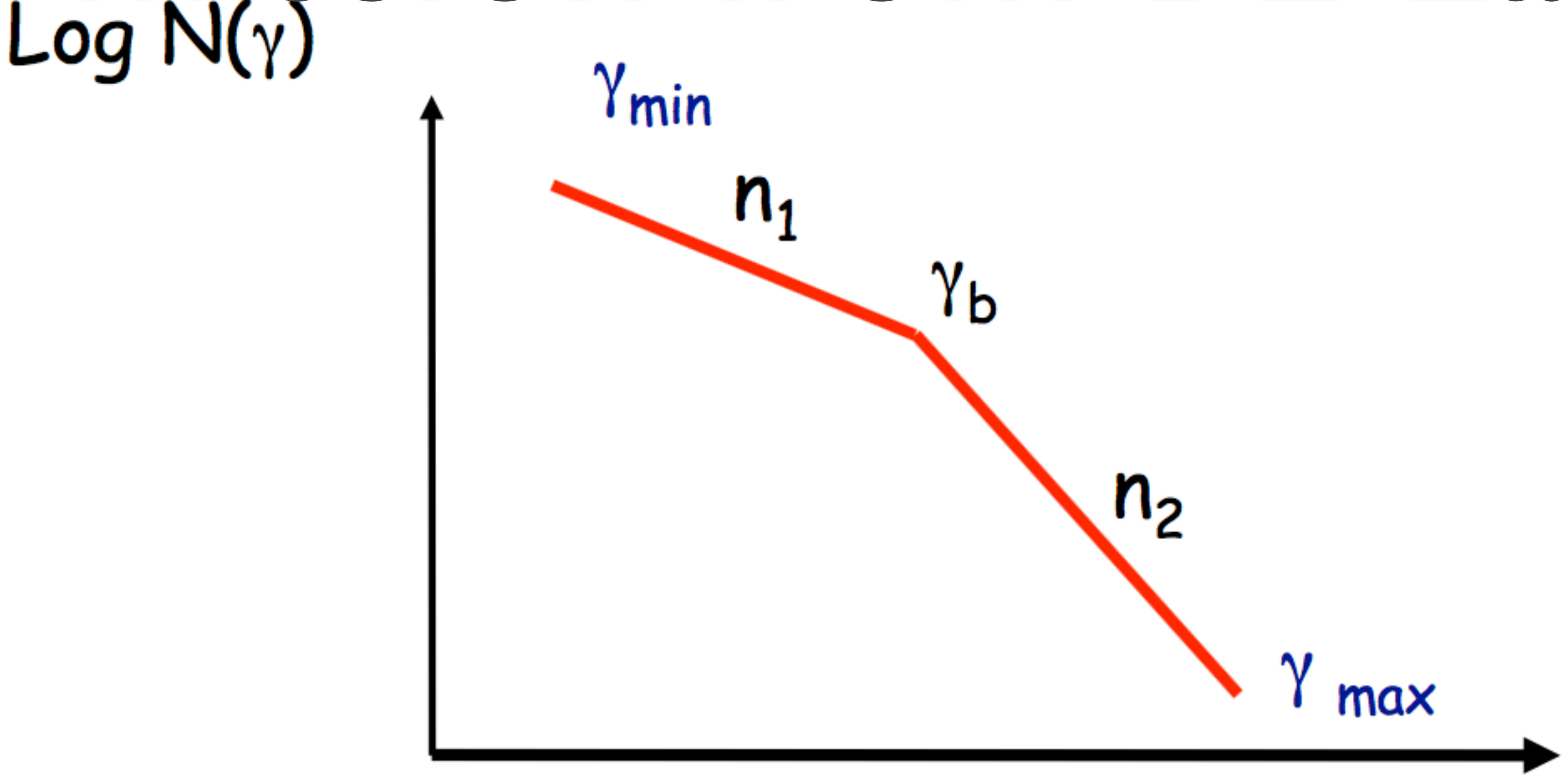


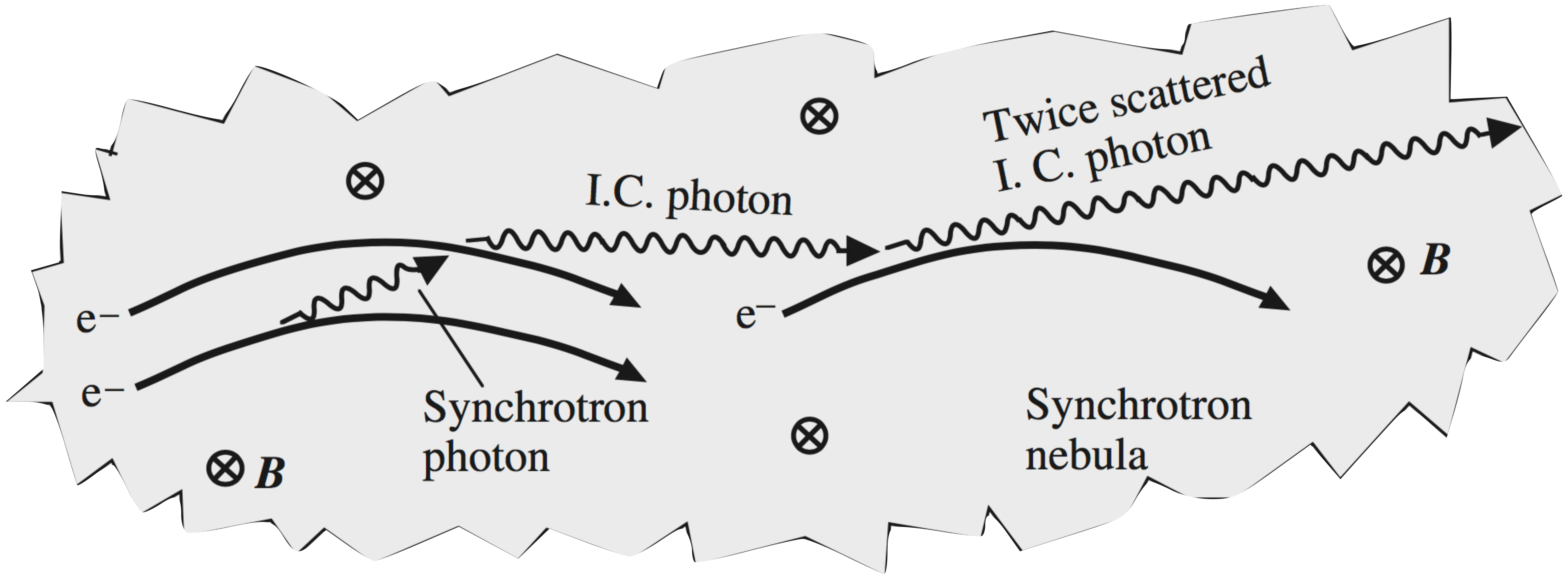


Relativistic electrons in a compact, relativistic region moving at $\beta \sim 1$

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

Emission from BL Lac objects



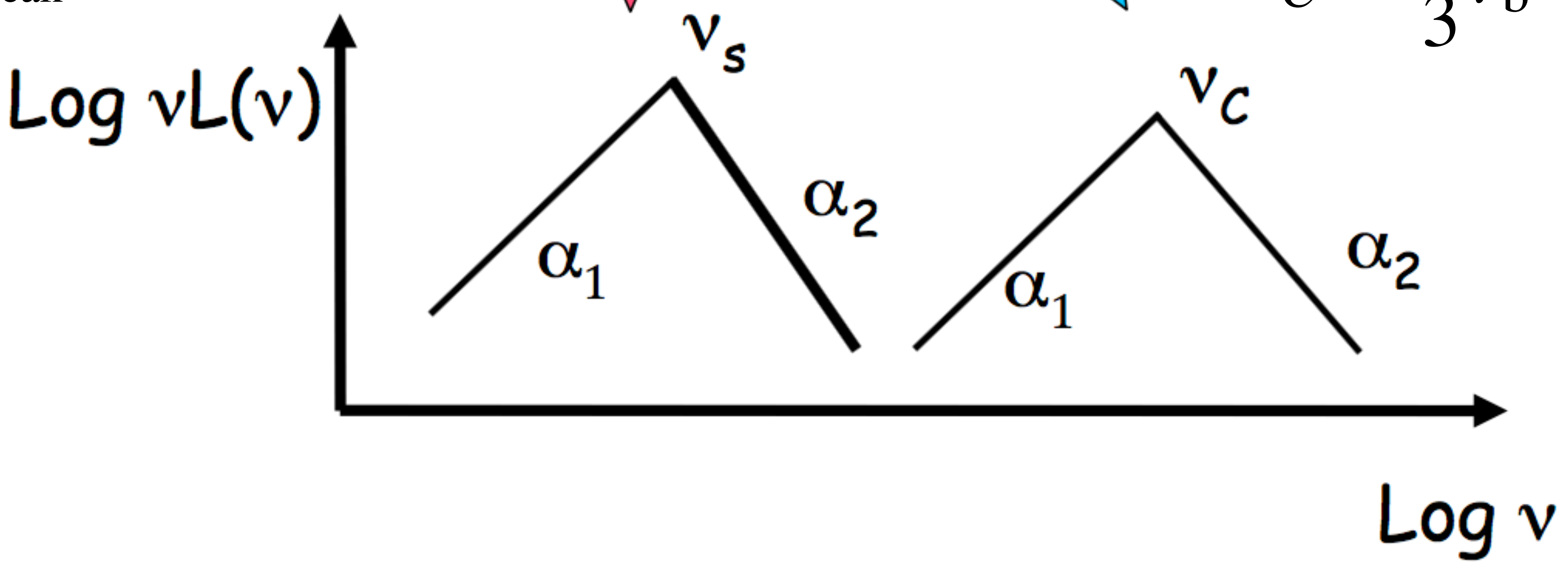


Synchrotron

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

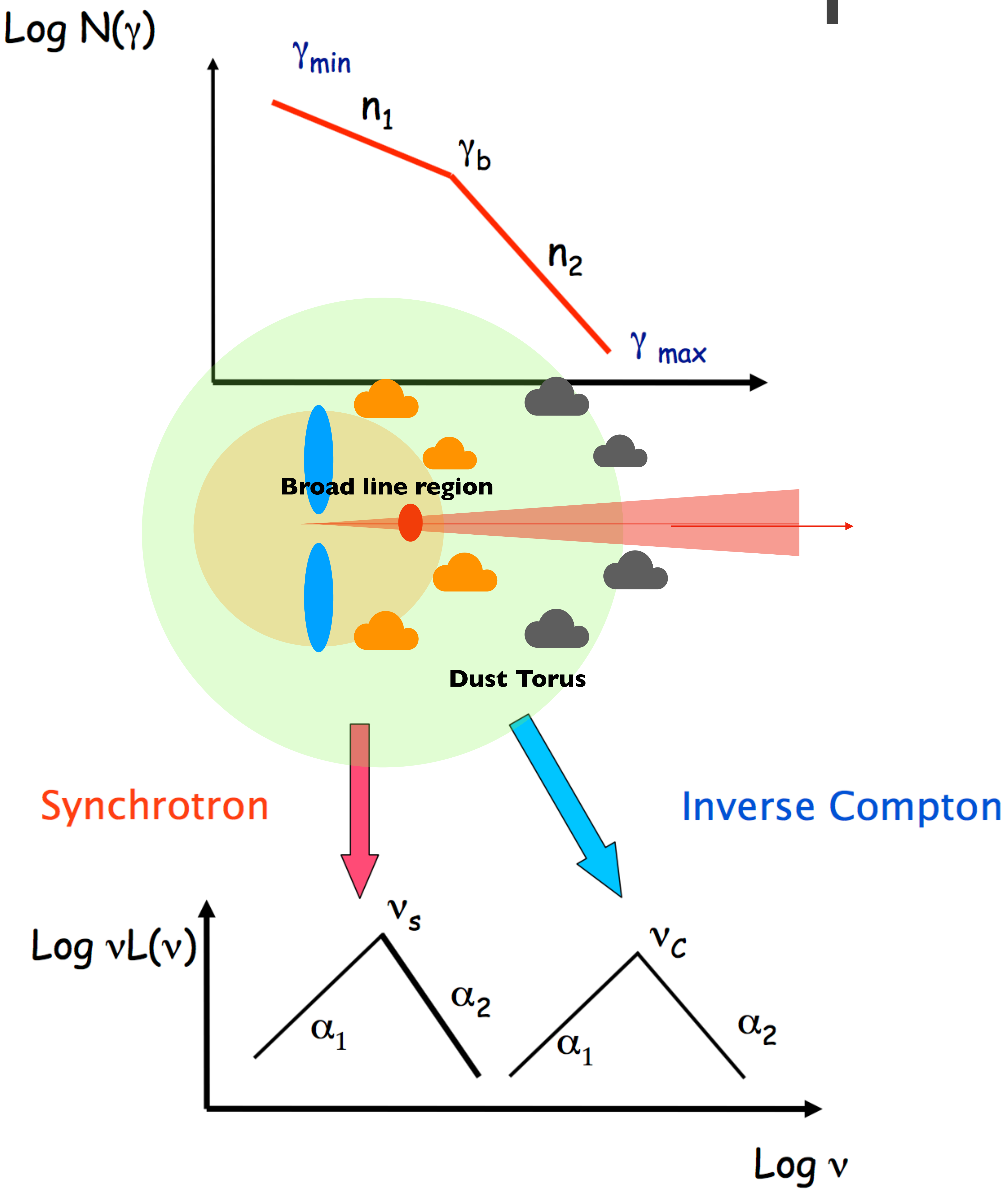
Inverse Compton

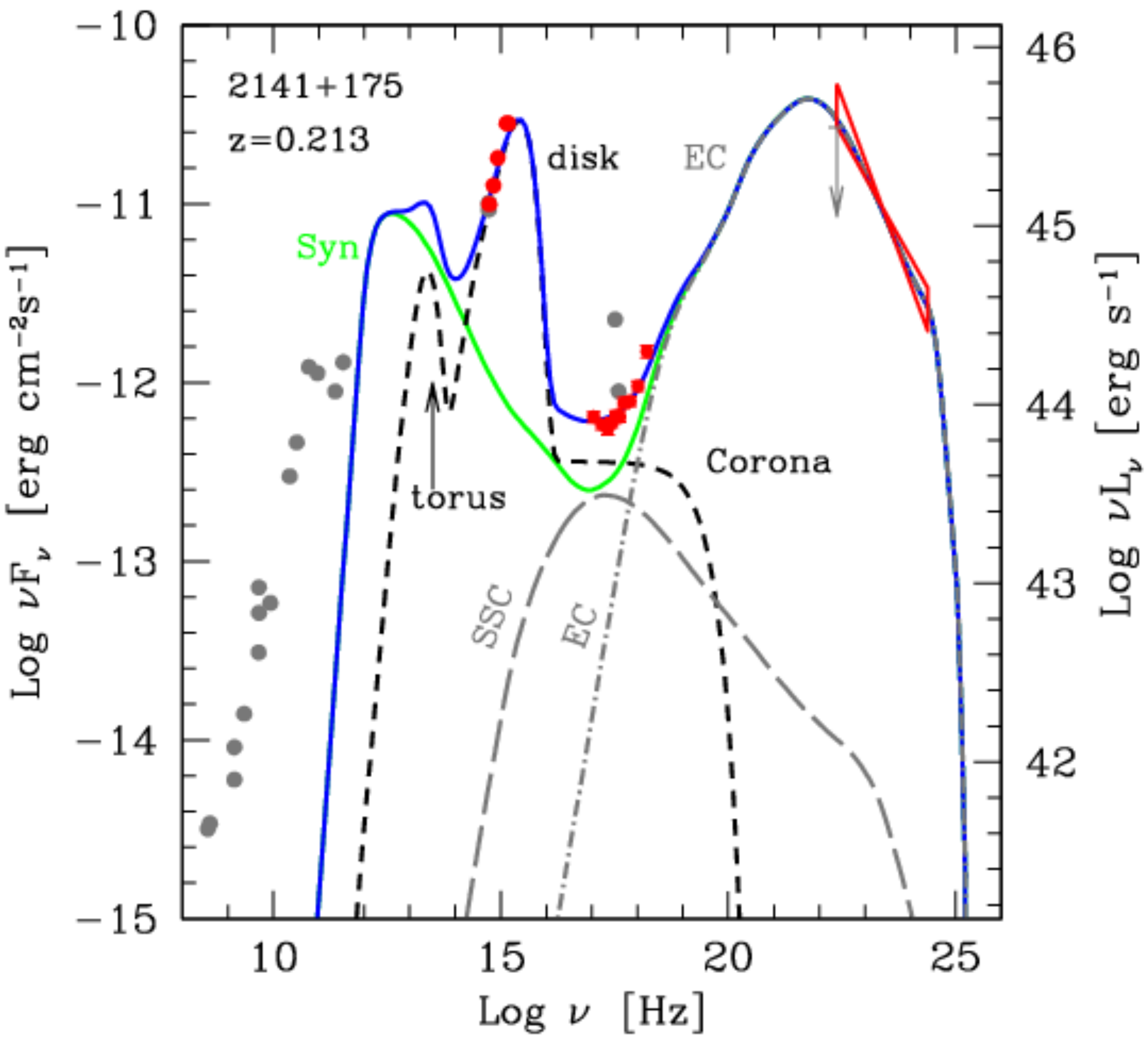
$$\nu_C = \frac{4}{3}\gamma_{\mathrm{b}}^2 \nu_S$$



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





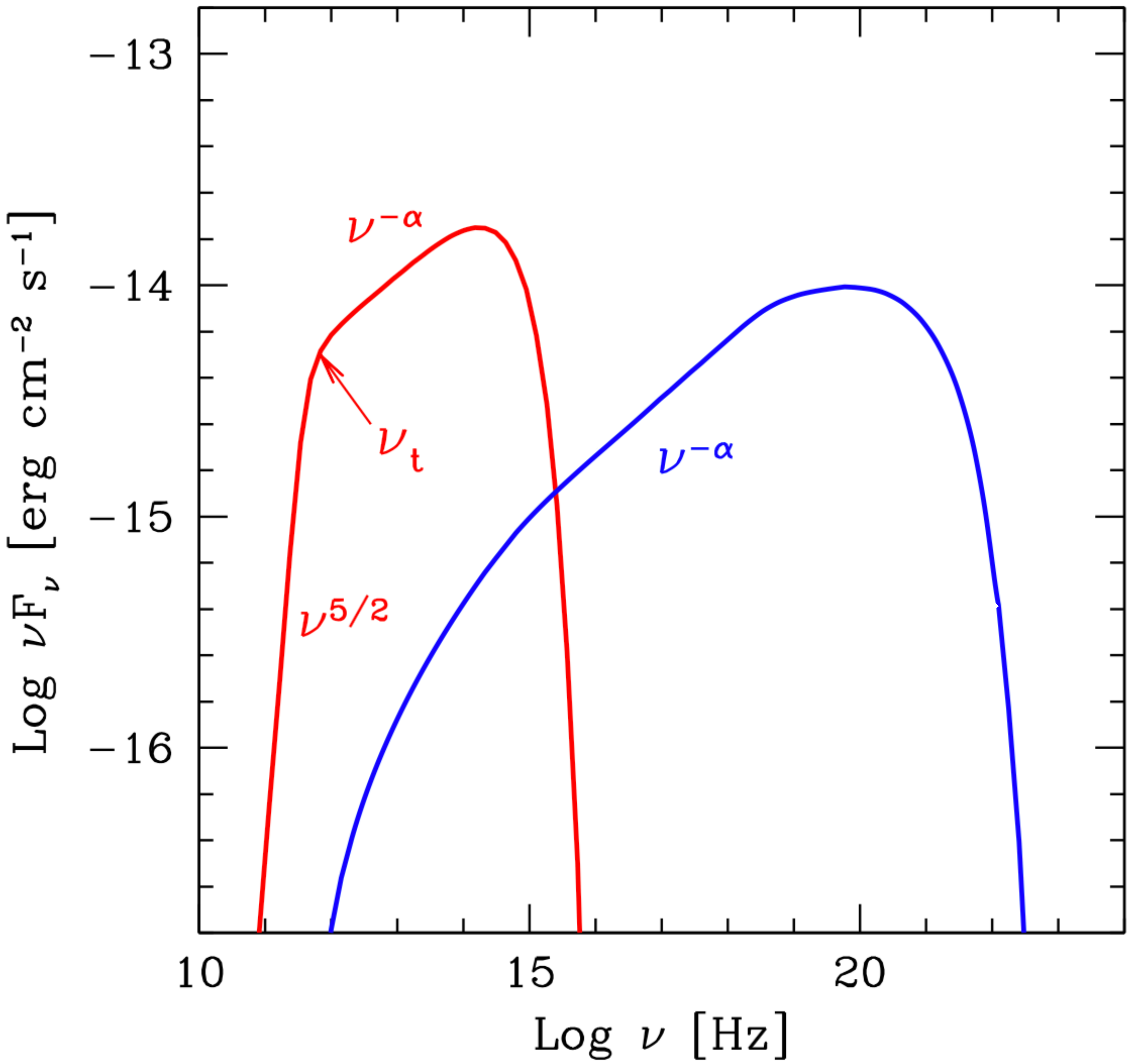
What we can infer from the blazar SED

From the peak frequencies we have,

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

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

For OJ 287 $\gamma_{\rm break} = \left(\frac{\nu_C \sim 10^{21}}{\nu_S \sim 10^{13}}\right)^{1/2} \sim 10^4$



What we can infer from the blazar SED

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

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

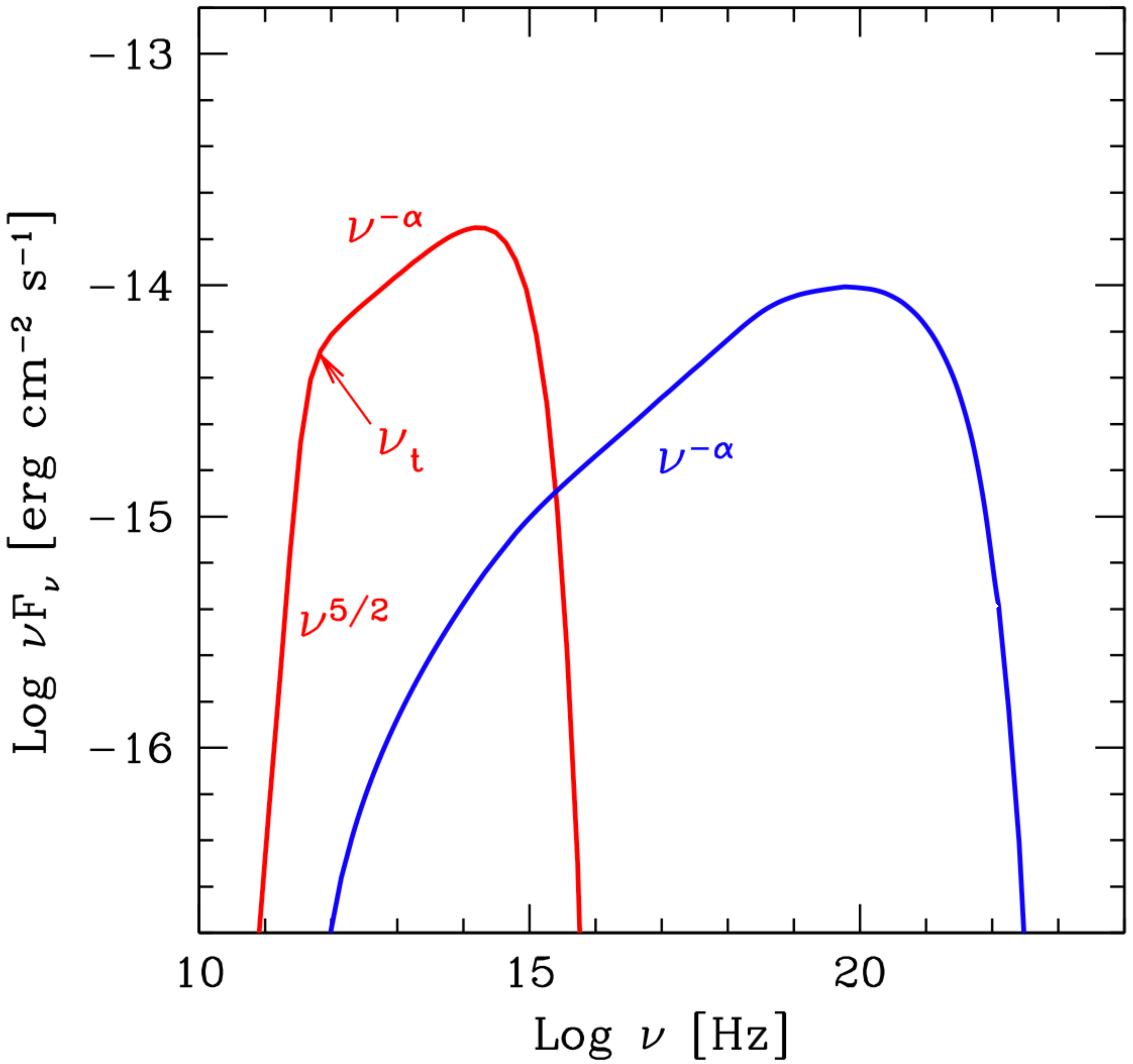
$$U_B = \frac{B^2}{8\pi} - (2)$$

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

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

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

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



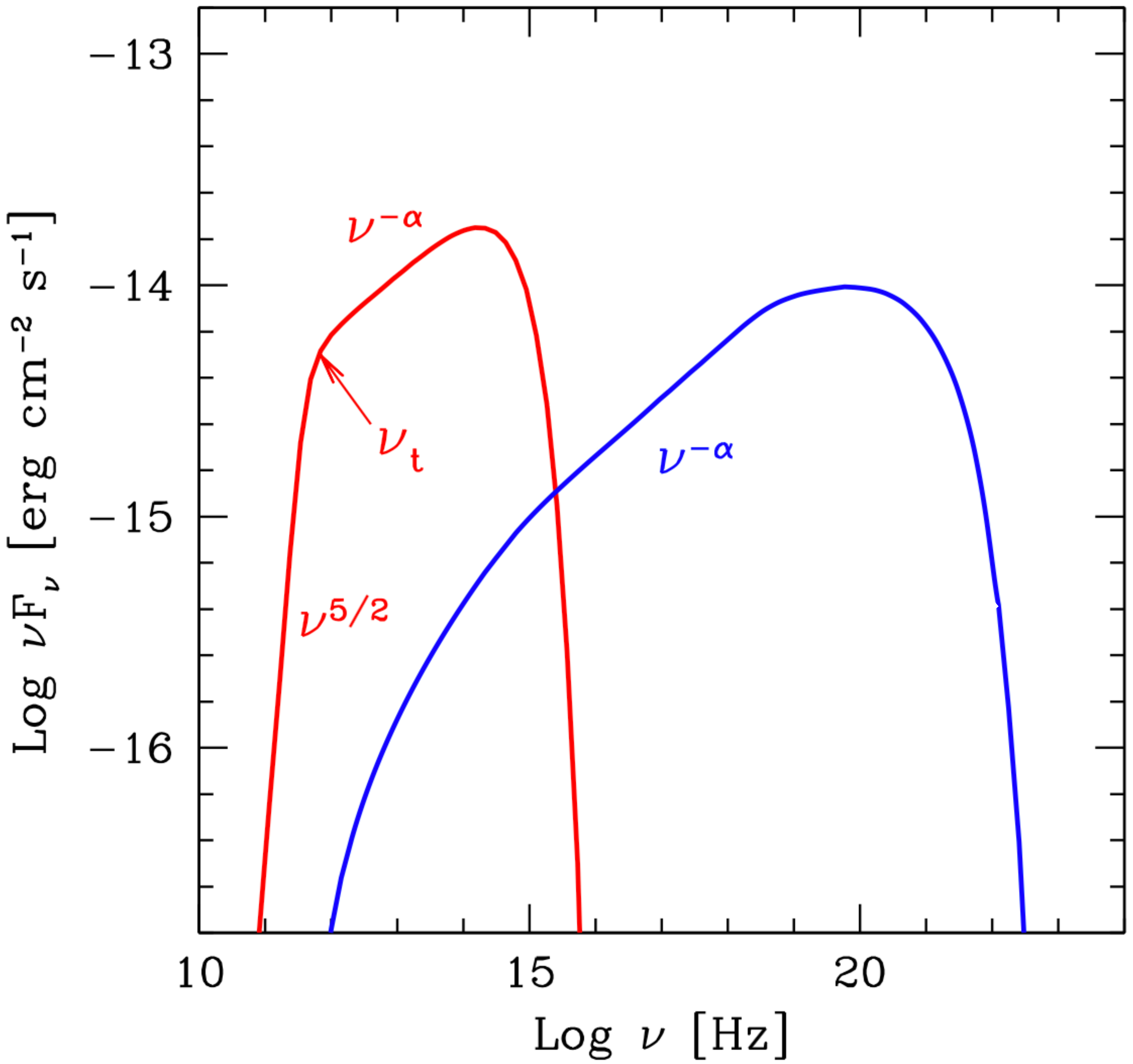
What we can infer from the blazar SED

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,

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



What we can infer from the blazar SED

From the peak frequencies we have,

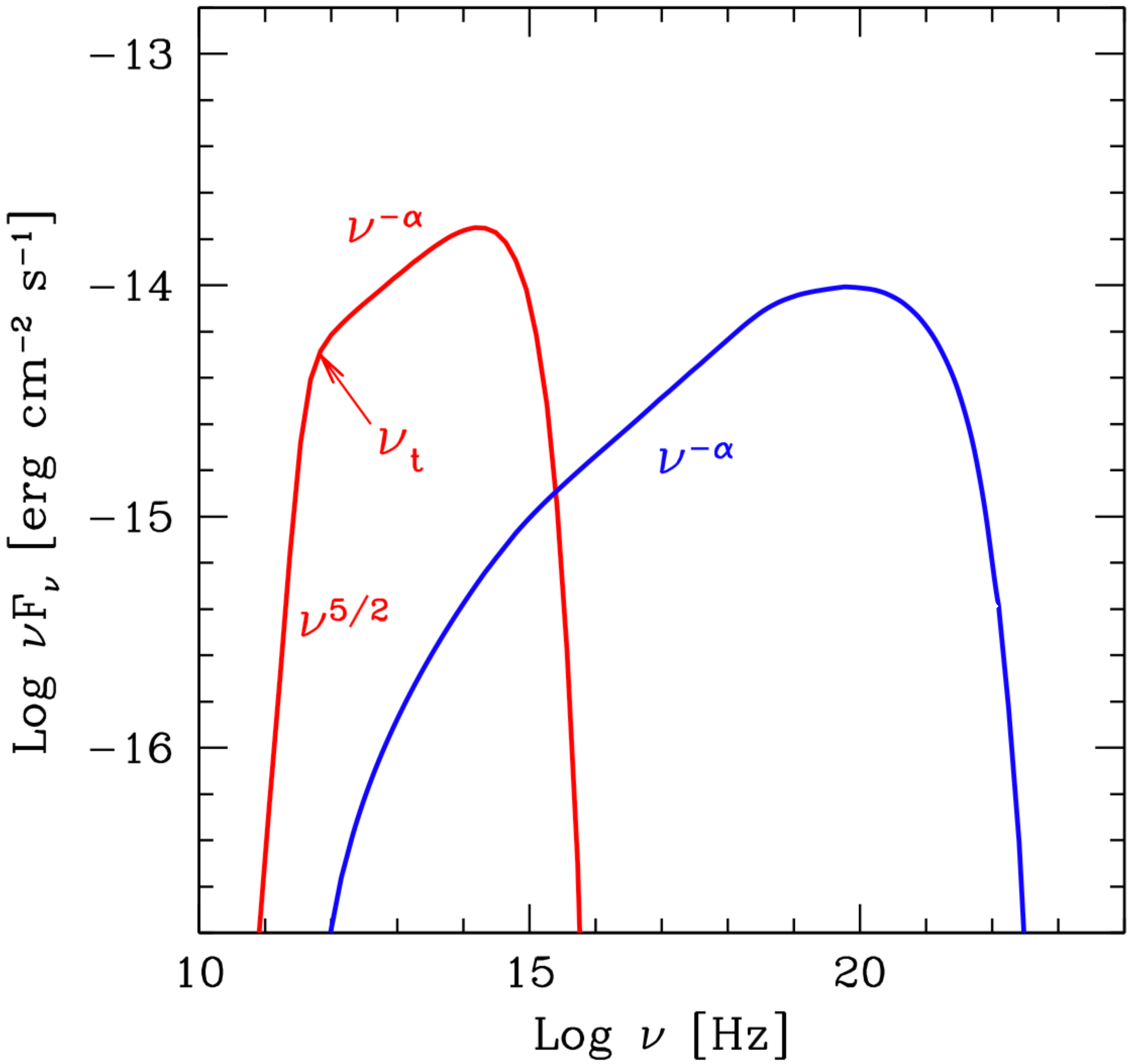
$$\nu_C = \frac{4}{3}\gamma_{\rm break}^2 \nu_S$$

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

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

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

UHECR acceleration?

For OJ 287:

$$t_{\rm var} \sim 10^4~{\rm s}, \nu_{\rm s} \sim 5\times10^{13}~{\rm Hz}, \nu_{\rm c} \sim 10^{21}~{\rm Hz}$$

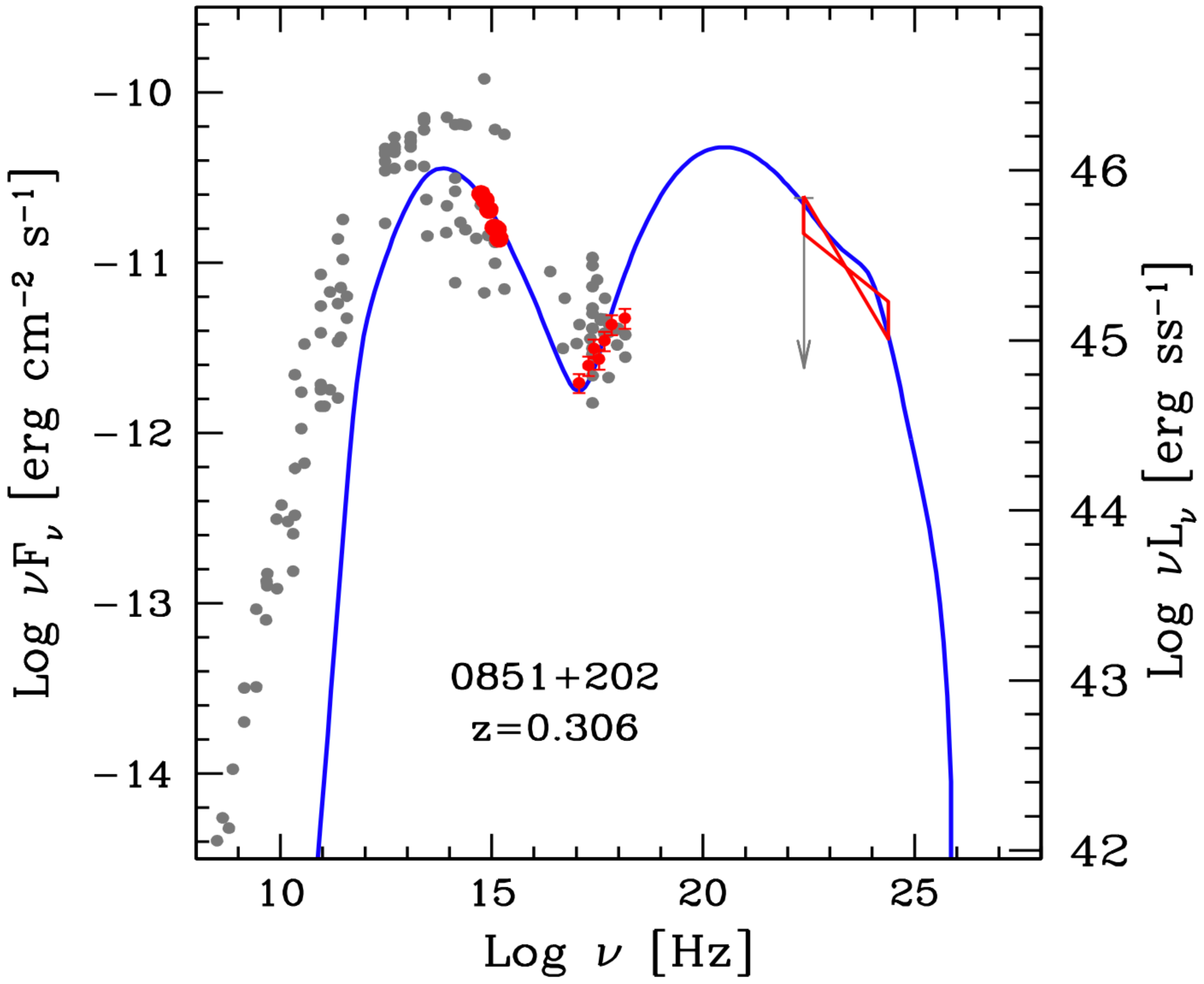
$$L_C \sim L_S \sim 10^{46}~{\rm erg/s}$$

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

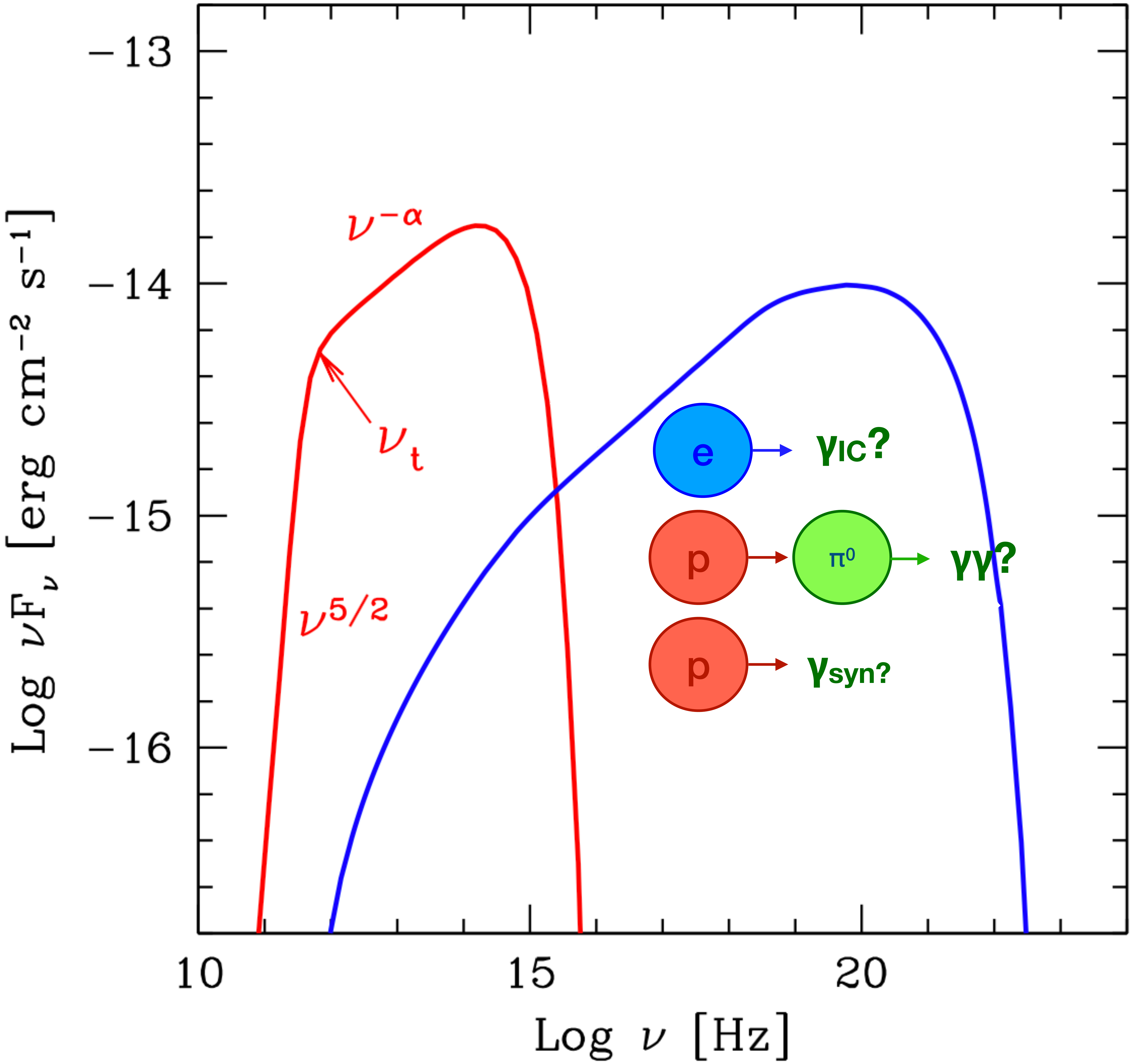
$$E_{\rm max} \sim ZeB\Gamma R \sim Z\cdot 4\times10^{20}~{\rm eV}$$

For typically inferred parameters

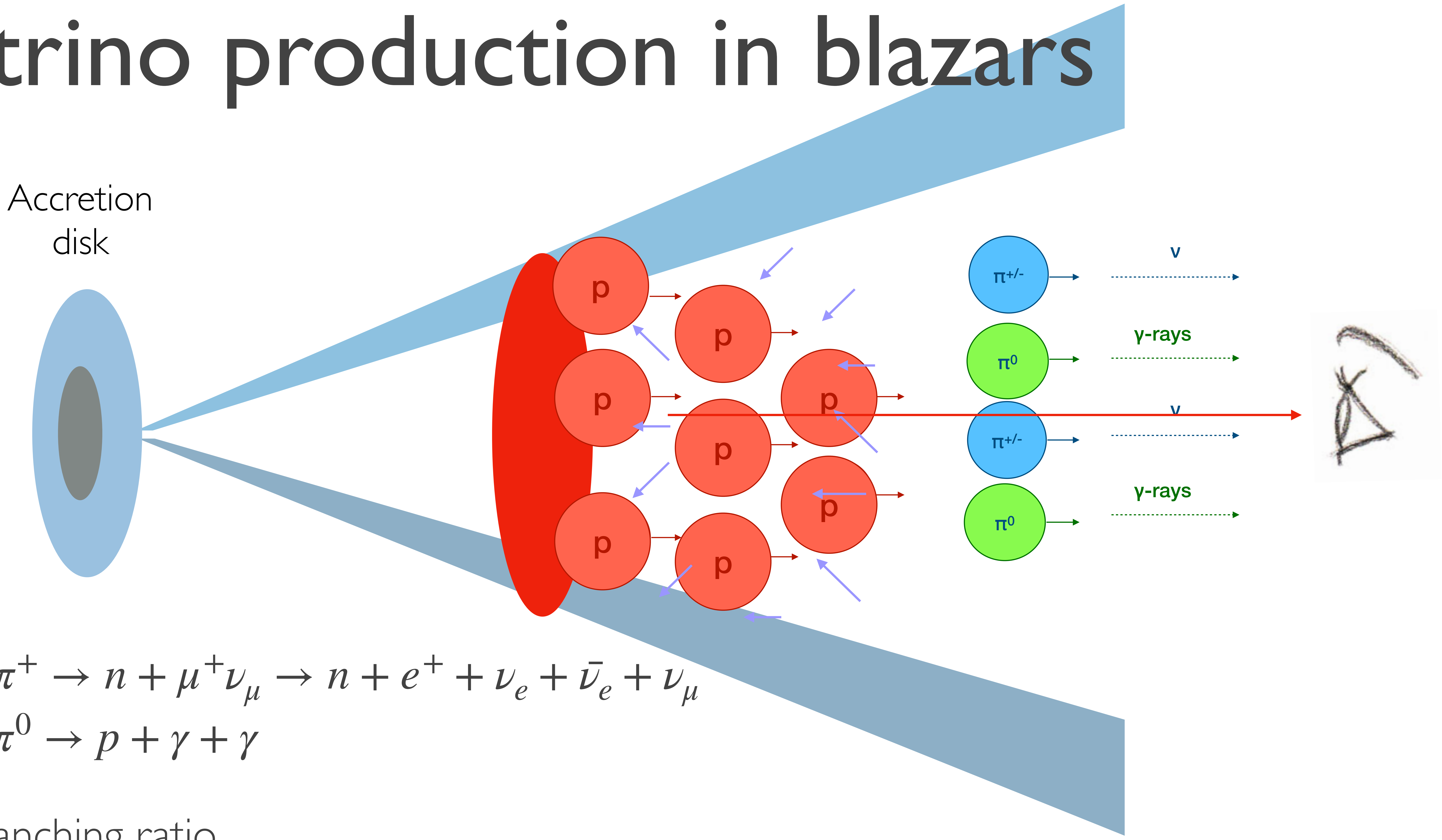
$B' \sim 0.1 - 1~{\rm Gauss}$
$\Gamma \sim \delta \sim 10 - 50$
$R' \lesssim \delta t_{\rm Var} c,~t_{\rm Var} \sim {\rm day}$
$E_{\rm max} \sim ZeB'\Gamma R' \gtrsim Z\cdot {\rm few}\times10^{19}~{\rm eV}$



Neutrino production in blazars



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,

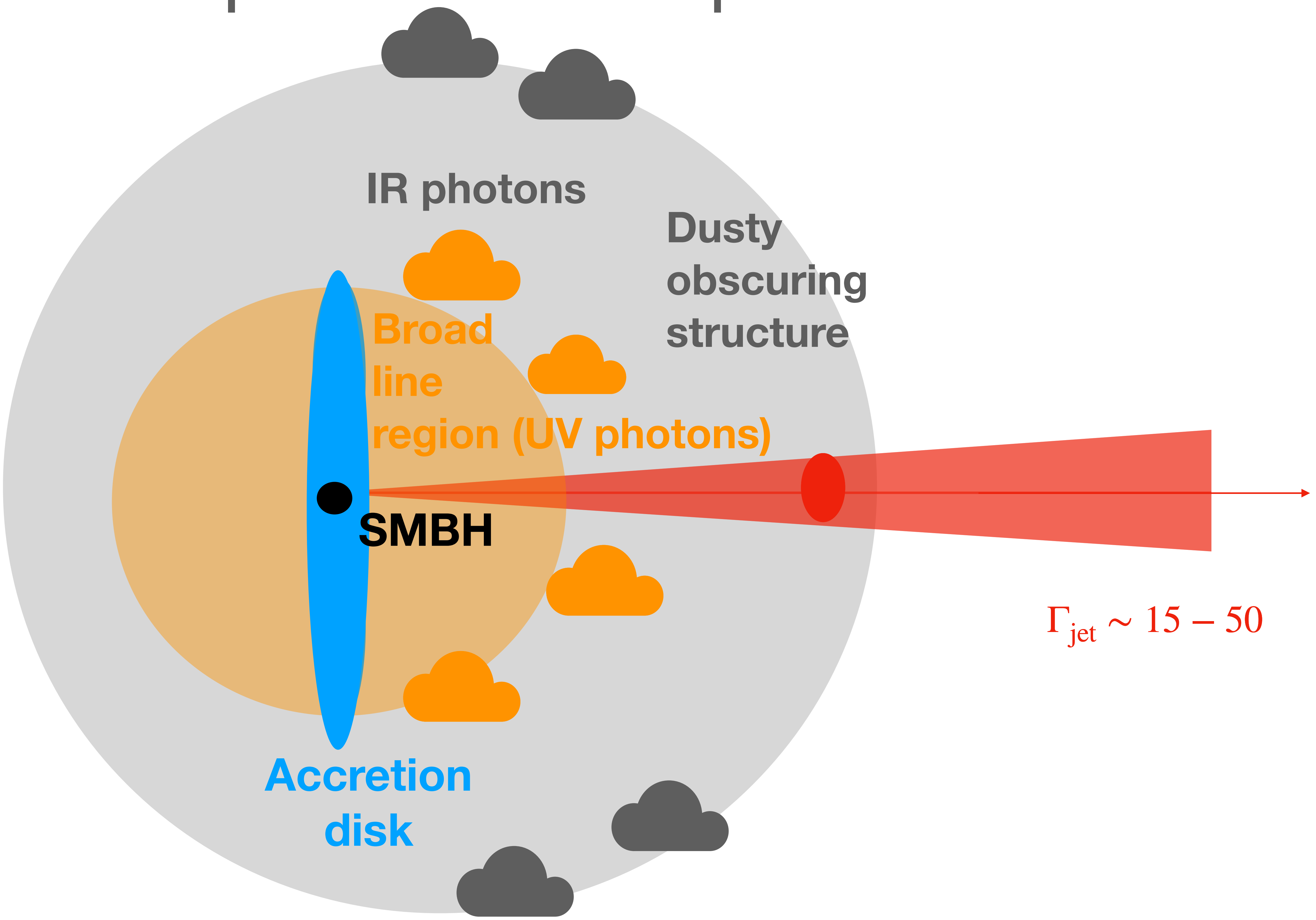
$$R_\pi = \frac{\Gamma(\rightarrow \pi^{+/-})}{\Gamma(\rightarrow \pi^0)} \sim 1$$

$$E_\nu^2 \frac{\mathrm{d}N}{\mathrm{d}E_\nu} = \frac{3}{2}\frac{1}{2} E_\gamma^2 \frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\Big|_{E_\gamma = 2E_\nu}$$

$\longrightarrow$ gamma-rays give us an upper limit to the neutrino flux

Blazar subclasses and photon fields

Flat spectrum radio quasars

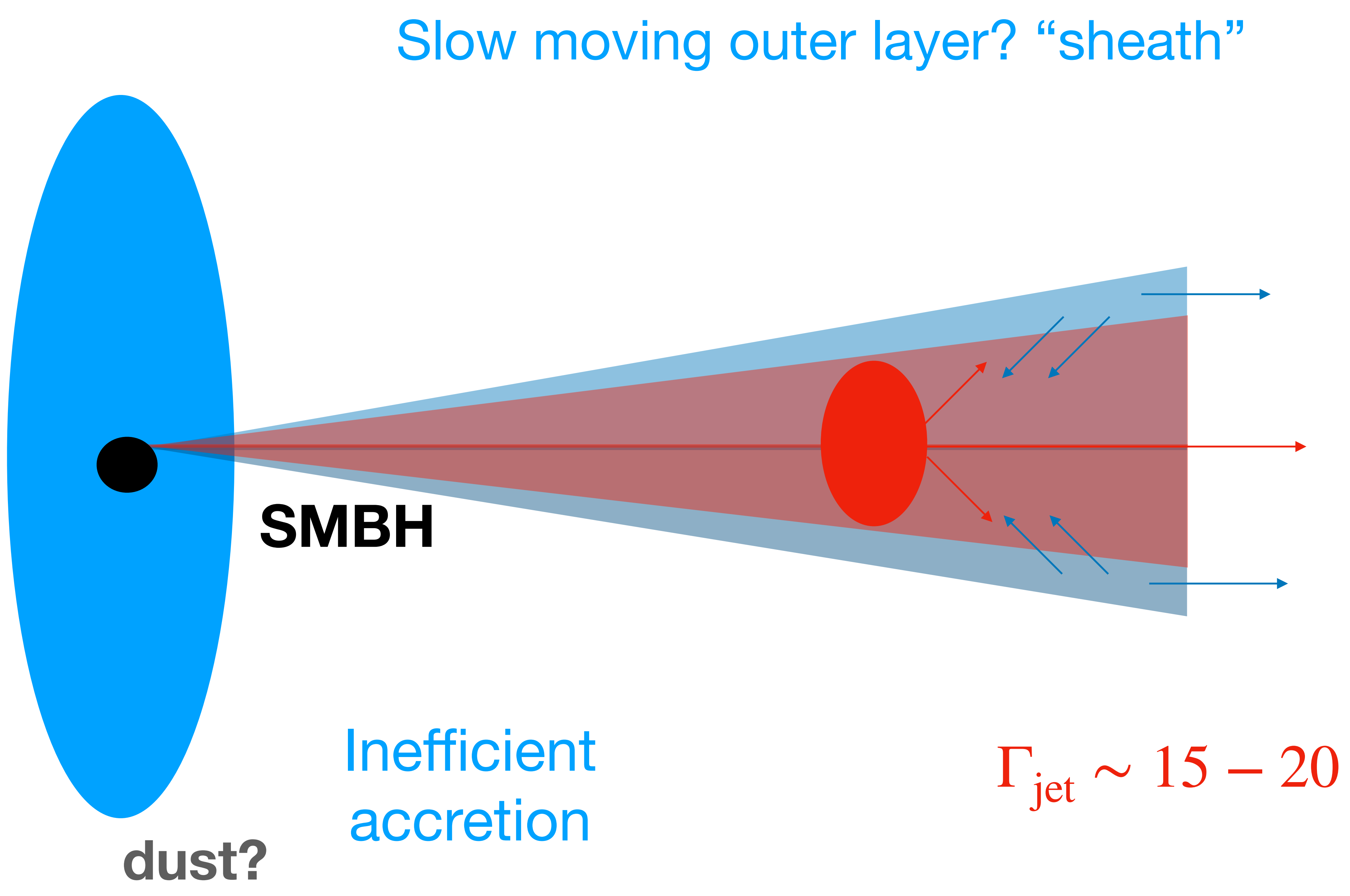


Very powerful collimated jets

Radiatively efficient accretion disk

Luminosity close to Eddington limit

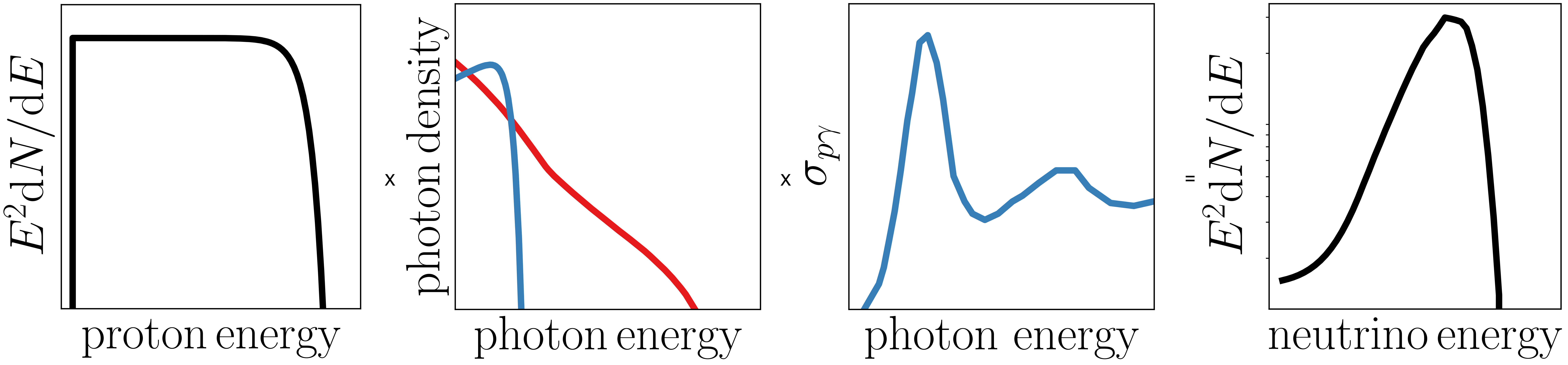
BL Lac Objects



Less collimated jets

Radiatively inefficient accretion disk

Neutrino production in blazars



$$E_{\rm BLR} = 10.2 \text{ eV}$$

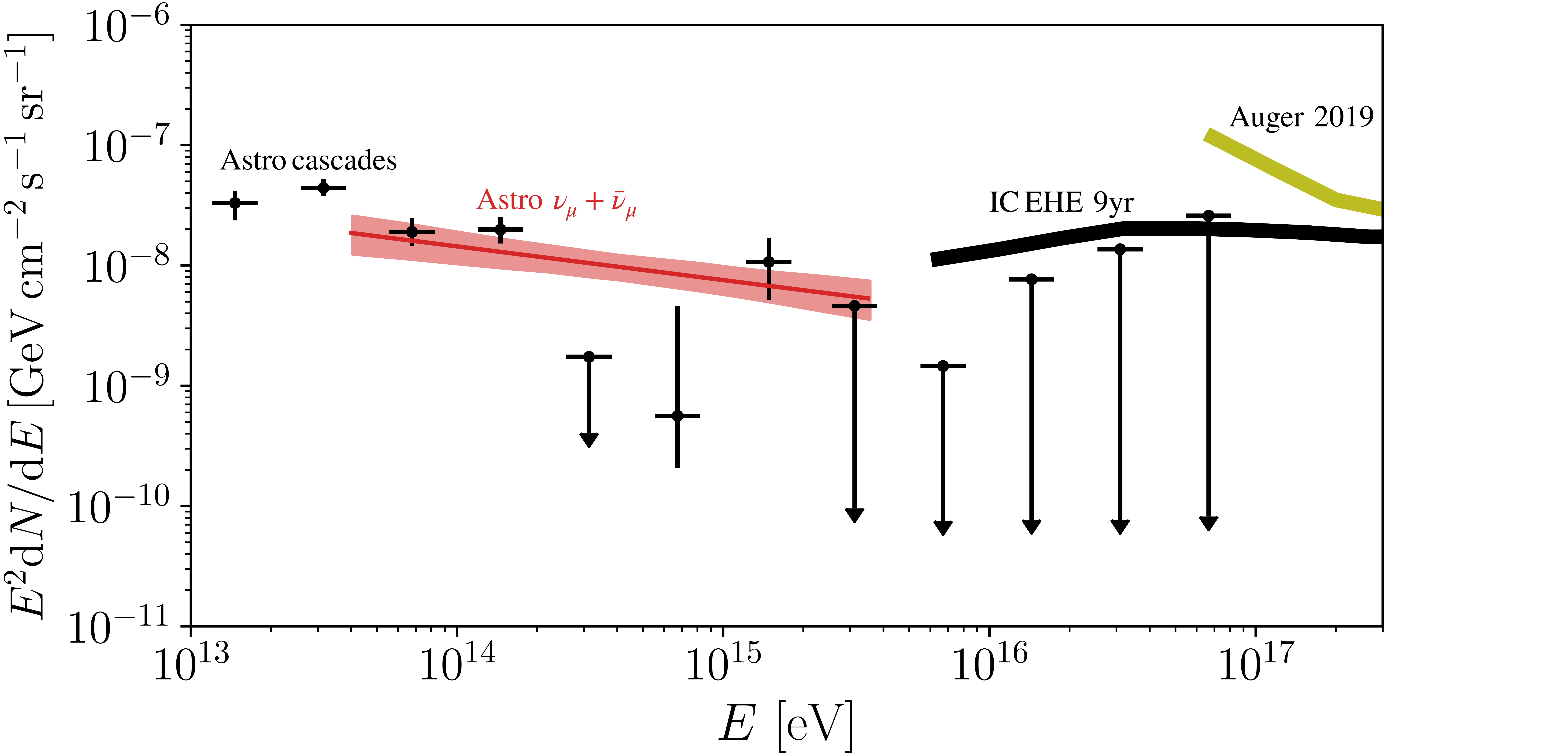
$$E_{\rm dust\ torus} = 0.1 \text{ eV}$$

Neutrino typical energy:

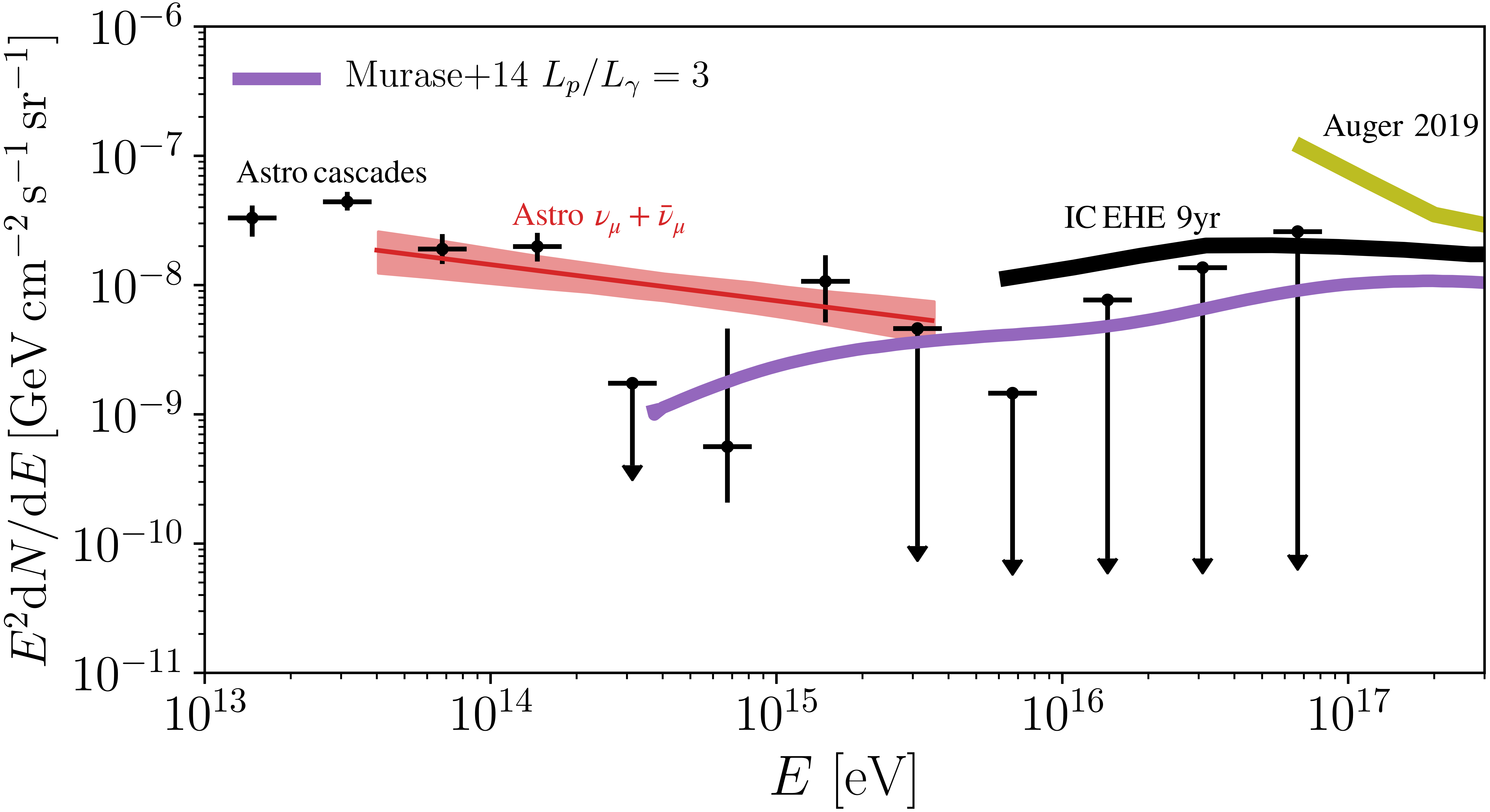
$$E_{\nu,\rm BLR} = \frac{80 \text{ PeV}}{(1+z)^2} \left(\frac{\delta}{10}\right)^2 \frac{10 \text{ eV}}{E_\gamma}$$

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

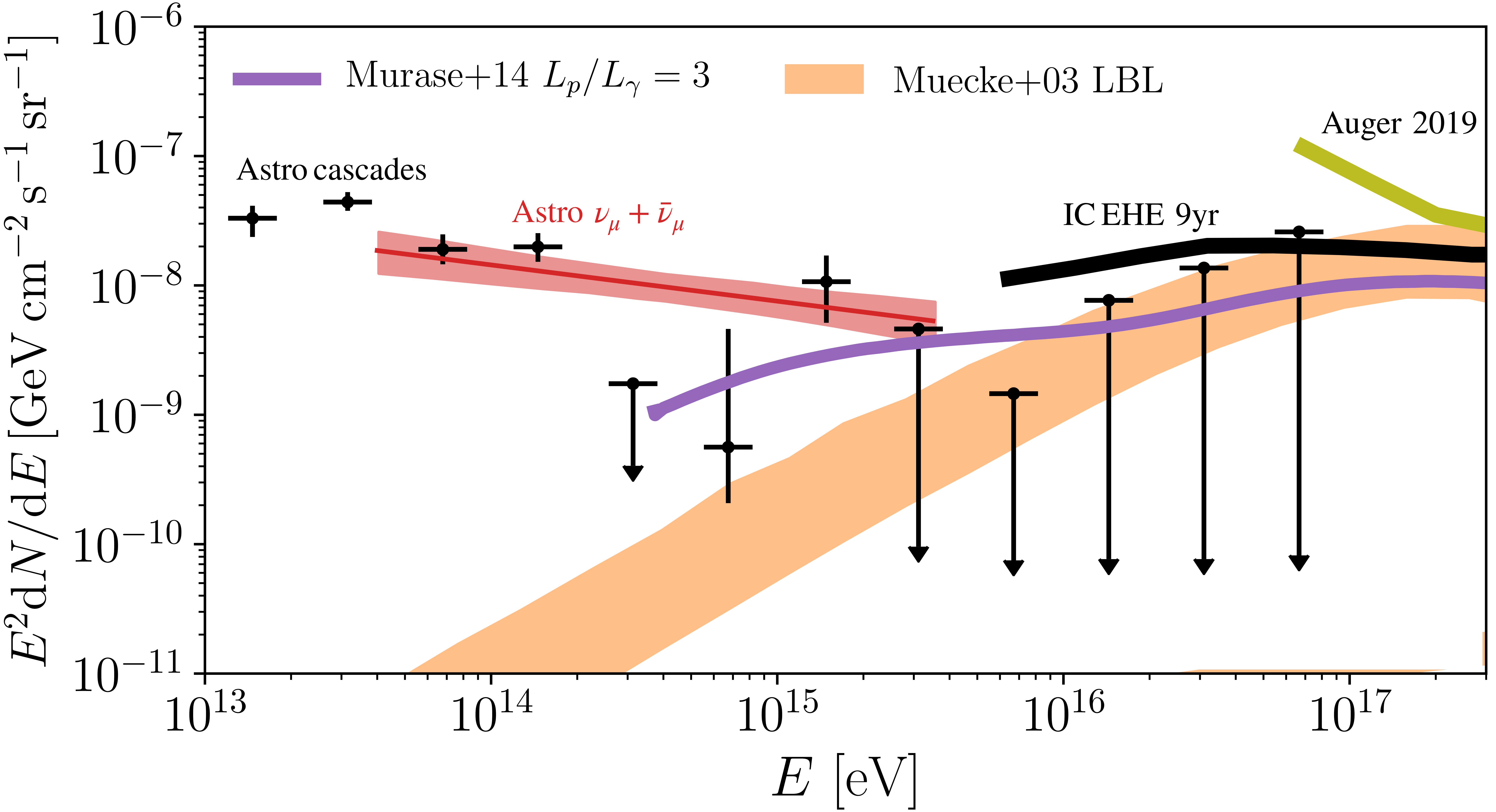
Possible contribution of blazars to the diffuse neutrino flux



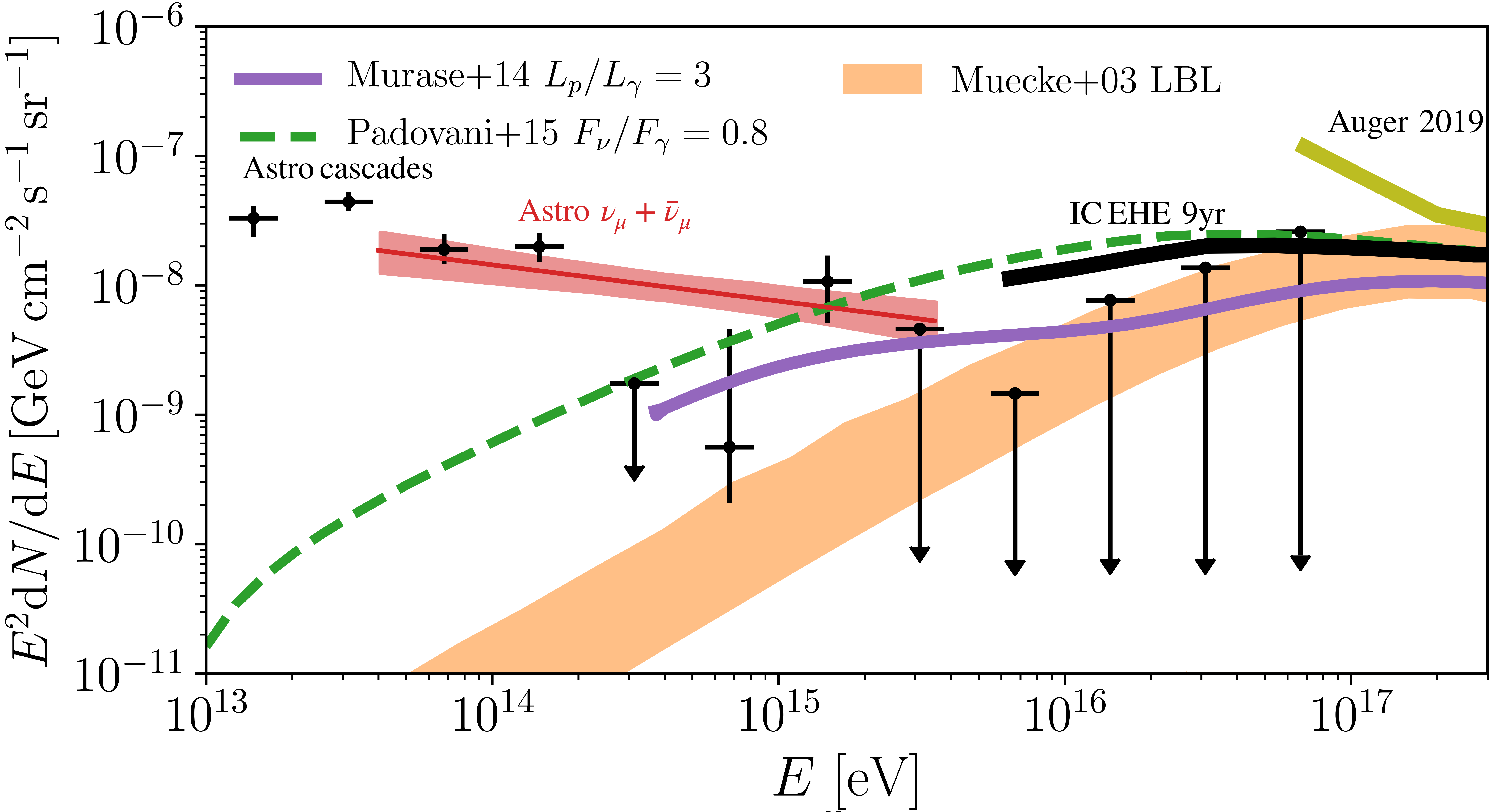
Possible contribution of blazars to the diffuse neutrino flux



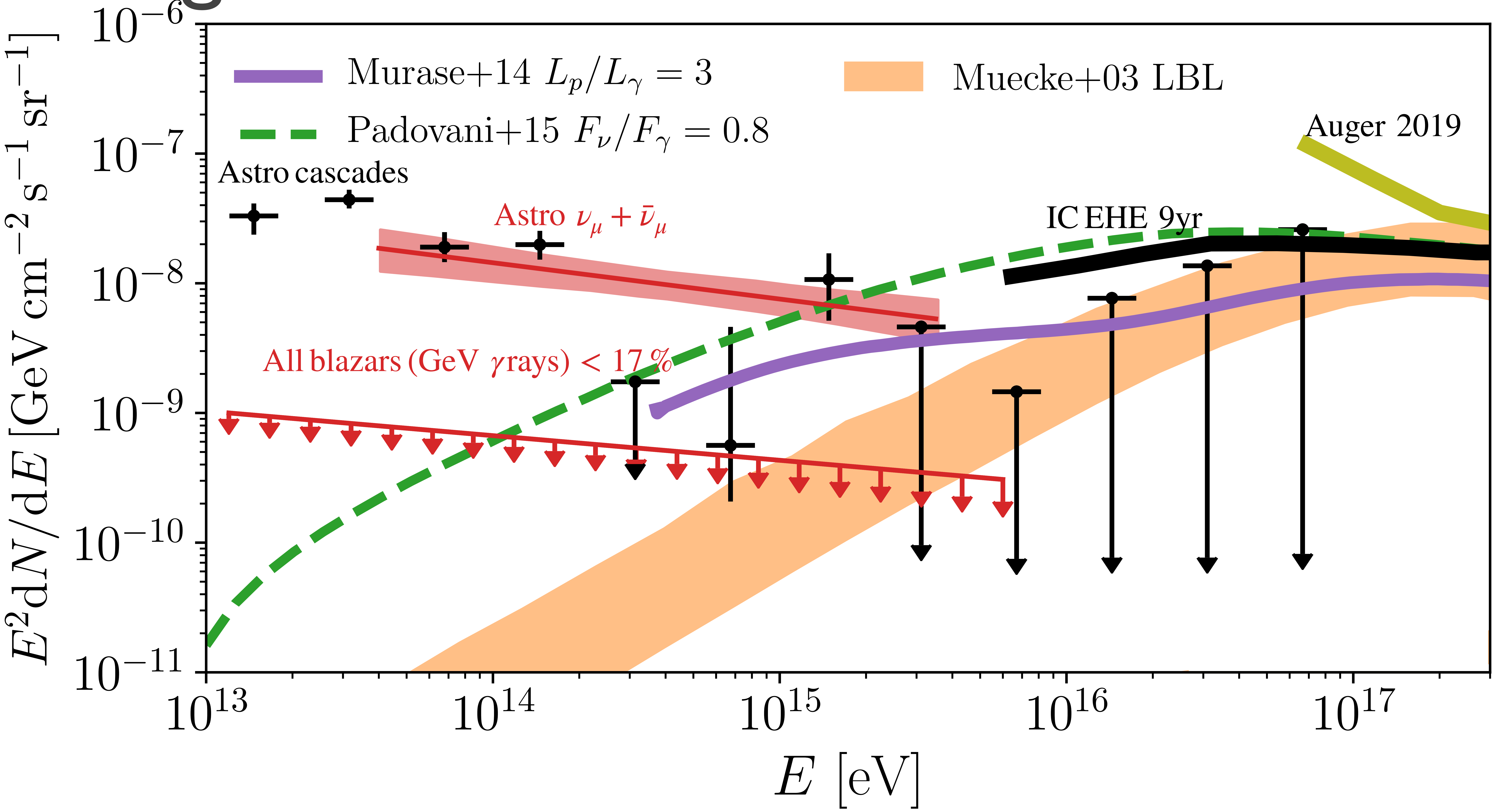
Possible contribution of blazars to the diffuse neutrino flux



Possible contribution of blazars to the diffuse neutrino flux



Stacking limits from IceCube



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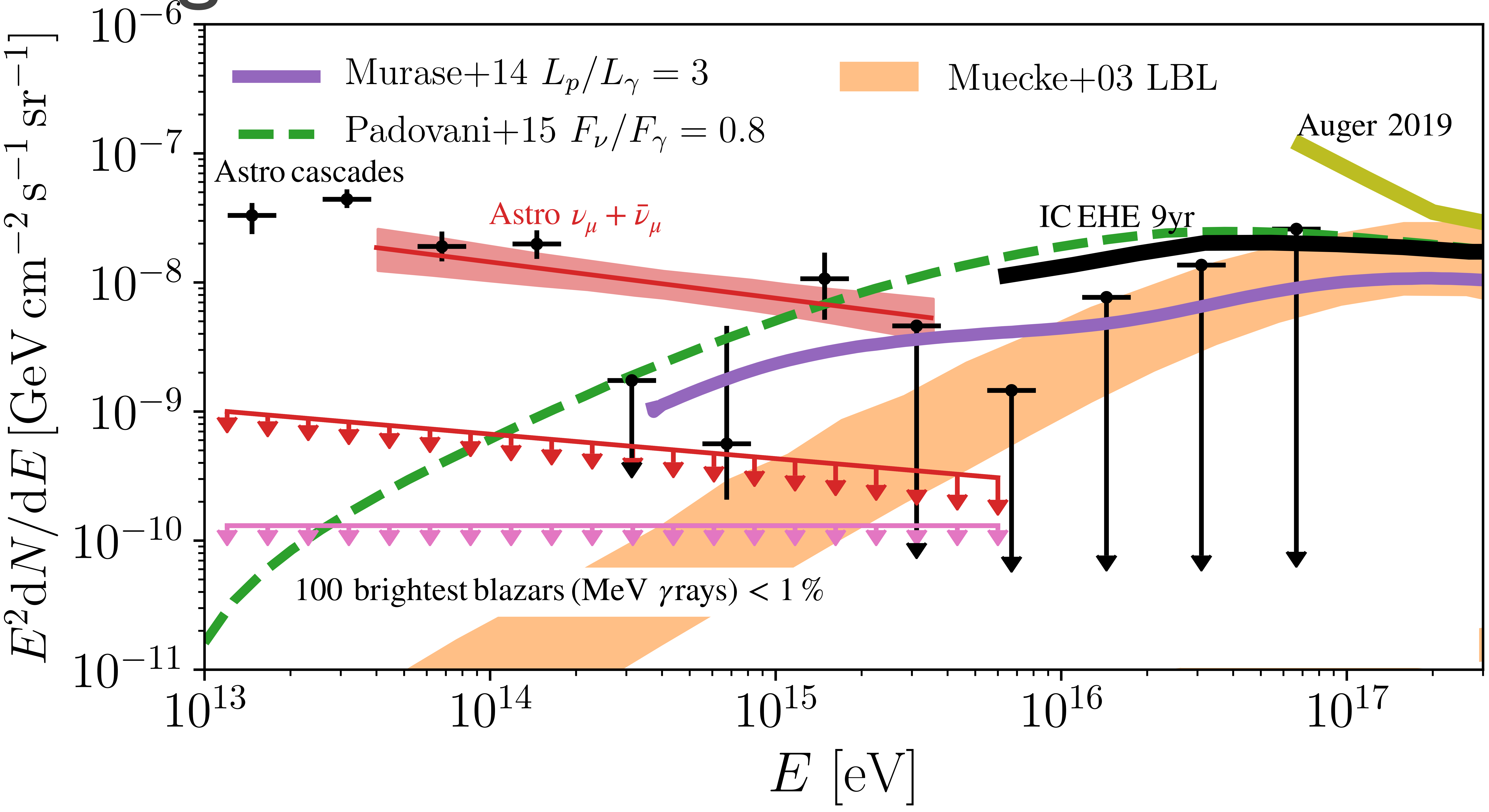
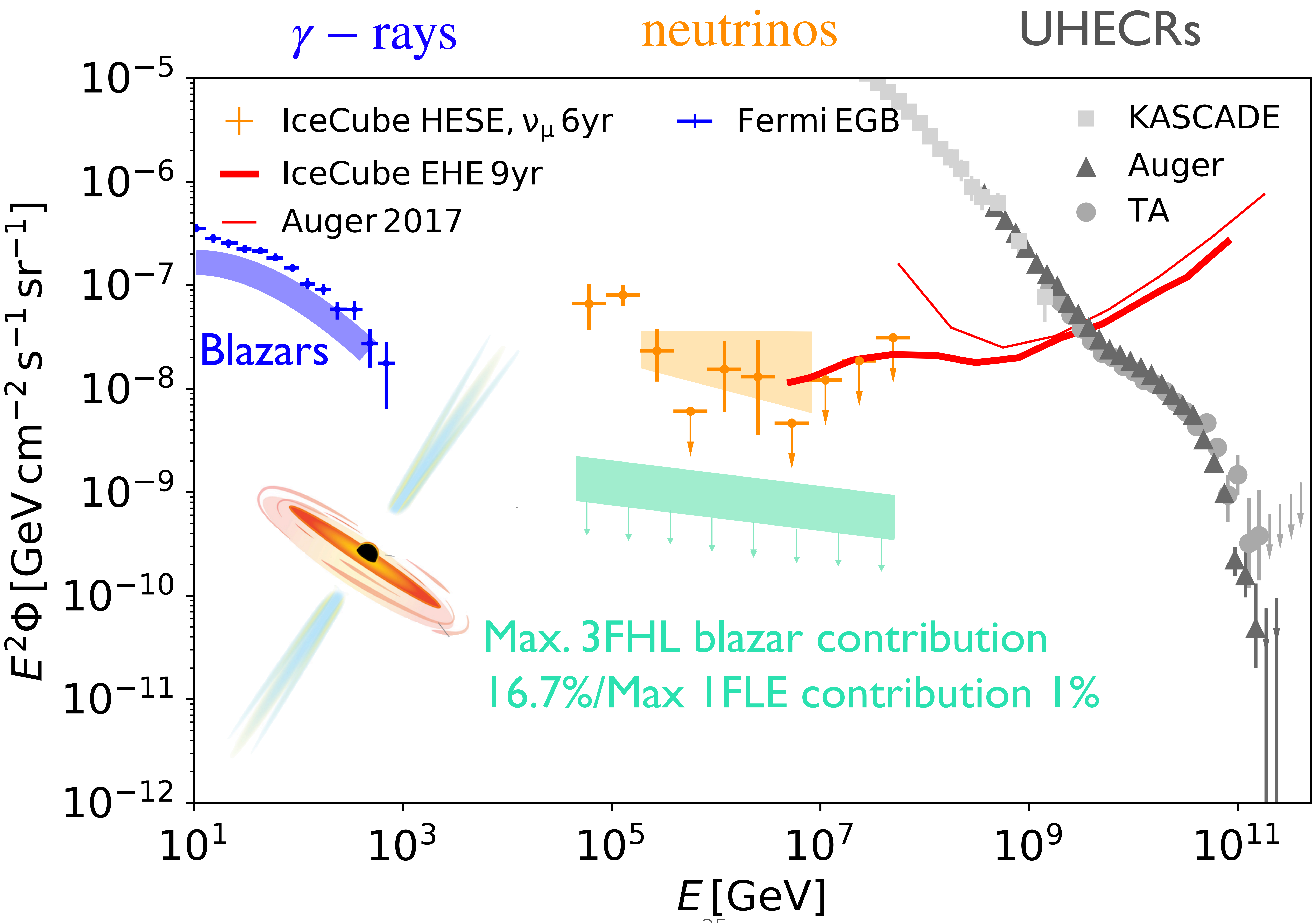
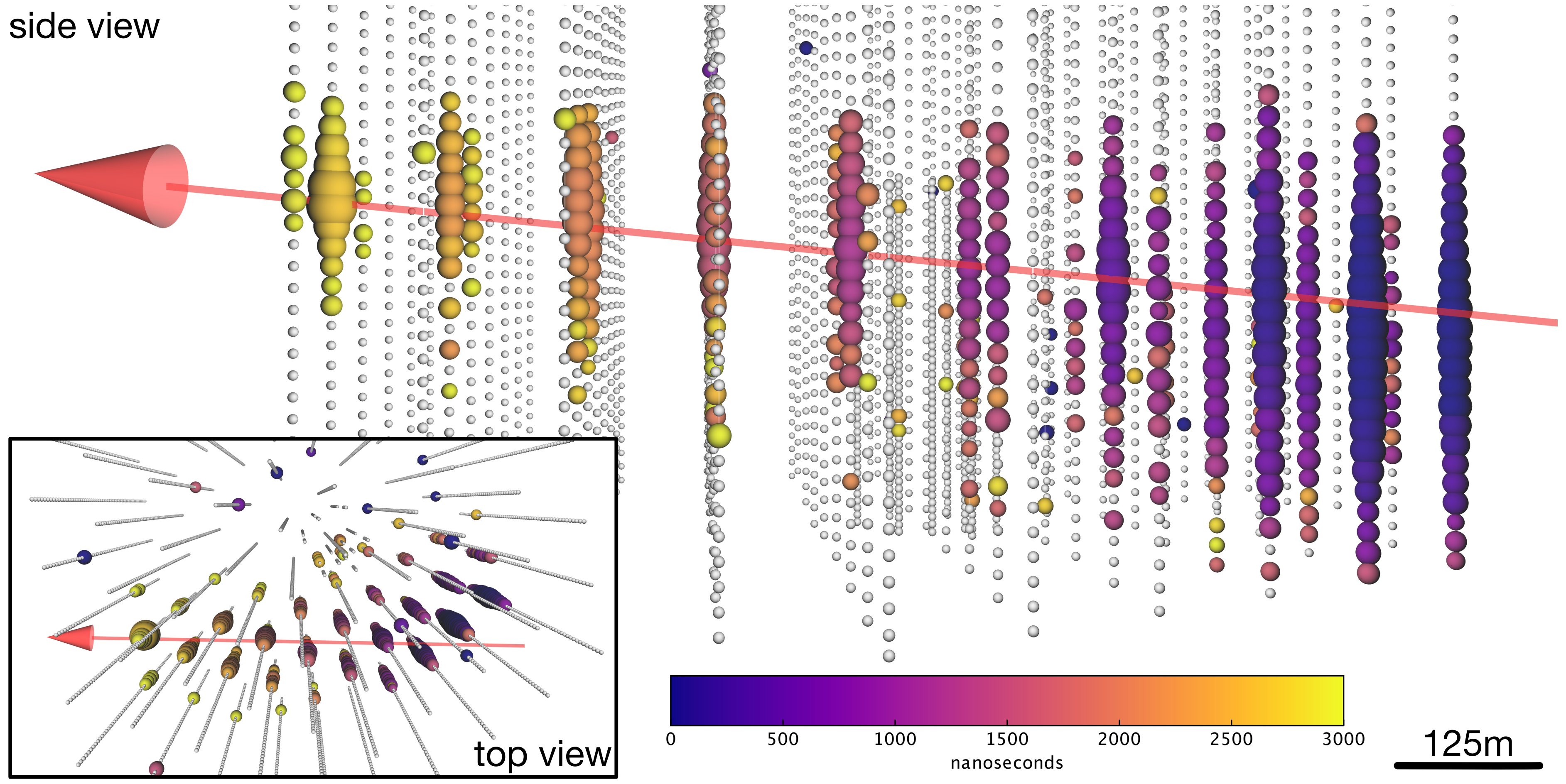


Stacking limits from IceCube

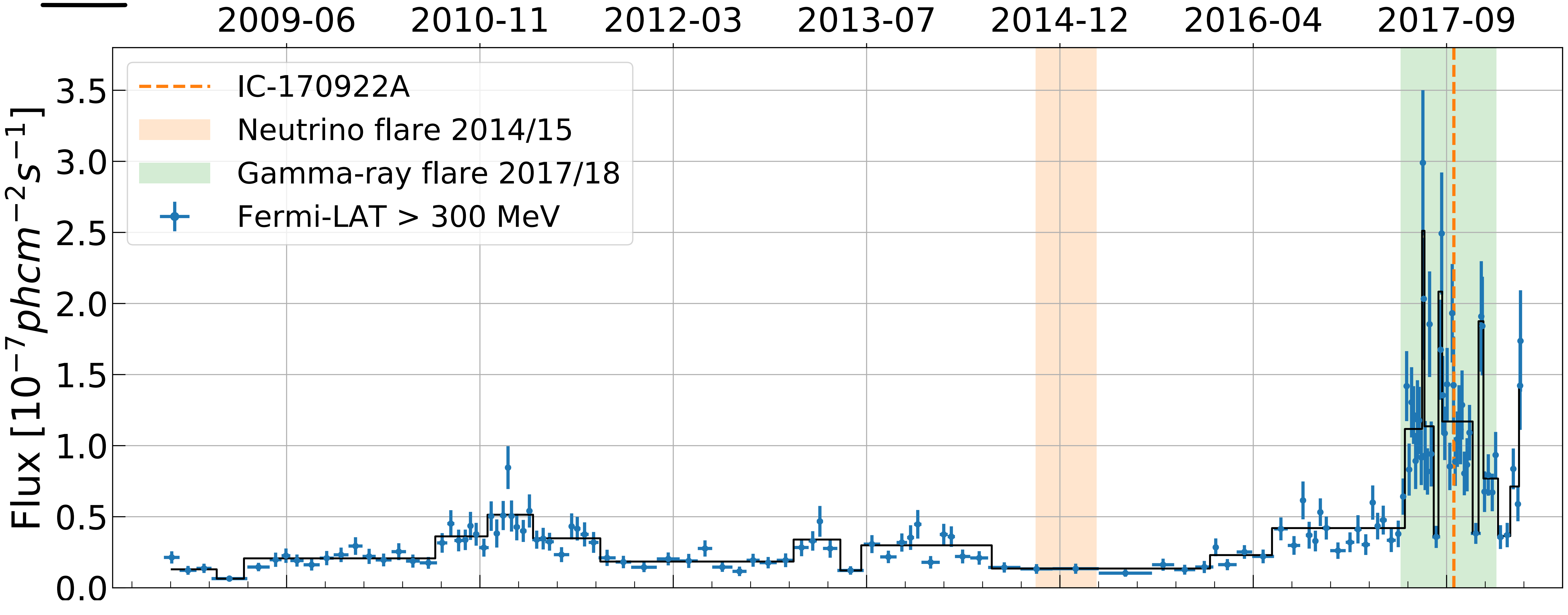


TXS 0506+056-IC 170922A

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



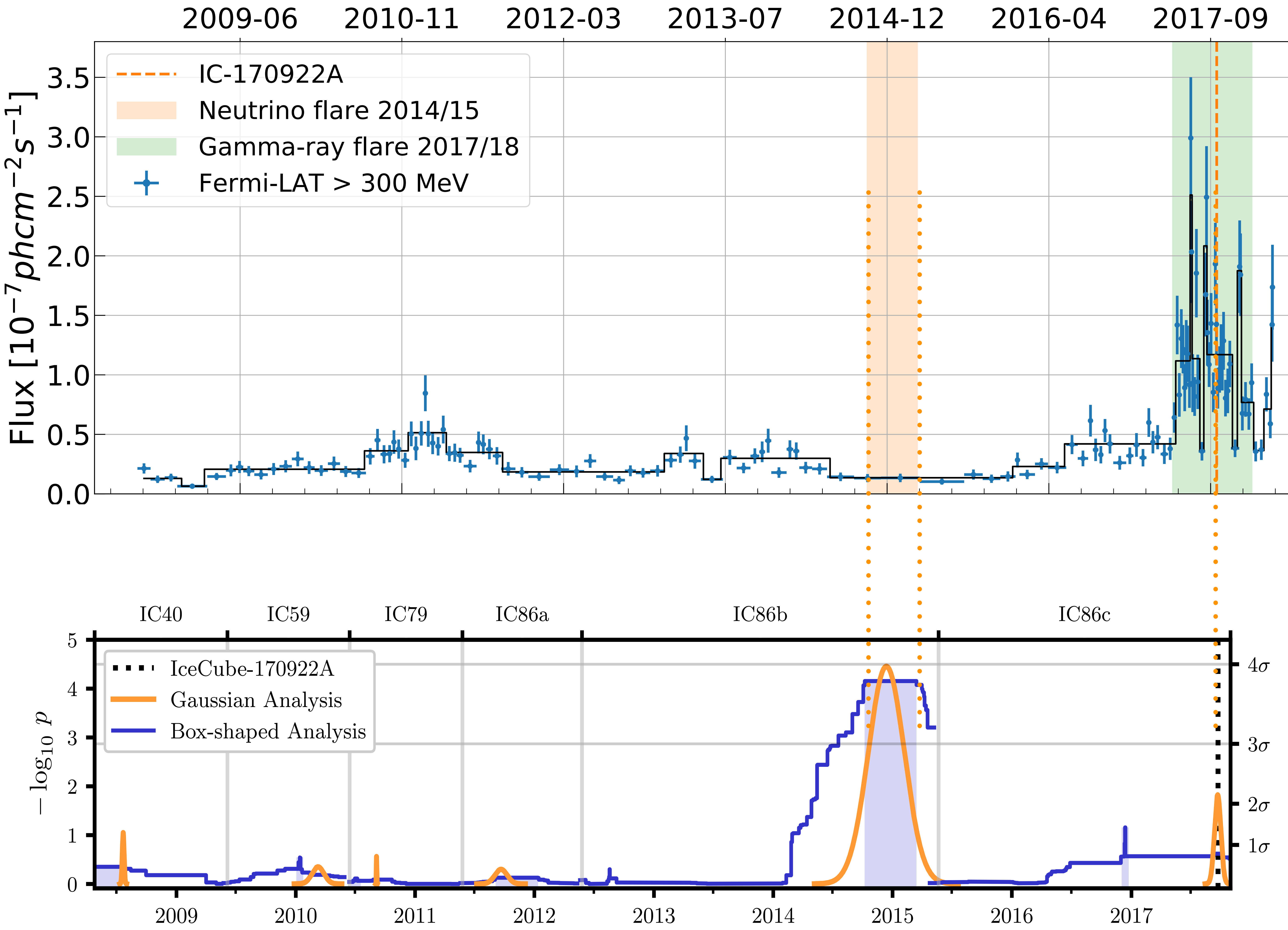
Background fluctuation? Chance probability ~0.3%



IceCube archival search 13±5 more neutrinos!

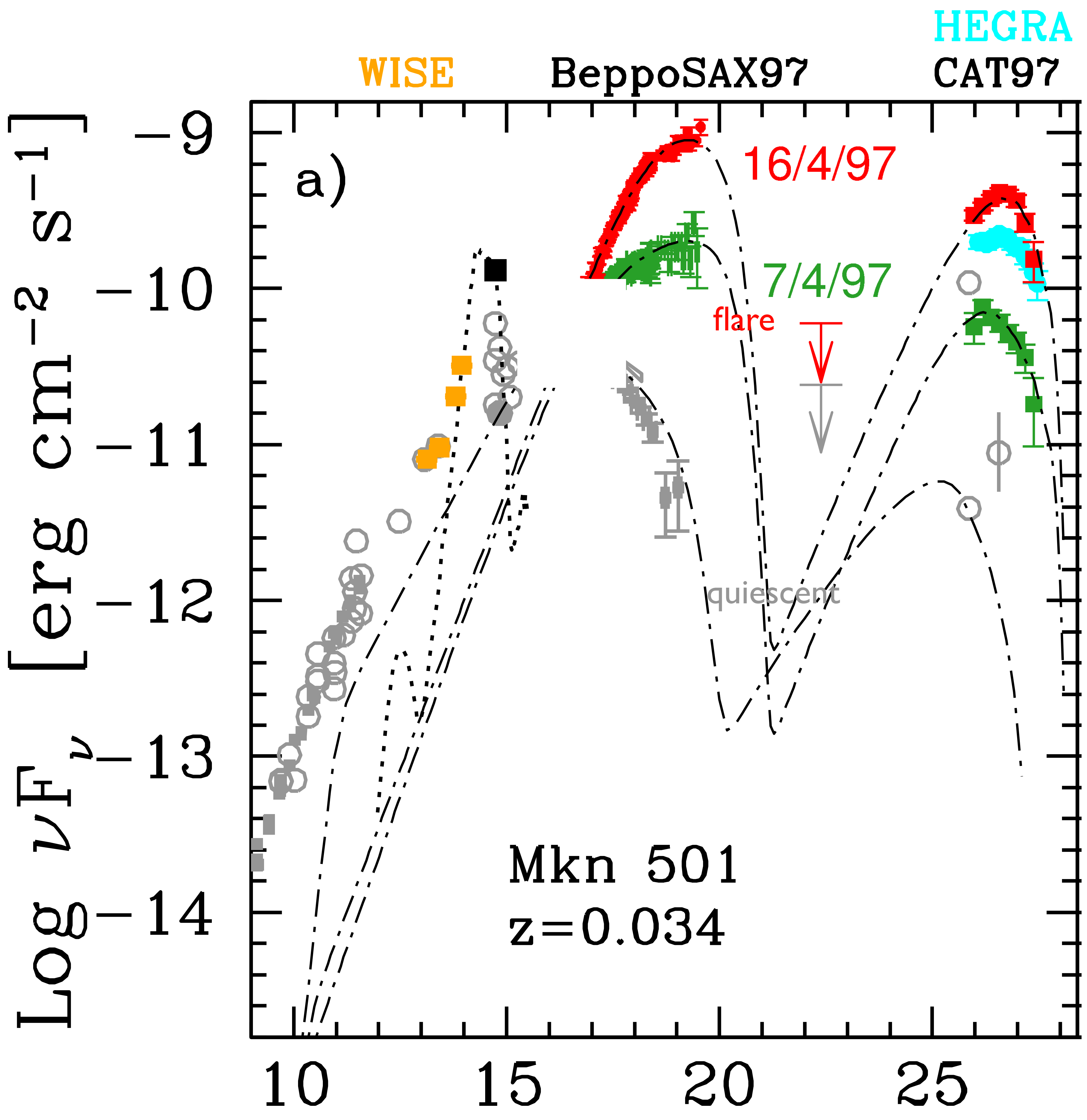
γ-rays

neutrinos



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

Blazar flares: Interesting as neutrino point sources



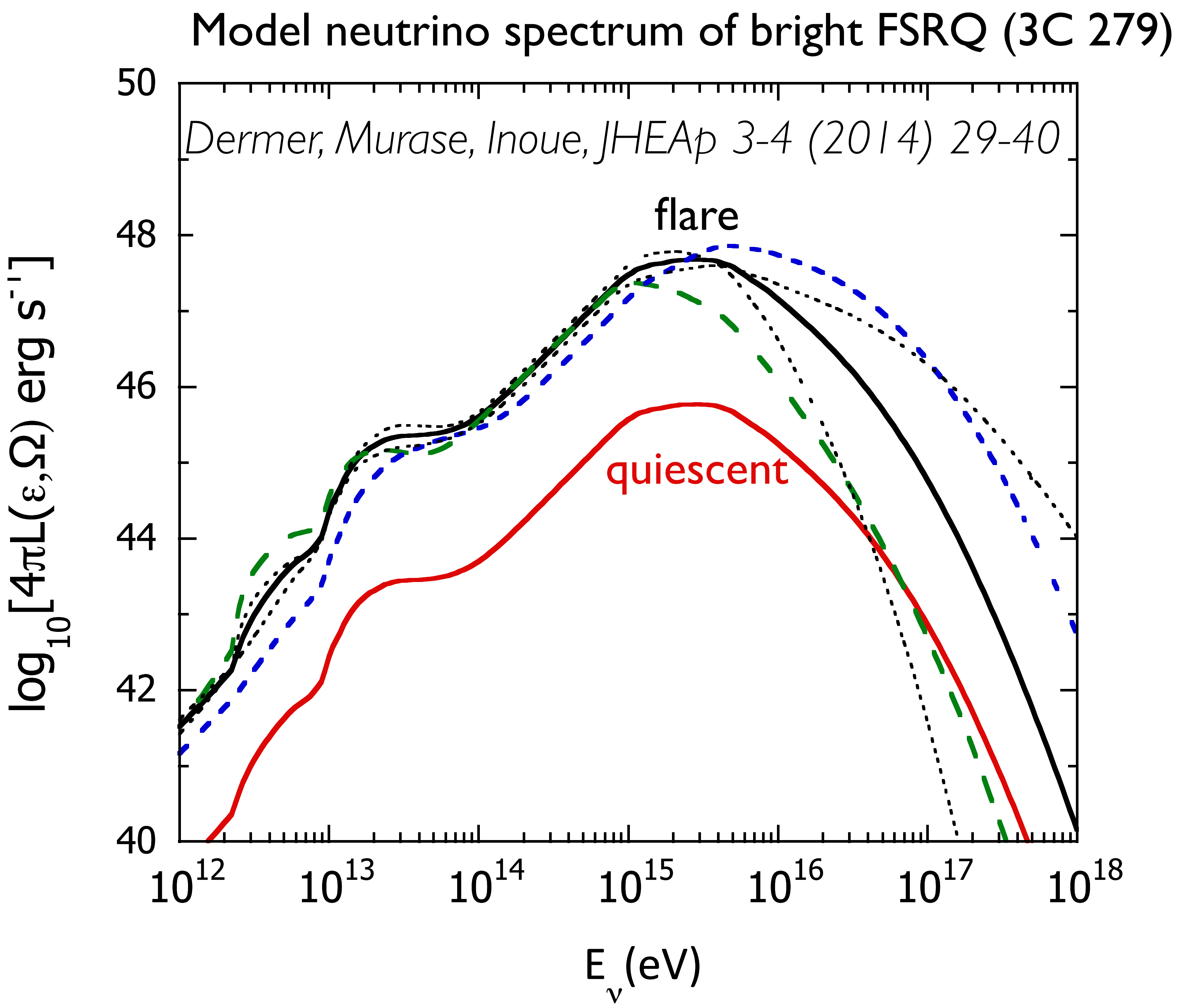
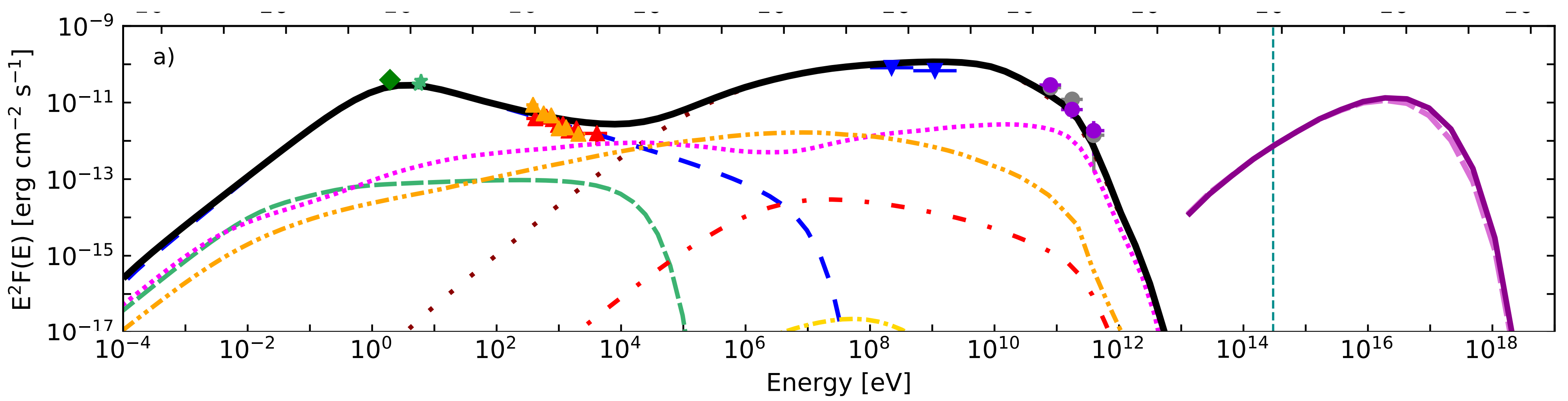


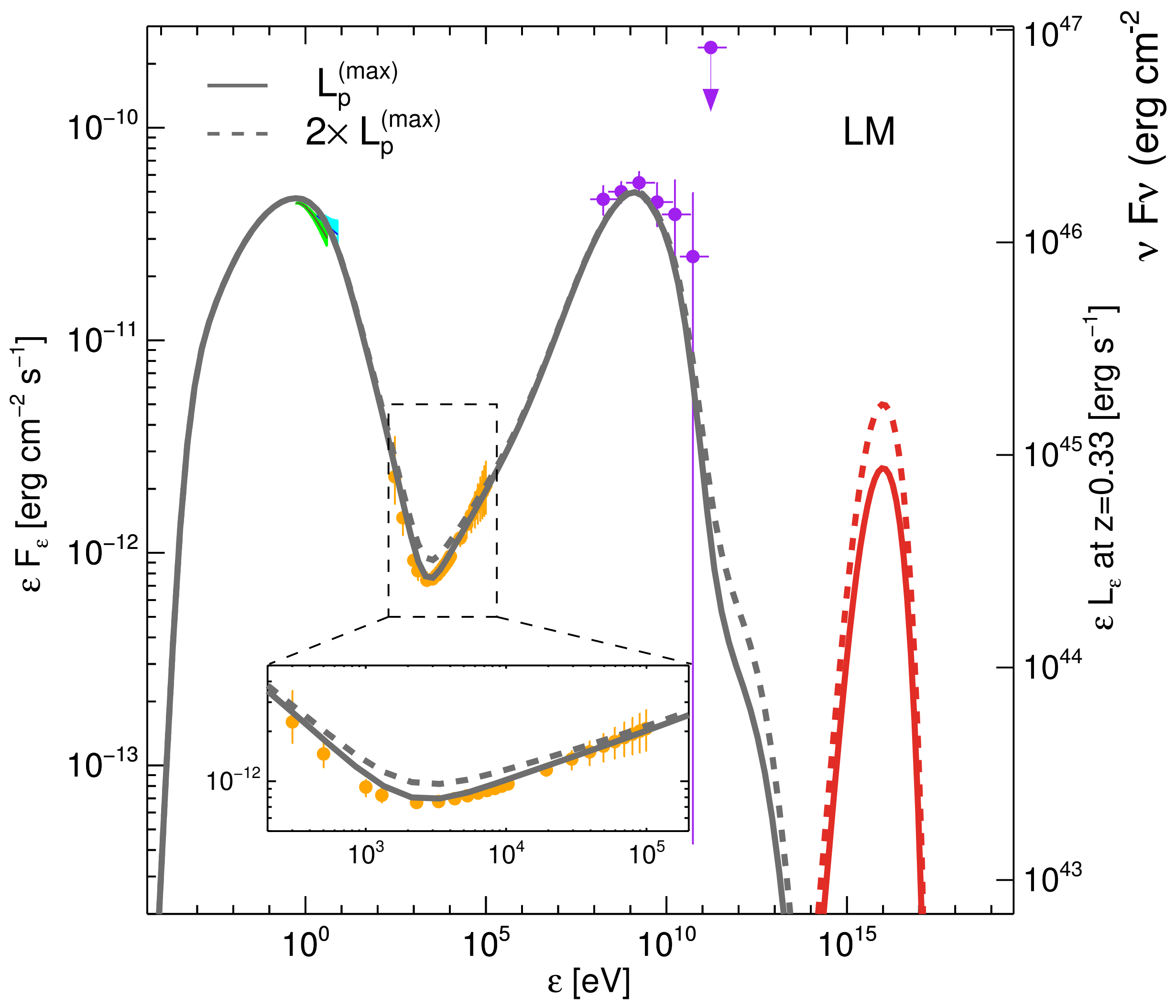
Image from Biteau, Prandini, Costamante+ Nat. Astr 4, 124–131(2020)

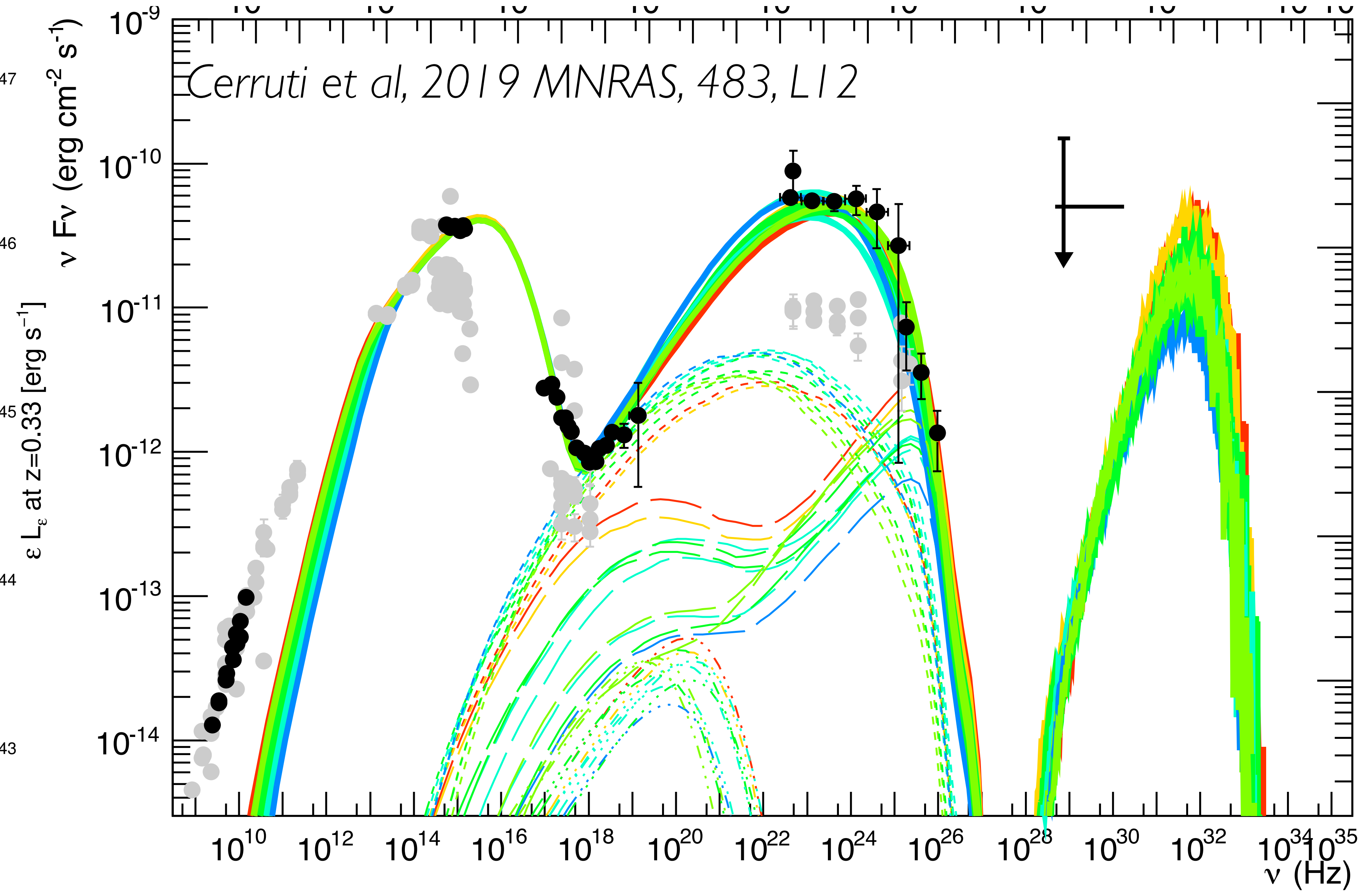
Neutrino production in TXS 0506+056 in 2017

MAGIC Coll 2018, ApJ, 863, L10

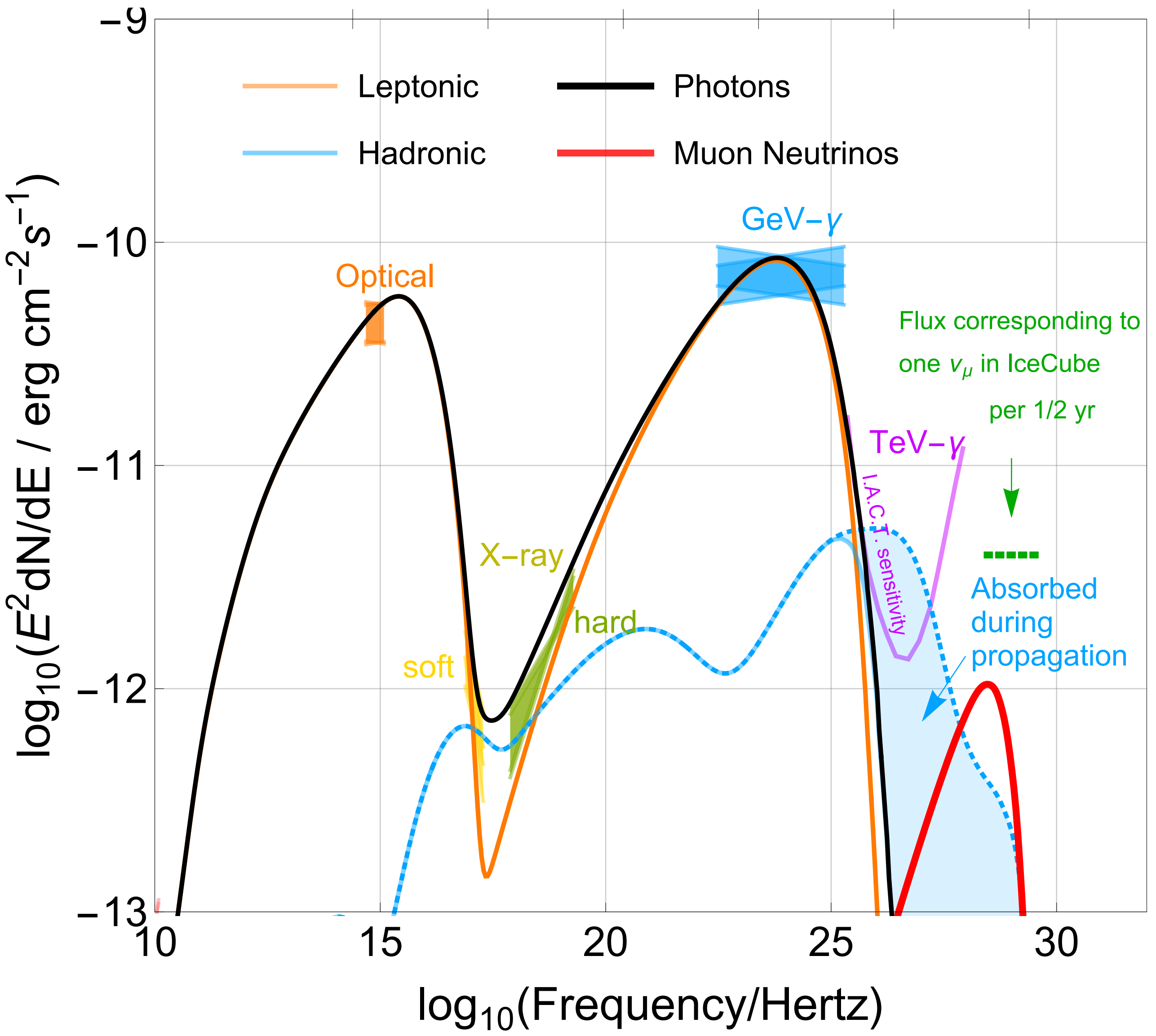


Keivani et al. 2018, ApJ, 864, 84





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?

Optical depth to **p**γ interactions

$$\tau_{p\gamma}(E'_p) \approx \sigma_{p\gamma} r_b n_{\epsilon'_t}\big|_{\epsilon'_t = m_\pi c^2(m_\pi c^2 + m_p c^2)/2E'_p}$$

At the same time γγ,

$$\tau_{\gamma\gamma}(\varepsilon'_\gamma) \approx \sigma_{\mathrm{T}} r'_{\mathrm{b}} n_{\epsilon'_t}\big|_{\epsilon'_t = m_e^2/E'_\gamma}$$

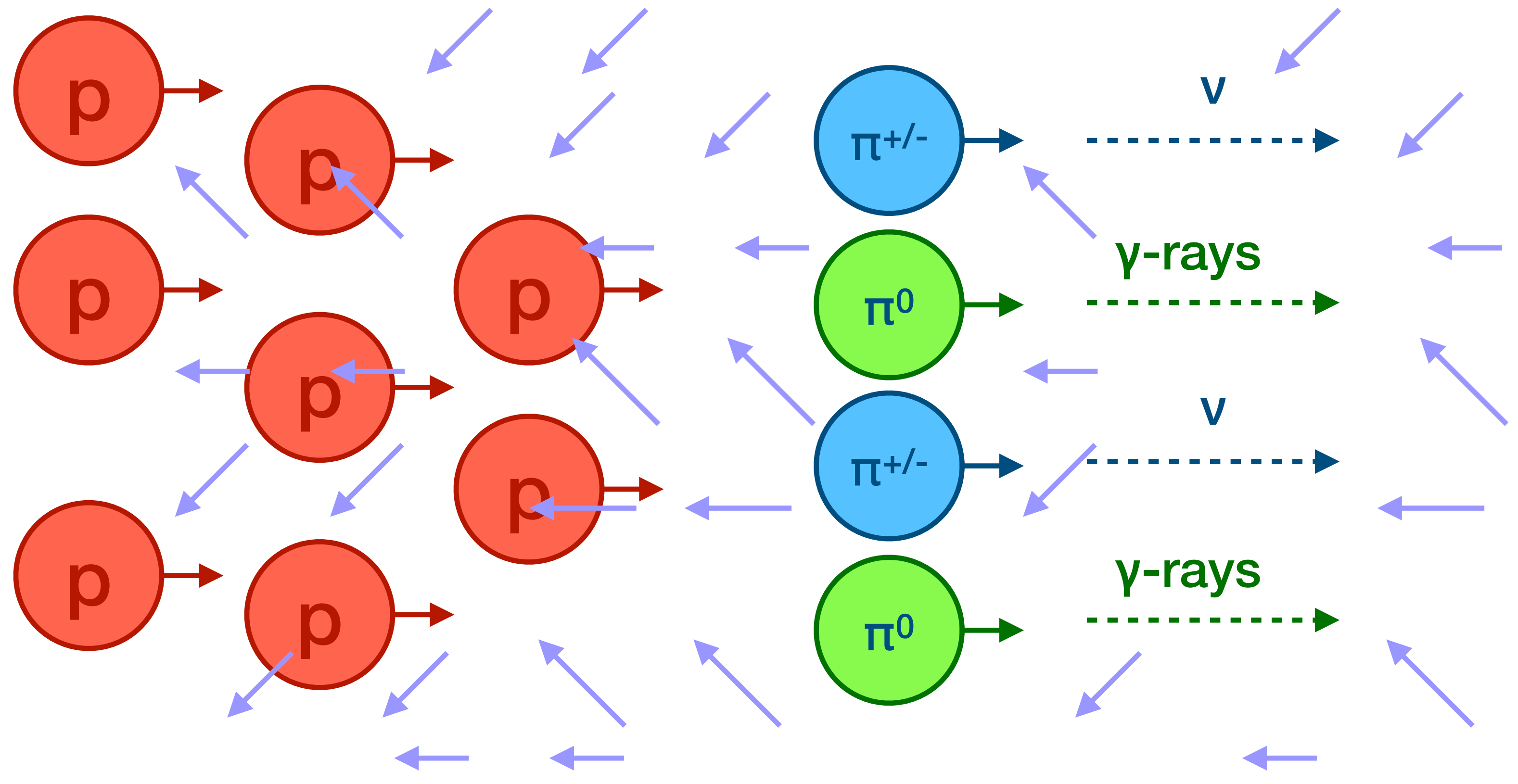
Ratio of optical depths is then,

$$\tau_{p\gamma}(E'_p) \approx \frac{\kappa_{p\gamma}}{\kappa_{\gamma\gamma}}\frac{\sigma_{\gamma p}}{\sigma_{\gamma\gamma}}\tau_{\gamma\gamma}(E'_\gamma) \approx \frac{10^{-28}\ \mathrm{cm}^2}{10^{-25}\ \mathrm{cm}^2}\tau_{\gamma\gamma}(E'_\gamma) \approx 10^{-3}\tau_{\gamma\gamma}(E'_\gamma)$$

At energy,

$$E'_\gamma \sim 15\ \mathrm{GeV}\left(\frac{E'_p}{6\ \mathrm{PeV}}\right) \sim 15\ \mathrm{GeV}\left(\frac{E'_\nu}{300\ \mathrm{TeV}}\right)$$

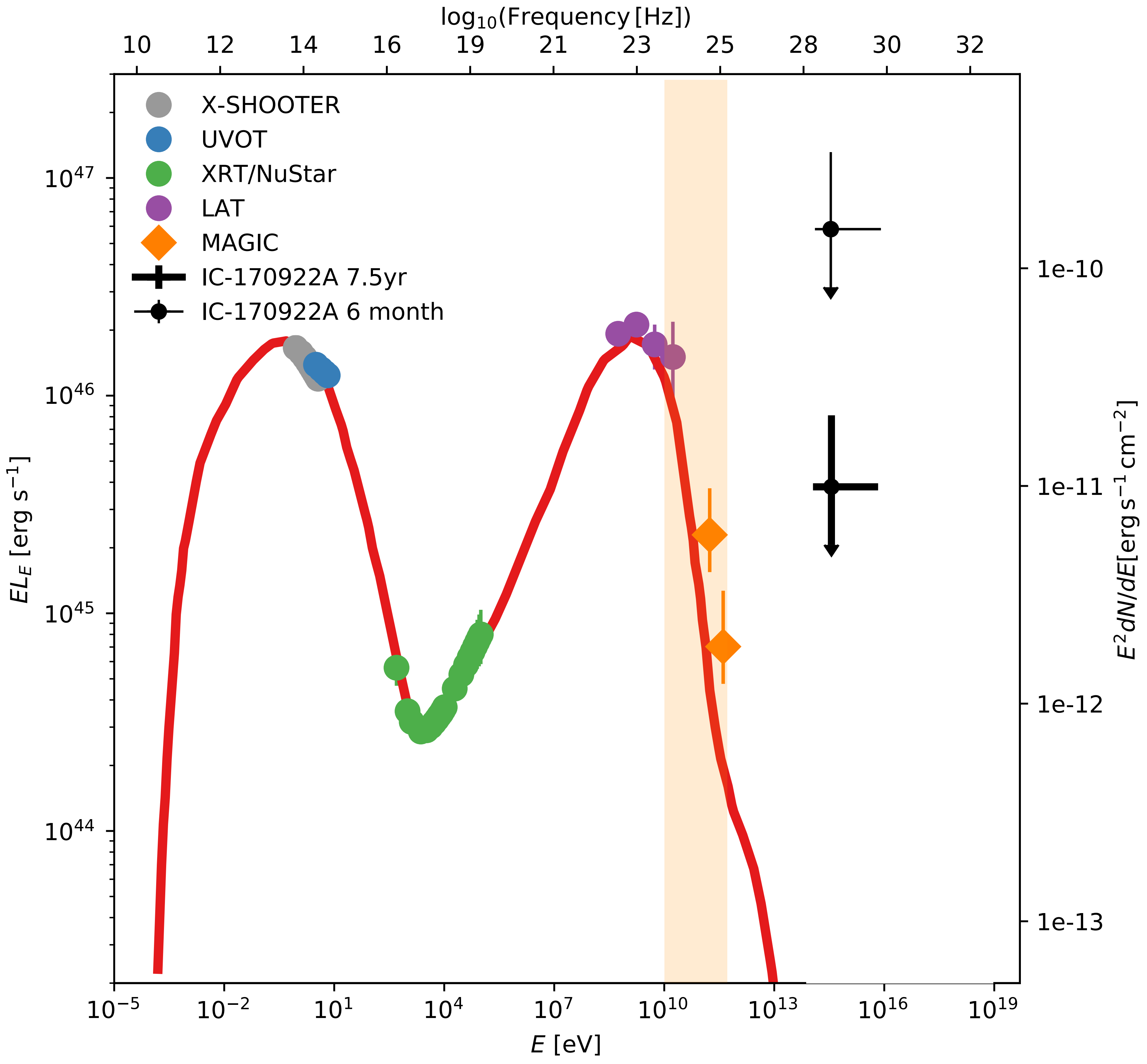
This implies that sources optically thin to gamma-rays have inefficient TeV neutrino production

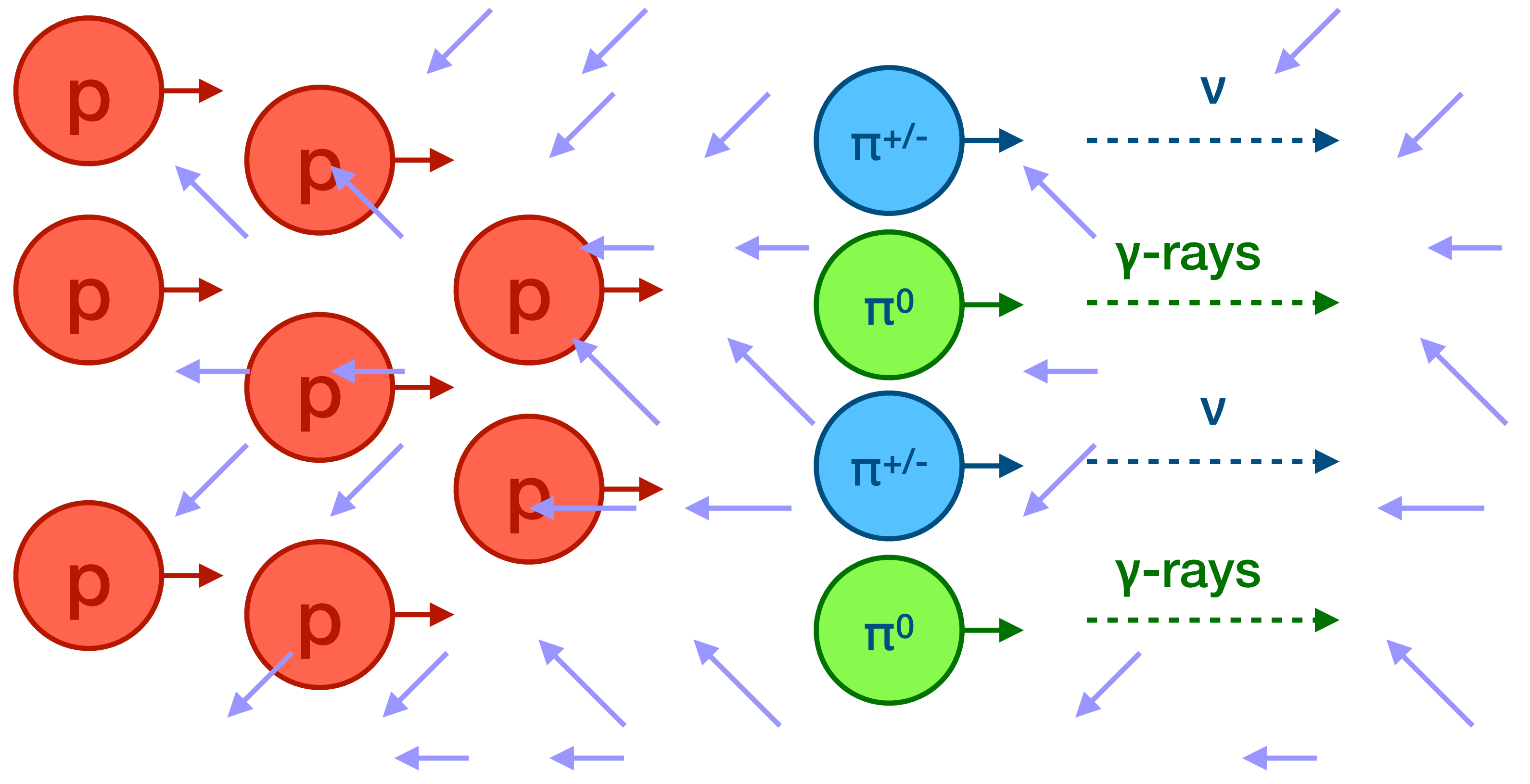


$$p + \gamma \rightarrow \pi + X$$
$$\gamma + \gamma \rightarrow e^+ + e^-$$

What sets the neutrino flux upper limit?

1. $\tau_{\gamma\gamma}(10 - 100\,\mathrm{GeV}) \lesssim 1$





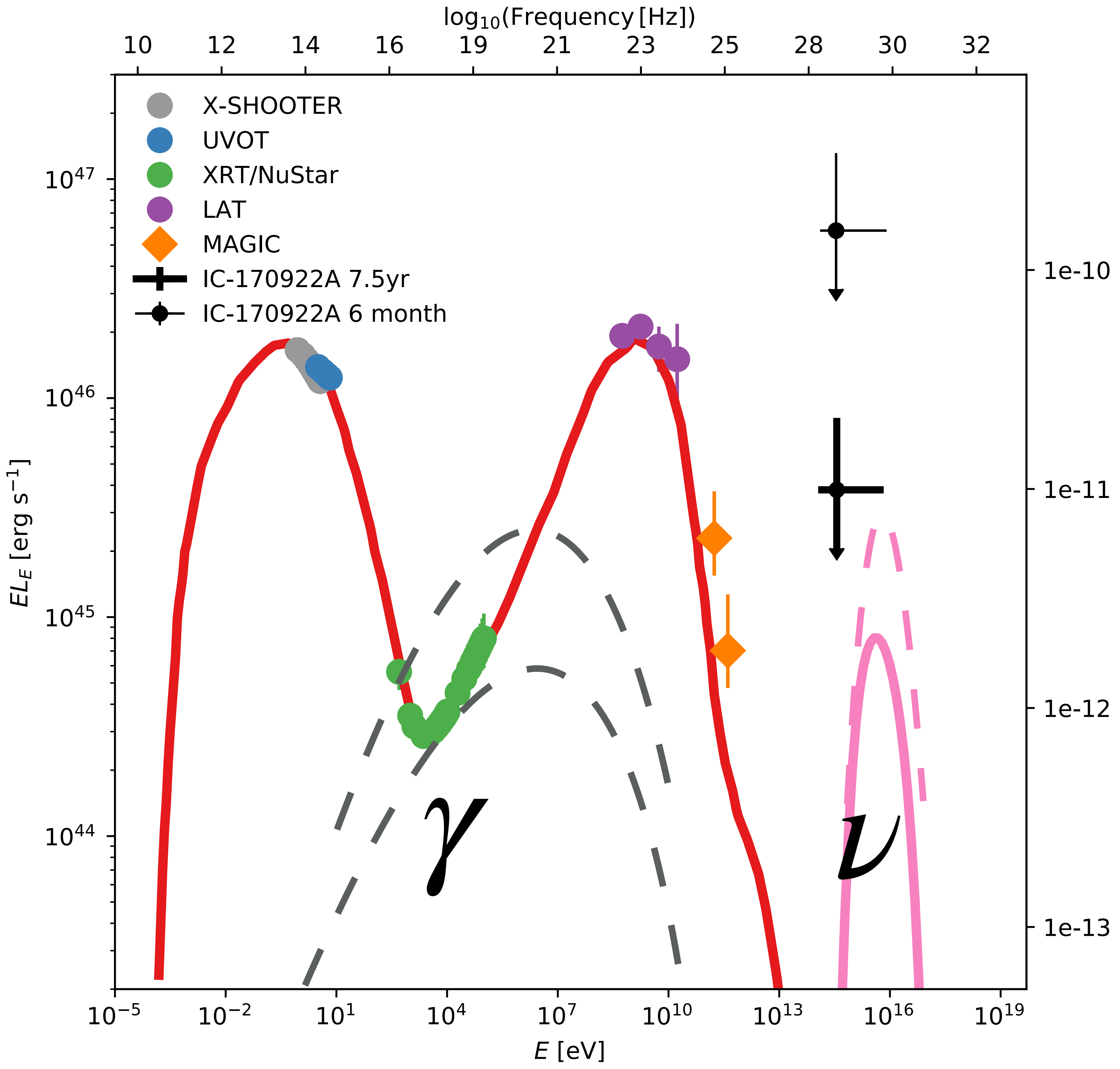
At energy,

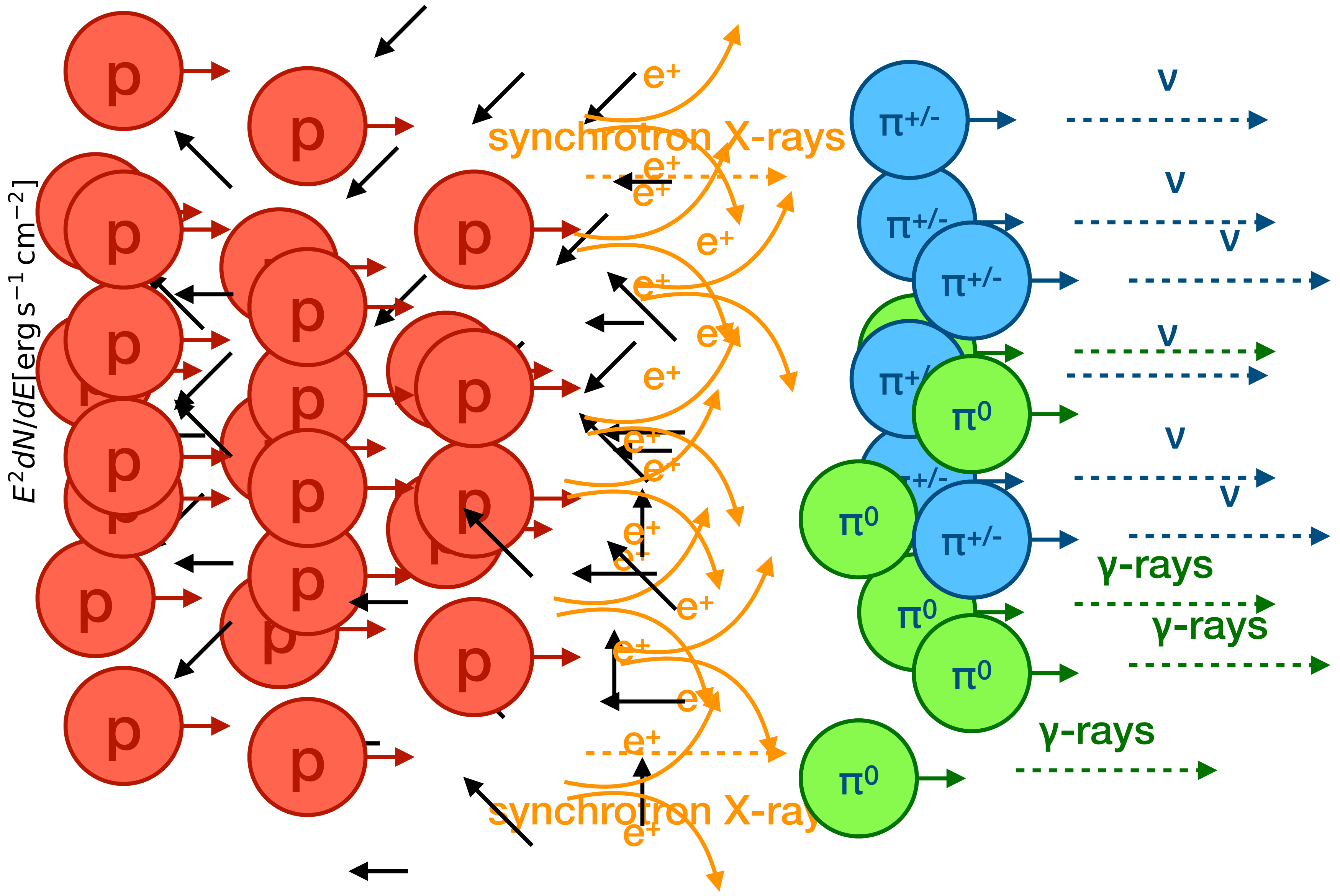
$$E'_\gamma \sim 15\ \mathrm{GeV}\left(\frac{E'_p}{6\ \mathrm{PeV}}\right) \sim 15\ \mathrm{GeV}\left(\frac{E'_\nu}{300\ \mathrm{TeV}}\right)$$

$$\tau_{\gamma\gamma}(E'_\gamma) \approx 10^3 \tau_{p\gamma}(E'_p)$$

What sets the neutrino flux upper limit?

$p_{\mathrm{PeV}} + \gamma \rightarrow p + e^{+} + e^{-} \rightarrow$ the electrons undergo synchrotron or Inv. Compton $\rightarrow$ cascade that peaks in keV band

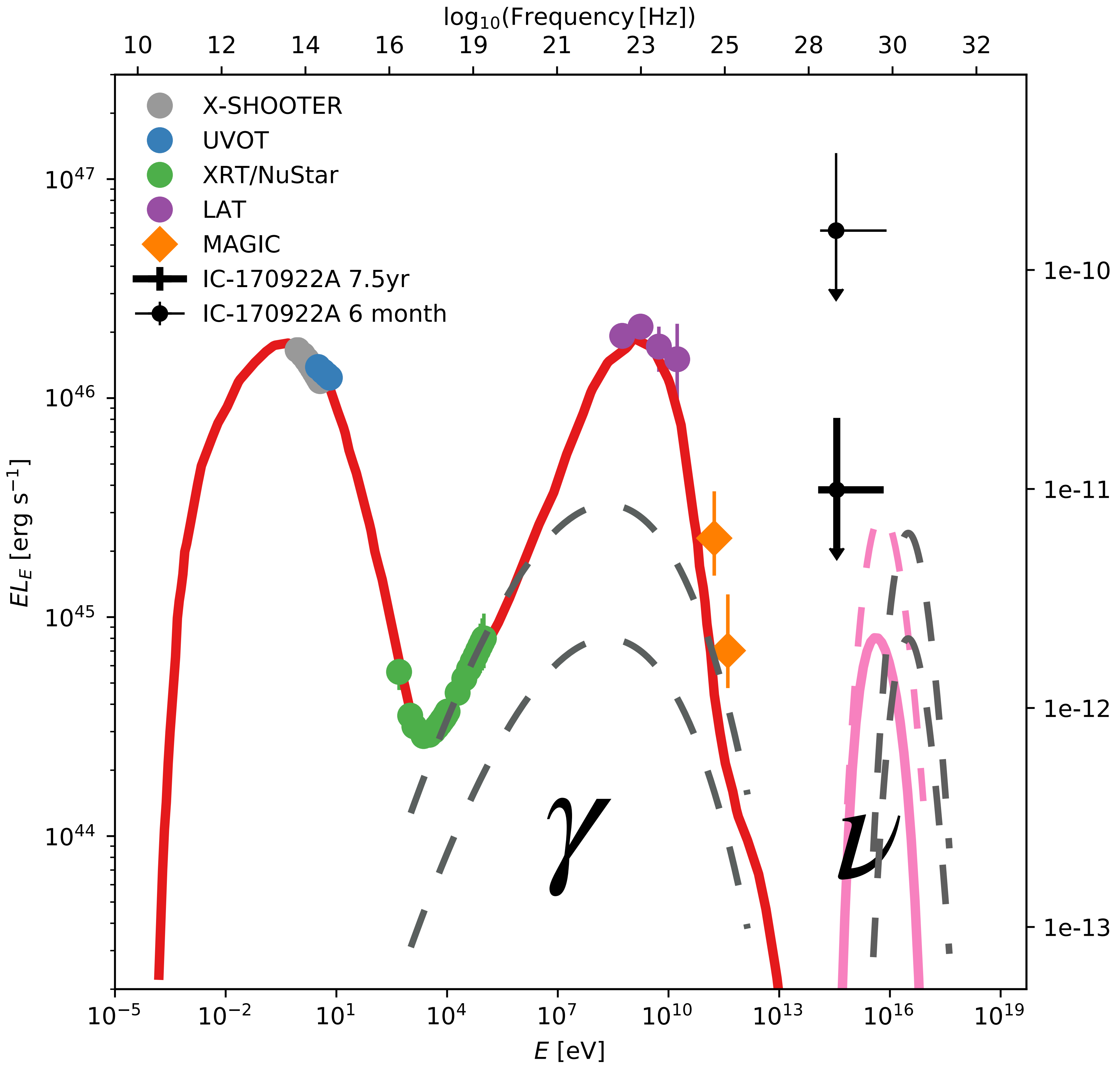


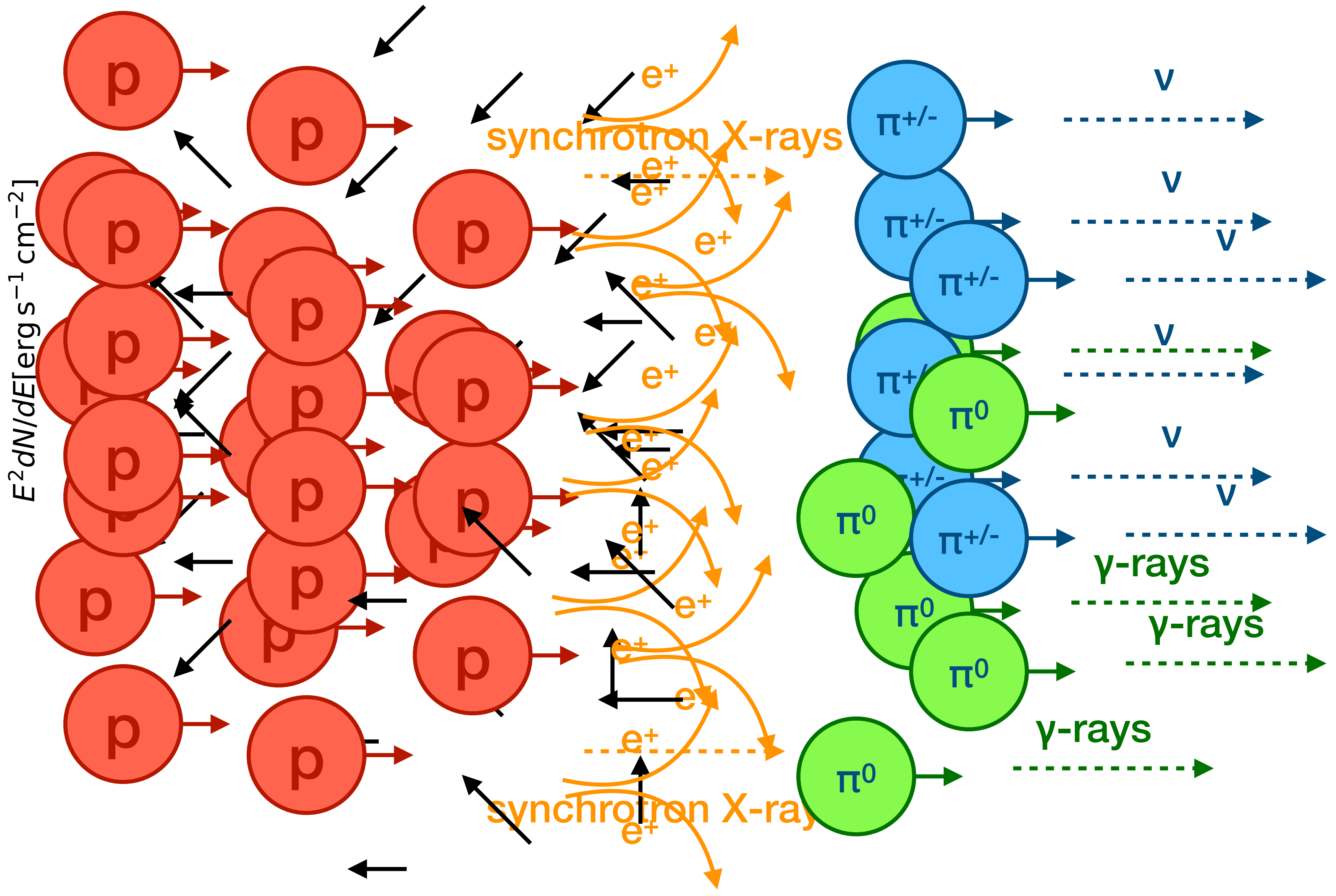


3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

What sets the neutrino flux upper limit?

$p_{\mathrm{PeV}} + \gamma \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma$ $\gamma + \gamma_{\mathrm{jet/BLR}} \rightarrow e^+e^- \rightarrow \text{synchrotron or inv. Compton}$

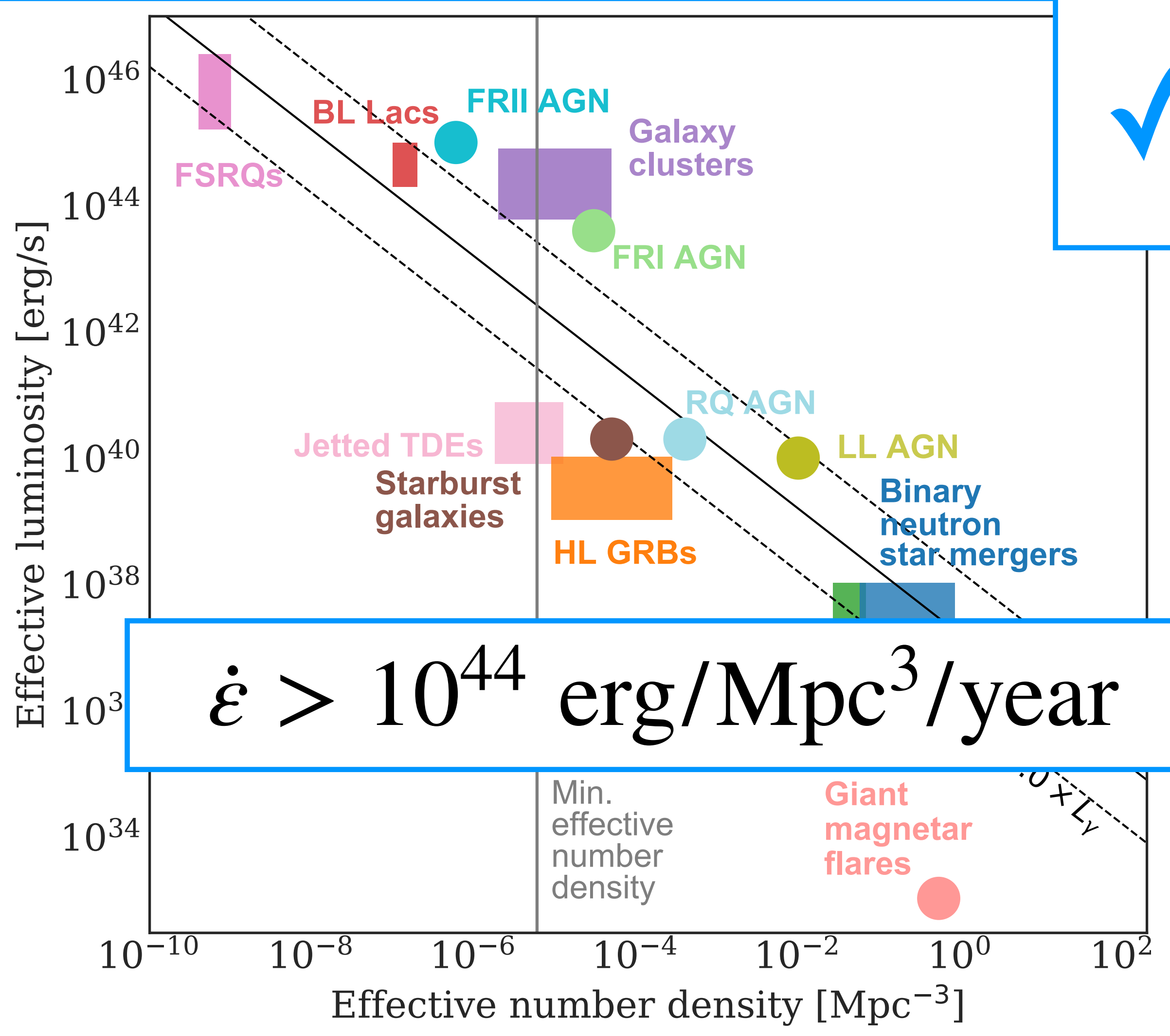




3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

Blazar contribution to UHECR/neutrino flux?

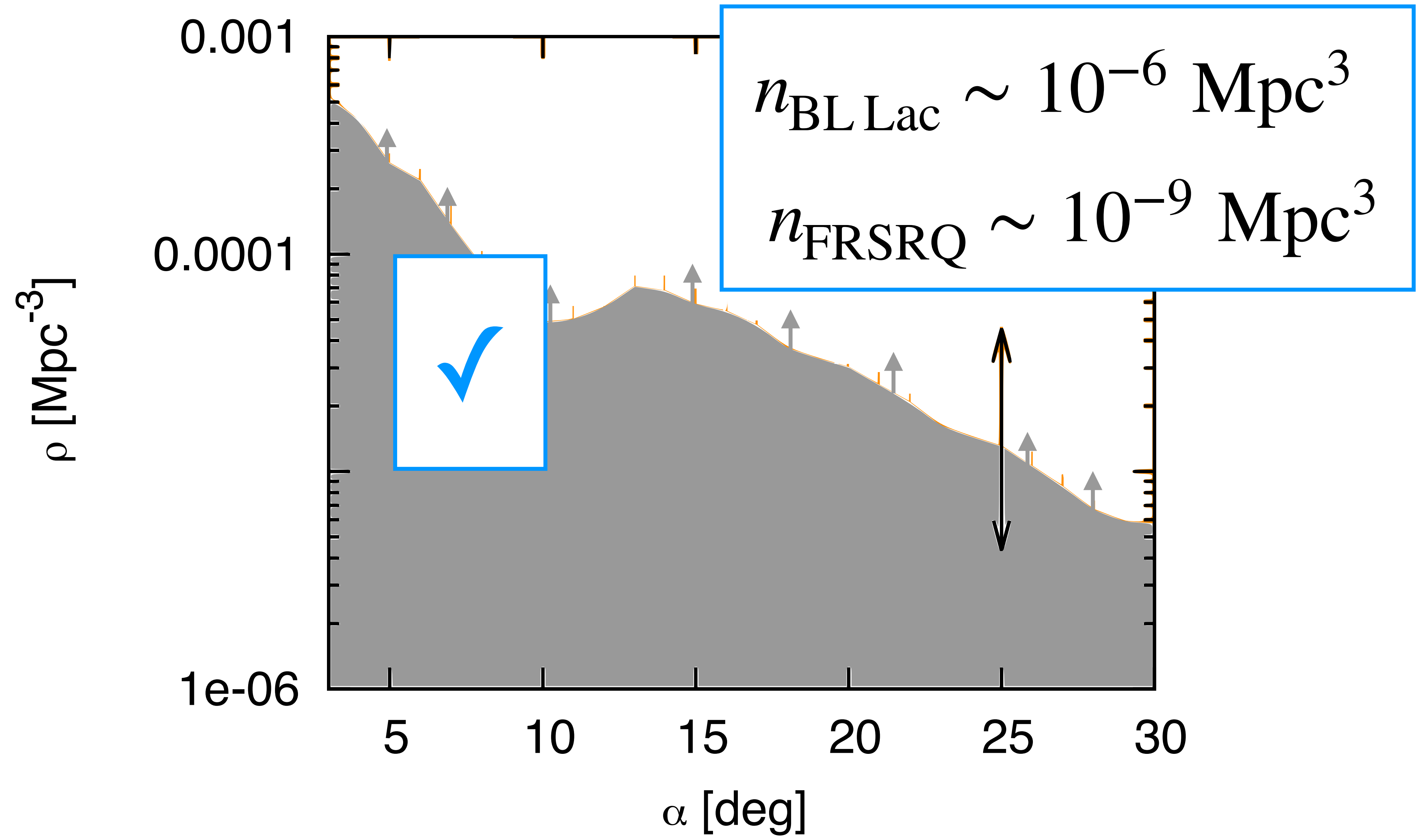
UHECR Emissivity



✓

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

UHECR number density

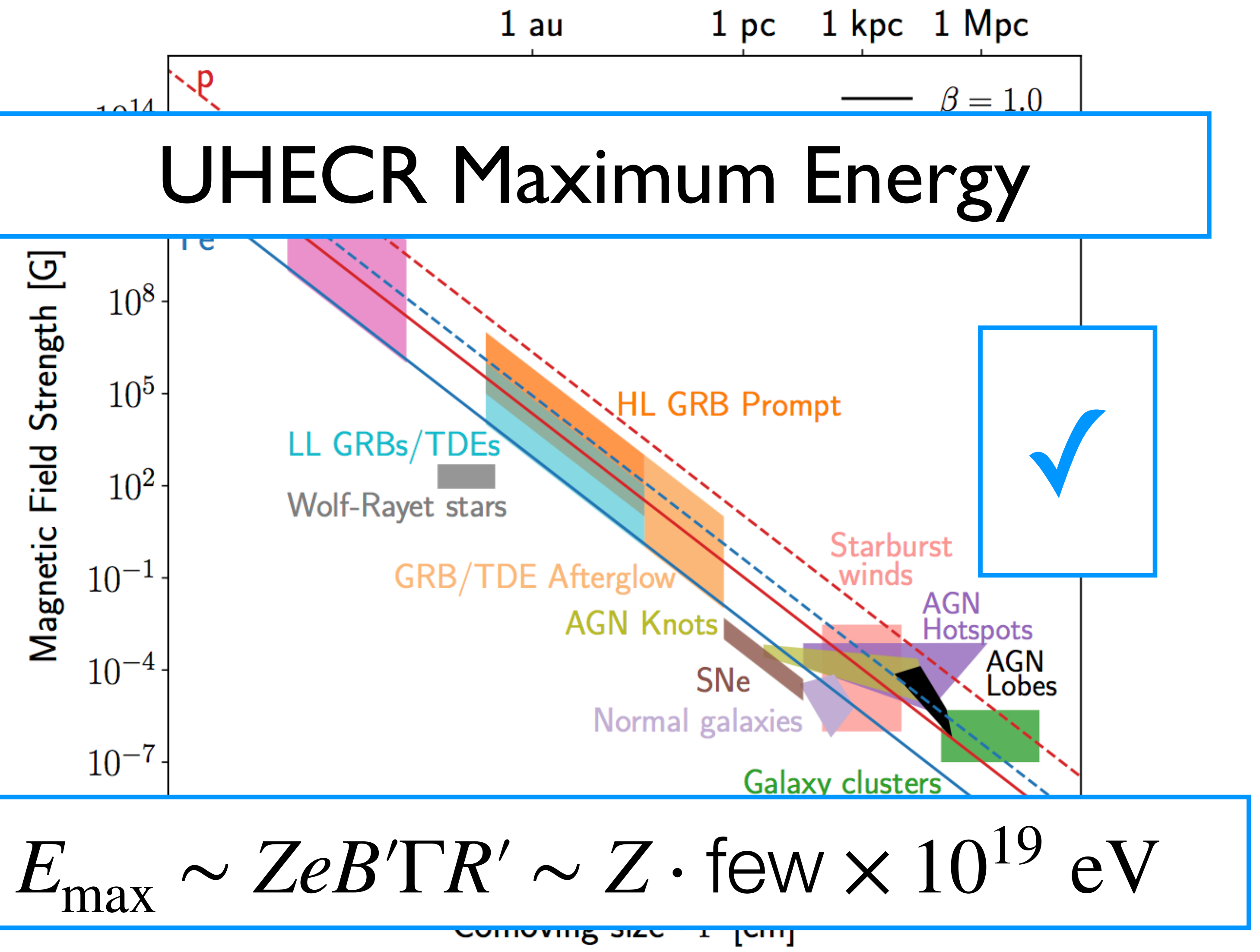


✓

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

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

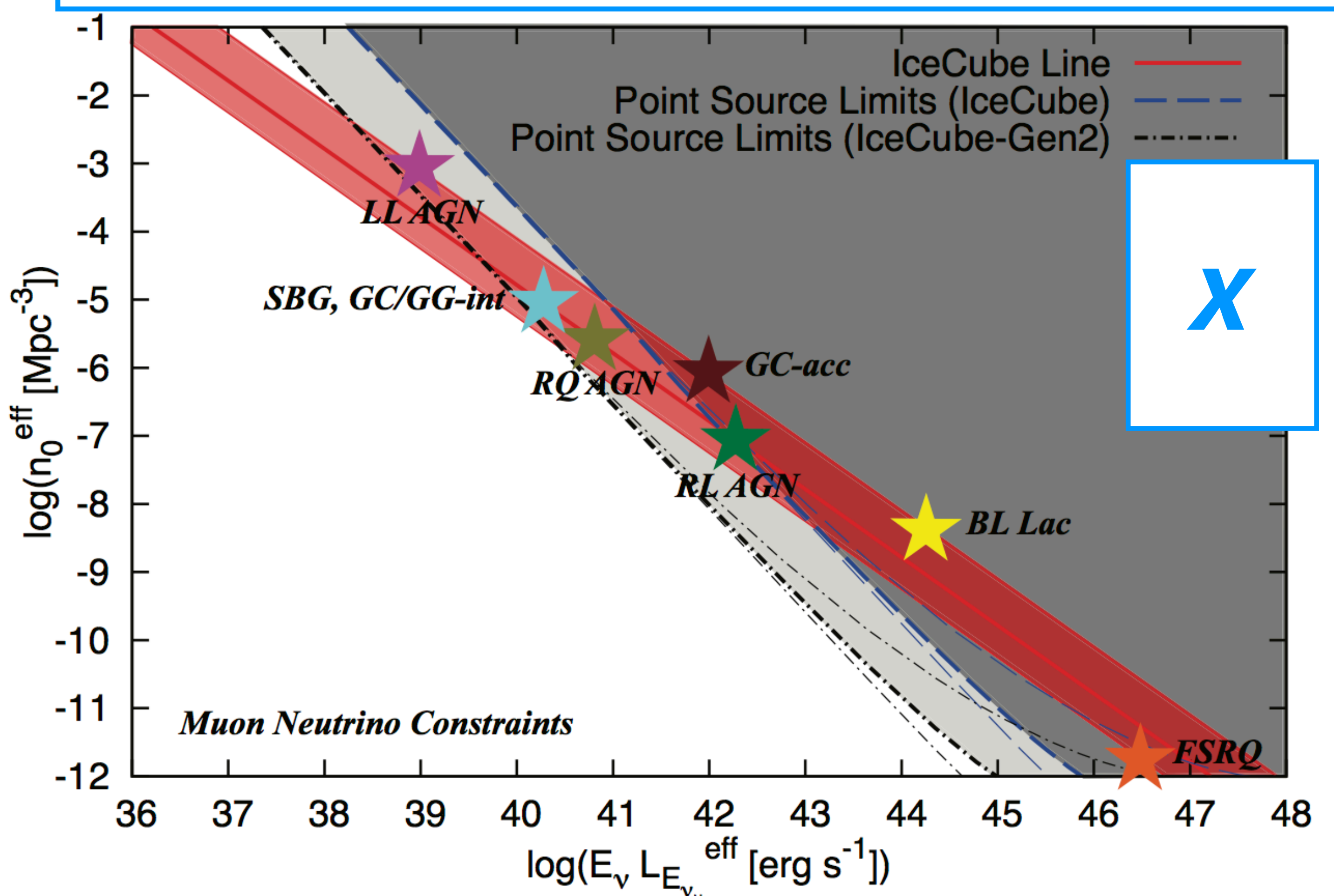
UHECR Maximum Energy



✓

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

Neutrino clustering constraints

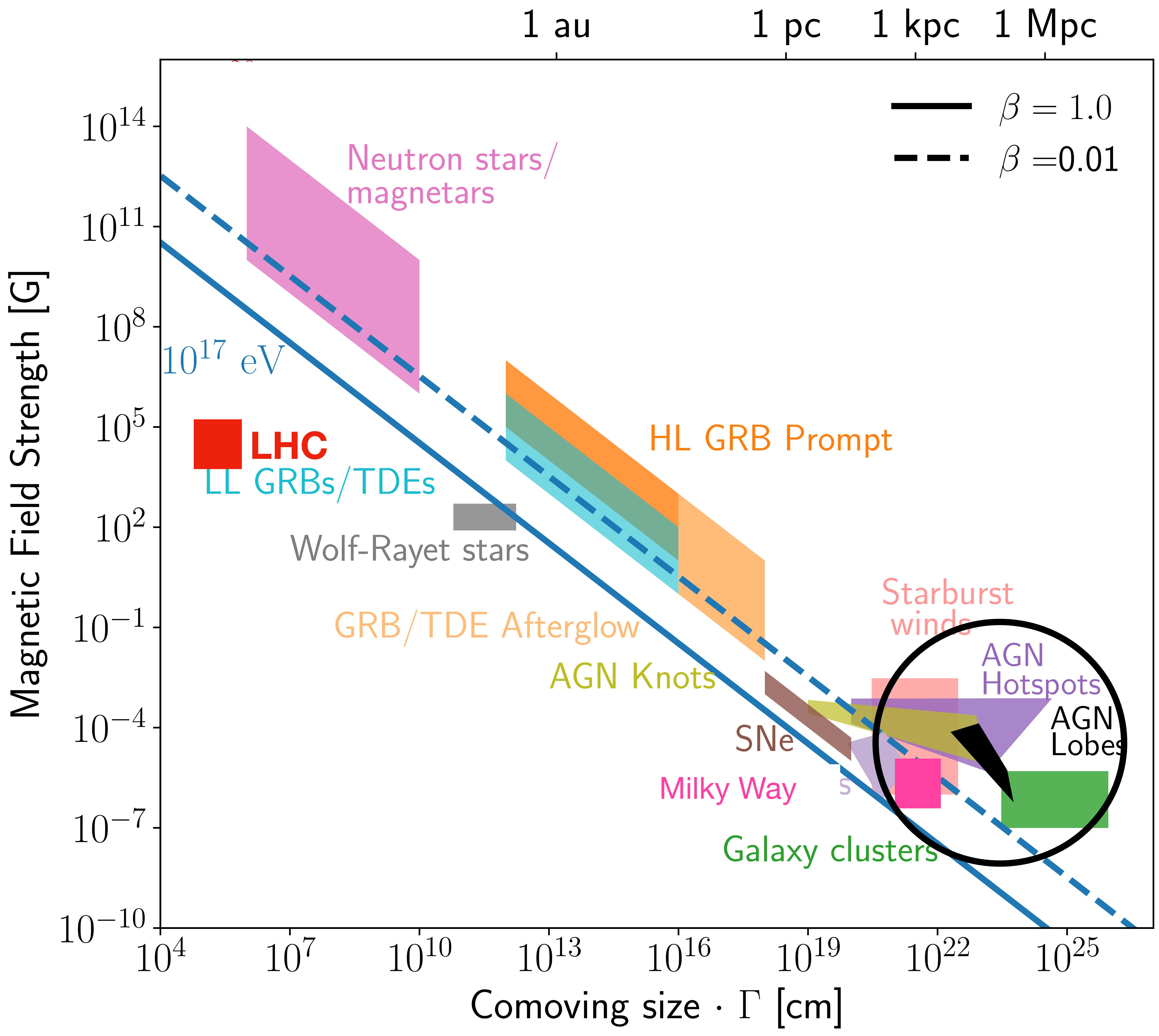


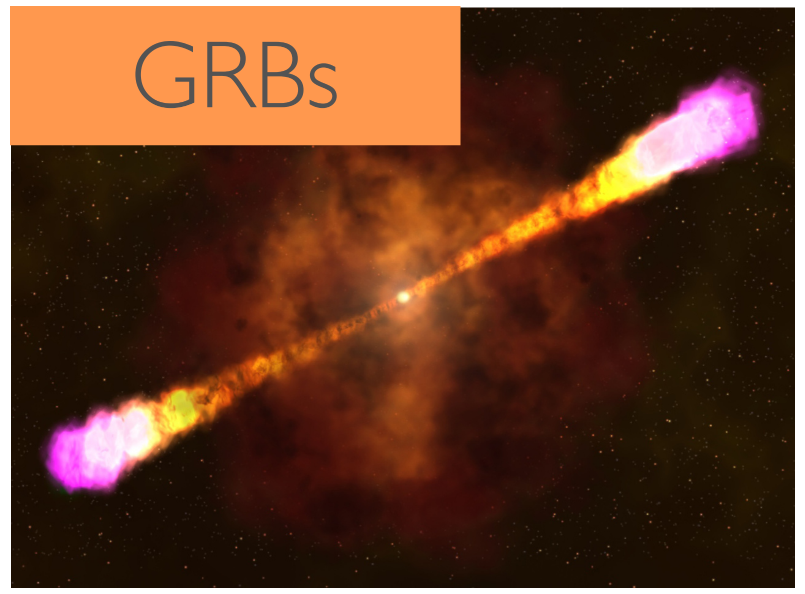
X

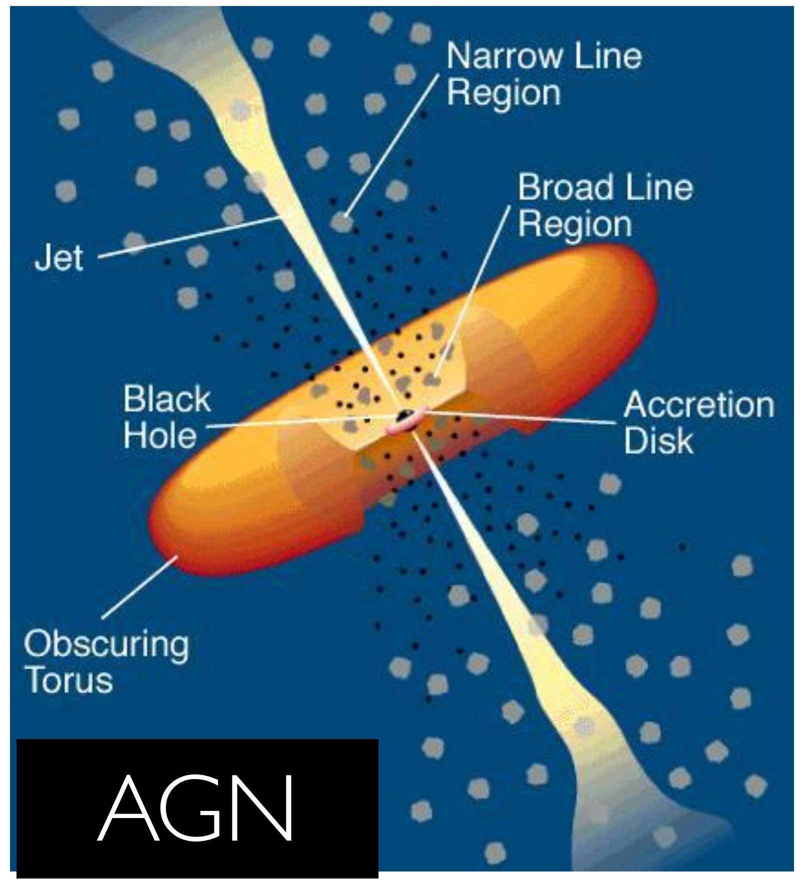
Scorecard

	E_{max}	$\bar{n}_{\mathrm{eff,UHECR}}$	$\bar{n}_{\mathrm{eff},\nu}$	$\dot{\varepsilon}_{\mathrm{UHECR}}$
BL Lac	not for H	😞	😞	😀
FSRQs	😀	😞	😞	😀
FR I	not for H	😀	😀	😀
FR II	😀	😀	~😞	😀
Starbursts				
HL GRBs				
LL GRBs				
Pulsars				
TDEs				

Cosmic-ray accelerators that satisfy the confinement r

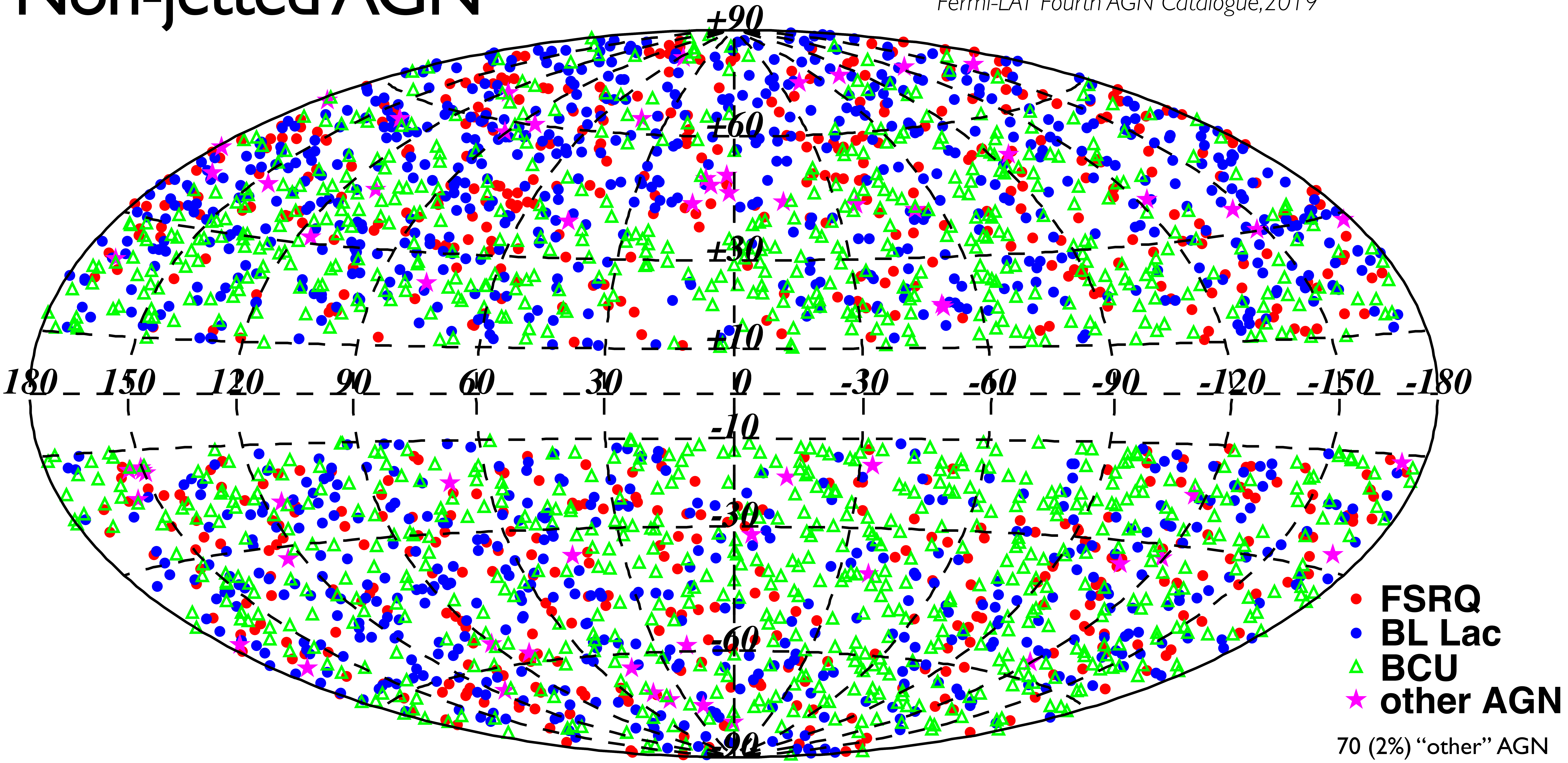






Non-jetted AGN

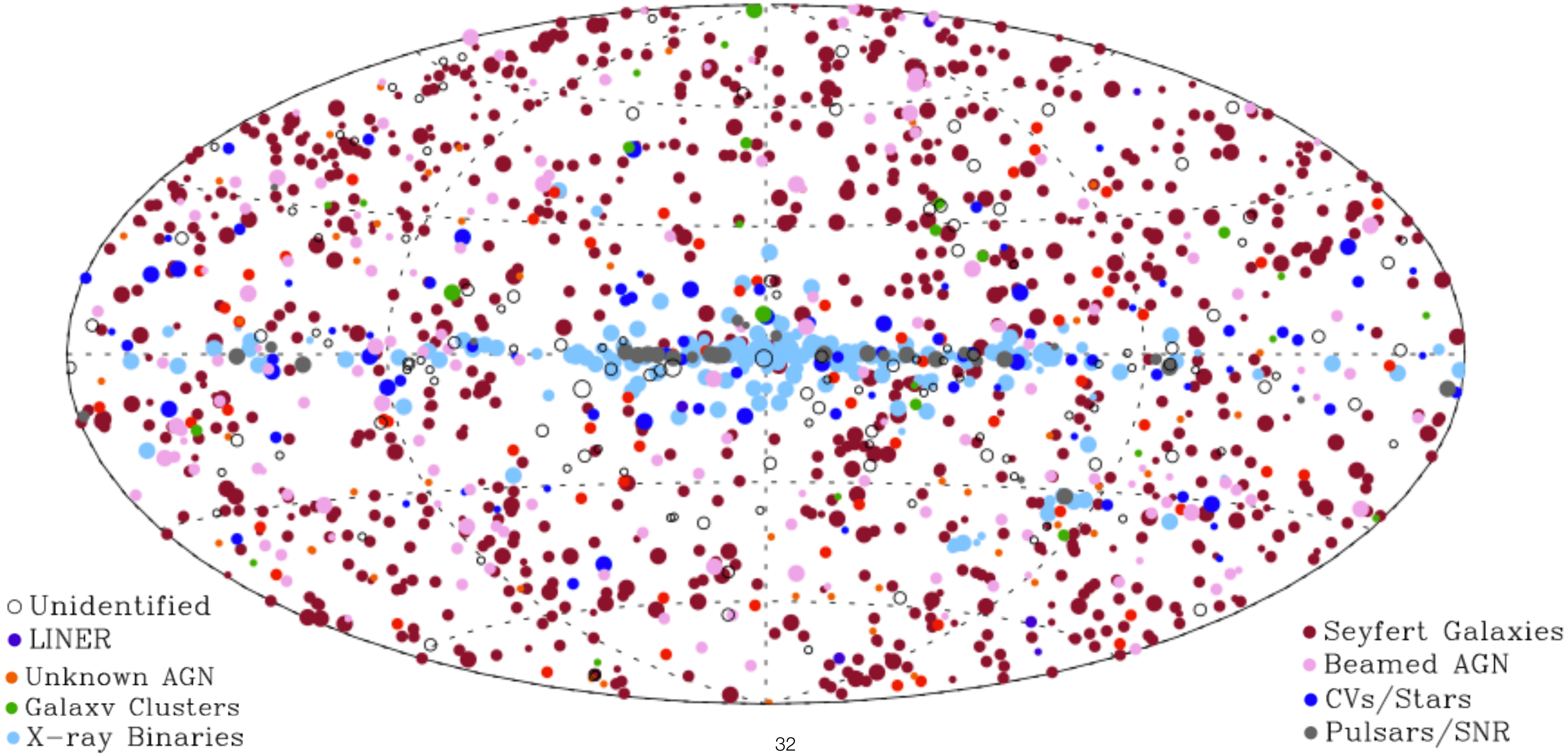
Fermi-LAT Fourth AGN Catalogue, 2019



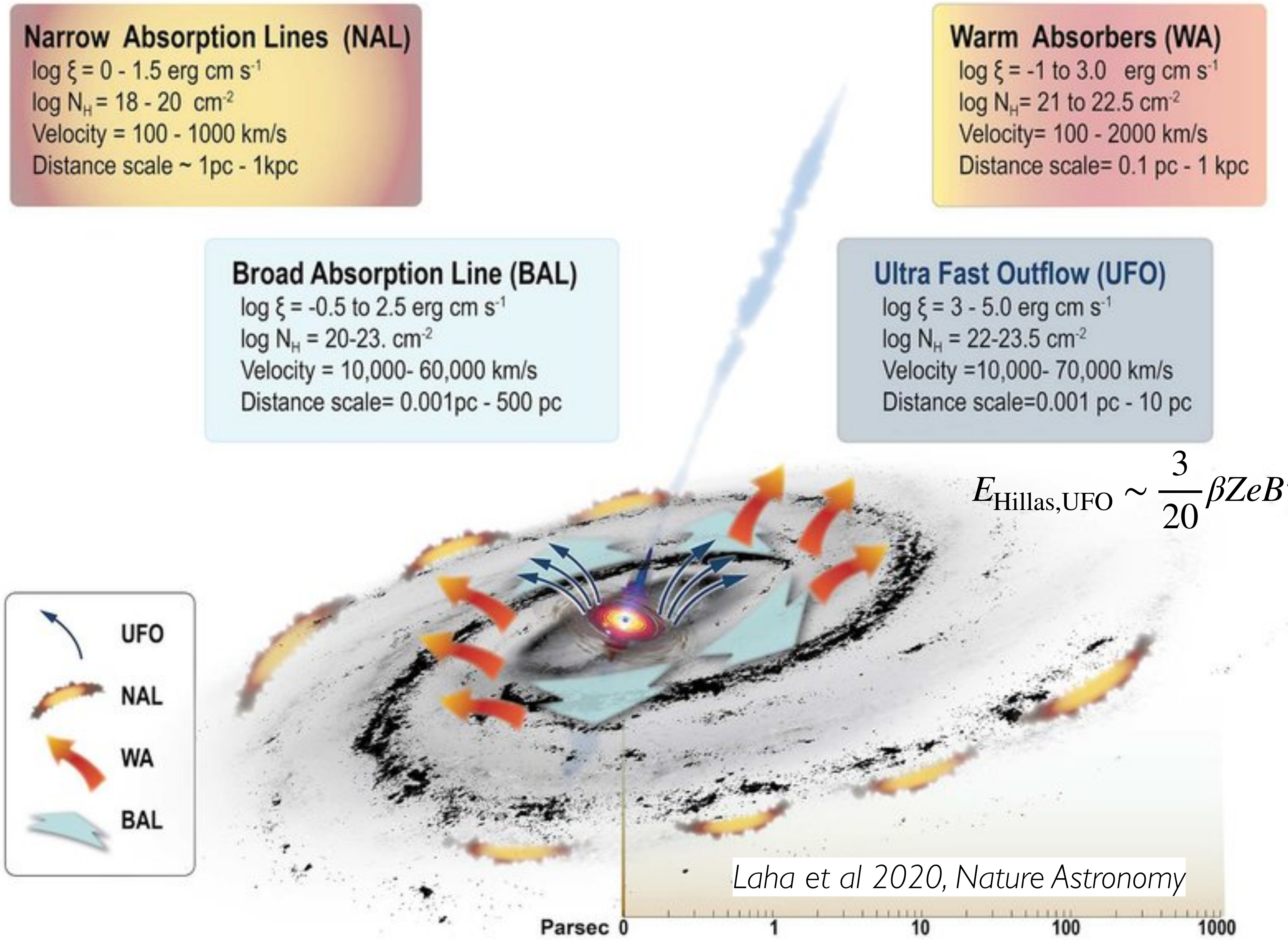
70 (2%) "other" AGN
~10 non-jetted AGN

Non-jetted AGN

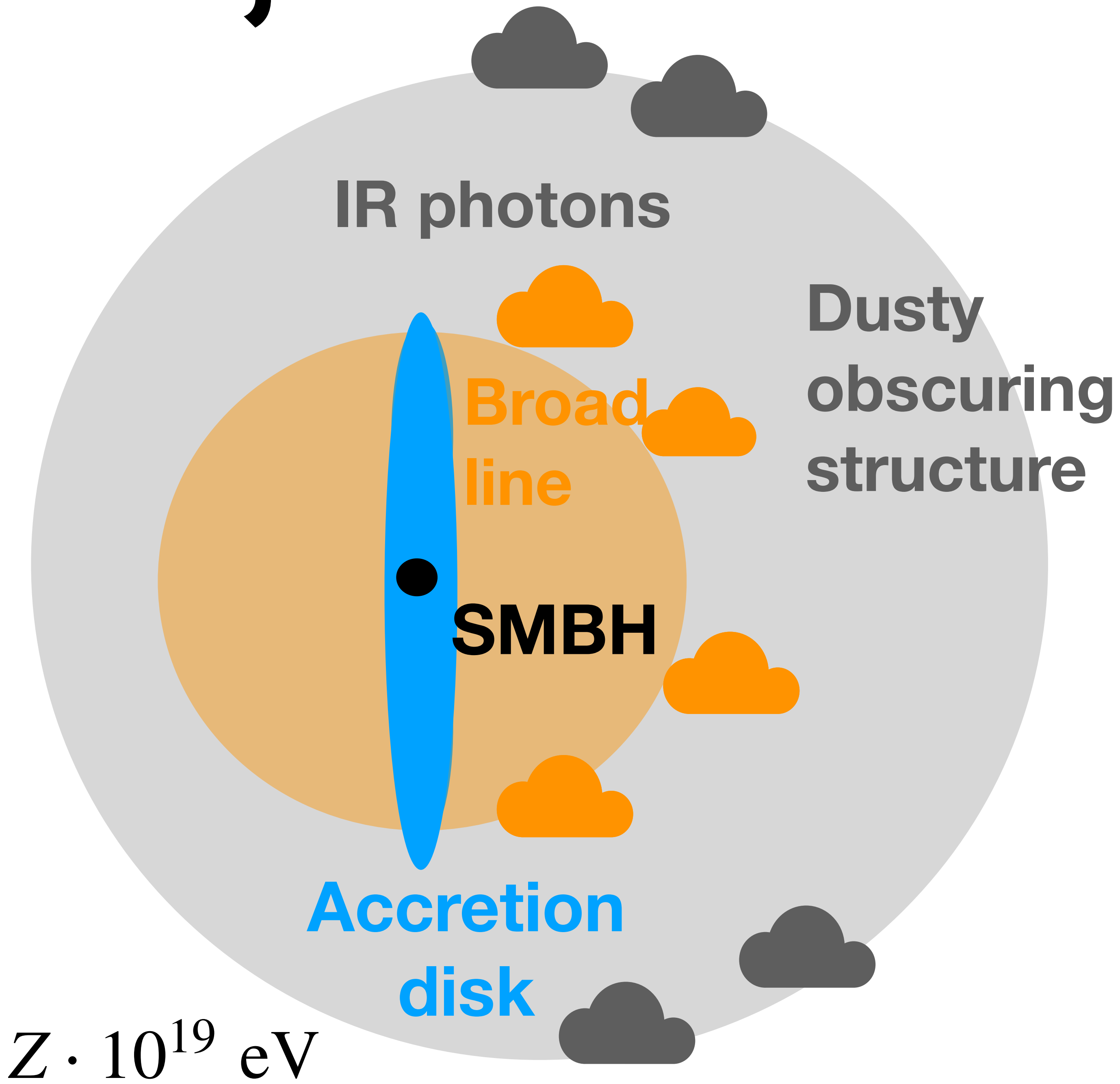
Swift-BAT 105-month hard-X-ray catalogue 2018



Possible sites of UHECR acceleration in non-jetted AGN

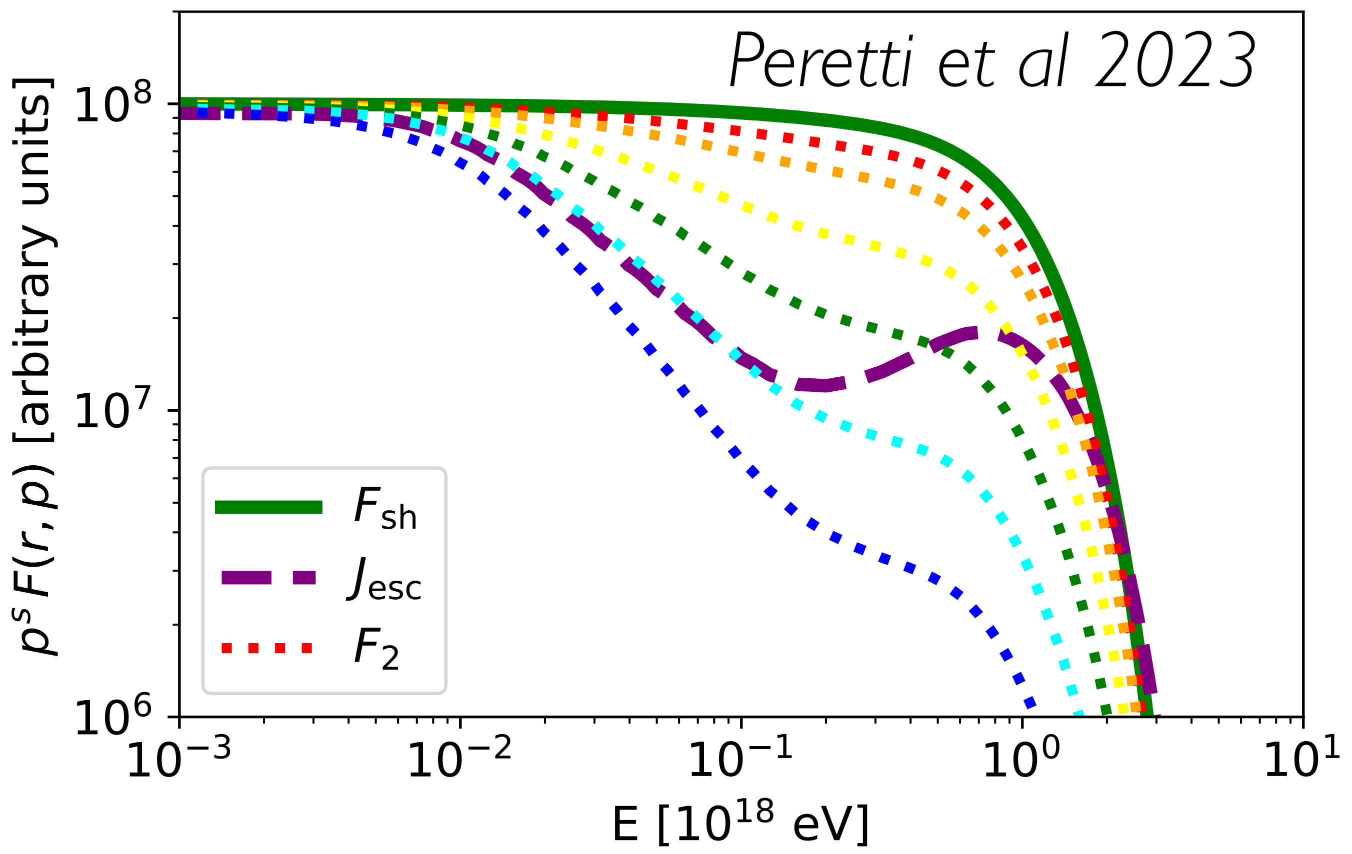


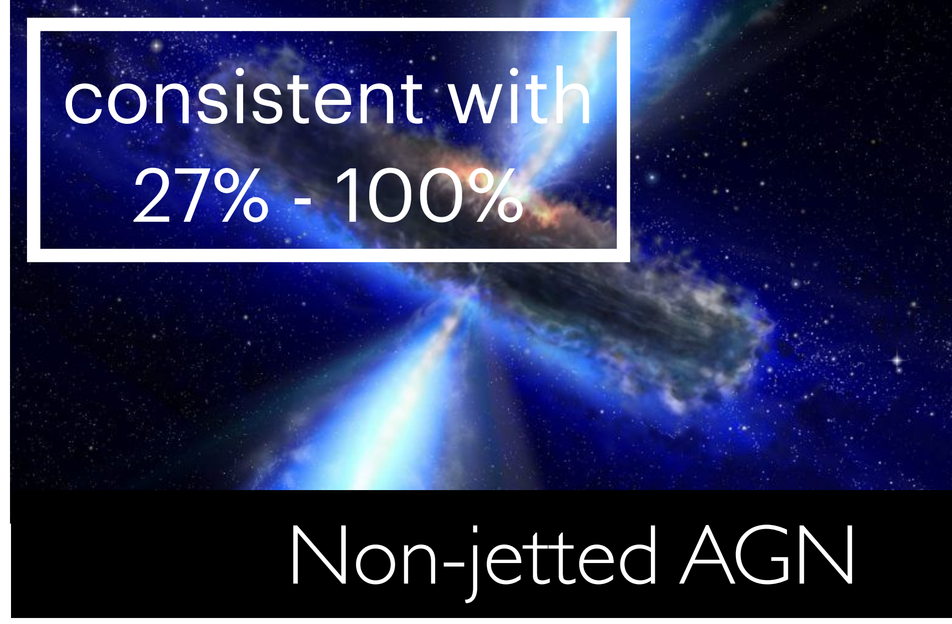
Laha et al 2020, Nature Astronomy



$$E_{\mathrm{Hillas,UFO}} \sim \frac{3}{20}\beta Z e B' \Gamma R' \sim Z \cdot 10^{19}\ \mathrm{eV}$$

Energy losses limit maximum energy



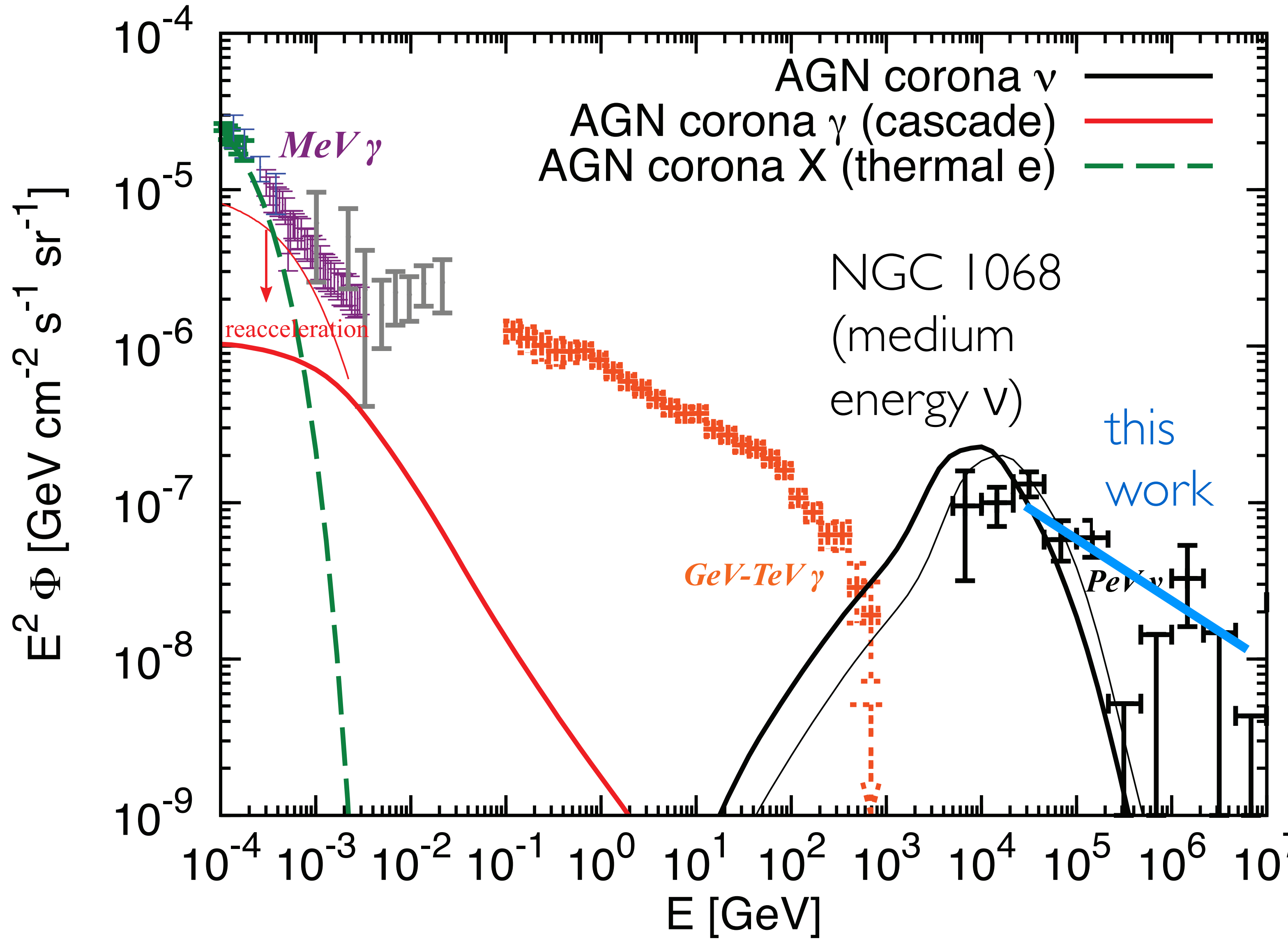


Non-jetted AGN contribution to the cosmic-neutrino flux

Infrared selected (ALLWISE) AGN with soft-X-ray weights ~ 32,249 AGN

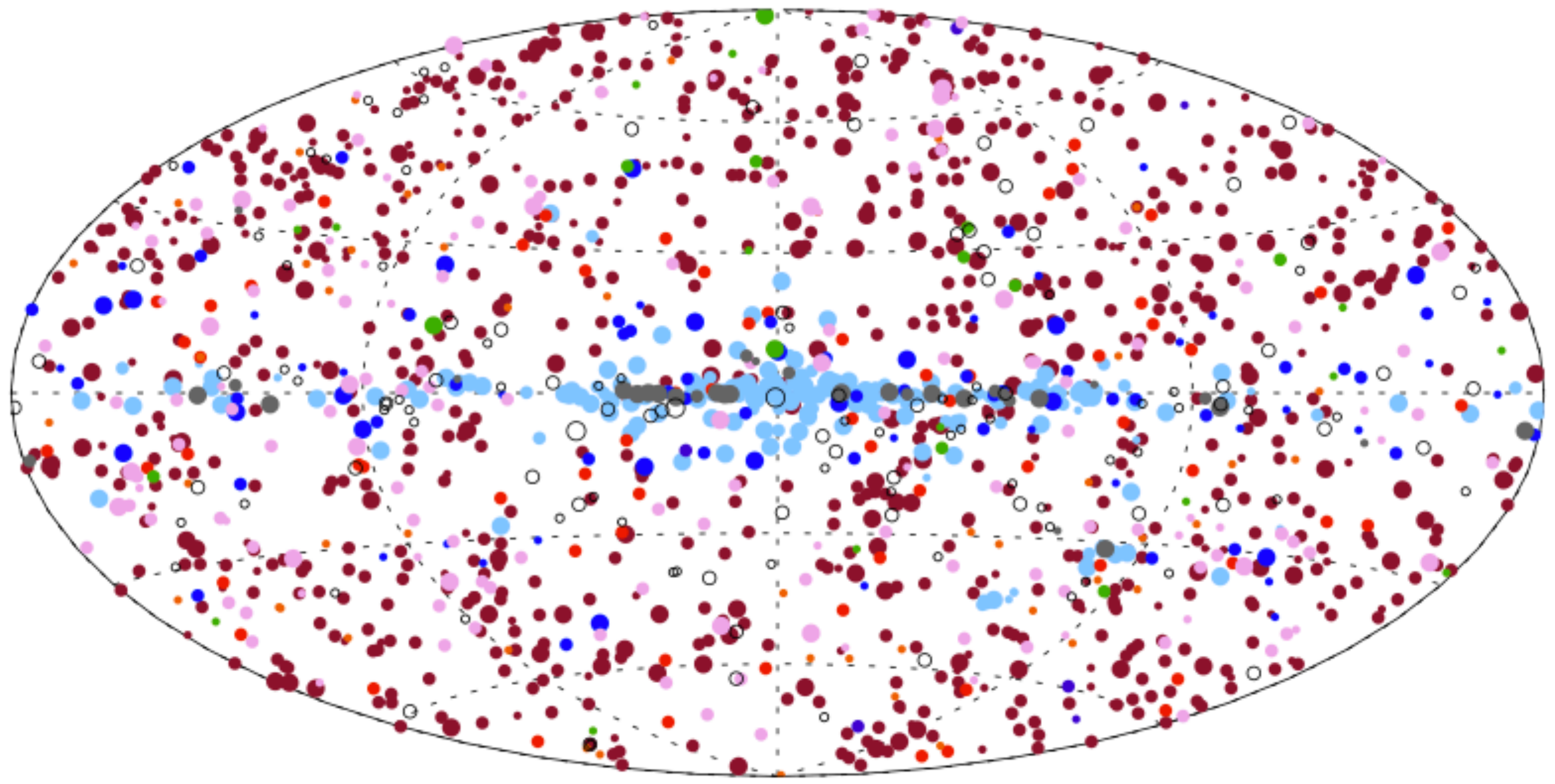
2.6σ excess w.r.t. background expectations

Best-fit spectral index $\dfrac{\mathrm{d}N}{\mathrm{d}E} \sim E^{-2}$

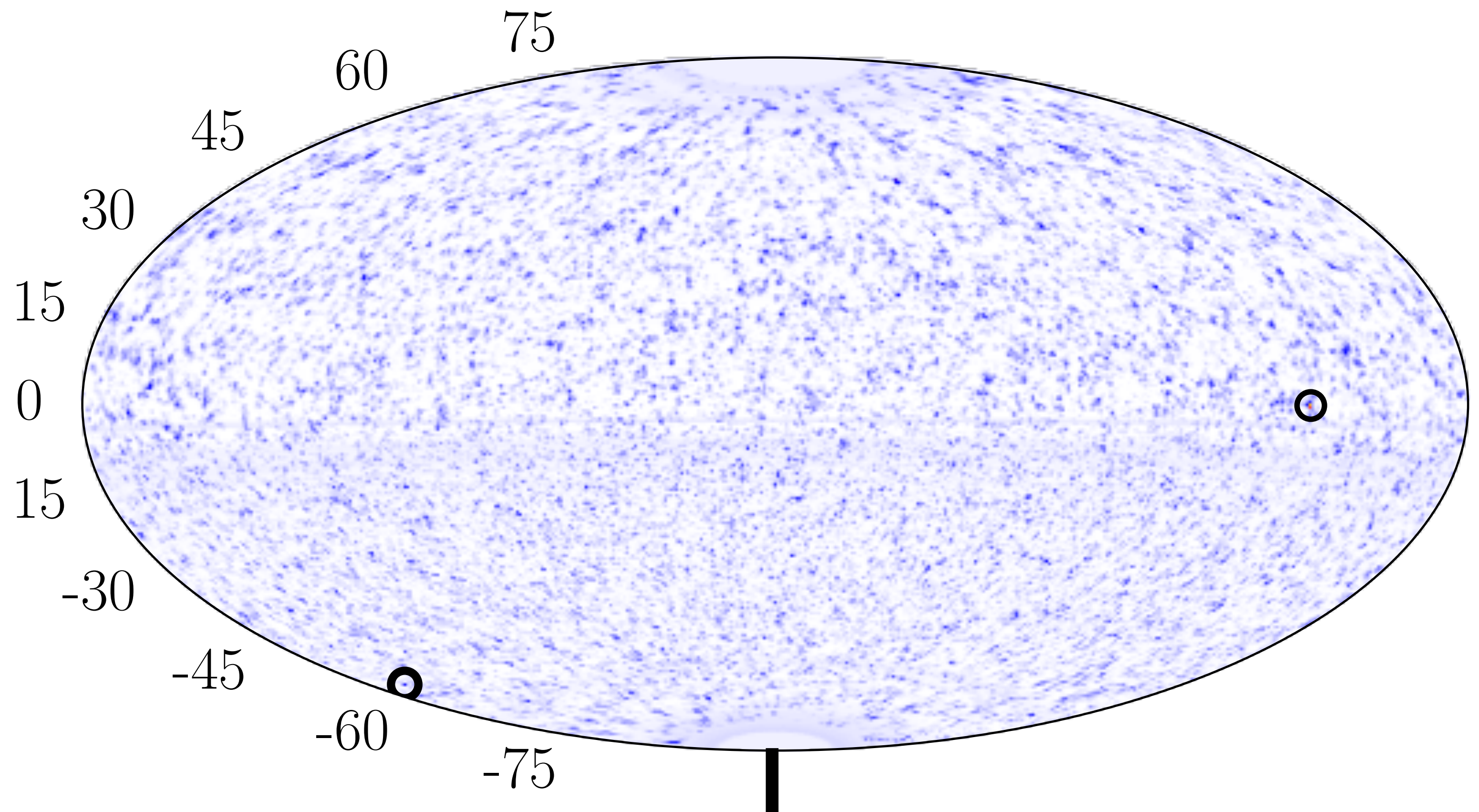


NB: Different energy range than NGC 1068

AGN sky-map



IceCube Point-Source Events

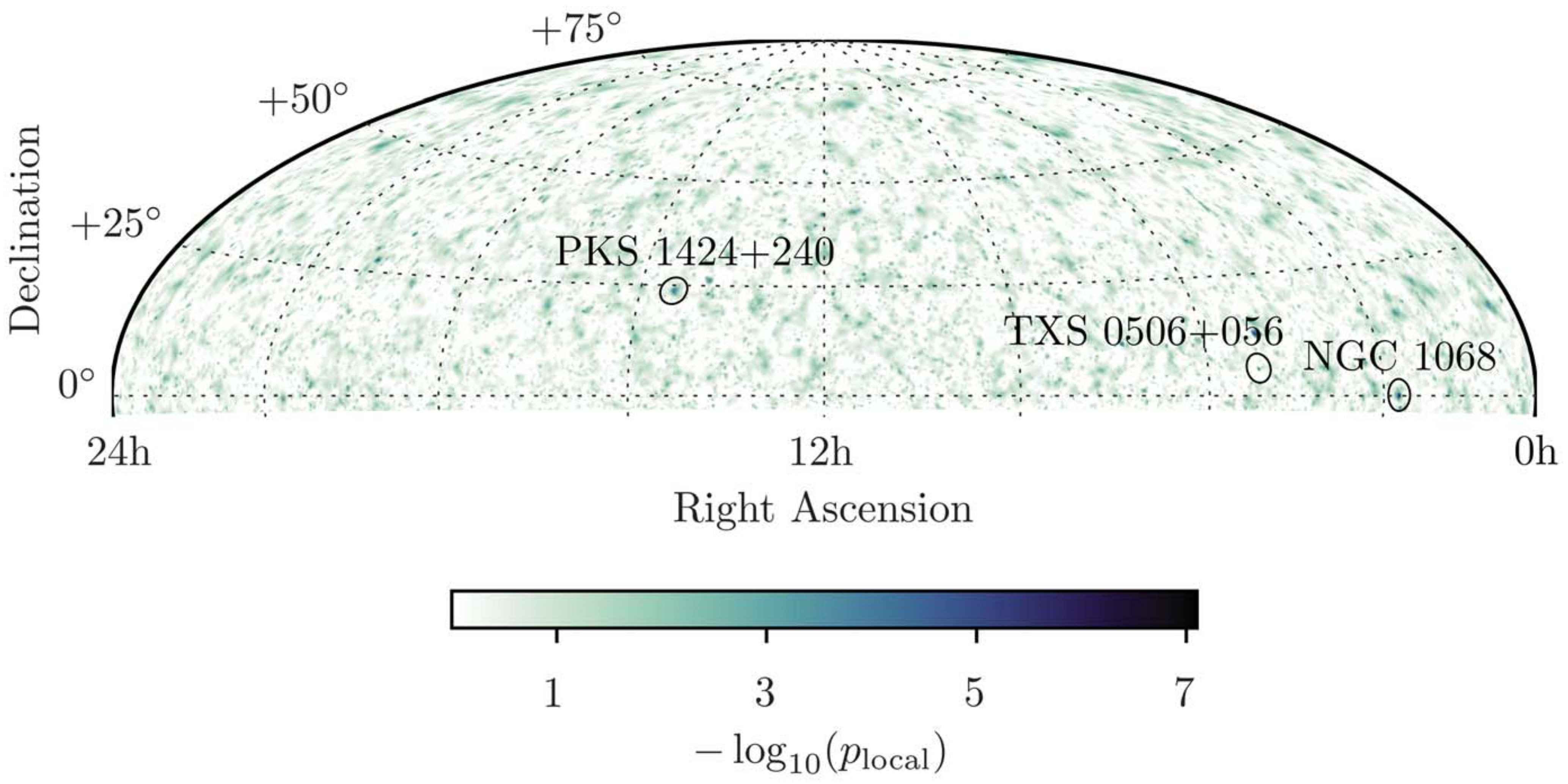


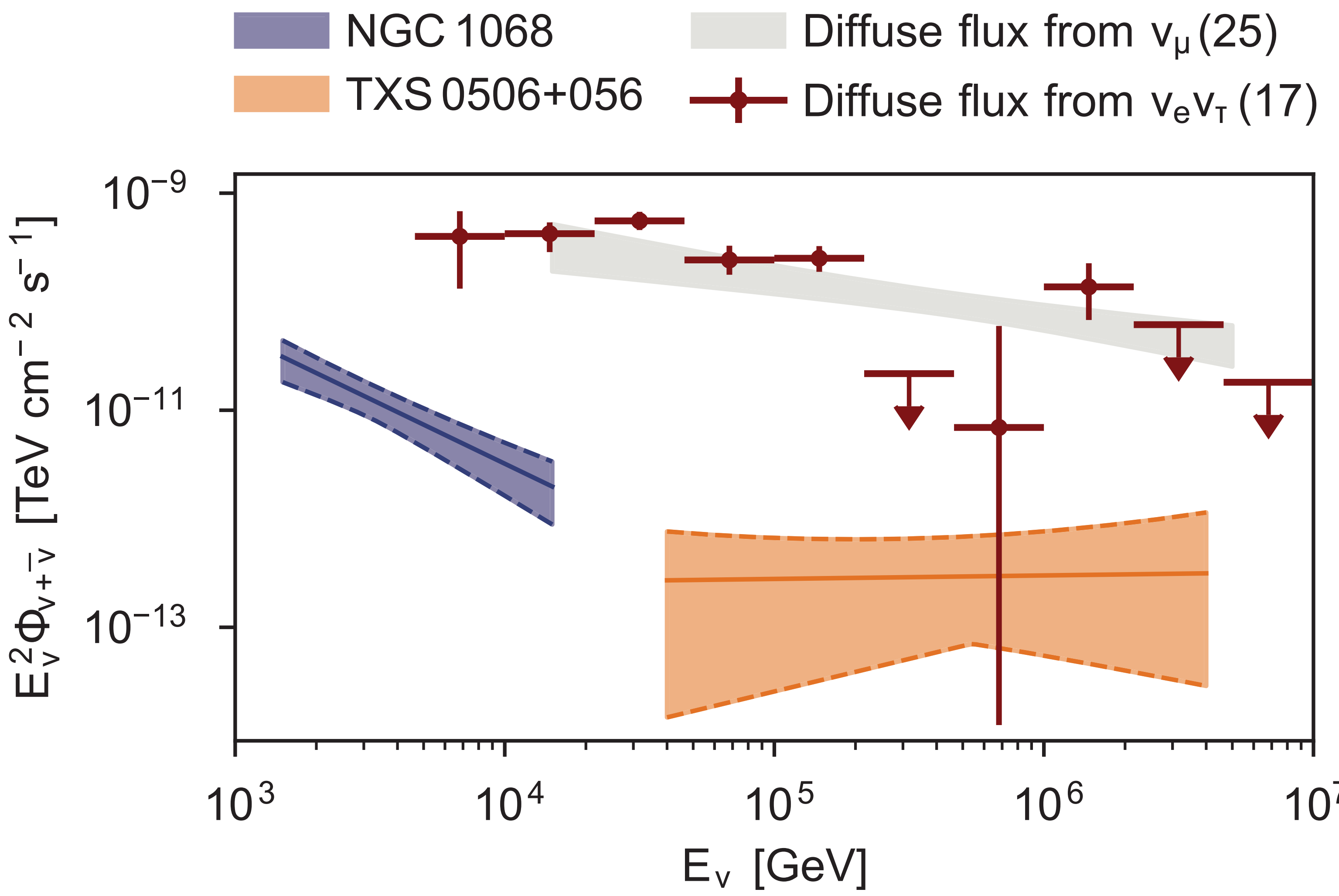
could account for 27-100% of diffuse neutrino flux at 100 TeV

IceCube Coll 2022, PRD

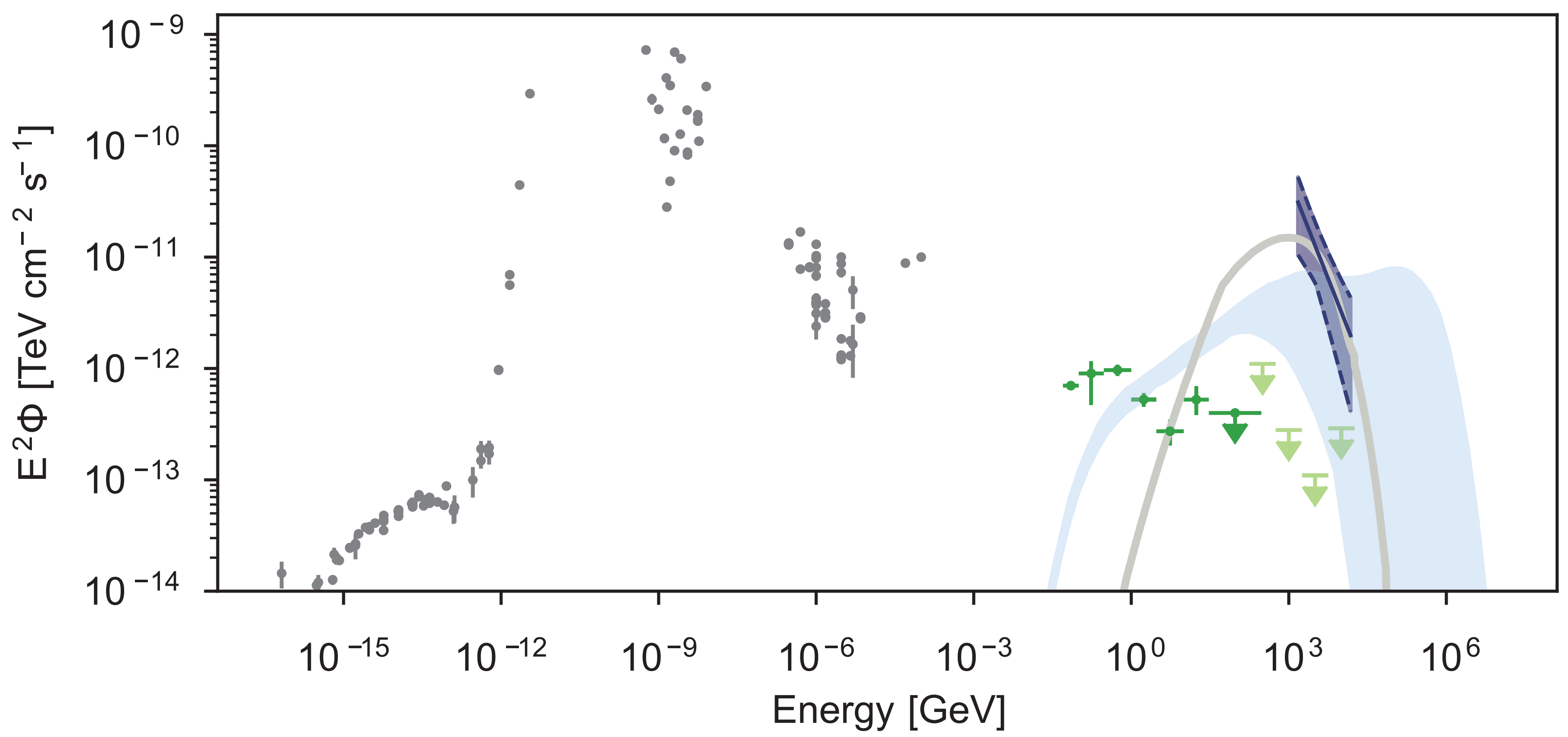
NGC 1068

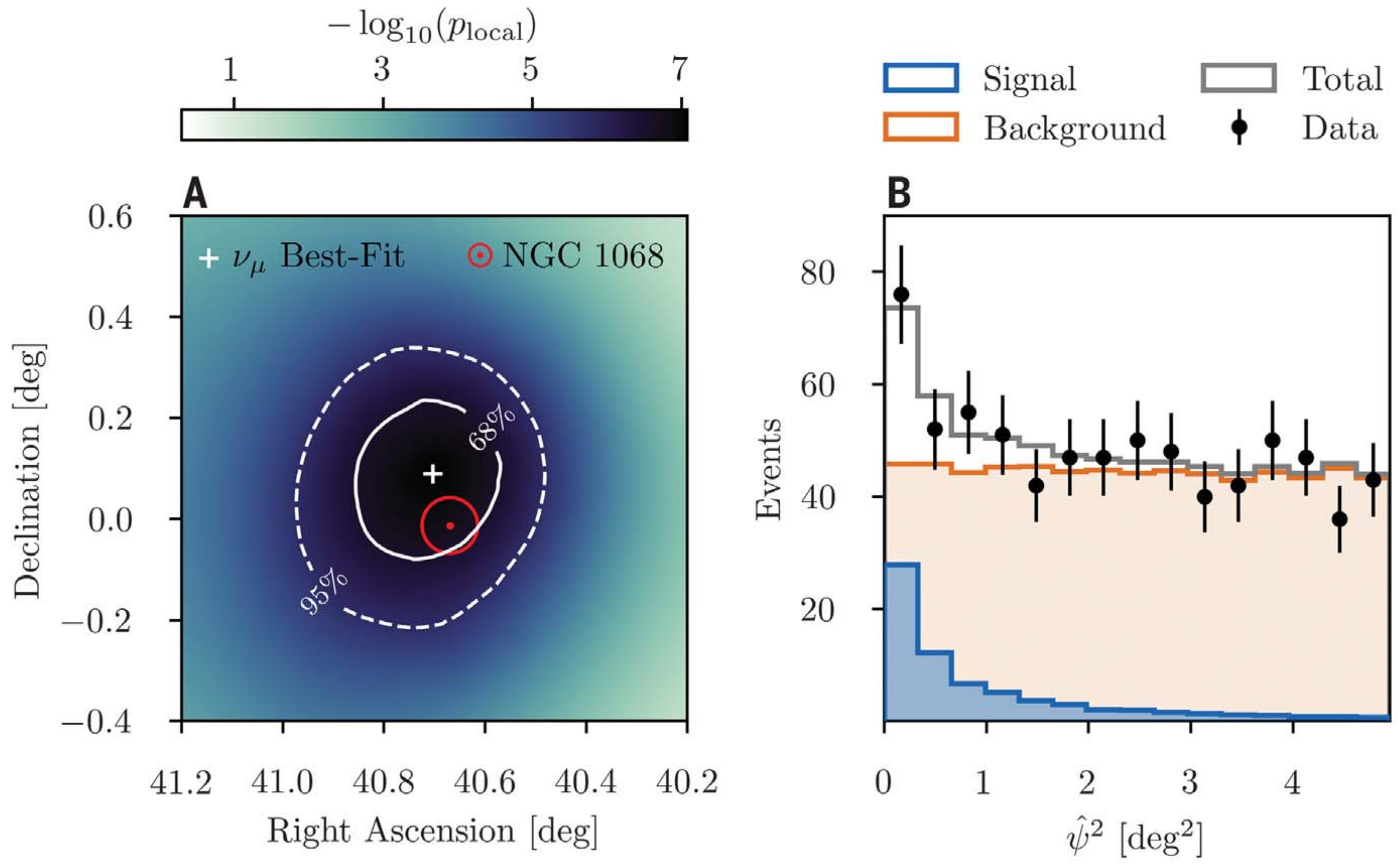
Icecube Coll 2023 - Science





Equatorial

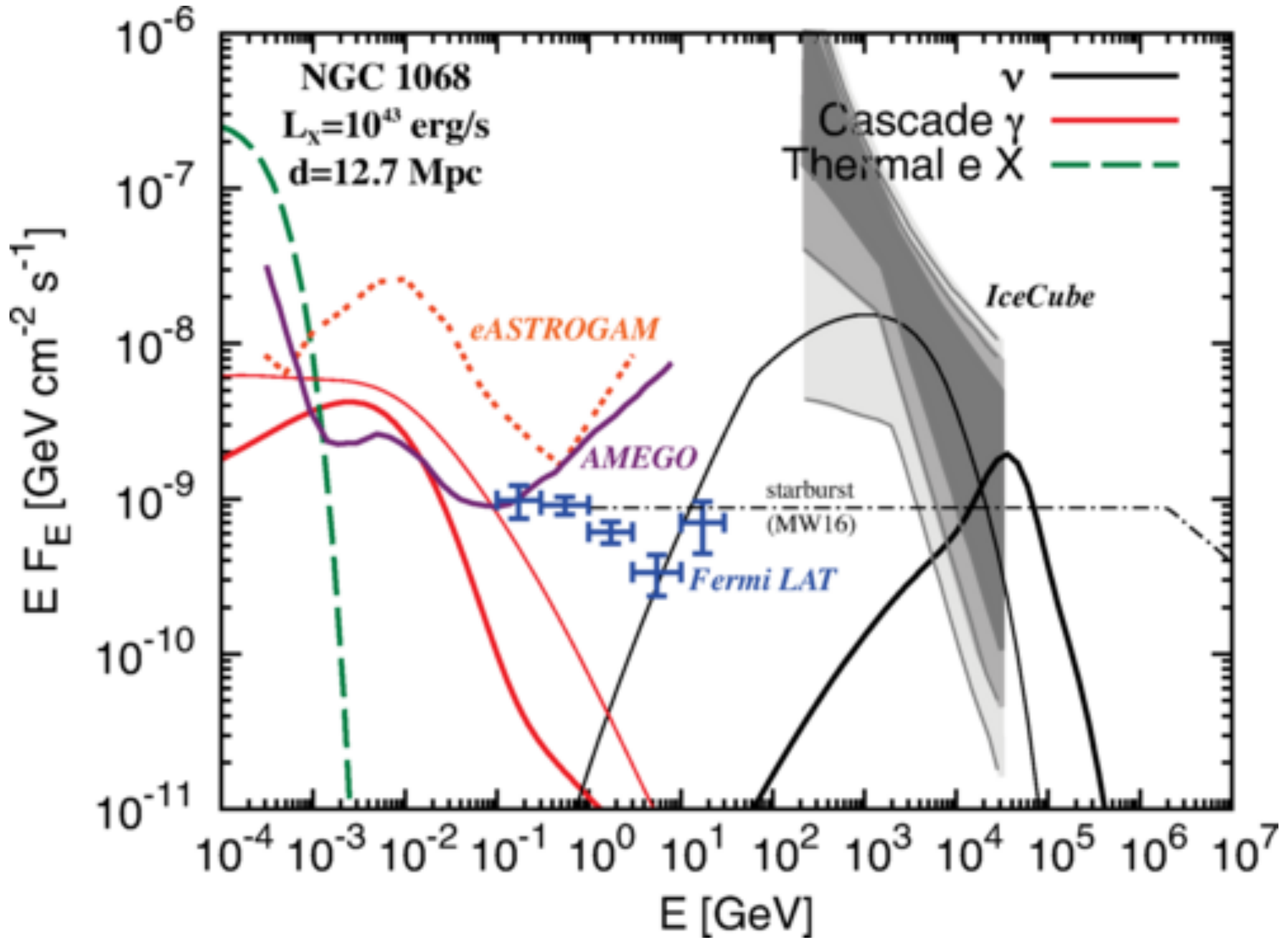




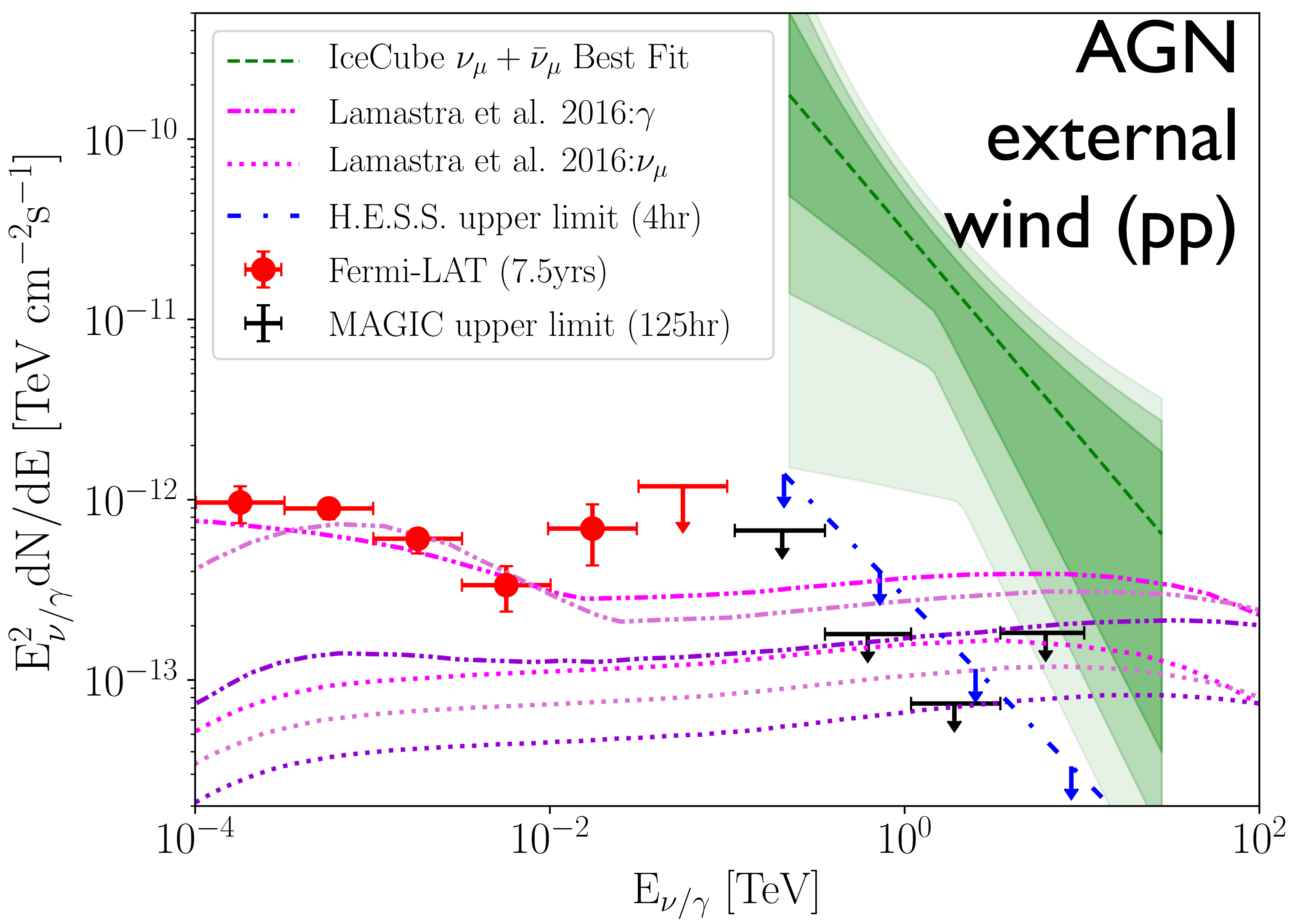
Neutrino production in NGC 1068

see also Kheirandish et al 2021
Anchordoqui et al 2021

AGN corona (pp) *Murase et al 2020*

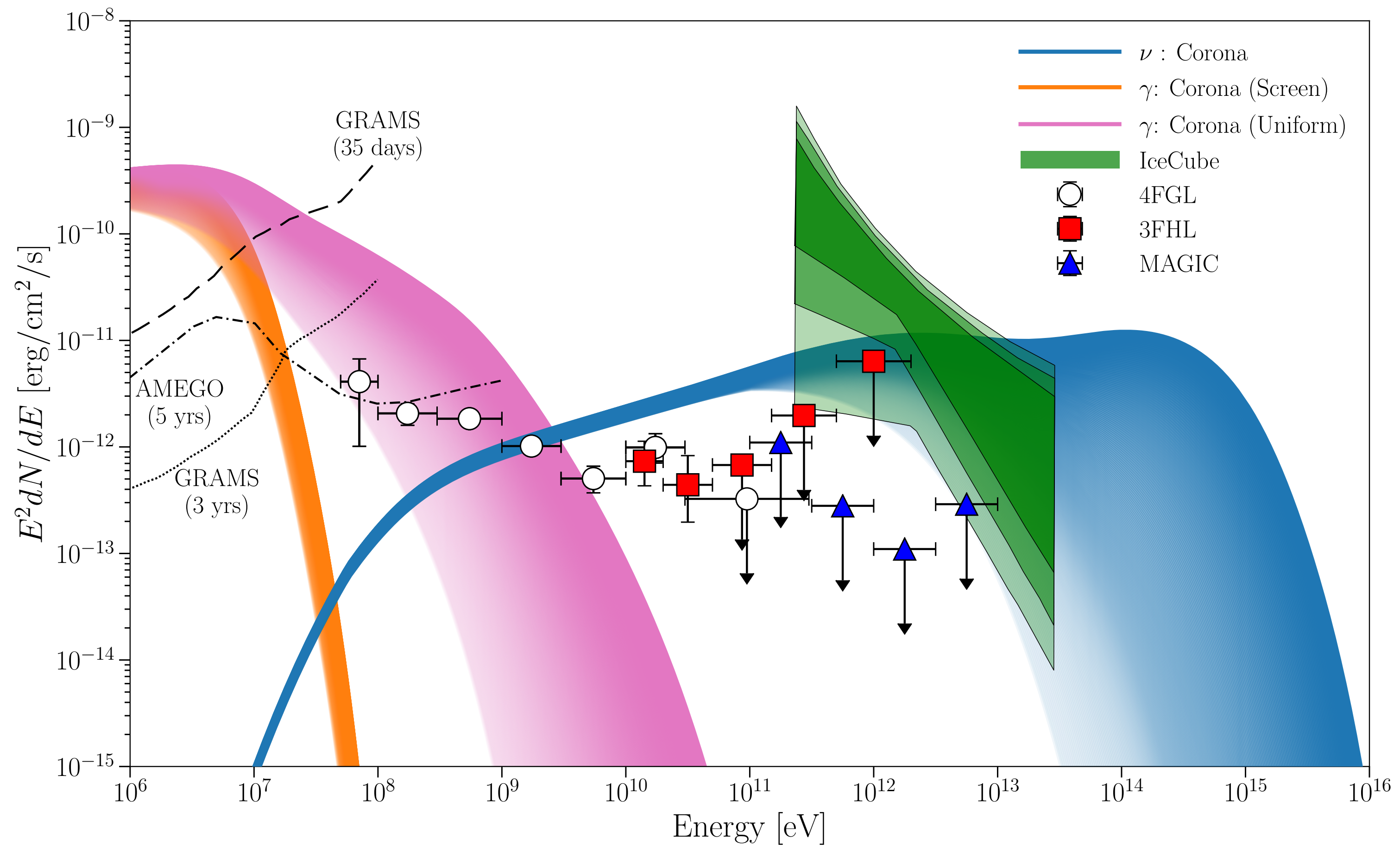


AGN external wind (pp)



Lamastra 2016, 2019

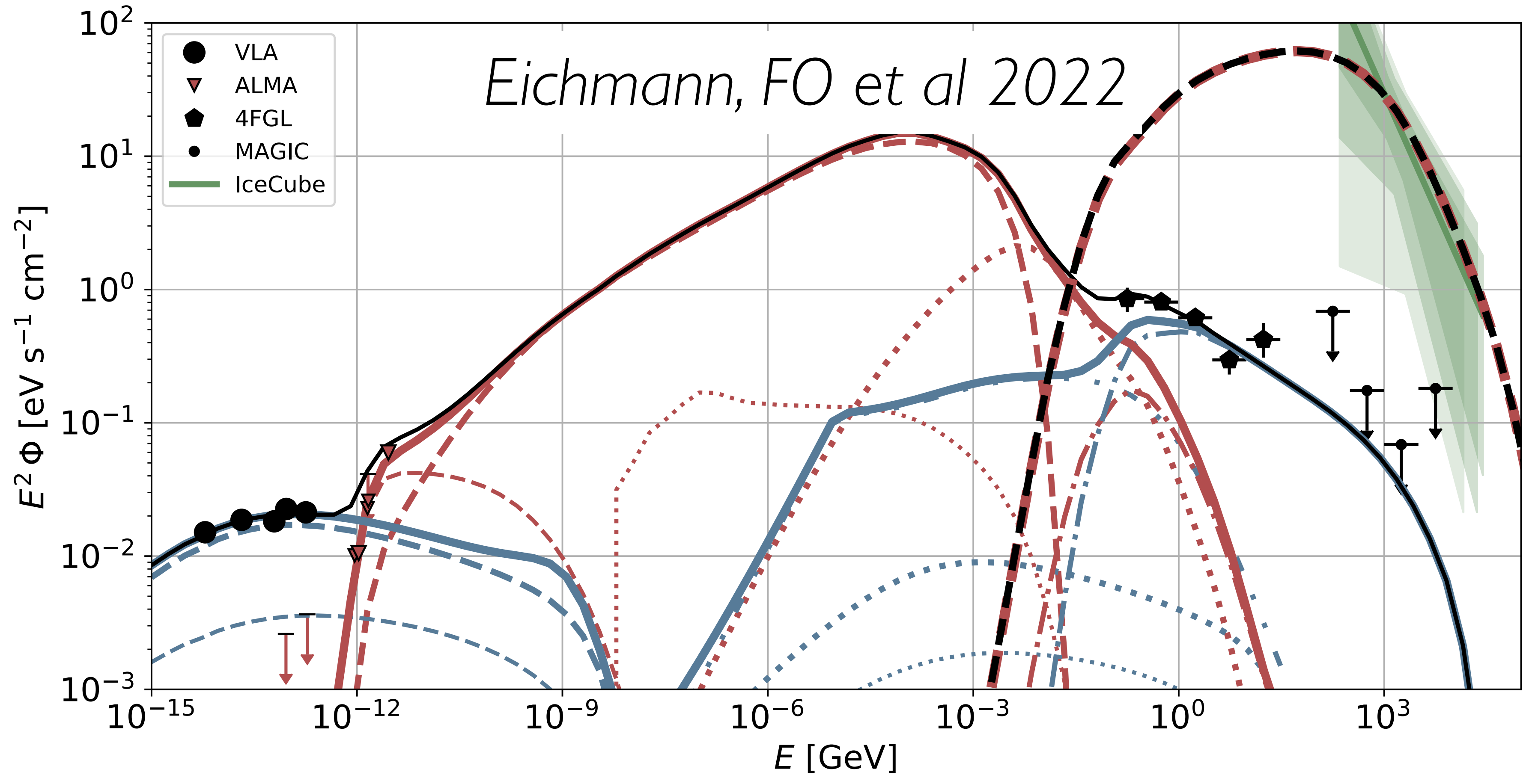
AGN corona "screened" (pp) *Y. Inoue et al 2019*

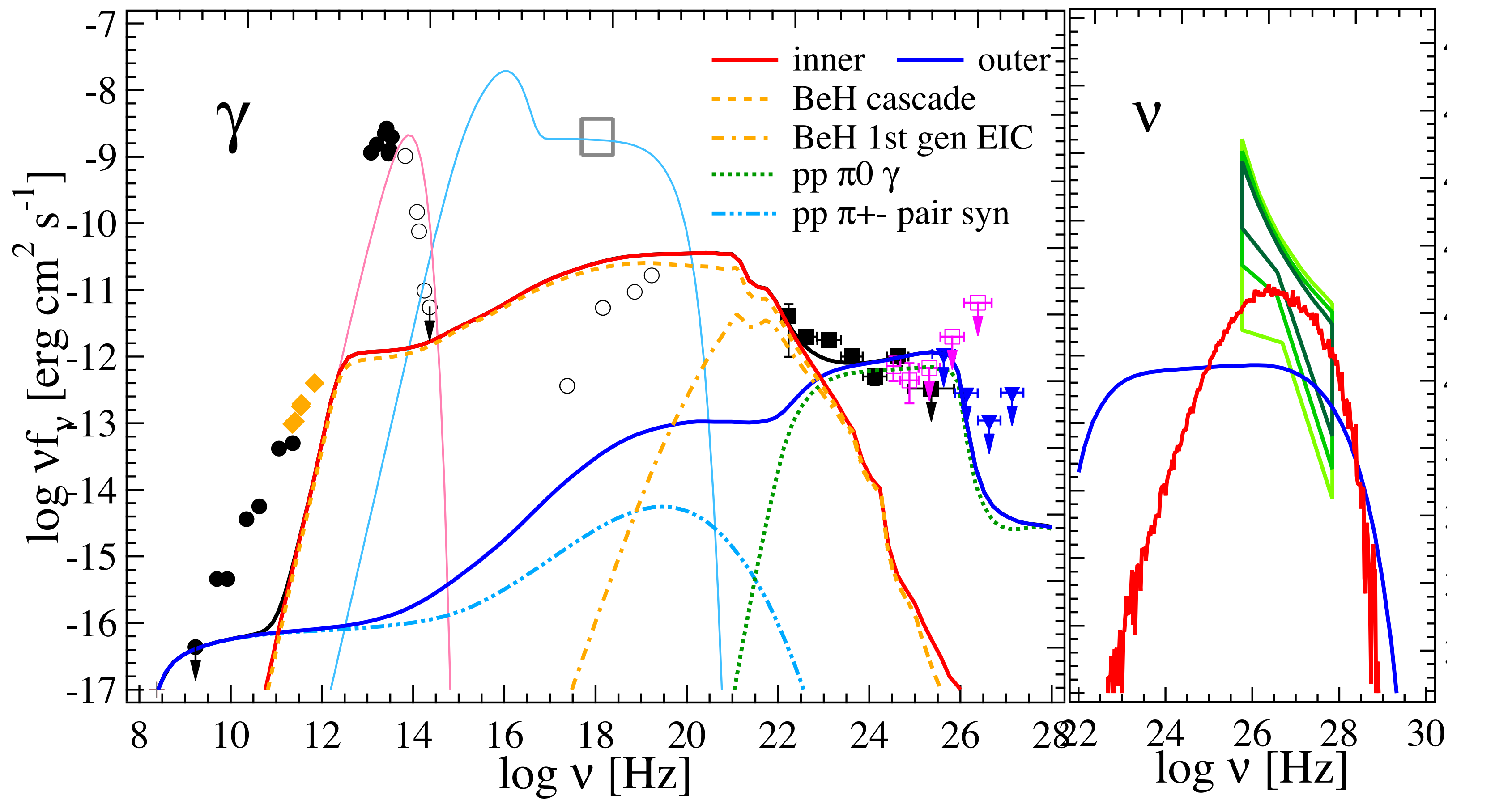


$$R_{\rm neutrinos} \leq 30 R_{\rm Sw}$$

Murase 2022
Halzen 2023

Starburst + AGN corona composite (pp)

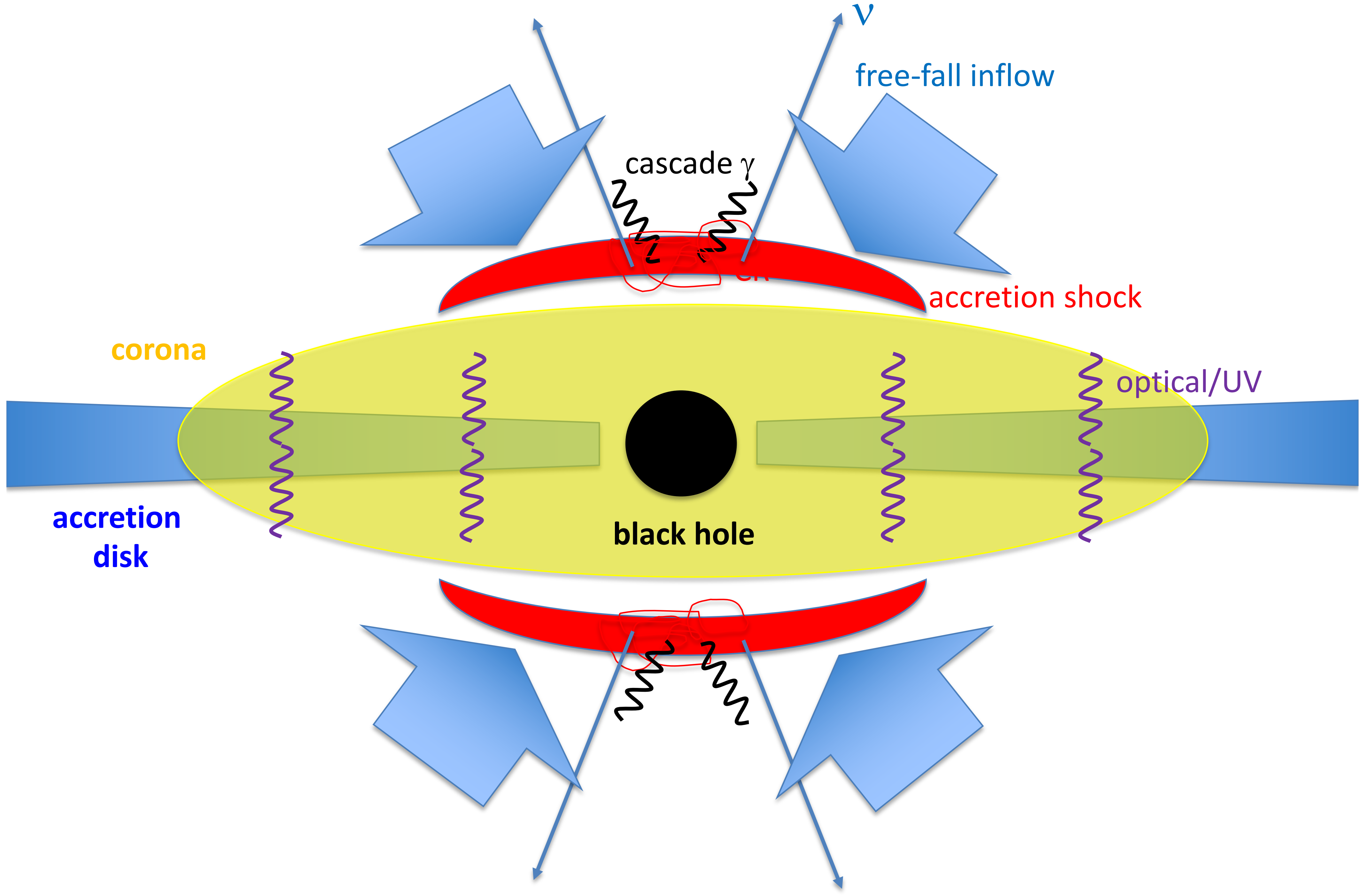


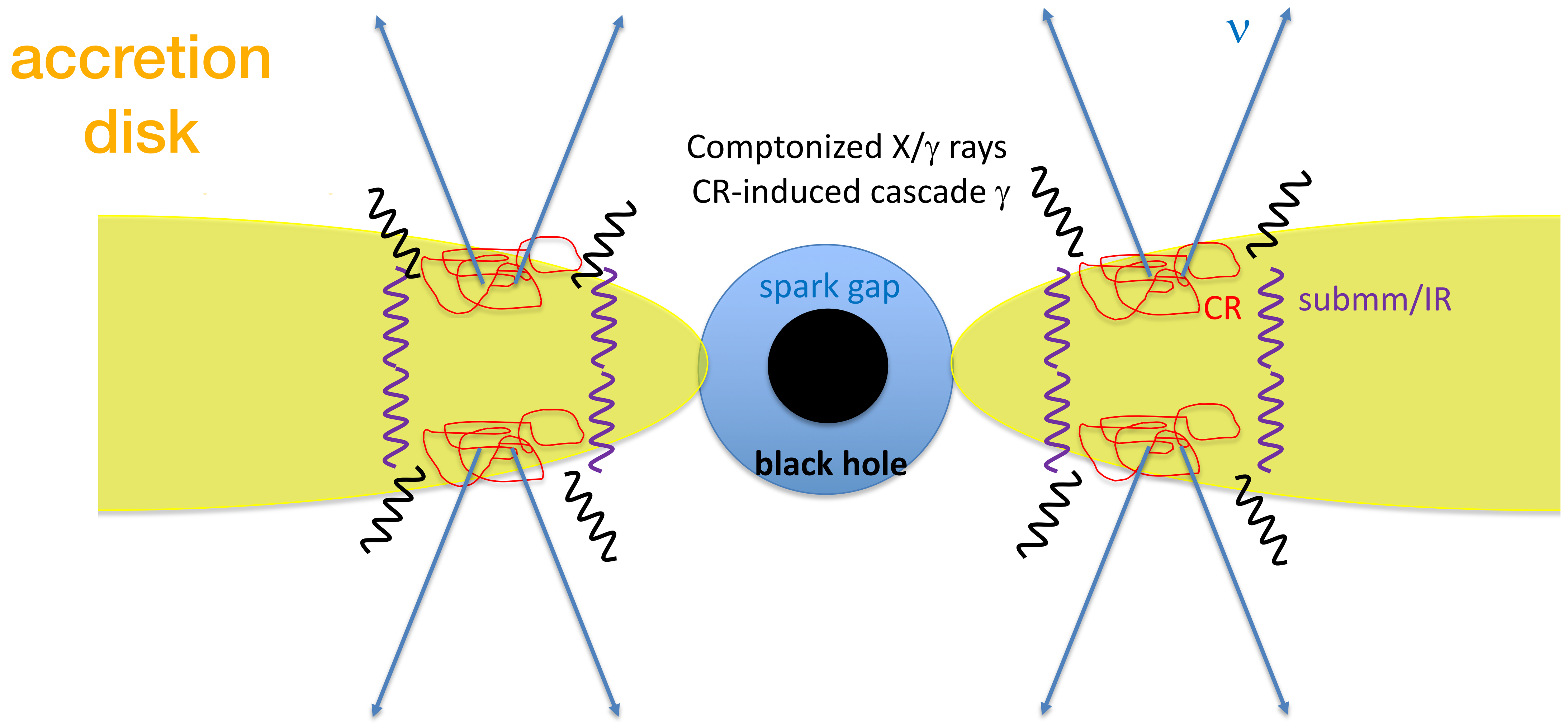


AGN internal wind (pγ) *S. Inoue et al 2022*

Possible sites of neutrino production consistent with NGC 1068

F. Stecker, Phys. Rev. Lett. 66, 2697 (1991)



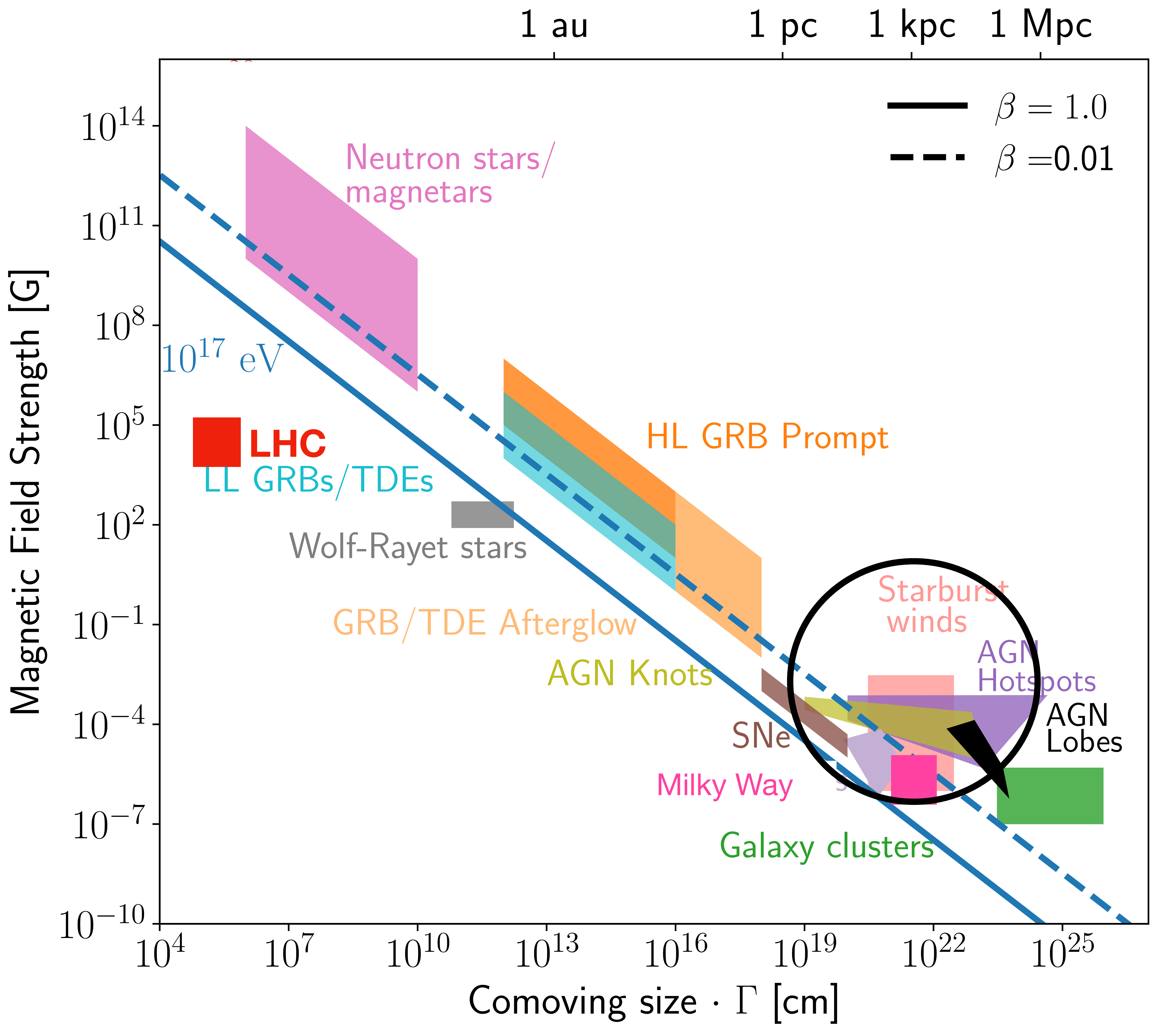


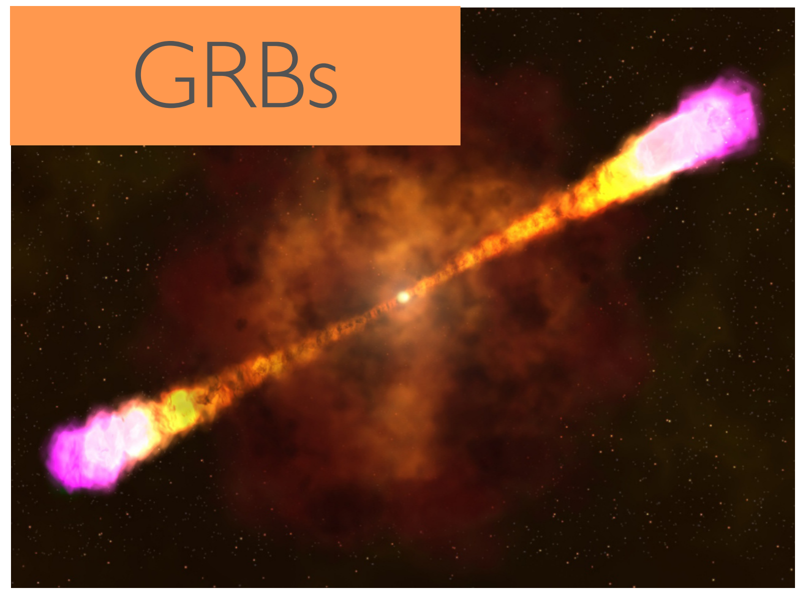
K. Murase, F. Stecker "Neutrino Physics & Astrophysics" Review 2022

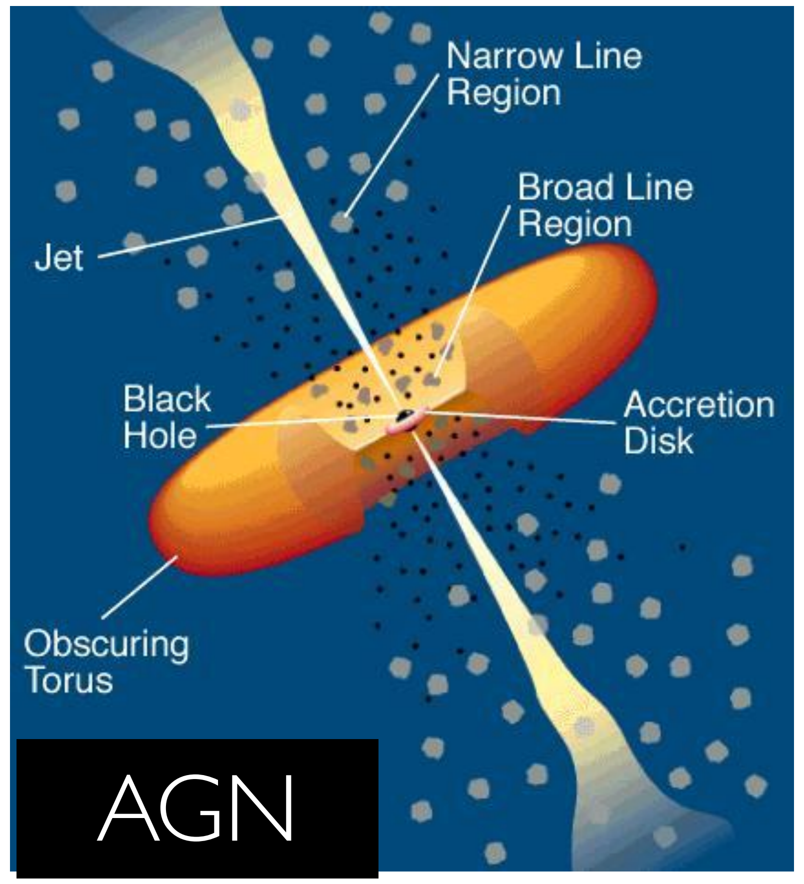
Scorecard

	E_{max}	$\bar{n}_{\mathrm{eff,UHECR}}$	$\bar{n}_{\mathrm{eff},\nu}$	$\dot{\varepsilon}_{\mathrm{UHECR}}$
BL Lac	not for H	😞	😞	😀
FSRQs	😀	😞	😞	😀
FR I	not for H	😀	😀	😀
FR II	😀	😀	~😞	😀
Non jetted AGN	~ 😞	😀	😀	😀
Starbursts				
GRBs (LL GRBs)				
jetted TDEs (non jetted)				

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







Starburst galaxies

Starburst definition: High star-formation rate per unit stellar mass compared to average galaxy at that redshift (> 100 x Milky Way)

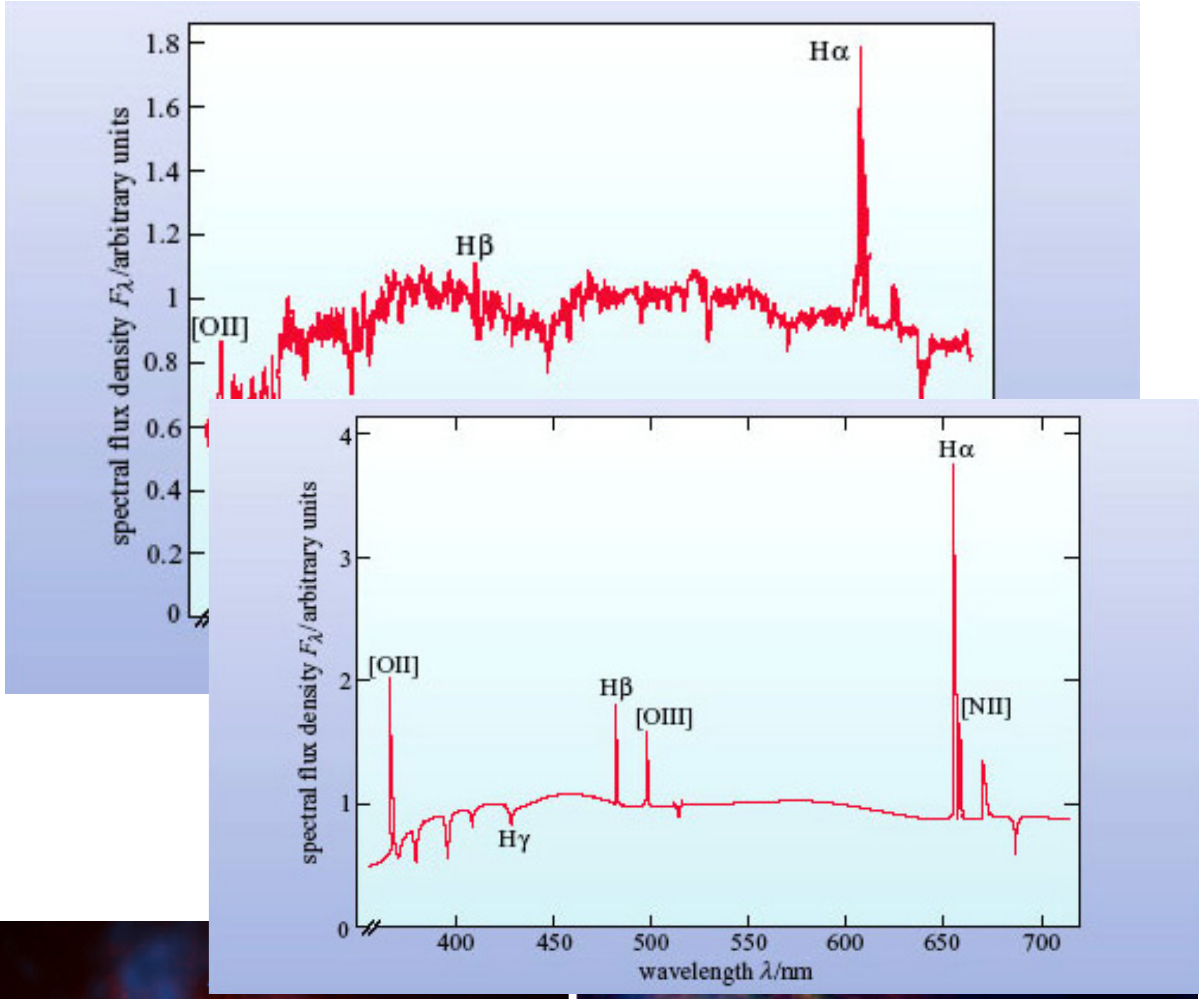
Starburst episodes are short-lived (<10^8 yrs)

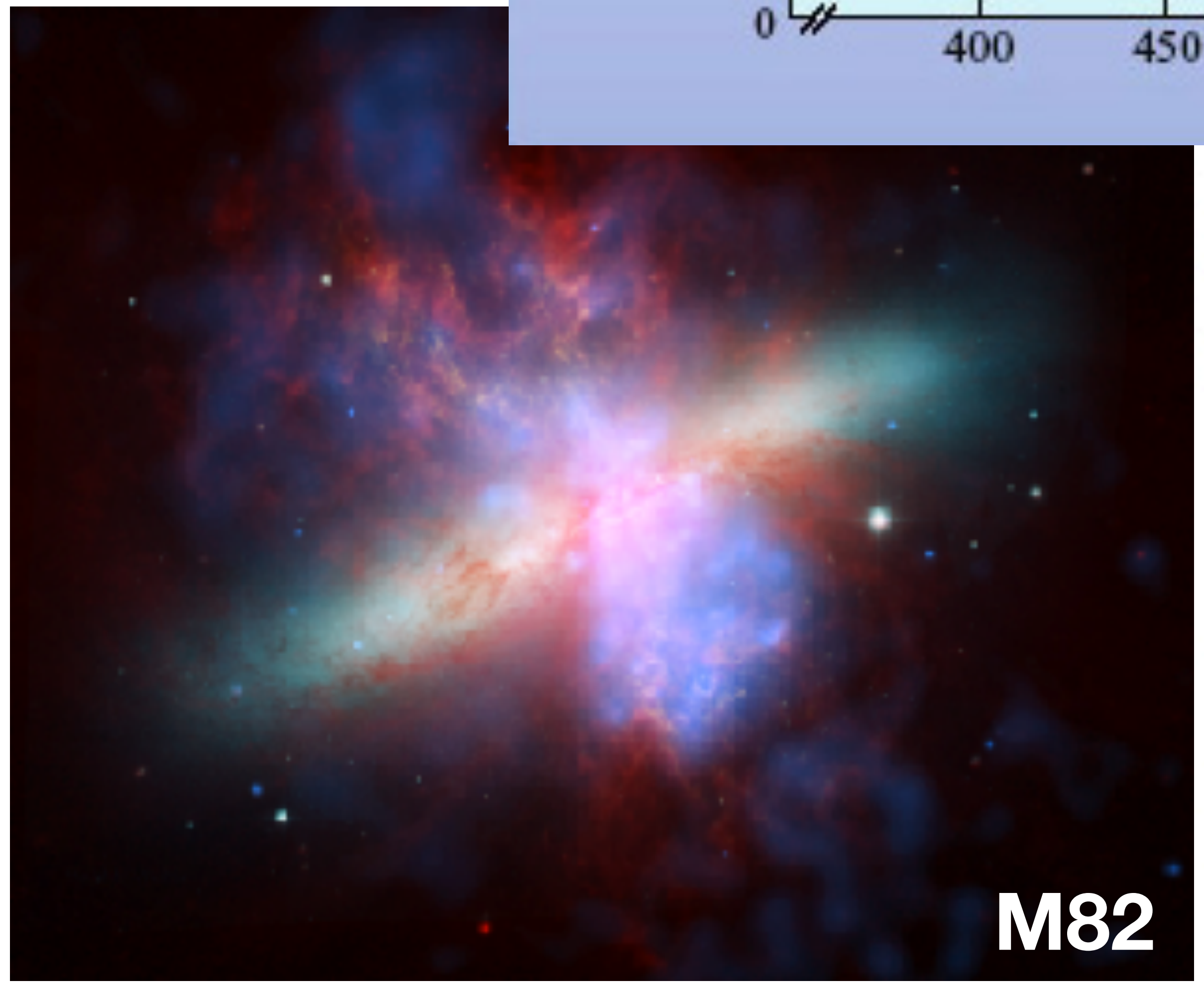
Centrally driven strong outflows (``superwinds'')

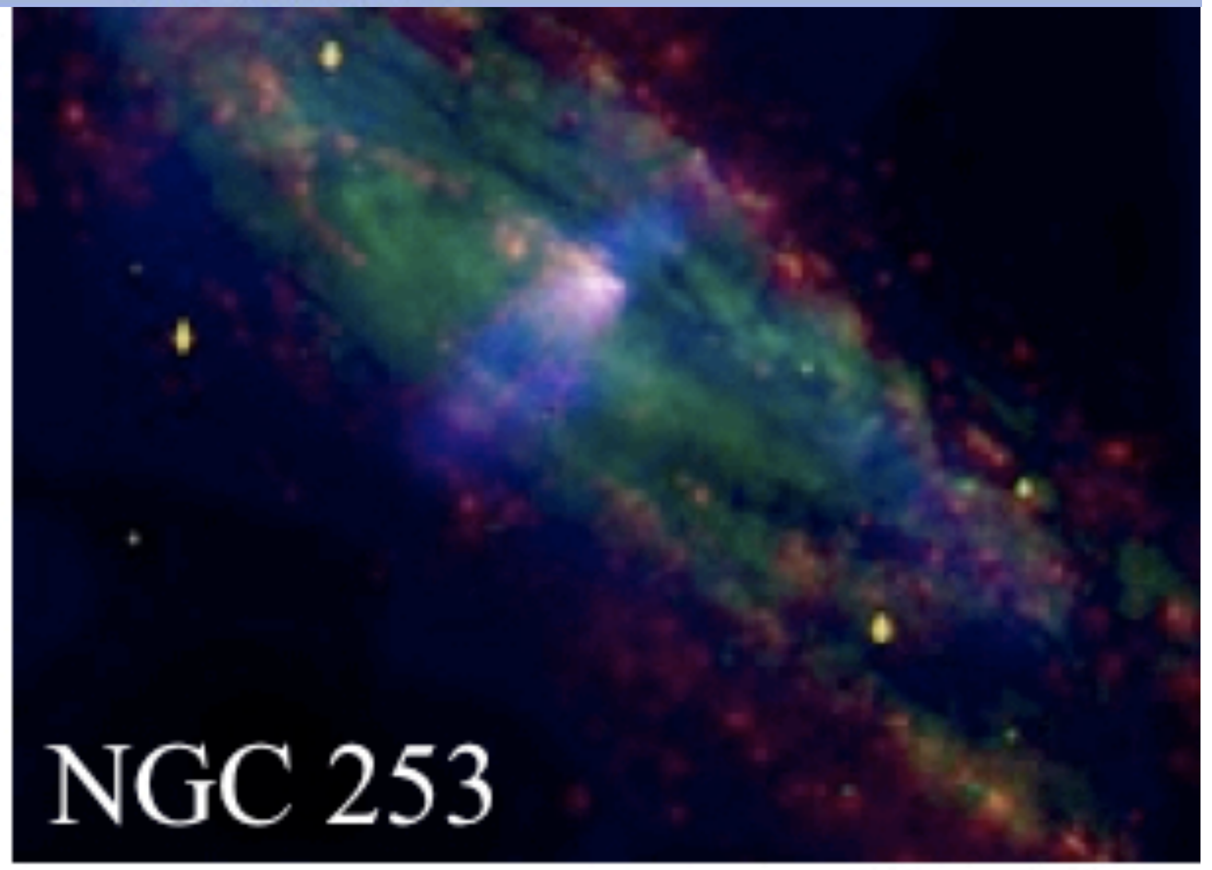
Column densities $\Sigma_g > 0.1 g/cm^2$ and magnetic fields B ~ 1 mG ($B \propto \Sigma_g$), which are much larger than those of ``normal'' spiral galaxies ($\Sigma_g \approx 0.003 g/cm^2$, B ~ 5μG in the Milky way)

TeV gamma-ray detections from NGC 253 (~3 Mpc) & M82 (~4 Mpc) - consistent with point like at VHE

And a handful more in GeV gamma-rays (NGC4945, NGC1068, Circinus, Arp 220)







UHECRs from starburst galaxies?

- Wind

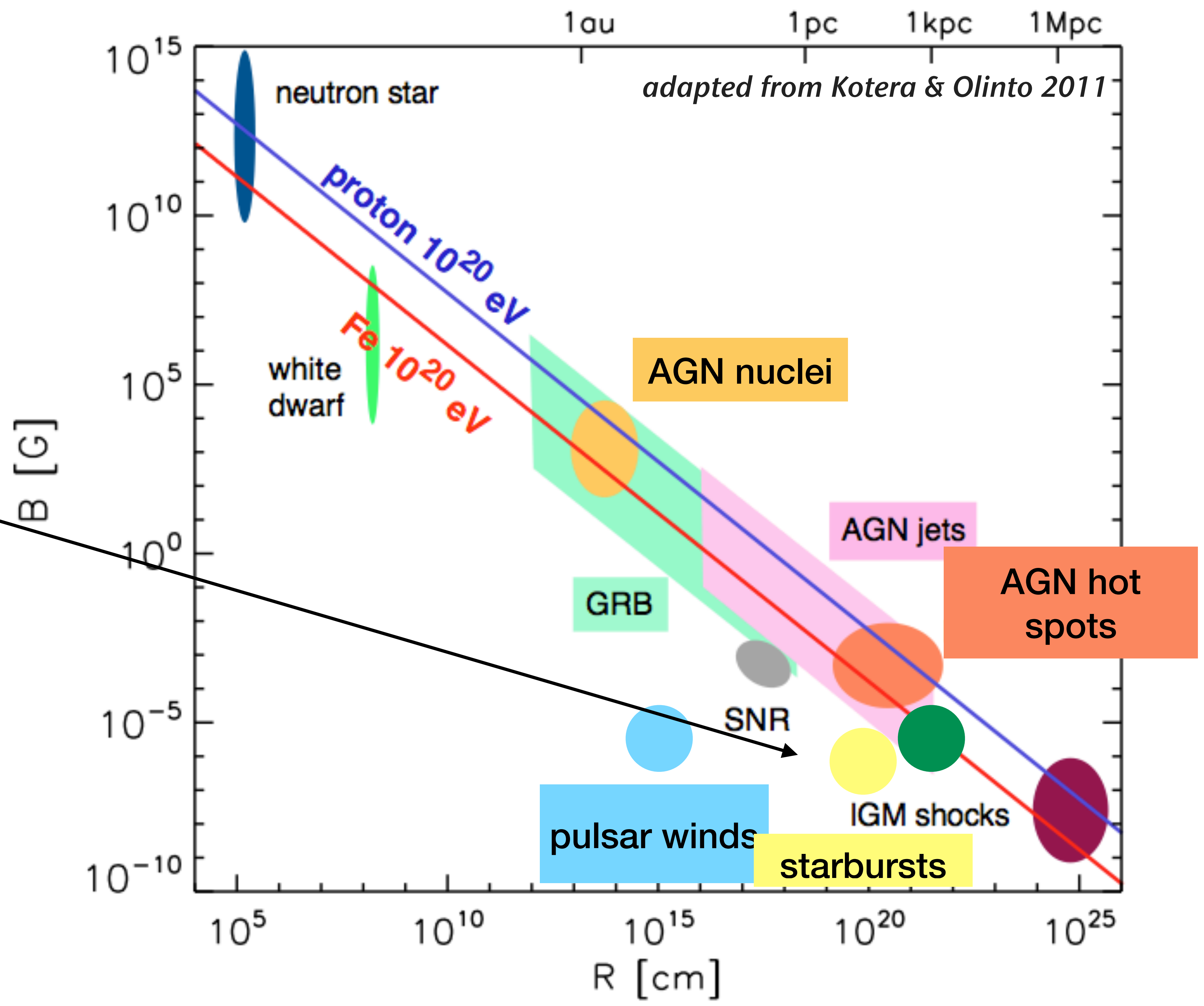
Particle acceleration in the superwinds of starburst galaxies

G. E. Romero[1,2], A.L. Müller[1,3,4], M. Roth[3]

no!

generally E_{max} (Fe) ~ 10^{18} eV but possible if strong amplification of MF by cosmic-rays

- Reservoir model: Hypernovae/LL GRBs could do the job



$$E_{\rm max} = \frac{3}{20}\,\beta\, c\, R\, B\, Z\, e\, \Gamma$$

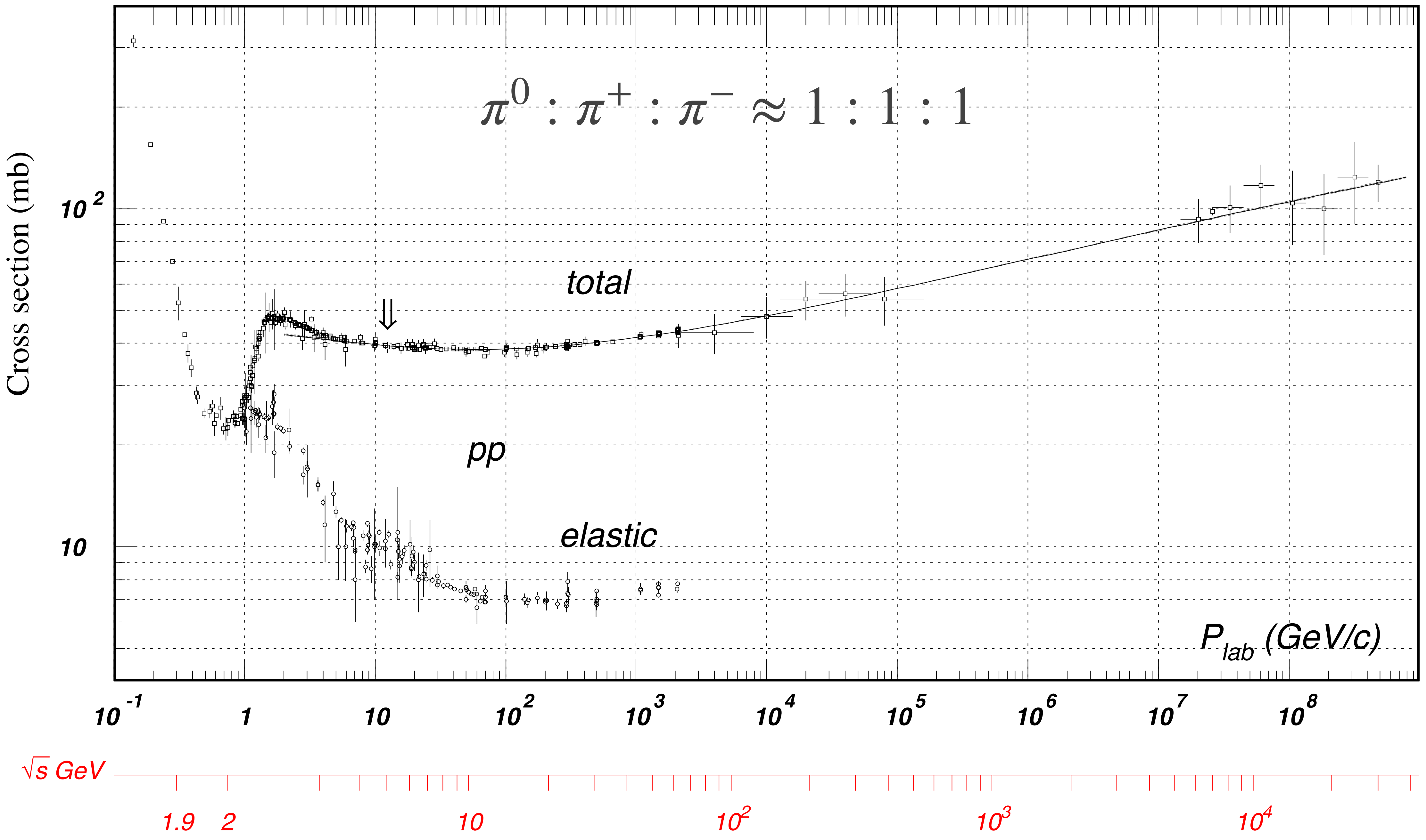
$$\beta < 1/300$$

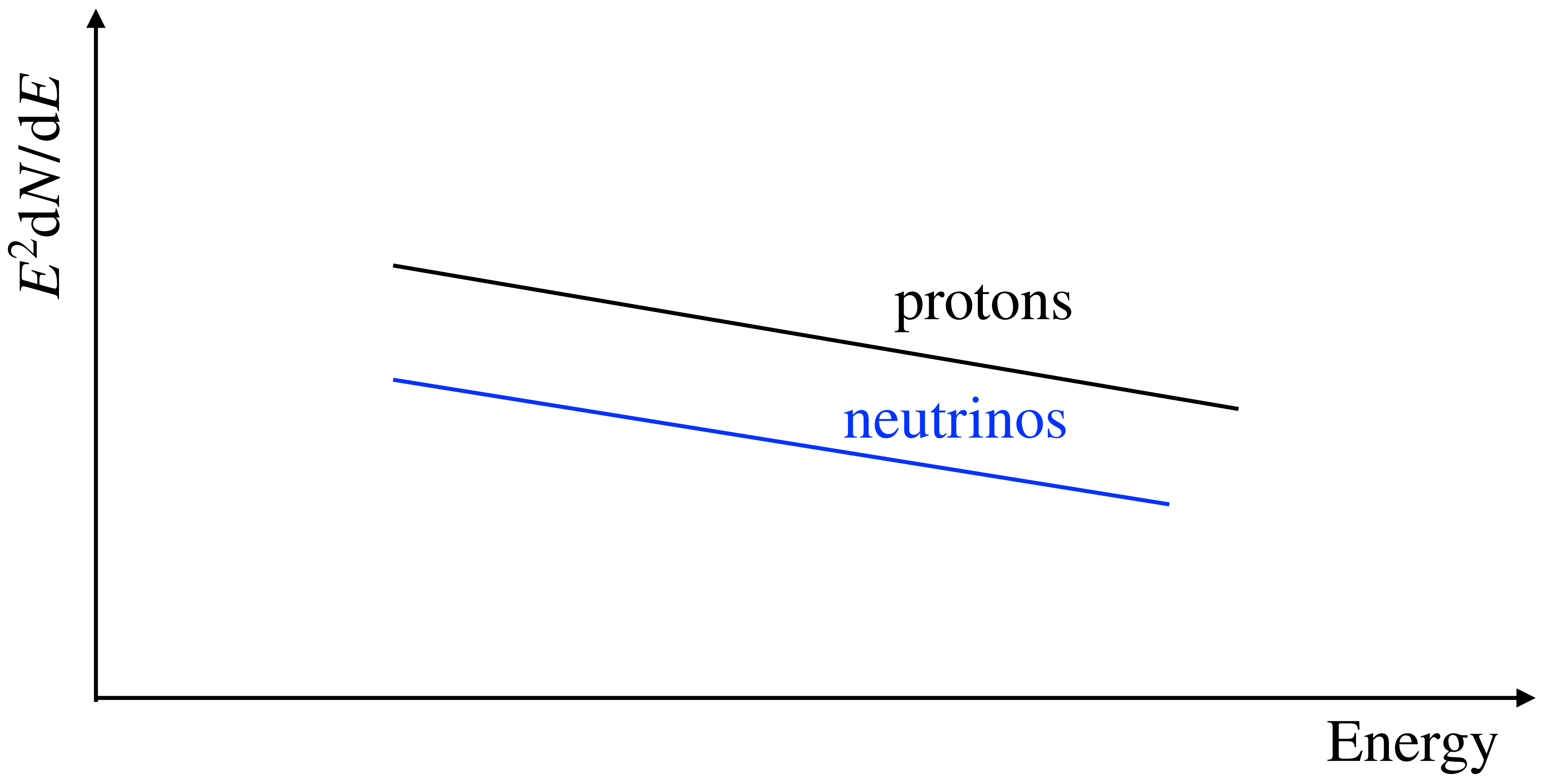
Proton-proton interactions

Gas reservoirs (Starburst galaxies, Galaxy Clusters…)

$$p + p \to N\pi + X$$

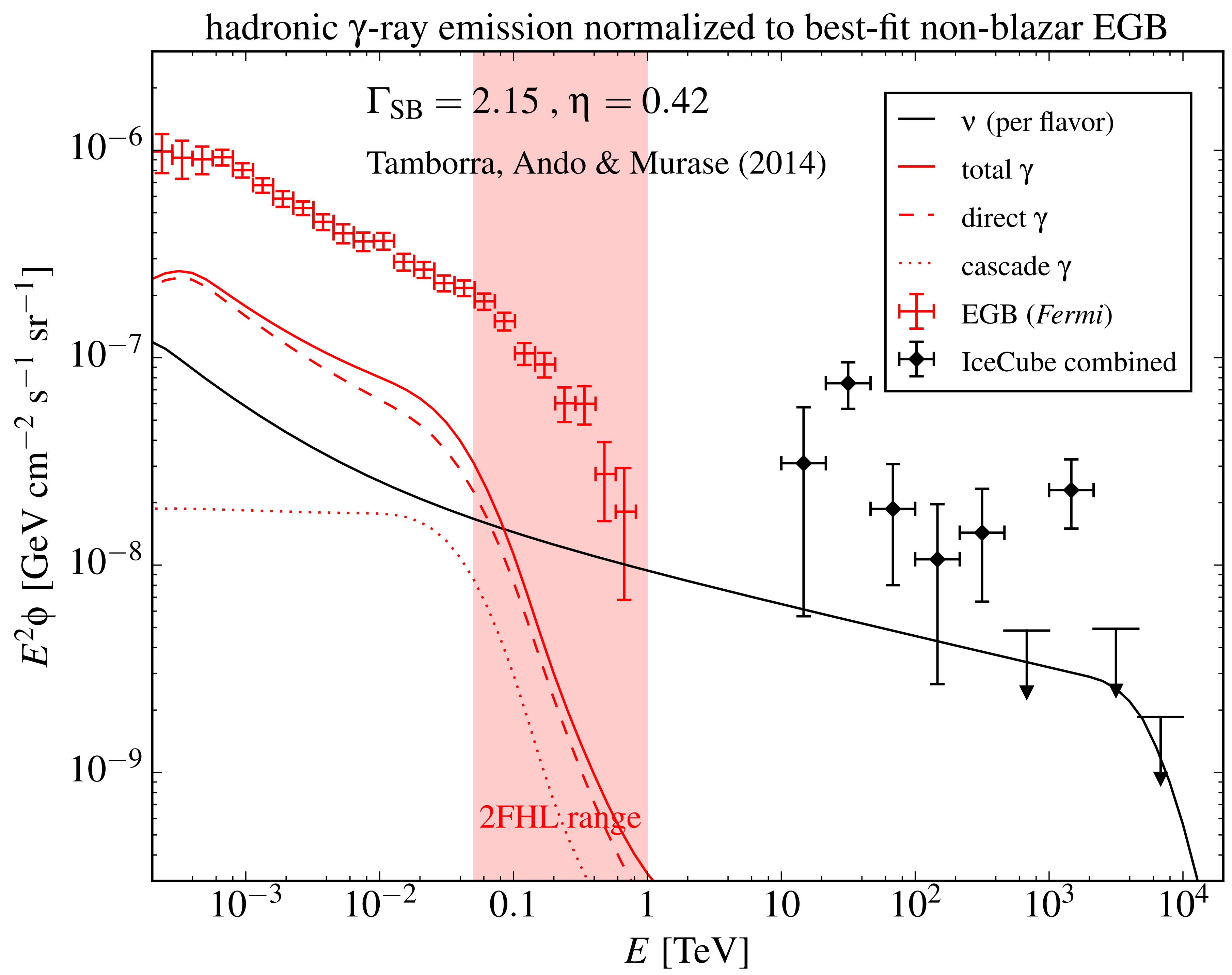
$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e \dots$$

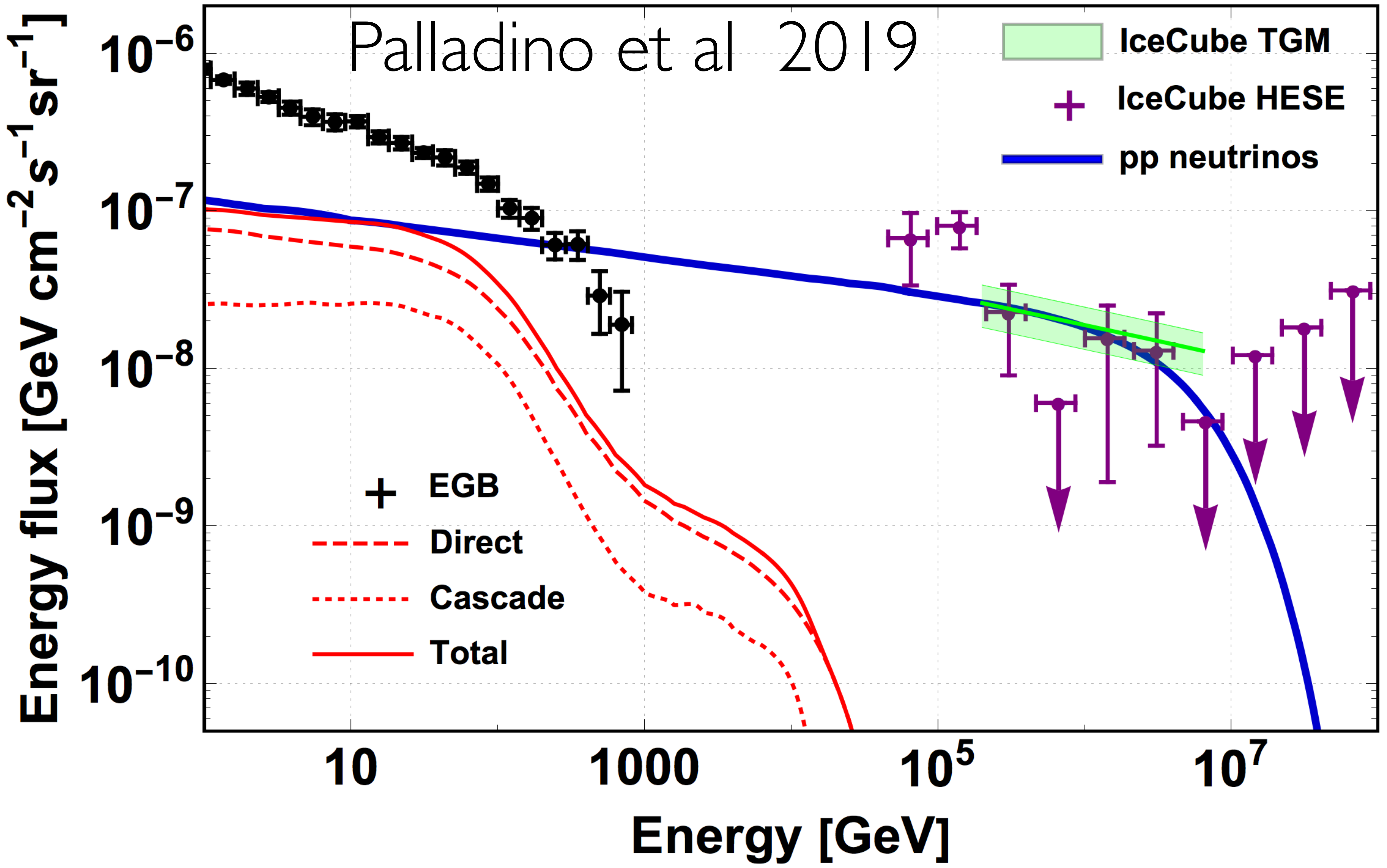




Neutrinos from starburst galaxies

Cannot produce the IceCube flux unless we focus on >100 TeV data only due to diffuse gamma-ray constraints

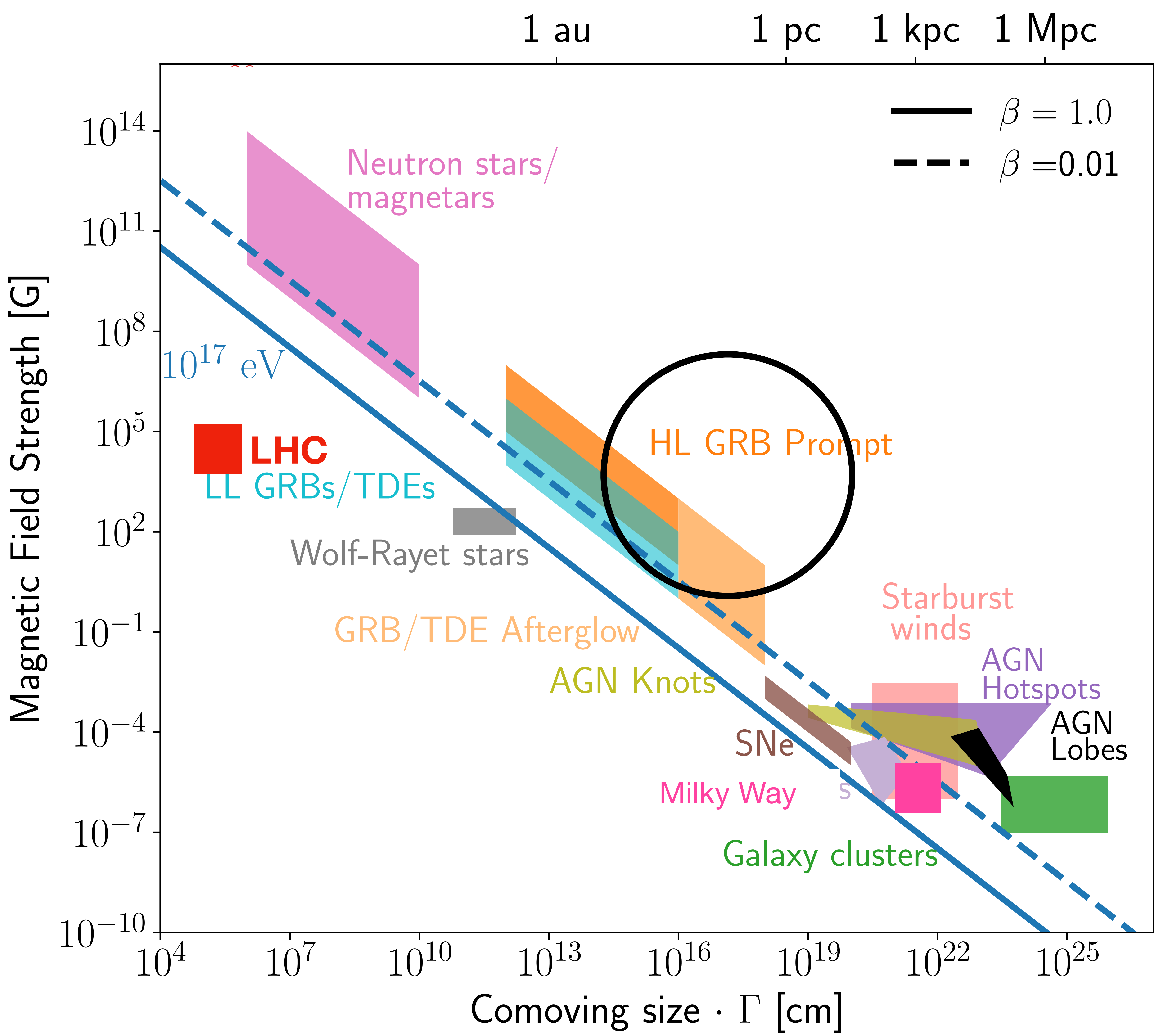


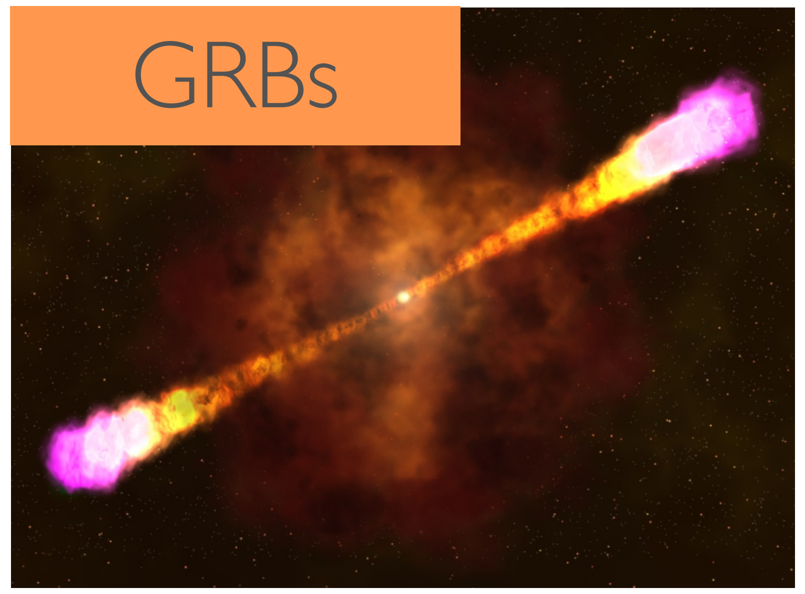


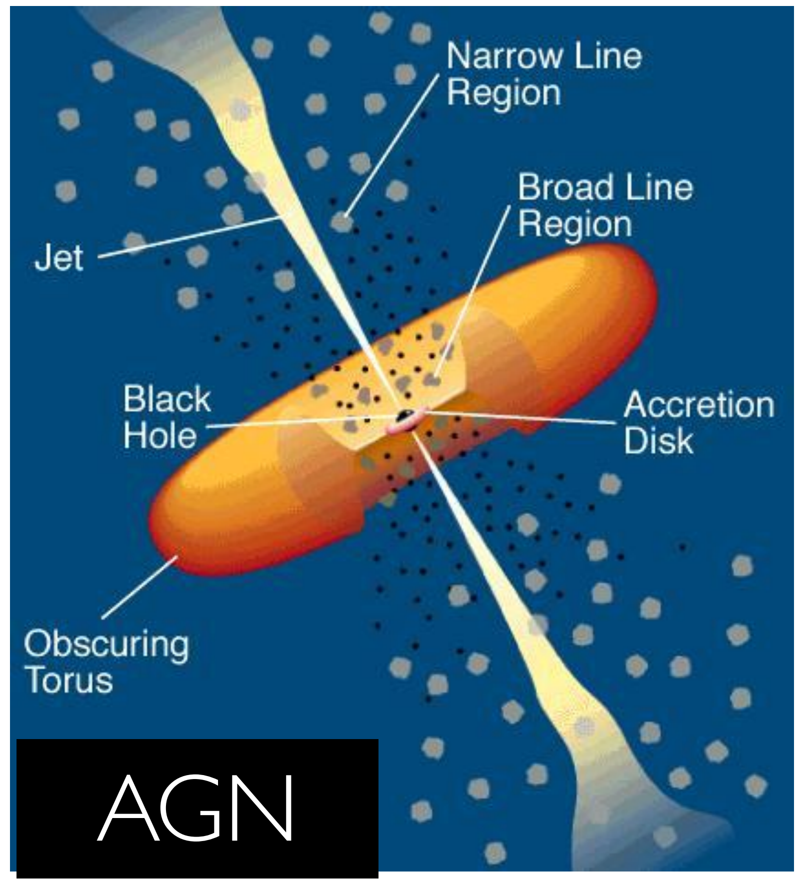
Scorecard

	$E_{\rm max}$	$\bar{n}_{\rm eff,UHECR}$	$\bar{n}_{\rm eff,\nu}$	$\dot{\varepsilon}_{\rm UHECR}$
BL Lac	not for H	😞	😞	😀
FSRQs	😀	😞	😞	😀
FR I	not for H	😀	😀	😀
FR II	😀	😀	~😞	😀
Non jetted AGN	~ 😞	😀	😀	😀
Starbursts	😞	😀	😀	😀
GRBs (LL GRBs)				
jetted TDEs (non jetted)				

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



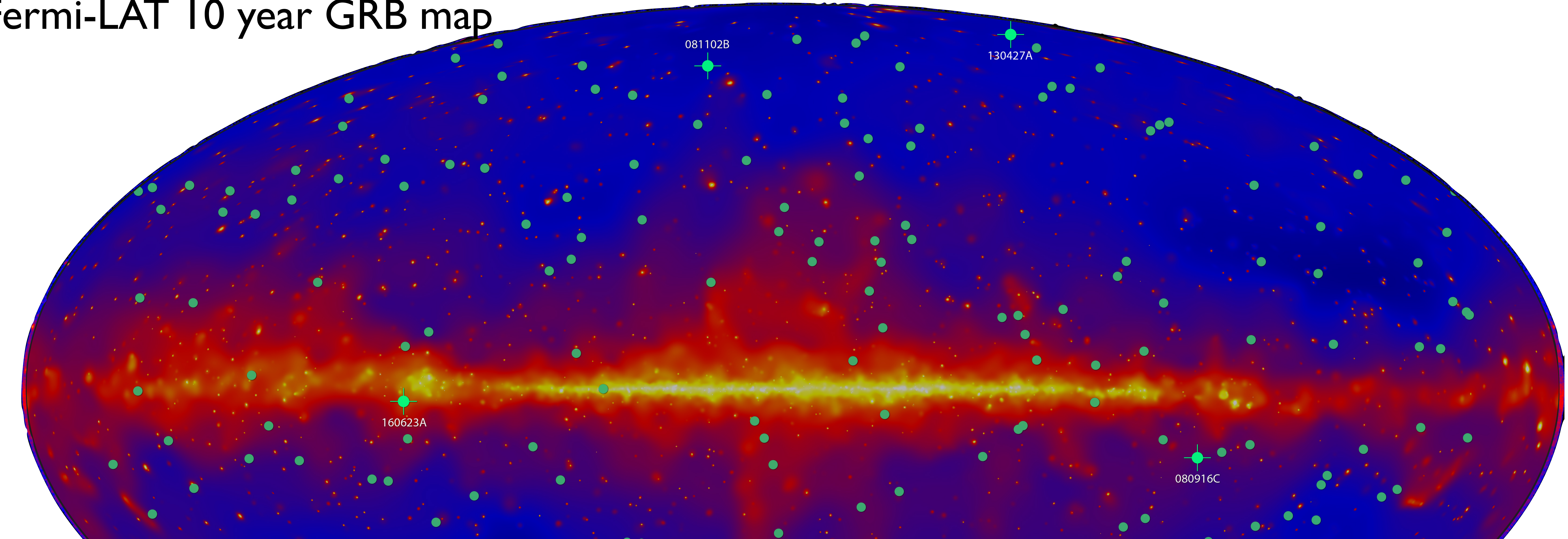


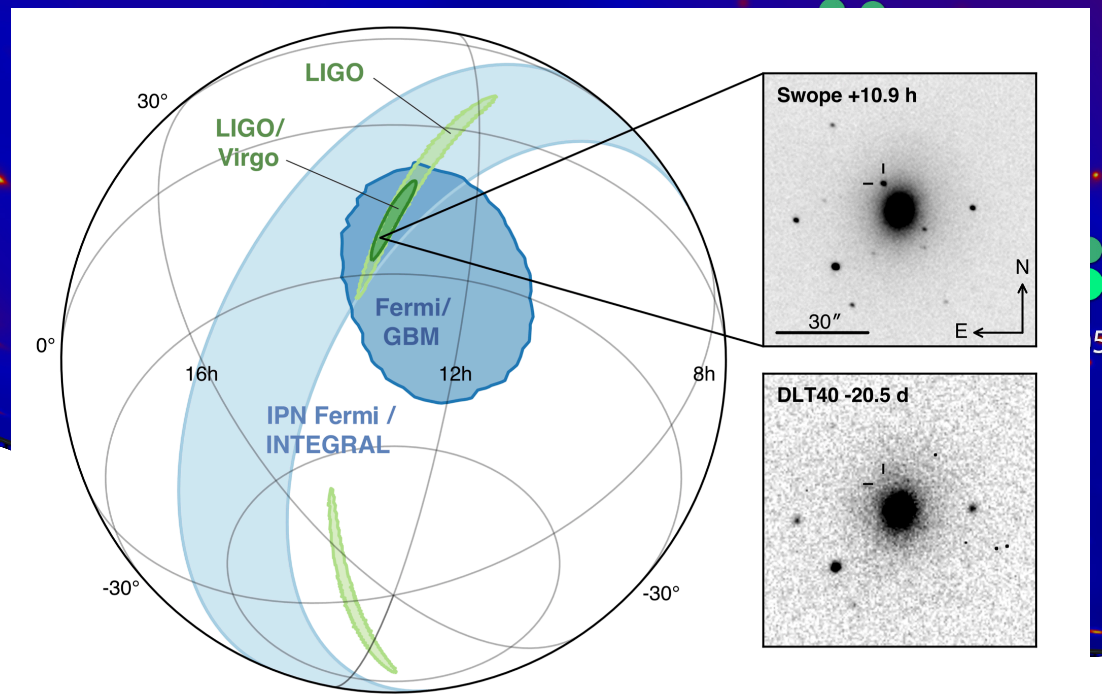


Gamma-ray bursts

Fermi-LAT 10 year GRB map

Fermi-LAT 2nd GRB Catalogue,2019

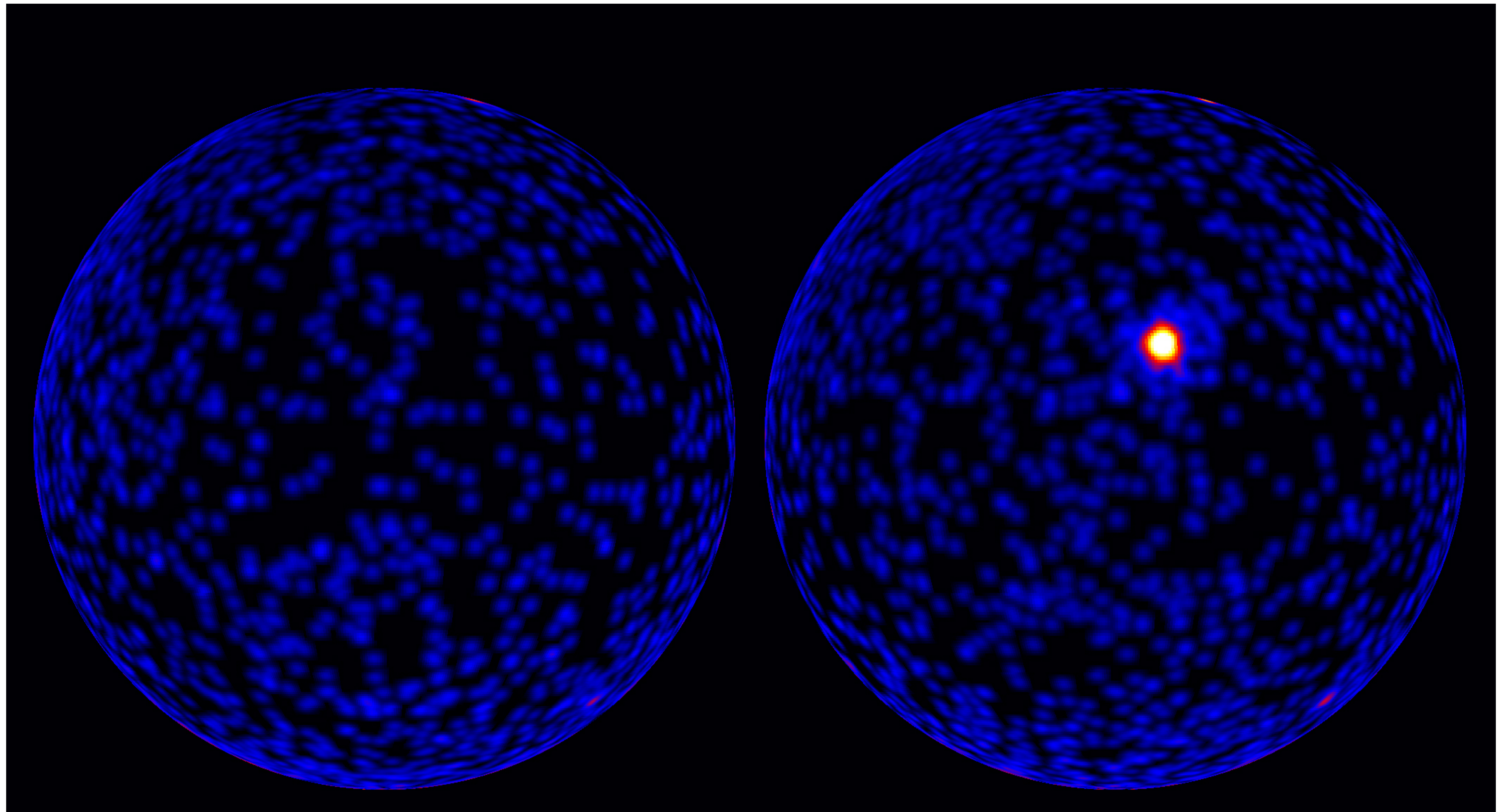




>2000 GRBs with Fermi-GBM
~200 with Fermi-LAT
5 with H.E.S.S.

Gamma-ray bursts, basic facts

- Discovered serendipitously in 1967
- Intense short flashes of light peaking in the 10 keV -1 MeV range
- Isotropic equivalent energy release ~10^{52}-10^{55} erg (cf <10^{49} erg/s in AGN)
- Rate ~ 1000 year occur in the Universe
- Short (0.3 second) and long (50 second) bursts - two distinct populations
- ``Afterglow'' fading emission for hours to months..



Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

Gamma-ray bursts, basic facts

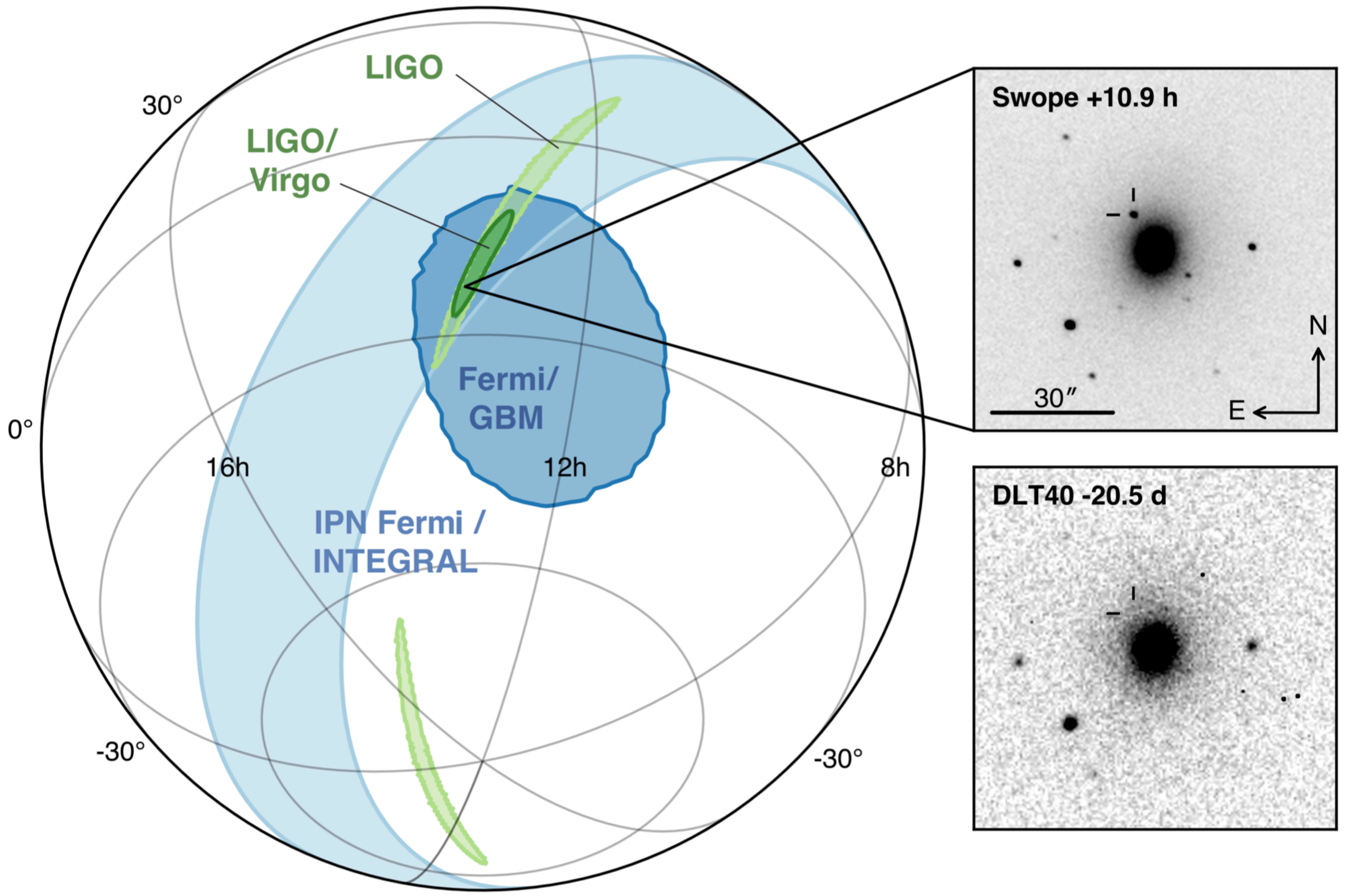
On August 17th, 2017 LIGO and Virgo reported the detection of GWs from the coalescence of a binary neutron star system

Fermi GBM independently detected the sGRB GRB170817A, 1.7s later

An extensive observational campaign localised SGRB in the early type NGC 4993, at d ~ 40 Mpc

GW170817 and GRB170817A confirm binary neutron stars as progenitors of SGRBs (p_{chance} ~10^{-8})

LIGO, Virgo, Fermi Coll+ many others, Astrophys.J. 848 (2017) no.2, L12



Gamma-ray bursts, basic facts

- ``Compactness'' problem: Photons are crowded in GRBs. The observed luminosity implies that gamma-rays shouldn't be able to escape

- But, $\tau_{\gamma\gamma}$ (10 GeV) < 1, since we observe these photons (gamma-rays that escape are ~ $e^{-\tau_{\gamma\gamma}}$)

$\gamma\gamma \rightarrow e^+e^-$, at threshold, $\varepsilon'_{\gamma,1}\varepsilon'_{\gamma,2}(1-\cos\theta) \geq 2m_e^2$. For head-on collision $\cos\theta = \pi$, $\varepsilon'_{\gamma,1} = m_e^2/\varepsilon'_{\gamma,2}$

But $\varepsilon = \varepsilon'\Gamma$, thus, $\varepsilon_{\gamma,1} = m_e^2\Gamma^2/\varepsilon_{\gamma,2}$

$$\tau_{\gamma\gamma} = \sigma_\mathrm{T} n'_\gamma R'$$

$$\tau_{\gamma\gamma} = \sigma_\mathrm{T} \frac{L_\mathrm{iso}(\varepsilon_\gamma)}{4\pi R^2 c \Gamma \varepsilon_\gamma} \frac{ct_\mathrm{v}}{\Gamma}$$

Implies $\Gamma > 10^3$ for the brightest GRBs

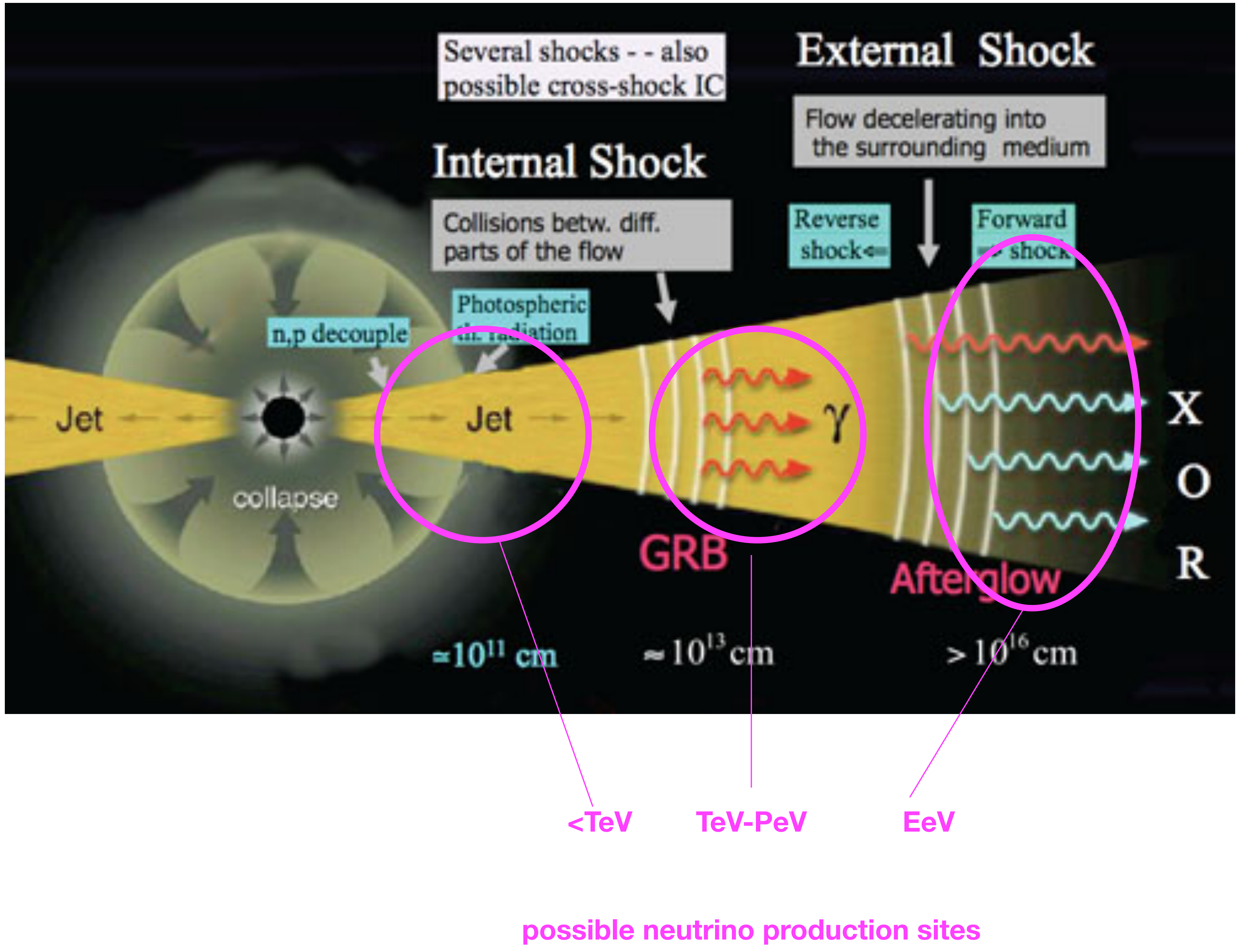
Maximum energy

Very high Lorentz factors

Highly magnetised expanding jet

$$E_{\rm max} \approx 10^{20}\ {\rm eV} \left(\frac{\dot{\varepsilon}_{\rm GRB}}{10^{51}\ {\rm erg}} \right)$$

Waxman 1995, Vietri 1995



Neutrino production in GRBs

Ample photon fields $\longrightarrow$photopion interactions

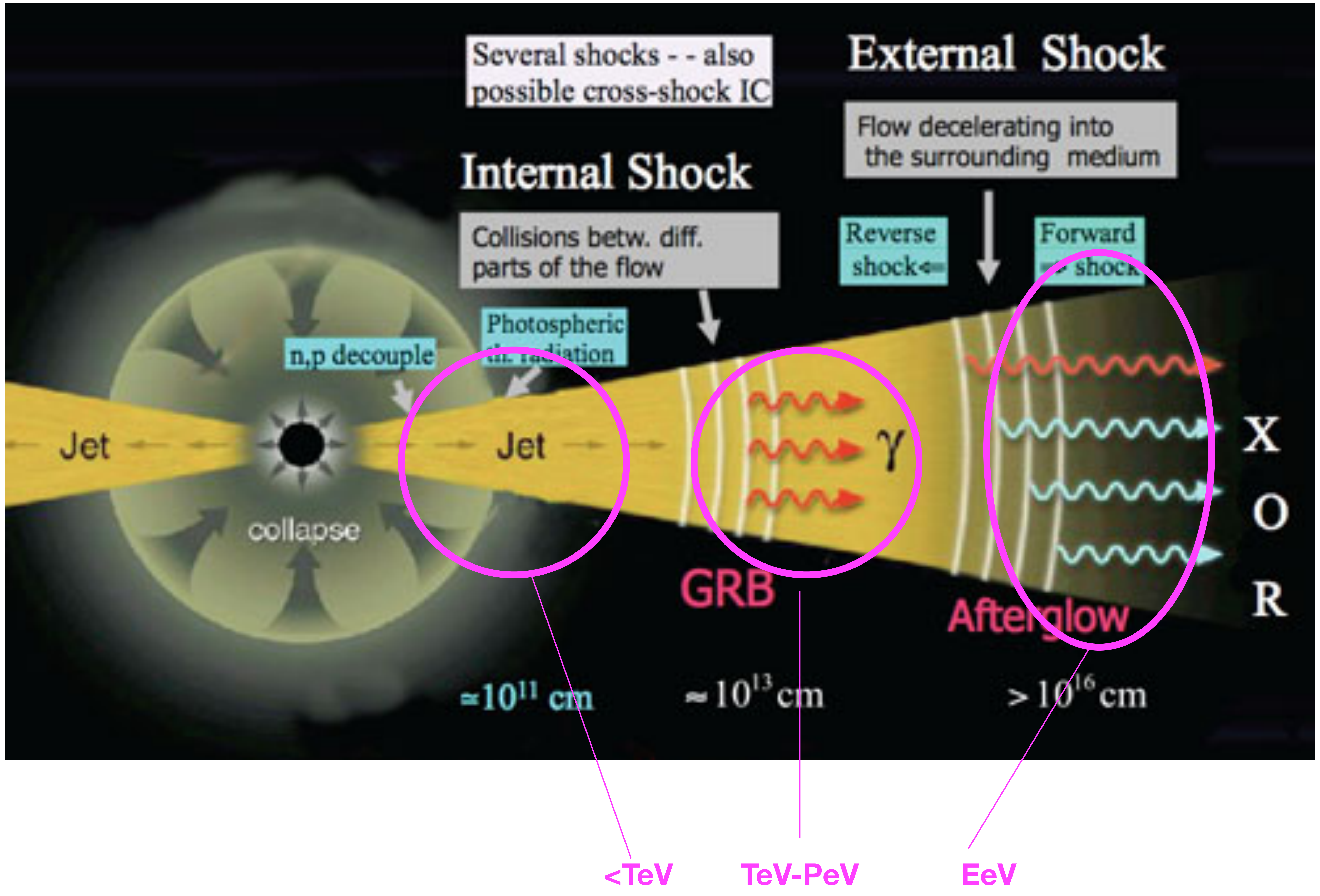
$$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow n/p + \pi^+/\pi^0$$

$$E_p E_\gamma \gtrsim \frac{m_\Delta^2 - m_\pi^2}{4}\left(\frac{\Gamma}{1+z}\right)^2 = 0.16\ \mathrm{GeV}\left(\frac{\Gamma}{1+z}\right)^2$$

$$E_\nu \geq 8\ \mathrm{GeV}\left(\frac{\Gamma}{1+z}\right)^2\left(\frac{E_\gamma}{\mathrm{MeV}}\right)^{-1}$$

e.g. prompt emission,

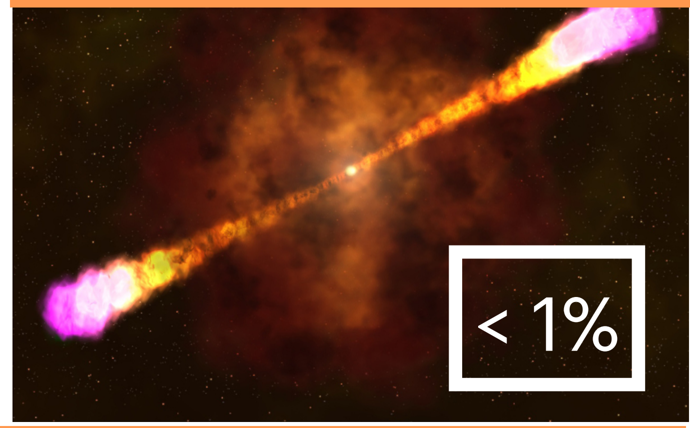
$$z = 1,\ \Gamma^2 = 10^5,\ E_\gamma \sim 250\ \mathrm{keV} \rightarrow E_\nu \sim \mathrm{PeV}$$



possible neutrino production sites

GRB contribution to the cosmic-neutrino flux

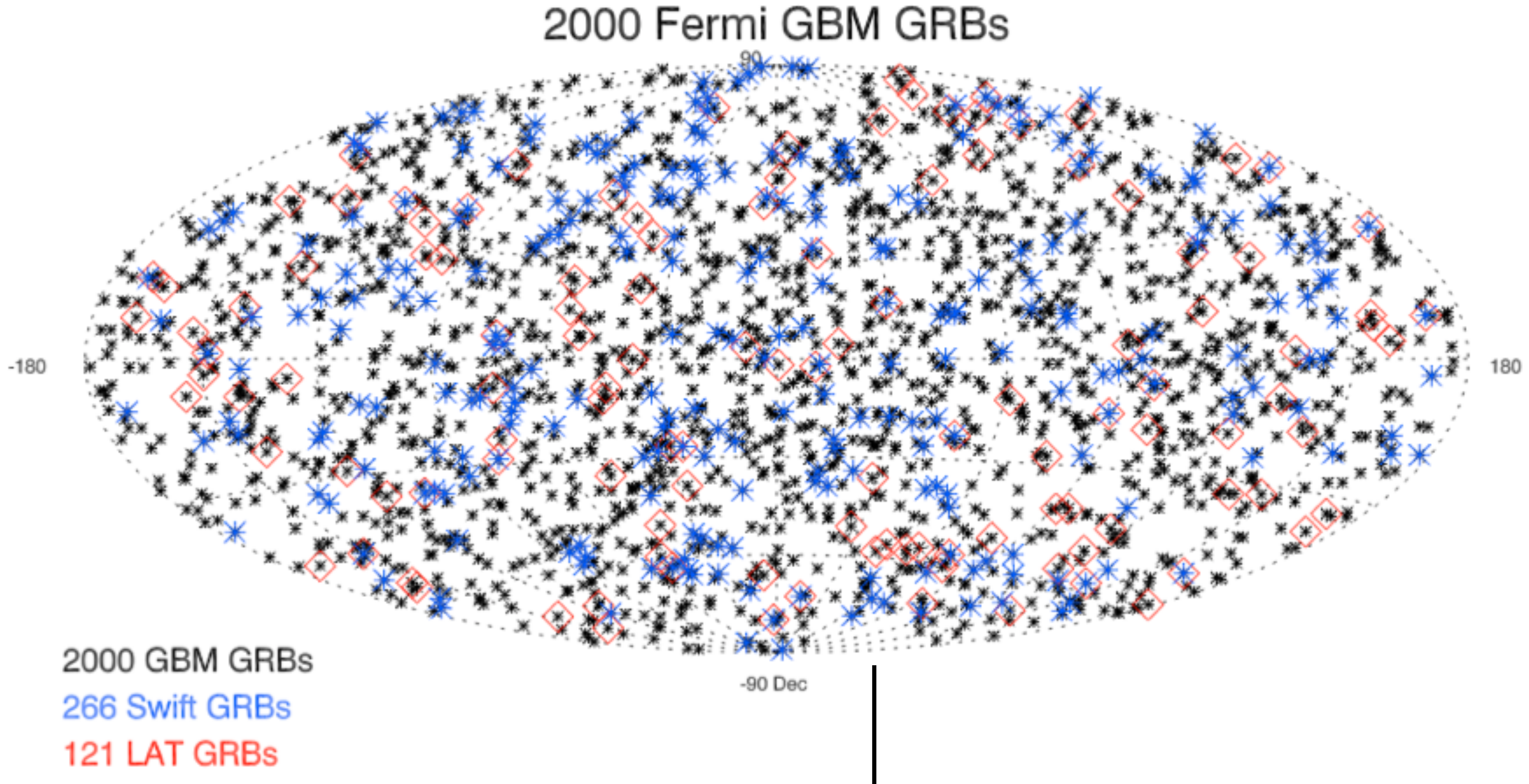
GRBs

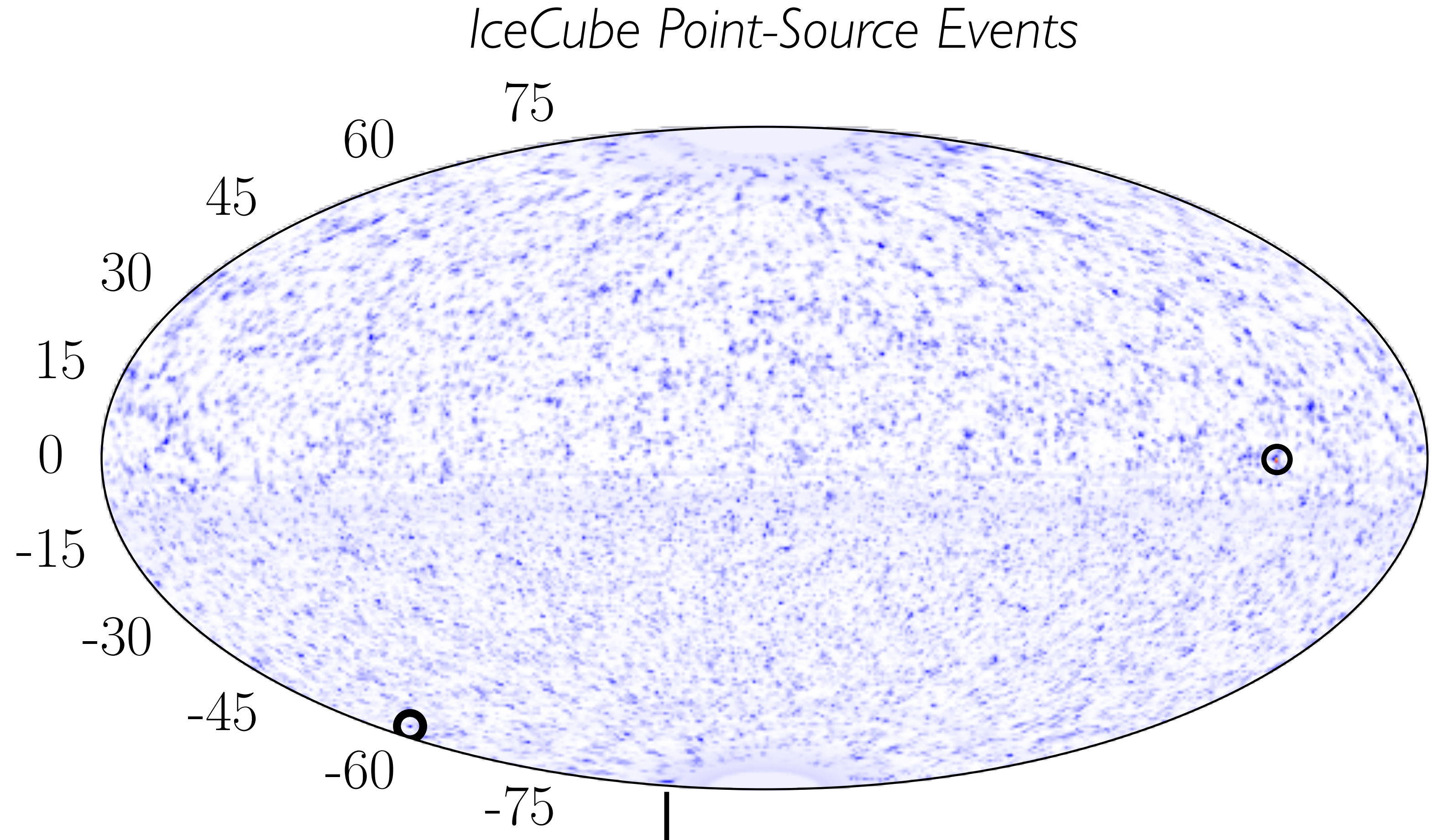


NS/NS Mergers

Stacked search for neutrinos coincident with prompt GRB emission.

2091 GRBs





IceCube Coll, ApJ 843 (2017) 112
IceCube Coll., Fermi GBM Coll, Apj 939 (2022) 2
+strong limits from GRB221009A (the ``BOAT")
IceCube Coll ApJL 946 L26 (2023)
ANTARES Coll MNRAS 469 906 (2017)

Prompt (ΔT_{promt} ~1-100s): < 1% diffuse neutrino flux

Precursor/Afterglow ($\Delta T_{afterglow}$ ± 14d): < 24% diffuse neutrino flux

Scorecard

	$E_{\max}$	$\bar{n}_{\mathrm{eff,UHECR}}$	$\bar{n}_{\mathrm{eff},\nu}$	$\dot{\varepsilon}_{\mathrm{UHECR}}$
BL Lac	not for H	😞	😞	😀
FSRQs	😀	😞	😞	😀
FR I	not for H	😀	😀	😀
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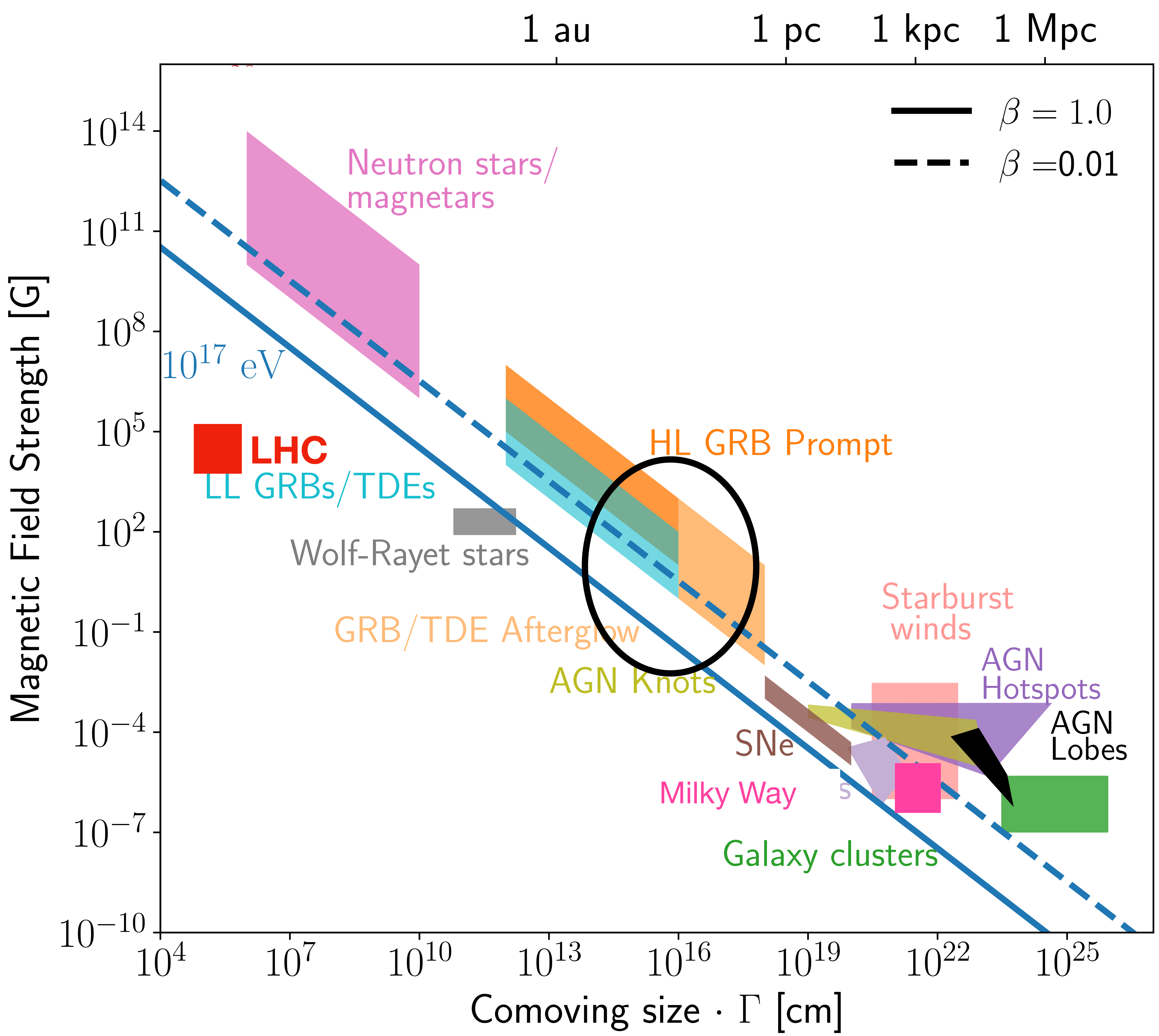
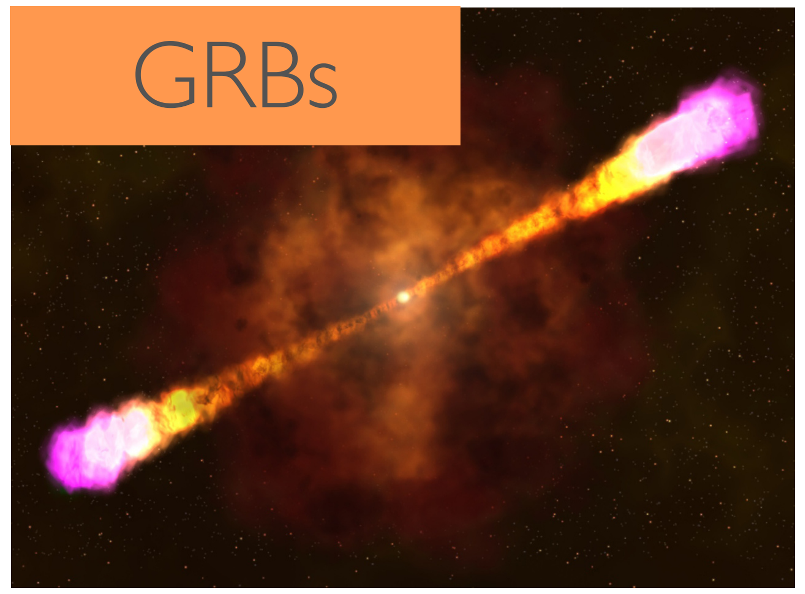
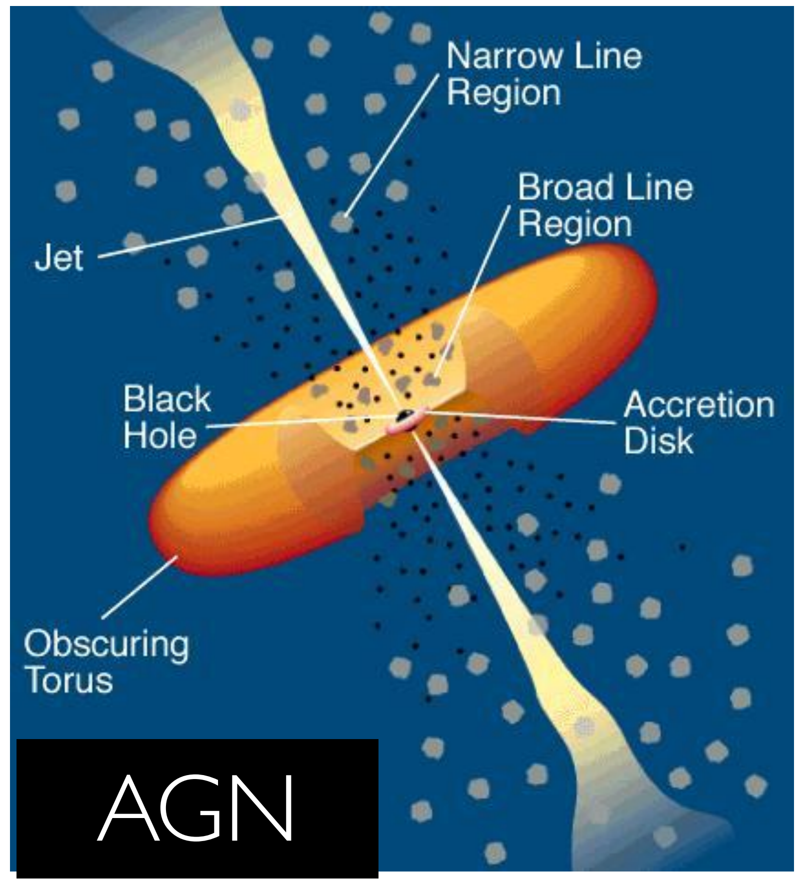
Non jetted AGN	😕	😀	😀	😀
Starbursts	😞	😀	😀	😀
GRBs (LL GRBs)	😀(?)	😞(😀)	😞(😀)	😞(😀)
jetted TDEs (non jetted)				

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







Tidal disruption events

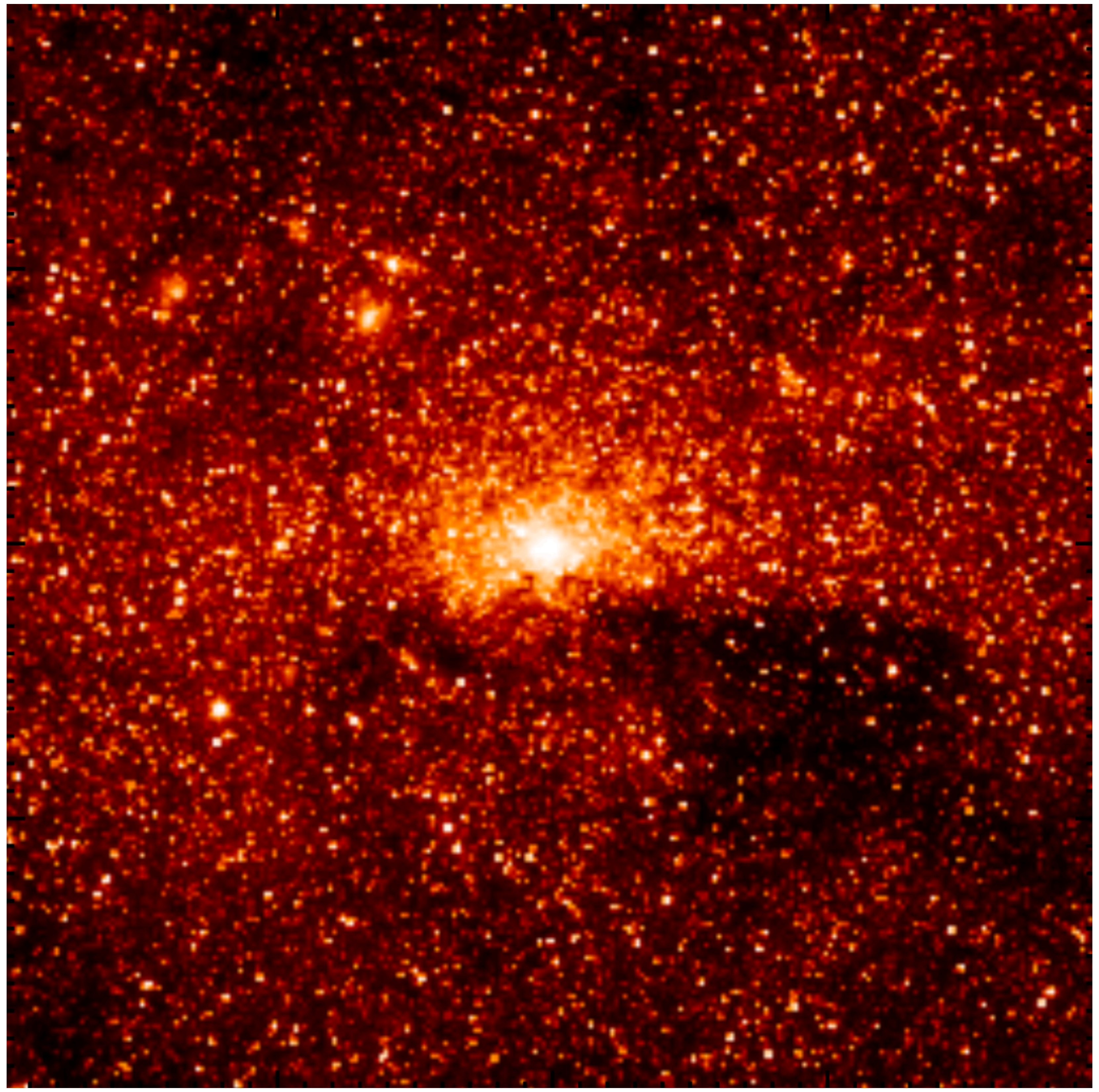
Super Massive Black Holes are orbited by star clusters

Millions or billions of stars in random orbits

Tidal forces may deform, or tear into pieces a star approaching too closely

Predicted rates of 1 TDE in 10000 to 10^9 years per super massive black hole (SMBH)

For tidal forces to be relevant they must be stronger than the star's self gravity



Tidal acceleration > Accel. due to self gravity

$$\frac{GM_{\mathrm{SMBH}}R_\star}{R_t^3} = \frac{GM_\star}{R_\star^2}$$

Tidal disruption events

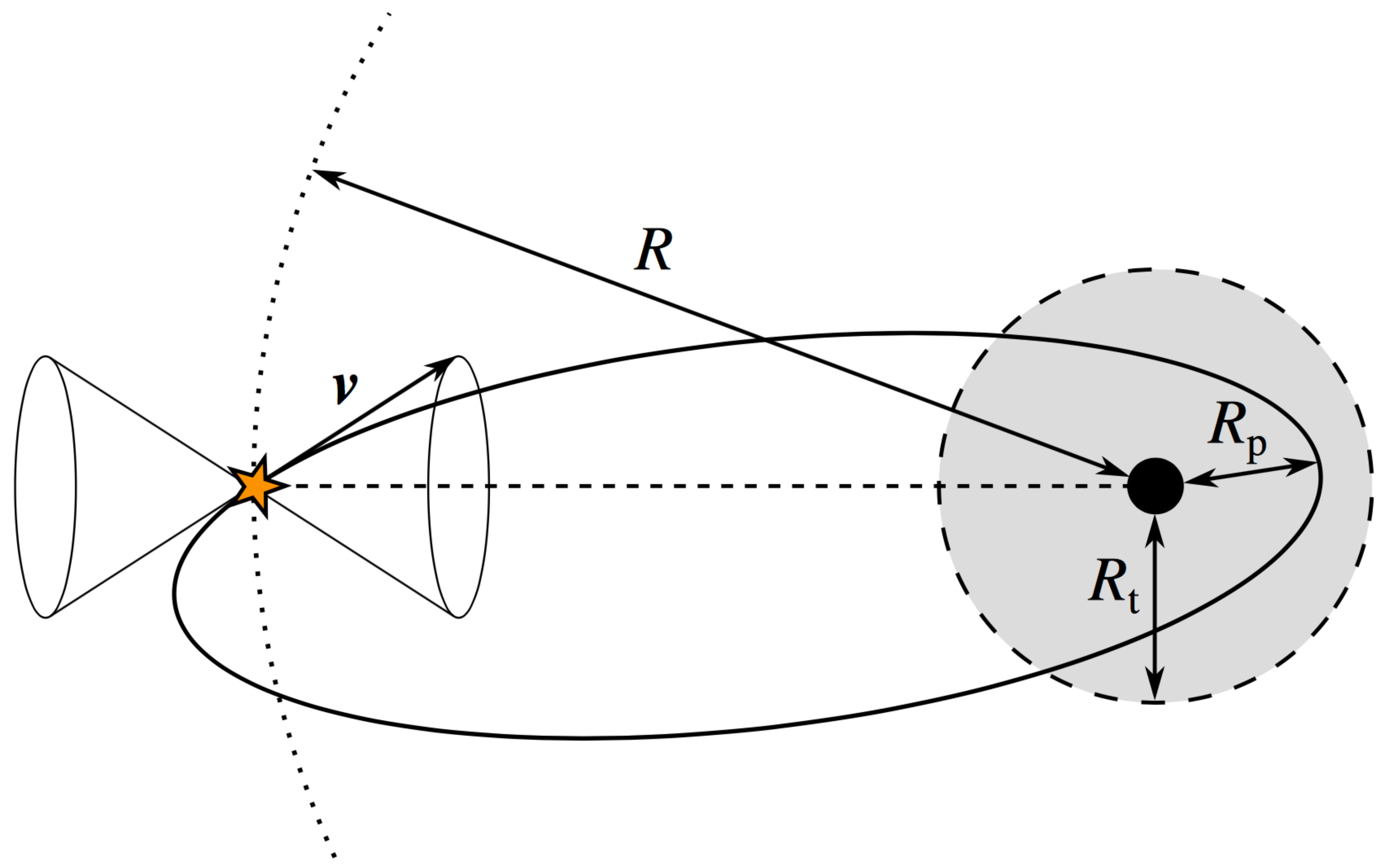
For tidal disruption to occur $R_p < R_t$

R_t must be outside the event horizon for visible TDE

The Schwarzschild radius is

$$M_{\rm SMBH} \leq M_\star^{-1/2} \left(\frac{c^2 R_\star}{2G} \right)^{3/2} \approx 10^8 M_\odot \left(\frac{R_\star}{R_\odot} \right)^{3/2} \left(\frac{M_\star}{M_\odot} \right)^{-1/2}$$

For $R_t > r_s$



Tidal disruption events

Flare of electromagnetic radiation at high peak luminosity (X-rays)

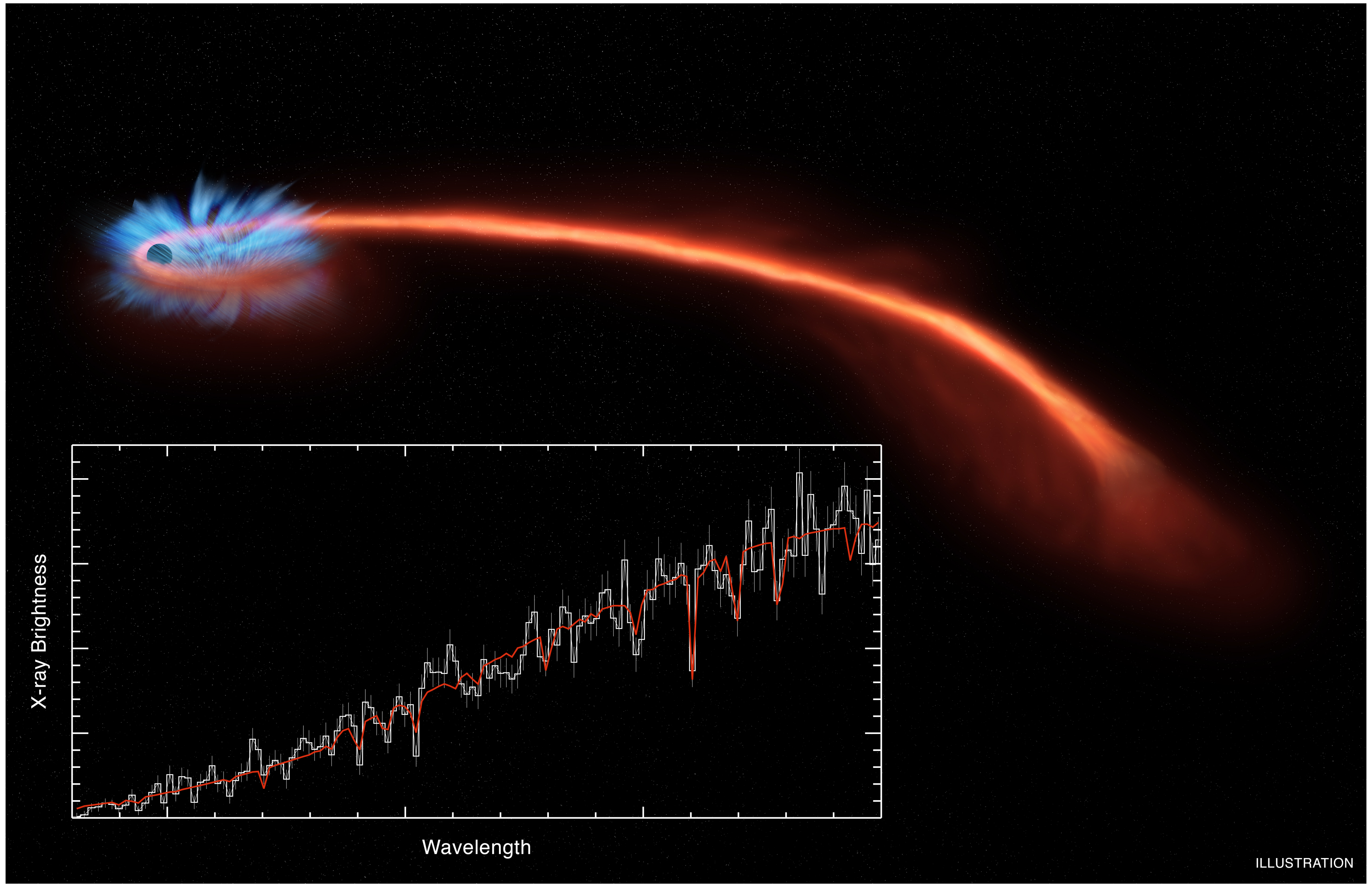
Located in the core of an otherwise quiescent, inactive galaxy

Extreme flares can host a relativistic hadronic jet

Typically 50% of the star's mass expected to stay bound to the SMBH and be ultimately accreted

~100 candidate TDEs observed so far, 3 with jets (hard X-ray spectrum)

Timescale of months to years



Swift J1644+57

Test case, Swift J1644+57, jetted TDE observed in ``blazar'' mode

Observed for ~600 days, in a small quiescent galaxy in the Draco constellation at z = 0.35

$$E_{\rm max} \sim 10^{20}\ {\rm eV}\, Z \frac{BR}{3\times 10^{17}\ {\rm G\ cm}} \frac{\Gamma}{10}$$

Neutrinos from TDEs?

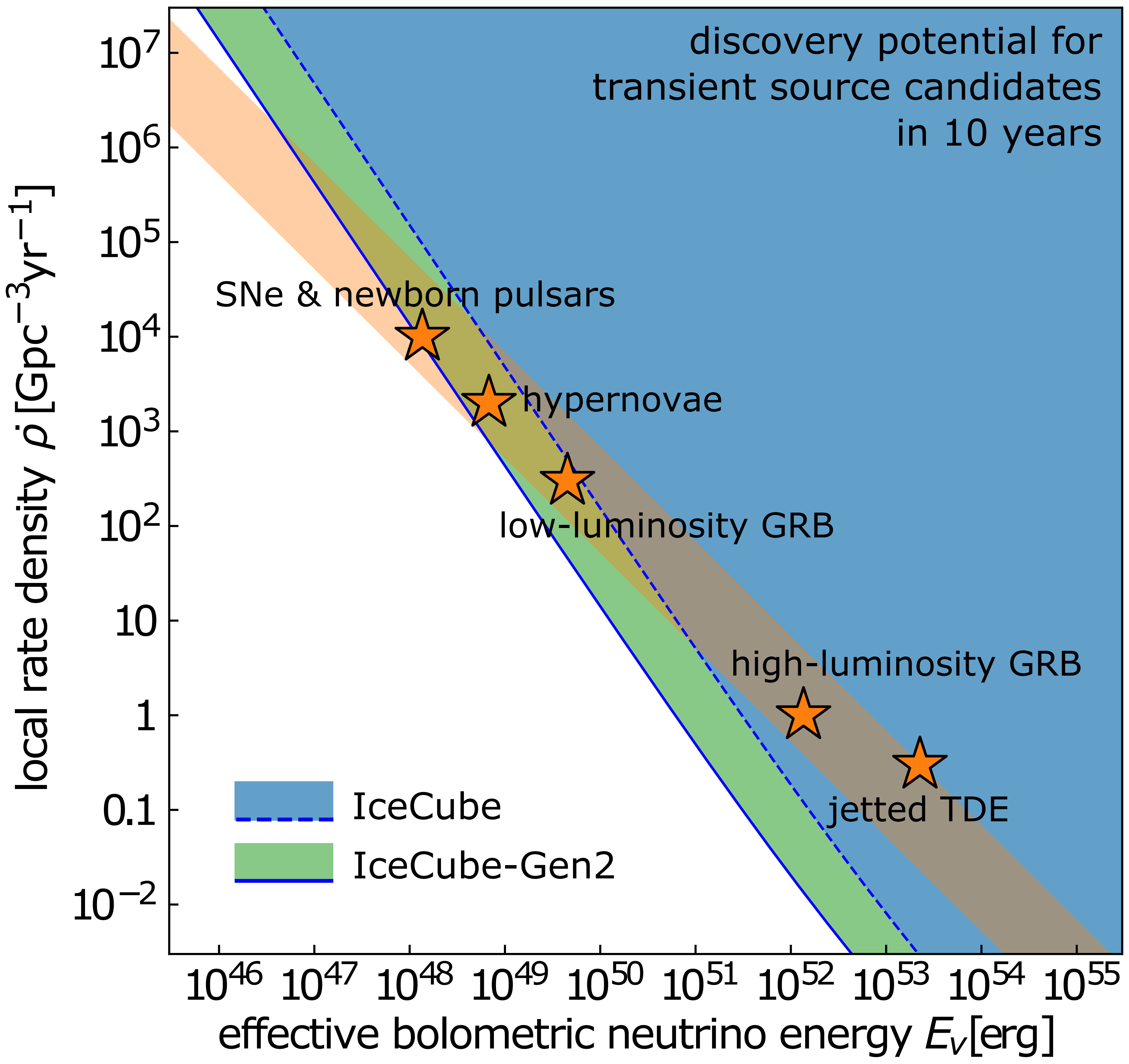
Photopion interactions in the jet (conditions similar to AGN/GRB)

One problem is that jetted TDEs are very rare

n = 10^{-11} Mpc^3 cf GRBs, n = 10^{-9} Mpc^3

Non-jetted TDEs 10 -100 times more numerous, but not clear if (where?) they accelerate 10^{17} eV protons

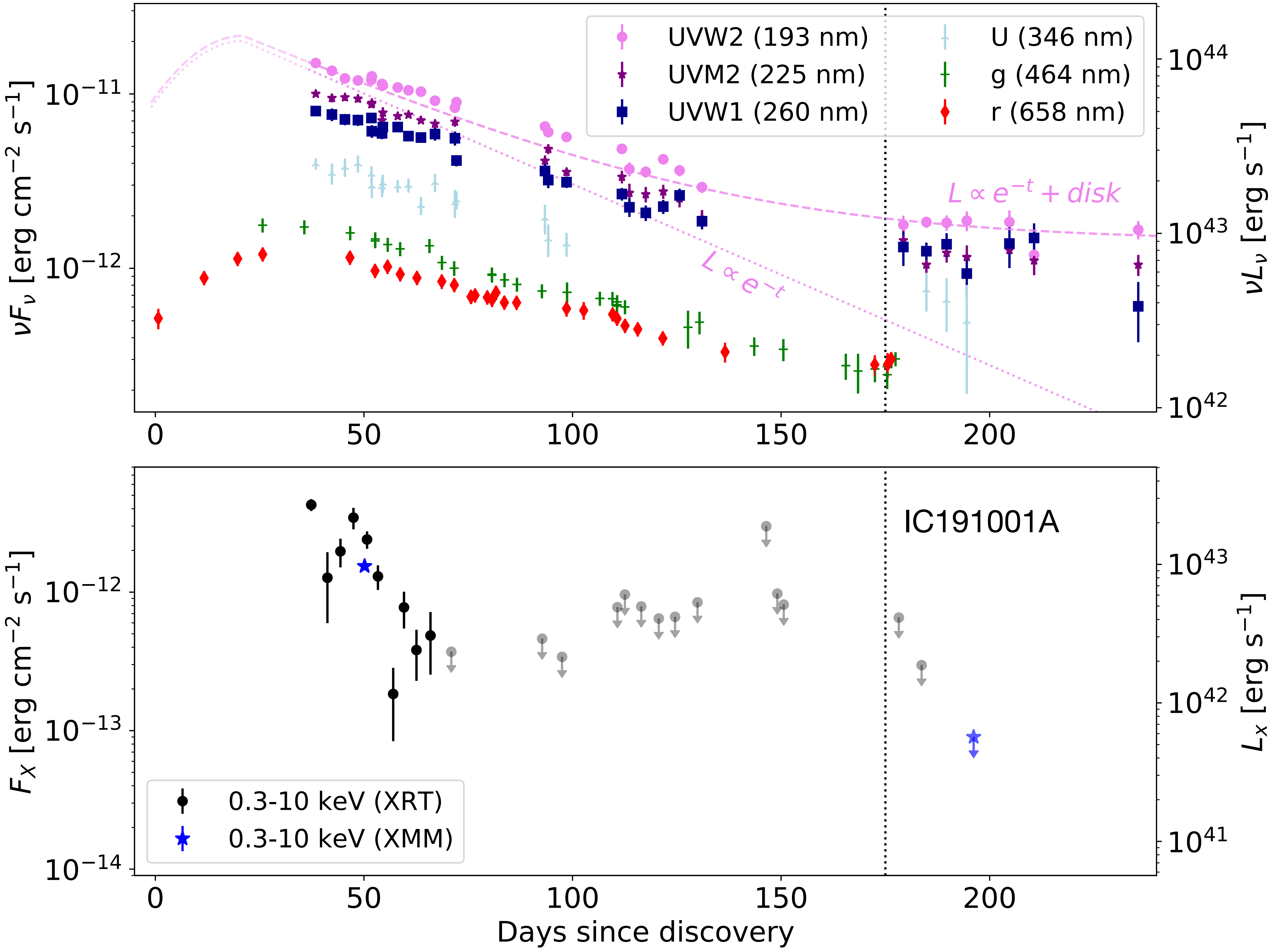
Stacking limits from IceCube (jetted TDEs < 1%, non-jetted < 26%)



AT2019dsg + IC191001A

UV optical flux

X-ray flux



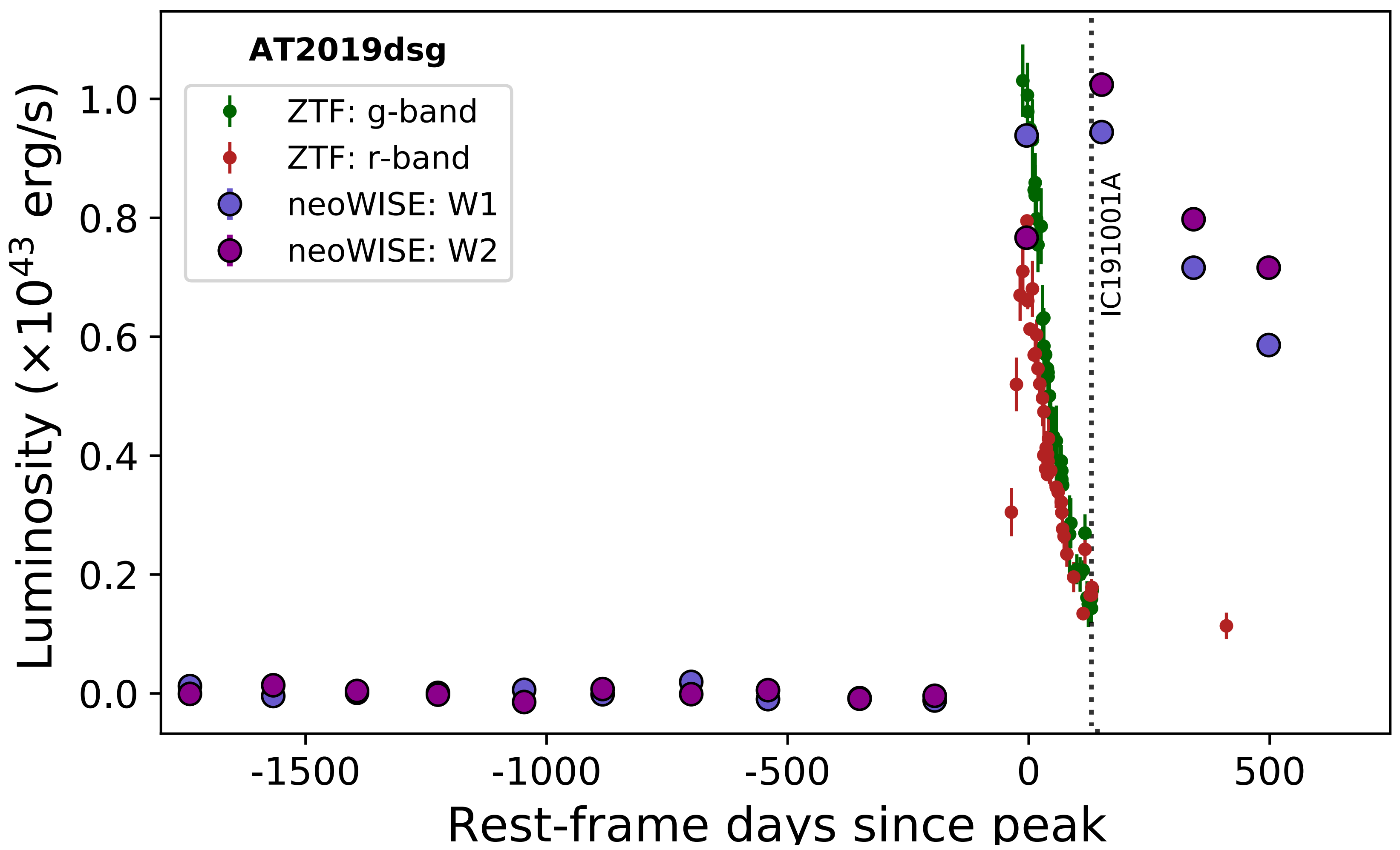
IC 191001A was a 200 TeV muon neutrino (pAstro ~ 60%)

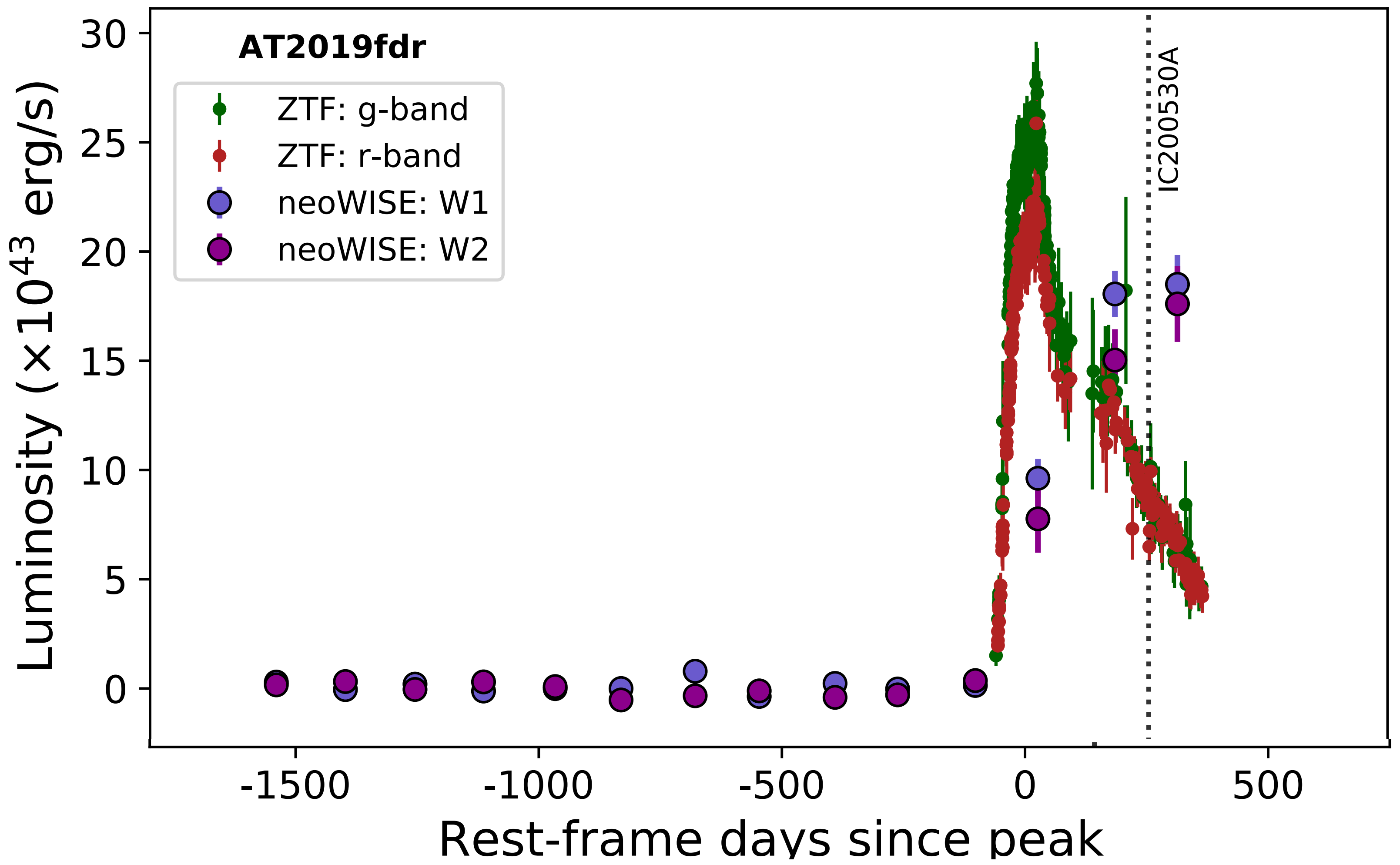
AT 2019dsg was a rare (radio emitting) TDE sign of jet?

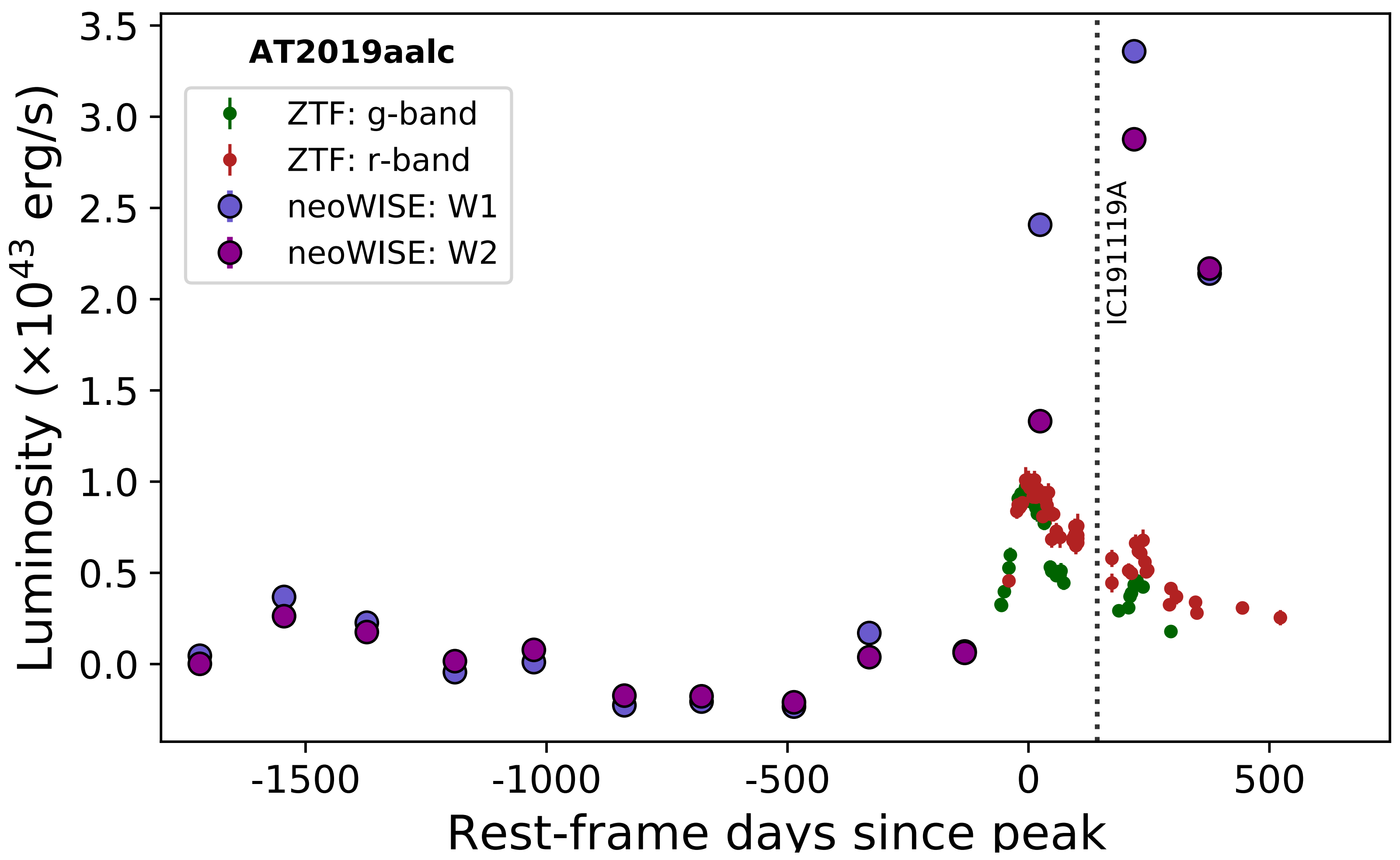
IC 191001A +AT 2019dsg association by chance? p = 0.5%

AT2019fdr+IC200530A, AT2019aalc+IC191119A

Van Velzen et al 2021.09391







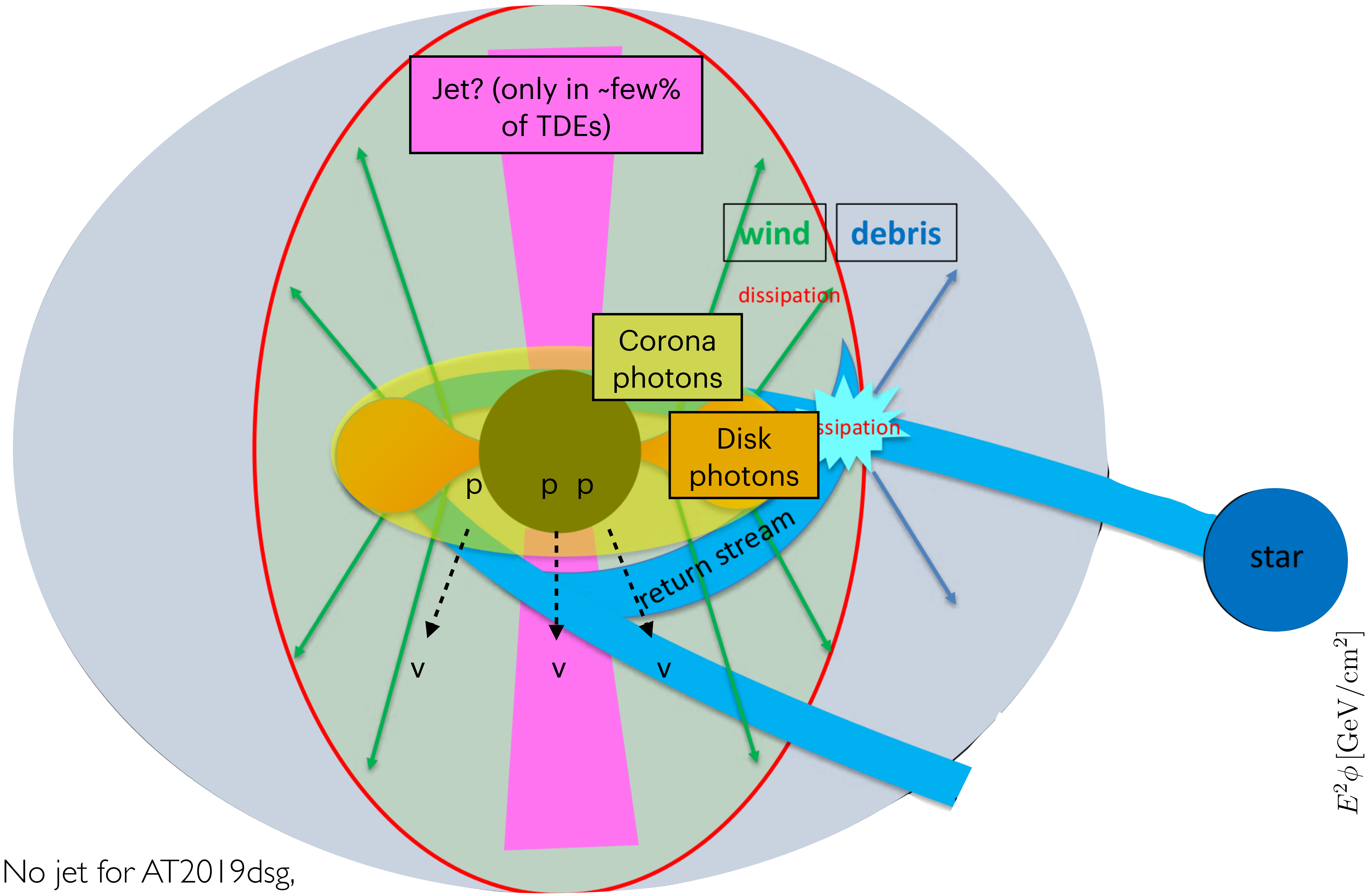
Combined significance 3.7σ

If the associations are real they point to very extreme physical conditions

"super_Eddington" accretion

Neutrino production in AT2019dsg

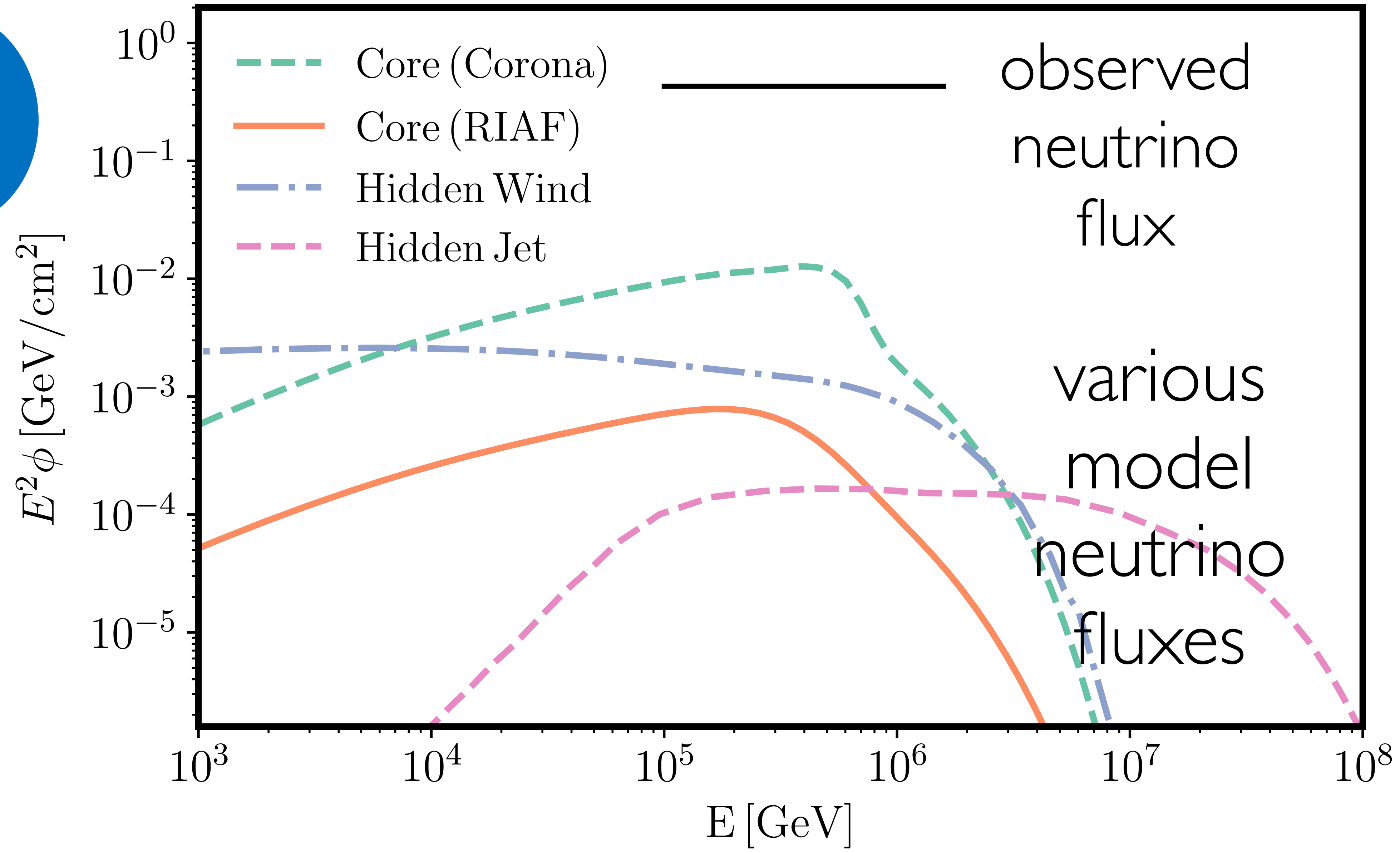
see also Hayasaki et al 2019
Winter, Lunardini 2020
Winter, Lunardini 2022
Banik & Bharda 2022



No jet for AT2019dsg, AT2019fdr, AT2019aalc
(Cendes et al 2021, Matsumoto et al 2021)

Example neutrino spectra (AT2019dsg)

Murase, Zhang, Kimura, FO, Petropoulou 2020



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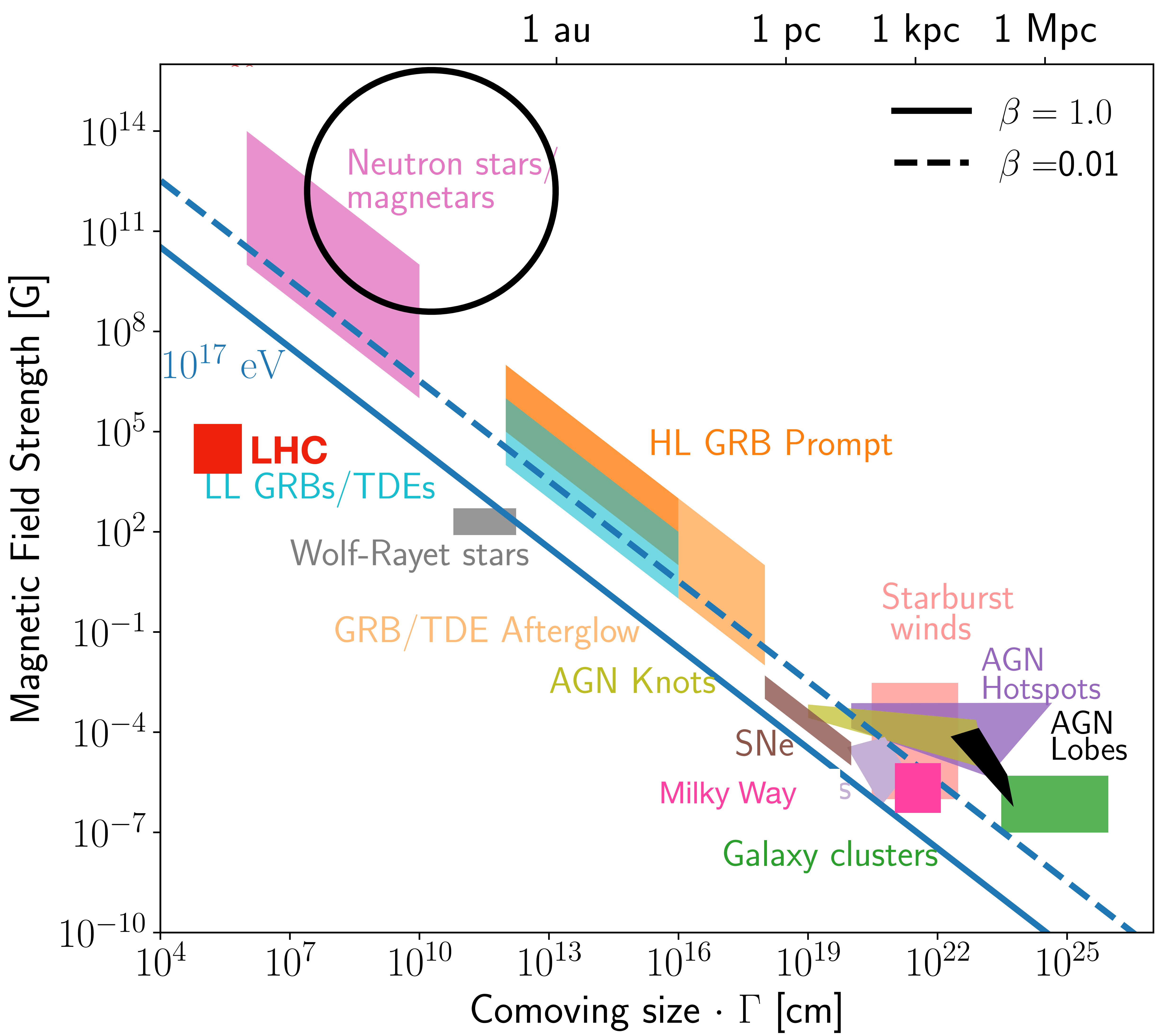
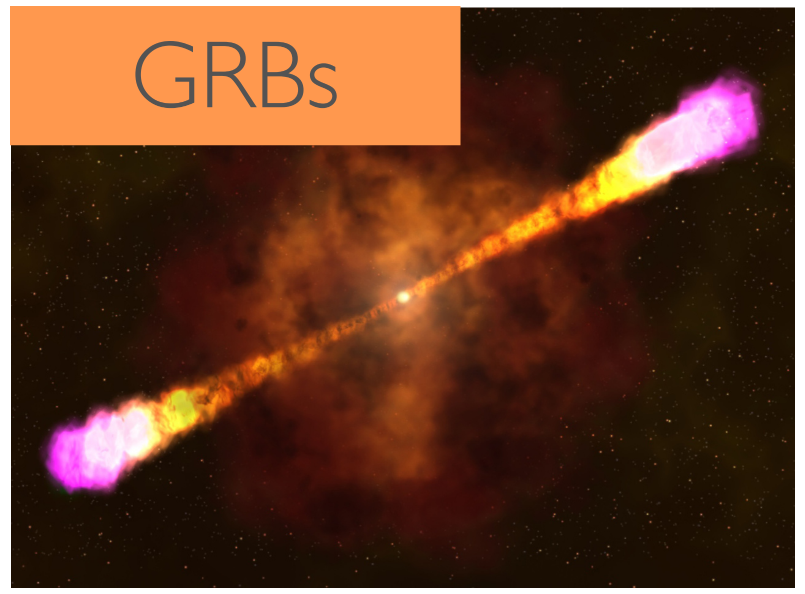
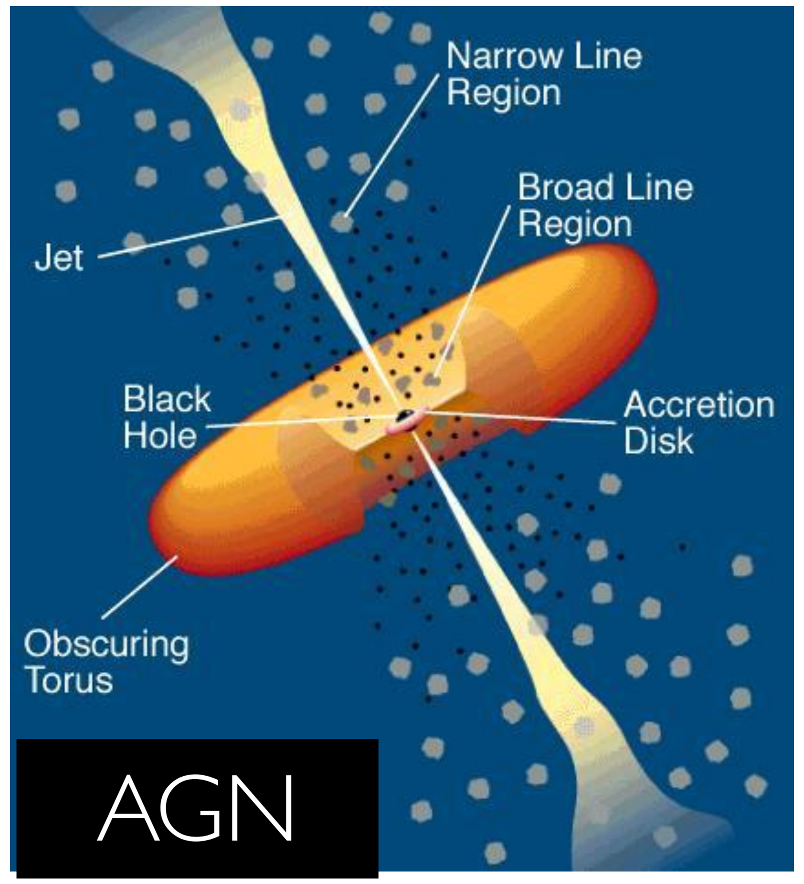
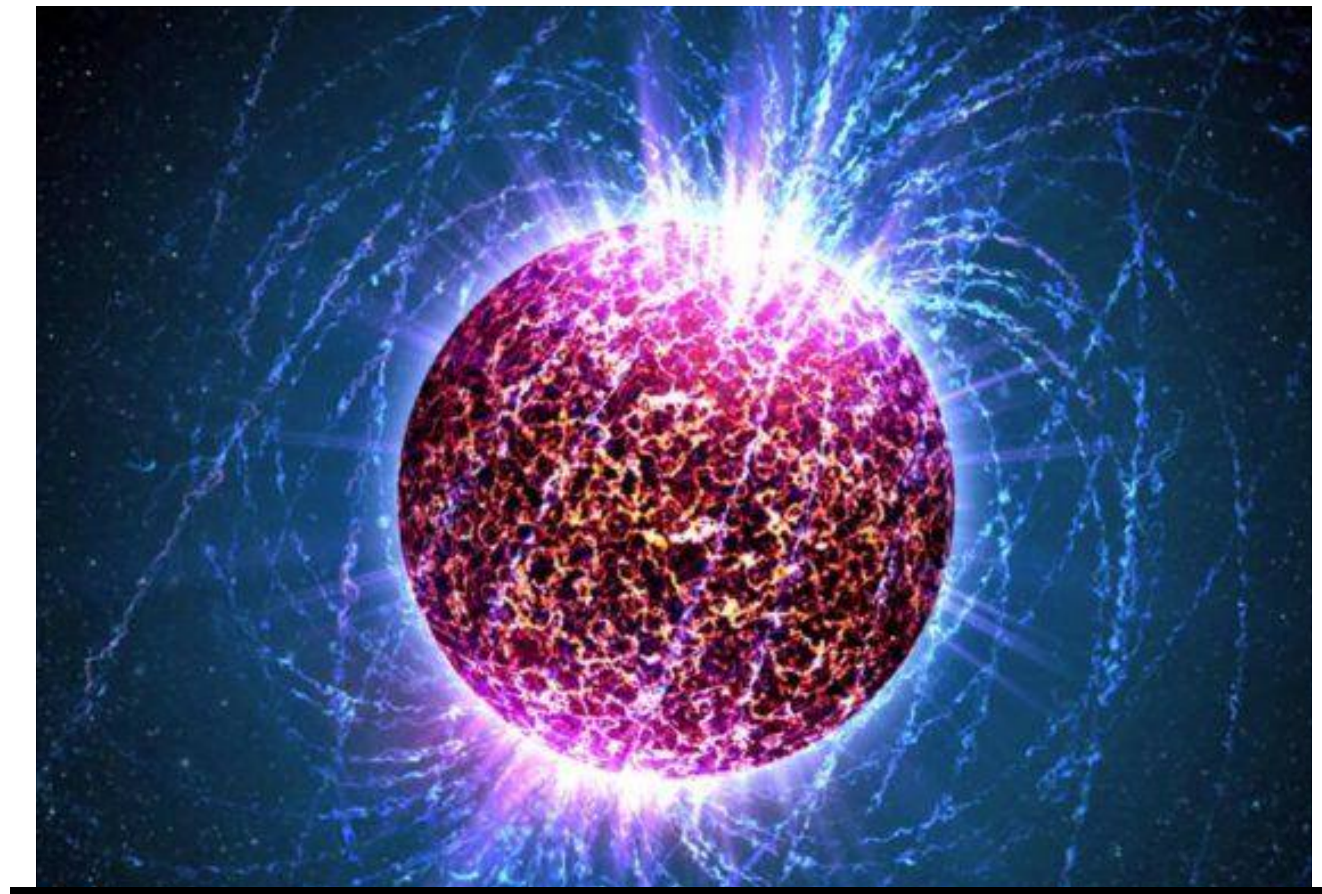
Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)

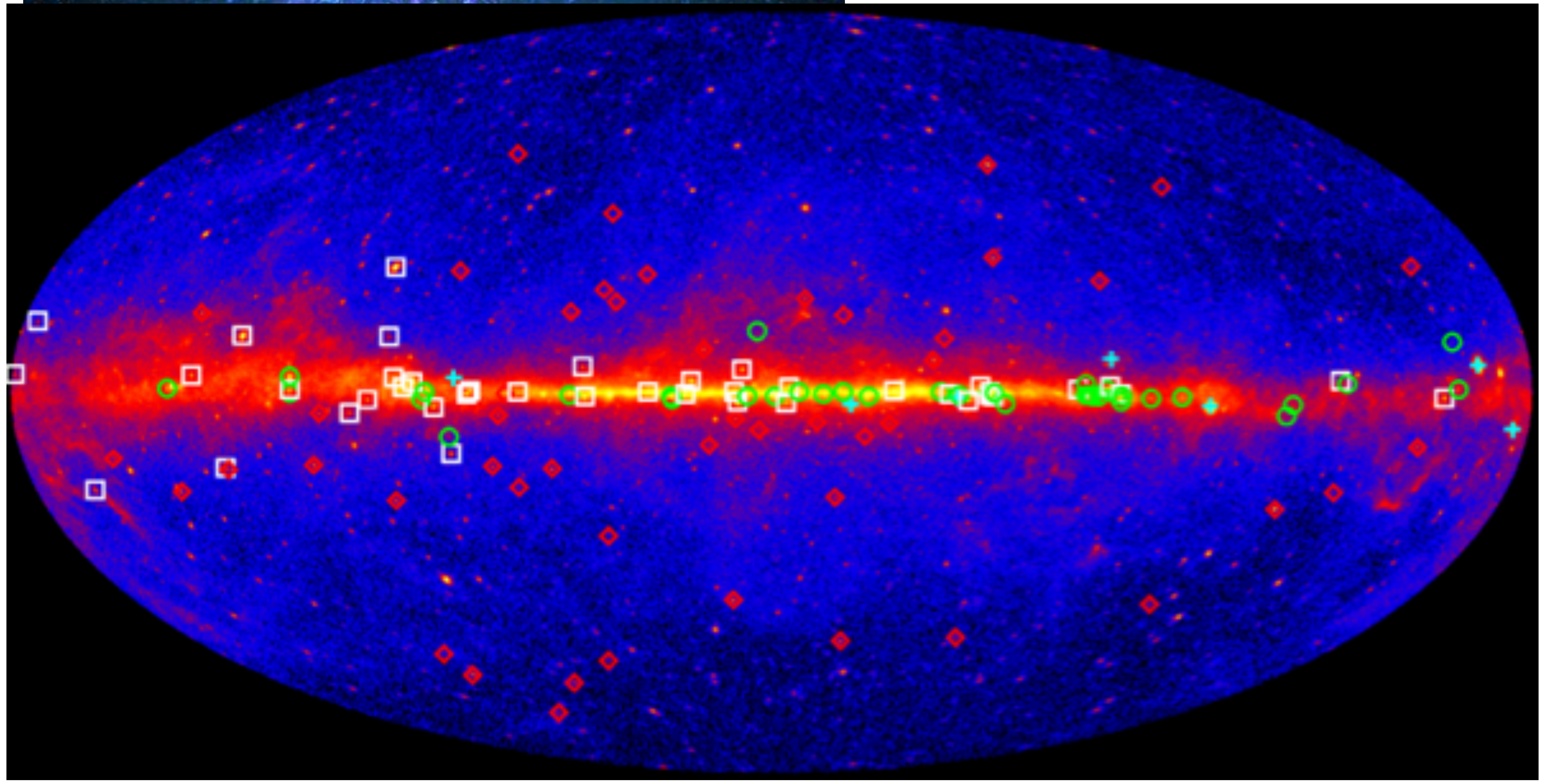






Neutron stars





Fermi has detected >200 Galactic pulsars

Collapsing stars with mass > 8 M_{Sun}

Collapse leads to heating up and density approaches nuclear densities

$$e^- + p^+ \rightarrow n + \nu_e$$

"neutronisation"

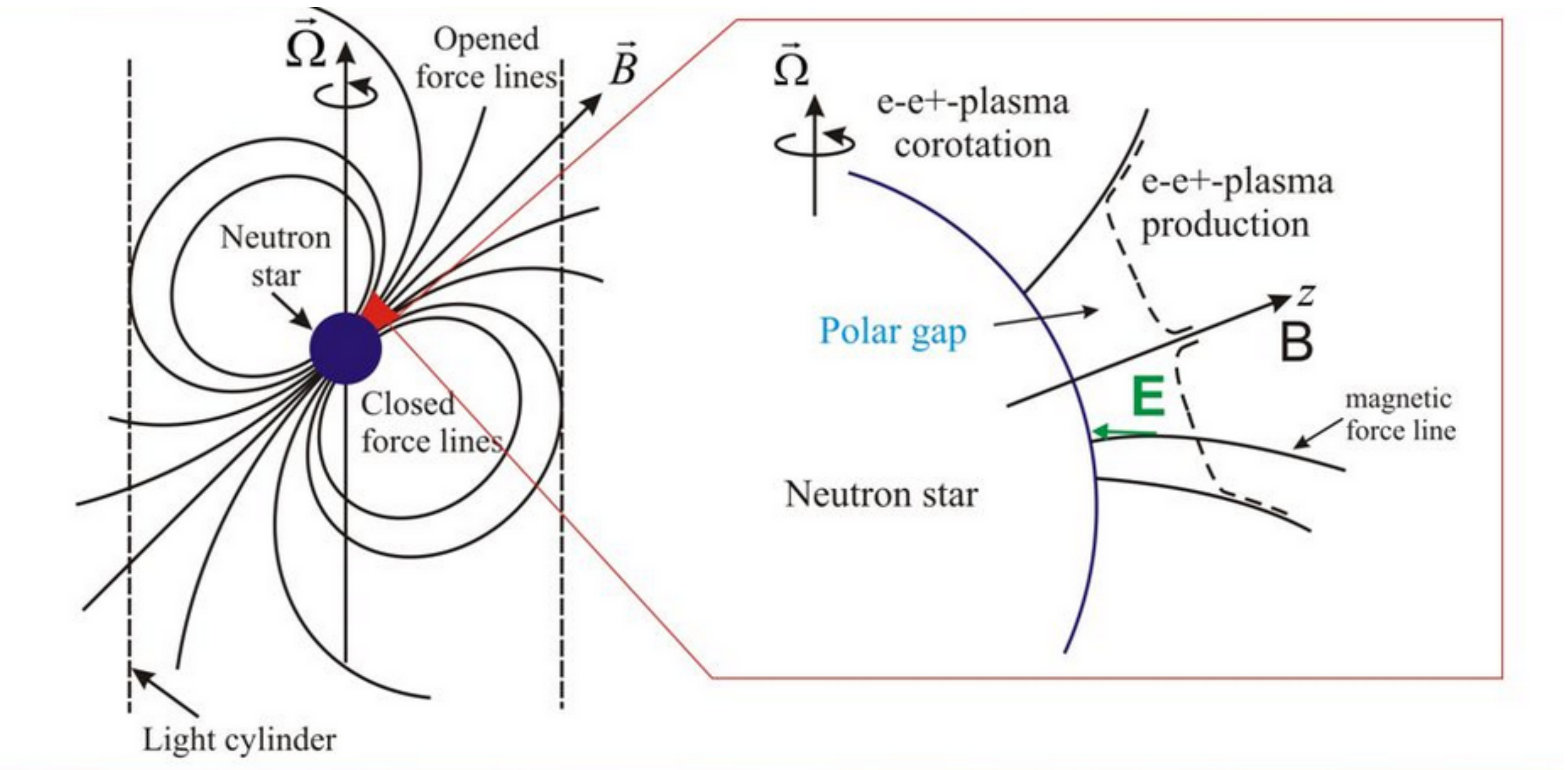
The core of the star was originally $R_{star} \sim 10^{3-4}$ km

whereas the neutron star radius is $R_{NS} \sim 10$ km

Conservation of angular momentum leads to spin periods ~second

Conservation of magnetic flux leads to B ~10^{10} G

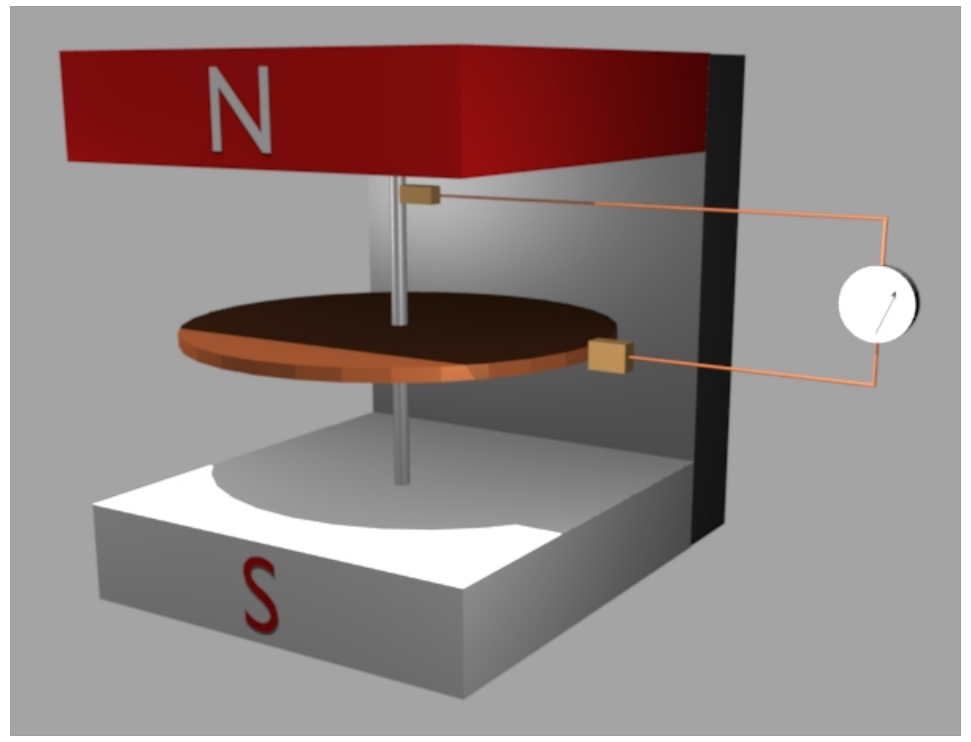
Pulsar UHECR acceleration



Unipolar inductor:

strong magnetic field, B

fast rotation velocity, Ω



Maximum acceleration energy
for fastest spinning sources:

$$\gamma_{\rm acc}^{\rm max} = \frac{Ze}{Am_N}\Delta\phi = 7\times10^{10}\frac{Z}{A}\left(\frac{B}{10^{13}\ \mathrm{G}}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^3\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2}$$

SN envelope = dense baryonic background

UHECR experience hadronic interactions

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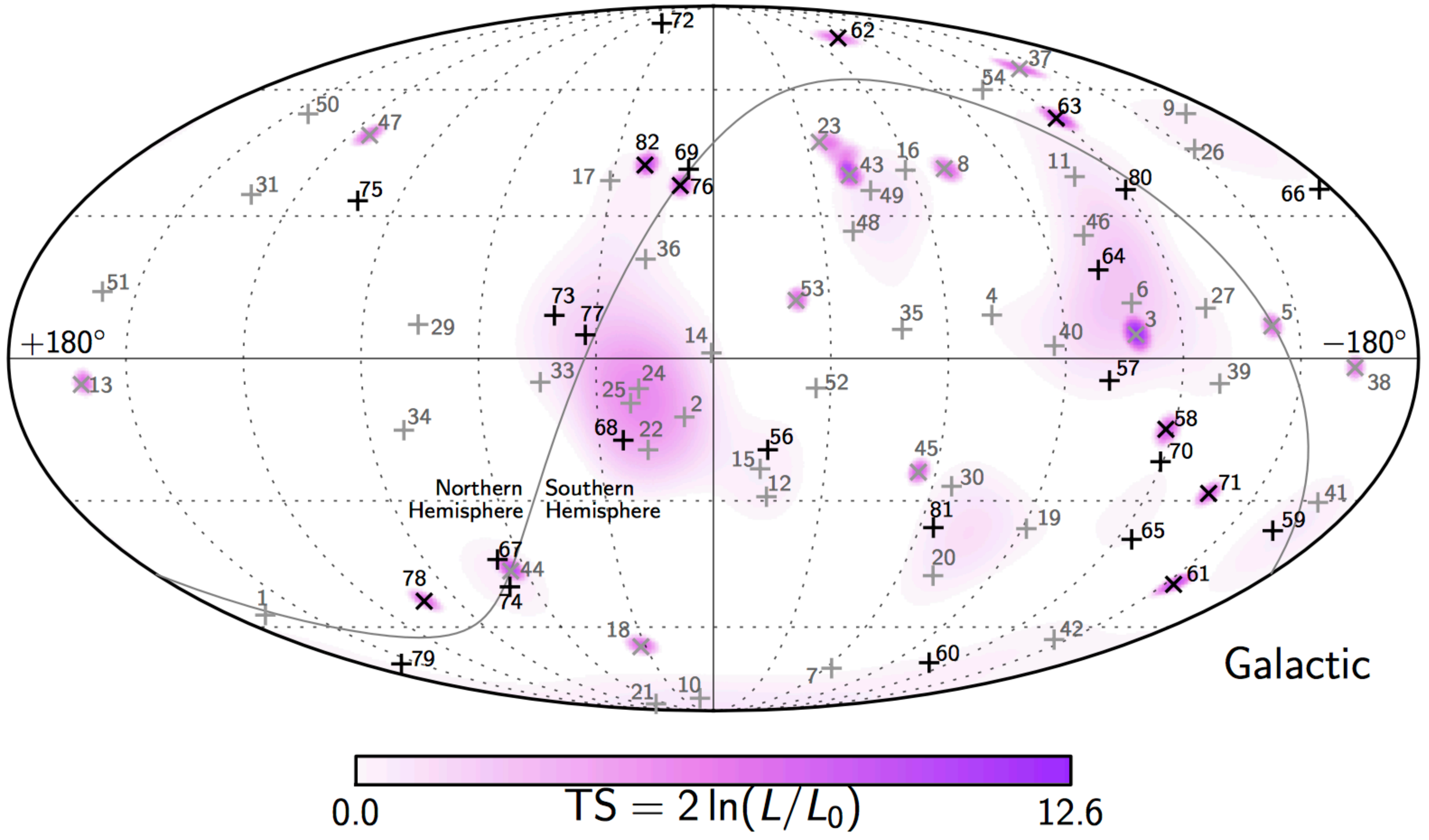
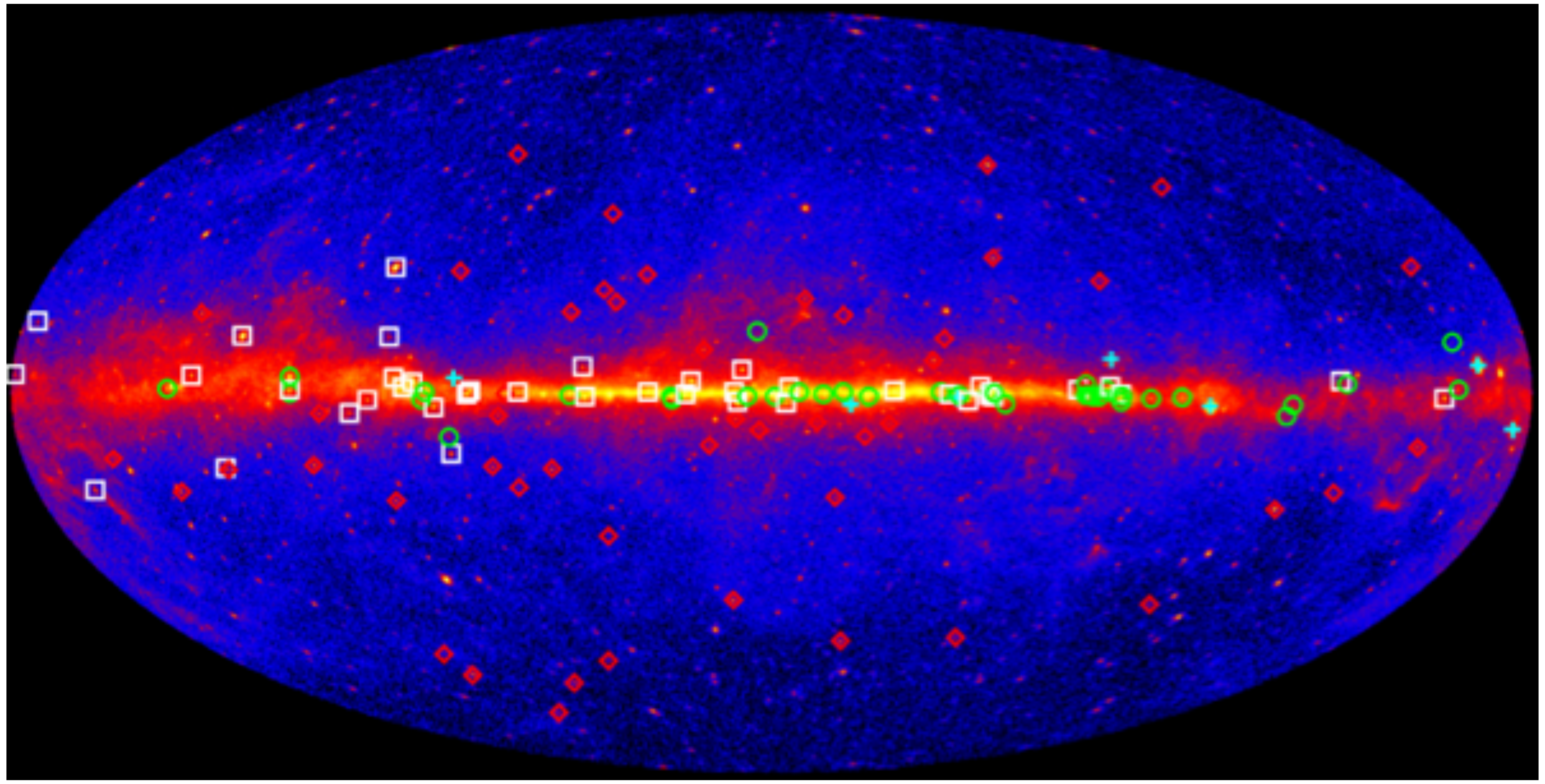
Pulsar origin of IceCube neutrinos?

IceCube Coll. PoS(ICRC2017)981

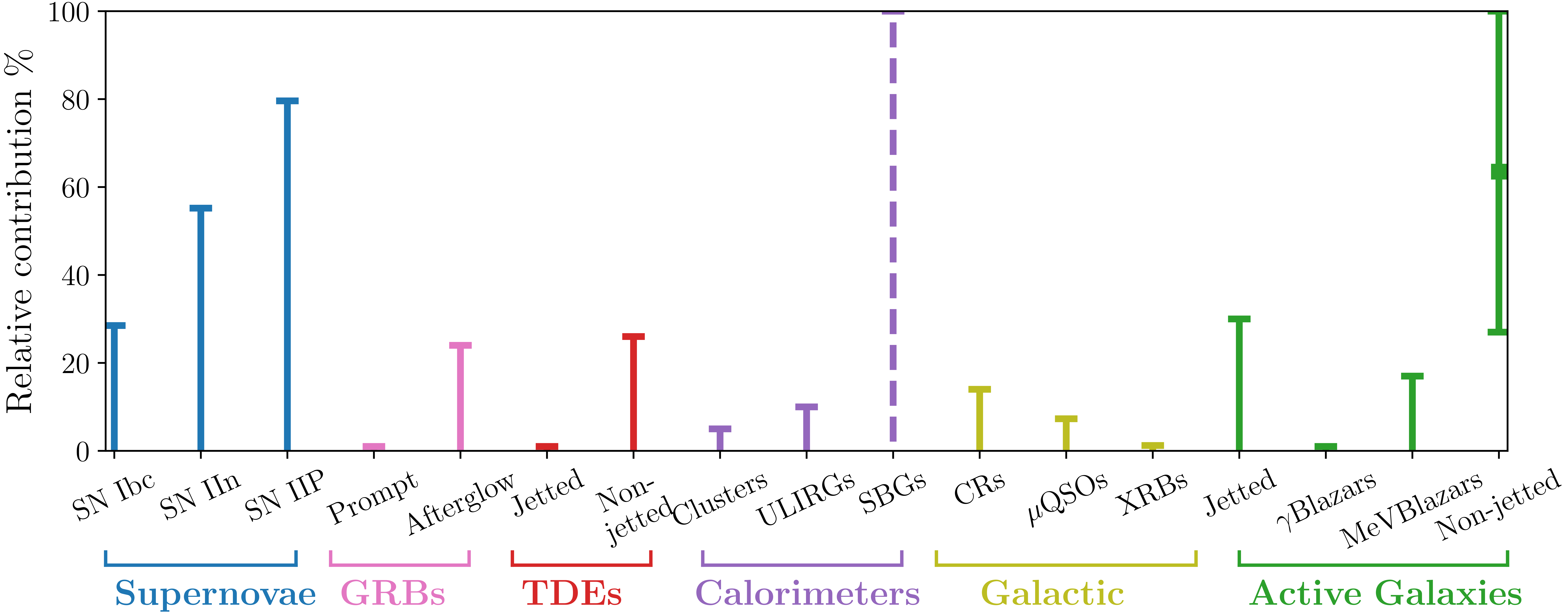




Fermi has detected >200 Galactic pulsars

The current landscape: Stacking upper limits

summary of IceCube stacking analyses results,
list of references in
FO PoS ICRC2021 (2022) 030, arXiv:2201.05623



Thank you for your attention!