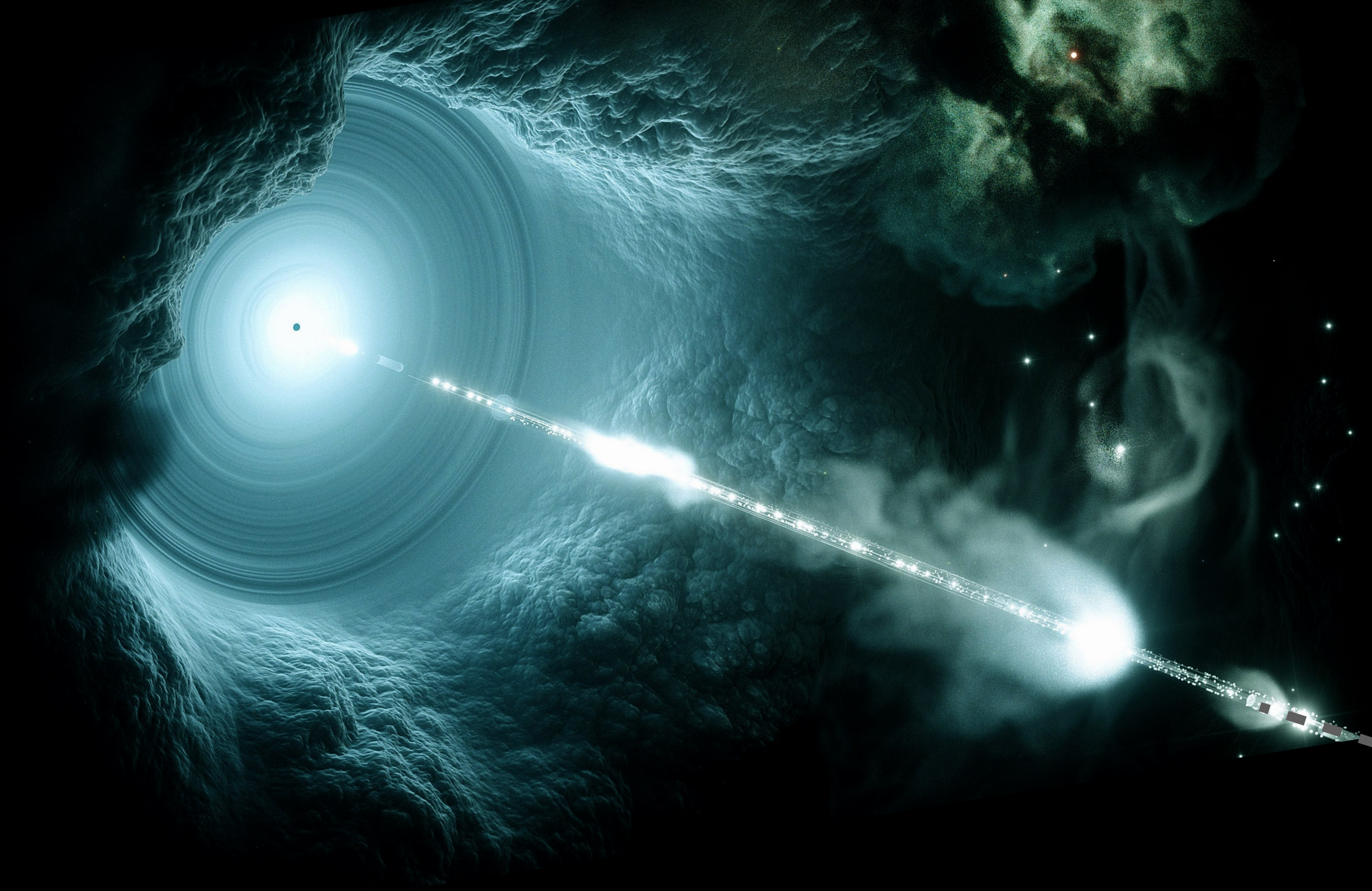
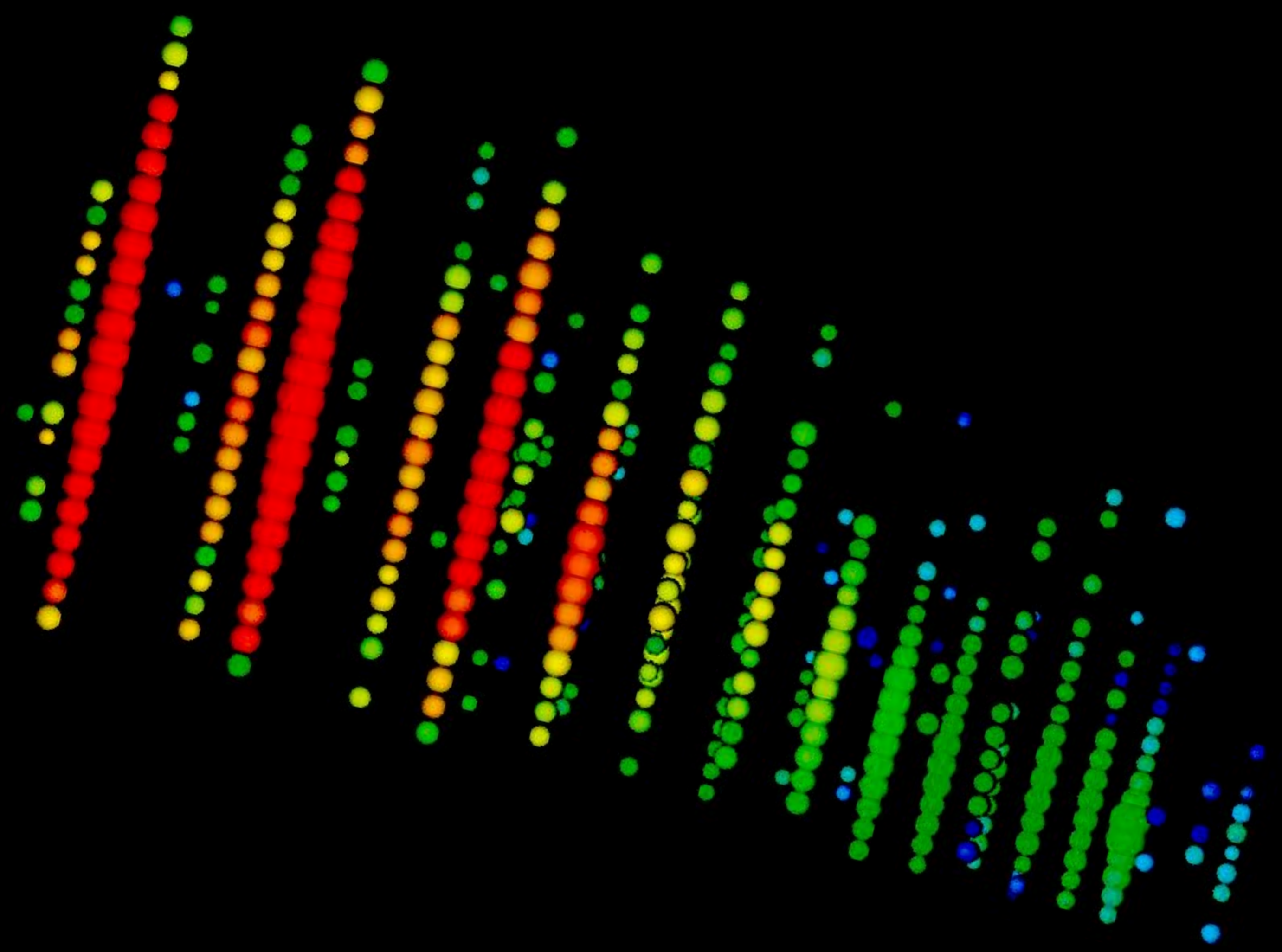




Introduction to Astroparticle Physics

Foteini Oikonomou

Bad Honnef, Tuesday 20/1/26

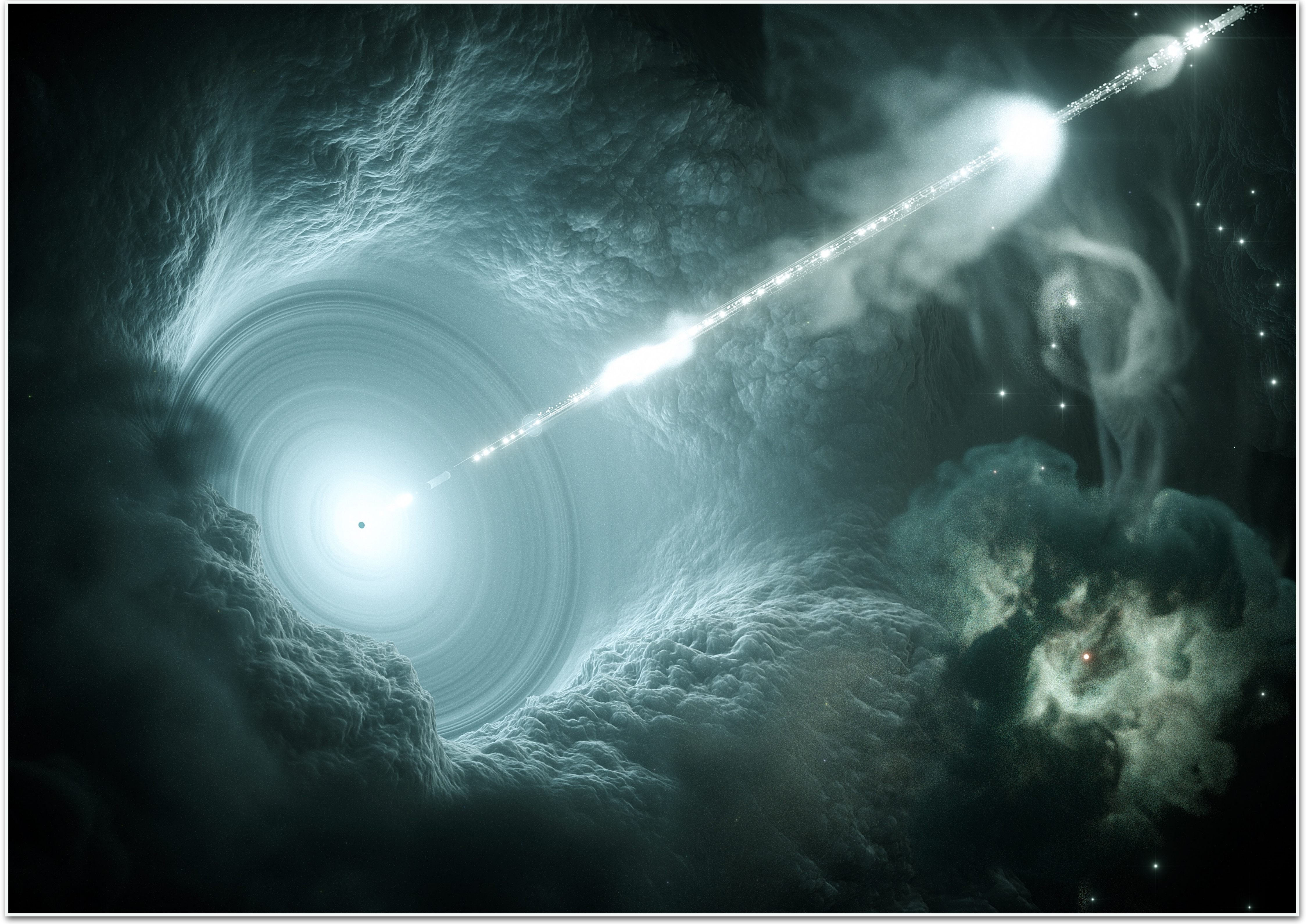
NTNU
Norwegian University of
Science and Technology

About me

Norwegian University of Science and Technology (Trondheim)

Research interests:

- Ultra-high energy cosmic rays: sources, phenomenology
- High-energy neutrinos: astrophysical origins
- Active galactic nuclei as cosmic accelerators



Contact: foteini.oikonomou@ntnu.no

Further reading

T.K. Gaisser, R. Engel & E. Resconi - Cosmic Rays and Particle Physics,
Cambridge University Press (2016)

C. Dermer & G. Menon - High-energy radiation from black holes: Gamma-rays,
Cosmic Rays, and Neutrinos,
Princeton University Press (2009)

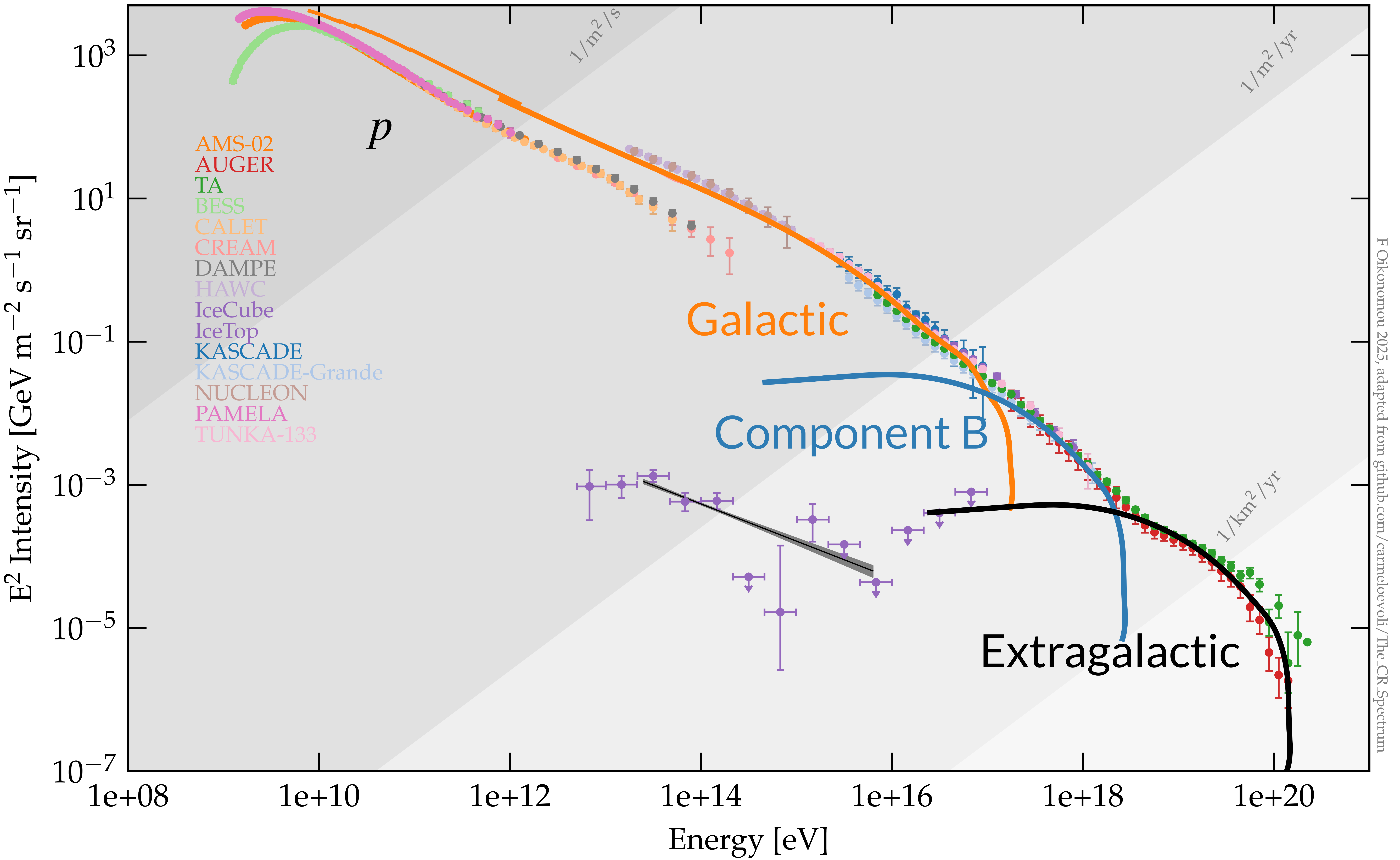
G. Ghisellini - Radiative processes in High Energy Astrophysics,
Springer (2012)
https://arxiv.org/abs/1202.5949

R. Alves-Batista et al. - Open Questions in Cosmic Ray Research at Ultrahigh
Energies. Front.Astron.Space Sci. 6 (2019) 23 arXiv:1903.06714

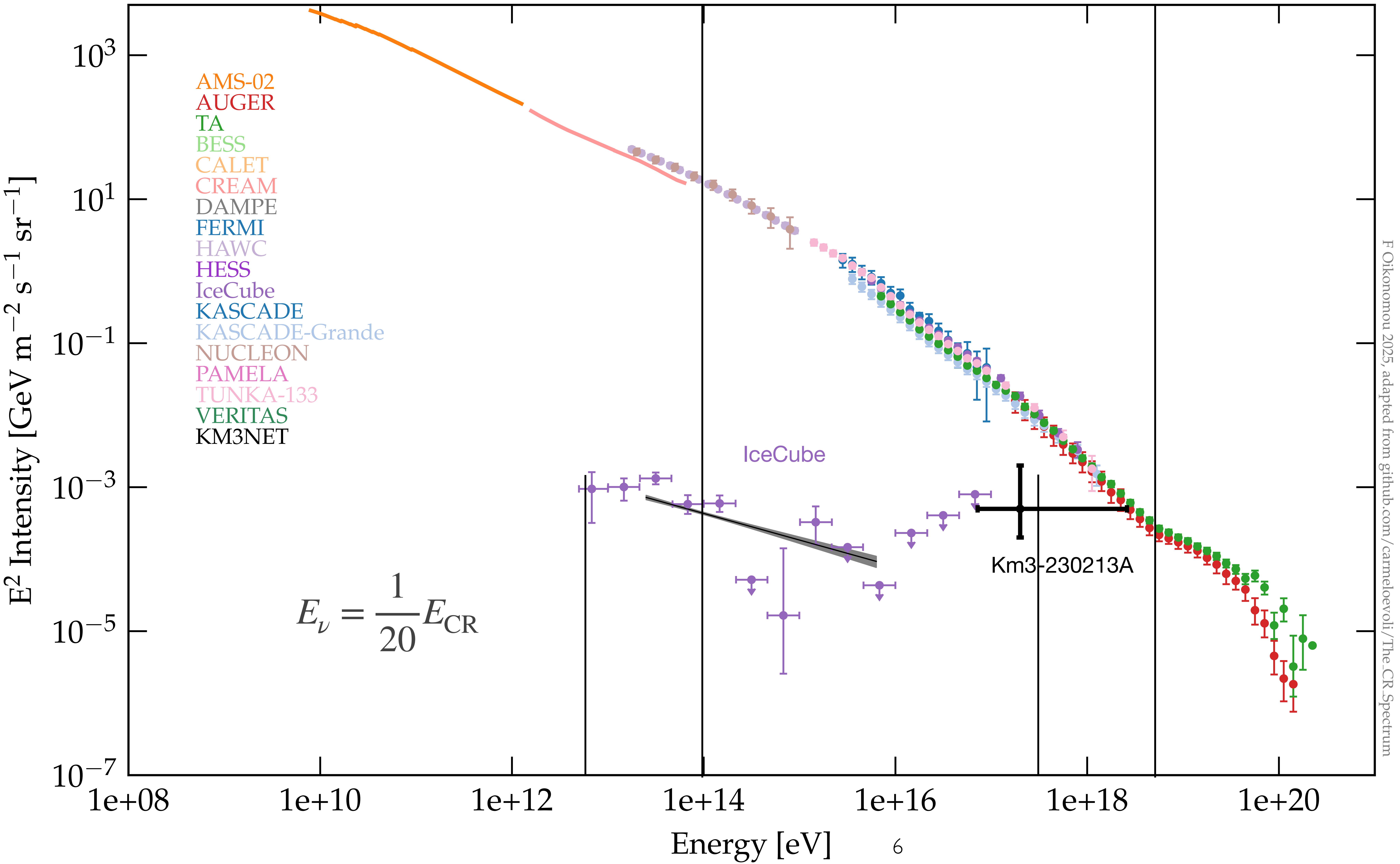
Lecture plan

- Generic source properties (number density, emissivity, maximum energy)
- Active Galactic Nuclei
- Starburst galaxies
- Gamma-ray bursts
- Tidal-disruption events

Ultra-high-energy cosmic rays

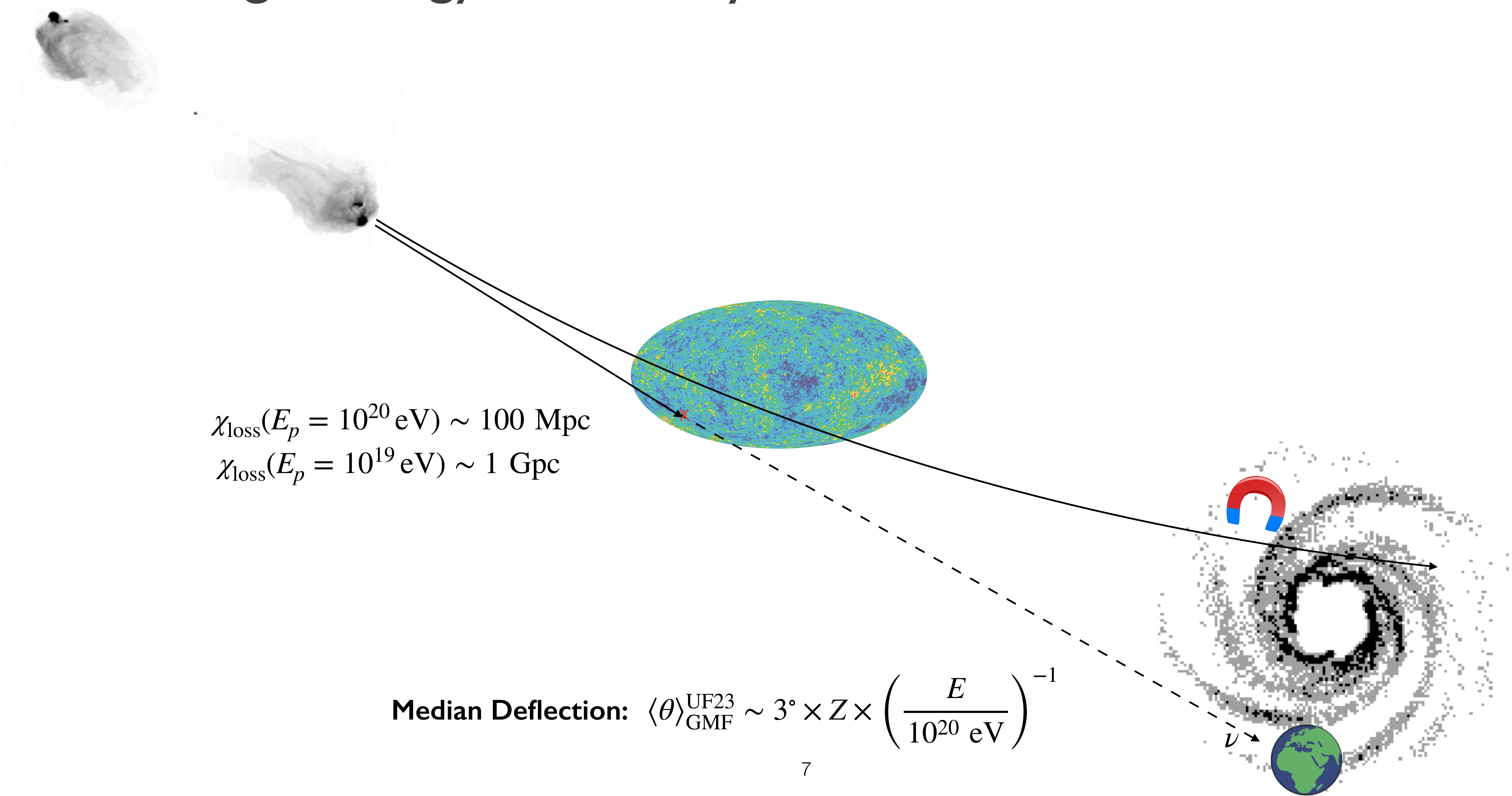


Neutrinos



AMS-02
AUGER
TA
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
IceCube
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
TUNKA-133
VERITAS
KM3NET
IceCube
Km3-230213A
$E_\nu = \frac{1}{20} E_{CR}$
E² Intensity [GeV m⁻² s⁻¹ sr⁻¹]
Energy [eV]
1e+08
1e+10
1e+12
1e+14
1e+16
1e+18
1e+20
F Oikonomou 2025, adapted from github.com/carmeloevoli/The_CR_Spectrum

Ultra-high-energy cosmic rays

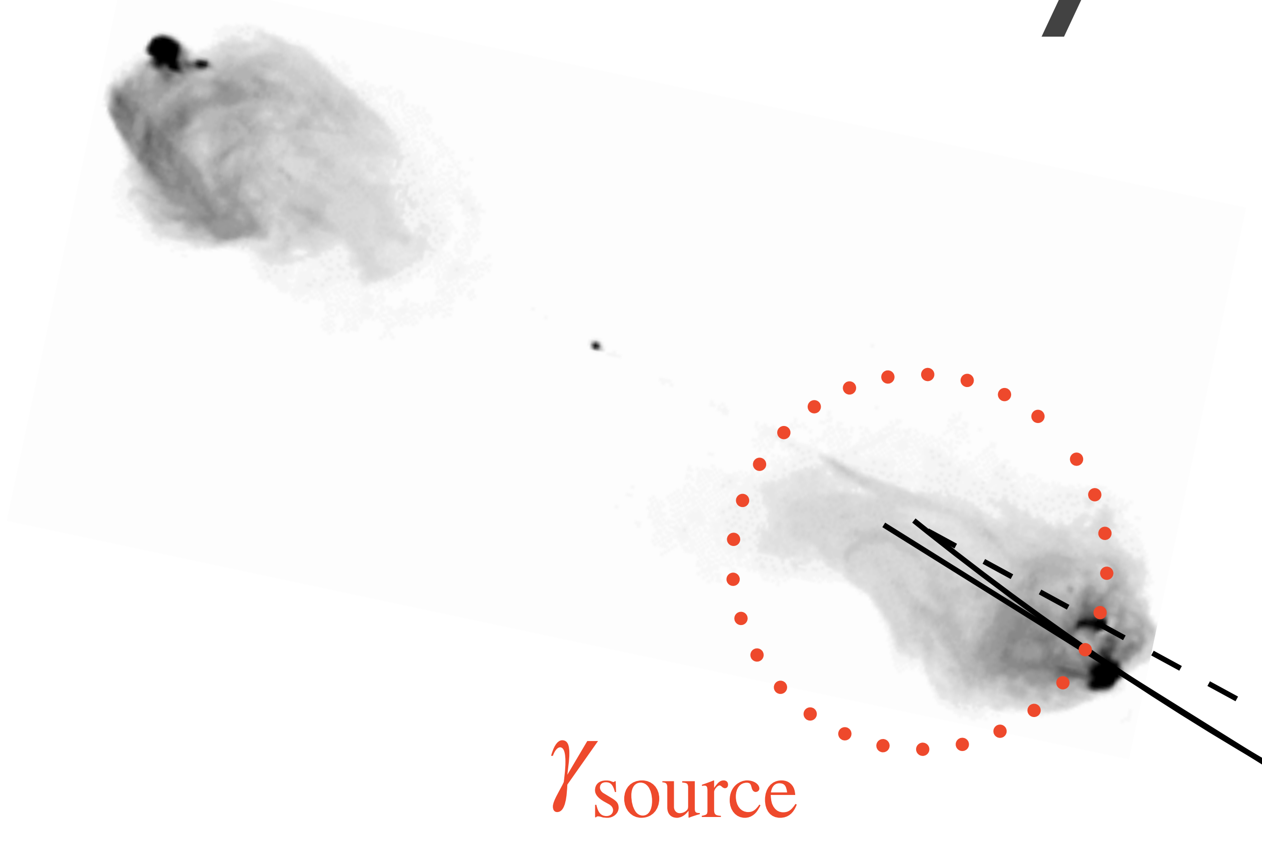


$\chi_{\mathrm{loss}}(E_p = 10^{20}\,\mathrm{eV}) \sim 100\ \mathrm{Mpc}$

$\chi_{\mathrm{loss}}(E_p = 10^{19}\,\mathrm{eV}) \sim 1\ \mathrm{Gpc}$

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

Secondary messengers



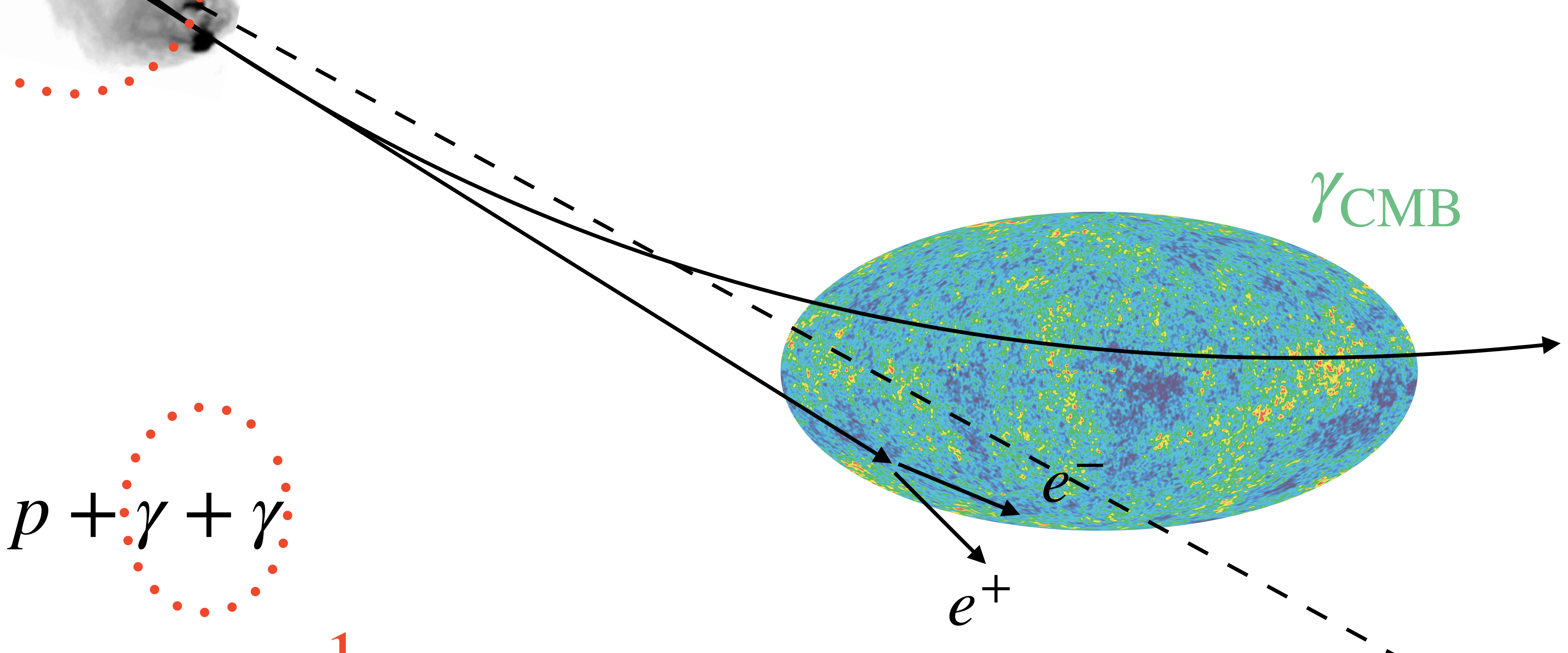
$$p + \gamma_{\mathrm{CMB/source}} \rightarrow p + e^{+} + e^{-}$$

$$p + \gamma_{\mathrm{CMB/source}} \rightarrow n + \pi^{+} \rightarrow n + \mu^{+} + \nu_{\mu} \rightarrow n + e^{+} + \nu_{e} + \nu_{\mu} + \bar{\nu}_{e}$$

"Greisen, Zatzepin, Kuzmin" process

neutrinos!

$$E_{\nu} = \frac{1}{20} E_{\mathrm{proton}}$$



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

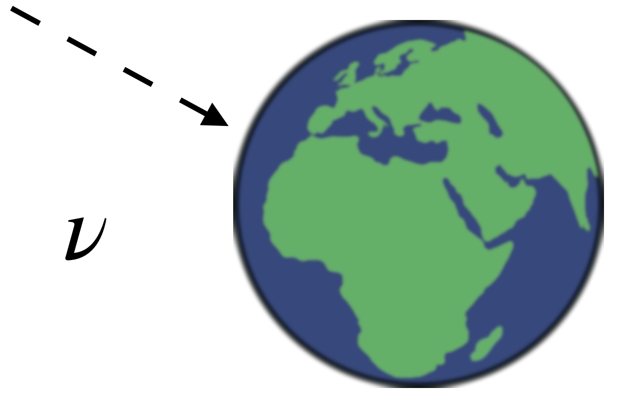
$$E_{\gamma} = \frac{1}{10} E_{\mathrm{proton}}$$

Averaged branching ratio,

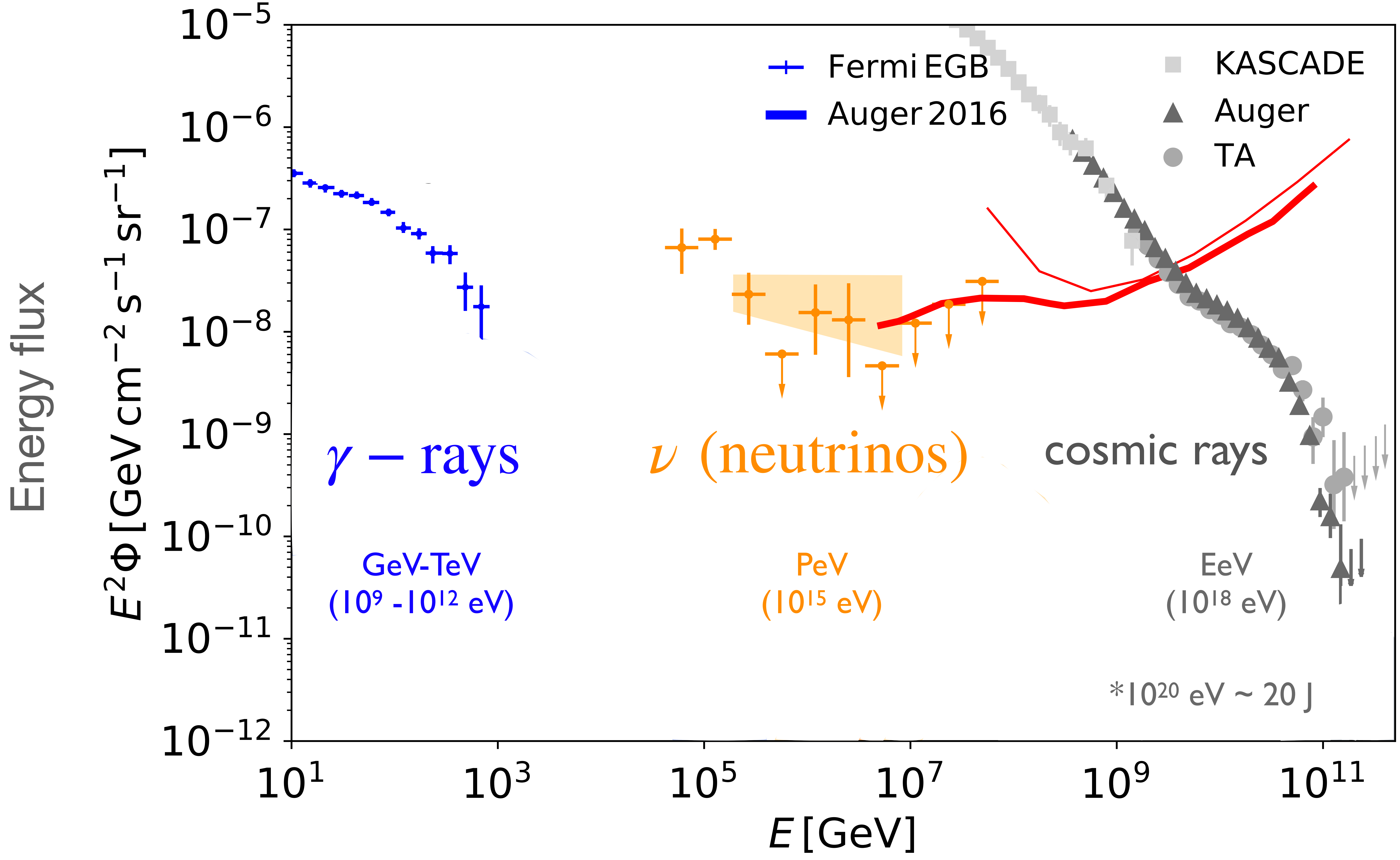
$$R_{\pi} = \frac{\Gamma(\rightarrow \pi^{+/-})}{\Gamma(\rightarrow \pi^{0})} \sim 1$$

Relative gamma-ray/neutrino energy flux:

$$E_{\nu}^{2} \frac{\mathrm{d}N}{\mathrm{d}E_{\nu}} = \frac{3}{4} E_{\gamma}^{2} \frac{\mathrm{d}N}{\mathrm{d}E_{\gamma}} \Big|_{E_{\gamma} = 2E_{\nu}}$$



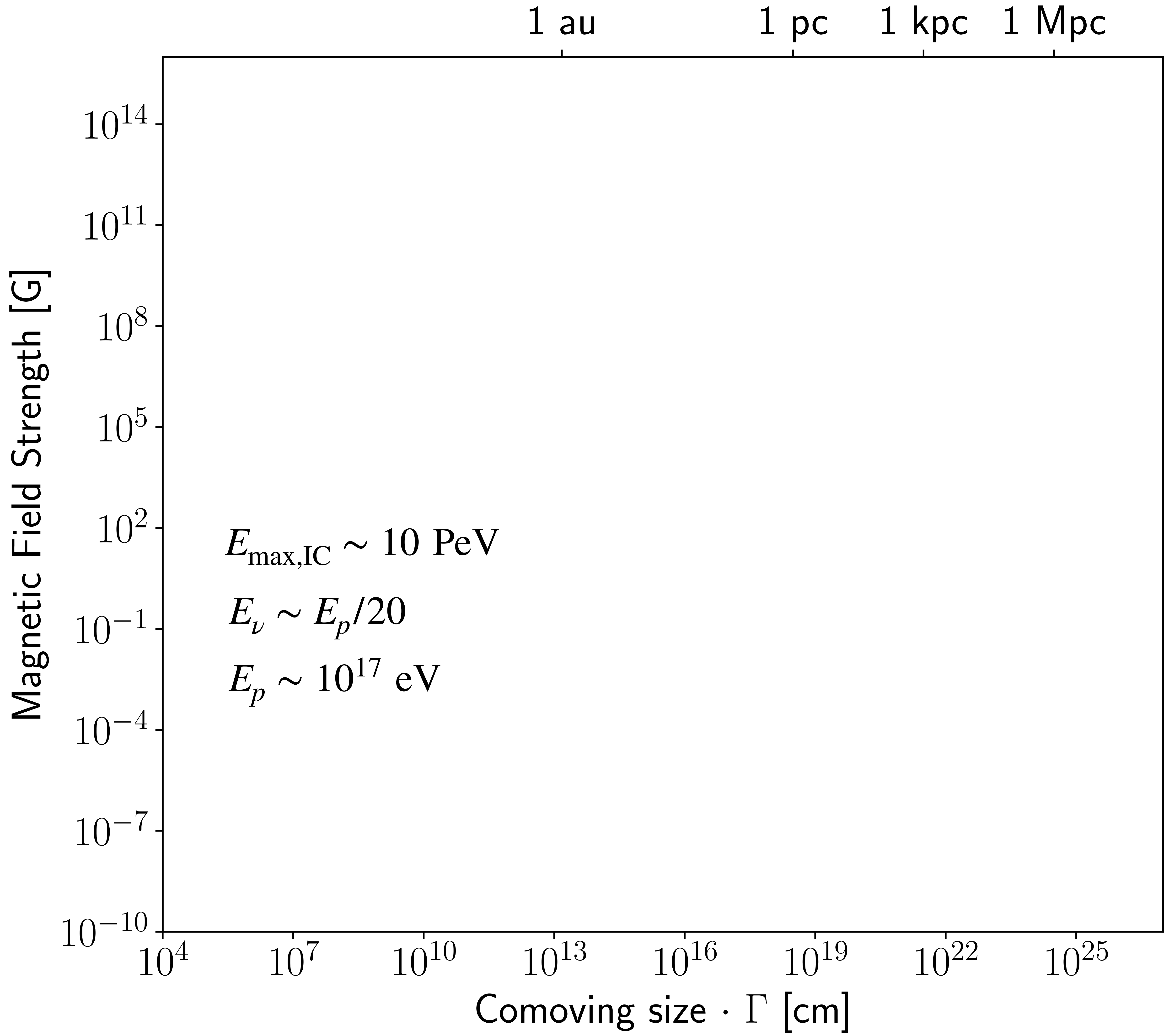
Multimessenger diffuse fluxes



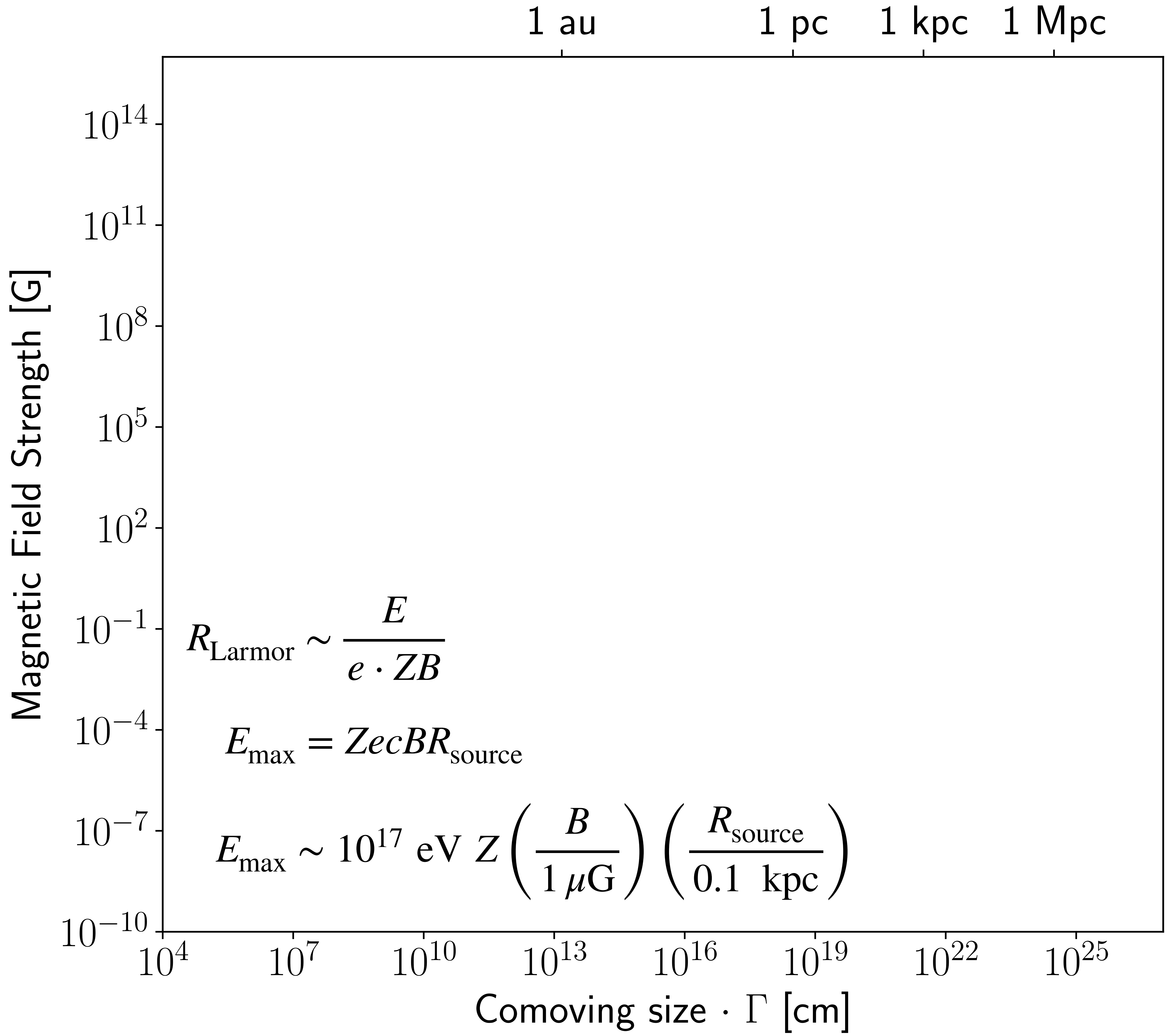
Generic source properties

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

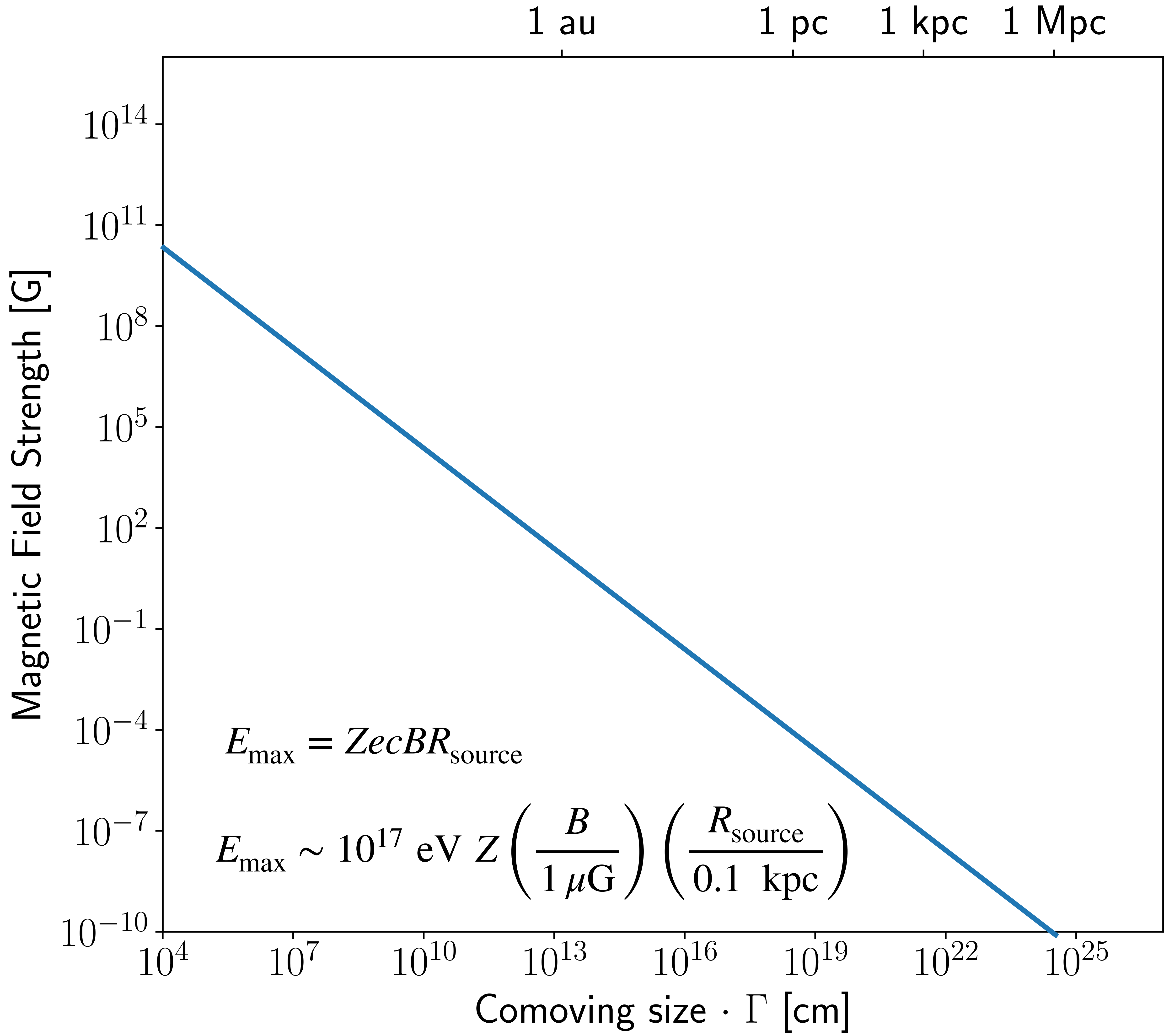
Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)



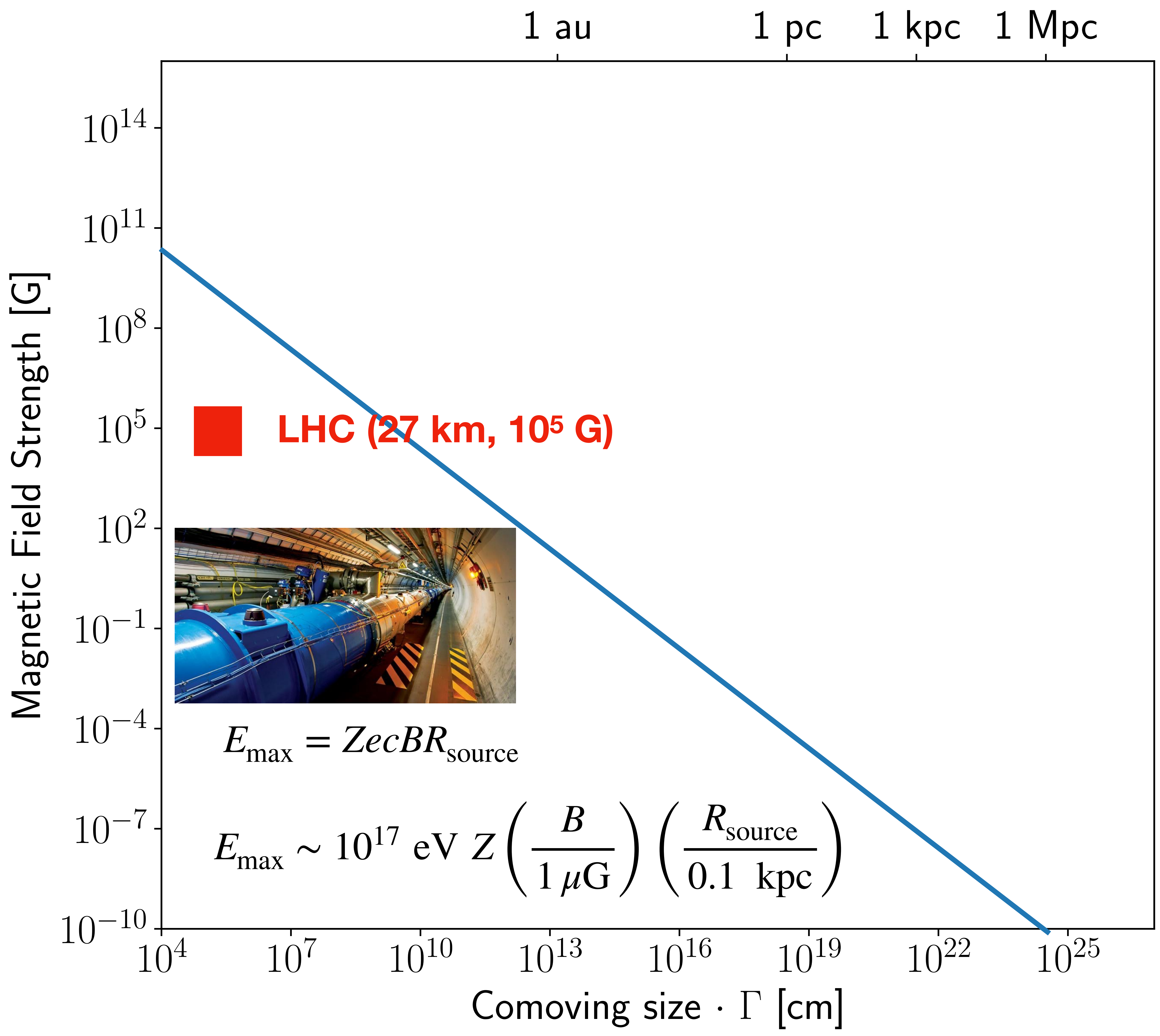
Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)



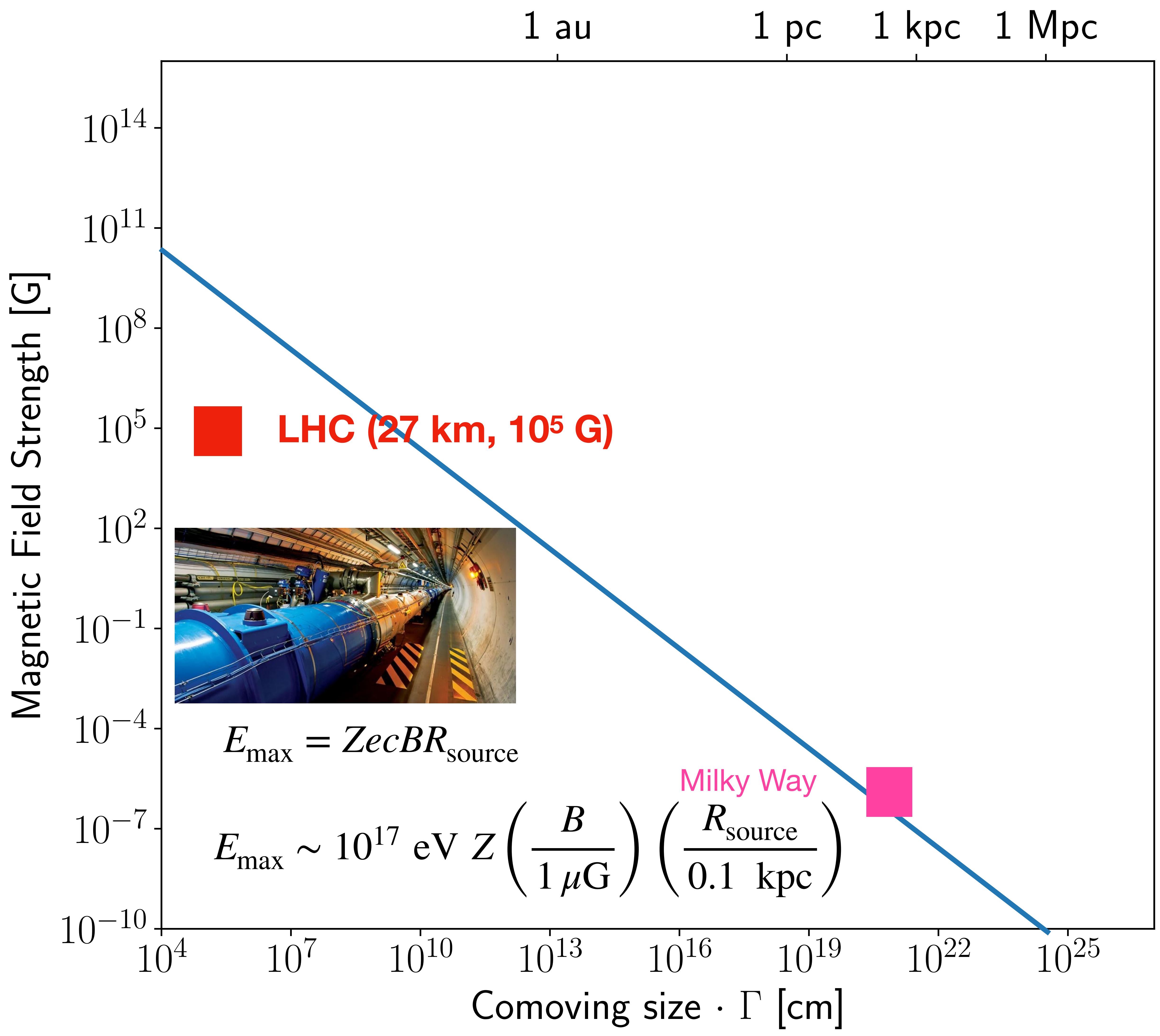
Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)



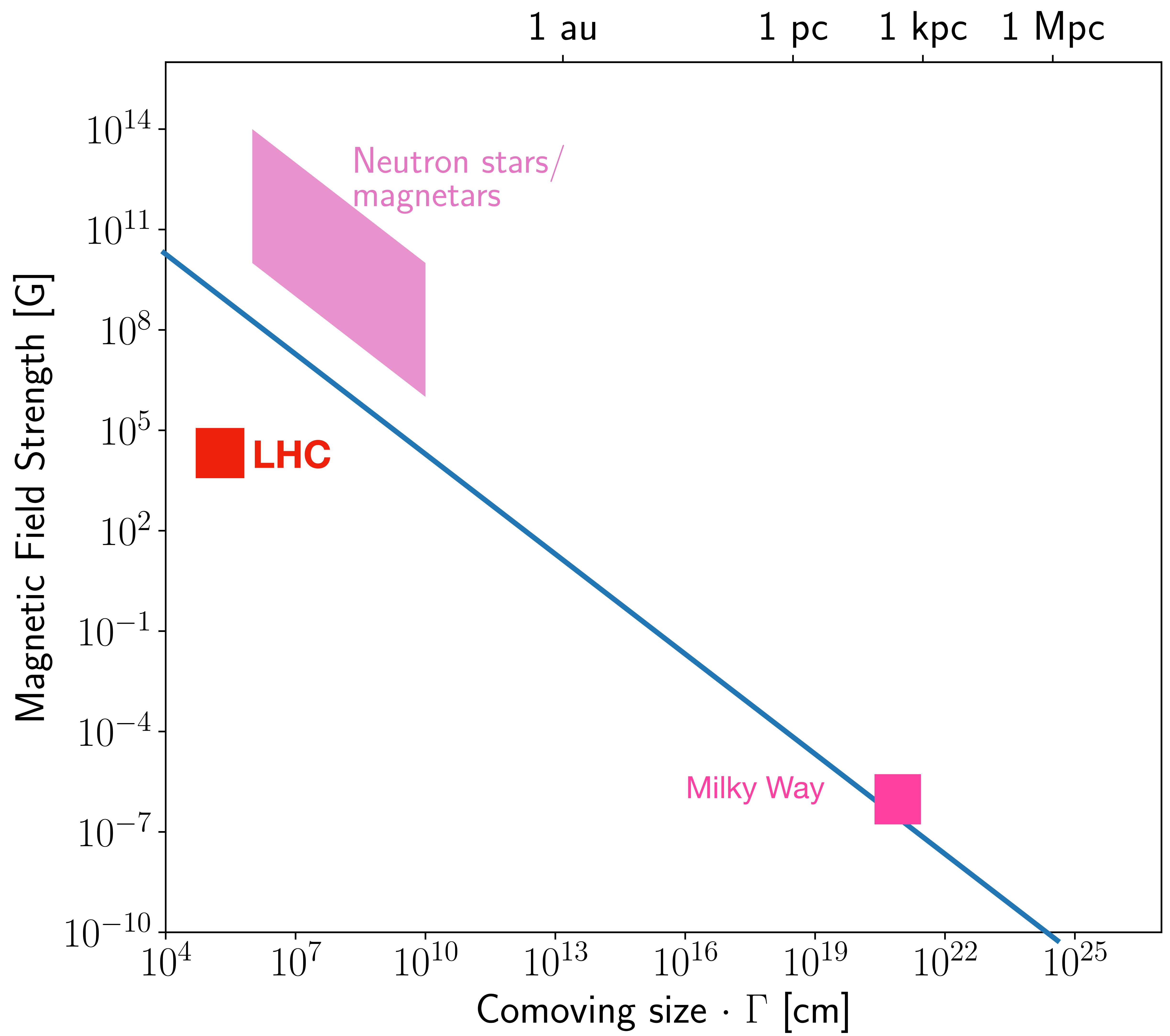
Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)



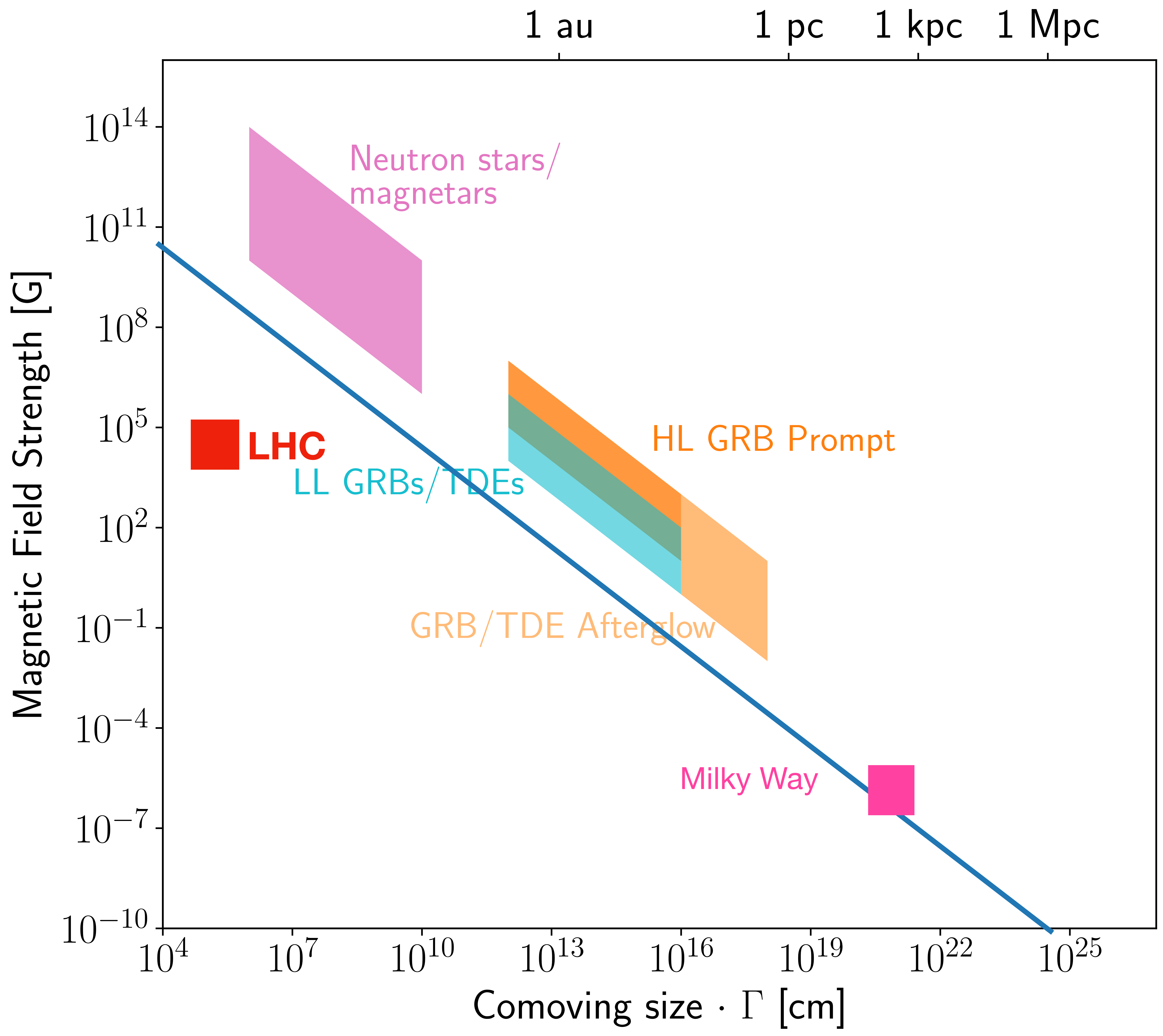
Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)

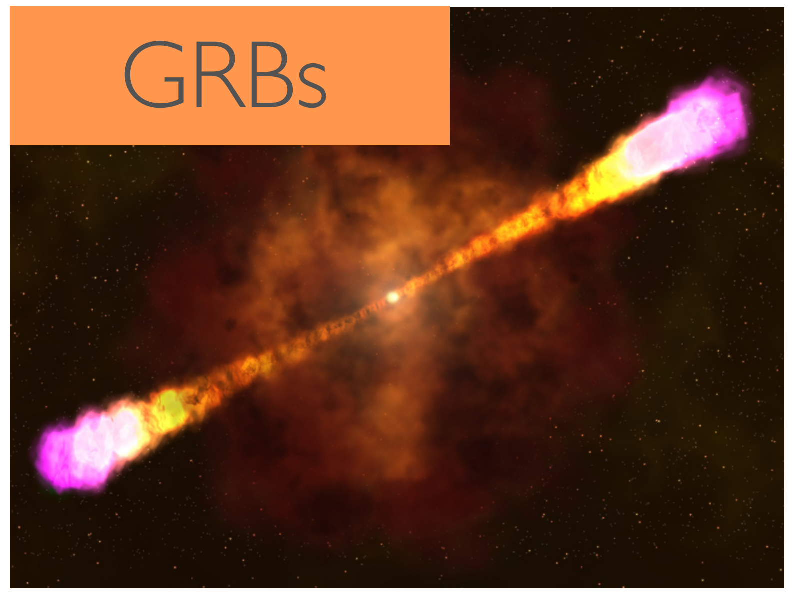


Cosmic-ray accelerators that satisfy the confinement req ... ^{17} eV)

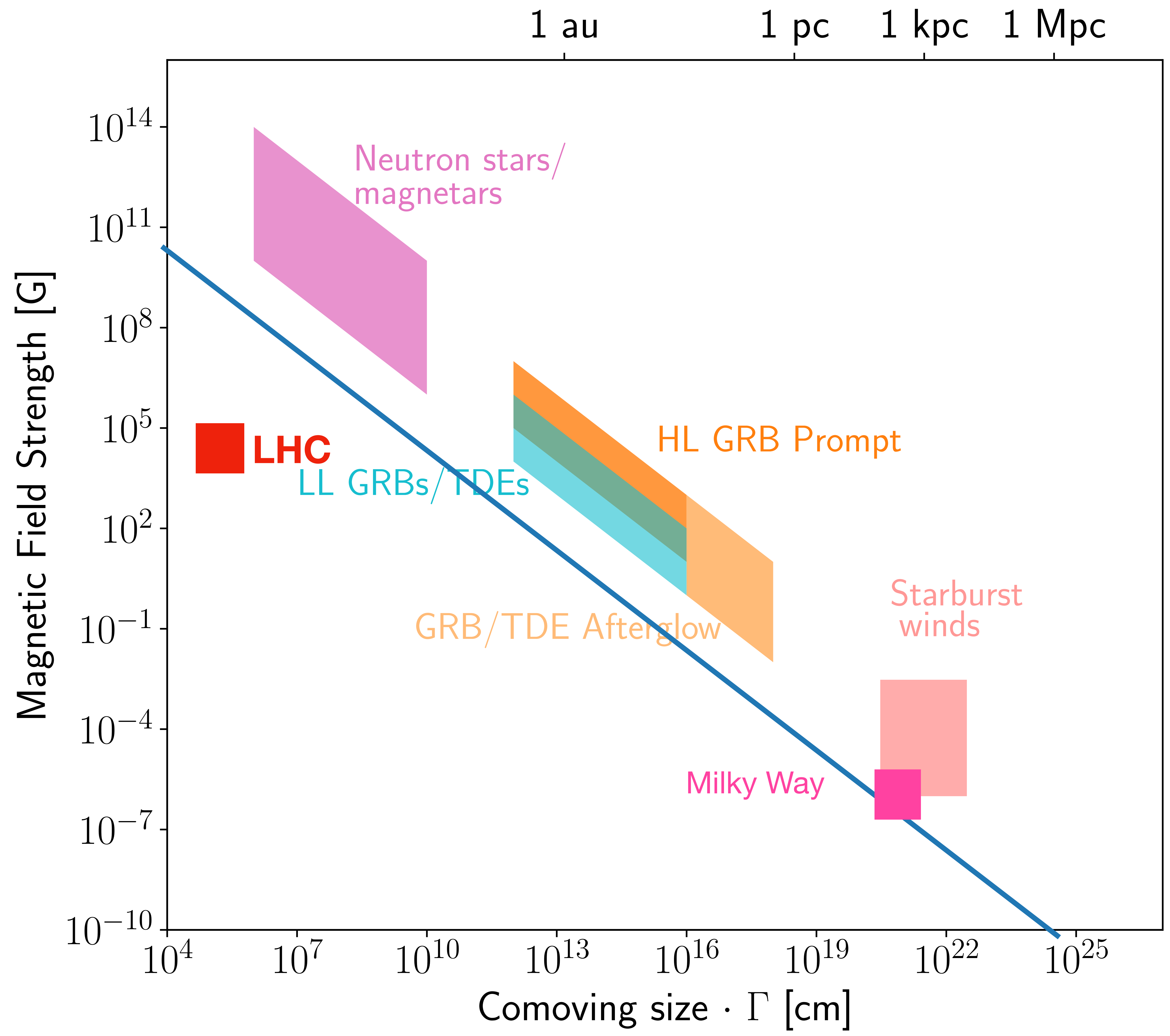


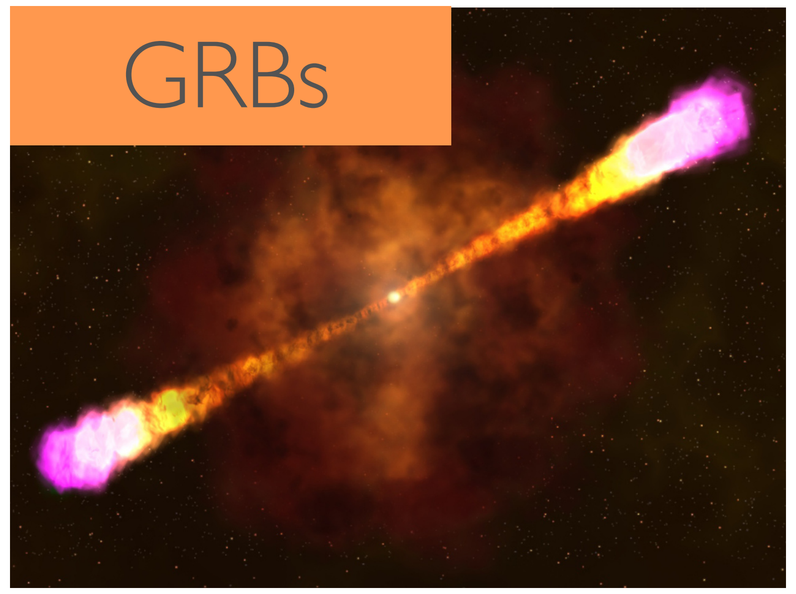
Cosmic-ray accelerators that satisfy the confinement req… ^{17} eV)



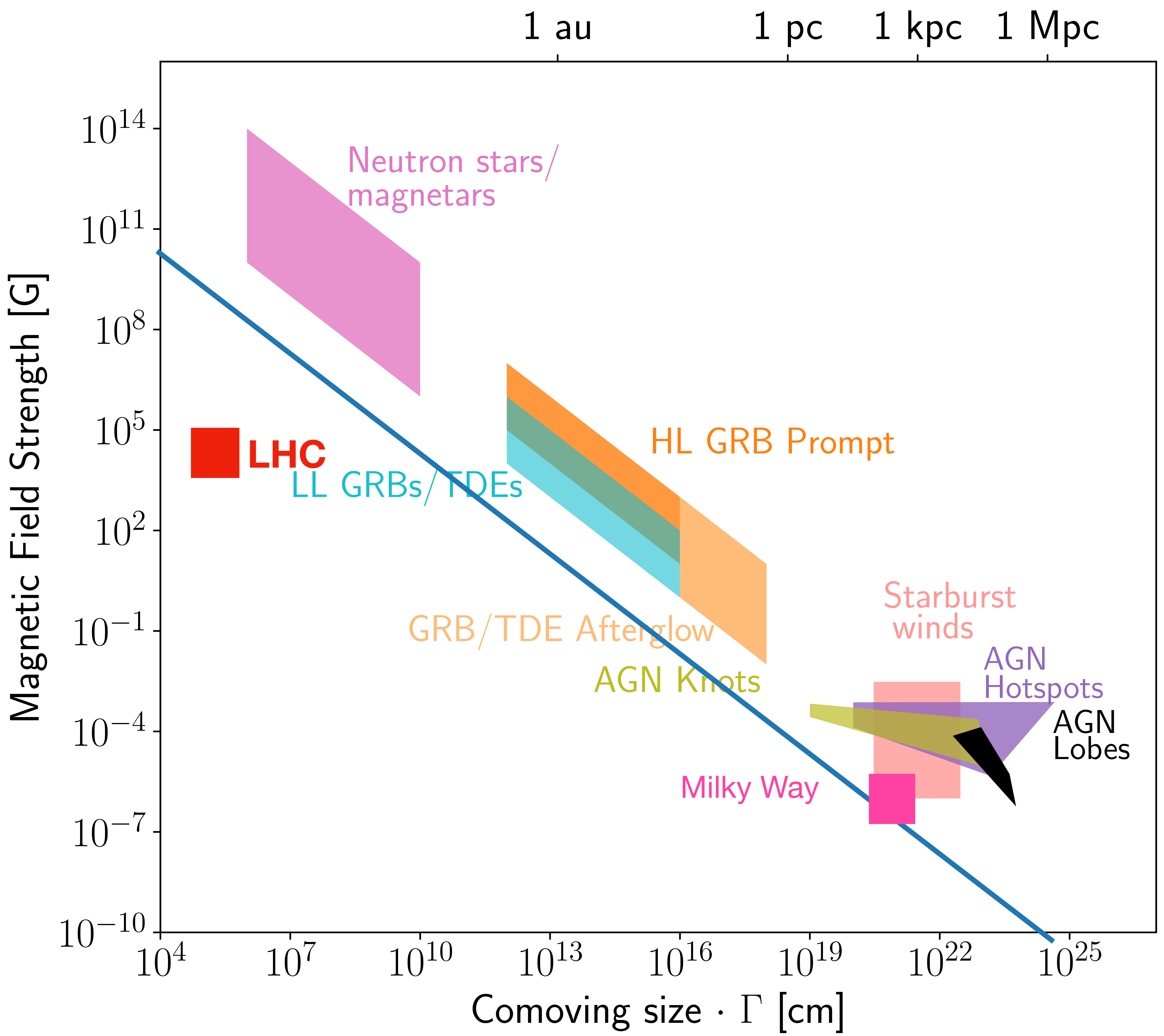


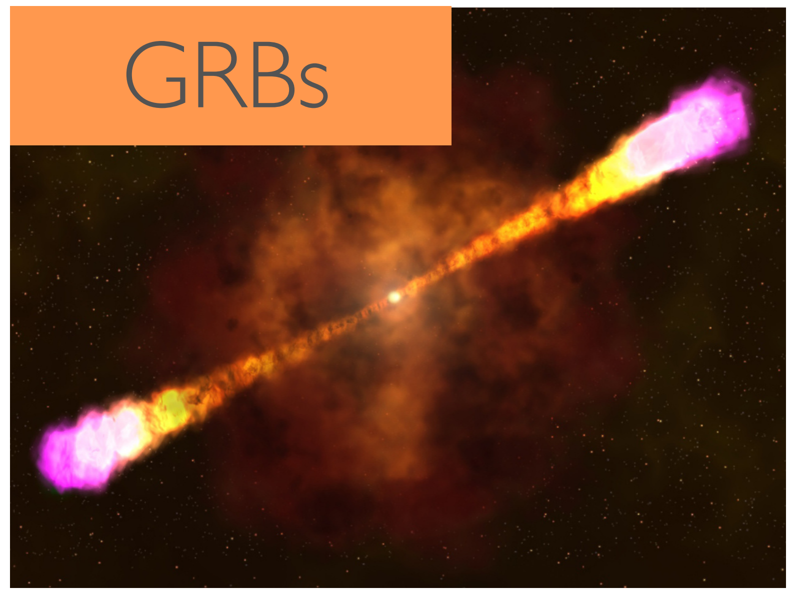
Cosmic-ray accelerators that satisfy the confinement req … ^{17} eV)

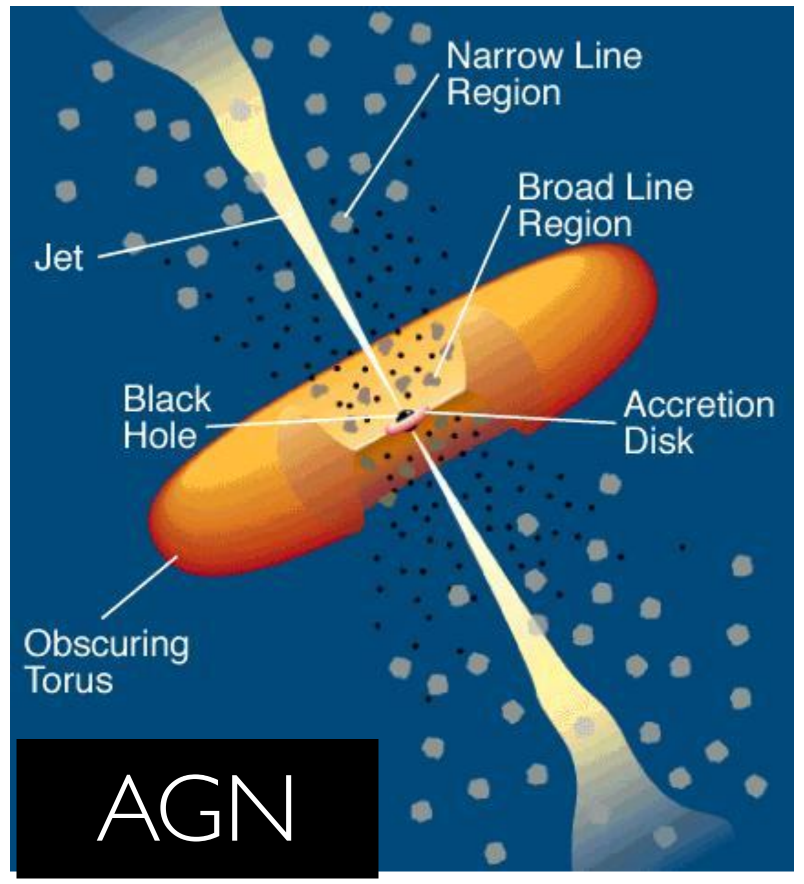




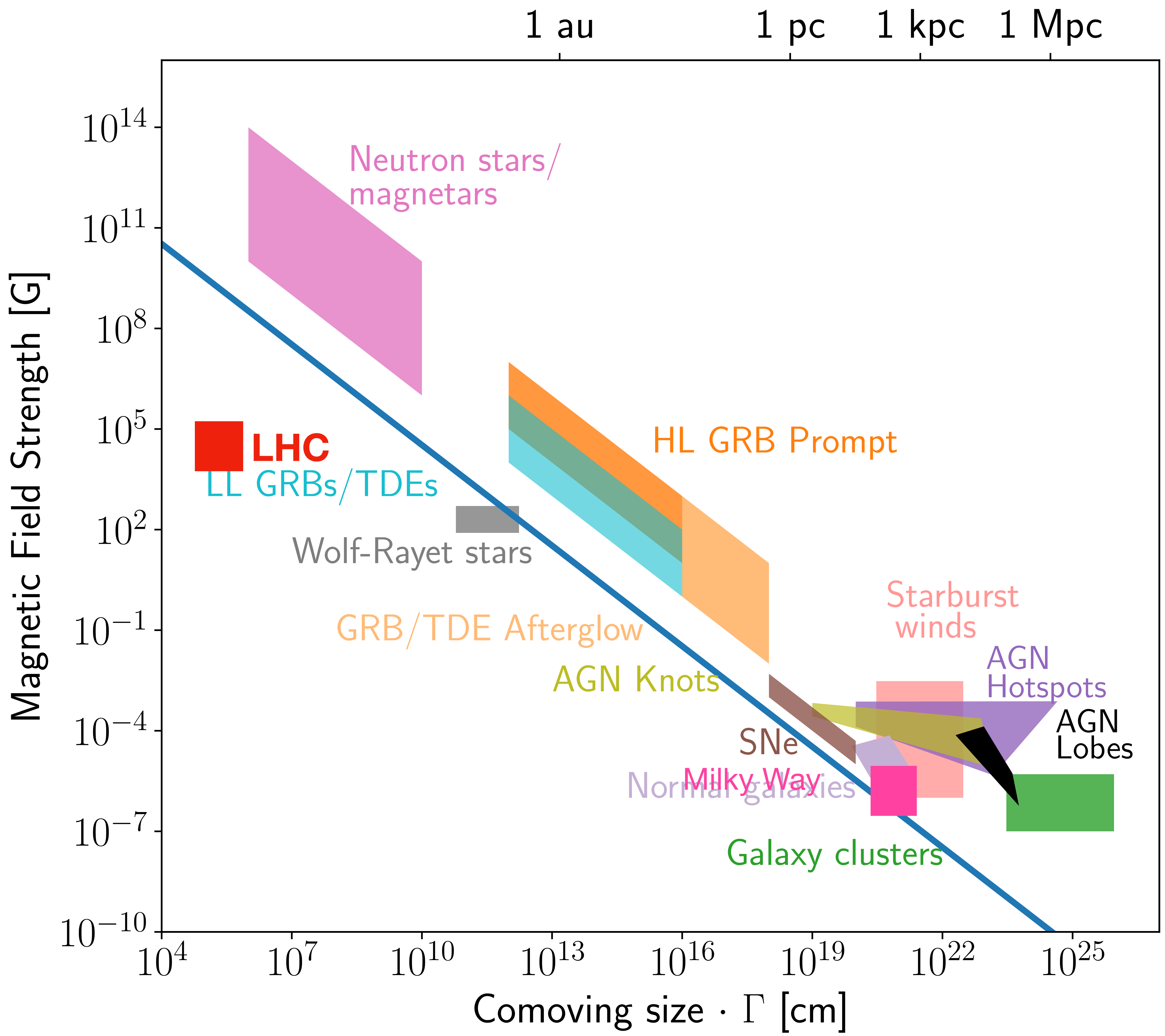
Cosmic-ray accelerators that satisfy the confinement req ... 17 eV)

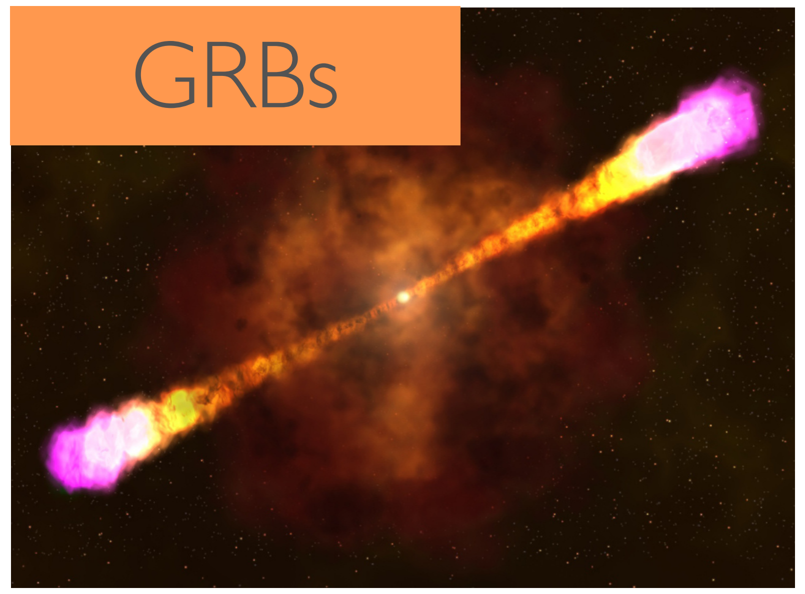


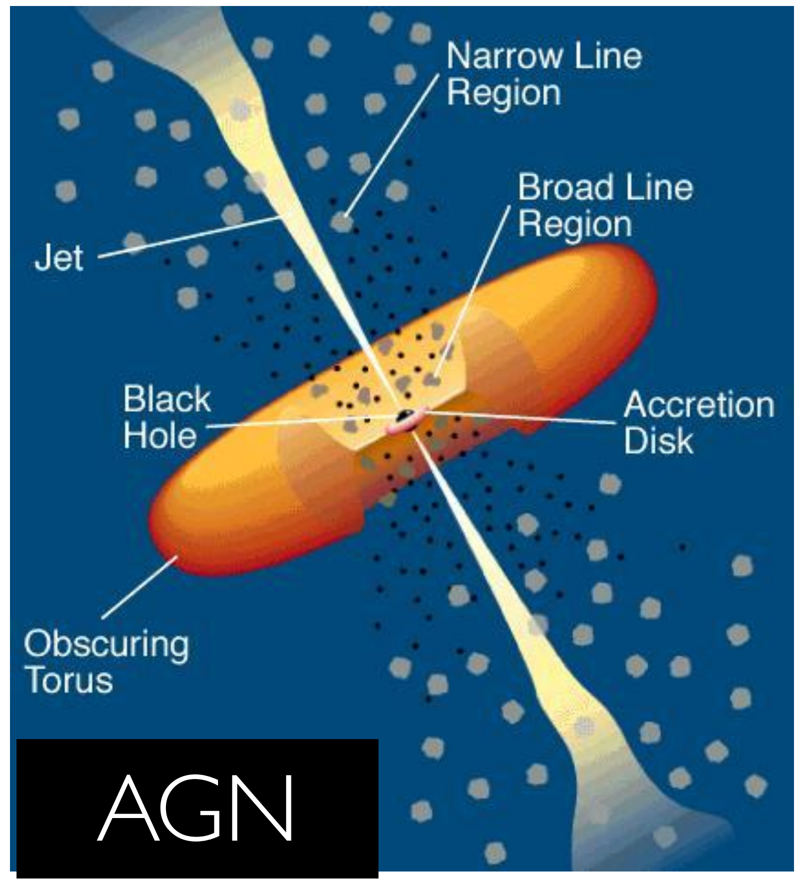




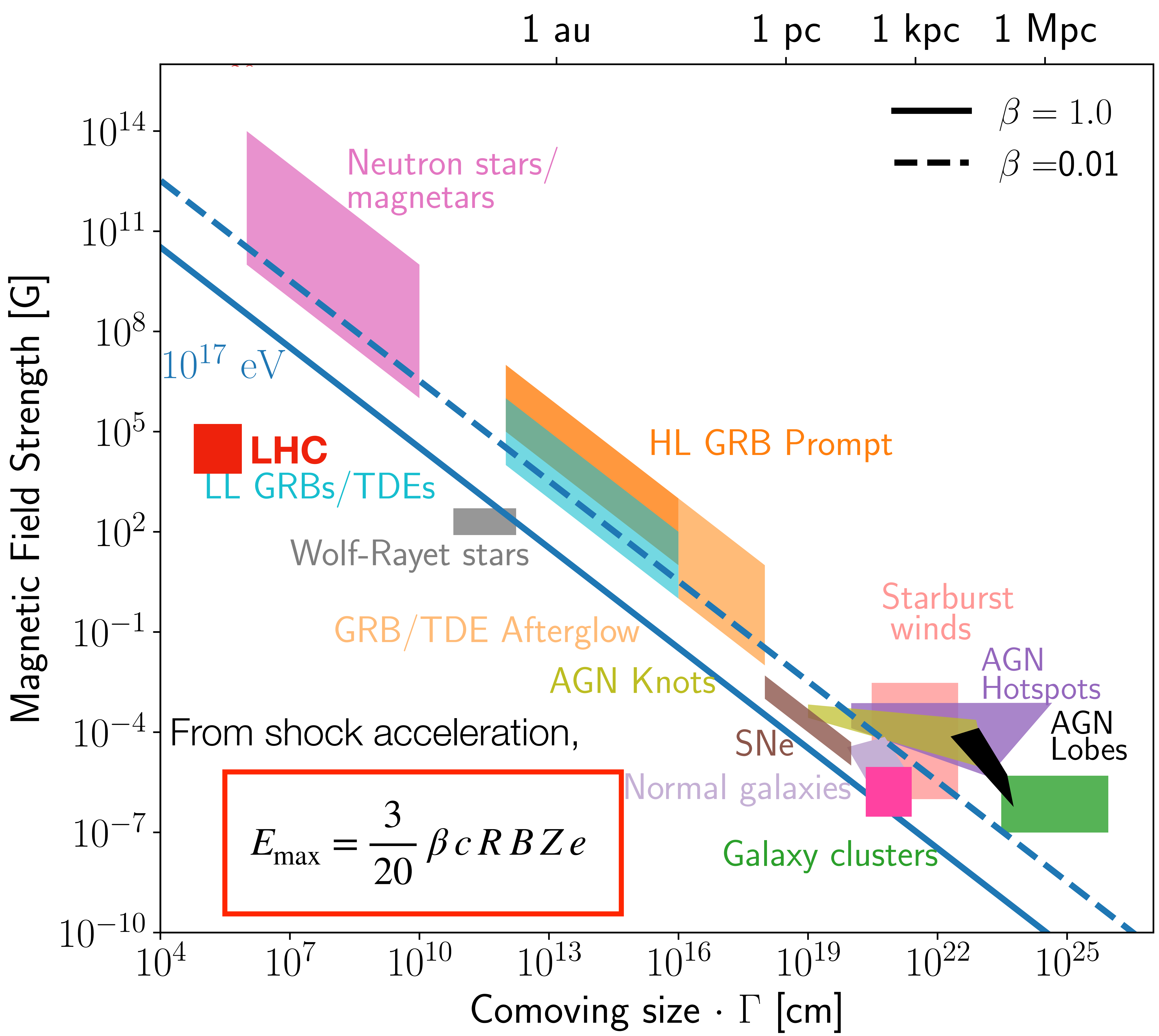
Cosmic-ray accelerators that satisfy the confinement req ... 17 eV)

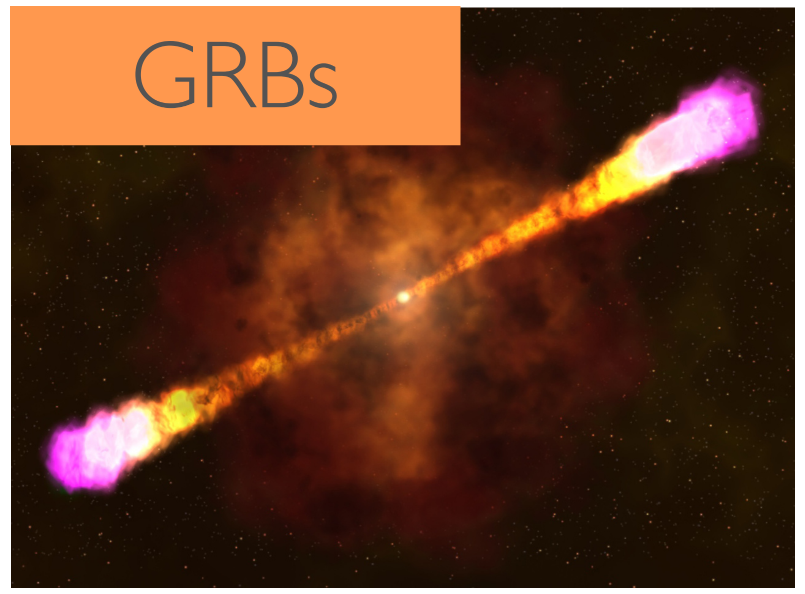


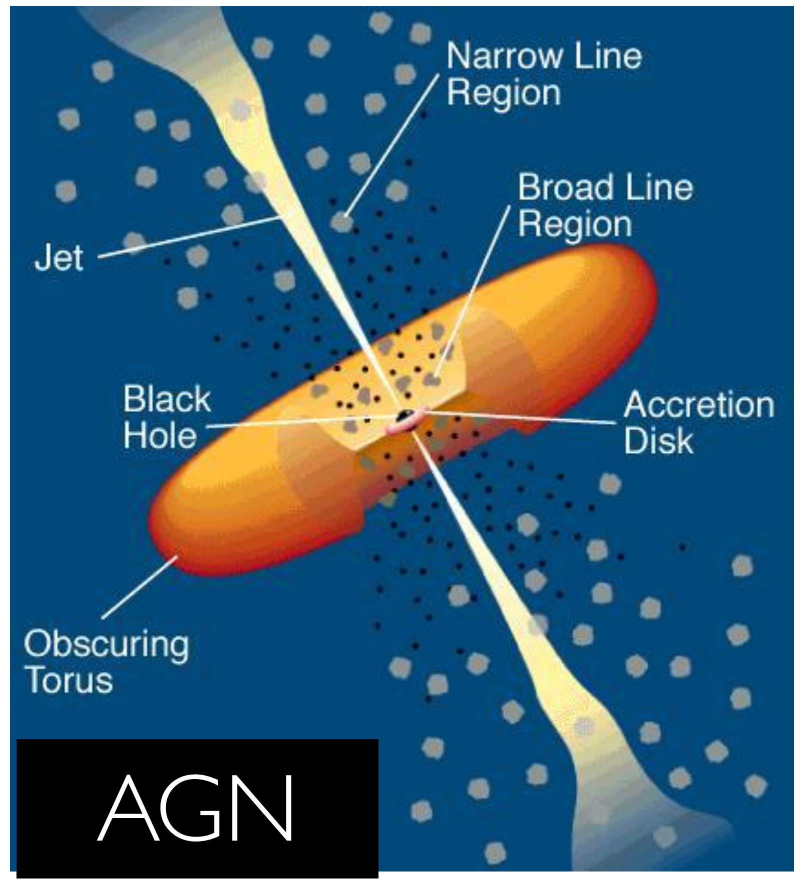




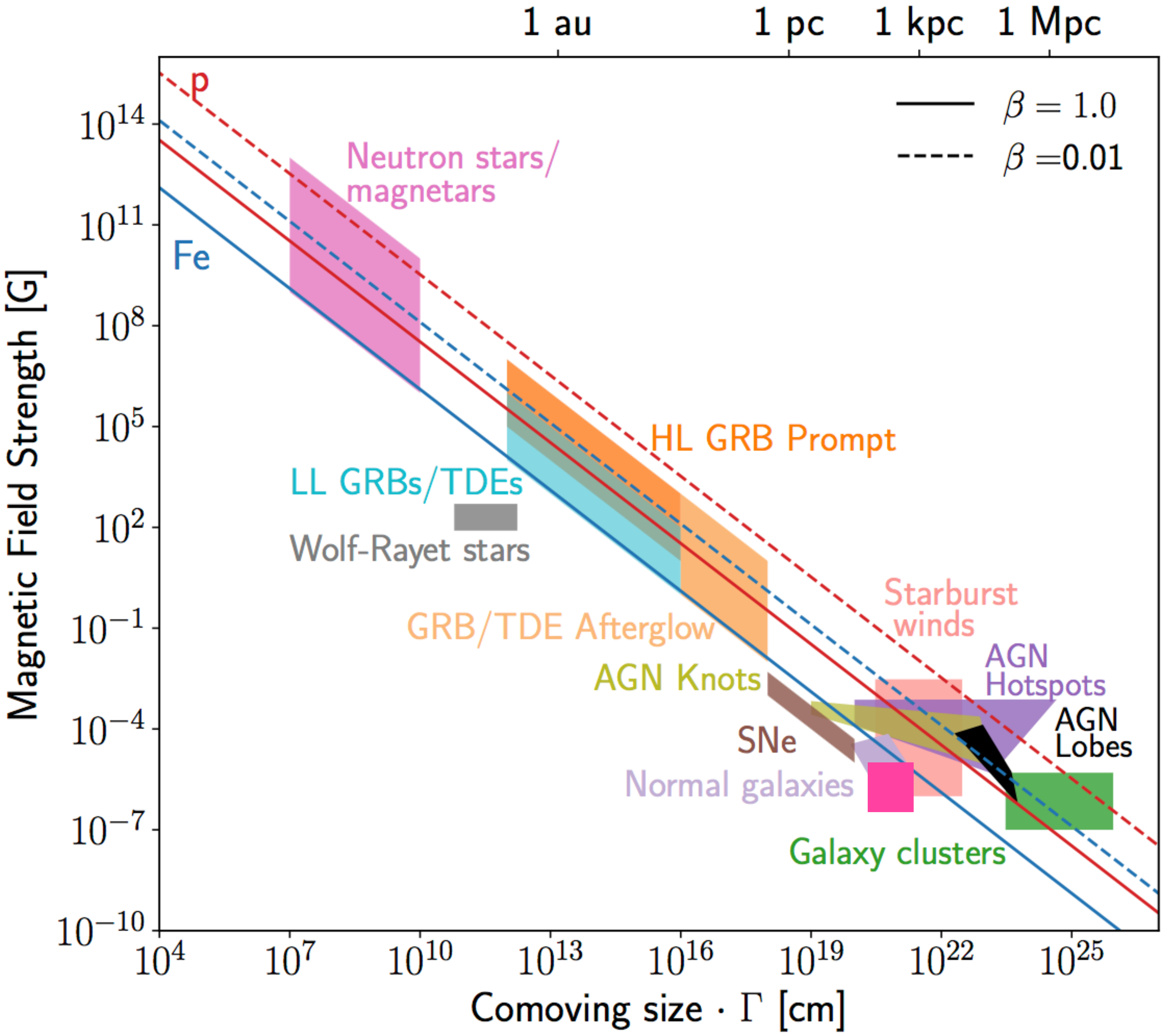
Cosmic-ray accelerators that satisfy the confinement req… ^{17} eV)

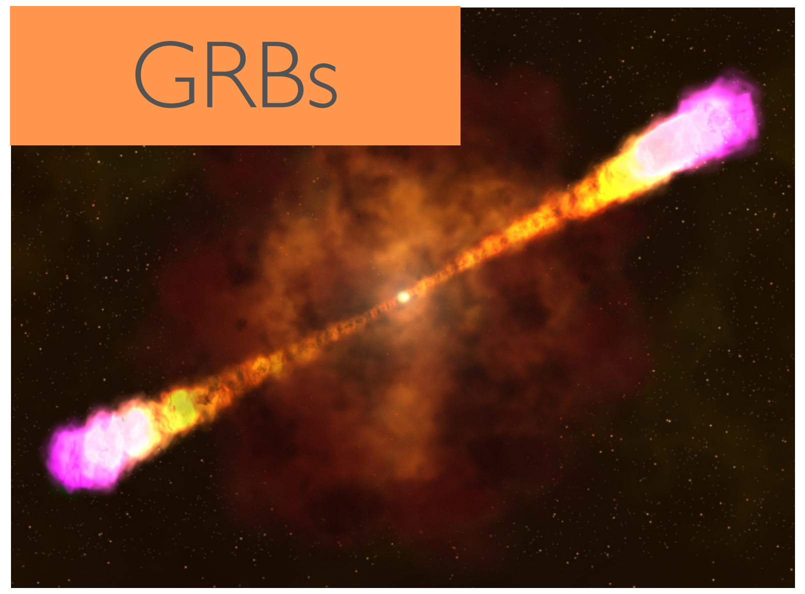


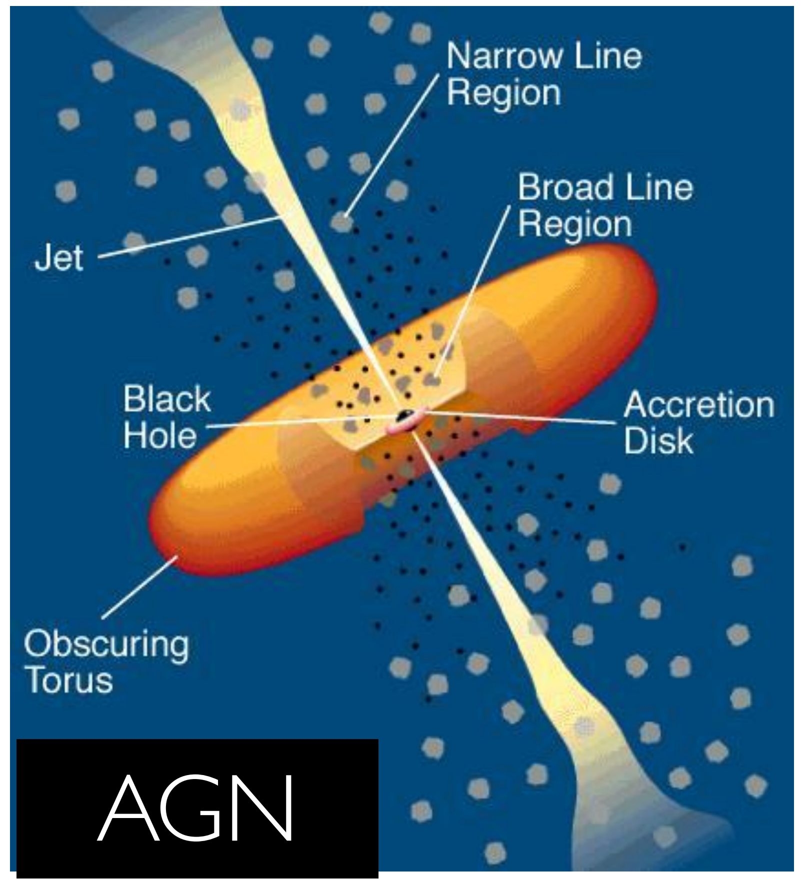




Hillas criterion for 10^{20} eV CRs



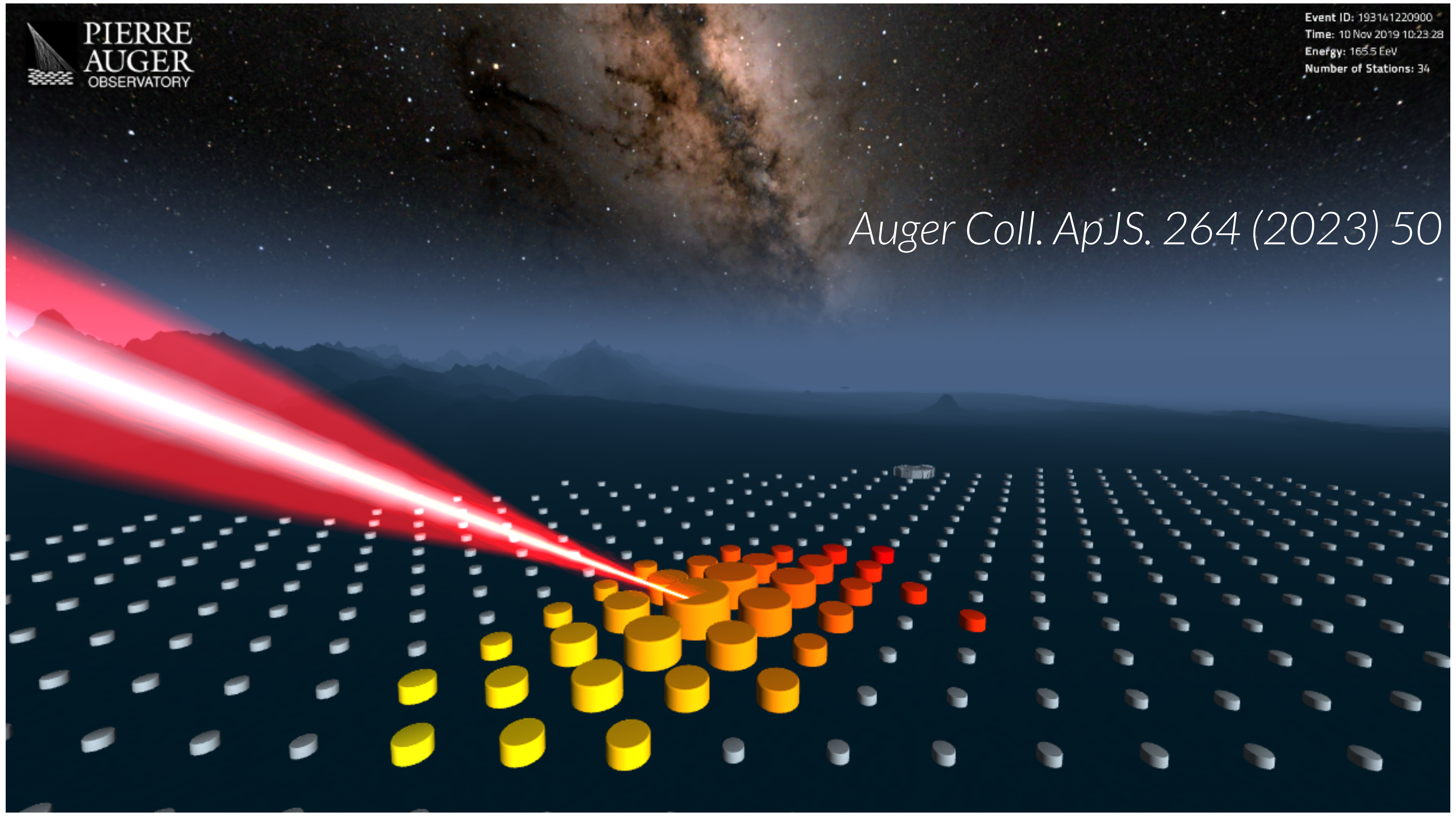




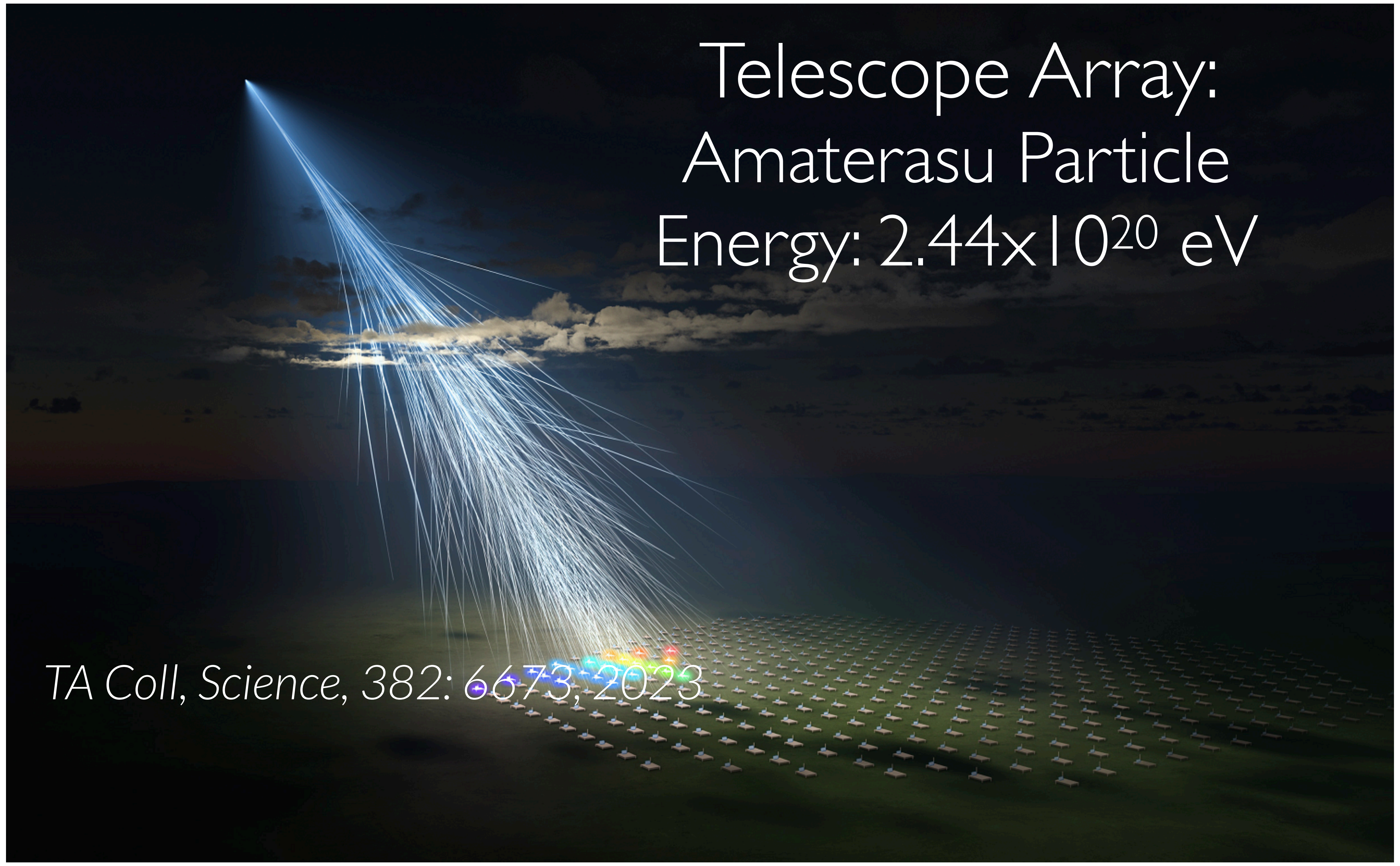
Generic source properties

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

Lower limit on the number density of UHECR sources

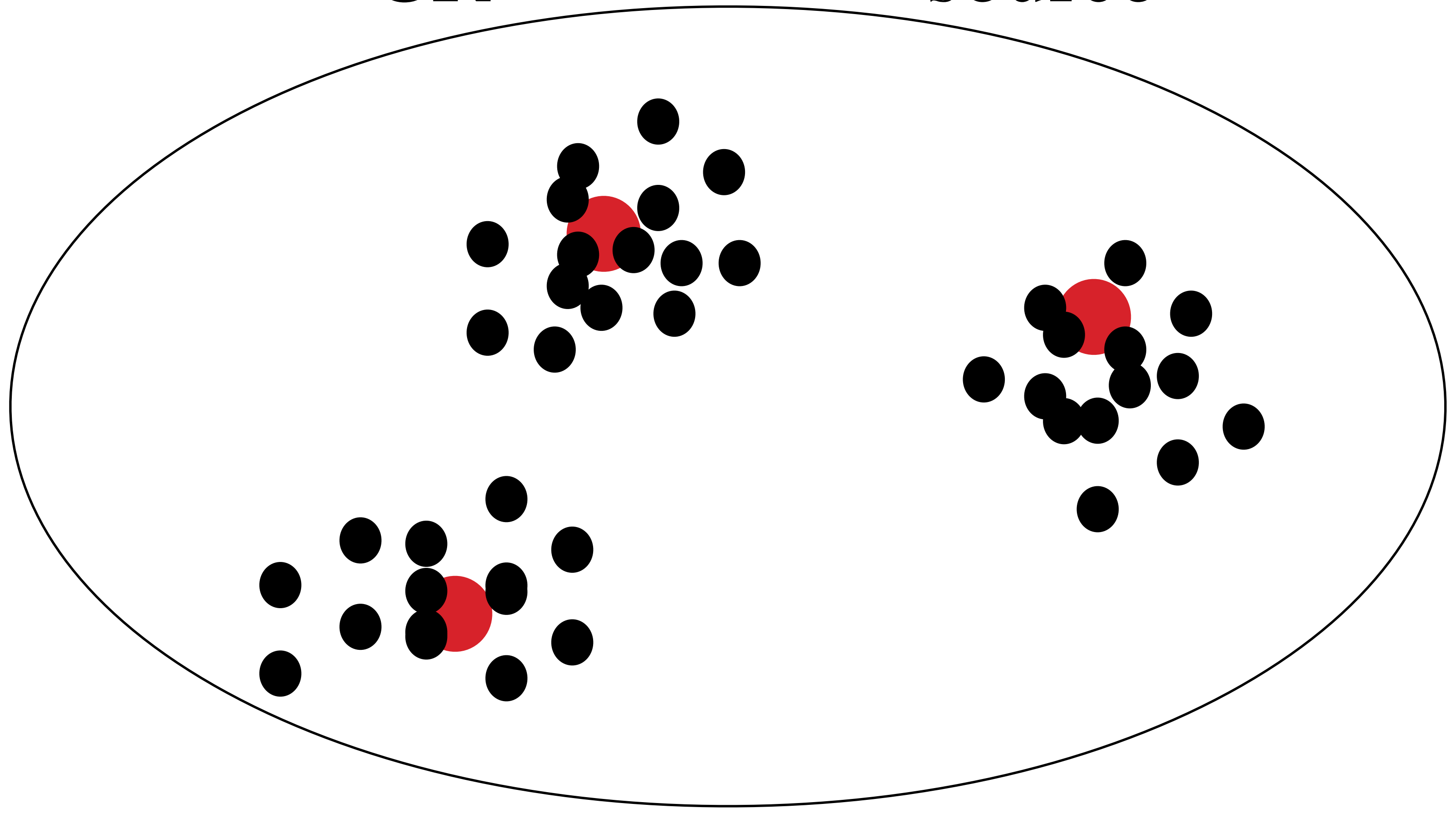


Pierre Auger Observatory:
50,000 UHECRs above 8×10^{18} eV
40 UHECRs above 10^{20} eV



Lower limit on the number density of UHECR sources

$$N_{CR} = 43,\ N_{source} = 3$$



The absence of doublets of UHECRs gives a lower limit to the source number density:

The expected number of events from each source (assuming equal fluxes) is:

$$n_* = N_{CR}/N_{sources}$$

The Poisson probability to see 0 events from a source is

$$P(0) = e^{-n_*}\frac{n_*^0}{0!} = e^{-n_*}$$

The Poisson probability to see 1 event from a source is

$$P(1) = e^{-n_*}\frac{n_*}{1!} = e^{-n_*}n_*$$

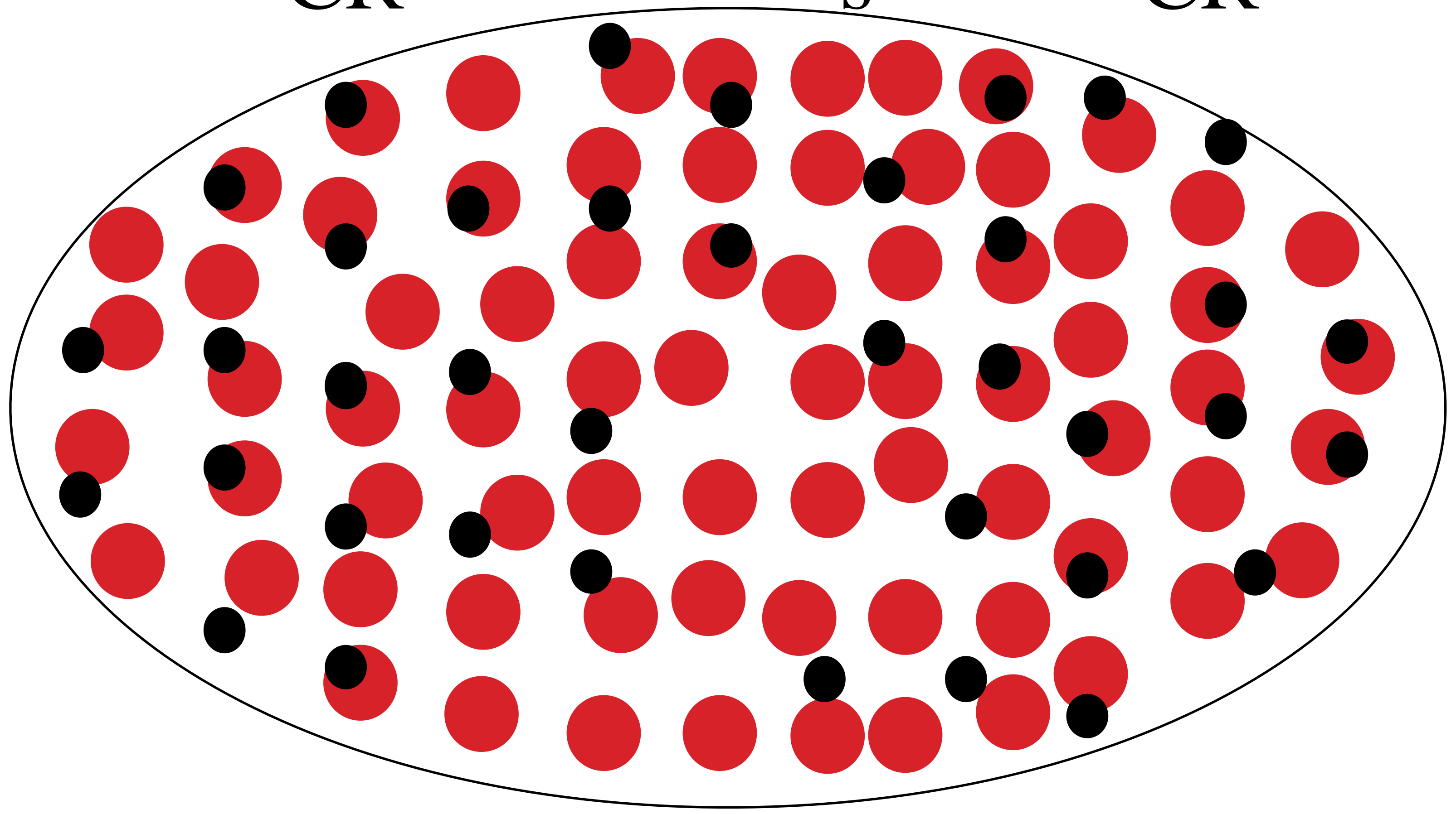
The probability to see no doublet is

$$P(\text{no doublet}) = (1 - P(\geq 2))^{N_{sources}}$$

$$= (P(0) + P(1))^{N_{sources}}$$

$$= (e^{-n_*}(1 + n_*))^{N_{sources}}$$

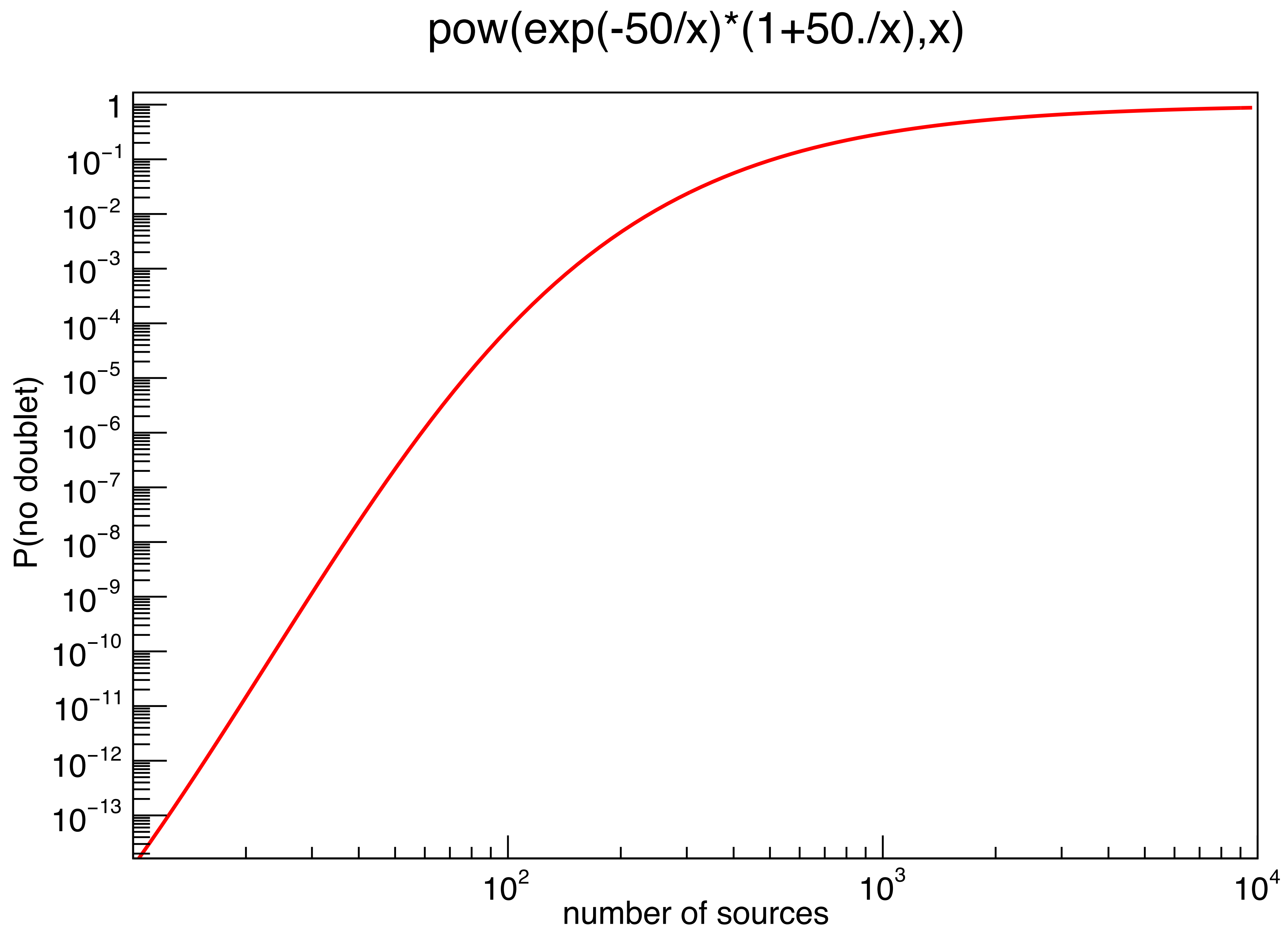
$$N_{CR} = 43,\ N_s \gg N_{CR}$$



Lower limit on the number density of UHECR sources

The probability to see no doublet is

$$P(\text{no doublet}) = (1 - P(\geq 2))^{N_\text{sources}}$$
$$= (e^{-n_*}(1 + n_*))^{N_\text{sources}}$$
$$= e^{-N_{ev}}\left(1 + \frac{N_\text{CR}}{N_\text{sources}}\right)^{N_\text{sources}}$$



P(no doublet) ~ 1% if > 200 sources

$$\bar{n}_s \sim \frac{N_s = 200}{4/3\pi R_\text{GZK}^3} \sim 10^{-5}\ \text{Mpc}^{-3}$$

Galaxies - 10^{-2} Mpc^{-3}

Starbursts - 10^{-4} Mpc^{-3}

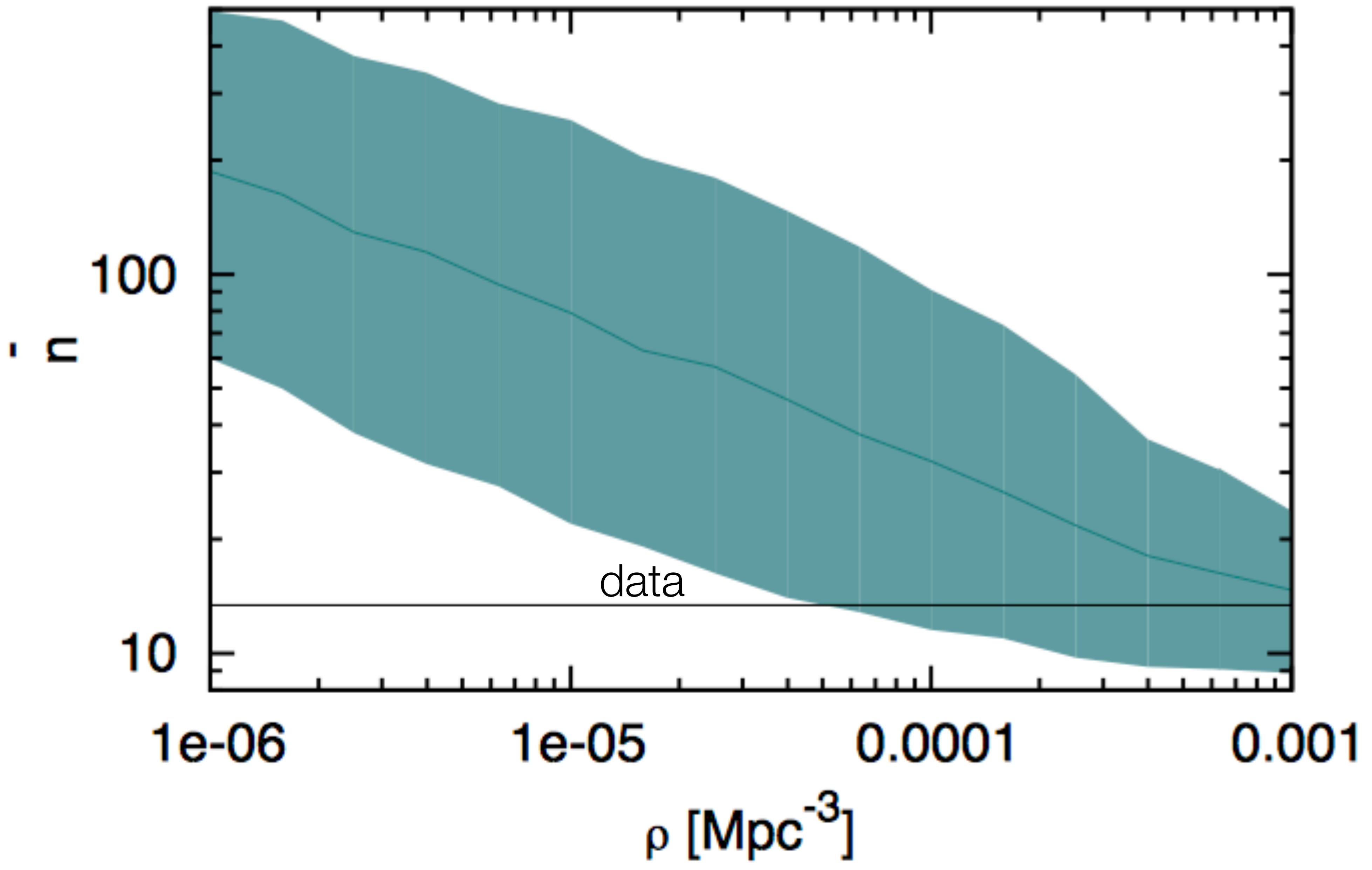
BL Lac Objects - 10^{-6} Mpc^{-3}

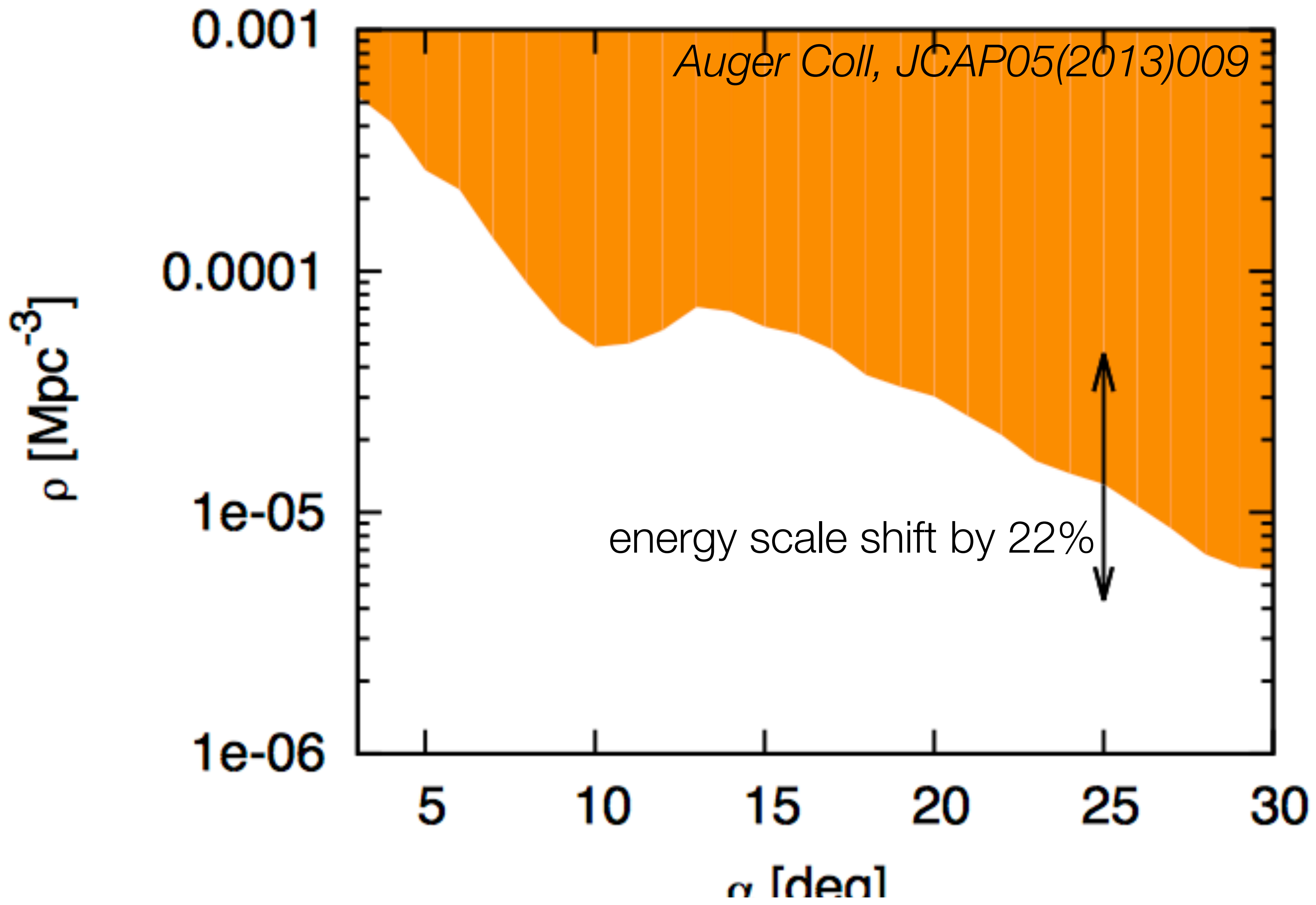
Flat Spectrum Radio Quasars - 10^{-9} Mpc^{-3}

Lower limit on the number density of UHECR sources

Application to Auger data (43 events)

Expected number of pairs in 90% of realisations (10 degree smearing):





Conclusion #1: UHECR sources are numerous

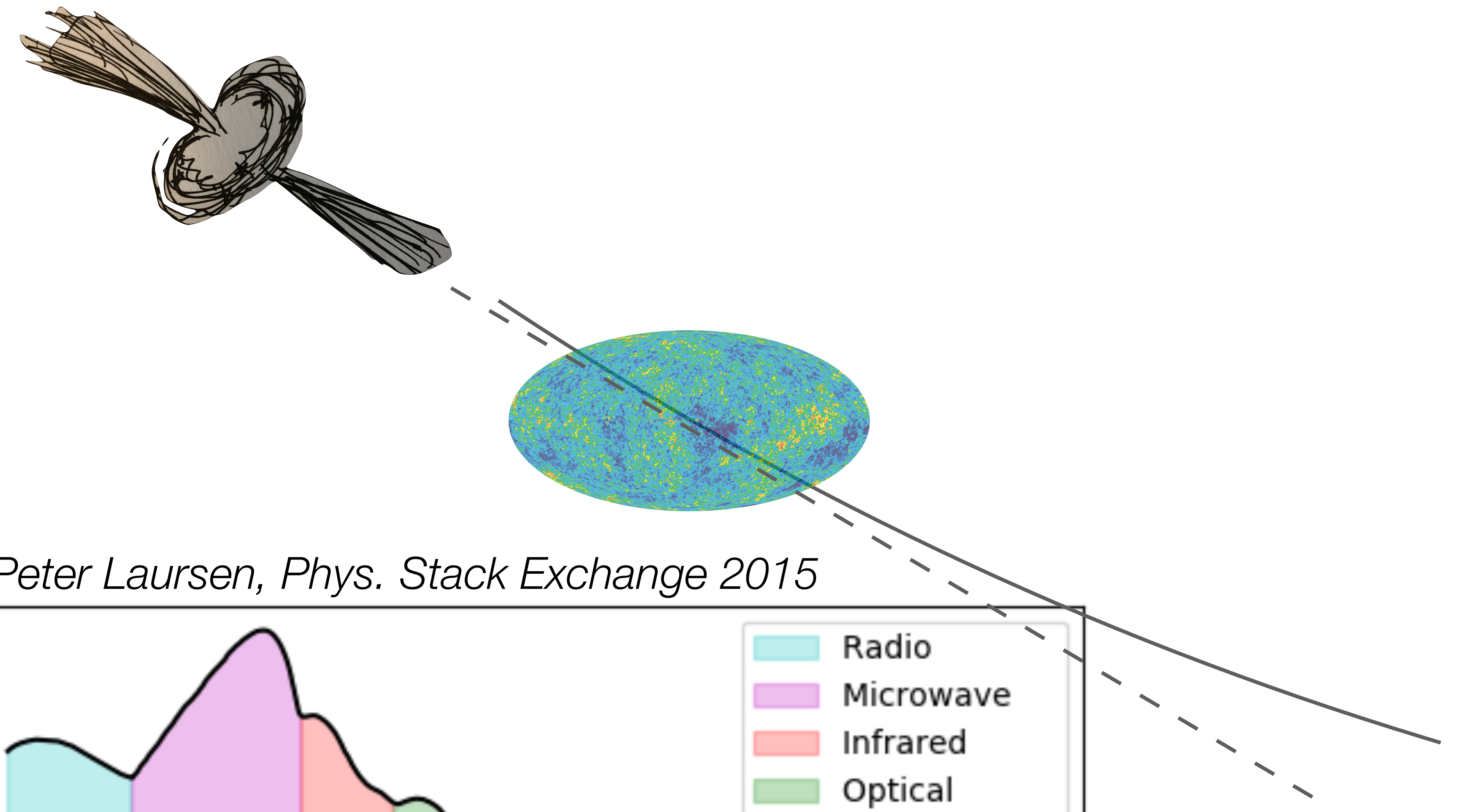
more recent result

FO, Connolly, Thomas, Abdalla, Lahav, Waxman, JCAP05(2013)015

Generic source properties

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

1. UHECR energy loss length



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

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

Energy loss per unit length

$$\frac{\mathrm{d}E}{\mathrm{d}x} \sim \frac{\Delta E}{\lambda} \sim -\frac{\kappa(E)E}{\lambda(E)}$$

Energy loss length, i.e. loss of $\mathcal{O}(1)$fraction of energy:

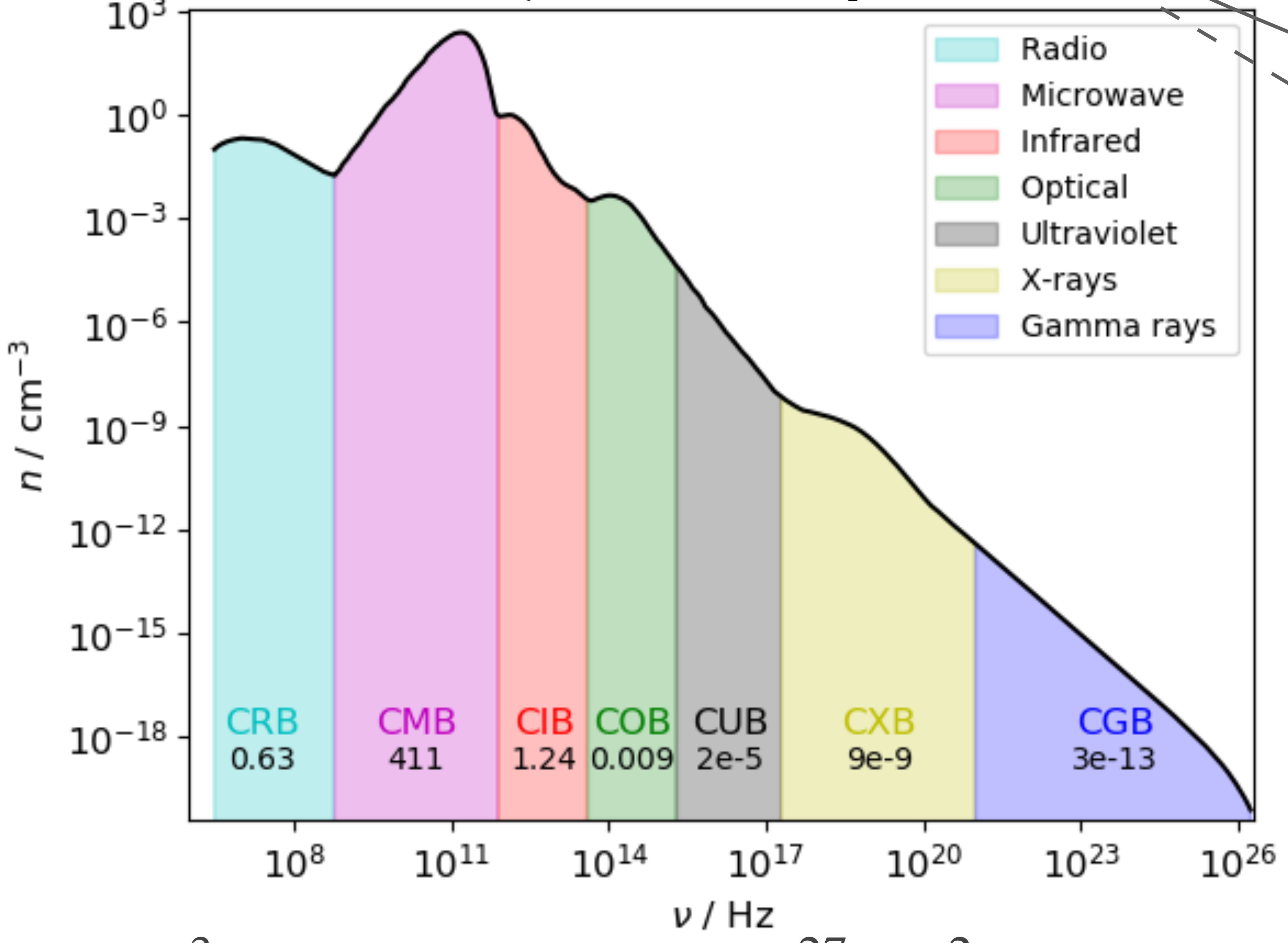
$$\chi_{\mathrm{loss}}(E) \equiv \frac{E}{|\mathrm{d}E/\mathrm{d}x|} \sim \frac{\lambda(E)}{\kappa(E)}$$

Photo-pair production (Bethe-Heitler process):

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

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

Peter Laursen, Phys. Stack Exchange 2015



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

$$\lambda^{ee}_{p\gamma} \sim 1/(n_{\mathrm{CMB}} \cdot \sigma^{ee}_{p\gamma}) \sim 1\,\mathrm{Mpc}$$

$$\chi_{\mathrm{BH,loss}} \sim \lambda^{ee}_{p\gamma}/\kappa \sim 1\mathrm{Gpc}$$

1. UHECR energy loss length

Photo-pion production (GZK process when target is the CMB)

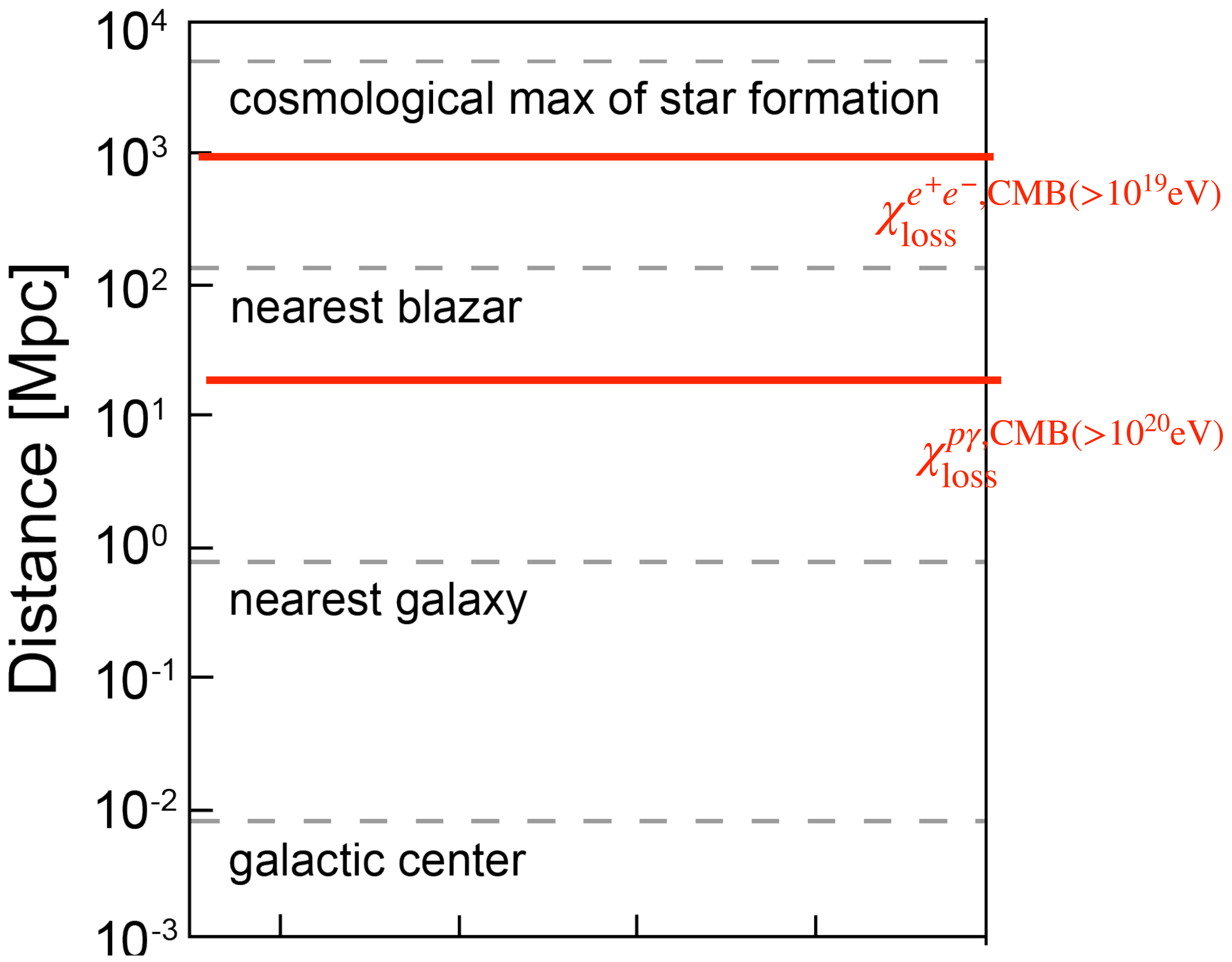
Photo-pion production:

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

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

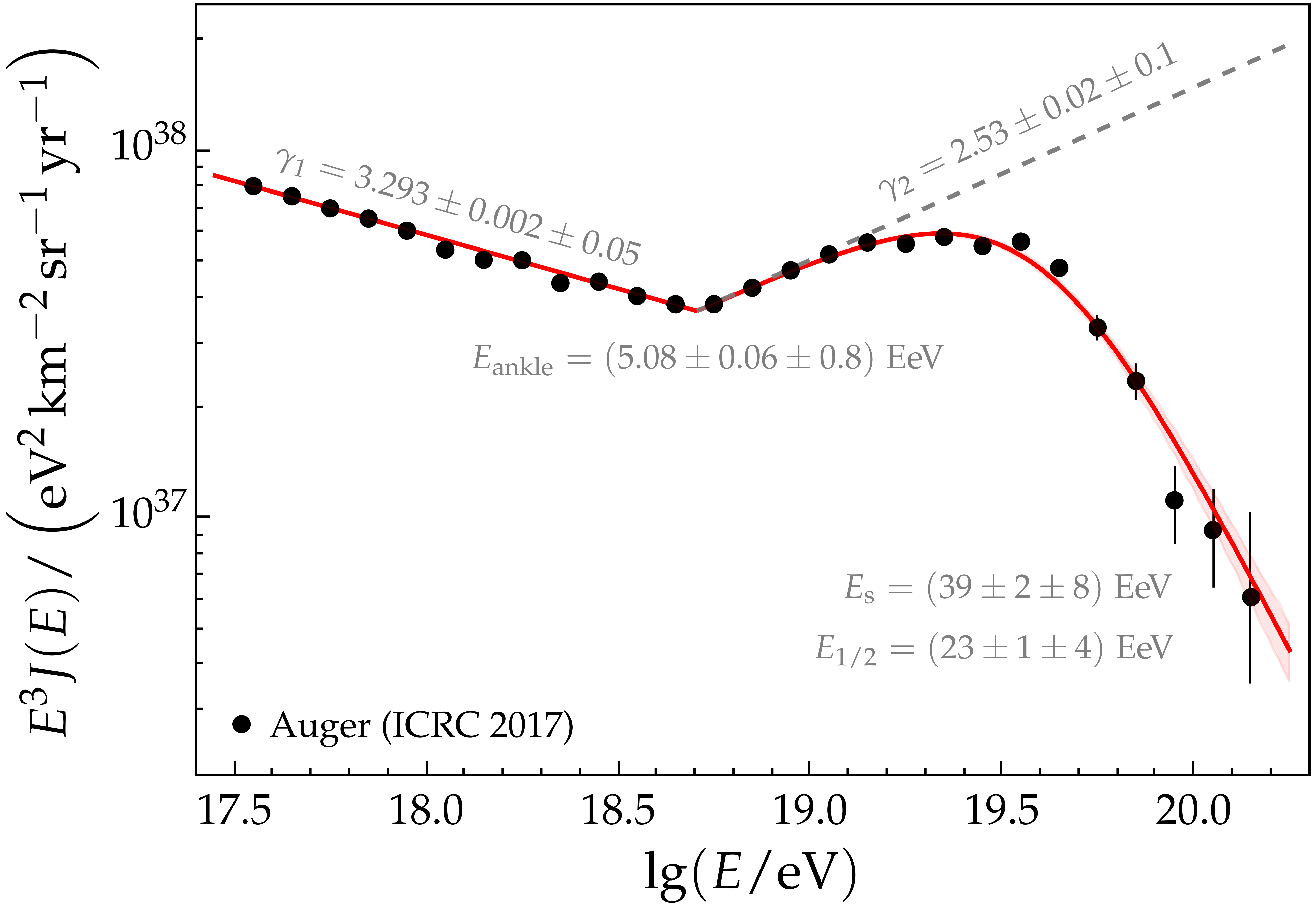
$$\left[\kappa \approx m_\pi / m_p \approx 0.2, \sigma_{p\gamma} \approx 10^{-28}\,{\rm cm}^2 \right]$$

$$\lambda_{p\gamma,\rm CMB} = 1/n\sigma \sim 10\,{\rm Mpc},\ \chi_{\rm loss} = \lambda/\kappa \sim 50\,{\rm Mpc}$$



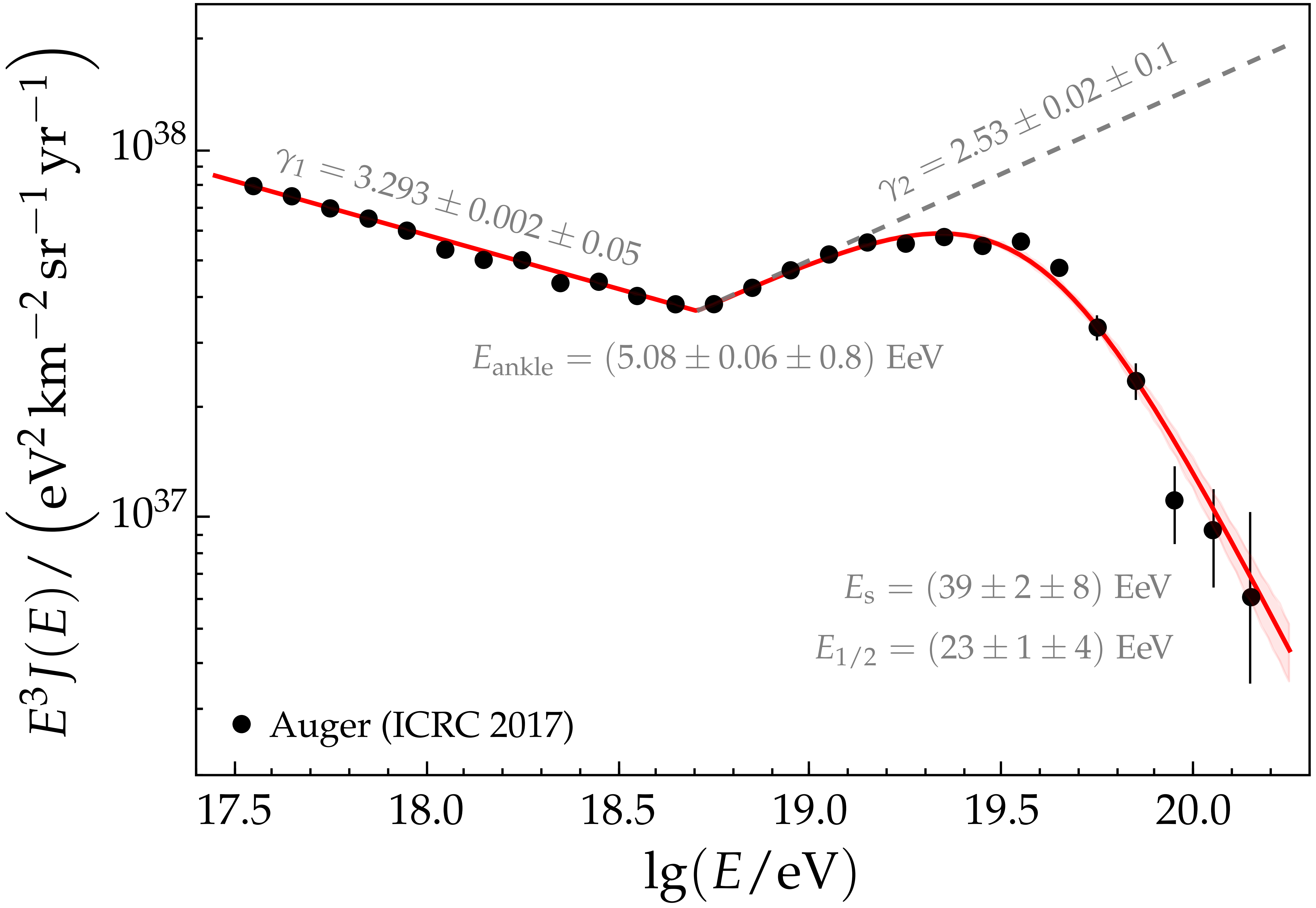
UHECR energy density

Auger Coll, ICRC 2017 (see also Auger Coll 2020 PRL)



UHECR energy density

(see Auger Coll 2025 PRL for the most recent update)



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

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

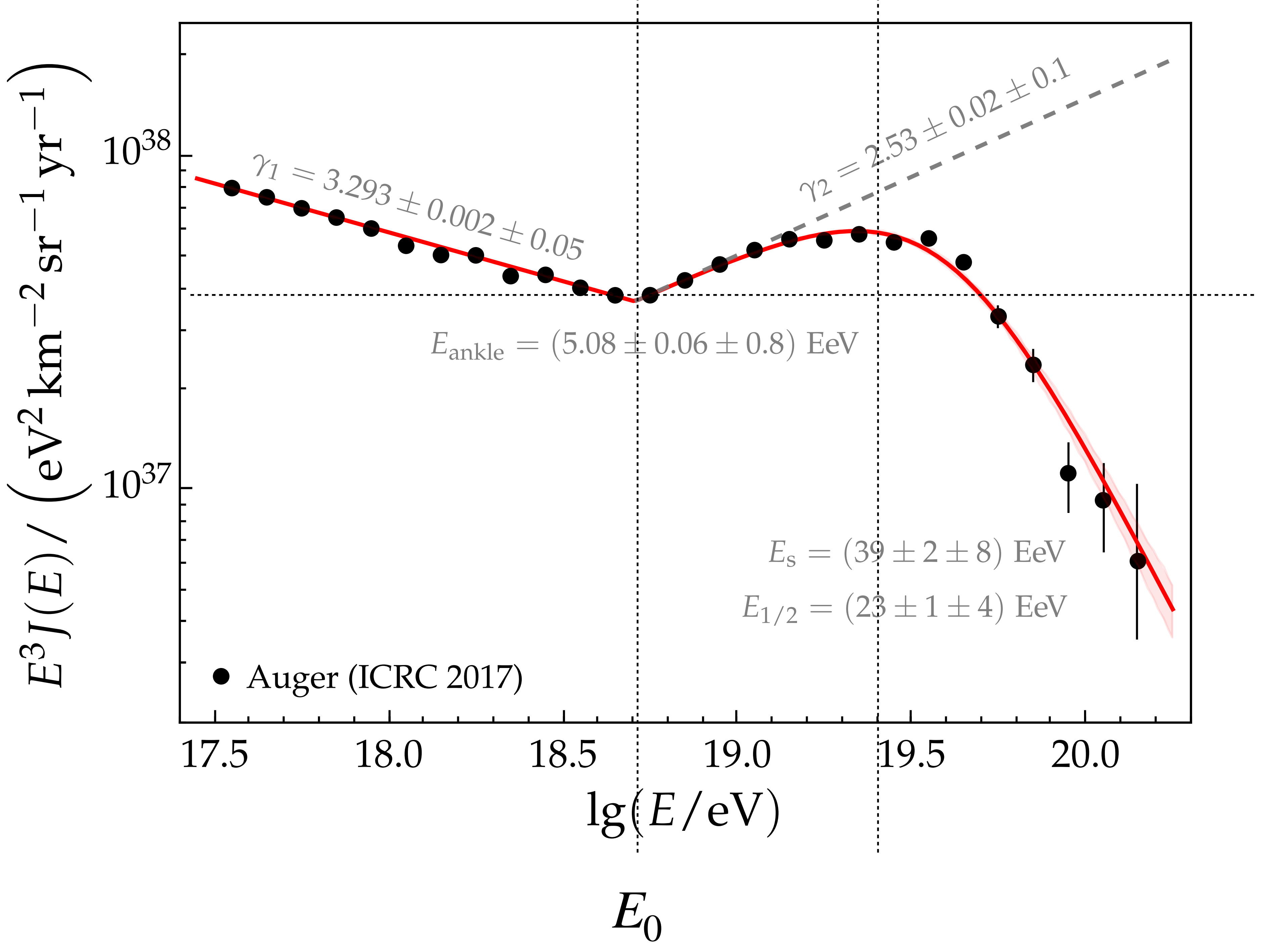
The number density of particles is

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

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 density



At 5 EeV we measure,

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

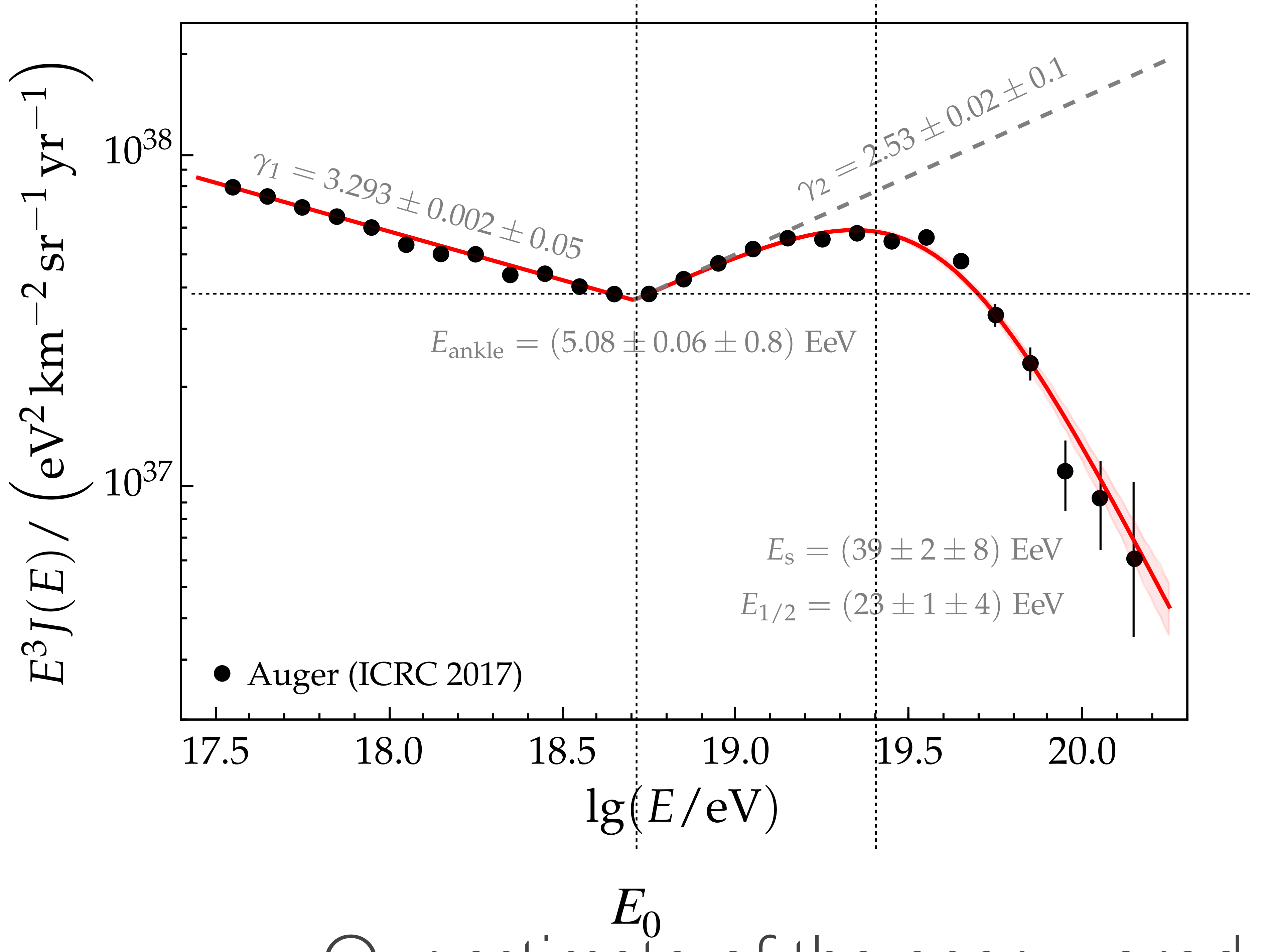
which corresponds to (for an E^{-2} spectrum),

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

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

UHECR emissivity

Auger Coll, ICRC 2017 (see also Auger Coll 2020 PRL)



At 5 EeV we measure,

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

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

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

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

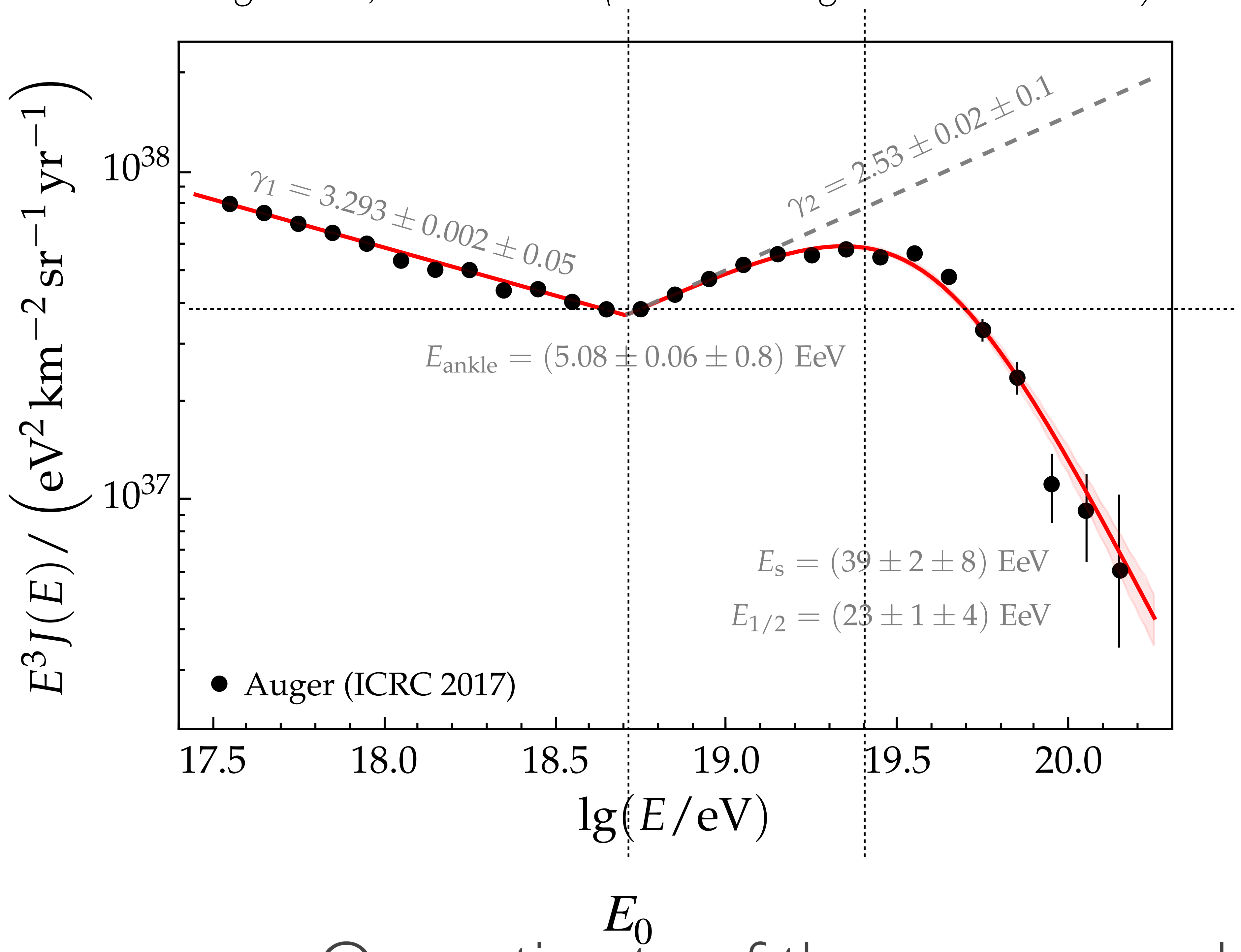
1 erg ~ 1 TeV!

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

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

UHECR emissivity

Auger Coll, ICRC 2017 (see also Auger Coll 2020 PRL)



At 5 EeV we measure,

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

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

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

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

1 erg ~ 1 TeV!

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

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

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

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

3. UHECR emissivity: Comparison to source classes

Object	Power [erg/s]/ Energy [erg]	Number density / rate	Luminosity density	Duration	Emissivity
Milky Way like galaxies	10^{42} erg s^{-1}	1	10^{42} erg $s^{-1}gal^{-1}$	Gyr	10^{47} erg Mpc^{-3} yr^{-1}
Core collapse supernovae	10^{51} erg	10^{-2} gal^{-1} yr^{-1}	10^{41} erg $s^{-1}gal^{-1}$	kyr	10^{47} erg Mpc^{-3} yr^{-1}
Neutron stars (magnetars)	10^{40} erg s^{-1}	10^{-3} gal^{-1} yr^{-1}	10^{40} erg $s^{-1}gal^{-1}$	kyr	10^{47} erg Mpc^{-3} yr^{-1}
Gamma-ray burst (on-axis)	10^{51} erg	10^{-7} gal^{-1} yr^{-1}	10^{38} erg $s^{-1}gal^{-1}$	1 - 100s	10^{42} erg Mpc^{-3} yr^{-1}
Jetted TDE (on-axis)	10^{46-48} erg s^{-1}	10^{-9} gal^{-1} yr^{-1}	10^{37} erg $s^{-1}gal^{-1}$	~yr	10^{41} erg Mpc^{-3} yr^{-1}
TDE	10^{44} erg s^{-1}	10^{-5} gal^{-1} yr^{-1}	10^{39} erg $s^{-1}gal^{-1}$	~yr	10^{43} erg Mpc^{-3} yr^{-1}
Starburst galaxies	10^{43} erg s^{-1}	10^{-2}	10^{41} erg $s^{-1}gal^{-1}$	~Myr	10^{45} erg Mpc^{-3} yr^{-1}
Non-jetted AGN	10^{44-45} erg s^{-1}	10^{-2}	10^{42} erg $s^{-1}gal^{-1}$	~Myr	10^{46} erg Mpc^{-3} yr^{-1}
Blazars	10^{47-49} erg s^{-1}	10^{-5}	10^{42} erg $s^{-1}gal^{-1}$	~Myr	10^{46} erg Mpc^{-3} yr^{-1}

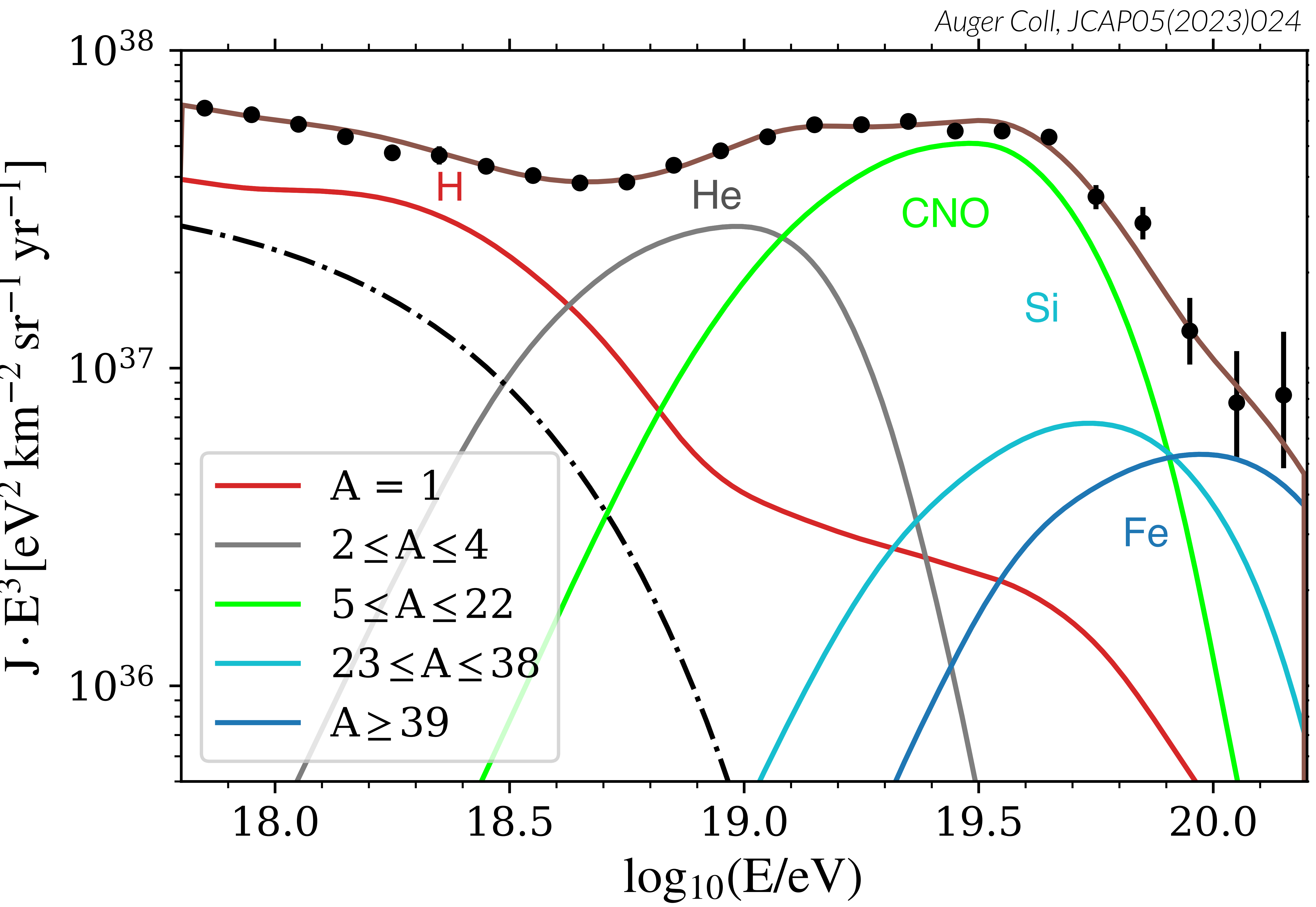
Conclusion #2: Emissivity for most sources OK.

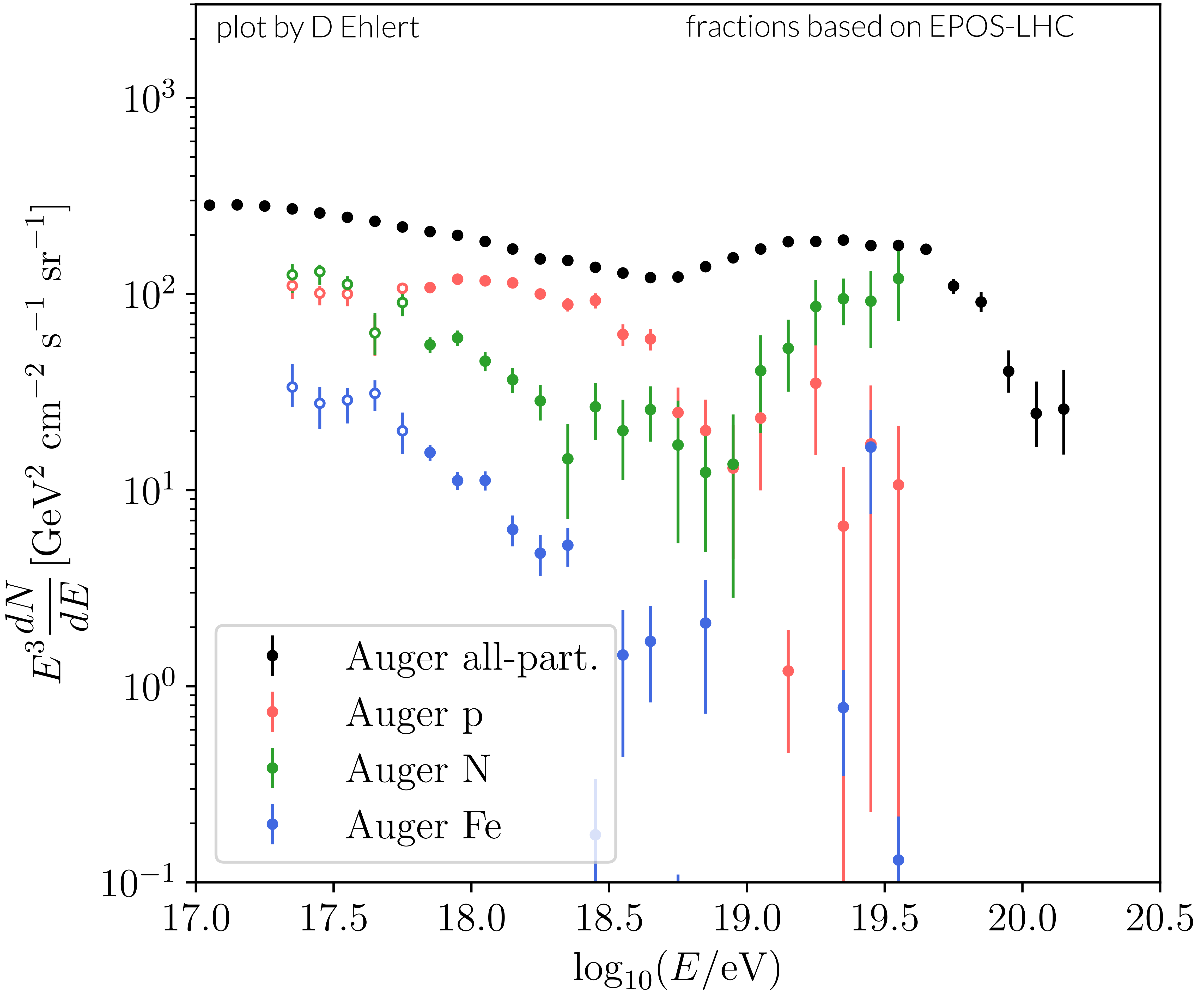
Generic source properties

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

UHECR source diversity?

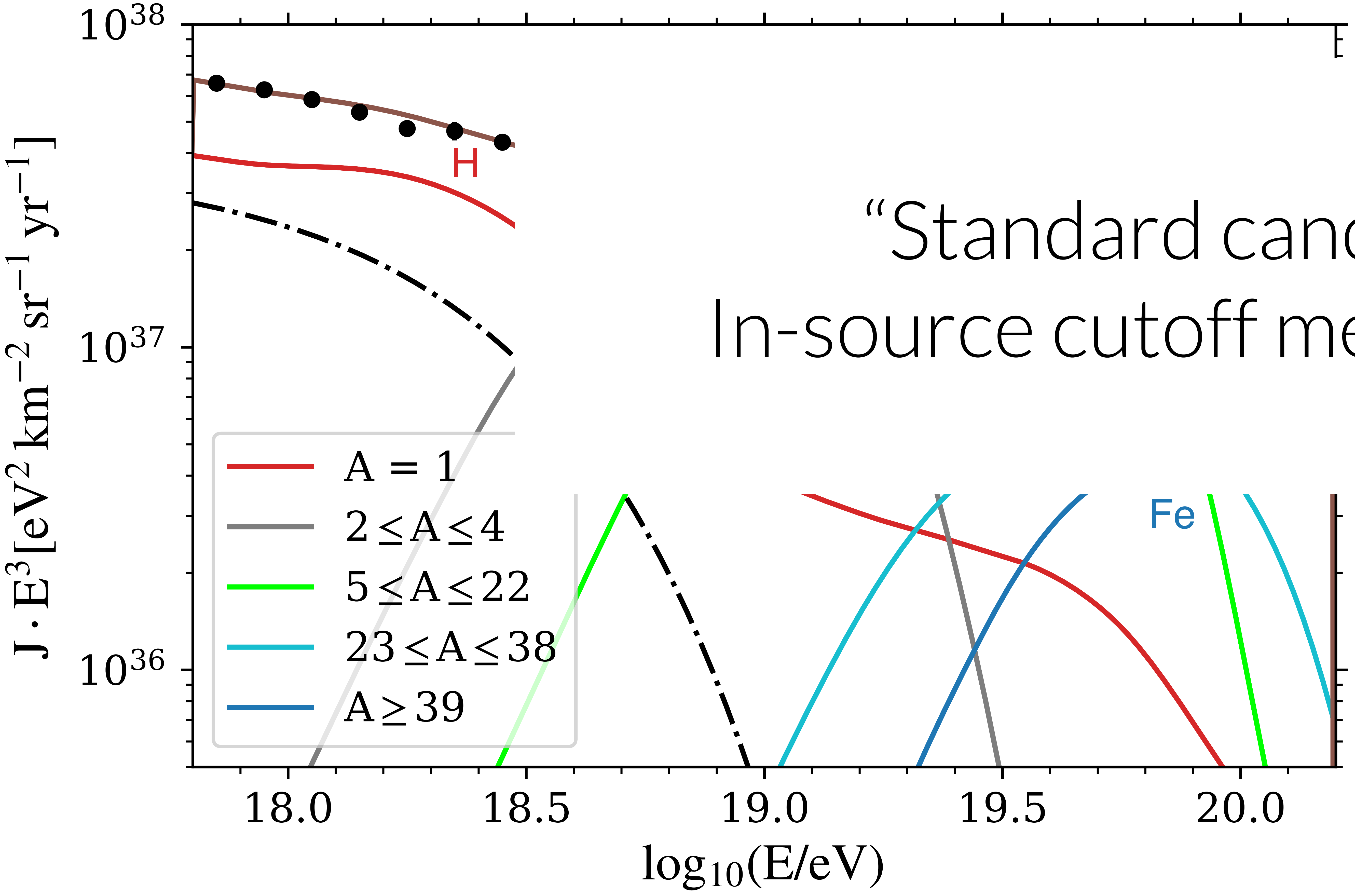
Auger Coll, PRL, 125, 121106, 2020
Tkachenko for Auger Coll, PoS(ICRC2023)438
Auger Coll, PRL, 134, 021001, 2024





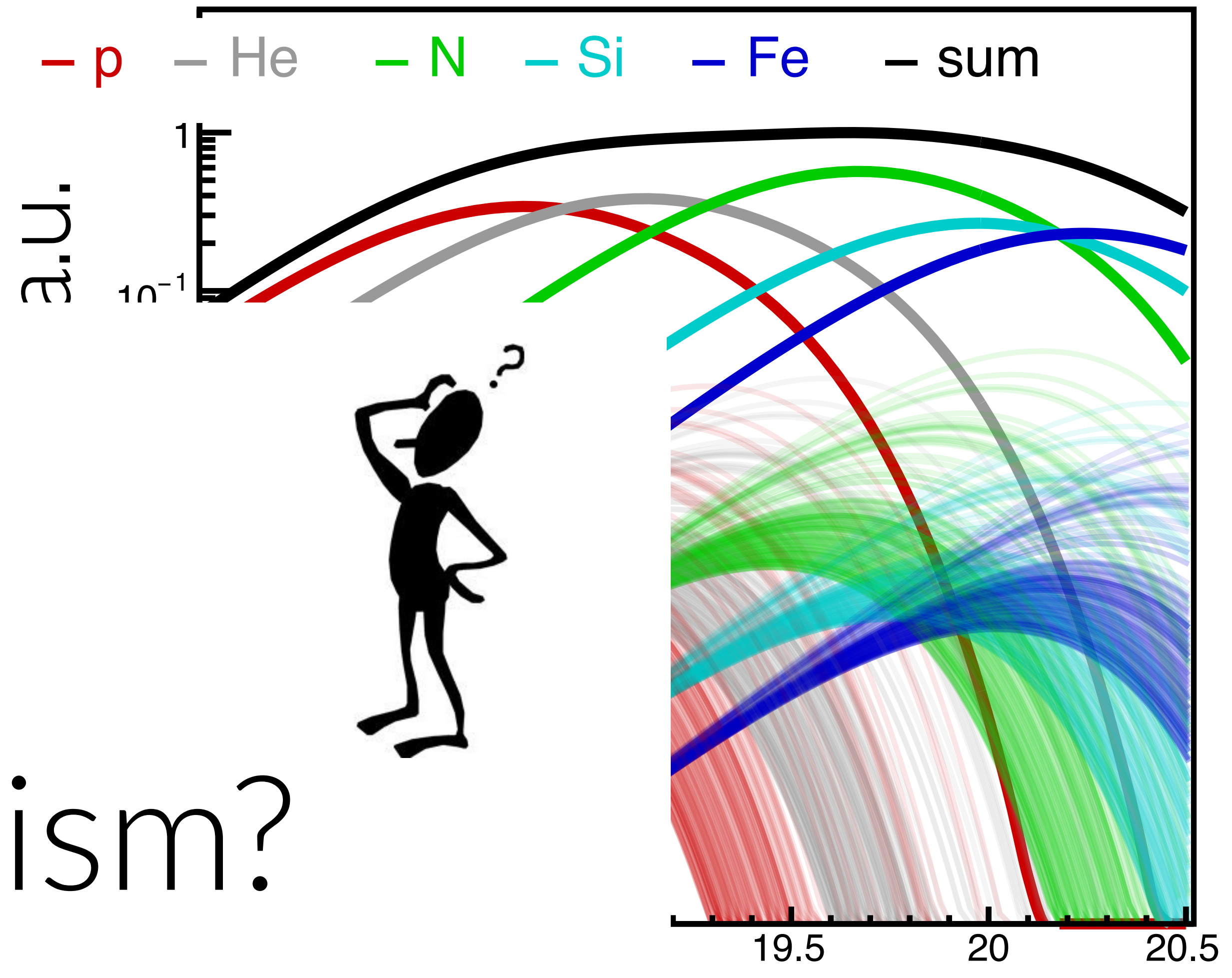
UHECR source diversity?

D. Ehlert, FO, M. Unger, PRD 107 (2023) 10



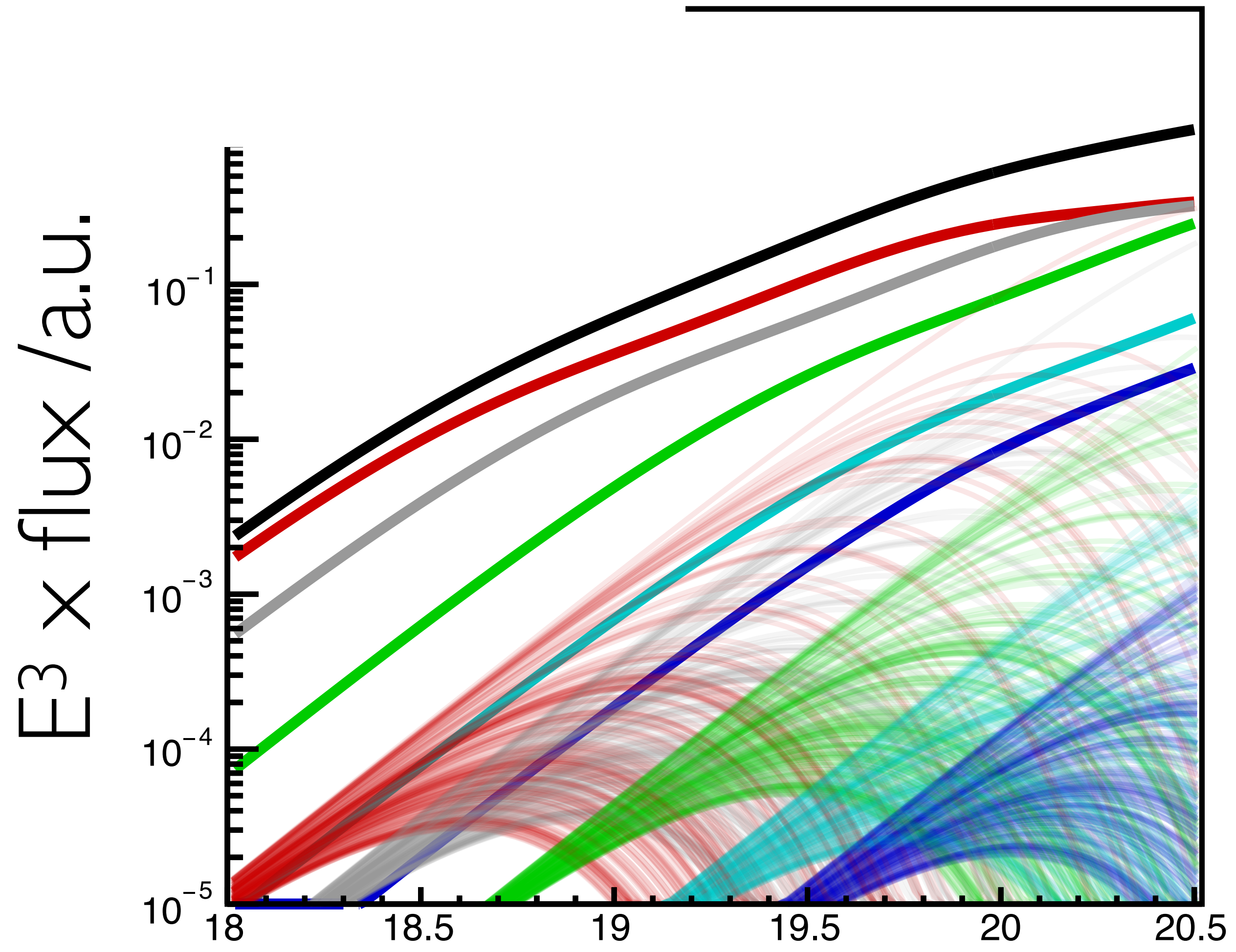
“Standard candles”?

In-source cutoff mechanism?



Diffuse spectrum from:

-near-identical sources



-non-identical sources

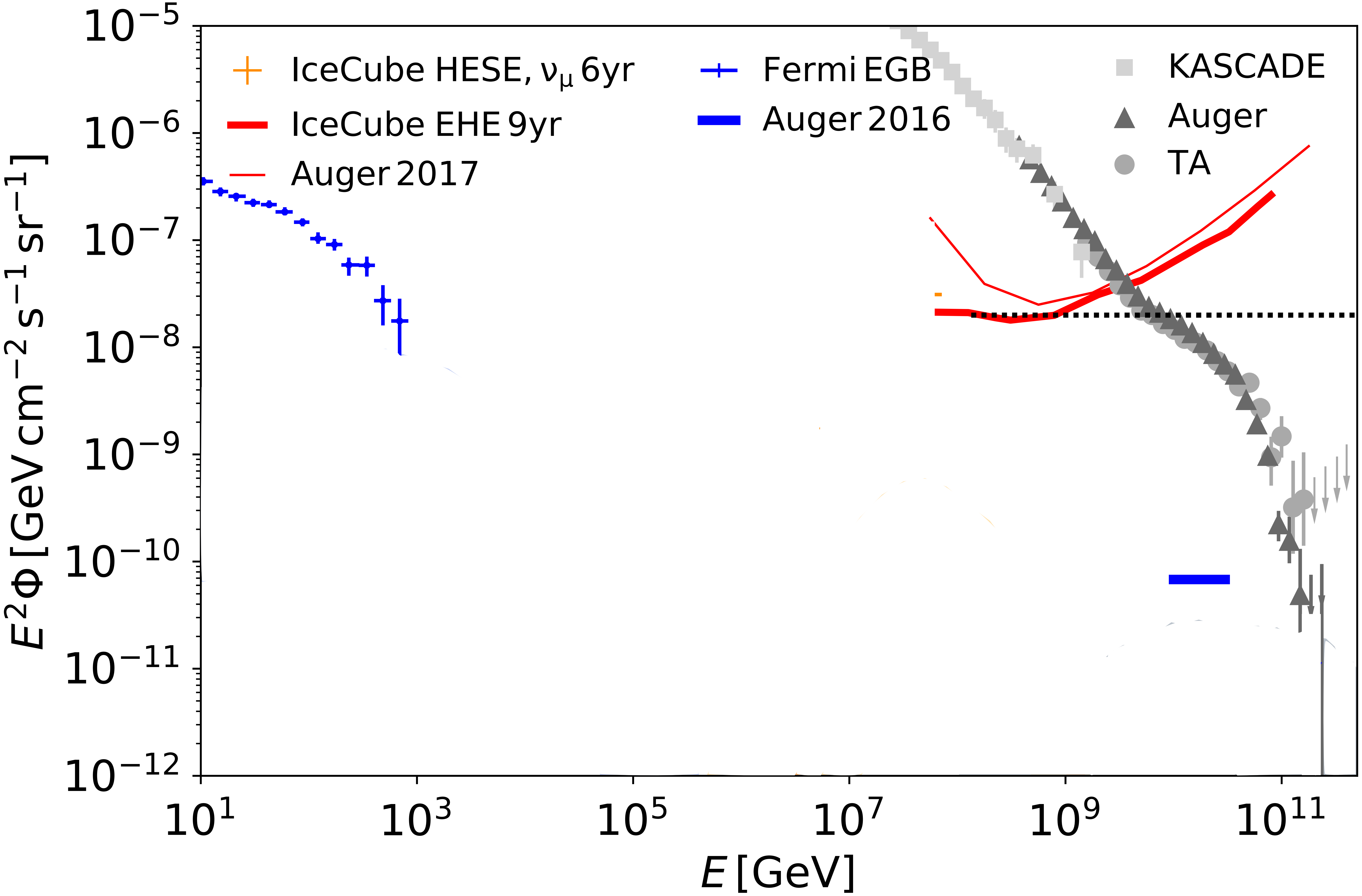
Conclusion: UHECR sources are few or near-identical

Generic source properties

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

Waxman-Bahcall bound

E. Waxman, J. Bahcall, PRD 1998



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

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

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

- Proton loses fraction, ϵ, of its energy

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

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

$p + \gamma \rightarrow p + \pi^0$ – BR 50 %

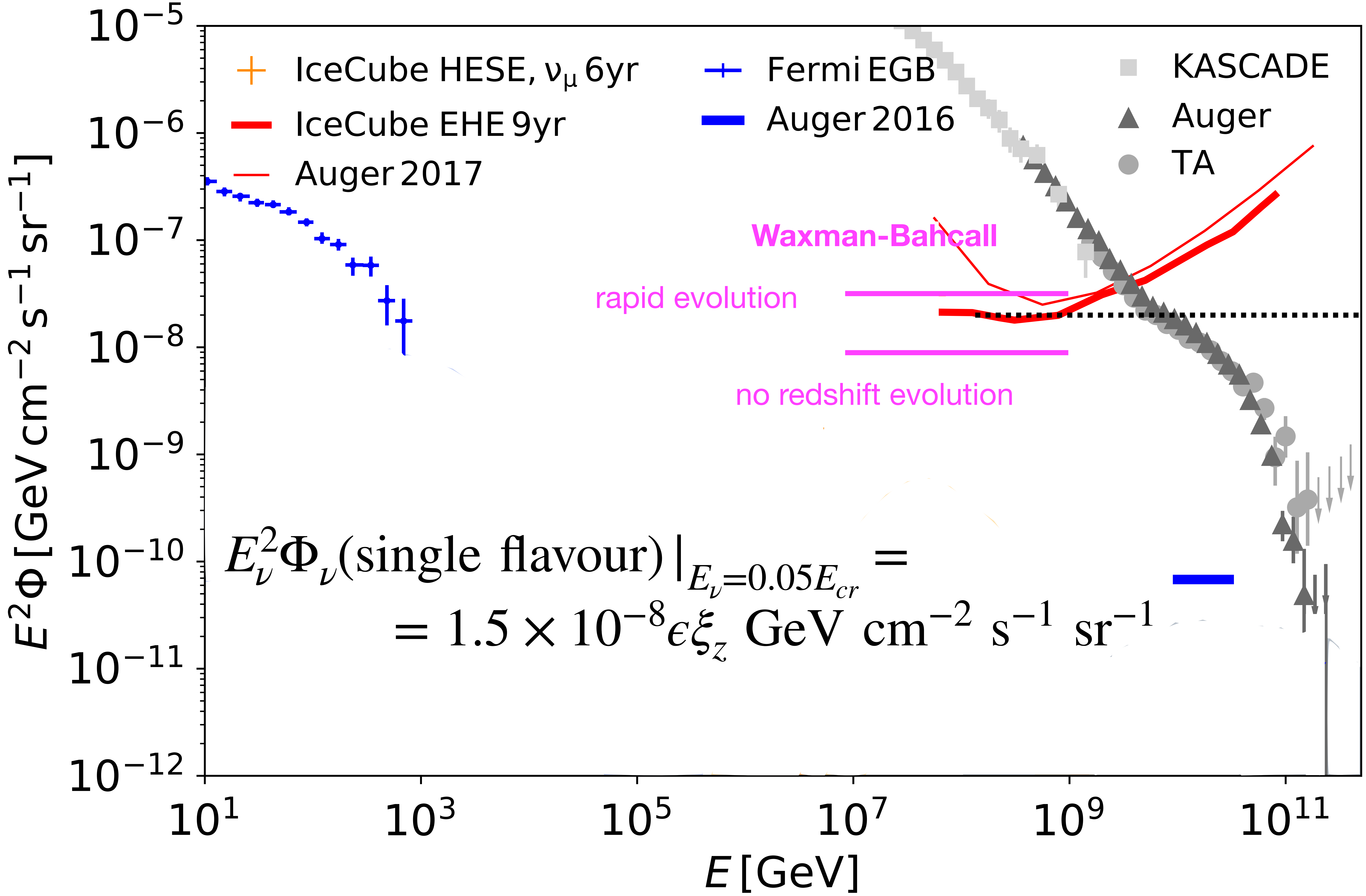
$p + \gamma \rightarrow n + \pi^+$ – BR 50 %

$\xi_z \sim 0.6$ (no evolution) – 10 (rapid evolution)

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

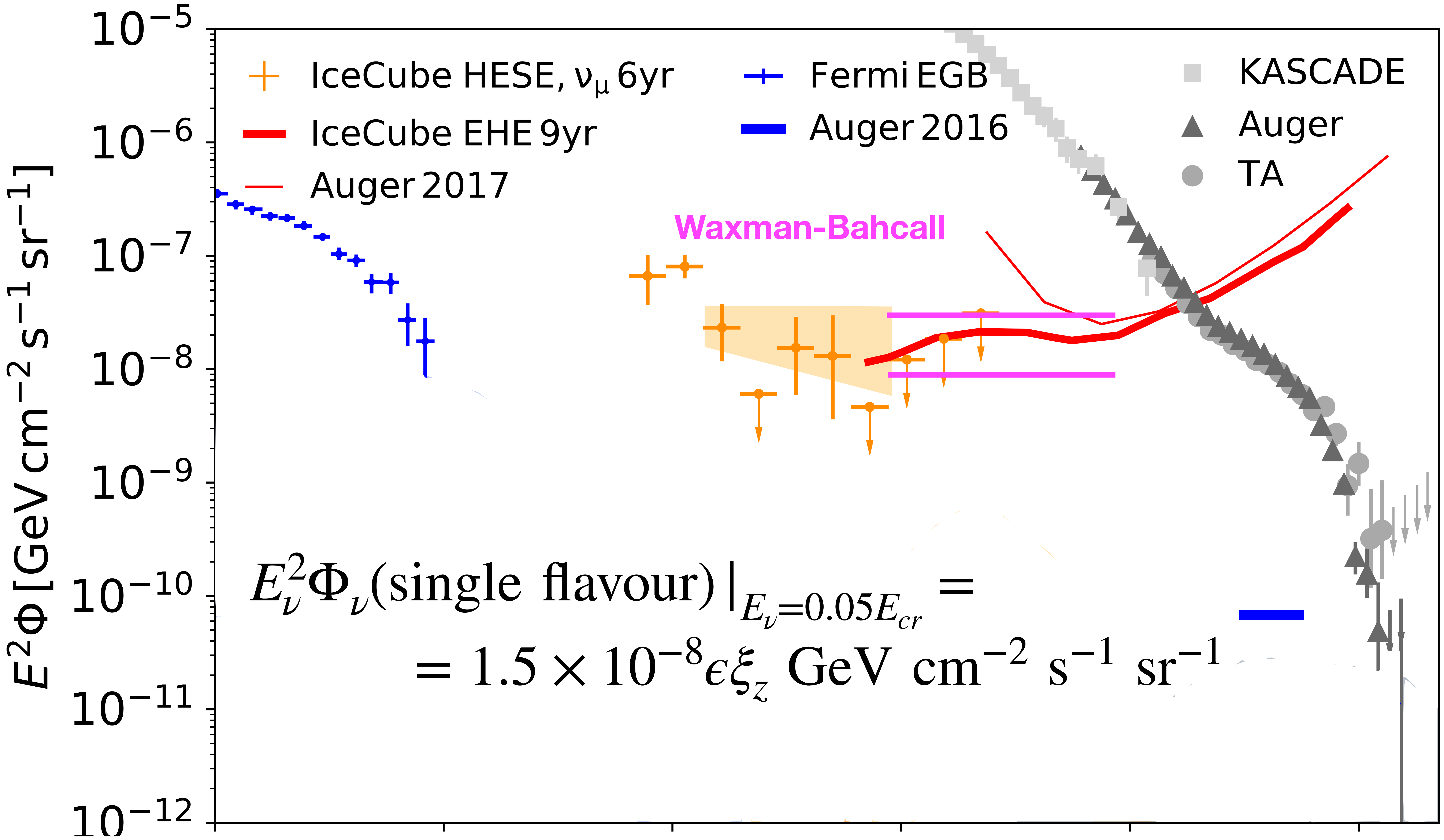
50% of E_{π^+}

Waxman-Bahcall bound



$$E_\nu^2 \Phi_\nu(\text{single flavour})\big|_{E_\nu = 0.05 E_{cr}} = \\ = 1.5 \times 10^{-8} \epsilon \xi_z \text{ GeV cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}$$

Waxman-Bahcall bound



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

Conclusion #3: IceCube neutrinos consistent with WB (could be coincidence)

Generic source properties

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

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

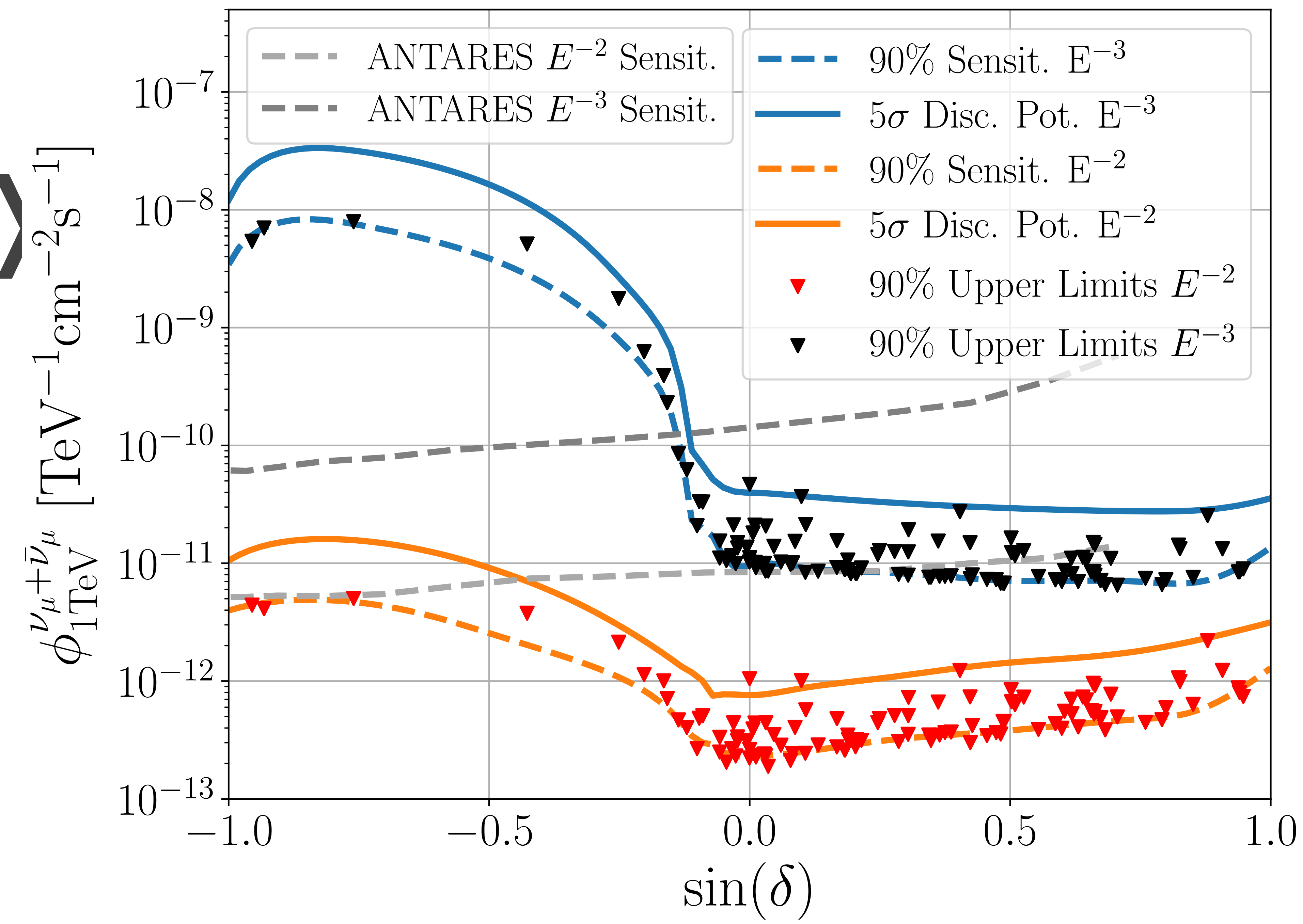
$$\text{luminosity density} \sim \langle L \rangle \cdot n$$

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

$$V_1 = \frac{4\pi r_1^3}{3} \sim \frac{1}{n}$$

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

$$\langle r_1 \rangle \sim \left(\frac{4\pi n}{3}\right)^{-1/3} \quad -(1) \qquad \text{e.g. } n = 10^{-4}\mathrm{Mpc}^{-3}, \quad r_1 = 10\ \mathrm{Mpc}$$

- 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

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

(BL Lac)	
Starburst galaxies	10^{-5}
Galaxy clusters	10^{-5}
Jetted AGN	10^{-4}
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

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

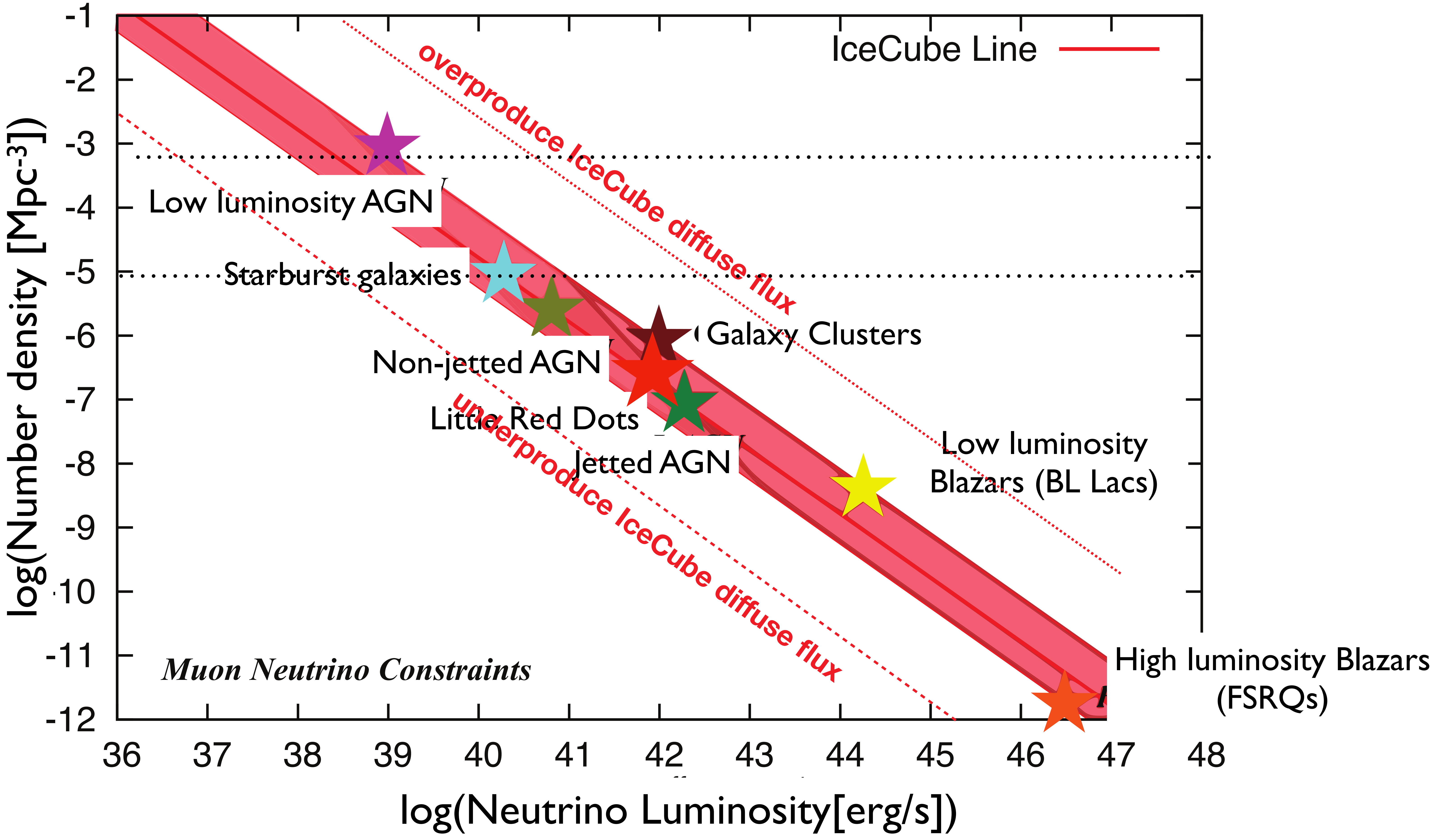
where we used Eq. (1) $r_1 \sim \left(\frac{4\pi n}{3} \right)^{-1/3}$

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

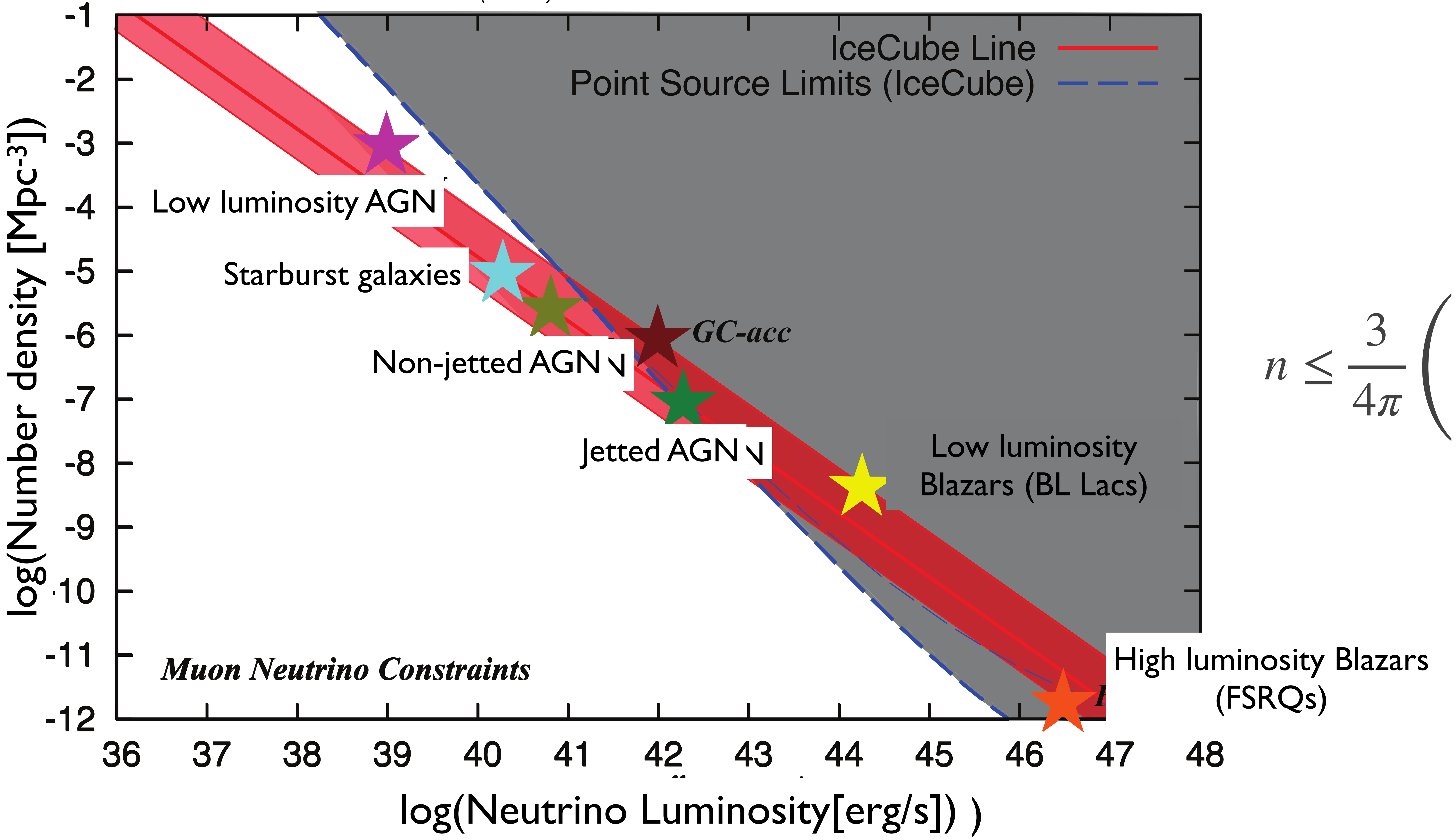
see also Lipari PRD78(2008)083011
Ahlers & Halzen PRD90(2014)043005
Kowalski 2014,
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan et al 2019,
Capel, Mortlock, Finley 2020.
Mørch-Groth, Ahlers 2025
Kuze et al 2026 (Little Red Dots)

Murase & Waxman 16, PRD 94 (2016) 103006



Neutrino source number density

Murase & Waxman 16, PRD 94 (2016) 103006



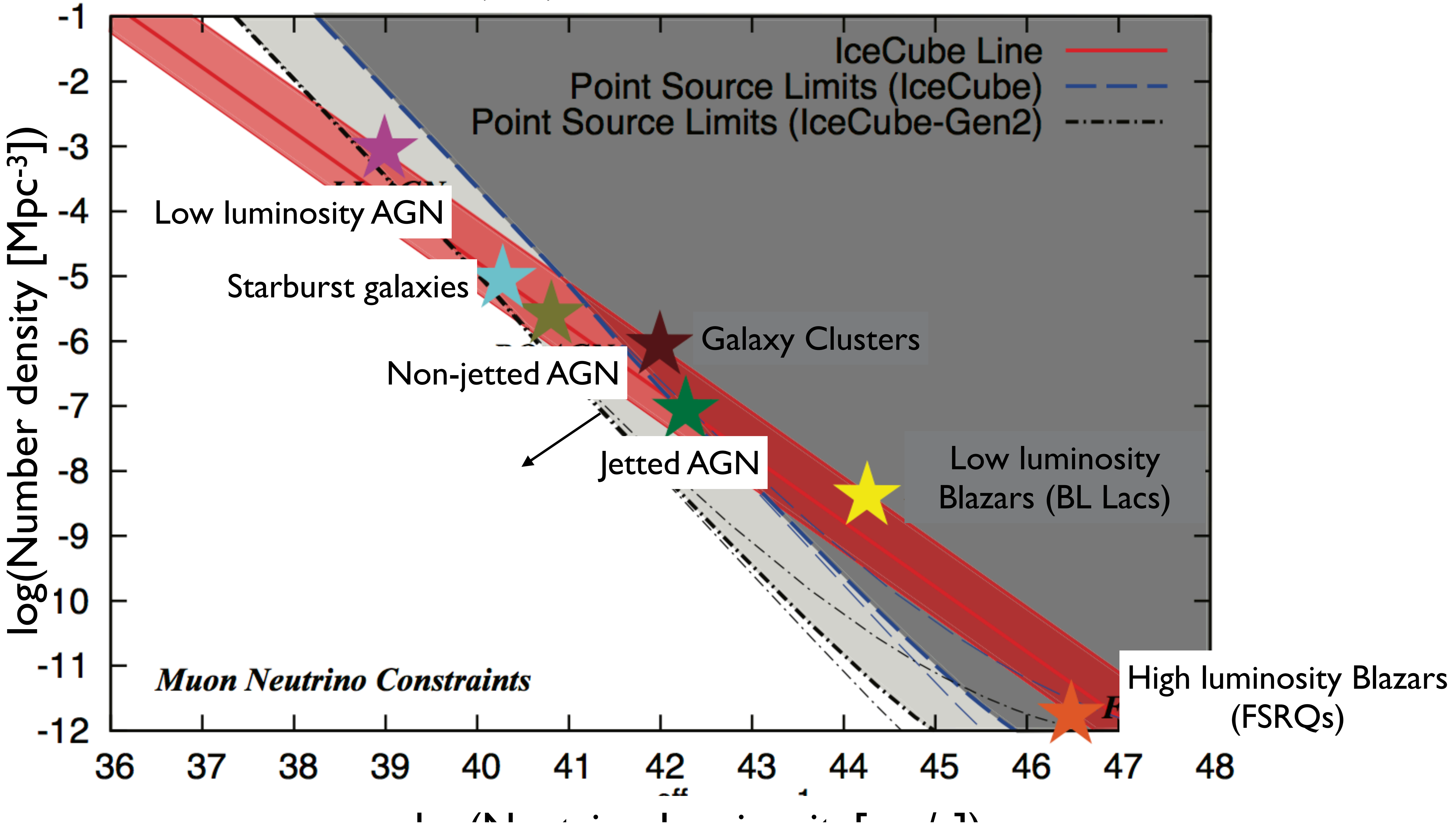
$$n \leq \frac{3}{4\pi}\left(\frac{L}{4\pi F_{lim}}\right)^{-3/2}$$

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
Ahlers & Halzen PRD90(2014)043005
Kowalski 2014,
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan et al 2019,
Capel, Mortlock, Finley 2020.
Mørch-Groth, Ahlers 2025

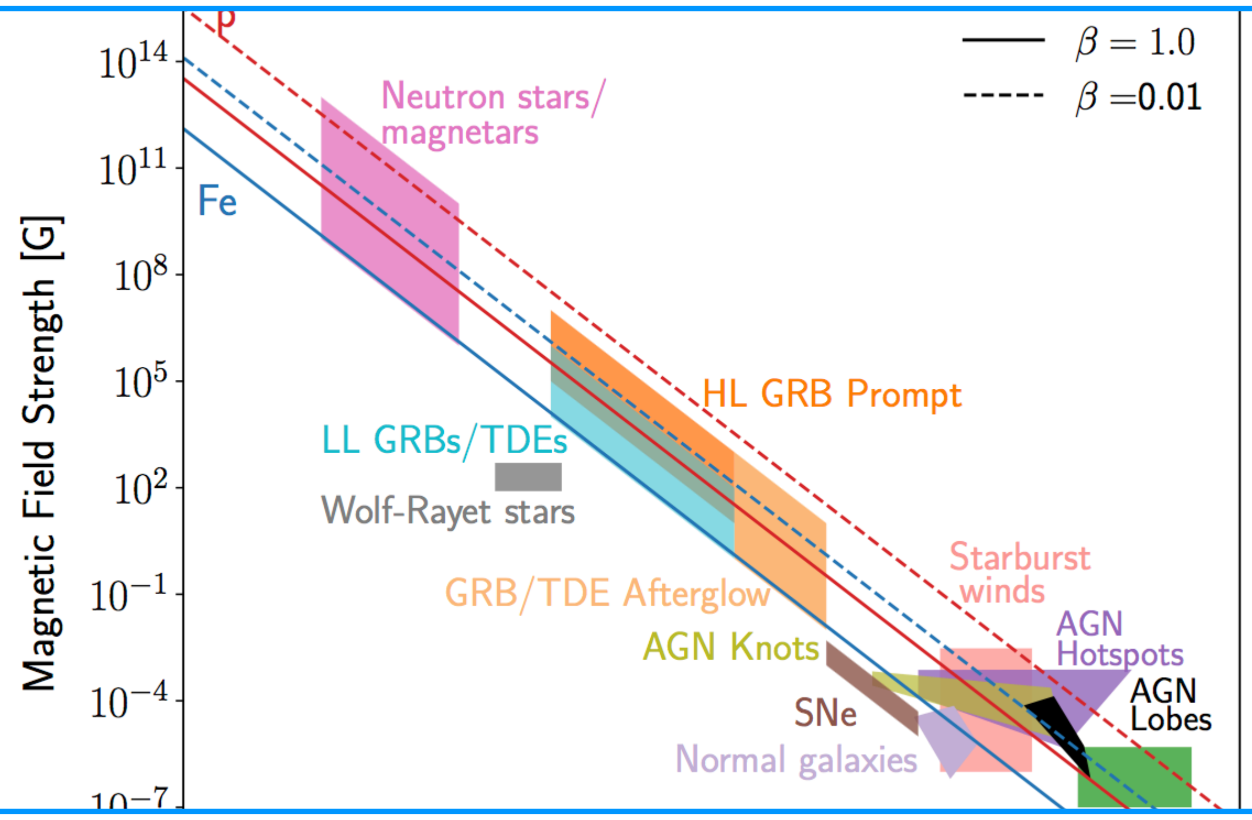
Murase & Waxman 16, PRD 94 (2016) 103006



Conclusion #4: Neutrino sources are not rare and powerful

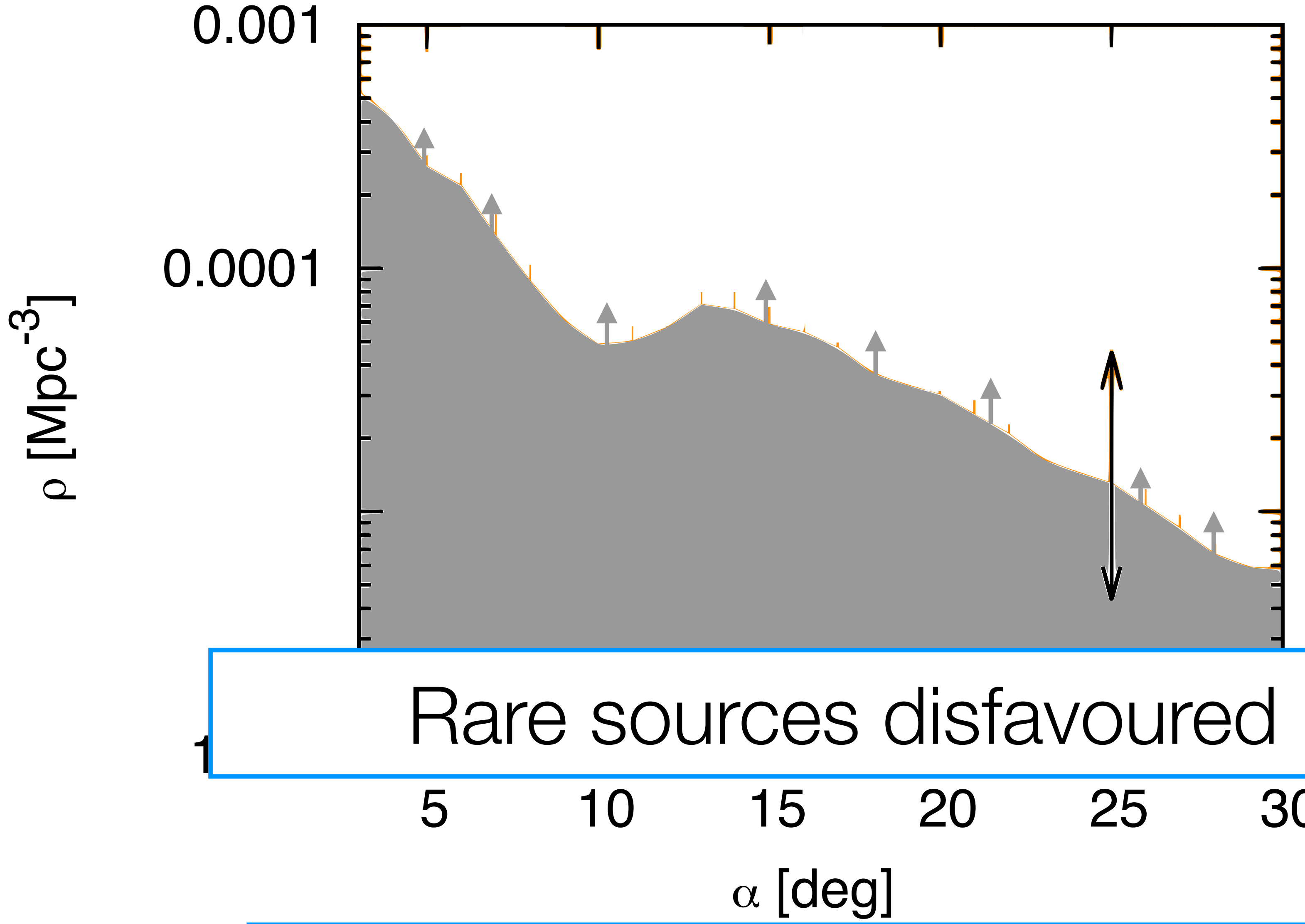
Recap

UHECR Maximum Energy



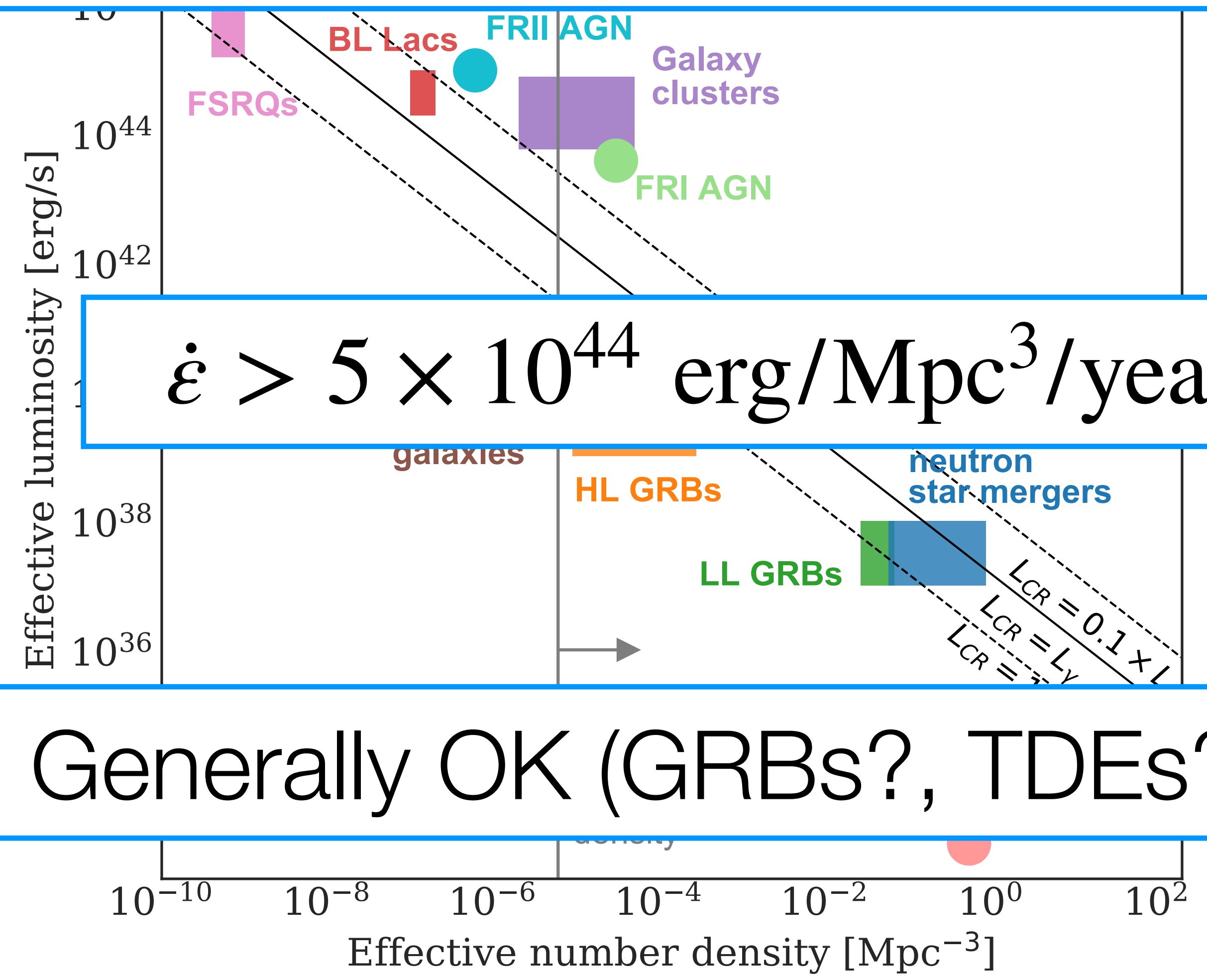
constraining, but several classes OK for nuclei

UHECR number density



Rare sources disfavoured

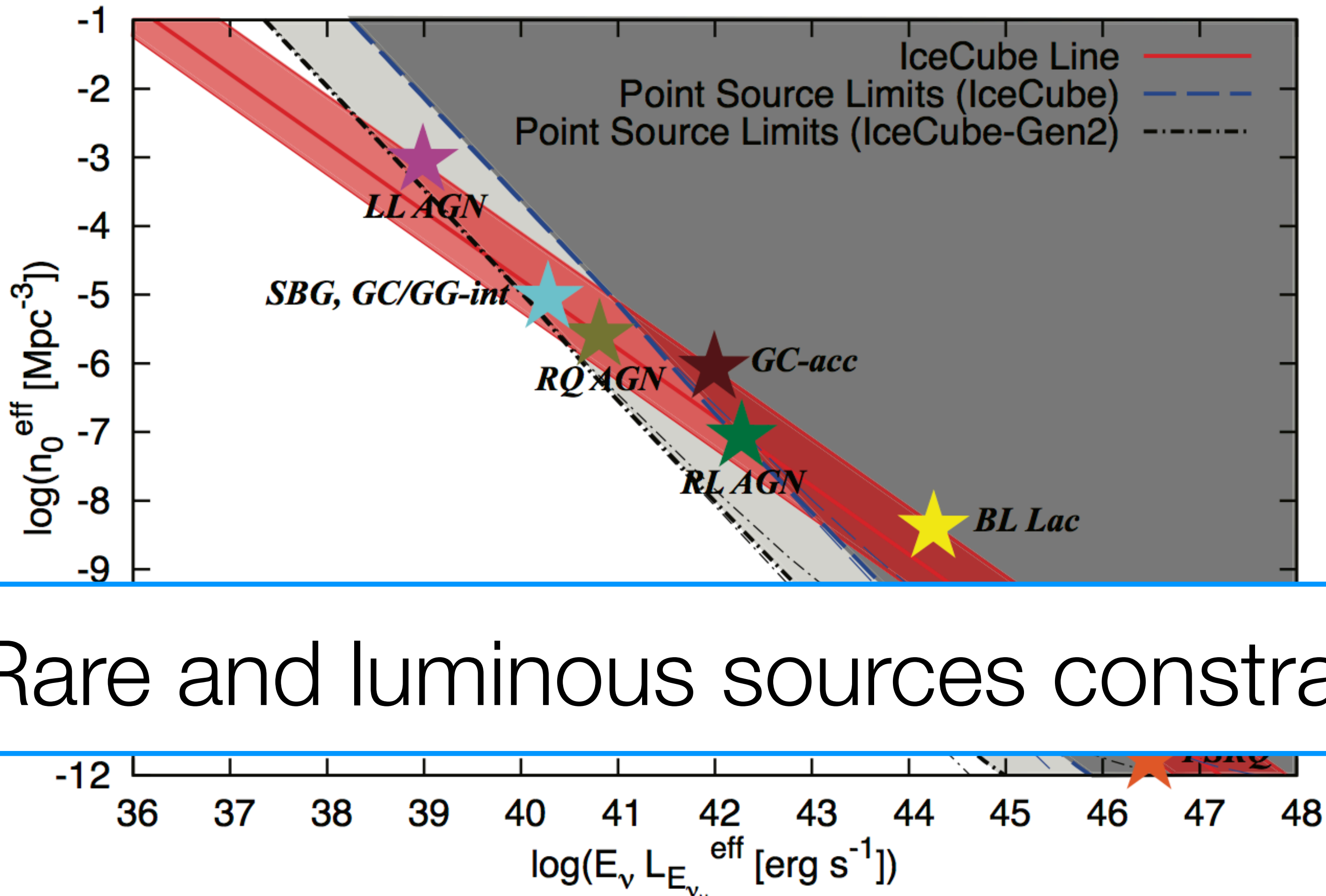
UHECR Emissivity



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

Generally OK (GRBs?, TDEs?)

Neutrino clustering constraints

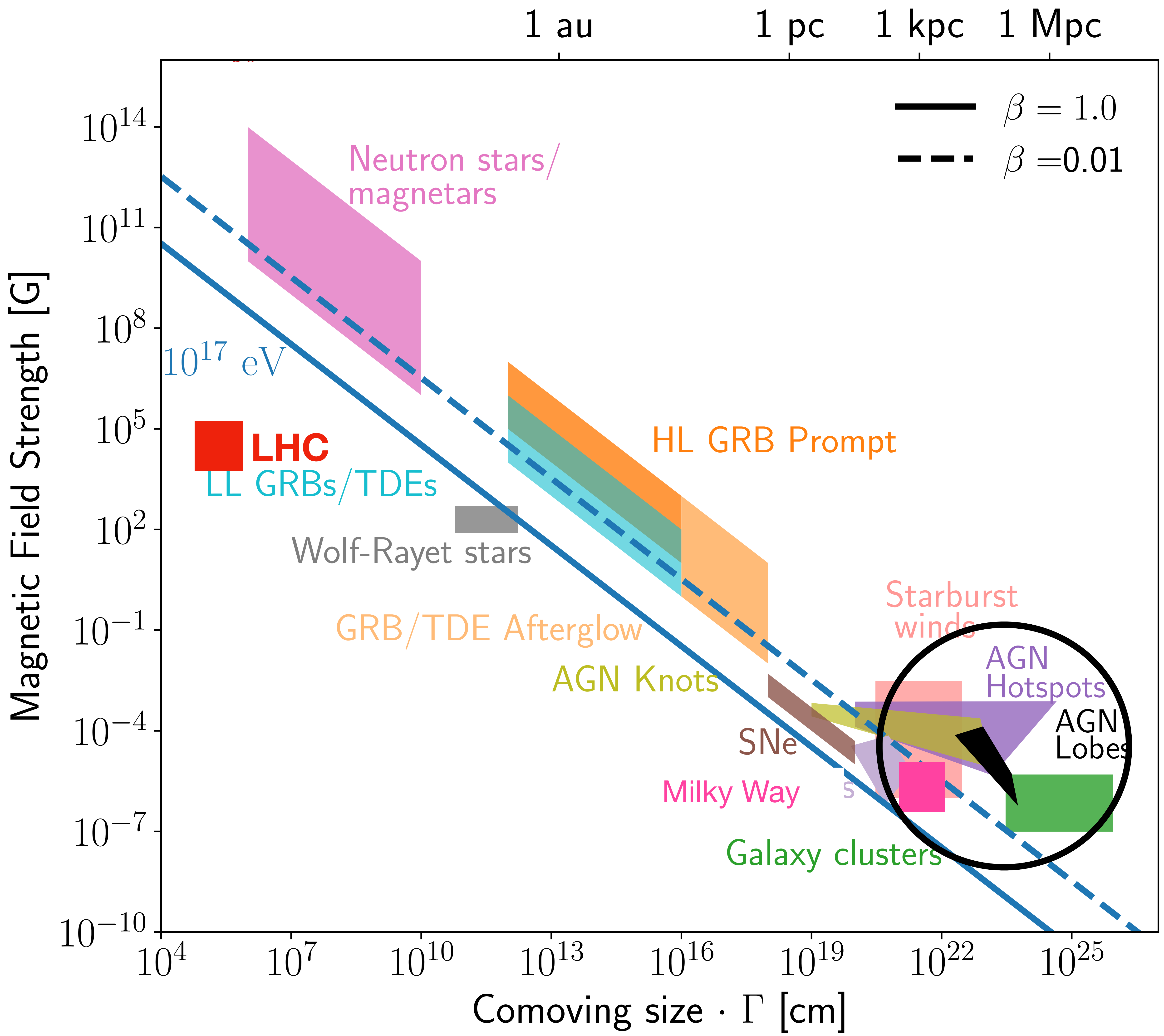


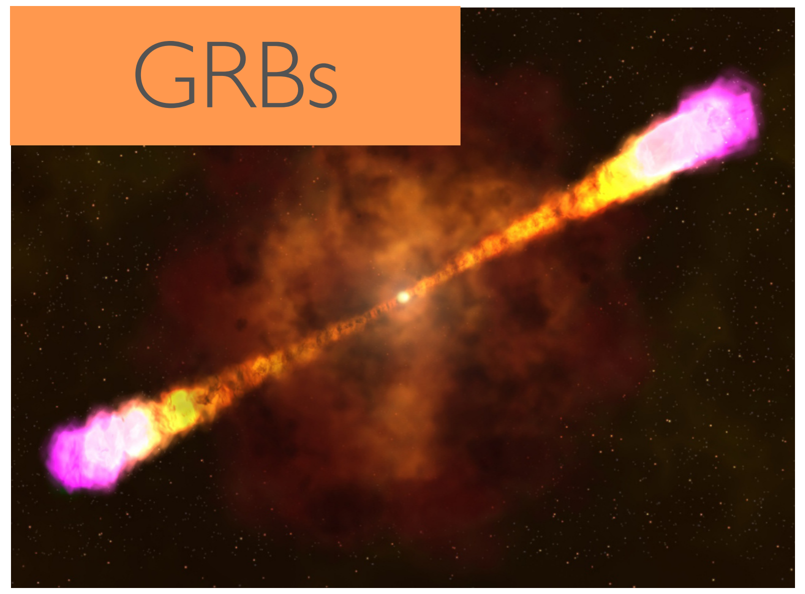
Rare and luminous sources constrained

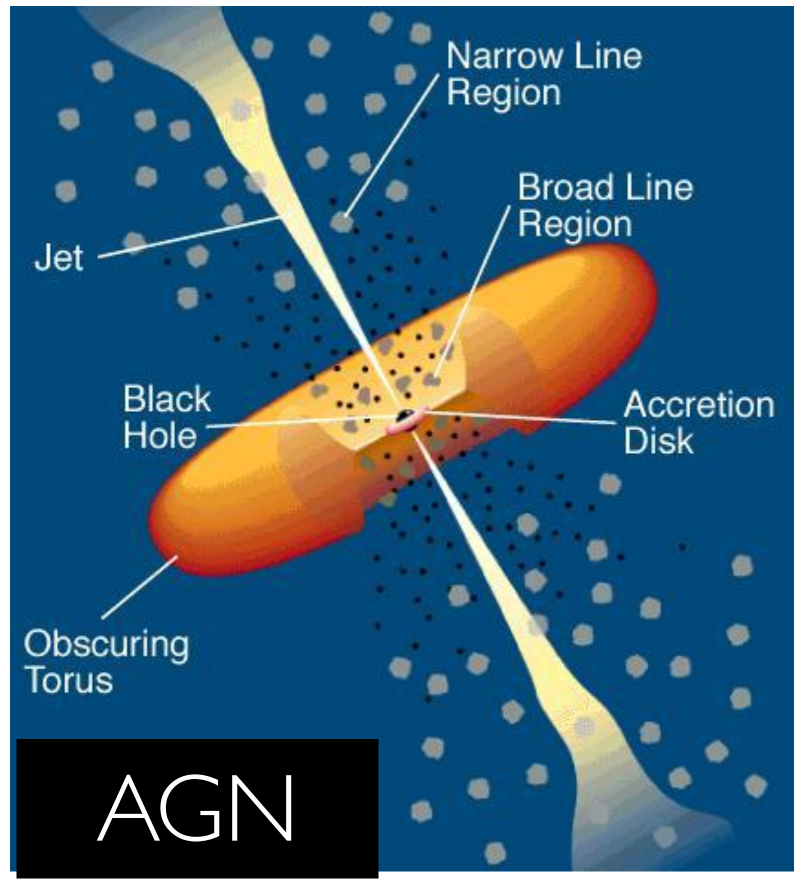
Lecture plan

- Generic source properties (number density, emissivity, maximum energy)
- Active Galactic Nuclei
- Starburst galaxies
- Gamma-ray bursts
- Tidal-disruption events

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







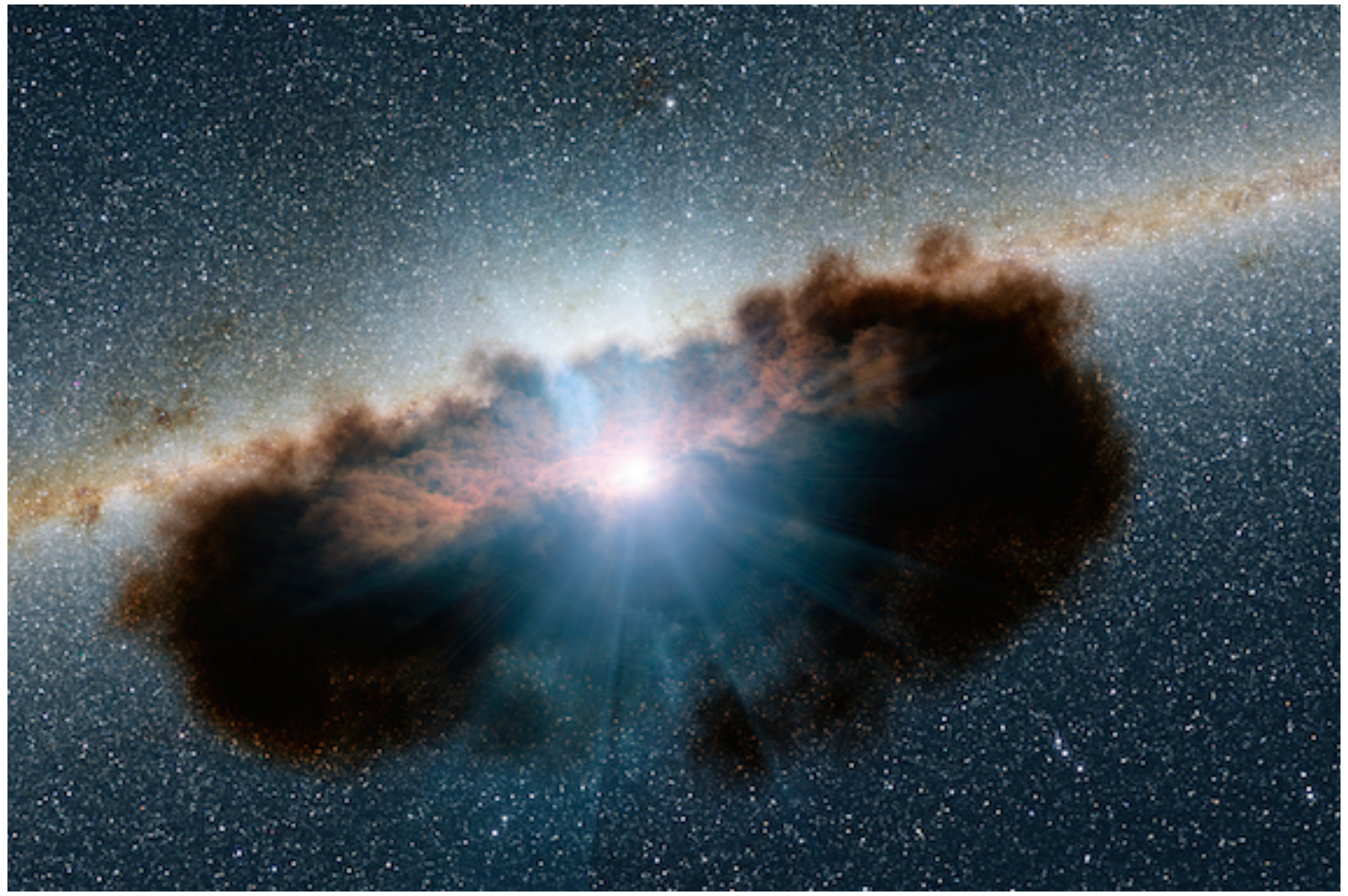
Active Galactic Nuclei

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

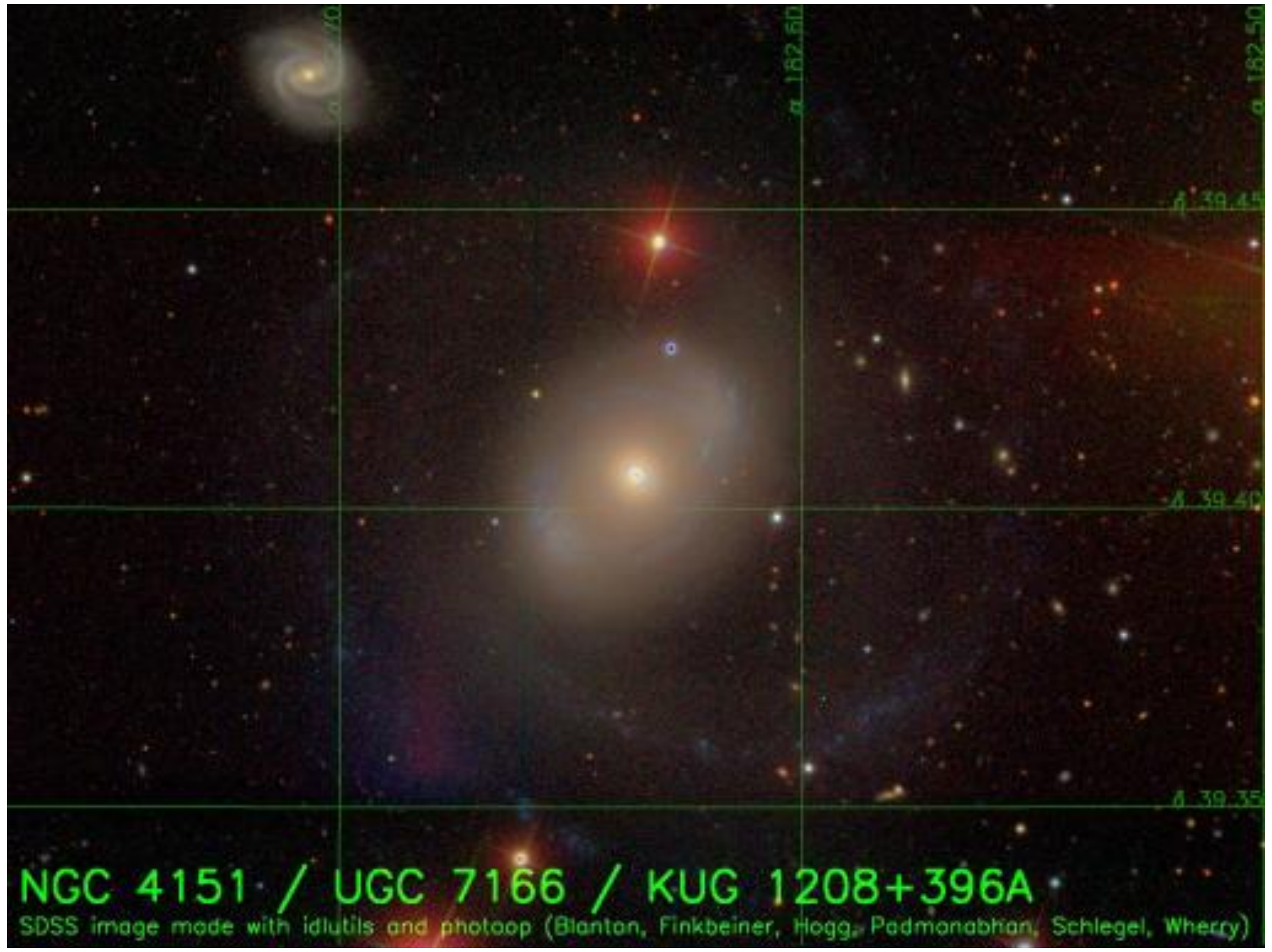
They host a super-massive black hole (SMBH) (10^6-10^{10} M_{sun}). ``Active'' as emission >> stars in the galaxy - accretion on to SMBH

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

1% of galaxies active



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



Active Galactic Nuclei

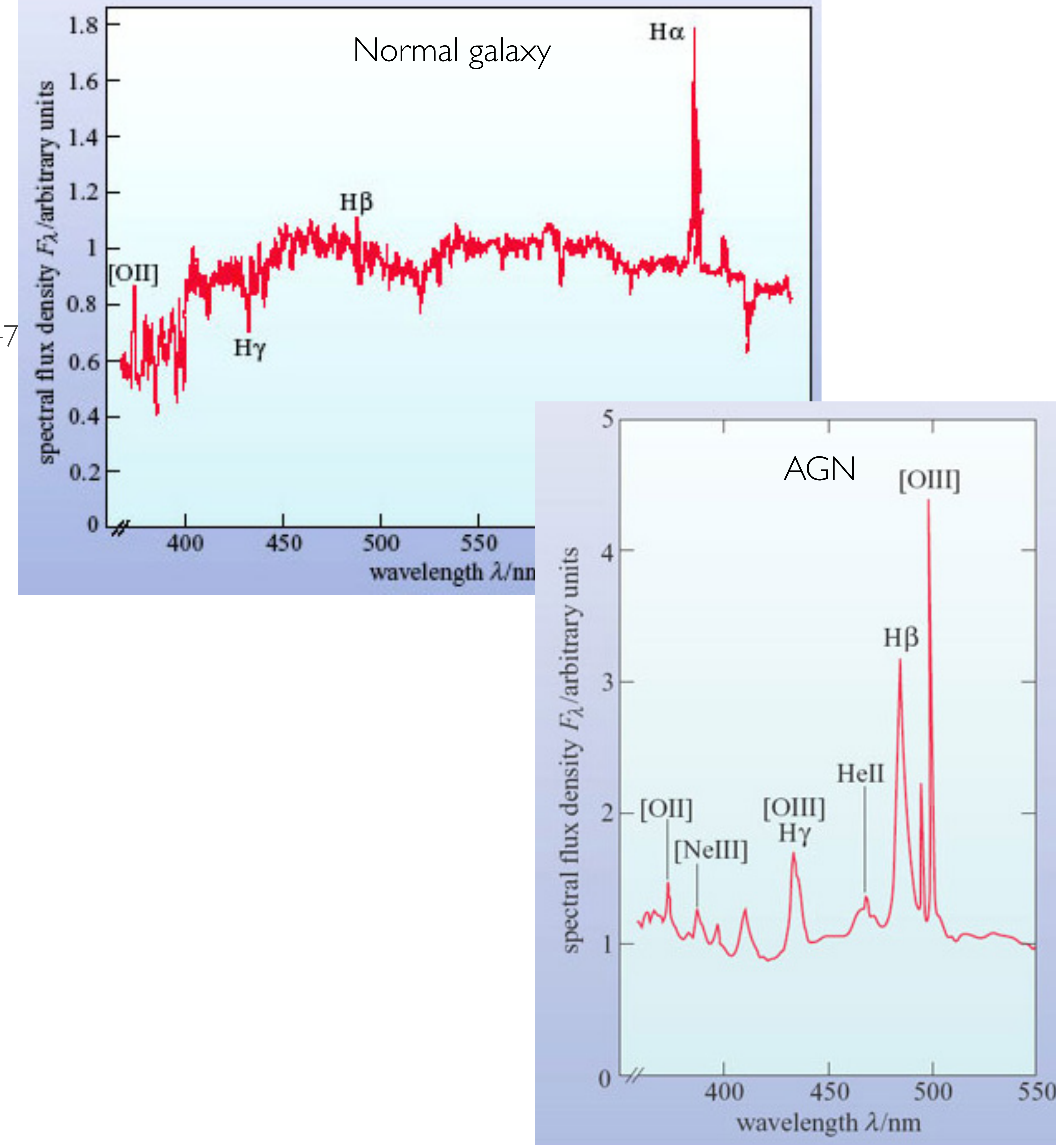
Most powerful ``steady'' sources in the Universe ($L \geq 10^{47}$ erg/s) > 1000 bright Galaxies!

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



[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

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

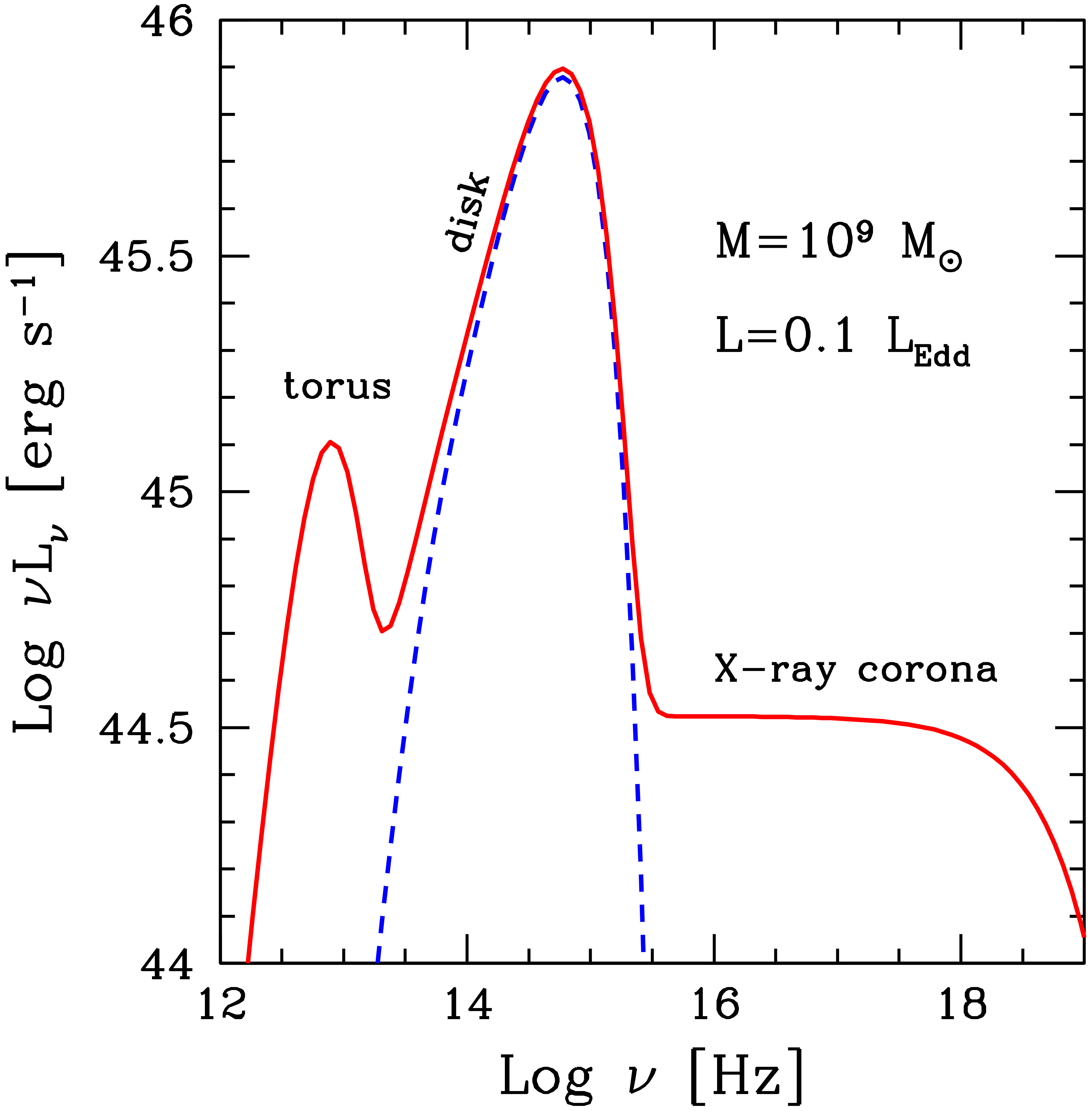
In solar masses per year, the requirement is

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

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

The engine

For an AGN with disk luminosity

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

and time variability

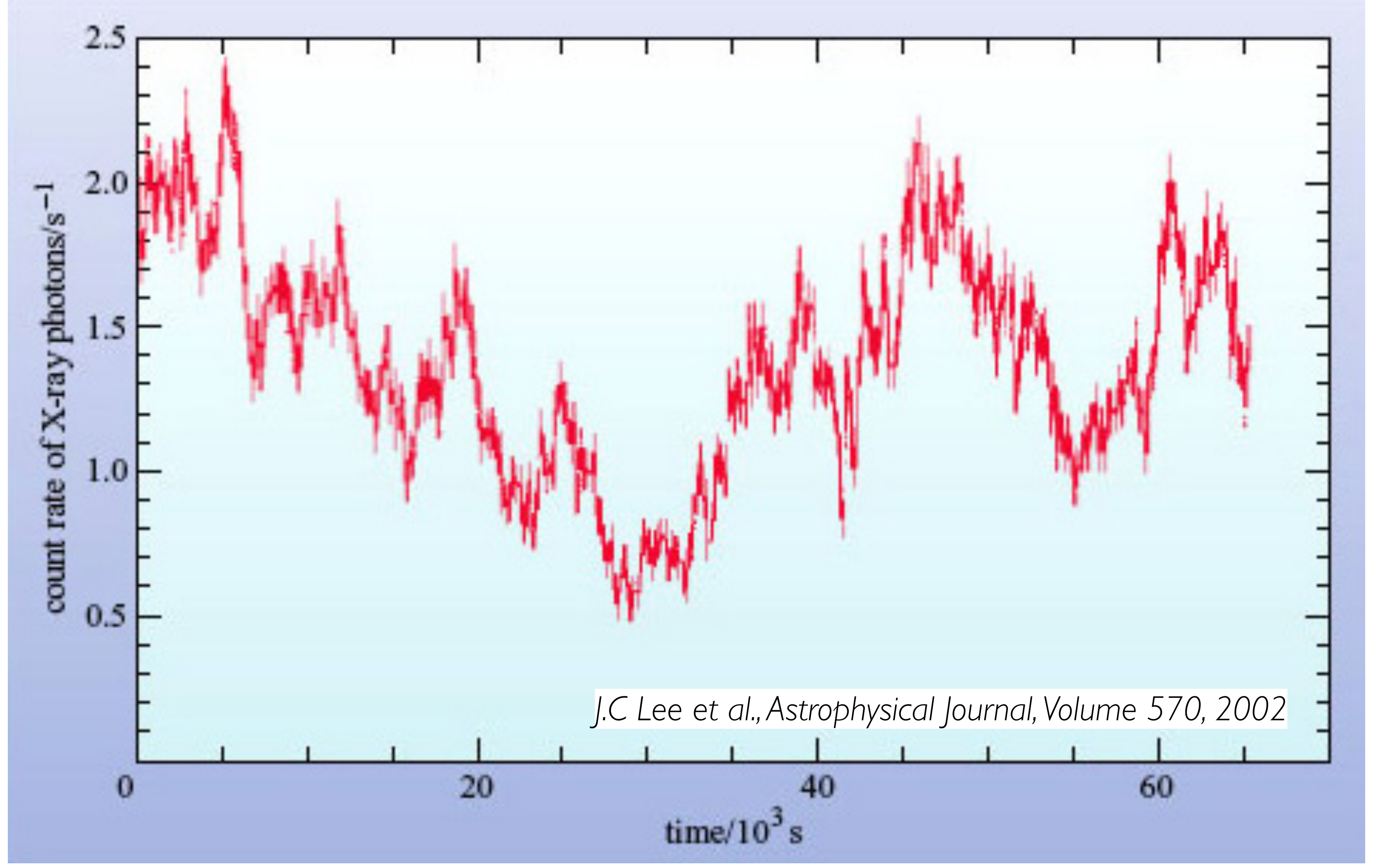
$$\Delta t = 10^4\ {\rm s}, \text{ causality dictates } R \sim c\Delta t = 0.01\ {\rm pc} = 20\ {\rm AU}$$

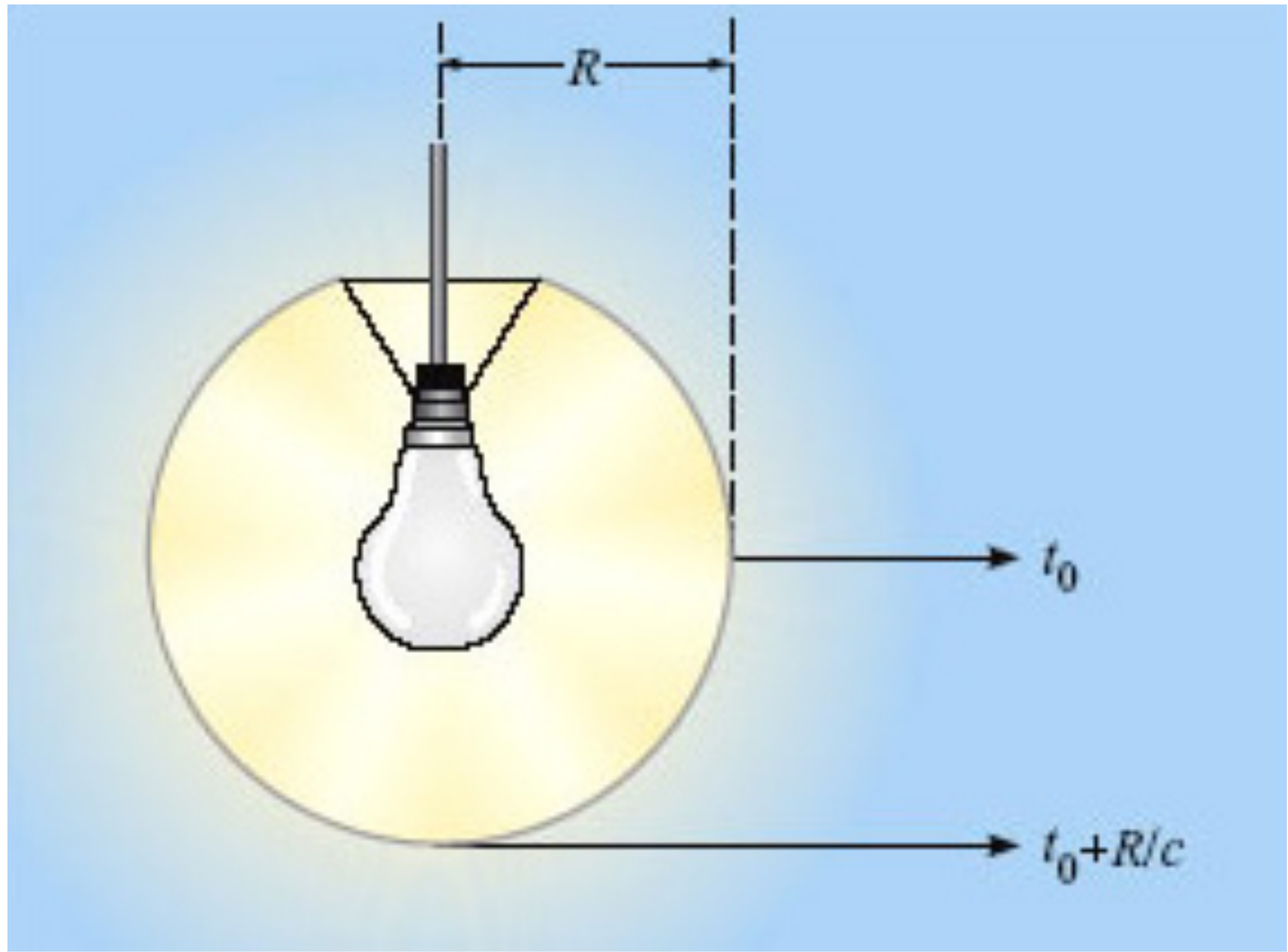
We need a supermassive black hole due to the Eddington limit!

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

I.e. we need,

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



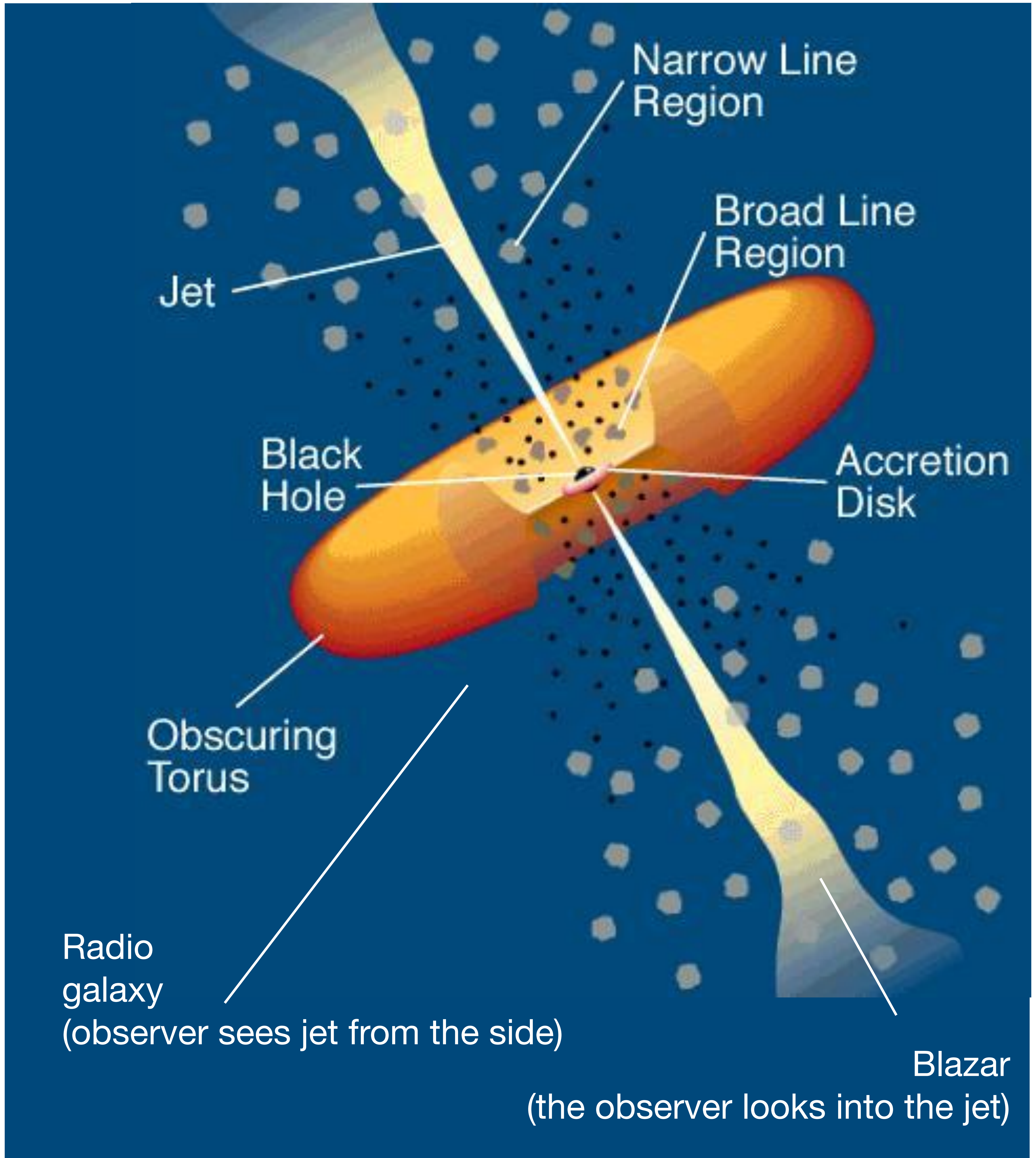


AGN Unification

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

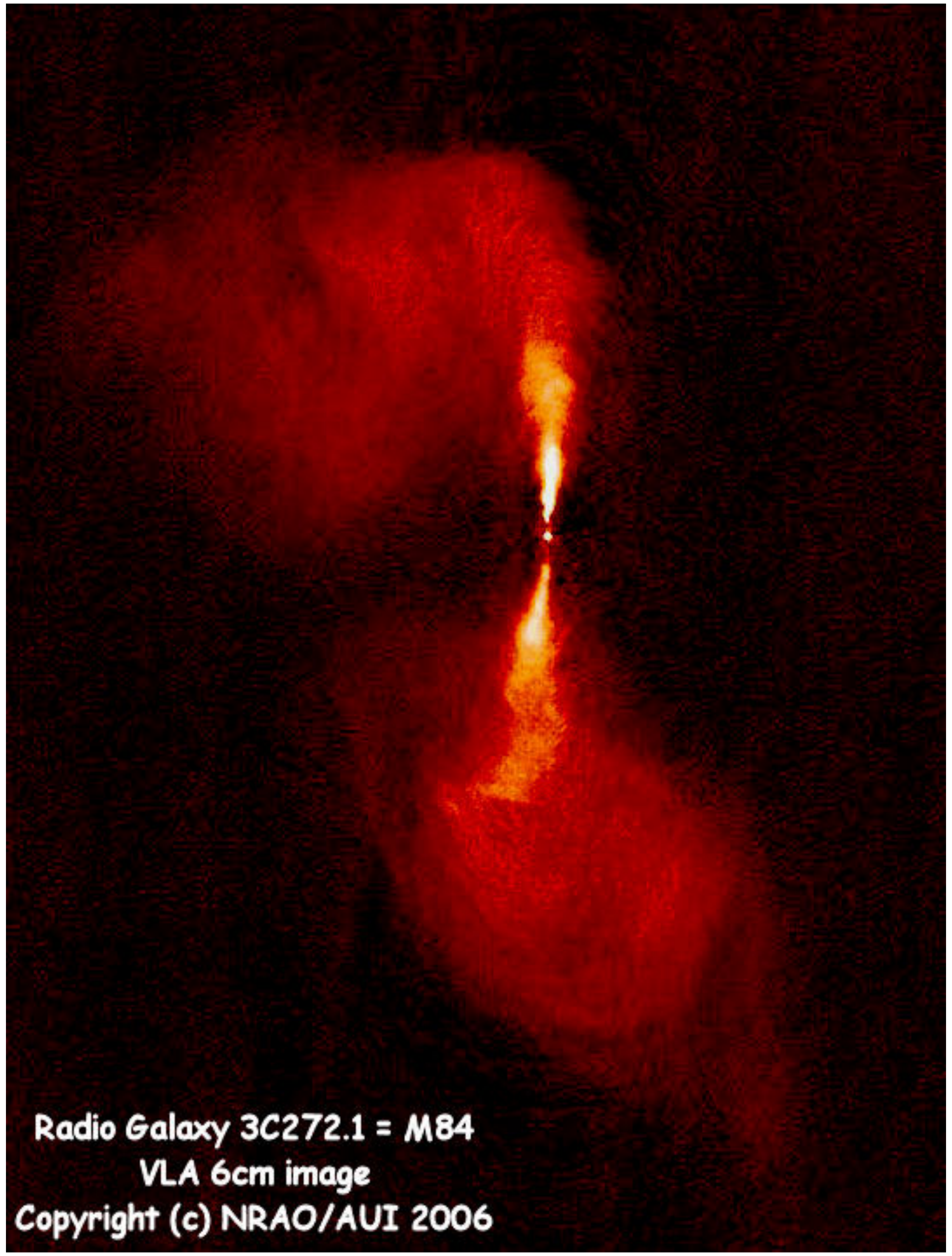
- Orientation
- Presence of jet or not (10% have it)
- Radiative efficiency

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

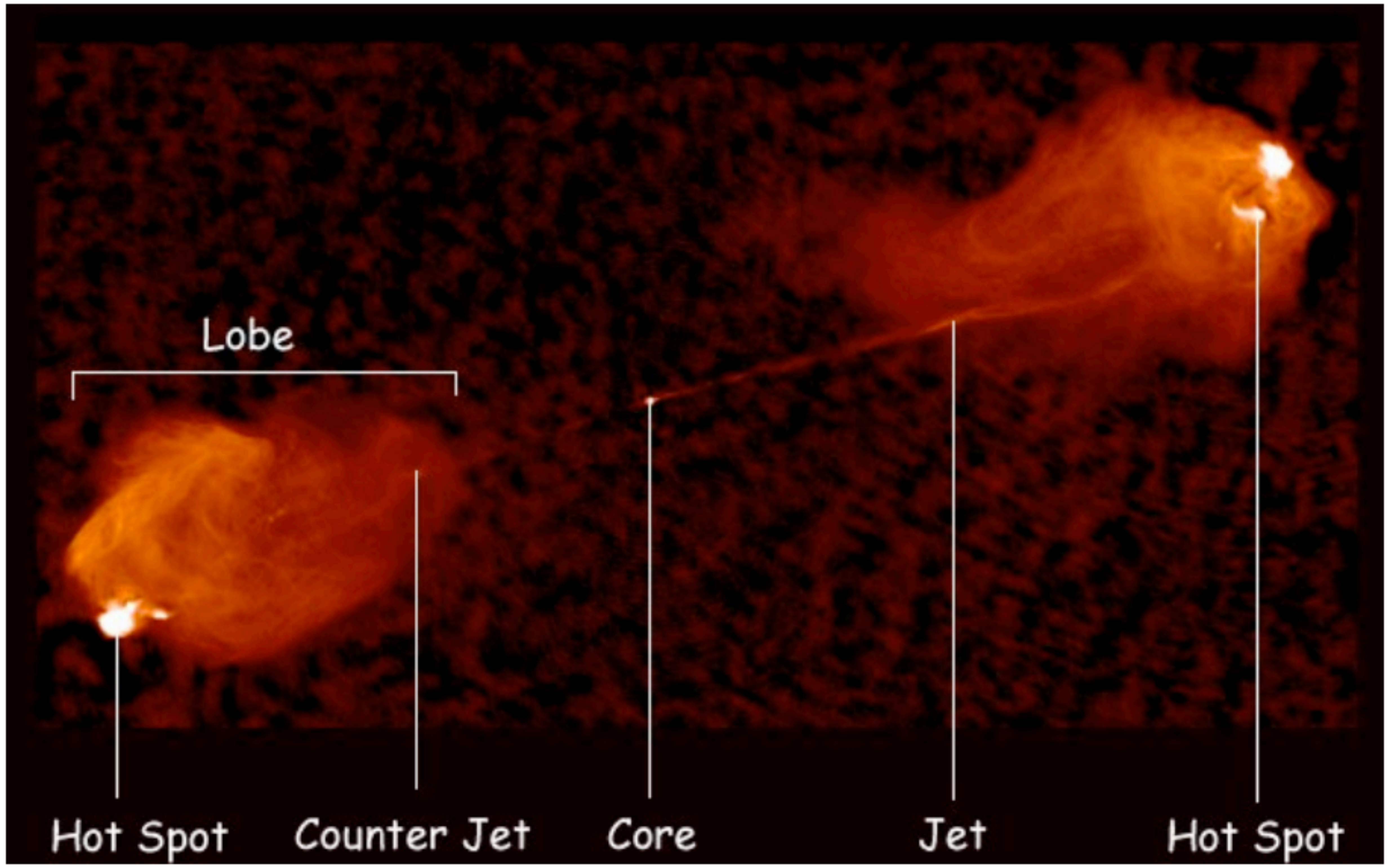


10% of AGN host jets

FRI



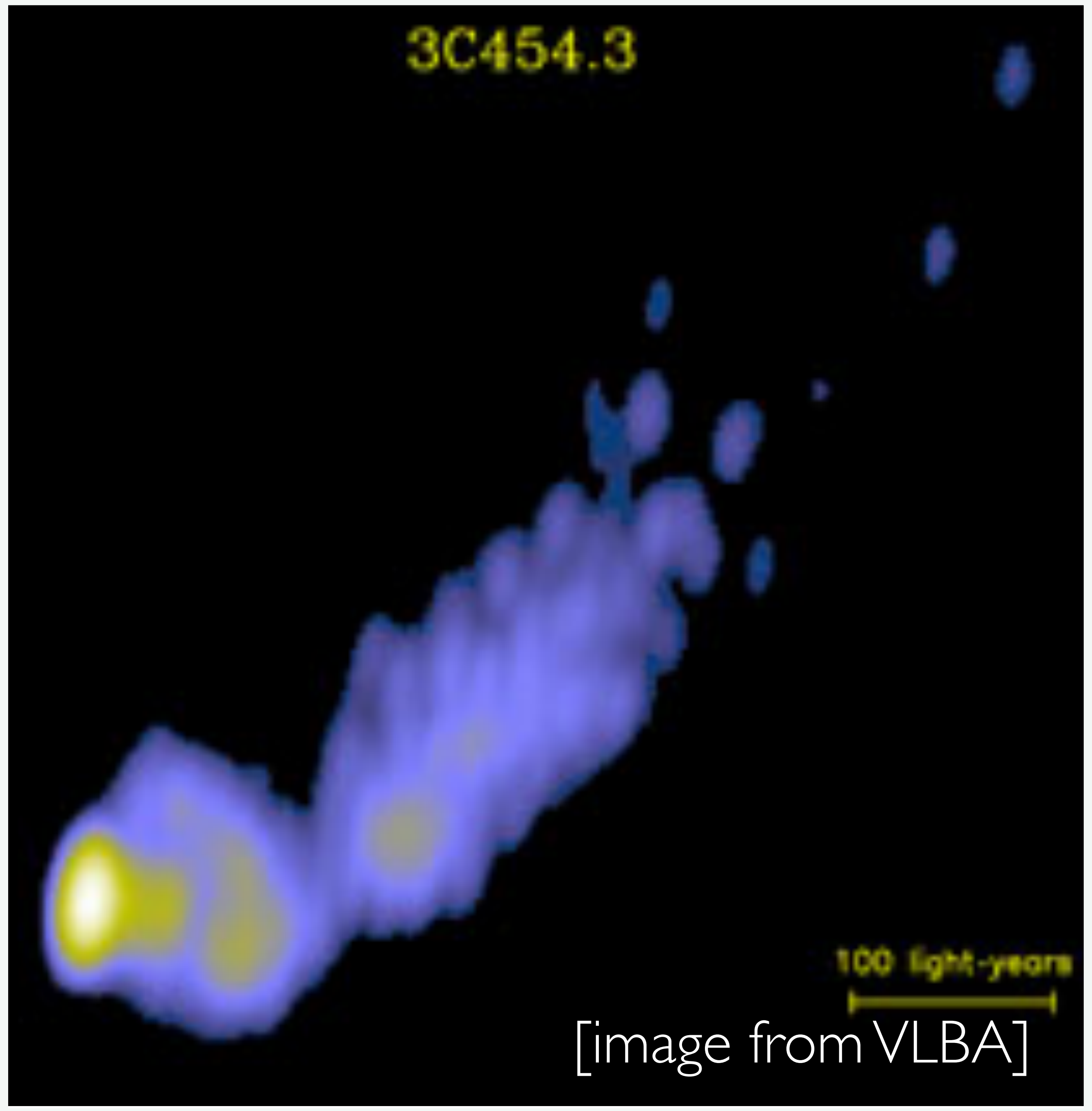
FRII



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

Blazars: Star-like appearance

Radio

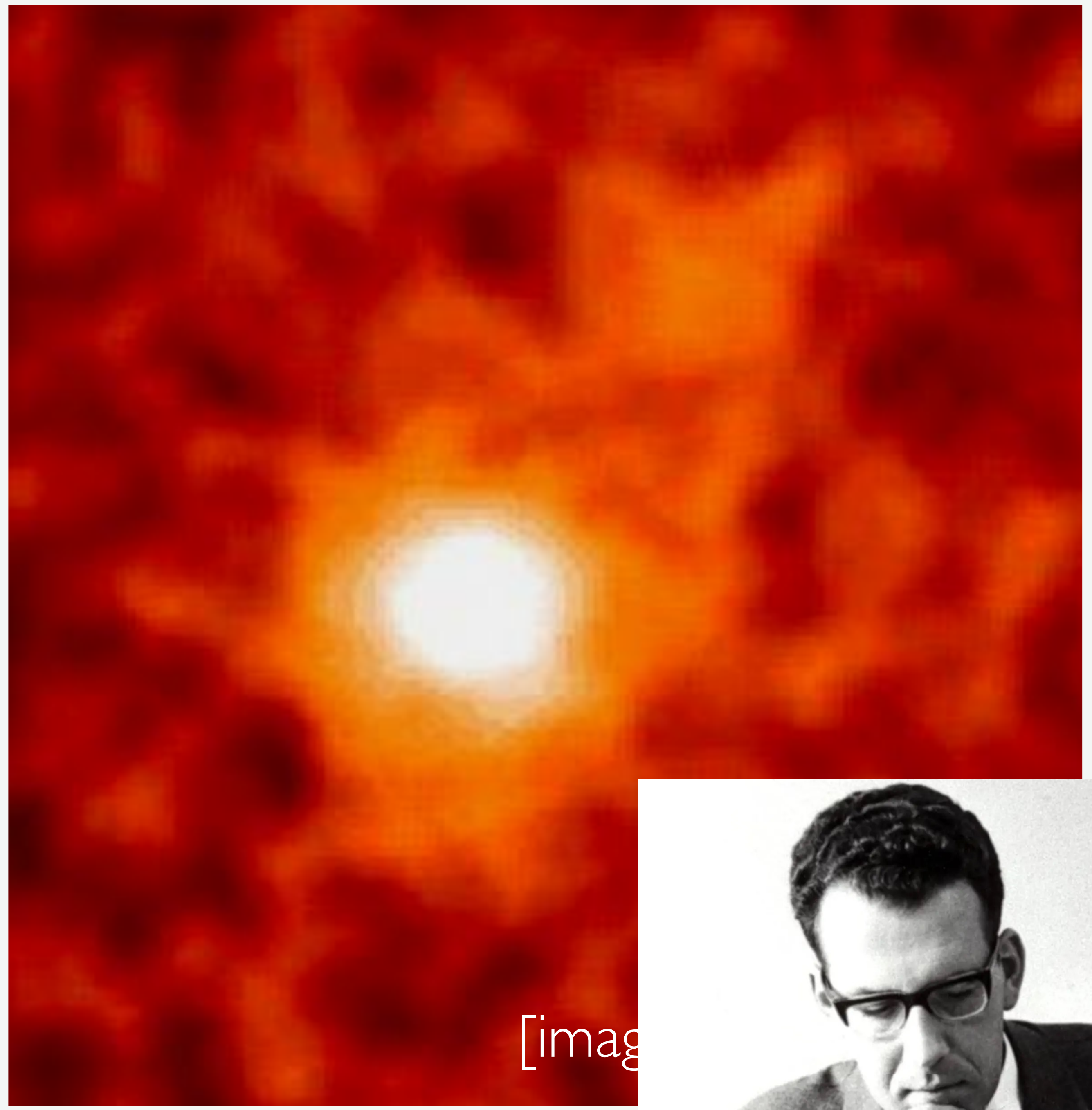


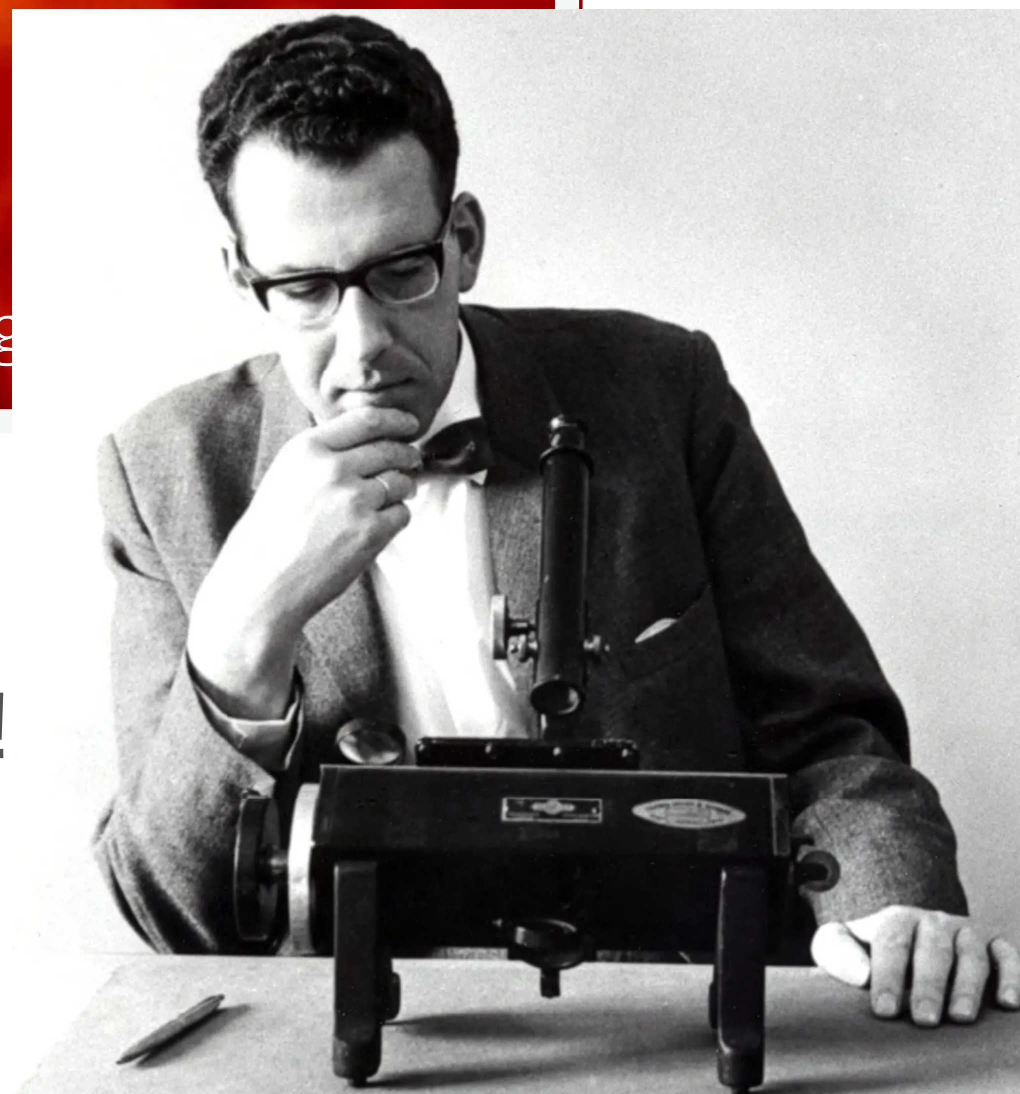
[image from VLBA]

Optical


[image from SDSS]

γ-rays

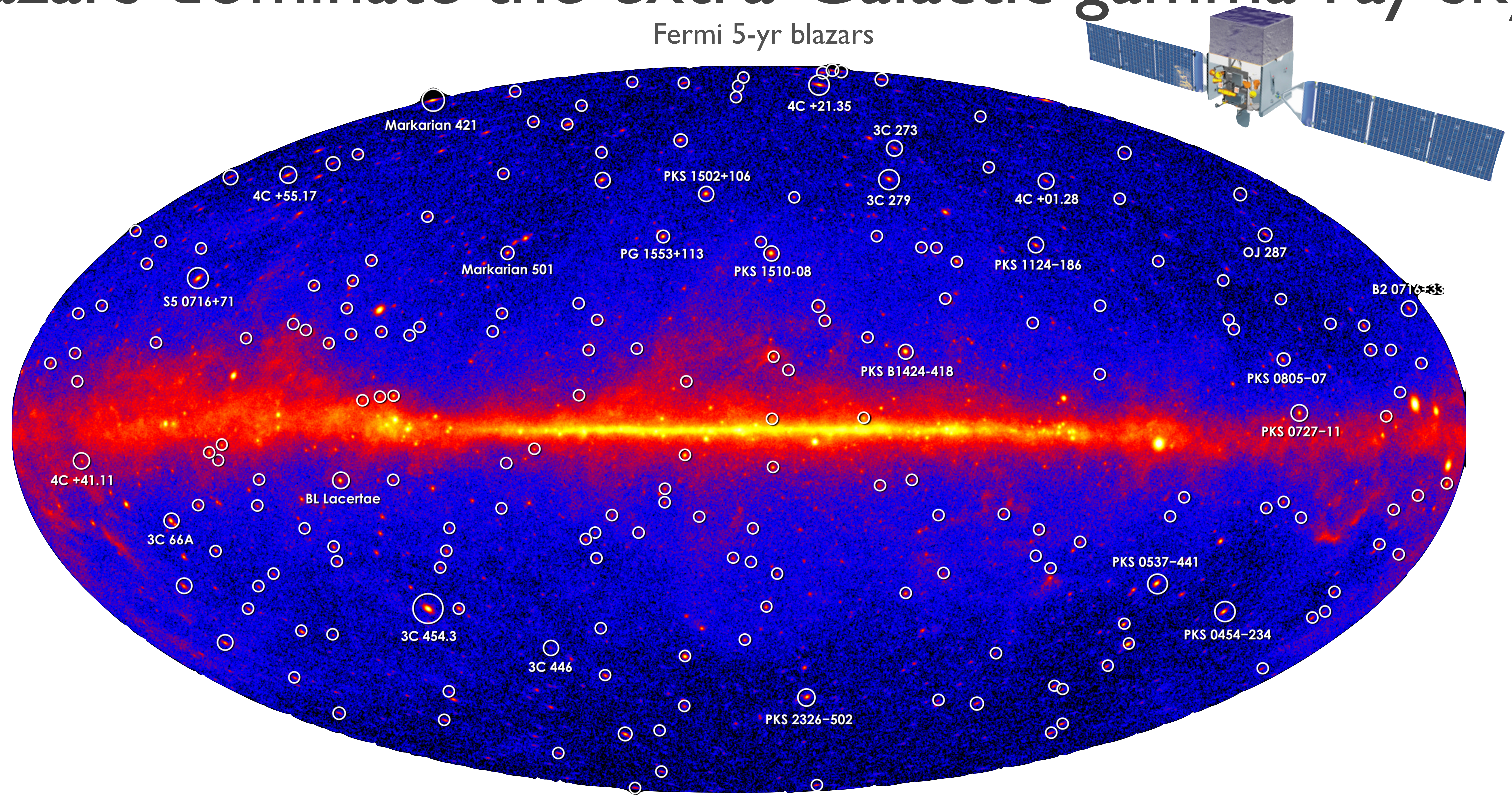

[imag



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

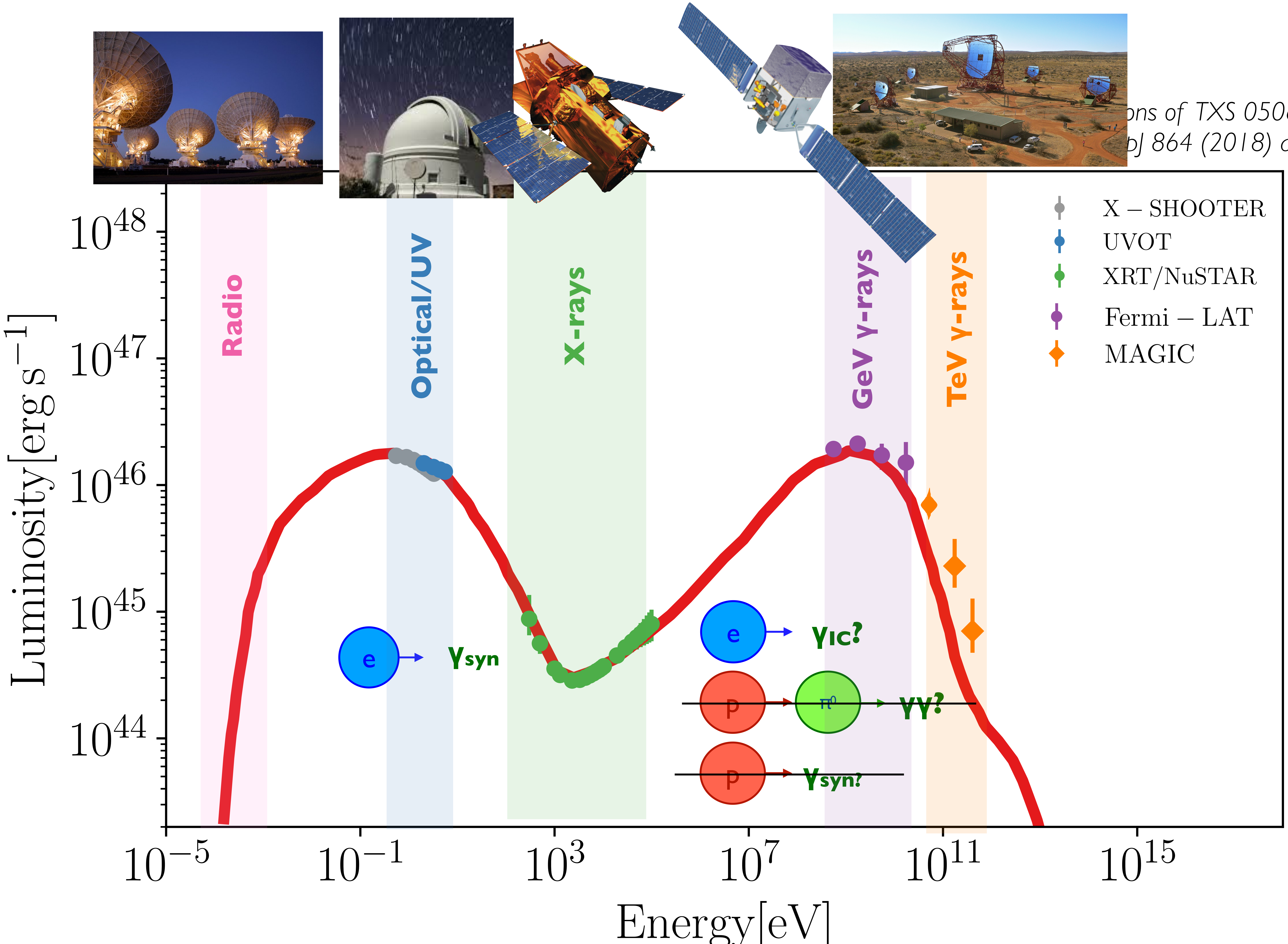
Blazars dominate the extra-Galactic gamma-ray sky

Fermi 5-yr blazars



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

Blazar broadband emission



...ons of TXS 0506+056 in 2017 and model SED
...bJ 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

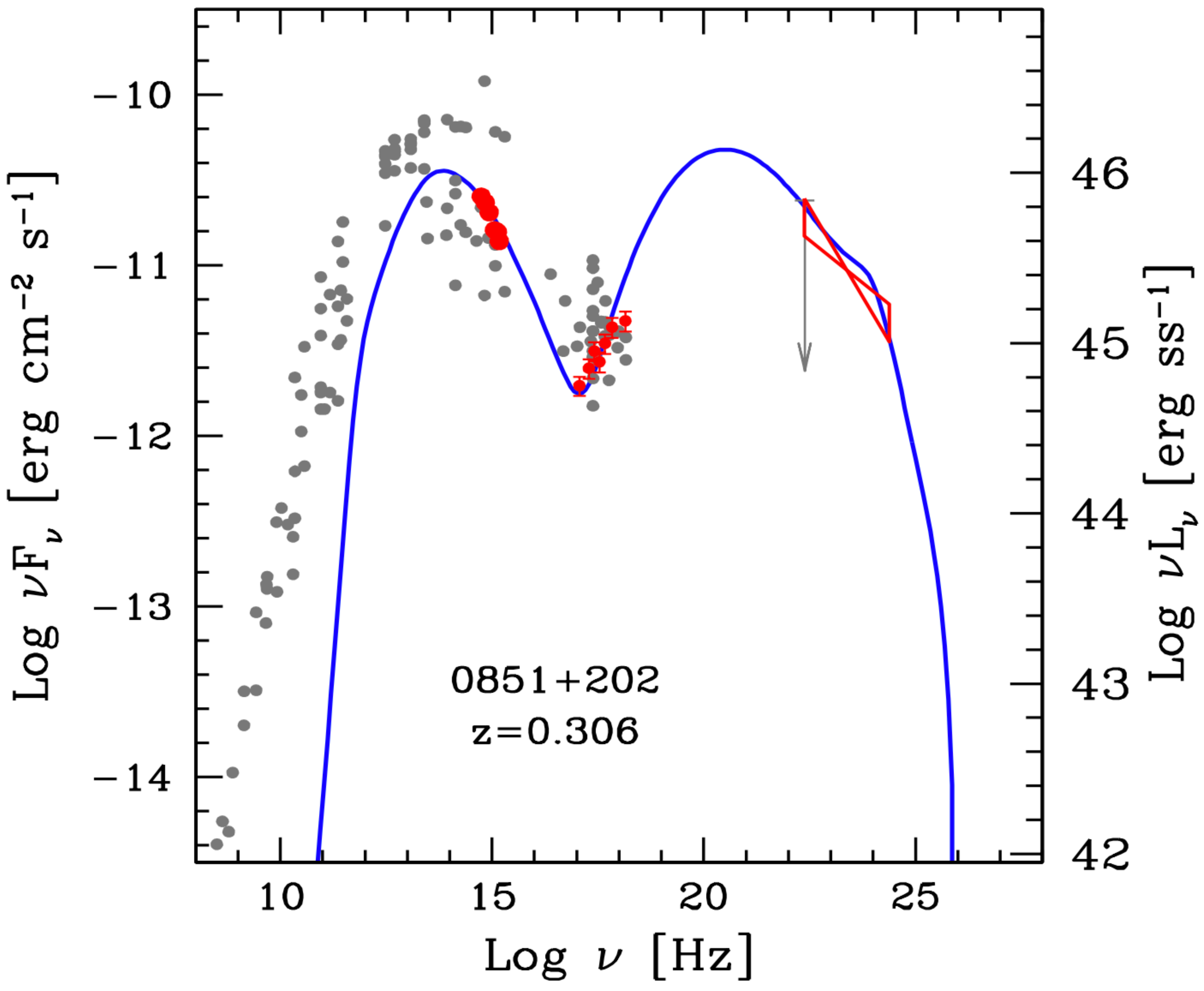
$t = t'/\delta(1+z)$ – time

see Ghisellini T3.1 pg. 45

Emission radius

$$R \le c t_{\rm var} \frac{\delta}{1+z}$$

Measured



What we can infer from the blazar SED

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

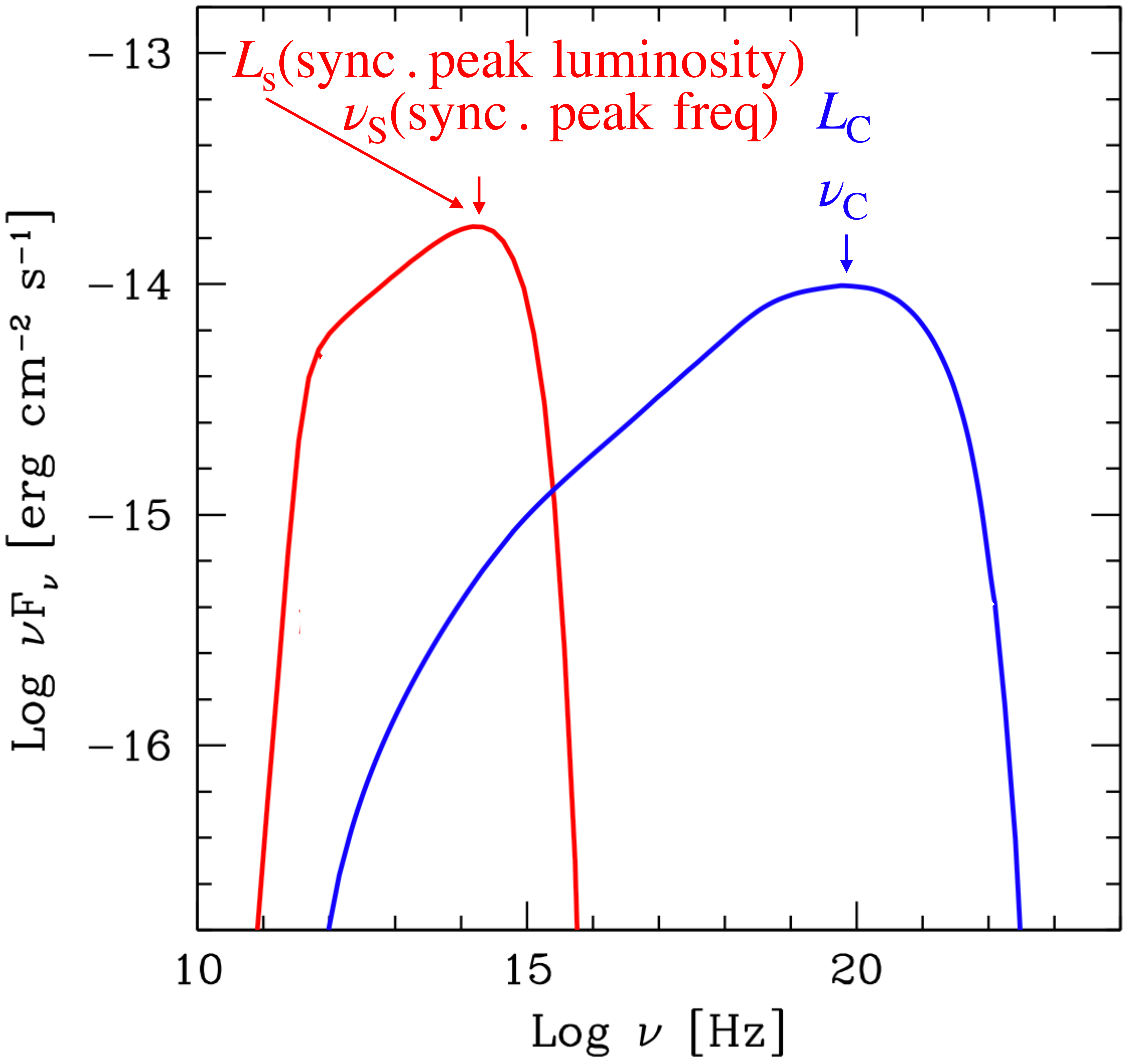
$$L_s \propto U_B - (1)$$

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

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

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

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



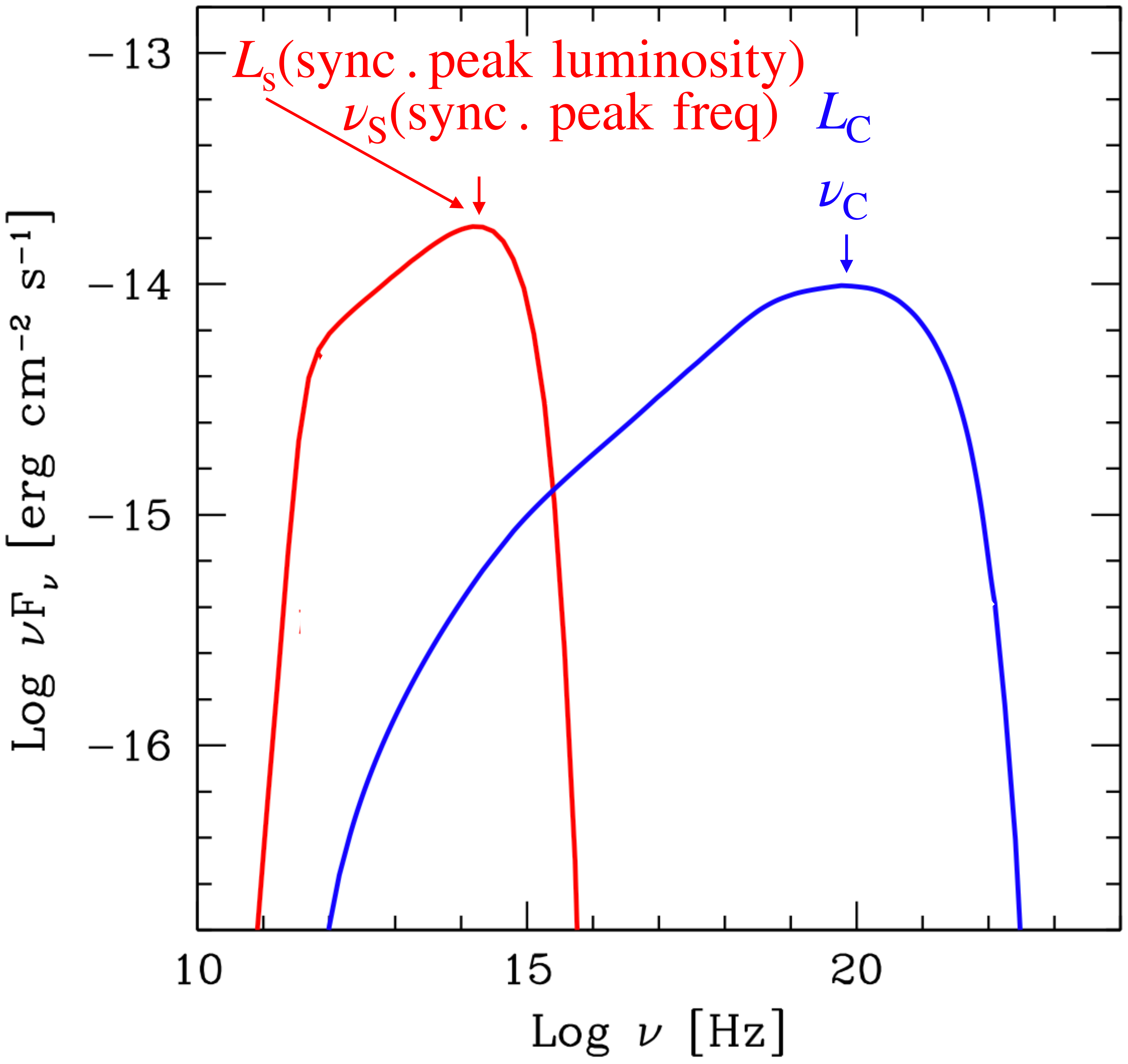
What we can infer from the blazar SED

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

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

Rearranging, we get,

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



What we can infer from the blazar SED

From the peak frequencies we have,

γ_{break} – Lorentz factor of emitting elec .

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

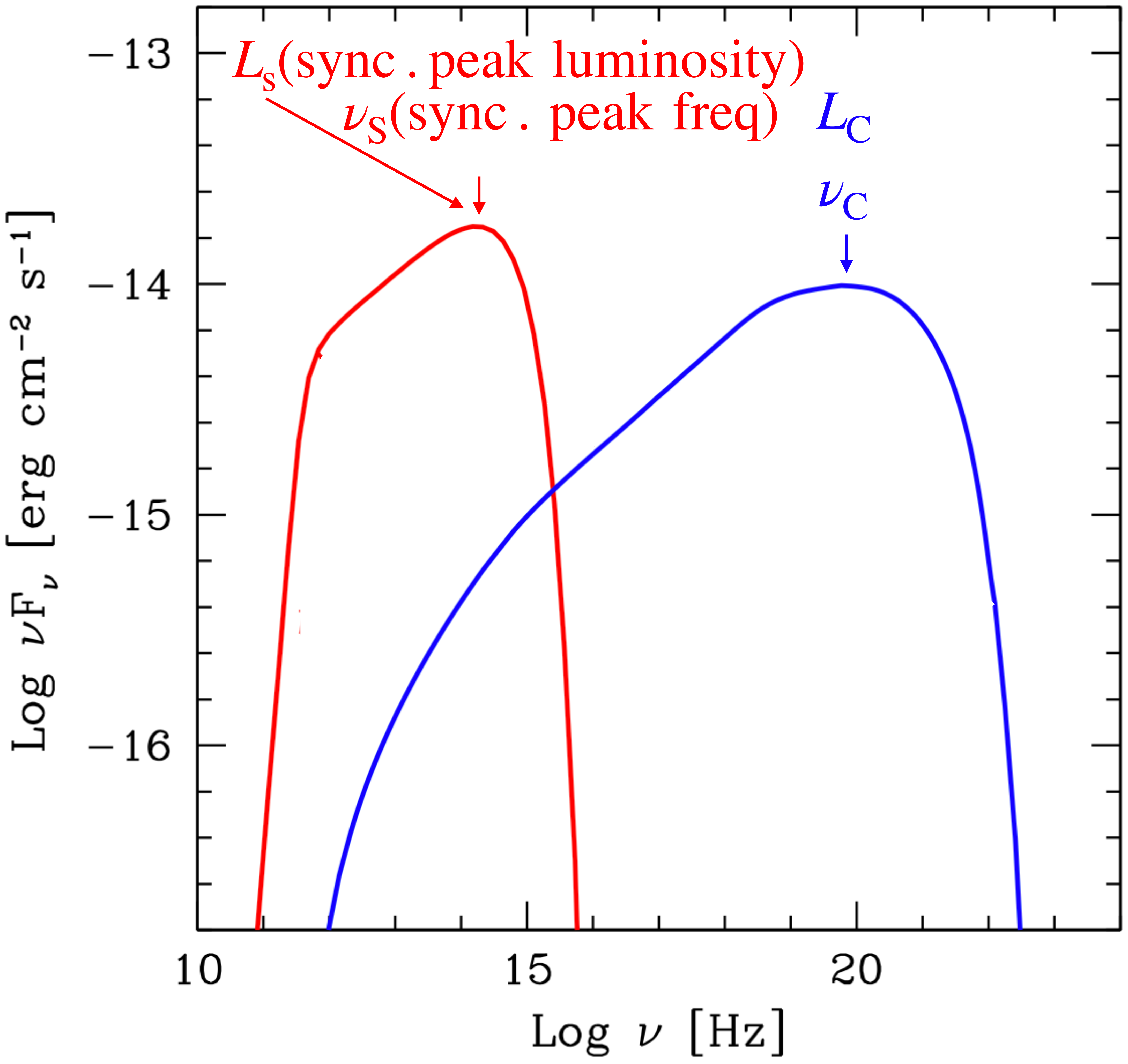
$$\gamma_{\mathrm{break}} = \left(\frac{3\nu_C}{4\nu_S}\right)^{1/2} \quad - (6)$$

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

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:

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

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

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

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

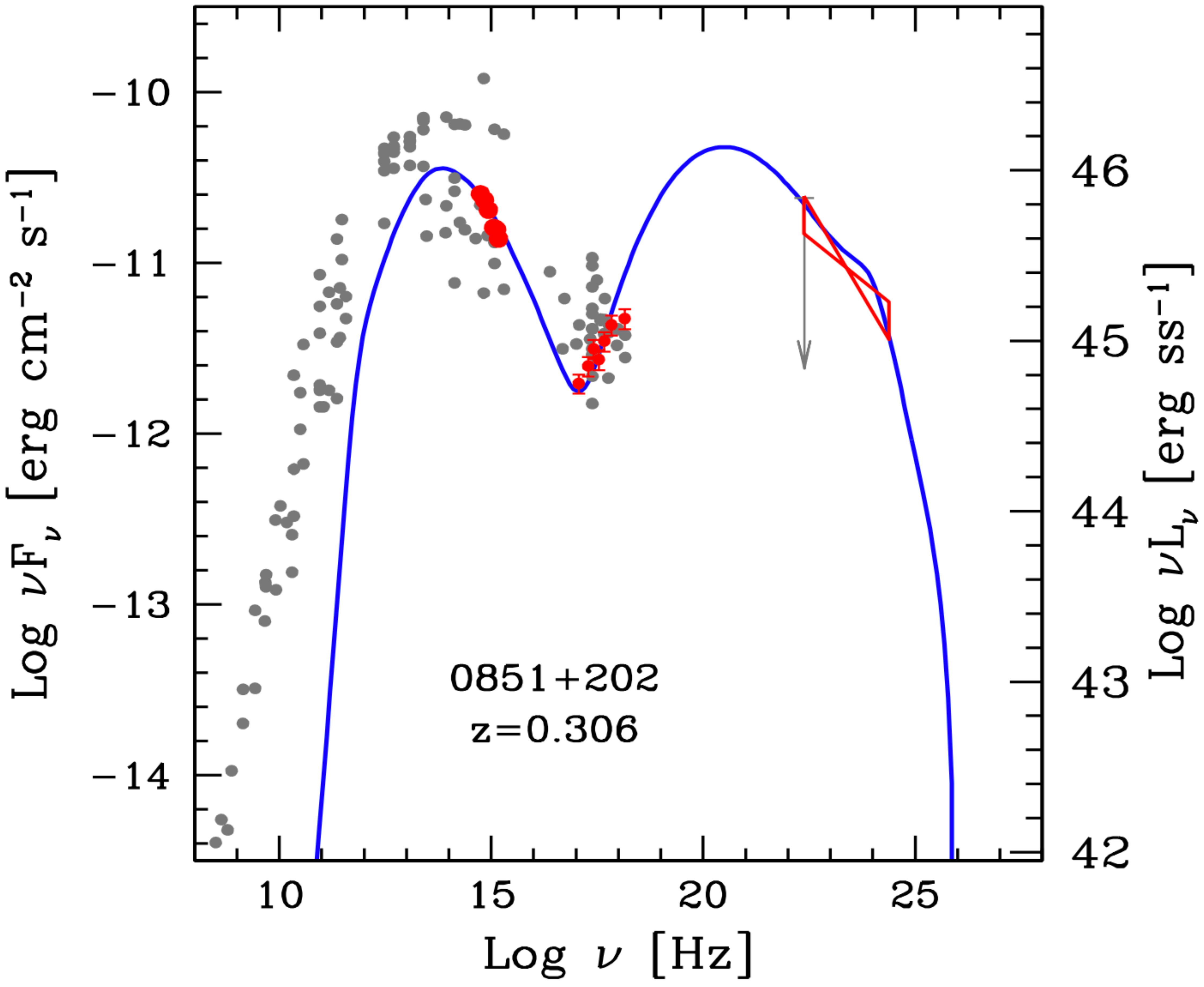
For typically inferred parameters

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

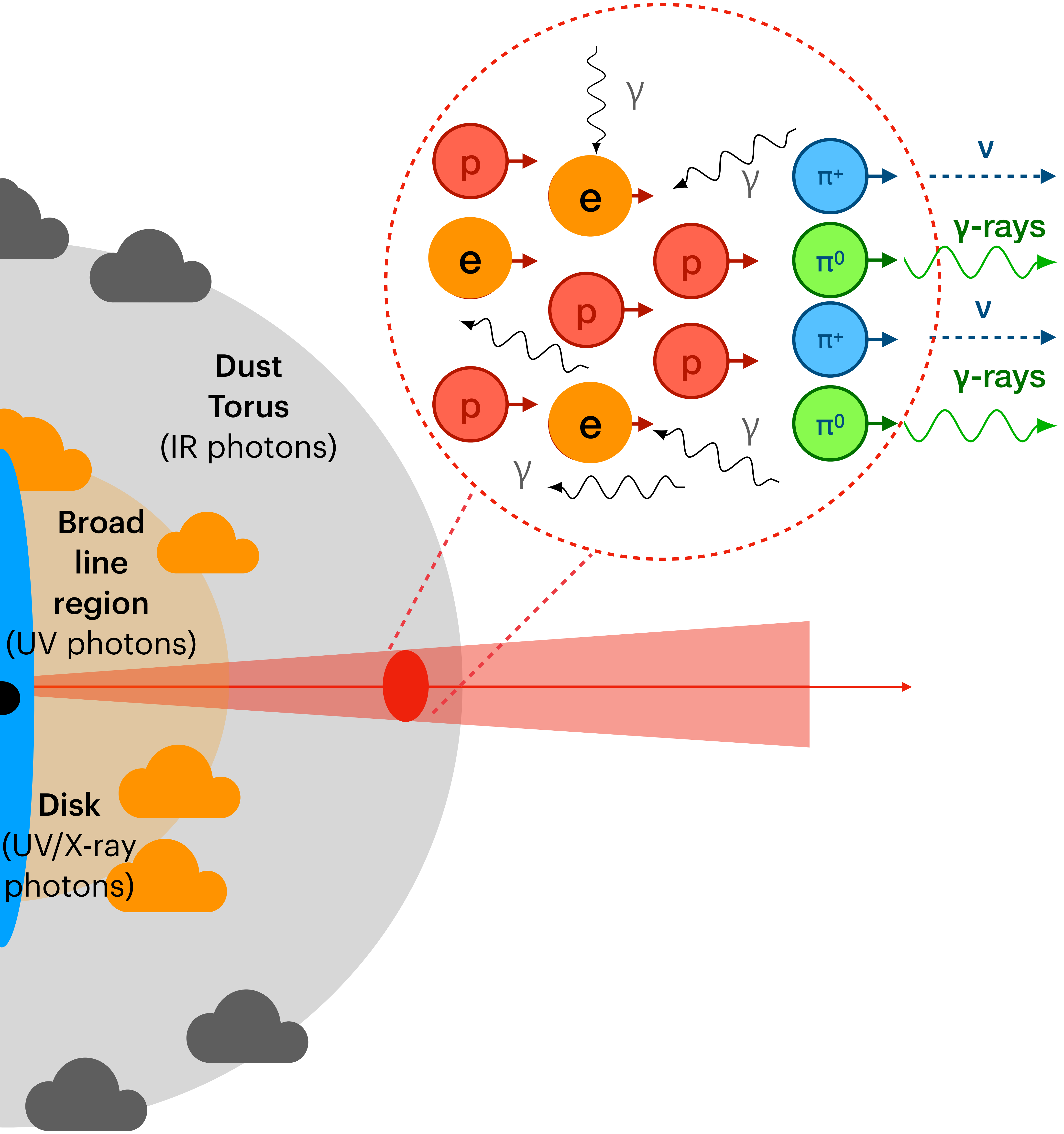
$\Gamma \sim \delta \sim 10 - 50$

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

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



Neutrino production in blazars



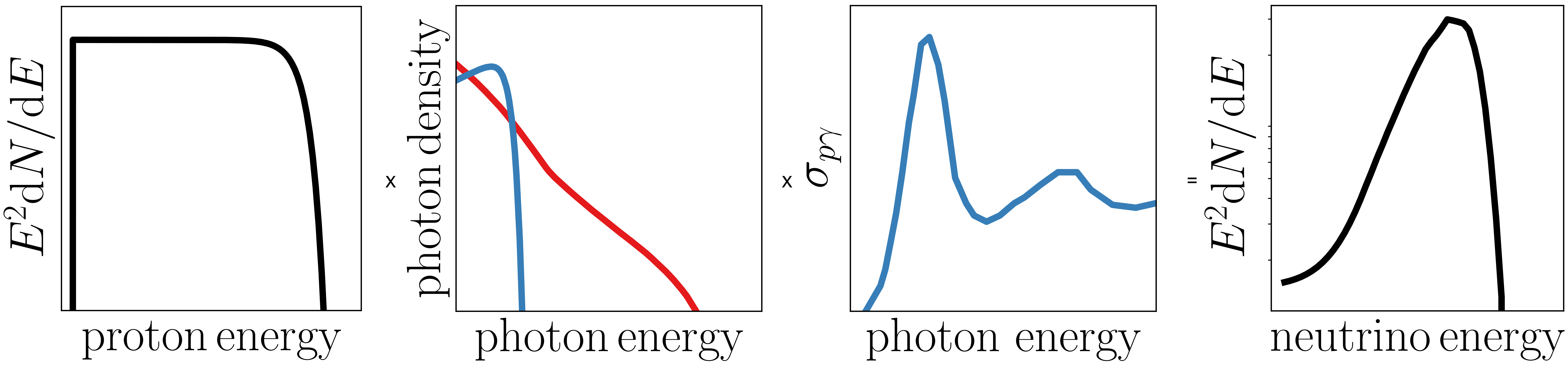
TXS 0506+056 observations:
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. Science 361, 2018,
MAGIC Coll. Astrophys.J. 863 (2018) L10
IceCube Collaboration: M.G. Aartsen et al. Science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



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

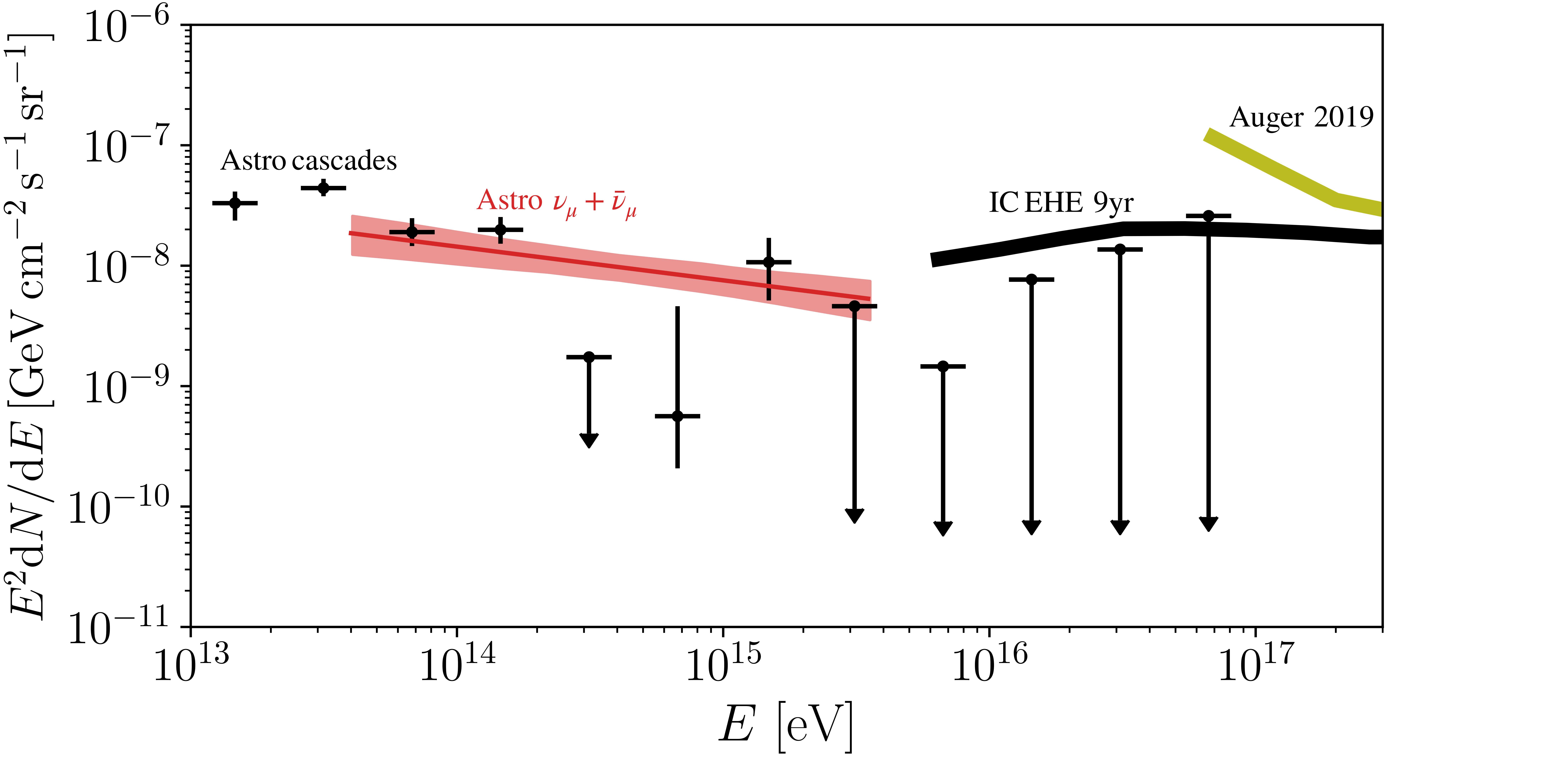
$$E_{\text{dust torus}} = 0.1 \text{ eV}$$

Neutrino typical energy:

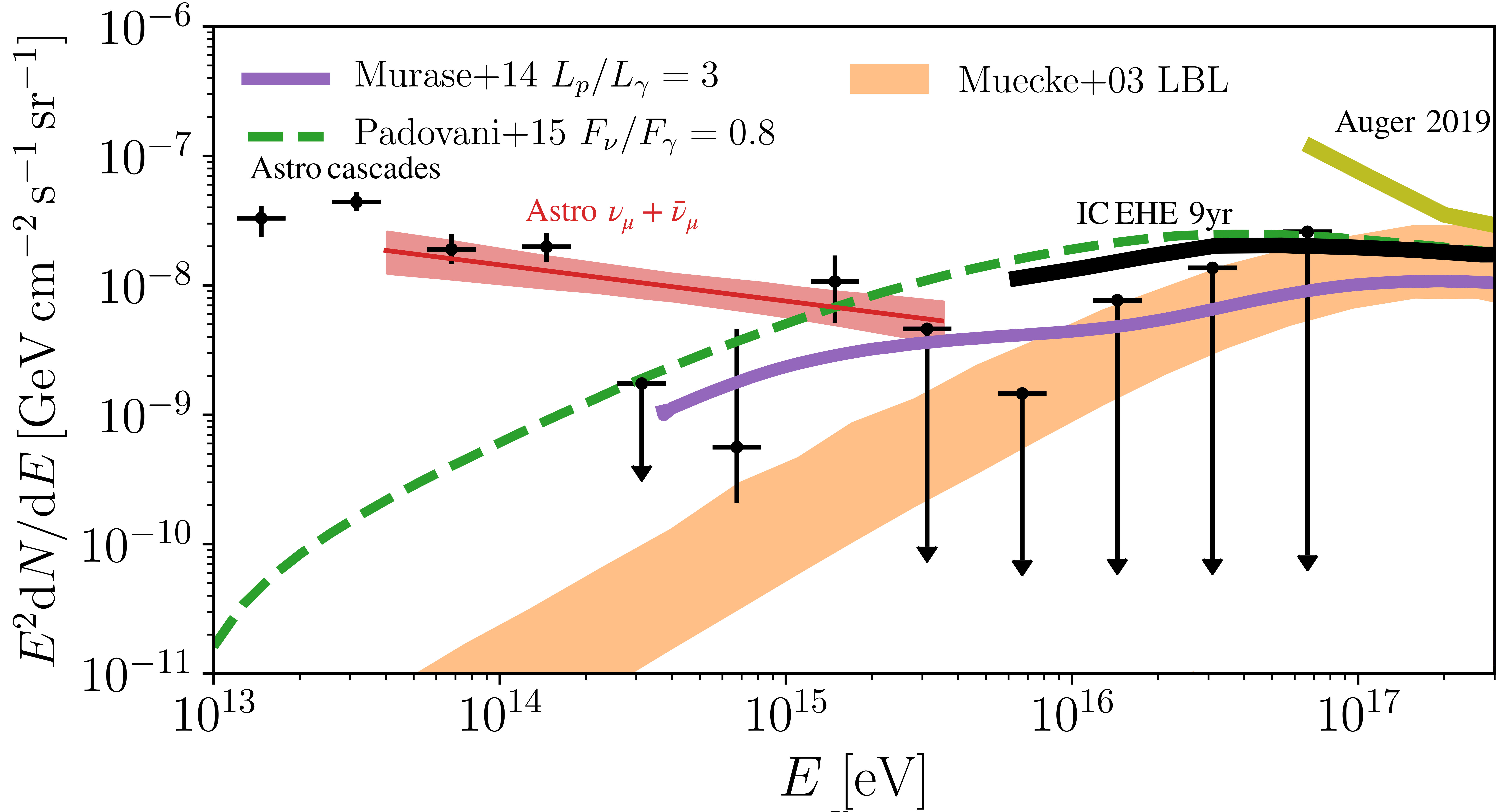
$$E_{\nu,\text{BLR}} = \frac{80 \text{ PeV}}{(1+z)^2} \left(\frac{\delta}{10}\right)^2 \frac{10 \text{ eV}}{E_\gamma}$$

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

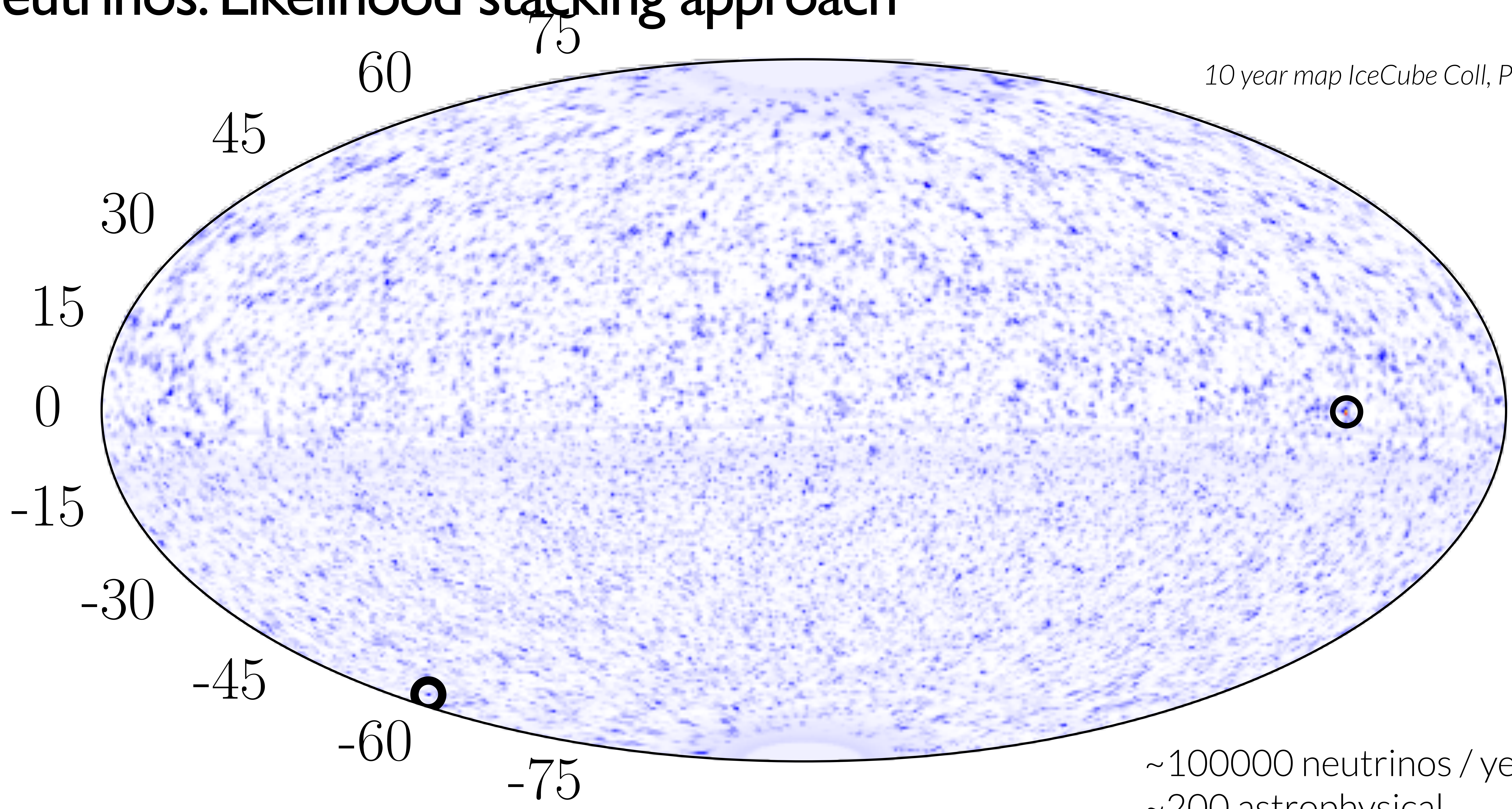
Possible contribution of blazars to the diffuse neutrino flux



Possible contribution of blazars to the diffuse neutrino flux



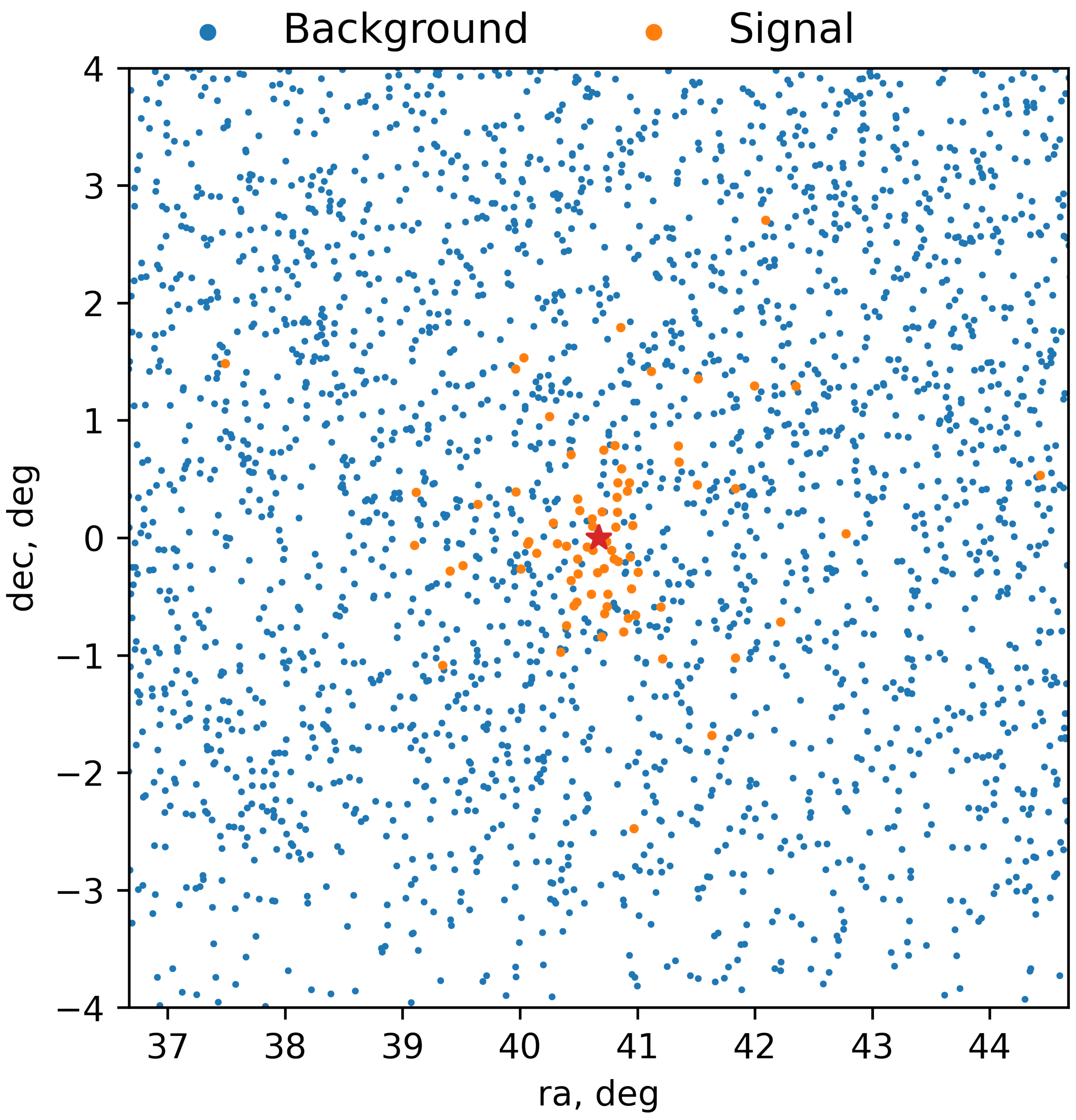
Neutrinos: Likelihood stacking approach



10 year map IceCube Coll, PRL 2020

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

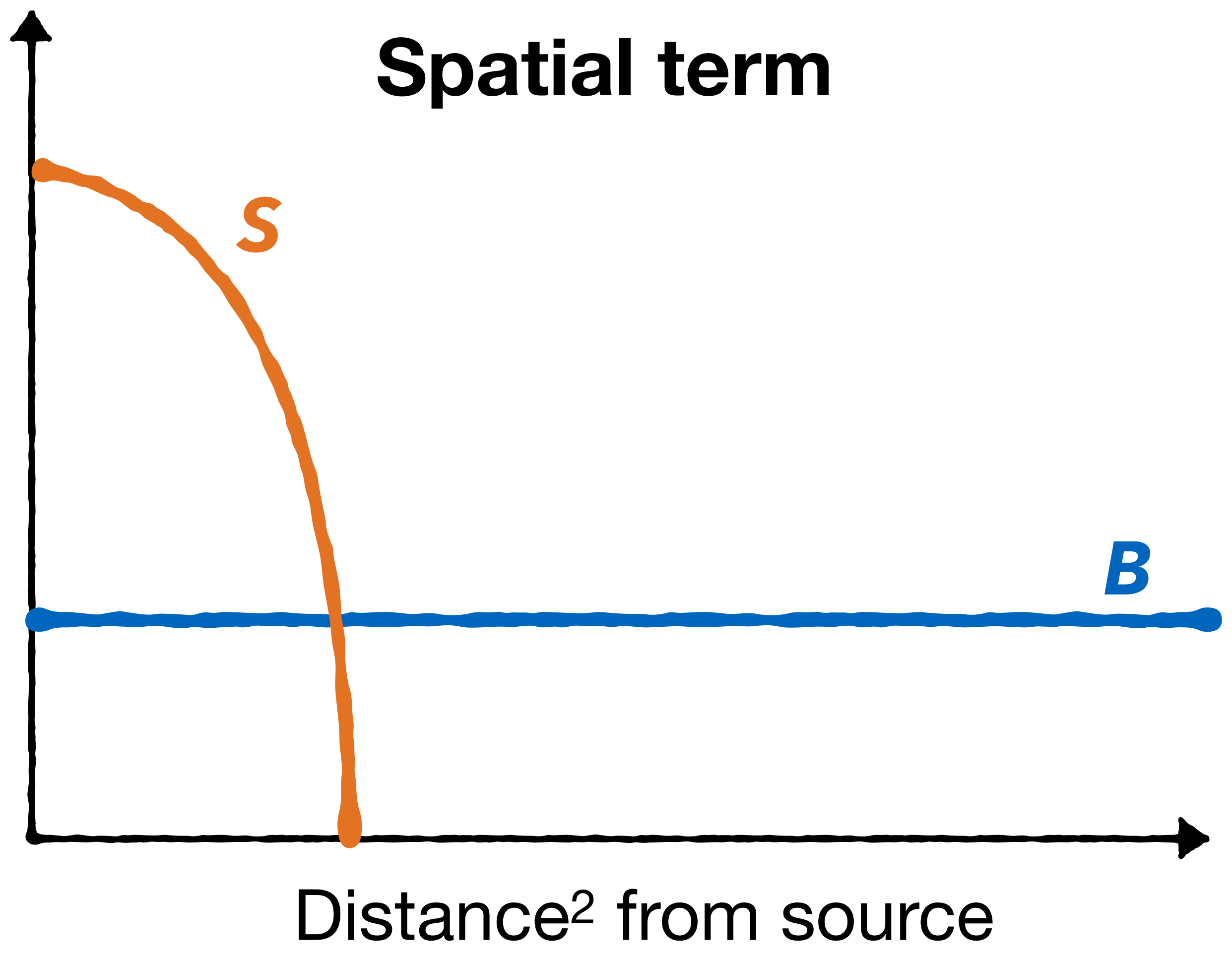
Neutrinos: Likelihood stacking approach

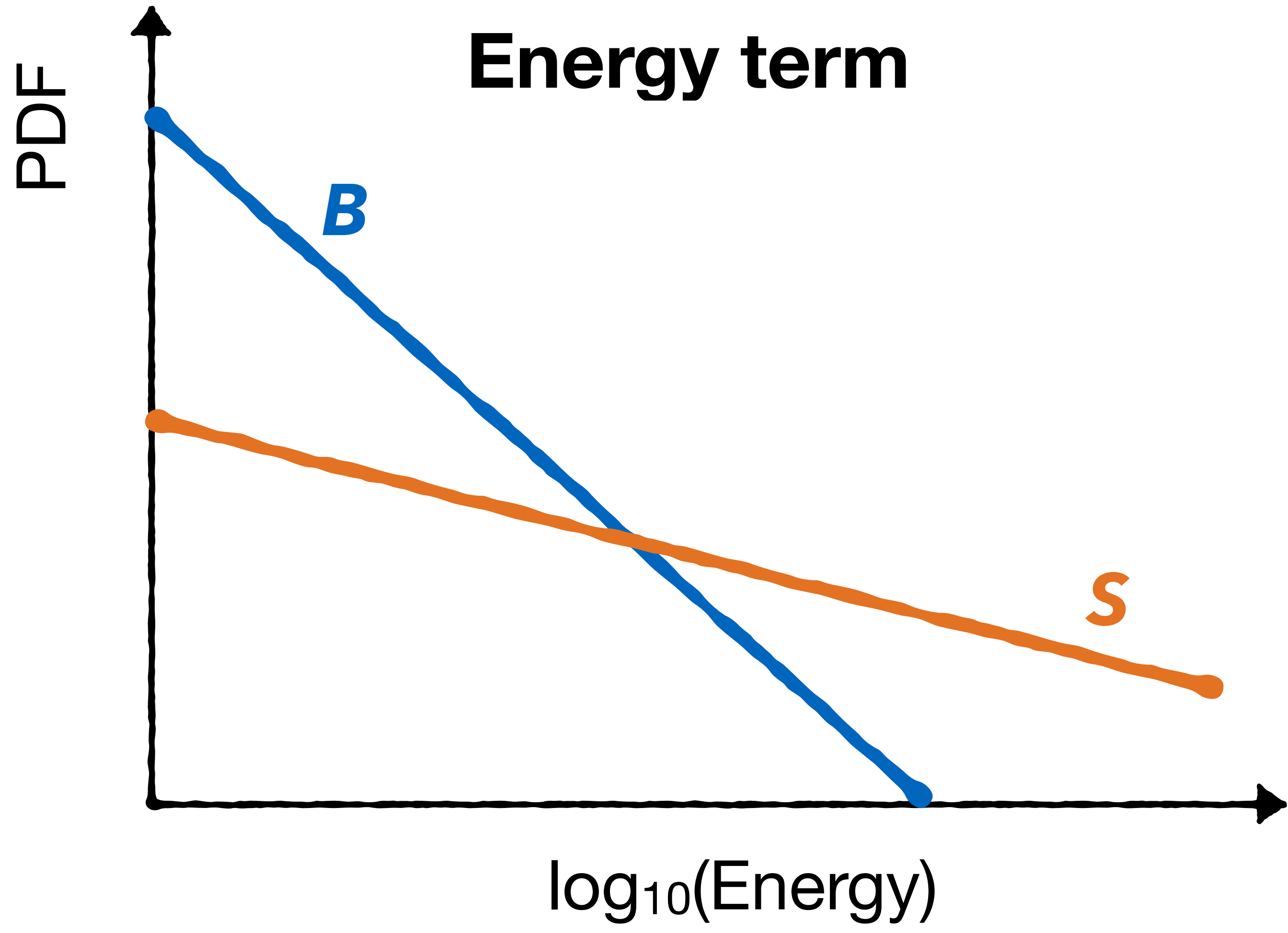


The unbinned likelihood approach:

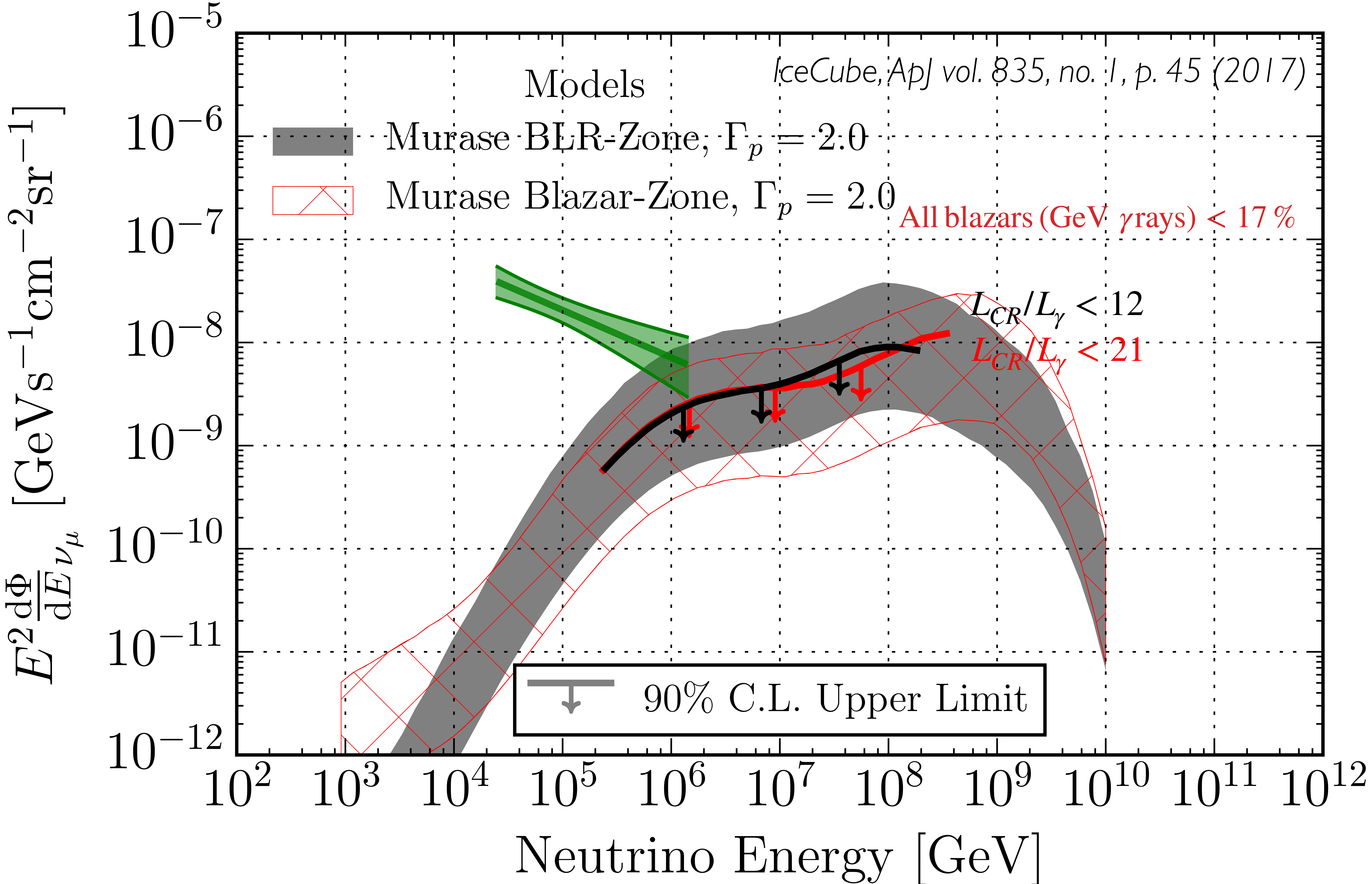
Signal — Background

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

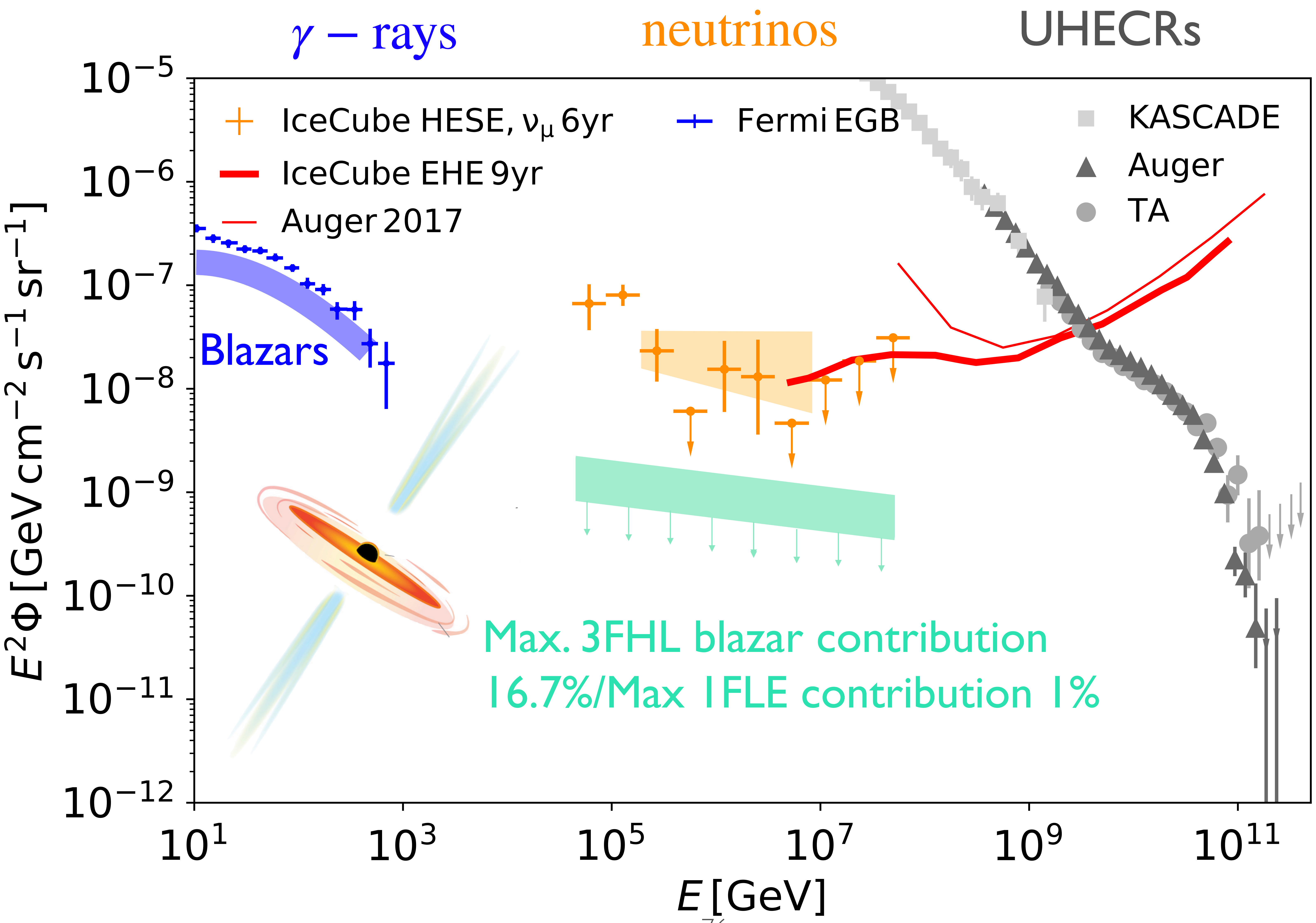




Population limits from IceCube (and Auger)



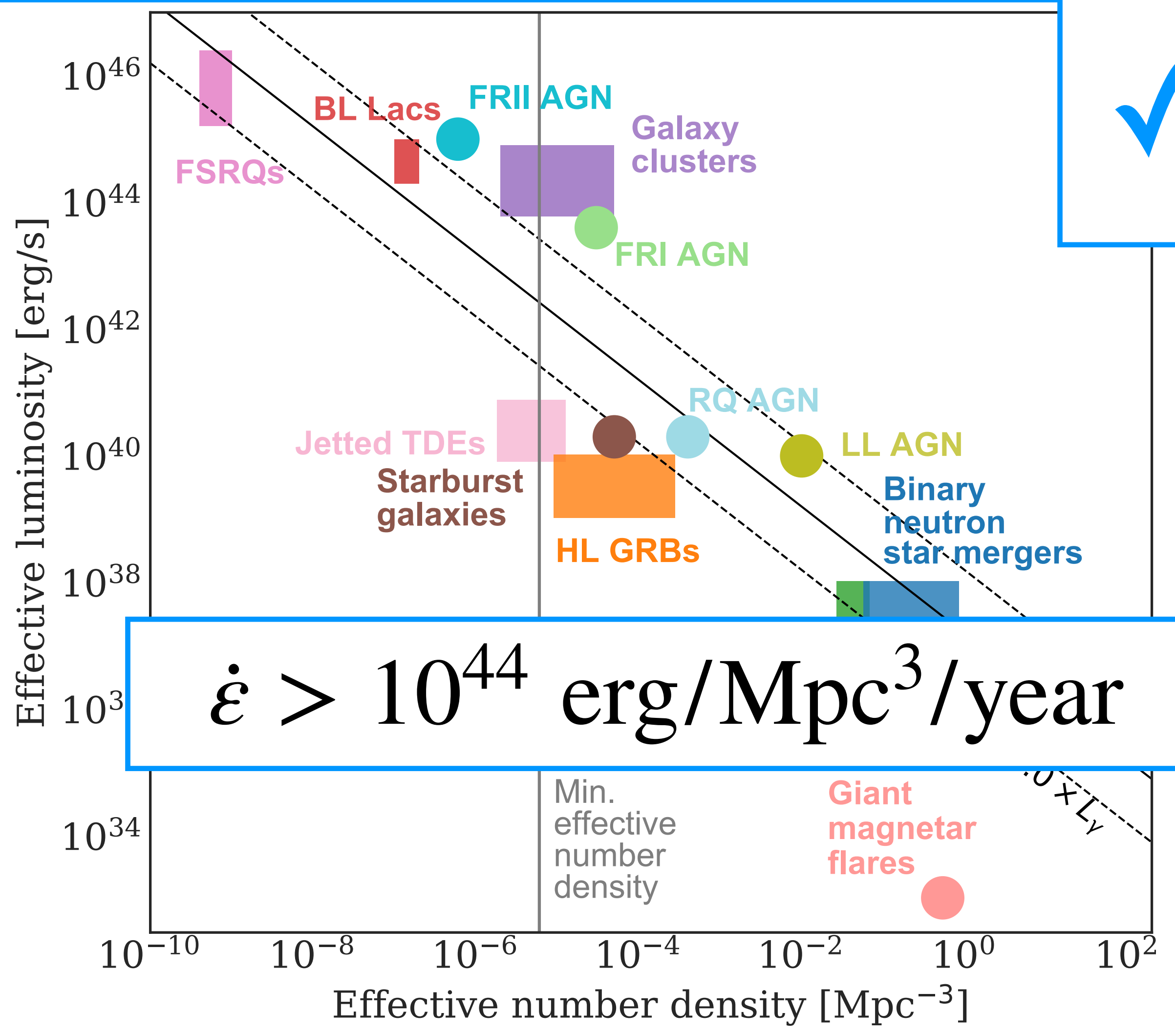
Stacking limits from IceCube



Blazar/radio galaxy contribution to UHECR/neutrino flux?

UHECR Emissivity

✓



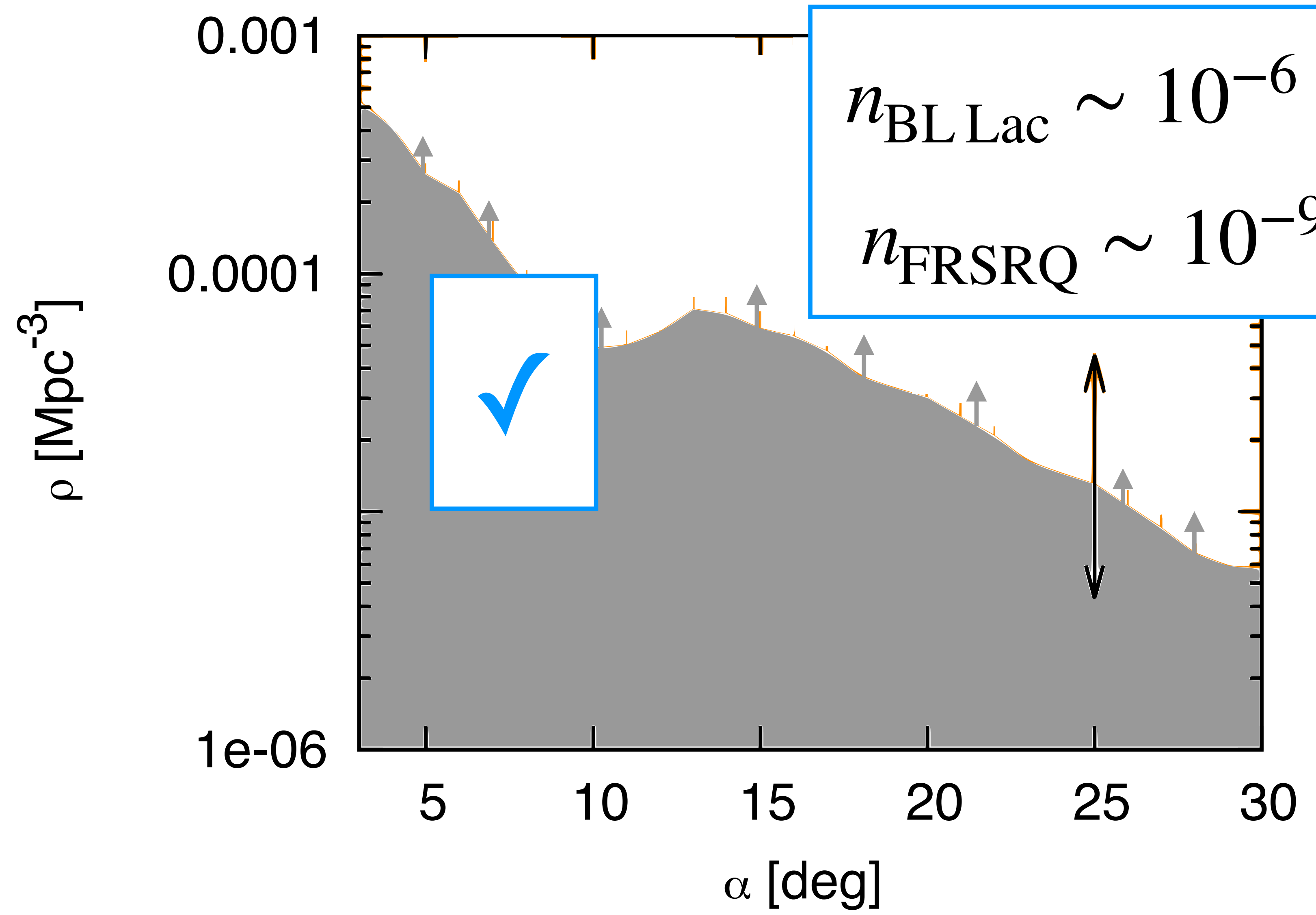
$\dot{\varepsilon} > 10^{44}$ erg/Mpc^3/year

UHECR number density

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

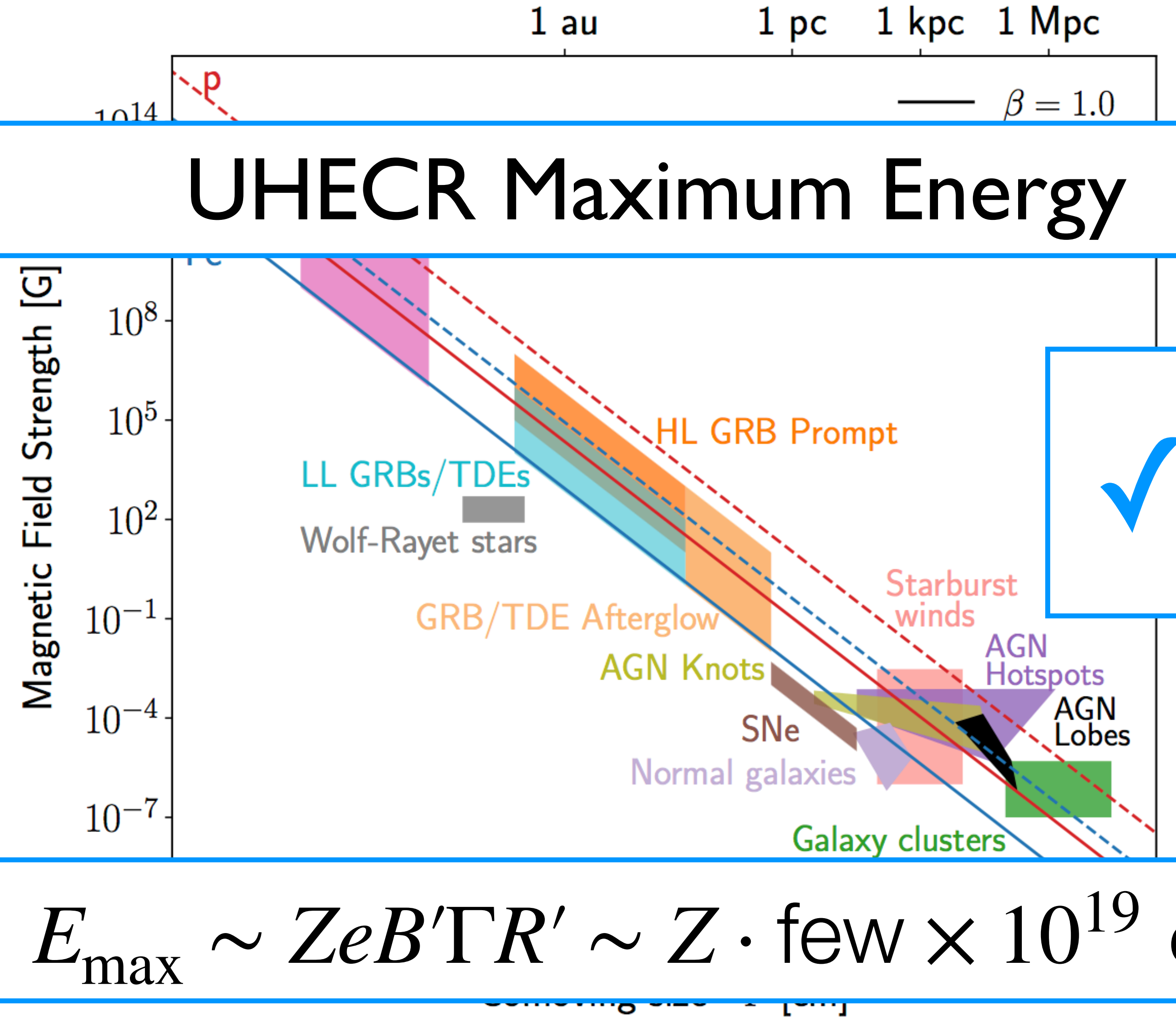
$n_{\mathrm{FRSRQ}} \sim 10^{-9}$ Mpc^3

✓



UHECR Maximum Energy

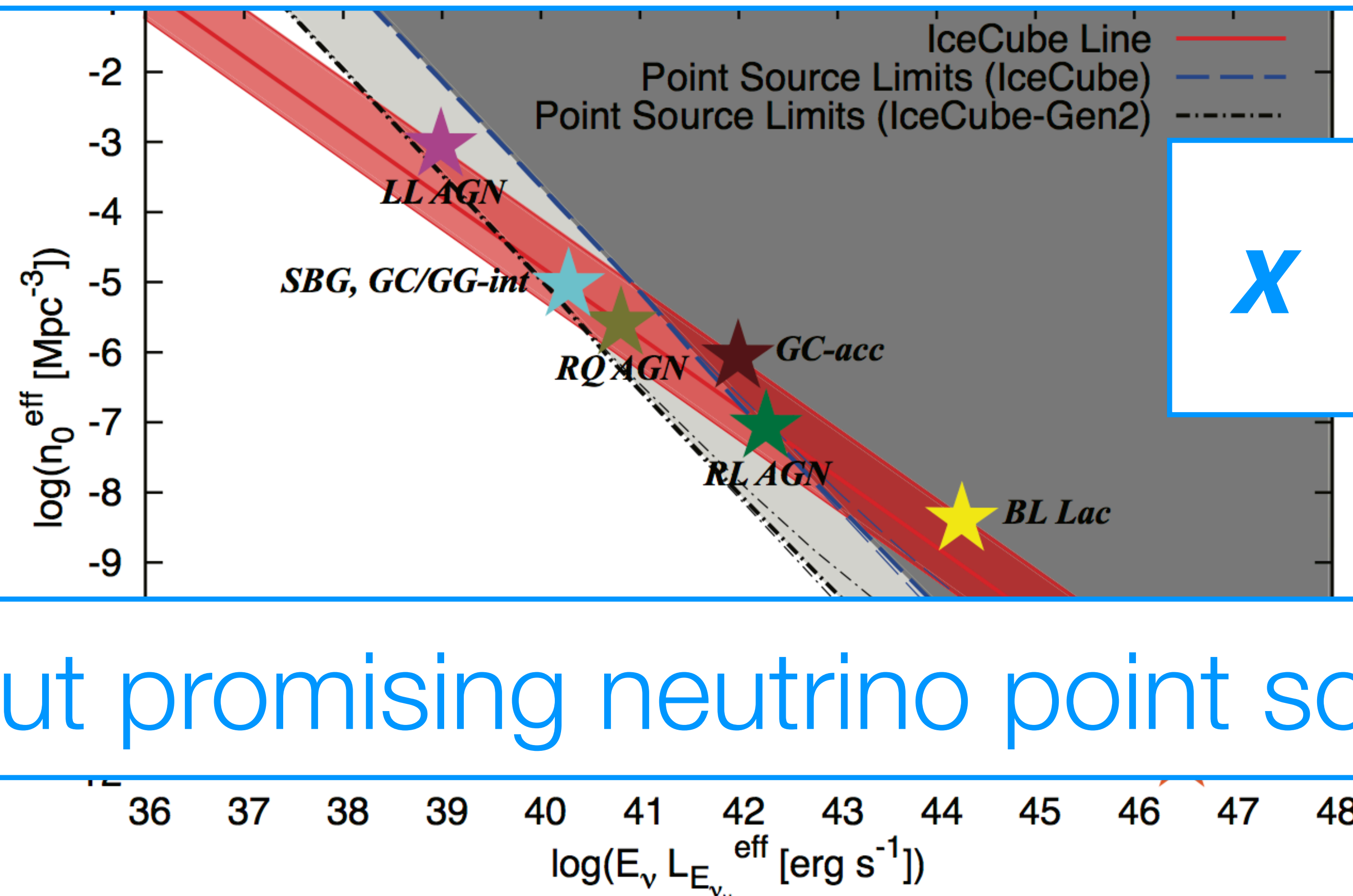
✓



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

Neutrino clustering + stacking constraints

X

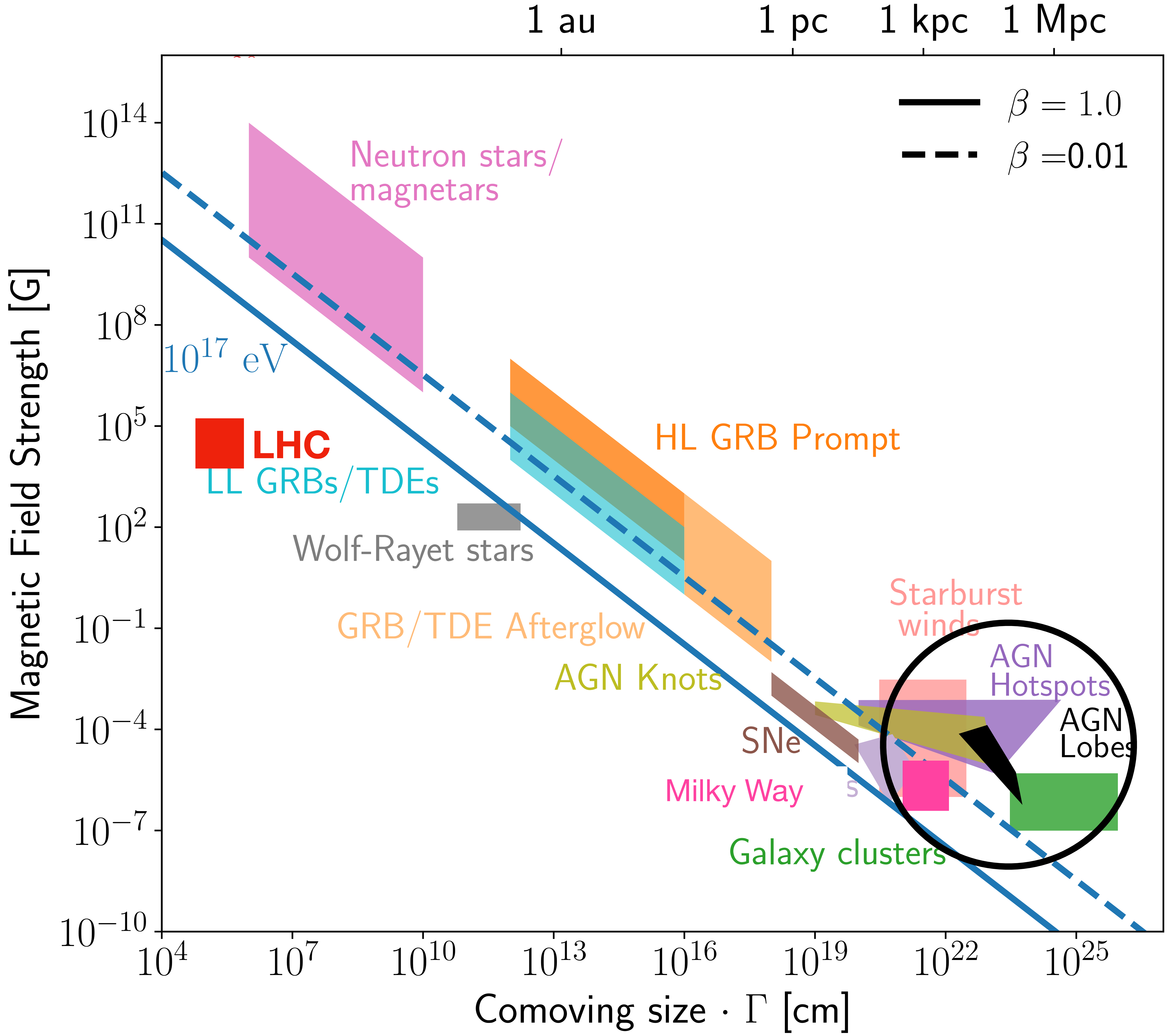


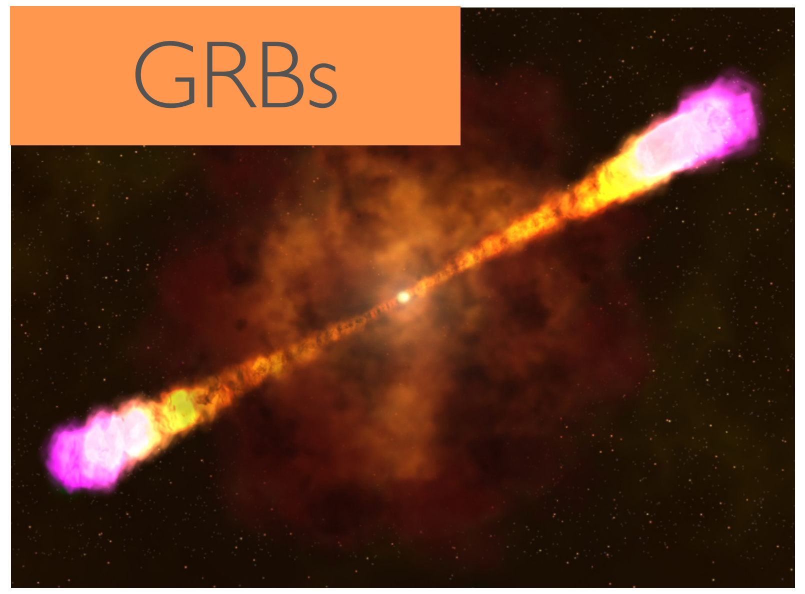
..but promising neutrino point sources!

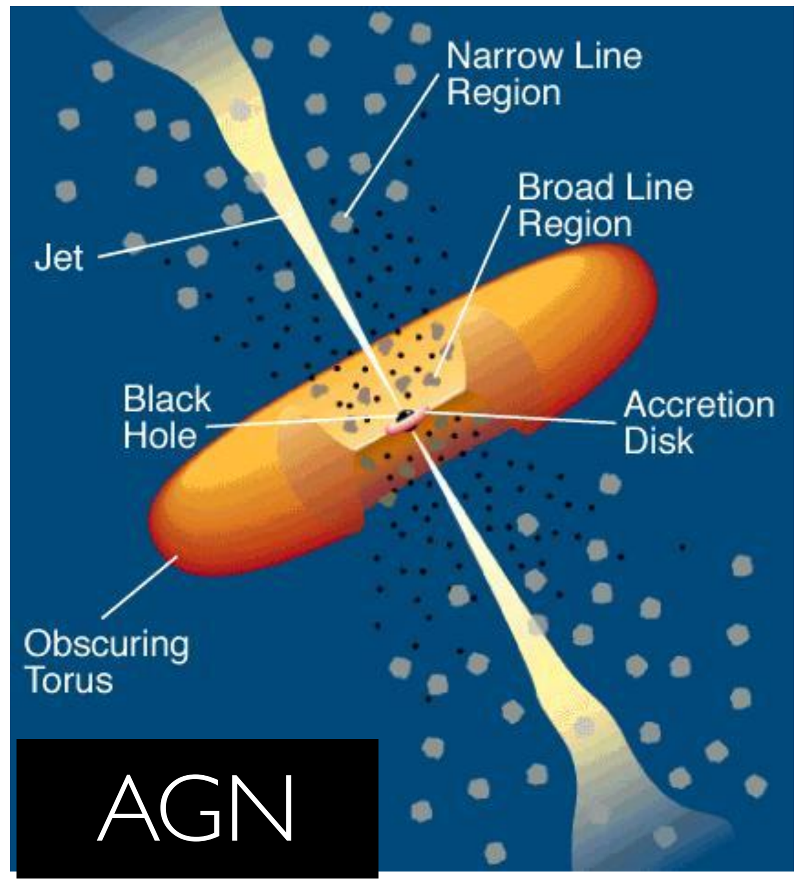
Scorecard

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

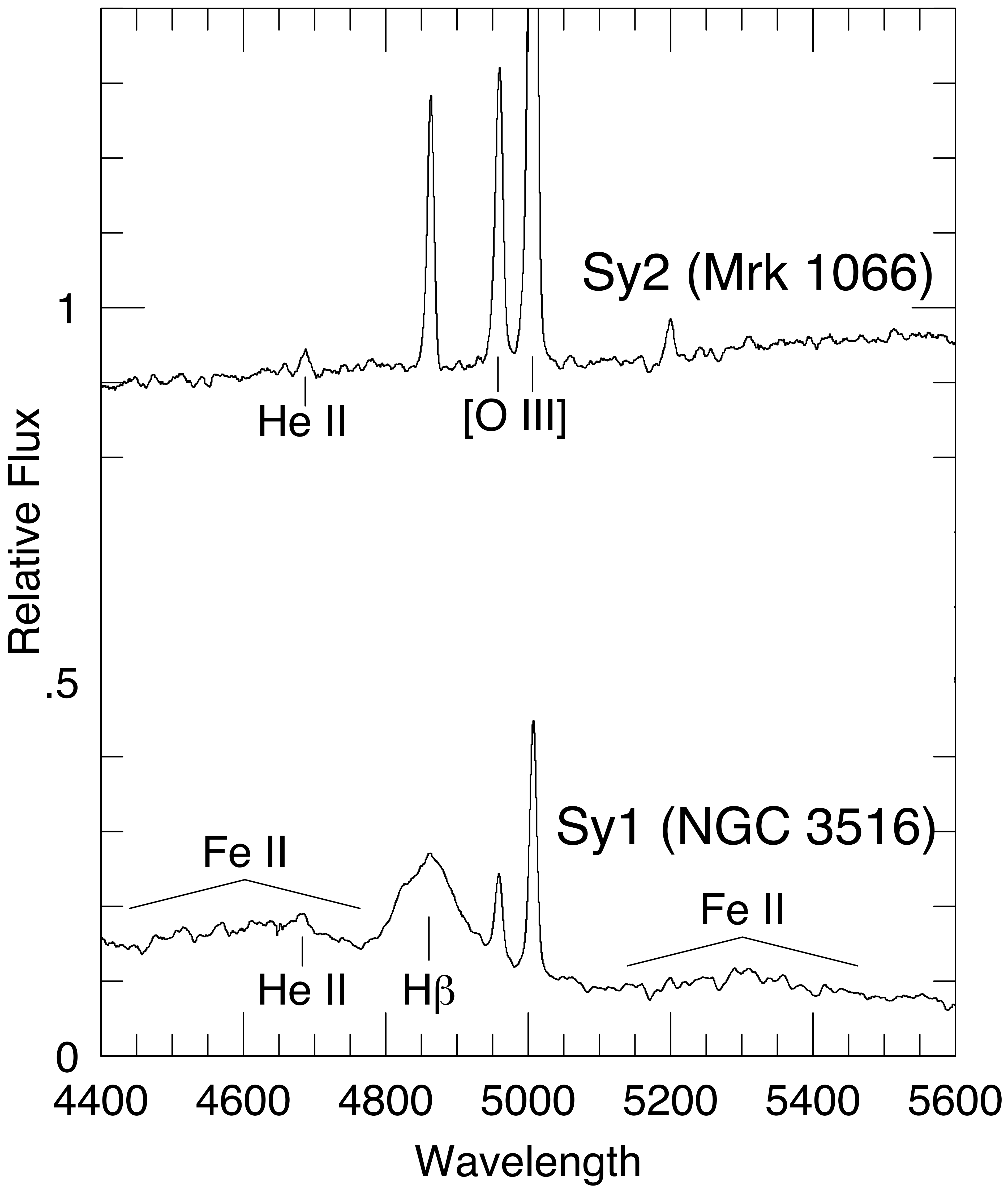
Cosmic-ray accelerators that satisfy the confinement r

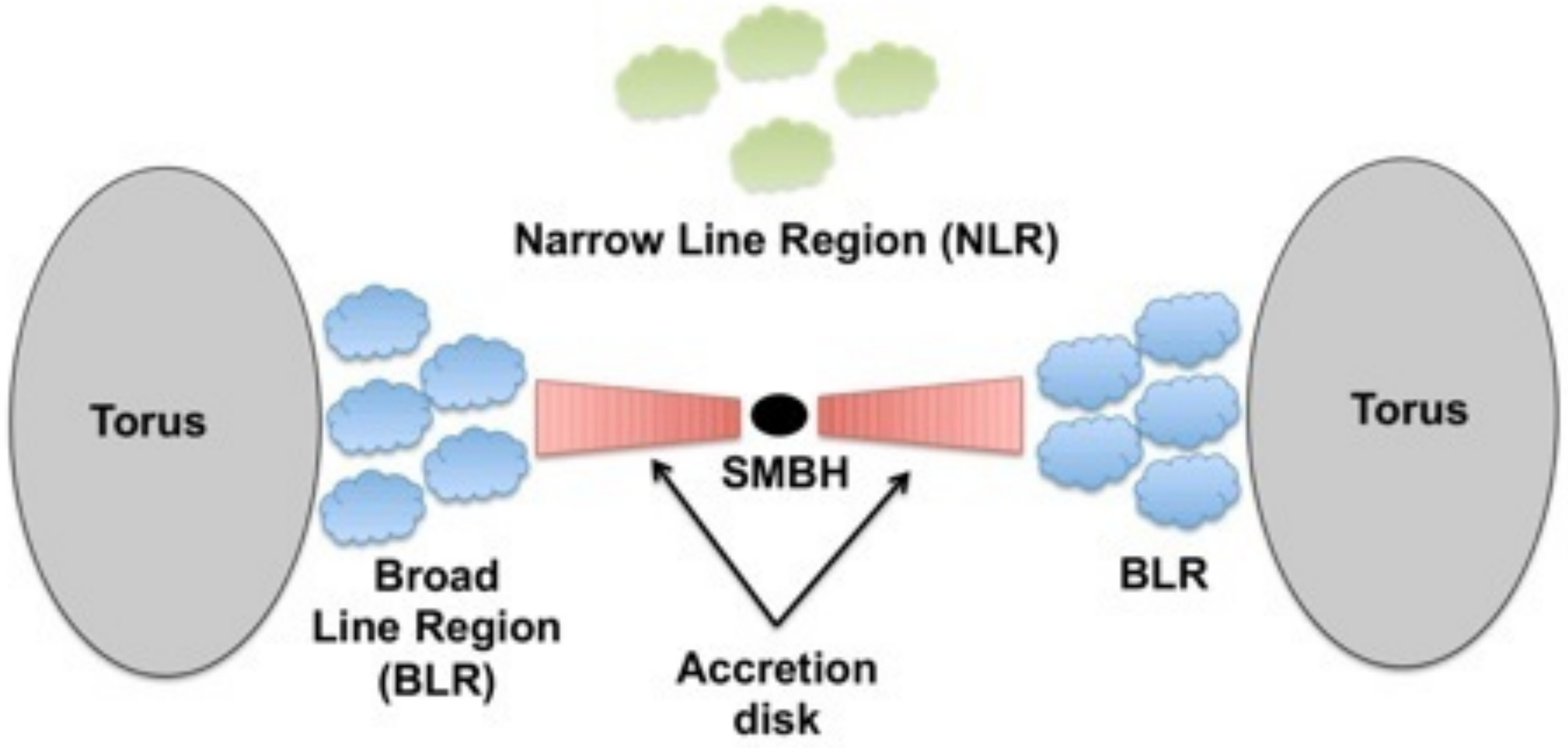


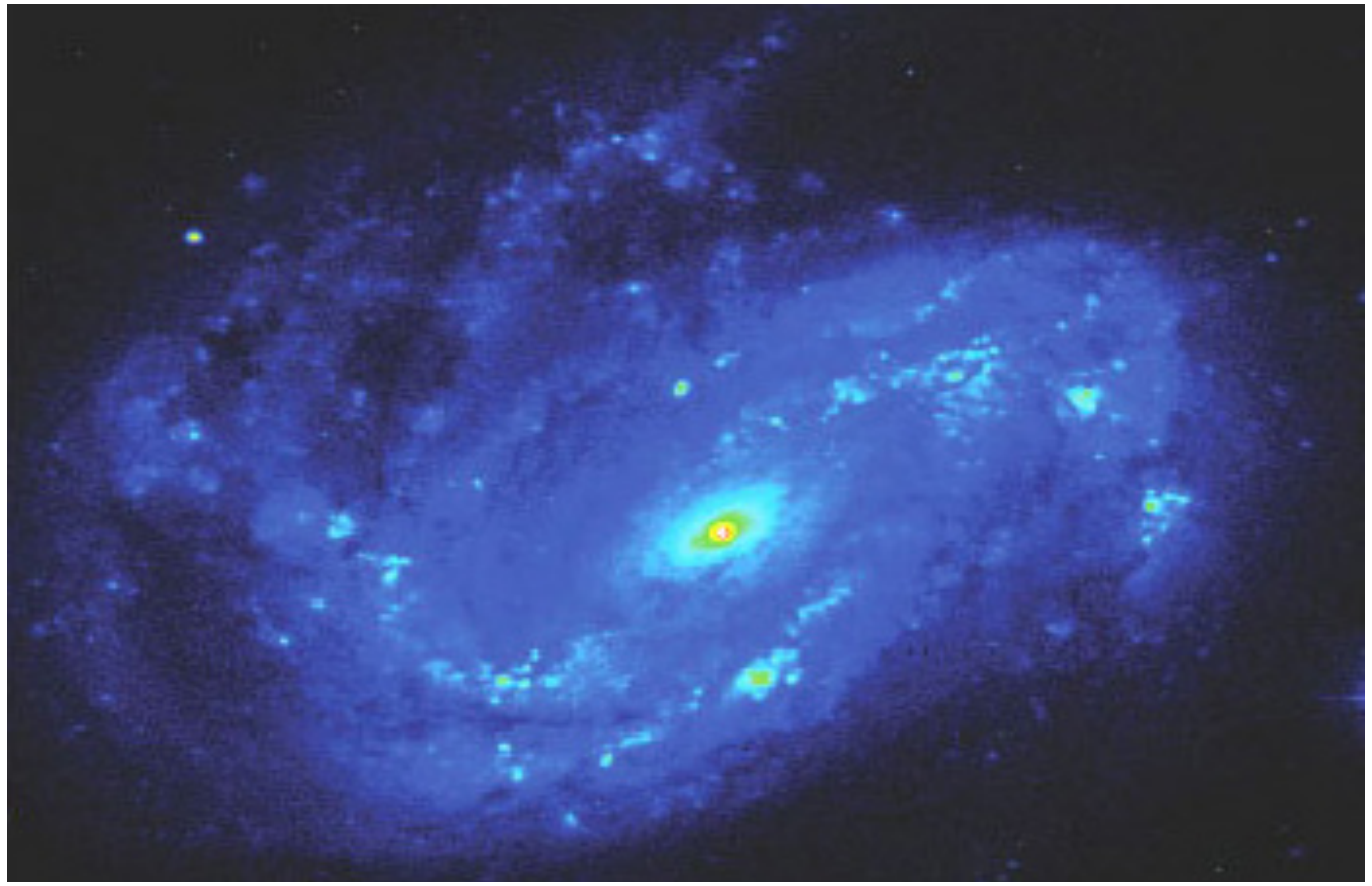




Non-jetted AGN

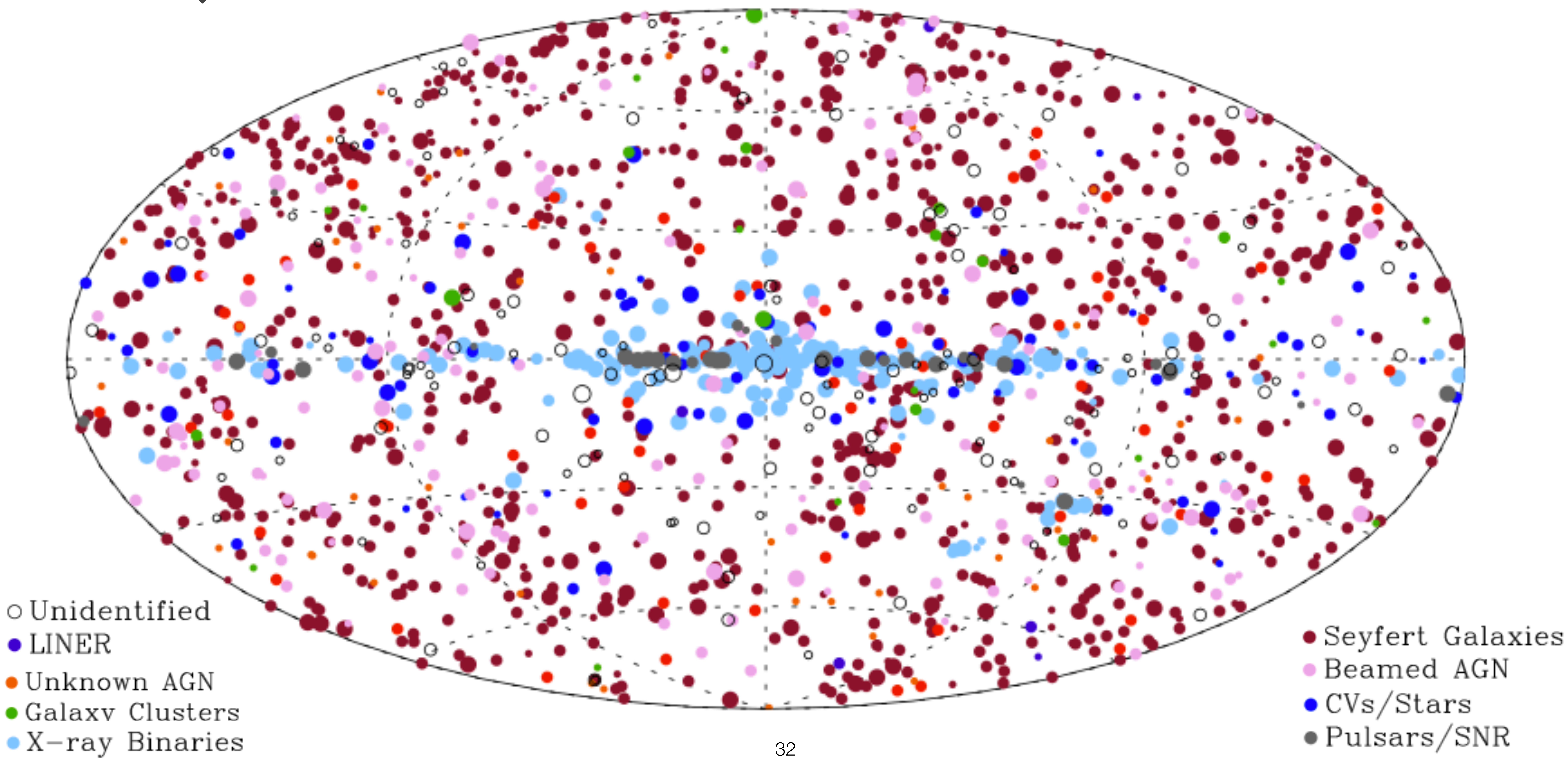




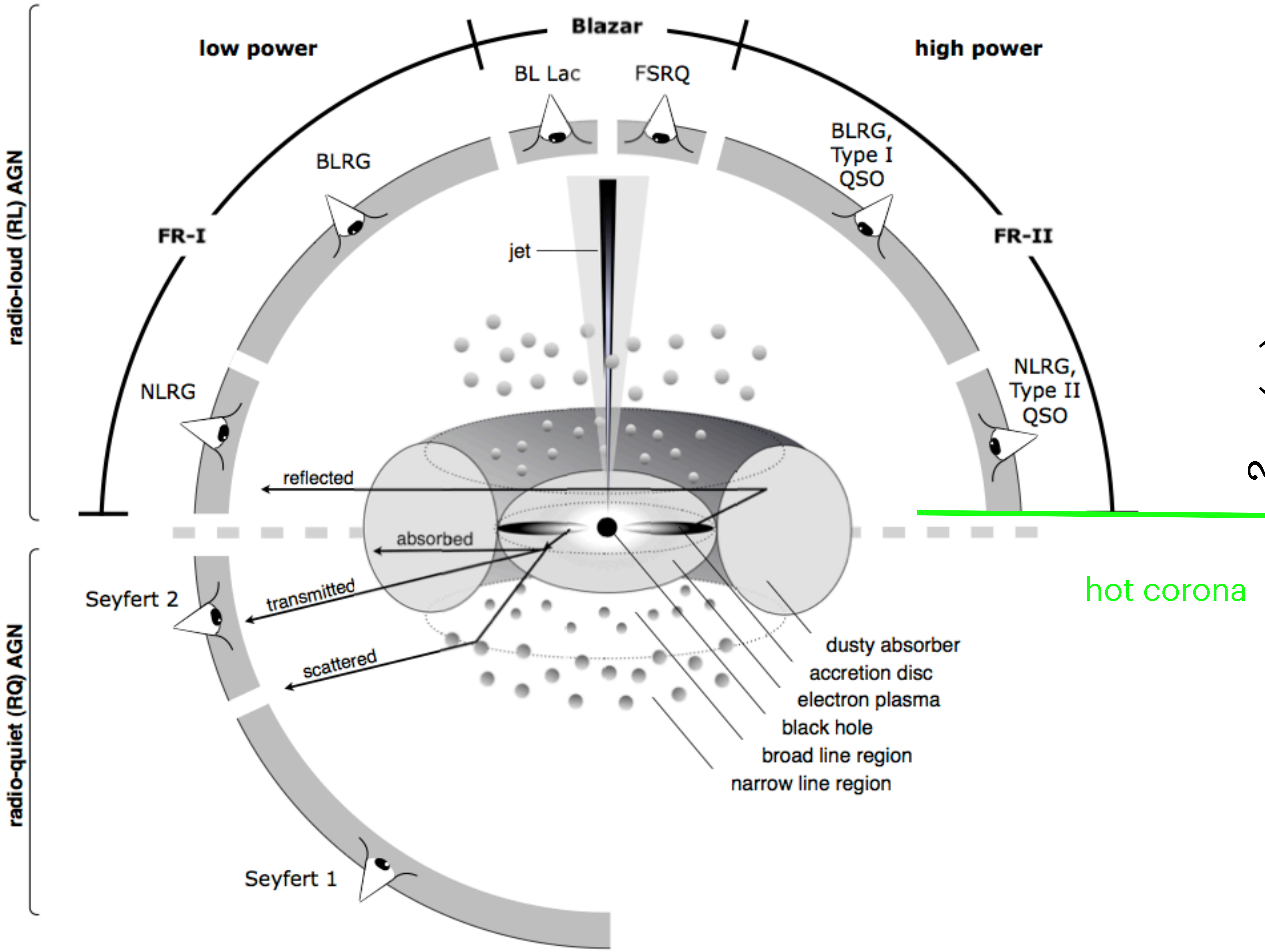


Non-jetted AGN

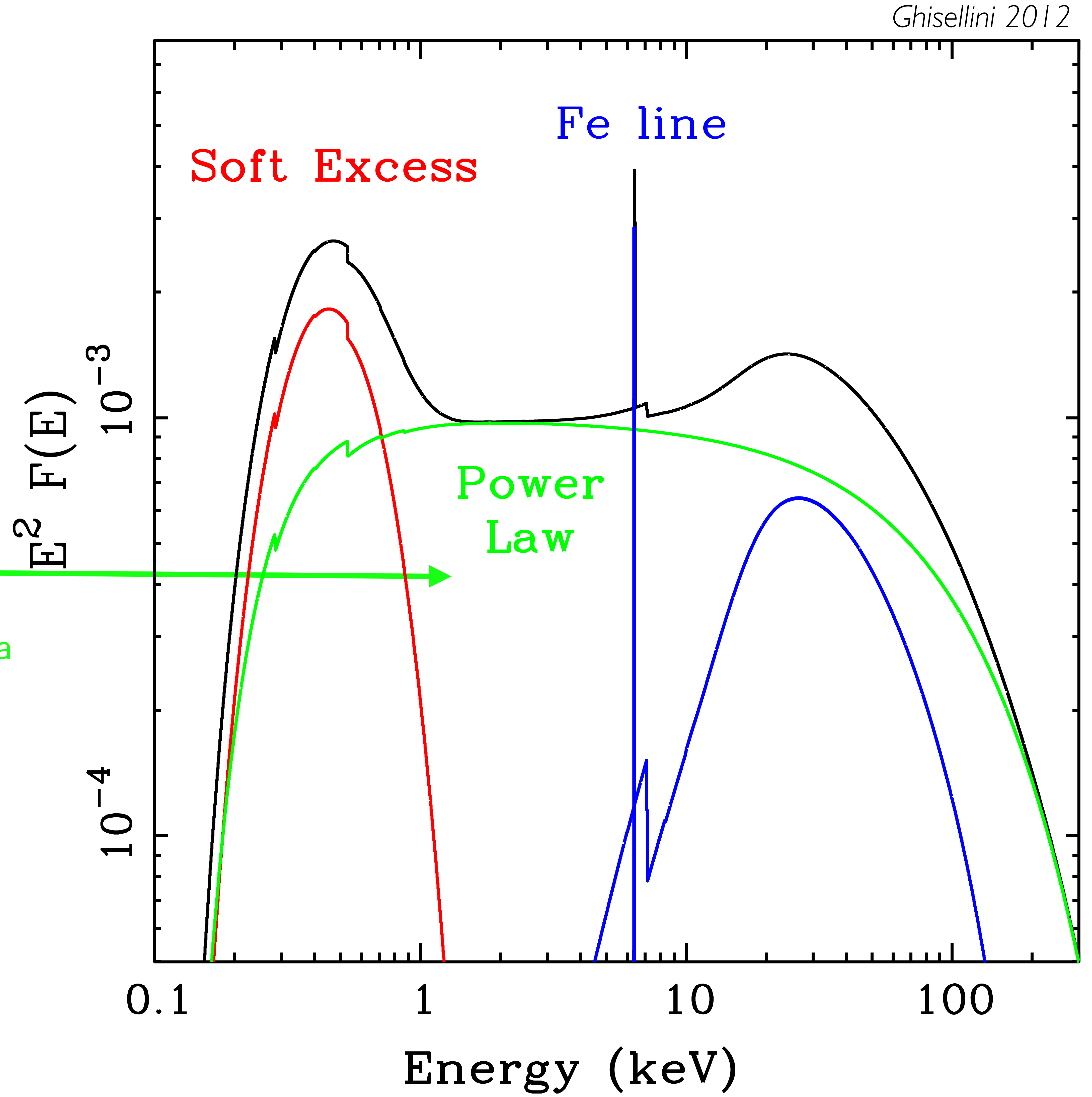
Swift-BAT 105-month hard-X-ray catalogue 2018



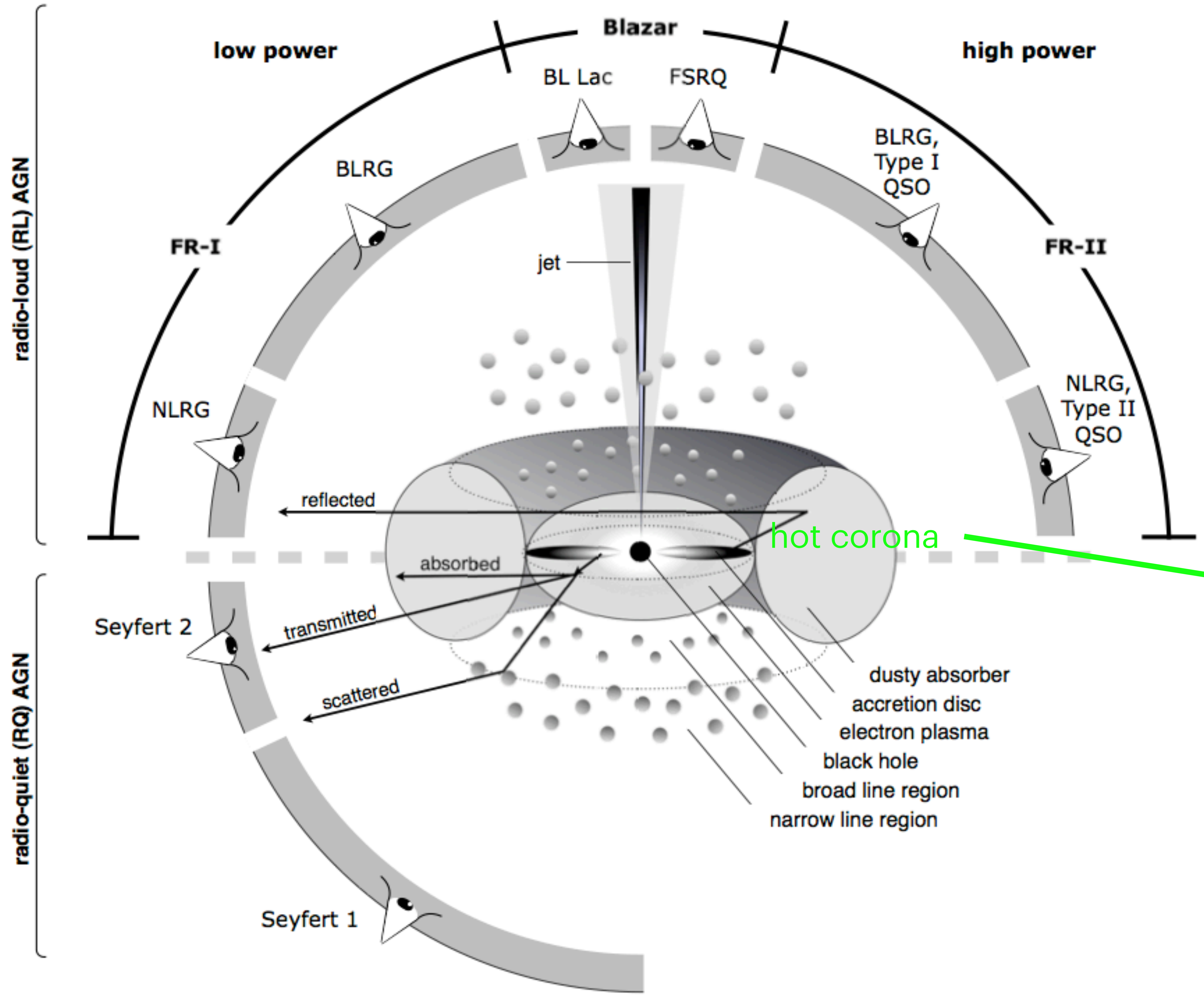
X-ray absorbers in AGN



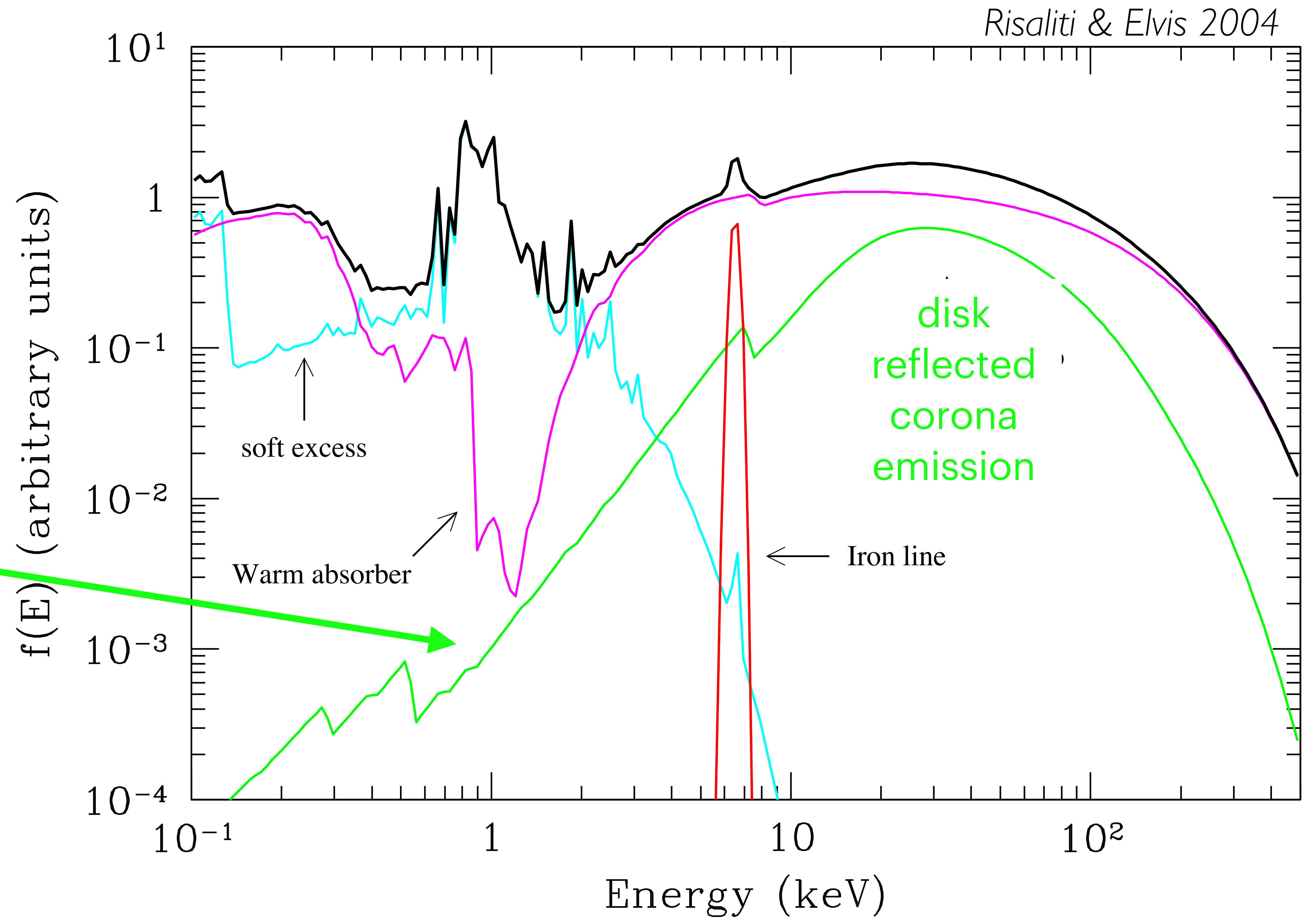
Beckmann & Shrader 2012

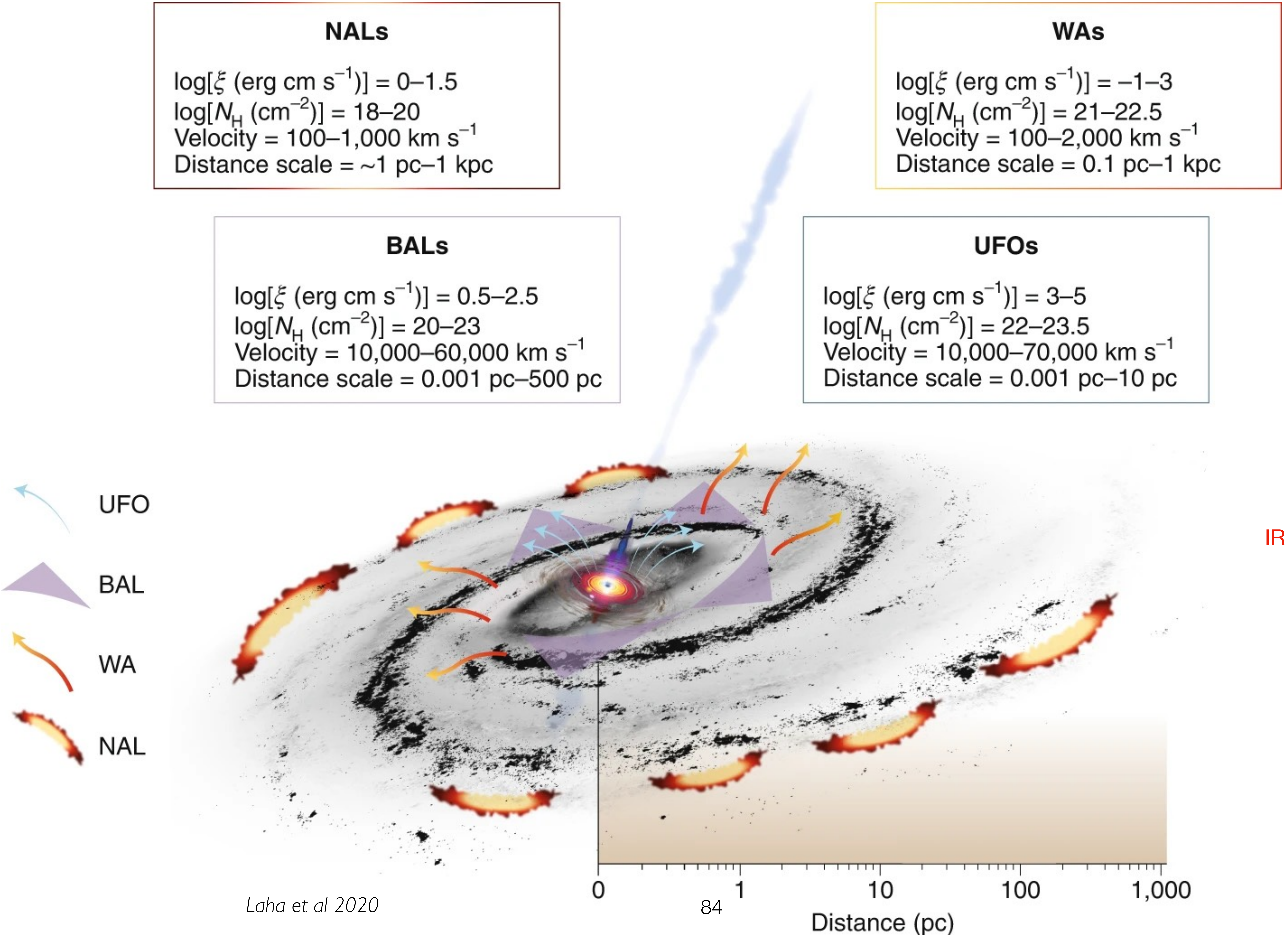


X-ray absorbers in AGN



Beckmann & Shrader 2012





Laha et al 2020

Observed in ~50% of Seyfert I

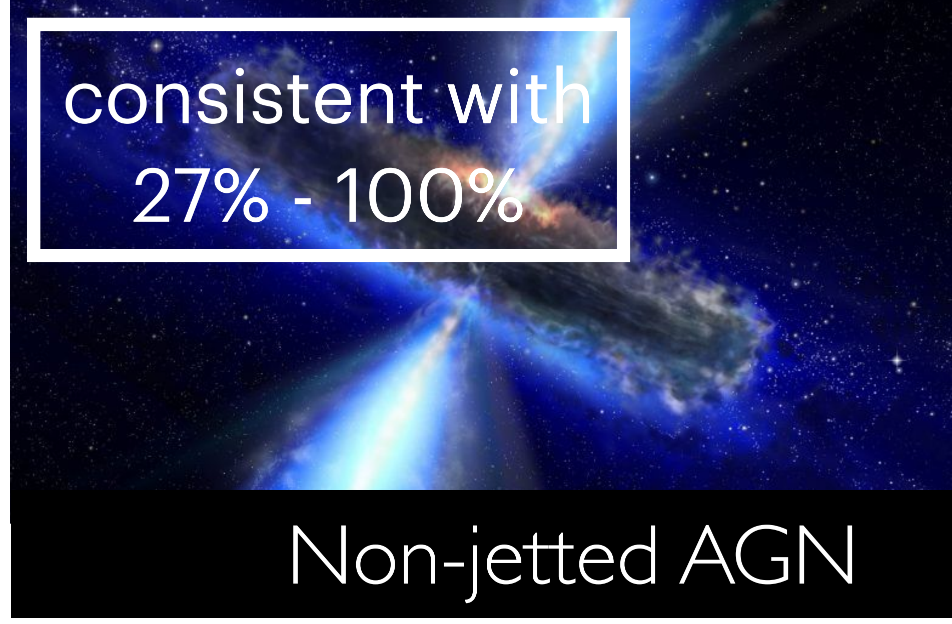
Observed in ~40% of radio loud and radio quiet AGN

v ~ 0.03 - 0.3 c

(Tombesi et al 2010,2011, 2012, 2014)

Hillas criterion OK!
(but interactions with
IR photons limit max energy)

Non-jetted AGN contribution to the cosmic-neutrino flux

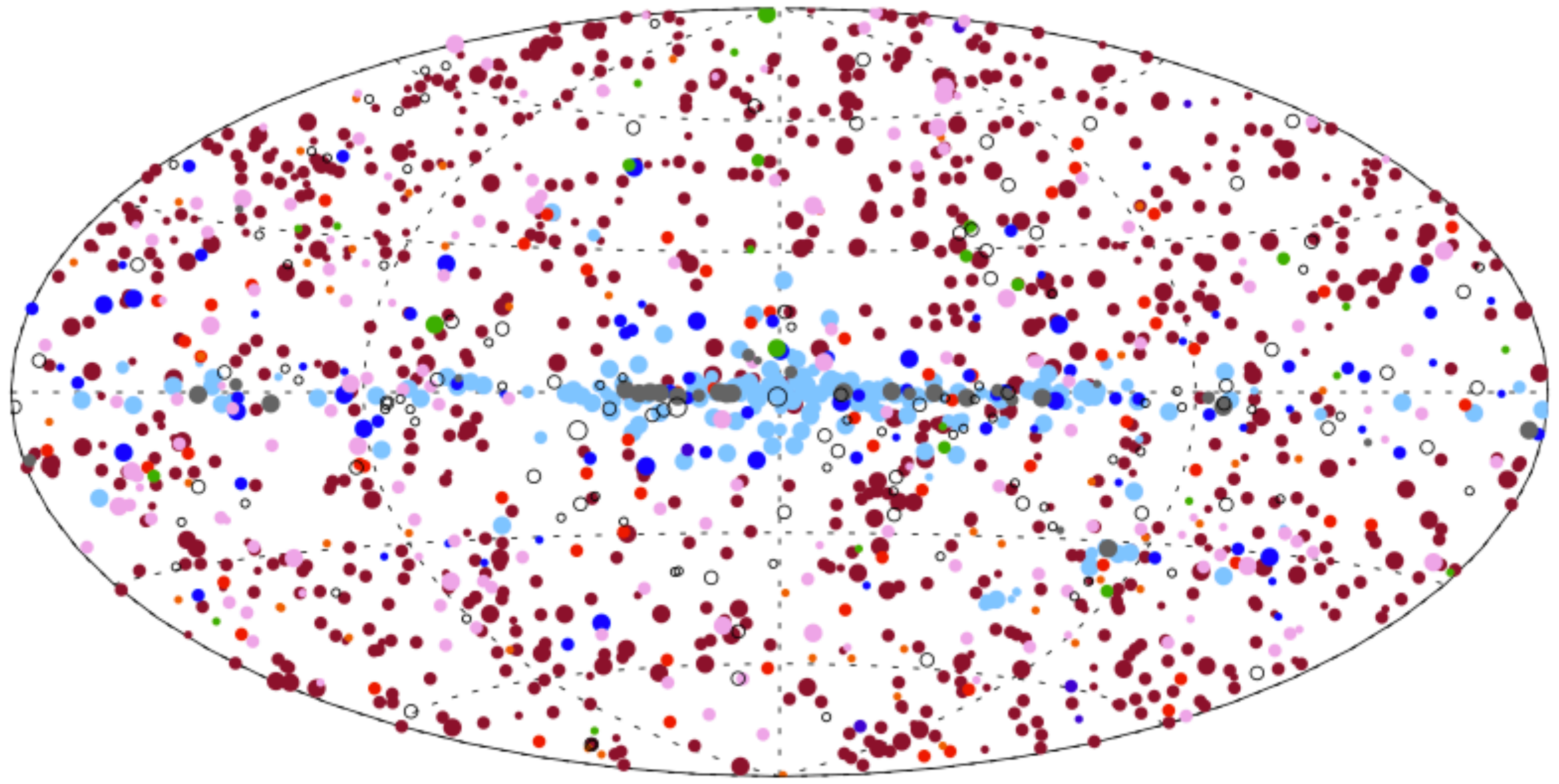


Infrared selected (ALLWISE) AGN with soft-X-ray weights ~ 32,249 AGN

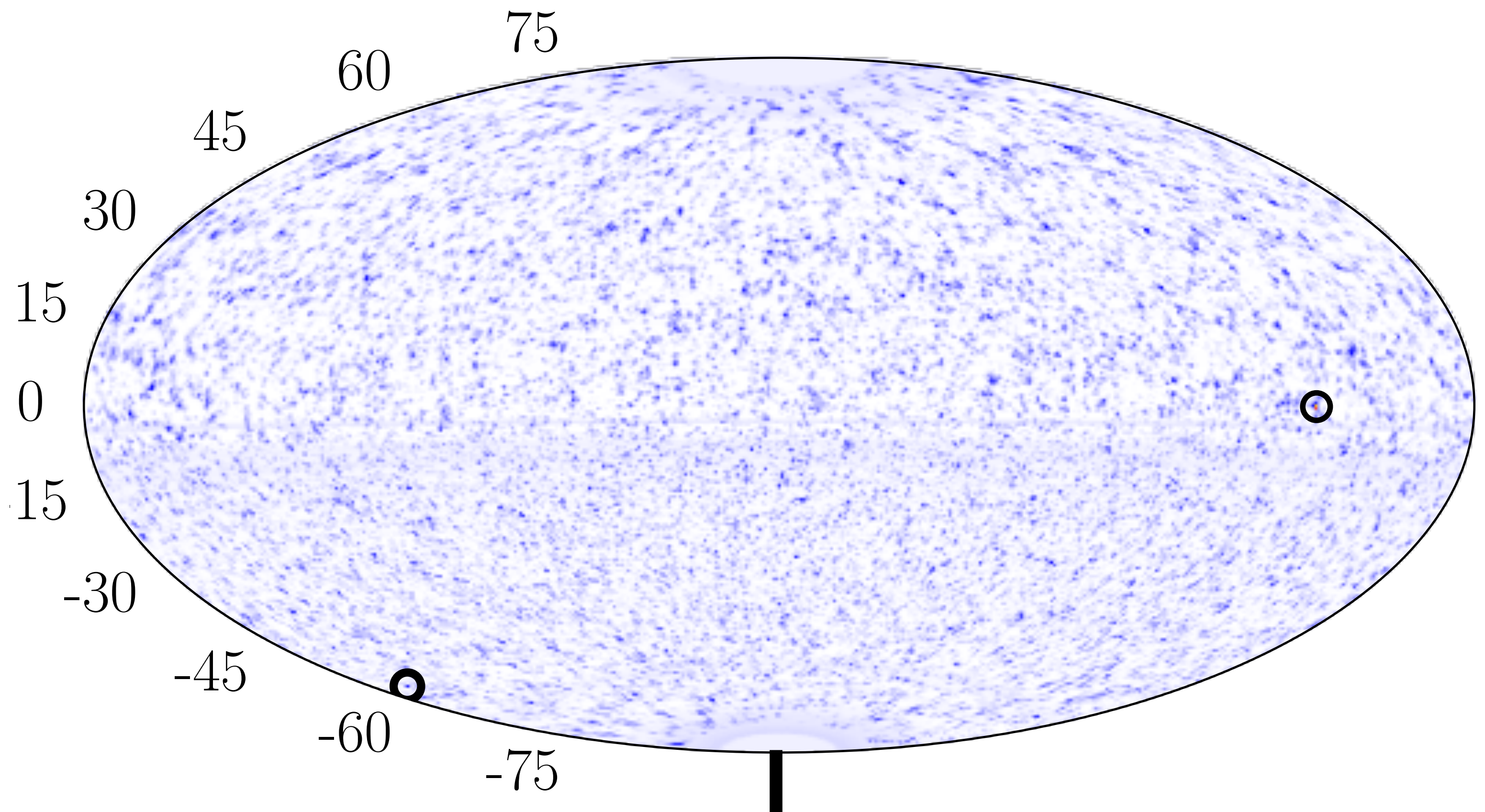
2.6σ excess w.r.t. background expectations

Best-fit spectral index $\frac{dN}{dE} \sim E^{-2}$

AGN Catalog



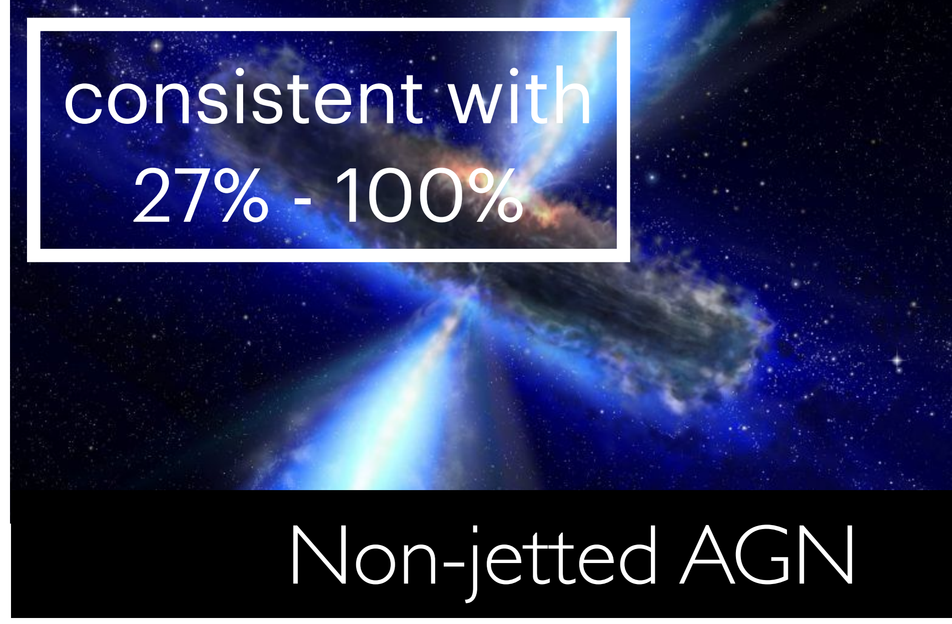
IceCube Point-Source Events

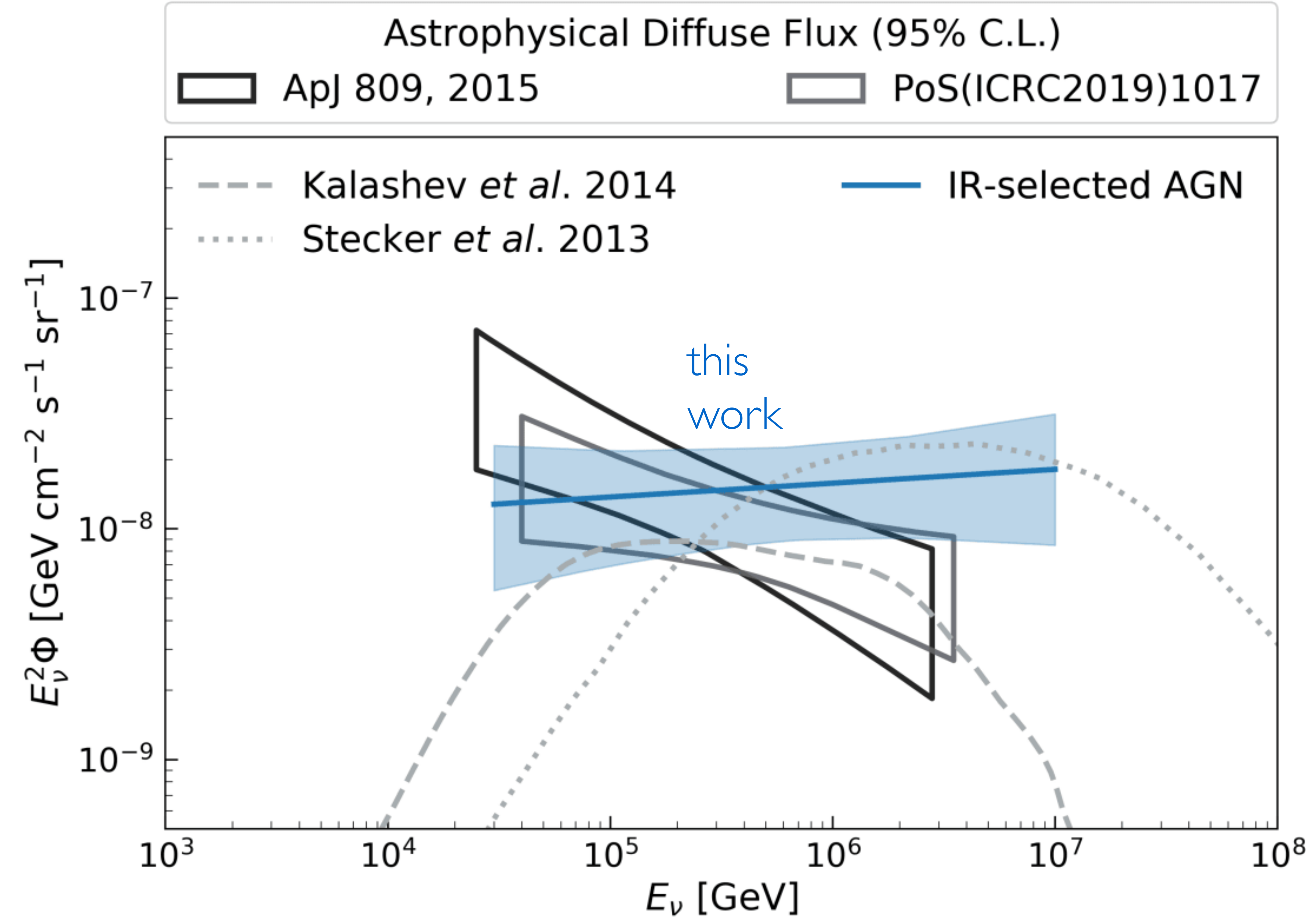


could account for 27-100% of diffuse neutrino flux at 100 TeV

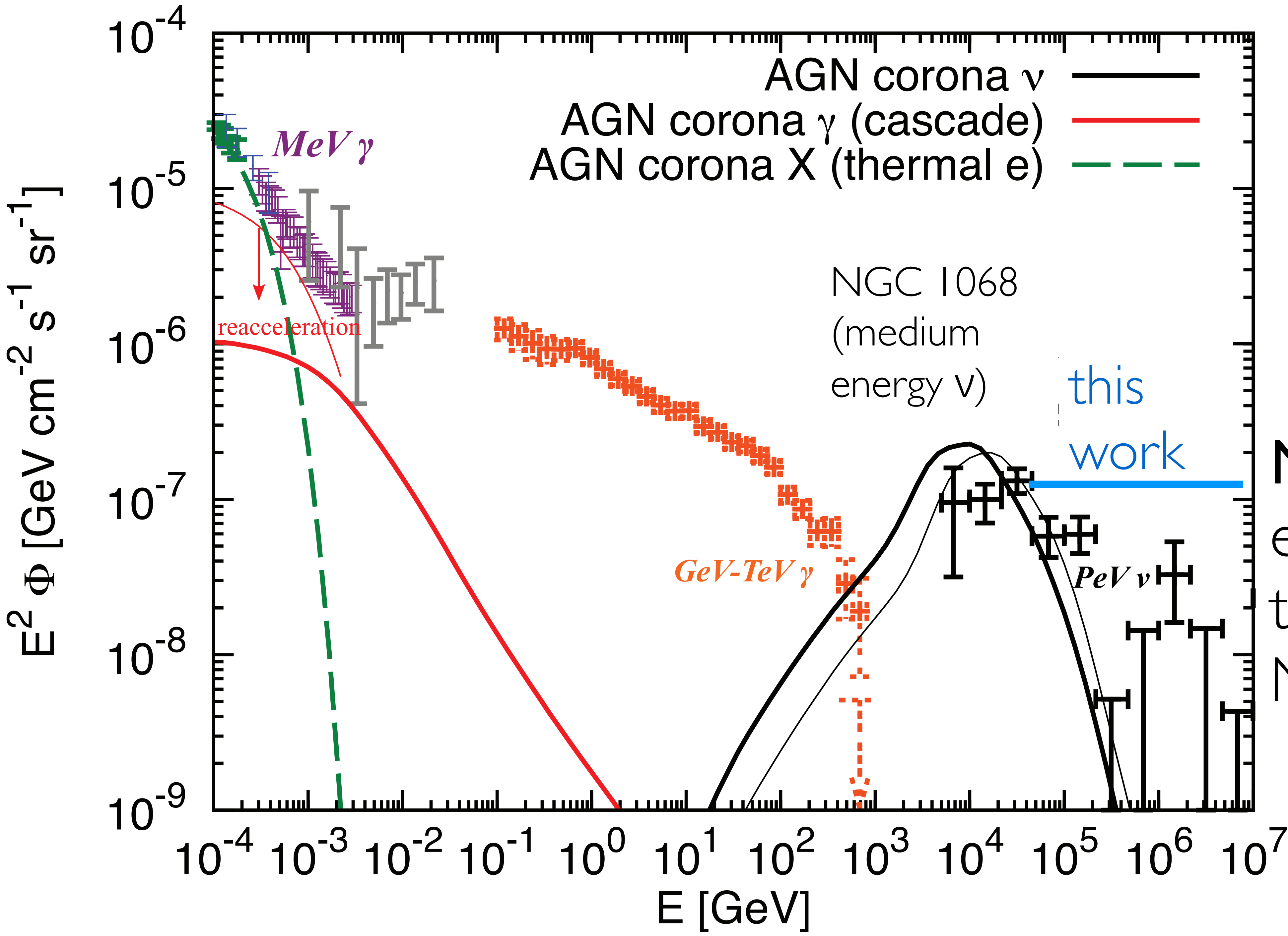
IceCube Coll 2022, PRD

Non-jetted AGN contribution to the cosmic-neutrino flux





several mechanisms proposed and consistent with this signal
E.g. UFOs (Ehlert, FO, Peretti 2025)



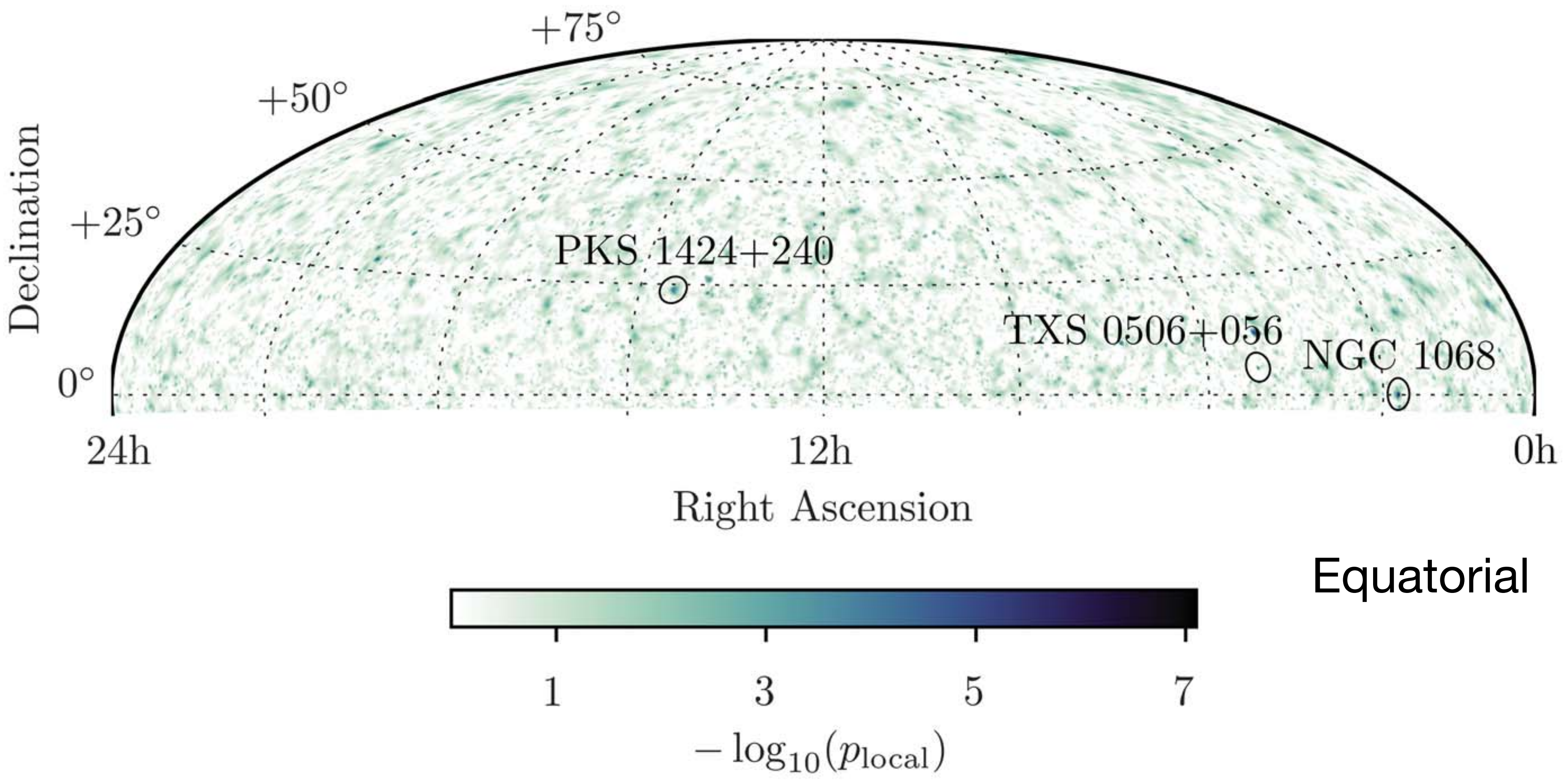
NB: Different energy range than NGC 1068

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

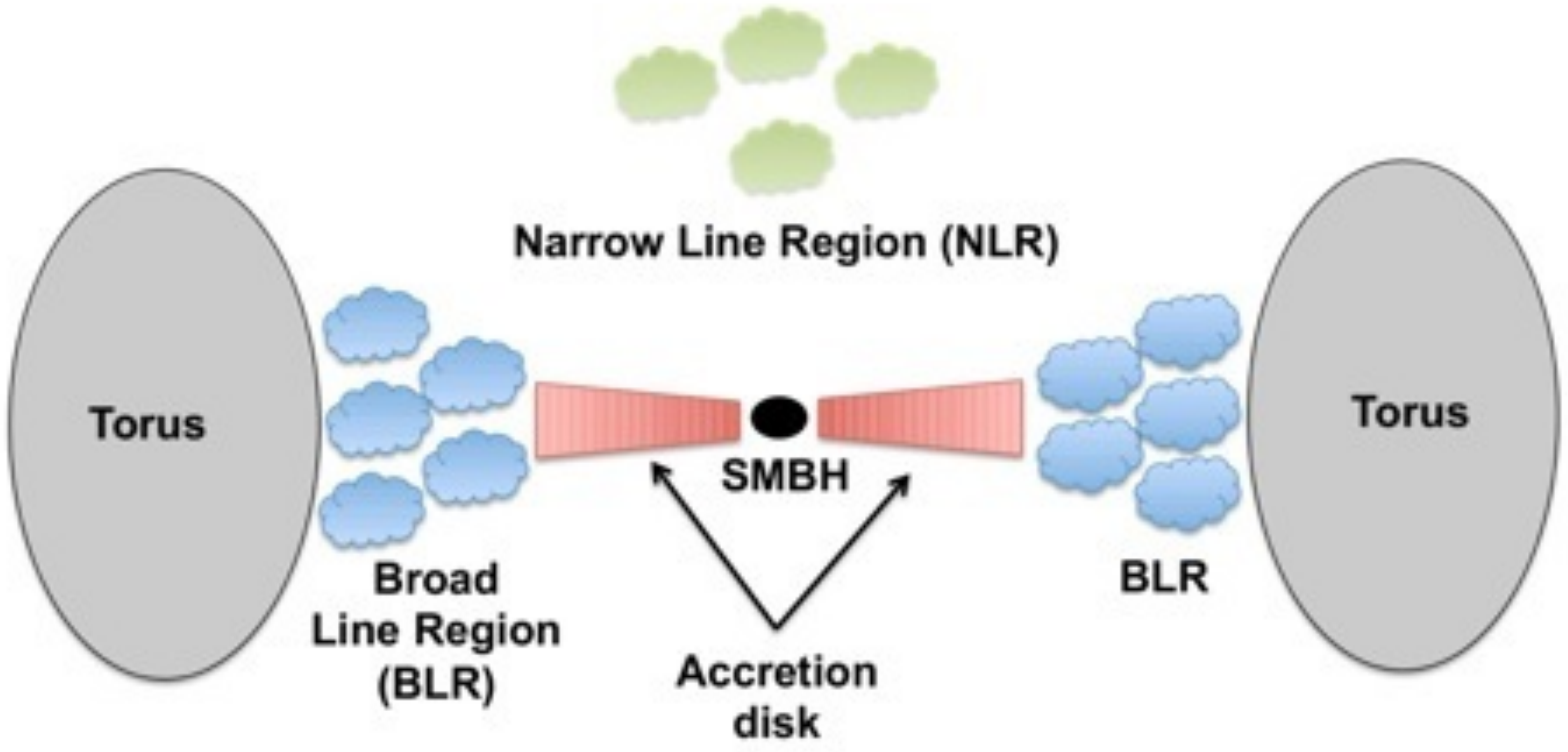
IceCube Coll 2022, PRD

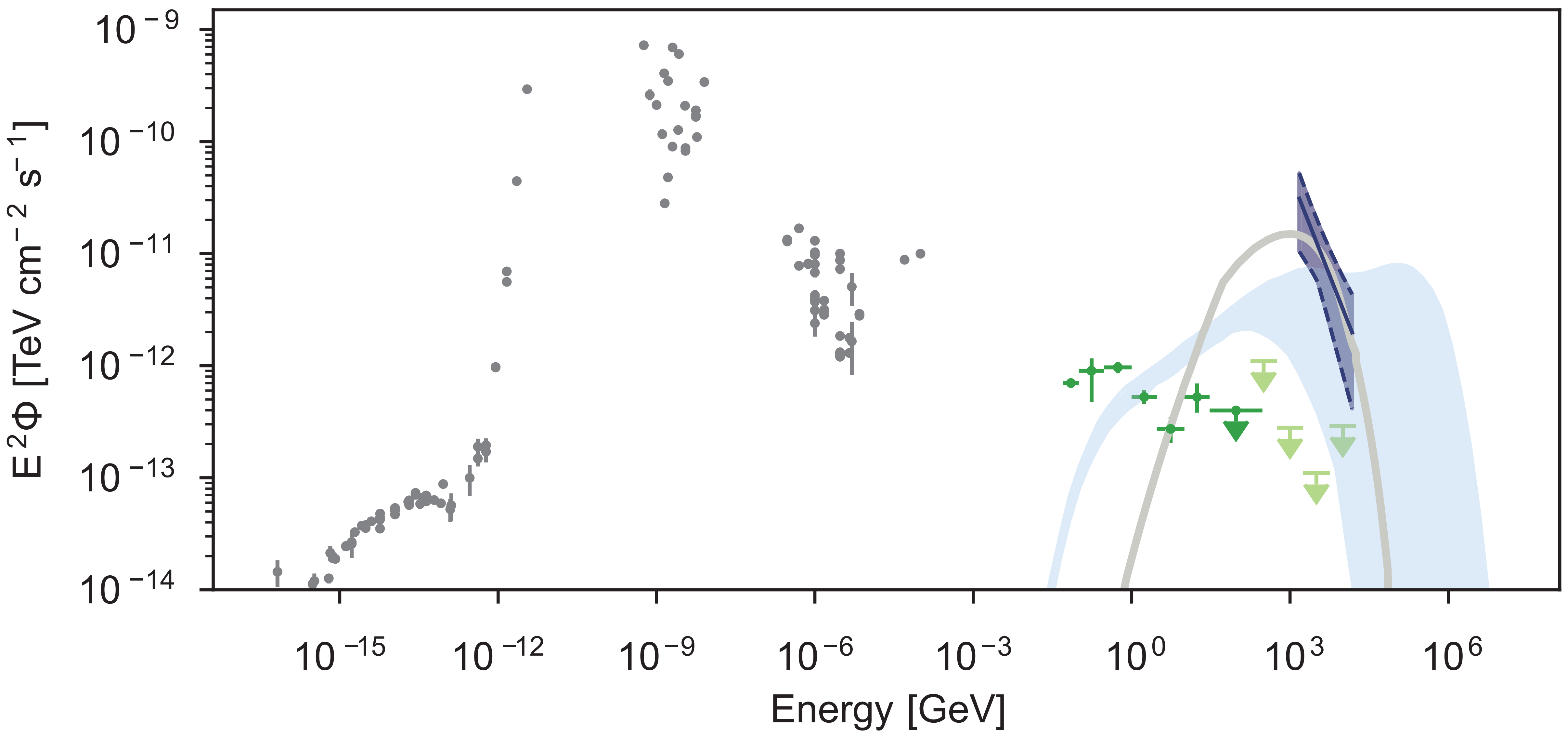
NGC 1068

Icecube Coll 2023 - Science



Test type	Pretrial *P* value, P_{local} (local significance)	Posttrial *P* value, P_{global} (global significance)
Northern Hemisphere scan	5.0×10^{-8} (5.3σ)	2.2×10^{-2} (2.0σ)
List of candidate sources, single test	1.0×10^{-7} (5.2σ)	1.1×10^{-5} (4.2σ)
List of candidate sources, binomial test	4.6×10^{-6} (4.4σ)	3.4×10^{-4} (3.4σ)

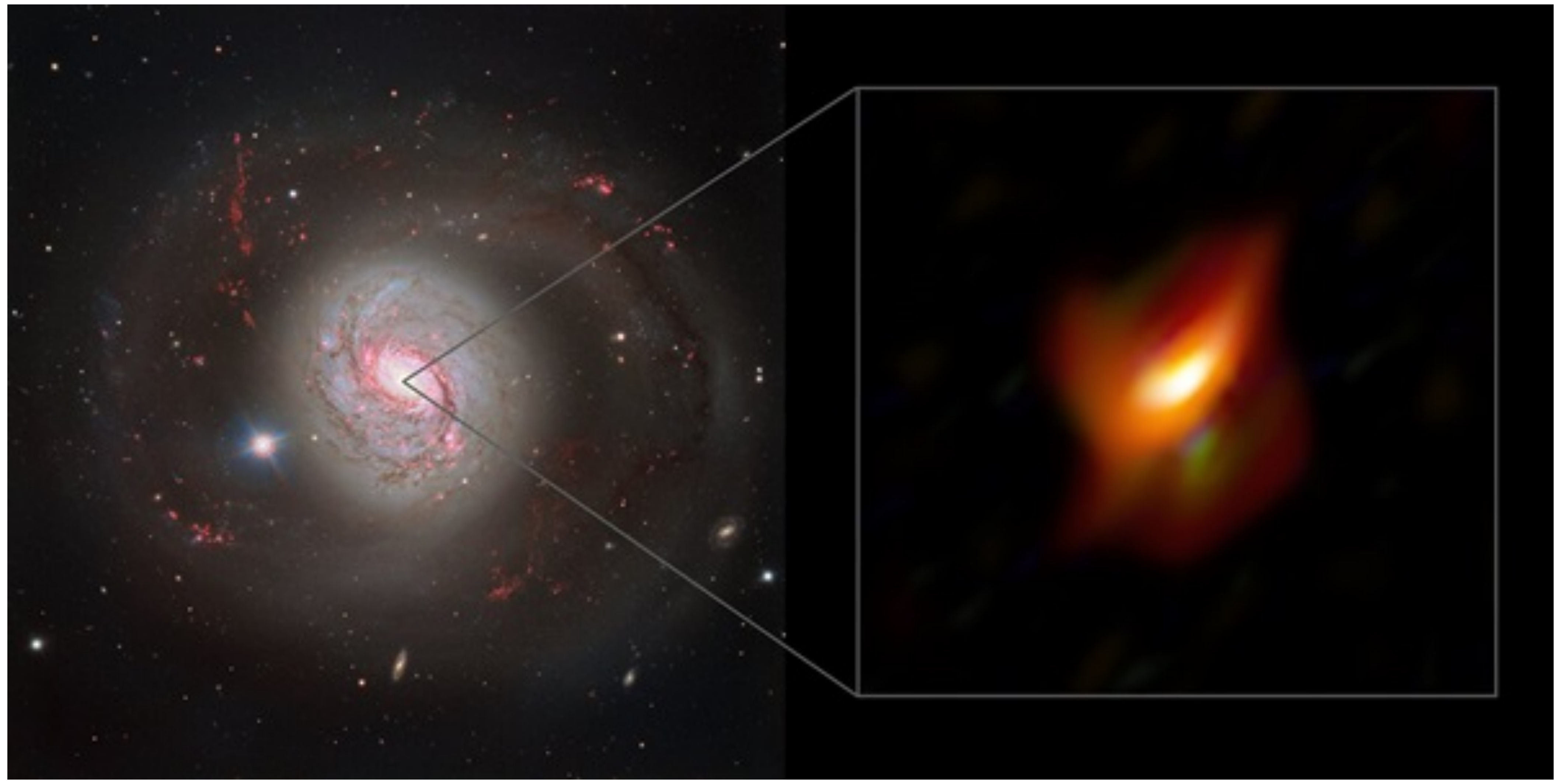


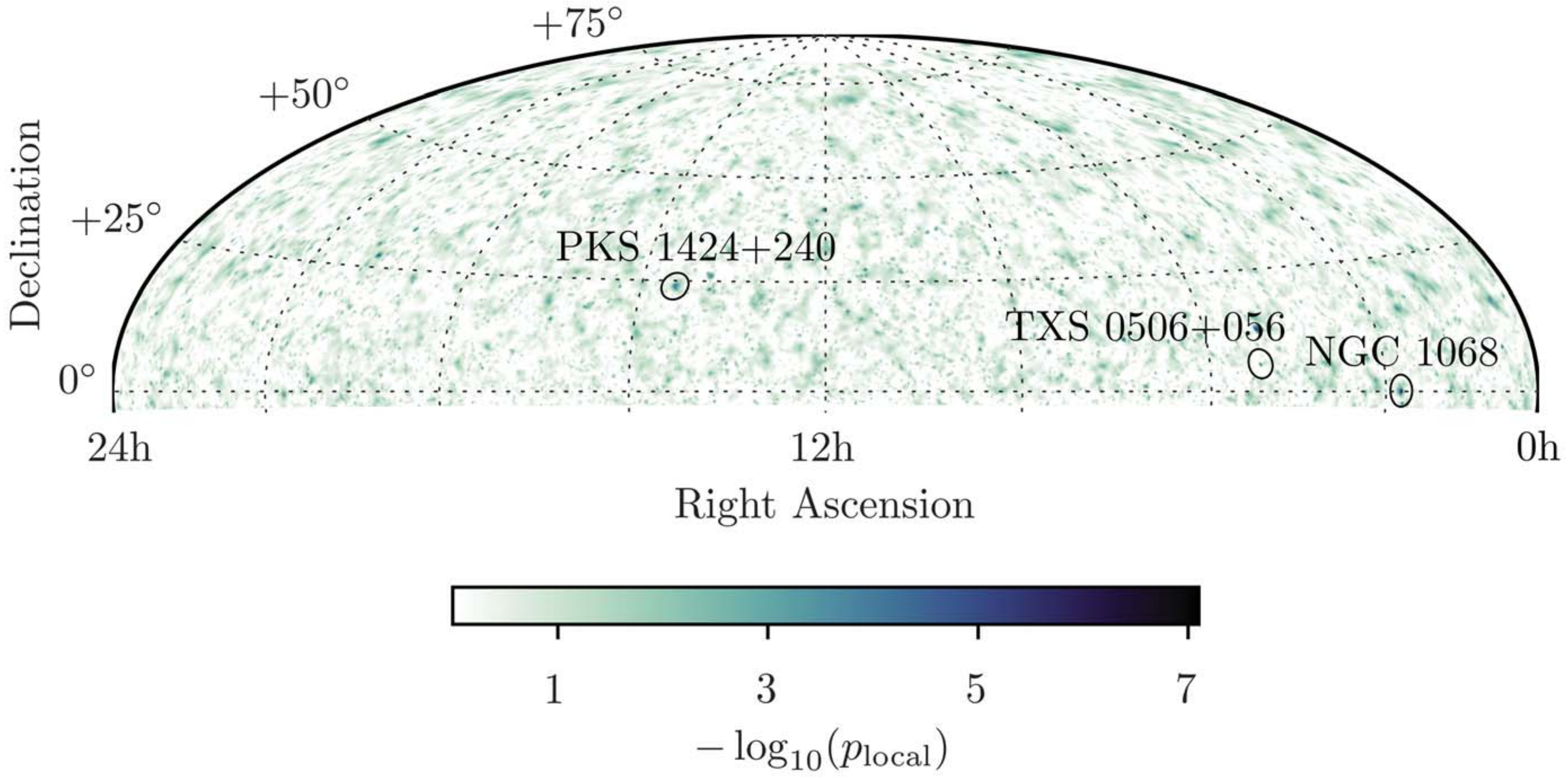


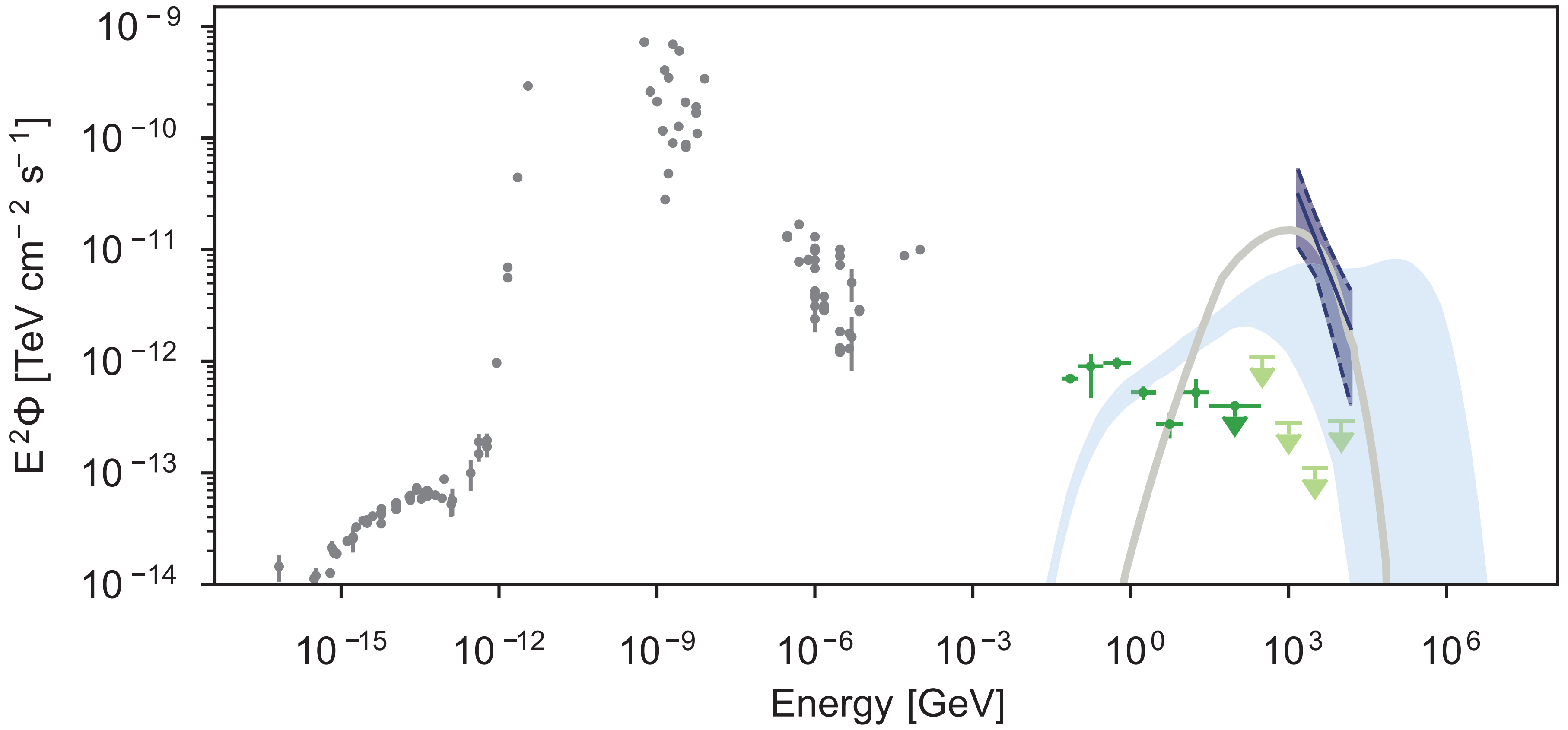
NGC 4151, CGCG 420-015 ~ 3σ

NGC 1068

Icecube Coll 2023 - Science







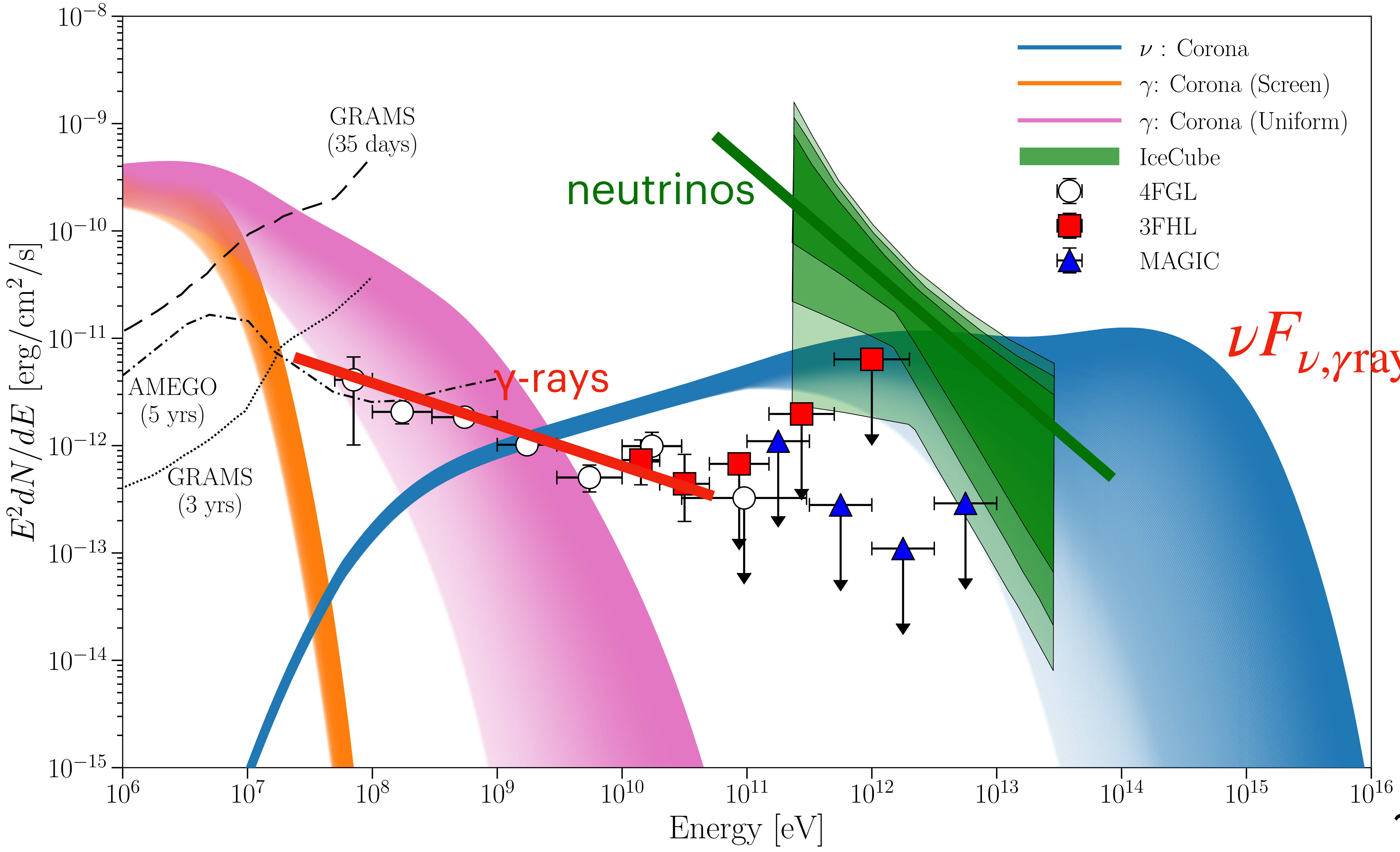
Seyfert 2 galaxy with heavily obscured nucleus

Prototypical nearby Seyfert 2 (14.4 Mpc)

High infrared luminosity: high-level of star formation

Neutrino production in NGC 1068

Y. Inoue et al 2019



$\pi^0 \rightarrow \gamma\gamma : \pi^{+/-} \rightarrow \nu_e \nu_\mu \bar{\nu}_\mu$

$\nu F_{\nu,\gamma\mathrm{rays}}|_{E_\gamma=2E_\nu} \sim \nu F_{\nu,\mathrm{neutrinos}}$

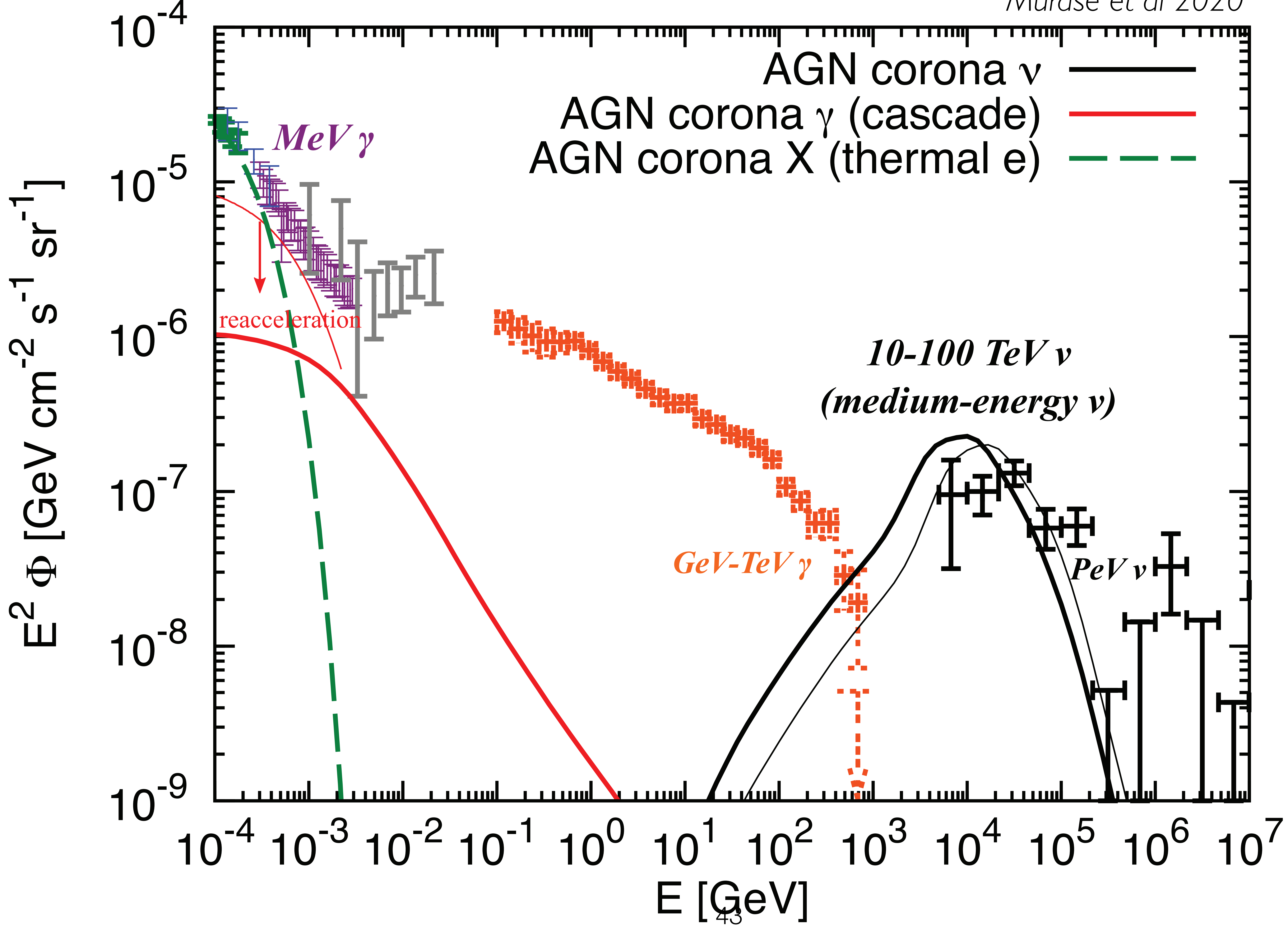
$R_{\mathrm{neutrinos}} \leq 5R_{\mathrm{Sw}}$

Murase 2022, Halzen 2023,
newer Fermi-LAT analysis:
Murase 2024, Das et al 2024,
Saurenhaus et al 2025

~the size of the AGN corona

Neutrino production in AGN Coronae

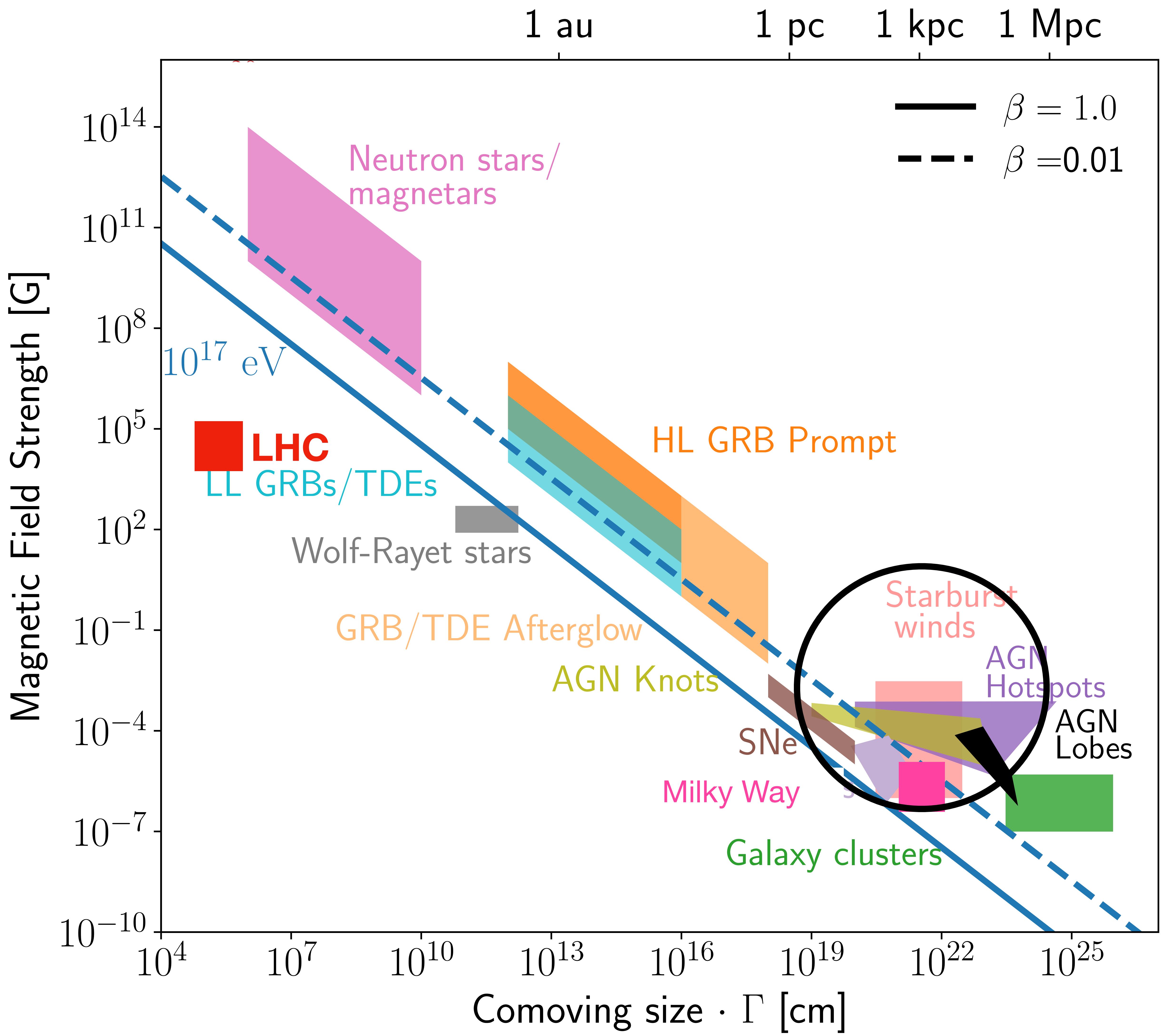
Murase et al 2020

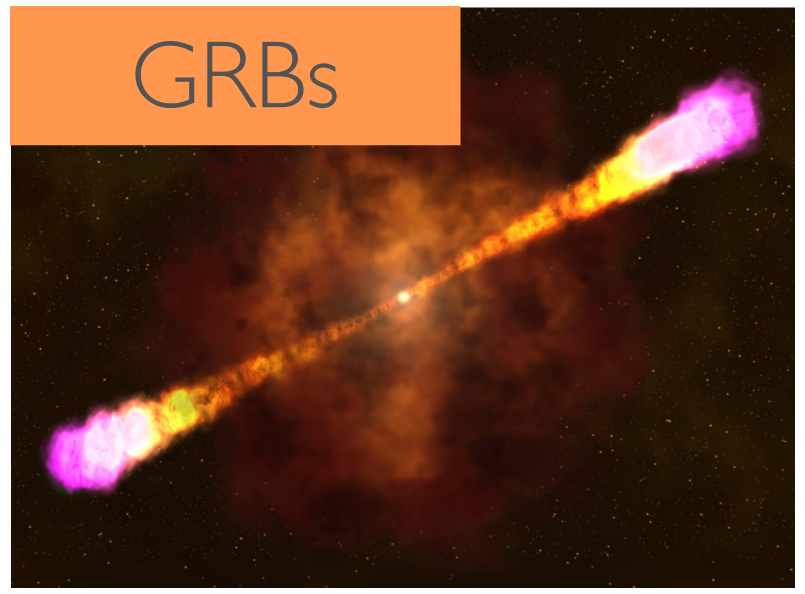


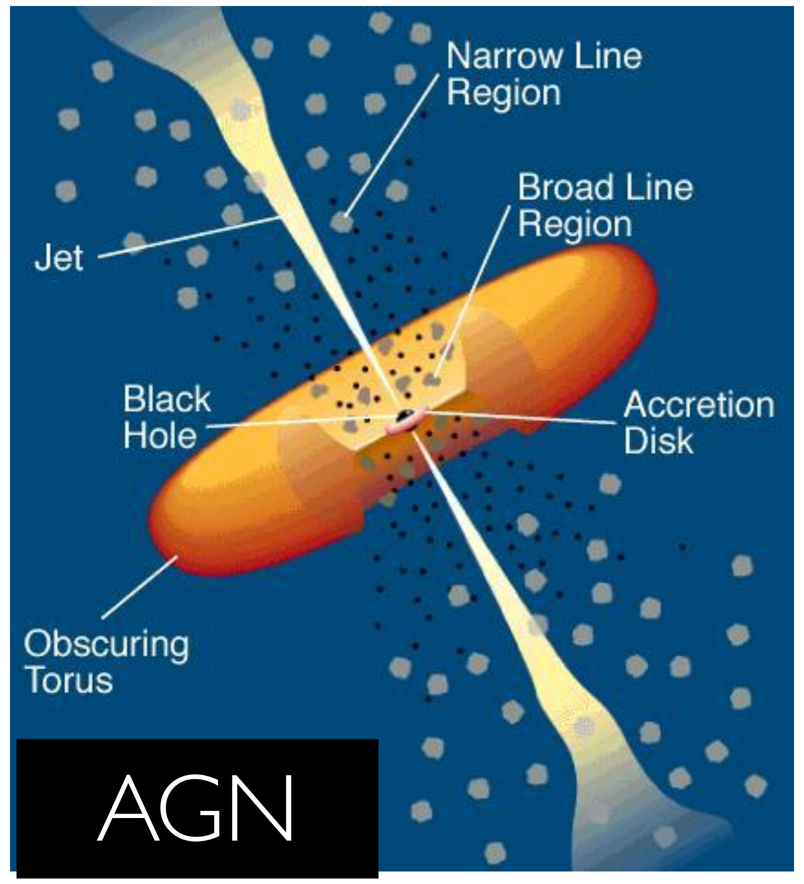
Scorecard

	$E_{\rm max}^{\rm UHECR}$	$n_{\rm UHECR}$	$\dot{\varepsilon}_{\rm UHECR}$	n_{ν}	Stacking UL
BL Lacs	😀	😞	😀	😞	≲20%
FSRQs	😀	😞	😀	😞	≲20%
FR I	😀	😀	😀	😀	≲20%
FR II	😀	😀	😀	😀	≲20%
Non-jetted AGN UFOs	😀	😀	😀	😀	≲100%
Non-jetted AGN Corona	😞	😀	😀	😀	≲100%
Starburst galaxies					
HL GRBs					
LL GRBs					
Pulsars					
TDEs					

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







Starburst galaxies

High star-formation rate (> 100 x Milky Way)

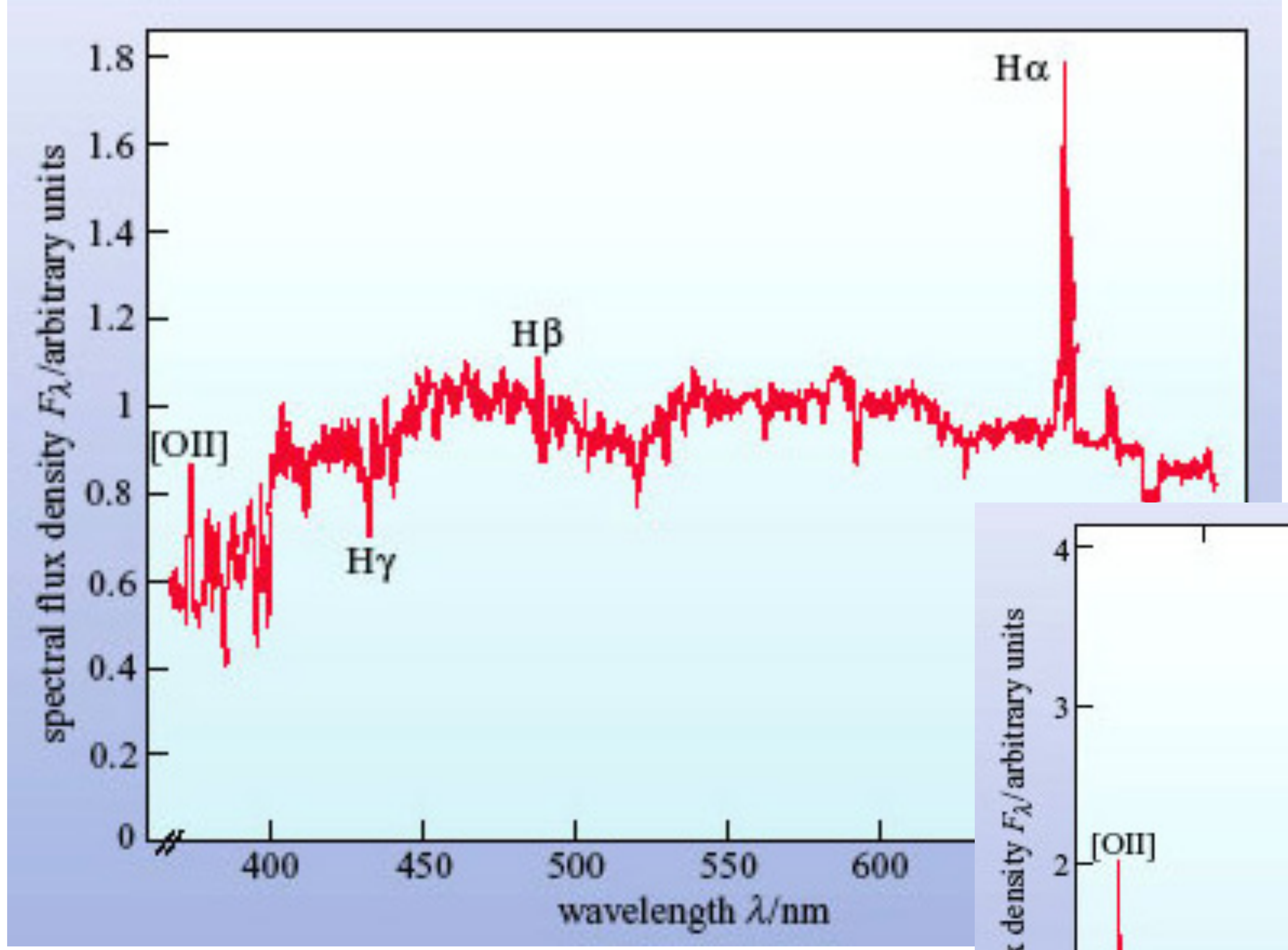
Starburst episodes are short-lived (<10^8 yrs)

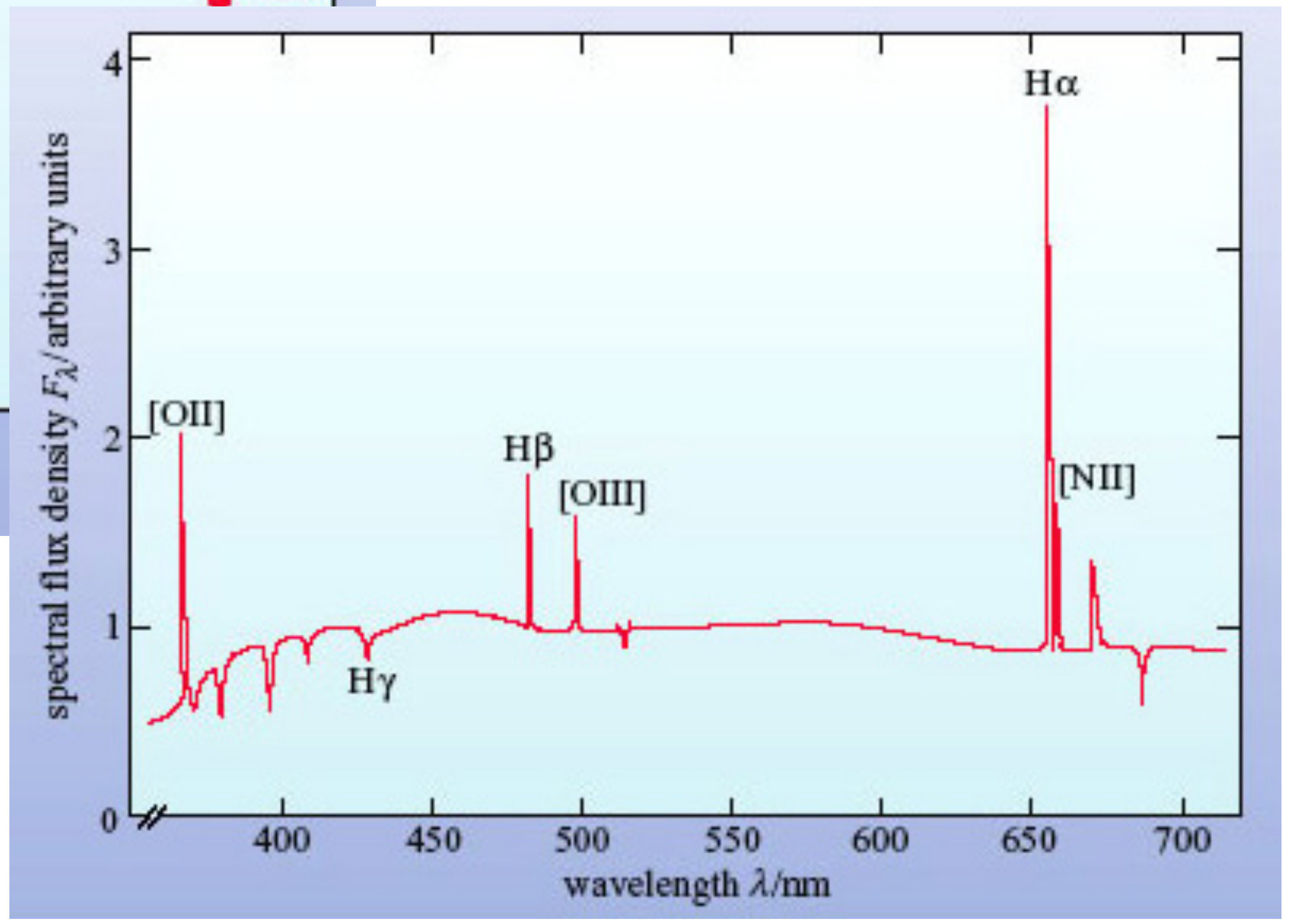
Centrally driven strong outflows (``superwinds'')

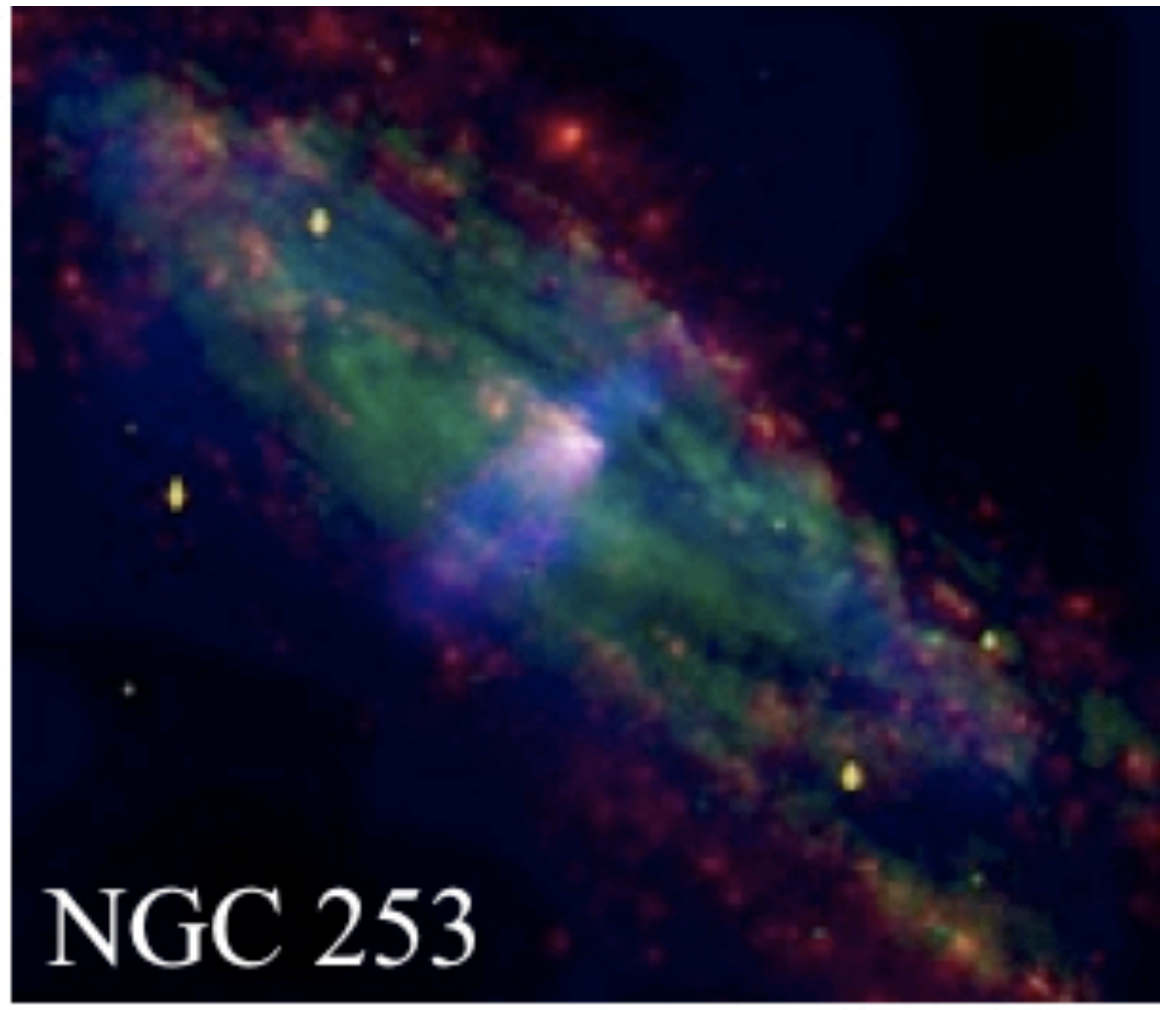
Column densities Σ_g > 0.1g/cm^2 and magnetic fields B ~ 1 mG (cf $\Sigma_g \approx$ 0.003g/cm^2, B ~ 5μG in the Milky way)

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)



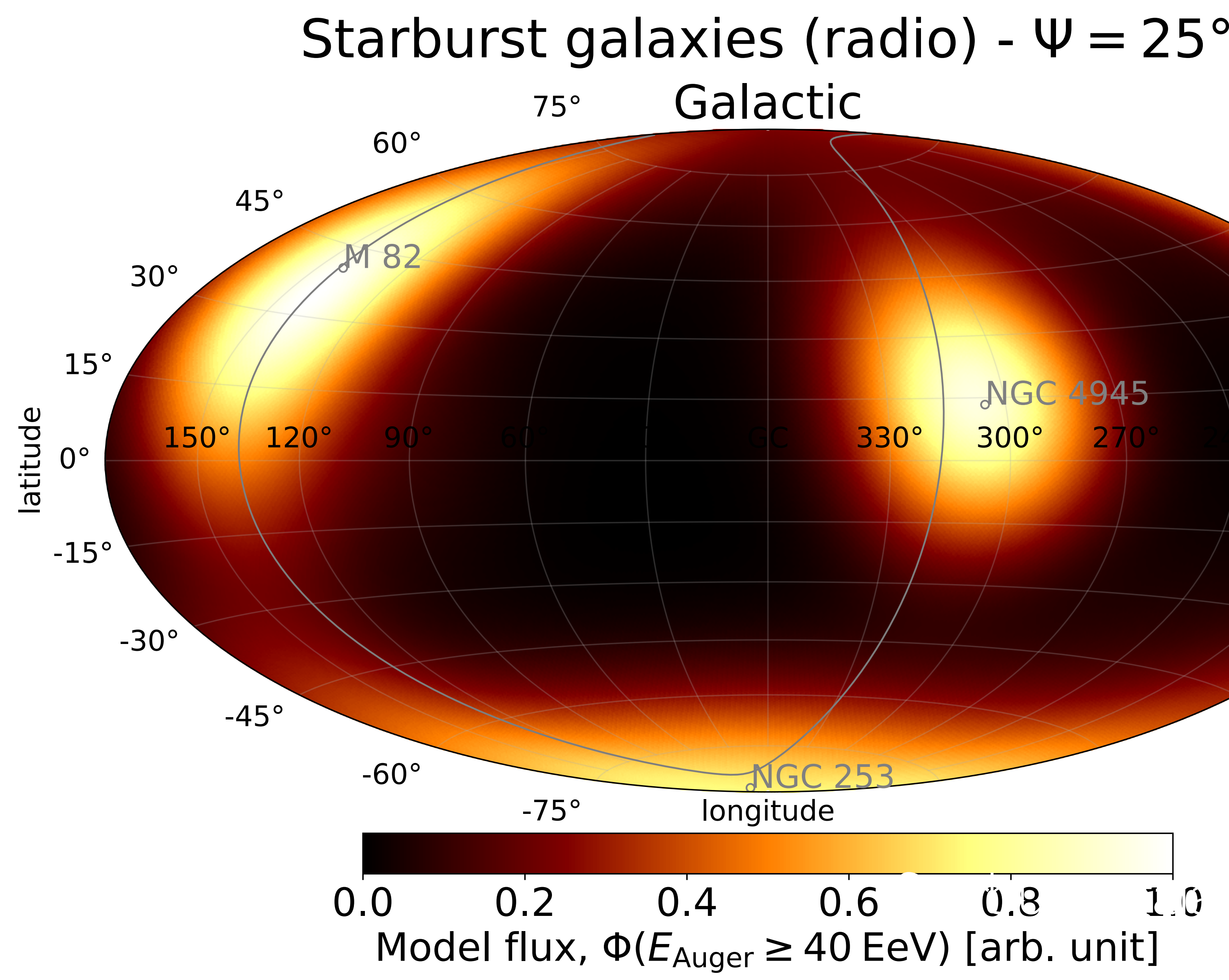




UHECRs from starburst galaxies?

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

Auger Coll, ApJL, 853, L29, 2018, Auger Coll 2022, ApJ 935 (2022) 2, 170



Starburst galaxies (radio flux weights)

E ≥ 38 EeV, Flux fraction 10%

Correlation could be related to transients

inside the starburst (GRBs etc)

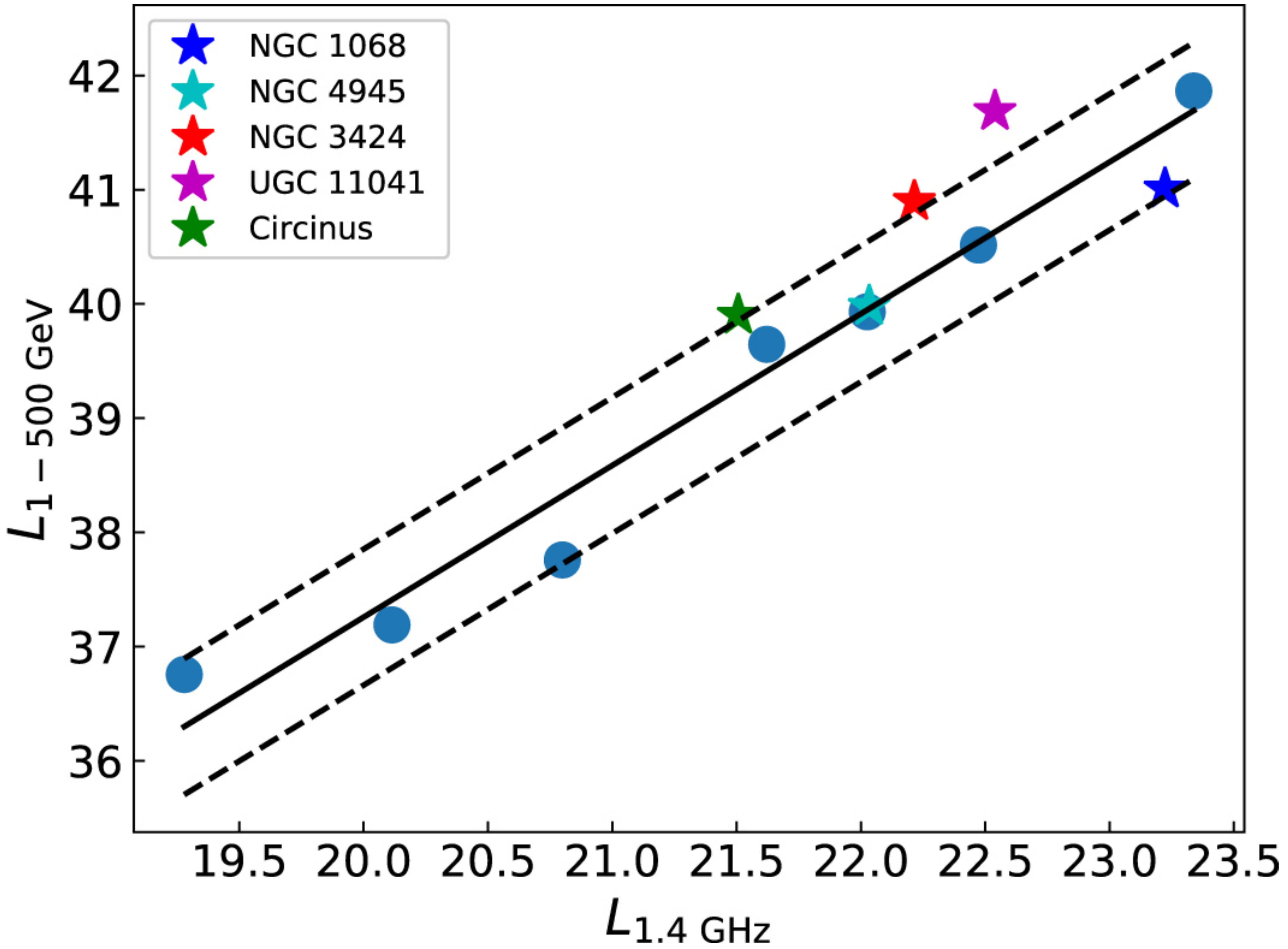
post-trial significance: 4.2σ

$$U_{\rm rad} \gtrsim U_B$$

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

$$L_{\rm min} \sim 10^{45}\ \text{erg/s} \cdot \left(\frac{E}{10^{20}\ \text{eV}}\right)^2 \left(\frac{Z}{10}\right)^{-2} \left(\frac{u}{10^{-3}c}\right)^{-1}$$

Peng et al 2019



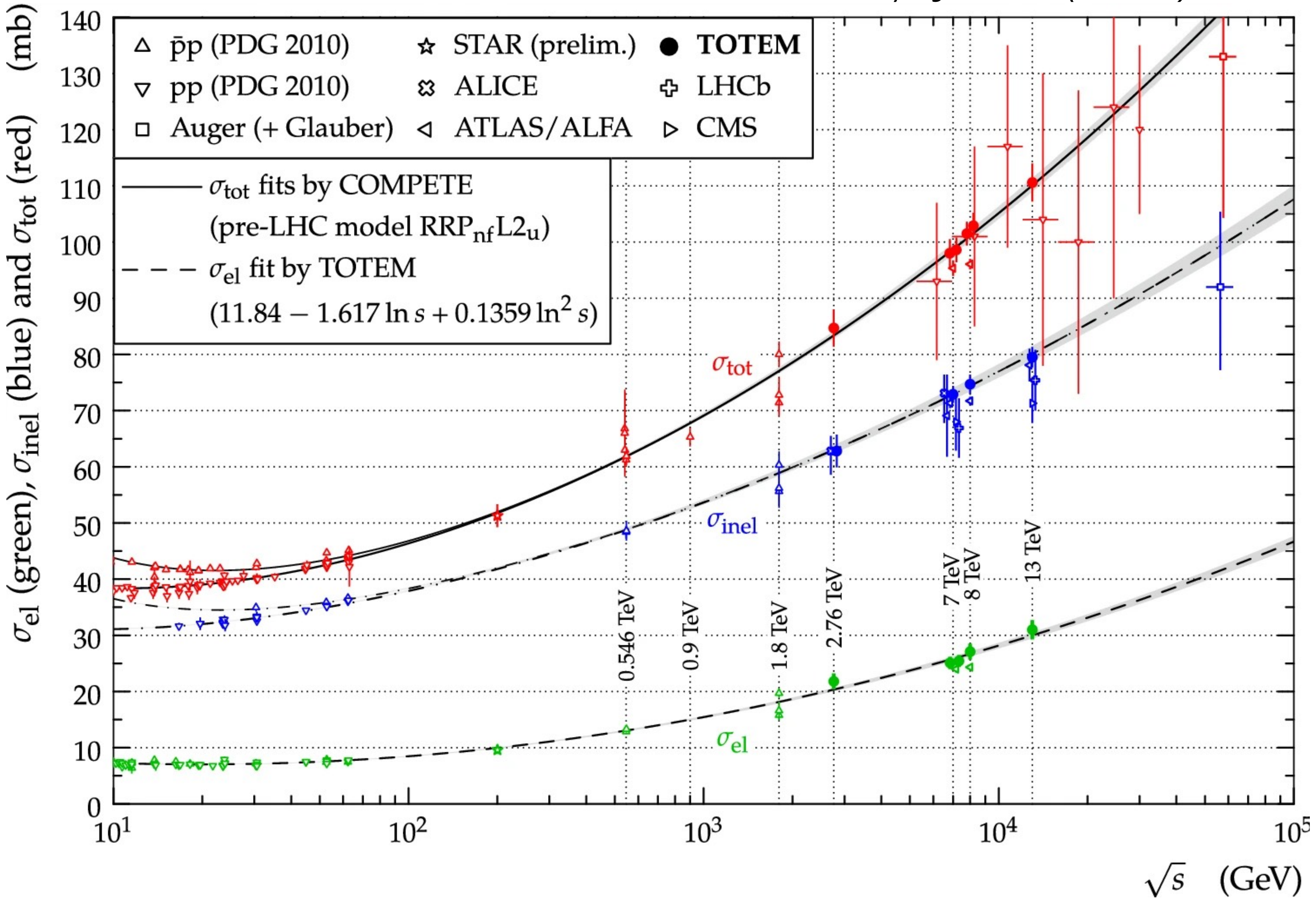
Neutrino production in proton-proton interactions

Gas reservoirs (Starburst galaxies, Galaxy Clusters…)

$$p + p \to p + p + N\pi^+ + N\pi^- + N\pi^0$$

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

TOTEM Coll. Eur.Phys.J.C 79 (2019) 103



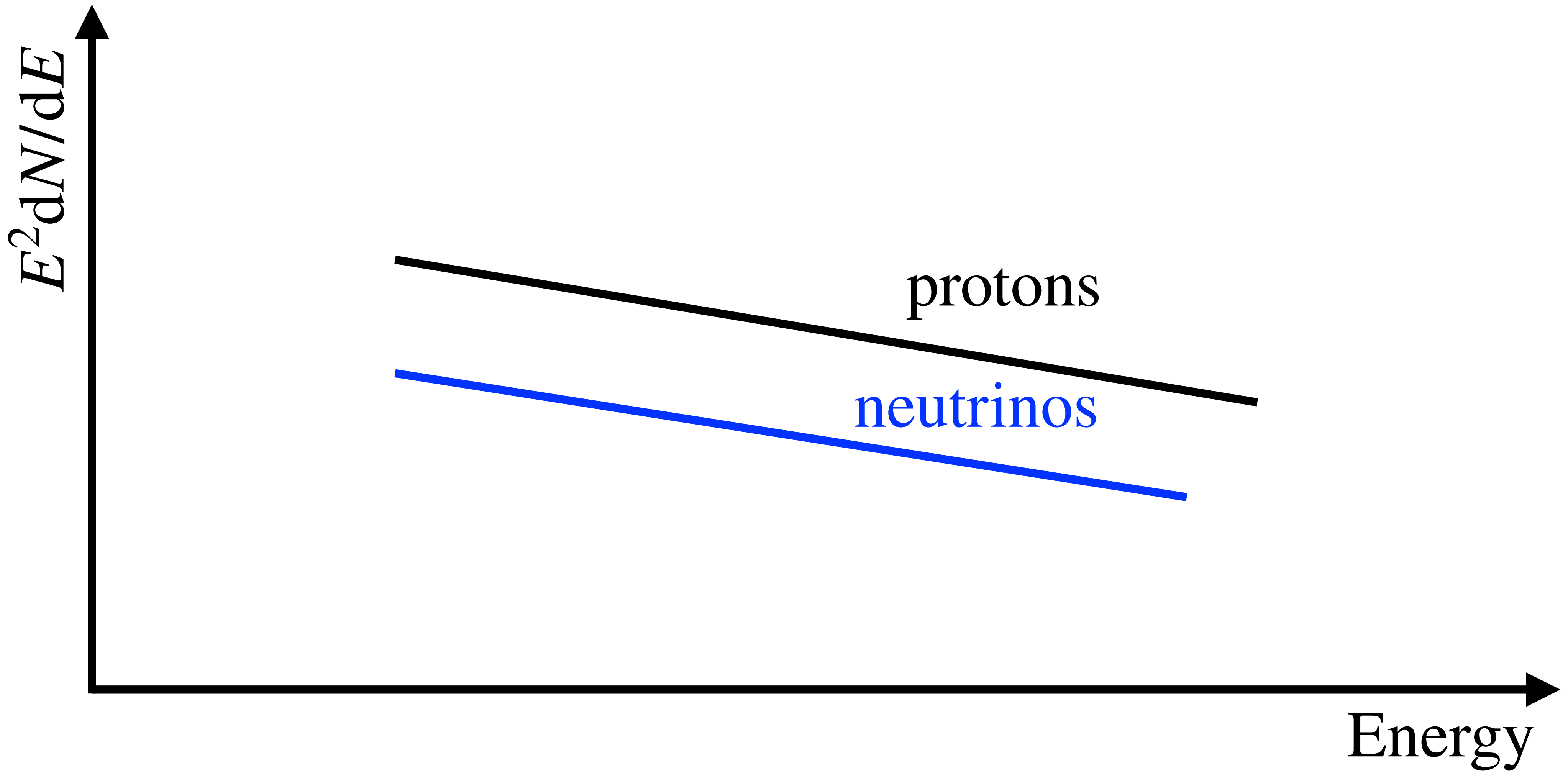
Since interaction length $\lambda(E) \propto 1/\sigma(E) \approx \text{const}$.

and meson production spectra

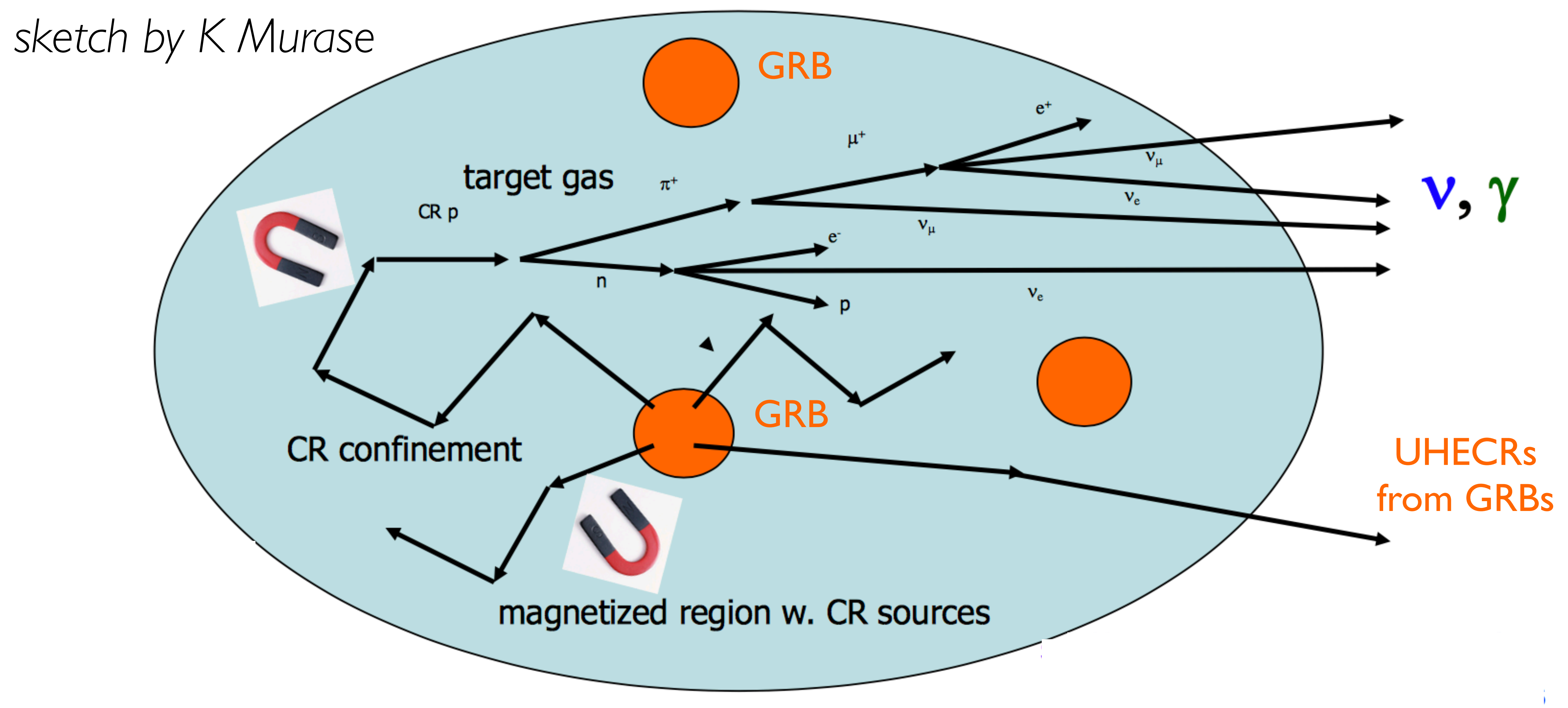
$$f(E_\pi, E_p) \approx f(E_\pi/E_p)$$

For $\mathrm{d}N/\mathrm{d}E \sim E_p^{-\gamma}$

$$\mathrm{d}N/\mathrm{d}E_\nu \sim \mathrm{d}N/\mathrm{d}E_\pi \sim E_p^{-\gamma}$$



Neutrinos from starburst galaxies: Reservoir model



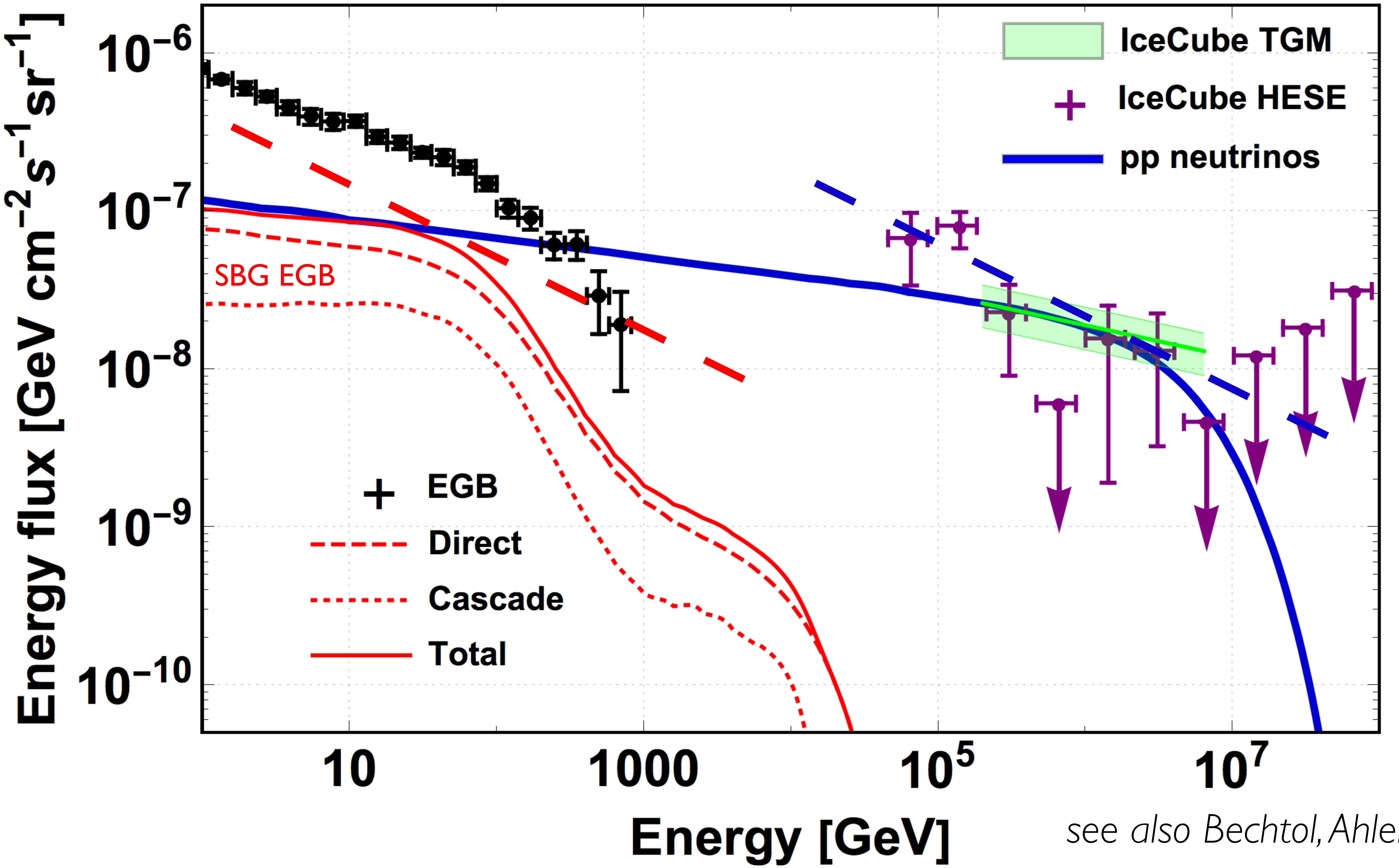
High gas density, high B environment

The highest energy cosmic rays escape (observed)

Lower energy CRs lose all their energy in pp interactions

Neutrinos from starburst galaxies

Palladino et al 2019

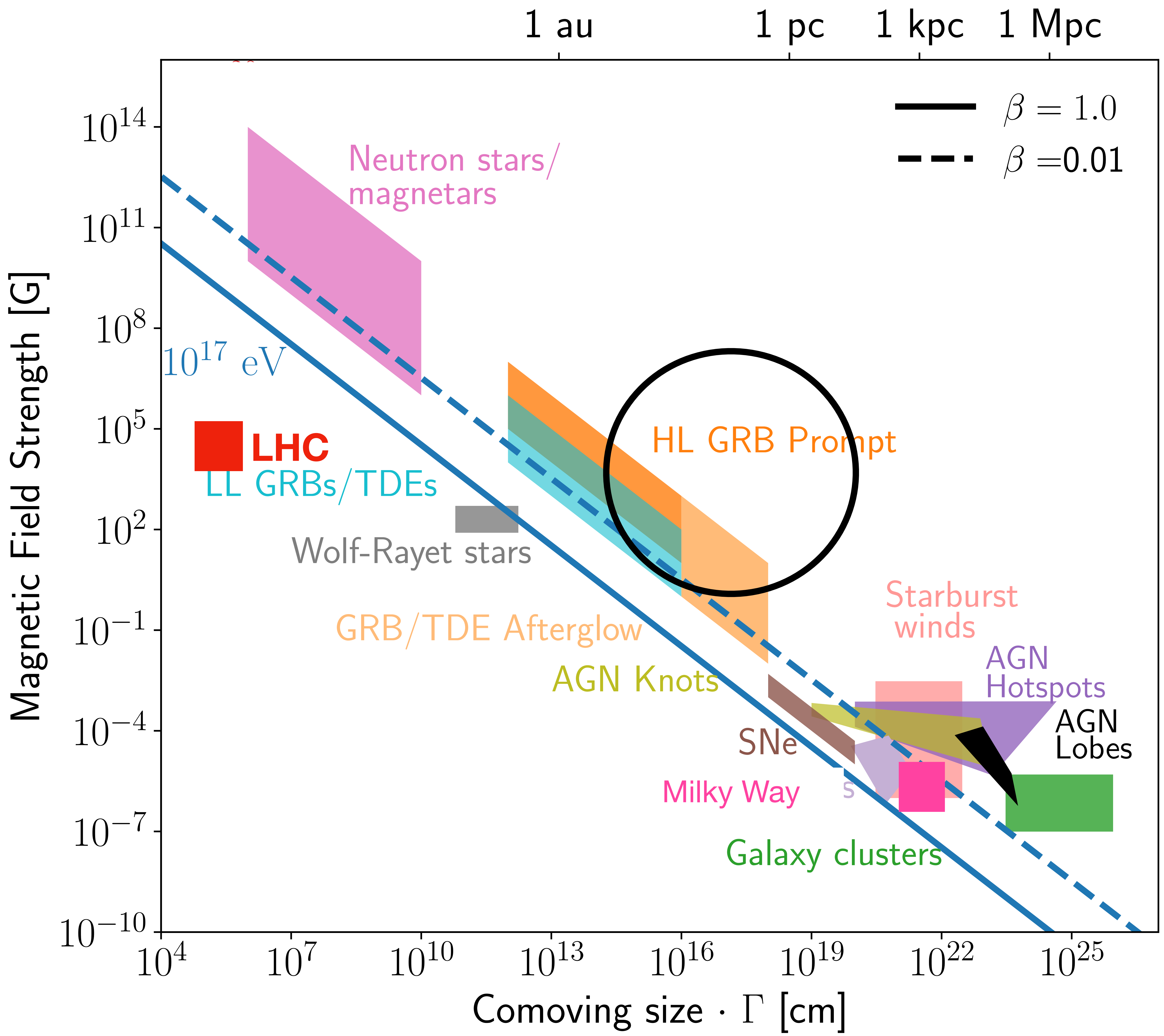


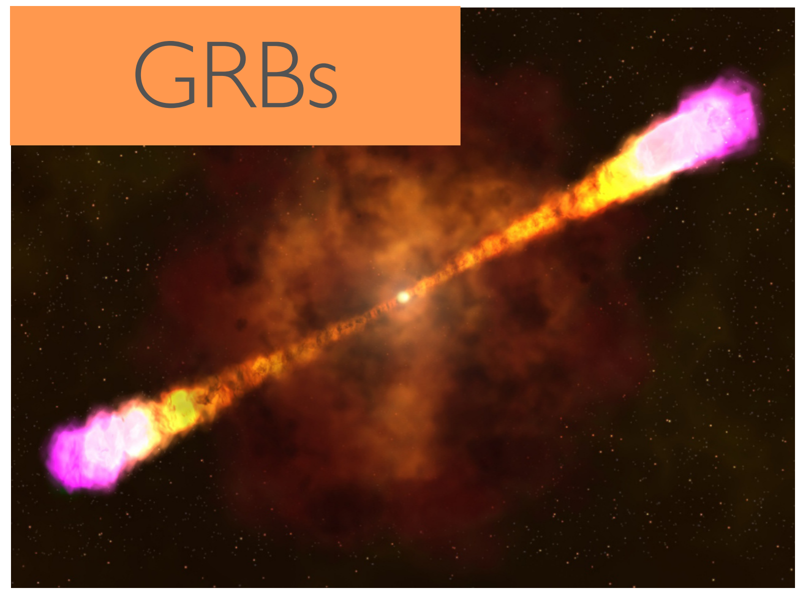
see also Bechtol, Ahlers et al 2015

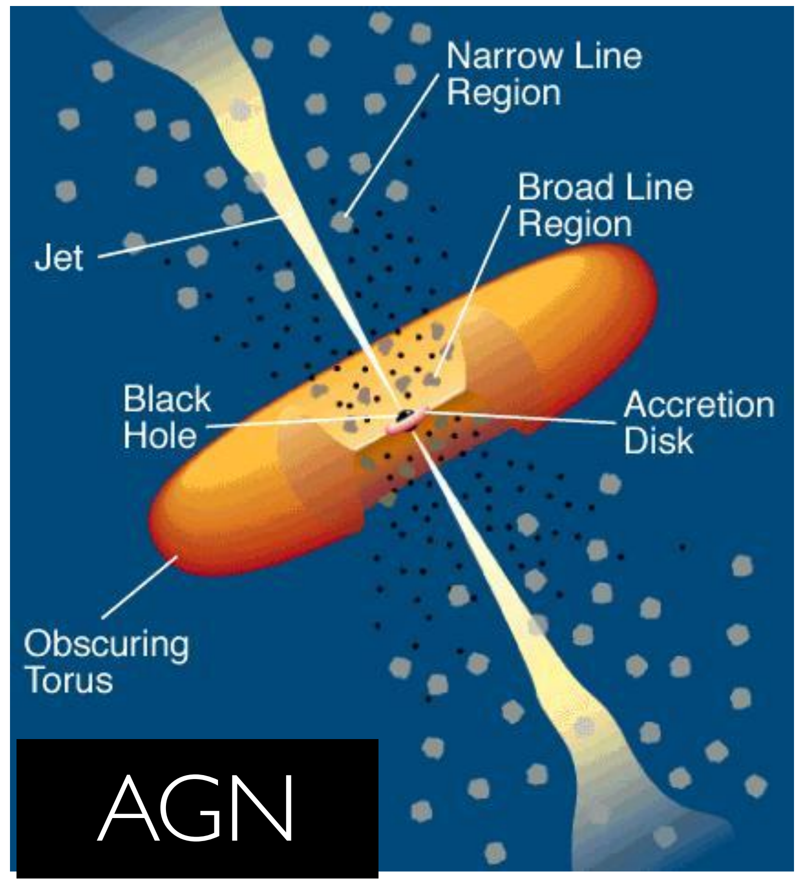
Scorecard

	$E_{\max}^{\mathrm{UHECR}}$	n_{UHECR}	$\dot{\varepsilon}_{\mathrm{UHECR}}$	n_{ν}	Stacking UL	
BL Lacs	😀	😞	😀	😞	≲20%	
FSRQs	😀	😞	😀	😞	≲20%	
FR I	😀	😀	😀	😀	≲20%	
FR II	😀	😀	😀	😀	≲20%	
Non-jetted AGN	😐	😀	😀	😀	≲100%	
Starburst galaxies	😞	😀	😀	😀	≲100%	*(but problems at medium E)
HL GRBs						
LL GRBs						
Pulsars						
TDEs						

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







Gamma-ray bursts

Discovered serendipitously in 1967

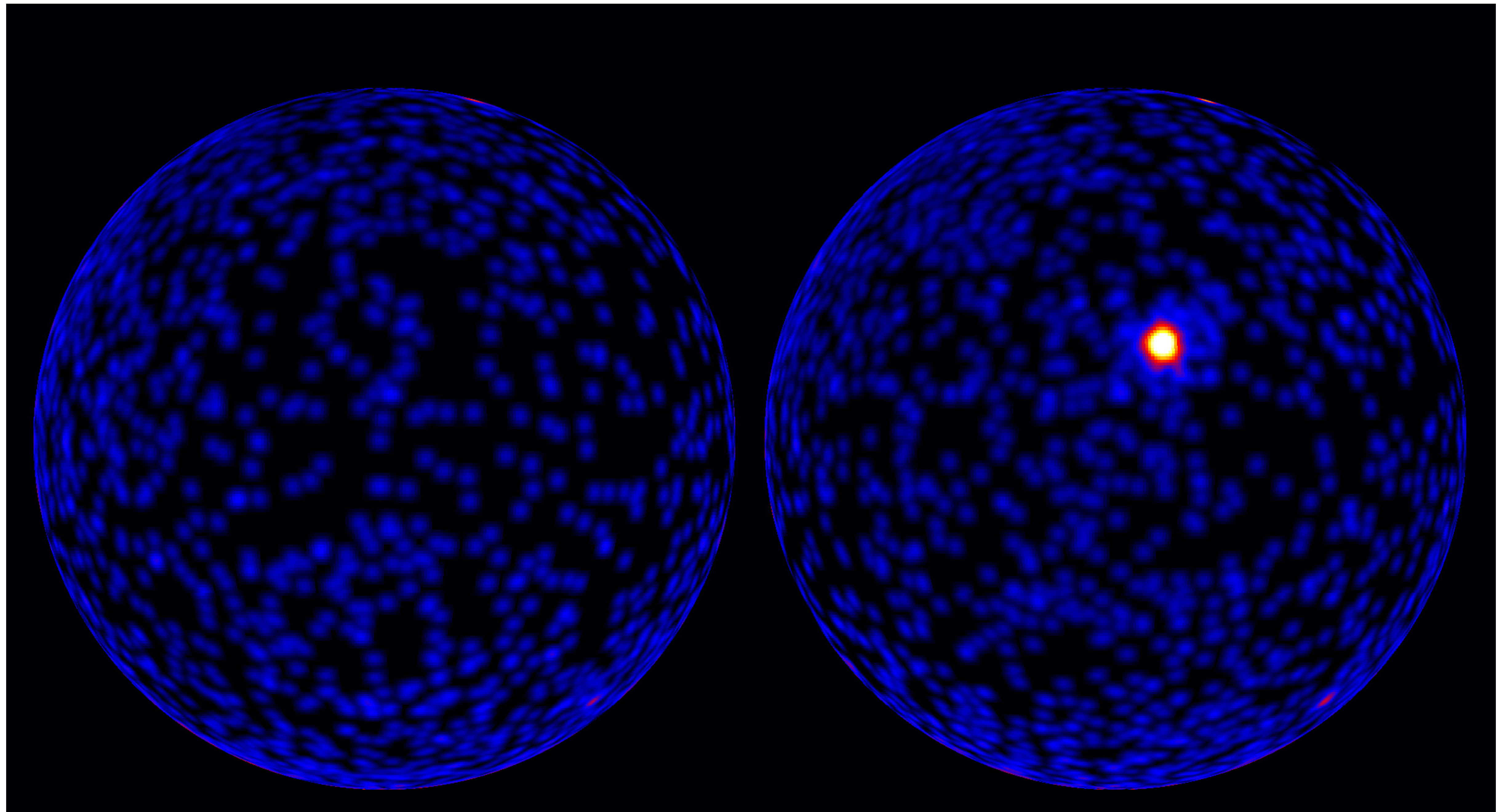
Intense short flashes of light peaking in the 10 keV -1 MeV range

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

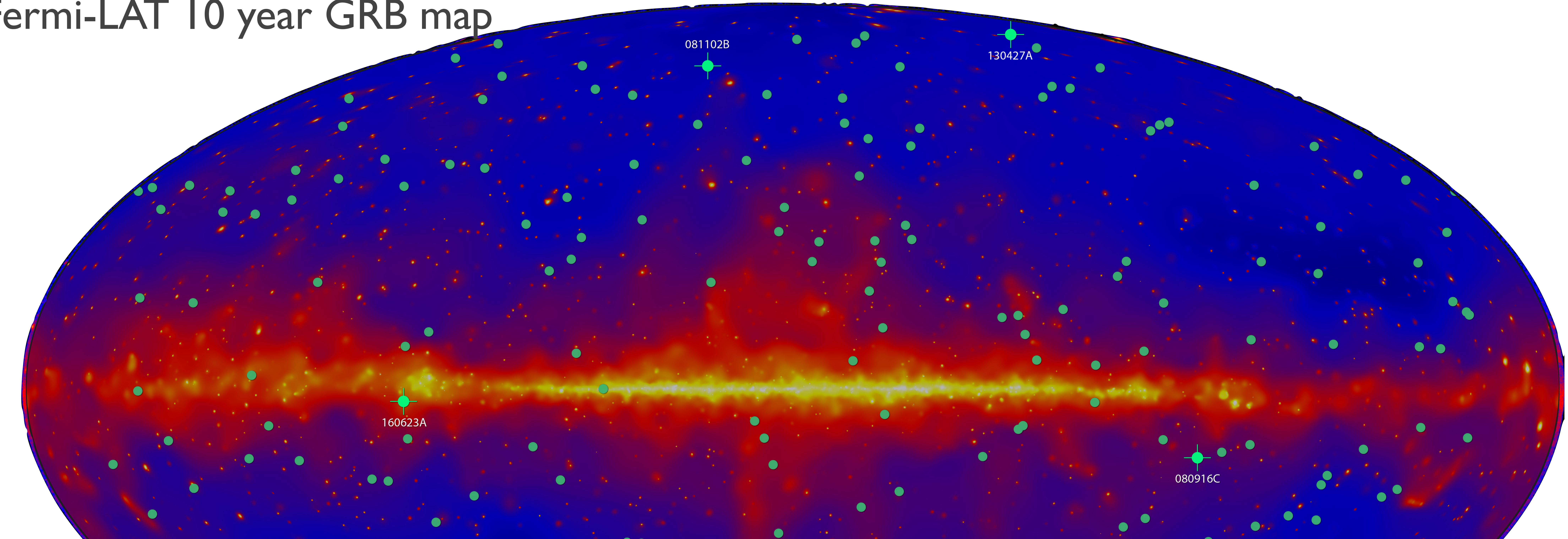


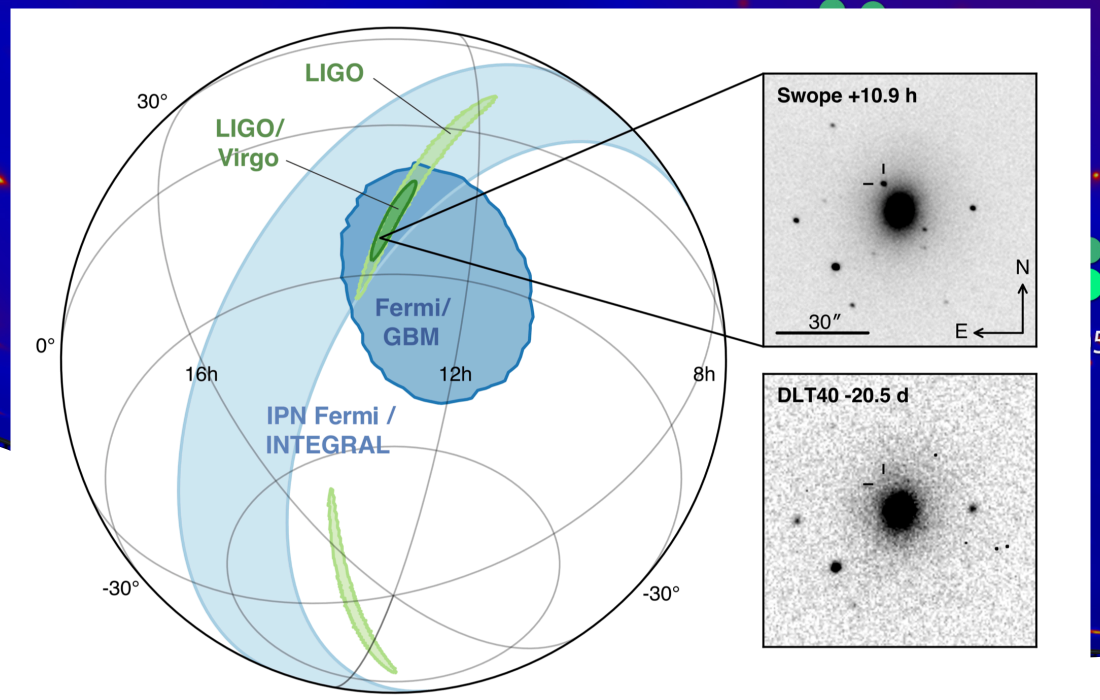
Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

Gamma-ray bursts

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.

UHECR maximum energy

Very high Lorentz factors

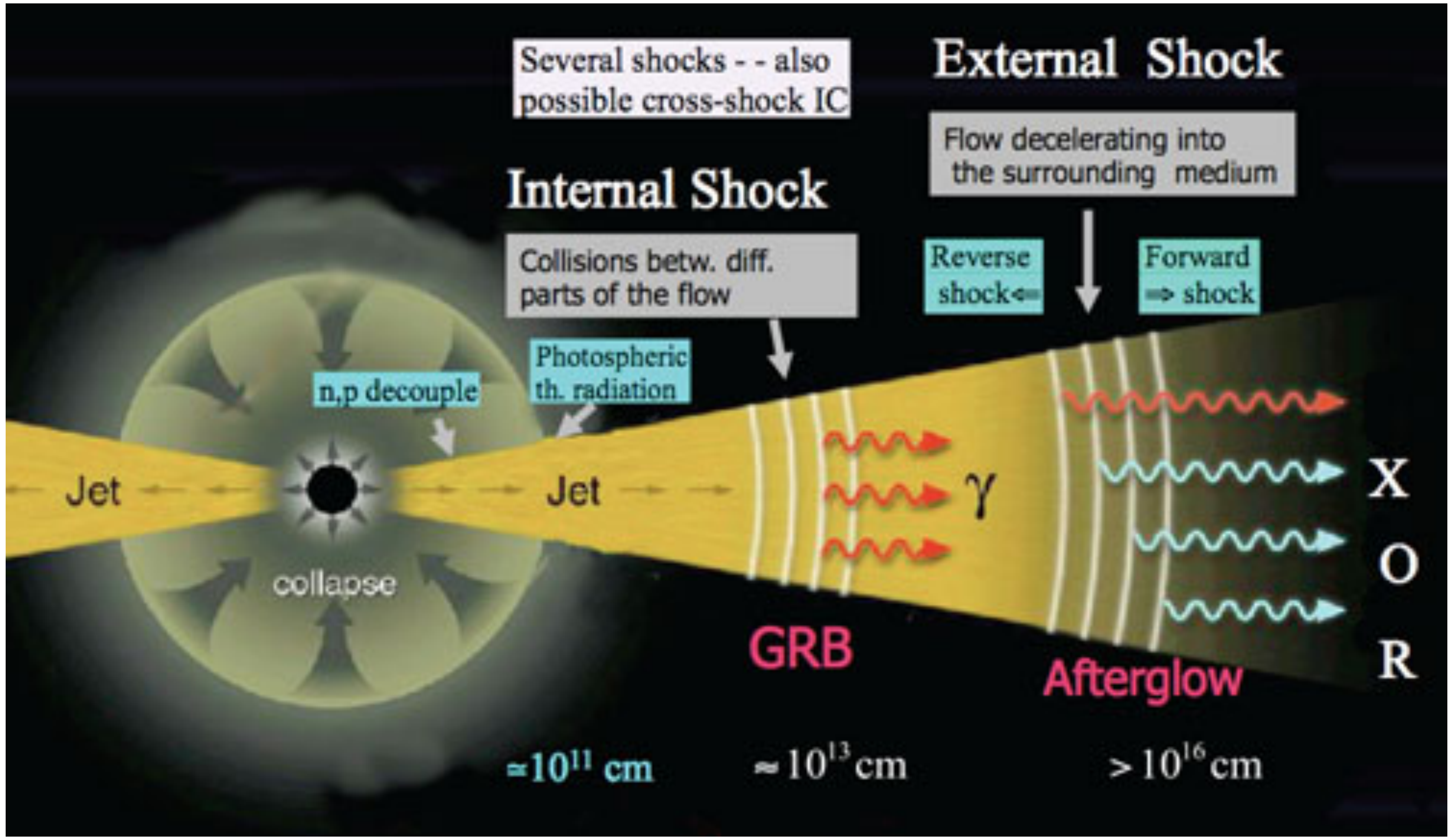
Highly magnetised expanding jet

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

Waxman 1995, Vietri 1995

Maximum energy OK for protons

Nuclei survival in GRB photon fields?



Neutrino production in GRBs

Ample photon fields

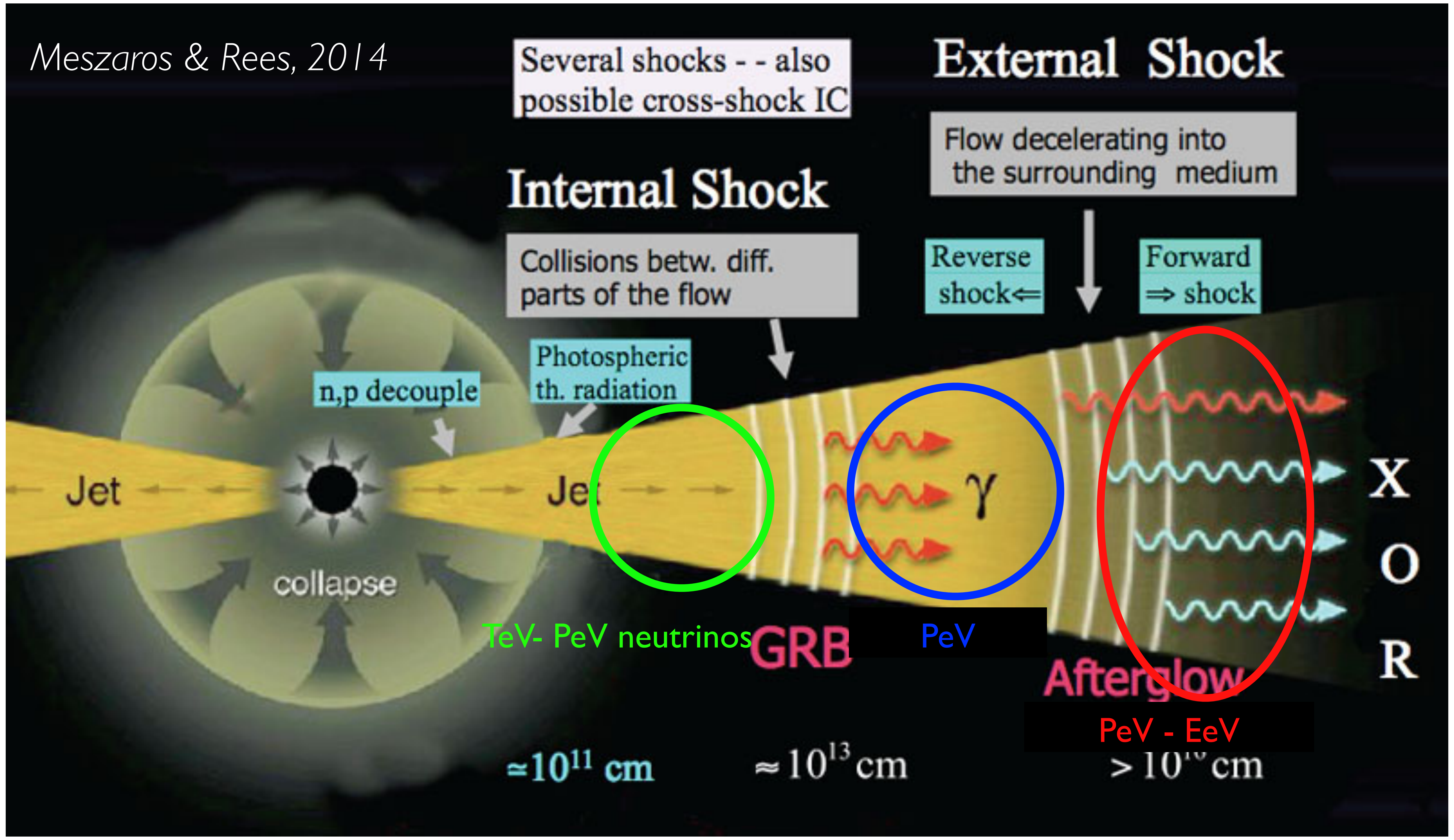
$$p + \gamma_{\text{jet}} \rightarrow n/p + \pi^+/\pi^0$$

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

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

e.g. prompt emission,

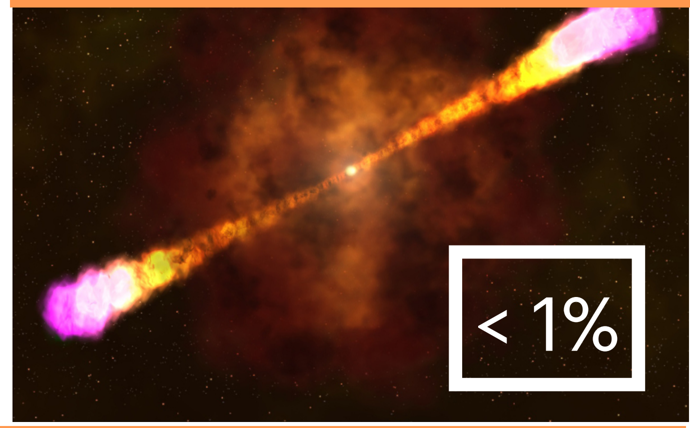
$$z = 1,\ \Gamma^2 = 10^5,\ E_\gamma \sim 250\ \text{keV} \rightarrow E_\nu \sim \text{PeV}$$



>100 publications on theoretical expectations:
see e.g. review "Neutrinos from GRBs" (Kimura 2022)

GRB contribution to the cosmic-neutrino flux

GRBs

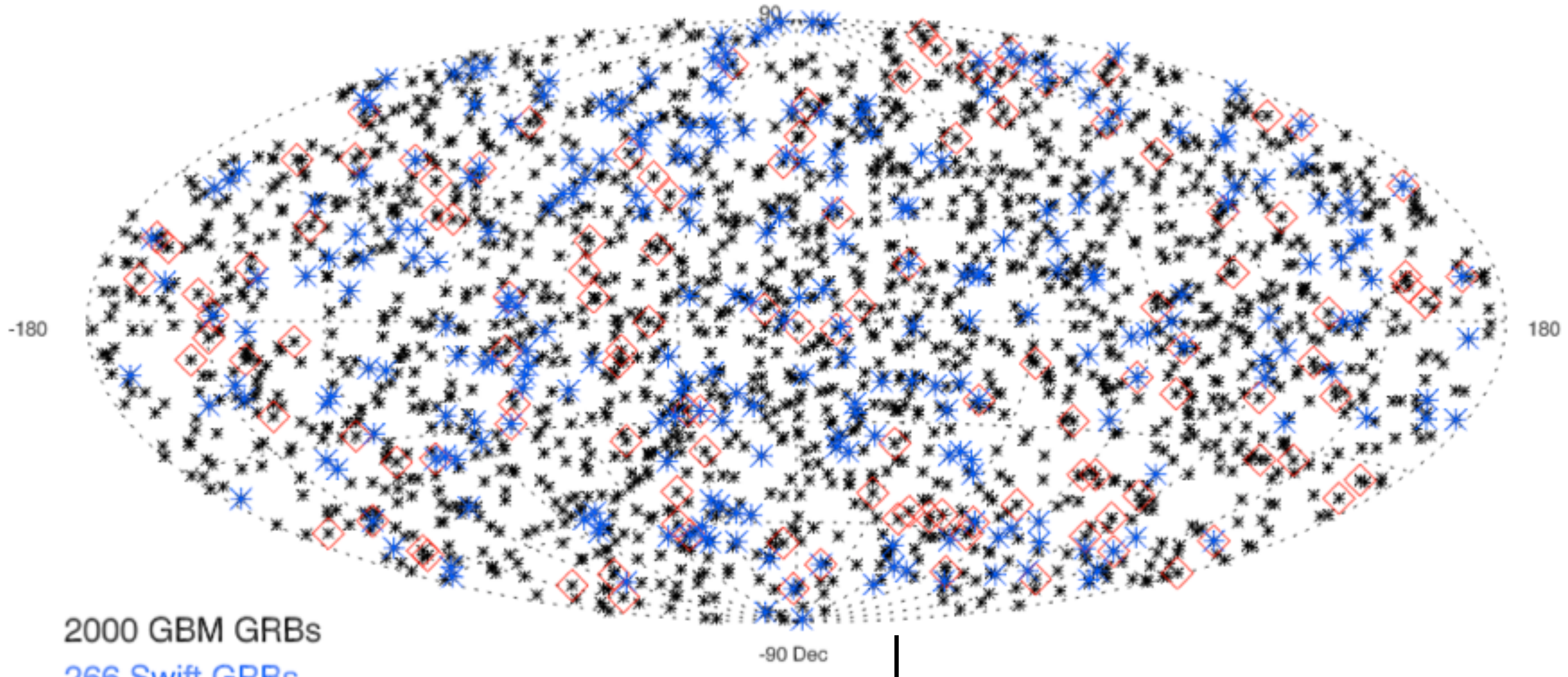


NS/NS Mergers

Stacked search for neutrinos coincident with prompt GRB emission.

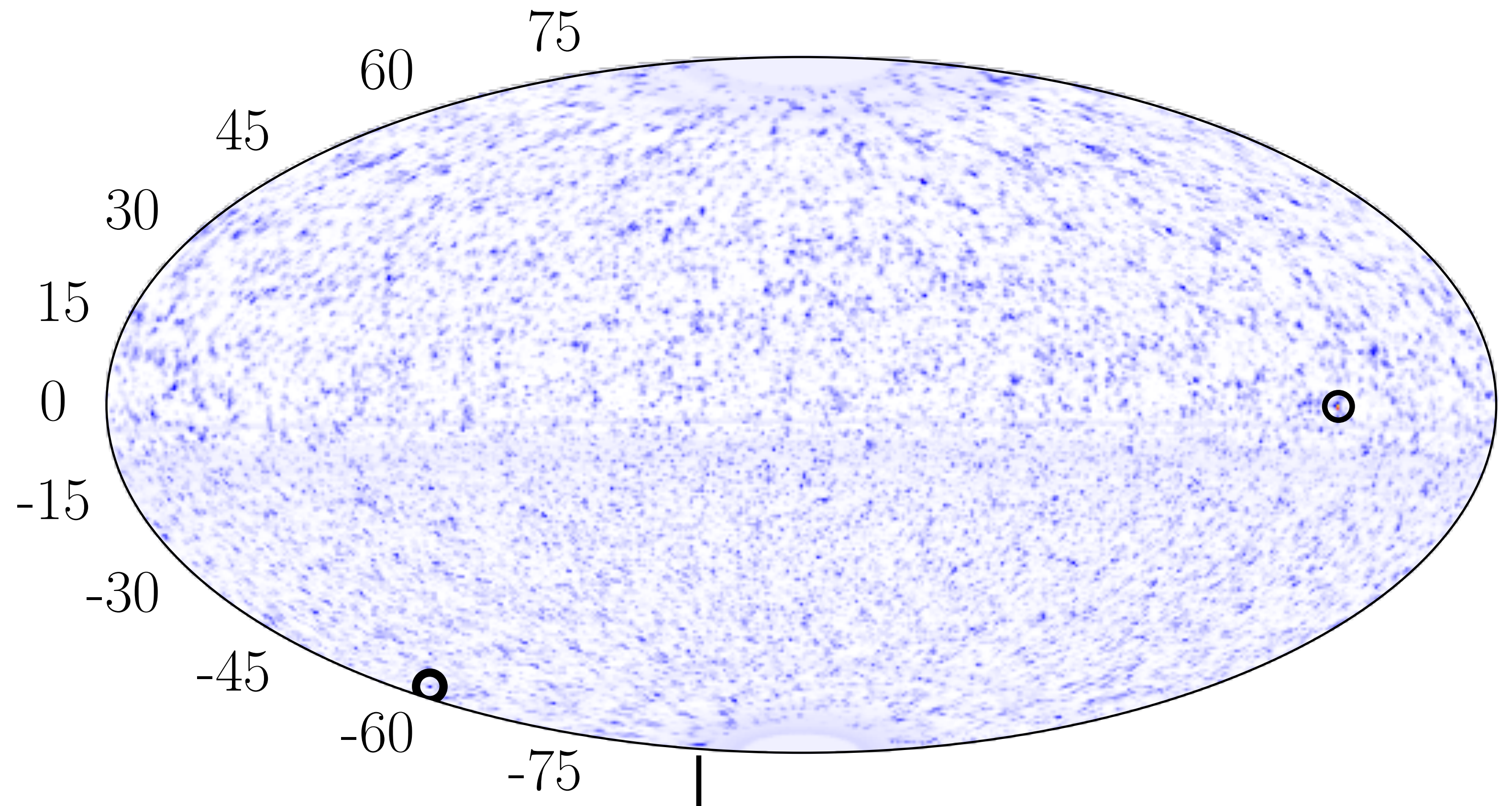
2091 GRBs

2000 Fermi GBM GRBs



2000 GBM GRBs
266 Swift GRBs
121 LAT GRBs

IceCube Point-Source Events



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)

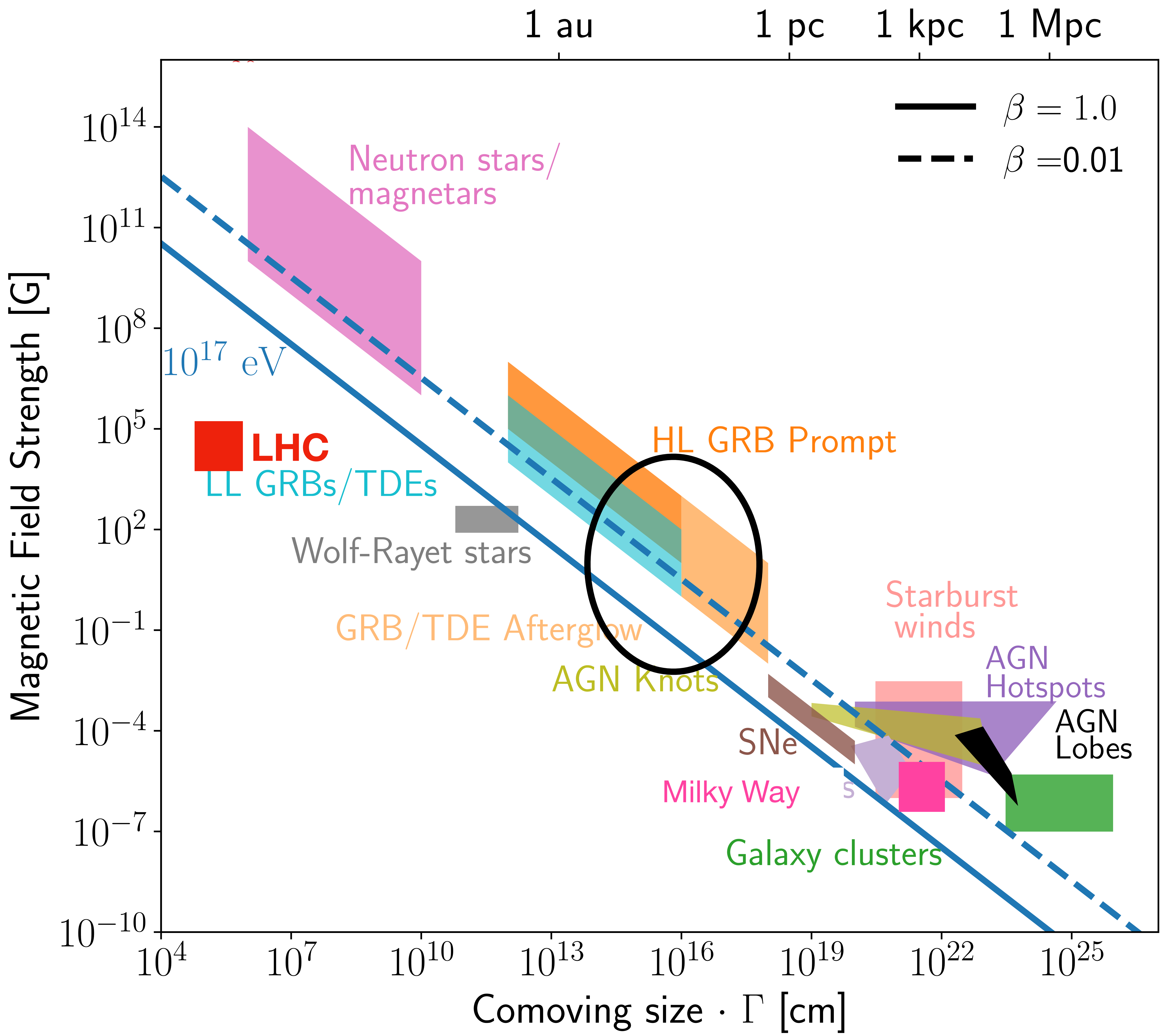
Prompt (ΔT_{promt} ~1-100s): < 1% diffuse neutrino flux

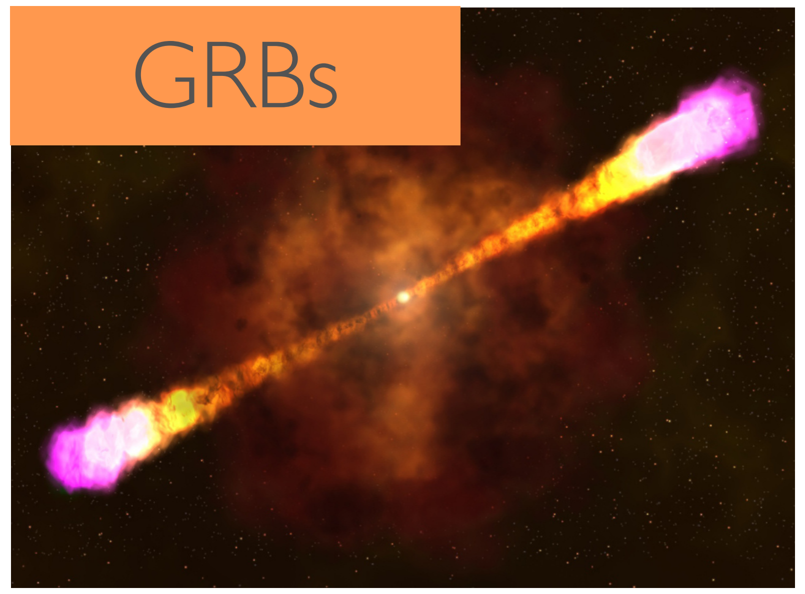
Precursor/Afterglow ($\Delta T_{afterglow}$ ± 14d): < 24% diffuse neutrino flux

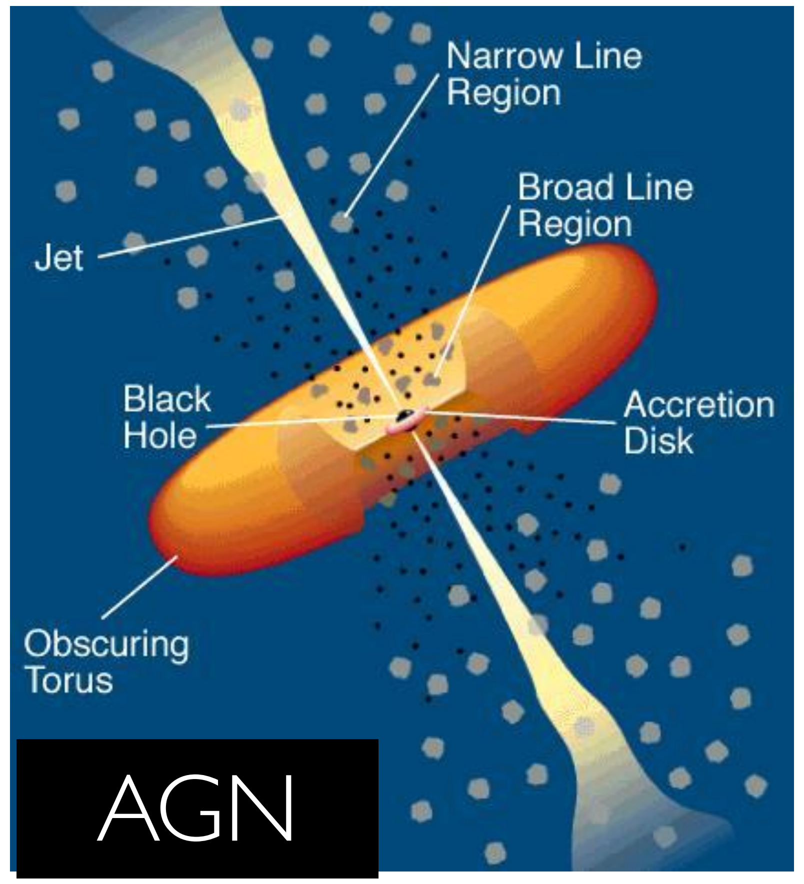
Scorecard

	E_{max}^{UHECR}	n_{UHECR}	$\dot{\varepsilon}_{UHECR}$	n_ν	Stacking UL
BL Lacs	😀	😞	😀	😞	≲20%
FSRQs	😀	😞	😀	😞	≲20%
FR I	😀	😀	😀	😀	≲20%
FR II	😀	😀	😀	😀	≲20%
Non-jetted AGN	😐	😀	😀	😀	≲100%
Starburst galaxies	😞	😀	😀	😀	≲100%
GRBs	😀	😐	😐	😐	≲1%
TDEs					

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







Tidal disruption events

SMBHs are orbited by star clusters

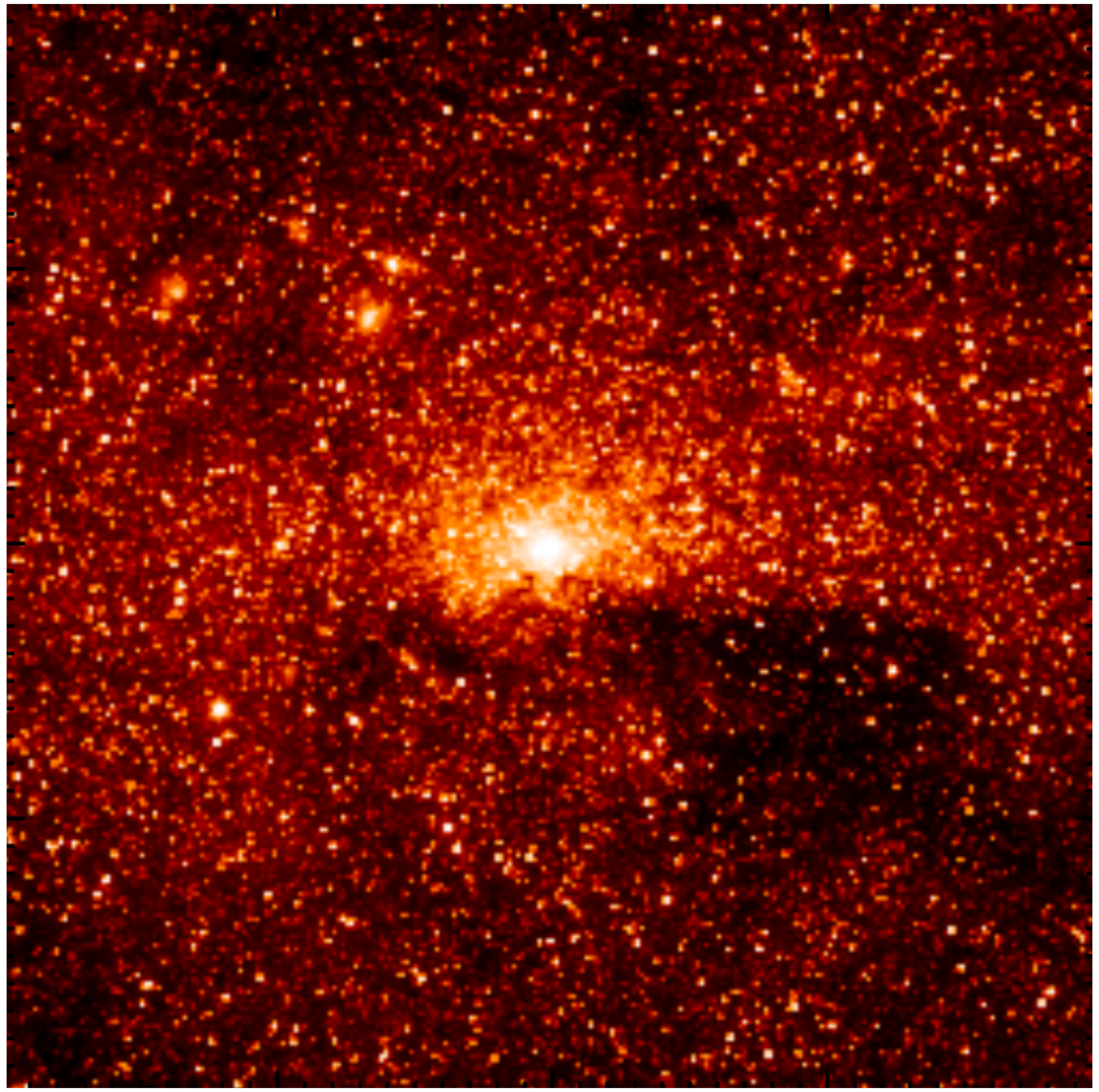
Millions of stars in random orbits

Tidal forces may deform, or tear into pieces a star

One TDE in 10^4-10^9 years per SMBH

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

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



Tidal disruption events

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

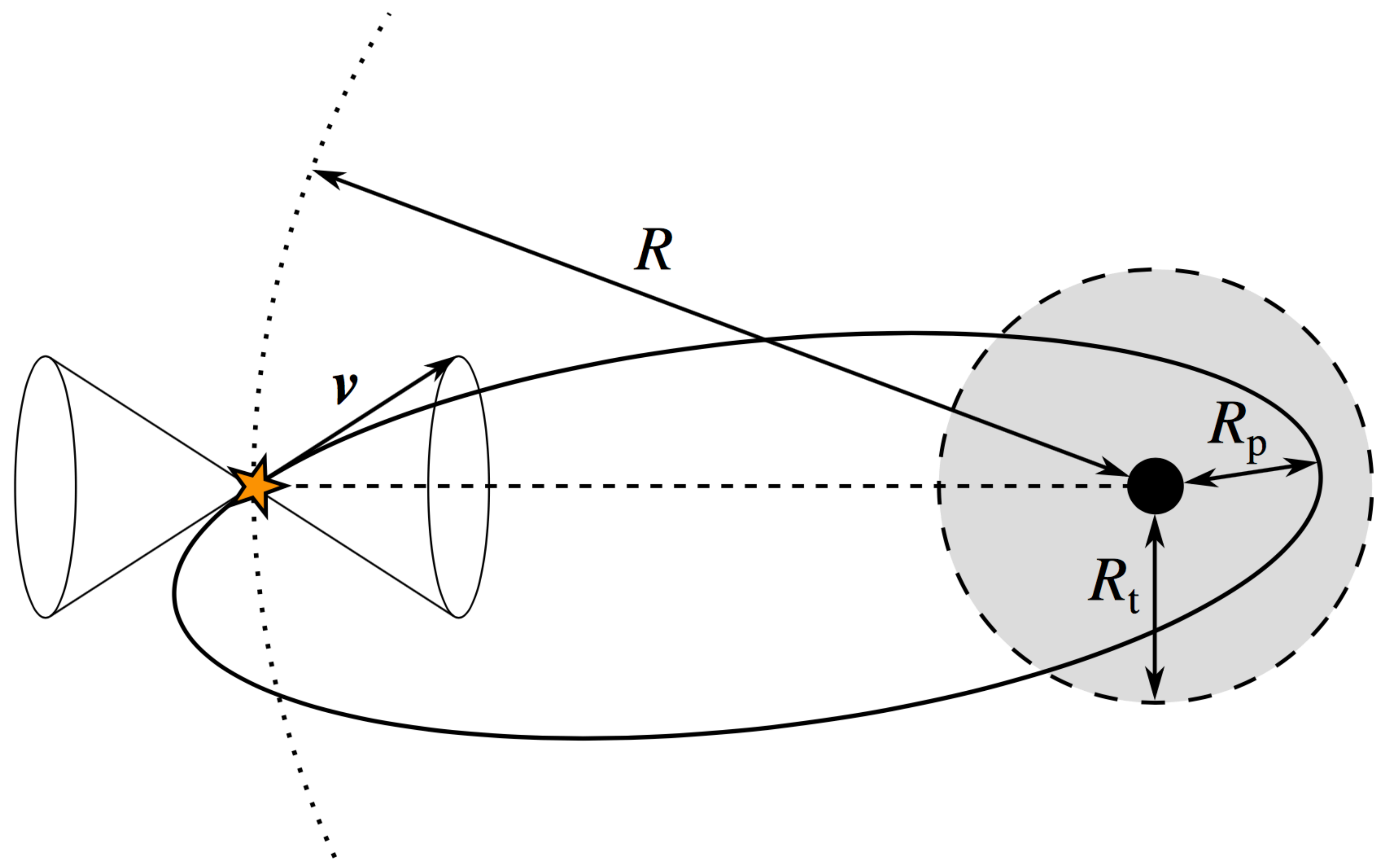
For tidal disruption to occur $R_p < R_t$

R_t must be outside the event horizon for visible TDE

The Schwarzschild radius is

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

For $R_t > r_s$



Tidal disruption events

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

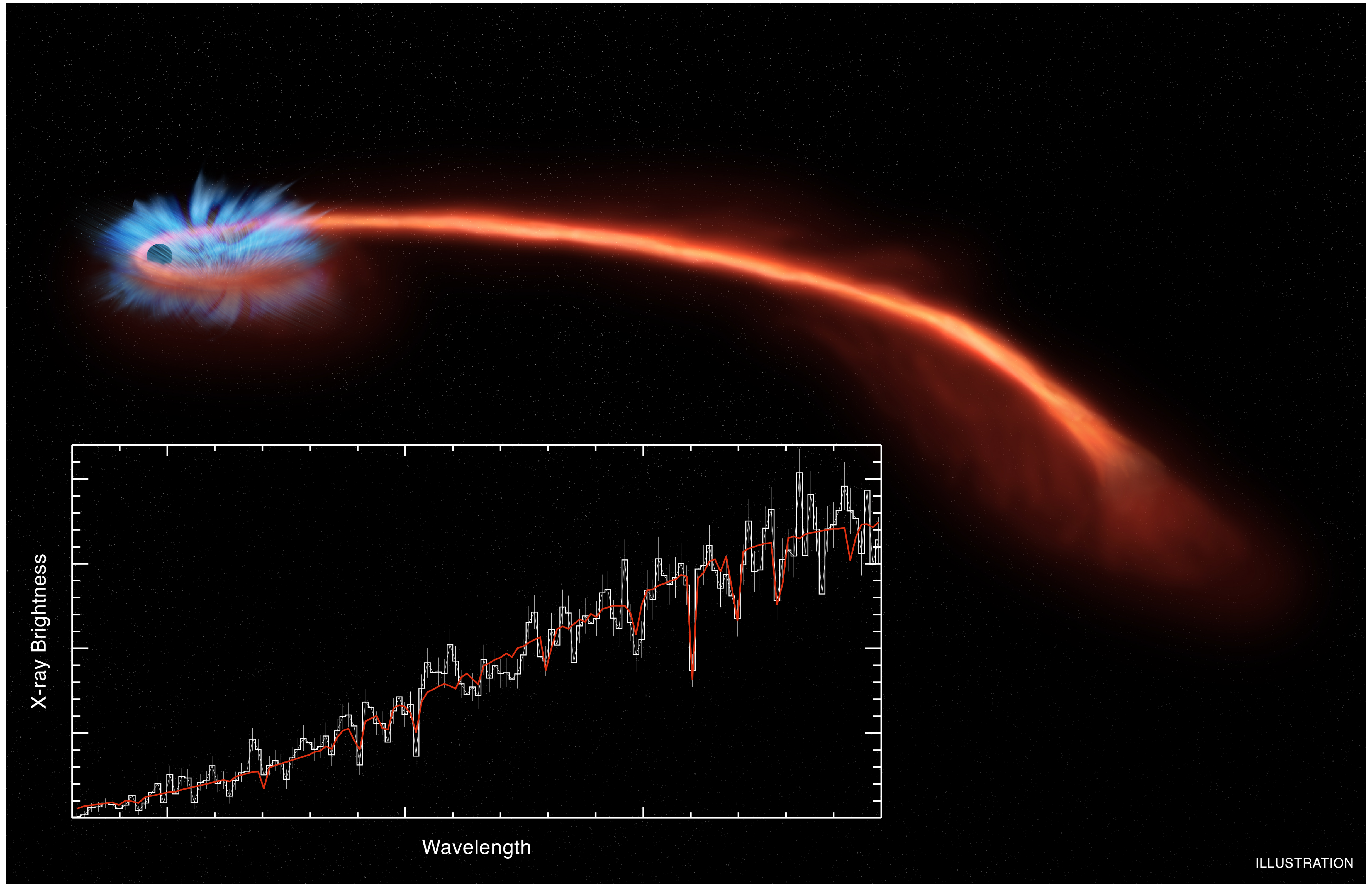
Located in the core of an otherwise quiescent, inactive galaxy

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

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

Swift J1644+57

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

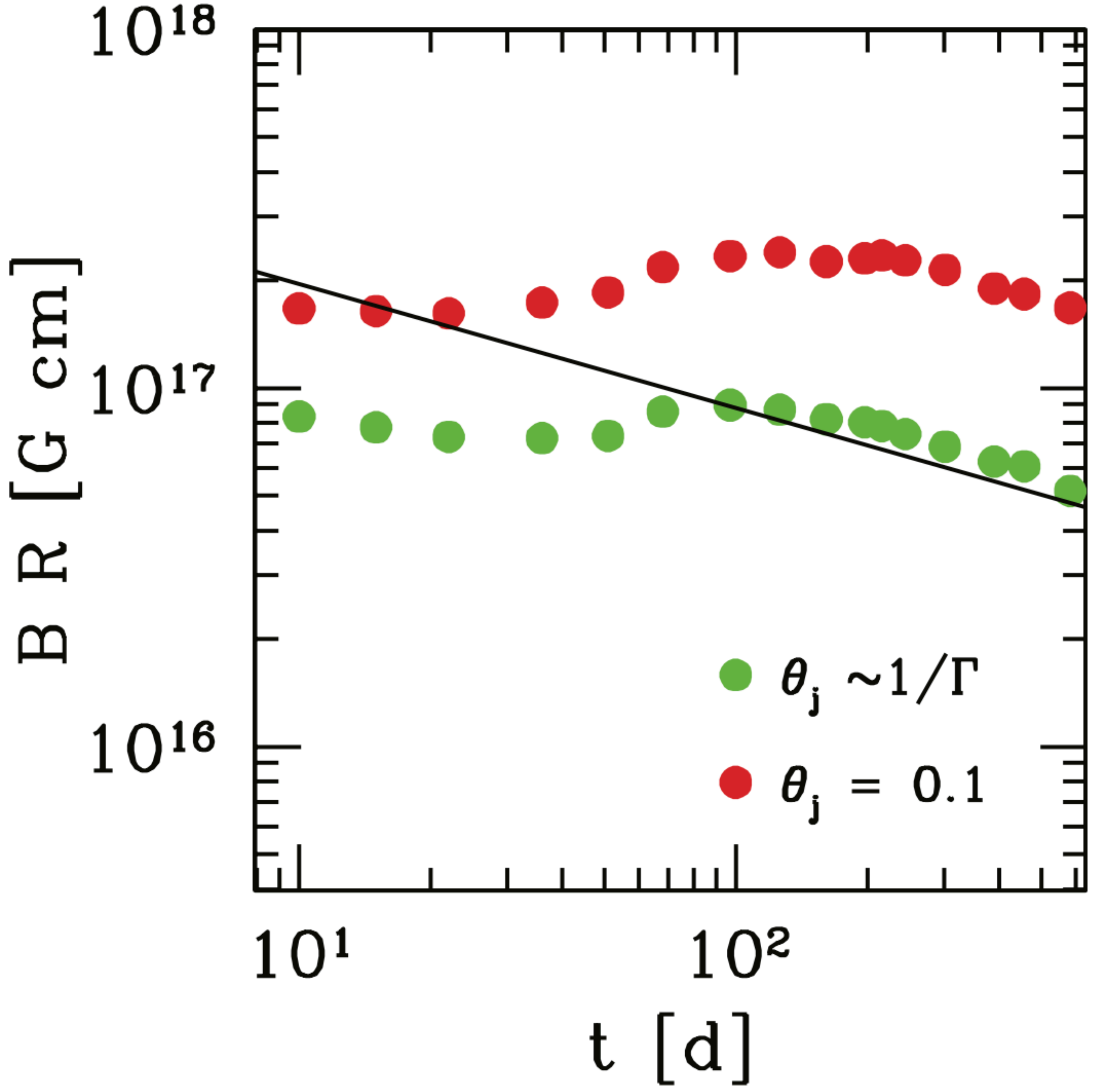
Observed for ~600 days, in a small quiescent galaxy in the Draco constellation at z = 0.35

$$E_{\rm max} \sim 10^{20}\ {\rm eV}\ Z \frac{BR}{3\times10^{17}\ {\rm G\ cm}} \frac{\Gamma}{10}$$

For Swift J1644+57 from radio observations in the outer jet (but dependent on assumed opening angle of jet)

$$BR \gtrsim 1-3\times10^{17}\ {\rm G\ cm}$$

Farrar & Piran 2014



Can TDEs be the main sources of UHECRs?

The ``apparent" source number density must satisfy the observational bound, with δt the spread in arrival times

$$n_{\text{eff}} \sim \delta t \cdot \rho$$

From Auger

$$n_{\text{UHECR}} \gtrsim 2 \times 10^{-5}\ \text{Mpc}^{-3}$$

The observed rate of jetted TDEs

$$\rho \approx 10^{-11} - 10^{-10}\ \text{Mpc}^{-3}\ \text{year}^{-1}$$

TDEs can satisfy the number density requirement if

$$\delta t_{\text{delay}} \approx 10^5\ \text{yr} \cdot \left(\frac{D}{100\,\text{Mpc}}\right)^2 \left(\frac{E}{10^{20}\,\text{eV}}\right)^{-2} \left(\frac{\lambda_{\text{coh}}}{1\,\text{Mpc}}\right) \left(\frac{B}{1\,\text{nG}}\right)^2$$

Neutrinos from TDEs?

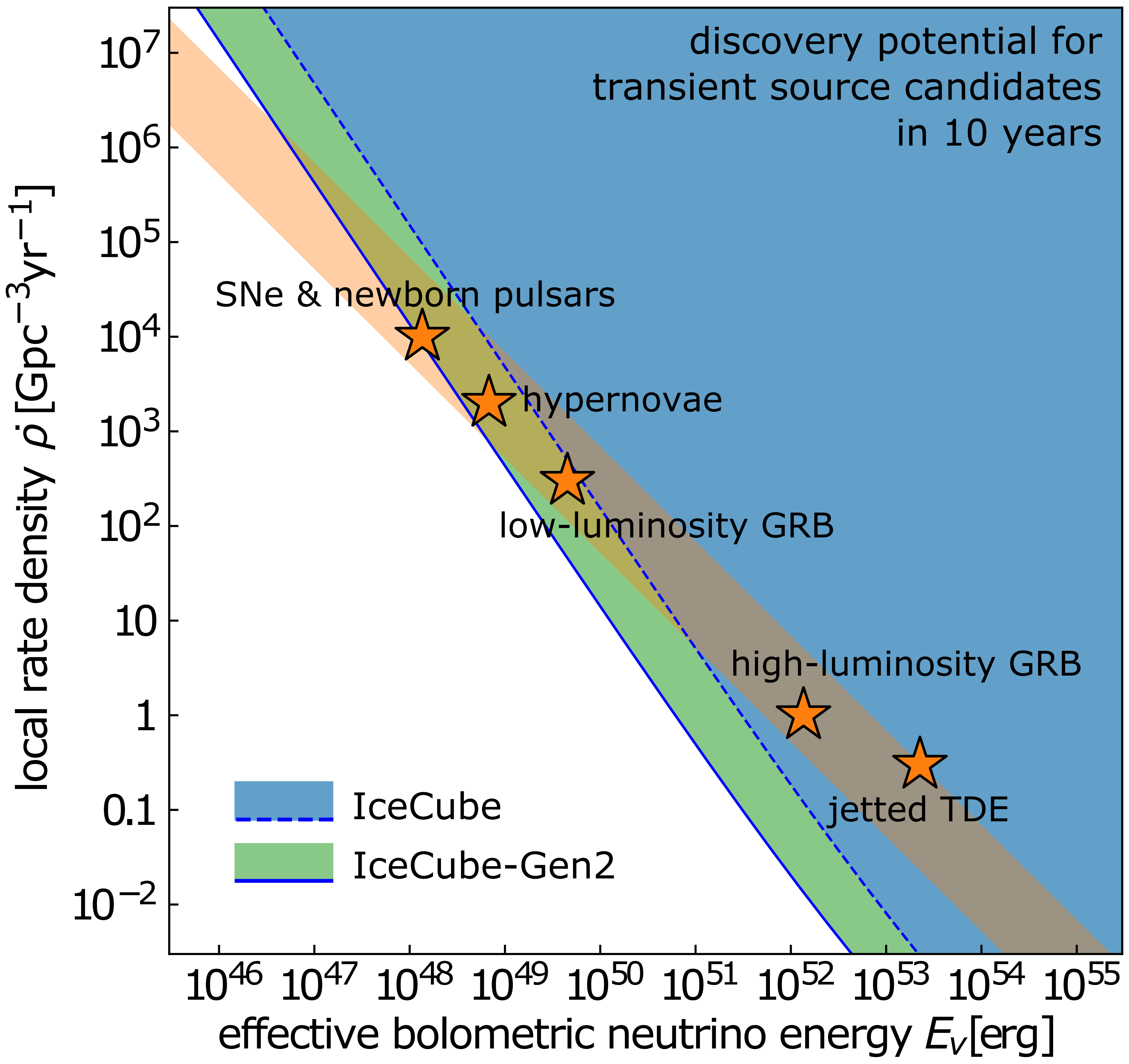
Photopion interactions in the jet (conditions similar to AGN/GRB)

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

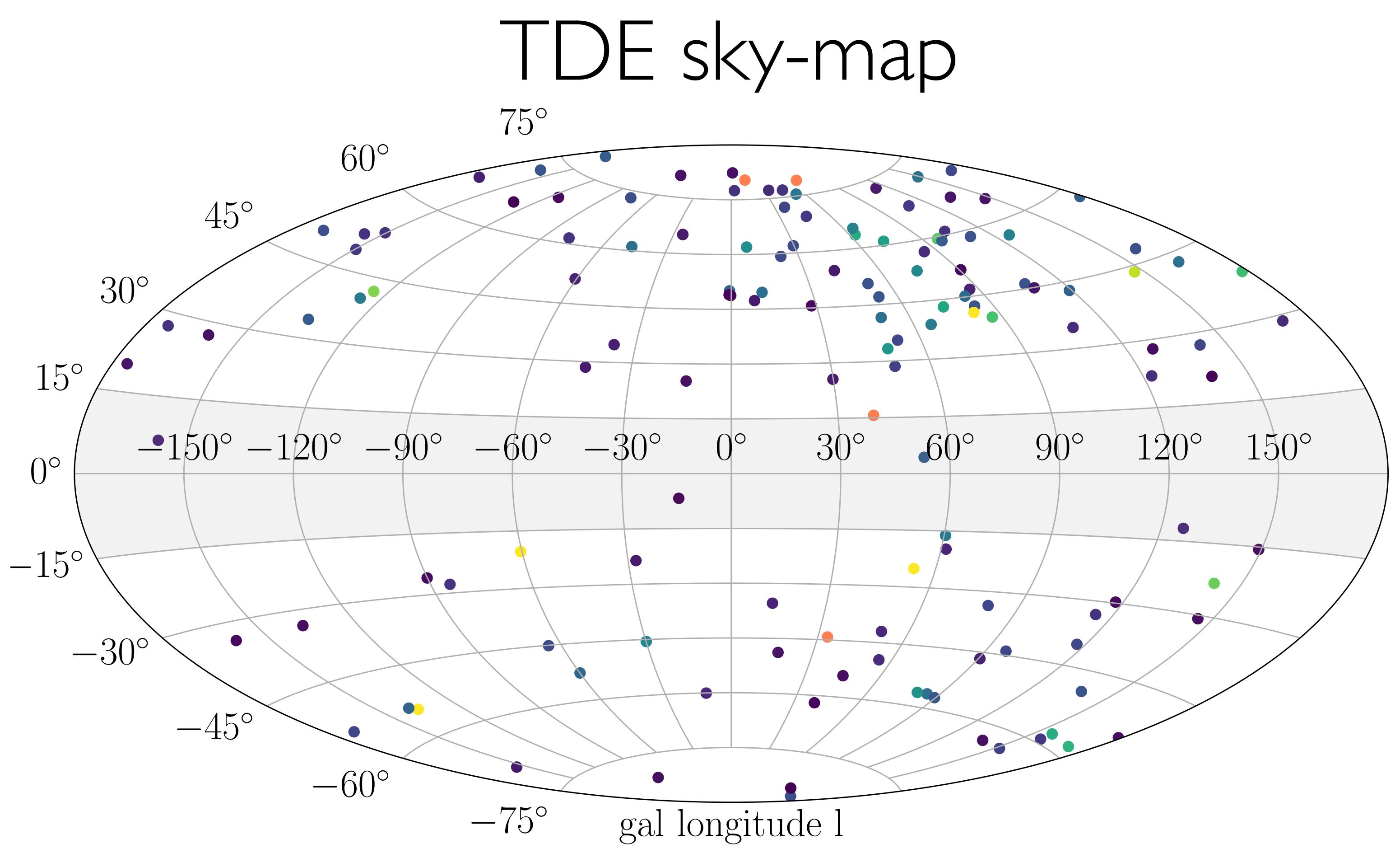
Stacking limits from IceCube (jetted TDEs < 1%, non-jetted < 26%)

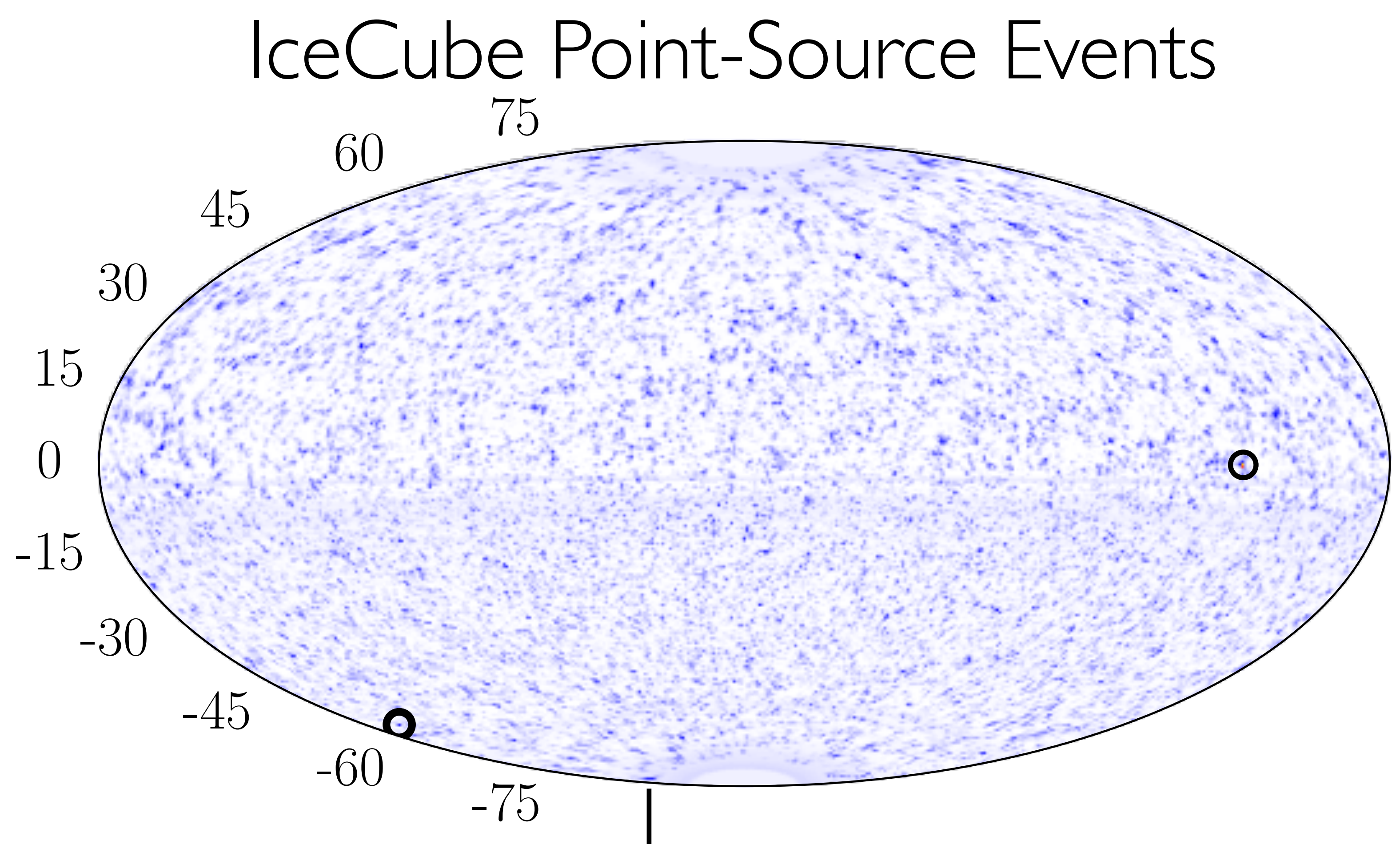


TDE contribution to the cosmic-neutrino flux

3 jetted TDEs
40 non-jetted TDEs (mixture of X-ray / UV / optical TDEs)

Updated search in 2022 ZTF TDEs with neoWISE flare (``dust echo'') Y. Necker TeVPA 2022 - No excess





IceCube Coll PoS ICRC 2019
Necker et al 2022 (ASAS-SN Coll)
Stein et al 2022 (ZTF Coll)

Jetted TDEs: < 3% diffuse neutrino flux

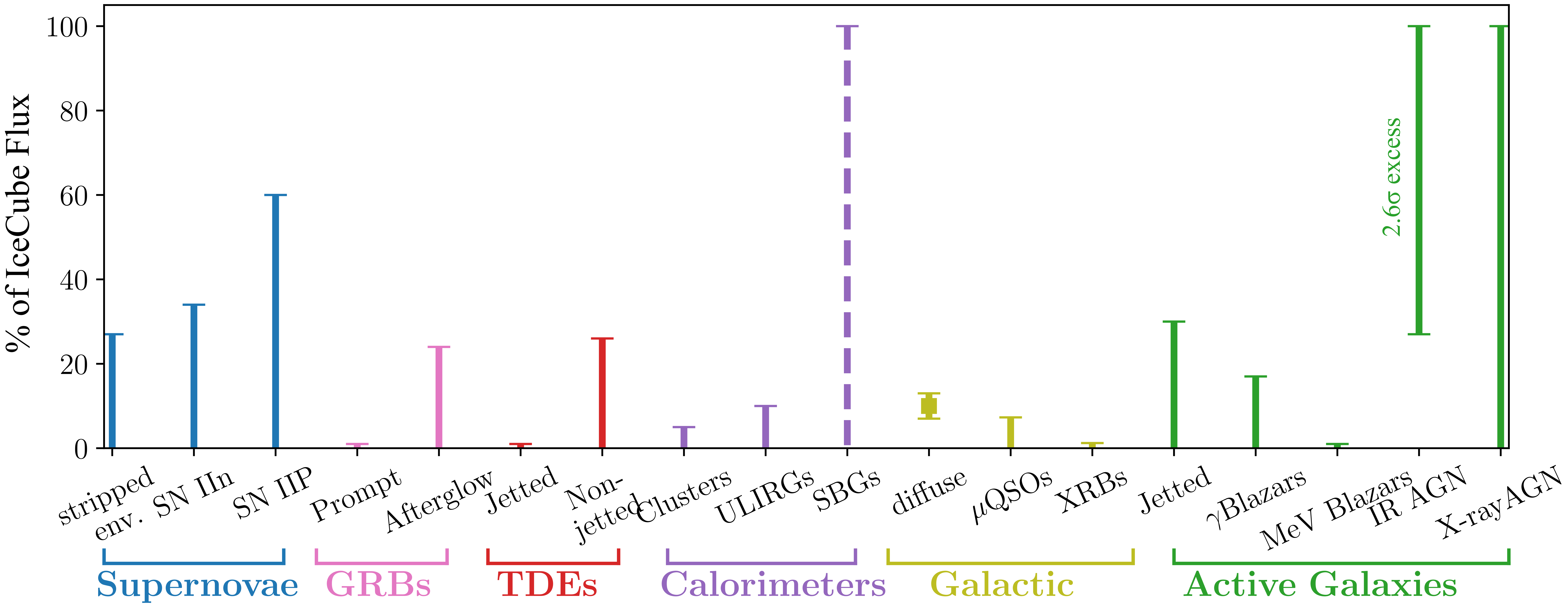
Non-jetted < 26%

Scorecard

	$E_{\max}^{\mathrm{UHECR}}$	n_{UHECR}	$\dot{\varepsilon}_{\mathrm{UHECR}}$	n_ν	Stacking UL
BL Lacs	😀	😞	😀	😞	≲20%
FSRQs	😀	😞	😀	😞	≲20%
FR I	😀	😀	😀	😀	≲20%
FR II	😀	😀	😀	😀	≲20%
Non-jetted AGN	😐	😀	😀	😀	≲100%
Starburst galaxies	😞	😀	😀	😀	≲100%
GRBs	😀	😐	😐	😞	≲1%
Jetted TDEs	😀	😞	😞	😞	≲3%

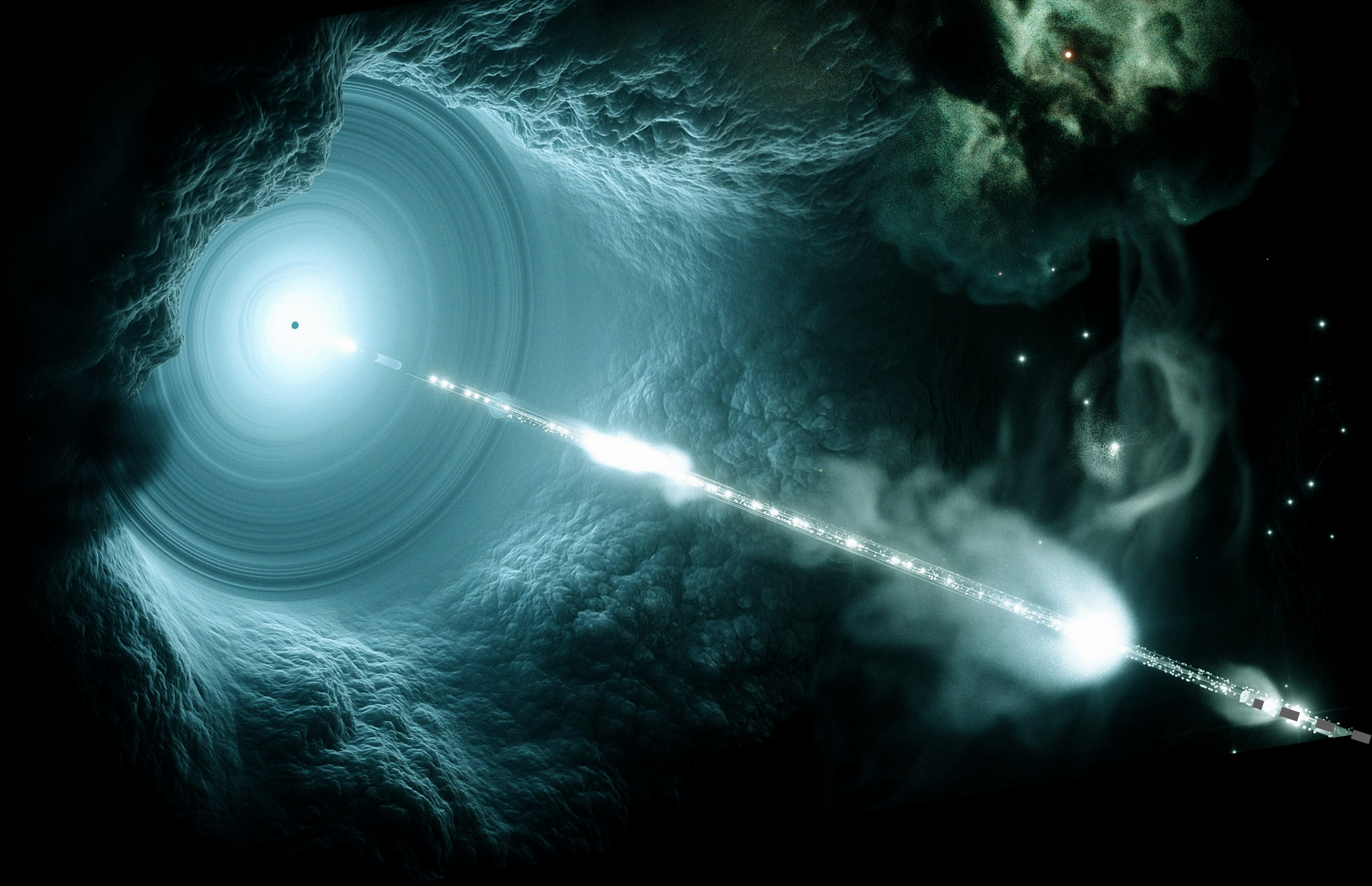
The current neutrino source landscape: Stacking upper limits

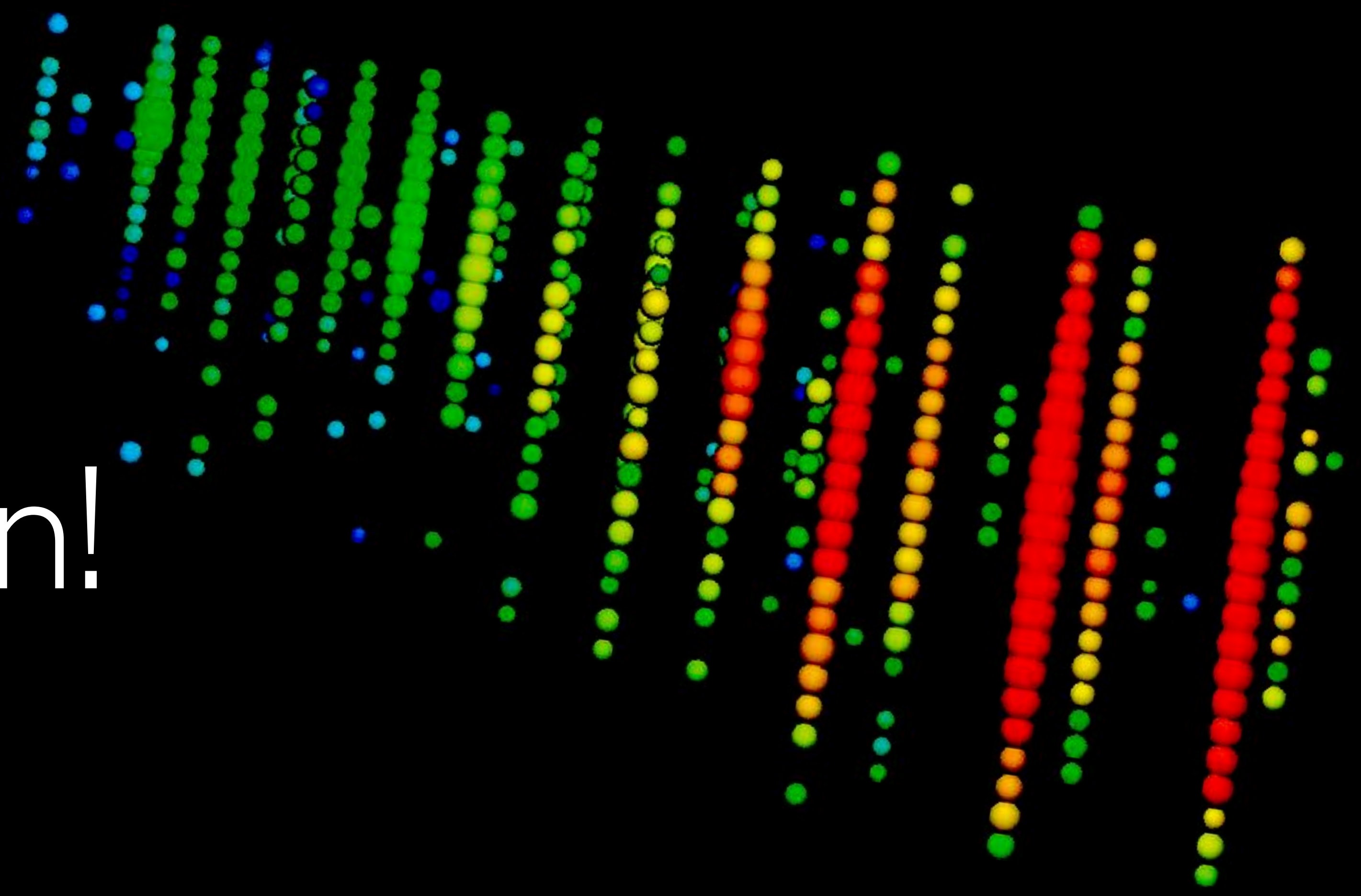
plot from FO PoS ICRC2021 (2022) 030, based on numerous IceCube analyses, see arXiv:2201.05623 for references



Scorecard

	$E_{\max}^{\rm UHECR}$	$n_{\rm UHECR}$	$\dot{\varepsilon}_{\rm UHECR}$	n_ν	Stacking UL	
BL Lacs	😀	😞	😀	😞	≲20%	
FSRQs	😀	😞	😀	😞	≲20%	
FR I	😀	😀	😀	😀	≲20%	
FR II	😀	😀	😀	😀	≲20%	
AGN Winds	😀	😀	😀	😀	≲100%	
AGN Coronae	😞	😀	😀	😀	≲100%	
Starburst galaxies	😞	😀	😀	😀	≲100%	*(but problems at medium E)
GRBs	😀	😐	😐	😞	≲1%	
Jetted TDEs	😀	😞	😞	😞	≲3%	





Thank you for your attention!