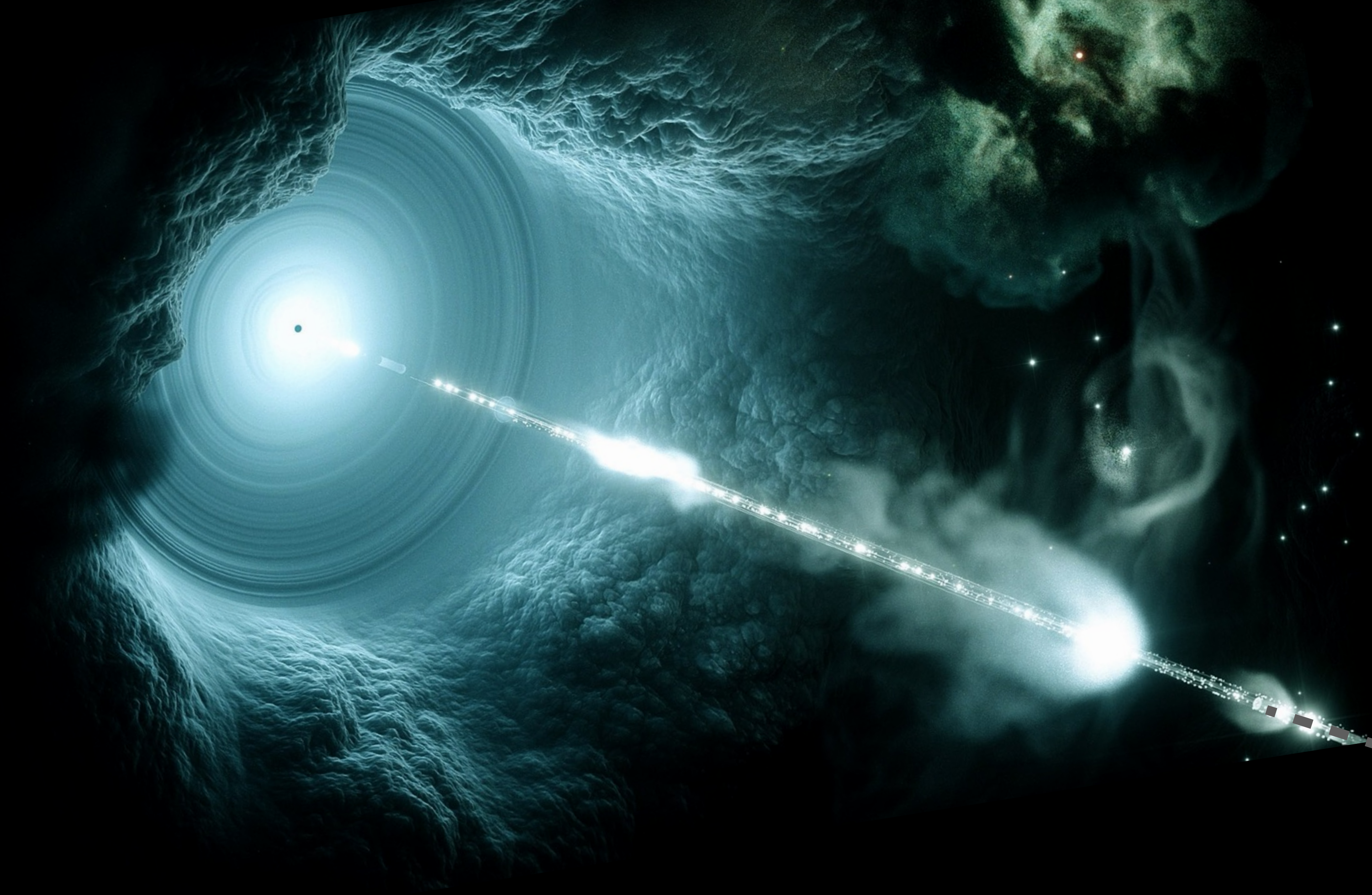
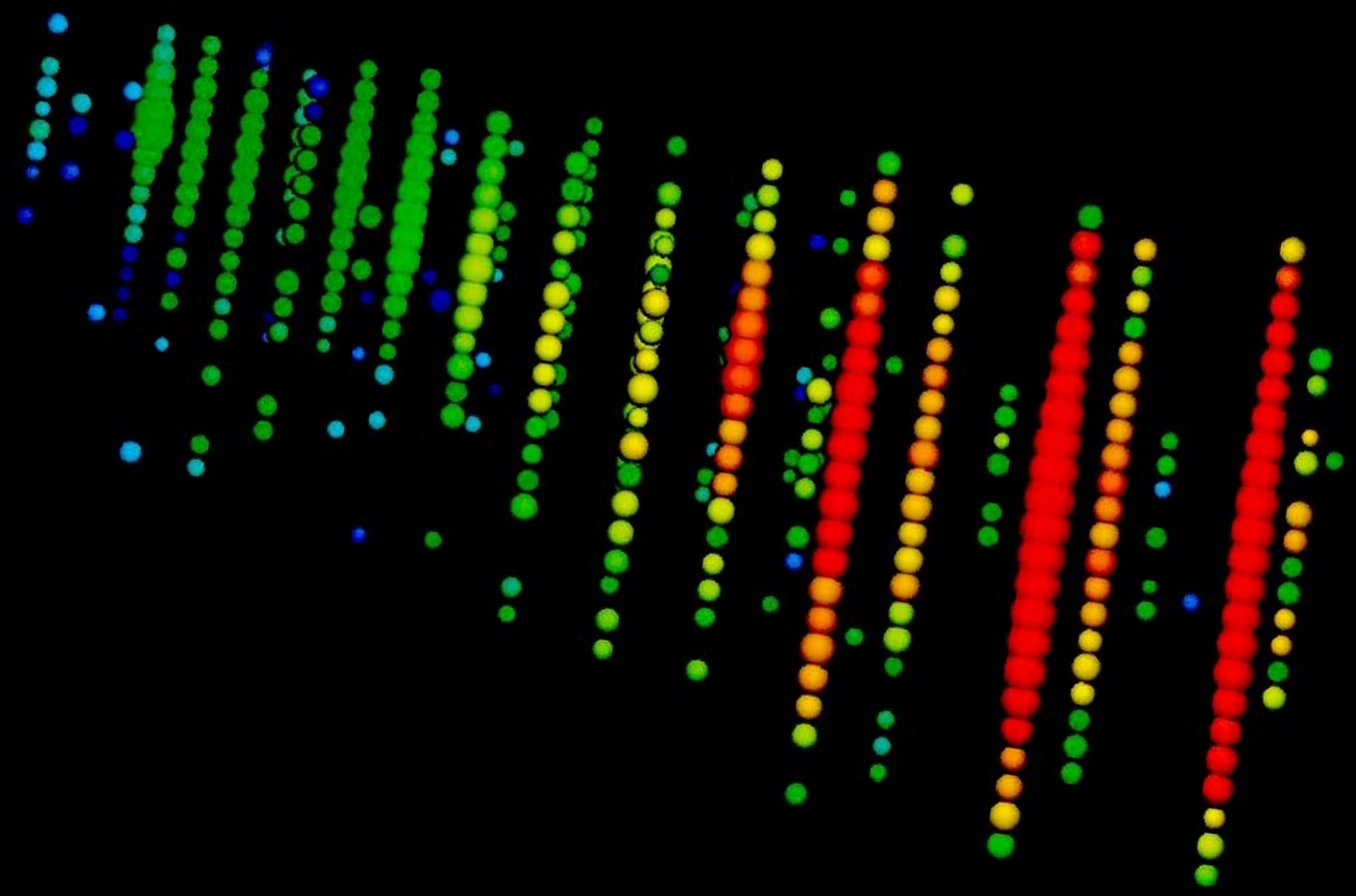




Multimessenger Astroparticle Physics
ISCRA Erice 2024

Foteini Oikonomou

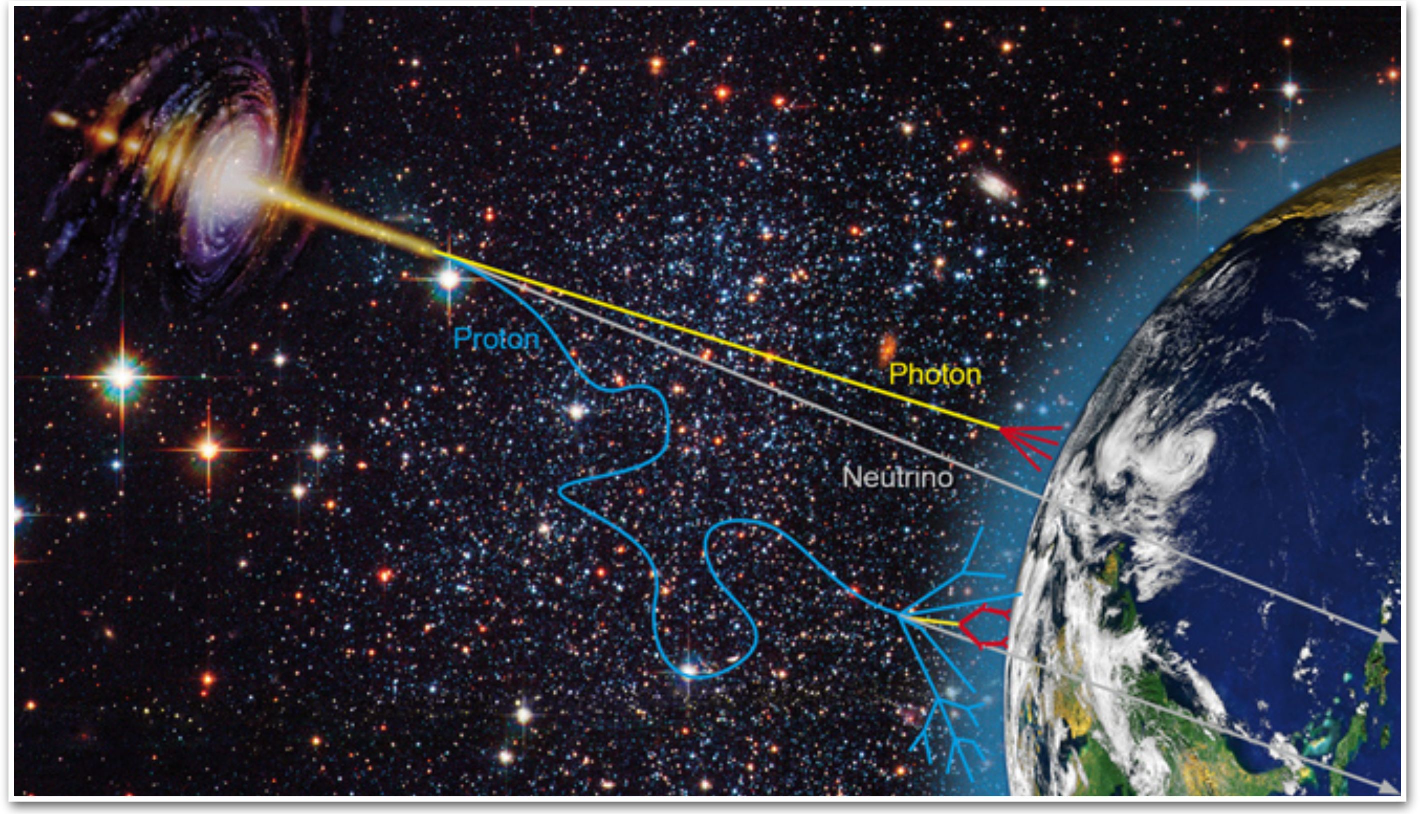
July 21st-28th

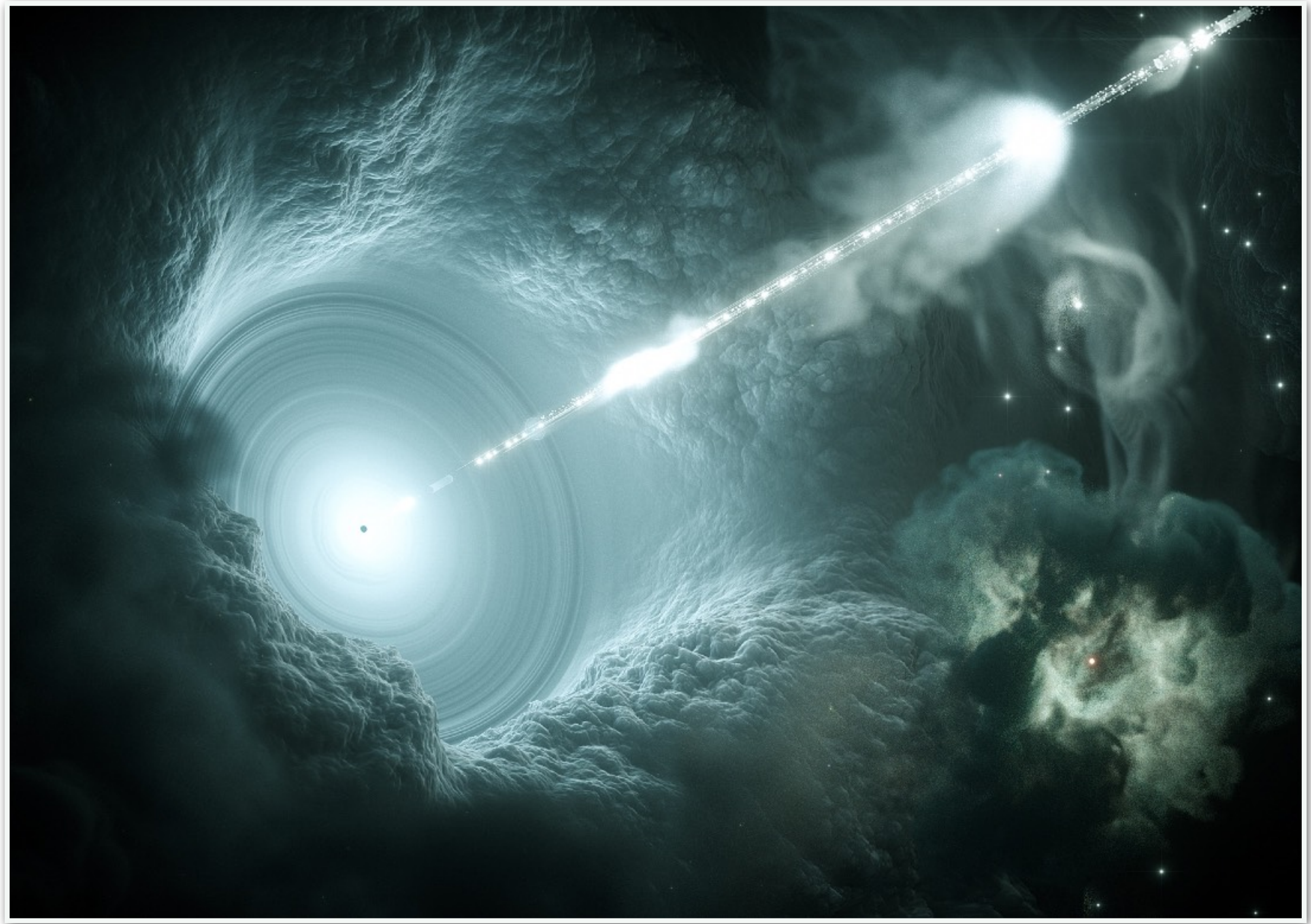
NTNU
Norwegian University of Science and Technology

About me

foteini.oikonomou@ntnu.no

- NTNU Trondheim
- Main research interests:
    - Ultra-high energy cosmic rays (sources, phenomenology)
    - Astrophysical sources of high-and ultra-high energy neutrinos
    - Active-galactic nuclei as cosmic accelerators





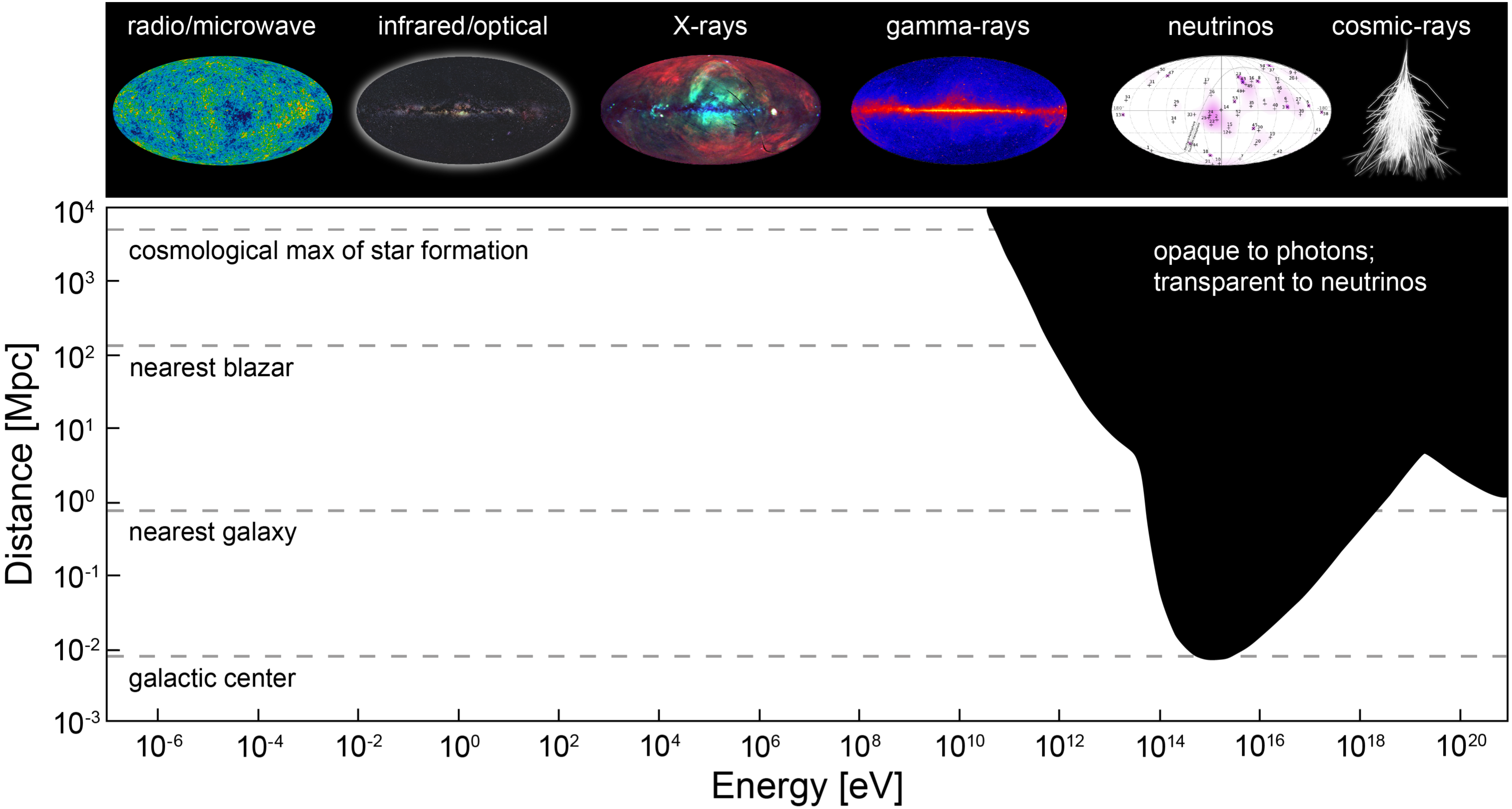
Lecture plan

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

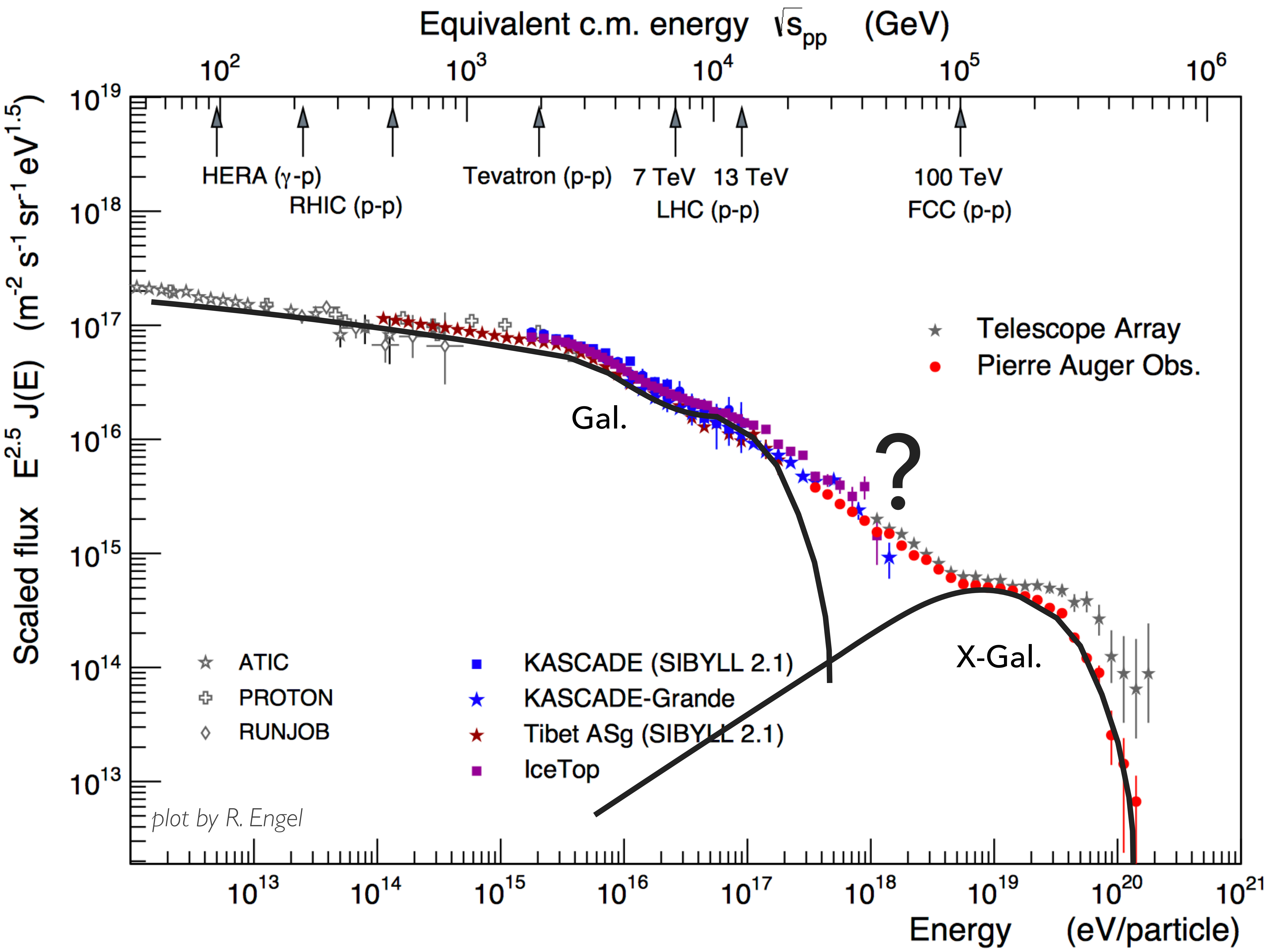
Resources

- 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

High-energy messengers of the non-thermal Universe



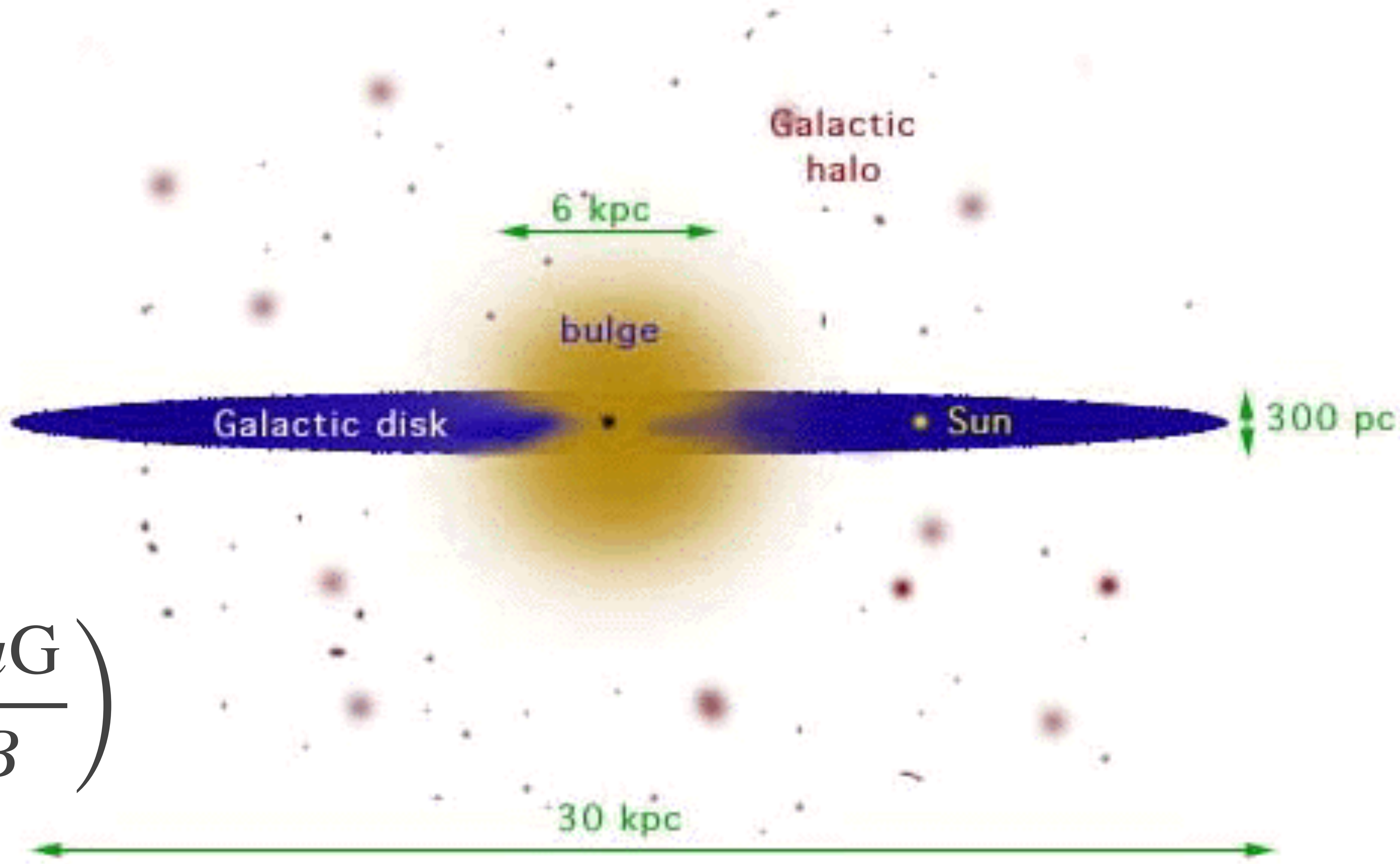
Highest-energy cosmic rays



Extragalactic origin above 10^{18} eV

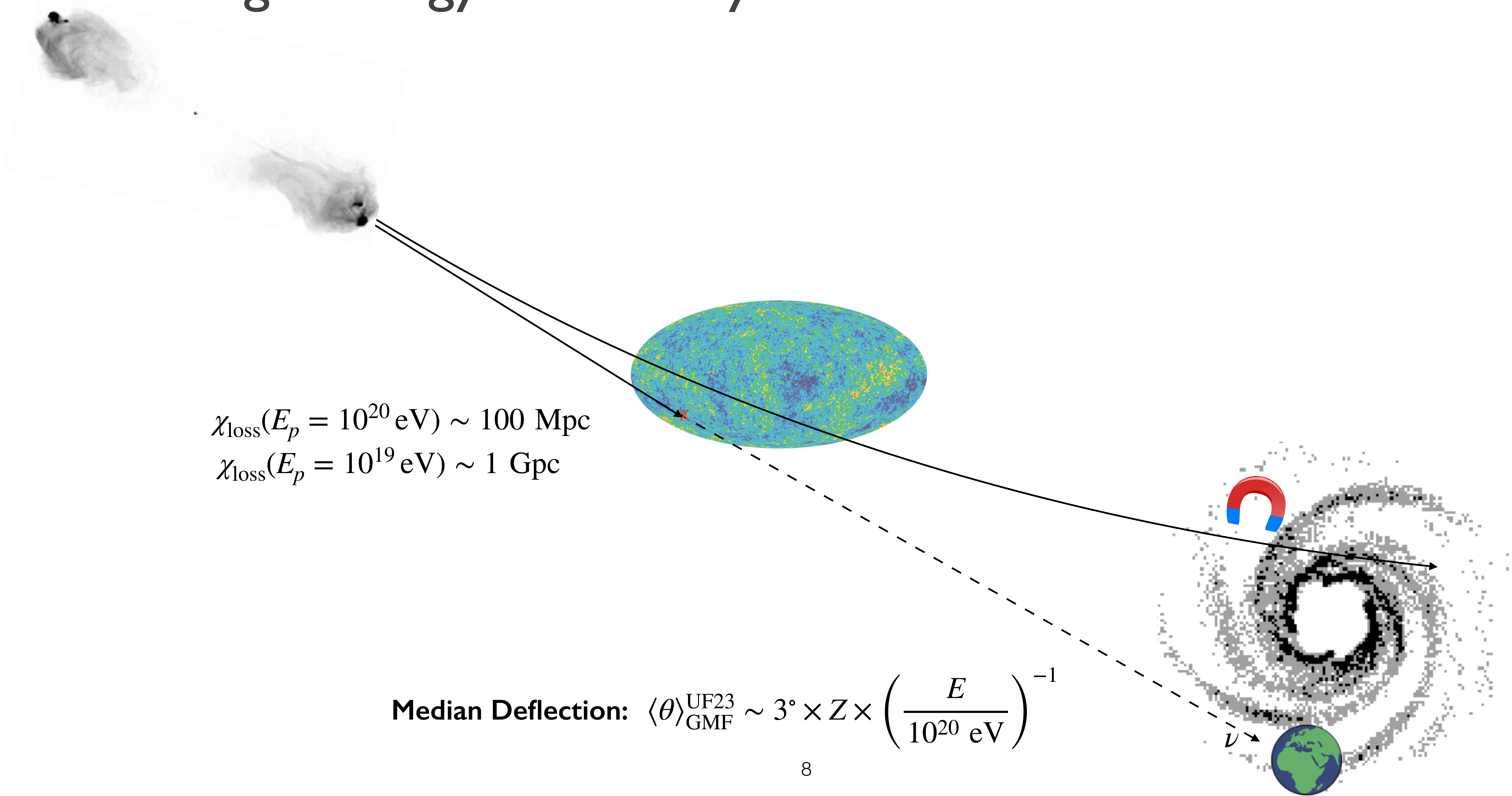
- Galactic B-field in the disk ~ 3 μG
- Larmor radius of cosmic rays

$$R_{\text{Larmor}} = \frac{E}{e \cdot ZB} \sim \frac{1}{\text{kpc}} \left(\frac{1}{Z}\right) \left(\frac{E}{10^{18.5}\ \text{eV}}\right) \left(\frac{3\mu\text{G}}{B}\right)$$



[+ Observational evidence: No anisotropy from the Galaxy]

Ultra-high-energy cosmic rays



$$\chi_{\rm loss}(E_p = 10^{20}\,{\rm eV}) \sim 100 \text{ Mpc}$$
$$\chi_{\rm loss}(E_p = 10^{19}\,{\rm eV}) \sim 1 \text{ Gpc}$$

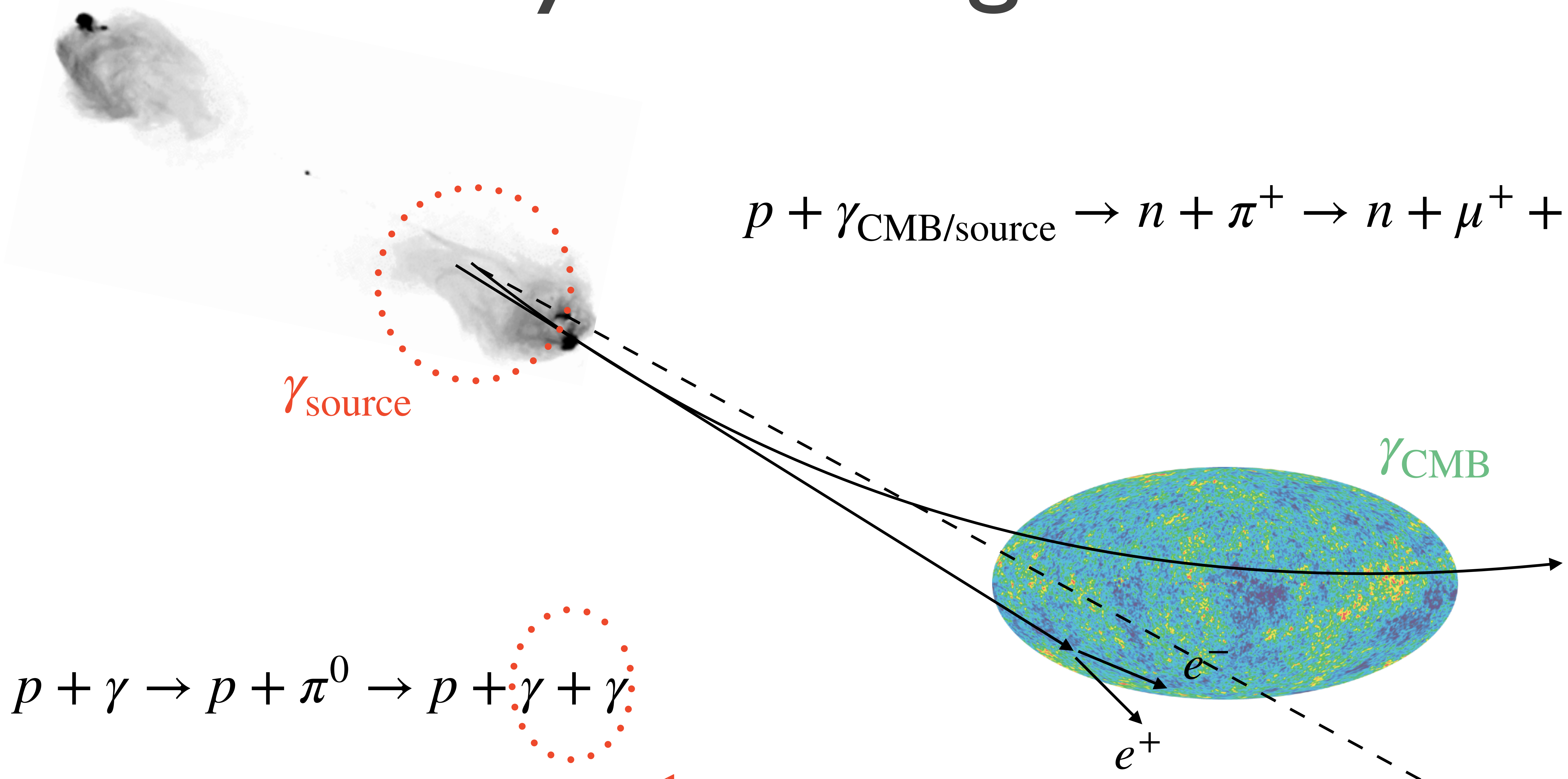
Median Deflection: $\langle\theta\rangle^{\rm UF23}_{\rm GMF} \sim 3^\circ \times Z \times \left(\frac{E}{10^{20}\ {\rm eV}}\right)^{-1}$

Secondary messengers

$$p + \gamma_{\text{CMB/source}} \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_e$$

neutrinos!

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



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

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

Averaged branching ratio,

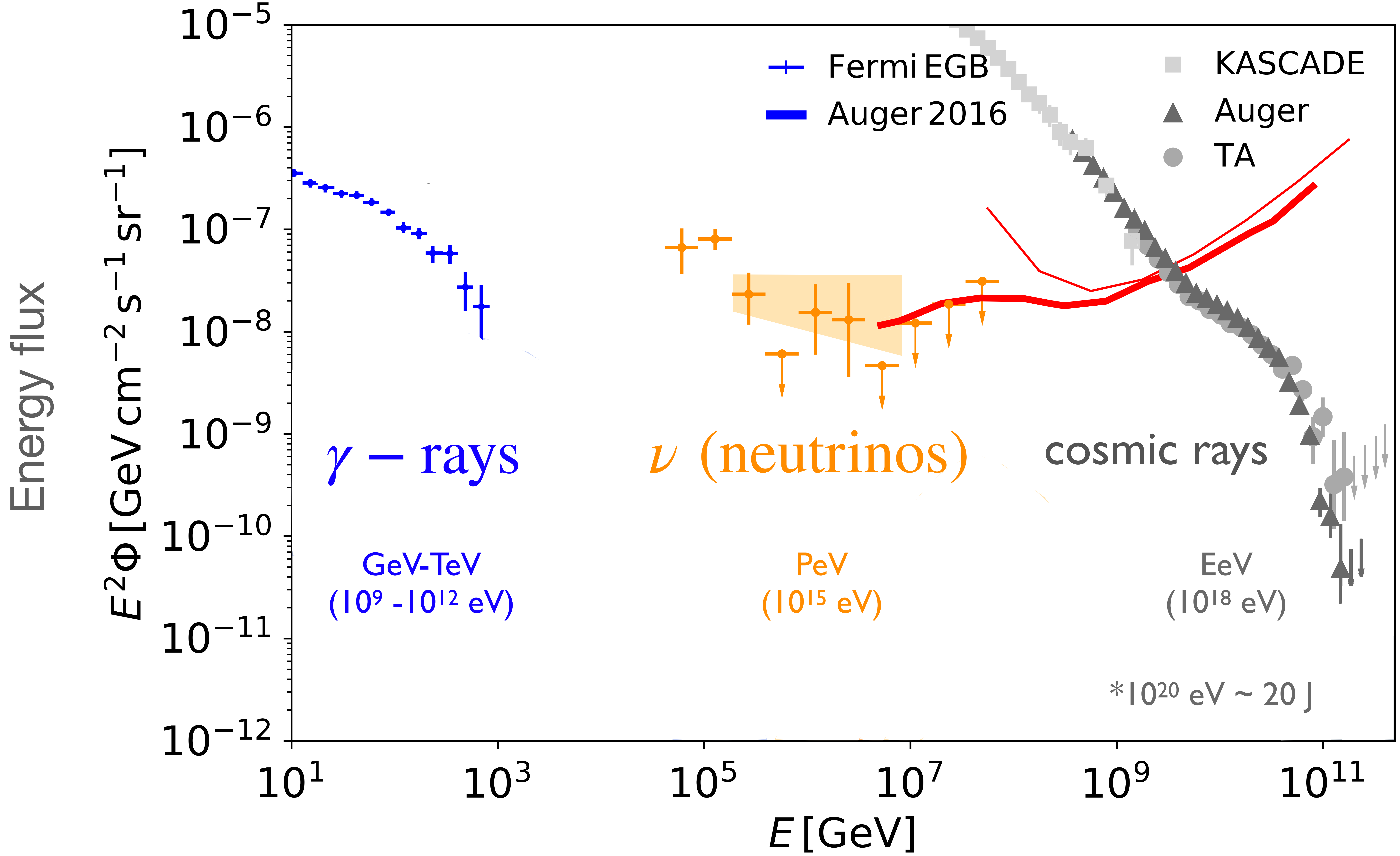
$$R_\pi = \frac{\Gamma(\rightarrow \pi^{+/-})}{\Gamma(\rightarrow \pi^0)} \sim 1$$

Relative gamma-ray/neutrino energy flux:

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

ν

Multimessenger diffuse fluxes



Generic source properties

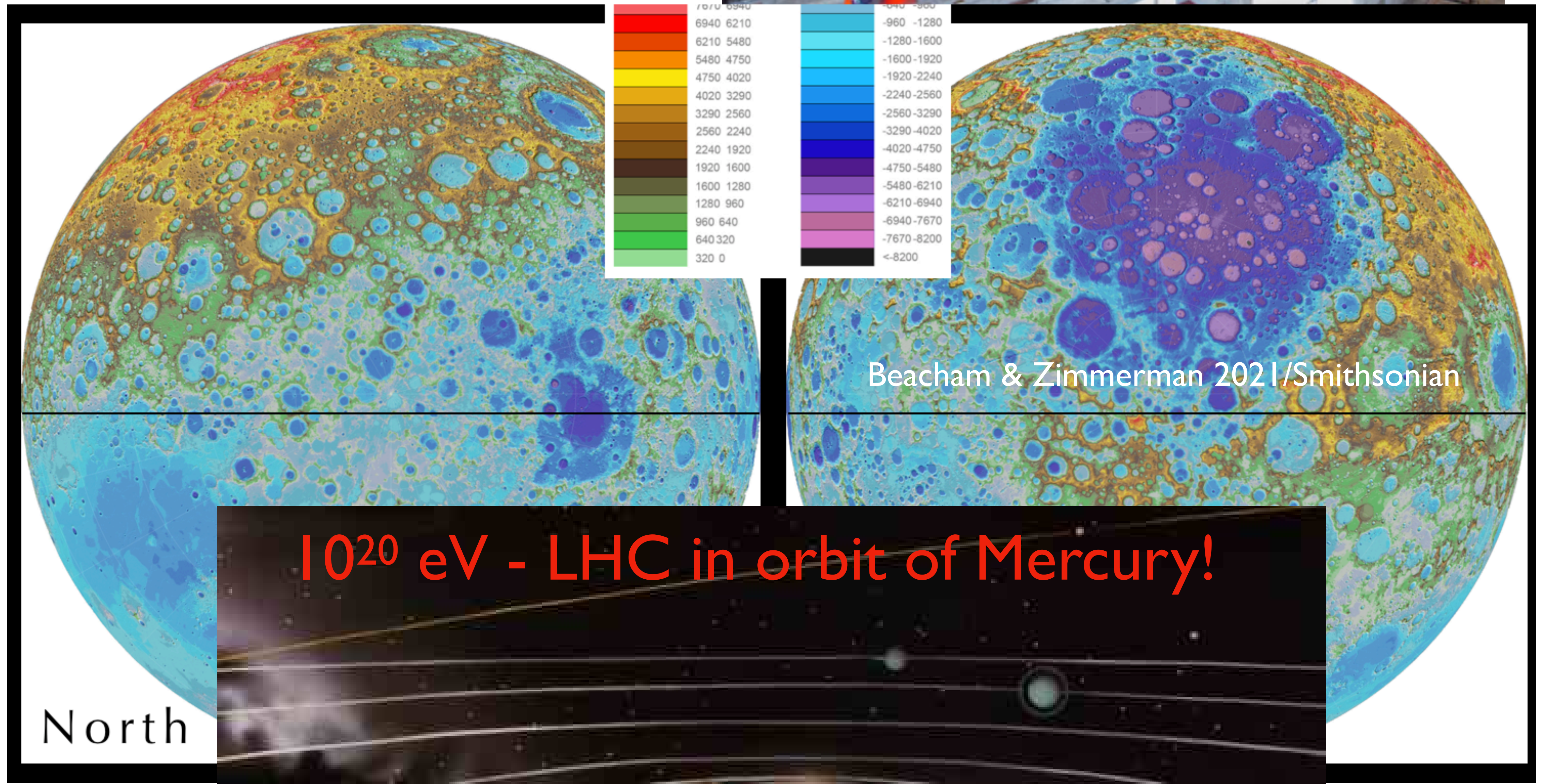
- Hillas criterion for acceleration and plausible sources
- UHECR emissivity and number density
- Waxman & Bahcall neutrino bound (possible connection to UHECRs)
- Neutrino source emissivity
- Neutrino source number density and implications

Cosmic-ray accelerators

Minimum requirement: Confinement (Hillas 1984)

TeV = 10^{12} eV

PeV = 10^{15} eV

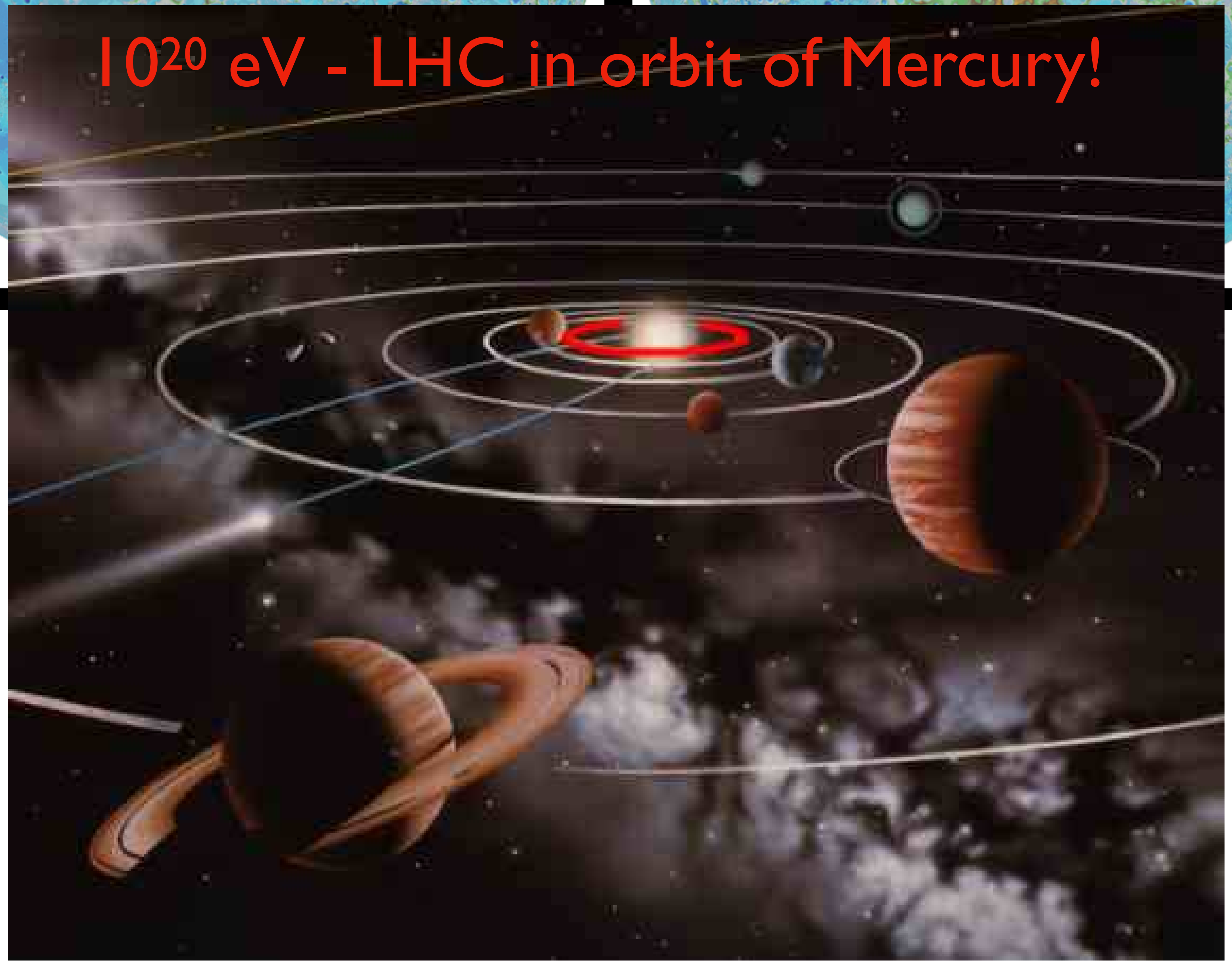


$$R_{\rm source} > r_{\rm Larmor} = \frac{E}{ZBec}$$

Maximum energy,

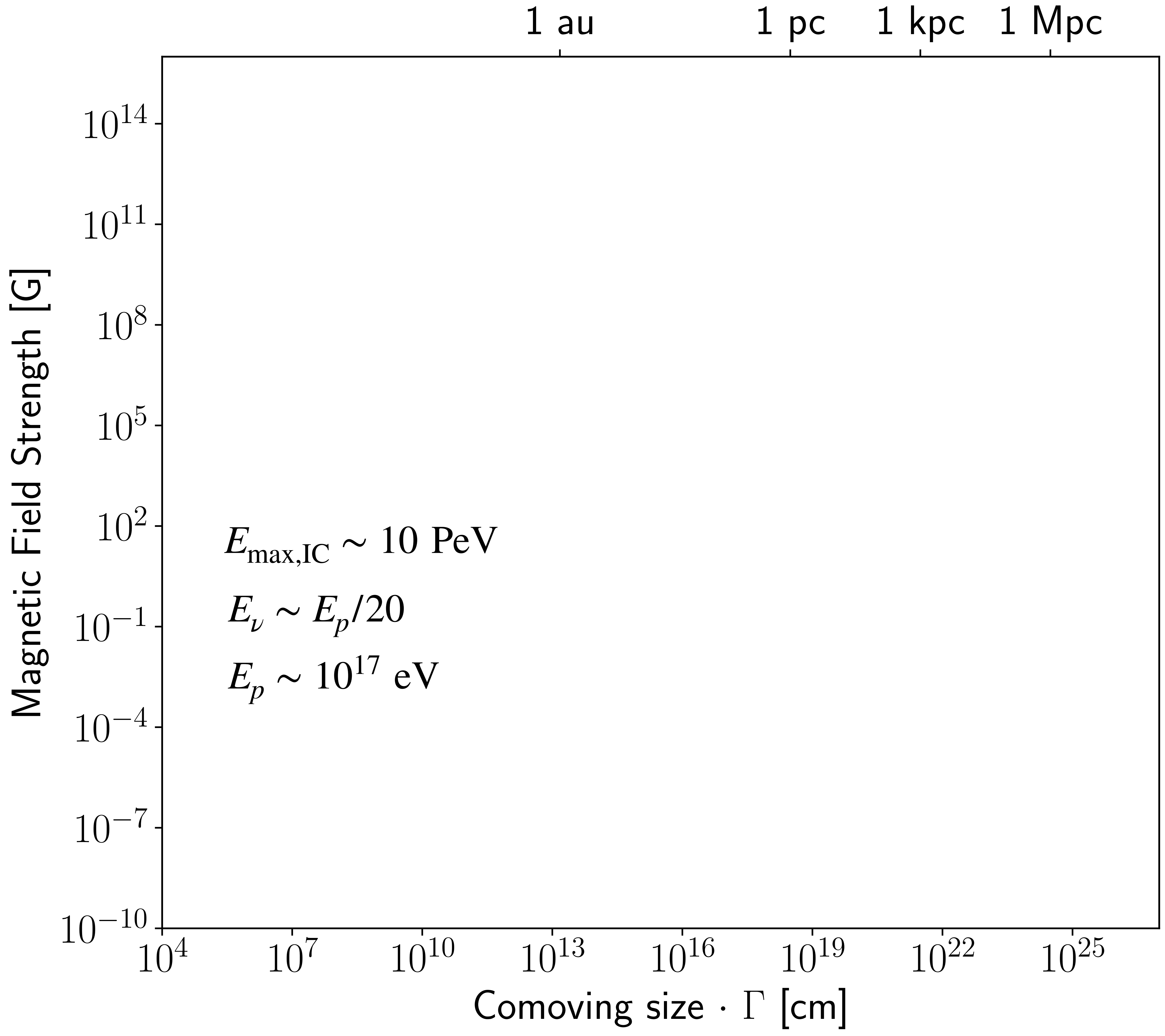
$$E_{\rm max} = ZecBR_{\rm source}$$

$$E_{\rm max} \sim 1 \text{ EeV } Z \left(\frac{B}{1\ \mu\text{G}}\right)\left(\frac{R_{\rm source}}{1\ \text{ kpc}}\right)$$

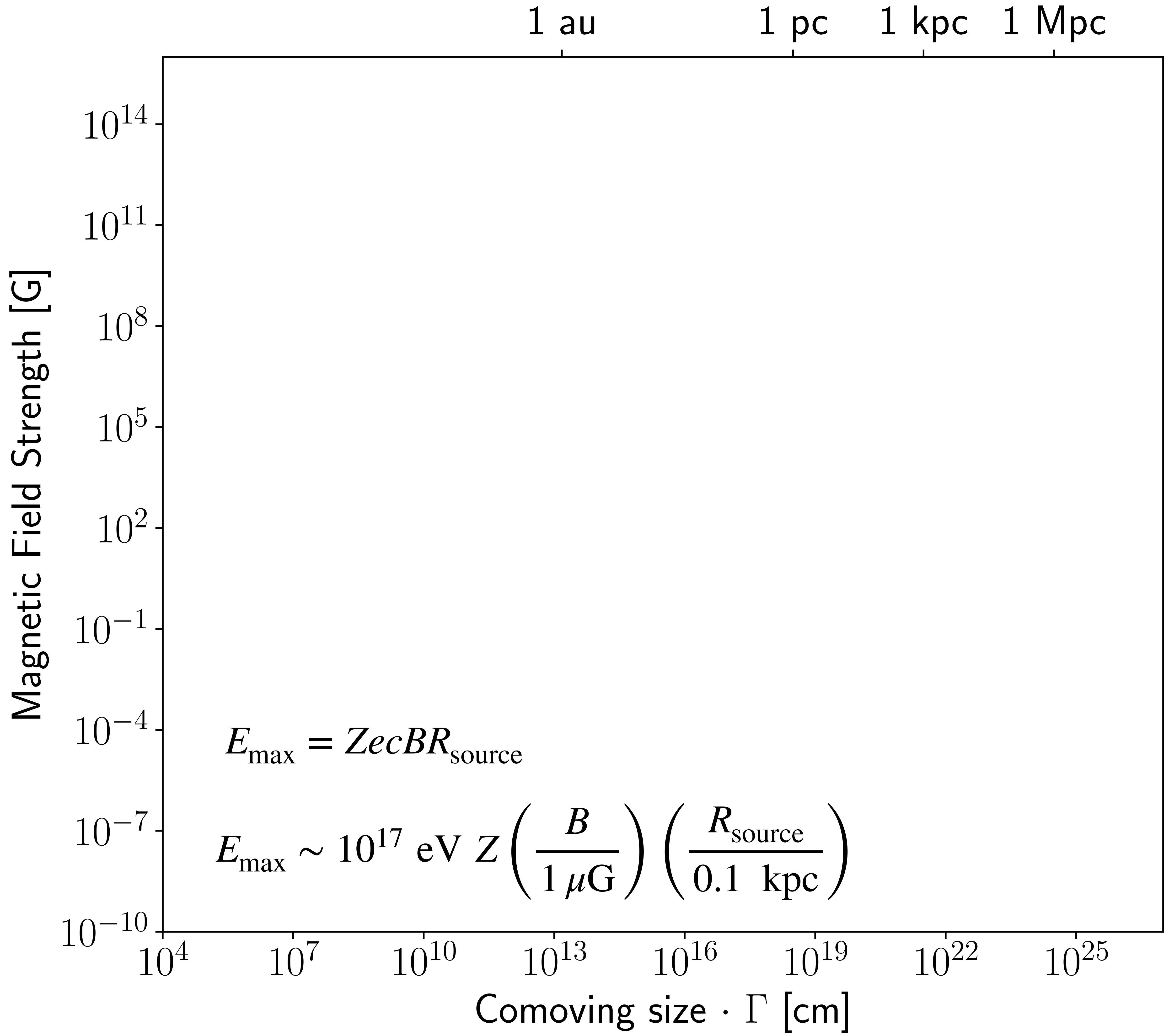


EeV = 10^{18} eV, ZeV = 10^{21} eV

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



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



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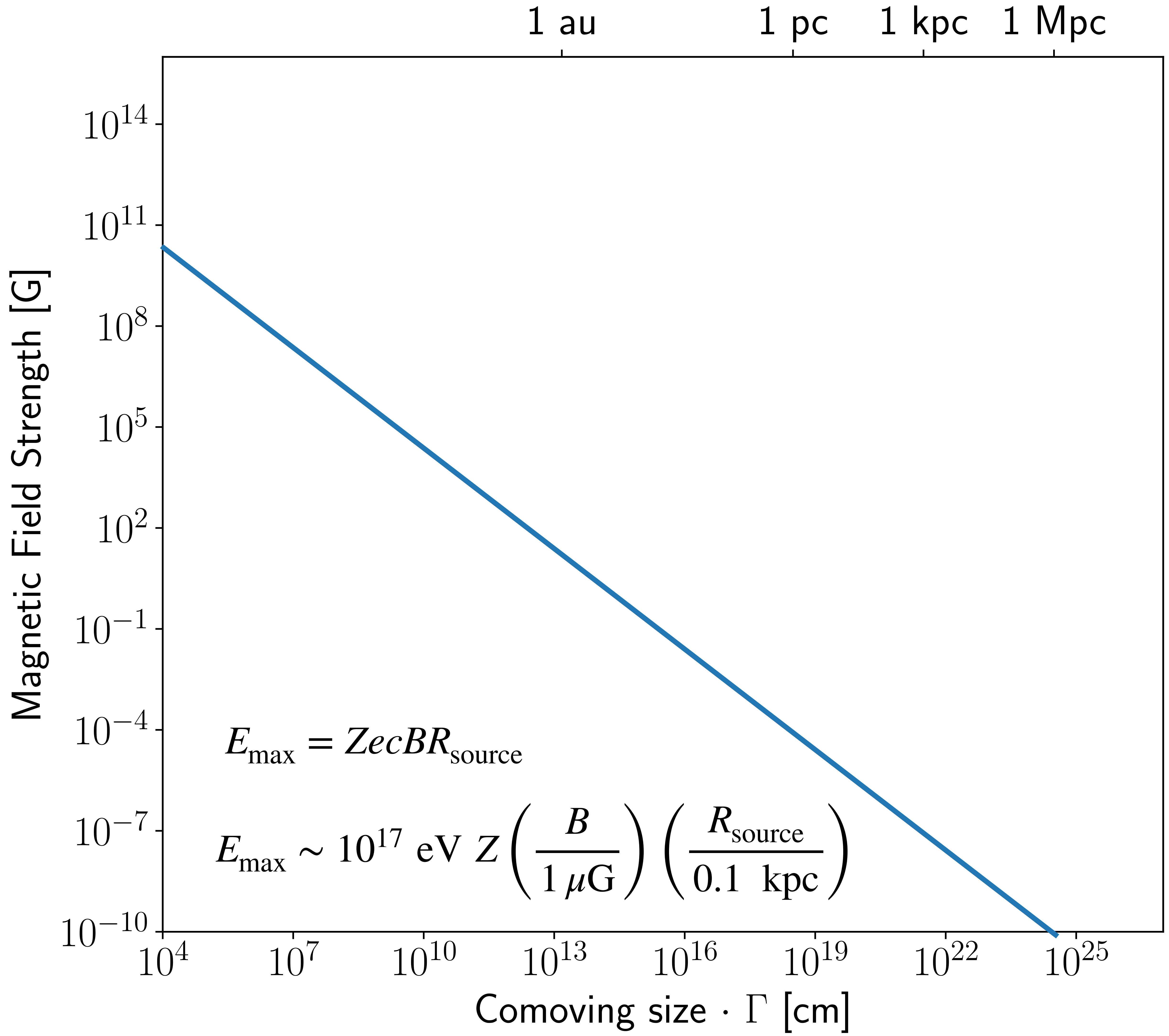
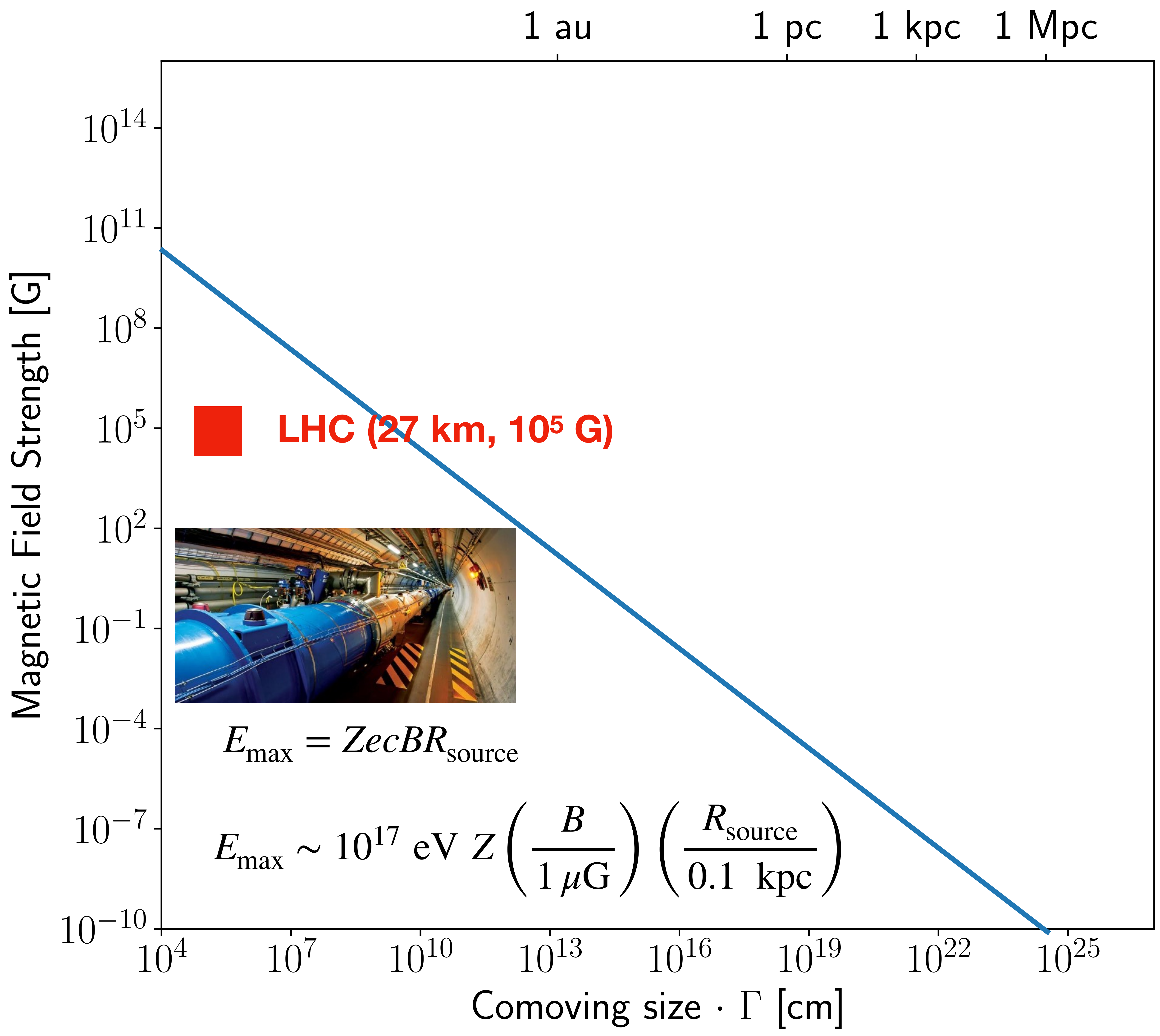
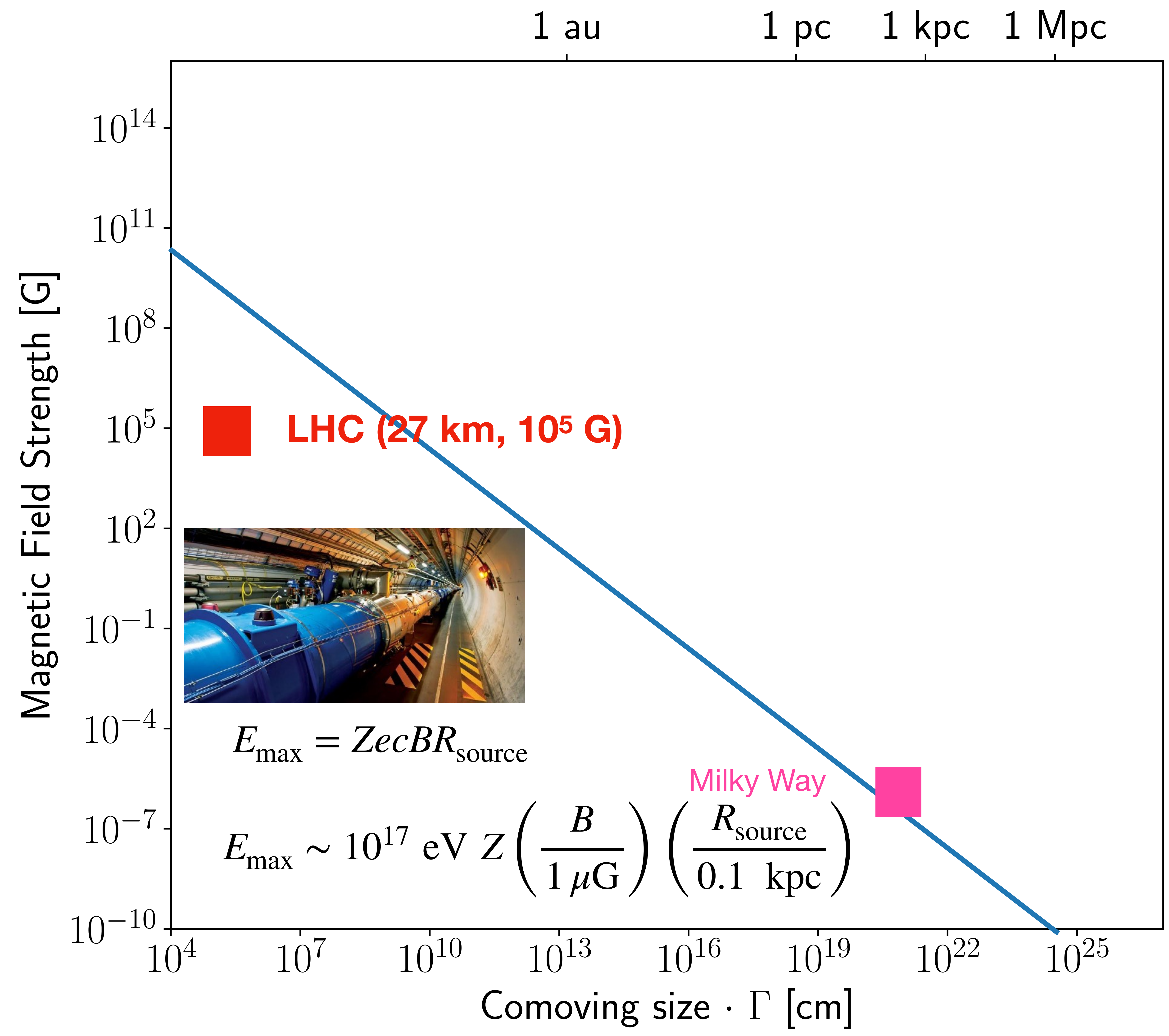


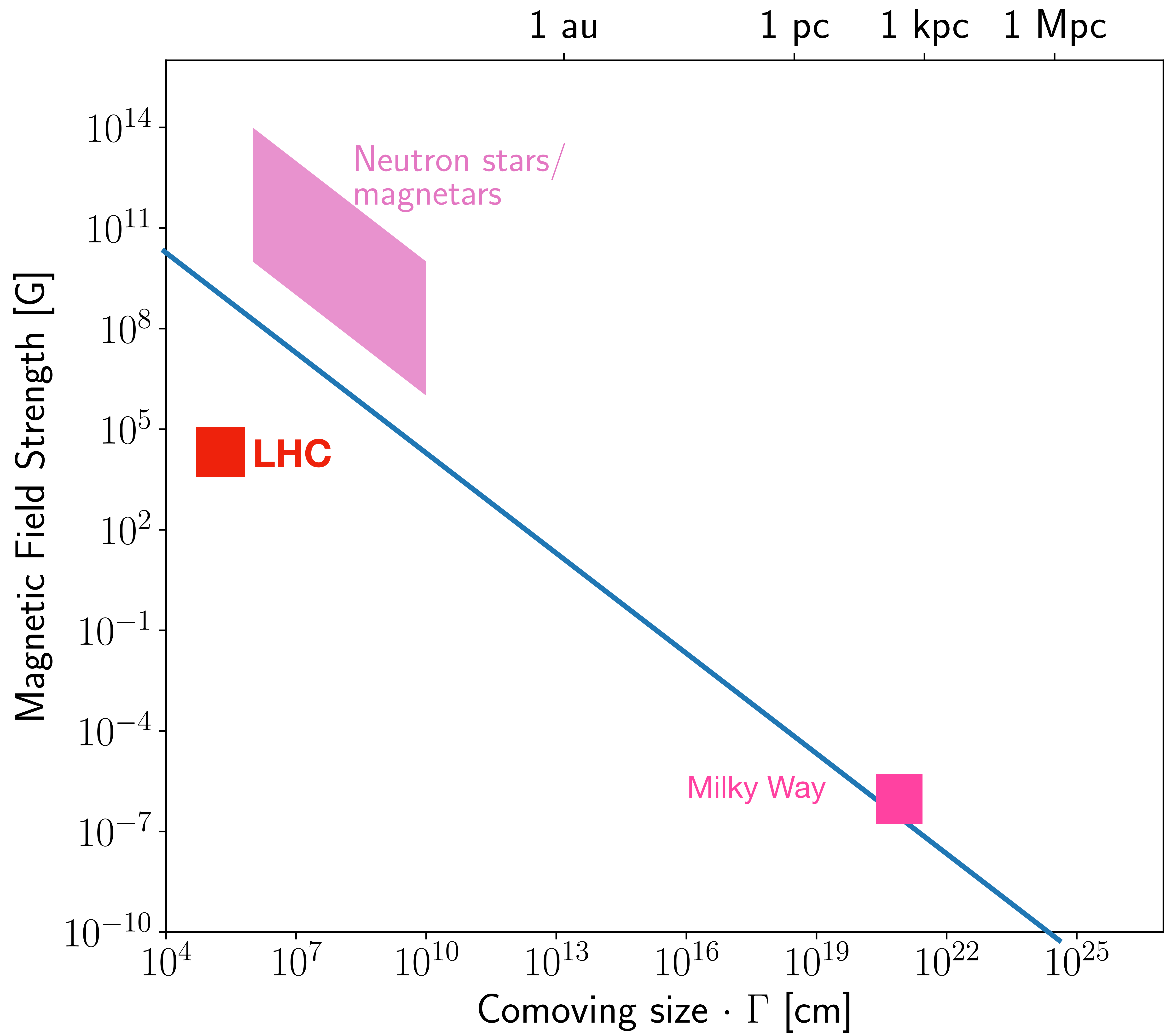
Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)



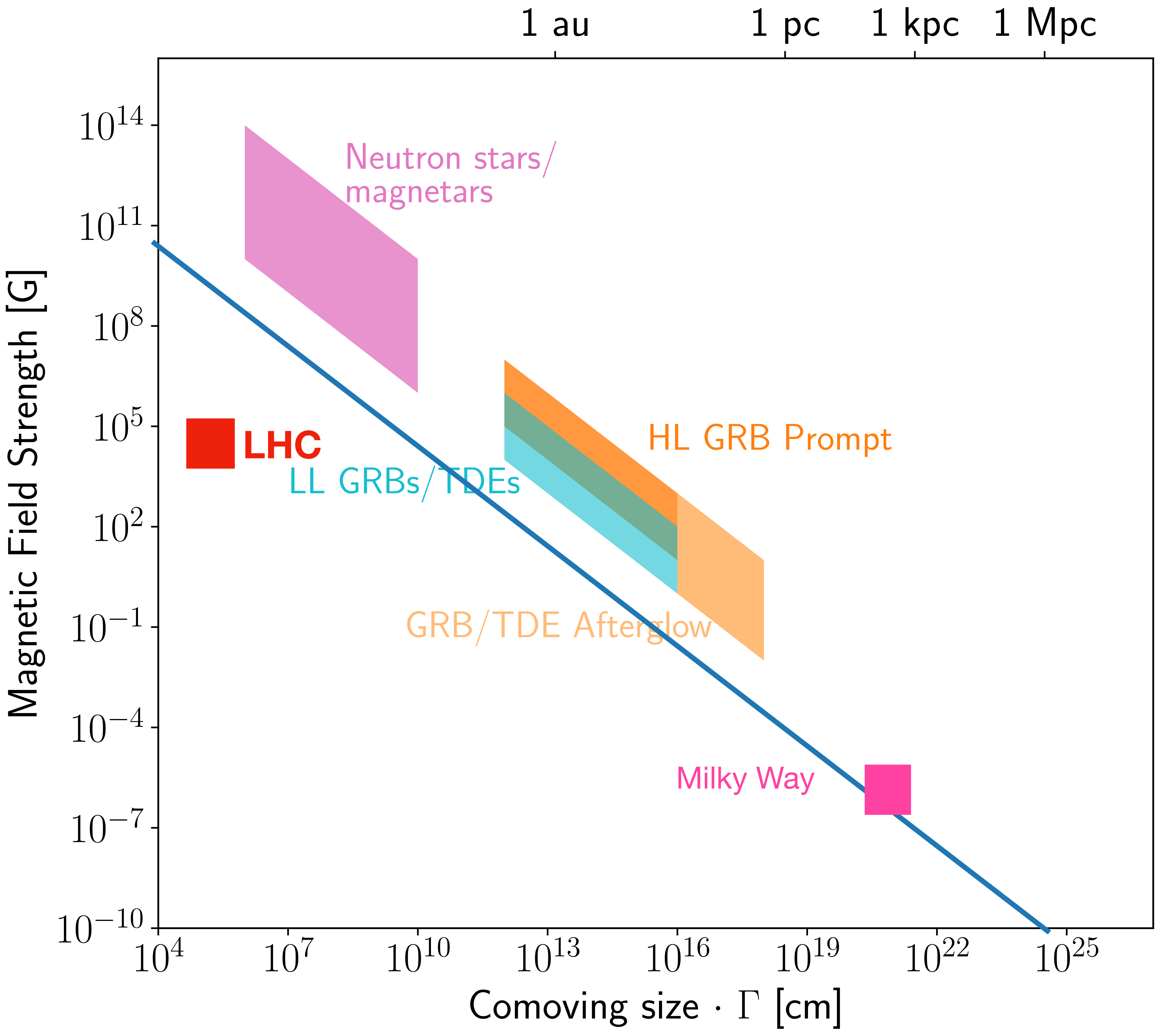
Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)

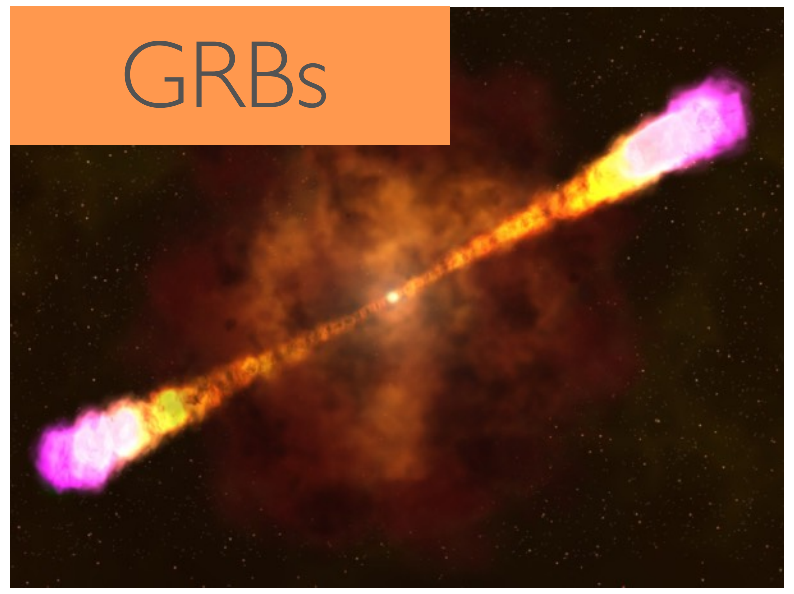


Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)

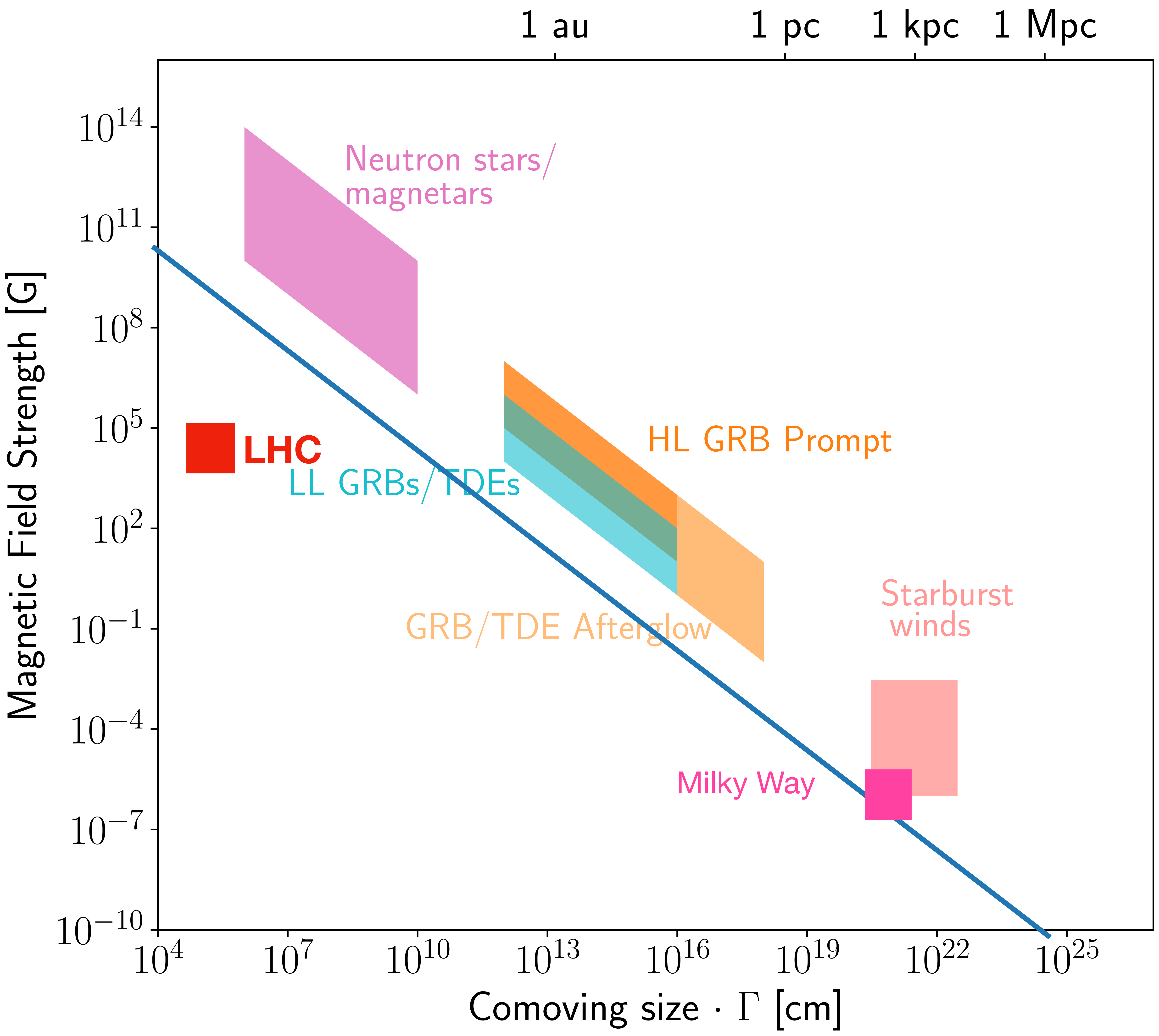


Cosmic-ray accelerators that satisfy the confinement req … 17 eV)

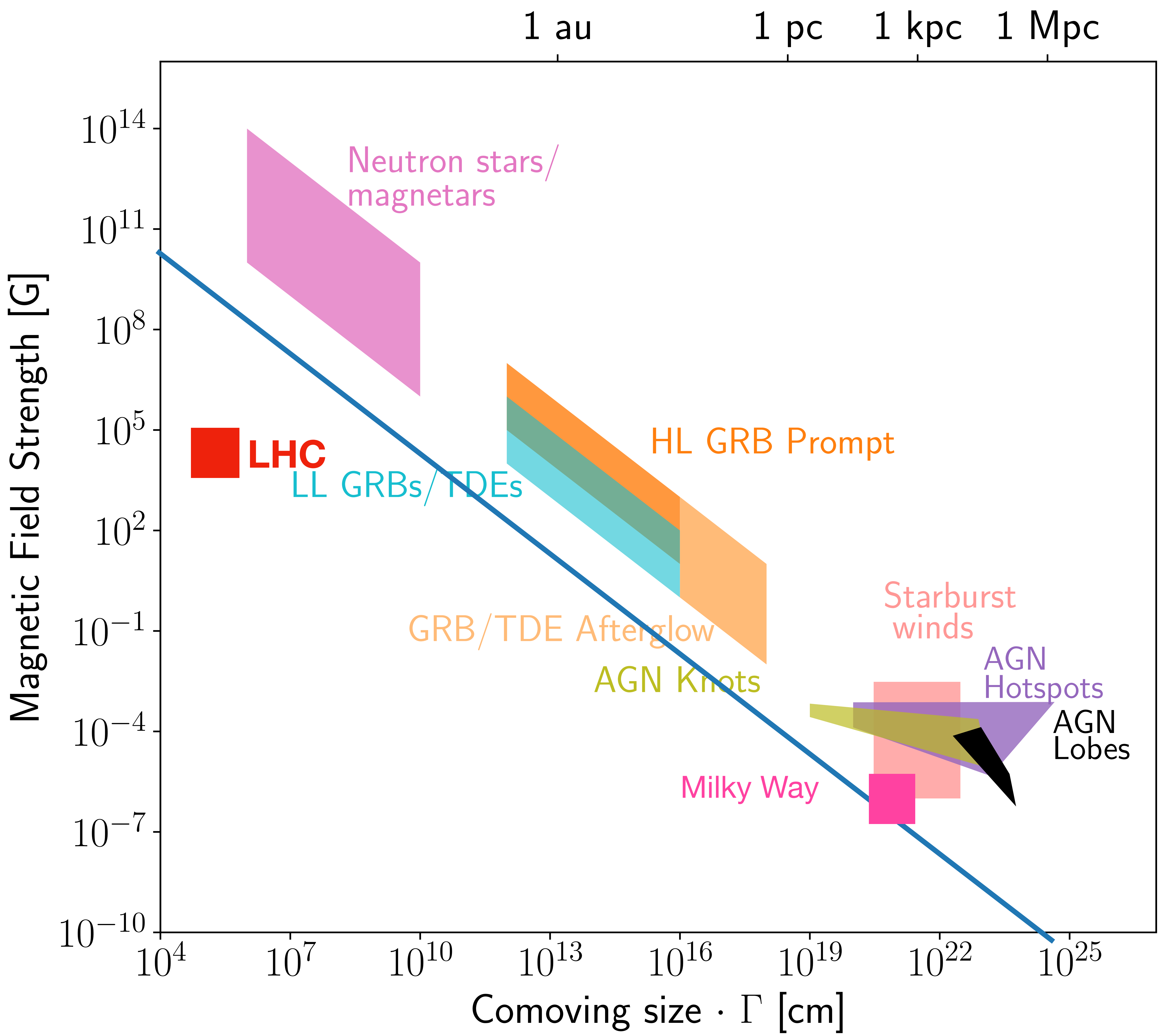


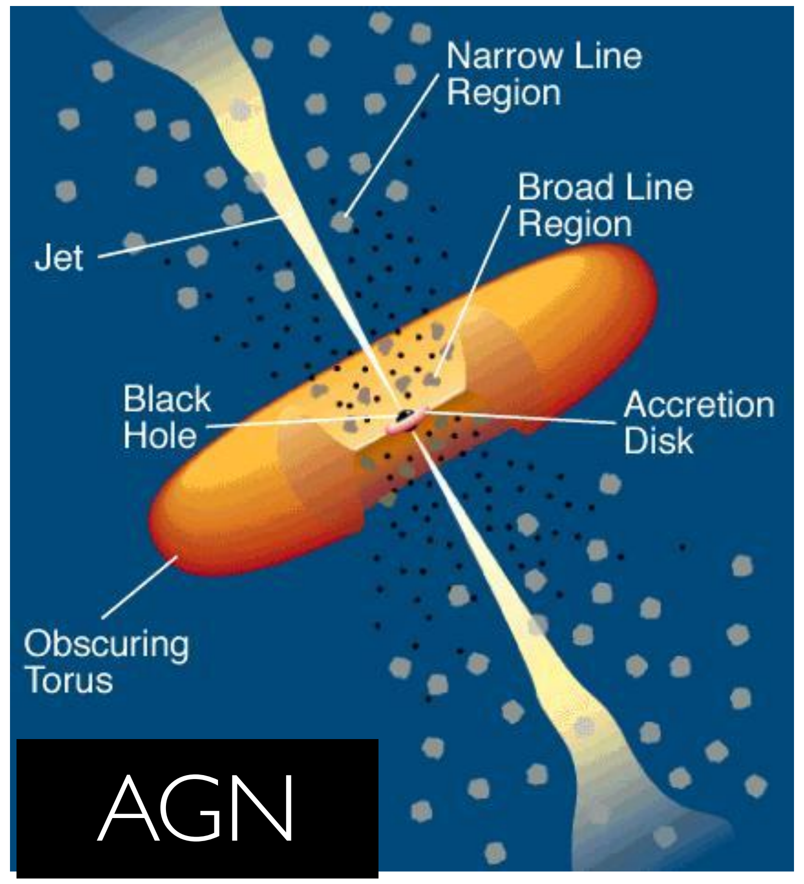


Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)

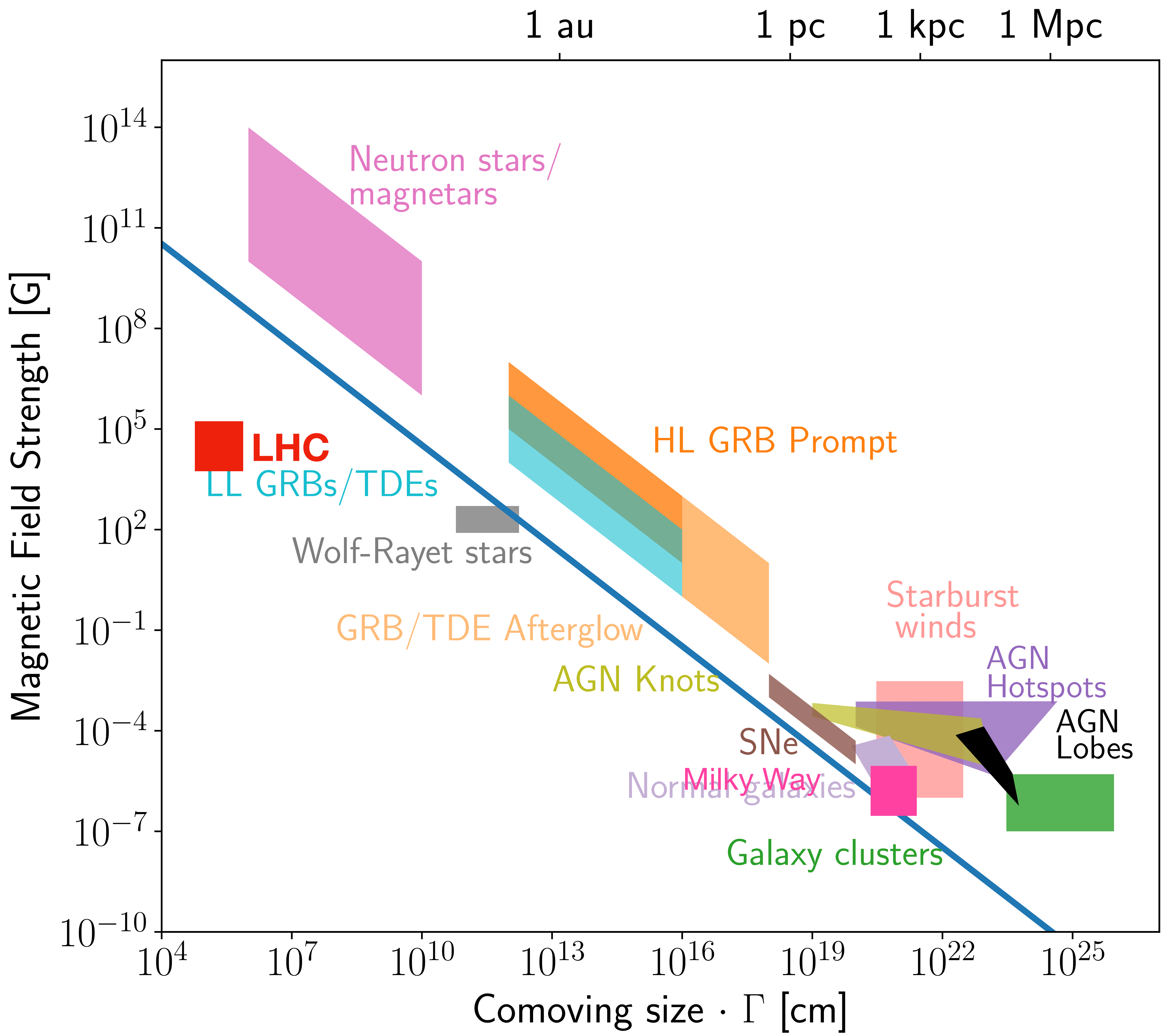


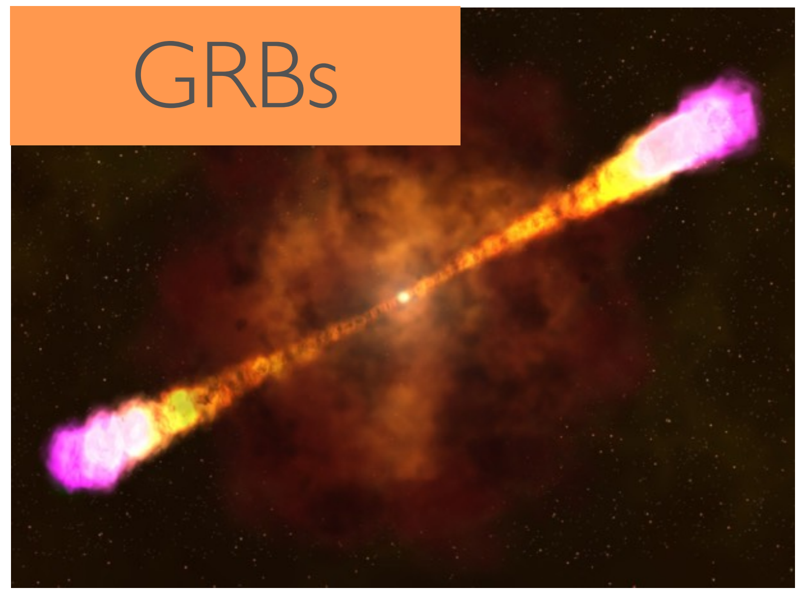
Cosmic-ray accelerators that satisfy the confinement req… 17 eV)

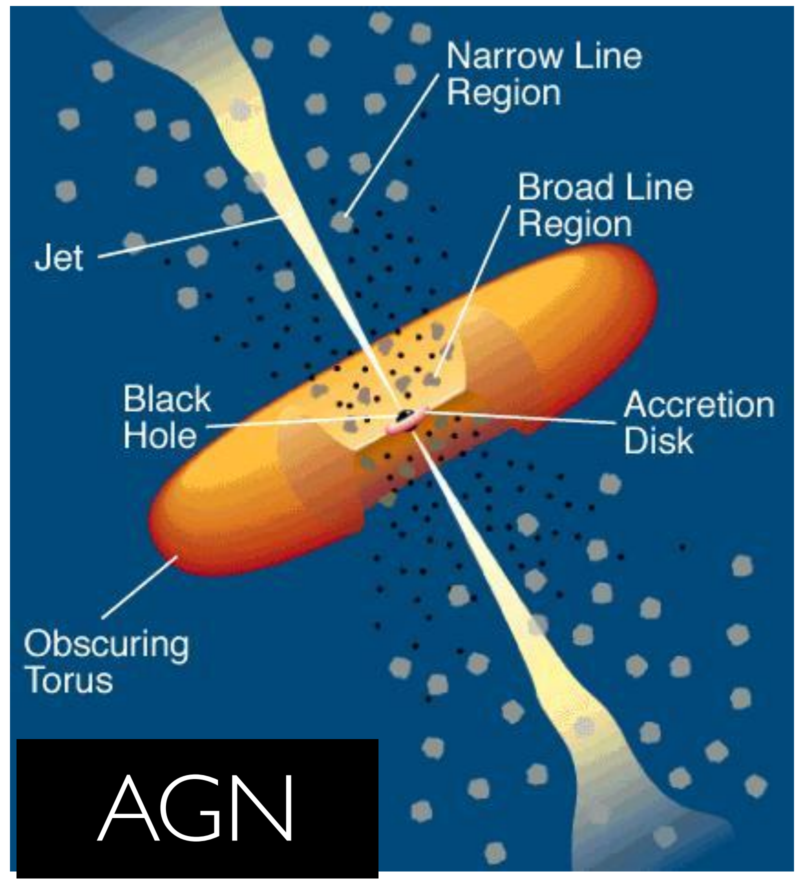




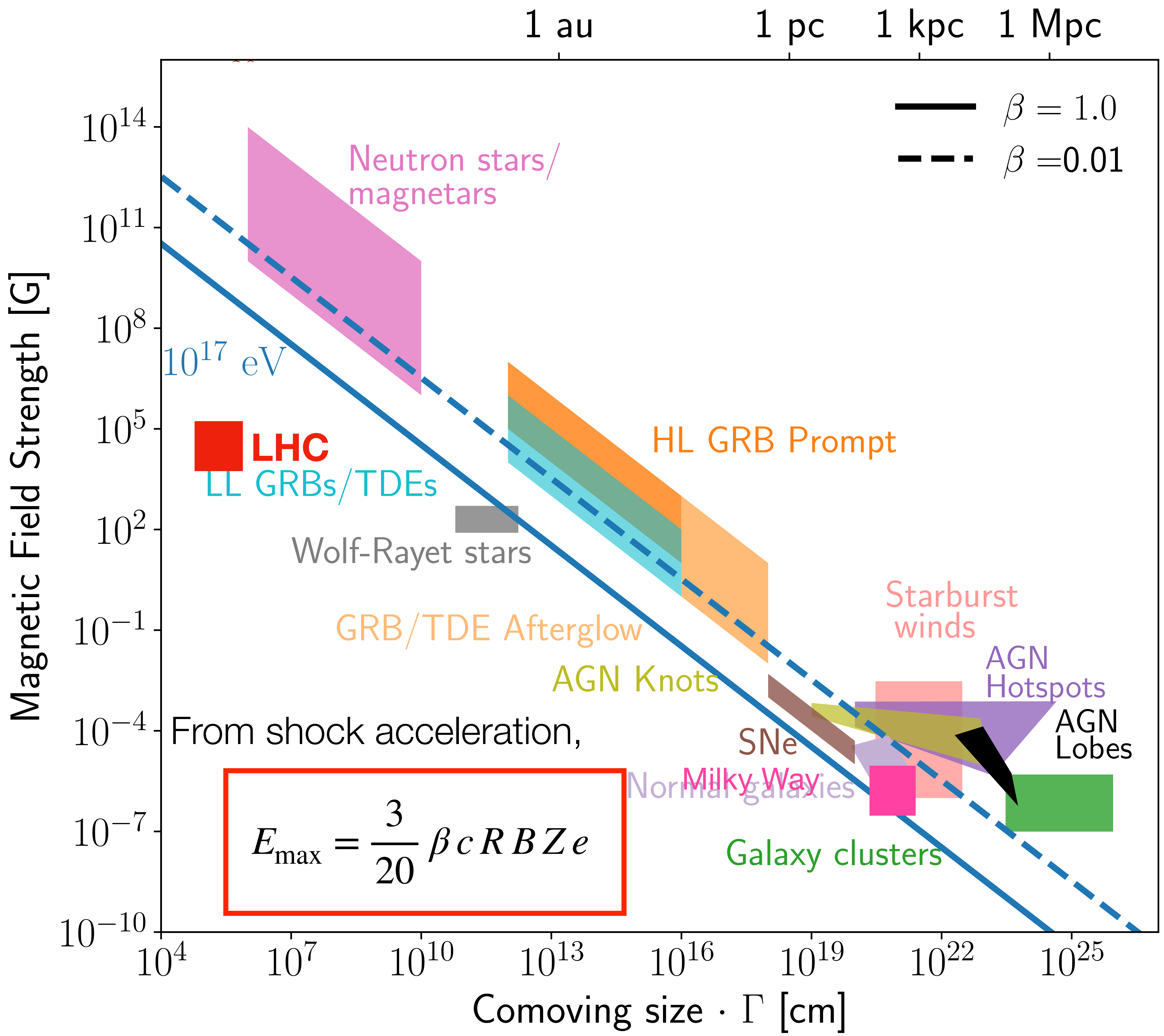
Cosmic-ray accelerators that satisfy the confinement req... 10^{17} eV)

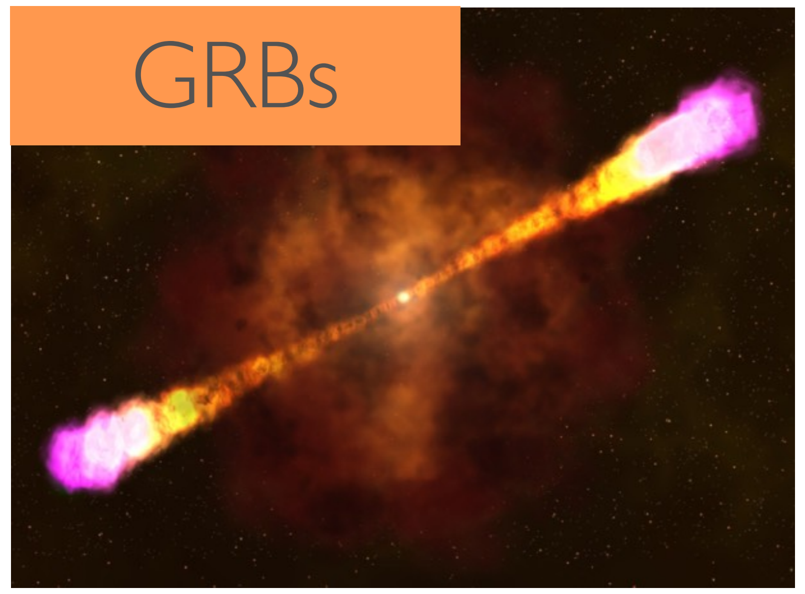


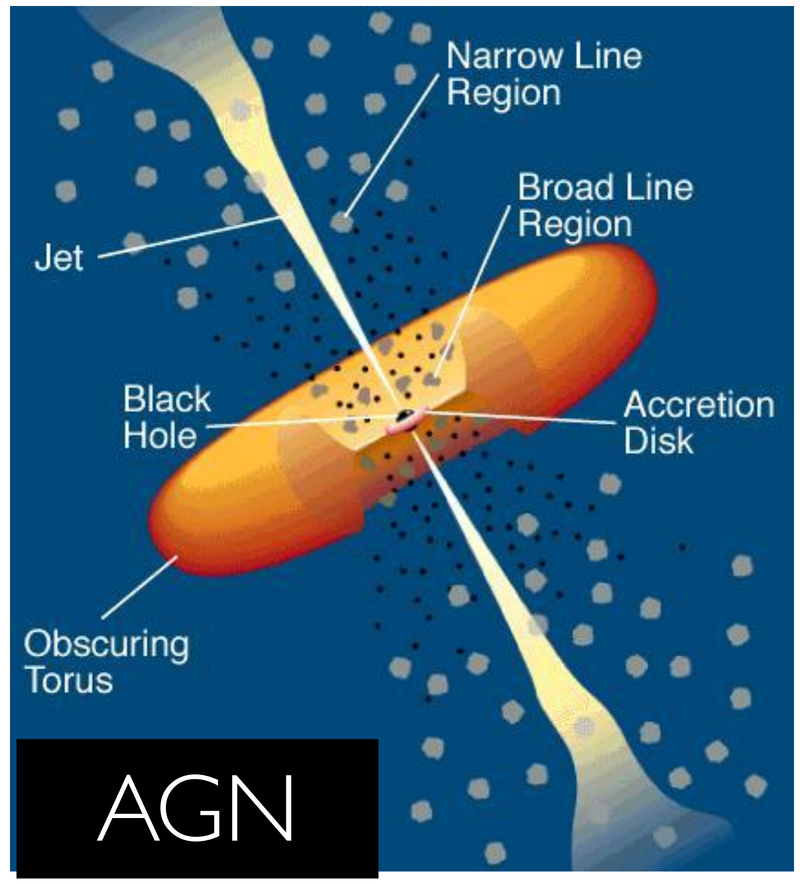




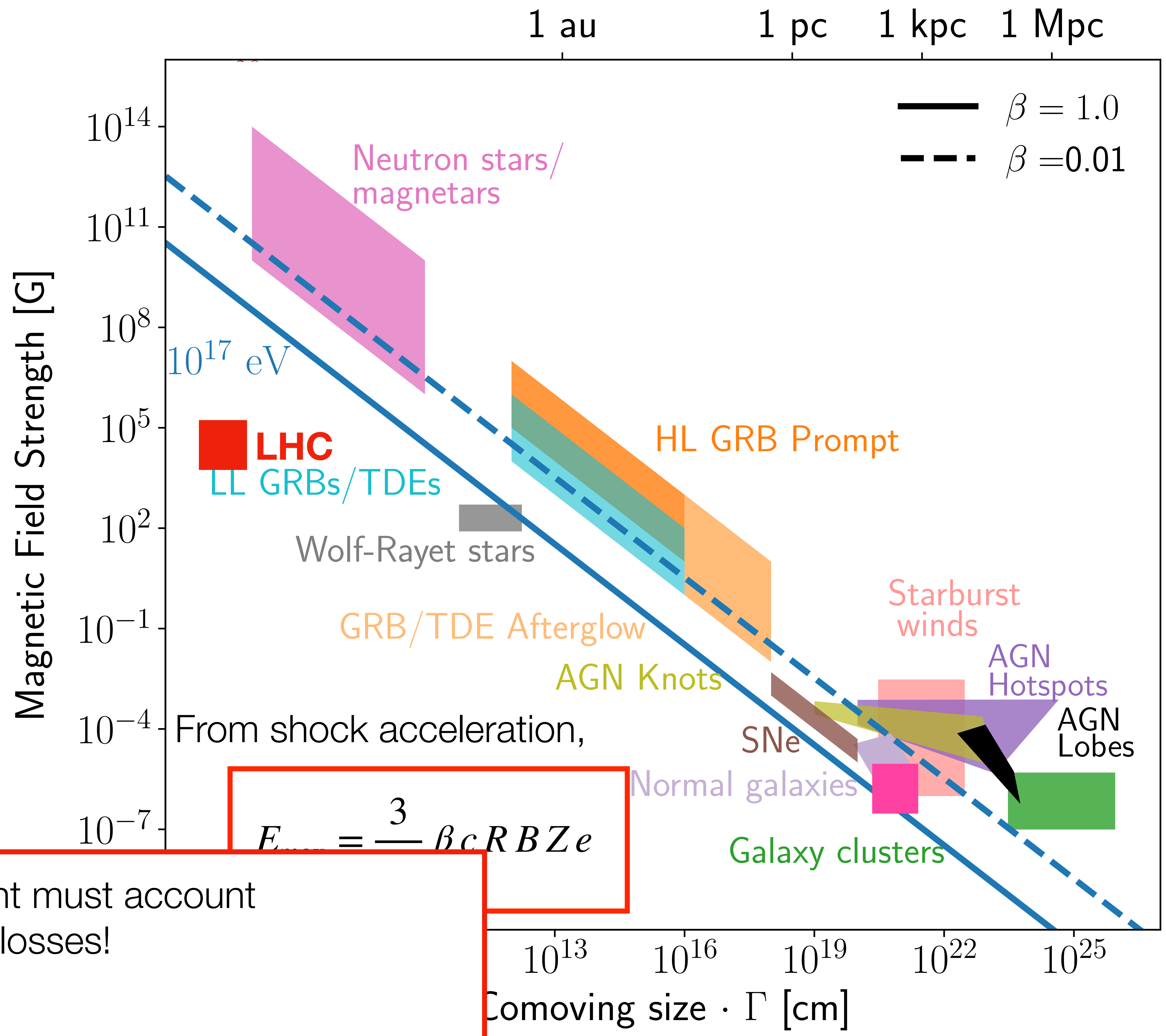
Cosmic-ray accelerators that satisfy the confinement req… 17 eV)







Cosmic-ray accelerators that satisfy the confinement req… 10^{17} eV)



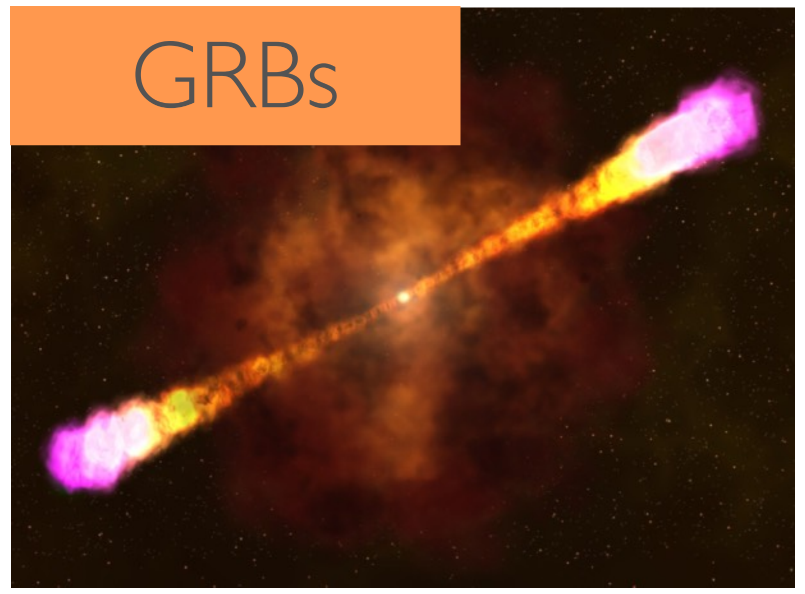
From shock acceleration,

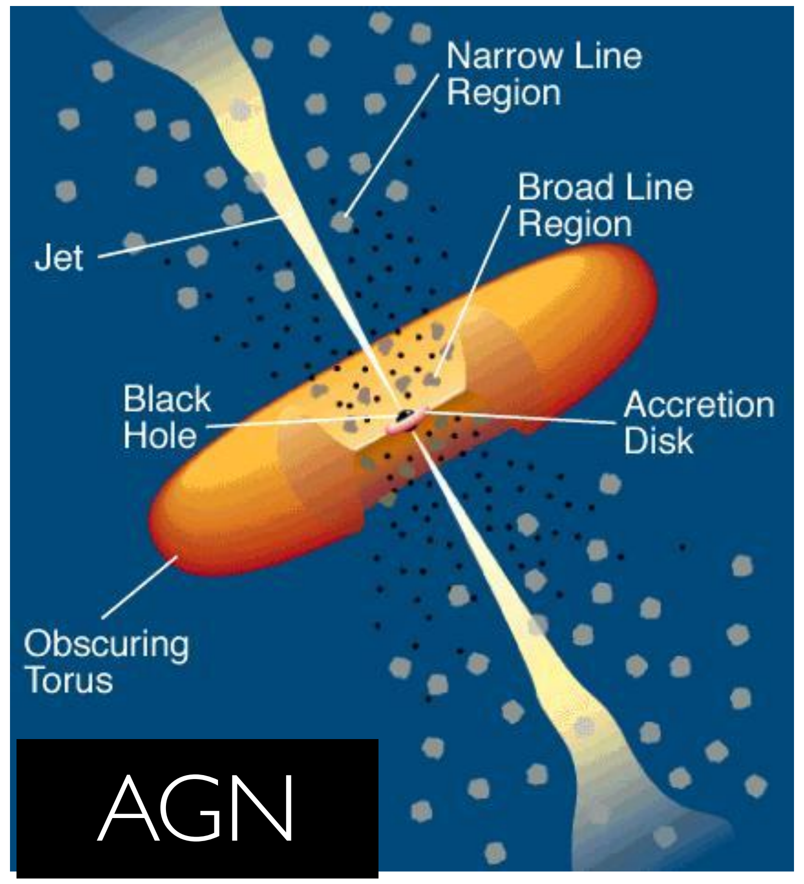
$$E_{max} = \frac{3}{\;}\,\beta c R B Z e$$

Full treatment must account for radiative losses!

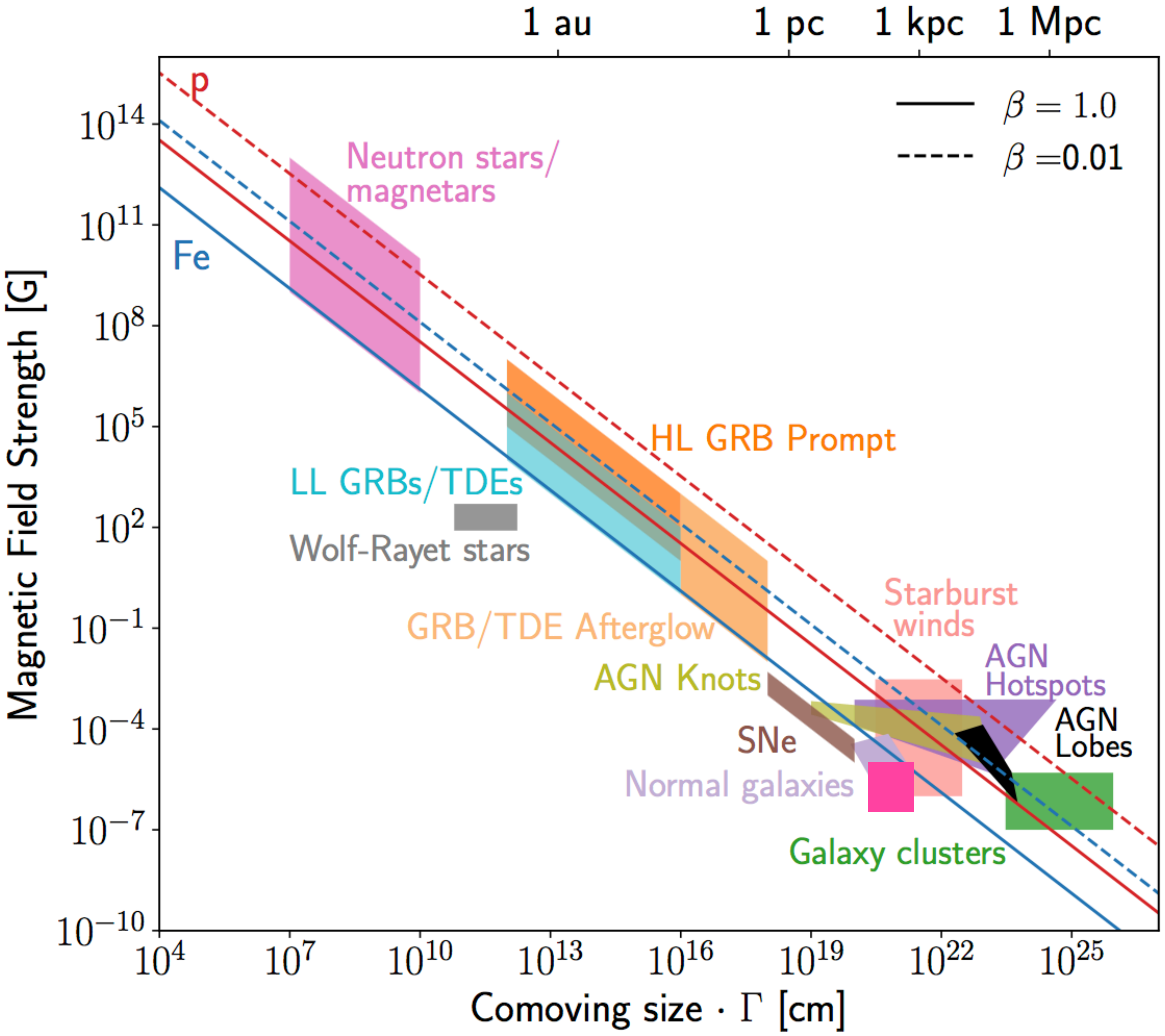
$$t_{acc} < t_{cool}$$

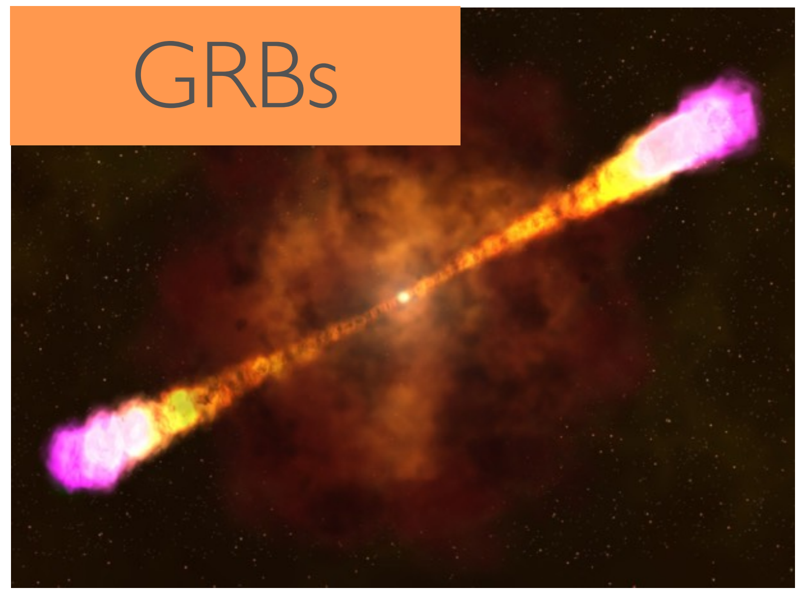
$$t_{cool} = (t_{Synchrotron} + t_{escape} + t_{interaction})^{-1}$$

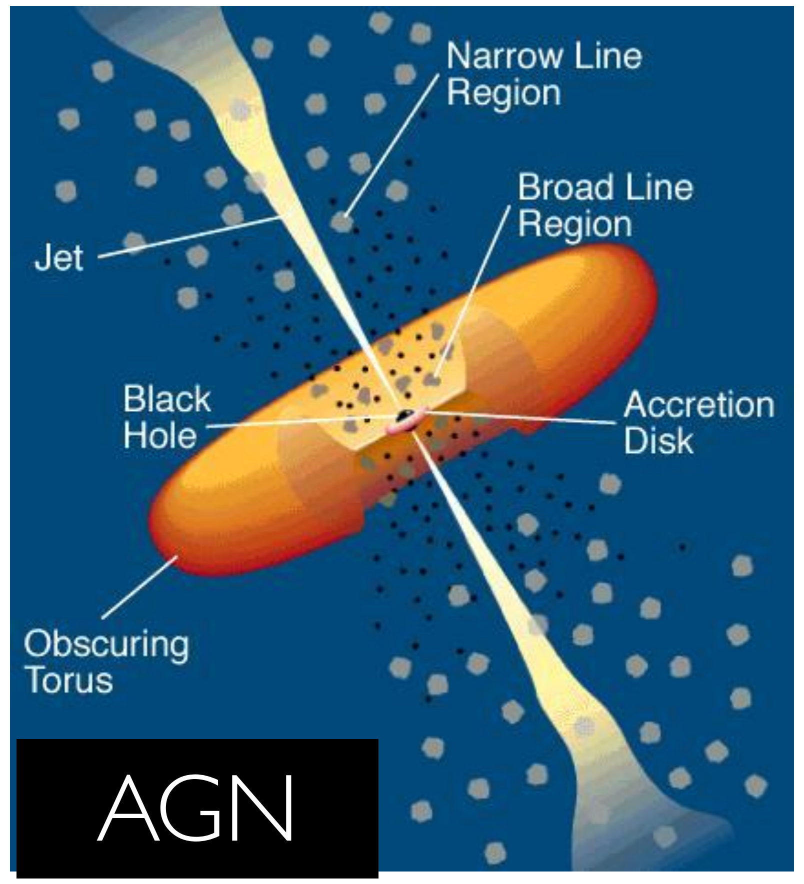




Hillas criterion for 10^{20} eV CRs

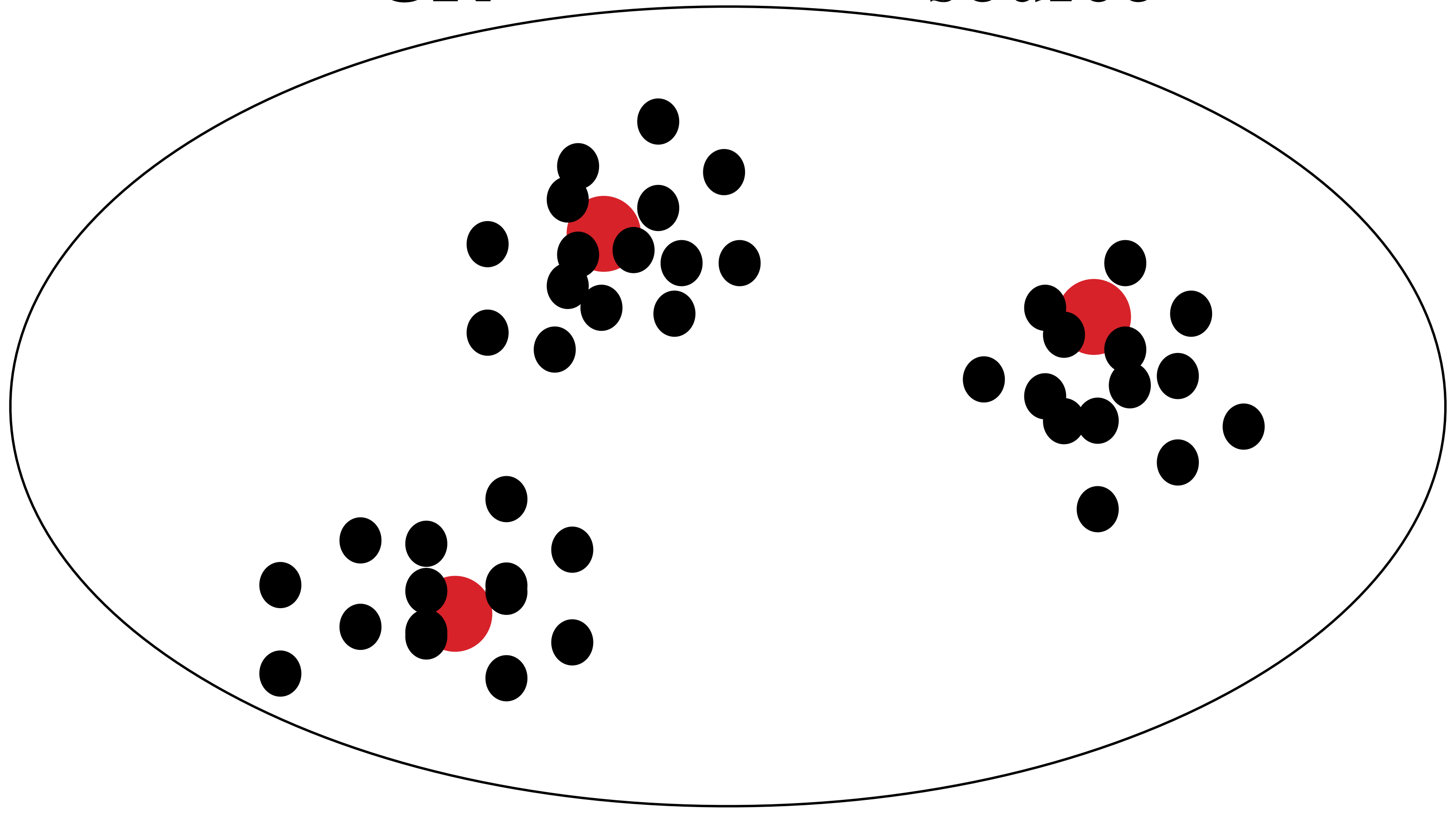




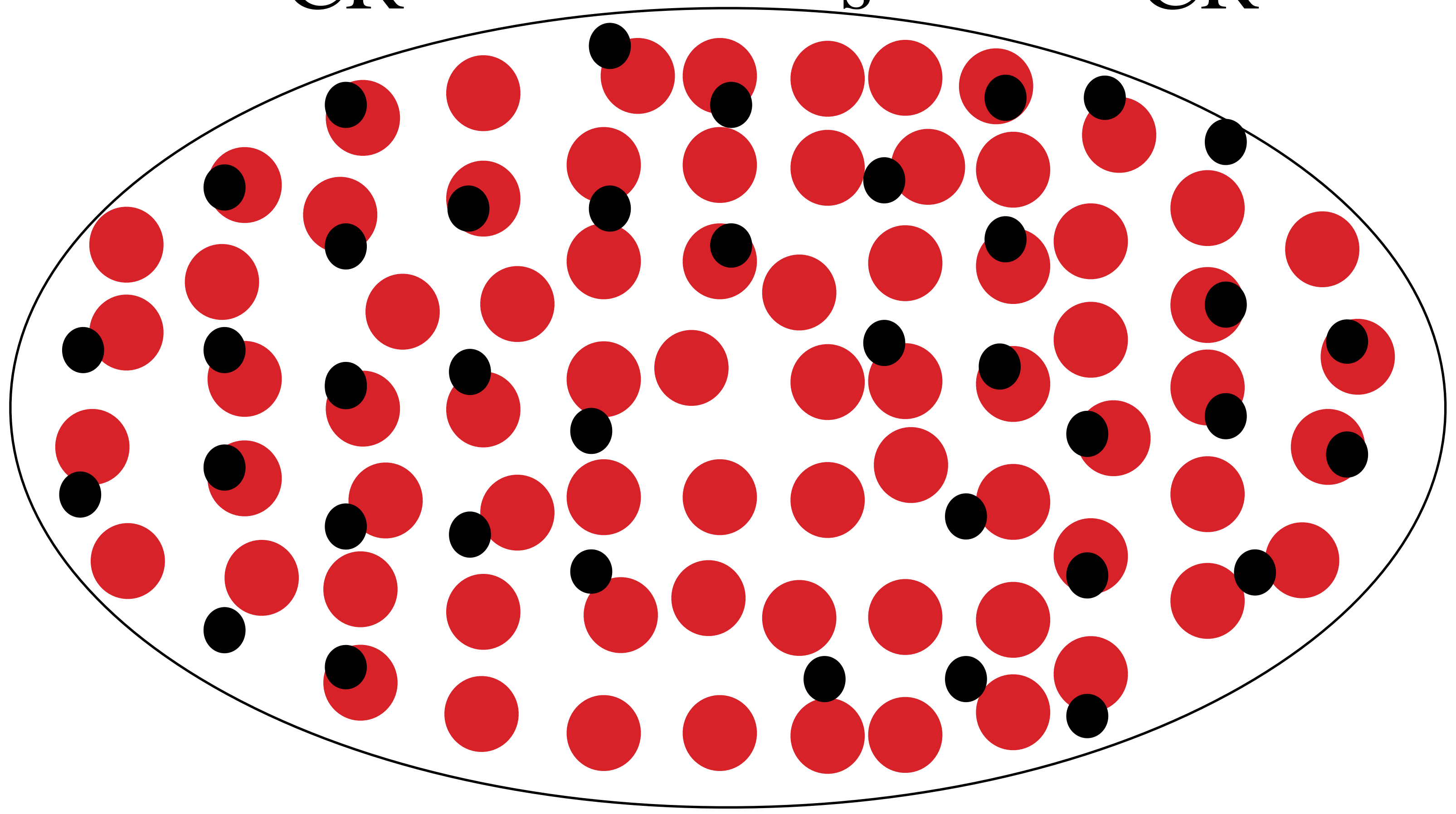


Lower limit on the number density of UHECR sources

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



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



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

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

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

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

Lower limit on the number density of UHECR sources

The probability to see no doublet is

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

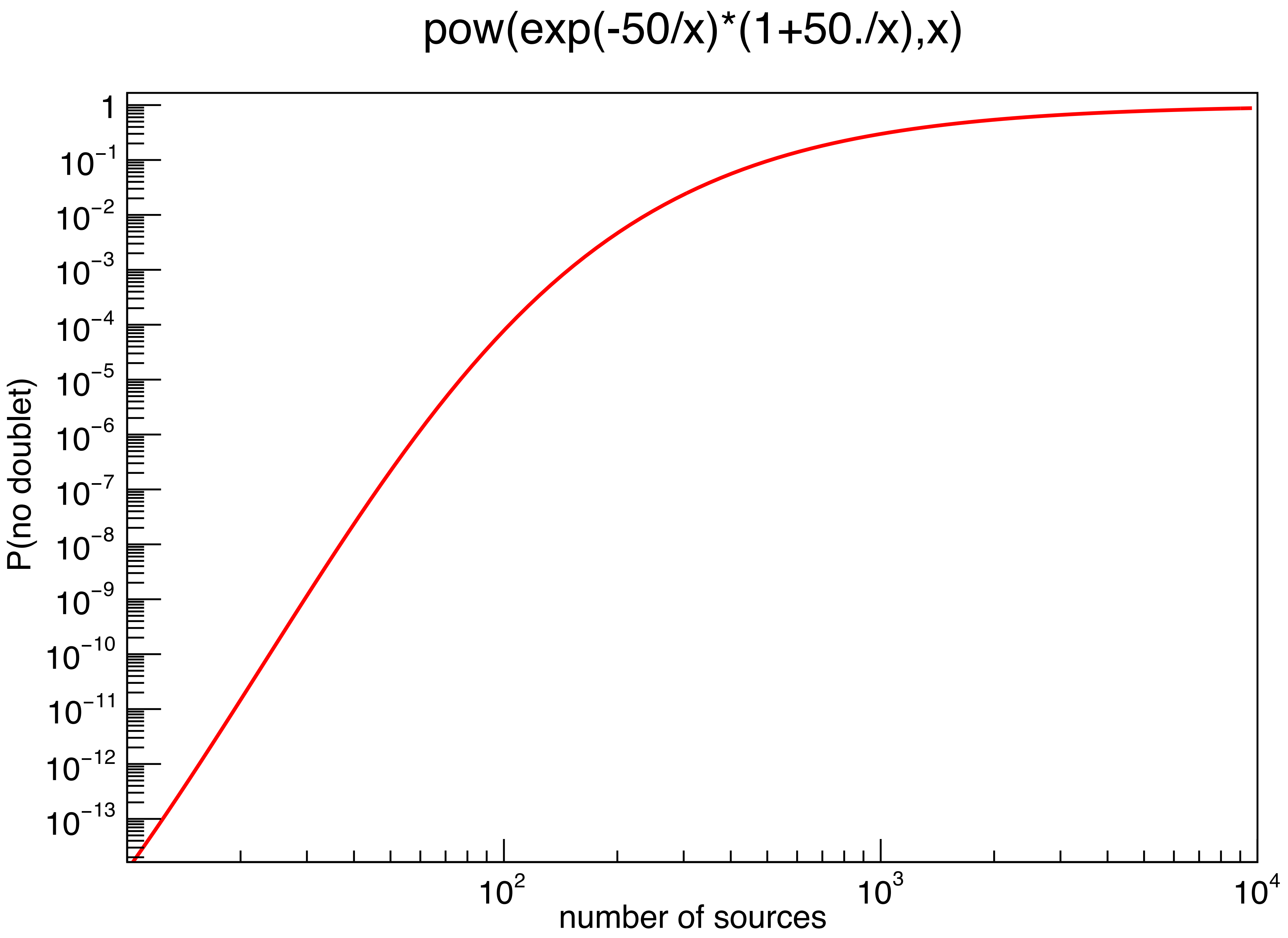
P(no doublet) ~ 1% if > 200 sources

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

Often in the literature (in absence of multiplets):

$$P(\text{no doublet}) = e^{-N_{\text{CR}}}\left(1 + \frac{N_{\text{CR}}}{N_s}\right)^{N_{\text{sources}}} \approx 1 - \frac{1}{2}\frac{N^2_{\text{CR}}}{N_S}$$

$$N_S \approx \frac{1}{2}\frac{N^2_{\text{CR}}}{1 - P(\text{no doublet})} \qquad N_S \gtrsim \frac{1}{2}N^2_{\text{CR}}$$



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

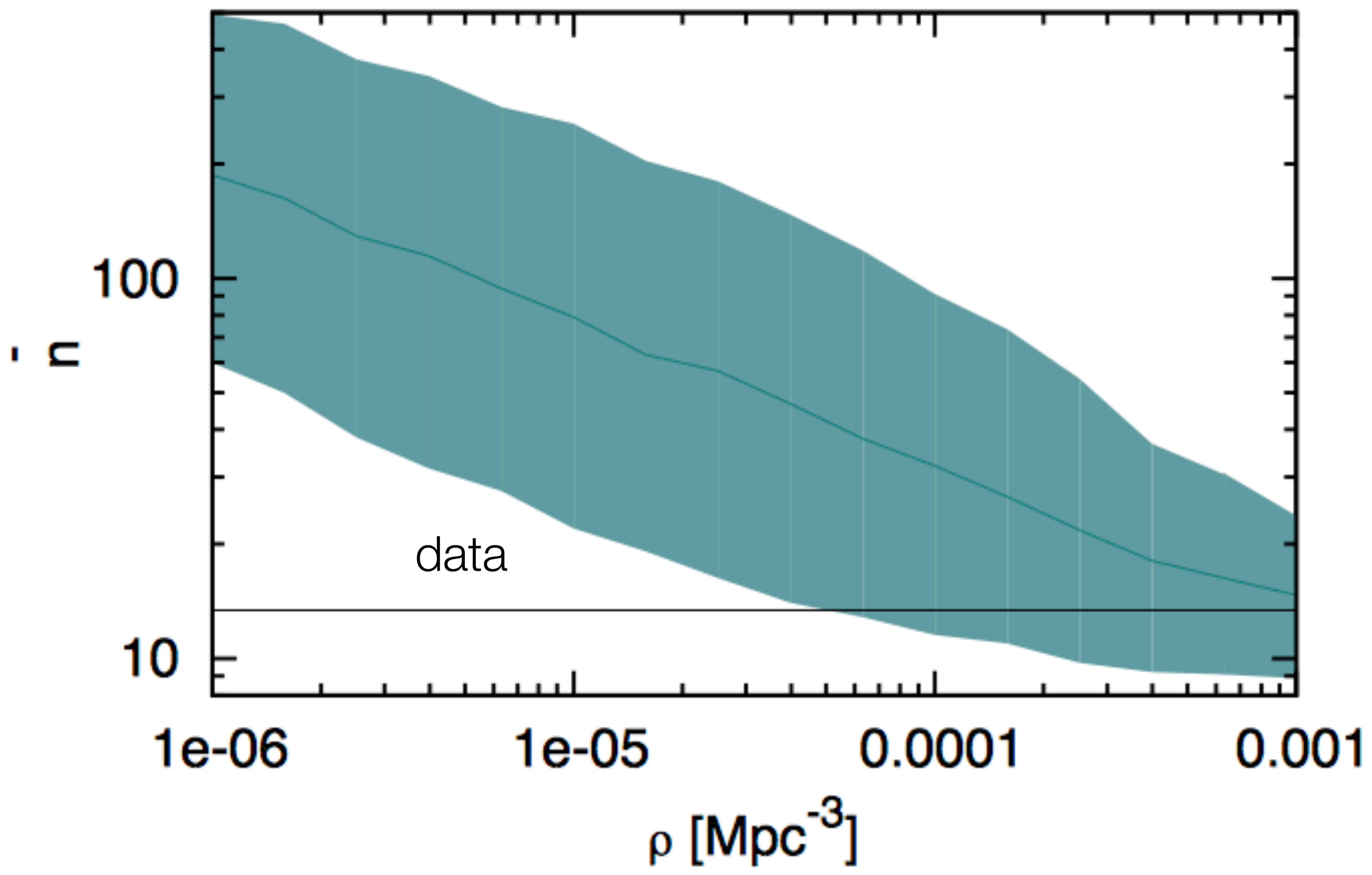
Starbursts - 10^{-4} Mpc^{-3}

Jetted AGN - 10^{-4} Mpc^{-3}

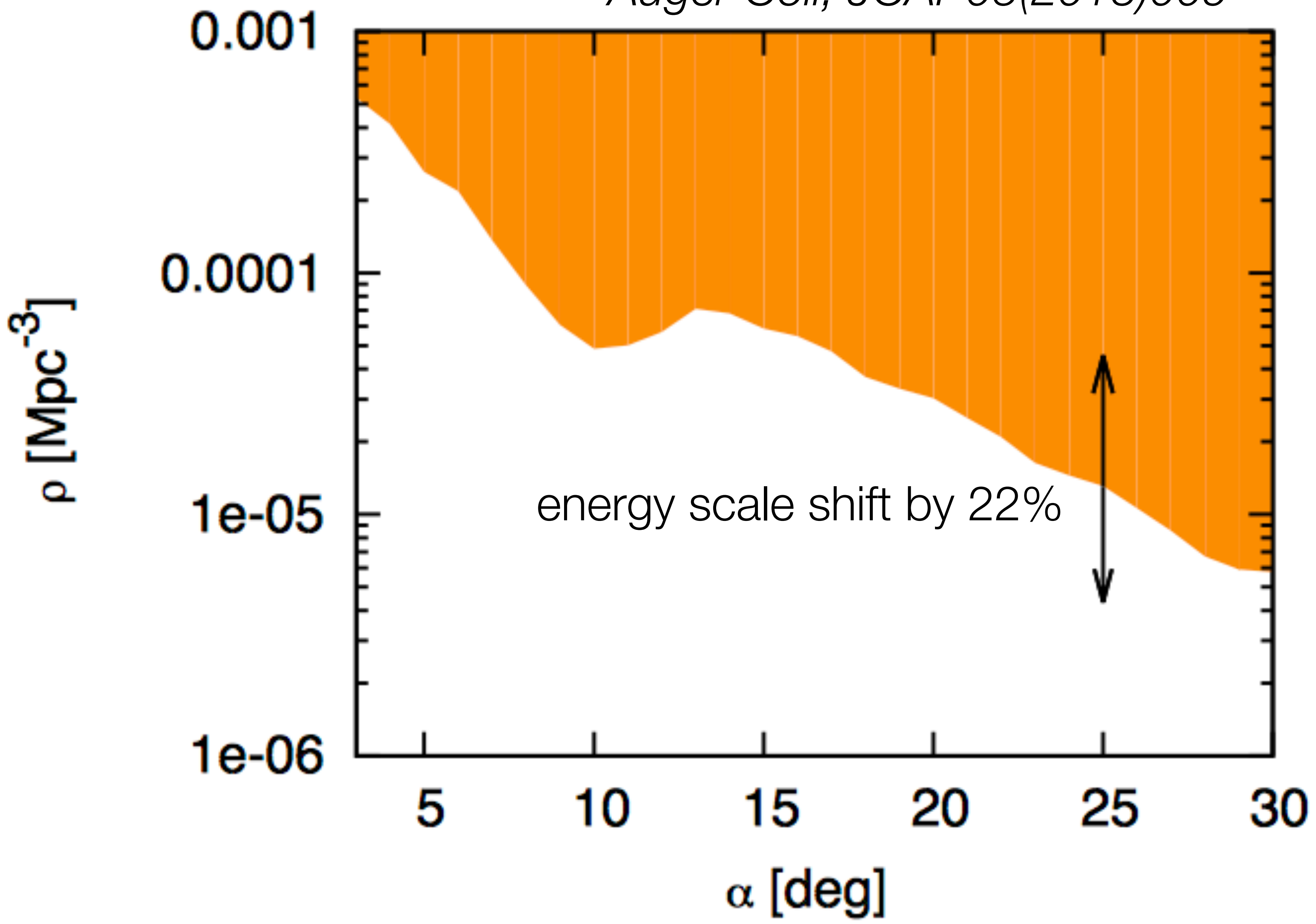
Lower limit on the number density of UHECR sources

Application to Auger data with E > 70 EeV (43 events):

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



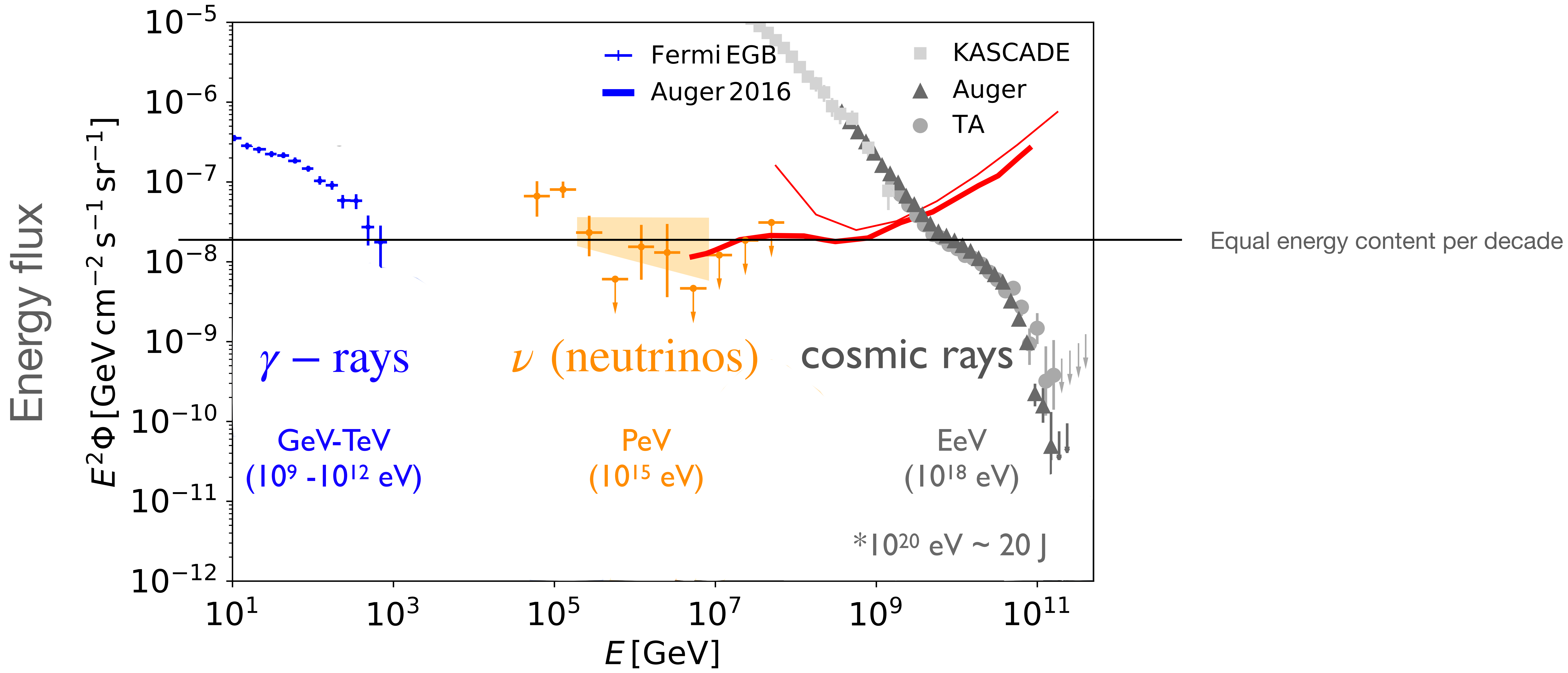
Auger Coll, JCAP05(2013)009



as well as Waxman, Fisher, Piran , ApJ 1997
Dubovski, Tinyakov, Tkachev, PRL85(2000)1154
Takami & Sato, Astrop.Phys.30 (2009) 306
FO, Connolly ,Thomas, Abdalla, Lahav, Waxman, JCAP05(2013)015

see Teresa's talk for a different approach!

Neutrino energy flux and multimessenger connections

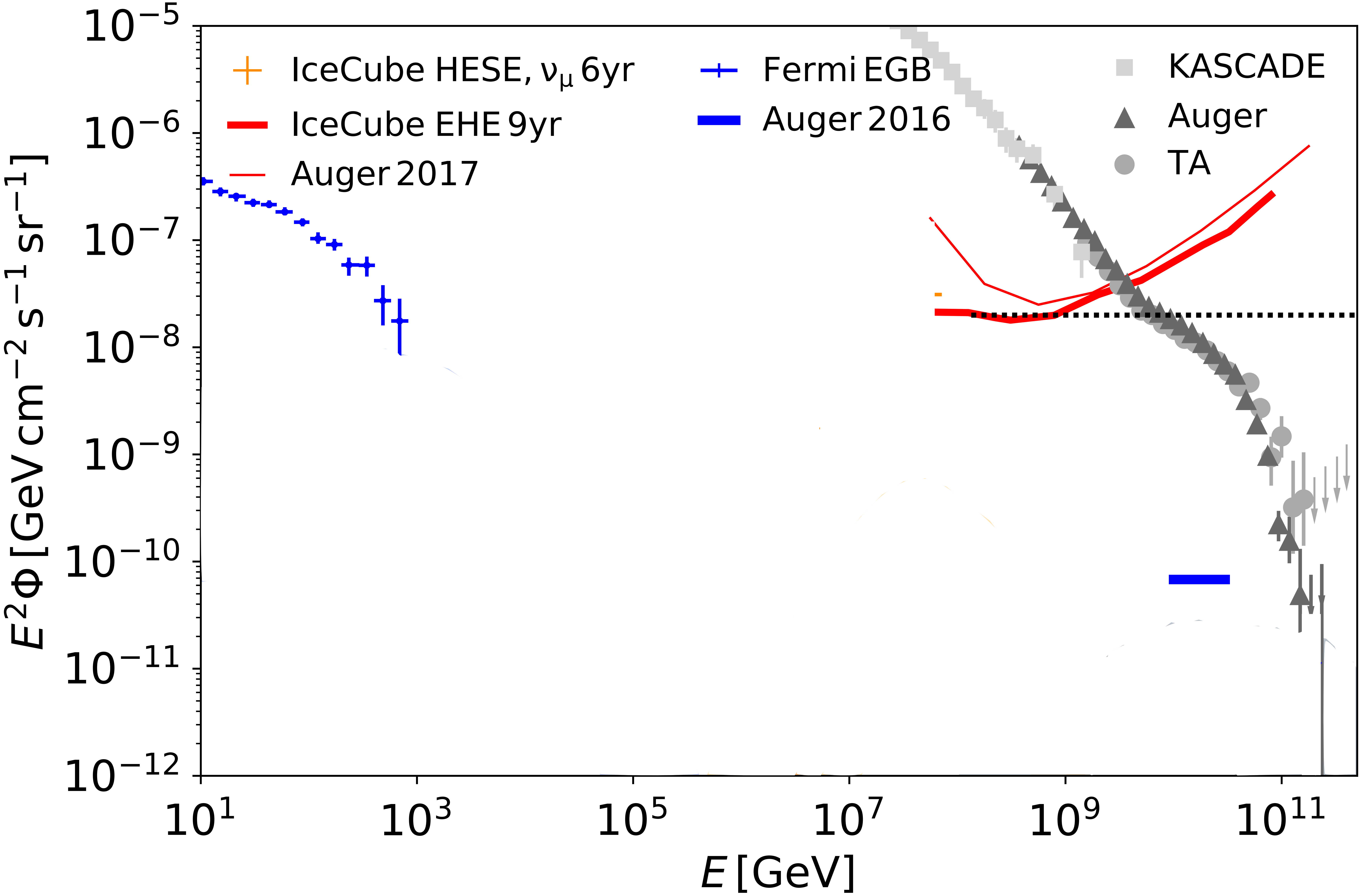


$$p + \gamma \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

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

Waxman-Bahcall bound

E. Waxman, J. Bahcall, PRD 1998



1. UHECR energy loss length

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

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

Relative energy loss per unit time:

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

Energy loss length:

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

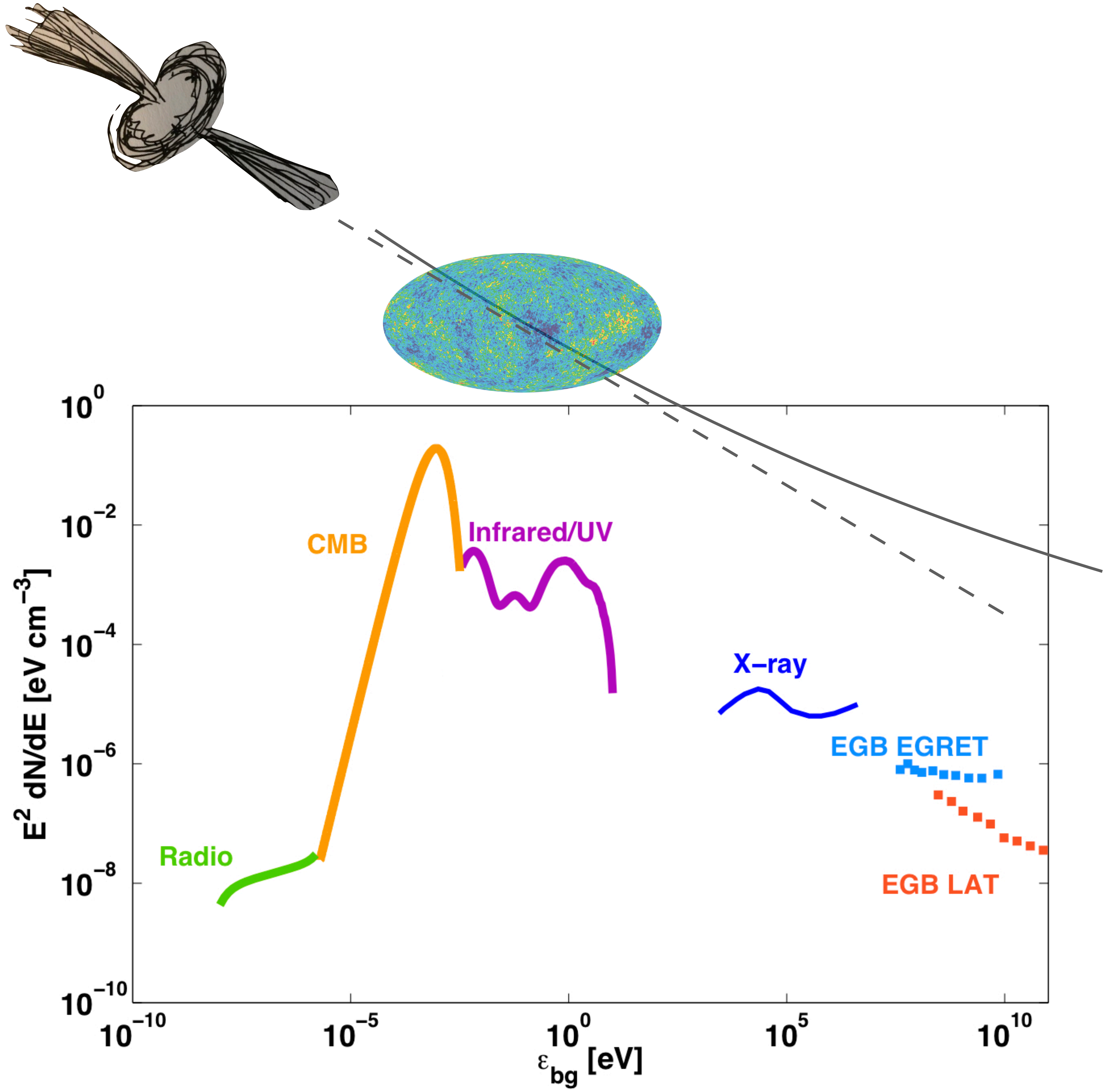


Photo-pair production (Bethe-Heitler process):

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

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

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

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

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

1. UHECR energy loss length

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

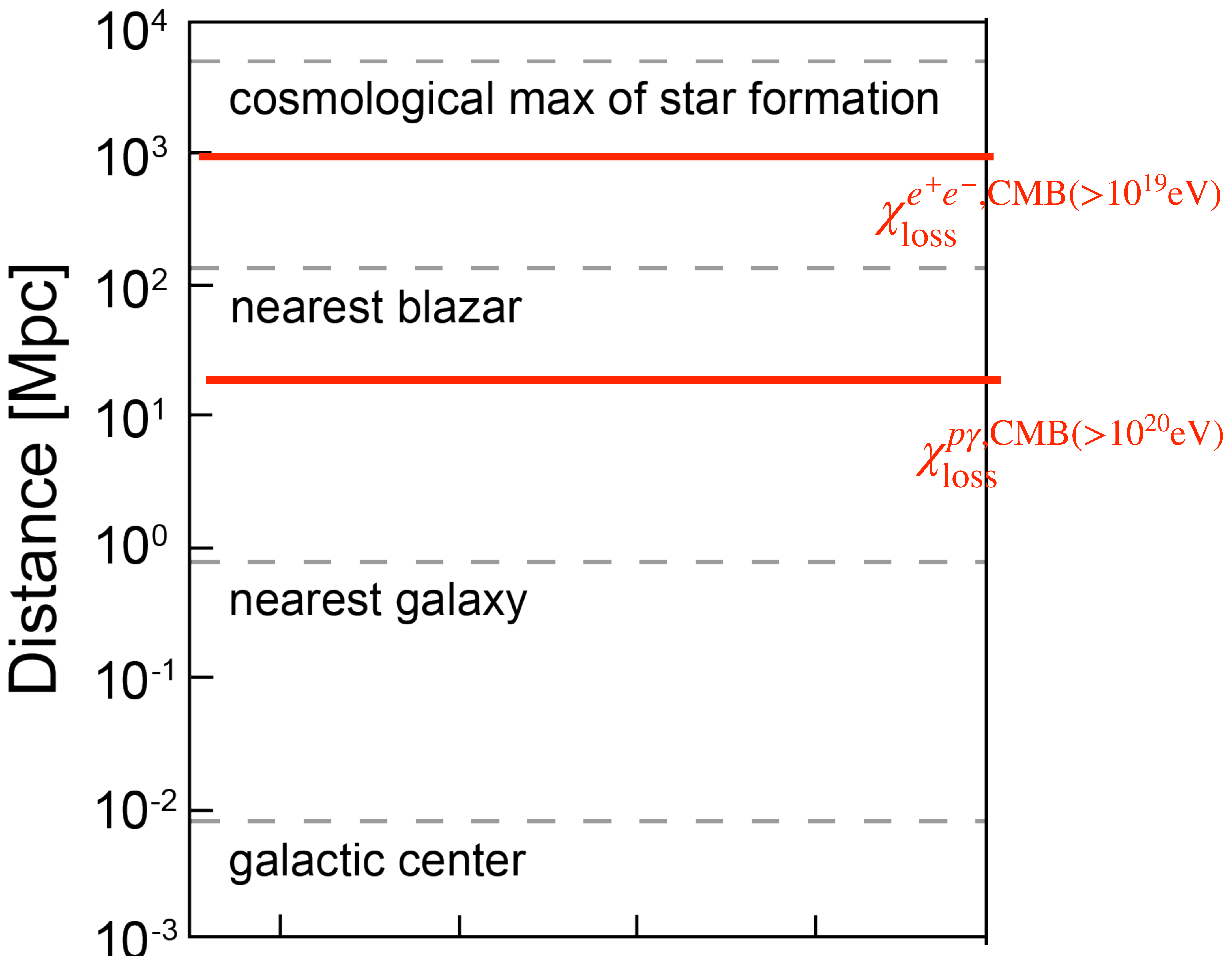
Photo-pion production:

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

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

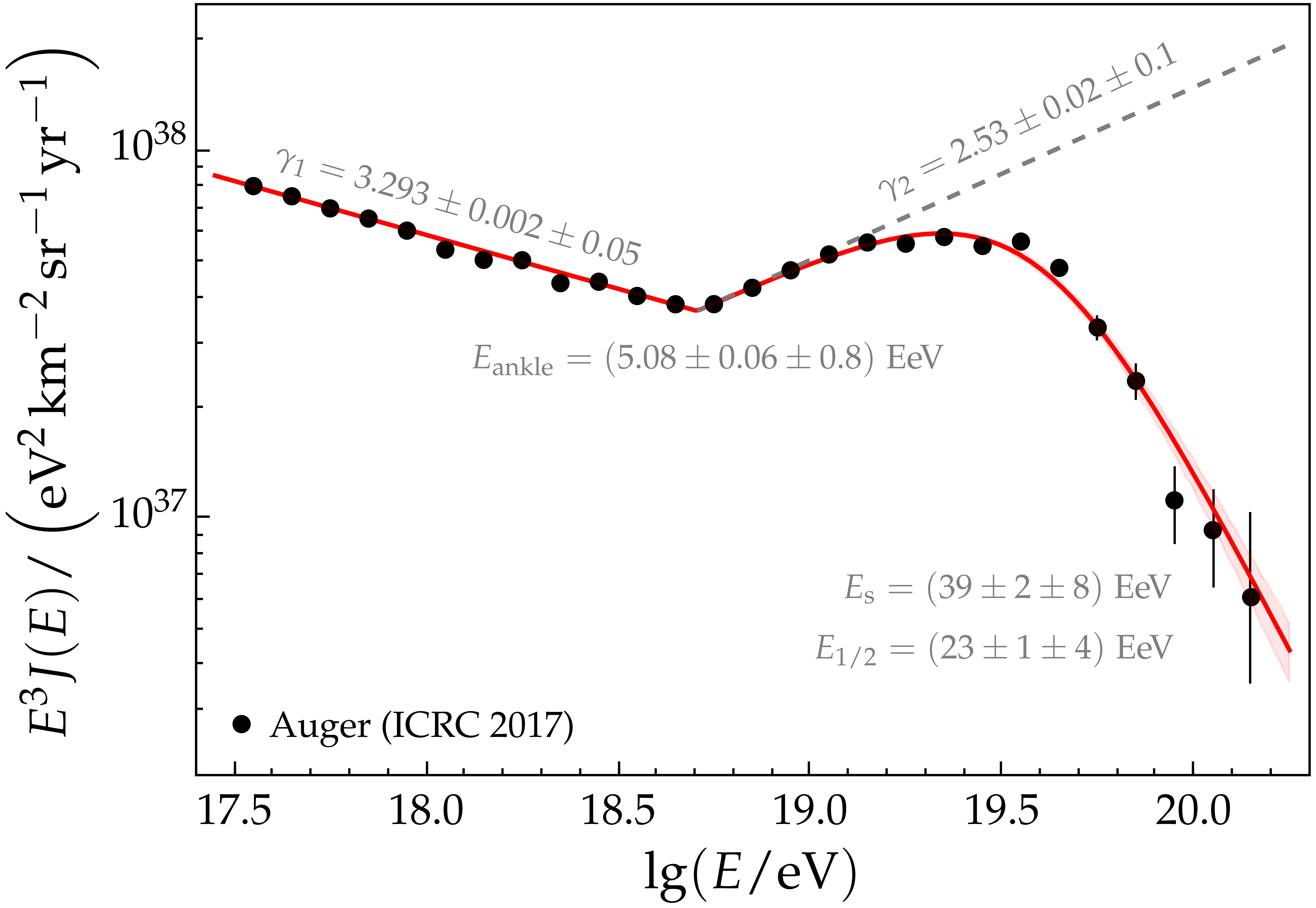
$$\left[\kappa \approx m_\pi/m_p \approx 0.2, \sigma_{p\gamma} \approx 10^{-28}\,{\rm cm}^2\right]$$

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



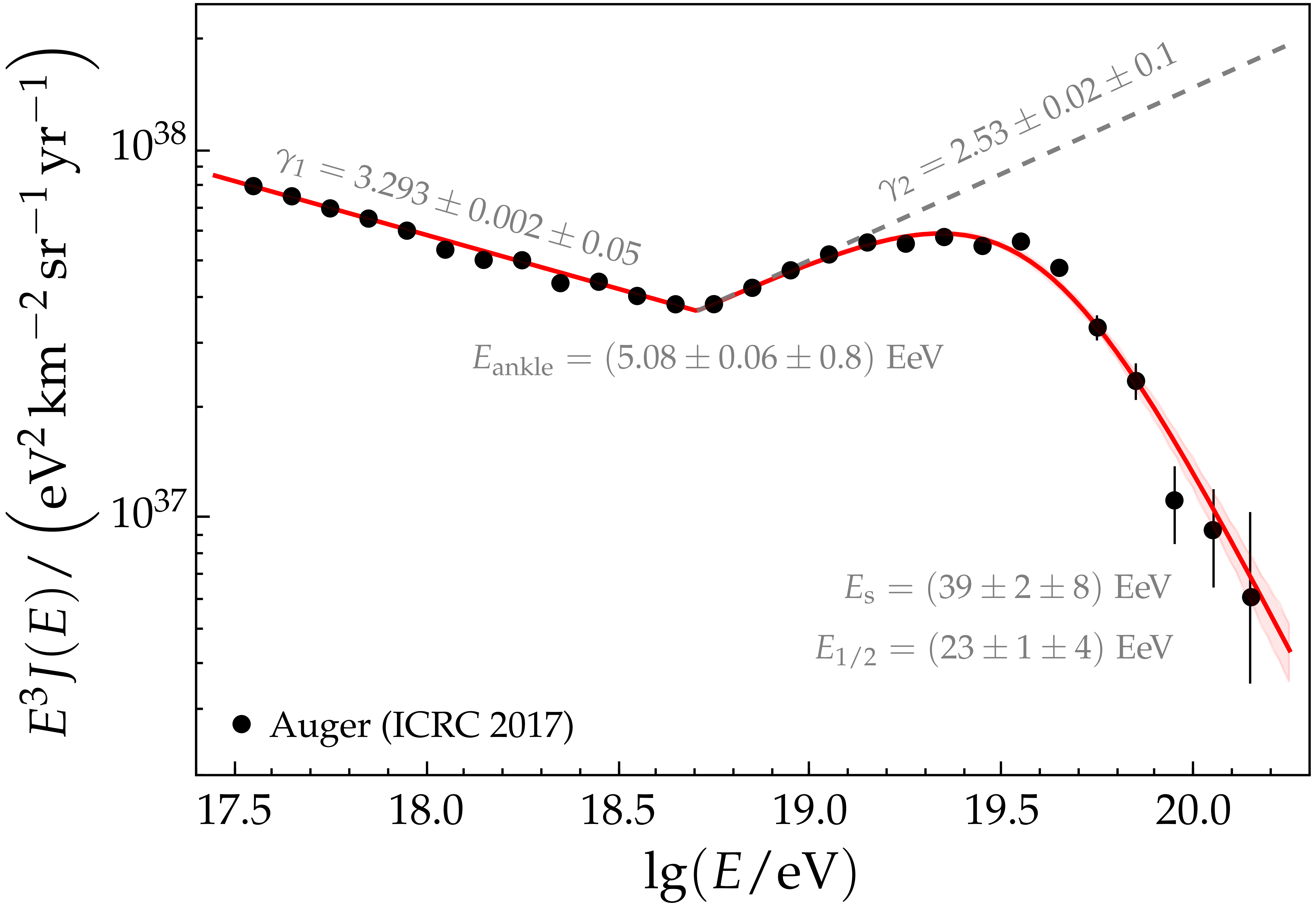
2. UHECR energy density

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



2. UHECR energy density

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



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

$$J(E) = \frac{dN}{dE\,dA\,dt\,d\Omega}$$

The number density of particles is

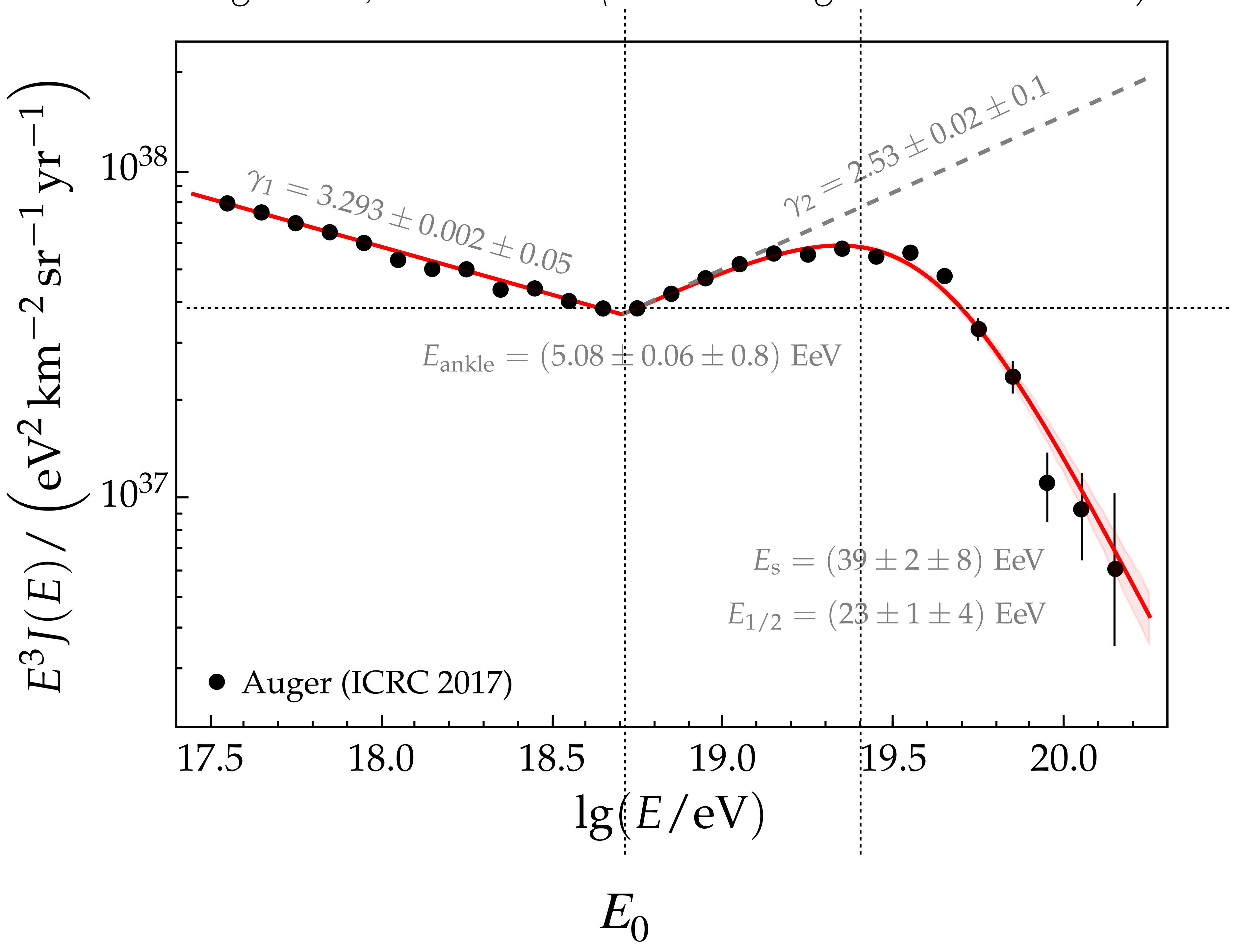
$$n(E) = \frac{dN}{dE\,d^3x} = \frac{dN}{dE\ dl\ dA} = \frac{dN}{dE\ c dt\ dA} = \frac{4\pi}{c} J(E)$$

and the energy density is

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

2. UHECR energy density

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



At 5 EeV we measure,

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

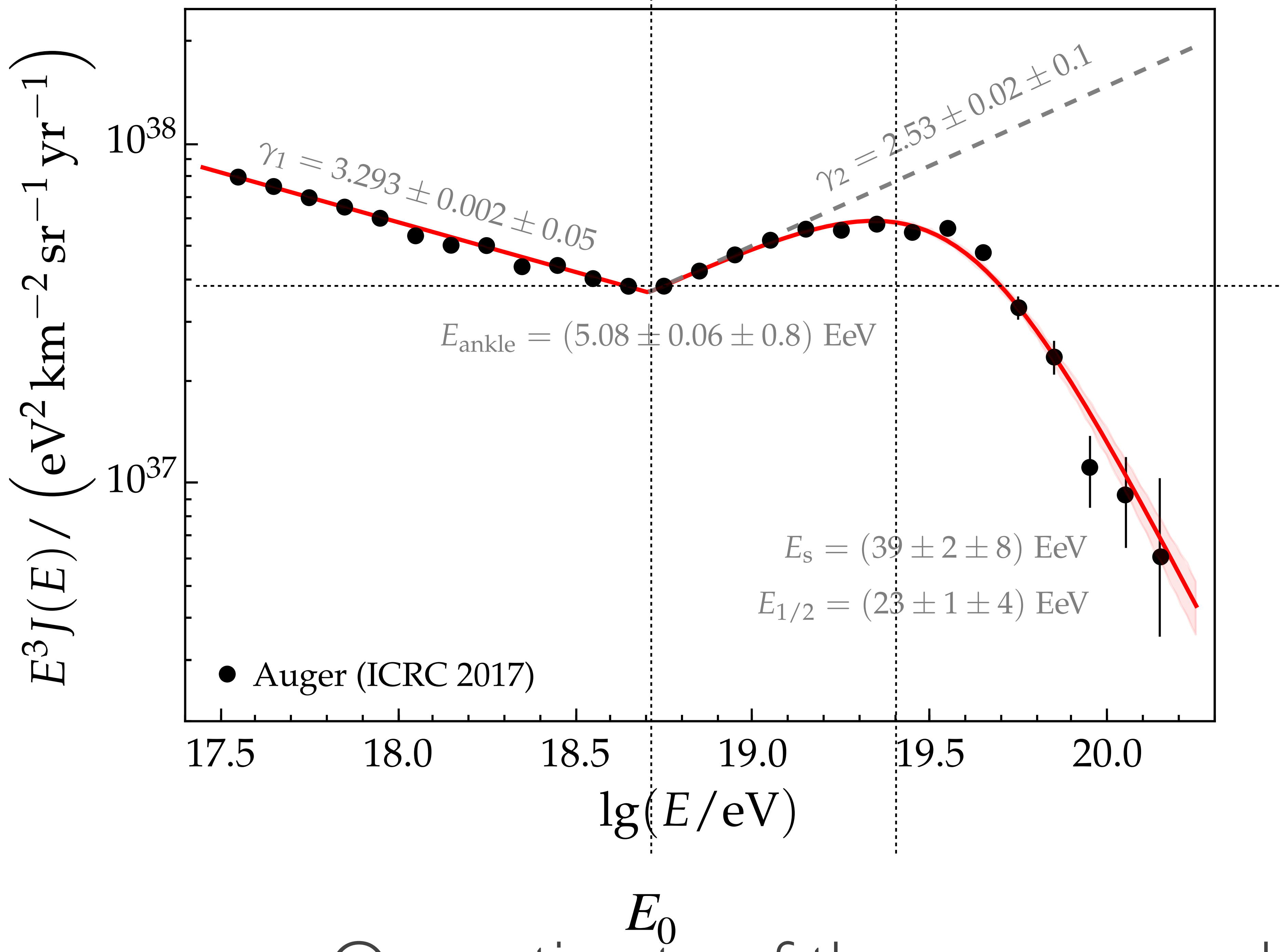
which corresponds to (for an E^{-2} spectrum),

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

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

3. UHECR emissivity

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



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

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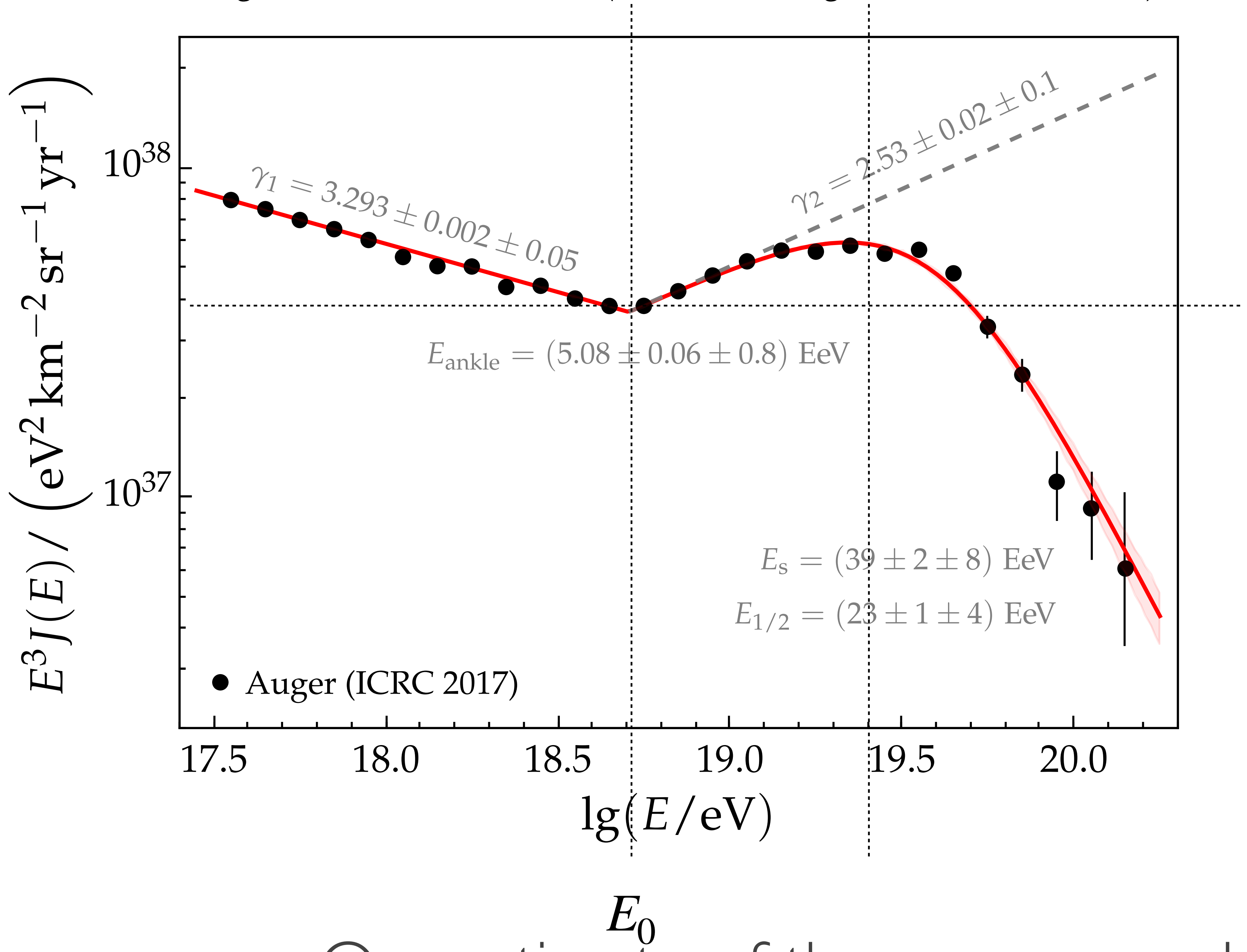

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Full derivation based on simulated ***intrinsic*** source spectra:

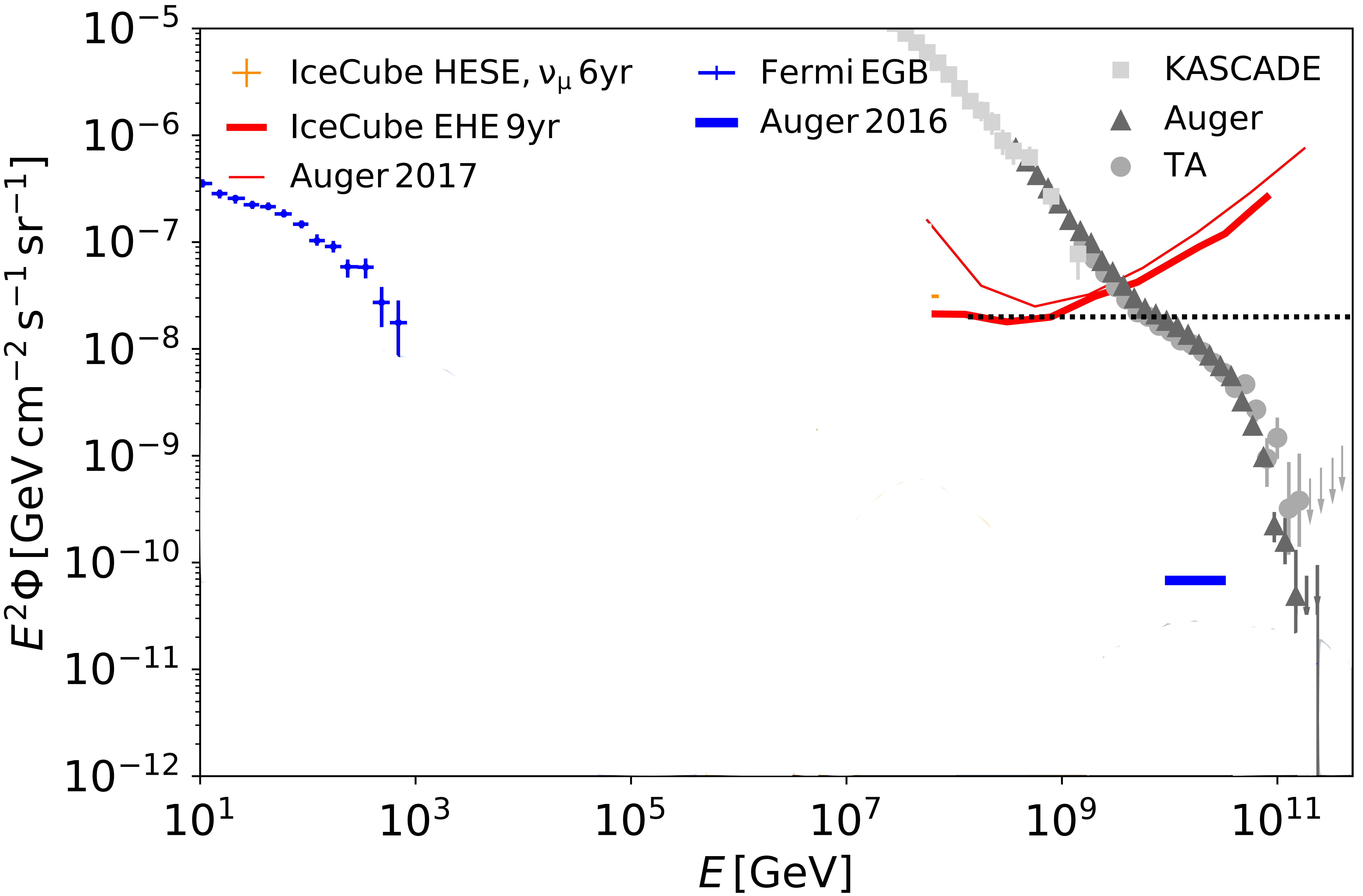
$$\dot{\epsilon}_{\mathrm{Auger\ combined\ fit}} \approx 5 \times 10^{44}\ \mathrm{erg\ Mpc^{-3}\ year^{-1}}$$

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^{-2} 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^{-2} 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^{-2} 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^{-2} 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^{-2} 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^{-2} yr^{-1}
Starburst galaxies	10^{43} erg s^{-1}	10^{-2}	10^{41} erg $s^{-1}gal^{-1}$	~Myr	10^{45} erg Mpc^{-2} 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^{-2} yr^{-1}
Blazars	10^{47-49} erg s^{-1}	10^{-5}	10^{42} erg $s^{-1}gal^{-1}$	~Myr	10^{46} erg Mpc^{-2} yr^{-1}

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

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

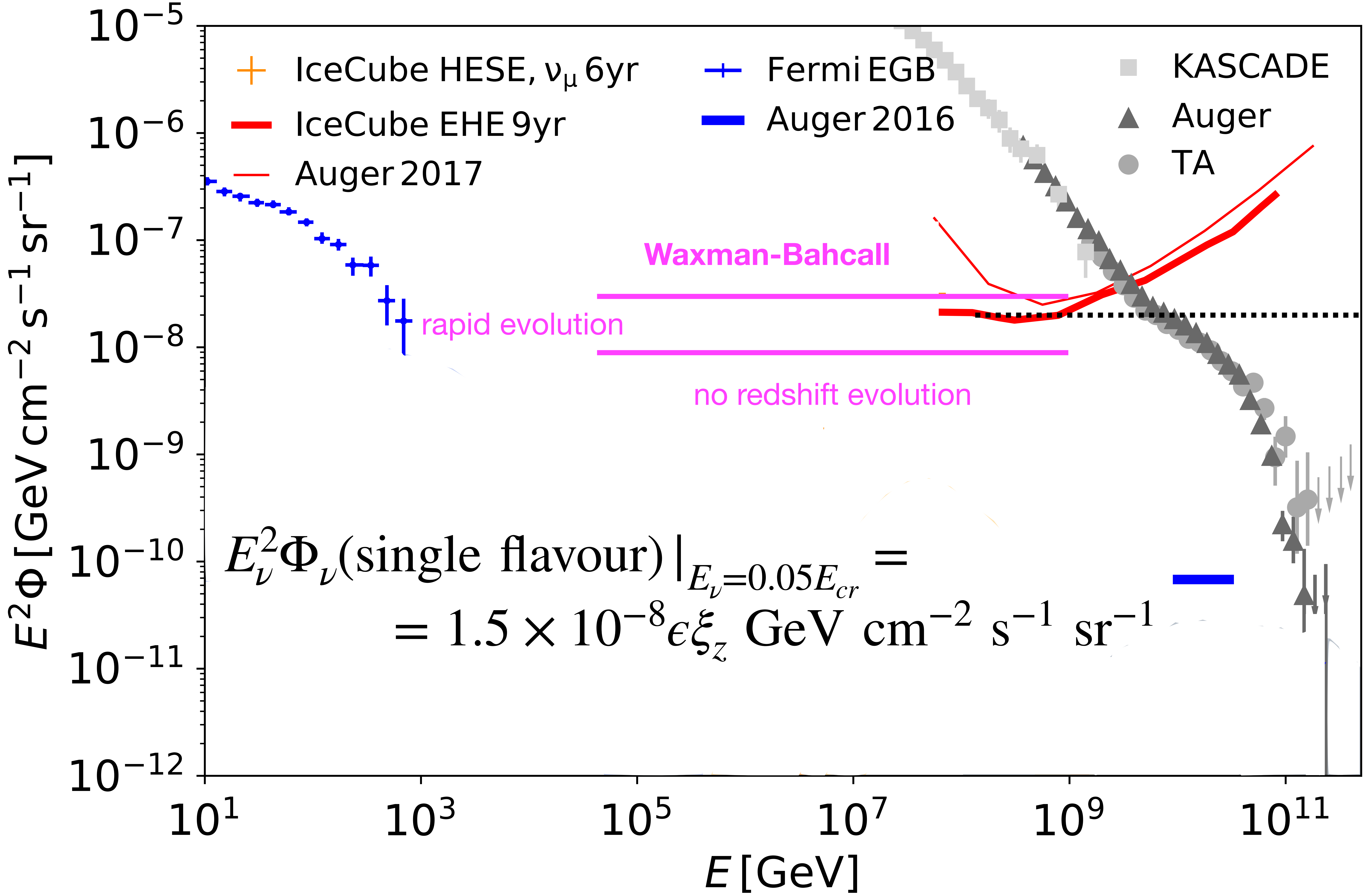
$$p + \gamma_{\rm CMB} \to n + \pi^+ - \text{BR } 50\,\%$$

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

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

50% of E_{π^+}

Waxman-Bahcall bound



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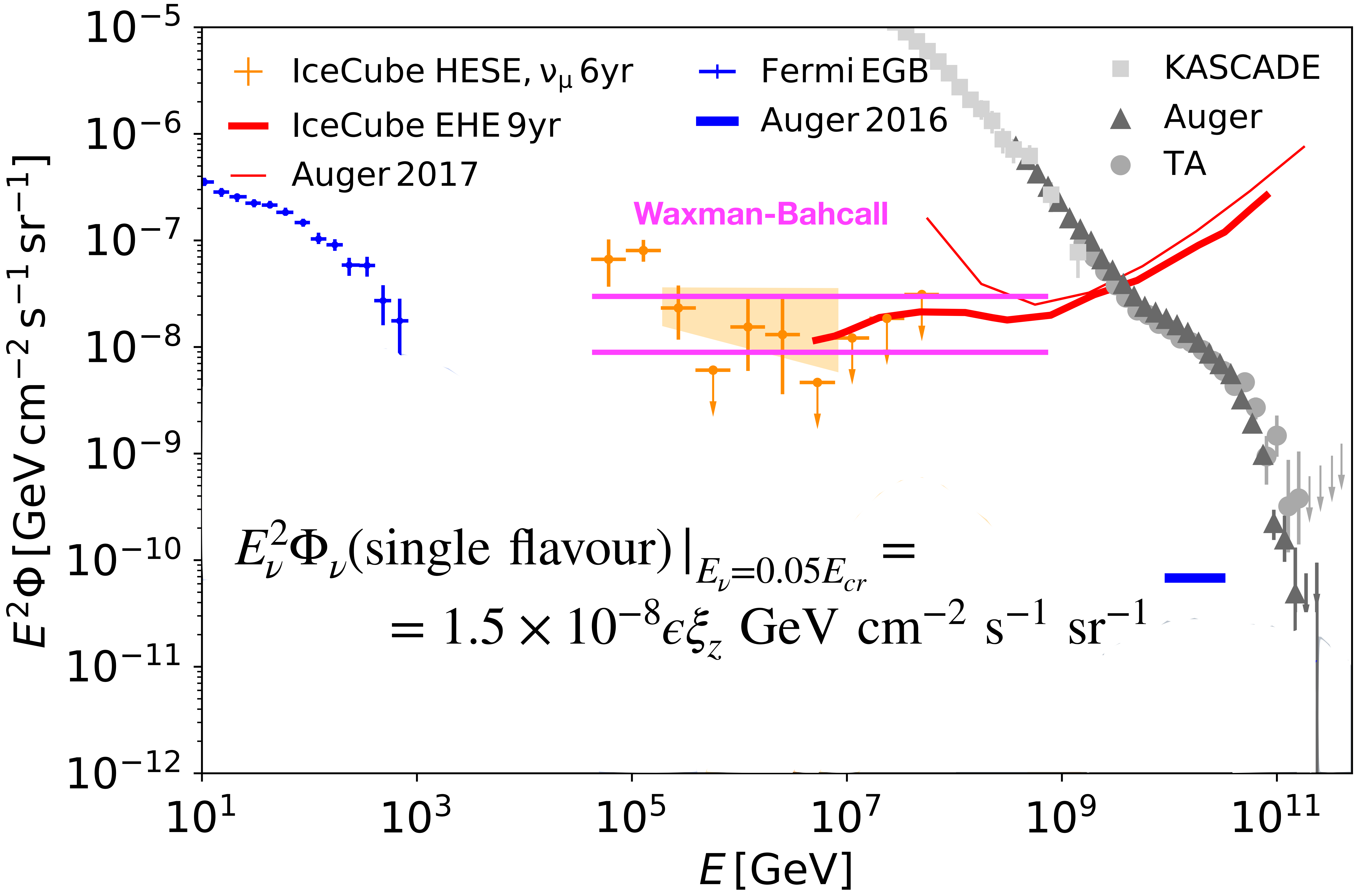

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Neutrino source number density

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

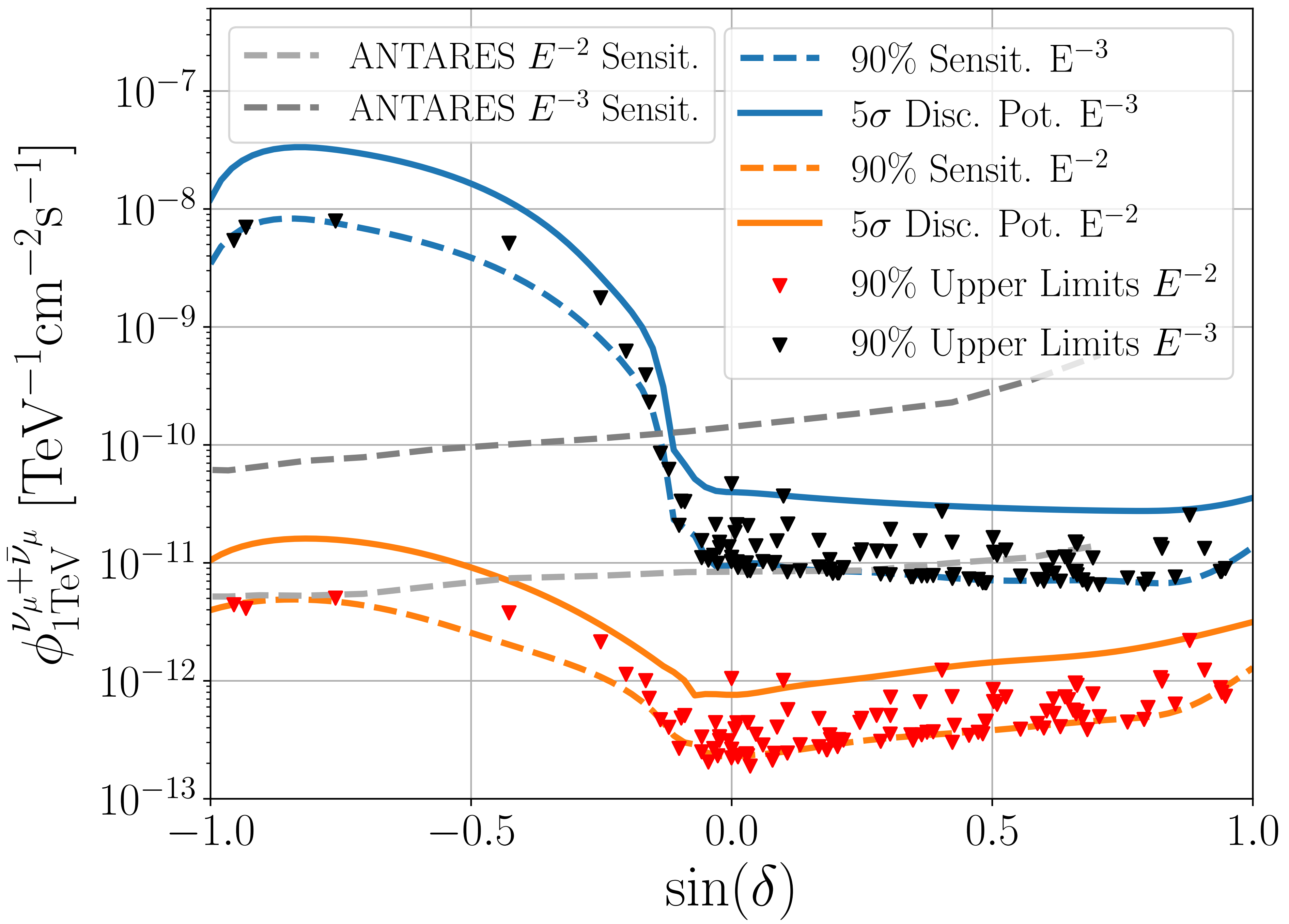
$$\text{luminosity density} \sim L \cdot n$$

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

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

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

Neutrino source number density



- The nearest neutrino source must therefore be at distance

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

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

- 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}
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Neutrino source number density

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

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

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

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

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

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Neutrino source number density

see also Lipari PRD78(2008)083011
Ahlers & Halzen PRD90(2014)043005
Kowalski 2014,
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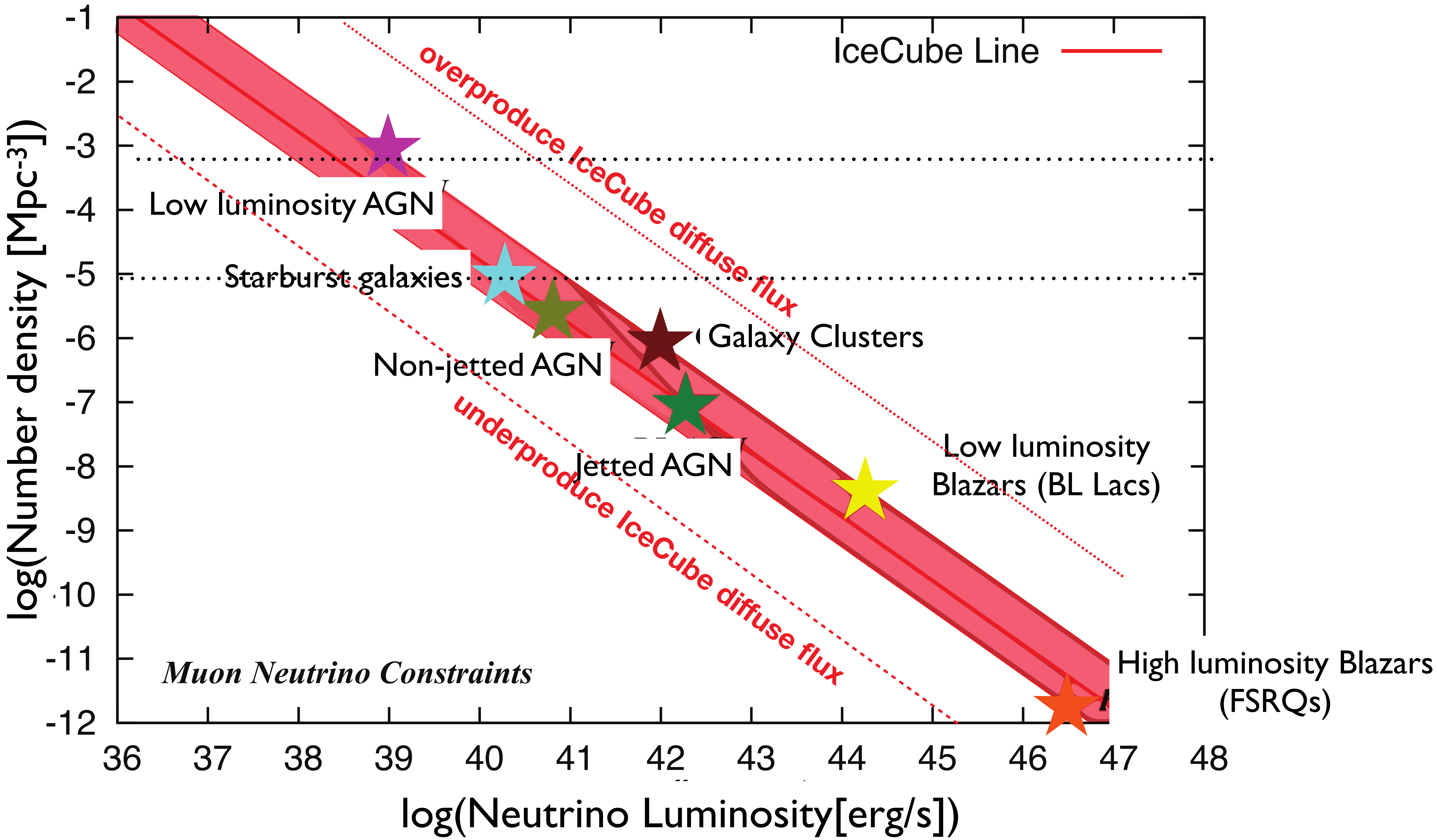
Murase & Waxman 16, PRD 94 (2016) 103006



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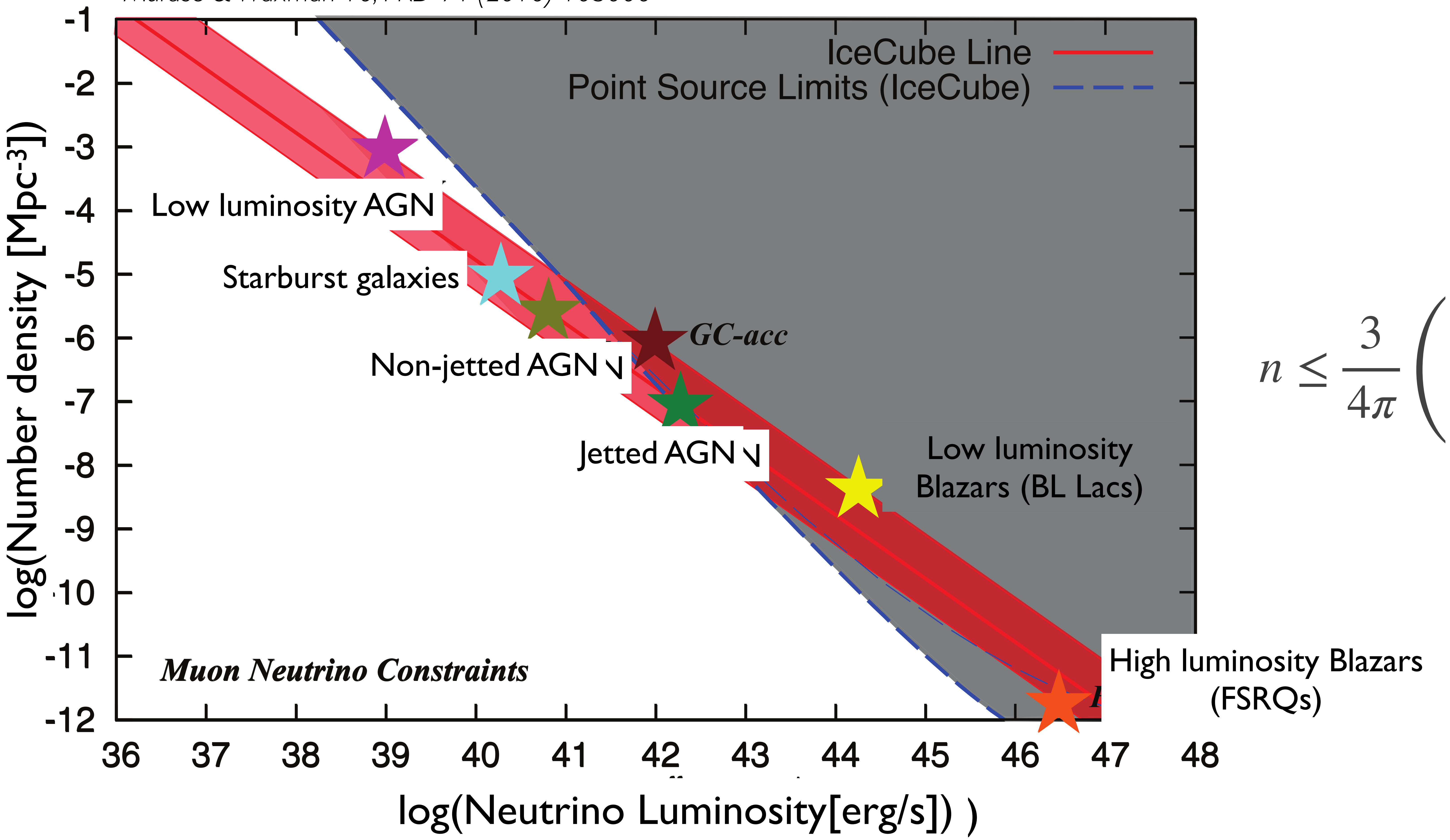

$$n \leq \frac{3}{4\pi}\left(\frac{L}{4\pi F_{lim}}\right)^{-3/2}$$

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

Neutrino source number density

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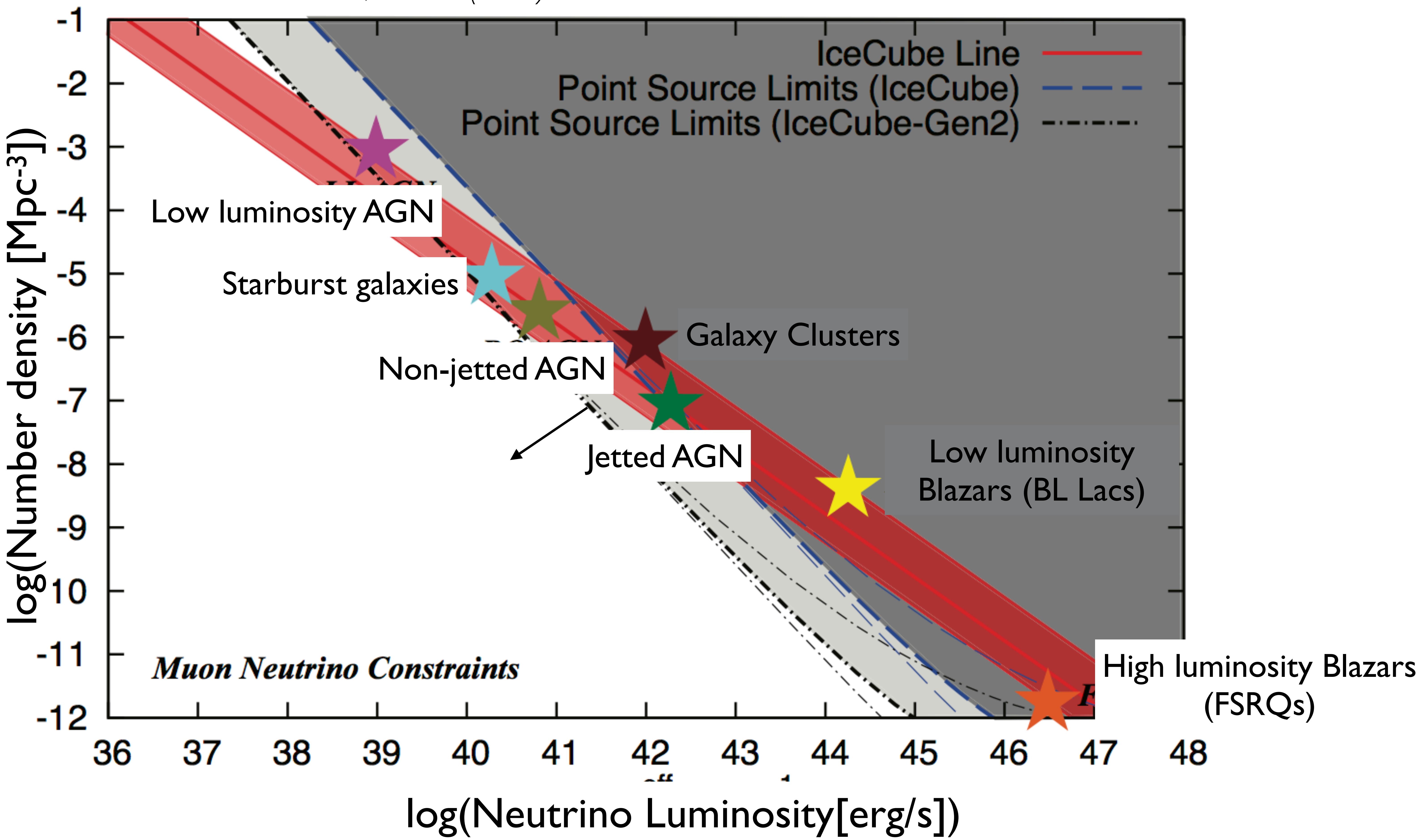

Summary

- UHECR sources must have sufficient energy budget (ok except for GRBs, TDEs)
- Hillas criterion: Very constraining, but several possibilities for UHE nuclei
- IceCube flux at the level predicted by Waxman & Bahcall (common origin of UHECRs and neutrinos or coincidence)
- Neutrino number density constraints disfavour rare and luminous source classes