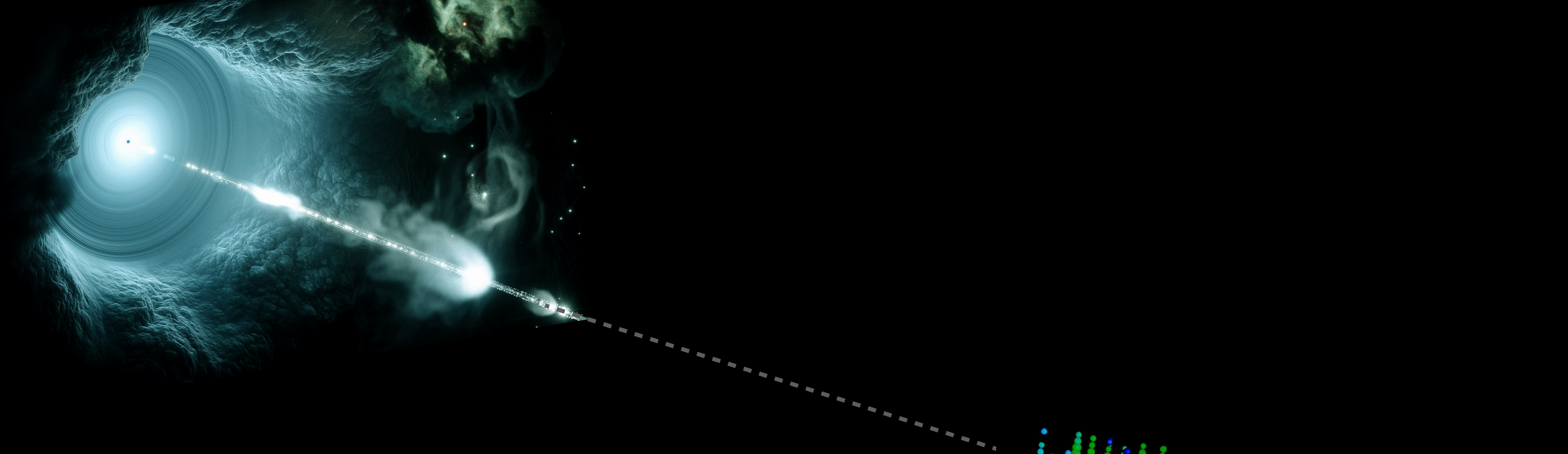
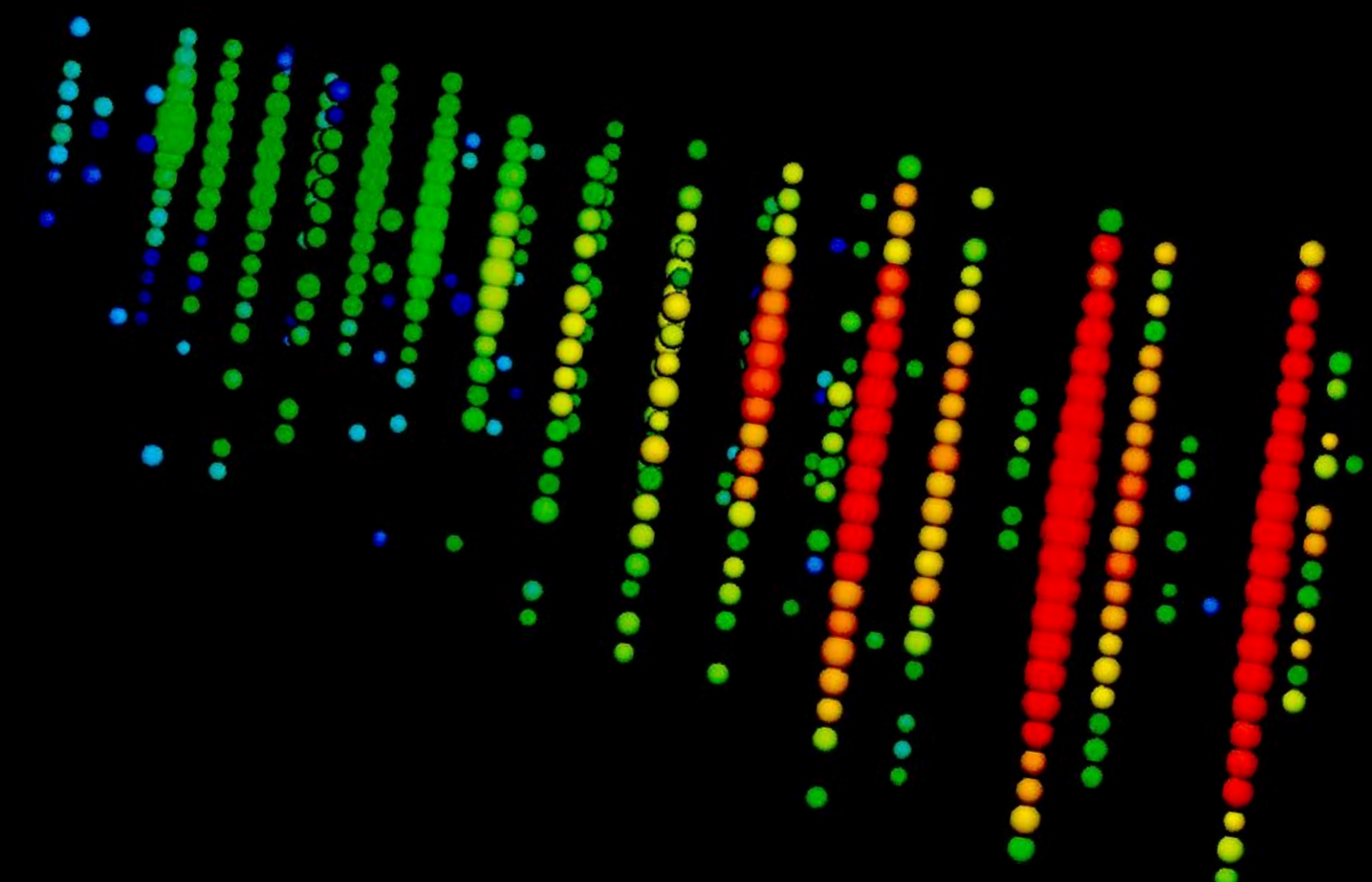


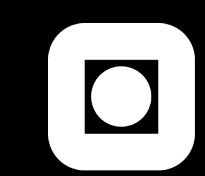


Multimessenger Astroparticle Physics

ISCRA Erice 2026



Foteini Oikonomou

 NTNU

Norwegian University of
Science and Technology

Plan

UHE cosmic rays - cosmic neutrinos - electromagnetic counterparts

Today: generic source properties

Tomorrow: active galactic nuclei

Saturday: starburst galaxies, gamma-ray bursts, tidal-disruption events

Further reading

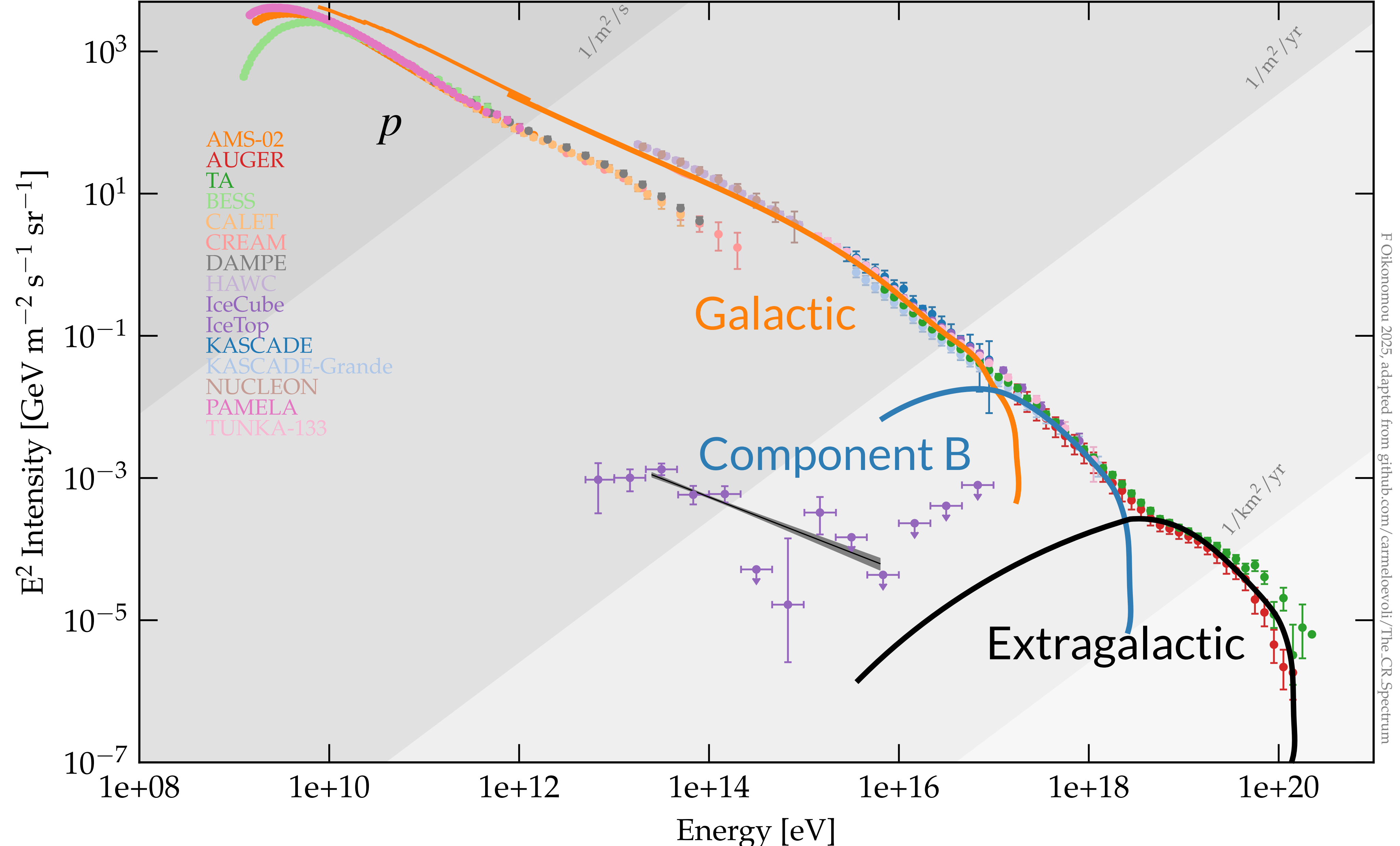
T.K. Gaisser, R. Engel & E. Resconi - Cosmic Rays and Particle Physics,
Cambridge University Press (2016)

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

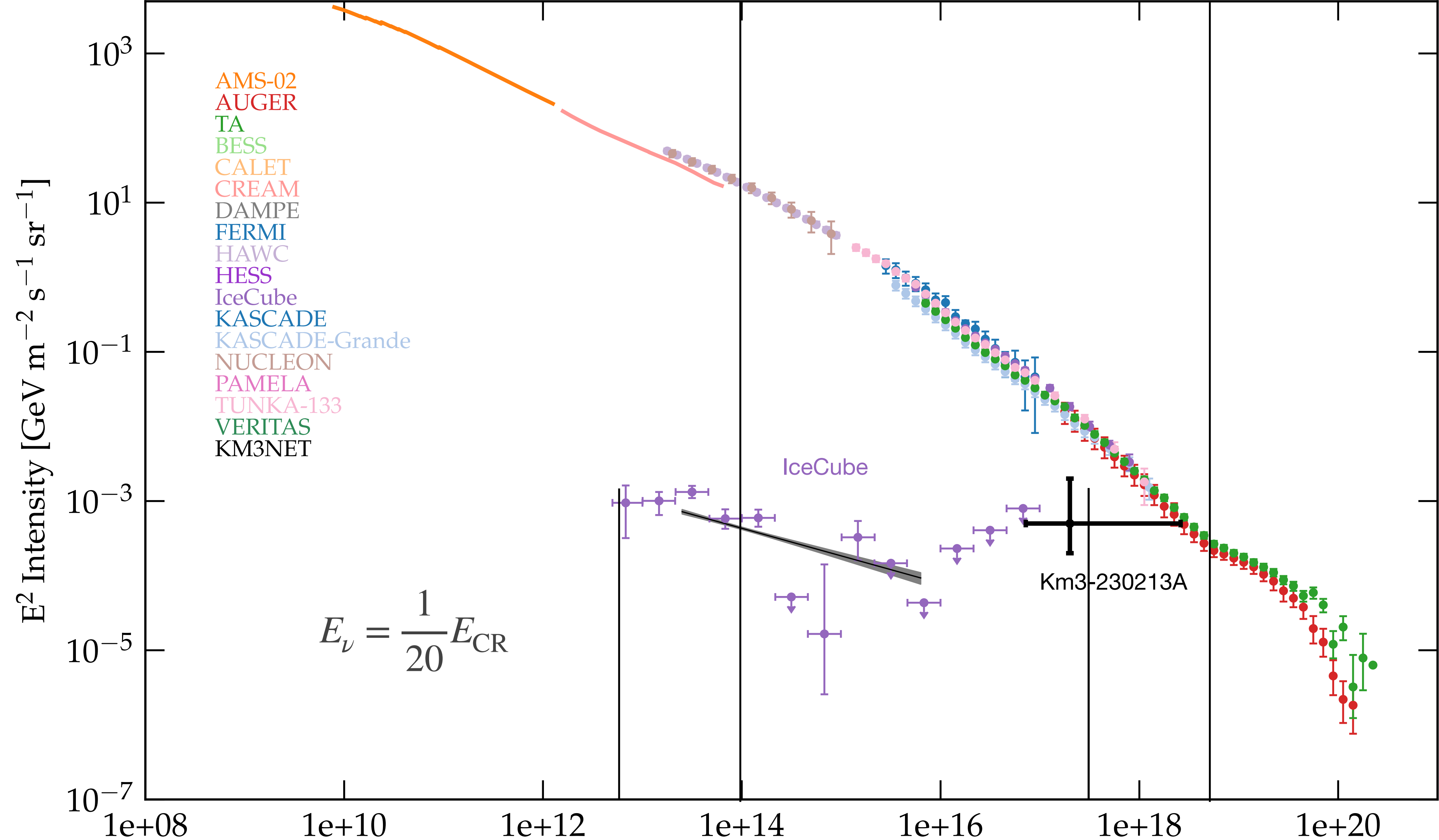
G. Ghisellini - Radiative processes in High Energy Astrophysics,
Springer (2012)
<https://arxiv.org/abs/1202.5949>

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

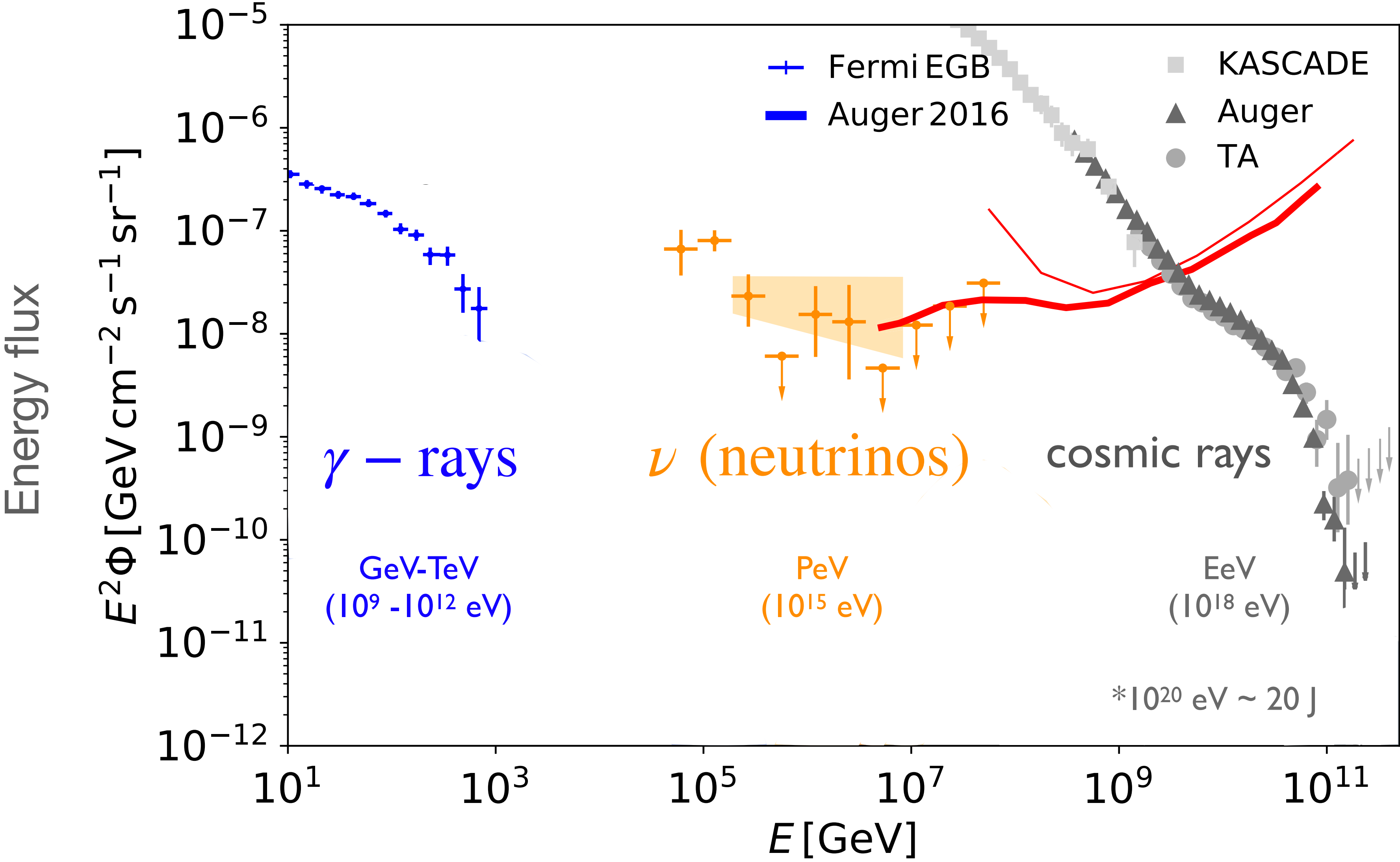
Ultra-high-energy cosmic rays



Neutrinos



Multimessenger diffuse fluxes

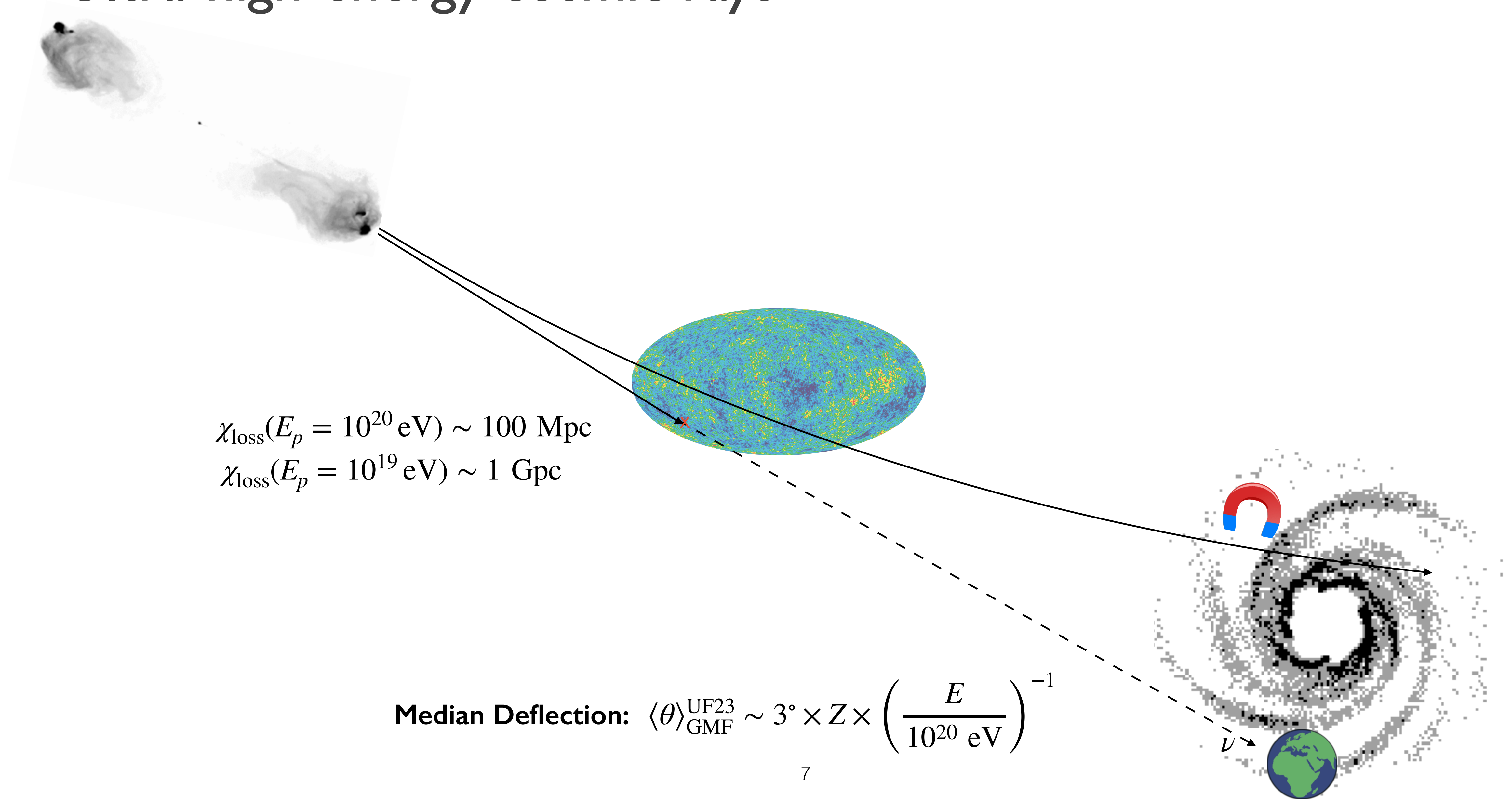


Ultra-high-energy cosmic rays

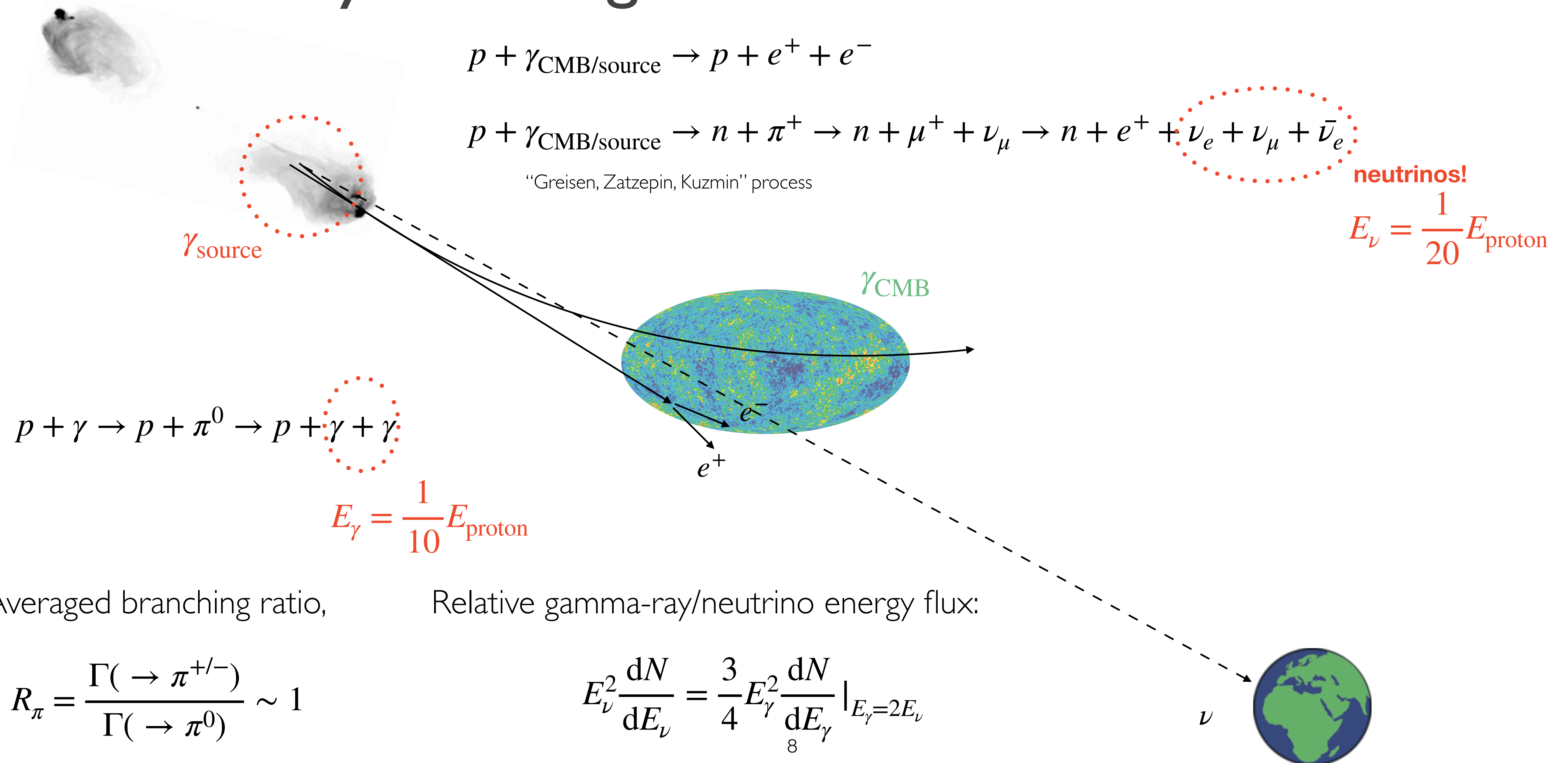
$$\chi_{\text{loss}}(E_p = 10^{20} \text{ eV}) \sim 100 \text{ Mpc}$$

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

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



Secondary messengers



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

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

“Greisen, Zatsepin, Kuzmin” process

neutrinos!

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

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

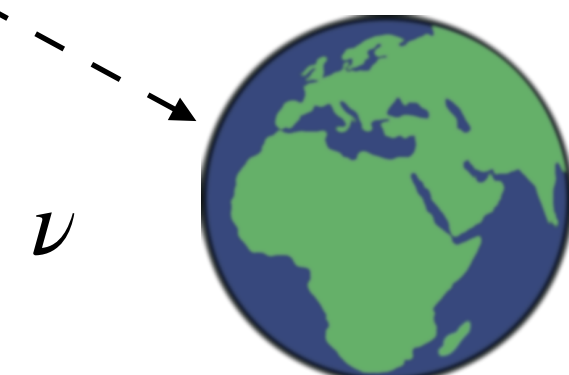
$$E_\gamma = \frac{1}{10} E_{\text{proton}}$$

Averaged branching ratio,

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

Relative gamma-ray/neutrino energy flux:

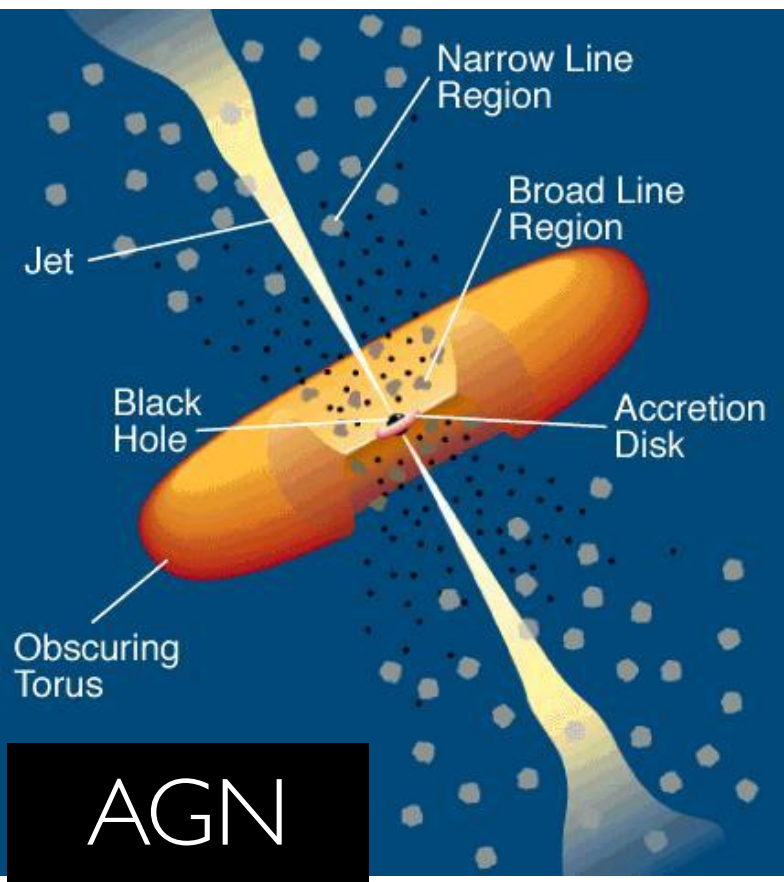
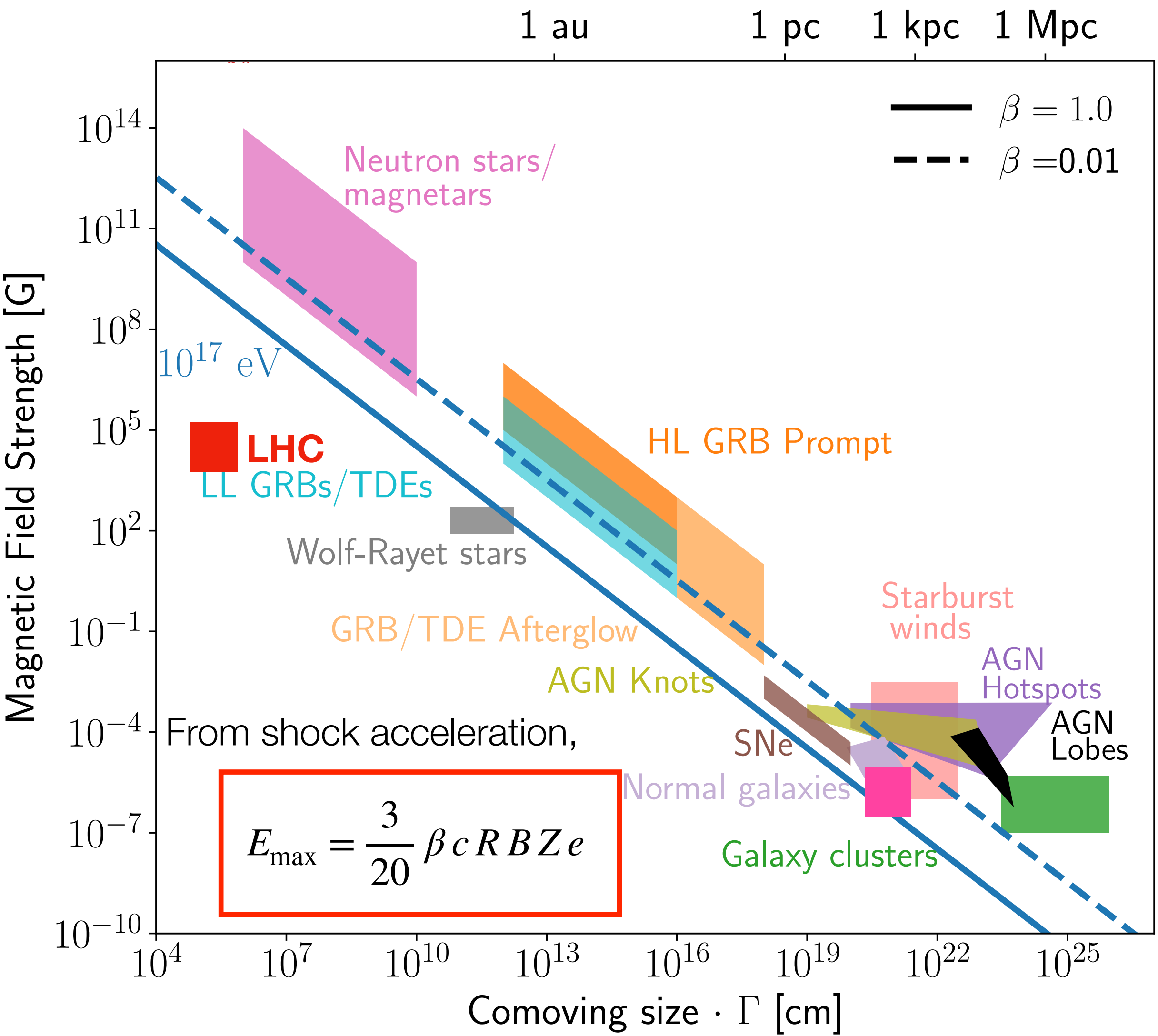
$$E_\nu^2 \frac{dN}{dE_\nu} = \frac{3}{4} E_\gamma^2 \frac{dN}{dE_\gamma} \Big|_{E_\gamma=2E_\nu}$$



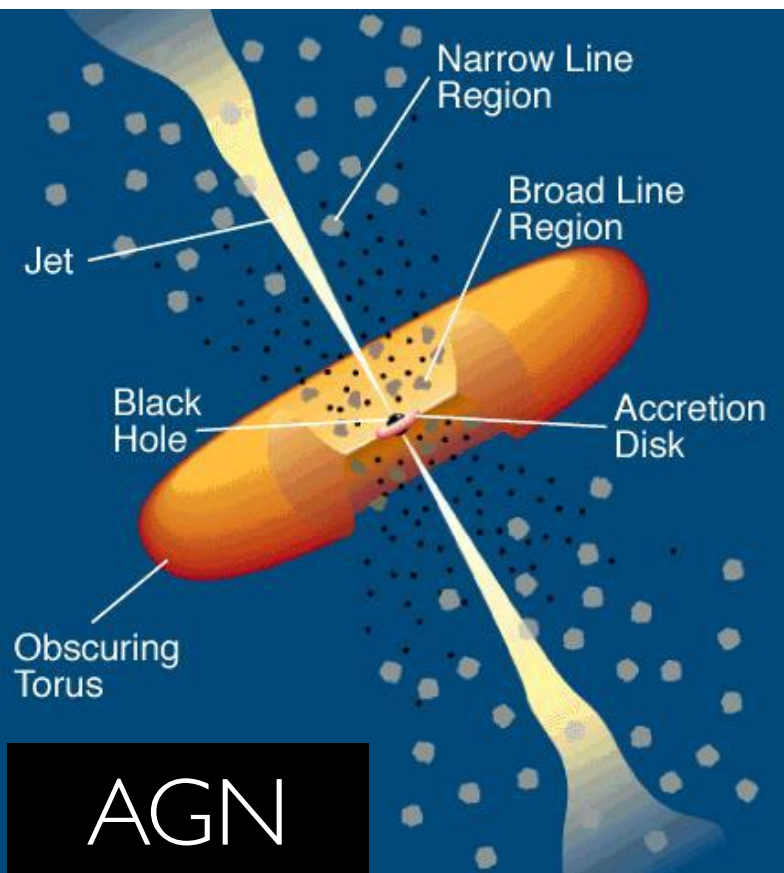
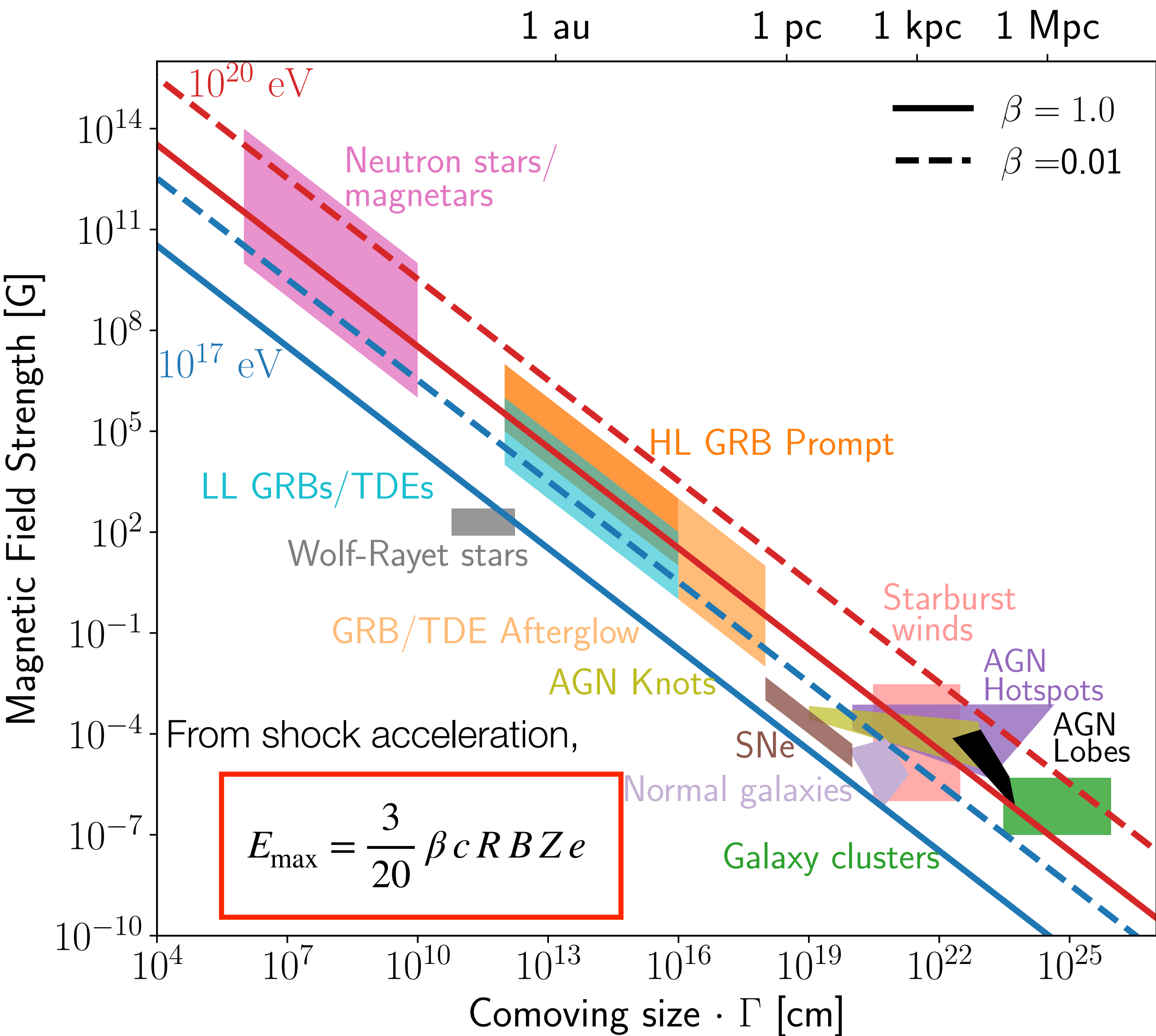
Generic source properties

- 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 req (10¹⁷ eV)



Cosmic-ray accelerators that satisfy the confinement



Generic source properties

- Hillas criterion for acceleration and plausible sources
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I. UHECR energy loss length

Mean free path = $1 / (\text{number density of targets} \times \text{cross-section})$

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

Energy loss per unit length

$$\frac{dE}{dx} \sim \frac{\Delta E}{\lambda} \sim - \frac{\kappa(E)E}{\lambda(E)}$$

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

$$\chi_{\text{loss}}(E) \equiv \frac{E}{|dE/dx|} \sim \frac{\lambda(E)}{\kappa(E)}$$

Photo-pair production (Bethe-Heitler process):

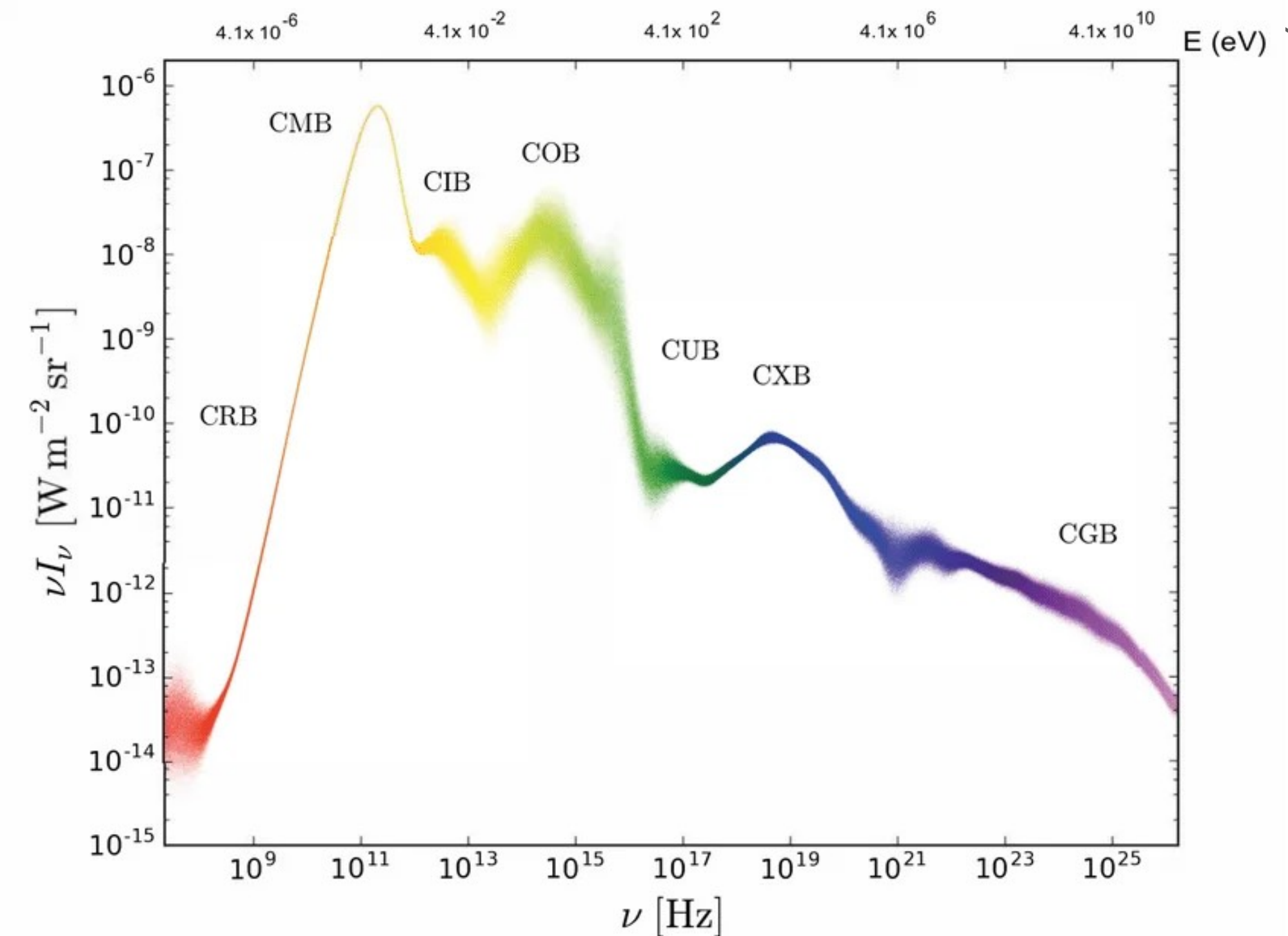
$$p + \gamma_{\text{bg}} \rightarrow p + e^+ + e^- \quad [\kappa_{p\gamma}^{ee} = 2m_e/m_p \approx 10^{-5}, \sigma_{p\gamma, \text{thresh}}^{ee} \approx 1.2 \cdot 10^{-27} \text{ cm}^2, n_{\text{CMB}} \approx 411 \text{ cm}^{-3}]$$

$$E_p \gtrsim \frac{m_p m_e c^4}{\epsilon_\gamma} \sim 8 \times 10^{17} \text{ eV} \left(\frac{\epsilon_\gamma}{6 \times 10^{-4} \text{ eV}} \right)^{-1}$$

23

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

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



I. UHECR energy loss length

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

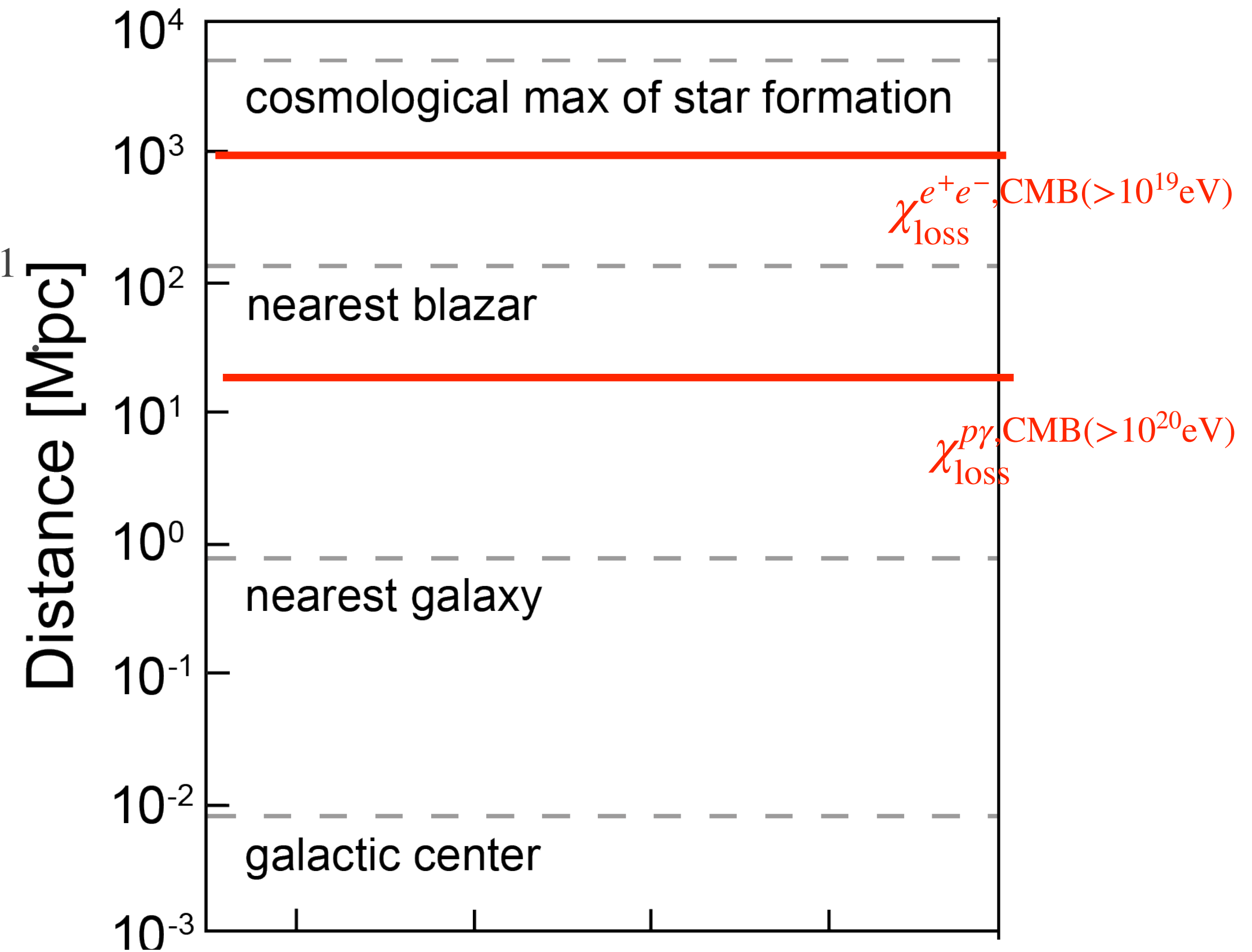
Photo-pion production:

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

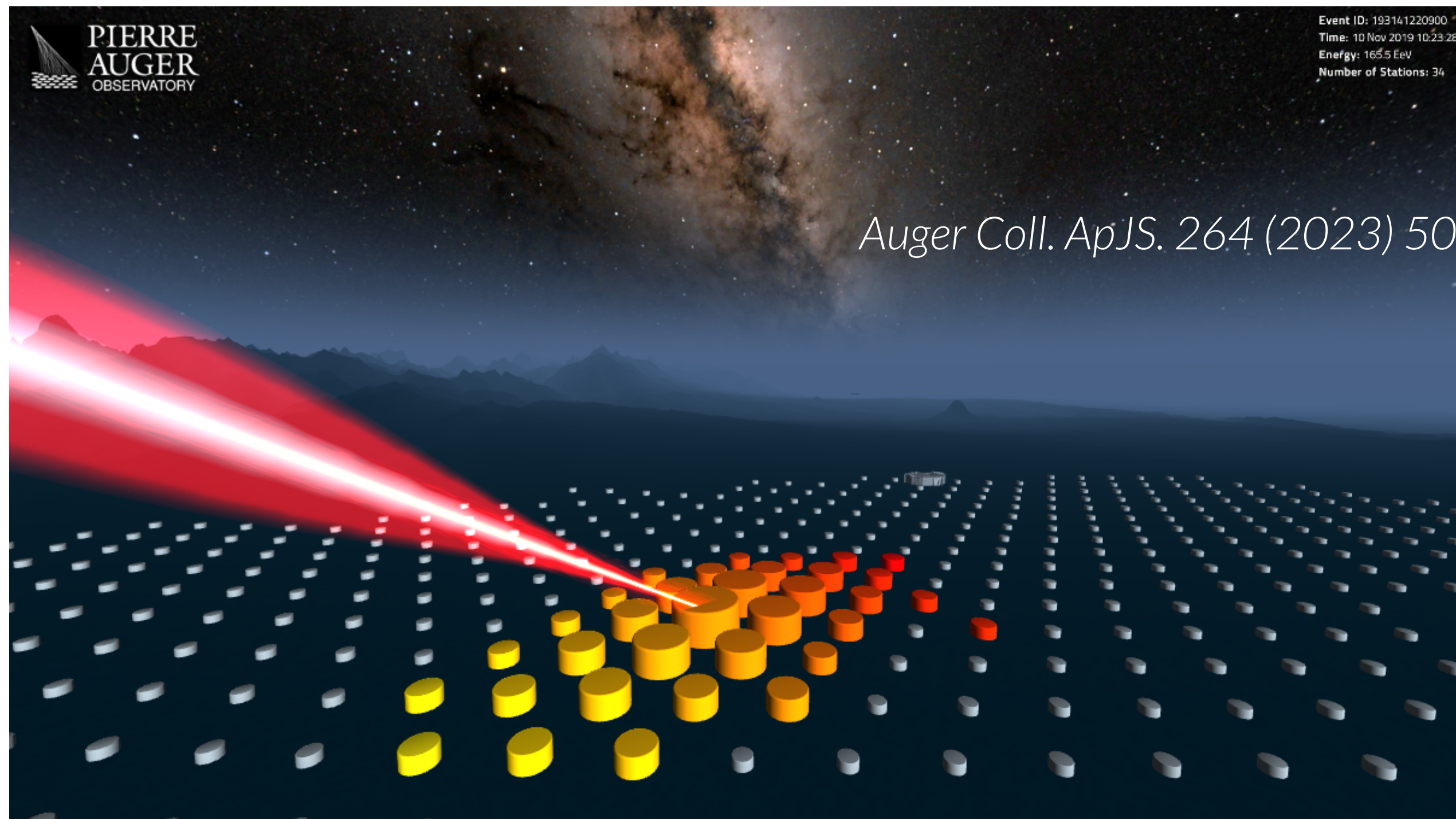
$$E_p \gtrsim \frac{m_\pi(2m_p + m_\pi)c^4}{4\varepsilon_\gamma} \simeq 1.1 \times 10^{20} \text{ eV} \left(\frac{\varepsilon_\gamma}{6 \times 10^{-4} \text{ eV}} \right)^{-1}$$

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

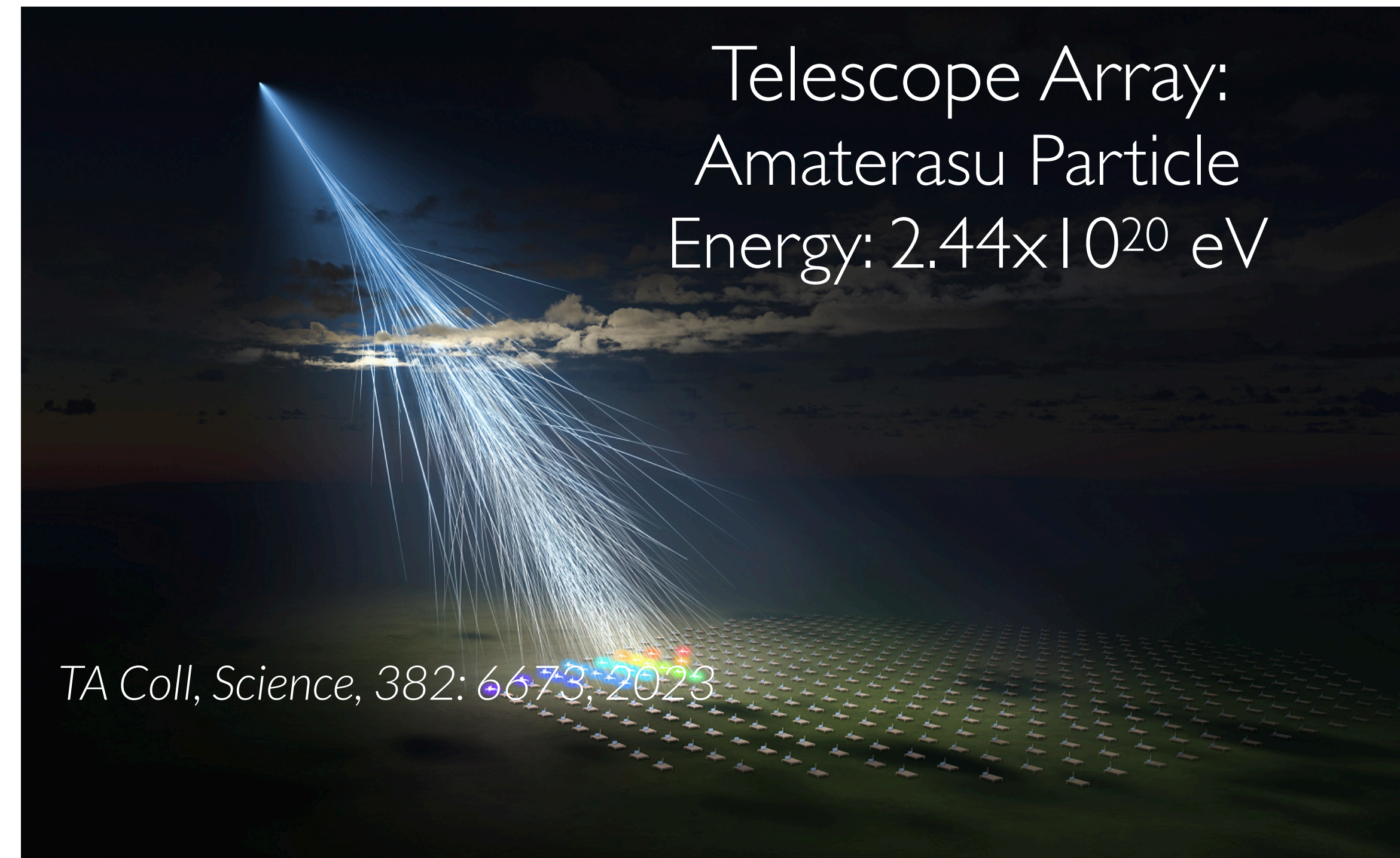
$$\lambda_{p\gamma, \text{CMB}} \sim 1/n\sigma \sim 10 \text{ Mpc}, \chi_{\text{loss}} \sim \lambda/\kappa \sim 50 \text{ Mpc}$$



Estimate of 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

The absence of clustering (multiplets) of UHECR arrival directions gives a lower limit to the source number density:

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

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

The Poisson probability to see 0 events from a source is

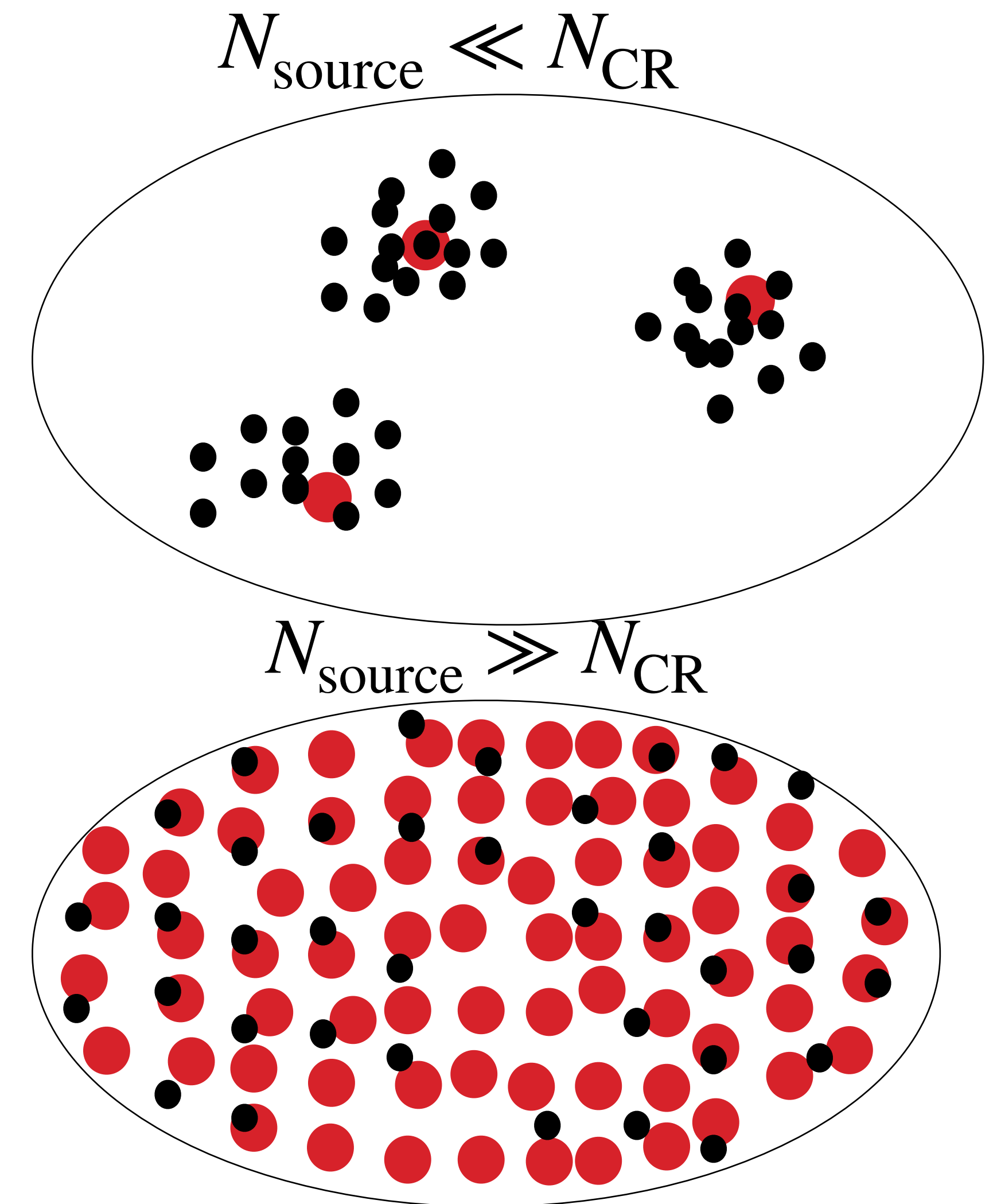
$$P(0) = e^{-n_*} \frac{n_*^0}{0!} = e^{-n_*}$$

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 multiplet in the whole dataset is

$$\begin{aligned} P(\text{no multiplet}) &= (1 - P(\geq 2))^{N_{\text{sources}}} \\ &= (P(0) + P(1))^{N_{\text{sources}}} \\ &= (e^{-n_*}(1 + n_*))^{N_{\text{sources}}} \end{aligned}$$



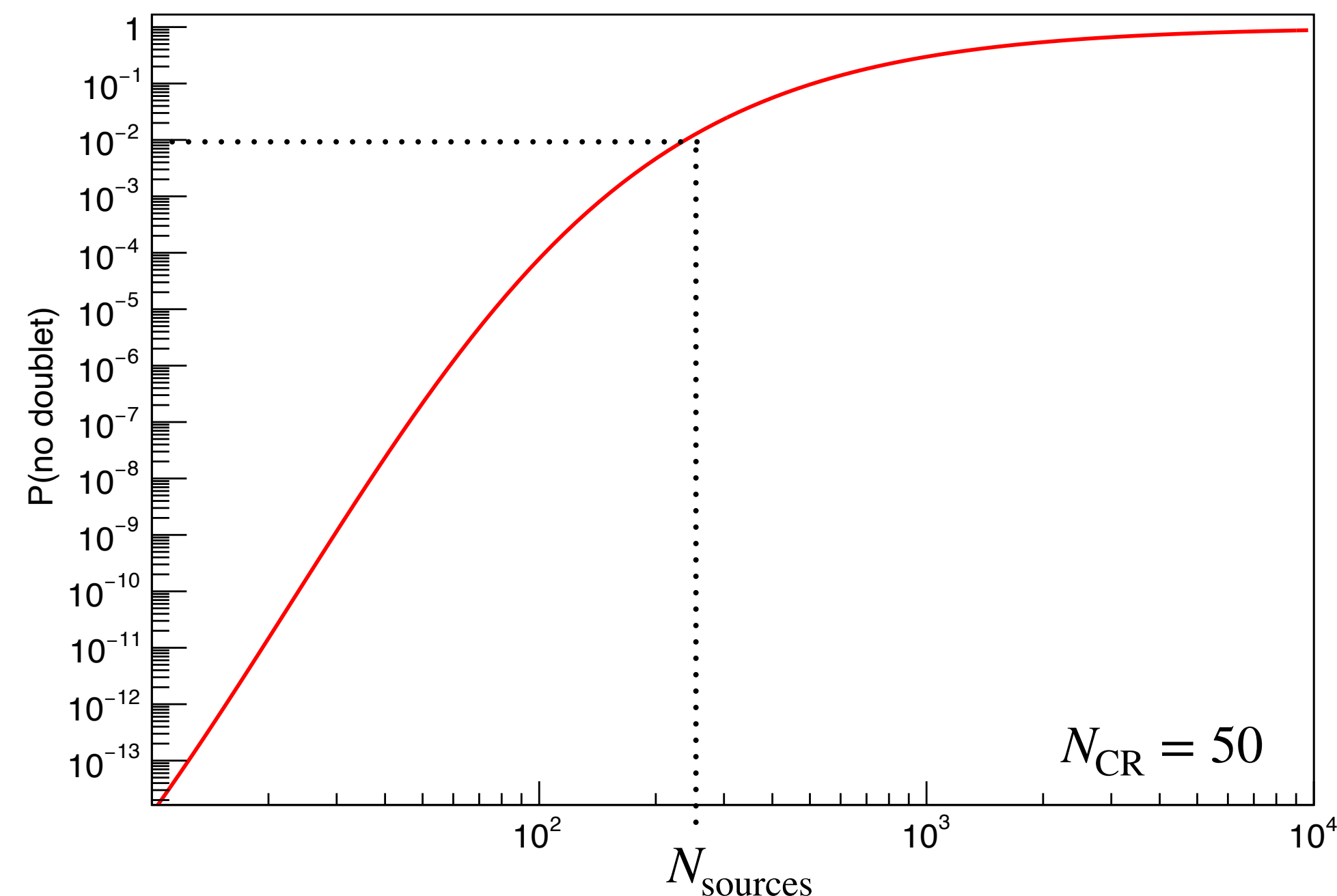
Lower limit on the number density of UHECR sources

The probability to see no multiplet is

$$\begin{aligned}
 P(\text{no multiplet}) &= (1 - P(\geq 2))^{N_{\text{sources}}} \\
 &= (e^{-n_*}(1 + n_*))^{N_{\text{sources}}} \\
 &= e^{-N_{\text{CR}}} \left(1 + \frac{N_{\text{CR}}}{N_{\text{sources}}} \right)^{N_{\text{sources}}}
 \end{aligned}$$

$P(\text{no multiplet}) \sim 1\%$ if > 200 sources

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



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

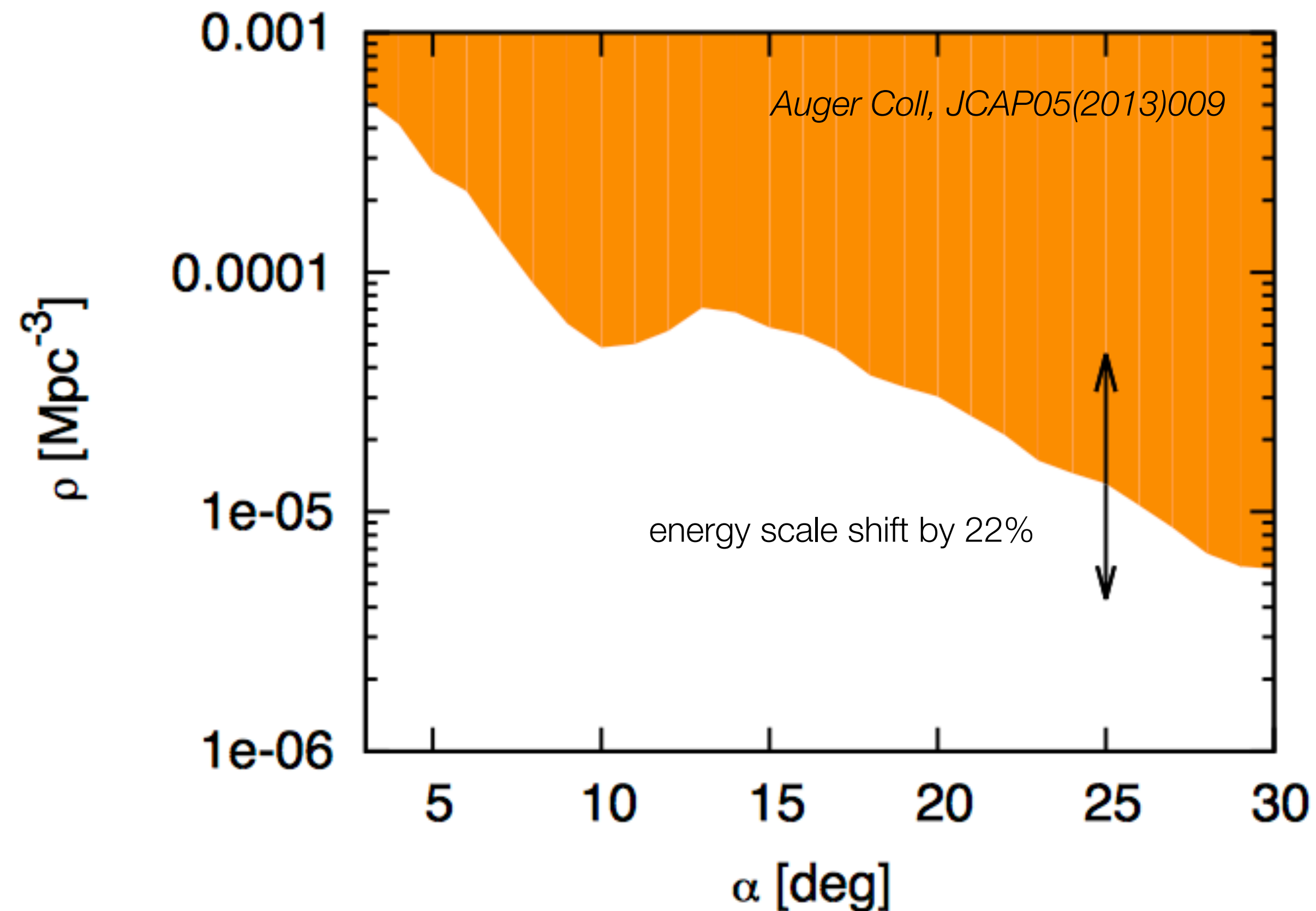
Starbursts/Radio Galaxies - 10^{-4} Mpc^{-3}

.....
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 arrival directions (43 events, $E > 7 \times 10^{19}$ eV)



Conclusion #1: UHECR sources are numerous

more recent result

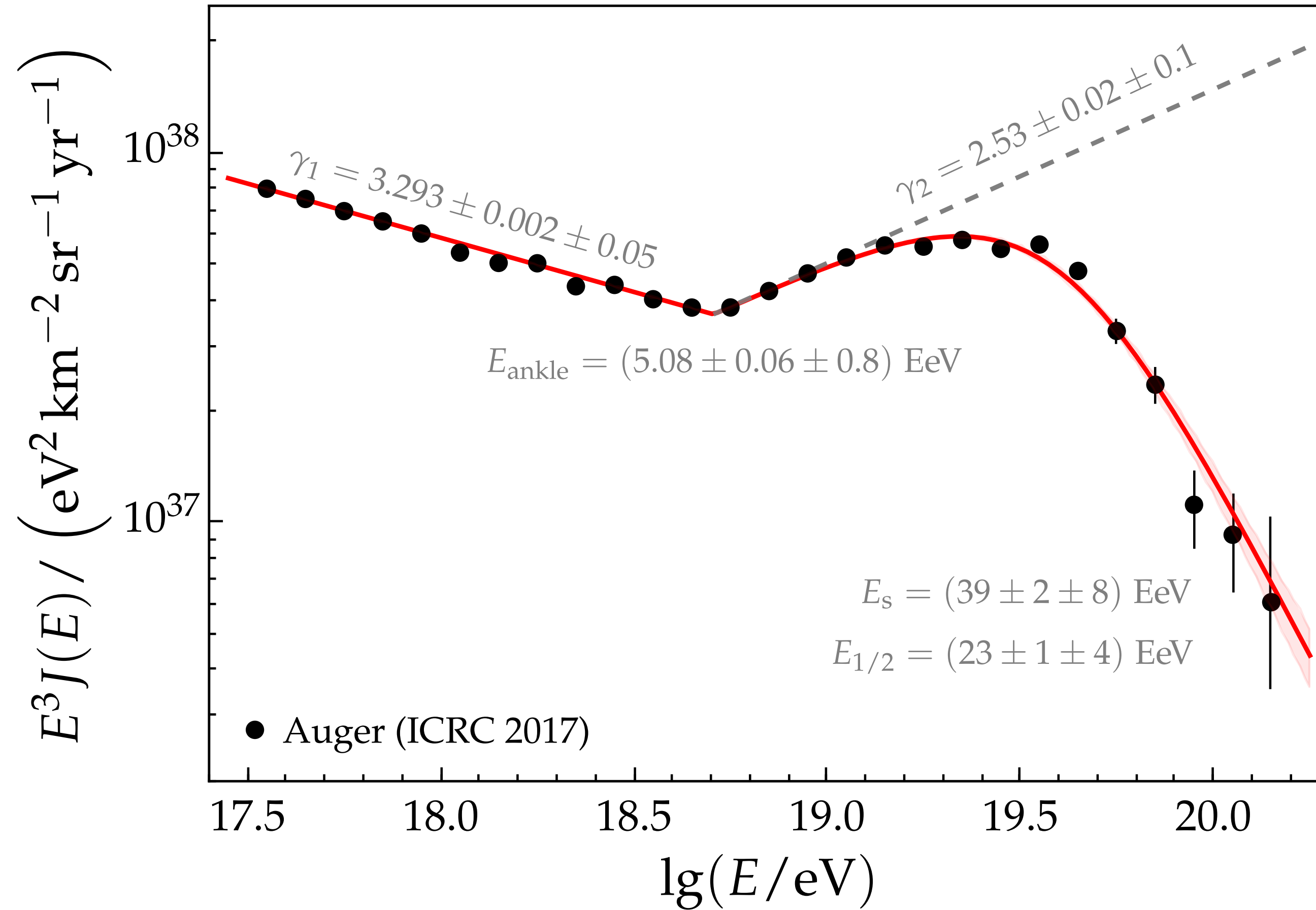
28

Generic source properties

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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

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

The number density of particles is

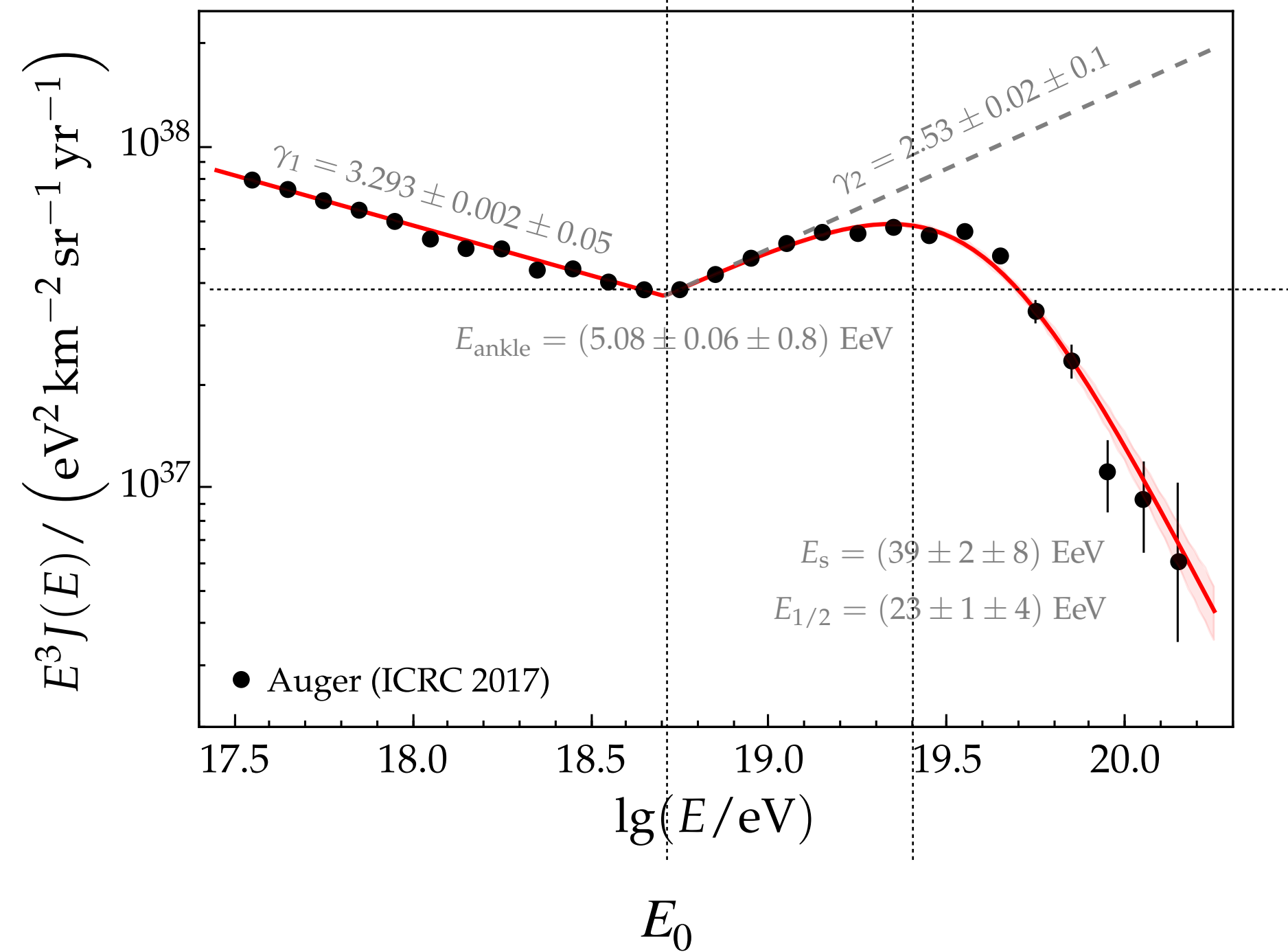
$$n(E) = \frac{dN}{dE d^3x} = \frac{dN}{dE dl dA} = \frac{dN}{dE c dt dA} = \frac{4\pi}{c} J(E)$$

and the energy density is

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

UHECR energy density

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



At 5 EeV we measure,

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

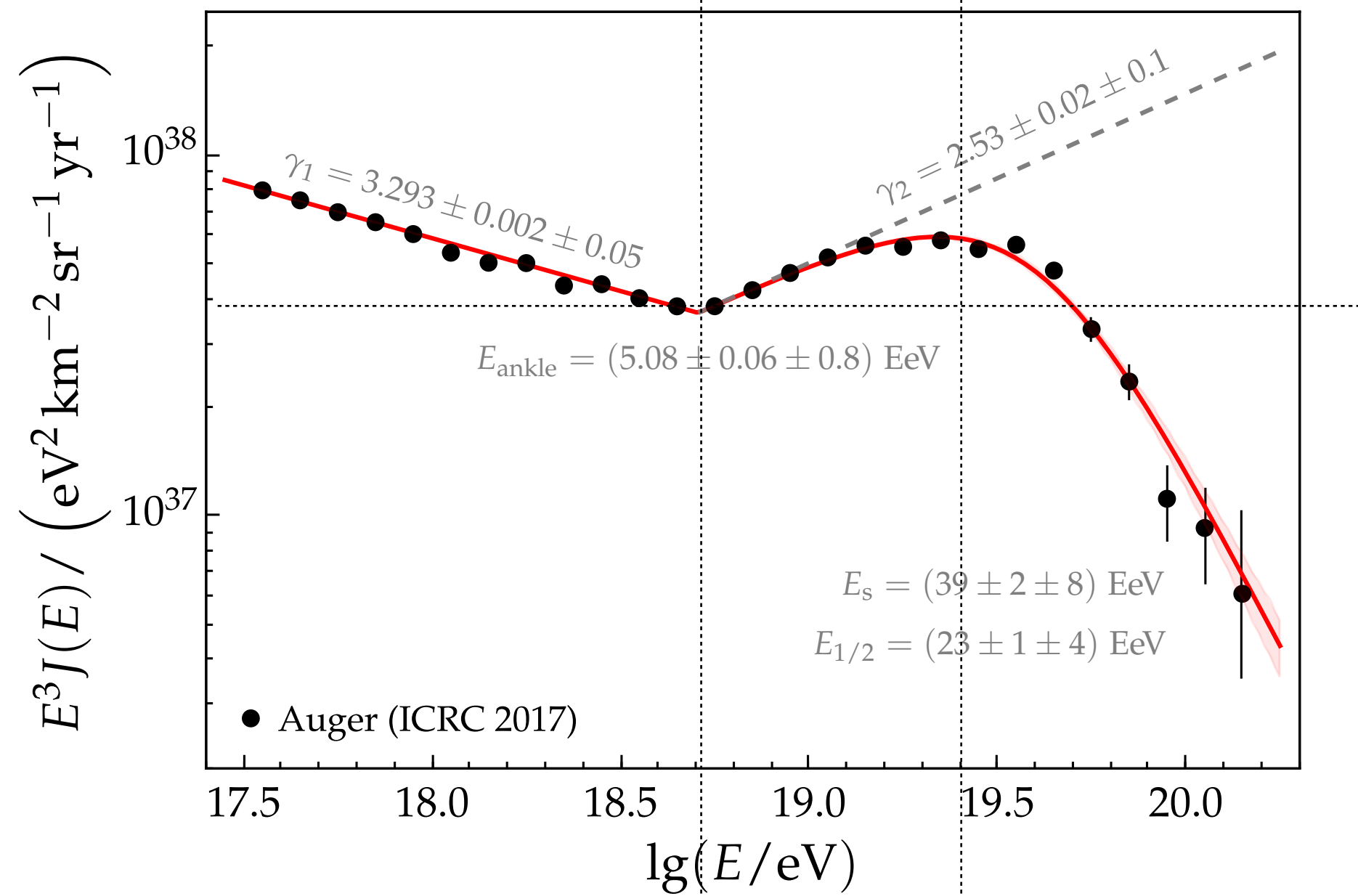
which corresponds to (for an E^{-2} spectrum),

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

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

UHECR emissivity

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



At 5 EeV we measure,

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

1 erg ~ 1 TeV!

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

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

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

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

3. UHECR emissivity: Comparison to source classes

$\dot{\epsilon}_{\text{UHECR}} \approx 2 \times 10^{44} \text{ erg Mpc}^{-3} \text{ year}^{-1}$

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

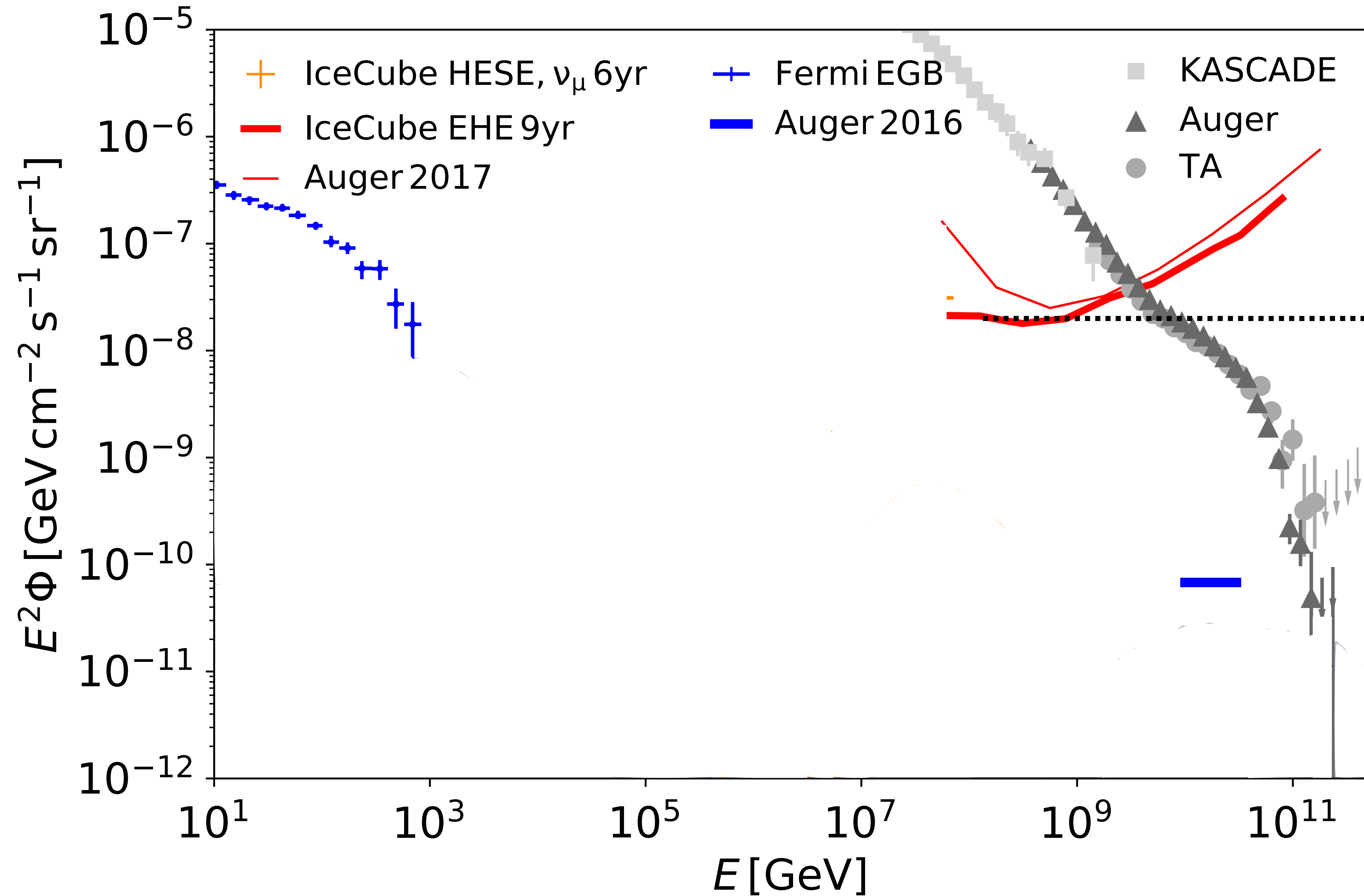
Conclusion #2: Emissivity for most sources OK.

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

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

$$E_{\text{CR}}^2 dN_{\text{CR}}/dE_{\text{CR}} \sim E_{\text{CR}}^{-2} \text{ (at the source)}$$

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

- Proton loses fraction, ϵ , of its energy

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

we called it J before...

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

$$p + \gamma \rightarrow p + \pi^0 - \text{BR } 50 \%$$

$$p + \gamma \rightarrow n + \pi^+ - \text{BR } 50 \%$$

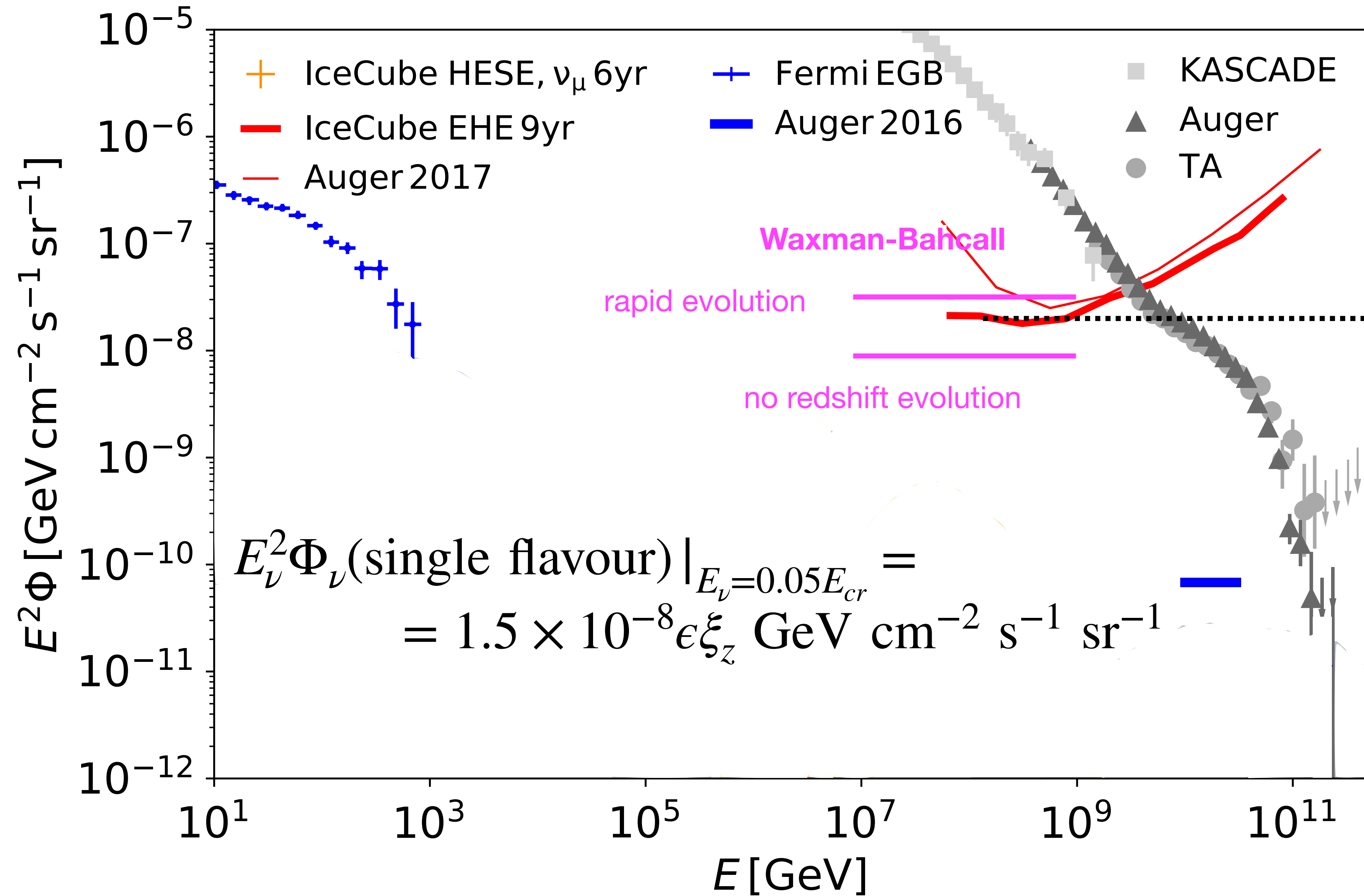
$$\pi^+ \rightarrow \mu^+ + \nu_{\mu} \rightarrow e^+ + \nu_e \quad \underbrace{\bar{\nu}_{\mu} \nu_{\mu}}$$

50% of E_{π^+}

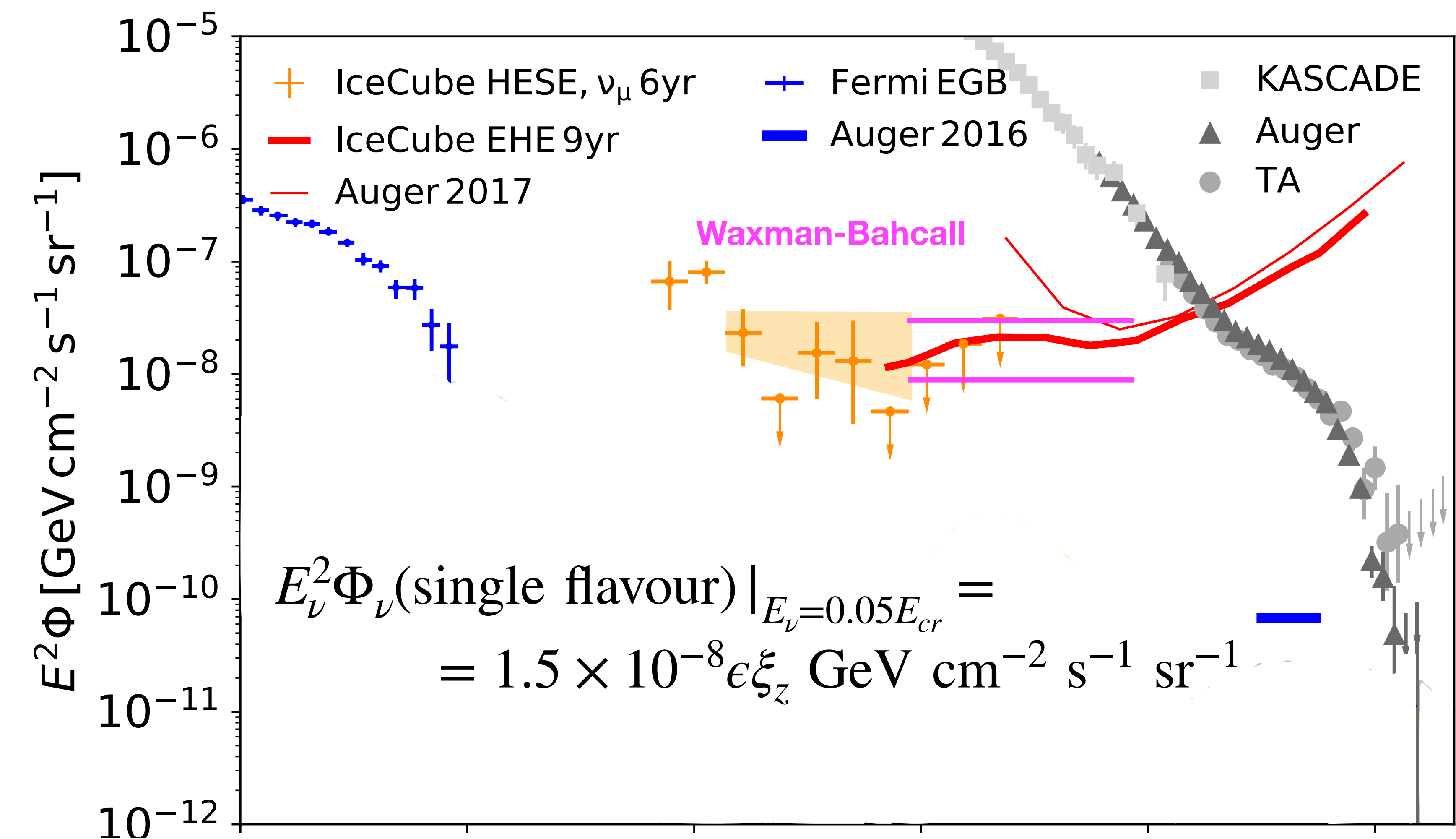
Hubble time

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

Waxman-Bahcall bound



Waxman-Bahcall bound



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

Emissivity/luminosity density $\sim \langle L \rangle \cdot n$

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

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

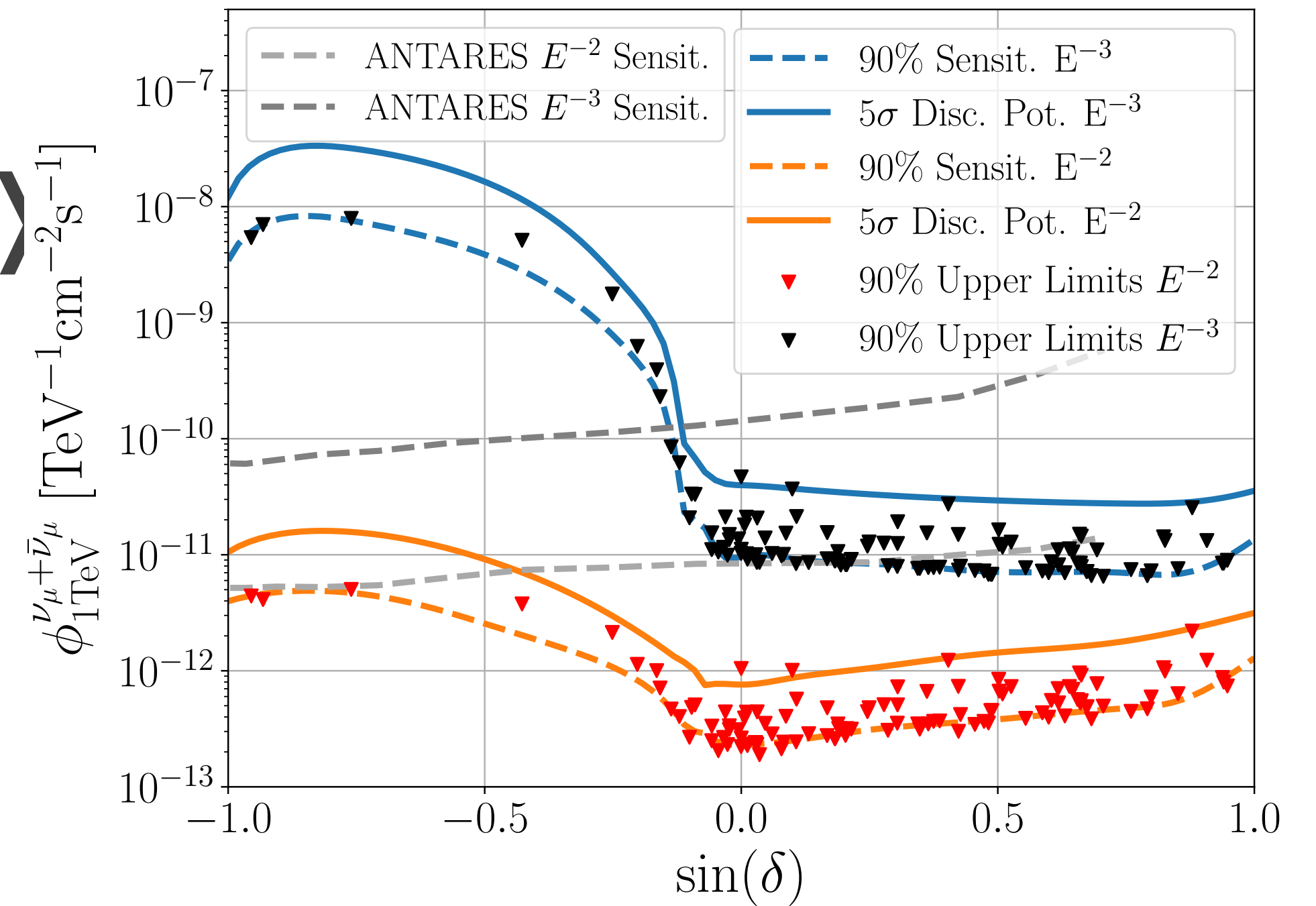
Neutrino source number density

- The nearest neutrino source must therefore be at distance

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

- The flux expected from an individual source with neutrino luminosity L is $f \sim \frac{L}{4\pi r^2}$
- Sources below the IceCube point-source flux sensitivity F_{lim} must therefore satisfy

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



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

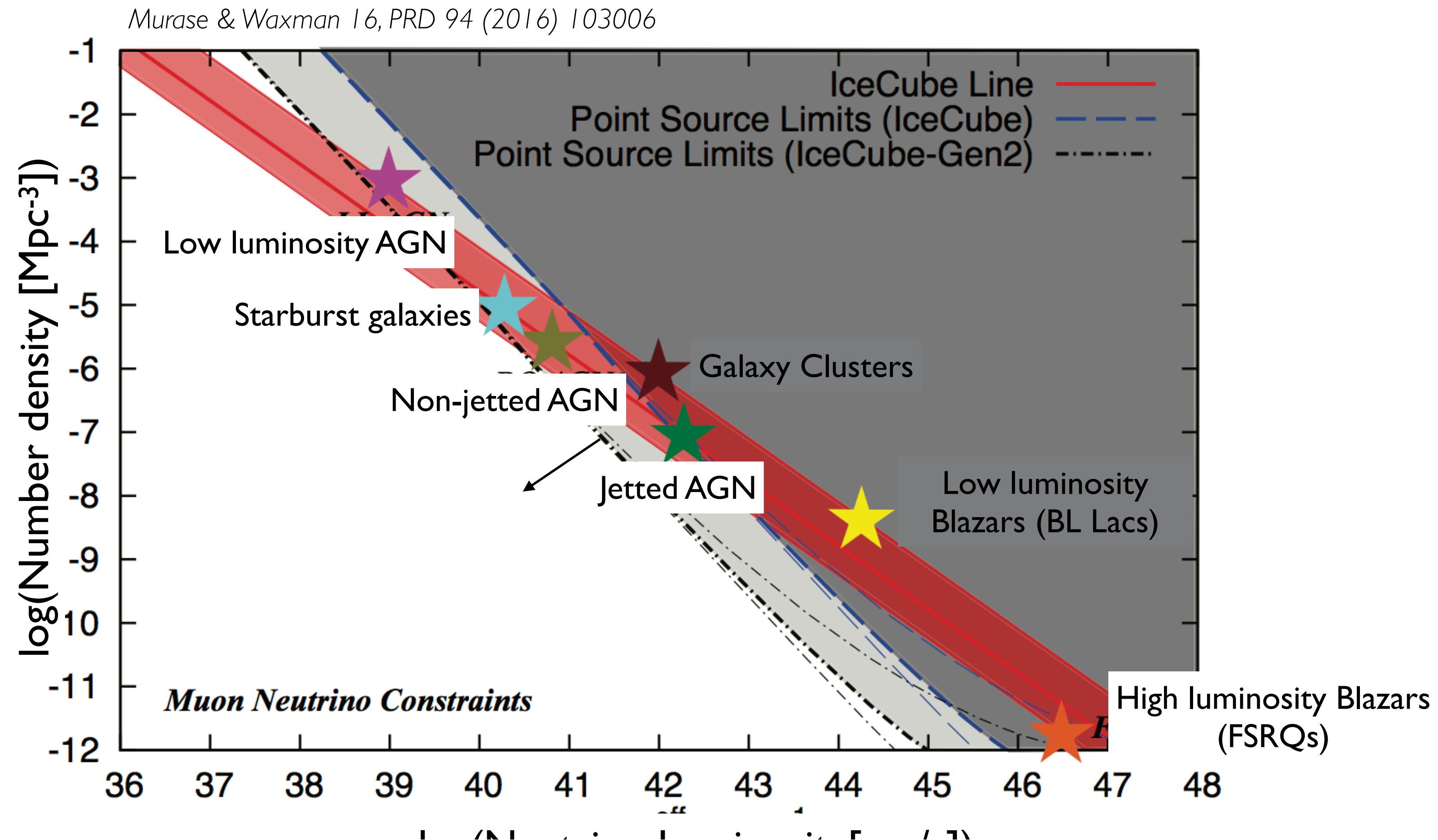
$$n \leq \frac{3}{4\pi} \left(\frac{L}{4\pi F_{lim}} \right)^{-3/2}$$

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



Conclusion #4: Neutrino sources are not rare and powerful