Constraining the Baryon Loading Factor of AGN Jets: an Implication from the Gamma-ray Emission of the Coma Cluster

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Outline

- Background

  baryon loading factor; the Coma cluster

- In the Coma Cluster,
  - radial density profile of cosmic rays
  - γ-ray production
  - baryon loading factor

    time averaged η_p / radiation related $\eta_{p,\mathrm{rad}}$

- Discussion & Conclusions

Baryon Loading Factor of AGN Jets

- AGN jets: promising acceleration sites of ultra-high energy cosmic rays
- The baryon loading: $\eta_{p,rad} = L_p / L_\gamma$
- Blazar one-zone model:

  the required L_p is significantly higher than the observed radiative luminosity (Keivani 2018; Xue 2019, 2020)

- If blazars can account for the diffuse neutrinos detected by IceCube, $\eta_{p,\mathrm{rad}} \sim 3 - 300$ is required (Murase 2014)
- $t_{\mathrm{cool}} \gg t_{\mathrm{esc}}$ in AGN jets
- Galaxy clusters ? pp collision with ICM

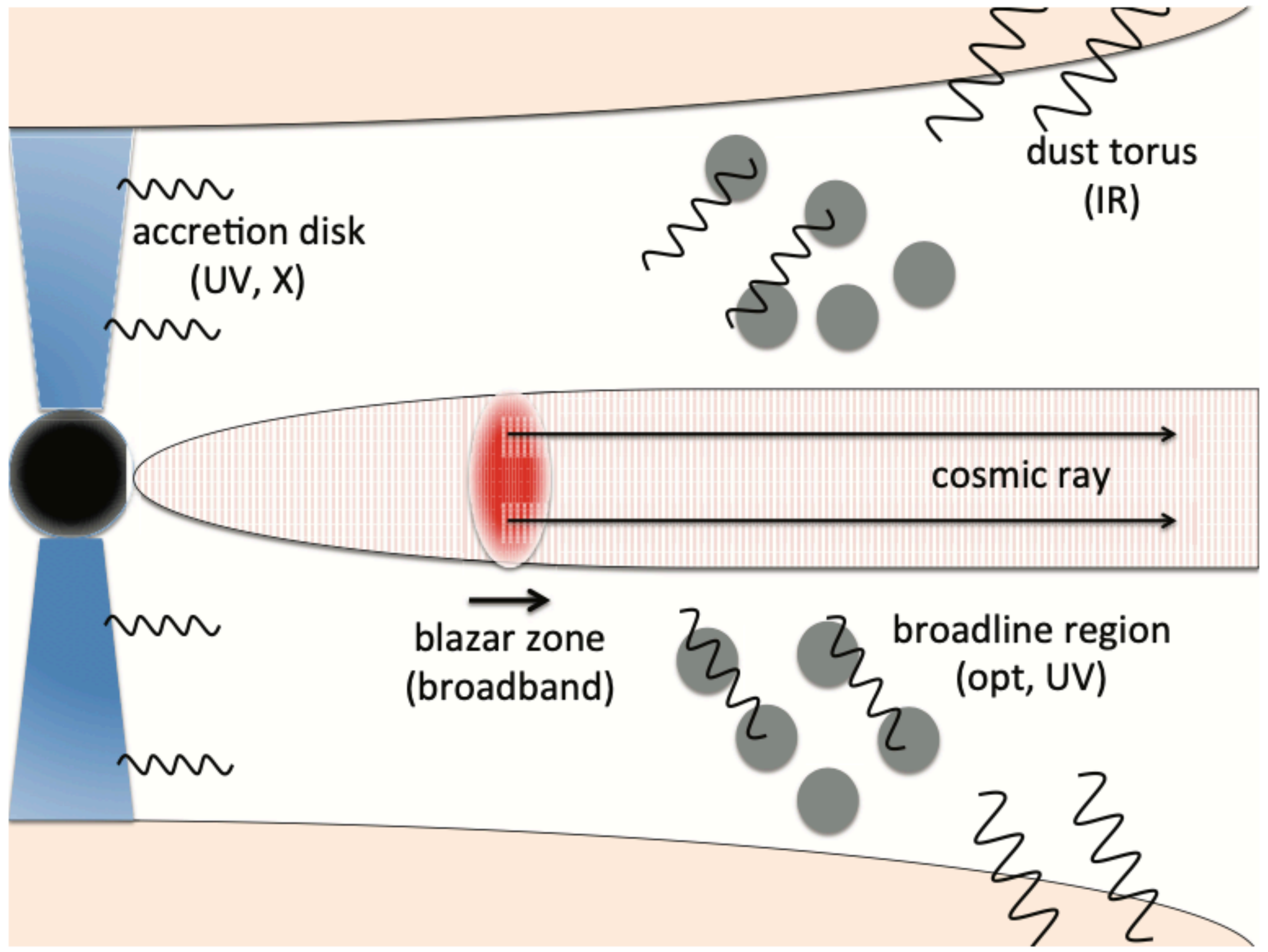

FIG. 1: Schematic picture of a blazar, showing external radiation fields relevant for neutrino production.

(Murase 2014)

The Coma Cluster

Abell 1656

at a distance of ~100 Mpc

redshift z = 0.023

total black hole mass (Ensslin 1998)

$$M_{\mathrm{BH,tot}} \approx 5.8 \times 10^{10} M_{\odot}$$

total extracted gravitational energy

$$W_{\mathrm{g}} \approx 0.2 M_{\mathrm{BH,tot}} c^2 \approx 2.1 \times 10^{64}\ \mathrm{erg}$$

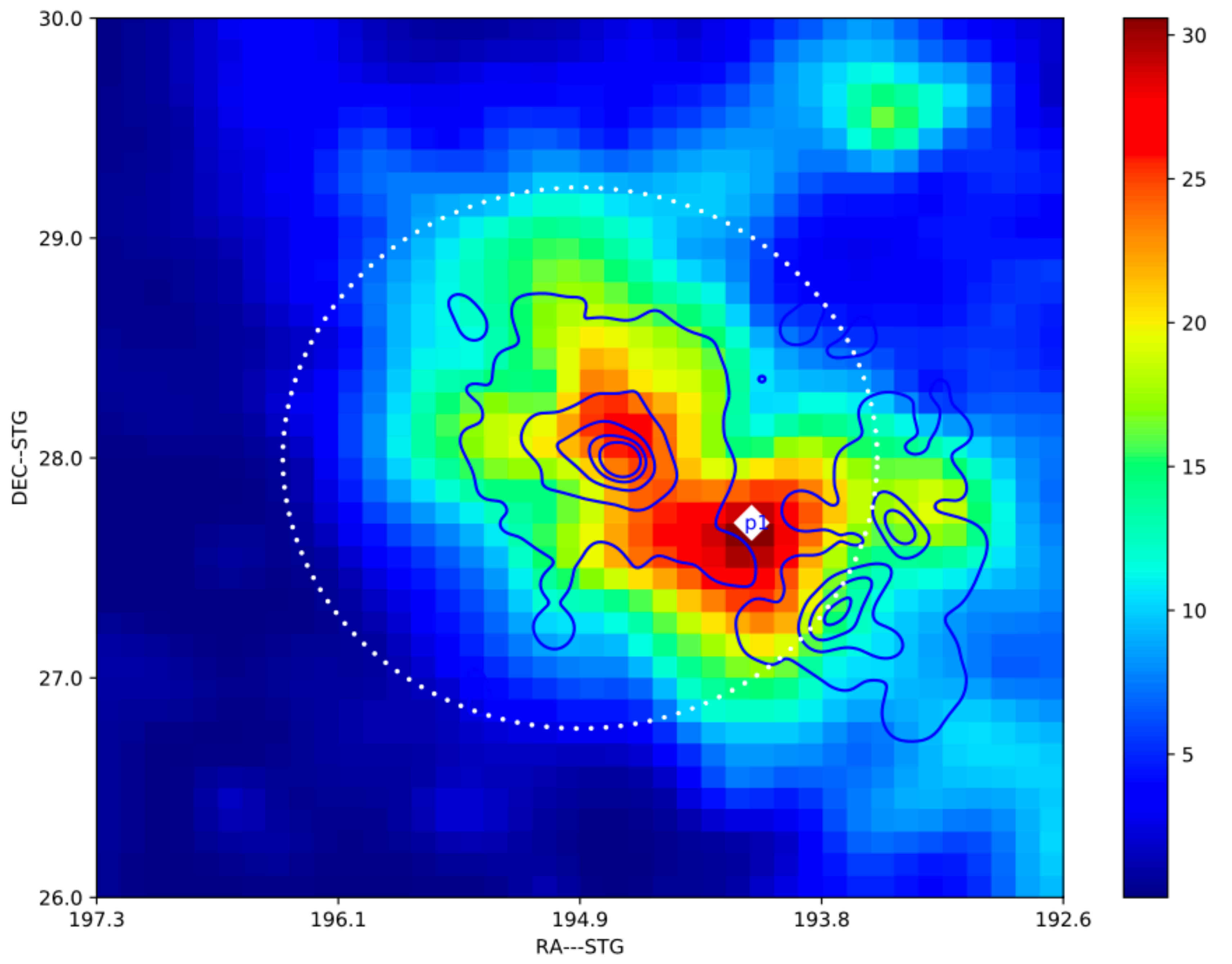

FIG. 1: Gaussian kernel ($\sigma = 0.1°$) smoothed TS map of the Coma cluster region output from *gttsmap* in the energy band 0.2 - 300 GeV. The map has a dimension of $4° \times 4°$ and a resolution of $0.1°$ per pixel. The white dashed circle is the region subtended by the virial radius, $\theta_{200} = 1.23°$. The diamond p1 represents the position of TS value peak. The contours correspond to measurements of the Coma cluster using the Westerbork Synthesis Telescope (WSRT) at a central frequency of 352 MHz ([37]). The WSRT observations are smoothed with gaussian kernel ($\sigma = 0.05°$). Contours start at 1 mJy beam^{-1} and increase in steps of 6 mJy beam^{-1}.

(Xi 2018)

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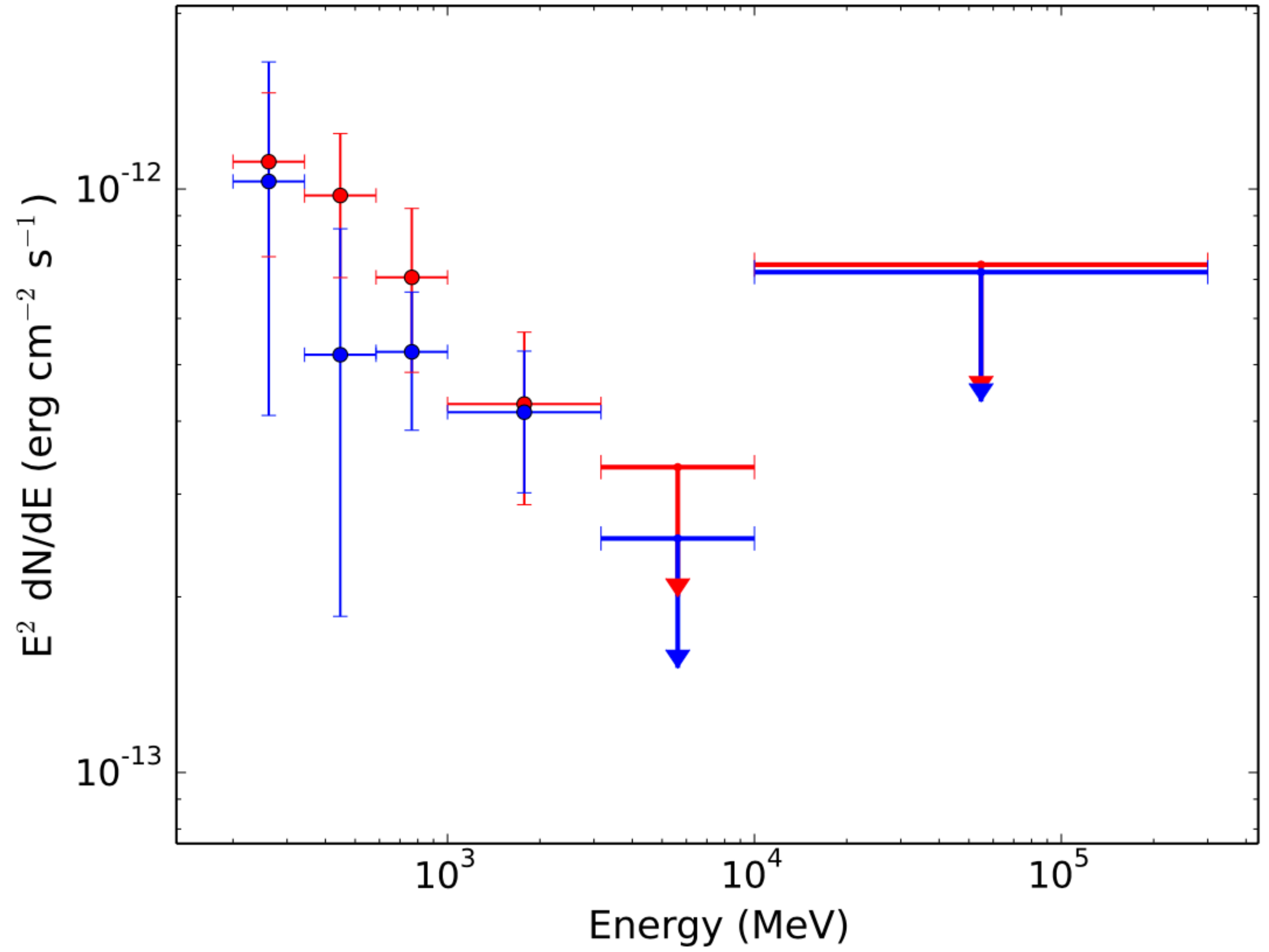


FIG. 3: Spectral energy distributions (SEDs) of the extended emission component of the Coma cluster for the single radio model (red) and radio + p1 model (blue). The upper limits at 95% confidence level are derived when the TS value for the data points are lower than 4.

(Xi 2018)

Radial Density Profile of CRs in the Coma Cluster

The diffusion coefficient

$$D_{\rm cl} = \frac{1}{3}\left(\frac{B}{\delta B}\right)^2 c r_{\rm L}^{2-w} l_{\rm c}^{w-1}$$

$$\approx 8.3 \times 10^{31} \left(\frac{l_{\rm c}}{0.3\ \rm Mpc}\right)^{2/3} \left(\frac{E_p}{1\ \rm PeV}\right)^{1/3} \times \left(\frac{BZ}{5\ \mu \rm G}\right)^{-1/3}\ \rm cm^2 s^{-1}$$

(w= 5/3 Kolmogorov diffusion) $l_c = 10\,\%\, r_{\rm vir}, r_{\rm vir} \sim 3\ \rm Mpc$

$E_p = 1$ TeV, the diffusion timescale $t_{diff} \sim 16.4$ Gyr ➡ longer than the Hubble time

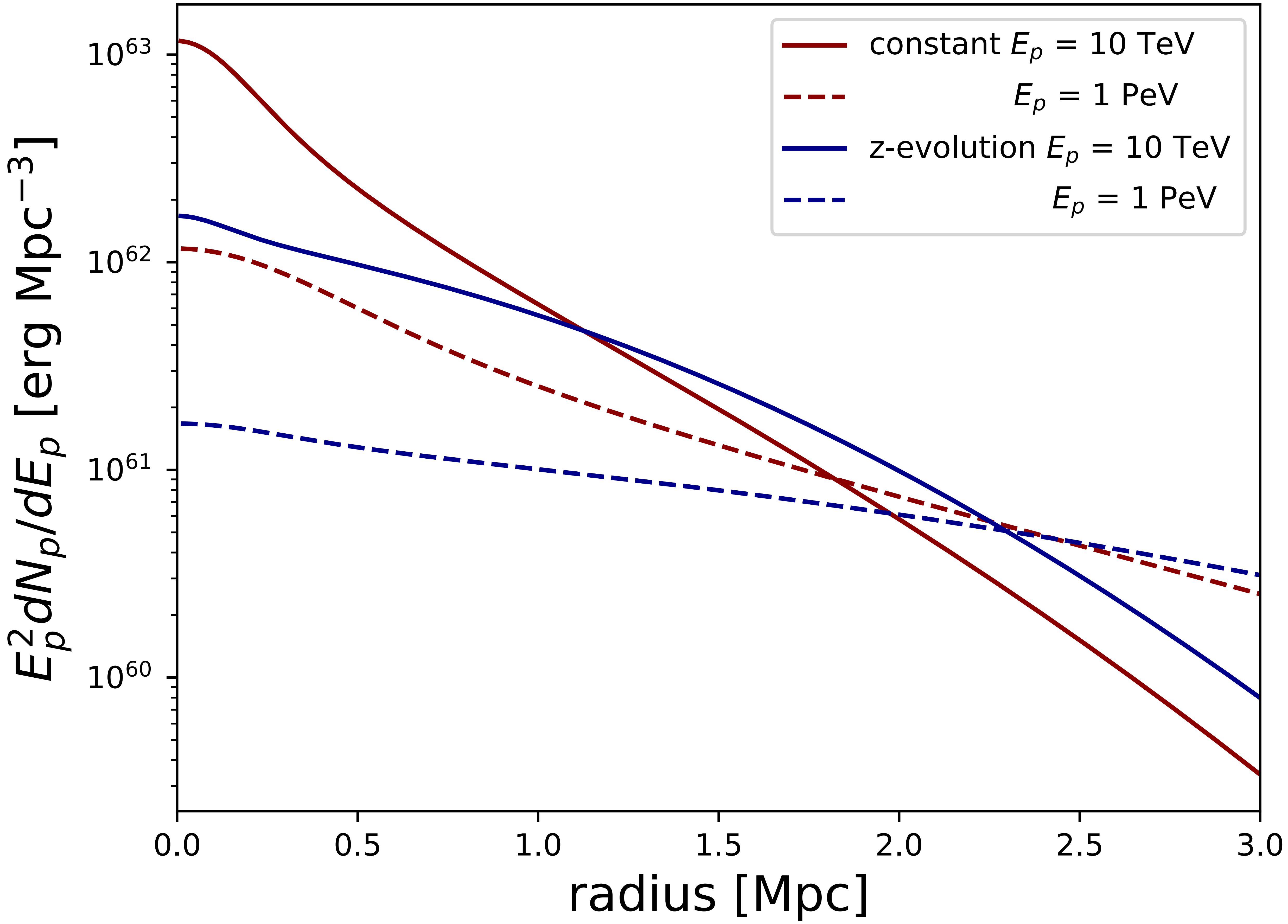
Radial Density Profile of CRs in the Coma Cluster

The radial density distribution

$$\frac{dN_p(E_p, r)}{dE_p dV} = \int_0^{t_{\max}} Q_p(E_p, t) p(E_p, r, t) dt$$

$$p(E_p, r, t) = \frac{e^{-r^2/\left(4D_{\rm cl}(E_p)t\right)}}{8\pi^{3/2}\left(D_{\rm cl}(E_p)t\right)^{3/2}}$$

$$Q_p(E_p, t) \propto E_p^{-\alpha},\ \alpha = 2$$



Two injection history:

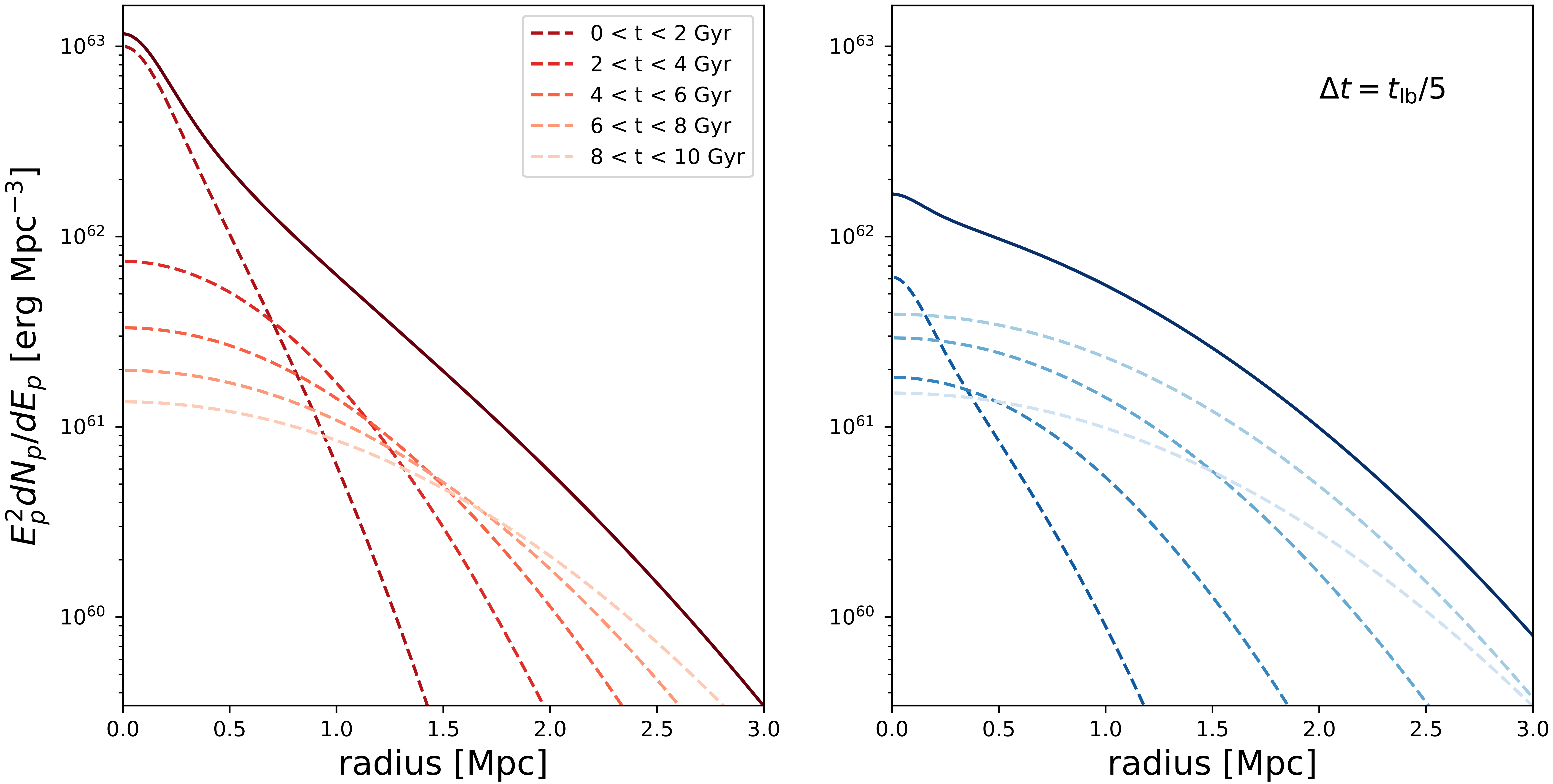
I: constant $Q_p(t) = const$

II: redshift evolution $Q_p(t) \propto L(t_{\rm lb})$ (Hasinger 2005; Ajello et al. 2012)

Radial Density Profile of CRs in the Coma Cluster

I: constant

II: redshift evolution peaked at $z = 1{\sim}2$, $t_{lb} = 6{\sim}8$ Gyr



The γ-ray emissivity of *pp* interaction (Kelner 2006)

$$J_\gamma(E_\gamma, \mathbf{r}) = c n_{\mathrm{ICM}}(\mathbf{r}) \int_{E_\gamma}^{\infty} \sigma_{pp}(E_p) \frac{dN_p(E_p, \mathbf{r})}{dE_p dV} \times F_\gamma(\frac{E_\gamma}{E_p}, E_p) \frac{dE_p}{E_p}$$

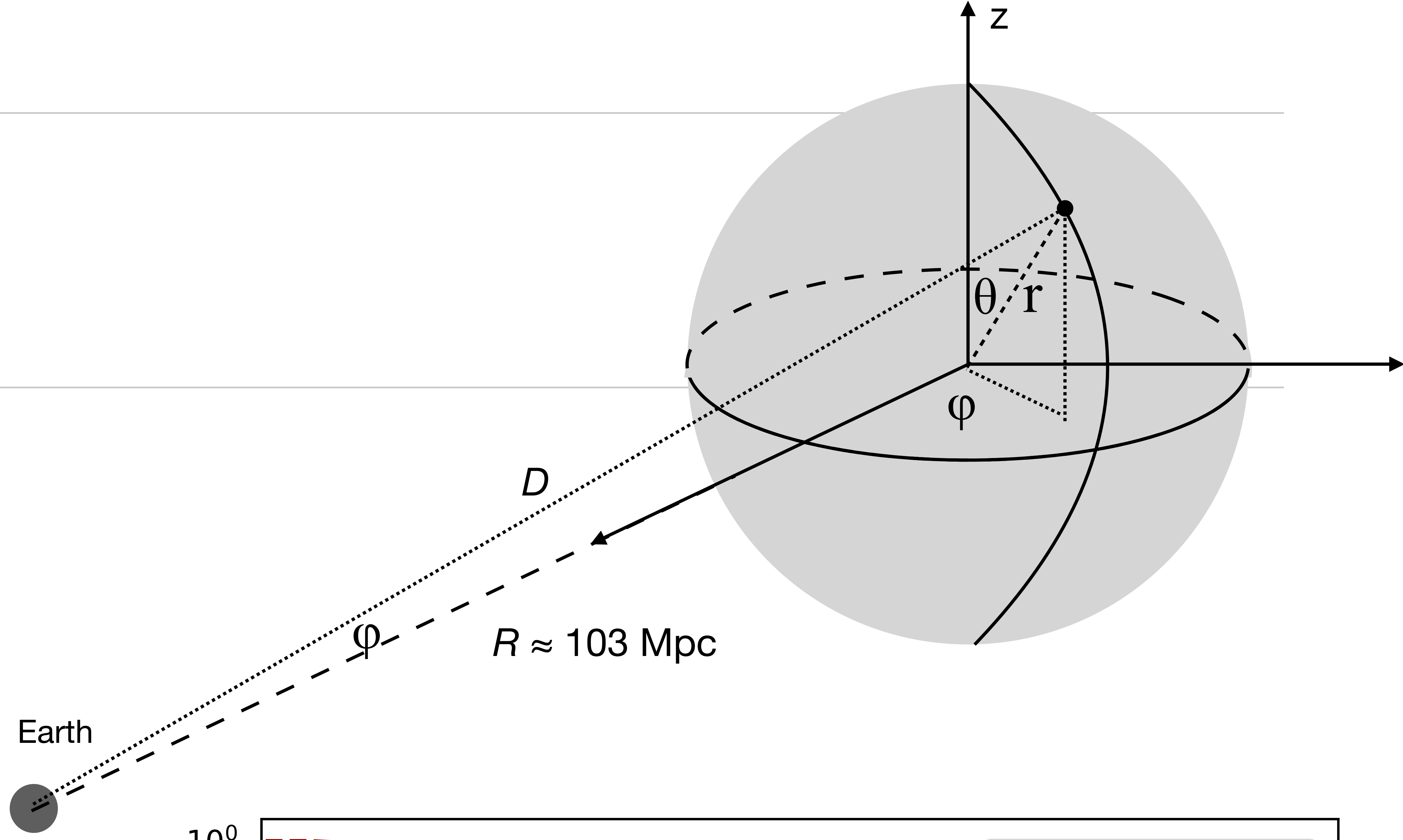
"Beta-model" (Cavaliere 1976)

$$n_{\mathrm{ICM}}(r) \approx n_{\mathrm{ICM}}(0)\left[1 + \left(r/r_c\right)^2\right]^{-3\beta/2}$$

$n_{\mathrm{ICM}}(0) = 3.42 \times 10^{-3}\ \mathrm{cm}^{-3}$,

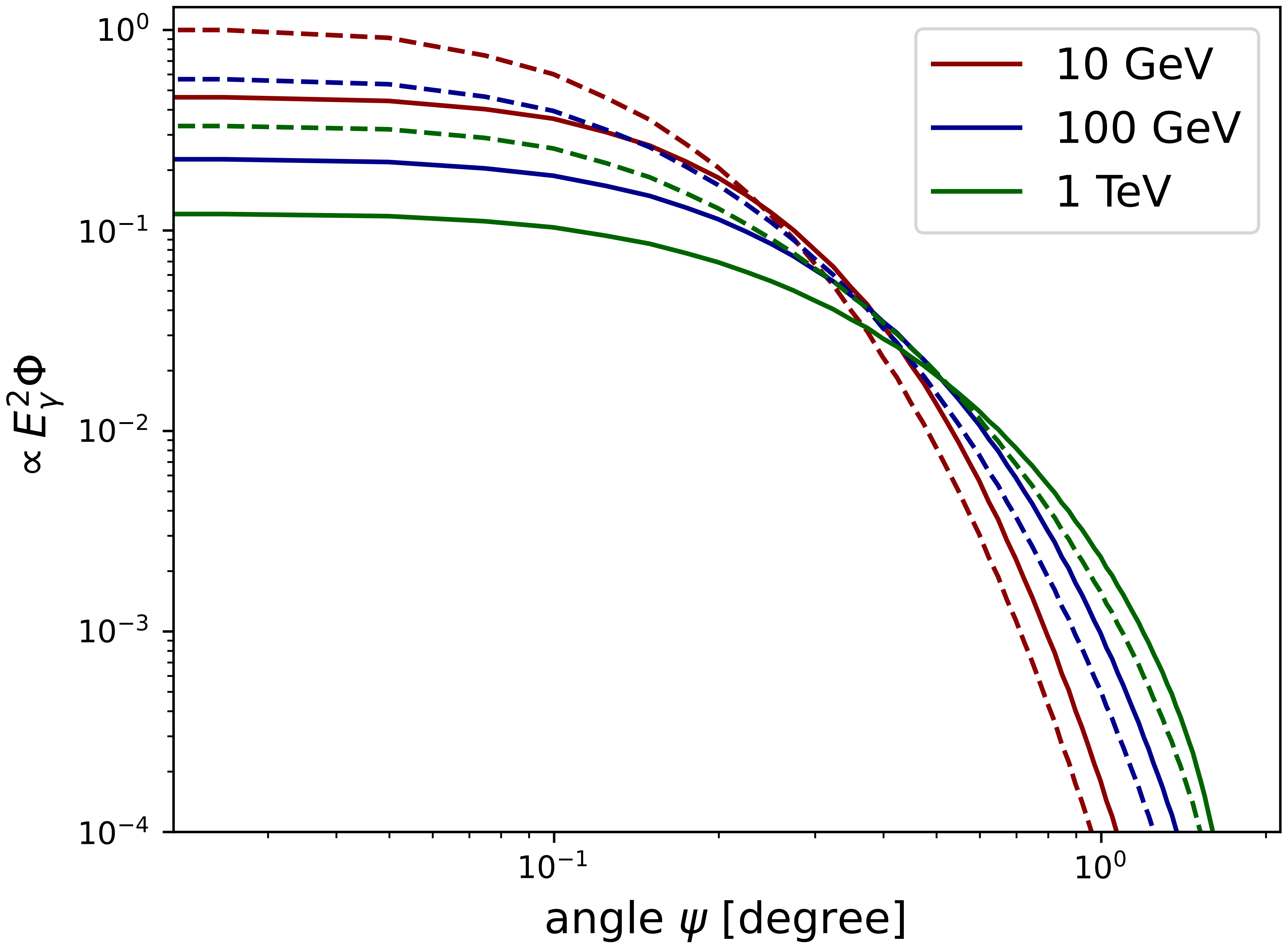
$r_c = 290\ \mathrm{kpc} \sim 0.1 r_{\mathrm{vir}}, \beta = 0.75$

the spectrum of the secondary γ-ray in a single collision



The γ-ray intensity profile average over the solid angle

$$\Phi(E_\gamma, \psi) = \frac{1}{2\pi(1 - \cos\psi_{\mathrm{vir}})} \int \frac{J_\gamma(E_\gamma, \mathbf{r})}{4\pi D^2} dV,$$



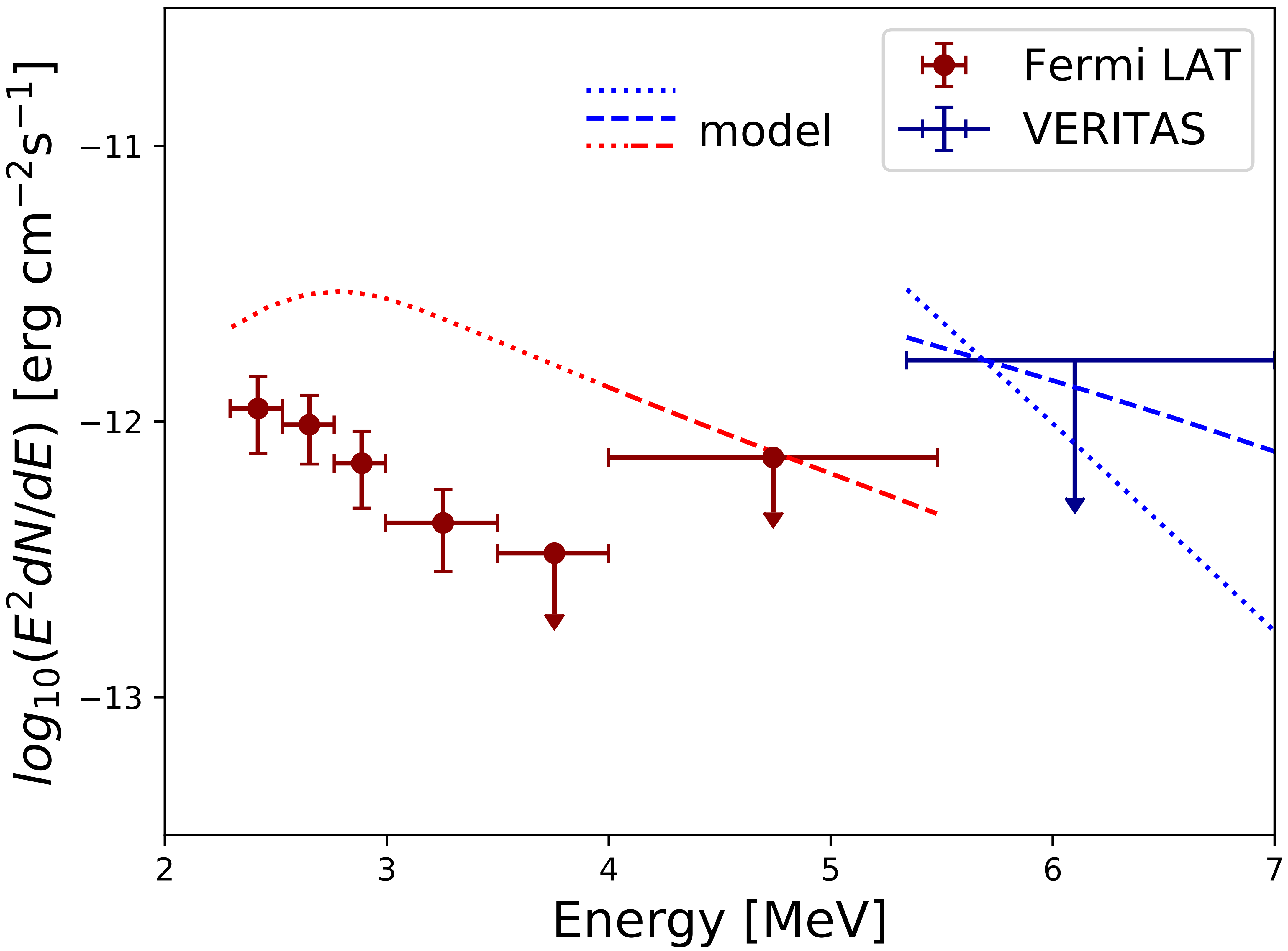
Baryon Loading Factor in the Coma Cluster

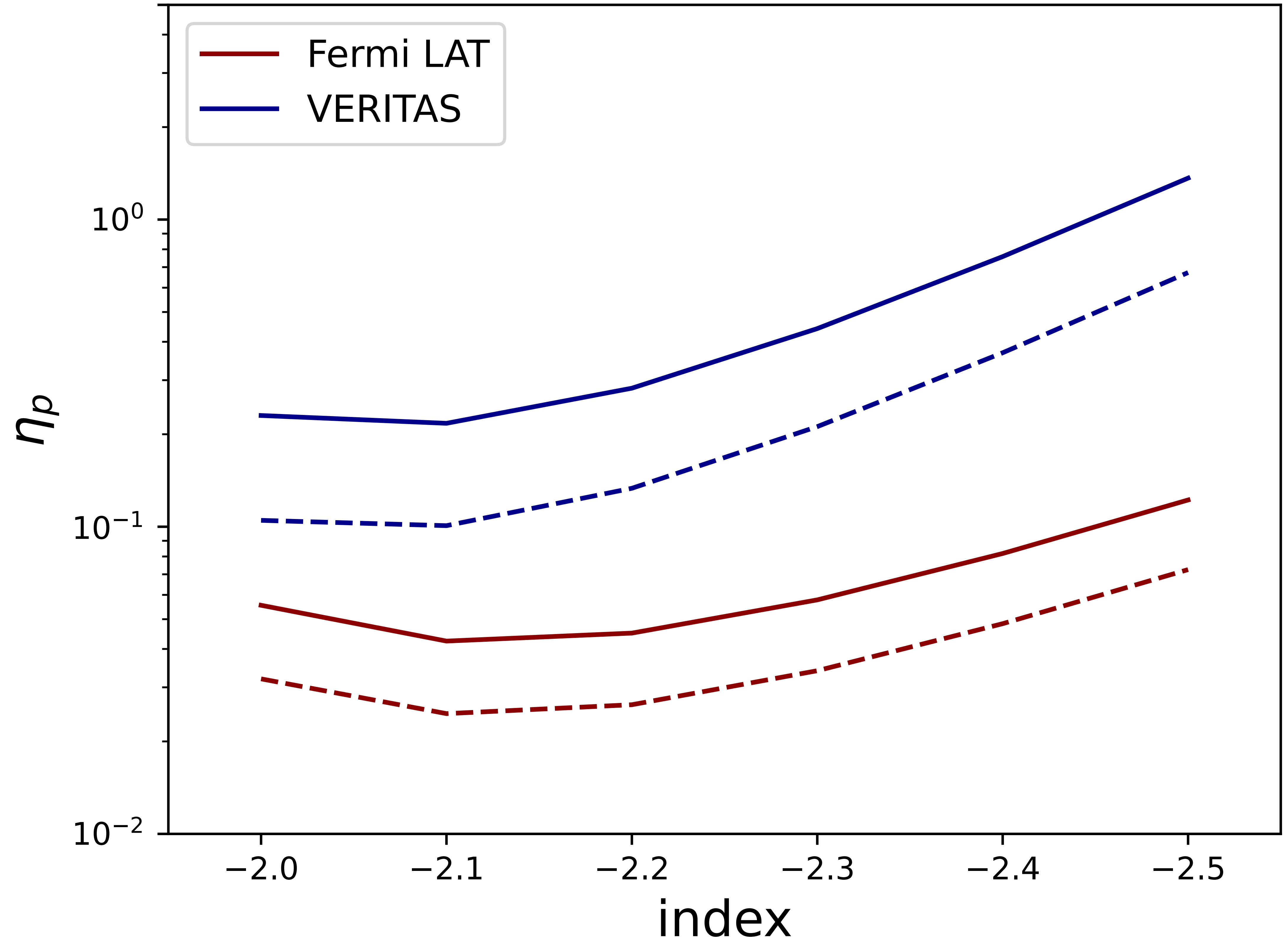
I: The time-averaged baryon loading factor:

$$\eta_p \approx \frac{W_{p,\mathrm{tot}}}{W_\mathrm{g}}$$

The best constraint:

	Fermi $\alpha = 2.1$	VERITAS $\alpha = 2$
constant:	$\eta_p \lesssim 0.02$	$\eta_p \lesssim 0.1$
z evolution:	$\eta_p \lesssim 0.04$	$\eta_p \lesssim 0.2$





Baryon Loading Factor in the Coma Cluster

II: The radiation related baryon loading factor:

Definition in Murase et al. (2014):

$\eta_{p,rad} = L_p / L_\gamma$

L_p: the total CR luminosity; L_γ: the bolometric radiation luminosity of the jet

$$\eta_{p,\mathrm{rad}} = \frac{W_{p,\mathrm{tot}}}{W_\gamma} = \eta_p / \langle \eta_\gamma \rangle$$

where $\eta_\gamma = W_\gamma / W_\mathrm{g} = P_\mathrm{rad} t_\mathrm{Sal} / (0.2 M_\mathrm{BH} c^2)$

P_rad: the radiative power, t_Sal: the Salpeter time

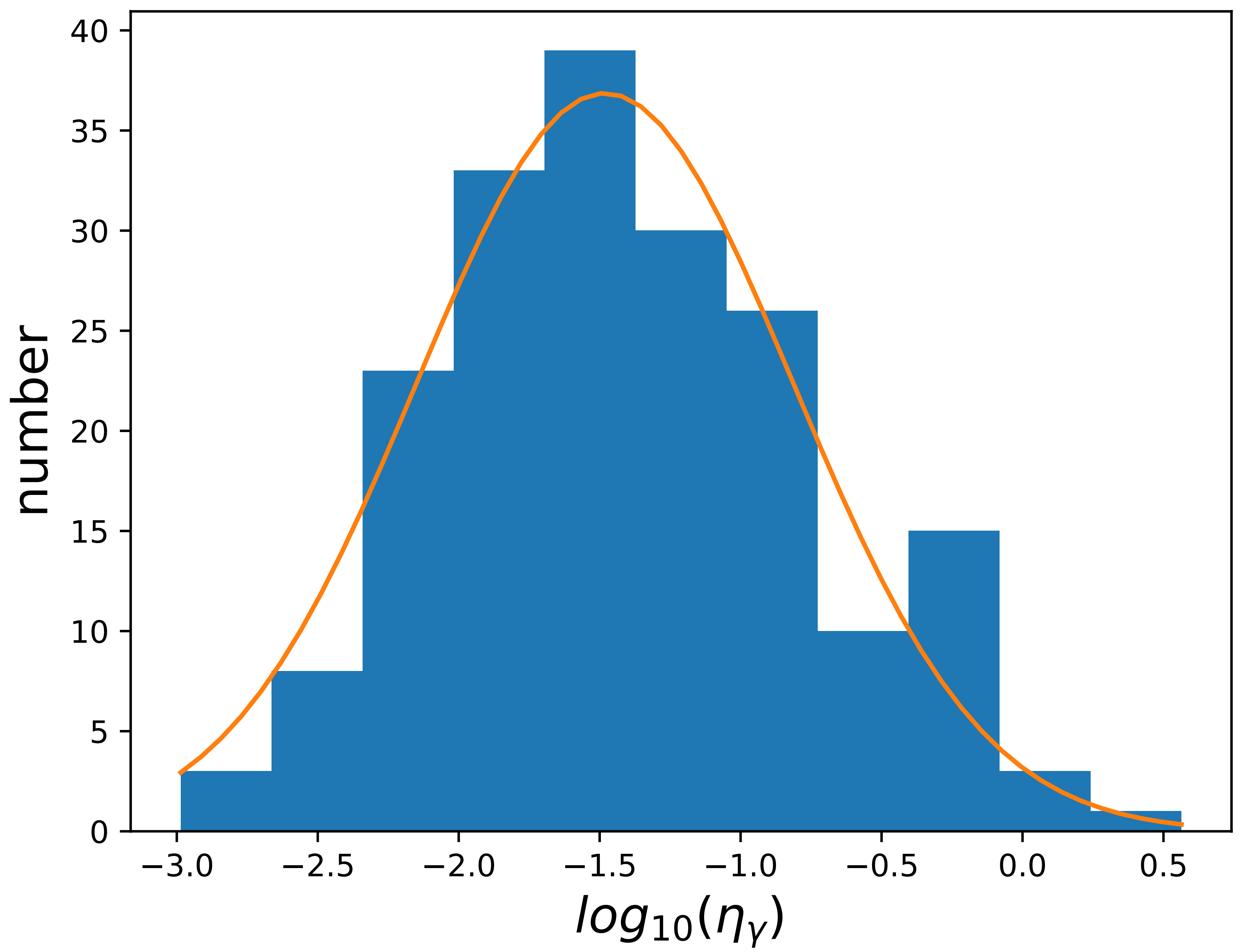
Baryon Loading Factor in the Coma Cluster

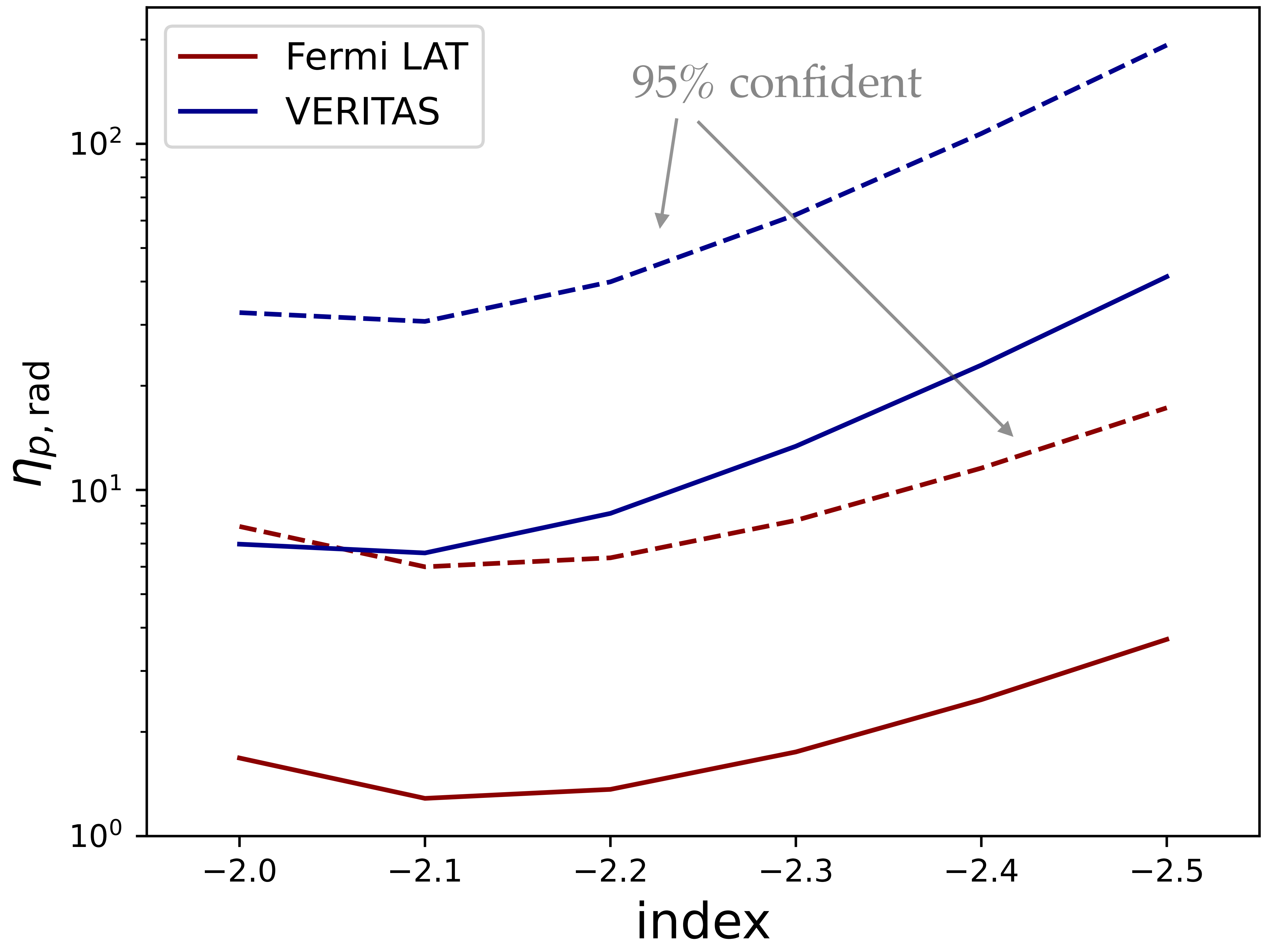
II: The radiation related baryon loading factor:

Sample: 217 blazars (composed by 191 FSRQs and 26 BL Lac object) (Ghisellini 2014)

The best constraint:

	Fermi	VERITAS
z evolution:	$\eta_{p,\mathrm{rad}} \lesssim 1$	$\eta_{p,\mathrm{rad}} \lesssim 10$





$\langle \eta_{\gamma,\mathrm{FSRQ}} \rangle \approx 0.03$,
with 95% confidence interval $\eta_{\gamma,\mathrm{FSRQ}} \in [0.007, 1.5]$

Discussion

- Redshift evolution have slight effect on the result
- The Coma cluster may be undergoing the merging process

  the gamma-ray profile

- Typical AGN phase lifetime $\sim 10^5$ yr (Schawinski 2015), the total growth time $\sim 10^7 - 10^9$ yr (Fabian 1999; Yu 2002)

  might not apply to one short, specific status of AGNs, such as an intense flare

- Extrapolation of the result to the total AGN populations

  might not appropriate for X-ray luminous AGNs, due to significant suppression of X-ray luminous AGN redshift evolution

Conclusions

- Assuming all the observed γ-ray emission of galaxy clusters from the *pp* collision of cosmic rays and ICM, we can obtain the total required proton energy and study the baryon loading factor of AGN jets.
- The Coma cluster: the propagation and distribution of cosmic rays
- Constraints on the average baryon loading factor using the γ-ray observations from Fermi LAT and VERITAS of the Coma cluster

	Fermi $\alpha = 2.1$	VERITAS $\alpha = 2$
constant:	$\eta_p \lesssim 0.02$	$\eta_p \lesssim 0.1$
z evolution:	$\eta_p \lesssim 0.04$	$\eta_p \lesssim 0.2$
	$\eta_{p,\mathrm{rad}} \lesssim 1$	$\eta_{p,\mathrm{rad}} \lesssim 10$

lower than that required to account for diffuse neutrino flux in the conventional blazar models

Thank you for your attention!