UFRJ

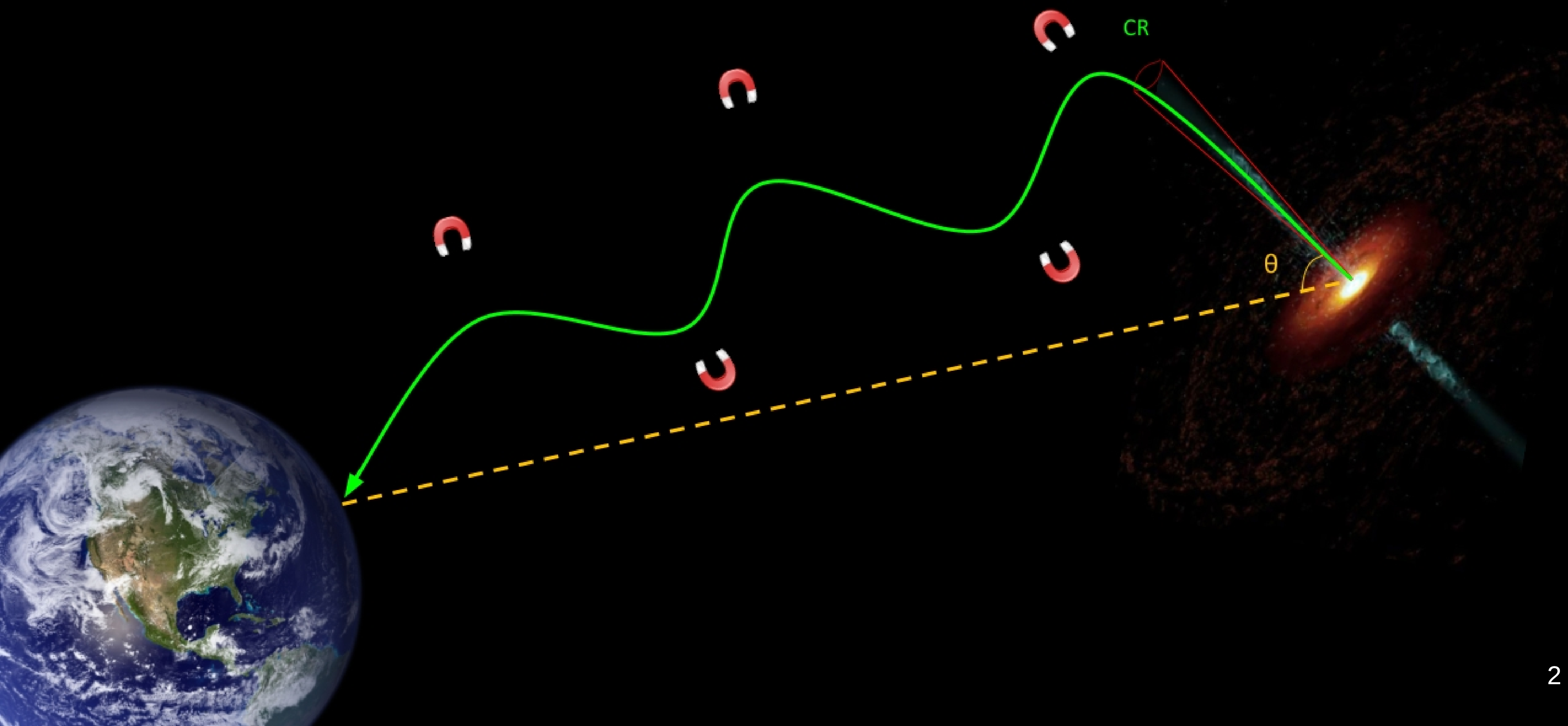
CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

Sarah Soares Sippert

Effects of extragalactic magnetic field on the spectra of UHECRs from jetted sources

International School of Cosmic Ray Astrophysics, Maurice M. Shapiro, 24th Course: Particles and the Cosmos – Bridging the Infinitesimal and the Infinite

Erice, Sicily, Italy
Jul 2026

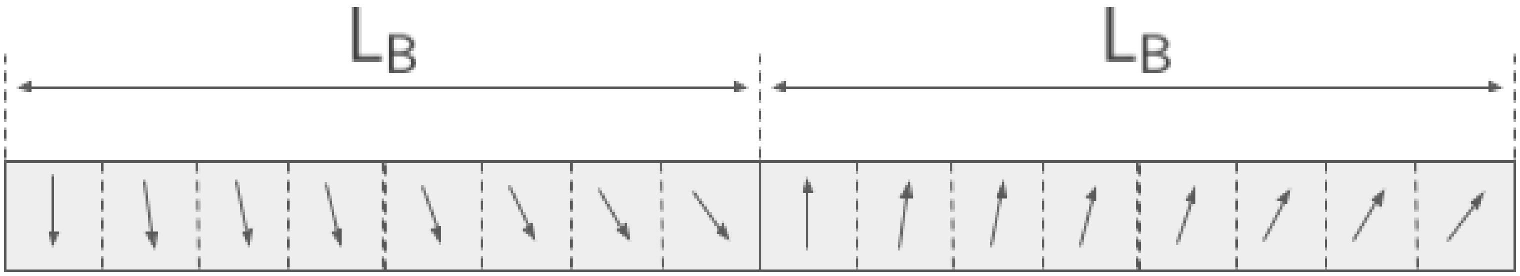

CR
θ

Extragalactic magnetic field (EGMF)

→ The EGMF has a turbulent behavior: its strength and direction are altered randomly in space.

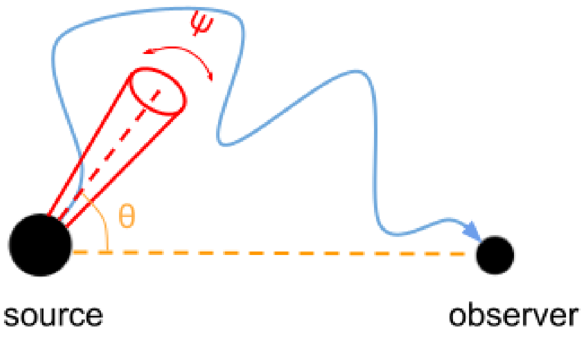
One of its most used models is based on the Kolmogorov spectrum [1], where it is characterized by the RMS of strength field, $B = \sqrt{\langle B^2(x) \rangle}$, and a parameter named coherence length L_B.

- L_B defines the maximum spatial scale over which the magnetic field remains correlated.



Simulation

→ The aim of this work is to investigate the impact of the EGMF and the emission geometry on the observed energy spectrum of the UHECRs at Earth when these are emitted by astrophysical jets.



The jet has an opening angle Ψ and is oriented at an angle θ relative to the line of sight between the source and the Earth.

→ The simulations were done using the CRPROPA framework [2], assuming that the source emits particles with energy spectrum proportional to

$$\frac{dN}{dE} \propto E^{-\gamma},$$

where γ is the source spectral index.

Simulation

→ We took into account all the relevant energy loss processes during the propagation.
→ The reference spectral index was $\gamma = 1$ and the particles were emitted with a minimum energy of $10^{17}\,eV$ and maximum $10^{21}\,eV$.
→ The propagation is terminated if the particle reaches energy below $10^{17}\,eV$ or if its time exceed the Universe age.

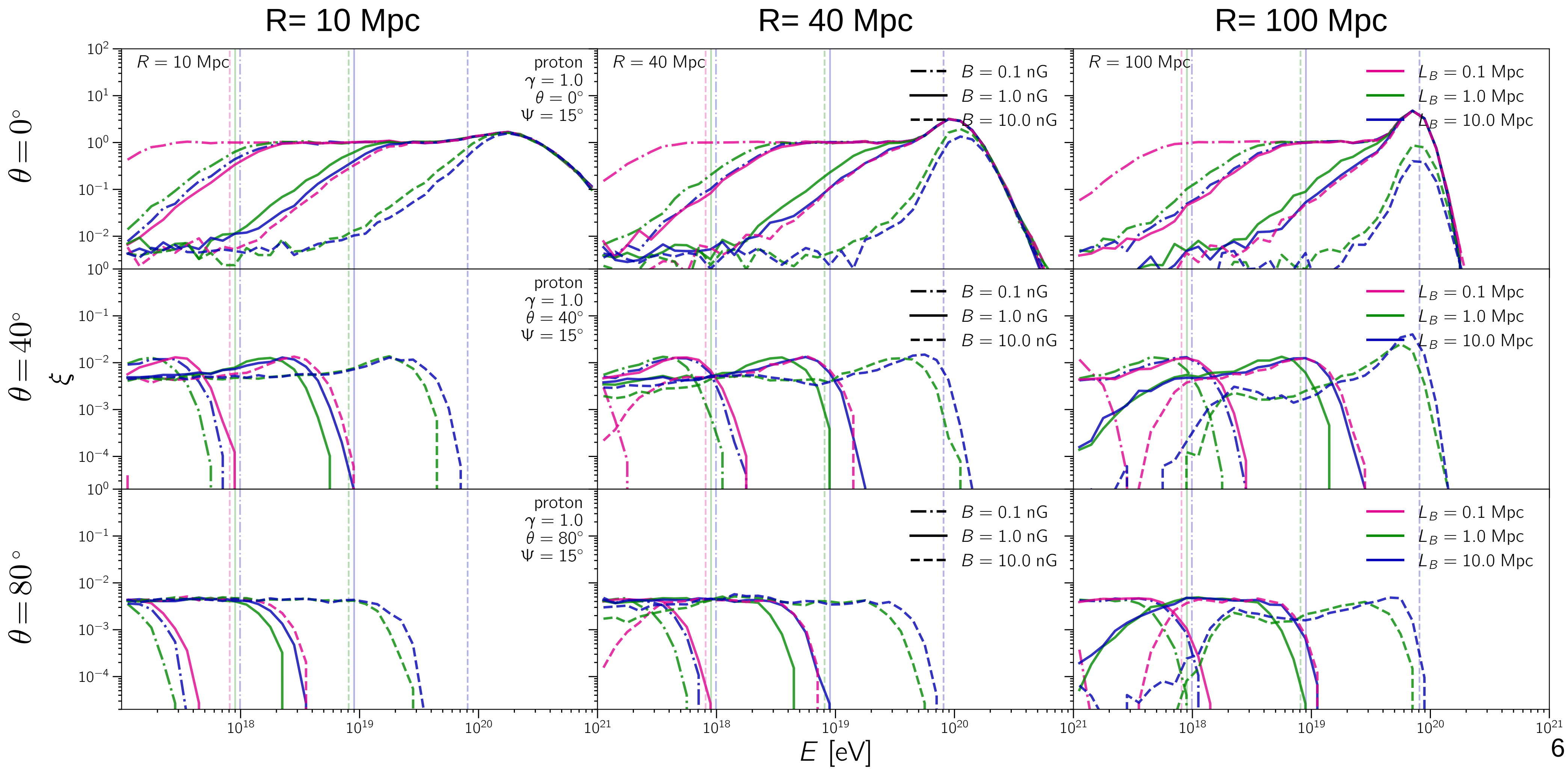
The combined effect of the emission geometry and the EGMF was quantified through the modification factor parameter ξ

$$\xi = \frac{J(E)}{J_0(E_0)}$$

- We considered several combinations of the following parameters:
  - B = 10 nG, 1 nG, 0.1 nG;
  - L_B = 100 kpc, 1 Mpc, 10 Mpc;
  - θ = 0º , 40º , 80º;
  - R = 10 Mpc, 40 Mpc, 100 Mpc.

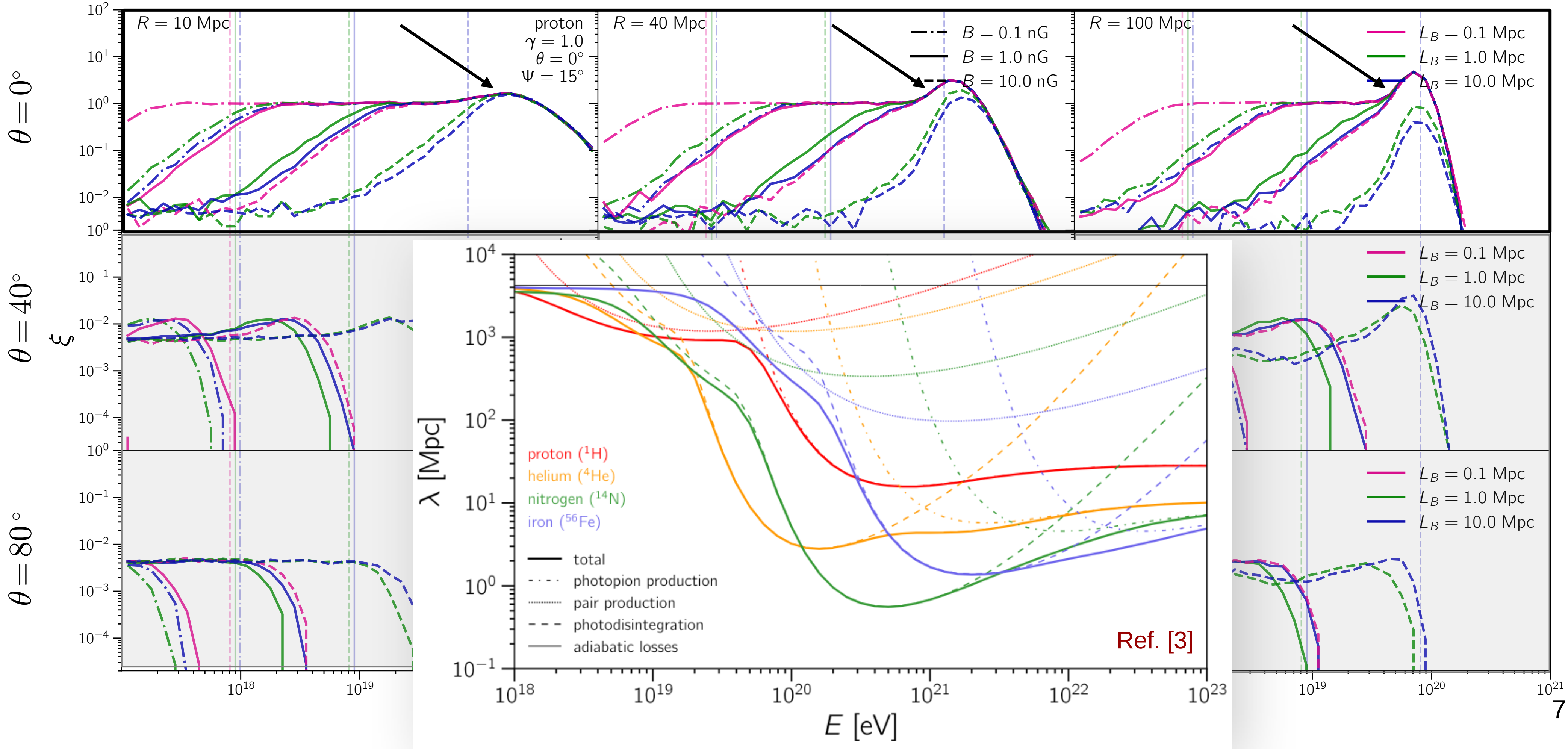
- The default value for the jet opening angle was Ψ = 15º .

Pure-proton scenario

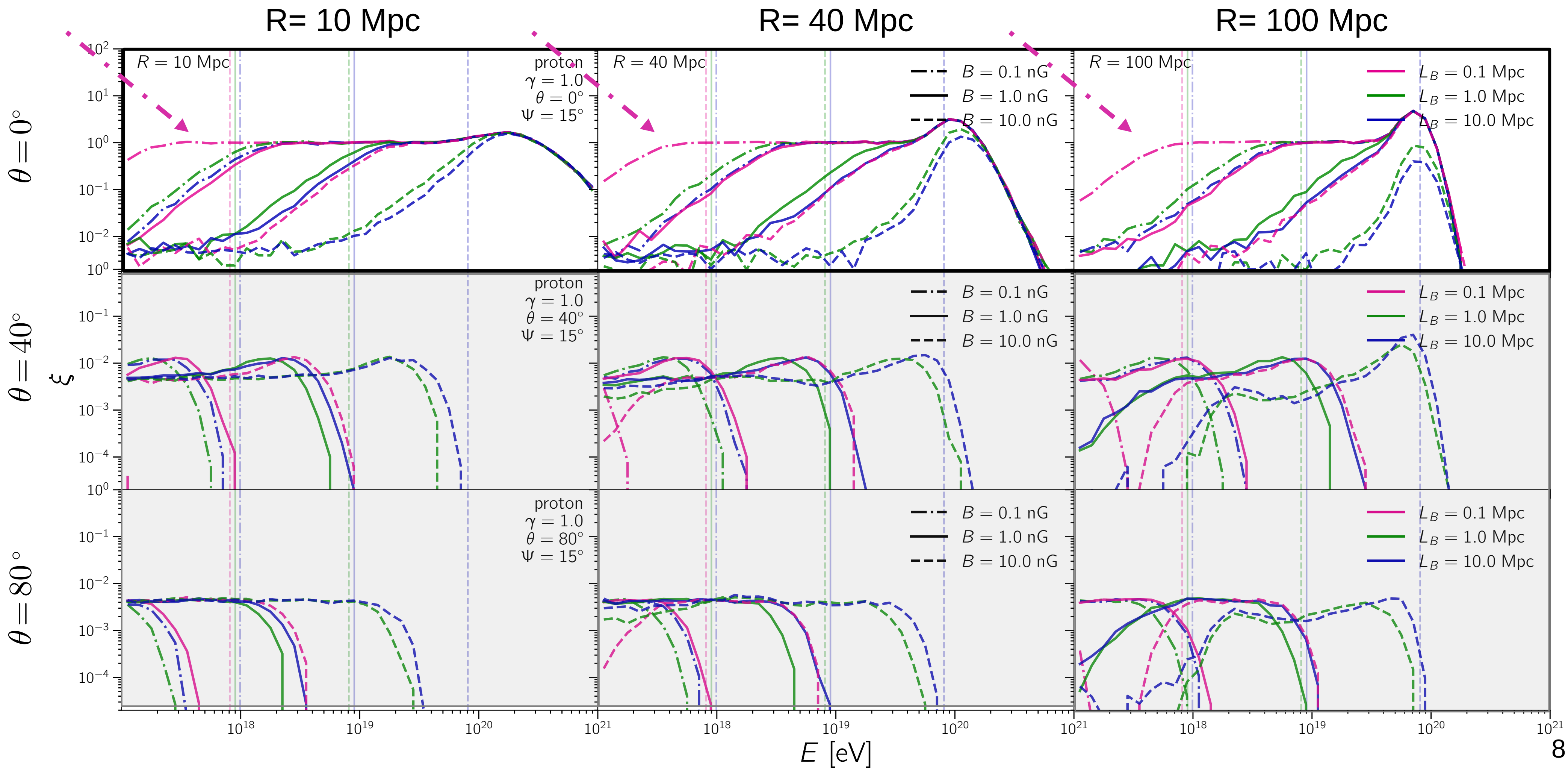


Pure-proton scenario

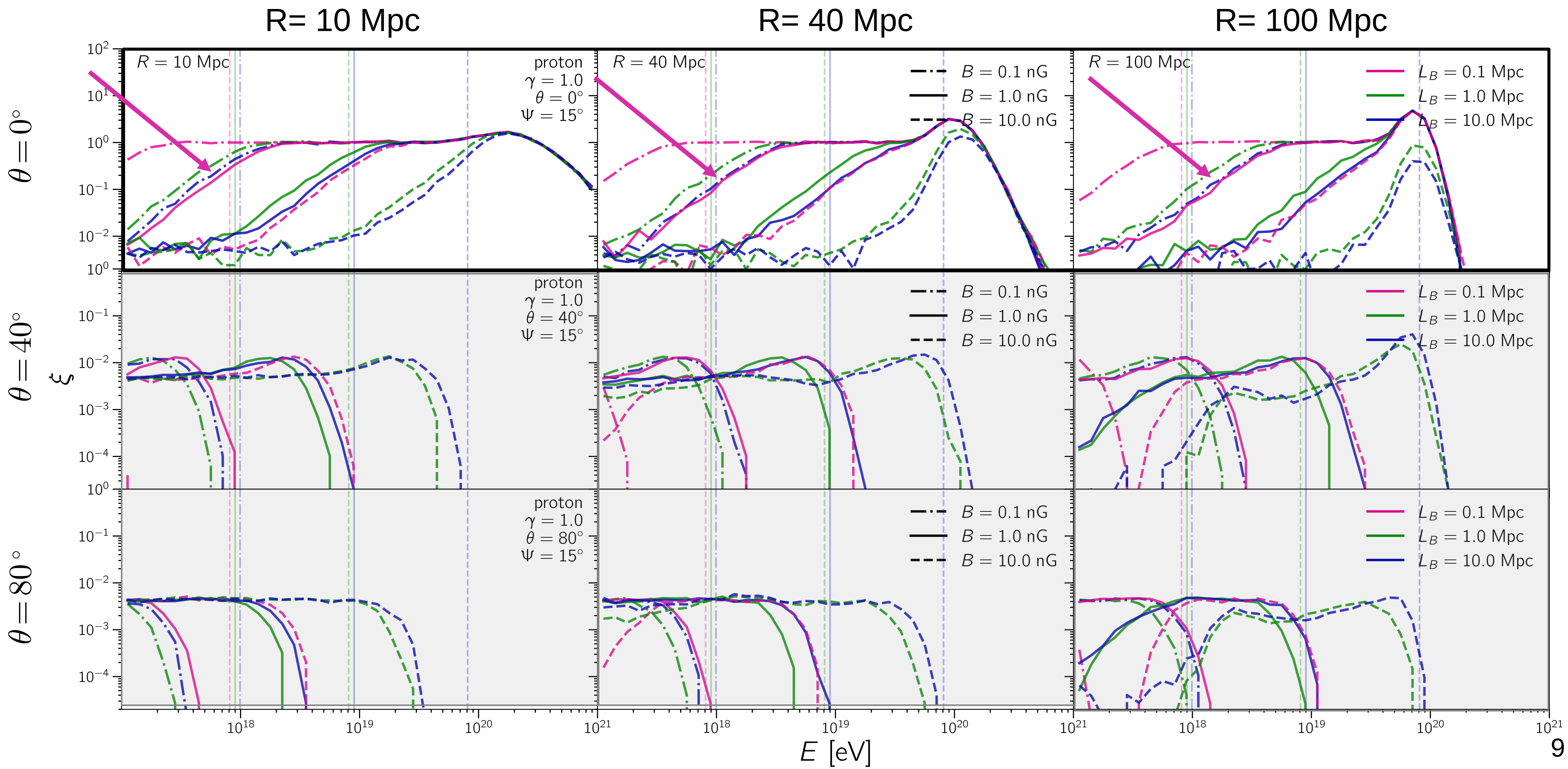
R= 10 Mpc　　R= 40 Mpc　　R= 100 Mpc



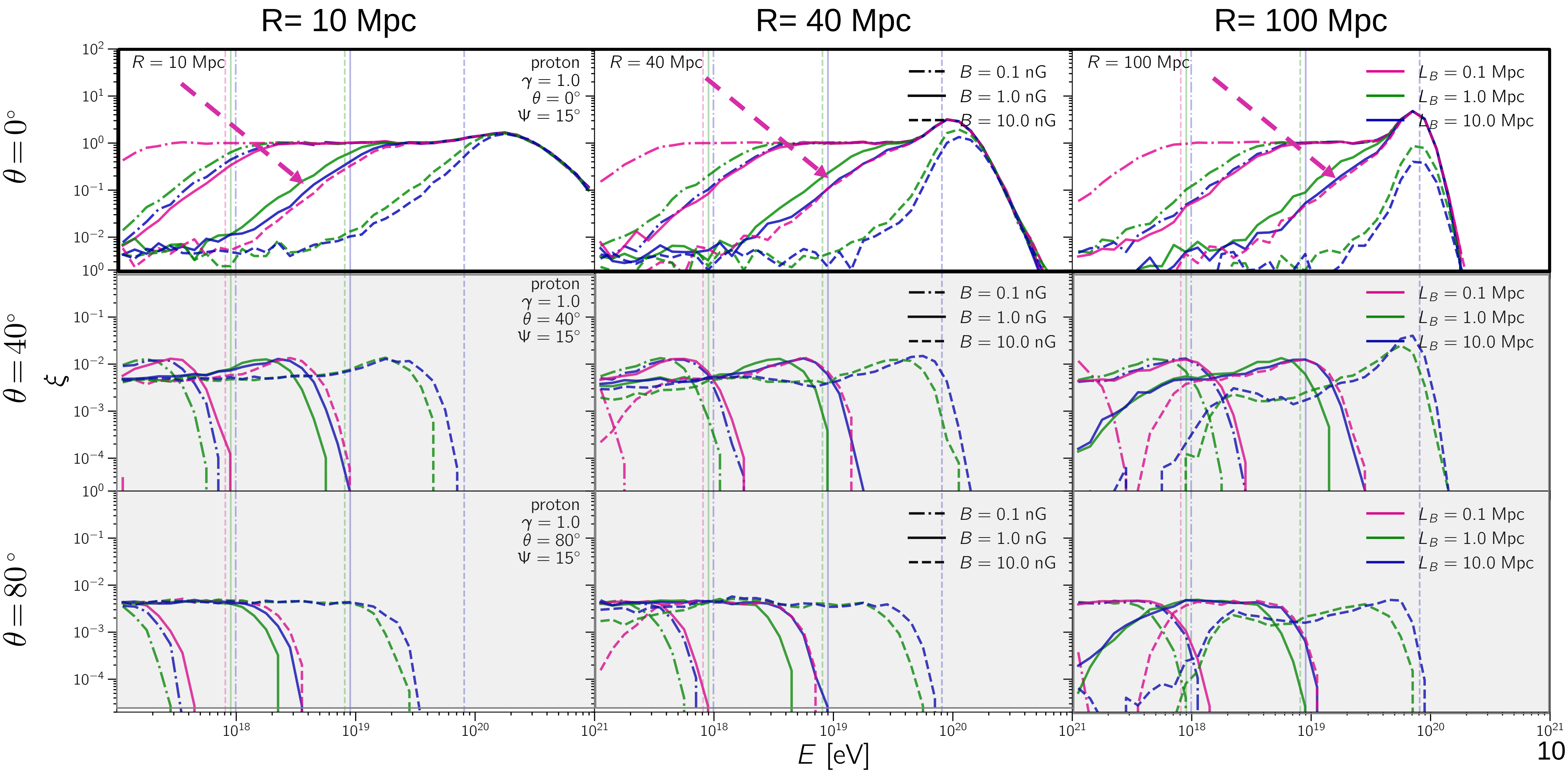
Pure-proton scenario



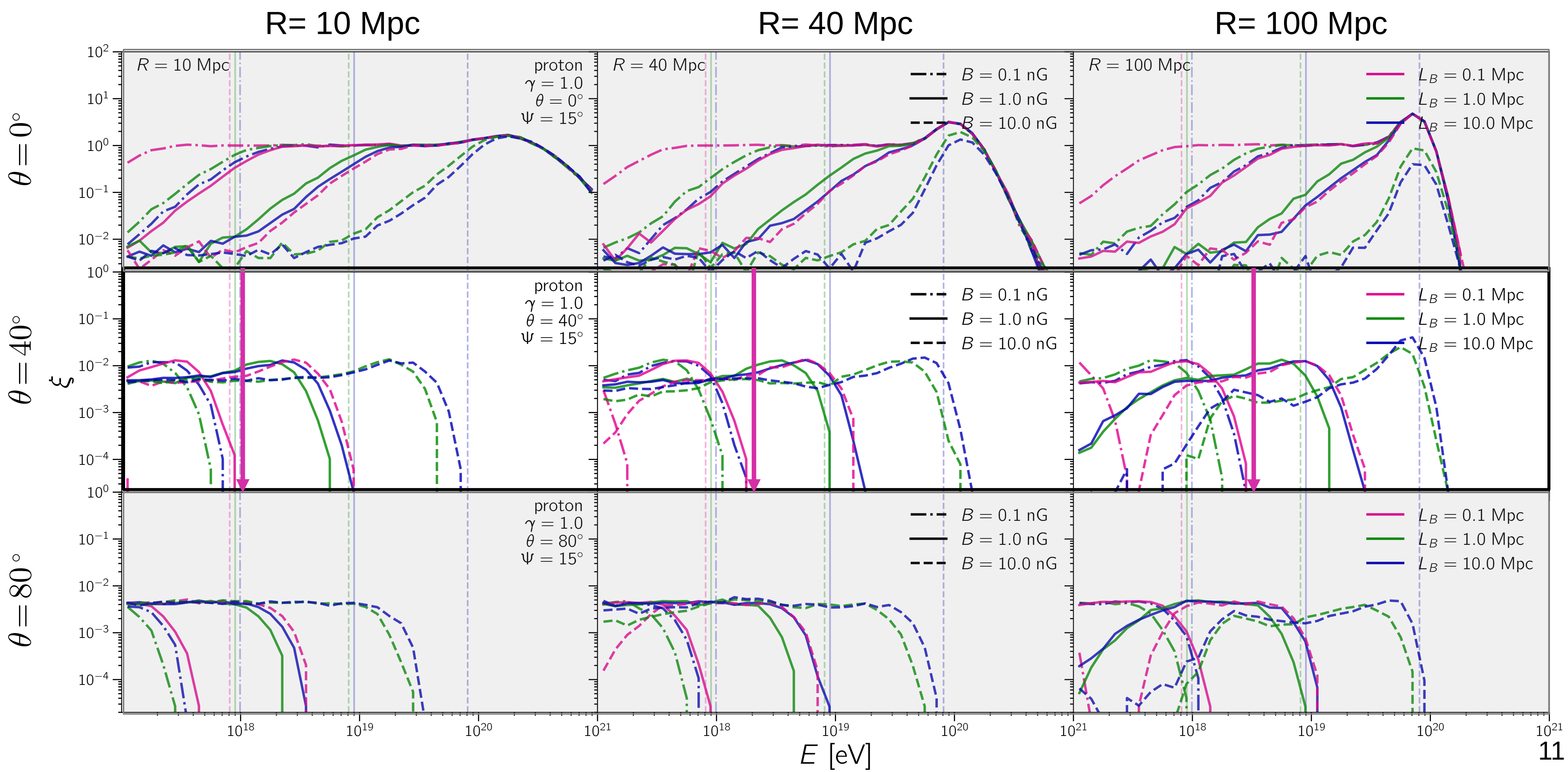
Pure-proton scenario



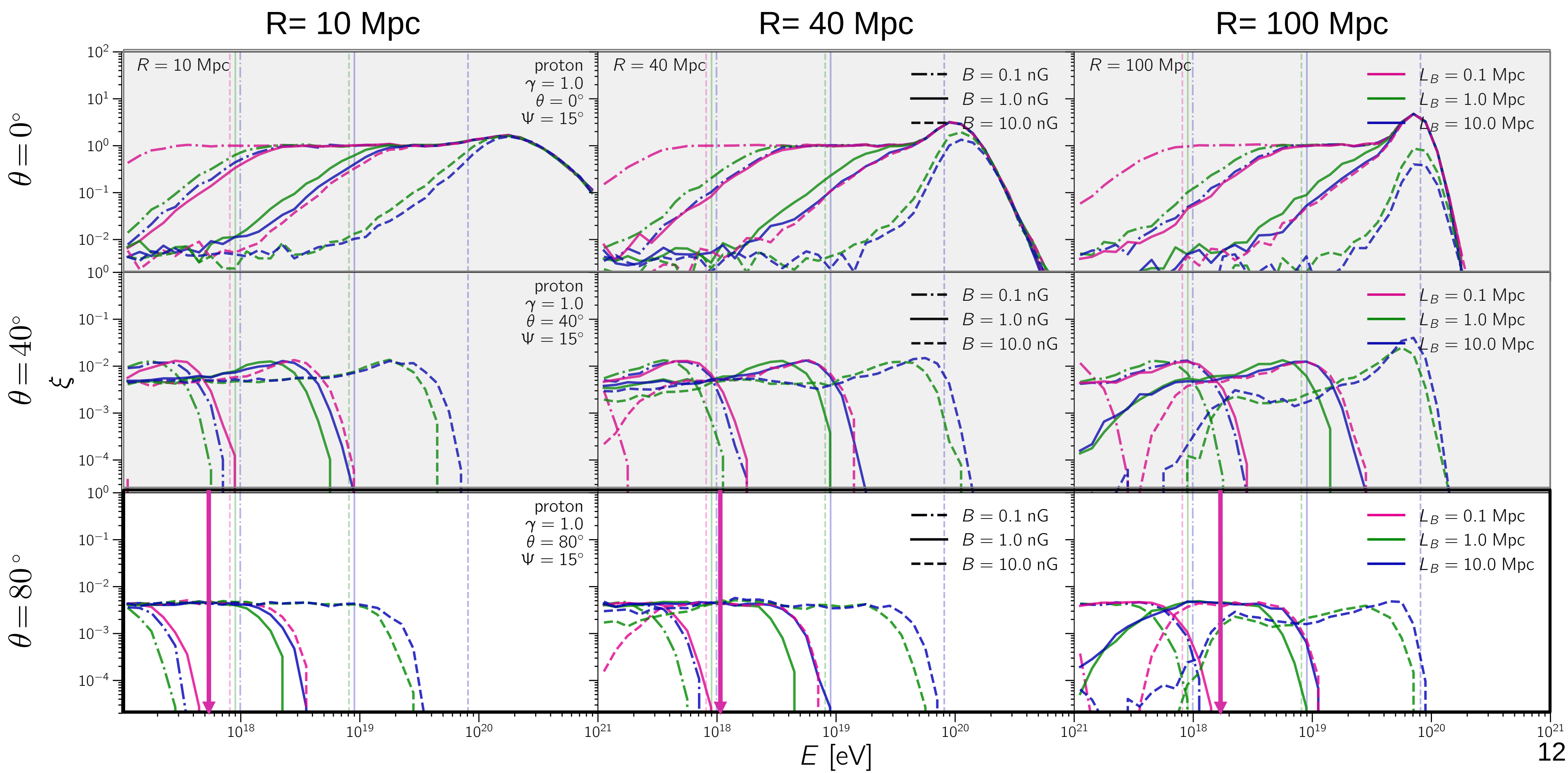
Pure-proton scenario



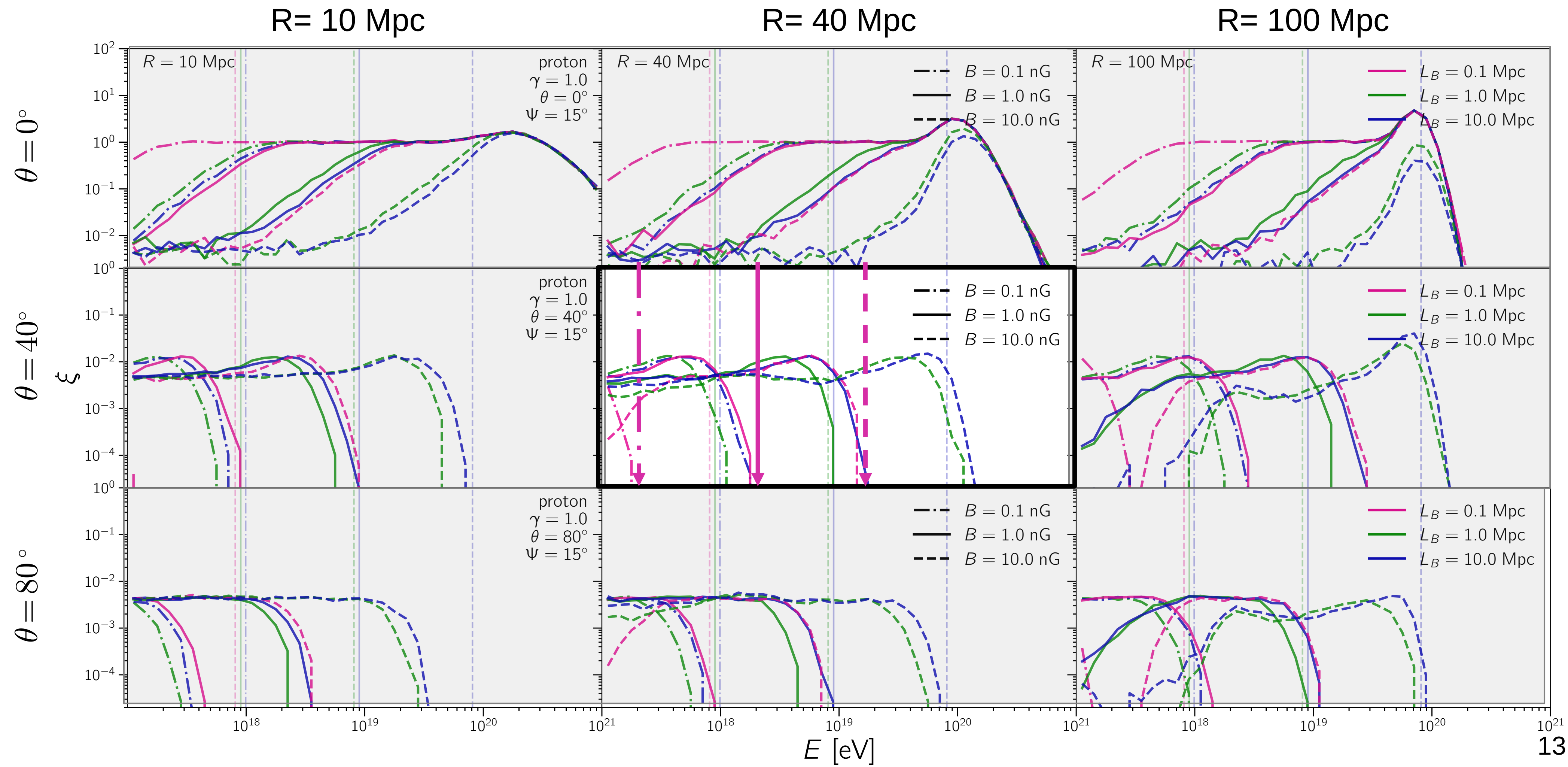
Pure-proton scenario



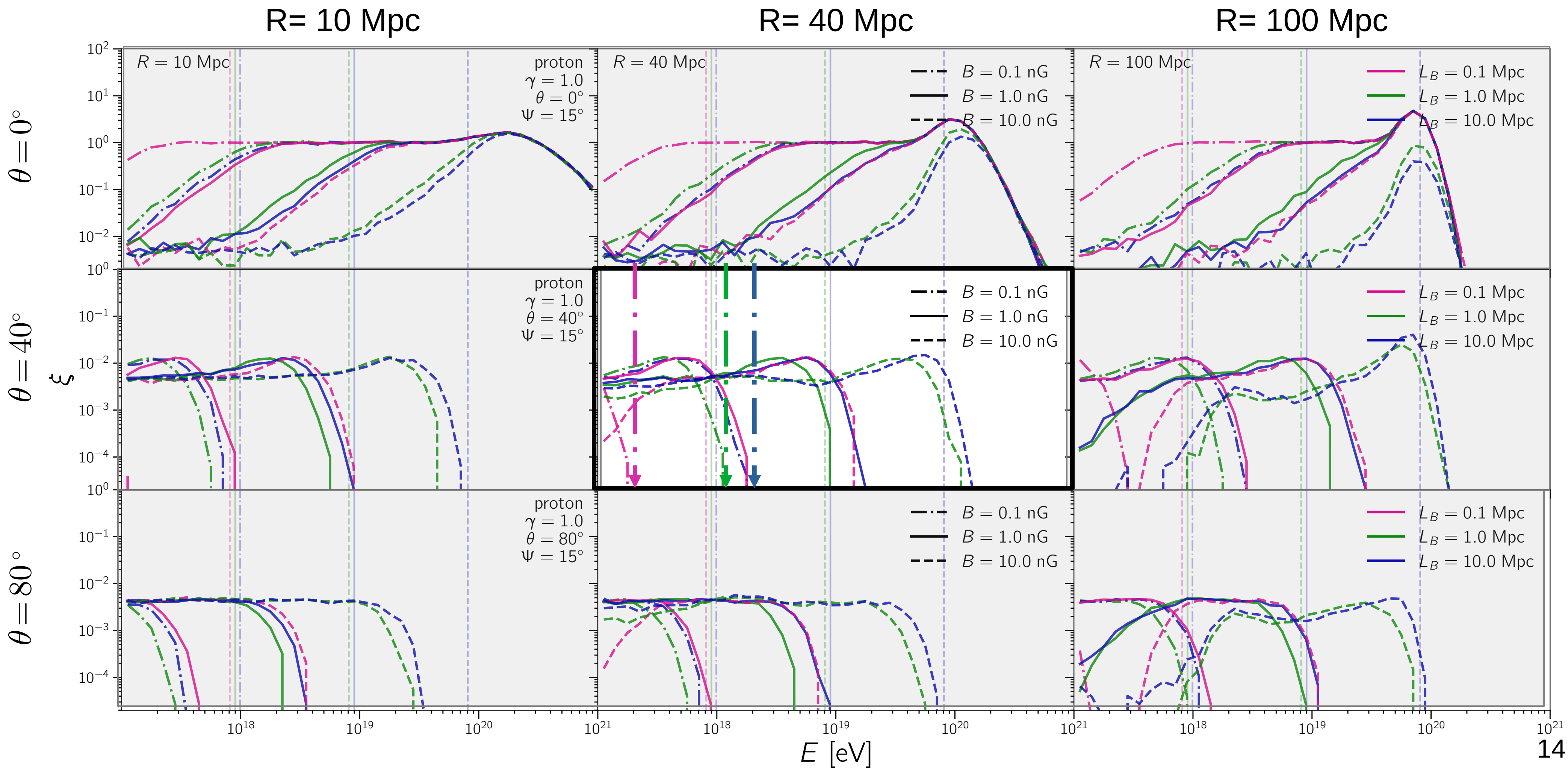
Pure-proton scenario



Pure-proton scenario



Pure-proton scenario



Conclusions

➔ The results of this study highlighted that:
- Extragalactic magnetic fields have a large impact on the spectra of UHECRs;
- For strong magnetic field strengths and/or large coherence length, misaligned jets can contribute to the total observed spectrum of UHECRs;
- Even for weak fields, we can see that in some scenarios the misaligned jetted sources can be important contributors to the lower-energy part of the spectrum;
- It is possible to constrain combinations of magnetic field strength and coherence length under the hypothesis of the dominant sources for UHECRs (undergoing analysis);

➔ For more details see Ref. [1].

Thank you!

Conselho Nacional de Desenvolvimento Científico e Tecnológico

References

[1] Sarah Soares Sippert, Carlos Magno R. da Costa, Rogerio M. de Almeida, Rafael Alves Batista and João R. T. de Mello Neto, Phys. Rev. D **112**, 083060 (2025)
[2] R. Alves Batista, A. Dundovic, and A. O. Erdmannn, J. Cosmol. Astropart. Phys. **09** (2022) 035
[3] A. N. Kolmogorov, Dolk. Akad. Nauk SSSR **30**, 301 (1941)
[4] R. Alves Batista, A. Saveliev, G. Sigl, and T. Vachaspati, Phys. Rev. D **94**, 083005 (2016)
[5] Andrea Addazi et al. Progress in Particle and Nuclear Physics, 2022.

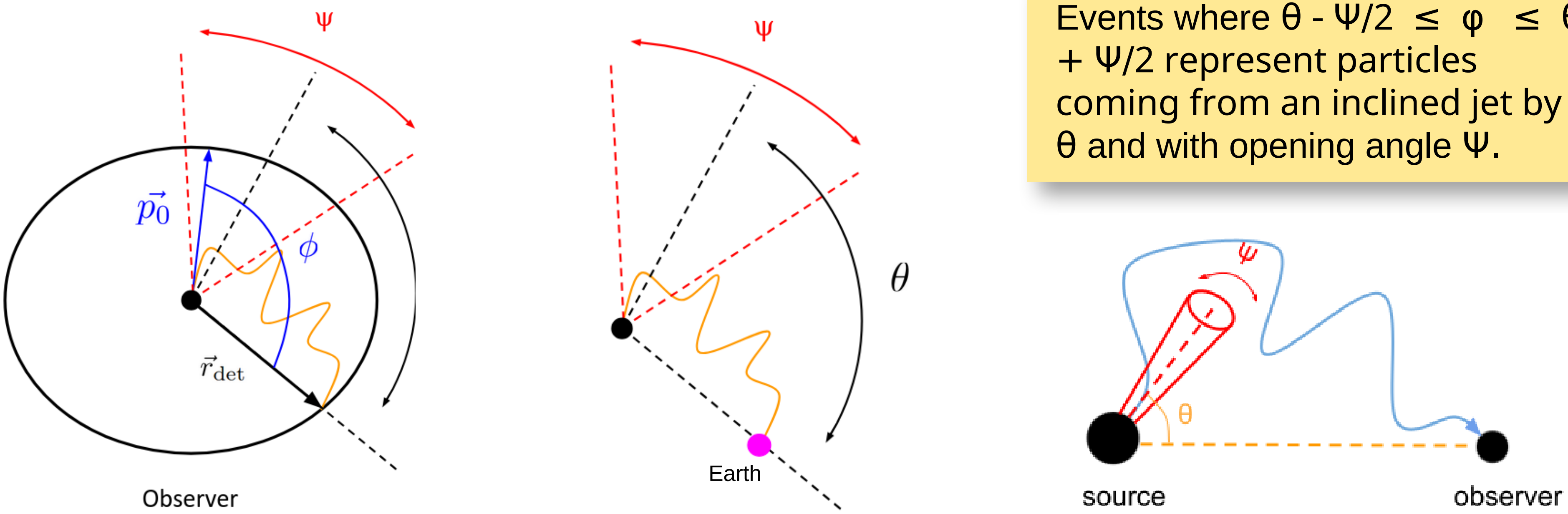
BACKUP

Simulation

→ Since the Earth dimension is negligible when compared to the vastness of the Universe, performing a 3-dimensional forward simulation of particle propagation from a specific extragalactic location to Earth is extremely time consuming and nearly impossible to achieve.

→ To overcome this issue, we use the large sphere approach [2].

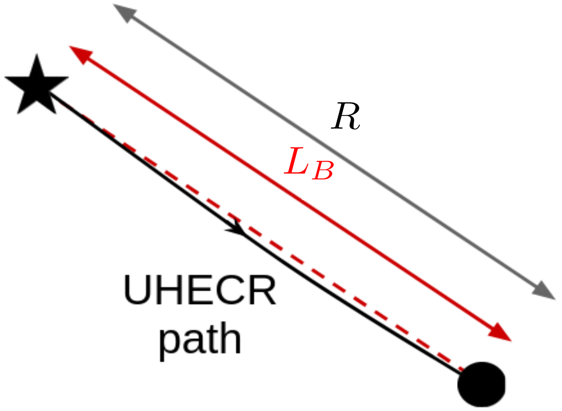
Events where $\theta - \Psi/2 \leq \varphi \leq \theta + \Psi/2$ represent particles coming from an inclined jet by θ and with opening angle Ψ.



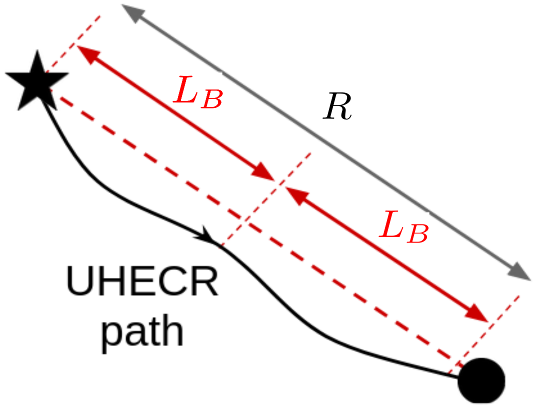
In the context of diffuse propagation, we define a critical energy E_c

$$E_c = Z|e|BL_B = 0.9Z\ (B/\mathrm{nG})\ (L_B/\mathrm{Mpc})\ \mathrm{EeV}.$$

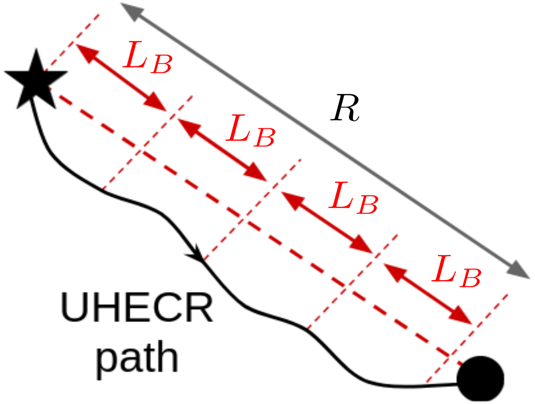
Ballistic regime: E $\gg$ E_c and $R \lesssim L_B$.



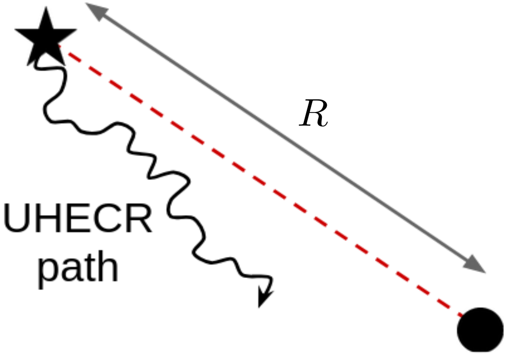
Non-resonant diffusion: E $\simeq$ E_c and $R \gtrsim L_B$.



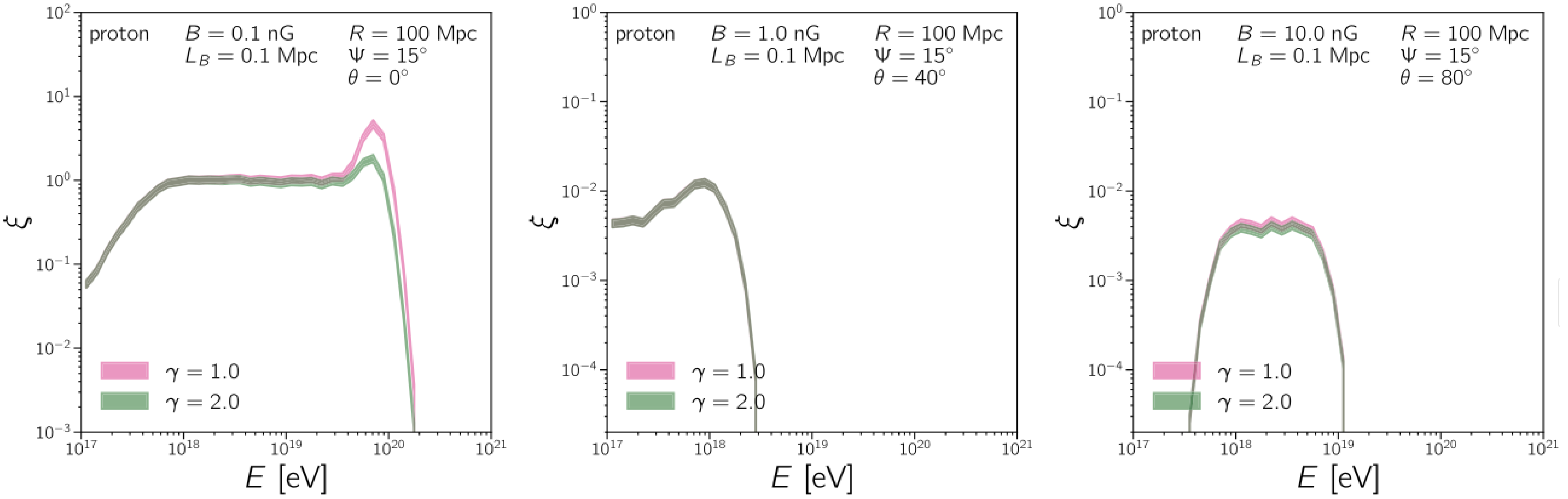
Resonant diffusion: E < E_c and $R > L_B$.



Magnetic horizon: E $\ll$ E_c and $R \gg L_B$.

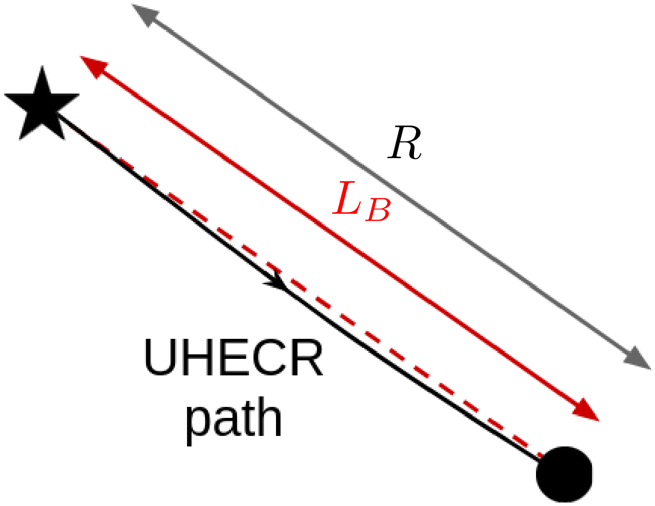


Comparison between different spectral index γ

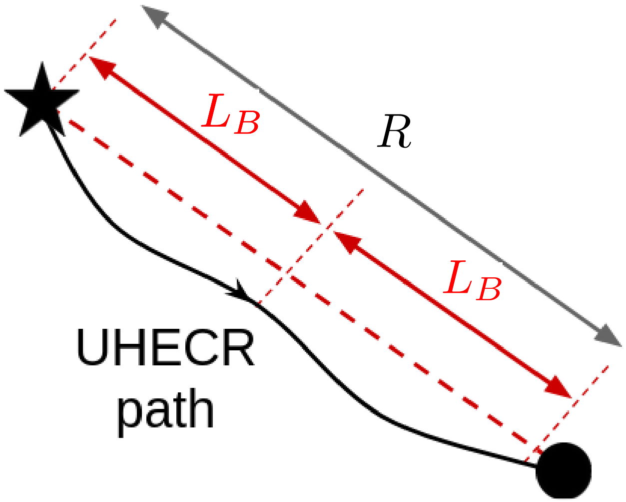


There is not significant change when altering the spectral index.

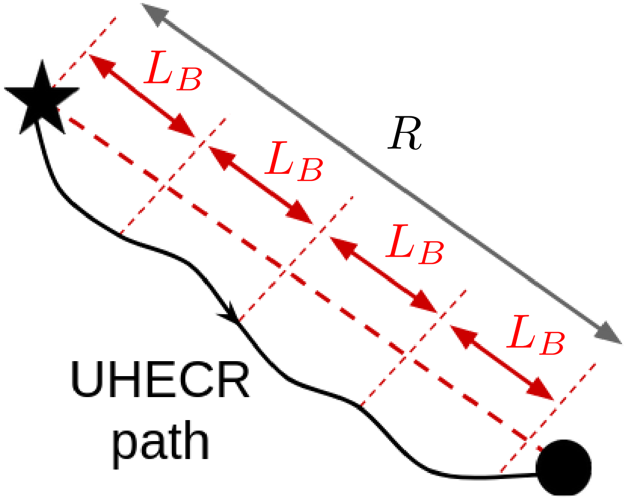
Ballistic regime: E $\gg$ E_c and $R \lesssim L_B$.



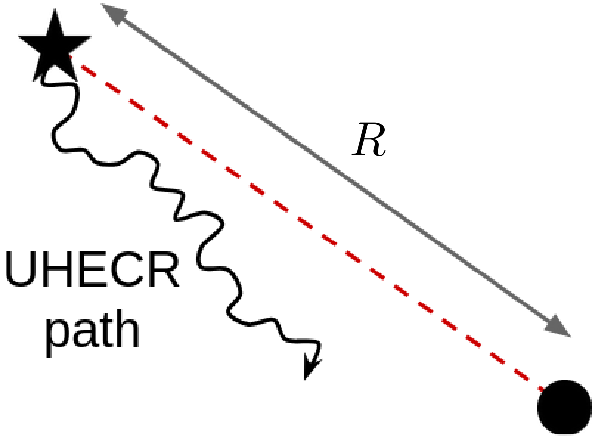
Non-resonant diffusion: E $\simeq$ E_c and $R \gtrsim L_B$.



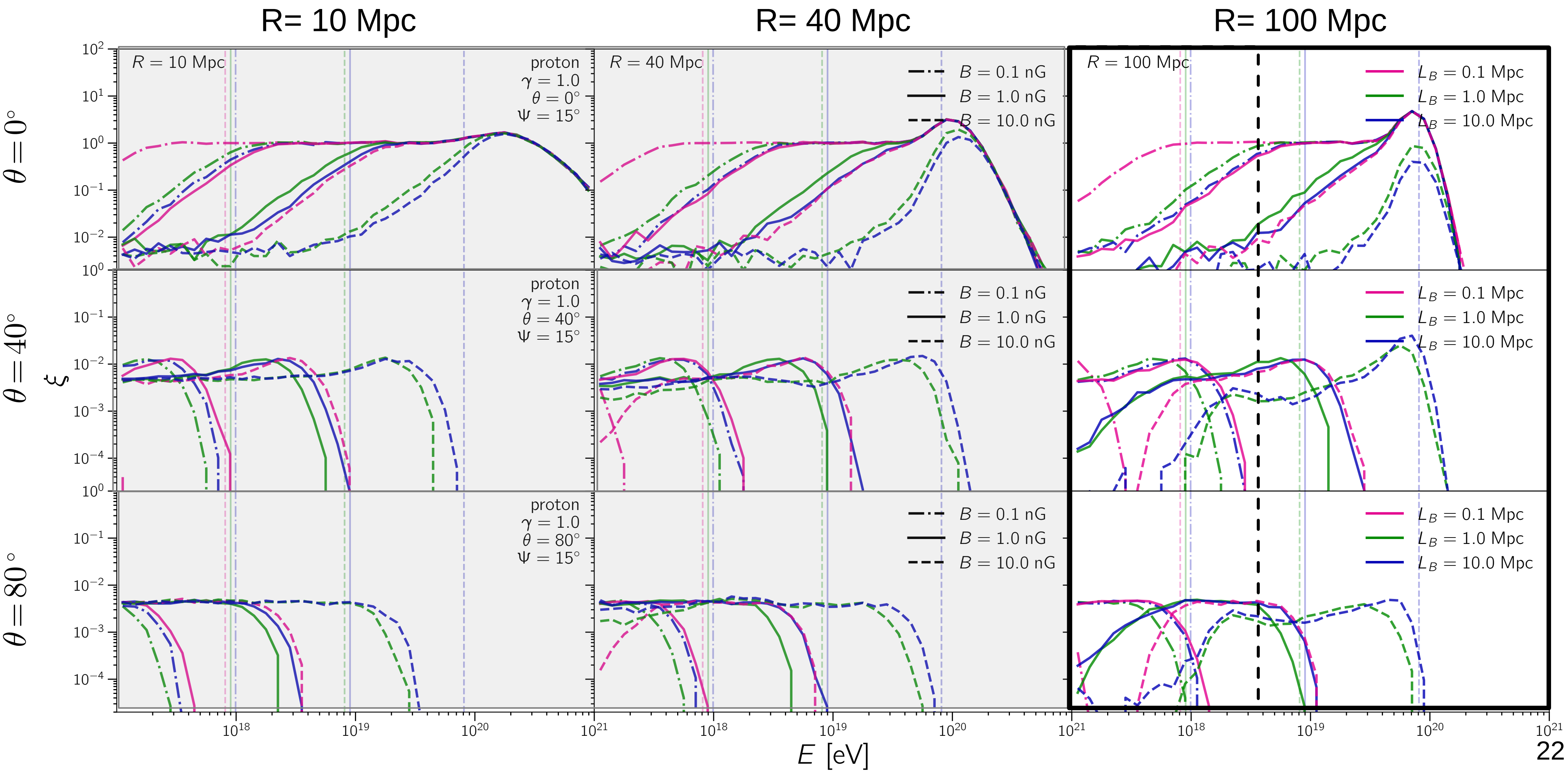
Resonant diffusion: E < E_c and $R > L_B$.



Magnetic horizon: E $\ll$ E_c and $R \gg L_B$.



Pure-proton scenario

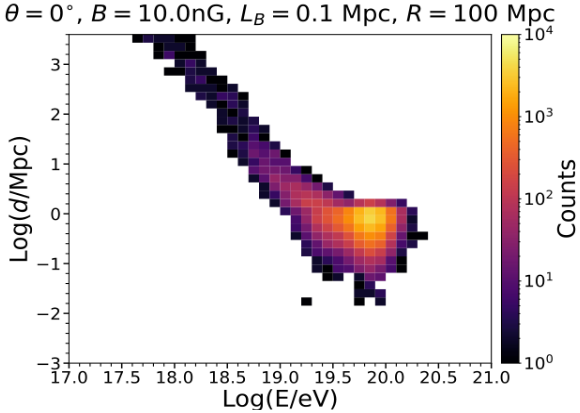


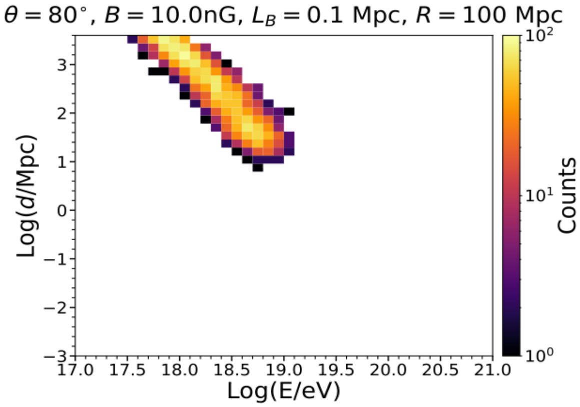
Trajectory elongation d

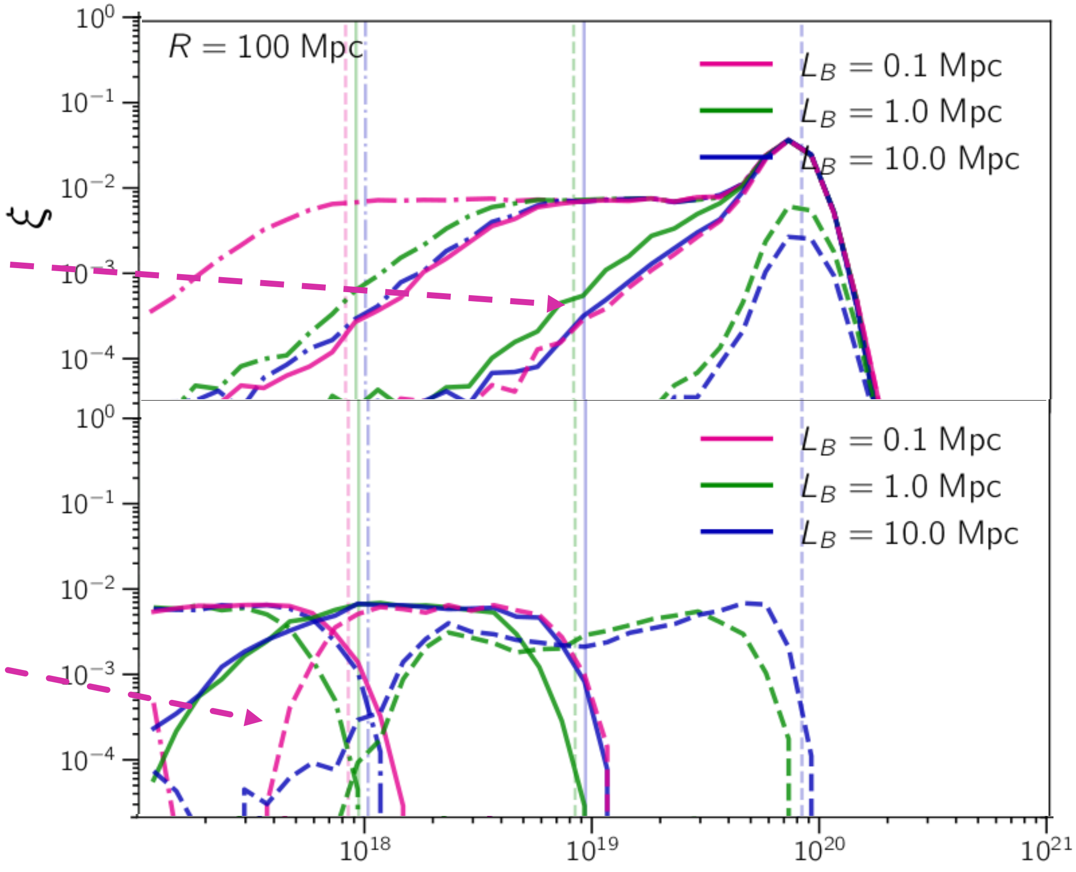
The trajectory elongation is defined as the difference between the distance traveled by the particle and the source-Earth distance.

$$d \equiv c\tau - R$$

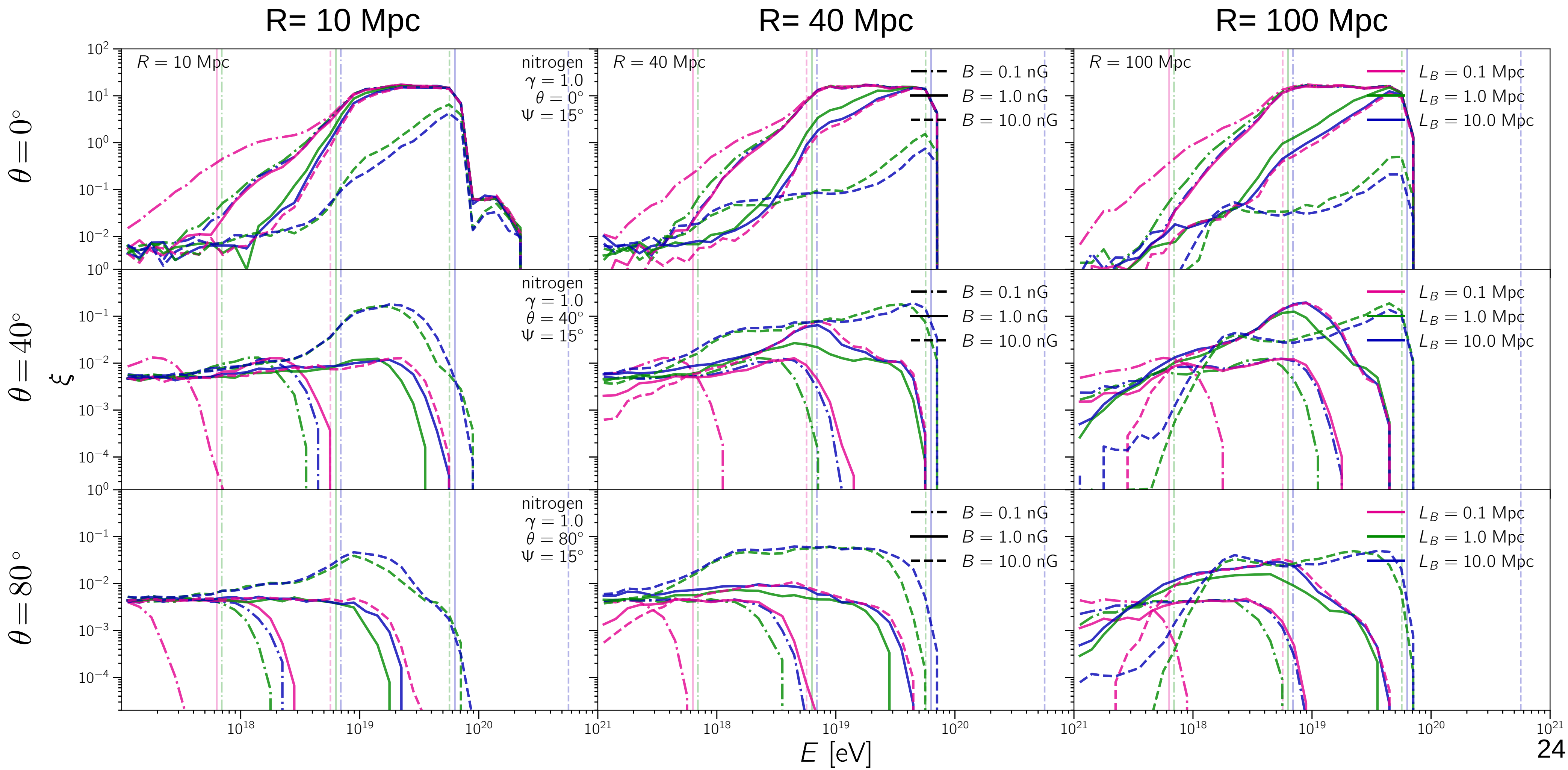
Analyzing two cases of interest



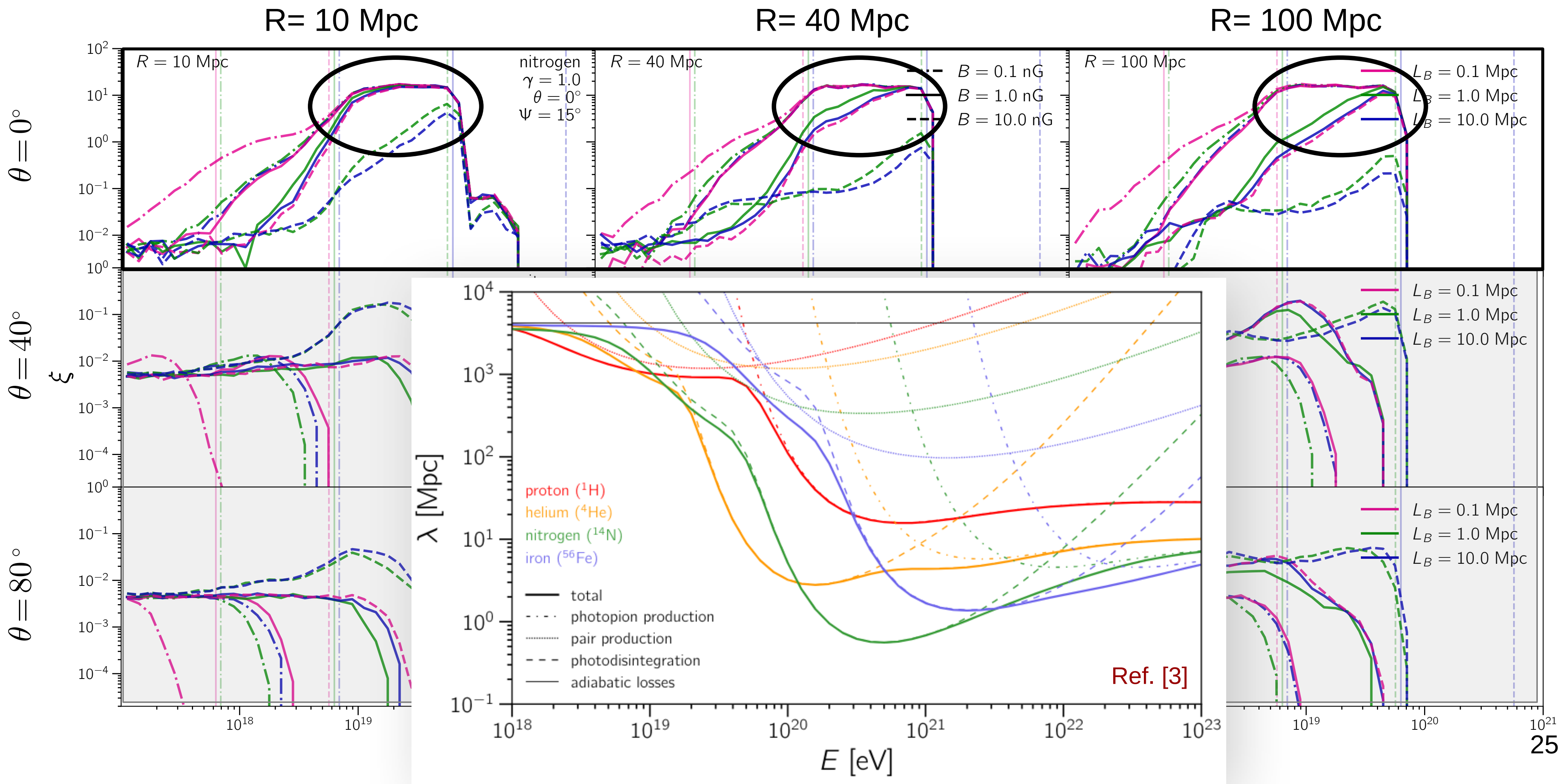




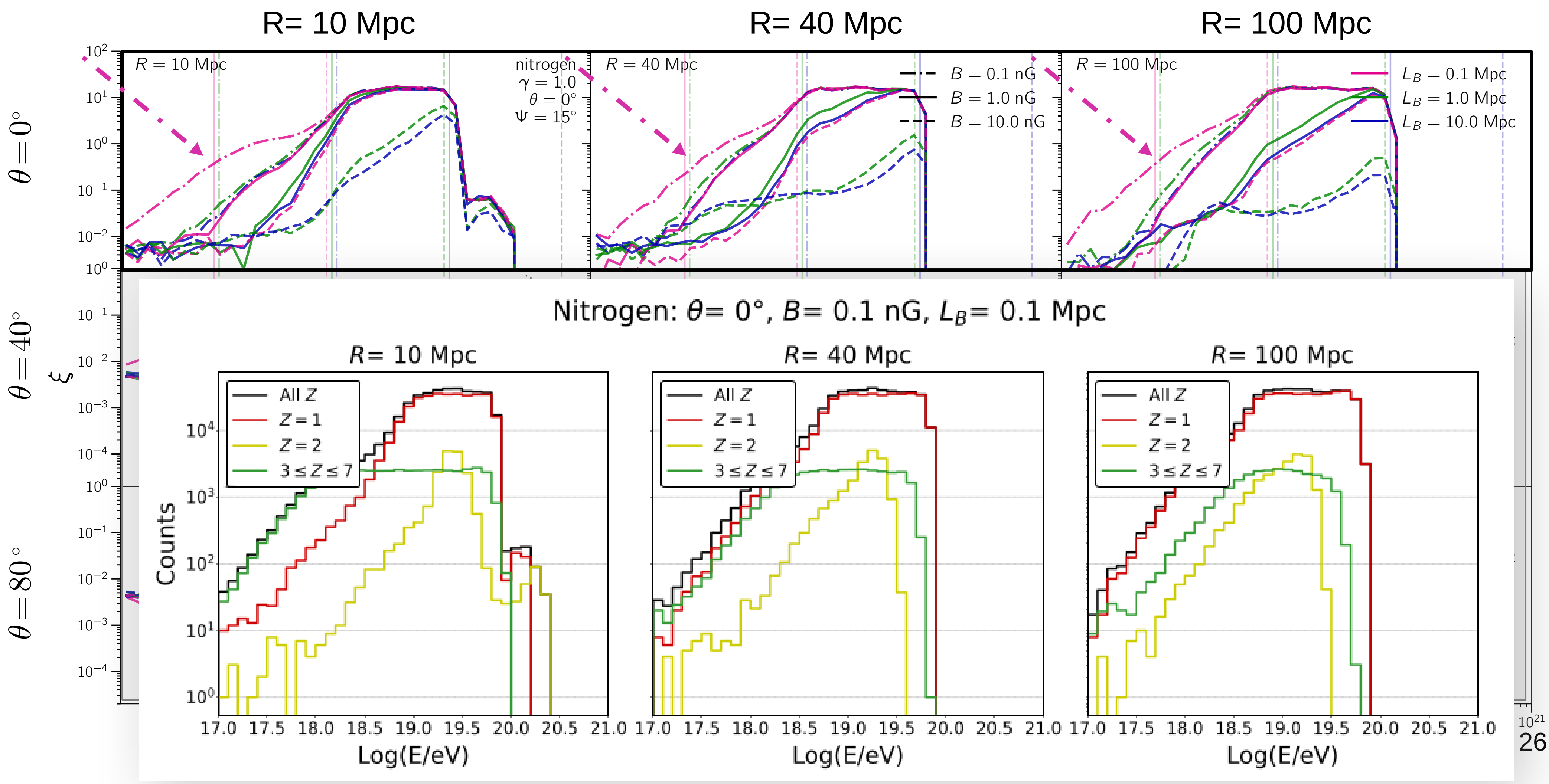
Case of nuclei – Nitrogen primary



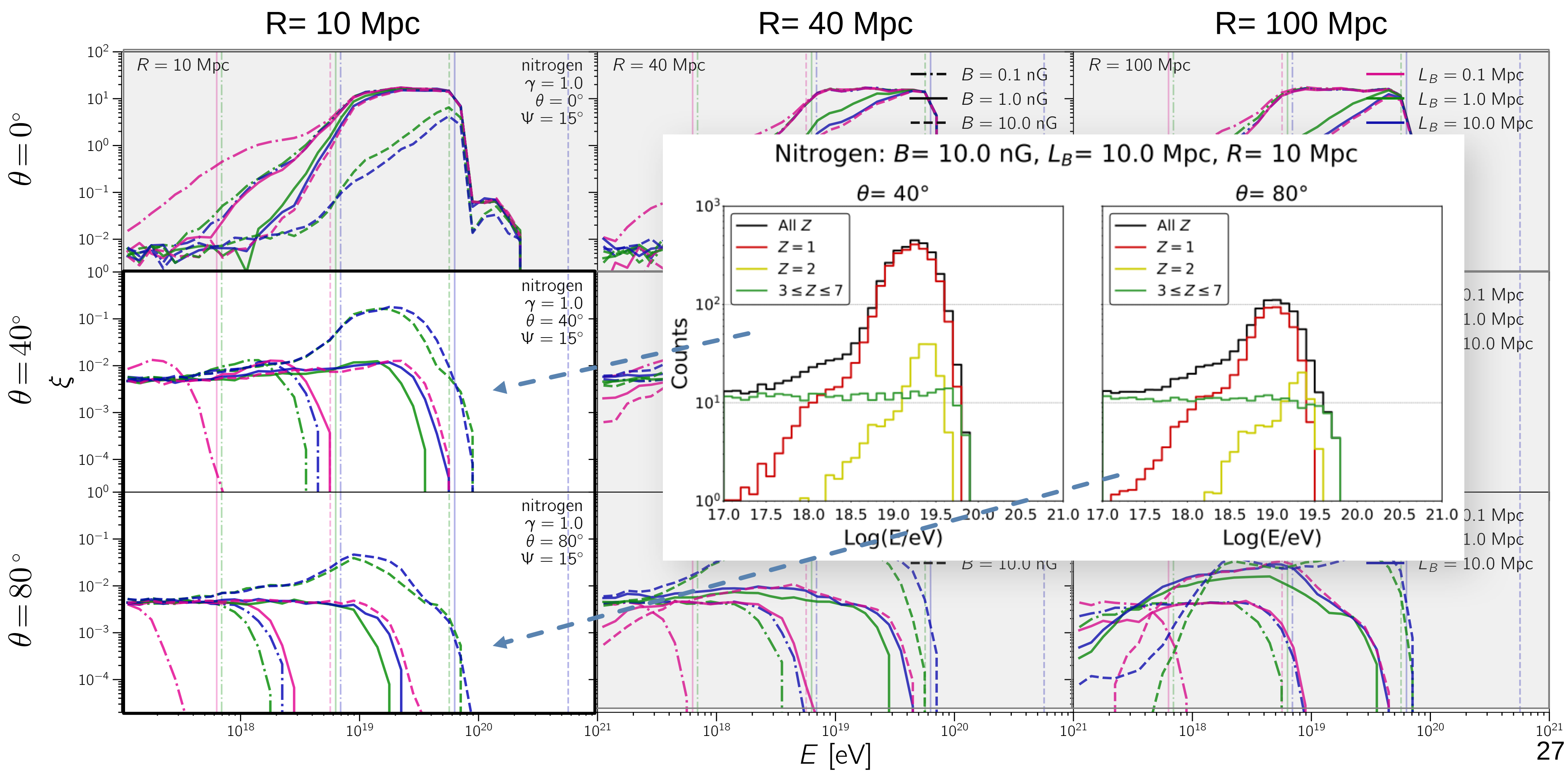
Case of nuclei – Nitrogen primary



Case of nuclei – Nitrogen primary

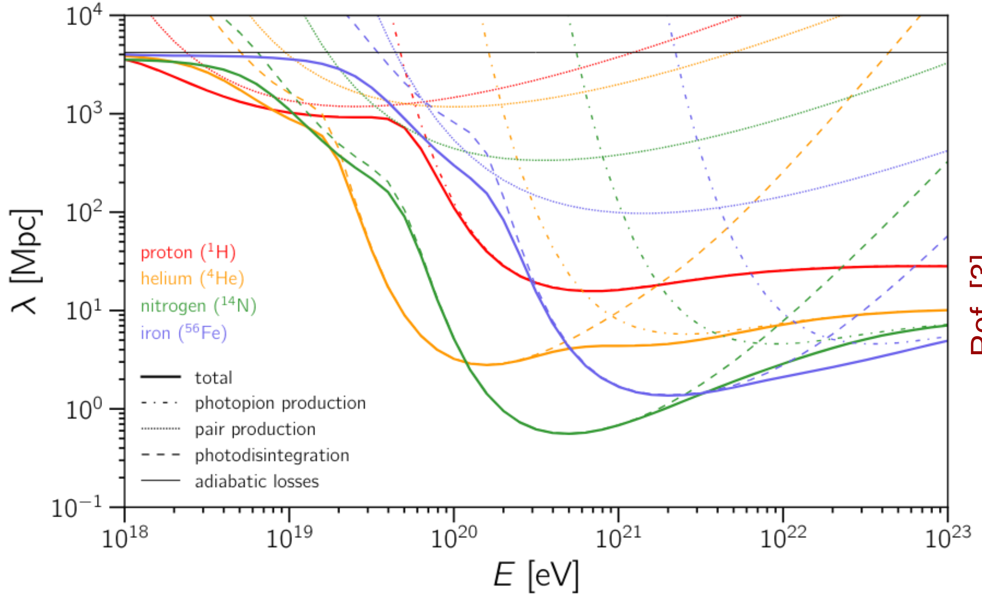


Case of nuclei – Nitrogen primary



Energy loss processes

$$\lambda^{-1} = -\frac{1}{E}\frac{dE}{dR}.$$



Ref. [3]