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Effects of cosmic voids on the propagation of VHE gamma rays and the spectra of GRB 221009A


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Abstract

The recent detection of gamma-ray burst GRB 221009A has attracted attention due to its record brightness and first-ever detection of > 10 TeV gamma rays from a GRB. Despite being the second-nearest GRB ever detected, at a redshift of z = 0.151, the distance is large enough for severe attenuation of gamma-ray flux at these energies due to gamma-gamma pair production with the extragalactic background light (EBL). We have investigated whether the presence of cosmic voids along the line of sight can significantly impact the detectability of VHE gamma rays from distant sources. We find that the gamma-gamma opacity for VHE gamma rays can be reduced by approximately 10% and up to 30% at around 13 TeV, the highest-energy photon detected from GRB 221009A, for intervening cosmic voids along the line-of-sight with a combined radius of 110 Mpc, typically found from voids catalogs, and 250 Mpc, respectively. This reduction is substantially higher for TeV photons compared to GeV photons, attributable to the broader target photon spectrum that TeV photons interact with. This finding implies that VHE photons are more susceptible to variations in the EBL spectrum, especially in regions dominated by cosmic voids. Our study sheds light on the detection of > 10 TeV photons from GRB 221009A in particular, and on the detection of extragalactic VHE sources in general.

GRB 221009A

- GRB 221009A has been detected by LHAASO in the 0.2-20 TeV range.
- At a redshift 0.151 TeV γ rays are significantly attenuated by EBL due to γγ → e+e- production, requiring huge energy to be injected from GRB 221009A to explain observations.
- After checking with the SDSS DR7 void catalog, we find that it is plausible that GRB 221009A took place inside a cosmic void and γ rays propagated to Earth through mostly void regions.
- The γγ opacity is reduced for γ rays propagating in voids because of lower EBL density.
- We fit spectrum of GRB 221009A measured by LHAASO in two time intervals: T_0 + (230-300s) and T_0 + (300-900s) using γ-ray propagation both in homogeneous EBL and in voids.
- Using a likelihood analysis, we find that TeV data is fitted better with the voids, although the required size of the void regions depends on EBL models.
- Energy requirement to power VHE emission is reduced with the voids.

Cosmic voids affect γ-ray propagation

Emissions from stars and dust:

$$\epsilon j^{stars}(\epsilon, z_e) = m_e c^2 \epsilon^2 f_{esc}(\epsilon) \int_{m_{\min}}^{m_{\max}} dm\, \xi(m) \times \int_{z_e}^{z_{\max}} dz_1 \left|\frac{dt_*}{dz_1}\right| \psi(z_1) \dot{N}(\epsilon, m, t_*[z_e, z_1])$$

$$\epsilon j^{dust}(\epsilon, z_e) = \frac{15}{\pi^4} \int d\epsilon \left[\frac{1}{f_{esc}(\epsilon)} - 1\right] j^{stars}(\epsilon, z_e) \times \sum_{n=1}^{3} \frac{f_n}{\Theta_n^4} \frac{\epsilon^4}{\exp\left(\frac{\epsilon}{\Theta_n}\right) - 1}$$

$$\left|\frac{dt_*}{dz_1}\right| = \frac{1}{H_0(1+z_1)\sqrt{\Omega_m(1+z_1)^3 + \Omega_\Lambda}} \qquad \epsilon' = \epsilon(1+\tilde{z}) = \frac{(1+\tilde{z})}{(1+z)}\epsilon_p$$

EBL density:

$$\epsilon_p u_{\mathrm{EBL},p}(\epsilon_p, z, \Omega) = (1+z)^4 \int_z^{z_{\max}} d\tilde{z} \left|\frac{dt}{d\tilde{z}}\right| \frac{\epsilon' j(\epsilon', \tilde{z}, \Omega)}{(1+\tilde{z})} f_{\mathrm{void}}(z, \tilde{z}, \Omega)$$

$$f_{\mathrm{void}}^{\mathrm{outside}} = \begin{cases} 0 & \text{if } \ell_1(\theta) < \tilde{\ell} < \ell_2(\theta) \\ 1 & \text{otherwise,} \end{cases} \qquad f_{\mathrm{void}}^{\mathrm{inside}} = \begin{cases} 0 & \text{if } \tilde{\ell} < \ell_1(\theta) \\ 1 & \text{otherwise,} \end{cases}$$

γγ opacity:

$$\tau_{\gamma\gamma}(E, z_s) = c \int_0^{z_s} dz_1 \left|\frac{dt}{dz_1}\right| \int_0^\infty d\epsilon_1 \times \oint d\Omega \frac{\mu_{\epsilon_1}(\epsilon_1, z_1, \Omega)}{\epsilon_1} (1-\mu)\sigma_{\gamma\gamma}(s)$$

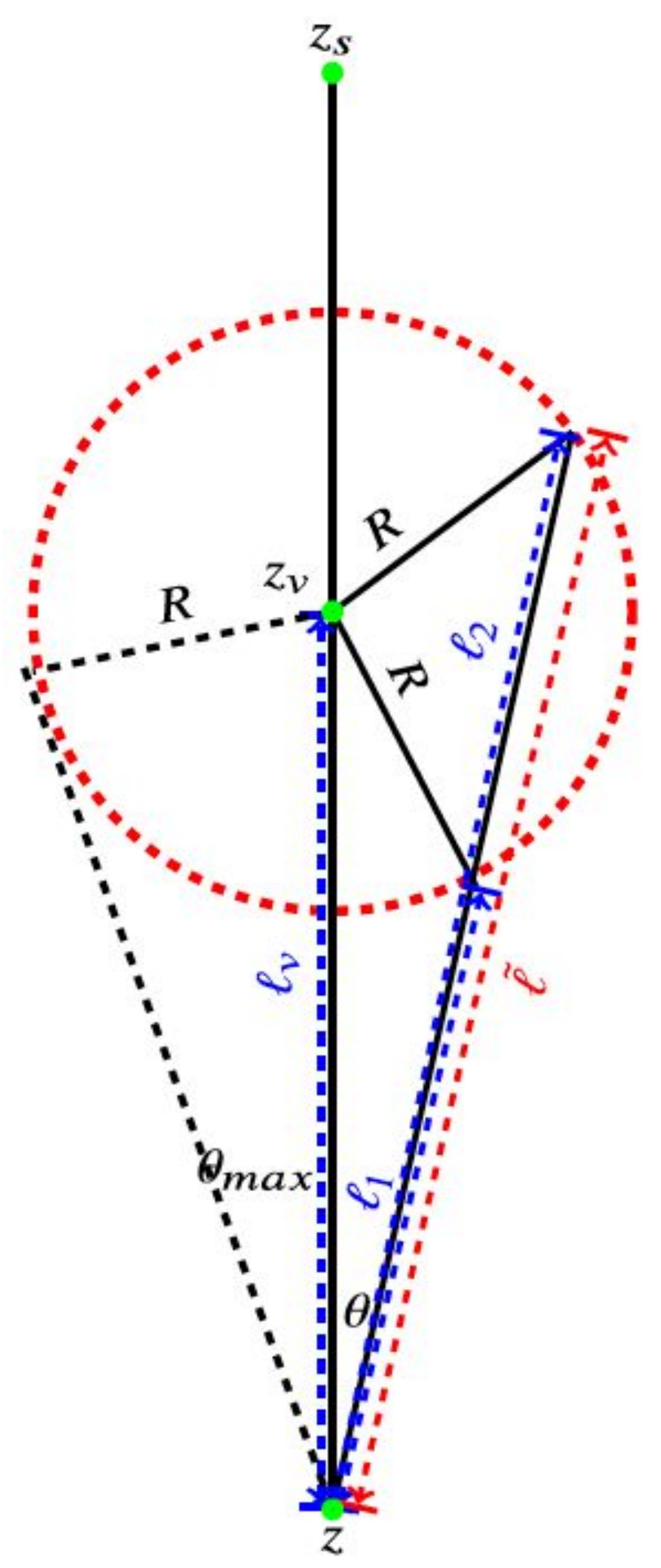
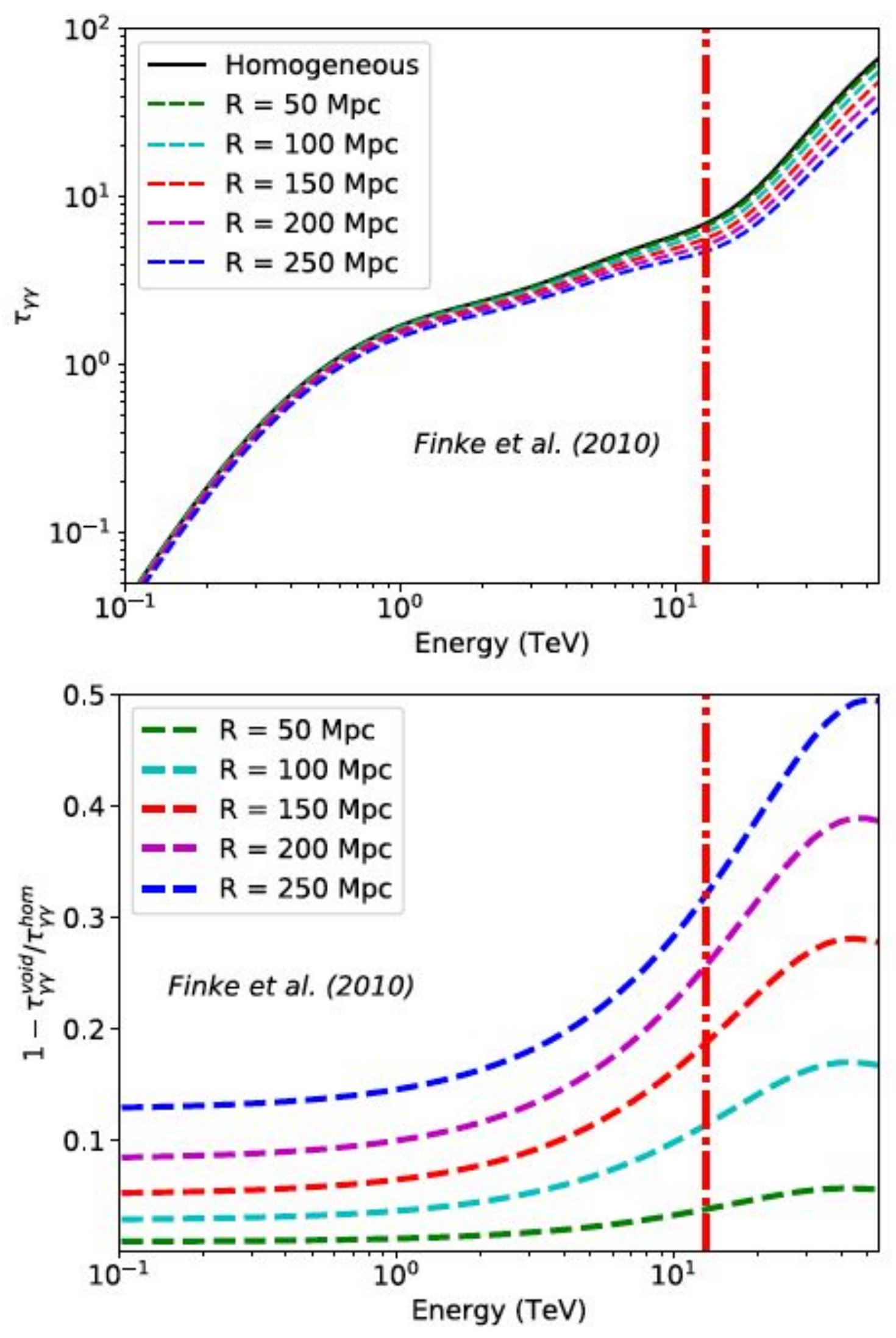


Illustration of an underdense region (void) situated between us and the source at redshift z_s, where a gamma-ray photon is emitted from the source and travelling towards the observer. The void is assumed to have a radius of R, and the redshift at its centre is denoted as z_v. The distances $l_{1,2}$ represent the points where the direction of travel of the EBL photon intersects the boundaries of the void. l_v is the distance from the photon's position at redshift z to the centre of the void, and θ_{max} represents the maximum angle at which the direction of travel of the EBL photon still intersects the boundary of the void at one point (Abdalla et al. 2024).

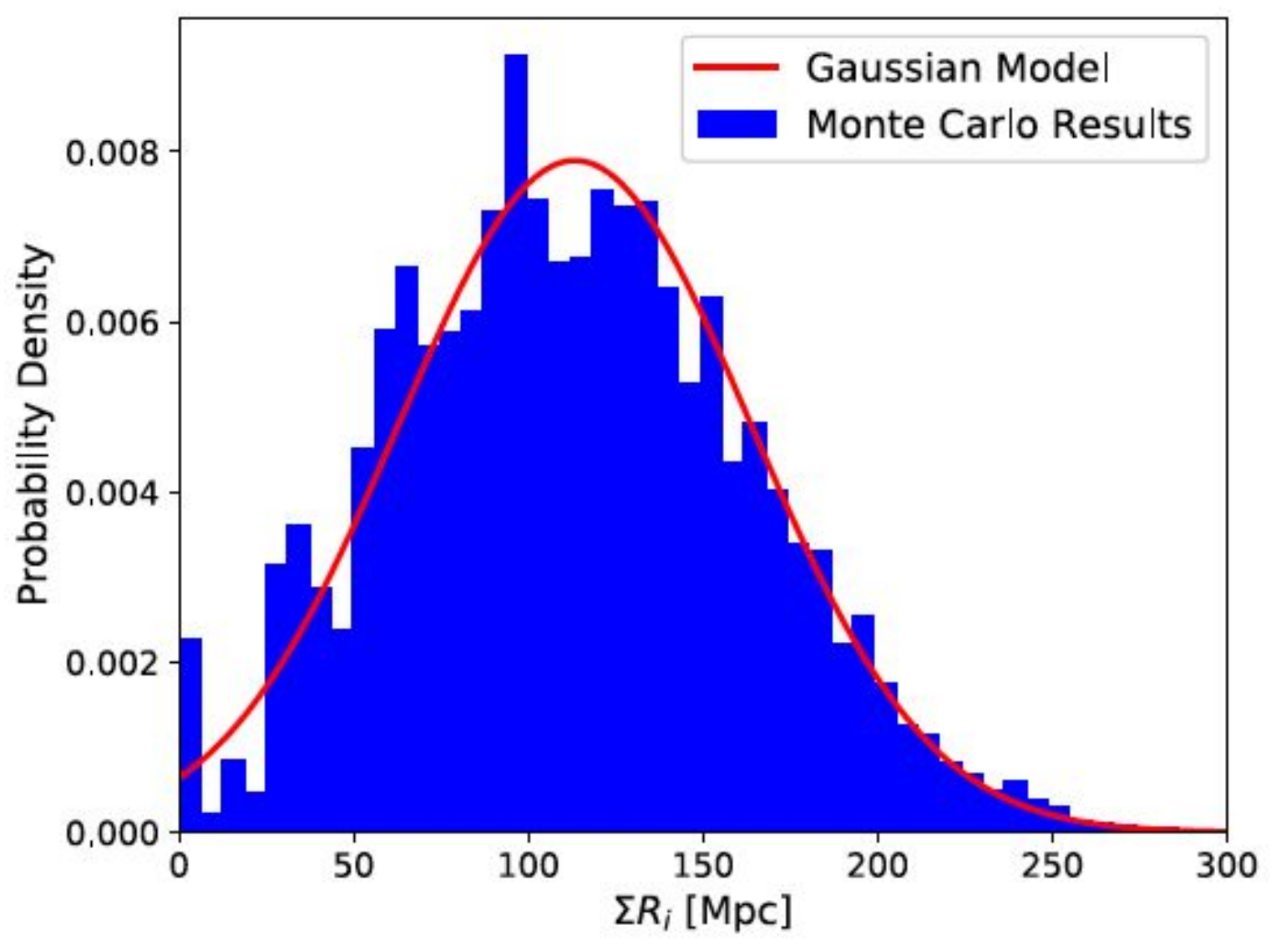
Impact of voids on γγ opacity



Top panel: γγ → e+e- optical depth due to the EBL as a function of the γ-ray energy for a source located at redshift z = 0.151. The black solid line indicates the optical depth for a homogeneous EBL distribution. The dashed lines show the opacities in the presence of voids of various sizes, as indicated by the legend. The vertical red dot-dashed line in both panels indicates a photon energy of 13 TeV.
Bottom panel: Relative deficit of the optical depth with and without voids as a function of the γ-ray energy for the same cases as in the top panel (Abdalla et al. 2024).

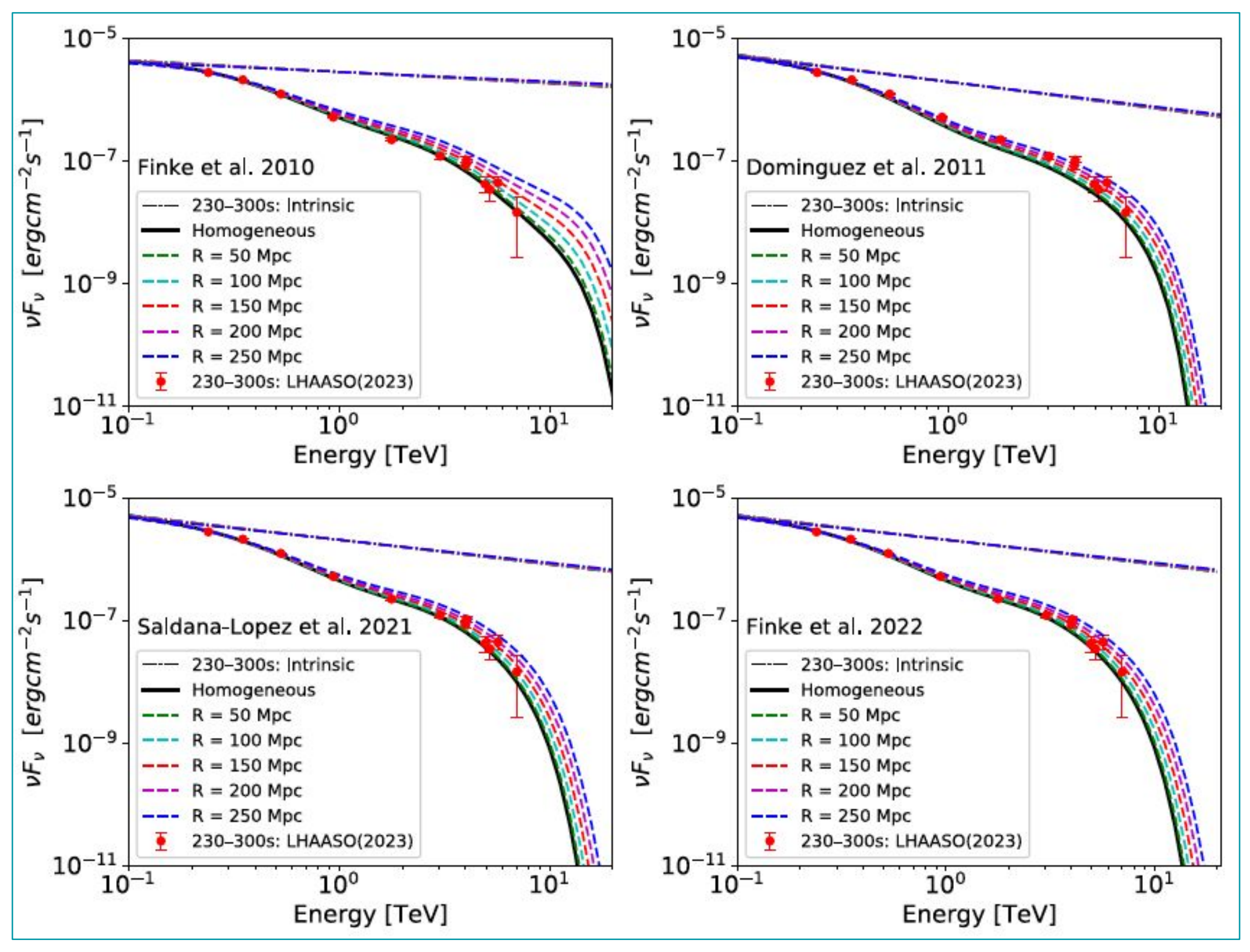
Fitting TeV data with voids

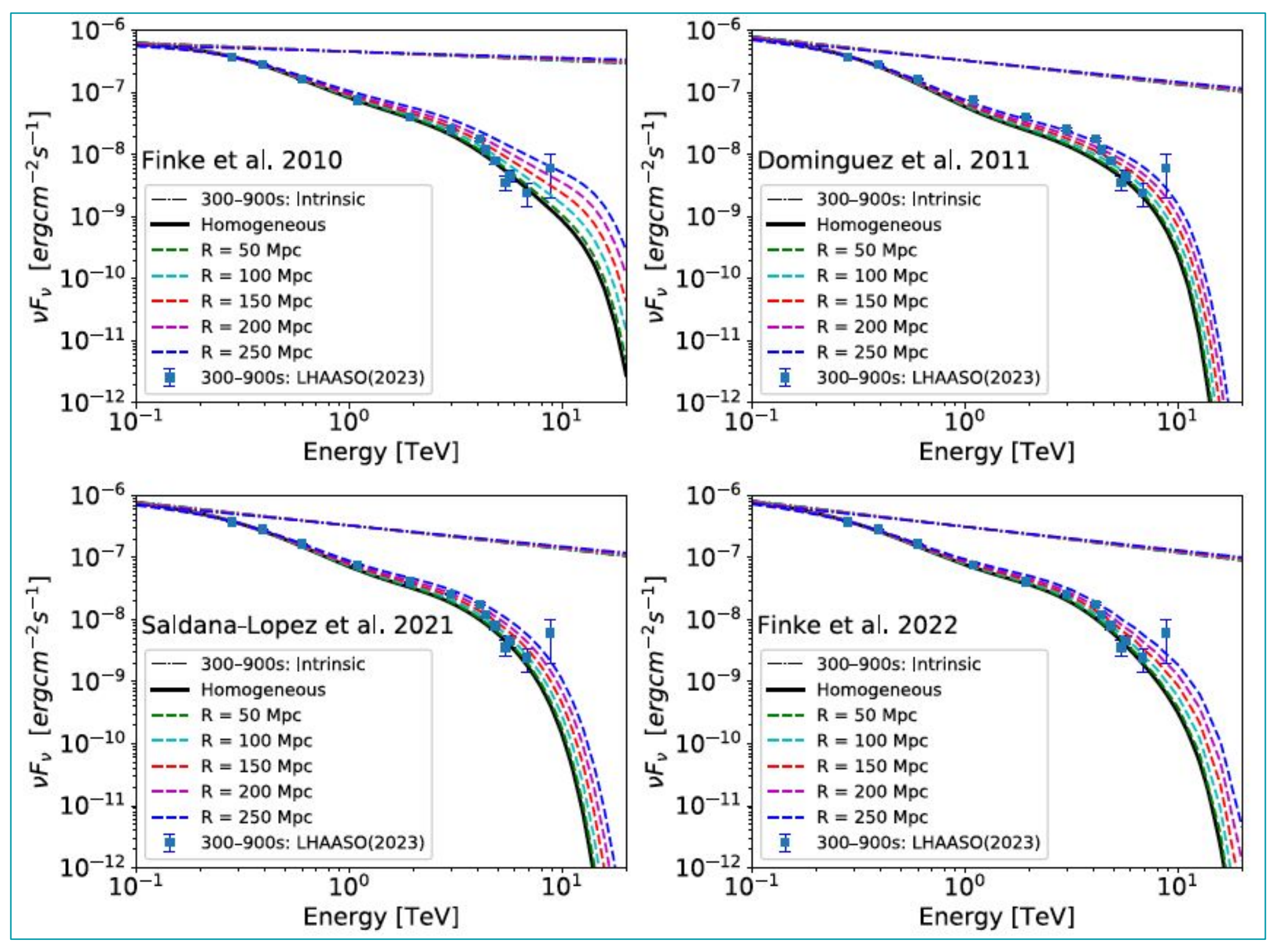
Typical size of void regions



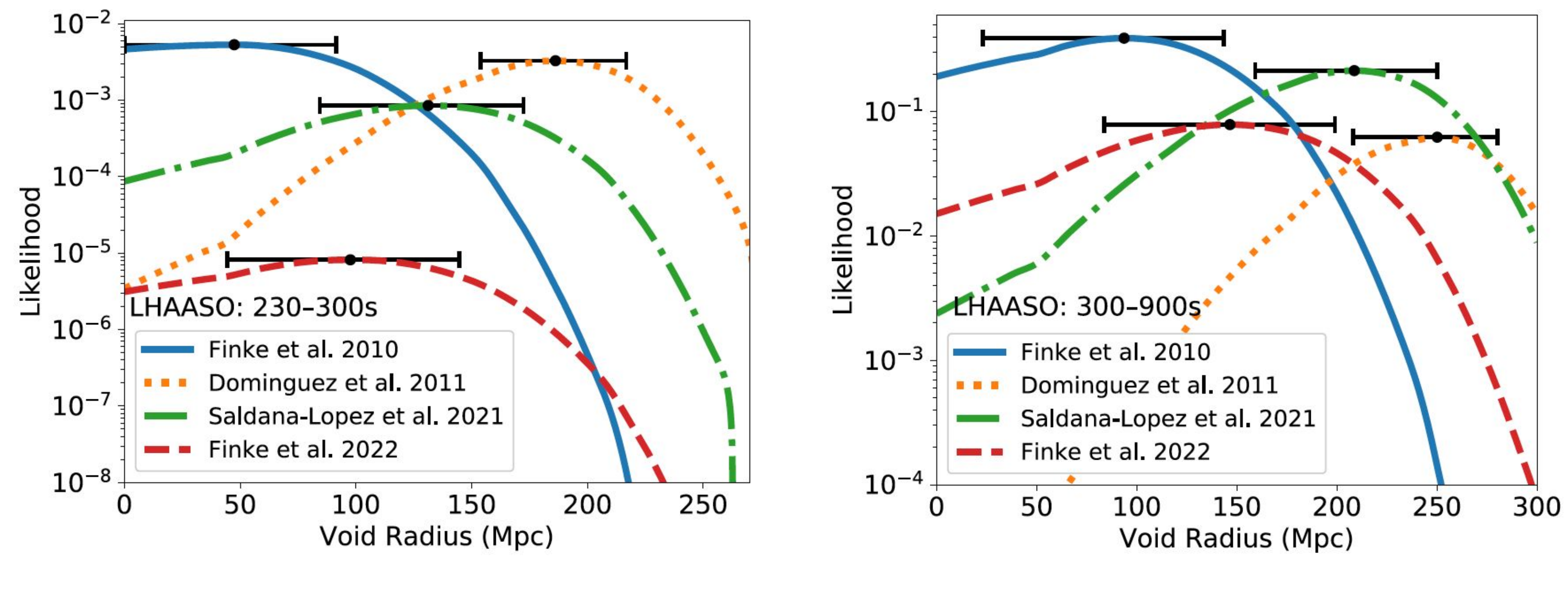
Results of Monte Carlo simulations of the cumulative effective radii of voids within spherical regions, situated between us and various random coordinates, based on SDSS DR7 void catalog (Douglass et al. 2023). These coordinates fall within the Right Ascension (RA) range of 140° to 230° and the Declination (Dec) range of 10° to 60°. The Gaussian distribution, depicted by the red line, has a mean of 113 Mpc and a standard deviation of 50 Mpc.

LHAASO spectra during two intense emission periods





The data points are LHAASO observations for the interval from T_0 + 230 s to T_0 + 300 s (**top 4 panels**) and T_0 + 300 s to T_0 + 900 s (**bottom 4 panels**), and the intrinsic spectrum obtained through a power- law (PL) model is represented by the solid line, employing the EBL models described in Finke et al. (2010, 2022), Domınguez et al. (2011), and Saldana- Lopez et al. (2021). The anticipated EBL-induced absorption, as estimated by the indicated EBL models, is represented by the solid line. Additionally, we explore the influence of cosmic voids by incorporating various void sizes, depicted as dashed lines.



The likelihood for the data set from both intervals, T_0 + 230 s to 300 s (**left panel**) and T_0 + 300 s to 900 s (**right panel**), obtained by fitting a power-law (PL) model under various EBL models while assuming different quantities of voids in each scenario, is depicted by the solid line. The maximum likelihood value for each model is marked by vertical dashed lines, with colours corresponding to each specific EBL model represented by the solid lines.

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