INVESTIGATION OF THE INFLUENCE OF AN UPDATED MODEL FOR THE EXTRAGALACTIC BACKGROUND LIGHT ON THE MULTIMESSENGER SIGNATURES OF BLAZAR 3C279 WITH CRPROPA

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MOTIVATION AND CONTEXT

In recent decades, the analysis of various multimessenger signals of secondary particles, such as photons and neutrinos, has proven to be very promising for the investigation of extragalactic sources of cosmic rays and their intrinsic mechanisms and properties. Numerical simulations are often undertaken to comprehensively analyze the information carried by these messengers and to investigate the validity of various astrophysical scenarios. Since physical predictions taking into account cosmic particle interactions depend significantly on modeling extragalactic photon fields, in this work an updated model for the extragalactic background light was incorporated into the CRPropa simulation software to study its effects on γ signals from the source 3C279. After the successful implementation in CRPropa, this revealed some differences from previous models. In particular, the updated photon field showed a higher prediction of scattered photons due to the Inverse Compton Effect when studying electromagnetic cascades, while the general opacity of the universe for gamma rays is lower than in other modeling.

EXTRAGALACTIC BACKGROUND LIGHT

Across many orders of magnitude of the electromagnetic spectrum, a diffuse radiation field of photons can be identified, which approximately isotropically permeates extragalactic space. While for example the origin and shape of the cosmic microwave background is well known, a large number of different models and empirical constraints exist for large portions of this radiation. Regarding the interactions explained below, three domains of the total radiation field - the cosmic radio background (CRB), the microwave background (CMB) and the extragalactic background light (EBL) - are now mainly relevant. For the latter, an updated model by Finke et al. 2022 was examined in this work.
The EBL is dominated by starlight from many epochs of cosmic history, either through direct (optical) emissions or through absorption and (thermal) reemission of dust particles. Against this background, its typical spectral shape and in particular the formation of the intensity peaks around $10^{-2}\,\mathrm{eV}$ and $1\,\mathrm{eV}$ can be well understood. Even if, for example, galaxy counting makes it possible to provide certain lower limits, there is still no general consensus on the exact shape of the EBL.

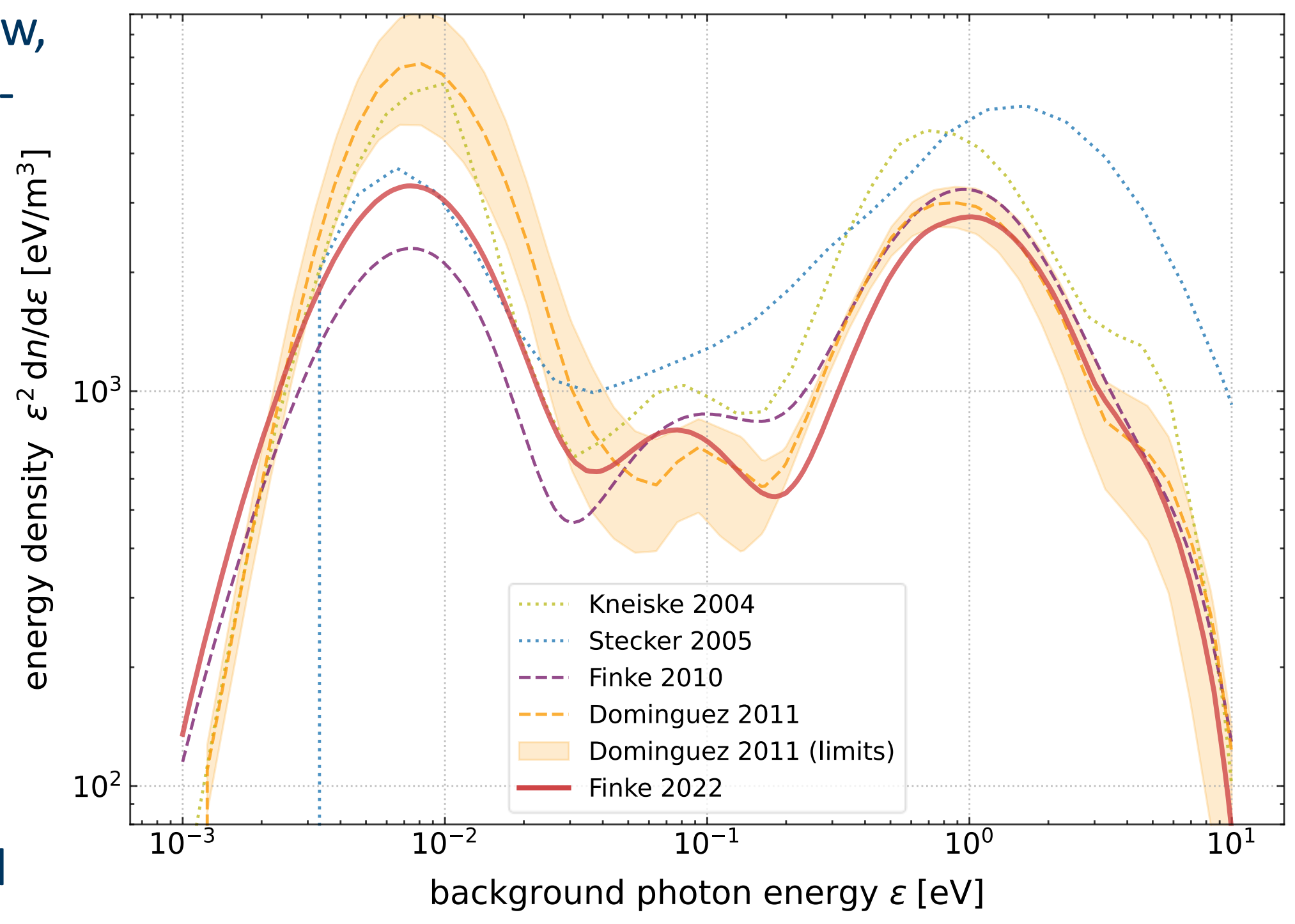

Fig. 1: Some modelings of the EBL (at z=0) in comparison. The predominantely important model from Finke et al. 2022 for this work is highlighted in red here.

INTERACTIONS

Charged cosmic rays interact via various processes with gas and radiation fields in the vicinity of sources as well as with photon fields during their propagation through extragalactic space, producing high-energy photons and neutrinos. Since the trajectories of these uncharged particles are not influenced by magnetic fields, they potentially point to their original source and therefore prove to be ideal indirect messengers. While neutrinos propagate essentially unaffected by any interaction, the universe is opaque to high-energy γ-photons due to extragalactic photon fields. In so-called $\gamma\gamma$-interactions, they effectively experience significant absorption by generating e^-e^+-pairs and thus initiate electromagnetic cascades that influence the measured flux at Earth.

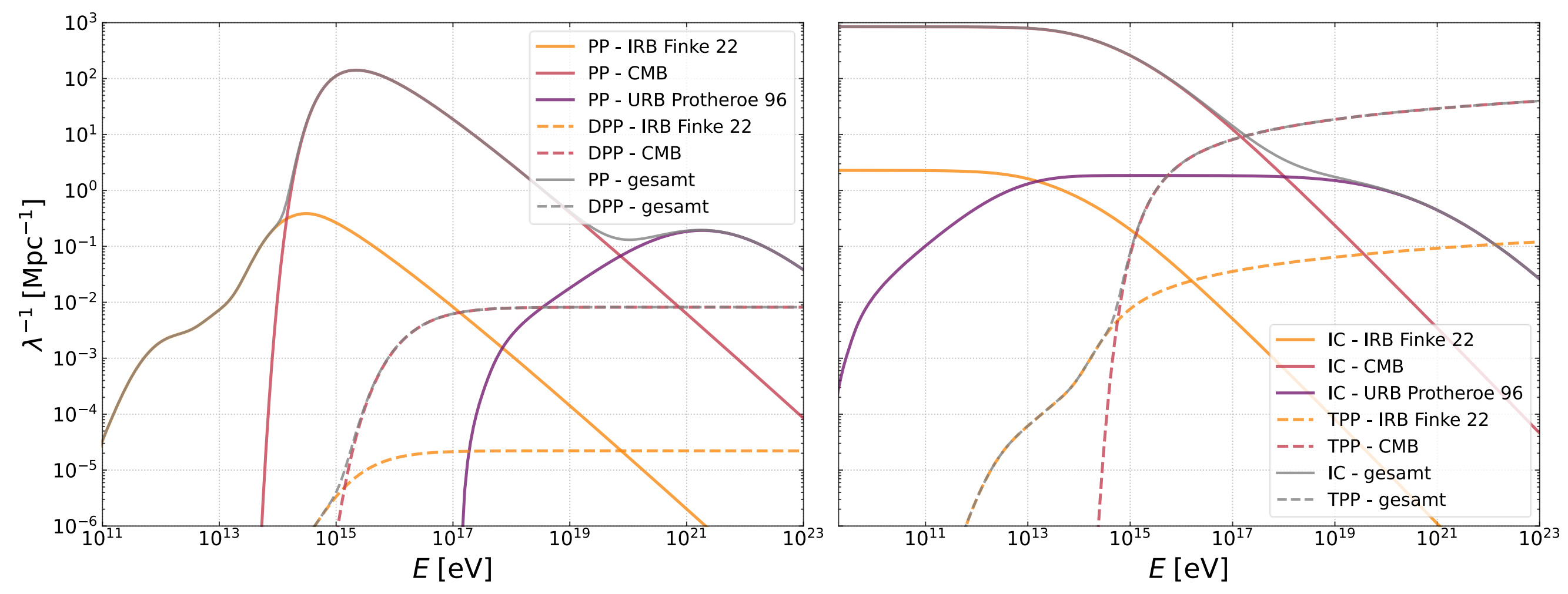

Fig. 2: Interaction rates for photons *(left)* and electrons *(right)* for different interaction processes and various extragalactic photon fields (z=0).

The interactions relevant for photons are the Breit-Wheeler pair production $(\gamma_{\mathrm{HE}} + \gamma \rightarrow e^+ + e^-)$ and double pair production $(\gamma_{\mathrm{HE}} + \gamma \rightarrow 2(e^+ + e^-))$, whereby former process generally dominates and double pair production becomes relevant only at very high particle energies $(E \geq 10^{20}\,\mathrm{eV})$. In this respect, the optical depth $\tau_{\gamma\gamma}$ of the UHE photons, which depends on the density of the photon field and the effective cross section σ_{pp}, is particularly important for determining the intrinsic spectra of extragalactic sources. Inverse Compton (IC) scattering $(e^\pm + \gamma \rightarrow e^\pm + \gamma_{\mathrm{HE}})$ and triple pair production (TPP) are relevant for the cooling of the leptonic secondary particles. Here, the IC process dominates up to particle energies of $10^{17}\,\mathrm{eV}$, while above this energy TPP is the more relevant one.

CRPropa SOFTWARE FRAMEWORK

CRPropa 3.2 is a publicly available framework based on the Monte Carlo algorithm, which was developed for numerical simulations of diffusive and ballistic propagation, in particular of UHECR, but also of their secondary particles in (extra-)galactic space. Simulations can be embedded in a 1D or 3D setting, whereby magnetic deflections or interactions of the particles with photon fields and also cosmological effects can be taken into account for individual injection characteristics. While the software is basically written in C++, additional tools such as SWIG13 provide a very accessible Python interface with high computational efficiency and performance at the same time. The modular structure provides an easy way to custumize parts of the software and add new functionalities to enable a fully user-defined simulation setup.

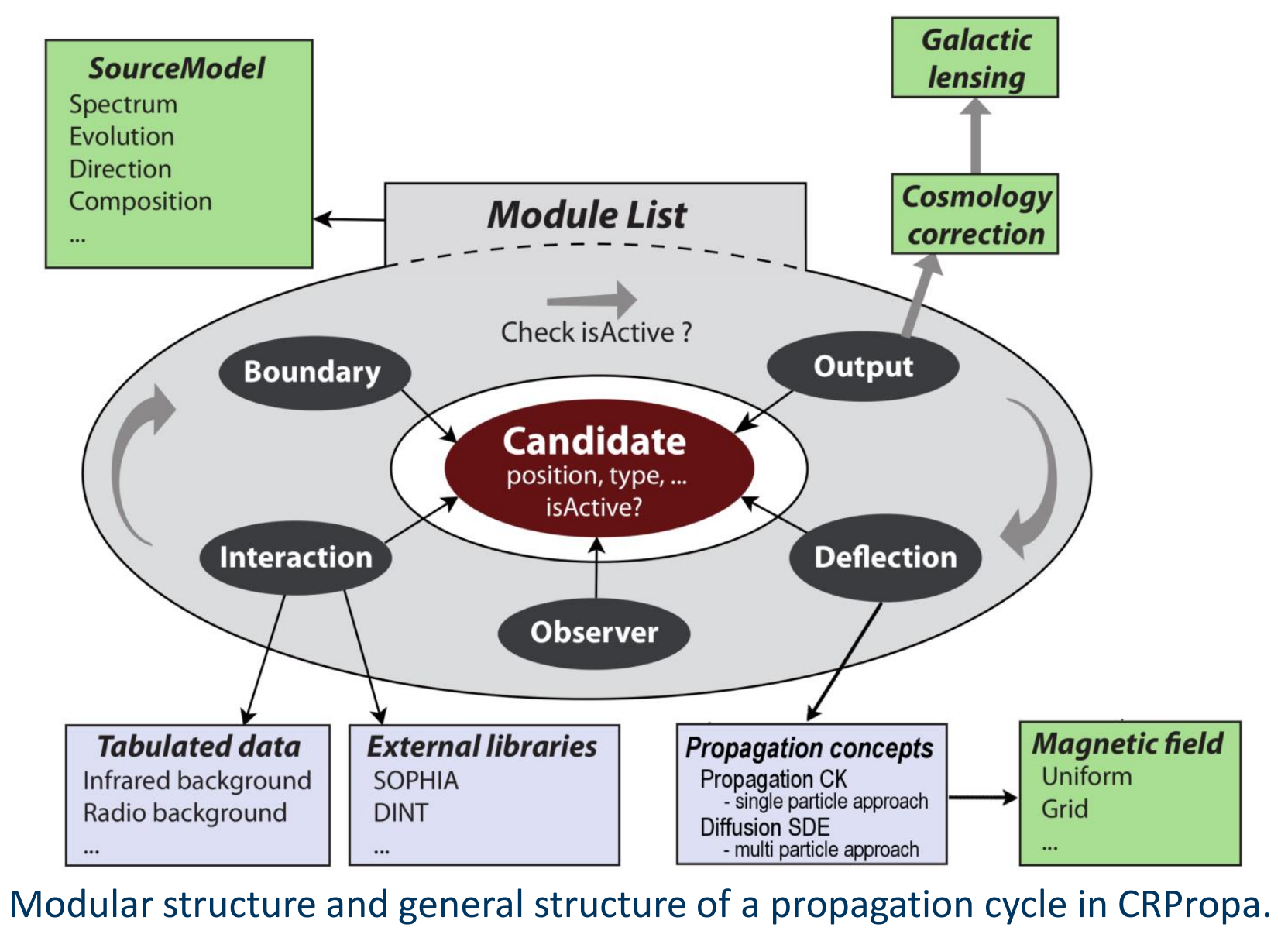

Fig. 4: Modular structure and general structure of a propagation cycle in CRPropa.

BLAZAR 3C279 AS A STUDY OBJECT

In order to investigate the effects of the newly implemented EBL on gamma signals from the Flat Spectrum Radio Quasar 3C279 (z=0.536), observational data from a high-energy flare detected by the MAGIC telescopes in 2007 were used. The propagation of the gamma rays could then be investigated, with the initial energies of the particles being distributed according to the intrinsic spectrum. A 1D simulation in CRPropa (15000 test particles), in which the discussed interactions are also taken into account was implemented. The resulting electromagnetic cascade is propagated over the entire distance from the source to Earth.

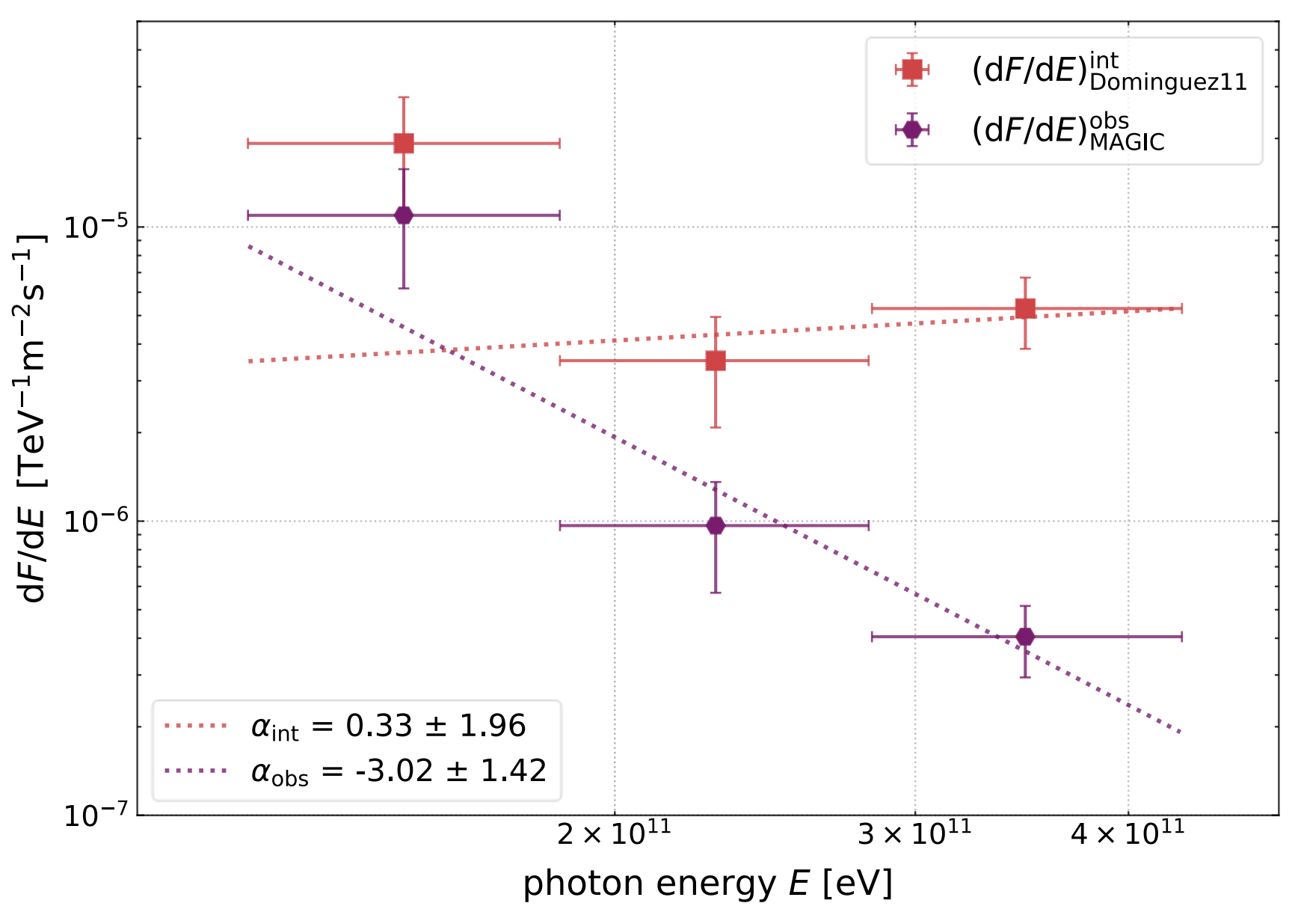

Fig. 5: Detected and EBL-deabsorbed spectra of a gamma ray flare by the FSRQ Blazar 3C279 from January 16th 2007.

STUDY FINDINGS: PHOTON SPECTRA

After the simulation results were normalized to a physical flux with the VHE measurement data, a few clear results could be found. Generally the choice of an EBL model seems to have just little influence on the overall spectral shape. Nevertheless, it can be identified, that the updated model from Finke et al. forecasts a lower high energy gamma ray absorption than other models. Thus fewer particles will be initiated into the electromagnetic cascade and the VHE spectrum is flatter. The influences on the em cascade in general can be largely directly determined by the specific characteristics of the IR/optical peaks of the EBL model. A closer look to the specifics of the simulated cascade reveals also that for the updated EBL model there is a higher prediction of scattered photons by the inverse Compton effect in comparison with most of the other models.

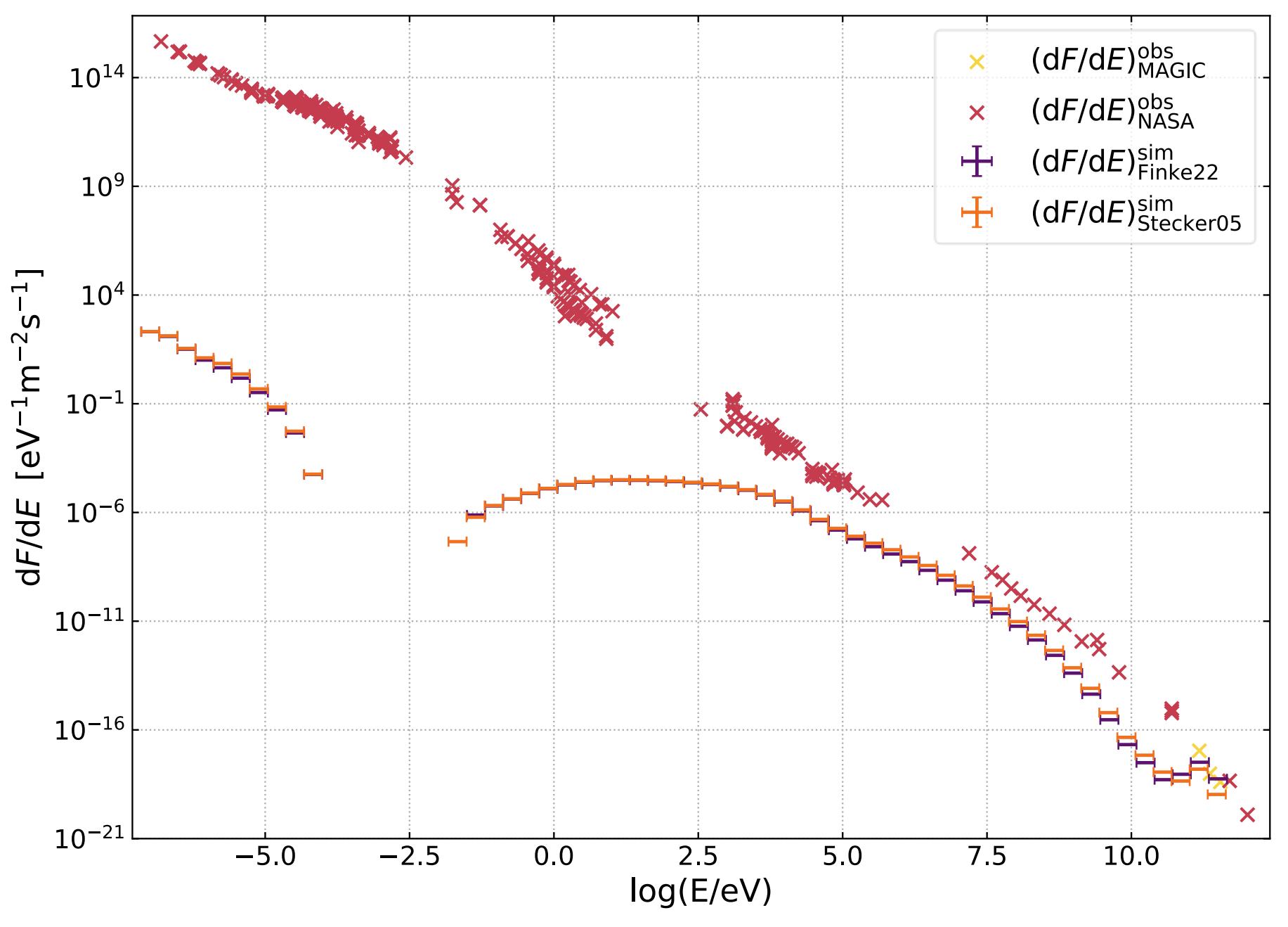

Fig. 6: Binned photon energy spectra, resulting from the simulated 1D em cascade with the EBL from Finke et al. and Stecker 2005 in comparison with measurements (IPAC/MAGIC) from the source.

GAMMA RAY ABSORPTION

Through evaluating the optical depths for different EBL models those reults are reinforced once again. Up to about $10\,\mathrm{TeV}$ Finke 2022 predicts the lowest absorptions i.e. the general opacity of the universe for gamma rays is lower than in other modeling. However, for even higher photon energies, which the source under consideration propably did not emit, the models predictions for the strength of absorption exceeds those of other modelings. A significant absorption according to the Fazio-Stecker relation, i.e. a so called gamma horizon, where most of the radiation will be absorbed at a certain distance, is predicted at approximately $0.2\,\mathrm{TeV}$ for a source redshift of z=0.536.

$$\tau_{\gamma\gamma}(E_0, z_0) = \int_0^{z_0} \frac{\partial L}{\partial z}(z)\,\mathrm{d}z \int_0^{\infty} \frac{\partial n}{\partial \varepsilon_\gamma}(\varepsilon_\gamma, z)\,\mathrm{d}\varepsilon_\gamma \int_{-1}^{1} \frac{1-\mu}{2}\,\sigma_{\mathrm{pp}}(\beta)\,\mathrm{d}\mu \longrightarrow \left(\frac{\mathrm{d}F}{\mathrm{d}E}\right)_{\mathrm{int}} = \left(\frac{\mathrm{d}F}{\mathrm{d}E}\right)_{\mathrm{obs}} \cdot \exp[\tau_{\gamma\gamma}(E_\gamma, z)]$$

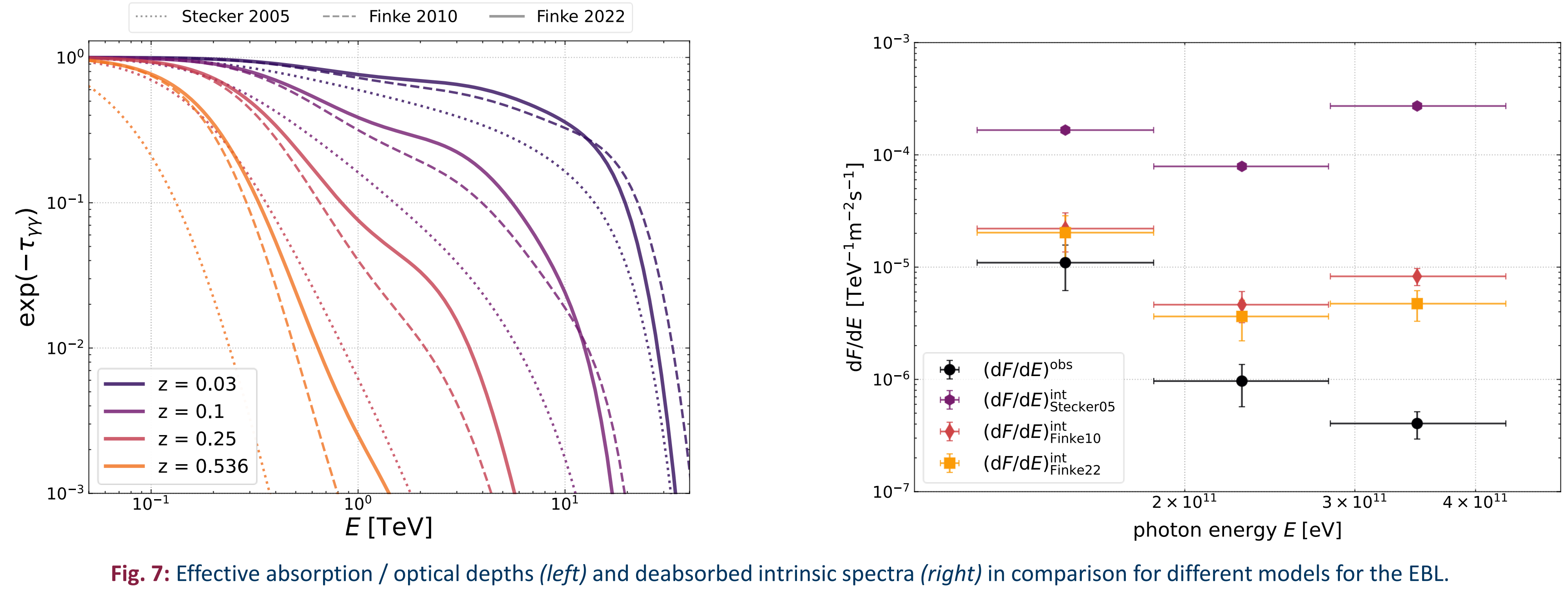

Fig. 7: Effective absorption / optical depths *(left)* and deabsorbed intrinsic spectra *(right)* in comparison for different models for the EBL.

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