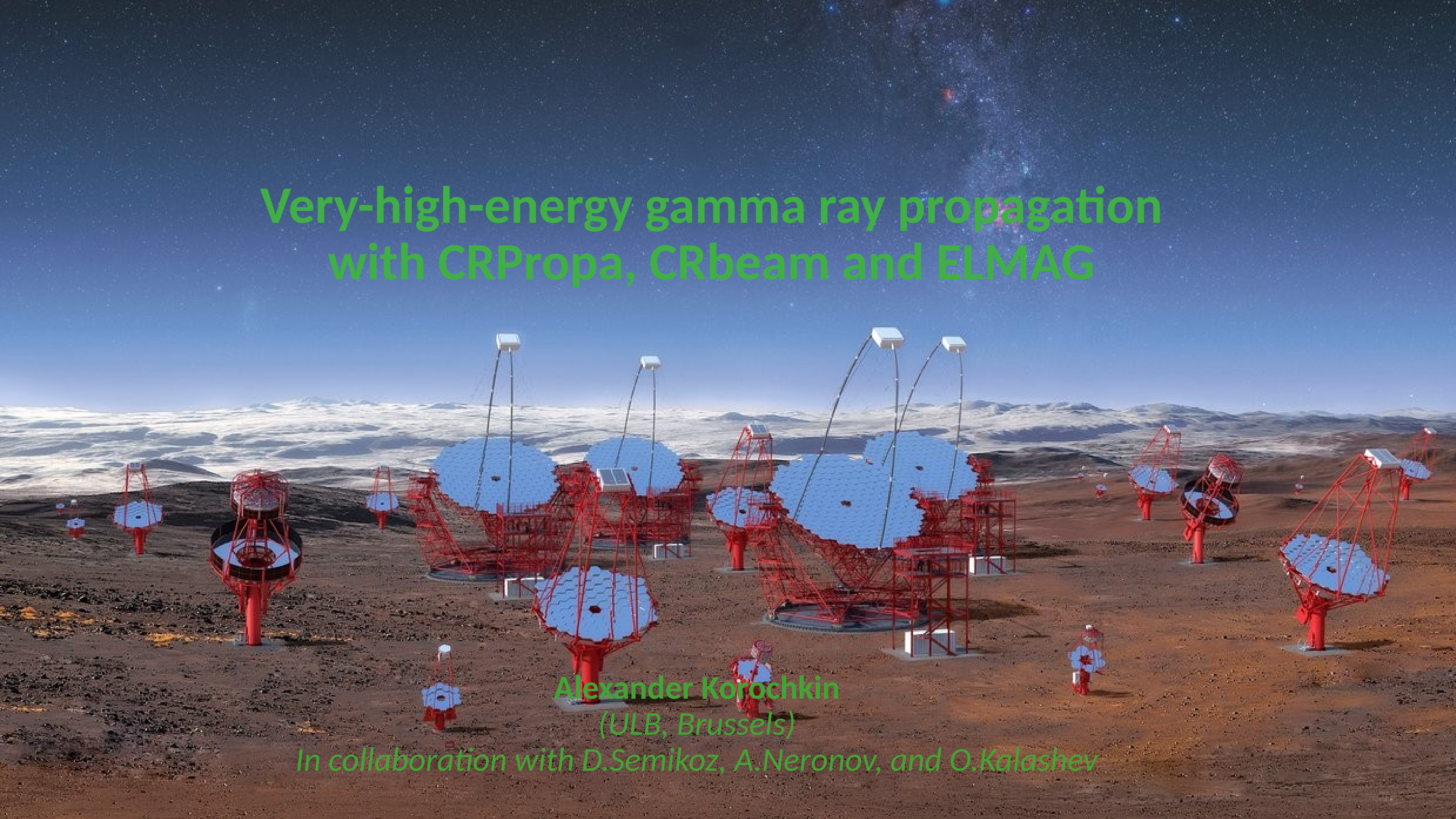

Very-high-energy gamma ray propagation with CRPropa, CRbeam and ELMAG

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(ULB, Brussels)
In collaboration with D.Semikoz, A.Neronov, and O.Kalashev

Overview:

- Modeling propagation of gamma rays is important different kind of studies

  - Intergalactic magnetic fields (IGMF)
  - Extragalactic gamma-ray background (EGRB)
  - ALPs
  - EBL
  - …

Monte Carlo codes

CRPropa

ELMAG

M. Kachelriess, S. Ostapchenko…

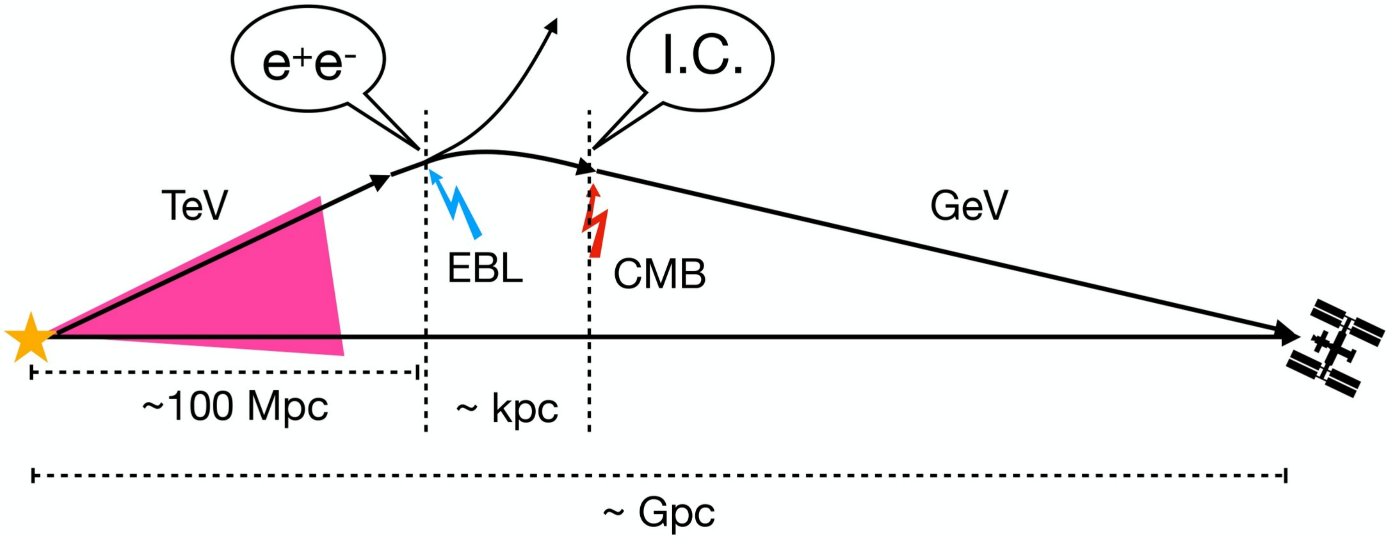
CRbeam

O.Kalashev

available on github

Compare the accuracy of these codes

Electromagnetic cascades



pic from T.Vachaspati arXiv:2010.10525

1) $\gamma_{HE}\,\gamma_b$ -> e+e- (pair production)

2) γ_b e- -> γ_{HE} e- (inverse Compton scattering)

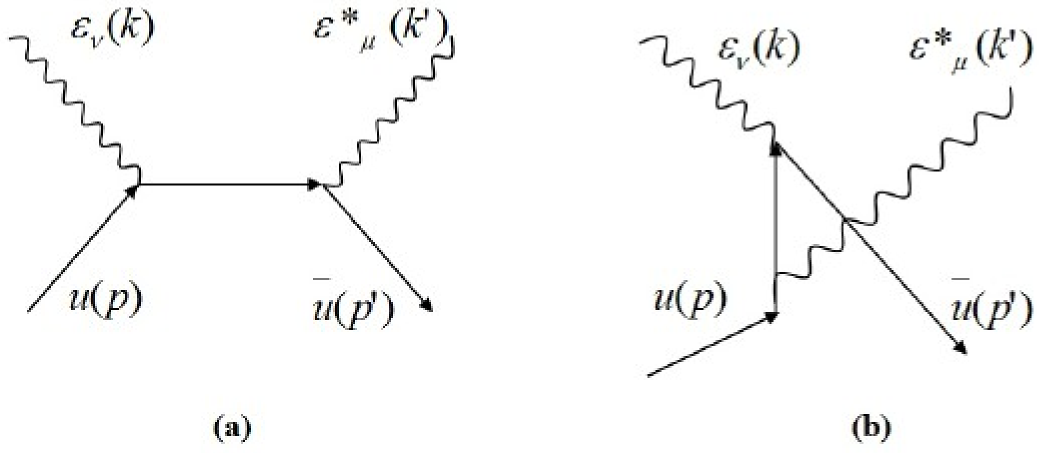
Pair production process creates **electron-positron pairs** whose deflections are proportional to the strength of the magnetic field.

Then **secondary gamma rays** are produced by **inverse Compton scattering** off CMB photons.

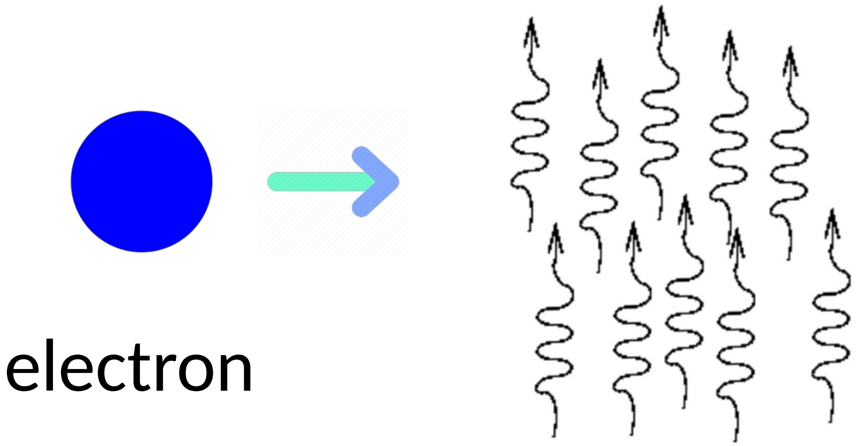
Electromagnetic cascade

A.Neronov, D.Semikoz arXiv:astro-ph/0604607

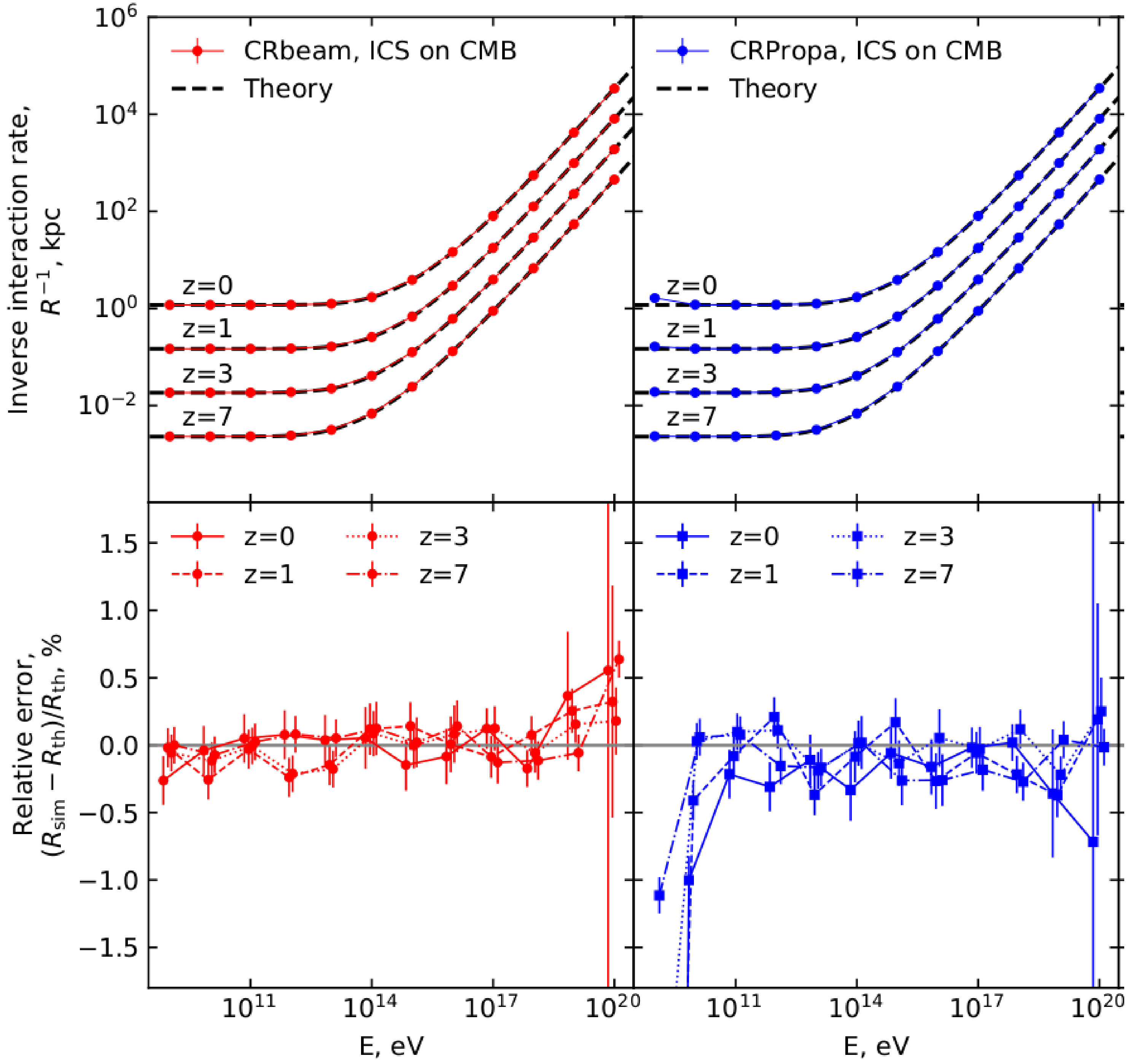
Inverse Compton scattering (ICS)



Interaction rate and energy distribution of particles after interaction can be computed analytically

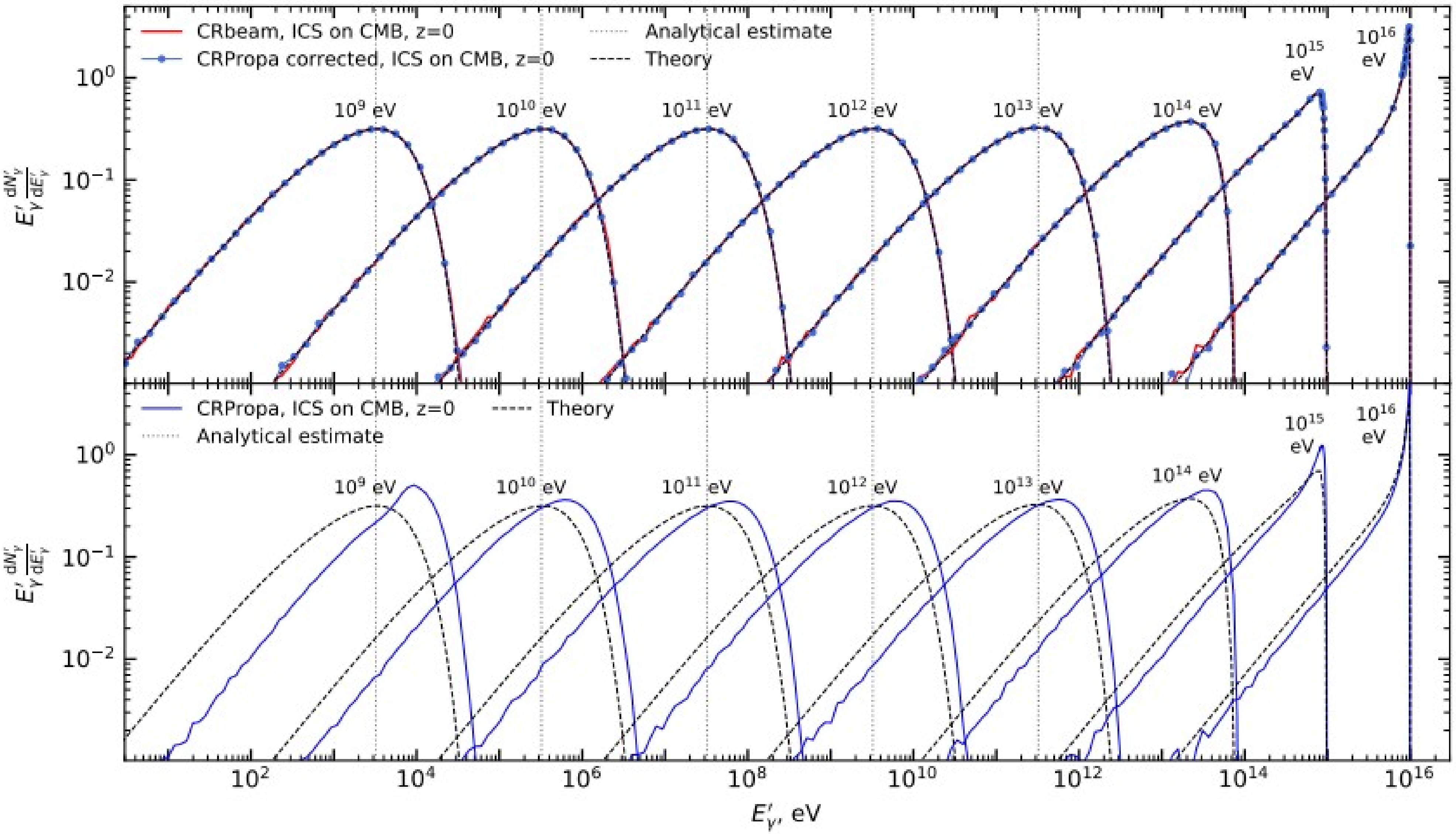


Propagate monochromatic electrons through the CMB and EBL. Deactivate each electron after interaction and catch secondary gamma ray



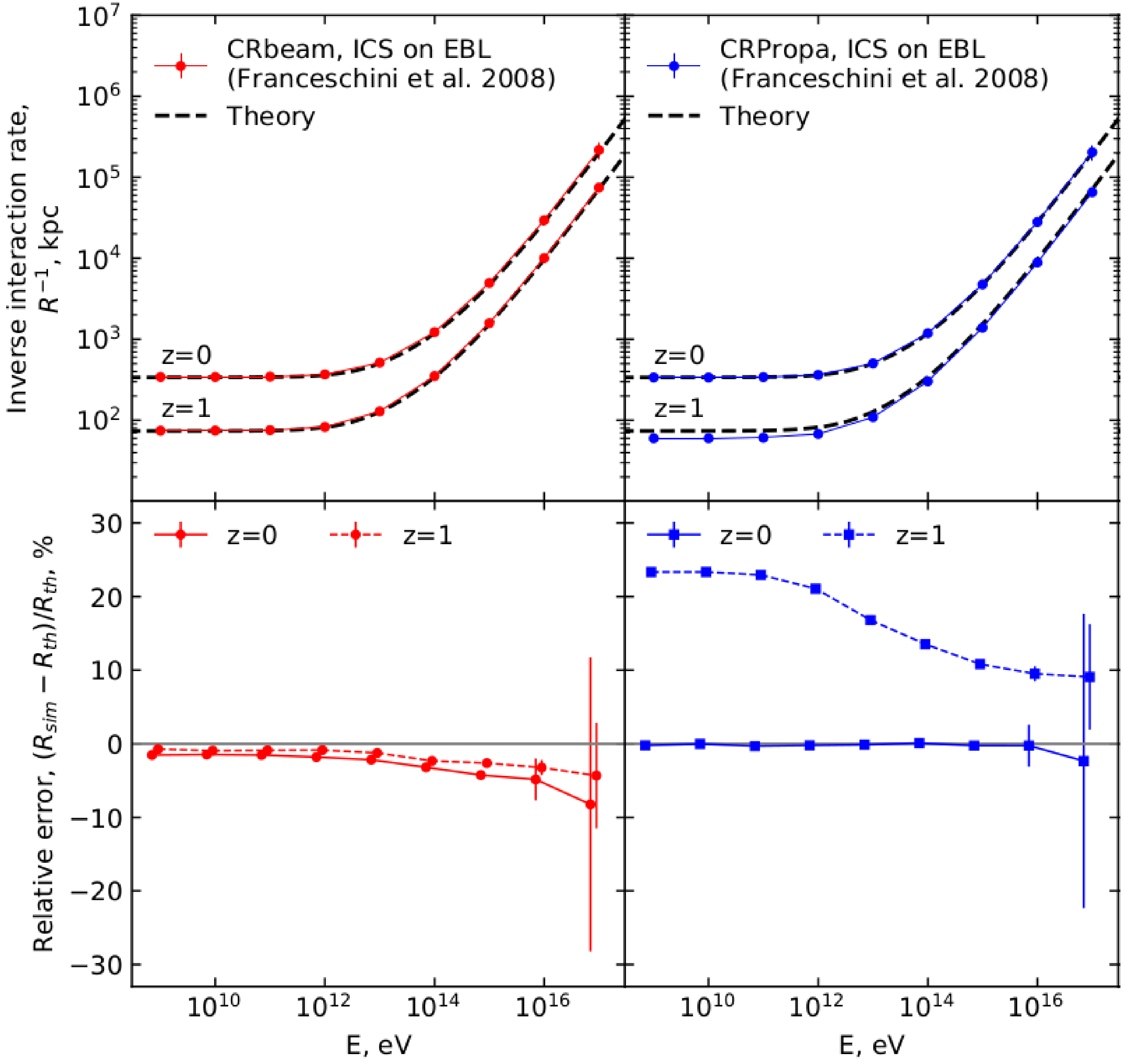
Electron interaction rates with CMB (mean free paths) agree with the theory at sub-percent level
at any redshift

Difference <~0.5% !!!



Energy distribution of secondary gamma rays deviates from theory in CRPropa 3.1
Bug was fixed in CRPropa 3.2 (problem with precomputed interaction tables)

Precision better than <<1%

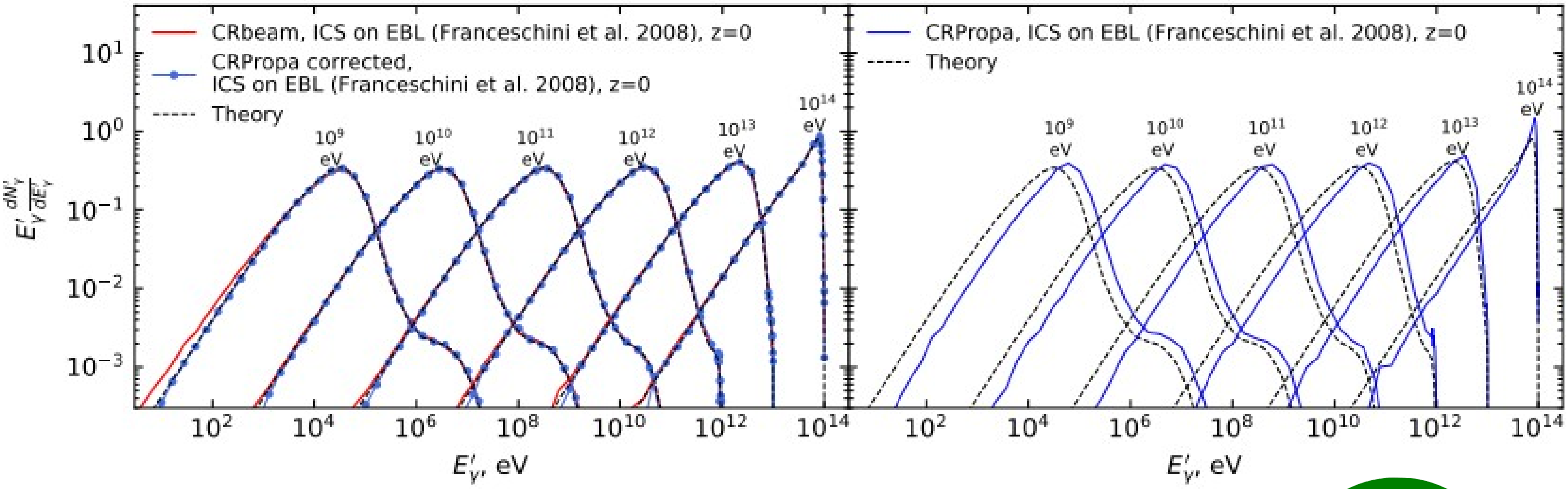


Electron interaction rates with EBL (mean free paths):

CRbeam agrees with theory

CRPropa deviates at high redshift redshift

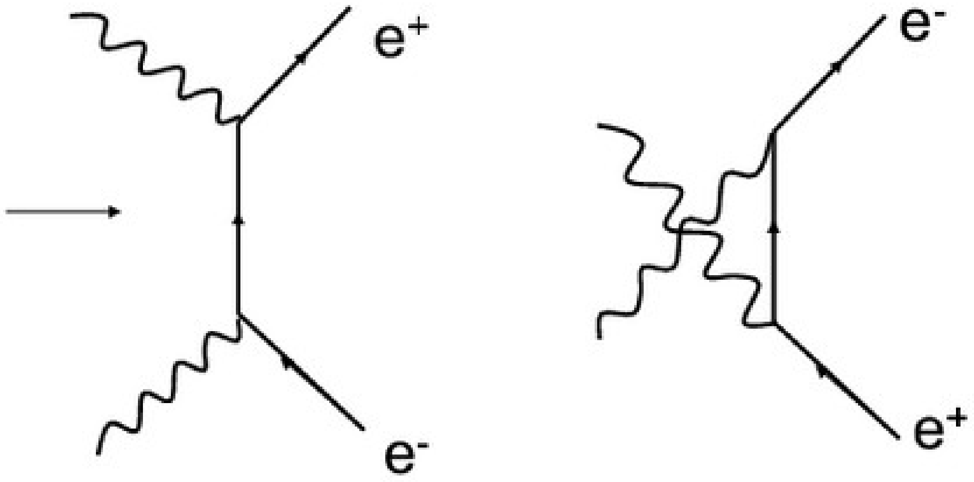
Fortunately, ICS on EBL almost always subdominant compared to ICS on CMB



Energy distribution of secondary gamma rays deviates from theory in CRPropa 3.1
Bug was fixed in CRPropa 3.2 (problem with precomputed interaction tables, same as for the case of CMB)

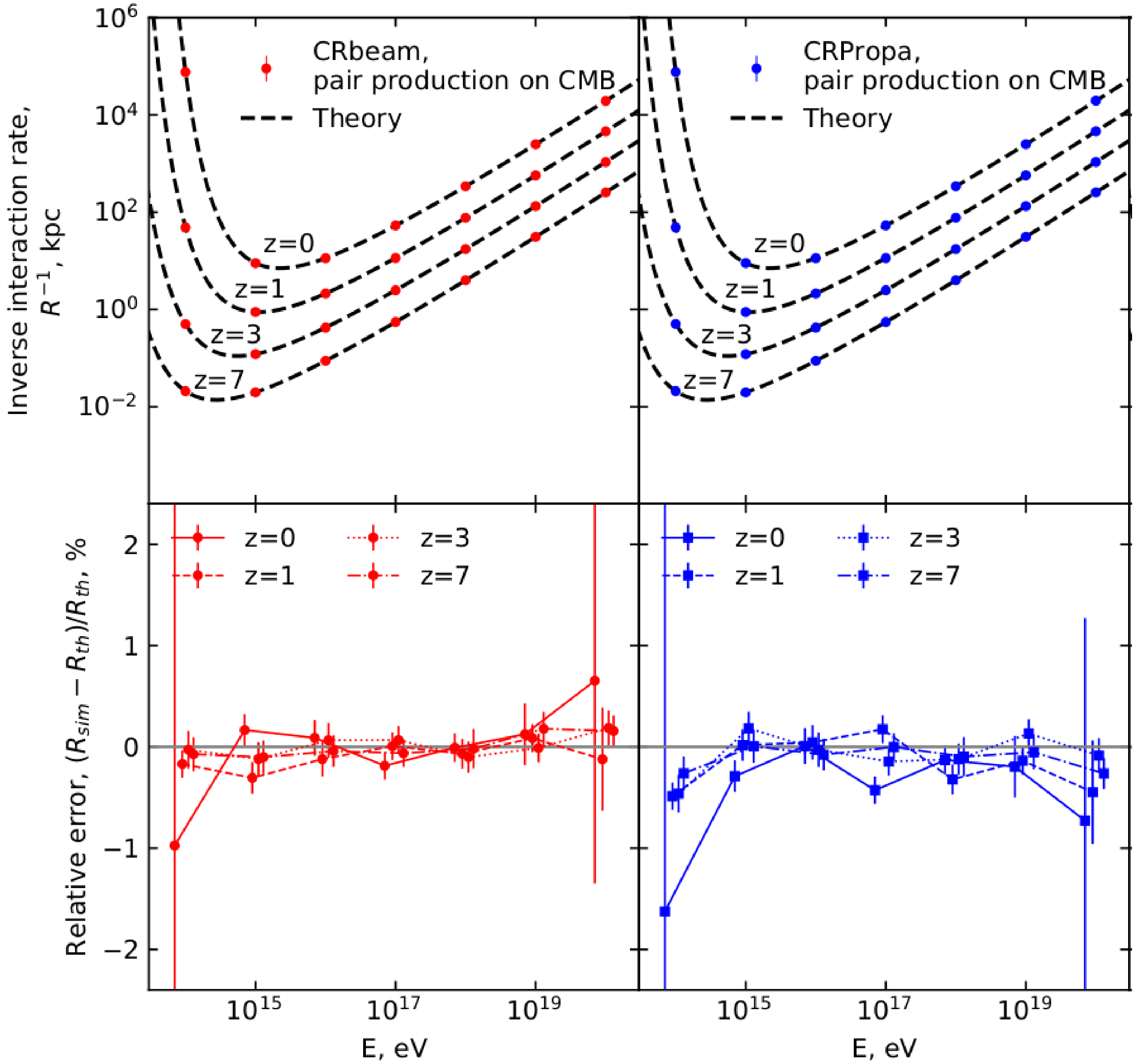
Percent level agreement with theory for most energies

Breit-Wheeler Pair Production (BW)



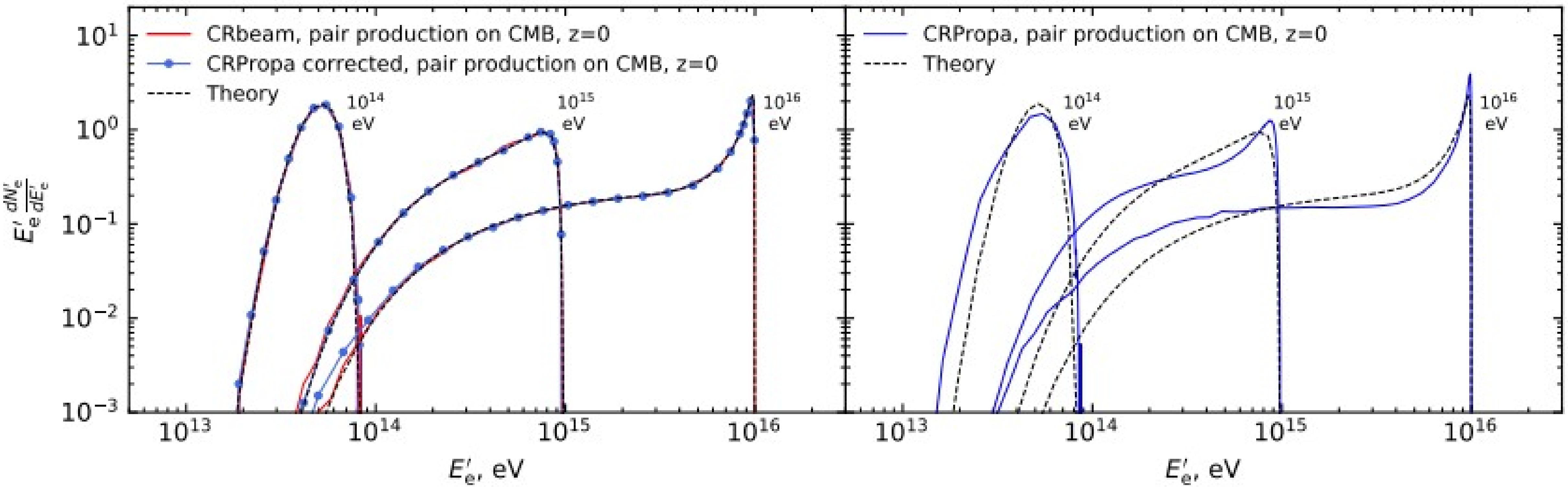
Standard QED process: cross section and energy distribution of particles after interaction can be computed analytically

Propagate monochromatic gamma rays through the CMB and EBL. Deactivate each gamma ray after interaction and catch secondary pairs



Again, as for ICS, gamma ray interaction rates with CMB (mean free paths) agree with the theory at sub-percent level at any redshift

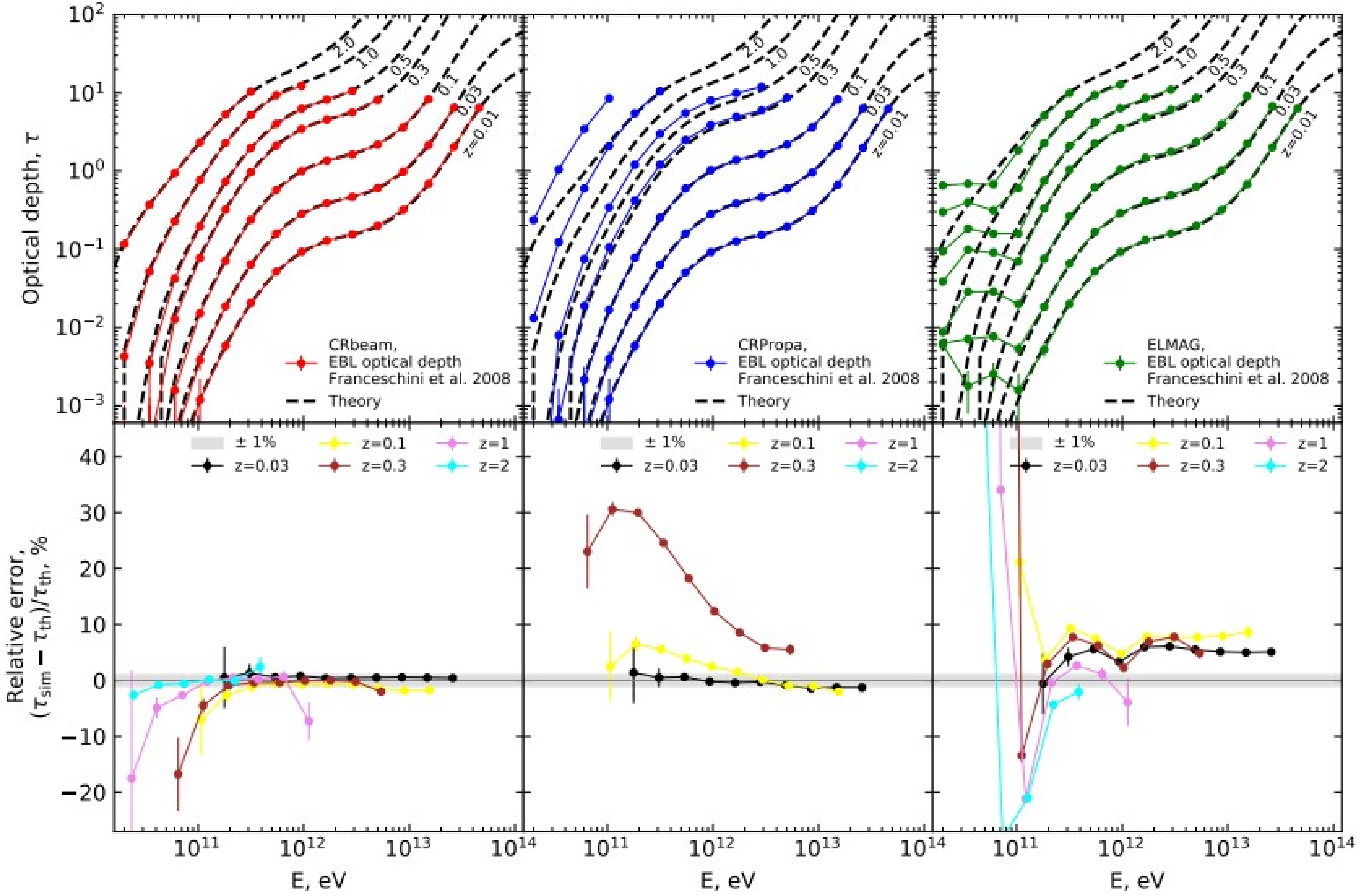
Difference <~0.5%



Energy distribution of secondary electrons deviates from theory in CRPropa 3.1…
Bug was fixed in CRPropa 3.2 (again, problem with precomputed interaction tables)

Precision for almost all energies better than <<1%

Gamma ray absorption on the EBL

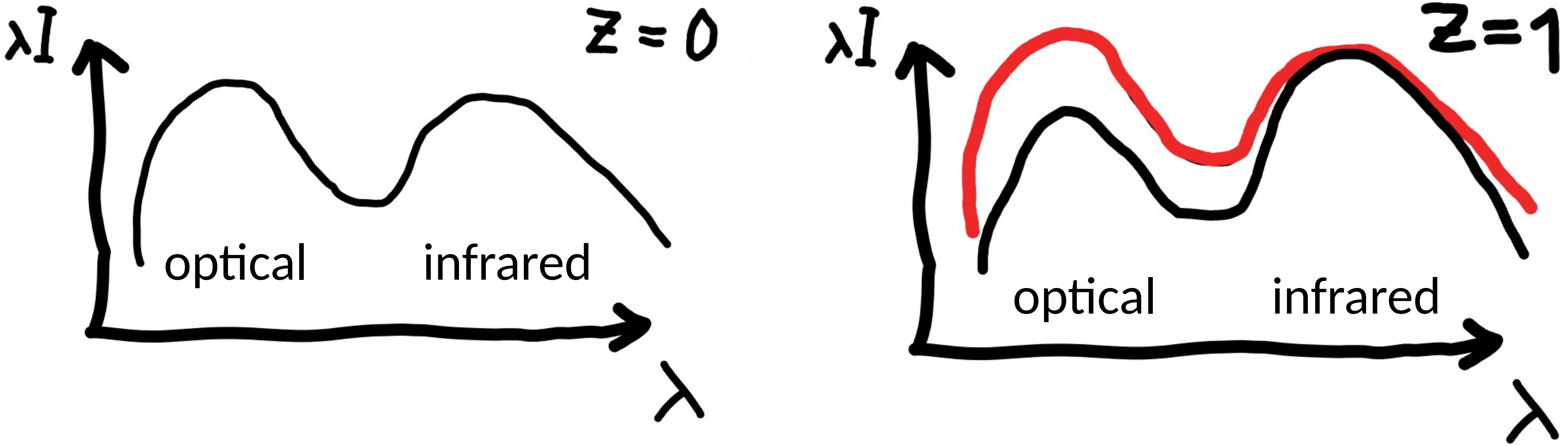


CRPropa strongly deviates from expected optical depth because it keeps fixes shape of the EBL spectrum at all redshifts

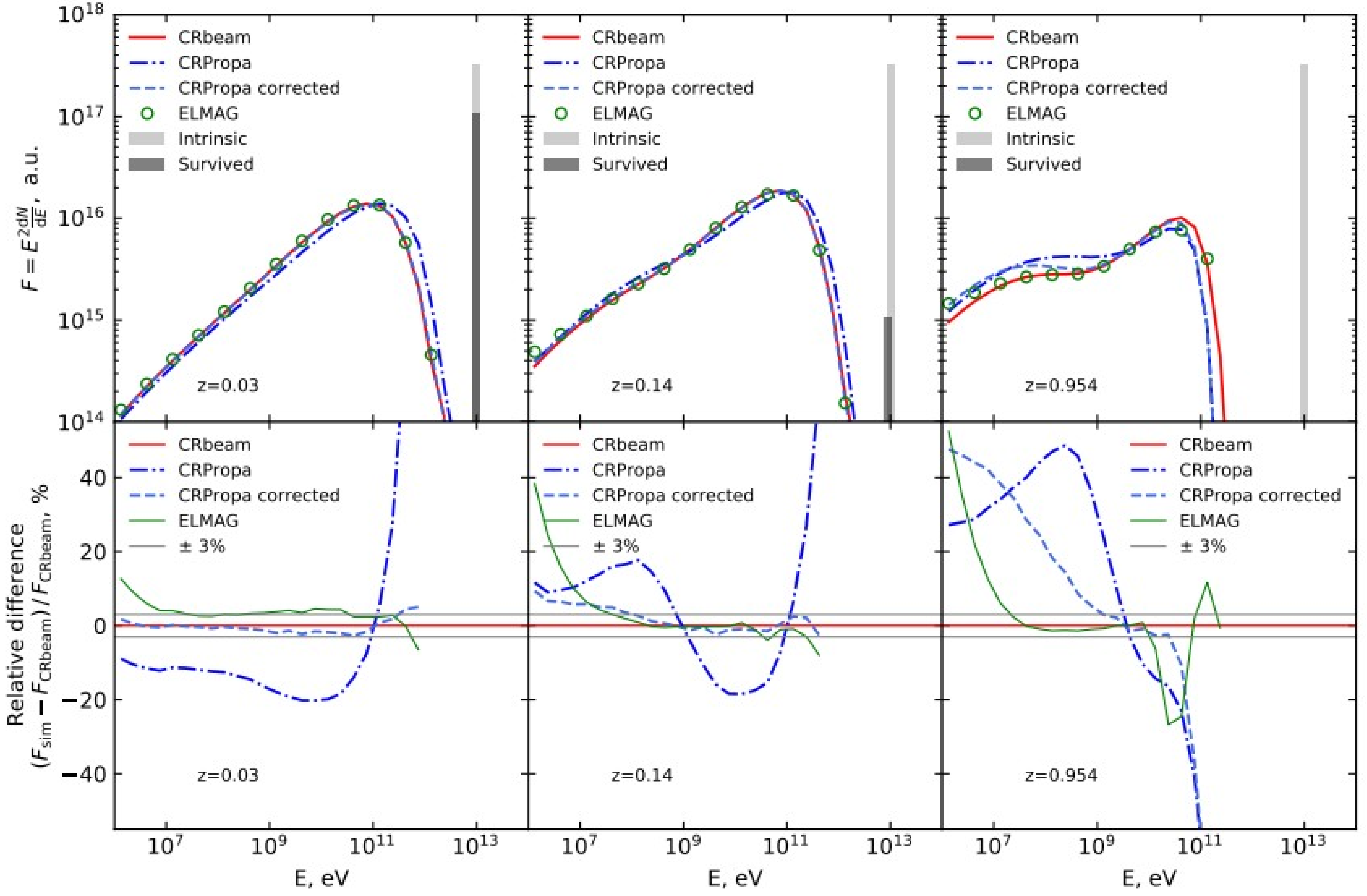
CRbeam performs the best

EBL simplification in CRPropa

To approximate EBL specturm at nonzero redshift CRPropa renormalizes EBL spectrum at z=0 to reproduce correct number density of photons



1D cascade with zero magnetic field and monochromatic injected gamma rays



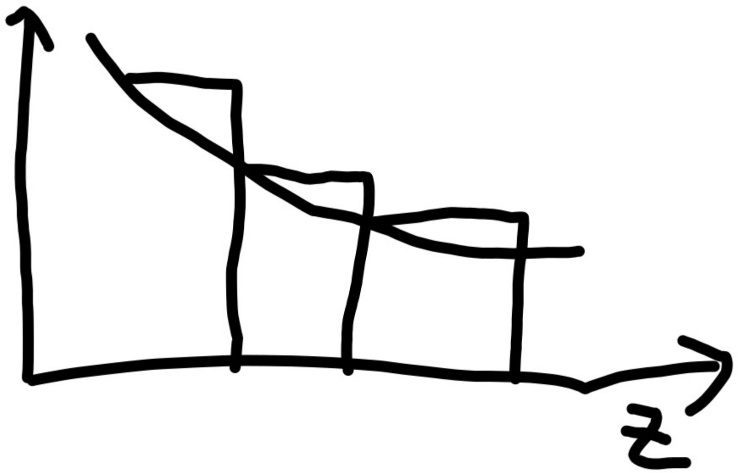
CRbeam
CRPropa
CRPropa corrected
ELMAG
Intrinsic
Survived
$F = E^2 \frac{dN}{dE}$, a.u.
z=0.03
z=0.14
z=0.954
± 3%
Relative difference
$(F_{sim} - F_{CRbeam}) / F_{CRbeam}$, %
E, eV

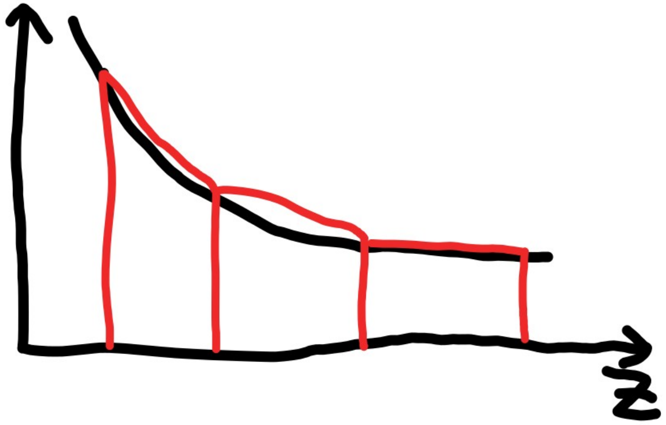
Conclusions for cascades without IGMF

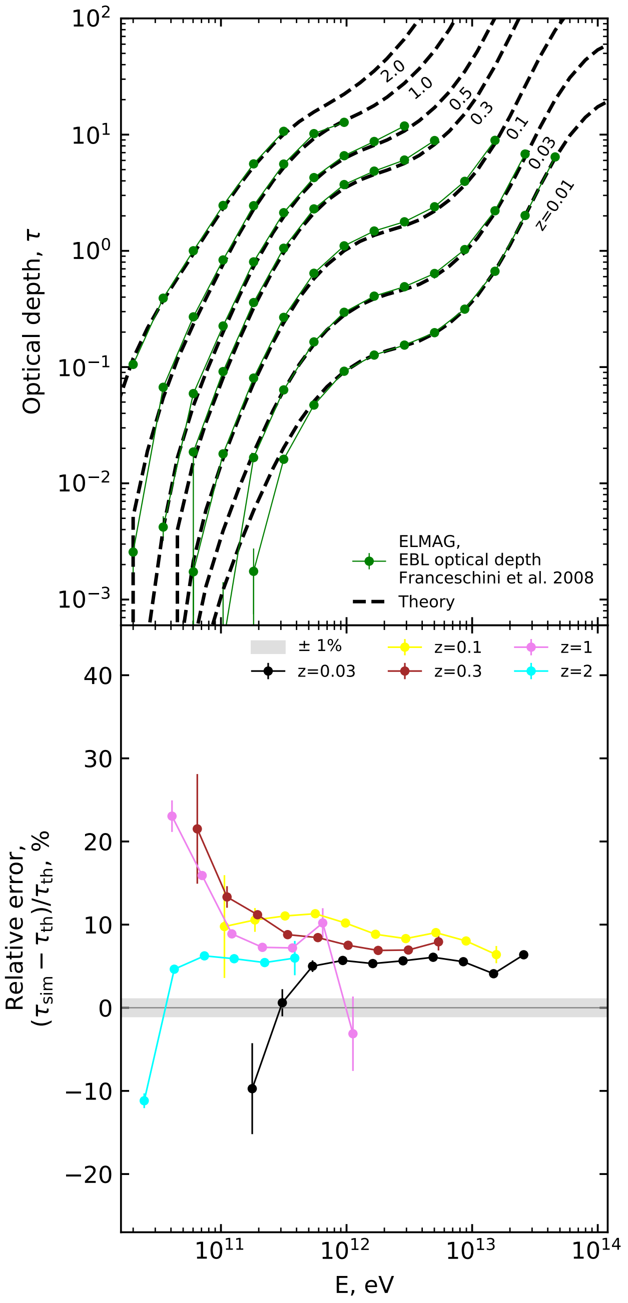
- After corrections, all codes show subpercent level of agreement at the level of individual interactions not involving high redshift EBL
- Percent level agreement for 1D cascade calculations with zero IGMF at low redshifts (z <~ 0.1)
- Simplified treatment of the EBL in CRPropa is the main obstacle for reaching agreement at high redshifts
- Once EBL in CRPropa corrected, cascades with zero IGMF will be at percent level agreement for all redshifts
- Intrinsic delay of the cascade is not taken into account

Caveat

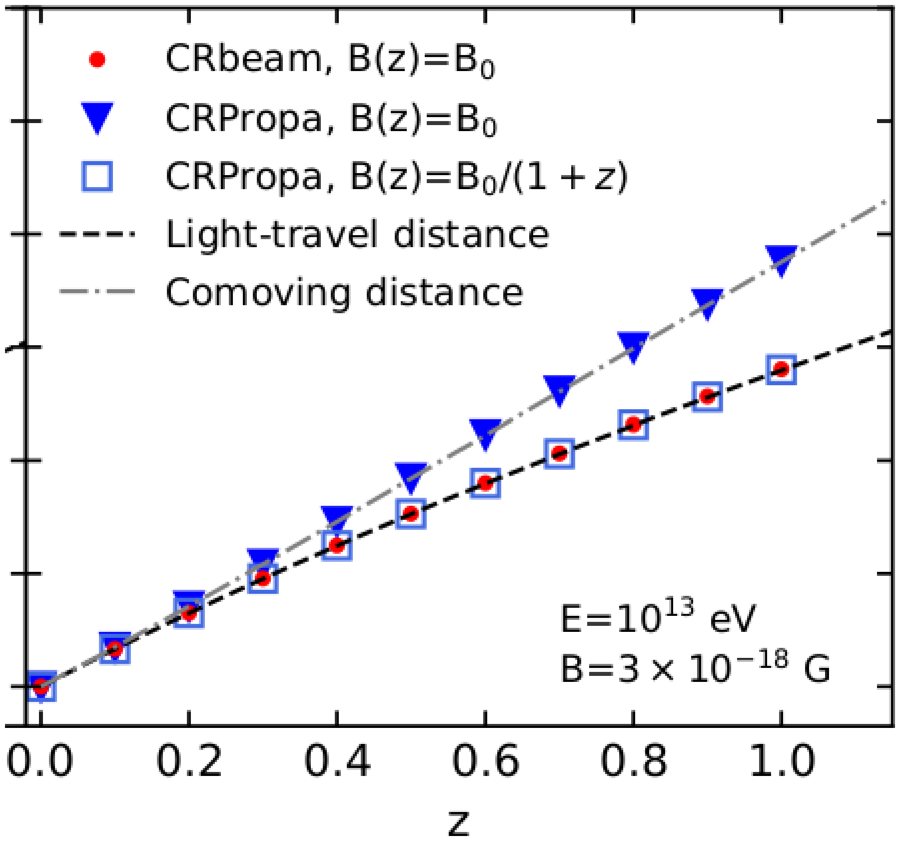
Carefully select
gamma ray step size!







Including IGMF



All interactions are disabled,
constant magnetic field all across the Universe

Caveat!

CRPropa uses comoving coordinates, so the deflection angle is proportional to the comoving distance element which is (1+z) larger than light-travel.

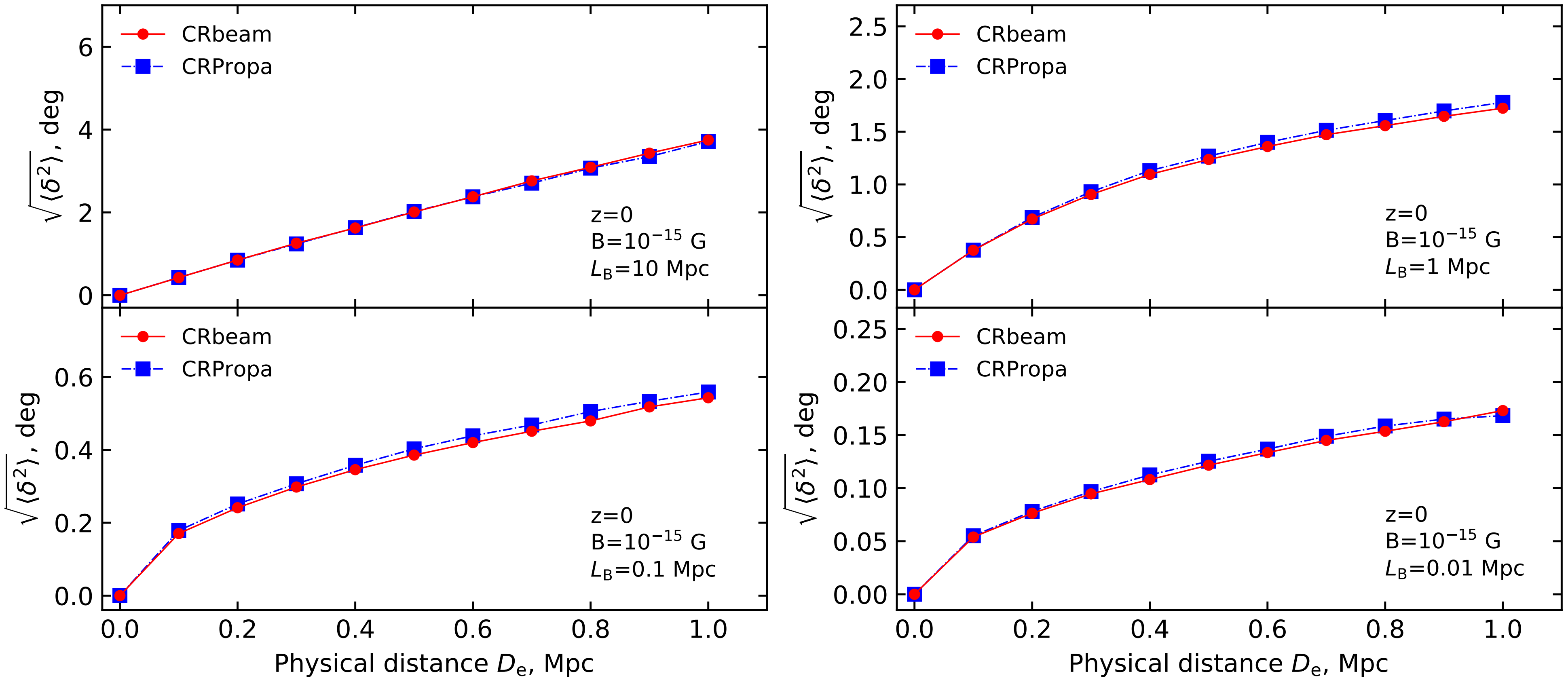
In order to have correct deflection angle you have to rescale magnetic field by factor 1/(1+z)

For example, use B(z)=B(0)*(1+z) instead of B(0)*(1+z)^2

Important for magnetic horizon calculations

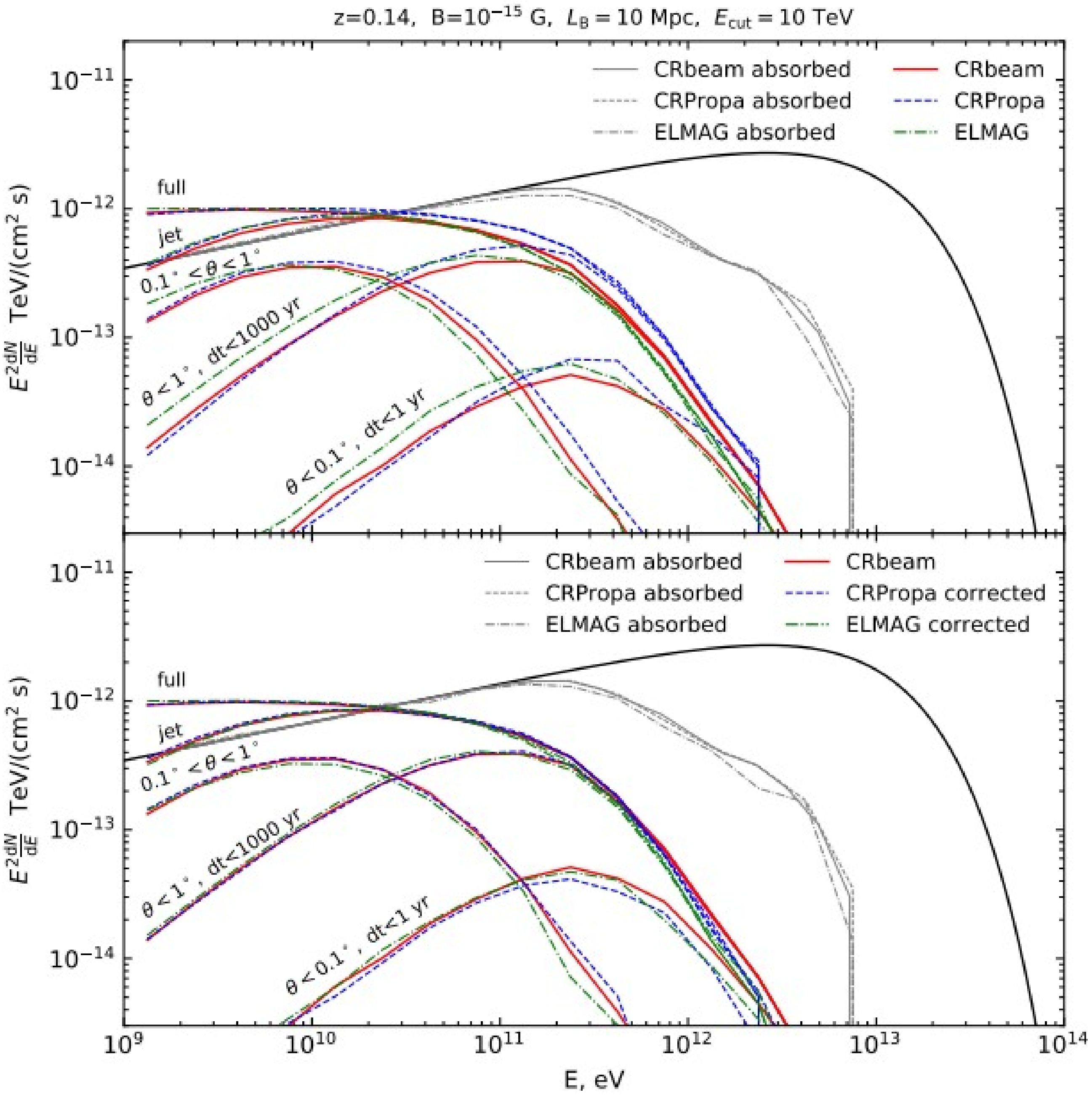
Both codes correctly solve equations of motion

Testing turbulent magnetic field generators



10% difference in small angle deflection regime

CRPropa: IGMF on the grid
CRbeam: IGMF as a sum of plane waves


z=0.14, B=10^{-15} G, L_B = 10 Mpc, E_{cut} = 10 TeV
CRbeam absorbed
CRPropa absorbed
ELMAG absorbed
CRbeam
CRPropa
ELMAG
full
jet
$0.1^\circ < \theta < 1^\circ$
$\theta < 1^\circ$, dt<1000 yr
$\theta < 0.1^\circ$, dt<1 yr
CRbeam absorbed
CRPropa absorbed
ELMAG absorbed
CRbeam
CRPropa corrected
ELMAG corrected
full
jet
$0.1^\circ < \theta < 1^\circ$
$\theta < 1^\circ$, dt<1000 yr
$\theta < 0.1^\circ$, dt<1 yr
$E^2 \frac{dN}{dE}$ TeV/(cm^2 s)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
E, eV

Conclusions

- Codes showed good agreement in general
- After fixing EBL issues in CRPropa, CRbeam and CRPropa will show percent level agreement for cascades in zero IGMF (without taking into account intrinsic cascade delays)
- Absorption in ELMAG is always 5-10% stronger (probably because of too large steps)
- Apart from EBL, the difference comes from turbulent IGMF generators
- Overall, current the systematic uncertainty between the codes is at the level of 10%