SimProp is a Monte Carlo code for simulating the propagation of Ultra-High-Energy Cosmic Rays through intergalactic space

SimProp run:
- $N$ events are simulated $\rightarrow$ $N$ primary particles with mass number $A_{inj}$
- The initial energy $E_{inj}$ is sampled from a power-law distribution from $E_{\text{min}}$ and $E_{\text{max}}$ with spectral index $-\gamma$
- The source redshift $z_{inj}$ is sampled from a uniform distribution between $z_{\text{min}}$ and $z_{\text{max}}$
- The propagation of particles (primary and secondary) is followed

Magnetic field are neglected $\rightarrow$ 1-dimensional propagation
Introduction

Processes taken into account:

- **Redshift energy loss**
  \[
  \left( -\frac{1}{E} \frac{dE}{dt} \right)_{ad} = H(t) = H_0 \sqrt{(1 + z)^3 \Omega_m + \Omega_\Lambda}
  \]

- **Interactions with background photons**:
  - Electron-positron pair production
  - Photodisintegration of nuclei
  - Pion photoproduction (approximated as single pion production)

- **Decays of neutrons and unstable nuclei** (instantaneous decay is always assumed)

Phenomenological models are used in UHECR studies

→ Several **photo disintegration models** are available in SimProp (command-line -M)

PSB with Stecker-Salamon thresholds is the default one
Introduction

Photon background taken into account:
- **CMB photons** (well known)
- **EBL photons** (not directly measured)

Phenomenological models are used for the **EBL spectrum and its evolution with redshift**

→ Several **EBL models** are available in SimProp (command-line -L )

<table>
<thead>
<tr>
<th>No.</th>
<th>model</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>none (CMB only)</td>
</tr>
<tr>
<td>1</td>
<td>Stecker et al. 2006 (default)</td>
</tr>
<tr>
<td>2</td>
<td>power-law approximation</td>
</tr>
<tr>
<td>3</td>
<td>Kneiske et al. 2004</td>
</tr>
<tr>
<td>4</td>
<td>Domínguez et al. 2011 best fit</td>
</tr>
<tr>
<td>5</td>
<td>Domínguez et al. 2011 lower limit</td>
</tr>
<tr>
<td>6</td>
<td>Domínguez et al. 2011 upper limit</td>
</tr>
<tr>
<td>7</td>
<td>Gilmore et al. 2012 fiducial</td>
</tr>
</tbody>
</table>
• Compile the software:  make
• Run SimProp with default options:  ./SimProp | grep Event

** Events to be generated: 100
** Event 0 .................................................................
** Event 1 .................................................................
** Event 2 .................................................................
** Event 3 .................................................................
** Event 4 .................................................................
...

Input parameters

• Compile the software:  **make**
• Run SimProp with default options:  **./SimProp | grep Event**

**./SimProp -h**

```
SimProp -N [number of events, D=100] -s [random seed, D=65539] 
   -A [A (0 for all), D=56] -e [min energy log10(Emin/eV), D=17.] 
   -E [max energy log10(Emax/eV), D=21.] 
   -g [injection spectral index, D=1.] 
   -z [min redshift, D=0.] -Z [max redshift, D=1.] 
   -r [source relative distance (Mpc), D=0.] 
   -L [EBL, 0=none, 1=Stecker+ '06, 2=power law, 3=Kneiske+ '04, 
       4=Dominguez+ '11 (best), 5=Dominguez (lower), 6=Dominguez (upper), 
       7=Gilmore+ '12 (fiducial), D=1] 
   -M [nuclear model type, 0=Stecker-Salamon, 1=arb. Gaussians, 
       2=arb. Breit-Wigner, 3=arb. Breit-Wigner with alpha, 
       4=arb. Gaussians with alpha, D=0] 
   -n [scales nucleon photodis. cross sections (only with M>=3), D=1.] 
   -a [scales alpha photodis. cross sections (only with M>=3), D=1.] 
   -D [beta decay, 0=none, 1=istantaneous, D=1] 
   -S [pion photoproduction, -1=continuous for protons only, 
       0=continuous for all nuclei, 1=stochastic on CMB only, 
       2=stochastic on CMB+EBL, D=1] 
   -p [e+e-, 0=neglected, 1=individually written to output (WARNING: very 
       large files!), 2=binned in z, 3=only total energy written, D=0] 
   -o [output types, 0=all branches, 1=summary tree, 2=both, D=0]
```
Input parameters

- `s` seed of the random number generator
- `N` number of events to be generated
- `A` mass number of primary nuclei, $A_{\text{inj}}$ (chosen at random for each event with -A 0)
- `e` $\log_{10}(E_{\text{min}}/\text{eV})$, where $E_{\text{min}}$ is the minimum injection energy
- `E` $\log_{10}(E_{\text{max}}/\text{eV})$, where $E_{\text{max}}$ is the maximum injection energy
- `g` injection spectral index, $\gamma$
- `z` minimum source redshift, $z_{\text{min}}$
- `Z` maximum source redshift, $z_{\text{max}}$
- `r` distance between sources, $L_s$, in Mpc
- `L` EBL model
- `M` photodisintegration model
- `n` nucleon ejection scaling factor (only with -M 3 and -M 4)
- `a` alpha-particle ejection scaling factor (only with -M 3 and -M 4)
- `D` beta decay: 0 disabled, all nuclei treated as their respective beta-decay stable isobars; 1 enabled, treated as instantaneous
Input parameters

-S  treatment of pion production:  -1 continuous energy loss approximation for protons, neglected for other nuclei (as in SimProp v2r0); 0 continuous energy loss for both protons and other nuclei; 1 stochastic, on the CMB only; 2 stochastic, on both the CMB and the EBL

-p  electrons and positrons:  0 disregarded, 1 individually written to output file (warning: results in very large output files), 2 binned according to production redshift (by default \([10^{-4.0}, 10^{-3.8}], \ldots, [10^{+0.8}, 10^{+1.0}]\), but can be changed in the file src/Output.h before compiling), 3 only total energy written

-o  output type (see below):  0 old (nuc and ev trees); 1 new (summary tree); 2 both
Simulate one event

./SimProp -N 1 -A 56 -e 18. -E 18. -g 1. -z 1 -Z 1 -o 1

>> SimProp v2r4 <<

Authors: D. Boncioli, A. di Matteo, A.F. Grillo, S. Petrera and F. Salamida

events             : 1
random seed        : 65539
A                  : 56
Emin               : 1e+18 eV
Emax               : 1e+18 eV
inj. spectr. index : 1
zmin               : 1
zmax               : 1
dist. btw. sources : 0
EBL model          : 1
nuclear model      : 0
nucleon ej. scaling: 1
alpha ej. scaling  : 1
beta decay         : 1
pion photoprod.    : 1
pair photoprod.    : 0
output type        : 1

SimProp v2r4
** Initial nucleus is: 56
** Losses are: CMB + EBL (Stecker et al. 2006)
** Limits on redshift are: 1 1
** Limits on energy are: 1e+18 eV 1e+18 eV
** Output files is: SimProp-v2r4_N1_A56_e18.0_E18.0_g1.00_z1.00_Z1.00_r0.00_L1_M0_n1.00_a1.00_D1_S1_p0_o1_s65539.root
Simulate one event

./SimProp -N 1 -A 56 -e 18. -E 18. -g 1. -z 1 -Z 1 -o 1

Events to be generated: 1

Event 0 ****************************************

== Primary nucleus (A,Z,E,z): 56 26 1e+18 1

... propagating nucleus (56, 26) Ecurr 1e+18 from z 1

... stacking 1 p + 0 n, z=0.938395, E=1.73071e+16

... int. type 1 (56, 26) -> (55, 25) zfin=0.938395 Efin=9.37011e+17

... propagating proton (1, 1) Ecurr 1.73071e+16 from z 0.938395

... reaches Earth with E = 8.92857e+15

... propagating nucleus (55, 25) Ecurr 9.5189e+17 from z 0.938395

... stacking 2 p + 2 n, z=0.908095, E=1.70366e+16

... int. type 4 (55, 25) -> (51, 23) zfin=0.908095 Efin=9.37011e+17

... propagating proton (1, 1) Ecurr 1.70366e+16 from z 0.908095

... reaches Earth with E = 8.92857e+15

... propagating nucleus (51, 23) Ecurr 9.5189e+17 from z 0.908095

... stacking 1 p + 0 n, z=0.938395, E=1.73071e+16

... int. type 1 (51, 23) -> (50, 23) zfin=0.938395 Efin=9.69197e+17

... propagating proton (1, 1) Ecurr 1.73071e+16 from z 0.938395

... reaches Earth with E = 8.92857e+15

... propagating proton (1, 1) Ecurr 1.70366e+16 from z 0.908095

... reaches Earth with E = 8.92857e+15

... propagating neutron (1, 0) Ecurr 1.70366e+16 from z 0.908095

nucleus 1.69991e+16; electron 2.90856e+13; neutrino 8.33471e+12

... neutron decays into 3 particles at z=0.908095

... propagating neutron (1, 0) Ecurr 1.70366e+16 from z 0.908095

nucleus 1.70034e+16; electron 2.00091e+13; neutrino 1.31574e+13

... neutron decays into 3 particles at z=0.908095

... propagating proton (1, 1) Ecurr 1.69991e+16 from z 0.908095

... reaches Earth with E = 8.92857e+15

... propagating nucleus (50, 24) Ecurr 6.60571e+17 from z 0.908095

... stacking 1 p + 0 n, z=0.479724, E=1.25254e+16

... int. type 1 (50, 24) -> (49, 23) zfin=0.479724 Efin=6.60571e+17

... propagating electron antineutrino (0, 0) Ecurr 6.99588e+12 from z 0.479724

... reaches Earth with E = 4.72783e+12

... propagating electron (0, -1) Ecurr 1.33551e+13 from z 0.479724

... electron produced with E=1.33551e+13 at z=0.479724

... electron antineutrino (0, 0) Ecurr 5.31909e+12 from z 0.479724

... reaches Earth with E = 3.59465e+12

... propagating proton (1, 1) Ecurr 1.31878e+16 from z 0.479724

... reaches Earth with E = 8.91235e+15

... propagating electron antineutrino (0, 0) Ecurr 6.13744e+17 from z 0.402886

nucleus 6.13722e+17; electron 1.38019e+13; neutrino 8.12668e+12

... nucleuses decays into 3 particles at z=0.402886

... propagating proton (1, 1) Ecurr 1.25254e+16 from z 0.402886

... reaches Earth with E = 8.9283e+15

... propagating electron antineutrino (0, 0) Ecurr 6.13722e+17 from z 0.402886

... reaches Earth with E = 5.79283e+12

... carrier photon (1, 0) Ecurr 1.30819e+13 from z 0.402886

... positron produced with E=1.30819e+13 at z=0.402886

... propagating electron (0, -1) Ecurr 1.86877e+13 from z 0.402886

... electron produced with E=1.86877e+13 at z=0.402886

... electron neutrino (0, 0) Ecurr 8.12668e+12 from z 0.402886

... reaches Earth with E = 3.59465e+12

... positron (0, 1) Ecurr 1.30819e+13 from z 0.402886

... reaches Earth with E = 8.91235e+15

... electron antineutrino (0, 0) Ecurr 2.06049e+12 from z 0.402886

... reaches Earth with E = 2.00153e+12

... electron (0, -1) Ecurr 7.37087e+12 from z 0.402886

** event ended - elapsed time (s) 0.06129
Simulate one event

./SimProp -N 1 -A 56 -e 18. -E 18. -g 1. -z 1 -Z 1 -o 1

++++  Succesfully processed 1 events ++++

<table>
<thead>
<tr>
<th>Nucleus Type</th>
<th>Number reaching Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>48</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
</tr>
</tbody>
</table>

photon from pi0 decay: 0
electrons produced: 5
positrons produced: 1

<table>
<thead>
<tr>
<th>Neutrino Type</th>
<th>Number reaching Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron neutrinos:</td>
<td>1</td>
</tr>
<tr>
<td>electron antineutrinos:</td>
<td>5</td>
</tr>
<tr>
<td>muon neutrinos:</td>
<td>0</td>
</tr>
<tr>
<td>muon antineutrinos:</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
</tr>
</tbody>
</table>
Simulate 5000 events

./SimProp -N 5000 -A 56 -e 18. -E 22. -g 1. -z 0.1 -Z 0.1 -o 1 | grep Event

root SimProp-v2r4_N5000_A56_e18.0_E22.0_g1.00_z0.10_Z0.10_r0.00_L1_M0_n1.00_a1.00_D1_S1_p0_o1_s65539.root
root [0] summary->Print()
root [0] summary->Draw("nucEnergy")

Summary tree
(one entry for each event)