Status and future simulation prospects of cosmic-ray ensembles generated by synchrotron radiation

Oleksandr Sushchov

CREDO Visegrad Workshop, Kraków, INP PAS, 17 January 2024

Outline

1. Motivation. Cosmic-ray ensembles (CRE)

2. CRE simulations with CRPropa

3. CRE-Pro

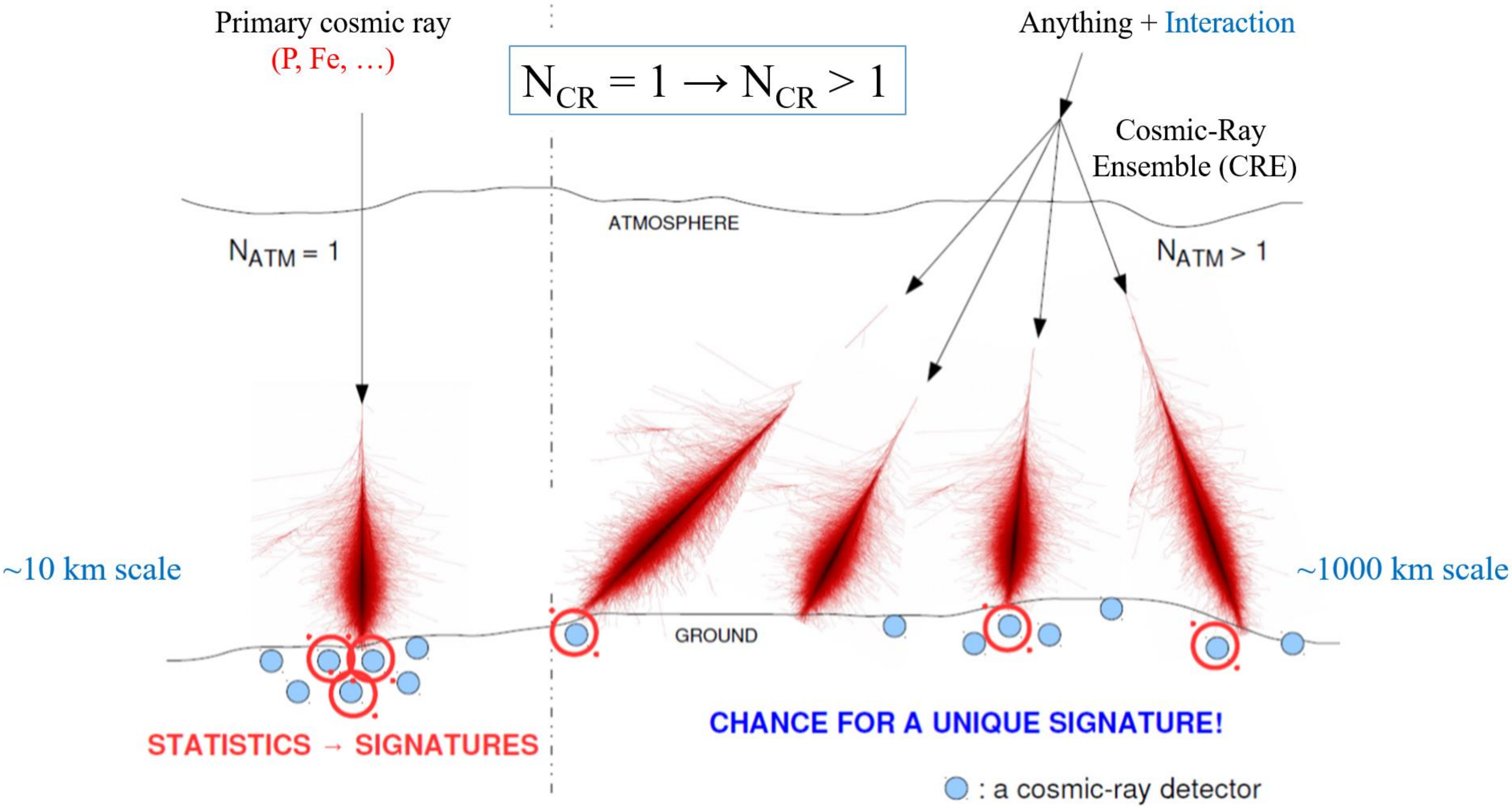
4. Example CRE-Pro use

5. Analysis of the simplest astrophysics scenarios

6. CRE-Pro updates and preliminary results

7. Outlook

Cosmic rays detection



Cosmic-Ray Ensembles: road map

Theoretical scenarios (ongoing) ✓
non-exotic / exotic

↓

CRE standalone simulations → particle distributions at the top of the atmosphere (ongoing) ✓ Current talk

↓

Air shower simulations (ongoing) ✓

↓

Detector response (ongoing) ✓

↓

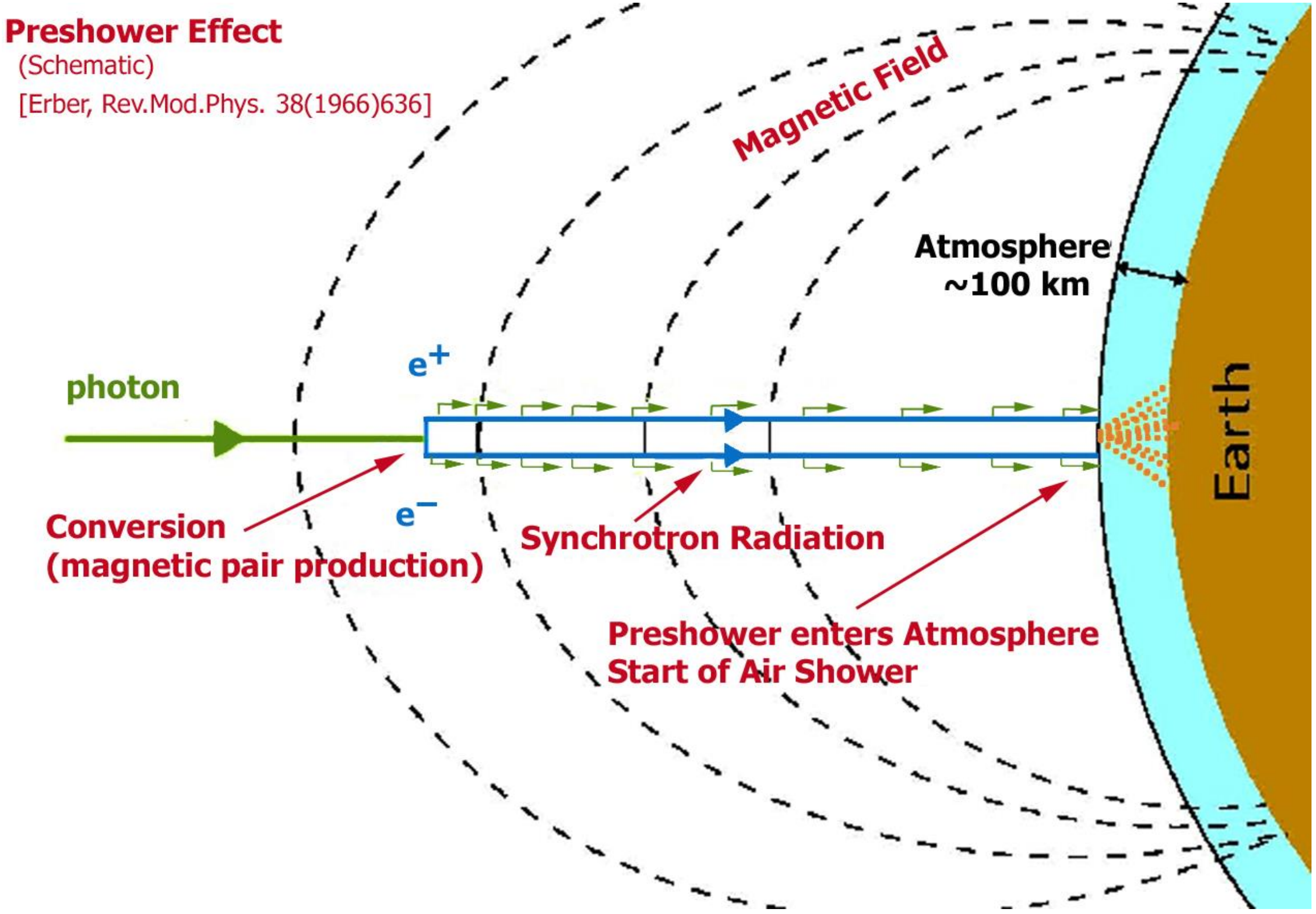
Observation / upper limits

Example non-exotic scenario: preshowers

Preshower (important for E > 10^{19} eV):

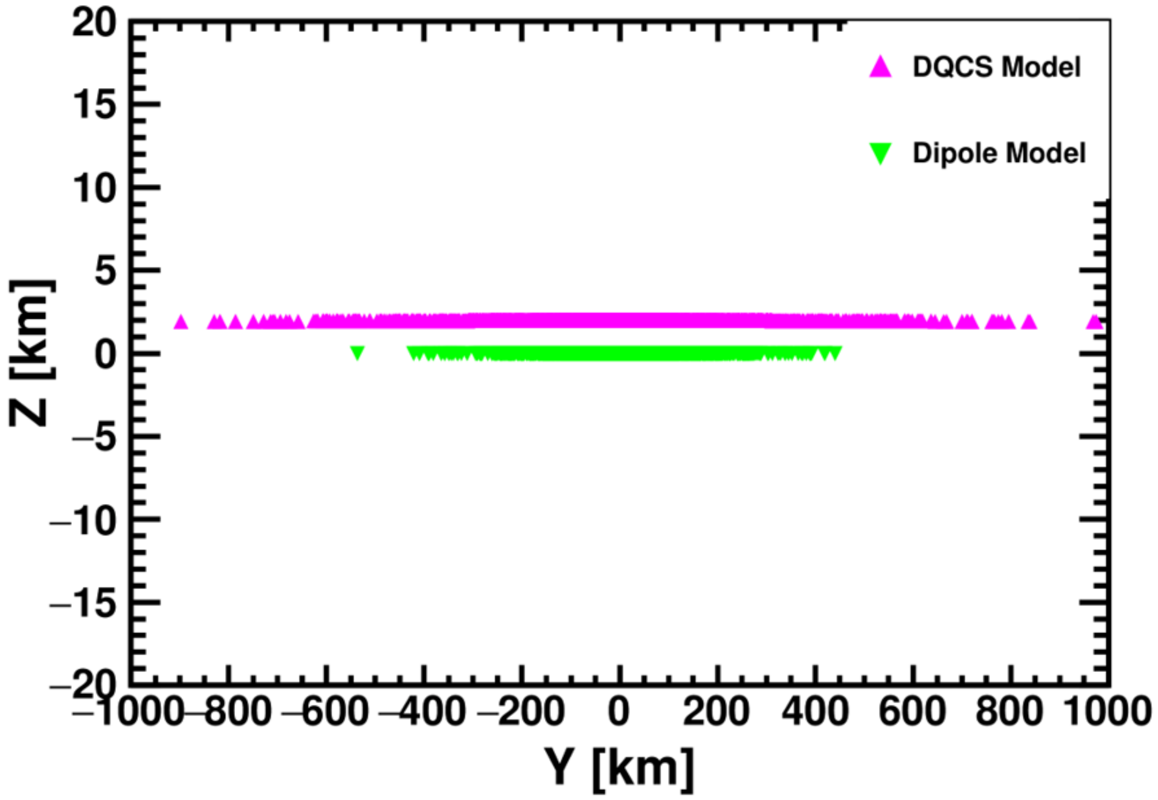
→ contains typically 100 particles; ~ cm size

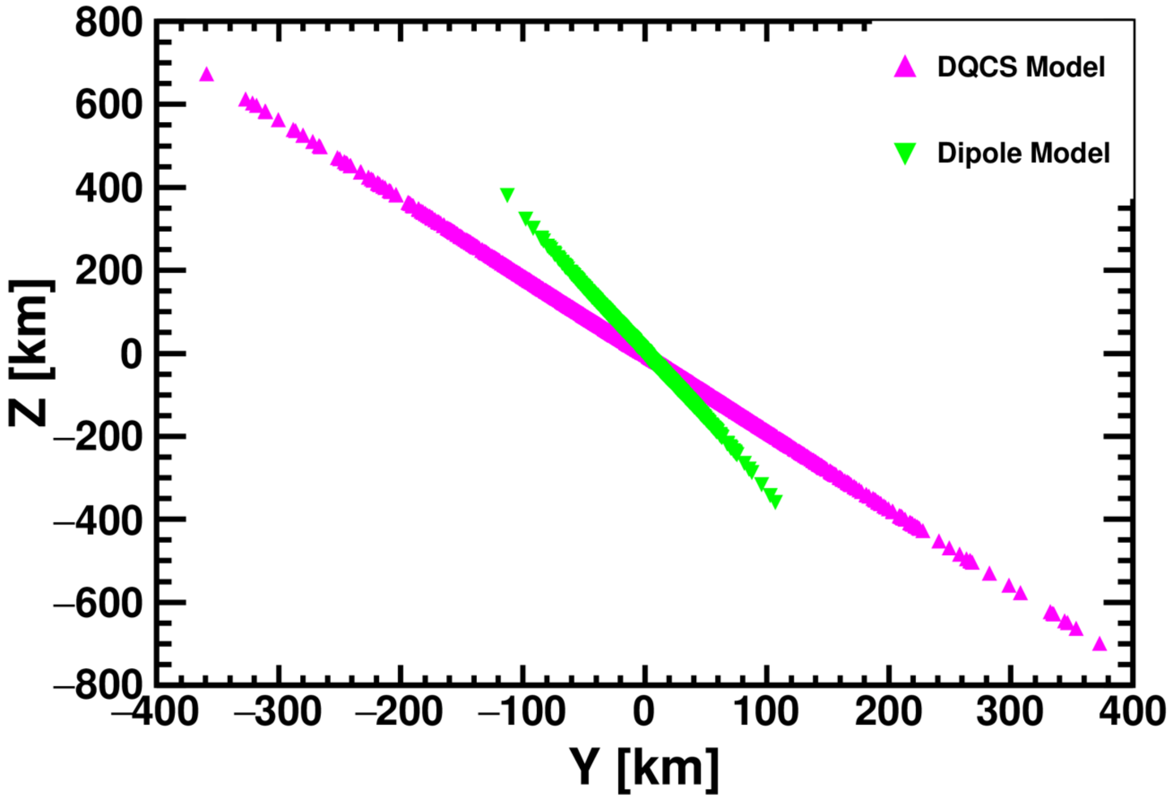
(created at around 1000 km a.s.l.)



Example non-exotic scenario: Sun super-preshowers

Spatial distribution of photons on top of the Earth atmosphere for a sun CRE produced by a 100 EeV photon





*N. Dhital et al (CREDO collaboration) [https://arxiv.org/abs/1811.10334v2]

CRPropa simulation setup

https://crpropa.desy.de

Steering card fragment

…

sim.add(PropagationCK(B,10^{-4}, L_{min}, L_{max}))

…

ObserverLargeSphere(Vector3d(**x_0,y_0,z_0**), **R_{obs}**)

…

source = Source()

source.add(SourceParticleType()) **PDG (11)**

source.add(SourceEnergy(**E_0**))

source.add(SourcePosition(Vector3d(**x_0,y_0,z_0**)))

source.add(SourceDirection(Vector3d(**x_1,y_1,z_1**)))

…

sim.add(MinimumEnergy(**E_{br}**))

…

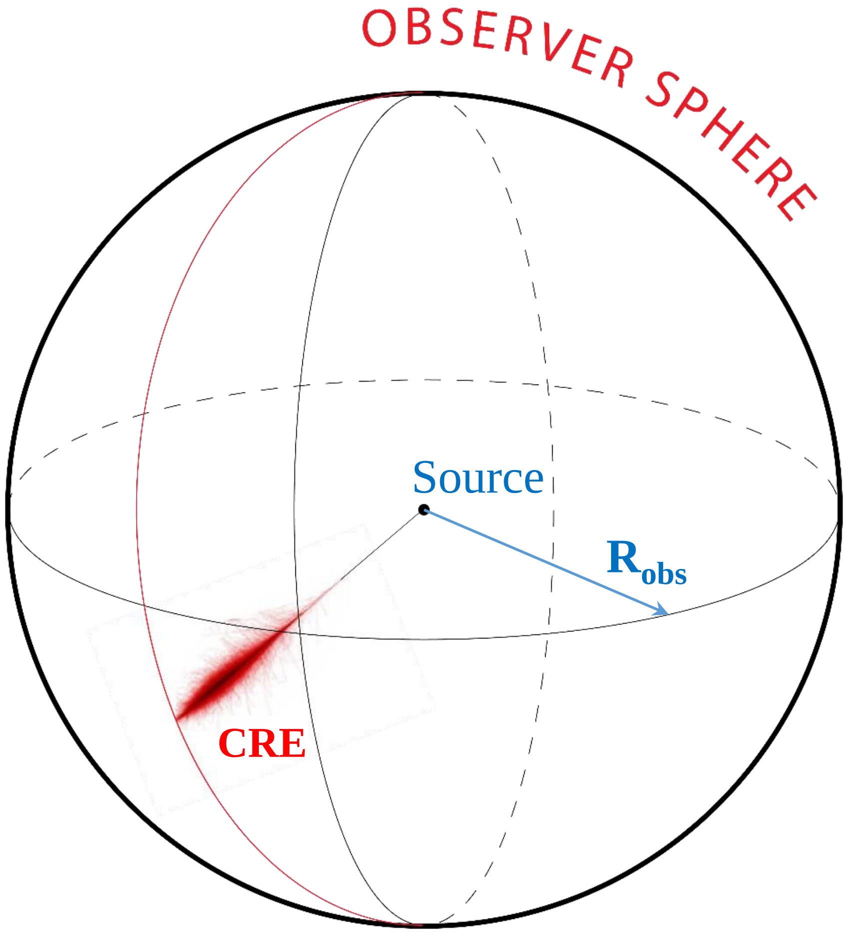
synch = SynchrotronRadiation(**B**, True)

synch.setSecondaryThreshold(**E_{synch}**)

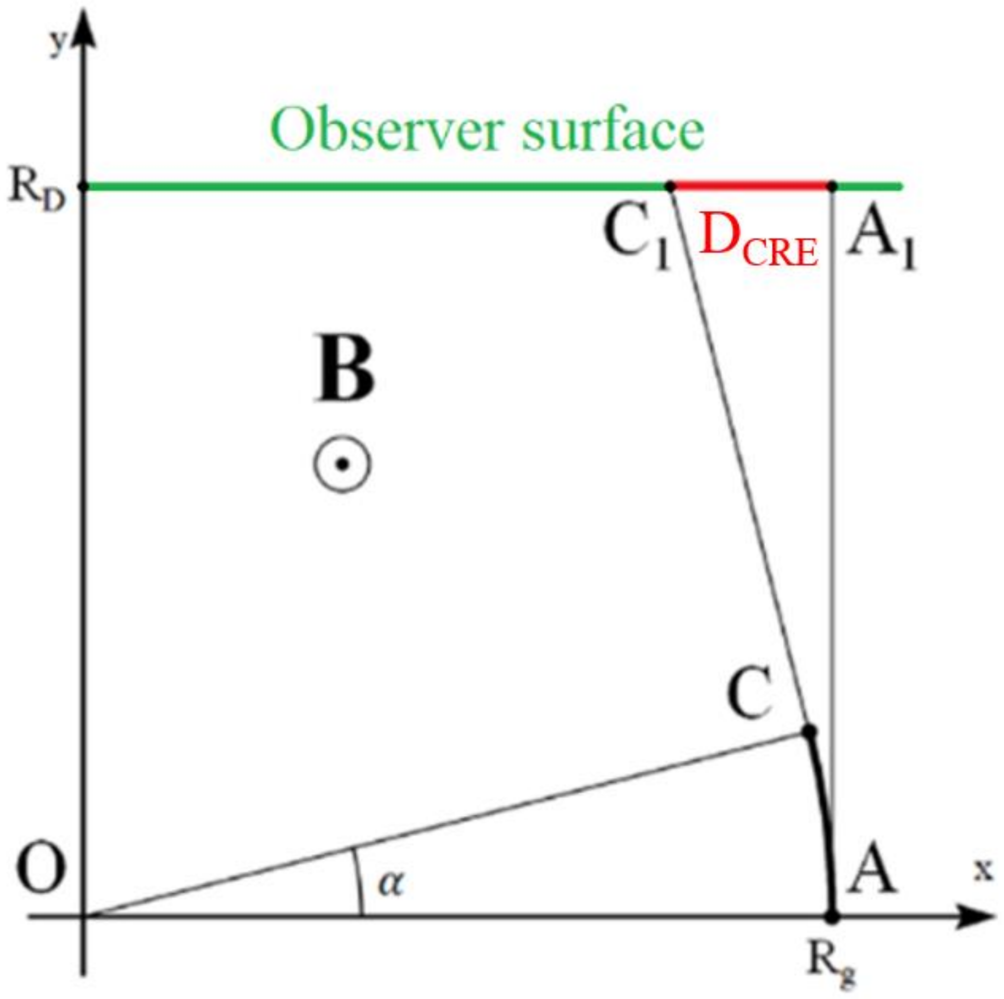
…

sim.run(source, 1)

Setup scheme



CRE-Pro method



$$D_{CRE} = R_g - \frac{R_g}{\cos\alpha} + R_D \tan\alpha$$

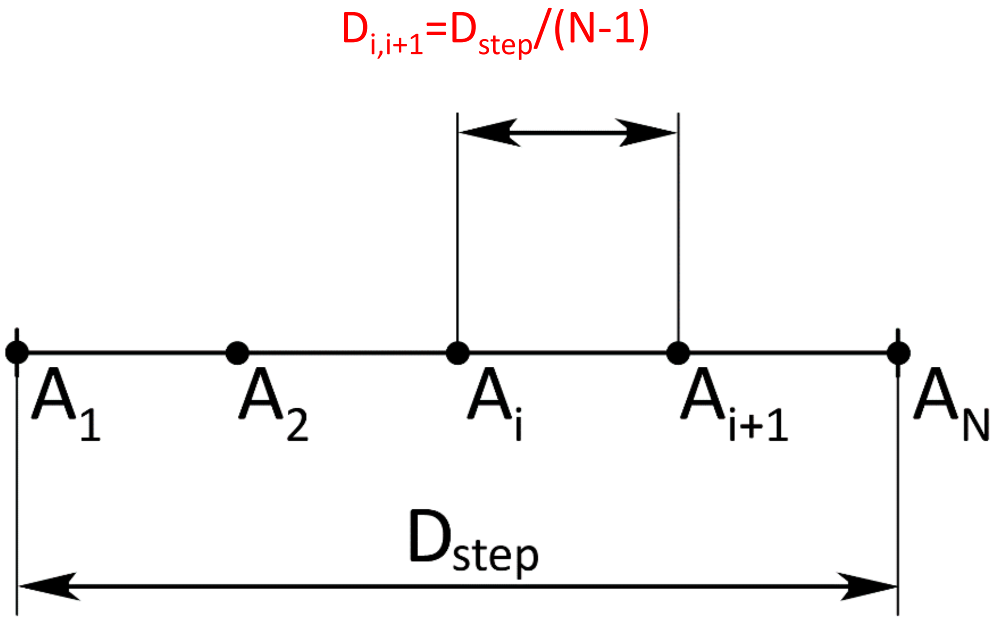
$$\alpha = \frac{D_{step}}{R_g}$$

$$R_g = \frac{E}{cBe}$$

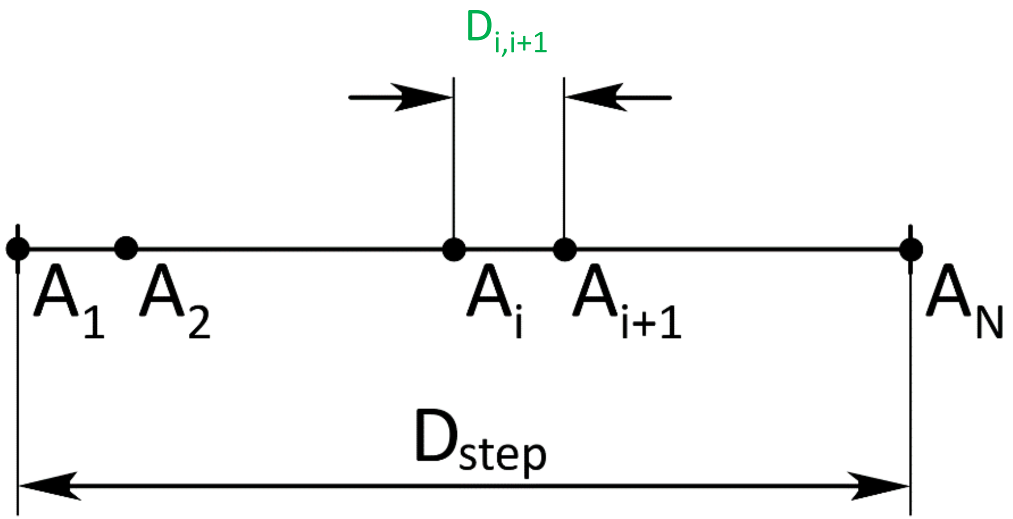
*O. Sushchov et al. (CREDO collaboration) https://doi.org/10.3390/sym14101961

Example CRE-Pro use. Photons distribution

Equidistant



Proportional



$$\frac{D_{CRE}}{D_{step}} = \frac{D_{Earth}}{D_{i,i+1}}$$

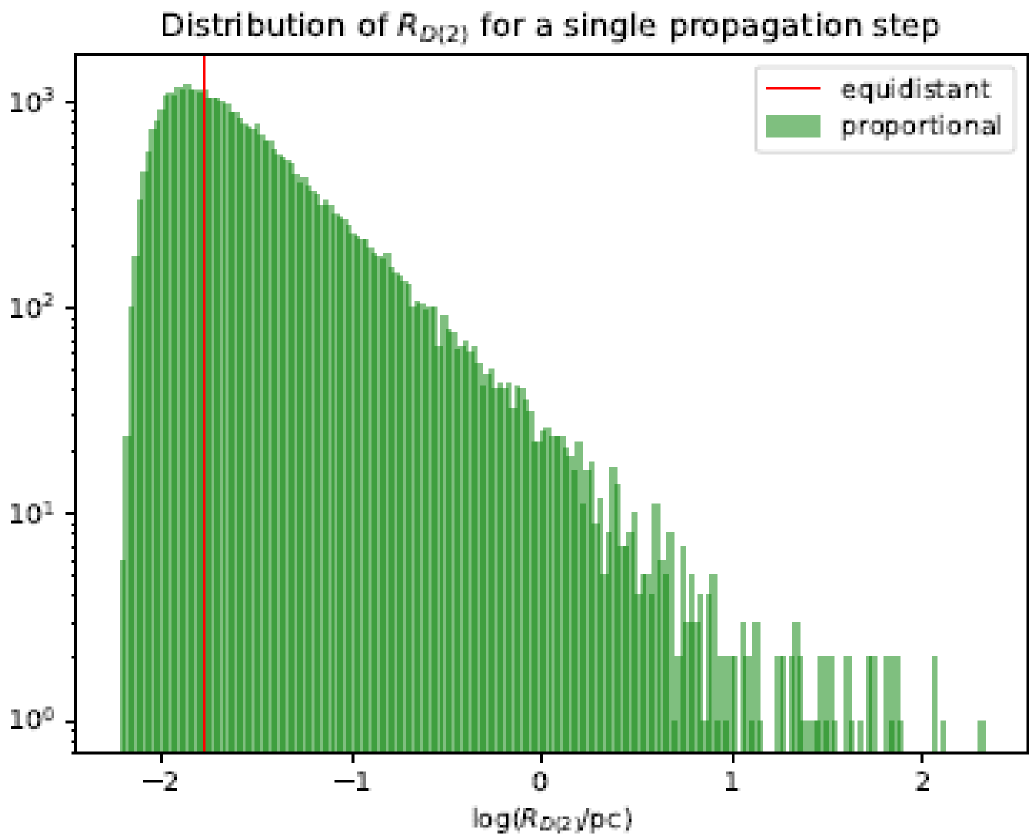
$$R_{D(2)} = \frac{D_{Earth}}{tan\alpha}\frac{D_{step}}{D_{i,i+1}} + Rg\frac{1 - cos\alpha}{sin\alpha}$$

Example CRE-Pro use

Simulation parameters

- The primary electron starting energy: E_0=3.981 EeV
- The minimum energy threshold: E_{br}=10 PeV
- The initial position: (0.0, 0.0, 0.0) (the Galactic center)
- The initial direction: (-1.0, 0.0, 0.0) (towards the Solar System)
- The Galactic magnetic field described by the JF12 model
- The synchrotron radiation threshold: E_{synch} = 1 GeV
- The propagation module (PropagationCK, 10^{-4}, 10^{-5} pc, 10^{-2} pc)

Single propagation step

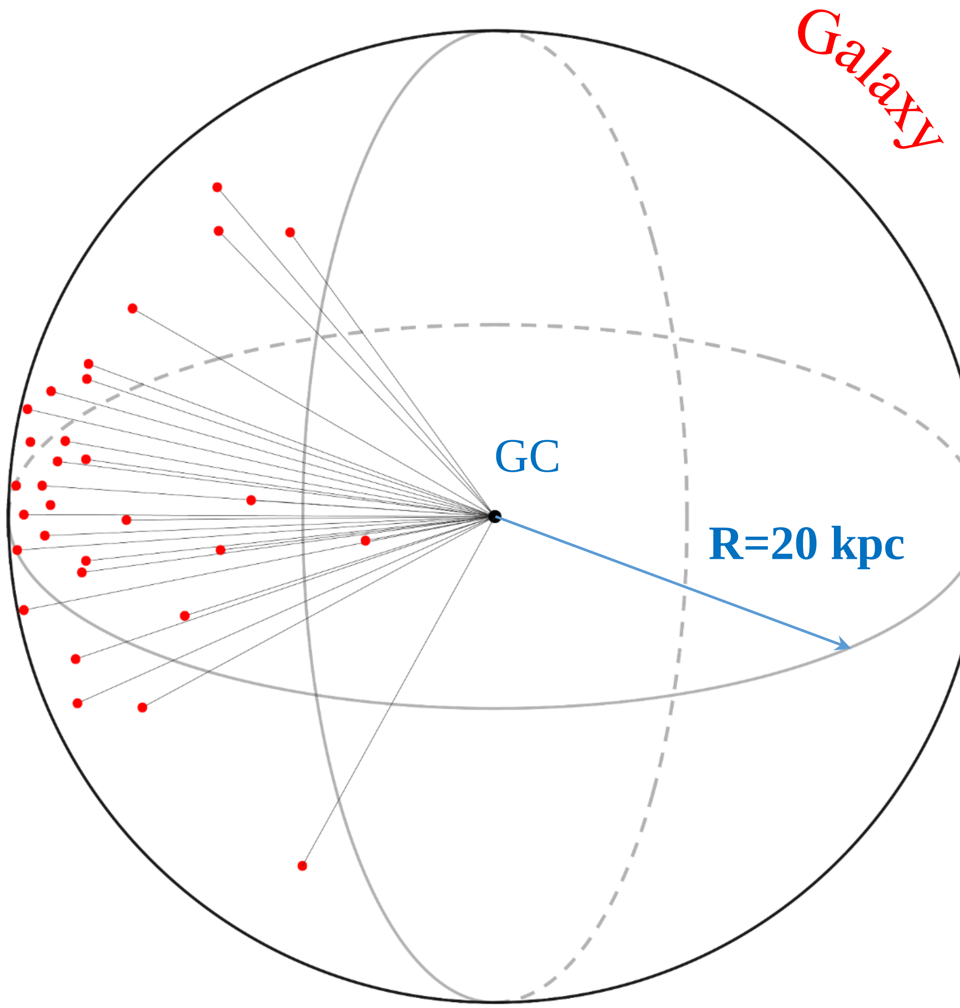


Astrophysics scenarios. Galactic center (GC) model

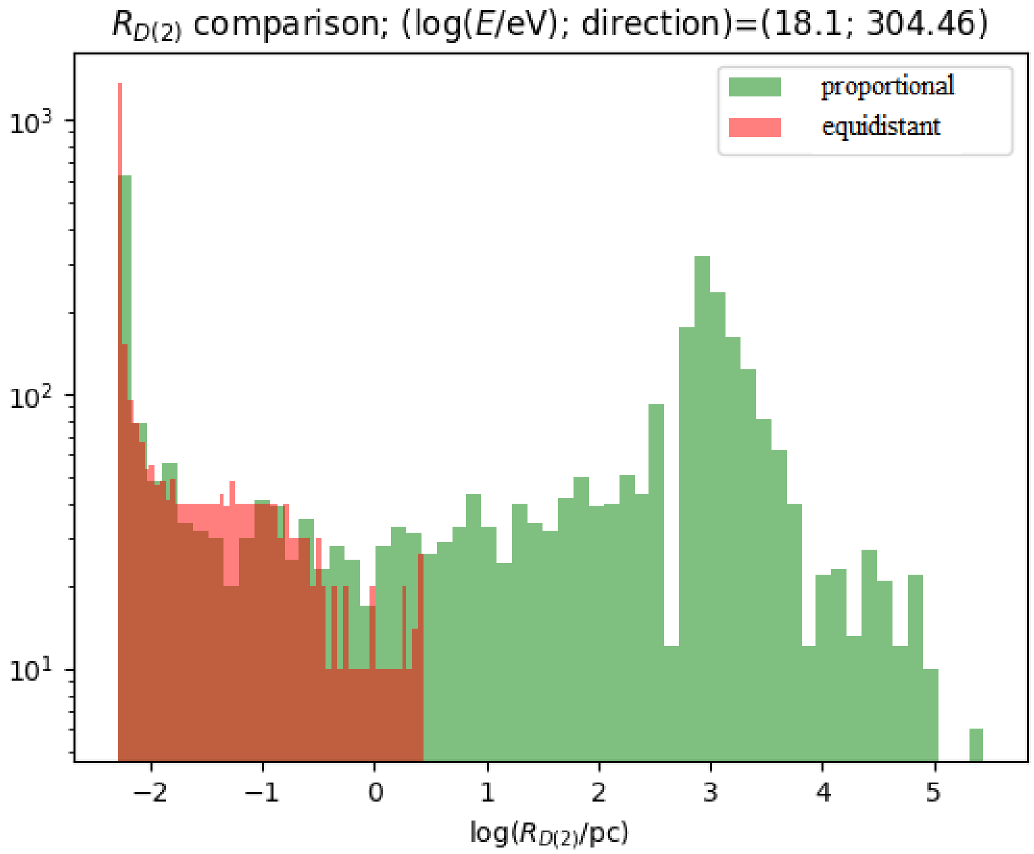
Simulation parameters

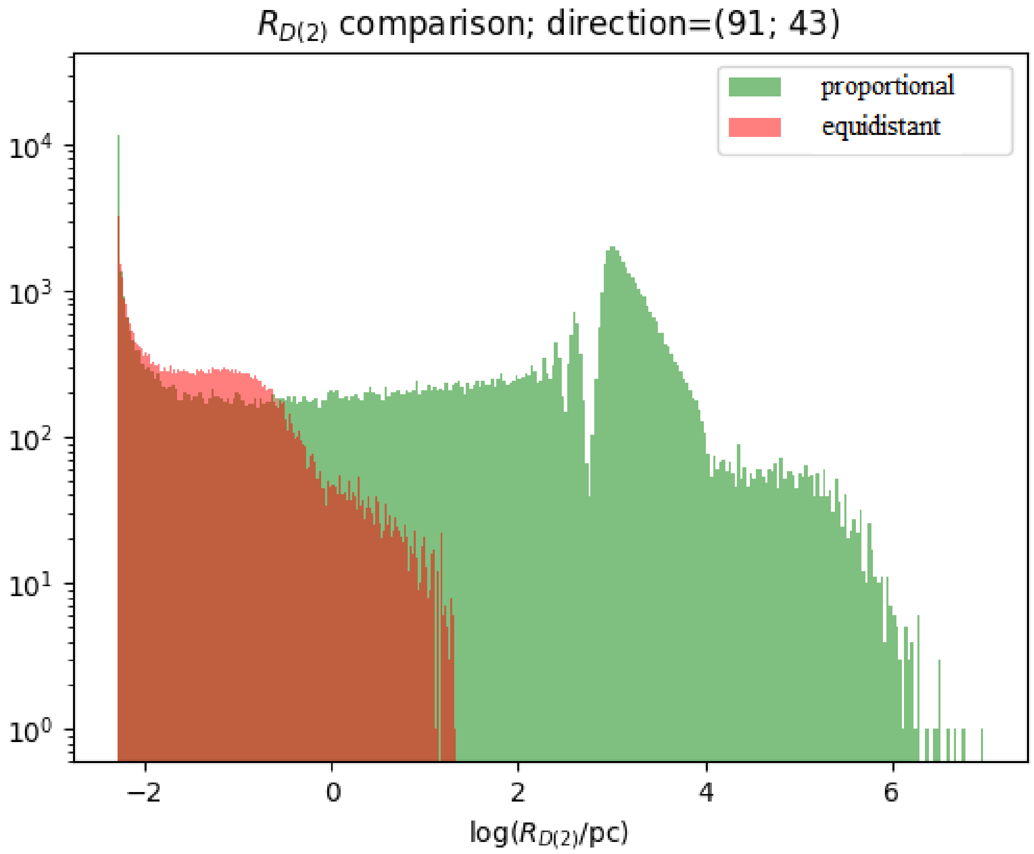
- The primary electron starting energy (21 values in total): $10^{17} \leq \log(E_0/eV) \leq 10^{19}$ with the step $\Delta(\log(E_0/eV))=0.1$
- The initial position: GC
- The minimum energy threshold: E_{br}=10 PeV
- The initial directions: 11 randomly chosen
- The Galactic magnetic field described by the JF12 model
- The synchrotron radiation threshold: E_{synch} = 1 GeV
- The propagation module (PropagationCK, 10^{-4}, 10^{-5} pc, 10^{-2} pc)
- 10 runs in every energy/direction combination
- 2310 runs overall

Setup scheme

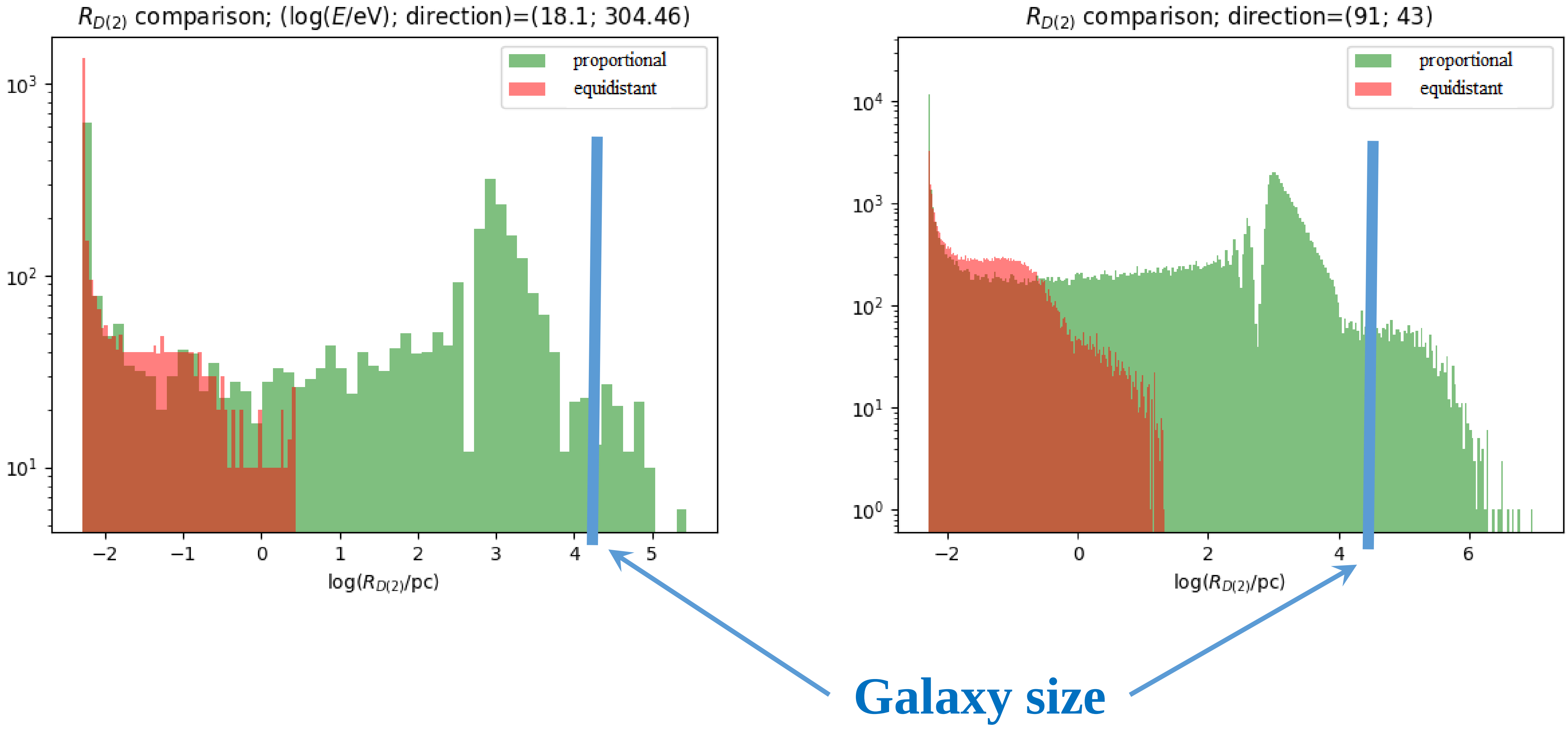


Astrophysics scenarios. GC model





Astrophysics scenarios. GC model

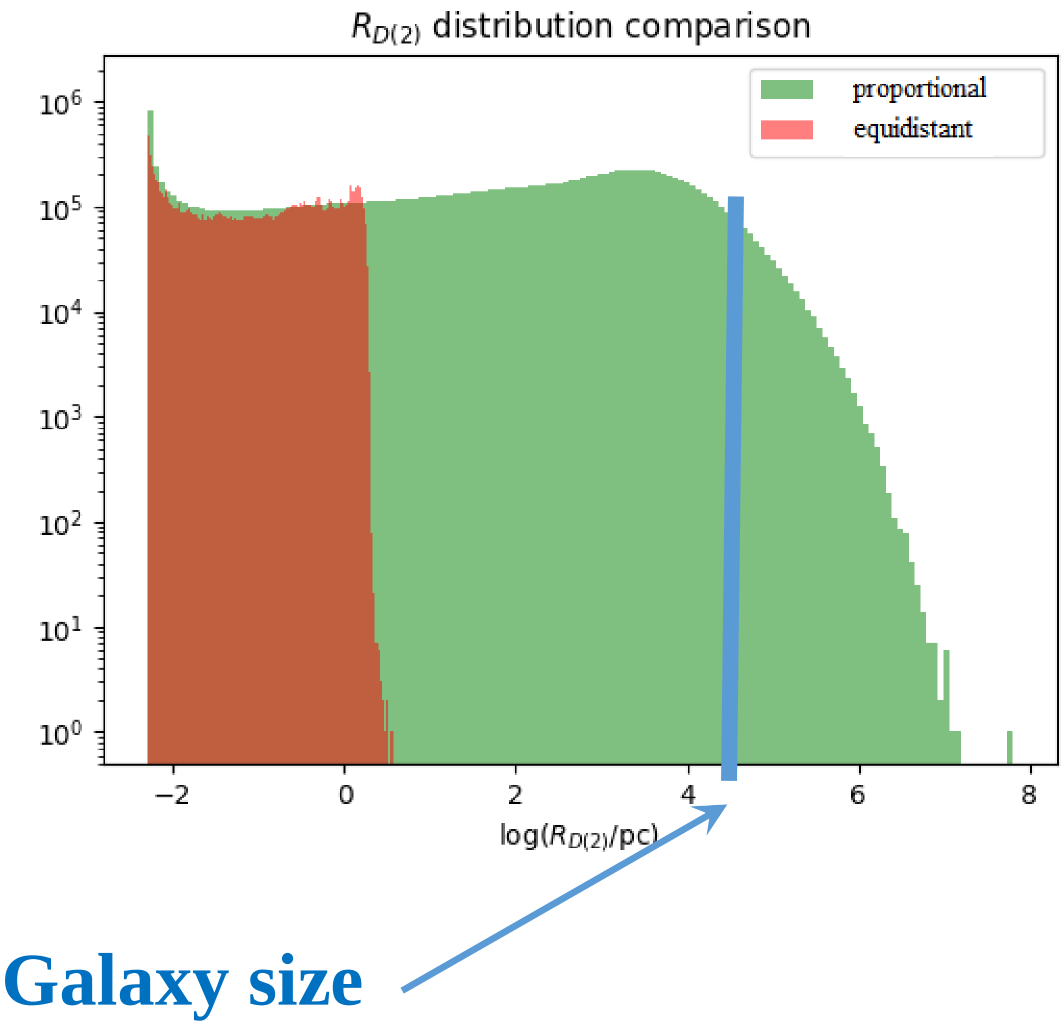


Astrophysics scenarios. SHDM model

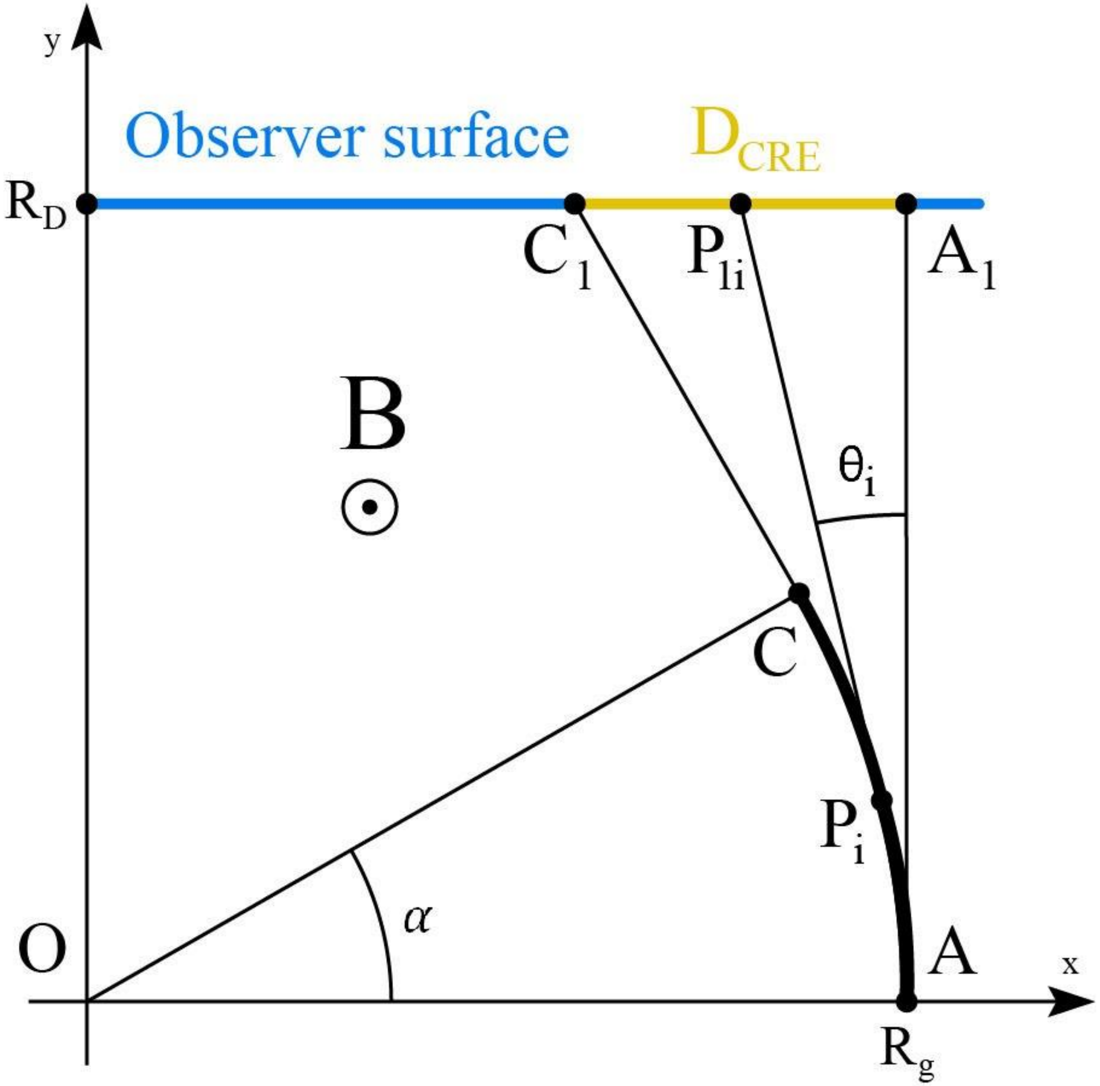
Simulation setup

- The primary electron starting energy: E_0=1 EeV
- The minimum energy threshold: E_{br}=10 PeV
- The initial positions: 292 random points of the Galaxy
- The initial directions: towards the Solar System
- The Galactic magnetic field described by the JF12 model
- The synchrotron radiation threshold: E_{synch} = 1 GeV
- The propagation module (PropagationCK, 10^{-4}, 10^{-5} pc, 10^{-2} pc)
- 292 runs overall

The whole picture



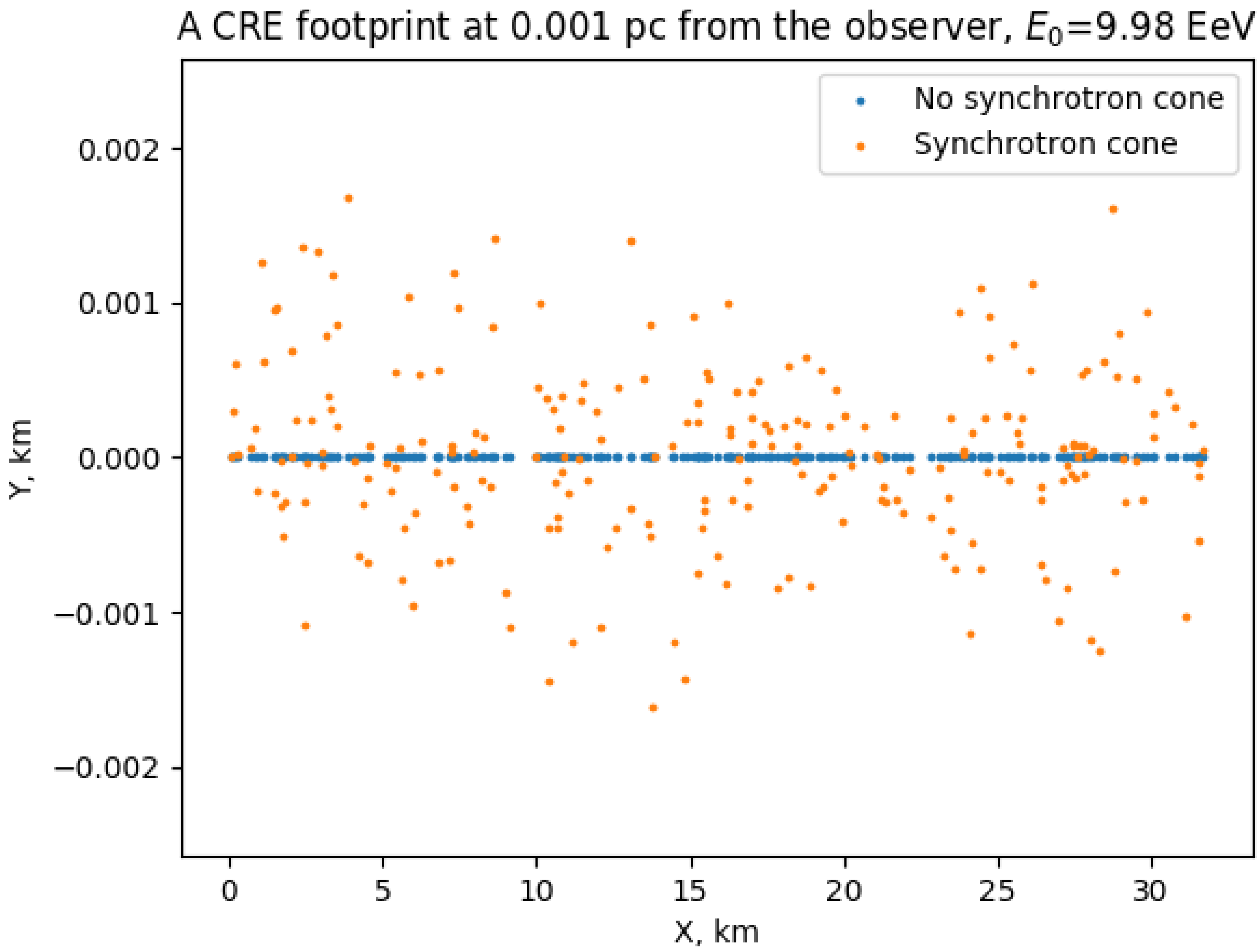
CRE-Pro updates



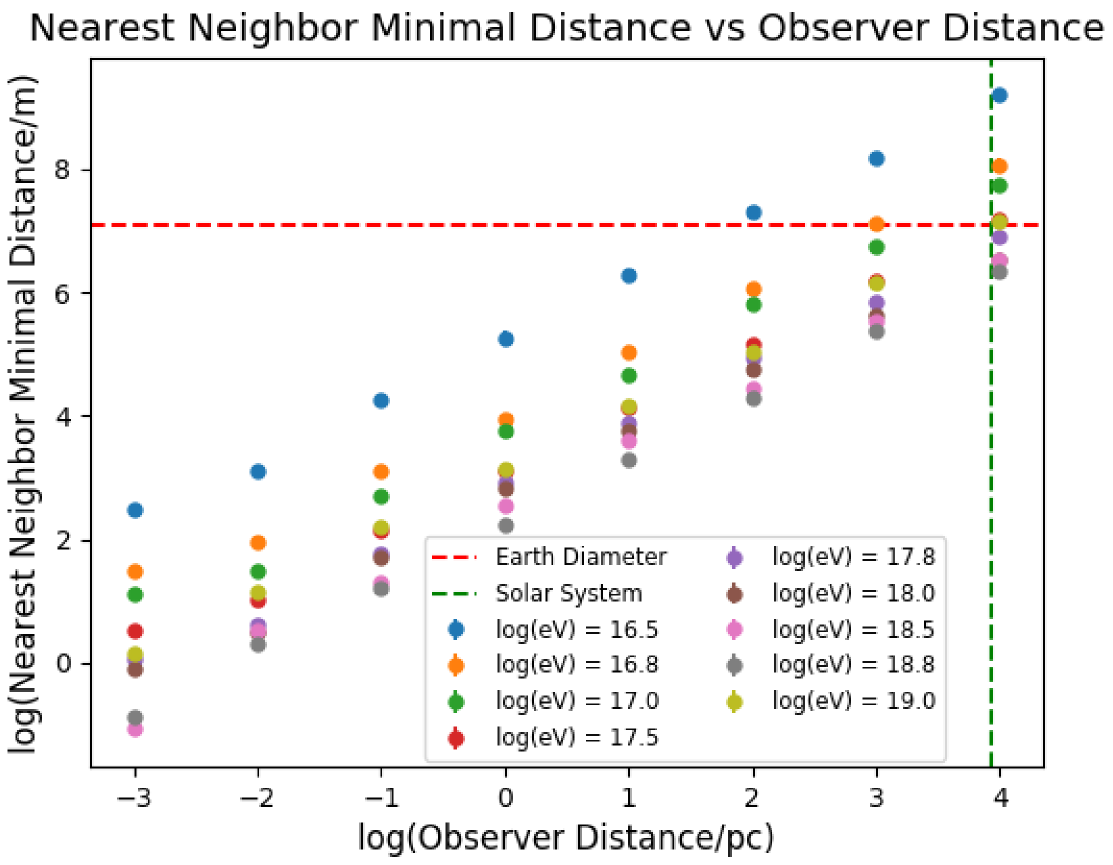
- More precise scaling of the orthogonal projection
- Synchrotron cone implementation
- Gradual energy loss (varying Lorentz factor introduced)

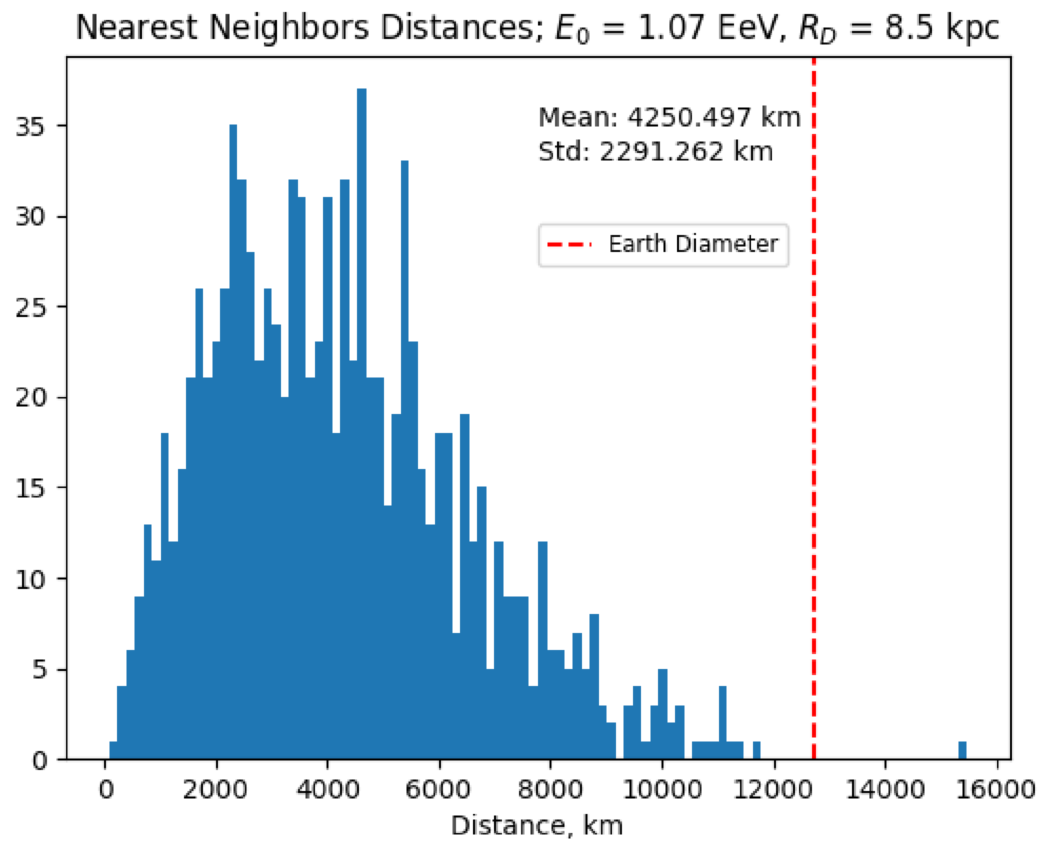
*O. Sushchov et al. (CREDO collaboration) DOI: [10.22323/1.444.0351](https://doi.org/10.22323/1.444.0351)

Example CRE footprint



Updated results





Summary and outlook

- Some/significant fraction of photons of energies exceeding 1 GeV is expected to reach the Earth as groups (CRE).
- There might be a chance of observing a CRE originating from synchrotron radiation even as far as over 10 Mpc away from the Earth.
- CRE-Pro is a helpful and flexible tool in the CRE-oriented analysis of simulations output.
- More detailed simulations (accounting for different energy loss mechanisms, extending the range of simulation parameters, e.g. primary / product particle energies are needed to uncover a wider physics picture
- Estimation of CRE flux on top of the Earth atmosphere is needed to complete the corresponding step of the road map