



# Formation and Propagation of Cosmic-Ray Ensembles

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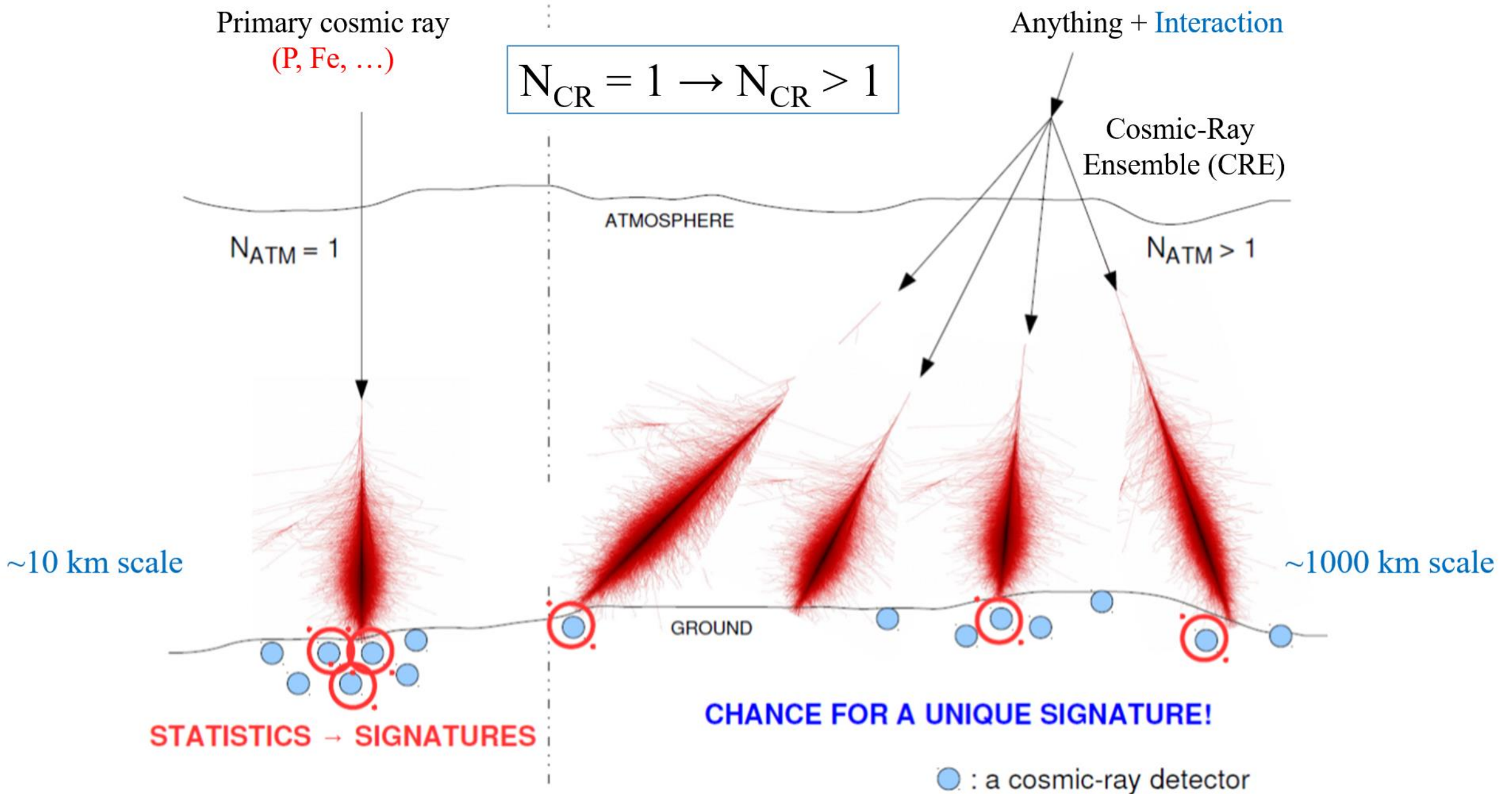
on behalf of the CREDO collaboration

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# Outline

1. Motivation. Cosmic-ray ensembles (CRE)
2. CRPropa simulations
3. External “CRE-Pro” script
4. Example CRE-Pro use
5. Astrophysics scenarios
6. Outlook

# Generalized detection of cosmic rays



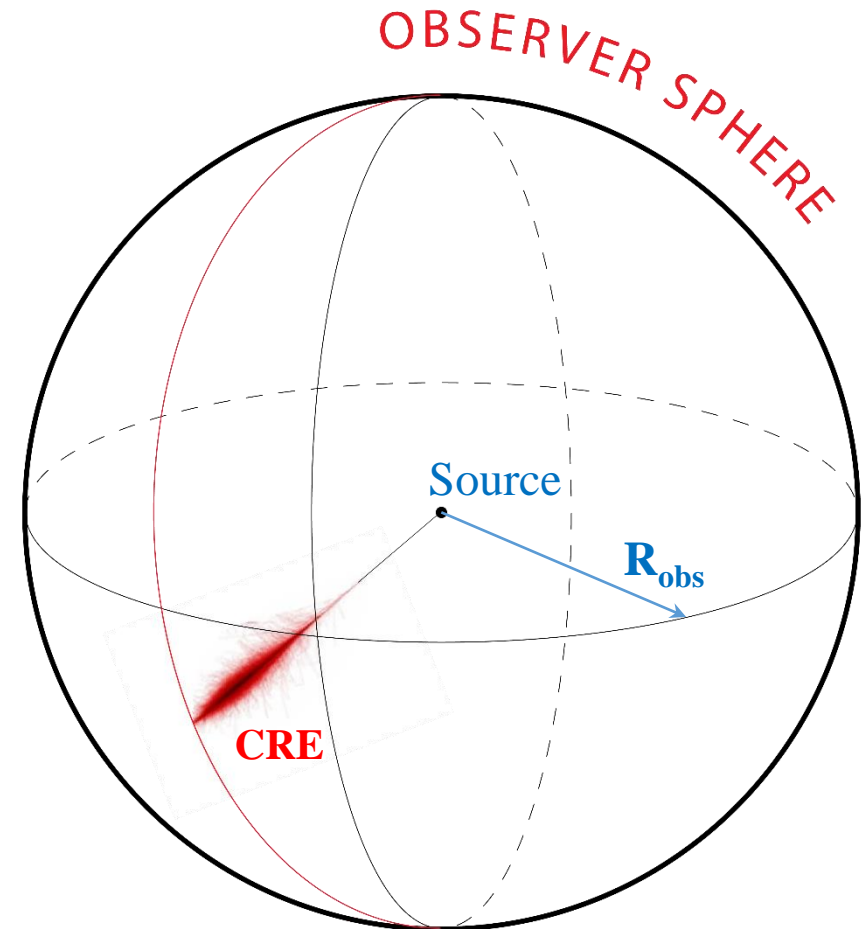
# CRPropa simulation setup

<https://crpropa.desy.de>

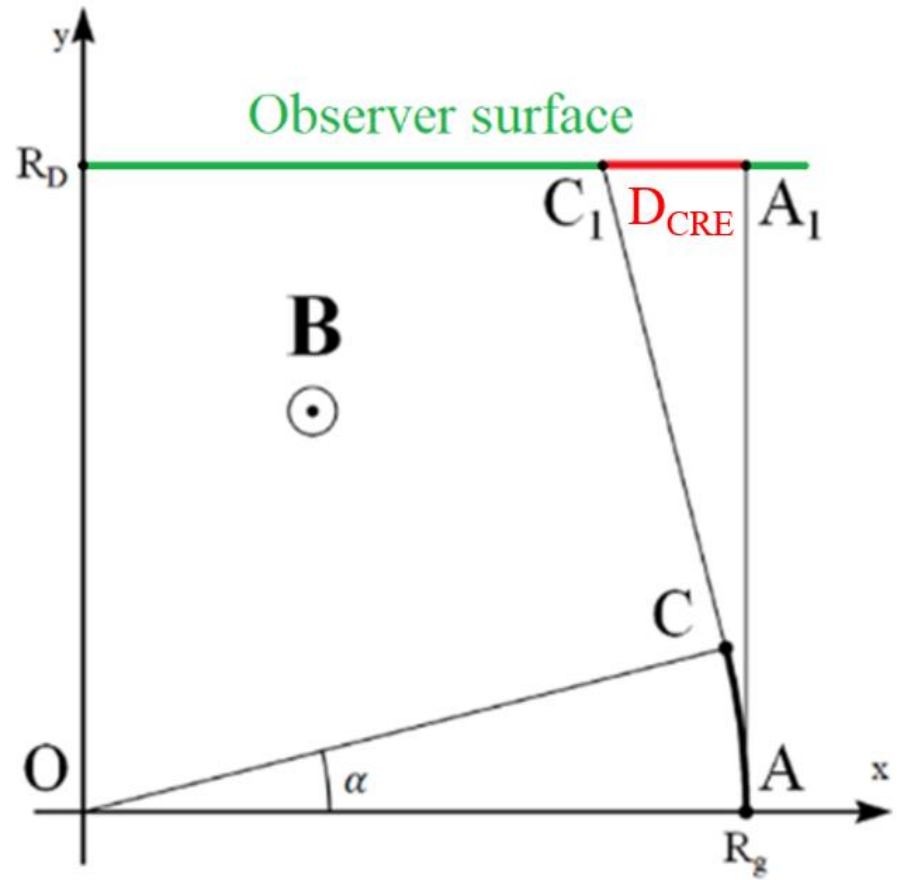
## Steering card fragment

```
...
sim.add(PropagationCK(B,10-4, Lmin, Lmax))
...
ObserverLargeSphere(Vector3d(x0,y0,z0), Robs)
...
source = Source()
source.add(SourceParticleType()) PDG (11)
source.add(SourceEnergy(E0))
source.add(SourcePosition(Vector3d(x0,y0,z0)))
source.add(SourceDirection(Vector3d(x1,y1,z1)))
...
sim.add( MinimumEnergy( Ebr ) )
...
synch = SynchrotronRadiation(B, True)
synch.setSecondaryThreshold(Esynch)
...
sim.run(source, 1)
```

## Setup scheme



# CRE-Pro script



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

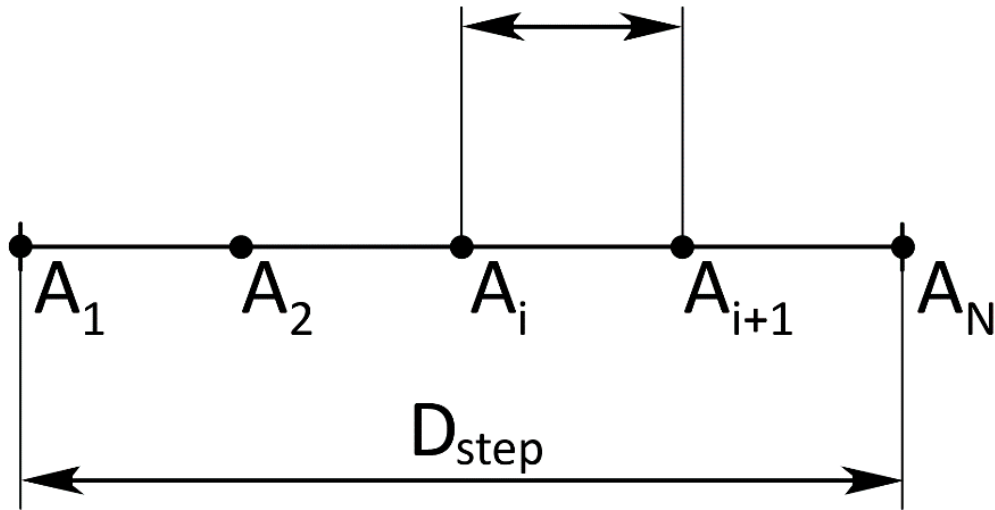
$$\alpha = \frac{D_{step}}{R_g}$$

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

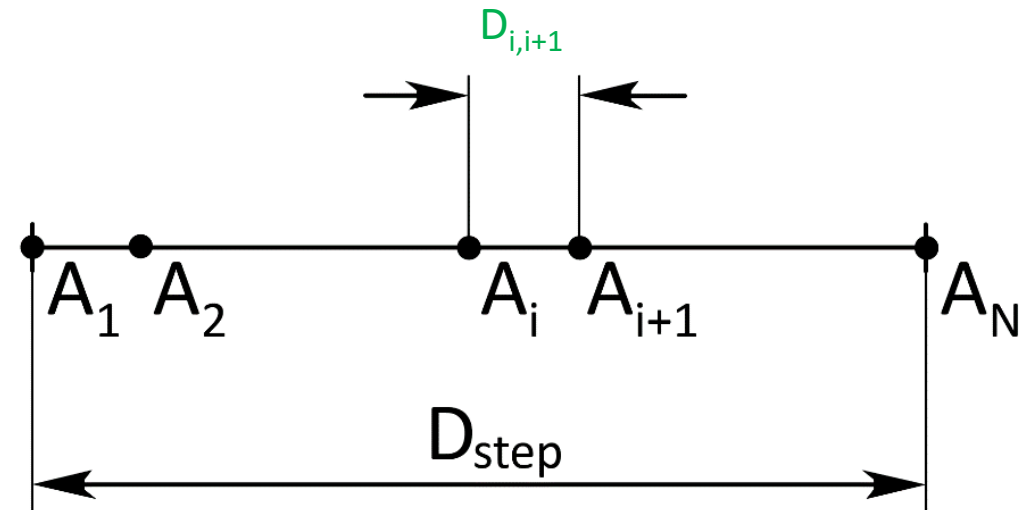
# Example CRE-Pro use. Photons distribution

**Equidistant**

$$D_{i,i+1} = D_{\text{step}} / (N-1)$$



**Proportional**



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



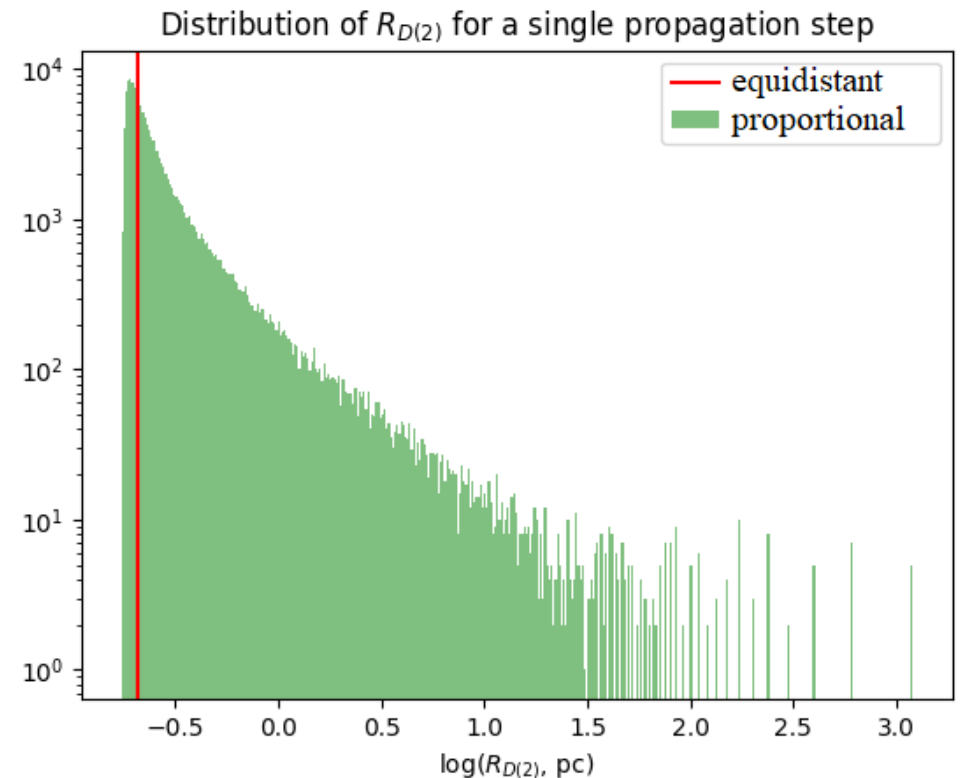
$$R_{D(2)} = \frac{D_{Earth}}{\tan \alpha} \frac{D_{\text{step}}}{D_{i,i+1}} + Rg \frac{1 - \cos \alpha}{\sin \alpha}$$

# 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

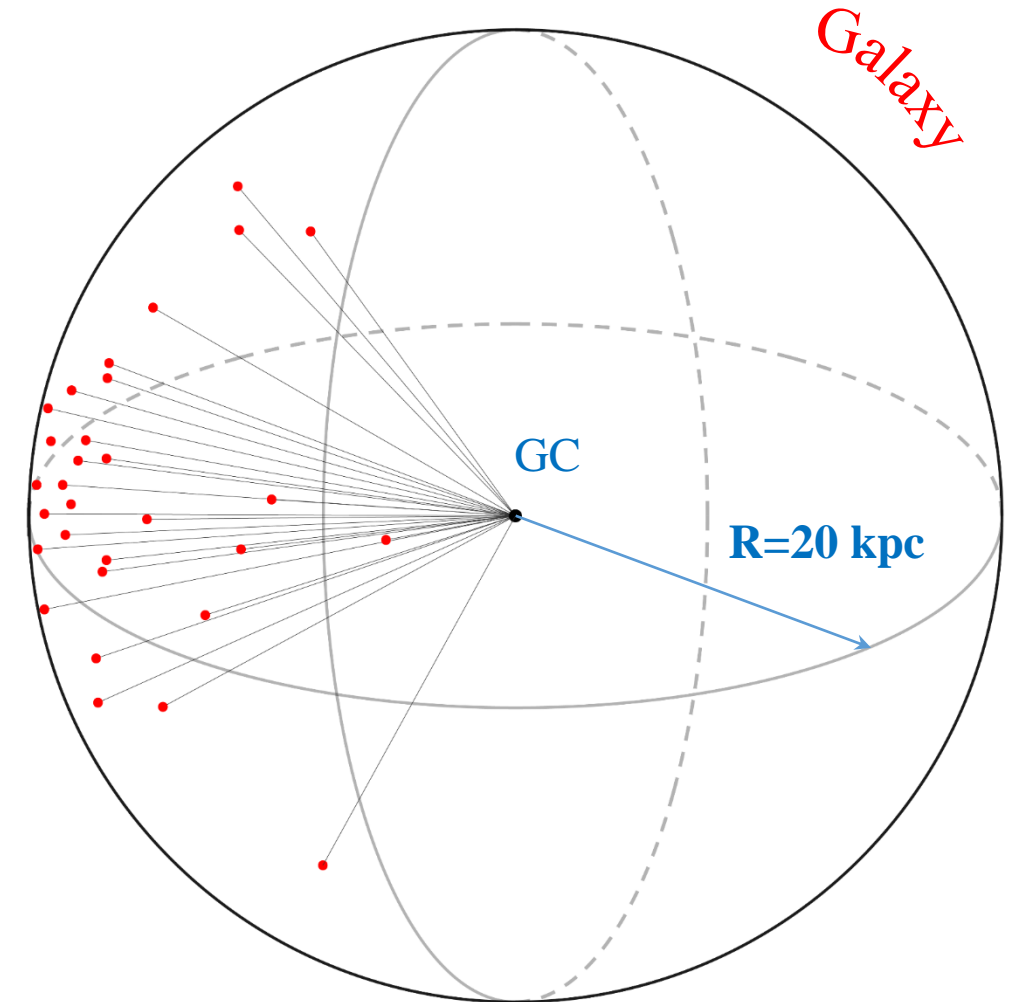


# Astrophysics scenarios. Galactic center (GC) model

## 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

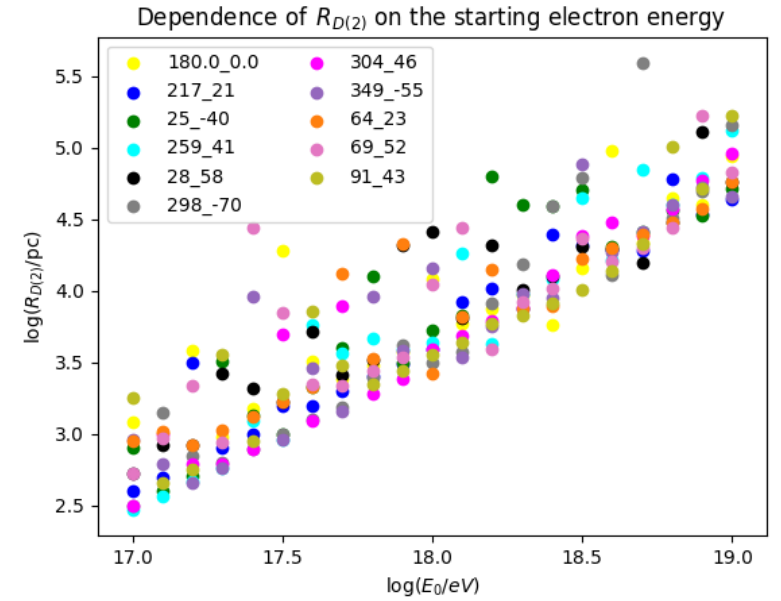
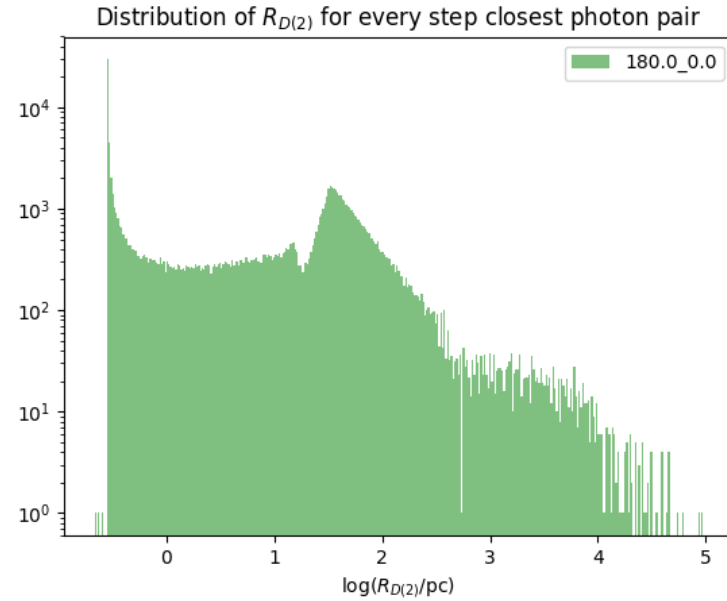
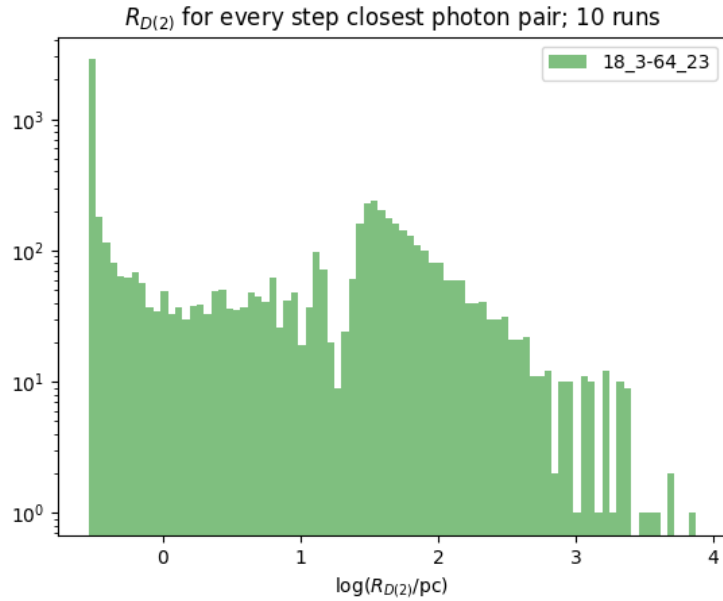
## Setup scheme



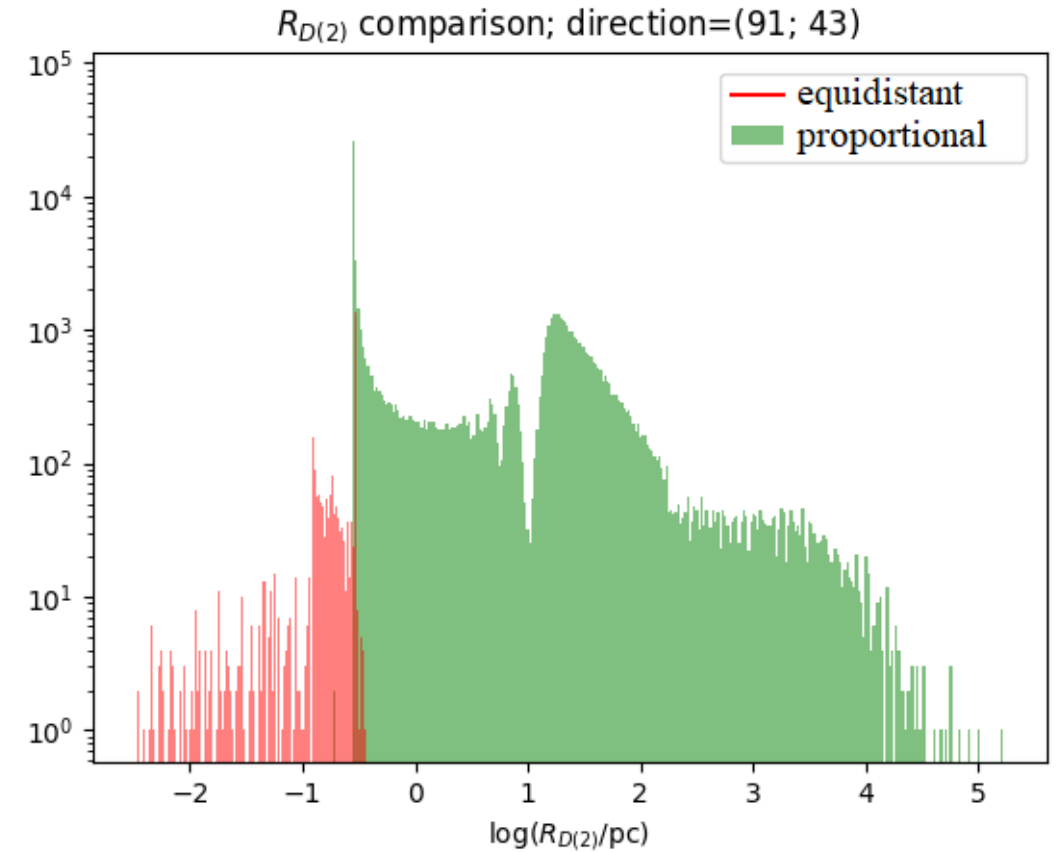
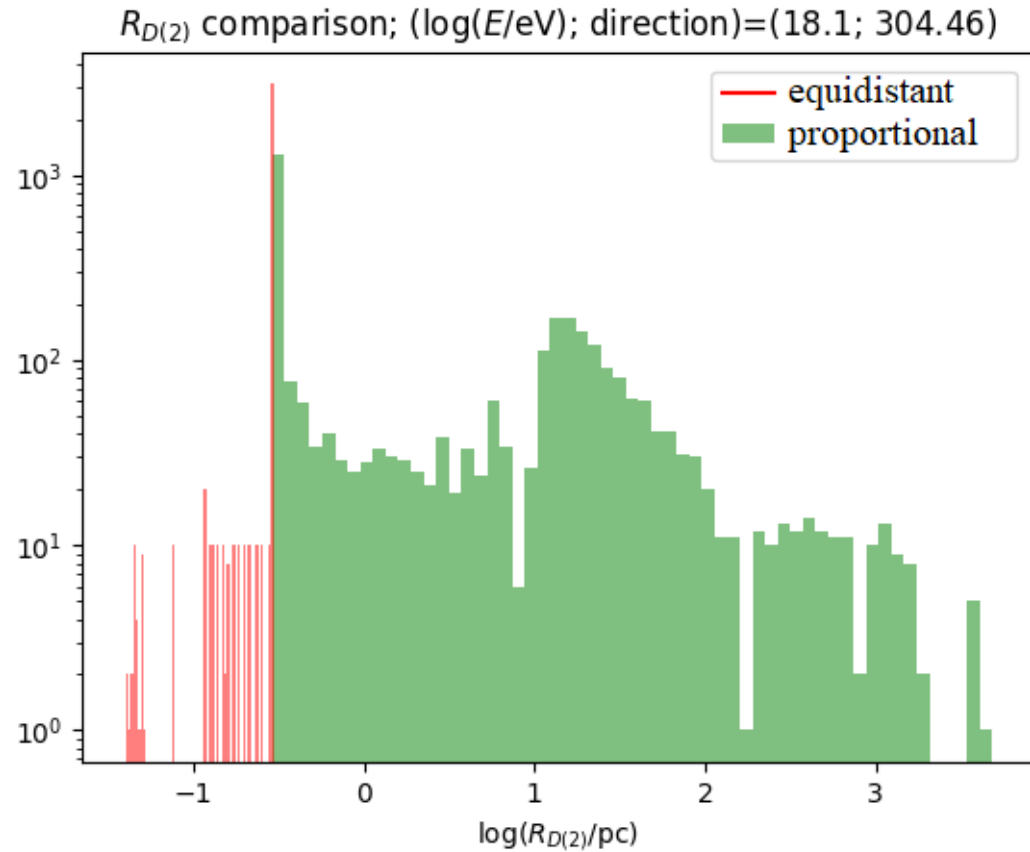


# Astrophysics scenarios. GC model.

## Proportional photon distribution



# Astrophysics scenarios. GC model. Comparison

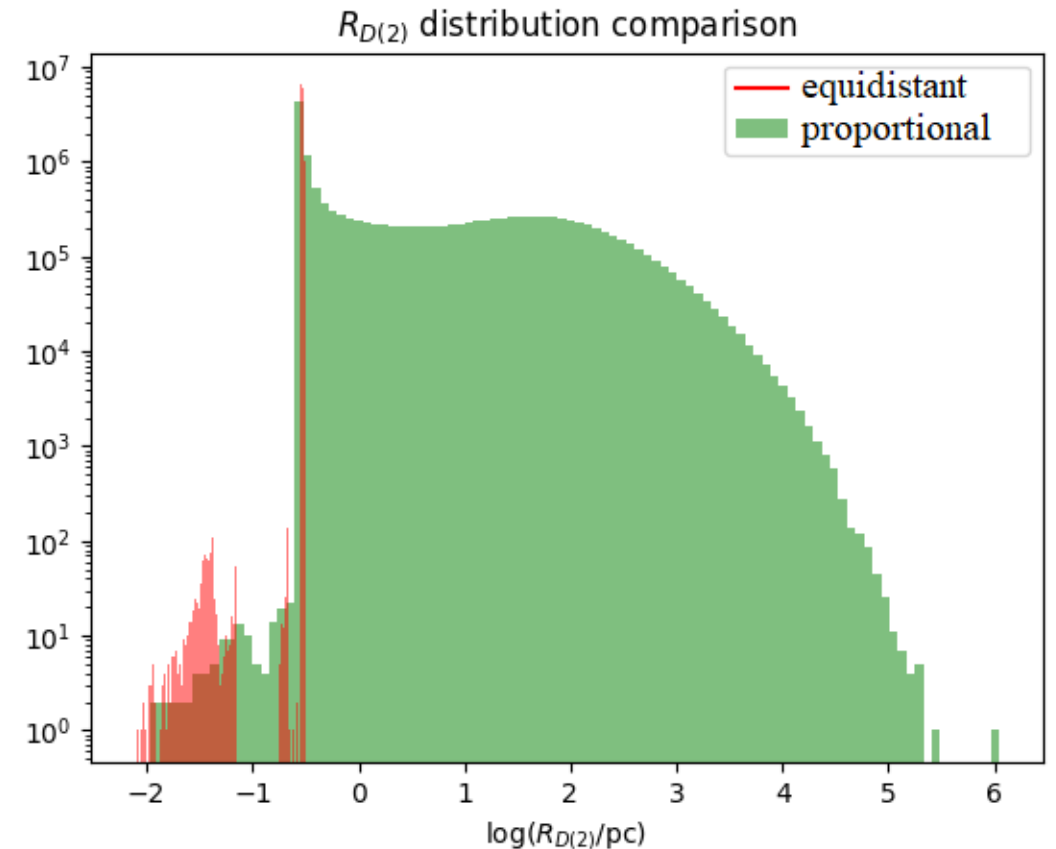


# Astrophysics scenarios. SHDM model

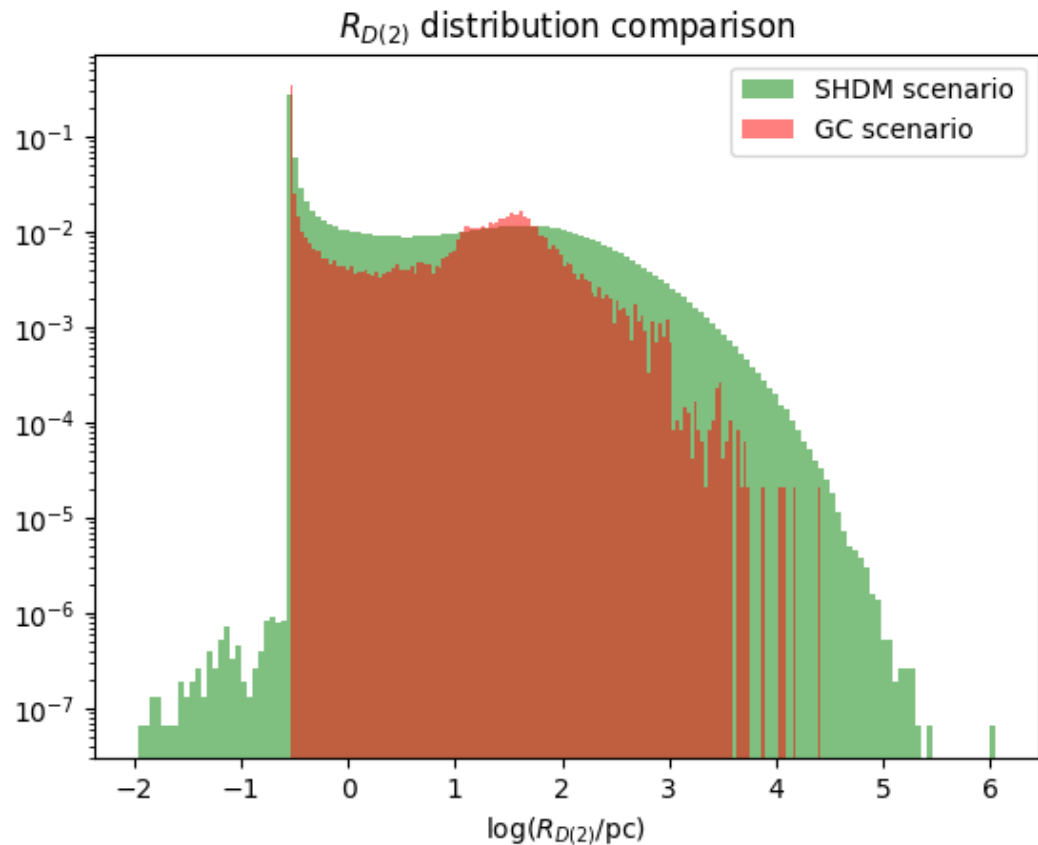
## Simulation setup

- The primary electron starting energy:  $E_0=1$  EeV
- The minimum energy threshold:  $E_{\text{br}}=10$  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:  $E_{\text{synch}} = 1$  GeV
- The propagation module (PropagationCK,  $10^{-4}$ ,  $10^{-5}$  pc,  $10^{-2}$  pc)
- 292 runs overall

## The whole picture



# Conclusions



- Some fraction of gamma rays of energies exceeding 1 GeV reach the Earth as groups (CRE).
- A new research channel focused on observation and studying large scale cosmic ray correlations.
- There might be a chance of observing a CRE originating from synchrotron radiation occurring even as far as 1 Mpc away from the Earth.
- CRE-Pro is a helpful and flexible tool in the CRE-oriented analysis of simulations output