Simulation of formation and propagation of cosmic-ray ensembles: status and perspectives

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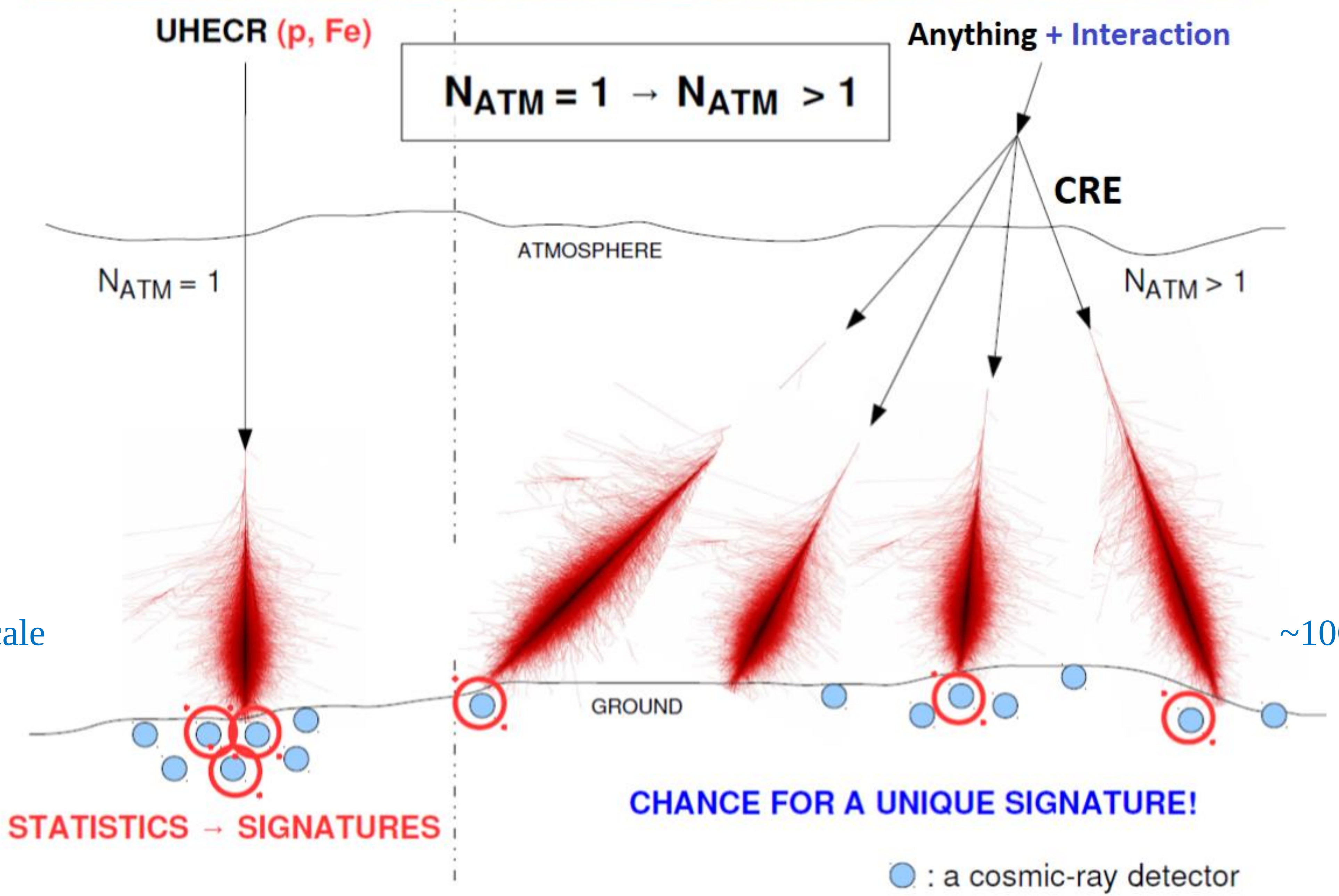
Outline

1. Motivation. Cosmic-ray ensembles
2. Example exotic scenario
3. Scenario 1. Sun SPS simulations
4. Scenario 2. Galactic and extragalactic CRE
5. Summary and outlook

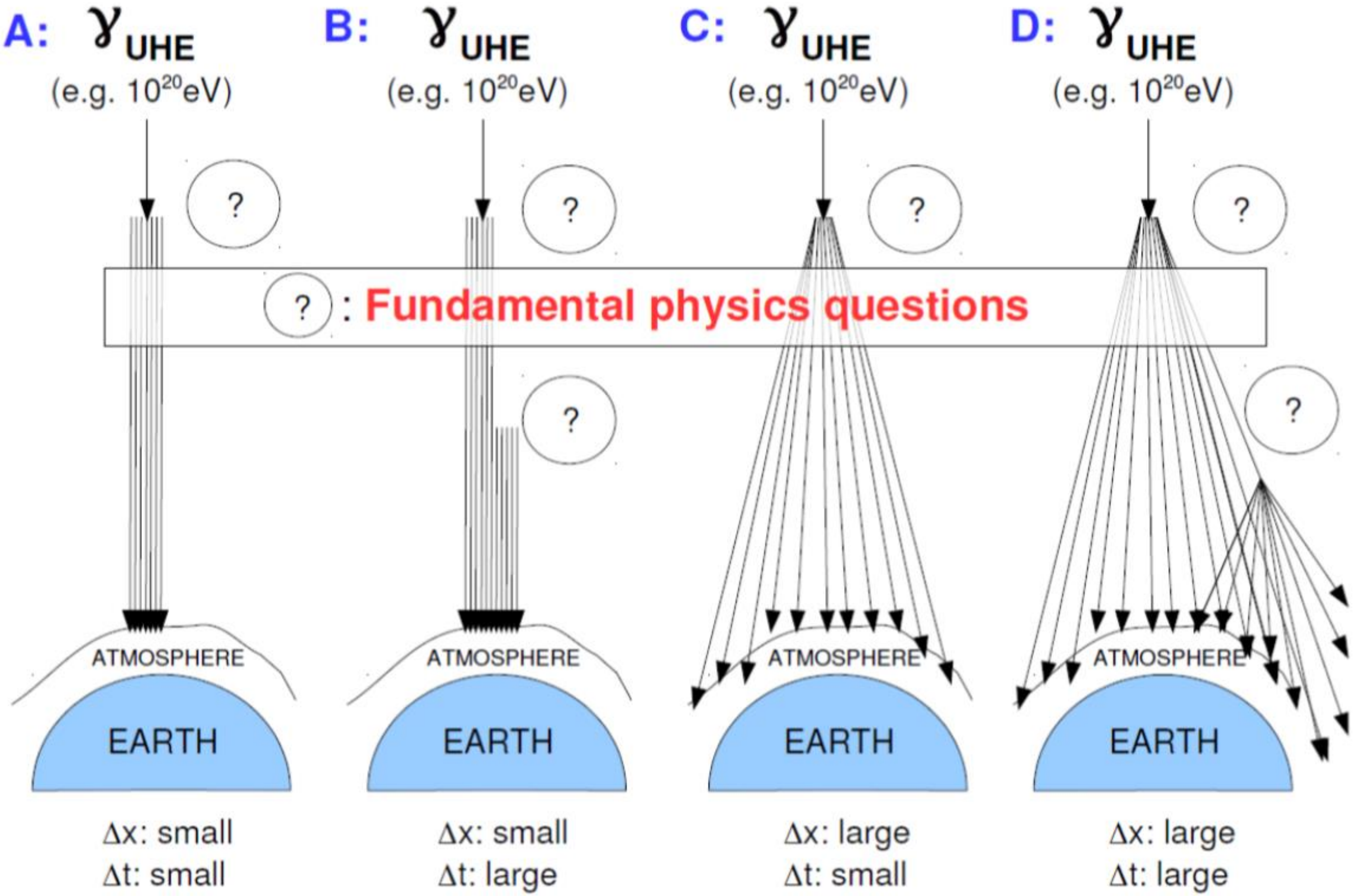
Generalized detection of cosmic rays

~10 km scale



~1000 km scale

Classes of cosmic-ray ensembles



Cosmic-ray ensembles: road map

Theoretical scenarios (ongoing)
non-exotic / exotic ✓

↓

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

↓

Air shower simulations (ongoing) ✓

↓

Detector response (ongoing) ✓

↓

Observation / upper limits

Example exotic scenario: Lorentz invariance violation

- κ endows the vacuum with an effective index of refraction, leading to a **modification of the photon dispersion relation**

$$\omega(q) = \frac{1}{n_{\text{eff}}}\, q = \sqrt{\frac{1-\kappa}{1+\kappa}}\, q$$

- This modification allows for processes which are **kinematically forbidden** in the conventional Lorentz-invariant theory
  - $\kappa > 0$: **vacuum Cherenkov radiation** possible above a threshold $E_{\text{thr}}(\kappa)$

    $$f \to f + \tilde{\gamma}$$

    efficient energy loss mechanism for charged particles, current constraints ($\kappa < 6 \times 10^{-20}$ at 98 % C.L.) derived from **observations of UHECRs** [Klinkhamer & Risse 2008] [Klinkhamer & Schreck 2008]
  - $\kappa < 0$: **photon becomes unstable** above a threshold $\omega_{\text{thr}}(\kappa)$

    $$\tilde{\gamma} \to e^{+} + e^{-}$$

    decay length is very small, current constraints ($\kappa > -9 \times 10^{-16}$ at 98 % C.L.) derived from **gamma-ray astronomy** [Klinkhamer & Schreck 2008]

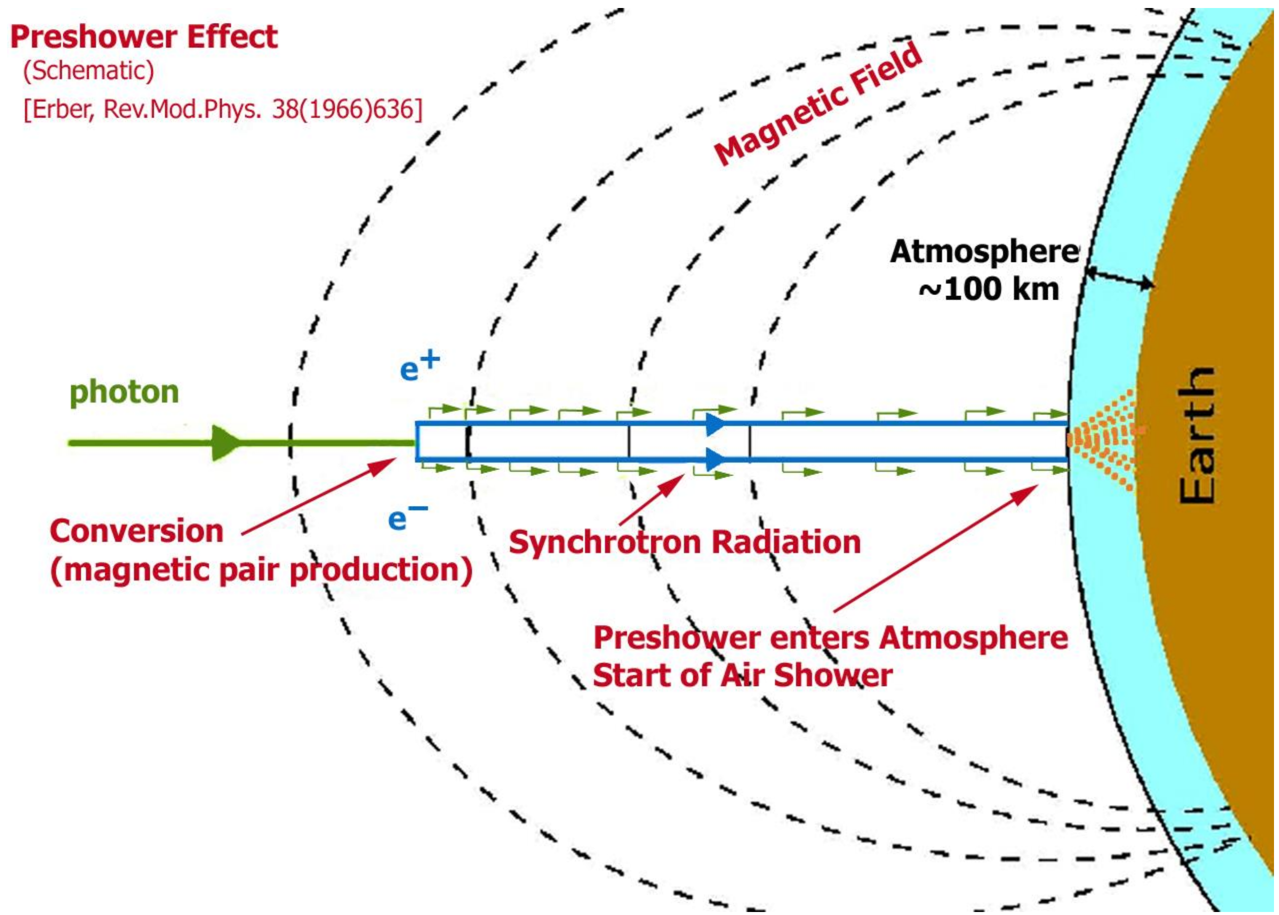
ALL UHE photons initiate CRE!!!

F.R. Klinkhamer, M. Niechciol, M. Risse. arXiv:1710.02507

A phenomenon in CREDO's reach: Super-Preshower

Preshower:

- Cascade of EM particles produced by interaction of UHE photons with geomagnetic field.
- Typical altitude 1000 km a.s.l.
- N_{part} at the top of the Earth's atmosphere ~100.



Super-preshower (SPS):

- Cascade of particles produced due to exotic/non-exotic processes.
- Typical distance of cascade development is **very far**.
- N_{part} at the top of the Earth's atmosphere >> **100**.

Simulation of SPS at vicinity of the Sun

- Development of SPS at Sun’s vicinity is **analogous to** the development of **preshower** in geomagnetic field. Solar magnetic field is responsible for SPS production.
- When a UHE photon heading towards Earth traverses through region close to Sun, pair production and synchrotron emission from electron/positron created thereof will produce a cascade comprising of a **large number** of photons and a few electrons/positrons.
- Simulation of UHE photon propagation and SPS development at the Sun’s vicinity is performed using modified PRESHOWER[1] code. Currently, only the **first conversion** is taken into account.

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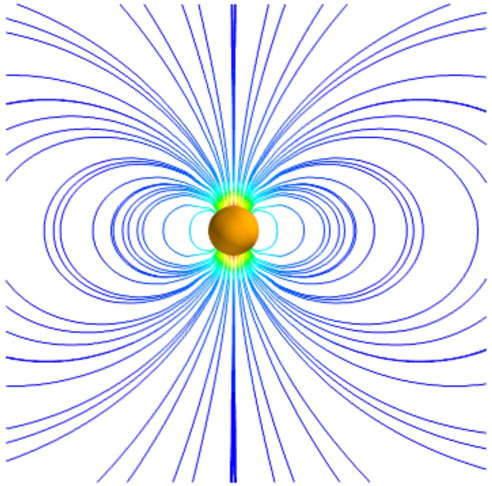
[1]Homola et al. 2005, Comput. Phys. Commun.

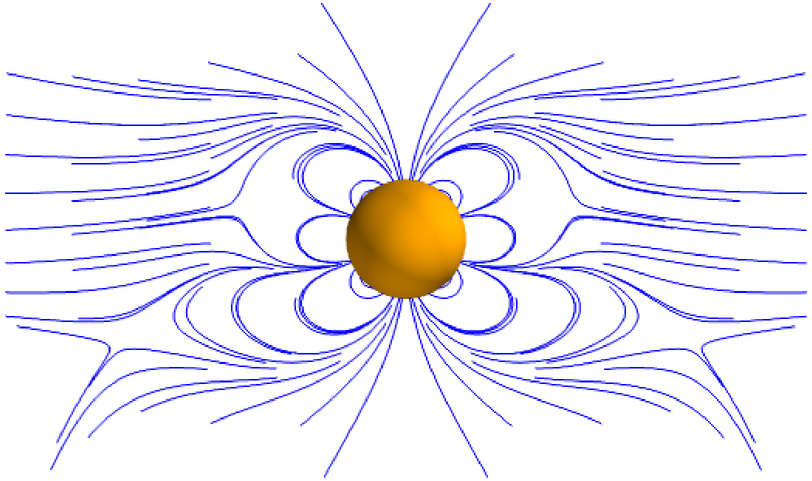
Simulation of SPS at vicinity of the Sun

Modifications:

- First studies were performed using magnetic field of the Sun modelled as **dipole** field[1] with Magnetic moment of Sun $M_S = 6.87 \times 10^{32}\ \mathrm{G} \cdot \mathrm{cm}^3$ (good for sanity check!).
- Dipole - quadrupole - current sheet (**DQCS**)[2] model replaces it now (more realistic than the dipole model even at larger distances from the Sun).



Dipole model



DQCS model

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[1]W. Bednarek 1999, arXiv:astro-ph/9911266
[2]Banaszkiewicz et al. 1998, A&A

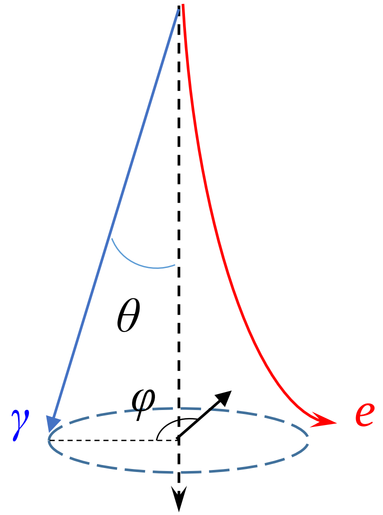
Simulation of SPS at vicinity of the Sun

Modifications:

- **Tracking of particle motion** (position and time) in solar magnetic field
- **Emission angles** for synchrotron photons:

$$\theta = m_e/E$$

⇒ larger deflections for smaller energies

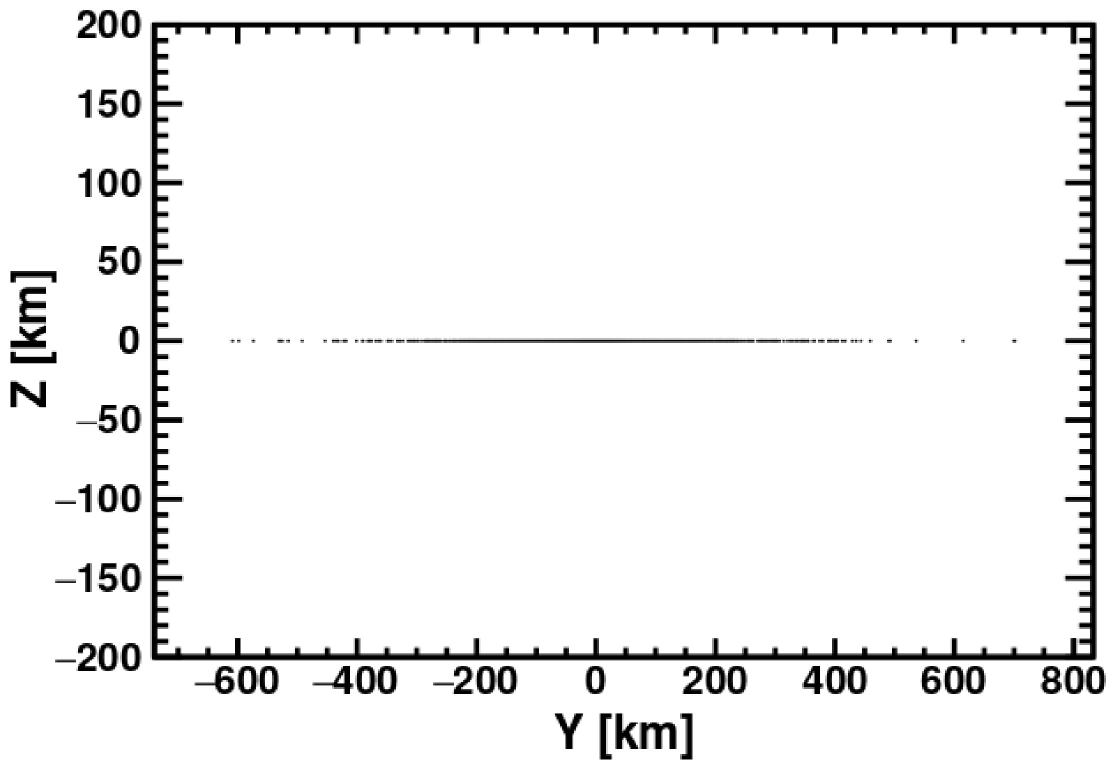


emission angle of synchrotron photons

Results from the simulation: **position, energy, direction and arrival time** of particles at the top of the Earth's atmosphere.

Simulation of SPS at vicinity of the Sun

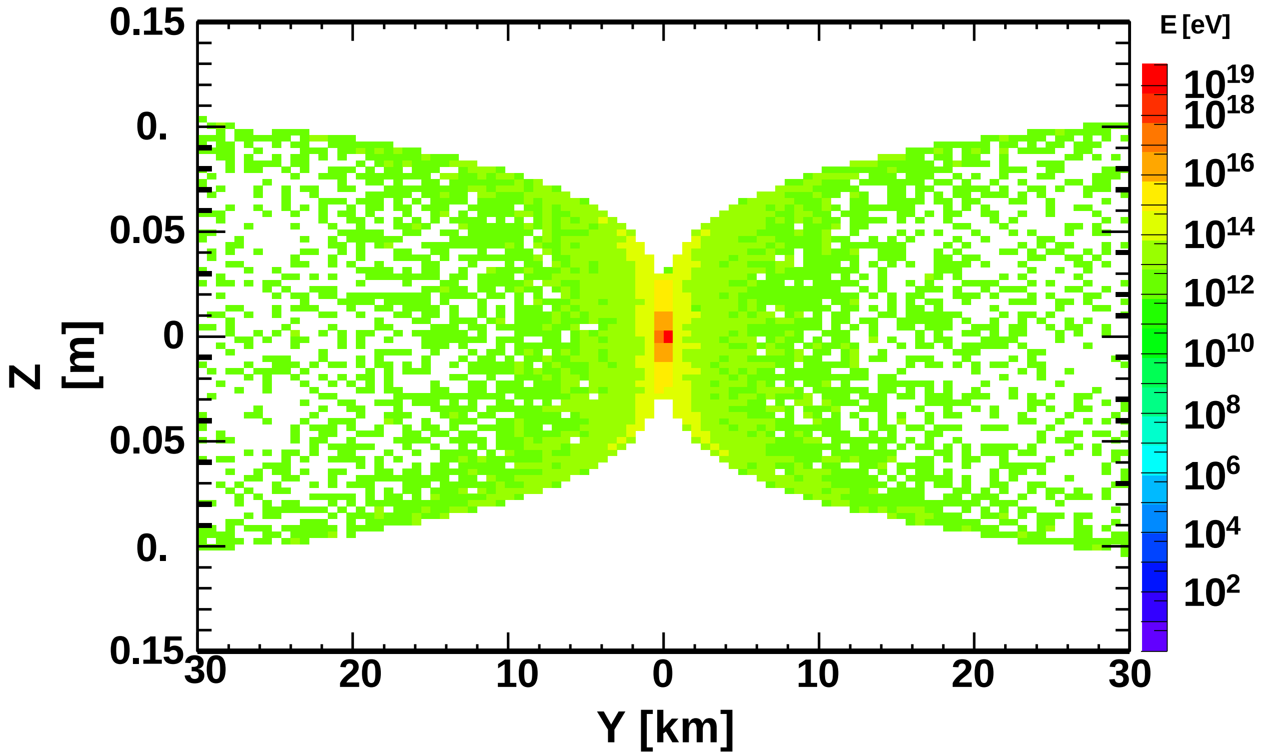
Example 1: Magnetic moment of the Sun is along its rotation axis. Primary photon heading towards Earth travels in the Sun's **equatorial** plane.



- **Large number of photons** (50000) at the top of the Earth's atmosphere.
- Photons distributed over a **very large distance** along a **line**.

Distribution of photons (with $E > 10^{13}$ eV) at the top of the Earth's atmosphere.
Energy of the primary photon = 100 EeV, impact parameter = 2.5 R_{SUN}

Simulation of SPS at vicinity of the Sun



Zoomed-in, previous plot

- smaller deflection of photons

↓

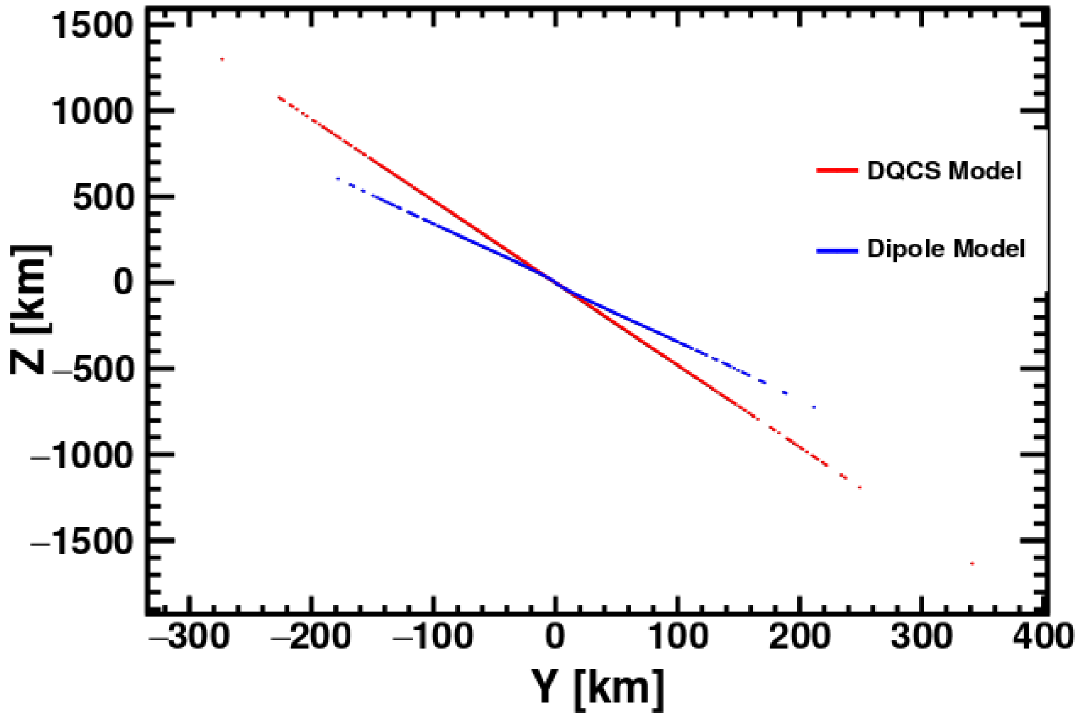
- higher energy

↓

- photons more confined in the "core region"

Simulation of SPS at vicinity of the Sun

Example 2: Magnetic moment of the Sun is along its rotation axis. Primary photon heading towards Earth passes through the Sun's "**mid-latitude**" side.

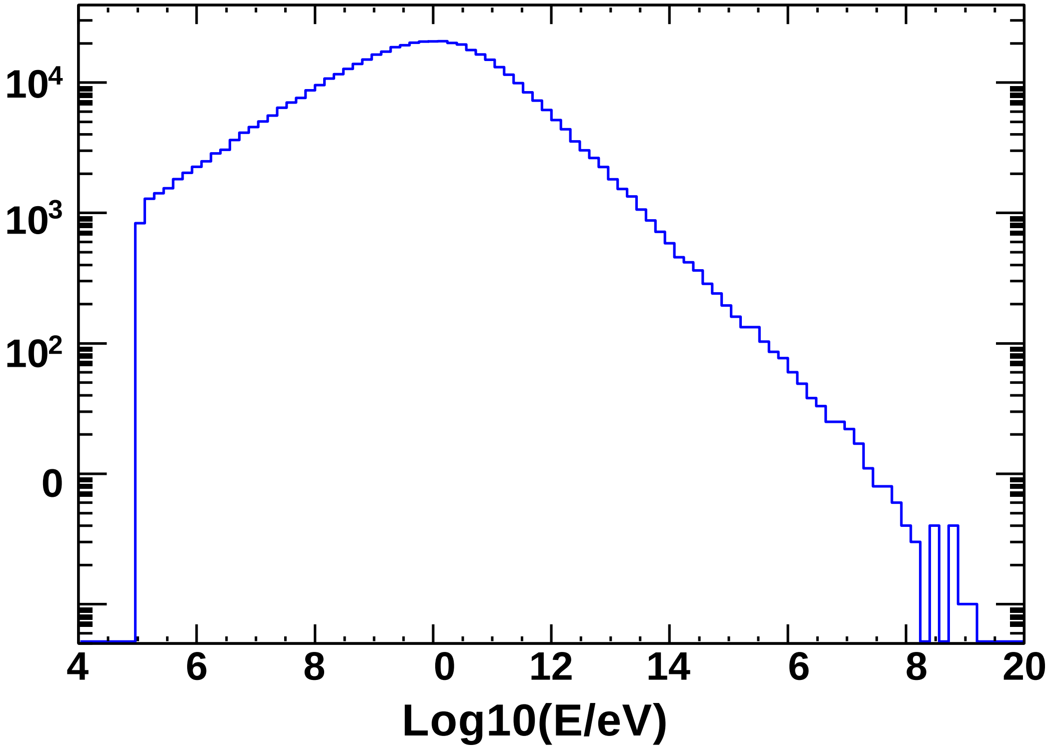


- Both DQCS and Dipole models give similar results (photons distributed along a **line**).
- **Orientation** of the "line" depends on the **region** nearby Sun through which primary photon traverses.

Distribution of photons (with $E > 10^{13}$ eV) at the top of the Earth's atmosphere.
Energy of the primary photon = 100 EeV, impact parameter = 2.5 R_{SUN}.

Simulation of SPS at vicinity of the Sun

Typical energy distribution of photons at the top of the Earth's atmosphere.

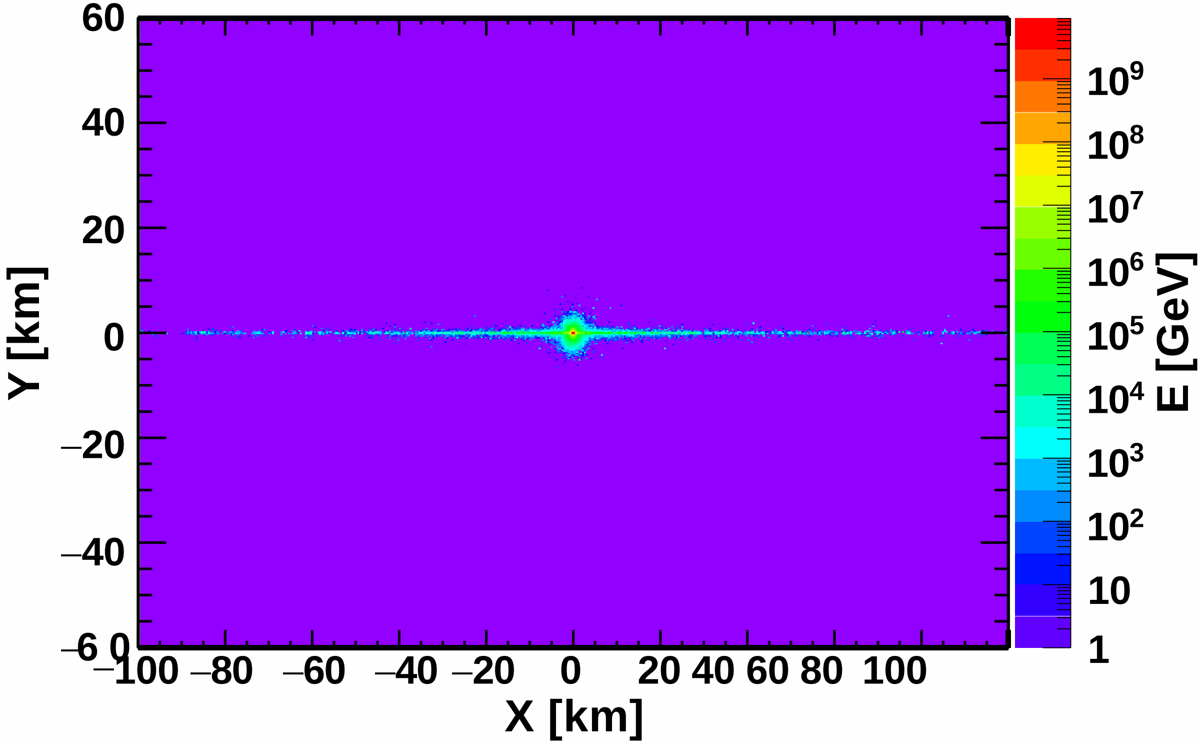


SPS is initiated by a 100 EeV primary photon.

Cross-checks of the calculation:
energy conservation and energy-spectrum of synchrotron photons

Simulation of SPS at vicinity of the Sun

Typical particle distribution at the ground from CORSIKA simulation of SPS.



- A **very elongated footprint** at the ground of a shower initiated by SPS.
- Such signatures can be detected by CREDO.

Distribution of particles at the ground weighted by energies.
The SPS is initiated by a 30 EeV primary photon traveling in the Sun's equatorial plane

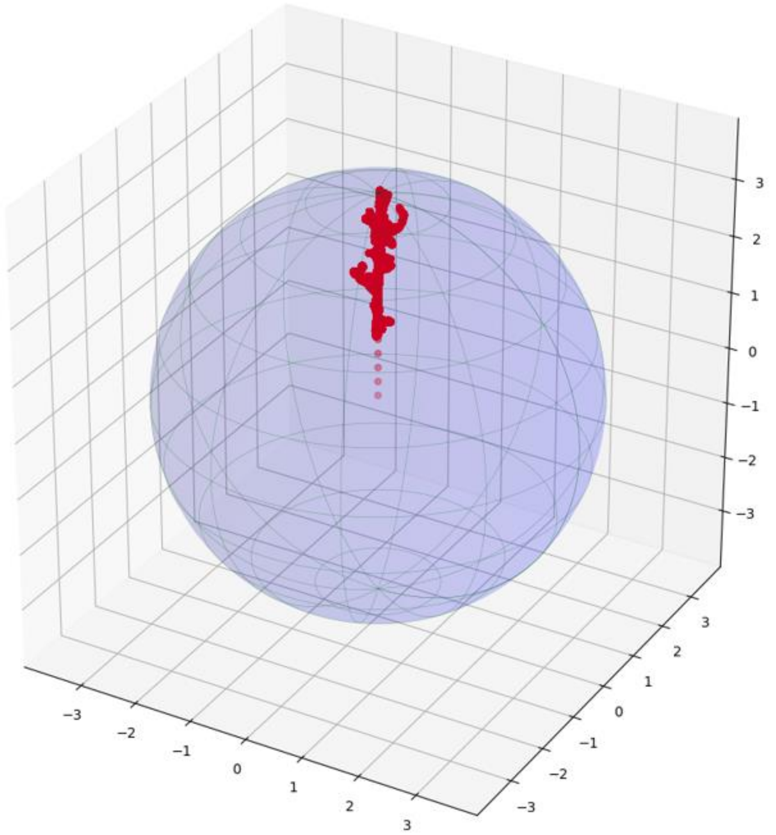
Sun SPS summary and outlook

- Necessary **modifications** have been made in PRESHOWER code to simulate development of super-preshowers (SPSs) originating from UHE photons passing through the vicinity of the Sun. A peculiar signature of a shower produced by such SPS is a **very elongated footprint** at the ground **transverse** to the shower direction.
- CREDO should be in principle suitable for the detection of phenomena like these, thanks to the extended secondary particle distribution at the ground.
- **Estimation** of Sun-SPS rate expected in different scenarios of UHE photon production (e.g. super heavy dark matter decay/annihilation, topological defects, etc.) and **testing / constraining** the models might be possible.
- An **alternative method** for **photon search / limit** based on SPS seems to be feasible.

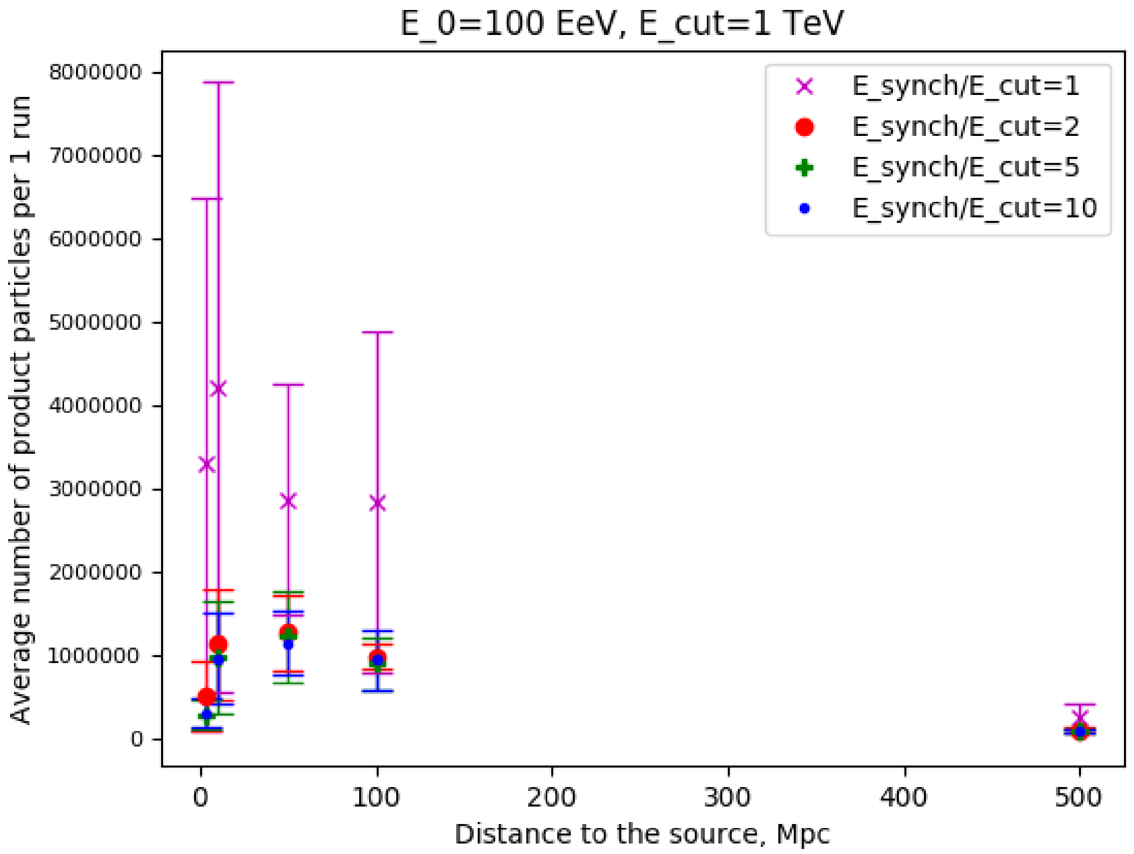
*N. Dhital et al. [https://arxiv.org/abs/1811.10334v2]

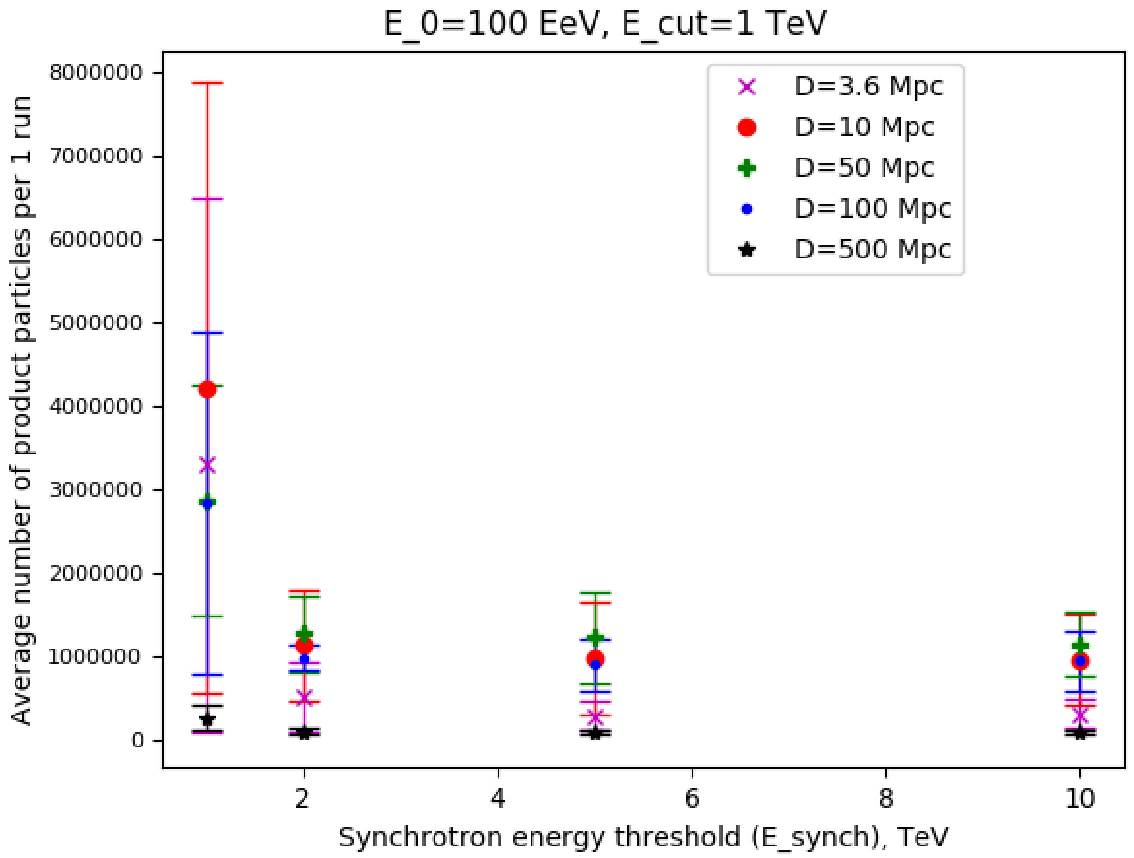
Setup

```
…
sim.add(PropagationCK(B,1e-4, Lmin, Lmax))
…
ObserverLargeSphere(Vector3d(x0,y0,z0),D)
…
source = Source()
source.add(SourceParticleType(11))
source.add(SourceEnergy(E_0))
source.add(SourcePosition(Vector3d(x0,y0,z0)))
source.add(SourceDirection(Vector3d(x1,y1,z1)))
…
sim.add( MinimumEnergy( E_cut) )
…
synch = SynchrotronRadiation(B,True)
synch.setSecondaryThreshold(E_synch)
…
sim.run(source, 1)
```

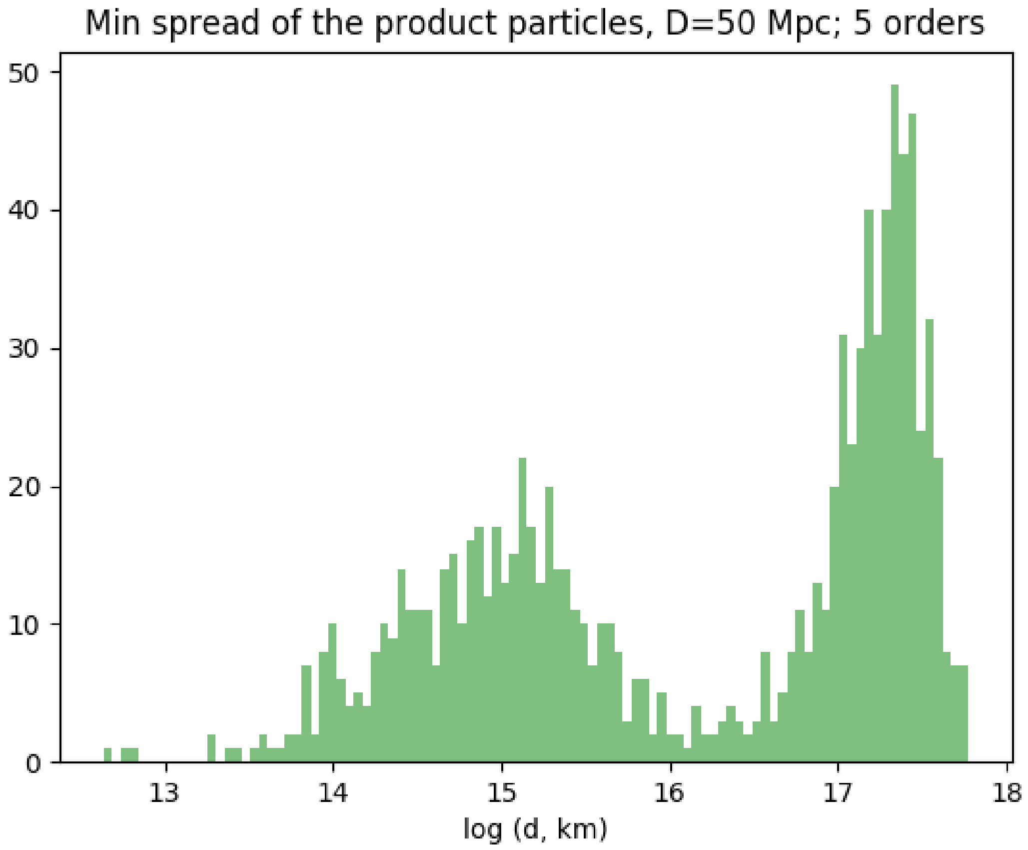


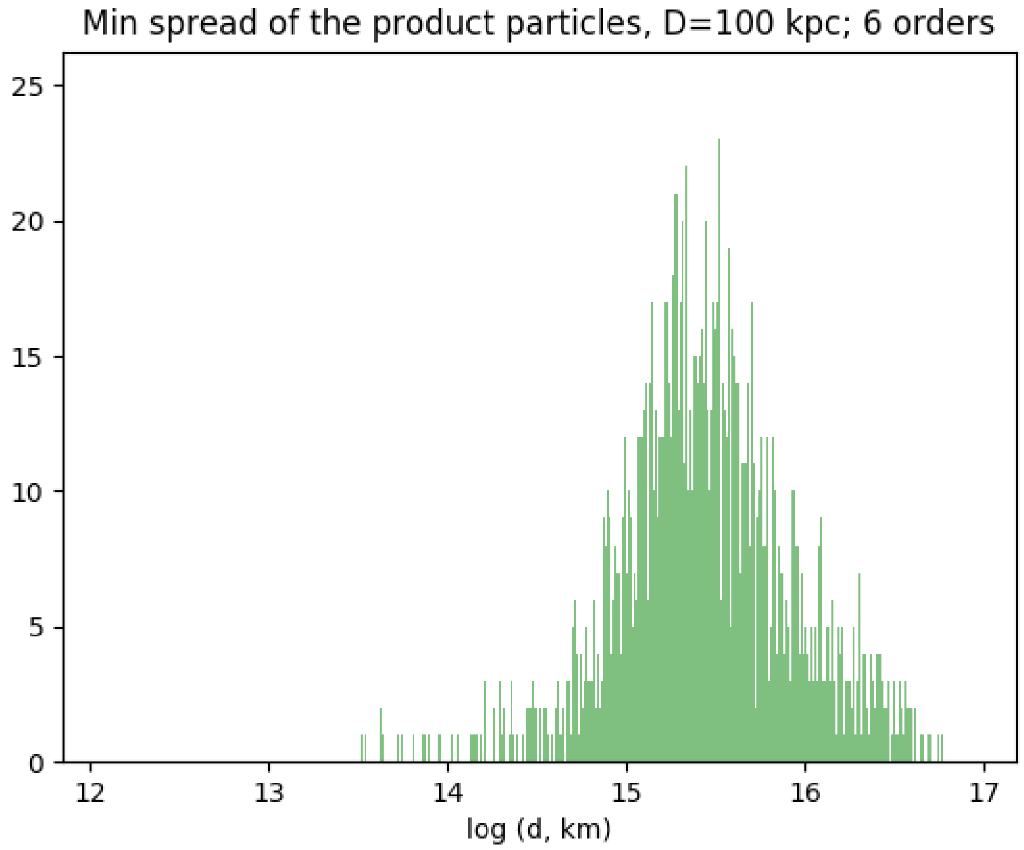
Extragalactic magnetic field. Photon CRE size



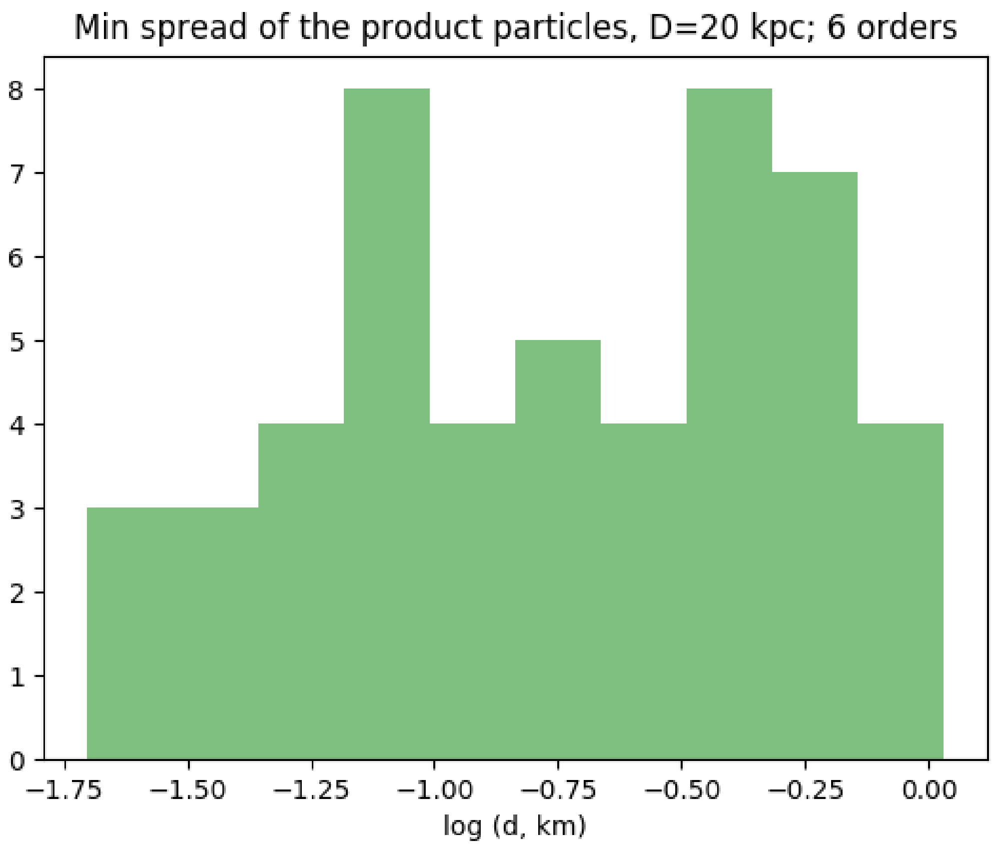


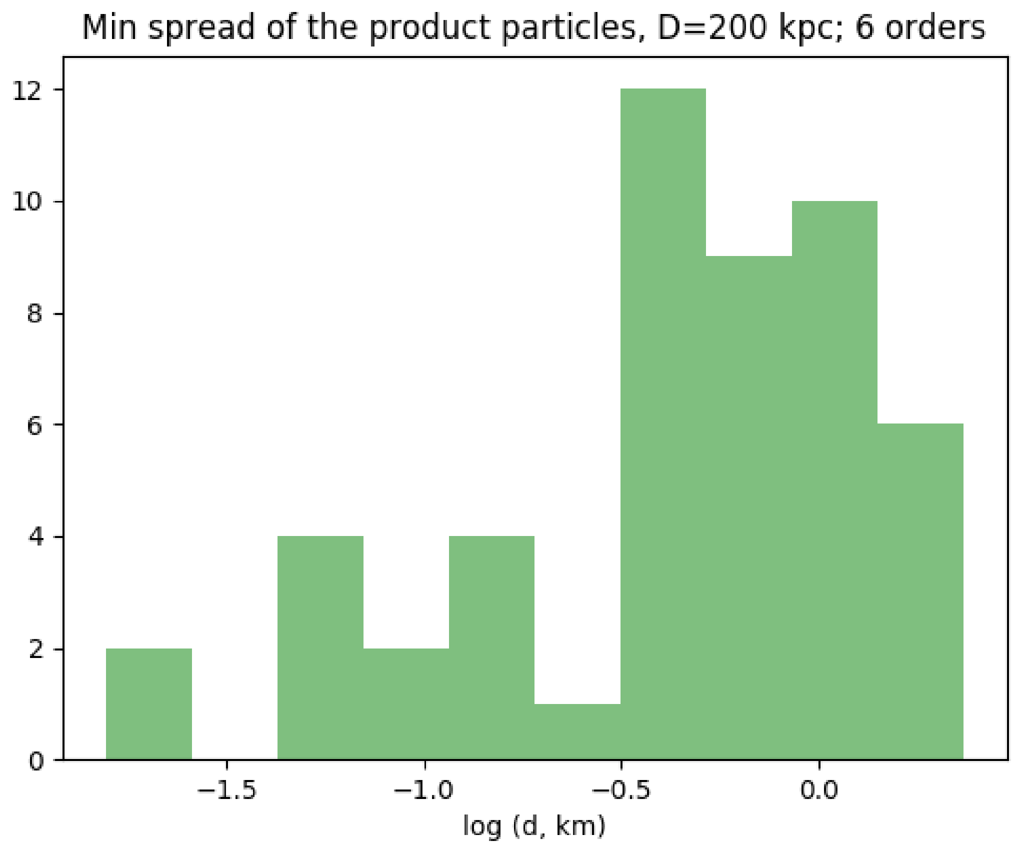
EGMF. Minimal spread of product particles



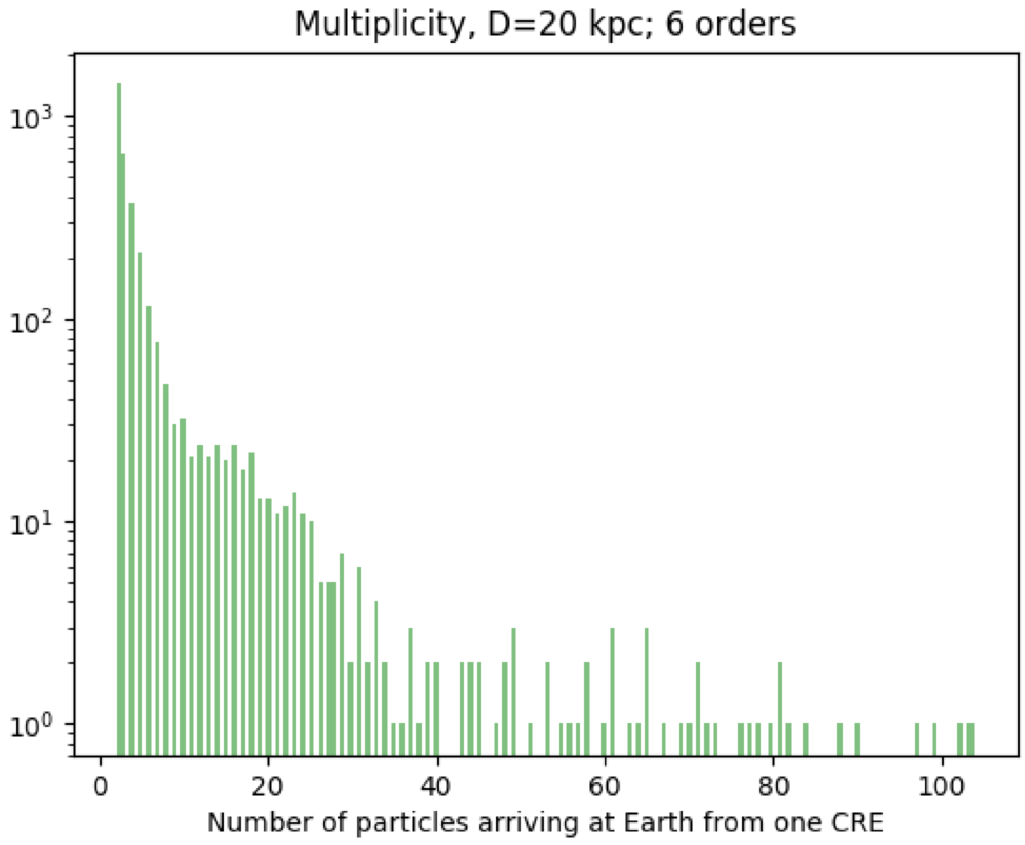


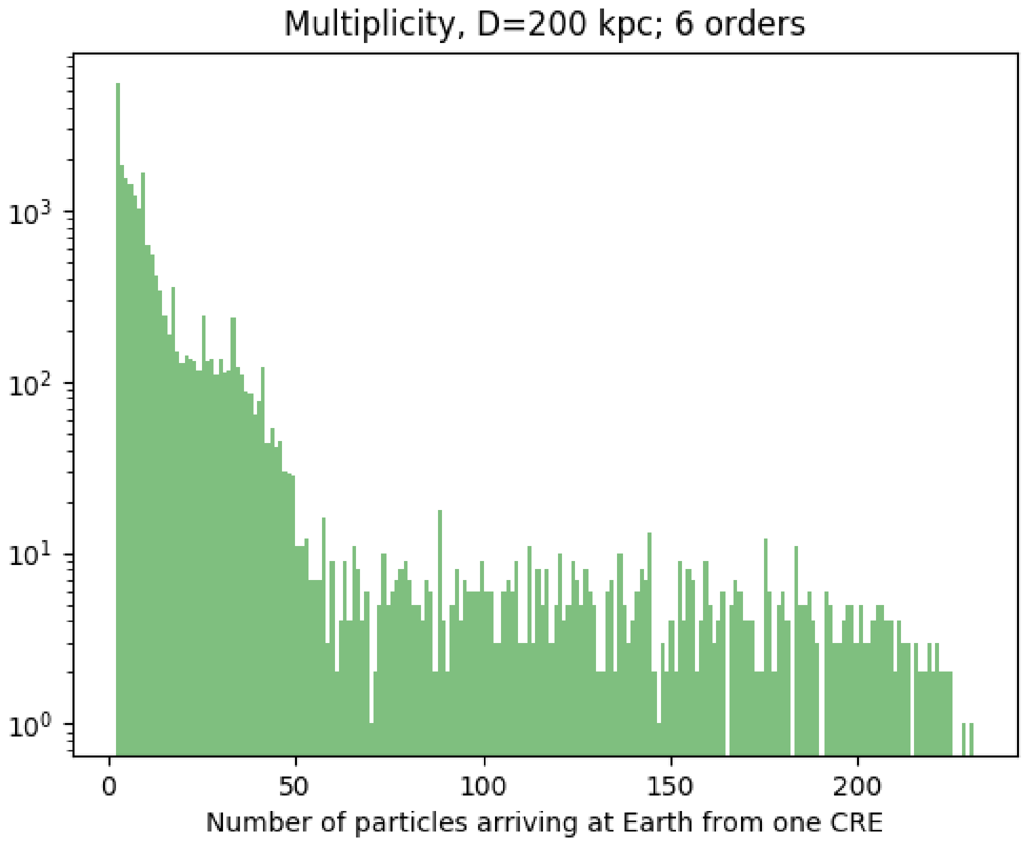
Toy model (uniform 3 μG field)



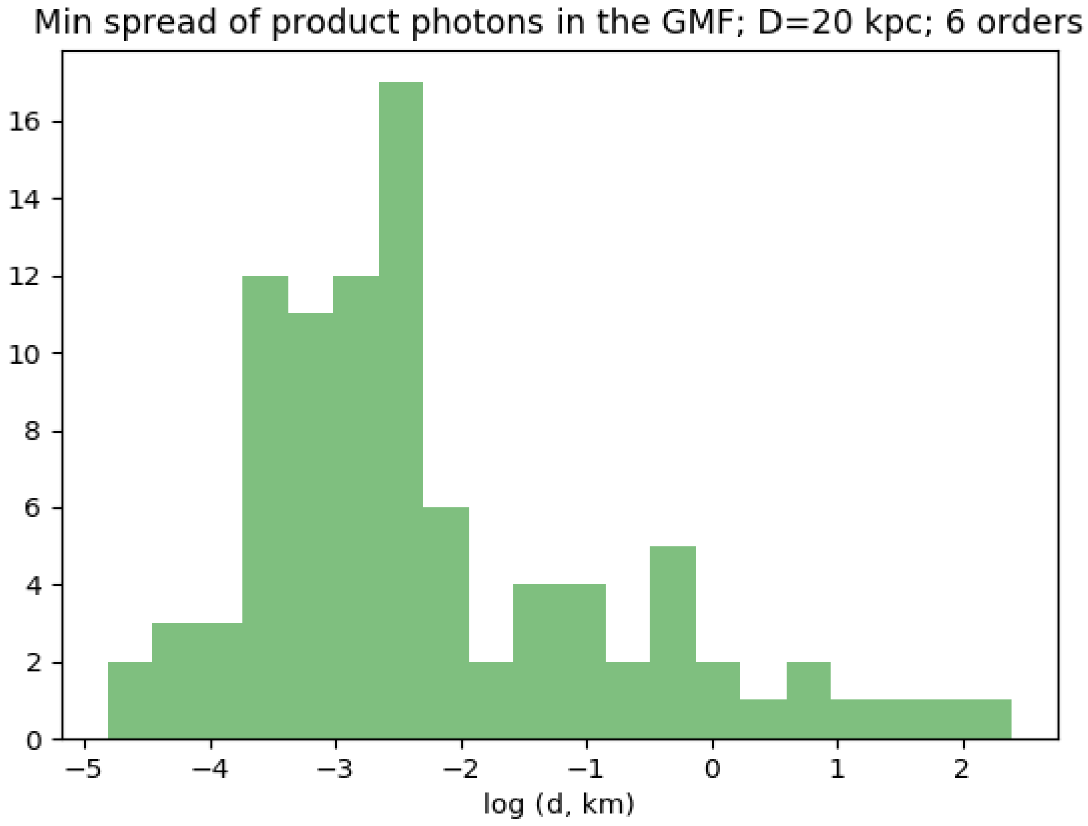


Uniform field. Number of particles on “toy Earth”

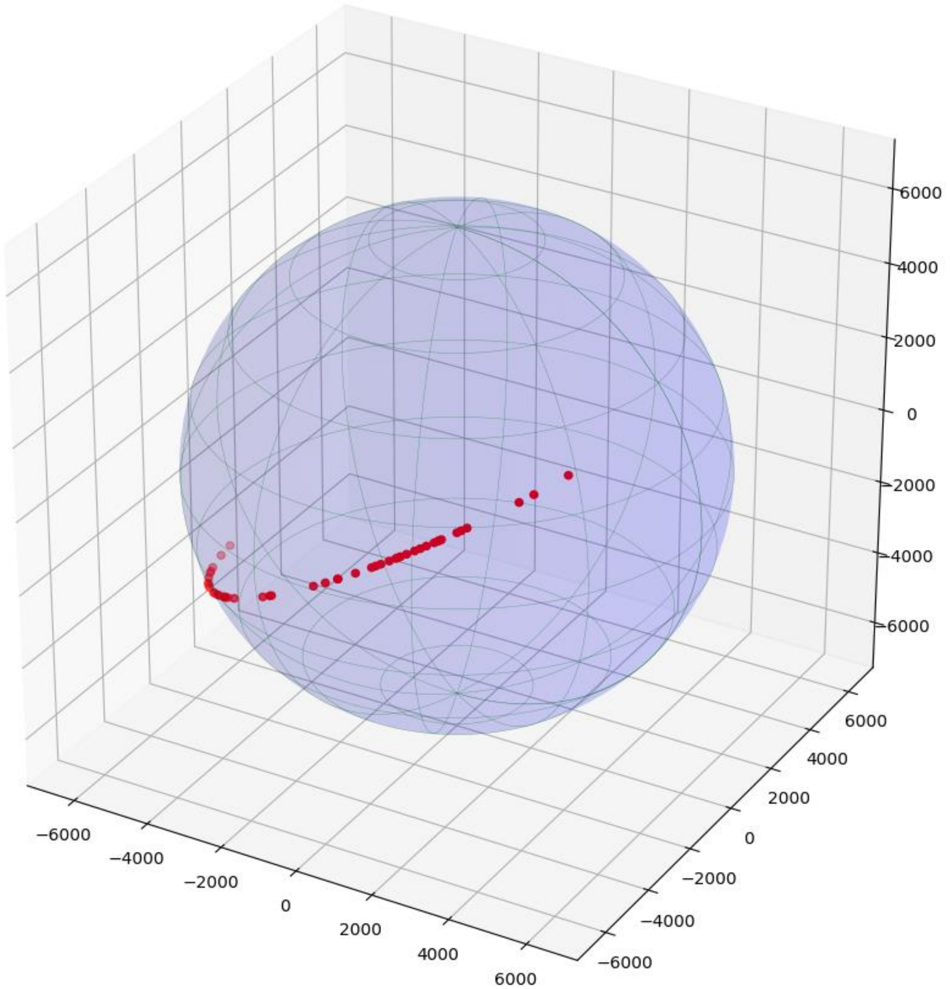




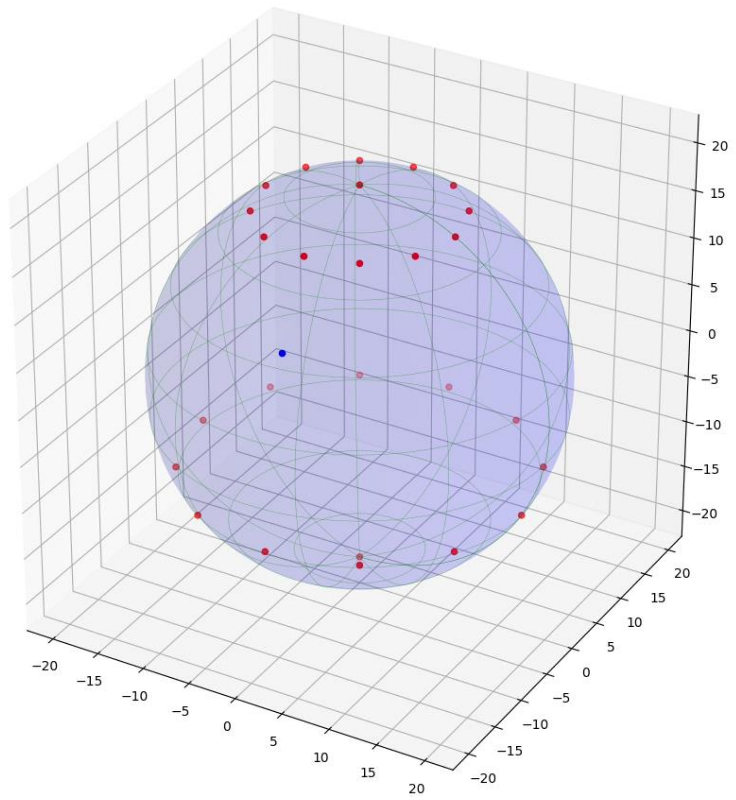
Toy model 2. Galactic magnetic field (JF12)

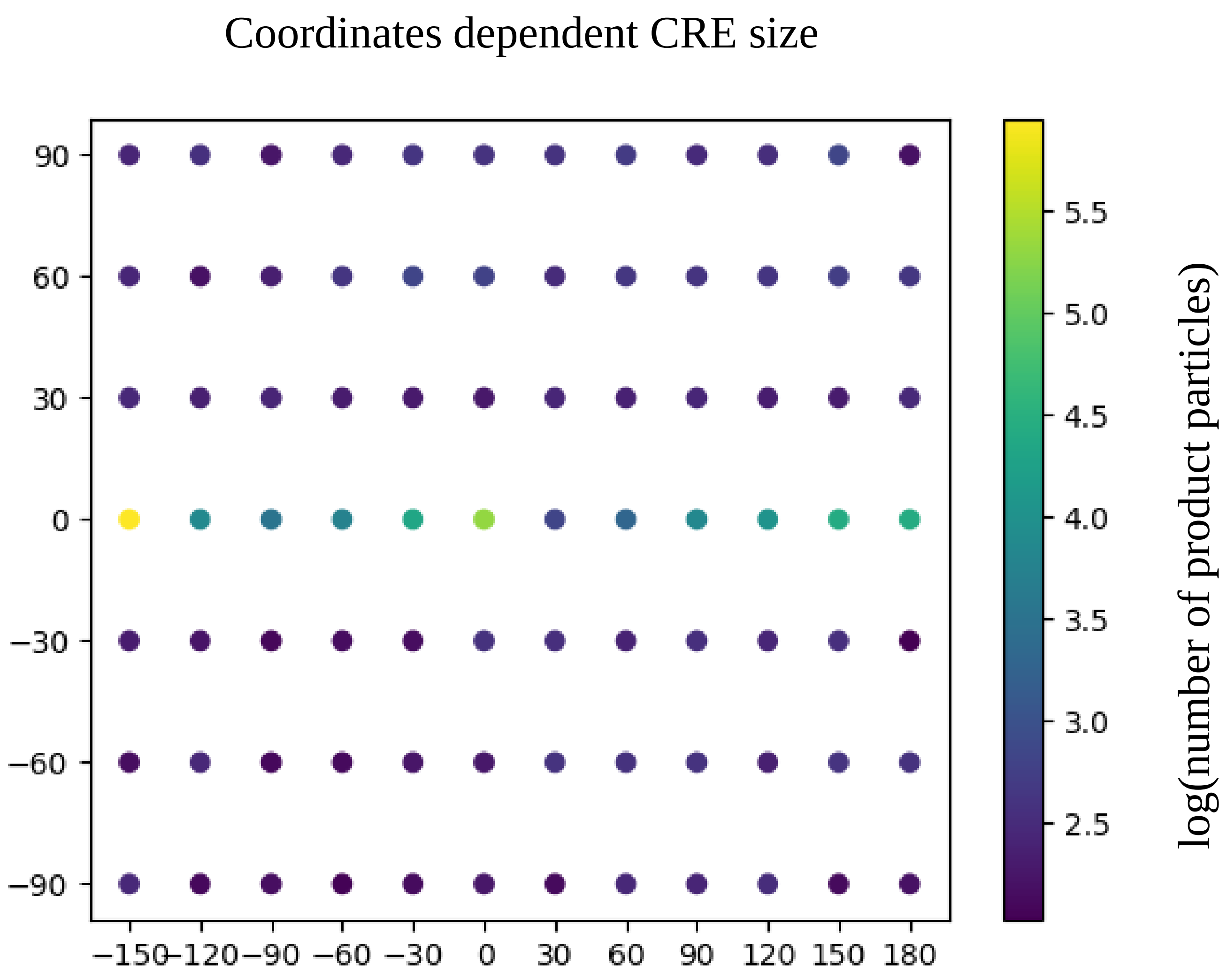


CRE footprint on a “toy Earth”

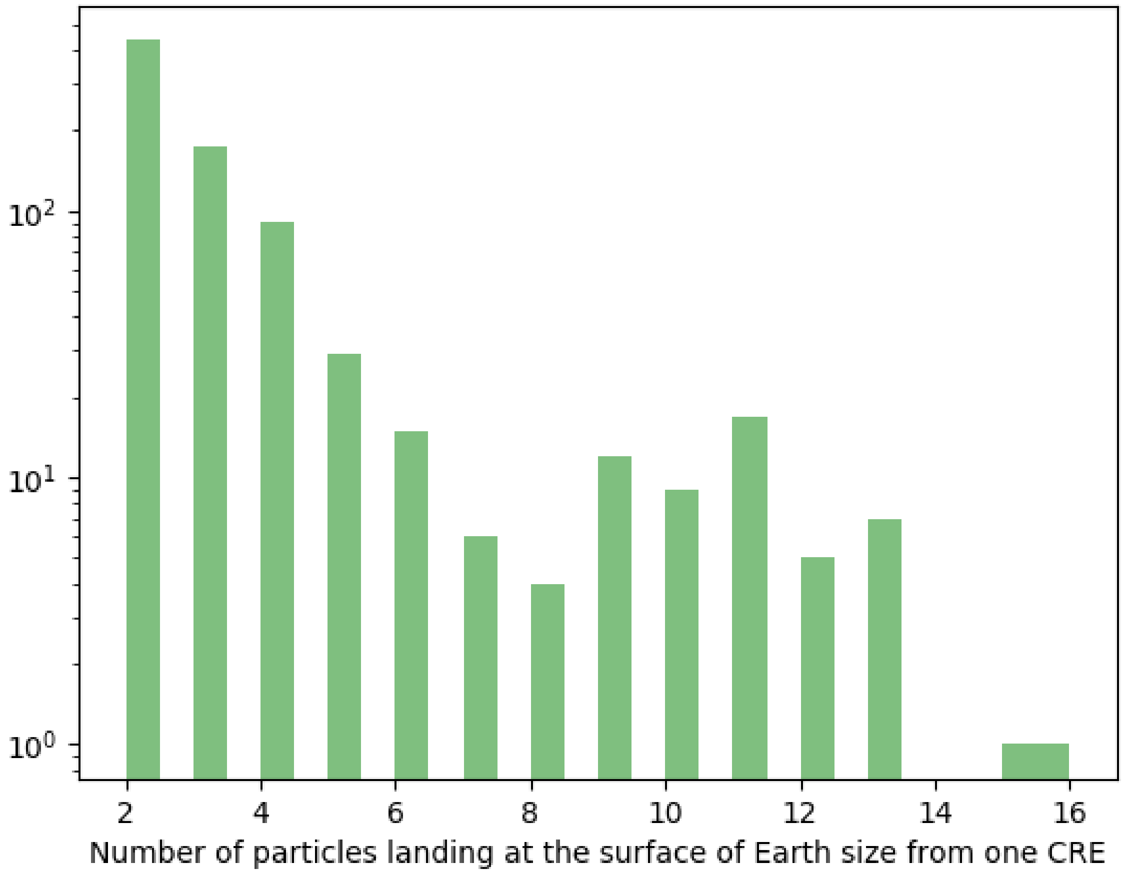


Galactic magnetic field (JF12)

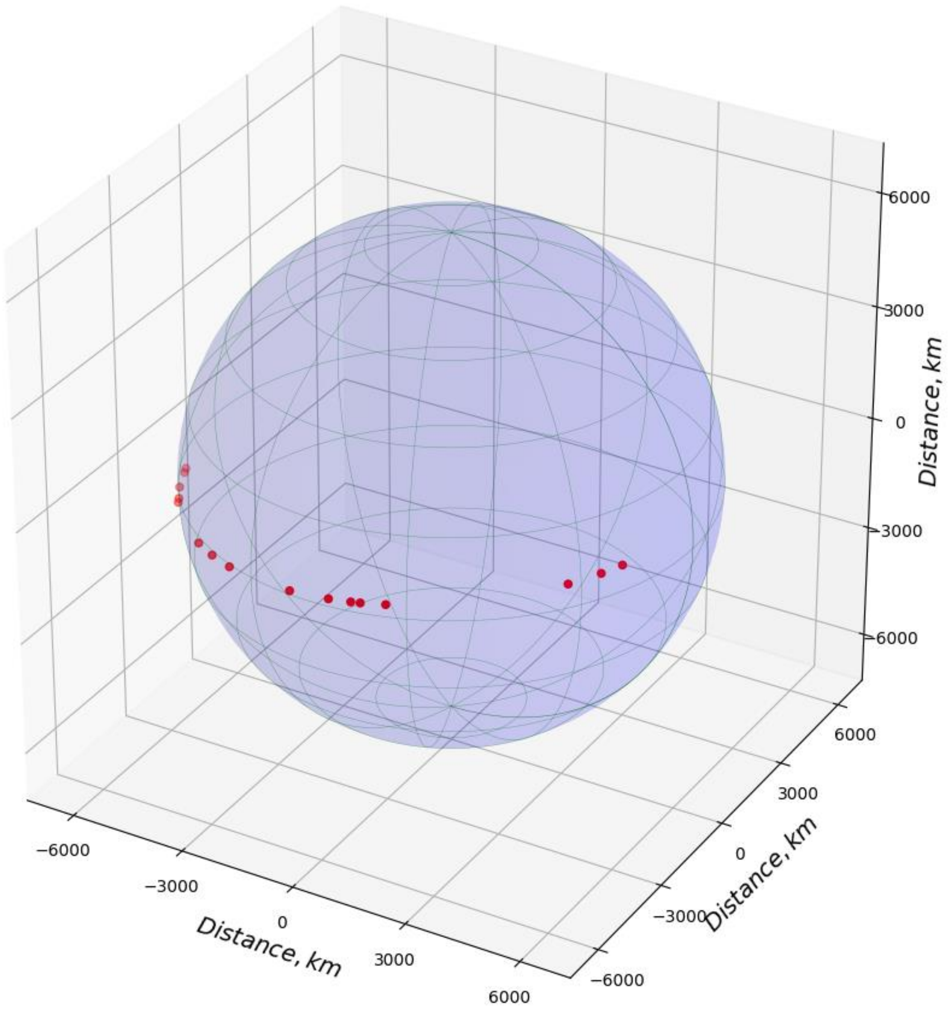




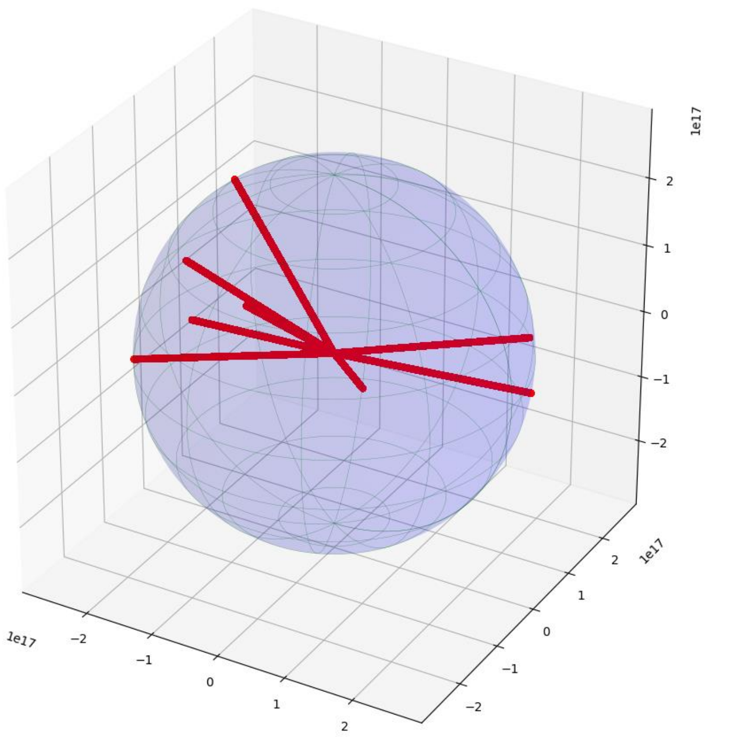
Galactic magnetic field (JF12)



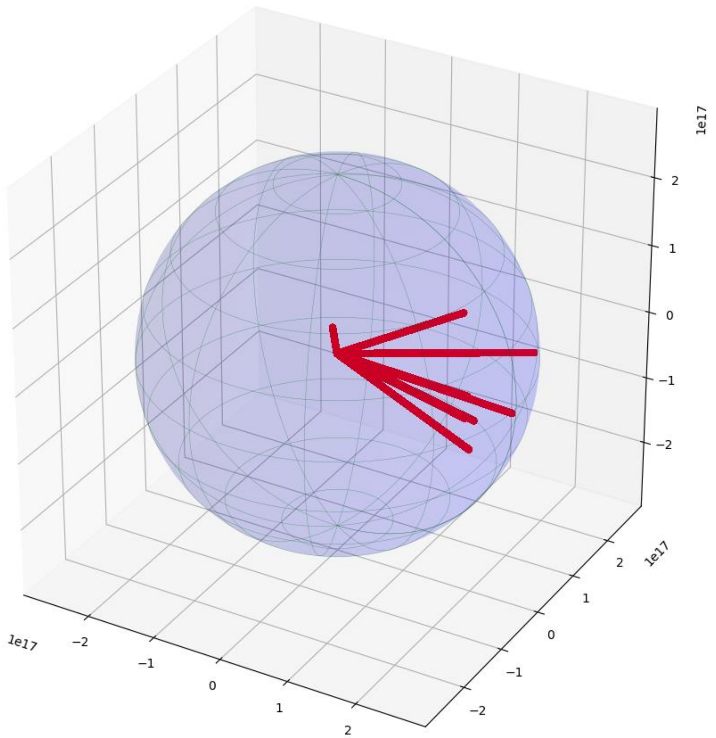
CRE footprint on a "toy Earth"



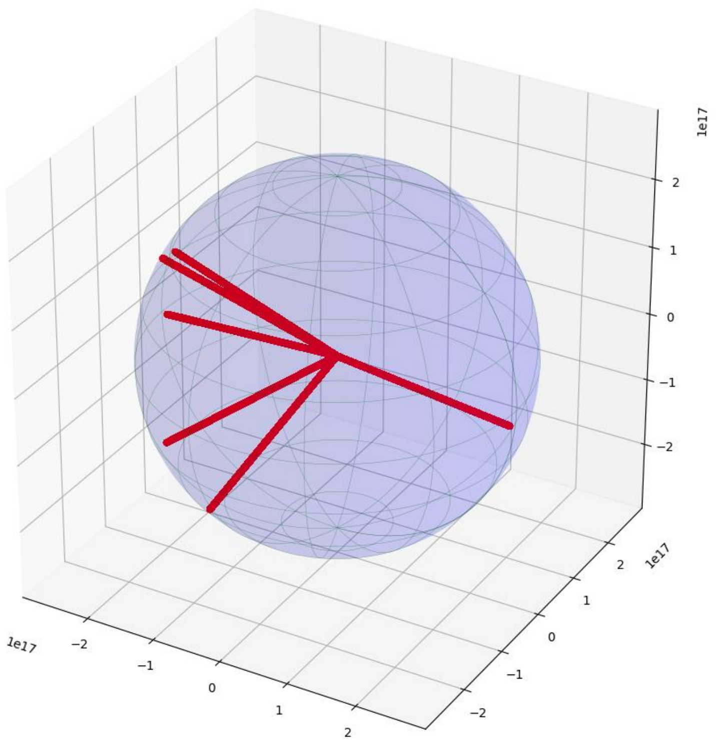
Galactic center as a source?



a) 1 PeV electron



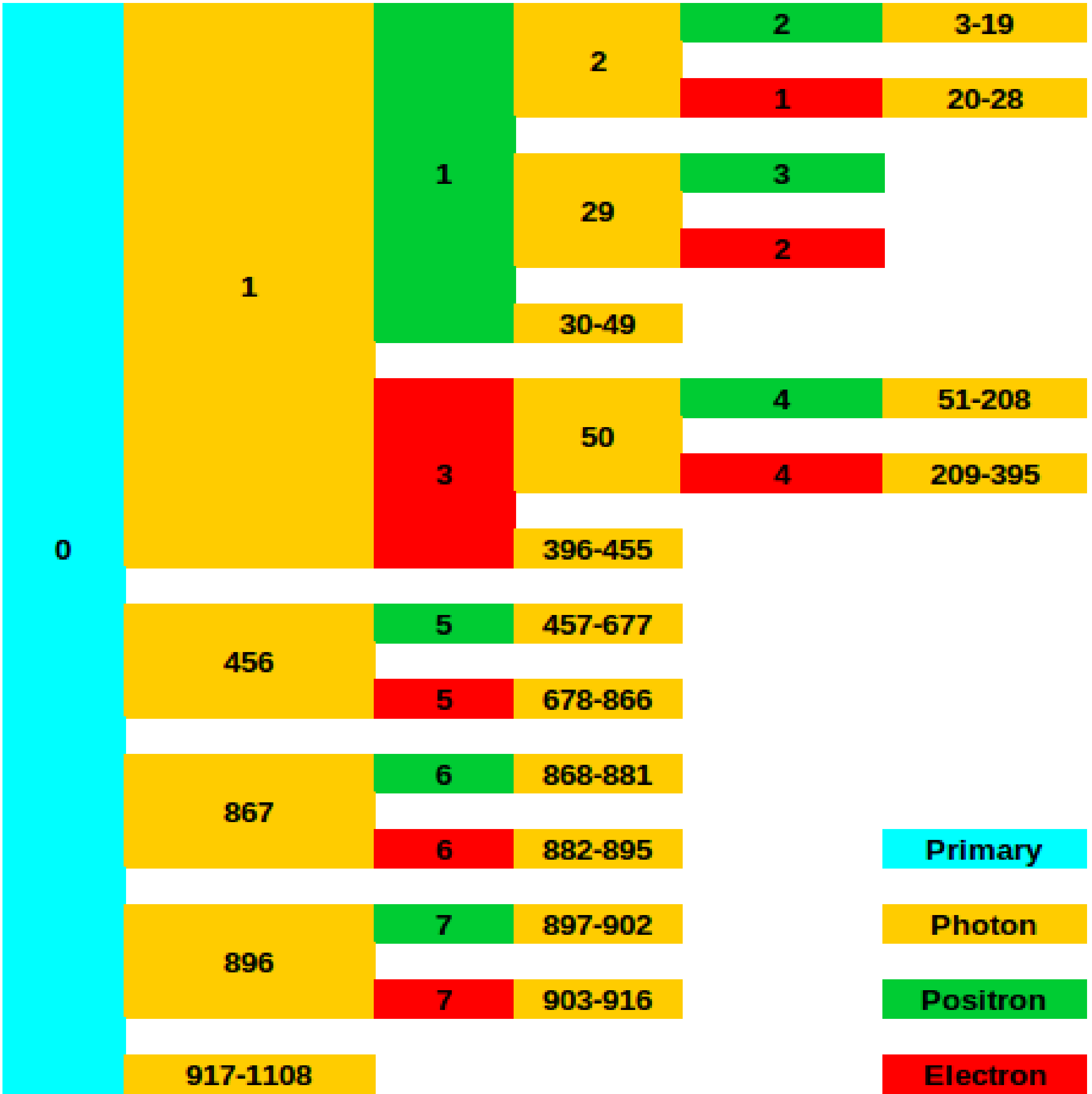
b) 10 PeV electron



c) 100 PeV electron

Outlook

CRE scheme



What's next?

1. Step-by-step simulation control
2. Specific astrophysical conditions
3. Targeted search?
4. …