What is Cosmic-Ray Extremely Distributed Observatory?

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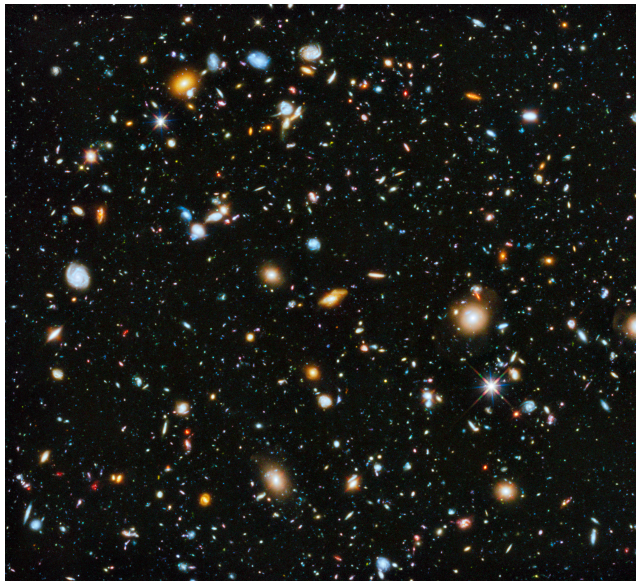
Institute of Nuclear Physics PAN, Kraków

CREDO Anniversary Symposium 2018

Visegrad Fund

Motivation



At every "corner of the Universe", near and far, "things" exist and "stuff" are (were) happening. At the simplest level, these *m*ay be classified as:

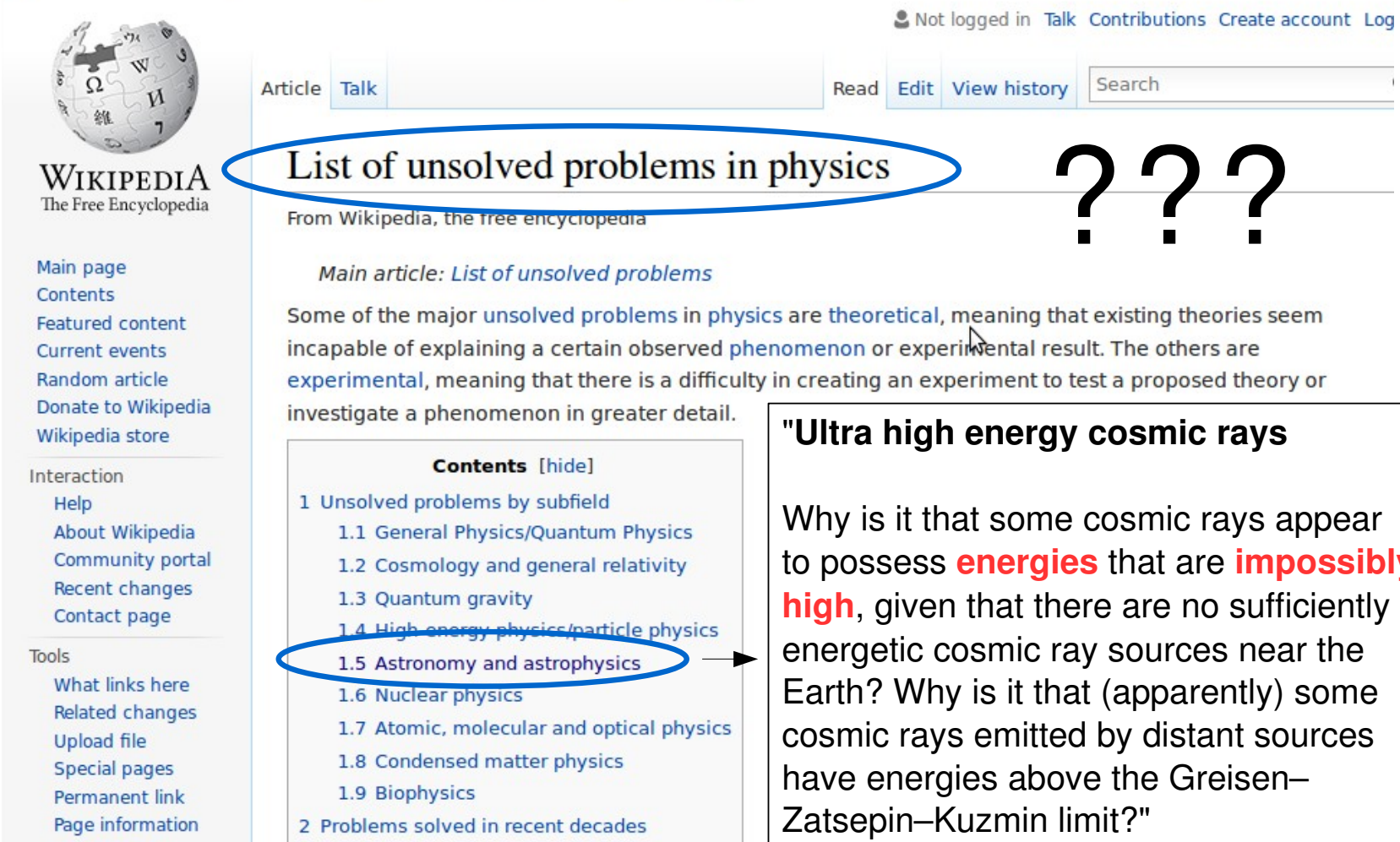
- ✓ the ones which we know/understand about and,
- ✗ the ones which we do not.

One of the main objectives of any science we do (are doing) is to put our effort to push the item ✗ towards item ✓.

Motivation

Zooming into a subset of sciences, Physics, Yeah☺ !!

here's a list of some unsolved physics problems from Wikipedia



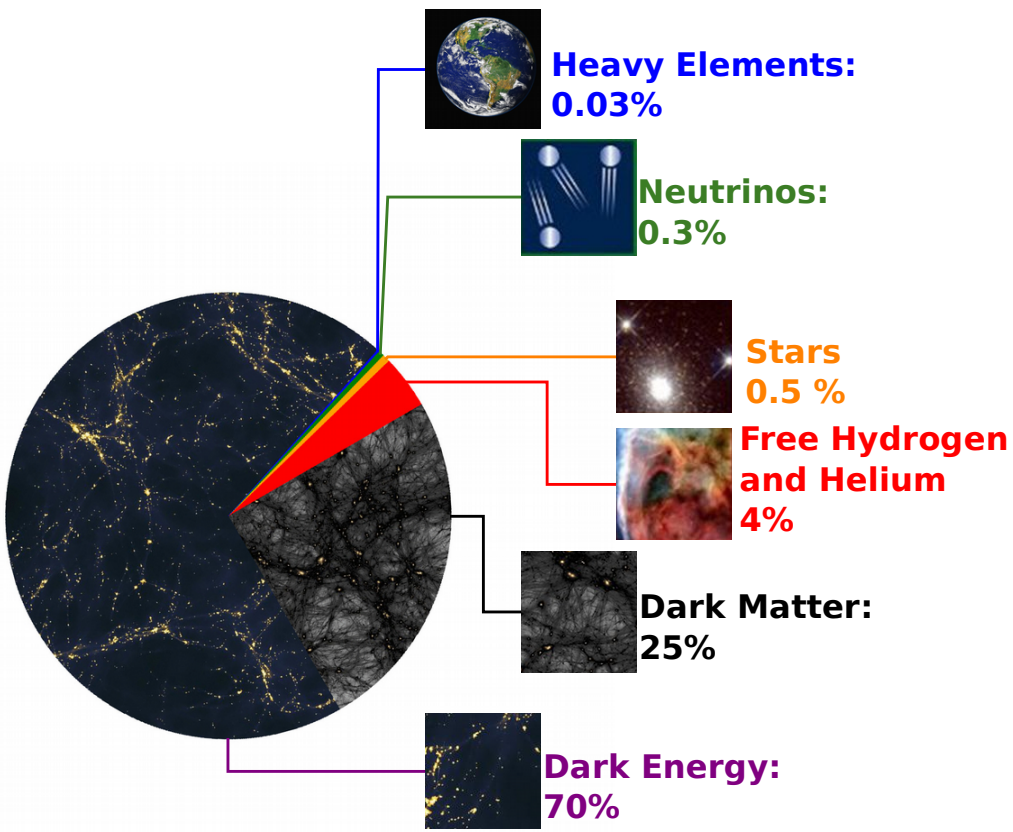
"Ultra high energy cosmic rays

Why is it that some cosmic rays appear to possess **energies** that are **impossibly high**, given that there are no sufficiently energetic cosmic ray sources near the Earth? Why is it that (apparently) some cosmic rays emitted by distant sources have energies above the Greisen–Zatsepin–Kuzmin limit?"

Motivation

?

COMPOSITION OF THE COSMOS



Motivation

Some important questions of contemporary astrophysics:

- **Nature of dark matter:**

  e.g., decay or co-annihilation $\rightarrow \gamma$, otherparticles

- **Better understanding of UHECRs:**

  any UHECR we detect at the Earth a γ?

  any UHE γ produced at some "corner of the Universe" even if we are unable to detect them here?

- **New physics:**

  LIV, space-time foam?

Motivation

γ_{UHE} —no interactions / screening→ Earth

NOT OBSERVED

γ_{UHE} —unexpected interactions, screening, ...→ ELECTROMAGNETIC CASCADES (COSMIC RAY ENSEMBLES) → Earth

NOT TRIED SO FAR...

Cosmic-ray research phase transition:

N = 1	$\longrightarrow$	**N> 1**
Single CR	$\longrightarrow$	**CRE**

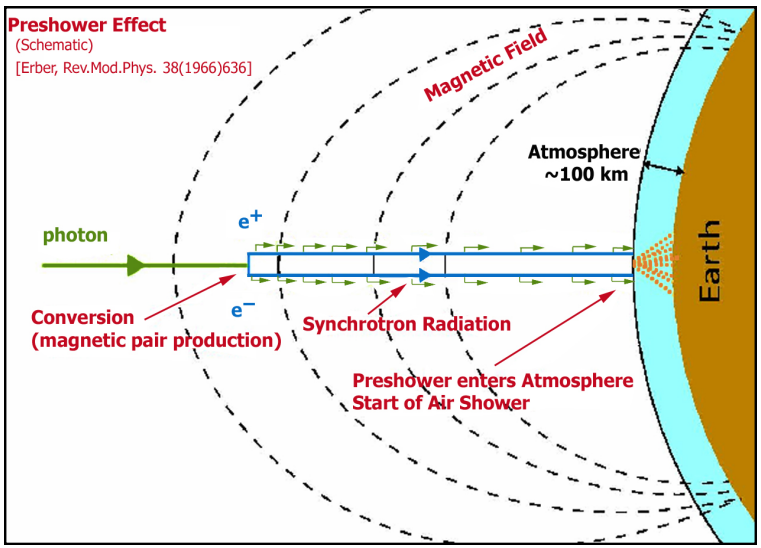
N: No. of CR particles correlated in time

Motivation

Example non-exotic scenarios: Preshower and super-preshower

Preshower:

- Cascade of EM particles produced by interaction of UHE-γ with geomagnetic field.
- Typical altitude $\sim$ 1000 km a.s.l. $N \sim 100$



Super-preshower (SPS):

- Cascade of EM particles produced by interaction of UHE-γ with solar magnetic field.
- Typical distance of cascade development is **very far**. $N \gg 100$!!

Example exotic scenario

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 ($\kappa < 6\times10^{-20}$ 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 ($\kappa > -9\times10^{-16}$ at 98 % C.L.) derived from **gamma-ray astronomy** [Klinkhamer & Schreck 2008]

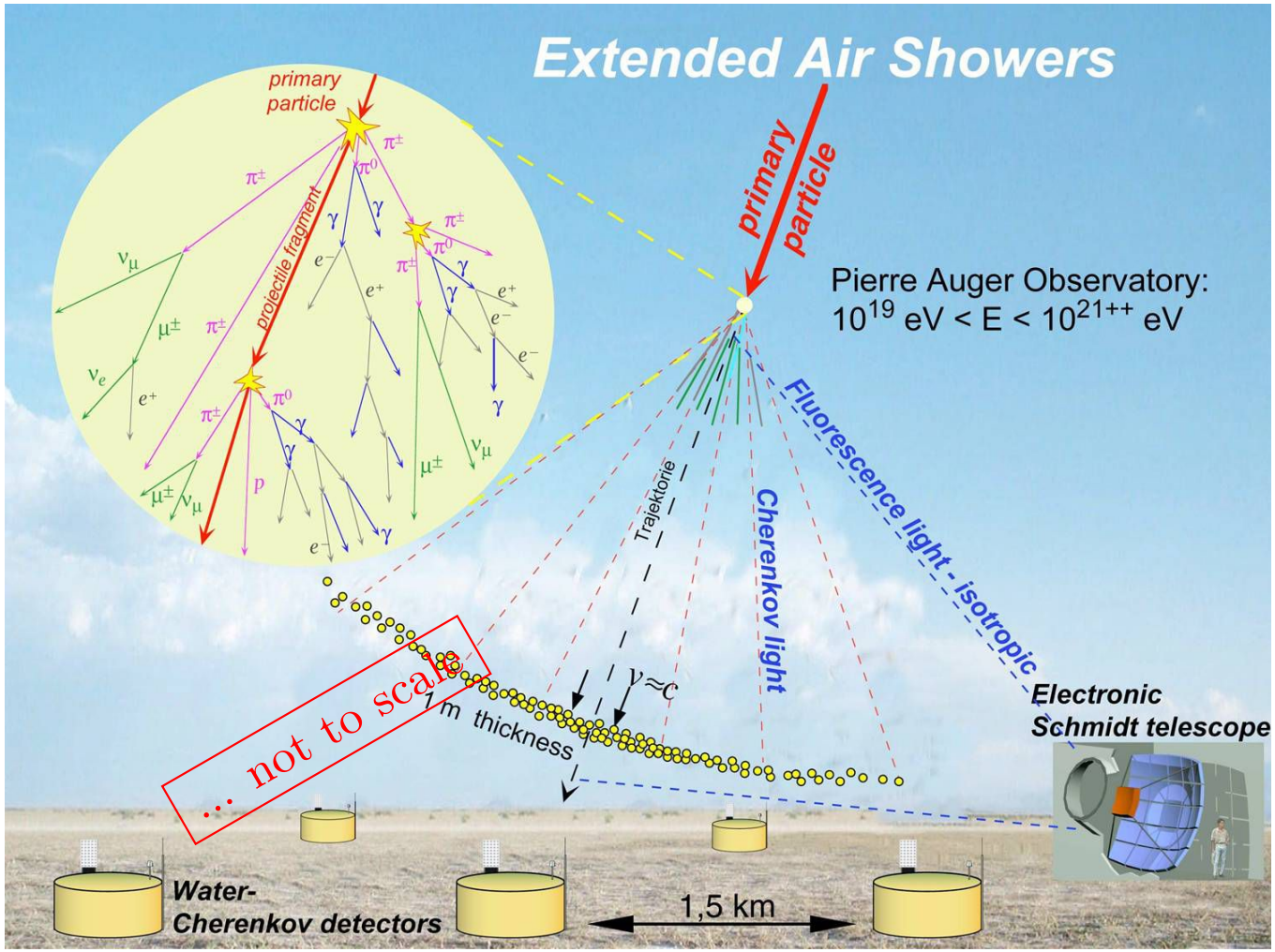
ALL UHE photons initiate CRE!!!

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

Slide from O. Sushchov's talk

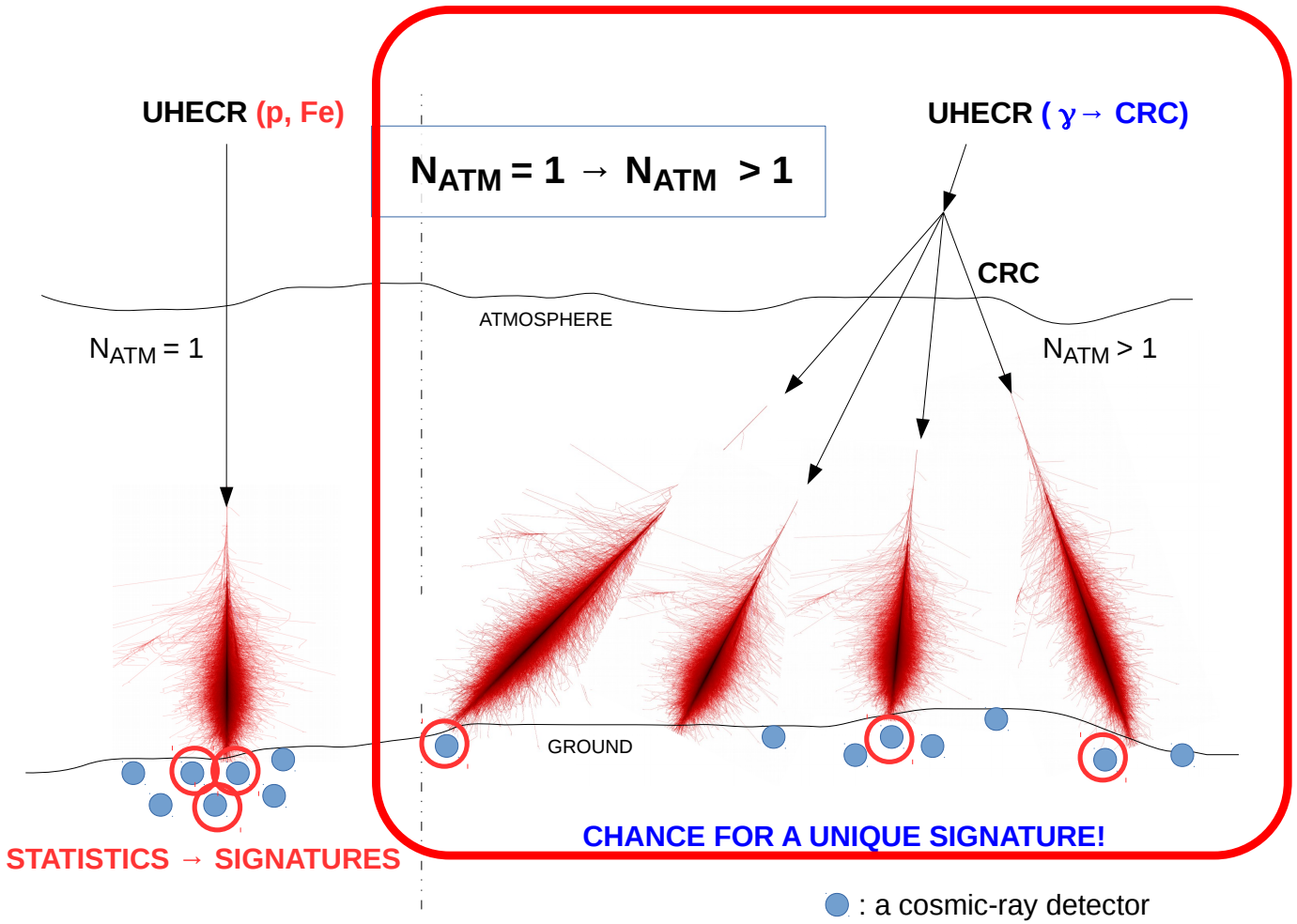
Single CR vs. CR Ensembles

State-of-the-art detection of cosmic rays: $N_{\mathrm{ATM}} = 1$



Single CR vs. CR Ensembles

Generalized detection of cosmic rays: $N_{\mathrm{ATM}} \geq 1$



Single CR vs. CR Ensembles

$N_{\mathrm{ATM}} > 1$ motivated by observation!

VOLUME 50, NUMBER 26 PHYSICAL REVIEW LETTERS 27 JUNE 1983

Possible Observation of a Burst of Cosmic-Ray Events in the Form of Extensive Air Showers

Gary R. Smith, M. Ogmen, E. Buller, and S. Standil
Physics Department, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

(Received 7 April 1983)

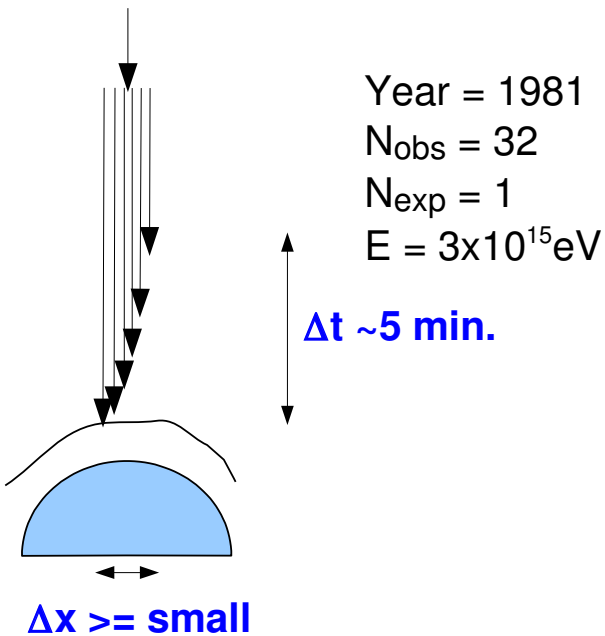
A series or burst of 32 extensive air showers of estimated energy 3×10^{15} eV was observed within a 5-min time interval beginning at 9:55 A.M. (CST) on 20 January 1981 in Winnipeg, Canada. This observation was the only one of its kind during an experiment which recorded 150 000 such showers in a period of 18 months between October 1980 and April 1982.

PACS numbers: 94.40.Pa, 96.40.Rc, 95.30.-k

Forgotten (!) treasure (?) no. 1

Correlated cosmic rays?

$N_{\mathrm{ATM}} > 1$?



Single CR vs. CR Ensembles

$N_{ATM} > 1$ motivated by observation!

VOLUME 51, NUMBER 25 PHYSICAL REVIEW LETTERS 19 DECEMBER 1983

Observation of a Burst of Cosmic Rays at Energies above 7×10^{13} eV

D. J. Fegan and B. McBreen
Physics Department, University College Dublin, Dublin 4, Ireland
and
C. O'Sullivan
Physics Department, University College Cork, Cork, Ireland
(Received 14 September 1983)

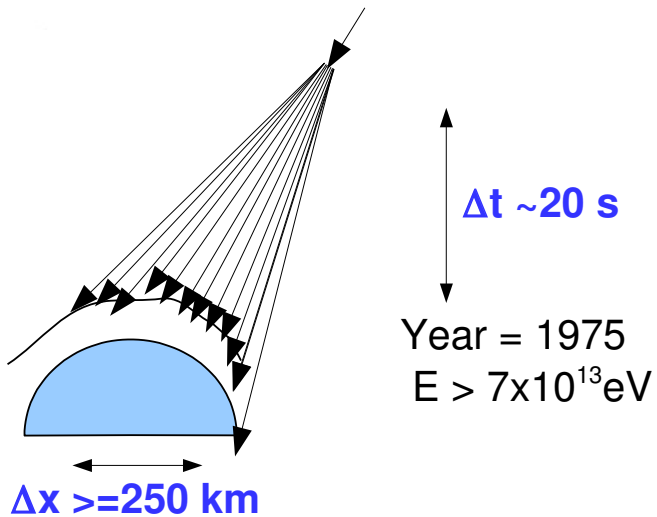
The authors report on an unusual simultaneous increase in the cosmic-ray shower rate at two recording stations separated by 250 km. The event lasted for 20 s. This event was the only one of its kind detected in three years of observation. The duration and structure of this event is different from a recently reported single-station cosmic-ray burst. The simultaneity of the coincident event suggests that it was caused by a burst of cosmic gamma rays. There is a possibility that this event may be related to the largest observed glitch of the pulsar in the Crab Nebula.

PACS numbers: 94.40.Pa, 95.85.Qx, 97.80.Jp

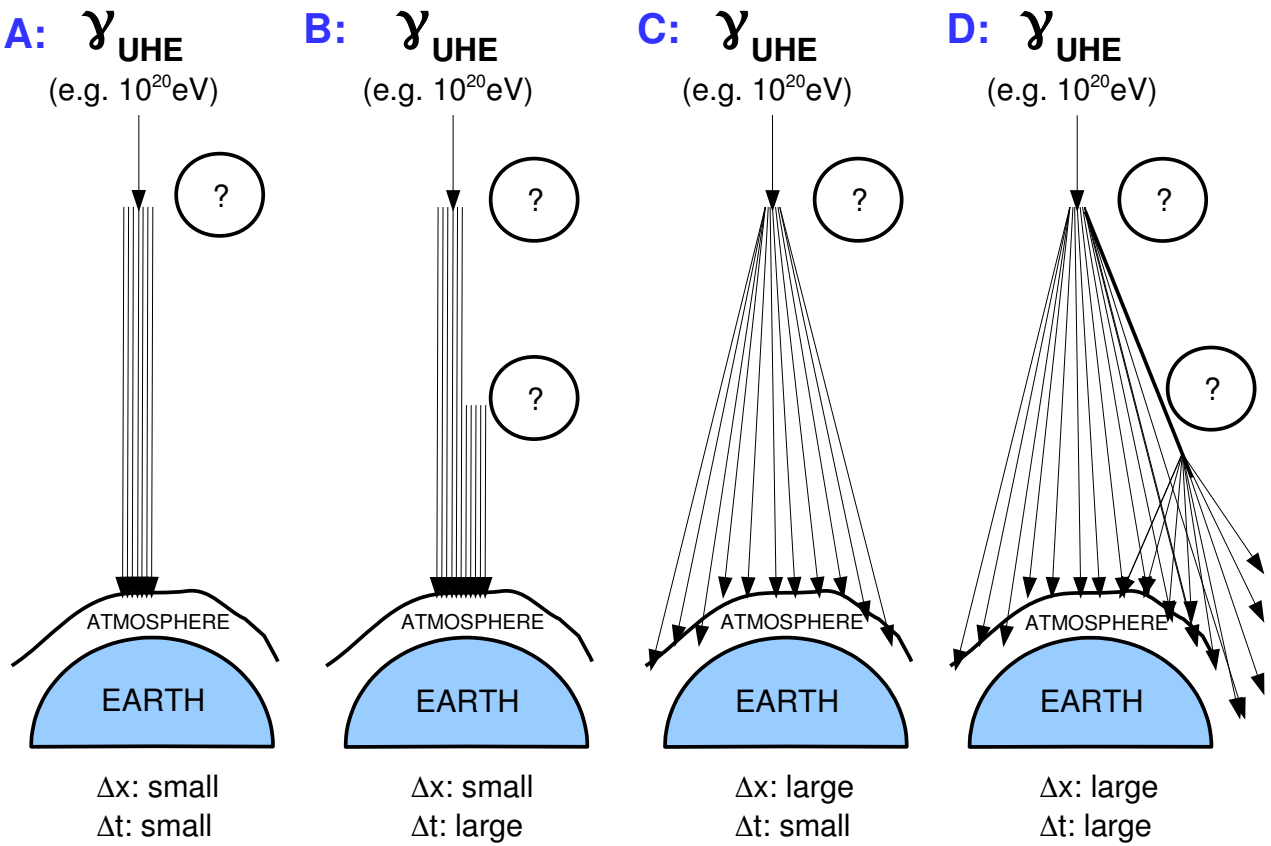
Forgotten (!) treasure (?) no. 2

Correlated cosmic rays?

$N_{ATM} > 1$?



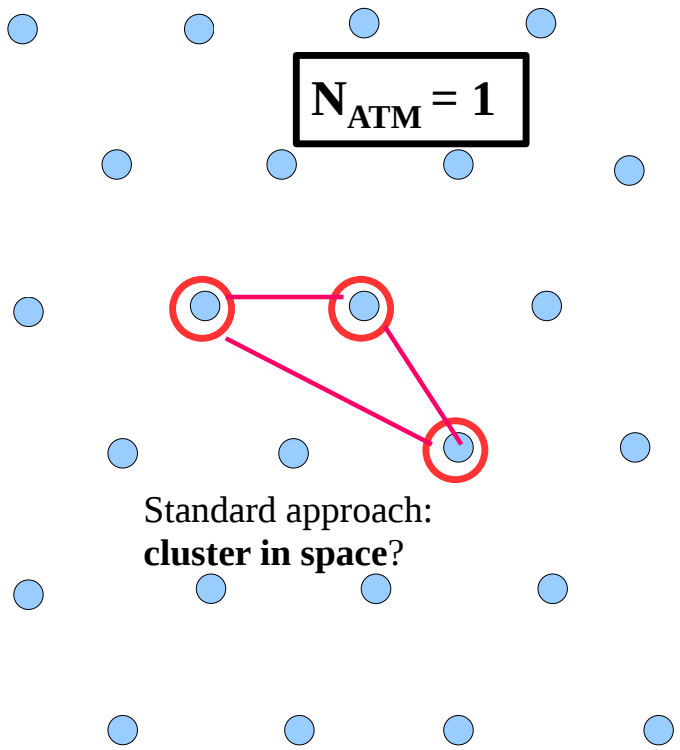
Single CR vs. CR Ensembles



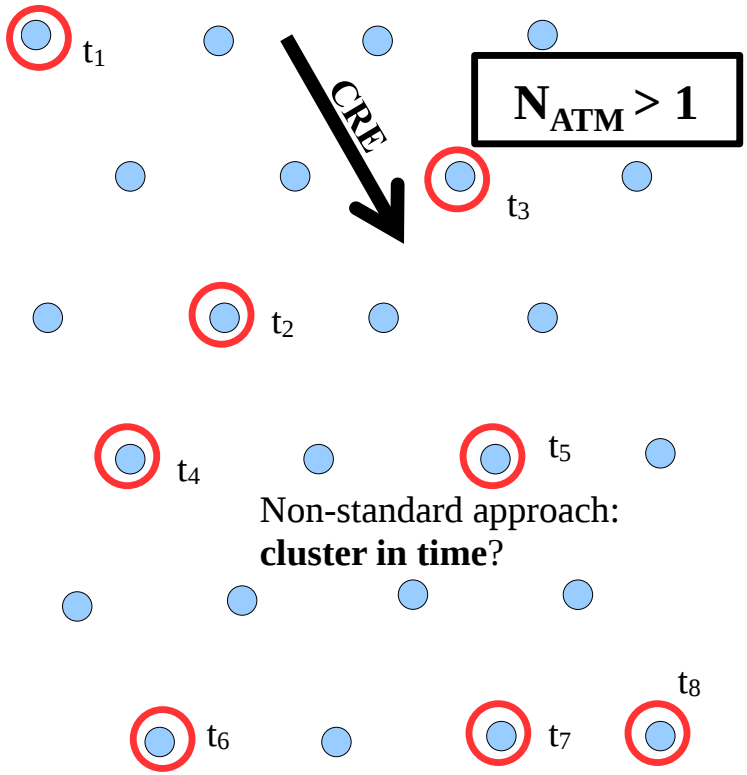
Various types of CREs arriving at the Earth.
Question marks represent unknown or uncertain physics processes at UHE.

Single CR vs. CR Ensembles

A chance for unique signature!



Standard approach:
cluster in space?



Non-standard approach:
cluster in time?

1) $t_n - t_1 < \sim 1\ \mu s$
2) $t_1 < \ldots < t_n$,

: a cosmic-ray detector

CREDO: What is it?

Cosmic Ray Extremely
Distributed Observatory

Central database/interface: access to everything for everybody

In short, **CREDO is a global scale cosmic-ray observatory which is accessible to all**
and comprises of **every type of cosmic-ray detectors possible**!

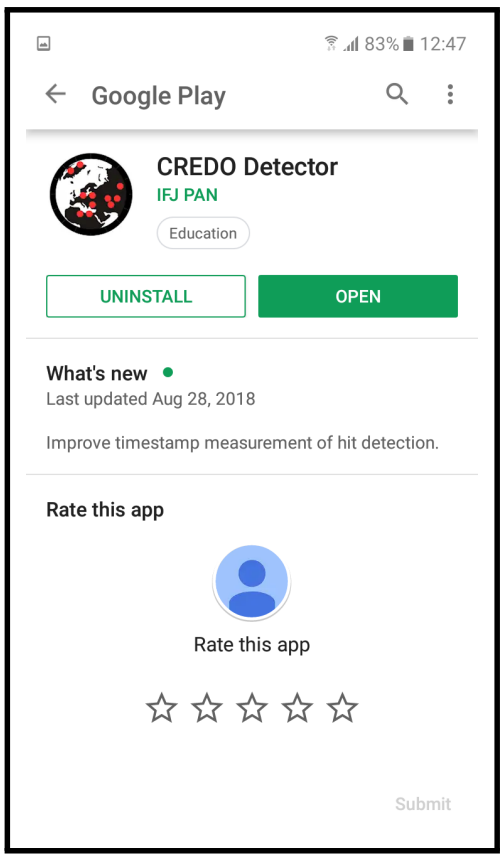
More details at: `http://credo.science`

CREDO: Why?

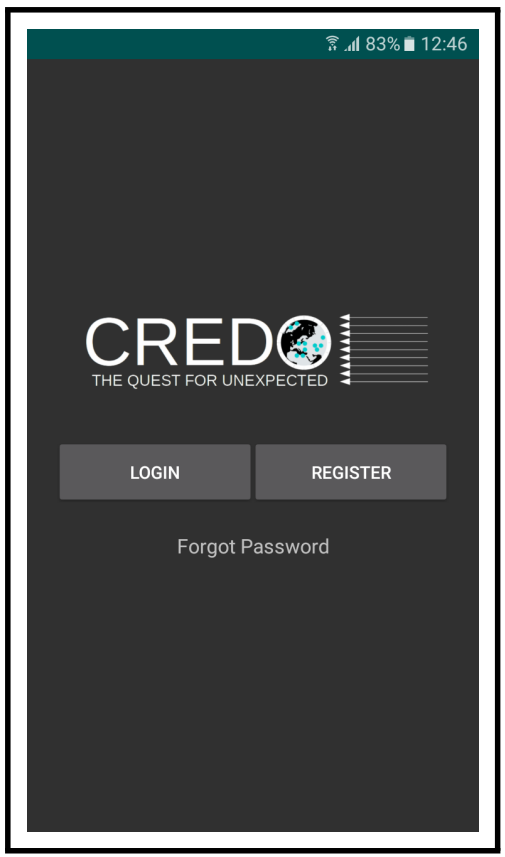
- **Fundamental science:**
  - Nature of dark matter.
  - Better understanding of UHECRs.
  - Search for new physics.
- **Interdisciplinary studies:**
  - Geophysics, e.g., possibility of using cosmic rays as earthquake precursors.
  - Possibility of monitoring of spaceweather.
- **Education and outreach:**
  - Easy access to everyone for understanding fundamental science.
  - Invlovement of all interested for collaborative tasks.

CREDO Detector App

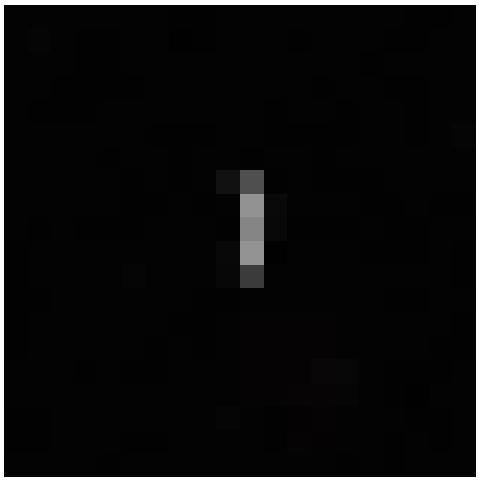
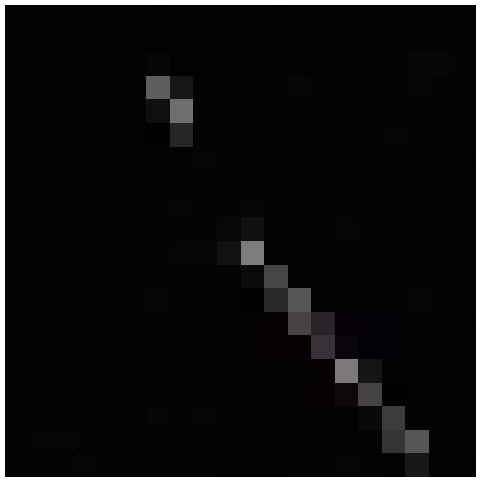
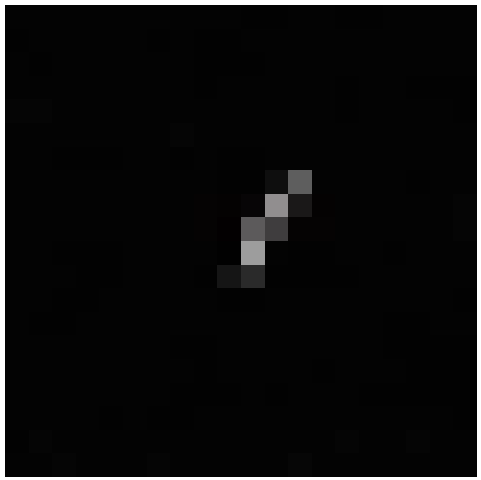
Smartphone App for cosmic ray detection developed in the Collaboration.



https://play.google.com/store/apps/details?id=science.credo.mobiledetector



CREDO Detector App

Some examples of cosmic ray hits detected by CMOS sensor of smartphones. In addition to the images of hits, other relevant information (e.g., timestamp, geogrpahic location etc.) are also recorded.

Images of CR hits can be browsed at:
`https://api.credo.science` !

CREDO Monitor

CREDO monitor is a daily automated list of tasks whose ultimate objective is a search of Cosmic Ray Ensembles.

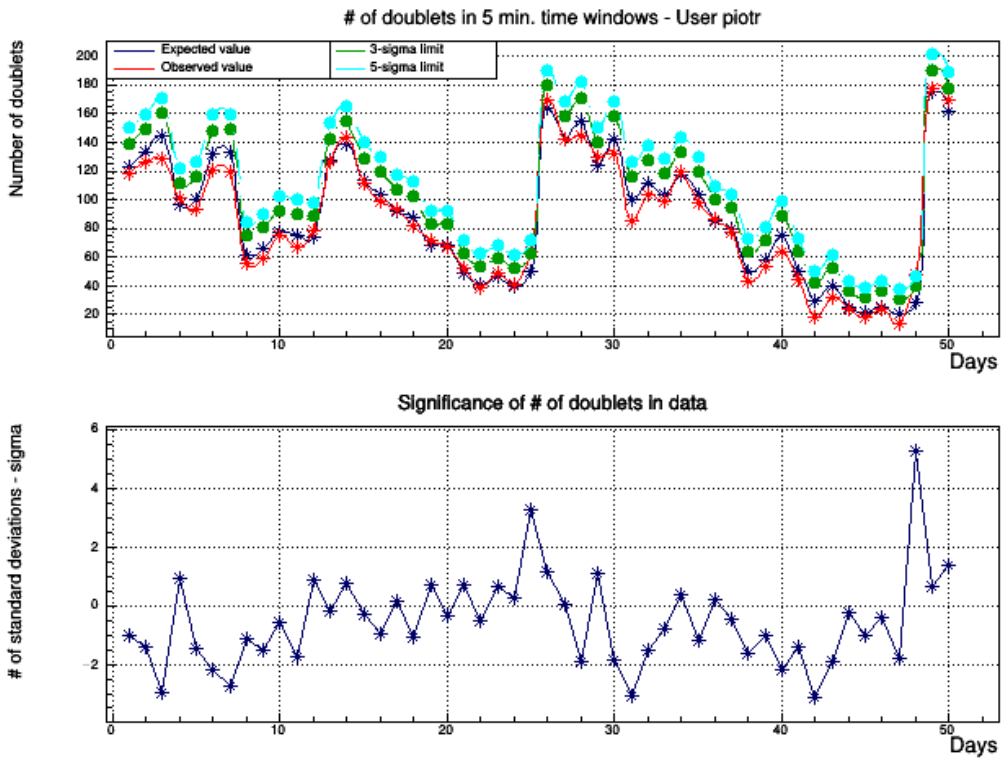
- **Get the data:** Obtain detection data (cosmic ray hits) and ping data (for detector ontime calculations).
- **Data update:** Update of data periodically (currently once per day).
- **Data Preprocessing:** Sorting and syncing data.
- **Selection/cuts:** Filter out and discard artefacts in data.
- **Analysis:** Use algorithms to look for possible CRE signatures.
- **Share the results:** Sharing (interesting) results.

The storage, monitoring and computing tasks of CREDO are hosted by ACC Cyfronet AGH-UST.

An example of Cluster in Time scenario:

What do the results look like?

- Each point correspond to one timestamp file <=> one 24h period



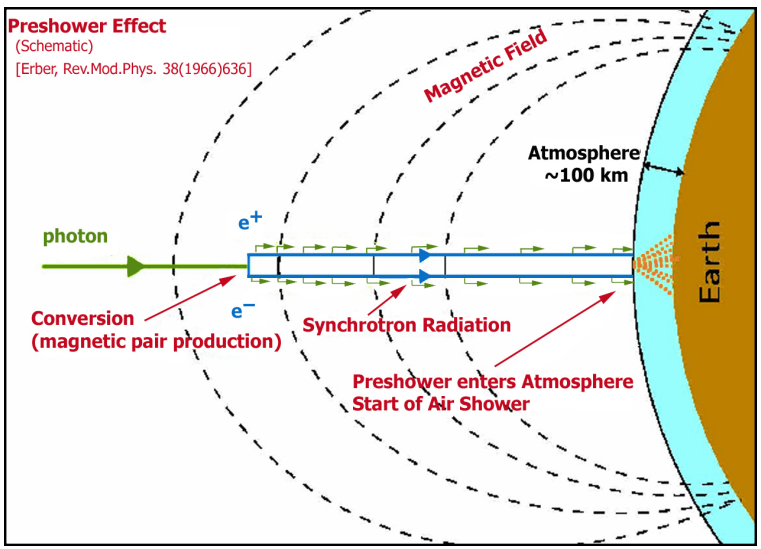
Slide from K. Almeida Cheminant's talk

CRE scenario: Super-preshower

Example non-exotic scenarios: Preshower and super-preshower

Preshower:

- Cascade of EM particles produced by interaction of UHE-γ with geomagnetic field.
- Typical altitude $\sim$ 1000 km a.s.l. $N \sim 100$



Super-preshower (SPS):

- Cascade of EM particles produced by interaction of UHE-γ with solar magnetic field.
- Typical distance of cascade development is **very far**. $N \gg 100$!!

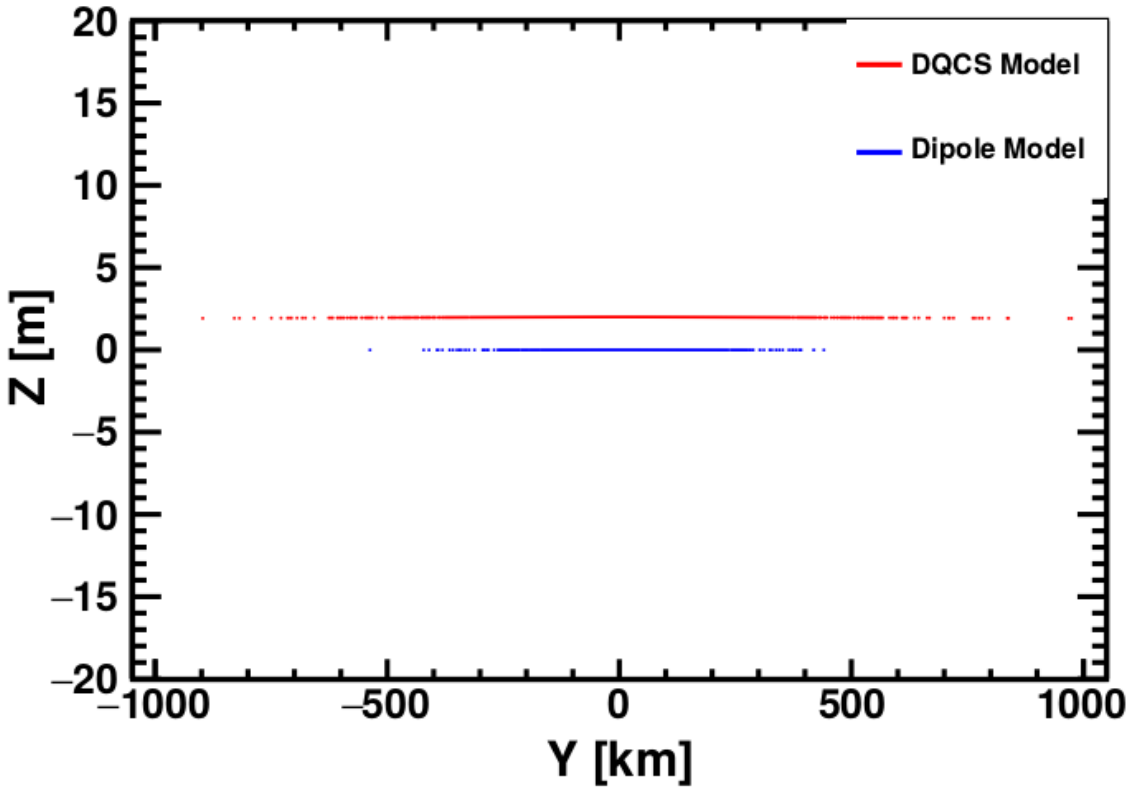
CRE scenario: Super-preshower

SPS simulation Considerations

- 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 done for two models of solar magnetic fields (dipole and DQCS models).

CRE scenario: Super-preshower

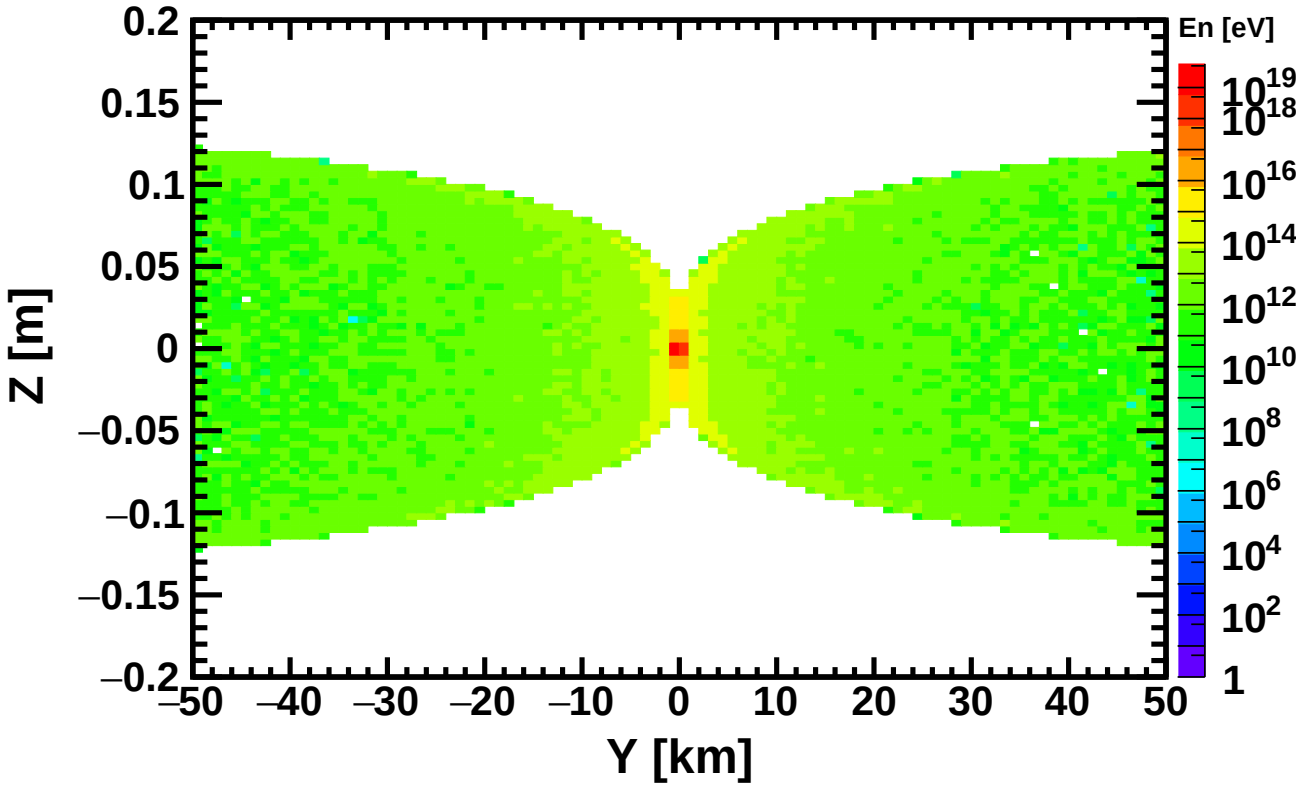
Example 1: Primary photon heading towards Earth travels via the Sun's **polar** region.



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

Distribution of photons (with $E > 10^{12}$ eV) at the top of the Earth's atmosphere. Energy of the primary photon = 100 EeV, impact parameter = 3 $R_{\odot}$.

CRE scenario: Super-preshower



Previous plot but zoomed in and photons weighted by energy

- smaller deflection of photons

↓

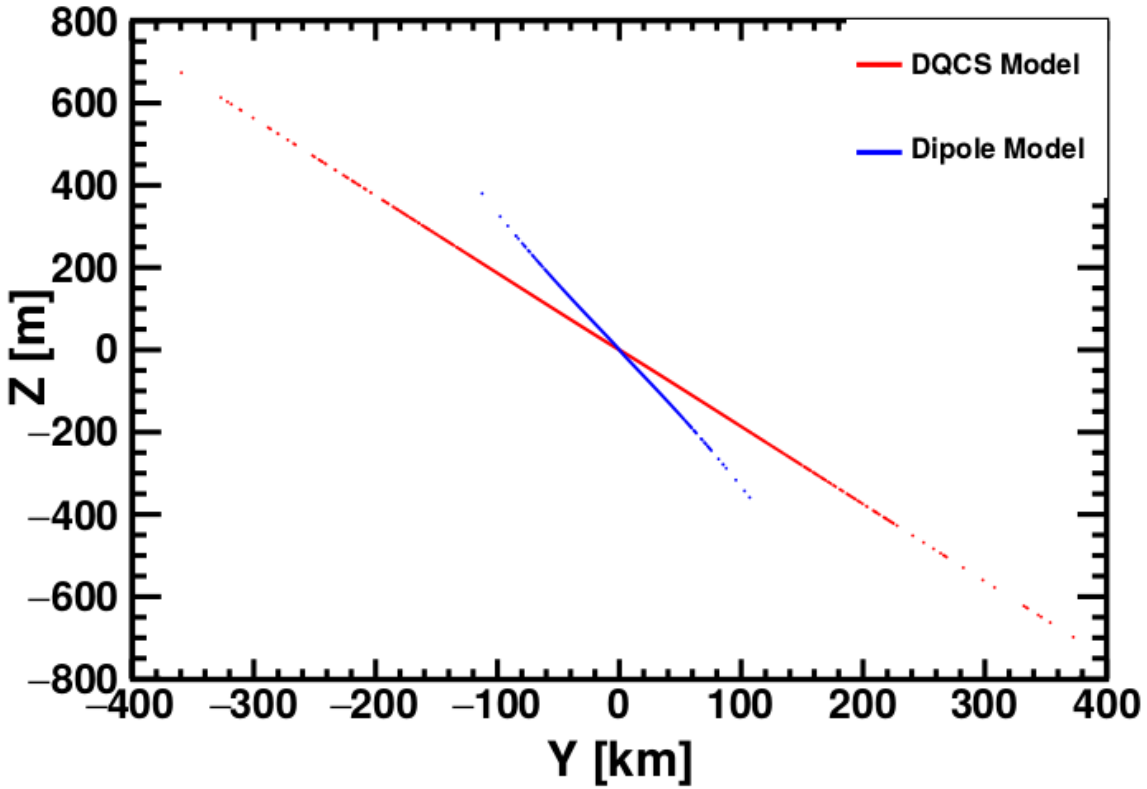
- higher energy

↓

- photons more confined in the "core region"

CRE scenario: Super-preshower

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.

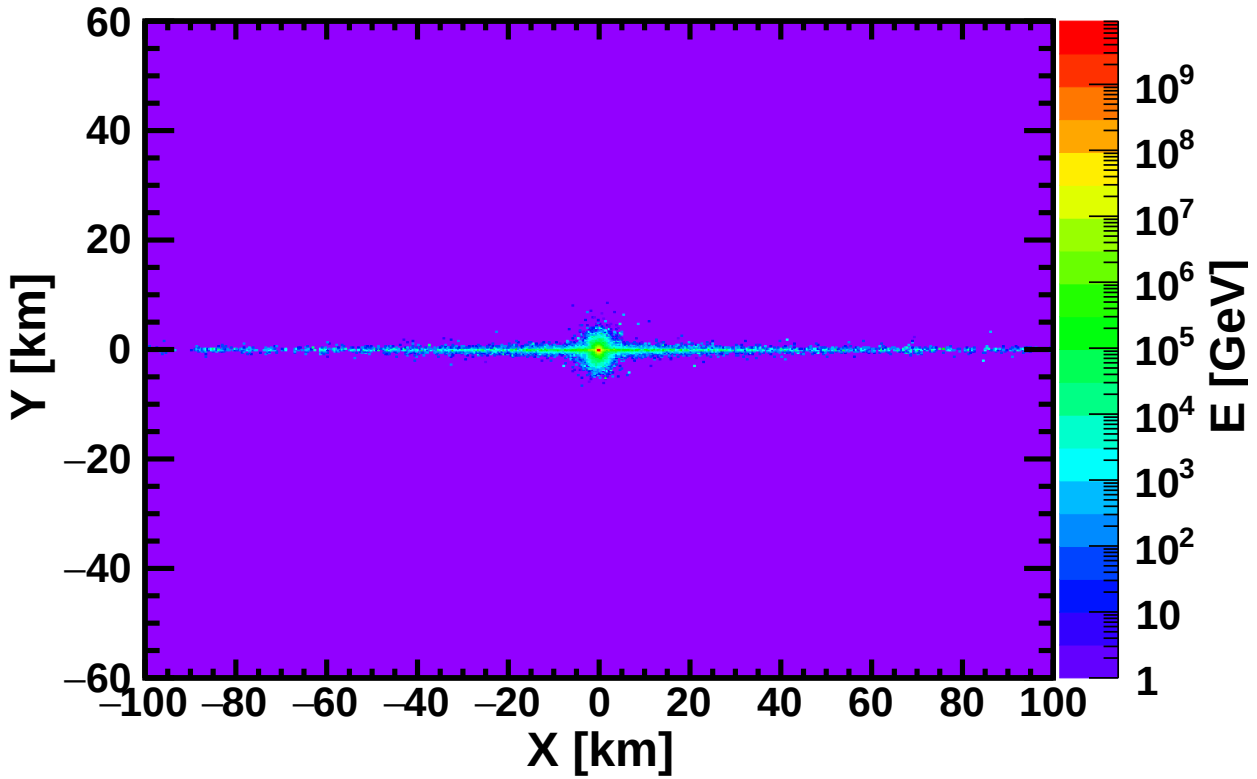


- Both DQCS and Dipole models give similar results (photons distributed along a **line**).
- **Orientation** of the "line" depends on the **region** nearby Sun through which primary photon traverses.

Distribution of photons (with $E > 10^{12}$ eV) at the top of the Earth's atmosphere. Energy of the primary photon = 100 EeV, impact parameter = 3 $R_\odot$.

CRE scenario: Super-preshower

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

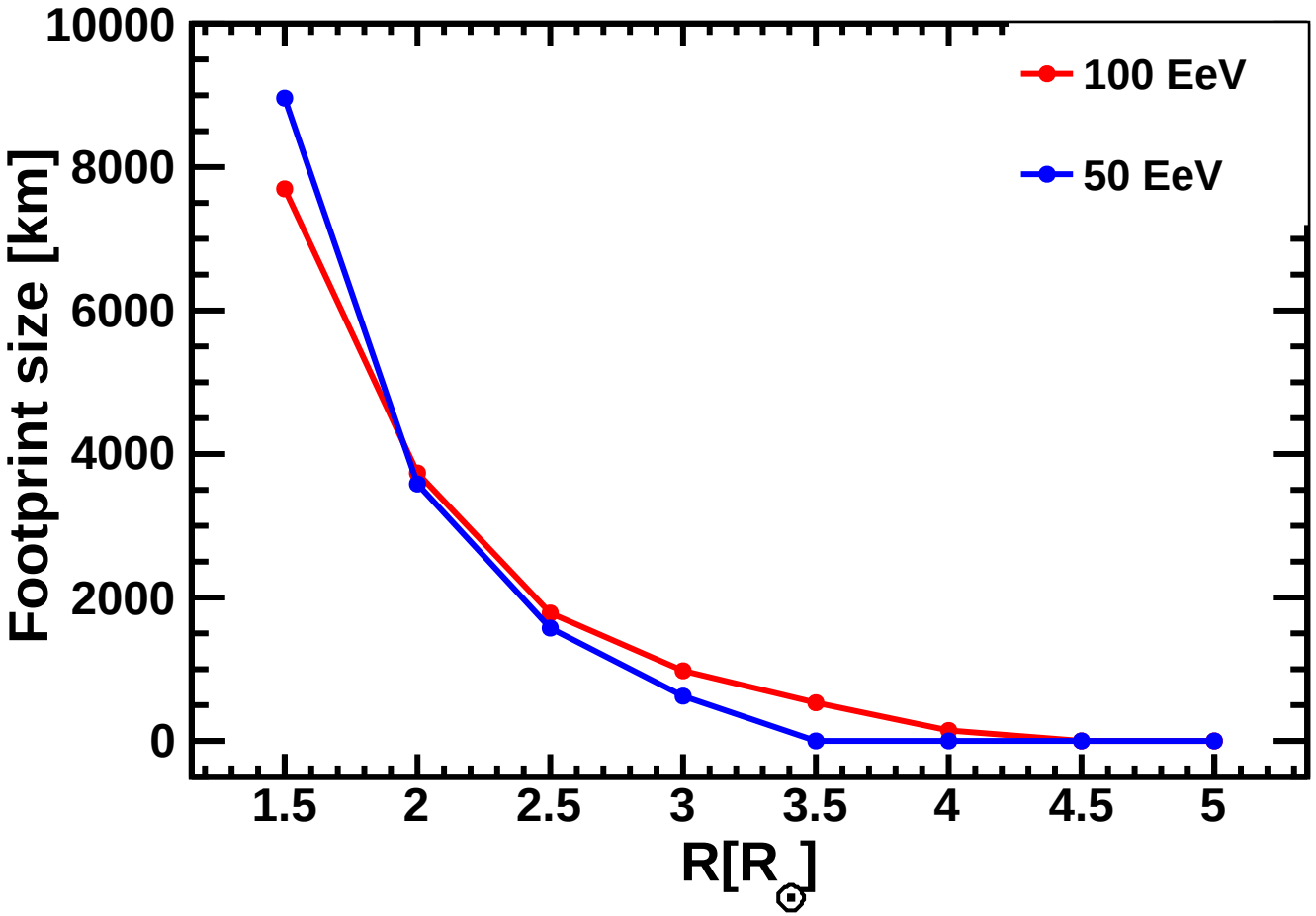


Distribution of particles at the ground weighted by energies. The SPS is initiated by a 30 EeV primary photon traveling in the Sun's equatorial plane

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

CRE scenario: Super-preshower

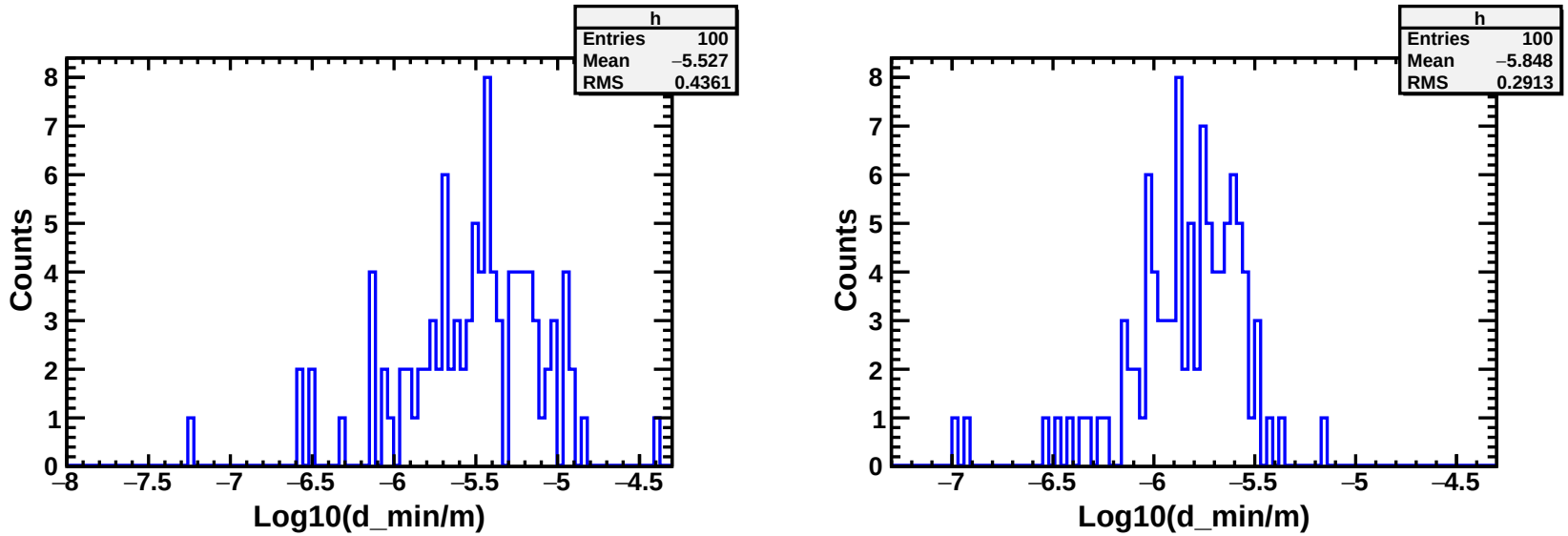
"Footprint" at the top of the atmosphere is very extended spatially



Footprint size as a function of impact parameter.

CRE scenario: Super-preshower

A glance at the nearest photons at the core of the SPS at the Earth

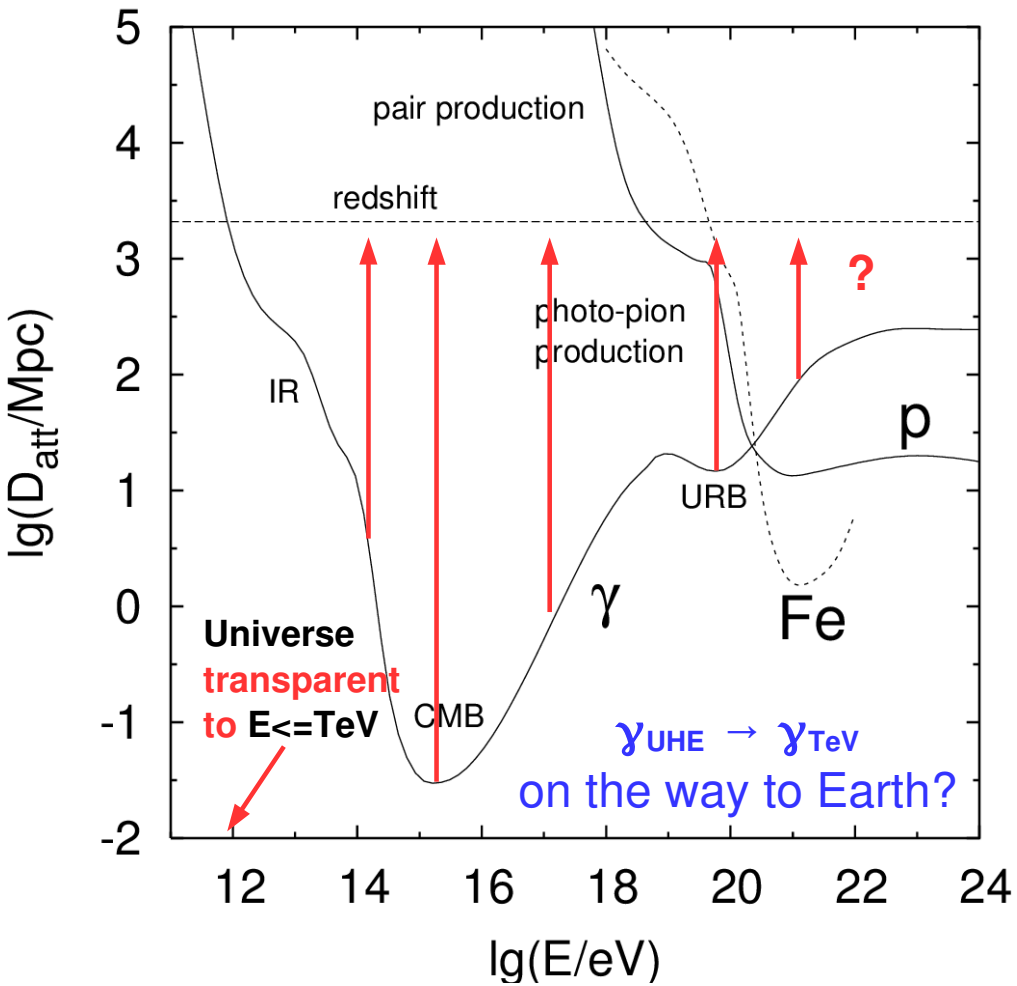


Distributions of separation between pair of closest photons in SPS.
Left: for SPS photons with energies $1 - 10$ TeV (left). Right: > 1 EeV.

For similar process at a large distance (e.g., a neutron star):
if two nearest photons are simultaneously detected very far at earth (say 10 000 km apart, i.e, d_min = 10 000 km),
CREDO's horizon will be hundreds of Mpc.

CRE scenario: Super-preshower

For comparison: $\gamma-$ ray mean free path as a function of energy



CRE scenario: Super-preshower

Manuscript of a collaboration paper on SPS simulation results to be submitted to a peer-reviewed journal is ready

Cosmic ray ensembles as signatures of ultra-high energy photons interacting with the solar magnetic field

Niraj Dhital for the CREDO Collaboration*
Institute of Nuclear Physics PAN, Cracow 31–342, Poland

Propagation of ultra-high energy photons in the solar magnetosphere gives rise to cascades comprising thousands of photons. We study the cascade development using Monte Carlo simulations and find that the photons in the cascades are spatially extended over hundreds of kilometers as they arrive at the top of the Earth's atmosphere. We compare results from simulations which use two magnetic field models of the solar magnetic field, and show that although signatures of such cascades are different for the models used, for practical detection purpose in the ground-based detectors, they are similar.

PACS numbers: 02.70.Uu, 13.85.Tp, 95.85.Ry

Introduction: Detection of ultra-high energy (UHE) photons will have a significant impact in the understanding of fundamental science. As an example, dark matter (DM) searches up to the electroweak scale ($\sim$ 100 GeV) so far have not been able to produce conclusive evidence of DM particles [1–3]. For this reason, it is quite instinctive that the mass regime corresponding to the other natural scales– the GUT and the Planck scale be explored abling us to place stringent upper limits on UHE photon fraction (flux) [9, 10], but also observation of an excess of muons in data compared to what one would expect from simulations of hadronic showers [11, 12]. Given such a discrepancy between the measurements and the results from simulations of hadronic showers, which is possibly inherited to the simulations from a lack of complete understanding of physics at the UHE regime, it is very ap-

.. and efforts are ongoing not only on the data analysis but also on identification and simulation of the scenarios interesting to CREDO.

Summary

- **CREDO** opens a new channel to explore the Universe (CREs) and has a wide range of potential fields it can serve (fundamental science, interdisciplinary studies, education).

- **Current status:**
  Up and Running.
  More than 2100 users and around 400 000 detections.
  Work on the data analysis, detector development, simulation studies etc. are ongoing.

- **Outlook:**
  Expansion of CREDO.
  Development of Data Analysis Framework.
  Science and Simulation tasks.

- **For more info:**
  Please visit `https://credo.science` and contribute to CREDO science