Search for Extensive Photon Cascades with the Cosmic-Ray Extremely Distributed Observatory

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Understanding the Photon Structure

Photon efforts

many GeV-TeV photons $\rightarrow$ terrestrial instruments

few TeV-PeV photons $\rightarrow$ gamma rays

Very few hypothetic EeV-ZeV photons $\rightarrow$ cosmic rays

Singular present: Cosmic rays (N = 1)

Plural future: Cosmic-ray cascades (N > 1) this talk

N: number of cosmic ray particles correlated in time
Motivation for cosmic-ray cascades

Comic-ray research phase transition:

\[ N = 1 \rightarrow N > 1 \]

N: number of cosmic ray particles correlated in time

→ cosmic-rays (N=1): strong paradigm on non-observation of UHE photons; non-observation often interpreted as non-existence: logically UNFAIR!

→ cosmic-ray cascades (N>1):
  unprobed channel, must-check to complete the UHE photon study, potential to completely change the photon landscape
Generalization of UHECR research

$N_{ATM} = 1 \rightarrow N_{ATM} > 1$

UHECR ($p, Fe$)

$N_{ATM} = 1$

STATISTICS $\rightarrow$ SIGNATURES

UHECR ($\gamma \rightarrow SPS$)

$N_{ATM} > 1$

GROUND

CHANCE FOR A UNIQUE SIGNATURE!

: a cosmic-ray detector
Testing ASTRO/COSMO models

→ millions of photons at $E > \text{TeV}$, arriving simultaneously at the top of the atmosphere, spread worldwide!

Let us hunt for coincidences!
CREDO

THE QUEST FOR UNEXPECTED

Scientific FISHING

Just cast the (global) cosmic-ray Net and see which truth gets in...
Diffuse UHE photon search: hybrid limits

UHECR COMPOSITION PARADIGM
At the highest energies photon fractions < 1%

→ Severe limitations for exotic scenarios? *)
→ and for (special) Lorentz Invariance Violation? *)

*) Understand well: limits apply to single photons, assume no screening eg. within exotic models of interactions, structure of a photon and the spacetime structure that could manifest at UHE...
Experimental evidence about $\gamma_{\text{UHE}}$

- $\gamma_{\text{UHE}}$ \(\xrightarrow{\text{no interactions / screening}}\) Earth
  - NOT OBSERVED

- $\gamma_{\text{UHE}}$ \(\xrightarrow{\text{unexpected interactions, screening, ...}}\) ELECTROMAGNETIC CASCADES (SUPER-PRESHOWERS) \(\xrightarrow{}\) Earth
  - NOT TRIED SO FAR...

\[\text{CREDO!}\]
(Super-)preshowers: a must to study UHE photons

(Super-)preshower:
→ contains typically (>1000) 100 particles
→ created at around (>10000) 1000 km a.s.l.

Preshower Effect
(Schematic)
[Erber, Rev.Mod.Phys. 38(1966)636]

?: fundamental uncertainties
- electrodynamics linear?
- photon structure?
- spacetime: extra dimensions?

→ dependence on E and B⊥ (to be seen in data?)
Classes of super-preshowers (SPS)

A: $\gamma_{UHE}$ (e.g. $10^{20}$eV)
- $\Delta x$: small
- $\Delta t$: small

B: $\gamma_{UHE}$ (e.g. $10^{20}$eV)
- $\Delta x$: small
- $\Delta t$: large

C: $\gamma_{UHE}$ (e.g. $10^{20}$eV)
- $\Delta x$: large
- $\Delta t$: small

D: $\gamma_{UHE}$ (e.g. $10^{20}$eV)
- $\Delta x$: large
- $\Delta t$: large

: Fundamental physics questions
Super-preshowers on Earth: untouched ground

\(\gamma_{\text{UHE}}\)
(e.g. \(10^{20}\)eV)

\(\Delta x: \sim \text{few km}\)

\(\text{obvious detection}\)

exponentially accessible
but still untouched, scientific
\text{terra incognita}\n
\(\gamma_{\text{UHE}}\)
(e.g. \(10^{20}\)eV)

\(\Delta x > \text{Earth size}\)

\(\text{obvious extinction}\)
Super-preshower on Earth: untouched ground

\( \gamma_{\text{UHE}} \) (e.g. \(10^{20}\) eV)

\( \Delta x: \sim \text{few km} \)

\( \Delta x < \text{Earth size} \)

\( \Delta x > \text{Earth size} \)

\( \text{ATMOSPHERE} \)

\( \text{EARTH} \)

\text{obvious detection}

\text{obvious (unchecked) "between"}

\text{obvious extinction}
Generalization of UHECR research

$N_{\text{ATM}} = 1 \rightarrow N_{\text{ATM}} > 1$

UHECR (p, Fe)

$N_{\text{ATM}} = 1$

UHECR ($\gamma \rightarrow \text{SPS}$)

$N_{\text{ATM}} > 1$

ATMOSPHERE

GROUND

STATISTICS $\rightarrow$ SIGNATURES

CHANCE FOR A UNIQUE SIGNATURE!

: a cosmic-ray detector
Super-preshowlers road map

Theoretical review (ongoing)
  non-exotic / exotic

  ↓

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

  ↓

Air shower simulations (ongoing)

  ↓

Detector response

  ↓

observation / upper limits
\( \gamma_{\text{UHE}} \) travelling through the Universe: paradigm
Lorentz invariance violation and super-preshowers

Isotropic, nonbirefringent LV

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

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

- This modification allows for processes which are **kinematically forbidden** in the conventional Lorentz-invariant theory
  - $\kappa > 0$: **vacuum Cherenkov radiation** possible above a threshold $E_{\text{thr}}(\kappa)$
    $$f \rightarrow f + \tilde{\gamma}$$
    efficient energy loss mechanism for charged particles, current constraints $(\kappa < 6 \times 10^{-20}$ at 98\% C.L.) derived from **observations of UHECRs** [Klinkhammer & Risse 2008]
  - $\kappa < 0$: **photon becomes unstable** above a threshold $\omega_{\text{thr}}(\kappa)$
    $$\tilde{\gamma} \rightarrow e^+ + e^-$$
    decay length is very small, current constraints derived from **gamma-ray astronomy** [Klinkhammer & Schreck 2008]

ALL UHE photons initiate super-preshowers!!!
The figure illustrates the interaction of ultra-high energy (UHE) gamma rays ($\gamma_{UHE}$) travelling through the Universe. The diagram shows the attenuation length ($D_{att}$) in megaparsecs ($\text{Mpc}$) plotted against the logarithm of the energy ($E$) in electron-volts ($\text{eV}$). The $\gamma_{UHE}$ propagates through the Universe, potentially undergoing pair production and photo-pion production. The question mark marks a point of interest: $\gamma_{UHE} \rightarrow \gamma_{TeV}$ on the way to Earth? If the Universe is transparent to energies less than or equal to TeV ($E \leq \text{TeV}$), it might suggest that the high-energy gamma rays could reach Earth.
Non-exotic examples of “obvious” SPS between Earth and Sun.

\[ \gamma_{\text{UHE}} \]
(e.g. \(10^{20}\) eV)

\[ B_{\text{SUN}} \]
e\(^+\)e\(^-\)

[SUN]

ATMOSPHERE

EARTH

NOW: with PRESHOWER

\[ \gamma_{\text{UHE}} \]
(e.g. \(10^{20}\) eV)

FAR FAR AWAY

e\(^+\)e\(^-\)

SOON: with CRPropa 3

[OUT OF SCALE:]

EARTH

ATMOSPHERE
Distribution of photons at the top of the atmosphere.

**SUN SPS, $10^{19}$ eV, top of the atmosphere**

Distribution of photons ($E > 10^{13}$ eV) at the top of the atmosphere.

$E_\gamma = 10$ EeV, Impact parameter = $2.5 R_S$.
Sun super-preshowers: colorful air shower physics?

Distribution of photons weighted by their energies.

Distribution of photons at the top of the Atm

SUN SPS, $10^{19}$eV, top of the atmosphere

weighted by $E$

Distribution of photons ($E > 10^{15}$ eV) at the top of the atmosphere.

$E_\gamma = 10$ EeV, Impact parameter = $2.5 R_S$. 

slide by Niraj Dhital, INP PAS
Super-preshowers shortcut road map

Theoretical review (ongoing) ✓

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

Air shower simulations (ongoing) ✓

Detector response

observation / upper limits

unique signature fishing
A chance for a unique super-preshower signature

$N_{\text{ATM}} = 1$

Standard approach: cluster in space?

$N_{\text{ATM}} > 1$

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
How a super-preshower can look like?

Simulation by Paweł Jagoda & Łukasz Bratek
(assumed CREDO stations: locations of the airports)
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 mean energy $3 \times 10^{15}$ 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, 94.40.Rc, 95.30.-k

PH: Super-preshower class B?

Year = 1981
$N_{\text{obs}} = 32$
$N_{\text{exp}} = 1$
$E = 3 \times 10^{15}$ eV

$\Delta t \sim 5 \text{ min.}$

$\Delta x \geq \text{ small}$
Observation of a Burst of Cosmic Rays at Energies above $7 \times 10^{13}$ 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

PH: Super-preshower class D?
CREDO: mission organized for super-preshower showers

Cosmic-Ray Extremely Distributed Observatory

Status March 2016: „an idea“

Central database/interface: access to everything for everybody
Citizens strengthen trigger capabilities of the educational arrays with smartphone networks

→ indirect search for New Physics manifestations!
→ verification of „classic” QED predictions (preshower @ Sun)

Status August 2016: „the collaboration”

γ_{UHE} (e.g. $10^{20}$eV)

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

Citizens browse the data looking for „improbable” time-space coincidences
CREDO Inauguration Meeting, 30.08.2016, INP PAS

[47 registrants]

Diversified community
(13 nationalities)

Colorful science

Outreach potential

Masz smartfona? Zostań odkrywczą, obserwuj promieniowanie kosmiczne
CREDO Computing Infrastructure
For Data Storage and Processing

Data Access and RT Alert Interface

Data Export Interface (experiment specific, common protocol)

- aggregated Data Analysis
→ Science (or Nature :)

Pierre Auger Observatory
Baikal-GVD
Atlas CERN
MAGIC/CTA, ....

by Piotr Poznański
Vision: the potential to complete the CR study

Would be a pity not to spot such a beauty...
Cosmic-Ray Cascades (Extensive Photon Cascades, Super Preshowers):
- **Unprobed and easily accessible information channel about Universe!**

Cosmic-Ray Extremely Distributed Observatory:
- **the pioneer receiver, already operating, stay tuned!**

Photon context:
- **a chance for unique signatures of photons at \( \sim 10^{23} \) eV?**
- astrophysical constraints to photon interactions producing large cascades?

CREDO call:
Have in mind a **fancy photon-cascadig astro-scenario**? Get in touch :)
 Visit credo.science... 

 Cosmic-Ray Extremely Distributed Observatory (CREDO) 
 Enables a strategy for a global analysis of cosmic-ray data to reach the sensitivity to extremely extended cosmic-ray phenomena, we call them super-preshower, invisible for individual detectors or observatories. So far, the cosmic-ray research has been oriented on detecting single air showers only, while the search for ensembles of cosmic-ray events induced by super-preshowers is a scientific terra incognita. 

 Read More 

 ... and contribute to CREDO science.