Cosmic Ray Extremely Distributed Observatory 2021

Piotr Homola (IFJ PAN / CREDO), IFJ PAN,
Institute Seminar, Kraków, 29.04.2021

CREDO
THE QUEST FOR THE UNEXPECTED

key reference: *Symmetry* **2020**, *12*(11), 1835; **https://doi.org/10.3390/sym12111835**

Outline

1. Cosmic Ray Ensembles (CRE)
2. Cosmic Ray Extremely Distributed Observatory (CREDO)
3. Examples of scientific challenges being addressed by the CREDO Collaboration: highlights 2021
    a. UHECR / Dark Matter puzzle (puzzles) and the challenge in the far-end of the cosmic ray energy spectrum
    b. Spacetime structure: probing with CRE
4. Summary/Outlook/Invitation

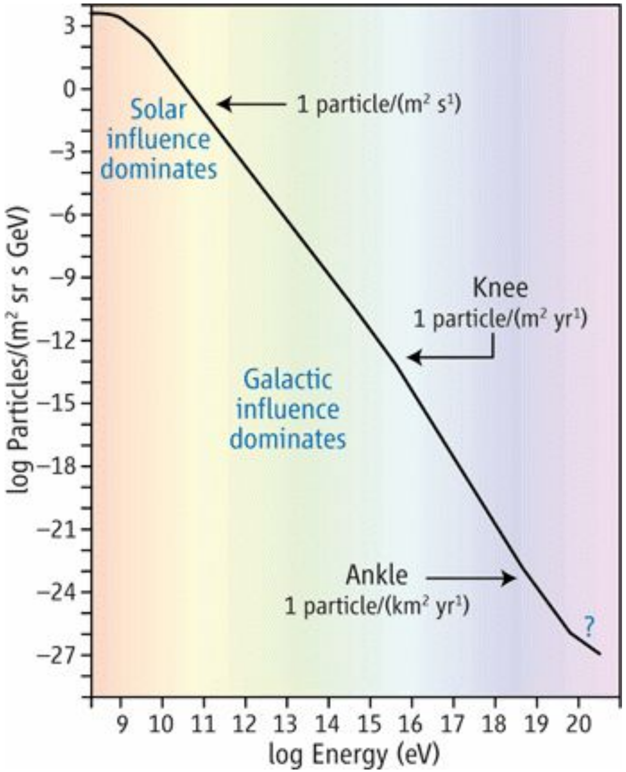
Cosmic Rays!

Ranges:
energy: > 10 orders of magnitude
flux: > 30 orders of magnitude
→ diverse physics (sources)
→ diverse detection techniques

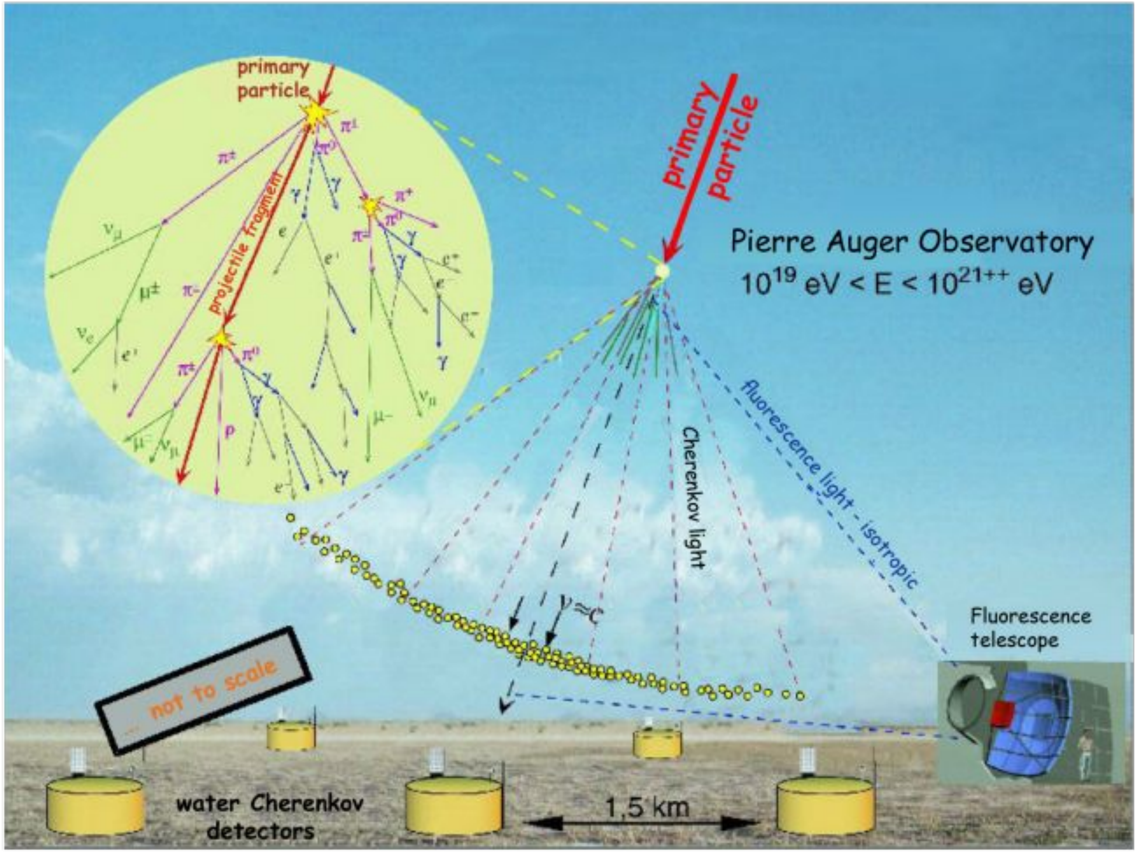
Flux rapidly decreases with energy (~10^{-3}),
Highest energies → the most demanding challenges:

→ technical:
extremely low flux (at E=10^{20}eV
1 particle / km^2 millenium), but now:
the Pierre Auger Observatory (~3000 km^2)

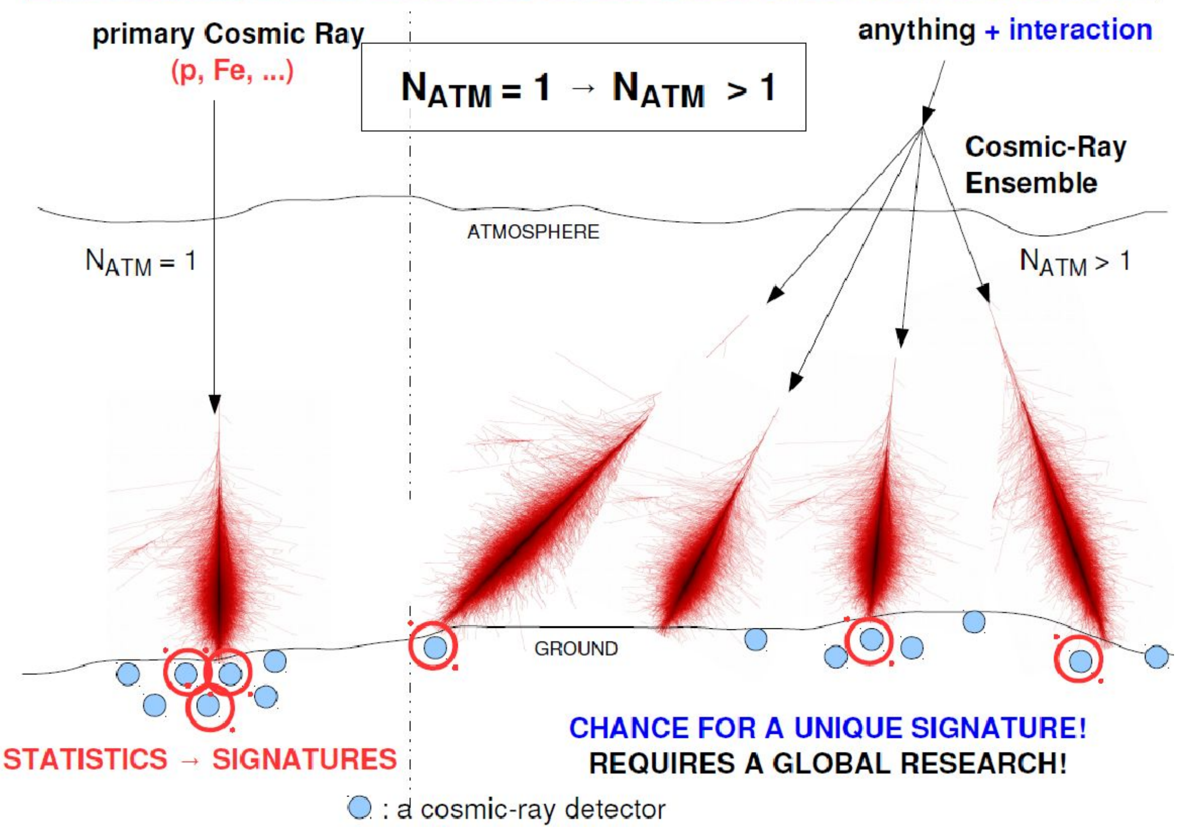
→ scientific:
What are Ultra-High Energy Cosmic Rays (UHECR)?
Where they come from?
How do they propagate?



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

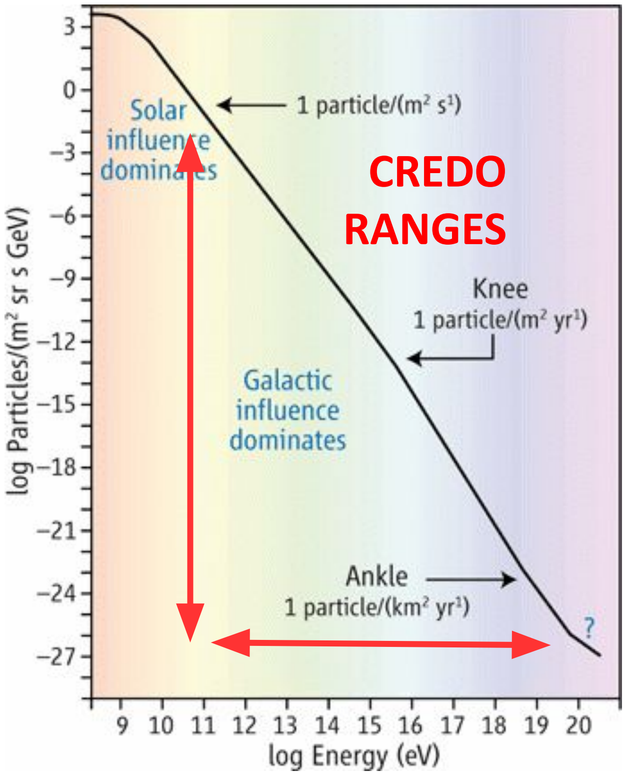


multi-primary approach: cosmic ray large scale correlations

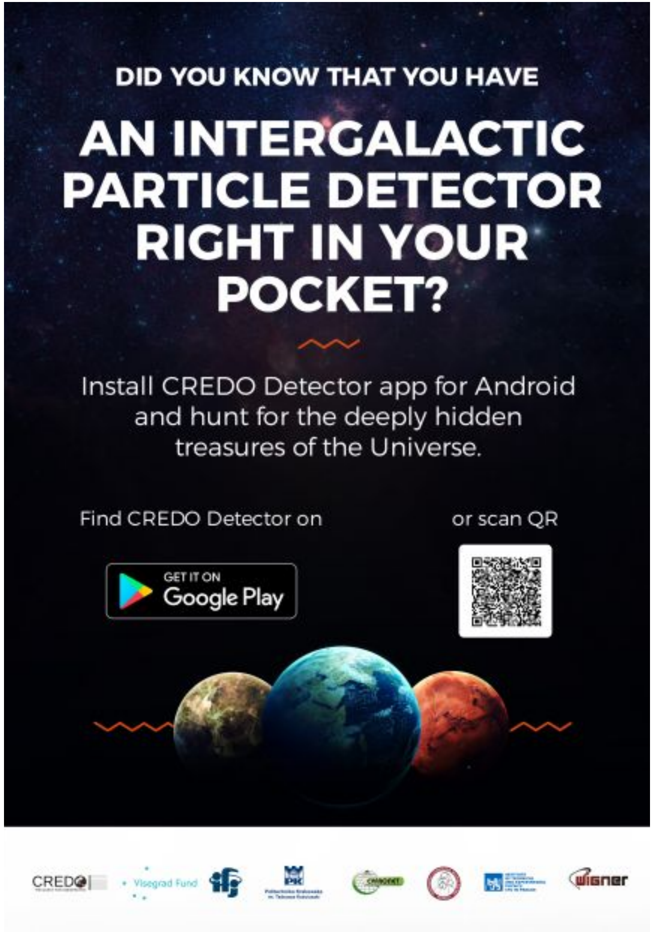


CREDO
THE QUEST FOR THE UNEXPECTED

Cosmic Ray Ensembles (CRE)! Full energy spectrum!



Novel global concept: **cloud of clouds**



-> "new data"!

CREDO Memorandum of Understanding

Cosmic Ray Extremely Distributed Observatory (CREDO)

CREDO
THE QUEST FOR THE UNEXPECTED

since 2.10.2018

This multi-beneficiary Memorandum of Understanding (MoU) is made

BETWEEN:

the Institutions named in Section 8: Signatories, henceforth referred to as "Parties", with the Effective Date being the date of signing by each of the Parties,

in relation to the Project entitled

COSMIC RAY EXTREMELY DISTRIBUTED OBSERVATORY (CREDO), henceforth referred to as "Project".

THEREFORE, IT IS AGREED THAT:

Section 1: Background

The Parties agree to cooperate in exploring the multidisciplinary potential of a widely distributed network of cosmic ray detectors, under the name of the Cosmic Ray Extremely Distributed Observatory (CREDO). As an initiative of the Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences the CREDO concept has been under development since 30th August 2016.

Section 2: Purpose

The purpose of this MoU is to stipulate, in the context of the Project, the relationship between the Parties. In particular, this concerns the distribution of work between the Parties, the management of the Project and the rights and obligations of the Parties.

CREDO Memorandum of Understanding

CREDO institutional members (21.04.2021):

- Australia (2)
- Canada (1)
- Czech Republic (3)
- Estonia (1)
- Georgia (1)
- Hungary (1)
- India (2)
- Italy (1)
- Mexico (1)
- Nepal (1)
- Poland (16)
- Portugal (1)
- Russia (1)
- Slovakia (1)
- Spain (2)
- Thailand (1)
- Ukraine (3)
- Uruguay (1)
- USA (3)

(43 institutions, 19 countries)

CREDO detectors today

CREDO Detector (Android app, ~2M track candidates, origin: IFJ PAN)

cosmicrayapp.com (iOS, ~7M track candidates, origin: Canada)

CREDO Web Detector (Chrome, in tests, origin: Kraków)

HEAMS - High Energy Astrophysics Muon System (8 x 1m^2 scintillator detectors, ~300k ~0.1 PeV air showers, location: Adelaide)

public resources:

Pierre Auger Observatory scaler data, Neutron Monitor Database

short term perspective: GELATICA, CZELTA, other public resources

Peer-reviewed publications "for the CREDO Collaboration":

published:

1. **"Determination of Zenith Angle Dependence of Incoherent Cosmic Ray Muon Flux Using Smartphones of the CREDO Project",** M. Karbowiak, T. Wibig, et al. (CREDO Collab.), *Appl. Sci.* 2021, *11*, 1185, January 2021. [DOI: 10.3390/app11031185].
2. **"Cosmic Ray Extremely Distributed Observatory",** P. Homola, et al. (CREDO Collab.), Symmetry 2020, 12(11), 1835, 2020. [DOI: 10.3390/sym12111835].
3. **"Towards A Global Cosmic Ray Sensor Network: CREDO Detector as the First Open-Source Mobile Application Enabling Detection of Penetrating Radiation",** Ł. Bibrzycki, et al. (CREDO Collab.), Symmetry, 12(11), 1802, 2020. [DOI: 10.3390/sym12111802].
4. **"The first CREDO registration of extensive air shower",** M. Karbowiak, T. Wibig, et al. (CREDO Collab.), Physics Education, 55(5), July 2020.[DOI: 10.1088/1361-6552/ab9dbc].
5. **"Search for ultra-high energy photons through preshower effect with gamma-ray telescopes: Study of CTA-North efficiency",** K. A. Cheminant, et al. (CREDO Collab.), Astroparticle Physics, 123, 102489, December 2020. [DOI: 10.1016/j.astropartphys.2020.102489].

submitted:

- "CNN based classifier as an offline trigger for the CREDO experiment", M. Piekarczyk, et al. (CREDO Collab.), to Sensors

in preparation:

- **"Cosmic ray ensembles as signatures of ultra-high energy photons interacting with the solar magnetic field"**
- **"A search for bursts at 0.1 PeV with a small air shower array"**
- "On the method of ascertainment of the possible historical proximity of two extensive air showers"

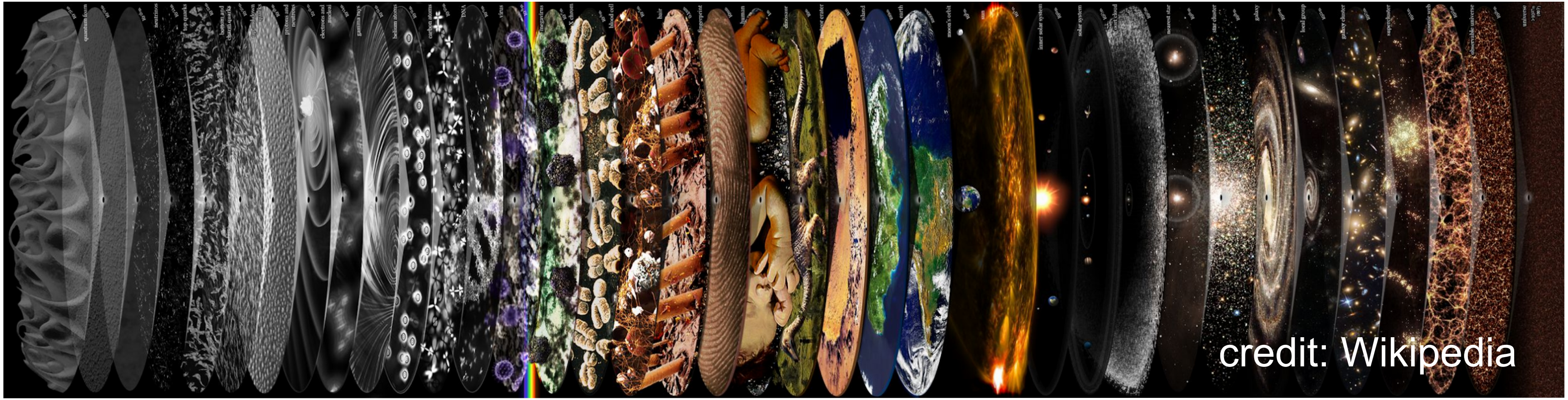
planned soon (selection):

- [UHE photon limit from CRE simulations & gamma astronomy]
- [CRE formation - simulations with CRPropa]
- [PRESHOWER 3.0 code]
- [The CREDO data ontology]

+ 15 accepted submissions to the 37th International Cosmic Ray Conference (compared to 5 articles at the 36th ICRC, Madison, USA, and 2 articles at the 35th ICRC Busan, South Korea)

CREDO Science Potential

10^{-35} m 10^{-5} m 10^{25} m



Space-time structure

Earthquake early warning system

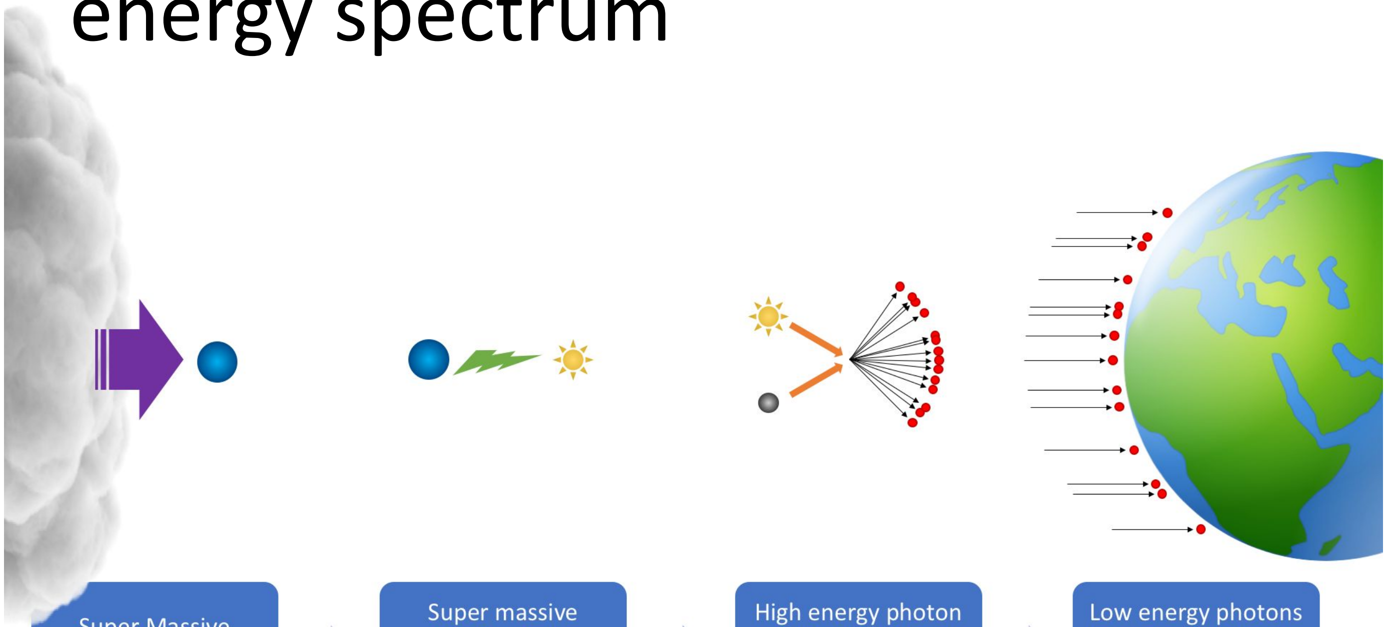
Cosmology, Dark Matter, ...

CREDO

THE QUEST FOR THE UNEXPECTED

more (popular level): https://credo.science/education-materialyeng/podcast/ (EN) / https://credo.science/education-materialypl/podcast/ (PL)

a. UHECR / Dark Matter puzzle (puzzles) and the challenge in the far-end of the energy spectrum



Super Massive Particles formed in the early Universe

Super massive particle decays to a very high energy photon

High energy photon collision creates lots of low energy photons

Low energy photons in a super-preshower are detected on the Earth

The tension in the UHECR energy spectrum

From: Deligny, O.; for the Pierre Auger and Telescope Array Collaborations. The energy spectrum of ultra-high energy cosmic rays measured at the Pierre Auger Observatory and at the Telescope Array. *PoS* **2020**, *ICRC2019*, 234.

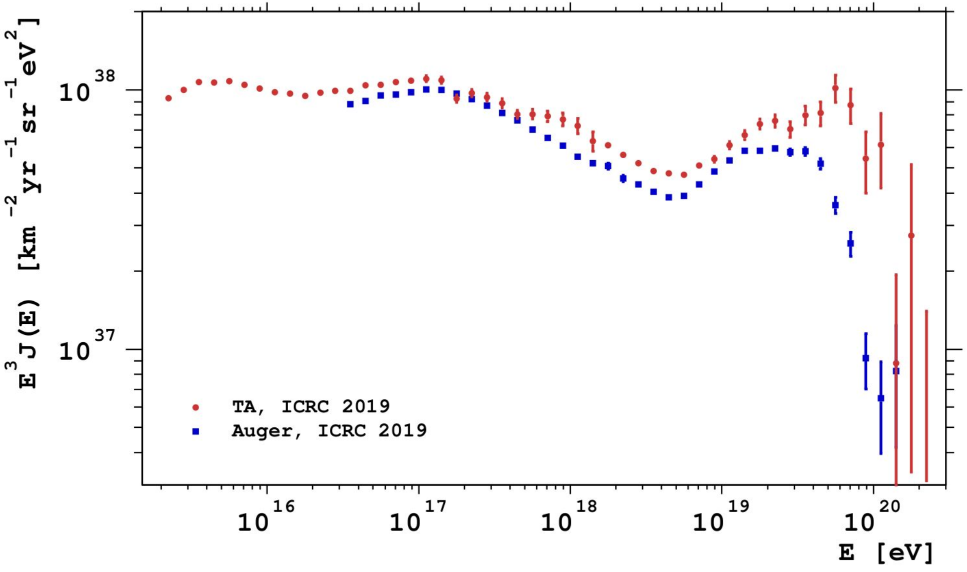
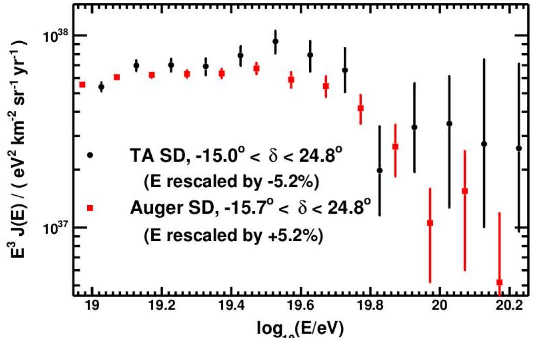
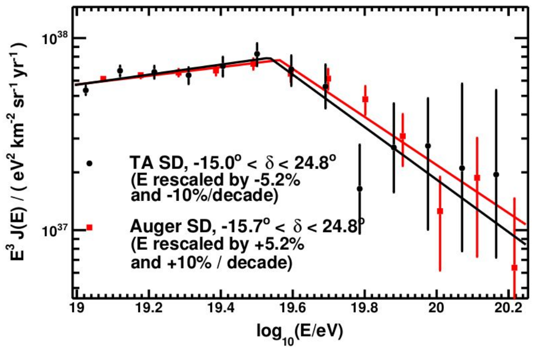


Figure 1: ICRC 2019 energy spectra of the Pierre Auger Observatory and the Telescope Array scaled by E^3. In each experiment, data of different detection techniques are combined to obtain the spectrum over a wide energy range.





The tension: energy dependent reconciliation

From: Deligny, O.; for the Pierre Auger and Telescope Array Collaborations. The energy spectrum of ultra-high energy cosmic rays measured at the Pierre Auger Observatory and at the Telescope Array. *PoS* **2020**, *ICRC2019*, 234.

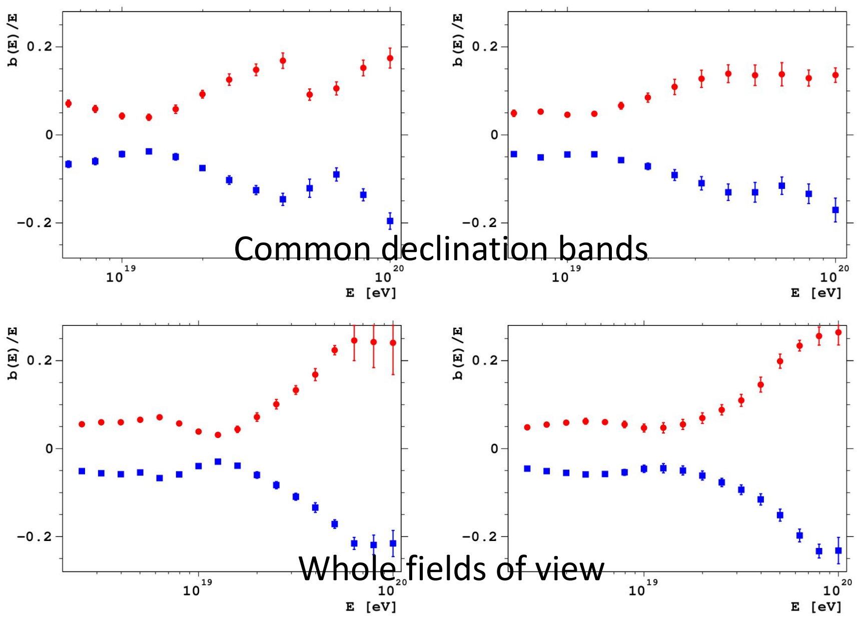


Figure 3: Energy shift term needed to bring the fitted differential spectra in agreement. Left: single broken power law for the underlying spectrum. Right: double broken power law for the underlying spectrum. Top: analysis in the common declination band, using an energy spectrum estimator free of directional-exposure distortions of anisotropies. Bottom: analysis in the whole fields of view of each observatory.

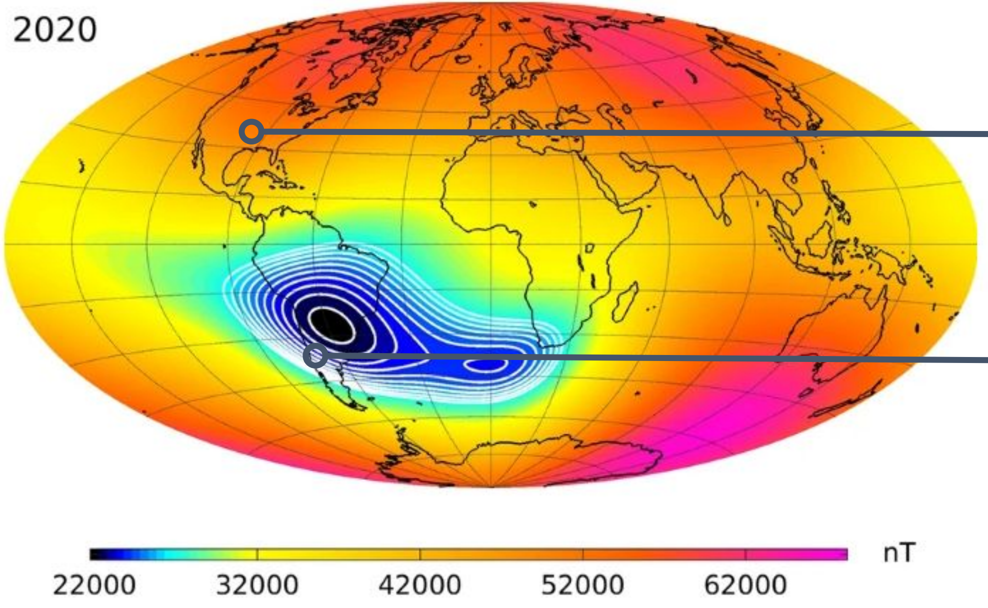
“On top of a global rescaling of energies, a **non-linearity is needed** to bring spectra in agreement in the **range of common declinations**

…

The **sources** of the non-linearity **have not been identified**, yet.”

Ideas: technology, mistakes, or physics?

The strength of Earth's magnetic field



<u>If physics:</u>

Telescope Array:
$|\vec{B}| \sim 55\ \mu T$

Pierre Auger Observatory:
$|\vec{B}| \sim 25\ \mu T$

Factor ~2 difference in the strength of the geomagnetic field

How can the geomagnetic field affect UHECR?

The preshower effect: a strong dependence of extensive air shower development on the geomagnetic field component transverse to the primary trajectory (**$B_\perp$**), and on **E_γ**.

From: **"Search for ultra-high energy photons through preshower effect with gamma-ray telescopes: Study of CTA-North efficiency",** K. A. Cheminant, et al. (CREDO Collab.), Astroparticle Physics, 123, 102489, December 2020.
[DOI: 10.1016/j.astropartphys.2020.102489].

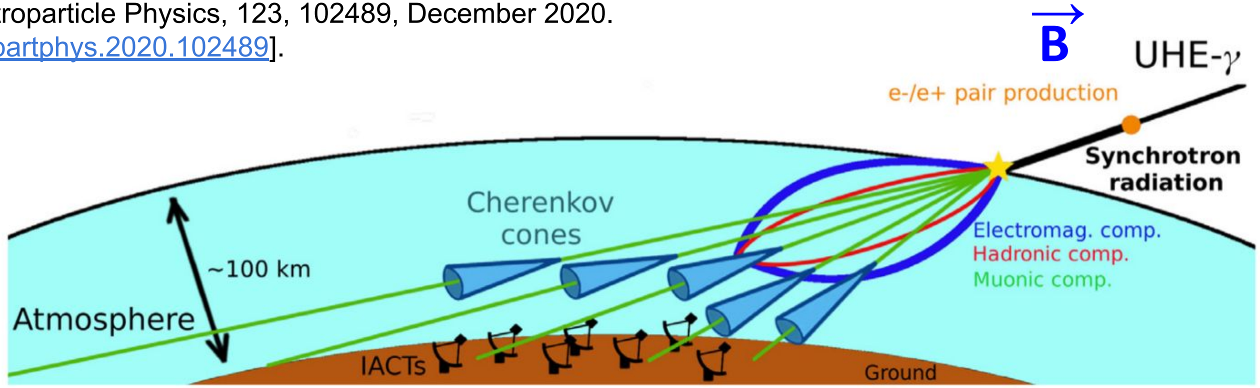
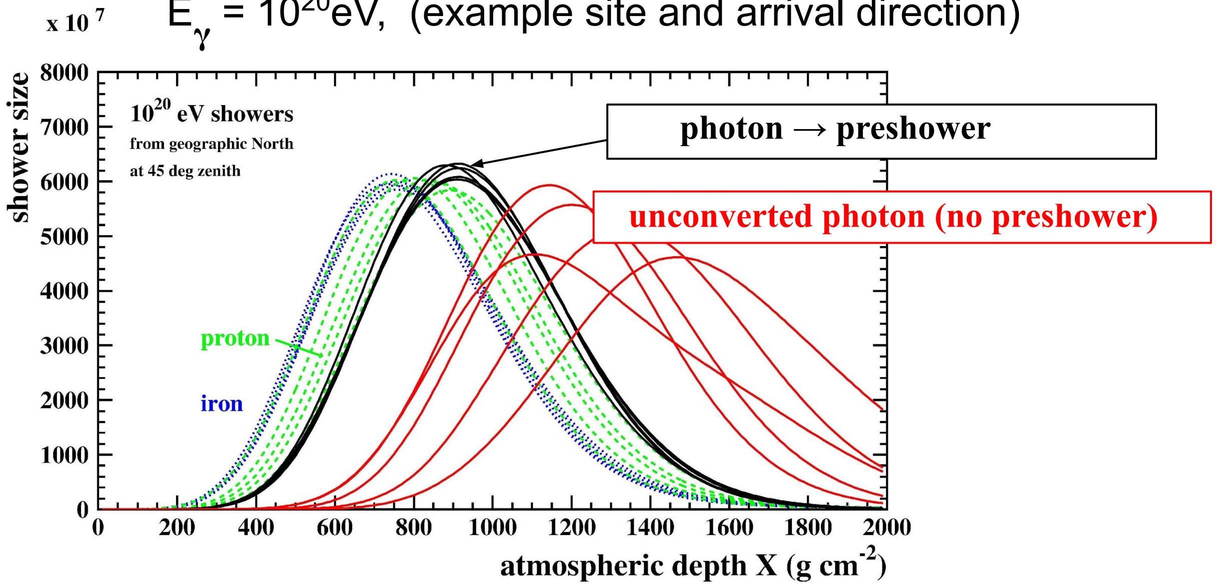


Fig. 1. A ultra-high energy photon interacting with the transverse component of the geomagnetic field produces an e^+/e^- pair ~ 1000 km above sea level which emits bremsstrahlung photons. As such process can repeat itself for some of these photons, a collection of particles (mainly photons and a few e^+ and e^-) reaches the top of the atmosphere. Consequently, atmospheric air showers are produced and in the case of nearly horizontal showers, only the muonic component reaches the Imaging Atmospheric Cherenkov Telescopess (IACTs) on the ground, which detect the Cherenkov emission of this component.

Preshowers and air shower development

$E_\gamma = 10^{20}$eV, (example site and arrival direction)



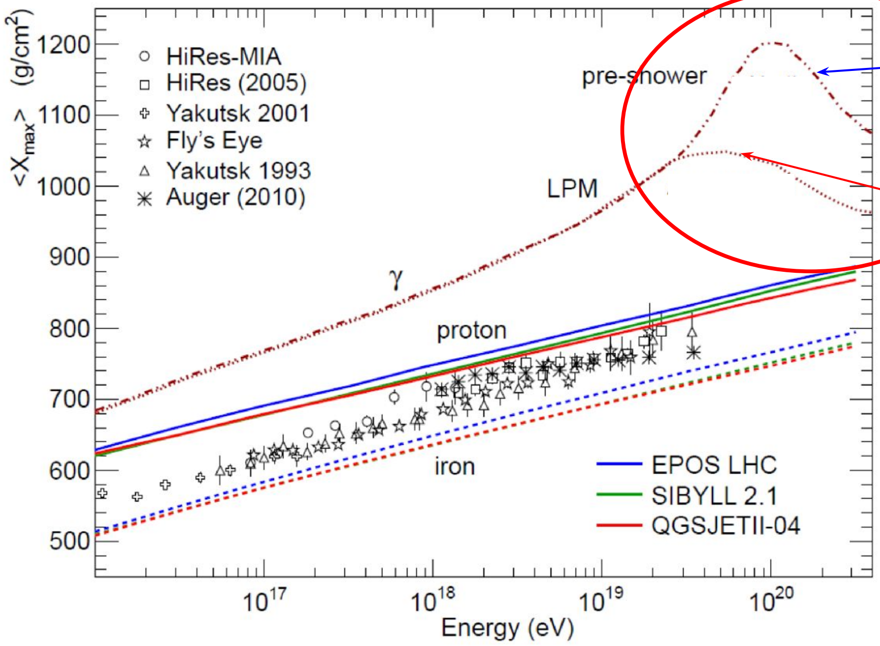
LPM (in top layers of atmosphere is important for $E_\gamma > 10^{19}$ eV):

→ **deep** X_{max}, **large** fluctuations of X_{max}

PRESHOWER (primary E_γ split into preshower particles):

→ **shallow** X_{max}, **small** fluctuations of X_{max}

UHE photon-induced air showers: Xmax$_{max}$ vs. E_{γ}



M. Settimo for the Pierre Auger Collaboration, Proceedings of Photon 2013 Conference

weak $|\vec{B}|$

preshower at higher E_{γ},
e.g. at the Pierre Auger Observatory site

strong $|\vec{B}|$

preshower at lower E_{γ},
e.g. at the Telescope Array site

Preshower effect:

→ non-linear, energy & site dependent impact on air shower development!

But… no UHE photons seen

From: Rautenberg, J.; for the Pierre Auger Collaboration. Limits on ultra-high energy photons with the Pierre Auger Observatory, *PoS* **2020**, *ICRC2019*, 398.

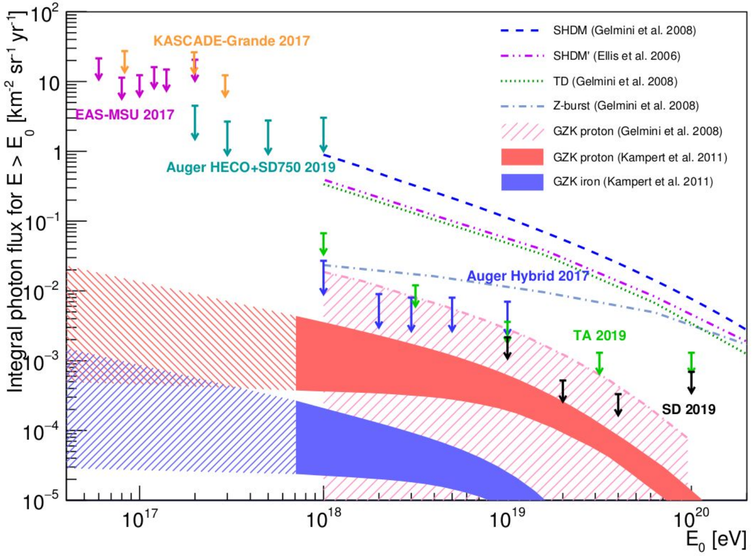
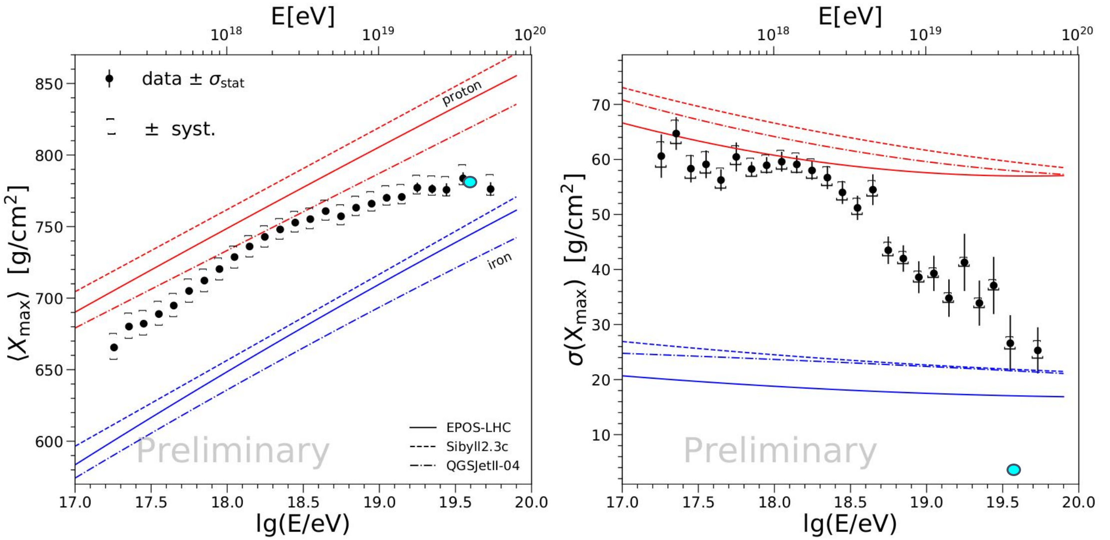


Figure 7: Photon flux limits at 95% C.L. for the different analysis of the Pierre Auger Observatory, compared to model predictions [14, 15, 16] and other experimental limits at 95% C.L. [17], as well as at 90% C.L. [18, 19].

But... what if the physics extrapolations by many orders of magnitude are slightly wrong (1)?

From: Yushkov, A.; for the Pierre Auger Collaboration. Mass composition of cosmic rays with energies above $10^{17.2}$ eV from the hybrid data of the Pierre Auger Observatory, *PoS 2020, ICRC2019, 482*.



[added by PH]:
example primary preshower
<Xmax>=783±3 g/cm²
Log(E/eV)=19.6
N particles = 1500
forced initiation at 17000 km a.s.l.
[typical initiation: 100-200 km a.s.l.]

Figure 1: Measurements of $\langle X_{max} \rangle$ (left) and $\sigma(X_{max})$ (right) at the Pierre Auger Observatory compared to the predictions for proton and iron nuclei of the hadronic models EPOS-LHC, Sibyll 2.3c and QGSJetII-04.

Physics at the highest energies uncertain -> more uncertainty in X_{max} likely?

But... what if the physics extrapolations by many orders of magnitude are slightly wrong (2)?

Muon “puzzles” in the news!

- muon excess in air showers; see popular article
- muon deficit in B meson decays (R_K flavour anomaly); see popular article
- muon g-2 anomaly (?); popular article

-> more uncertainty in hadronic interactions likely!

-> do not give up UHE photons as a potential explanation of the observed tension in the UHECR energy spectrum?

-> how can CREDO help? **Alternative check for UHE photon flux** (no dependence on hadronic interactions)

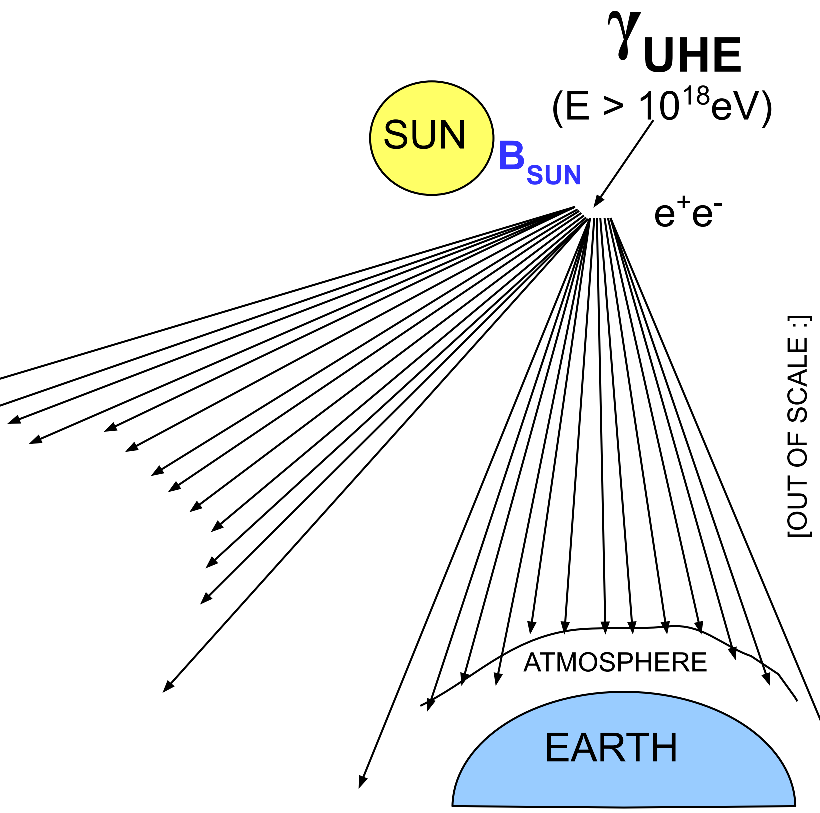
Prepared for submission to JCAP

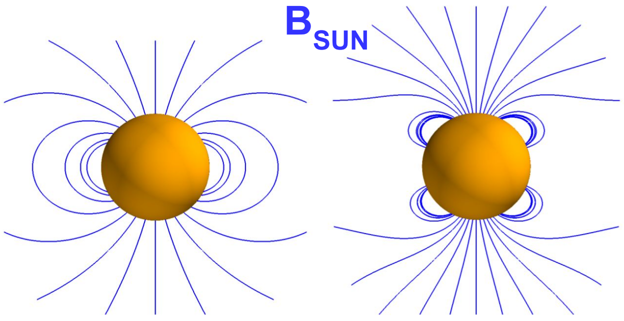
Cosmic ray ensembles as signatures of ultra-high energy photons interacting with the solar magnetic field

The CREDO Collaboration

N. Dhital,[a] P. Homola,[a] D. Gora,[a] H. Wilczyński,[a] K. Almeida Cheminant,[a] D. Alvarez-Castillo,[a,d] G. Bhatta,[b] T. Bretz,[c] A. Ćwikła,[e] A.R. Duffy,[f] B. Hnatyk,[g] P. Jagoda,[h,a] M. Kasztelan,[i] K. Kopański,[a] P. Kovacs,[j] M. Krupinski,[a] V. Nazari,[d] M. Niedźwiecki,[k] D. Ostrogórski,[h] K.Smelcerz,[k] K. Smolek,[l] J. Stasielak,[a] O. Sushchov,[a] T. Wibig,[m] K. Wozniak,[a] J. Zamora-Saa[n] and Z. Zimborás[j]

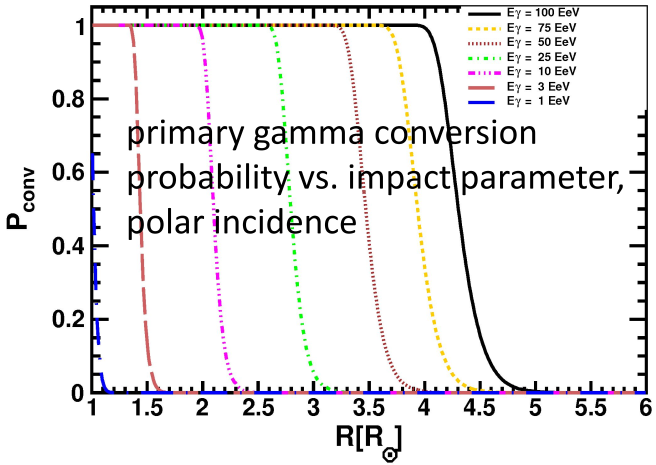
>=EeV photons nearby the Sun→ big CRE





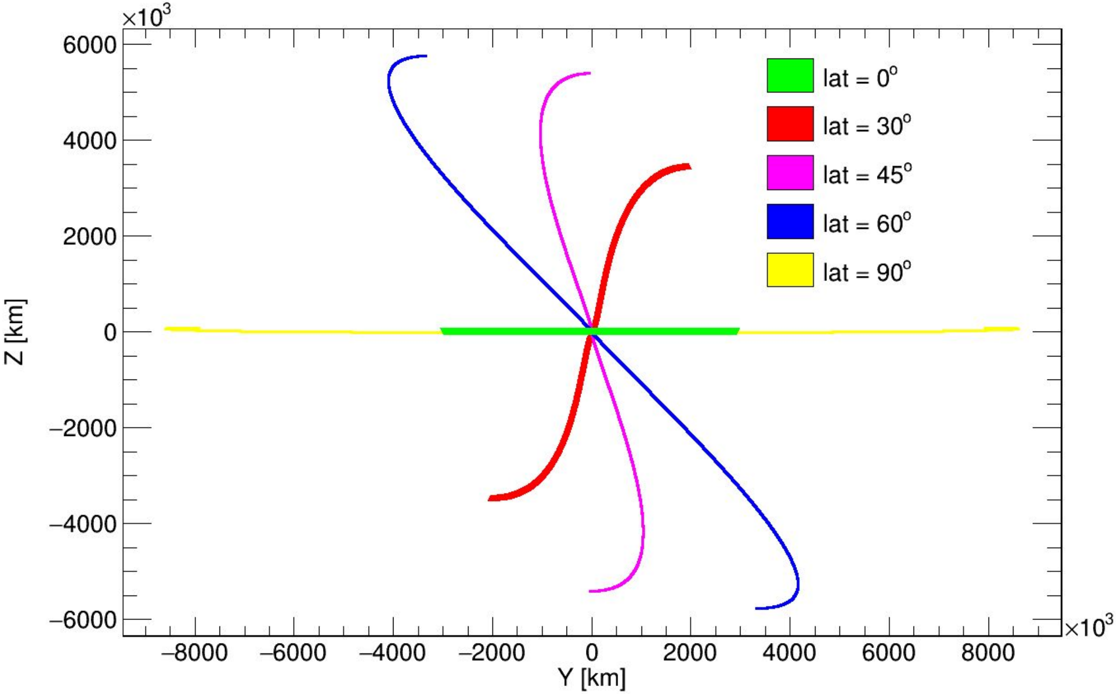
(a) Dipole field (b) DQCS field

the Sun-preshower effect starts at 1 EeV

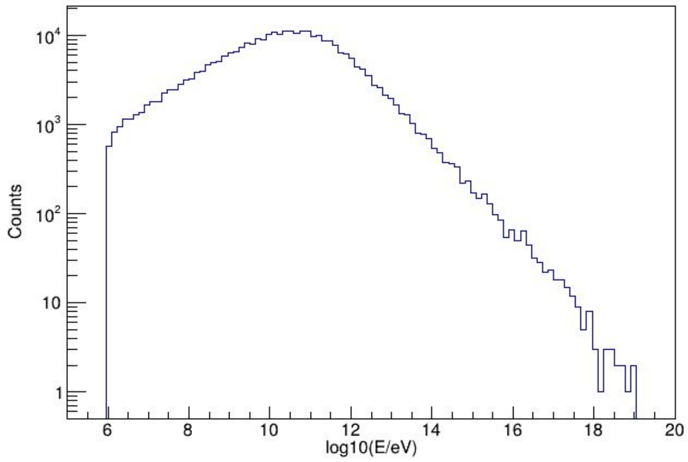


Sun-CRE: footprints up to 1AU, all photon energies

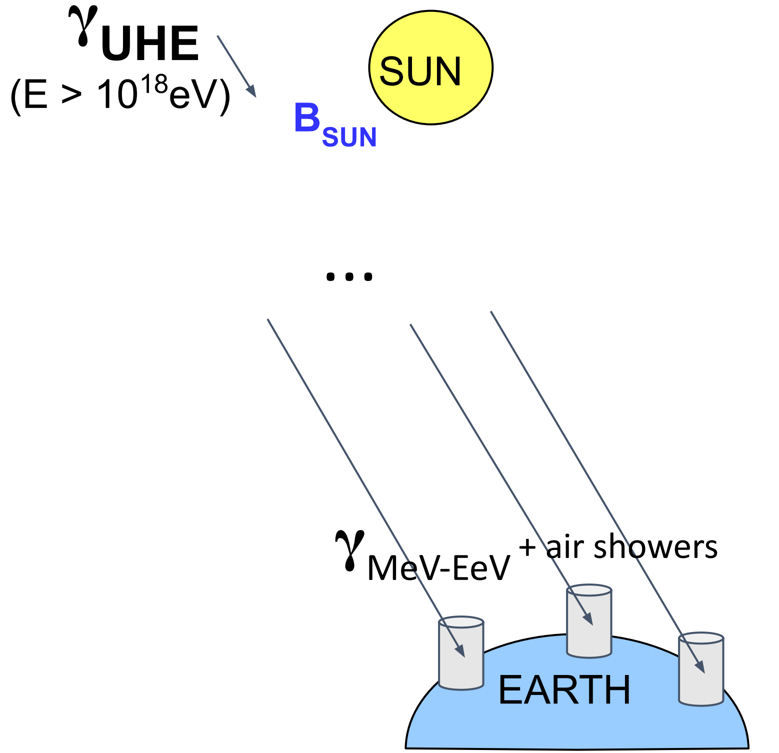
footprints very thin, up to 1 AU long, non-trivial shapes, dependent on incidence angle and impact parameter

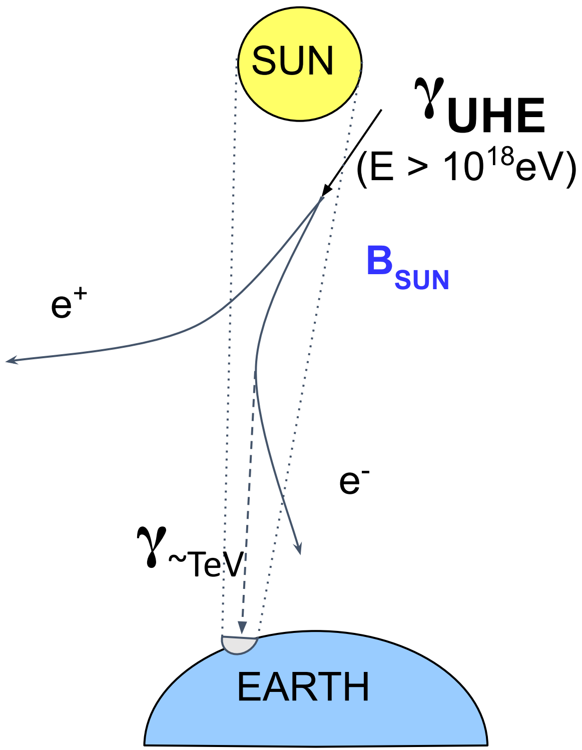


entire photon spectrum engaged



Sun-CRE: observe or constrain UHE photons



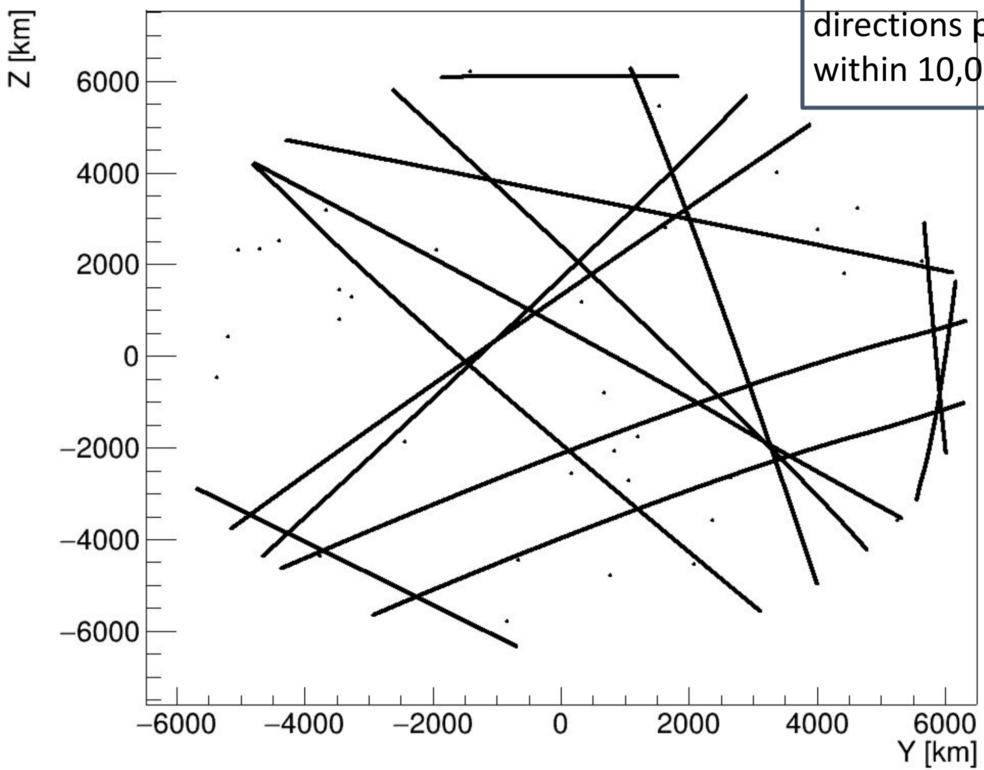


- displacement > ~100 km
- similar arrival directions
- consistent timing

- γ_{TeV} from the direction of the Sun
- characteristic E spectrum excess towards TeV

Sun-CRE random footprints: new astrophysical constraints

Sun CRE simulations: $E_\gamma=10^{20}$ eV, 100 random arrival directions passing near the Sun, CRE footprint cores within 10,000 km from the Earth center



From: BSc project of B. Poncyliusz (UW) with PH and Tomasz Bulik (UW) as supervisors, 2021

(!) Comparable with the existing observations of the Sun in gamma rays, e.g. A. Albert et al. (HAWC Collaboration), "First HAWC Observations of the Sun Constrain Steady TeV Gamma-Ray Emission" Phys. Rev. D 98, 123011 (2018); DOI: [10.1103/PhysRevD.98.123011](https://doi.org/10.1103/PhysRevD.98.123011) [credit: S. Casanova]

b. Spacetime structure: probing with CRE

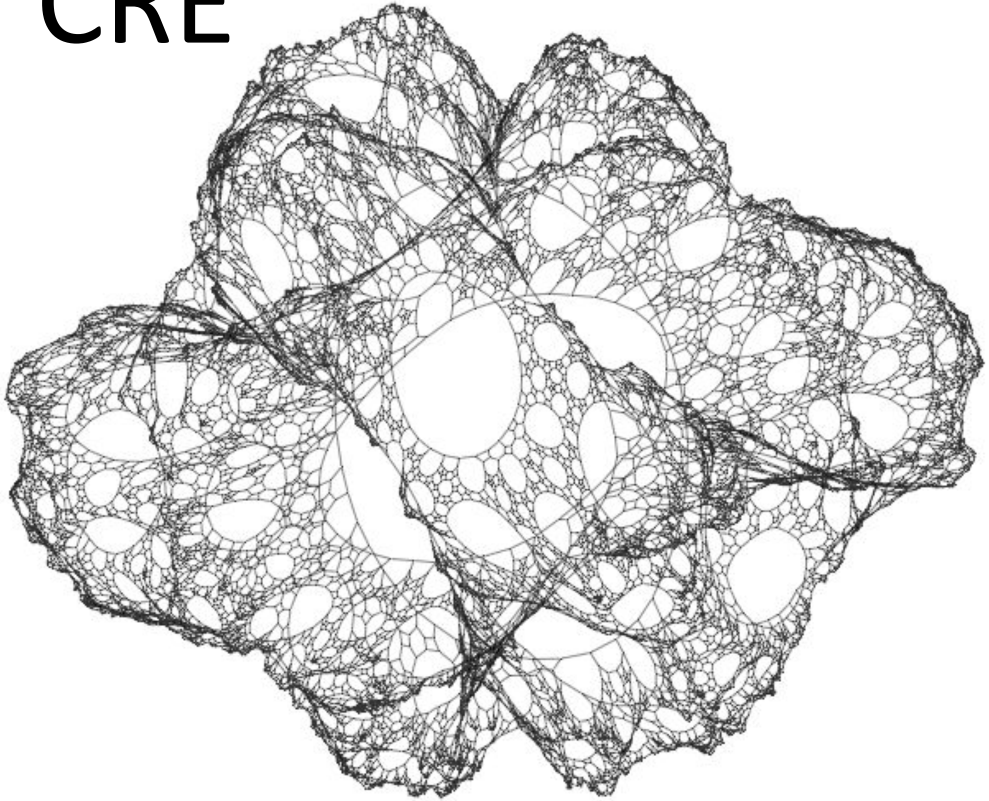


image source: https://writings.stephenwolfram.com/2015/12/what-is-spacetime-really/

Cosmic Ray Ensembles as spacetime probes

Low frequency (low energy)
→ low sensitivity to spacetime structure
(“big wheels”)

CRE

Cosmic Ray Ensembles composed of photons of significantly different energies: new potential of probing the spacetime structure

High frequency (high energy)
→ high sensitivity to spacetime structure
(“small wheels”)

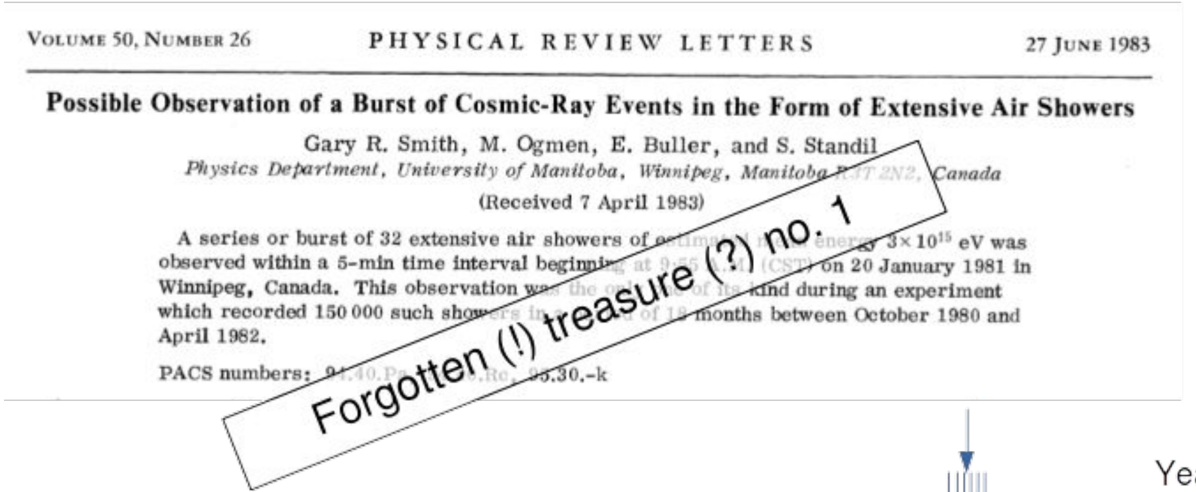
Spacetime structure and gamma astronomy

→ **maximum photon energies < ~10^{12} eV**
→ **testable scale of the spacetime „grain" ("foaminess") < 10^{-18} m** (see e.g. E. S. Perlman *et al* 2015 *ApJ* 805 10)

CREDO
THE QUEST FOR THE UNEXPECTED

→ **maximum photon energies in CRE (ensembles) < 10^{20} eV +**
→ **Potential sensitivity to the spacetime „grain" < 10^{-26} m**

$N_{ATM} > 1$ motivated by data! (1)



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

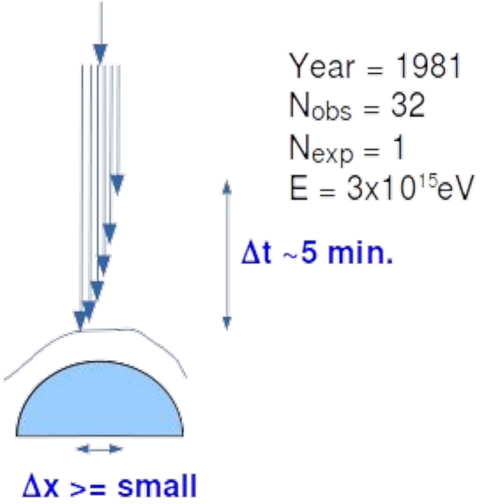
(Received 7 April 1983)

A series or burst of 32 extensive air showers of estimated primary 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

PH: Correlated cosmic rays?

$N_{ATM} > 1$?



-> "Pay attention to data"!

$N_{ATM} > 1$ motivated by data! (2)

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)

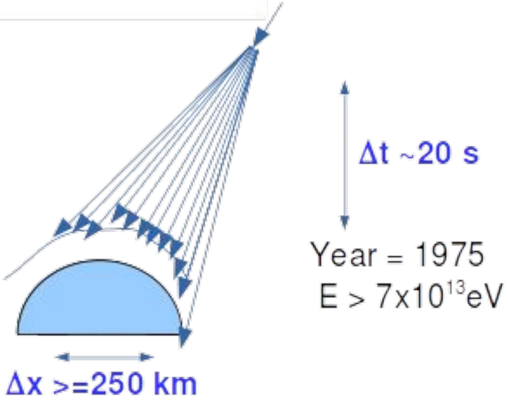
Forgotten (!) treasure (?) no. 2

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: Correlated cosmic rays?

$N_{ATM} > 1$?



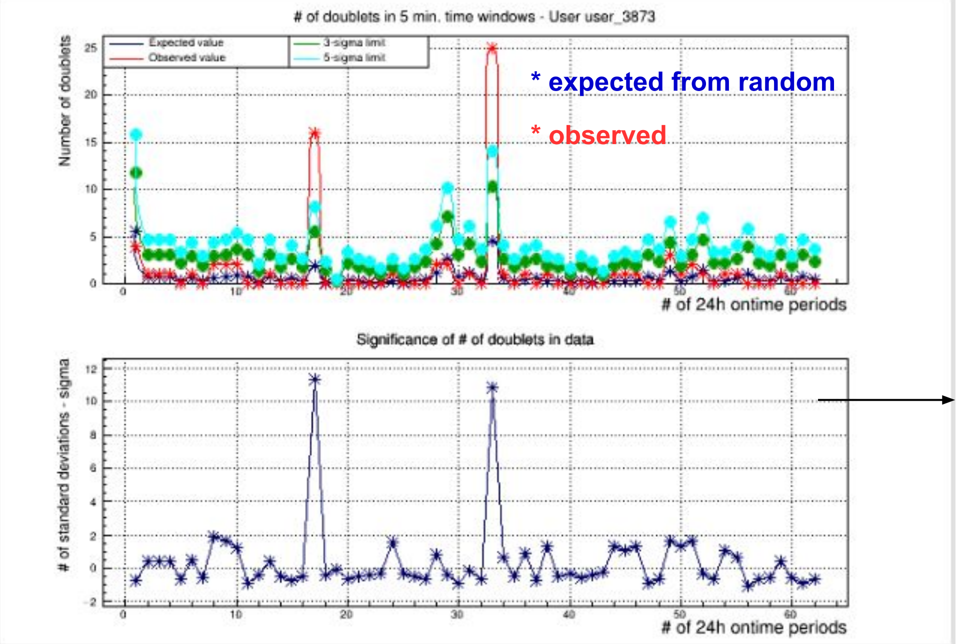
-> **"Pay attention to data"!**

Quantum Gravity Previewer: online experiment!

Cumulative number of hit pairs („doublets") within 5 min, in a single smartphone

by Kevin Almeida Cheminant, for the CREDO Collaboration

Number of doublets (two cosmic ray detections in an interval of 5 minutes) found in data (red) in every 24 hour period versus the expected value obtained from background simulations(dark blue). Number of doublets needed to obtain a 3 or 5 sigma effect are also given (green and light blue, respectively).



Significance of number of doublets (two cosmic ray detections in an interval of 5 minutes) found in data in every 24 hour period.

10σ

(significance)

See also the IFJ PAN / CREDO public release in EurekAlert! [HERE]

The search for air shower clusters: Adelaide

R. Clay, J. Singh, for the CREDO Collaboration
(a contribution accepted for the 37th International Cosmic Ray Conference 2021 https://indico.desy.de/event/27991/contributions/102215/)

A search for bursts at 0.1 PeV with a small air shower array

The Cosmic Ray Extremely Distributed Observatory (CREDO) pursues a global research strategy dedicated to the search for correlated cosmic rays, so-called Cosmic Ray Ensembles (CRE). Its general approach to CRE detection does not involve any a priori considerations and the search strategy encompasses both spatial and temporal correlations, on different scales. Here we search for time clustering of the cosmic ray events collected with a small sea-level air shower array at the University of Adelaide. The array consists of seven one square metre scintillators enclosing an area of 18.7 m x 9.7 m It has a threshold energy ~0.1 PeV, and records cosmic ray showers at a rate of ~6 mHz. We have examined event times over a period of almost two years (~294k events) to determine the event time spacing distributions between individual events and the distributions of time periods which contained specific numbers of multiple events. We find that the overall time distributions are as expected for random events. The distribution which was chosen a priori for particular study was for time periods covering four events. Overall, this fits closely with expectation but has two outliers of short 'burst' periods. **One of these outliers contains eight events within 48 seconds.**

The physical characteristics of the array will be discussed together with the analysis procedure, including a fit between the observed time distributions and expectation based on randomly arriving events.

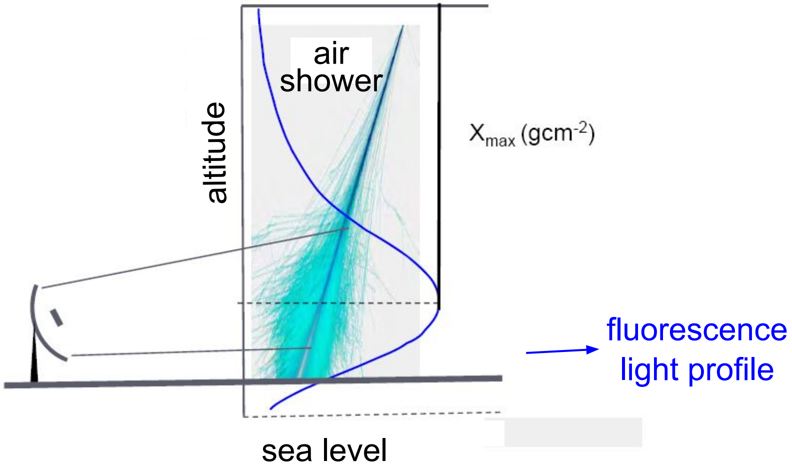
Summary and Outlook

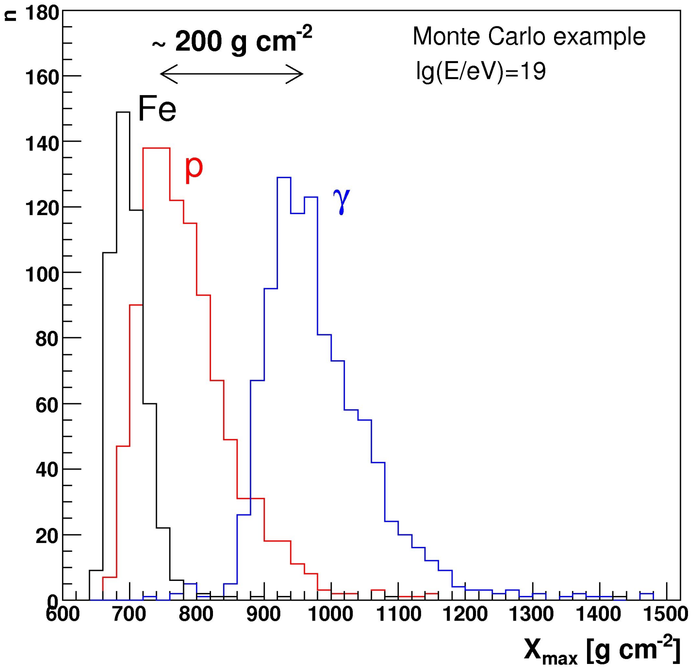
CREDO:

- in- and outward multi-messenger open observatory
- first exciting results round the corner

BACKUP

UHECR identification: X_{max}





X_{max}: atmospheric depth of shower maximum development

→ $\langle X_{max}(Fe)\rangle < \langle X_{max}(p)\rangle < \langle X_{max}(\gamma)\rangle$

→ $RMS[X_{max}(Fe)] < RMS[X_{max}(p)]$

Landau-Pomeranchuk-Migdal (LPM) effect I

LPM effect:
Pair prodution formation length ⩾ mean free path → destructive interference from several scattering centers: $\gamma \not\rightarrow e^+e^-$

Bremsstrahlung supressed as well. Confirmed by experiments.

Formation lenght: the lenght of the photon trajectory over which pair production happens
Pair production formation length icreases with photon energy $\mathbf{E_\gamma}$
Photon mean free path decreases with medium density ϱ

→ the **Bethe-Heitler cross-section** for pair production by photons, σ_{BH} (in air $\sigma_{BH} \approx 0.51$ b), can be **reduced** when E_γ and/or medium density ϱ **high**

$\kappa = E_\gamma E_{LPM}/[E_e(E_\gamma - E_e)]$, $E_{LPM} = m_e^2 c^3 \alpha X_0/(4\pi\hbar\varrho) \approx$ (7.7 TeV/cm) $\times X_0/\varrho$, $X_0 \sim 37$ g cm^{-2}
E_γ - photon energy, E_e - electron energy, ϱ - medium density, X_0 - radiation length

Approximation for $\kappa<1$: $\boldsymbol{\sigma_{LPM} = \sigma_{BH}\,\kappa^{1/2} \propto (\varrho\, E_\gamma)^{-1/2}}$
→ σ_{BH}/σ_{LPM} largest for a symmetric energy partition in the electron pair, $E_e \approx E_\gamma/2$

Landau-Pomeranchuk-Migdal (LPM) effect II

The LPM effect delays the development of an air shower initiated by a single UHE photon!

→ deep X_{max}

For atmospheric depths $X_2 > X_1$: $\sigma_{LPM}(X_2) < \sigma_{LPM}(X_1)$.

The deeper photon goes the smaller pair production probability!

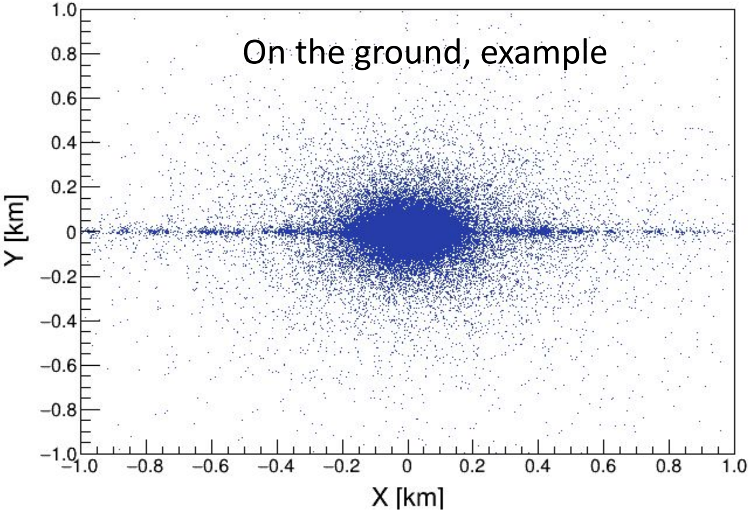
→ very large X_{max} fluctuations

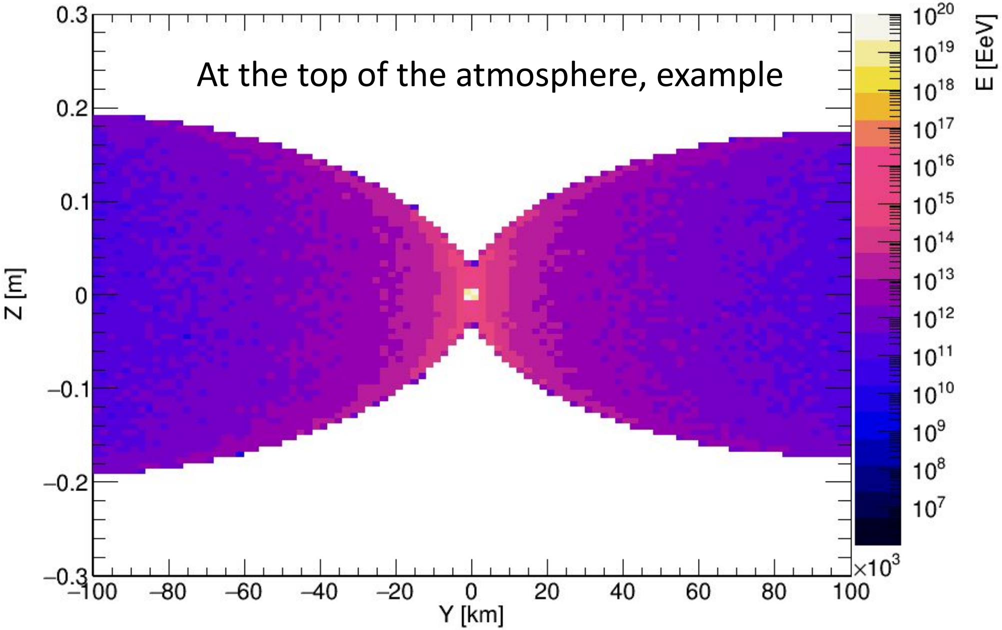
Both deep X_{max} and very large X_{max} fluctuations are **good photon signatures!**

The LPM effect is accounted for in CORSIKA.

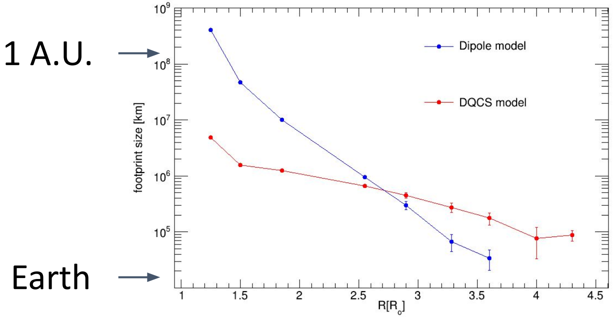
More:
PDG review and the references therein:
K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014)

The Sun-CRE footprints

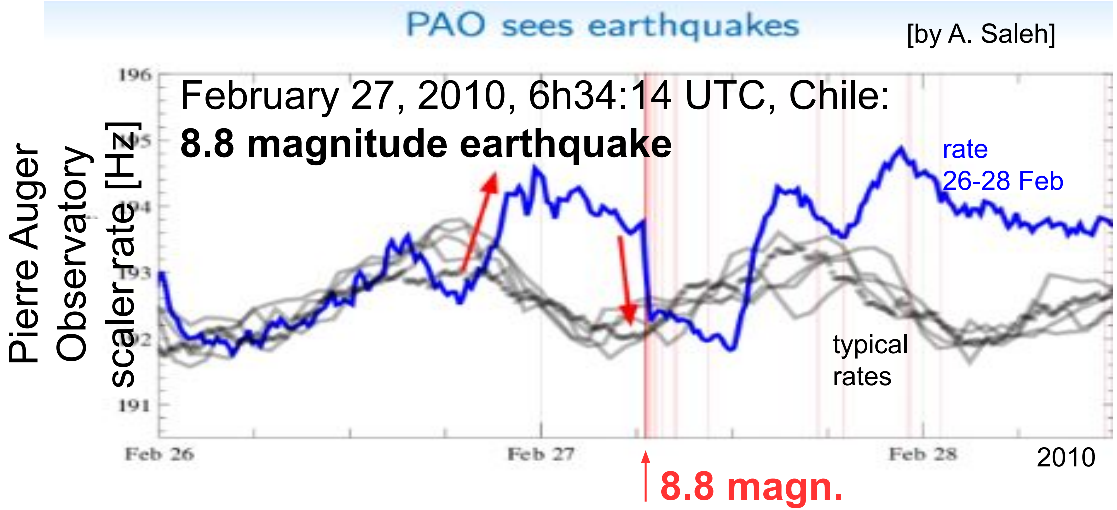




Sizes vs. impact parameter, on top of the atmosphere



The seismic precursor in cosmic rays: inspiration from the Pierre Auger Observatory



- Increase of CR before the earthquake
- Strong drop during the earthquake

→ **CREDO-earthquakes task**

Inhabitants of territories threatened by earthquakes [= potential CREDO public engagement target]:

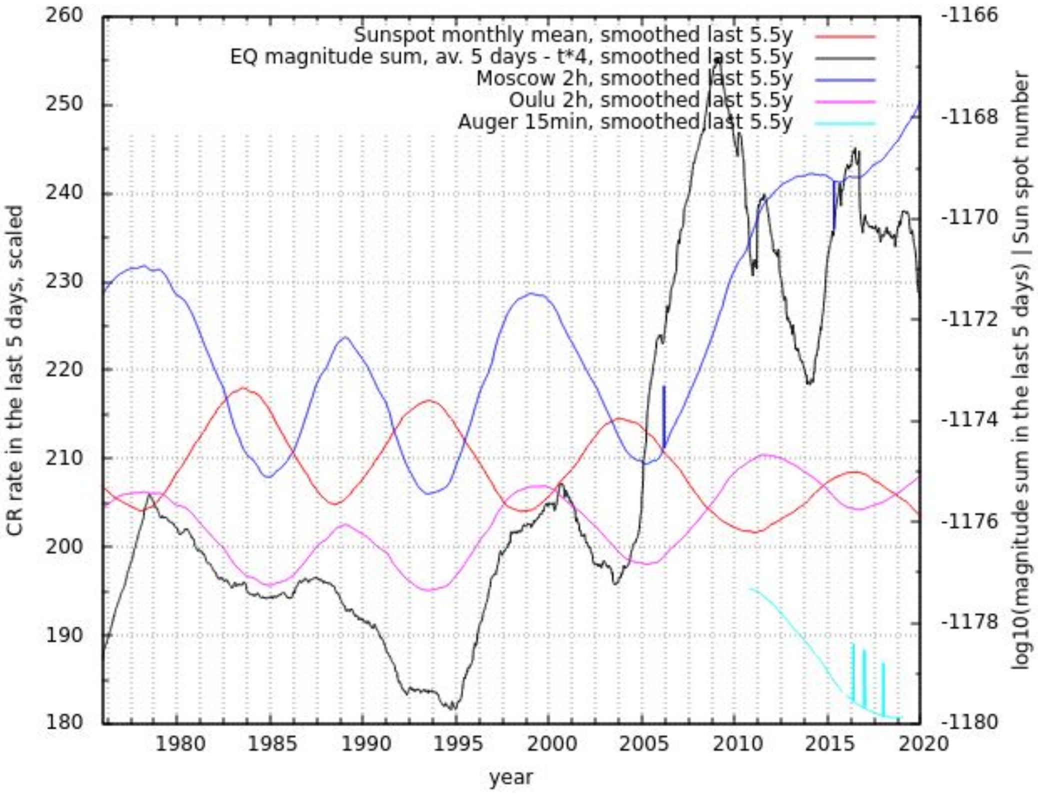
2,7 billion people

Science as a service to the human community?

Even the smallest chance to save lives

= **a must check!**

long term study: Sun responsible for (some) EQs?



Instead of Summary

ERC-2020-SyG (ERC Synergy Grant)
Acronym: **CREsearch**
Applicants: Piotr HOMOLA (corresponding PI); Tadeusz WIBIG; Mikhail MEDVEDEV
Title: **The search for New Physics phenomena manifesting in properties of Cosmic Ray Ensembles**
Amount Requested: 14 MEUR for 6 years
Final Panel Score: B (ranking range 66%-75%)

a sample review:

Ground-breaking nature and potential impact of the research project
The theoretical assumption is that there are families of cosmic particles that penetrate the atmosphere and generate cascades of showers, which the authors call cosmic-ray cascades. The idea is to observe them and to use them to understand their origin. Even the origin of single cosmic showers is not really understood, and this phenomenon sounds speculative, daring, exciting and promising. For me, **this is one of the strongest proposals I have read**. **If successful, the impact will be huge, and the consequences profound**. Being based on theoretical estimates there is a good chance that things turn out differently than anticipated, but I would not consider that a strong weakness, rather a mild inconvenience.

More about CREDO

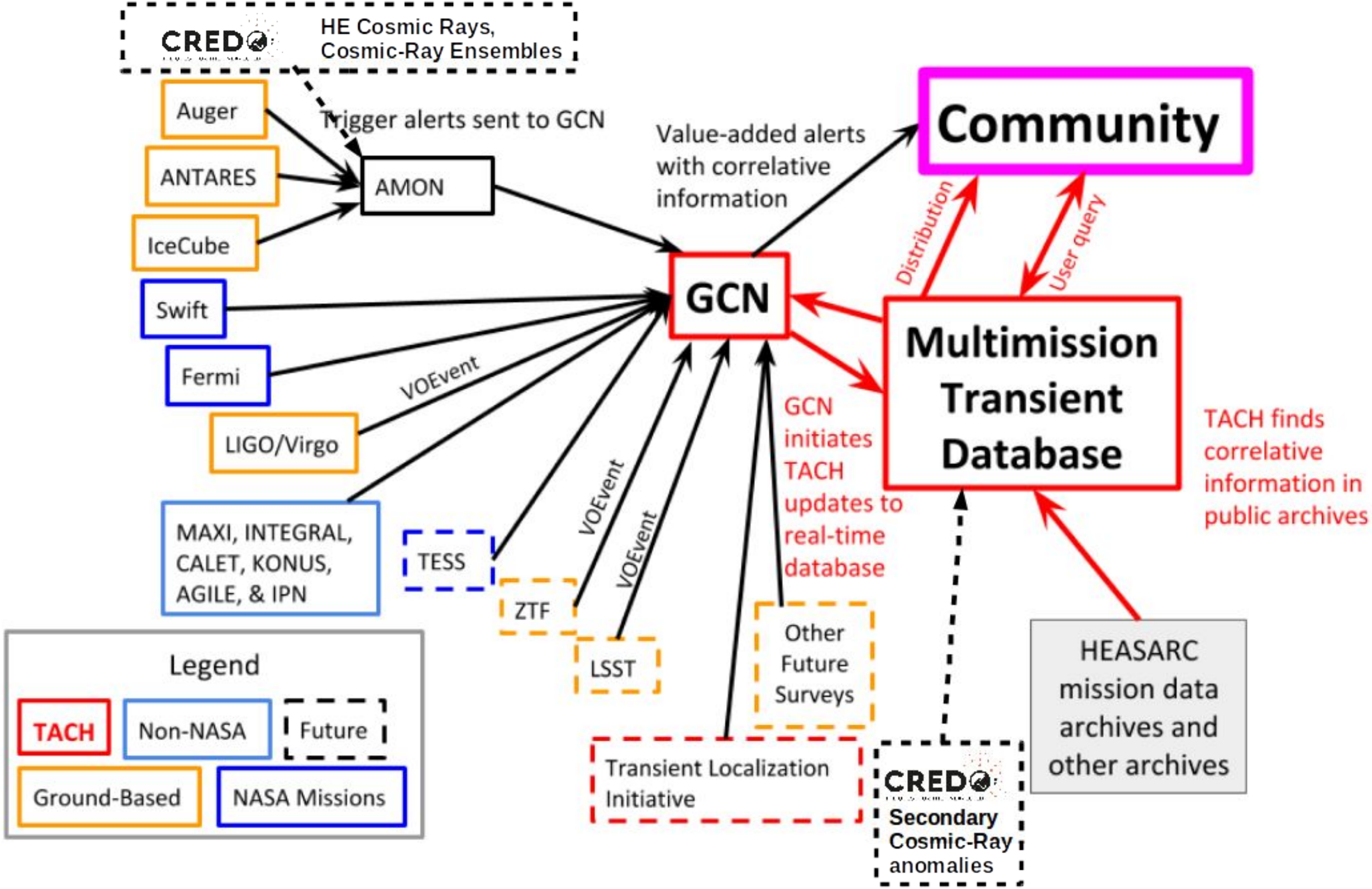
https://credo.science

Topic examples (PH): https://credo.science/practices/

Personal contact:

Piotr Homola / the CREDO Project Coordinator /
Piotr.Homola@credo.science / +48 502 294 333

the CREDO potential/ambition



The CREDO potential contributions to the Time Domain Astronomy Coordination Hub (TACH), a new NASA initiative (the CREDO logo has been positioned in two distinct places on top of the slide by Judith Racusin, NASA, from her invited talk at the New Era of Multi-Messenger Astrophysics Conference, Groningen, March 2019).

Cosmic-Ray Ensembles (CRE): 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

scenarios!

Cosmic-Ray Ensembles (CRE): shortcut road map

quest (fishing) for the unexpected

Theoretical review (ongoing) ✓

↓

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

↓

Air shower simulations (ongoing) ✓

↓

Detector response (ongoing) ✓

↓

observation / upper limits ← unique signature **fishing (ongoing)** ✓

CRE and Experimental Quantum Gravity

T. Jacobson, S. Liberati, and D. Mattingly, Annals Phys. 321 (2006) 150

Lorentz violation at high energy: concepts, phenomena and astrophysical constraints

Ted Jacobson [a], Stefano Liberati [b], David Mattingly [c]

[a] *Department of Physics, University of Maryland, USA*

[b] *International School for Advanced Studies and INFN, Trieste, Italy*

[c] *Department of Physics, University of California at Davis, USA*

extensive review). A partial list of such "windows on quantum gravity" is

- sidereal variation of LV couplings as the lab moves with respect to a preferred frame or directions
- cosmological variation of couplings
- cumulative effects: long baseline dispersion and vacuum birefringence (e.g. of signals from gamma ray bursts, active galactic nuclei, pulsars, galaxies)
- new threshold reactions (e.g. photon decay, vacuum Čerenkov effect)
- shifted existing threshold reactions (e.g. photon annihilation from blazars, GZK reaction)
- LV induced decays not characterized by a threshold (e.g. decay of a particle from one helicity to the other or photon splitting)
- maximum velocity (e.g. synchrotron peak from supernova remnants)
- dynamical effects of LV background fields (e.g. gravitational coupling and additional wave modes)

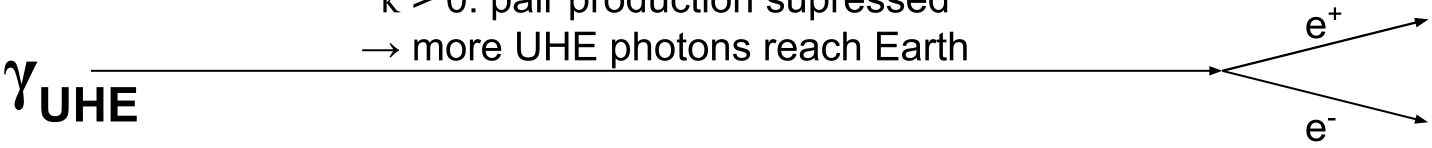
CRE and Lorentz Invariance Violation

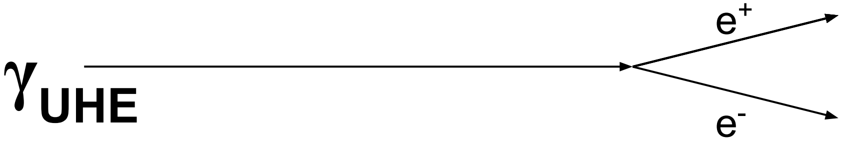
Modified dispersion relation of a photon:

$$E_\gamma(\vec{k}) = \sqrt{\frac{(1-\kappa)}{(1+\kappa)}}|\vec{k}|$$

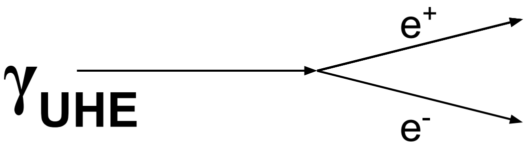
limits from gamma-ray astronomy,
98% C.L. (Klinkhamer & Schreck, 2008):
$6 \times 10^{-20} > \kappa > -9 \times 10^{-16}$

κ > 0: pair production supressed
→ more UHE photons reach Earth





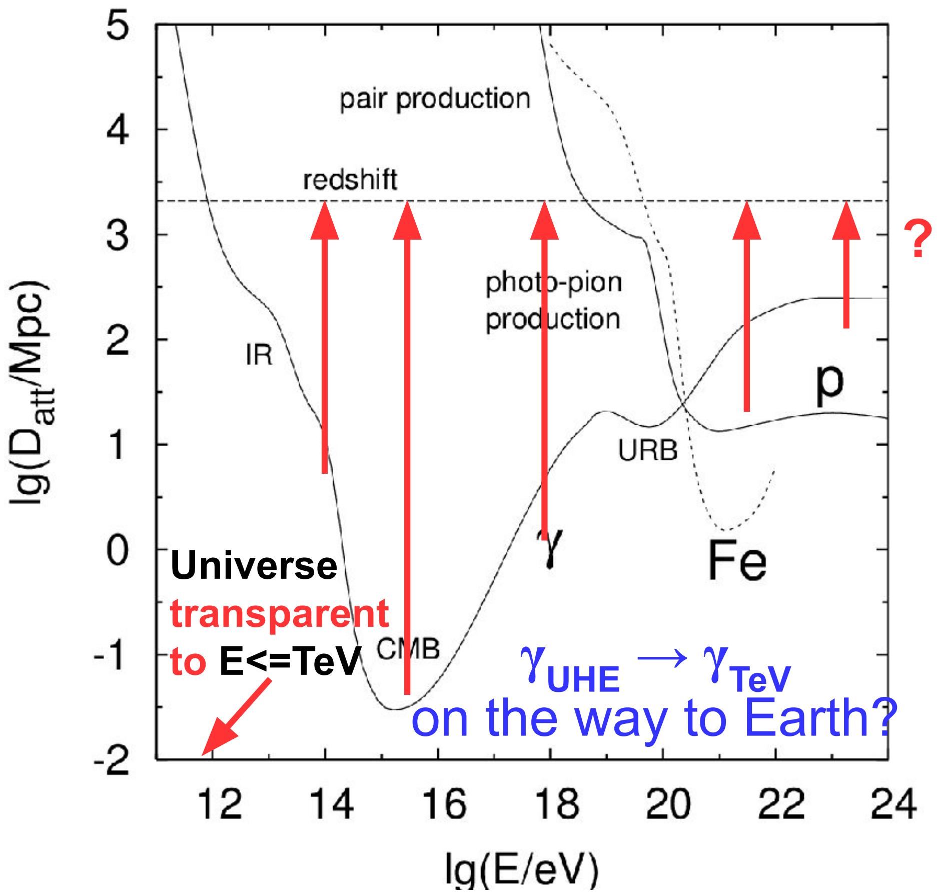
κ = 0: „normal” pair production



κ < 0: pair production enhanced
(photon lifetime ~ 1 sec.!)
→ no UHE photons reach Earth

→ critical importance for the UHE photon search!
Observation of **photon cascades** would point to κ < 0!

γ_{HE} travelling through the Universe: photon decay?



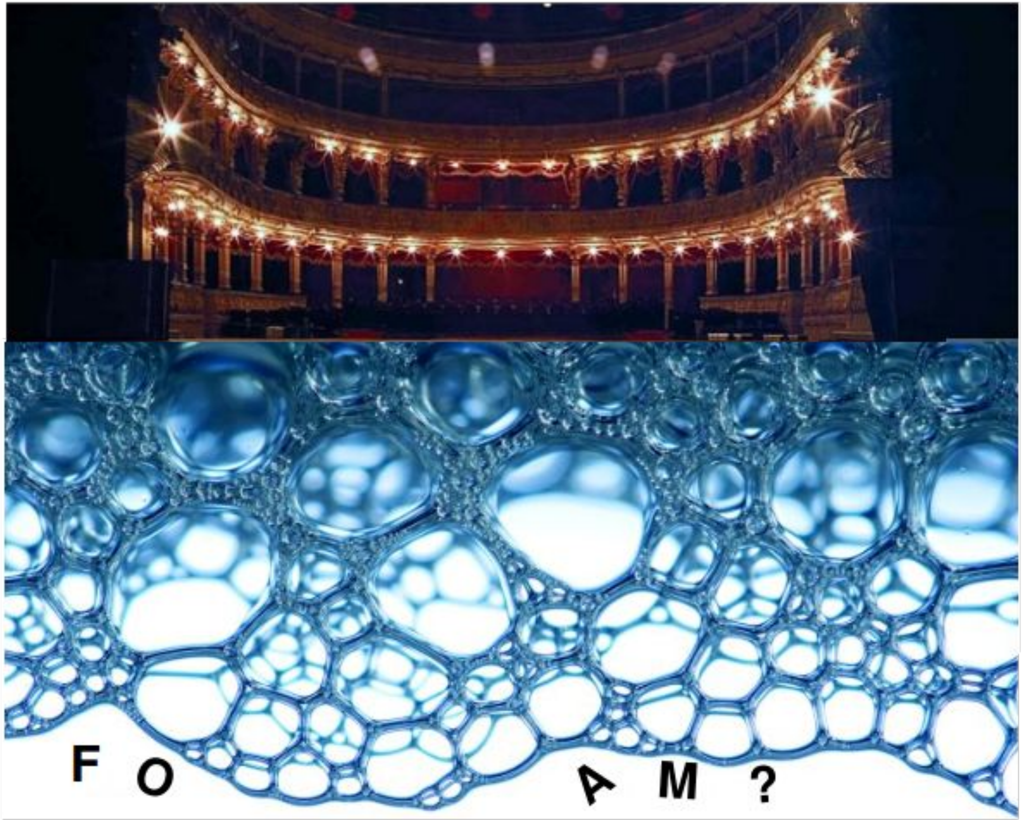
Foundation of foundations:
The spacetime

quest (fishing) for the unexpected

Smooth?

Foundation of foundations:
The spacetime

quest (fishing) for the unexpected



Big Wheel vs. Small Car (zespoły cząstek) jako testery sceny

quest (fishing) for the unexpected

Zespół promieni kosmicznych
o różnych energiach (CRE),
prędkość światła

START
(KOSMOS)

META
(ZIEMIA)

Czasoprzestrzeń: scena na której dzieje się Wszechświat?

Big Wheel vs. Small Car (zespoły cząstek) jako testery sceny

quest (fishing) for the unexpected

Zespół promieni kosmicznych
o różnych energiach (CRE),
prędkość światła

Czasoprzestrzeń: scena na której dzieje się Wszechświat?

Big Wheel vs. Small Car (zespoły cząstek) jako testery sceny

quest (fishing) for **the unexpected**

Zespół promieni kosmicznych
o różnych energiach (CRE),
prędkość światła

Czasoprzestrzeń: scena na której dzieje się Wszechświat?

Big Wheel vs. Small Car (zespoły cząstek) jako testery sceny

quest (fishing) for **the unexpected**

Zespół promieni kosmicznych
o różnych energiach (CRE),
prędkość światła

Czasoprzestrzeń: scena na której dzieje się Wszechświat?

Big Wheel vs. Small Car (zespoły cząstek) jako testery sceny

quest (fishing) for **the unexpected**

Niska częstotliwość - niska energia - duża długość fali (duże „koła"),
→ niska czułość na strukturę czasoprzestrzeni

CRE

Zespół promieni kosmicznych o zróżnicowanych energiach (CRE): NOWY pomysł na testowanie struktury czasoprzestrzeni

Wysoka częstotliwość - wysoka energia - krótka długość fali (małe „koła"),
→ wysoka czułość na strukturę czasoprzestrzeni

4 October 2018: CREDO's first light!

quest (fishing) for the unexpected

https://www.eurekalert.org/pub_releases/2018-10/thni-cfl100418.php

EurekAlert! The Global Source for Science News | AAAS

SEARCH ARCHIVE

ADVANCED SEARCH

HOME NEWS MULTIMEDIA MEETINGS PORTALS ABOUT LOGIN REGISTER

PUBLIC RELEASE: 4-OCT-2018

CREDO's first light: The global particle detector begins its collection of scientific data

THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

SHARE PRINT E-MAIL

Now everyone can become co-creator and co-user of the largest detector of cosmic ray particles in history - as well as a potential co-discoverer. All you need is a smartphone and the CREDO Detector application turned on overnight. Under development for over two years, the CREDO project is entering the era of its maturity. Today, at the Institute of Nuclear Physics of the Polish Academy of Sciences in Cracow, the "first light" of the

Media Contact

Dr. Piotr Homola
piotr.homola@ifj.edu.pl
48-126-628-341
http://www.ifj.edu.pl/?lang=en

More on this News Release

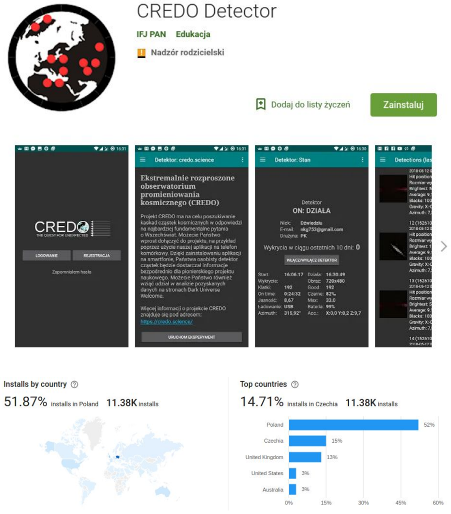
CREDO's first light: The global particle detector begins its collection of scientific data

THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

FUNDER
International Visegrad Fund (IVF)

MEETING
The Cosmic-Ray Extremely Distributed Observatory (CREDO) Week

Achievement (4.10.2018):
signal from the first automatized, mass participation scientific experiment on the CREDO infrastructure



EurekAlert! The Global Source for Science News | AAAS

HOME NEWS MULTIMEDIA MEETINGS PORTALS ABOUT

PUBLIC RELEASE: 4-OCT-2018

CREDO's first light: The global particle detector begins its collection of scientific data

THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

SHARE PRINT E-MAIL

Now everyone can become co-creator and co-user of the largest detector of cosmic ray particles in history - as well as a potential co-discoverer. All you need is a smartphone and the CREDO Detector application turned on overnight. Under development for over two years, the CREDO project is entering the era of its maturity. Today, at the Institute of Nuclear Physics of the Polish Academy of Sciences in Cracow, the "first light" of the

mobile app → data → scaling up → first results → dissemination

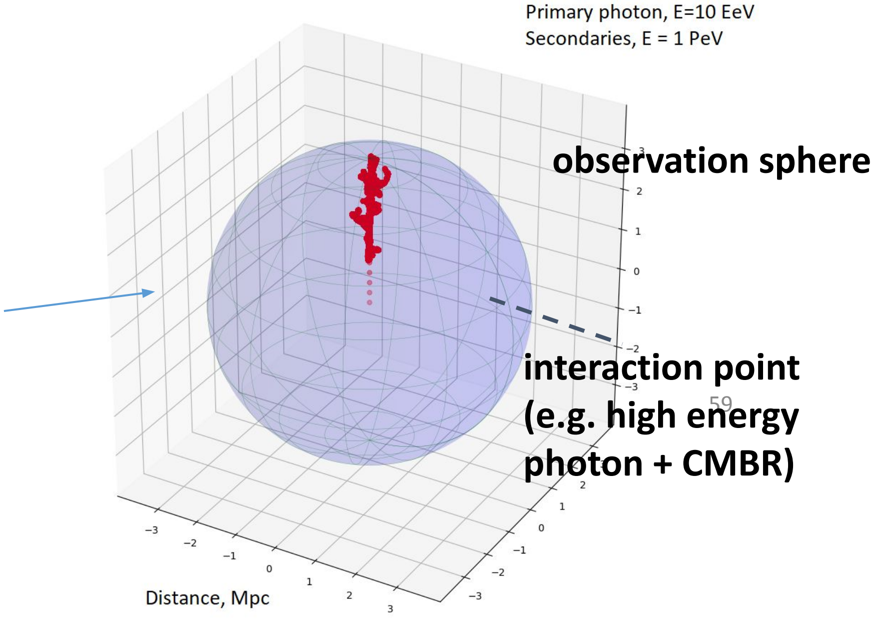
CRE exist! Simulations with CRPropa

CRPropa3 [https://github.com/CRPropa/CRPropa3,

https://arxiv.org/abs/1603.07142]

3D simulations of a photon primary propagation

1. Simplest case – { GMF (JF12) + } EGMF
2. Accounting for synchrotron radiation (computational issues)
3. Specific cases (e.g. neuron star environment)
4. Making use of [Kobzar O., Hnatyk B., Marchenko V., Sushchov O. MNRAS, Vol. 484, Issue 2, pp. 1790-1799, DOI: 10.1093/mnras/stz094].



scenarios!

credit: A. Sushchov, IFJ PAN

CREDO Detector: what do we see?

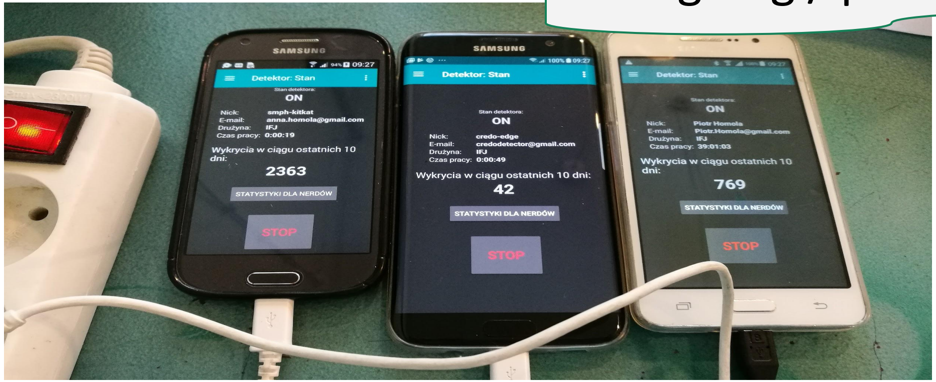
[work in progress, e.g. at IFJ PAN]

scenarios!

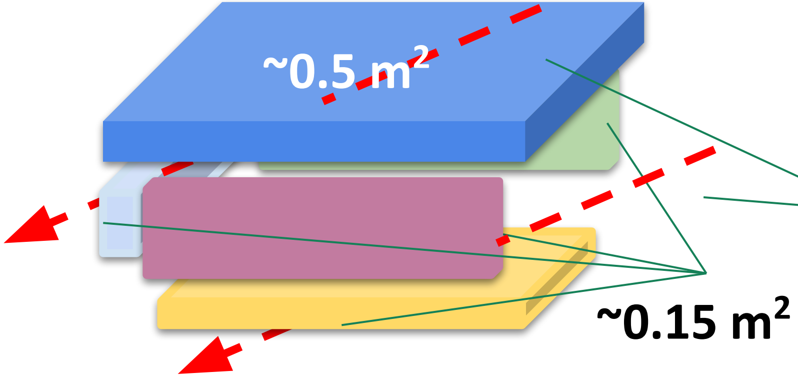
Smartphone detections: calibration for air showers and muons with scintillator plates

work at IFJ PAN,
credit Krzysztof Gorzkiewicz, PH

ongoing / preliminary



CANBERRA BEGe BE5030(Broad Energy Germanium) + 5 plastic scintillation detectors type EJ-200 by Scionix (2 horizontal and 3 vertical) + Digitizer CAEN DT5725

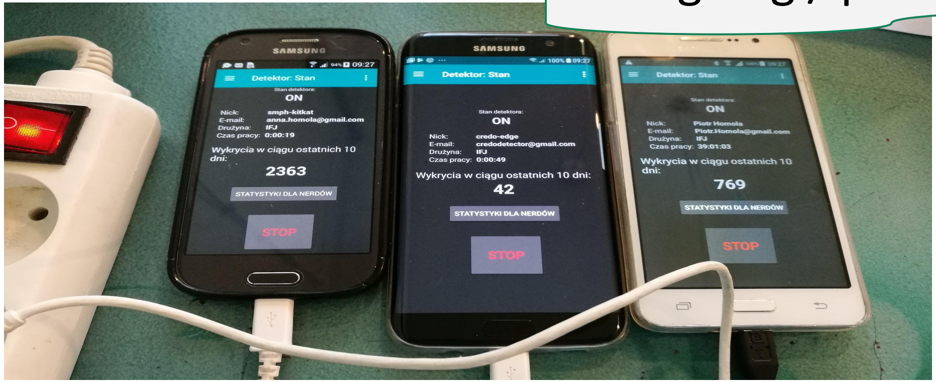


Events registered simultaneously in at least 3 different detectors
= air showers (N_{muon}>1)
observed ~15000 / day
(cf. c.a. 10000 10^{12} eV air showers expected per m^2 per day, verifying with simulations in progress)

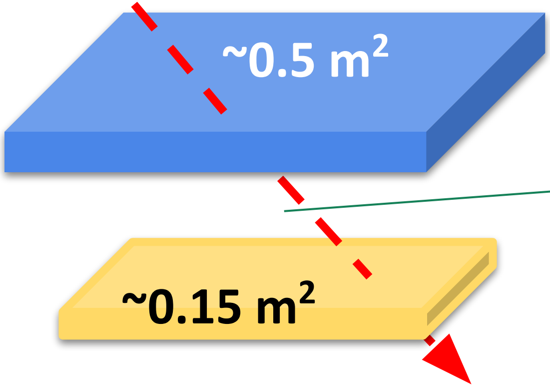
Smartphone detections: calibration for air showers and muons with scintillator plates

work at IFJ PAN,
credit Krzysztof Gorzkiewicz, PH

ongoing / preliminary



CANBERRA BEGe BE5030(Broad Energy Germanium) + 5 plastic scintillation detectors type EJ-200 by Scionix (2 horizontal and 3 vertical) + Digitizer CAEN DT5725



Events registered simultaneously in the top and bottom detectors
= air shower muons
observed ~400,000 / day
(compatible with background vertical muons expected per 0.15 m^2 per day, data)

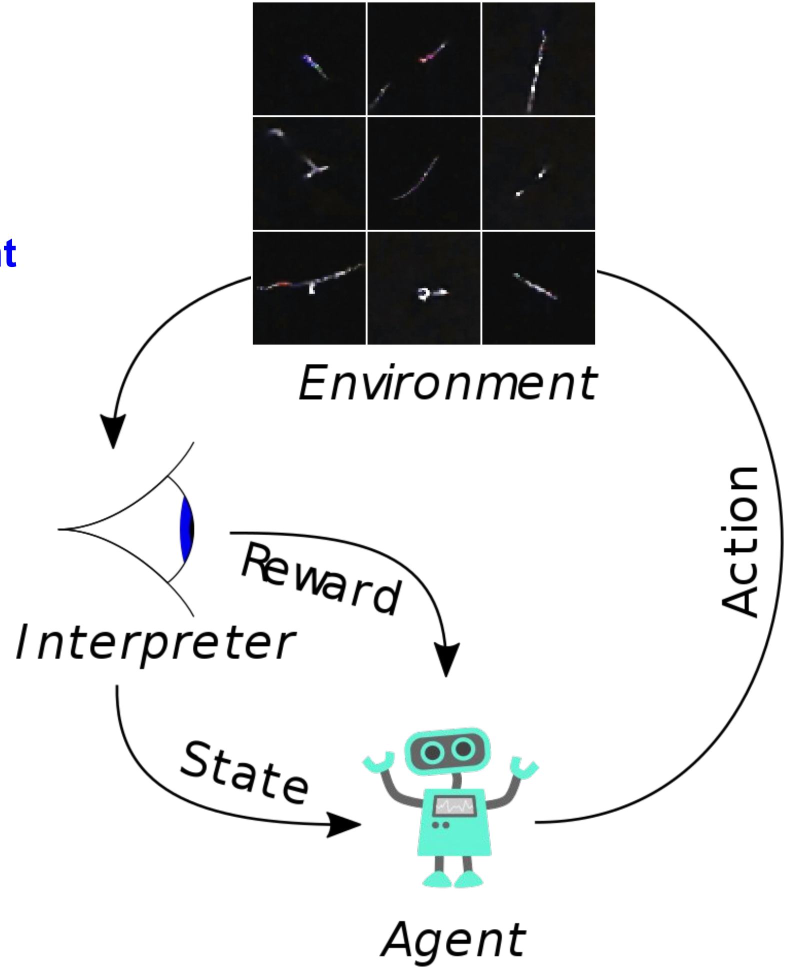
CREDO
THE QUEST FOR THE UNEXPECTED

"Citizen science support for reinforcement learning - a case of CREDO experiment"

Michał Niedźwiecki (PK) - PhD topic
Robert Kamiński (IFJ PAN) - supervisor
Krzysztof Rzecki (PK) - assistant supervisor

PhD/publication perspective: 24 months

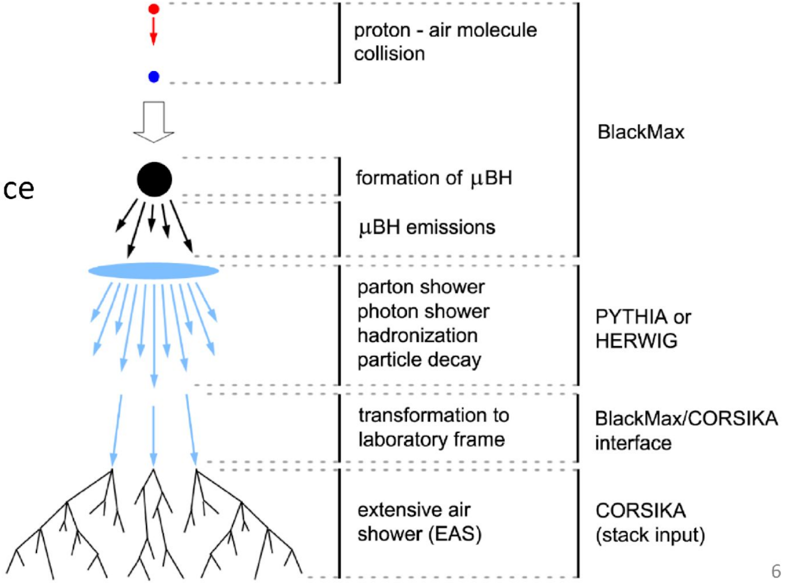
Wikipedia:
machine learning paradigms:
- supervised learning
- unsupervised learning
- **reinforcement learning**



Wikipedia / CREDO

Detection of μBHs at the PAO

- Main research idea: Prepare an interface between two Monte Carlo simulators and check, if μBH induced extensive air showers (EAS) can be separated from normal cosmic ray EAS
- Simulators used: BlackMax (μBH evaporation) and CORSIKA (development of EAS)
- Formation of μBHs assumes existence of extra dimensions
- Use longitudinal development of an EAS and X^{μ}_{max} as a separation indicator



Credit: Gasper Kukec, University Nova Gorica, Slovenia

CREDO Theatre!

https://www.youtube.com/watch?v=TaKB2zhZ8j4

Trailer, Part I, Part II: CREDO YouTube