# Introduction to Cosmic-Ray Extremely Distributed Observatory



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- <sup>2)</sup> http://credo.science

\_take home:

 $N_{ATM} >= 1!$ 

CREDO Anniversary Symposium, Kraków, 29.08.2017

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#### outline

Mission (why?)

Strategy (what?)

Tactics (how?)

- tools
- users
- training



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#### **Energy spectrum of 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<sup>-3</sup>), **Highest energies** → **the most demanding challenges**:

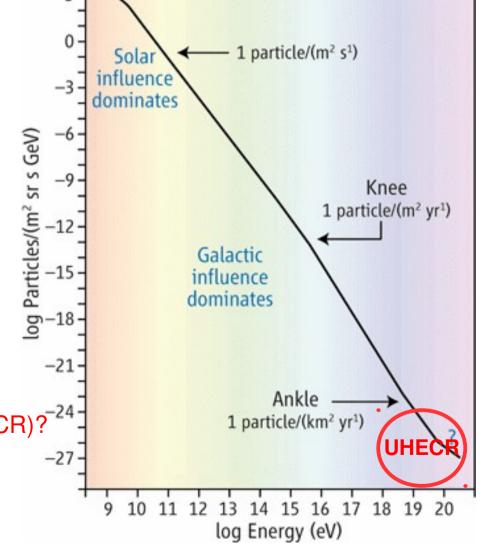
→ technical:
 extremely low flux (at E=10<sup>20</sup>eV
 1 particle / km² millenium), but now:
 the Pierre Auger Observatory (~3000 km²)

→ scientific:

What are Ultra-High Energy Cosmic Rays (UHECR)?

Where they come from?

How do they propagate?



Do photons contribute to the UHECR flux?

#### **Energy spectrum of cosmic rays in CREDO**

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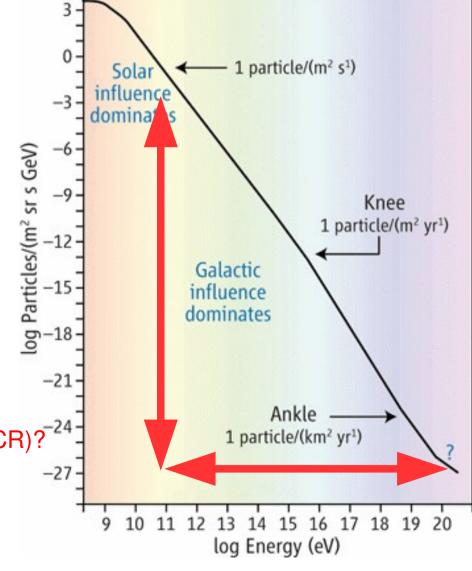
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Where they come from? How do they propagate? log Energy (eV) Do photons contribute to the UHECR flux?



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→ scientific:

Where they come from?

How do they propagate?

What are Ultra-High Energy Cosmic Rays (UHECR)? -24 1 particle/(km 18 log Energy (eV)

log Particles/(m² sr s GeV)

Do photons contribute to the UHECR flux?

1 particle/(m<sup>2</sup> s<sup>1</sup>)

Knee 1 particle/(m<sup>2</sup> yr<sup>1</sup>)

domina

domi

#### Photons as UHECR: testing astrophysical scenarios

#### <u>Astrophysical scenarios</u>

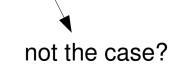
acceleration of nuclei (e.g. by shock waves)

- + "conventional interactions", e.g. with CMBR
- sufficently efficent astrophysical objects difficult to find
- small fractions of photons and neutrinos mainly nuclei expected

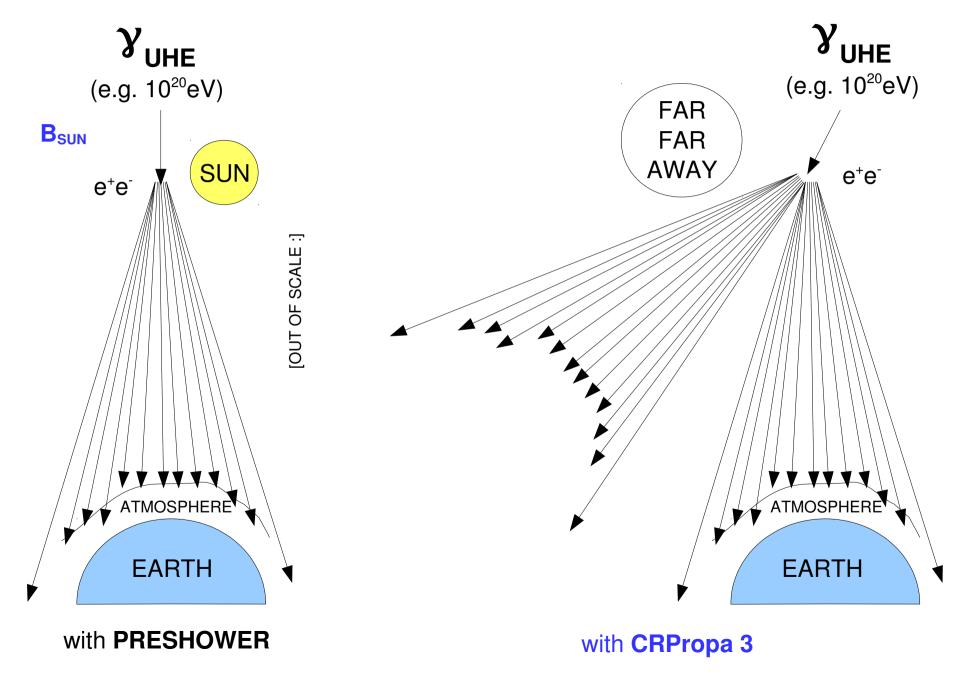
??? Exotic scenarios (particle physics) ???

Decay or annihilation the early Universe relics

- $\rightarrow$  hypothetic supermassive particles of energies  $\sim 10^{23} \text{ eV}$
- → decay to quarks and leptons → hadronization (mainly pions)
- large fraction of photons and neutrinos in UHCER flux



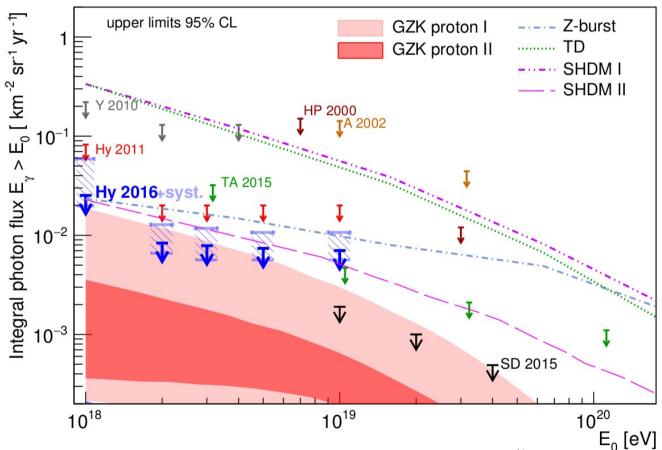
# **UHE photons** → **big cascades (classical examples)**



#### Diffuse UHE photon search: hybrid limits

#### **UHECR COMPOSITION PARADIGM**

At the highest energies photon fractions < 1%



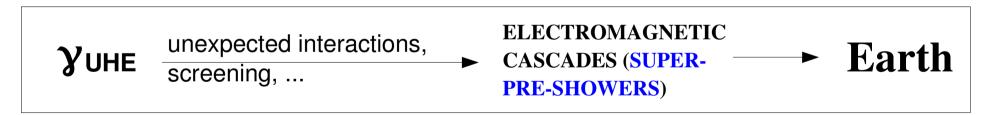
- → Severe limitations for exotic scenarios? \*)
- → and for (special) Lorentz Invariance Violation? \*)

<sup>\*)</sup> **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 manifets at UHE...

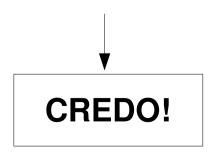
# Experimental evidence about $\gamma_{UHE}$

γυнε no interactions / screening Earth

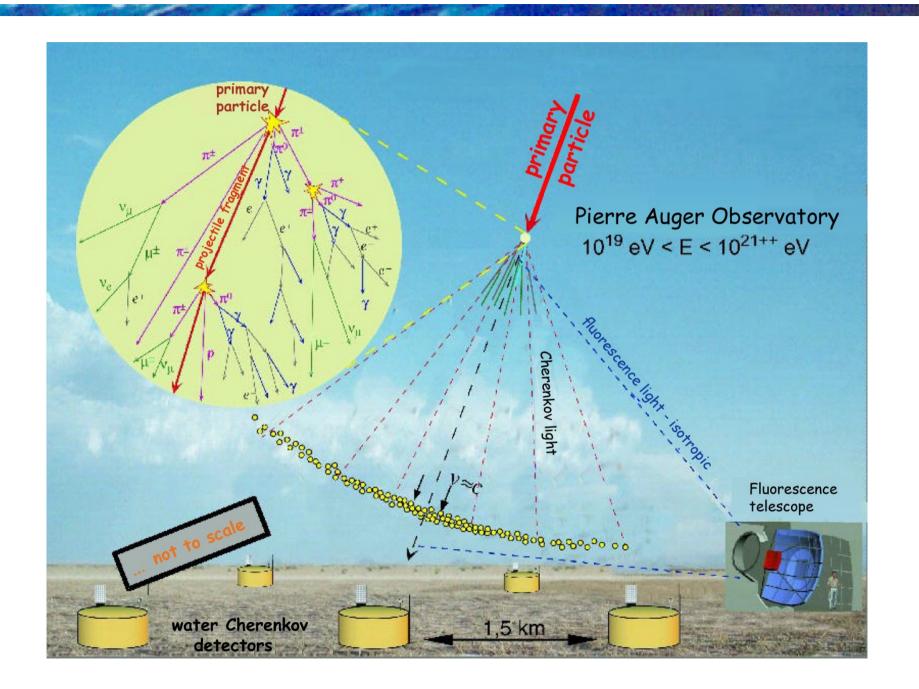
#### **NOT OBSERVED**



#### **NOT TRIED SO FAR...**



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



## Motivation for cosmic-ray cascades

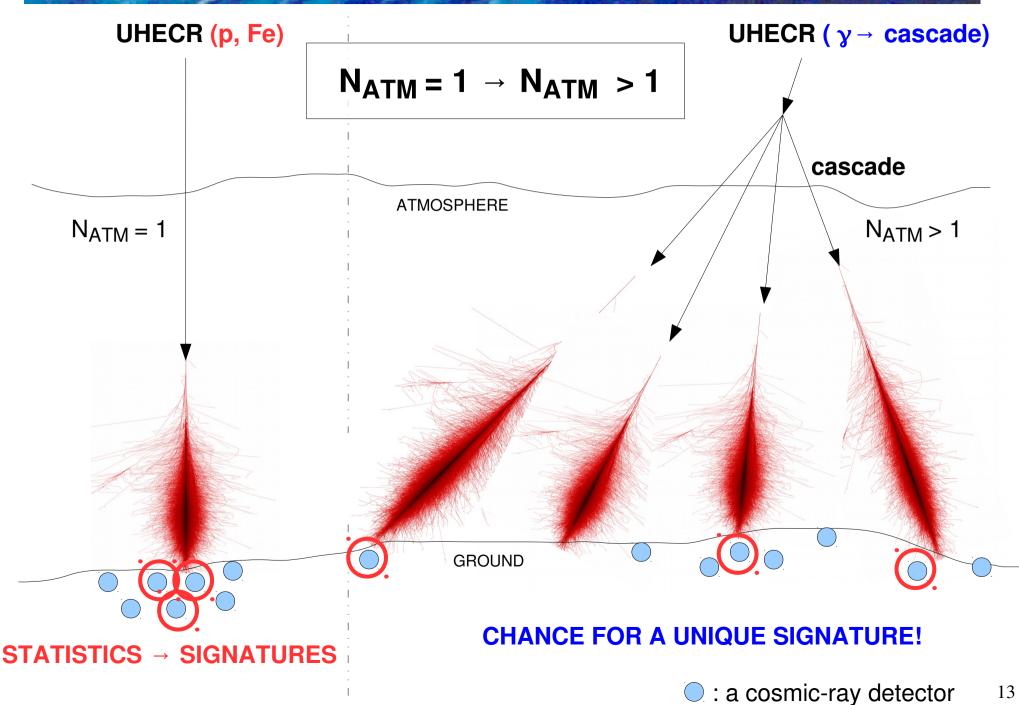
#### **Next generation cosmic-ray research:**

$$N = 1 \rightarrow N > = 1$$

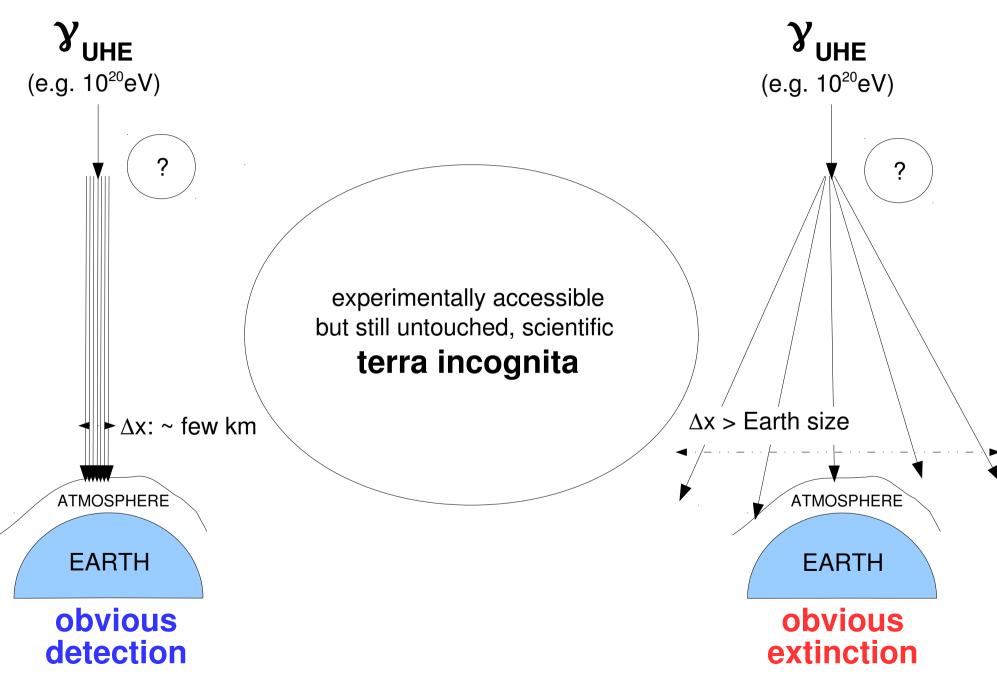
N: number of cosmic ray particles correlatated in time

- → 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

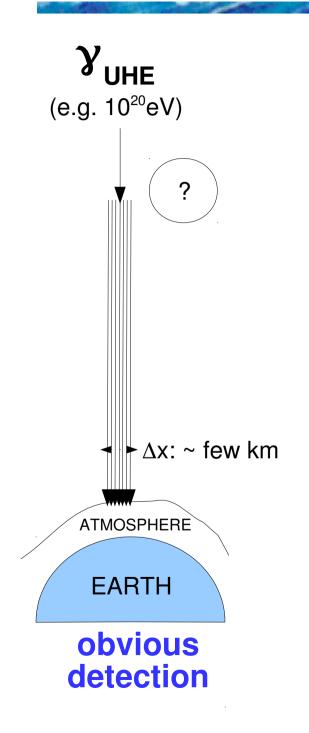
# Generalized detection of cosmic rays: $N_{ATM} >= 1$

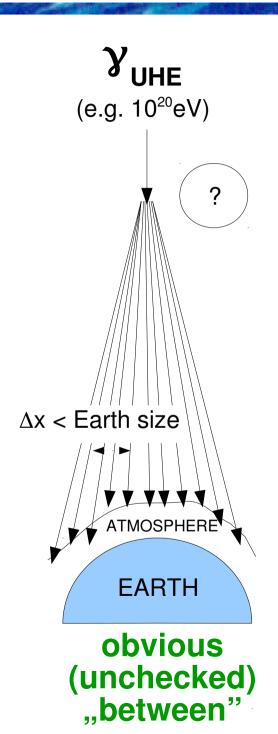


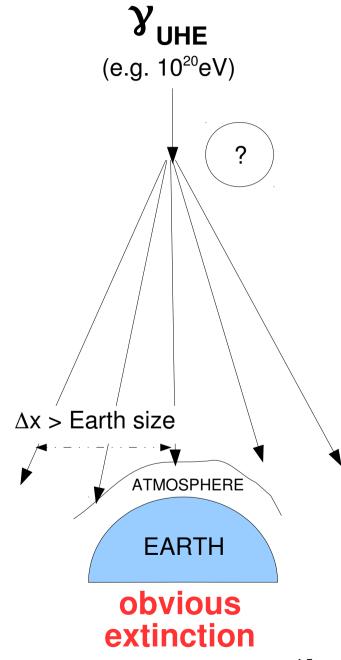
# $N_{ATM} >= 1$ : untouched ground



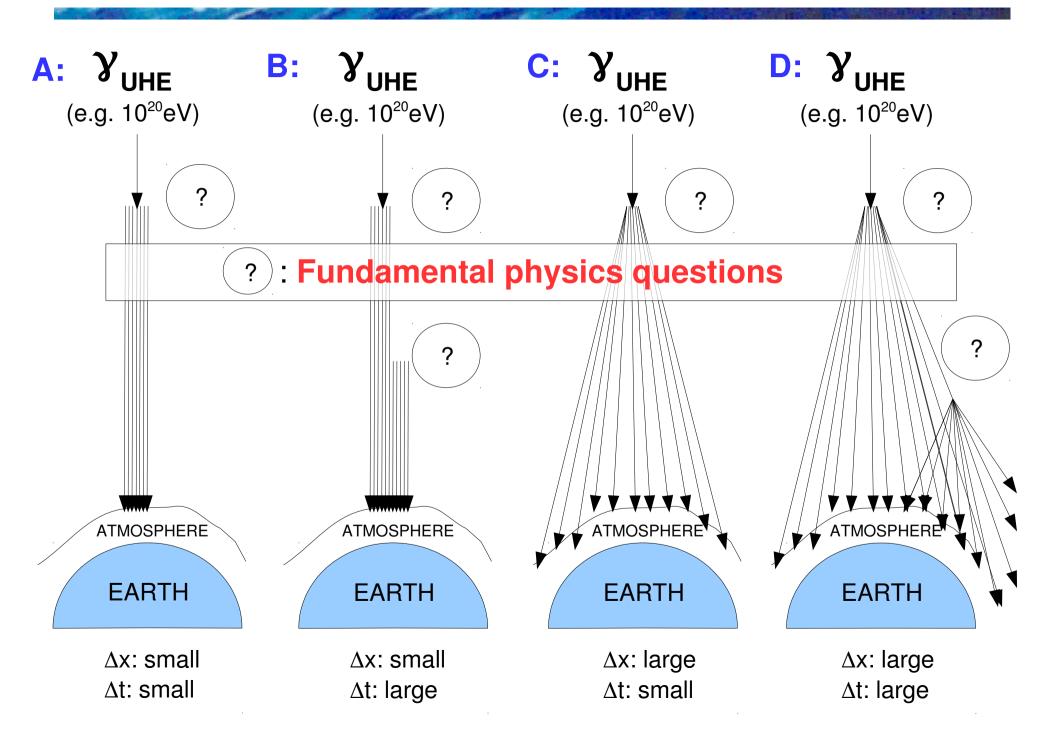
#### $N_{ATM} >= 1$ : untouched ground







#### $N_{ATM} > 1$ : the categories



# $N_{ATM} > 1$ 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 K3T 2N2, Canada

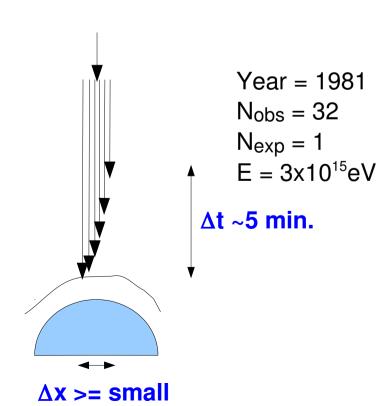
(Received 7 April 1983)

A series or burst of 32 extensive air showers of estimation in O estimation in Winnipeg, Canada. This observation was the optime of the which recorded 150 000 such showers in a Carrotte mon April 1982.

PACS numbers: 94.40.Potter. 95.30.-k observed within a 5-min time interval beginning at 9 months between October 1980 and

PH: Correlated cosmic rays?

 $N_{ATM} > 1$ , type B?



# $N_{ATM} > 1$ 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<sup>13</sup> eV

D. J. Fegan and B. McBreen

Physics Department, University College Dublin, Dublin 4, Ireland

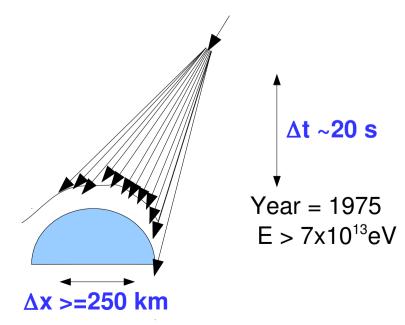
Physics Department, University

Note 14 Seps We 1983 Port 1983 The authors report on an unusual crease in the cosmic-ray shower rate at two recording stations The event lasted for 20 s. This event was the only one of its kind e years of observation. The duration and struca recently reported single-station cosmic-ray burst. ent 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.

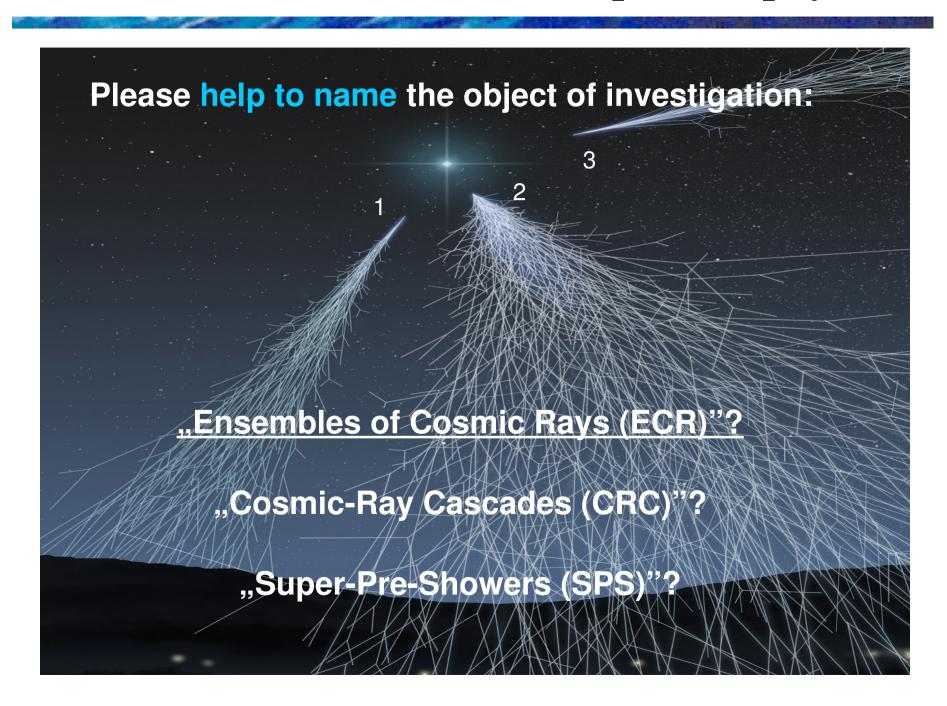
PACS numbers: 94.40.Pa, 95.85.Qx, 97.80.Jp

PH: Correlated cosmic rays?

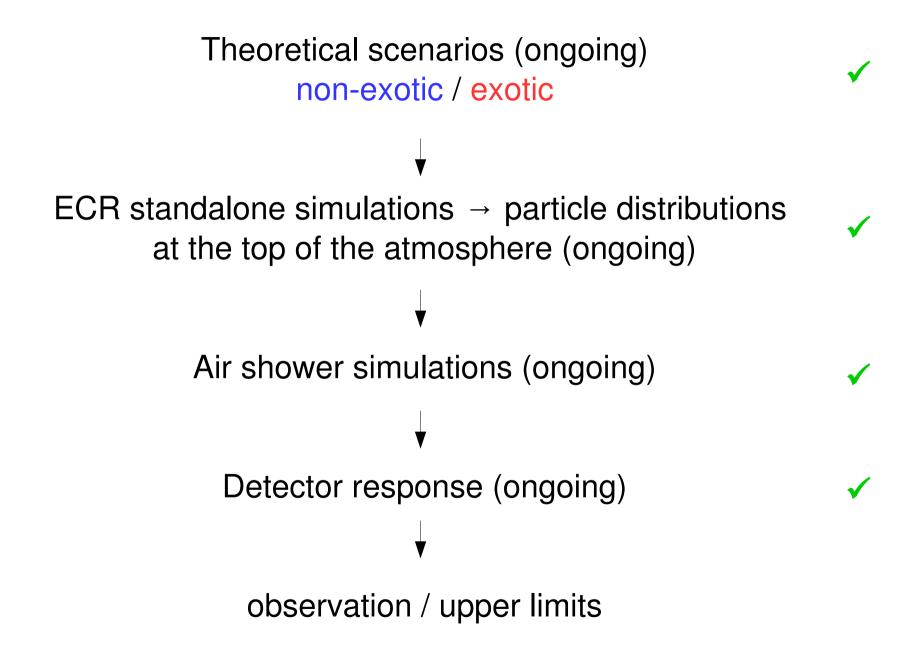
 $N_{ATM} > 1$ , type D?



#### $N_{ATM} > 1$ : new subfield of astroparticle physics!



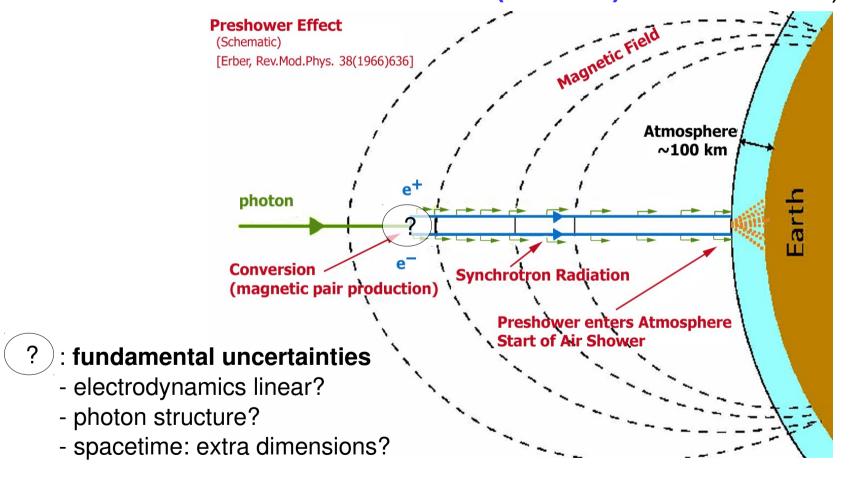
#### **Ensembles of Cosmic Rays (ECR): road map**



#### (Super-)preshowers: a must to study UHE photons

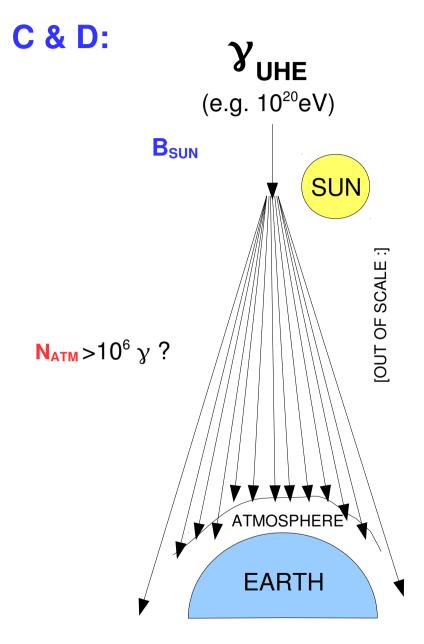
#### (super-)preshower:

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

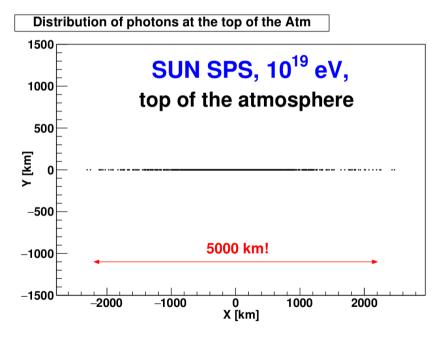


 $N_{ATM} > 1$ , type A, not observed?

## Super-preshowers from the vicinity of the Sun



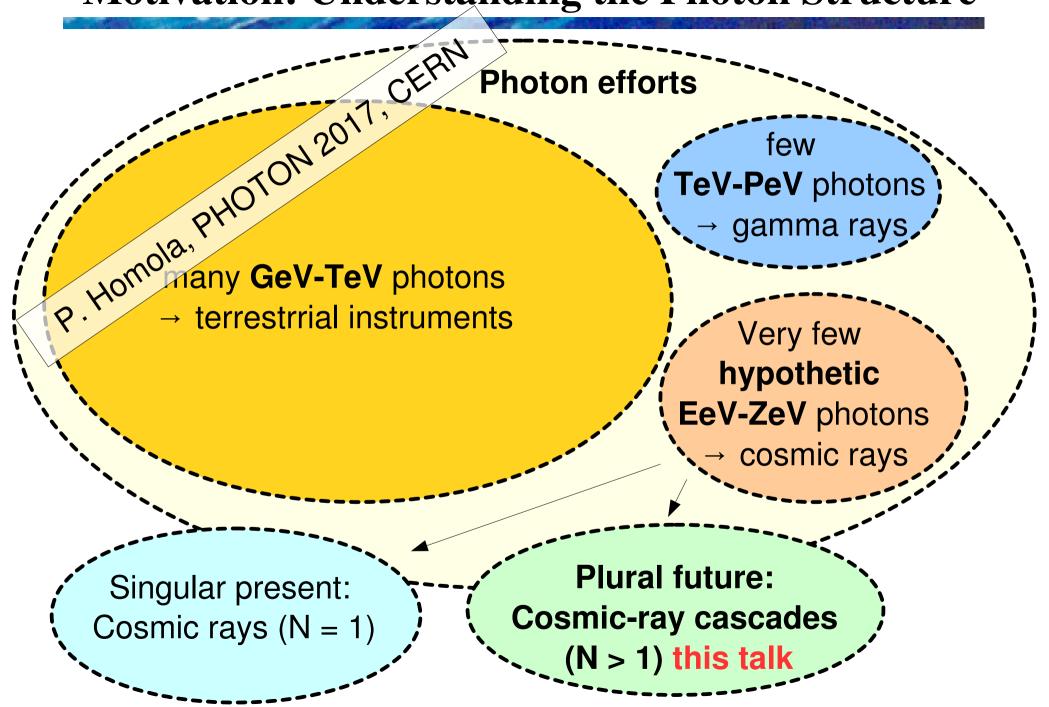
- → First calculations: W. Bednarek 1999 low energies not treated: extent ~ tens of km
- N. Dhital, 2017
   complete energy spectrum: extent
   ∼ thousands of km (see talk at 11:30)



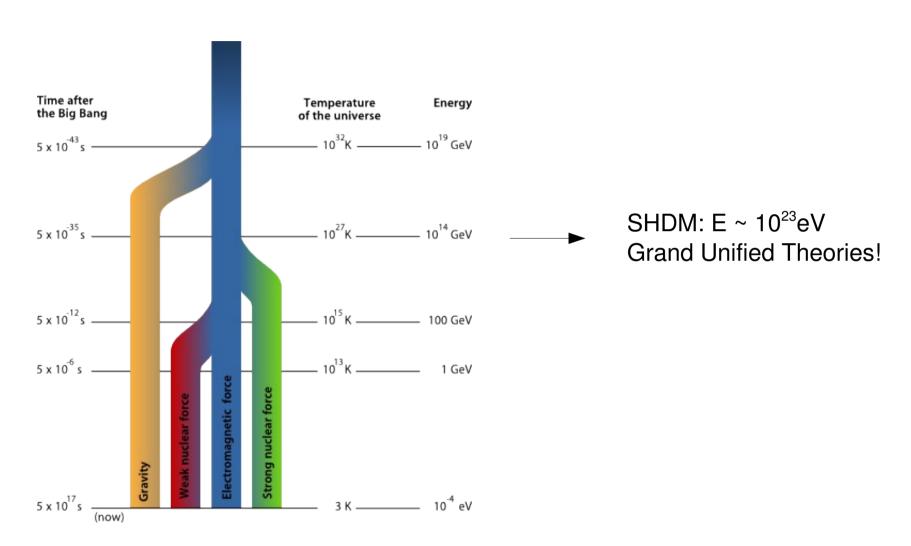
Distribution of photons  $(E>10^{13}~{\rm eV})$  at the top of the atmosphere.  $E_{\gamma}=$  10 EeV, Impact parameter  $=2.5R_{\rm S}.$ 

 $N_{ATM} > 1$ , type  $C \rightarrow$  observable (line 10000 km wide), not yet tried

## **Motivation: Understanding the Photon Structure**



# **Motivation: Super Heavy Dark Matter**



http://quantum-bits.org

#### **Lorentz Invariance Violation**

Modified dispersion relation of a photon:

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

Two-sided experimental limits derived from gamma-ray astronomy, 98% C.L. (Klinkhamer & Schreck, 2008):

$$-6 \times 10^{-20} > \kappa > -9 \times 10^{-16}$$

Trivial note:

 $\kappa > 0$ : pair production supressed

→ more UHE photons reach Earth

 $\kappa$  < 0: pair production enhanced (photon lifetime ~ 1 sec.!)

→ no UHE photons reach Earth

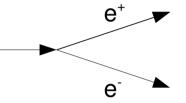
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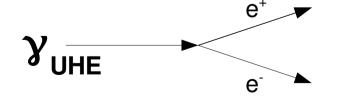
 $\kappa > 0$ : pair production supressed

→ more UHE photons reach Earth





 $\kappa$  = 0: normal pair production



 $\gamma_{\mathsf{UHE}}$ 

 $\kappa$  < 0: pair production enhanced (photon lifetime ~ 1 sec.!)

→ no UHE photons reach Earth

 $\rightarrow$  critical importance for the UHE photon search! Observation of **photon cascades** would point to  $\kappa$  < 0!

# **Motivation: 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

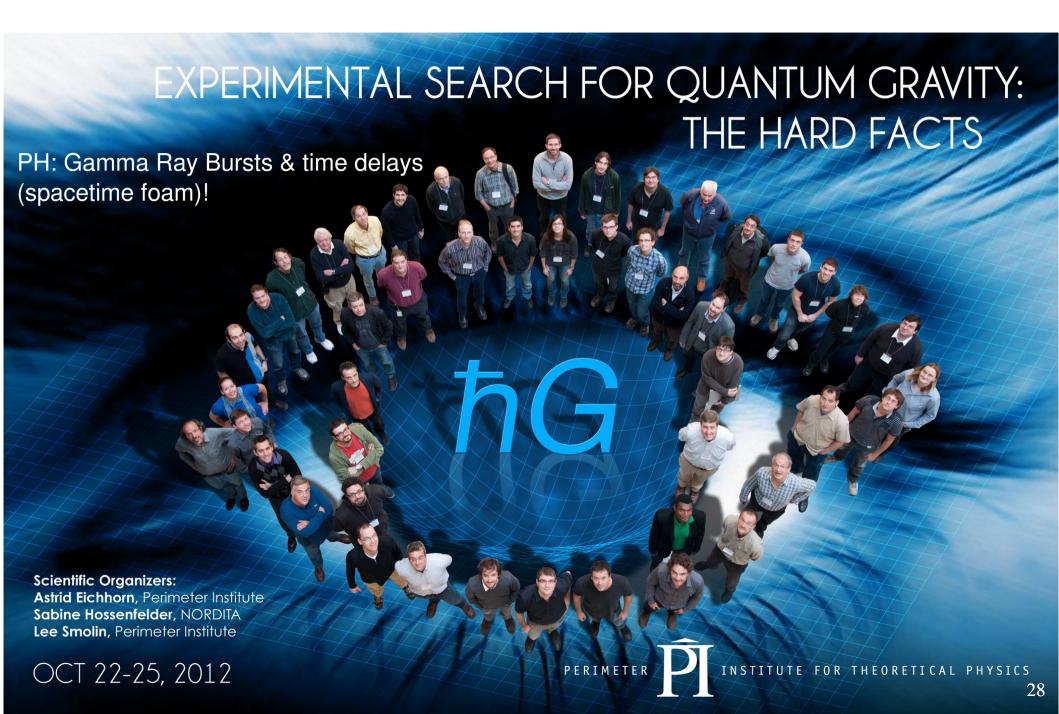
Ted Jacobson<sup>a</sup>, Stefano Liberati<sup>b</sup>, David Mattingly<sup>c</sup>

<sup>a</sup>Department of Physics, University of Maryland, USA
<sup>b</sup>International School for Advanced Studies and INFN, Trieste, Italy
<sup>c</sup>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)

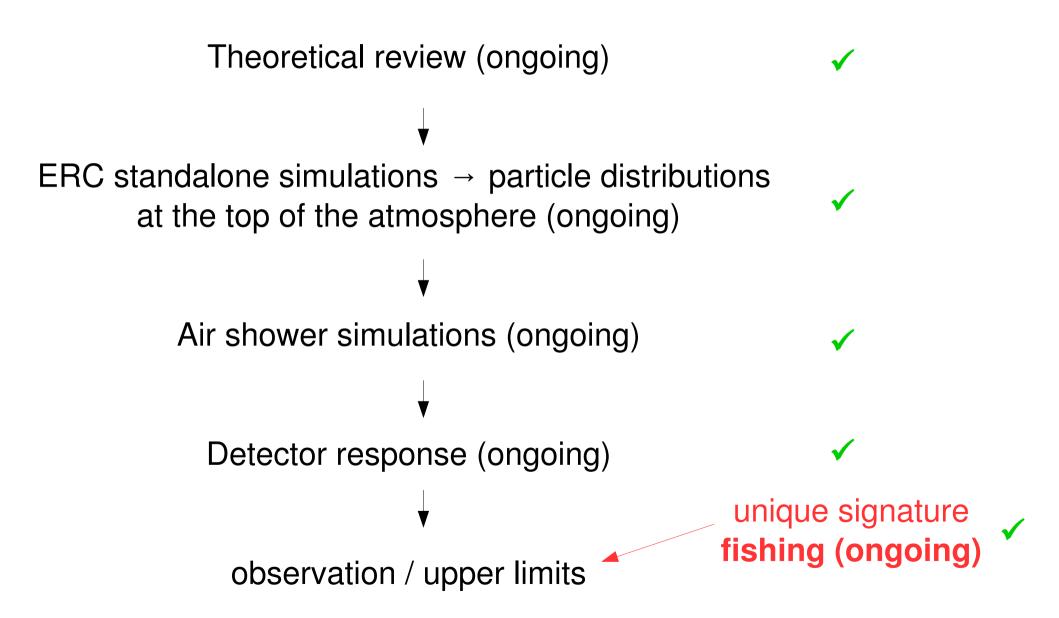
# **Motivation: Experimental Quantum Gravity**



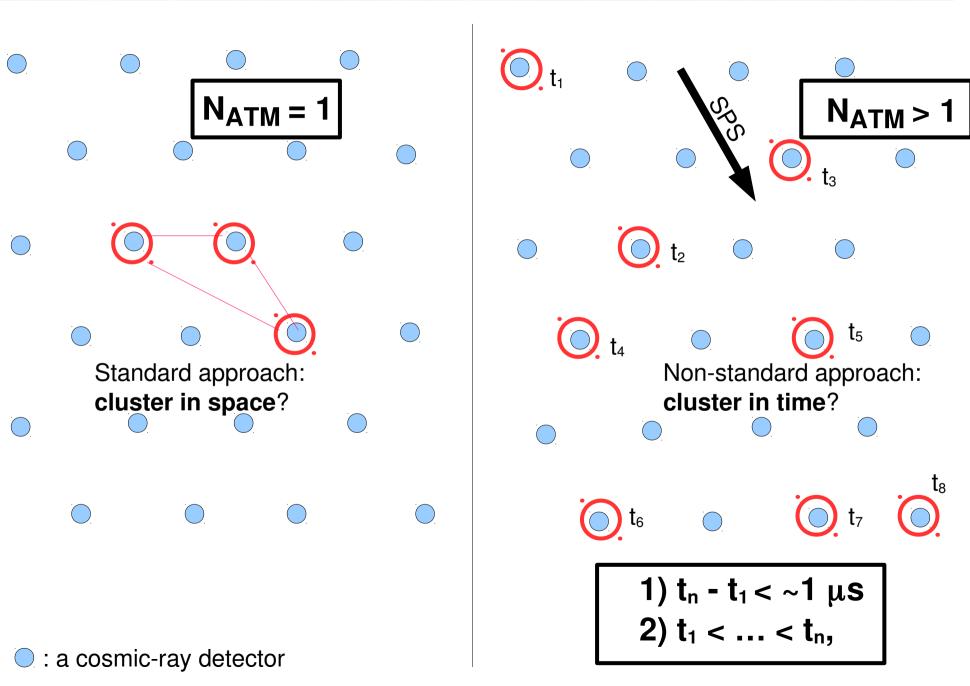
# **Motivation: Novel Experimental Quantum Gravity**



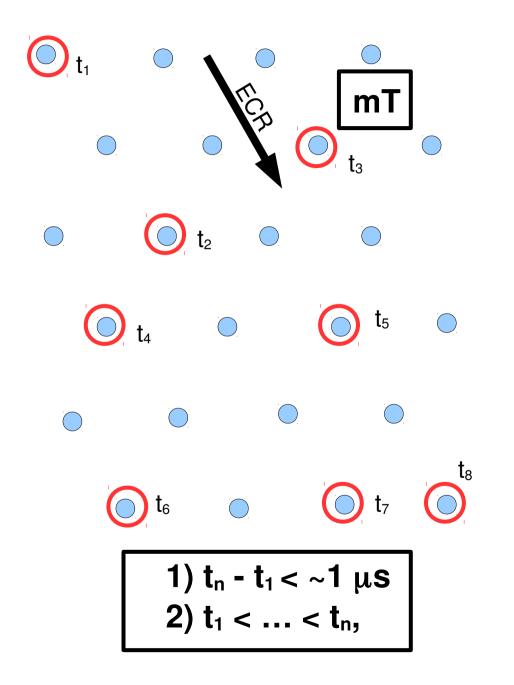
#### Ensembles of Cosmic Rays (ECR): shortcut road map



# A chance for a unique super-preshower signature



## mT: NEW & EASY trigger for ERC



#### mT (multiTrigger)

Chance for a statistical coincidence for n=30, assuming trigger rate 100 Hz:

$$P_{acc} = \sim 10/30! * 0.16^{30} = ridiculously small chance$$

sensitivity to  $n_{LOW} < n < 30$ 

$$n_{LOW} = ?$$

# $N_{ATM} >= 1$ mission (briefly)

#### **Scenarios**

# Time after the Big Bang 5 x 10<sup>-43</sup> s - 10<sup>32</sup> K - 10<sup>19</sup> GeV 5 x 10<sup>-12</sup> s - 10<sup>15</sup> K - 10<sup>16</sup> GeV 5 x 10<sup>-17</sup> s - 10<sup>18</sup> K - 10<sup>19</sup> GeV 5 x 10<sup>-18</sup> s - 10<sup>19</sup> GeV 3 K - 10<sup>14</sup> GeV

## **AND**

# **Fishing**





#### outline

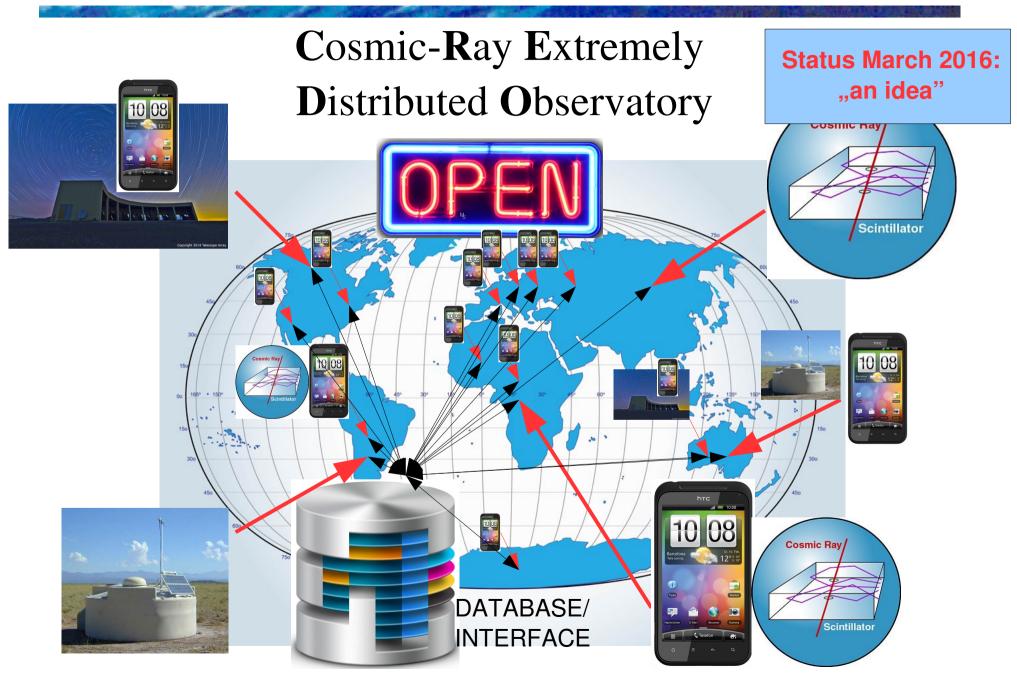
Mission (why?)

Strategy (what?)

#### Tactics (how?)

- tools
- users
- training

# **CREDO:** the first $N_{ATM} >= 1$ observatory



Central database/interface: access to everything for everybody



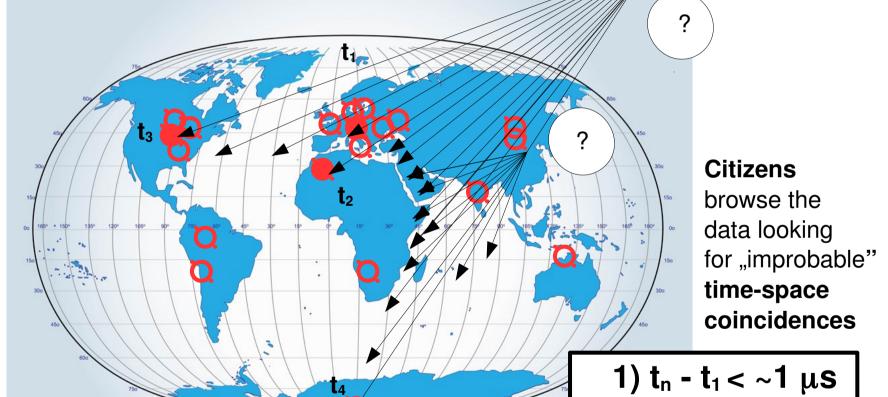
Status August 2016: "the collaboration"

2)  $t_1 < ... < t_n$ 

**OUHE** (e.g. 10<sup>20</sup>eV)



Citizens
strenghten
trigger
capabilities
of the
educational
arrays with
smartphone
networks



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

## **CREDO Inauguration Meeting, 30.08.2016, INP PAS**



Cosmic-Ray Extremely Distributed Observatory: Inauguration Meeting

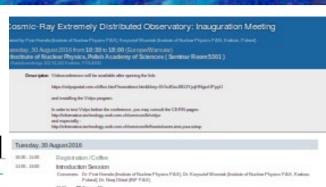
30 August 2016 Institute of Nuclear Physics, Polish Academy of Sciences.

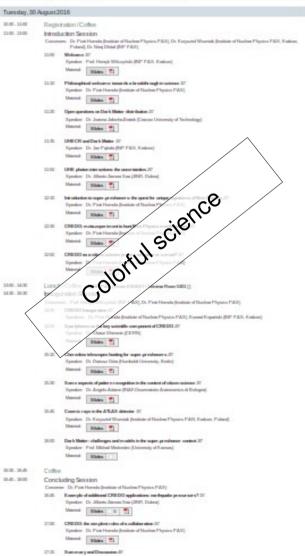
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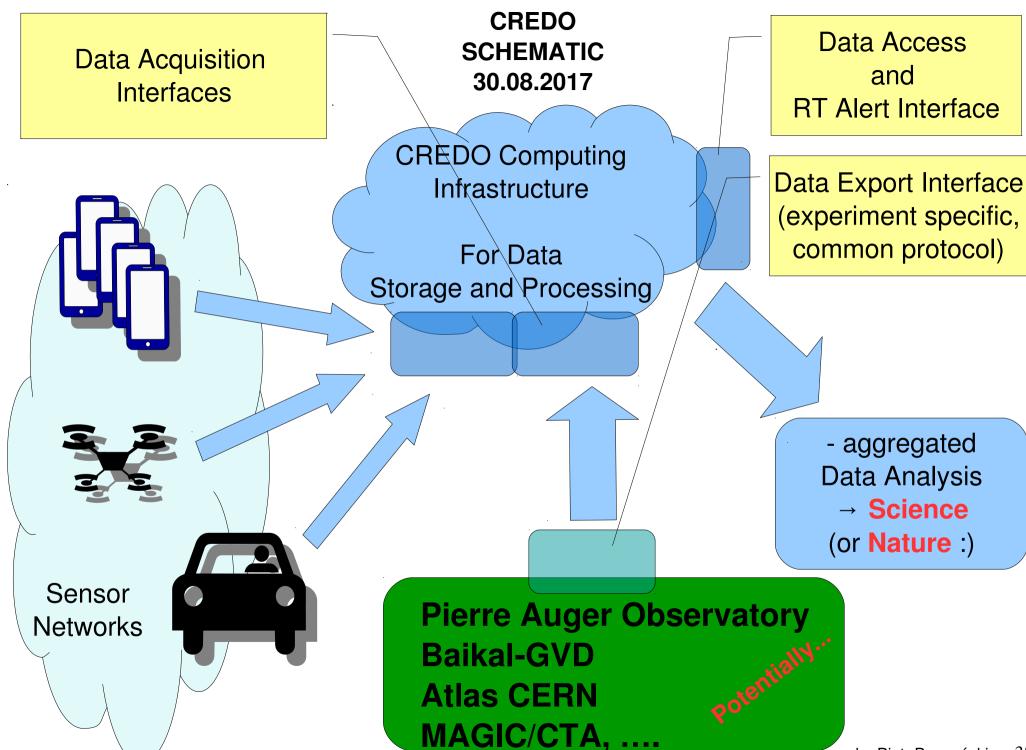


Miadomości Inwestycje Komunikacja Sport Kultura ∨ Magazyn Krakowski Więcej ∨ Kontakt
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Wyborcza.pl / Kraków / Wiadomości z Krakowa

Ada Chojnowska 05.09.2016 09:00

### Masz smartfona? Zostań odkrywcą, obserwuj promieniowanie kosmiczne





#### outline

Mission (why?)

Strategy (what?)

Tactics (how?)

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- training



2140 TFLOPS in CPUs + 256 TFLOPS in GPUs 2232 nodes, 53568 CPU cores, 279 TB RAM 10 PB usable disk space @ 180 GB/s



# 2.4 PFLOPS, #59 ON TOP500

## Coming this afternoon... CREDO mobile detector app

Mobile cosmic-ray detector application made in Poland!

Open source project!

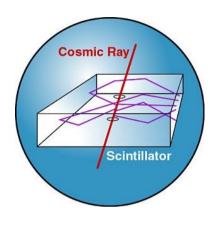
Introducing...

......[P. Poznański, 15:45]



# Cosmic ray detection: now









## Cosmic ray detection: tomorrow



# Cosmic ray detection: tomorrow



# **Educational toys: now**

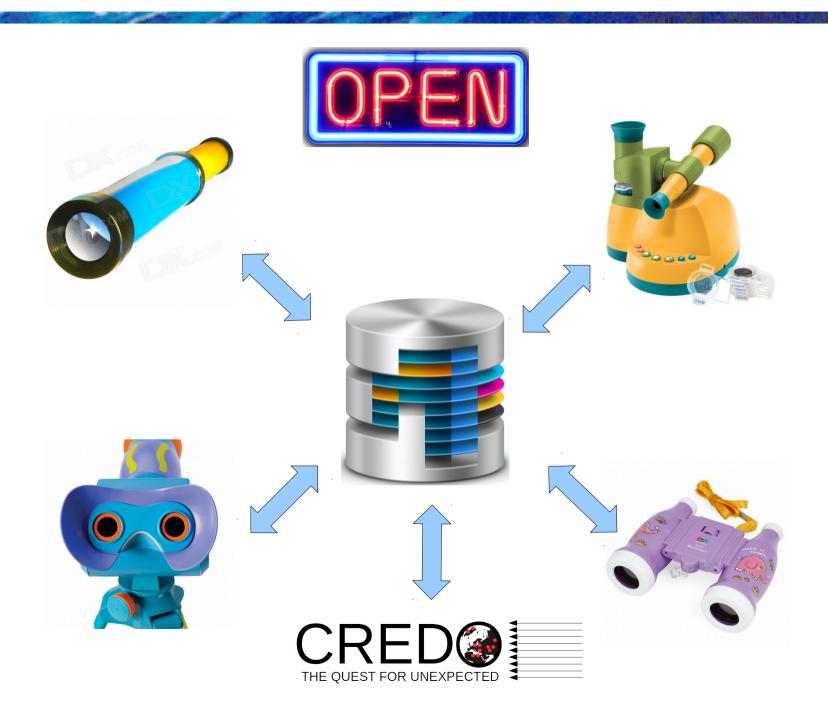




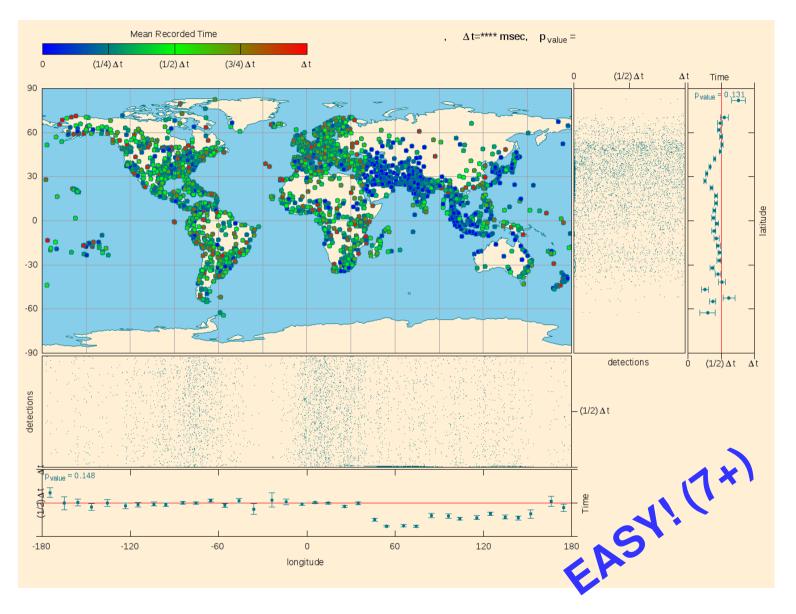




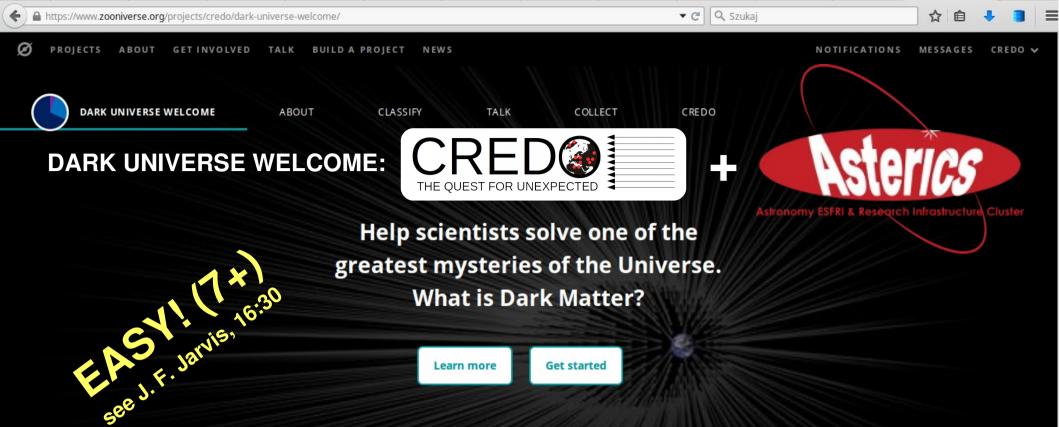
## **Educational toys: tomorrow**



## How an Ensemble of Cosmic Rays can look like?



Simulation by Paweł Jagoda & Łukasz Bratek (assumed CREDO stations: locations of the airports)





"Nobody has any idea what Dark Matter or Energy are, so working on this is really exciting! Dark Matter is responsible for the gravitational effects seen in galaxies, while Dark Energy may be the cause of the accelerating expansion of the Universe."

We've got a very big mystery on our hands! Everything we can see in the Universe; you, me, planets, stars and galaxies, only make up 5% of the mass of the Universe. We have very clear evidence that there is a lot more mass, more stuff, out there but we have no idea what it is.

This mysterious stuff is known by scientists as Dark Matter but even the smartest theorists and most advanced technology can't work out what it physically is. We many have a way of solving this mystery by looking for and grouping Dark Messengers - very high energy particle showers which exist because of Dark Matter. However, it's very difficult for us to predict what these groups will look like and how well hidden they are amongst other contaminants. We need your help to identify patterns in the world wide detections of high energy particles shared with the CREDO (Cosmic-Ray Extremely Distributed Observatory) collaboration so we can teach computers to better identify them.

Asterics

Dark Universe Welcome was developed with the help of the <u>ASTERICS Horizon2020</u> project.

ASTERICS is a project supported by the European Commission Framework Programme Horizon 2020 Research and
Innovation action under grant agreement n. 653477



#### outline

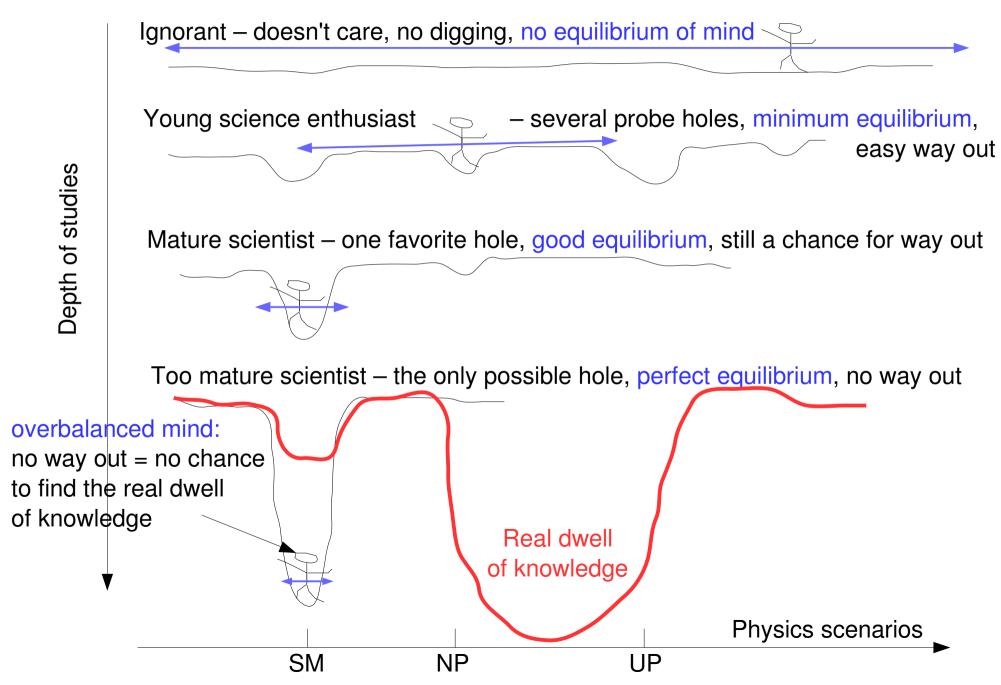
Mission (why?)

Strategy (what?)

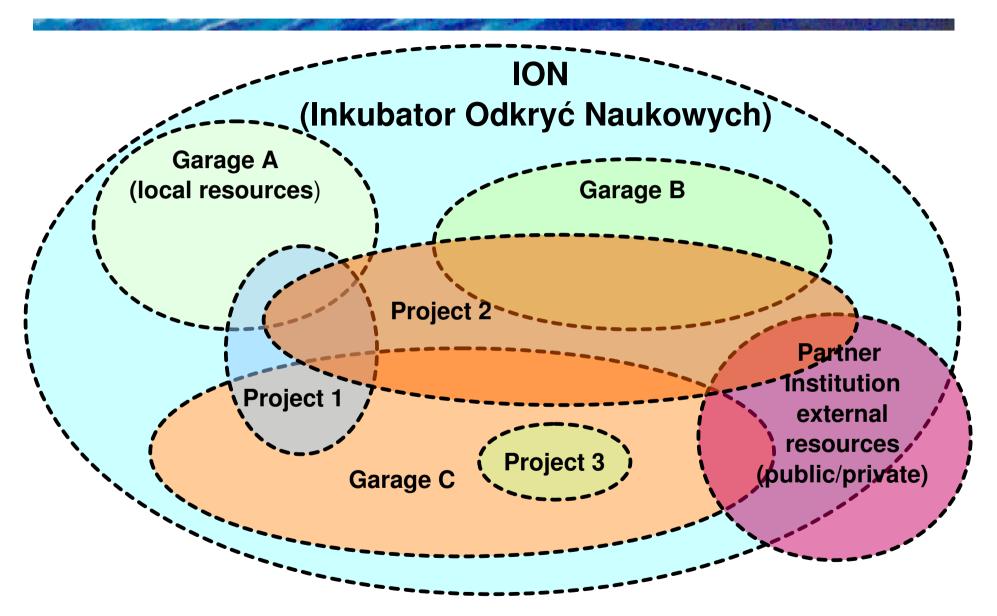
Tactics (how?)

- tools
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## Digging a well of knowledge or why young is good



### **Incubator of Scientific Discoveries: vision**

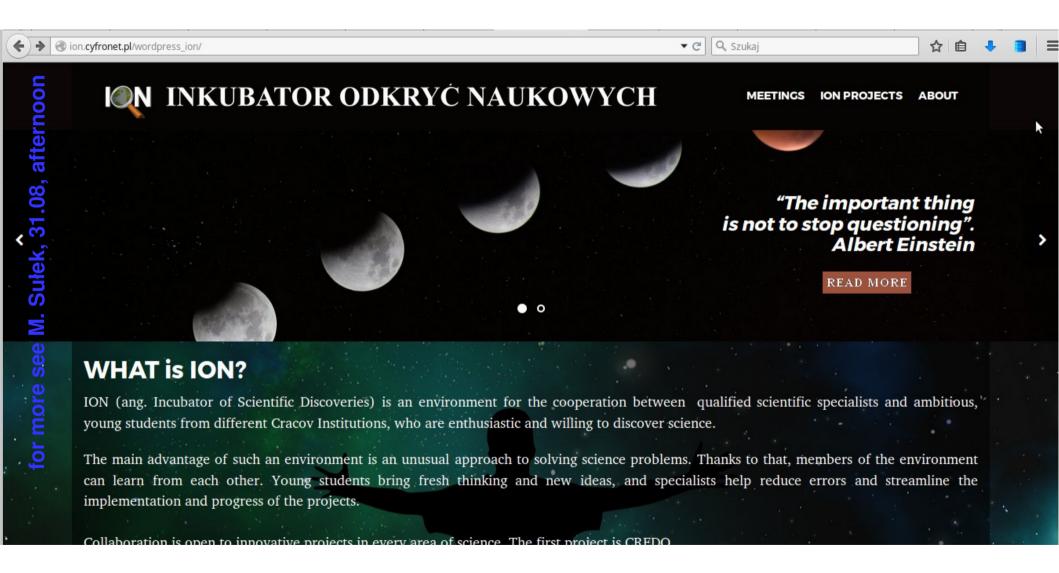


Resources: money, space, tools, skills, competencies, advise, ...

Projects!: team, goal, road map, budget, action, reports, continuity → discoveries!

**Distributed** = access to more resources = **synergy** = better chance for discoveries.

#### **Incubator of Scientific Discoveries**



## Begin your journey to the Nobel Prize early...

PH: Hey, ION, go global!



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## **Incubator: Discovery training**

#### **Incubator role:**

discoveries! (scientific think tank)

Training required

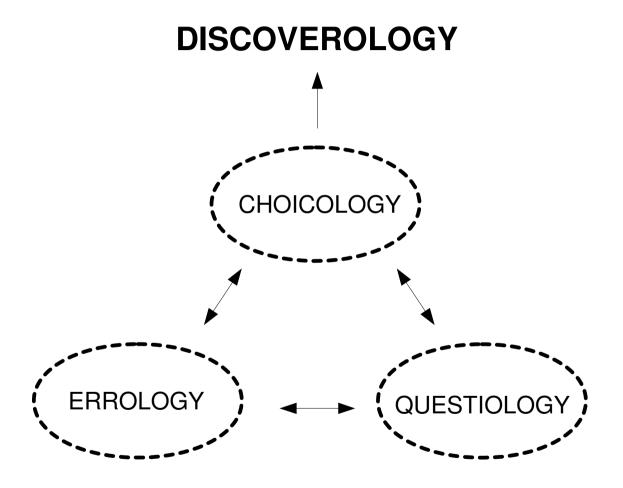
... but no "discovery education"

Consequtive approximation method...



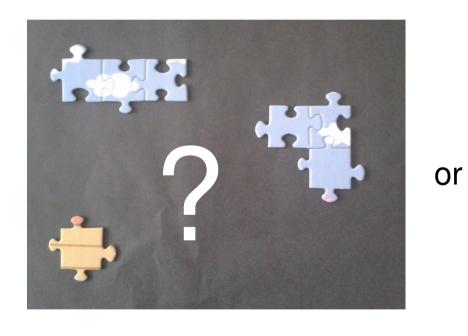
- → doing science (real discovery-oriented projects)
- → remove obstacles for independent thinking
- → practice the art of asking questions

# More than a training... discipline?



## **CHOICOLOGY:** what do I do?

#### **UNIVERSE A**



#### **UNIVERSE B**



?

#### ERROLOGY: do I do well?

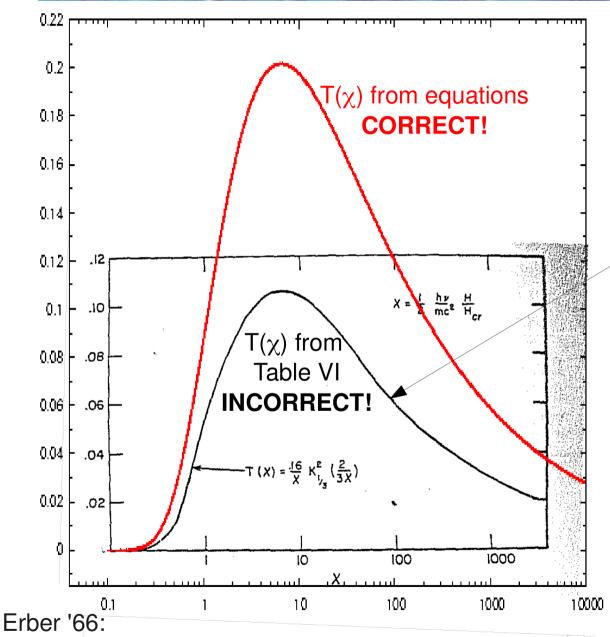


Fig. 9. The magnetic pair production function  $T(\chi)$ ; compare

(3.4a-d).

Erber '66:

Table VI. The magnetic pair production function  $T(\chi)$ .

χ	$T(\chi)$	
0.2 0.3 0.4 0.7 1.2 3.0 5.0 6.0 7.0 9.0 15 30	2×10 <sup>-4</sup> 2.2×10 <sup>-3</sup> 6.6×10 <sup>-3</sup> 0.026 0.055 0.094 0.10 0.10 0.10 0.10 0.10 0.099 0.085	Γ!

 $T(\chi)$  from equations significantly larger than in Table VI of the standard reference Erber '66.

Taking  $T(\chi)$  values from Table VI leads to an **underestimation** of pair production probability [!].

Mistake mentioned in:

- → Homola et al. 2005
- → Klein 2006

## **QUESTIOLOGY:** what are my questions?

Example:

Does



really

makes sense?



#### in one slide (summary v.1)

#### **Mission**

 $N_{ATM} >= 1 \rightarrow scenarios + fishing$ 

#### <u>Strategy</u>

Spread globally & grow giant → "1 million colleagues"

#### **Tactics**

- tools: variety of detectors
- users: young + old
- training: discoverology

## Summary v. 2

Ensembles of Cosmic Rays (Cosmic-Ray Cascades, Super Pre-Showers):

- Unprobed and easily accessible information channel about Universe! [terra incognita but... might be a desert]

Cosmic-Ray Etremely Distributed Observatory:

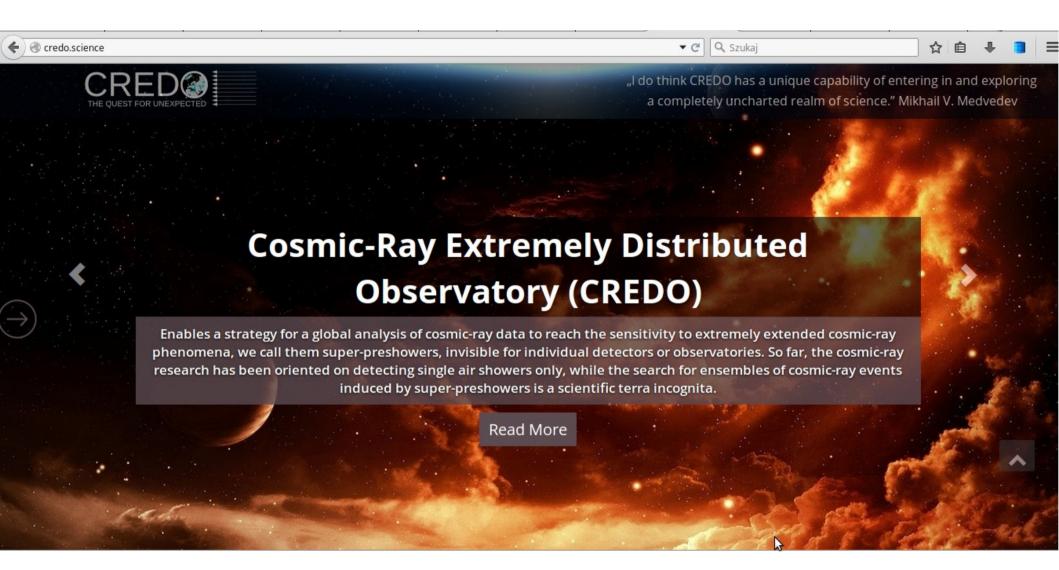
- the pioneer receiver, already operating, stay tuned!

#### CREDO,, more than 1 million" potential:

- top science motivation with super easy method
- data everywhere and for free
- massive data requires massive participation
- cheap massive detectors (toys?) possible
- mulitdisciplinary (astro, geo, bio)

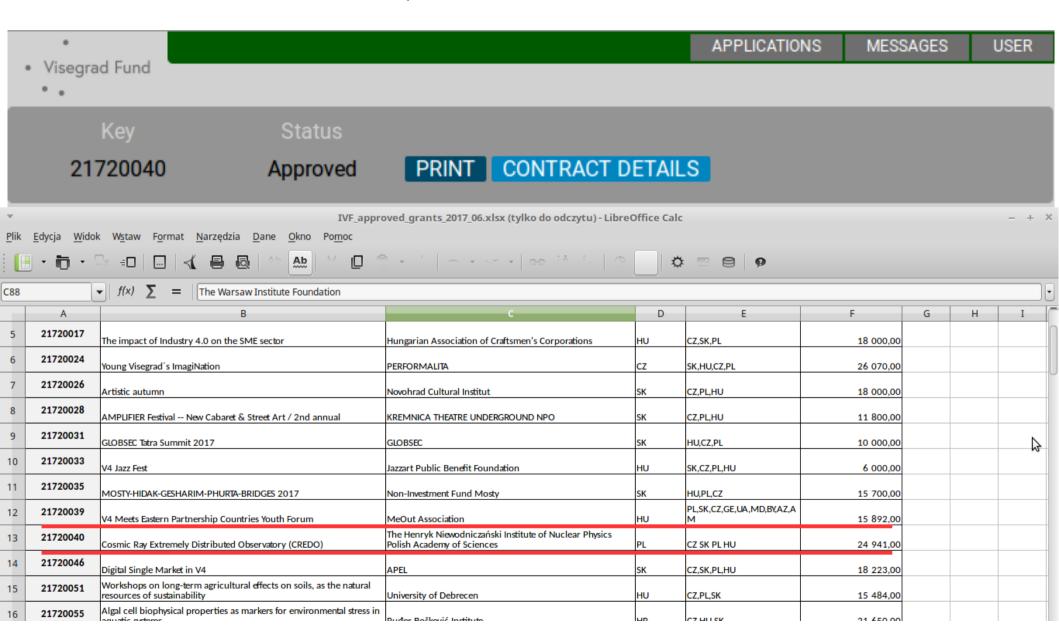
.... to engage even the youngest science enthusiasts

#### Visit credo.science...

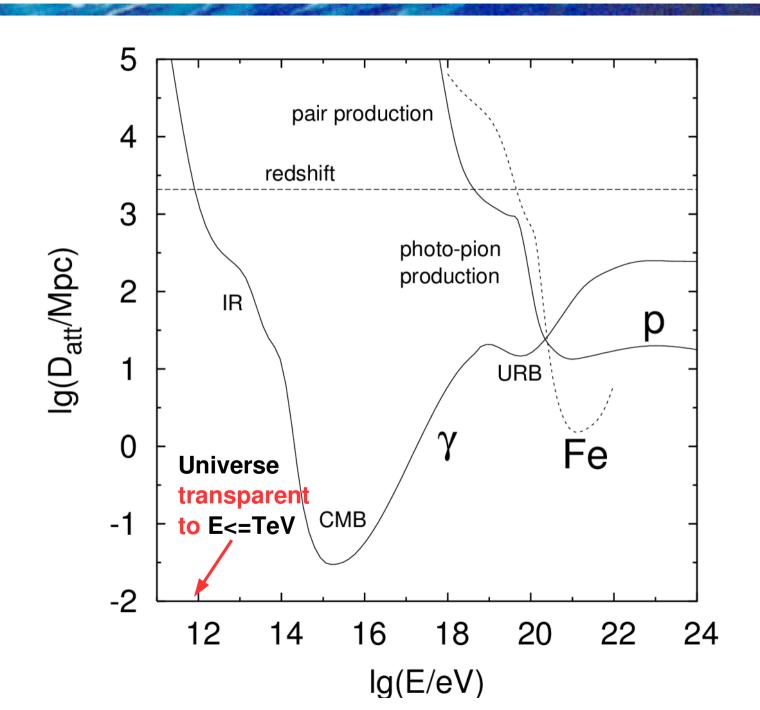


... and contribute to CREDO science.

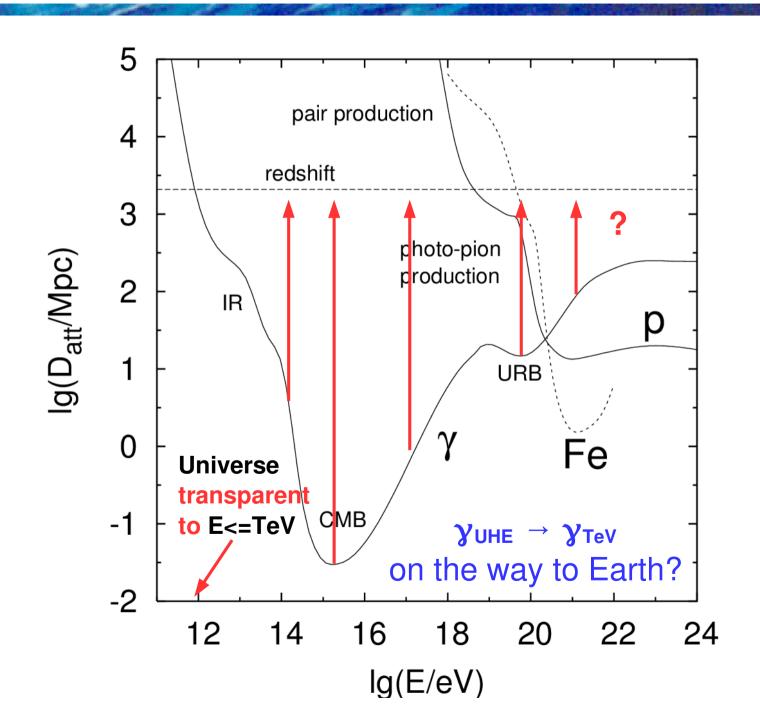
# Visegrad Grants 2017/06 Cosmic Ray Extremely Distributed Observatory (CREDO) – science & education 24,941 EUR / 12 months



## $\gamma_{UHE}$ travelling through the Universe: paradigm



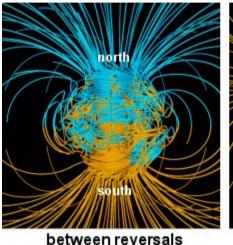
## $\gamma_{\text{UHE}}$ travelling through the Universe: exotic example

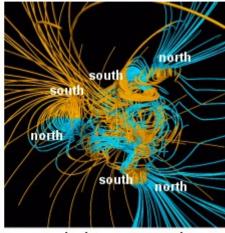




# Scientific diversity: GEO

Wikipedia: "Geomagnetic reversal"

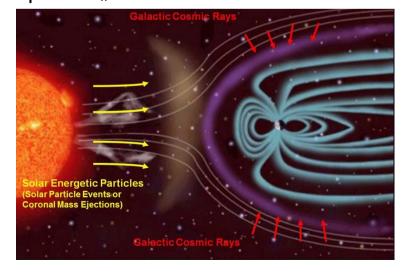




50111001110101010

during a reversal

Wikipedia: "Health threat from cosmic rays"



Earth outer core: Liquid (molten iron)

→ geomagnetism

Impulse (tidal forces)

→ hydrodynamics: waves

- → Mechanical wave upwards (slow, hours?)
  - → Electromagnetic wave ("instant", ms)

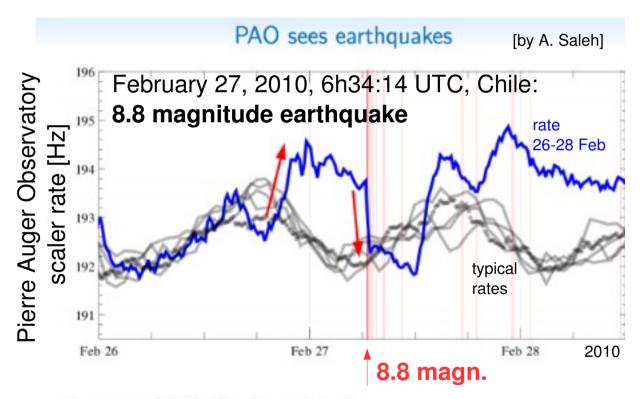
Local geomagnetic field vector changes AND seismic effect might occur!

Variation of the CR rate!

**Earthquake precursors?** 



## Scientific diversity: GEO



- Increase of CR before the earthquake
- Strong drop during the earthquake
  - → CREDO-earthquakes task [already existing]