Cosmic-Ray Extremely Distributed Observatory*

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Polish Academy of Sciences, Kraków, Poland

*) http://credo.science

take home:
$N_{ATM} >= 1$!

Astrofizyka Cząstek w Polsce, Kraków, 20.09.2017

Energy spectrum of cosmic rays

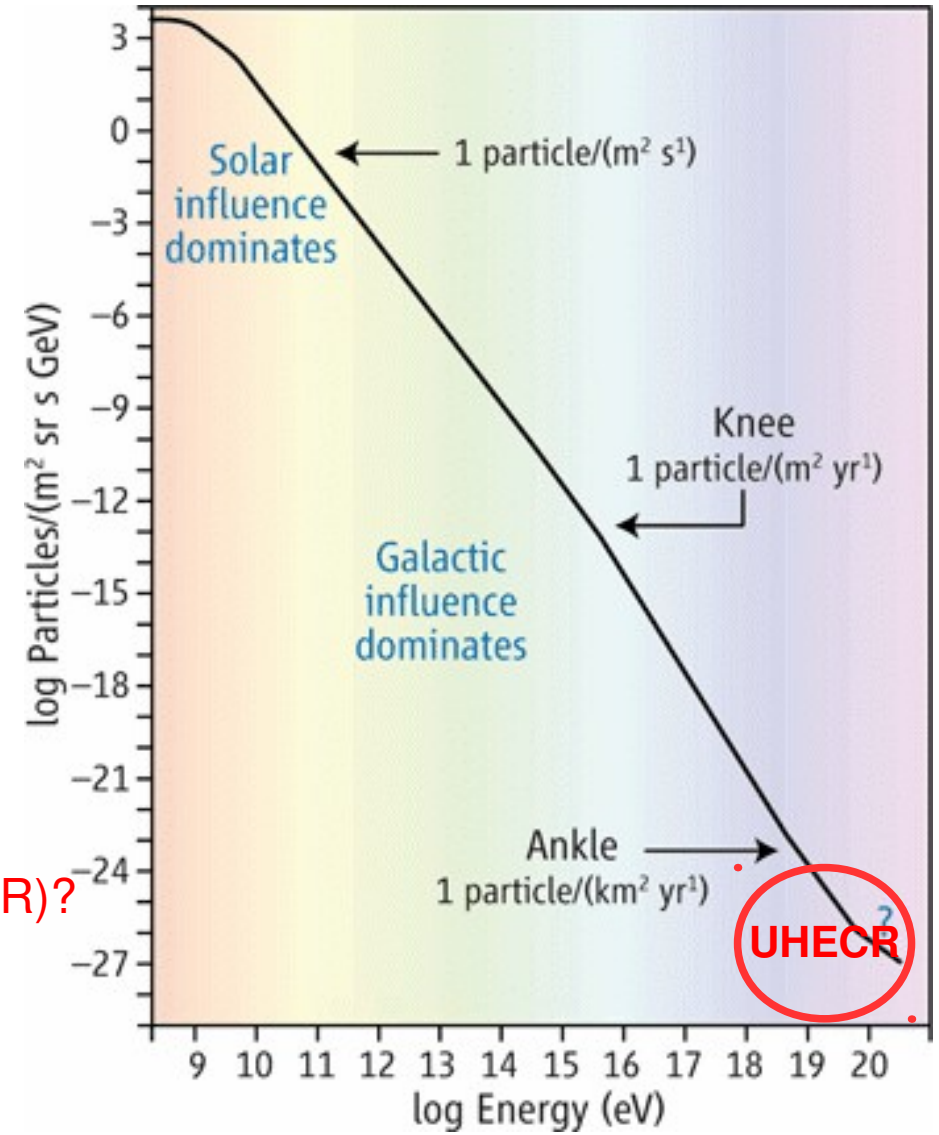
Ranges:
energy: > 10 orders of magnitude
flux: > 30 orders of magnitude
→ diverse physics (sources)
→ diverse detection techniques

Flux rapidly decreases with energy (~E^{-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?

Do photons contribute to the UHECR flux?



Energy spectrum of cosmic rays in CREDO

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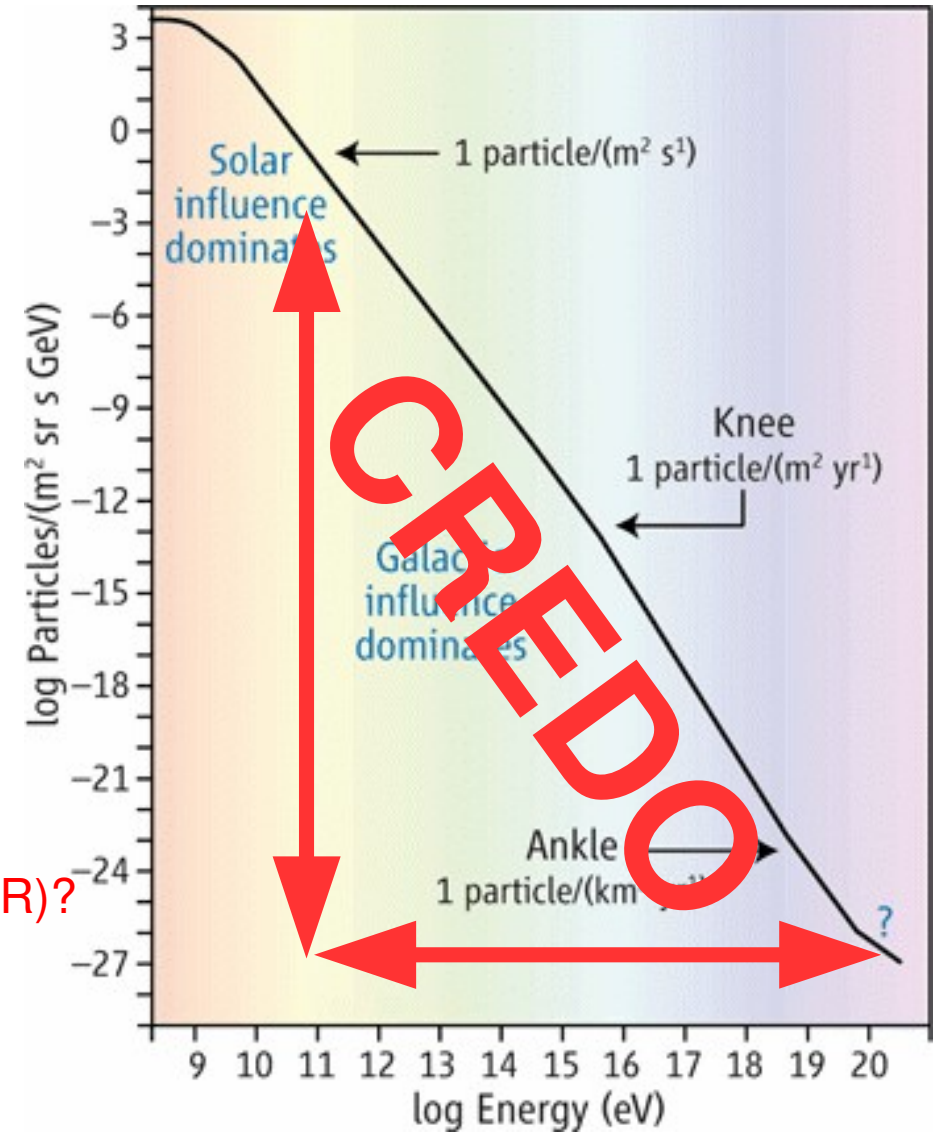


Photons as UHECR: testing astrophysical scenarios

Astrophysical scenarios

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

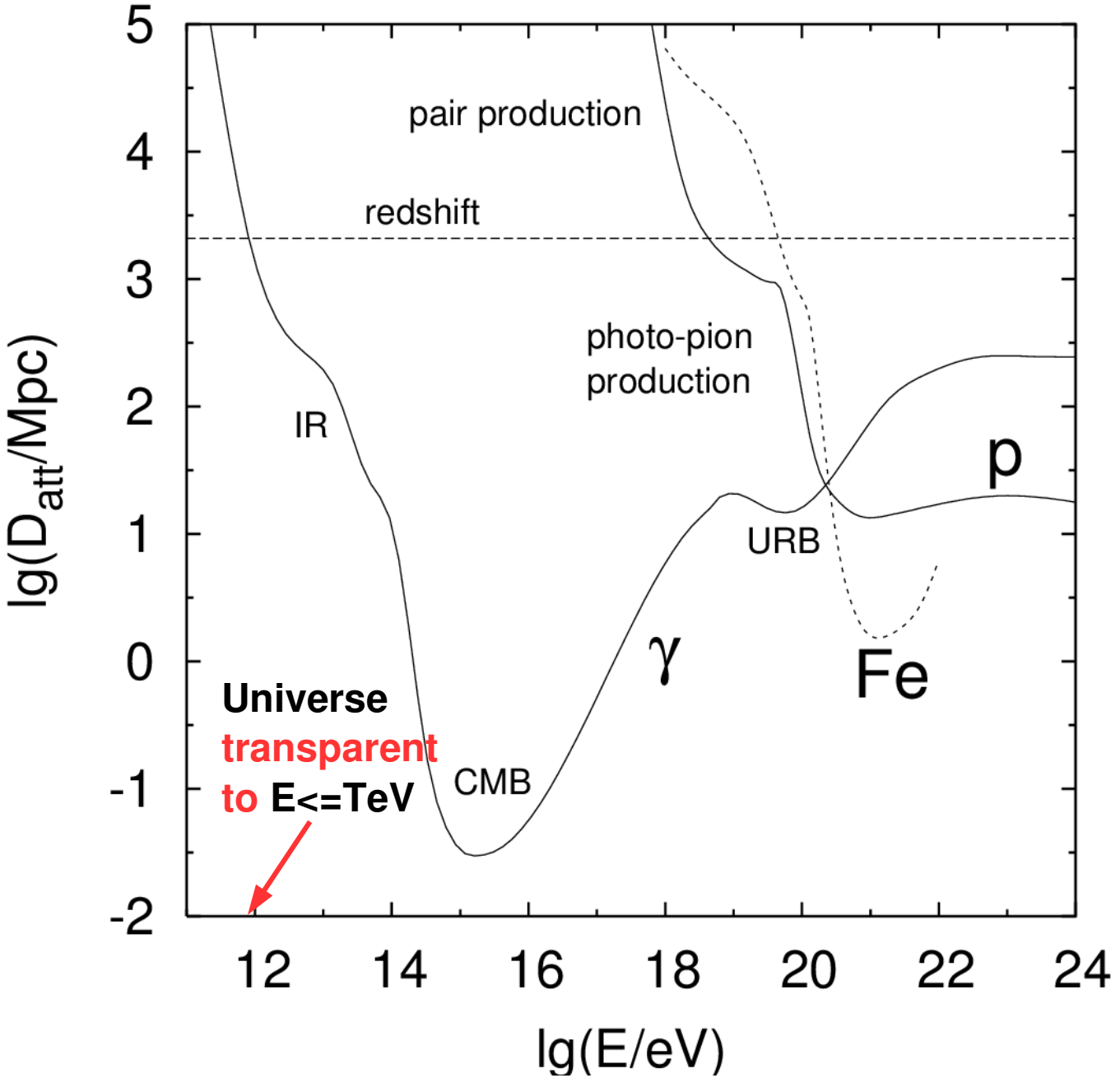
??? Exotic scenarios (particle physics) **???**

Decay or annihilation the early Universe relics
→ hypothetic supermassive particles of energies $\sim 10^{23}$ eV
→ decay to quarks and leptons → hadronization (mainly pions)

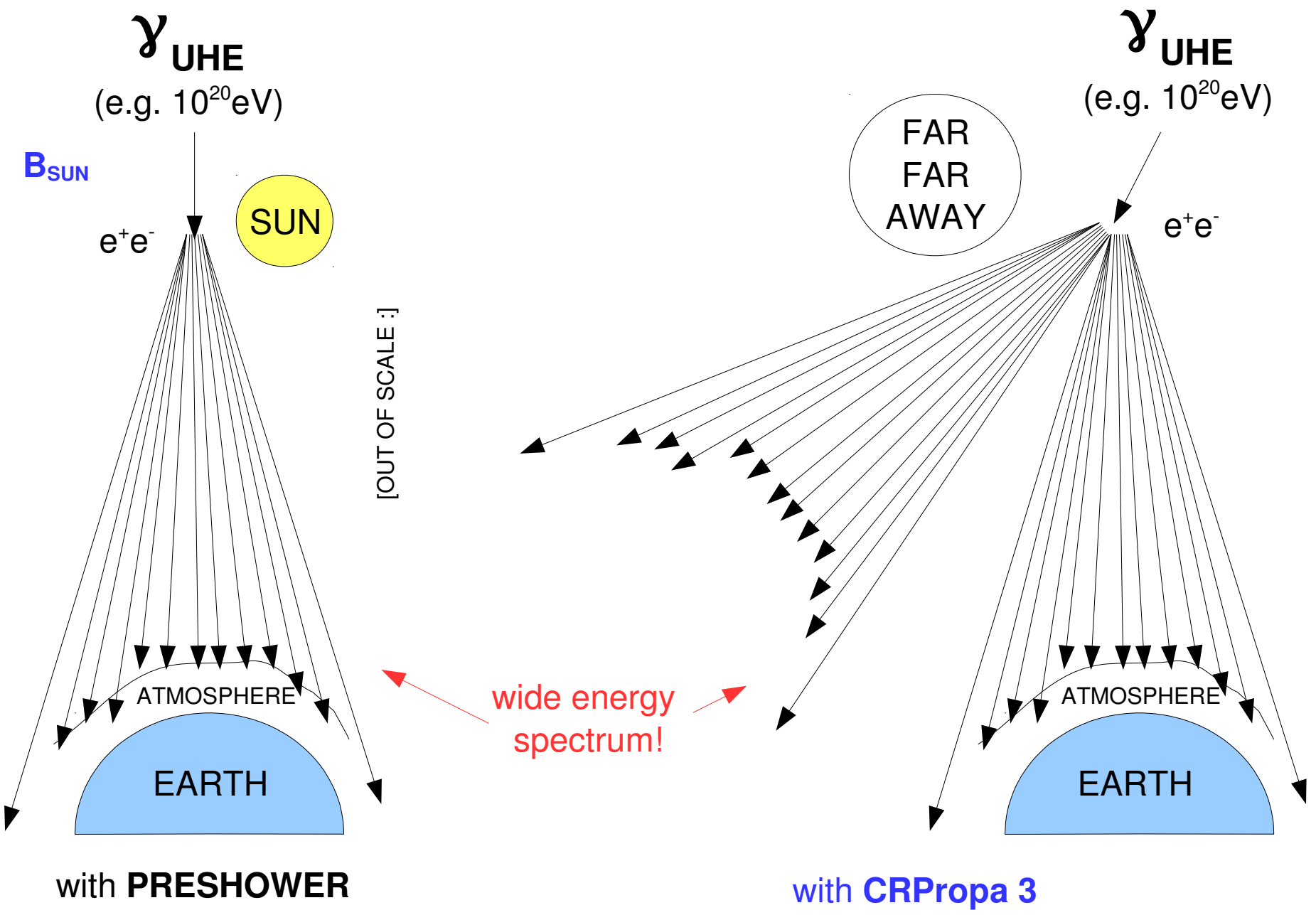
- large fraction of photons and neutrinos in UHCER flux

not the case?

γ_{UHE} travelling through the Universe: paradigm



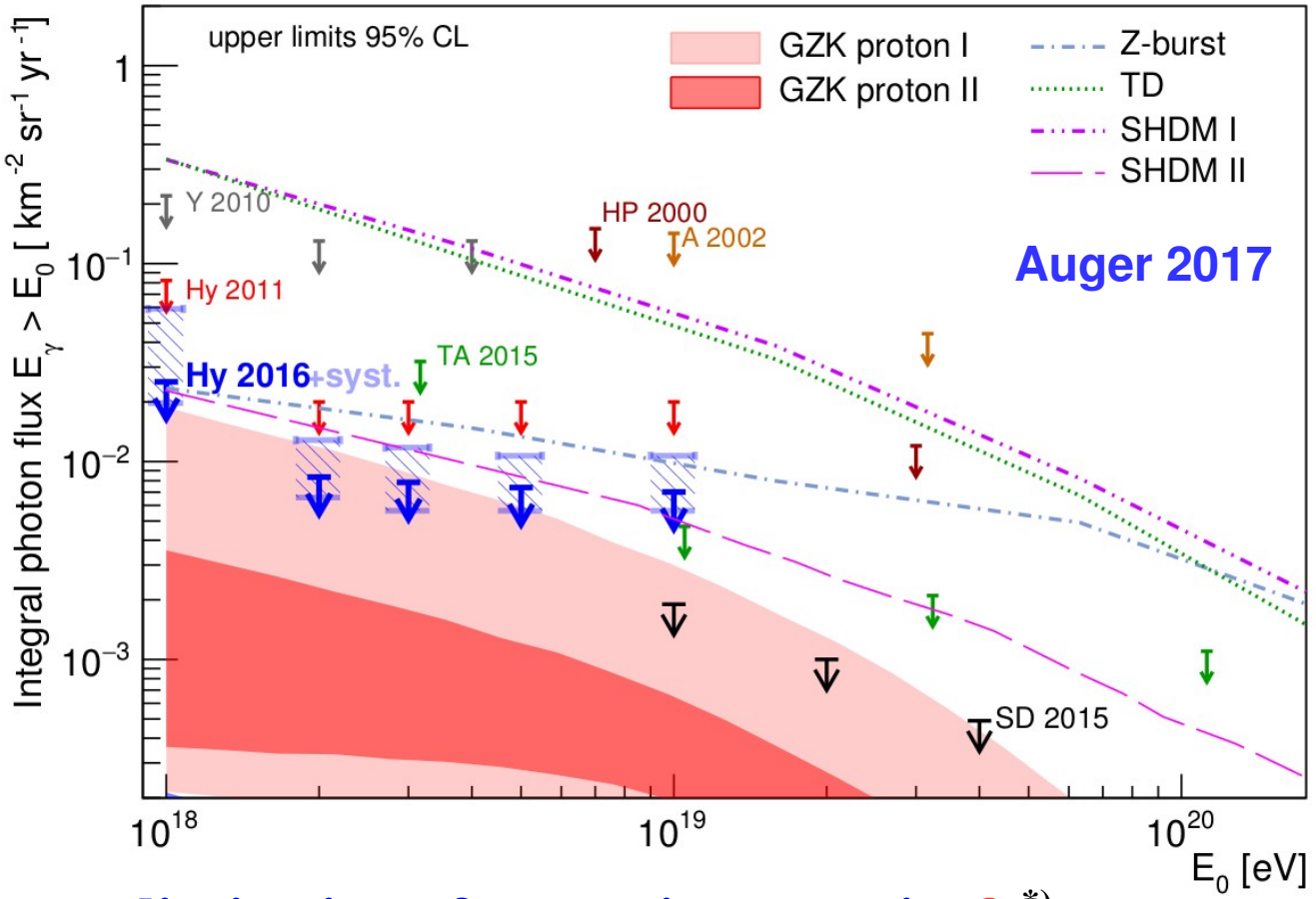
UHE photons → big cascades (classical examples)



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?** *)

*) **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 γ_{UHE}

γ_{UHE} —no interactions / screening→ **Earth**

NOT OBSERVED

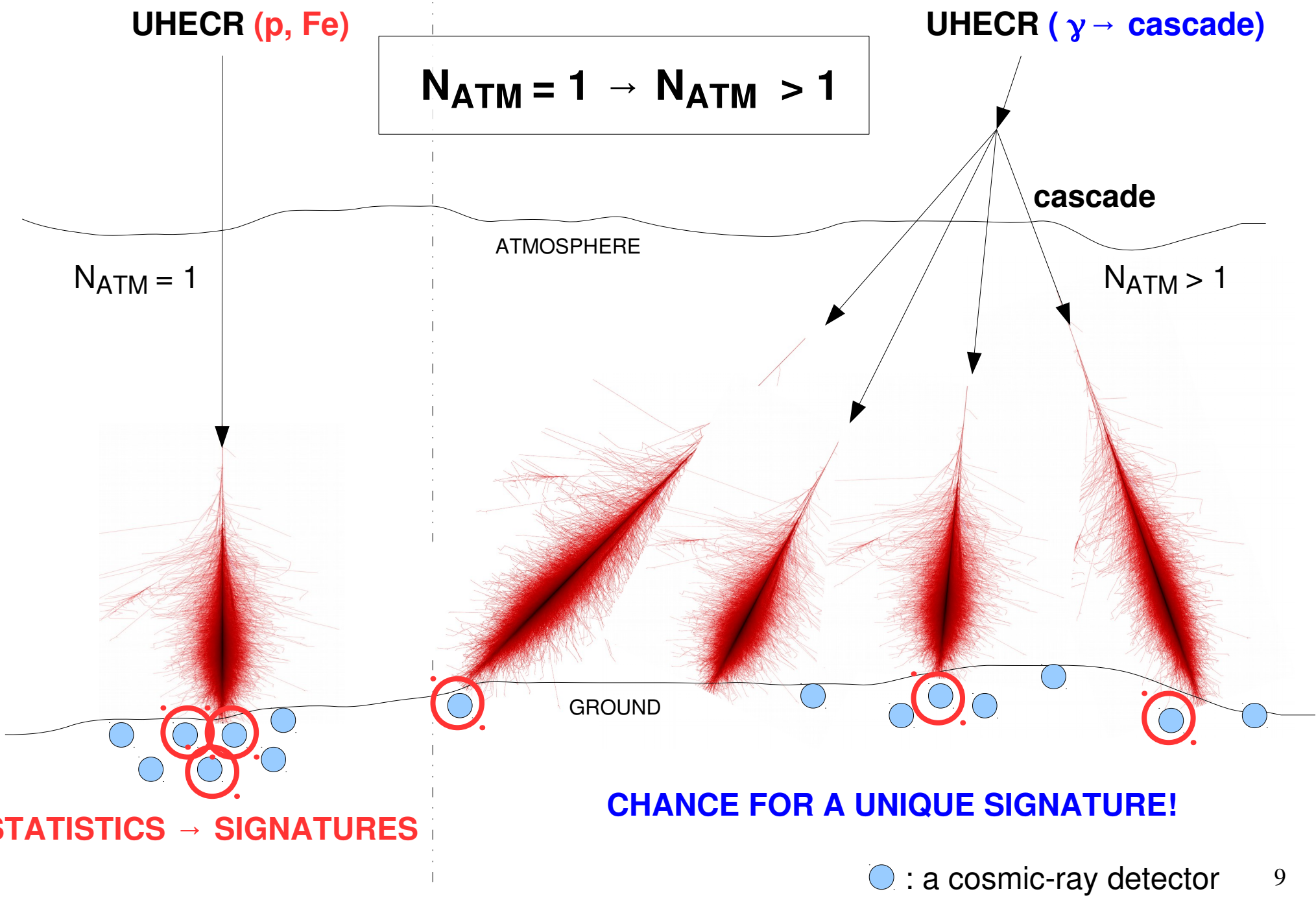
γ_{UHE} —unexpected interactions, screening, ...→ **ELECTROMAGNETIC CASCADES (SUPER-PRE-SHOWERS)** → **Earth**

NOT TRIED SO FAR...

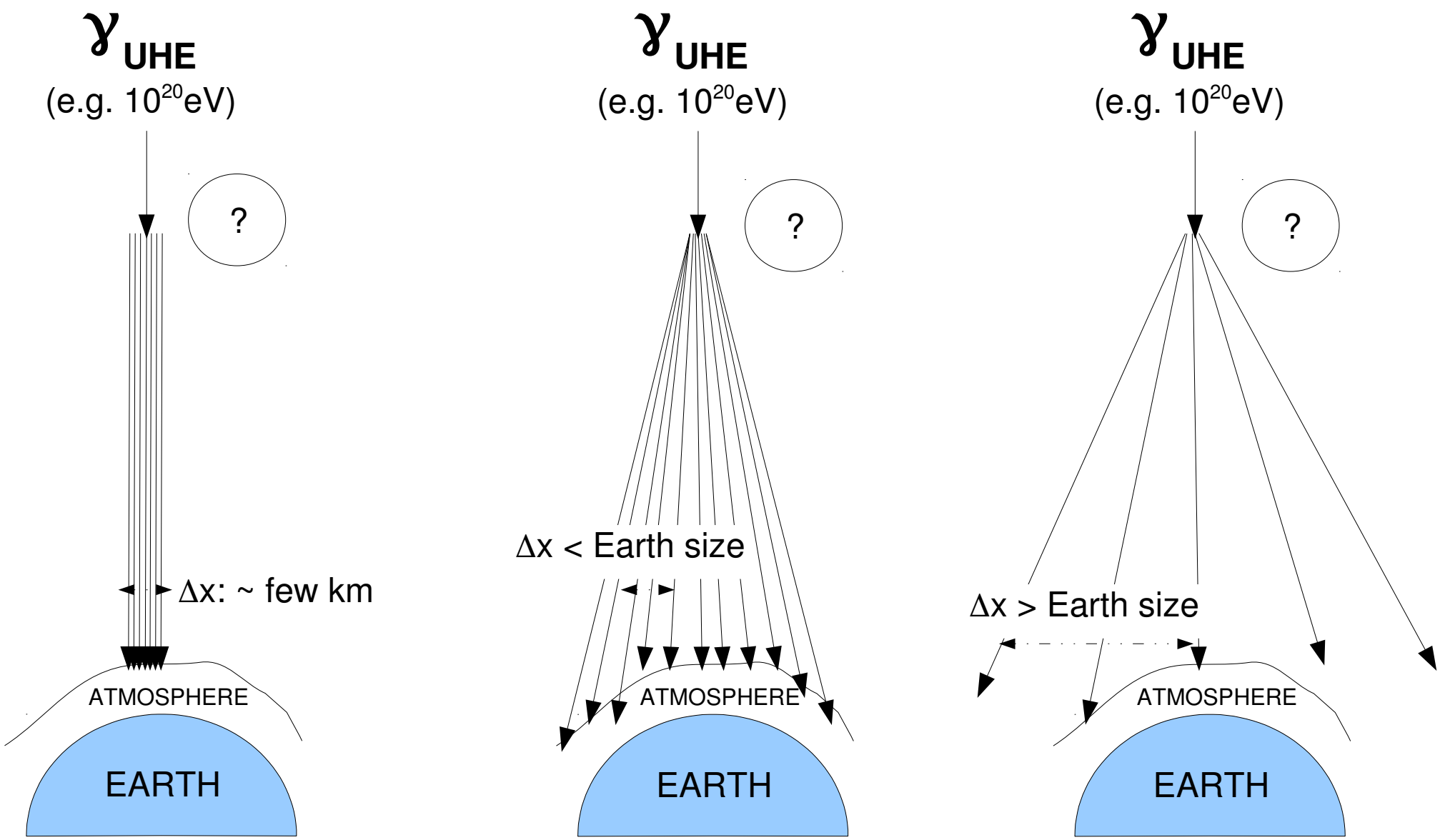
↓

CREDO!

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



N_{ATM} >= 1: untouched ground



$N_{ATM} > 1$ 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)

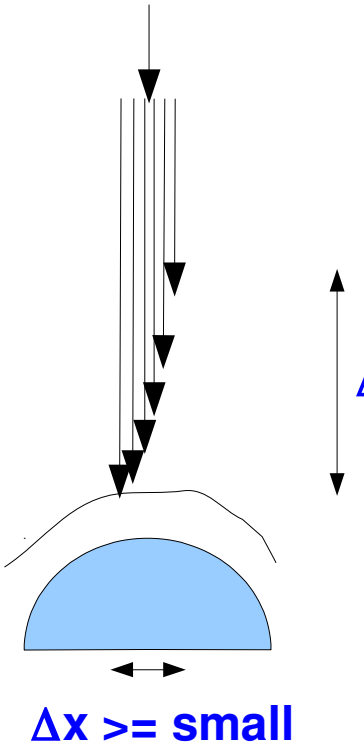
A series or burst of 32 extensive air showers of estimated mean energy 3×10^{15} eV was observed within a 5-min time interval beginning at 9:55 A.M. (CST) on 20 January 1981 in Winnipeg, Canada. This observation was the only one of its kind during an experiment which recorded 150 000 such showers in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

PACS numbers: 94.40.Pa, 96.Rc, 95.30.-k

Forgotten (!) treasure (?) no. 1

PH: Correlated cosmic rays?

$N_{ATM} > 1$?



Year = 1981
N_{obs} = 32
N_{exp} = 1
E = $3x10^{15}$eV

$N_{ATM} > 1$ 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)

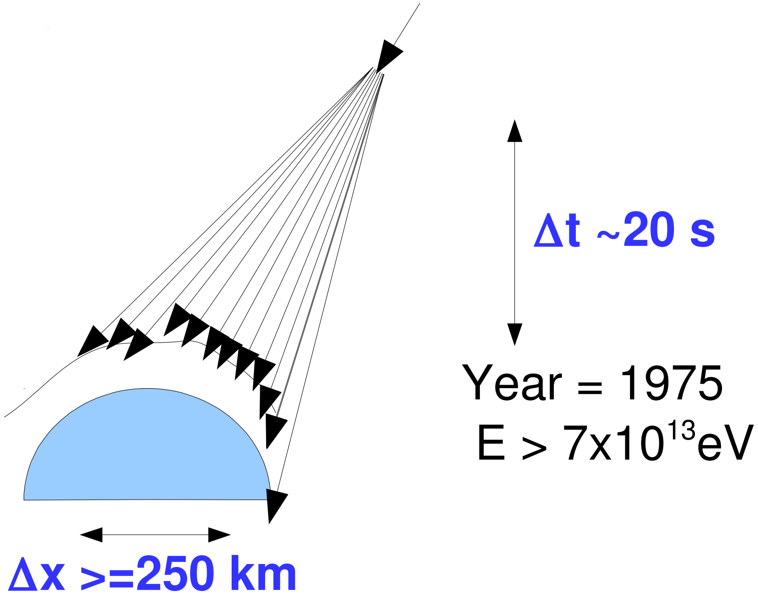
The authors report on an unusual simultaneous increase in the cosmic-ray shower rate at two recording stations separated by 250 km. The event lasted for 20 s. This event was the only one of its kind detected in three years of observation. The duration and structure of this event is different from a recently 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

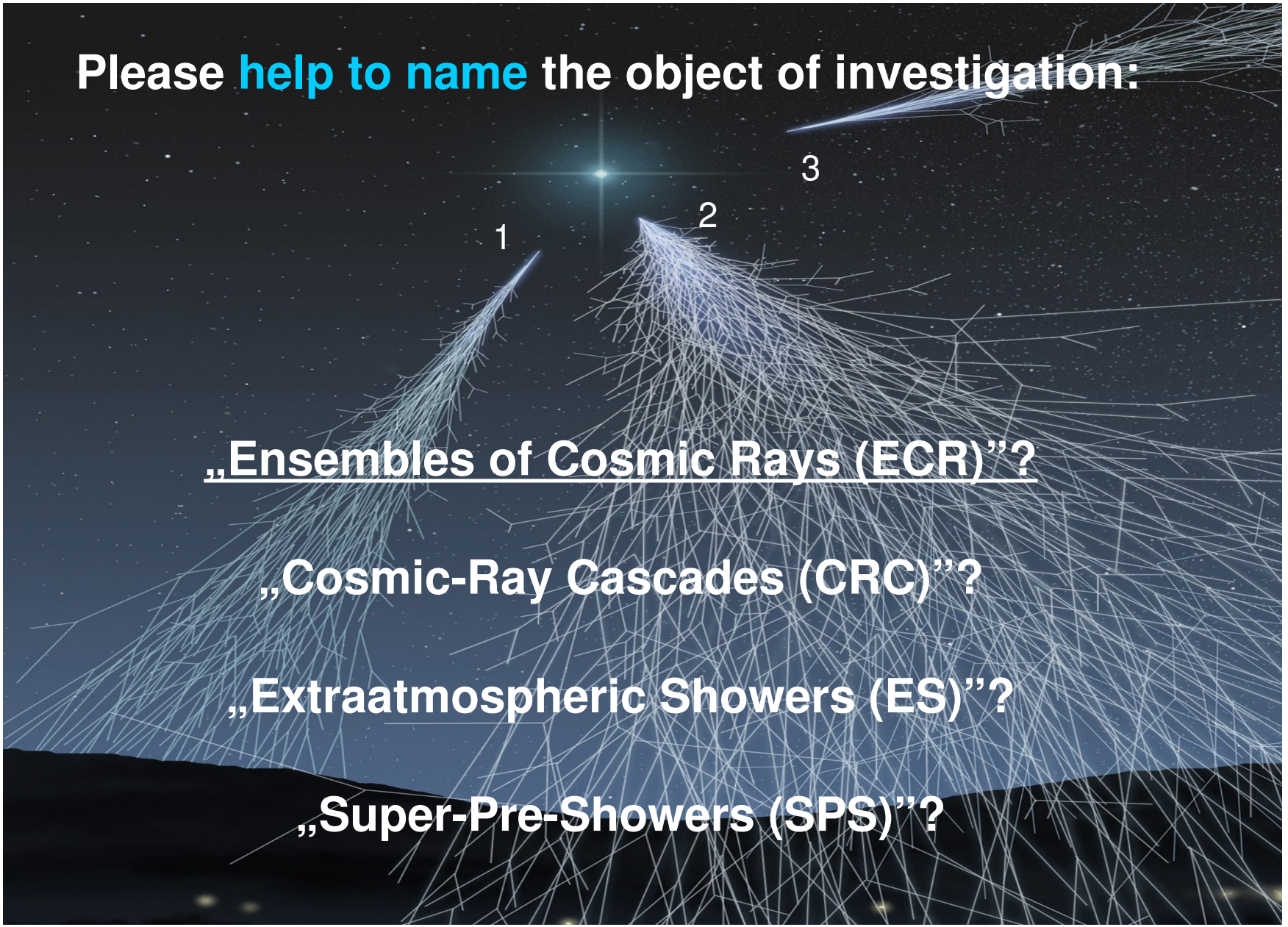
Forgotten (!) treasure (?) no. 2

PH: Correlated cosmic rays?

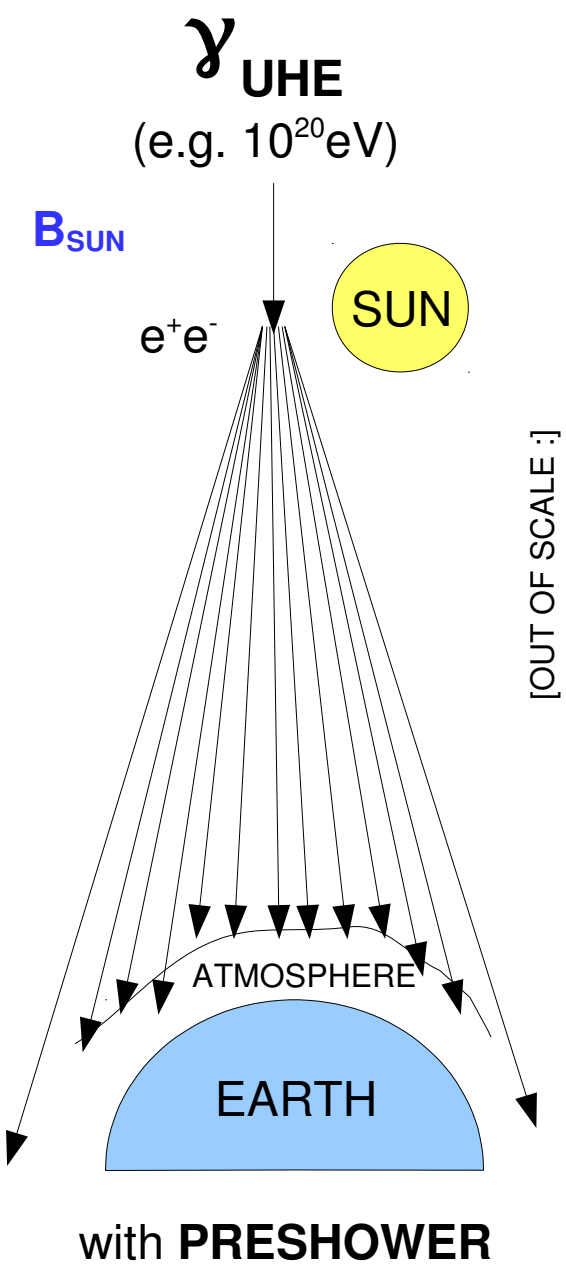
$N_{ATM} > 1$?



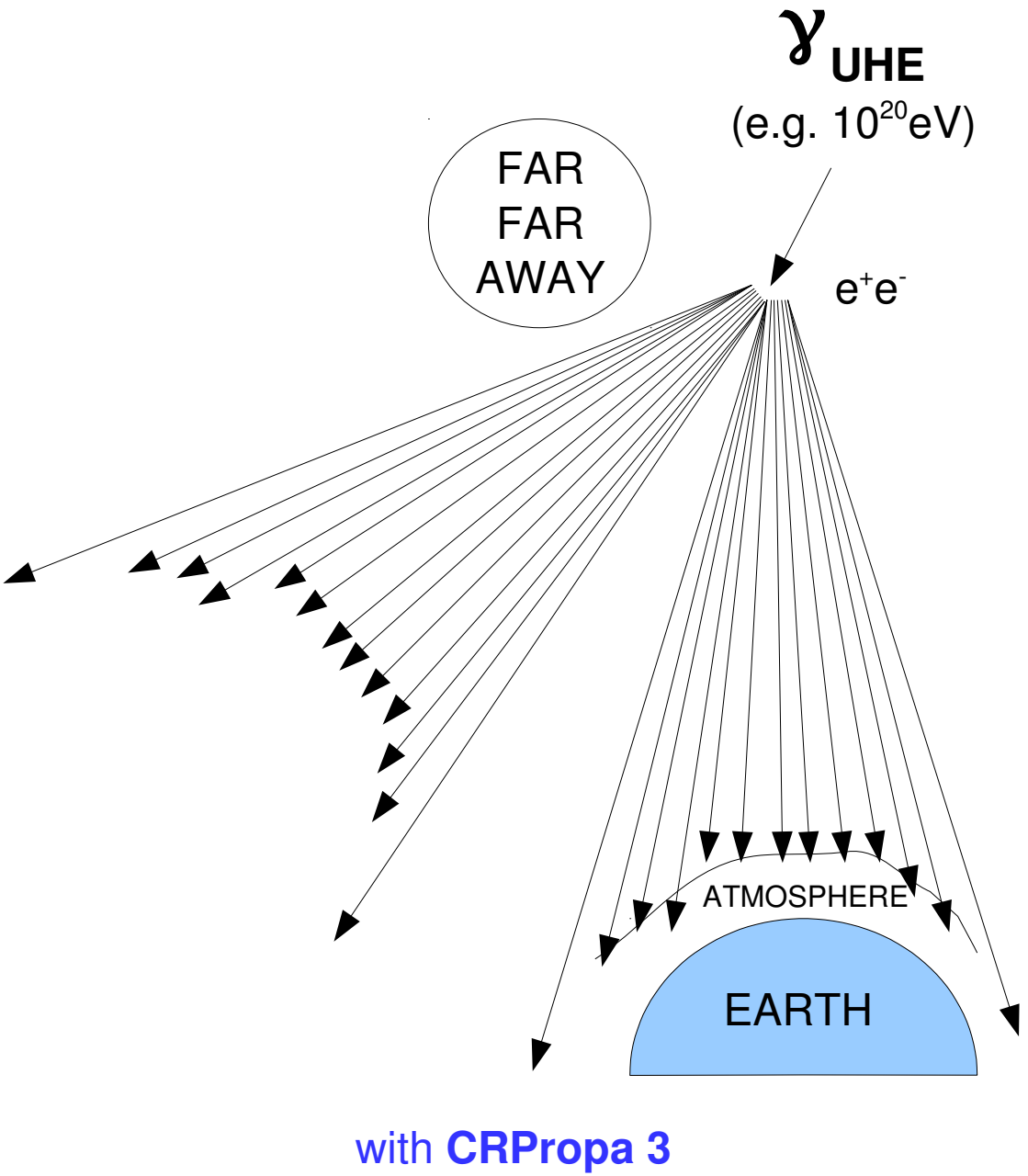
$N_{ATM} > 1$: new subfield of astroparticle physics!



UHE photons → big cascades (classical examples)



with **PRESHOWER**



with **CRPropa 3**

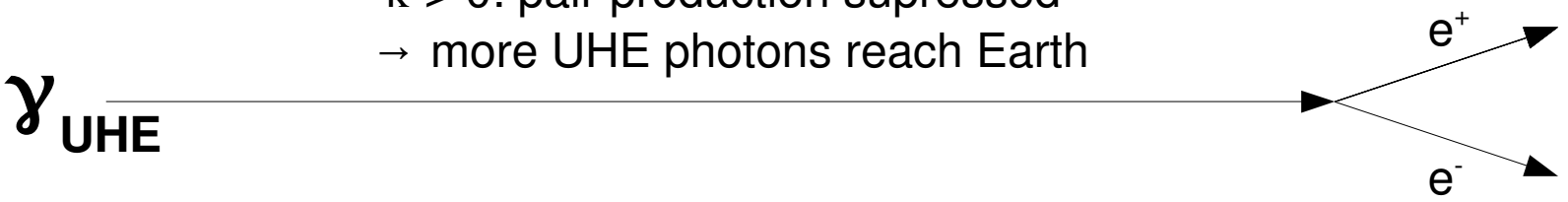
Motivation: Lorentz Invariance Violation

Modified dispersion relation of a photon:

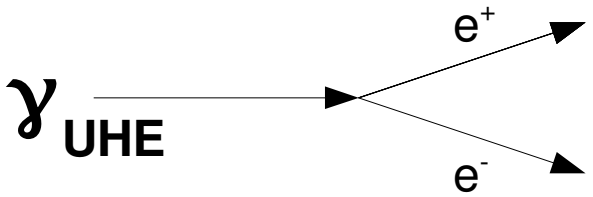
$$E_\gamma(\vec{k}) = \sqrt{\frac{(1-\kappa)}{(1+\kappa)}}|\vec{k}|$$

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

$\kappa > 0$: pair production supressed
→ more UHE photons reach Earth



$\kappa = 0$: „normal" pair production



$\kappa < 0$: 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 $\kappa < 0$!

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 [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*

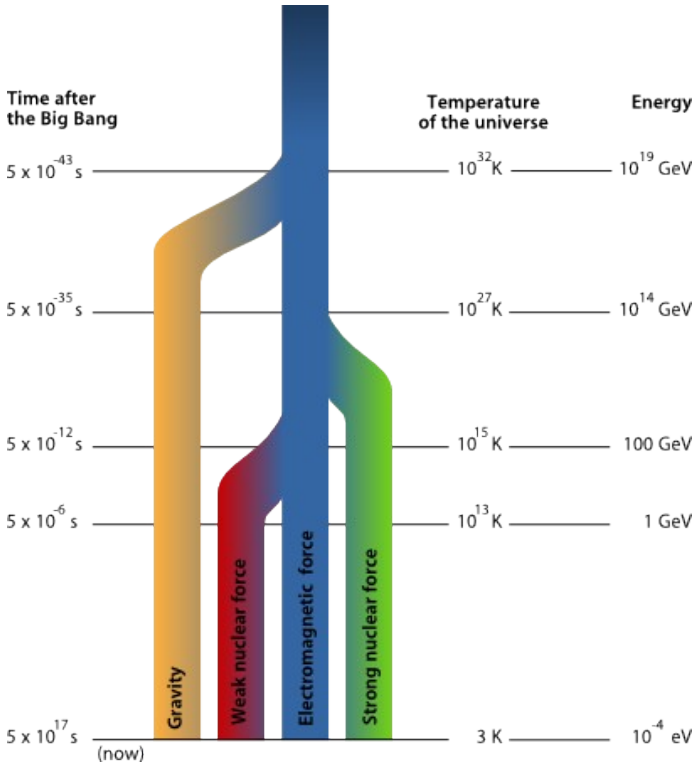
extensive review). A partial list of such "windows on quantum gravity" is

- 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)

Motivation: Novel Experimental Quantum Gravity

N_{ATM} >= 1 mission (briefly)

Scenarios AND Fishing



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

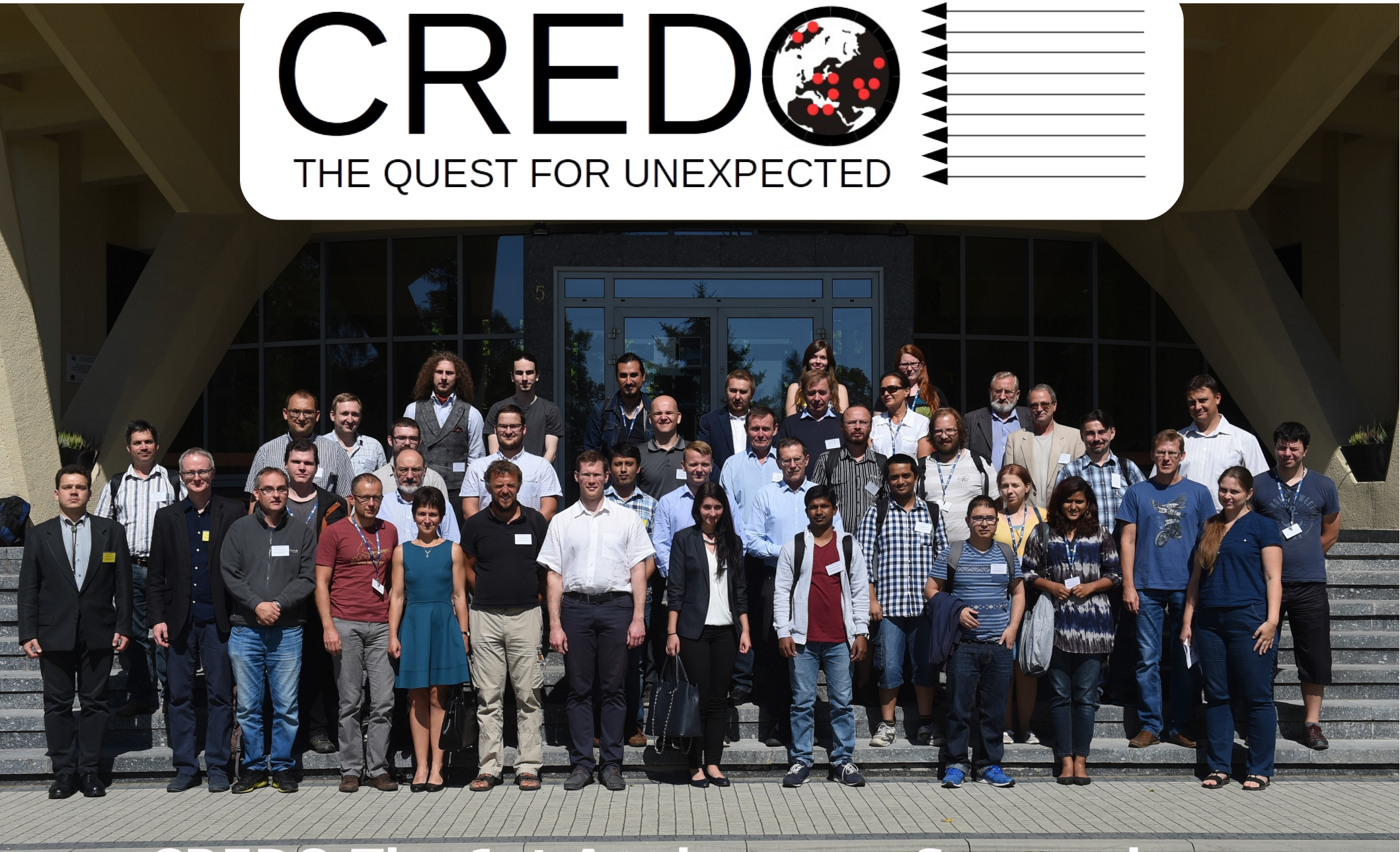
Cosmic-Ray Extremely Distributed Observatory

Status March 2016: „an idea"

Central database/interface: access to everything for everybody

CREDO

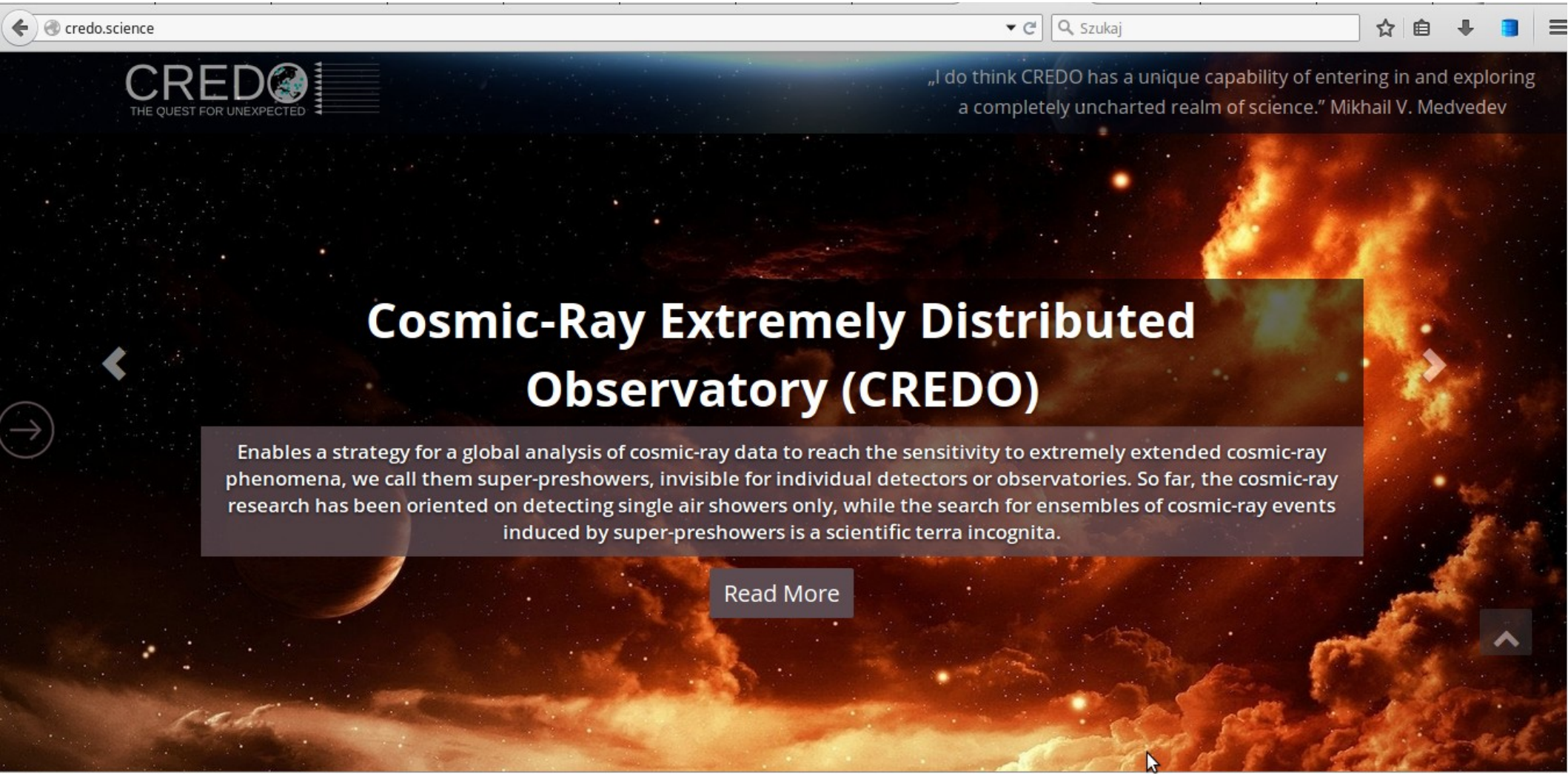
THE QUEST FOR UNEXPECTED



CREDO The 1st Anniversary Symposium
IFJ PAN Kraków, 30th August 2017

fot. Jan Zych

Visit credo.science...



… and contribute to CREDO science.

Summary

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]

Ensembles reach Earth? Most likely **photon ensembles**...

Cosmic-Ray Etremely Distributed Observatory:

- the pioneer receiver, already operating, stay tuned!

CREDO
THE QUEST FOR UNEXPECTED

SCHEMATIC, 8.09.2017

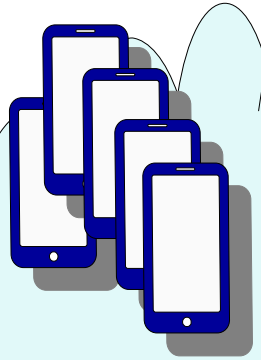
Data Acquisition Interfaces

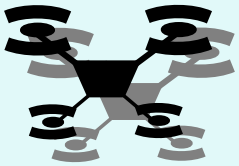
Data Access and RT Alert Interface

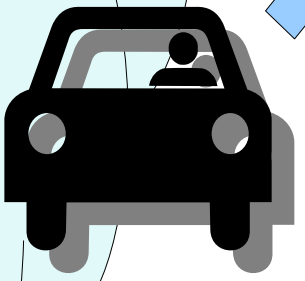
CREDO Computing Infrastructure

For Data Storage and Processing

Data Export Interface (experiment specific, common protocol)







Sensor Networks

- aggregated Data Analysis → **Science** (or **Nature** :)

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

Potentially...

Ensembles of Cosmic Rays (ECR): road map

Theoretical scenarios (ongoing)
non-exotic / exotic ✓

↓

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

↓

Air shower simulations (ongoing) ✓

↓

Detector response (ongoing) ✓

↓

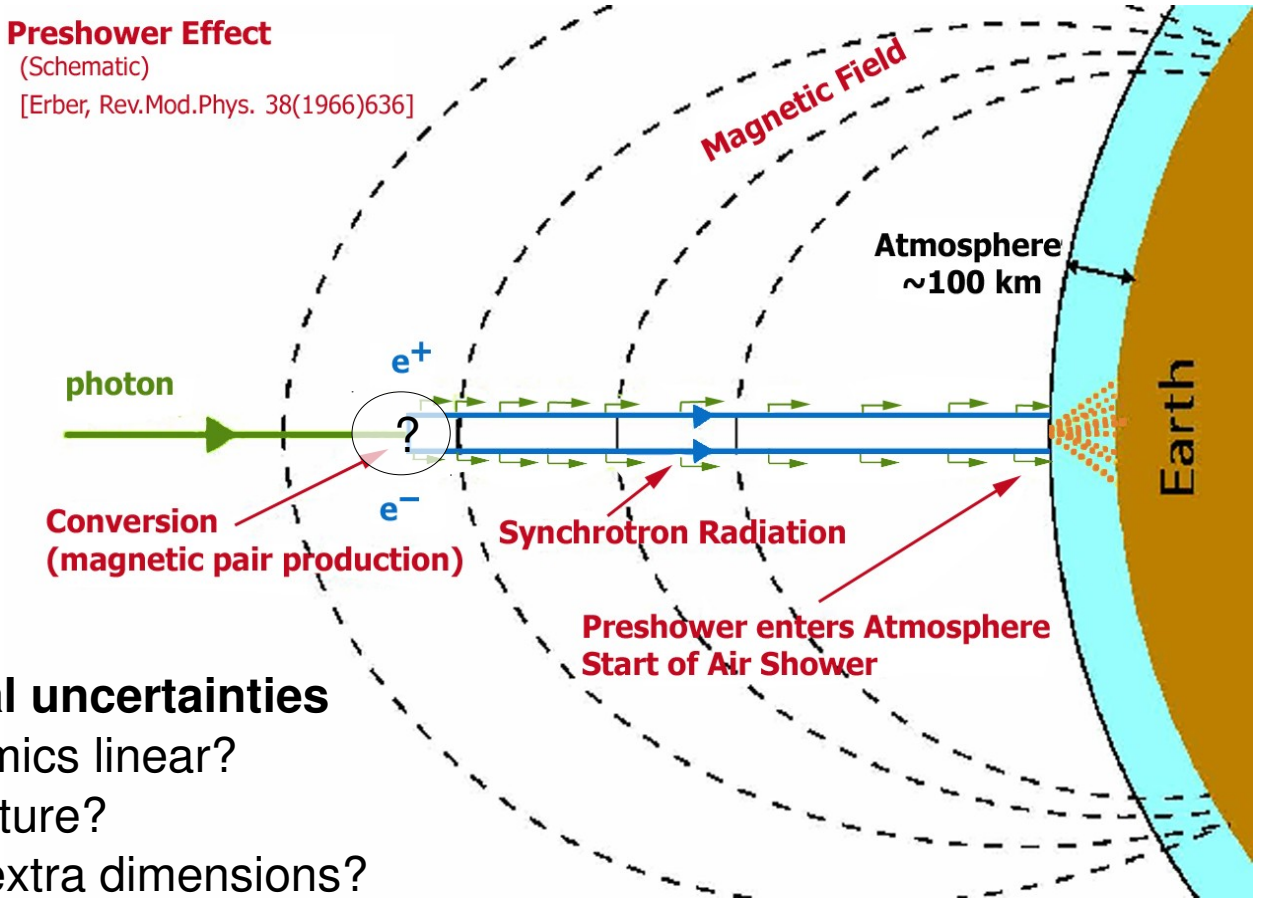
observation / upper limits

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

(super-)preshower:

→ contains typically **(>1000)** 100 particles

→ created at around **(>10000)** 1000 km a.s.l.)



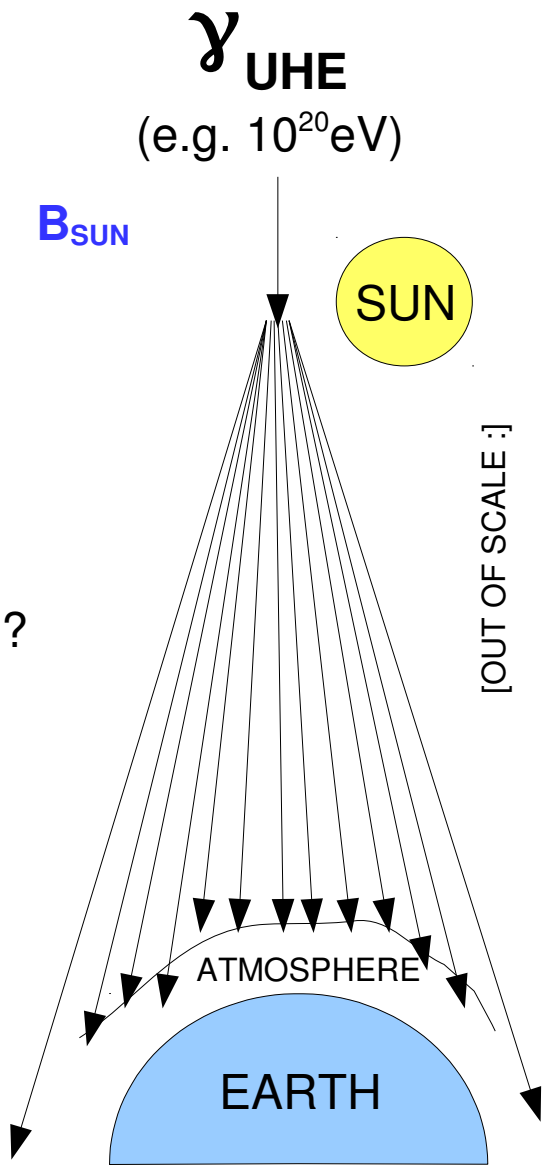
? : **fundamental uncertainties**

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

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

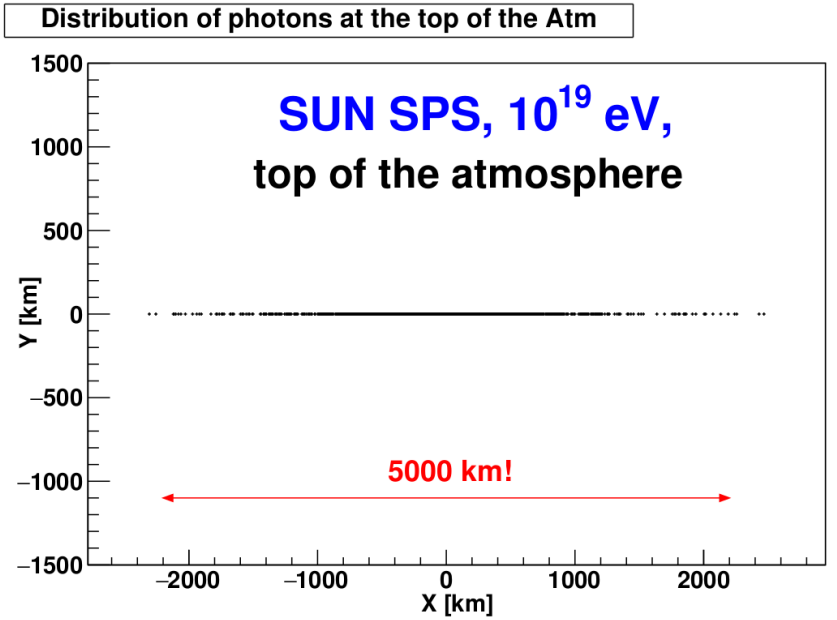
Super-preshowers from the vicinity of the Sun

C & D:



→ First calculations: W. Bednarek 1999
low energies not treated: extent ~ tens of km

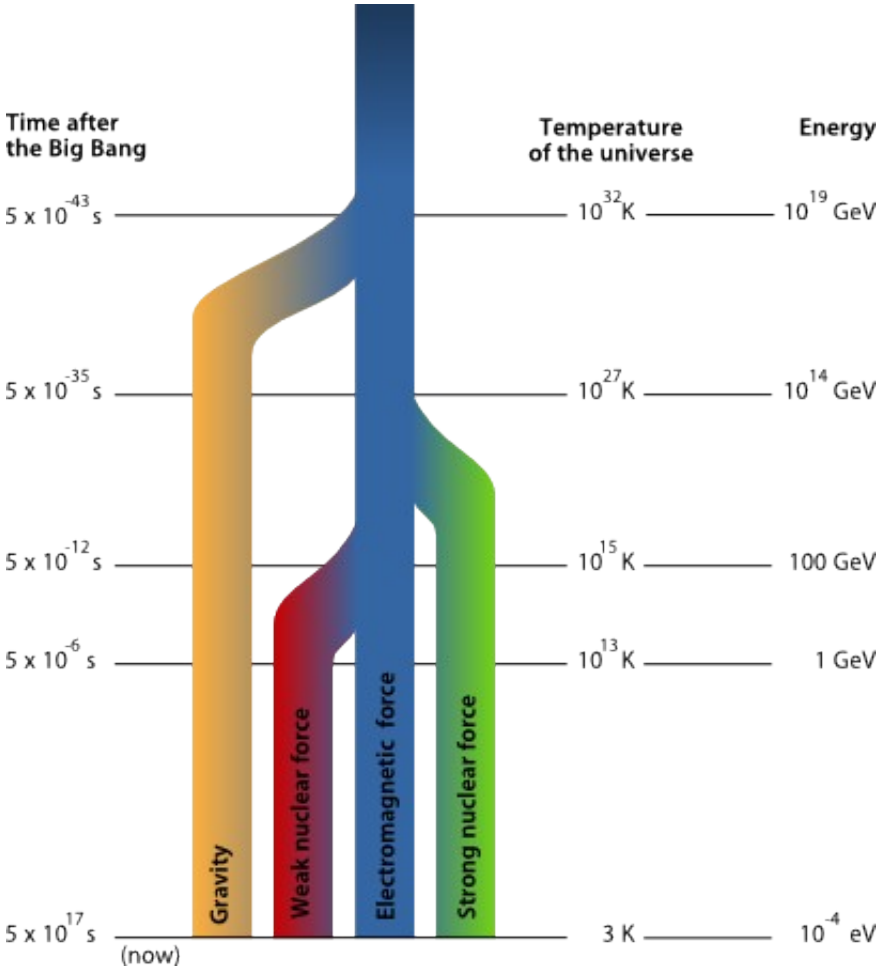
→ N. Dhital, 2017
complete energy spectrum: extent
~ thousands of km



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

N_{ATM} > 1, type C → observable (line ~10000 km wide), **not yet tried**

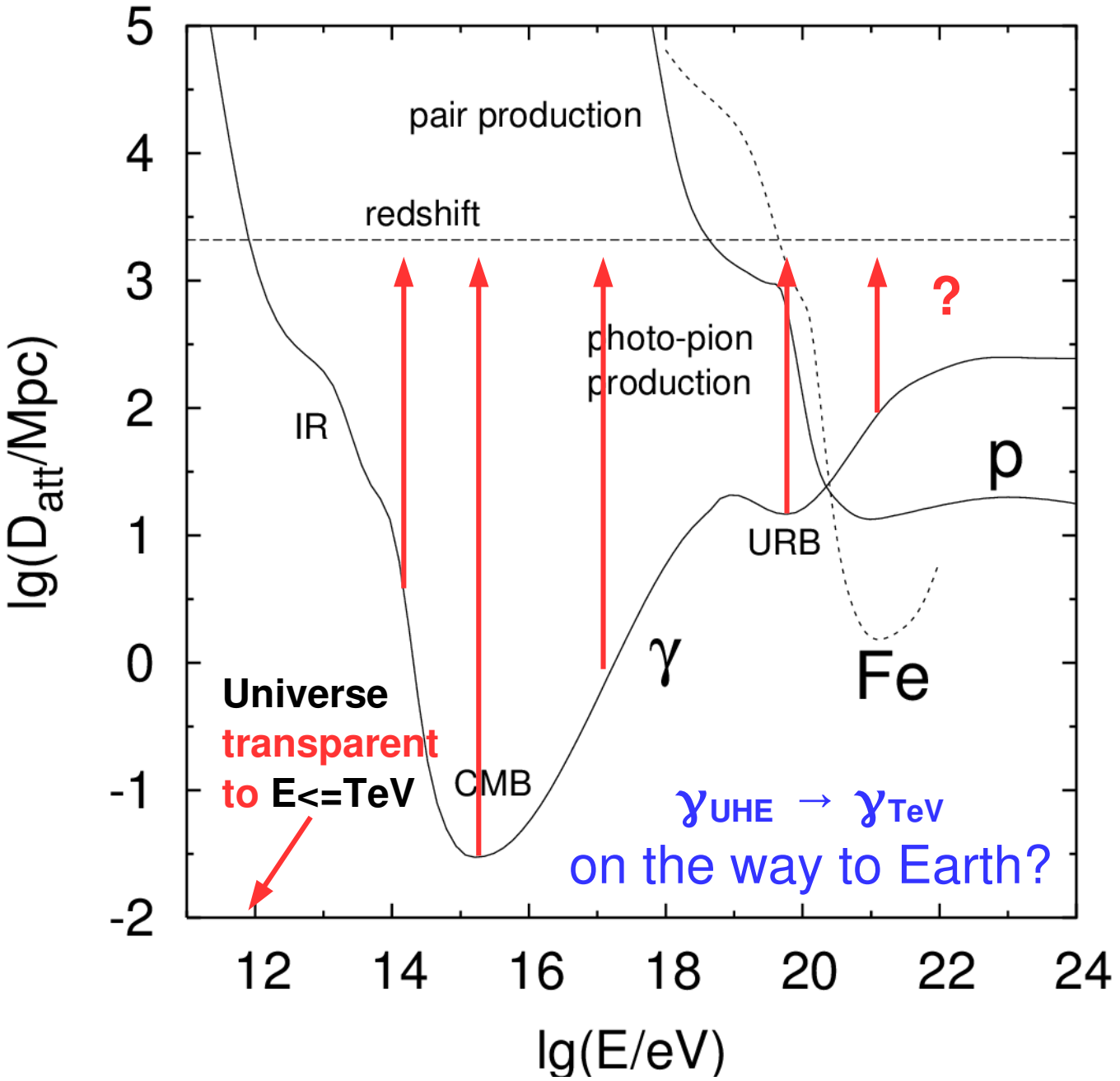
Motivation: GUT!



http://quantum-bits.org

SHDM: E ~ 10^{23}eV
Grand Unified Theories!

γ_{UHE} travelling through the Universe: exotic example



Ensembles of Cosmic Rays (ECR): shortcut road map

Theoretical review (ongoing) ✓

↓

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

↓

Air shower simulations (ongoing) ✓

↓

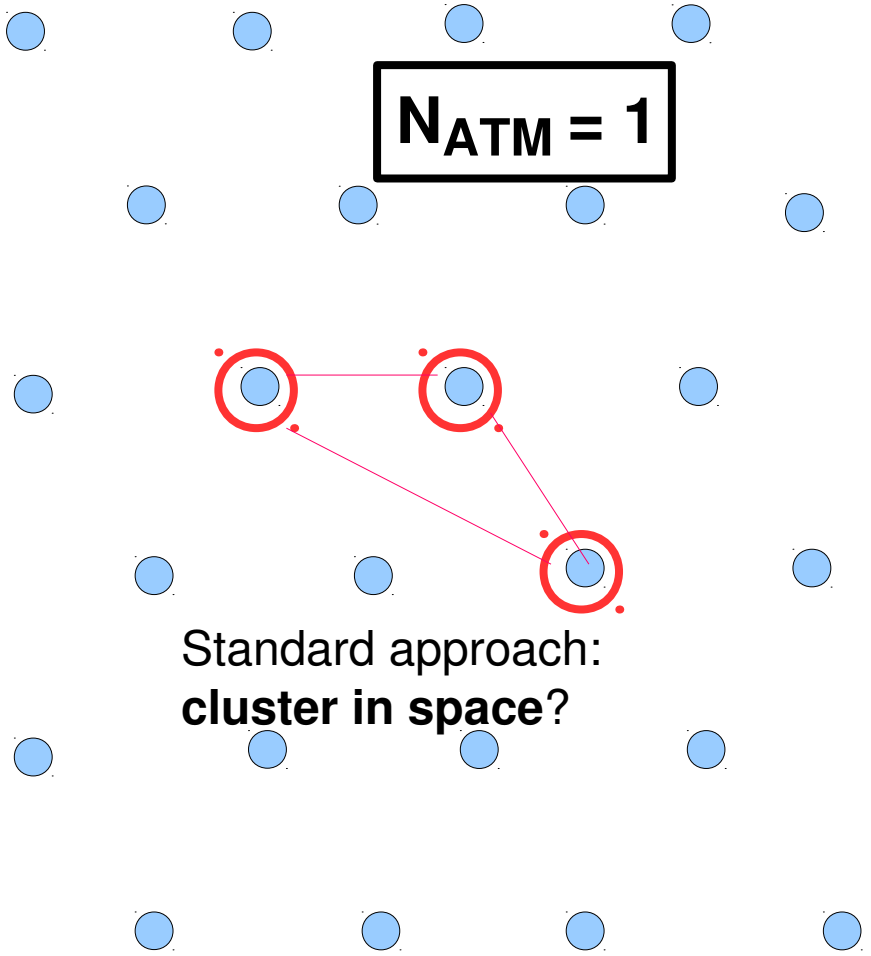
Detector response (ongoing) ✓

↓

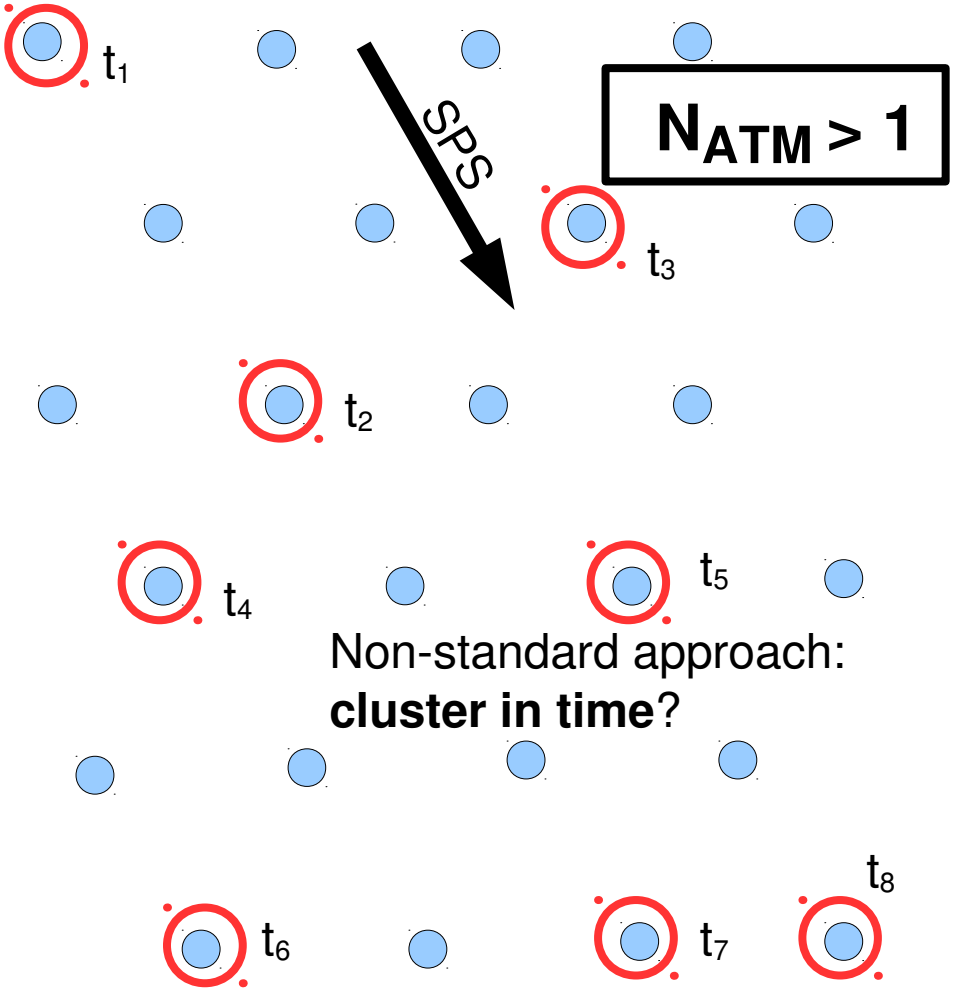
observation / upper limits

unique signature **fishing (ongoing)** ✓

A chance for a unique super-preshower signature



Standard approach:
cluster in space?



Non-standard approach:
cluster in time?

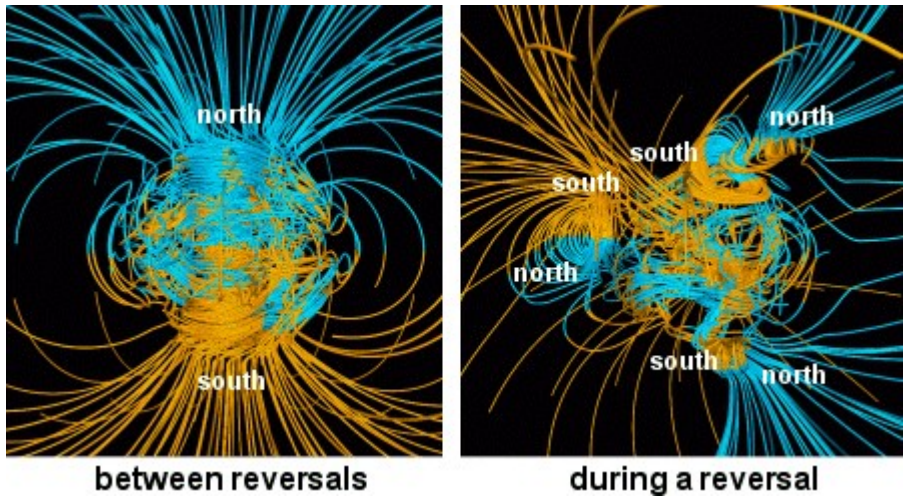
1) $t_n - t_1 < \Delta t$
2) $t_1 < \ldots < t_n$

: a cosmic-ray detector

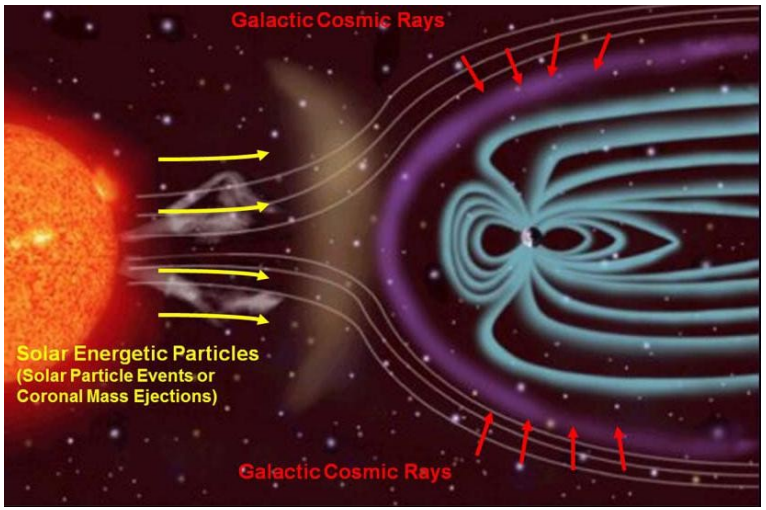
CREDO
THE QUEST FOR UNEXPECTED

Scientific diversity: GEO

Wikipedia: „Geomagnetic reversal”



Wikipedia: „Health threat from cosmic rays”



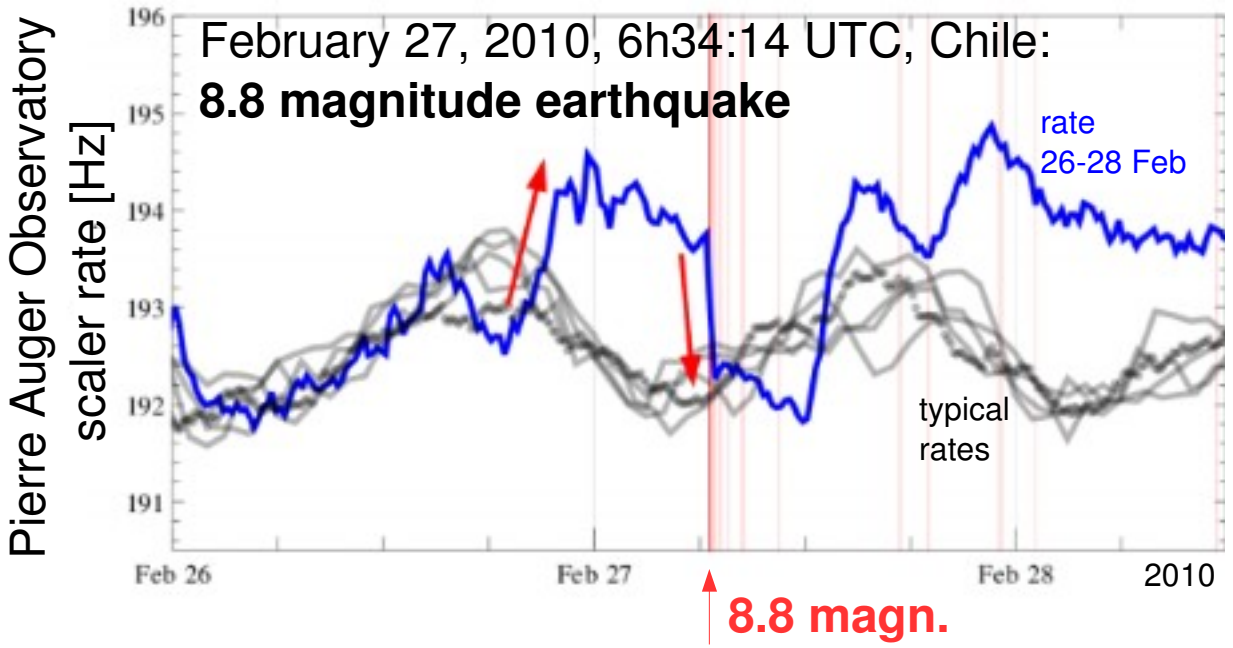
Earth outer core: Liquid (molten iron)
→ geomagnetism
↓
Impulse (tidal forces)
→ hydrodynamics: waves
↓
→ Mechanical wave upwards (slow, hours?)
→ Electromagnetic wave („instant”, ms)
↓
Local geomagnetic field vector changes
AND seismic effect might occur!
↓
Variation of the CR rate!
↓
Earthquake precursors?

CREDO

THE QUEST FOR UNEXPECTED

Scientific diversity: GEO

PAO sees earthquakes [by A. Saleh]



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

→ **CREDO-earthquakes task** [already existing]

Incubator: Discovery training

Incubator role:

discoveries! (scientific **think tank**)

↓

Training required

… but no „**discovery education**”

↓

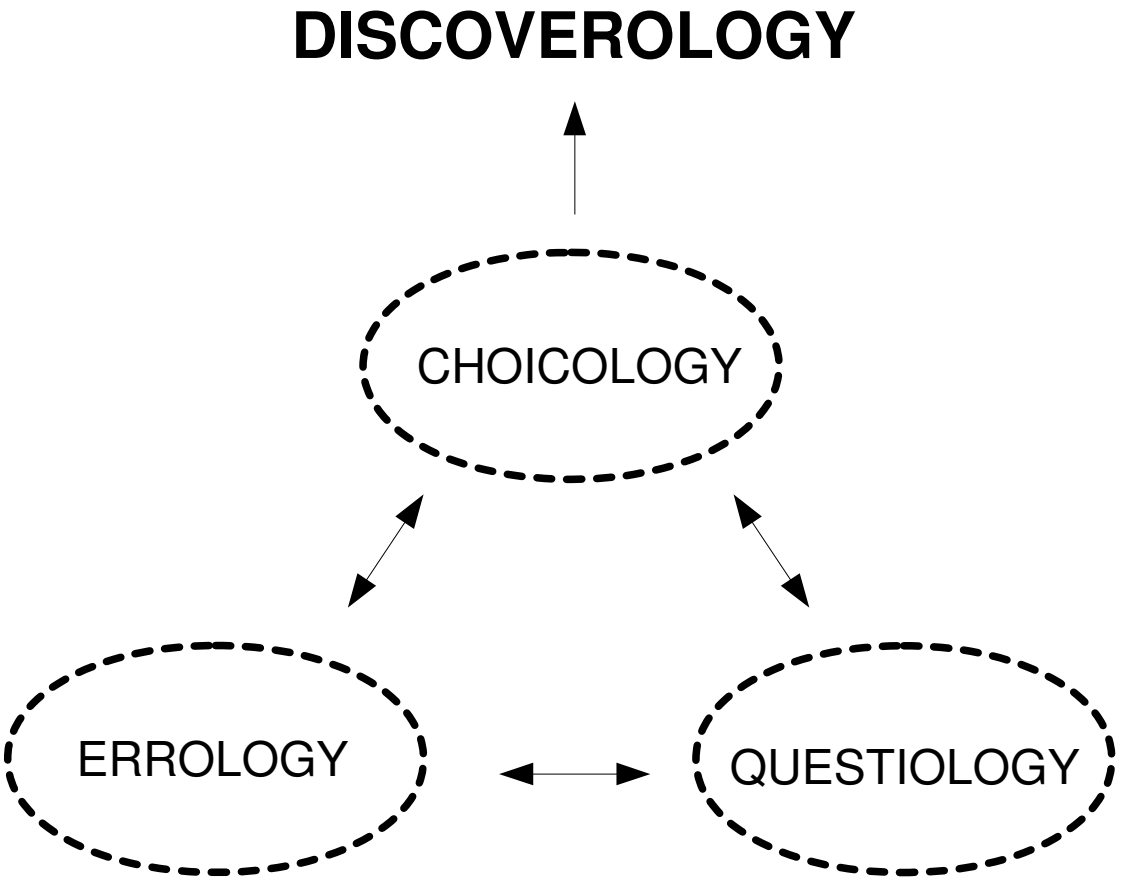
Consequtive approximation method...

→ doing science (real discovery-oriented projects)

→ **remove obstacles for independent thinking**

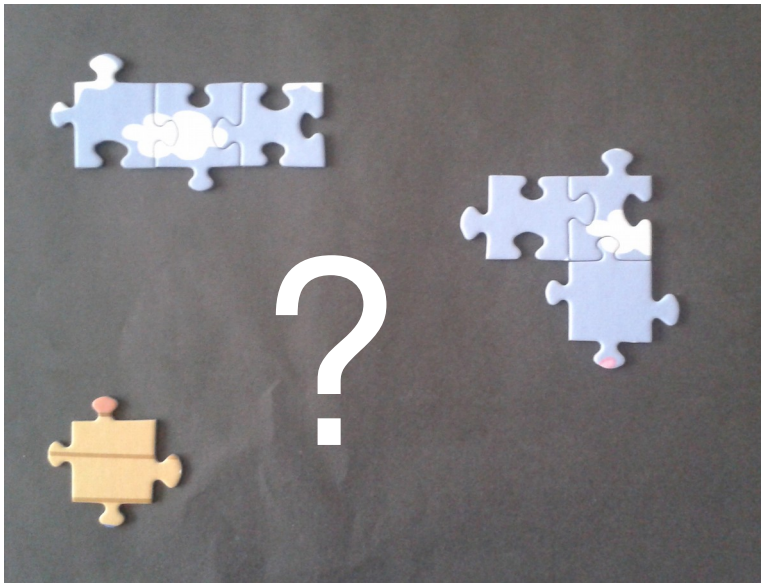
→ practice the **art of asking questions**

More than a training... discipline?



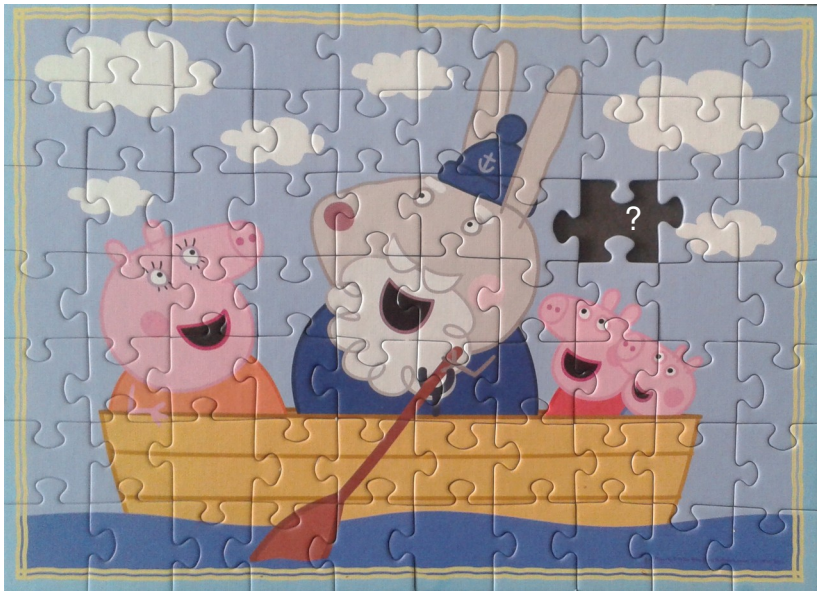
CHOICOLOGY: what do I do?

UNIVERSE A



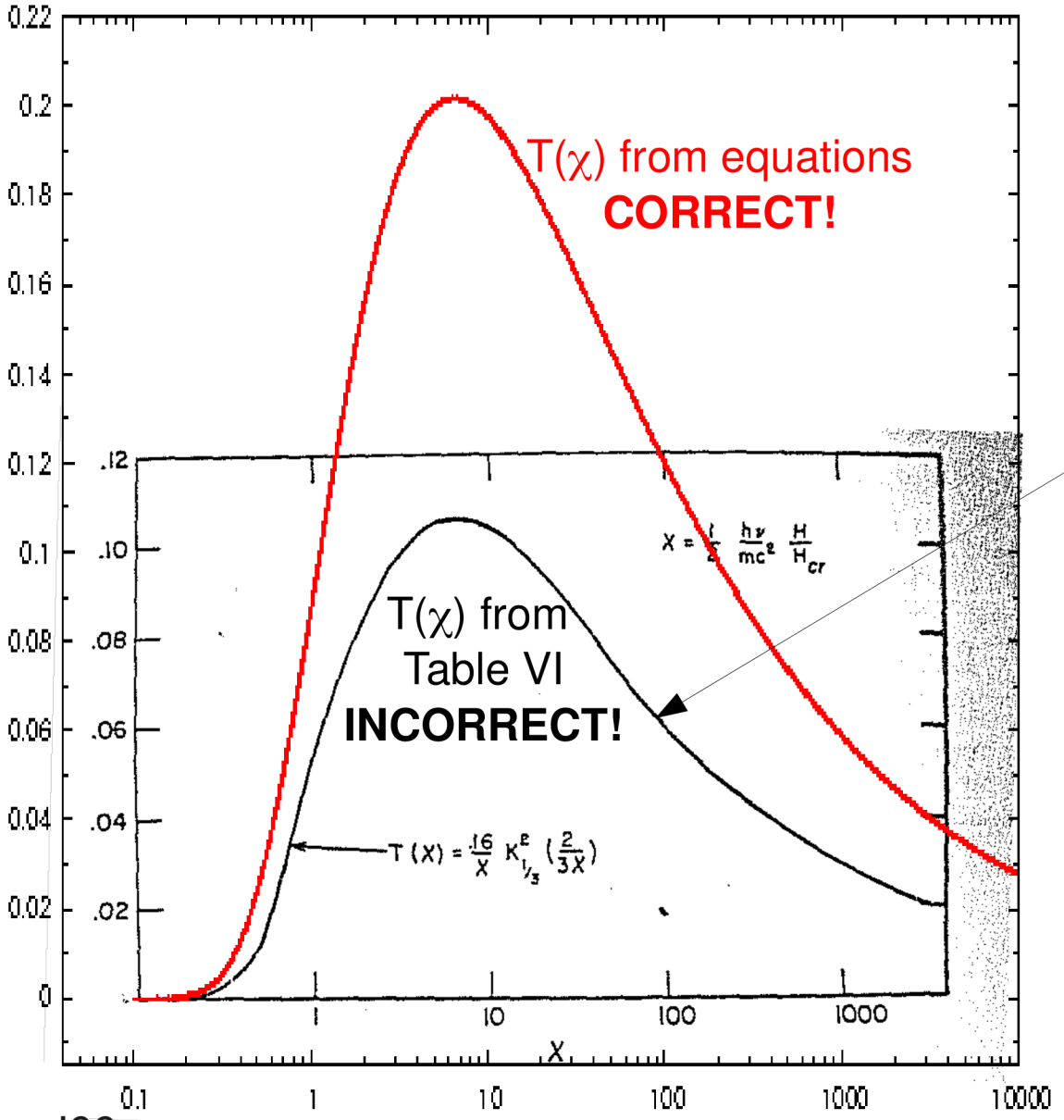
or

UNIVERSE B



?

ERROLOGY: do I do well?



Erber '66:

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	2×10^{-4}
0.3	2.2×10^{-3}
0.4	6.6×10^{-3}
0.7	0.026
1.2	0.055
3.0	0.094
5.0	0.10
6.0	0.10
7.0	0.10
9.0	0.10
15	0.099
30	0.085

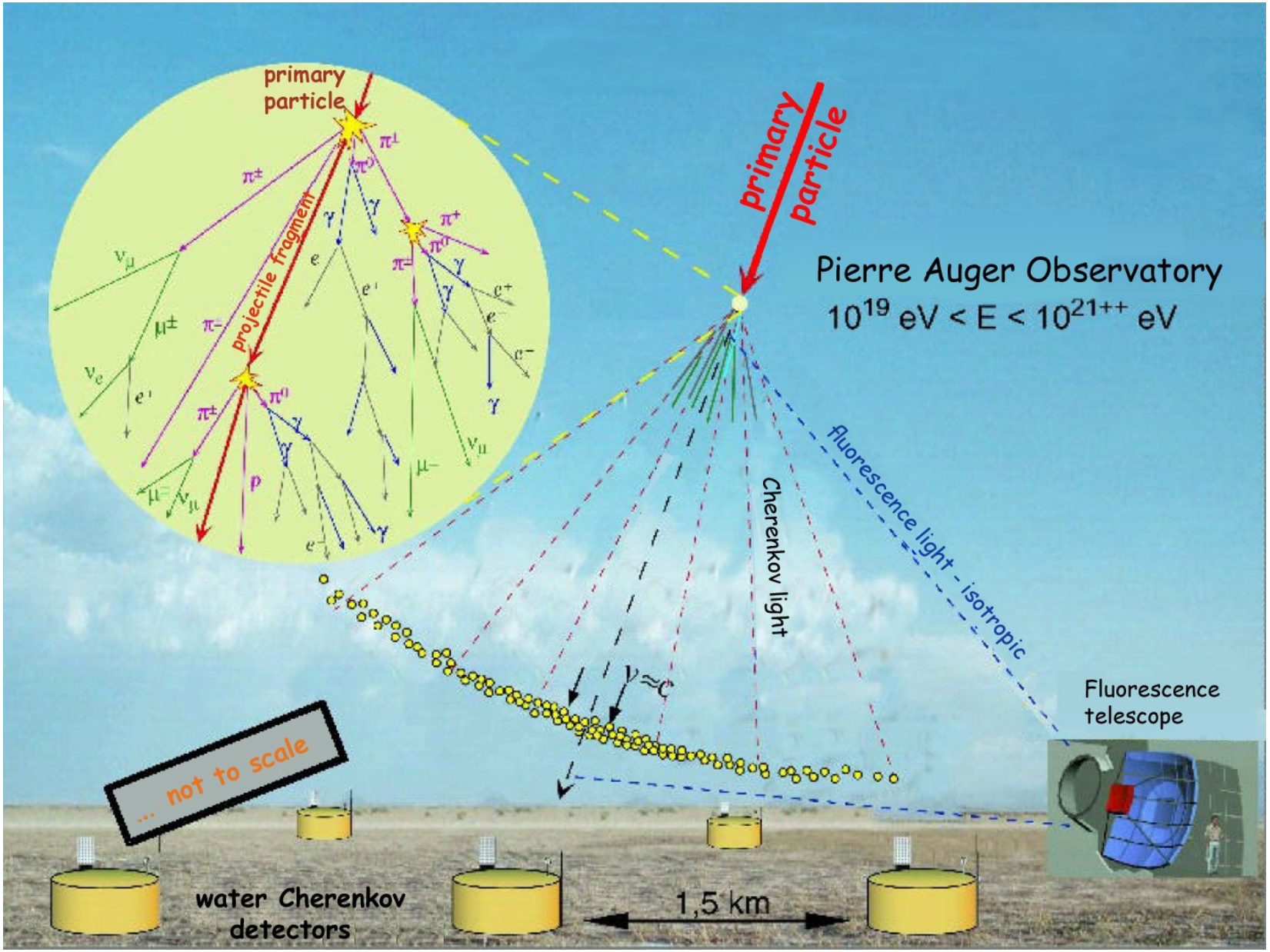
INCORRECT!

$T(\chi)$ 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

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



Motivation for cosmic-ray cascades

Next generation cosmic-ray research:

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

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 change the photon research landscape