The Cosmic Ray Extremely Distributed Observatory (CREDO)

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(ISVHECRI 2024)
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INCUBATOR OF SCIENTIFIC EXCELLENCE

UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

THE QUEST FOR THE UNEXPECTED

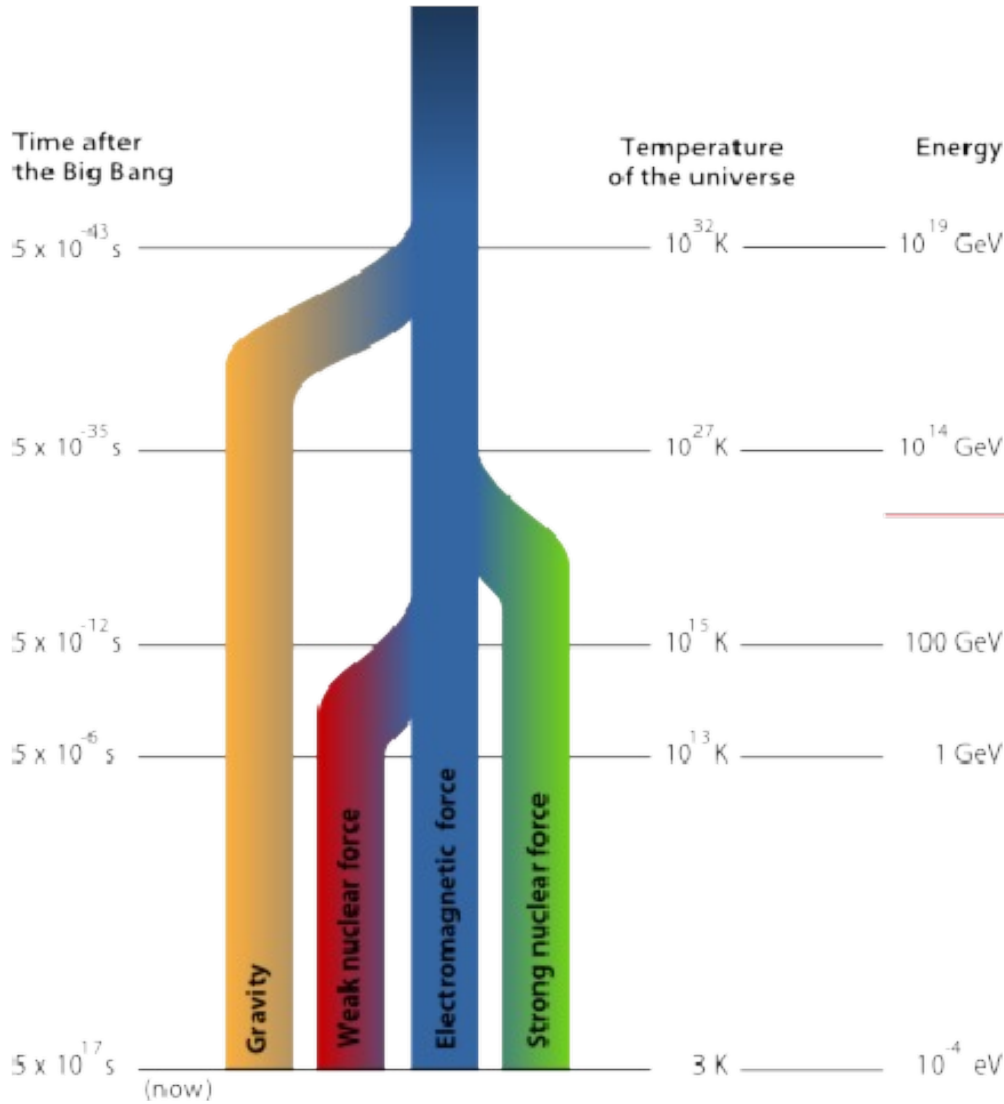
Outline

- Introduction to ultra high energy cosmic rays physics.
- Astrophysical sources of UHECRs
- Introduction to CREDO: multi-messenger astronomy
- Tests of space-time structure, LIV, Fundamental Constants Variation
- Compact Stars, Quark matter and the Axion
- Other possible applications of CREDO

Energy: the higher the better?

Theory of „Everything"
Quantum Gravity?

Grand Unified Theory?

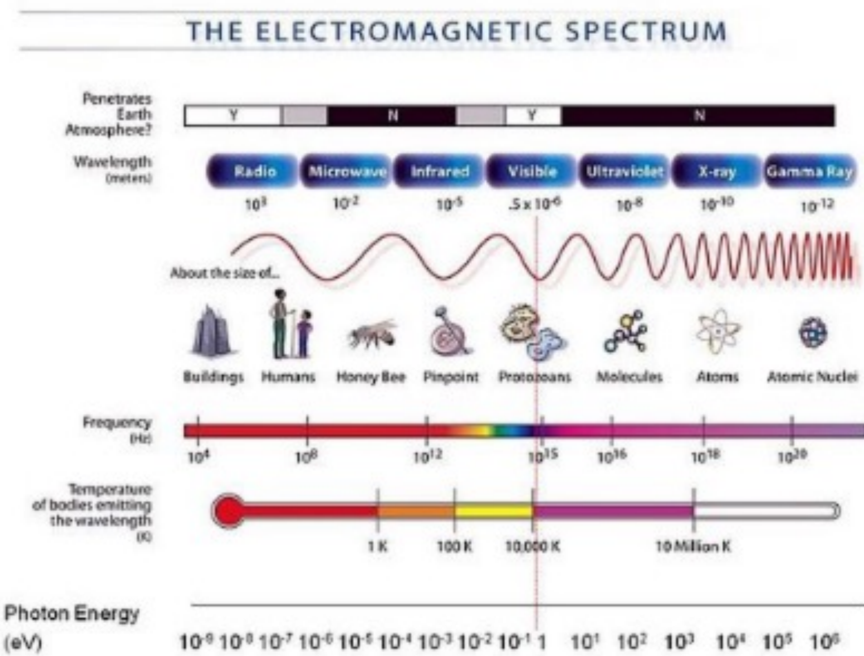


Planck scale

Ultra-high energies (10^{20} eV)

Energy!

Photons



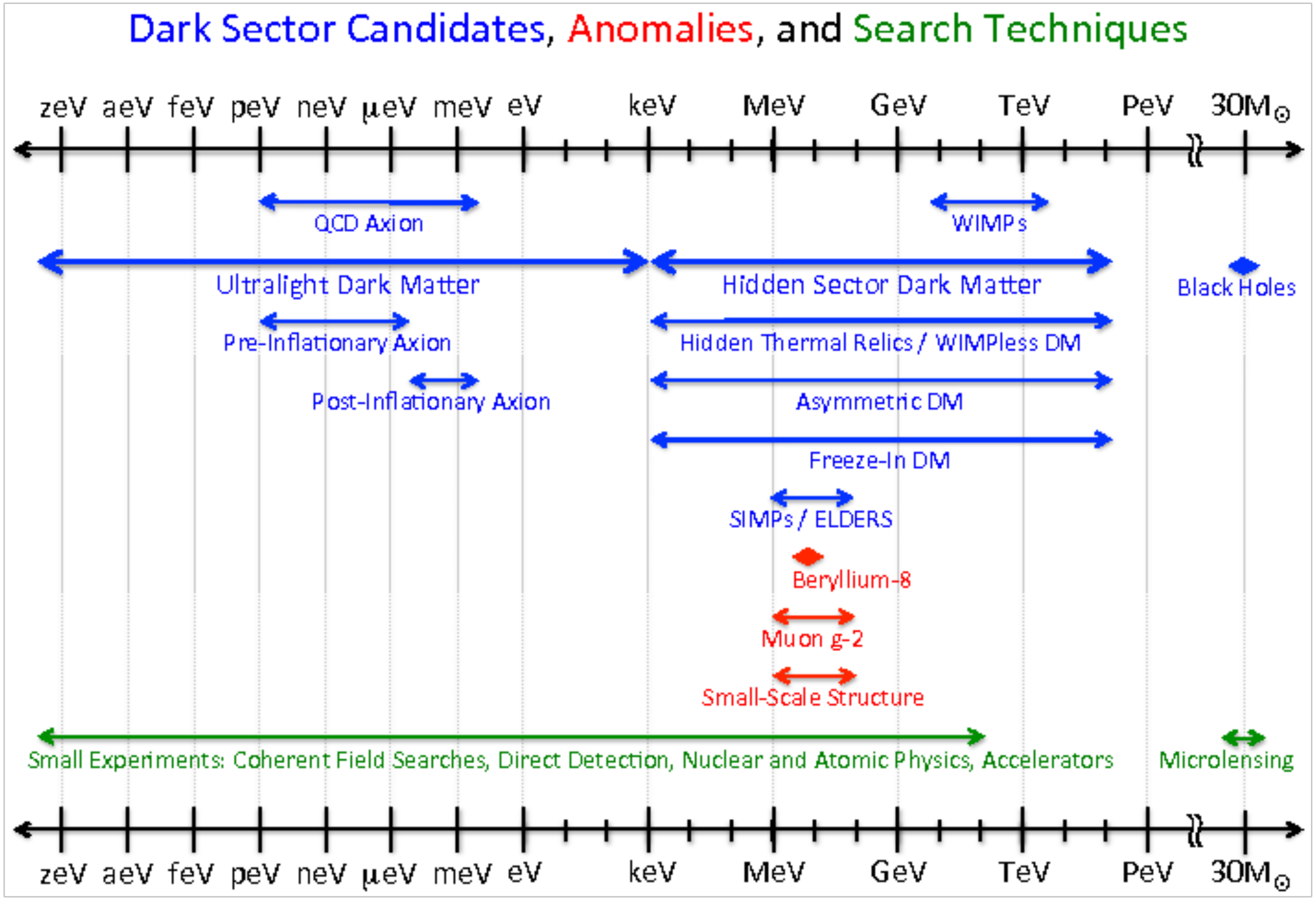
Acceleratars	Gamma astronomy	Cosmic rays	Planck scale
10^{-18}	10^{-21}	10^{-26} m	10^{-35} m
10^{26}	10^{29}	10^{34} Hz	10^{42} Hz
10^{12}	10^{15}	10^{20} eV	10^{28} eV

$\approx$16 J
(1 eV = 1.6×10^{-19} J)

$\approx$ 
150 km/h

The highest energy of a particle ever observed **$\sim 10^{20}$ eV**

Dark Matter Candidates and Searches



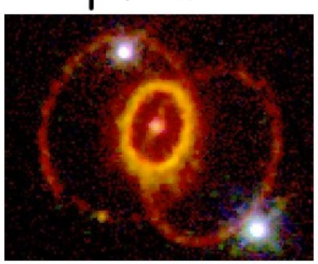
US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report - Battaglieri, Marco et al.
arXiv:1707.04591FERMILAB-CONF-17-282-AE-PPD-T

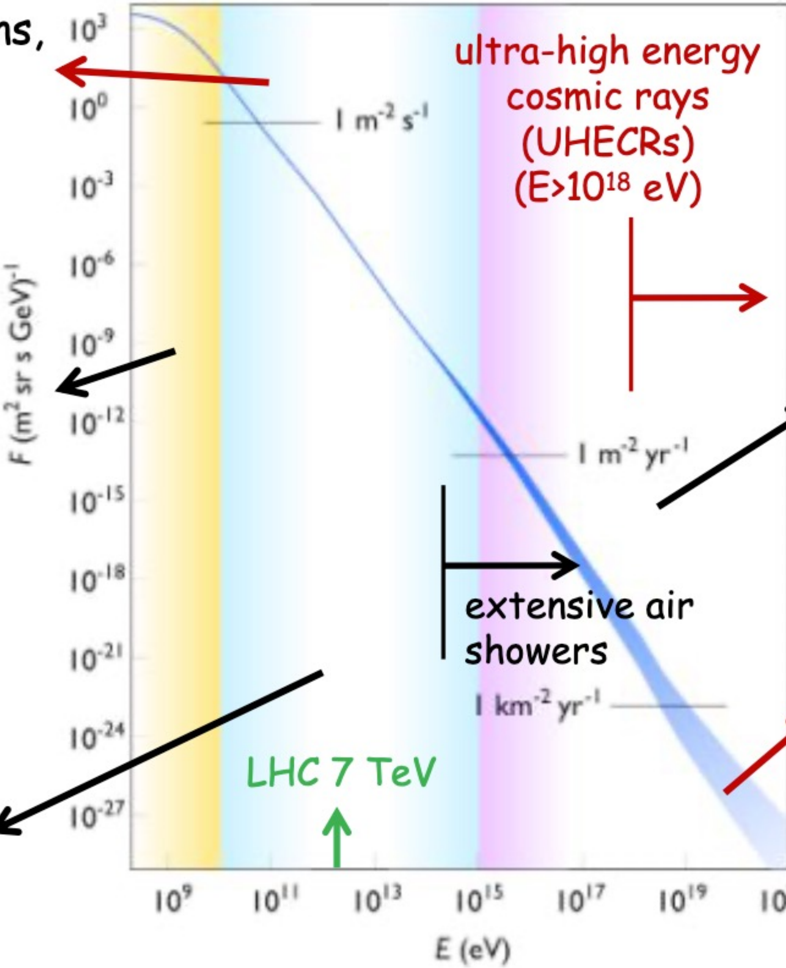
Cosmic rays (CRs) – high-energy particles coming from space
(protons, nuclei, neutrinos, photons, electrons,...)

direct observations, satellites, balloon-borne experiments

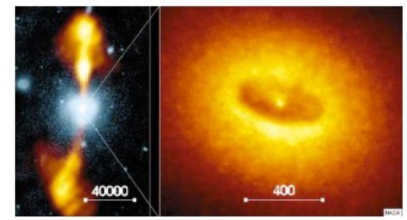
Sun

Supernovae, pulsars





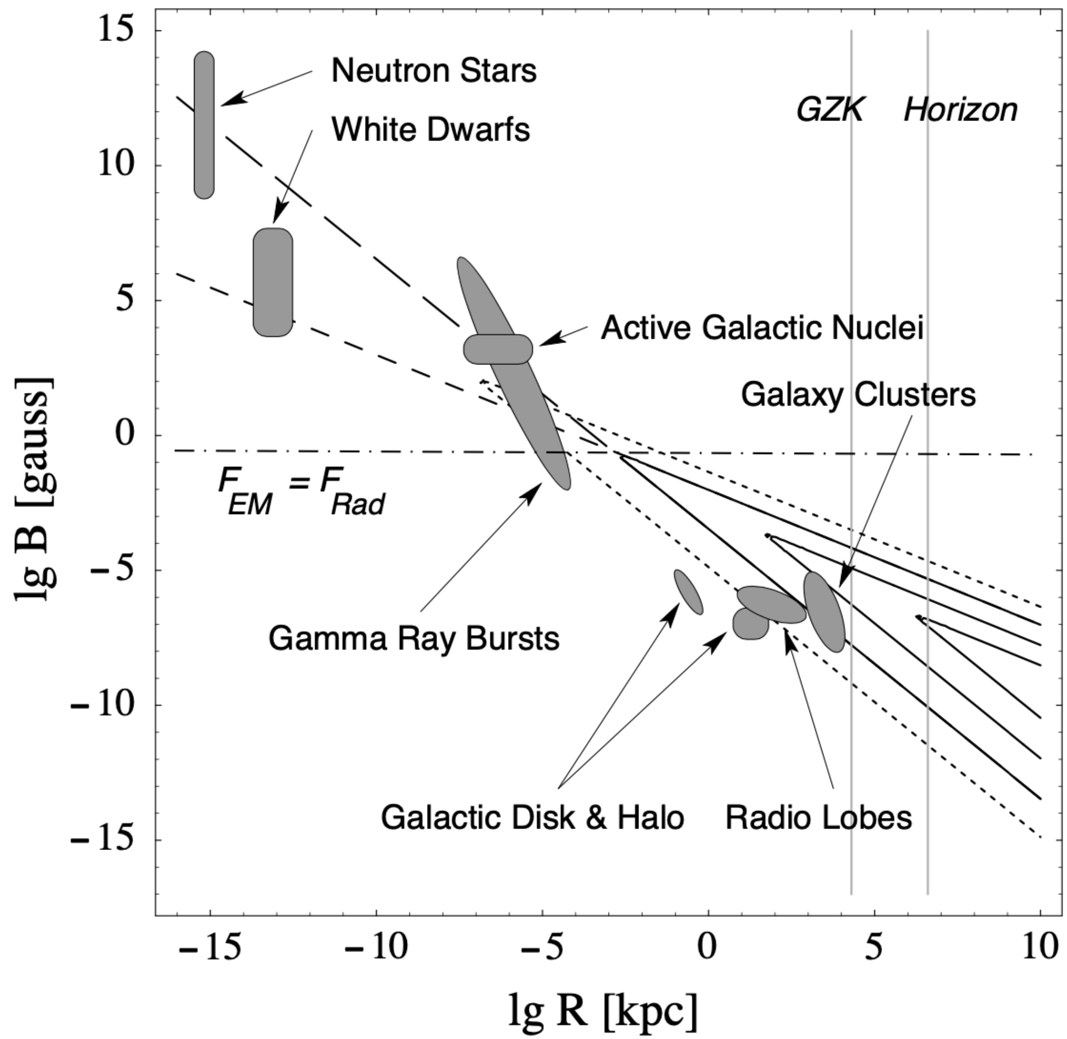
Sources unknown!
star burst galaxies, active galactic nuclei (AGNs) ???



$E>10^{20}$ eV, very low flux:
1 particle/km^2/1000 yr
(indirect observations, extensive air showers, detector arrays covering large area)

10^{20} eV in LHC technology → accelerator size of Mercury orbit

Constraint on electromagnetic acceleration of UHECR



Neutron star mergers

High-energy emissions from neutron star mergers

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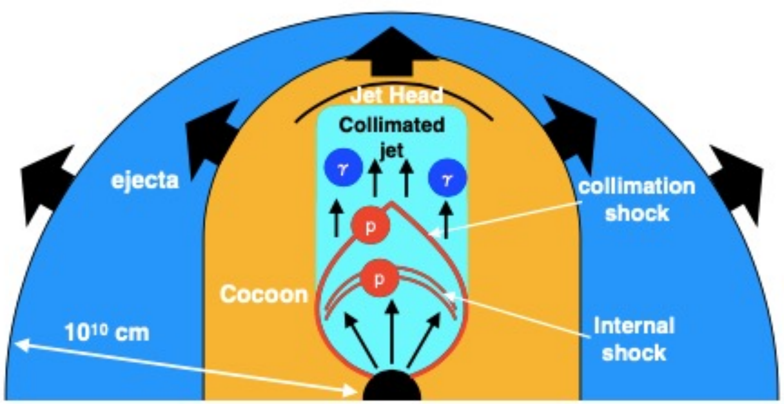
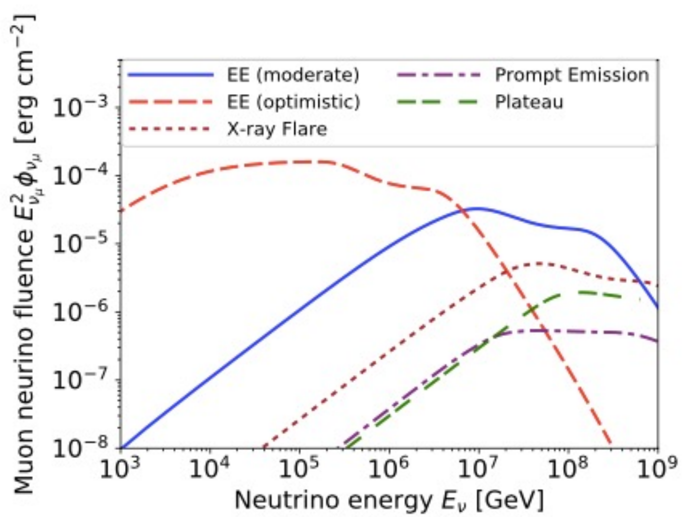
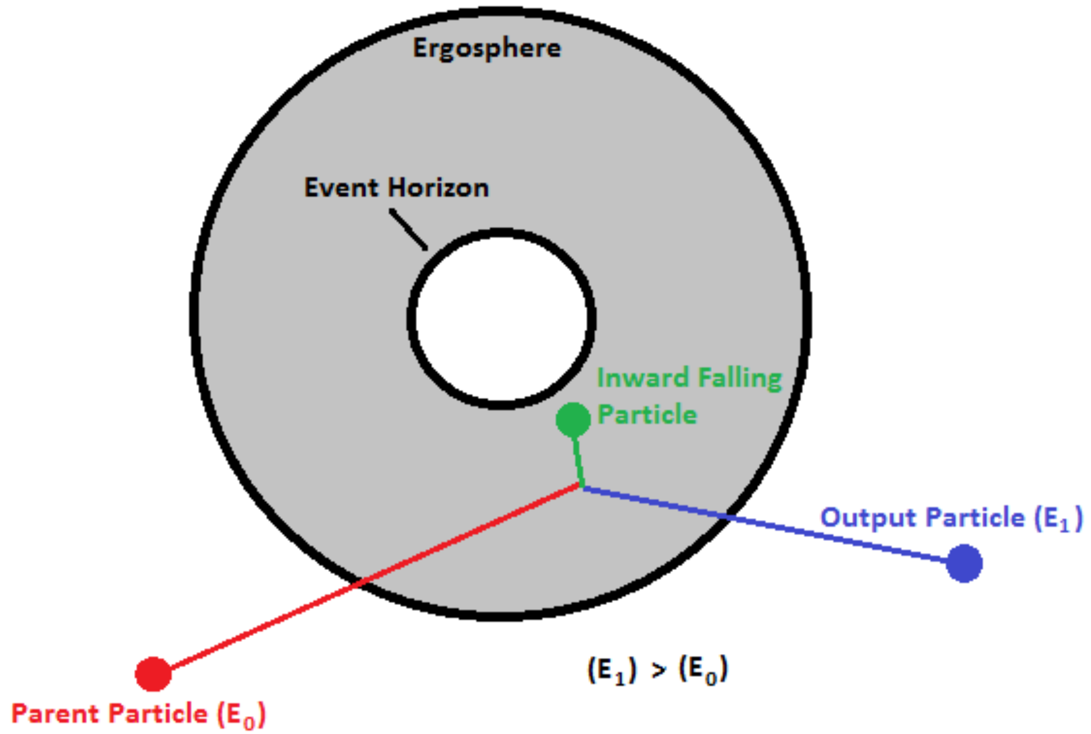
[3]Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, Pennsylvania, 16802, USA

Abstract. In 2017, LIGO-Virgo collaborations reported detection of the first neutron star merger event, GW170817, which is accompanied by electromagnetic counterparts from radio to gamma rays. Although high-energy neutrinos were not detected from this event, mergers of neutron stars are expected to produce such high-energy particles. Relativistic jets are launched when neutron stars merge. If the jets contain protons, they can emit high-energy neutrinos through photomeson production. In addition, neutron star mergers produce massive and fast ejecta, which can be a source of Galactic high-energy cosmic rays above the knee. We briefly review what we learned from the multi-messenger event, GW170817, and discuss prospects for multi-messenger detections and hadronic cosmic-ray production related to the neutron star mergers.





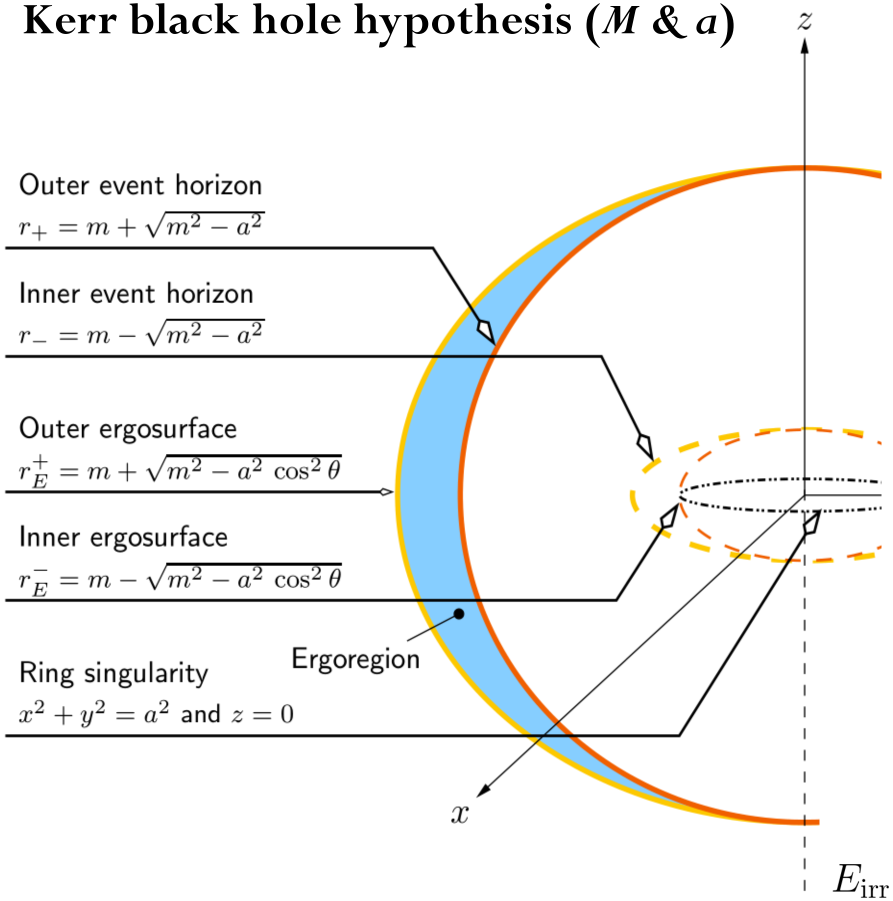
Magnetic Penrose Process



Naresh Dadhich, Arman Tursunov, Bobomurat Ahmedov, Zdeněk Stuchlík, The distinguishing signature of magnetic Penrose process, *Monthly Notices of the Royal Astronomical Society: Letters*, Volume 478, Issue 1, July 2018, Pages L89–L94

Can UHECRs be produced by black holes?

Kerr black hole hypothesis (M & a)



$$g_{tt} = \frac{2mr}{r^2 + a^2\cos^2\theta} - 1$$

Ergosphere: $g_{tt} = 0$

Inside the ergosphere g_{tt} changes its sign

$$E = -p_t = -mu_t = -mg_{tt}u^t - mg_{t\phi}u^\phi$$

$$L = p_\phi = mu_\phi = mg_{\phi\phi}u^\phi + mg_{\phi t}u^t$$

Entropy of black hole ~ to the event horizon area:

$$S_{\rm BH} = \frac{c^3}{4G\hbar}A_H$$

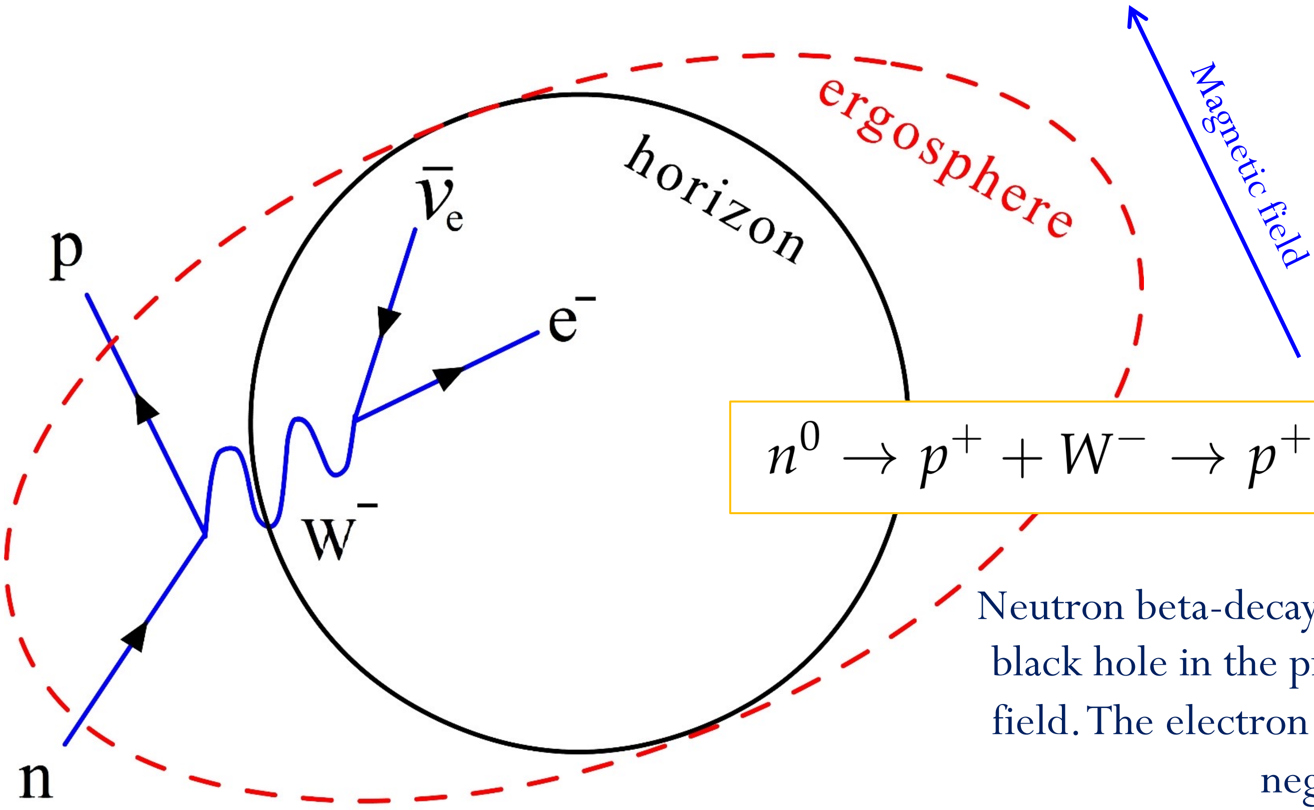
$$A_H = \int_0^{2\pi} d\phi \int_0^{\pi} \sqrt{\det g}\, d\theta = \frac{8\pi G}{c^2} M r_H$$

$$E_{\rm irr} = \sqrt{\frac{S_H \hbar c^5}{4\pi G k_{\rm B}}} \equiv \sqrt{\frac{A_H}{16\pi G^2}} c^4 = \frac{Mc^2}{\sqrt{2}}\left[1 + \sqrt{1 - \left(\frac{a}{M}\right)^2}\right]^{\frac{1}{2}}$$

Black hole mechanics and Thermodynamics have uncanny correspondence!
Black hole area non-decrease states that 29% of BH's energy is available for extraction.
For extremely rotating SMBH of 10^9 solar mass the available energy is 10^{74}eV

Credit: Arman Tursonov

Beta-decay in ergosphere



$$n^0 \to p^+ + W^- \to p^+ + e^- + \bar{\nu}_e,$$

Neutron beta-decay in the ergosphere of rotating black hole in the presence of external magnetic field. The electron falls into black hole with the negative energy.

In the hot and dense torus, with temperature of $\sim 10^{11}$ K and density $>10^{10}$ g$\cdot$cm^{-3}, neutrinos are efficiently produced. The main reactions that lead to their emission are the electron/positron capture on nucleons, as well as the neutron decay. Their nuclear equilibrium is described by the following reactions:

$$p + e^- \to n + \nu_e$$

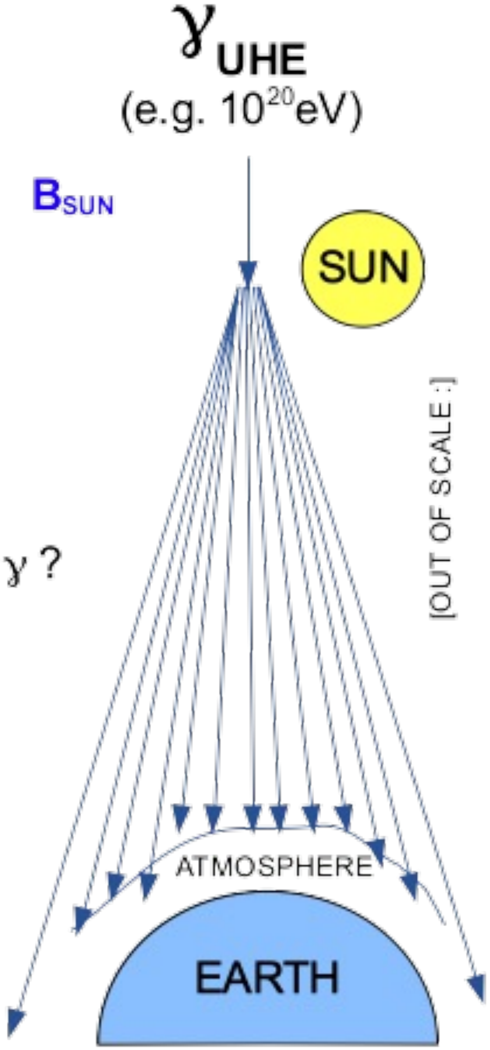
$$p + \bar{\nu}_e \to n + e^+$$

$$p + e^- + \bar{\nu}_e \to n$$

A. Janiuk et al, Galaxies 5, 15 (2017)

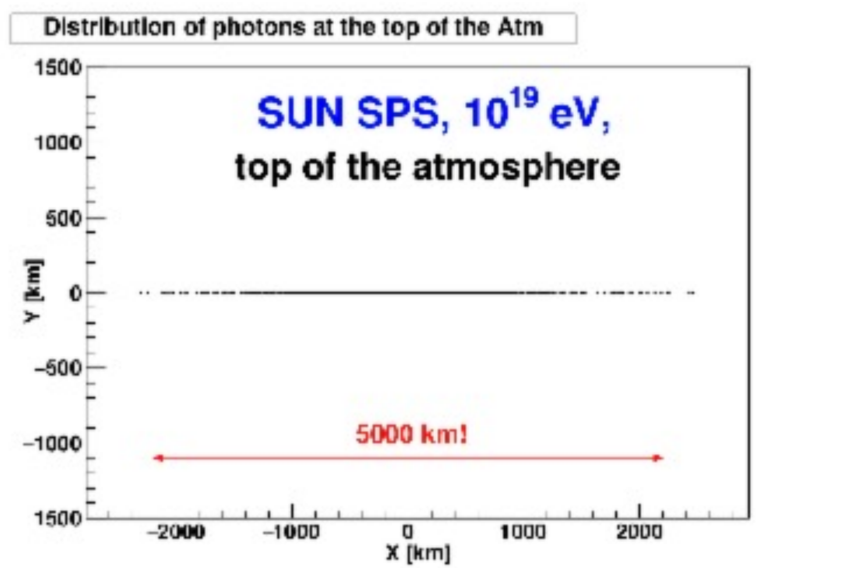
Credit: Arman Tursonov

Super-preshowers (SPS) from the vicinity of the Sun



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

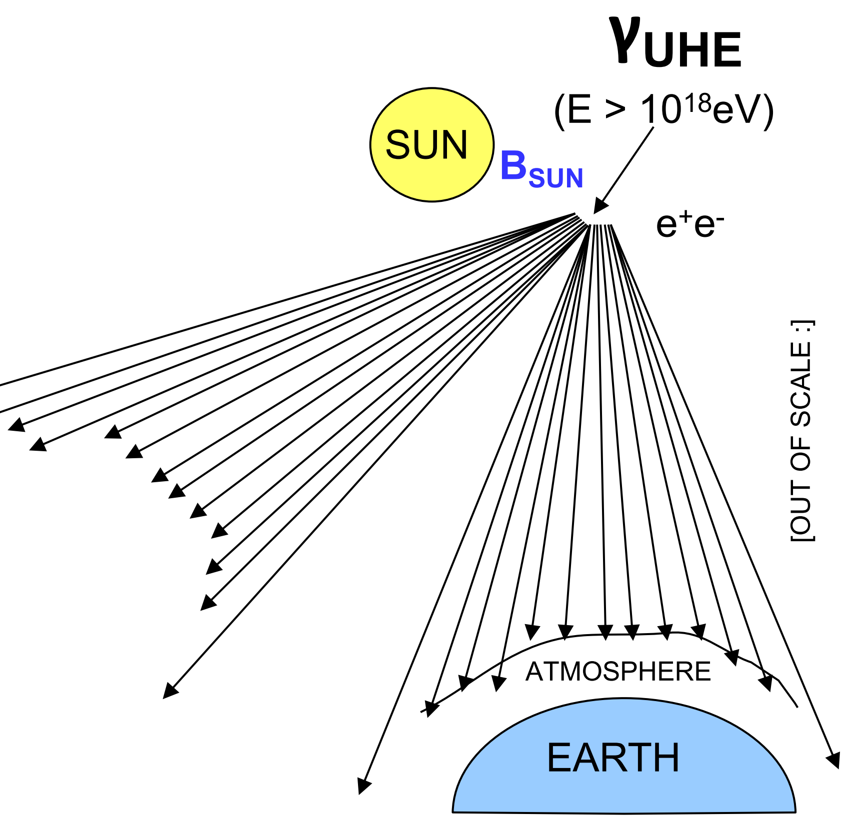
→ N. Dhital, 2018
complete energy spectrum: extent
~ thousands of km

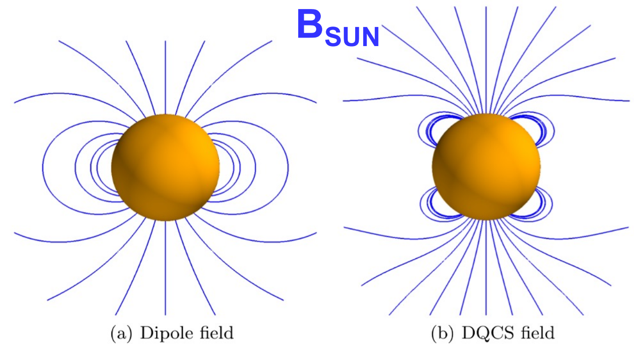


Distribution of photons ($E > 10^{13}$ eV) at the top of the atmosphere.
$E_\gamma = 10$ EeV, Impact parameter $= 2.5 R_\odot$.

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

>=EeV photons nearby the Sun→ big CRE

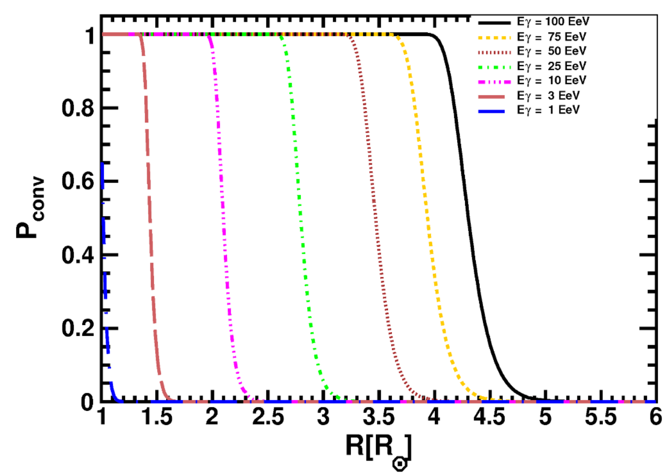




(a) Dipole field

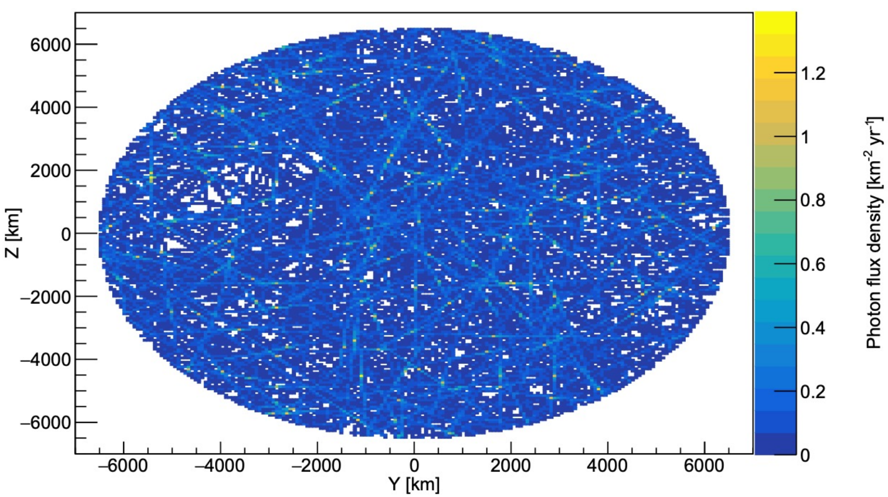
(b) DQCS field

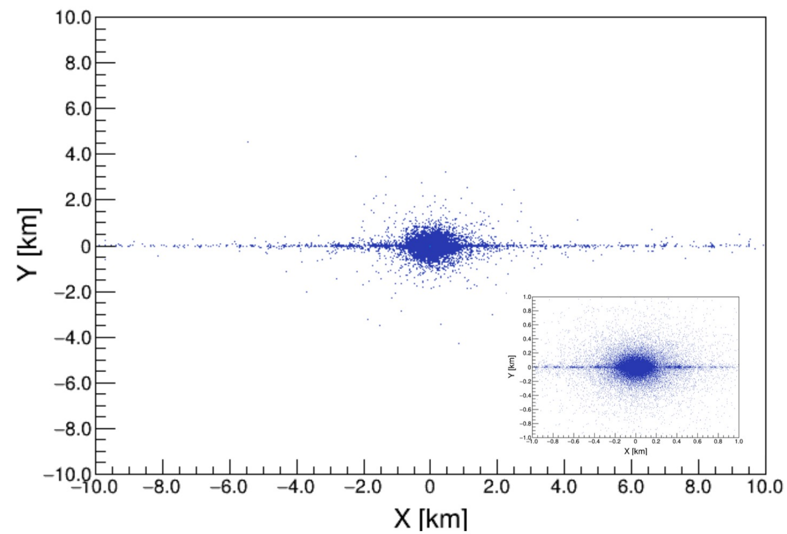
The Sun-preshower effect starts at 1 EeV



Primary gamma conversion probability vs. impact parameter, polar incidence

Simulations of SPS at the vicinity of the Sun

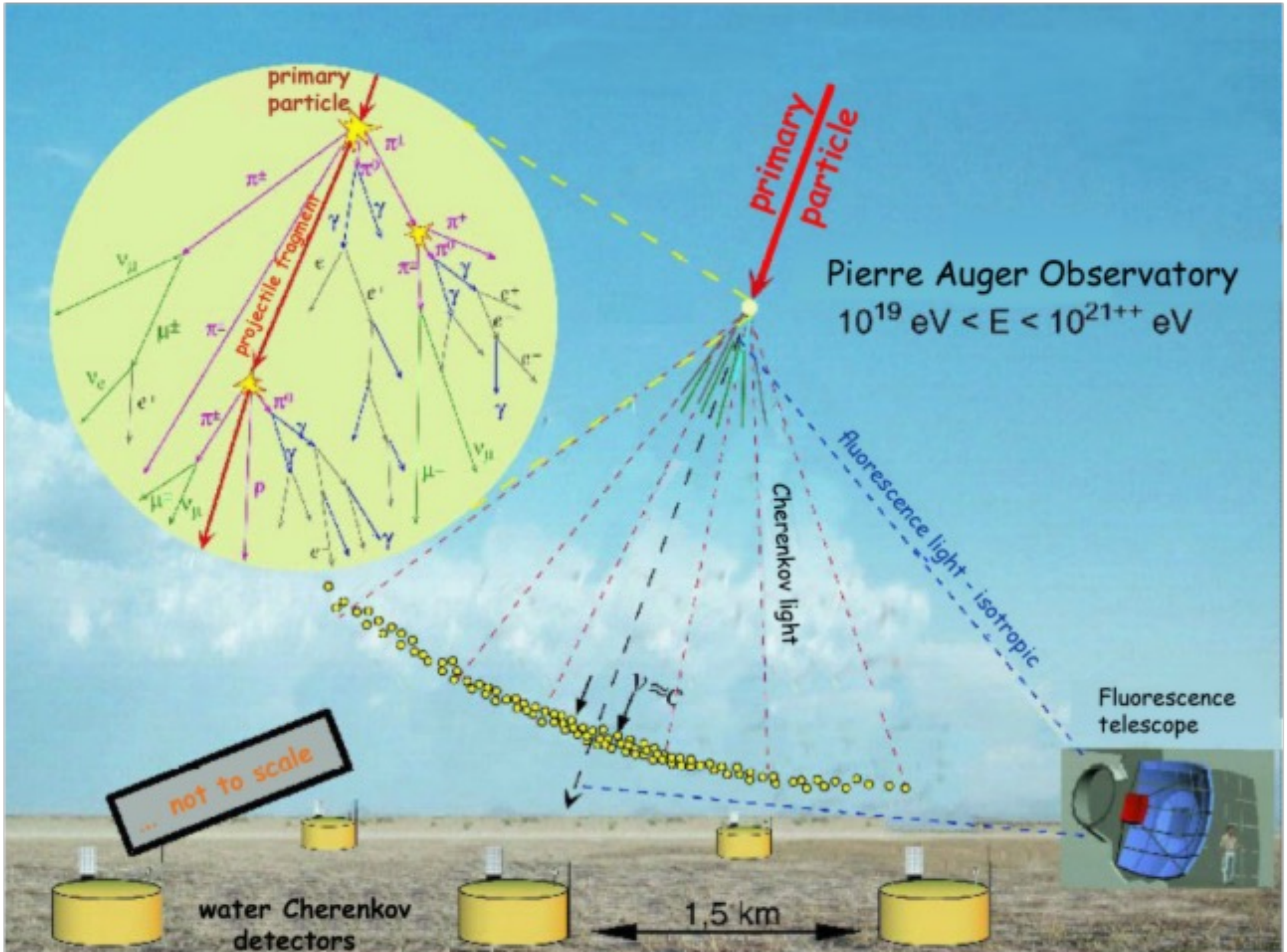




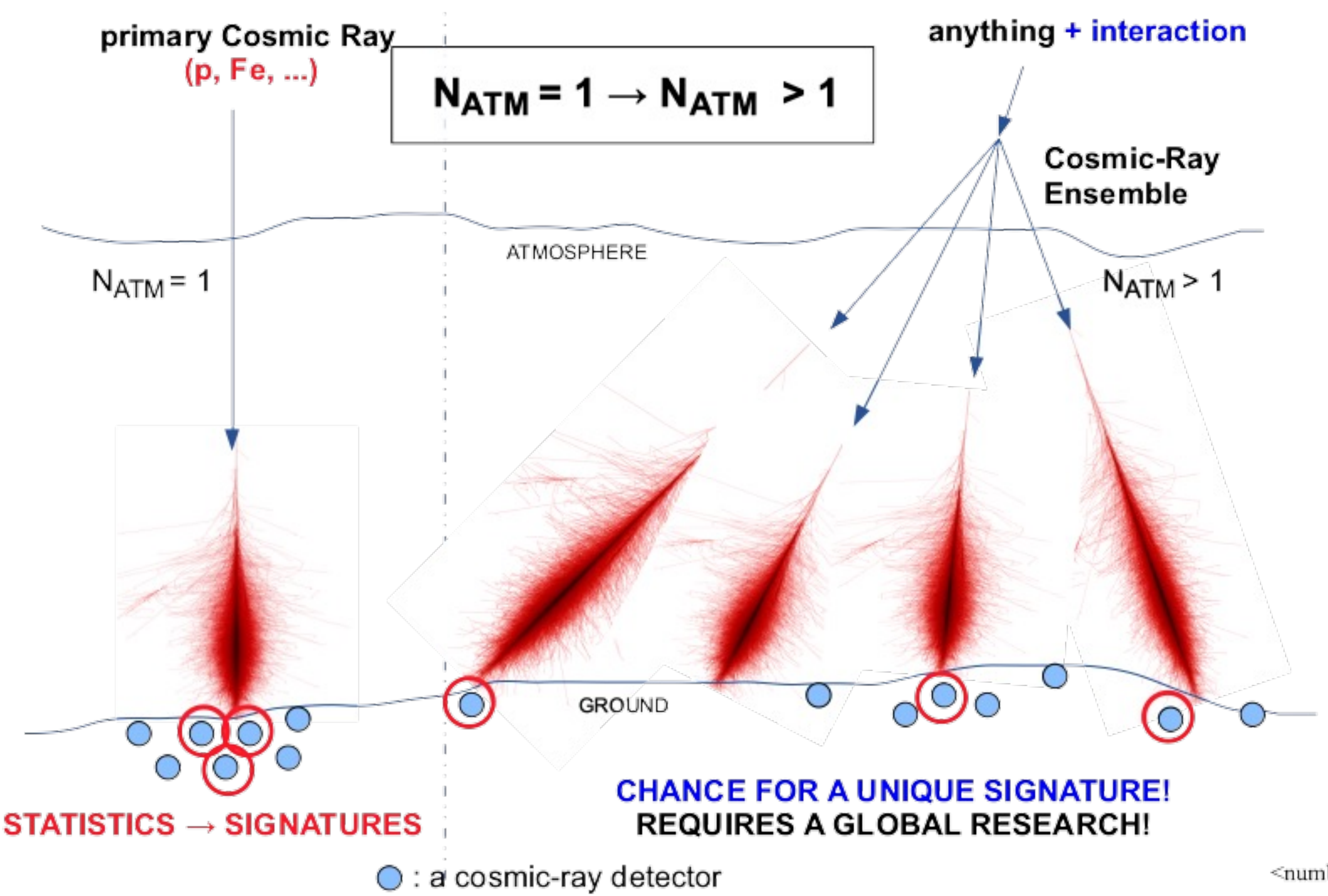
Left: The cumulative spatial distribution of secondary photons at the top of the atmosphere, for the primary photons energy 100 EeV. *Right*: Shower footprint derived from the CORSIKA simulation program for particles that are tracked through the atmosphere that eventually react with air nuclei. The inset displays the core of the footprint in a smaller area.

N. Dhital, P. Homola, D. Alvarez-Castillo et al.,
arXiv:1811.10334, JCAP03(2022)038
B. Poncyljusz, T. Bulik, N. Dhital et al.,
arXiv:2205.14266, Universe 8 (2022) 498

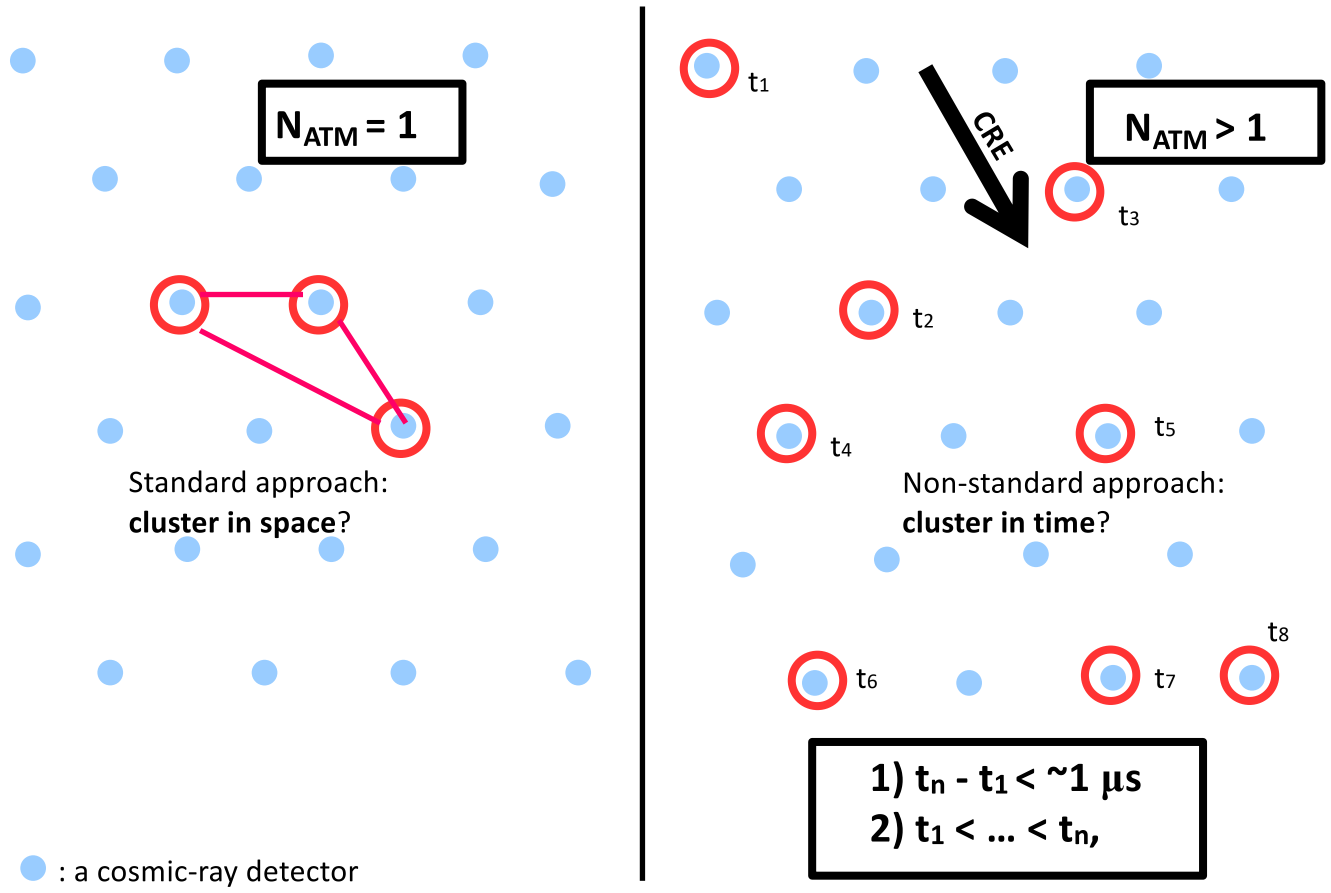
State-of-the-art detection of cosmic rays: $N_{ATM} = 1$



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



A chance for a unique CRE signature



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

Cosmic-Ray Extremely Distributed Observatory

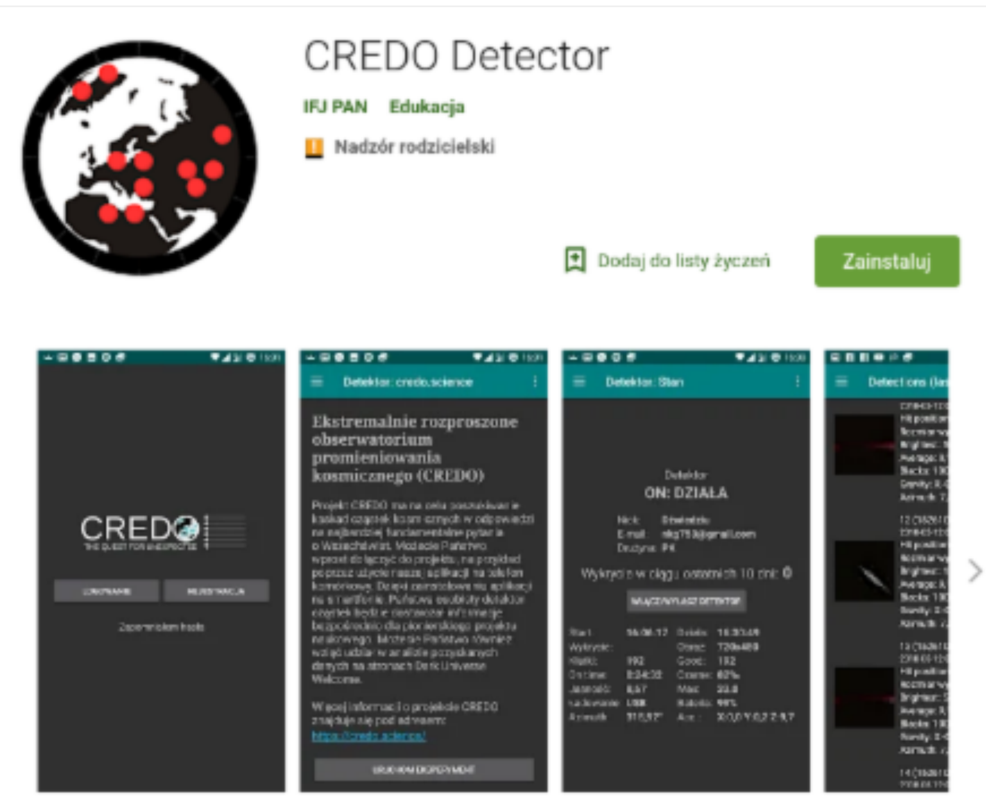
Central database/interface: access to everything for everybody

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

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

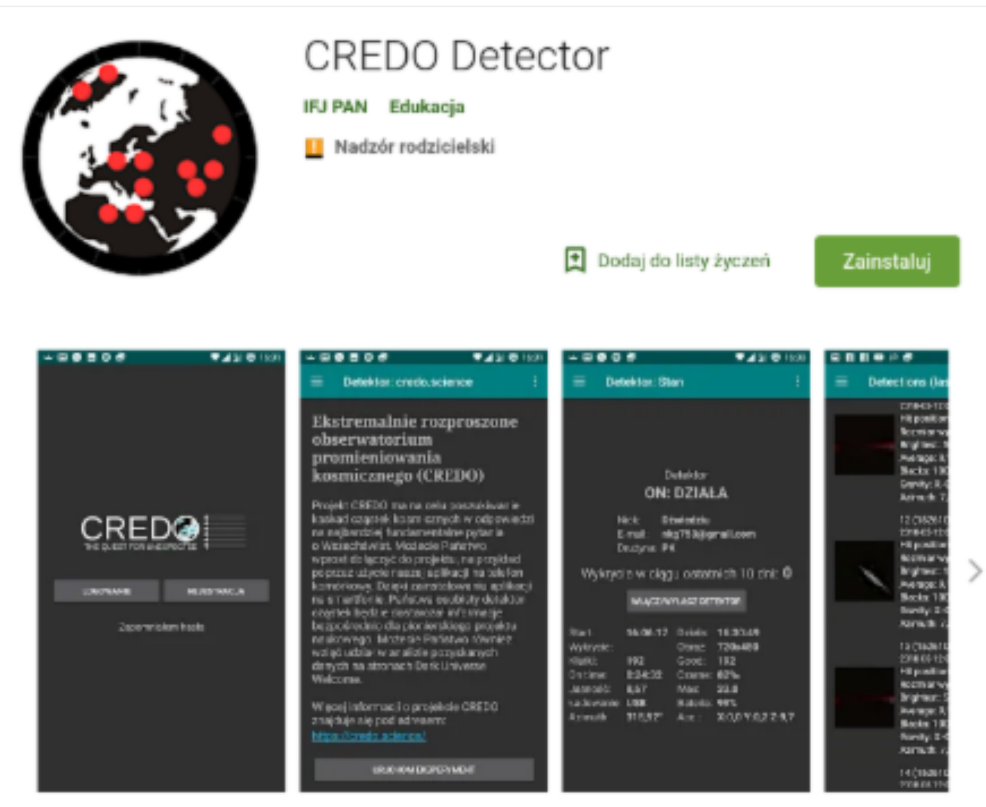
CREDO
THE QUEST FOR THE UNEXPECTED



data acquisition!

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

CREDO
THE QUEST FOR THE UNEXPECTED

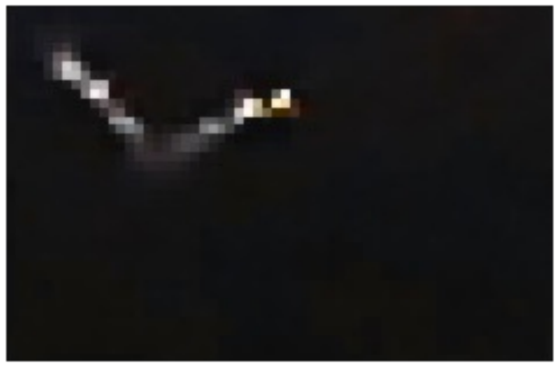


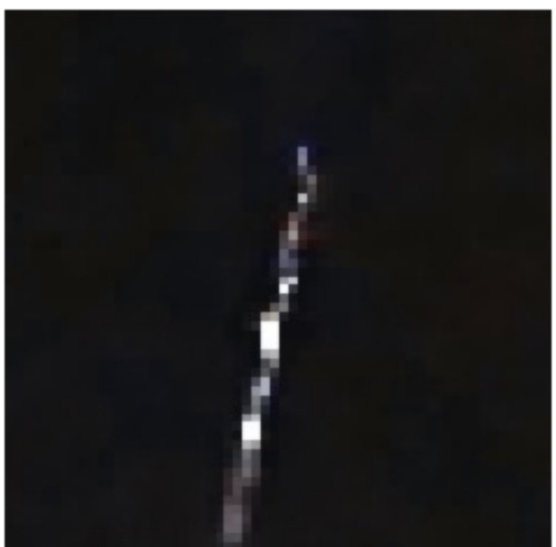
data acquisition!

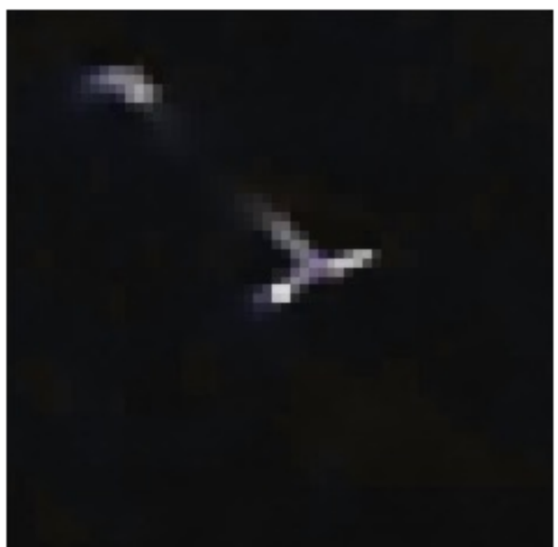
CREDO Detector: examples

User: „smph-kitkat", https://api.credo.science/web/user/smph-kitkat/
Device: Smasung SM-G357FZ, Android 4.4.4 (KitKat)
Average detection rate: ~10/hr
(flight to Kyiv on 29.05: 60/hr :)

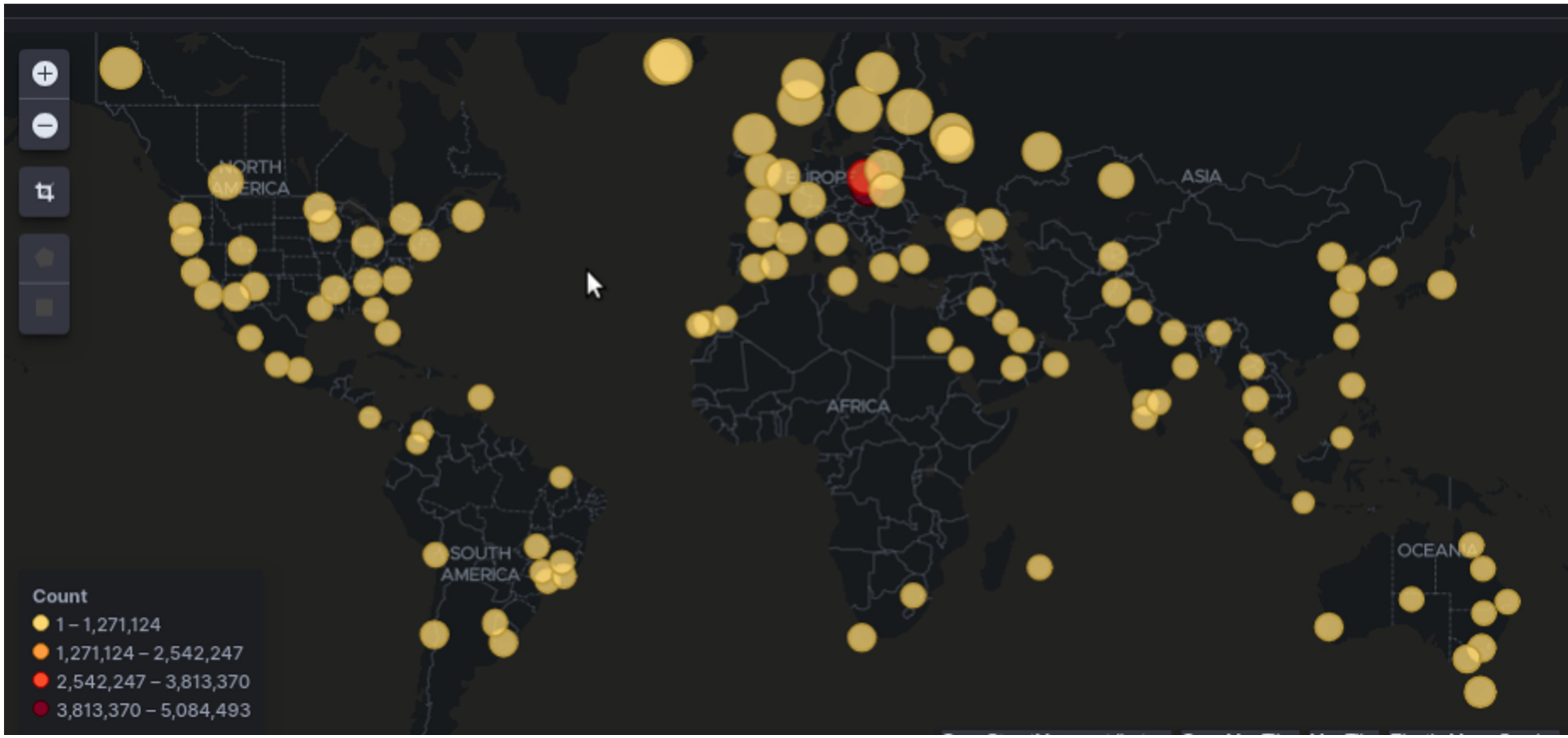
Example images:







CREDO: already global



42 institutions / 19 countries / 5 continents / ~ 11 900 users / ~ 4400 teams / > 10 000 000 smartphone detections / > 1100 smartphone work years

Why high energy photons interesting?

- they should exist

- they should initiate large scale cascades

- detection of large scale cascades unattempted

Photons as cosmic rays: 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?

Astro-tests of the space-time structure

→ maximum photon energies $< 10^{12}$ eV
→ testable scale of the space-time „grain" $< 10^{-18}$ m

CREDO
THE QUEST FOR THE UNEXPECTED

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

More on Experimental Quantum Gravity

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

PH: Gamma Ray Bu
(spacetime foam)!

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)

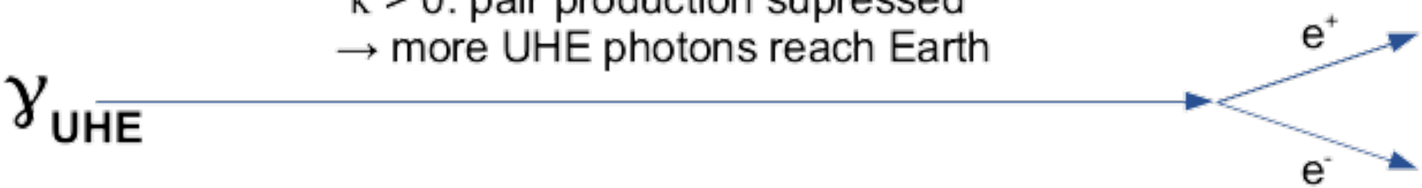
CRE and Lorentz Invariance Violation

Modified dispersion relation of a photon:

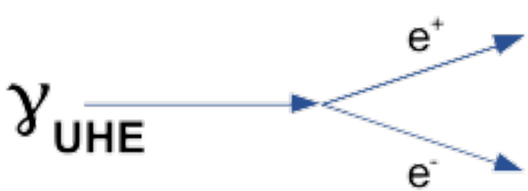
$$E_\gamma(\vec{k}) = \sqrt{\frac{(1-\kappa)}{(1+\kappa)}}|\vec{k}|$$

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

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

Studying the Variation of Fundamental Constants at The Cosmic Ray Extremely Distributed Observatory

D. Alvarez Castillo[a,b,1]

[a] Joint Institute for Nuclear Research, Dubna, Russia

[b] Institute of Nuclear Physics PAN, Cracow 31-342, Poland

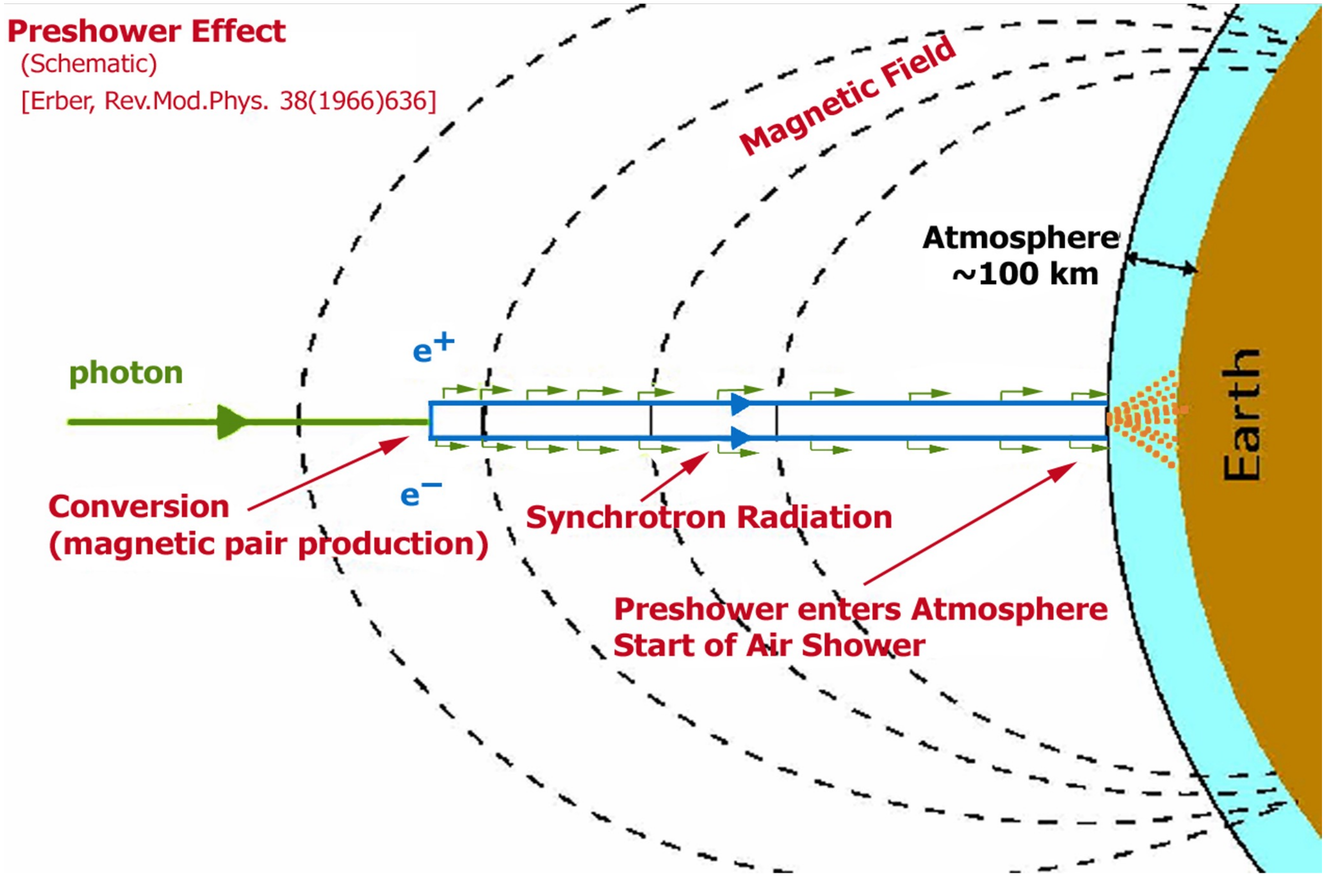
The Study of the Variation of Fundamental Constants through time or in localized regions of space is one of the goals of the The Cosmic Ray Extremely Distributed Observatory which consists of multiple detectors over the Earth. In this letter, the various effects which can be potentially identified through cosmic rays detections by CREDO are presented.

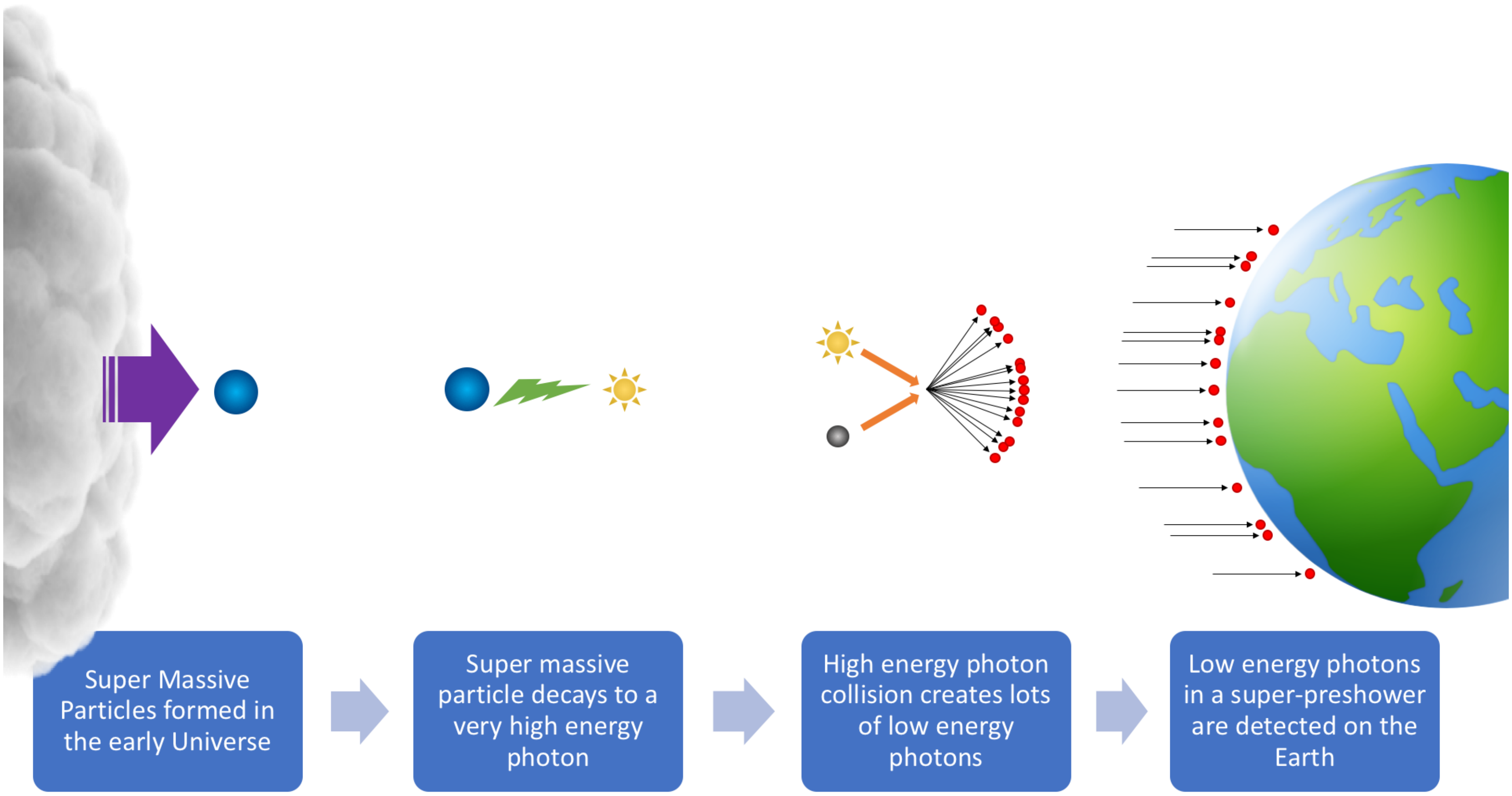
PACS: 06.20.Jr; 96.50.S−; 04.60.−m; 11.30.Cp

Phys.Part.Nucl. 53 (2022) 4, 825-828, arXiv:2208.09391

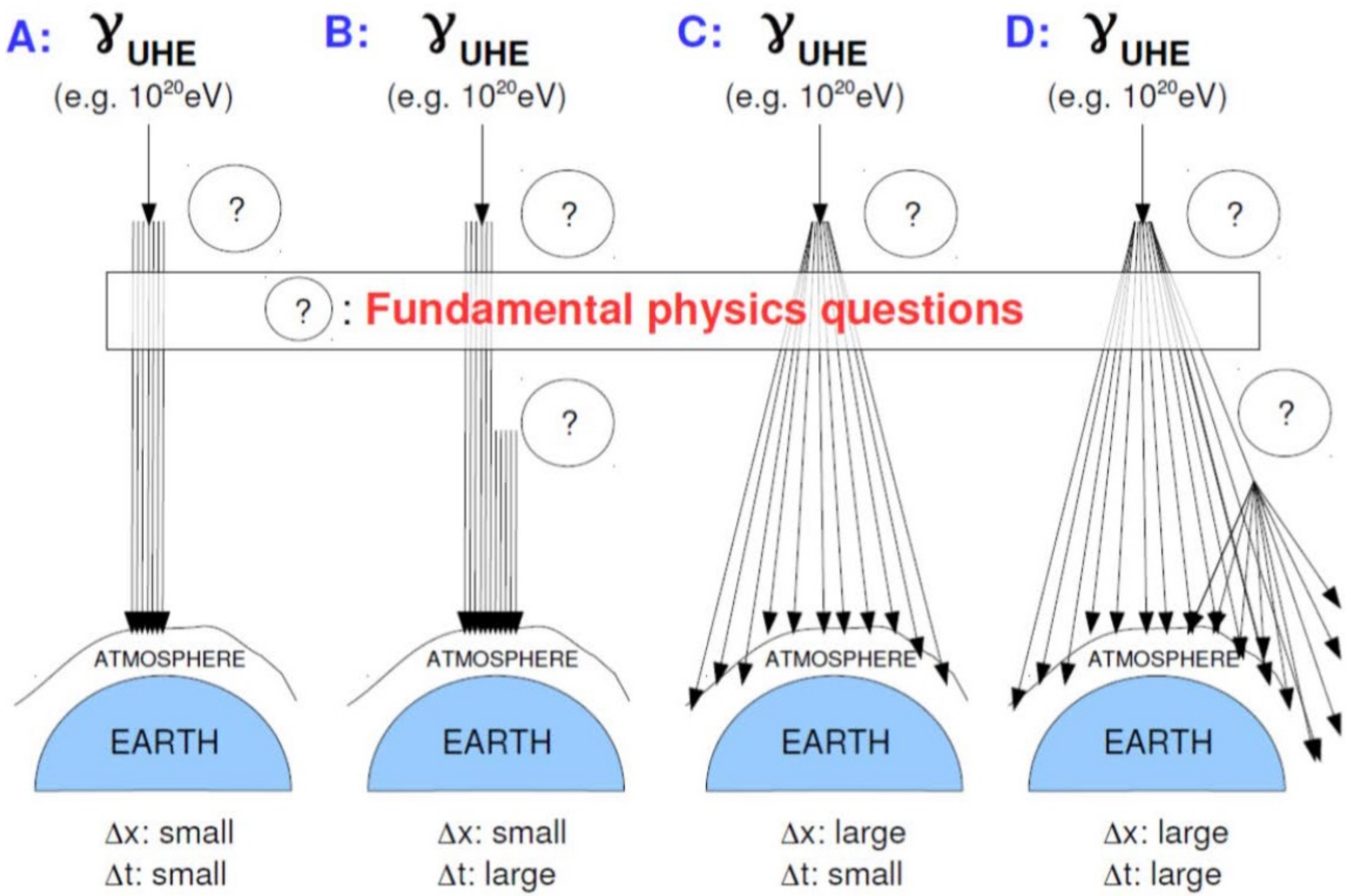
Example non-exotic scenario: preshowers

Preshower (important for E > 10^{19} eV):
→ contains typically 100 particles
(created at around 1000 km a.s.l.)




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

Classes of cosmic-ray ensembles



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

Experimental evidence about γ_{UHE}

γ_{UHE} $\xrightarrow{\text{no interactions or screening}}$ **Earth**

NOT OBSERVED

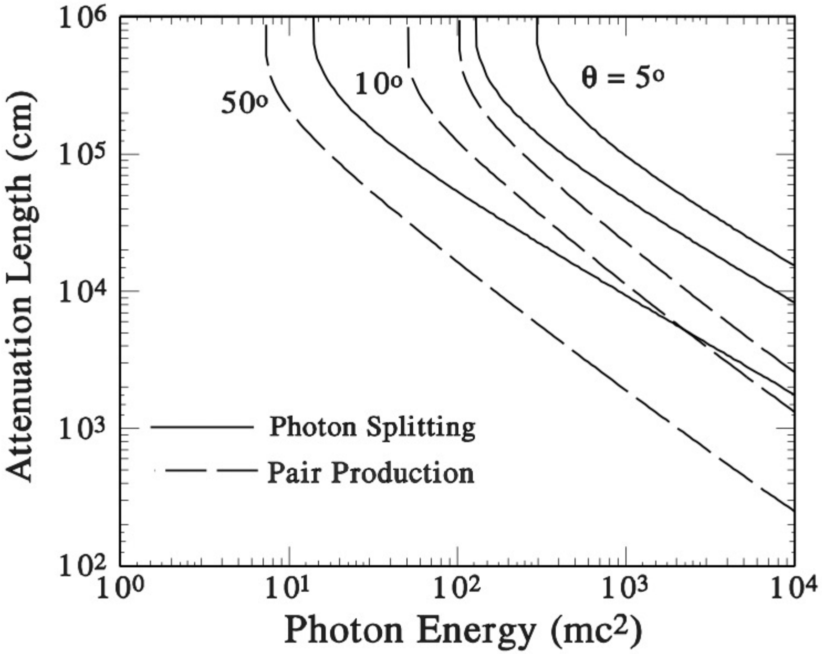
γ_{UHE} $\xrightarrow{\text{unexpected interactions, screening, ...}}$ ELECTROMAGNETIC CASCADES (COSMIC-RAY ENSEMBLES) $\longrightarrow$ **Earth**

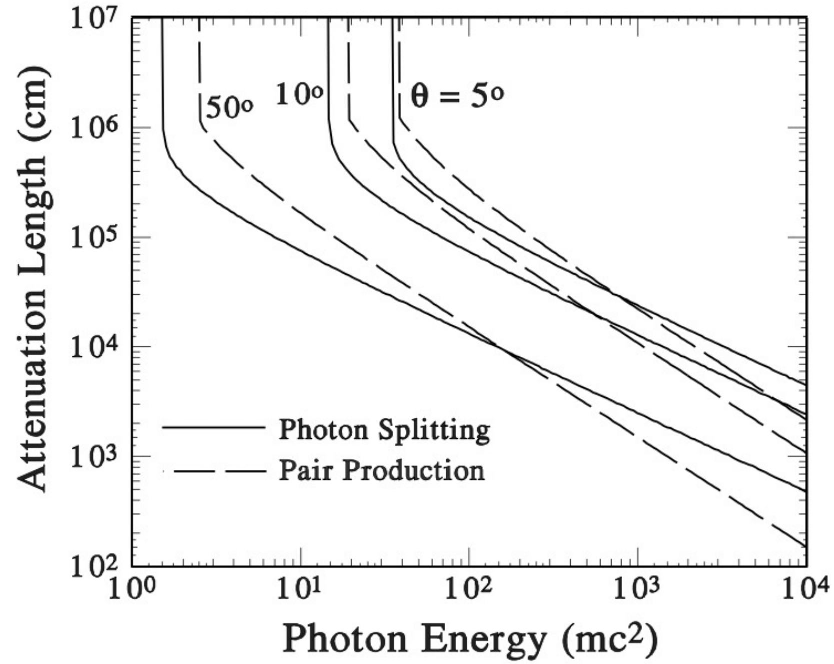
NOT TRIED SO FAR...

$\downarrow$

CREDO!

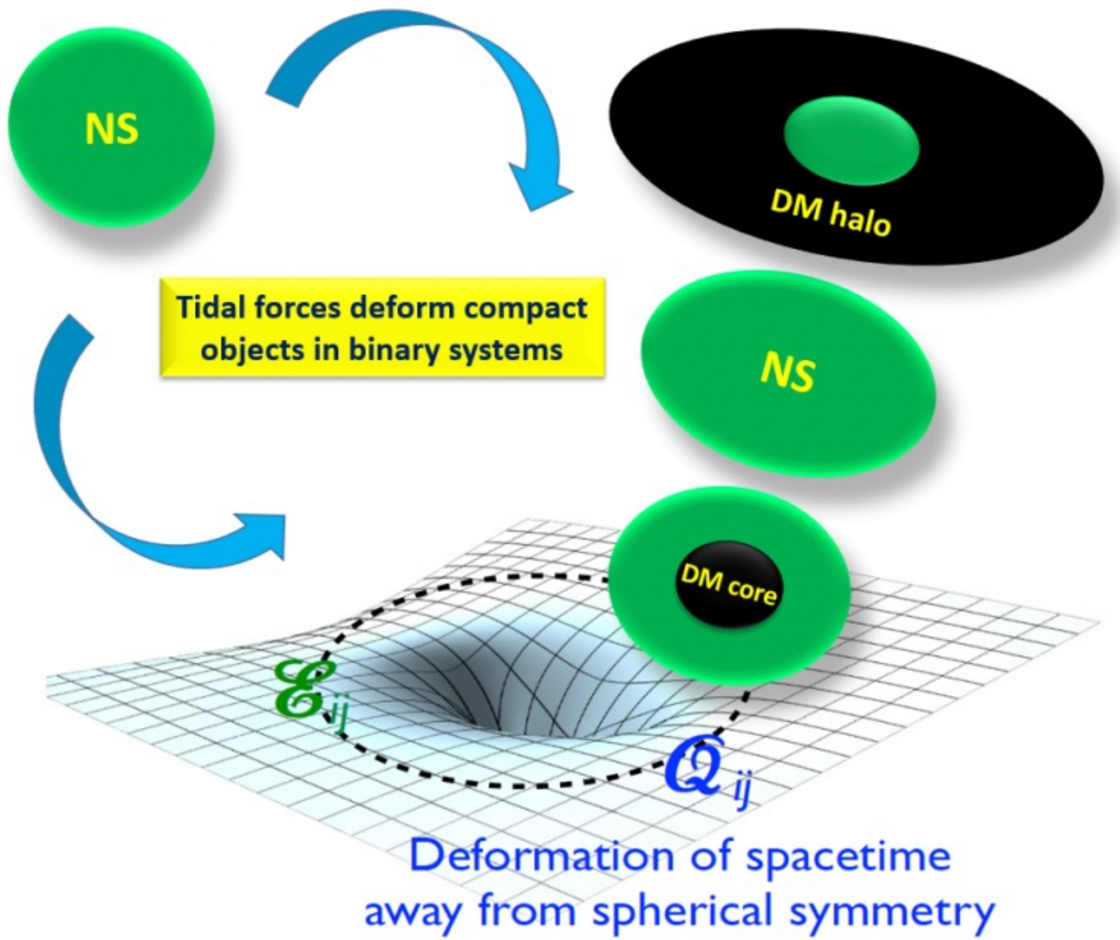
Photon Splitting around compact objects





Alice K. Harding, Matthew G. Baring, and Peter L. Gonthier - ApJ 476 246 (1997)

Bosonic Dark Matter in NS

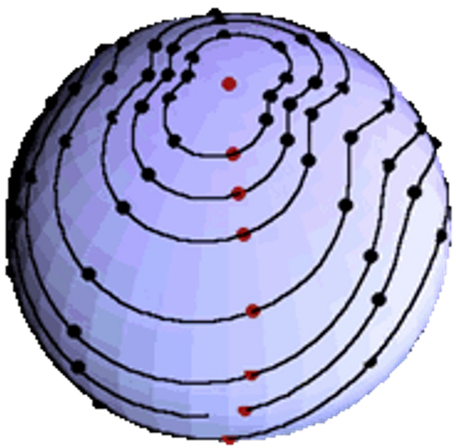


D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

Gravitational Waves from NS

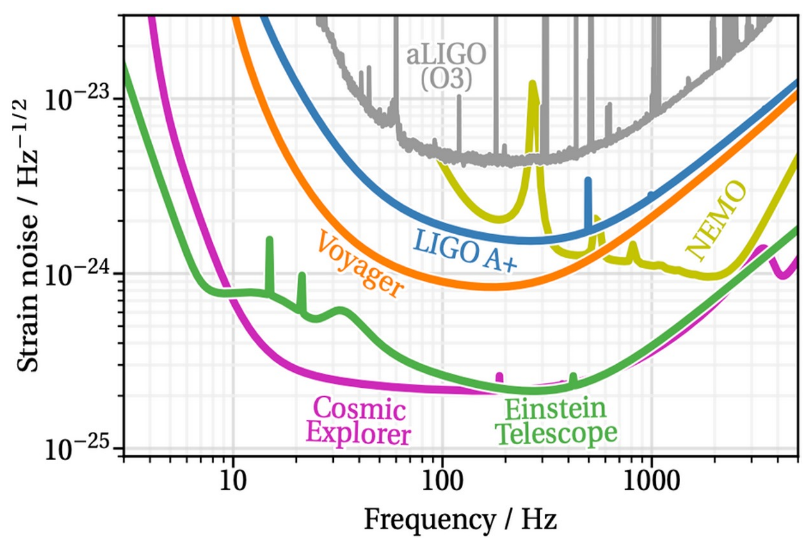
- Non-radial QNMs raised from time varying quadrupole deformations are source of GWs.

  - fundamental (f) mode,
    - no node, probe for mean density,(1 kHz < f < 3kHz)
  - pressure (p) mode,
    - Sound speed, (5 kHz < f < 10kHz)
  - gravity (g) mode,
    - (50 Hz < f < 500 Hz)
- R-mode, for rotating stars only.
  - Viscosity, (0.5 kHz < f < 2kHz)
- Space-time (w) mode.
  - 5 kHz< f



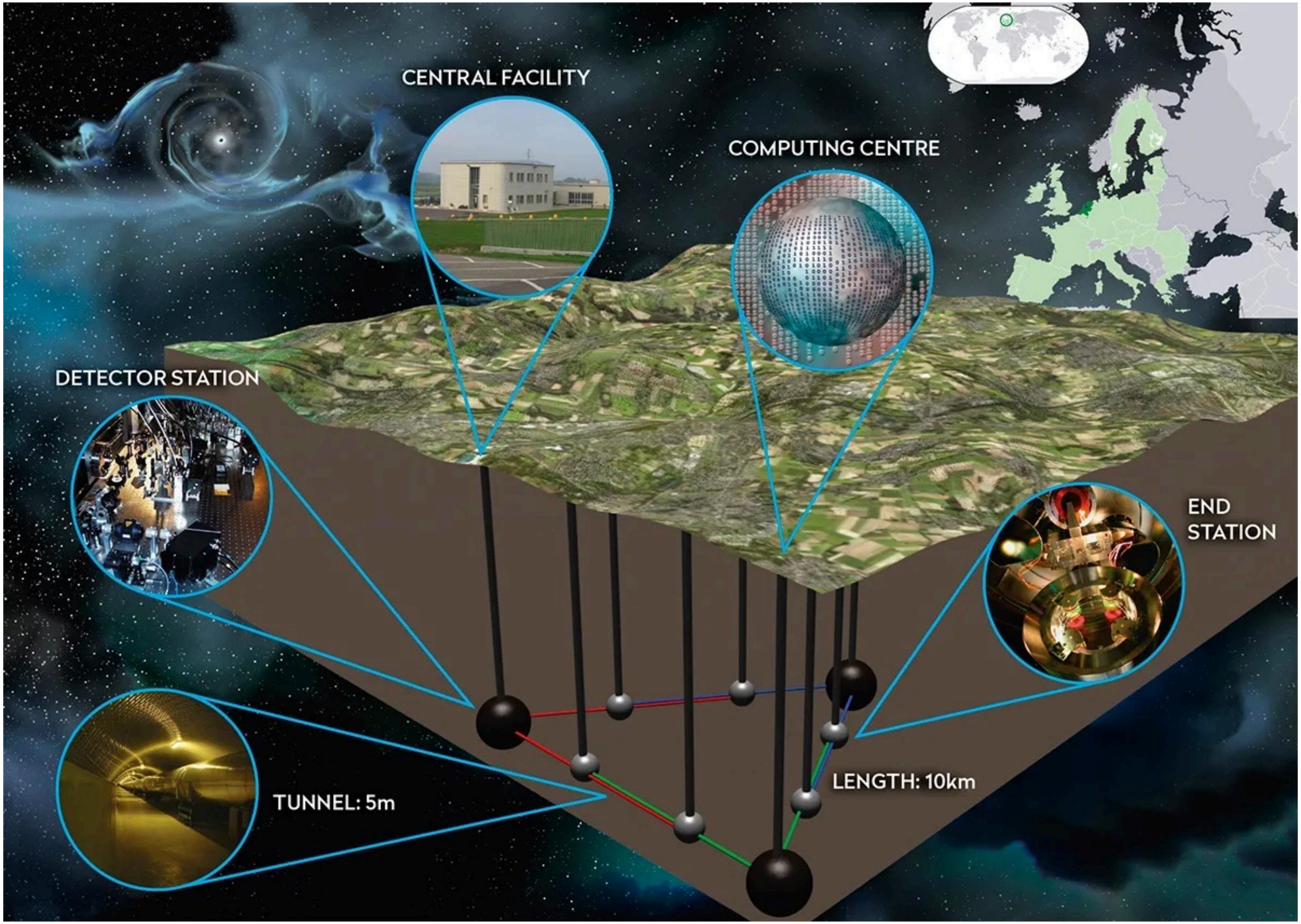
Credit: C. Hanna and B. Owen

Credit: CERN/Indico



PC: cosmicexplorer.org/sensitivity

Einstein Telescope



On the Magnetic Precursor of the Chilean Earthquake of February 27, 2010

N. V. Romanova[a, b], V. A. Pilipenko[a], and M. V. Stepanova[b]

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Abstract—Some recent publications reported on an anomalous geomagnetic disturbance that was observed three days before the strongest Chilean earthquake on February 27, 2010. The present paper analyzes in detail the data from magnetic station, photometers, and riometers in Canada, Chile, and Antarctica. The analysis unambiguously shows that the supposedly anomalous geomagnetic disturbance was not related to seismic activity and was caused by a standard isolated substorm.

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INTRODUCTION

Recent publications by Shestopalov et al. (2011a, 2011b, 2013) reported on a series of anomalous geophysical phenomena prior to the Chilean earthquake of February 27, 2010. In particular, it was reported that a significant geomagnetic disturbance had been observed three days before the event for about an hour long at different magnetic stations of the INTERMAGNET network. The authors thought it was endogenous disturbance (Belov, Shestopalov, and Kharin, 2009; Belov et al., 2010), because no magnetic storms took place that time.

However, an absence of magnetic storms in the analyzed period does not exclude effects from such natural geomagnetic disturbances as substorms, which are constantly observed in auroral zones in the absence of magnetic storms. The natural problem is whether the phenomenon analyzed in (Shestopalov et al., 2013) an anomalous disturbance or a common substorm. To solve this problem, we will consider a broader set of geophysical data.

ANALYSIS OF GEOMAGNETIC ACTIVITY PRIOR TO THE EARTHQUAKE

The strongest M 8.8 Chilean earthquake occurred on February 27, 2010 in 0634 UT at a depth of H = 35 km (the geographic coordinates of the epicenter are 35.93° S, 72.78° W). According to (Shestopalov et al., 2013), the magnetic precursor of this event was revealed on February 24, 2010, at different magnetic stations.

Let us consider the magnetograms of February 24, 2010, obtained at stations of the SAMBA (Chile) and CARISMA (Canada) networks (Mann et al., 2008), which form a latitudinal profile along the zero mag-

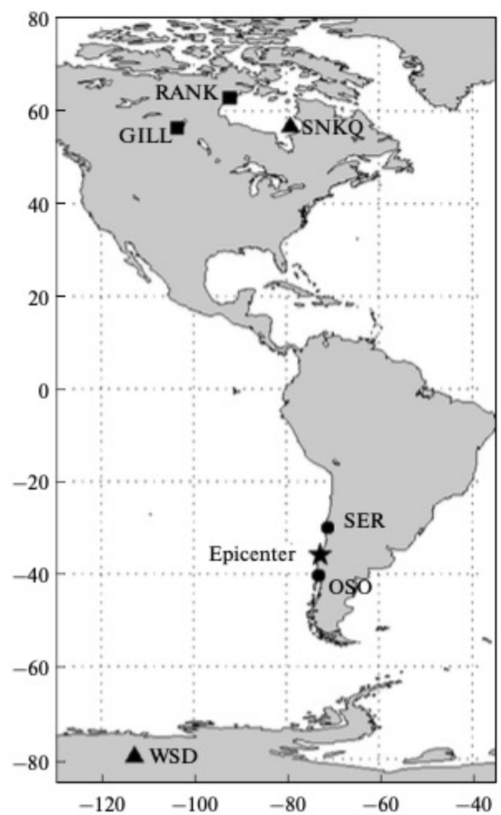
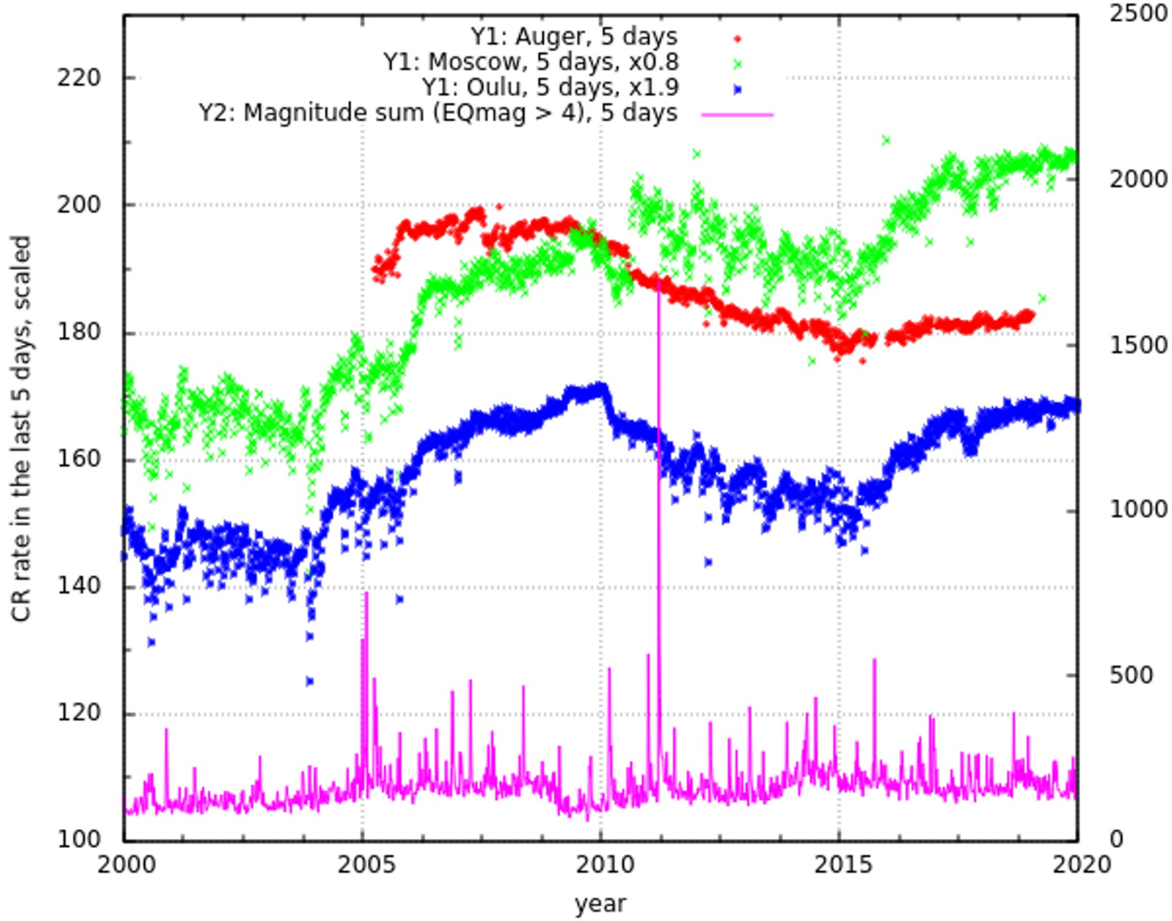


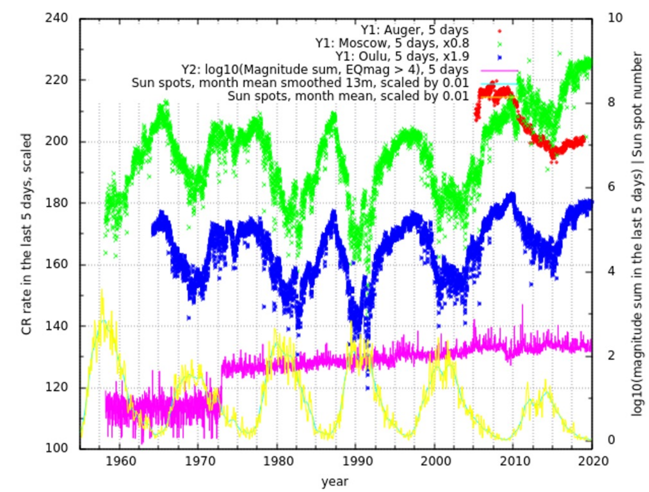
Fig. 1. Map of positions of the chosen stations and the earthquake epicenter.

The data



public resources of:

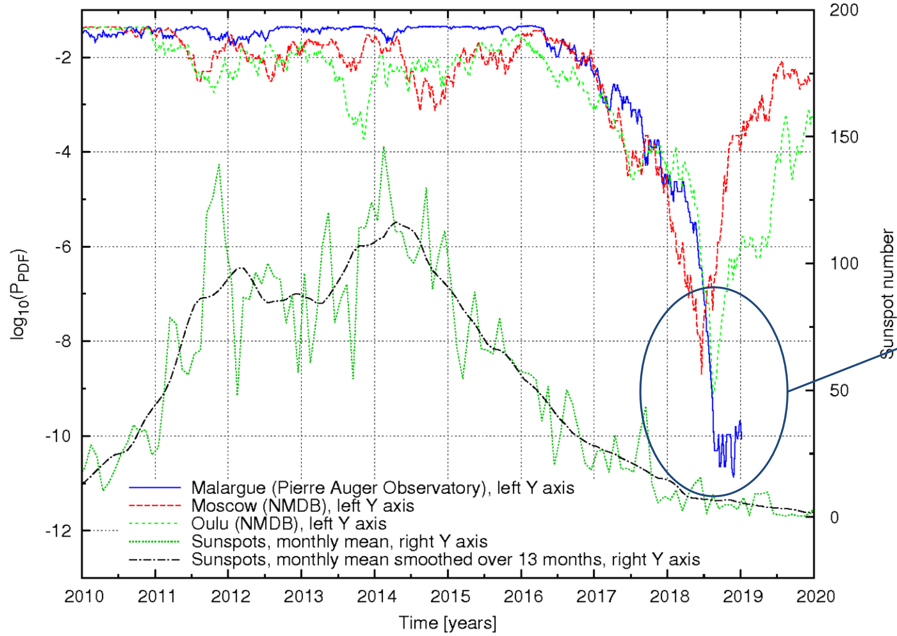
[Pierre Auger Observatory scaler data]
[Neutron Monitor Database]
[U.S. Geological Survey]
[Solar Influences Data analysis Center]



Checking for a correlation $|dN_{CR}|$ **vs.** Σ**magnitude**$_{EQ}$ using **5-day bins** over ~**4.5 yr windows**

Local cosmic dynamics vs. global seismicity: dependence on geographical location?

log10(chance probability)

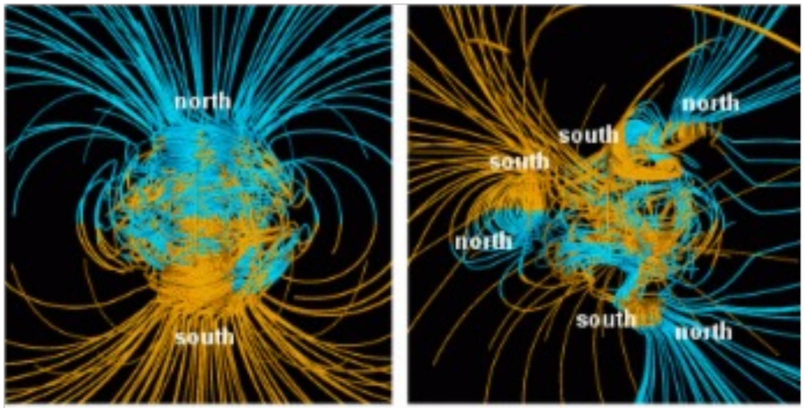


different cosmic ray sites see the correlation effect differently? Need for more detectors?

~6 σ significance of the effect in three technically independent CR data sets collected by the Moscow and Oulu NMDB stations, and by the Pierre Auger Observatory, compared to sunspot numbers. **Each point** illustrates the correlation effect during **the last ~4.5 years** (335 **five-day intervals**). All the significance curves were obtained after fine tuning of the parameter t_0 performed by applying 20 small shifts in time between 0 and 5 days.

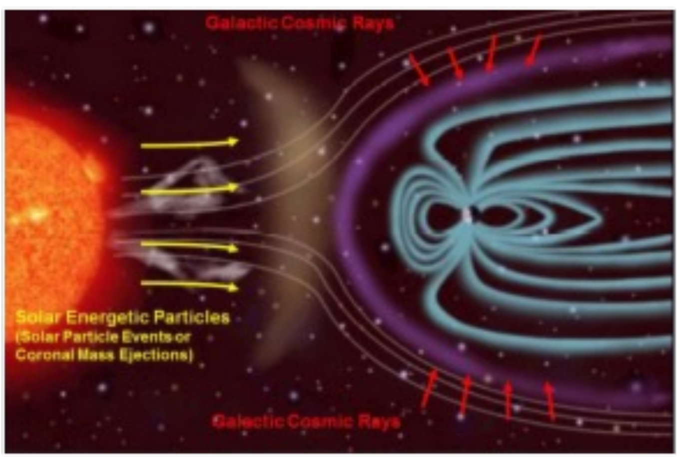
Cosmic Rays and earthquake early warning?

Wikipedia: „Geomagnetic reversal"



between reversals 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?

Seismic data and QGravity

arXiv:2401.01159

Bose-Einstein Condensate and Liquid Helium He^4: Implications of GUP and Modified Gravity Correspondence

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Utilizing the recently established connection between Palatini-like gravity and linear Generalized Uncertainty Principle (GUP) models, we have formulated an approach that facilitates the examination of Bose gases. Our primary focus is on the ideal Bose-Einstein condensate and liquid helium, chosen as illustrative examples to underscore the feasibility of tabletop experiments in assessing gravity models. The non-interacting Bose-Einstein condensate imposes constraints on linear GUP and Palatini $f(R)$ gravity (Eddington-inspired Born-Infeld gravity) within the ranges of $-10^{12} \lesssim \sigma \lesssim 3\times10^{24}$ s/kg m and $-10^{-1} \lesssim \bar{\beta} \lesssim 10^{11}$ m^2 ($-4\times10^{-1} \lesssim \epsilon \lesssim 4\times10^{11}$ m^2), respectively. In contrast, the properties of liquid helium suggest more realistic bounds, specifically $-10^{23} \lesssim \sigma \lesssim 10^{23}$ s/kg m and $-10^{9} \lesssim \bar{\beta} \lesssim 10^{9}$ m^2. Additionally, we argue that the newly developed method employing Earth seismic waves provides improved constraints for quantum and modified gravity by approximately one order of magnitude.

I am spearheading an application, along with a number of colleagues, for COST Action 2024, with the goal of bringing together researchers in the areas of (quantum) gravity, particle physics, seismology, and solid-state physics.

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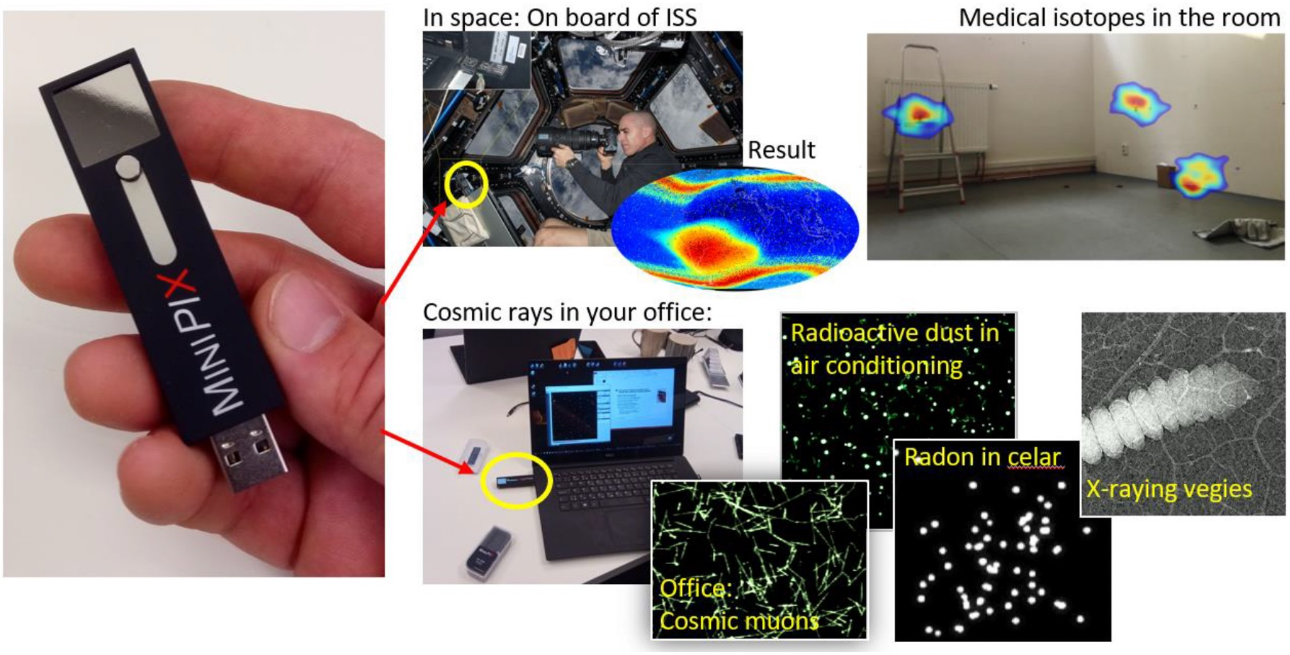
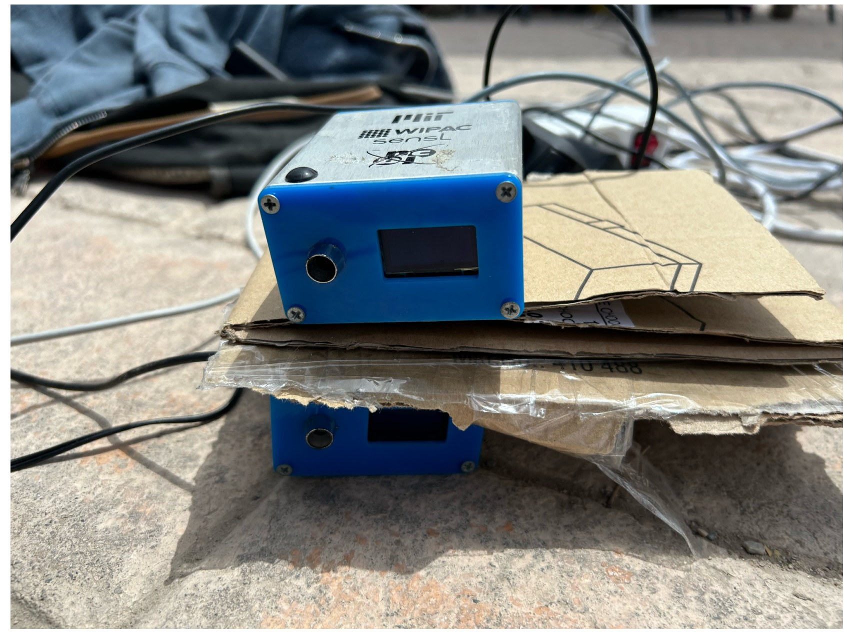
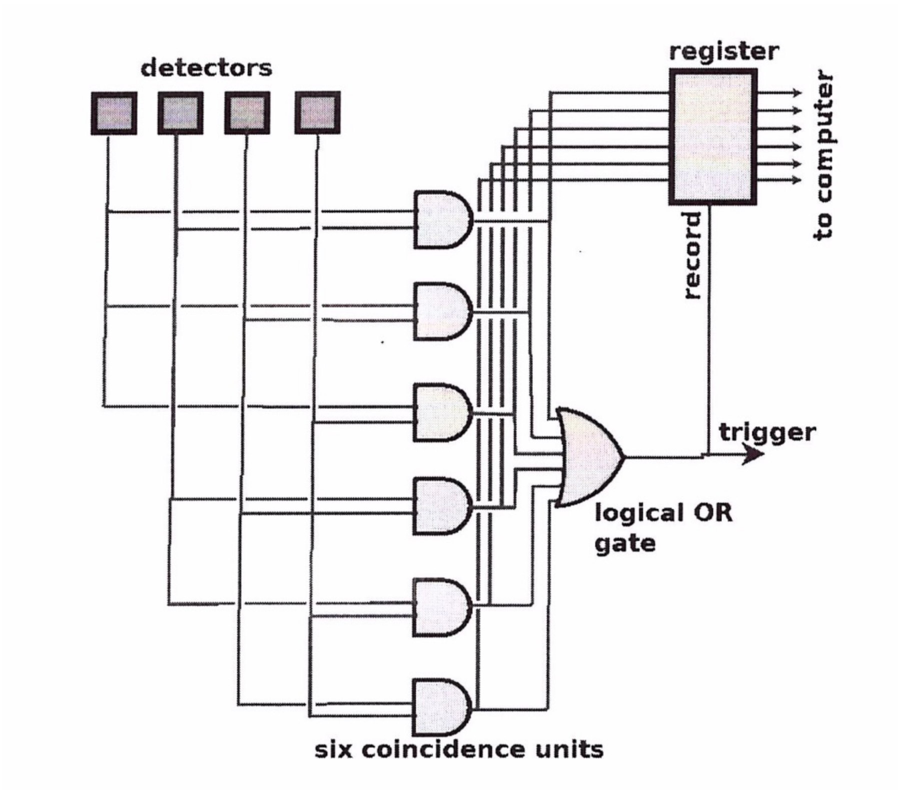
ADVACAM MiniPix



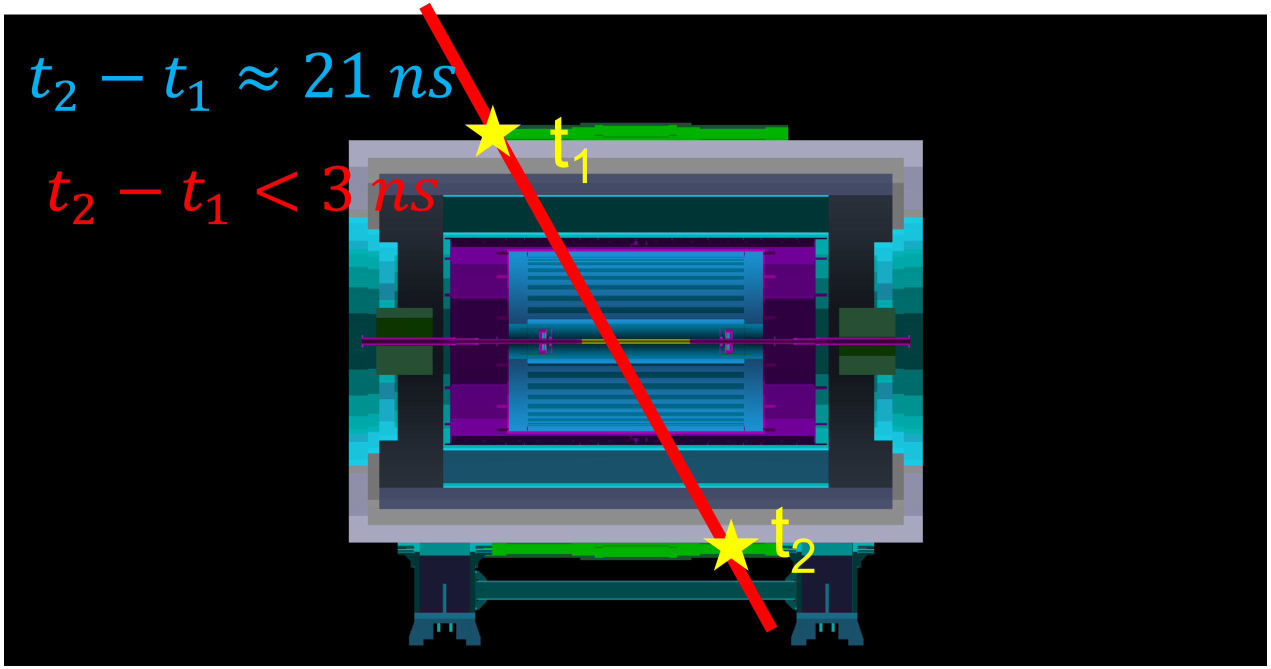
COSMIC WATCH



CREDO-MAZE Detector



Time of flight in colliders



Invitation to cooperation — distributing small detector arrays for CREDO

Jerzy Pryga [1]

[1]University of the National Education Commission

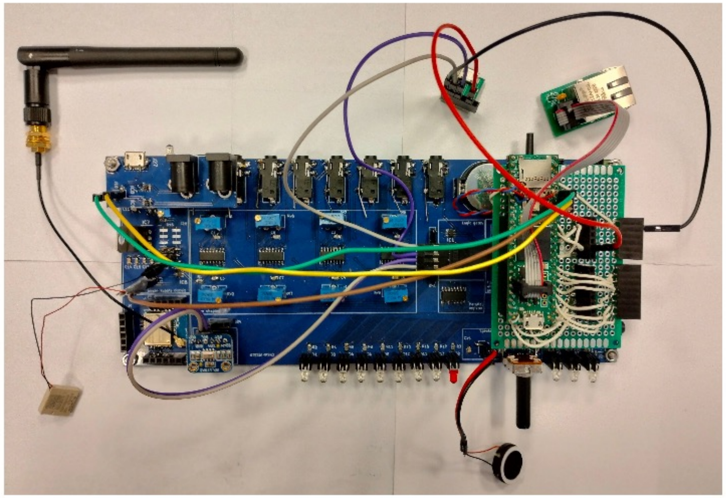
04.06.24

Cooperation offer

Installation in your institution

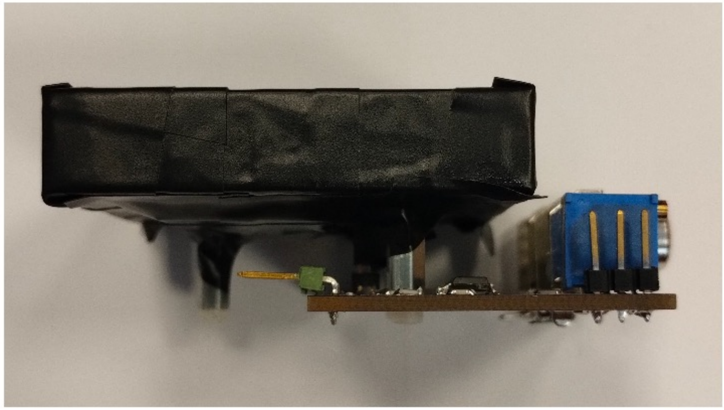
Workshop:

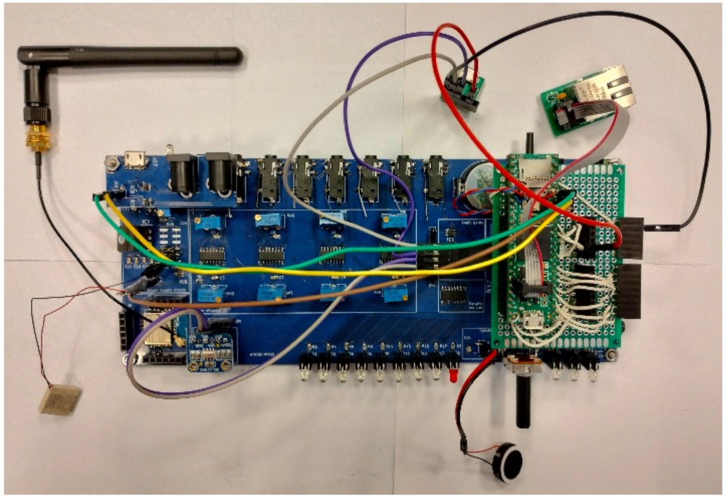
- Lecture about CREDO and cosmic rays.
- Hands-on training for students on how such detectors work and how to build them.
- Laboratory classes to practice how to conduct measurements.



What do we offer?

Detector station:
8 scintillators (top figure)
+ master unit (bottom figure).
Tools:
Housing for outdoors measurements, accessories for experiments with students.
Residence time:
At least to the end of the project (around 1.5 year).





Costs of such station is around 5000 PLN $\approx$ 1170 EUR.

You can buy parts and we can built it together if you want.

If you are interested in any cooperation — please contact me!

e-mail: `jerzy.pryga@wp.pl`

TOTAL SOLAR ECLIPSE 2024

The Physics Teacher

Solar Eclipse and Cosmic Ray Flux

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Published Online: 31 January 2022

Tamar A. Dallal, Jacob M. Miller, Michelle Matten, et al.

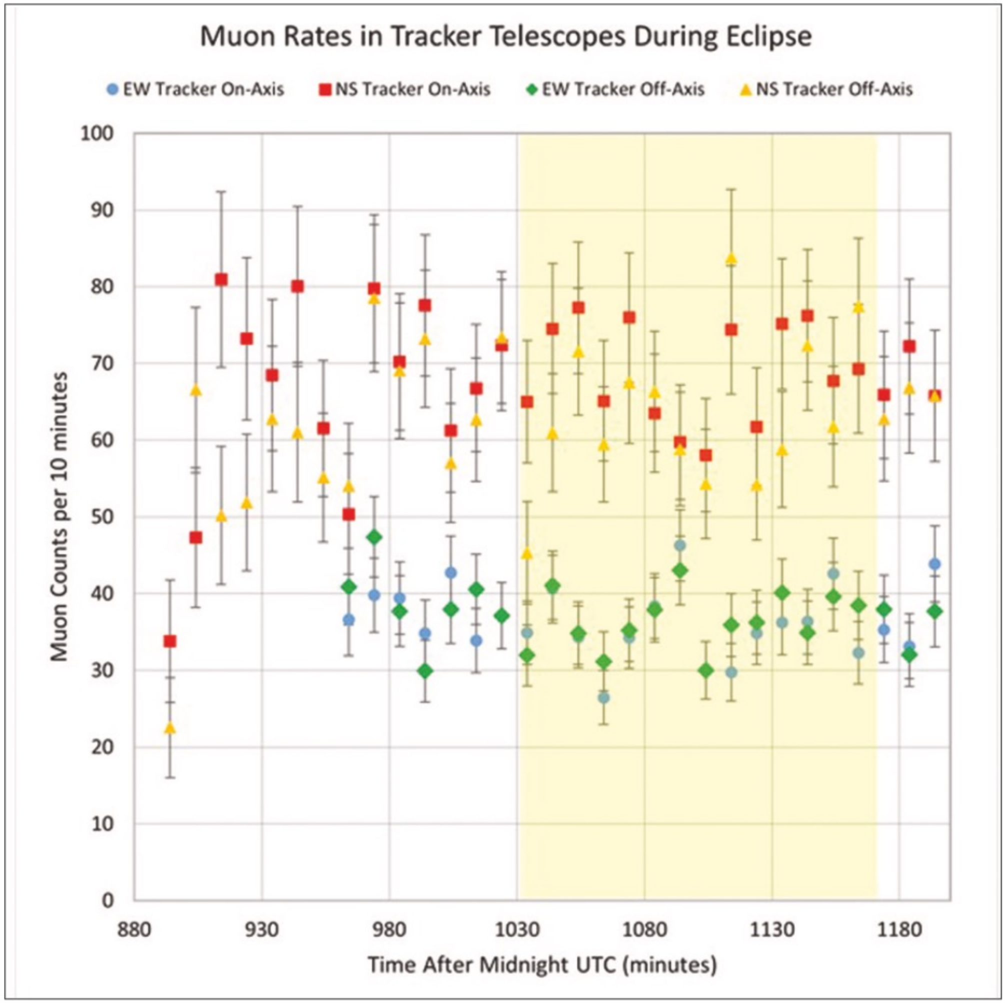

Fig. 8. Tracking telescope results of muon events per 10 minutes since midnight UTC. Presented are rates corrected for elevation: on-axis (*13+24*) for the EW (NS) tracker in blue circles (red squares); off-axis (*14*+23) for the EW (NS) tracker in green diamonds (yellow triangles). The yellow highlighted area marks the time interval of the eclipse.

TOTAL SOLAR ECLIPSE 2024


NICER
Neutron Star Interior Composition Explorer
LIGO
KAGRA
Virgo
ET
EINSTEIN TELESCOPE
ATHENA
STROBE-X
SKA
SKA AFRICA
SQUARE KILOMETRE ARRAY
MeerKAT
ngvla
eXTP
enhanced X-ray Timing and Polarimetry Mission

More about CREDO

https://credo.science

Personal contact:

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

Conclusions

- Cosmic Rays are potentially capable of bring insight into the solution of fundamental problems like the nature of dark matter

- Studying the nature of space-time structure and associated variation of constants is pursued by CREDO.

- Many astrophysical sources include compact objects.

- CREDO is a scientific project open to citizens as well which relies on support of many educational and scientific institutions.

- Many other possible applications of CREDO data are being studied as well: earthquakes.

Gracias