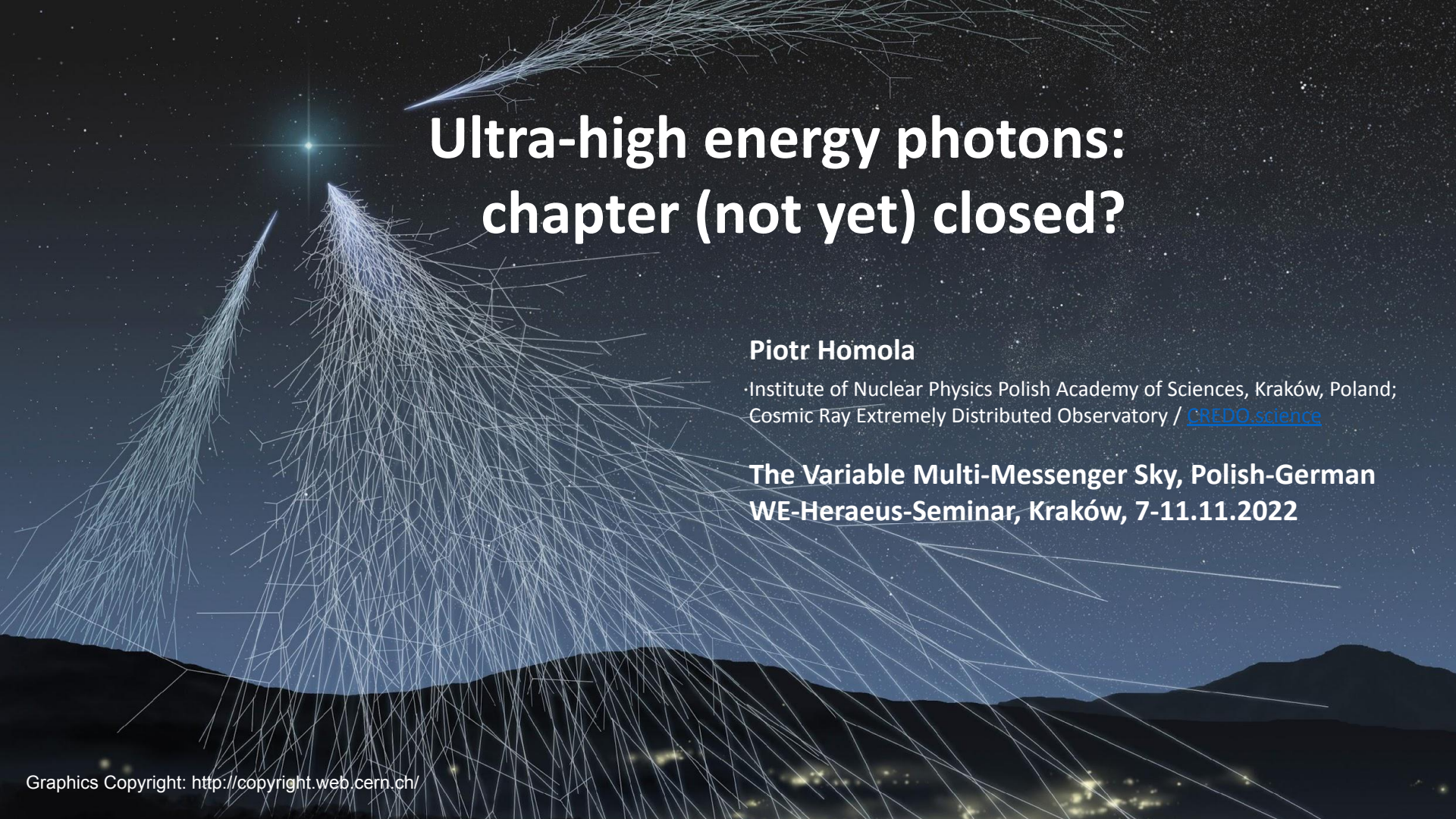


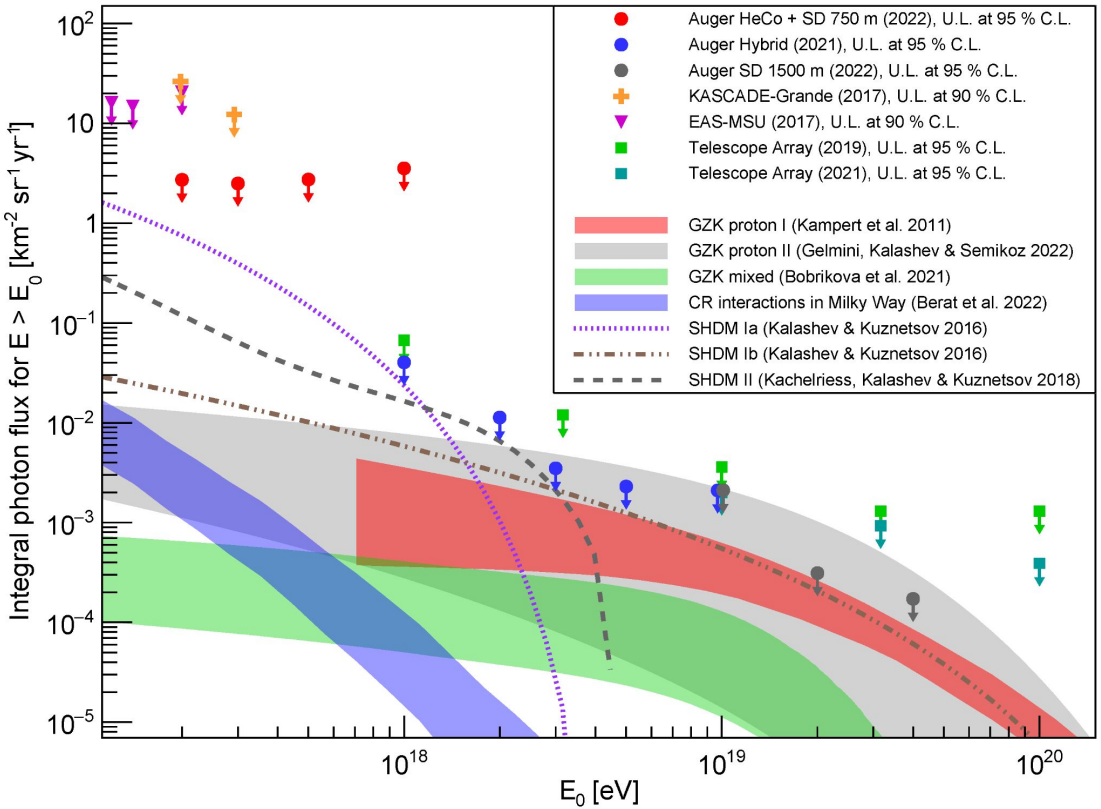
Ultra-high energy photons: chapter (not yet) closed?

Piotr Homola

Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland;
Cosmic Ray Extremely Distributed Observatory / CREDO.science

The Variable Multi-Messenger Sky, Polish-German WE-Heraeus-Seminar, Kraków, 7-11.11.2022

UHE photons: expected but not seen?



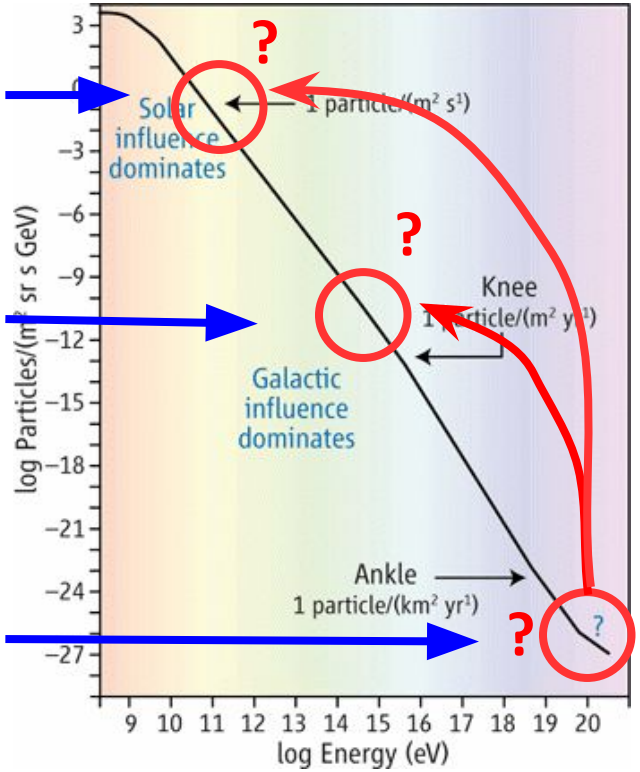
… the assumptions!

- physics understood?
- models correct?
- mean free paths?
- distribution of sources?
- …?

Pierre Auger Collaboration, *Universe* **2022**, *8*(11), 579;
https://doi.org/10.3390/universe8110579

Three unexplained observations

1. Cosmo-seismic precursor-like correlations with periodicity similar to the solar cycle (CREDO)
2. Hard gamma emission from the solar disk seen only during the solar minimum (Fermi-LAT)
3. Tension in the UHECR high-end energy spectrum (Pierre Auger Observatory & Telescope Array)



Can **UHE photons** be considered as a common explanation?

Tension in the UHECR high-end energy spectrum (Pierre Auger Observatory & Telescope Array)

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.

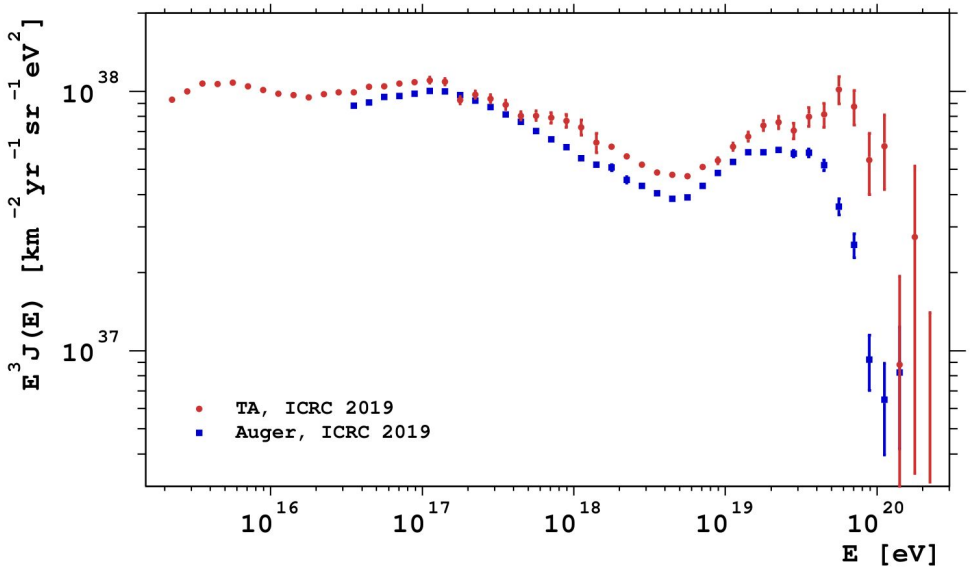
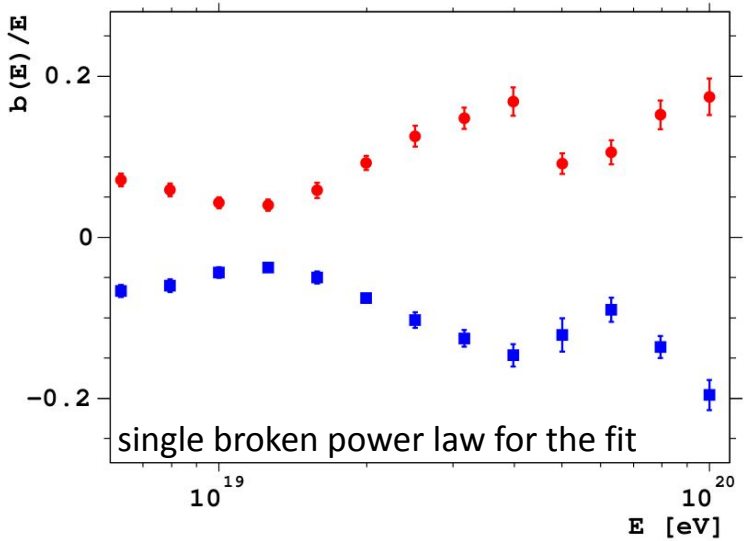
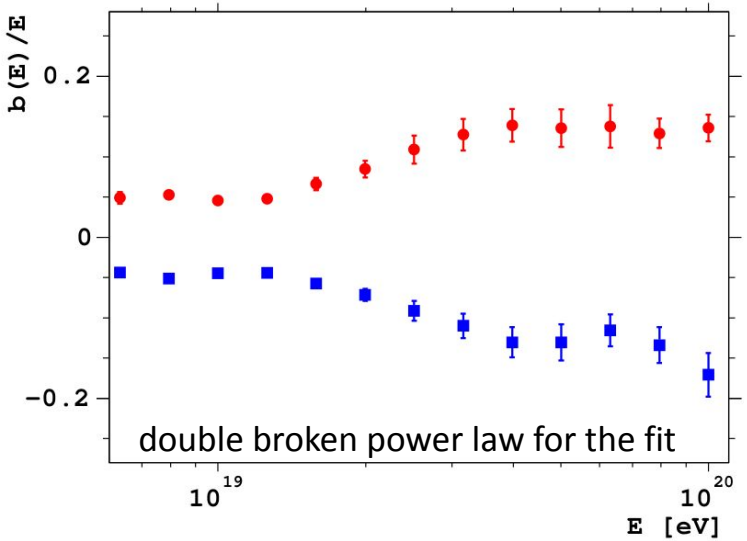


Figure 1: ICRC 2019 energy spectra of the Pierre Auger Observatory and the Telescope Array scaled by E^3. In each experiment, data of different detection techniques are combined to obtain the spectrum over a wide energy range.

The tension: energy dependent reconciliation

Energy shift term needed to bring the fitted differential spectra in agreement, common declination ranges.





"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."

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.

Ideas: technology, mistakes, or physics?

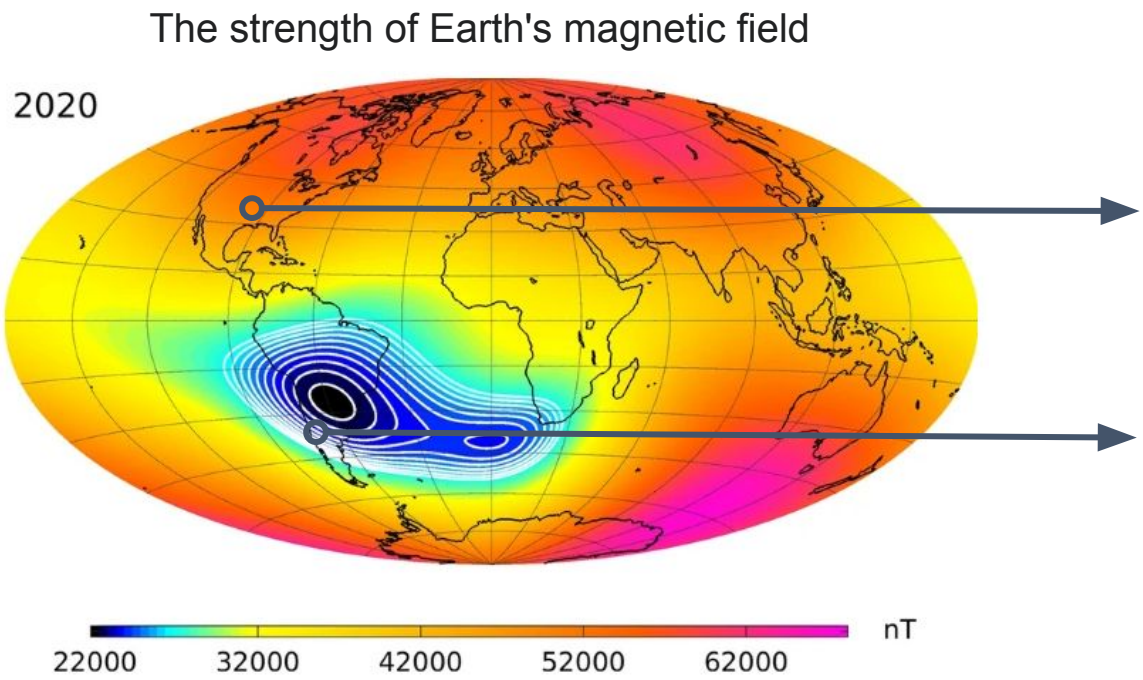


Image by Christopher C. Finlay, Clemens Kloss, Nils Olsen, Magnus D. Hammer, Lars Tøffner-Clausen, Alexander Grayver; Alexey Kuvshinov - The CHAOS-7 geomagnetic field model and observed changes in the South Atlantic Anomaly, Earth, Planets and Space, Volume 72, Article number 156 (2020), https://earth-planets-space.springeropen.com/articles/10.1186/s40623-020-01252-9, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=99760567

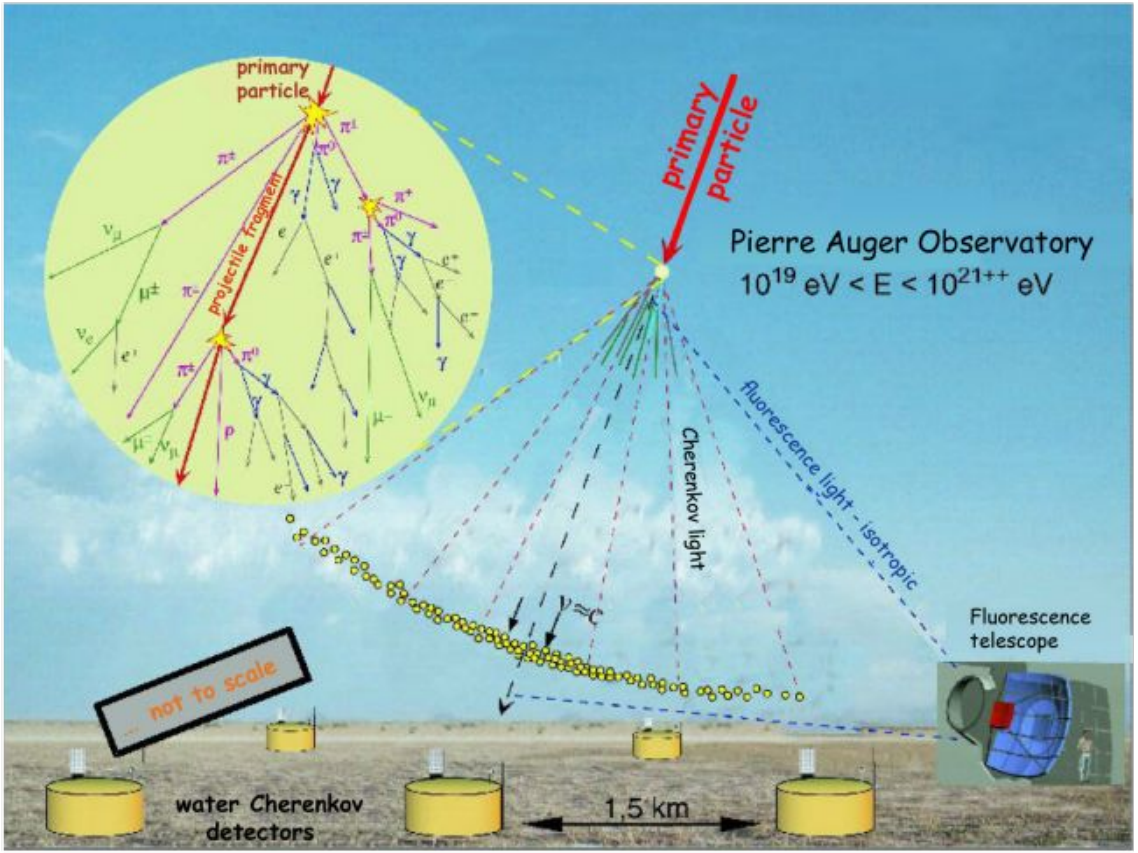
If physics:

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

Extensive air showers



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].

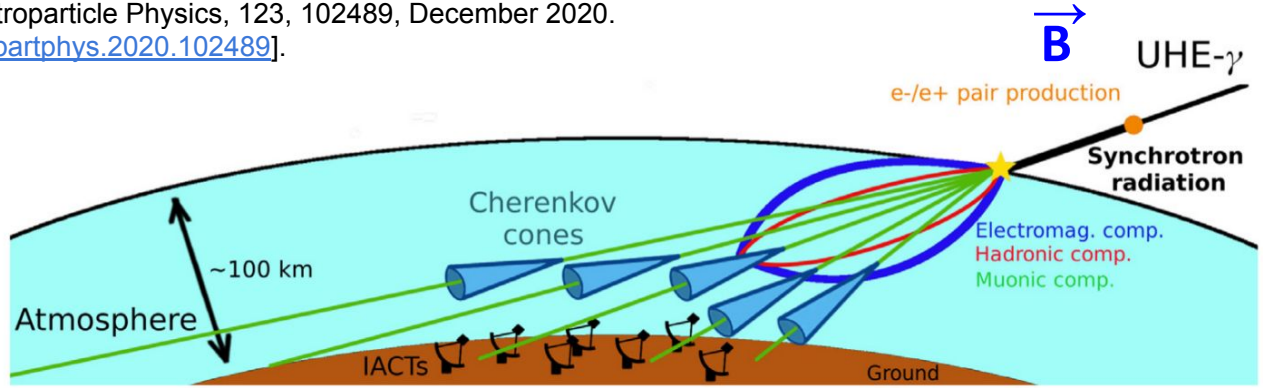
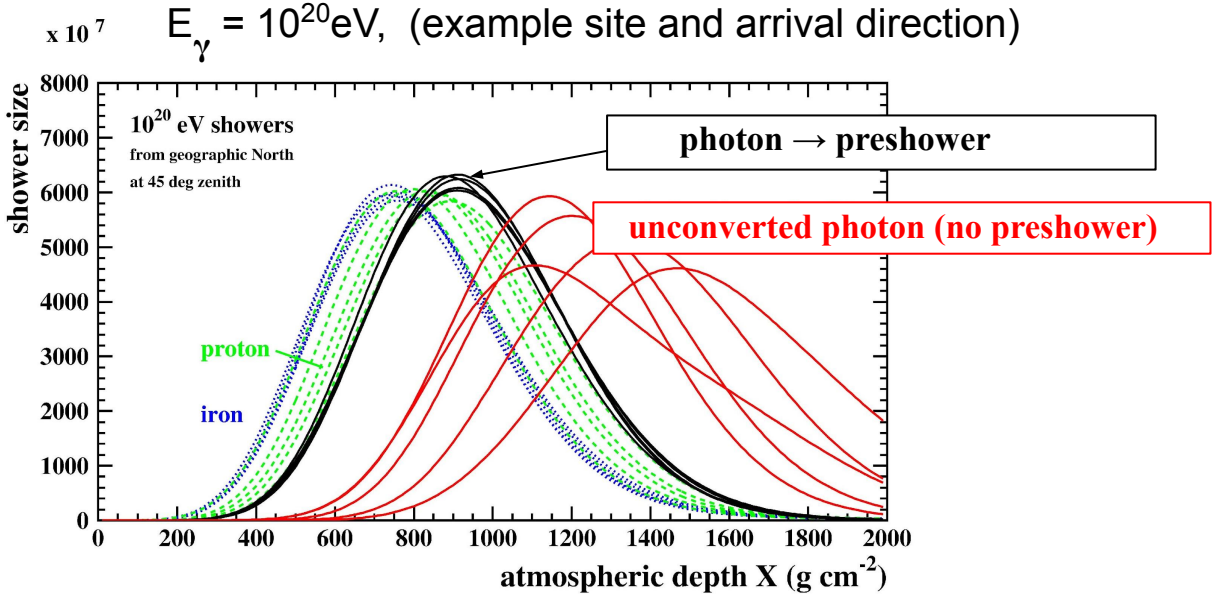


Fig. 1. A ultra-high energy photon interacting with the transverse component of the geomagnetic field produces an e^+/e^- pair ~ 1000 km above sea level which emits bremsstrahlung photons. As such process can repeat itself for some of these photons, a collection of particles (mainly photons and a few 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)

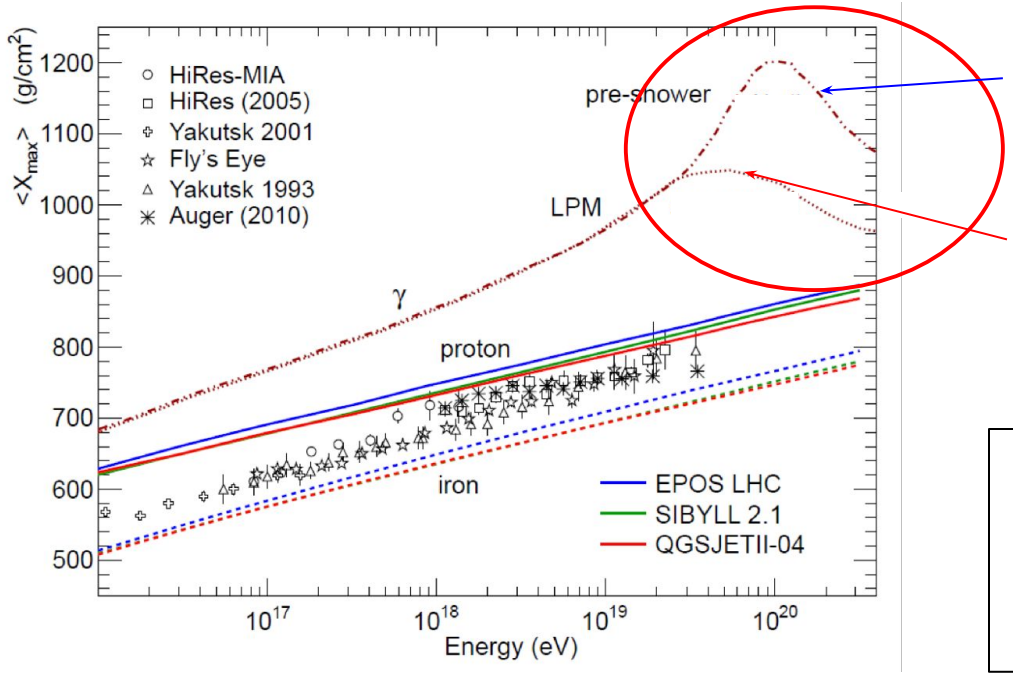
LPM (in top layers of atmosphere is important for $E_\gamma > 10^{19}$ eV):

→ **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: X_{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... what if the physics extrapolations by many orders of magnitude are slightly wrong?

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*.

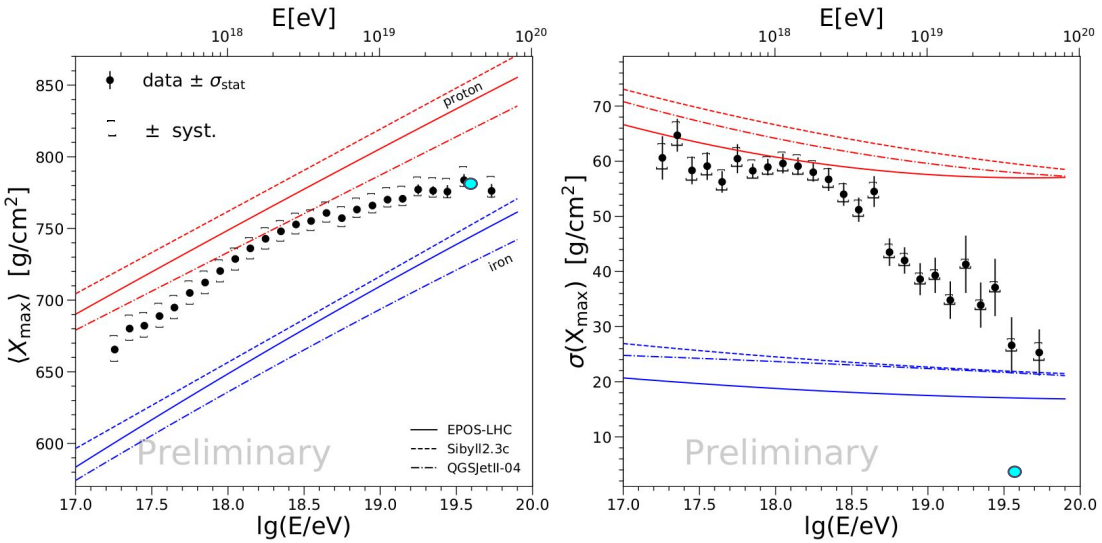


Figure 1: Measurements of $\langle X_{max} \rangle$ (left) and $\sigma(X_{max})$ (right) at the Pierre Auger Observatory compared to the predictions for proton and iron nuclei of the hadronic models EPOS-LHC, Sibyll 2.3c and QGSJetII-04.

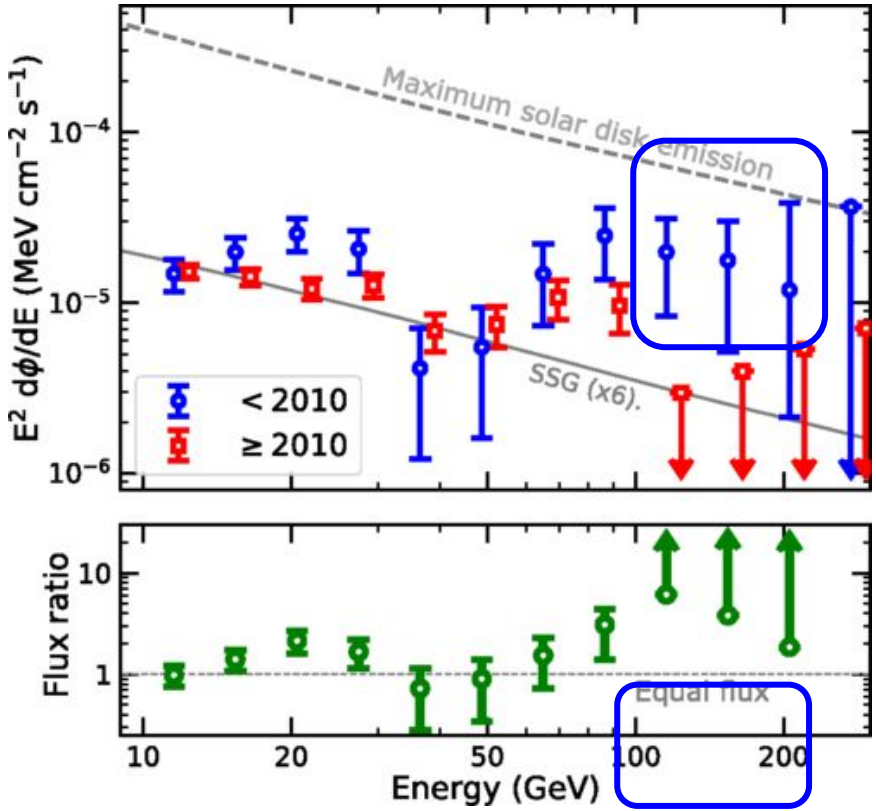
- [added by PH]:

example primary preshower
<Xmax>=783±3 g/cm^2
Log(E/eV)=19.6
N particles = 1500
forced initiation at 17000 km a.s.l.
[typical initiation: 100-200 km a.s.l.]

Physics at the highest energies uncertain -> more uncertainty in Xmax likely?

Hard gamma emission from the solar disk seen only during the solar minimum (Fermi-LAT)

Fermi-LAT: “a New Component of High-Energy Solar Gamma-Ray Production”, observed only during the solar minimum



(Top panel) The solar disk γ-ray spectrum during solar minimum (**before January 1, 2010; blue circles**) and after it (red squares). Small shifts along the x axis improve readability. The gray lines show the SSG model renormalized by a factor of 6 to fit the lowest-energy data point (solid line), and the maximum γ-ray flux that could be produced by hadronic cosmic rays (dashed line). (Bottom panel) The ratio of the γ-ray flux observed during and after solar minimum. All upper and lower limits are based on 2σ Poisson fluctuations in the photon count.

“These **observations** provide important new clues about the mechanisms behind solar disk γ-ray emission, which **remains mysterious**.”

[T. Linden, et al., Phys. Rev. Lett. 121, 131103, https://doi.org/10.1103/PhysRevLett.121.131103]

Journal of Cosmology and Astroparticle Physics

PAPER

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

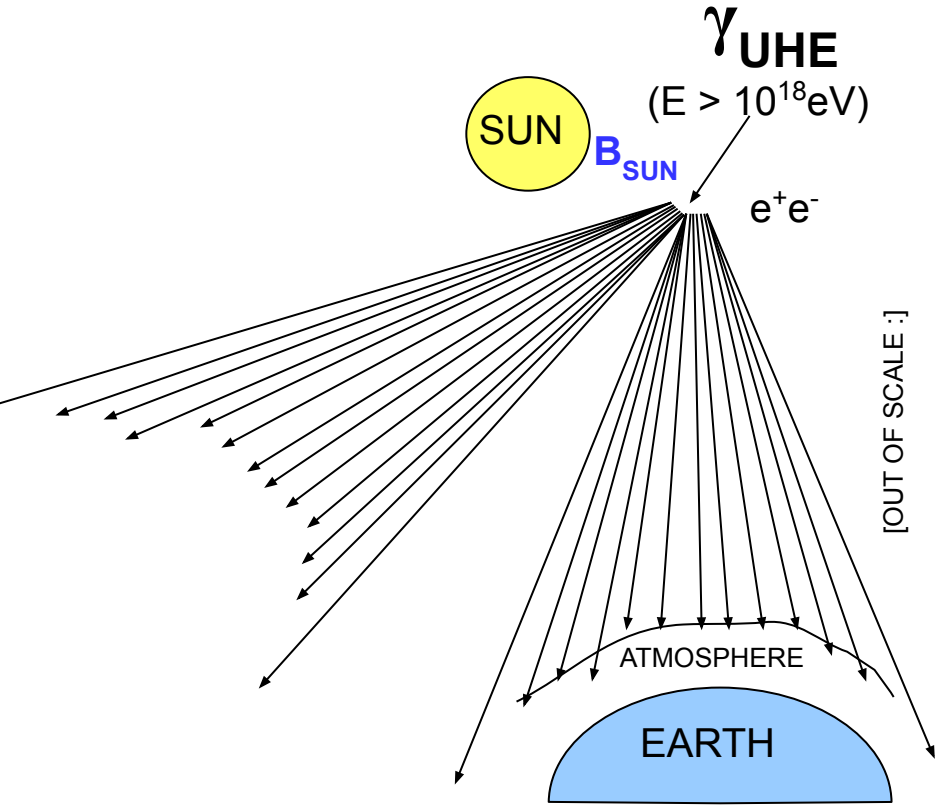
The CREDO collaboration, N. Dhital[1,2], P. Homola[2], D. Alvarez-Castillo[2,3], D. Góra[2], H. Wilczyński[2], K. Almeida Cheminant[2], B. Poncyljusz[4], J. Mędrala[5], G. Opiła[5], A. Bhatt[1], B. Łozowski[6], G. Bhatta[2], Ł. Bibrzycki[7], T. Bretz[8], A. Ćwikła[9], L. Del Peral[10], A.R. Duffy[11], A.C. Gupta[12], B. Hnatyk[13], P. Jagoda[5,2], M. Kasztelan[14], K. Kopański[2], P. Kovacs[15], M. Krupinski[2], M. Medvedev[16,17], V. Nazari[3], M. Niedźwiecki[18], D. Ostrogórski[5], M. Piekarczyk[7], M.D. Rodríguez Frías[10], K. Rzecki[5], K. Smelcerz[9], K. Smolek[19], J. Stasielak[2], O. Sushchov[2], T. Wibig[20], K. Wozniak[2], J. Zamora-Saa[21,22], Z. Zimborás[15] and A. Tursunov[23] – Hide full author list

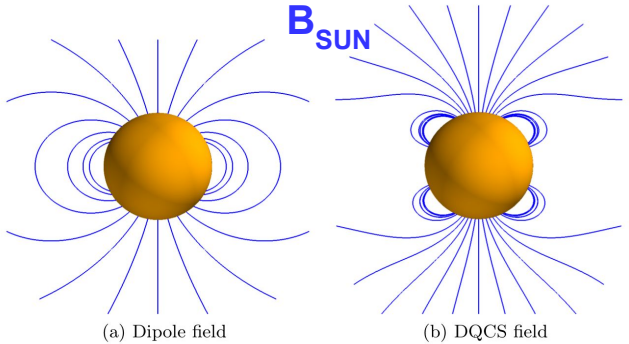
Published 16 March 2022 • © 2022 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2022, March 2022

Citation The CREDO collaboration *et al* JCAP03(2022)038

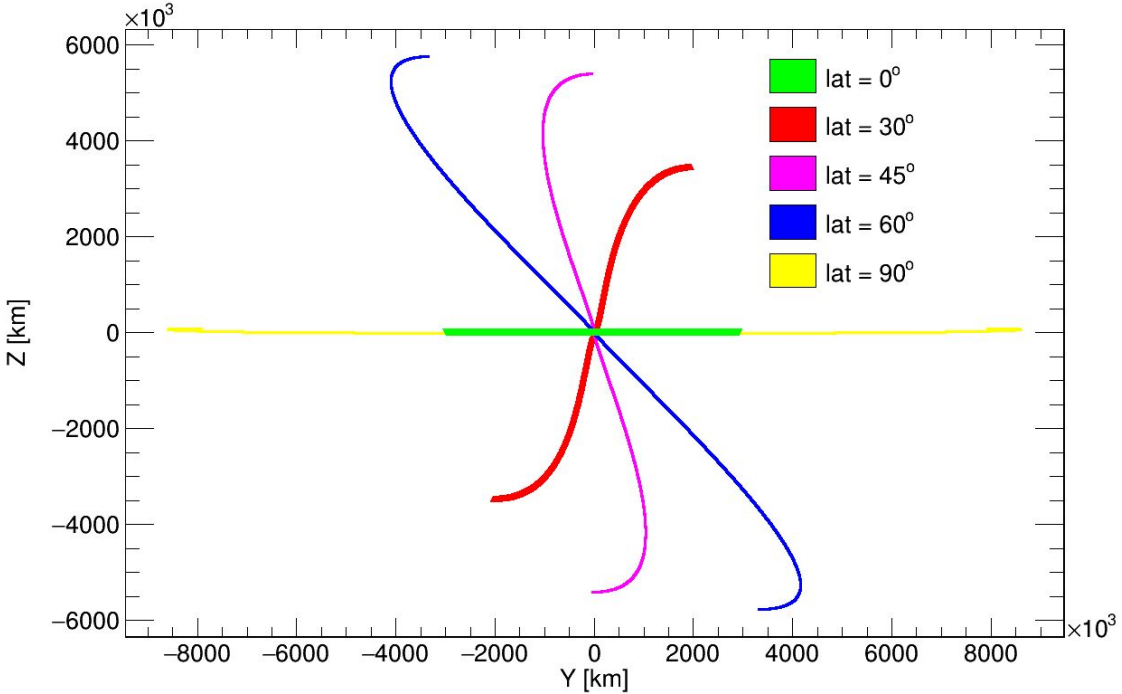
>=EeV photons nearby the Sun⟶ air shower walls



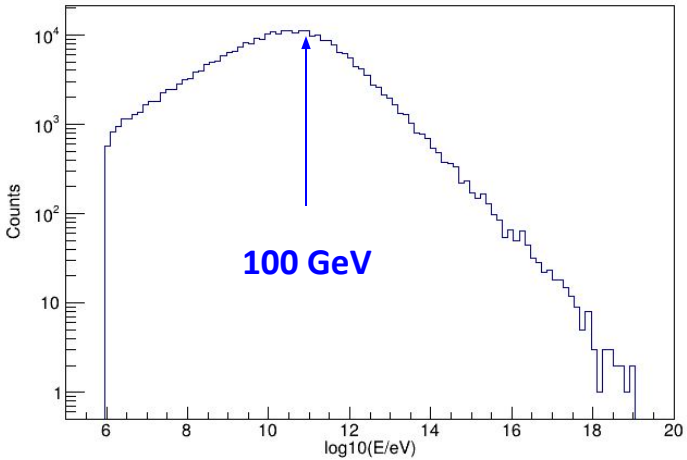


Air shower walls: footprints up to 1AU, all photon energies

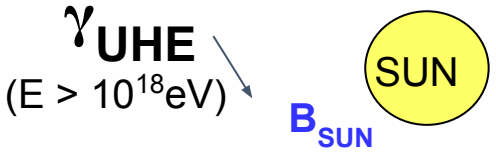
footprints very thin (~1m), up to 1 AU long, non-trivial shapes, dependent on incidence angle and impact parameter

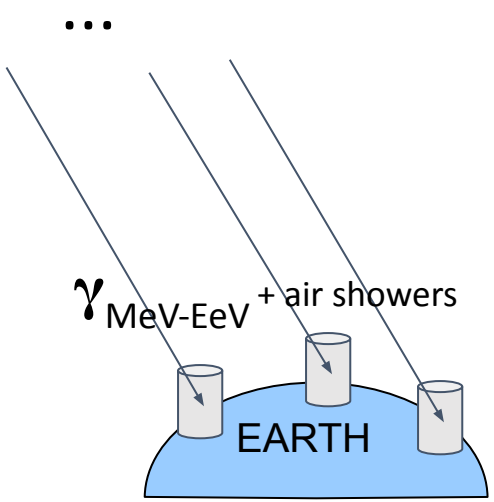


entire photon spectrum engaged

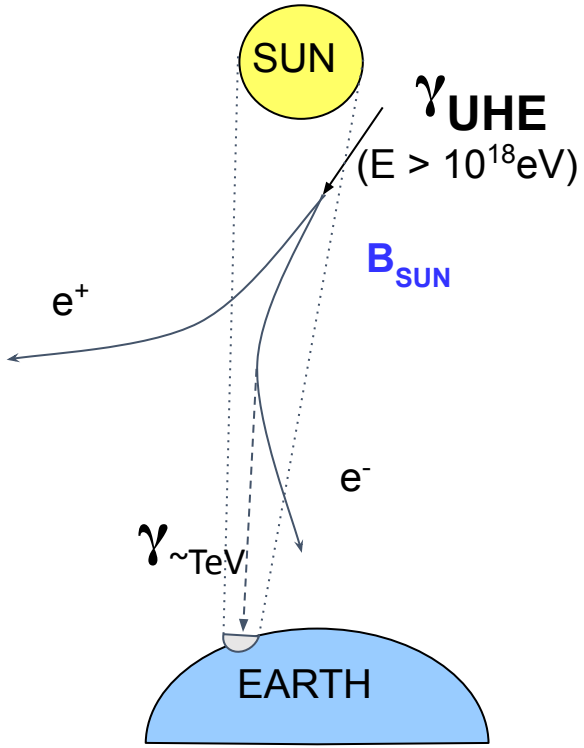


Air shower walls: observe or constrain UHE photons



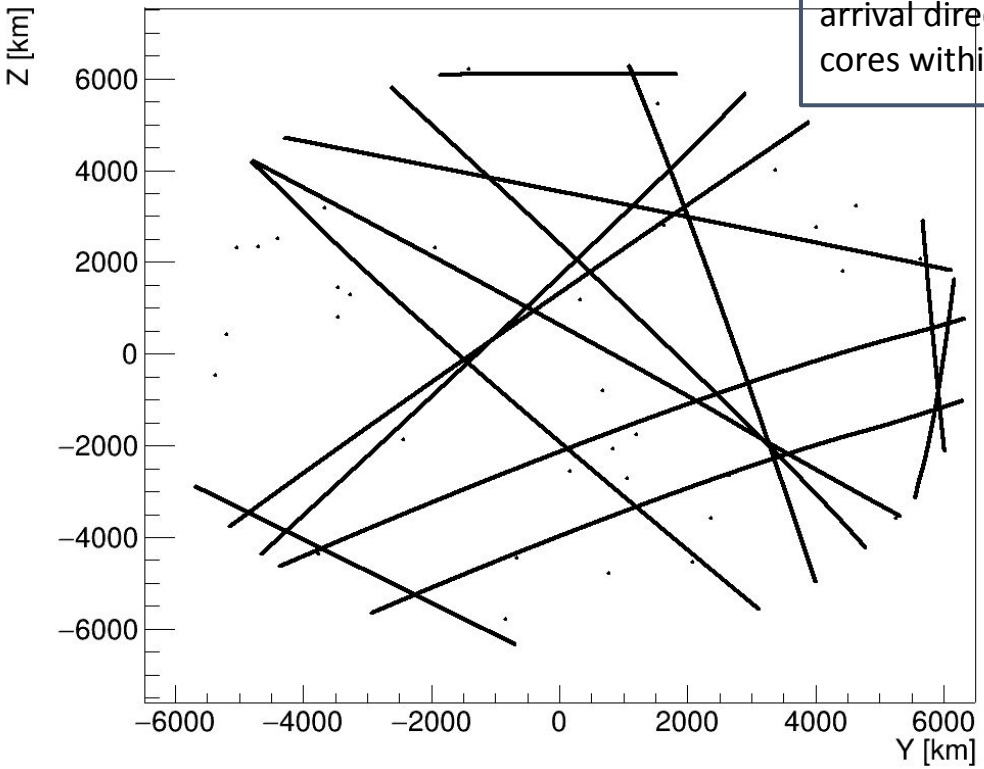


- displacement > ~100 km
- similar arrival directions
- consistent timing



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

Air shower walls & new astrophysical constraints



Air shower walls 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

(!) Comparable with the existing observations of the Sun in gamma rays, e.g. Fermi-LAT [T. Linden, et al., Phys. Rev. Lett. 121, 131103; 10.1103/PhysRevLett.121.131103], HAWC [A. Albert et al. (HAWC Collaboration), Phys. Rev. D 98, 123011 (2018); 10.1103/PhysRevD.98.123011

->

B. Poncyljusz et al. (CREDO Collaboration), *Universe* **2022**, *8*(10), 498; https://doi.org/10.3390/universe8100498

\+ work in progress

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

Earthquakes and cosmic rays: towards early warning system and/or Dark Matter discovery?

Interdisciplinary potential: contribution to earthquake early warning system?

Physics > Geophysics

[Submitted on 26 Apr 2022]

Observation of large scale precursor correlations between cosmic rays and earthquakes

P. Homola, V. Marchenko, A. Napolitano, R. Damian, R. Guzik, D. Alvarez-Castillo, S. Stuglik, O. Ruimi, O. Skorenok, J. Zamora-Saa, J.M. Vaquero, T. Wibig, M. Knap, K. Dziadkowiec, M. Karpiel, O. Sushchov, J. W. Mietelski, K. Gorzkiewicz, N. Zabari, K. Almeida Cheminant, B. Idźkowski, T. Bulik, G. Bhatta, N. Budnev, R. Kamiński, M.V. Medvedev, K. Kozak, O. Bar, Ł. Bibrzycki, M. Bielewicz, M. Frontczak, P. Kovács, B. Łozowski, J. Miszczyk, M. Niedźwiecki, L. del Peral, M. Piekarczyk, M. D. Rodriguez Frias, K. Rzecki, K. Smelcerz, T. Sośnicki, J. Stasielak, A. A. Tursunov

The search for correlations between secondary cosmic ray detection rates and seismic effects has long been a subject of investigation motivated by the hope of identifying a new precursor type that could feed a global early warning system against earthquakes. Here we show for the first time that the average variation of the cosmic ray detection rates correlates with the global seismic activity to be observed with a time lag of approximately two weeks, and that the significance of the effect varies with a periodicity resembling the undecenal solar cycle, with a shift in phase of around three years, exceeding 6 sigma at local maxima. The precursor characteristics of the observed correlations point to a pioneer perspective of an early warning system against earthquakes.

Comments: 16 pages, 4 figures in the main article and 11 pages and 4 figures in the Suplementary Material

Subjects: **Geophysics (physics.geo-ph)**; Earth and Planetary Astrophysics (astro-ph.EP); High Energy Astrophysical Phenomena (astro-ph.HE); Solar and Stellar Astrophysics (astro-ph.SR)

Cite as: arXiv:2204.12310 **[physics.geo-ph]**

(or arXiv:2204.12310v1 **[physics.geo-ph]** for this version)

https://doi.org/10.48550/arXiv.2204.12310

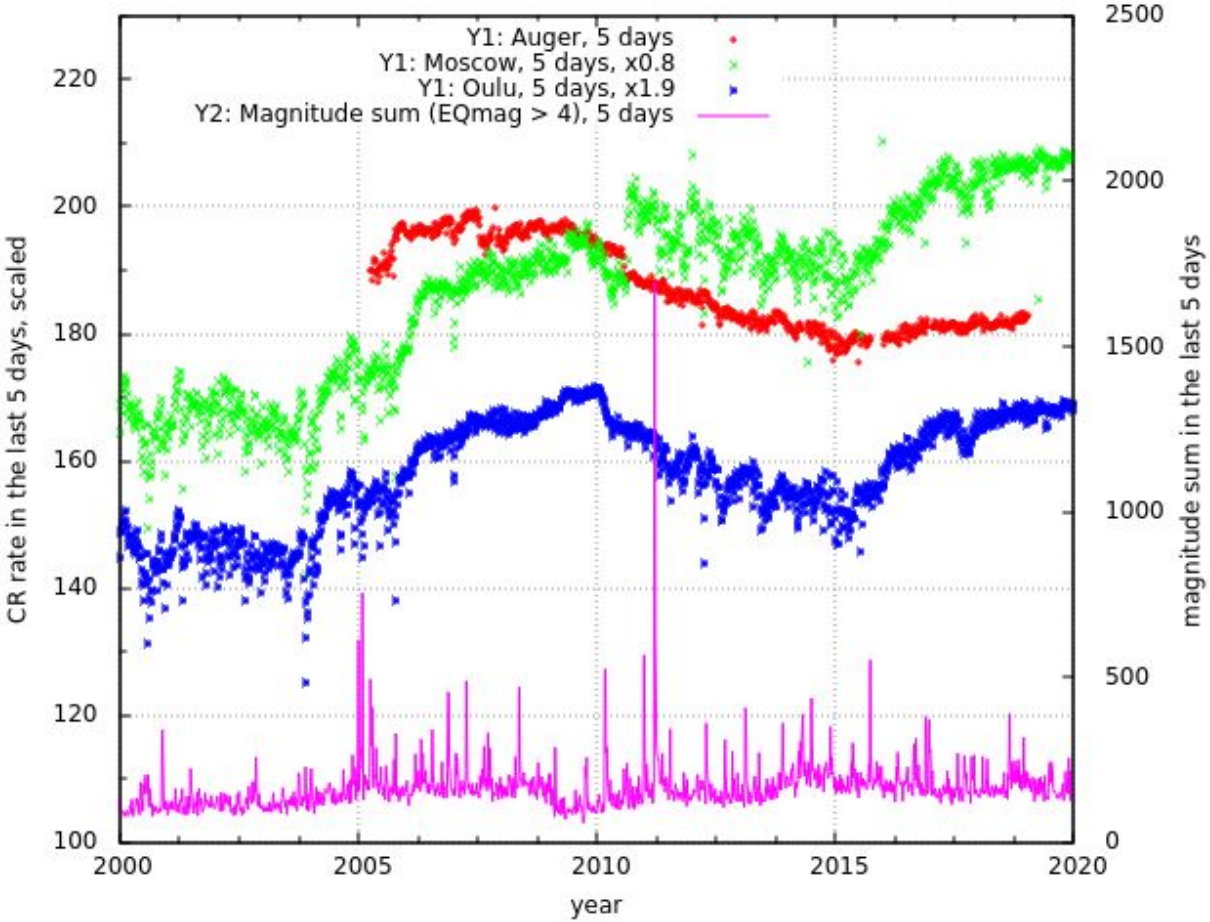
Submission history

From: Piotr Homola Dr. [view email]

[v1] Tue, 26 Apr 2022 13:37:03 UTC (1,085 KB)

(in review @ JASTP)

The data



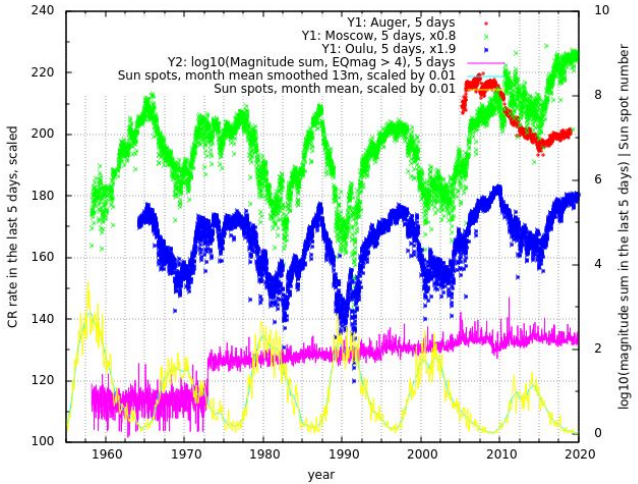
public resources of:

[Pierre Auger Observatory scaler data]

[Neutron Monitor Database]

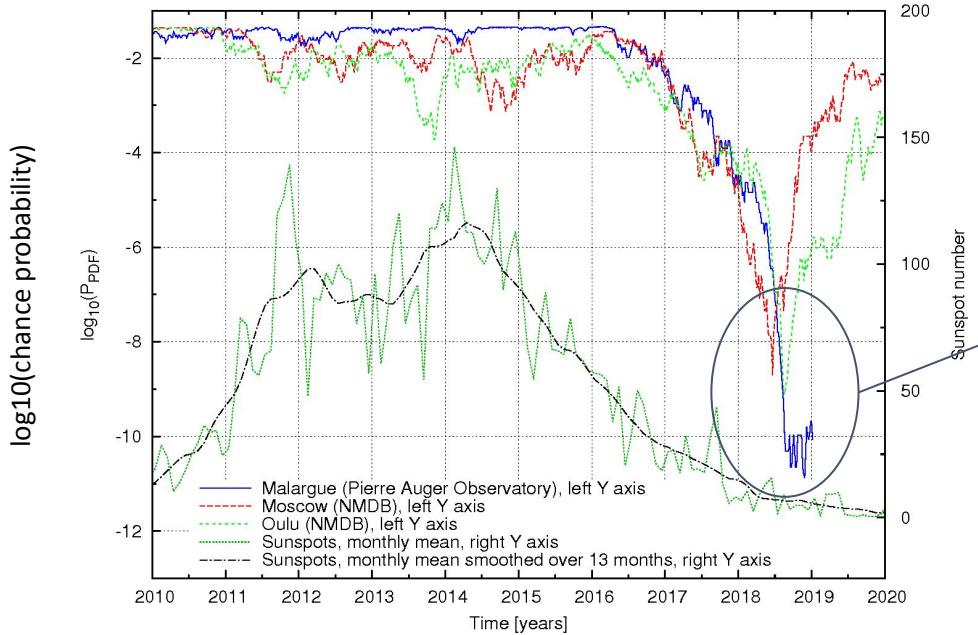
[U.S. Geological Survey]

[Solar Influences Data analysis Center]



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

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



different cosmic ray sites see the **dichotomic** 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.

23

Cosmic ray variation 15 days before the corresponding change in seismic activity!

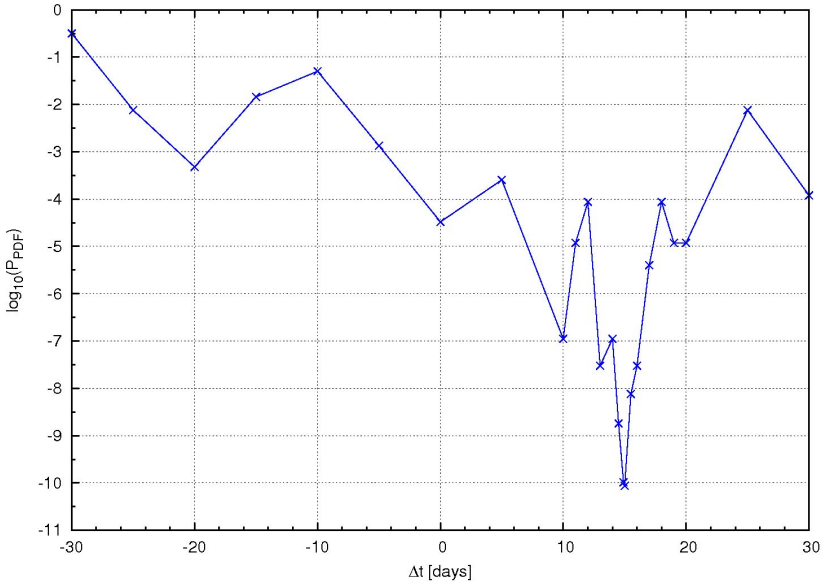


Fig. 3: The dependence of the significance of the *cosmo-seismic* correlations on the time shift t of the EQ data with respect to the Auger CR data, for the optimum free parameter set defined in Eq. 1. The positive or negative values of t correspond to the situations in which one compares the secondary cosmic ray data in a given time interval to the seismic data recorded in time intervals in the future or in the past, respectively.

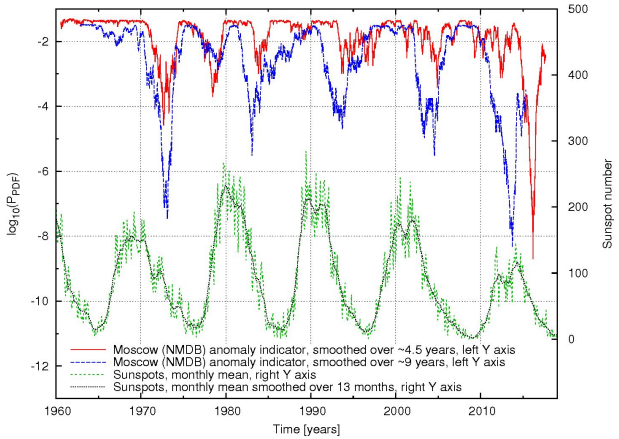
A dependence of the effect on the observation site?

-> possible ultimate ambition: **cosmic ray station in every school and BTS station + citizen science**

Interpretation: Role of the Sun or DM stream?

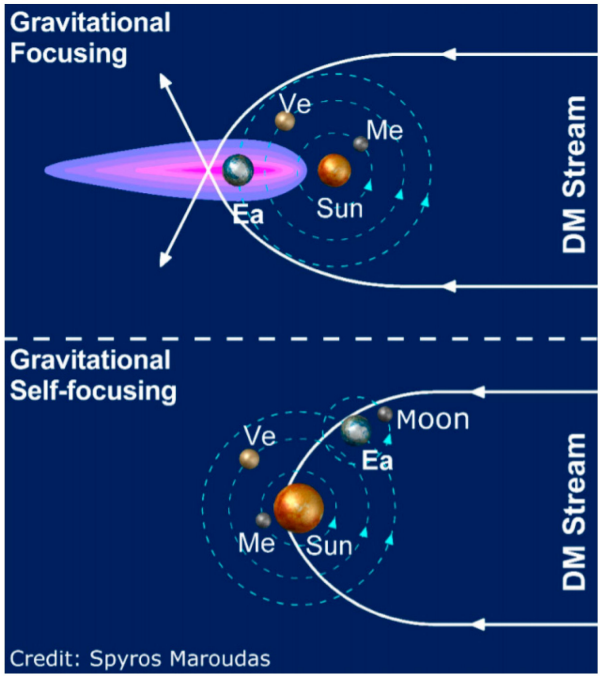
P. Homola et al., 2022: https://arxiv.org/abs/2204.12310

log10(chance probability)



The anomaly indicator in the Moscow NMDB data set compared to the sunspot number. Each point on the correlation significance curves corresponds to the effect found over the smoothing window length of **~4.5 years (1675 days, in red)** and ~9 years (3350 days, in blue), with the curve points located at the centers of the windows.

K. Zioutas et al., 2021
Phys. Sci. Forum **2021**, *2*(1), 10; https://doi.org/10.3390/ECU2021-09313



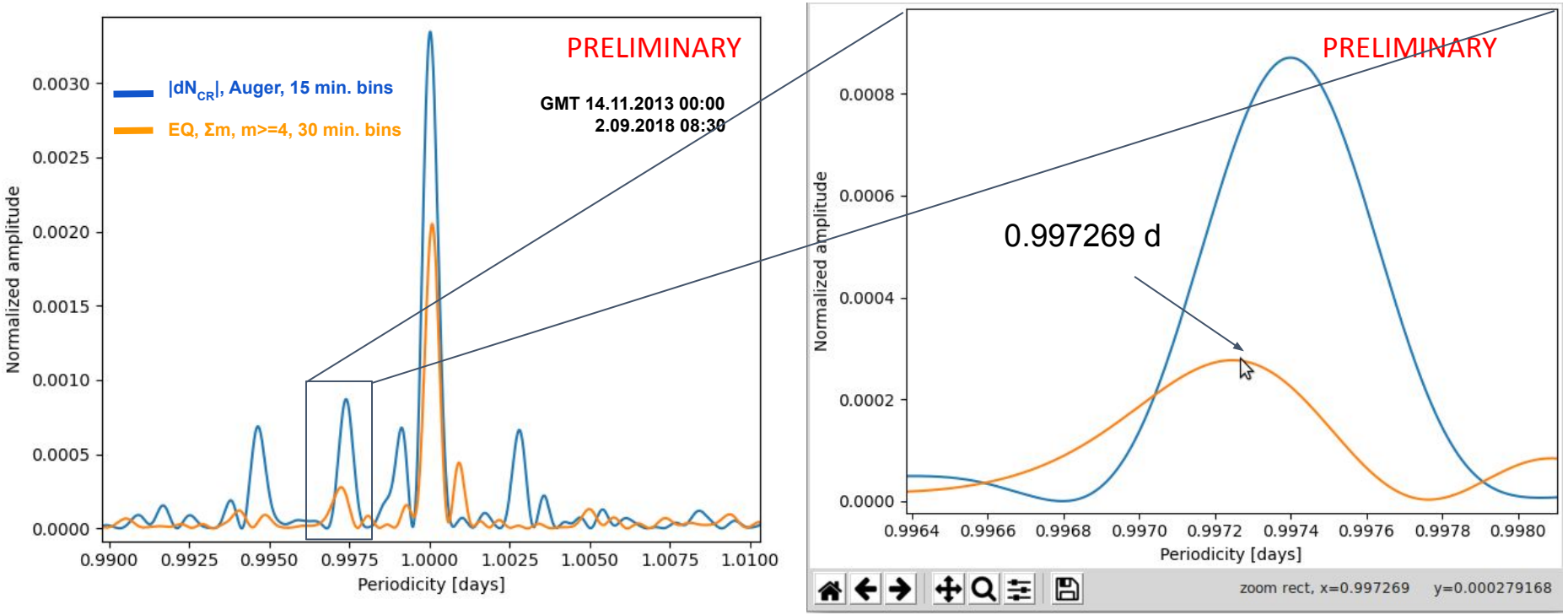
PH: (SH)DM overdensities -> (periodic) CR excesses?

Preliminary!

(caution!)

24h and sidereal day (SD) periodicities in $|dN_{CR}|$ and Σm_{EQ}

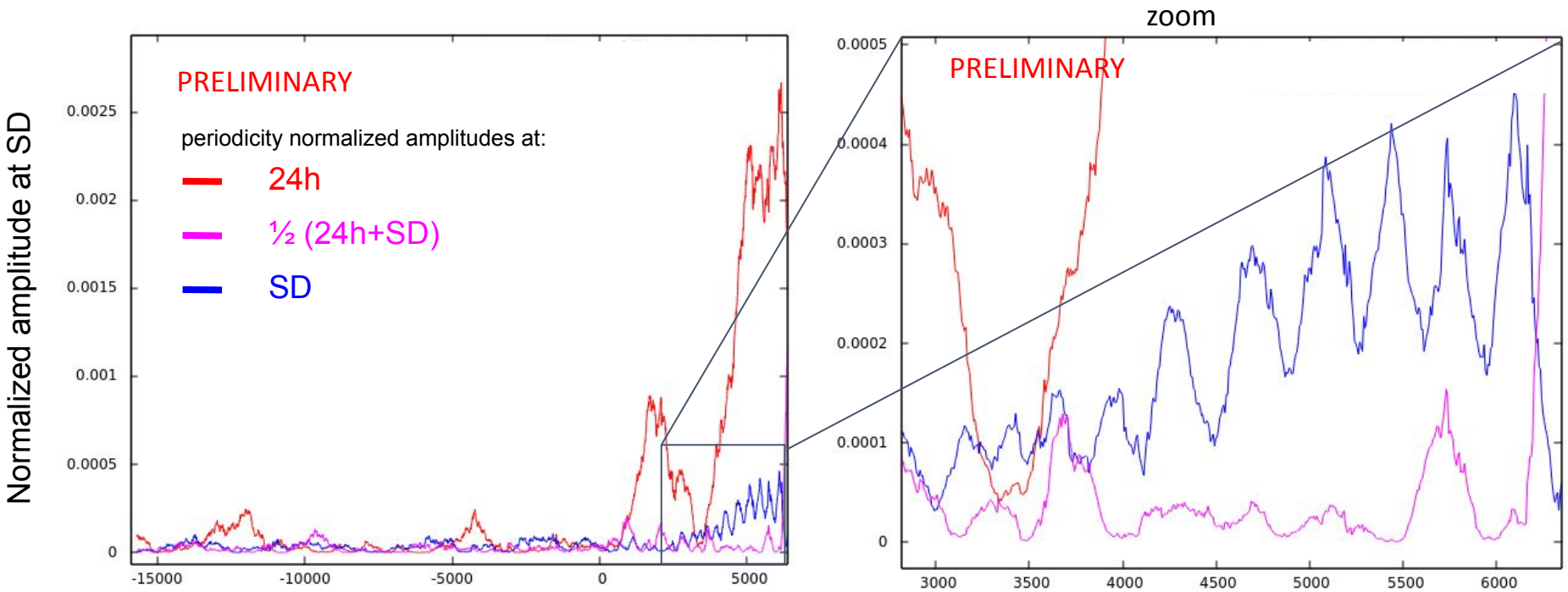
1 sidereal day = 23.9344696 hours -> 0.997269567 day; Lomb-Scargle periodograms



Clear 24h and sidereal day periodicities both in CR and EQ data, appearing only during the cosmo-seismic correlation maximum? Responsible for the periodicity of the effect?? Does the exact 0.99727 d periodicity in (part of) EQ data confirm the “external impact”?

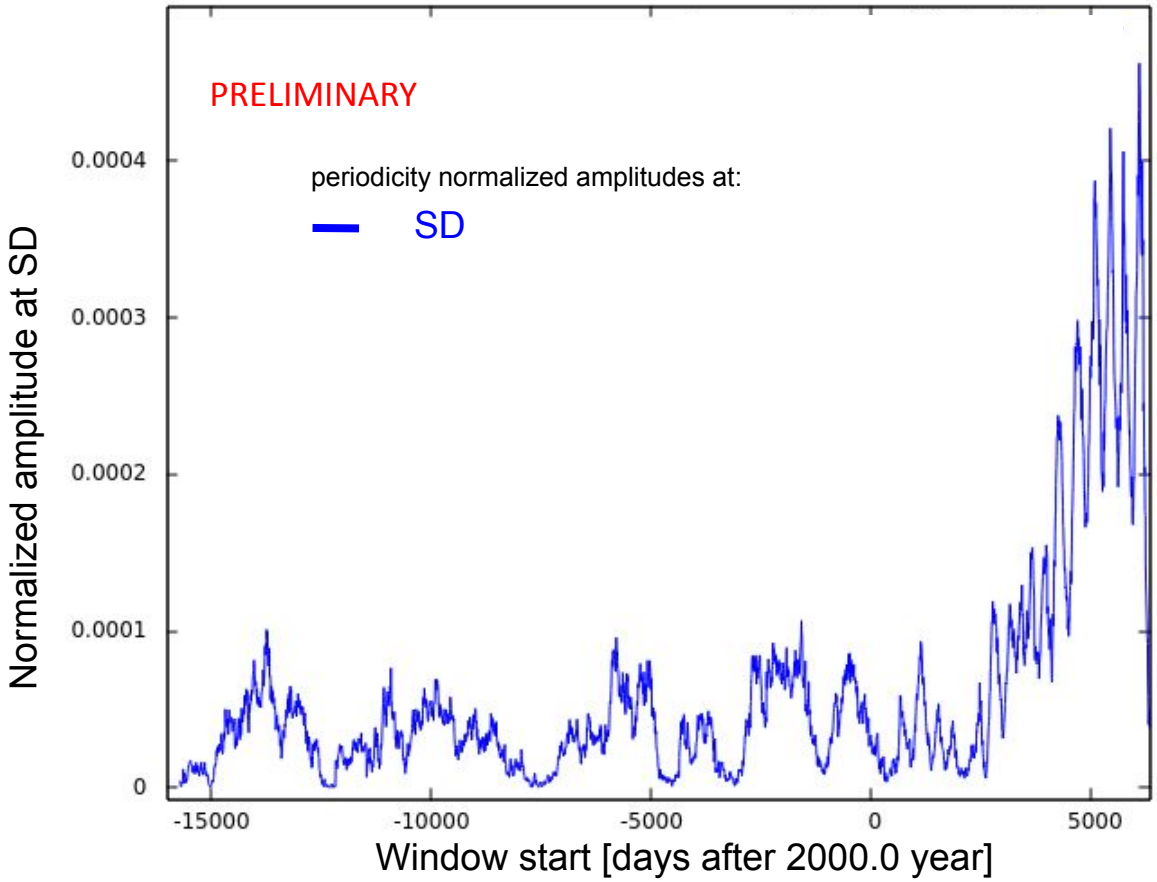
Time evolution of the 24h & sidereal day (SD) periodicities:

EQ data, N_{EQ}, 30min. bins, m >= 4, time window width: 4.5 yrs, step: 1 week



Time evolution of the sidereal day (SD) periodicity:

EQ data, N_{EQ}, 30 min. bins, m >= 4, time window width: 4.5 yrs, step: 1 week



First fits (credit Maria Pycior):

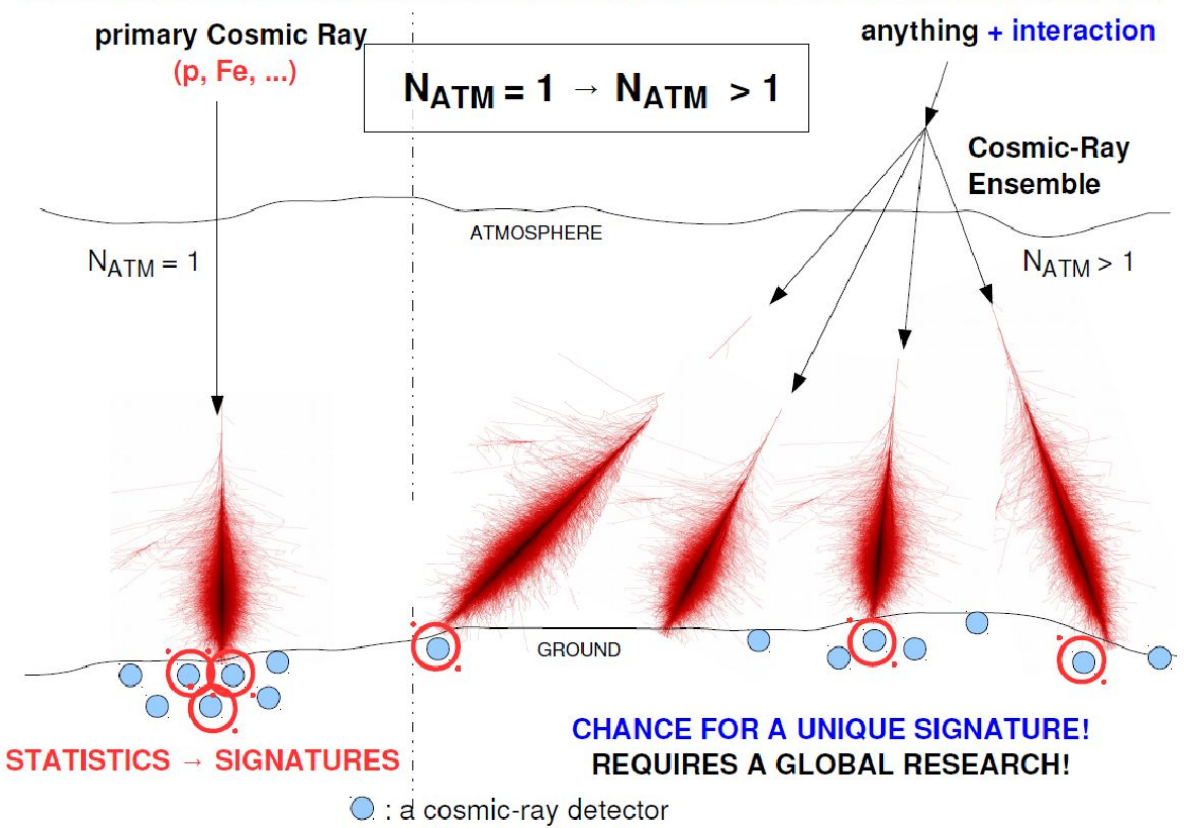
- ~390 d of the right part
- ~11 y of the left

398.85d: period of the Earth & Jupiter synod

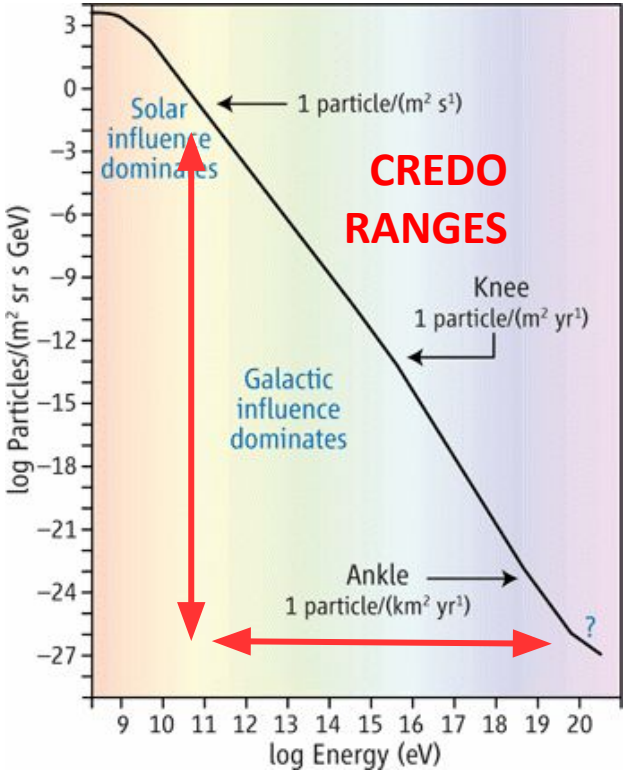
What could be the final experimental confirmation of the DM stream? Similar subthreshold "behavior" in various channels / datasets?

Conclusions & outlook

multi-primary approach: cosmic ray large scale correlations



Cosmic Ray Ensembles (CRE)! Full energy spectrum!

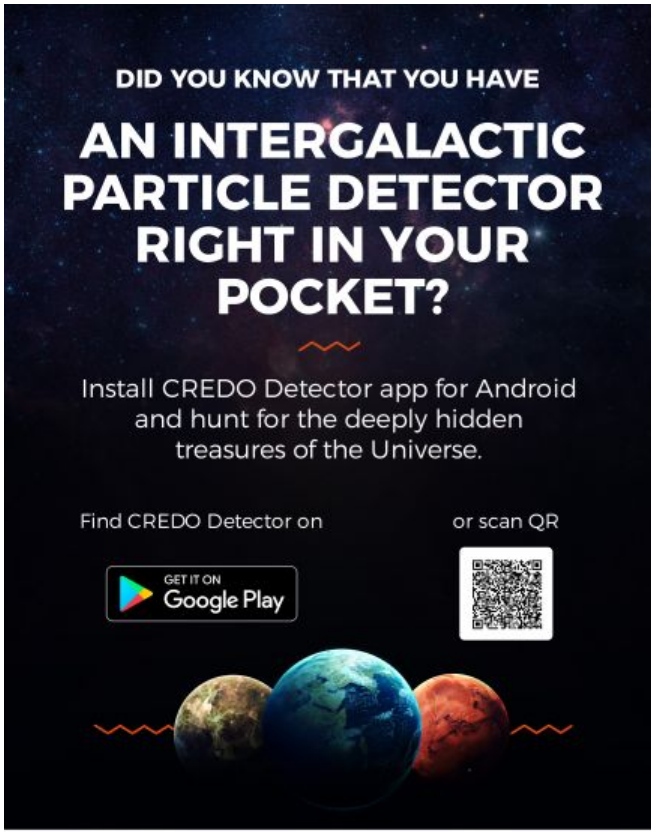


CREDO
THE QUEST FOR THE UNEXPECTED

->

Cosmic Ray Extremely Distributed Observatory

Novel global concept: **cloud of clouds**



CREDO Memorandum of Understanding

Cosmic Ray Extremely Distributed Observatory (CREDO)

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 institutional members (10.11.2022):

- Australia (2)
- Canada (2)
- Chile (1)
- Czech Republic (3)
- Estonia (1)
- Georgia (1)
- Hungary (1)
- India (2)
- Italy (1)
- Mexico (1)
- Nepal (1)
- Poland (18)
- Portugal (1)
- Russia (1)
- Slovakia (1)
- Spain (2)
- Thailand (1)
- Ukraine (3)
- Uruguay (2)
- USA (3)

(48 institutions, 20 countries)

CREDO

- **in- and outward multi-messenger** open observatory
- first exciting results round the corner
- synergies with the other global projects?
- e.g. common points with GNOME:
  - globality needed
  - UHE photons
  - magnetic fields play role

QUEST FOR THE UNEXPECTED

Open

Multi

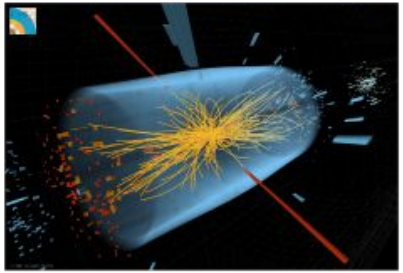
Messenger

Organization?

Organizing cosmic observations?

production → (acceleration) → interactions → particle ensemble → conclusions

Laboratories (experiments)
accelerators & collinders



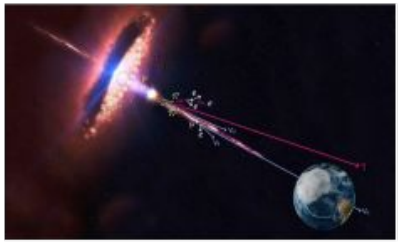
Investment:
~100 mld $ ~0 $

Energies
$<10^{12}$ eV $<10^{20}$ eV+

Availability:
Rich countries Everybody

Data flux:
huge small

Cosmos (observations)
accelerator & collider



Multi-messenger science & big discovery?

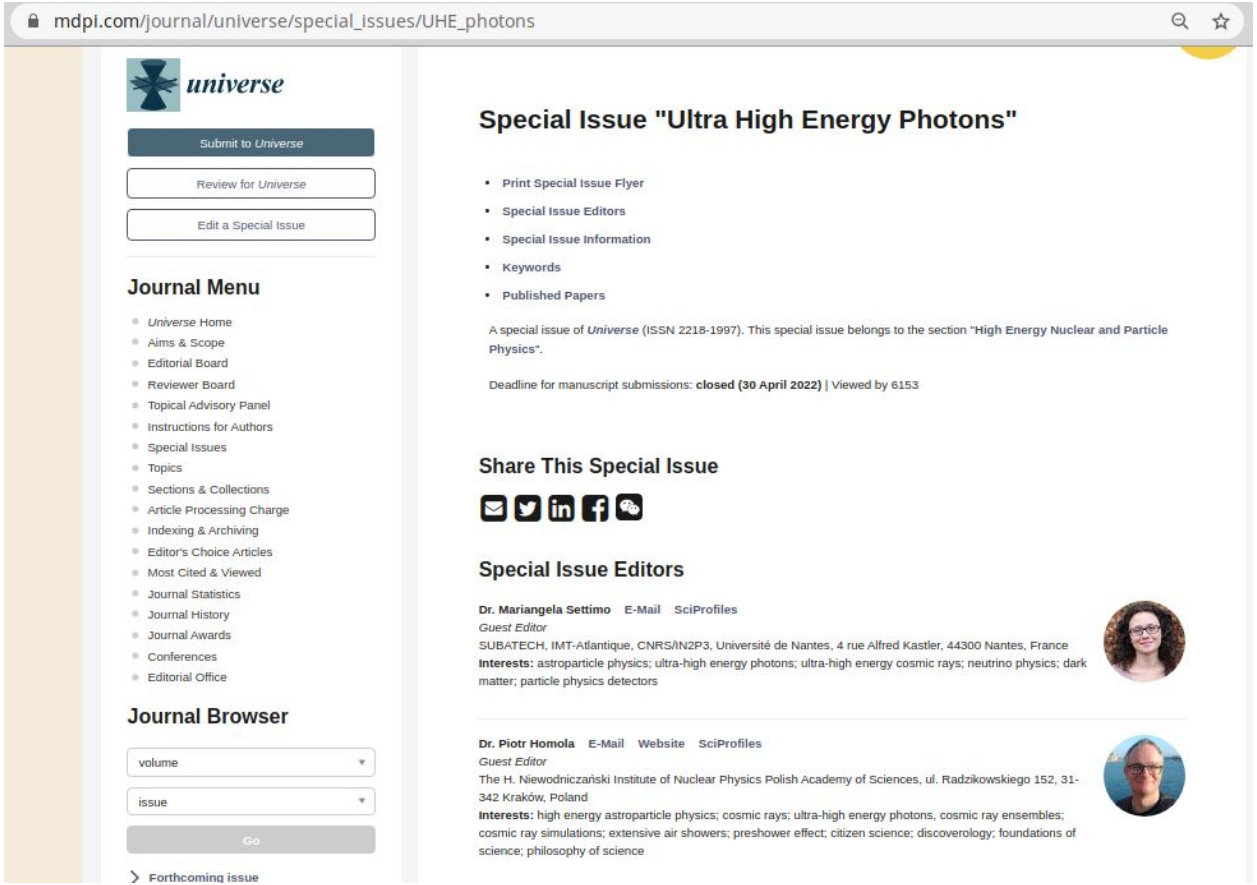
Predicting earthquakes?? Probing DM streams??? Testing Quantum Gravity scenarios??? With smartphones????
-> possible ultimate ambition: **cosmic ray station in every school and BTS station + citizen science**
-> global scale organizational concept: e.g. **Open Multi Messenger Organization** (OMMO)

→ large geographical spread

→ inter-collaboration cooperation

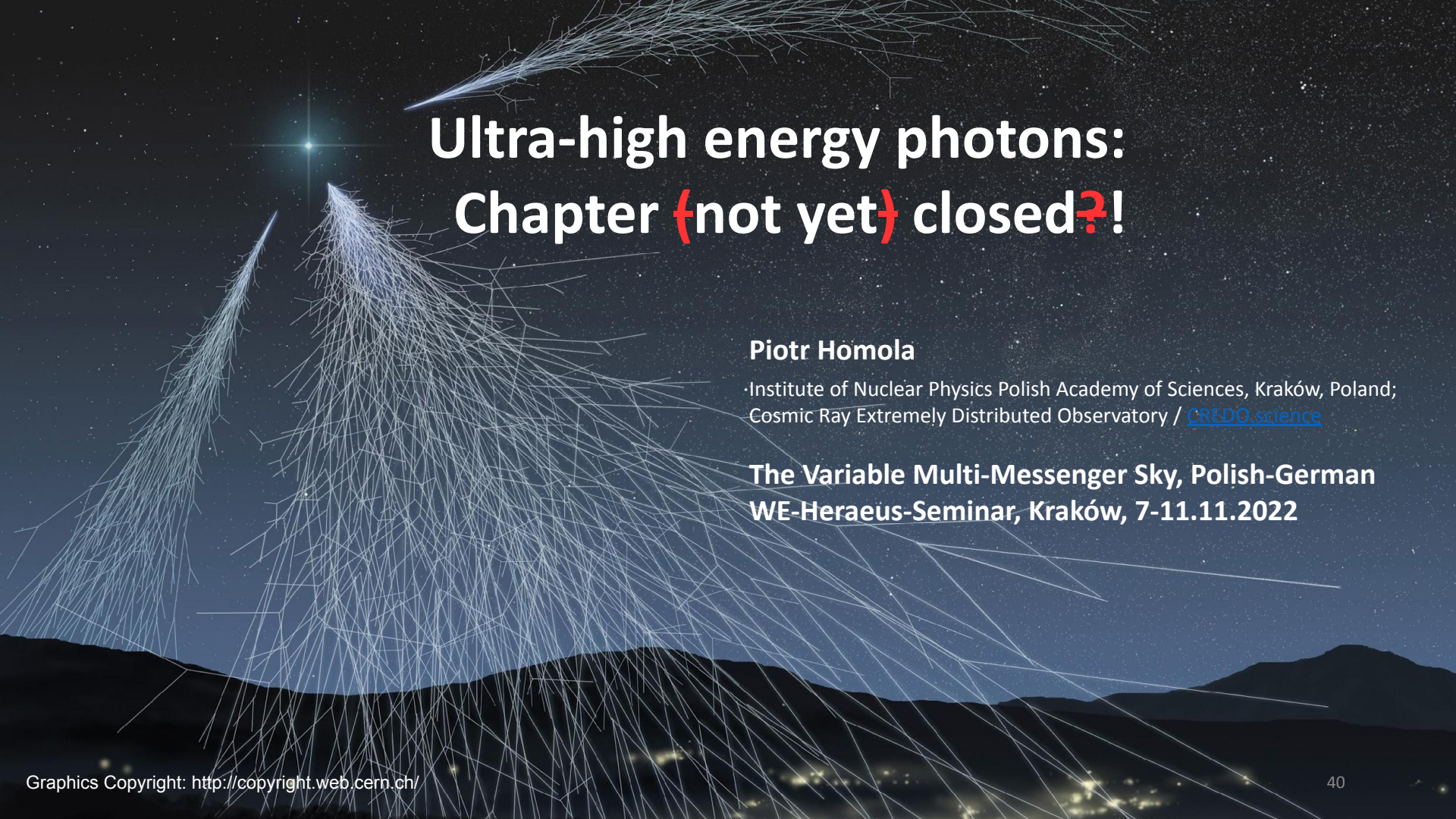
→ massive public engagement

Universe - the Special Issue on UHE Photons: Nov 2022



11 articles
(7 research + 4 review):

G. Gelmini
D. Semikoz
O. Kalashev
V. de Souza
B. Qiang-Ma
Y. Jack Ng
E. Perlman
T. Bulik
T. Wibig
S. Casanova
G. Bhatta
Ł. Bratek
M. Biesiada
The Pierre Auger Collaboration
…



Ultra-high energy photons: Chapter (not yet) closed?!

Piotr Homola

Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland;
Cosmic Ray Extremely Distributed Observatory / CREDO.science

The Variable Multi-Messenger Sky, Polish-German WE-Heraeus-Seminar, Kraków, 7-11.11.2022