Cosmic Rays and $g - 2$

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Bezmiechowa Góra 2024

Schedule

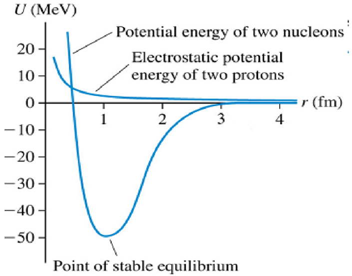
Cosmic Rays as the source of fundamental particles,
CREDO project

- what is cosmic radiation?
- where does it come from?
- how do we register it?
- what can we learn?
- CREDO project

Particles discovered in cosmic rays

- muons ($\sim$ 105 MeV) - not Yukawa potential (screened Coulomb potential) particles:
  $V(r) = -g^2 \frac{e^{-\alpha m r}}{r}$

  Found in 1936, while studying cosmic radiation. Carl D. Anderson at Caltech noticed particles that curved less sharply than electrons and more sharply than protons. Initially called "Yukon" as was initially thought to be Yukawa's particle. Later it was proven that it is too light and that the mediator of the nuclear force is a pion (140 MeV) - also found in cosmic rays (1947).



- pions ($\sim$ 140 MeV, u, d quarks),
- positrons (found)

Cosmic rays, conferences ICRC

36th July 2019, Medison USA, 35th July 12-20, 2017 - Bexco, Busan, Korea, 34th July 30-August 6, 2015 - The Hague, Netherlands, 33rd July 2-9, 2013 - Rio de Janeiro, Brazil, 32nd August 11-19, 2011 - Beijing, China, 31st July 7-15, 2009 - Lodz, Poland, 30th 2007, Merida, Mexico, 29th 2005, Pune, India, 28th 2003, Tsukuba, Japan, 27th 2001, Hamburg, Germany, 26th 1999, Salt Lake City, United States, 25th 1997, Durban, South Africa, 24th 1995, Rome, Italy, 23rd 1993, Calgary, Canada, 22nd 1991, Dublin, Ireland, 21st 1990, Adelaide, Australia, 20th 1987, Moscow, USSR, 19th 1985, La Jolla, United States, 18th 1983, Bangalore, India, 17th 1981, Paris, France, 16th 1979, Kyoto, Japan, 15th 1977, Plovdiv, Bulgaria, 14th 1975, Munich, Germany, 13th 1973, Denver, United States, 12th 1971, Hobart, Australia, 11th 1969, Budapest, Hungary, 10th 1967, Calgary, Canada, 9th 1965, London, United Kingdom, 8th 1963, Jaipur, India, 7th 1961, Kyoto, Japan, 6th 1959, Moscow, USSR, 5th 1957, Varenna, Italy, 4th 1955, Guanajuato, Mexico, 3rd 1953, Bagnères-de-Bigorre, France, 2nd 1949, Como, Italy, **1st 1947, Cracow, Poland**

Cosmic rays and IFJ PAN

Division of Particle Physics and Astrophysics (NO 1)

prof. Henryk Wilczyński

Department of Cosmic Rays and Neutrins (NZ15)

prof. Dariusz Góra

what are cosmic rays?

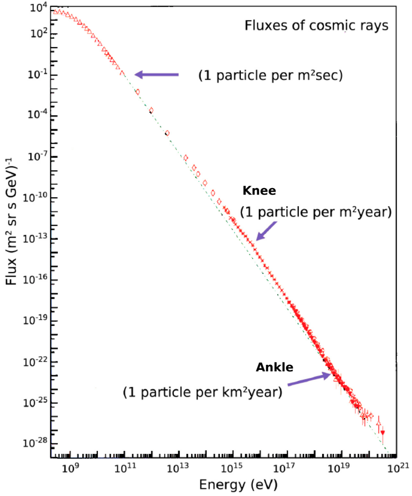
Primary cosmic rays:

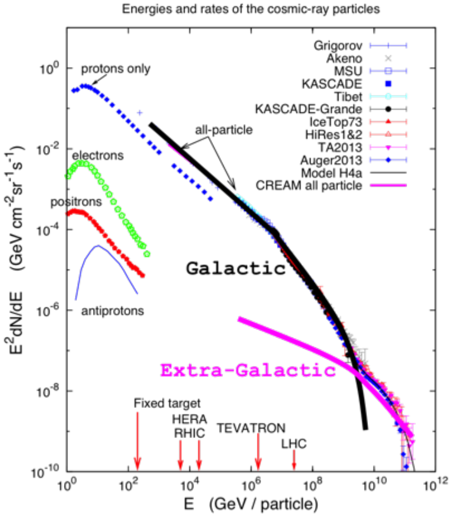
- Mostly high-energy protons and atomic nuclei (99% - the nuclei and 1% electrons),
- the nuclei: 90% - protons, 9% α and 1% nuclei of heavier elements,
- solar particles - mostly protons (primarily from solar eruptions),
- heavier particles - nucleosynthesis end products - mostly from outside the Solar System,
- Carbon and oxygen nuclei collide with interstellar matter to form lithium, beryllium and boron in a process termed cosmic ray spallation,
- Collisions of iron and nickel nuclei with interstellar matter,
- The proportions change with increasing energy: heavier nuclei have larger abundances in some energy ranges,
- Names:
  a) "cosmic rays": high-energy particles with intrinsic mass (often used to refer to only the extrasolar flux),
  b) "gamma rays": photons or X-rays,
  c) HZE ions: Cosmic rays made up of charged nuclei heavier than helium (HZE: high (H) atomic number (Z) and energy (E)),

what are cosmic rays?

Types of Primary cosmic rays:

1. solar energetic particles, high-energy particles (predominantly protons primarily from solar eruptions),
2. galactic cosmic rays (GCR),
3. extragalactic

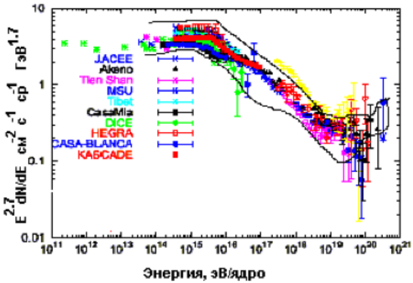




OBSERVED ENERGY SPECTRUM of high-energy cosmic rays.green points: an E^{-3} falloff for comparison

knee and ankle

Knee in CR spectrum



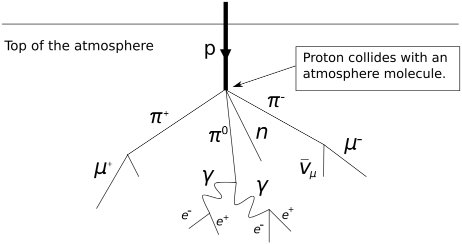
- Knee was discovered by Kulikov
- and Khristiansen in data of MSU
- Experiment in 1958
- It was confirmed by all new
- independent eperiments

- For long time it was 2 explanations: astrophysical and particle physics one. In partile physics explanation it was assumed that either interaction changes or new particle dominates. Tevatron and LHC finally killed this interpretation.

what is cosmic radiation?

Secondary cosmic rays:

- First particles - neutron and pions,



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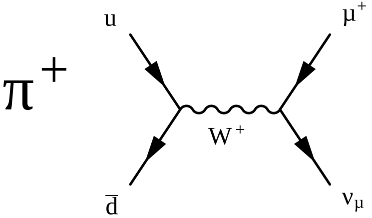
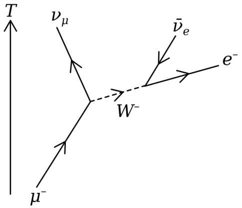
- x-rays, protons, alpha particles, pions, muons, electrons, neutrinos, and neutrons,
- they continue onward on paths within about one degree of the primary particle's original path,
- example: if h = 35 km then D = 1.2km

cosmic ray showers

• Every minute, about 10,000 muons from cosmic rays fly through $1 m^2$ on the surface of the Earth . They come from the decays of pions resulting from collisions of high-energy cosmic rays (mainly protons) with the atmosphere. Such relativistic muons reach the Earth's surface and penetrate, for example, rocks to a depth of up to tens of meters.





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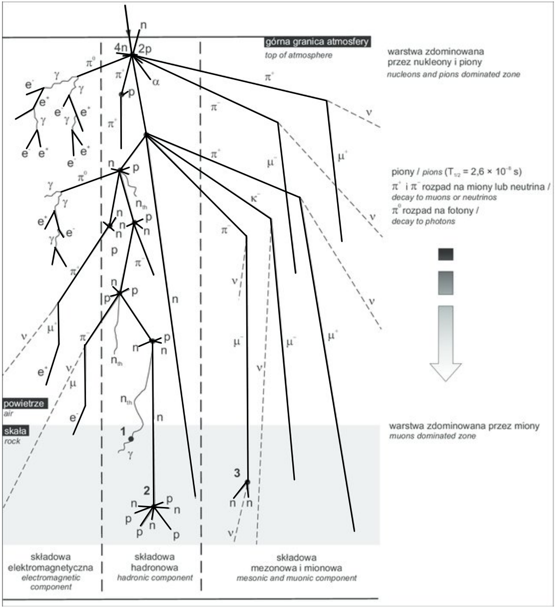
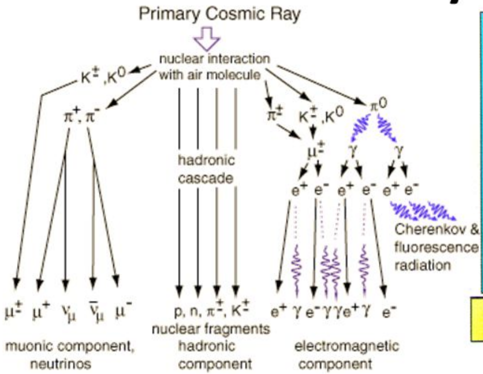
https://commons.wikimedia.org/wiki/File:Muon_Decay.svg

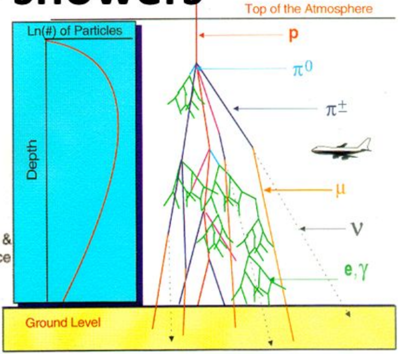
• Non-relativistic muons would travel about 456 meters, but due to time dilation they reach the Earth's surface.

cosmic ray showers



Cosmic ray showers





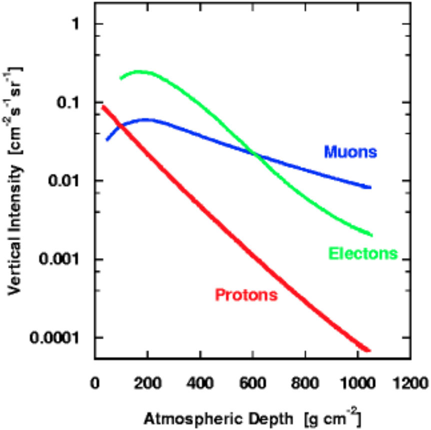
Extensive Air Showers

p,n,π → near the shower axis
μ, e, γ → widely spread
e, γ → from π^0 , μ decays (10 MeV)
μ → from $\pi^{\pm}$, K decays (1 GeV)

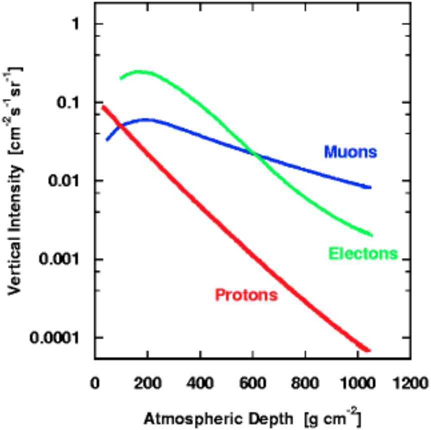
Details depend on

- Interaction cross sections
- Hadronic and electromagnetic particle production
- Decays, transport of particles at energies from MeV's to 10^{20} eV (above accelerators e

cosmic ray showers



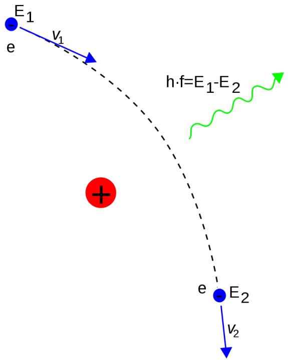
cosmic ray showers



Muons accelerate more slowly than electrons in EM fields so emit less bremsstrahlung. Can penetrate far deeper into matter because the deceleration of electrons and muons is primarily due to energy loss by the bremsstrahlung. Muons created by cosmic rays hitting the atmosphere, can penetrate the atmosphere and reach Earth's land surface and even into deep mines.

bremsstrahlung

(*bremsen Strahlung*: "to brake radiation")



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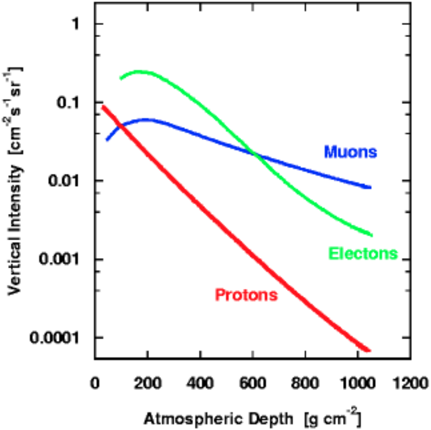
cosmic ray showers



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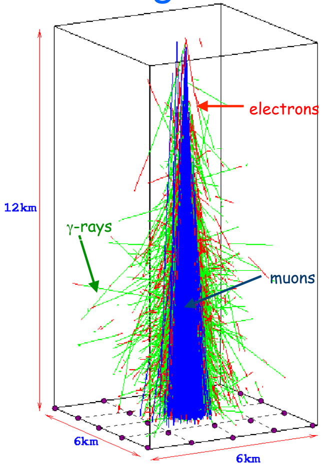
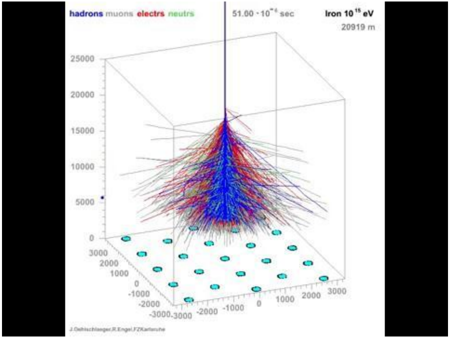
Detection of showers on ground

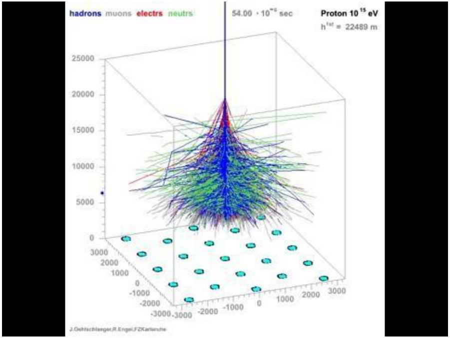
- Ground array measure footstep of the shower. Final particles at ground level are gamma-rays, electrons, positrons and muons.
- Typically 10^{10-11} photons, electrons and positrons in area 20-50 km^2. It is enough to have detectors with area of few m^2 per km^2. Number of low energy particles is connected to primary energy.
- Space/time structure of signal give information on arrival direction.
- Number of muons compared to number of electrons give information on primary particle kind.



Air Showers

X_{max} air showers



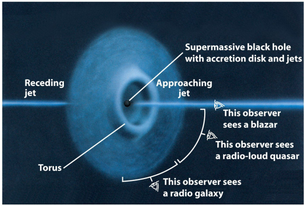


IRON **PROTON**

https://web.ikp.kit.edu/corsika/movies/Movies.htm

where does it come from?

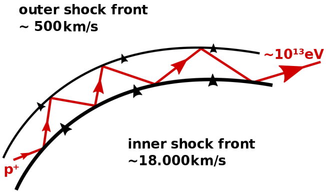
- 1951: Sekido et al. identified the Crab Nebula as a source of cosmic rays,
- since then: supernovae, active galactic nuclei, quasars, and gamma-ray bursts,
- 2009: Pierre Auger observatory at the International Cosmic Ray Conference (ICRC) showed ultra-high energy cosmic rays (UHECRs) originating from a location in the sky very close to the radio galaxy Centaurus A,
- 2009 - 2013: Very Large Telescope (confirmed by Fermi) - supernovae are sources of cosmic rays. Each explosion producing roughly $3 \times 10^{42} - 3 \times 10^{43}$ J of cosmic rays,
- 2013: supernova explosions: significant fraction of primary cosmic rays - data from the Fermi Space Telescope,
- 2018: active galactic nuclei (AGN) - observations of neutrinos and gamma rays from blazar TXS 0506+056 - centrifugal mechanism of acceleration



where does it come from?

Energies:

- enormous energies might be achieved by means of the centrifugal mechanism of acceleration in AGN,
- 15 October 1991: the highest-energy ultra-high-energy cosmic rays (the *"Oh-My-God particle"*) have energies $(3.2 \pm 0.9) \times 10^{20}$ eV (51 ± 14 J $\sim$ kinetic energy of a 90-km/h baseball).
- how much produce supernovae? shock front acceleration method:



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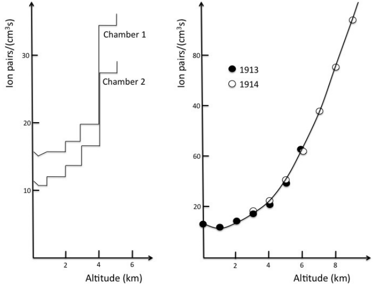
- 2017: Pierre Auger - observation of a weak anisotropy in the arrival directions of the highest energy cosmic rays - evidence for the extragalactic origin of cosmic rays at the highest energies.

how do we register it?

- first observations: XIXth century:
  higher levels of radiation at the top of the Eiffel Tower (300m) than at its base and lower at a depth of 3m from the surface,
- 1912: Victor Hess makes a balloon ascent (5300m) during a near-total eclipse and finds that the ionization rate increases approximately fourfold over the rate at ground level. In this way he rules out the Sun as the radiation's source (Nobel Prize in Physics in 1936).



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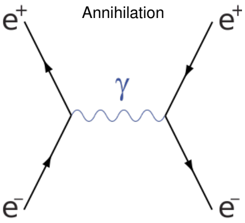
how do we register it?

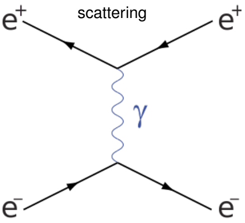
- 1920-1930: Erich Regener - very rapid development of techniques for measuring radiation at high altitudes and under water,
- 1920-1930: observation of the differences between the radiation intensity at the equator and greater latitudes $\rightarrow$ particles must be charged,
- 1929: Bothe and Kolhörster: charged cosmic-ray particles can penetrate 4.1 cm of gold BUT! Charged particles of such high energy could not be produced by photons from interstellar fusion process of hydrogen into the heavier elements,
- 1930-1945: primary cosmic rays are mostly protons, and the secondary radiation produced in the atmosphere is primarily electrons, photons and muons,
- nuclear emulsions carried by balloons to near the top of the atmosphere: 10% of the primaries are alpha particles and 1% are heavier nuclei of elements such as carbon, iron, and lead,

how do we register it?

Discovery of the cosmic ray showers:

- 1930's: Bruno Rossi - "*...recording equipment is struck by very extensive showers of particles, which causes coincidences between the counters, even placed at large distances from one another*
- 1937: Pierre Auger - sees the same and concludes that high-energy primary cosmic-ray particles interact with air nuclei high in the atmosphere, initiating a cascade of secondary interactions that ultimately yield a shower of electrons, and photons that reach ground level,
- 1937: Homi J. Bhabha (Bhabha scattering) described how primary cosmic rays from space interact with the upper atmosphere to produce particles observed at the ground level. Bhabha and Heitler explained the cosmic ray shower formation by the cascade production of gamma rays and positive and negative electron pairs





how do we register it?

Short history of ultra-high energy cosmic rays (UHECR)

Particles coming to Earth from Space

1912. Electroscopes discharge faster with increasing altitude → rays of extraterrestrial origin: V. Hess (Nobel prize 1936).

1932. Discovery of antimatter (positron): C. Anderson (Nobel prize 1936).

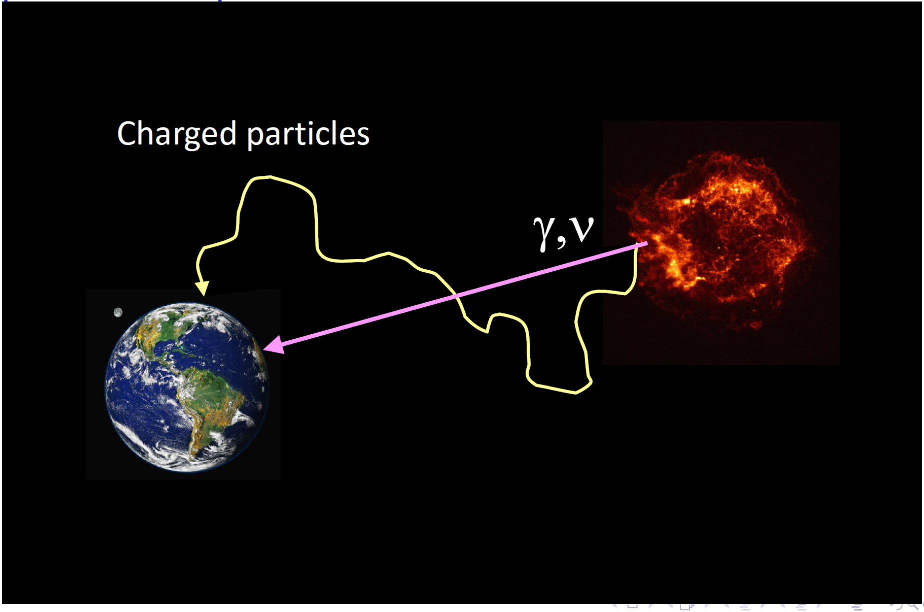
1937. Discovery of muons: S. Neddermeyer and C. Anderson → particle physics begins.

1938. Extensive air showers (EAS) → E > 10^{15} eV: P. Auger

1962. First EAS at 10^{20} eV: J. Linsley
→ what and why can have so huge energies???

.... high time for a next breakthrough?

Detection: the path of charged and neutral cosmic particles in space



Detection

- direct detection of the primary cosmic rays: ISS or at high altitude by balloon-borne instruments,
- indirect detection: two main categories:

  1. the detection of secondary particles forming extensive air showers (EAS) or

  a) cloud chambers, bubble chambers, problem: segregate background effects from cosmic rays,

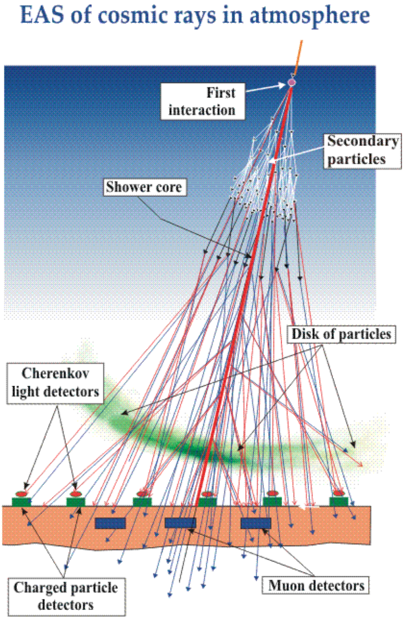
  b) recently (2016): the CMOS devices in smartphone cameras to detect air showers from ultra-high-energy cosmic rays (UHECRs) (CREDO project),

  2. detection of electromagnetic radiation emitted by EAS in the atmosphere

  a) Cherenkov telescopes - extremely good at distinguishing between background radiation and that of cosmic-ray origin BUT! restricted to clear nights without the Moon shining,

  b) detects the light from fluorescence caused by the excitation of nitrogen in the atmosphere by the shower of particles BUT! restricted to clear nights

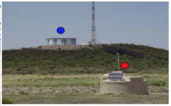
Detection of cosmic ray showers



Motivation: typical strategy

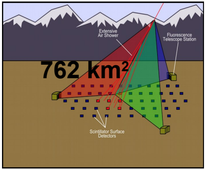
A ***single particle*** *hits the atmosphere and produces a* ***single air shower*** *that can be reconstructed by detector on the ground via various channels of observation, such as Cherenkov radiation or fluorescence light.*

Typical strategy: **looking for ONE shower**
i.e. *Pierre Auger Observatory, Telescope Array, IceTop ....*



set of fluorescence telescopes

Cherenkov detector



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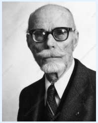
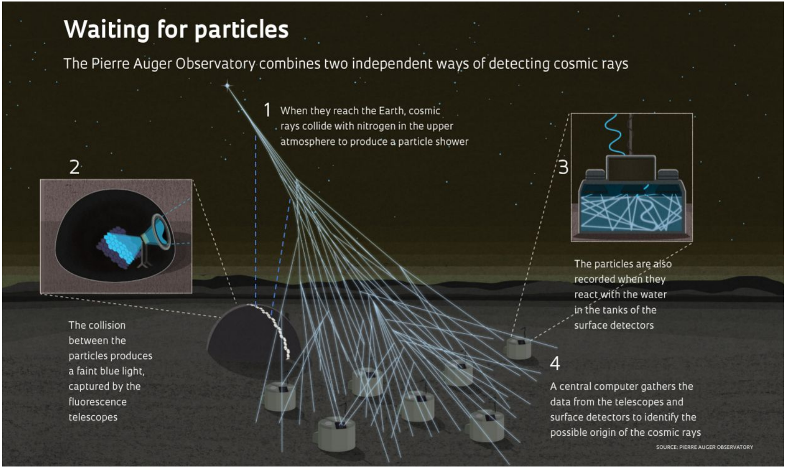


Pierre Auger Observatory
(Malargüe, Mendoza, Argentina)



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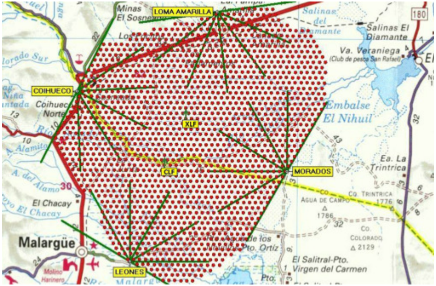


Pierre Auger Observatory

what can we learn about the Standard Model?

- Pierre Auger: ....The results are expected to have important implications for particle physics and cosmology, due to a theoretical Greisen-Zatsepin-Kuzmin (GZK) limit to the energies of cosmic rays from long distances (about 160 million light years)

- High-energy gamma rays (>50 MeV photons) discovered in the primary cosmic radiation by an MIT experiment carried on the OSO-3 satellite in 1967. Components of both galactic and extra-galactic origins were separately identified at intensities much less than 1% of the primary charged particles.

- The most recent is the Fermi Observatory, which has produced a map showing a narrow band of gamma ray intensity produced in discrete and diffuse sources in our galaxy, and numerous point-like extra-galactic sources distributed over the celestial sphere.

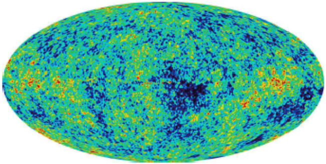
Greisen-Zatsepin-Kuzmin limit '1966 (GZK limit)

- Theoretical upper limit on the energy of cosmic ray protons traveling from other galaxies through the intergalactic medium to our galaxy,
- The limit is 5×10^{19} eV (50 EeV ∼8 joules or the energy of a proton travelling at 99.99999999999999999998% the speed of light). The limit is set by slowing interactions of the protons with the microwave background radiation over long distances (∼ 160 million light-years),
- cosmic rays with energies over the threshold energy of 5×10^{19} eV would interact with cosmic microwave background photons relatively blueshifted by the speed of the cosmic rays, to produce pions through the Δ resonance

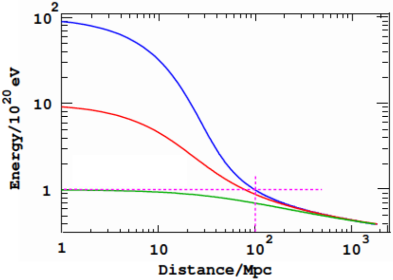
  $\gamma_{CMB} + p \rightarrow \Delta^+ + p + \pi^0$ and
  $\gamma_{CMB} + p \rightarrow \Delta^+ + n + \pi^+$

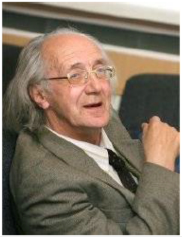
  The pion production process continues until the cosmic ray energy falls below the pion production threshold
- BUT!!! Pierre Auger Observatory: the most ultra-high energy cosmic rays are heavier elements

Greisen-Zatsepin-Kuzmin Effect



$$p + \gamma_{\text{CMB}} \rightarrow N + \pi$$





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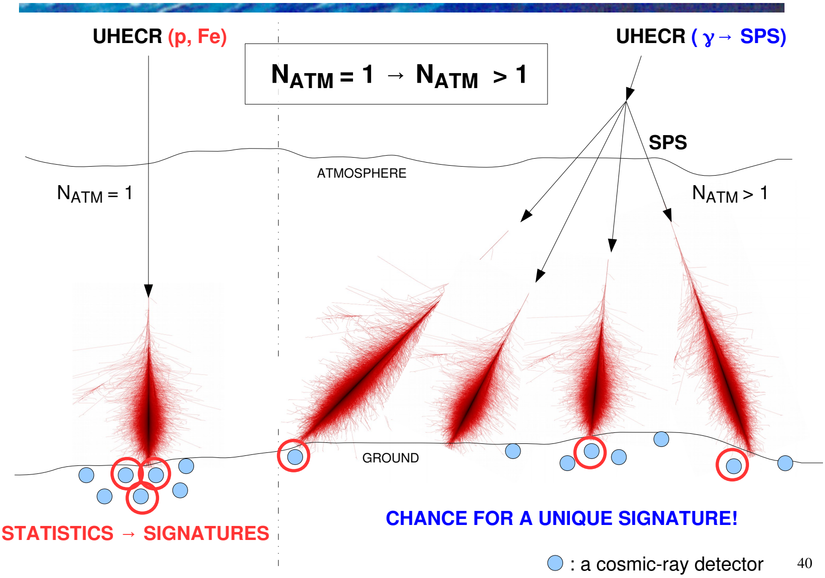
CREDO project

CREDO project

Generalization of UHECR research



CREDO - What is it?

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Cosmic Ray Extremely Distributed Observatory

The idea created in 2016 by Piotr Homola (INP PAS, Krakow)

(Division of Particle Physics and Astrophysics (NO1)

Department of Cosmic Rays and Neutrins (NZ15))

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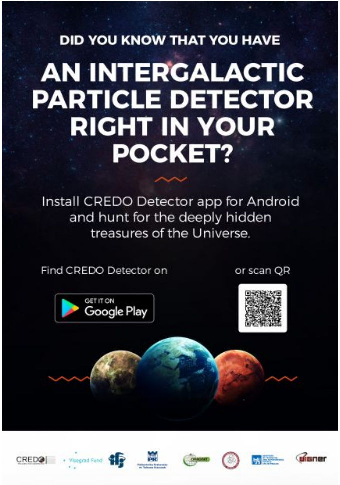
CREDO project

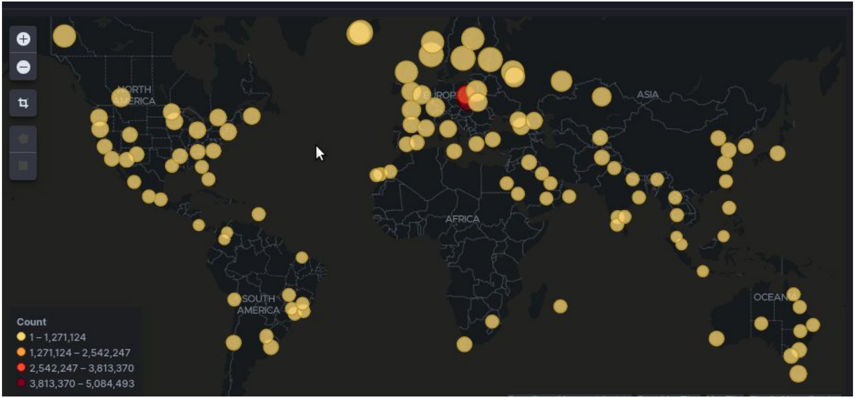
Novel Global Solution: **cloud of clouds**



-> “new data”!

CREDO project

CREDO: already global



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

CREDO project

Mobile application

> Smartphone application developed by CREDO collaboration, PoS(ICRC2019)367

Motivation: D. Groom, *Cosmic rays and other nonsense in astronomical CCD imagers*, Experimental Astronomy (2002) 14, 45

Principle:
particles hitting the camera senso
and triggering pixels by depositing
energy*

- Detections are filtered to remov
artifacts and stored in a central
database (Cyfronet AGH-UST).
- Analysis are run to search for
peculiar signal signatures.
- Users can access the data they
collected and see the results fro
the analysis run on their data

STIMULATES CITIZEN SCIENCE !

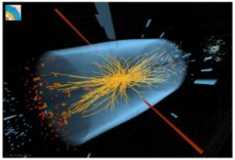
The DECO/CRAFIS project demonstrate discrimination between GeV cosmic-ray muon tracks and MeV electron, see Journal of Instrumentation 2016 11, P04019; M. Winter et al., Particle Identification In Camera Image Sensors Using Computer Vision, Astropart. Phys. (2019), 104, 92. However, large number of smartphones (~10^6 M. Unger and G. Farrar, [arXiv:1505.04777] are needed to reach the sensitivity comparable to the largest cosmic-rays observatories.)

CREDO project

Where to find new data? A biased view

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

Laboratories (experiments)
accelerators & collinders



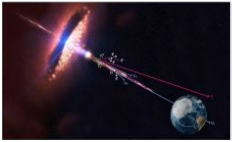
Investment:
~100 mld $ ~0 $

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

Availability:
Rich countries Everybody

Data flux:
huge small

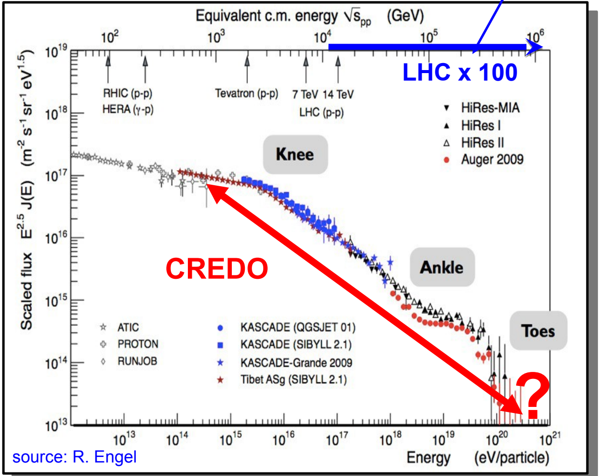
Cosmos (observations)
accelerator & collider



CREDO project

The Ultra-High-Energy Cosmic Ray mystery

Particle physics beyond the reach of colliders



> What's their composition?

> Where do they come from?
→ *anisotropies weakly correlated to known possible sources: active galactic nuclei, gamma-ray burst, …*

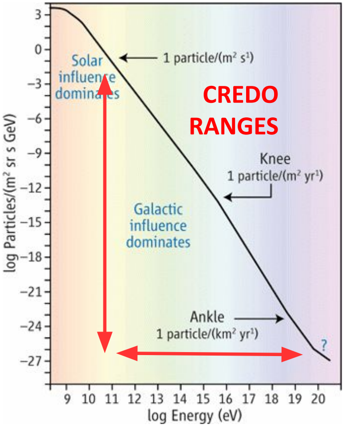
> How do they reach such tremendous energies?

Spectrum suppression:
in the past: *the GZK cut-off*

now: *rather the efficiency limit of particle acceleration by sources*

CREDO project

Cosmic Ray Ensembles (CRE)! Full energy spectrum!

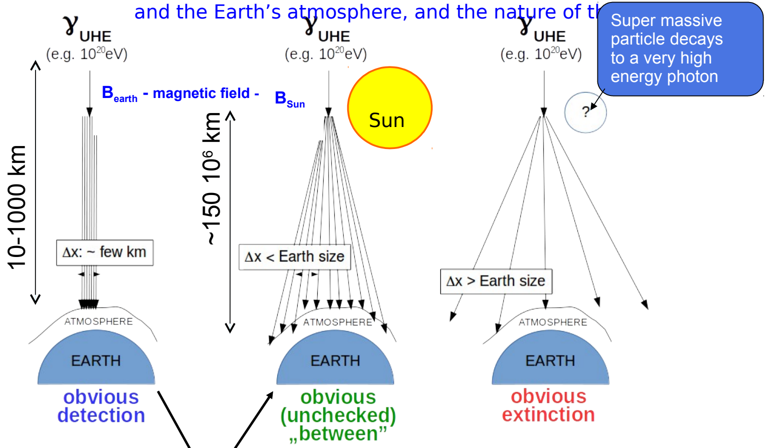


CREDO project

Classes of CRE

Multiple scenarios: are possible based on the distance between the interaction point

and the Earth's atmosphere, and the nature of th



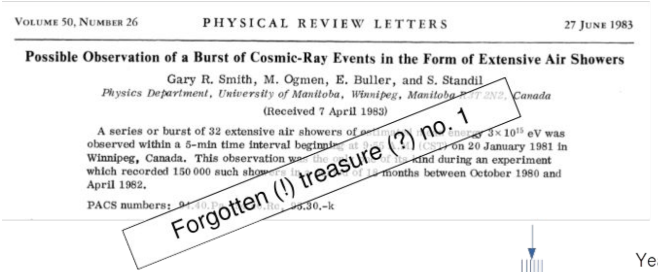
N_{cr} > 1 scenario have been reported in the literature:

G.R. Smith et al., Phys. Rev. Lett. 50 (1983) 2110;177; D.J. Fegan and B. McBreen, Phys. Rev. Lett. 51 (1983) 2341

but they have not been observed repeatedly until now.

CREDO project

$N_{ATM} > 1$ 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

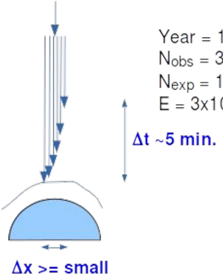
Gary R. Smith, M. Ogmen, E. Buller, and S. Standil
Physics Department, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada
(Received 7 April 1983)

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, [illegible].Rc, 95.30.-k

PH: Correlated cosmic rays?

$N_{ATM} > 1?$

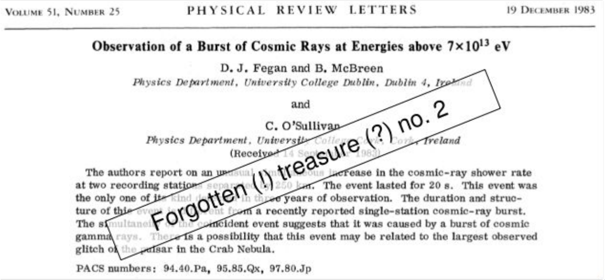


Year = 1981
N_{obs} = 32
N_{exp} = 1
E = 3×10^{15} eV

"Pay attention to data"!

CREDO project

$N_{ATM} > 1$ 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

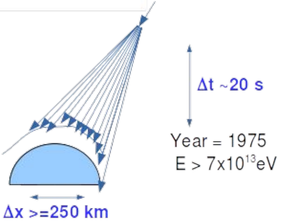
(Received 14 September 1983)

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

PH: Correlated cosmic rays?

$N_{ATM} > 1$?



"Pay attention to data"!

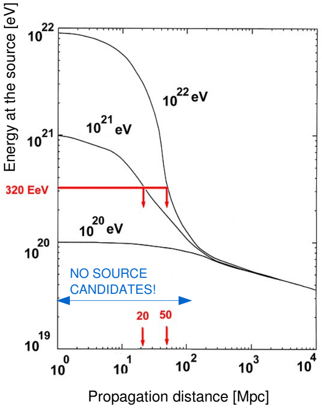
CREDO project

UHECR propagation: no source candidates?

UHECR protons of high energies ($E > \sim 5 \times 10^{19}$eV) should interact with background radiation (CMBR):

$$p\gamma_{CMBR} \rightarrow p\pi^0 / n\pi^+$$

$\rightarrow \gamma$ (GZK photons)



→ proton energy reduced, mean free path limited
→ characteristic cut-off of the energy spectrum

effect predicted in 1966 by
K. Greisen, G. T. Zatsepin, V. A. Kuzmin

10^{20} eV cosmic rays **are nuclei**? Known acceleration mechanisms in known sources not efficient enough, **no source candidates...**

10^{20} eV: impossibly high energies...

CREDO project

Photons as UHECR: testing astrophysical scenarios

Bottom → Up: 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

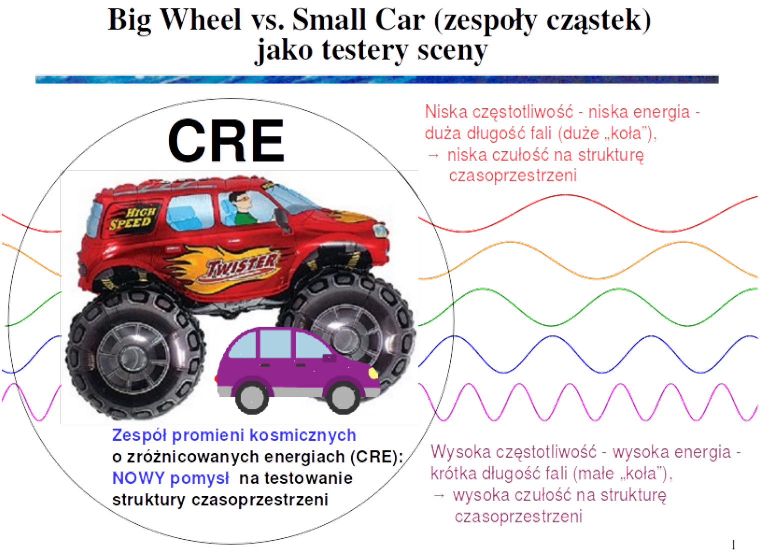
Top → Down: Exotic scenarios (particle physics)

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

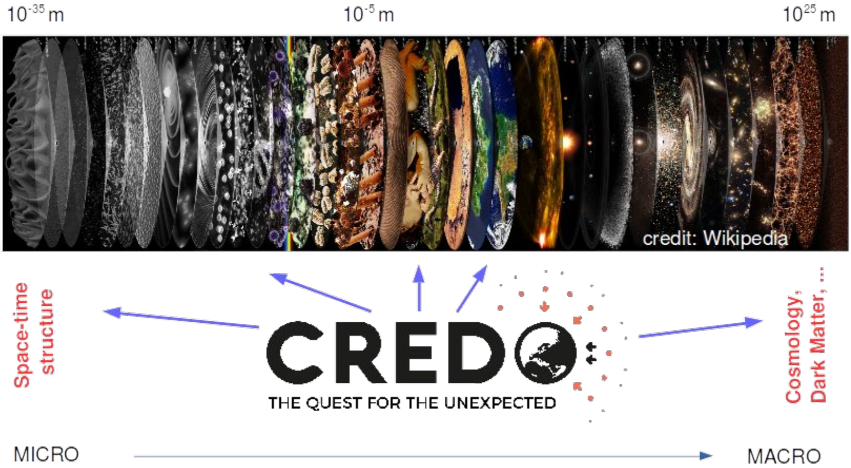
DARK MATTER!

CREDO project, why UHECR?



CREDO project

CREDO Science Potential

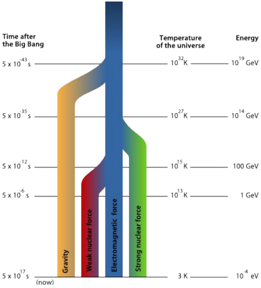


more (popular level): https://credo.science/education-materialyeng/podcast/ (EN) / https://credo.science/education-materialypl/podcast/ (PL)

CREDO project

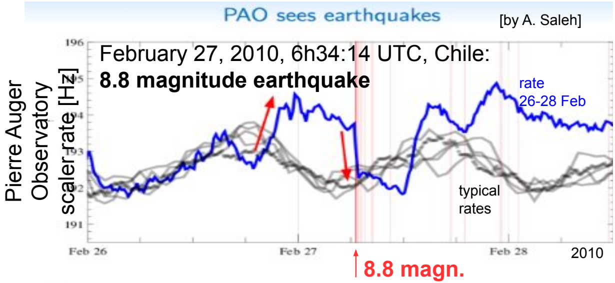
N_{ATM} >= 1 mission (briefly)

Scenarios AND Fishing



CREDO project

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



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

→ **CREDO-earthquakes task**

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

2,7 billion people

Science as a service to the human community?

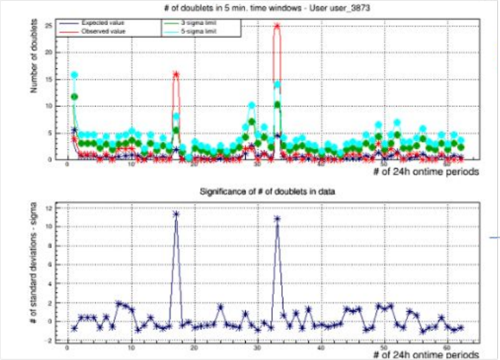
Even the smallest chance to save lives

= **a must check!**

CREDO project

Quantum Gravity Previewer: online experiment!

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



expected from random
observed

10σ
(significance)

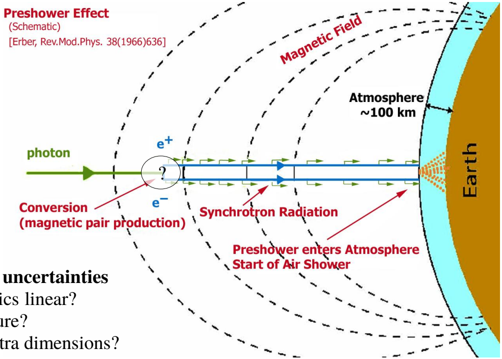
quest (fishing) for **the unexpected**

by Kevin Almeida Cheminant, for the CREDO Collaboration

Request zoom in, track back, investigate!
Privately, locally, and globally!
Get engaged!

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

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

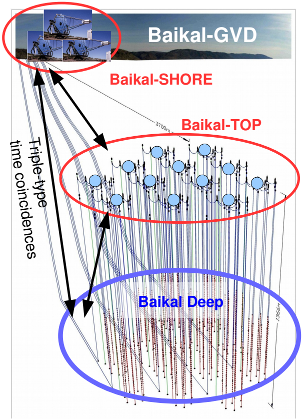


? : **fundamental uncertainties**
- electrodynamics linear?
- photon structure?
- spacetime: extra dimensions?

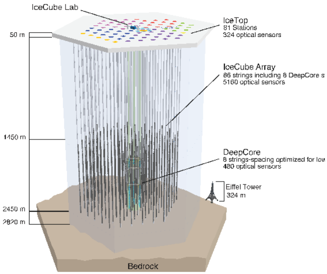
→ dependence on E and $B_\perp$ (to be seen in data?)

CREDO project

Baikal-GVD: the leading CREDO site?

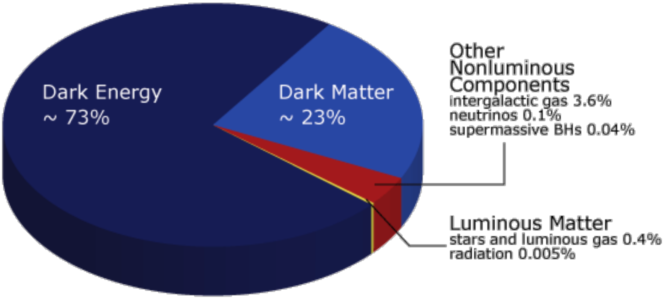


Baikal-TOP a la IceTop (VETO role)



● : a detector (scintillator?) in buoy

Standard Model - known and unknown



Interesting about cosmic rays

- continuous production of a number of unstable isotopes, such as carbon-14 through the reaction:
  $n + ^{14}N \rightarrow p + ^{14}C$
  what kept the level of carbon-14 in the atmosphere roughly constant (70 tons) for at least the past 100,000 years (until the beginning of above-ground nuclear weapons testing in the early 1950s)

- Role in ambient radiation:
  13% of total background for sea-level, for higher-altitude cities can reach 25%,

- studies by IBM in the 1990s: computers typically experience about one cosmic-ray-induced error per 256 megabytes of RAM per month! Examples:
  1. in 2008, data corruption in a flight control system caused an Airbus A330 airliner to twice plunge hundreds of feet, resulting in injuries to multiple passengers and crew members.
  2. a high-profile recall in 2009-2010 involving Toyota vehicles with throttles that became stuck in the open position may have been caused by cosmic rays

- radioactive materials and cosmic rays may substantially limit the coherence times of qubits if they aren't shielded adequately which may be critical for realizing fault-tolerant superconducting quantum computers in the future,

- cosmic ray energy density averages about ≈ 1 eV/cm^3 depends on time (on a scale of thousands of years)

Interesting about cosmic rays

- galactic cosmic rays: important barriers standing in the way of plans for interplanetary travel by crewed spacecraft. In 2010, a malfunction aboard the Voyager 2 space probe was credited to a single flipped bit, probably caused by a cosmic ray,
- flying 12 kilometres high, passengers and crews of jet airliners are exposed to at least 10 times the cosmic ray dose that people at sea level receive. Aircraft flying polar routes near the geomagnetic poles are at particular risk,
- it has been proposed that essentially all lightning is triggered through a relativistic process, or "runaway breakdown", seeded by cosmic ray secondaries,
- 62-million-year cycles in biological marine populations correlate with the motion of the Earth relative to the galactic plane and increases in exposure to cosmic rays.
- a handful of studies conclude that a nearby supernova or series of supernovas caused the Pliocene marine megafauna extinction event by substantially increasing radiation levels to hazardous amounts for large seafaring animals,
- the flux of incoming cosmic rays depends on the solar wind, the Earth's magnetic field ($\rightarrow$ dependence on latitude, longitude, and azimuth angle), and the energy of the cosmic rays. About 94 AU from the Sun, the solar wind undergoes a transition (termination shock). The region between the termination shock and the heliopause acts as a barrier to cosmic rays, decreasing the flux at lower energies (< 1 GeV) by about 90%.