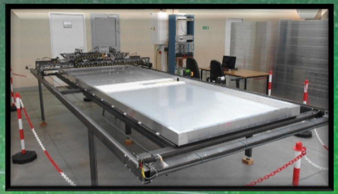
Prof. dr hab. Henryk Wilczyński and Cosmic Rays

Dariusz Góra (IFJ PAN)

E564 experiment

JACEE experiment

AugerPrime



CROME experiment

Cosmic rays: charged particles coming to Earth from space

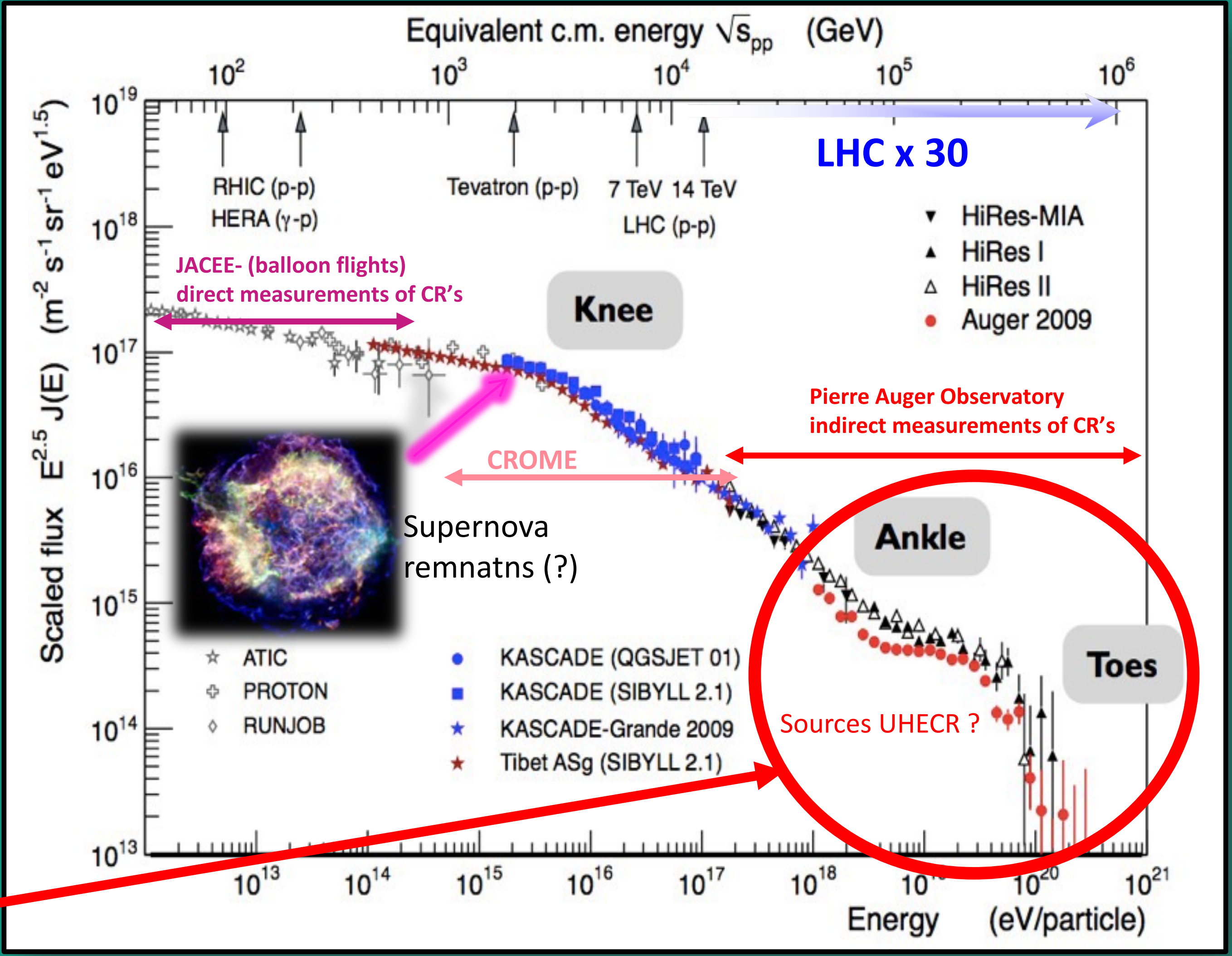
Discovered over 100 years ago (V. Hess, 1912), but due to the low flux of 1 particle/km^2 per century (above 10^{19} eV),

Still open questions:

- 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?
  (past the GZK cut-off ! or efficiency limit of the particle acceleration by sources)

Spectrum of cosmic rays (CR's)

UHECR -- *cosmic rays with ultra-high energies, above 10^{18} eV*



Highest energy cosmic rays > 10^{18} eV (UHECRs)

- At ultra-high energies (> 10^{18} eV), particle physics beyond the reach of Earth's colliders

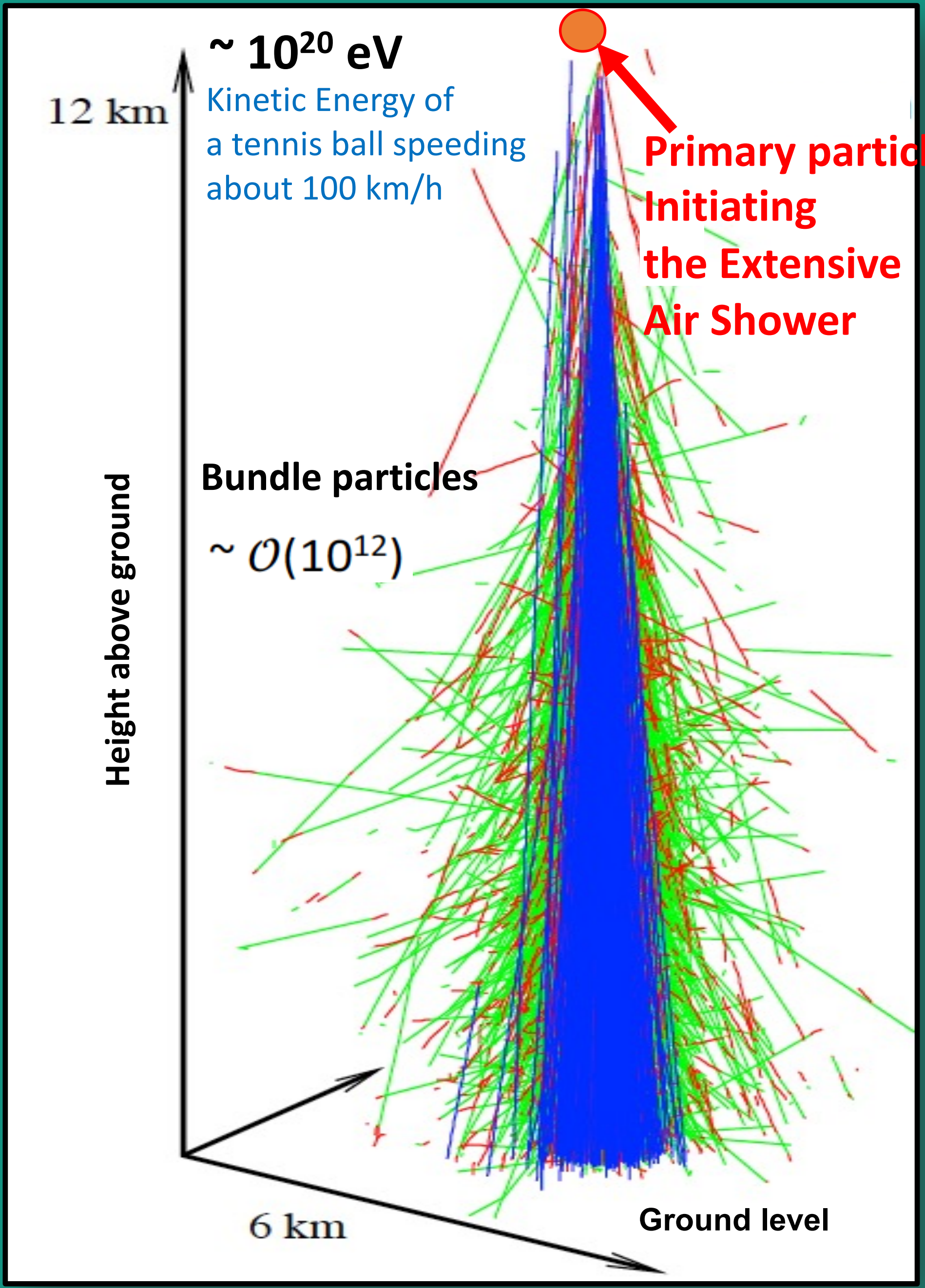
Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with LHC technology

(Unger, 2006)

We would need an accelerator the size of Mercury's orbit to achieve an energy of 10^{20} eV using Large Hadron Collider (LHC) technology

- Possibility to study hadron interactions for LHC x 30 energy (in C.M.)

Extensive air shower (EAS)



~ 10^{20} eV

Kinetic Energy of a tennis ball speeding about 100 km/h

Primary particle Initiating the Extensive Air Shower

Bundle particles

~ $\mathcal{O}(10^{12})$

Short CV:

Prof. Dr hab. Henryk Wilczyński

- Master of science - Jagiellonian University, Faculty of Mathematics, Physics and Chemistry - **physics 1974**

- PhD - Institute of Nuclear Physics in Kraków - **physics 1985**

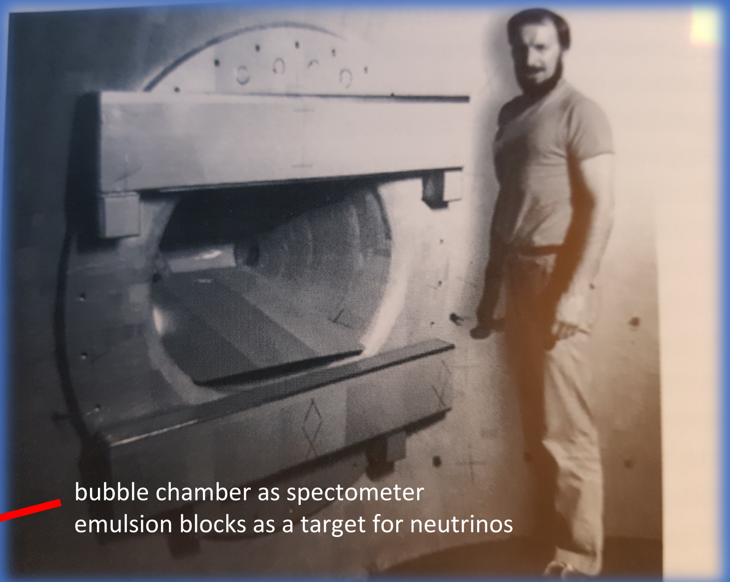
  Produkacja cząstek w oddziaływaniach Neutrin z Jądrami Emulsji Fotograficznej
  Particle production in Neutrino interactions with Photo Emulsion Nuclei

- Habilitation - Institute of Physics in Kraków - **physics 1996**

  Badania widma energetycznego i oddziaływań jądrowych pierwotnego promieniowania kosmicznego
  Studies of the energy spectrum and nuclear interactions of primary cosmic radiation

- Full profesor - Institute of Nuclear Physics PAN in Kraków – **physics 2005**

(1) During stay in USA,E564 experiment Fermi National Accelerator Laboratory (Fermilab),



bubble chamber as spectometer
emulsion blocks as a target for neutrinos

(2) JACEE (Japanese-American Collaborative Emulsion Experiment) 1985-1997

(3) Pierre Auger Observatory: 1997-present

(4) CROME (Cosmic Ray Observation via Microwave Emission): 2010-2014

PhD - Institute of Nuclear Physics in Kraków - physics 1985

Produkacja cząstek w oddziaływaniach Neutrin z Jądrami Emulsji Fotograficznej

Particle production in Neutrino interactions with Photo Emulsion Nuclei

E564 experiment

- Results based on 169 events studied: particle multiplicity distributions, pseudorapidity distributions, particles energy and momentum …
- Results showed a lack of agreement with model predictions at the time

(1) During stay in USA,E564 experiment Fermi National Accelerator Laboratory (Fermilab),

Hybrid experiment: The combination of the very good resolution of the emulsion chambers with the bubble chamber as a spectrometer gives the possibility of precise measurement of the vertex of the neutrino interaction

Photo of a case of Neutrino-Emulsion Interaction recorded in a bubble chamber. The traces of the produced charged particles are curved by the magnetic field, allowing their momentum to be measured.

IFJ group from 1981
Prof. R. Hołyński, Prof. B. Wosiek,

JACEE EXPERIMENT

from 1985

JACEE EXSPERIMENT

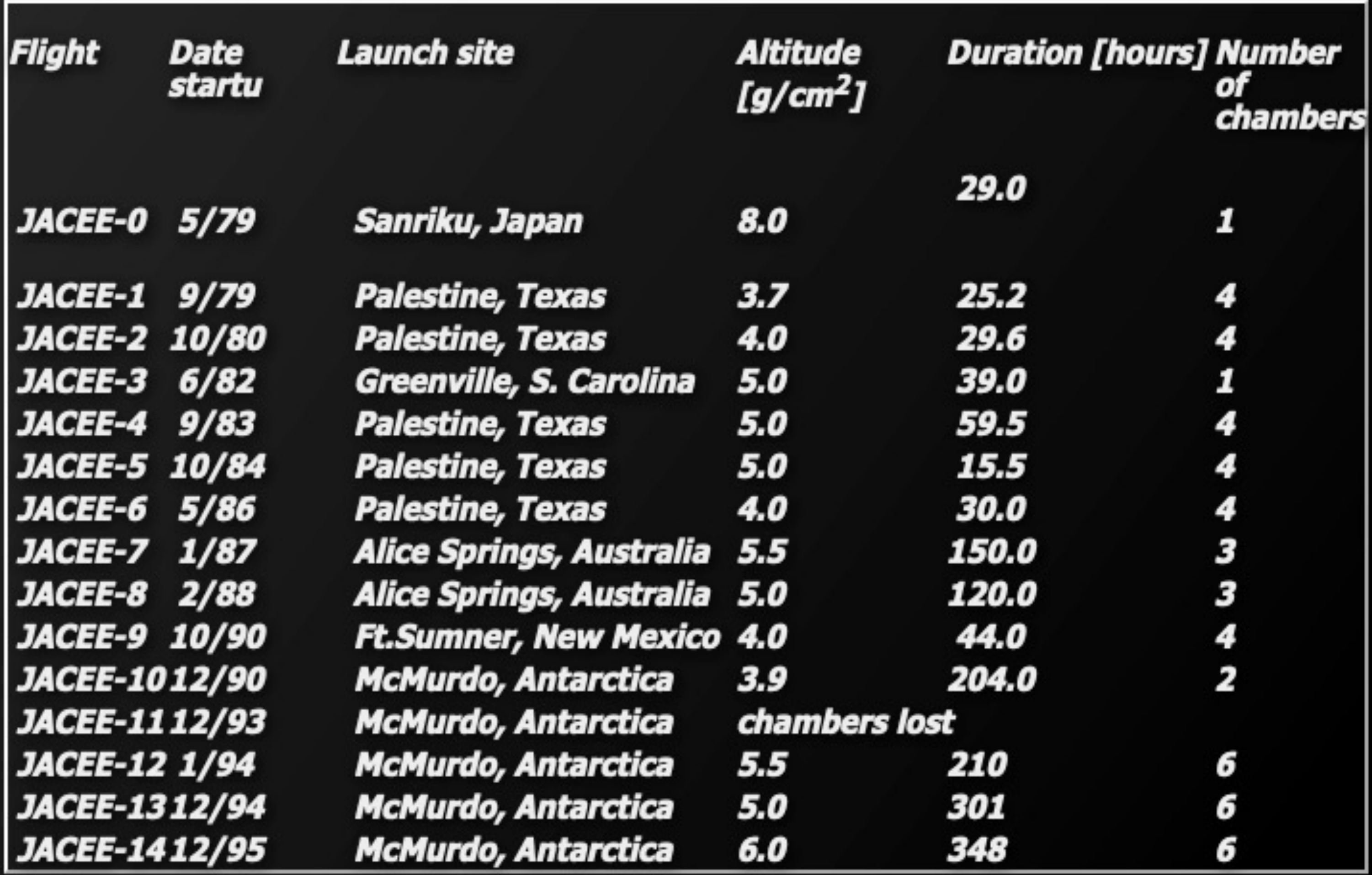
The JACEE Experiment was carried out by a collaboration of american laboratories (NASA/Marshall Space Flight Center, University of Alabama in Huntsville, Louisiana State University and University of Washington), japanese ones (Universities of Tokyo, Kobe, Okayama and Hiroshima) and Institute of Nuclear Physics in Kraków, Poland. The main goal of the experiment was to study composition and spectra of cosmic rays in the energy range 10^{12} - 10^{15} eV.

The experiment was done using a technique of emulsion chambers which were exposed to cosmic rays in high altitude balloon flights. The JACEE balloons flights were carried out by the National Scientific Balloon Facility (NSBF) in Texas.

Preparations to balloon launch in Texas. Filling balloons with helium.

Initially, the JACEE flights were made in continental United States; only the JACEE-0 flight was launched from Japan. Later, intercontinental flights were performed from Australia to South America, as well as a series of circumpolar flights in Antarctica. The table below shows details of the flights performed.

Initially, the JACEE flights were made in continental United States; only the JACEE-0 flight was launched from Japan. Later, intercontinental flights were performed from Australia to South America, as well as a series of circumpolar flights in Antarctica. The table below shows details of the flights performed.

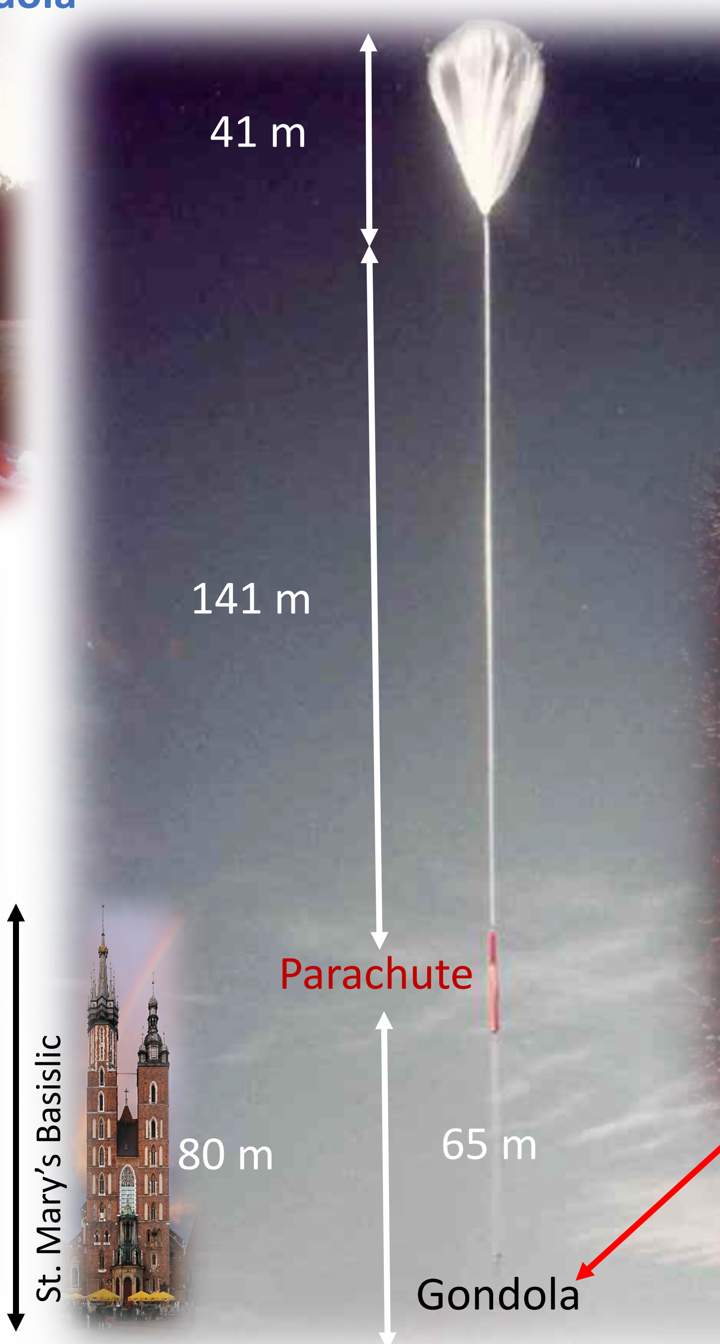


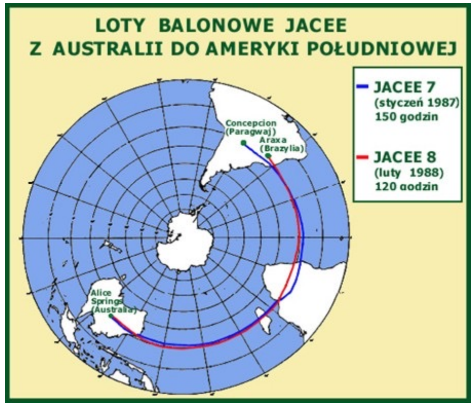
Flight	Date startu	Launch site	Altitude [g/cm^2]	Duration [hours]	Number of chambers
JACEE-0	5/79	Sanriku, Japan	8.0	29.0	1
JACEE-1	9/79	Palestine, Texas	3.7	25.2	4
JACEE-2	10/80	Palestine, Texas	4.0	29.6	4
JACEE-3	6/82	Greenville, S. Carolina	5.0	39.0	1
JACEE-4	9/83	Palestine, Texas	5.0	59.5	4
JACEE-5	10/84	Palestine, Texas	5.0	15.5	4
JACEE-6	5/86	Palestine, Texas	4.0	30.0	4
JACEE-7	1/87	Alice Springs, Australia	5.5	150.0	3
JACEE-8	2/88	Alice Springs, Australia	5.0	120.0	3
JACEE-9	10/90	Ft.Sumner, New Mexico	4.0	44.0	4
JACEE-10	12/90	McMurdo, Antarctica	3.9	204.0	2
JACEE-11	12/93	McMurdo, Antarctica	chambers lost		
JACEE-12	1/94	McMurdo, Antarctica	5.5	210	6
JACEE-13	12/94	McMurdo, Antarctica	5.0	301	6
JACEE-14	12/95	McMurdo, Antarctica	6.0	348	6

In order to record primary cosmic rays, the detector must be placed at highest altitude possible, to avoid cosmic ray interactions in atmosphere above the detector. The JACEE balloons flew at altitude higher than 35 km above the ground. The corresponding atmospheric pressure is less than 5 g/cm2, which is less than interaction path of heavy nuclei (about 17 g/cm^2 for iron nuclei in the air). Flights at such altitudes are possible using largest balloons available, with capacities on order of million cubic meters.

Filling the balloon with helium before launch.
In order to minimize the stresses godola is placed on the truck

Balloon is fully released

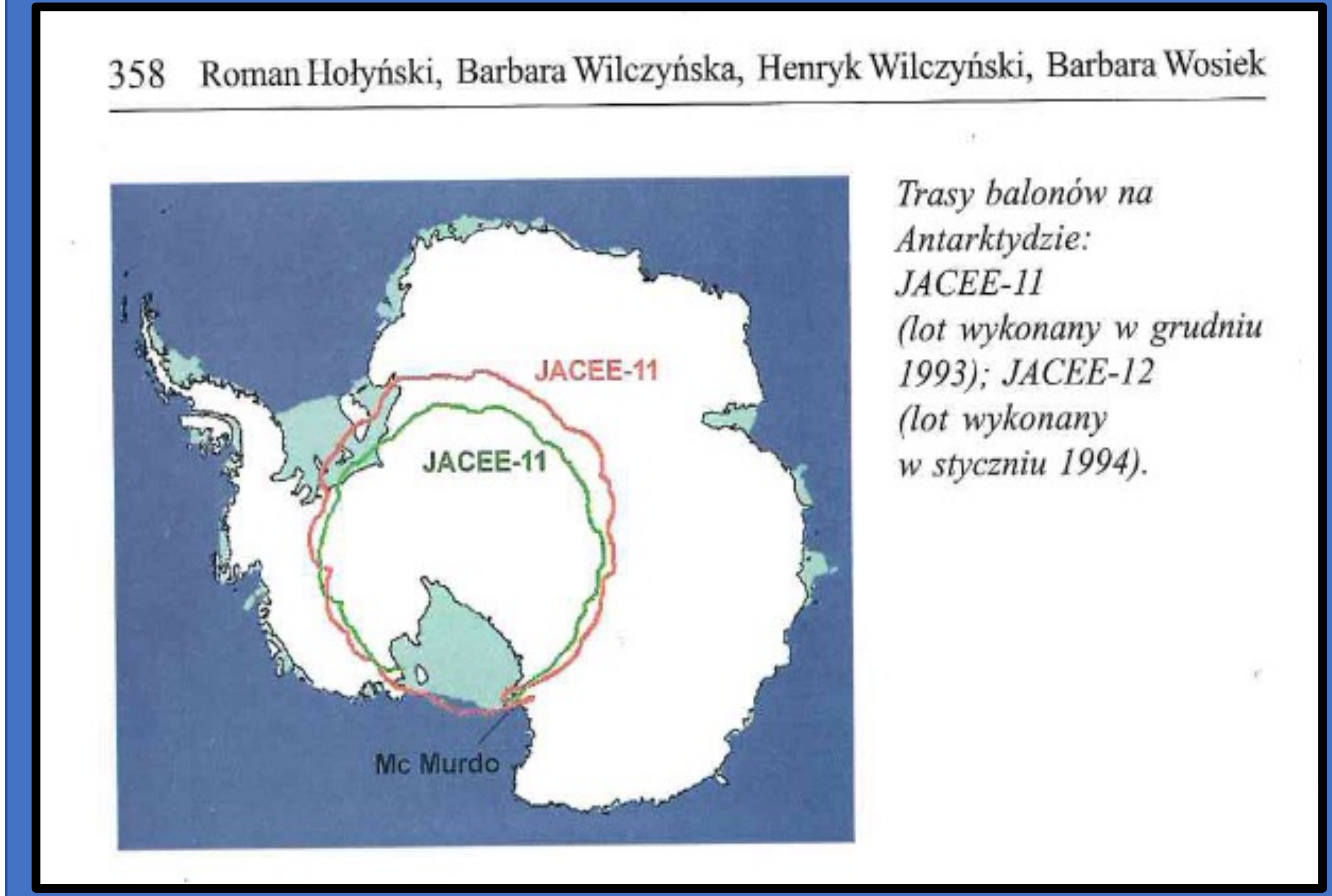




JACEE-7 gondola after landing in the Paraguayan jungle

As soon as possible after the flight, locate where the payload gondola landed and secure the emulsion chambers. The nuclear emulsion must be stored at low temperature before development, so it is important that it be out of the temperature-controlled environment as briefly as possible.

JACEE-11, JACEE-12



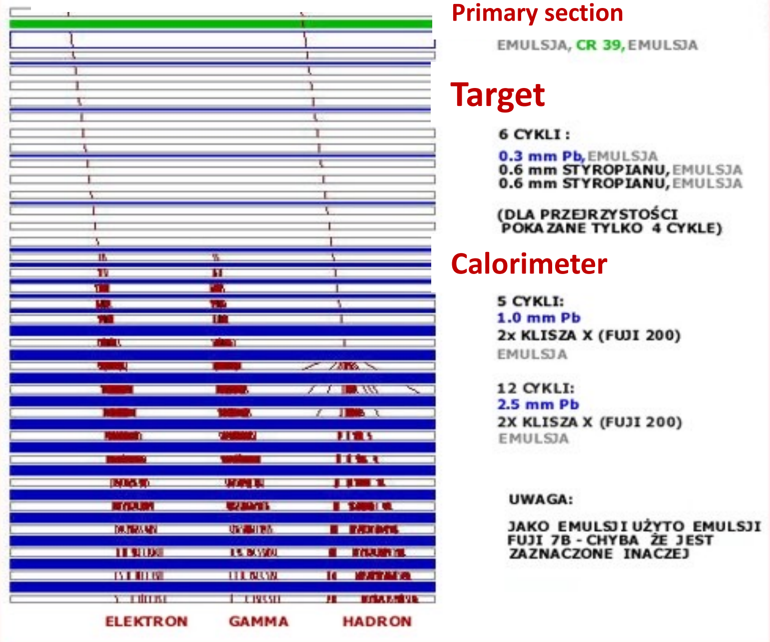
358 Roman Hołyński, Barbara Wilczyńska, Henryk Wilczyński, Barbara Wosiek

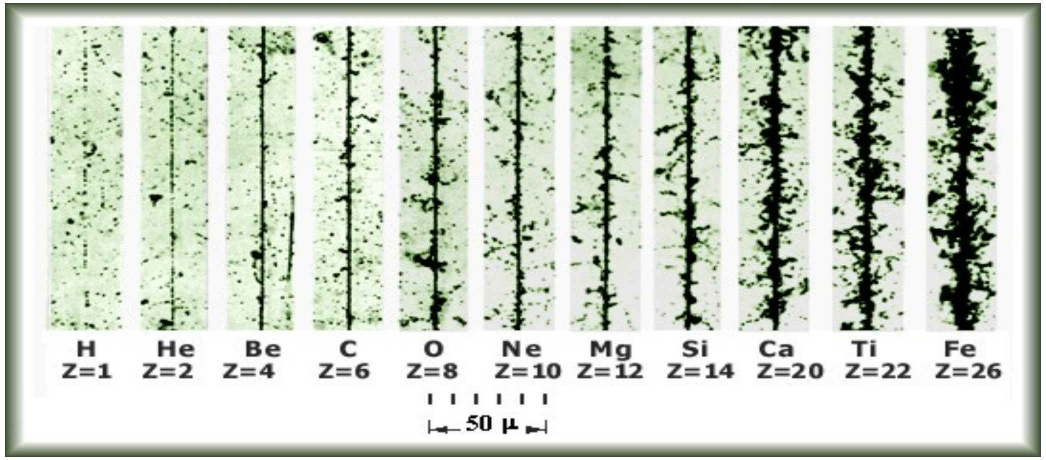
Trasy balonów na Antarktydzie: JACEE-11 (lot wykonany w grudniu 1993); JACEE-12 (lot wykonany w styczniu 1994).

Nucleus-nucleus interactions at energies of several tens GeV per nucleon were first studied in the JACEE experiment, many years before accelerator beams of heavy ions became avaiable at these energies.

The cosmic ray study led to emergence of a new science - the particle physics.

JACEE 10 chamber structure



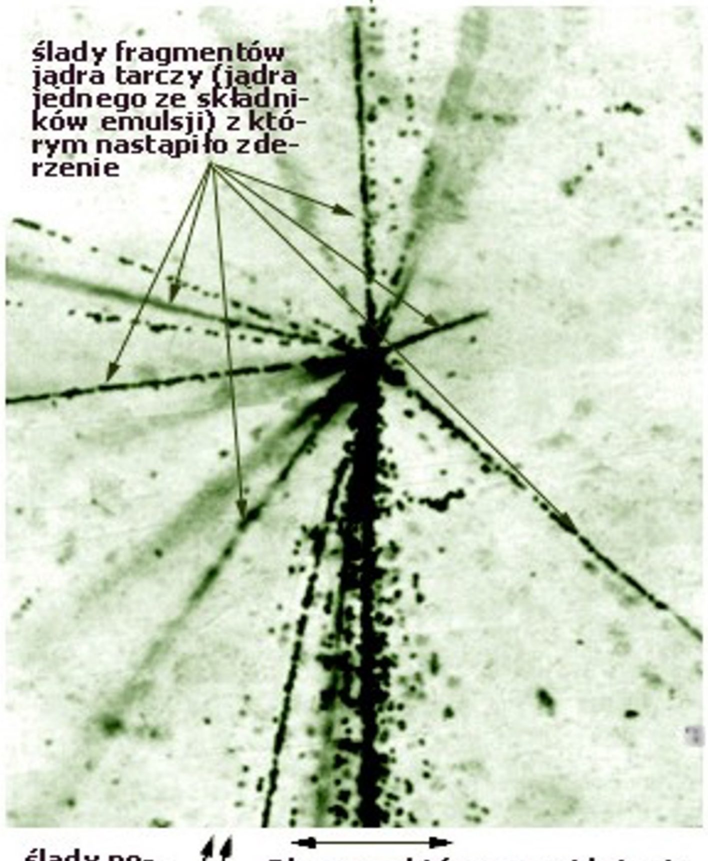


Advantages of the emulsion chamber:

- very good resolution at the micrometer level
- 4pi coverage
- simultaneous registration of produced particles and fragments of the target

The appearance of an interaction in a nuclear emulsion caused by a He nucleus

ślad pozostawiony przez cząstkę pierwotną, (w tym wypadku jądro He o energii 30 TeV), która zderzyła się z jednym z jąder atomów w emulsji



ślady fragmentów jądra tarczy (jądra jednego ze składników emulsji) z którym nastąpiło zderzenie

ślady pojedynczych cząstek wyprodukowanych w zderzeniu

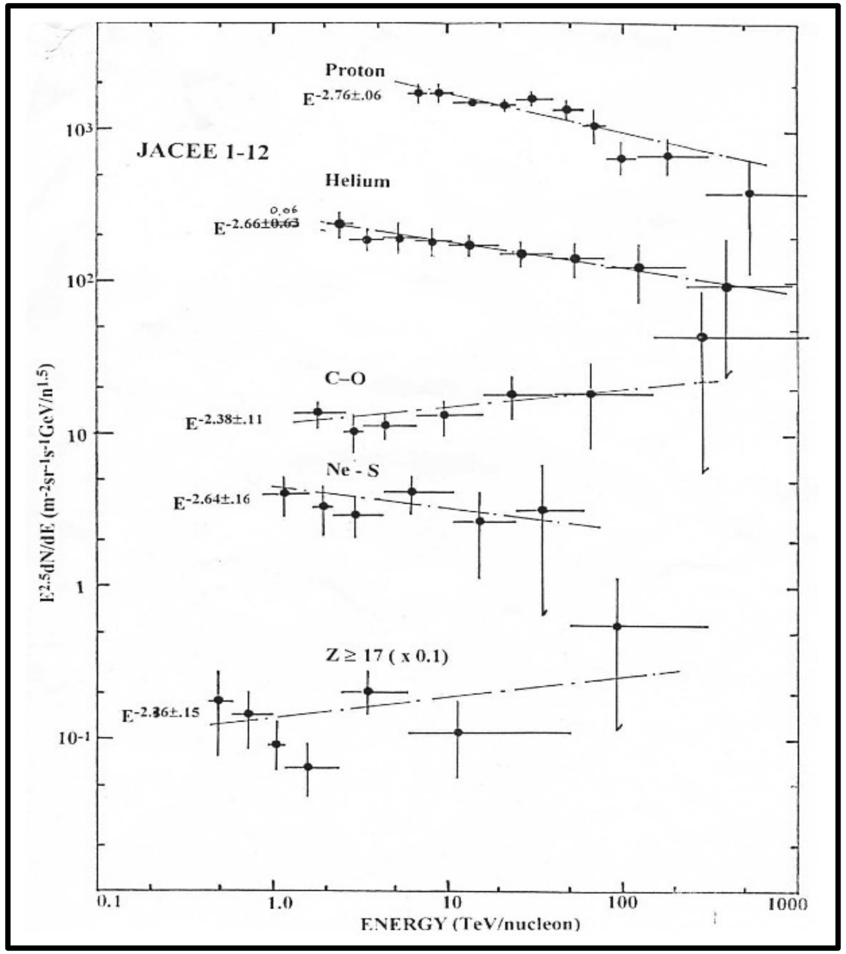
Obszar, w którym znajduje się wiele nałożonych na siebie śladów cząstek wyprodukowanych w zderzeniu (wśród nich ślad s4 pokazany obok)

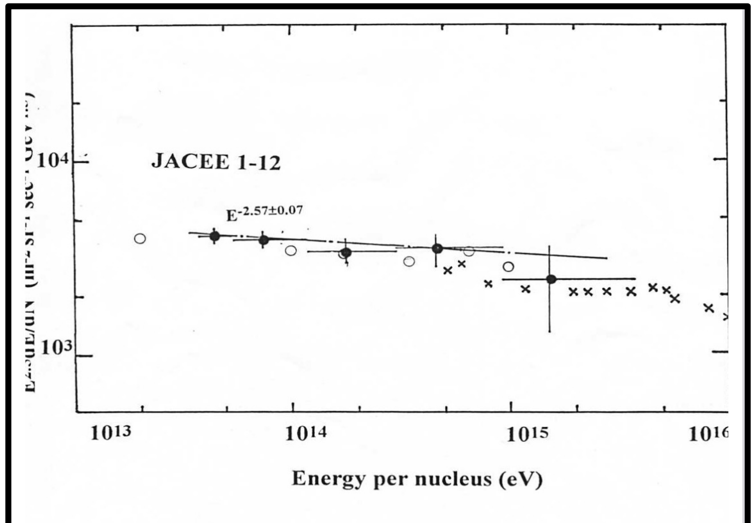
JACEE experiment

- Habilitation - Institute of Physics in Kraków - **physics 1996**

  Badania widma energetycznego i oddziaływań jądrowych pierwotnego promieniowania kosmicznego

The first habilitation from cosmic rays in IFJ





The " all-particle" cosmic ray spectrum in total energy

Reference letters from:

James Cronin - Chicago University,

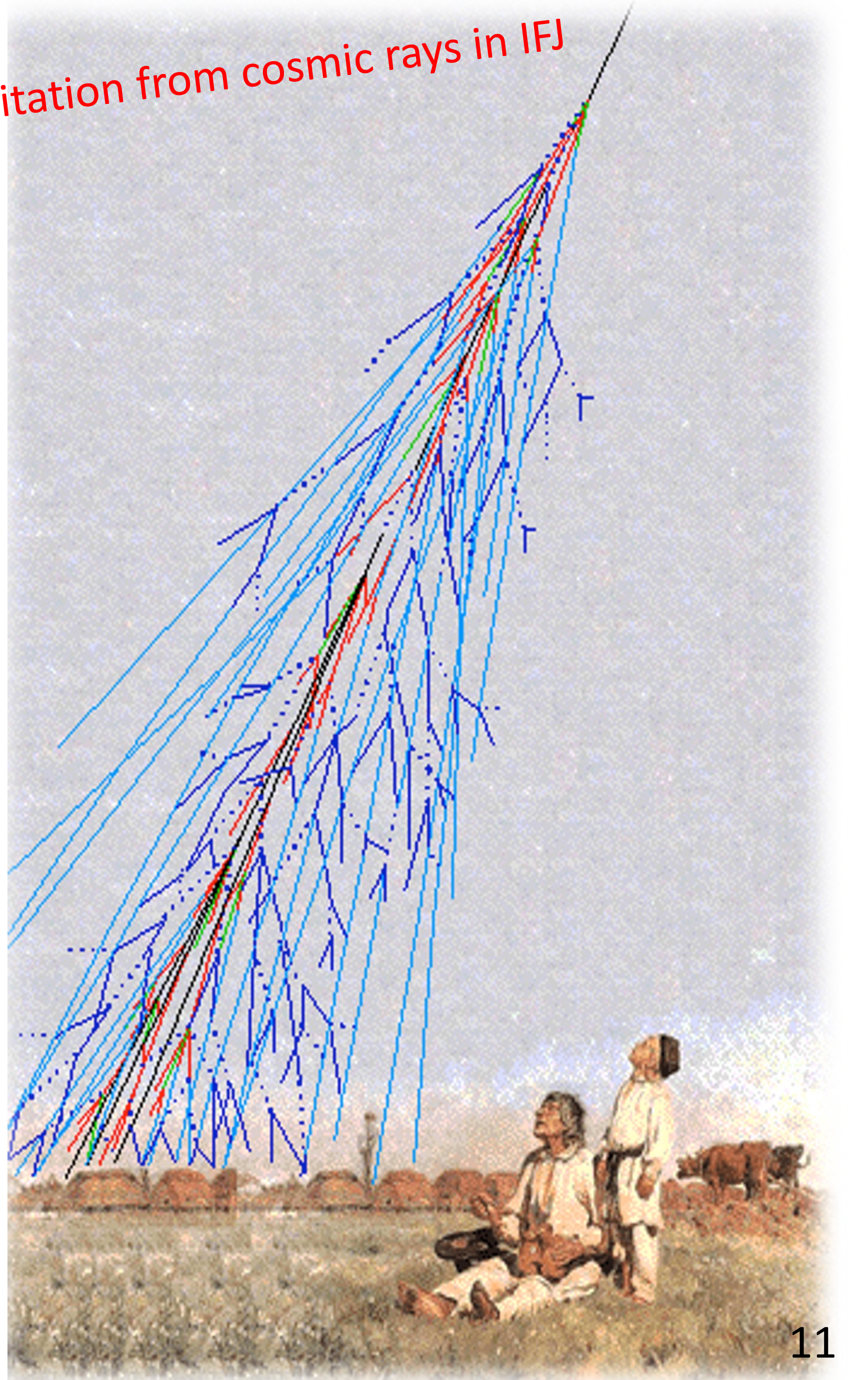
„I have enormous respect for the scientific contributions Henryk has made to the project. He is an able physicists with sound judgement and excelent taste …”

John P. Wefel - Louisiana State University

Hans Blumer - Forschungszentrum Karslruhe

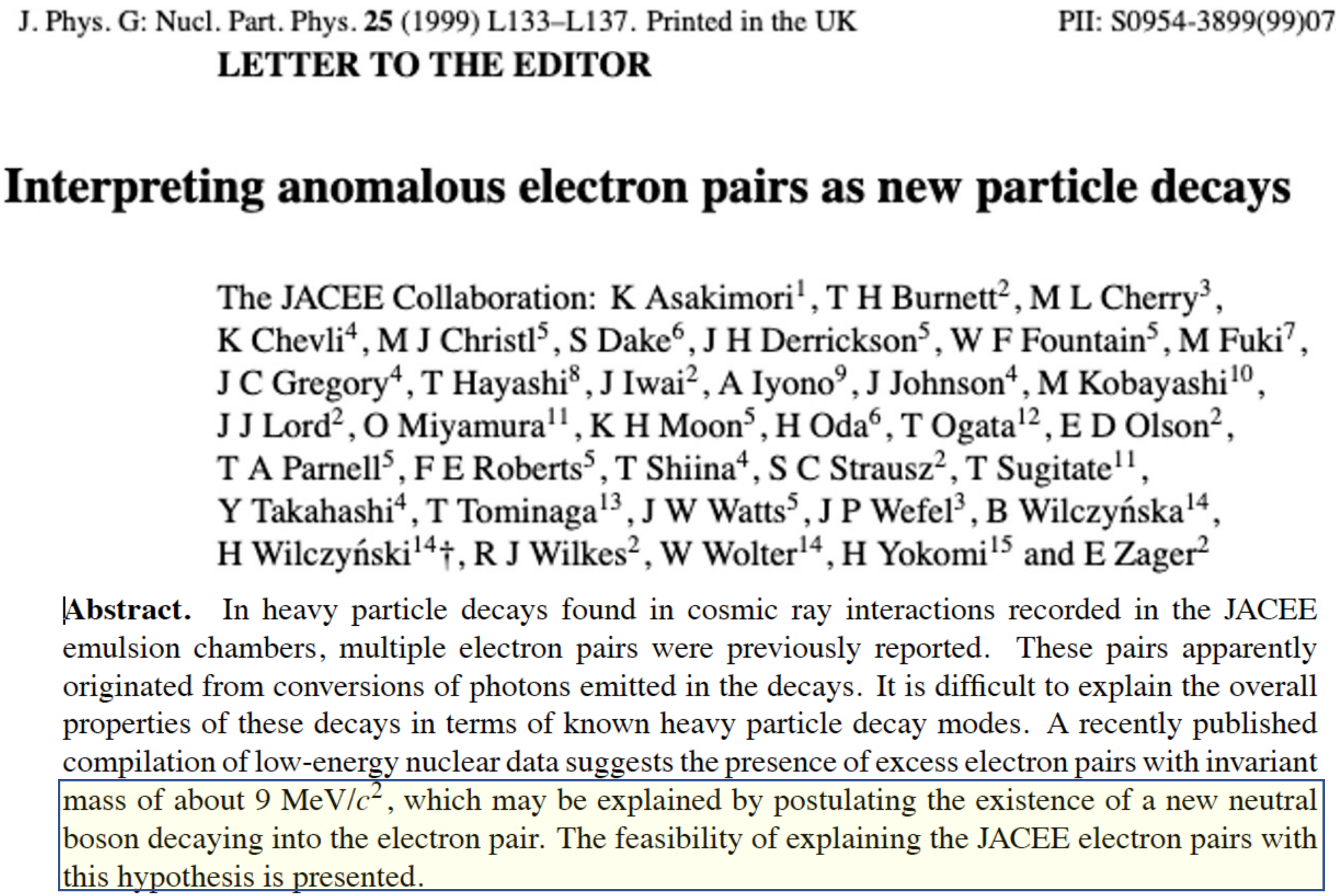
emphasizing the world-class work

of Prof. H. Wilczyński



Spectrum of cosmic rays derived by Prof. H. Wilczyński and collaborators
at energy range: 10^{12} -10^{15} eV was one of the most prominent over many years

The discovery of single unknown neutral particle (neutral bosons with a mass about 9 MeV/c^2) by Prof. H. Wilczyński consisting in the emission of a large number of pions, which later decay to gammas



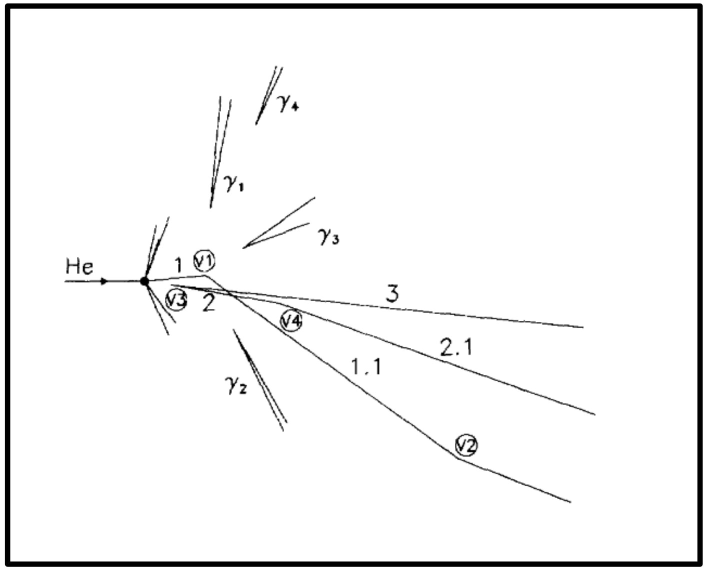
J. Phys. G: Nucl. Part. Phys. **25** (1999) L133–L137. Printed in the UK PII: S0954-3899(99)07535-0

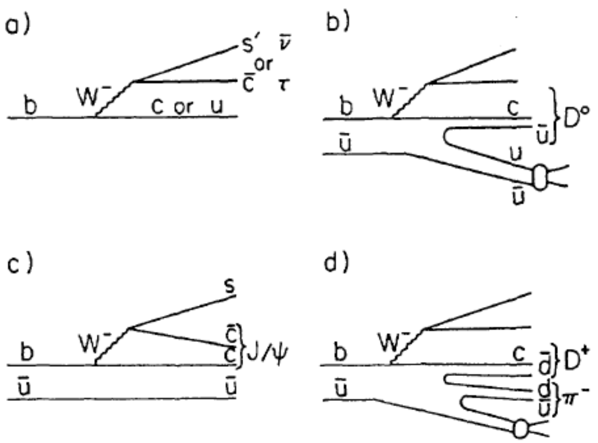
LETTER TO THE EDITOR

Interpreting anomalous electron pairs as new particle decays

The JACEE Collaboration: K Asakimori[1], T H Burnett[2], M L Cherry[3], K Chevli[4], M J Christl[5], S Dake[6], J H Derrickson[5], W F Fountain[5], M Fuki[7], J C Gregory[4], T Hayashi[8], J Iwai[2], A Iyono[9], J Johnson[4], M Kobayashi[10], J J Lord[2], O Miyamura[11], K H Moon[5], H Oda[6], T Ogata[12], E D Olson[2], T A Parnell[5], F E Roberts[5], T Shiina[4], S C Strausz[2], T Sugitate[11], Y Takahashi[4], T Tominaga[13], J W Watts[5], J P Wefel[3], B Wilczyńska[14], H Wilczyński[14]†, R J Wilkes[2], W Wolter[14], H Yokomi[15] and E Zager[2]

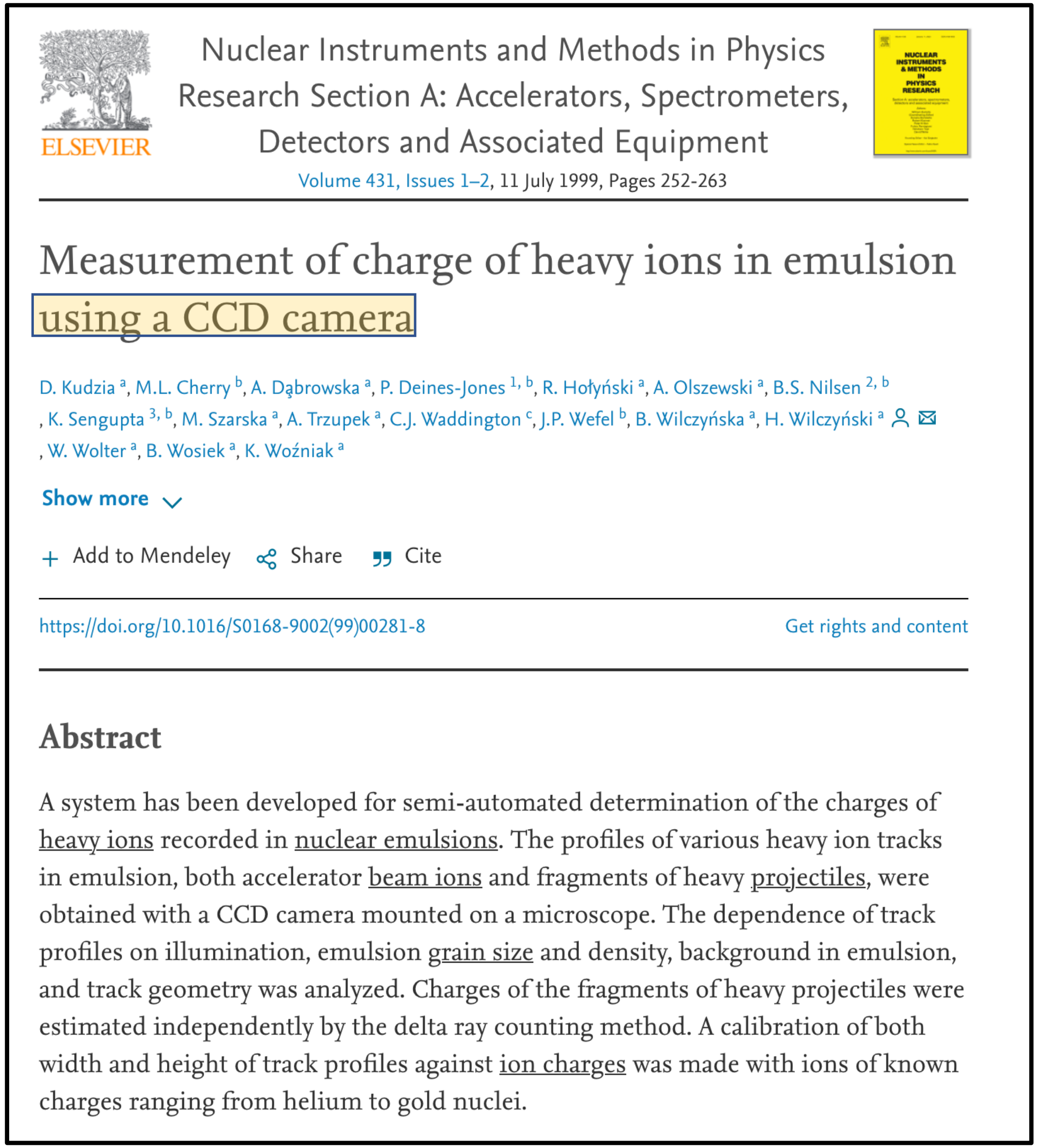
Abstract. In heavy particle decays found in cosmic ray interactions recorded in the JACEE emulsion chambers, multiple electron pairs were previously reported. These pairs apparently originated from conversions of photons emitted in the decays. It is difficult to explain the overall properties of these decays in terms of known heavy particle decay modes. A recently published compilation of low-energy nuclear data suggests the presence of excess electron pairs with invariant mass of about 9 MeV/c^2, which may be explained by postulating the existence of a new neutral boson decaying into the electron pair. The feasibility of explaining the JACEE electron pairs with this hypothesis is presented.





The editors, upon receipt of the article, showed readiness to publish the work immediately and encouraged the submission of more work.

Other important work:



Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 431, Issues 1–2, 11 July 1999, Pages 252-263

Measurement of charge of heavy ions in emulsion using a CCD camera

D. Kudzia [a], M.L. Cherry [b], A. Dąbrowska [a], P. Deines-Jones [1, b], R. Hołyński [a], A. Olszewski [a], B.S. Nilsen [2, b], K. Sengupta [3, b], M. Szarska [a], A. Trzupek [a], C.J. Waddington [c], J.P. Wefel [b], B. Wilczyńska [a], H. Wilczyński [a], W. Wolter [a], B. Wosiek [a], K. Woźniak [a]

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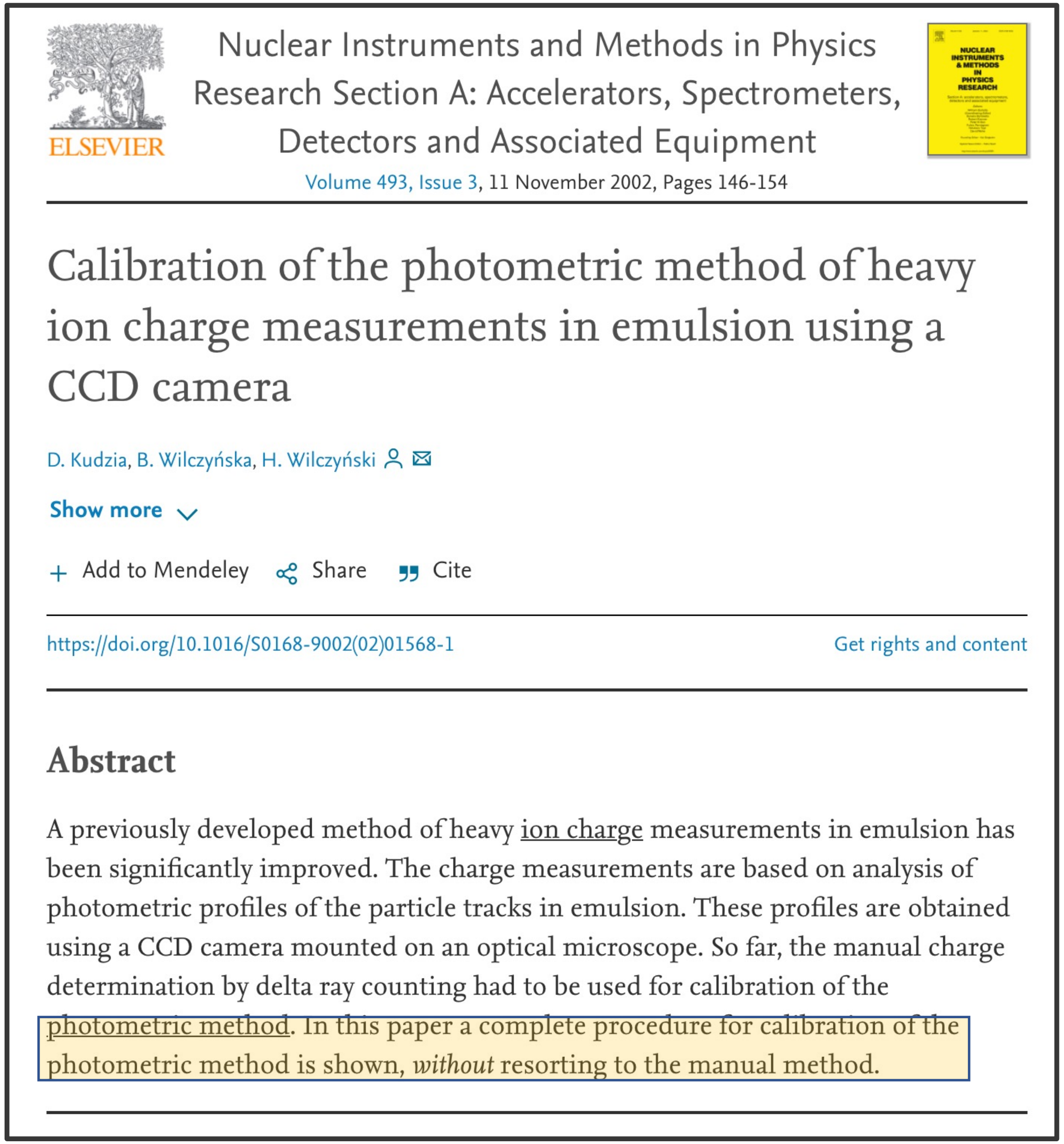
https://doi.org/10.1016/S0168-9002(99)00281-8 Get rights and content

Abstract

A system has been developed for semi-automated determination of the charges of heavy ions recorded in nuclear emulsions. The profiles of various heavy ion tracks in emulsion, both accelerator beam ions and fragments of heavy projectiles, were obtained with a CCD camera mounted on a microscope. The dependence of track profiles on illumination, emulsion grain size and density, background in emulsion, and track geometry was analyzed. Charges of the fragments of heavy projectiles were estimated independently by the delta ray counting method. A calibration of both width and height of track profiles against ion charges was made with ions of known charges ranging from helium to gold nuclei.



Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 493, Issue 3, 11 November 2002, Pages 146-154

Calibration of the photometric method of heavy ion charge measurements in emulsion using a CCD camera

D. Kudzia, B. Wilczyńska, H. Wilczyński

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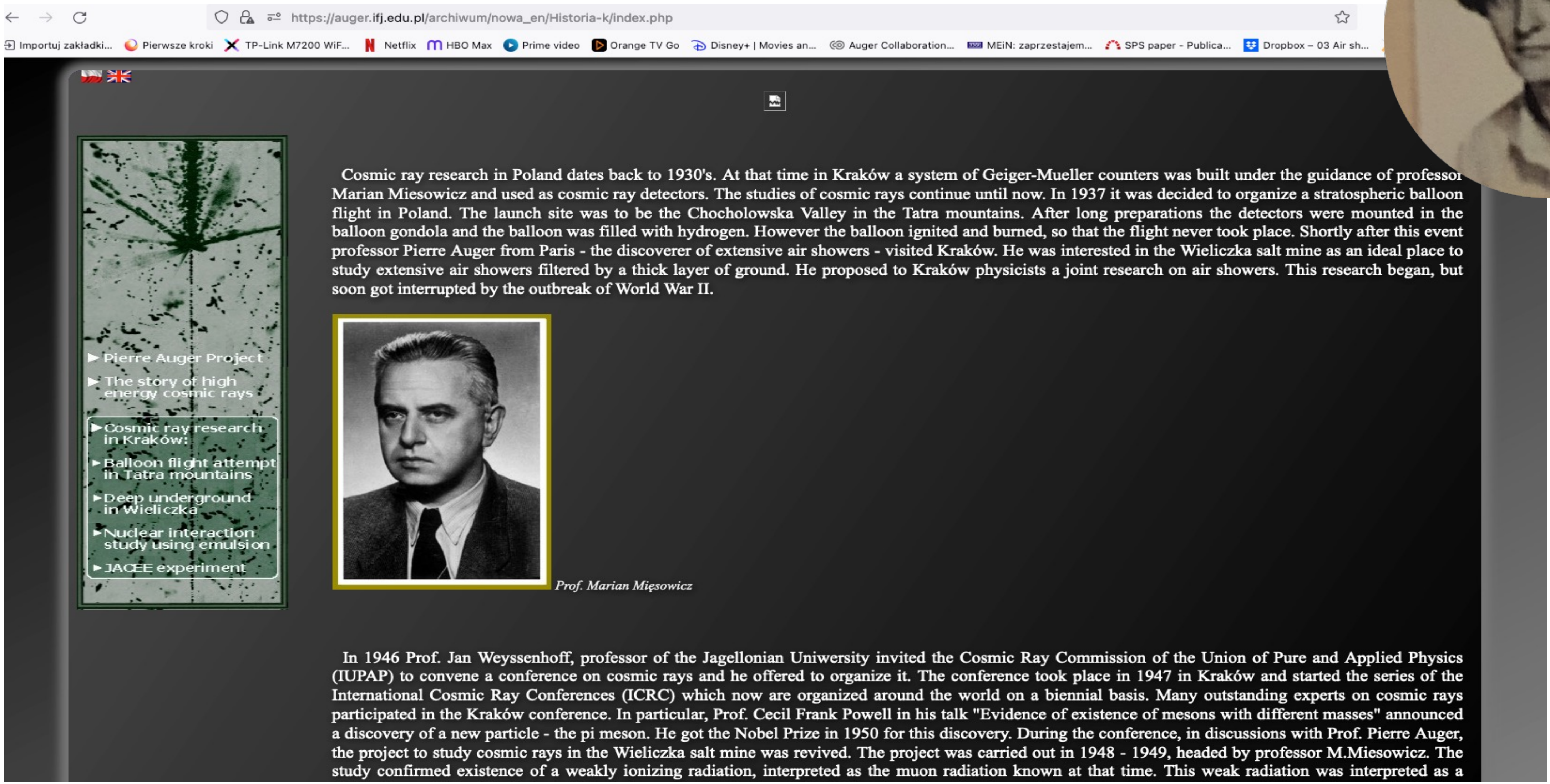
https://doi.org/10.1016/S0168-9002(02)01568-1 Get rights and content

Abstract

A previously developed method of heavy ion charge measurements in emulsion has been significantly improved. The charge measurements are based on analysis of photometric profiles of the particle tracks in emulsion. These profiles are obtained using a CCD camera mounted on an optical microscope. So far, the manual charge determination by delta ray counting had to be used for calibration of the photometric method. In this paper a complete procedure for calibration of the photometric method is shown, *without* resorting to the manual method.

Web page created by Barbara Wilczyńska

https://auger.ifj.edu.pl/archiwum/Auger/



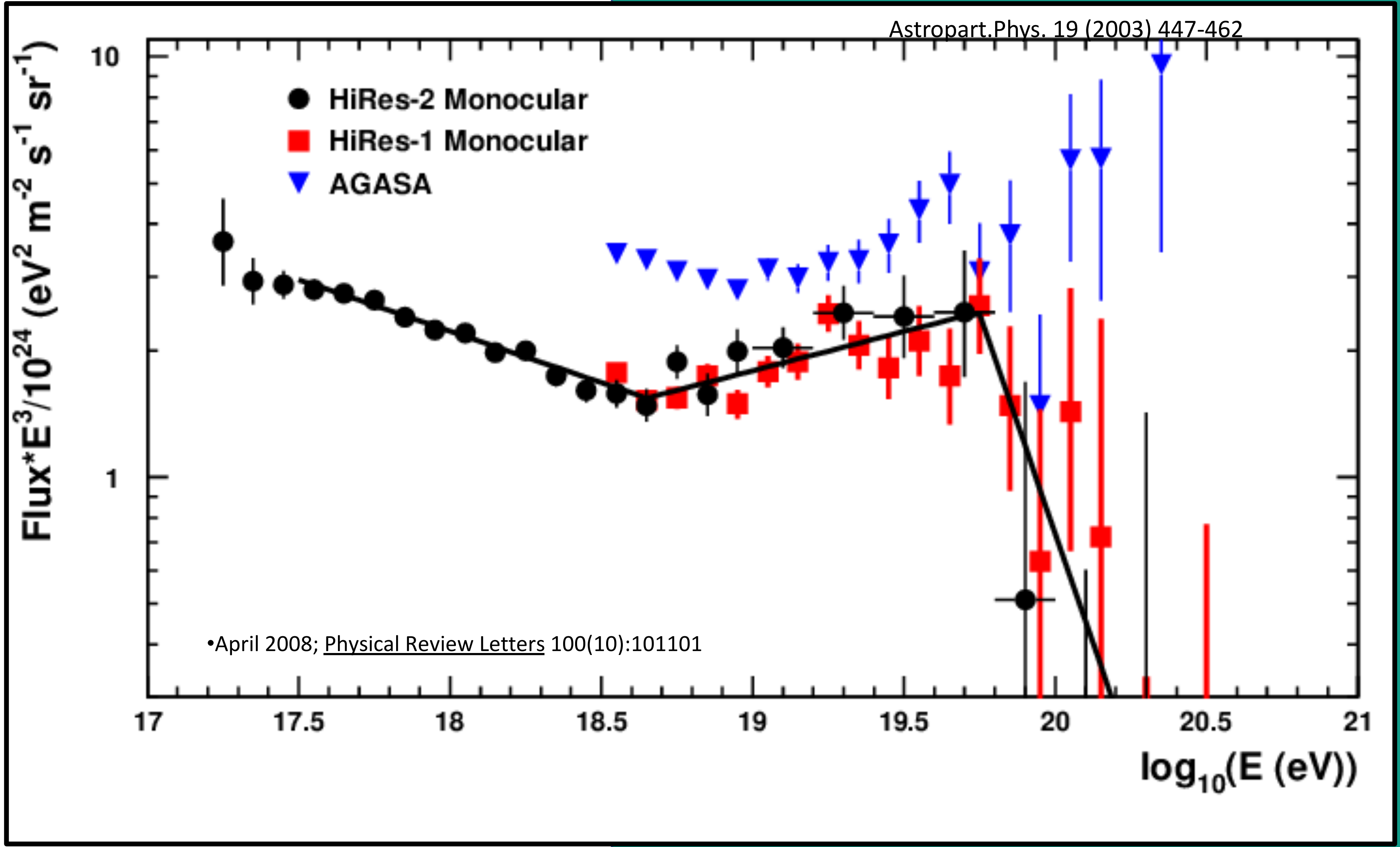
Cosmic ray research in Poland dates back to 1930's. At that time in Kraków a system of Geiger-Mueller counters was built under the guidance of professor Marian Miesowicz and used as cosmic ray detectors. The studies of cosmic rays continue until now. In 1937 it was decided to organize a stratospheric balloon flight in Poland. The launch site was to be the Chocholowska Valley in the Tatra mountains. After long preparations the detectors were mounted in the balloon gondola and the balloon was filled with hydrogen. However the balloon ignited and burned, so that the flight never took place. Shortly after this event professor Pierre Auger from Paris - the discoverer of extensive air showers - visited Kraków. He was interested in the Wieliczka salt mine as an ideal place to study extensive air showers filtered by a thick layer of ground. He proposed to Kraków physicists a joint research on air showers. This research began, but soon got interrupted by the outbreak of World War II.

Prof. Marian Mięsowicz

In 1946 Prof. Jan Weyssenhoff, professor of the Jagellonian Uniwersity invited the Cosmic Ray Commission of the Union of Pure and Applied Physics (IUPAP) to convene a conference on cosmic rays and he offered to organize it. The conference took place in 1947 in Kraków and started the series of the International Cosmic Ray Conferences (ICRC) which now are organized around the world on a biennial basis. Many outstanding experts on cosmic rays participated in the Kraków conference. In particular, Prof. Cecil Frank Powell in his talk "Evidence of existence of mesons with different masses" announced a discovery of a new particle - the pi meson. He got the Nobel Prize in 1950 for this discovery. During the conference, in discussions with Prof. Pierre Auger, the project to study cosmic rays in the Wieliczka salt mine was revived. The project was carried out in 1948 - 1949, headed by professor M.Miesowicz. The study confirmed existence of a weakly ionizing radiation, interpreted as the muon radiation known at that time. This weak radiation was interpreted as a

These web pages are a well-known source of information about the history of cosmic rays in Kraków, web page cited in several journals

Energy spectrum measured by AGASA and HiRes



Status 2003

inconsistency of spectra due to the use of different detection techniques ?

Solution of this puzzle: Hybrid detector

Pierre Auger Collaboration

- **1991:** a proposal to build the Pierre Auger Observatory (James Cronin and Alan Watson),
- International cooperation: Currently: **16 countries, 98 institutions, 400+members**

James Cronin, 1931-2016

Group from IFJ PAN under the leadership of Prof. Henryk Wilczyński since 1997 in the experiment of Pierre Auger Observatory

Salt Lake City meeting - 1997

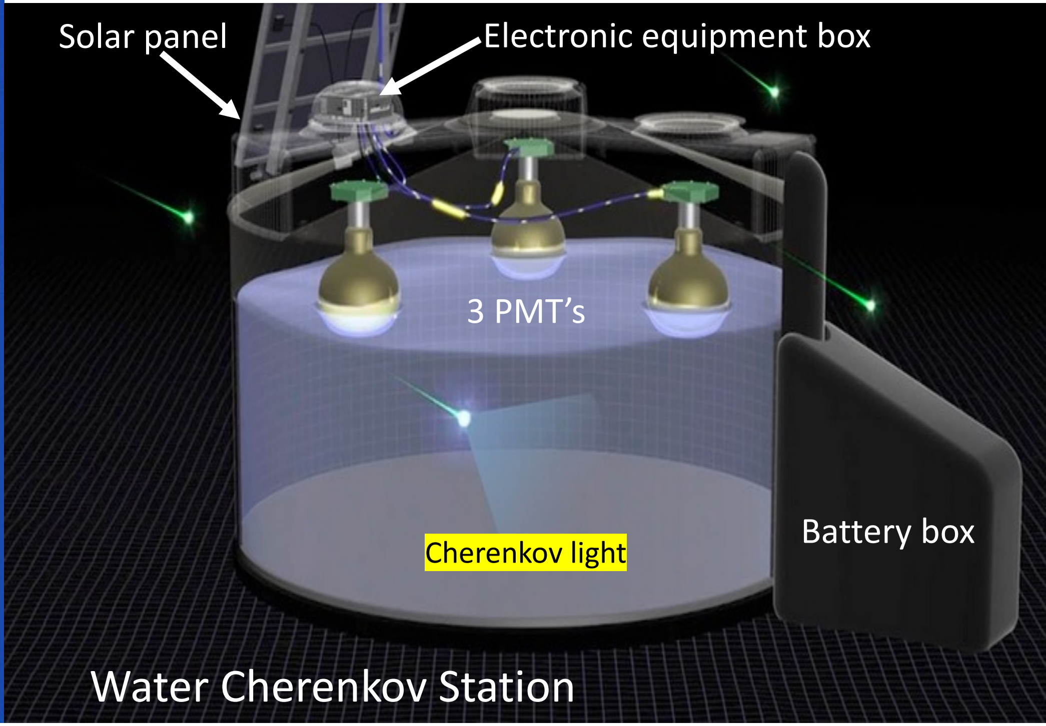
Participants of the Auger Collaboration meeting, CERN, 1997

Surface Detector of the Pierre Auger Observatory

12 Tn of pure water
3 PMT's per detector

SD's sensitive"

- **e+,e-** (signal proportional to energy)
- **gamma's** (signal proportional to energy)
- **muons** (signal proprtional to trace length)

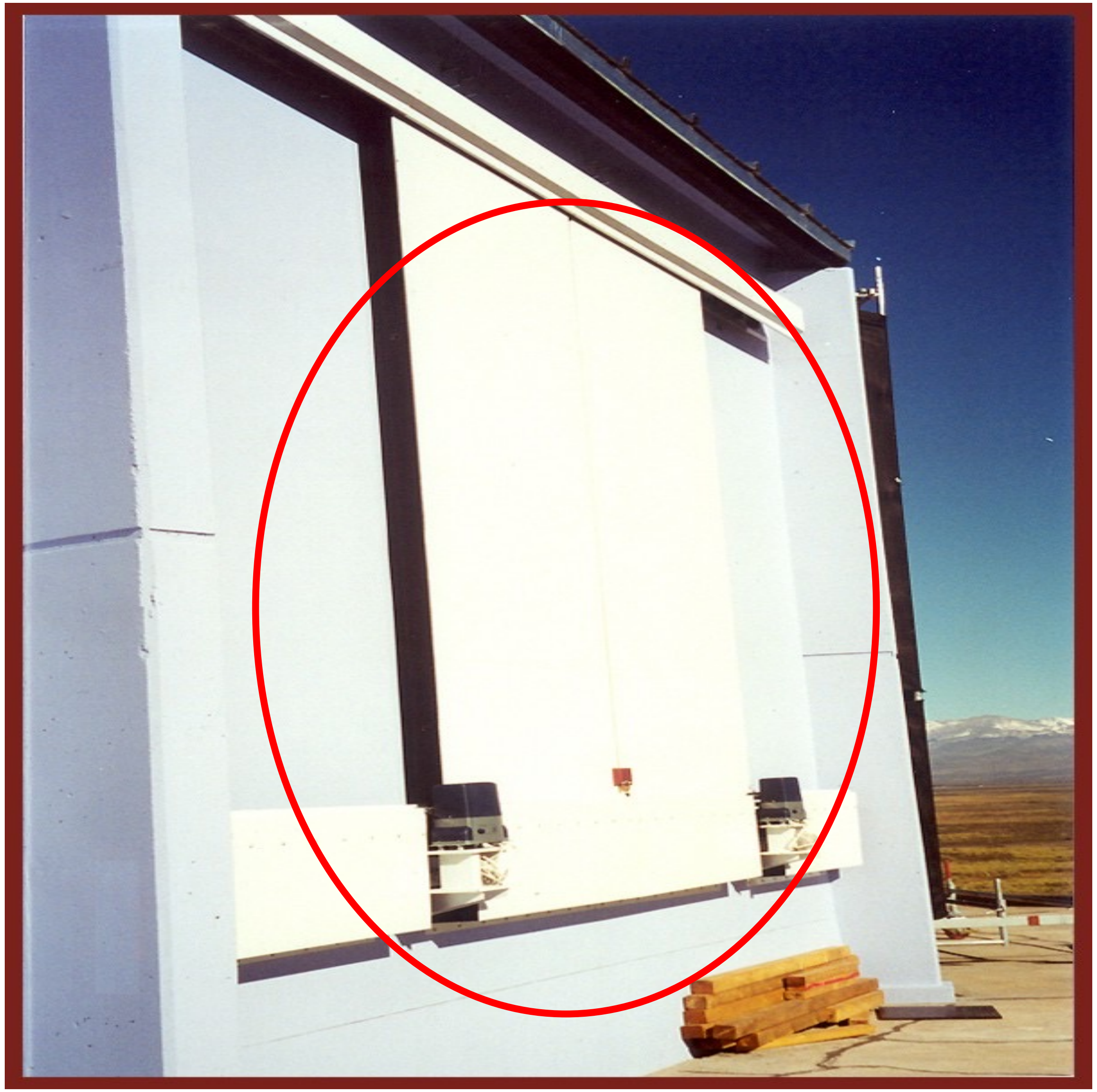


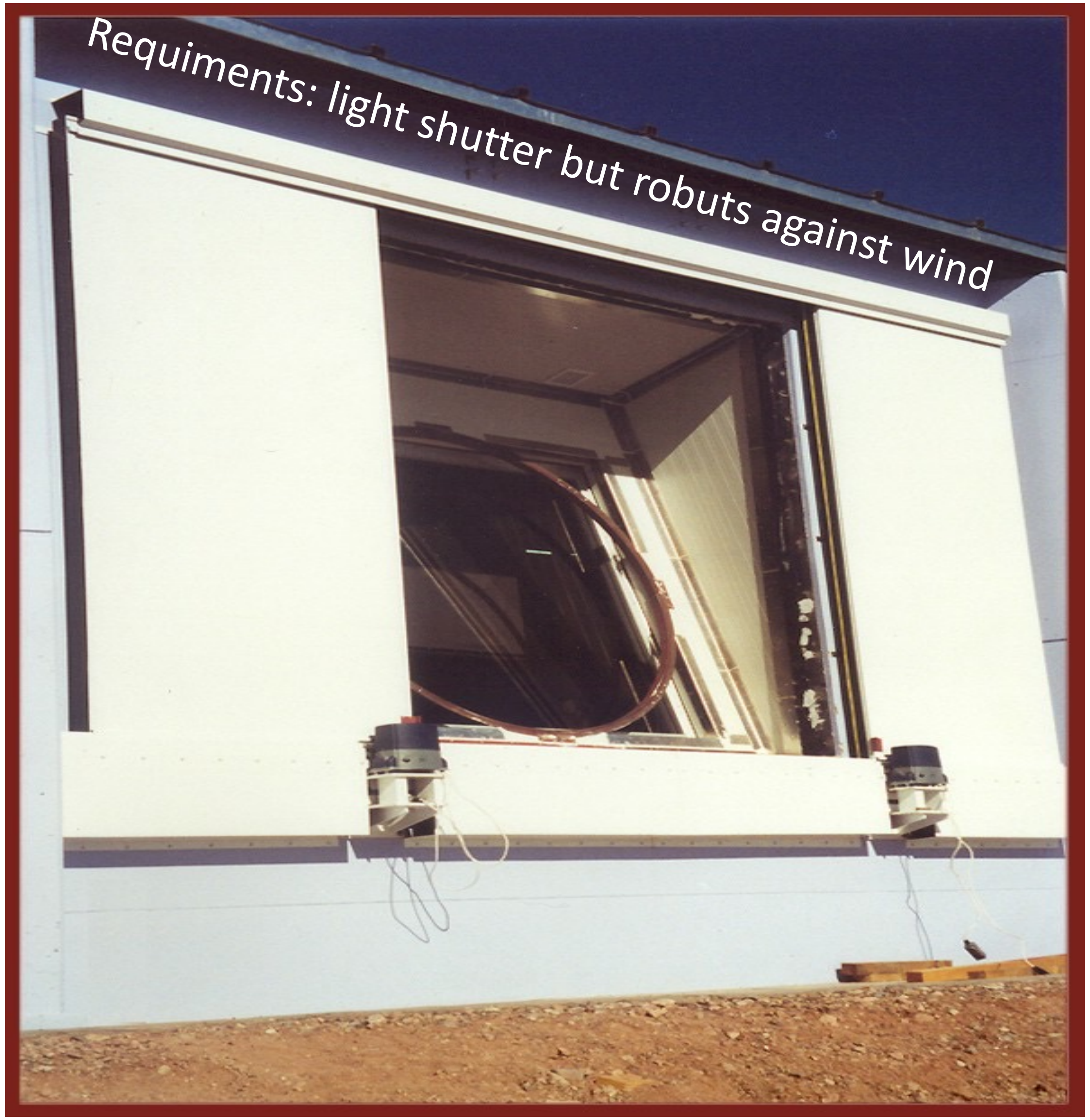
Fluorescence Telescopes (FD's)

Los Leones

One of the first photographs taken by Henryk Wilczyński

First hardware contribution: Shutter to the Fluorescence detector



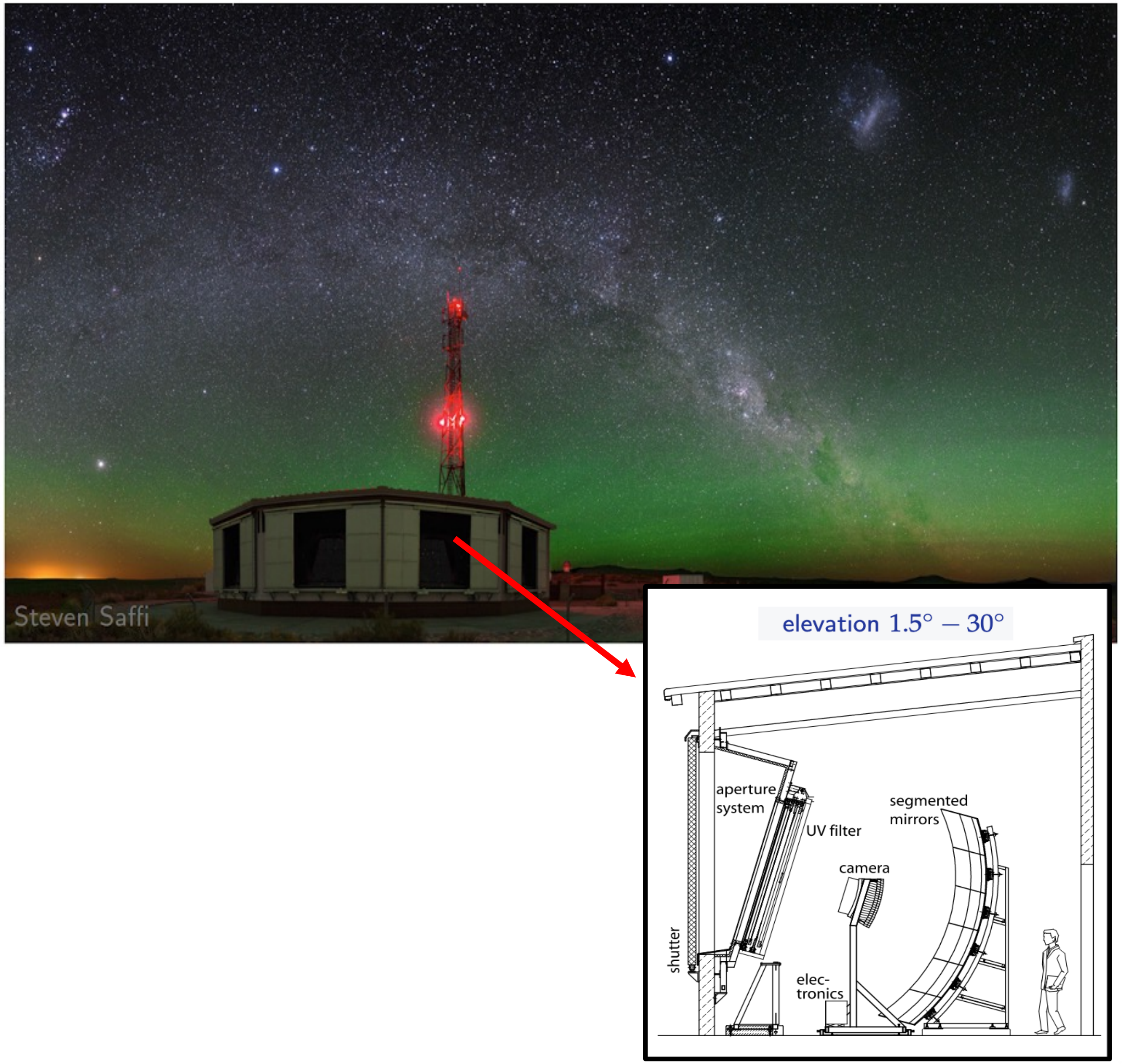


Requiments: light shutter but robuts against wind

Note: in the Argentine Pampas, it is very common for winds to blow at around 50 km/h, sometimes even over 100 km/h

Fluorescence Telescopes (FD's)

FD telescopes at Los Morados

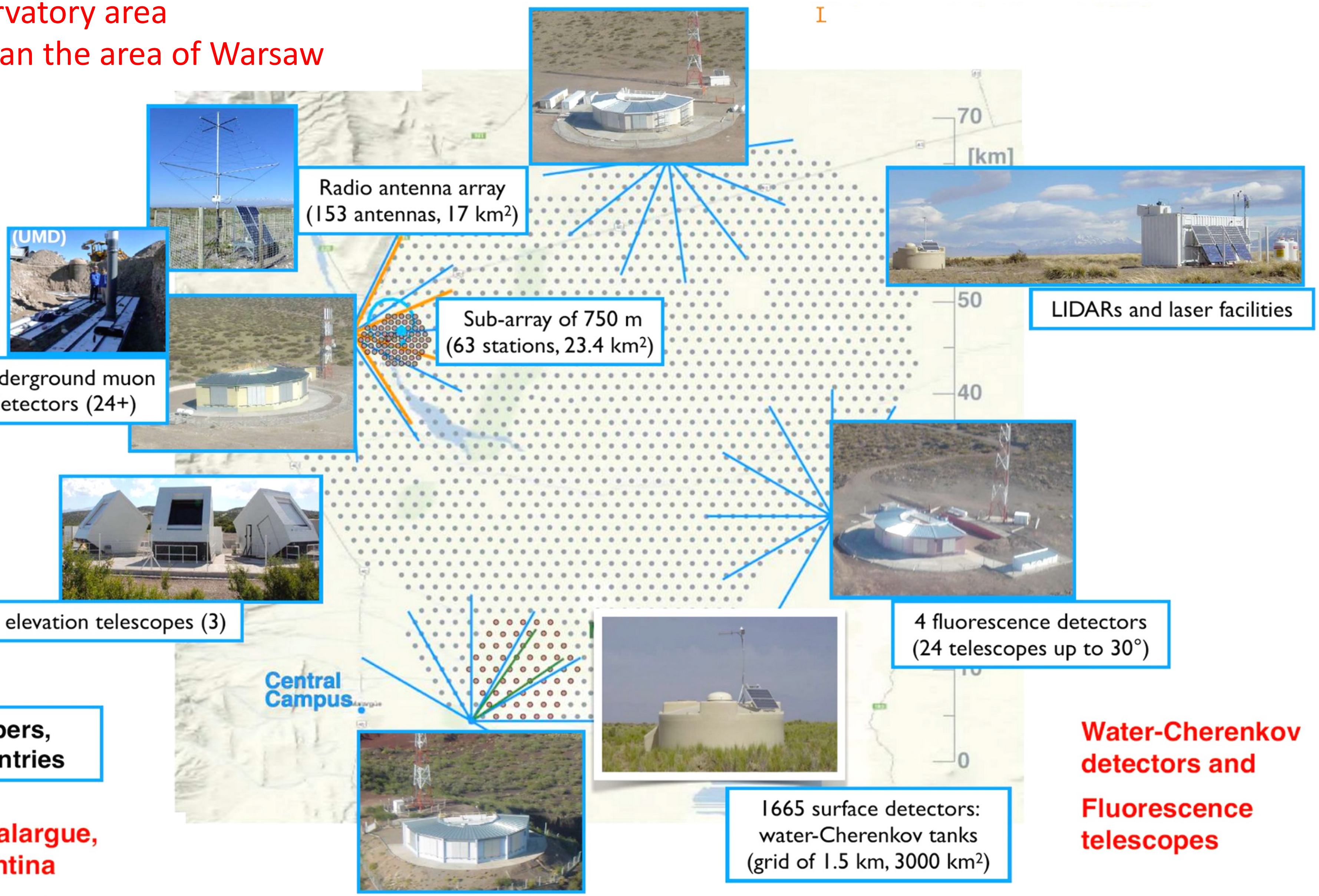


elevation $1.5° - 30°$

Pierre Auger Observatory – the world's largest cosmic ray detector, the energy range above 10^{17} eV

Observatory area
6 times larger than the area of Warsaw

Pierre Auger Observatory
Province Mendoza, Argentina



Radio antenna array
(153 antennas, 17 km²)

Underground muon
detectors (24+)

Sub-array of 750 m
(63 stations, 23.4 km²)

LIDARs and laser facilities

High elevation telescopes (3)

4 fluorescence detectors
(24 telescopes up to 30°)

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)

More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue,
Province Mendoza, Argentina

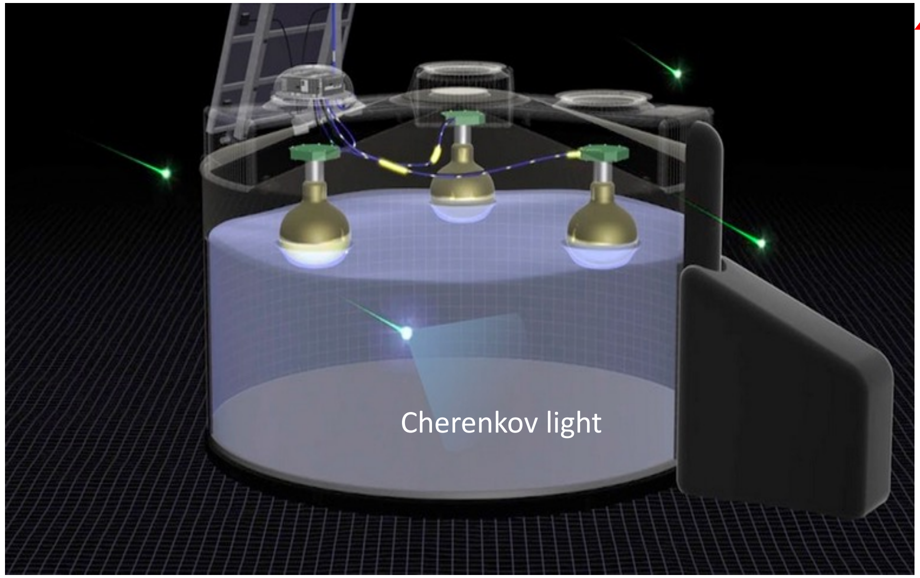
Water-Cherenkov
detectors and

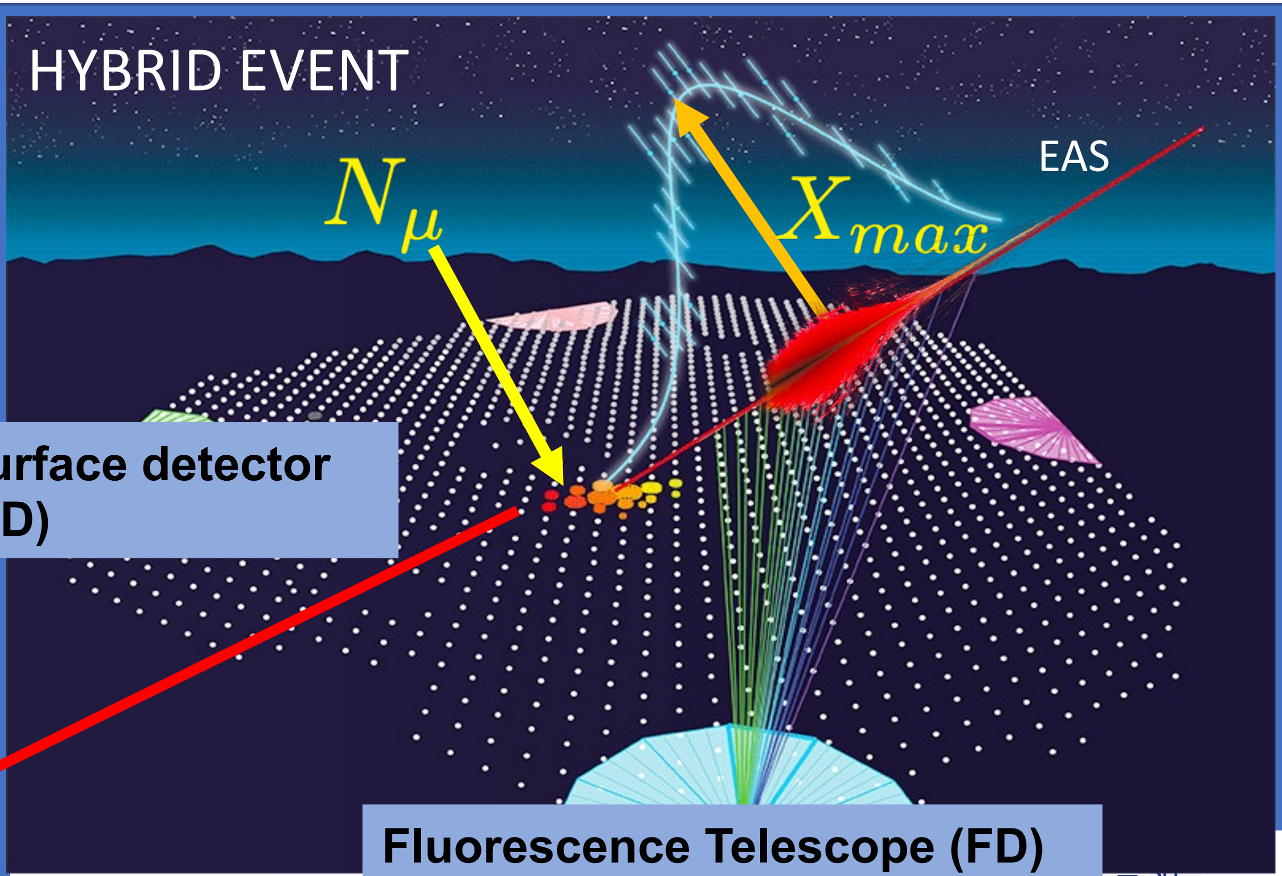
Fluorescence
telescopes

Measured Observables in the experiment of Pierre Auger

- **Fluorescence detectors (FD):**
  Depth of maximum development X_{max}
  Currently, the most precise estimator of the mass of the particle initiating the large atmospheric shower

- **Surface detectors (SD):**
  Number of muons on earth N_μ correlated with the type of primary particle
  measures the time of arrival and the signal of the bunch secondary particles reaching the ground

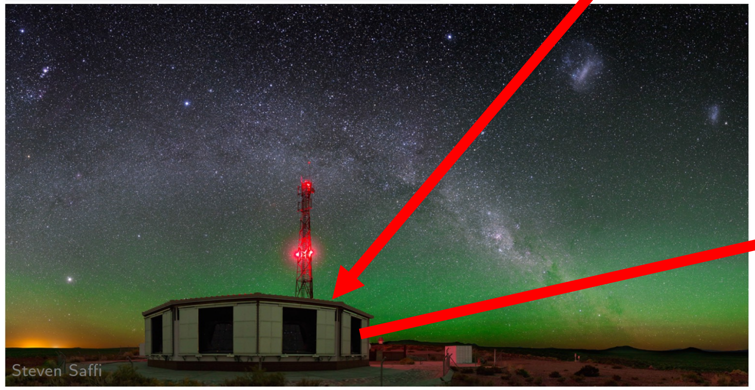


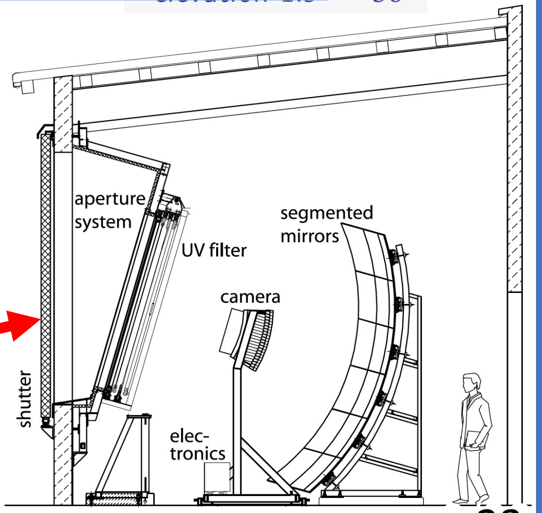


Surface detector (SD)

Fluorescence Telescope (FD)

FD telescopes at Los Morados


Steven Saffi



UHECR energy spectrum from the surface detector

- **Scenario (A)**

  Observed truncation in spectrum:
  Effect related to maximum source efficiency:
  acceleration in the source $E_{max}(A) = Z\ E_{max}(p)$

- **Scenario (B)**

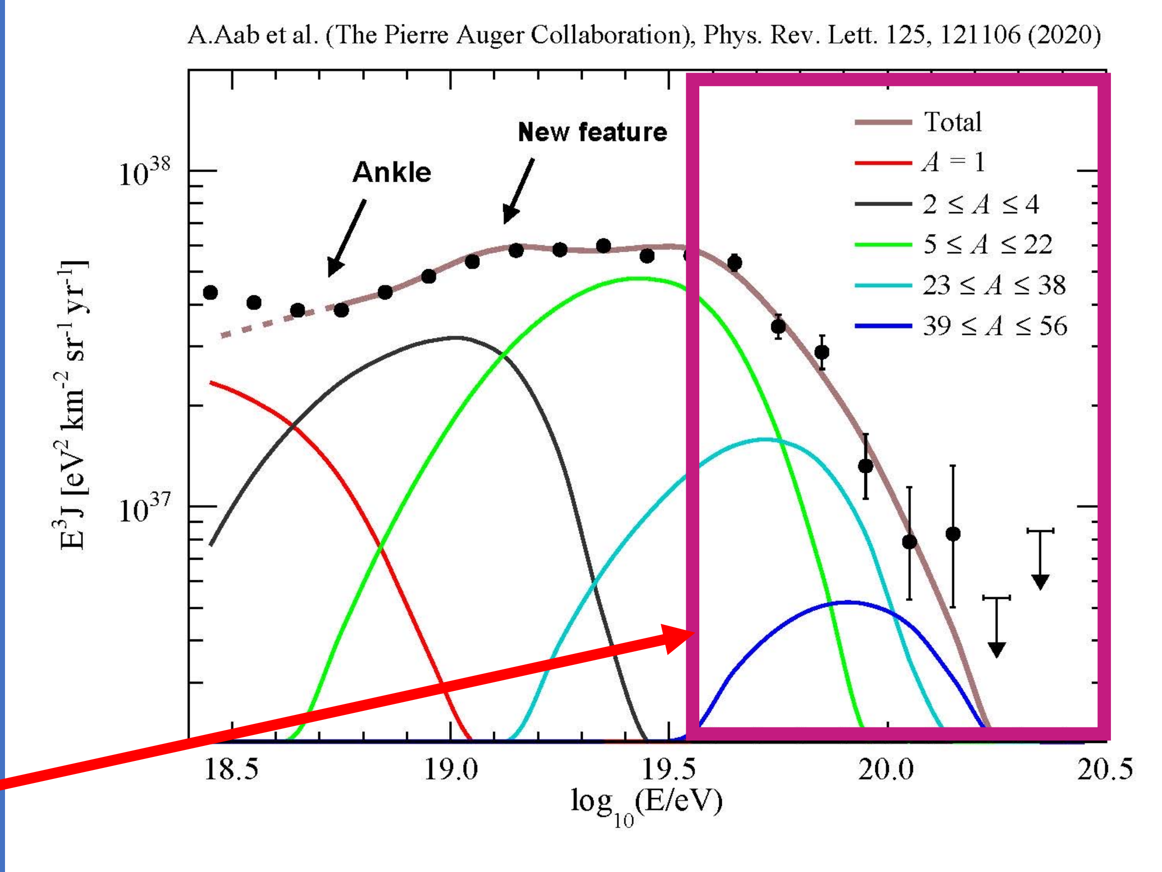
  Truncation of cosmic rays may be caused by the GZK effect

  GZK: cosmic rays interact with the background microwave radiation (expected spectrum truncation at $4 \cdot 10^{19}$ eV, maximum source distance 50 - 100 Mpc)

Do we see protons at the highest energies?

- The need for precise composition measurements, at the moment, the measurement of the mass of the primary particle only up to the energy of 10^{19} eV, from the data of the fluorescence detector

The energy spectrum of the highest energy particles in the Universe


A.Aab et al. (The Pierre Auger Collaboration), Phys. Rev. Lett. 125, 121106 (2020)

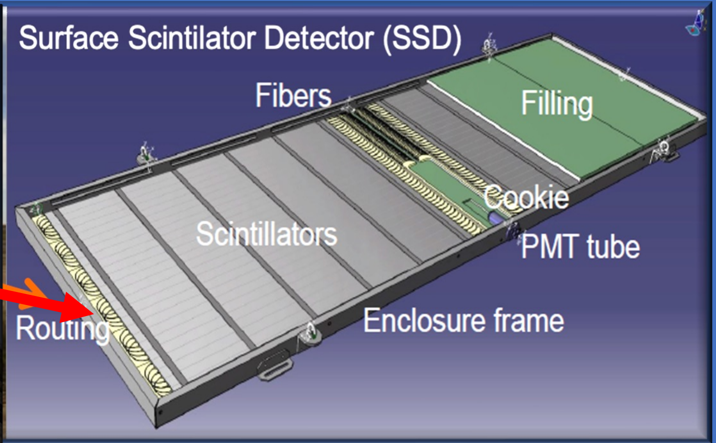
Phys. Rev. Lett. 125 (2020)121106
Phys. Rev. D 102 (2020) 062005

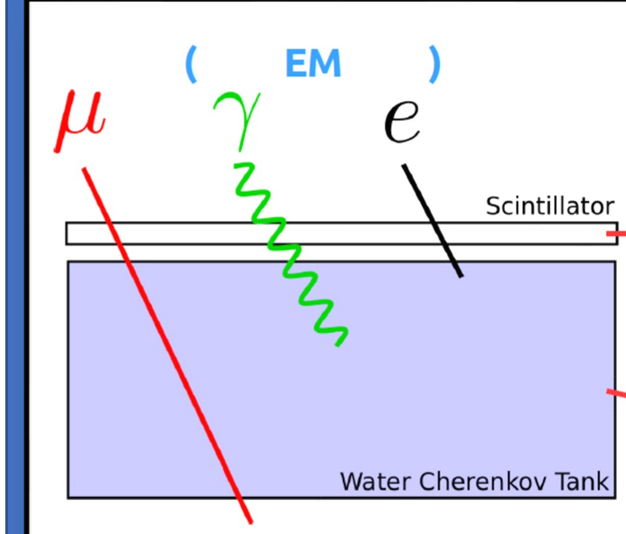
Modernization of the observatory: AugerPrime

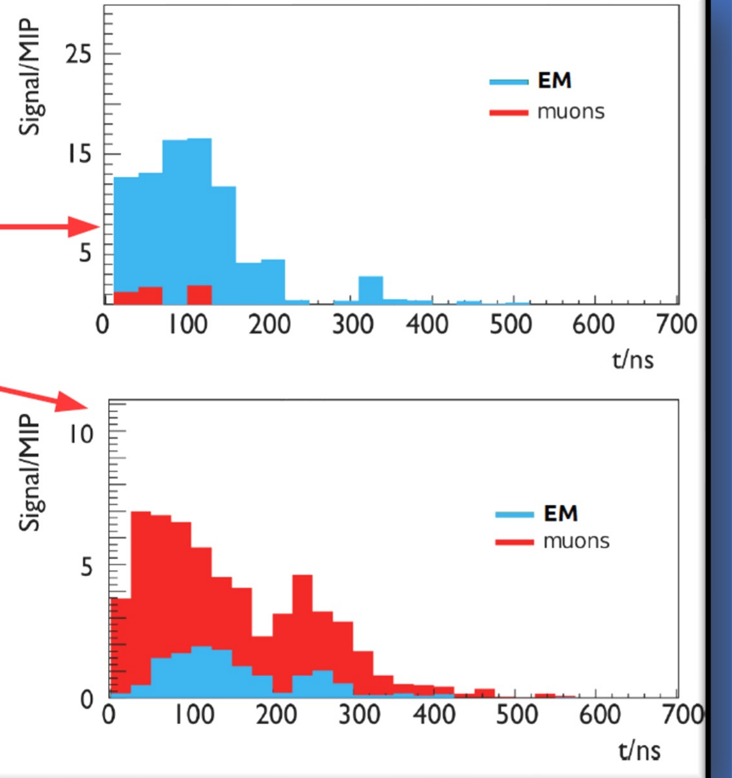
- equipping each of the ground detector stations with an additional scintillation detector with an area of 3.8 m^2 placed above the existing one Cherenkov detector
- Different response of detectors to the component electromagnetic and muons

AugerPrime: increase measurement accuracy mass composition enabling such measurements also for single events, in the observed spectrum truncation, i.e. above 10^{19} eV

Complementary response







$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$
$$S_{\mathrm{em},\mathrm{WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

Modernization of the detector: contribution of the Auger group from the IFJ PAN

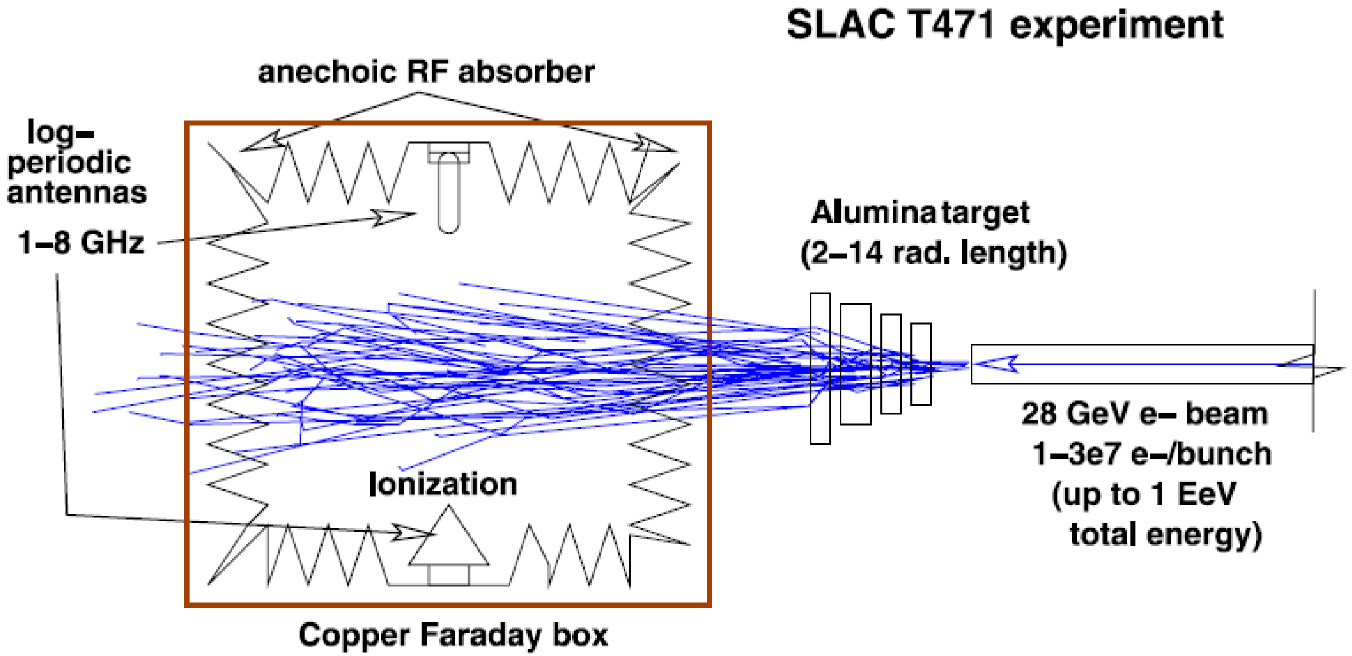
- Together with engineers from IFJ PAN, 228 (out of 1519) scintillation detectors (SSD) have been assembled and tested over the last years

Prof. Henryk Wilczyński,
co-leader of SSD task in the Pierre Auger Collaboration


Test bench
Assembling:
2017-2019

March 2021: the last conteiner sent to Argentina

Microwave emission of air showers



accelerator experiment:
Gorham et al., Phys Rev D 78 (2008) 032007

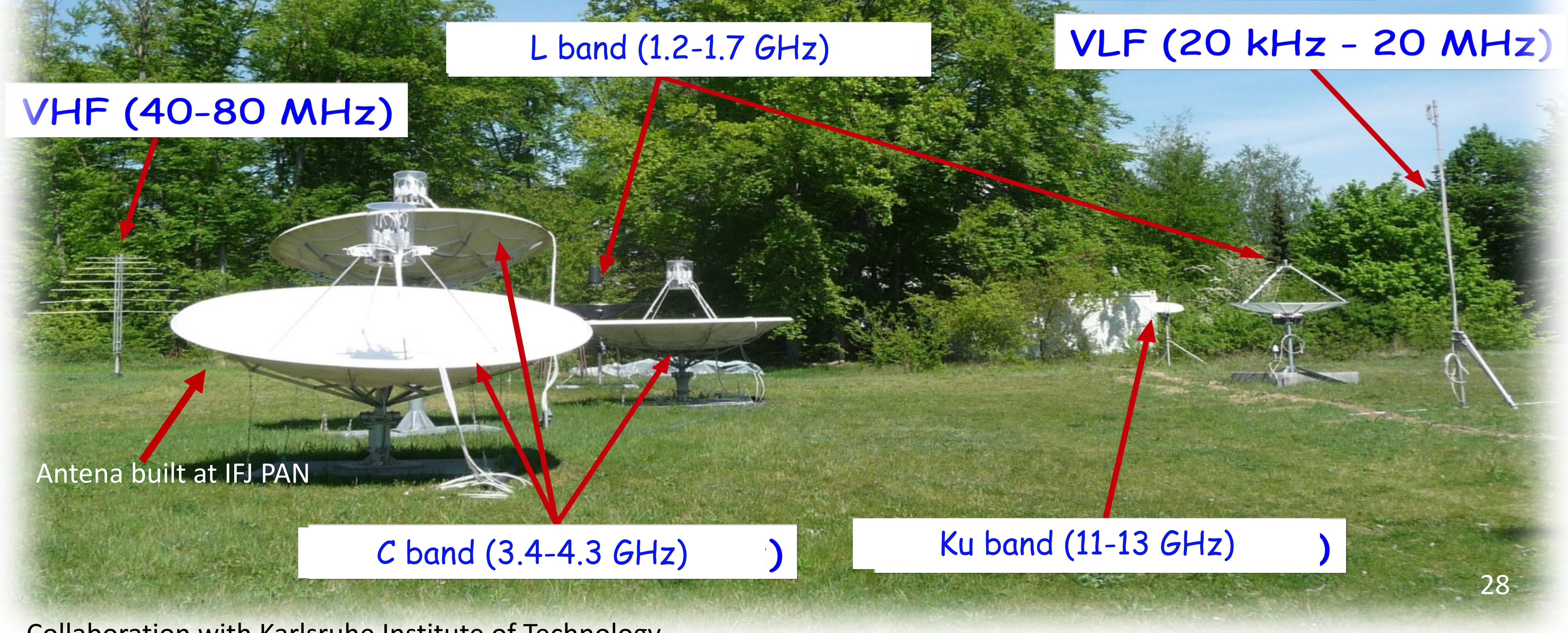
- Motivation: observation of microwave radiation (GHz frequency band) excited by a cascade of secondary particles in an air-filled chamber.
  Probable source: molecular bremsstrahlung (should be isotropic and unpolarized)

- **Perspective for a new air shower detection method (analogous to the fluorescence technique) with 100% duty cycle!**
  Advantages: 1) low background 2) almost perfect atmosphere transparency 3) available cheap, commercial low-noise receivers (satellite TV receivers)

Experiment CROME
Cosmic-Ray Observation via Microwave Emission

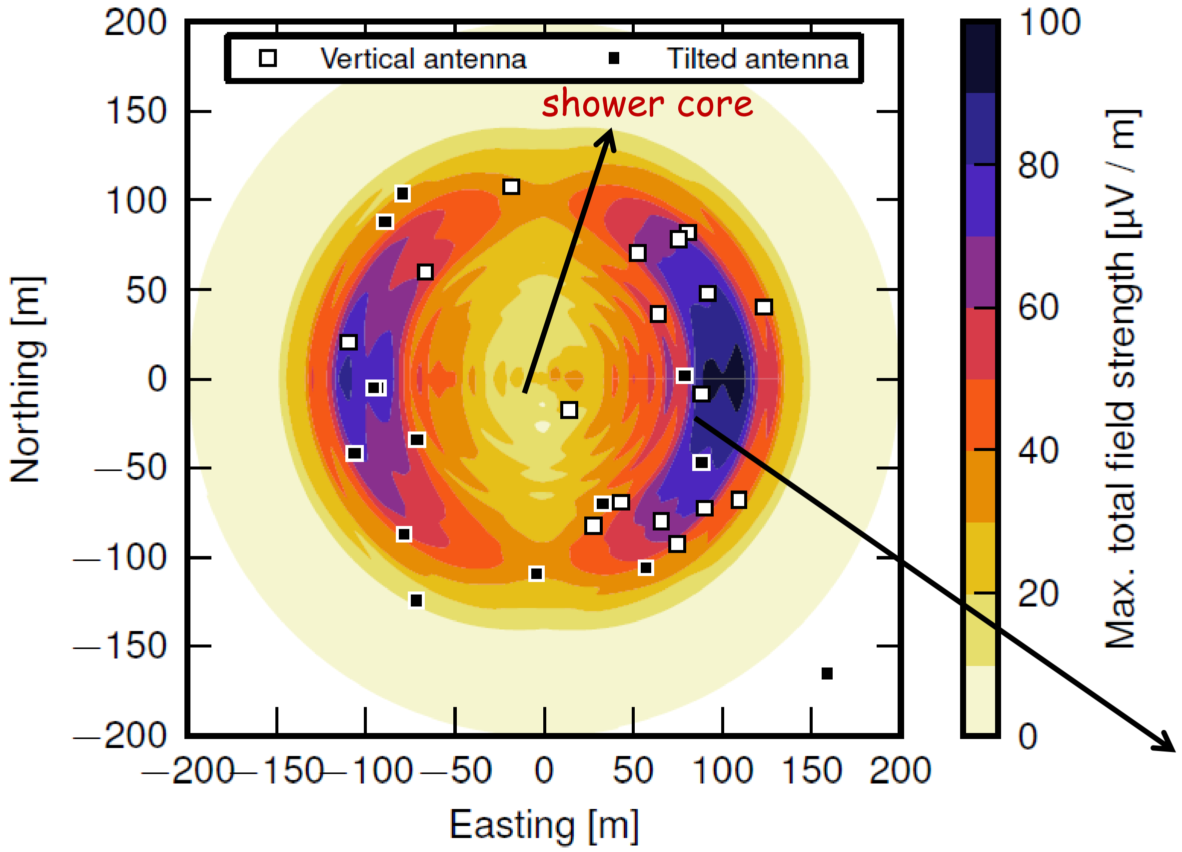
- ➢ detection in coincidence with KASCADE-Grande
- ➢ easier identification of the microwave signal

Octocopter used
to calibrate CROME detector



Collaboration with Karlsruhe Institute of Technology

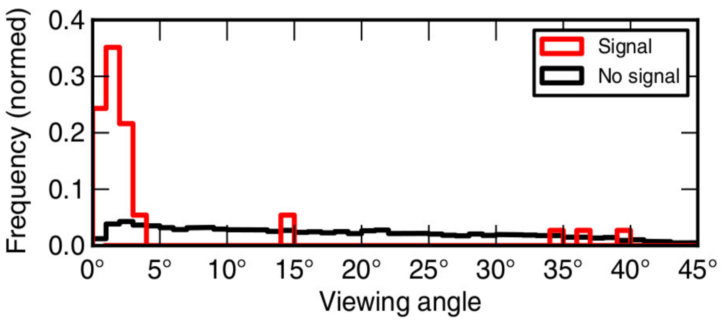
CROME results vs simulation of GHz radio emission of vertical shower



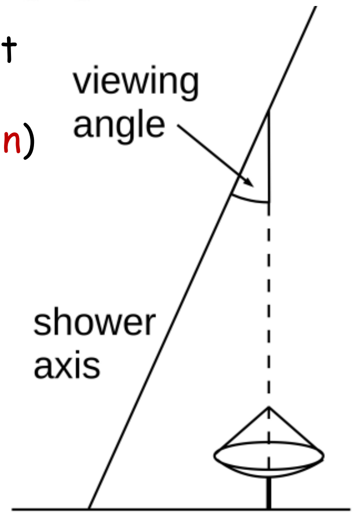
shower core

more events on the east side

Distribution of viewing angles



showers observed at Cherenkov angle (anisotropic emission)



- 37 showers detected in coincidence with KASCADE-Grande
- Both the structure of the Cherenkov-like ring and the east-west asymmetry observed in data are qualitatively well reproduced by the simulation of shower GHz radio emission
- The microwave signal is polarized. Polarization is consistent with the radio emission characteristics of showers.

Conclusions from the CROME observations

- **Microwave signal is the well-known MHz radio emission of shower, upshifted towards higher frequencies, close to the Cherenkov angle** (signal compressed in time due to geometry). The microwave emission is collimated in a cone about the Cherenkov angle.

- The CROME results are consistent with the lack of observation of the microwave signal by experiments dedicated to observe showers from a side (AMBER, MIDAS).

- The use of microwave technique for detection of UHECRs is impractical due to their very low flux and strong forward beaming of the microwave emission.

- Microwave technique seems to be an interesting alternative to the Cherenkov telescopes for air showers detection with energies above hundreds of TeV. Particularly, for inclined showers, where the footprint of the microwave signal extends over hundreds of meters.

Participation of the group from the IFJ PAN in the Pierre Auger experiment

The most important scientific outputs of these projects, under the leadership of Prof. Henryk Wilczyński, include:

- Description of fluorescence light distribution in an optical image of extensive air showers, Searching for neutrinos among high-energy cosmic rays, (Habilitation Dariusz Góra: Habilitation - 2010, Nataliia Borodai: PhD - 2013)
- Analysis of light scattering in the atmosphere and the resulting modification of the image of extensive air shower (Jan Pękala: MsC - 2001, PhD - 2007, Habilitation - 2017)
- Study of the impact of local changes in the Earth's atmosphere on the development of extensive air shower. The Earth's atmosphere is a key element of the system for detecting extremely high cosmic rays (Barbara Wilczyńska)

These improvements in the shower reconstruction procedure reduced the systematics uncertainty from 40% to 14%

- Analysis of the conversion of ultra-high energy photons in the geomagnetic field, leading to the formation of a cascade secondary particles before entering the atmosphere (the so-called preshower effect). Identification of photons among the highest energy cosmic ray particles (Piotr Homola: PhD - 2004, Habilitation - 2016)
- Development of microwave technology for extensive air showers and radar detection of extensive air showers (Jarosław Stasielak, Habilitation - 2020)

Piotr Homola
PhD 2004

Jan Pękala
PhD 2007

Nataliia Borodai

Dariusz Góra

Jarosław Stasielak

20th Anniversary of the Pierre Auger Observatory Scientists and guests from all over the world celebrated the 20th anniversary of the Pierre Auger Observatory in Malargüe, Argentina on November 14-16, 2019.


Parade in Malargue


Gaucho


Payún
VIAJES - EXCURSIONES


Payún

View on one of the largest flat areas in the world

Thanks of the Pierre Auger Collaboration to Henryk

(Auger Collaboration meeting September 2022)

Summary

- Prof. Henryk Wilczynski participated in leading or pionering cosmic rays experiments, which changed our knowledge about cosmic rays

- Group built in IFJ PAN under the leadership of Prof. Wilczyński is one of the most important in polish cosmic ray community

- Promotion of many scientific careers

…and this is not the end of the story, Prof. Henryk Wilczyński will still work with us

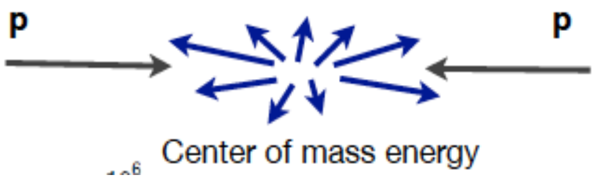
Extensive air showers

- **Different phase space for LHC and air showers:**

  EAS: most of the particles produced at midrapidity
  EAS: $N_{particle} \sim E$, most of energy carried by forward (backward) particles

- More LHC data needed in the forward directions and for heavier targets to fill required phase-space for EAS

LHC:



EAS:

$\eta \equiv -\ln(\tan(\theta/2))$

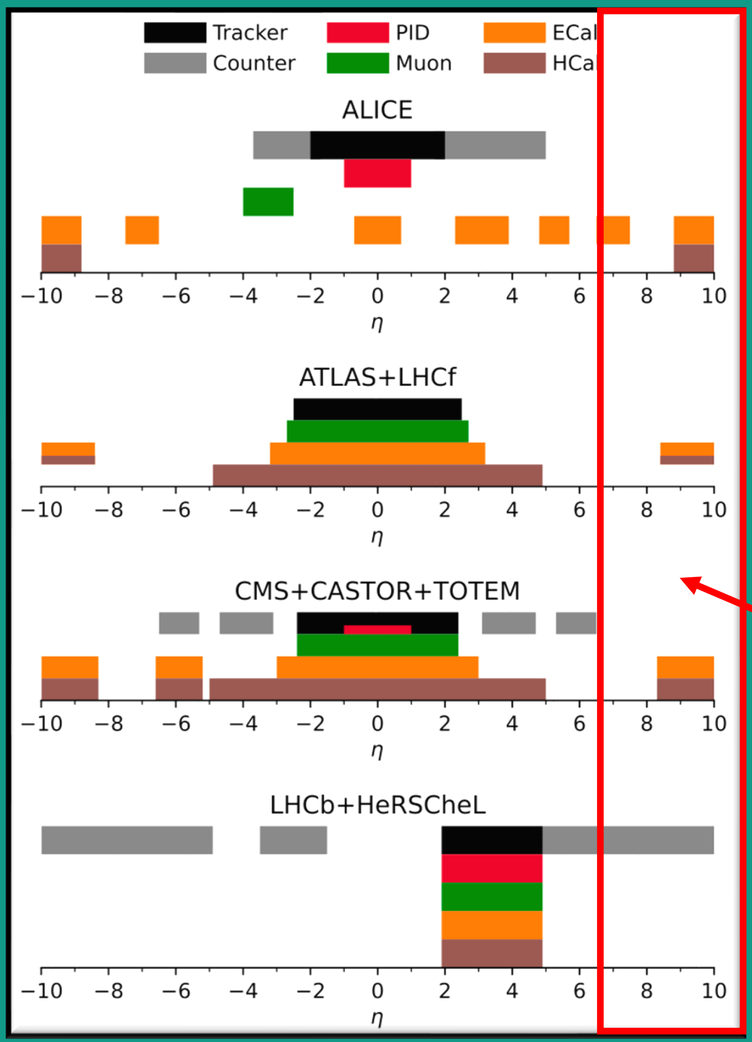
$\eta \gg 1$ is forward

$\eta = 0$ ($\theta = 90$) is midrapdity

$\eta \ll 1$ is backward

LHC acceptance and phase space

p-p data mainly from "central" detectors $|\eta| < 2.5$



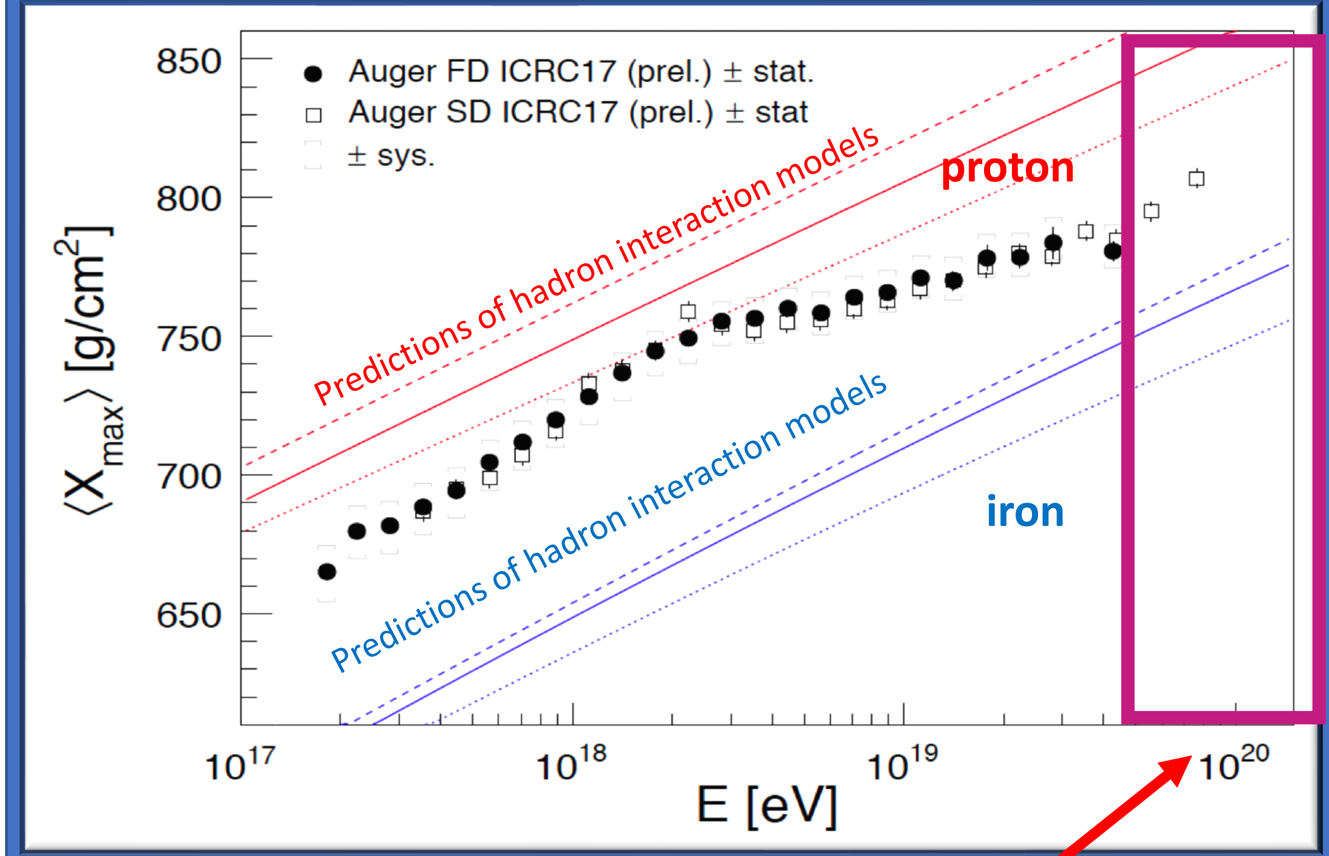
EAS

Albrecht, Johannes, et al. "The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider." *arXiv preprint arXiv:2105.06148* (2021)

Xmax distributions from the fluorescence detector

- Measurements X_{max} and fluctuations $\sigma(X_{max})$ suggest a change in composition to heavier particles above $3 \cdot 10^{18}$ eV, more likely scenario (A)

$\langle X_{max} \rangle$



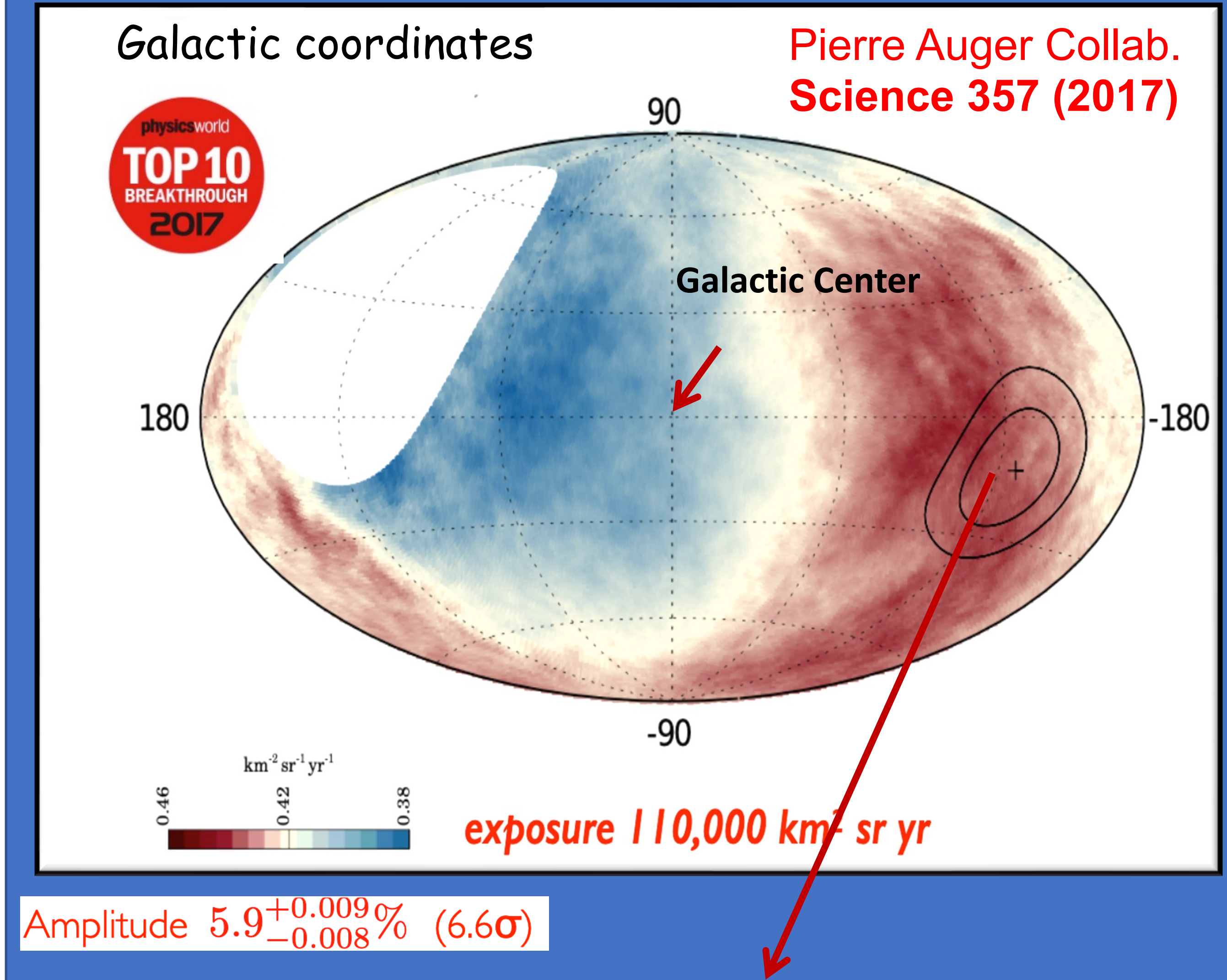
... but the lack of mass data in terms of the observed truncation in the spectrum of cosmic rays (the need to increase statistics in this area)

Observation of dipolar anisotropy above 8 EeV (Auger-SD)

- Large-scale anisotropy can result from: diffusion of cosmic rays in extragalactic magnetic fields even from nearby sources

- Determining the origin of cosmic rays is a difficult task because they are deflected as they propagate through intergalactic magnetic fieldsand the range of this angular deflection is of the order of several degrees

Rozkład kierunków



Pierre Auger Collab.
Science 357 (2017)

Amplitude $5.9^{+0.009}_{-0.008}\%$ (6.6σ)

Observed dipole ~120° from the Galactic Center
-> cosmic rays (>8•1018 eV) come from outside our galaxy

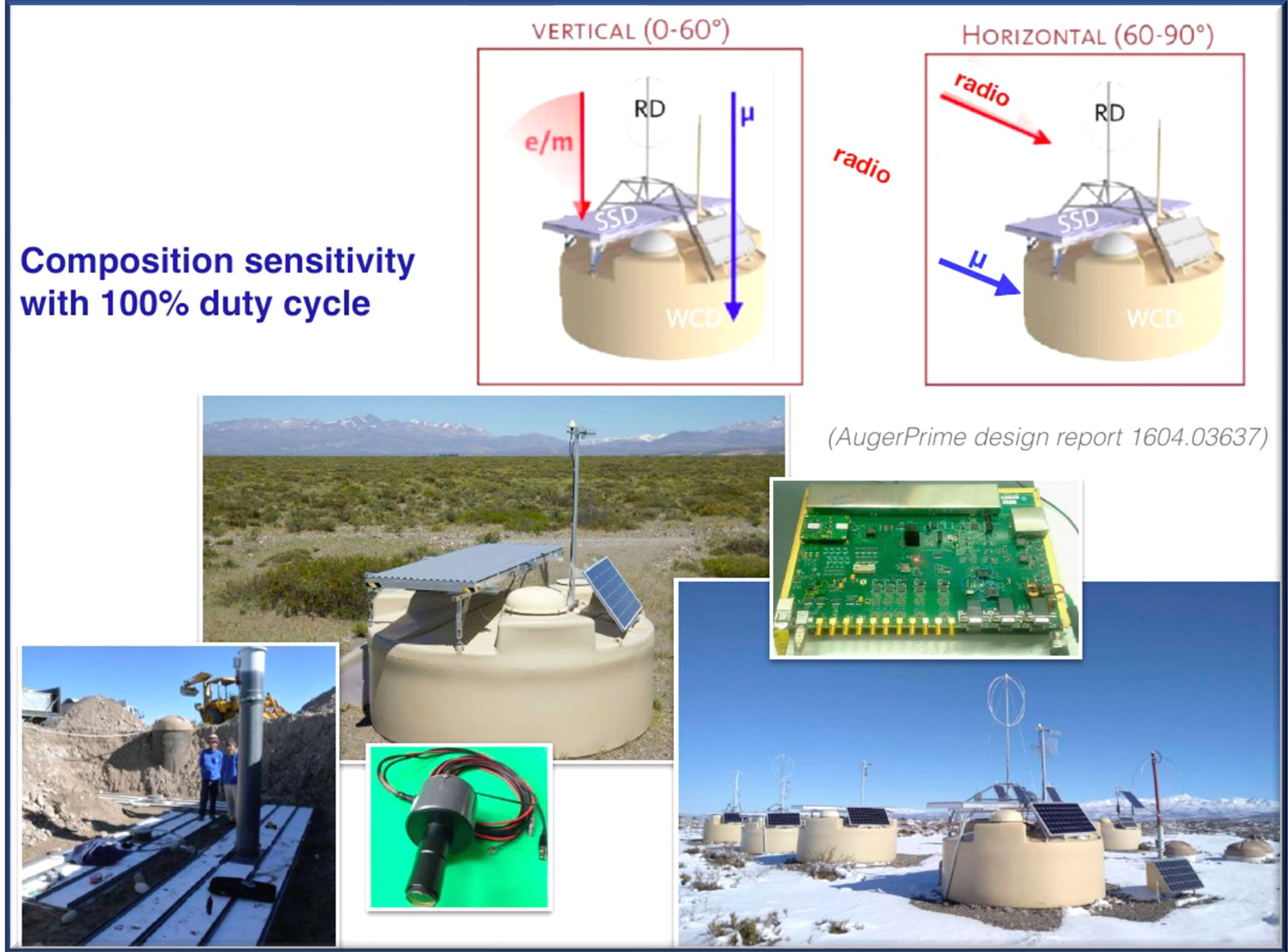
Detector upgrade: AugerPrime

- Motivation for modernization and main objectives:
  - measurement of composition to highest energies
  - composition of events after the event, particle astronomy?
  - testing of hadron interactions
  - reapplying new analyses to old data

- **Hardware changes**
  - additional scintillators
  - new electronics
  - small PMT
  - radio antennas
  - underground muon counters
  - extended FD duty cycle

AugerPrime – modernization of about 1600 detectors of the Cherenkov Observatory, modernized detectors will be operated at least until 2030.

Detector upgrade: adding a scintillation detector and radio antenna to the existing Cherenkov water detector



(AugerPrime design report 1604.03637)

AugerPrime TDR, arXiv:1604.03637

Muon studies with hybrid events (<60°)

- Idea: compare hybrid data with simulated showers
  match longitudinal FD light profile data
  with best simulation profile (p, He, N, Fe)

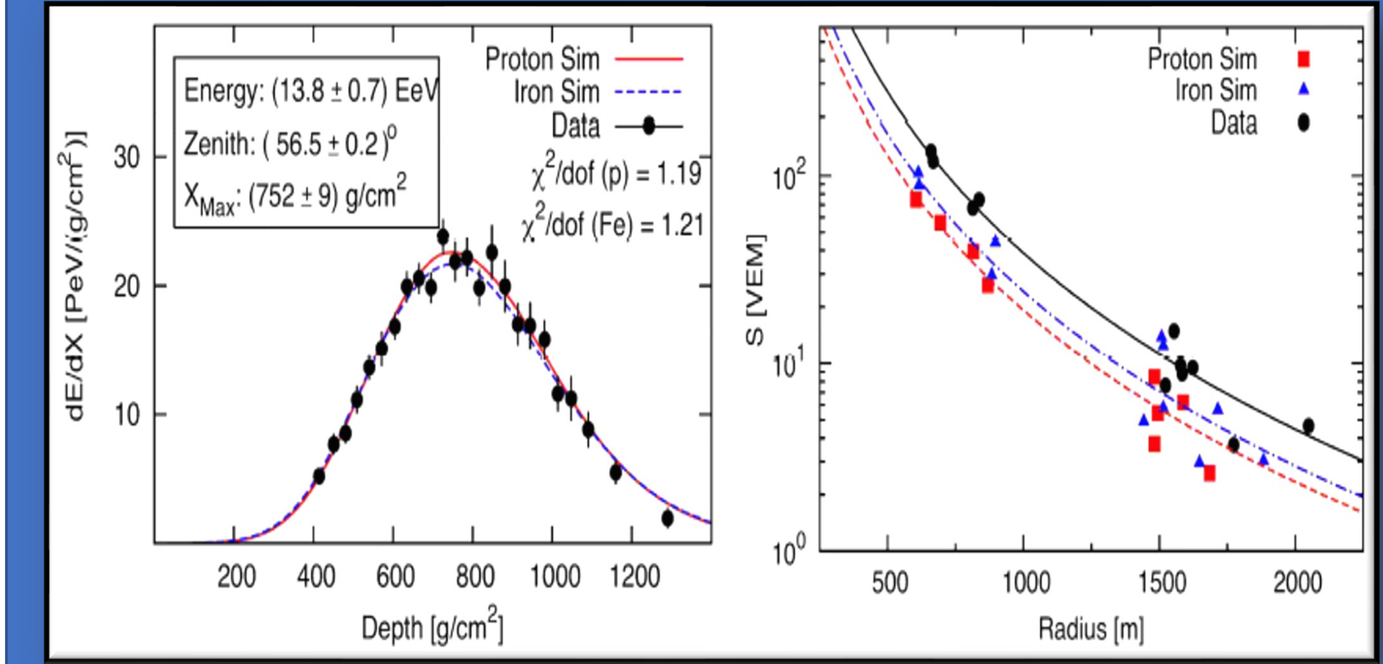
$$S_{\mathrm{resc}} = R_E\, S_{\mathrm{EM}} + R_{\mathrm{had}}\, R_E^{\alpha}\, S_{\mathrm{had}}$$

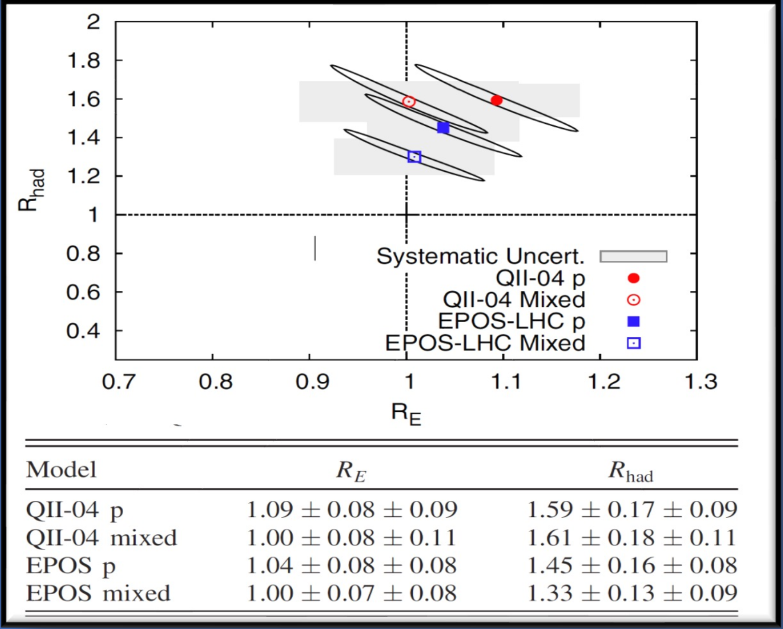
$$\alpha \simeq 0.9$$

$$R_\mu \approx 0.93\, R_E^{0.9}\, R_{\mathrm{had}} + 0.07\, R_E$$

extract S_{EM} and S_{had} from simulation
rescale simulated SD signal to match data
(extract R_E and R_{had})

- The observed muon signal is a factor 1.33 (EPOS-LHC) to 1.61 (QGSJET-II.04) larger than predicted by models





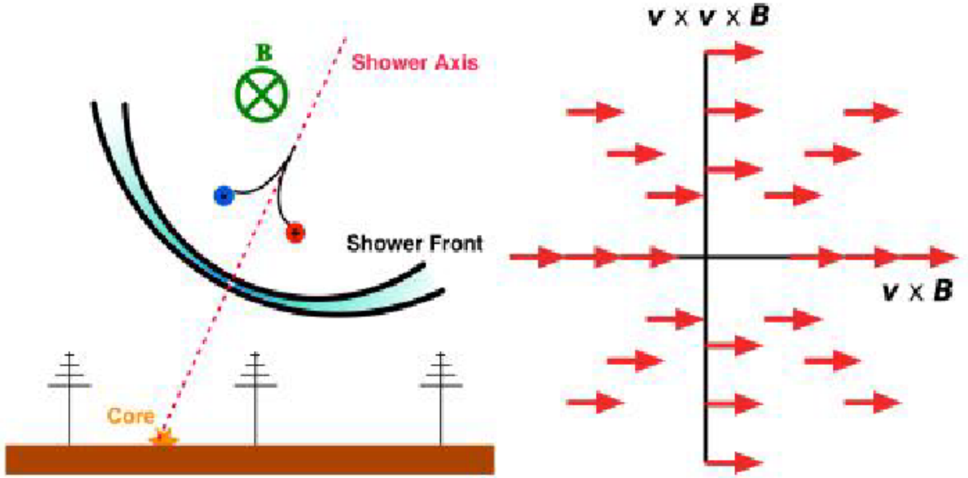
Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

Pierre Auger Collaboration, Phys. Rev. Lett. 117, 0192001 (2016)

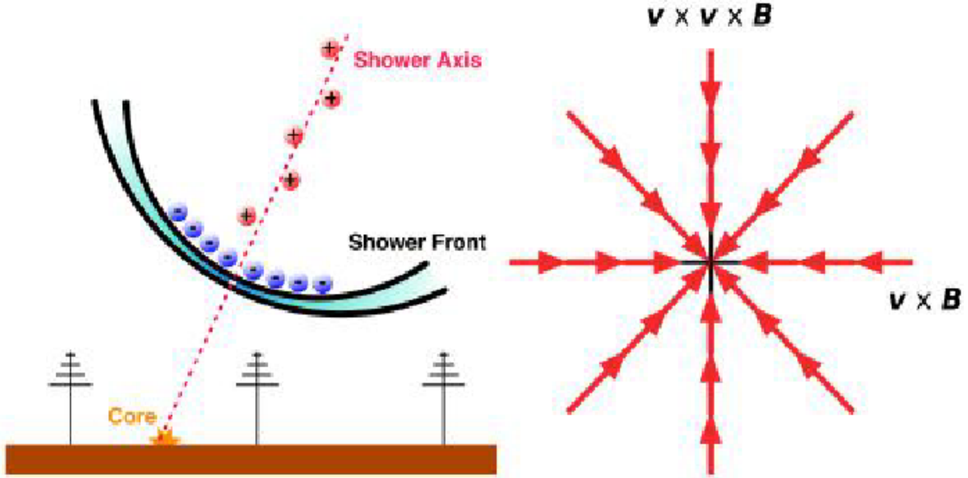
Radio emission of EAS

Mechanisms of air shower radio emission

- **Geomagnetic effect (main contribution, linearly polarized)**
  geomagnetic field deflects e^- and e^+ in the opposite directions
  ⬇
  transverse current varying over time



- **Askaryan effect (typical contribution ~10%, radially polarized):**
  e^+ annihilation in the shower front
  ⬇
  time variation of e^- excess



polarization in the plane perpendicular to the shower axis

Radio signal is a short pulse (~ 100ns). Signal compression in time (geometric effect) leads to its amplification in the forward direction.