The Pierre Auger Observatory: a review of recent results and prospects

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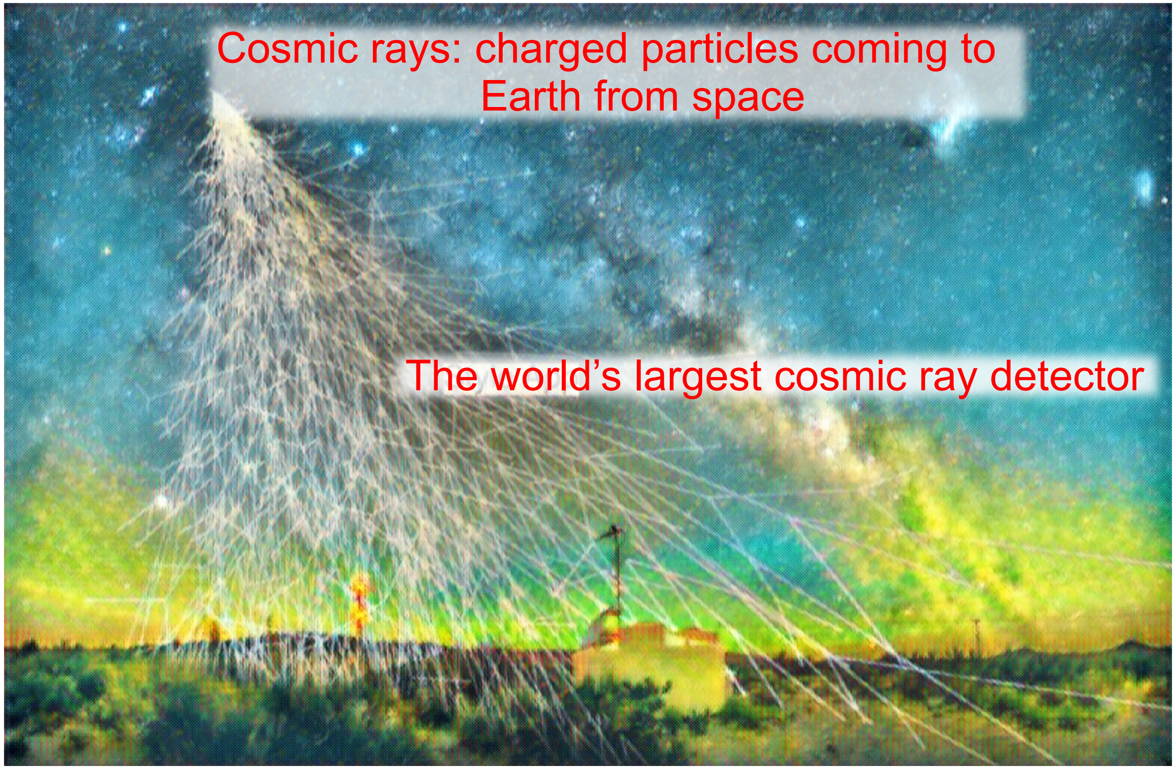


Cosmic rays: charged particles coming to Earth from space

The world's largest cosmic ray detector

Outline:

- ❖ Introduction
- ❖ Pierre Auger Observatory
- ❖ Results (spectrum, anisotropy, mass composition.
- ❖ AugerPrime and Summary

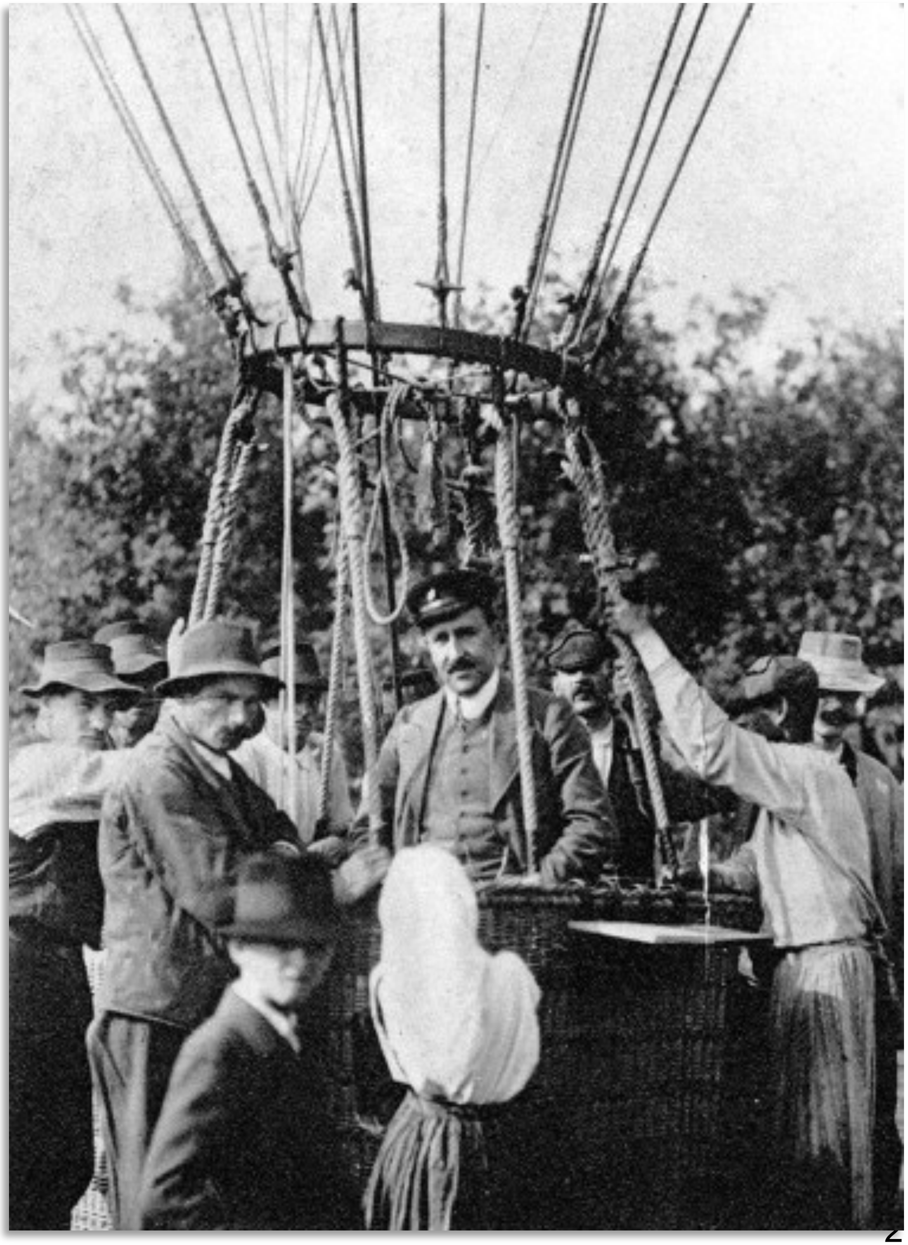
Questions for PhD students exam:

1. *Cosmic ray studies at the Pierre Auger Observatory*
2. *Air shower and its connections to hadronic interactions*

The Ultra-High-Energy Cosmic Rays

1912: Discovery of ionizing radiation of cosmic origin by Victor Hess

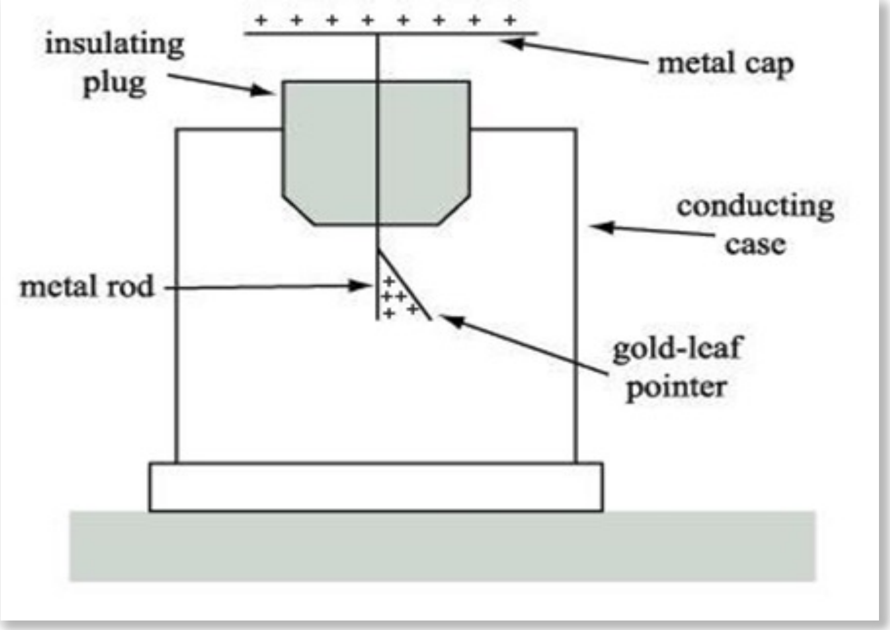
- **charged particles (mainly proton)**
- It increases as the balloon gains altitude
- The background radiation is of **cosmic origin!**

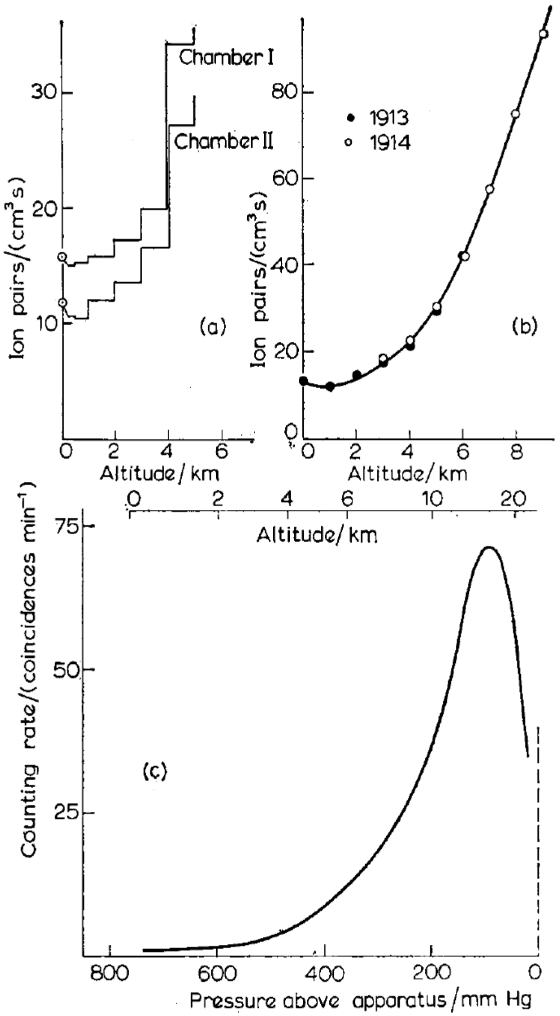


A brief history of cosmic rays

- **Beginning** of the *XX*th century: electroscopes are used to measure the radioactivity of materials.
- Discharge of electroscopes in the absence of any ionizing source → **existence of background radiation!**

  What is its nature ?

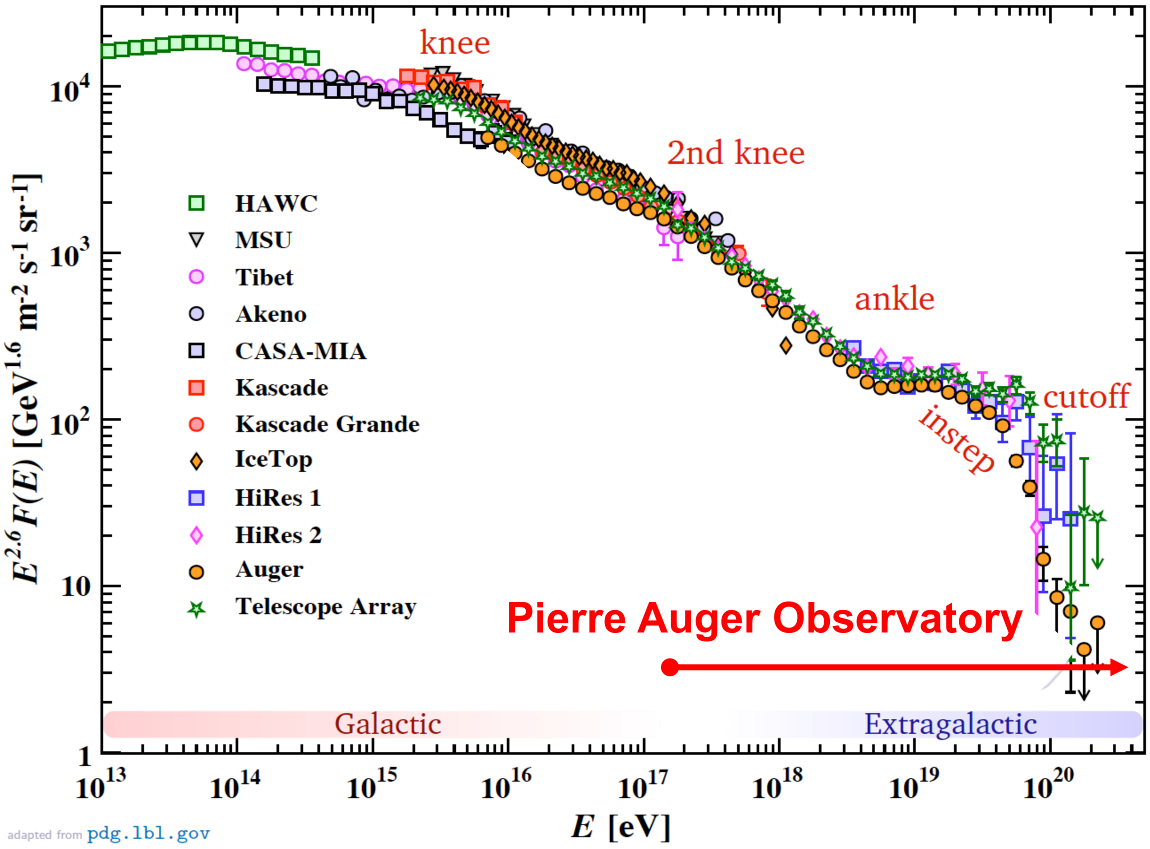




Altitude variation of ionization. (*a*) Balloon ascent by Hess (1912) carrying two ion chambers. (*b*) Ascents by Kolhörster (1913, 1914) using ion chambers. (*c*) Coincidence counter telescope flown by Pfotzer (1936).

Energy range of the Pierre Auger Observatory

Central objective (since 1912): find cosmic-ray sources



adapted from `pdg.lbl.gov`

Active Galactic Nuclei (AGNs)

Nustar-Caltech (NASA)

Starburst Galaxies

Nustar-Caltech (NASA)

Essential inputs:

- Anisotropies in arrival directions
- Features of the energy spectrum
- Mass composition
- or simply detect photons and/or neutrinos

Pierre Auger Collaboration

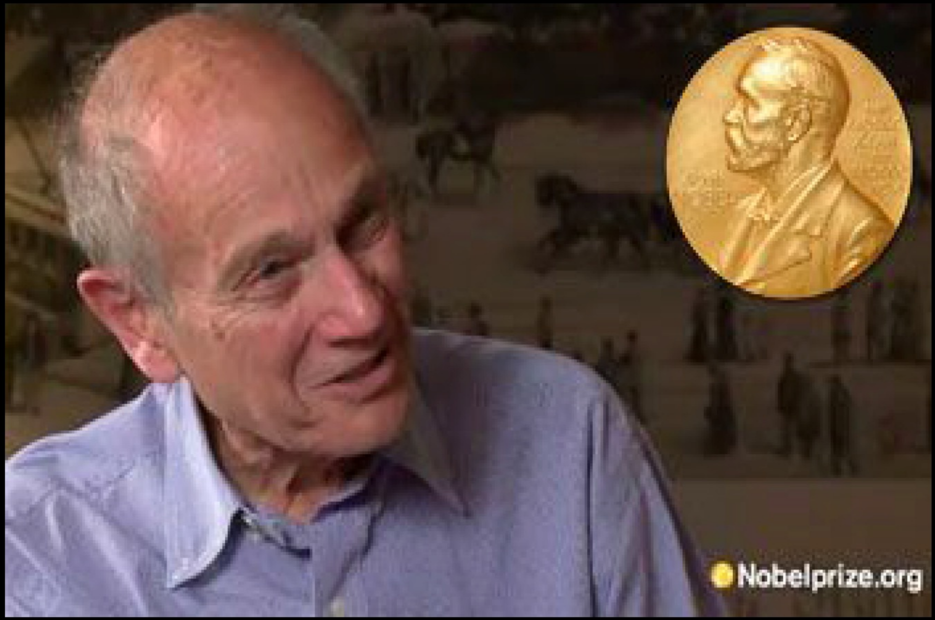
❖ **1991:** a proposal to build the Pierre Auger Observatory (James Cronin and Alan Watson),

International cooperation:

Currently:

16 countries,
98 institutions,
400+members

Alan Watson



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

Pierre Auger Collaboration

around 500 members from 18 countries

- Argentina
- Australia
- Belgium
- Brazil
- Colombia
- Czech Republic
- France
- Germany
- Italy
- Mexico
- Netherlands
- Peru
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- USA

located near Malargue, Argentina

Pierre Auger Observatory: hybrid detector

Fluorescence detector (FD)

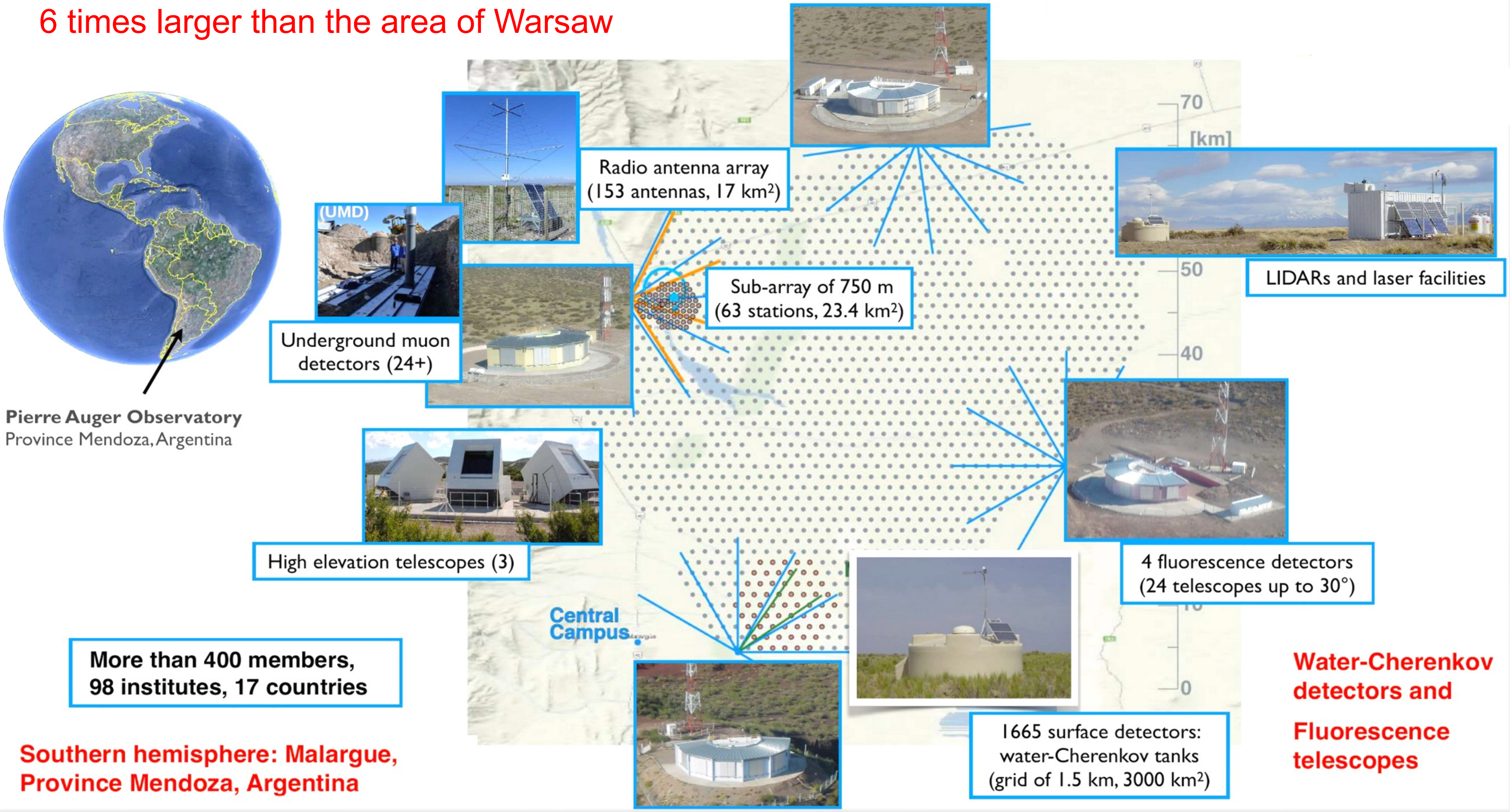
duty cycle 15%

24 + 3 fluorescence telescopes

Surface detector (SD)

duty cycle 100%

1660 water-Cherenkov detectors



6 times larger than the area of Warsaw

Pierre Auger Observatory
Province Mendoza, Argentina

Radio antenna array
(153 antennas, 17 km²)

(UMD)

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

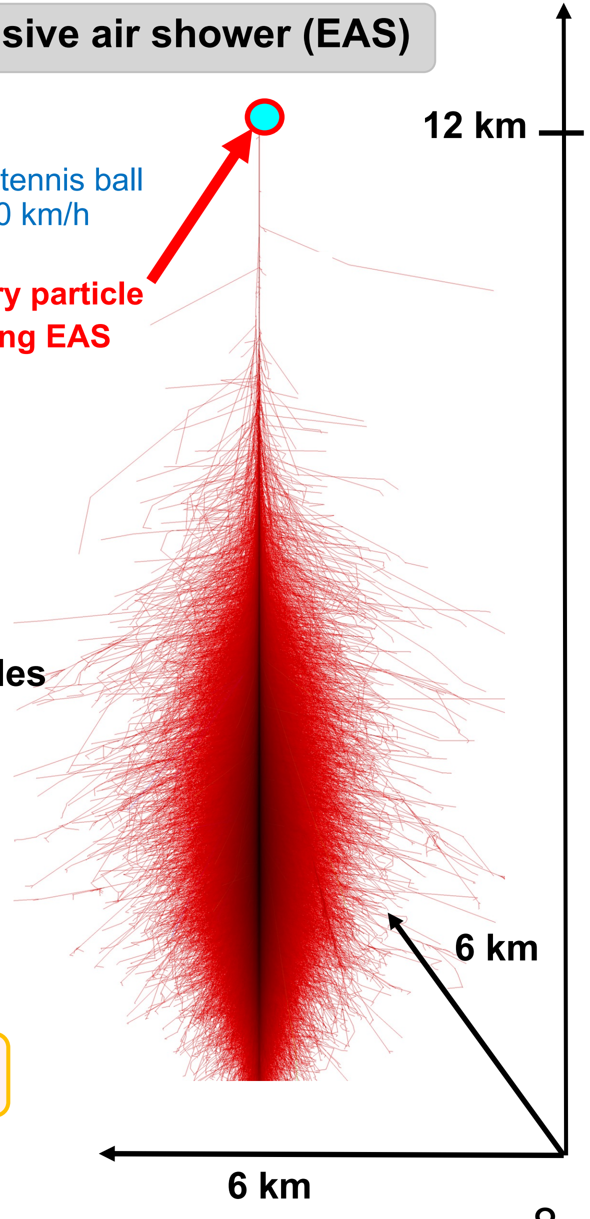
Highest energy cosmic rays > 10^{18} eV (UHECRs)

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

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

Extensive air shower (EAS)

EAS with 10^{20} eV:
kinetic energy of a tennis ball speeding about 100 km/h



Primary particle initiating EAS

Shower particles

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

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

Extensive air showers

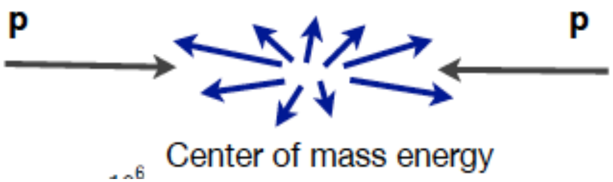
- **Different phase space for LHC and air showers:**

  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:

$\eta \gg 1$ is forward

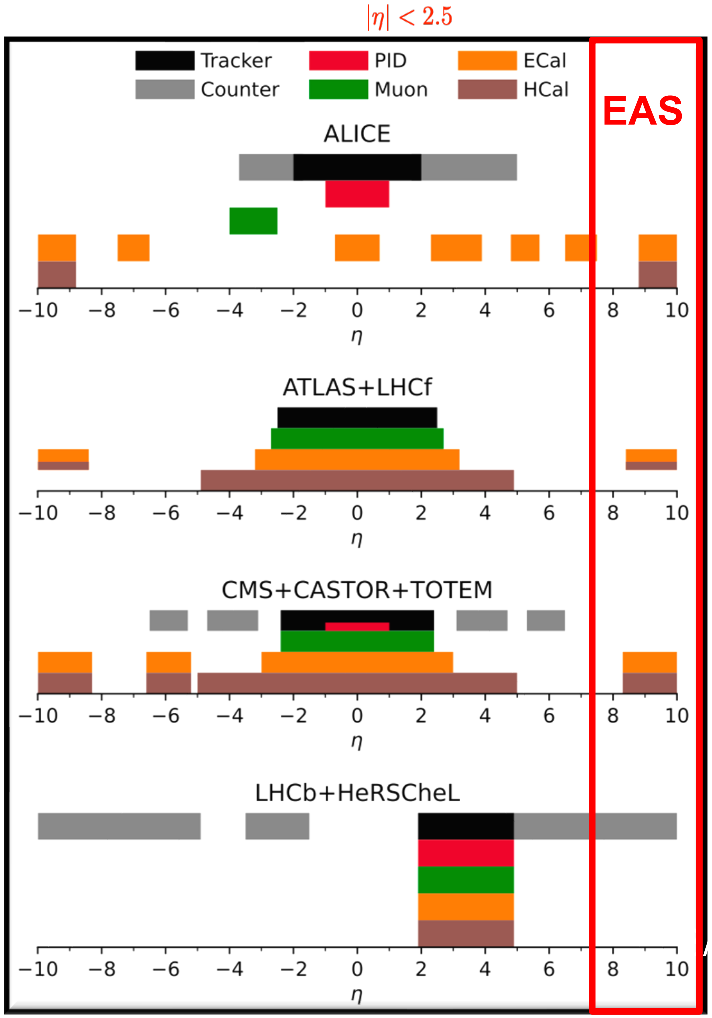
$\eta \ll 1$ is backward

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

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

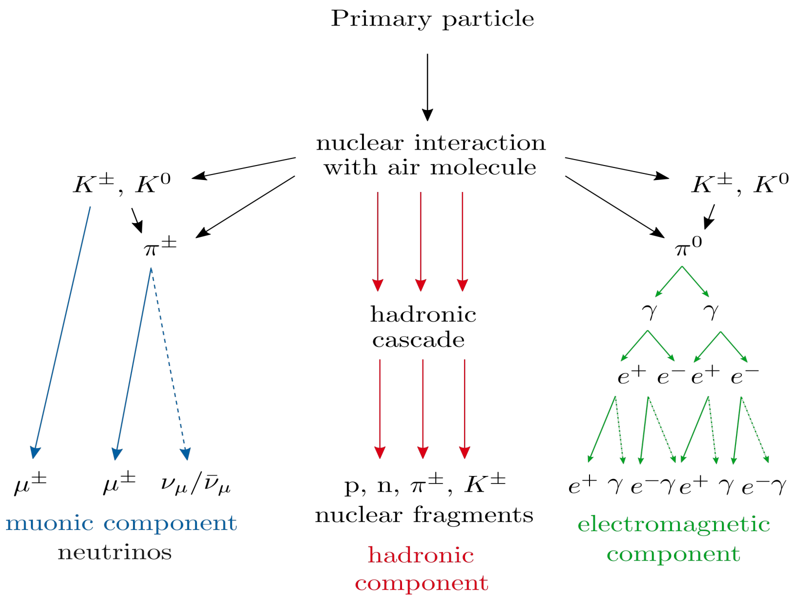
LHC acceptance and phase space

p-p data mainly from “central” detectors



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)

Air shower connetions to hadronic interactions



- **Electromagnetic part (EM)**: well understood

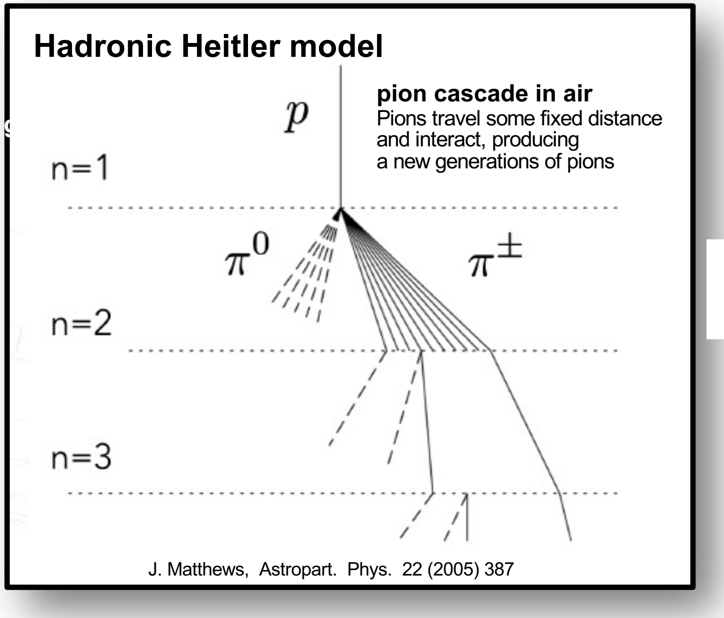
EM cascade takes **more than 50%** of energy from **1st, 2nd and 3rd** hadronic generations

$$\pi^0 \rightarrow \gamma\gamma$$

Sensitive to High Energy Physics

Hadronic cascade:

Keeps developing until critical energy of meso$\xi_c^{\pi^\pm}$



Hadronic Heitler model

pion cascade in air
Pions travel some fixed distance and interact, producing a new generations of pions

J. Matthews, Astropart. Phys. 22 (2005) 387

$$\pi^\pm \rightarrow \mu\nu_\mu$$

- **Muon part**: have large model uncertainties

Muon number

Measured observables: $\mathbf{N}_\mu \propto \mathbf{A}\mathbf{E}^\beta/(\mathbf{A}\xi_{\mathbf{c}}^{\pi^\pm})^\beta$

Muon number via parameter β depends on multiplicity, pion charge-ratio, and (in)elasticity, connection between air shower physics and hadronic interaction models

Sensitive to High & Low Energy Physics

Hadronic interactions models

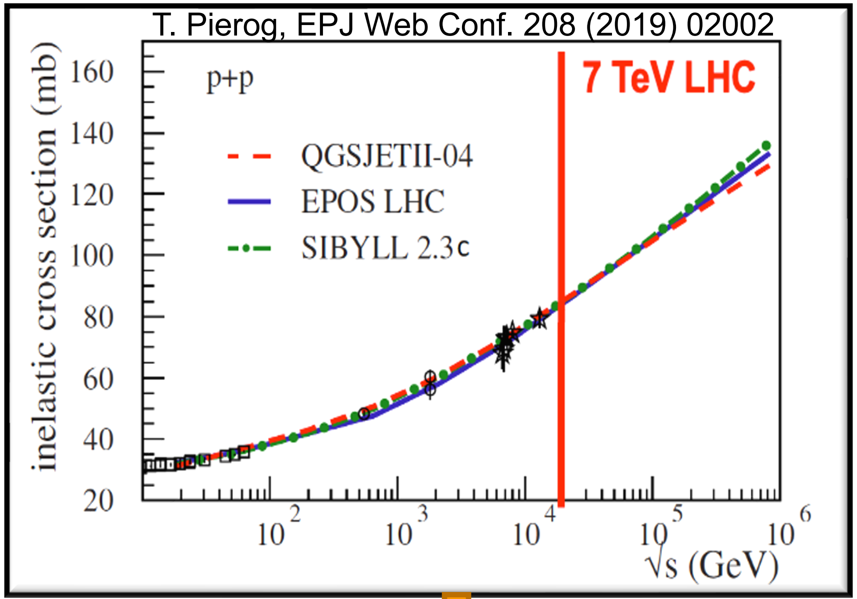
- ❖ Hadronic interaction models commonly used to simulate EAS were updated to take into account LHC data at 7 TeV:

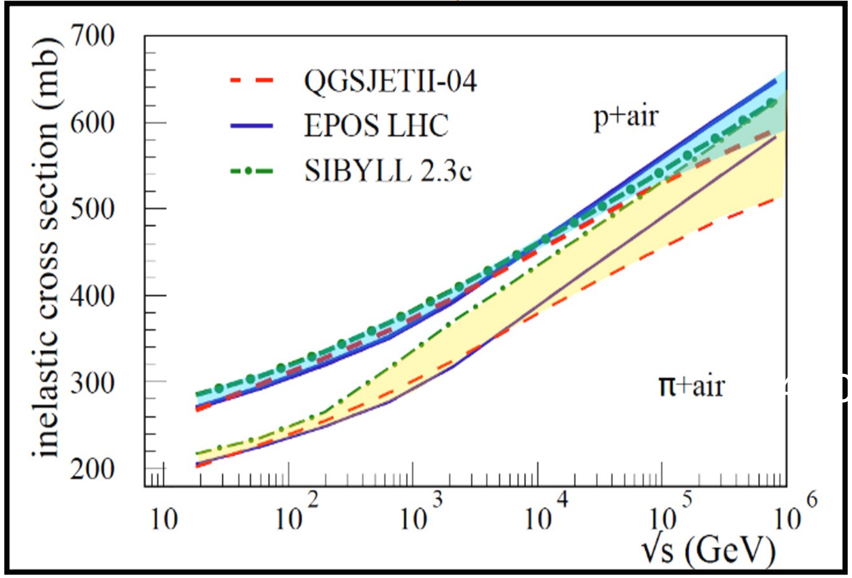
  QGSJETII-04: Phys. Rev. D 83, 014018
  EPOS-LHC: Phys. Rev. C 92, 034906
  SIBYLL-2.3c: Phys. Rev. D 80, 094003
  ….

- ❖ The p-p cross section is very well described up to the LHC energy (extrapolation up to the highest energies is very similar between models)

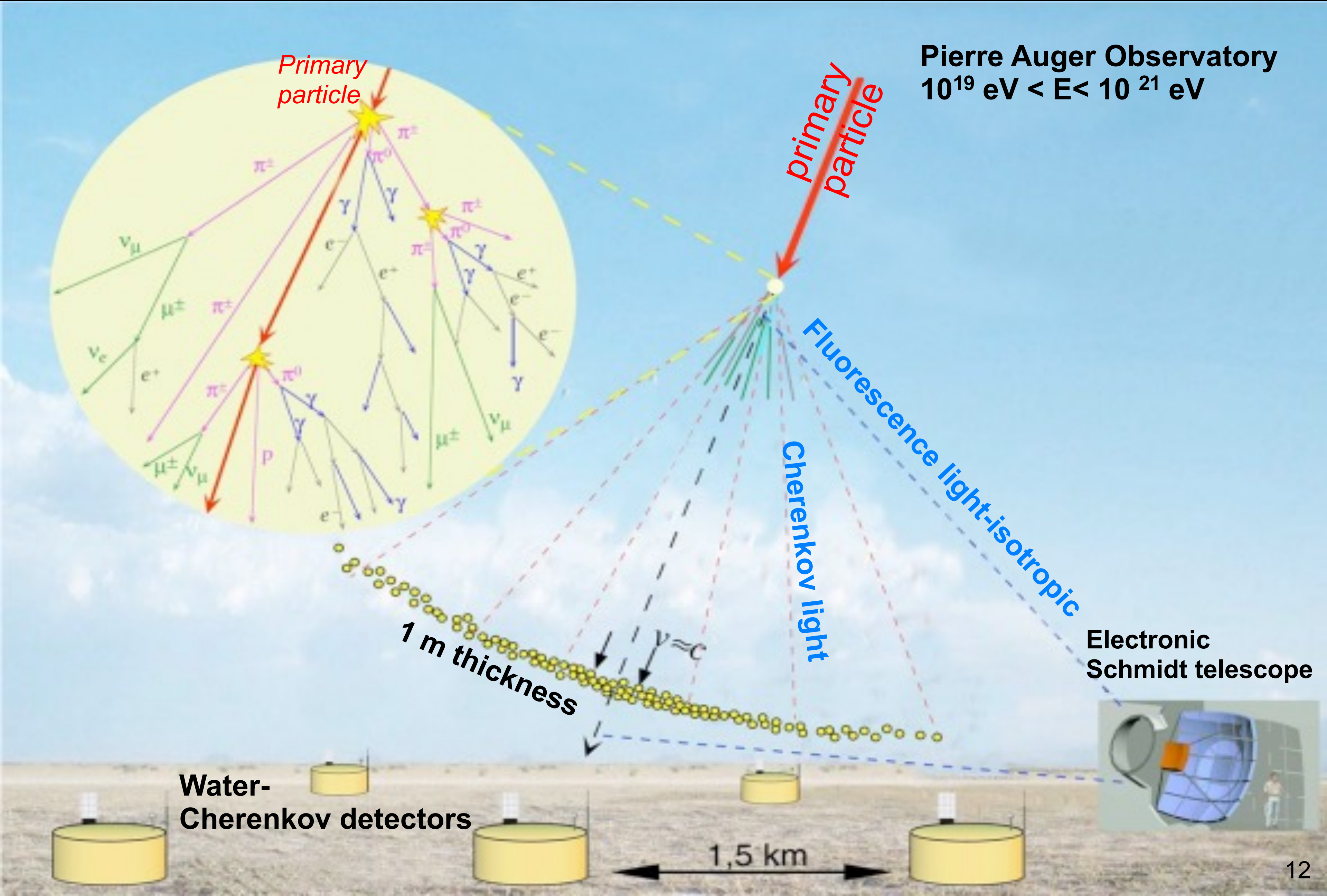
  … but differences in the extrapolations of the p-air and π-air inelastic cross-sections

- ❖ More LHC data needed in the forward directions and for heavier targets


T. Pierog, EPJ Web Conf. 208 (2019) 02002



Extended air showers



Pierre Auger Observatory
10^{19} eV < E< 10^{21} eV

Primary particle

primary particle

Fluorescence light-isotropic

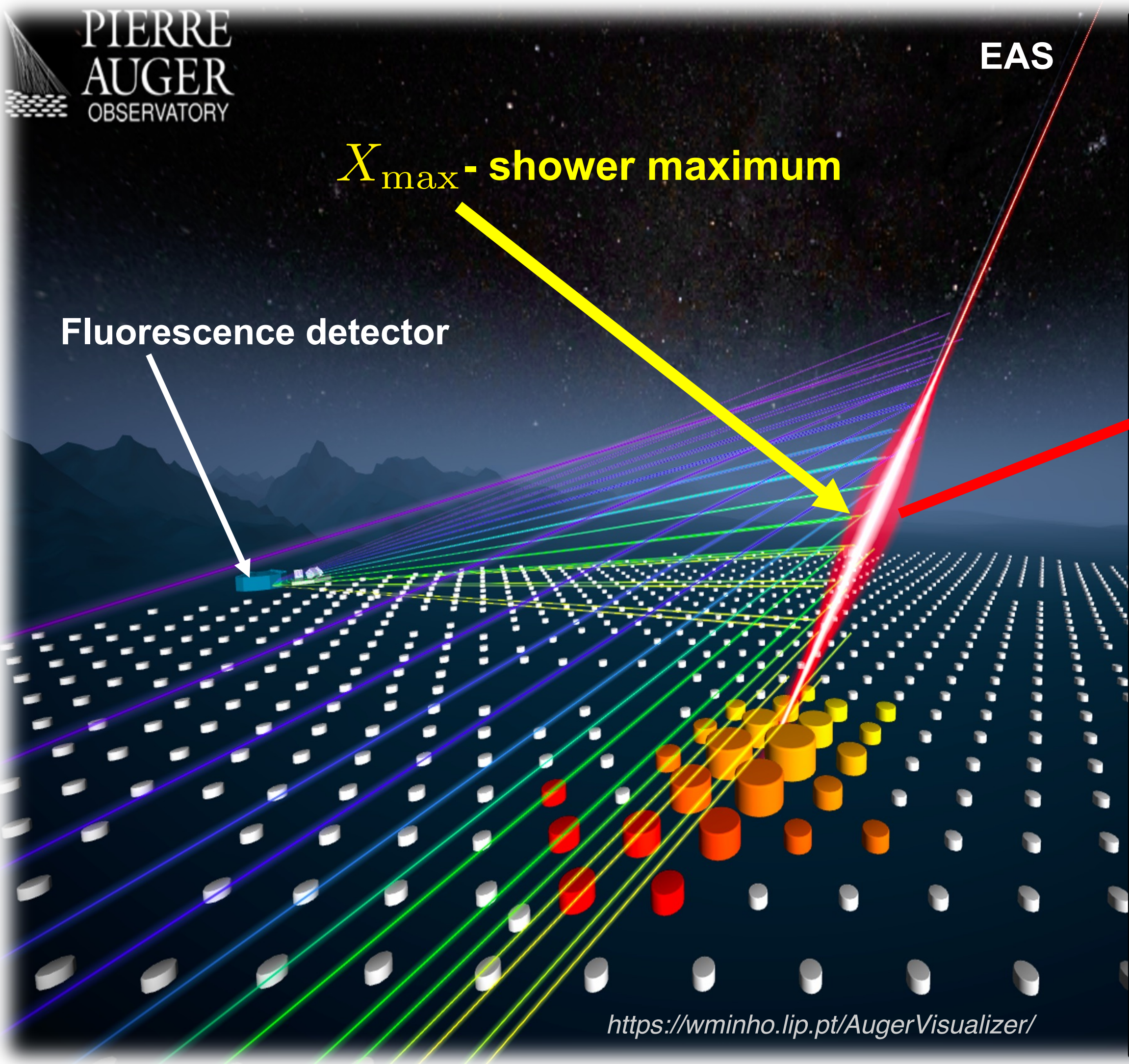
Cherenkov light

1 m thickness

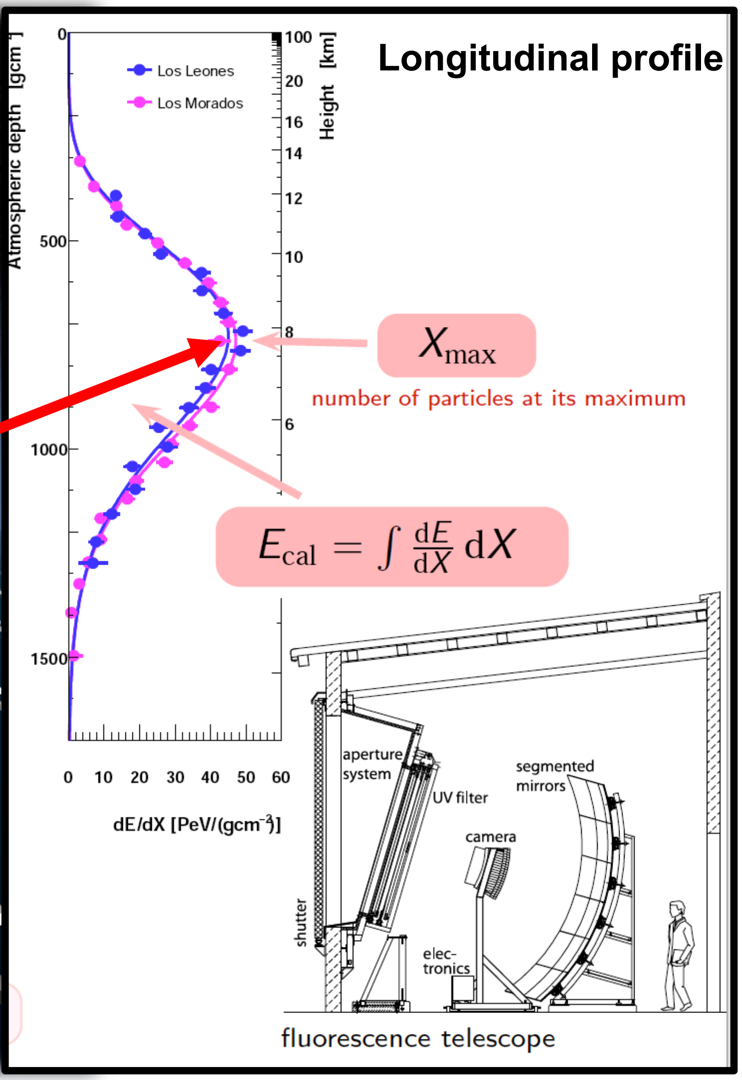
Electronic Schmidt telescope

Water-Cherenkov detectors

Energy estimation: use atmosphere as a calorimeter



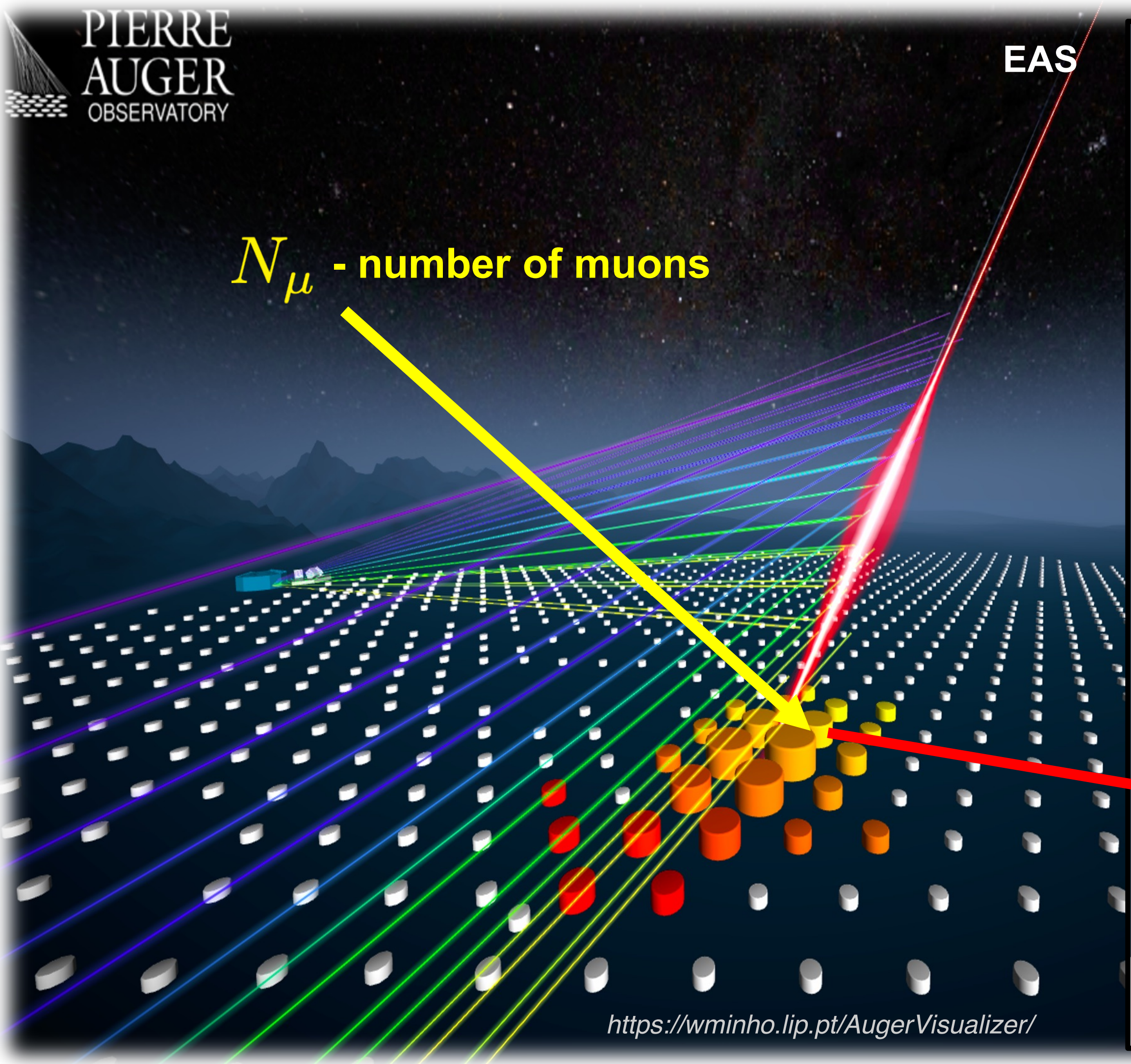
https://wminho.lip.pt/AugerVisualizer/



$$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$

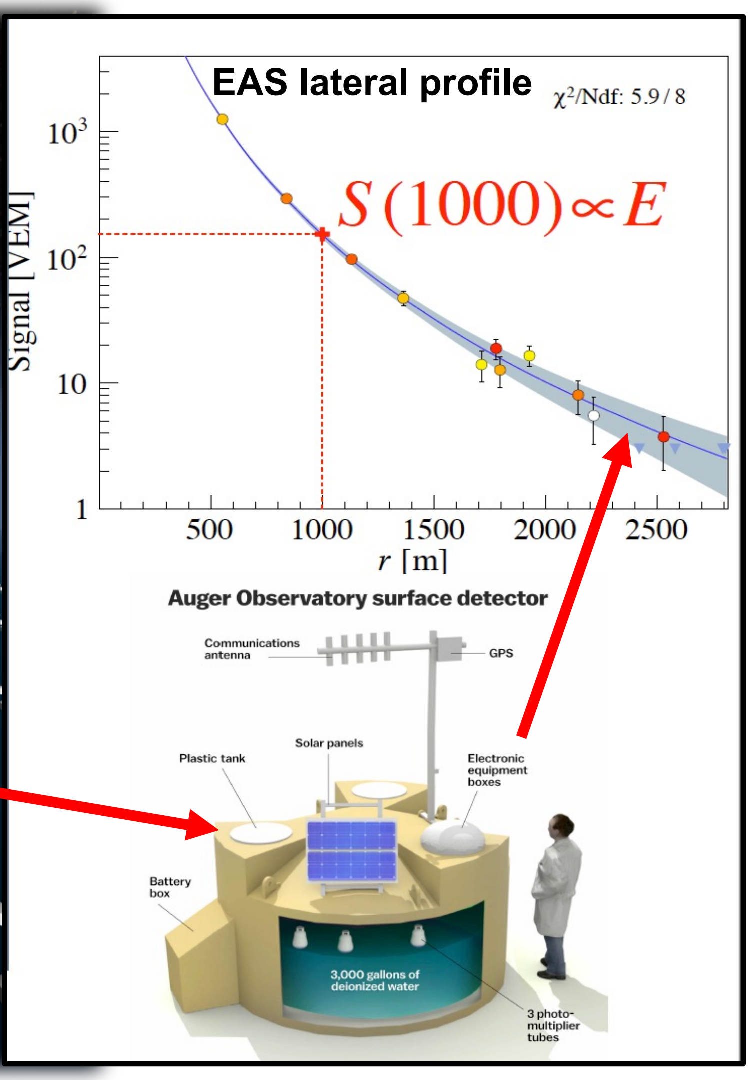
Measure longitudinal energy deposit via detection of fluorescence light

Energy estimation: use particles reaching ground (shower tail)



N_μ - number of muons

https://wminho.lip.pt/AugerVisualizer/



Measure lateral energy deposit of particles hitting surface detectors

Best mass composition parameters: **number of muons and X_{max}**

Difference proton – iron

- in depth where the number of shower particles is at maximum

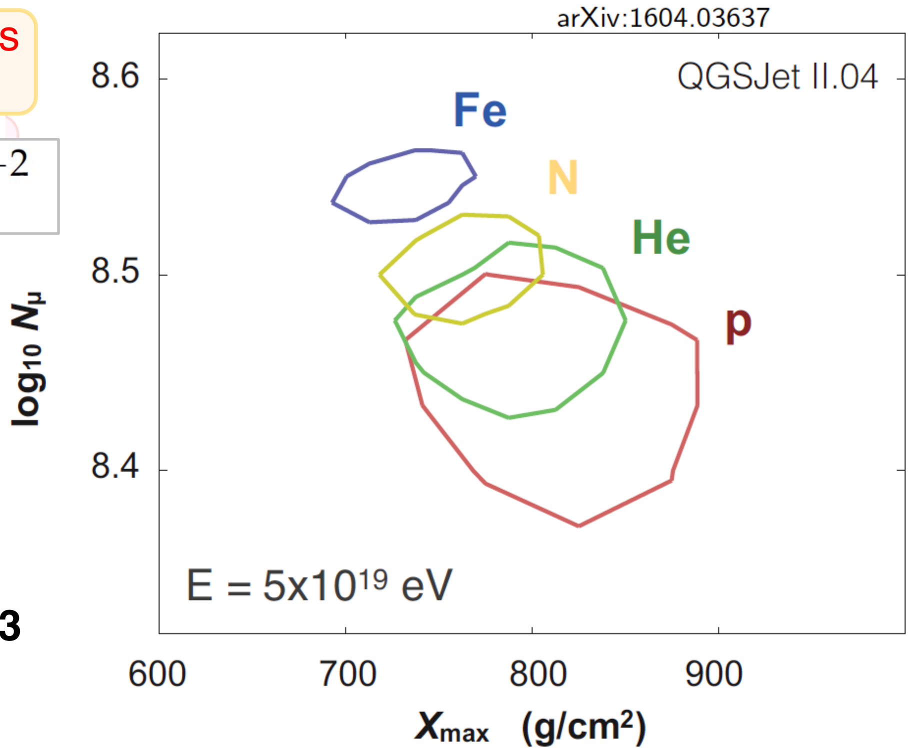
$$\langle X_{\max}^{p}\rangle - \langle X_{\max}^{\mathrm{Fe}}\rangle \approx (80 - 100)\ \mathrm{g\,cm^{-2}}$$

- in number of muons reaching the ground

$$\langle N_{\mu}^{\mathrm{Fe}}\rangle / \langle N_{\mu}^{p}\rangle \approx (1.3 - 1.4)$$

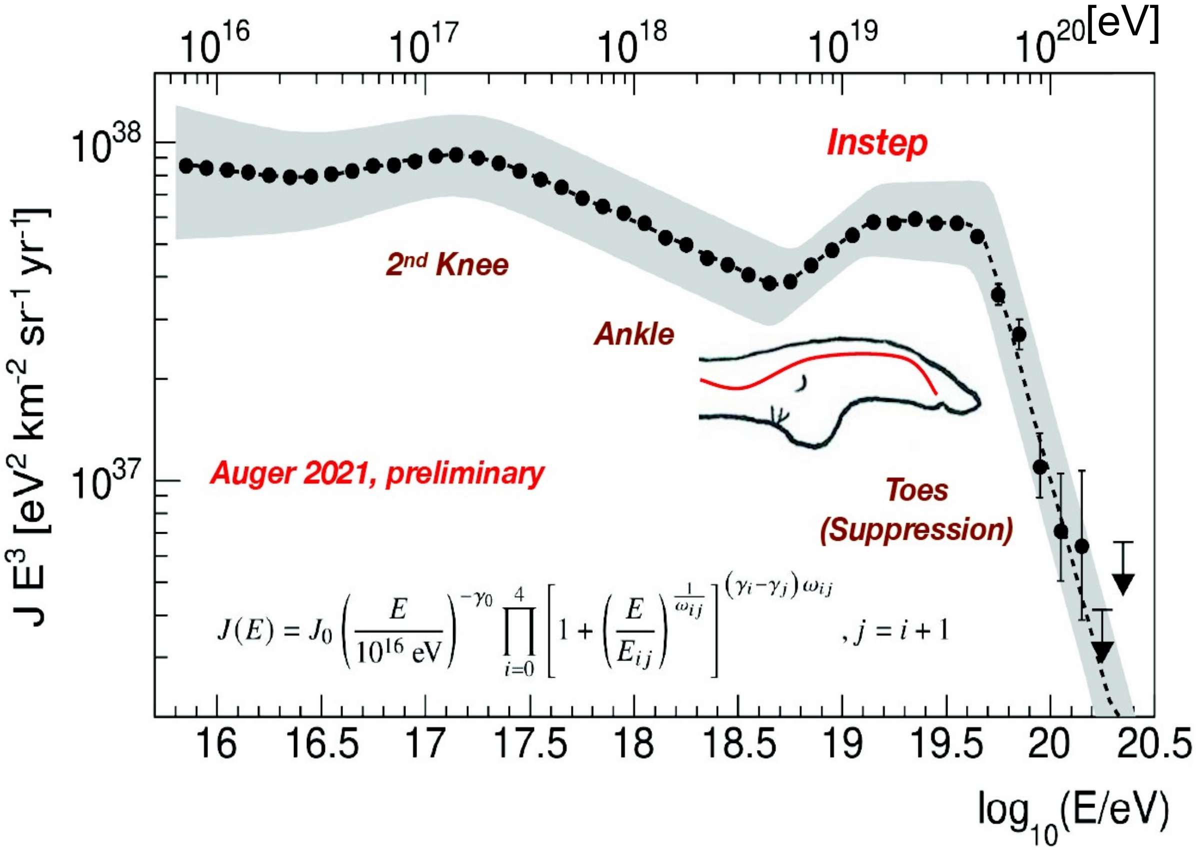
- In fluctuations of both parameters

shower-to-shower fluctuations **proton/iron** **≈ 3**



Energy spectrum

4 spectral features: 2nd knee, ankle, instep, suppresion



- ❖ instep — new and unexpected
- ❖ highest energies (cutoff)

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**

- ❖ mass composition is the key

PRL 125 (2020) 121106, PRD 102 (2020) 062005, Eur. Phys. J. C (2021) 81:966, PoS (ICRC2021) 324

Greisen–**Z**atsepin–**K**uzmin **effect**, expected spectrum truncation at $E_{GZK} \approx 4 \cdot 10^{19}$ eV: pion production by protons interacting with CMB photons (horizon ~ 100 Mpc), nuclei disintegration in such interactions happens at roughly similar energies.

Energy spectrum

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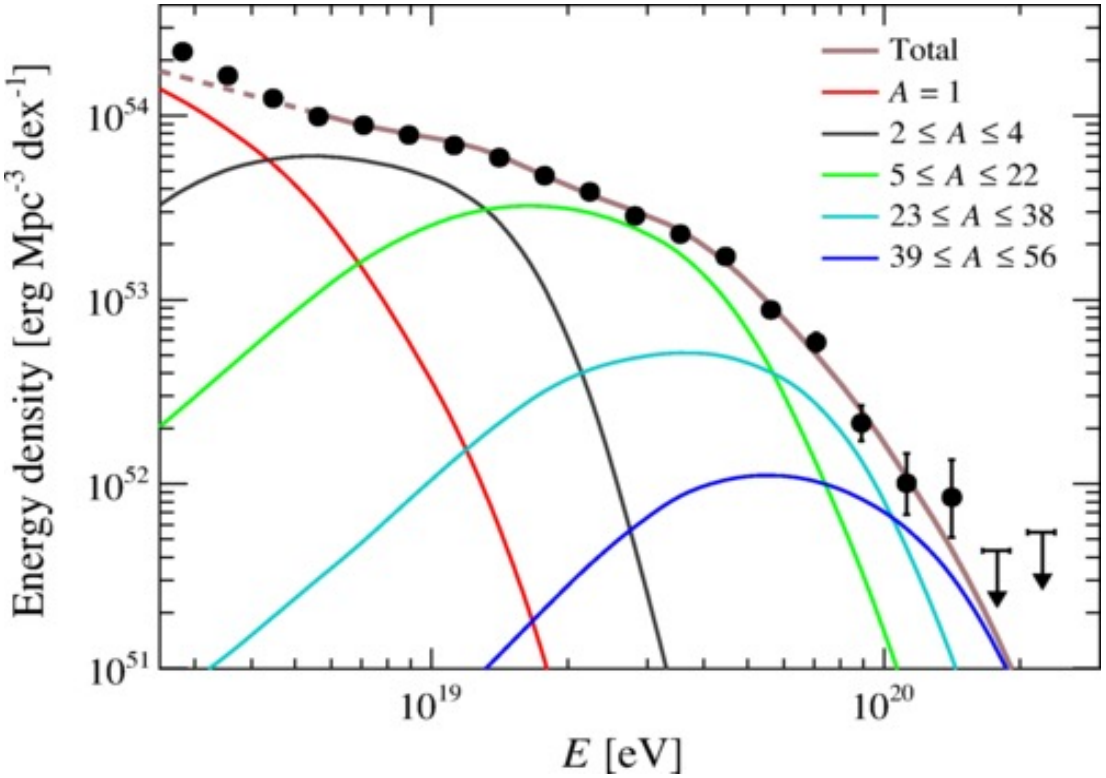

PRL 125 (2020) 121106, PRD 102 (2020) 062005, Eur. Phys. J. C (2021) 81:966, PoS (ICRC2021) 324

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Cosmogenic neutrinos and photons

> **UHE Neutrinos arise from decays of charged pions:**

Hadronic model:

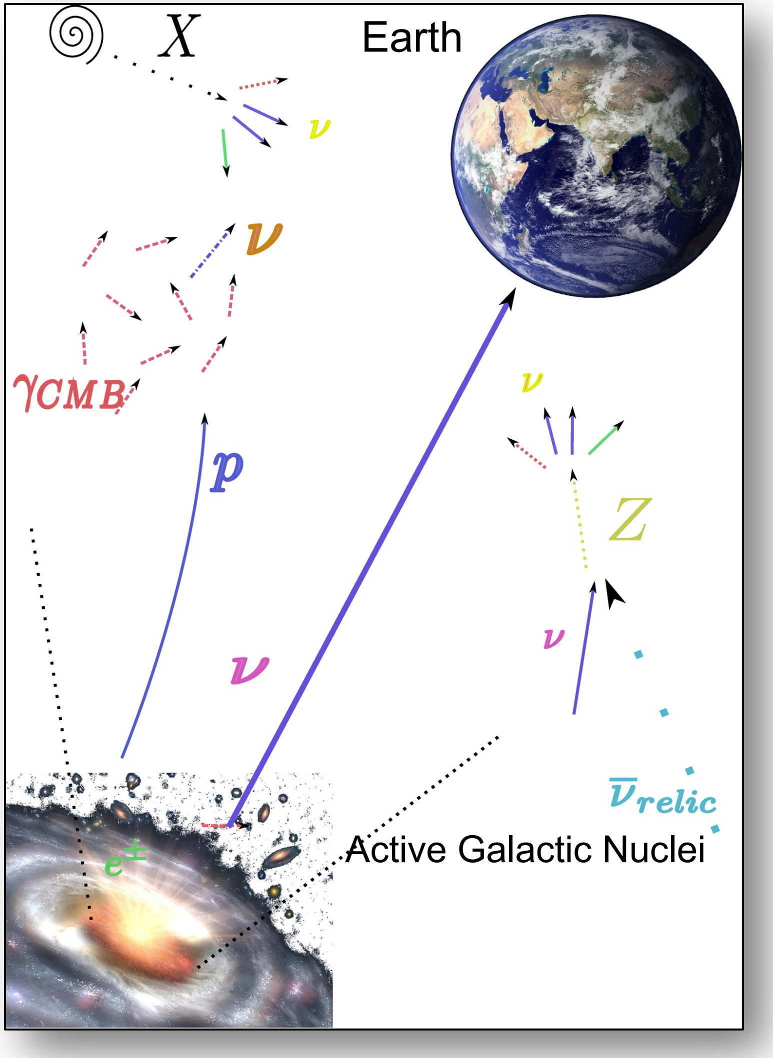
$$p + p(\gamma) \rightarrow \pi^{\pm} + X$$

$$\hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\hookrightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e})$$

$$p + p(\gamma) \rightarrow \pi^{0} + X$$

$$\hookrightarrow 2\gamma$$



> Sources: AGNs,GRBs, Supernova ...

$$\nu_{\mathbf{e}} : \nu_{\mu} : \nu_{\tau} = \mathbf{1 : 2 : 0}$$

> Flavour oscilations over cosmological distances:

$$\nu_{\mathbf{e}} : \nu_{\mu} : \nu_{\tau} \sim \mathbf{1 : 1 : 1}$$

In this scenario we expect tau neutrinos at Earth

> **Neutrinos are also produced from interaction of Cosmic-rays with Microwave Background (GZK or cosmogenic neutrinos)**

> **Present status:**

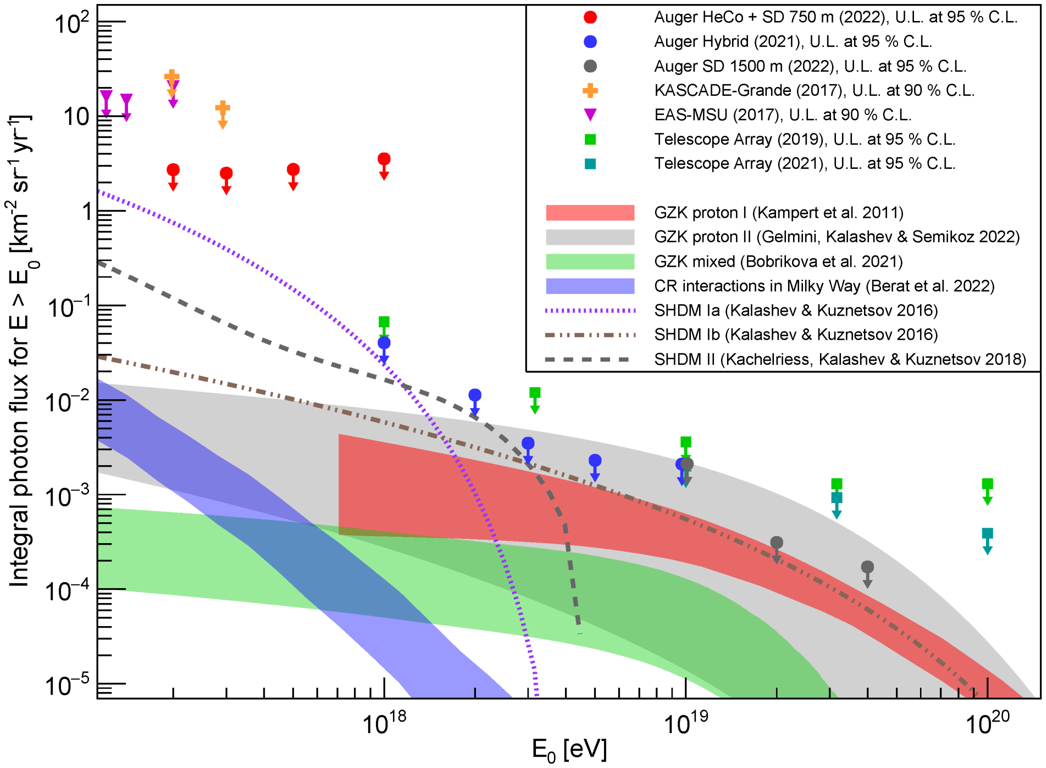
IceCube: 54 HE neutrino candidates (30 – 2000 TeV) (Phys. Rev. Lett. 113, 101101, 2014)

Fermi: evidence from pions of proton acceleration from Supernova Remnamts (60 MeV – 2 GeV) (Science,15 Feb 2013)

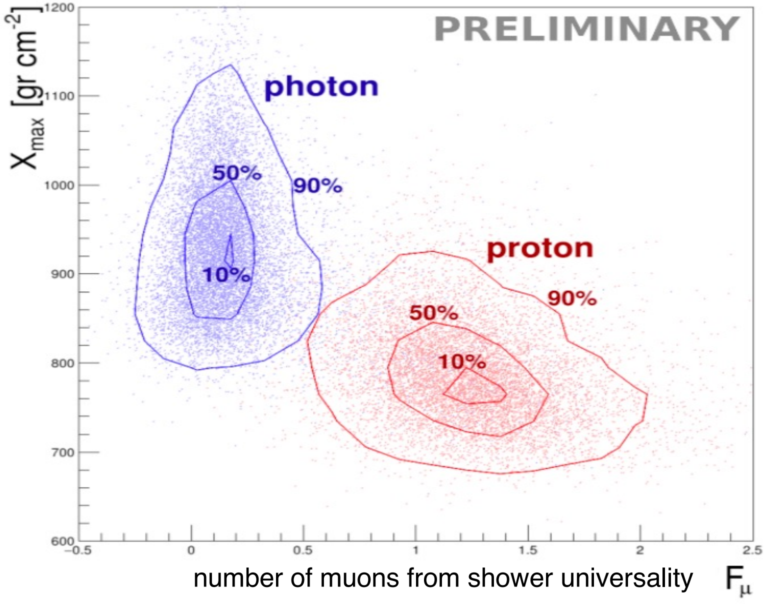
Direct identification of sources? Photon searches

No excess of photon candidates with respect to background

- Super-heavy dark matter models are strongly constrained by Auger limits
- Significant increase of exposure needed to constrain GZK proton scenarios



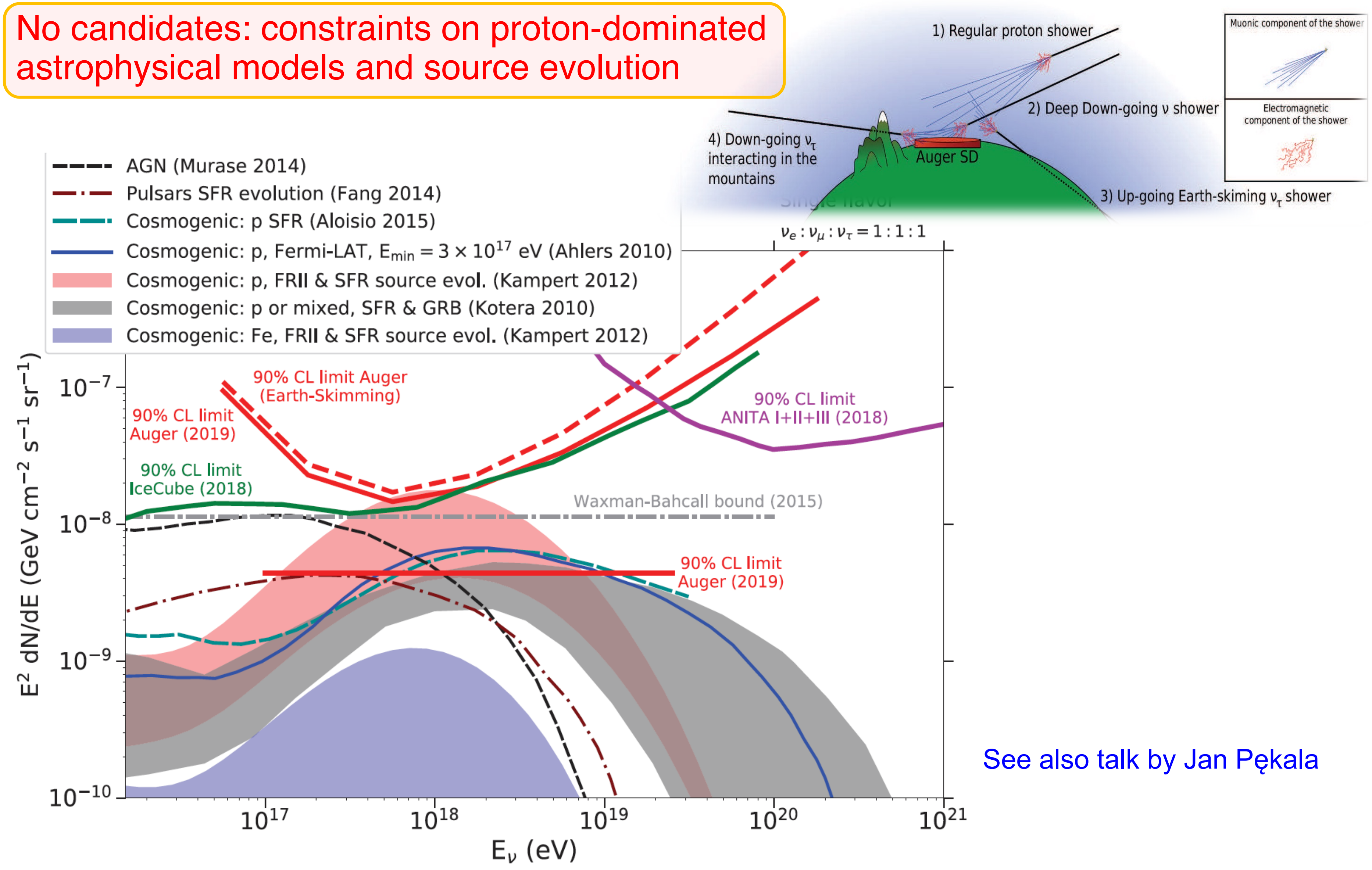
γ compared to protons:
deeper X_{max}, less muons



photon searches at Auger: *ApJ 789 (2014) 160; JCAP 04 (2017) 009; ApJL 837 (2017) L25; PoS (ICRC2021) 373; ApJ 933 (2022) 125*

Direct identification of sources? Neutrino searches

No candidates: constraints on proton-dominated astrophysical models and source evolution

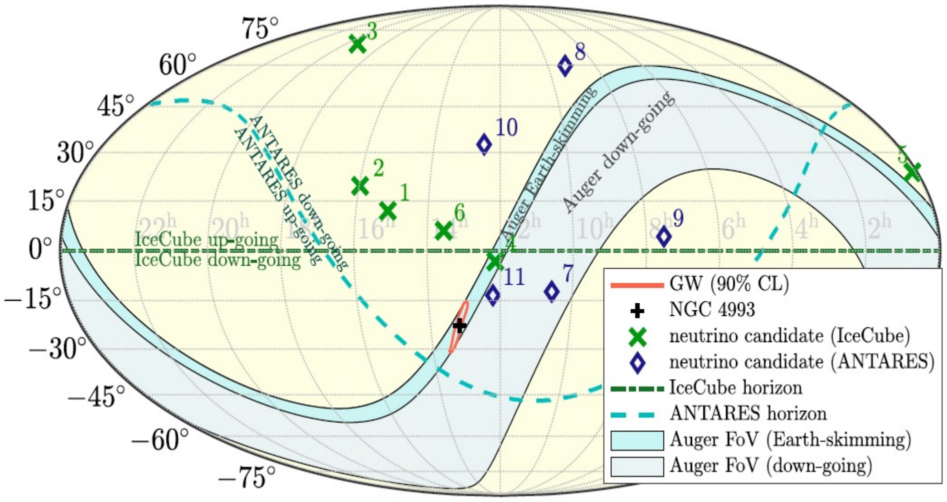


See also talk by Jan Pękala

neutrino searches at Auger: *JCAP 01 (2016) 037, PRD 94 (2016) 122007, ApJ Lett. 850 (2017) L35, JCAP 10 (2019) 022, 11 (2019) 004; ApJ 902 (2020) 105*

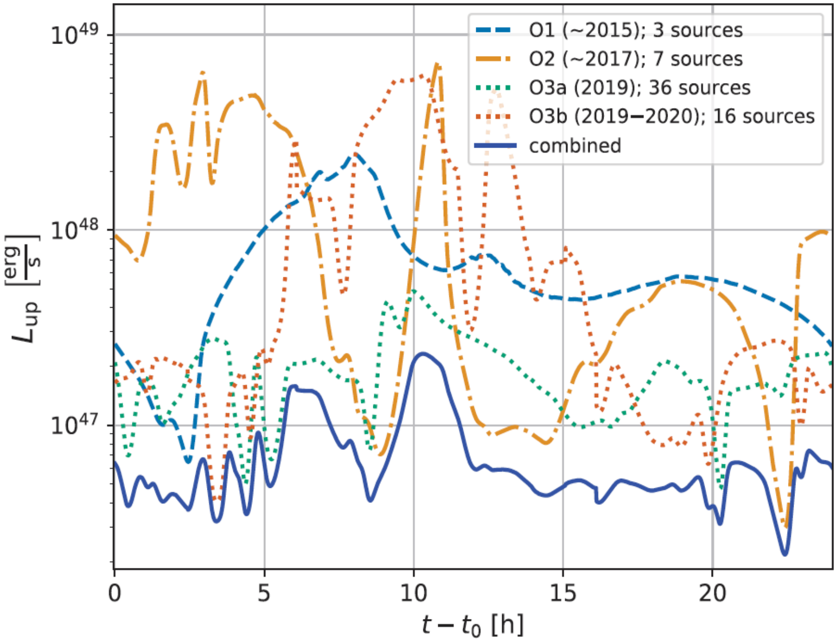
Follow-ups of astrophysical transients (neutrinos searches)

…no candidates from all LIGO-Virgo GWs: limits on isotropic neutrino luminosity (24h follow-ups)



GW170817

Astrophys. Journ. Lett., 850:L35 18



See also talk by Jan Pękala

GW follow-up searches: PoS (ICRC2021) 968

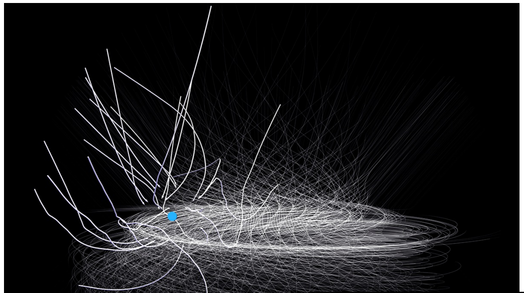
Energy range of Auger $E_\nu > 10^{17}$ eV

Zenith angle of optical counterpart within ±500 s (90.4 deg; 93.3 deg), Earth-skimming

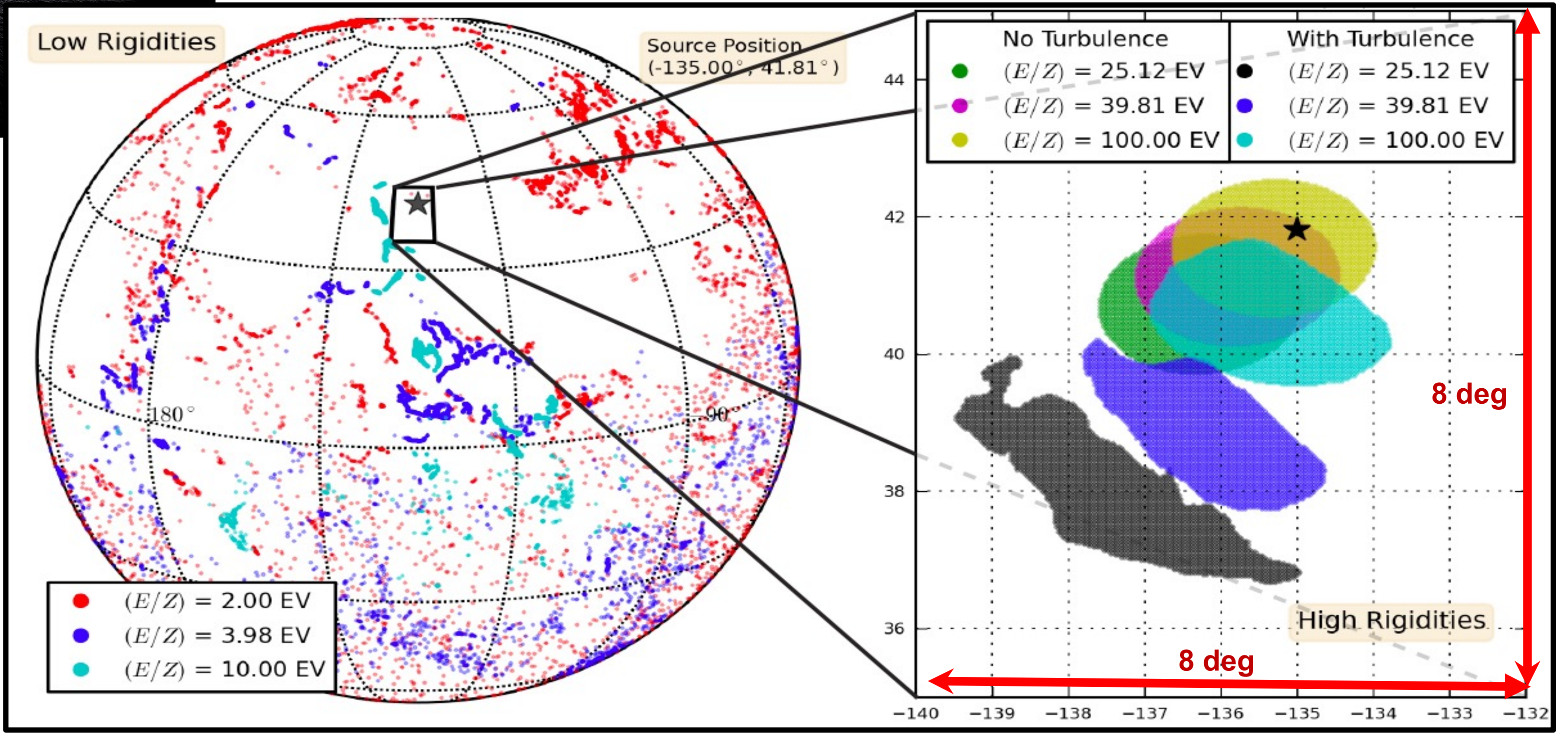
Search results no candidates in time windows ±500 s, +14 days

Charged-particle astronomy?

Arrival directions of particles with low rigidity R = E/Z are scrambled by galactic magnetic field



arrival directions from a single source (⋆ mark)



https://www.nas.nasa.gov/SC14/demos/demo4.html

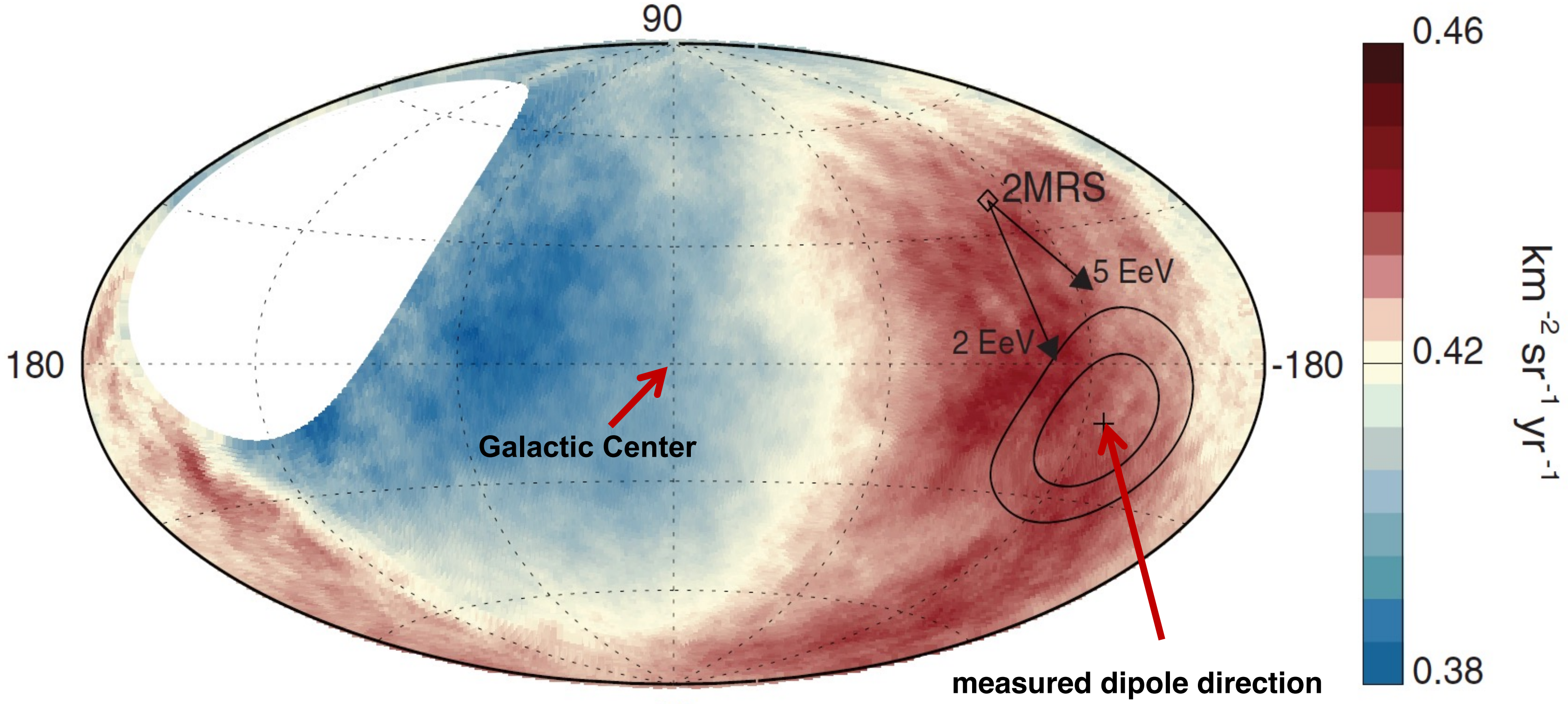
what is the cosmic rays rigidity at E > 10 EeV=10^{19} eV ?

Observation of large-scale anisotropy for E ≥ 8 EeV

physicsworld
TOP 10
BREAKTHROUGH
2017

Observed dipole ~120° from the Galactic Center
-> cosmic rays (> 8•10^{18} eV) come from outside our galaxy

Magnetic Fields change position of 2MRS dipole (as shown for E/Z = 2 EeV or 5 EeV)



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

***Science* 57 (2017) 1266**; *Astrophys. J. 868 (2018) 4, 891 (2020) 142; PoS(ICRC2021)335*

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

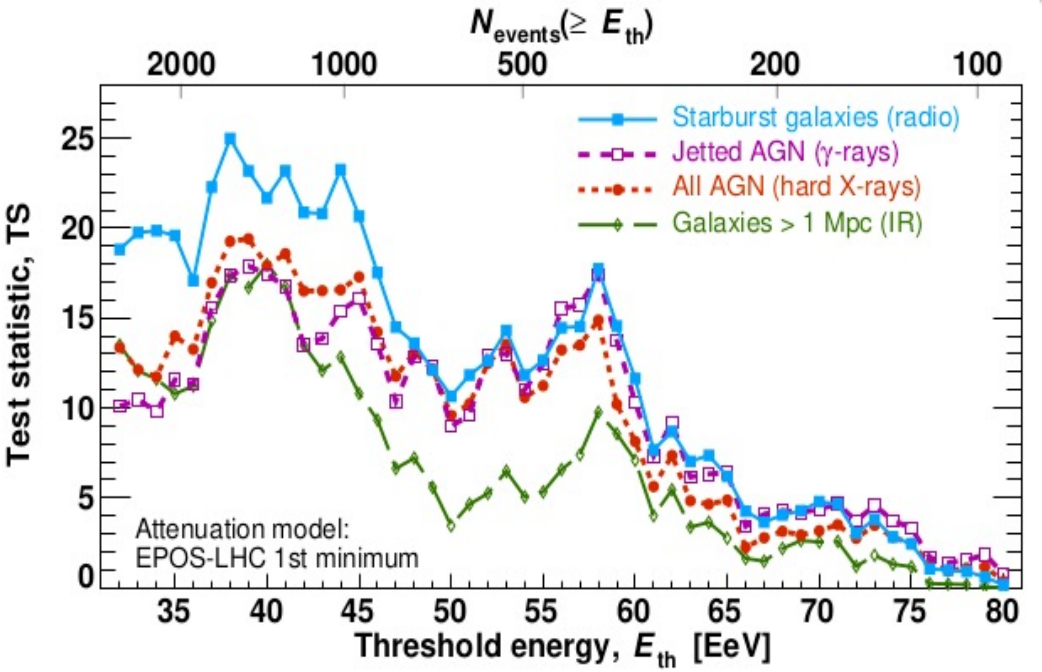
Anisotropies tested against catalogues of astrophysical objects

AGNs

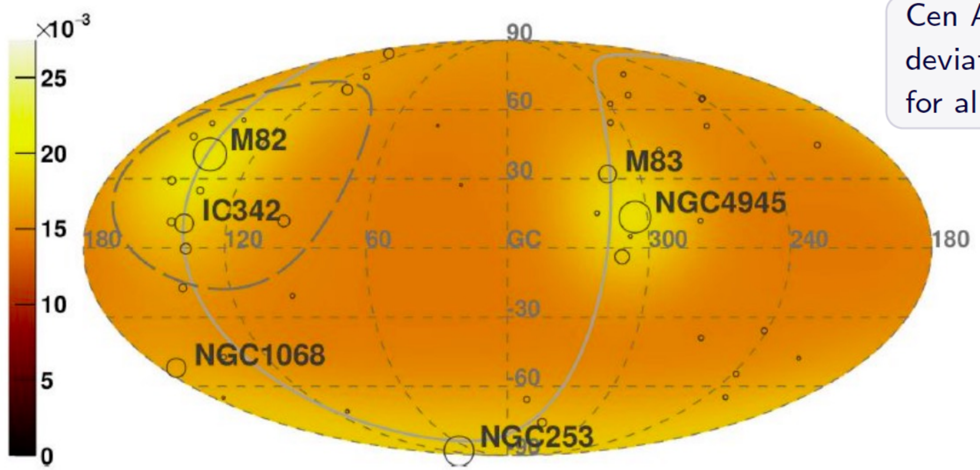
Significance 3.3σ, $E > 39$ EeV

Starburst galaxies

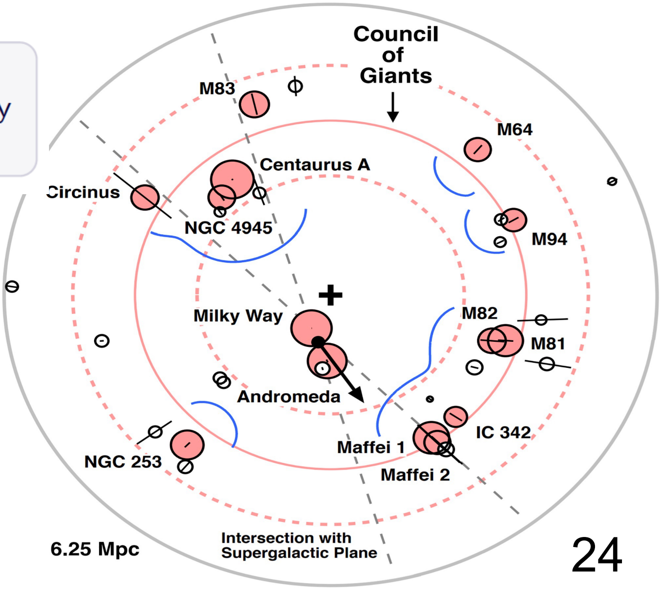
Significance 4.2σ, $E > 38$ EeV



Starburst galaxies (radio) - expected $\Phi(E_{\mathrm{Auger}} > 38\ \mathrm{EeV})$ [$\mathrm{km}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{yr}^{-1}$]



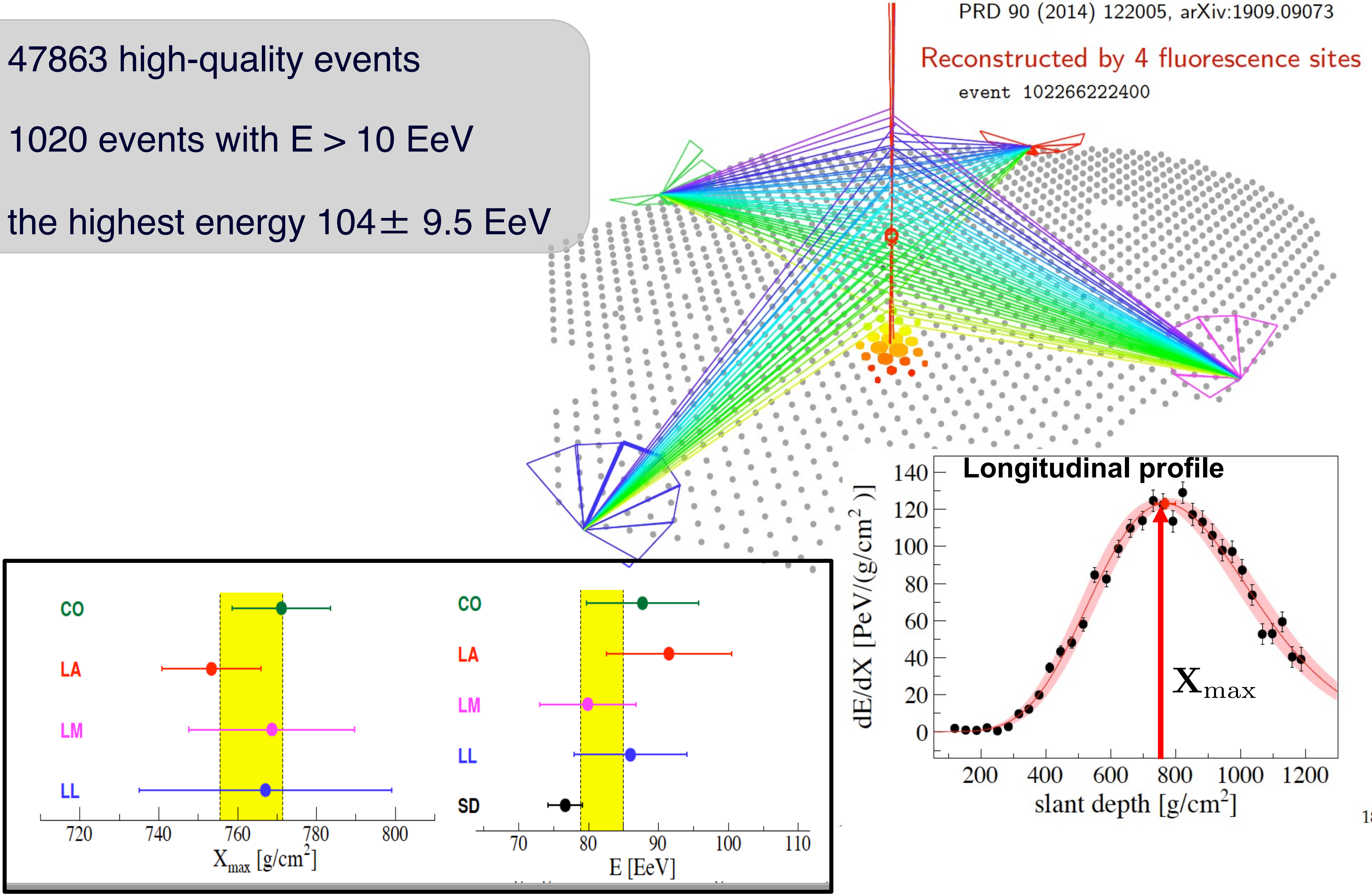
Cen A hotspot drives deviation from isotropy for all catalogues



ApJL 853 (2018) L29; PoS (ICRC2021) 307; ApJ 935 170 (2022)

Measurements of the depth of shower maximum X_{max}

- 47863 high-quality events
- 1020 events with $E > 10$ EeV
- the highest energy 104± 9.5 EeV



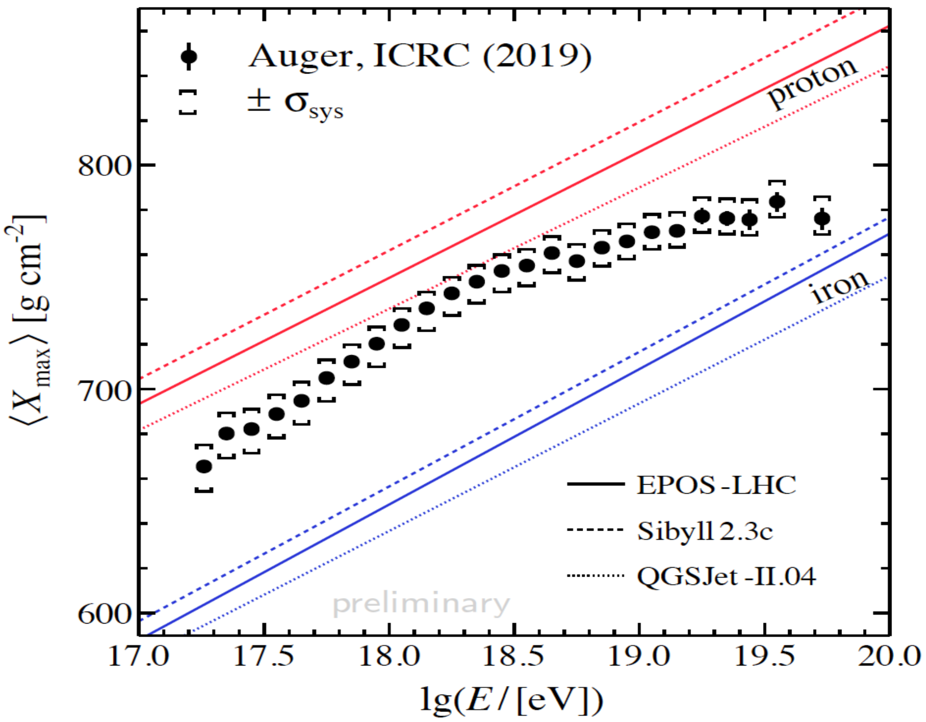
PRD 90 (2014) 122005, arXiv:1909.09073

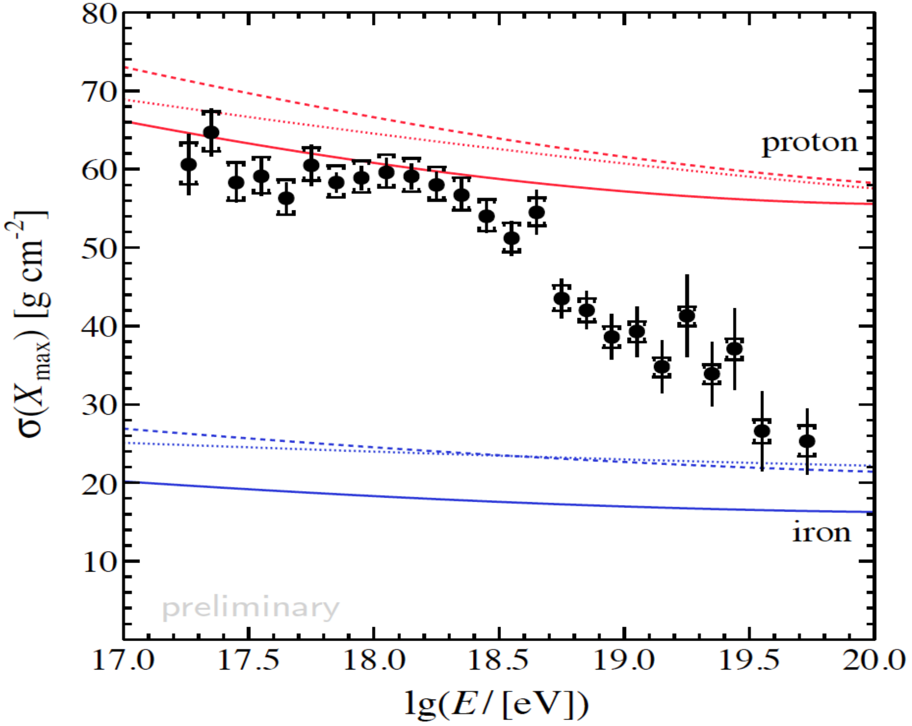
Reconstructed by 4 fluorescence sites

event 102266222400

Energy evolution of mean and standard deviation of X_{max}

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





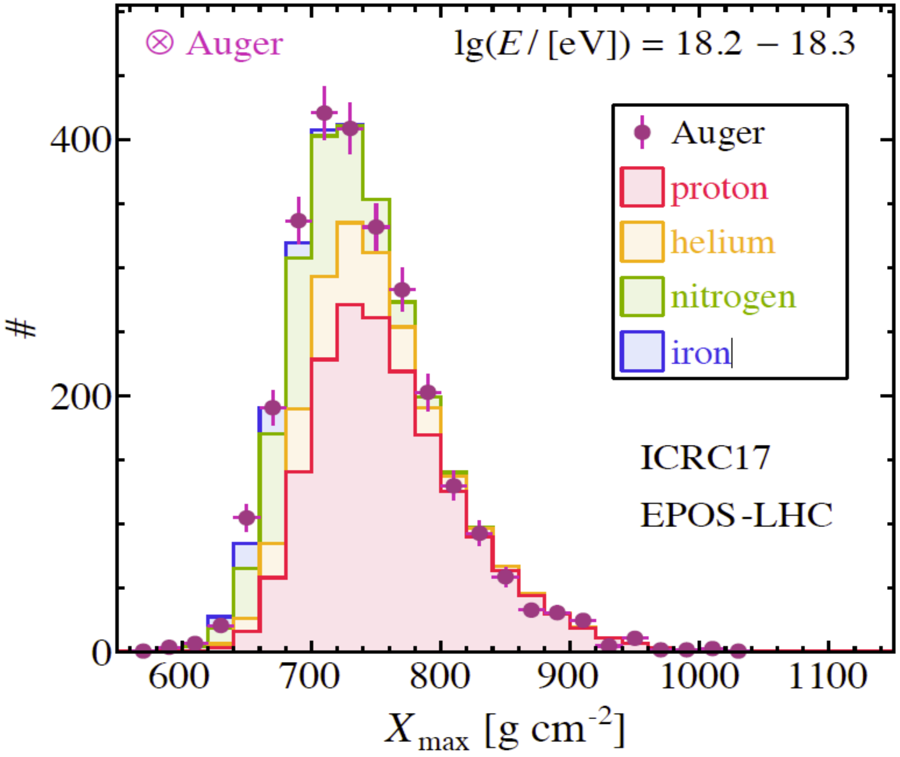
PRD 90 (2014) 122006, arXiv:1708.06592

... 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)

Individual nuclei: fits of X_{max} distributions with (p, He, N, Fe) templates

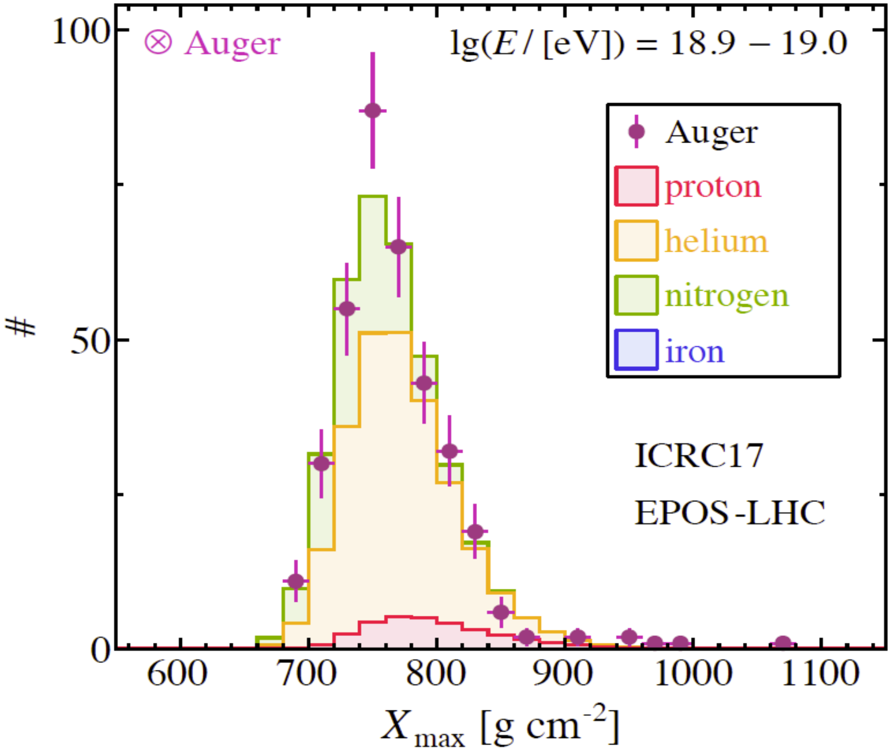
lg(E/eV) = 18.2 – 18.3

proton-dominated



lg(E/eV) = 18.9 – 19.0

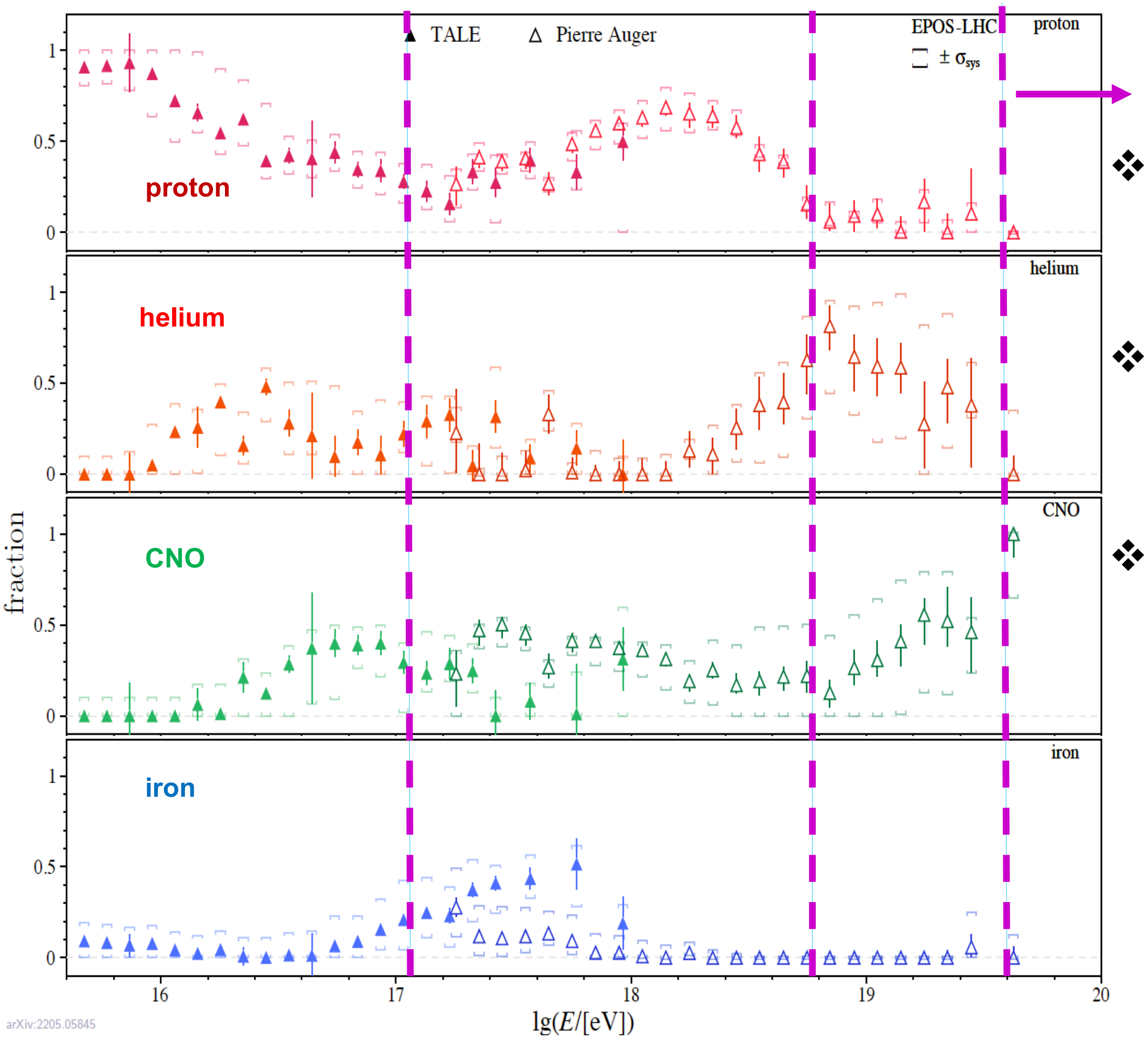
few protons,
helium-dominated



Fractions of primary nuclei: evolution with energy

TALE: Telescope Array data [ApJ 909 (2021) 178]

2nd knee ankle highest energies (cutoff)



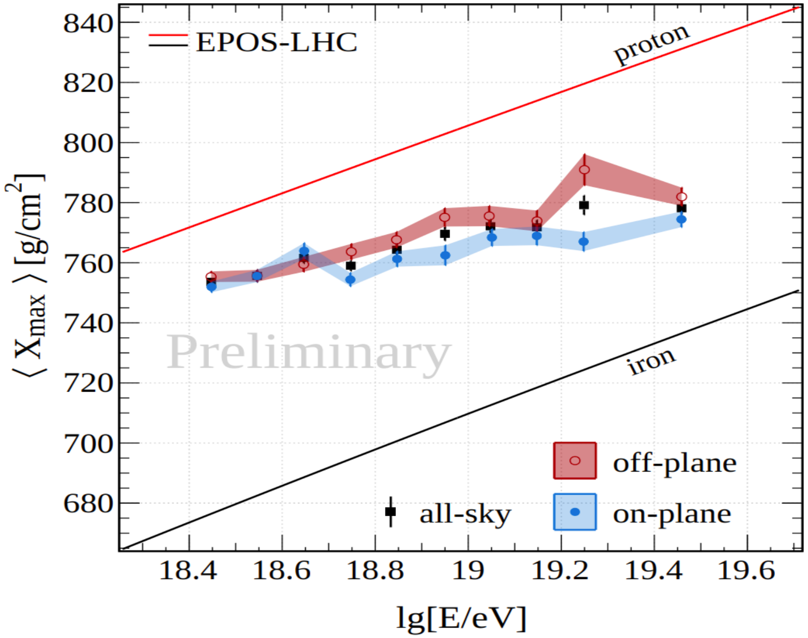
arXiv:2205.05845

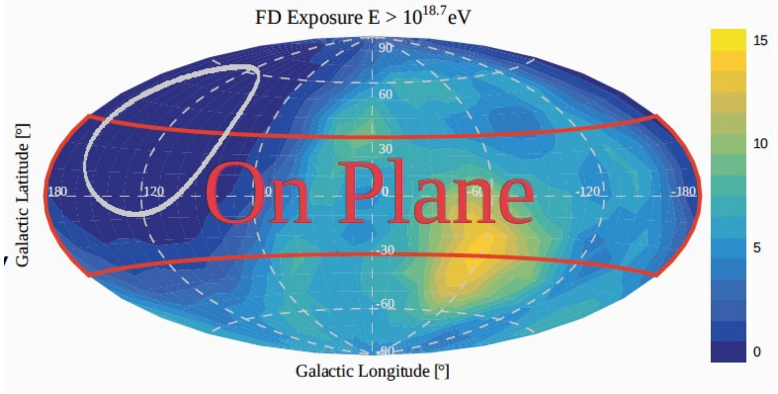
- ❖ 2nd knee (~ 10^{17} eV)
  decreasing iron contribution
- ❖ ankle ($10^{18.7}$ eV)
  disappearance of protons
- ❖ highest energies (cutoff)
  medium mass domination

Scenario A:
maximum energy in sources?

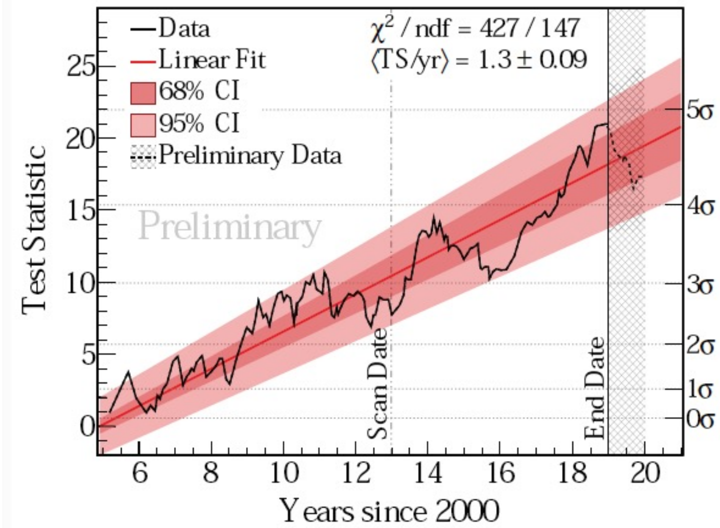
Indication on mass-dependent anisotropy in hybrid data

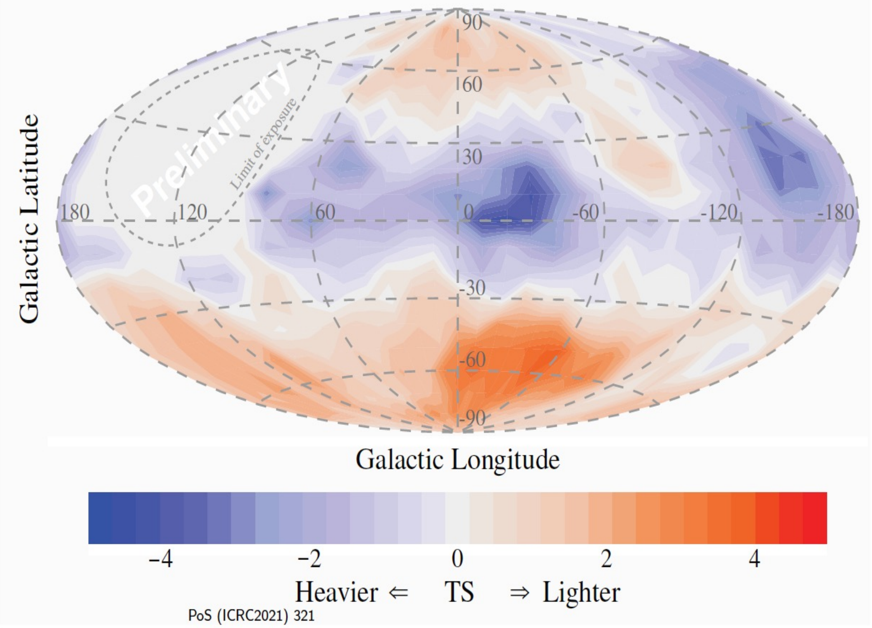
Compare FD X_{max} of data within 30deg from Galactic plane to the rest of events ($E > 10^{18.7}$ eV)





PoS(ICRC2021)321

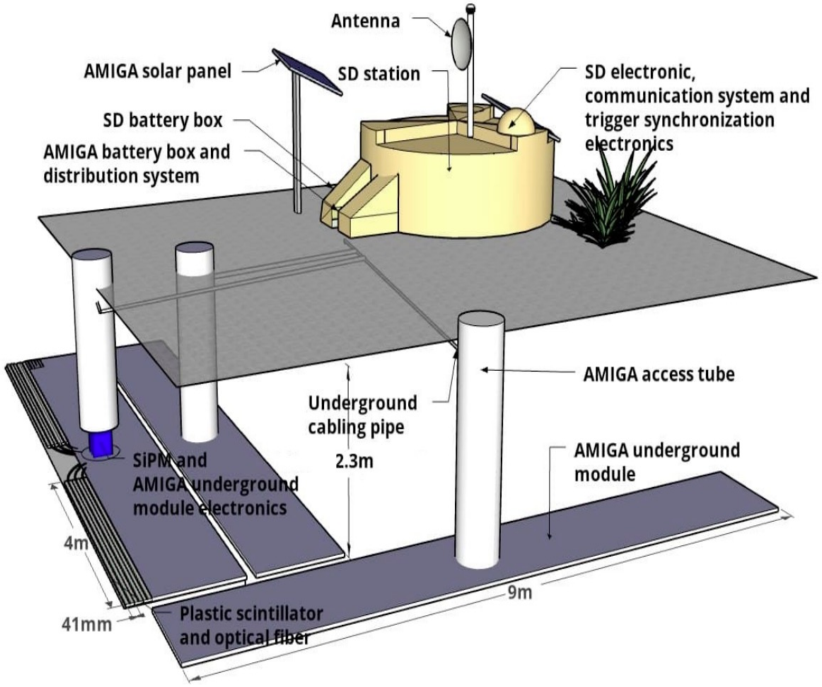




Indications on heavier on-plane mass composition (3.3σ including systematics)

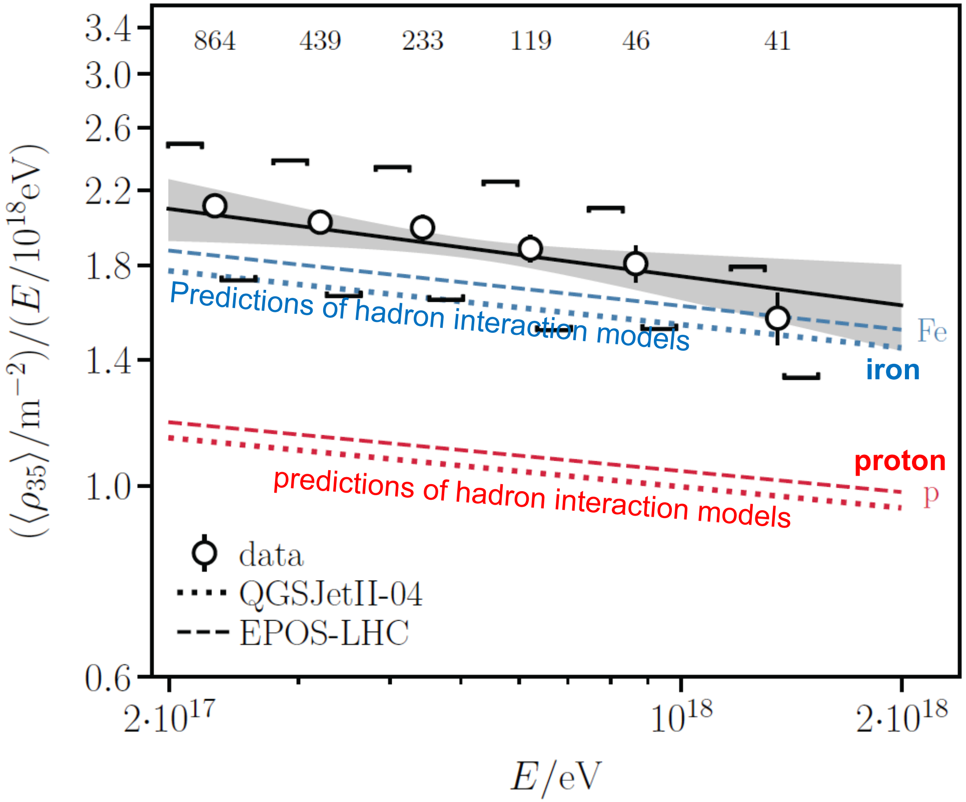
Hadronic interactions: measurements of muon shower content

Data are above MC predictions for iron, large systematics in ⟨ln A⟩ from surface detectors



Muon density with muon detectors AMIGA buried 2.3 m underground

Muon density



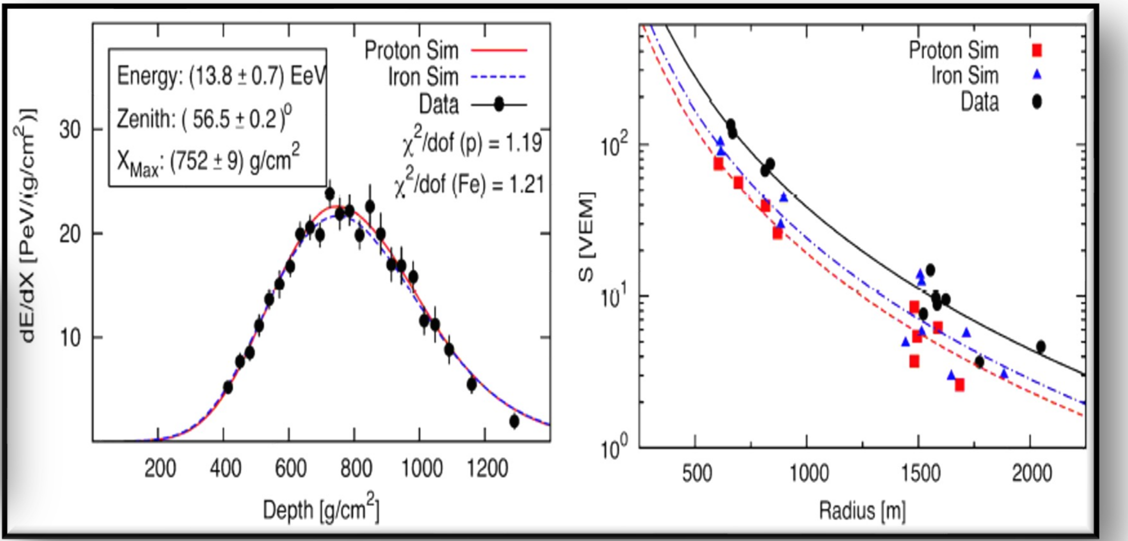
Eur. Phys. J. C 80 (2020) 751

see also talk by Kevin Almeida-Cheminant

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)

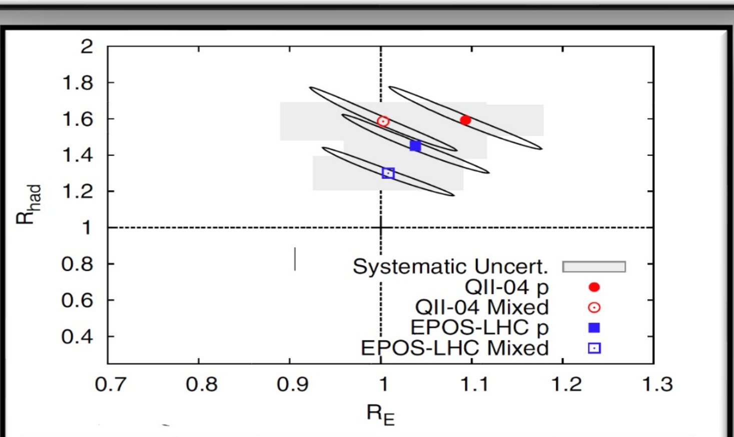


$$S_{\rm resc} = R_E\, S_{\rm EM} + R_{\rm had}\, R_E^{\alpha}\, S_{\rm had}$$

$$\alpha \simeq 0.9$$

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

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



Model	R_E	$R_{\rm had}$
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	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

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

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

Upgrade of the observatory: AugerPrime

For each Water Cherenkov Detector (WCD)

+ new electronics

+ small PMT

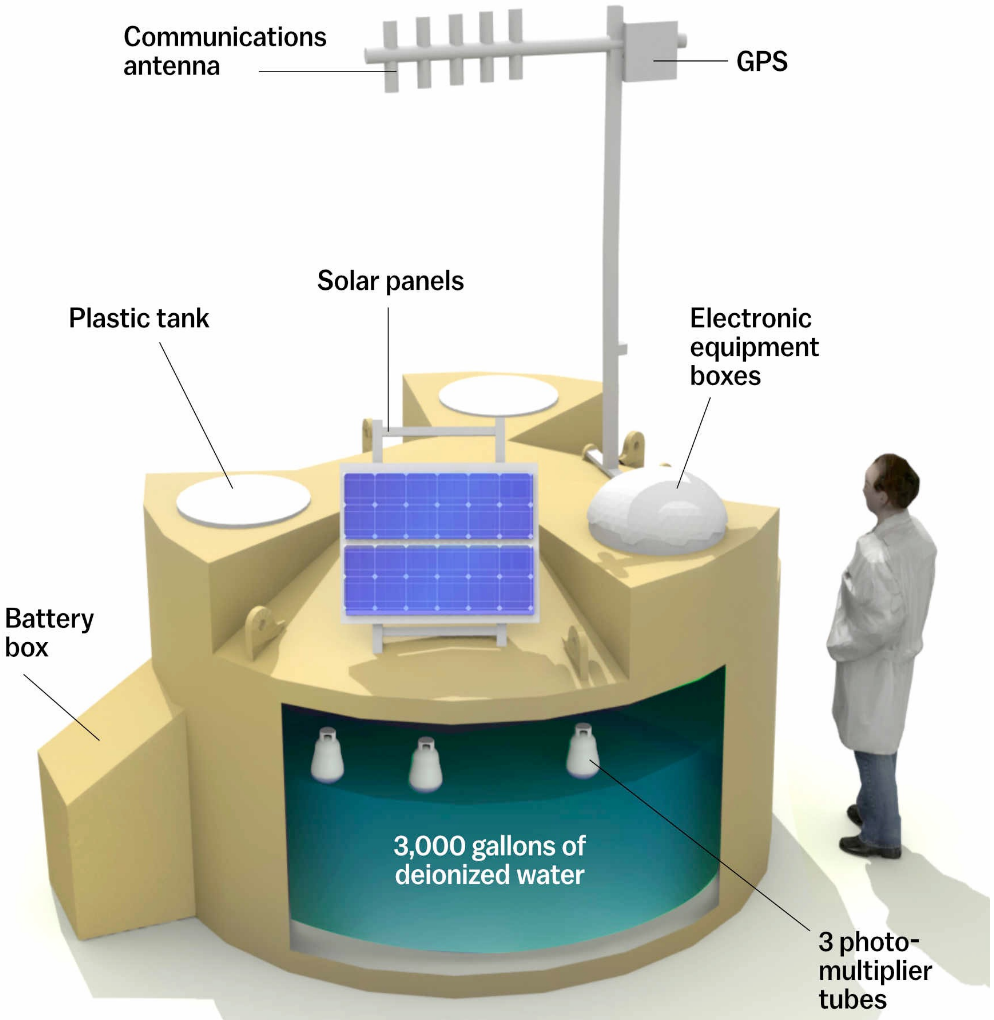
+ 3.8 m^2 scintillator detectors

+ radio antenna

SD (750 m) of 23.5 km^2 area

+ underground muon detectors

Auger Observatory surface detector



Source: Pierre Auger Observatory

Upgrade of the observatory: AugerPrime

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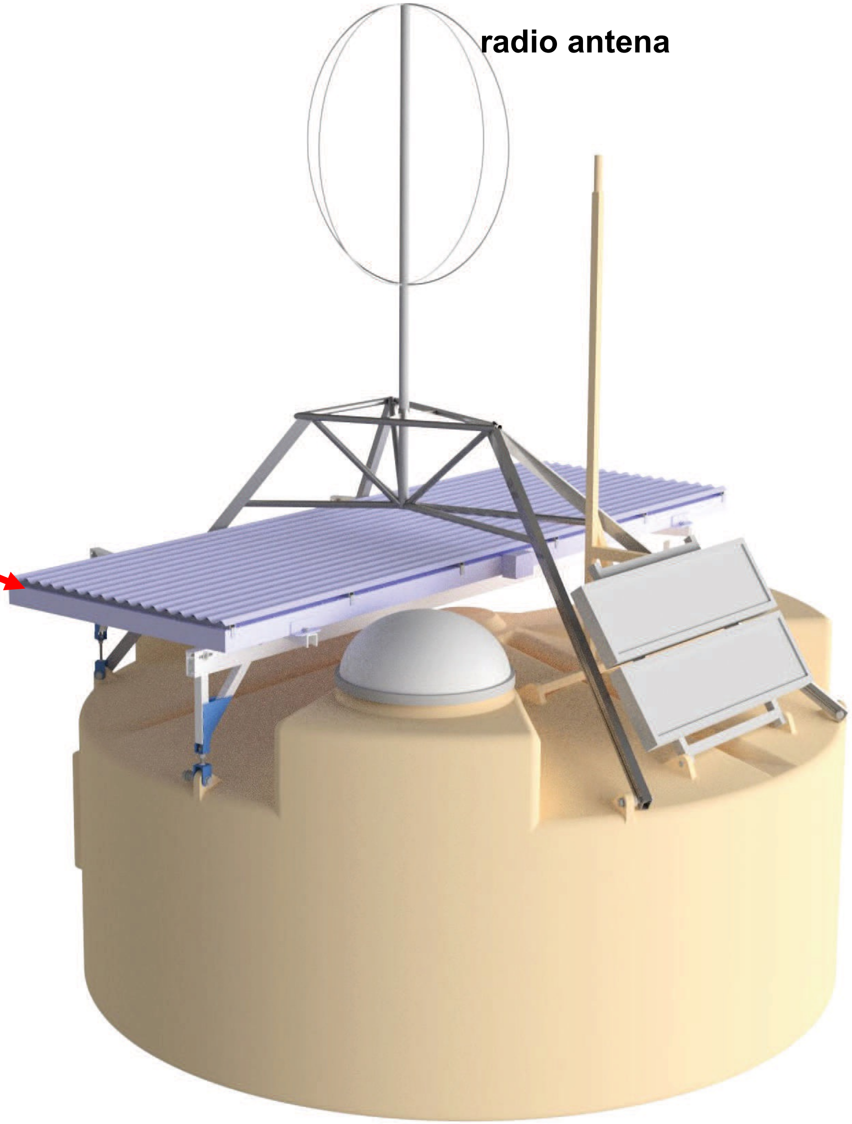

Upgrade of the observatory: AugerPrime

For each WCD

+ new electronics

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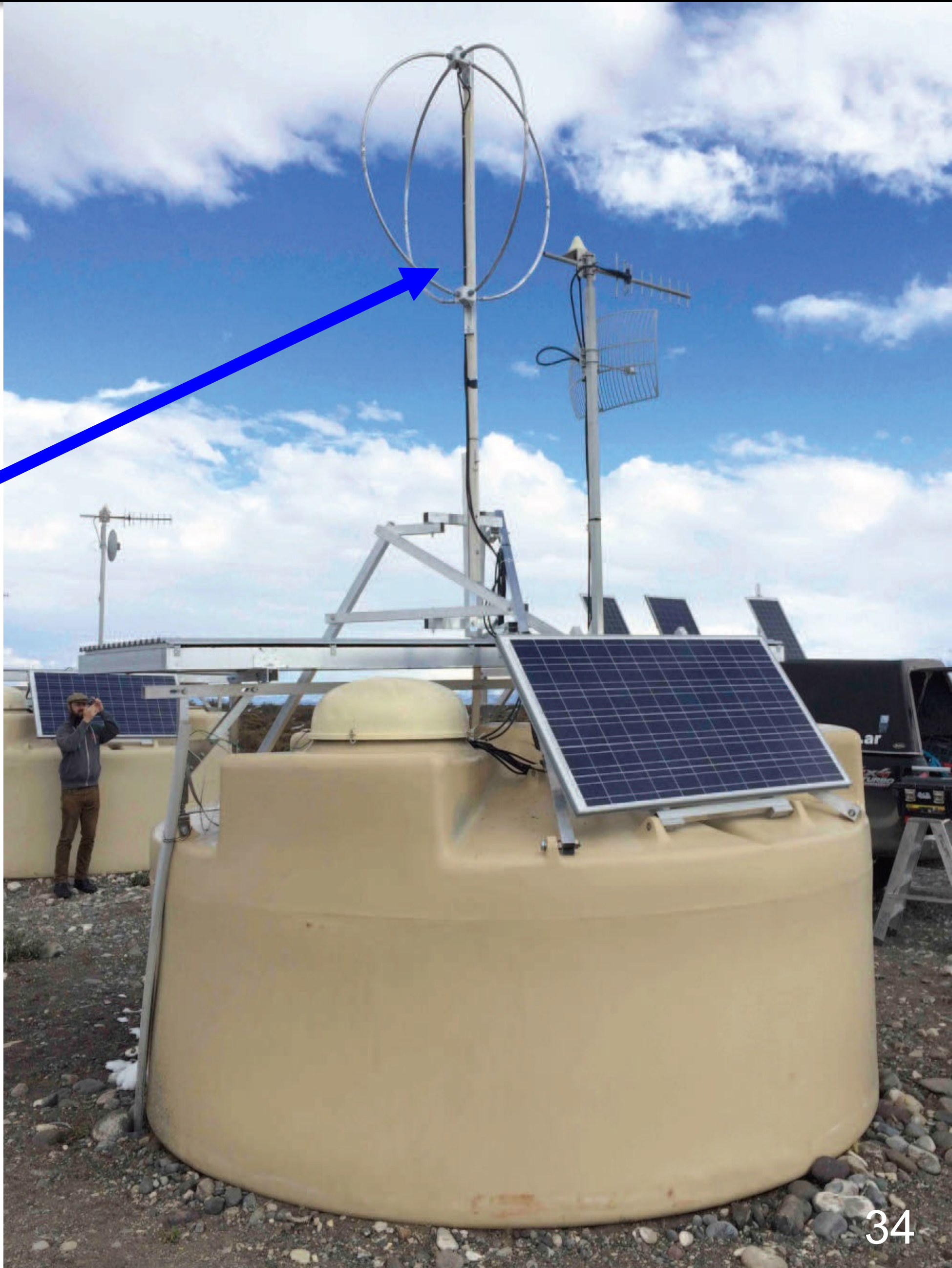
+ 3.8 m^2 scintillator detector

+ **radio antenna**

SD (750 m) of 23.5 km^2 area

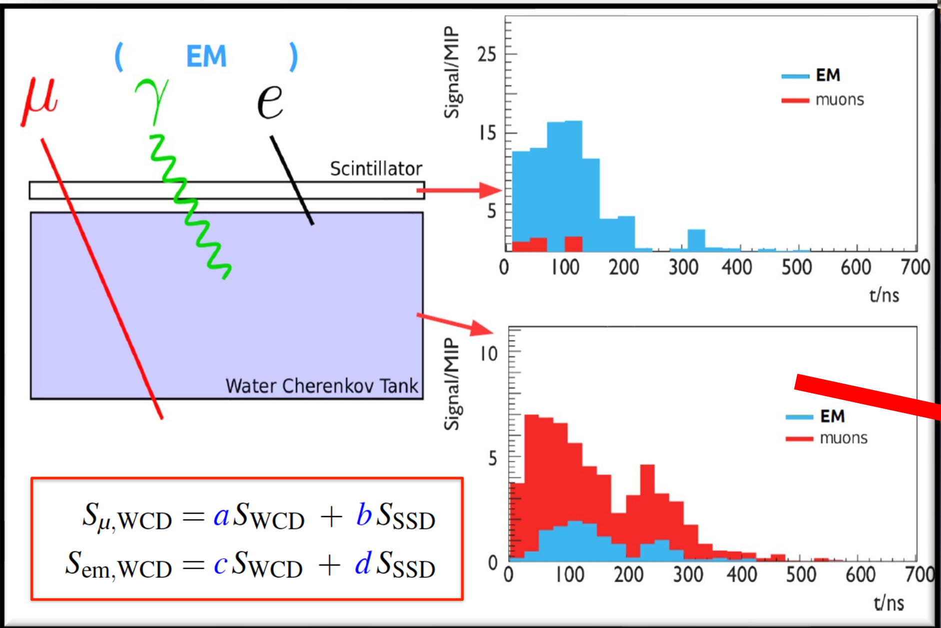
+ underground muon detectors

See also poster by Jarosław Stasielak

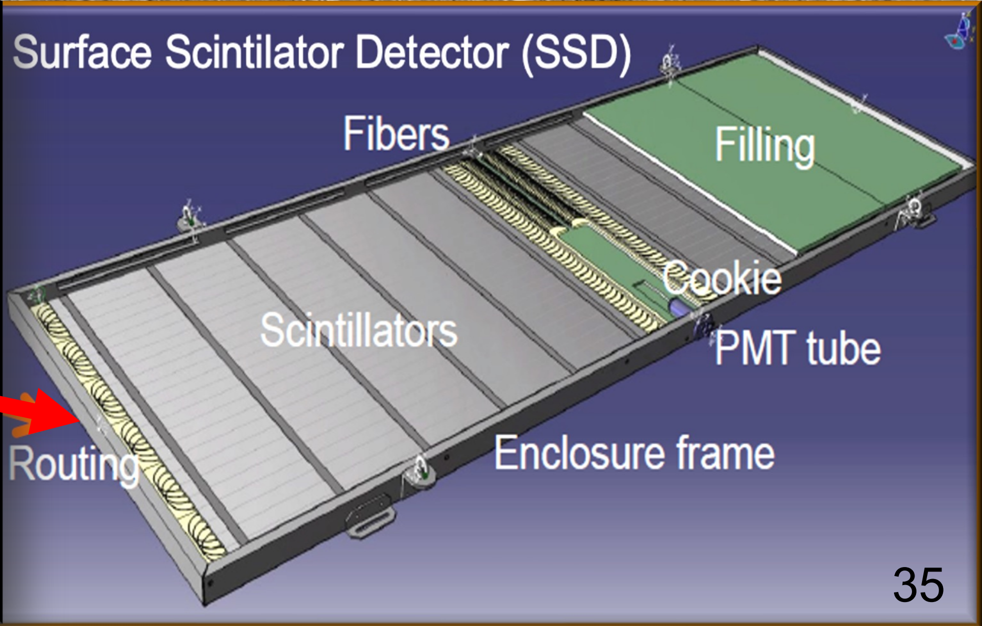


Upgrade of the observatory: AugerPrime

- 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



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



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

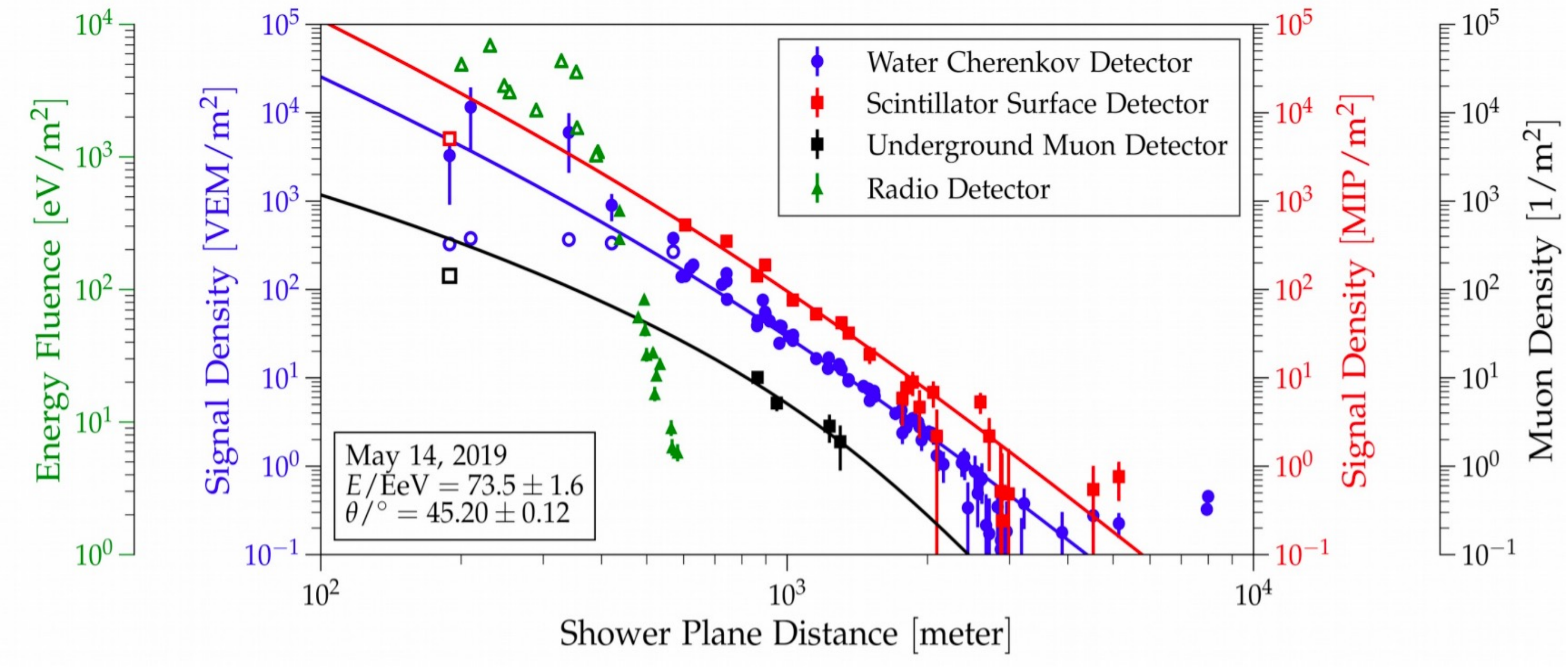
- Together with engineers from IFJ PAN, 228 (out of 1519) scintillation detectors (SSD) have been assembled and tested over the last years

Test bench Assembling: 2017-2019

March 2021: the last conteiner sent to Argentina

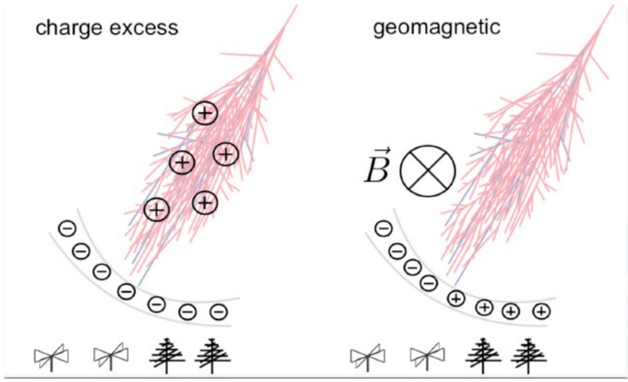
Scientific data: next decade

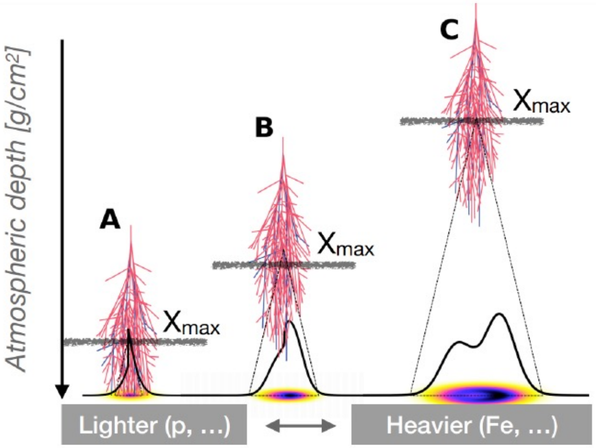
Multihybrid data from AugerPrime



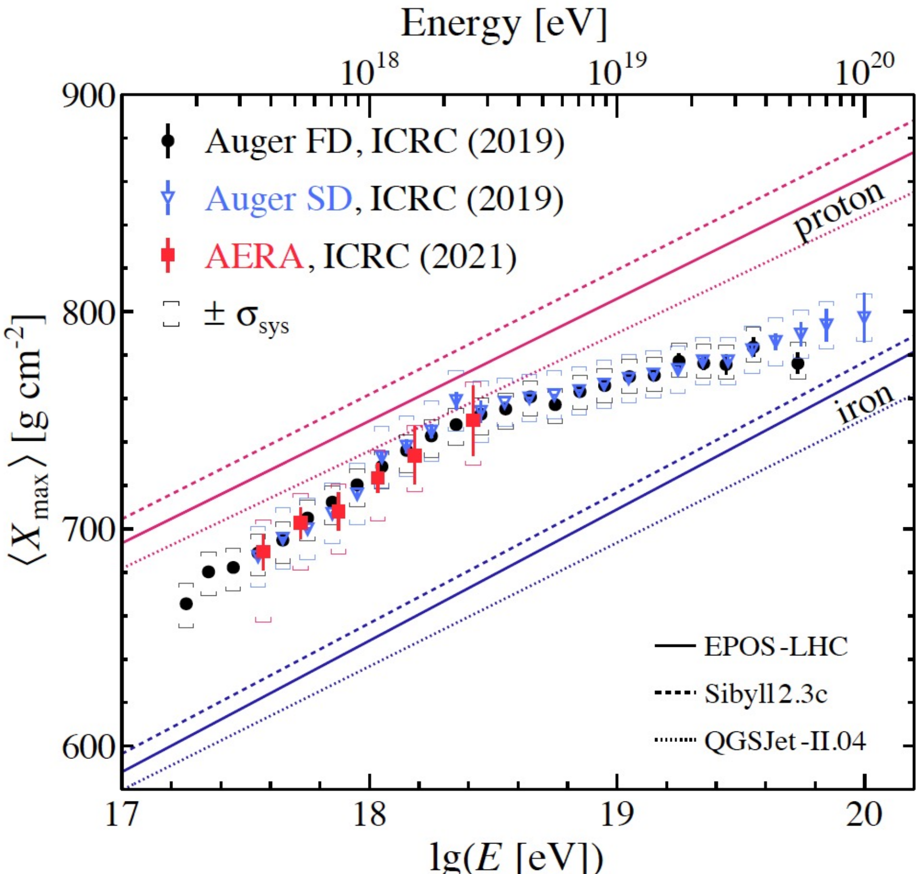
X_{max} measurements with radio detector AERA

Largest radio array for cosmic-ray detection





good agreement with other measurements

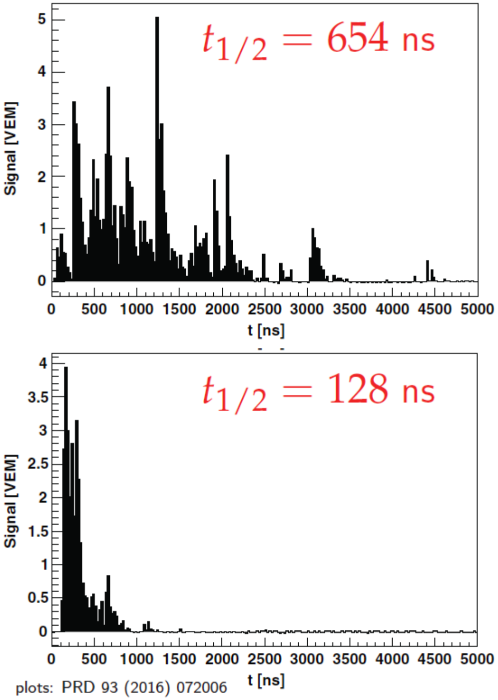


PoS(ICRC2021)387

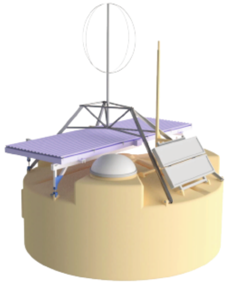
Extension of Xmax measurements to 10^{20} eV with the SD data (100% duty cycle)

Using arrival times of particles in surface stations

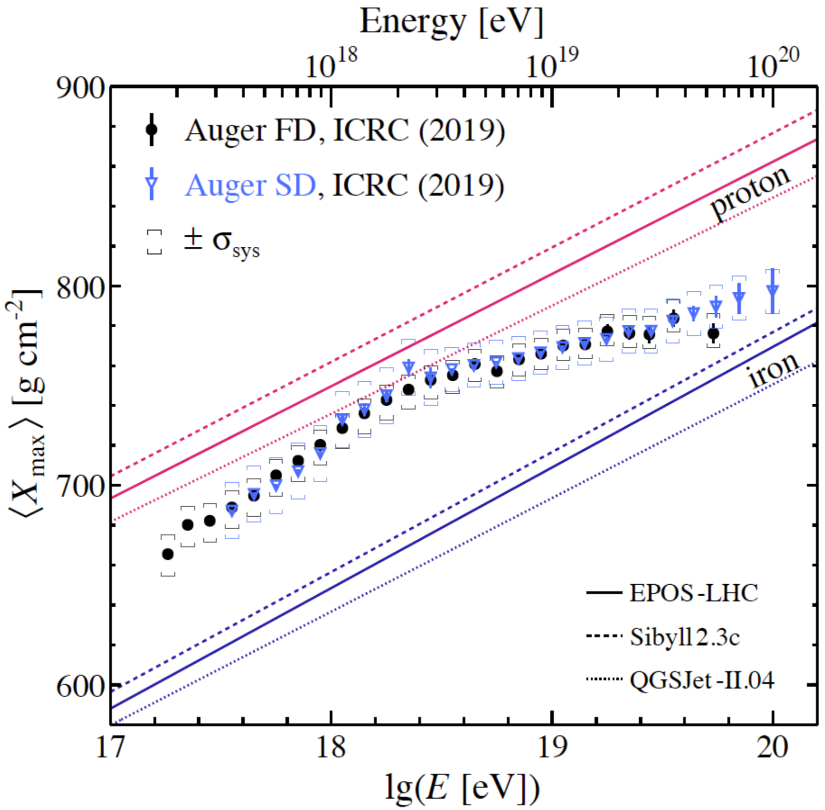
time traces of SD stations



plots: PRD 93 (2016) 072006



$\langle X_{\mathrm{max}}^{\mathrm{SD}} \rangle$ using calibration with FD



Phys. Rev. D 96 (2017) 122003, arXiv:1909.09073

extension of measurements to the highest energies

Scientific data: next decade

- Reduced systematics in hadronic interaction models
- Mass composition with SD (deep learning in Auger: JINST 16 (2021) P07016, P07019)
- Composition sensitivity in the flux suppression region
- Sensitivity to 10% proton fraction in this region (important for GZK photon and neutrino fluxes)
- Composition enhanced anisotropy studies
- Search for new phenomena in hadronic interactions
- Experience and data for the design of the next generation observatories