Activities of AUGER-CZ

Pierre Auger Observatory – participation of the Czech Republic

PIERRE AUGER OBSERVATORY

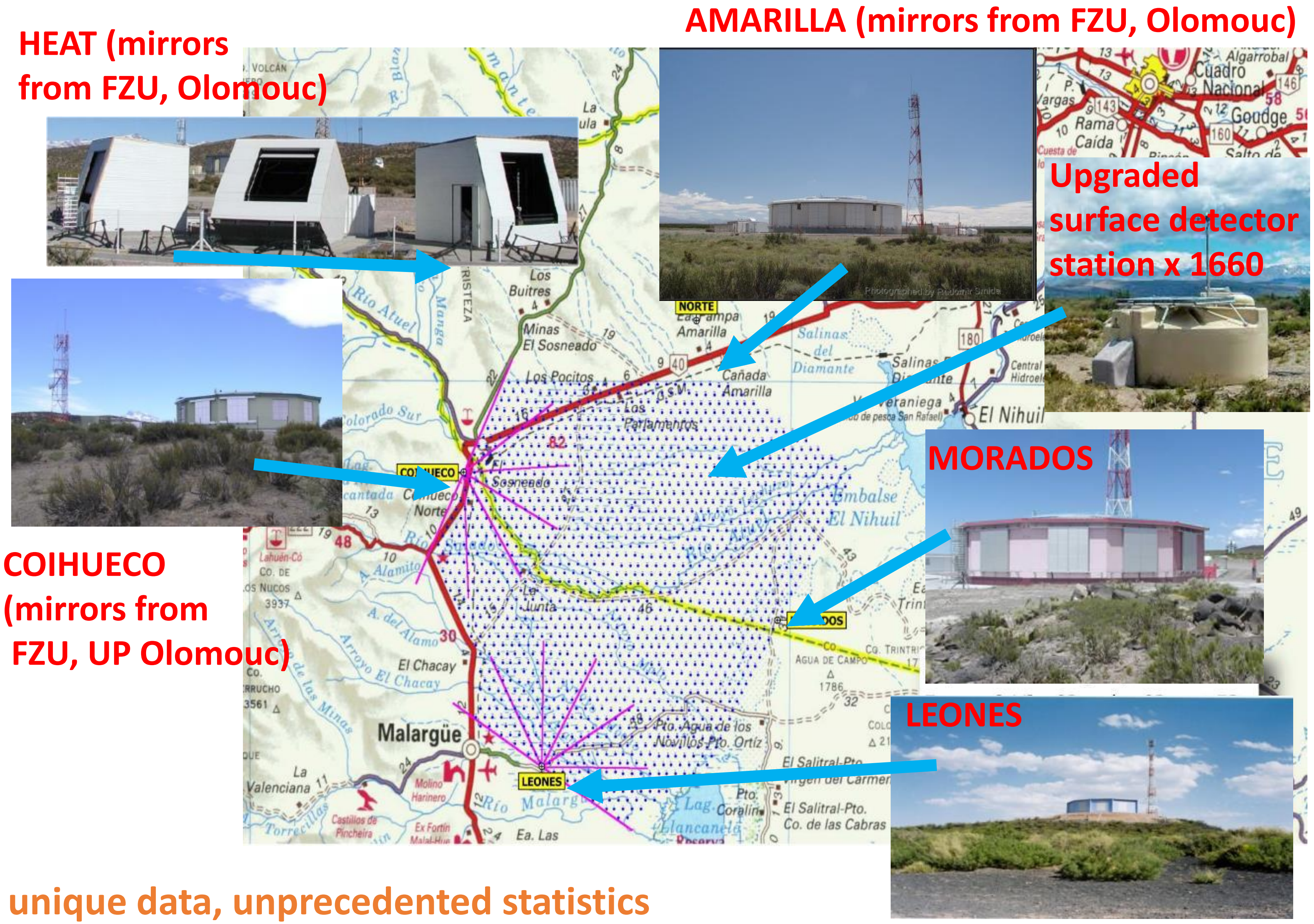
Institute of Physics of the Czech Academy of Sciences (FZU – Fyzikální ústav, AVCR)
– hosting institution
Charles University (CU)
Palacký University in Olomouc (PU)

FZU Institute of Physics of the Czech Academy of Sciences

Petr Travnicek - FZU

17th October, 2022, Prague; Day of Particle and Astroparticle Physics Inrastructures, Satelite event of ICRI

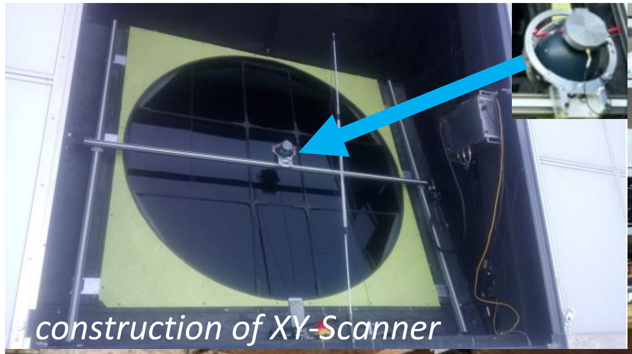
Pierre Auger Observatory

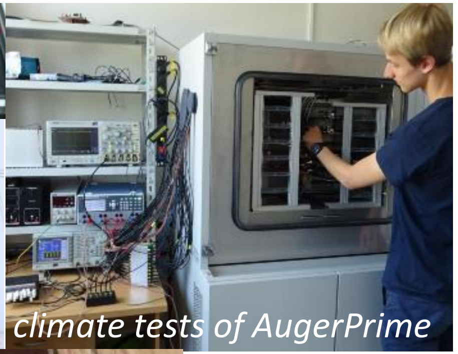


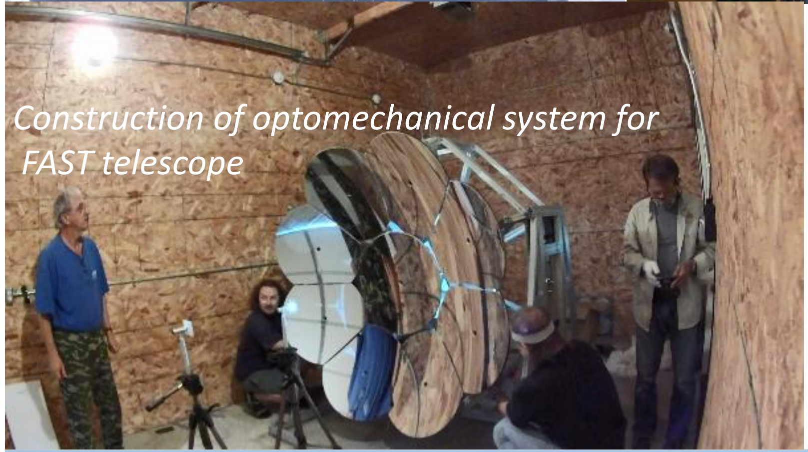
unique data, unprecedented statistics

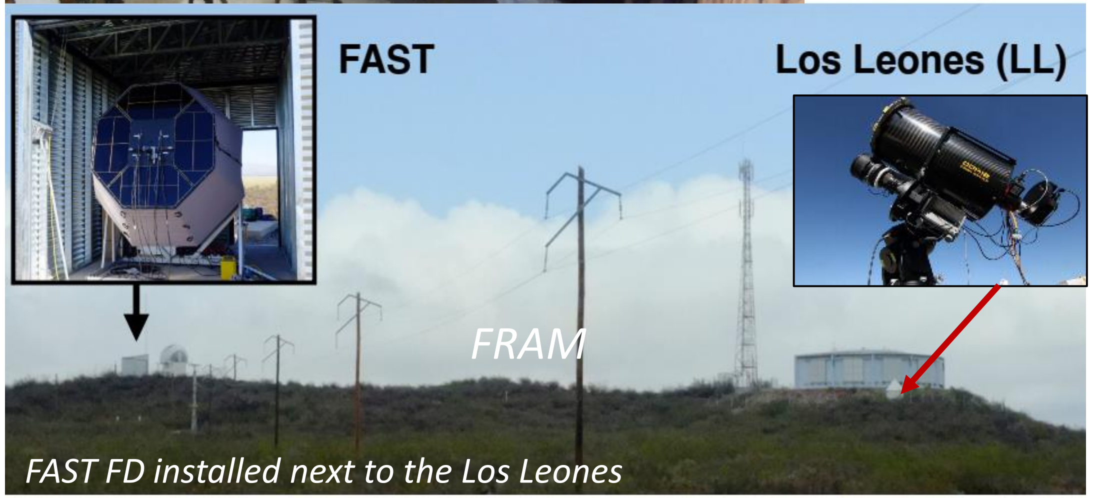
- ❑ World largest observatory
- ❑ to detect and study the highest energy cosmic rays
- ❑ 3000 km^2 array of (1600) surface detector stations
- ❑ 27 fluorescence telescopes
- ❑ 15 segmented mirrors (16 m^2) from Olomouc
- ❑ **Fluorescence detector (FD) under responsibility of the Czech groups**
- ❑ First CR hybrid detector
- ❑ Now in upgrade phase, new detectors
- ❑ Location: Mendoza, Argentina
- ❑ **AUGERPrime – recent upgrade with strong Czech contribution in electronics testing**

AUGER-CZ


construction of XY-Scanner


climate tests of AugerPrime


Construction of optomechanical system for FAST telescope



FAST FD installed next to the Los Leones

PIERRE AUGER
OBSERVATORY

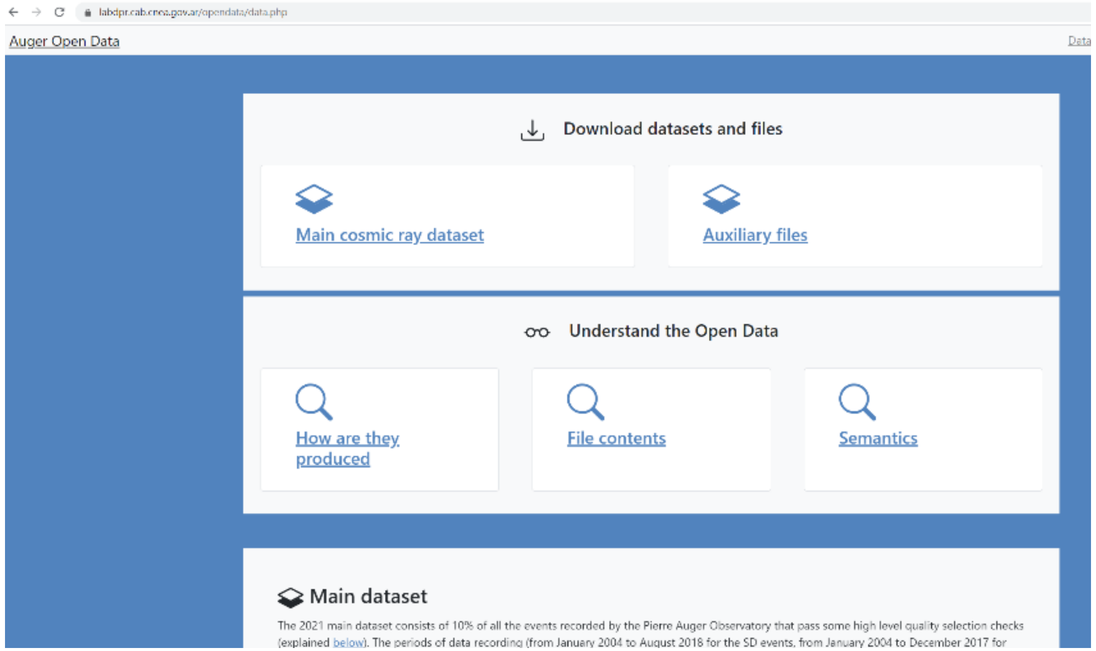
- **Optical lab for entire AUGER collaboration** (one of the best equipped in central Europe)
  - Mirrors production and maintenance
  - New calibration system **XY-Scanner -** Steerable extended uniform light source moved in front of the FD aperture (developed together with the Karlsruhe group); General purpose integrating sphere as the most suitable representative of the extended uniform light source (improved by the Olomouc group)
- **New FD detector** concept - Fluorescence detector Array of Single-pixel Telescopes (**FAST**) is a design concept for a next-generation UHECR observatory
  - Design and production of optical and mechanical system
- **Climate test of new electronics**
  - tests of entire production of 2000 electronics boards in Prague laboratory
- **FRAM telescopes and ALL SKY cameras for atmospheric monitoring**
  - broad experience and expertise in atmospheric monitoring
- **Leadership in Fluorescence detector working package**
  - Responsibility for organization of detector operation and maintenance
- **Leadership in Monte Carlo production work package**
  - VO AUGER founded and operated by AUGER-CZ, responsibility for MC library production

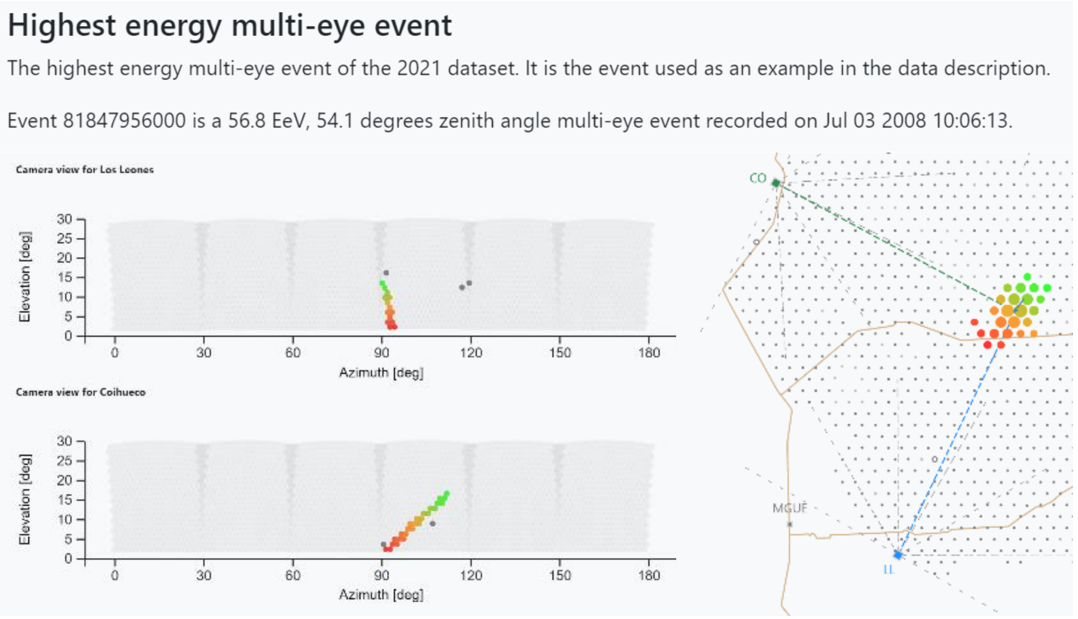
Development of AUGER-CZ

- 1990–1997 first conceptual ideas of AUGER
- 1997 Pierre Auger collaboration formed
- 1997–1999 Czech involvement negotiated
- 1997–2000 first projects in various countries, construction of engineering array started
- 2000–2004 construction of engineering array
- 2004–2008 construction of the main array
- **2004–2008 – construction of the fluorescence and HEAT telescopes with the Czech mirrors**
- **2004 construction of Czech FRAM telescope to monitor atmospheric conditions**
- **2004 –2010 – construction of the first Czech all-sky cameras**
- 2008–2014 full operation of the main array, preparation for the AUGER upgrade
- 2014 upgrade solution chosen
- 2014 international agreement regarding future operation of the Pierre Auger Observatory signed
- 2015 further plans regarding AUGER upgrade, proposal for climatic chamber in the Czech node
- 2015 FRAM in steady mode for observing showers within the Shoot-The-Shower program
- 2016 negotiations with MEYS about AUGER-CZ concluded and project LM2015038 started
- 2016 first upgraded detectors in the field of the Pierre Auger Observatory
- **2016 upgrade of the Czech all-sky cameras**
- **2017 climatic chamber installed in Prague for AUGERPrime electronics tests**
- **2017 The CTA Sun/Moon photometer has been temporarily installed to confirm the validity of the FRAM aerosol algorithms**
- **2018 In collaboration with the German partners we have worked on the preparation of the new device for the calibration of the fluorescence detectors**
- **2018 upgrade of FRAM finished**
- **2018 increased responsibility for creation of extensive libraries of simulated cosmic ray showers**
- **2019 partial installations on site in Argentina carried out for the new system for absolute calibration of the fluorescence detector**
- **2019 The first FAST telescope was installed at the Pierre Auger Observatory**
- **2020-2021 second FRAM system being produced and approved for the usage at the Observatory**
- **2020 first batches of 2000 UUBs being tested at the Prague laboratory**
- **2020 work on new calibration system for fluorescence telescopes continues together with the German partners**
- **2020 remote control room for fluorescence telescopes operation established in Prague**
- **2021 FRAMI at Coihueco**
- **2022 UUB tests (almost) finalized**

PIERRE AUGER OBSERVATORY

Data provided to the community – observatory level





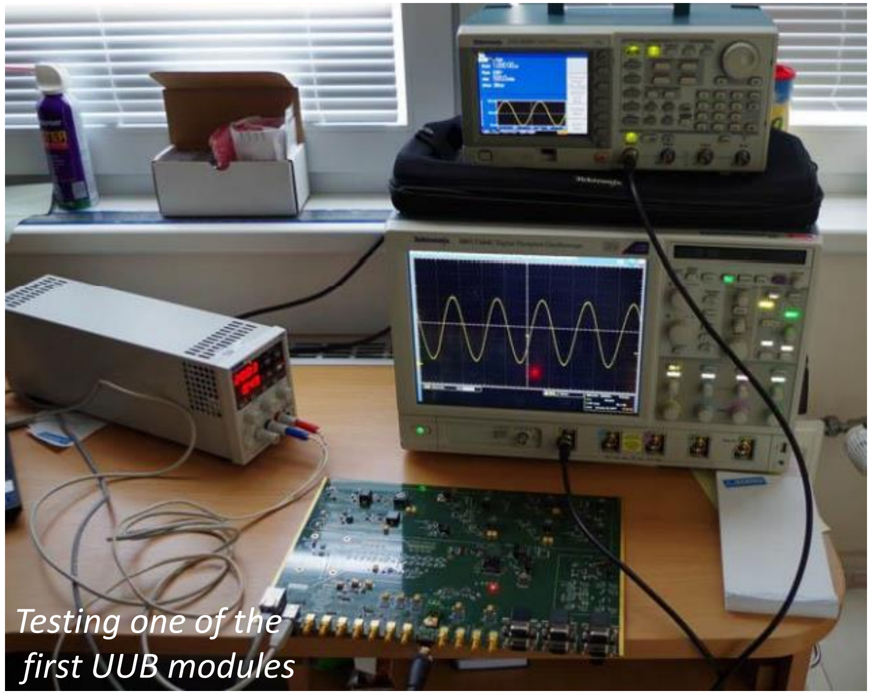
DATA:

Level 1 Open-access publication with additional numerical data provided to facilitate re-use;
Level 2 Regular release of cosmic-ray data in a simplified format, for education and outreach. This began in 2007 when 1% of the data was released and increased to 10% in 2019; increase to 50% under intensive discussion;
Level 3 Release of reconstructed cosmic-ray events, selected with the best available knowledge of the detector performance and conditions at the time of data-taking. Example codes derived from those used by the Collaboration for published analyses are also provided;
Level 4 Release of close-to-raw data associated with those events. An event-display, and codes to read these data, are also provided.

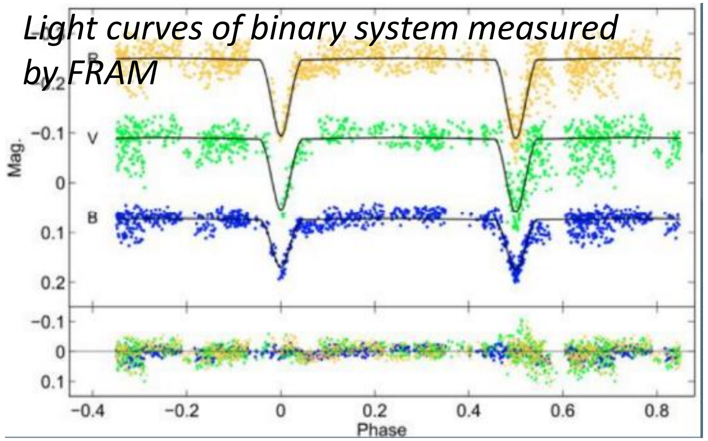
ACCESS TO OBSERVATORY:

Negotiable services to experts from other fields, such as climatology and atmospheric physics (interest also from CZ institutes)

Data provided to the community – AUGER-CZ level


Testing one of the first UUB modules


New installation of rack in computer farm

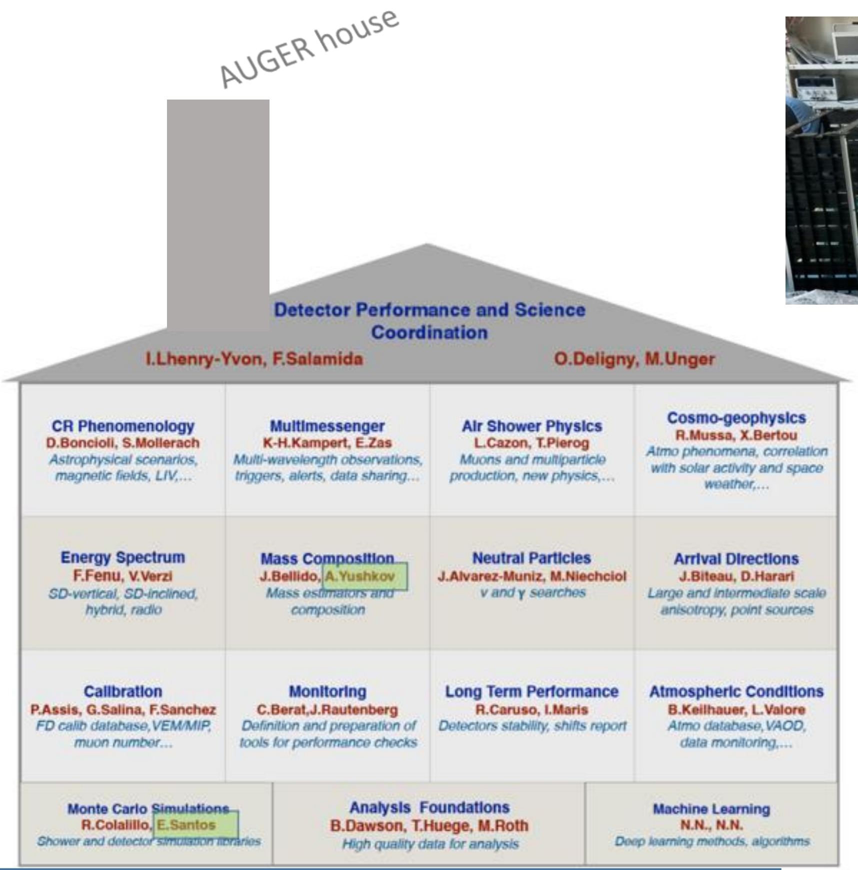


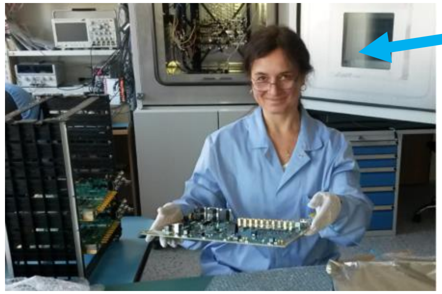
Light curves of binary system measured by FRAM

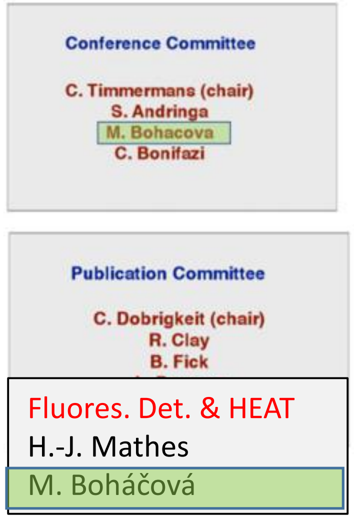
- Data from FRAM telescope are being made available to astronomers, including amateur astronomers
- Atmospheric monitoring data (FRAM and all sky cameras) are shared with the institutes in Pierre Auger Collaboration
- AUGER-CZ executing large-scale simulations of air shower development. These libraries are used by over 50 institutions worldwide. Most detailed library of cosmic ray air showers at ultra-high energies and further similar libraries are being developed.
- Grid VO AUGER founded and managed from Prague is supported by large computing centers around the globe
- The Joint Laboratory of Optics in Olomouc as a reference optical laboratory for the study of optical properties of various components of the detectors and their evolution in time. Tests of samples of mirrors and optical surfaces
- Testing of the electronics in laboratories in Prague for the entire collaboration

PIERRE AUGER OBSERVATORY

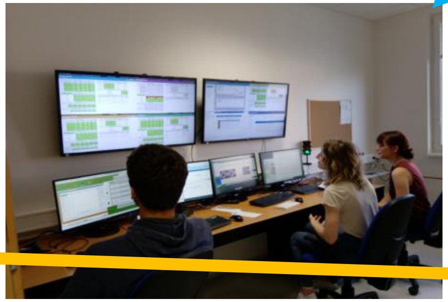
2023 – 2029, activities







- Before 2023 – finishing climate tests of new electronics in Prague
- Before 2023 – finishing installation of second FRAM at Coihueco
- 2023 – finishing installation of second FAST telescope
- 2023 - finishing deployment of AUGERPrime (CZ participates)
- 2024 – production and installation of the third FAST telescope
- 2023 – 2029 – operation of the upgraded Observatory
- 2023 – 2029 – continuing **responsibility** for fluorescence detector system including operator shifts onsite and remote
- 2023 – 2029 participation during calibration campaigns using new XY scanner
- 2023 – 2029 – continuing **responsibility** in Monte Carlo simulation tasks and scientific group regarding mass composition



Our people in AUGER house

Martina Bohacova
Task leader of FD

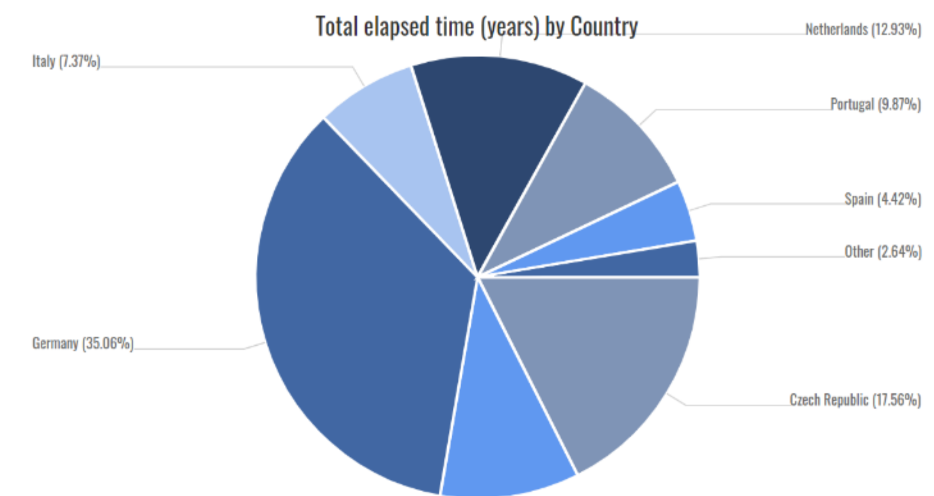
Alexey Yushkov
Task leader of mass composition

Eva Santos
Task leader of MC simulation

VO auger – already 11 years

General information

Name	auger
Status	Production
Validation date	2011-05-30
Last change	2022-09-26
Discipline	• Natural Sciences ◦ Physical sciences ▪ Astrophysics global ▪ Particle physics global ▪ Physics global
Enrollment Url	https://perun.metacentrum.cz/perun-registrar-cert/?vo=au



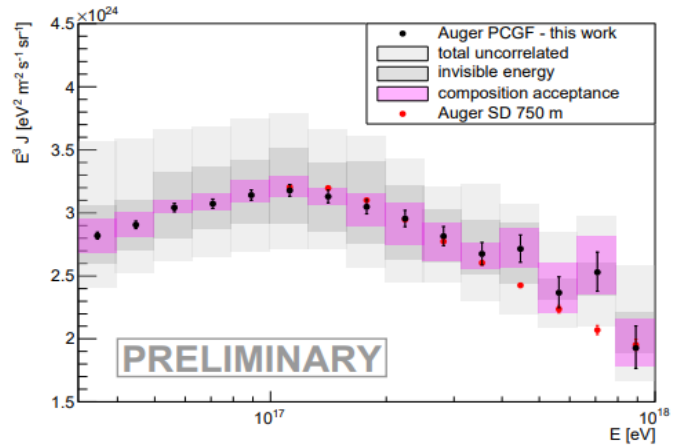
Let us centralize Auger MC production

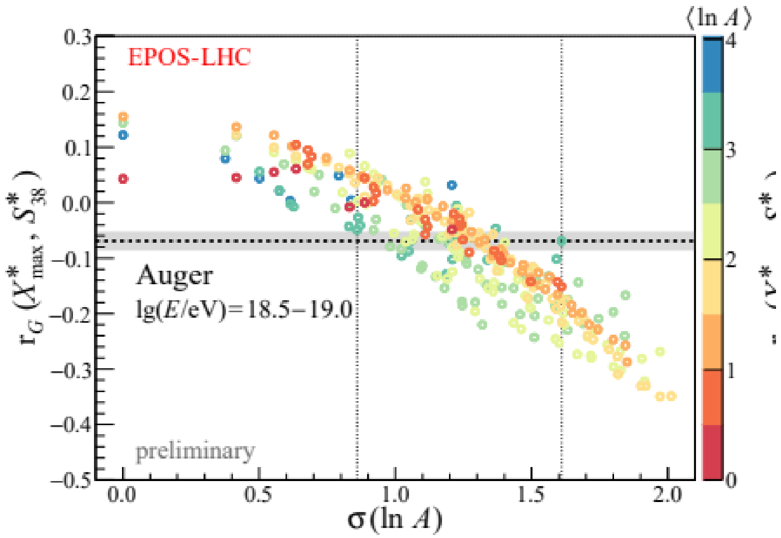
What about to use LHC know-how and move Auger simulations to grid? VO auger !

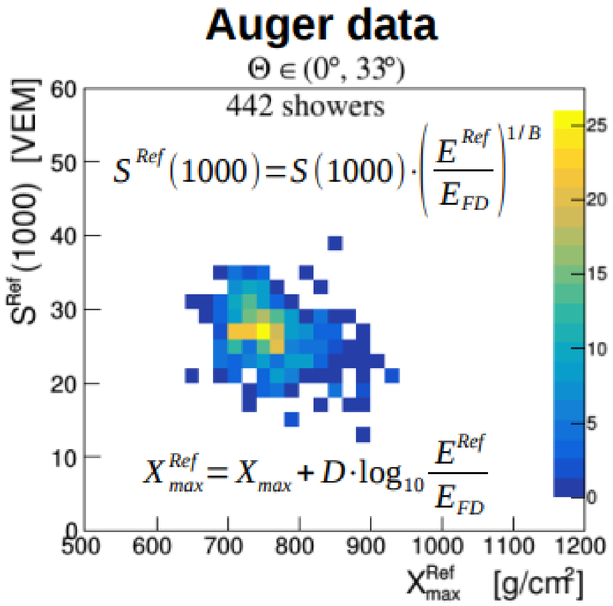
Is it enough if I prepare first production and GUI within a month?

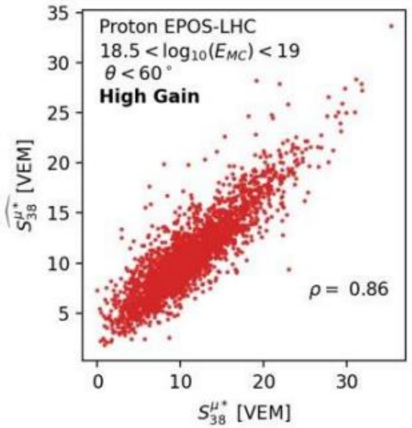
Physics analyses - CZ

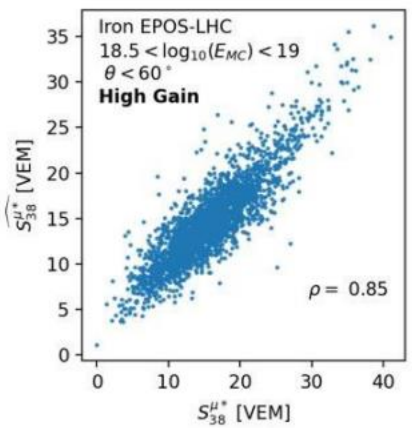
- Hadronic interactions
- Cosmic ray composition
- Arrival directions
- Energy spectrum – low energy extension
- Muon Production Depth
- Muon puzzle
- …







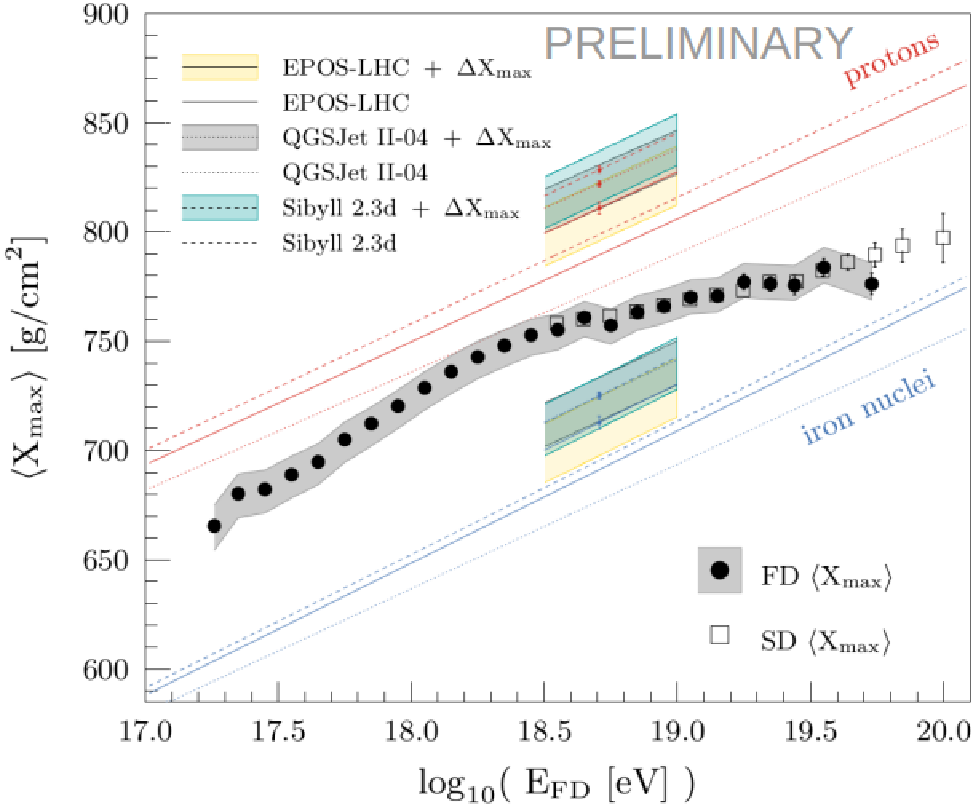


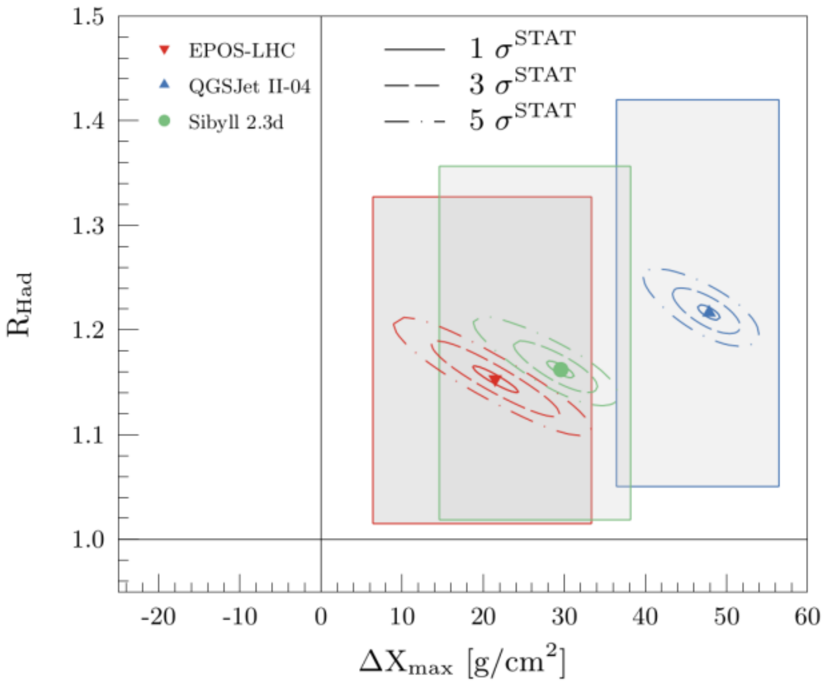


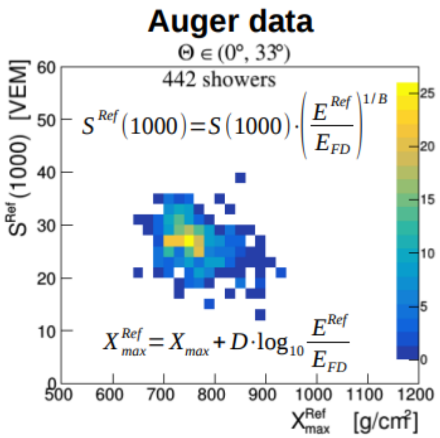
Ongoing Physics Analyses

Testing Model Predictions of Depth of Air-Shower Maximum and Signals in Surface Detectors using Hybrid Data of the Pierre Auger Observatory

Jakub Vícha[a] for the Pierre Auger Collaboration[b]







Global fit method

Simultaneous likelihood ratio fit of **two-dimensional distributions** of X_{max} and S(1000) in 5 zenith-angle bins with **MC templates** for combinations of four primary nuclei (p,He,O,Fe)

New !

Ongoing Physics Analyses

6th International Symposium on Ultra High Energy Cosmic Rays
UHECR 2022
L'Aquila, Italy October 3 - 7 2022

A Study of Modified Characteristics of Hadronic Interactions (MOCHI)

Jiri Blazek, Jan Ebr, Jakub Vicha, P. Travnicek, T. Pierog

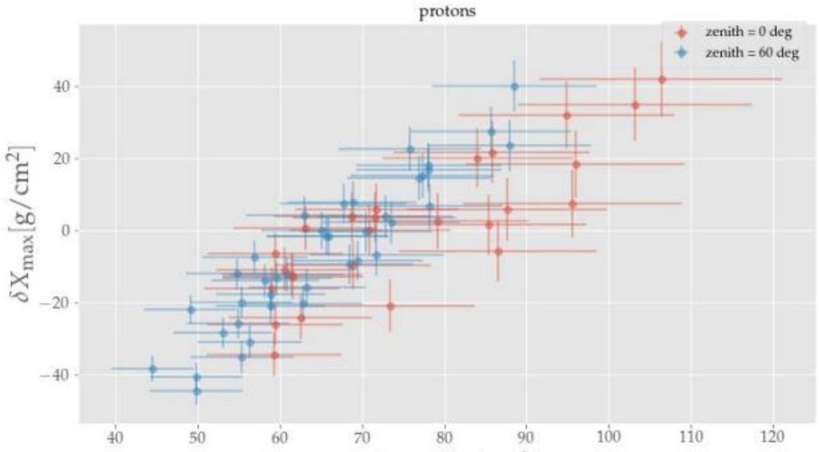
Parameters we try to modify:

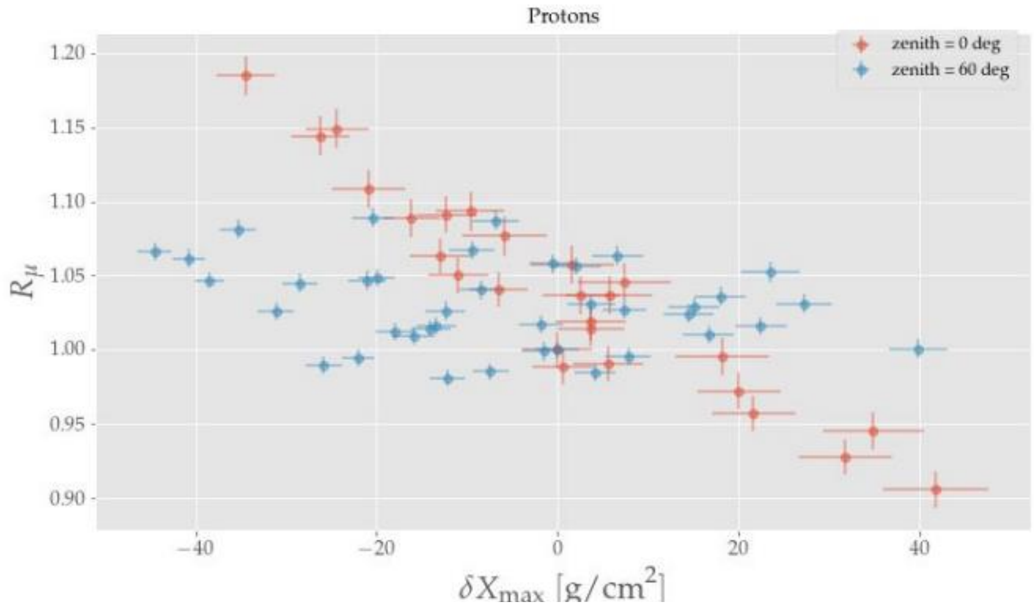
- Cross section (interaction length)
- Elasticity $\kappa_{el} = E_{leading}/E_{tot}$
- Multiplicity, the total number of particles escaping the interaction

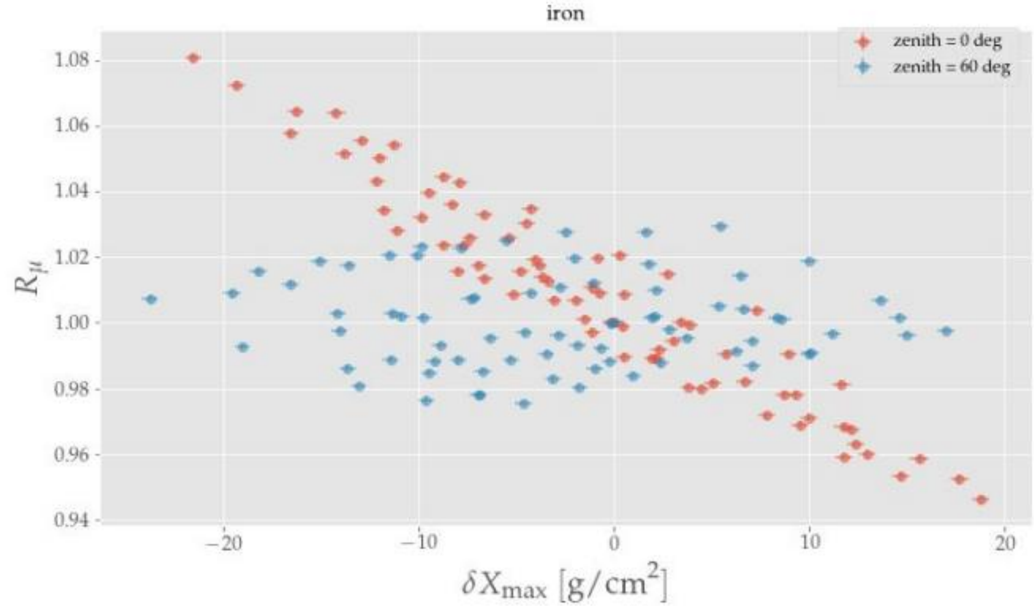
Ansatz for modification:

$$f(E, f_{19}) = 1 + (f_{19} - 1) \cdot F(E)$$

$$F(E) = \frac{\log_{10}(E/E_{thr})}{\log_{10}(10\,\mathrm{EeV}/E_{thr})}$$





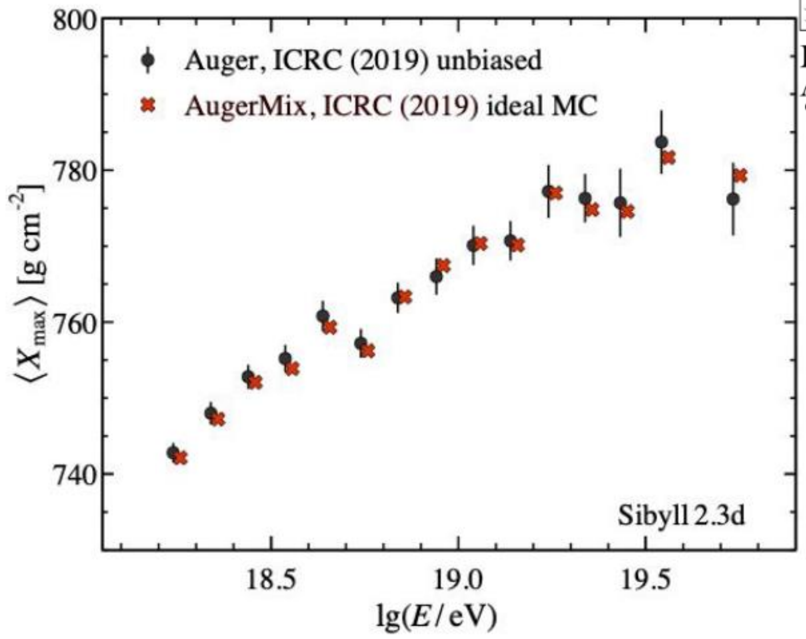


Ongoing Physics Analyses

Testing the Compatibility of the Depth of the Shower Maximum Measurements performed at Telescope Array and the Pierre Auger Observatory

Auger-TA Mass Composition Working Group Report

D.R. Bergman, J. Bellido, V. de Souza, R. Engel, Z. Gerber, J.H. Kim, E. Mayotte, O. Tkachenko, M. Unger, A. Yushkov for the TA and Auger collaborations



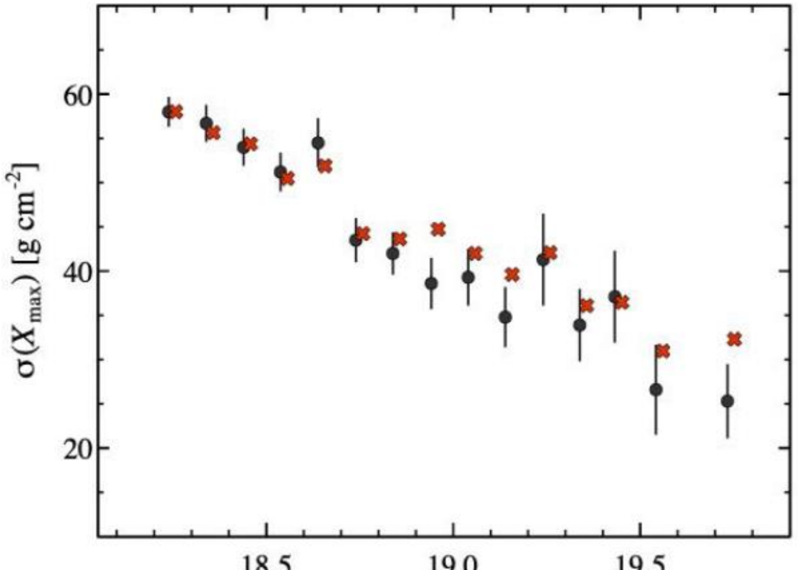
Conclusion

We have constructed a representation of Auger X_{max} measurements as would have been seen in the TA detector using the Sibyll 2.3d high-energy interaction model.

This representation agrees with TA $<X_{max}>$ measurements well, but there is disagreement at some energies in $\sigma(X_{max})$. This disagreement is plausibly due to the handling of X_{max} resolution due to varying aerosols at TA

A robust difference between the Auger and TA X_{max} measurements **has not been found**

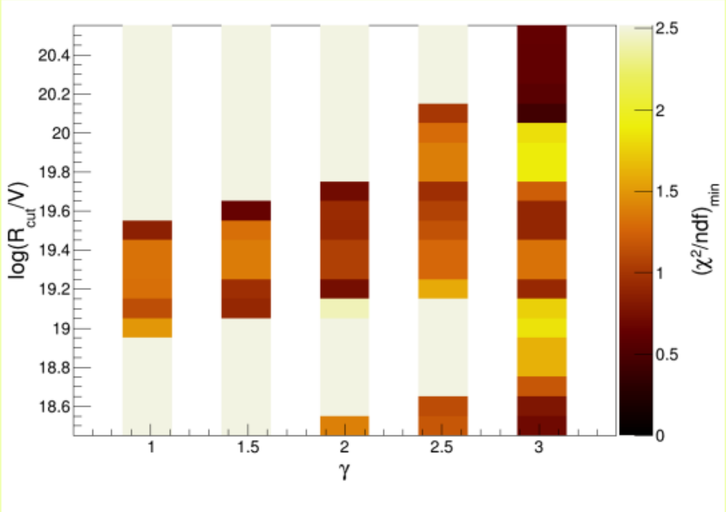
A journal publication from the Mass Composition Working Group is forthcoming

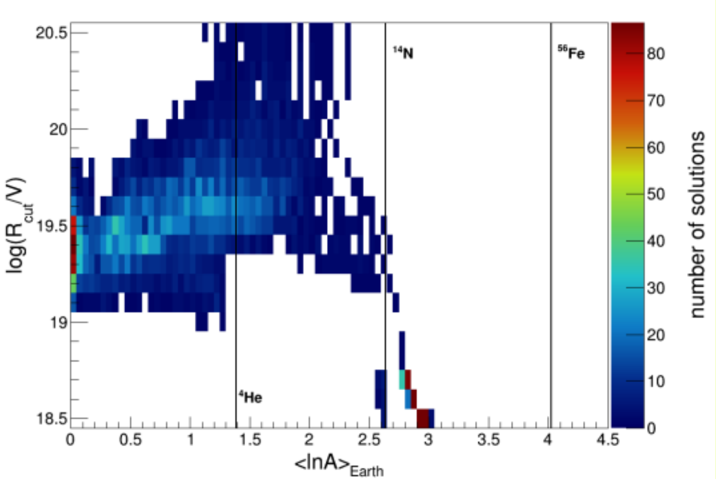


Ongoing Physics Analyses

Single source scenario describing the very end of the cosmic-ray energy spectrum

Alena Bakalová, Petr Trávníček, Jakub Vícha
FZU – Institute of Physics of the Czech Academy of Sciences

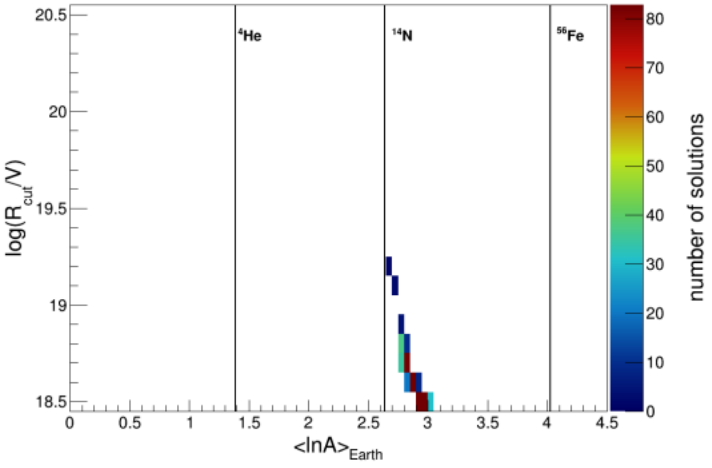


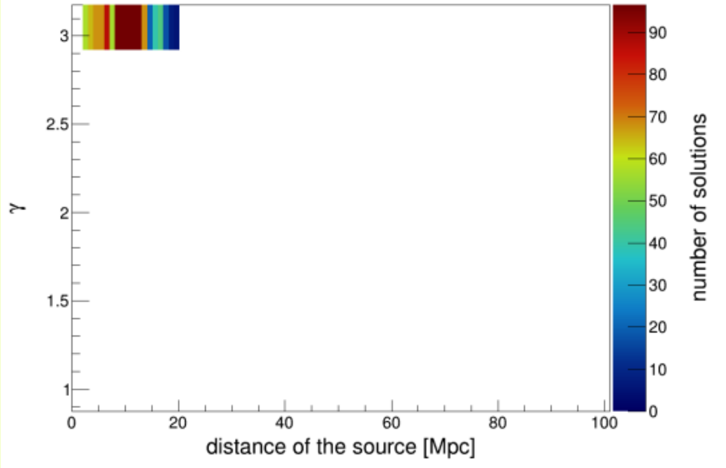


- 1D propagation of particles from a source to the Earth in CRPropa 3 [1]
- Interactions of cosmic rays with CMB and EBL background
  - Photo-pion production
  - Electron pair production
  - Photodisintegration
  - + nuclear decay and redshift energy losses
- Four primary particles: H, He, N, Fe
- Power-law energy spectrum with minimal energy $\log_{10}(E_{min}/eV) = 19.5$ and maximum rigidity $\log_{10}(R_{max}/V) = 20.5$

$\langle \ln A \rangle \gtrsim 2.6$

$\sigma^2(\ln A) \leq 0.5$





4. CONCLUSIONS

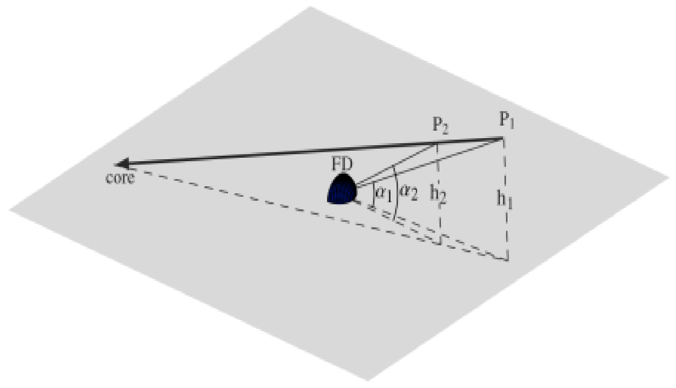
We find it is possible to describe the shape of the energy spectrum of cosmic rays measured by the Pierre Auger Observatory above $10^{19.5}$ eV by a single source with various source features in R_{cut}, γ and mass composition mix. When applying additional conditions on the mass composition on the Earth (heavy with low mixing) we restrict the number of possible solutions and find that such a source needs to be within 20 Mpc from the Earth, with rigidity cutoff $\log_{10}(R_{cut}/V) \leq 19.3$ and spectral index $\gamma \approx 3$.

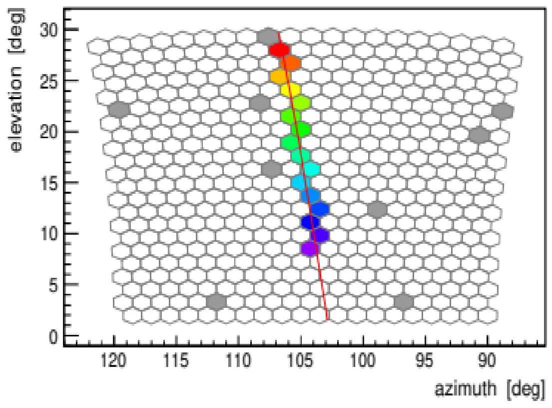
Ongoing Physics Analyses

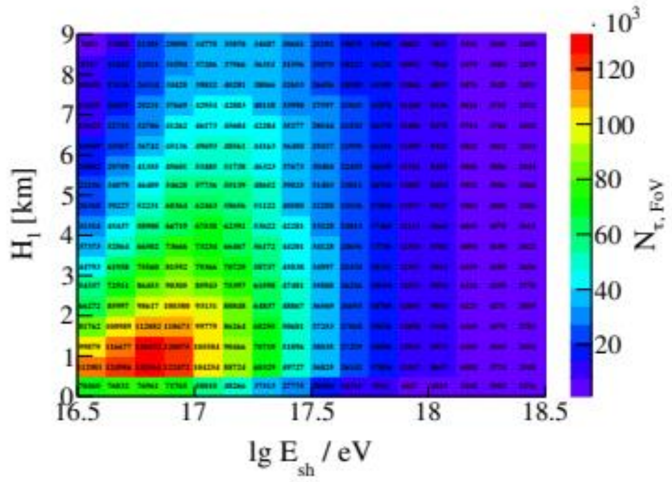
Search for upward-going showers with the Pierre Auger Observatory

Vladimír Novotný[a] for the Pierre Auger Collaboration[b]

[a]Institute of Particle and Nuclear Physics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[b]Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina
e-mail: spokespersons@auger.org
Full author list: https://www.auger.org/archive/authors_2022_10.html







Conclusions

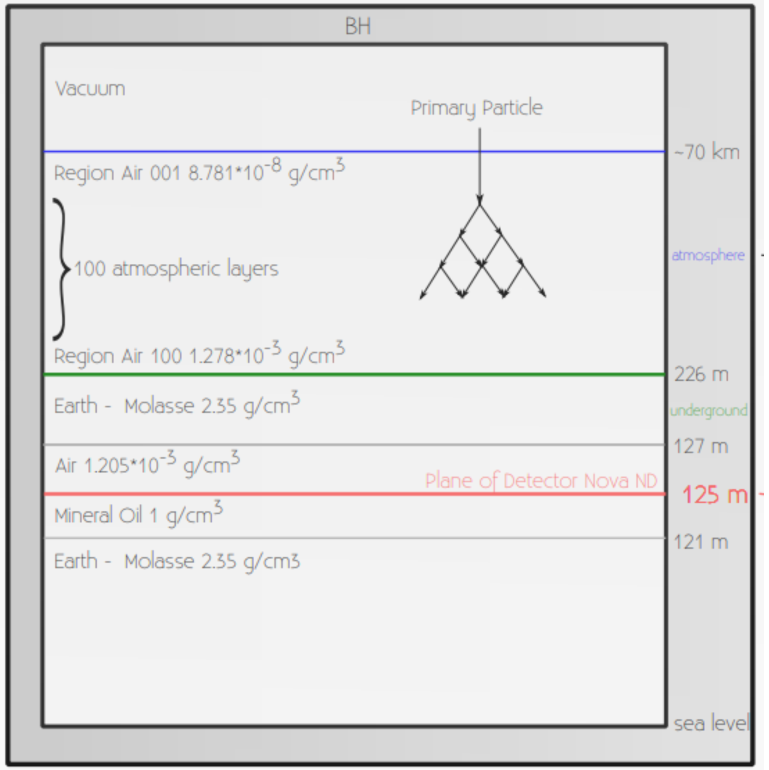
The data of 14 years of operation of the fluorescence detector of the Pierre Auger Observatory have been searched for upward-going showers with zenith angles between $110° - 180°$. One candidate event has been found, which is compatible with the background expectation of 0.45 ± 0.18 events, coming from wrongly reconstructed downward-going cosmic-ray showers. Integral upper limits on the flux of upward-going showers were determined for two spectral indices, $\gamma = 1, 2$, used in the calculation of an average exposure. The double-differential exposure of the fluorescence detector was presented, and was applied to derive upper limits on the τ lepton emergence near the ground.

Ongoing Physics Analyses

On the mystery of the multi-muon flux at the TeV cosmic-ray energy range

Jordi Tuneu[a] Eva Santos[a] Peter Filip[a]
[a]FZU - Institute of Physics of the Czech Academy od Sciences

FLUKA MODEL



CONCLUSIONS

We performed detailed atmospheric Monte Carlo simulations to treat the transport and interactions of primary and secondary particles in different media:

- Primary protons with different zenith angles show different profiles for winter and summer atmospheres modeled.
- Even though the number of muons passing through the detector plane is similar in winter and summer. Other factors like primary particle energy, zenith angle, and radial distance of the impact seem relevant to answer the work from [2].
- The preliminary results are from 100 TeV proton-initiated shower simulations. The complete dataset comprises more energetic showers up to 100 PeV involving randomized azimuth angles in a 360-degree range and other primary particle species. Full production is now running.
- This work may hint at problems in Monte Carlo simulation codes describing the multi-muon flux at several underground detectors.

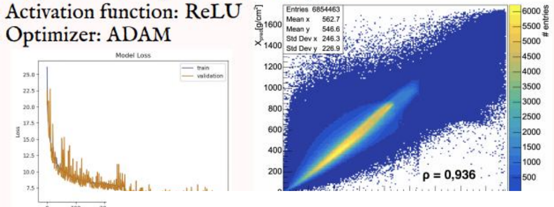
Ongoing Physics Analyses

Reconstruction of the muon production longitudinal profiles in extensive air showers

Antonín Kravka[1], Eva Santos[2], Alexey Yushkov[2]
[1]Czech Technical University - Faculty of Nuclear Sciences and Physical Engineering, Czech Republic
[2]FZU - Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

DNN performance

- Fully Connected Neural Network
  - 6 hidden layers
    - pyramid scheme (1024 ⟶ 32 nodes)
  - Activation function: ReLU
  - Optimizer: ADAM



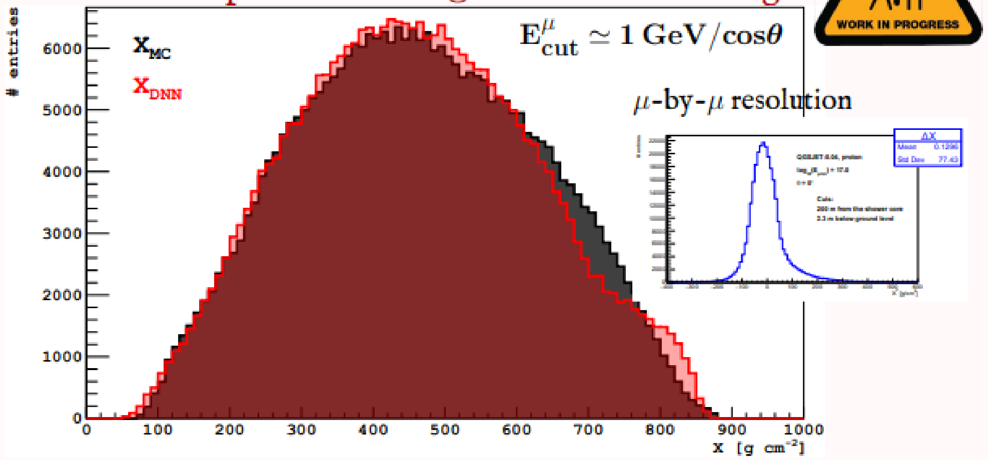
Summary and Conclusions

- We are working on an extension of the method proposed in [1,
  - $\theta < 60^\circ$
  - $r > 200$ m
  - $E > 10^{17}$eV
- Kinematic delay estimation is the largest source of systematic u
- Our kinematic delay parametrization obtained from fully conn
  - For muons reaching the ground and at 2.3 m depth
  - μ-by-μ reconstruction @ 2.3 m:
    - $\langle \Delta X \rangle < 10$ g cm^{-2}, $\sigma(\Delta X) \sim 80$ g cm^{-2}

Buried detectors improve the MPD reconstruction due to the removal of the electromagnetic contamination and low-energy muon component

Results - MPD @ 2.3m depth

2.3 m provide ~ 550 g cm^{-2} extra shielding



10^{17} eV proton initiated shower, zenith angle $\theta = 0^\circ$

Ongoing Physics Analyses

Extraction of the muon signals recorded by the Surface Detector of the Pierre Auger Observatory using Neural Networks

Margita Majercakova

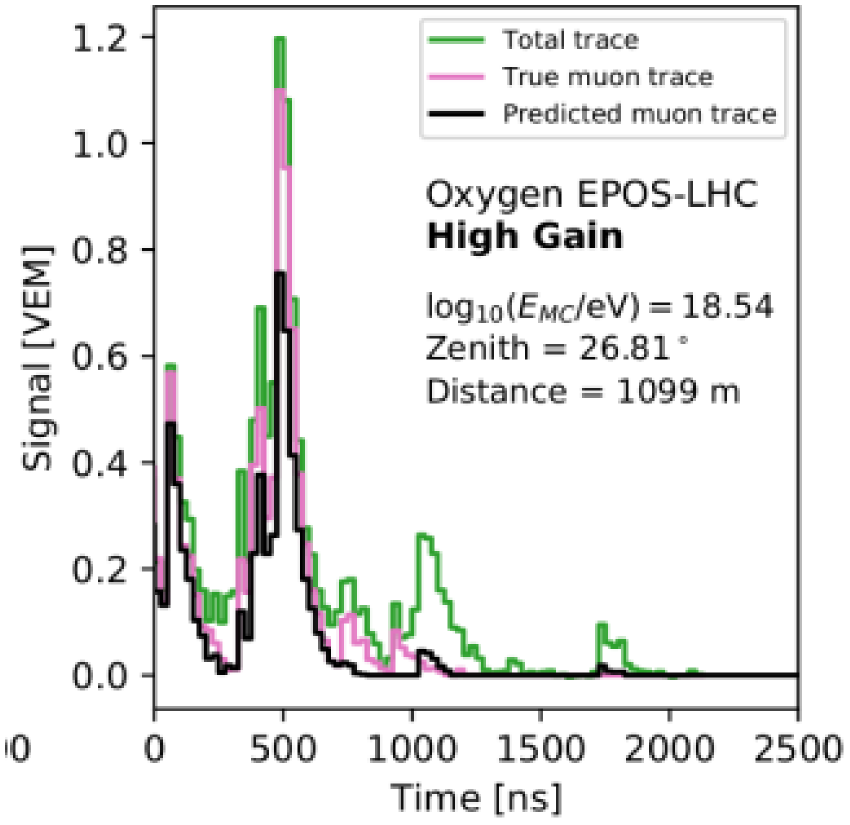
Conclusions

- Two types of neural networks were used to extract muon signal from Auger SD stations– FeedForward and Recurrent
- The largest biases on muon signal come from the stations at small distances to the shower core, dominated by an electromagnetic component producing smooth traces
- NN trained on Sibyll 2.3c was also tested on a different model (EPOS-LHC), no change in the muon signal biases was found
- **Muon signal and risetime can be extracted with a good accuracy for a certain ranges of distances to the shower core and zenith angles**
- The preliminary data application suggests the muon deficit in simulations (well-known problem)

Future plans

- Optimization of the network performances: architecture, input variables, application phase space
- Study of systematic uncertainties
- Application to the Auger and Auger upgrade (AugerPrime) data with the aim of publishing of the results on behalf of the Collaboration
- ...

Margita Majerčáková



Signal [VEM]

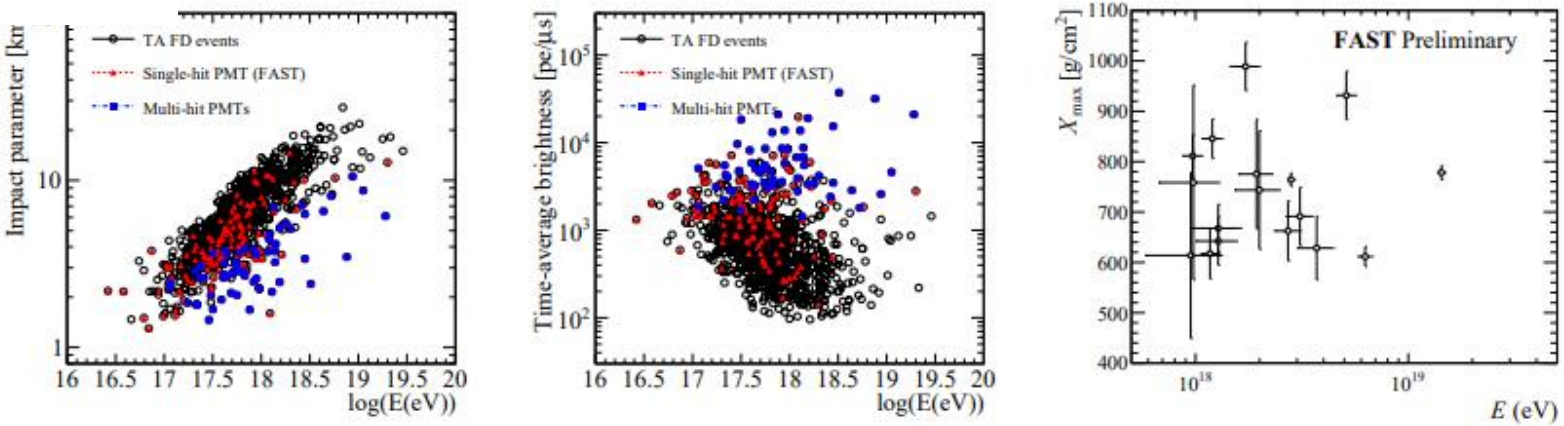
Ongoing Physics Analyses

PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Latest results of ultra-high-energy cosmic ray measurements with prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST)

Toshihiro Fujii,[a,b,*] Justin Albury,[c] Jose Bellido,[c] Ladislav Chytka,[d] John Farmer,[e] Petr Hamal,[d] Pavel Horvath,[f] Miroslav Hrabovsky,[d,f] Hidetoshi Kubo,[b] Jiri Kvita,[f] Max Malacari,[e] Dusan Mandat,[d,f] Massimo Mastrodicasa,[g] John Matthews,[h] Stanislav Michal,[d] Xiaochen Ni,[e] Seiya Nozaki,[b] Libor Nozka,[d] Tomohiko Oka,[b] Miroslav Palatka,[d] Miroslav Pech,[d] Paolo Privitera,[e] Petr Schovanek,[d] Francesco Salamida,[g] Radomir Smida,[e] Stan Thomas,[h] Akimichi Taketa,[i] Kenta Terauchi,[b] Petr Travnicek,[d,f] Martin Vacula[f] and Seokhyun Yoo[b]

(a) FAST prototypes installed at TA and Auger observatories



AUGER-CZ team thanks you for your attention

Relatively young team

Collaboration with Czech industry

Internationalization and significant team strengthening during last 5 years

Broad portfolio of activities in outreach including TV movie

Students come from 4 universities:

Backup slides

02

Pierre Auger Observatory – selected publications

[1] The Pierre Auger Collaboration, The Pierre Auger Cosmic Ray Observatory, Nucl. Instrum. Meth. A 798 (2015) 172 - 213.

[2] J. Ebr, J. Řídký, P. Nečesal, Soft particle production in very high energy hadron interactions, Astropart Phys. 90 (2017) 37 - 49.

[3] The Pierre Auger Collaboration, Testing Hadronic Interactions at Ultrahigh Energies with Air Showers Measured by the Pierre Auger Observatory, Phys. Rev. Lett. 117 (2016) 192001(1) - 192001(9).

[4] The Pierre Auger Collaboration, Evidence for a mixed mass composition at the 'ankle' in the cosmic-ray spectrum, Phys. Lett. B 762 (2016) 288 - 295.

[5] J. Vícha, P. Trávníček, D. Nosek, J. Ebr, Study of Dispersion of Mass Distribution of Ultra-High Energy Cosmic Rays using a Surface Array of Muon and Electromagnetic Detectors, Astropart Phys. 69 (2015) 11 - 17.

[6] D. Nosek, J. Ebr, J. Vícha, P. Trávníček, J. Nosková, Maximum entropy analysis of cosmic ray composition, Astropart Phys. 76 (2016) 9 - 18.

[7] J. Vícha, A. Yushkov, P. Trávníček, E. dos Santos, Testing Hadronic Interactions Using Hybrid Observables, Proceedings of Science, Volume 358 (2019) 452, Proceedings of 36th International Cosmic Ray Conference - ICRC2019, July 24th - August 1st, 2019, Madison, WI, U.S.A.

[8] A. Yushkov for the Pierre Auger and Telescope Array Collaborations, Depth of maximum of air-shower profiles: testing the compatibility of measurements performed at the Pierre Auger Observatory and the Telescope Array experiment, EPJ Web of Conferences 210 (2019) 01009(1)-01009(7). 210 (2019) 01009(1)-01009(7).

[9] A. Bakalová, P. Trávníček, J. Vícha, Influence of the Galactic Magnetic Field on Large-scale Anisotropies of Ultra-high Energy Cosmic Rays, Proceedings of Science, Volume 358 (2019) 183, Proceedings of 36th International Cosmic Ray Conference - ICRC2019, July 24th - August 1st, 2019, Madison, WI, U.S.A.

[11] P. Abreu et al. (J. Řídký, P. Trávníček, J. Vícha), MARTA: a high-energy cosmic-ray detector concept for high-accuracy muon measurement, Eur. Phys. J. C 78 (2018) 333(11) - 333(11).

[12] FAST collaboration, Detection of ultra-high energy cosmic ray showers with a single-pixel fluorescence telescope, Astropart Phys. 74 (2016) 64 - 72.

[13] The Pierre Auger Collaboration: Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8 x 10(18) eV: Science 357 (2017) 1266 - 1270.

[14] The Pierre Auger Collaboration, An Indication of Anisotropy in Arrival Directions of Ultra-high-energy Cosmic Rays through Comparison to the Flux Pattern of Extragalactic Gamma-Ray Sources: Astrophys. J. Lett. 853 (2018) L29(1).

02 Instruments for atmospheric calibration of astroparticle experiments – selected publications

[20] J. Blazek et al., Searching for Anomalous Longitudinal Profiles with the FRAM Telescope, EPJ Web of Conferences, 144 (2017) 01009 (4pp), Proceedings of the International Workshop on ATmospheric MOnitoring for High Energy Astroparticle Detectors (AtmoHEAD), Olomouc, CZECH REPUBLIC, SEP 12-14, 2016.

[21] J. Blažek for the Pierre Auger Collaboration (z FZU: J. Blažek), The FRAM Telescope at the Pierre Auger Observatory, Proceedings of 35th International Cosmic Ray Conference - ICRC2017, PoS ICRC2017 (2018) 362.

[22] J. Ebr, J. Blažek, M. Prouza, D. Mandát, M. Pech for the Pierre Auger Collaboration, M. Mašek, J. Juryšek, P. Janeček, P. Kubánek, J. Eliášek, M. Jelínek, I. Ebrová, Aerosol Measurements with the FRAM Telescope, EPJ Web of Conferences 144 (2017) 01011(1)-01011(9). Proceedings of the International Workshop on ATmospheric MOnitoring for High Energy Astroparticle Detectors (AtmoHEAD), Olomouc, CZECH REPUBLIC, SEP 12-14, 2016, ISSN 2100-014X.

[23] C. Fruck, M. Gaug, J.-P. Ernenwein, D. Mandát, T. Schweizer, D. Häfner, T. Bulik, M. Cieslar, H. Costantini, M. Dominik, J. Ebr, M. Garczarczyk, Lorentz, G. Pareschi, M. Pech, I. Puerto-Giménez, M. Teshima, Instrumentation for comparing night sky quality and atmospheric conditions of CTA site candidates, JINST 10 (2015) P04012(1).

[24] P. Janeček, M. Prouza, J. Ebr, FRAM for CTA, 2nd Conference on Atmospheric Monitoring for High Energy AstroParticle Detectors, AtmoHEAD 2014, EPJ Web Conf. 89 (2015) 03006.

[25] Petr Janeček, Jan Ebr, Jiří Blažek, Michael Prouza, Martin Mašek, Jiří Eliášek, (for the CTA Consortium), FRAM for the Cherenkov Telescope Array: an update, EPJ Web of Conferences 144 (2017) 01012. Proceedings of the International Workshop on ATmospheric MOnitoring for High Energy Astroparticle Detectors (AtmoHEAD),Olomouc, CZECH REPUBLIC, SEP 12-14, 2016, ISSN 2100-014X.

Instruments for atmospheric calibration of astroparticle experiments – selected publications

[26] P. Janeček et., FRAM telescopes and their measurements of aerosol content at the Pierre Auger Observatory and at future sites of the Cherenkov Telescope Array , EPJ Web of Conferences, 197 (2019) 02008 (4pp), ATMOSPHERIC MONITORING FOR HIGH ENERGY ASTROPARTICLE DETECTORS (ATMOHEAD) 2018, Proceedings of the International Workshop on Atmospheric Monitoring for High Energy Astroparticle Detectors (AtmoHEAD), Anacapri, Italy, SEP 24-26, 2018. ISSN: 2100-014X.

[27] J. Ebr, et al., New developments in aerosol measurements using stellar photometry, EPJ Web of Conferences, 197 (2019) 02007 (4pp), ATMOSPHERIC MONITORING FOR HIGH ENERGY ASTROPARTICLE DETECTORS (ATMOHEAD) 2018, Proceedings of the International Workshop on Atmospheric Monitoring for High Energy Astroparticle Detectors (AtmoHEAD), Anacapri, Italy, SEP 24-26, 2018. ISSN: 2100-014X.

[28] S. Karpov, R. Cunniffe, J. Ebr, P. Janecek, Testing the nonlinearity of the Moravian Instruments G4-16000 CCD camera, As. Na. 339 (2018) 391 - 396.

[29] M. Prouza, et al., Prototype operations of atmospheric calibration devices for the Cherenkov Telescope Array , Proceedings of Science, Volume 358 (2019) 769, Proceedings of 36th International Cosmic Ray Conference - ICRC2019, July 24th - August 1st, 2019, Madison, WI, U.S.A

[30] J. Juryšek a M. Prouza, Sun/Moon photometer for Cherenkov Telescope Array – first results, Proceedings of Science 301 (2017) 1-8.

[31] J. Ebr, et al. Atmospheric calibration of the Cherenkov Telescope Array, Proceedings of Science, 2017, Vol. 301, pp. 833(1)-389(8), Proceedings of 35th International Cosmic Ray Conference - ICRC2017, 10-20 July, 2017, Bexco, Busan, Korea.

[32] J. Ebr, et al, Characterization of atmospheric properties at the future sites of the Cherenkov Telescope Array, Proceedings of Science, Volume 358 (2019) 667, Proceedings of 36th International Cosmic Ray Conference - ICRC2019, July 24th - August 1st, 2019, Madison, WI, U.S.A.

Selected scientific outputs using data of the Pierre Auger Observatory - Energy spectrum

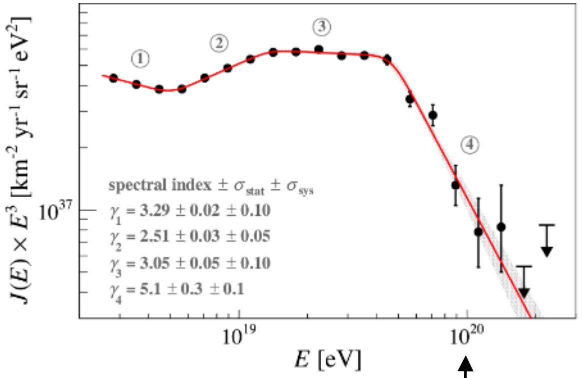
New feature in the energy spectrum - possible to be explained with rigidity dependent cutoff

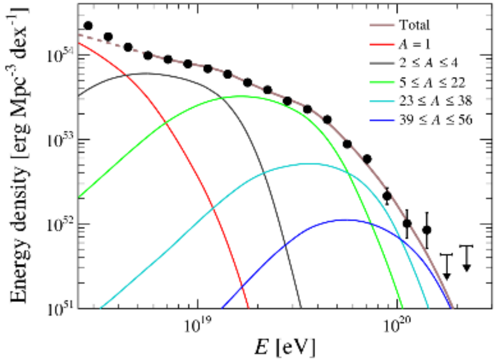
[Phys. Rev. Lett. 125 (2020) 121106](#)

[Phys. Rev. D 102 (2020) 062005](#)

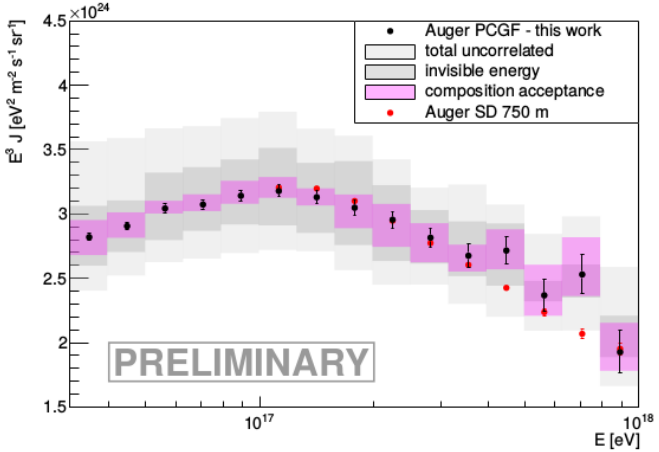
Low-energy extension using Cherenkov-dominated events

PoS(ICRC2019)374





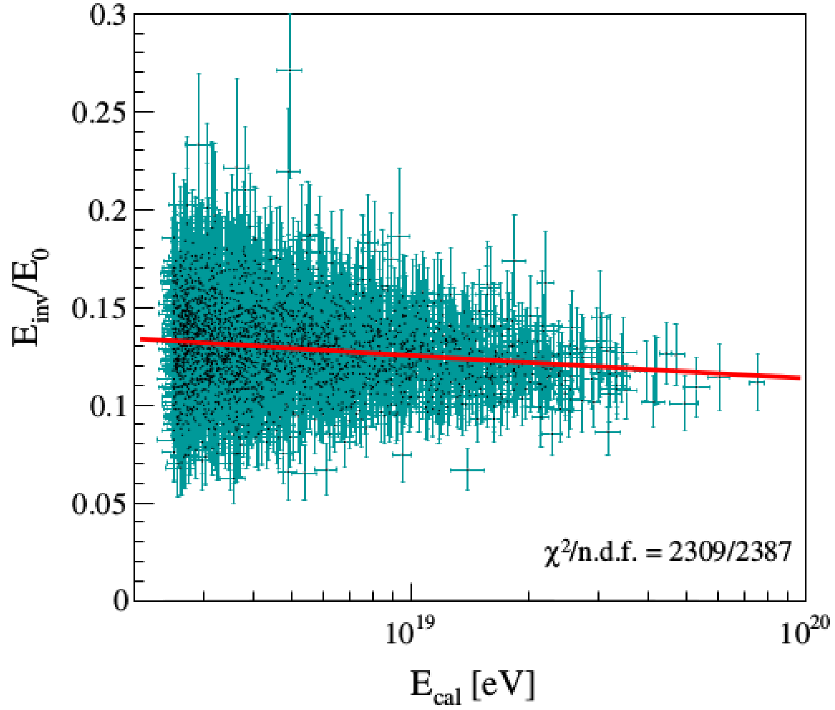
√s≈400 TeV !

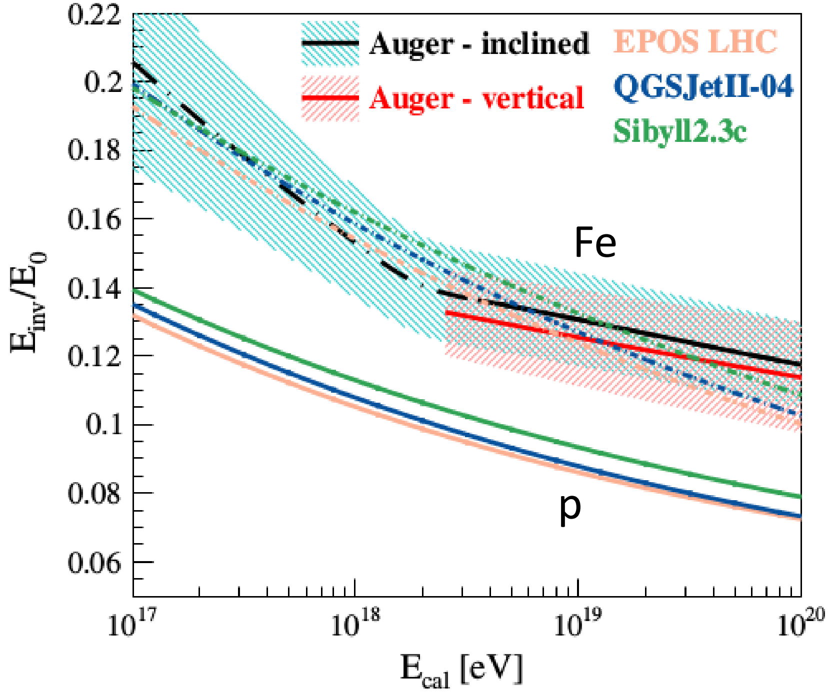


Selected scientific outputs using data of the Pierre Auger Observatory – Hadronic interactions I

Data-driven estimation of the invisible energy

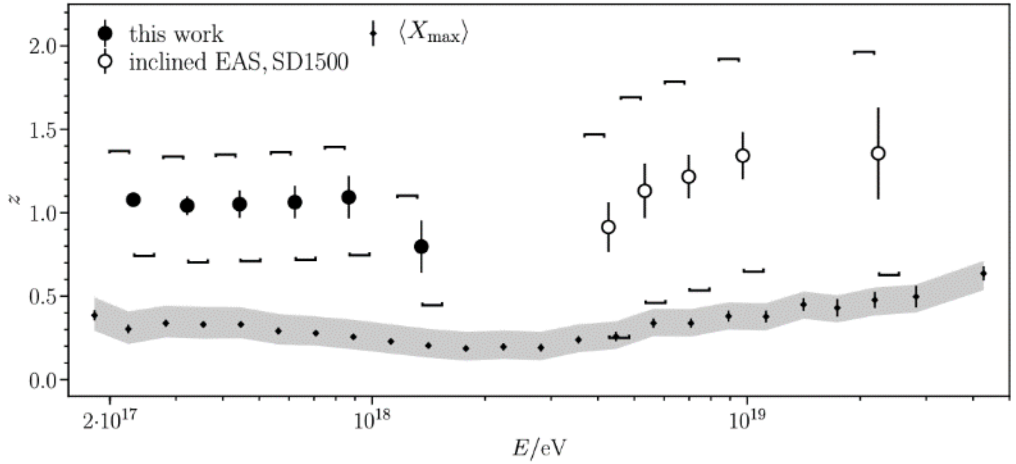
- higher than model predictions
- [Phys. Rev. D 100 (2019) 082003](#)





Selected scientific outputs using data of the Pierre Auger Observatory – Hadronic interactions II

$z = \frac{\langle \ln x\rangle - \langle \ln x\rangle_p}{\langle \ln x\rangle_{Fe} - \langle \ln x\rangle_p}$; x represent muon density

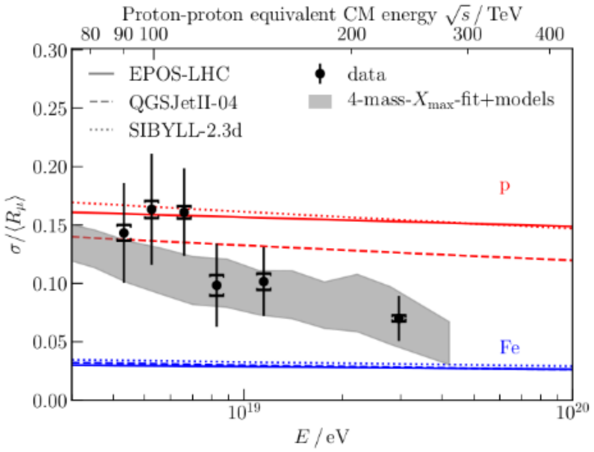


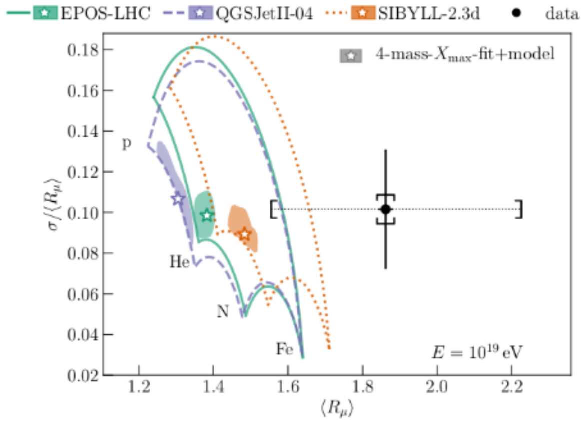
Problem in AMIGA muons

- Inconsistency with shower description using fluorescence and surface data
- [Eur. Phys. J. C 80 (2020) 751]

No problem in muon fluctuations

- Muon problem rather cumulative effect than only first interaction problem
- [Phys. Rev. Lett. 126 (2021) 152002]





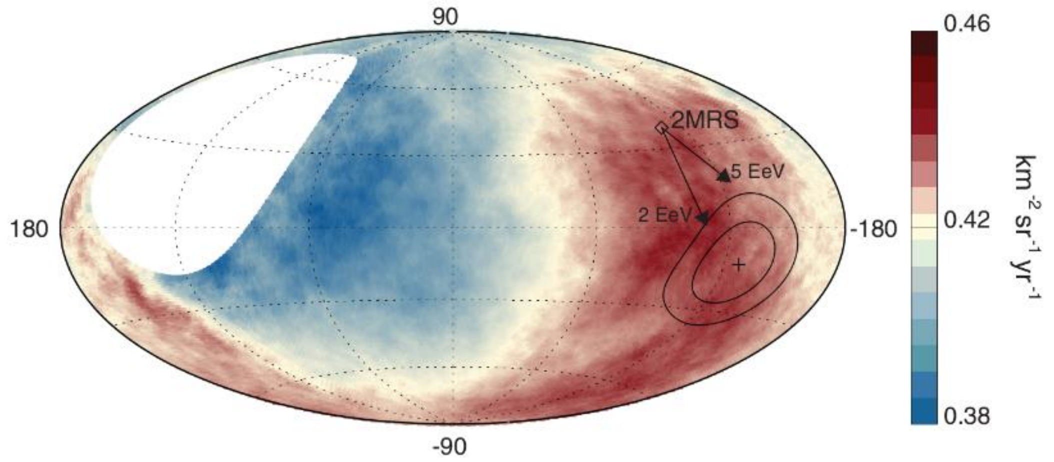
Selected scientific outputs using data of the Pierre Auger Observatory – Anisotropies I

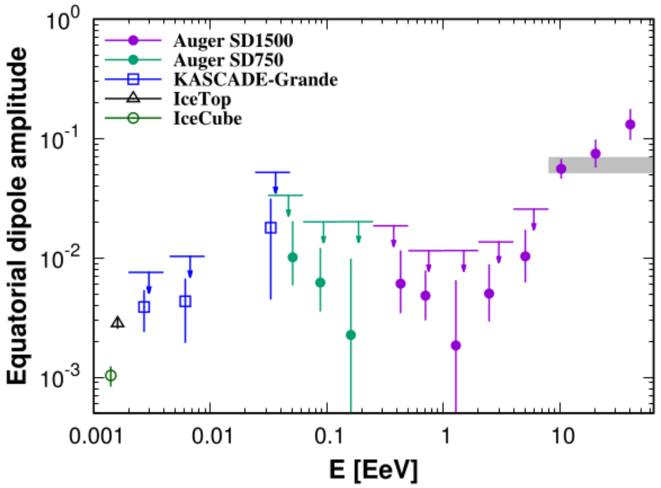
5σ dipole in arrival directions above 8 EeV with direction ~120° from Galactic center

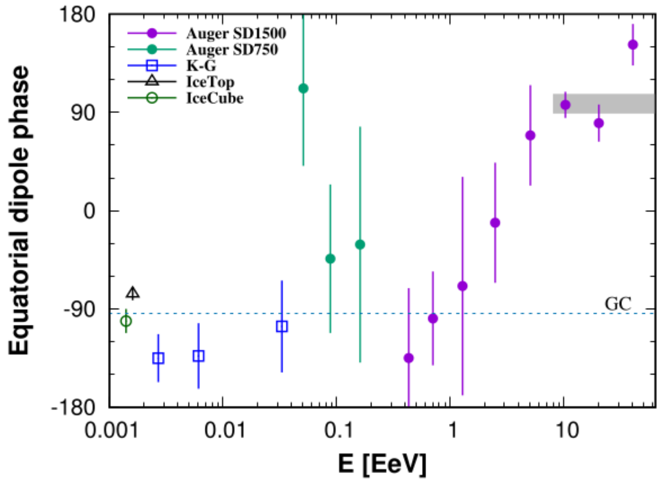
- evidence of extragalactic origin
- Science 357 (2017) 1266

Energy evolution of dipole anisotropies

- Transition from Galactic center direction
- ApJ 891 (2020) 142



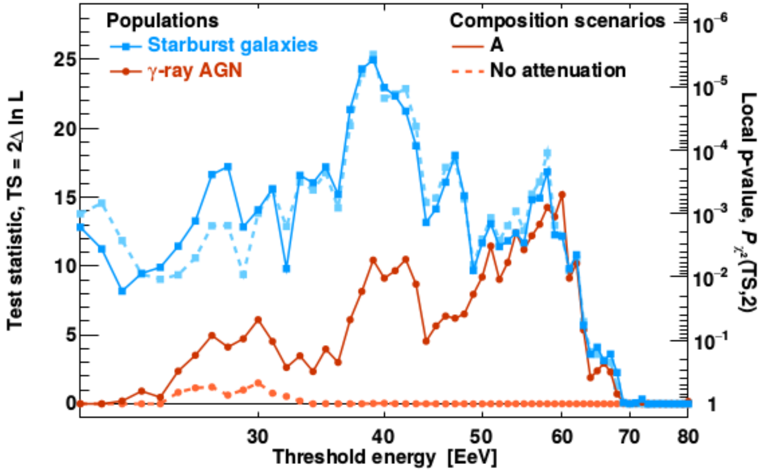


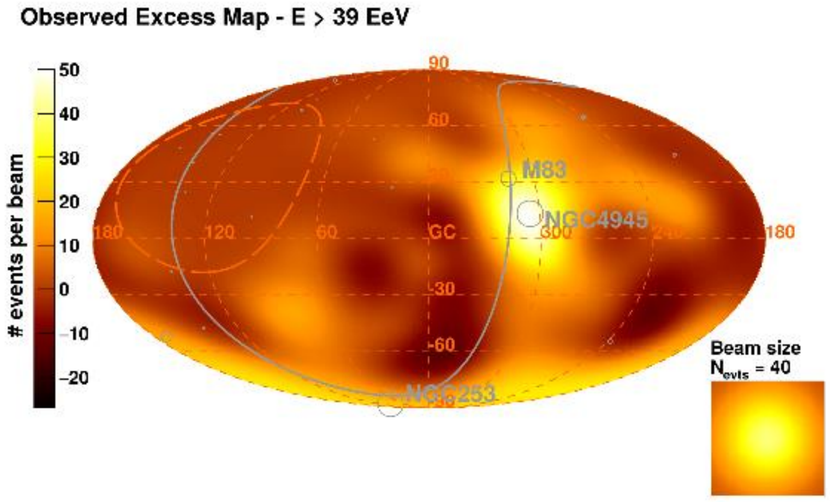


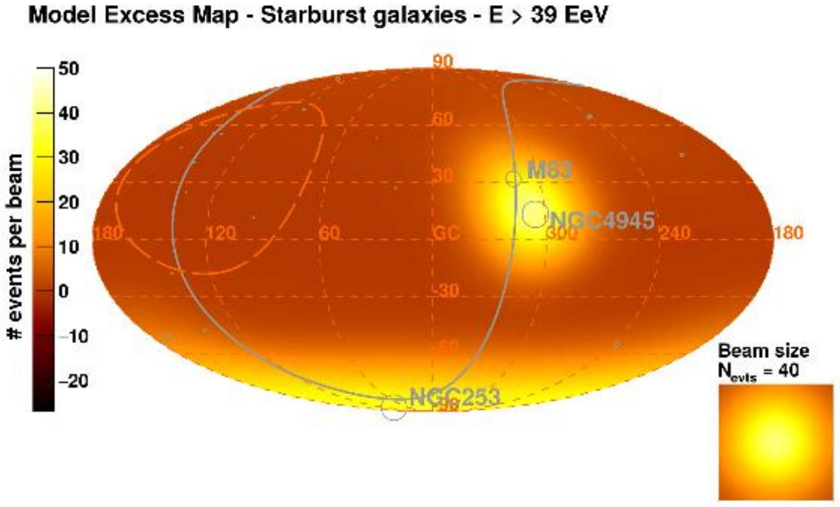
Selected scientific outputs using data of the Pierre Auger Observatory – Anisotropies II

Indication of excess from directions of Starburst galaxies

The Astrophysical Journal Letters 853 (2018) L29







Selected scientific outputs using data of the Pierre Auger Observatory – Multi-messenger Astronomy

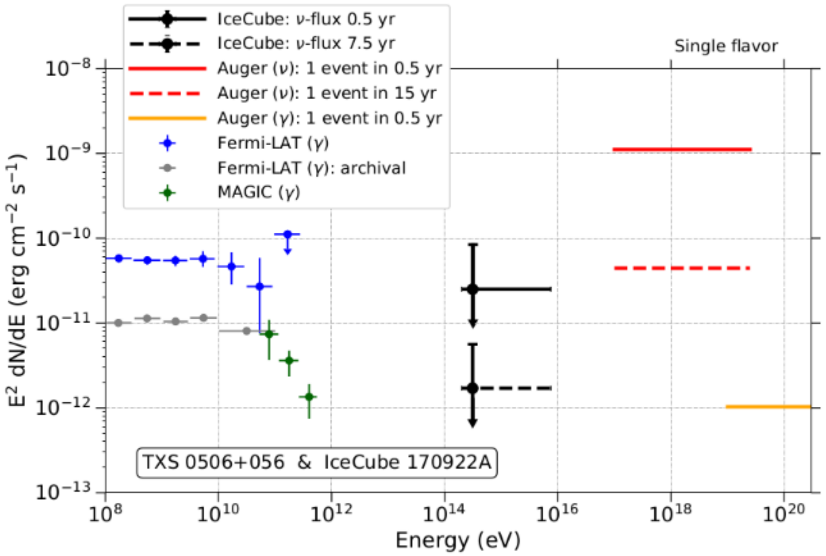
PIERRE AUGER OBSERVATORY

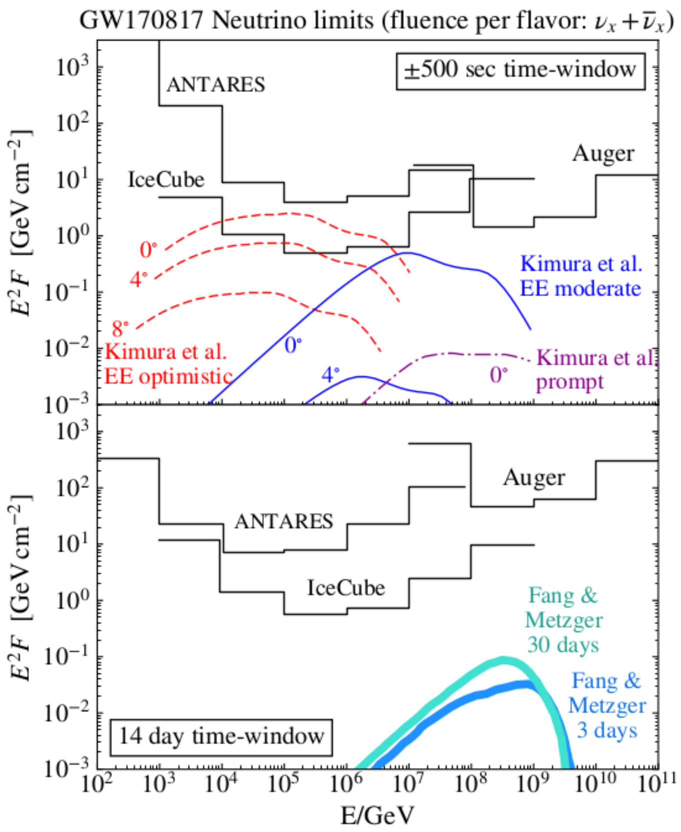
Multi-messenger Observations of a Binary Neutron Star Merger

- limits on neutrino flux from GW170817
- The Astrophysical Journal Letters 848 (2017) L12
- The Astrophysical Journal Letters, 850 (2017) L35

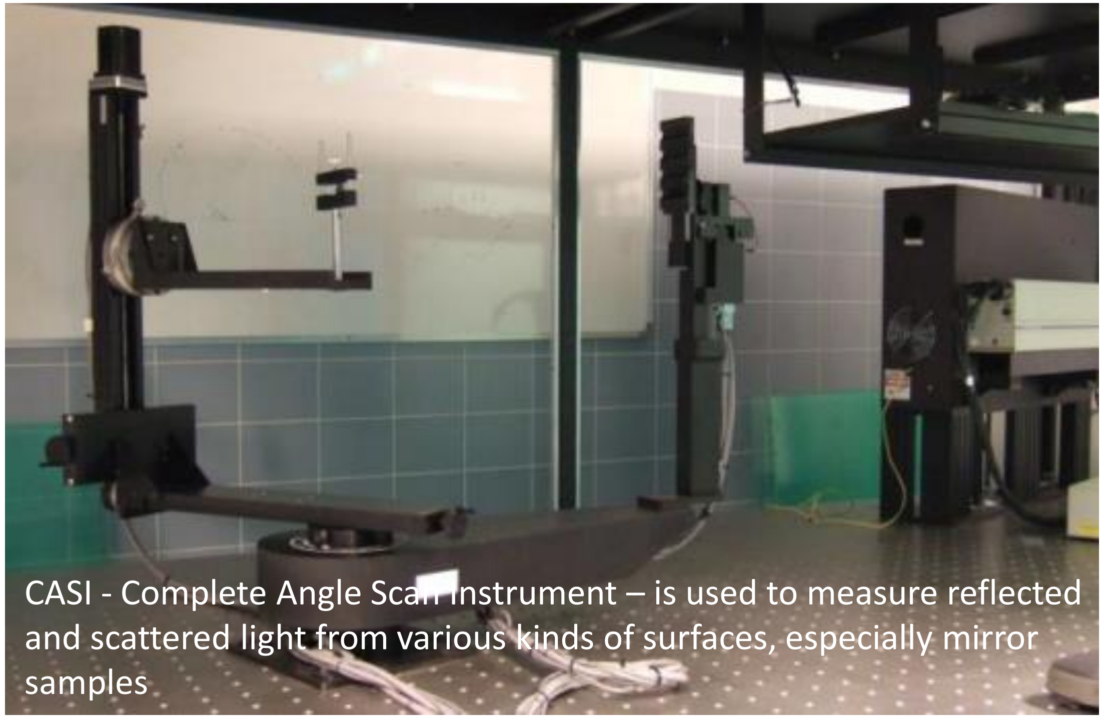
Neutrino flux limit from Blazar TXS 0506+056

- The Astrophysical Journal, 902 (2020) 105





Key milestones 2023 – 2029, technology upgrades


CASI - Complete Angle Scan instrument – is used to measure reflected and scattered light from various kinds of surfaces, especially mirror samples

- The Olomouc laboratories
  - Replacement of very old conventional milling machine by a new CNC 5D device
  - Replacement of a 15-years-old instrument for measuring the roughness of surfaces based on light scattering parameters, which makes the laboratory unique in the whole AUGER collaboration
- The Prague laboratory
  - new VME crate
  - oscilloscope with Linux support and a frequency of at least 1 GHz, a pulse generator reaching at least 250 MHz
  - spectrum and vector analyzer
- Equipment in Argentina for FRAMs
  - New cameras technologies - CCD and CMOS cameras
  - potentially new installation of the FRAM telescope
- Prague computing resources
  - server with a GPU card and water-cooled racks to verify the possibilities of this technology for cosmic ray shower simulations
  - reinvestment to grid disk servers for storing simulated data, virtualization clusters and their associated disk arrays, NFS servers for storing local data and other computational clusters

Data management principles and the data management policy

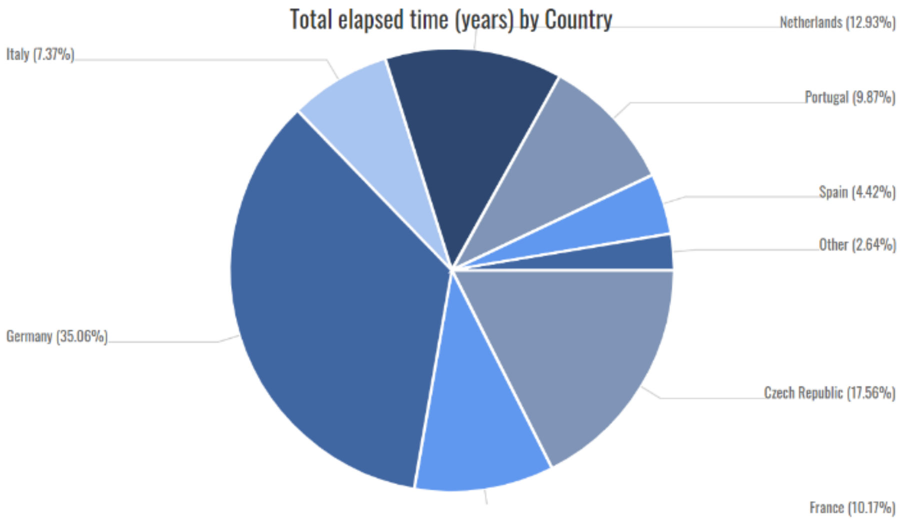
Data & Tables

- **Combined Spectrum data 2019**
  published in
  "Measurement of the energy spectrum of ultra-high energy cosmic rays using the Pierre Auger Observatory"
  Proceedings of the 36th International Cosmic Ray Conference, Madison, USA, PoS(ICRC2019)450
  https://pos.sissa.it/358/450/ [arxiv: 1909.09073]

- **Xmax and ln(A) moments 2019**
  published in
  "Mass Composition of Cosmic Rays with Energies above $10^{17.2}$ eV from the Hybrid Data of the Pierre Auger Observatory"
  Proceedings of the 36th International Cosmic Ray Conference, Madison, USA, PoS(ICRC2019)482
  https://pos.sissa.it/358/482/ [arxiv: 1909.09073]

- **Arrival Directions Source Weights ICRC 2019**
  Code to generate attenuated flux weights as used in
  "Anisotropies of the Highest Energy Cosmic-ray Events Recorded by the Pierre Auger Observatory in 15 years of Operation"
  Proceedings of the 36th International Cosmic Ray Conference, Madison, USA, PoS(ICRC2019)206
  https://pos.sissa.it/358/206/ [arxiv: 1909.09073]

  (updated version of the code used for
  "An Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources"
  Astrophys.J. 853 (2018) no.2, L29



- ➢ Construction of the observatory was completed in 2008
  - Scientific data available even earlier
- ➢ All data stored in Computing Centre in Lyon, where every collaboration member can get an account and access to full dataset
- ➢ Internal documents describe data management plan and data formats
- ➢ Processed data (results) are released under the CC BY-SA 4.0
  - Available at web: https://www.auger.org/index.php/document-centre/viewcategory/115-data
- ➢ 10% of reconstructed cosmic-ray events released with example codes and documentation for their processing
  - https://www.auger.org/index.php/science/data-2
  - there are plans to release more
- ➢ Chain of MC simulation for entire collaboration and big productions organized by AUGER-CZ. Opening of MC data samples to general public being discussed

PIERRE AUGER OBSERVATORY

Data provided to the community – observatory level

PIERRE AUGER OBSERVATORY

Data & Tables

- **Combined Spectrum data 2019**
  published in
  "Measurement of the energy spectrum of ultra-high energy cosmic rays using the Pierre Auger Observatory"
  Proceedings of the 36th International Cosmic Ray Conference, Madison, USA, PoS(ICRC2019)450
  https://pos.sissa.it/358/450/ [arxiv: 1909.09073]

- **Xmax and ln(A) moments 2019**
  published in
  "Mass Composition of Cosmic Rays with Energies above $10^{17.2}$ eV from the Hybrid Data of the Pierre Auger Observatory"
  Proceedings of the 36th International Cosmic Ray Conference, Madison, USA, PoS(ICRC2019)482
  https://pos.sissa.it/358/482/ [arxiv: 1909.09073]

- **Arrival Directions Source Weights ICRC 2019**
  Code to generate attenuated flux weights as used in
  "Anisotropies of the Highest Energy Cosmic-ray Events Recorded by the Pierre Auger Observatory in 15 years of Operation"
  Proceedings of the 36th International Cosmic Ray Conference, Madison, USA, PoS(ICRC2019)206
  https://pos.sissa.it/358/206/ [arxiv: 1909.09073]

  (updated version of the code used for
  "An Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources"
  Astrophys.J. 853 (2018) no.2, L29
  https://doi.org/10.3847/2041-8213/aaa66d)

Outline

- Pierre Auger Observatory
- Energy spectrum measurement
- Depth of shower maximum, Composition related studies
- Large and medium size anisotropies
- Neutral particles - for studies of transient objects see P. Ruehl: Multimessenger Astronomy of Transient Point Sources at the Pierre Auger Observatory (after coffee break)
- Muon puzzle
- Future of the Observatory - AugerPrime scientific potential

UHECR observatory – connecting Particle physics and Astrophysics

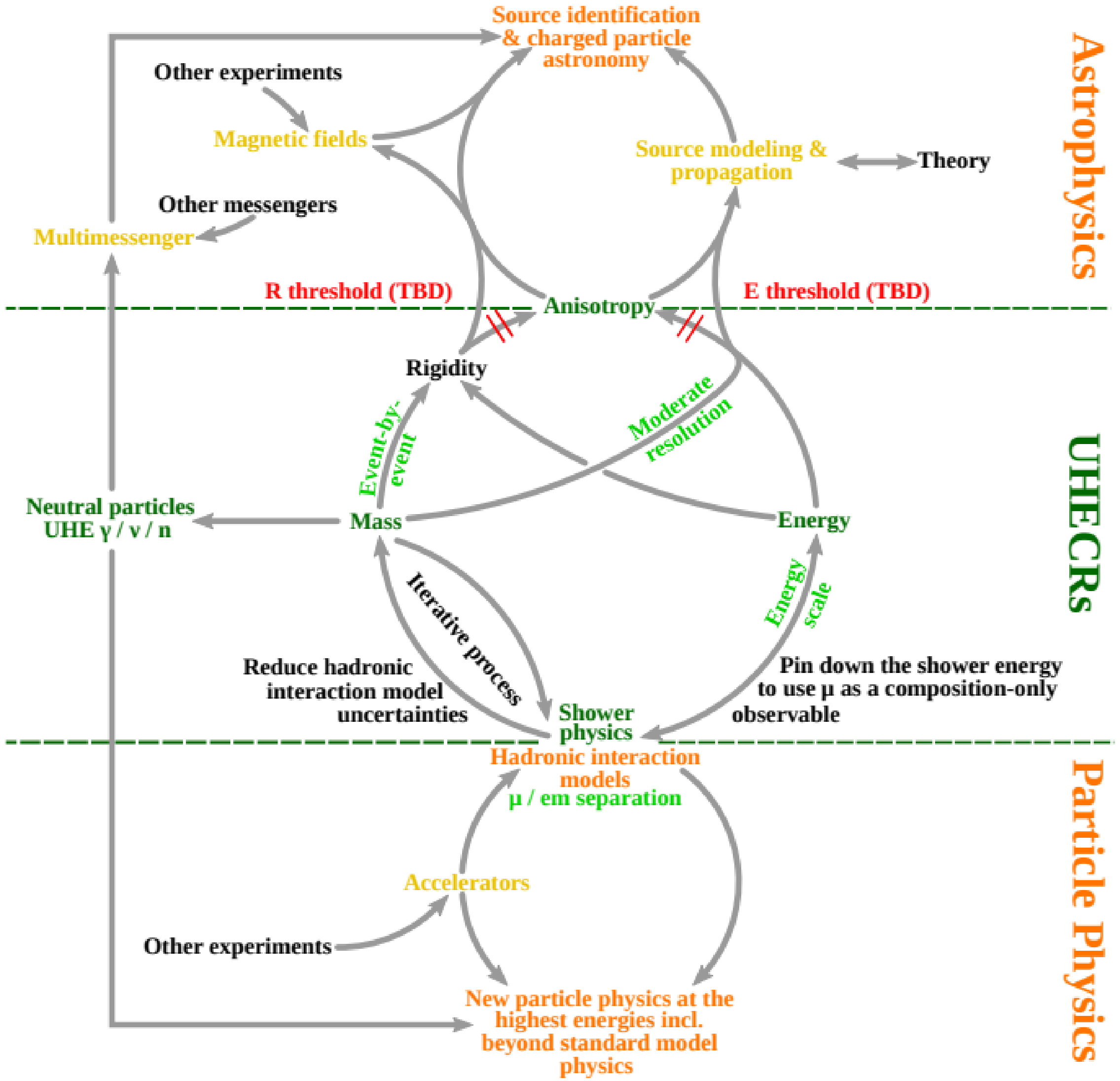
Picture from https://arxiv.org/pdf/2205.05845.pdf

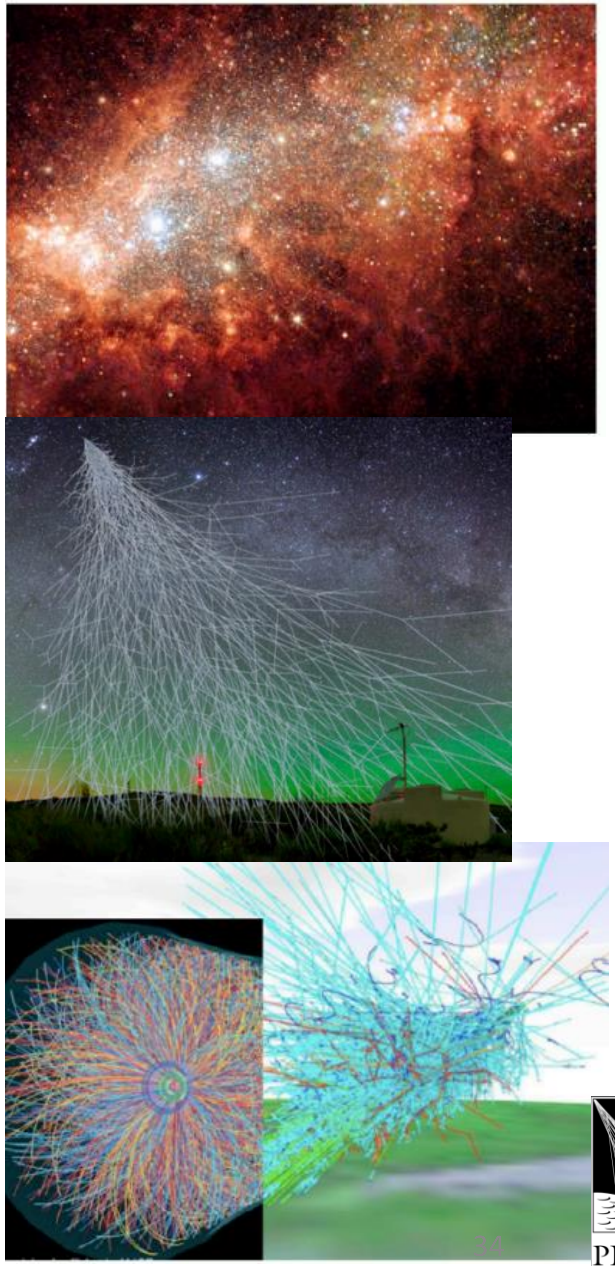
50 years of searching for UHECR sources

New opportunities in multi-messenger observations

Revealing unknown UHECR composition

Particle physics beyond LHC capabilities



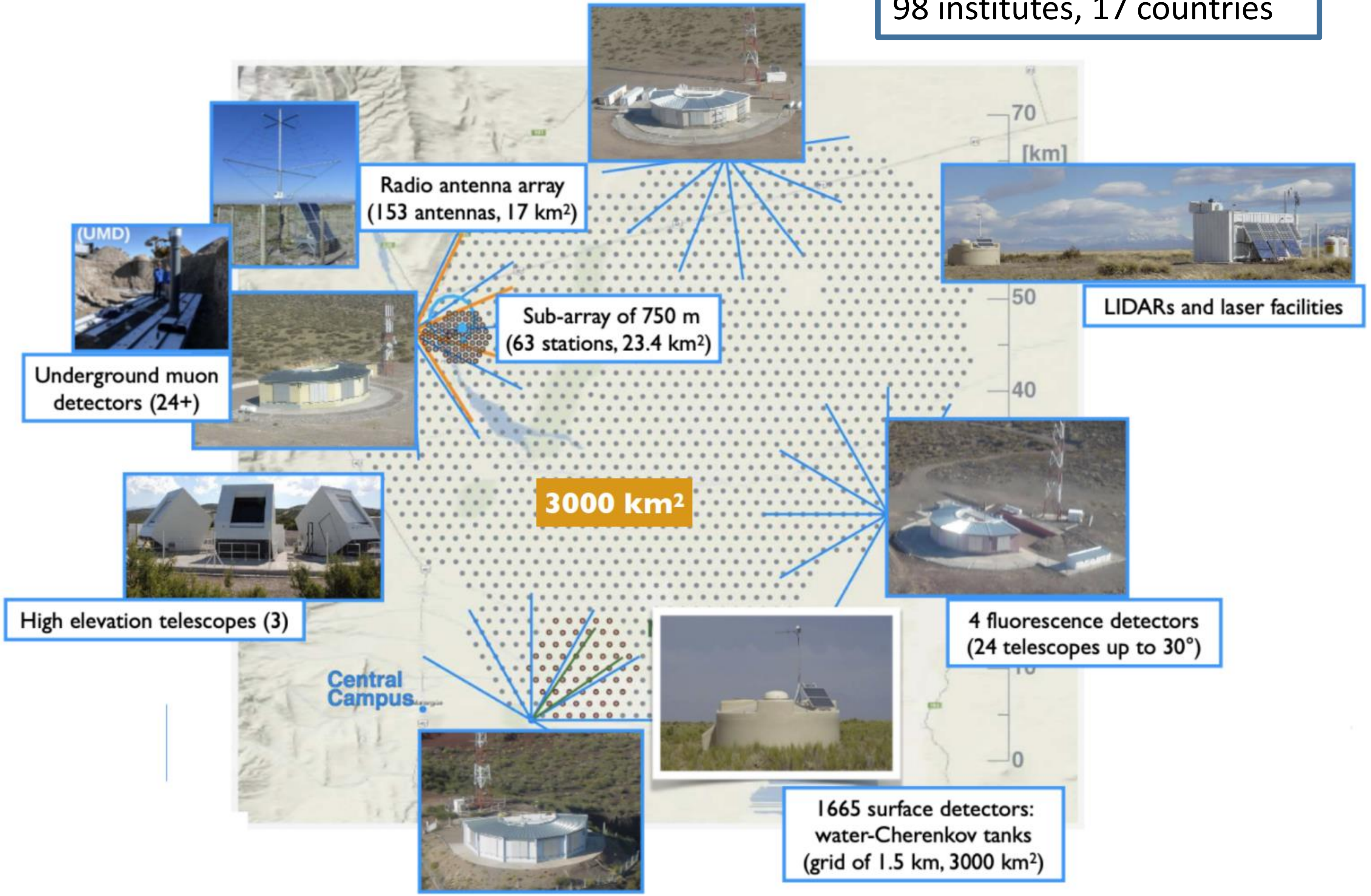


FZU Institute of Physics of the Czech Academy of Sciences

PIERRE AUGER OBSERVATORY

Pierre Auger Observatory

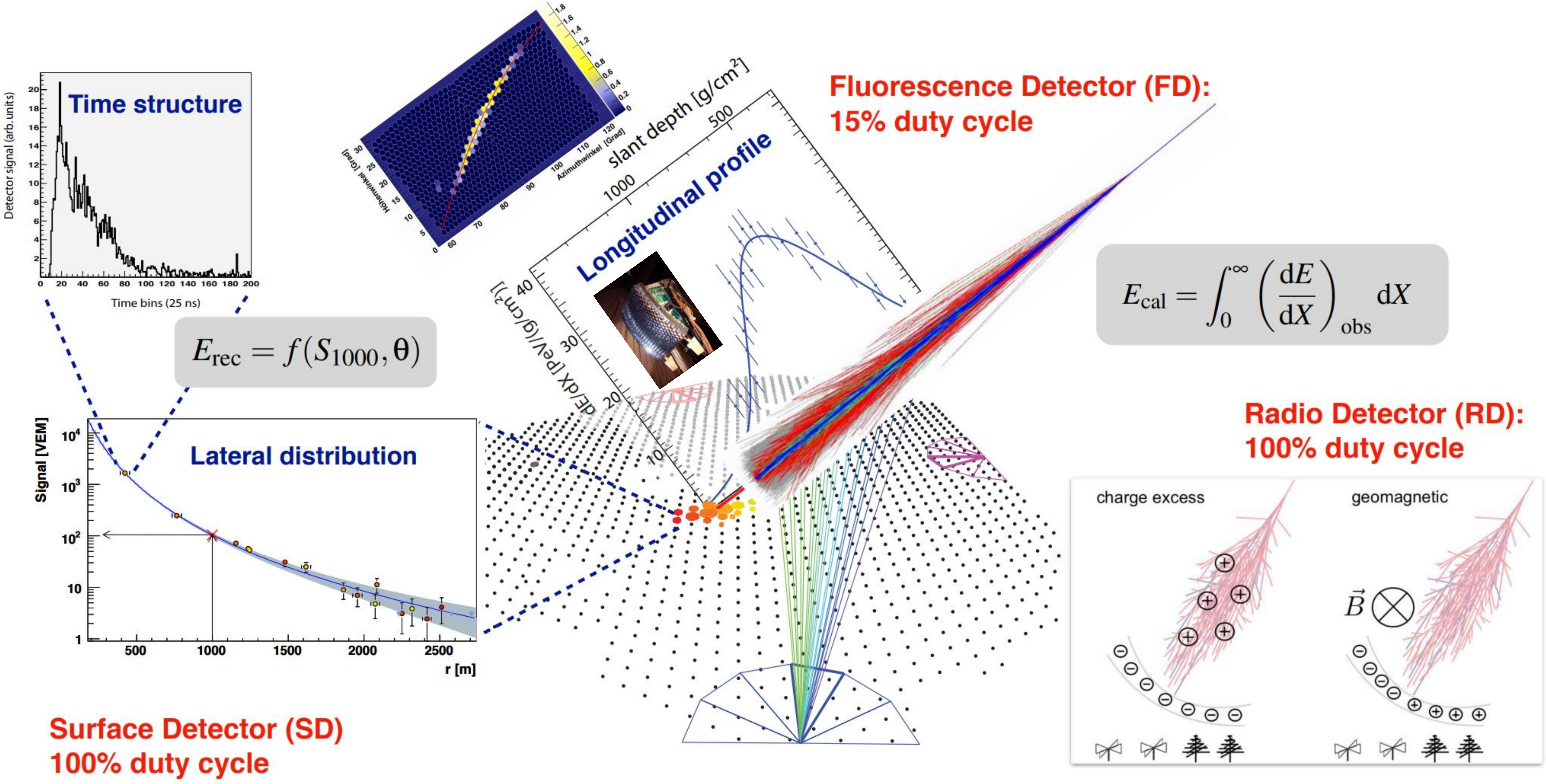
More than 400 members, 98 institutes, 17 countries



Phase 1 : data taking from 2004 on (from 2008 with the full array in operation):
✓ Over 120, 000 km^2 sr yr for anisotropy studies
✓ Over 90, 000 km^2 sr yr for spectrum studies

Phase 2 : the AugerPrime upgrade Data taking from 2023 to 2030…
✓ + 40, 000 km^2 sr yr
✓ Multi-hybrid events : FD, SD, SSD, RD, UMD

How Pierre Auger Observatory measures UHECR ?



Picture from Ralph Engel, ICRC2021

How precise is the reconstructed energy?

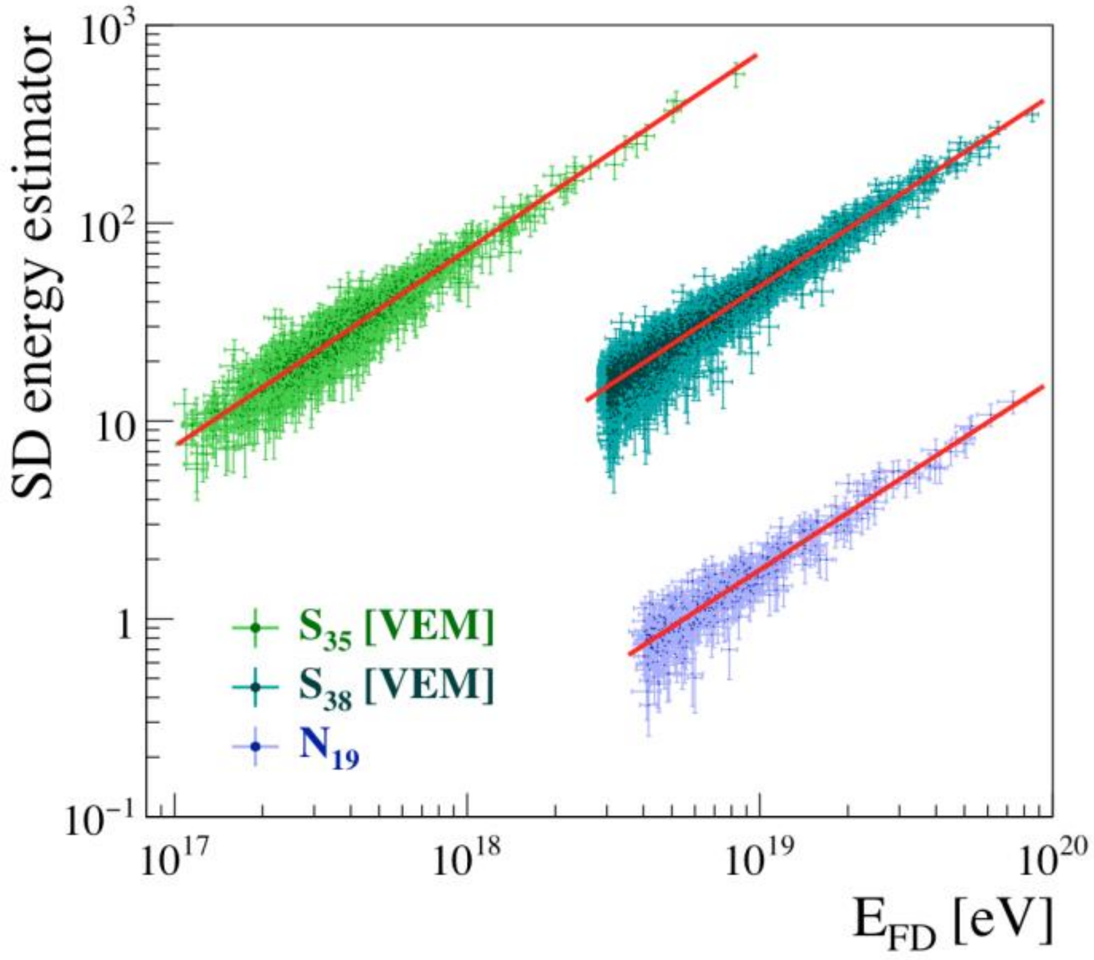
Energy systematic uncertainties:

FD profile reconstruction, Atmospheric conditions, Stability of the energy scale, Fluorescence yield, Invisible energy, Statistical error of SD calibration fit

FD energy scale: 14%

SD resolution for energy reconstruction: **Energy: 20% (@2 EeV) to 7% (@ >20 EeV)**

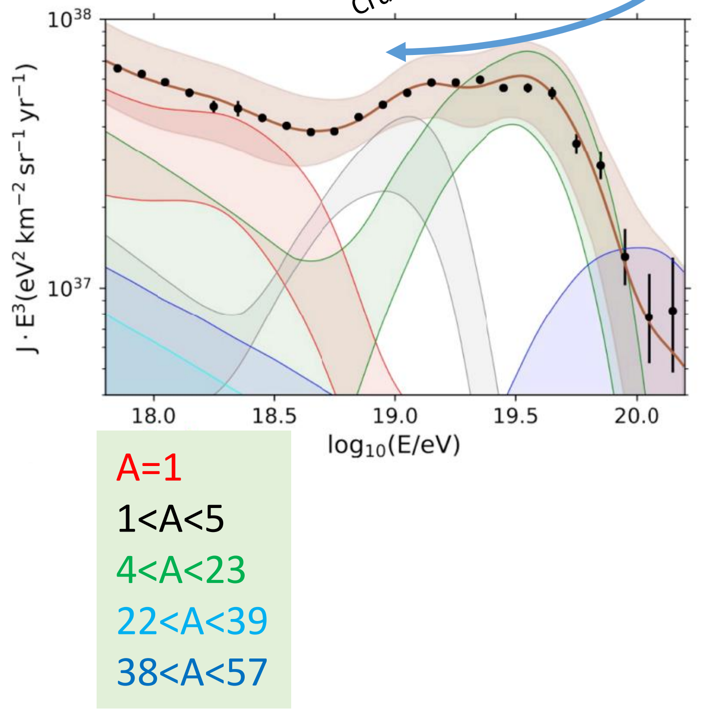
Hybrids (FD + at least 1 SD station): **Energy resolution 7.4%**

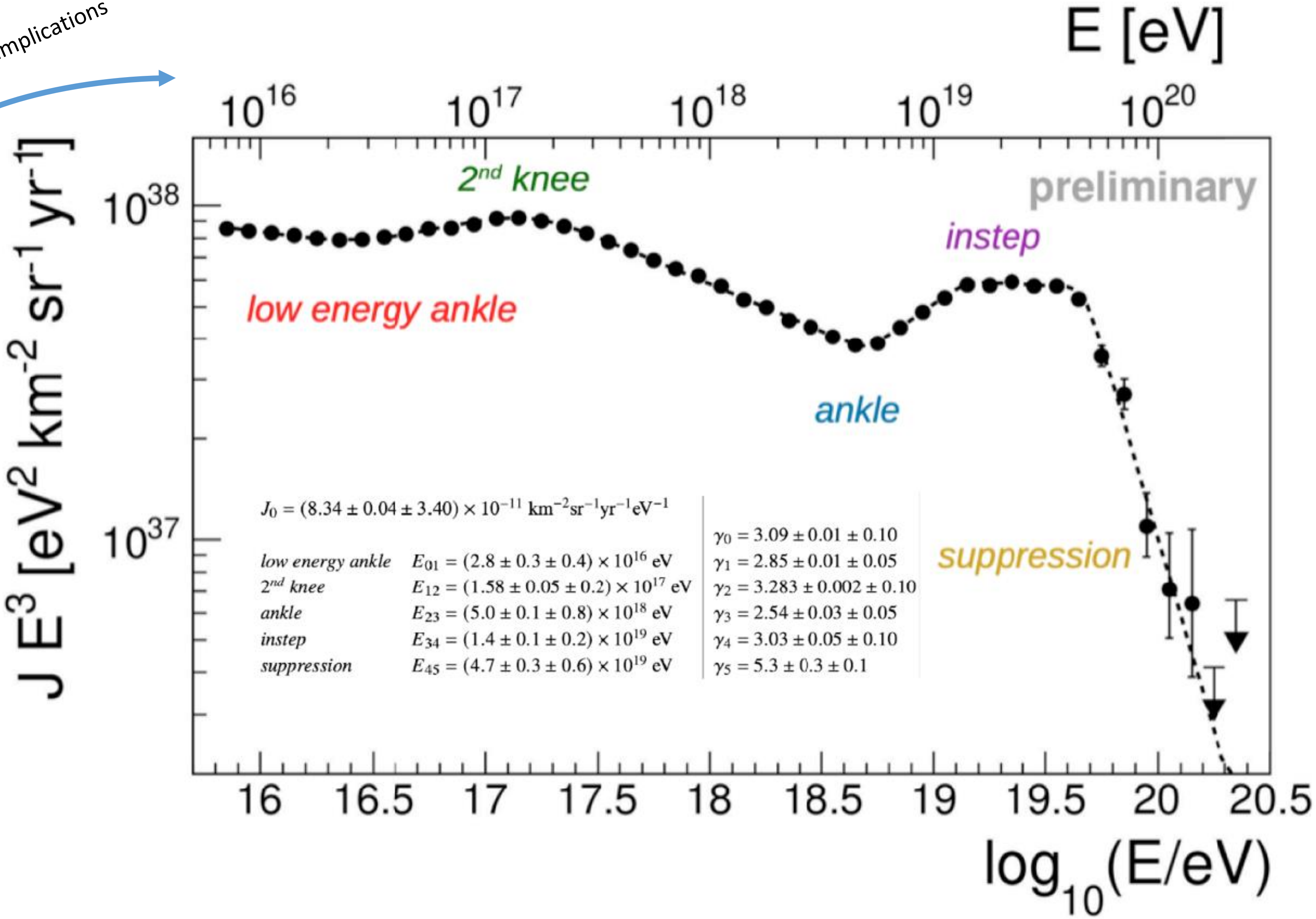


Features of the energy spectrum of cosmic rays above 2.5 x 10^{18} eV using the Pierre Auger Observatory, Phys. Rev. Lett. 125, 121106 (2020)
Measurement of the cosmic ray energy spectrum above 2.5 x 10^{18} eV using the Pierre Auger Observatory, Phys. Rev. D 102, 062005 (2020)

Energy spectrum of UHECR

Crucial measurement with astroph. implications

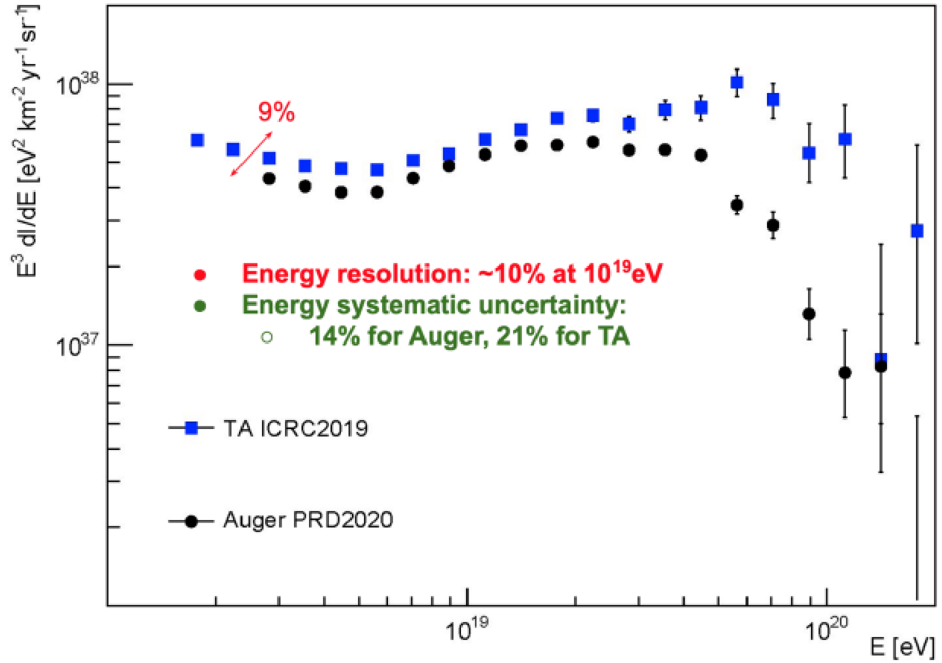


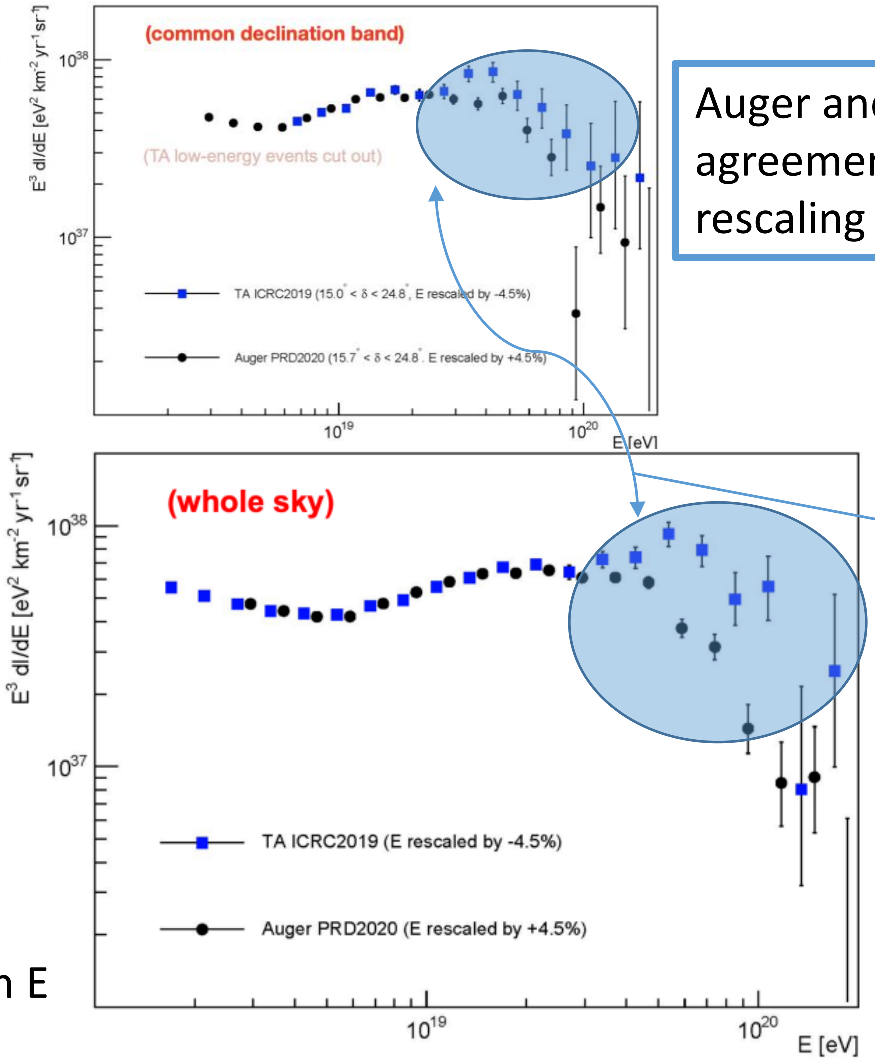


A.Aab et al., PRL 125, 121106 (2020)
A.Aab et al., PRD 102, 062005 (2020)
A.Aab et al., Eur. Phys. J. C81 (2021)
V.Novotny for the Pierre Auger Coll., ICRC 2021, #324

UHECR spectrum compared to Telescope Array

Y. Tsunesada (Auger-TA working group), ICRC 2021, #337





Auger and TA data can be brought to better agreement using a +/- 4.5% energy rescaling (well within systematics)

Further studies needed to understand agreement at the UHE

Differences Auger/TA

- $E_{invisible}$
- Fluorescence yield
- different methods to relate SD observable with E

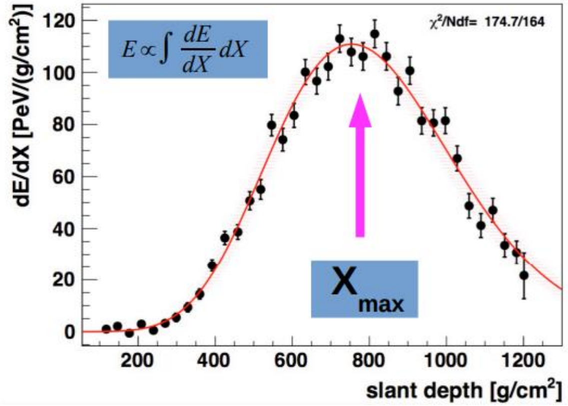
Cross-calibration of Auger and TA

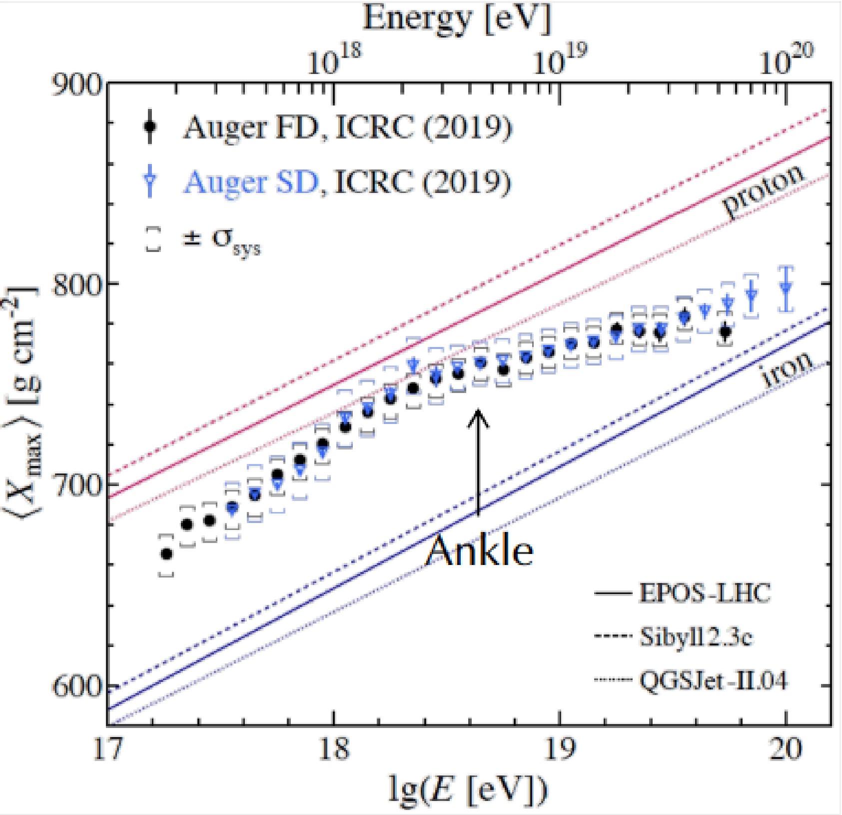
Deployment of an Auger hexagon within Telescope Array

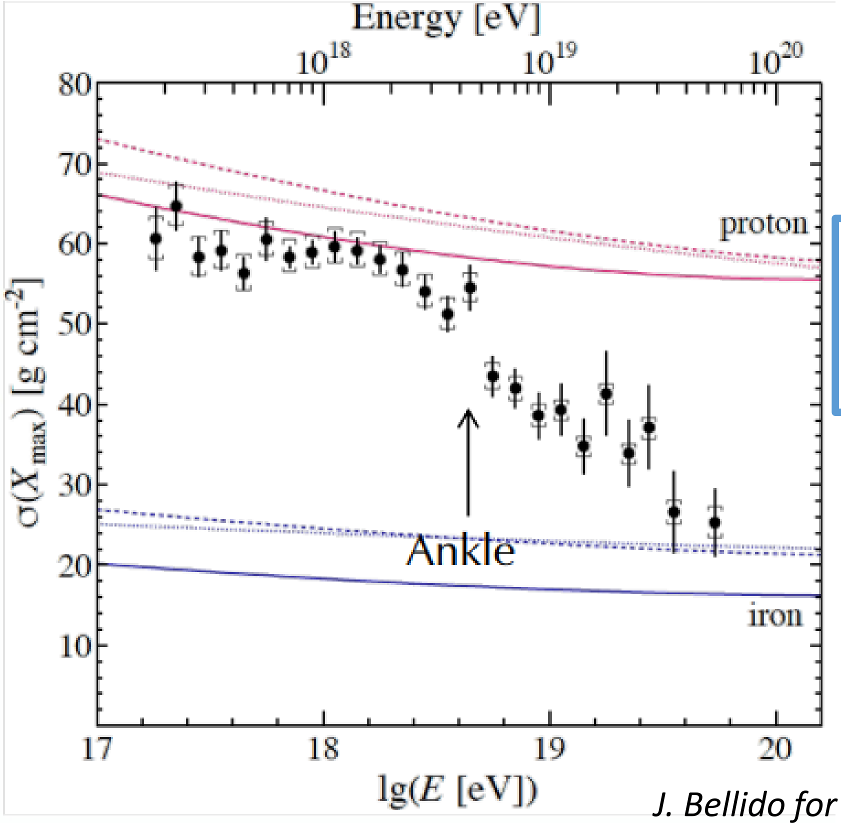
- Independent operation / reconstruction (the standard Auger reconstruction)
- Auger single-PMT SD station fitted with regular Auger electronics
- Triplet set of detectors at the center for station-level comparisons
- Will include Surface Scintillator Detector (SSD) Upgrade

Position of shower maximum

- Transition towards heavier composition around 2 EeV
- Break in <X_{max}> vs E below the Ankle energy (break in RMS(X_{max}) at roughly the same energy)



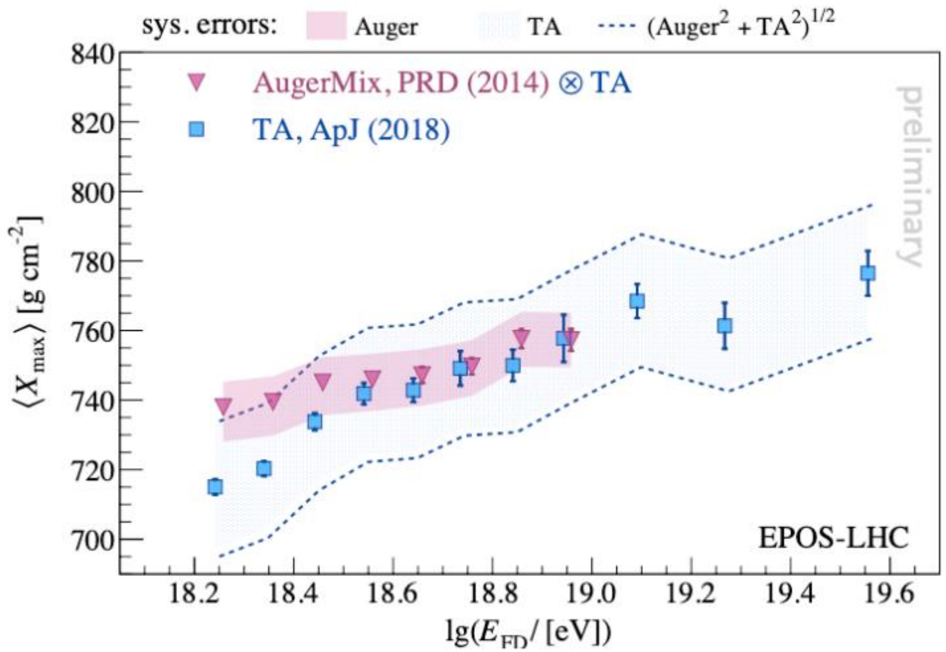




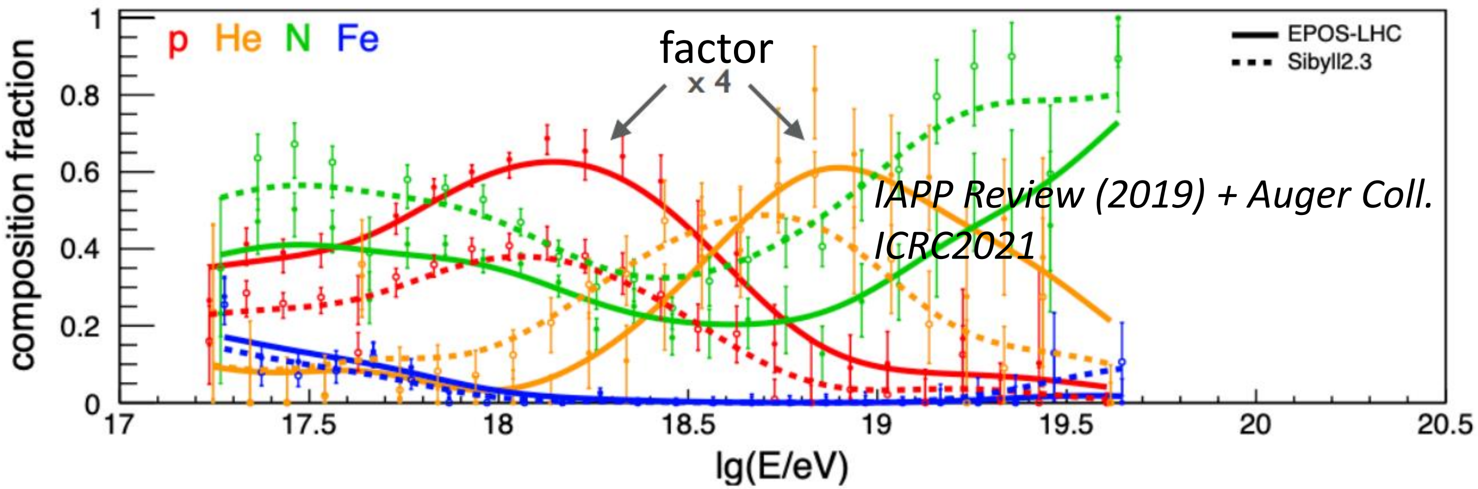
Elongation rates
(80+1) g/cm^2/decade below and
(26+2) g/cm^2/decade above ~ 2 EeV

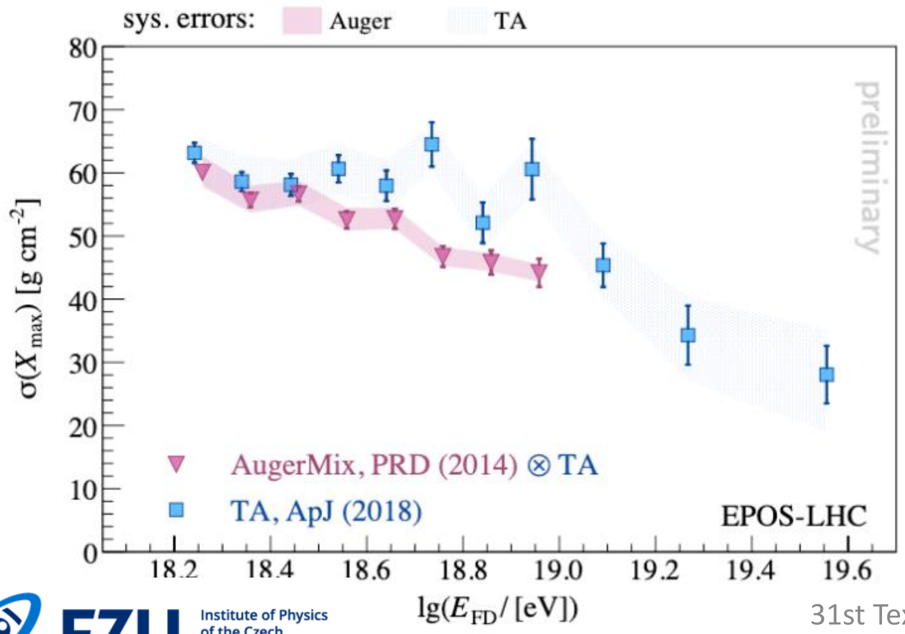
J. Bellido for the Pierre Auger Collaboration, ICRC 2017
A. Aab et al., Phys. Rev. D96 (2017) 122003
A. Yushkov for the Pierre Auger Collaboration, ICRC 2019
Auger Coll., Phys.Rev.D90 (2014) 122005

Consistency between Auger and Telescope Array in terms of < X_{max} > and RMS(X_{max})



The Auger composition fractions input to the TA simulations;

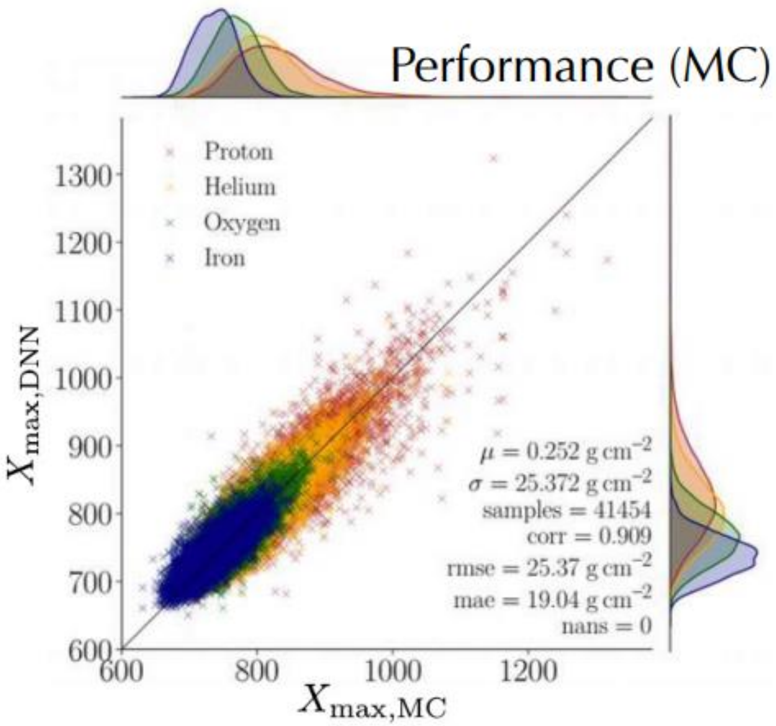


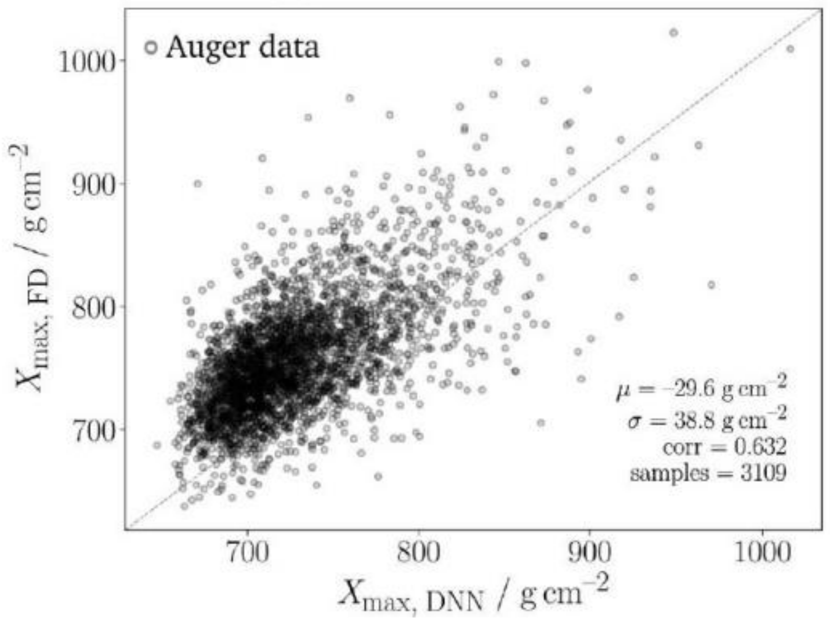


TA data consistent with proton AND with Auger-mix composition to ≈ 10 EeV

Auger&TA working group, JPS Conf.Proc. 9 (2016) 010016 Auger&TA working group, EPJ Web of Cons. 210 (2018) 010009

Extend X_{max} analysis to SD data – new method based on ML - DNN



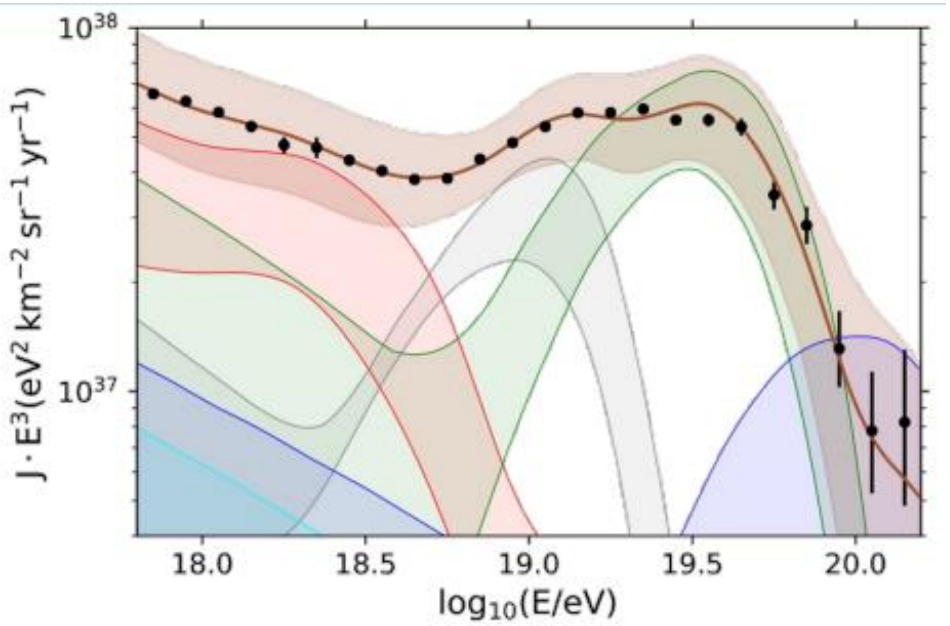


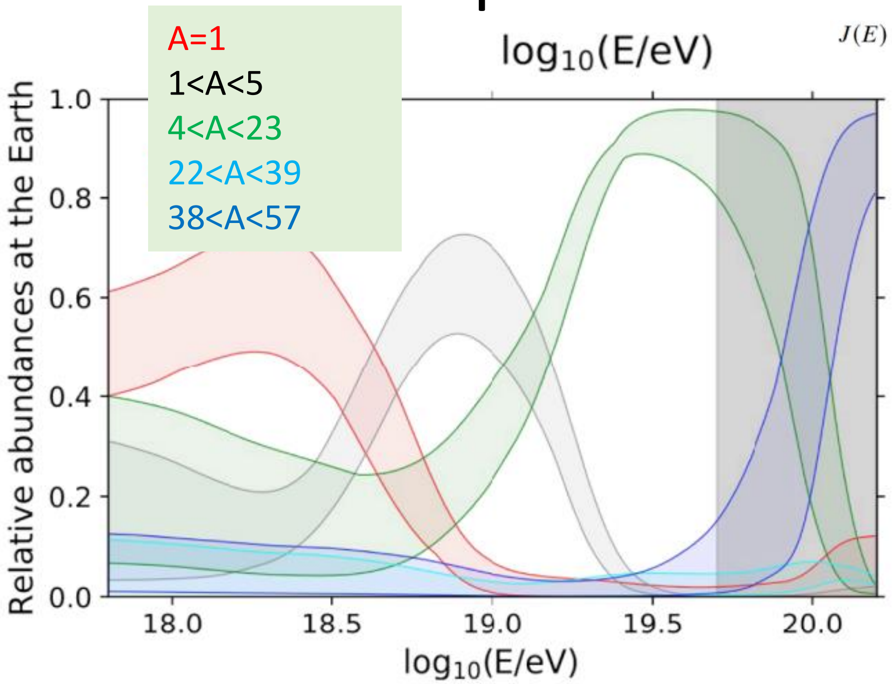
- Works well in MC
- Observed bias with the data. X_{max},DNN is predicted to be shallower than the data
- Similar effort wrt muon number from SD traces

Xmax: Pierre Auger Collaboration, JINST 16 (2021) P07019
Muon: Pierre Auger Collaboration, JINST 16 (2021) P07016

Big potential during AugerPrime phase - use of ML to extract better primary mass information

Combined fit: spectrum + composition





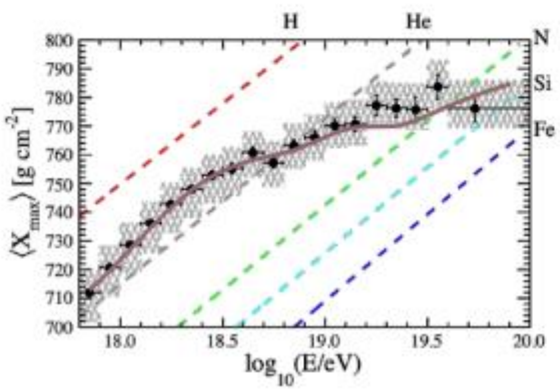
$$J(E) = \sum_A f_A \cdot J_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma} \cdot \begin{cases} 1, & E < Z_A \cdot R_{cut} \\ \exp\left(1 - \frac{E}{Z_A \cdot R_{cut}}\right), & E > Z_A \cdot R_{cut} \end{cases}$$

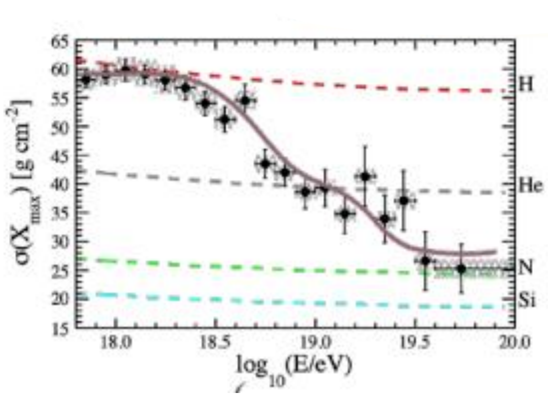
BEST FIT

1) EG: hard HE component + soft LE component
2) possible Galactic component (N)

Scenarios compatible within systematics

- AGN Source evolution for the HE component excluded
- Dominant experimental systematics, subdominant from models

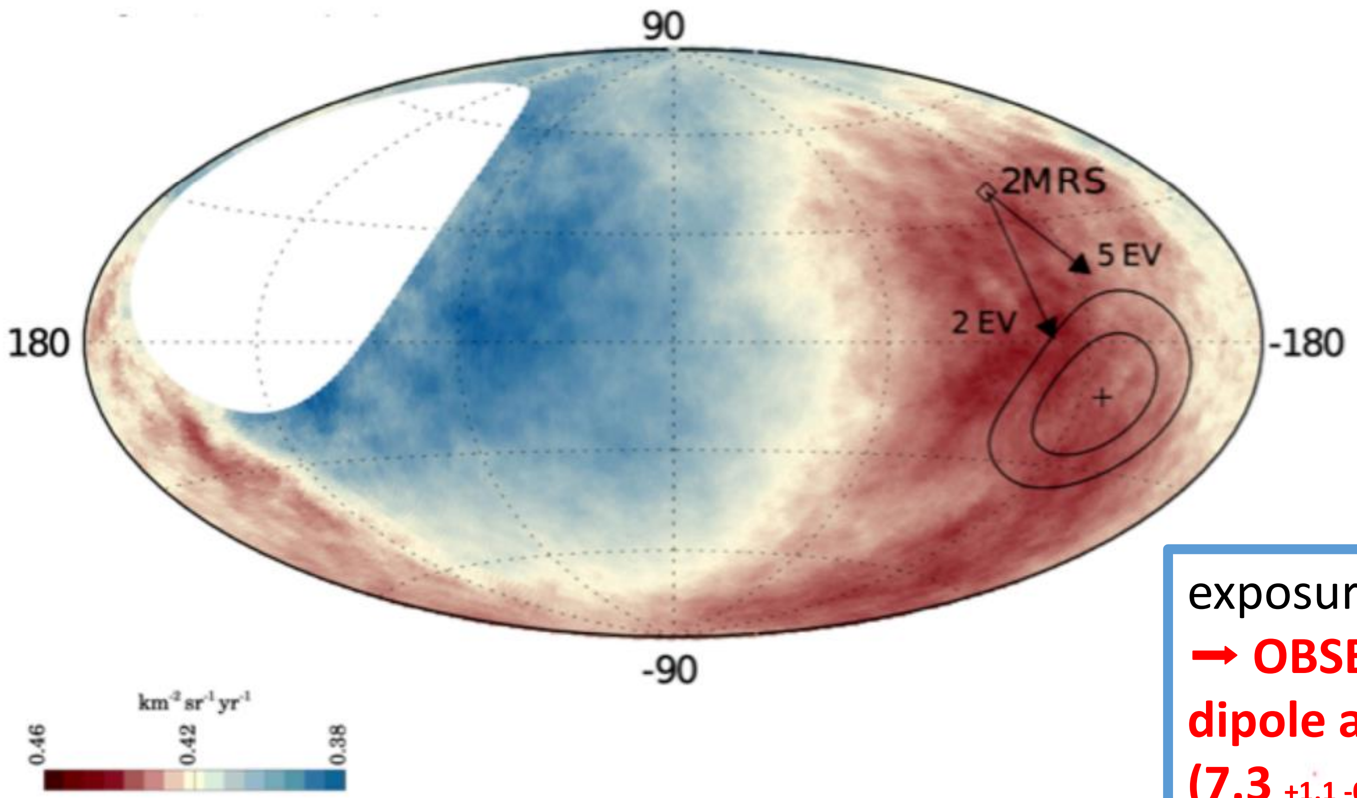




Maximum rigidity scenario with $R_{cut} \sim 1.5 \times 10^{18}$V (sources run out of power) and very hard spectral index < 1 (although not strongly constrained)

A.Aab et al., PRL 125, 121106 (2020)
E.Guido for the Pierre Auger Collaboration, ICRC2021 #311
Paper to be submitted to JCAP

Large scale anisotropy



Auger Coll., Science 357 (2017) 1266;
ApJ. 891 (2020) 142;
R. De Almeida, PoS(ICRC2021) 335

exposure 110,000 km^2 sr yr
➞ OBSERVATION (stat.significance 6.6σ): 3D dipole above 8 EeV at (α,δ)=(95 deg,-36 deg): (7.3 $_{+1.1\ -0.9}$) %

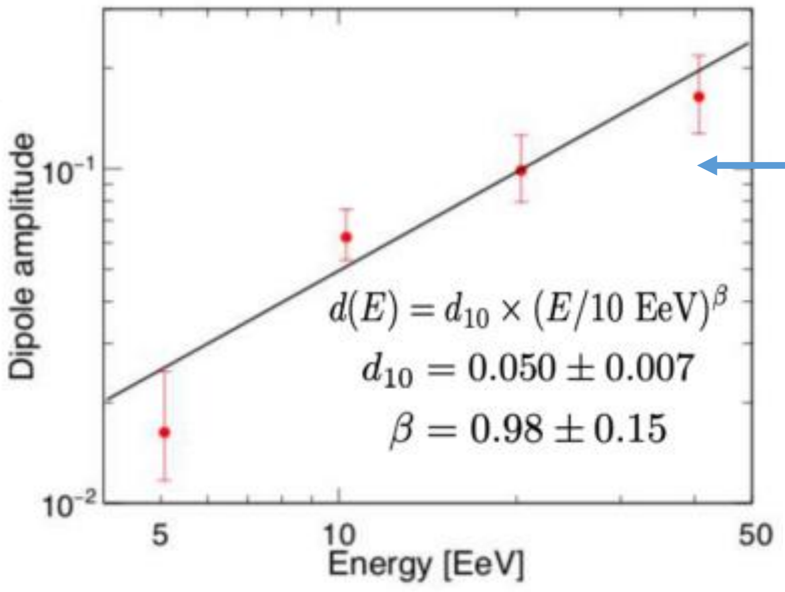
➞ the **UHECRs are extra-galactic** above 8 EeV, while predominantly Galactic below few EeV

Important factors

- Mass composition
- Source distributions
- Magnetic fields deflections
- Quadrupole components not significant

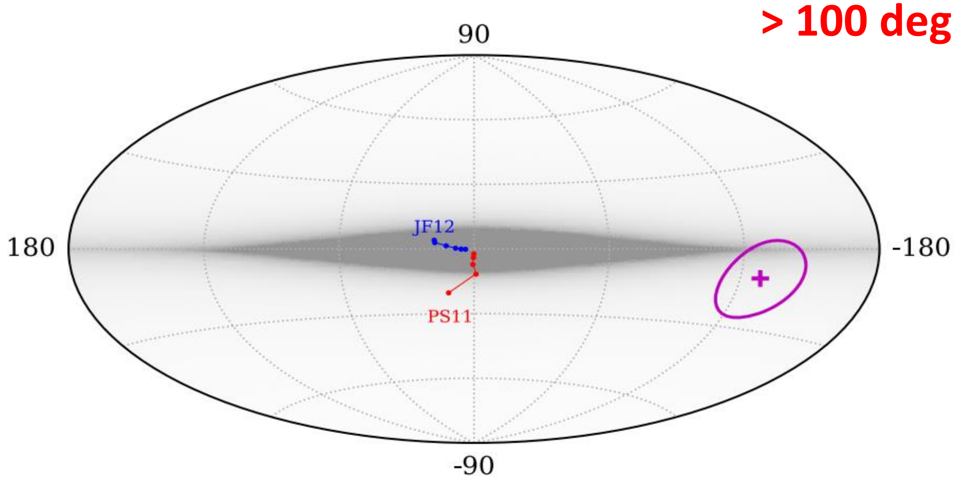
Large scale anisotropy

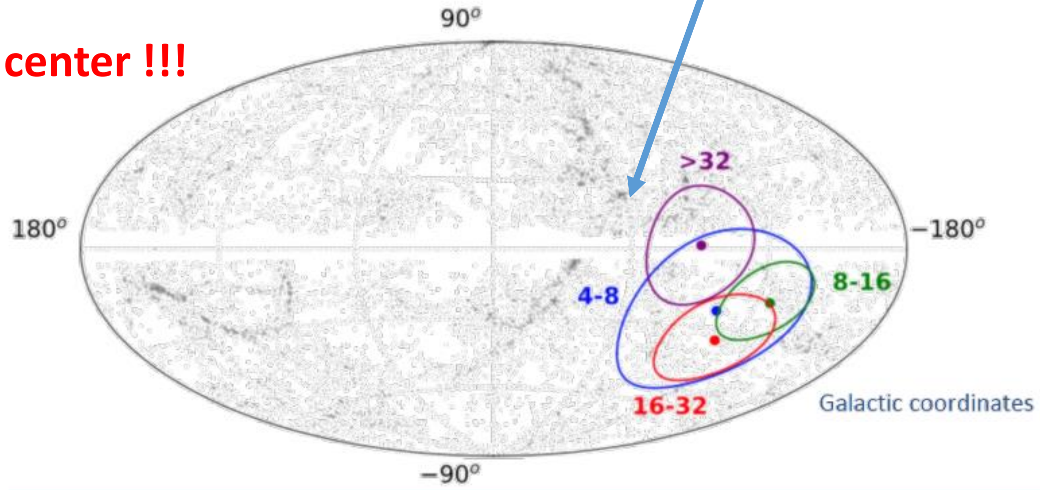
Auger Coll., Science 357 (2017) 1266; ApJ. 891 (2020) 142; R. De Almeida, PoS(ICRC2021) 335



- Increase of amplitude with energy
- Dipole direction stays in the same region
- Location consistent with mixed composition deflected by galactic magnetic fields

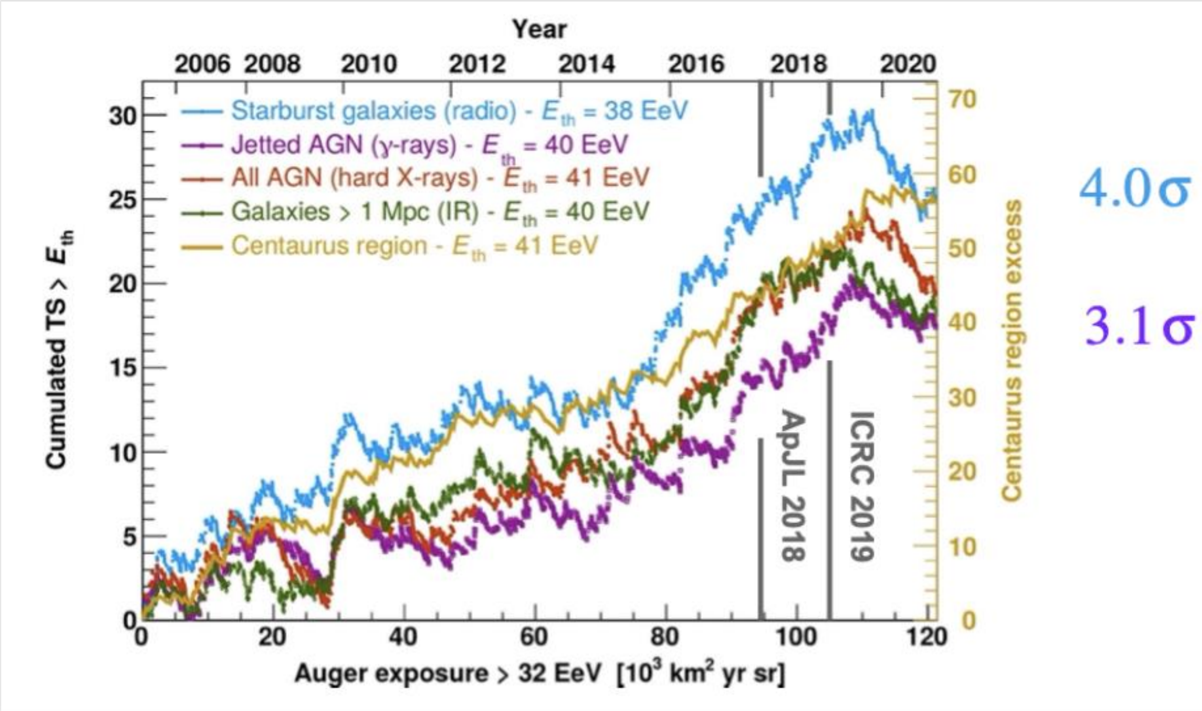
> 100 deg from Galactic center !!!





Intermediate scale anisotropy

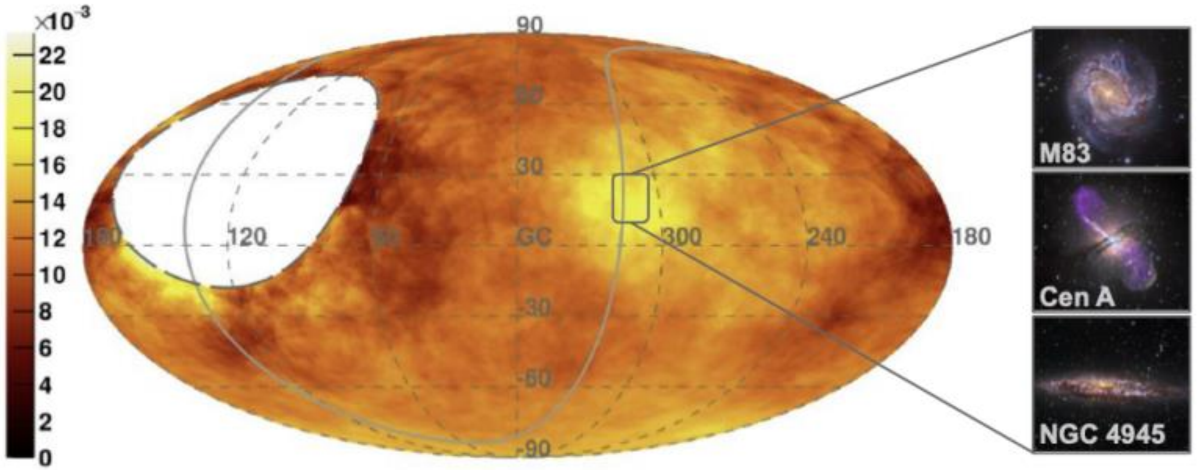
J.Biteau for the Pierre Auger Collaboration, ICRC2021 #307
A.Aab et al., Ap. J. Lett 853 L29 (2018)
The Astrophysical Journal 935 (2022)170



4.0σ

3.1σ

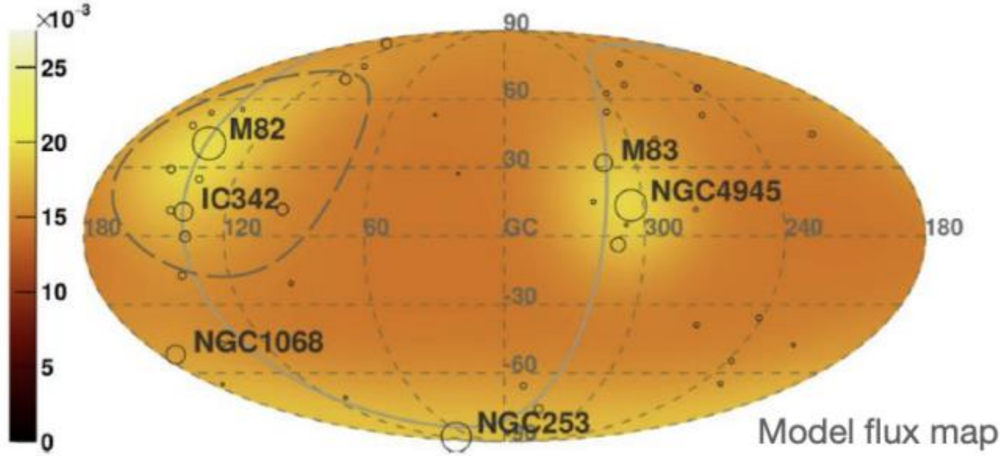
$\Phi(E_{Auger} > 41$ EeV) [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24°$



Direction fixed to that of Cen A, free E_{th} and Ψ

$E_{th} > 41$ EeV, $\Psi = 27°$: **3.9σ post-trial** deviation from isotropy (5% excess)

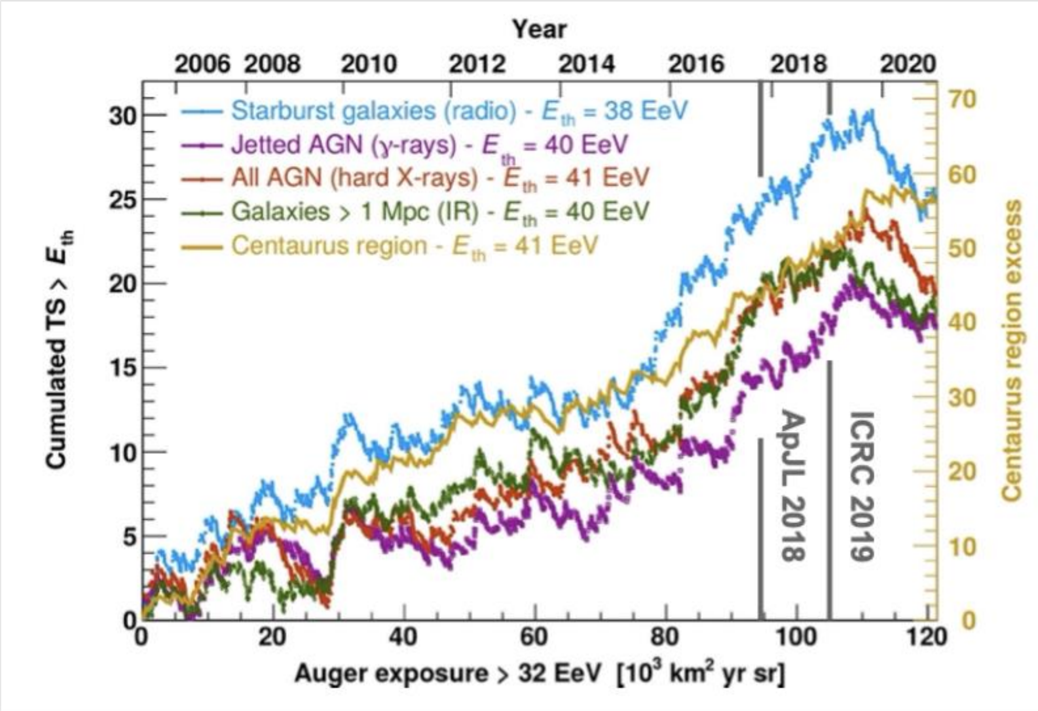
Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38$ EeV) [km^{-2} sr^{-1} yr^{-1}]



AugerPrime – larger exposure and more complex data !!!

Intermediate scale anisotropy

J.Biteau for the Pierre Auger Collaboration, ICRC2021 #307
A.Aab et al., Ap. J. Lett 853 L29 (2018)
The Astrophysical Journal 935 (2022)170



All catalogs:

- Most significant signal at E>38-41 EeV on top-hat scale 23-27 degrees with signal fraction 6-15%
- Significance compatible with linear growth within expected variance
- Observation (discovery) level (≳5σ) can be expected within few years

4.0σ

3.1σ

AugerPrime– discoveries reachable

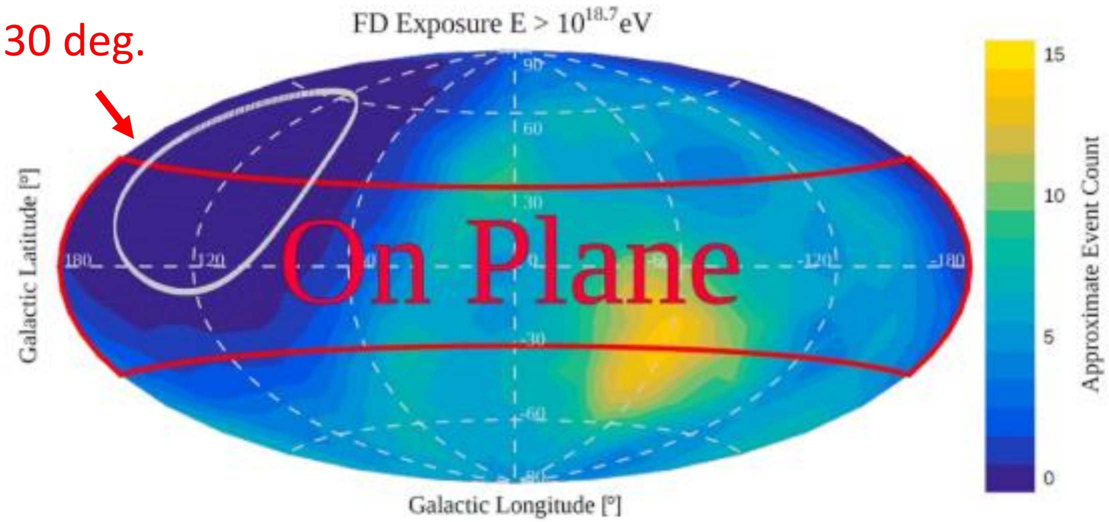
Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}

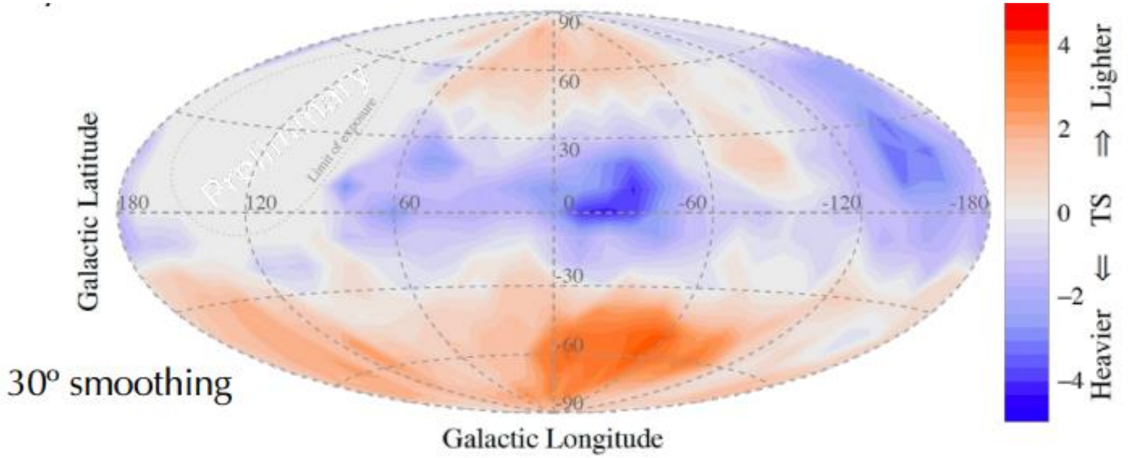
Composition enhanced anisotropy studies

E. Mayotte for the Pierre Auger Collaboration, ICRC 2021 #321

Is the sky uniform in primary composition or are there differences that are potentially correlated with magnetic field strengths (Galactic plane)?

- Scan of data before Jan 1, 2013
- Indication of a lighter composition far from the galactic plane (with b>30 deg)
- magnetic fields effect only? Or local source distribution, mass-dependent horizons and propagation play a role in the same direction?

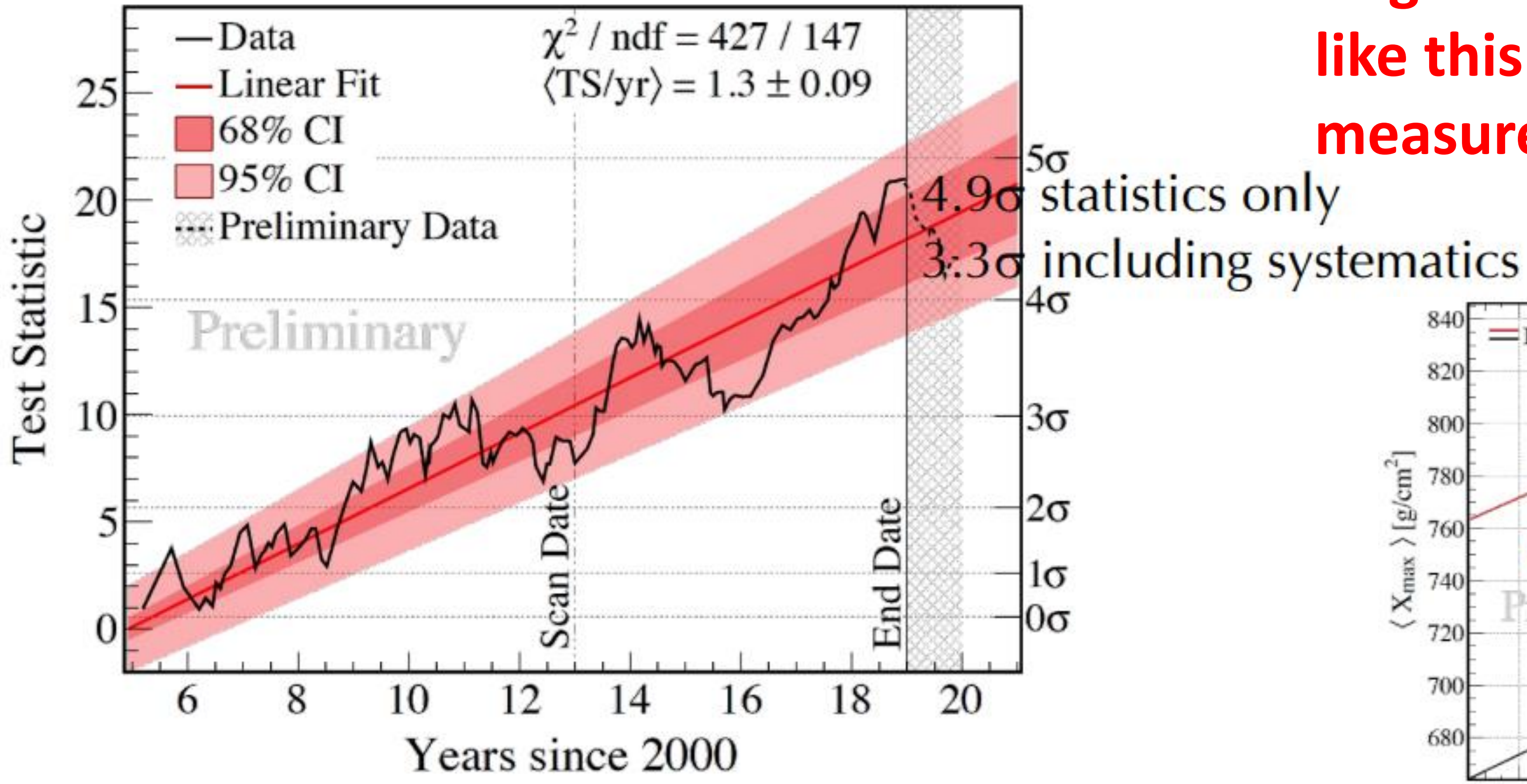


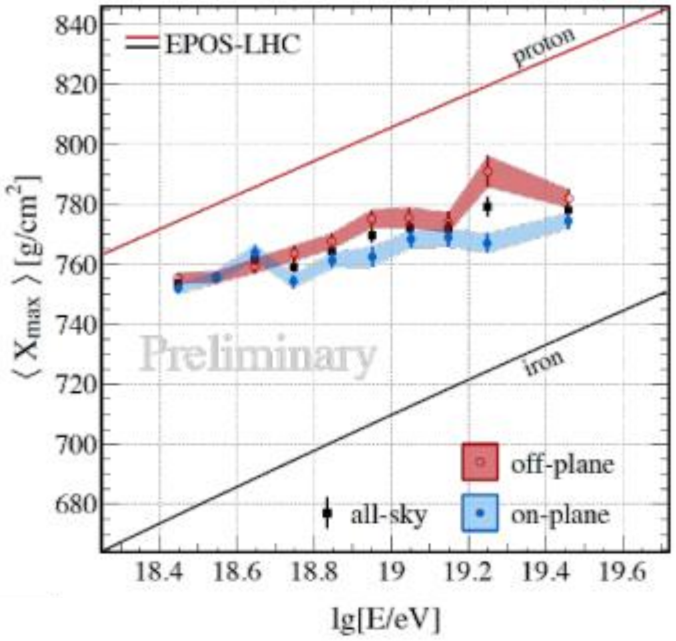


Composition enhanced anisotropy studies

E. Mayotte for the Pierre Auger Collaboration, ICRC 2021 #321

AugerPrime – more studies like this and using also SD measurements !!!

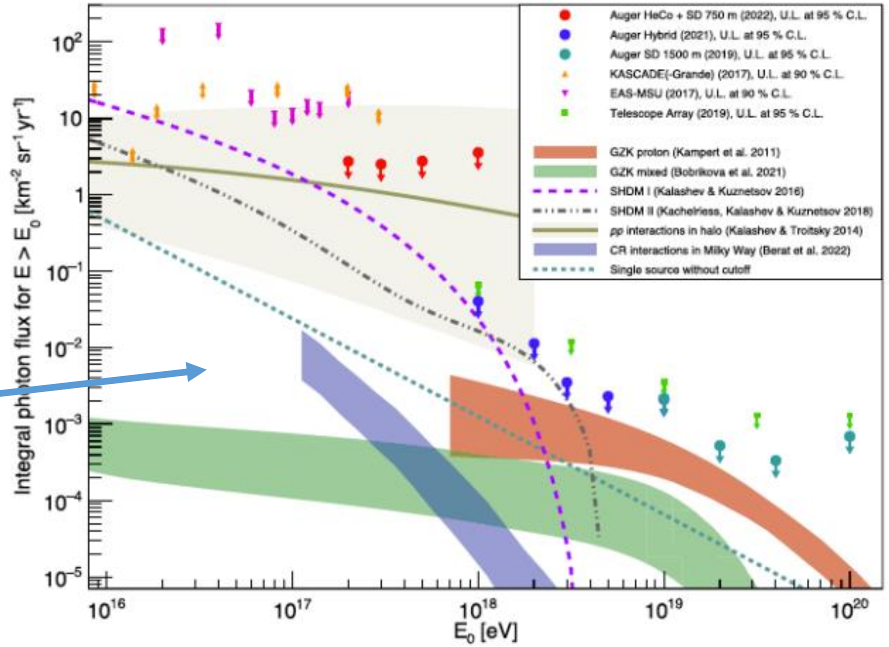




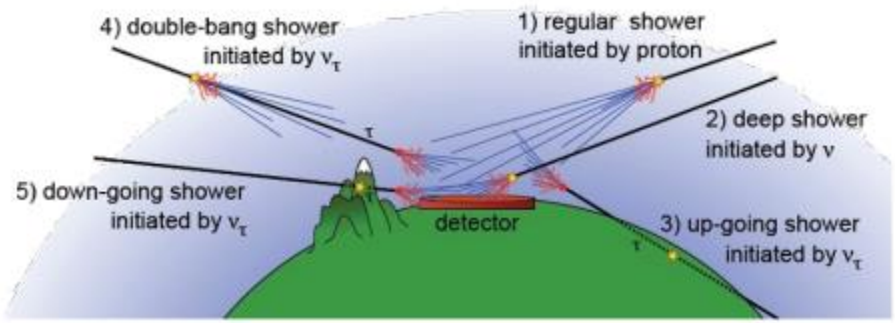
Neutral particles

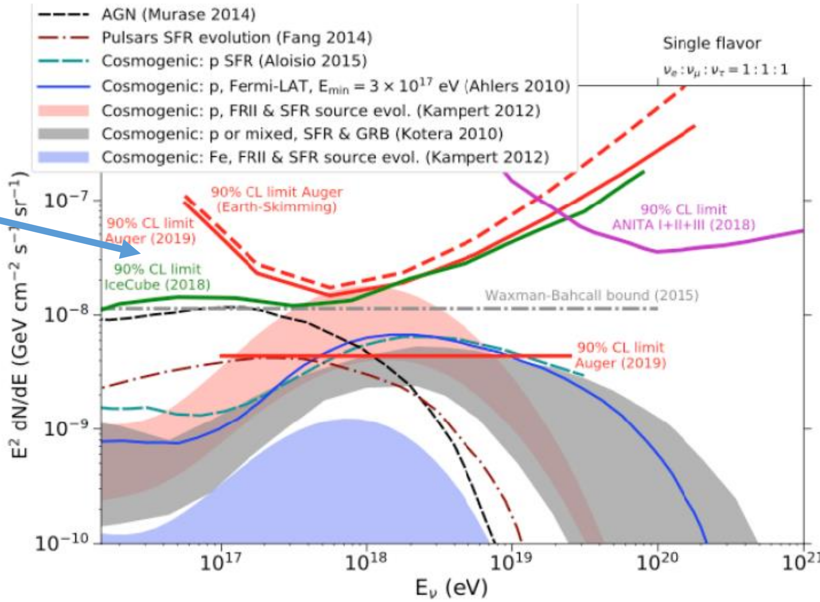
Photons: Pierre Auger Collaboration, Astrophys. J. 933 (2022)
Neutrinos: Aab et al., JCAP 10 (2019), JCAP 11 (2019)

- Photon limits background dominated
- more data for γ/hadron separation needed
- an increased sensitivity to photons required for probing unexpected phenomena, e.g. Milky Way sources, interaction in the halo, decay of SHDM



- different models of cosmogenic and astrophysical neutrino production excluded





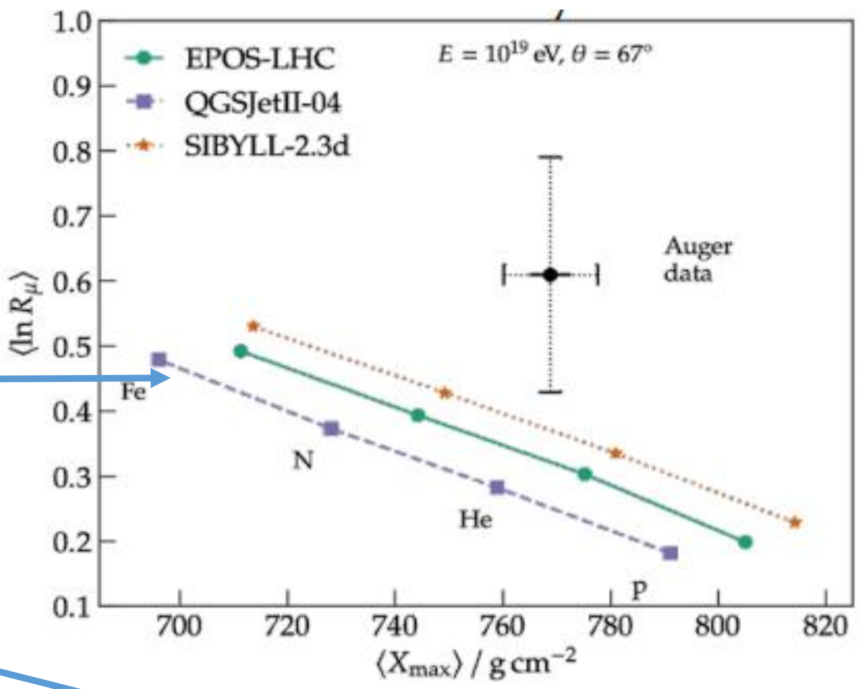
Neutrinos used and photons in multimessenger studies of transient phenomena – P. Ruehl talk

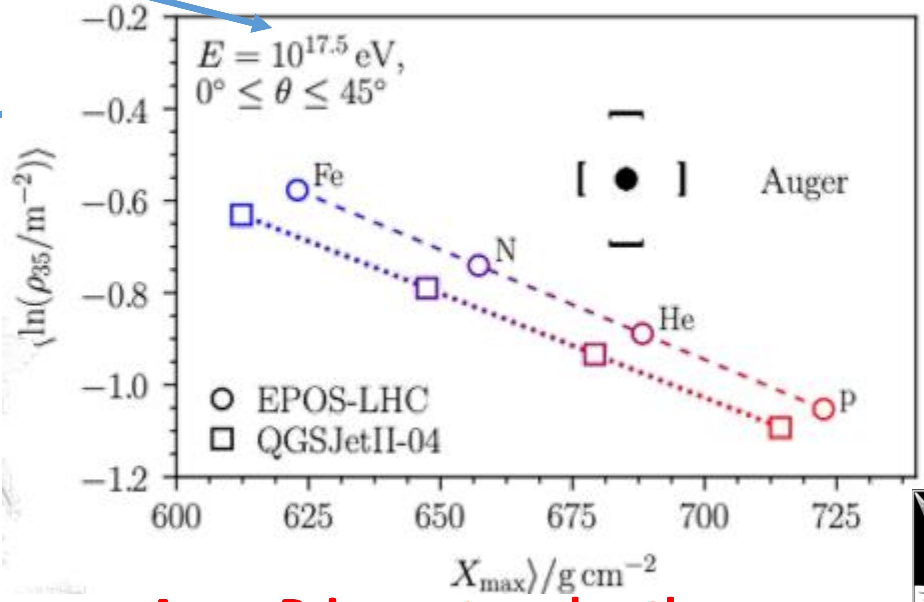
Muon puzzle

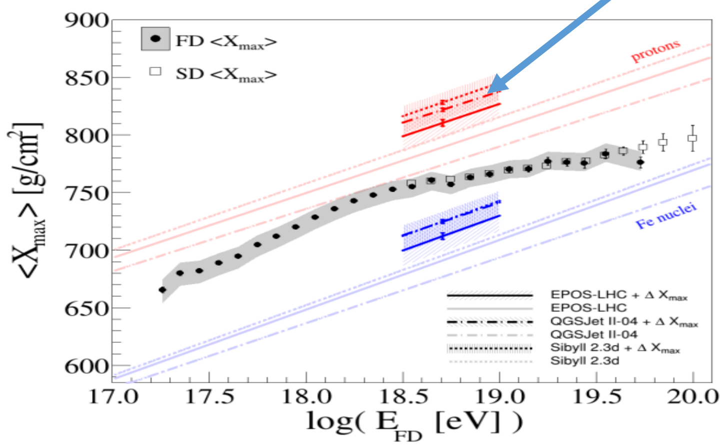
A.Aab et al., PRL 126 (2021) 152002
Pierre Auger Collaboration, Eur. Phys. J. C80 (2020)
J. Vicha, et al, PoS(ICRC2021)310

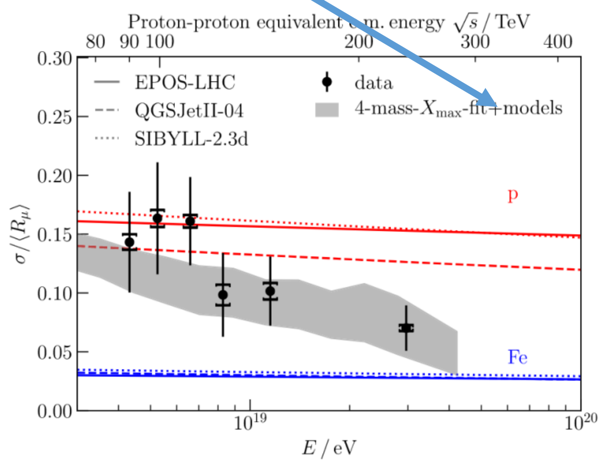
- Muon excess (30 - 80 %) in data wrt simulations seen in all analyses
- Inclined hybrid events
- Muon detectors (AMIGA)
- SD only – universality
- Muon number fluctuations OK (cumulation effect in many interactions)

- Many attempts to explain muon puzzle – modification of interaction models, phenomenology, data driven (muon and X_{max} shifts) …





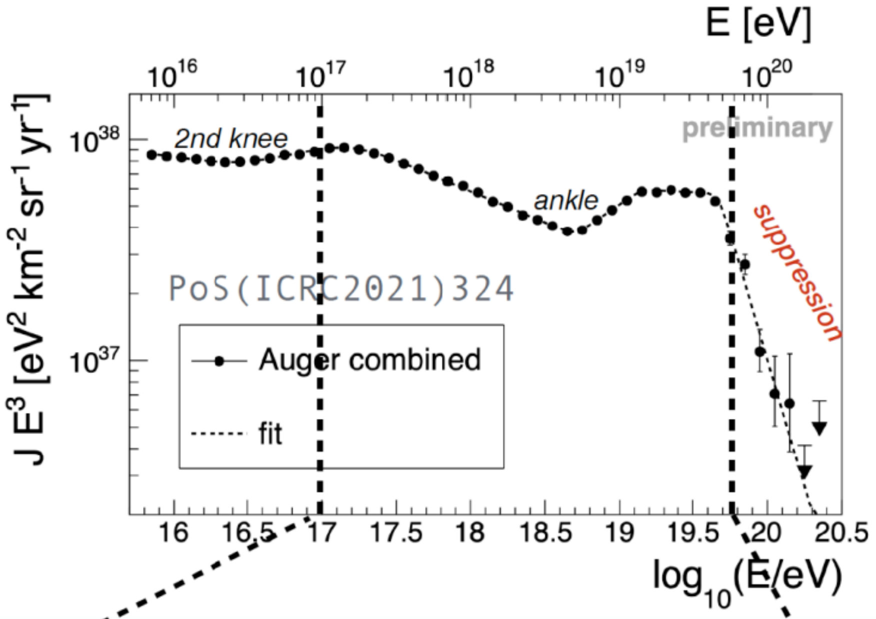


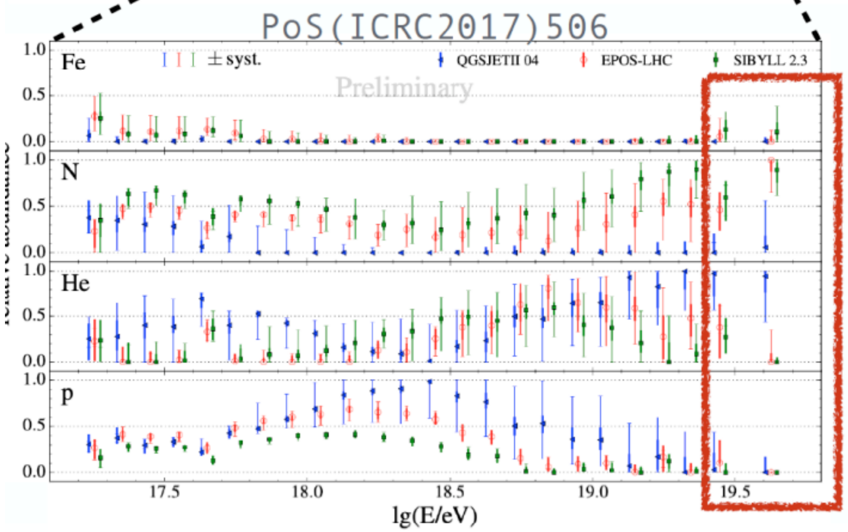


AugerPrime – to solve the muon puzzle !

Results of Phase I (before AugerPrime)

- **Flux suppression well established** : the UHECR sources must be nearby (< 200 Mpc)
- **Composition mixed and heavier above ~ 2x10^{18} eV** from Xmax measurements … but statistics too low above ~10$^{19.5}$ eV due to FD duty cycle ~15%
- **Large scale dipolar anisotropy (6.6 σ) : extragalactic origin for UHECR > 8 EeV** + Hints of correlation with SBG/AGN ➞ Quest for sources still open
- **Muon puzzle**: muon content in simulations lower than in data ➞ Tension with all hadronic models
- **Strong limits on the flux of neutrinos and gammas**: “standard” astrophysical scenarios of UHECR production
- … and many more





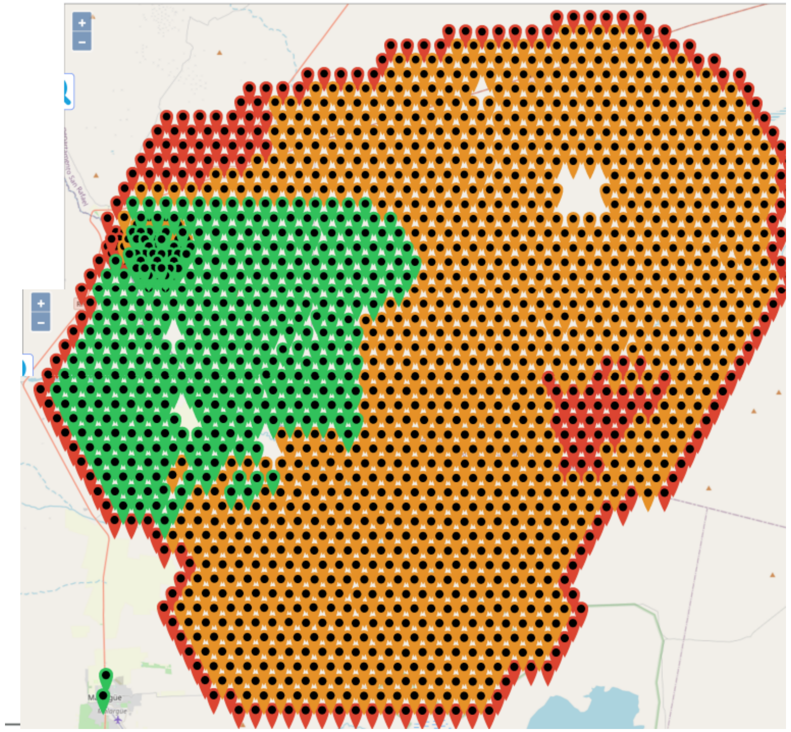
Future of the Observatory - AugerPrime – Phase 2

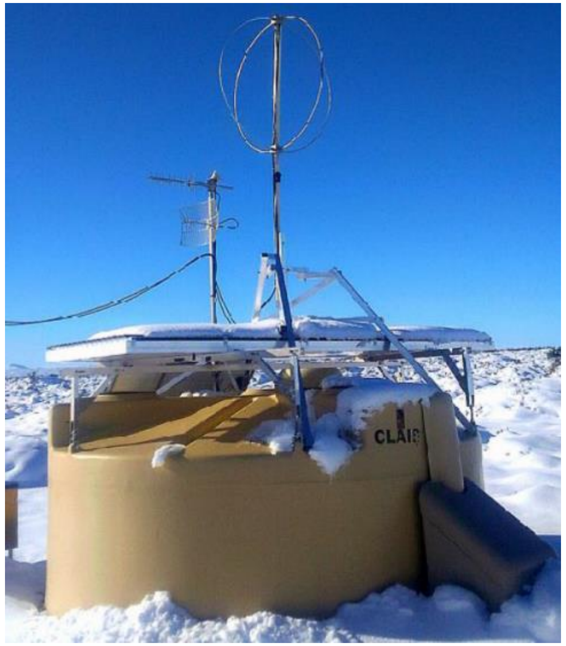
Water-Cherenkov station (WCD):

- addition of the the SSD (Surface Scintillator Detector) - to measure the mass composition in combination with the WCD
- addition of the RD (Radio Detector) - to measure the radio emission of showers in atmosphere (30-80 MHz)
- New electronics, wider dynamic range - to process the signals of all detectors (40 MHz -> 120 MHz, better GPS timing), small PMT (sPMT) to increase the dynamic range of the WCD ($\gtrsim$ 20,000 VEM)

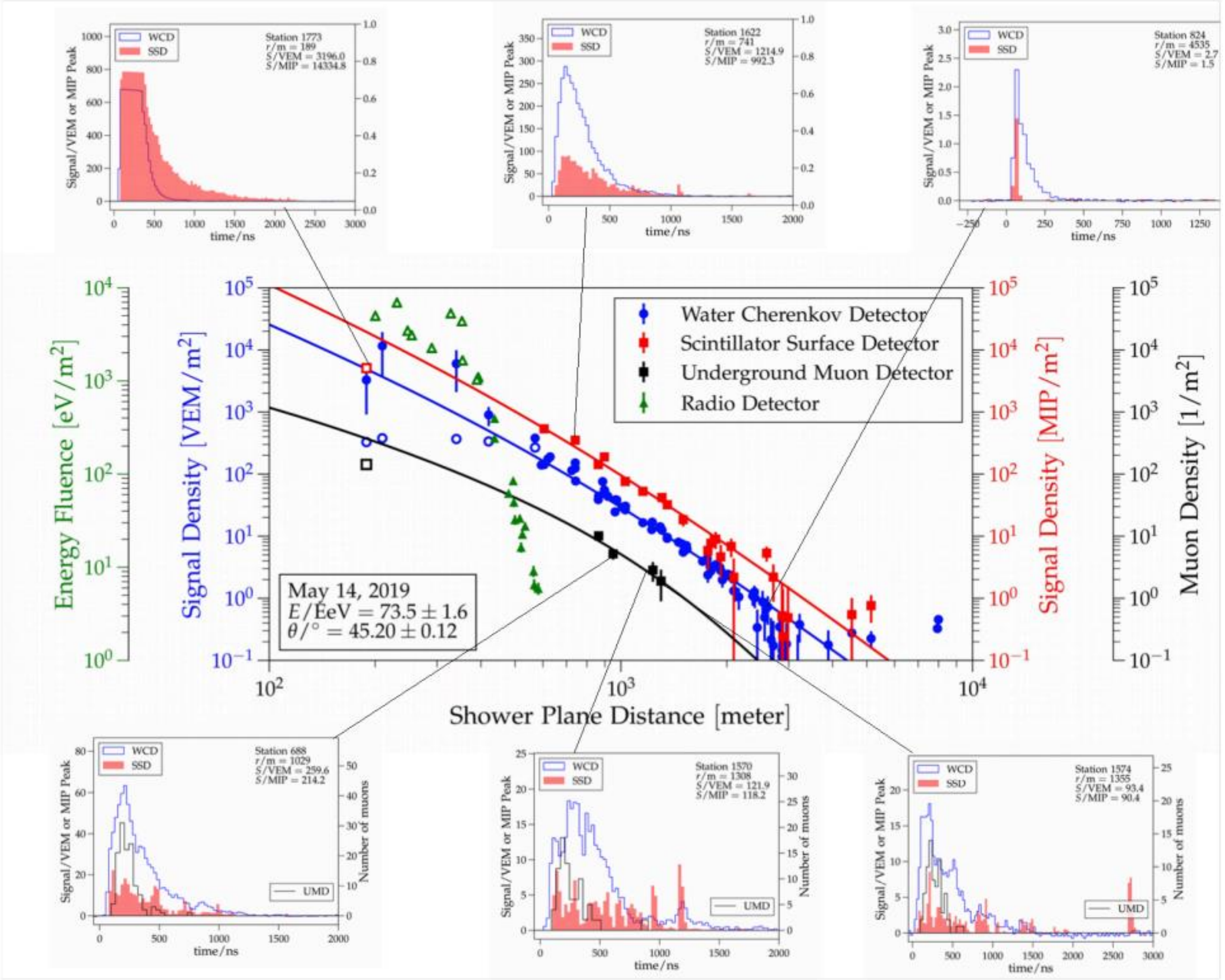
Infill region (61 WCD):

- the UMD (Underground Muon Detector) - to have a direct muon measurement (infill area, 30 m^2, 2.3 m underground)





Future of the Observatory –AugerPrime - Phase 2

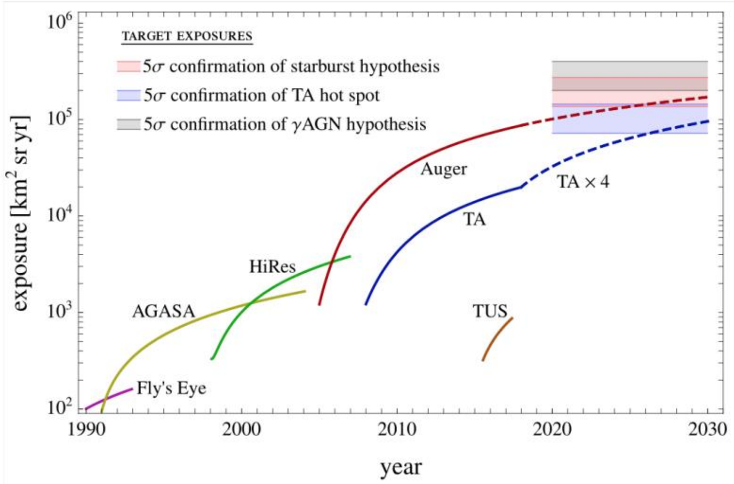


SCIENCE CASE

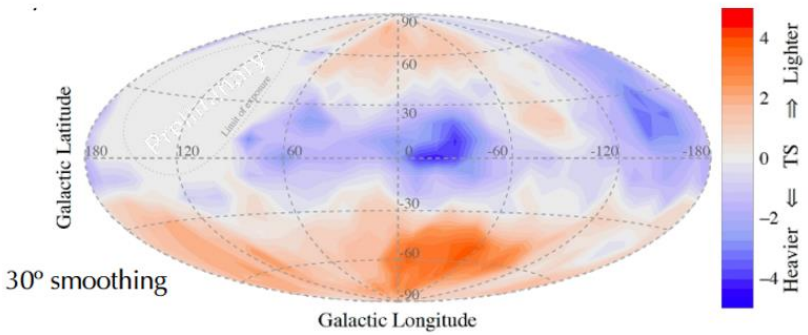
1. **Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario** - fundamental constraints on UHECR sources - galactic vs extragalactic origin - reliable prediction of GZK ν- and -γ fluxes
2. **Search for a flux contribution of protons up to the highest energies at a level of ~ 10%** - proton astronomy up to highest energies - prospects of future UHECR experiments
3. **Study of extensive air showers and hadronic multiparticle production above √s=70 TeV** - particle physics beyond man-made accelerators - derivation of constraints on new physics phenomena

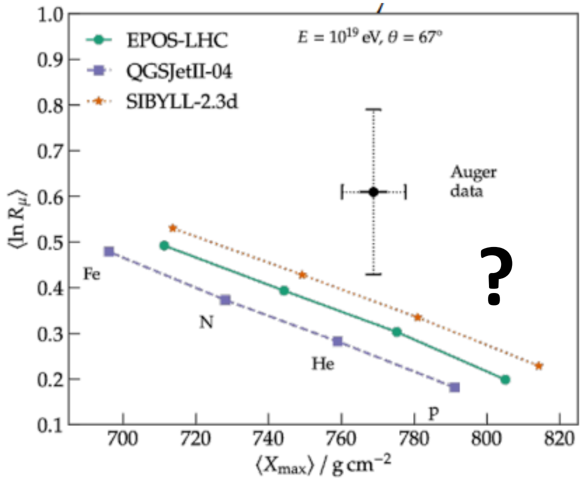
Future of the Observatory - AugerPrime – Phase 2

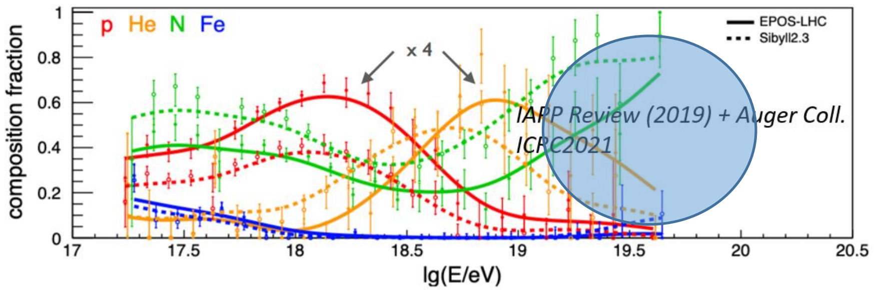
Discovery potential

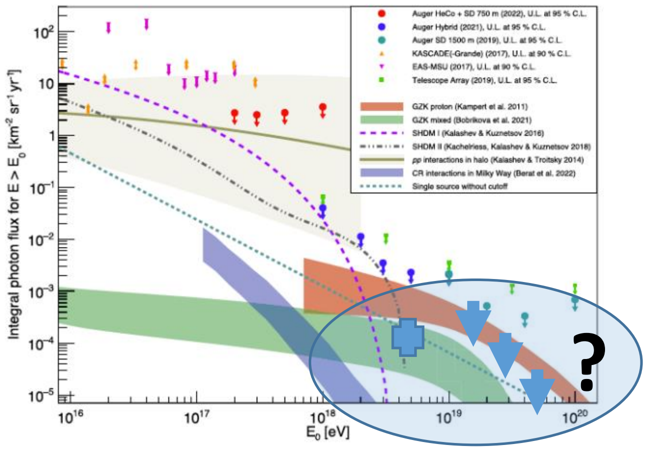


A.Castellina, EPJ Web Conf., 210 (2019) 06002







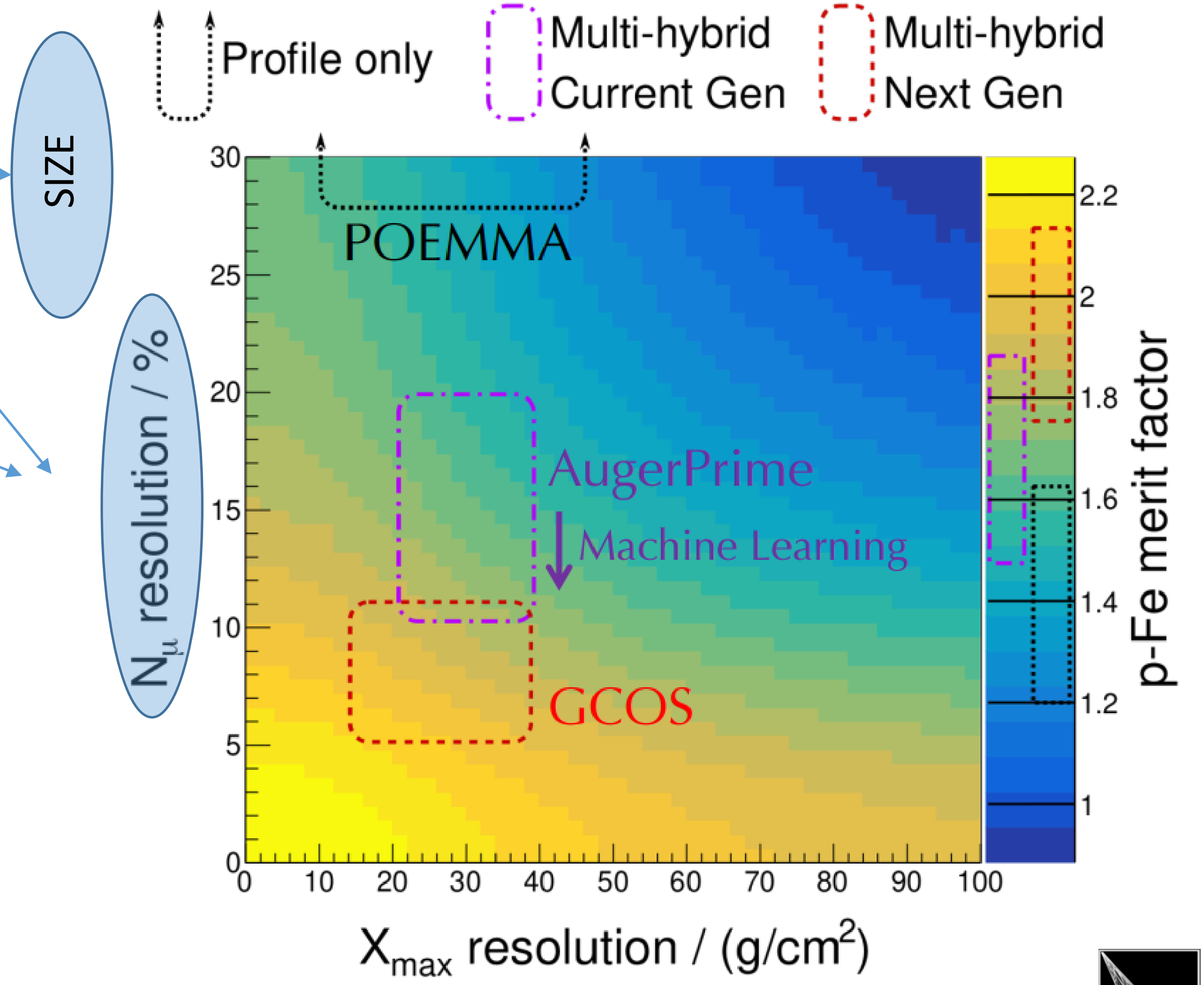


AugerPrime (+ TA extension) - preparing path to future Observatory?

AugerPrime SCIENCE CASE

1. **Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario** - fundamental constraints on UHECR sources - galactic vs extragalactic origin - reliable prediction of GZK ν- and -γ fluxes
2. **Search for a flux contribution of protons up to the highest energies at a level of ~ 10%** - proton astronomy up to highest energies - prospects of future UHECR experiments
3. **Study of extensive air showers and hadronic multiparticle production above √s=70 TeV** - particle physics beyond man-made accelerators - derivation of constraints on new physics phenomena

The concept of future observatory will strongly depend on the results from AugerPrime and TA extension



Snowmass UHECR white paper, arXiv:2205.05845 (2022)