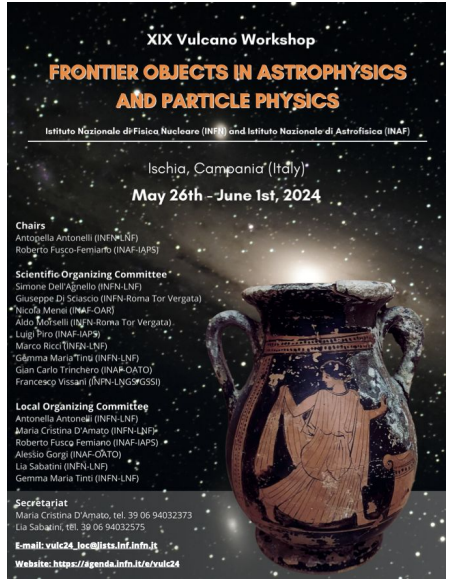
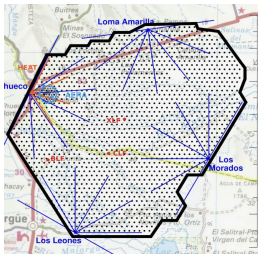
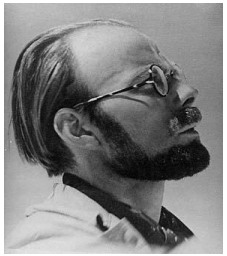
UNIVERSITÀ DEGLI STUDI DELL'AQUILA

DSFC
Dipartimento di Scienze Fisiche e Chimiche



PIERRE AUGER OBSERVATORY





HIGHLIGHTS FROM THE PIERRE AUGER OBSERVATORY

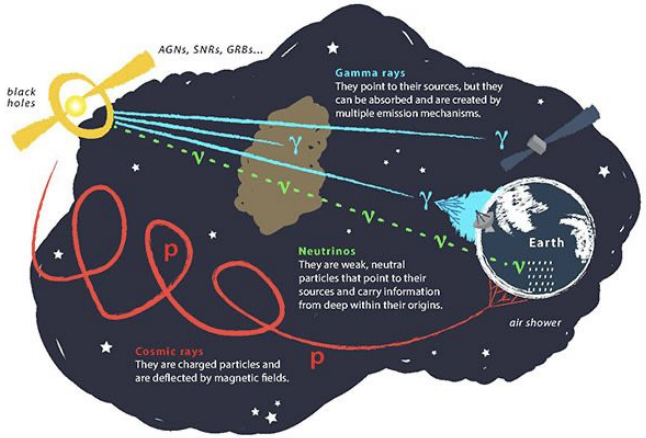
Francesco Salamida University of L'Aquila and INFN LNGS
on behalf of the Pierre Auger Collaboration

XIX Vulcano Workshop on Frontier Objects in Astrophysics and Particle Physics
26th May - 1st June 2024

The Science Case of Ultra High Energy Cosmic Rays

ASTROPHYSICS

- What is the nature of UHECRs?
- What is causing the suppression of the flux at the highest energies?
- Which are the sources? … and can we perform UHECRs astronomy?
- How are UHECRs accelerated to such extreme energies?
- Can UHECRs contribute to multi-messenger astronomy providing complementary information?



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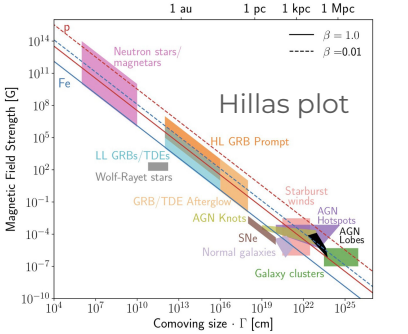
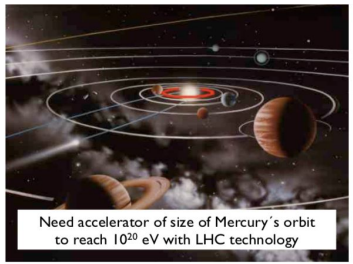
FUNDAMENTAL PHYSICS

- Tests of fundamental interactions and their models in extreme energy regimes
- Constrain or find hints of new phenomena (e.g. Lorentz invariance violation, physics beyond Standard model, Dark Matter)

… and cosmo-geophysics, detector R&D

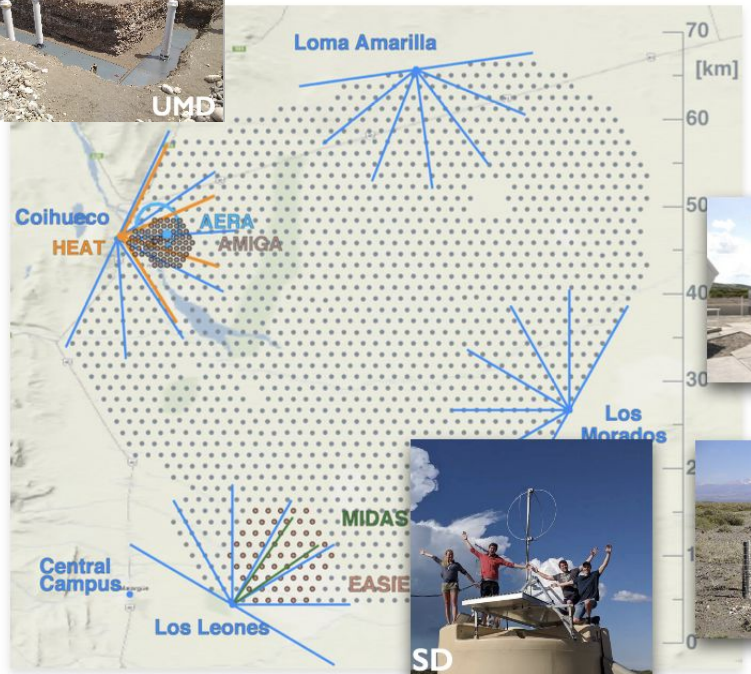


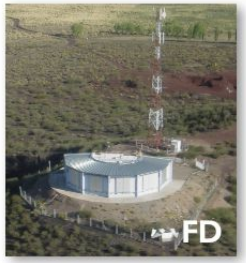


The Pierre Auger Collaboration

~400 members from 18 countries and

The Pierre Auger Observatory





Southern hemisphere: Malargue, Province Mendoza, Argentina

Surface detector (SD)
- 1600 stations in 1.5 km grid, 3000 km^2 E > $10^{18.5}$ eV
- 61 stations in 750 m grid, 23.5 km^2, E > $10^{17.5}$ eV
- 19 stations in 433 m grid, E > 6 10^{16} eV

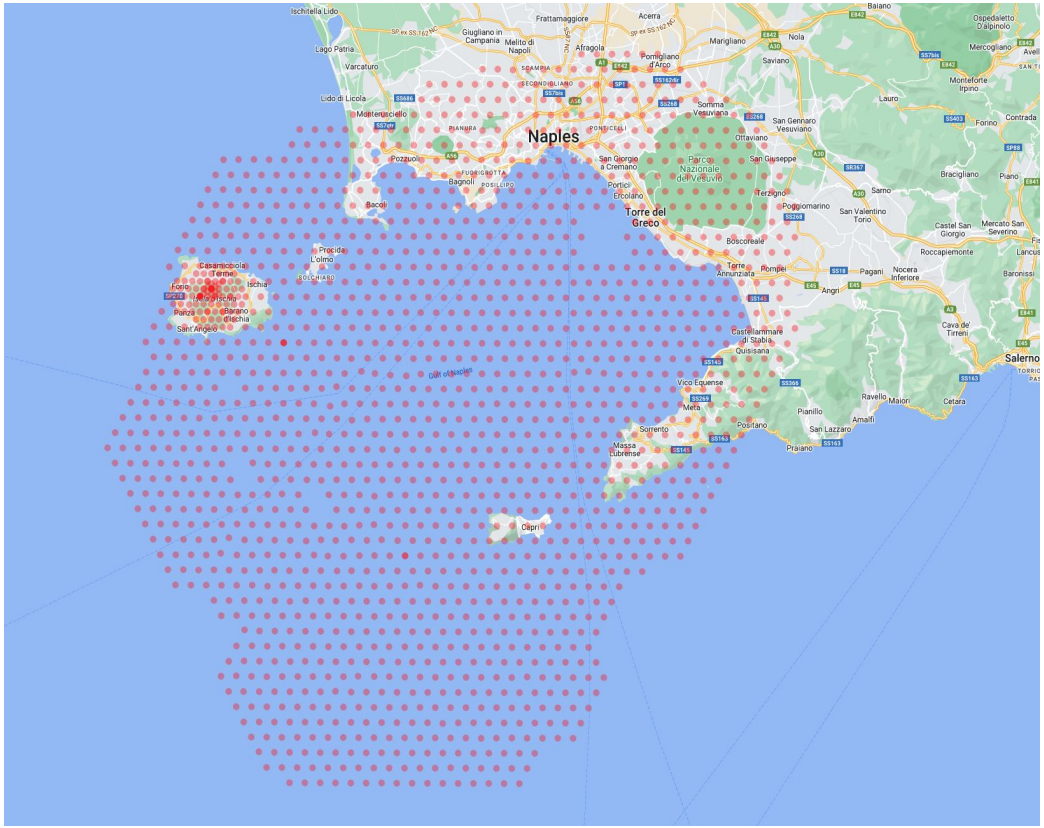
Fluorescence detector (FD)
- 24 telescopes in 4 sites, FoV: 0-30°, E>10^{18} eV
- HEAT (3 telescopes), FoV: 30 - 60°, E>10^{17} eV

Auger Engineering Radio Array (AERA)
- 153 antennas in 17 km^2 array, E> 4 10^{18}eV

Underground muon detector
- 19(61) stations in 433(750)m array $10^{16.5}$<E< 10^{19} eV

Auger Phase I data taking from 2004 on (from 2008 with the full array) to 2021
Auger Phase II data taking from 2022 to 2035 with AugerPrime detectors

The Pierre Auger Observatory



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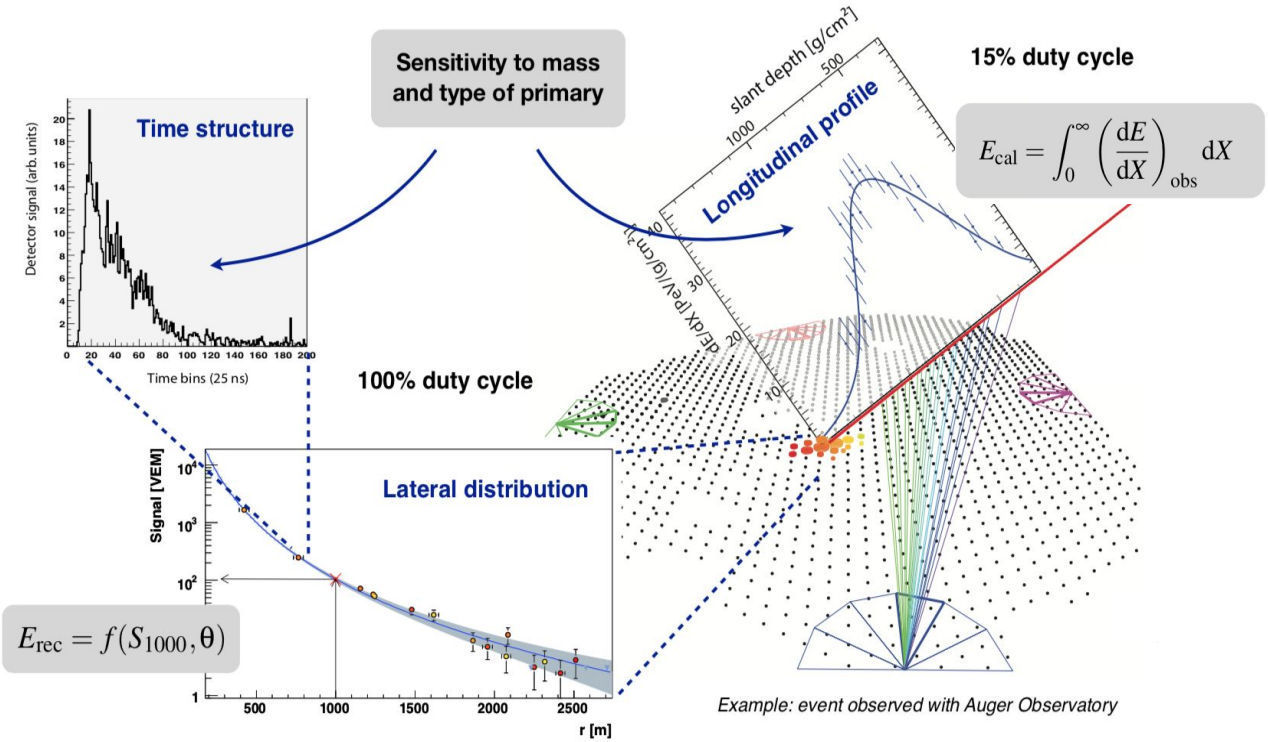
The Hybrid Detection

Measure the same air showers with independent detectors



Fluorescence Detector (FD):

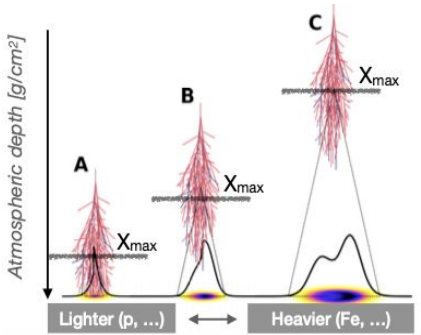
- calorimetric measurement of energy
- ca.15% duty cycle

Surface Detector (SD):

- data driven shape of Lateral Distribution function (LDF)
- optimal distance at 1000 m
- ca. 100% duty cycle

Radio Detector

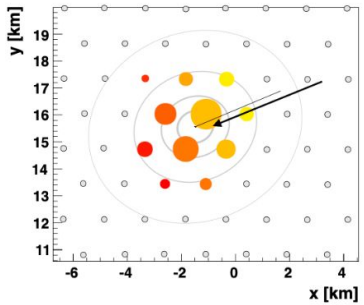
- inclined showers - Auger Phase II (see J. Hörandel))

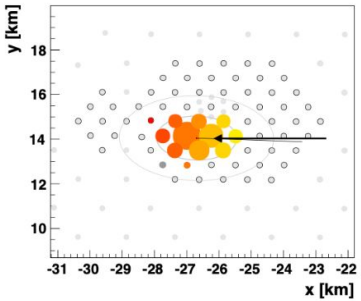


Phase I: showers footprints and calibration

Events footprints depends on geometry and energy

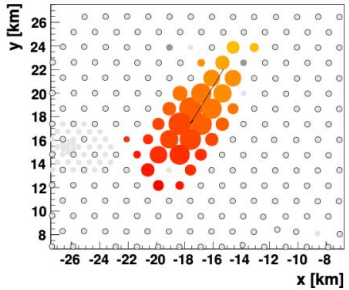
- 1500 m
- θ < 60°
- 100% eff. @ 3 EeV
- $E = A\, S_{38}^{B}$

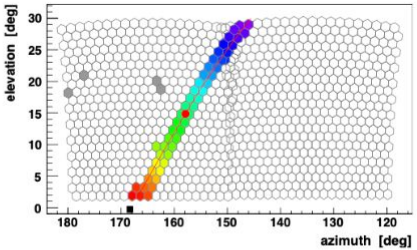




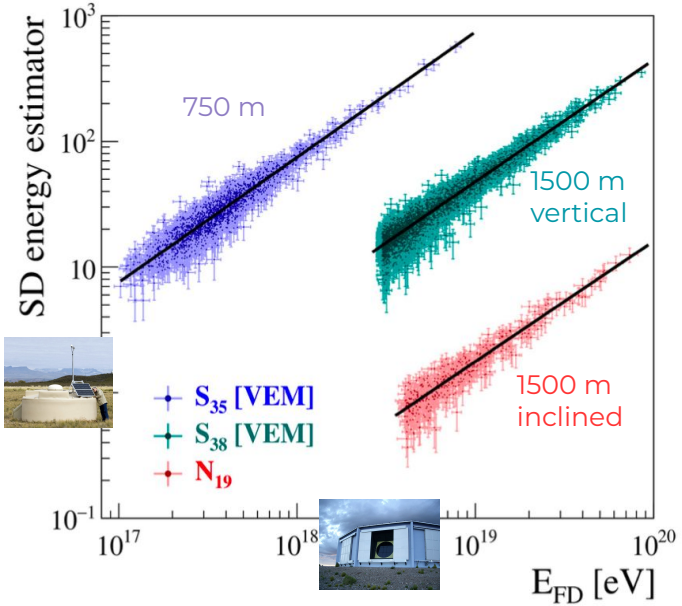
- 750 m
- θ < 55°
- 100% eff. @ 0.3 EeV
- $E = A\, S_{35}^{B}$

- 1500 m
- 60°< θ < 80°
- 100% eff. @ 4 EeV
- $E = A\, N_{19}^{B}$





- FD + 1 SD
- θ < 60°
- 100% eff. @ 1 EeV
- $E = E_{FD}$



Energy resolution

SD: < 20% (zenith < 60° and E > 2.5 10^{18} eV)

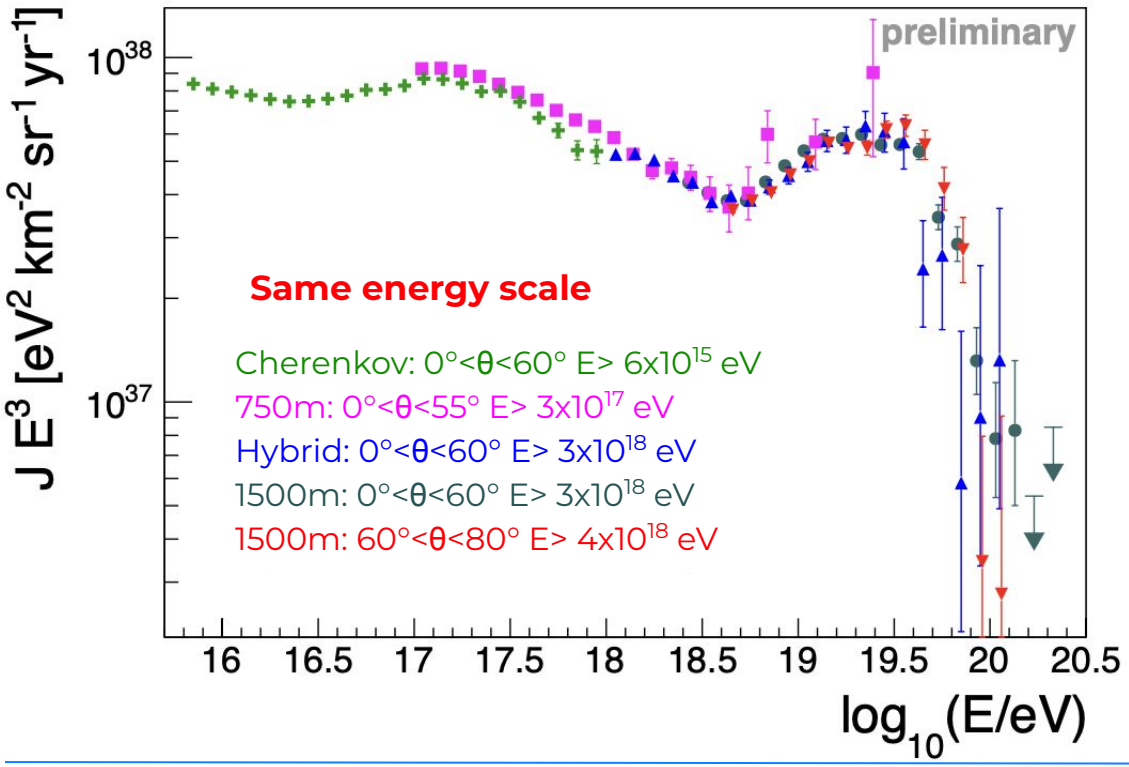
Hybrid: 6-8 % Hybrid [ICRC 2019

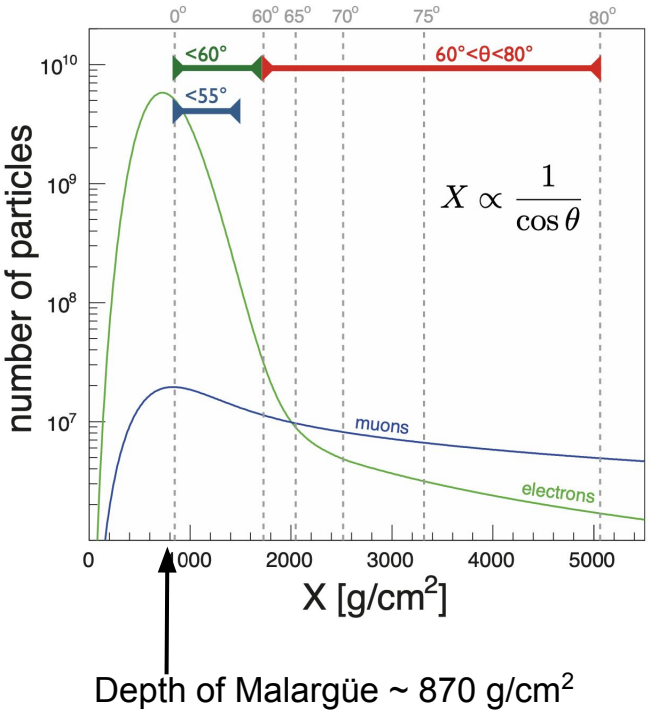
Energy scale systematics

14% (from FD)

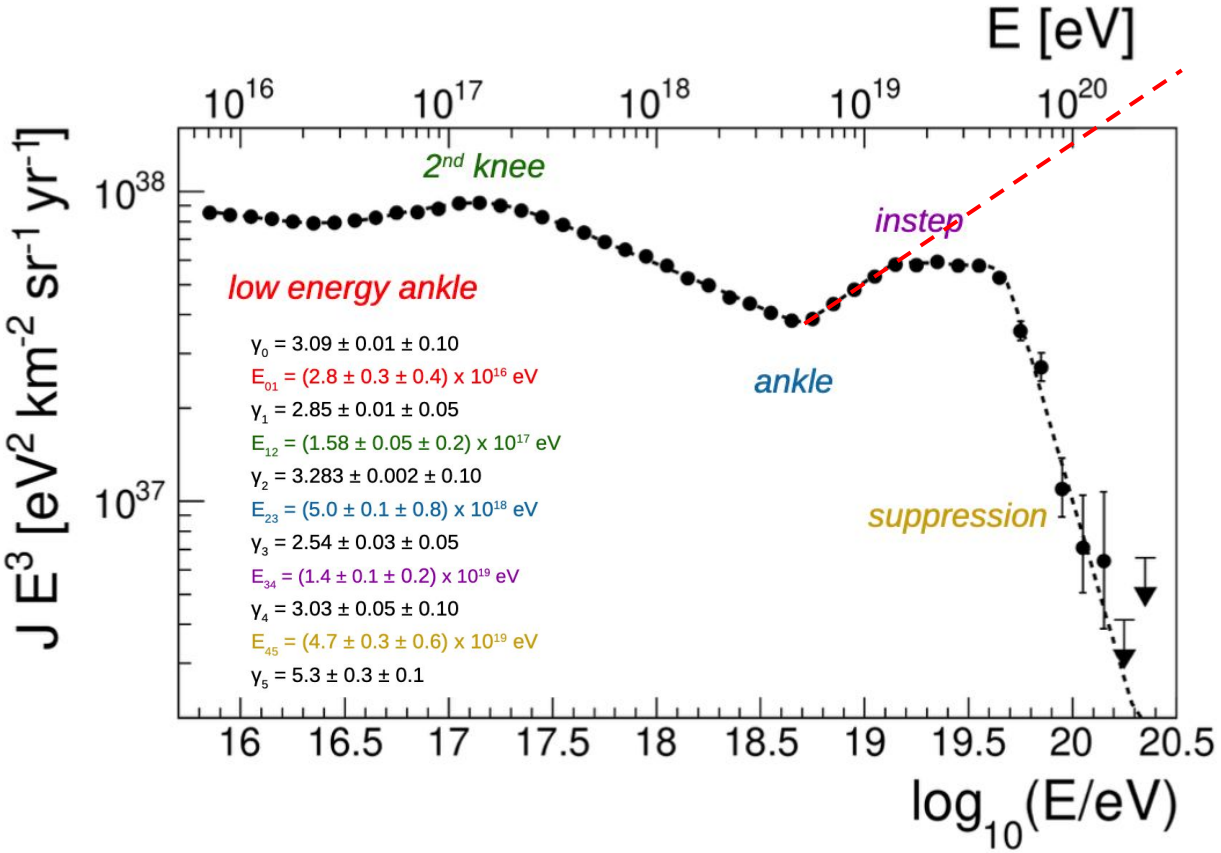
Auger Energy Spectra

- 5 different measurements
- Fluxes in agreement **(1%-7%)** within systematics





Combined Energy Spectrum



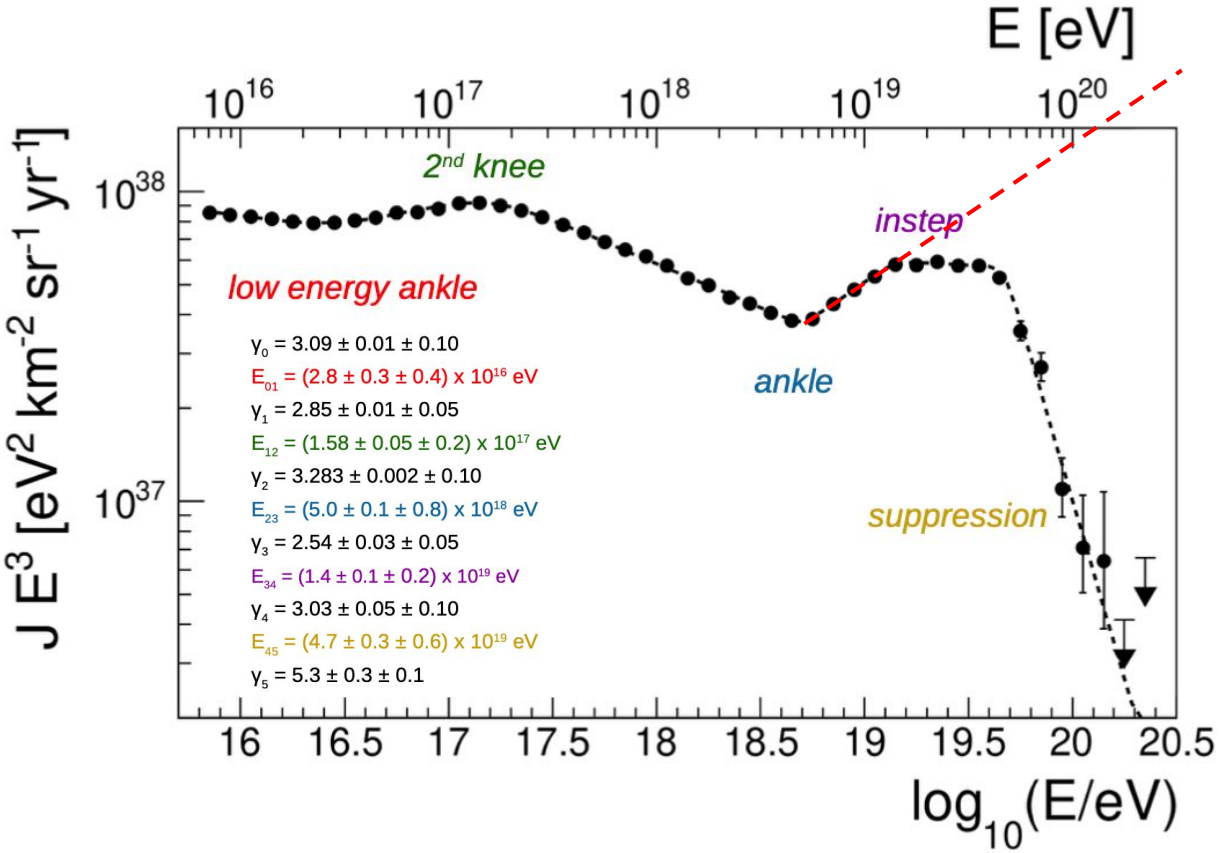
SPECTRUM FEATURES

- Strong suppression at ~ 5 10^{19} eV
- New feature “instep” at ~ 10^{19} eV
- Ankle at ~ 5 10^{18} eV
- 2nd knee at ~ 2 10^{17} eV
- Hint for low energy ankle at ~ 10^{17} eV

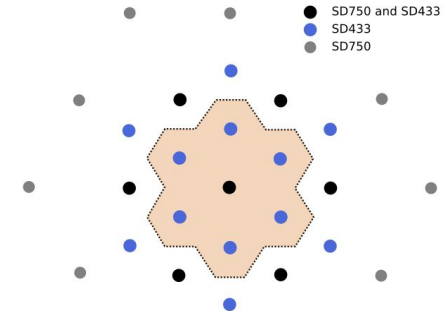
Spectrum shape and Instep not compatible with source models of single mass group (p, ..., Fe)

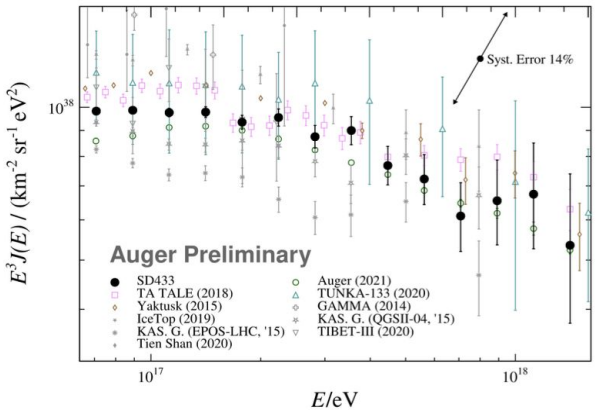
Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
PoS(ICRC 2021) 324

Combined Energy Spectrum



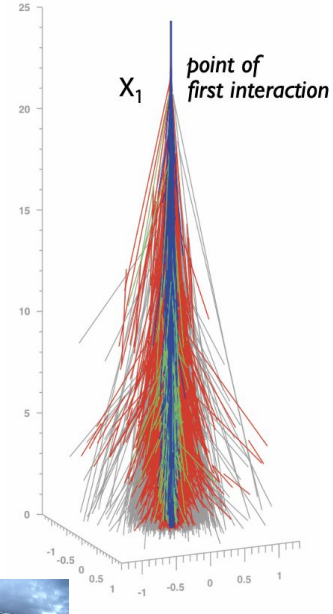
Additional robust measurement of the 2nd knee at **2.3 10^{17} eV** with **SD 433m**

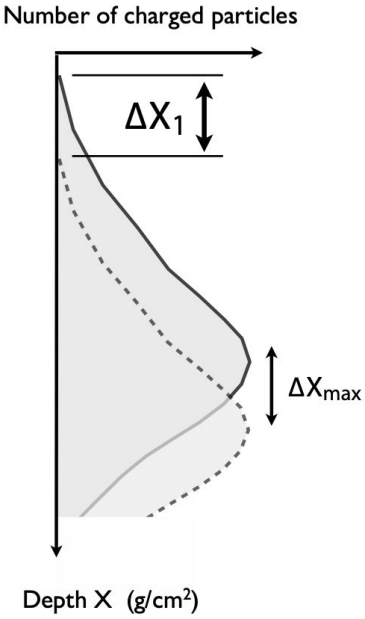


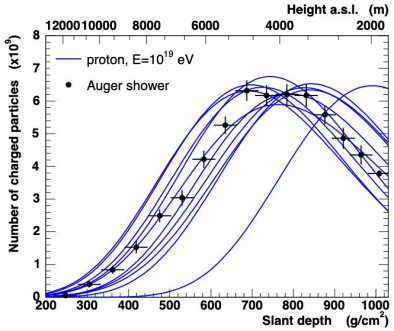


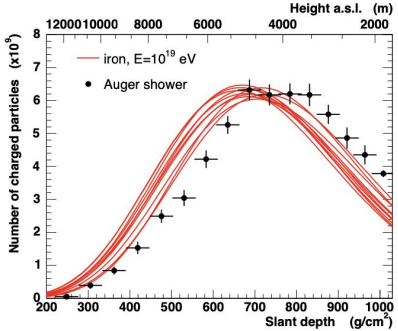
Mass Composition Measurements

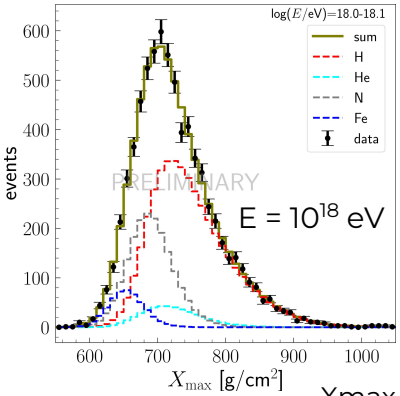
The position of shower maximum **Xmax** is the most accurate mass estimator

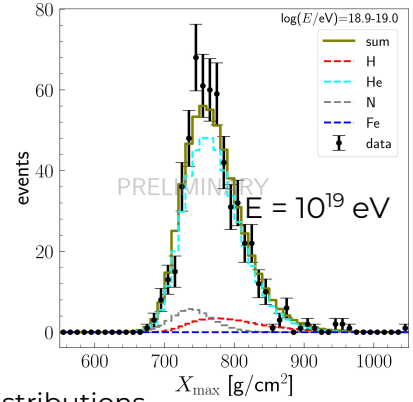












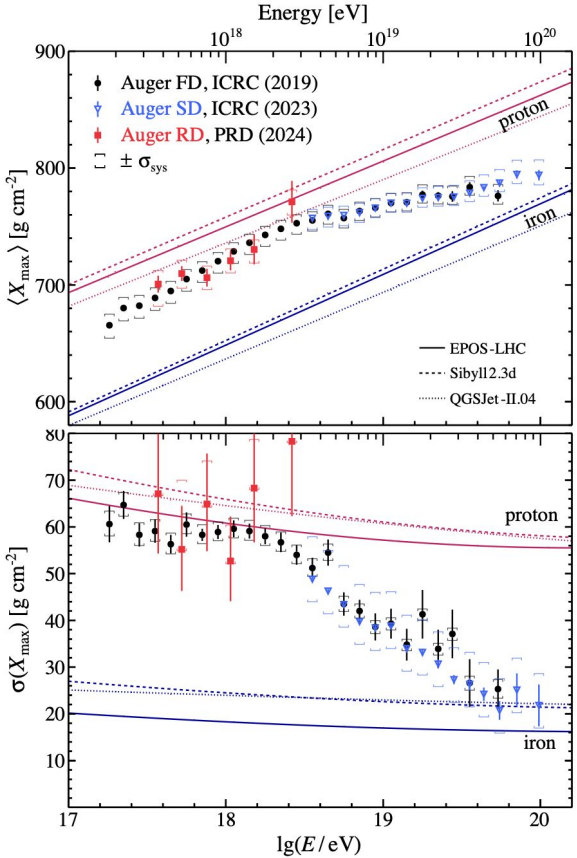
Xmax distributions

Mass Composition Measurements

$$\langle X_{max} \rangle \propto \ln A + D \ln \frac{E}{E_0}$$

Do elongation rate *D* show breaks

Shower-by-shower fluctuations very small



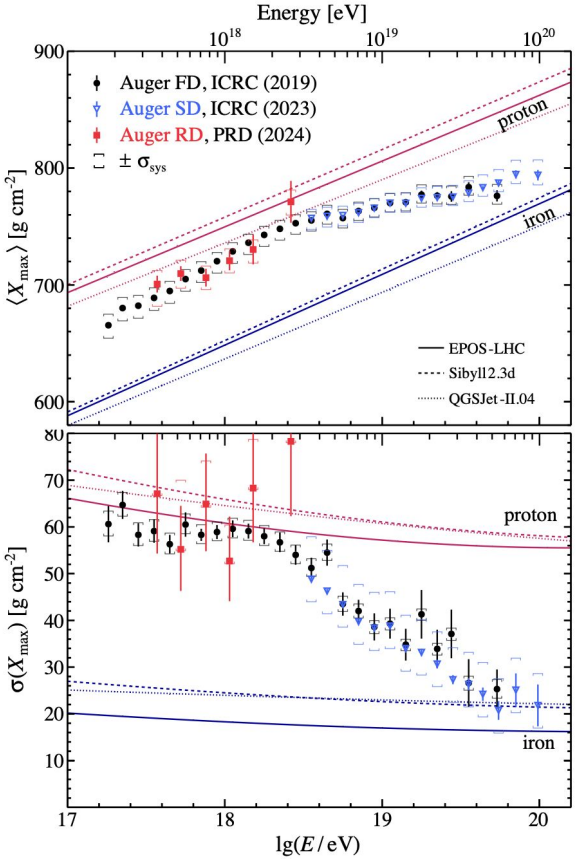
- <Xmax> indicates composition becoming lighter up to 2 10^{18}eV (clear break)and heavier again as the energy increases
- σ(Xmax) shows that composition is more mixed below 2 10^{18} eV and more pure at higher energies.

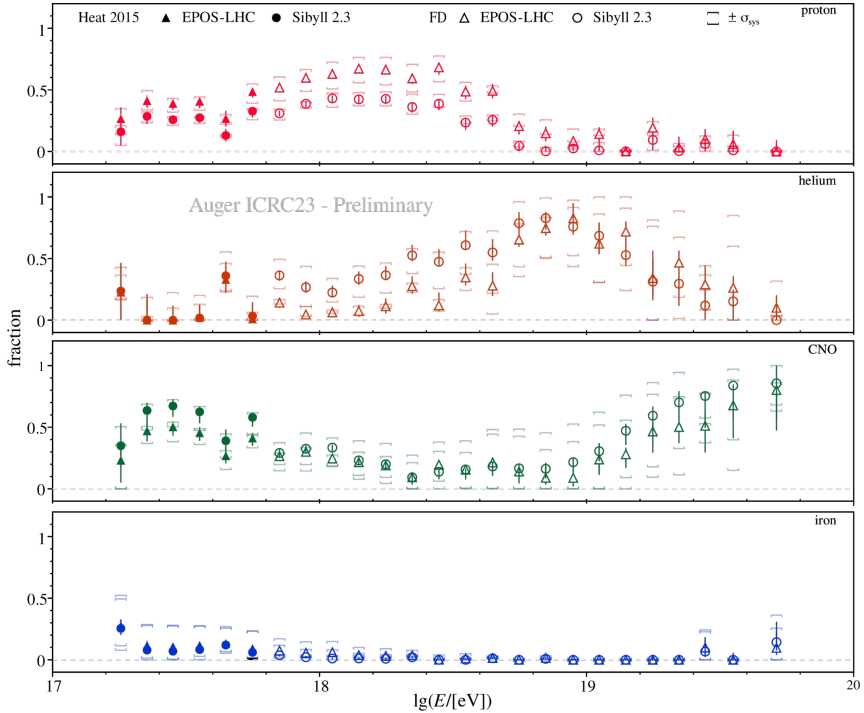
Mass Composition Measurements

$$\langle X_{max} \rangle \propto \ln A + D \ln \frac{E}{E_0}$$

Do elongation rate *D* show breaks?

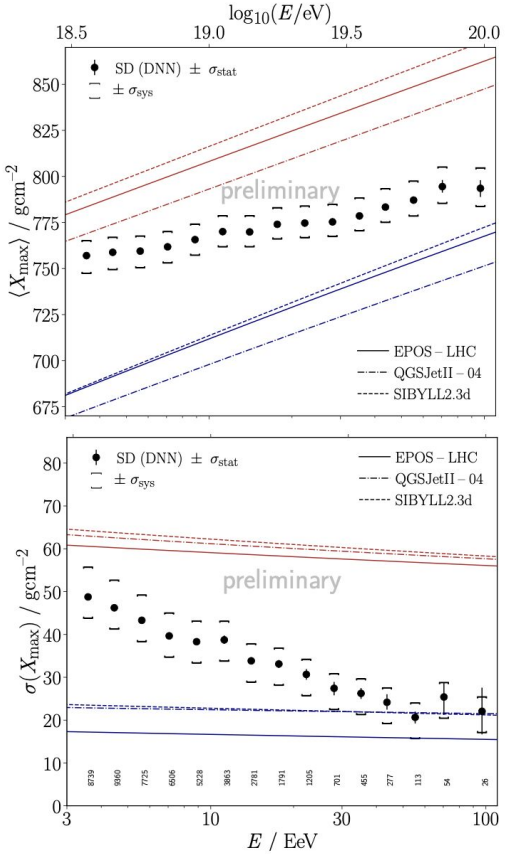
Shower-by-shower fluctuations very small



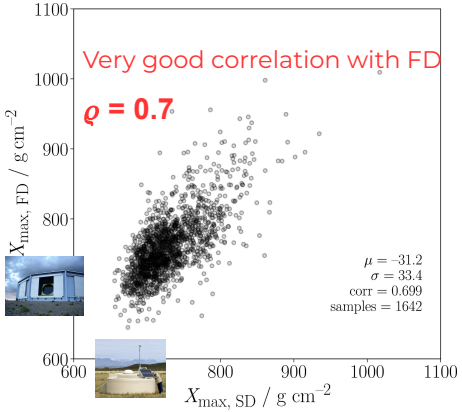


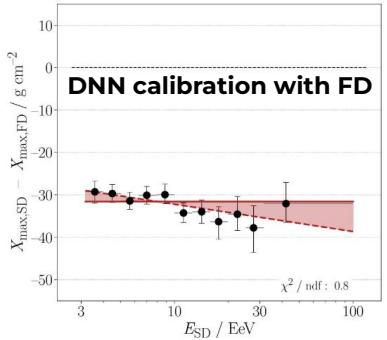
- Constrains photo-pion GZK from non dominance of protons at all energies
- peaks suggest dependence on mass number

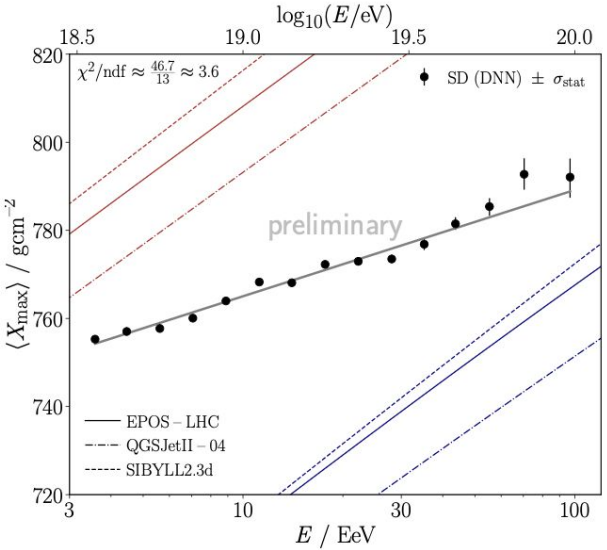
X_{max} from SD using DNN



- About **50000** SD events above 3 10^{18} eV (factor ~10 more then FD)
- Arrival times and traces fed to CNN + RNN networks

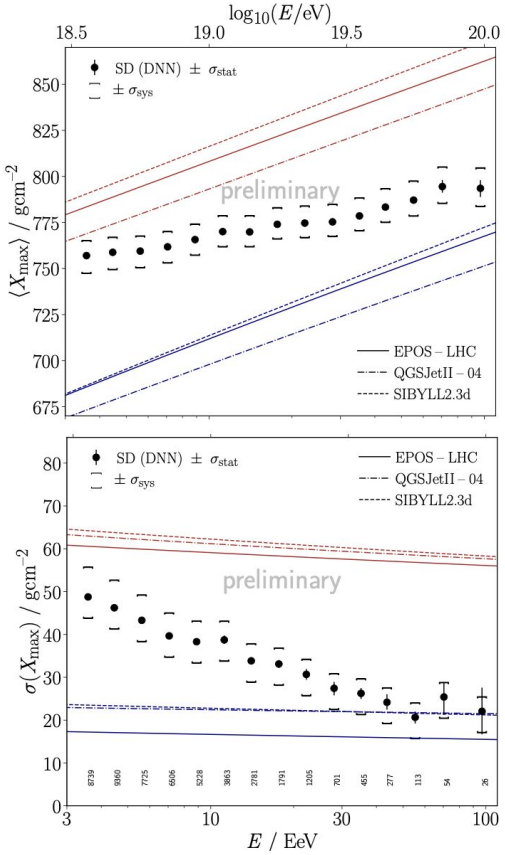






Constant elongation rate excluded at **4.4σ**

X_{max} from SD using DNN



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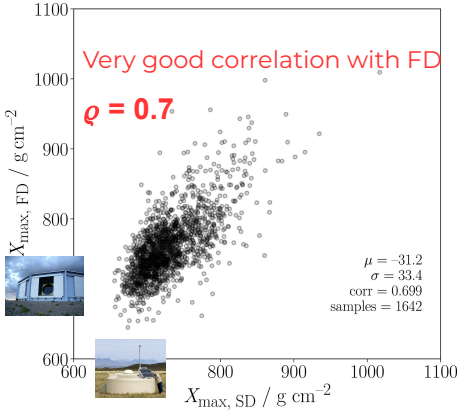
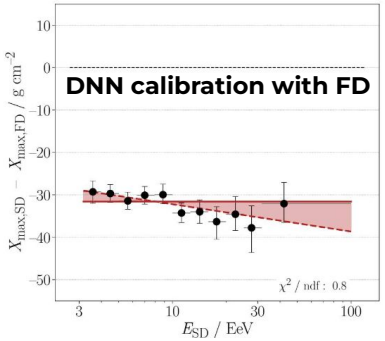
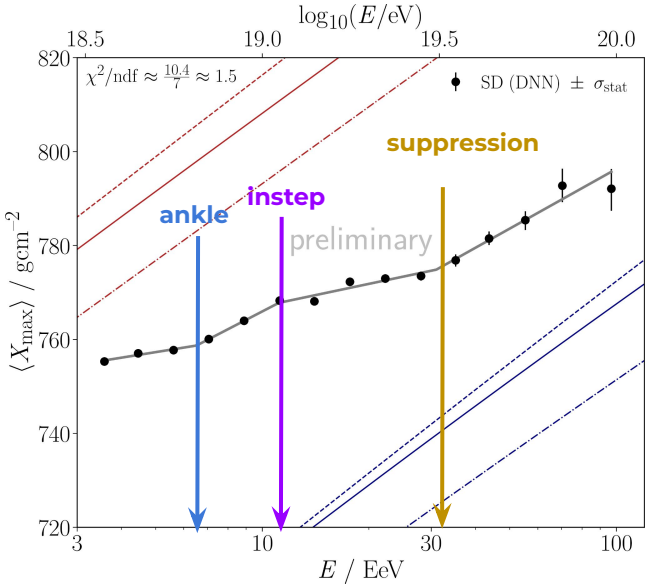




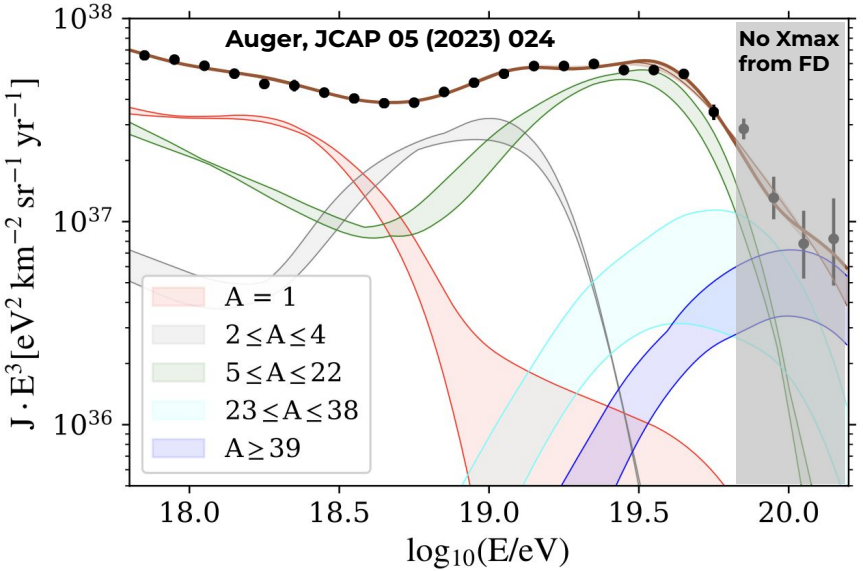


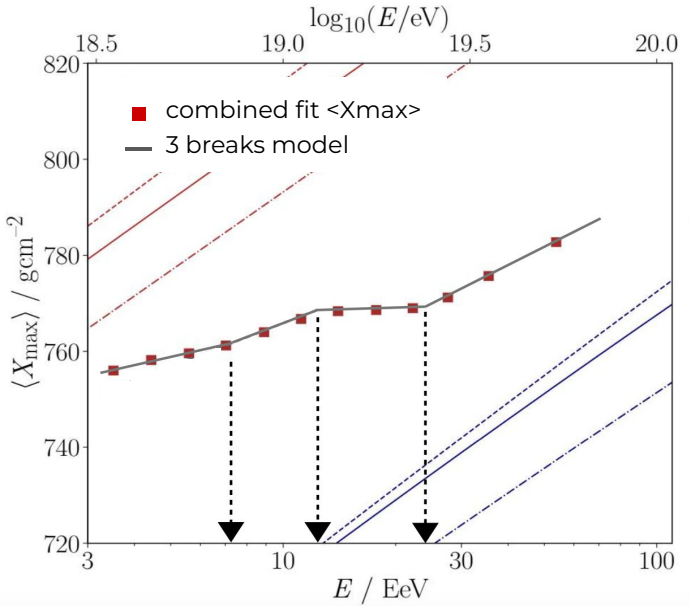
- positions of the breaks correlated with spectrum features
- confirmation that mass composition is lighter and mixed at lower energies, getting heavier and more pure as the energy increase

Astrophysical scenarios and mass composition

SCENARIO: identical source populations uniformly distributed

- proton-only accelerating sources **disfavoured**, nuclei-only accelerating sources **favoured**
- rigidity dependenent scenario **favoured** with hard spectral indexes

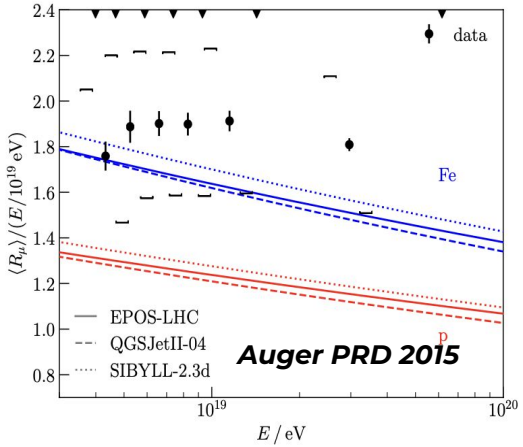


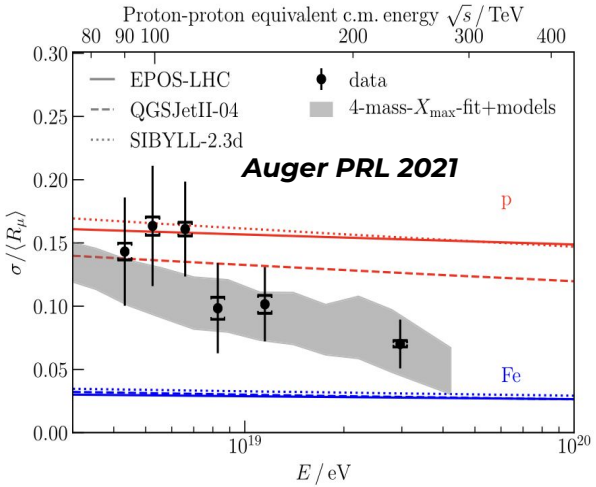


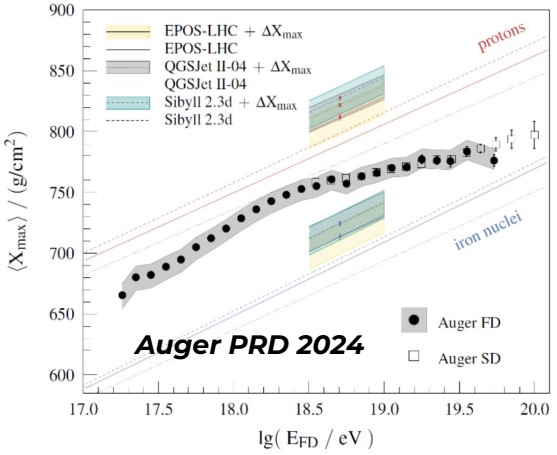
Prediction from combined fit reproduce the breaks as seen in the DNN analysis

Muons and mass composition

SD data, sensitive to the muon content of air showers, suggest heavier primary masses compared to Xmax data, leading to what's known as the 'Muon Puzzle'. (see D. Soldin)

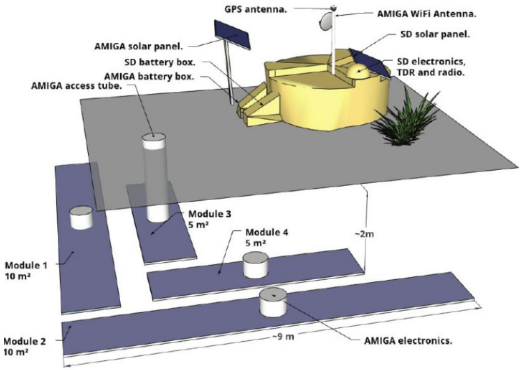




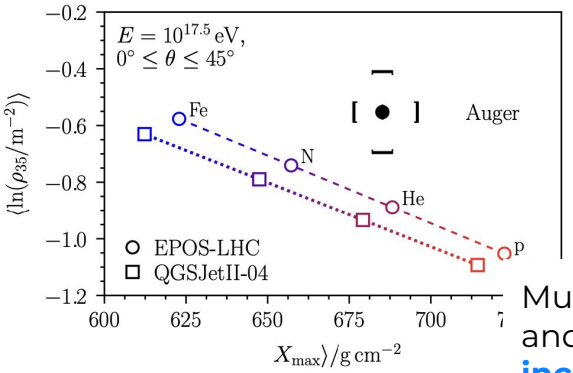


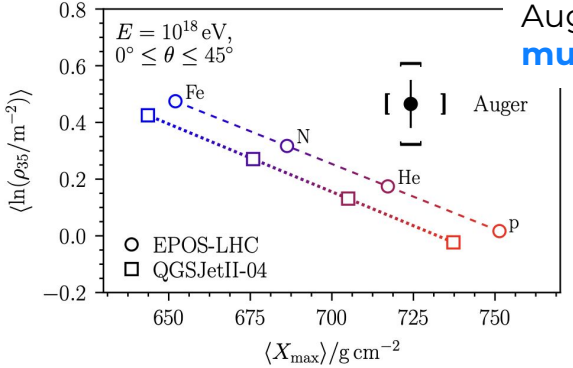
- Discrepancy of muon number (20–30%), but **not** in relative shower-to-shower fluctuations
- 70% of fluctuations are from first interaction (Astropart. Phys. 36 (2012) 21, Phys. Lett. B784 (2018) 68 Phys. Rev. D103 (2021) 022001)
- Discrepacy due to small effect accumulating during shower development
- SD+FD indicates Xmax scale for all models need a 20-50 g/cm² shift to deeper values suggesting that UHECR primary mass can be heavier than current models indicate (model revisions)

Auger Underground Muon Detector



Results form engineering array

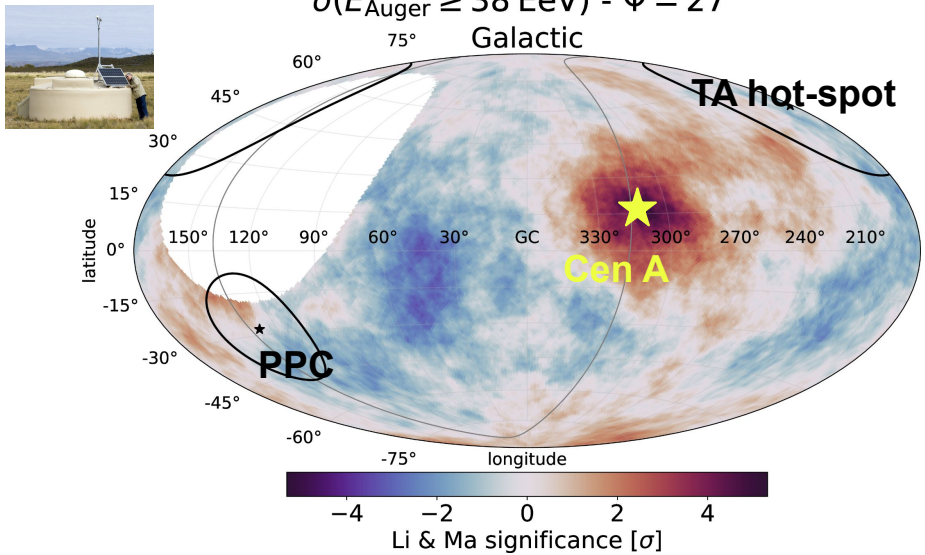


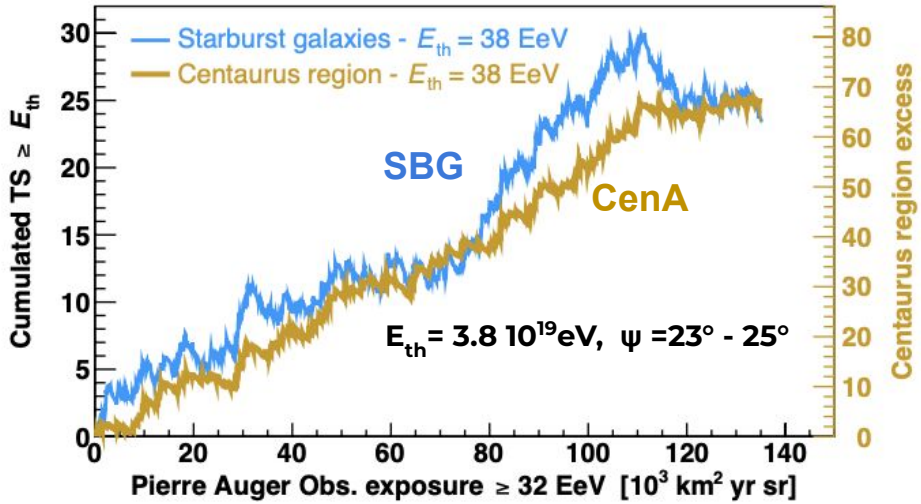


Muon content and Xmax **inconsistent** with Auger data: **muon deficit**

Arrival directions: intermediate scales

overdensity map in Galactic coordinates

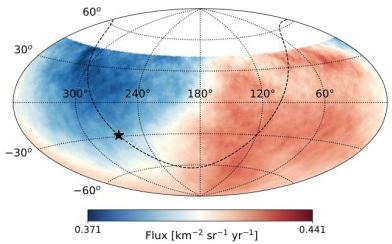




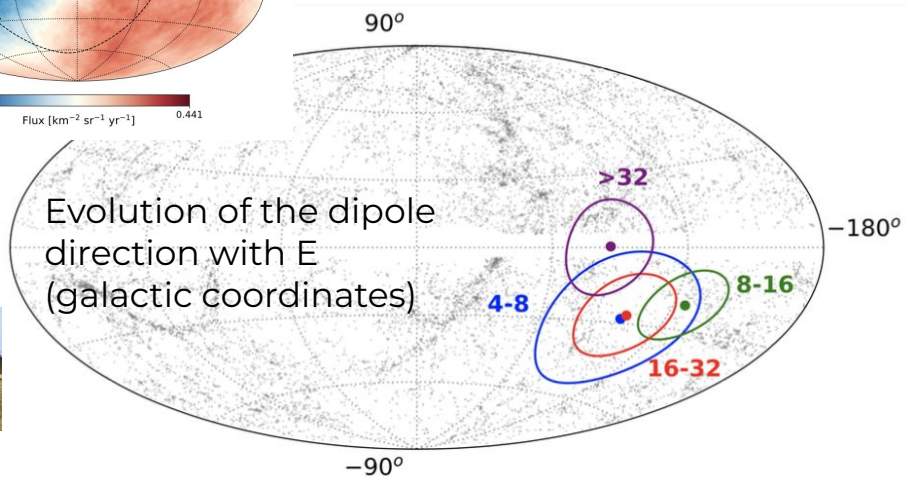
- The most significant excess at **Cen A** **4.0σ** (**5.0σ** expected in >2025)
- TA-hotspot and excesses close to Perseus-Pisces cluster **not confirmed** by Auger

- Likelihood test for correlation of arrival direction with astrophysical catalogs
- Most significant signal at **3.8σ** for SB galaxy catalog

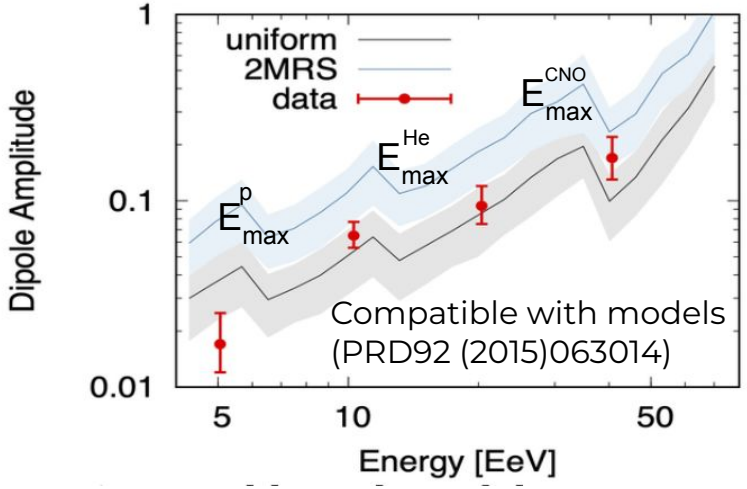
Arrival directions: large scale



Rayleigh analysis: update of Science 315 (2017) 1266



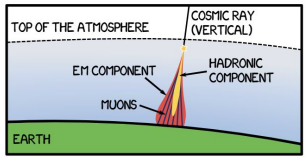
Evolution of the dipole direction with E (galactic coordinates)

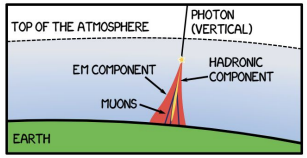


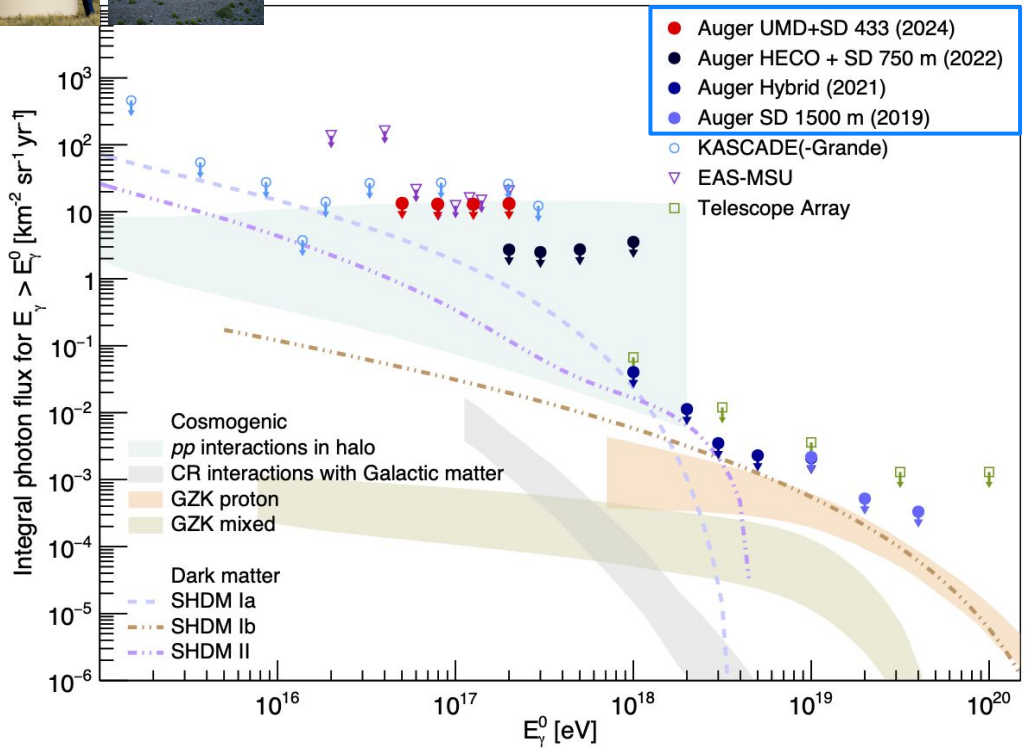
- Dipole pointing ~113° away from the GC established at **6.9σ** for energies **>8 10^{18} eV**
- Growth of dipole amplitude would be steeper for a constant composition, but here the mass and charge are increasing with energy
- In the near future mass composition with AugerPrime will improve our results

Multimessenger searches: photons

ɣ signature: deeper (vertical) showers + fewer muons



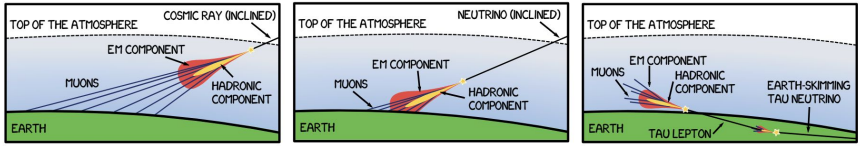


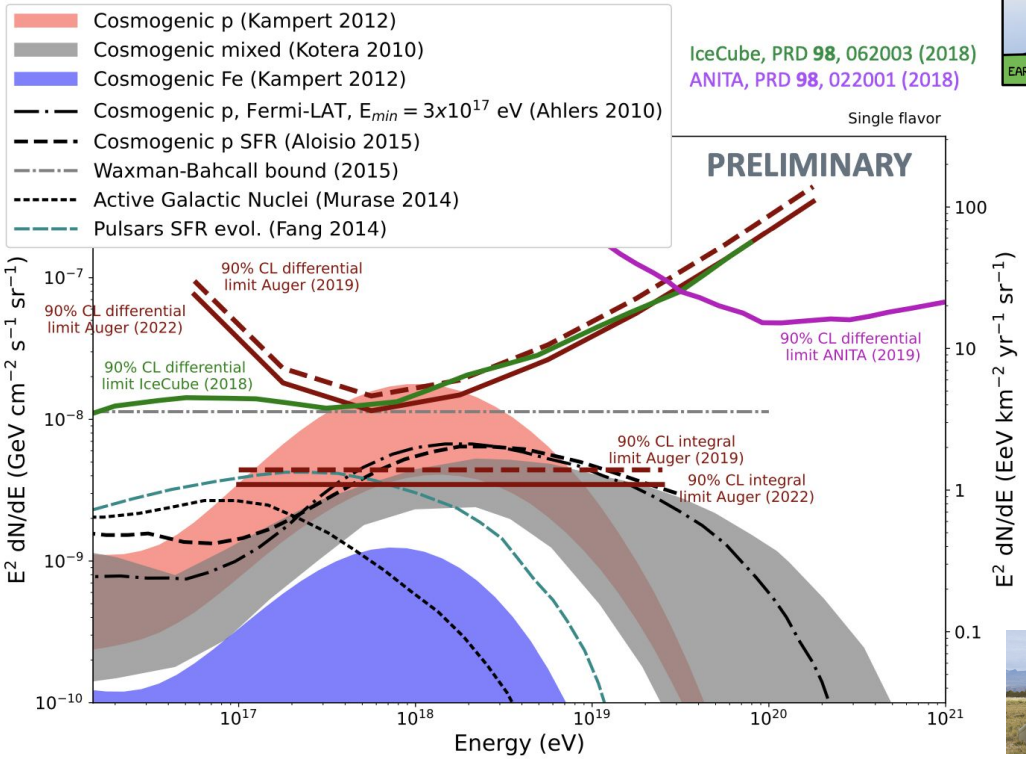


- 4 different measurements available
- no primary photon observed: set the most stringent limits on the diffuse flux of UHE ɣs over ~4 order of magnitude in energy
- approaching predictions for cosmogenic models involving GZK
- limits allow to constrain BSM predictions involving SHDM particles (*PRL 130 2023, PRD 130 2023, PRD 109 2024*) and LIV (*JCAP 01 2022*)

Multimessenger searches:UHE Neutrino searches

ν SIGNATURE: inclined "young"showers (μ + e.m)

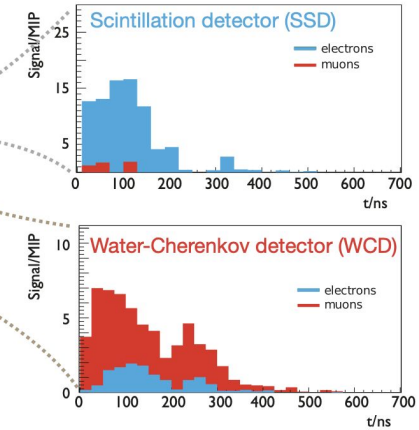




- best sensitivity to UHE neutrinos slightly below 10^{18} eV, comparable to IceCube
- limits on point-like sources of neutrinos complement IceCube
- integral limit for neutrino energies between 10^{17} eV and 2.5×10^{19} eV starting to exclude proton-only accelerating sources scenarios

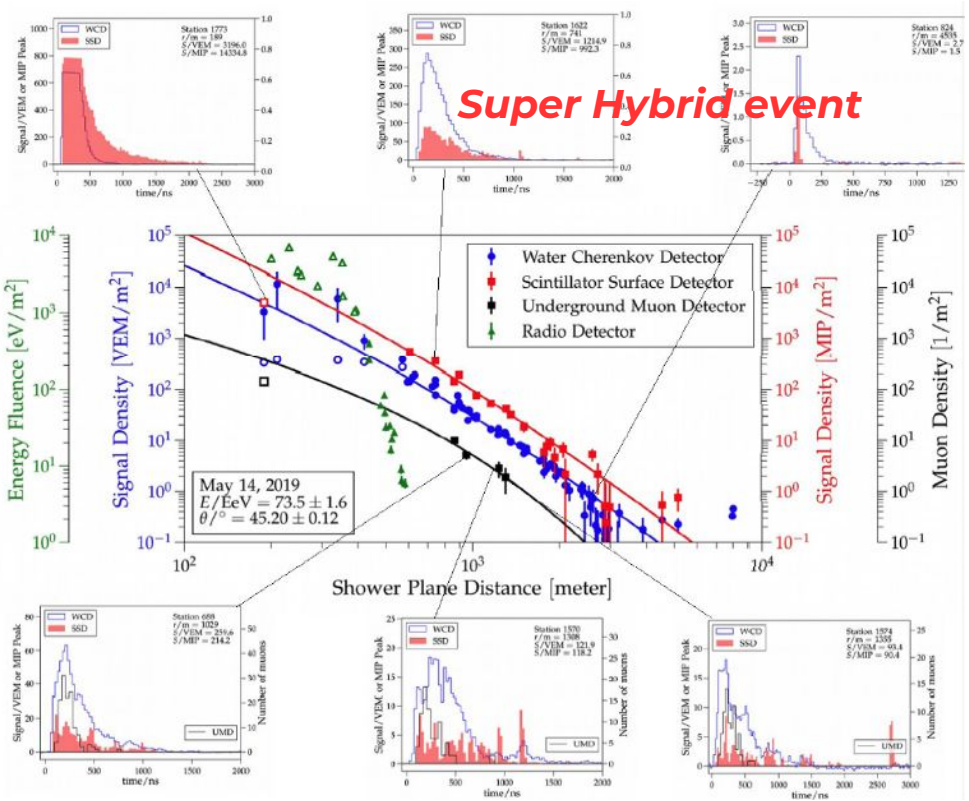
Observatory Phase II: AugerPrime

Complementary detectors to discriminate em. and muonic components



Status of Upgrade

- Scintillators: 1450 installed
- Muon detectors: 38 installed
- Radio: 904 (411) installed (*see J. Hörandel*)



Summary

- Increasingly coherent picture emerging from Auger Phase I data
- Observed correlated changes in flux, mass composition and arrival directions of Ultra High Energy Cosmic Rays:
  - energy spectrum features appear correlated with changes in evolution of mass composition
  - growth of dipole anisotropy with energy is consistent with the increase of mean primary mass with energy
  - results are consistent with neutrals: limits for neutrino and photon fluxes starting to scratch GZK models.
- Tension between currrent hadronic interaction models and Auger data
- AugerPrime and new analysis techniques offer great promises for Phase II science