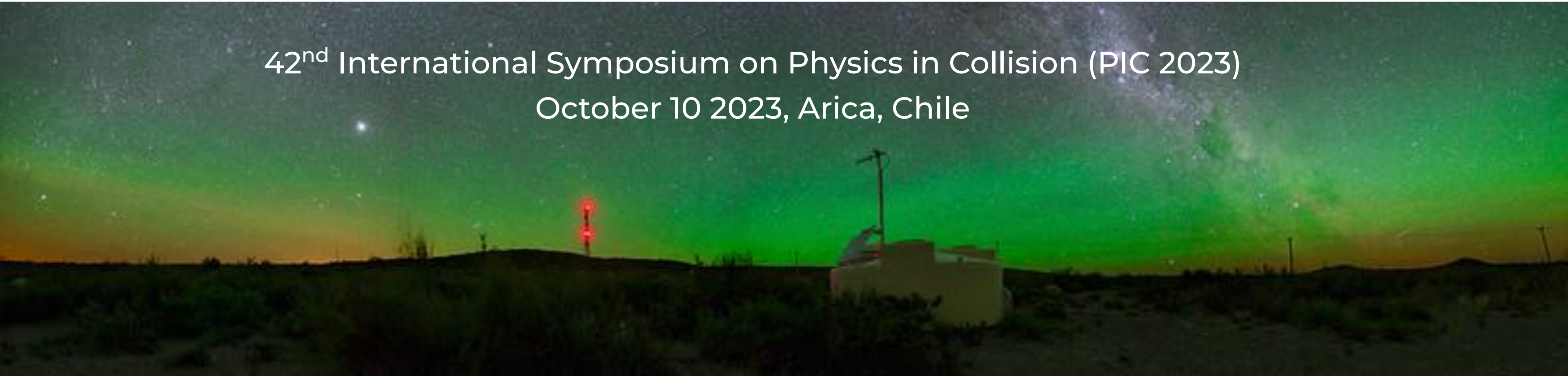
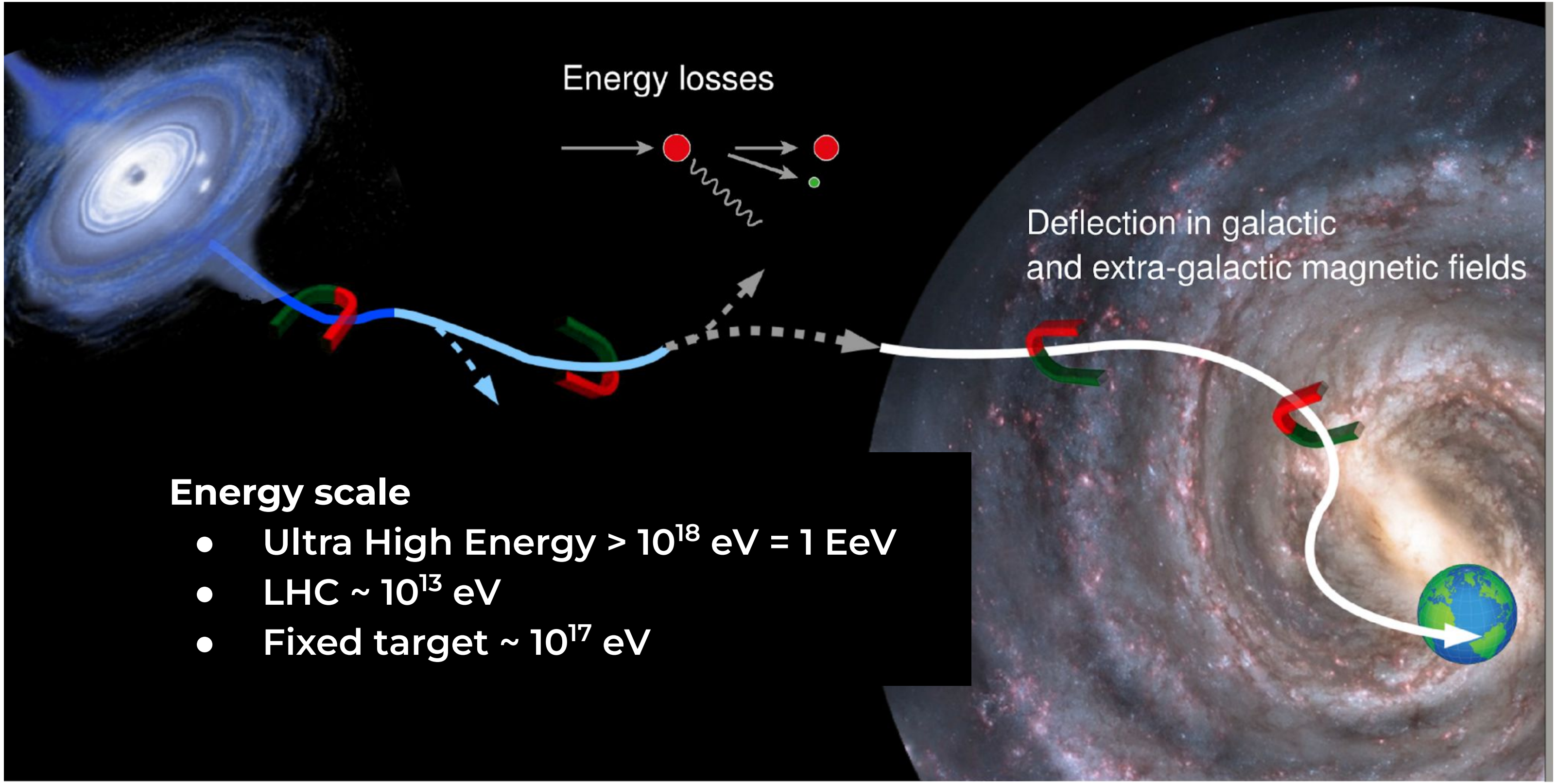
Highlights of the cosmic rays observed with the Pierre Auger Observatory

Diego Ravignani for the Pierre Auger Collaboration
ITeDA, Argentina



42nd International Symposium on Physics in Collision (PIC 2023)
October 10 2023, Arica, Chile

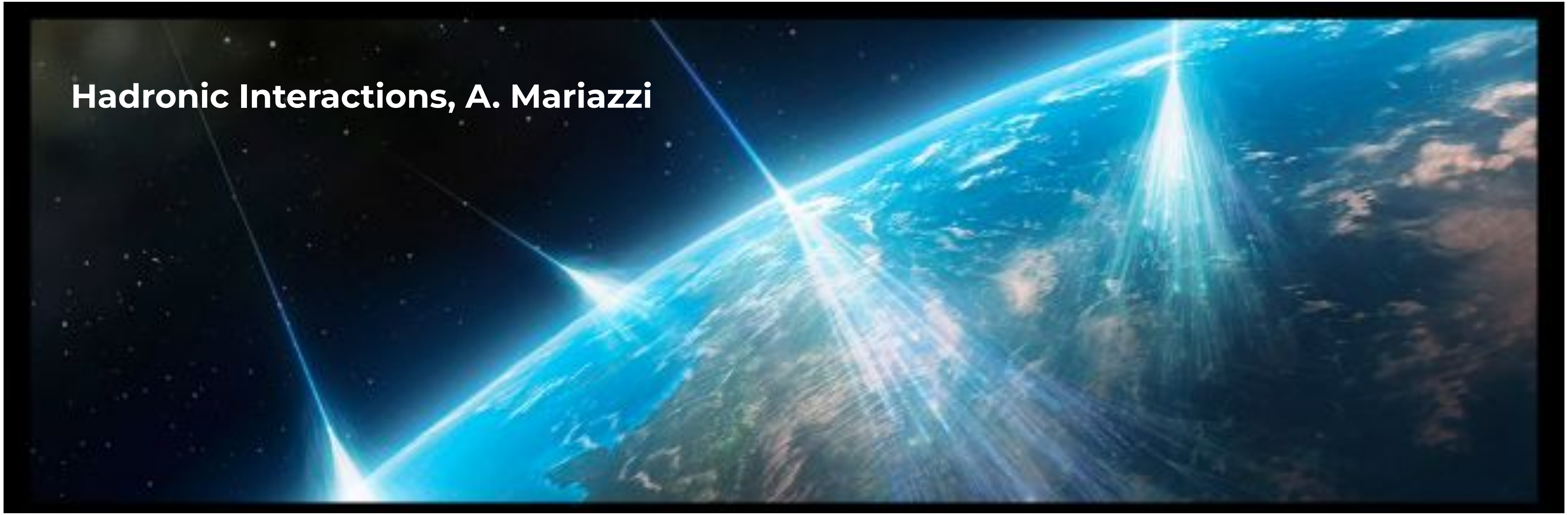
Cosmic rays



Energy scale

- Ultra High Energy > 10^{18} eV = 1 EeV
- LHC ~ 10^{13} eV
- Fixed target ~ 10^{17} eV

Extended air showers



The Strange Science Case of the Ultra High Energy Cosmic Rays

Strange Case Of The Cosmic Rays, Frank Capra (1957)

ASTROPHYSICS

- What particles are they?
- Which are the sources?
- How can be accelerated?

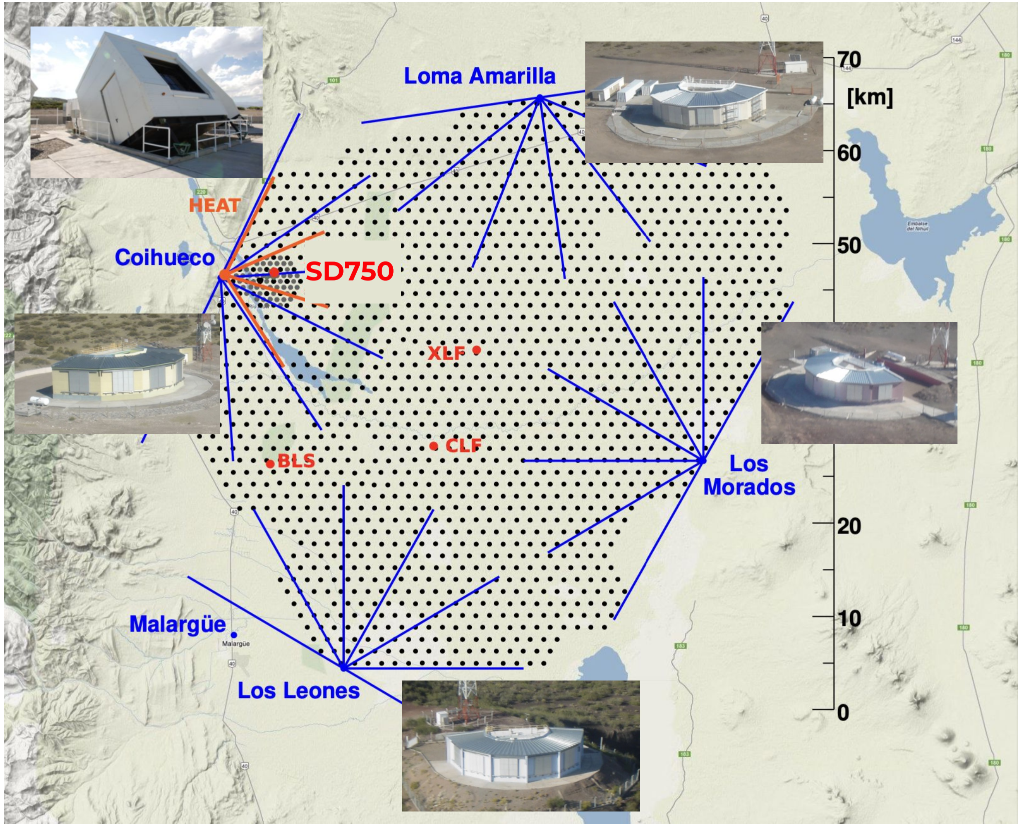
FUNDAMENTAL PHYSICS

- Tests of fundamental interactions
- New phenomena

The Pierre Auger Collaboration

~400 members from 18 countries and …. the local staff !

The Pierre Auger Observatory

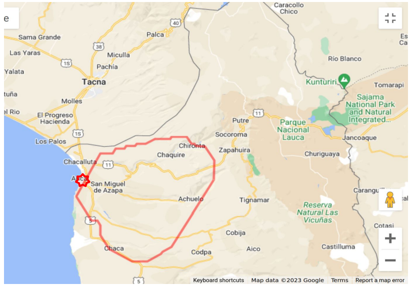


Surface detector (SD)

- 1600 stations in 1.5 km grid, 3000 km^2
- 71 stations in 750 m grid, 23.5 km^2
- 19 stations in 433 m grid, 1 km^2

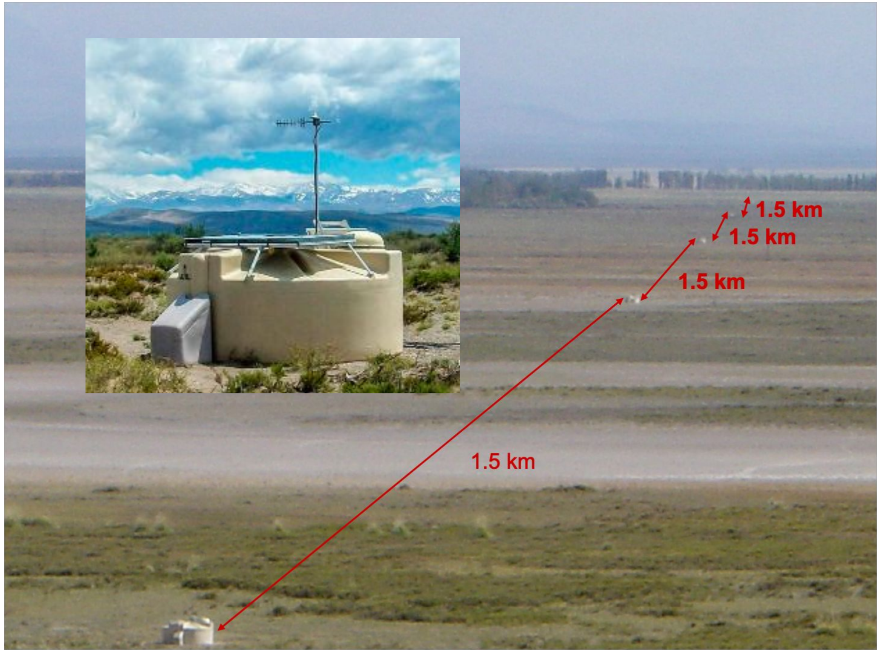
Fluorescence detector (FD)

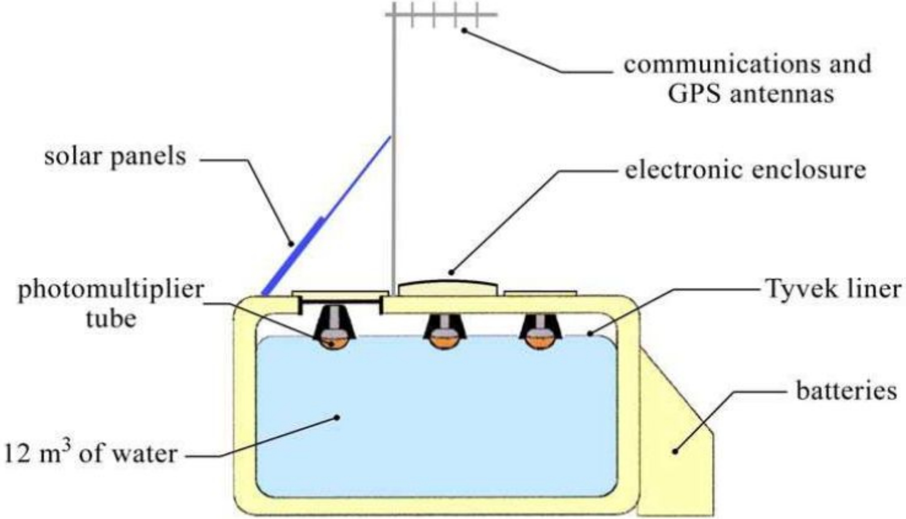
- 24 telescopes: FoV: 0-30°
- 3 telescopes: FoV: 30 - 60°



Auger Phase I from 2004 to 2023

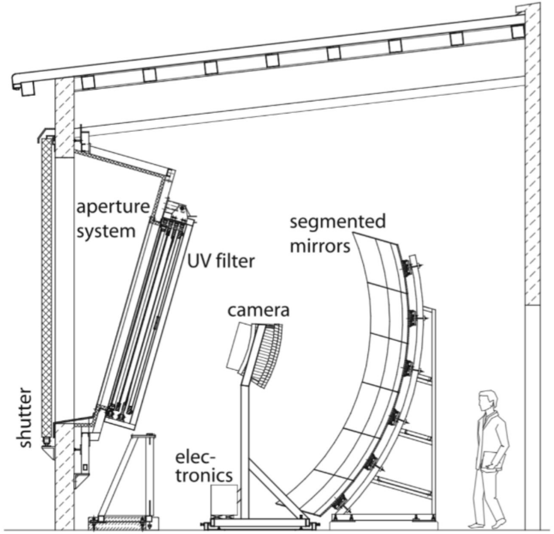
Surface detectors

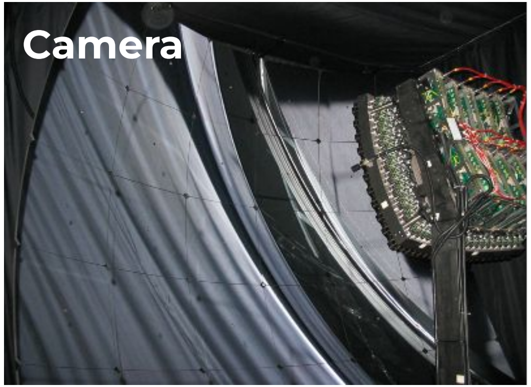


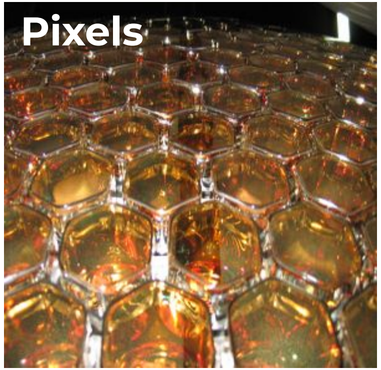


- Water Cherenkov detector
- ~100% duty cycle

Fluorescence detectors



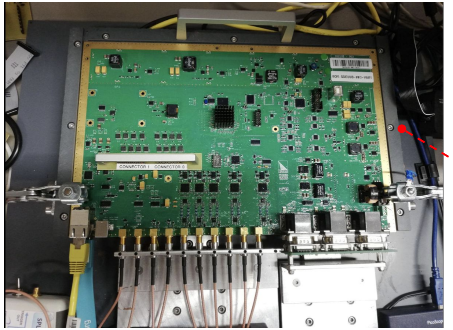




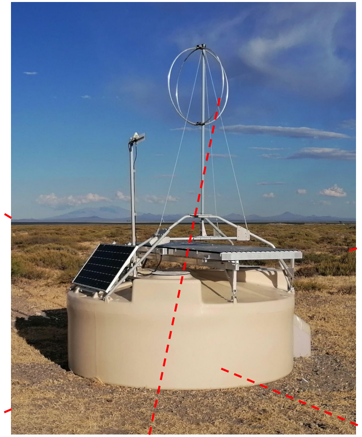
- Measures UV fluorescence light
- 30° x 30° field of view
- ~14% duty cycle

AugerPrime detectors

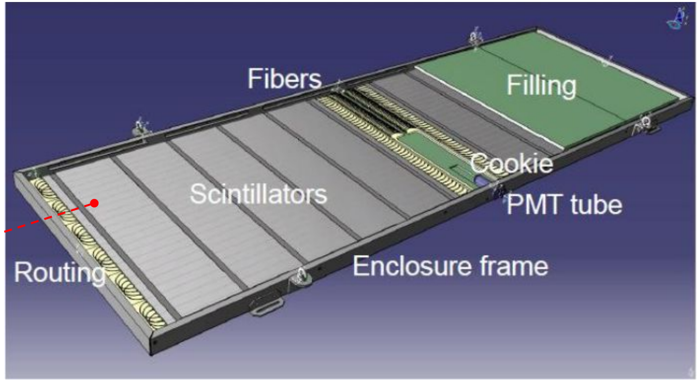
New electronics



Muon detector



Scintillator detector



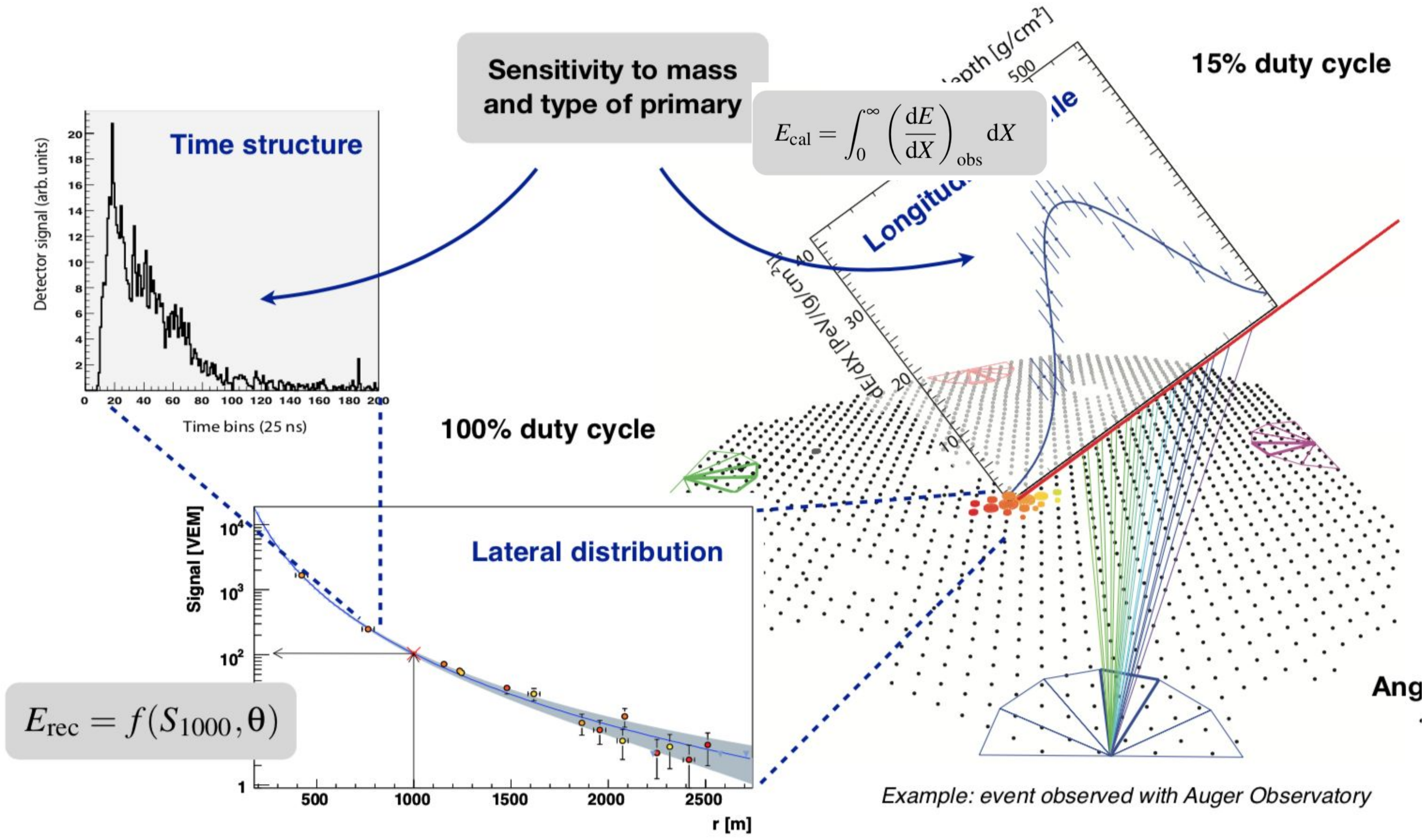
Small PMT

Radio antenna

Presented by C. Cruz

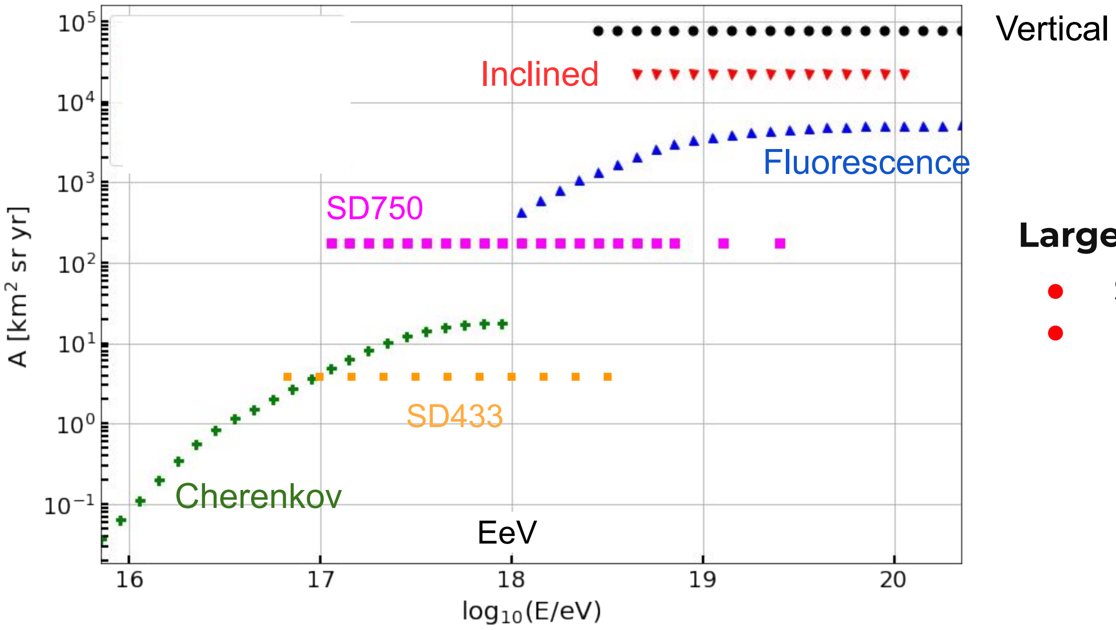
Data taking from 2024 to 2035

The hybrid concept



Example: event observed with Auger Observatory

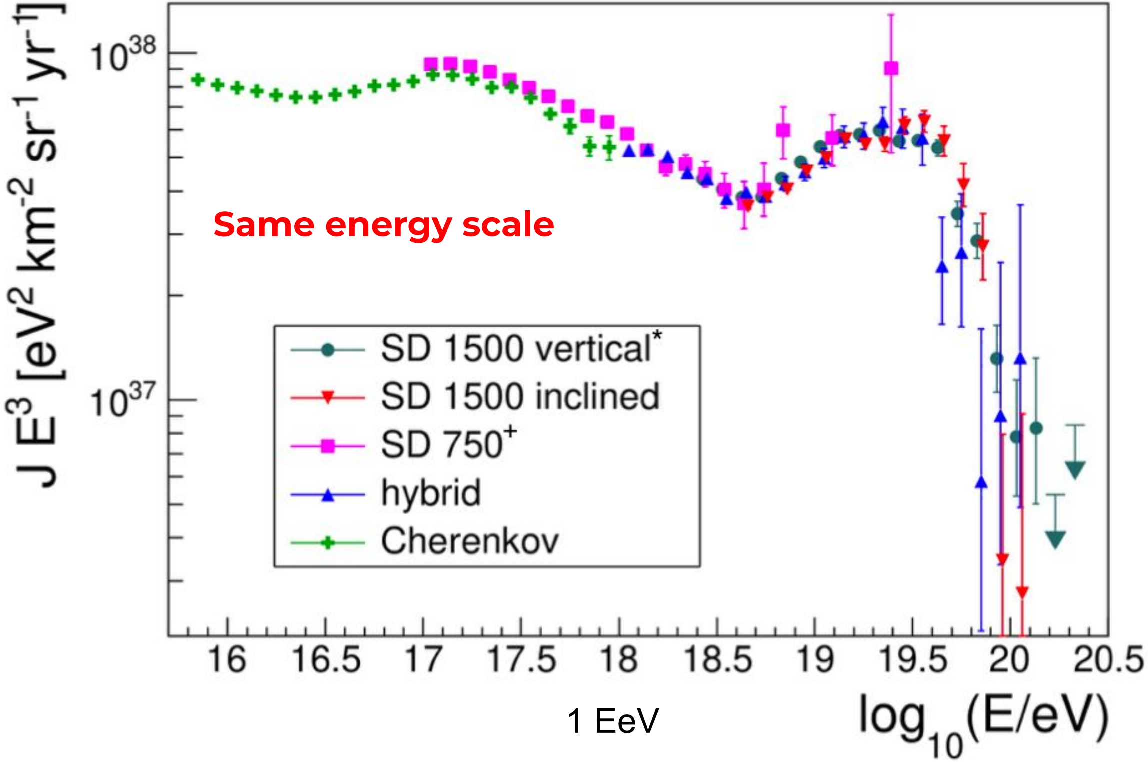
Auger Phase I data

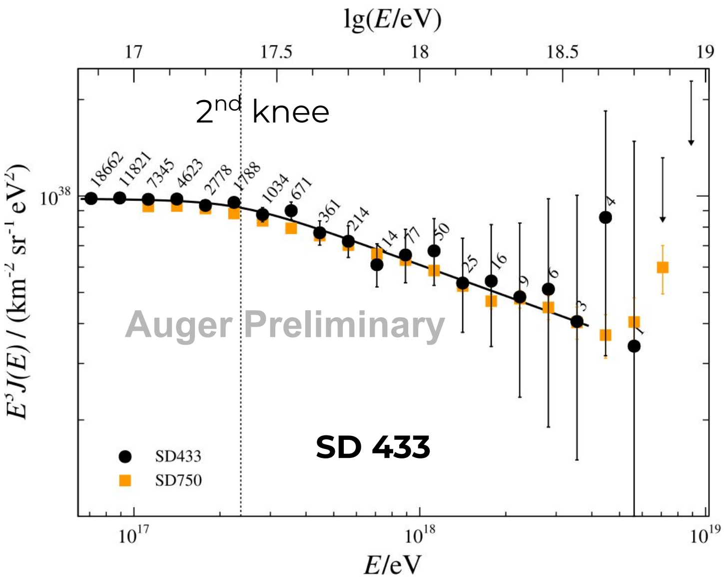


Largest exposure in the world

- **SD 1500** ~100,000 km^2 yr sr
- **FD** ~5,000 km^2 yr sr

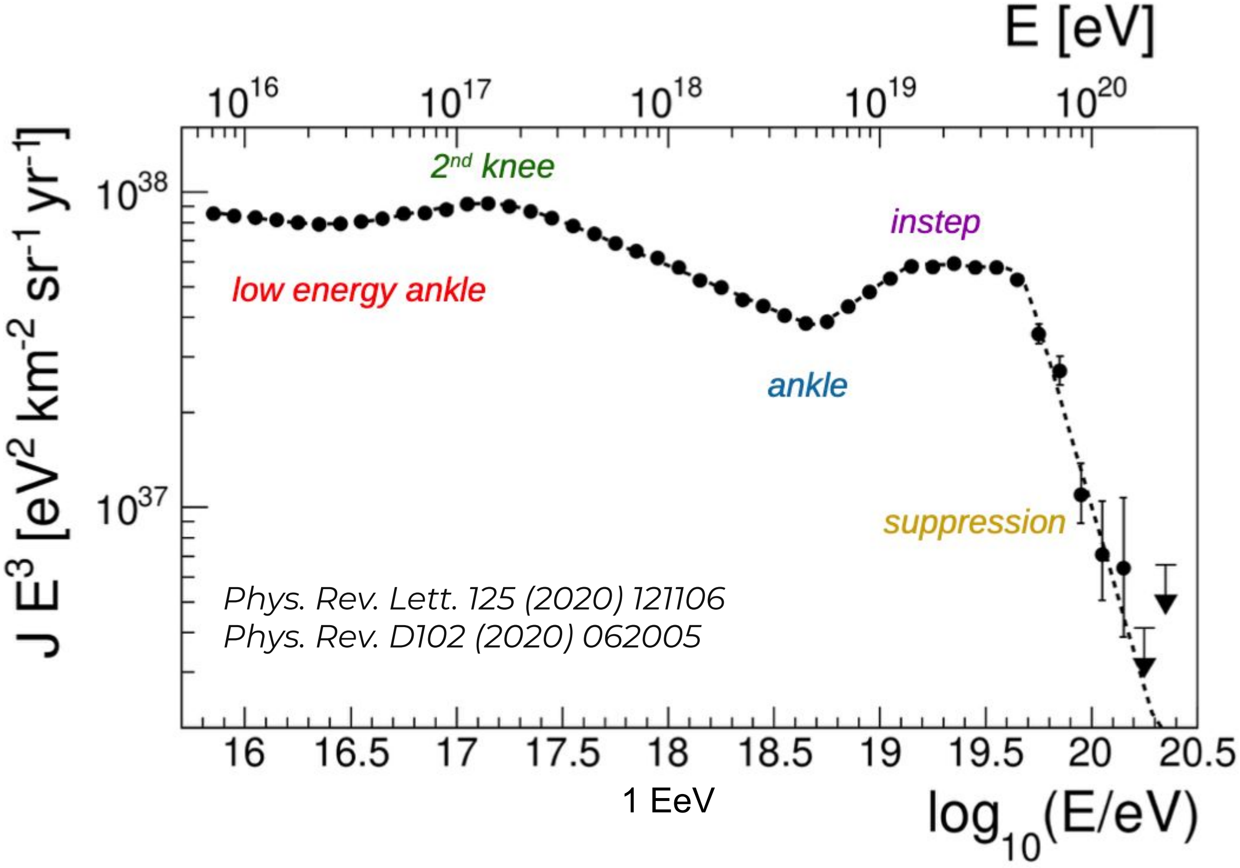
Energy spectrum



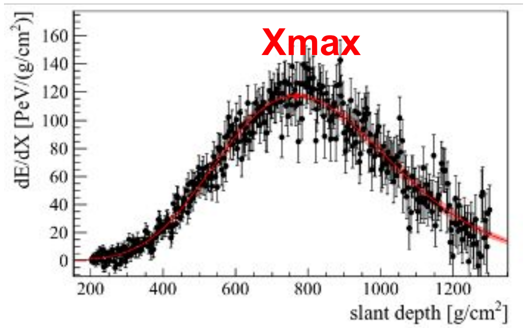


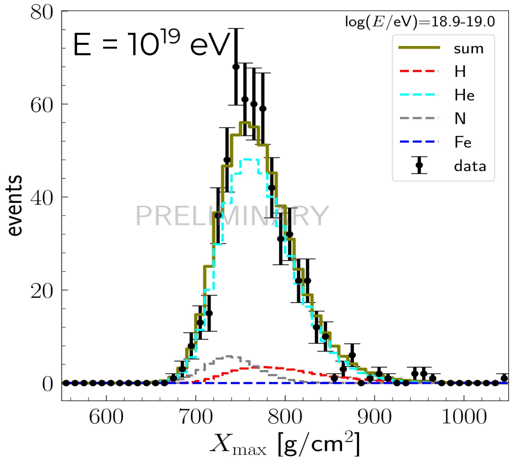
- Common energy scale
- Systematic within uncertainties

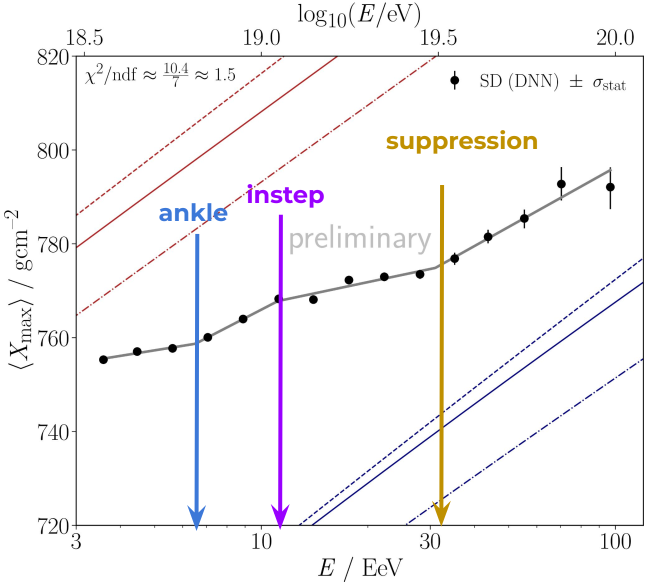
Spectrum features



Mass composition measurements





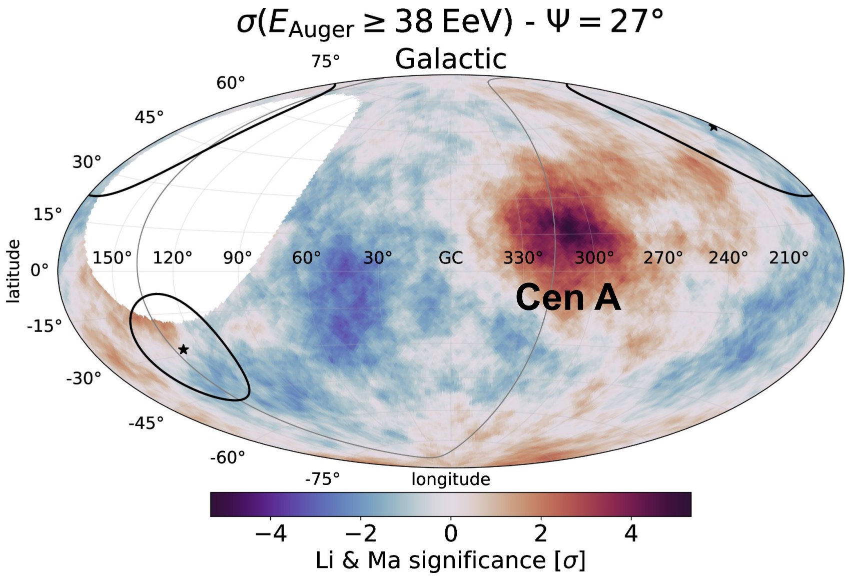


- Mass estimator Xmax
- Four mass groups
- Composition changes at spectrum breaks
- He-N dominance > 3 EeV

Mass composition, F Gollan

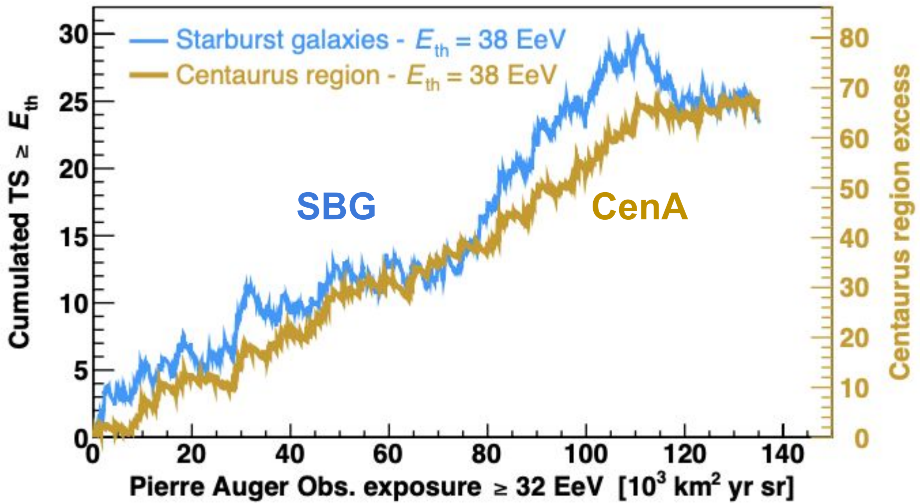
Arrival directions: intermediate scales

Excess map



- **4.0σ** excess at Centaurus A

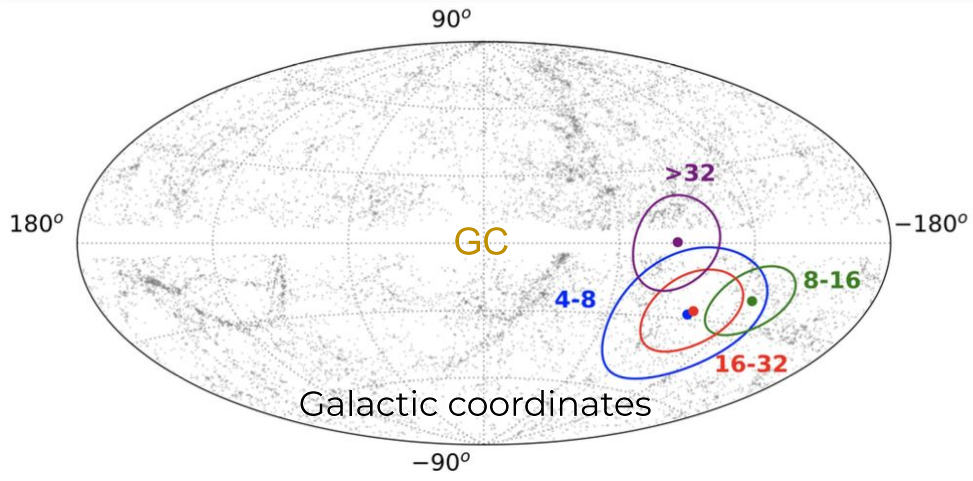
Likelihood ratio test



- **3.8σ** signal for starburst galaxies

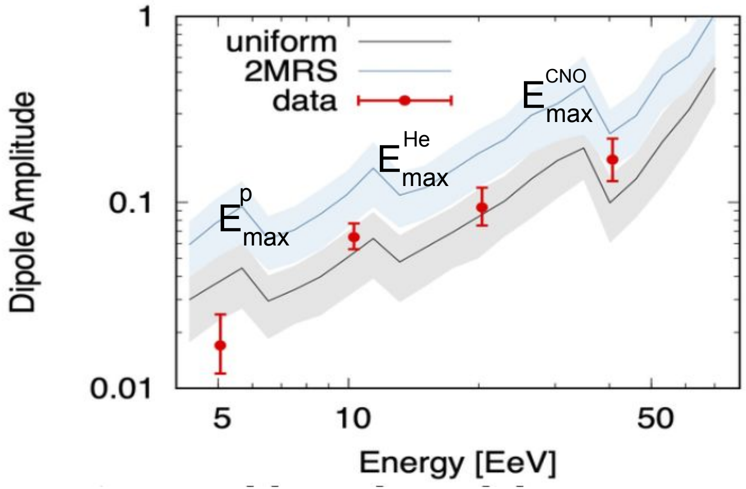
Arrival directions: large scale

Dipole direction



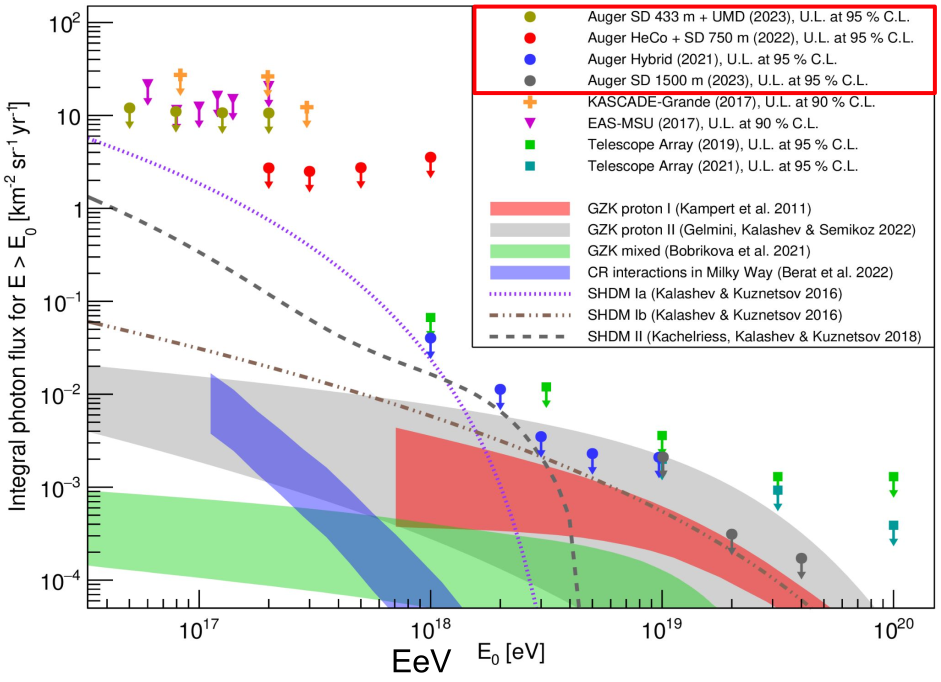
Update of ***Science 315 (2017) 1266***

Dipole amplitude

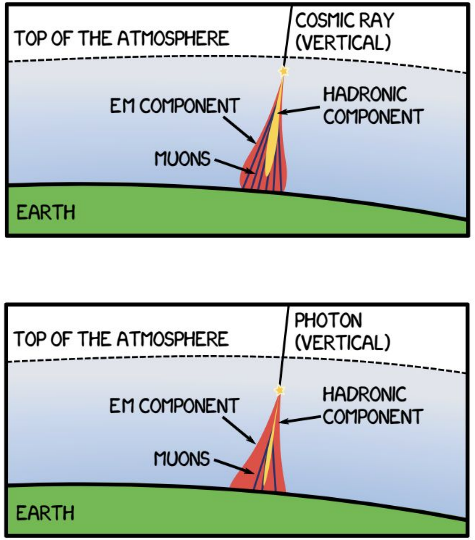


- Isotropic distribution rejected at **6.9σ** for energies > **8 EeV**
- Extragalactic origin of highest energy cosmic rays
- Dipole amplitude consistent with mass increase

Photon searches



Cosmic ray

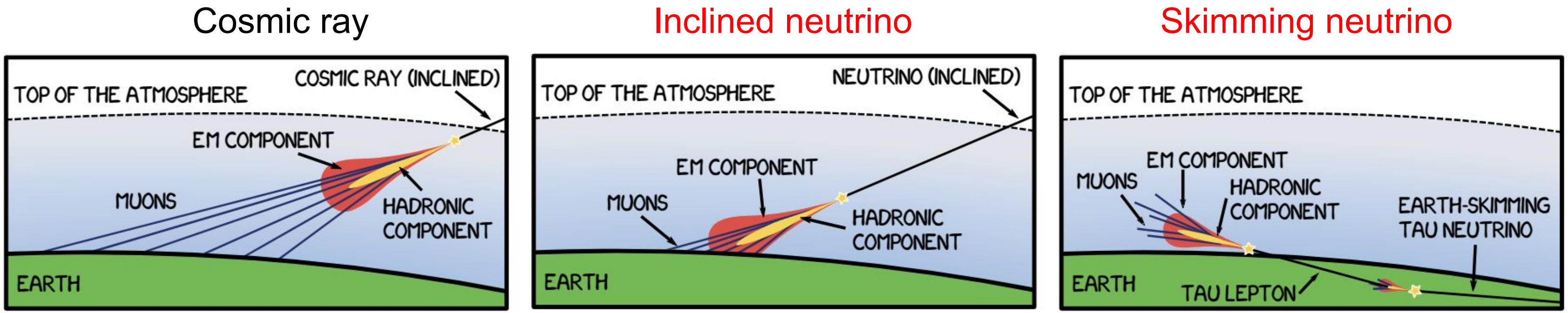


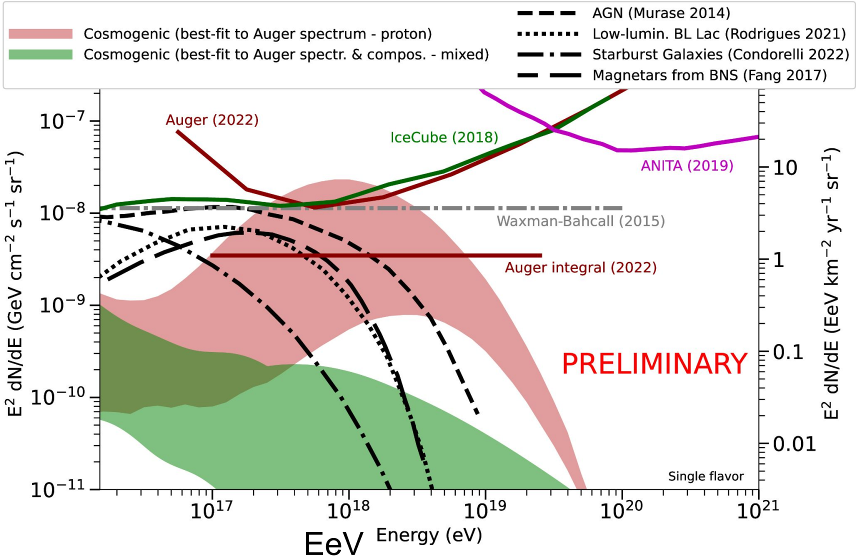
Photon

- No primary photon observed
- Limits over 4 decades
- Approaching model predictions

Phys. Rev.Lett. 130 (2023) 061001, Phys.Rev.D. 130 (2023) 061001

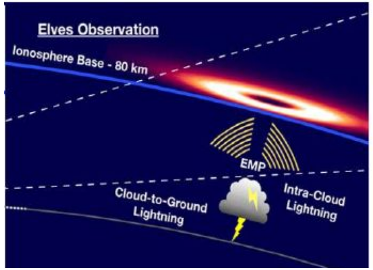
UHE Neutrino searches



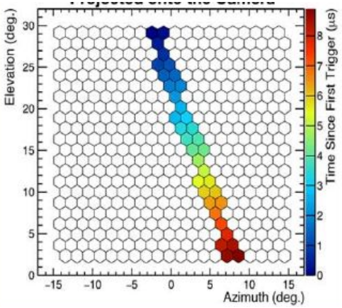


- No neutrinos observed
- Limits on point sources
- Excluding proton-only scenarios

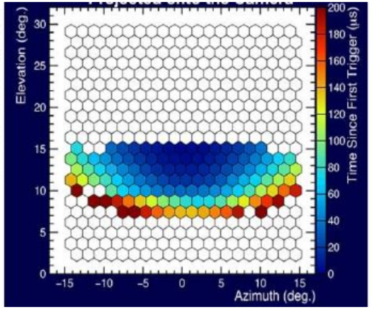
Auger as a cosmo-geophysics laboratory

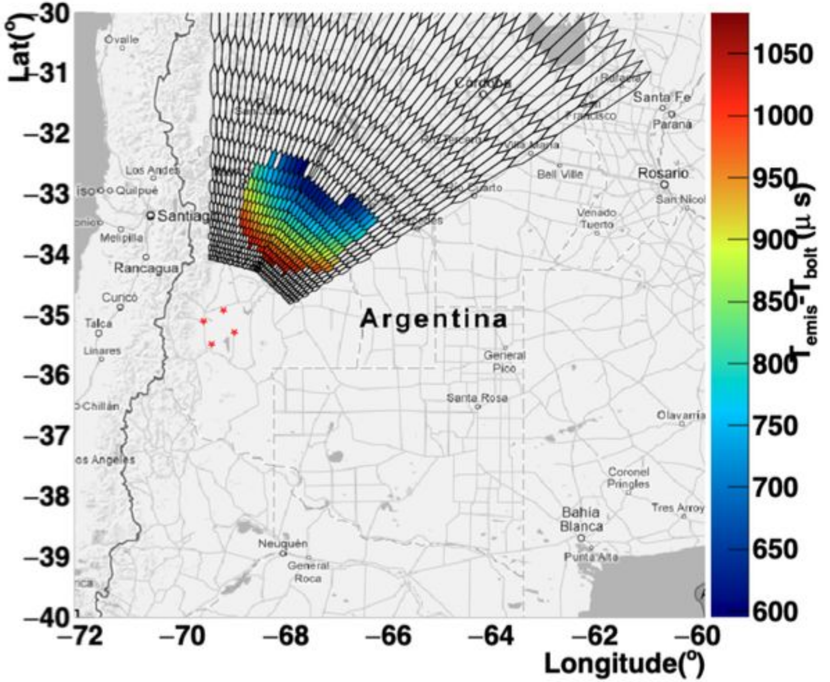


Cosmic ray



ELVES





- ELVES: **E**mission of **L**ight and **V**ery low-frequency perturbations due to **E**lectromagnetic pulse **S**ources

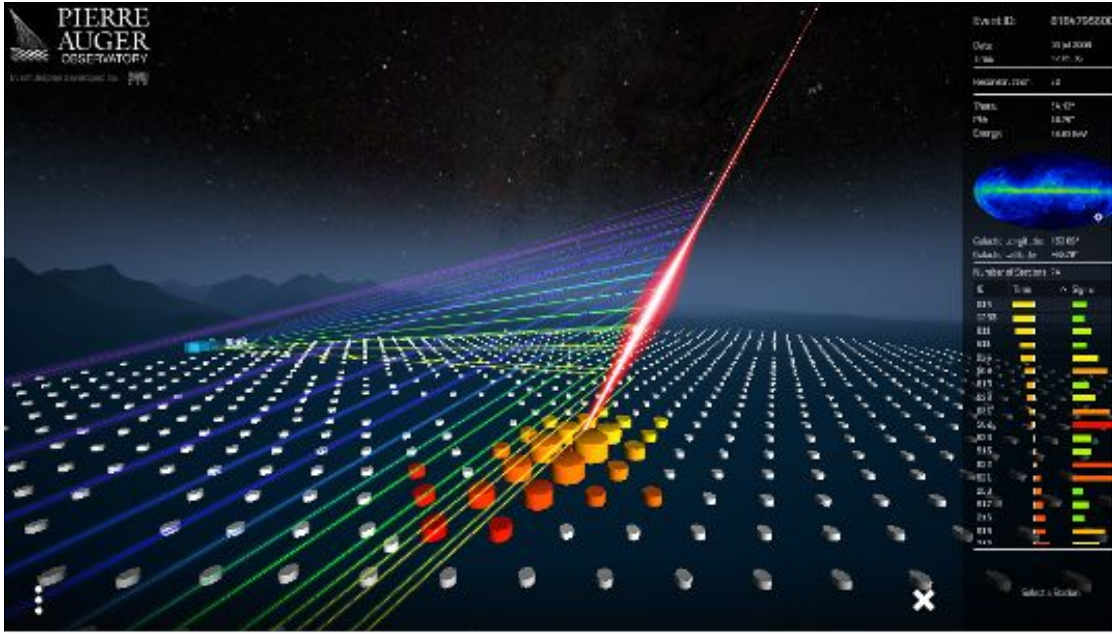
Auger Open Data and citizen science

v1.0 release
- 10% SD-1500 before 2019
- Visualization tools
- Python notebooks

Data usage
- >2000 downloads
- Science papers
- Master-classes
- Outreach

Future releases
2023: 100 most energetic events
2024: 30% Phase I data

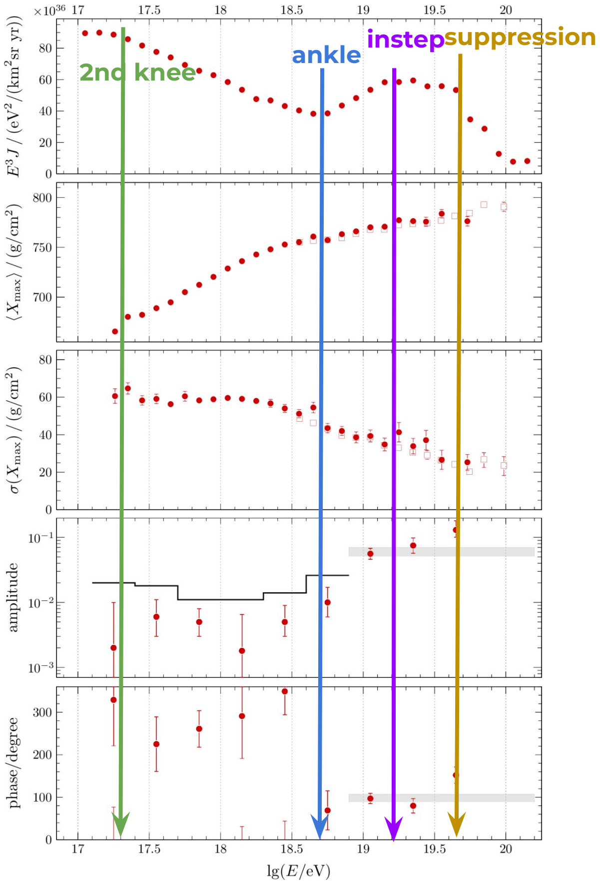
https://opendata.auger.org



Summary

- **Energy spectrum** features correlated with **mass composition** changes
- Dipole **anisotropy** consistent with increase of primary mass
- **Photon** and **neutrino** limits starting to scratch models

- **AugerPrime** offer great promises for Phase II science



Next Auger talks

- Exploring Hadronic Interactions Beyond Collider Energies (A. Mariazzi)
- Results from the Auger Radio Detector (C. Cruz)
- Mass composition analysis with the Pierre Auger Observatory (F. Gollan)

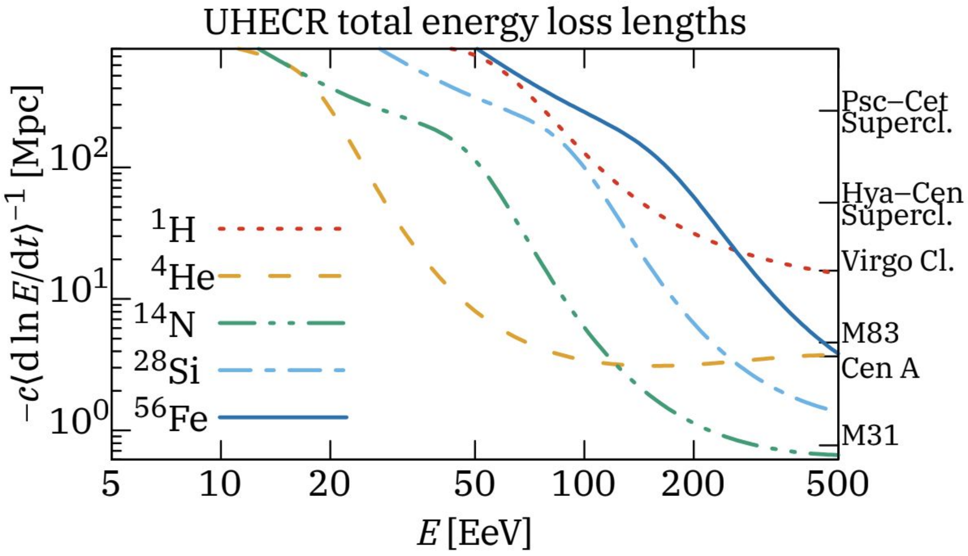
Thanks!

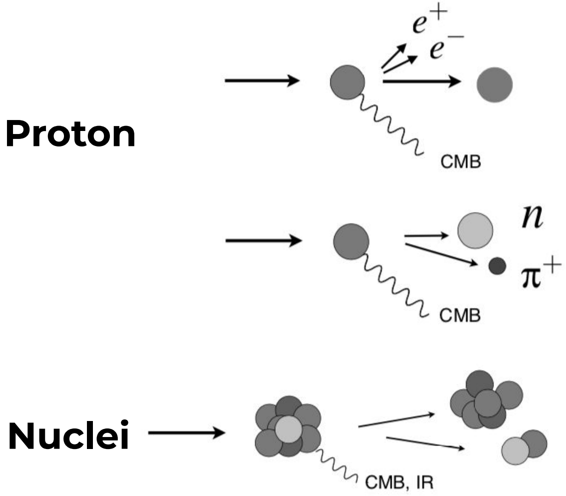
Backup slides

How they reach Earth?

Processes during extragalactic cosmic ray propagation

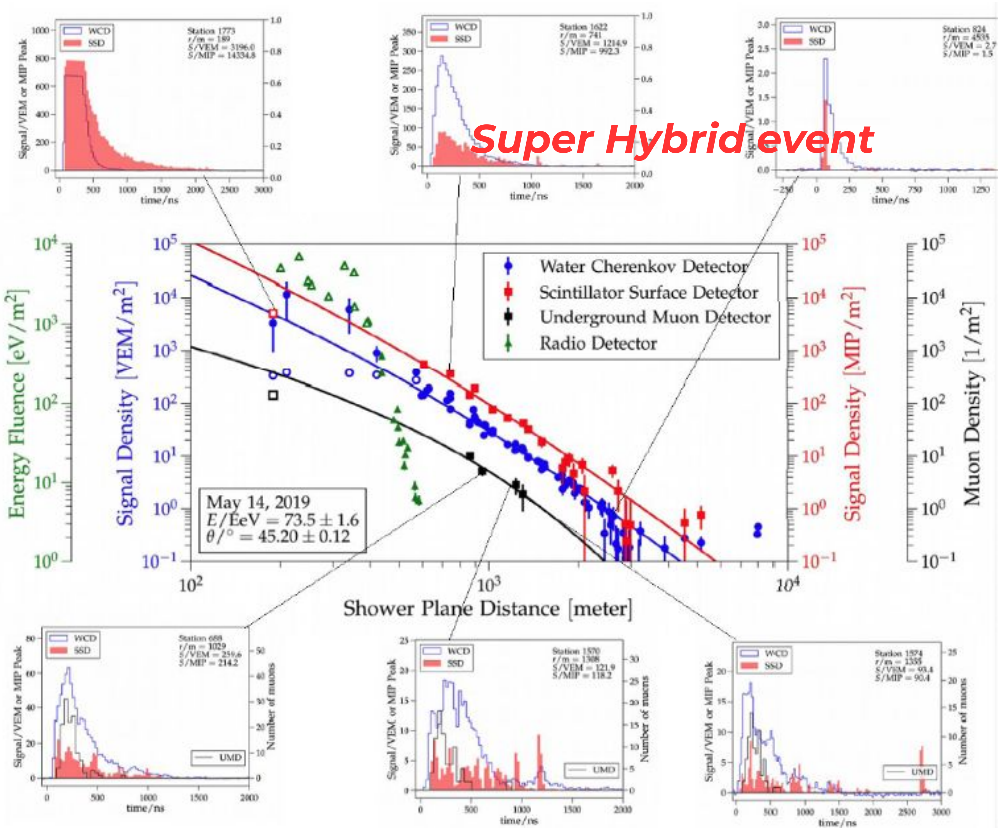
- Adiabatic energy losses due to the expansion of the Universe
- Interactions with photon backgrounds:
  - Pair production (Cosmic microwave background)
  - Disintegration (Extragalactic background light)
  - Pion production



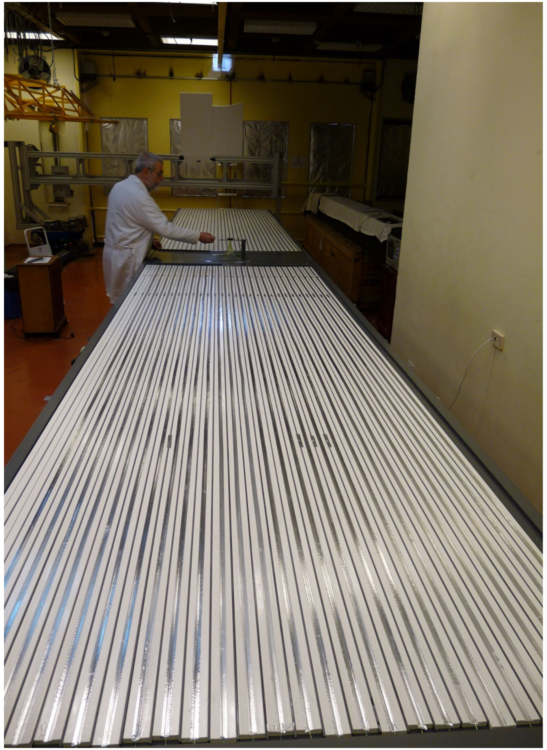


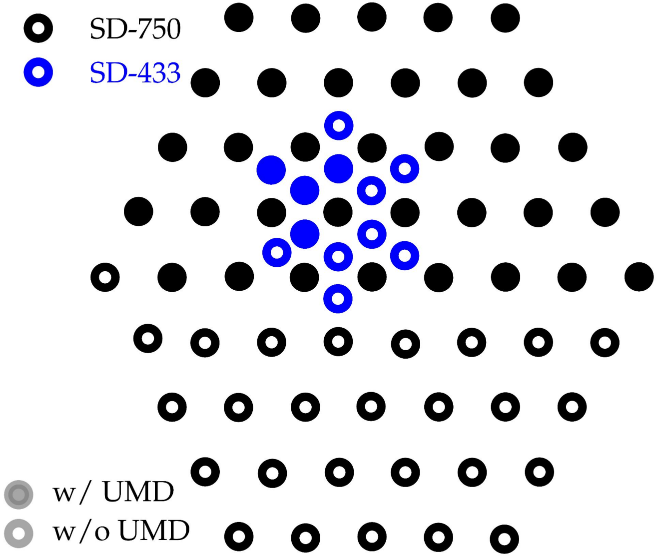
- NO He >50 EeV, CNO > 100 EeV expected
- Extreme-E CRs can only be: local, &/or protons, &/or heavy nuclei
- source or propagation scenario? Composition at the highest energies and the detection of cosmogenic neutrino and/or photons is of key importance

Auger Prime status



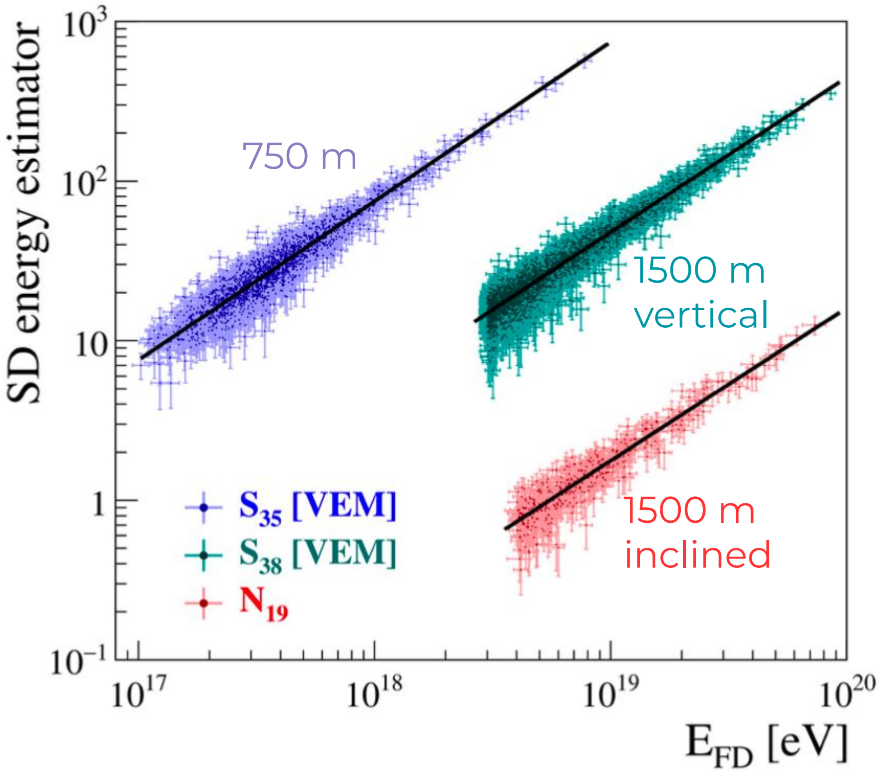
Muon detectors

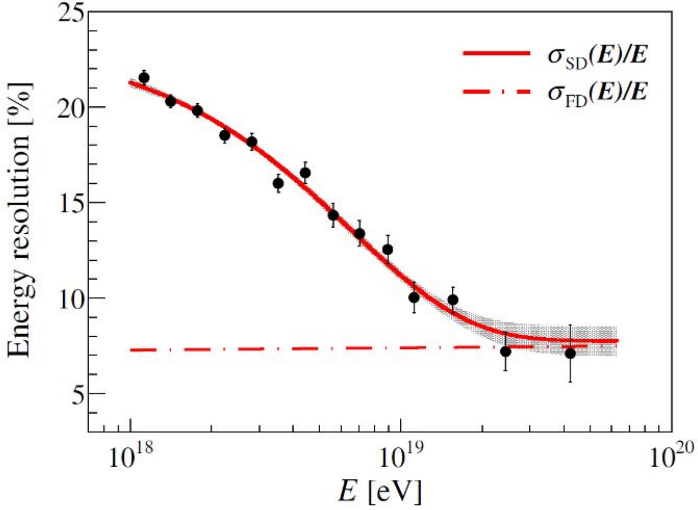




- Measures > 1 GeV muons
- Built by ITeDA

Energy calibration





Energy resolution

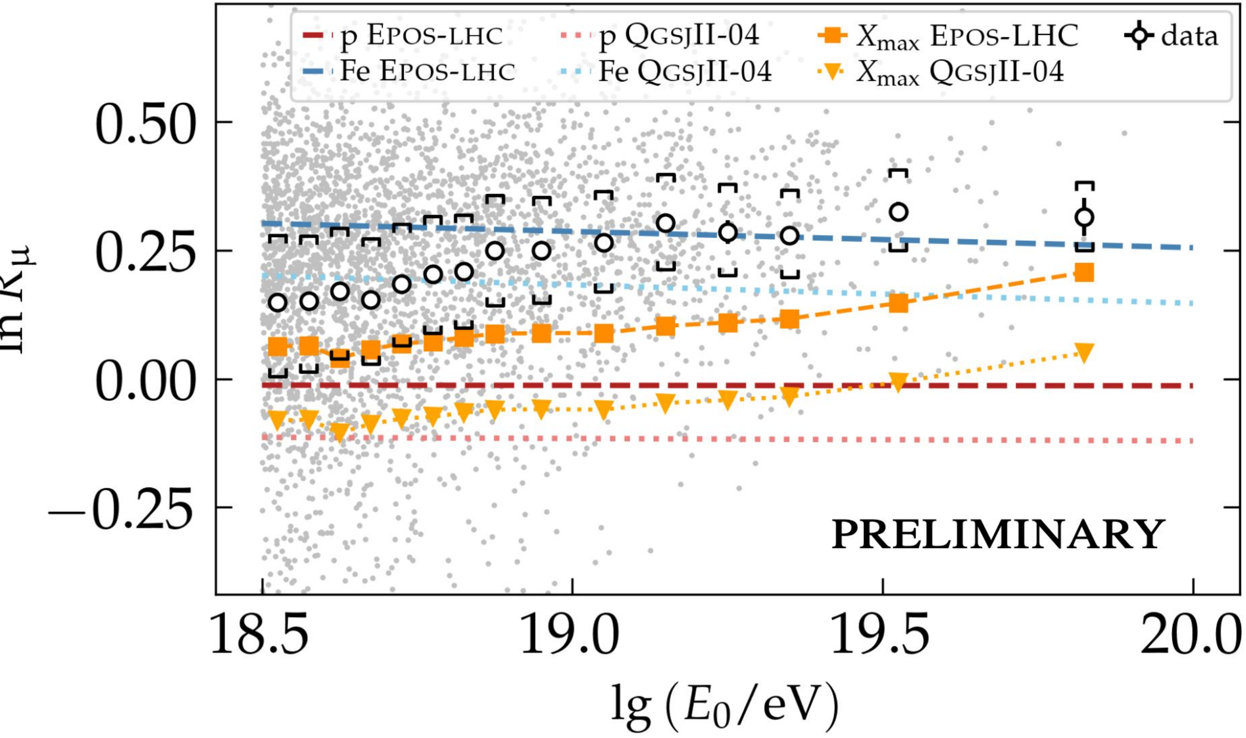
SD: ~10% - 20%

FD: ~7 % Hybrid

Energy scale systematics

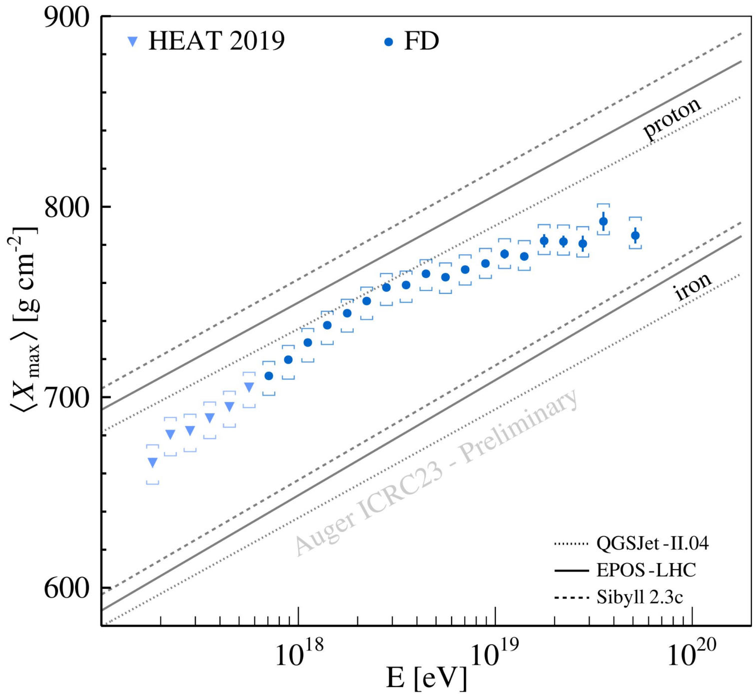
14% (from FD)

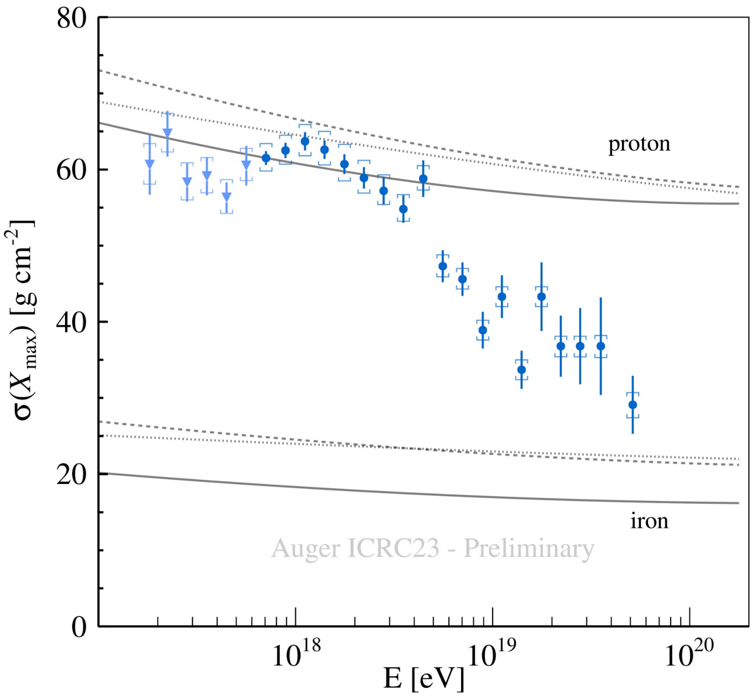
Hadronic interactions and the muon puzzle



- Deficit of muons in shower simulations

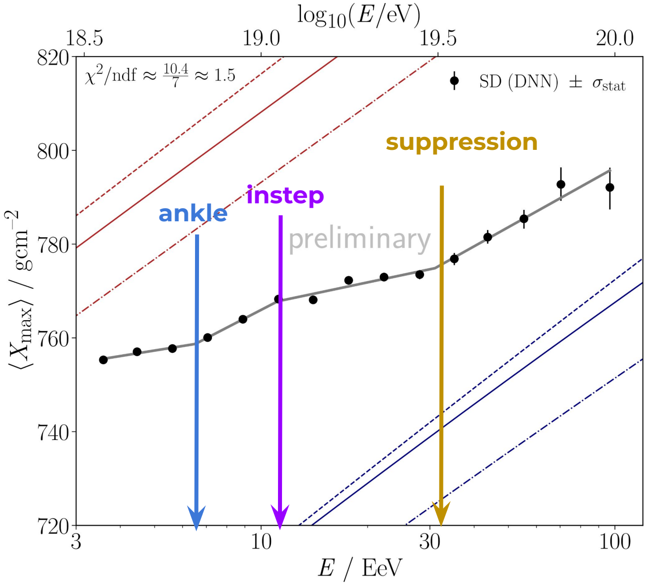
<Xmax> and σ(Xmax)

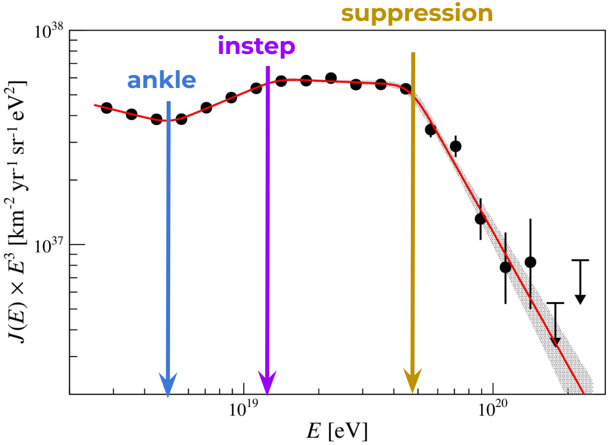


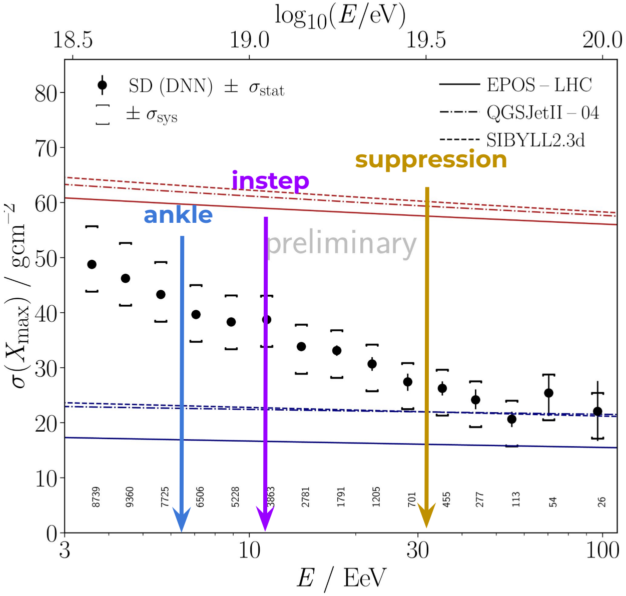


- change of slope of X_{max} and decrease of $\sigma(X_{max})$ around ~2 EeV
- X_{max} and $\sigma(X_{max})$ indicate lighter composition up to ~2 EeV, heavier and less mixed above

Mass composition with SD: energy evolution



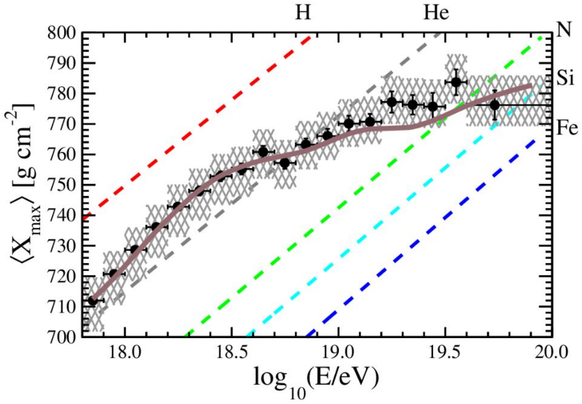


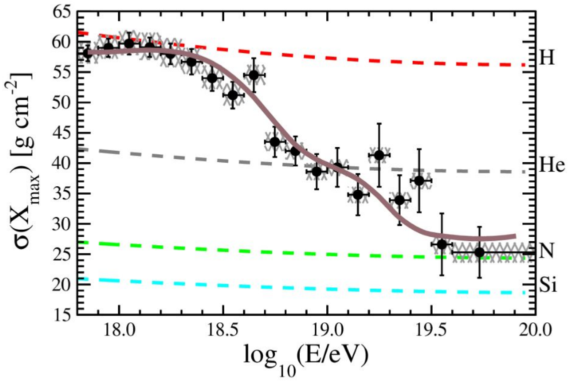


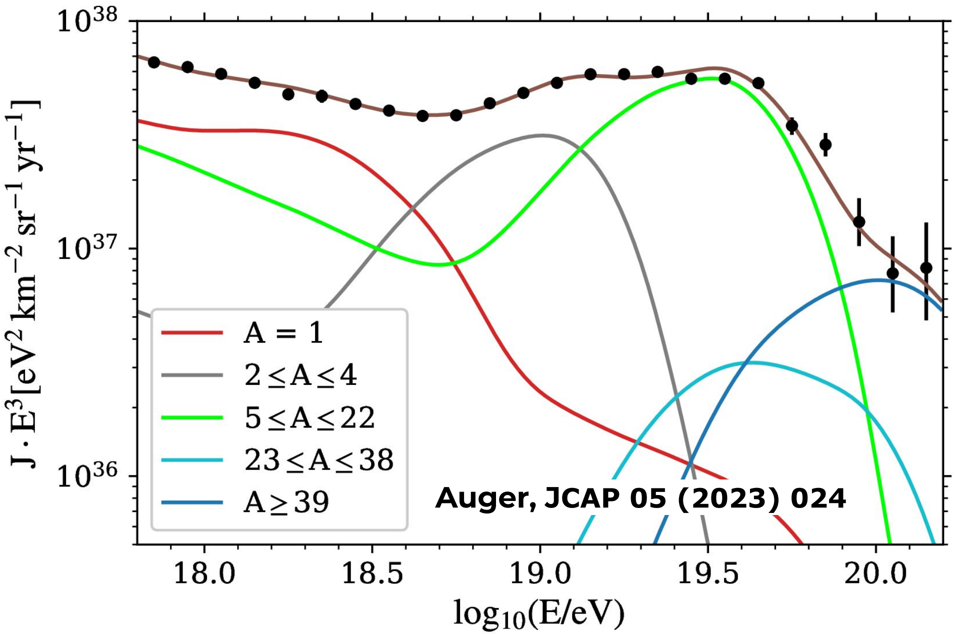
- Constant elongation rate excluded at **4.4σ**
- Break positions correlated with spectrum features
- independent confirmation that mass composition is lighter and mixed at lower energies, getting heavier and more pure as the energy increase

Astrophysical scenarios

Simultaneous fit of **flux** and **composition** to find source scenarios more compatible with data



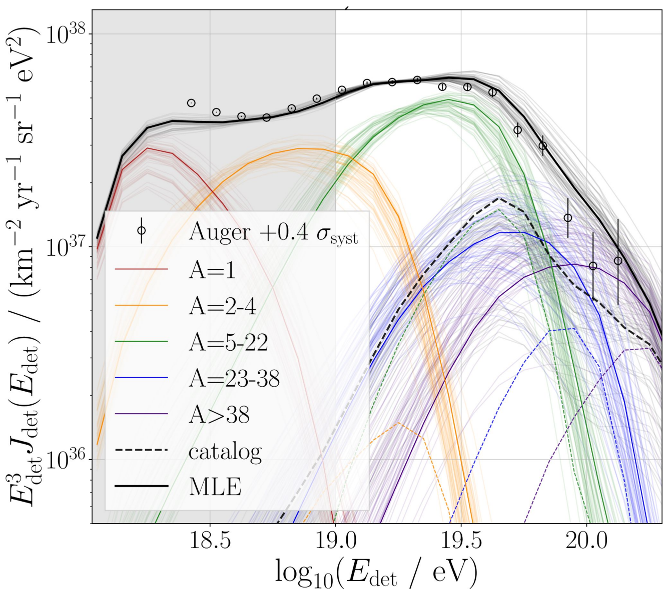




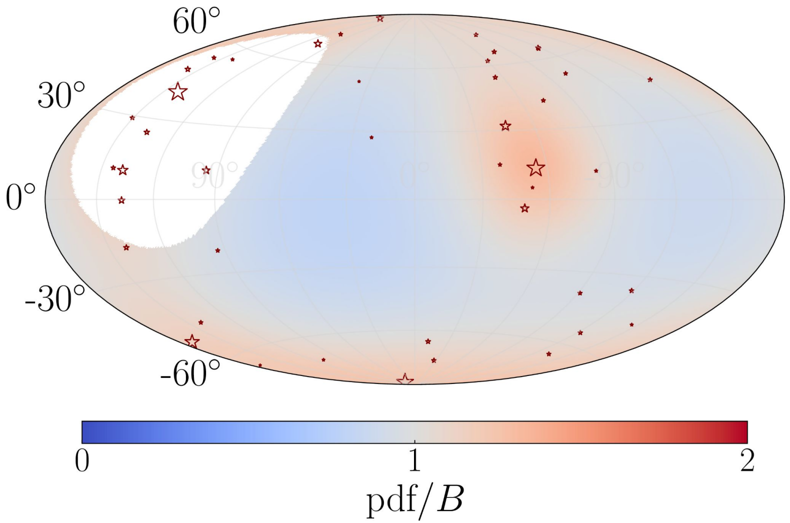
- CR propagated through interstellar medium
- magnetic fields deflections work in progress **J.Gonzalez this conference**

Arrival directions , spectrum and composition

Spectrum by mass



Arrival directions



- 20% starburst contribution > 40 EeV
- main contribution from CenA
- significance of 4.5 σ