DSFC
Dipartimento
di Scienze Fisiche
e Chimiche

UNIVERSITÀ
DEGLI STUDI
DELL'AQUILA

The Pierre Auger Observatory: experimental and phenomenological activities in the L'Aquila group

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Dipartimento di Scienze Fisiche e Chimiche
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Science Fair, GSSI, February 22, 2023

L'AQUILA GROUP

- **GSSI**: R. Aloisio, F. Barbato, I. De Mitri, C. Evoli, S. Petrera
- **University of L'Aquila**: E. Avocone, D. Boncioli, C. Petrucci, V. Rizi, F. Salamida

Responsible of the **Detector Performance** and leader of the local group of the Collaboration

Leader of the **Cosmic-Ray Phenomenology** task force in the Collaboration

PhD students in recent years:

G. A. Anastasi, A. Condorelli, M. Mastrodicasa, C. Trimarelli

Picture taken at the UHECR Symposium, L'Aquila,

3-7 October 2022

THE JOURNEY OF ASTROPARTICLES

Source
- Acceleration
- Interactions
- Magnetic fields
- Escape

Propagation
- Interactions
- Magnetic fields

Earth
- Development of shower in the atmosphere
- Detection

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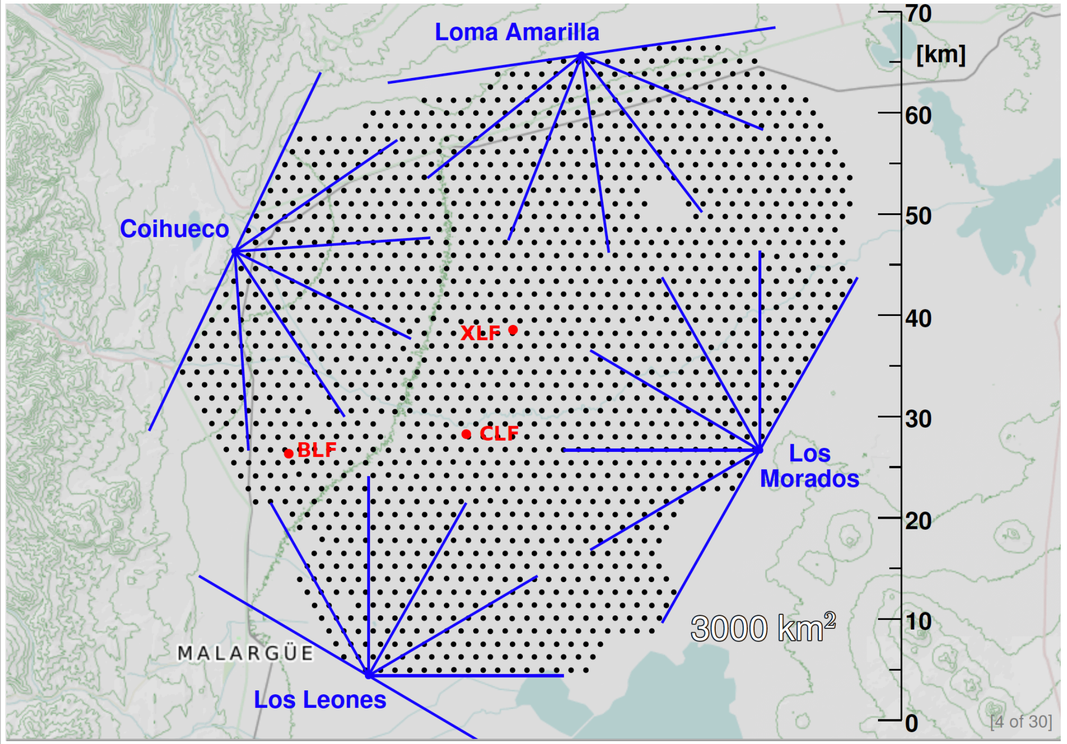
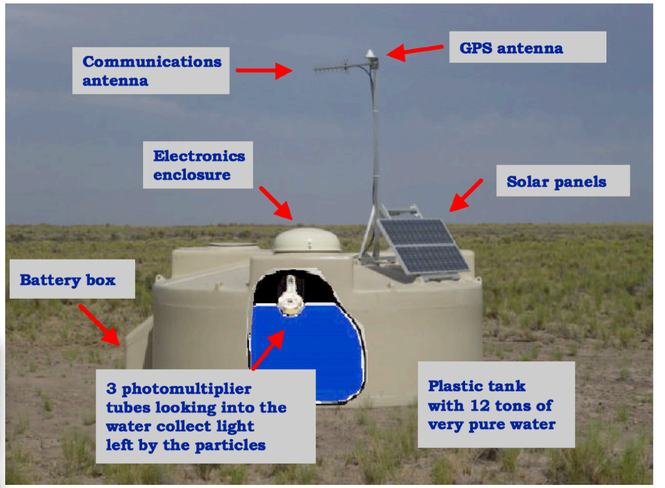
- Energy spectrum
- Nuclear species
- Source class (astronomy ?)
- Interactions at extremely high energy
- Fundamental symmetries

THE PIERRE AUGER OBSERVATORY



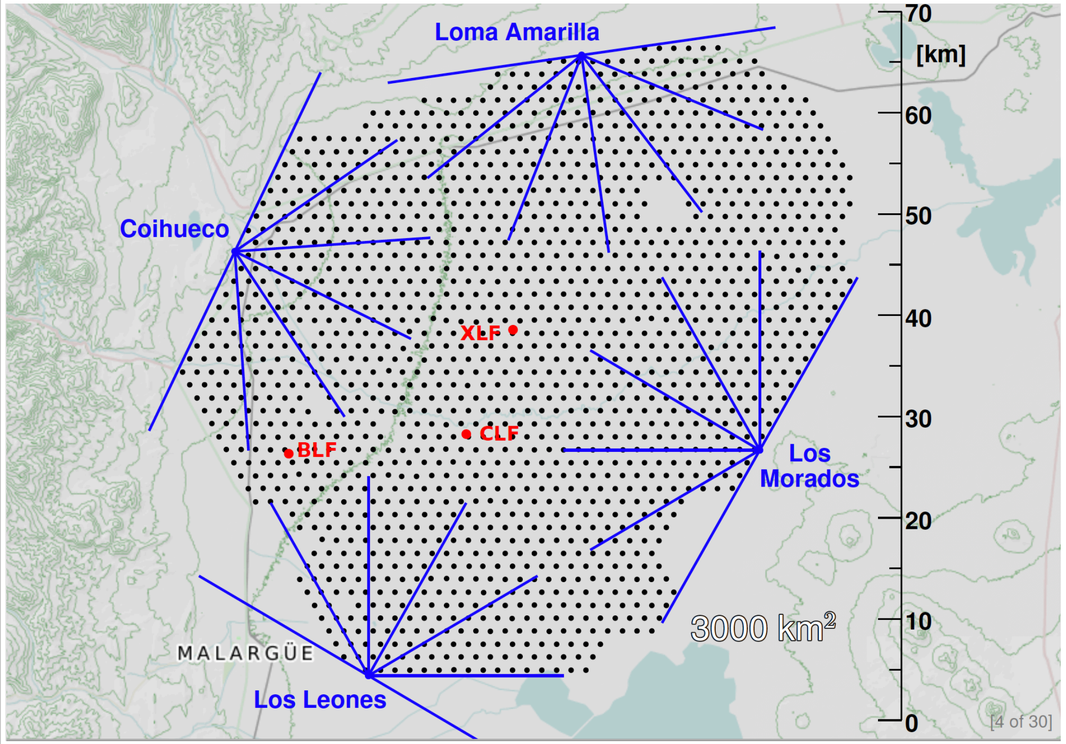
- Surface Detector (SD), Water Cerenkov tanks
  - 1660 tanks, 1.5 km spacing
  - $E>10^{18.5}$ eV



- Malargue, Mendoza, Argentinian pampa, 1400 m above sea level
- 3000 km^2
- 17 countries, ~90 institutions, ~450 authors

- Fluorescence Detector (FD)
  - 4 sites, 24 telescopes in total
  - $E>10^{18}$ eV

THE PIERRE AUGER OBSERVATORY



- Surface Detector (SD), Water Cerenkov tanks
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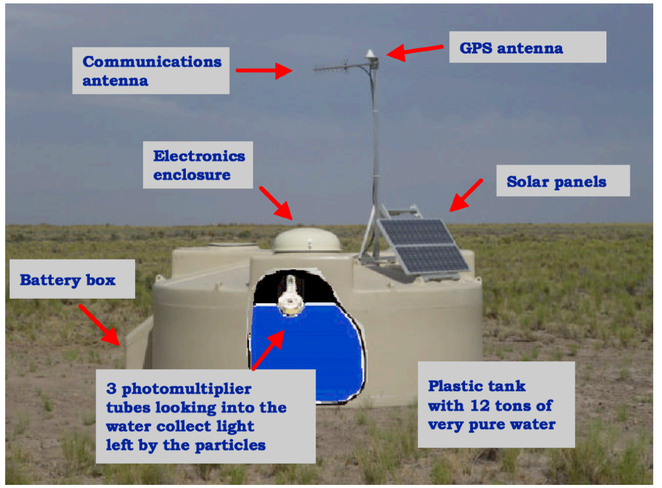
- Infill array
  - 61 tanks, 750 m spacing
  - $E>10^{17.5}$ eV



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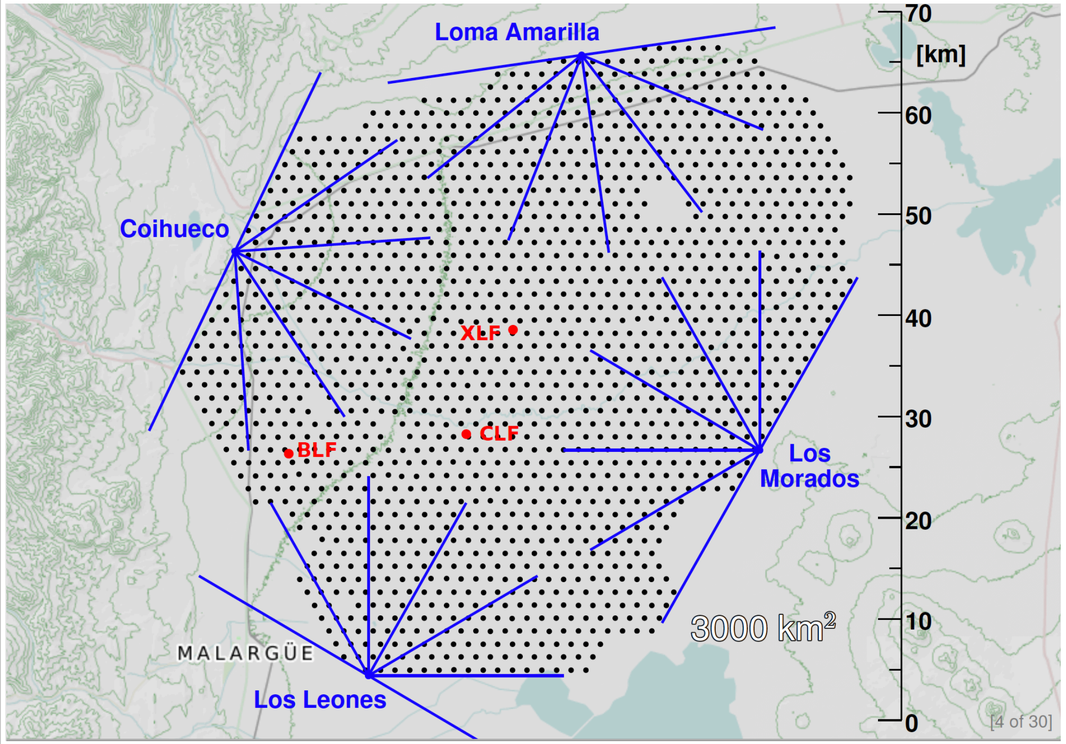

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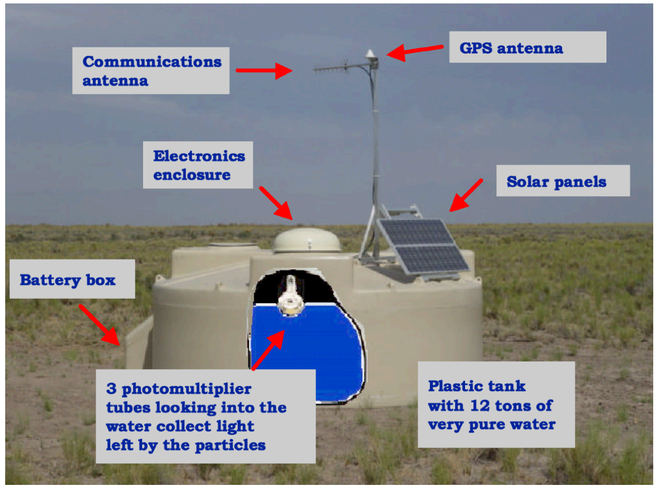

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- Auger Engineering Radio Array (AERA)
  - 153 antennas, 17 km² array

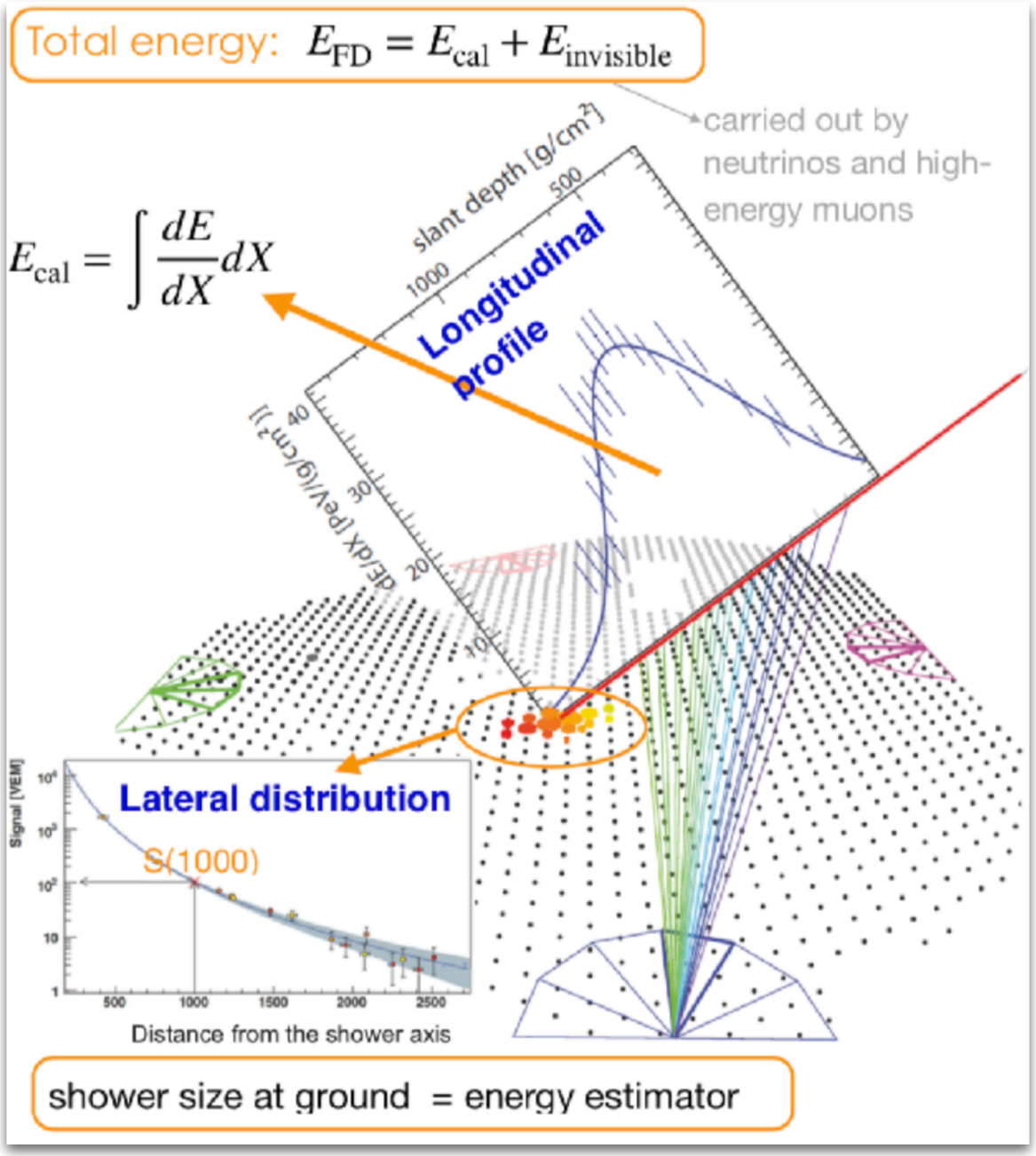
- LIDAR and laser facilities for atmospheric monitoring

Atmospheric monitoring

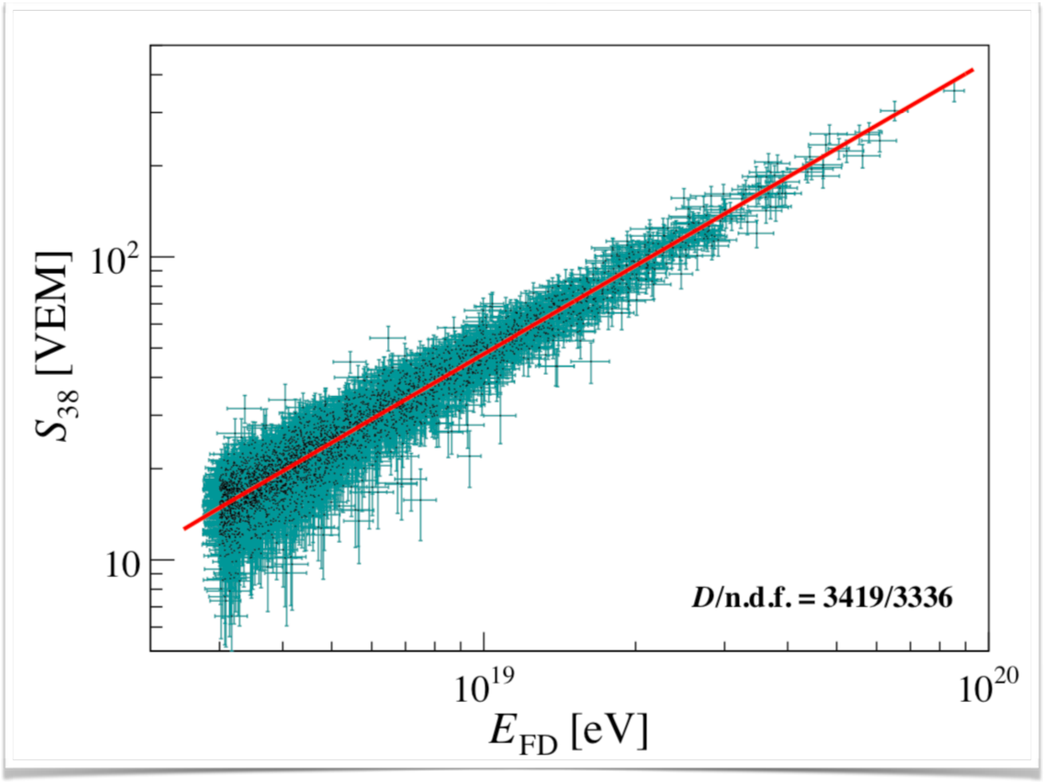
THE PIERRE AUGER OBSERVATORY *@ L'AQUILA*

NEW!!! The remote control room at the University of L'Aquila, Palazzo Camponeschi, **ready soon** for participating to night shifts for FD data taking

HYBRID DETECTION



- SD absolute calibration based on experimental data
- Systematic uncertainty on energy scale: 14%



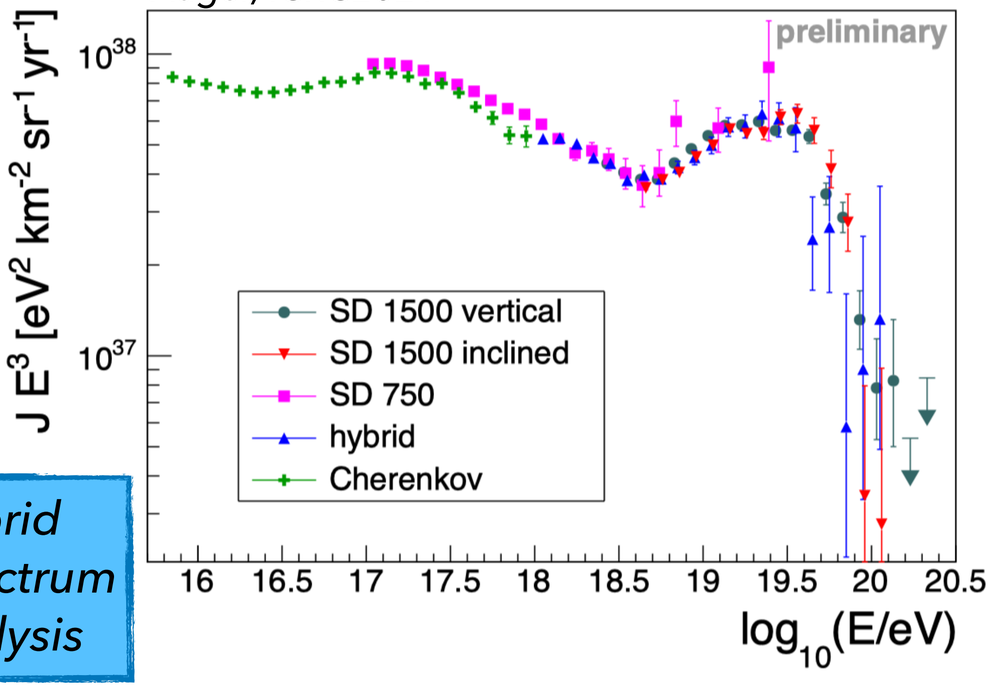
Auger, PRD 2020

ENERGY SPECTRUM

- 215030 events recorded with zenith angle <60 degrees;
- No declination dependence identified;
- Spectral features identified.

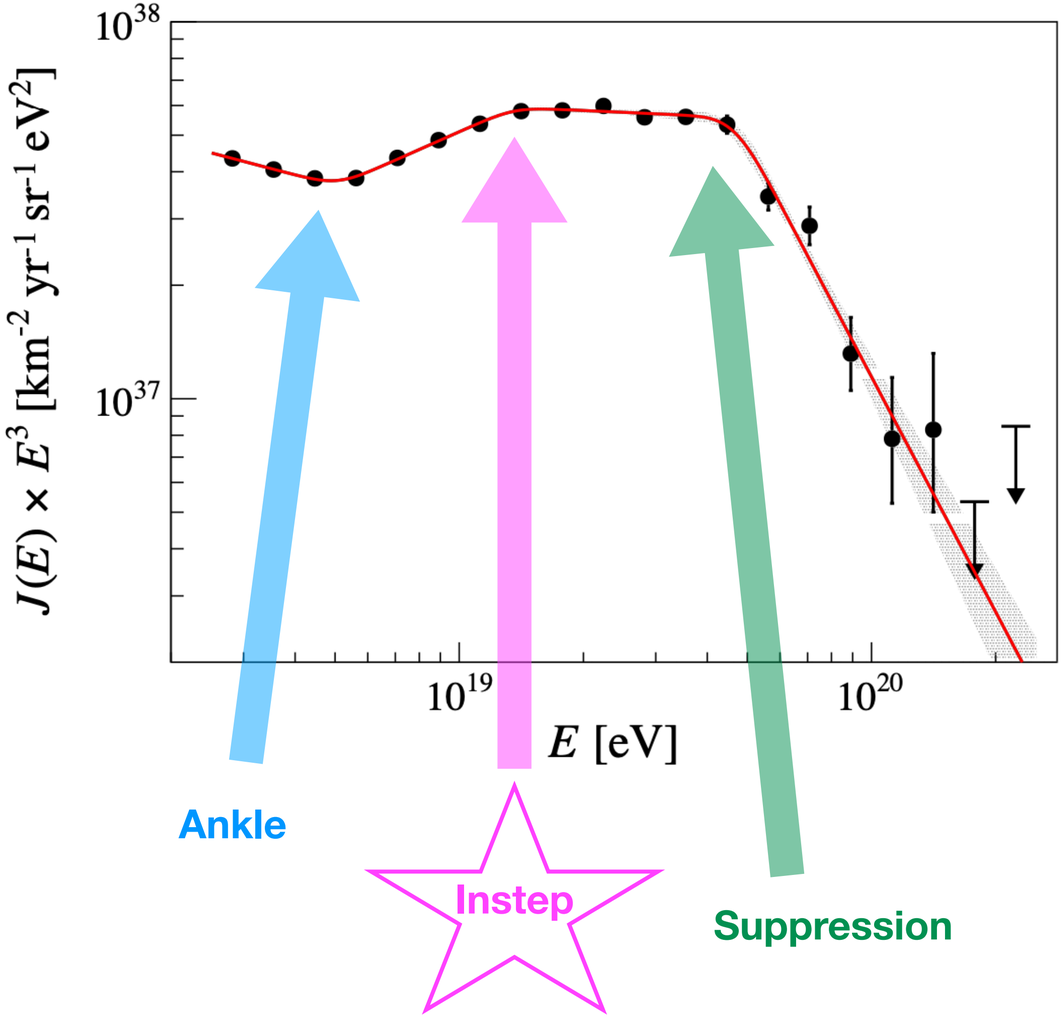
- Where do the features of the spectrum come from?

Auger, ICRC2021



Hybrid spectrum analysis

Auger, PRD 2020 & PRL 2020



MASS COMPOSITION

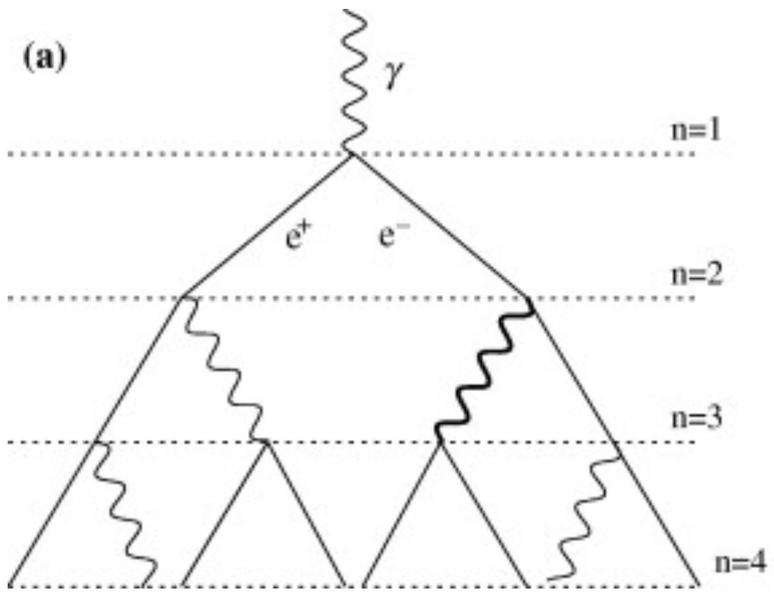
Generalized Heitler model

$$N(X) = 2^{X/\lambda}$$

$$E(X) = \frac{E_0}{N(X)}$$

$$N(X_{\max}) = \frac{E_0}{E_c}$$

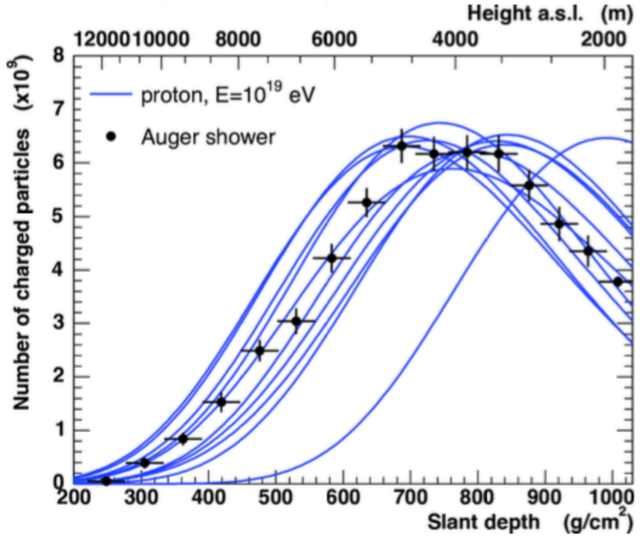
$$X_{\max} \propto \ln(E_0/E_c)$$

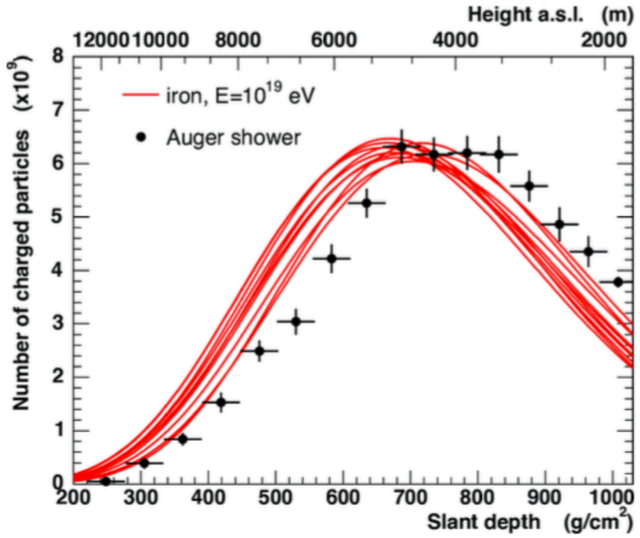


Modello di sovrapposizione:

$$^{A}X, E_0 \leftrightarrow A \times n, E_0/A$$

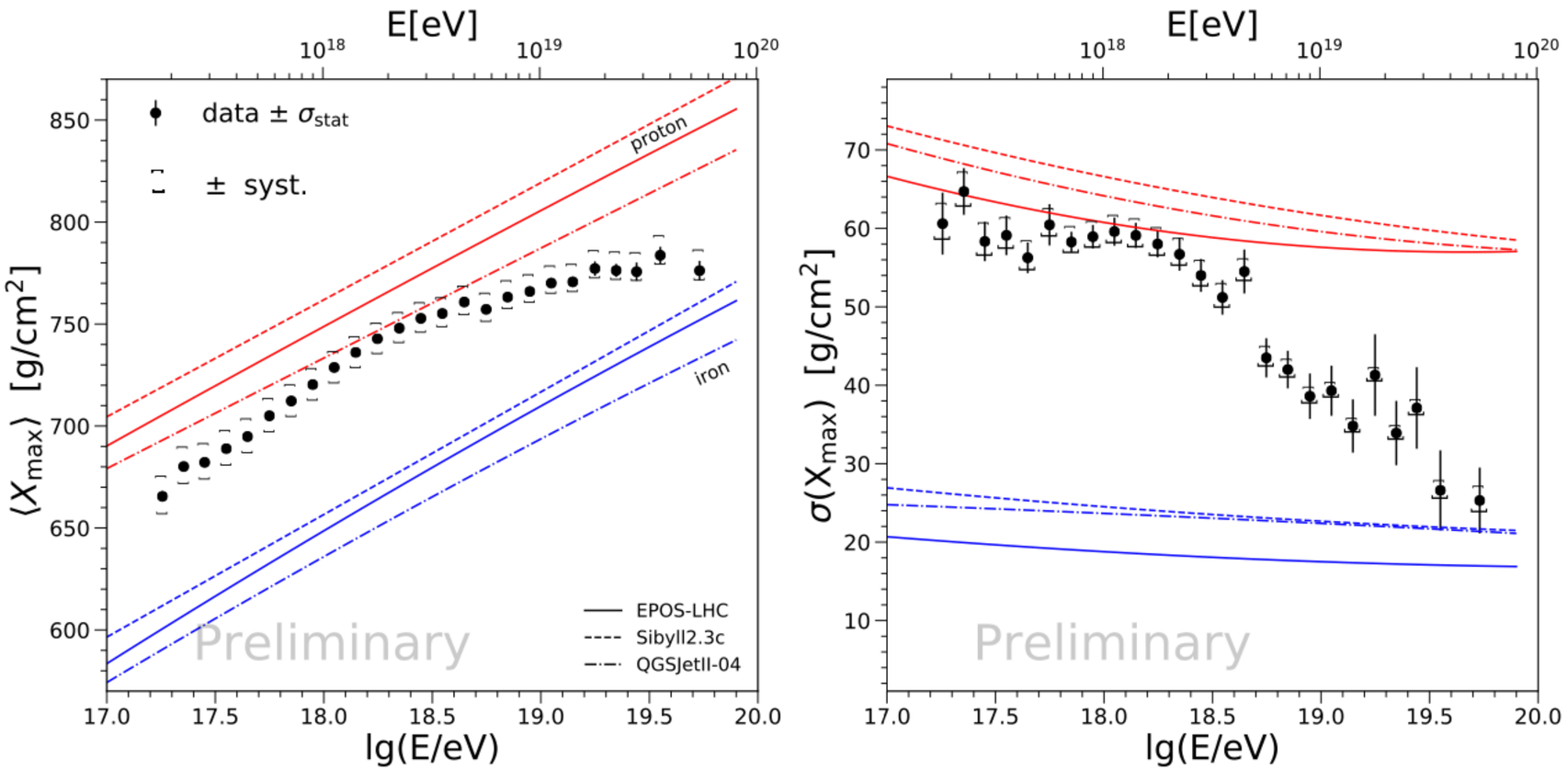
$$X^{A}_{\max} \propto X_{\max}(E_0/A)$$





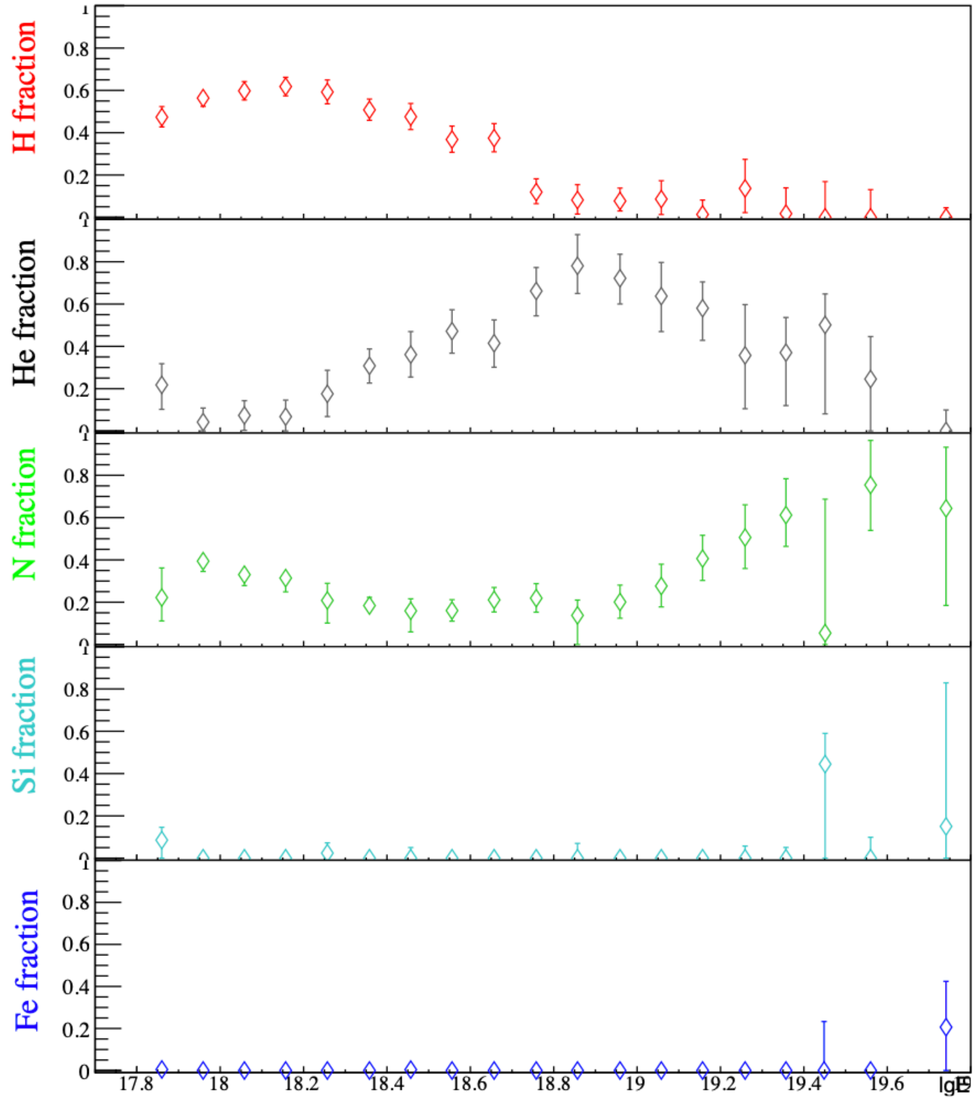
MASS COMPOSITION

Auger, ICRC2019



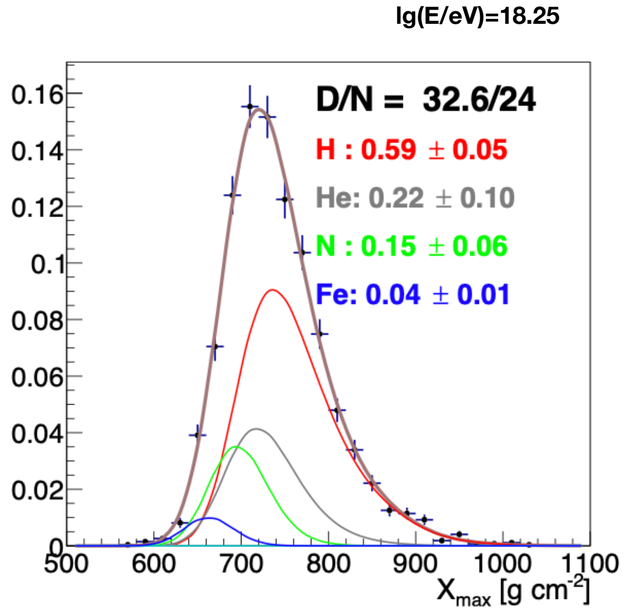
- Open issues: the hadronic interaction models used for interpretations are based on extrapolations of measurements at LHC
  - example: ”muon deficit" problem

MASS COMPOSITION



Fitting procedure for the interpretation of mass composition (bin-by-bin)

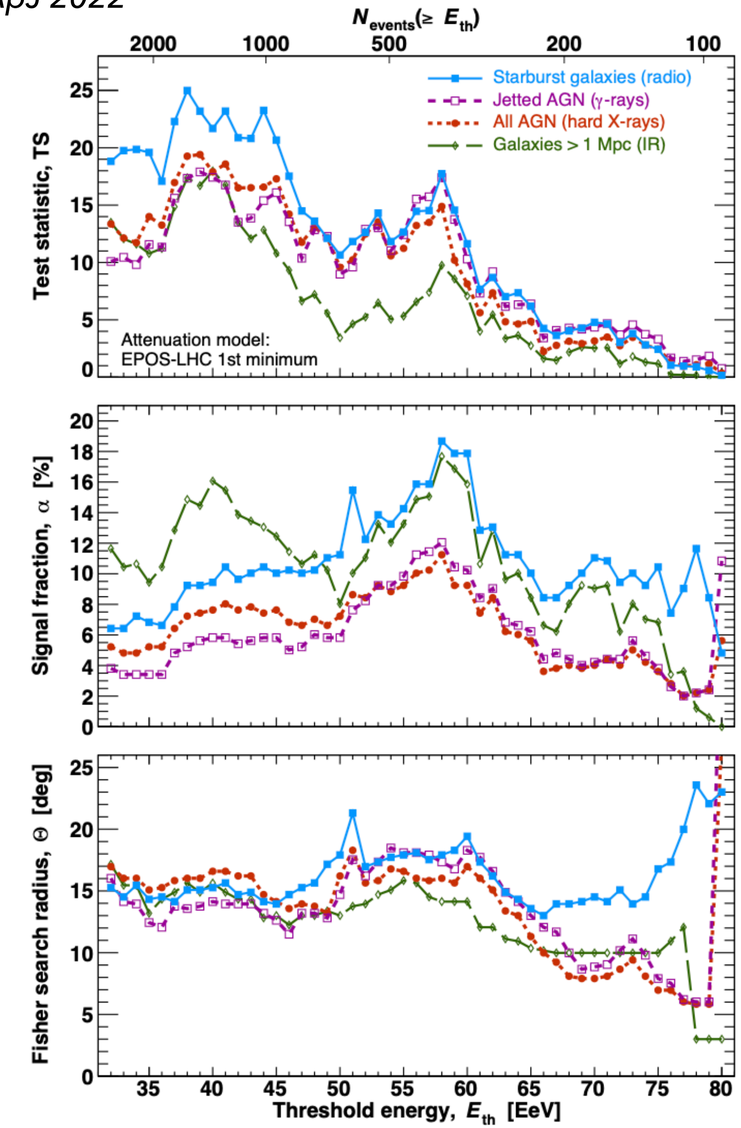
PhD Thesis by C. Trimarelli, Jan 2022



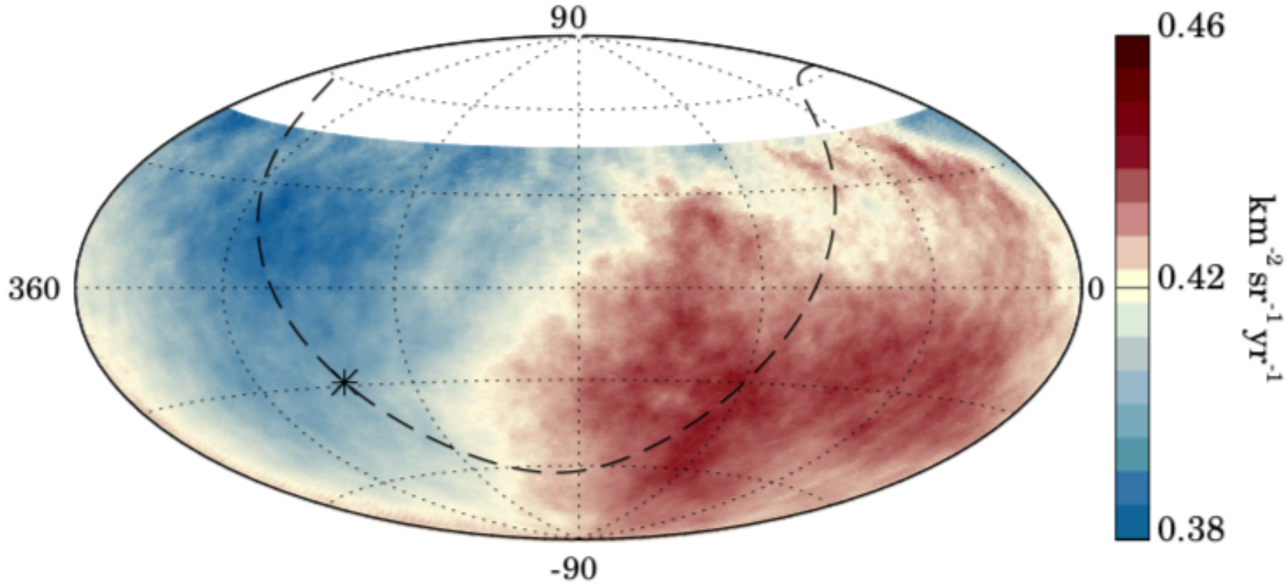
- Different nuclear species contributing at different energies
- Protons contributing at high energy
  - astronomy with cosmic rays?
  - connections to other messengers?

ARRIVAL DIRECTIONS

Auger, ApJ 2022



Auger, Science 2017

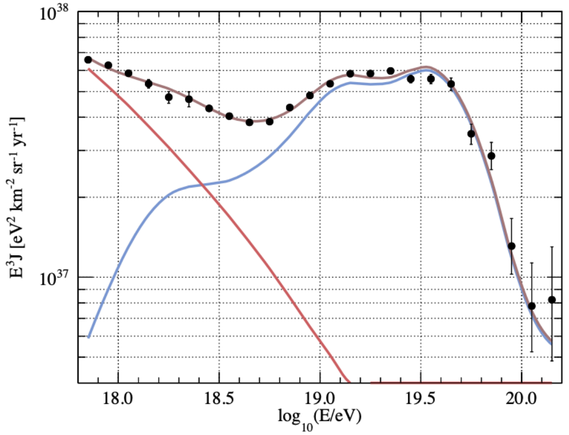


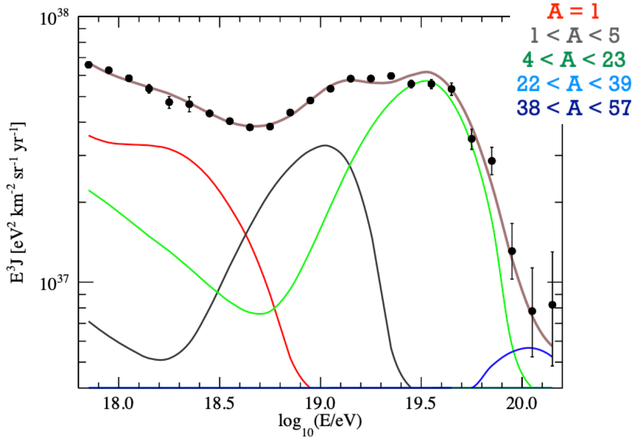
Magnitude and direction of the anisotropy support the hypothesis of extragalactic origin of UHECRs !

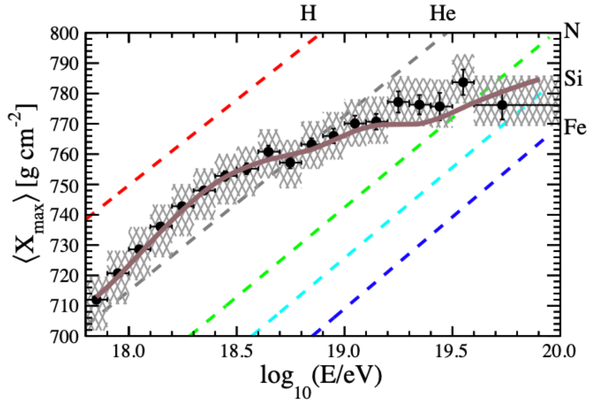
Isotropy disfavored at 3.3 - 4.2 sigma level, depending on the catalog

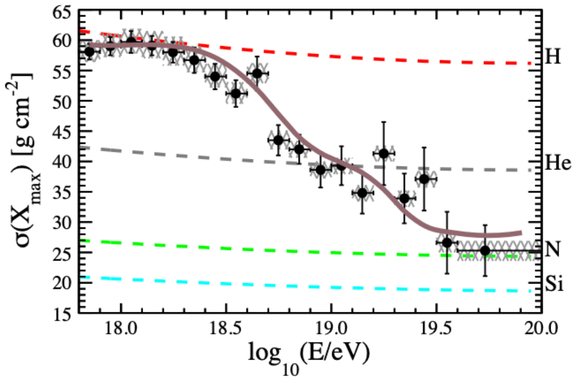
ASTROPHYSICAL SCENARIOS

Spectrum at escape from sources **x** Extragalactic propagation **=** Energy spectrum and mass composition at Earth









- *Submitted to JCAP*
- *Main contributions from AQ group*
  - *UHECR propagation code (see next slide)*
  - *Fitting procedure (PhD Thesis by A. Condorelli)*
- *Multimessenger connections: see talk by C. Petrucci*

- Several ideas for future analyses:
  - Include lower energy range, **towards the transition to Galactic cosmic rays?**
  - Include info about arrival directions (ongoing analysis)

UHECR INTERACTIONS

Source
- Acceleration
- Interactions
- Magnetic fields
- Escape

Propagation
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Earth
- Development of shower in the atmosphere
- Detection

From SimProp workshop, GSSI, October 2022

ONGOING PROJECTS AND IDEAS FOR THE FUTURE

PHYSICS

- Source environments (and multimessenger astrophysics)
  - Interactions in sources might explain the different spectral index (LE vs HE components) at the escape of sources, which could be responsible of the ankle
  - Connections with neutrinos and photons

- Magnetic fields & source distributions
  - Magnetic deflections (Galactic and extragalactic?) influence
    - Arrival directions
    - Spectral parameters
    - Mass distribution

- Interactions & Processes
  - Photohadronic interactions
    - Effects of uncertainties
  - Hadronic interactions
    - New in propagation codes (used in sources)
    - Effects of uncertainties (cross sections, …)
      - CR fluxes at escape
      - Secondary messengers ?
  - Electromagnetic cascade

- New physics
  - Modification of thresholds/cross sections

15

- *The **SimProp** simulation code for UHECR propagation in the extragalactic space*
  - *Many projects for future studies!*
  - *New SimProp version (**SimProp-Sirente**), available for being tested!*

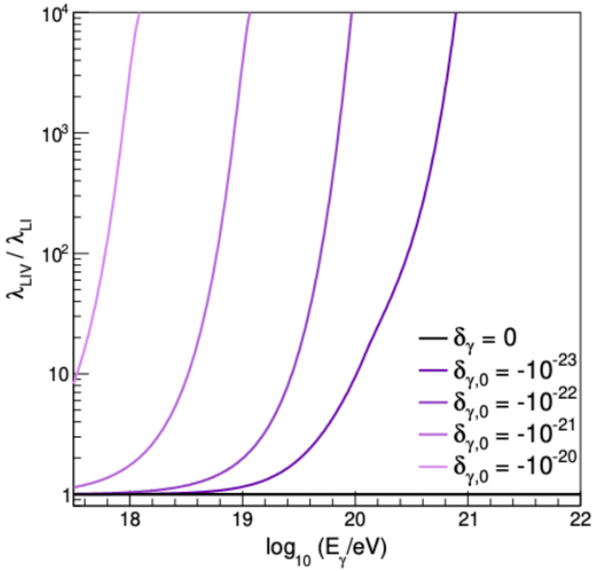
UHECR FOR STUDYING FUNDAMENTAL SYMMETRIES

- Modifications to the **UHECR interactions in the extragalactic space**, due to violation of Lorentz invariance, could alter:
  - The UHECR energy spectrum at the highest energies
  - The expected UHE photon spectrum at the highest energies

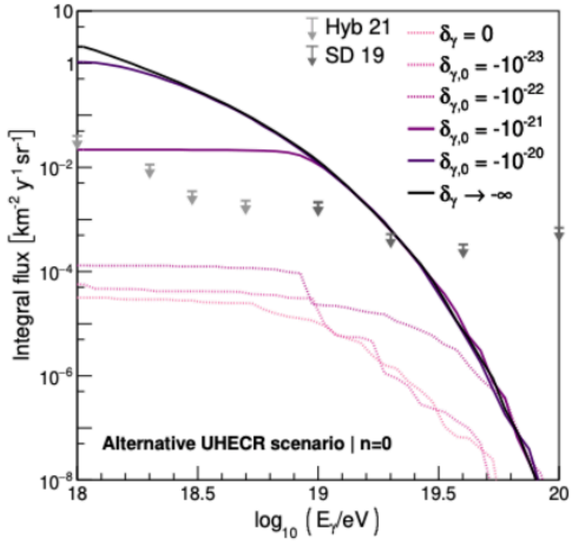
Main contributions from AQ group;

Ongoing projects with

- *SimProp*
- *CORSIKA, CONEX*



Auger, JCAP2022



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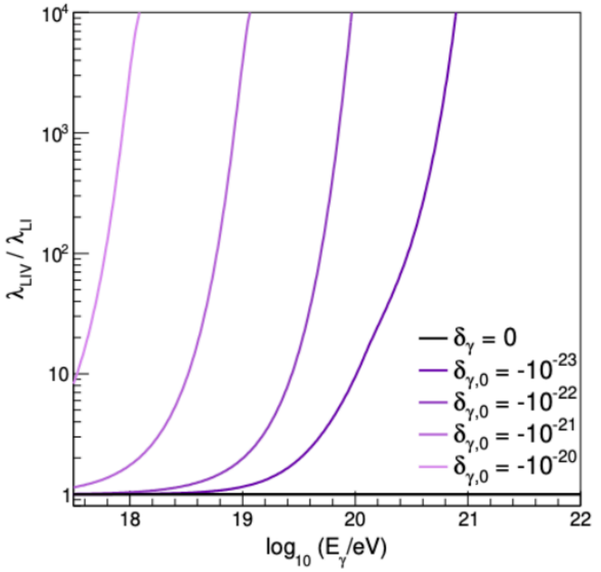
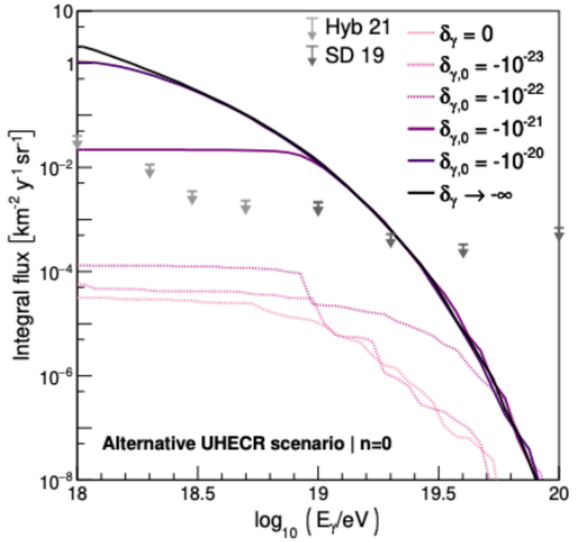
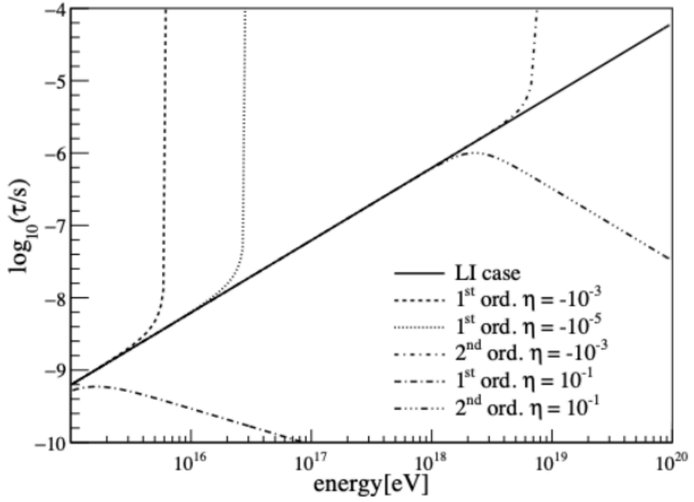


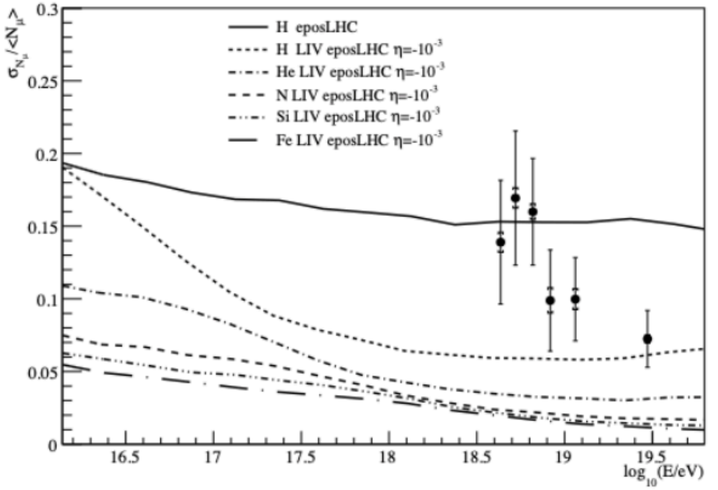
Auger, JCAP2022



- Modifications to the **UHECR interactions in the atmospheric development of the showers**, due to violation of Lorentz invariance, could alter:
  - The decay vs interaction of pions
    - The number of muons at Earth



Auger, ICRC2021; paper in preparation



UPGRADE

Physics motivation

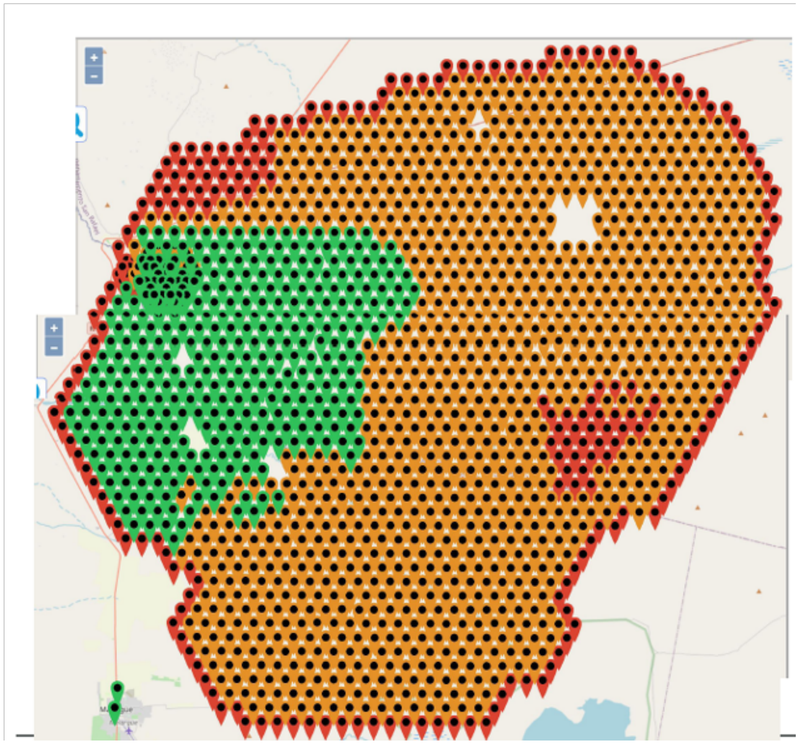
- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle Physics with air showers (muon estimate)
- Much better understanding of new and old data

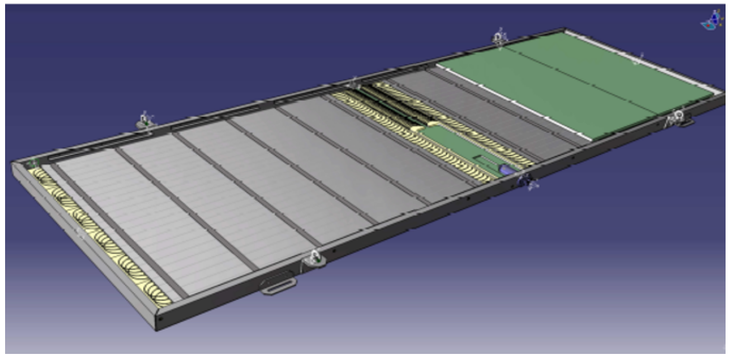
Auger Observatory Phase II

- Data taking 2022/23 – 2030
- AugerPrime (8 years, θ < 60°): 40,000 km² sr yr (Phase II), 80,000 km² sr yr (Phase I)
- Re-analysis of old data set (deep learning)

UPGRADE PLAN

- Scintillators **SSD**
- Upgraded and faster electronics **UUB** (40 MHz - 120 MHz)
- Extension of dynamic range with small **sPMT**
- Underground buried **UMD** detectors
- Radio antennas **RD**





1436 SSD stations **deployed**

25% of the array equipped with UUB and SSD-PMT and sPMT

Installation completed with UUBs in early 2023

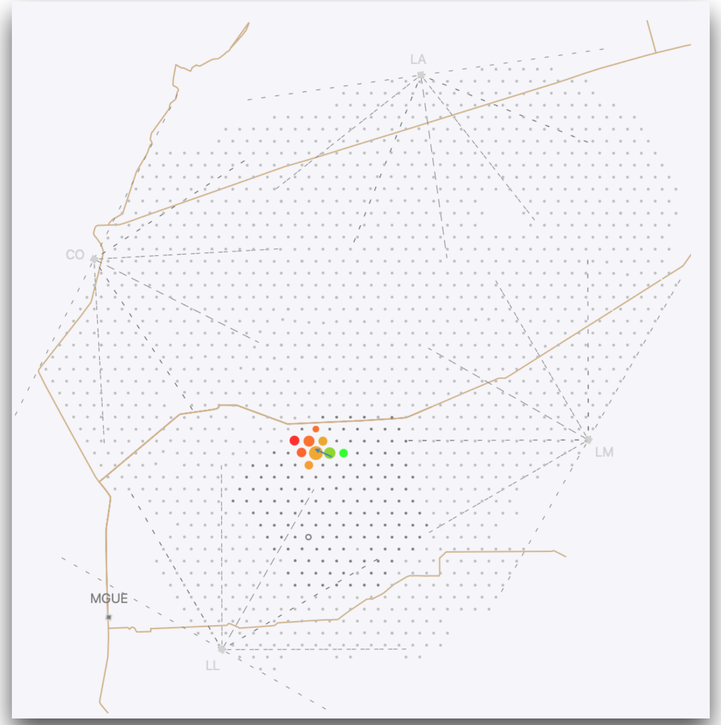
- Energy spectrum
- Nuclear species
- Source class (astronomy ?)
- Interactions at extremely high energy
- Fundamental symmetries

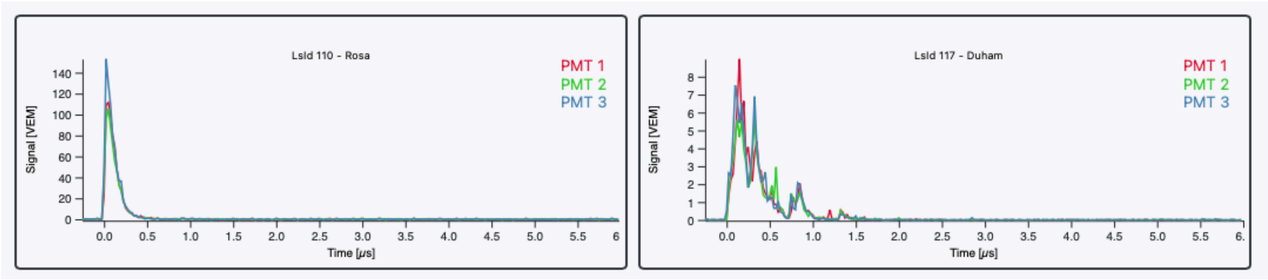
- OPEN QUESTIONS:
  - Source classes and acceleration mechanisms
  - Mass composition and hadronic interactions
    - Protons at the highest energies?
  - Shape of spectrum at Earth
  - Transition to Galactic cosmic rays

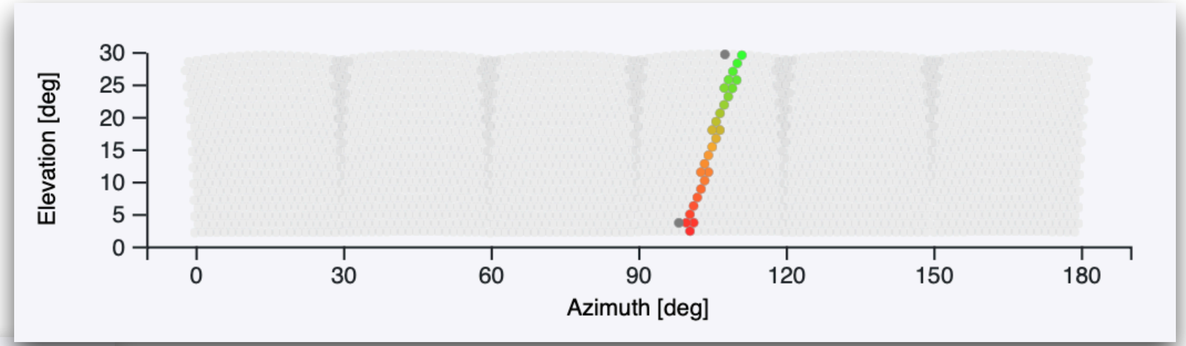
- FUTURE
  - Increase statistics
  - Better sensitivity to mass composition
  - Improve modelling of hadronic interactions
  - Multimessenger studies

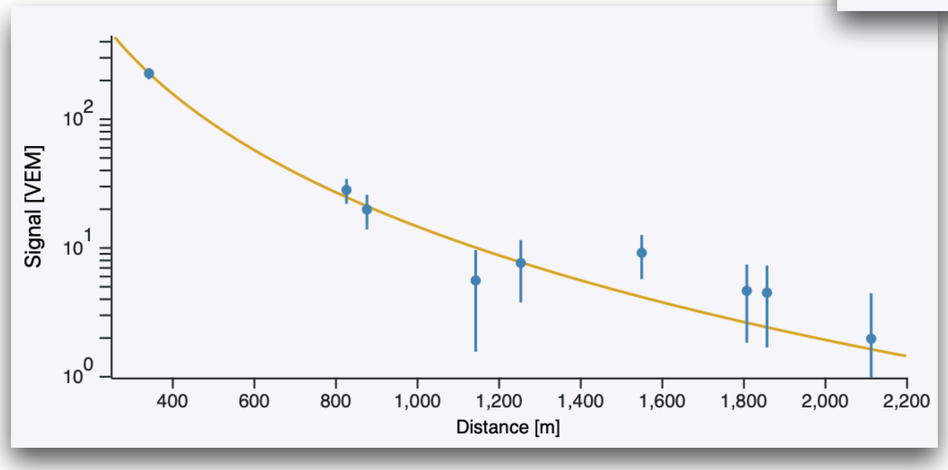
OPEN DATA

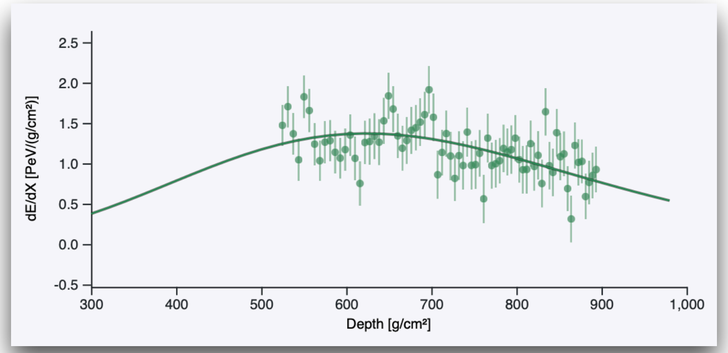
opendata.auger.org









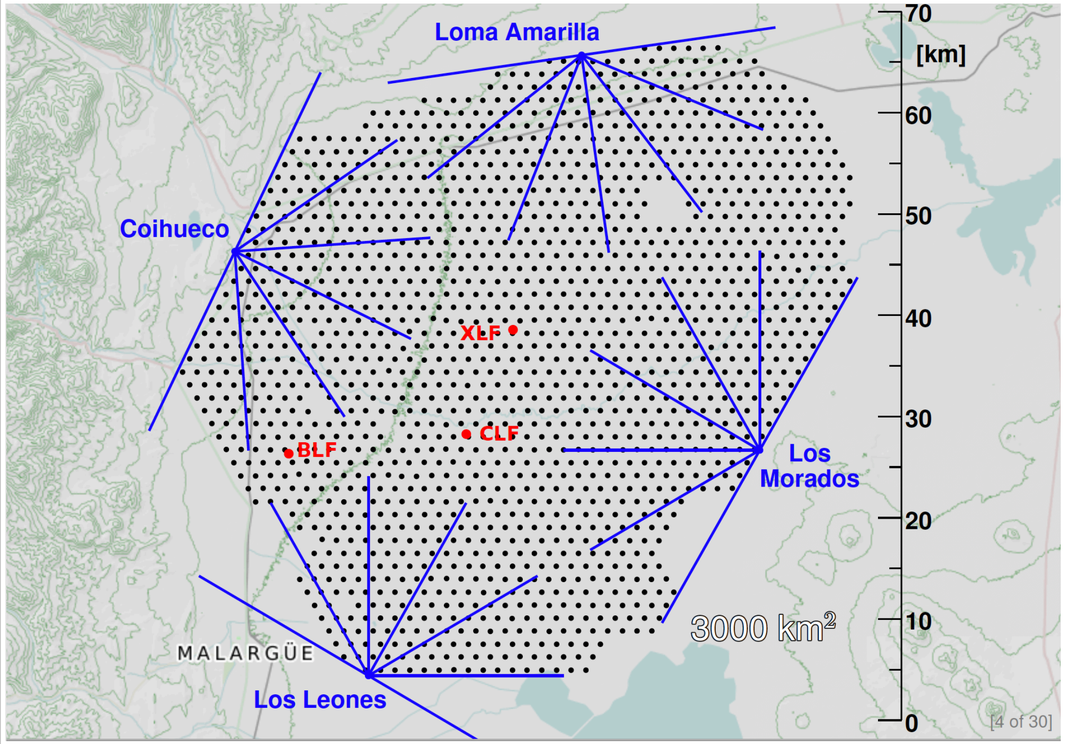


Next event:

***Auger Masterclass**, April 4th @UnivAQ*

BACKUP SLIDES

THE PIERRE AUGER OBSERVATORY



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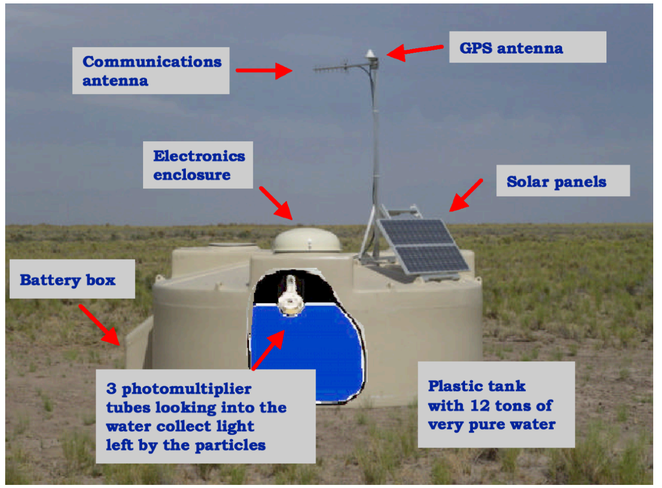

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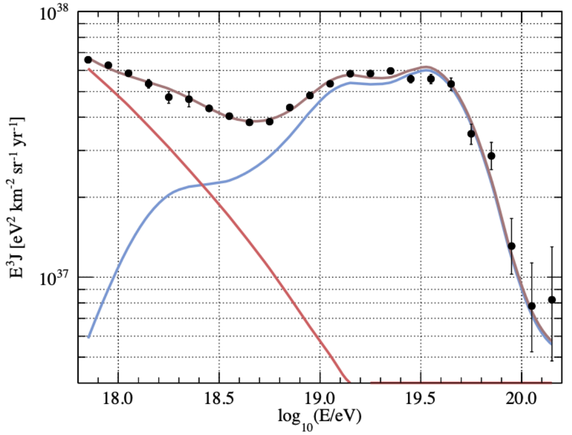
Auger Phase I

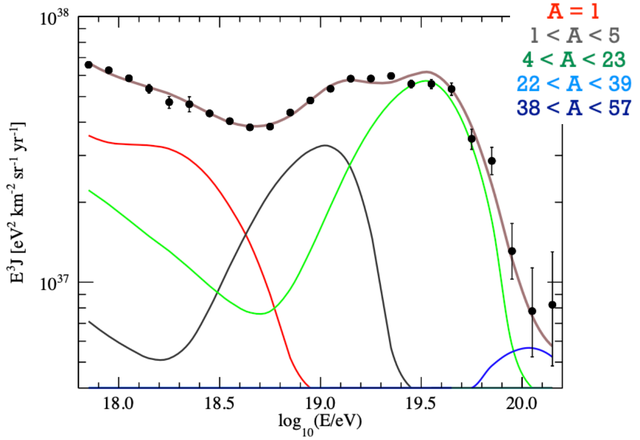
data taking from 2004 on (from 2008 with the full array):

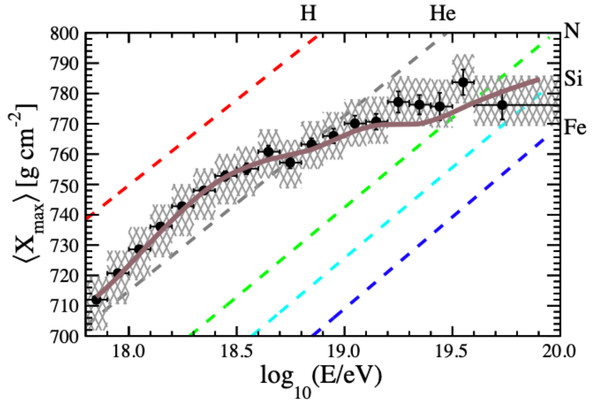
- > 120.000 km² sr yr for anisotropy
- > 90.000 km² sr yr for spectrum

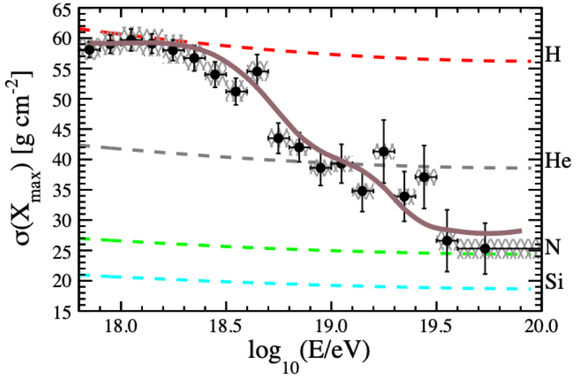
ASTROPHYSICAL SCENARIOS

Spectrum at escape from sources **x** Extragalactic propagation **=** Energy spectrum and mass composition at Earth

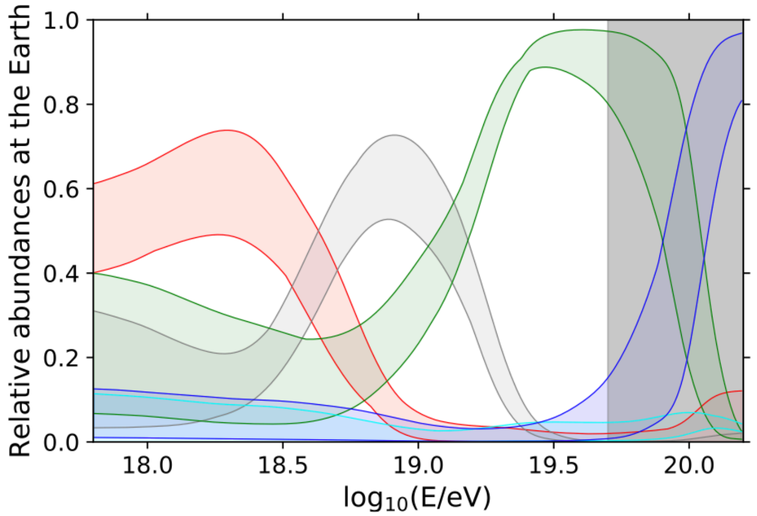








- *Submitted to JCAP*
- *Main contributions from AQ group*
  - *UHECR propagation code (see next slide)*
  - *Fitting procedure (PhD Thesis by A. Condorelli)*
- *Multimessenger connections: see talk by C. Petrucci*

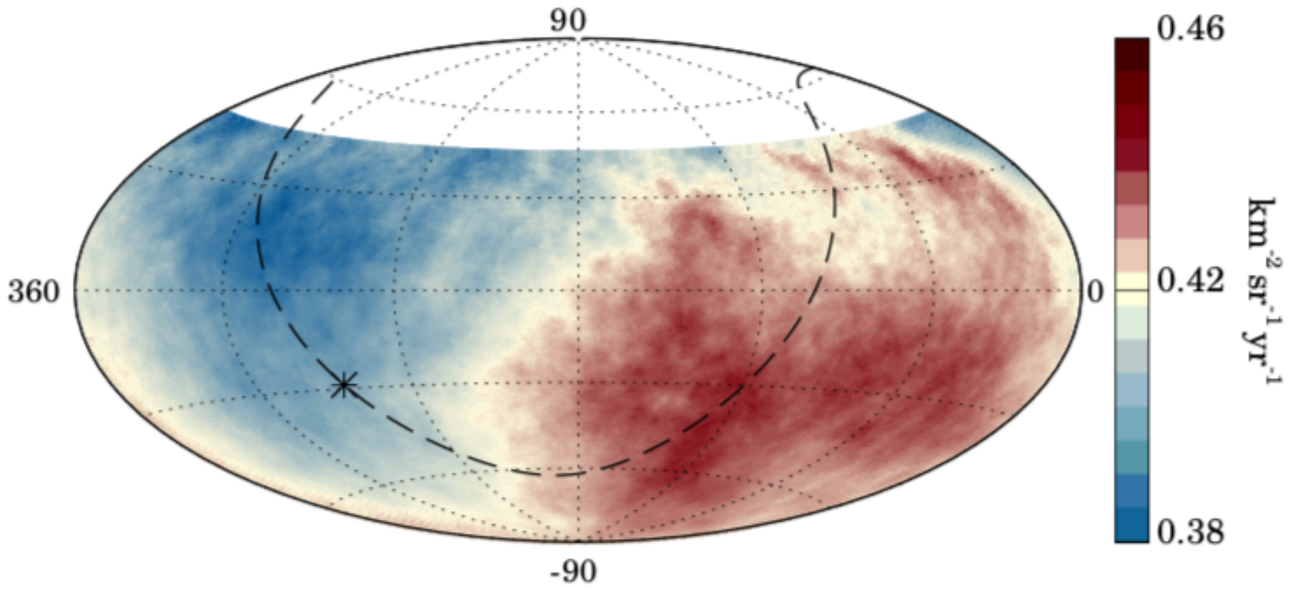


- Several ideas for future analyses:
  - Include lower energy range, **towards the transition to Galactic cosmic rays?**
  - Include info about arrival directions (ongoing analysis)

ARRIVAL DIRECTIONS

physicsworld BREAKTHROUGH OF THE YEAR 2017

- 114000 SD events
- 76800 km^2 sr yr exposure, 85% sky coverage
- Analysis of first harmonic in right ascension:
  - 4-8 EeV -> compatible with isotropy
  - >8 EeV: 3D dipole of amplitude 6.5% at 5.2 sigma



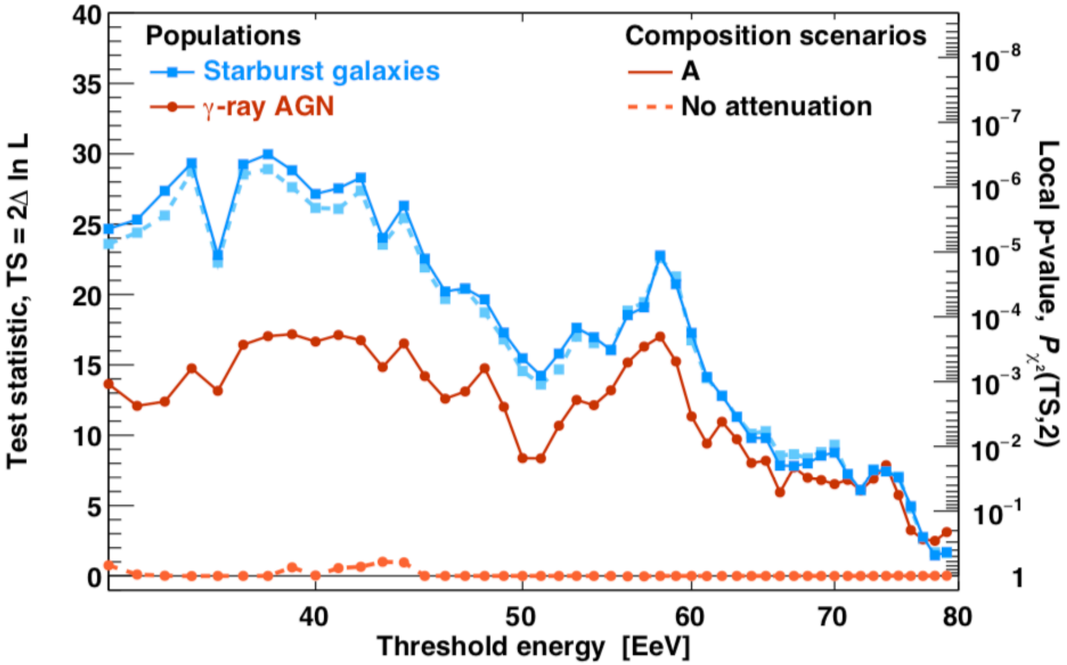
Magnitude and direction of the anisotropy support the hypothesis of extragalactic origin of UHECRs !

COMPARISON WITH EXTRAGALACTIC GAMMA-RAY CATALOG

- Events above 20 EeV, collected between Jan 2004 and April 2017, total exposure 89720 km2 yr sr.
- Fermi-LAT sources above 50 GeV (D<250 Mpc)
  - 17 AGN + 23 starburst galaxies

- Assumption: UHECR flux proportional to photon flux
- The attenuation of UHECRs due to propagation effects is taken into account (scenario A corresponds to combined spectrum composition fit, Auger JCAP 2017), but no Galactic/extragalactic magnetic fields are included

- Maximum signal for **Starburst Galaxies** found above 38 EeV



Auger, ICRC 2019