# Raggi cosmici carichi: introduzione e misure da terra

PIERRE AUGER OBSERVATORY

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Congresso SIF - 17 settembre 2021

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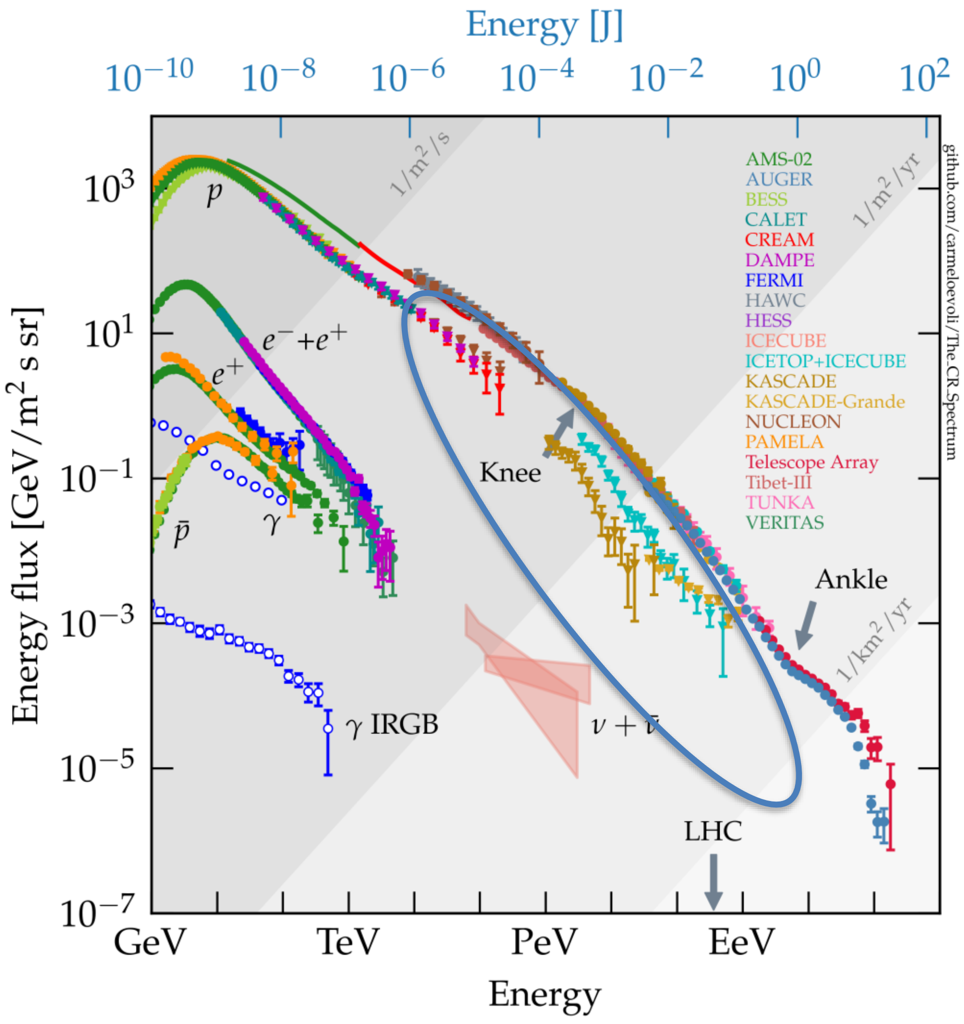
# Cosmic rays in a nutshell

- Cosmic rays (CRs) are protons, nuclei and electrons, with a small contribution of positrons and antiprotons, reaching the Earth’satmosphere with an approximatively isotropic flux
- Energy range: from $10^9$ eV up to $10^{20}$ eV
- The flux of CR entering the Earth's atmosphere above $10^{15}$ eV drops below a few tens of particle per square meters per year

**Above $10^{15}$ eV direct experiments are thus replaced with ground-based instruments that cover up to several thousands of km$^2$: the extensive air shower (EAS) arrays**

**Basic measurements:**
Energy spectrum
Mass composition
Anisotropy



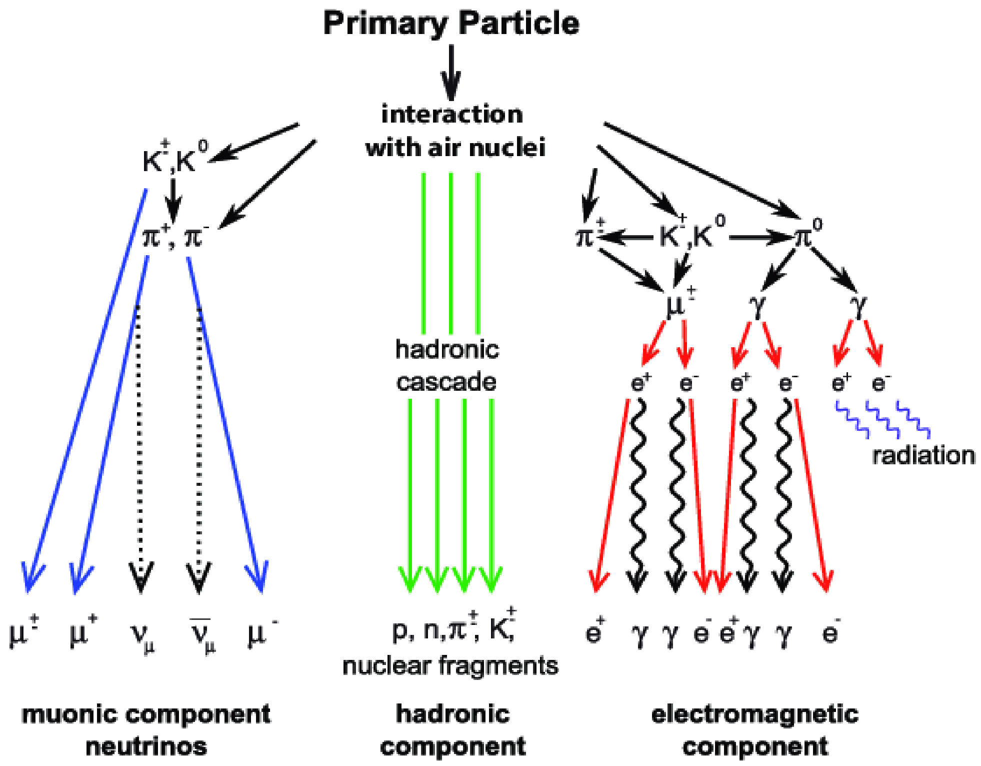

DOI/10.5281/zenodo.4396125.svg

# Indirect Measurements

**Extensive air showers:**

- interaction of primary CRs with a nucleus in the atmosphere ( 15-20 km from Earth)

In addition to the **hadronic component**, the decay of short-lived hadrons, such as pions, lead to a shower of photons, electrons and positrons, which constitute the **electromagnetic component**. Muons and neutrinos constituite the **penetrating component**.




**A $10^{19}$ eV proton produces (MC) at sea level about $3{\times}10^{10}$ particles with energy > 200 keV.**

- **99% are photons and electrons:** Energy ranged in 1–10MeV ; **85% of the total energy**

- **muons:** Energy about 4GeV, **10% of the total energy**

- **pions:** (few GeV, about **4% of the total Energy)**

- **neutrinos and hadrons:** (smaller proportions)

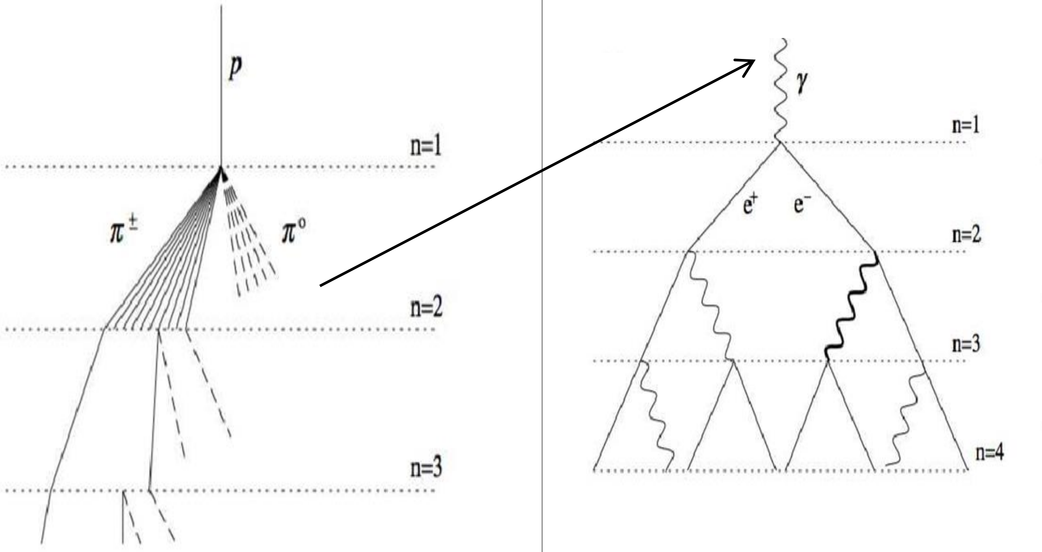
**Shower footprint on the ground over some km²**

# Indirect Measurements

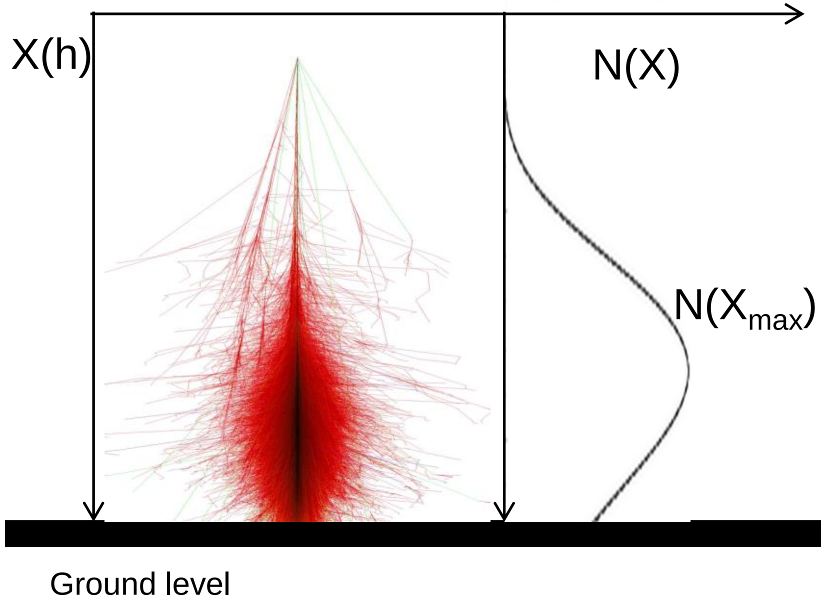
**Proton-initated shower: Heitler toy-model**

Hadronic shower

Electromagnetic shower




EAS




$$E_0 \propto (N_e + kN_\mu)$$

$$N_\mu^p \propto E_0^\beta$$

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

$$X_{max}^p \propto \ln\left(\frac{E_0}{E_c}\right) X_0$$

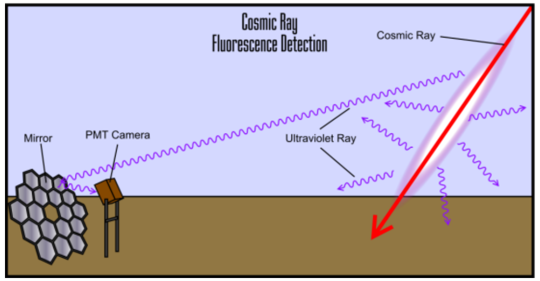
**Nuclei-initated shower: superposition model**

$$N_\mu^A \propto A\left(\frac{E_0}{A}\right)^\beta = A^{1-\beta} \cdot N_\mu^p$$

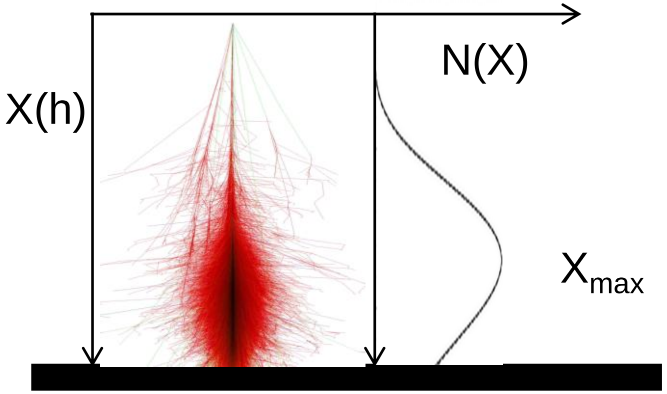
$$X_{max}^A \propto \ln\left(\frac{E_0}{A \cdot E_c}\right) X_0 = X_{max}^p - X_0 lnA$$

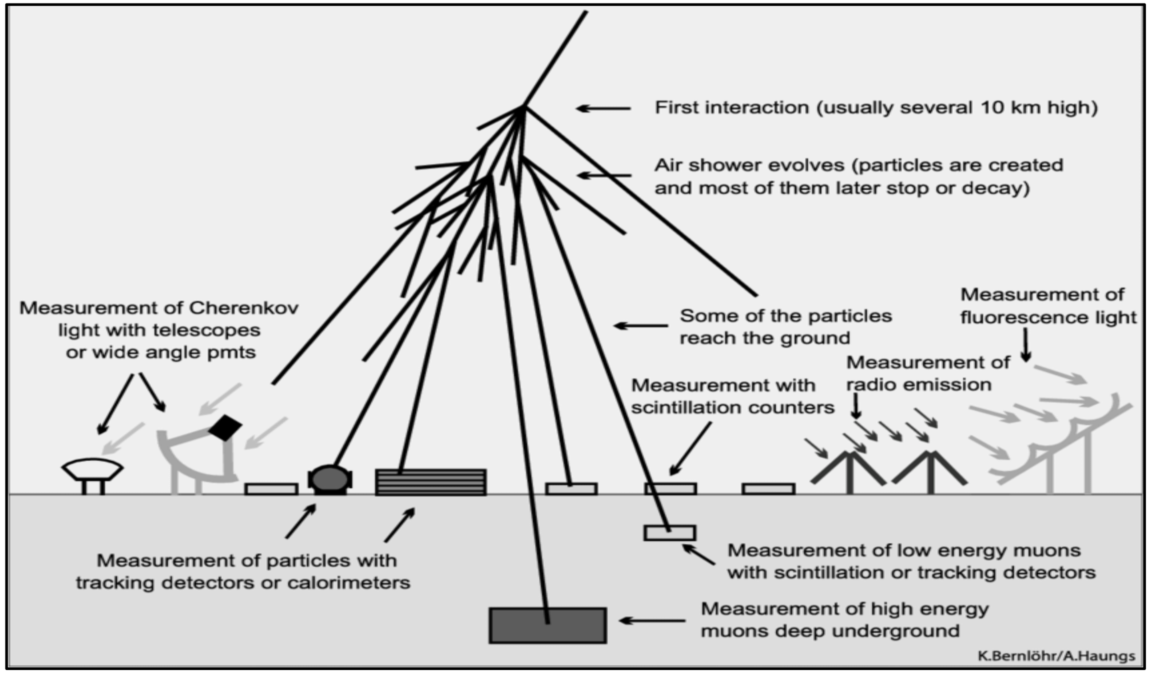
# Ground-based detectors

**Longitudinal development**



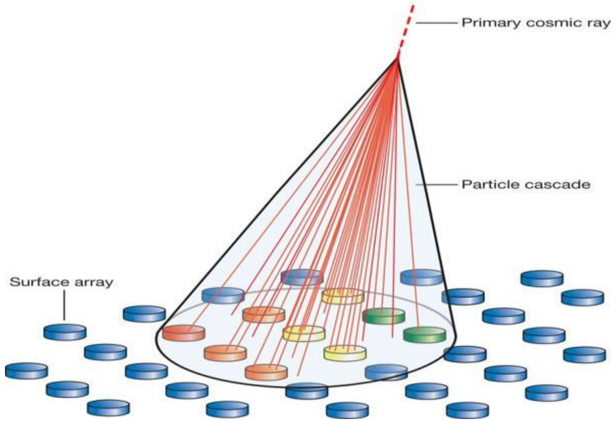

Detection of the radiation produced by the propagation of the EAS in the atmosphere (Cherenkov light, Fluorescence light, radio signals)



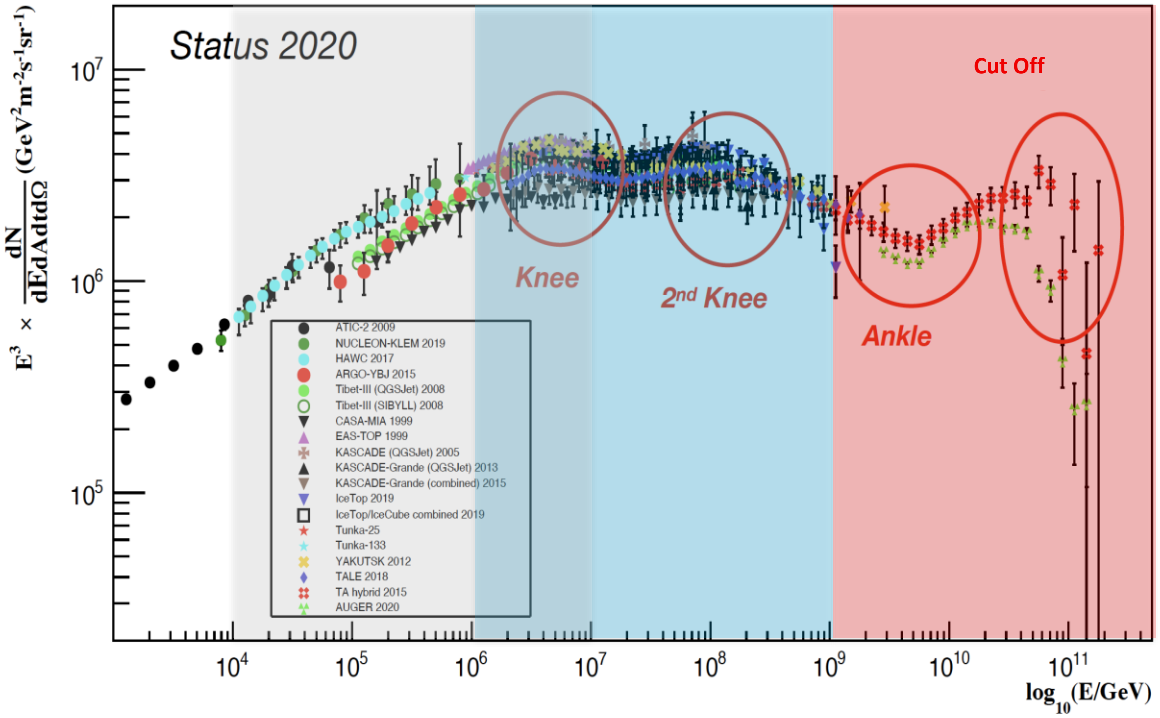




**Lateral distribution**

Particles densità at ground
($e$, $\gamma$, $\mu$)



# Ground-based detectors




Low energy ($10^{13}$ ~ $10^{16}$ eV):
**IceTop**, **HAWC**, **GRAPES-3**,
Imaging Cherenkov telescopes, water Cherenkov tanks, scintillation counters, underground muon detectors

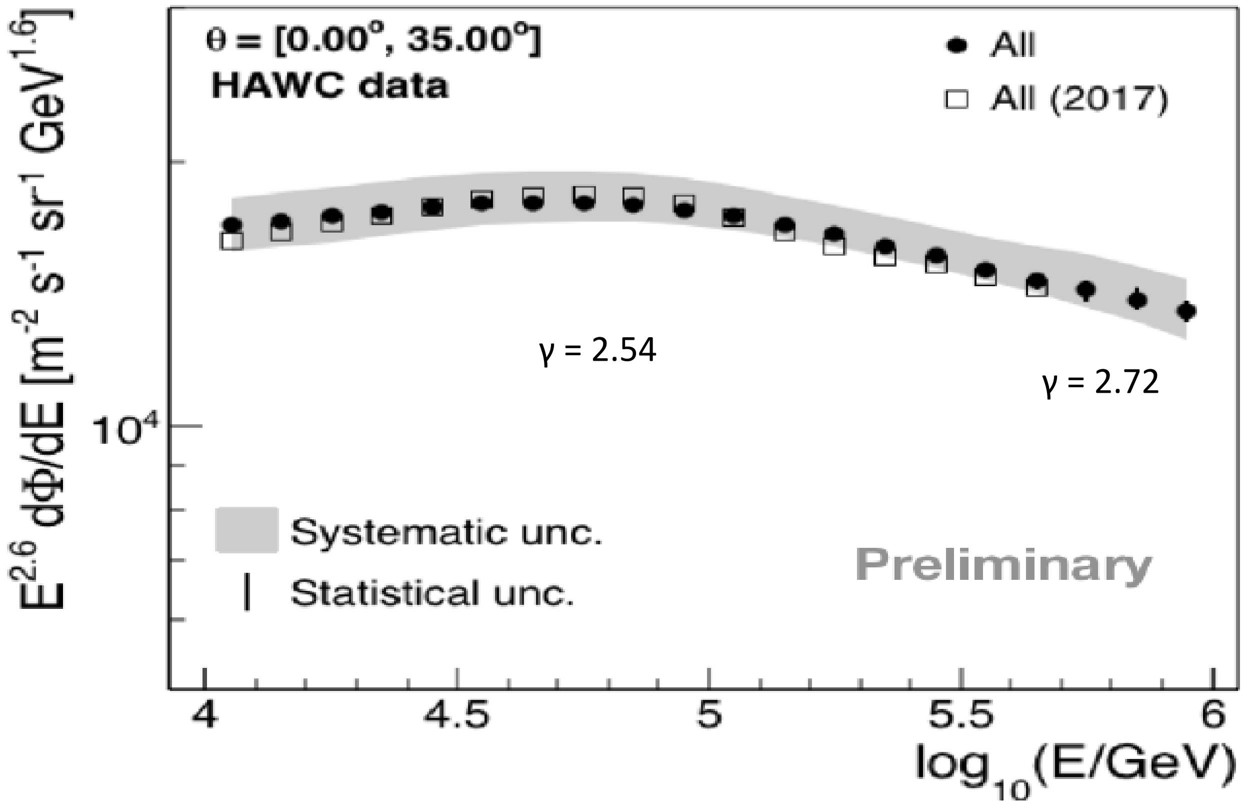
Mid energy ($10^{14}$ ~ $10^{18}$eV):
**Pierre Auger Observatory** and **Telescope Array**
Low-energy extension of Auger and TA High-elevation angle FD (HEAT, TALE-FD) Infill arrays (Auger 750om, TALE-SD)

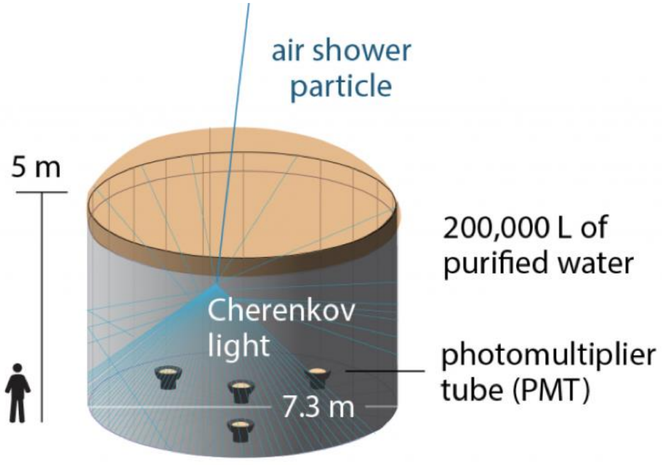
High energy ($10^{18}$ ~ $10^{20}$ eV):
Pierre Auger Observatory and Telescope Array **Auger + TA**

# HAWC

High Altitude Water Cherenkov (HAWC)

- 4100 m a.s.l. at the Pico de Orizaba Volcano in Puebla, Mexico
- 300 water Cherenkov tanks over an area of 22,000 m$^2$
- gamma-ray and cosmic-rays in the primary energy interval from 10 TeV to 1 PeV
- bridge between direct and indirect cosmic-ray detectors in the TeV regime




Physical Review D, 96(12), 122001 (2017)

PoS(ICRC2021)330

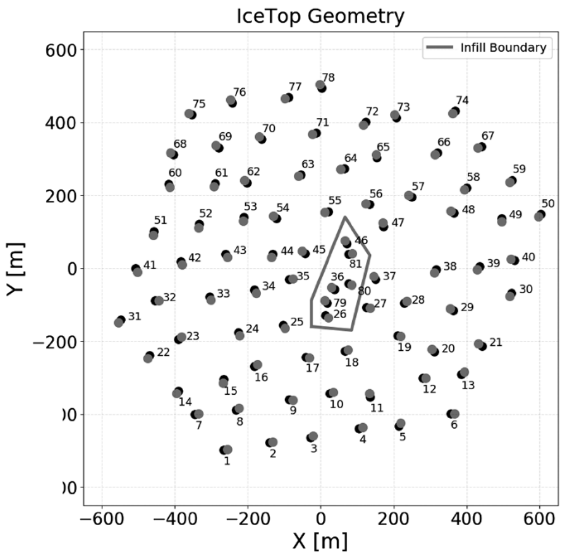
broken power law scenario
significance of 4.6σ

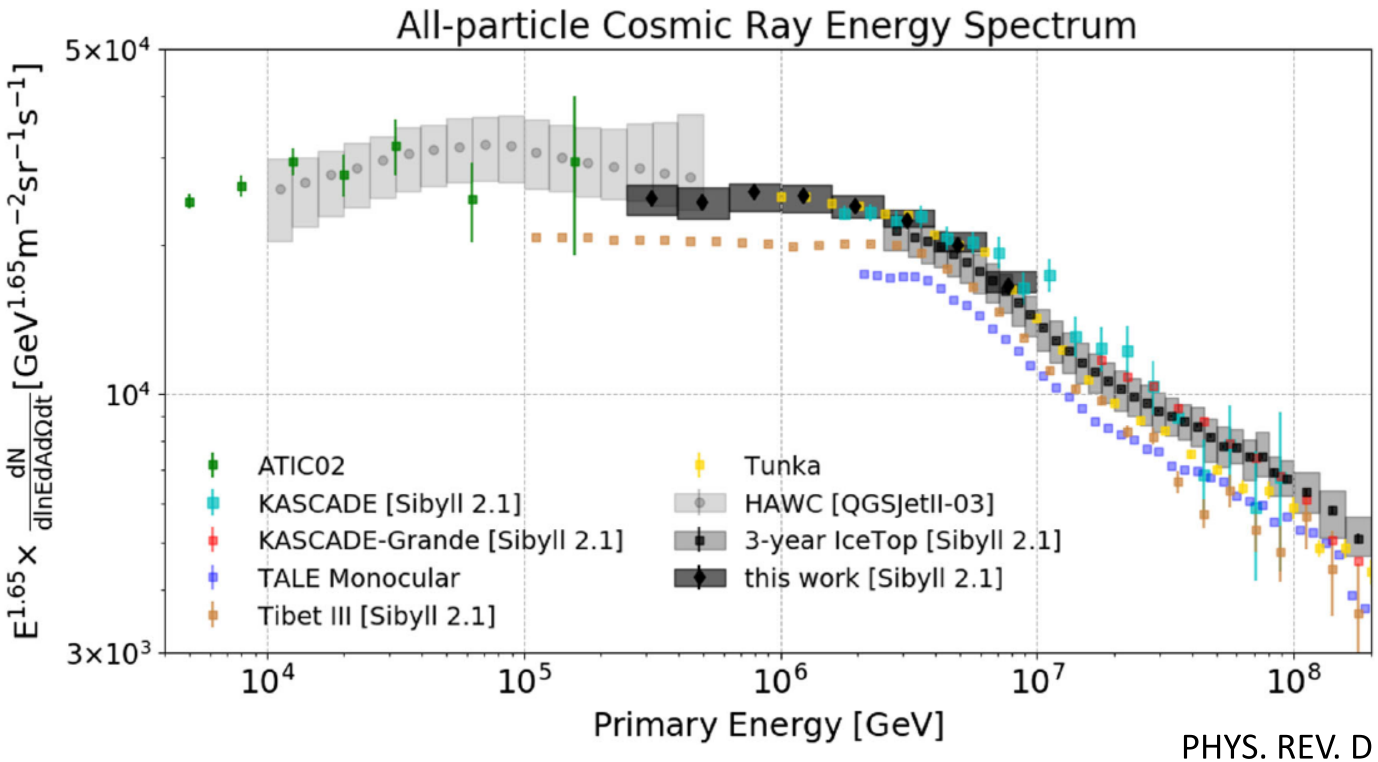
# IceTop

Surface detector of the IceCube Neutrino Observatory at the South Pole.

- 162 tanks filled with clear ice distributed in 81 stations, 125 m spaced (+ Infill)
- area of 1 $km^2$ , at an altitude of 2835 m above sea level

**Upgrade plans:**
hybrid array of scintillators and antennas  and
small air- Cherenkov telescopes





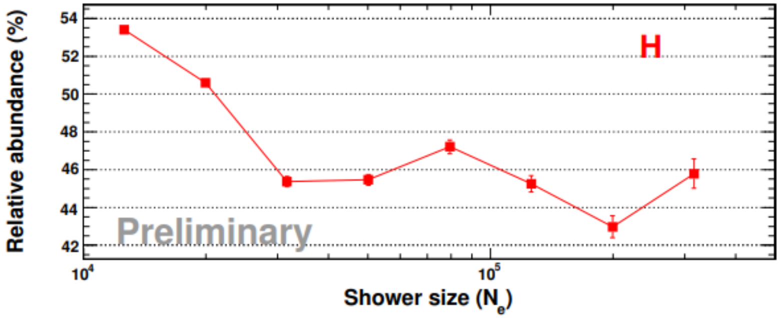
Installation of a detector

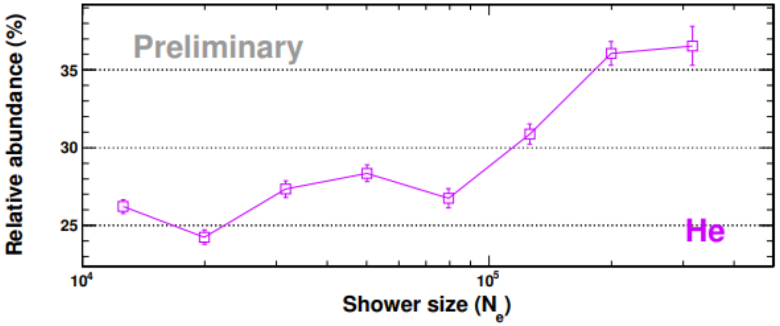
PHYS. REV. D 102, 122001 (2020)

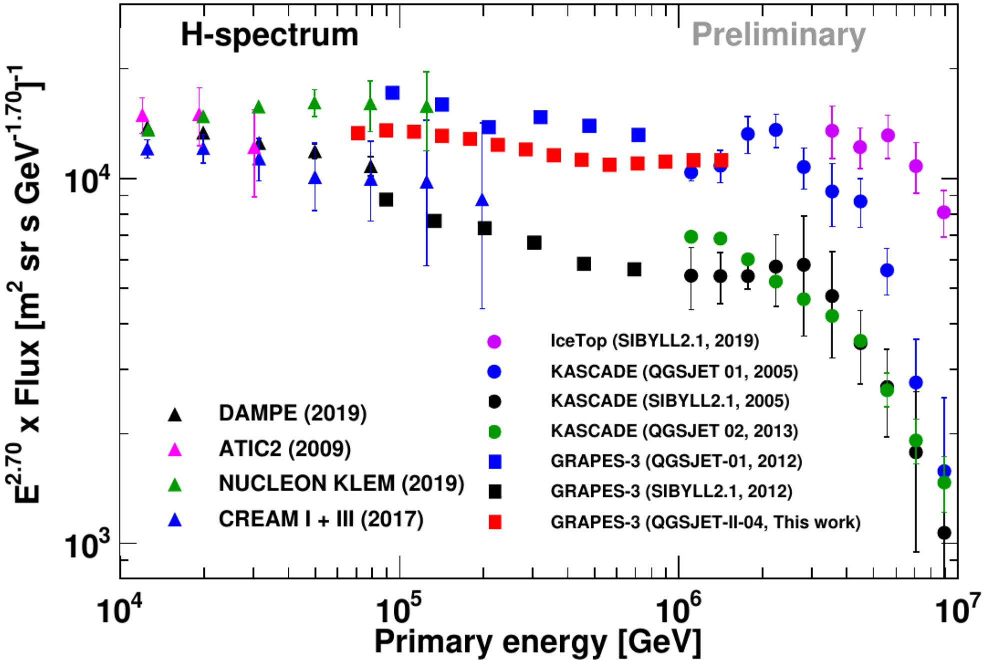
# GRAPES-3

Ooty, India (altitude 2200m)

- cosmic-rays, gamma-rays, solar and atmospheric phenomena.
- 400 plastic scintillator detectors of 1 $m^2$ area each with 8 m separation spread over 25000 $m^2$
- 560 $m^2$ area muon telescope consisting of 3712 proportional counters (6m x 0.1m x 0.1m)
- Scintillator detectors measure particle density and relative arrival time in EAS
- Energy sensitivity of the aray is in TeV-PeV range
- Muon telescope: 16 (35 $m^2$ each ) modules with
- 58 proportional counter x 4 Layers

# Cosmic rays at the highest energies

**Two detection techniques are principally employed to detect UHECRs:**

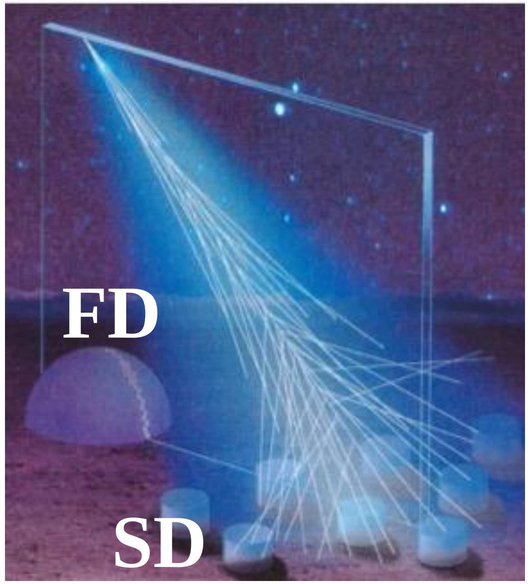
- **Arrays of particle detectors at ground level observing the density and pattern of the shower:** reconstruct the energy, direction, and parameters related to their composition

- **Arrays of optical telescopes detect the fluorescence emission from atmospheric nitrogen:**

measurement of the longitudinal profiles

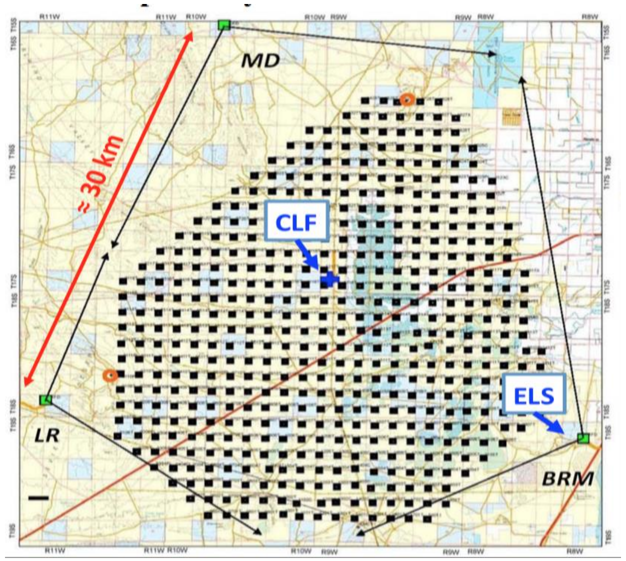
**Surface Detector array (SD)**
(+) duty cycle ~ 100%
(-) depend on models of shower and hadronic processes
(-) energy systematic uncertainties

**Fluorescence Detector (FD)**
(-) duty cycle ~ 13%
(+) calorimetric measurement of energy
(+) minimal dependence on hadronic interaction models



# The Telescope Array Observatory

**Located in Utah, USA, 1400m a.s.l. , 700 km$^2$**
Data since 2007






**Hybrid detector:**
fluorescence detectors (FD) and surface detectors (SD).

- **507 SD consisting of 3m$^2$ double layer scintillators 1200 m spaced**

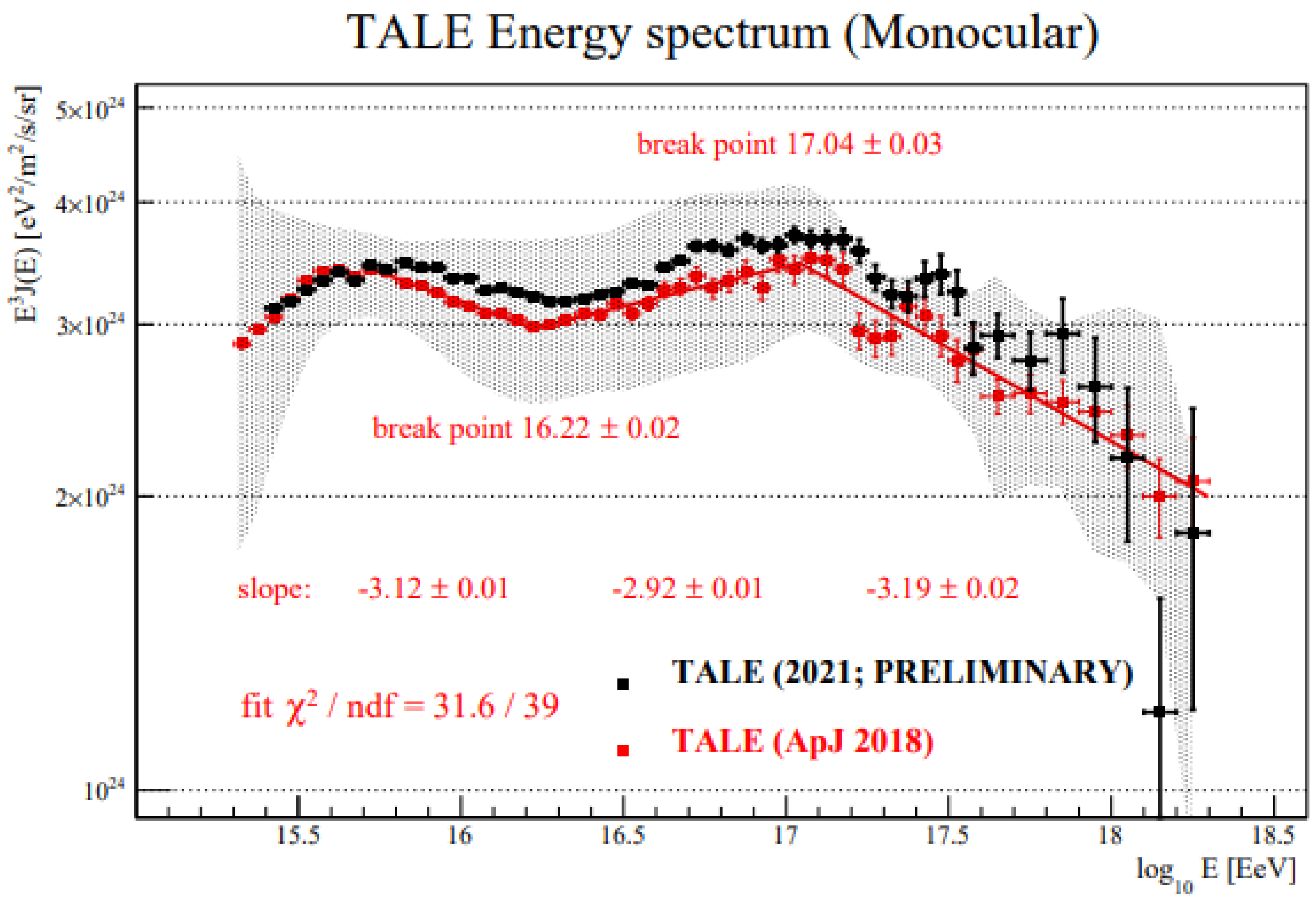
The SD have a full efficiency at $5 \times 10^{18}$eV and a zenith angle smaller than 45◦.

- **3 fluorescence sites, distanced 30 km, approx. equilateral triangle**

- 2 have 12 telescopes each with 256 PMTs with a field-of-view of 1° ×1°.
- 1 has 14 telescopes with cameras and electronics from HiRes-I and mirrors from HiRes-II.

- **TALE, the Telescope Array Low Energy** extension was designed to lower the energy threshold to about $10^{15.3}$ eV. TALE has a surface detector (SD) array made up of 103 scintillation counters (40 with 400 m spacing, 36 with 600 m spacing and 27 with 1.2 km spacing) and a Fluorescence Detector (FD) station consisting of ten FD

# The Telescope Array Observatory: TALE

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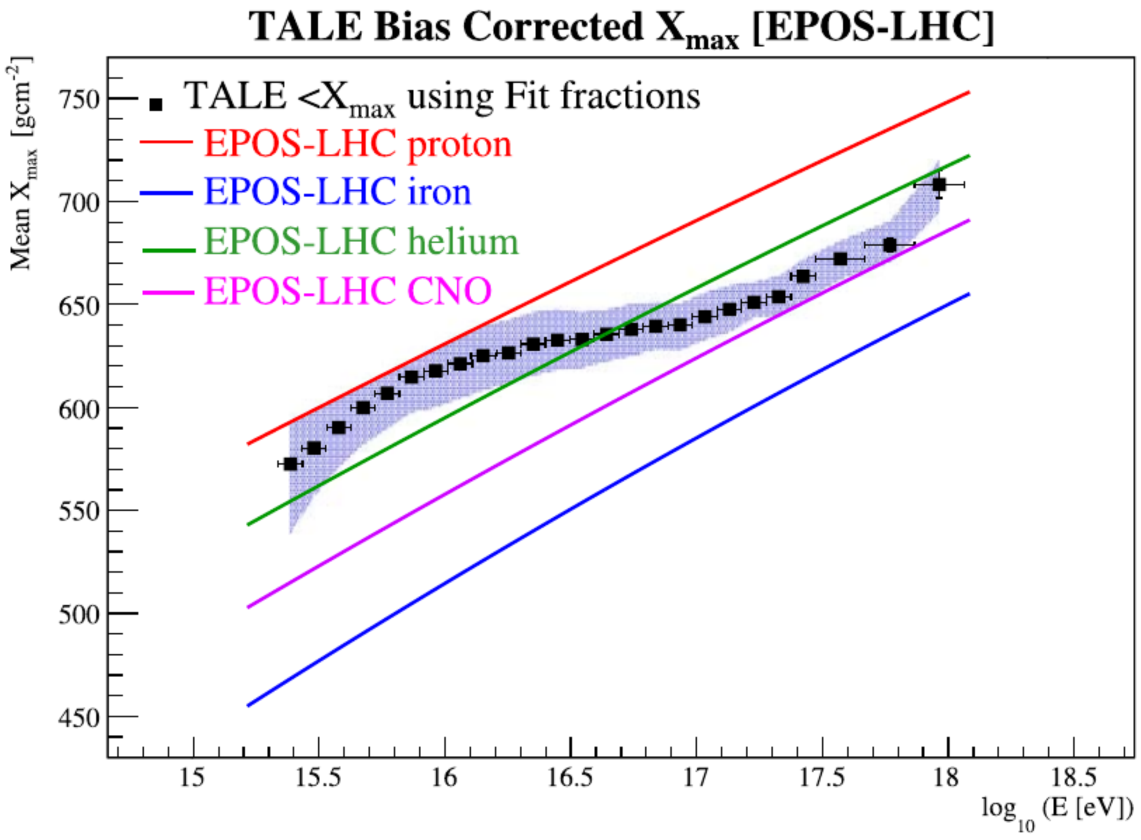
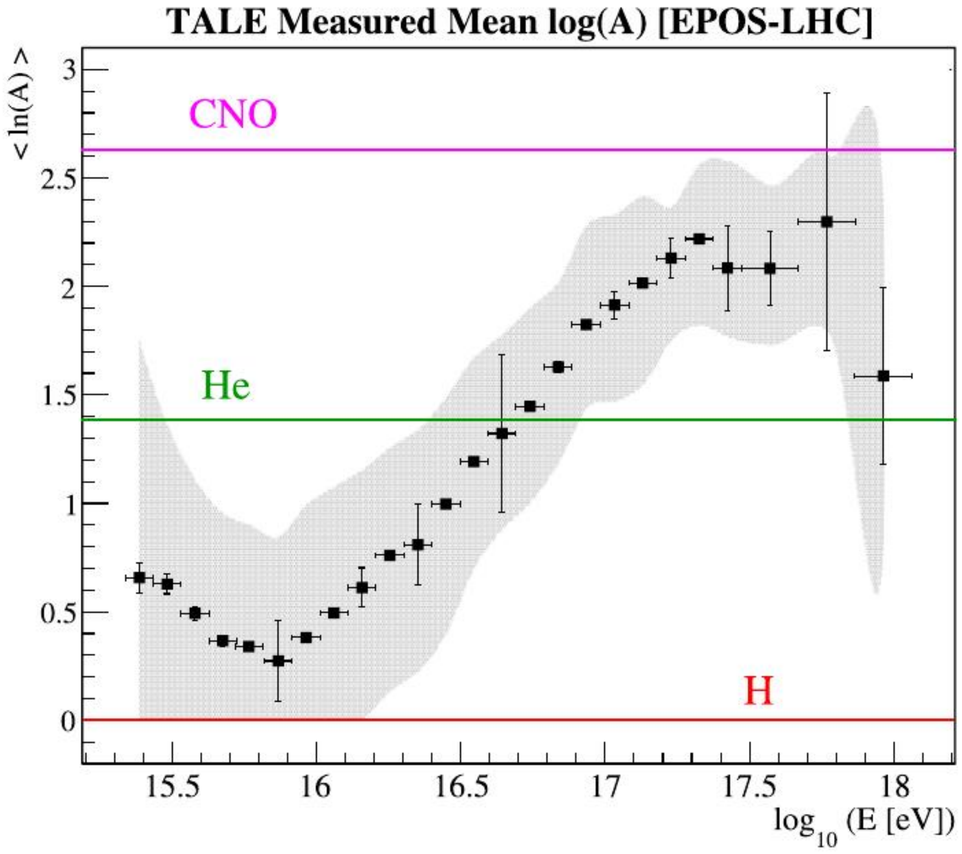
# The Telescope Array Observatory: TALE



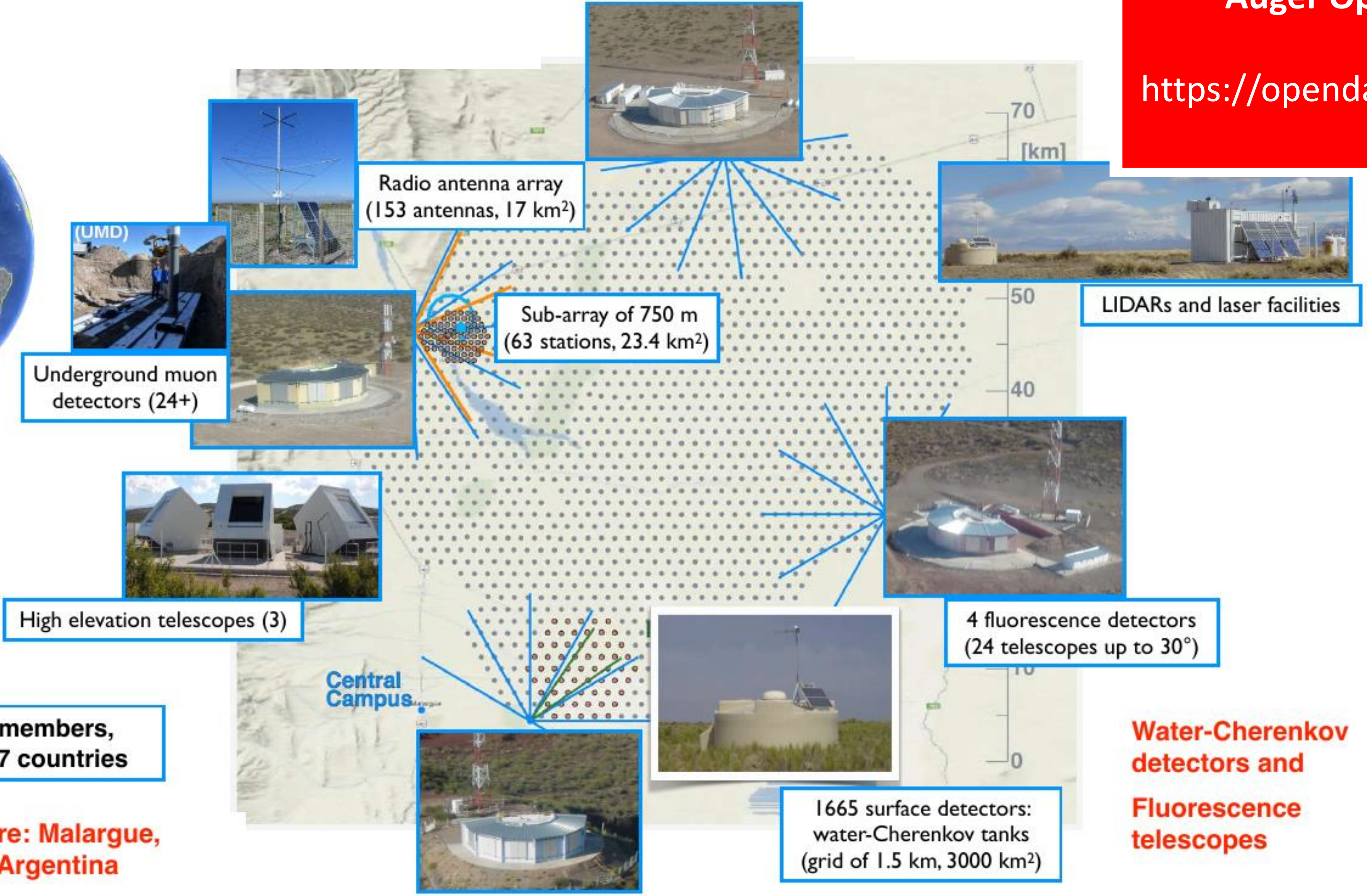




Astrophys. J. 909, no.2, 178 (2021)

# The Pierre Auger Observatory

**Auger Open Data**

https://opendata.auger.org/


**More than 400 members, 98 institutes, 17 countries**

**Southern hemisphere: Malargue, Province Mendoza, Argentina**

**Water-Cherenkov detectors and**

**Fluorescence telescopes**

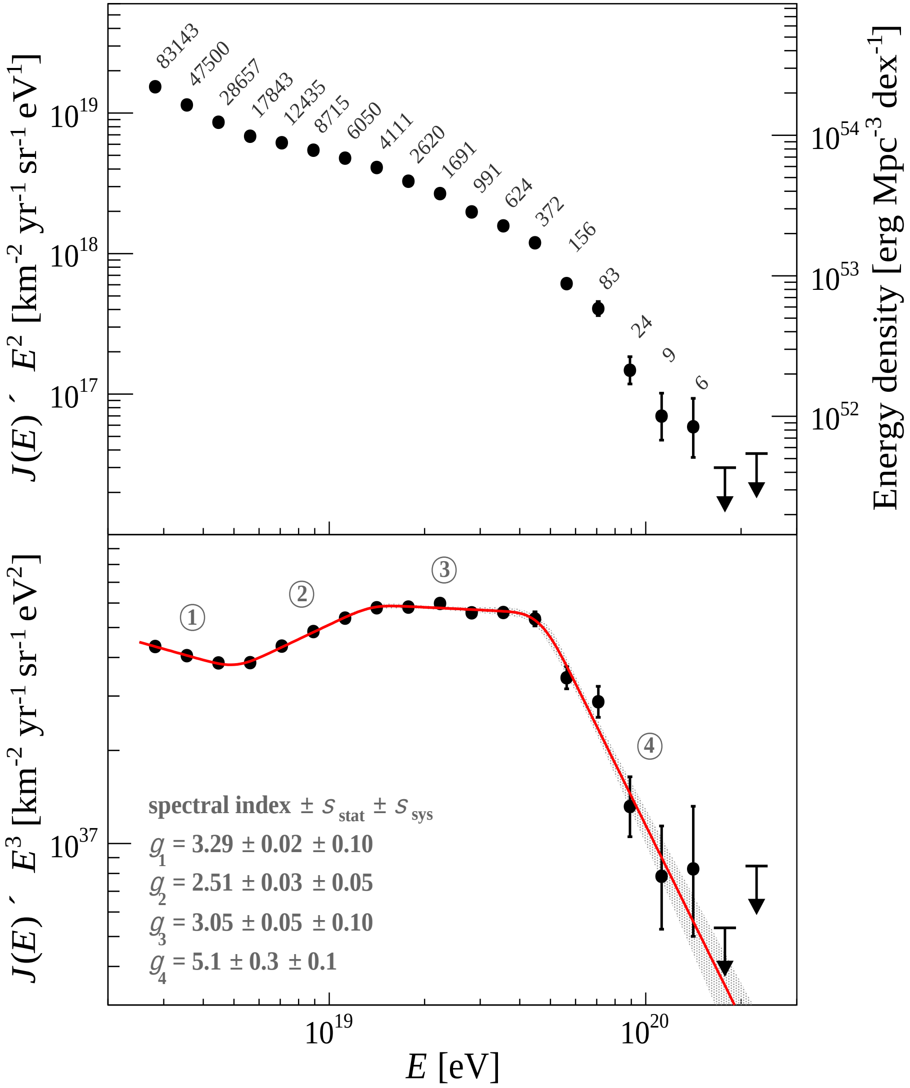
# The Pierre Auger Observatory: spectrum

**Main features:**

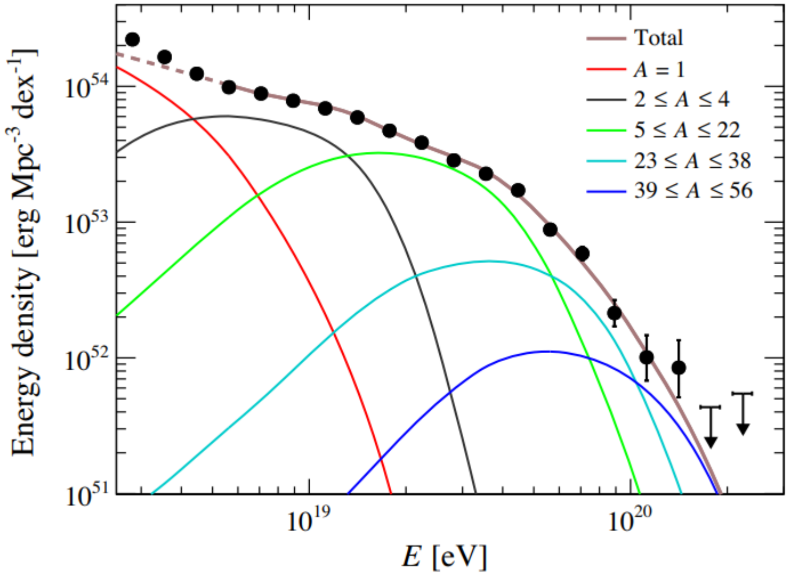
- A flattening of the spectrum near 5 $10^{18}$eV, the ''ankle''
- The steepening of the spectrum at around 5 $10^{19}$ eV
- ''instep'' in the region above the ankle the spectral index γ changes from 2.51 to 3.05

**The energy spectrum between the ankle and the cut off cannot be described by a simple power law**

Phys. Rev. D 102, 062005 (2020)



# The Pierre Auger Observatory: spectrum



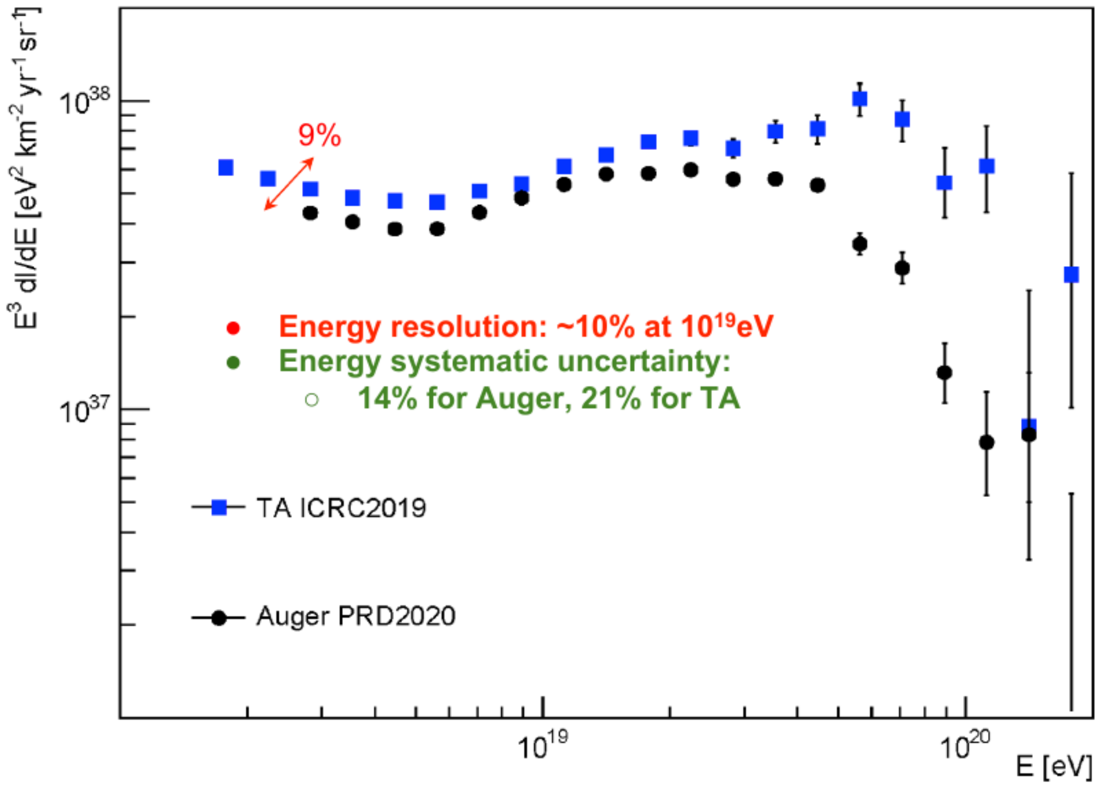

Phys. Rev. Lett. 125, 121106 (2020)

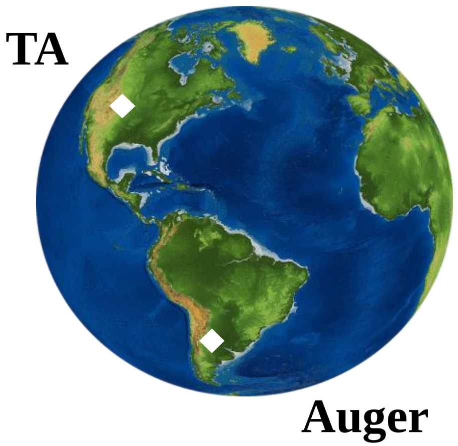
Astrophysical implications

- a pure proton composition expectation ( or only p-He) in the ankle region, (3-5) $10^{18}$ eV is excluded at the 6.4σ level
- the energy spectrum does not vary as a function of declination in the range accessible at the Auger Observatory

- The steepening at ≈$10^{19}$ eV arising from interaction between the flux contributions of the helium with carbon- nitrogen-oxygen components
- Results fit with a scenario in which several nuclear components contribute to the total intensity
- This scenario explains the tendency toward heavier masses with increasing energy
- Nuclei are accelerated in electromagnetic fields that permeate source environments to a maximum energy proportional to their charge Z.
- In this scenario, the steepening observed above ≈5 × $10^{19}$ eV results from the combination of the maximum energy of acceleration of the heaviest nuclei at the sources and the GZK effect.

# Auger & TA: spectrum



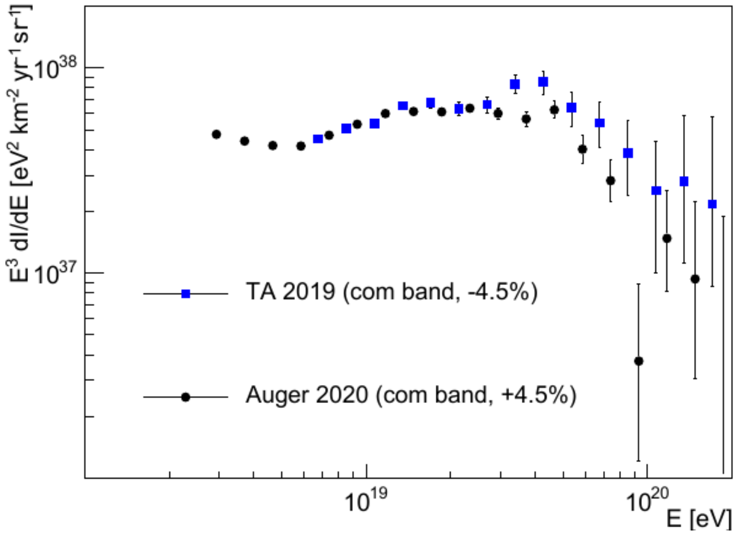




**Good agreement at energies below 2 × $10^{19}$ eV**

**Significative difference for $E_{1/2}$**
(the energy at which the integral flux drops to half of what would be expected with no cut-off )

**The cut-off at the end of the spectrum are evident in the Auger data as for TA.**

# Auger & TA: spectrum

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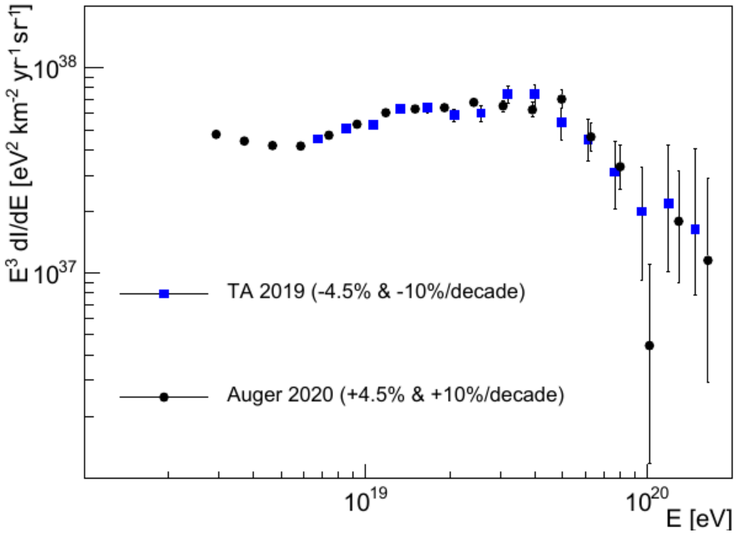
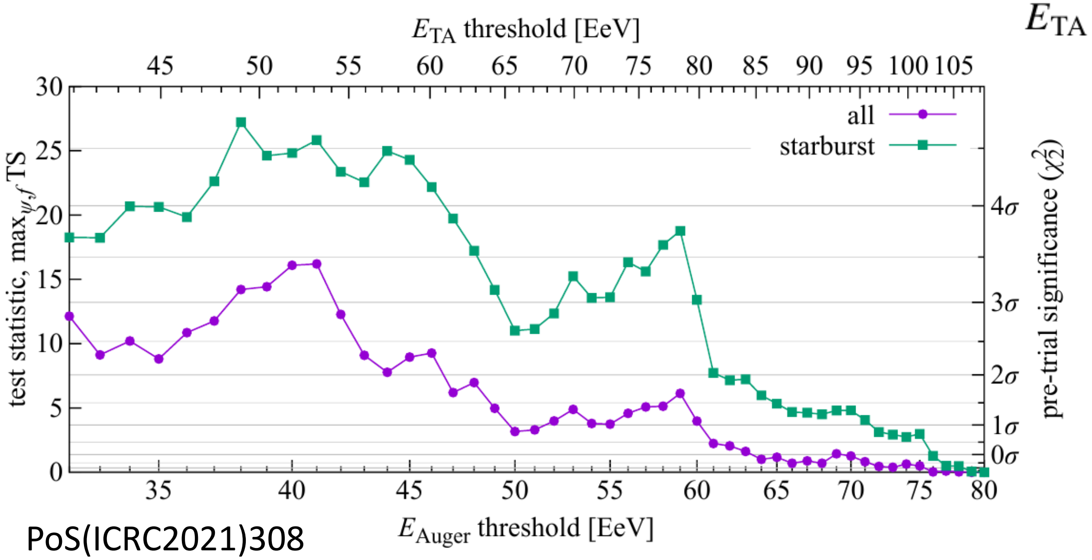



**- Differences due to Northern and Southern Hemispheres.**
**- Different energy calibration FD-SD**
**- influence of the fluorescence yield (TA -14%)**
**- Different efficiency**
**- correction factor for invisible energy (TA+ 7%)**

The spectral shape and the position of the steepening in the TA spectrum can be fit by a “GZK scenario” in which a pure-proton composition is assumed. On the other hand, the Auger spectrum and composition data are suggestive of cosmic rays getting heavier with energy. In this scenario, the steepening is caused by both the GZK effect and the maximal acceleration energy at the sources close to $10^{20}$ eV

# Auger & TA: anisotropy




PoS(ICRC2021)308

$$E_{TA} \mapsto E_{Auger} = 8.57\,(E_{TA}/10\text{ EeV})^{0.937}\text{ EeV}$$

angular scale of around 16°

Catalogs:

- 44 113 galaxies of all types at distances 1 Mpc ≤ D < 250 Mpc, based on the 2MASS catalog
- 44 starburst galaxies at distances 1 Mpc ≤ D < 130 Mpc from , J. Cosmol. Astropart. Phys. 10 (2019) 073

Starburst galaxy model: TS = 27.2 corresponds to a 4.2σ post-trial significance @ $E_{auger}$=38 EeV

All-galaxy model TS = 16.2 corresponds to a 2.9σ post-trial significance @ $E_{auger}$=42 EeV

Correlation between the arrival directions of 11.8% of cosmic rays detected with E ≥ 38 EeV by Auger or with E > 49 EeV by TA and the position of nearby starburst galaxies on a 15.5° angular scale, with a 4.2σ

# Future perspectives: AugerPrime

**The Auger Prime upgrade consist of:**

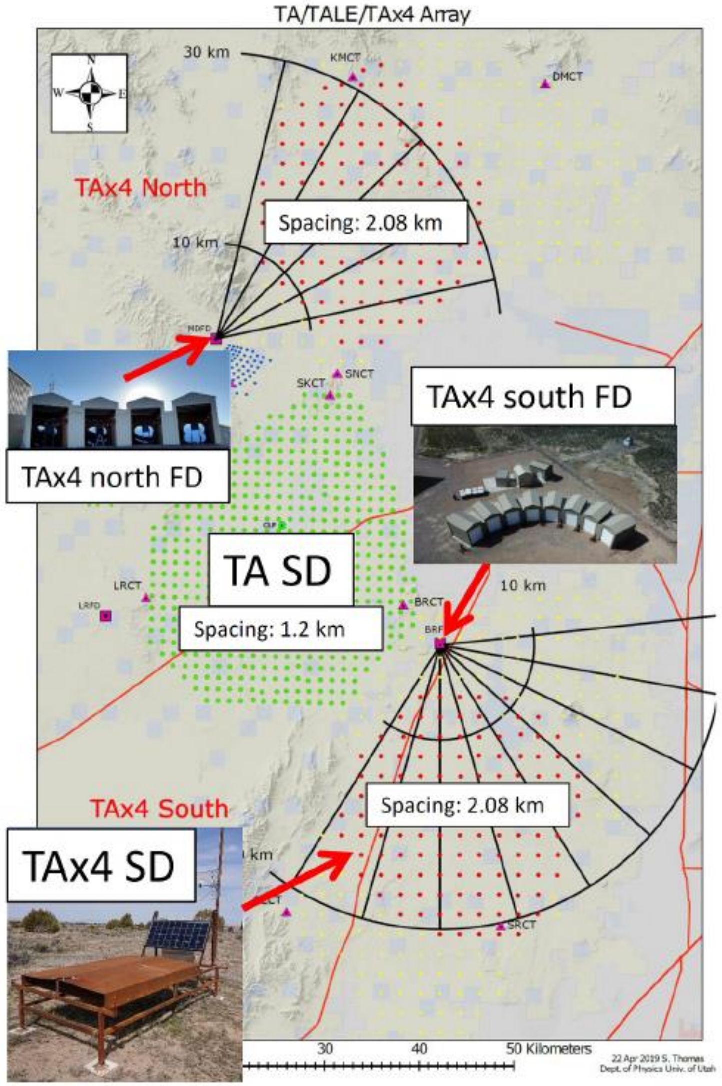
- a Surface Scintillator Detector (SSD) to measure the mass composition in combination with the (WCD).
- Addition a small PMT to increase dynamic range of the WCD.
- Upgrade the Surface Detector Electronics to improve the performance of WCD and acquire SSD and the small PMT.
- Underground Muon Detector to have a direct muon measurement
- Radio detector array for horizontal showers

# Future perspectives: TAx4

**TAx4 will quadruple the size of the surface array of scintillation detectors to almost 3000km²**
(comparable to the size of Auger)

500 new SDs with 2.08 km spacing and two new FD stations were designed for the TAx4 experiment.
More than half of the TAx4 SDs (257 SDs) were deployed in 2019.

The post-trial significance of the hotspot analysis is expected to be approximately 6σ in 2025



# Future perspectives

- Increase in quality results from higher experimental precision and studies of systematic uncertainties
- Theoretical models used for the interpretation of the measurements get  tested by cosmic-ray measurements
- Most of the upgrades and new experiments combining two or even more detection techniques
- Several efforts to increase the accuracy for the measurement of the energy and mass composition
- Higher statistics alone may be insufficient for further progress