The Pierre Auger Observatory

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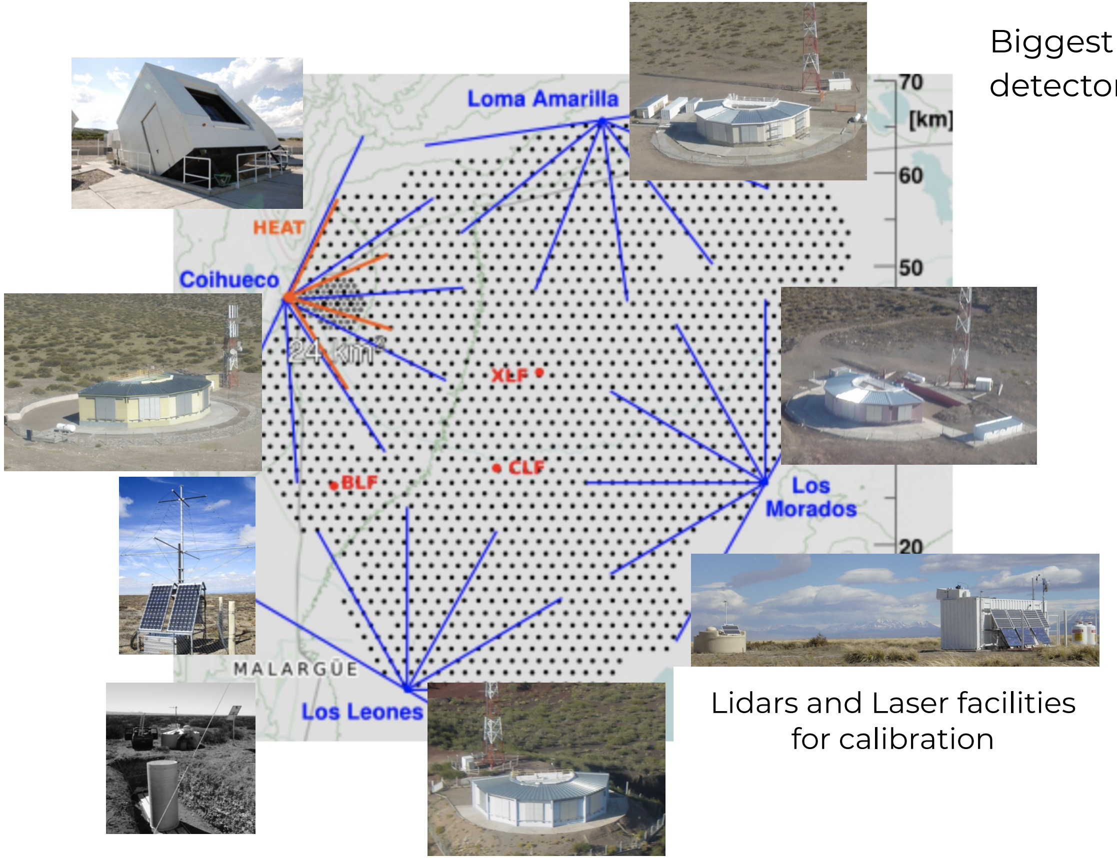
Kick-off Meeting COST Action CA18108 QG-MM
2-4 October 2019

The Pierre Auger Observatory



Lidars and Laser facilities for calibration

Biggest Ultra High Energy Cosmic Ray (UHECR) detector located in Argentina, Malargüe

Surface detector (SD)

- 1660 Water Cherenkov detectors in 1.5 km grid, 3000 km^2 E > $10^{18.5}$ eV
- 61 stations in 0.75 km grid, 23.5 km^2,E > $10^{17.5}$ eV
- 100% duty cycle

Fluorescence detector (FD)

- 24 tel.in 4 sites, FoV: 0-30°, E>10^{18} eV
- HEAT (3 tel.), FoV: 30 - 60°, E>10^{17} eV
- 15% duty cycle

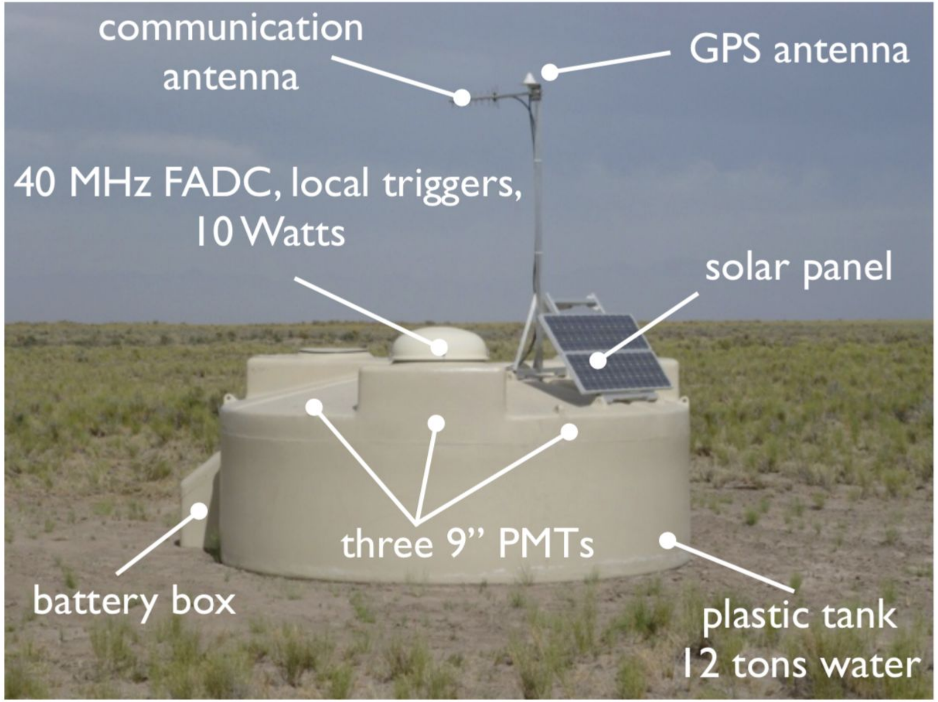
Auger Engineering Radio Array (AERA)

- 153 antennas in 17 km^2 array

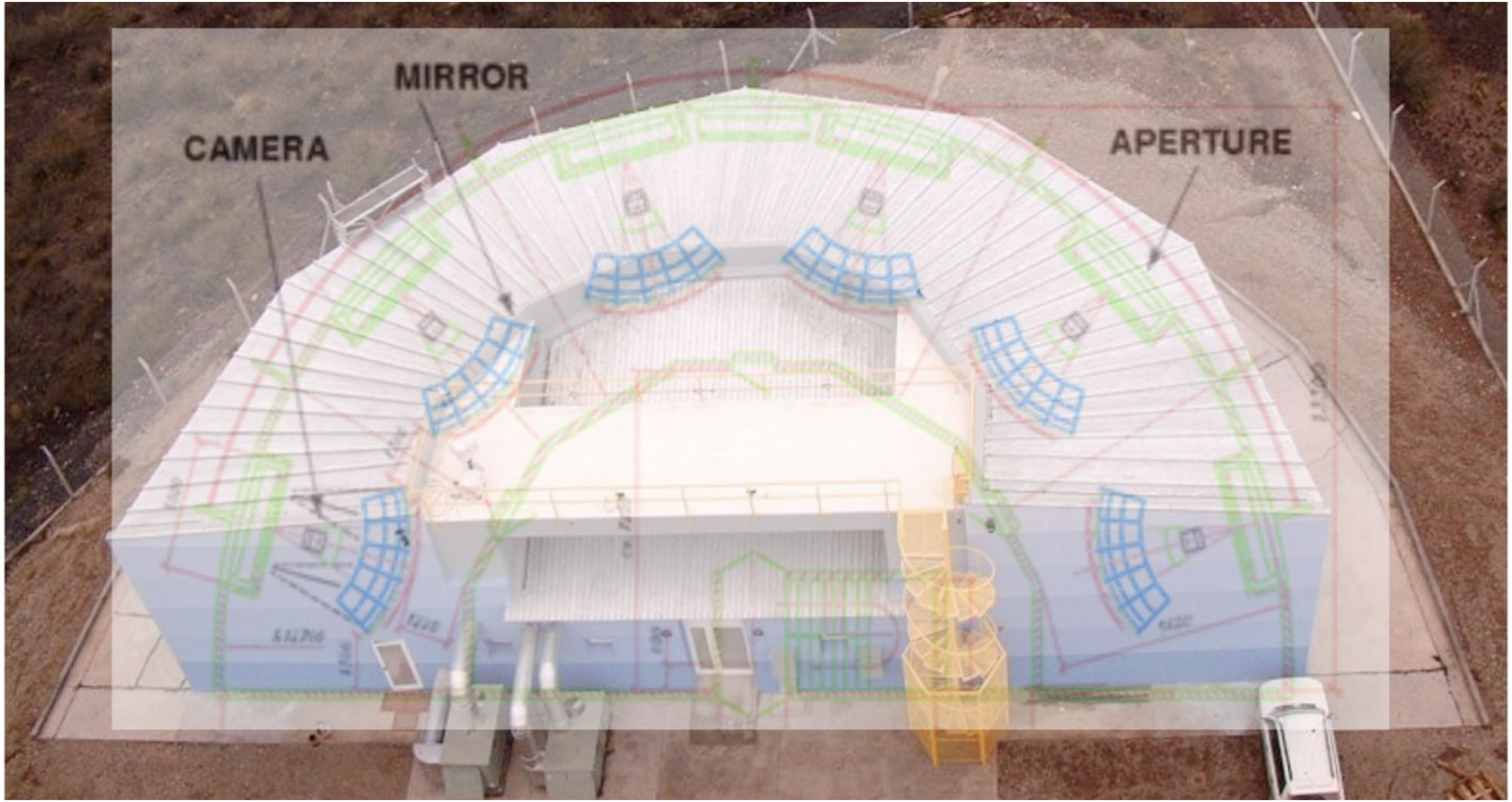
Underground muon detector(AMIGA)

- 17 buried scintillators

The Surface Detector (SD) + AERA + AMIGA



The Fluorescence Detector (FD)



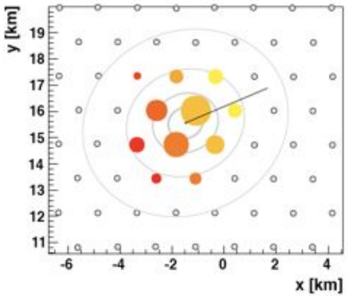
The Auger bestiary

SD 1500 m

$\theta < 60°$

$E > 10^{18.4}$ eV

100% duty cycle

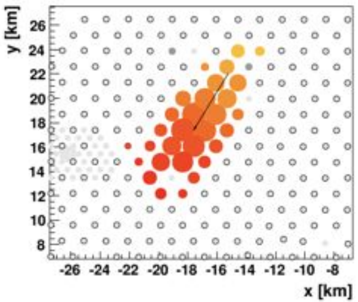


SD 1500 m

$60° < \theta < 80°$

$E > 10^{18.6}$ eV

100% duty cycle

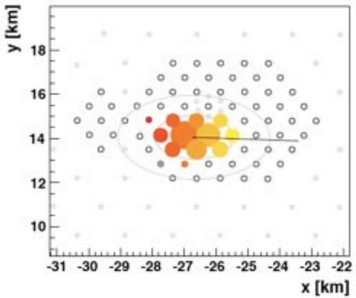


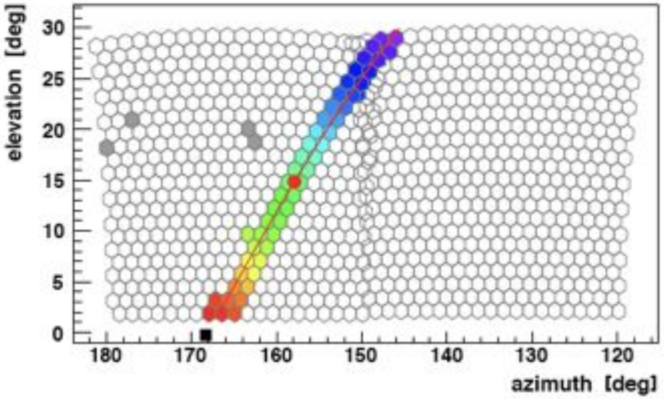
SD 750 m

$\theta < 40°$

$E > 10^{17}$ eV

100% duty cycle





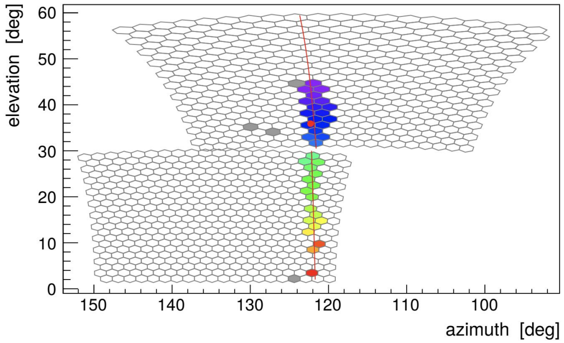
FD Hybrid

FD + 1 SD

$\theta < 60°$

$E > 10^{18}$ eV

15% duty cycle



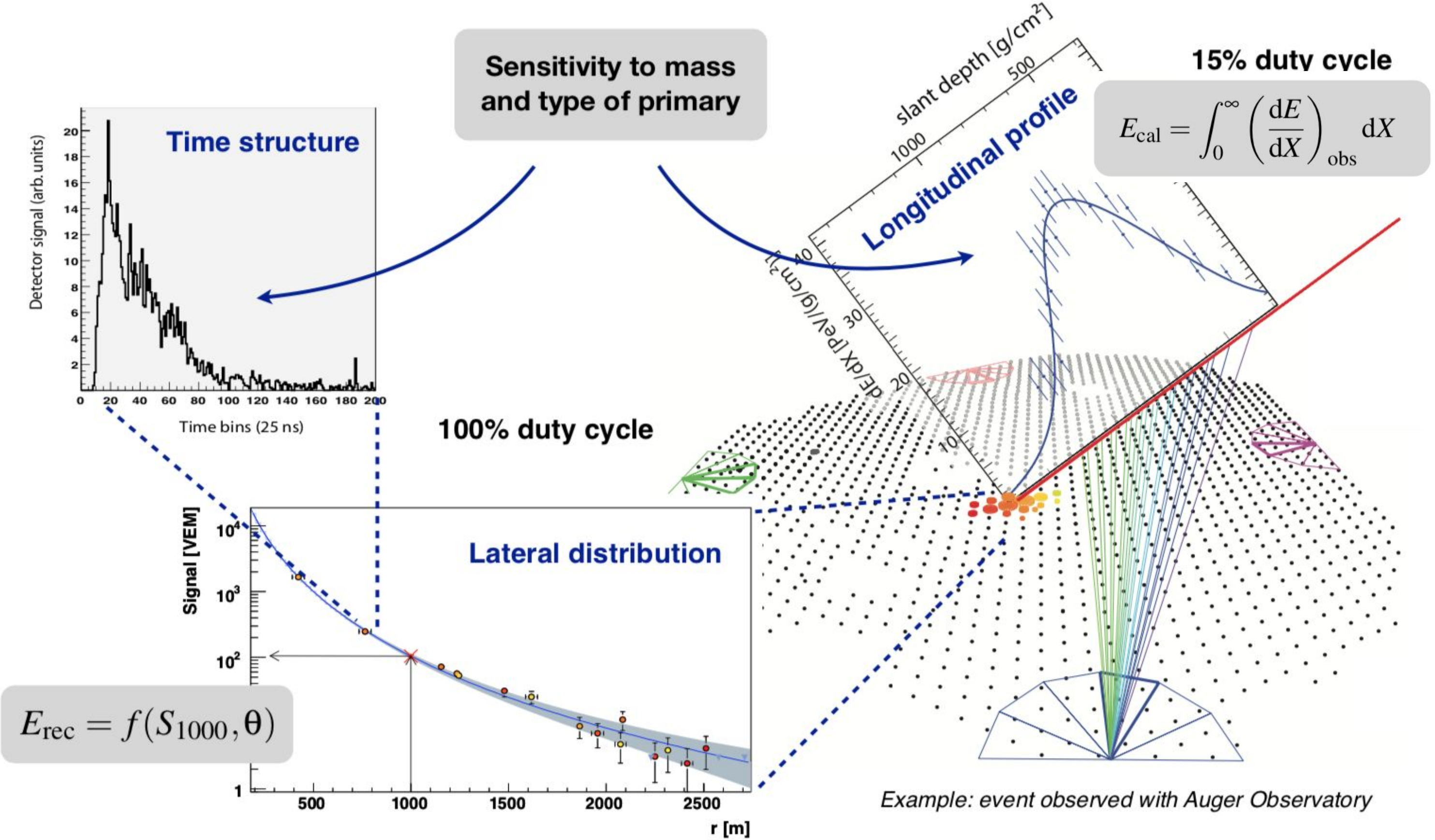
FD-HEAT Cherenkov

$10^{15} < E < 10^{18}$ eV

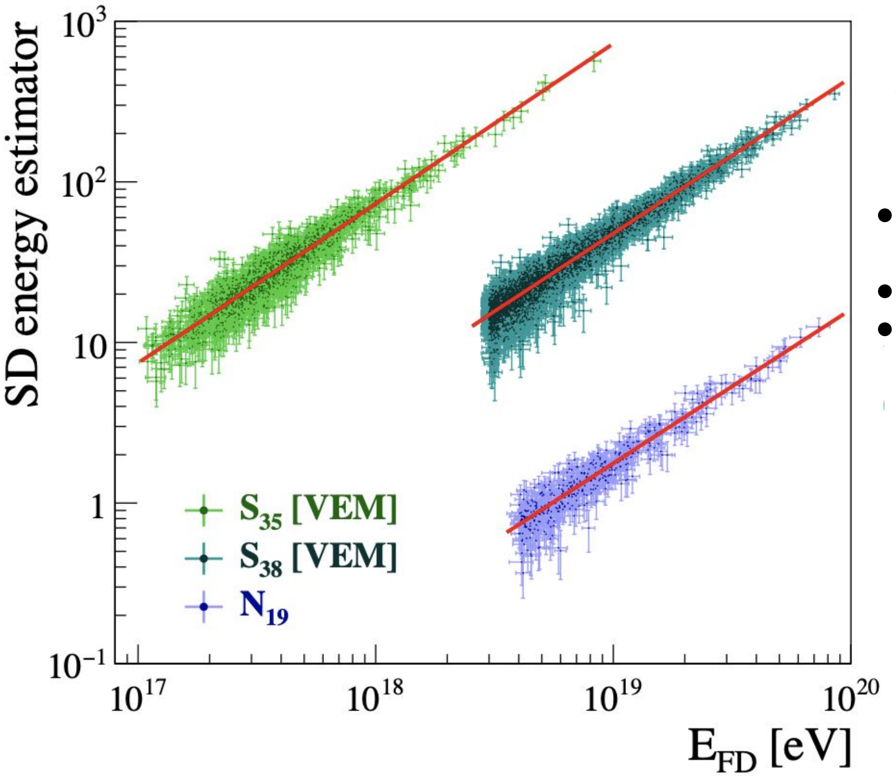
15% duty cycle

Energy spectrum over 4 decades in energy

Event reconstruction - Hybrid



Energy Scale



FD: calorimetric energy measurement

Hybrid events: absolute calibration of the full SD sample

$\sigma(E_{FD})/E_{FD} \sim 8\%$

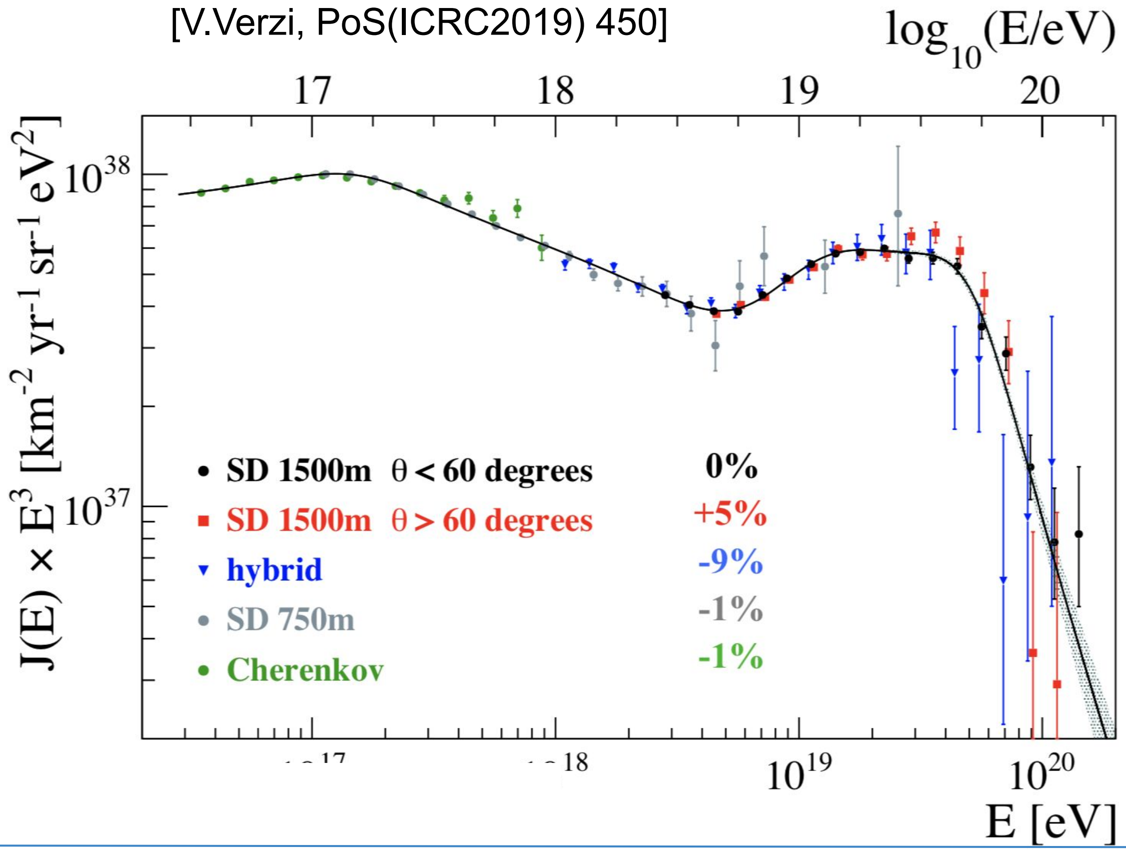
- high-quality events independently triggered/reconstructed by SD and FD
- correlation well described by a power-law relationship
- maximum-likelihood fit using a "bootstrap" estimate of the p.d.f. and event-by-event uncertainties

ICRC 2013

Systematic uncertainty in the energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Stability of energy scale	5%
TOTAL	14%

The Auger energy spectrum

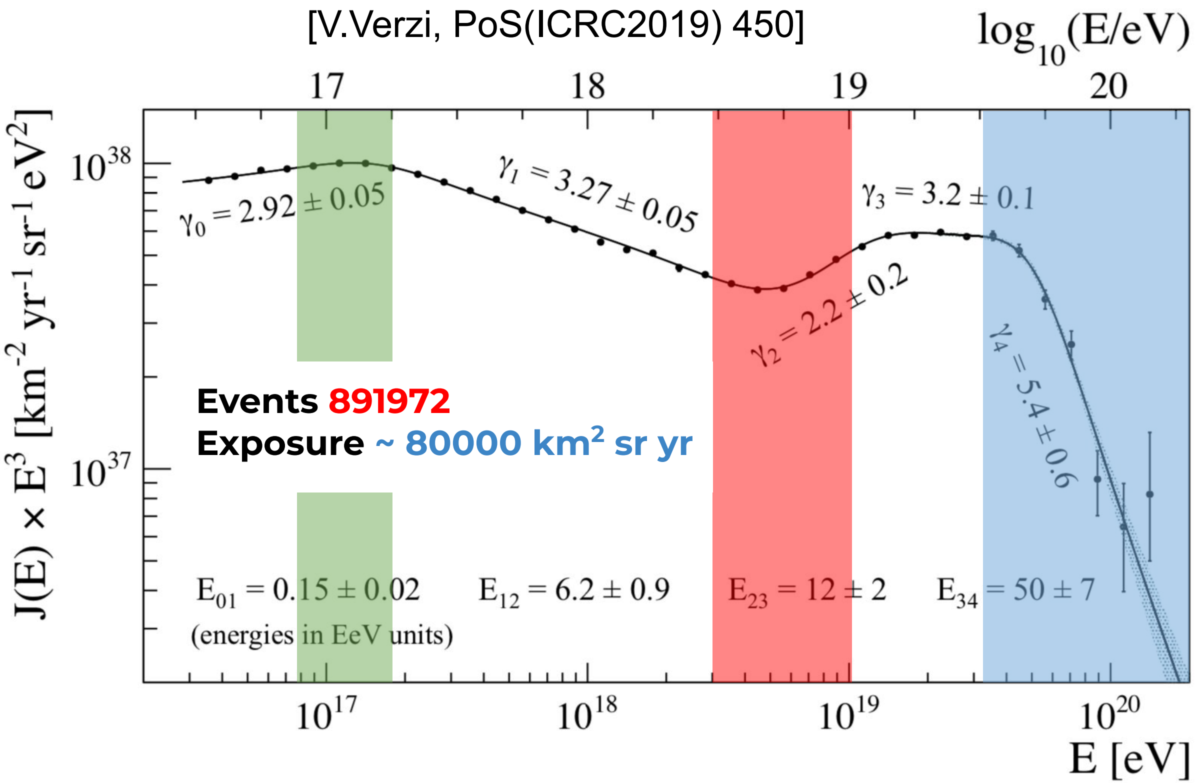
[V.Verzi, PoS(ICRC2019) 450]



AUGER COMBINED SPECTRUM

All the different fluxes are in good agreement among them once rescaled by normalization factors that are consistent with the systematic uncertainties

The Auger energy spectrum



2nd knee

- different models: more than one Galactic component? (H4a, GST)
- is the 2nd knee the iron one? (rigidity dependent cut-off)

ankle region

- dip model
- mixed models: superposition of heavier nuclei

suppression region

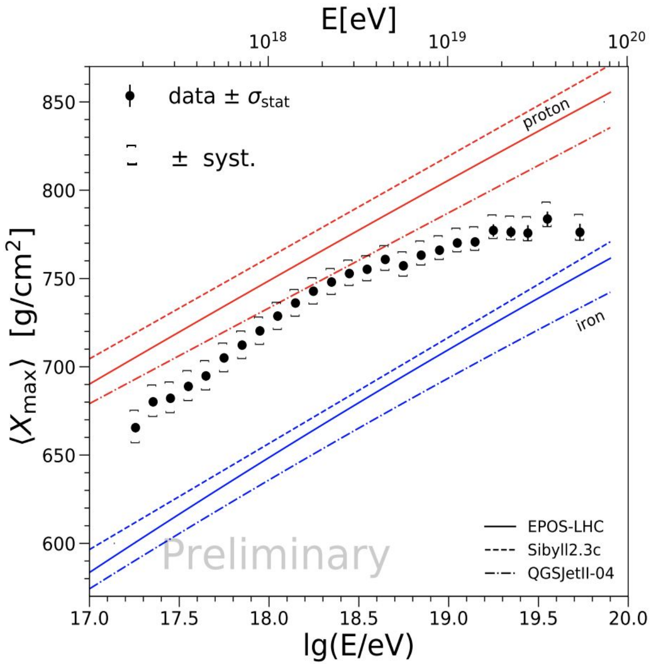
light composition (p + <10% heavier)

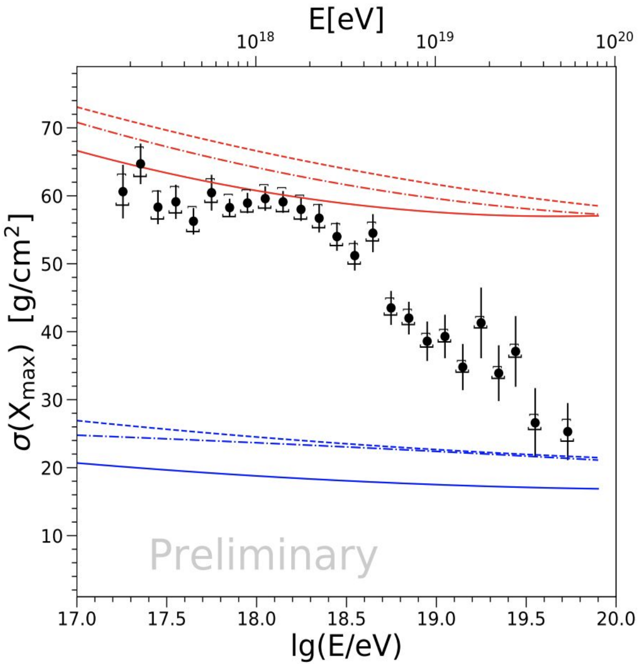
- soft injection spectrum (slope ~ 2)
- production of cosmogenic ν

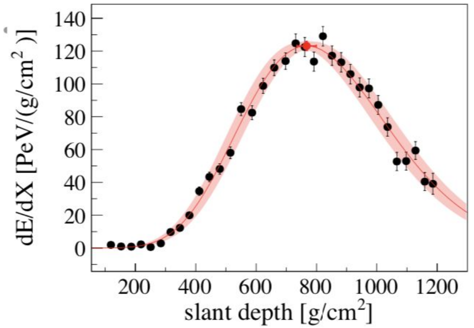
mixed composition

- hard injection spectrum (slope ~ 1)
- cosmogenic ν and γ suppressed

Mass composition(X_{max} moments)





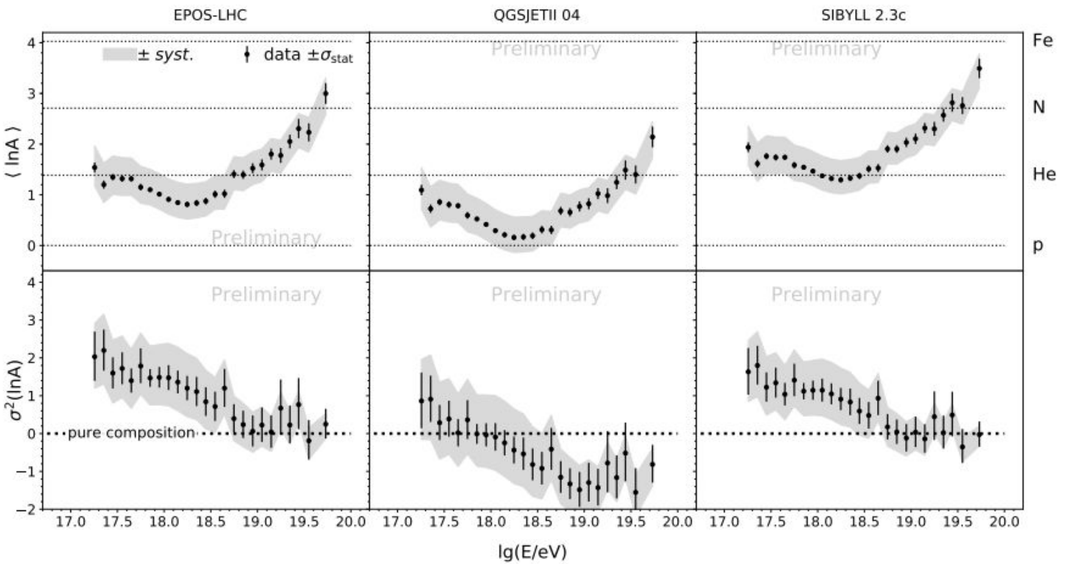


systematics < 10 g cm^{-2}
resolution:
40 g cm^{-2} at $10^{17.2}$ eV
25 g cm^{-2} at $10^{17.8}$ eV
15 g cm^{-2} for E > $10^{19.0}$ eV

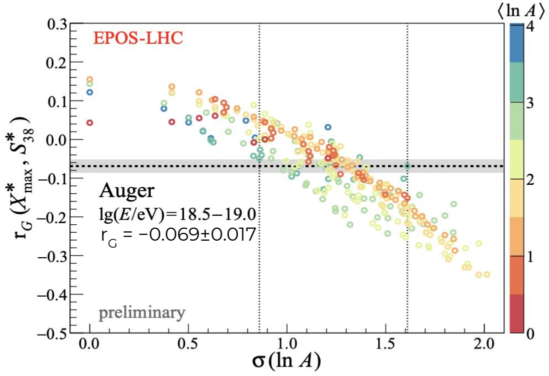
- From X_{max} and $\sigma(X_{max})$ lighter composition up to ~2 EeV, heavier above this energy
- Above $E_0 \approx$ 2 EeV both Xmax moments are becoming compatible to MC predictions for heavier nuclei

⟨ln A⟩ and σ^2(ln A) and $r_G(X_{max}, S_{38})$

$$\langle X_{max}\rangle = \langle X_{max}\rangle_p + f_E\langle lnA\rangle \qquad \sigma^2(X_{max}) = \langle \sigma^2_{sh}\rangle + f_E\sigma^2(lnA)$$



- Smaller X_{max} and larger muon content expected in showers by heavier nuclei.
- For pure compositions non-negative correlations are found in simulations
- Anticorrelation between Xmax and Nμ is expected for mixed compositions



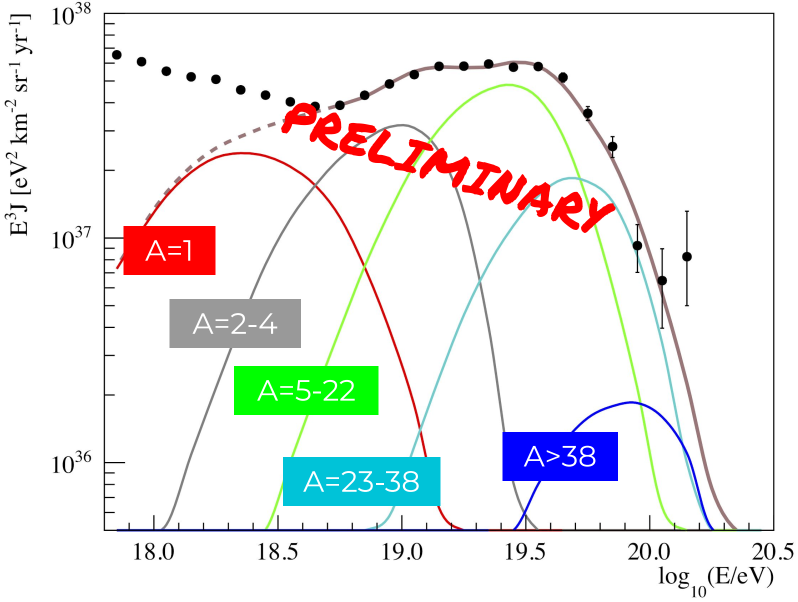
- below the ankle the correlation in data is significantly, at 6.4σ from zero, negative
- pure compositions and proton-helium mixes (all having $r_G > 0$) are excluded
- data are compatible to mixed compositions with σ(ln A) = 0.85 − 1.60
- above the ankle there are indications on decrease of σ(ln A) (more statistics is needed)
- the uncertainties in the models are currently the main source of systematics

Astrophysical interpretation

Combined fit of energy spectrum and X_{max} distribution:

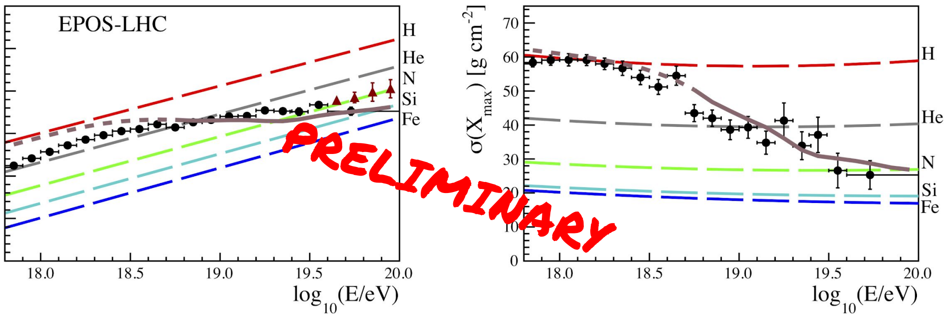
- sources uniformly distributed in a comoving volume
- nuclei are accelerated through a rigidity-dependent mechanism

- UHECR spectrum at Earth
- Composition at Earth
- Neutrino fluxes



AUGER @ ICRC 2019

- Suppression of flux dominated by maximum injection energy
- Very hard index of power law at injection



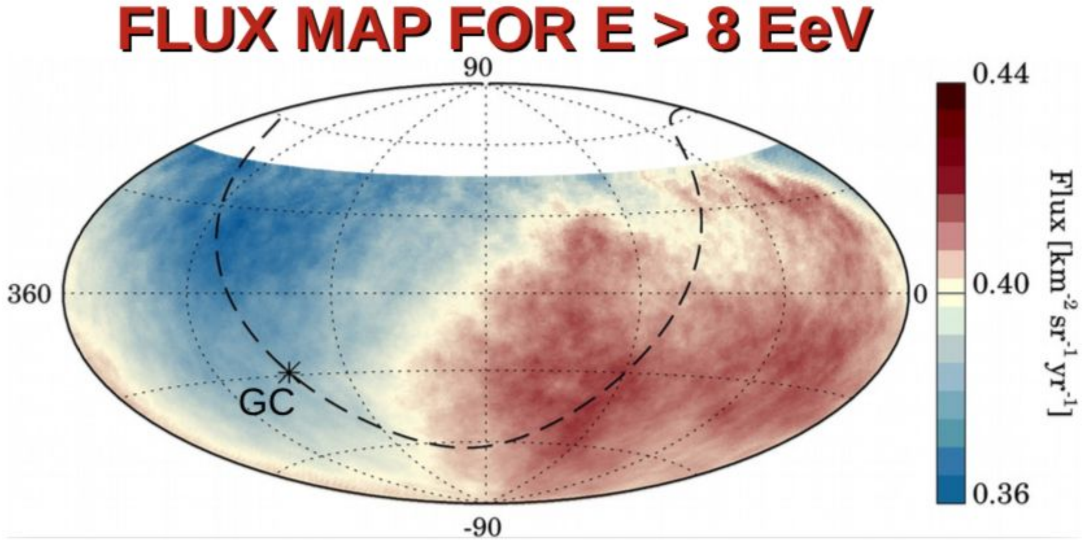
Suitable method to try constrain LIV

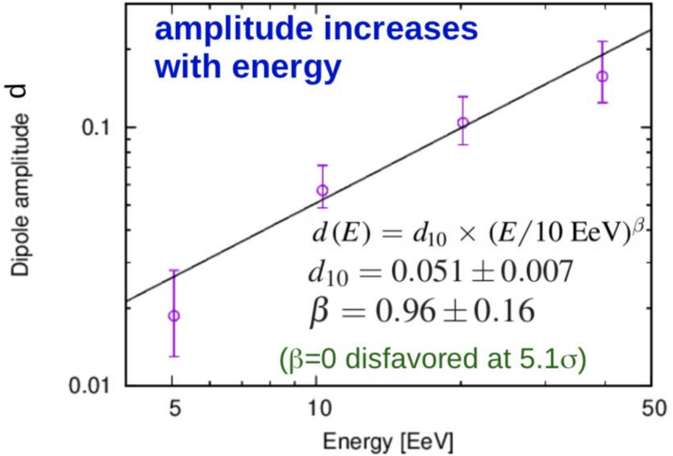
Large scale anisotropy

Weighted Fourier Analysis to obtain modulation in right ascension and azimuth

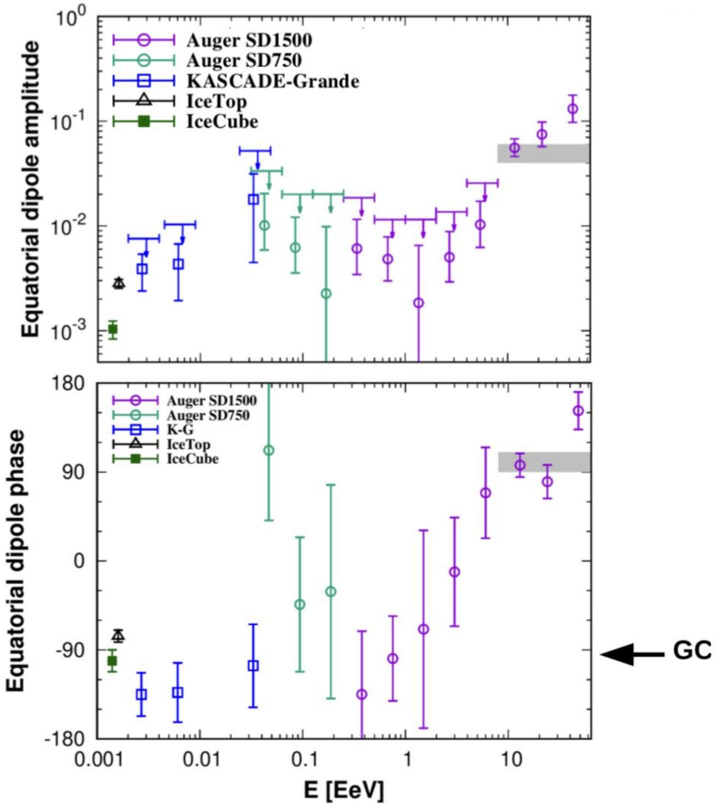
Auger data: Exposure >92000 km^2 sr yr

OBSERVATION (>5σ): 3D dipole above 8 EeV at (α,δ)=(98^0,-25^0): $(6.6^{+1.2}_{-0.8})$ %, 125^0 away from GC indicative of an extragalactic origin





Large scale anisotropy



Below full trigger efficiency the modulation in right ascension can still be obtained

- Use of Fourier analysis in RA for E > 2 EeV
- Use of East-West method below 2 EeV

RESULTS

- amplitudes grow, from below 1% to above 10%
- below 8 EeV the amplitudes not significant 99% CL upper bounds at the level of 1 to 3%
- phases shift, from ~GC to ~ opposite direction
- Suggests transition from anisotropies of Galactic origin below ~1 EeV to extragalactic origin above few EeV

Small scale anisotropy

Blind search - whole sky 1°x 1°grid

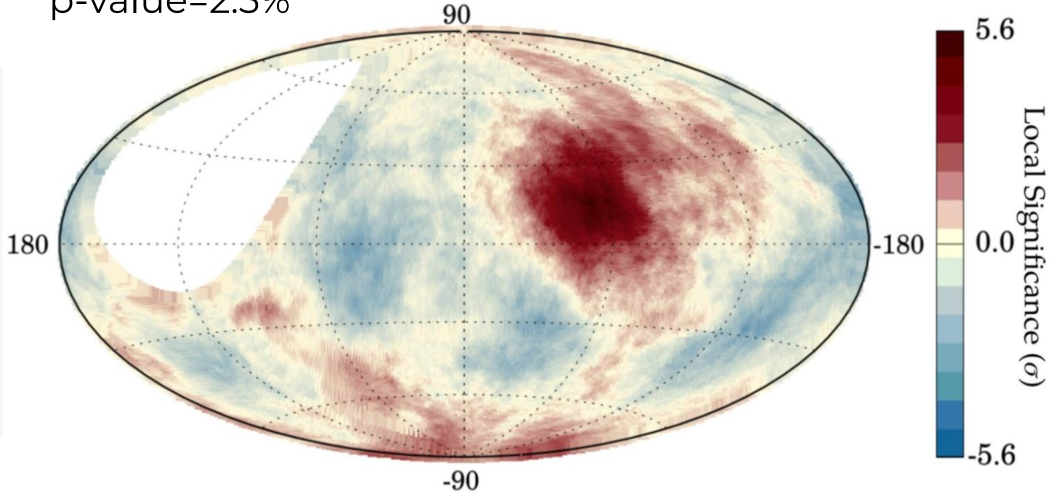
Scan:

$1° \leq \psi \leq 30°$ and $32 EeV \leq E_{th} \leq 80 EeV$

Most significant excess:

R.A.=202. Dec=-45. E_{th} = 38 EeV ψ=27°

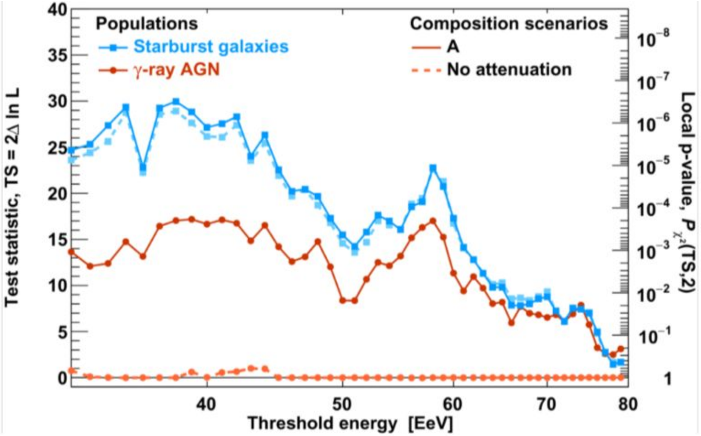
local Li-Ma significance=5.6**σ** post-trial p-value=2.5%



Likelihood test for anisotropy with astrophysical catalogs:

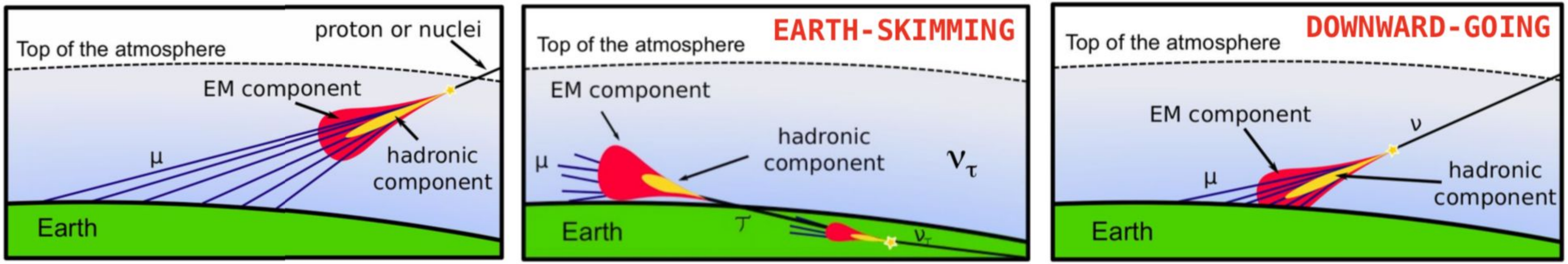
γ-emitting AGNs, Starburst Galaxies, Swift-BAT, 2MRS

Highest TS = 29.5 found for starburst galaxies with Eth=38 EeV



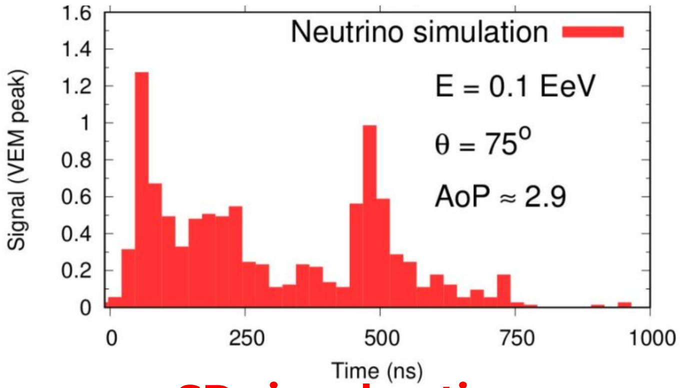
Neutrinos searches

Neutrino identification in inclined showers detected by Auger



Protons/nuclei initiate inclined showers high in the atmosphere. Shower front at ground: mainly muons (small electromagnetic component).

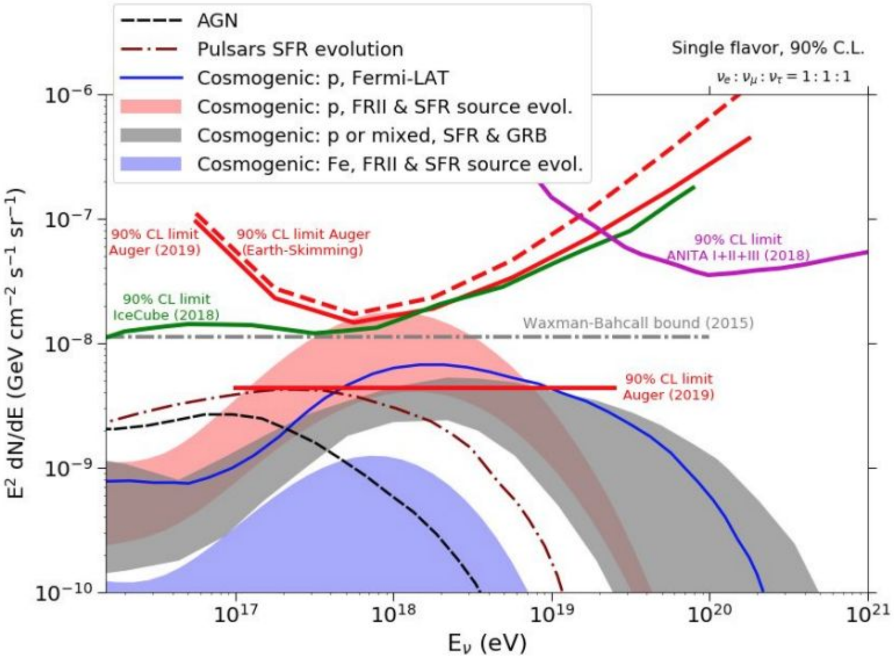
Neutrinos can initiate "deep" showers close to ground.
Shower front at ground: electromagnetic + muonic components



SD signal vs time

Neutrinos searches

Expected events:
Red band: 1.4 - 5.9
Gray band: 0.8 - 2.0
Blue band (top): 0.4



Maximum sensitivity around EeV k(90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

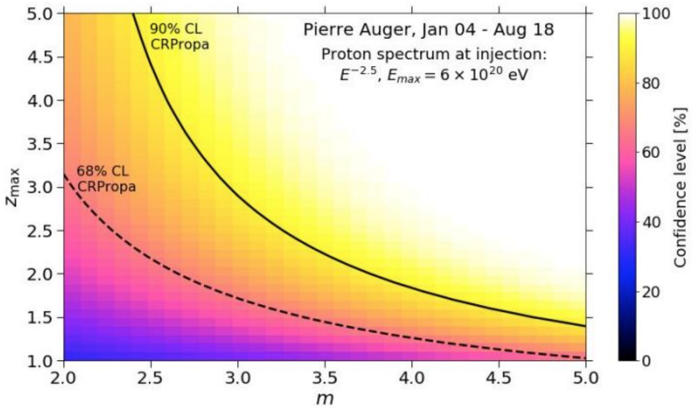
CONSTRAIN ON PROTON MODELS

UHECR source evolution models parameterized as :

$$\Psi(z) \propto (1+z)^m$$

m: source evolution parameter
z_{max}: the maximal redshift at which UHECR are accelerated

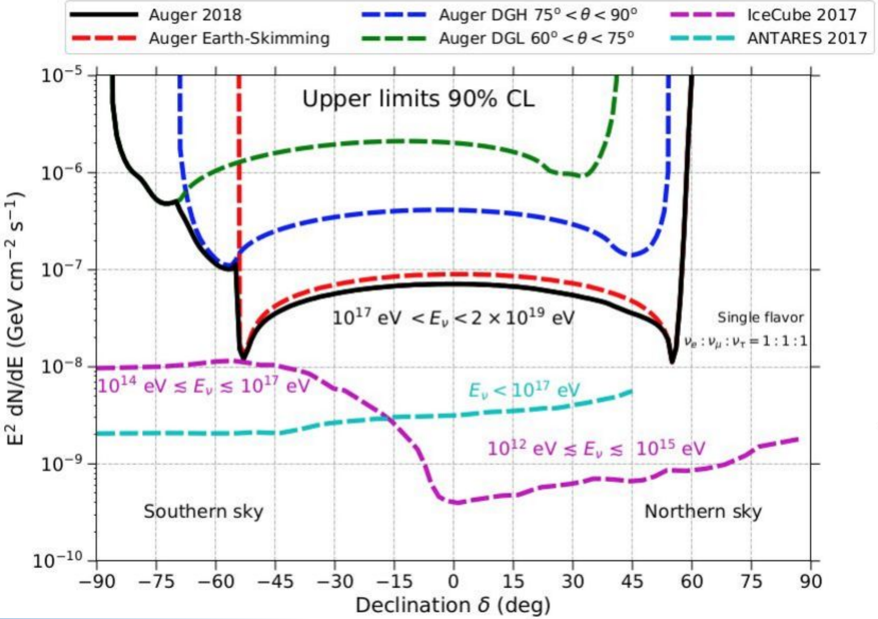
Exclusion of a significant region of parameter space (z_{max}, m) from non observation of ν



UHE neutrinos: point like sources

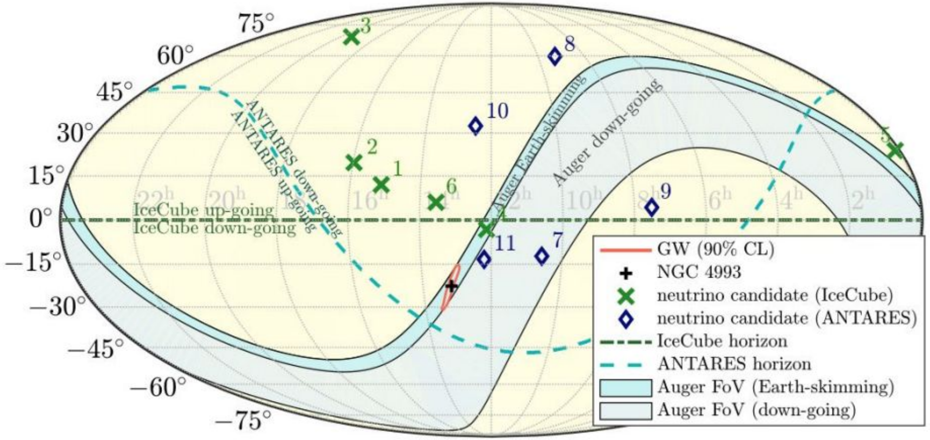
Steady sources

- Good sensitivity at EeV energies in a broad range in declination
- Energy range complementary to IceCube and Antares



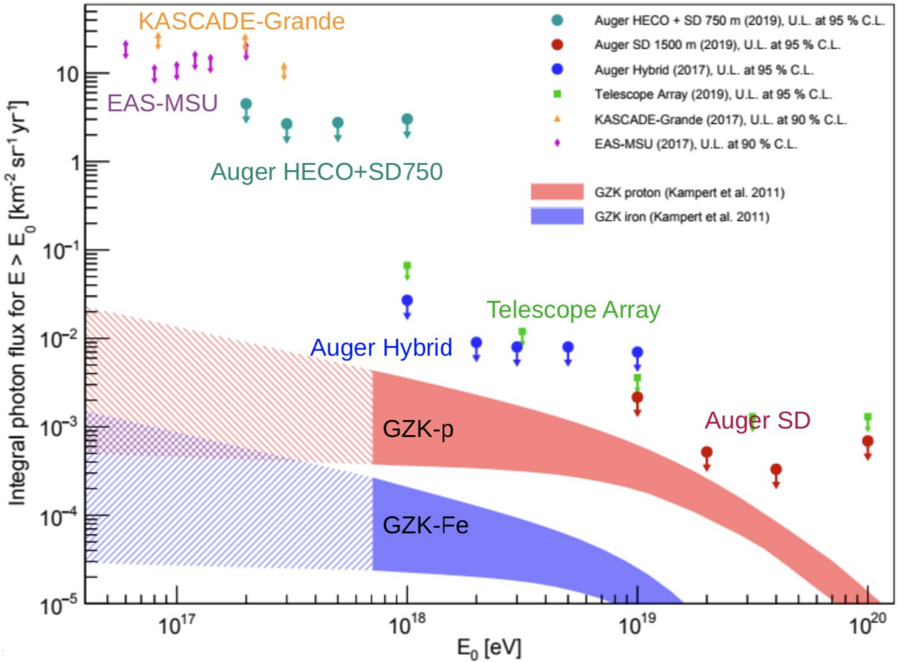
Transient sources (e.g GW)

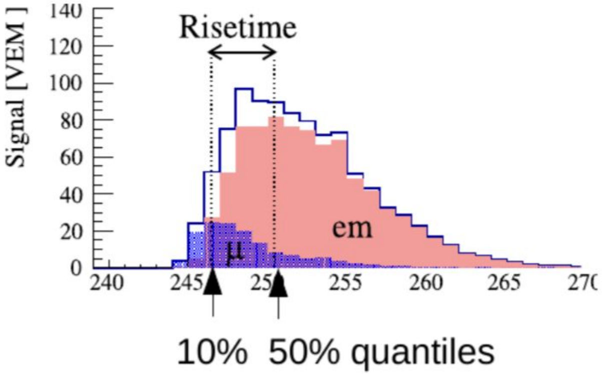
- ANTARES, Icecube & Auger searched for in coincidence with GW170817 from TeV to EeV
- Very good Auger sensitivity because source was in the FoV of Earth Skimming at the moment of merger



Photon searches

Production of photons in interaction with CMB
EM-shower penetrate deeper into atmosphere (narrower lateral spread)
EM-component arrives later w.r.t muonic (large “risetime”)
FD: X_{max} **SD**: lateral distribution function (LDF)

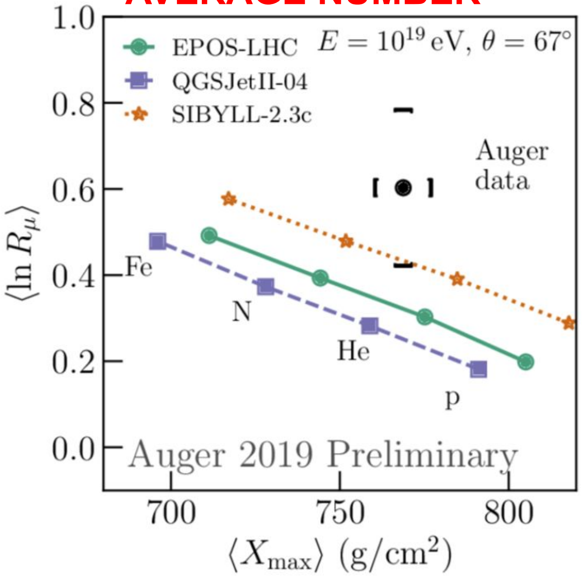




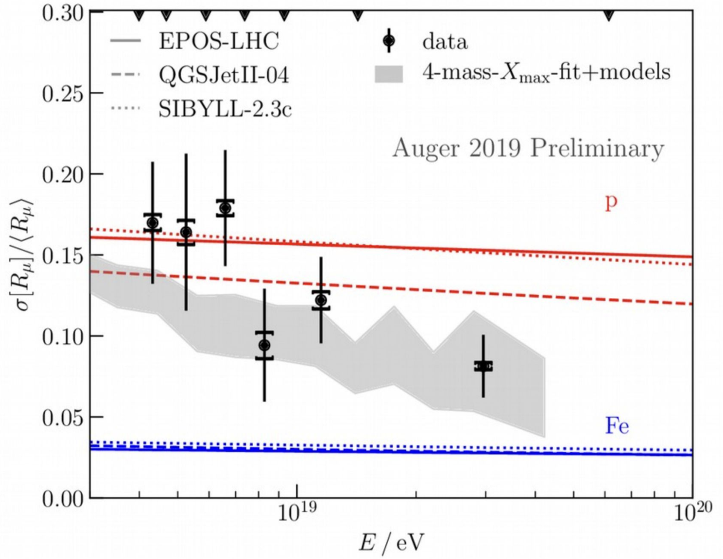
Most sensitive EAS detector for Eγ>0.8 EeV
Most top-down models excluded by experimental result
Most optimistic models with proton primaries already excluded

Muons measurements

AVERAGE NUMBER



FLUCTUATIONS



Using inclined showers Auger can measure:

- average number of muons - sensitive to shower development
- fluctuations in number of muons - sensitive to first interaction Phys. Lett. B 784 (2018) 68–76

EXPERIMENTAL FACTS:

- fluctuations compatible with model predictions and composition measurement
- Muon excess in average number
- not an effect of first interaction!
- small mismatch accumulating over shower development

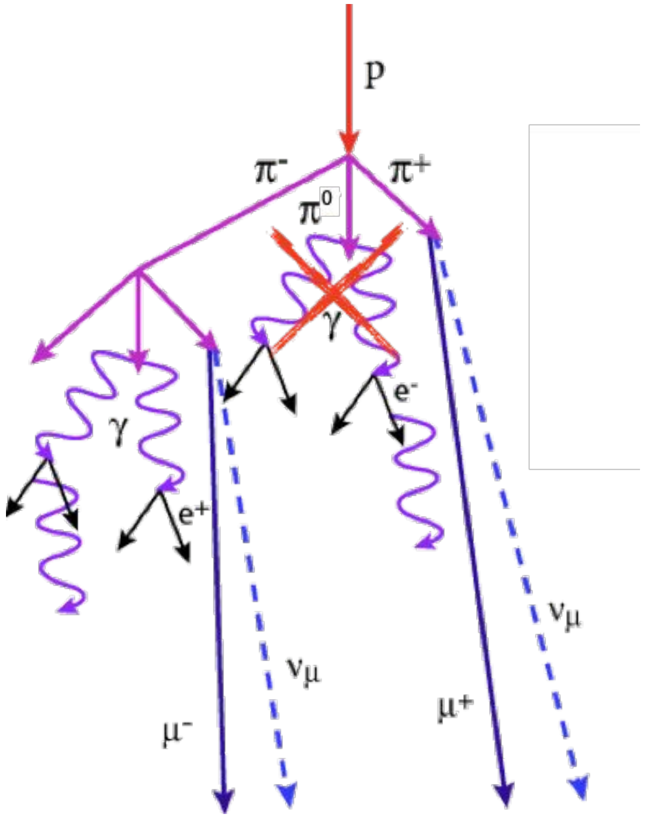
LIV studies: effects on shower development

$$E_i^2 - p_i^2 = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

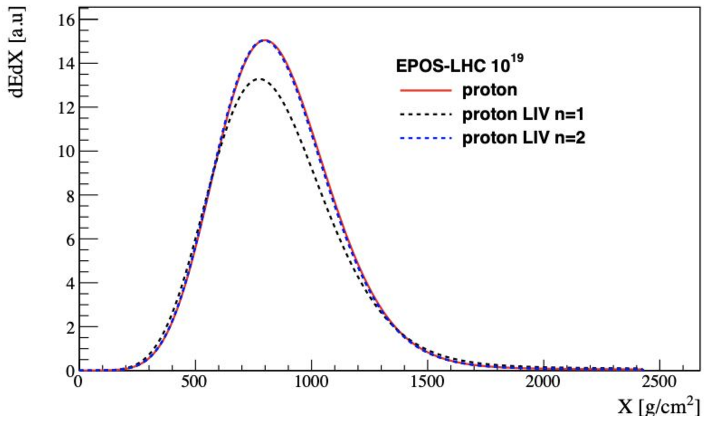
Consider as and example the neutral pion decay in two photons
In presence of LIV the decay can be forbidden if:

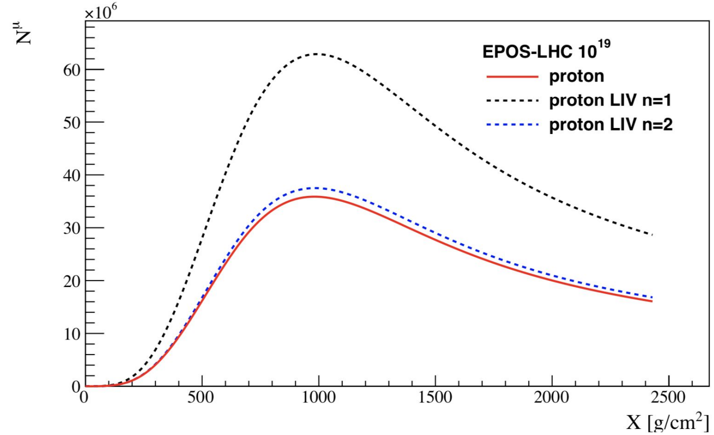
$$m_\pi^2 + \eta_\pi^{(n)} \frac{E^{n+2}}{M_{Pl}^n} < 0$$

This define a threshold in energy. Putting the effect into MC shower simulators we can forecast the effect on UHECR observables (e.g X_{max}, N_μ)

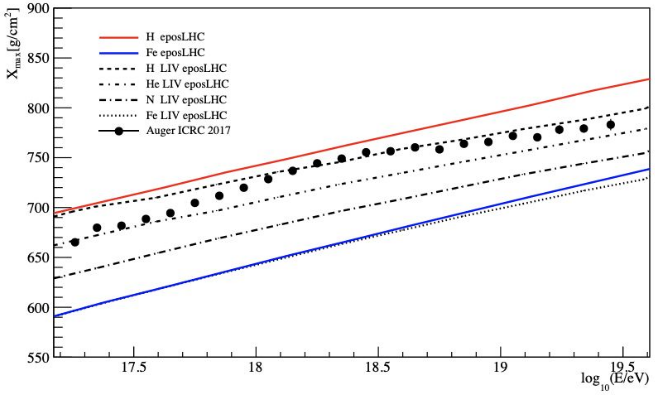


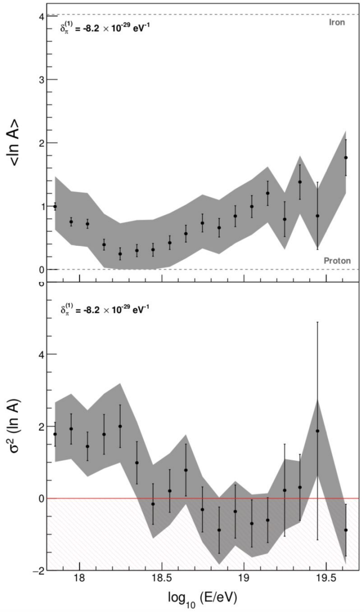
LIV studies: effects on shower development





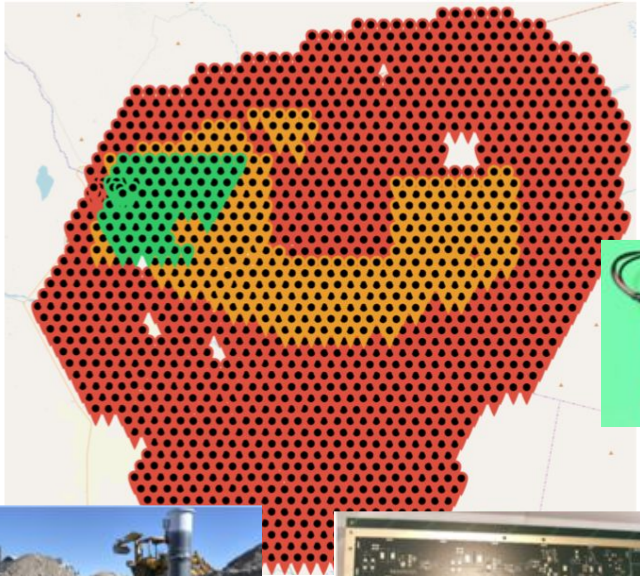
- Xmax moves (LIV proton mimic higher masses)
- Energy decreases (pions does not decay and produce more muons and neutrinos)
- Number of muons increases (can constrain LIV?)





Auger Prime

Aim: a large exposure detector with composition sensitivity above ~4 x 10^{19} eV



- 12 upgraded stations (Engineering Array) since 2016 with new electronics, higher sampling(120 MHz), large dynamic range (10 FADC ch)
- the SSD pre-production array: 80 stations (since March 2019)
- 356 SSD stations already deployed
- Underground Muon detector
- the world-largest radio detector (3000 km^2)

Conclusions

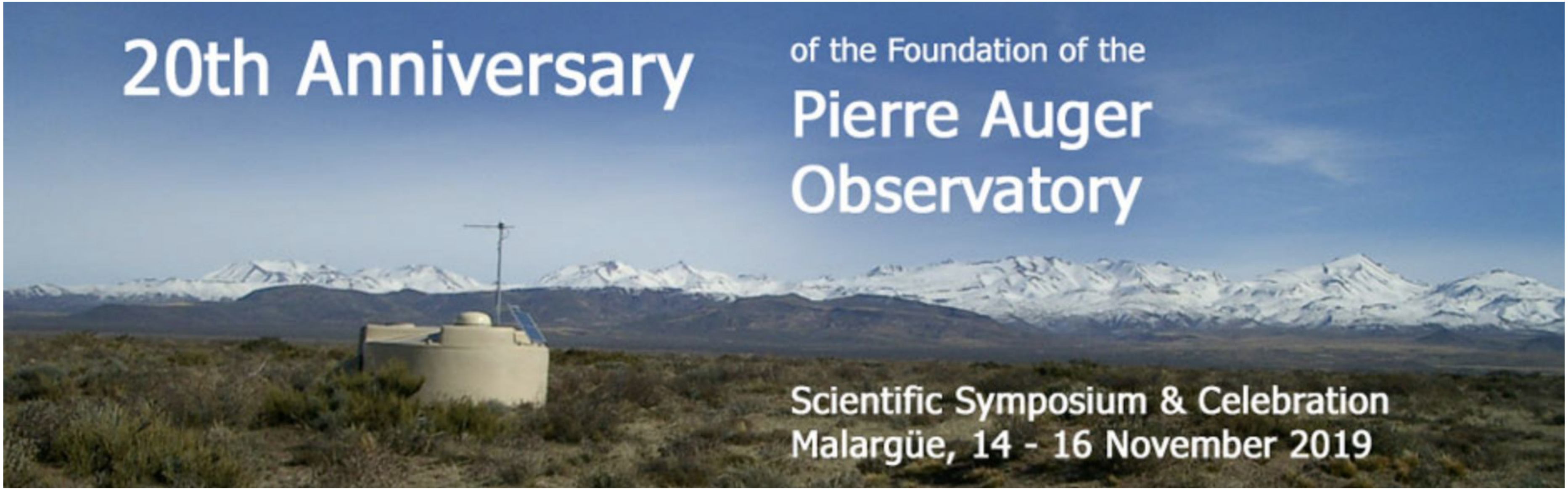
OPEN QUESTIONS

1. **What is the origin of flux suppression?**
   -fundamental constraints on sources and their properties
2. **is there a fraction of protons above ~5 10^{19}eV?**
   -feasibility of charged particle astronomy
   -proof for future experiments
3. **can we disentangle composition and hadronic interaction systematics ?**
   -constraints on hadronic multiparticle production from EAS
   -constraints on new physics beyond the reach of LHC
   -new measurements at accelerators
   -constraints of LIV

FUTURE STEPS

- Increase in statistics at UHE
- Composition sensitivity at and above the suppression region (E>4 10^{19} eV)
- More data on neutrinos (and photons)
- More information on hadronic interactions

Auger 20th Anniversary

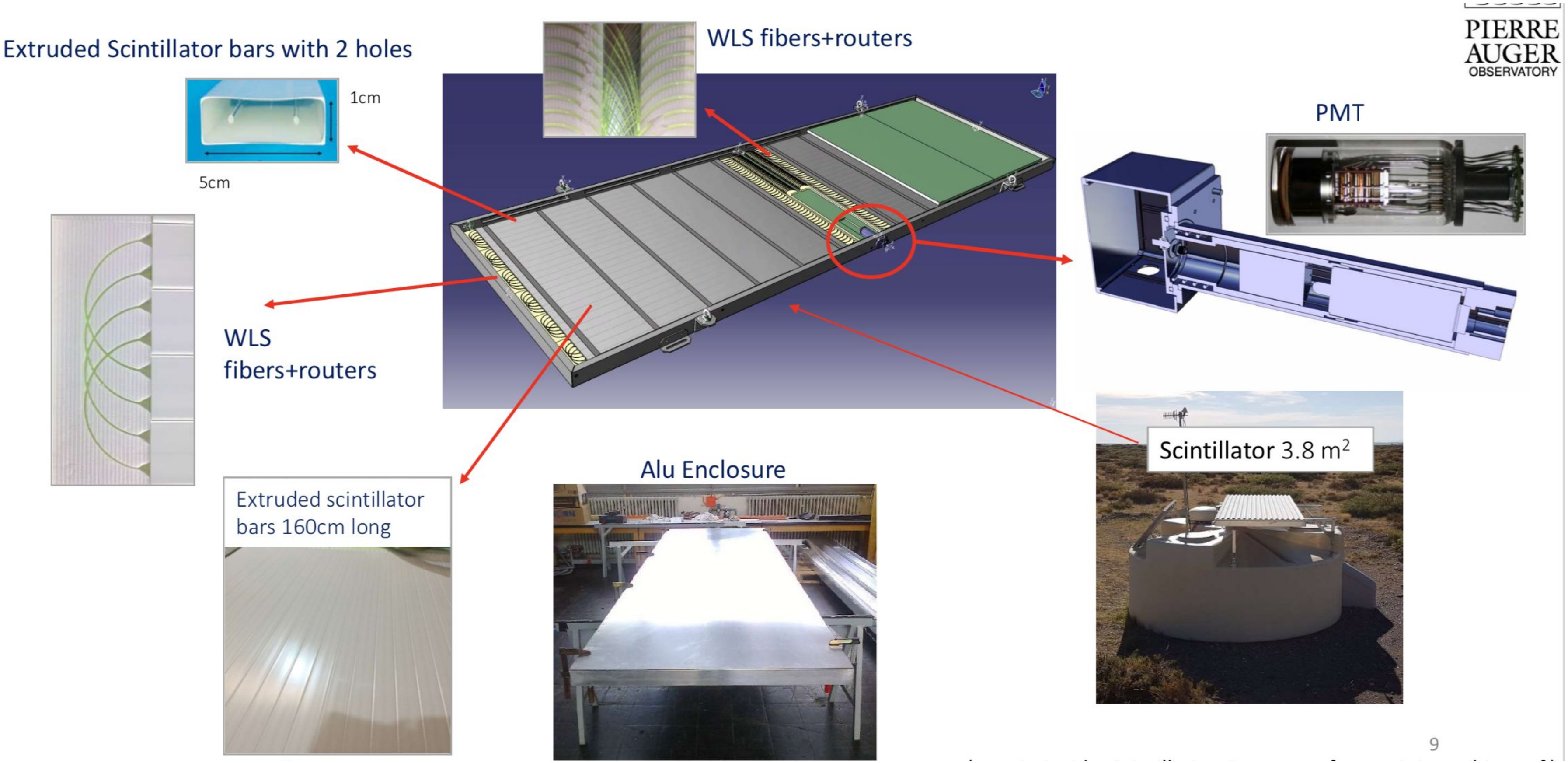


14-15 : Scientific Symposium
Guided tour to the Observatory
16 : Anniversary Celebration

JOIN US at https://www.auger.org/

Backup slides

The future of UHECR: Auger Prime detectors



The future of UHECR: Auger Prime electronics

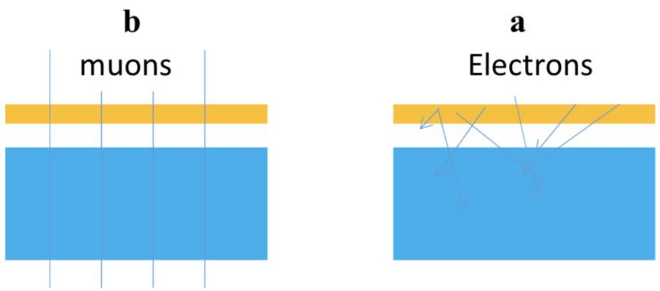
1. Increase of the data quality (better timing, dynamic range and μ identification):
   a) 10 FADC channels instead of 6
   b) faster sampling of ADC traces (40 → 120 MHz)
   c) more precise absolute timing accuracy (new GPS receiver)
2. Faster data processing and more sophisticated local triggers
   a) more powerful processor and FPGA
3. Improved calibration and monitoring capabilities
4. New components:
   1. Connection to the SSD and any additional (R&D) detectors
   2. Additional small PMT

Totally back-compatible with the old design

(same power communications, hardware interfaces...)

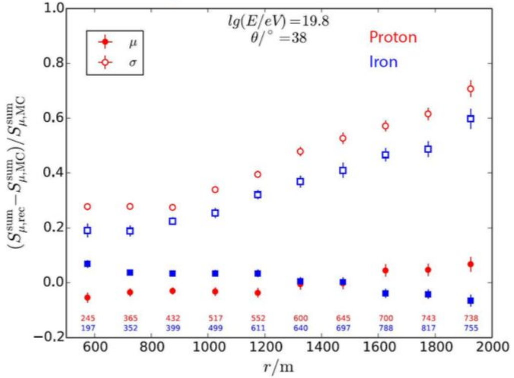
The Upgrade Unified Board (prototype)

SSD matrix inversion method



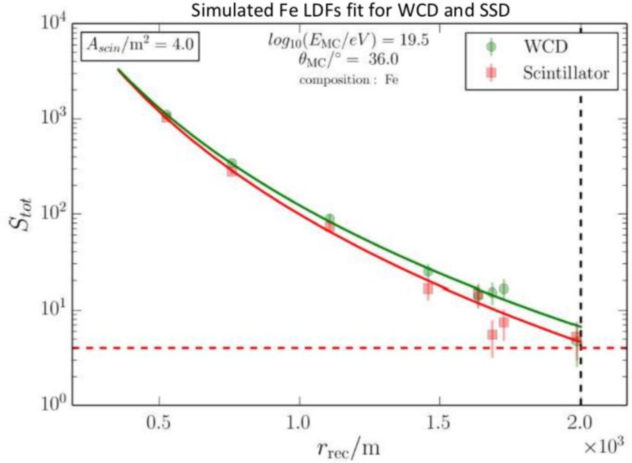
$$\begin{pmatrix} S_{top} \\ S_{bot} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{em} \\ S_{\mu} \end{pmatrix}$$

Single Station Analysis



Lateral Distribution Analysis

A parameterization of the LDF for the SSD was done using simulation.

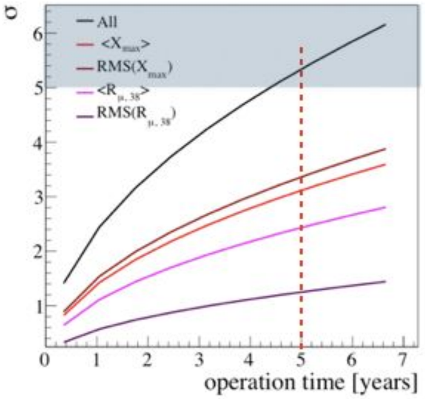


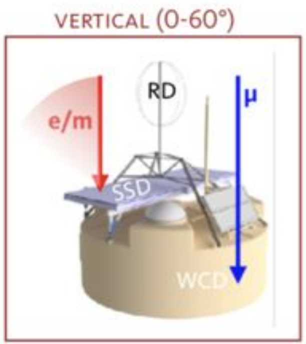
$$f_{p,Fe} = \frac{|\langle S_{Fe}\rangle - \langle S_p \rangle|}{\sqrt{\sigma(S_{Fe})^2 + \sigma(S_p)^2}} \sim 1.5$$

Figure of merit

The future of UHECR: Auger Prime detectors

VERTICAL SHOWERS



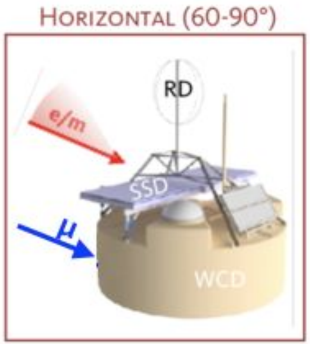


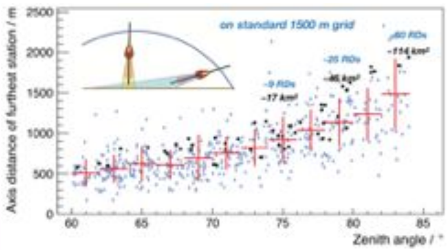
Significance of distinguishing two different realisations of "maximum rigidity model" :

- as it predicts, i.e. no protons at UHE
- adding 10% protons

>5σ in 5 years of operations

HORIZONTAL SHOWERS

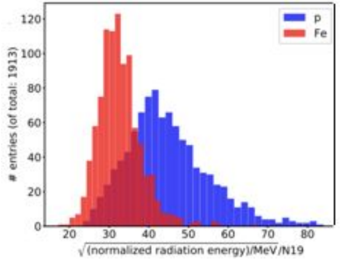


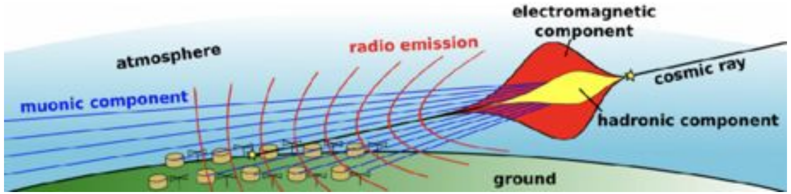


RADIO Hybrid:

E_{rad} from radio

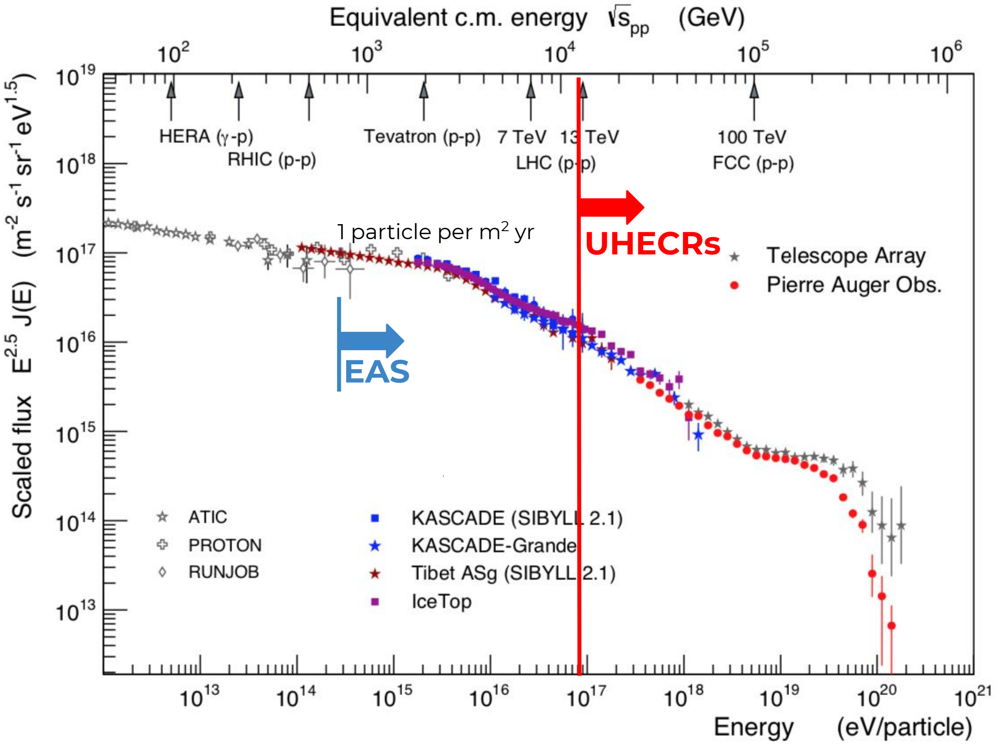
muons from WCD





Ultra High Energy Cosmic Rays (UHECRs)

Particles with E = 10^{17}-10^{20} eV , $\sqrt{s}$ = 14-450 Tev



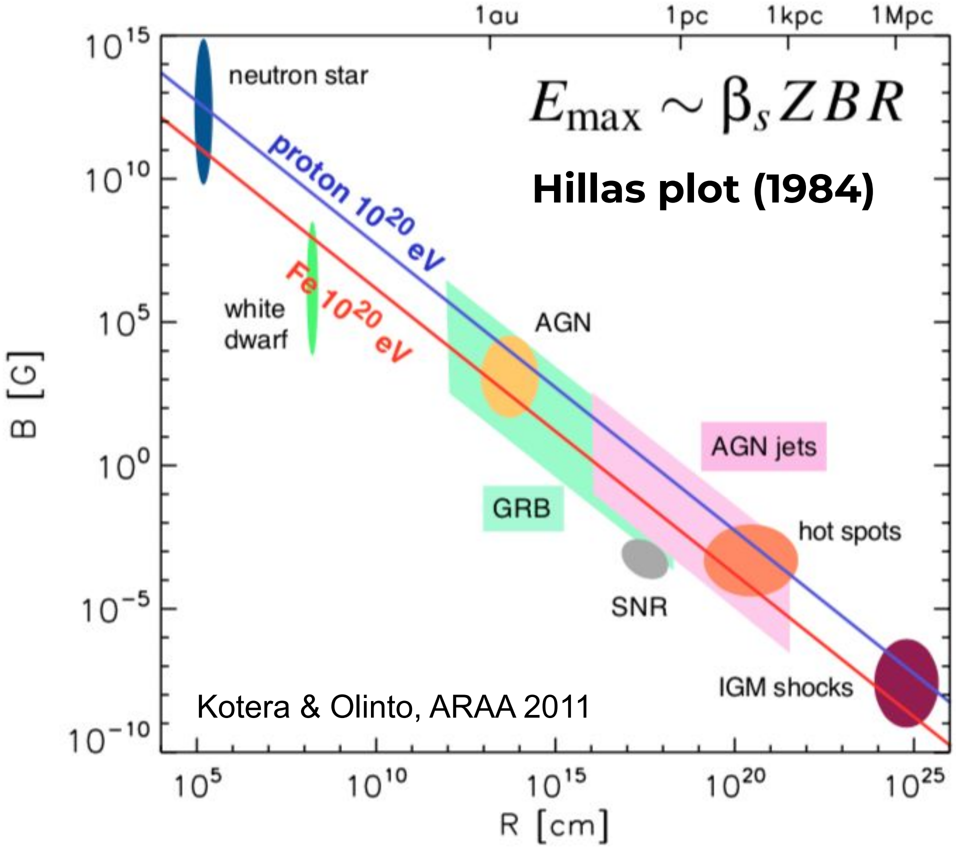
ASTROPHYSICS

- What is the nature and origin of UHECRs?
- What is causing the suppression of the flux at the highest energies?
- Which are the sources? can we perform UHECRs astronomy?
- How are UHECRs accelerated to such extreme energies?

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)

How are UHECR produced?



With LHC technology need accelerator of size of Mercury's orbit to reach 10^{20}eV

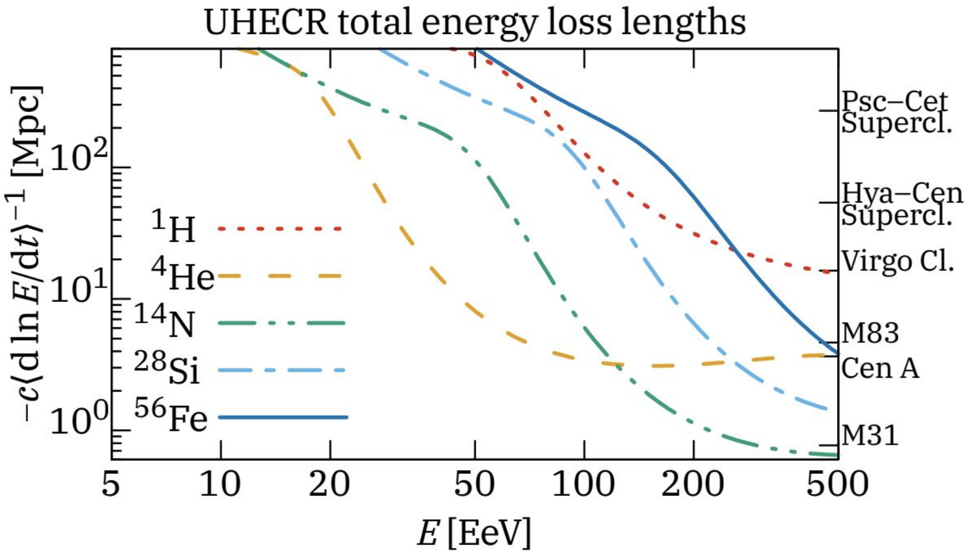
Realistic constraints more severe

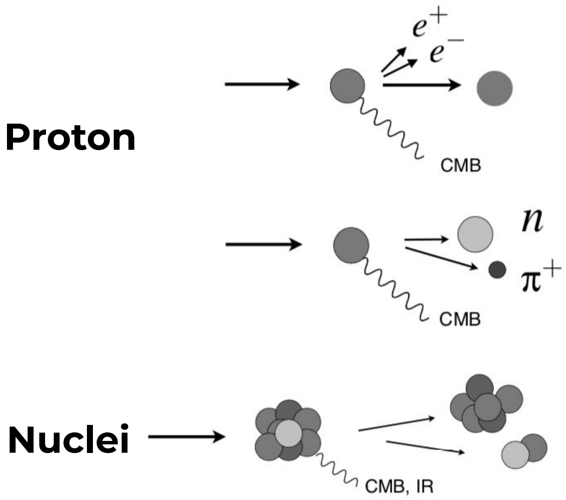
- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

How to get UHECRs at 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

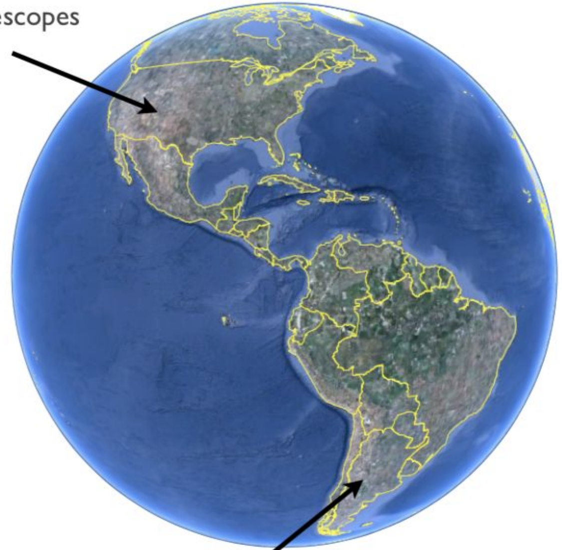




- NO He >50 EeV, CNO > 100 EeV expected
- Extreme-E CRs can only be: local, &/or protons, &/or heavy nuclei

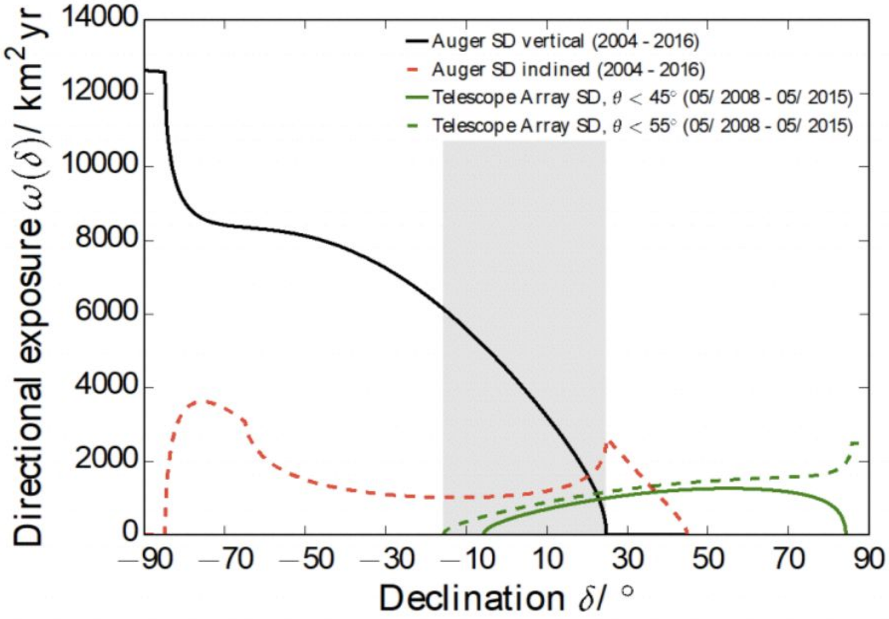
How to measure UHECRs?

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

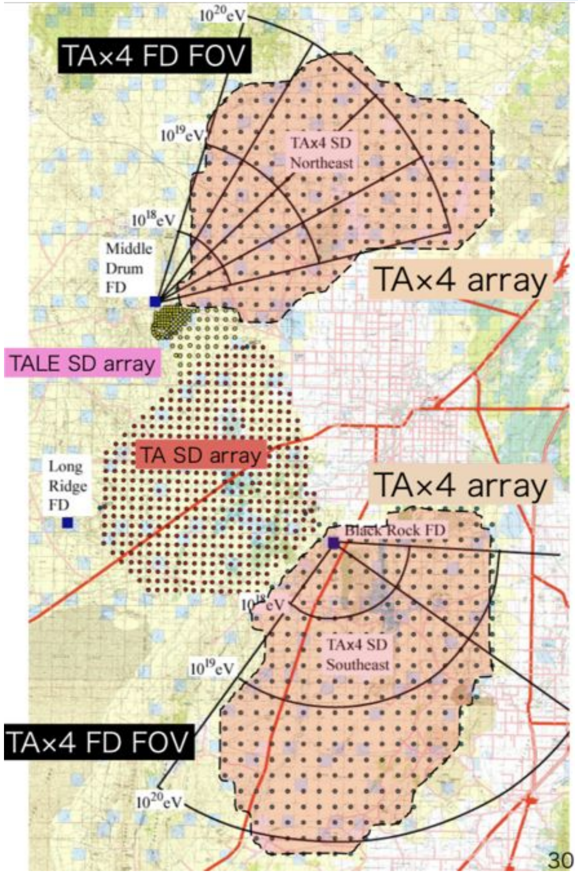


Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

Auger+TA have full sky coverage



The future of UHECR: TA x 4

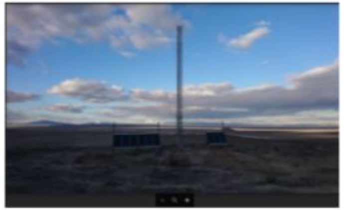


AIM: increase the coverage up to ~3000 km^2 to increment the statistics at UHE

- **SD array:** increased by 500 stations with 2 km spacing
- **FD telescopes:** increased by 4 FD in the Northern site, 8 in the Southern site

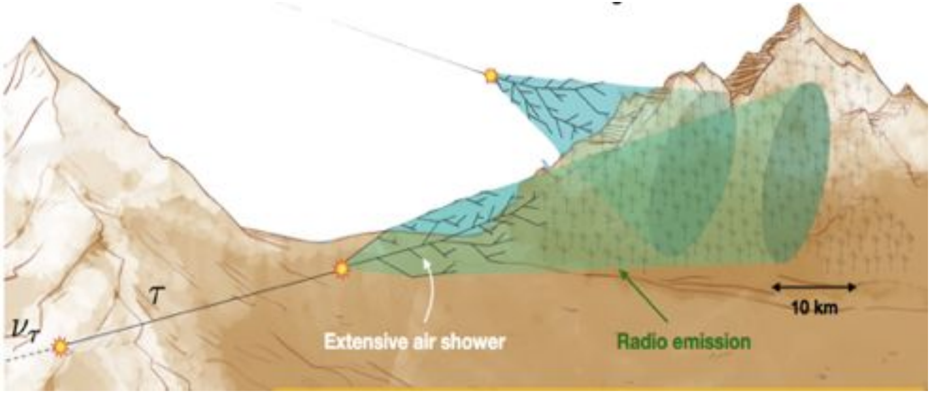
Feb. 19 - Mar. 12, 2019:

- 257 SDs
- 6 communication towers



The future of UHECR: GRAND

Giant **R**adio **A**rray for **N**eutrino **D**etection



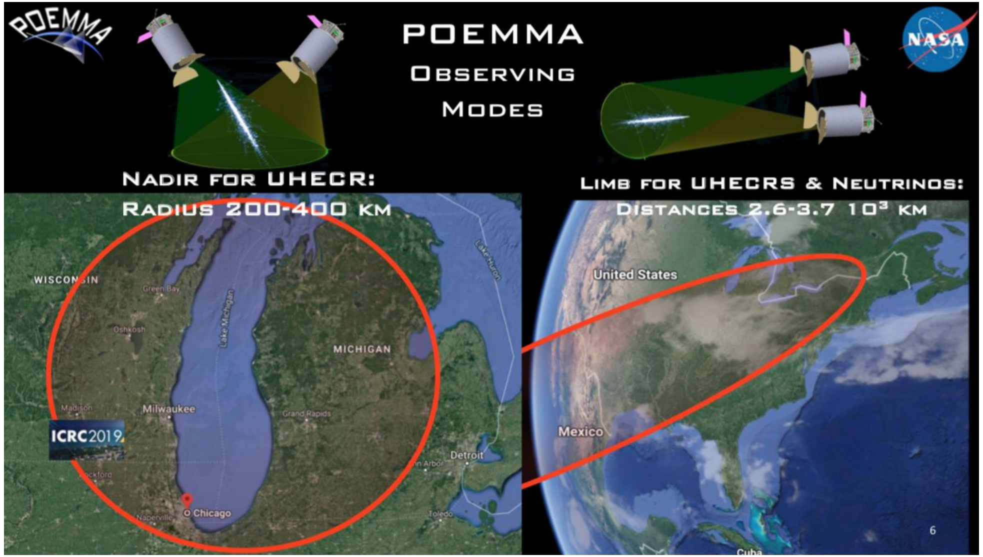
- 200000 antennas over 200000 km^2
- radio quiet regions around the world (half in China)
- autonomous radio detection of inclined air-showers in 50-200 MHz band

GOAL: observation of UHE cosmic particles with E>10^{18} eV to study their origin

- large exposure
- <1^0 angular resolution
- sensitivity to neutrinos

Prototype GRANDproto300 : 300 antennas on 200 km^2 in 2020/21

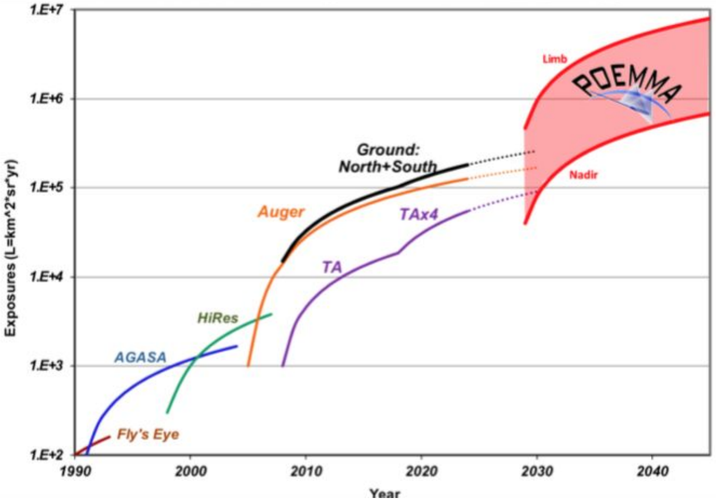
The future of UHECR: POEMMA



Probe **O**f **E**xtreme **M**ulti-**M**essenger **A**strophysics

- 2 satellites flying in loose formation
- 4 m wide FoV (45°) Schmidt mirrors
- fast (1μs) UV camera for fluorescence observation + ultrafast (10 ns) optical camera for Cherenkov obs.

GOAL: observation of UHE cosmic particles with E ≳ 10^{19} eV to study their origin



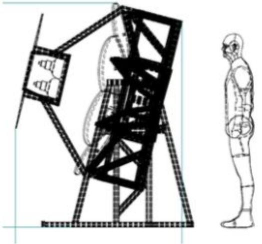
- huge gain in exposure (~10^5 km^2 sr yr) for both charged CRs and neutrinos
- full sky coverage of the celestial sphere
- sensitivity to neutrinos > 2 x 10^{19} eV from FD of ν-induced EAS
- follow-up of transients

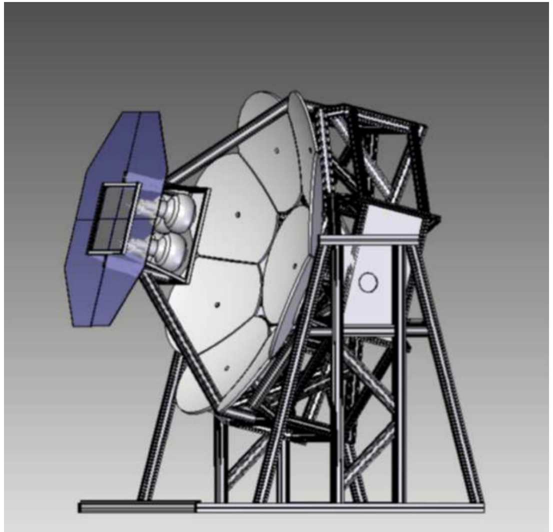
The future of UHECR: FAST

Fluorescence detector **A**rray of **S**ingle-pixel **T**elescopes

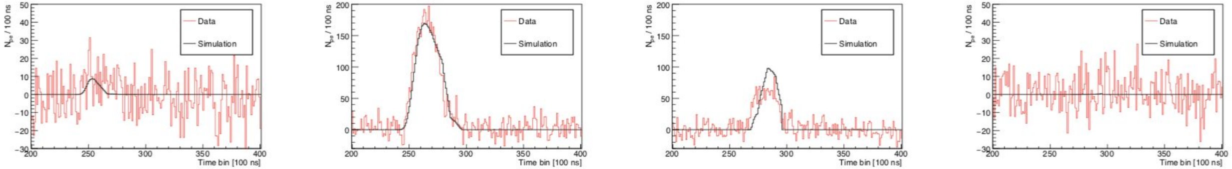
Reference: T. Fujii et al., Astropart.Phys. *74* (2016) 64-72

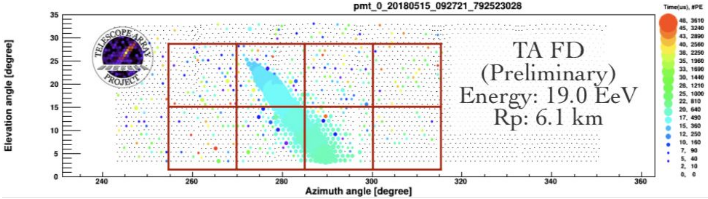
- UHECR and neutral particles **E > $10^{19.5}$ eV**
- mass discrimination on event by event basis
- huge target volume with lower cost w.r.t current FDs
- Deploy on a triangle grid with 20 km spacing, like "Surface Detector Array"





- Smaller optics and single or a few pixels 1 m^2 aperture, 15°×15° FoV
- Low-cost and simplified telescope
- installed for X-calibration and trigger at **Auger** and **TA**



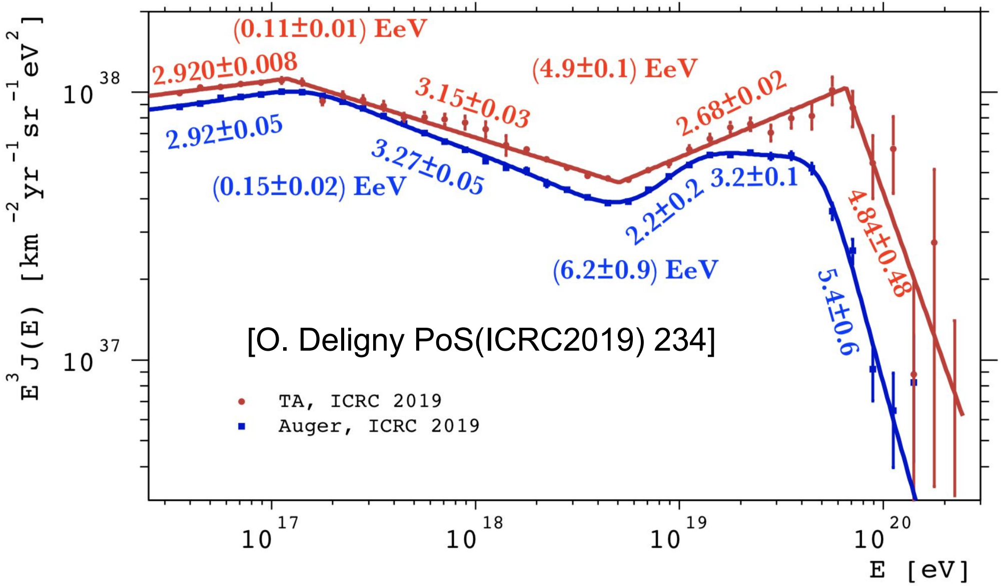


FAST top-down reconstruction (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
59.8 deg	-96.7 deg	7.9 km	-9.0 km	842 g/cm²	17.3 EeV

E = 1.73 x 10^{19}

The energy spectrum in Auger and TA

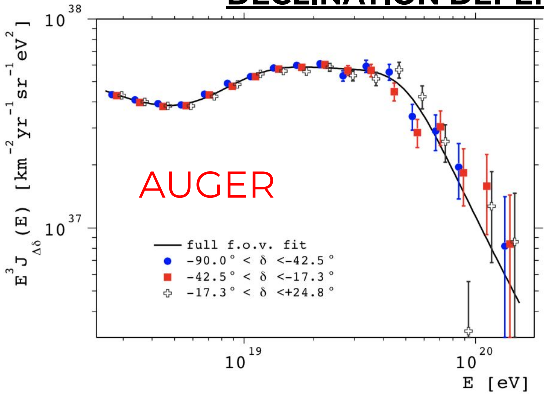


- Energy scale: different fluorescence yield and invisible energy models
- σ_{syst} on the two energy scales : **14% for Auger** and **21% for TA**

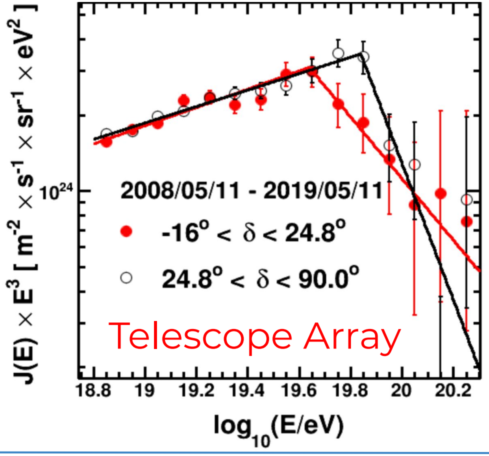
Low energy comparisons:

- **γ**0: is in agreement!
- 2nd knee position: within 1.8σ
- **γ**1: within 2.1σ

DECLINATION DEPENDENCE

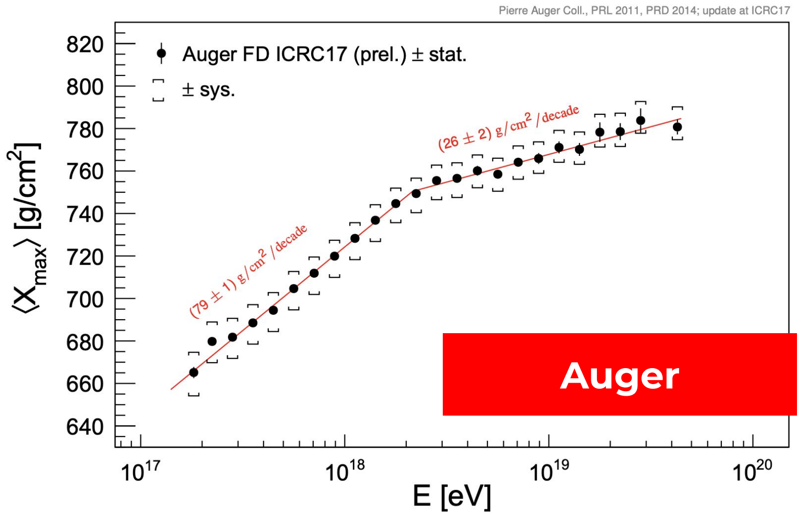


Auger: Only a trend for a slightly larger intensity in the South (consistent with dipole expectations)"

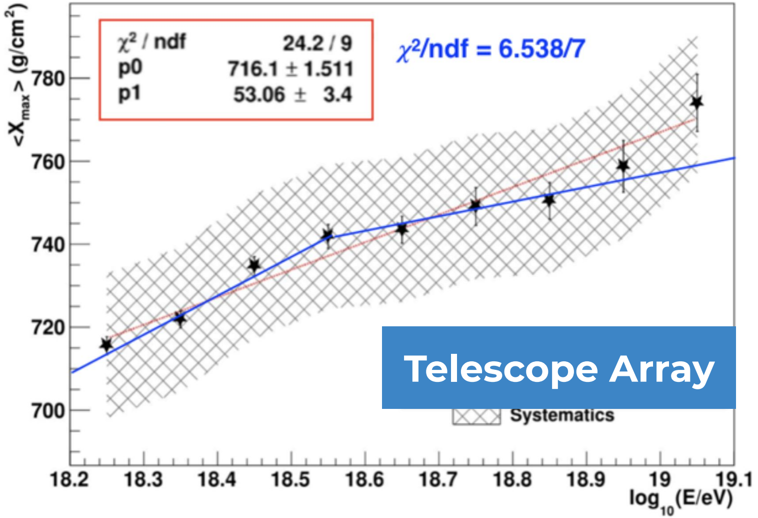


TA: Differences in the suppression energy, with an excess of intensity in the Northernmost sky

Tension on composition between Auger and TA?



- X_{max} res. ~25 to ~15 g cm^{-2} (from $10^{17.8}$ eV to >$10^{19.7}$ eV)
- Systematic uncertainty on X_{max} ≤ 10 g cm^{-2}



- X_{max} res. 17.2 g cm^{-2} (from $10^{18.2}$ eV to 10^{19} eV)
- Systematic uncertainty on X_{max} ~ 17 g cm^{-2}

Auger data show trend towards heavier composition above $10^{18.4}$ eV

- TA data have less statistical separation power and larger systematics
- TA data compatible with mix of 4 elements with 75% (p+He) below $10^{19.1}$ eV
- direct comparison is difficult (AUGER unbiased measurement, TA biased by detector acceptance)
- CAVEAT: TA analysis with QGSJetII-04 only [excluded by Auger σ(Xmax) measurement]

Full sky coverage with Auger + TA

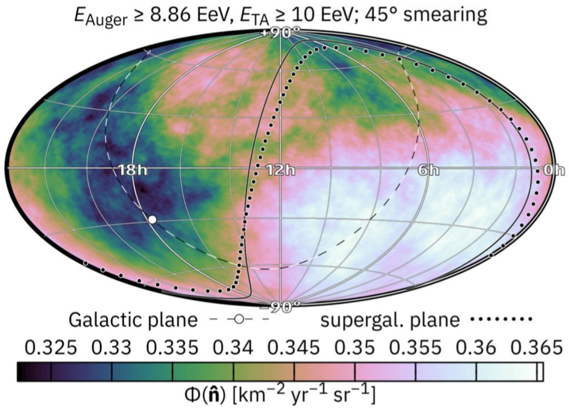
Large Scale Anisotropy

Energy threshold

- 8.86 EeV for Auger
- 10 EeV for Telescope Array

Events

- ~31000 events



- Agreement with Auger alone, smaller uncertainty
- Hint for a quadrupole moment

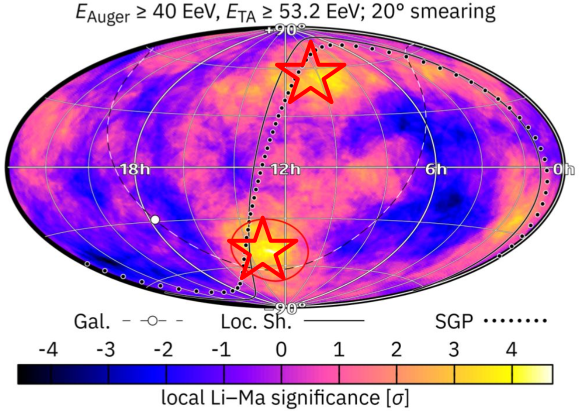
Intermediate Scale Anisotropy (<30^0)

Energy threshold

- 40 EeV for Auger
- 53.2 EeV for Telescope Array

Events

- 969 events

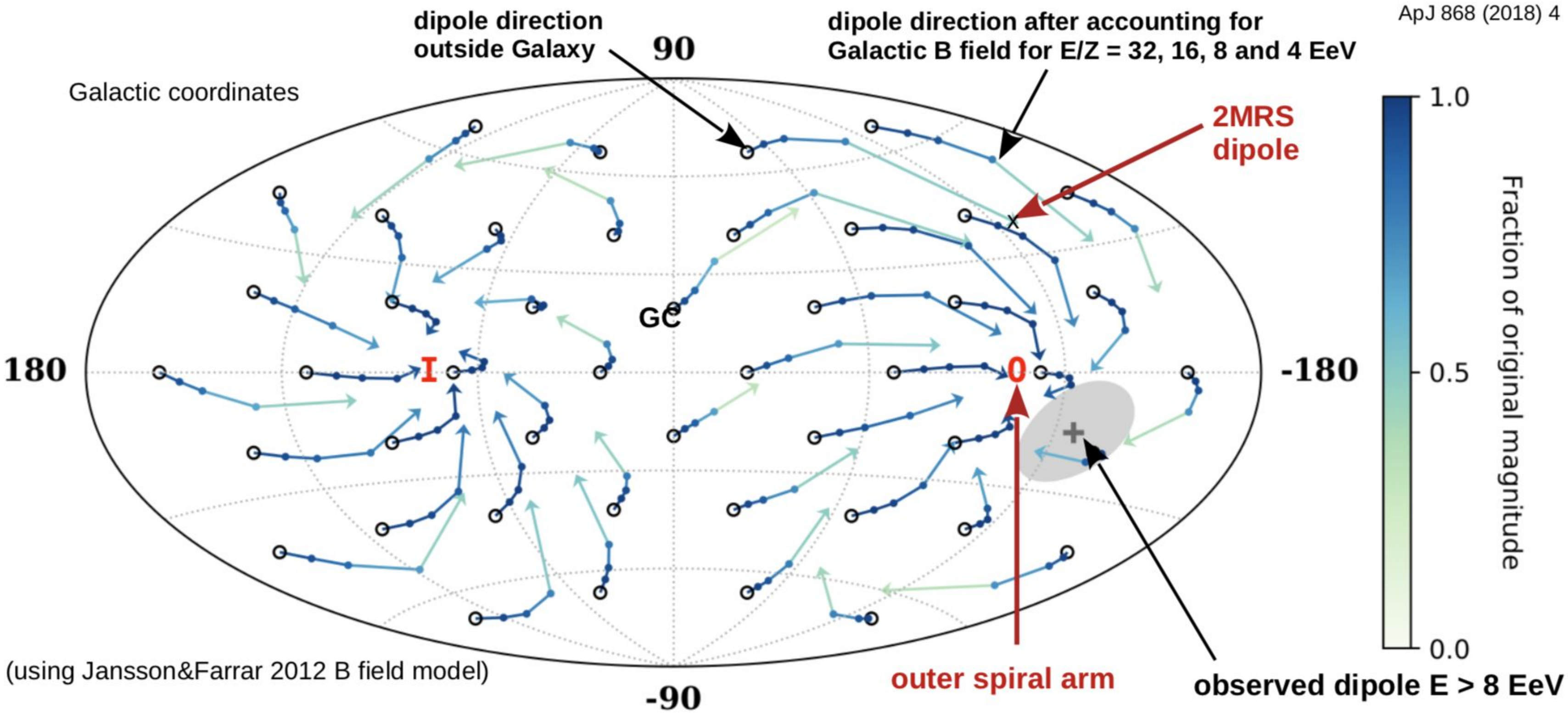


Blind search

20^0 radius around ($\boldsymbol{\alpha}$=12^{h}50^m, $\boldsymbol{\delta}$= - 50^0), 2.6σ post-trial

15^0 radius around ($\boldsymbol{\alpha}$= 9^{h}30^m, $\boldsymbol{\delta}$= +54^0), 1.5σ post-trial

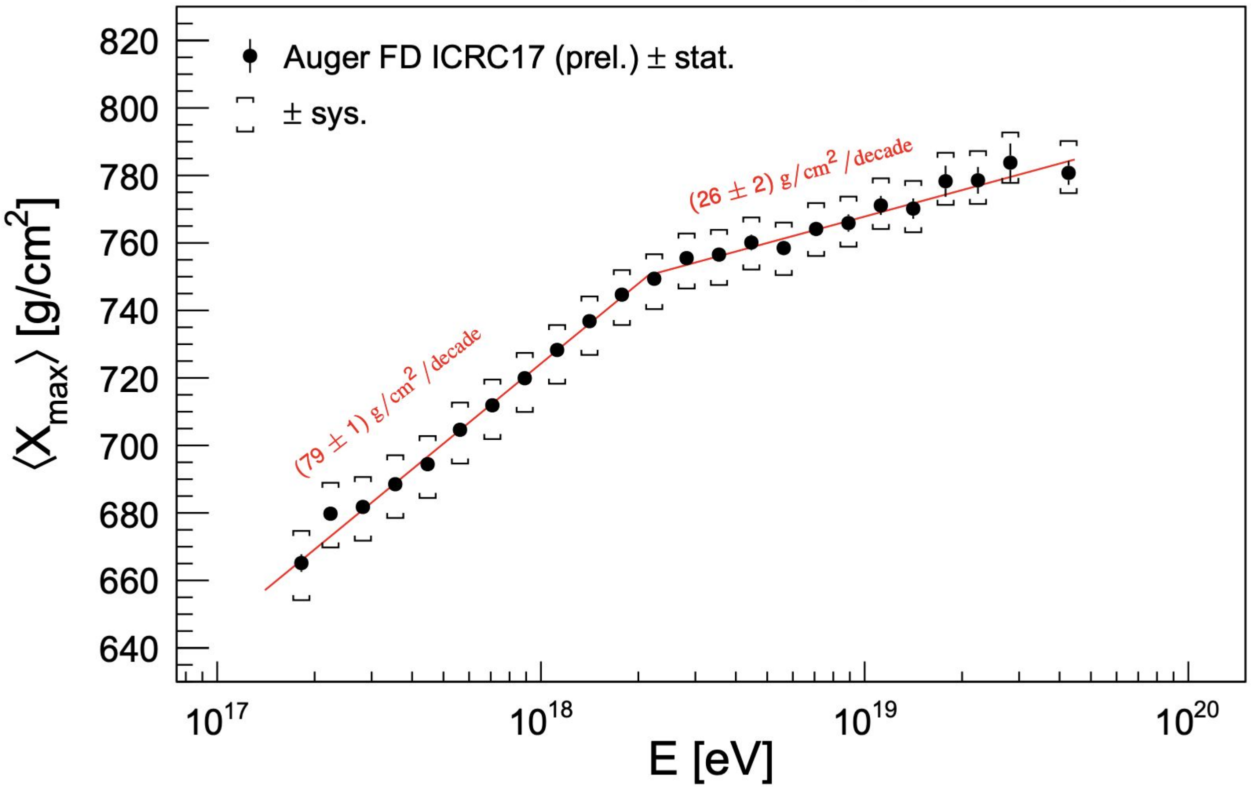
Effect of Galactic B field on extragalactic dipole direction (and amplitude)



extragalactic dipole direction gets shifted towards spiral arms by Galactic B field

Rate of change of X_{max} with energy

Pierre Auger Coll., PRL 2011, PRD 2014; update at ICRC17

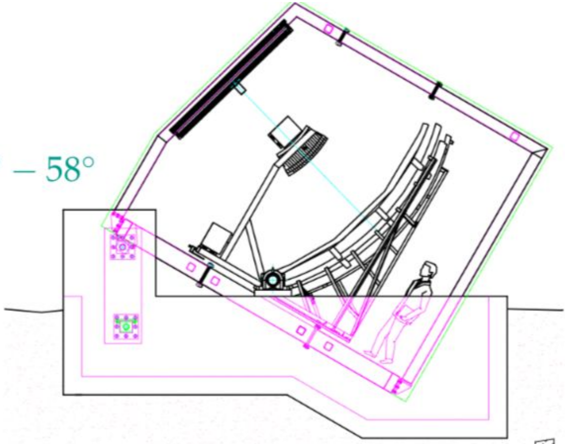


Fluorescence Detector

Fluorescence Detector

High elevation Auger telescopes

elevation $30^\circ - 58^\circ$



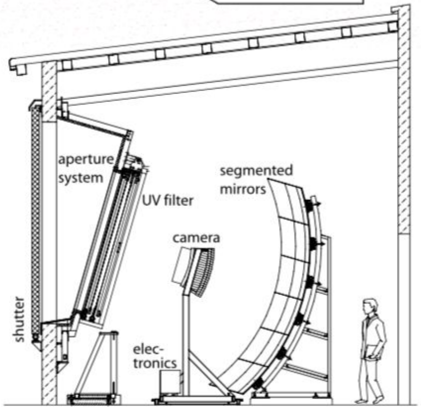
3 telescopes at Coihueco site

range of $X_{\max}$ analysis: $10^{17.2}$ eV $< E < 10^{18.1}$ eV

data: same to ICRC (2017) [J. Bellido, PoS(ICRC2017)506]

Standard telescopes

elevation $1.5^\circ - 30^\circ$



24 telescopes at 4 sites

range of $X_{\max}$ analysis: $E > 10^{17.8}$ eV

compared to ICRC (2017): update with 2016 – 2017 (+20% of statistics)

X_{max} measurement

Measurements of the depth of shower maximum X_{max}

47863 high-quality events

1020 events with $E > 10$ EeV

the highest energy 104 ± 9.5 EeV

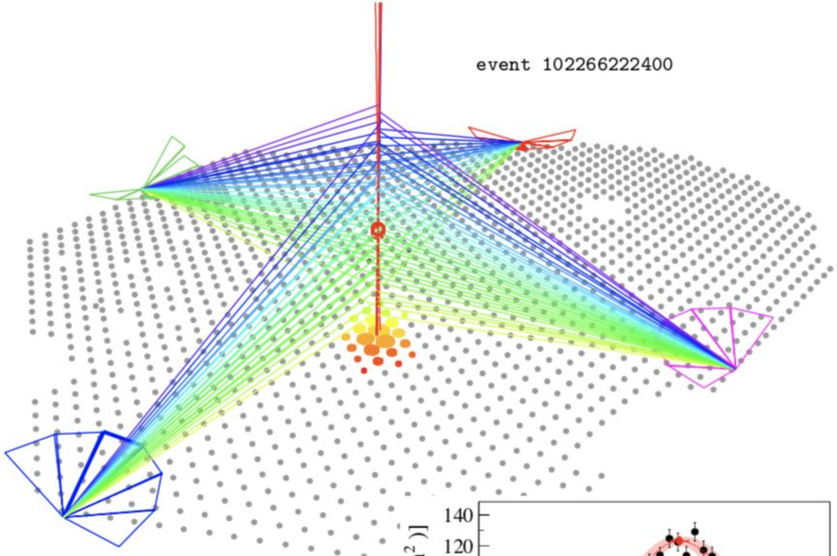
systematics $\lesssim 10\ \mathrm{g\,cm^{-2}}$

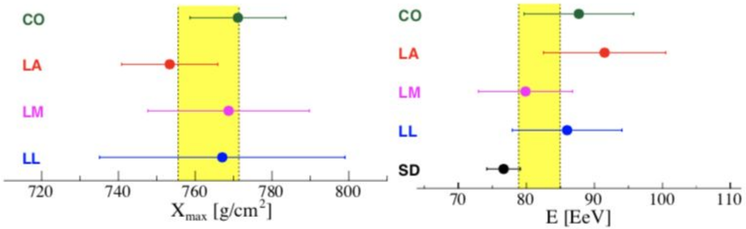
resolution

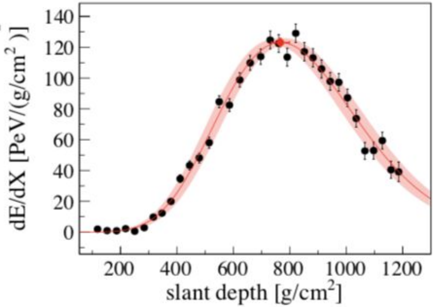
$40\ \mathrm{g\,cm^{-2}}$ at $10^{17.2}$ eV

$25\ \mathrm{g\,cm^{-2}}$ at $10^{17.8}$ eV

$15\ \mathrm{g\,cm^{-2}}$ for $E > 10^{19.0}$ eV



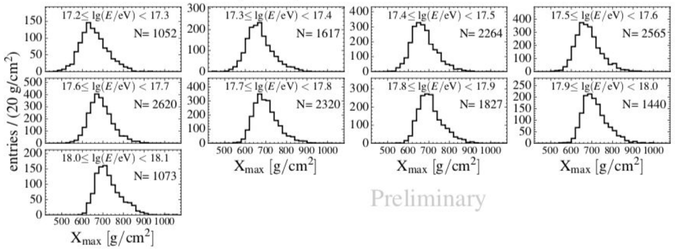




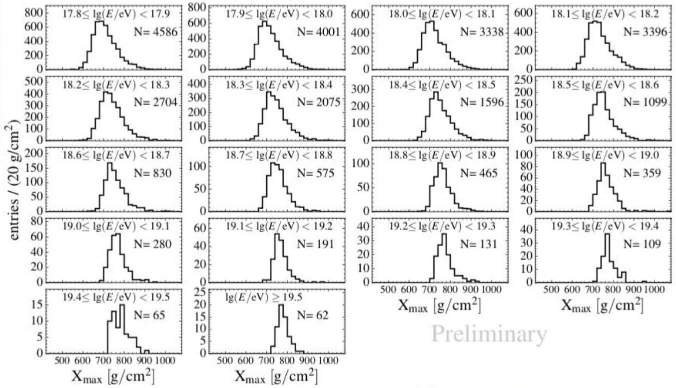
(p-He-N-Fe)-fit of X_{max} Distributions

FD data:

$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$

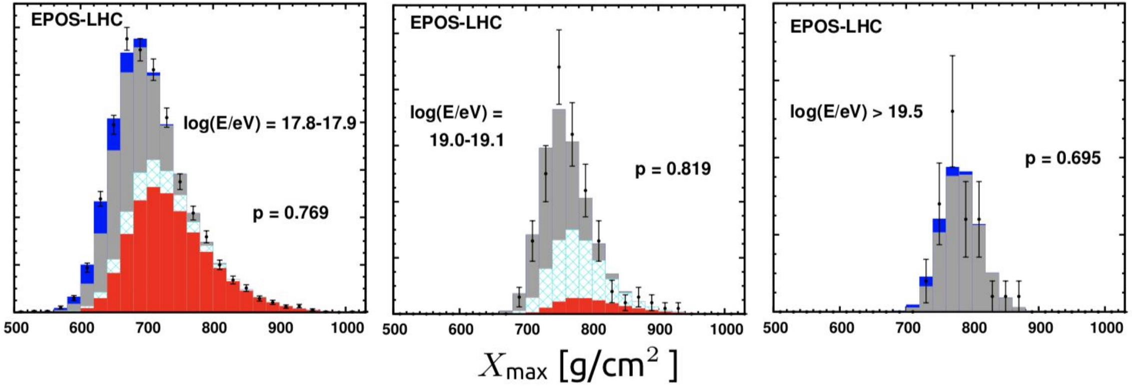


$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$



Examples of 4-component fit:

p He N Fe



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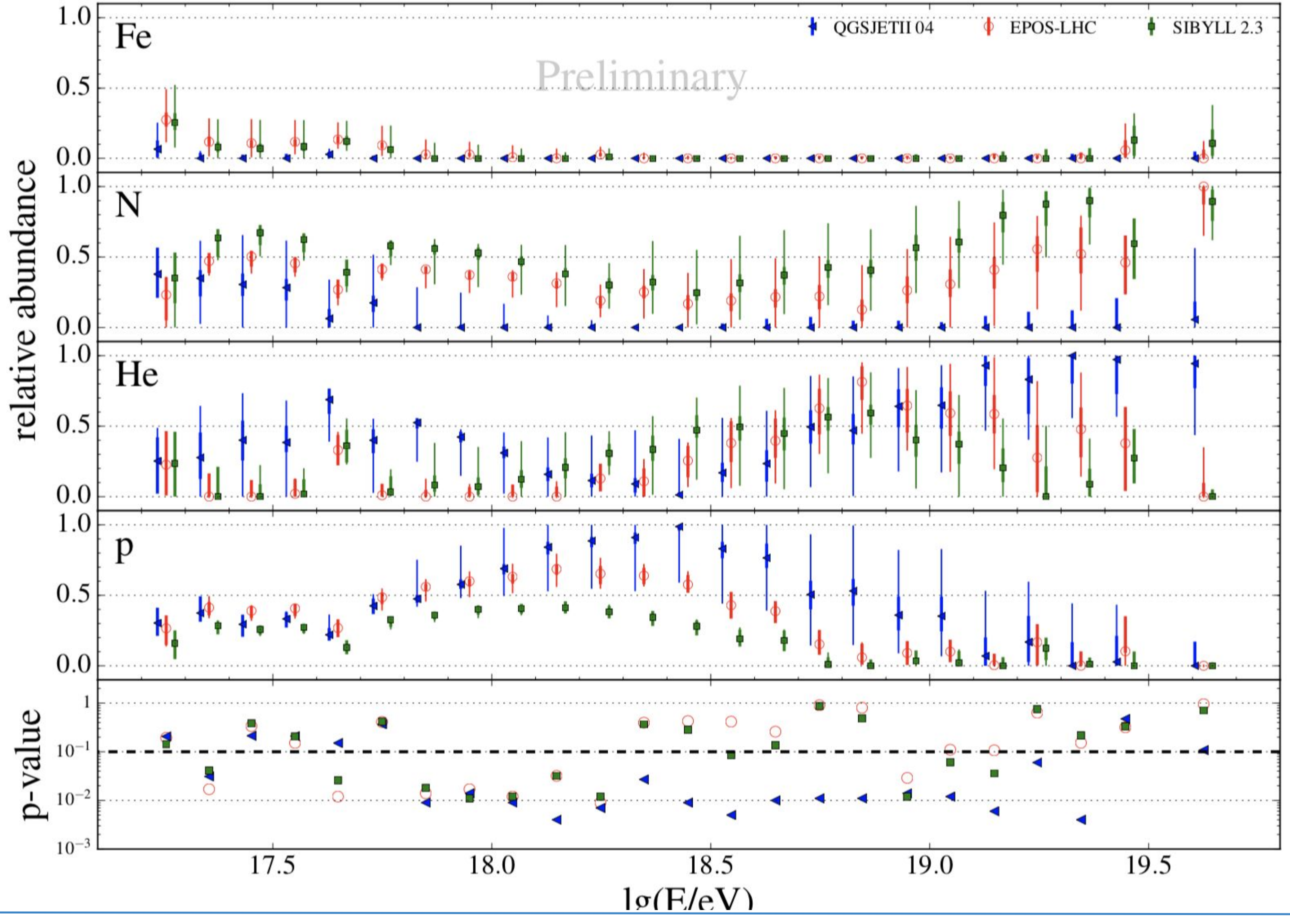
Composition Fractions



PCGF method

The PCGF method of shower axis geometry reconstruction was successfully implemented in the Offline software used at the Pierre Auger Observatory. The resolution of the χ0 reconstruction is 1.6◦, and the calorimetric energy is reconstructed with a resolution of 18%. Correspondence between the measured data and full simulations of air showers and the FD is at a reasonable level.

A preliminary energy spectrum of cosmic rays in the energy region of 1016.5 – 1018 eV was estimated. Dominant systematic uncertainties are in the FD energy scale (14% in energy) and MC simulations of the FD (15% in exposure). The reconstruction procedure and Cherenkov emission model contribute to the uncertainty in the Cherenkov energy scale by ca. 5% each. A presence of the second knee is robust against changes in the invisible energy even to the MC predictions for pure beams.