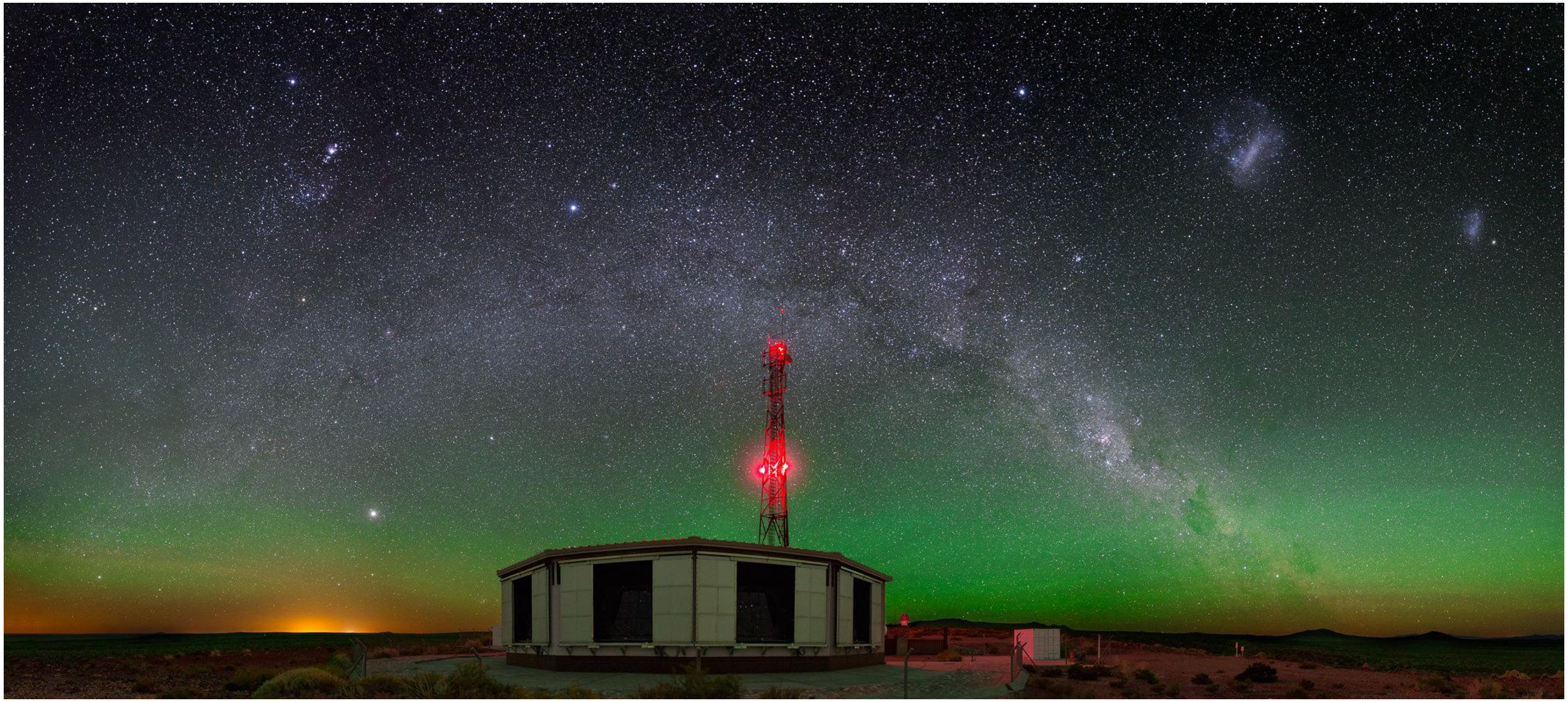
Ultra-high energy cosmic rays at the Pierre Auger Observatory



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Seminarium IFJ PAN

26 November 2020

Properties of UHECR

Detection

Energy spectrum

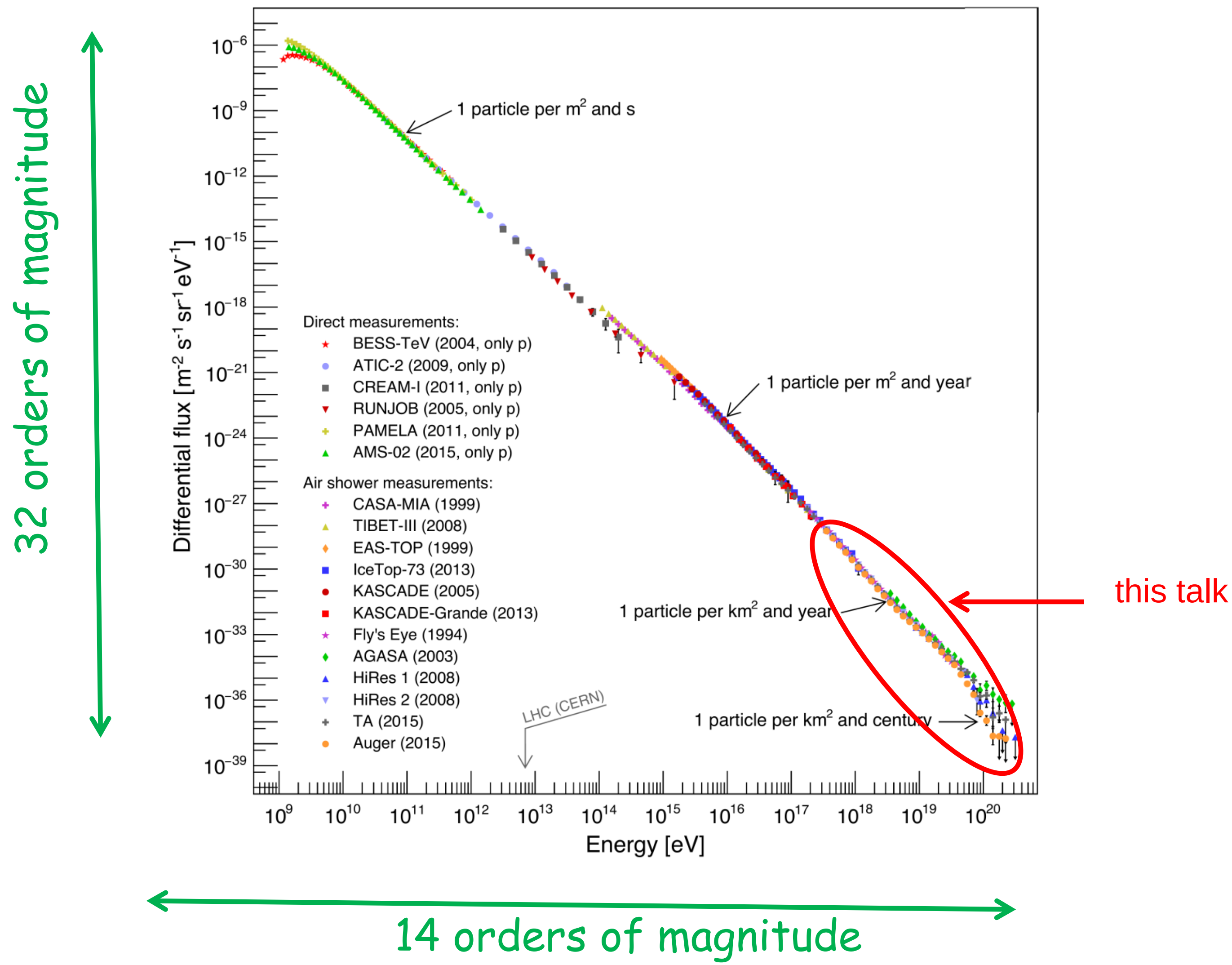
Composition

Arrival directions

Hadronic interactions

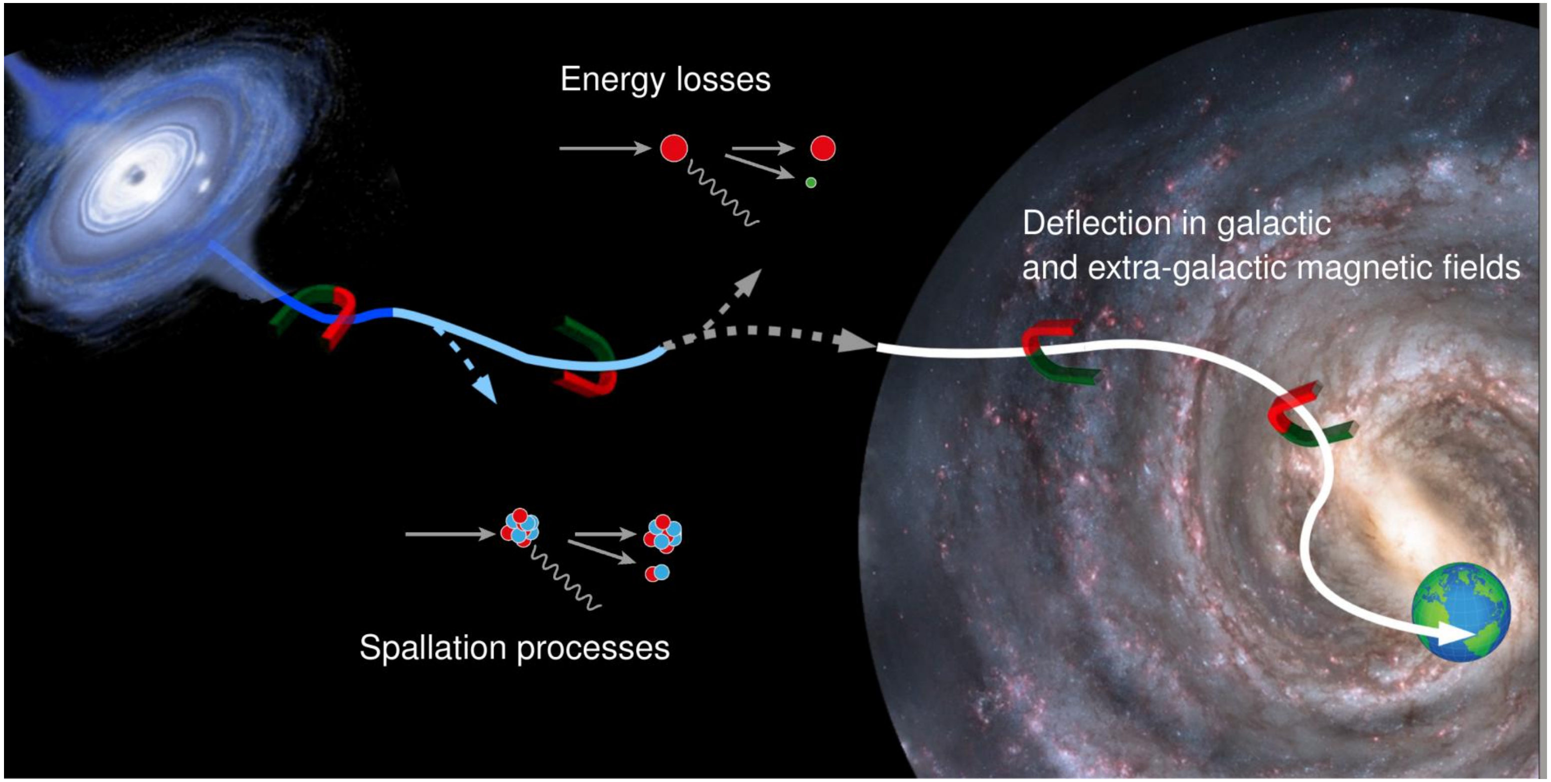
Future

CR energy spectrum



10^{20} eV in LHC technology $\rightarrow$ need accelerator size of Mercury orbit

Ultra-high energy cosmic rays (UHECRs)



Key questions:

- Origin?
- Composition?
- Acceleration process?
- Is there a limit to their energies?

CR propagation: modification of direction, energy, composition

Expect Greisen-Zatsepin-Kuzmin effect(GZK) : interactions with CMBR photons

$\rightarrow$ spectrum suppression above the threshold

$\rightarrow$ „pointing” to sources („charged particle astronomy”)

GZK effect

Greisen-Zatsepin-Kuzmin effect

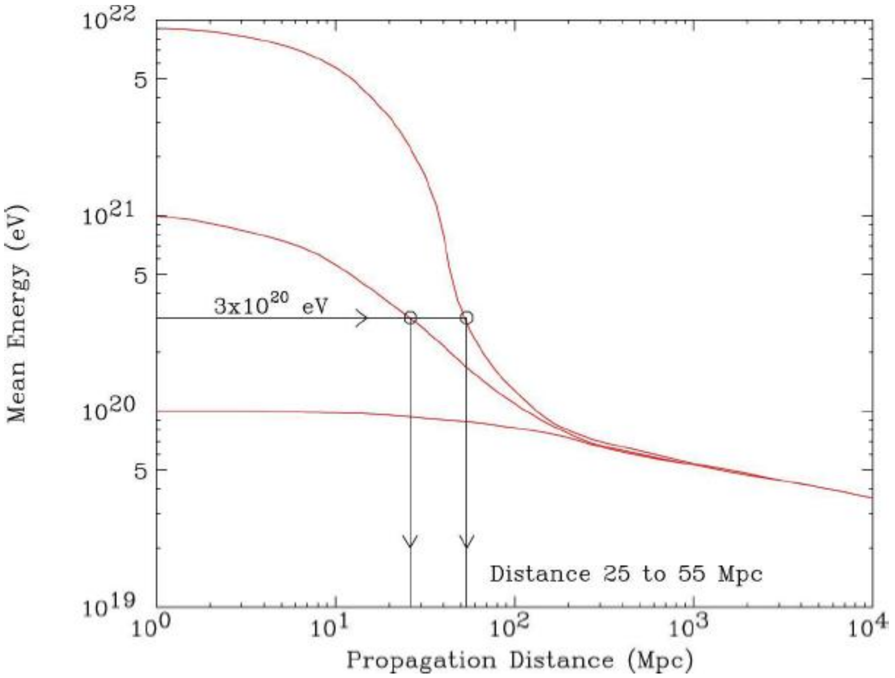
Cosmic ray interactions with CMB photons at $E > \sim 5\times10^{19}$ eV:

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$n + \pi^+$$

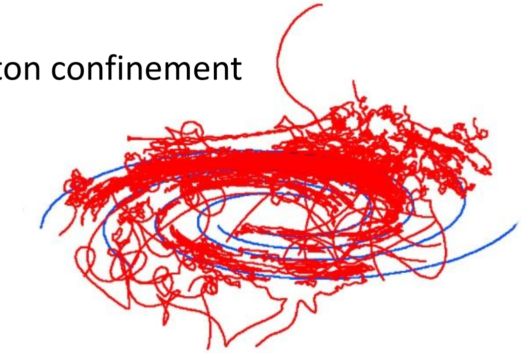
$\rightarrow$ reduction of proton energy
$\rightarrow$ spectrum steepening

For $E > 10^{20}$ eV the source must be within ~ 50 Mpc
source identification should be easy??

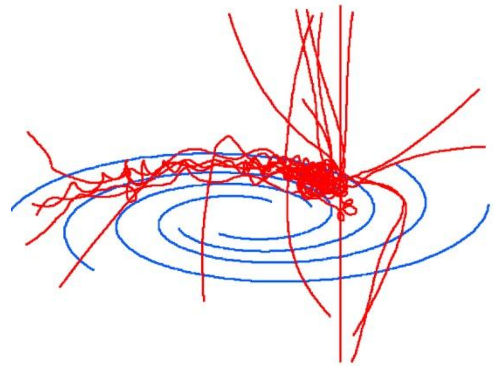
Charged particle astronomy should be possible



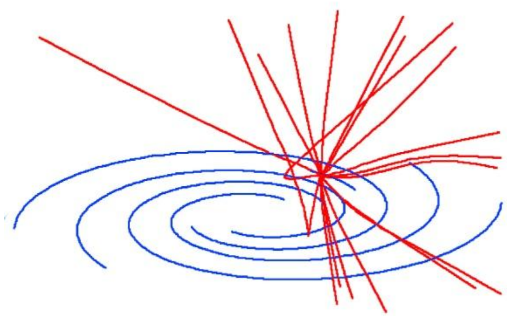
CR propagation in the Galaxy



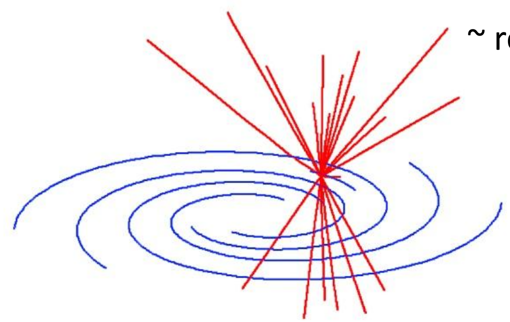
$10^{17} eV$



$10^{18} eV$



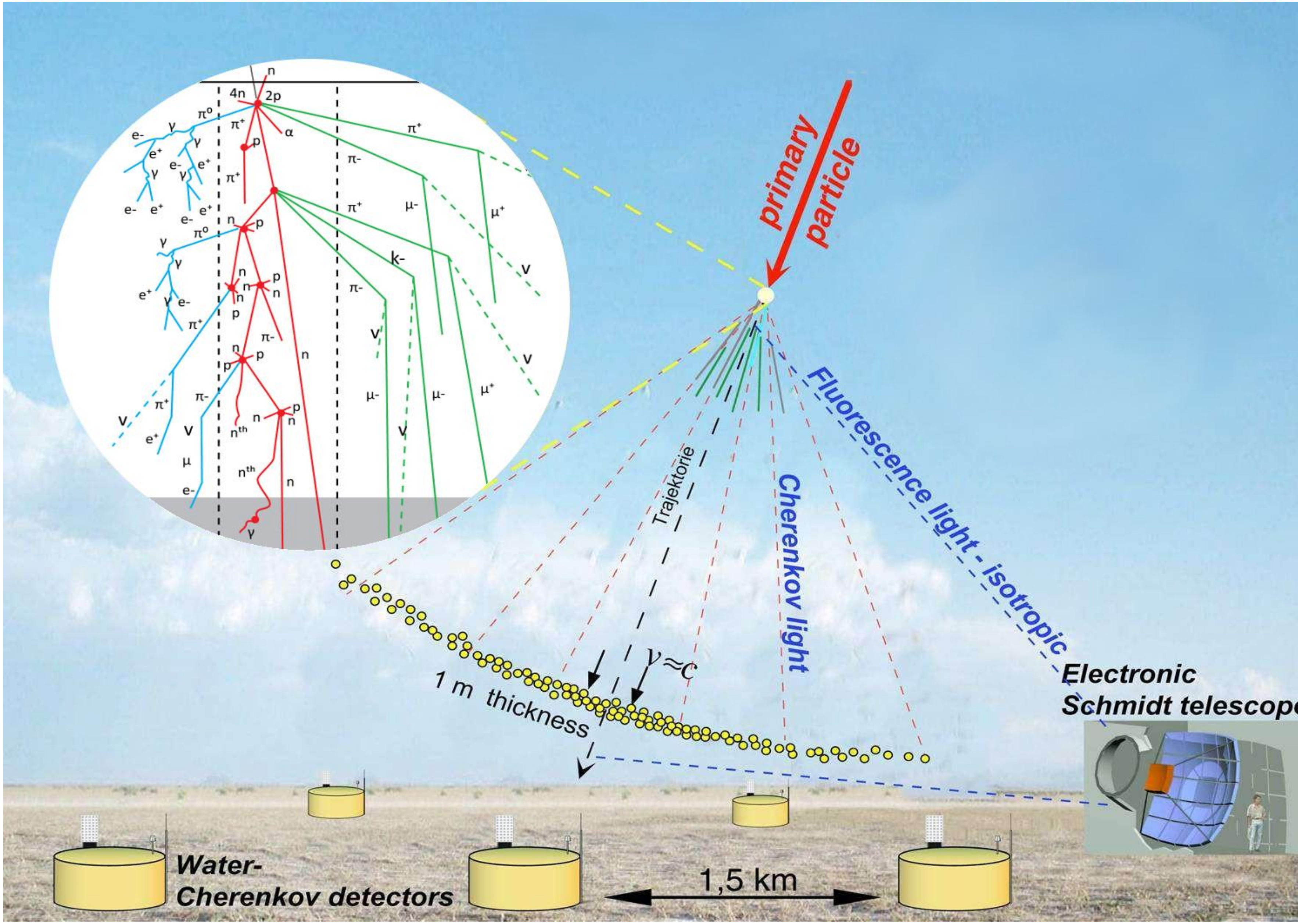
$10^{19} eV$



$10^{20} eV$

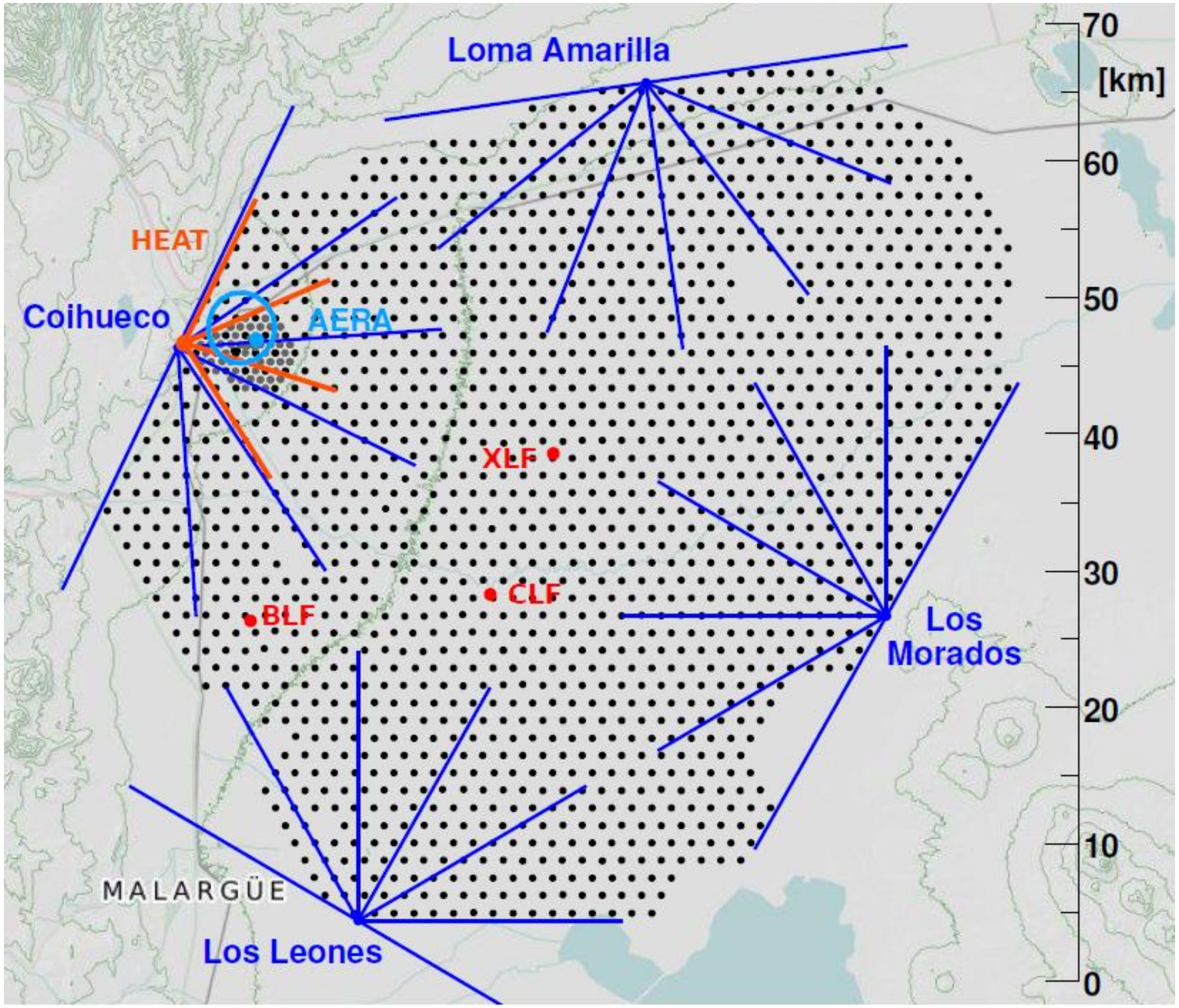
Pointing to sources at highest energies?

UHECR detection – extensive air showers



Pierre Auger Observatory

Located in Mendoza province, Argentina



Surface Detector (SD)

1660 detector stations
1.5 km spacing
3000 km^2
100% duty cycle
exposure calculated geometrically

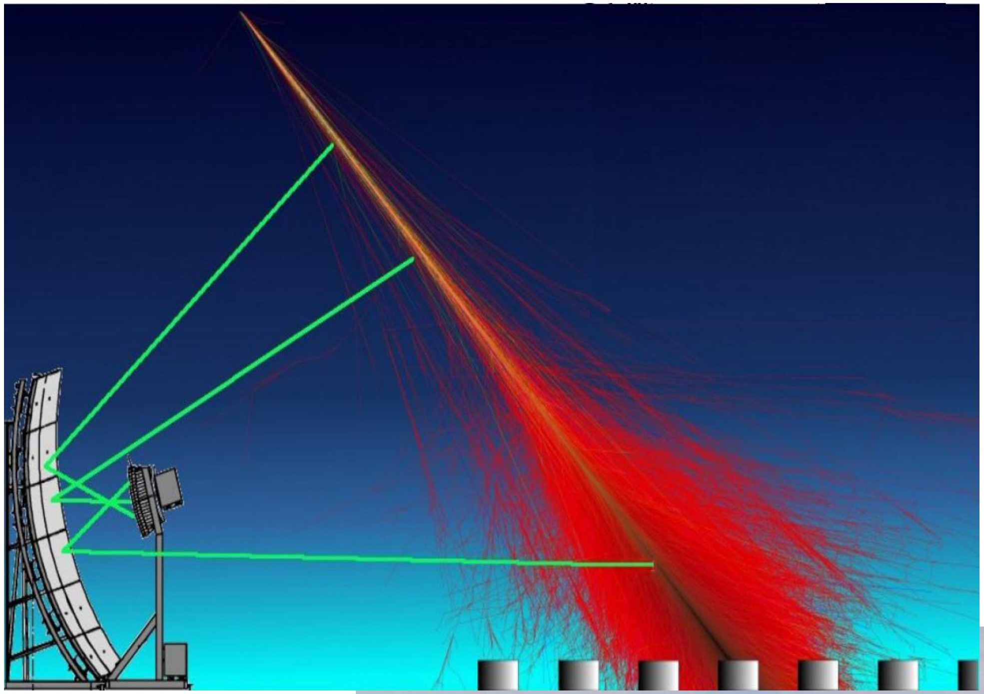
Fluorescence Detector (FD)

27 telescopes
calorimetric energy
duty cycle ~13%
exposure based on MC

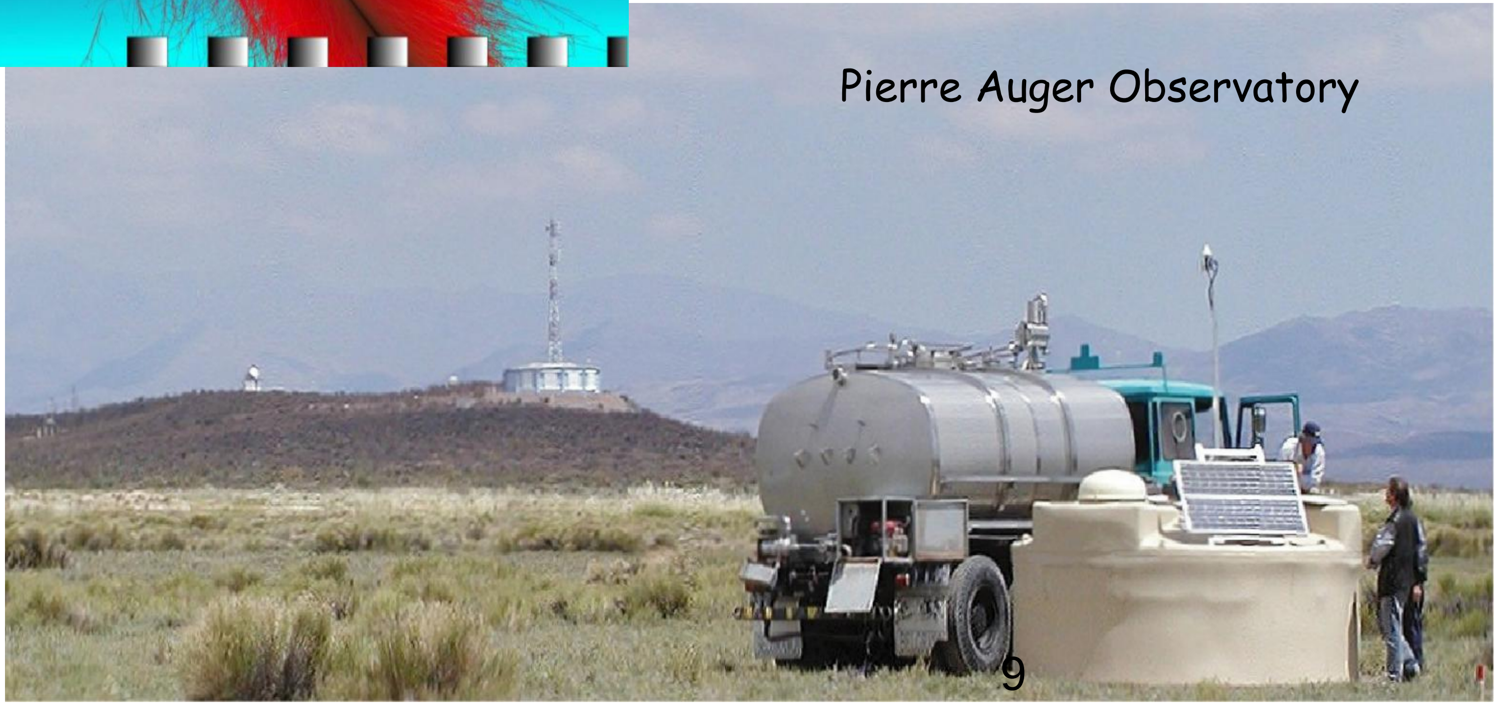
Underground Muon Detector

Radio Detector

Hybrid detection of extensive air showers

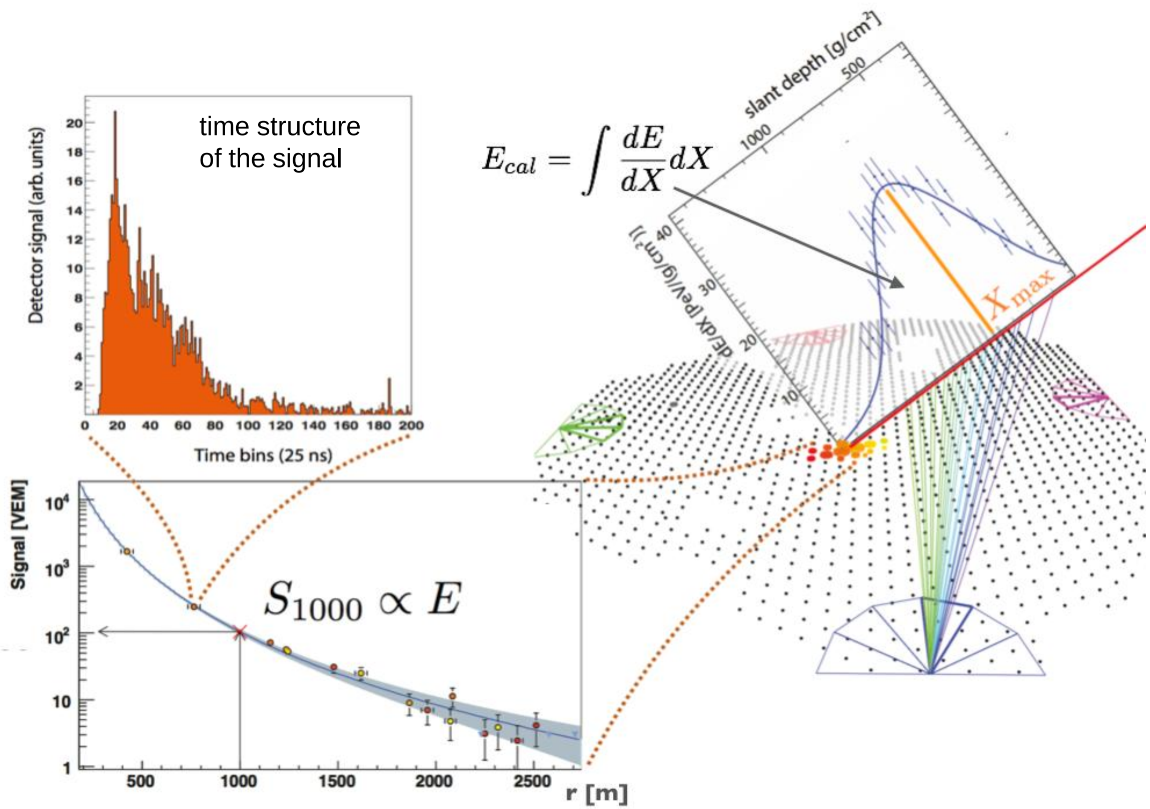


Use simultaneously both fluorescence detector (FD) and surface array (SD) techniques

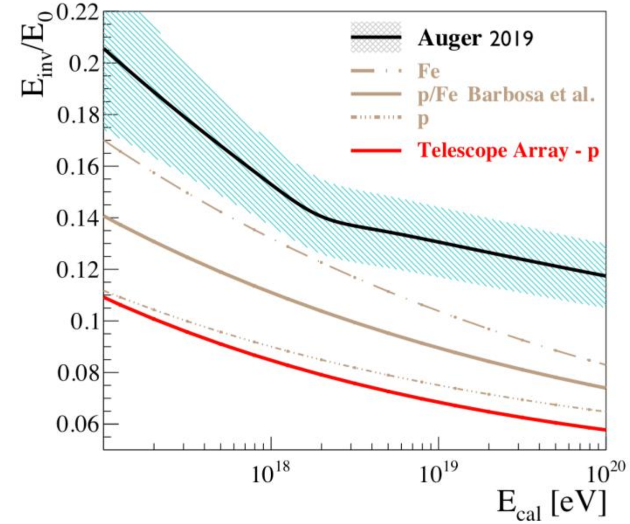


Pierre Auger Observatory

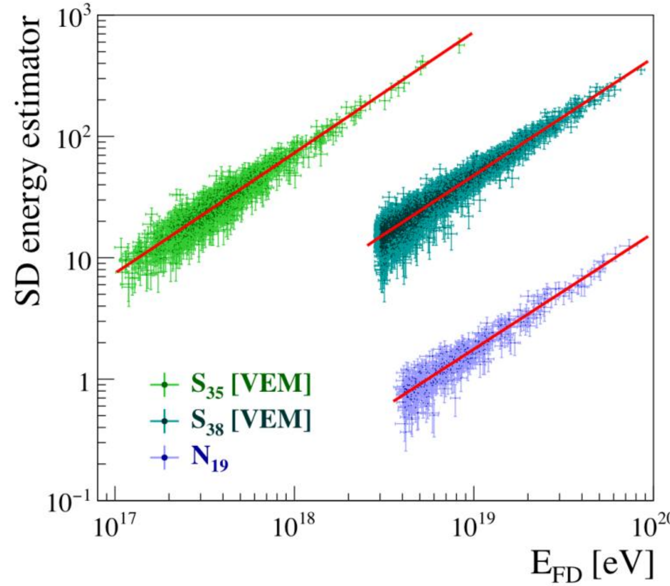
Hybrid reconstruction



invisible energy fraction



$E_{FD} = E_{cal} + E_{inv}$

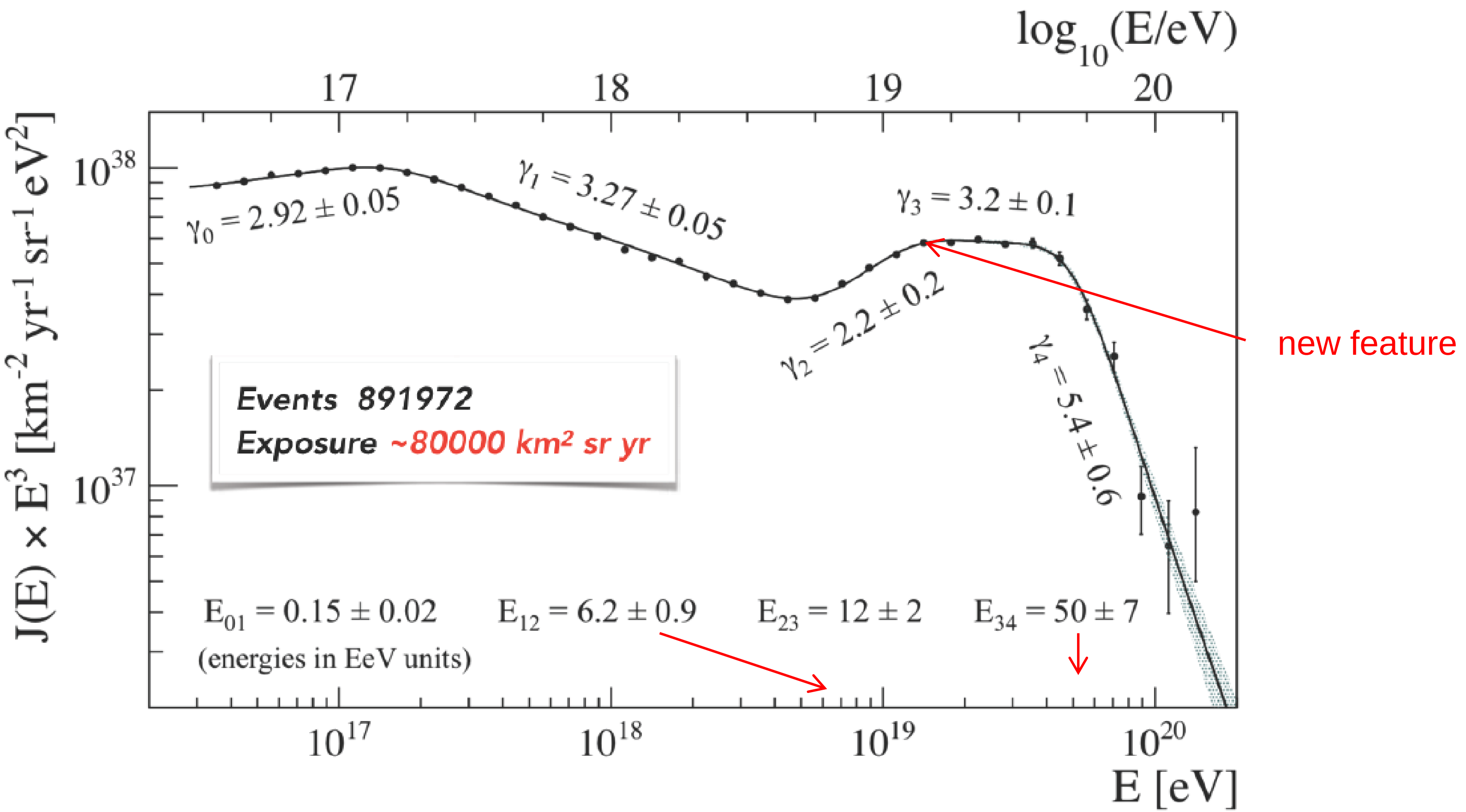


Energy scale set by Fluorescence Detector
$\sigma(E_{FD})/E_{FD} \sim 8\%$
Systematic uncertainty 14%

Combined energy spectrum

Hybrid FD+SD
SD 1500 m Θ< 60 deg
SD 1500 m Θ> 60 deg
SD 750 m
Cherenkov

combined



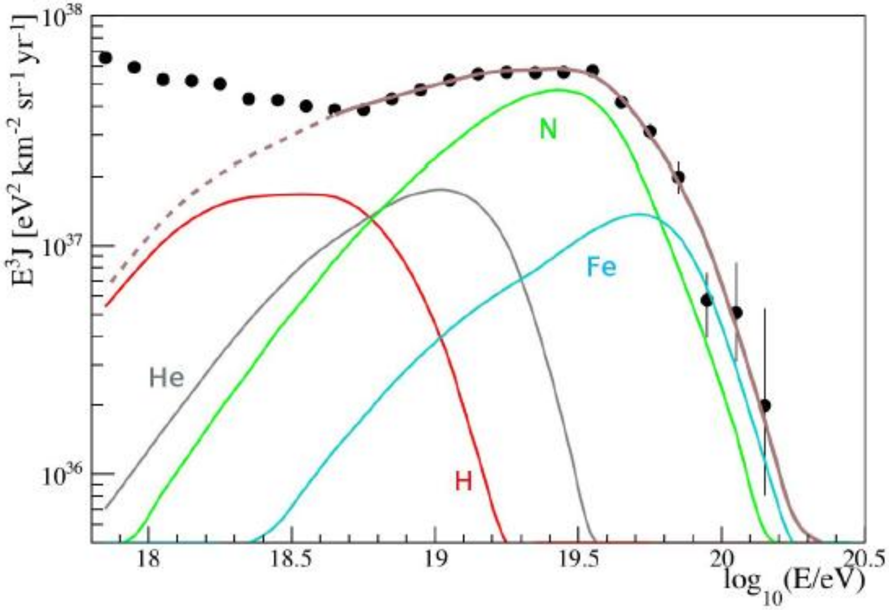
Except at the highest energies, uncertainties dominated by systematics

Astrophysical interpretation?

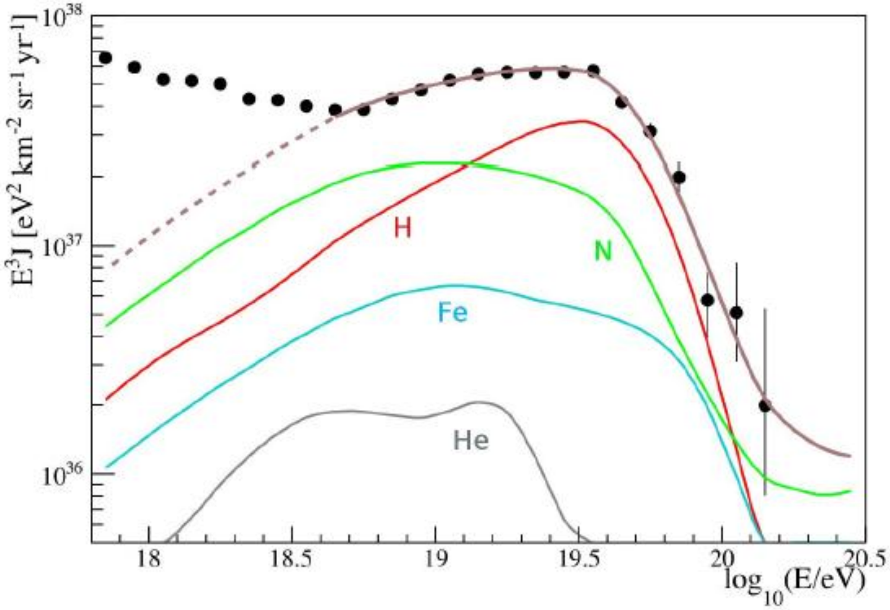
The flux suppression may be due to the GZK effect,
or to a limit of acceleration efficiency at the sources

Examples of spectrum scenarios:

Maximum acceleration efficiency
$E_{max}(A) = Z\, E_{max}(p)$

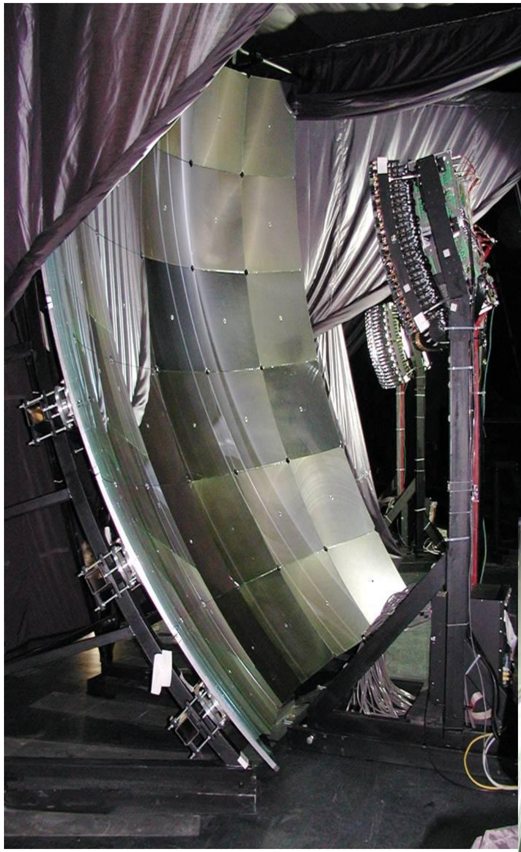


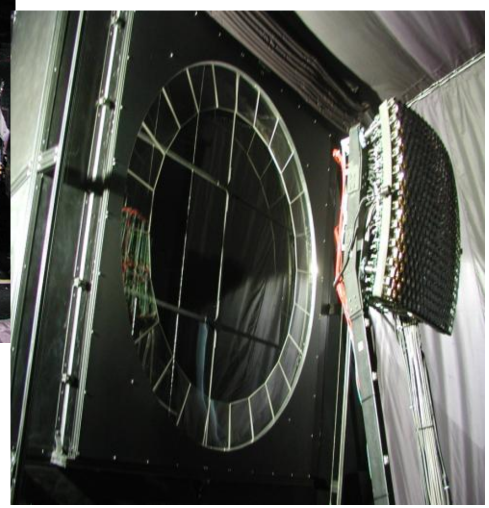
propagation effect
GZK/disintegration

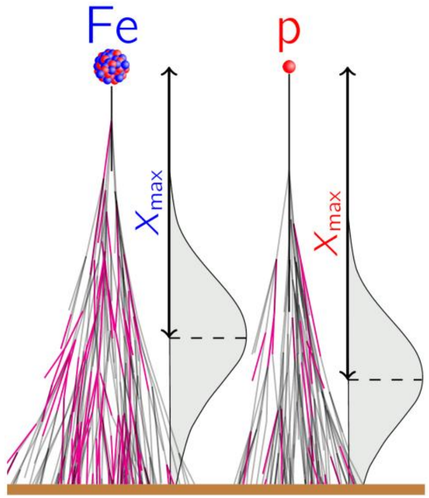


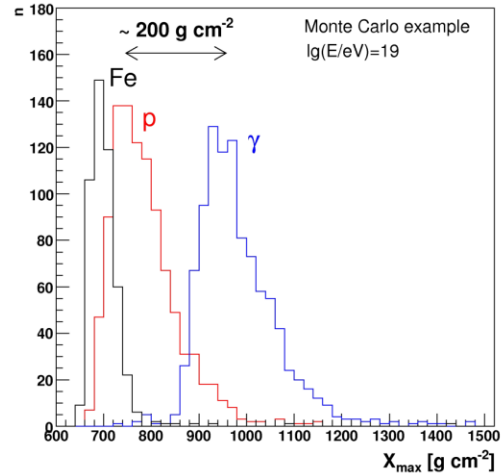
Need precise composition measurements

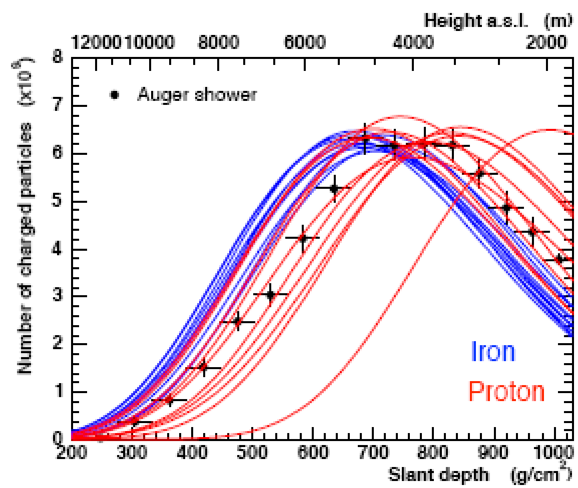
Mass composition with FD







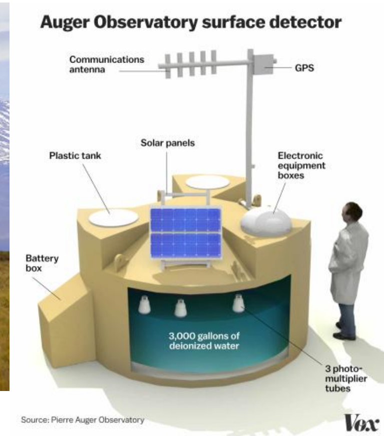


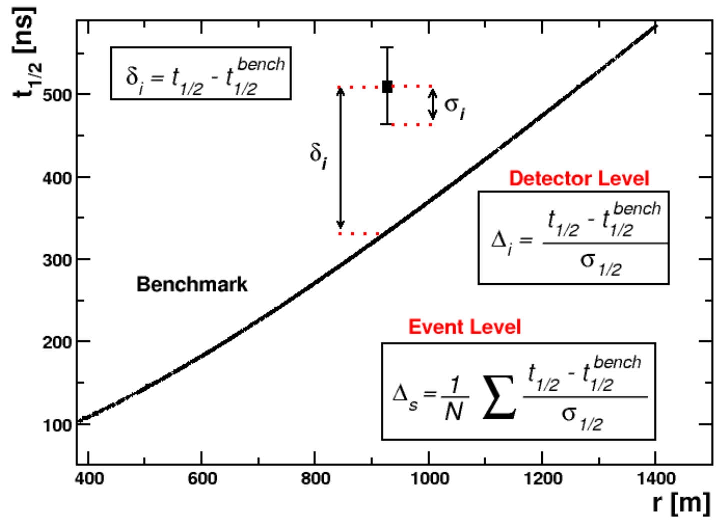


Heavy primaries produce shallower, less fluctuating showers

$X_{max}(Fe) < X_{max}(p) < X_{max}(\gamma)$ $RMS[X_{max}(Fe)] < RMS[X_{max}(p)]$

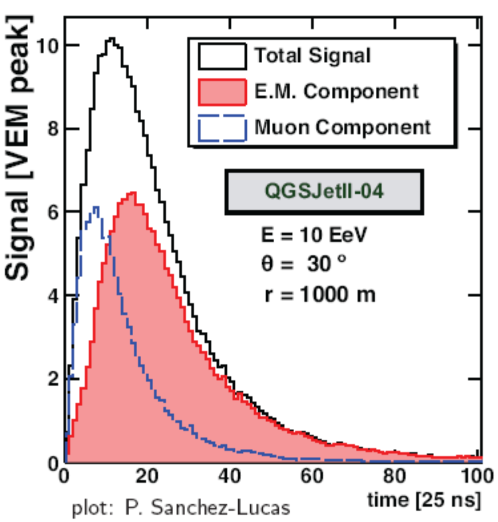
Mass composition with SD

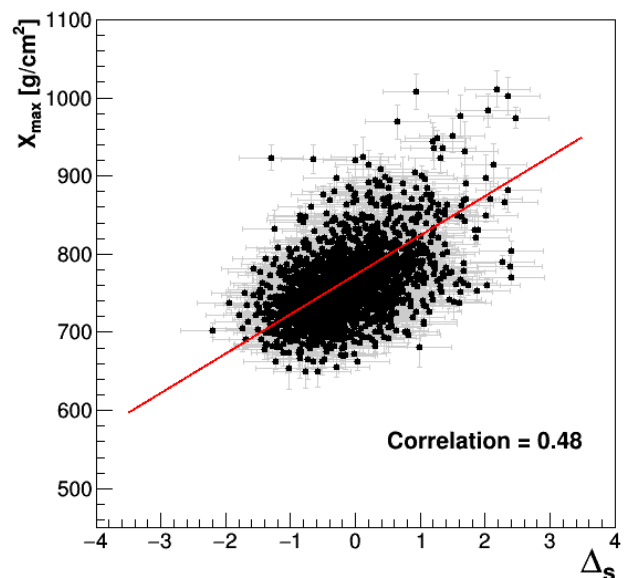




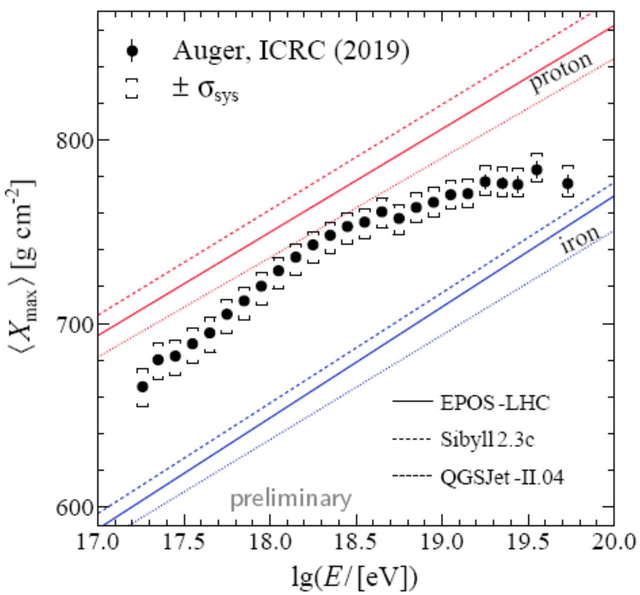
The Delta method based on signal rise time measurement

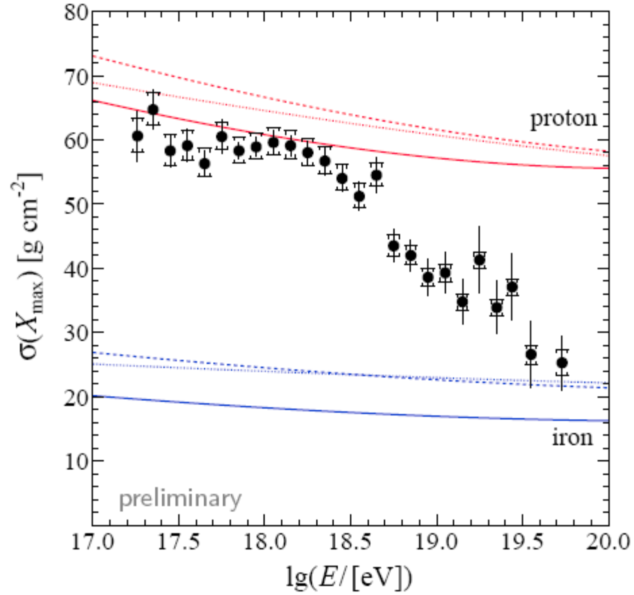
Muons arrive earlier in the shower front





Mass composition: X_{max}

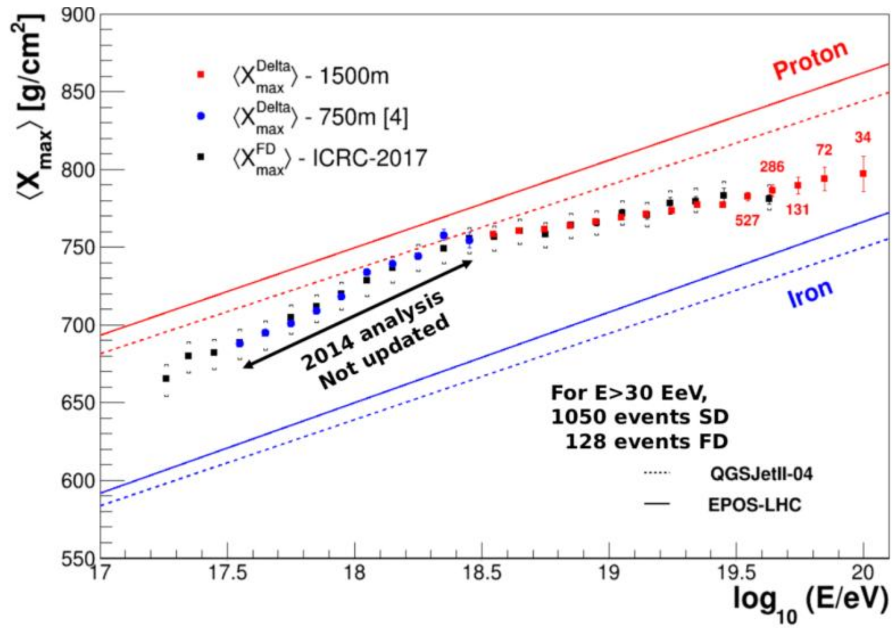




Composition NOT constant:
Lighter up to 2 EeV, heavier above.

FD and SD results consistent

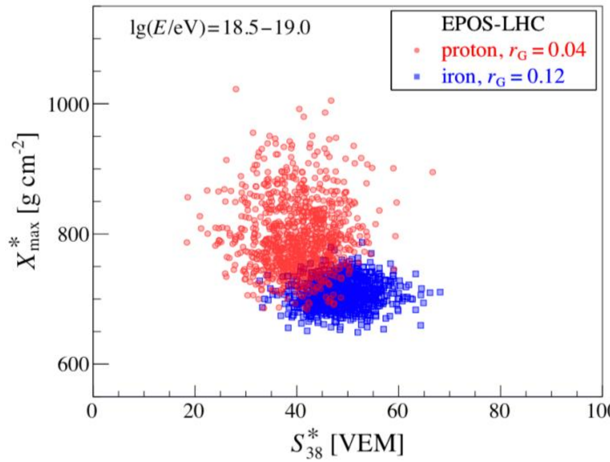
Result depends on model of hadronic interactions used

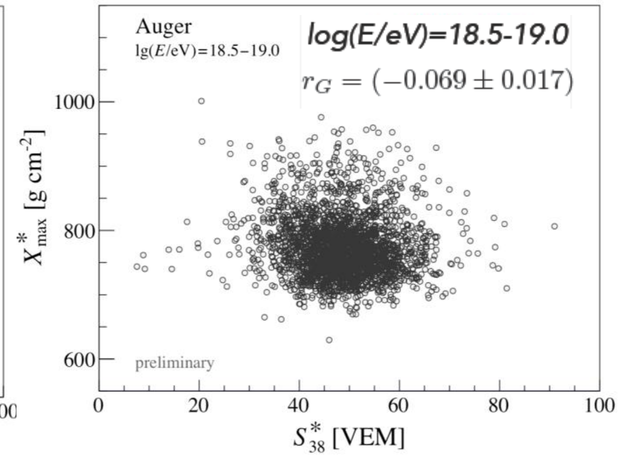


Mass composition at the ankle

Correlation of X_{max} and SD signal

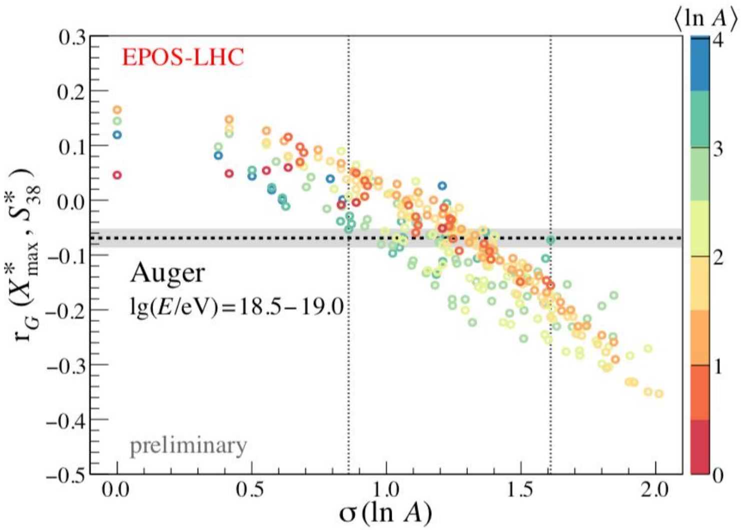
Expect negative correlation for mixed primaries

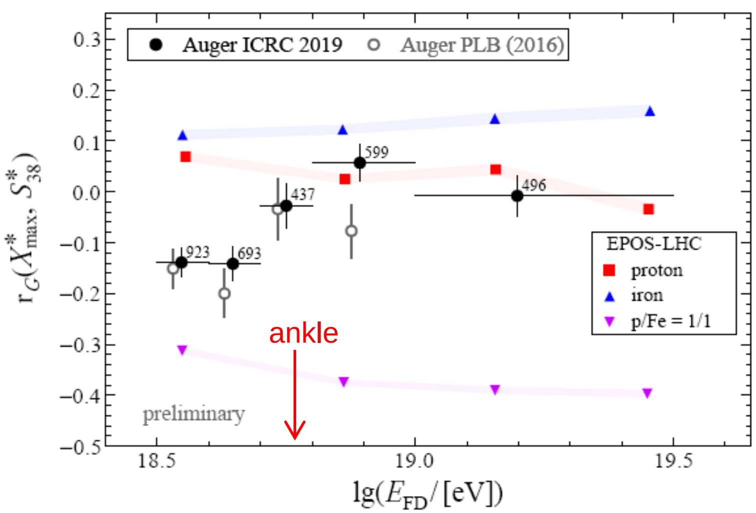




Up to the ankle pure or (p+He) compositions excluded at >6**σ**

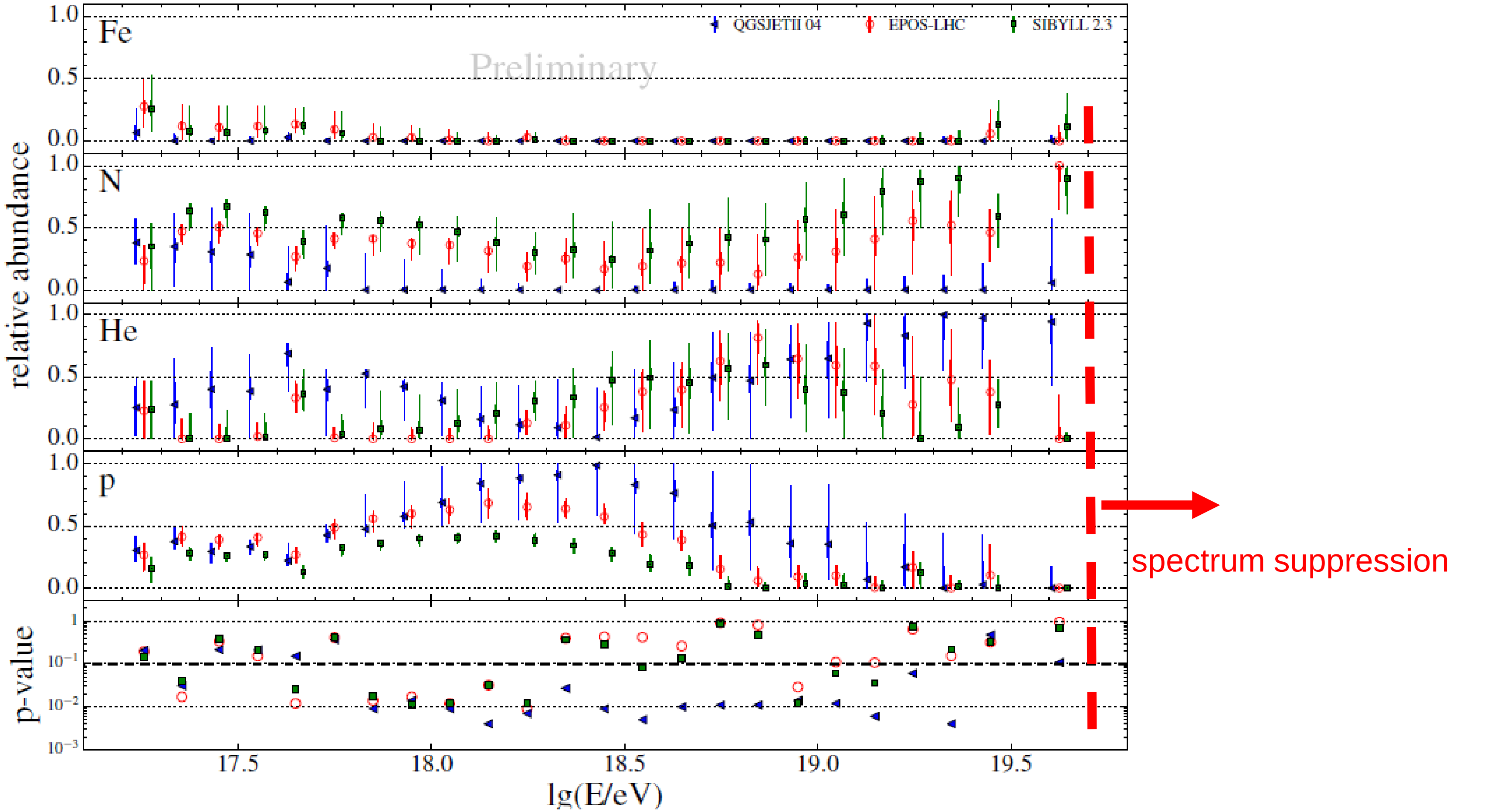
At higher energies, correlation consistent with less mixed composition





Composition fits

Fractions of different nuclei in CR spectrum, based on X_{max}



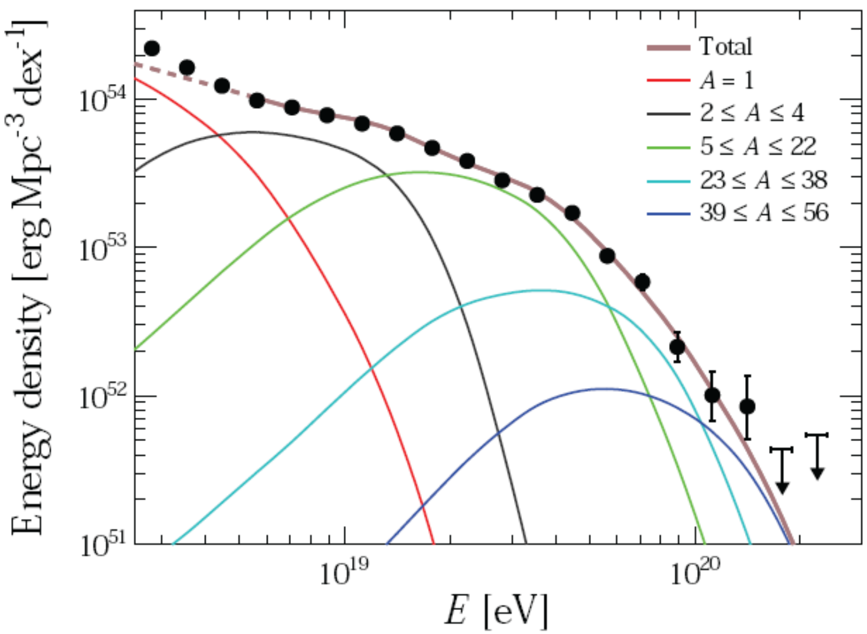
Are there protons at E > 5x10^{19} eV?

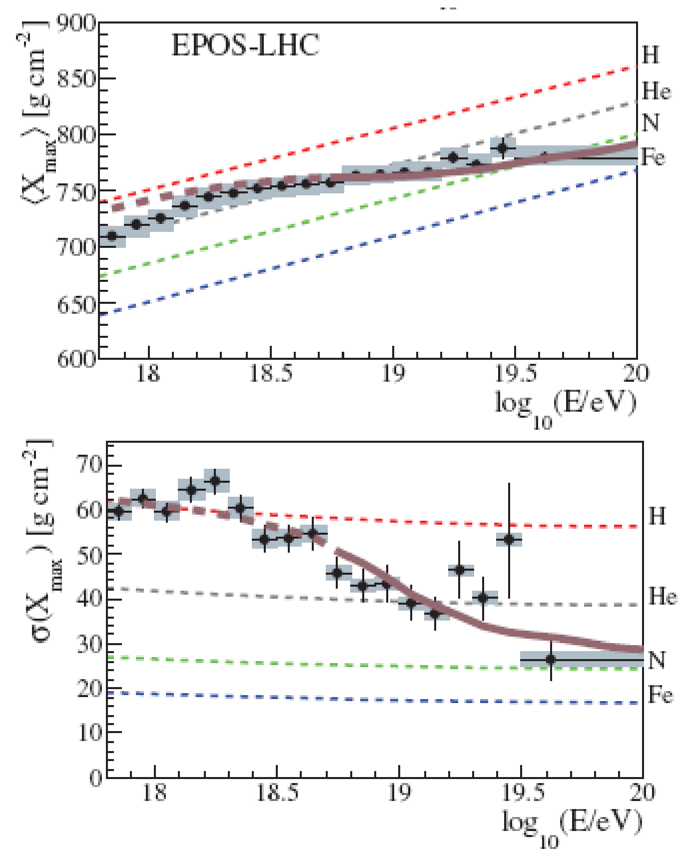
i.e. should one expect pointing to sources?

Origin of the spectrum suppression?

Is the suppression an effect of acceleration (max. acceleration efficiency?
or propagation (GZK)?

Energy from continuously emitting sources



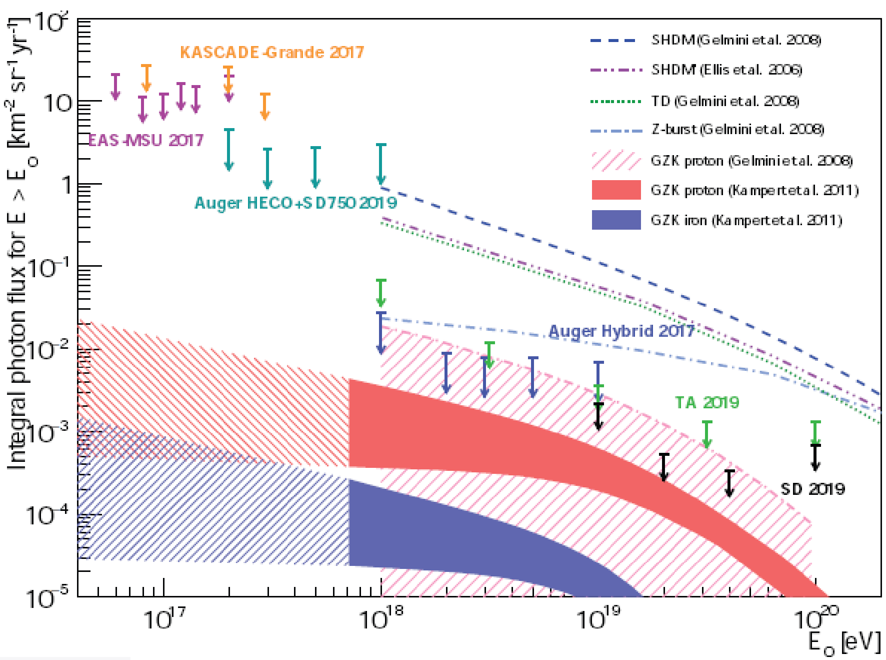


Scenario of maximum acceleration efficiency favoured (sources run out of steam)

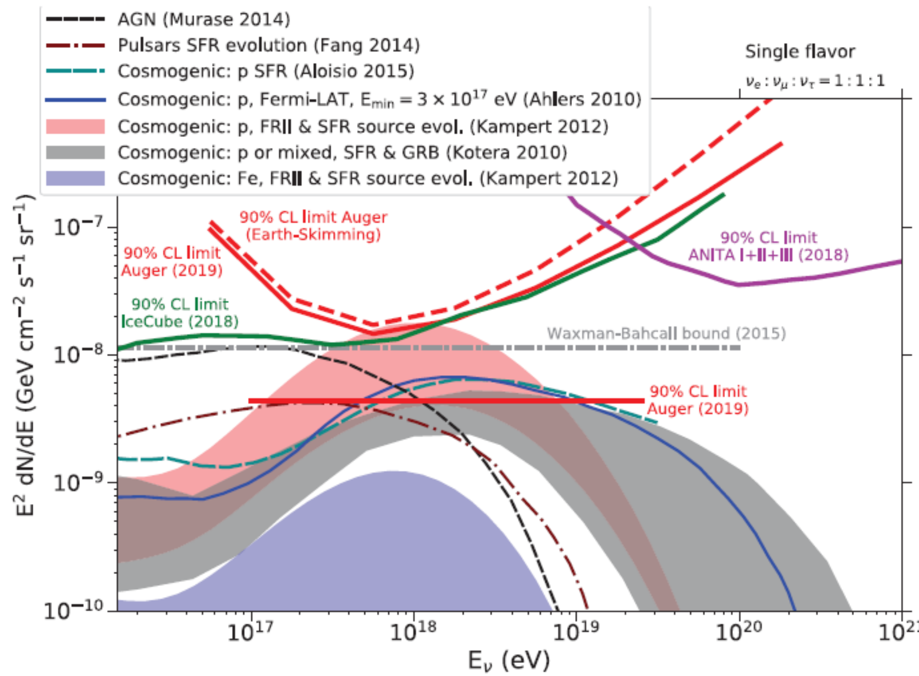
Cosmogenic photon and neutrino fluxes

Photons $p + \gamma \rightarrow p + \pi^0 \rightarrow \gamma + \gamma$

Neutrinos $p + \gamma \rightarrow n + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$



Most sensitive detector at E_γ > 0.2 EeV



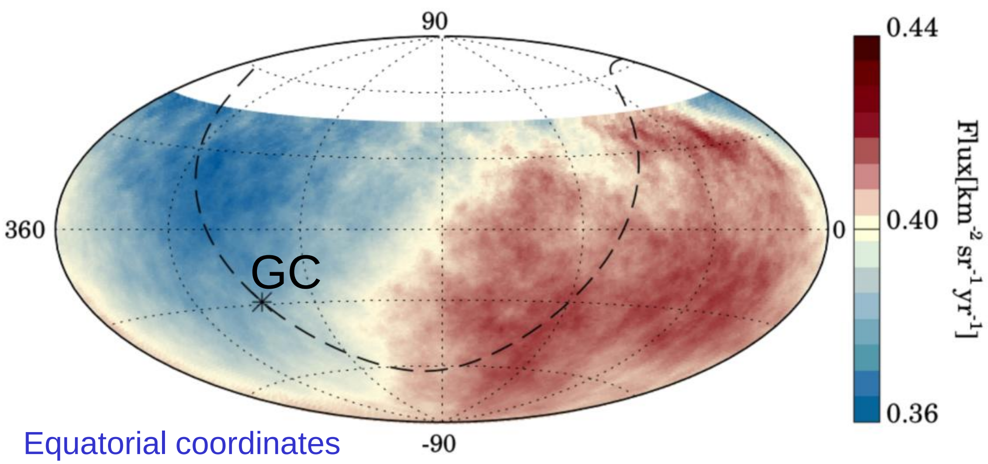
Maximum sensitivity around EeV
k (90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

No UHE photons nor neutrinos detected → exotic models of UHECR origin disfavoured
constraints on proton-dominated astrophysical sources

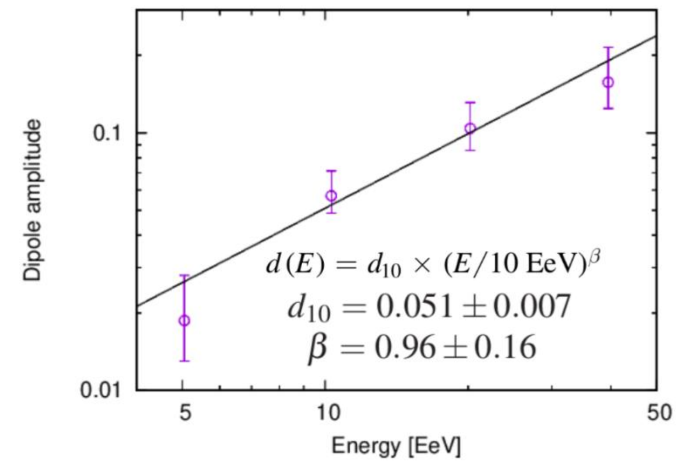
Large scale anisotropy

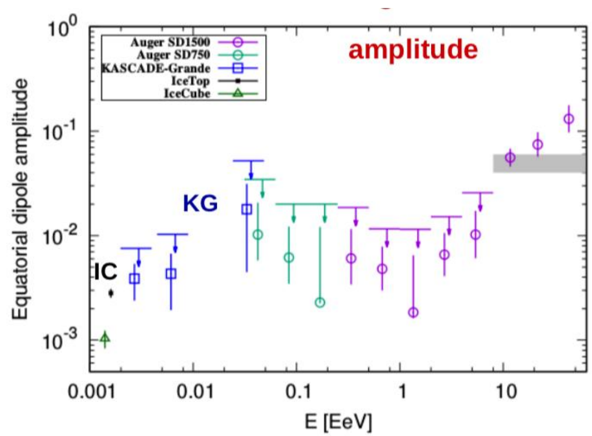
3-D dipole above 8 EeV at **(α,δ) = (98º,-25º)**
~125º away from Galactic center
amplitude: $(6.6^{+1.2}_{-0.8})\%$

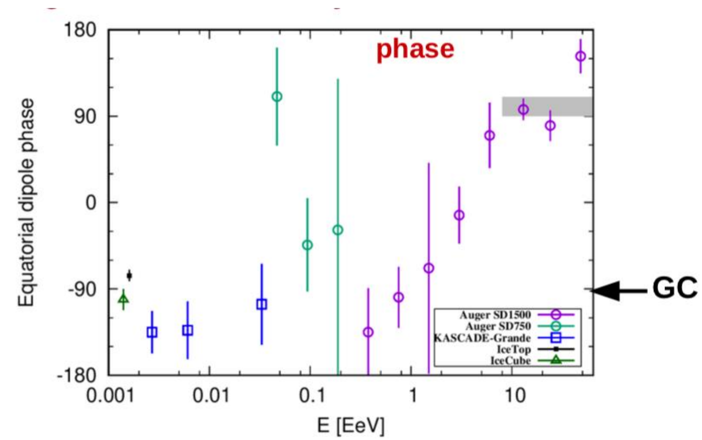
amplitude increasing with energy



Equatorial coordinates



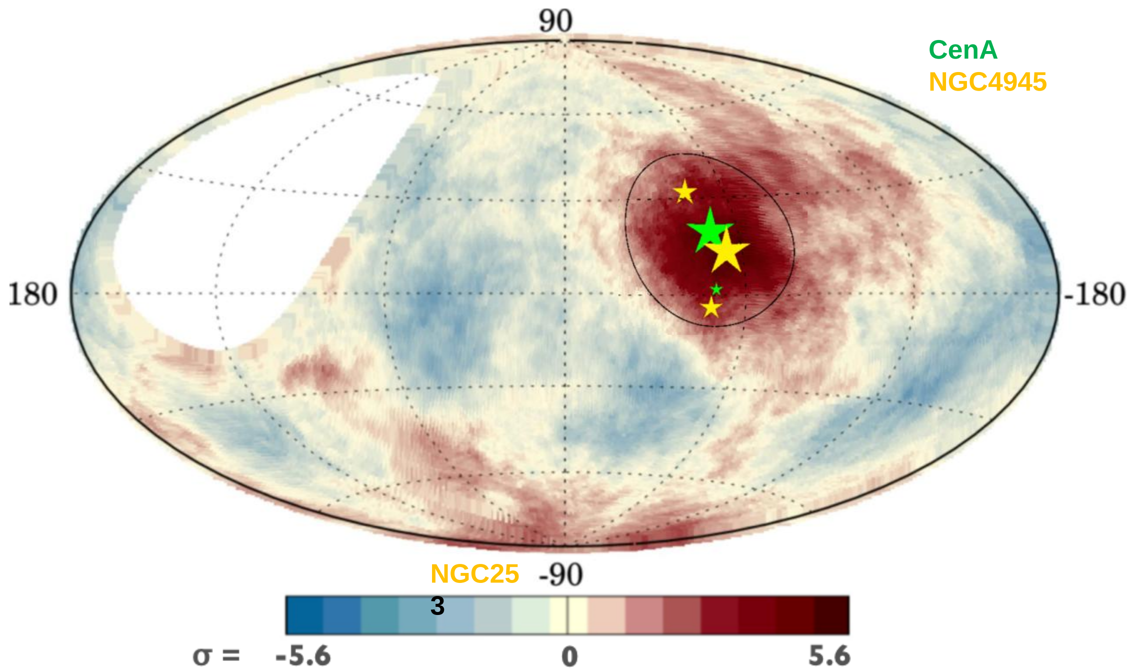




Predominantly Galactic origin below 1-2 EeV, extragalactic origin above

Intermediate scale anisotropy

2157 events with E > 32 EeV
Total exposure 101 400 km^2 sr yr



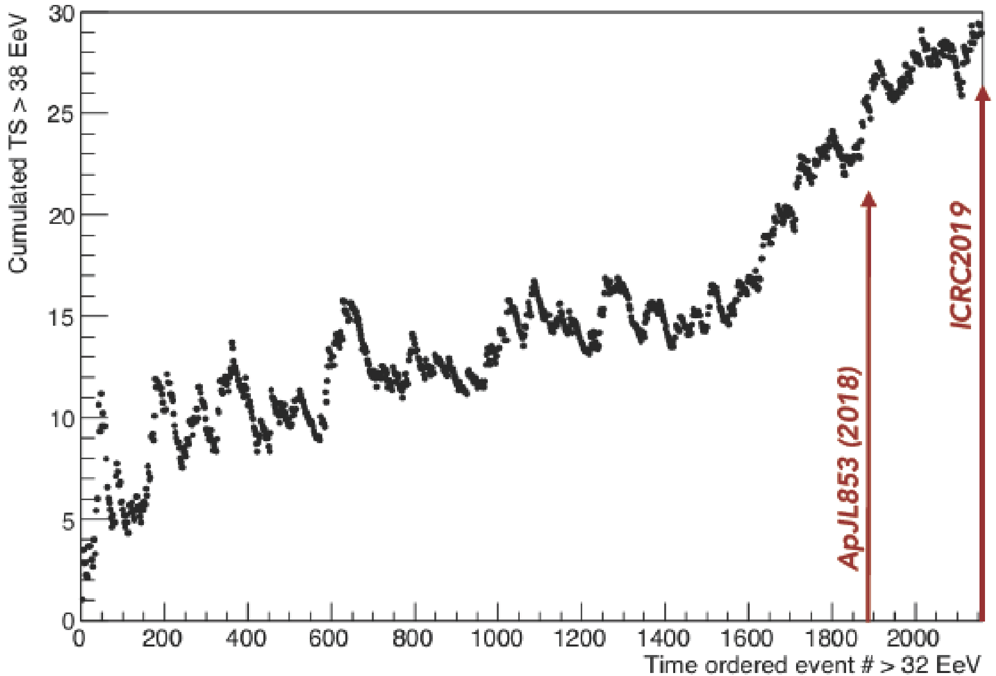
Blind search:
32 EeV ≤ E_{th} ≤ 80 EeV (1 EeV steps)
1° ≤ ψ ≤ 30° (1° steps)

Most significant excess for E>38 EeV: (α=202º, δ= -45º) ~2 º from CenA

CenA: 3.9 σ effect (post-trial) for E>37 EeV, 28° window

Intermediate scale anisotropy

Catalog search

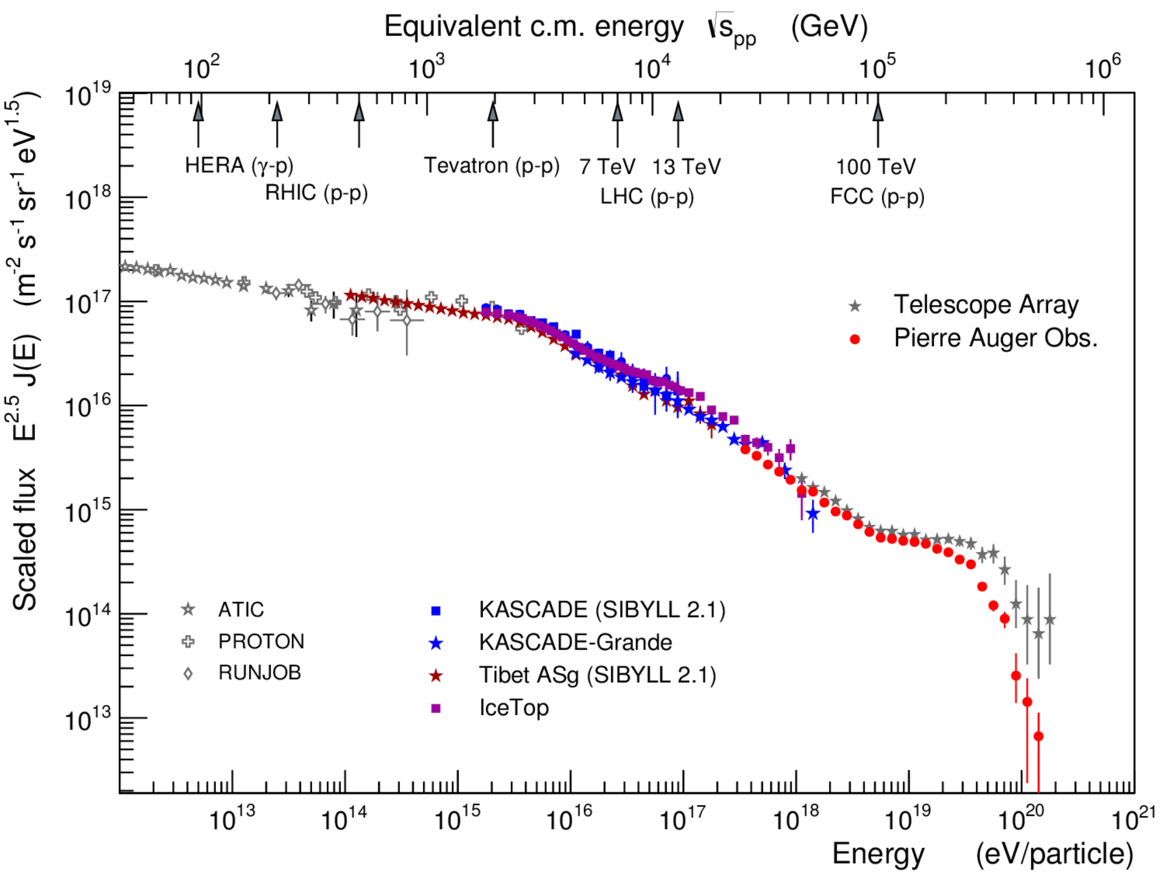


Rejection of isotropy hypothesis

ApJ Lett. (Jan 2004-Apr2017)	**4.0 σ**	for SBGs
	2.7 σ	for ϒ-AGN
ICRC2019 (Jan 2004-Aug2018)	**4.5 σ**	for SBGs
	3.1 σ	for ϒ-AGN

Significance increasing with time!

Cosmic ray and accelerator energies



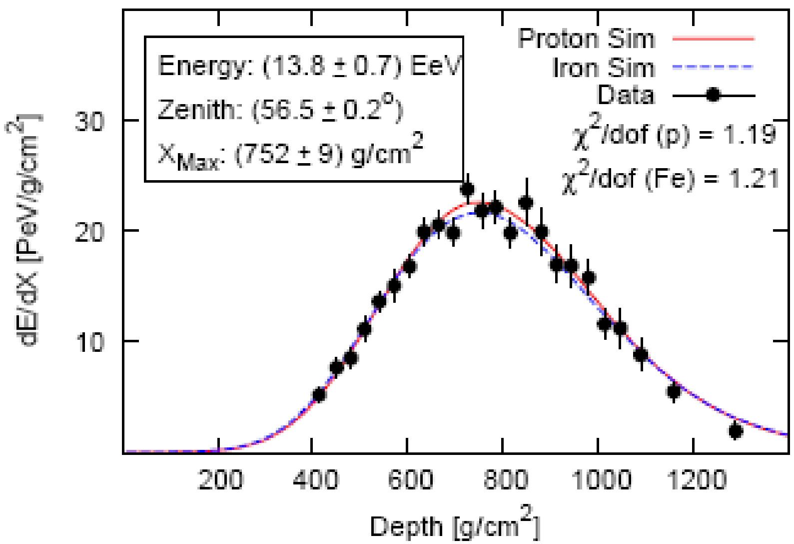
In modelling UHE showers, one needs to extrapolate properties of nuclear interactions from lower energies

Can do particle physics with cosmic rays

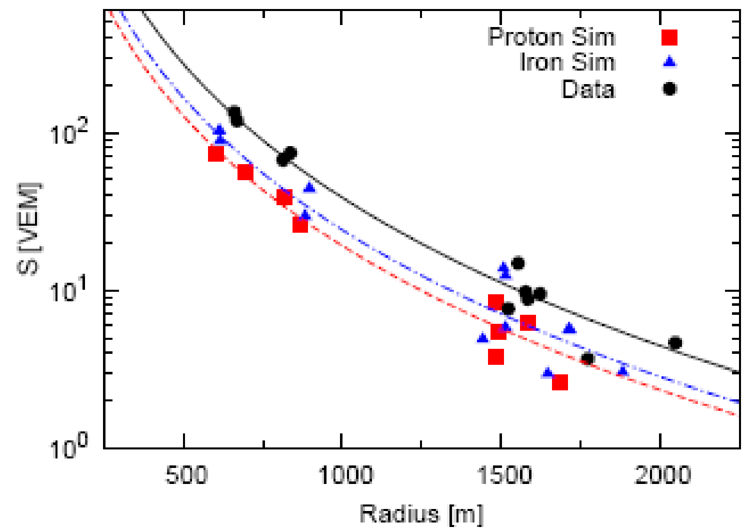
Hadronic interactions

Hybrid events (FD + SD)

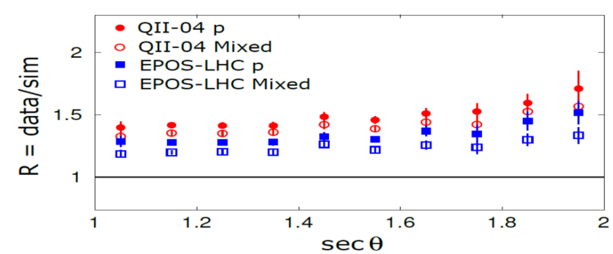
Measured shower and simulated longitudinal FD profile



Same shower and simulated SD signal



R = S(data)/S(sim)



Models underestimate the shower signal

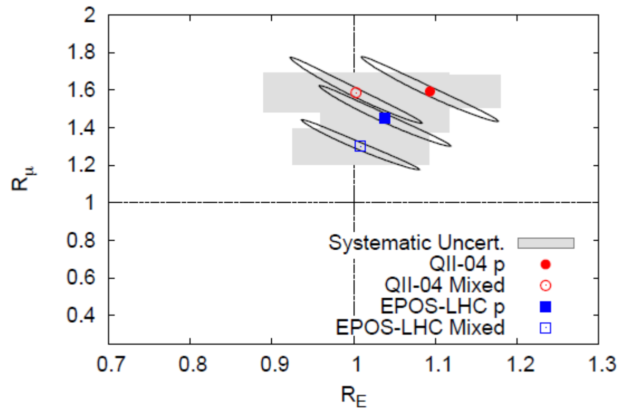
Hadronic interactions

Fitting models to data with rescaling of energy and muon component

$$S_{\rm resc}(R_E, R_\mu)_{i,j} \equiv R_E\, S_{{\rm EM},i,j} + R_E^{\alpha} R_\mu\, S_{\mu,i,j}$$

i = evt
j = primary type

and fitting to data

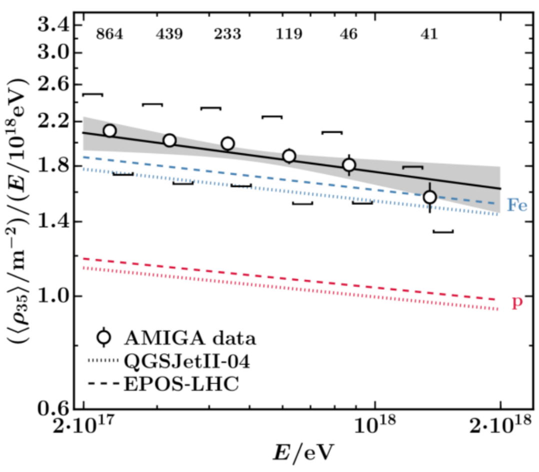


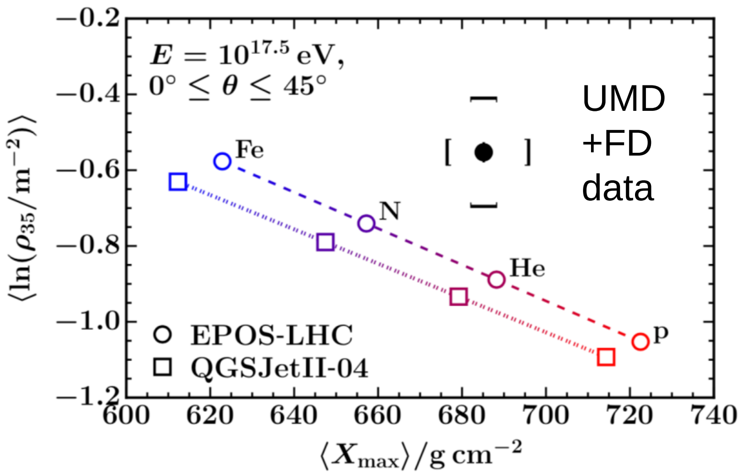
Muon deficit in simulations: 30-60 %

Energy ~ OK

PRL 117 192001 (2016)

New data from Underground Muon Detector (at lower energy)



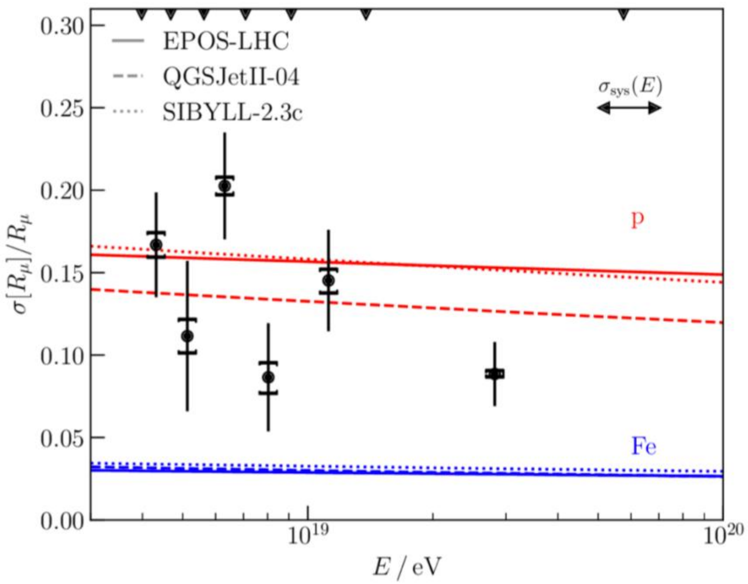


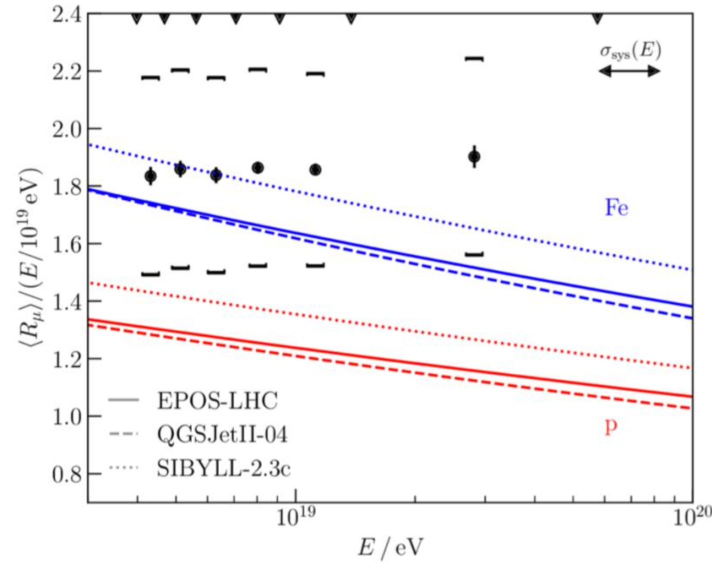
Models do not reproduce muon densities
Compatible with other analyses

Fluctuations in the muon content of showers

Inclined showers (62°<θ<80°) are muon-dominated at ground

muon ratio $R_\mu = N_\mu / N_\mu(10^{19}\ \text{eV})$





Fluctuations in the muon number dominated by the first interaction

compatible with expectations → the muon problem not due to the first interaction?

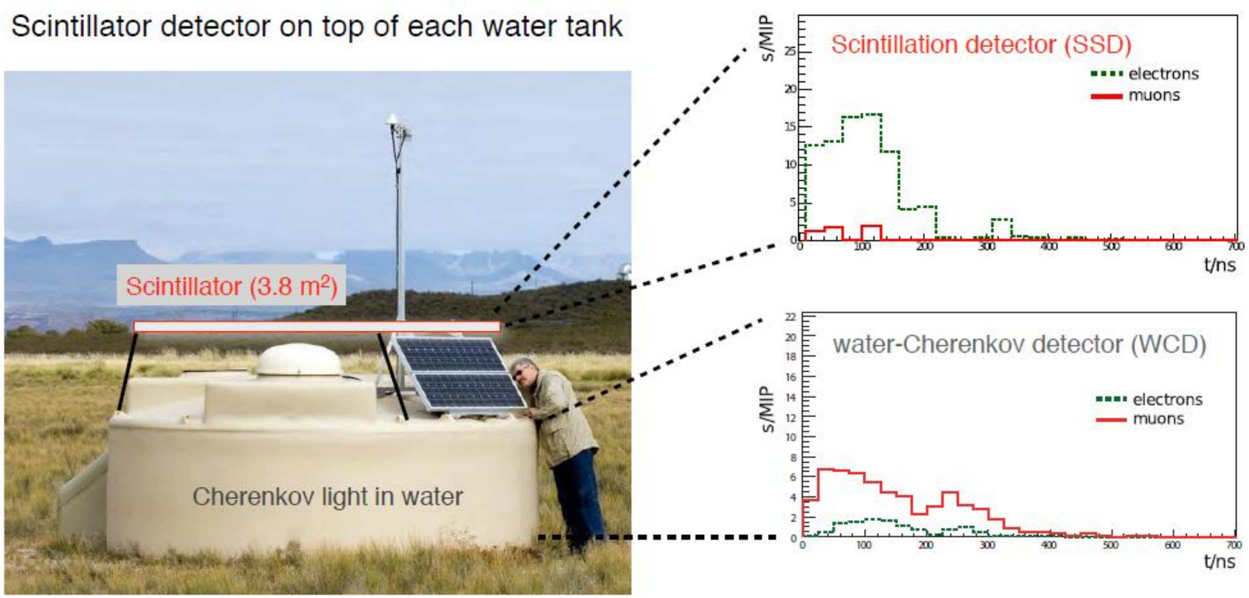
AugerPrime: the upgrade of the Observatory

• Study the spectrum suppression region with composition information
→ explain the origin of the suppression

• Select light primaries for charged particle astronomy

• Provide better estimates for UHE neutrino and photon fluxes → establish potential for future experiments

• Better measure shower components, study hadronic interactions at UHE, search for non-standard physics



Can measure simultaneously shower energy and ratio of muon to EM component of shower

AugerPrime: the upgrade of the Observatory

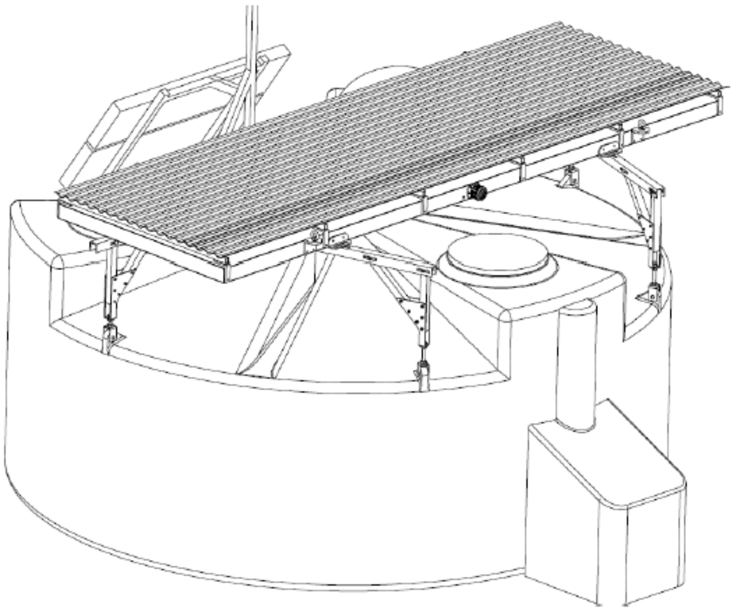
- New Scintillator Surface Detector (SSD) at each SD station
- New electronics: faster sampling, larger dynamic range
- Underground Muon Detector (UMD)
- Radio Detector (RD) at each SD station

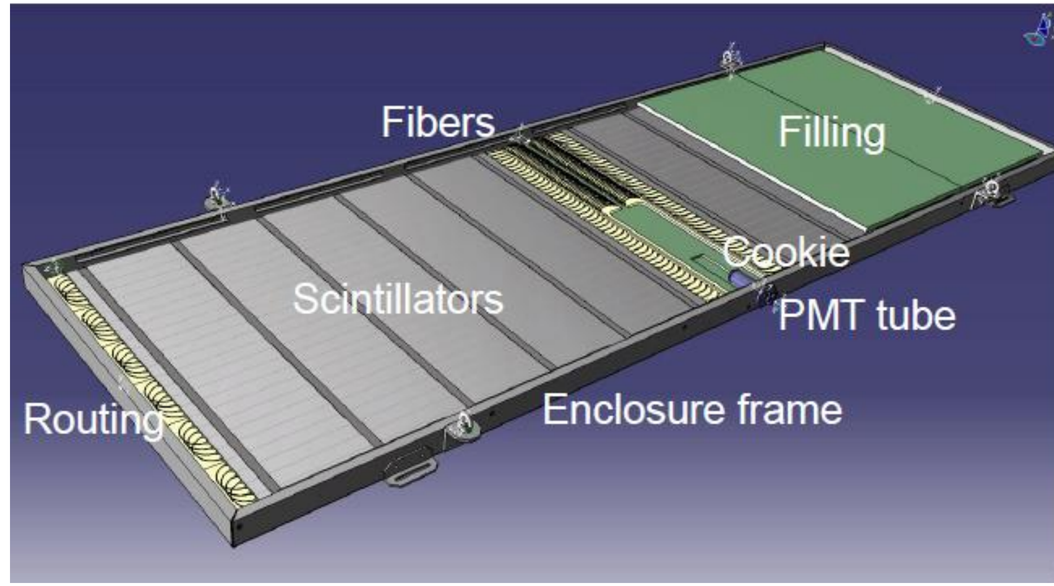
…under way:

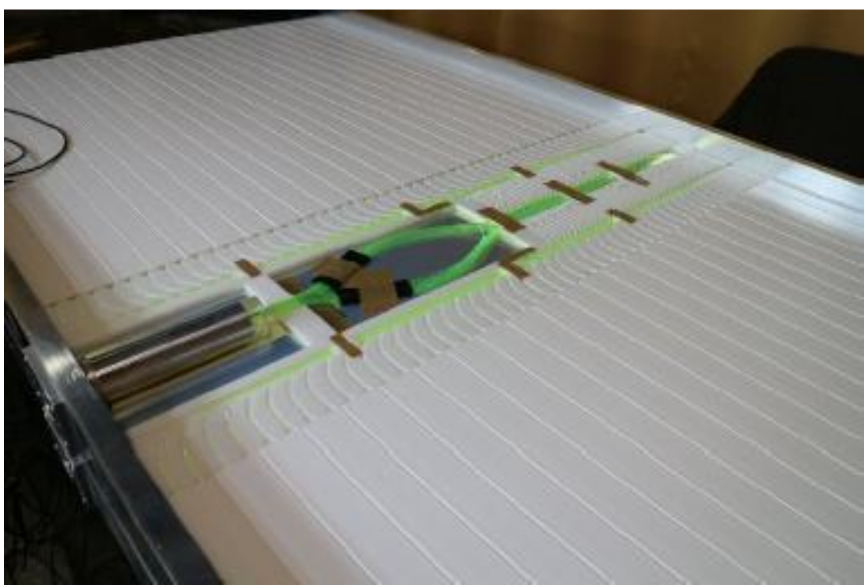
Deployment of SSD, UMD, RD ongoing

Engineering Array (12 upgraded stations) since 2016 and
Pre-production array (80 stations) since March 2019 are taking data

Assembling SSD detectors at IFJ PAN







Summary

Complex UHECR spectrum, strong suppression
Maximum acceleration efficiency scenario favoured (sources run out of steam)

Evidence for a mixed composition above 10 EeV

Large-scale anisotropy: evidence for extragalactic origin of UHECRs beyond 8 EeV

Understanding the origin of the muon excess in the data is a key to disentangle
CR composition from hadronic interaction effects

AugerPrime upgrade will enable solving the muon problem,
CR composition measurements event-by-event for charged-particle astronomy