Pierre Auger Observatory

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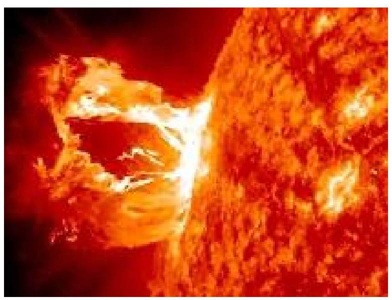
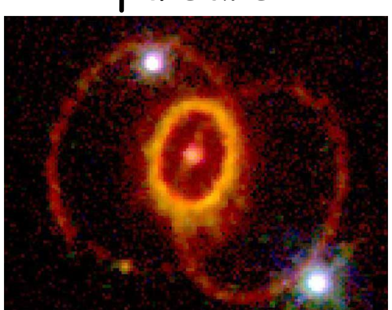
cosmic rays (CRs) – high-energy particles coming from space
(protons, nuclei, neutrinos, photons, electrons,…)

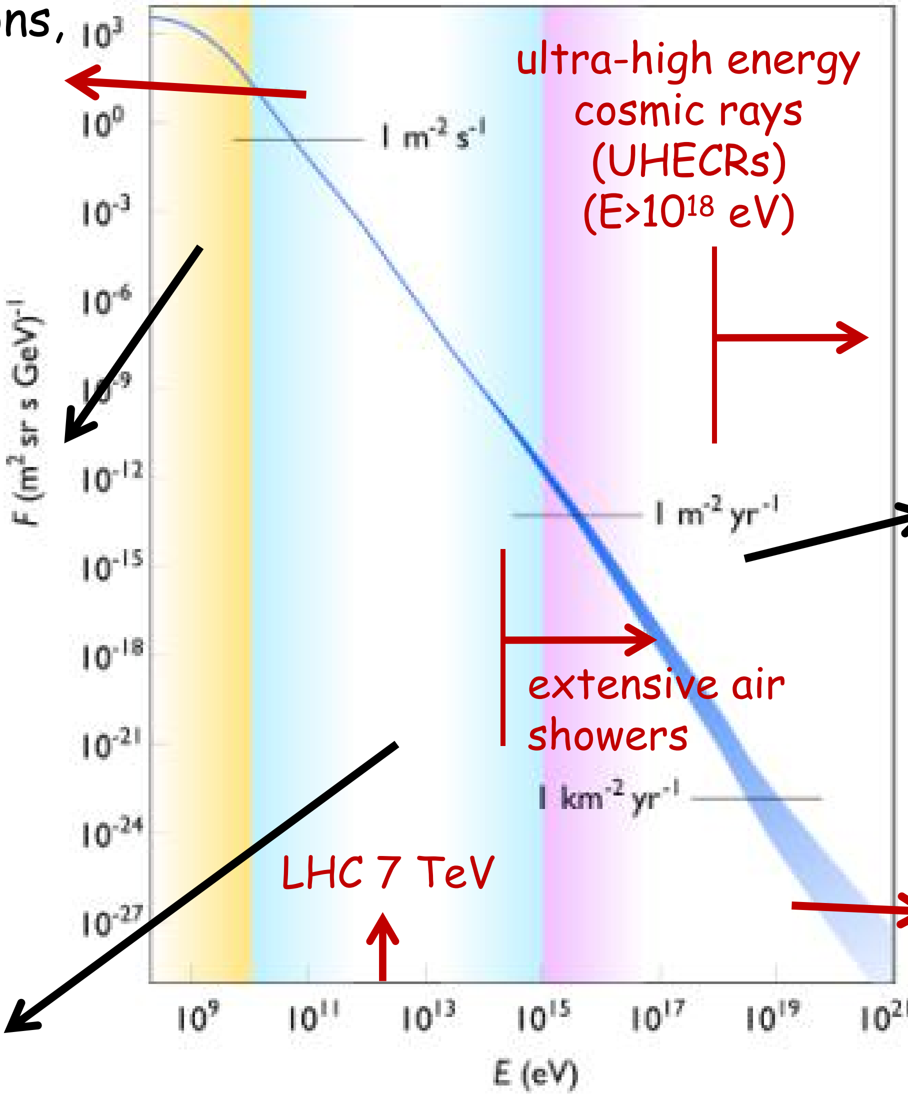
direct observations, satellites, balloon-borne experiments

Sun

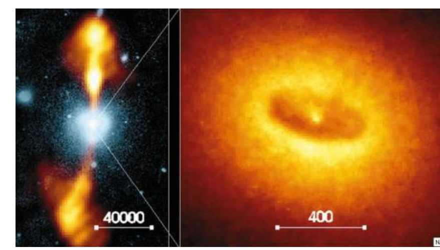


Supernovae, pulsars





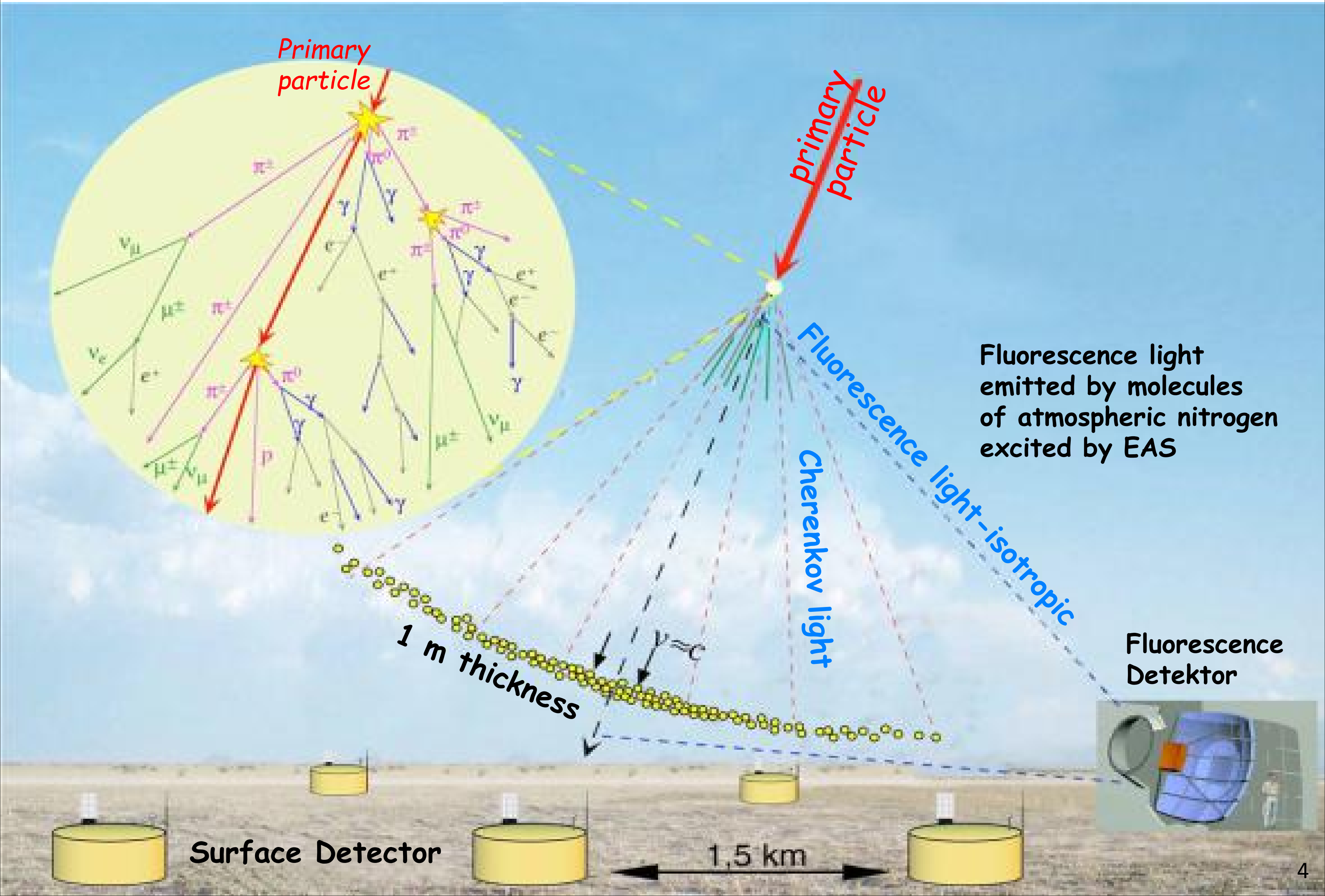
sources unknown, star burst galaxies, active galactic nuclei (AGNs) ???
see D. Góra talk
(„Theory of Cosmic Ray Origin")



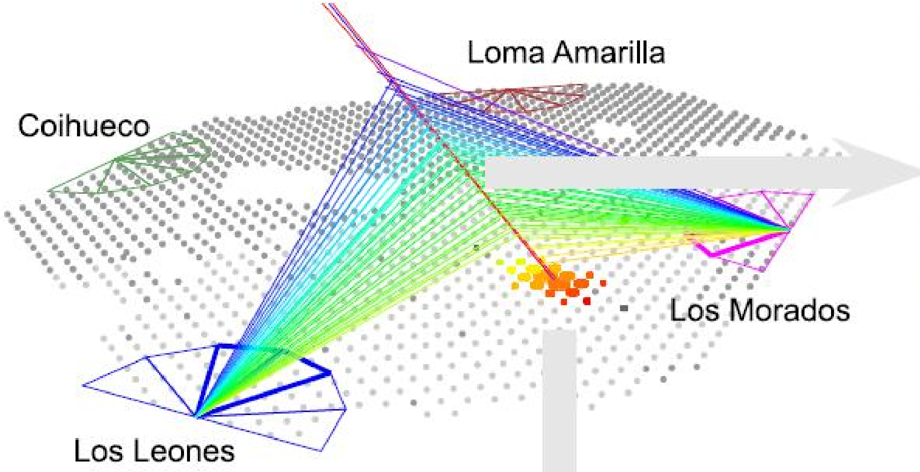
$E>10^{20}$ eV, low flux:
1 particle/km^{2}/1000 yr
(indirect observations, extensive air showers, detector arrays covering large area)

Detection

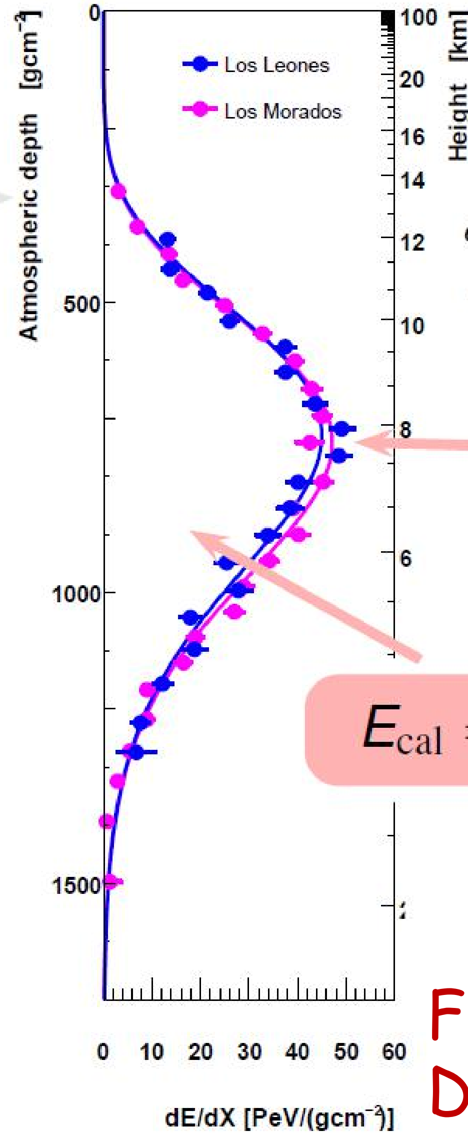
Extended air showers (EAS)



Detection of air showers



top of the atmosphere



duty cycle 13%

$\sigma X_{\max} \leq 20\,\mathrm{g/cm^2}$

$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

$X_{\max}$

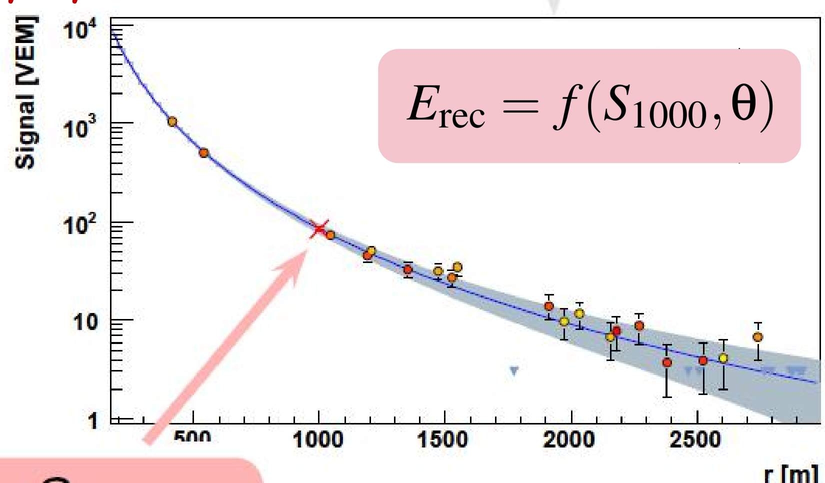
$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E / E \sim 8\,\%$

$\Delta_{\mathrm{sys}} \approx 15\,\%$

Fluorescence Detector (FD)

duty cycle 100%



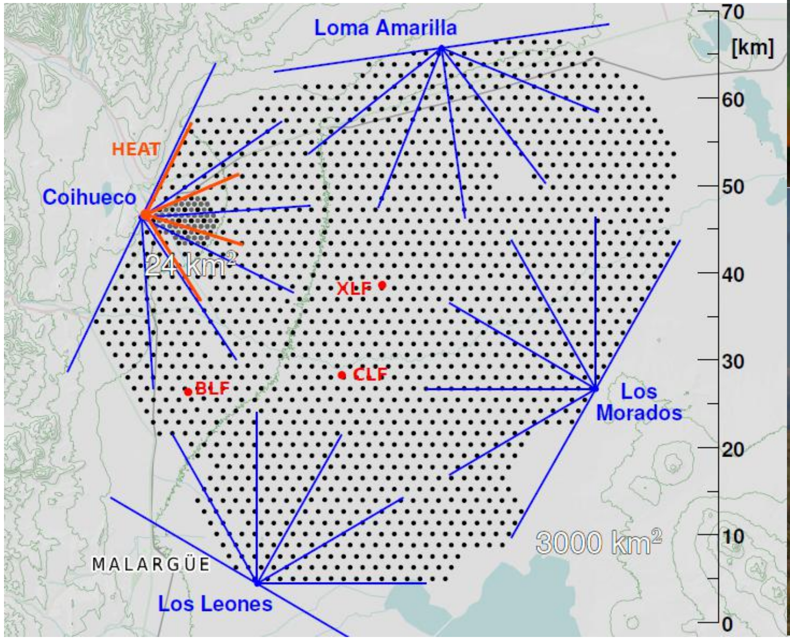
S_{1000}

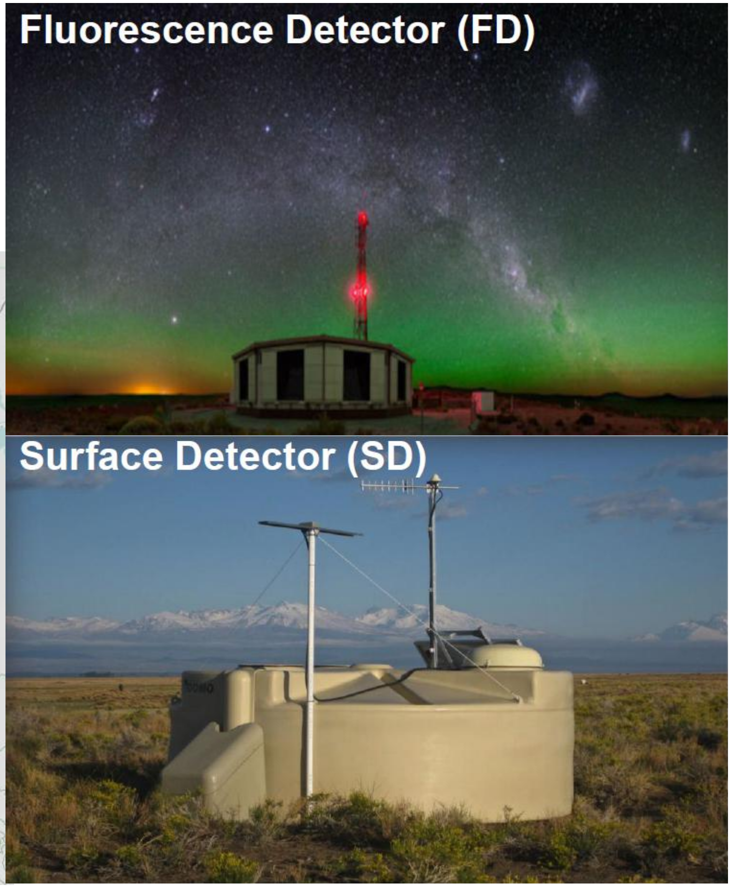
$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

Surface Detector (SD)

Pierre Auger Observatory - the largest detector of ultra-high energy cosmic rays

Southern hemisphere
Pierre Auger Observatory (Auger)
Area: 3000 km²
Location: Argentina





- 1660 SD stations over 3000 km² (1500 m spacing)
- 5 FD stations

What is/are:	**sources**	**spectrum**	**mass composition**

Arrival directions

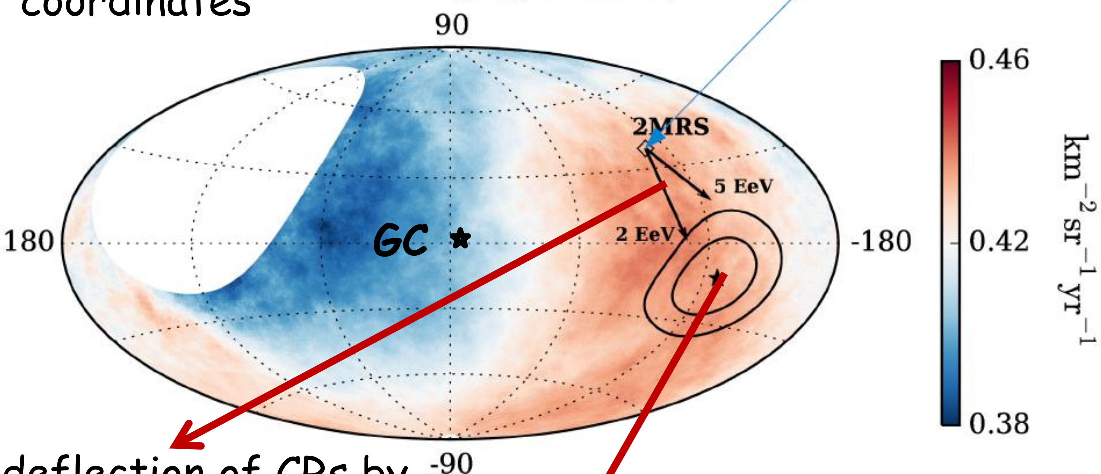
Auger observation of dipolar anisotropy in cosmic ray arrival directions above 8 EeV

Physics World: one of top 10 breakthroughs of 2017

The flux-weighted dipole from IR galaxy distribution in 2MRS points to (l,b)=(251°,38°) → ~55° from observed

[Erdogdu et al. 2006]

galactic coordinates



3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

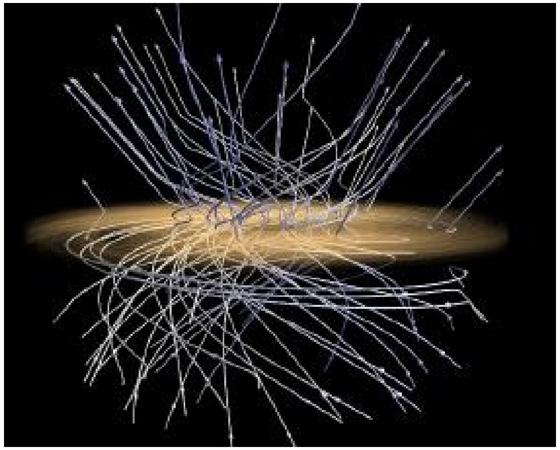
deflection of CRs by magnetic field

Observed dipole, Gal. coord. (l, b) = (233°, −13°), ~120° away from GC -> disfavours galactic origin

Large-scale anisotropy can arise from:

- inhomogeneous large-scale distribution of sources
- diffusion in magnetic fields

The outwardly-spiraling halo magnetic field of the Galaxy



Search for UHECRs correlation with:

➢ Starburst Galaxies

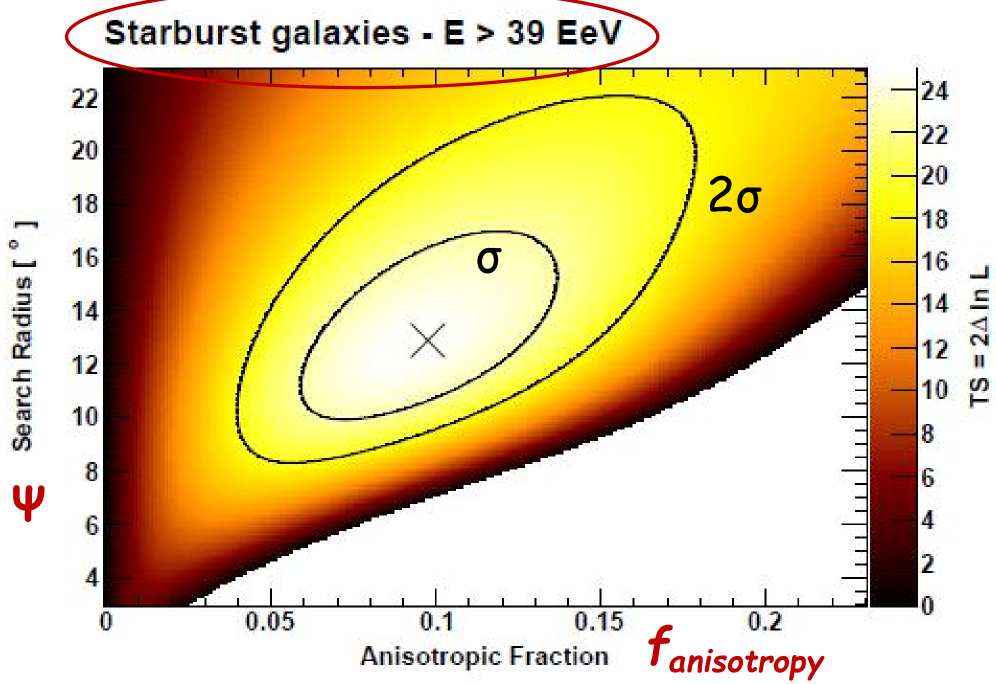
- *Fermi*-LAT search list for star-formation objects
- 23 objects within 250 Mpc

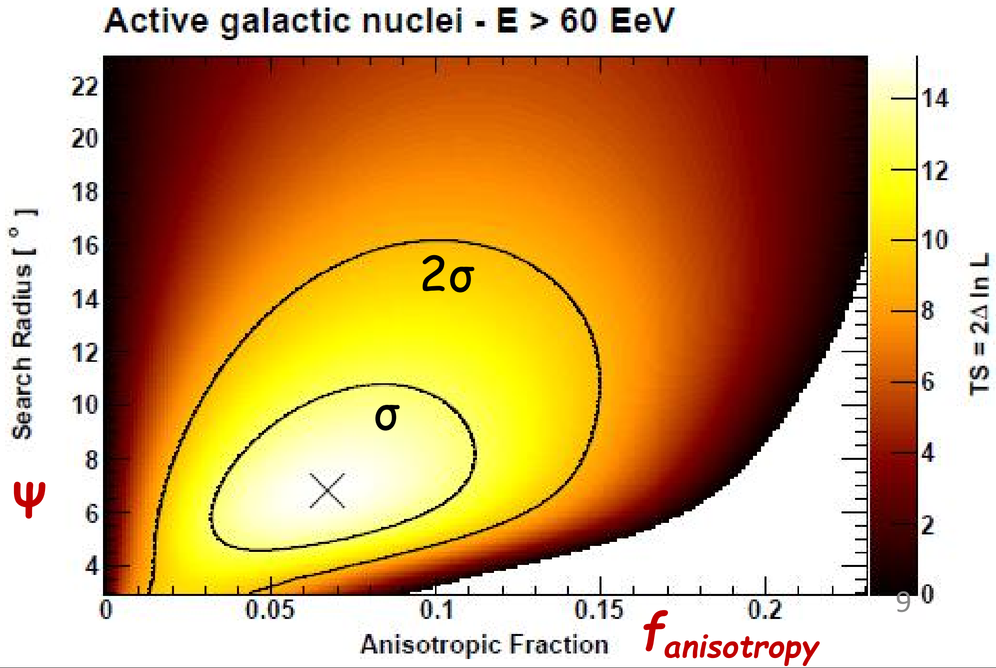
$f_{anisotropy}$ = 10%, Ψ = 13°
significance **3.9σ**

➢ γ-ray detected Active Galactic Nuclei

- 2FHL AGNs (*Fermi*-LAT)
- 17 objects within 250 Mpc

$f_{anisotropy}$ = 7%, Ψ = 7°
significance **2.7σ**



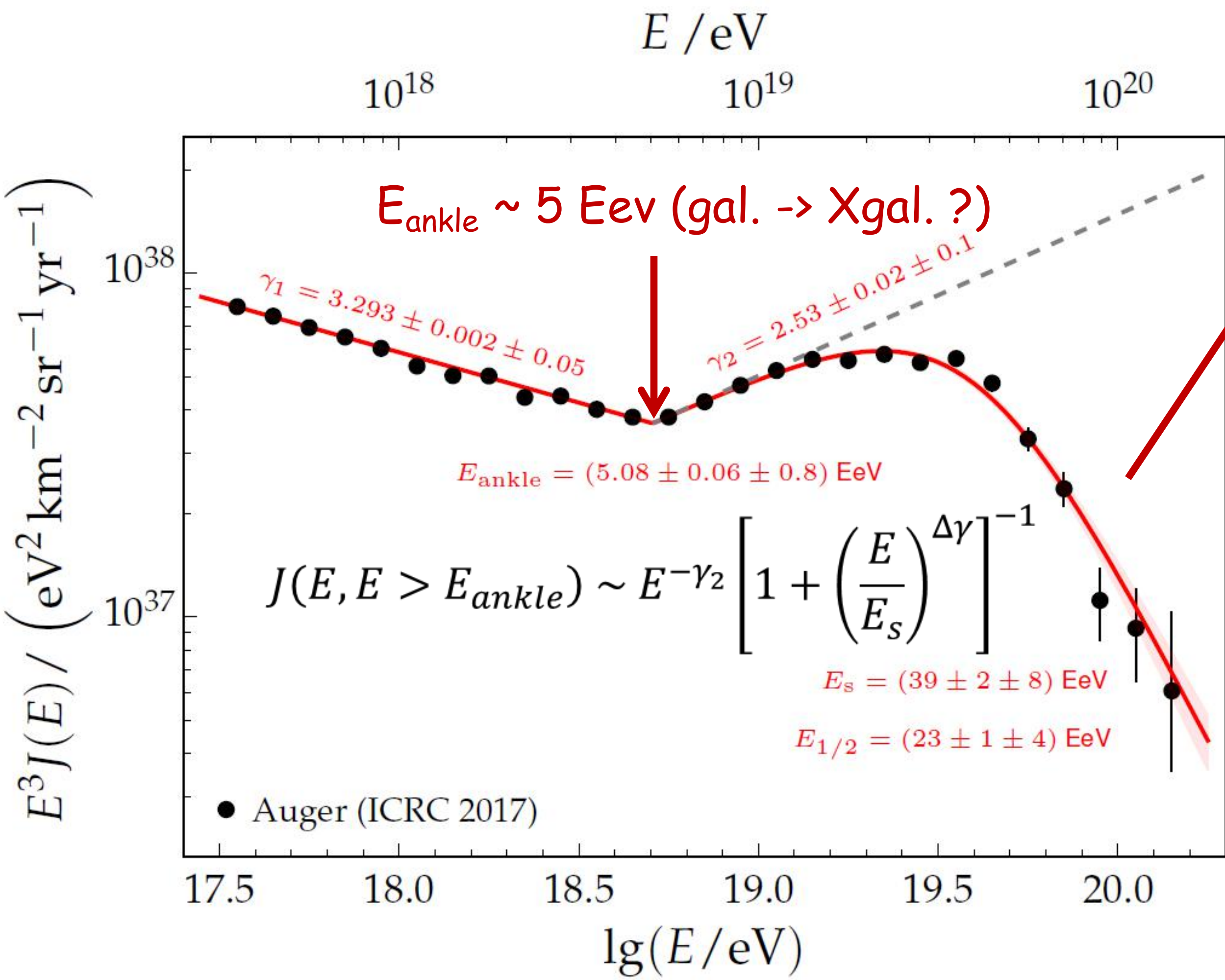


Likelihood ratio analysis

- correlation angle Ψ (takes into account the unknown deflections of the UHECRs in the magnetic field)
- H_0: isotropy
- H_1: (1-f) x isotropy + f x fluxMap(Ψ)
- Test Statistic = 2 log(H_1 / H_0)

Spectrum and mass composition

UHECRs energy spectrum: combined Auger spectrum



What is the origin of the flux suppression?

efficiency limit of the particle acceleration by sources (cutoff in the source spectrum, particles accelerated to maximum energies proportional to their charges: $E_{max} = R_{cut}Z$)

or

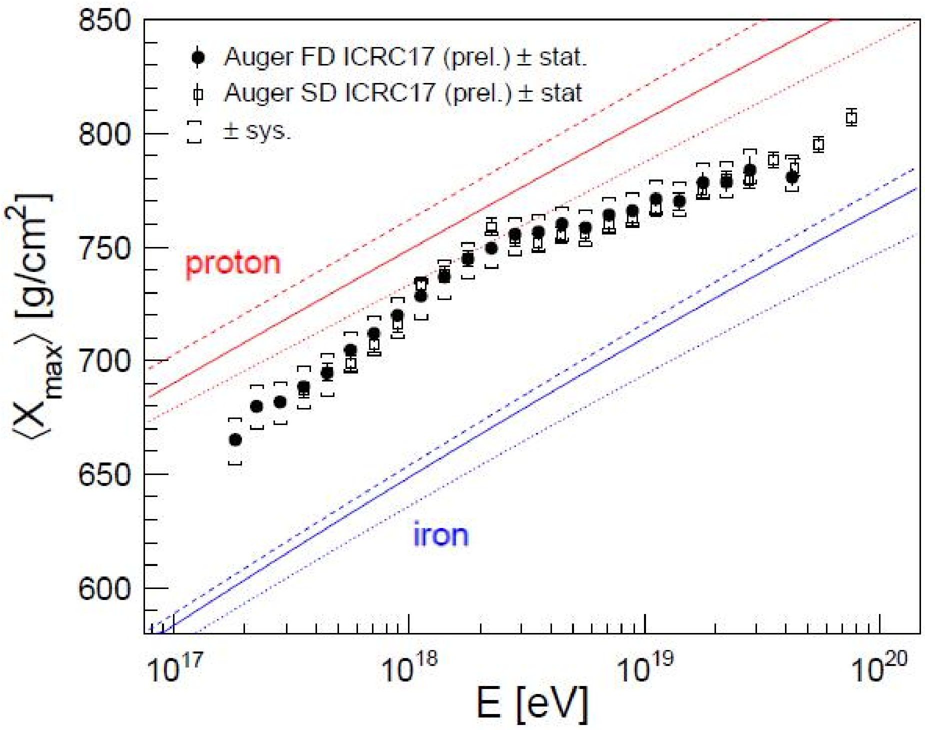
energy loss effects due to UHECRs propagation (GZK/Photo-disintegr.)?

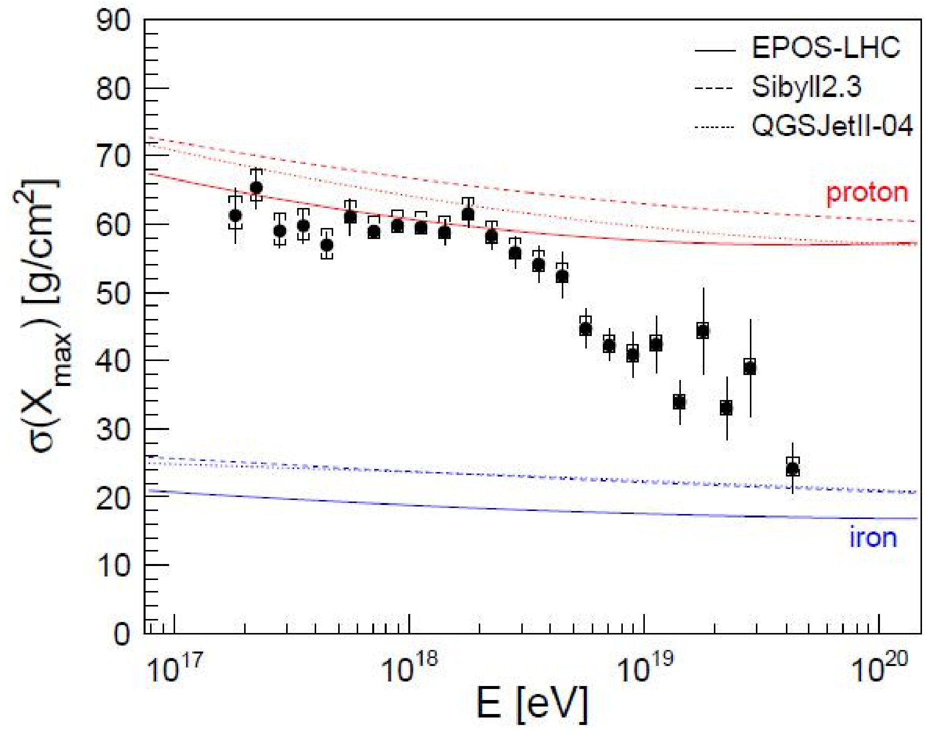
Suppression of the energy spectrum compatible with both scenarios.

Measurements of the mass composition of UHECRs are needed.

- The cosmic ray flux is well described by a broken power law plus a smooth suppression at the highest energies.

Mass composition: average X_{max} and X_{max}-fluctuations

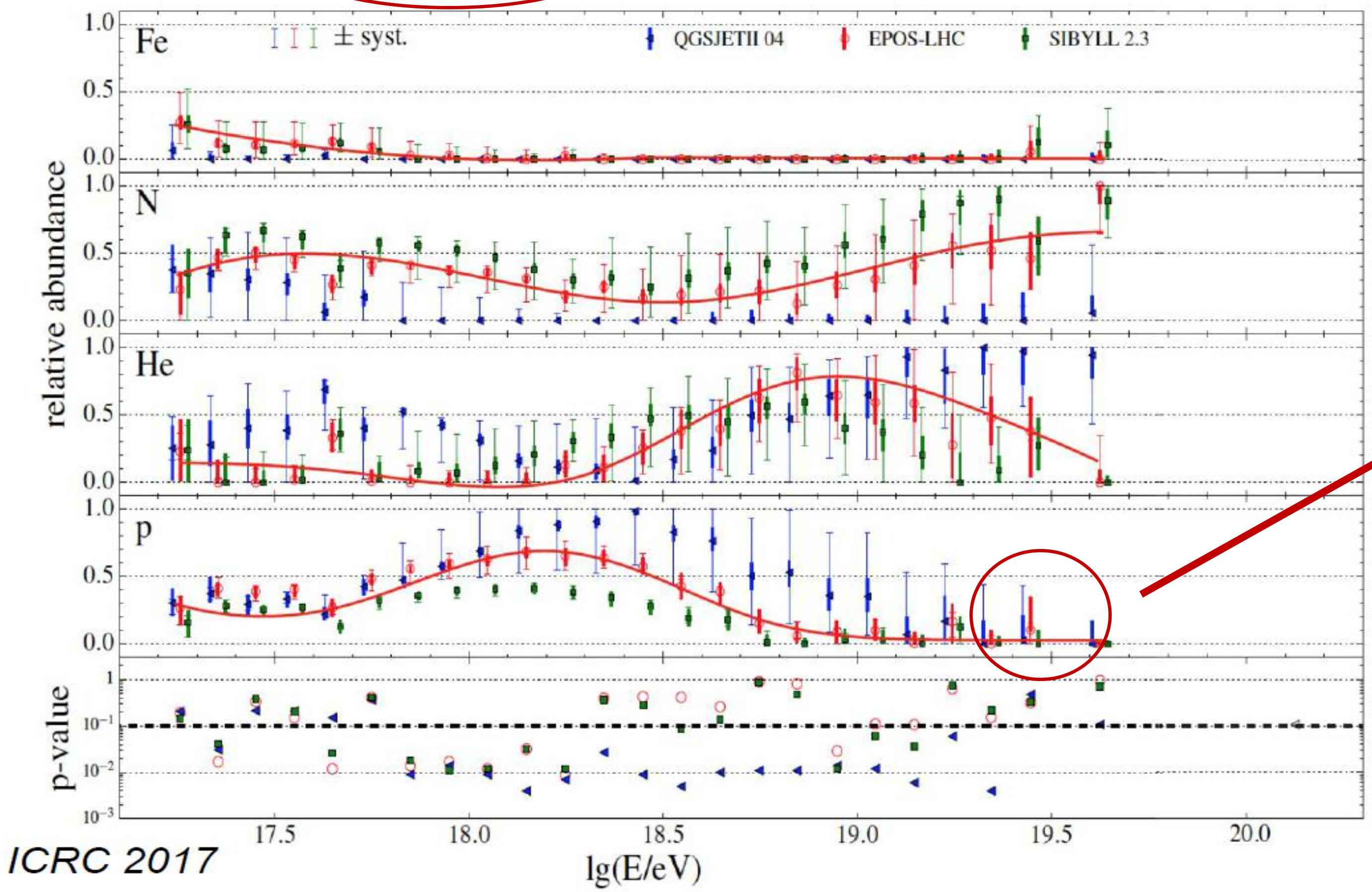




- X_{max} is an observable sensitive to mass composition.
- Data indicate changing mass composition with energy.
- Inconsistency of the two plots at the highest energies (mix or Fe).

- The inferred mass composition relies heavily on validity of hadronic interaction models (extrapolations of accelerator data to high energy is associated with high uncertainty).

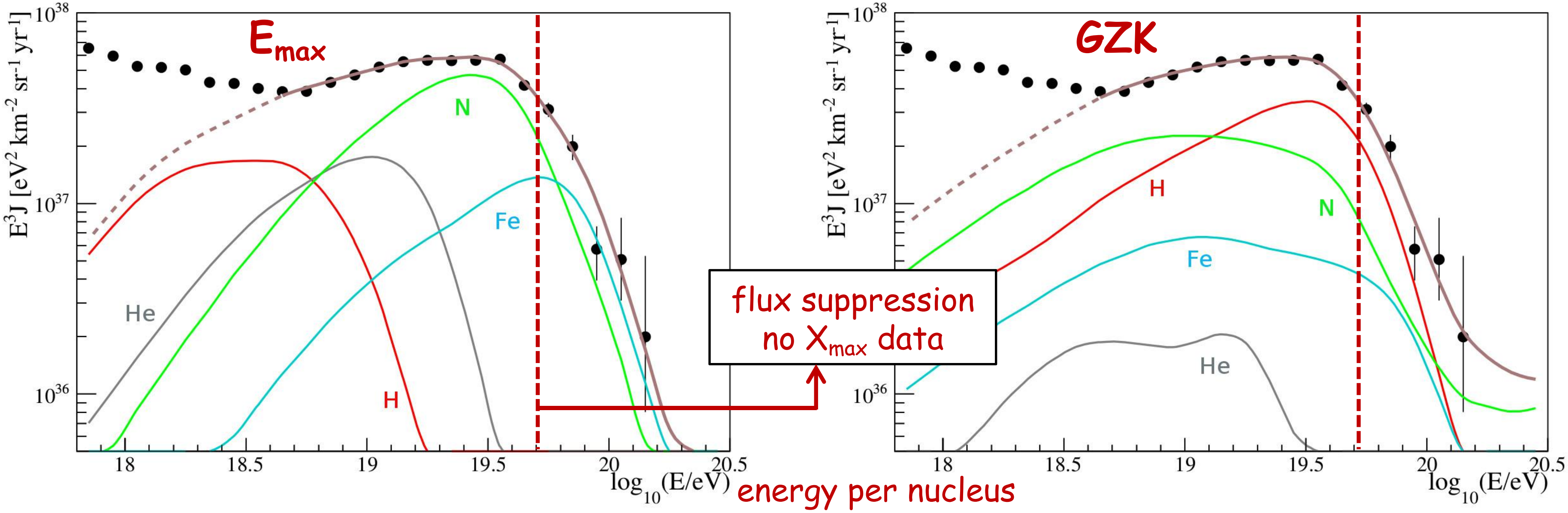
The composition which best describes Auger data is a mix of **p**, He and **N** nuclei, i.e. **AugerMix**



Small fraction of **p** ~10% to explain dipole anisotropy ?

- No ultra-high energy γ and ν identified - models of top-down production of UHECRs (exotic scenarios) disfavoured.
- No **Fe** needed to reproduce the data.
- The intermediate masses (He, **N**) have a strong model dependence.
- p-values indicates that **the hadronic interaction models have difficulties to reproduce observed X_{max} distribution.**

Models of the flux suppression origin best matching data



E_{max} scenario: Efficiency limit of particle acceleration by sources $E_{max} = R_{cut}Z$

or

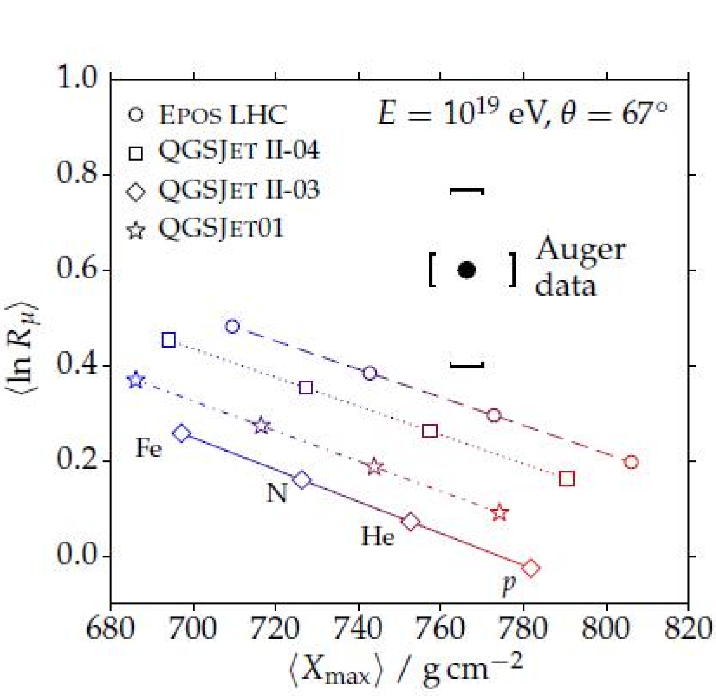
GZK scenario: GZK/Photo-disintegration of nuclei during propagation (presence of p above the energy of spectrum suppression)

- The data collected is not sufficient to discriminate between models.
- A more accurate determination of mass composition is required (no X_{max} measurements above the energy of spectrum suppression).

- Great hopes in measurements of muon component of EAS.

Hadronic interactions at ultra-high energy

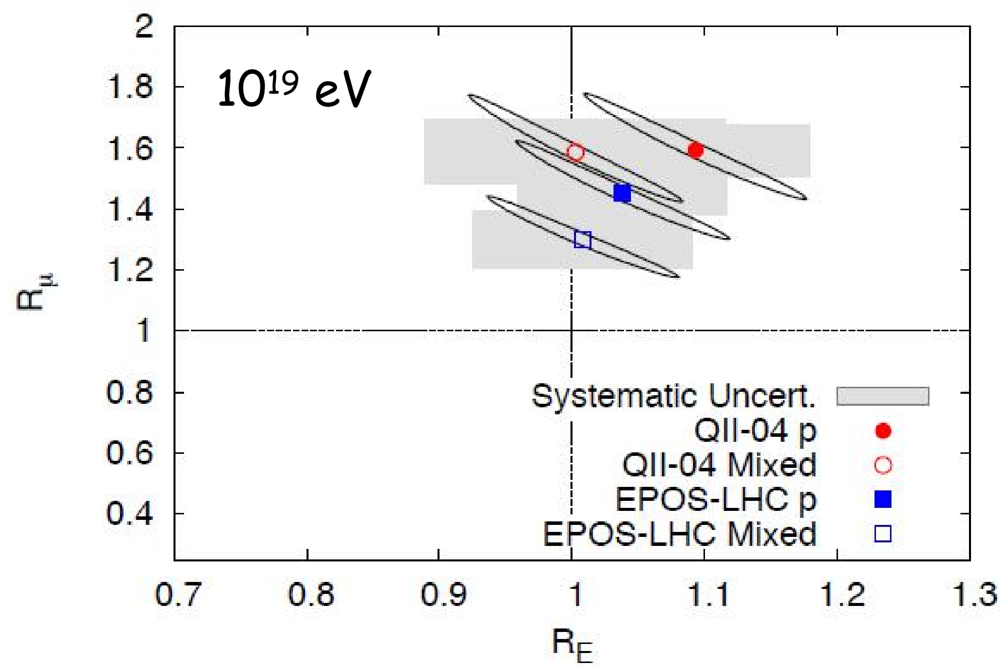
Mean number of muons R_μ relative to that of proton reference shower



Scaling factors R_μ and R_E for

- muon component of shower and
- primary energy

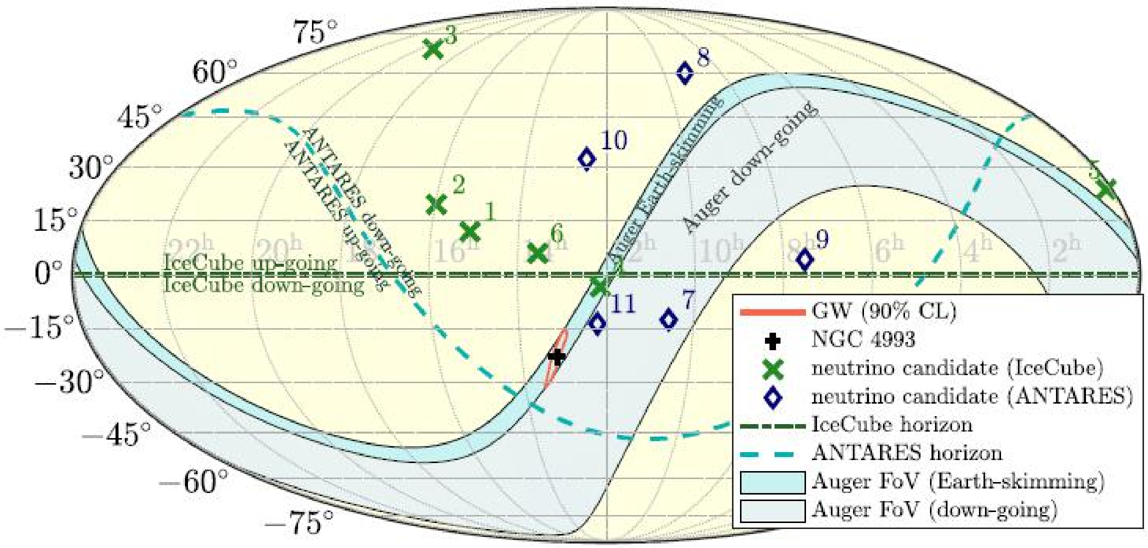
which bring a model calculation into agreement with data.

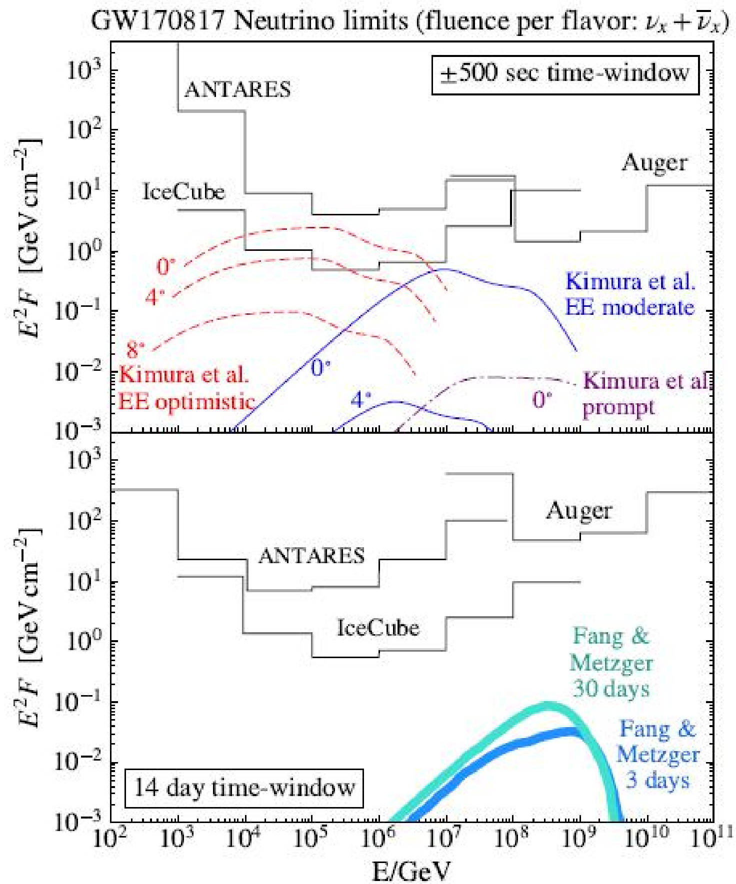


None of the hadronic interaction models can reproduce the muon number! (μ deficit in models)

Discrepancy between models and data

Search for high-energy neutrinos from binary neutron star merger (GW170817) with ANTARES, IceCube, and Auger





- The 3 detectors complement each other in the energy bands in which they are most sensitive.
- No significant neutrino counterpart within a ±500 s window, nor in the subsequent 14 days.
- Optimistic scenarios for on-axis (the angle between jet and the line of sight) ν emission are constrained by the present non-detection.

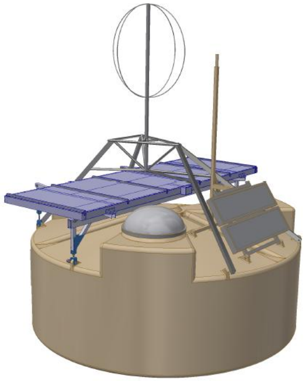
Pierre Auger Observatory upgrade
AugerPrime

Primary goal:

- much better composition determination than was possible until now
- utilizing muon component measurements

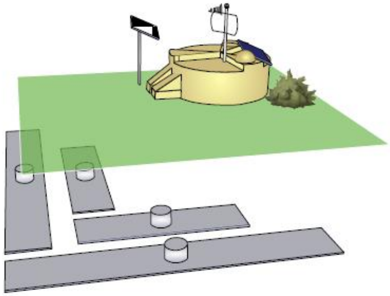
Detector upgrades for AugerPrime

- **Installation of a Surface Scintillator Detector (SSD) atop each Water Cherenkov Detector (WCD).**
  - Better separation of the muon and electromagnetic components.
  - Primary mass composition on event-by-event basis.
  - Upgrade of WCD electronics to increase data quality.
  - Add small PMT (increse of the dynamic range).



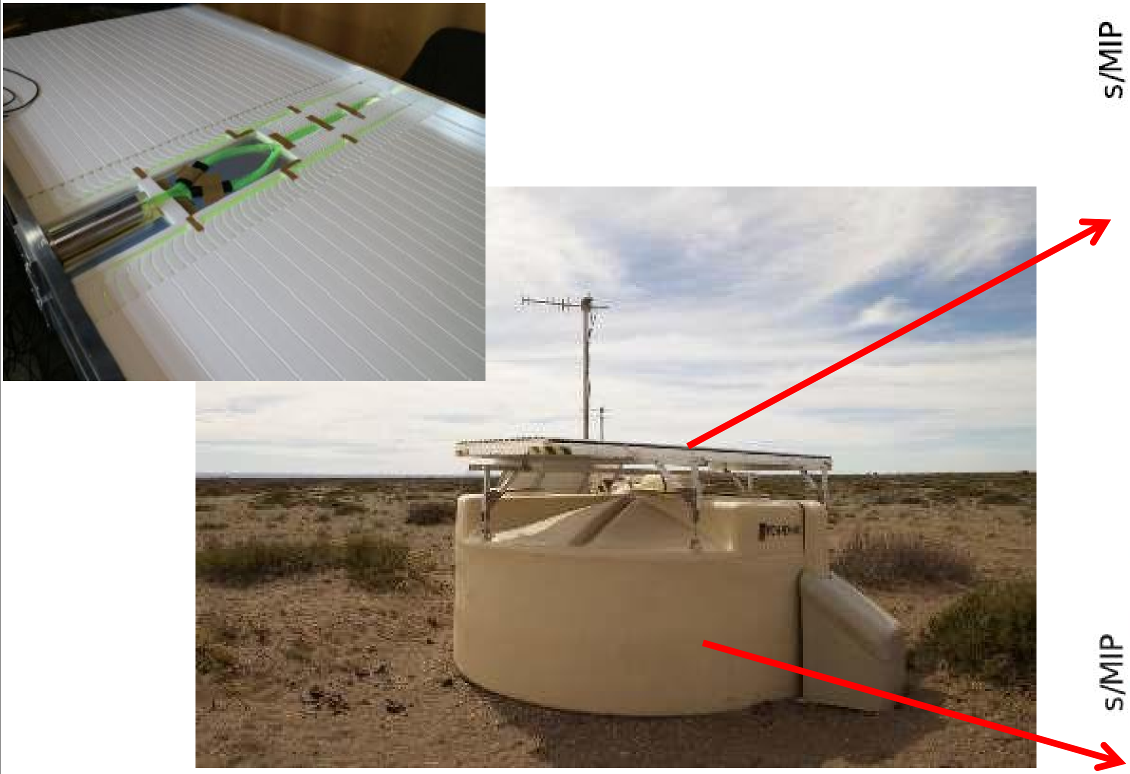
- **Installation of a radio detector atop each Surface Detector.**
  - Utilizing new technique of EAS detection.

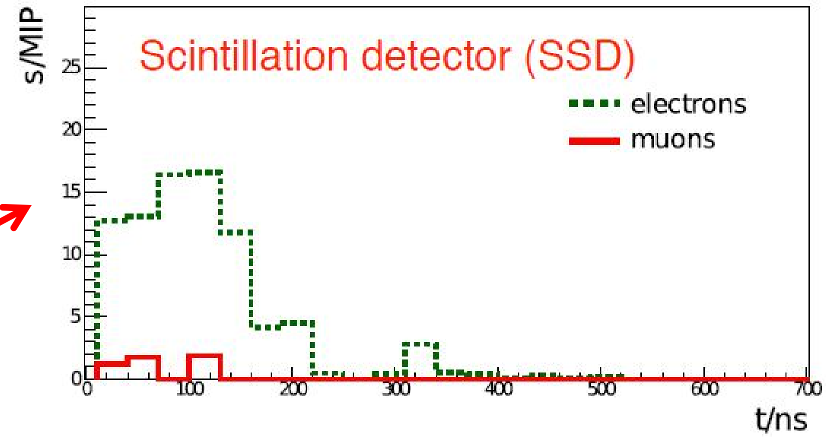
- **Extension of the Fluorescence Detector operation mode.**
  - More best-quality data.

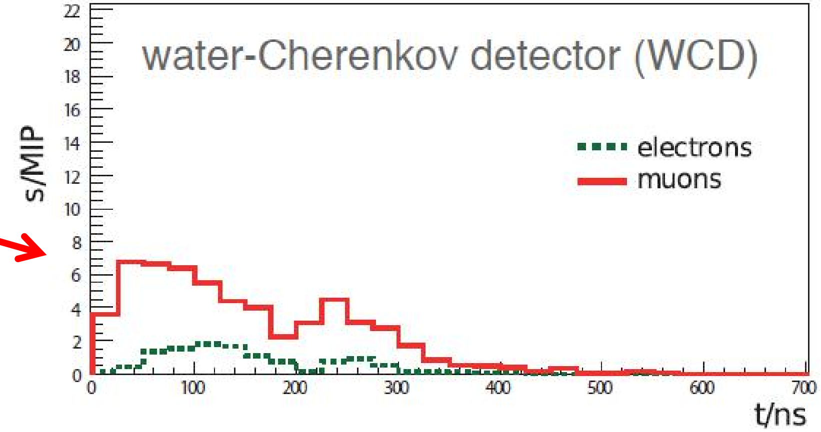


- **Underground Muon Detector array for direct muon measurements.**
  - Fine-tuning of different hadronic models.

Surface Scintillator Detector (SSD)





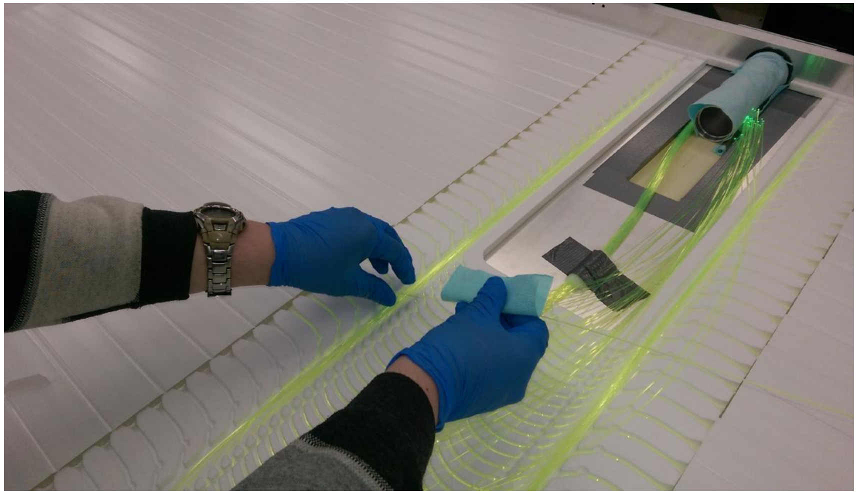


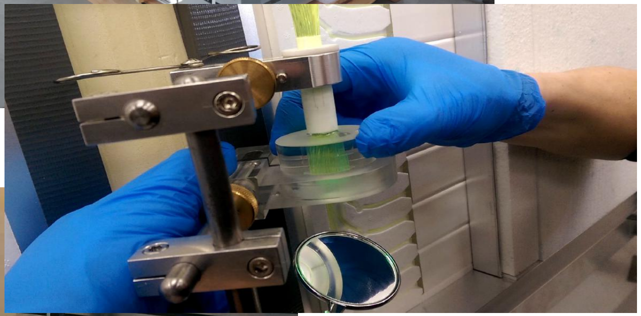
Scintillation and Cherenkov detectors are characterized by different response to muons and electrons

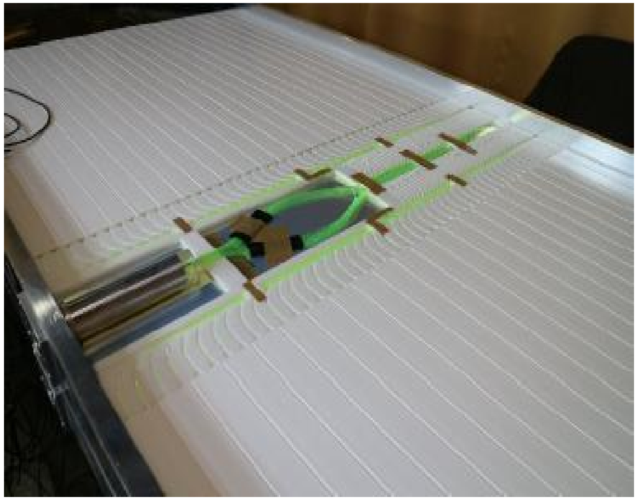
- ➢ **disentangle muon and electromagnetic components**
- ➢ **identification of the primary particles on event-by-event basis**

Surface Scintillator Detector (SSD)

- **Assembly and tests of 225 out of 1660 SSD detectors in IFJ PAN**



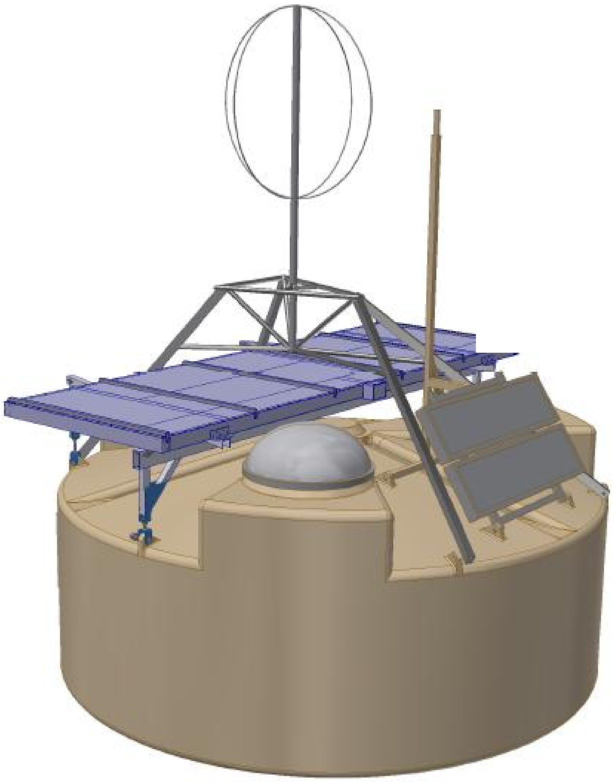




Radio - new promising technique of EAS detection

Array of radio detectors allows:

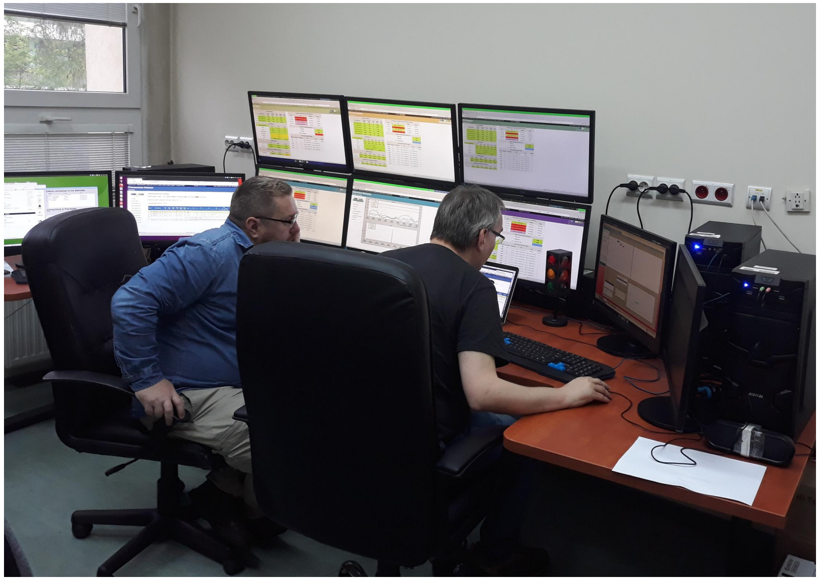
- calorimetric energy measurements
- direct measurements of (geometric) distance to the shower maximum, and thus X_{max} determination
- precise measurement of the shower geometry
- 100% duty cycle



Extension of the Fluorescence Detector operation mode - increase of the duty cycle

- FD enables direct measurements of X_{max} - currently the best method of mass composition determination.
- Main limitation: duty cycle of only ~13 %.

- Change operation mode of FD will allow data acquisition during high-moon fraction nights.
- Doubling the duty cycle (increase to ~25%).
- FD extension mode requires more data acquisition shifts - remote shifts will be helpfull.
- Auger remote control room in IFJ PAN fully operational from May 2019 (one of 13 functioning).



data acquisition
during full moon

Summary

- Suppression of the UHECR energy spectrum is compatible with both scenarios of
  - the GZK/photo-disintegration cutoff and
  - the efficiency limit of particle acceleration by sources.

- Orientation of the observed dipole anisotropy in the arrival directions of UHECRs indicates their extragalactic origin.

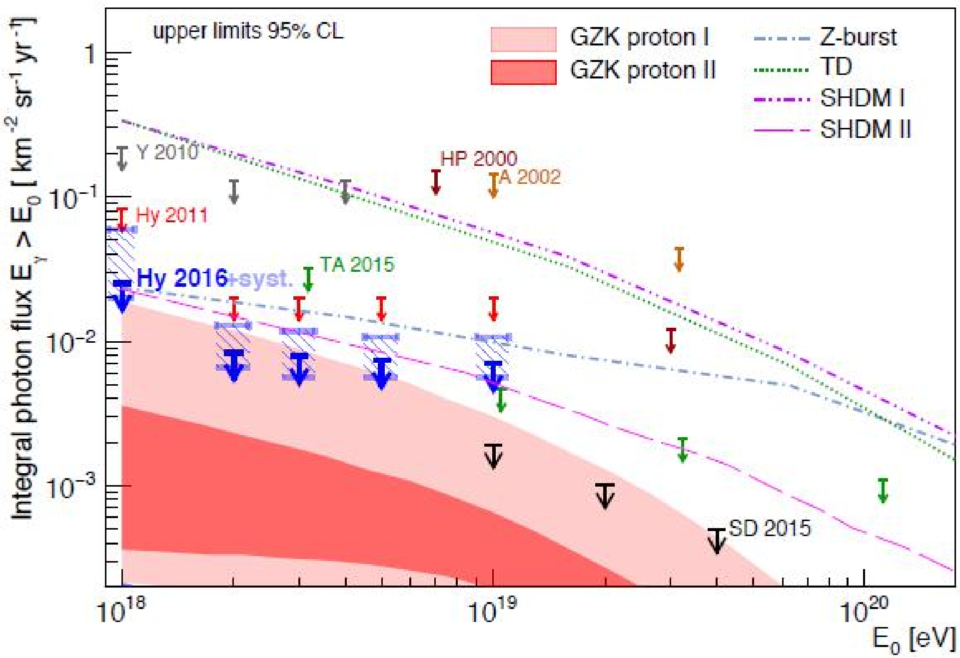
- UHECRs appear **proton**-like at 10^{18} eV and heavier (**N**-like) at the flux suppression region. No indication of **Fe** nuclei.

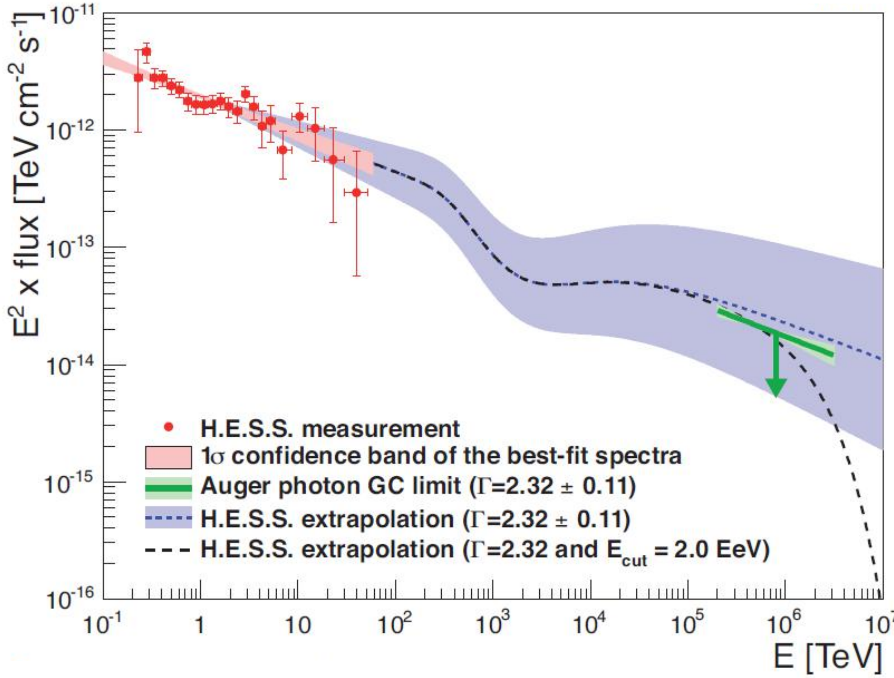
- Current hadronic interaction models have problem with reproducing muon number in showers (more muons are observed than predicted). Implication for UHECRs composition determination.

- Pierre Auger Observatory undergoes an upgrade (AugerPrime) to precisely measure composition of UHECRs.

Searches for cosmogenic photons

$$p + \gamma_{CMB} \rightarrow p + \pi^0 \qquad \pi^0 \rightarrow \gamma + \gamma$$

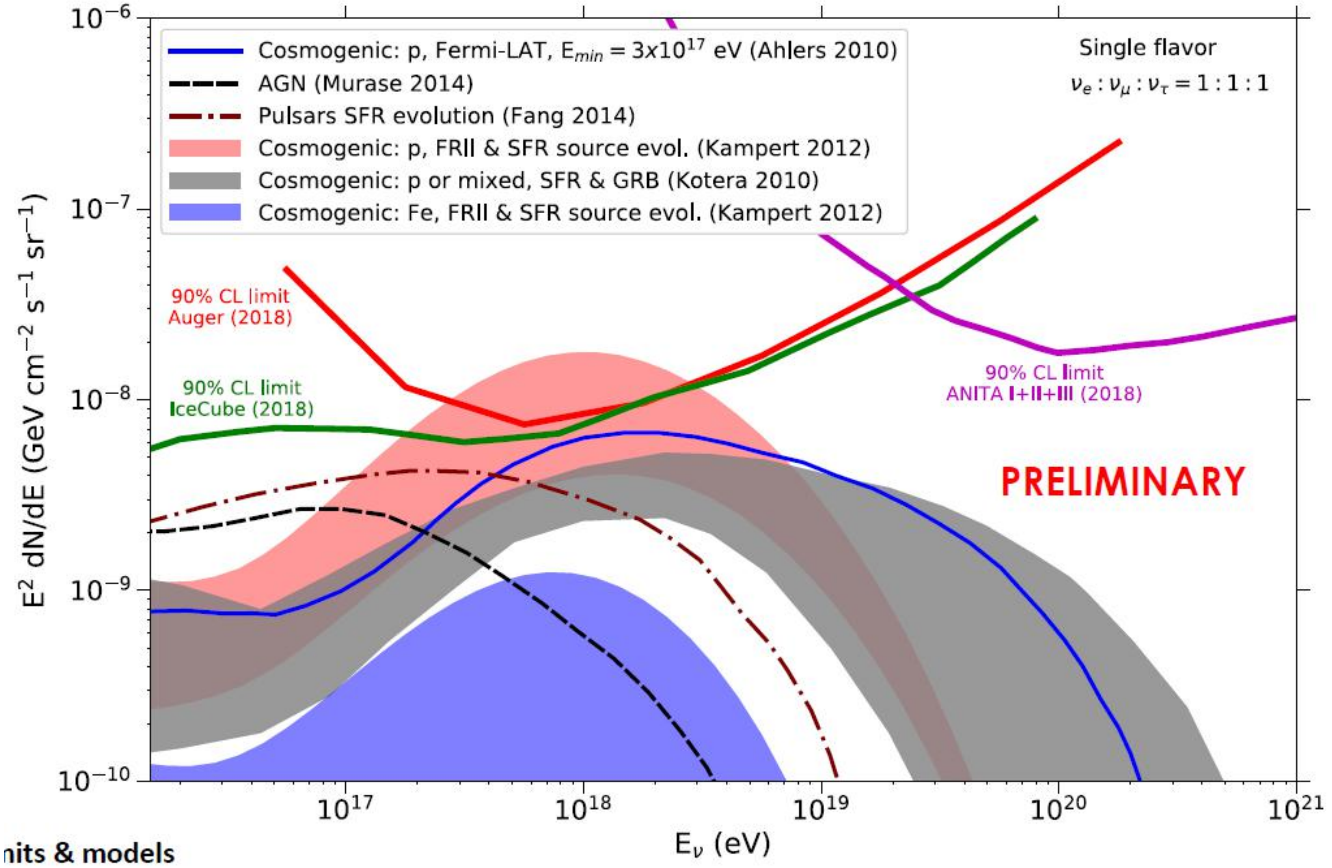




- Models of top-down production of UHECR (exotic scenarios) disfavoured at almost all energies.
- Models of cosmogenic photons assuming a pure proton composition can be tested.
- Constraints for photon flux spectrum from the Galactic center.

Searches for cosmogenic neutrinos

$p + \gamma_{CMB} \rightarrow n + \pi^+$ $\pi^+ \rightarrow e^+ + 3\nu$



- No neutrinos observed.
- Neutrino upper flux limits start testing the cosmogenic (GZK) ultra-high energy neutrino production models.

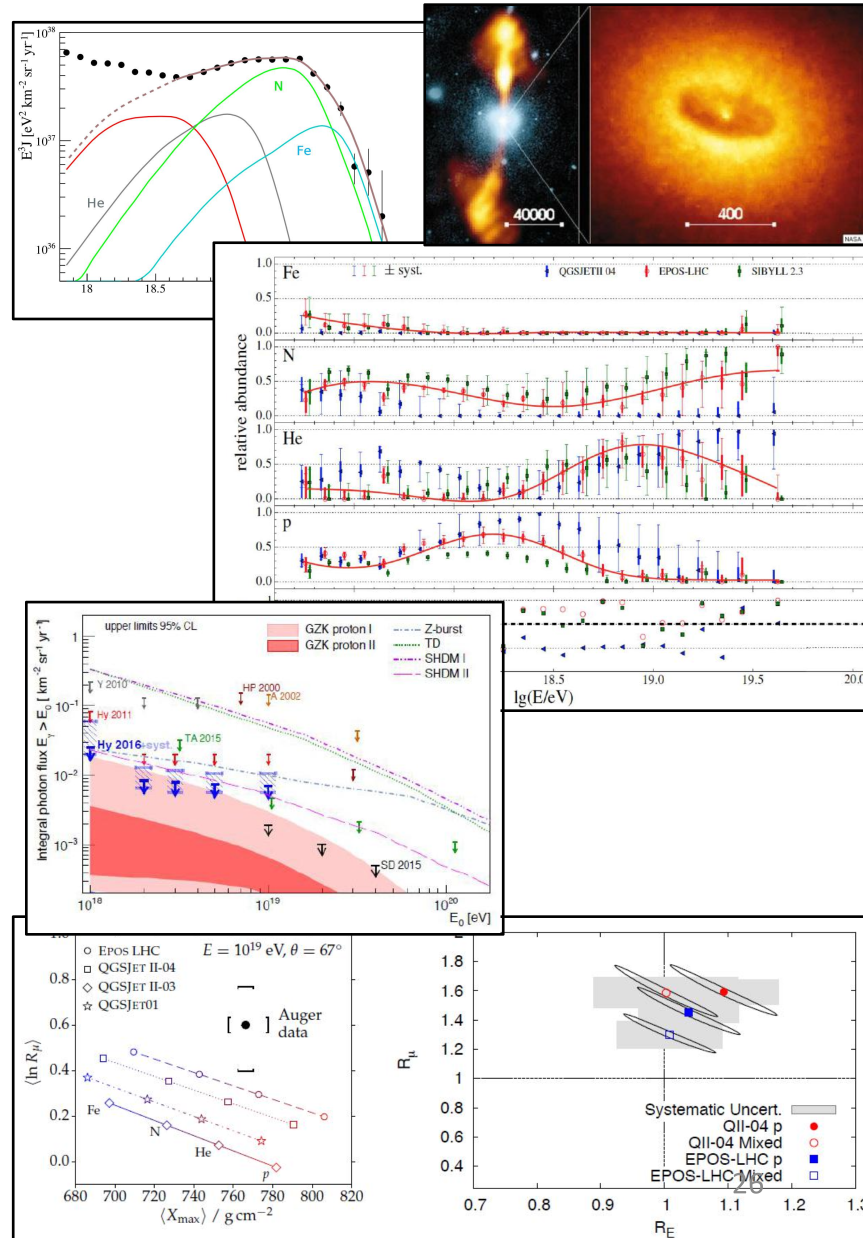
AugerPrime - goals of the upgrade

Upgrade necessary to ensure that the new data will provide additional information to allow us to address the following:

- **Elucidate the mass composition and the origin of the flux suppression at the highest energies.**
  - The differentiation between the energy loss effects due to propagation, and the maximum energy of particles injected by astrophysical sources.
  - Understanding the origin of the flux suppression will provide fundamental constraints on the astrophysical sources.

- **The search for a flux contribution of protons up to the highest energies.**
  - Aim to reach sensitivity to a contribution as small as 10% in the flux suppression region.
  - Prospects for proton astronomy.
  - The flux of secondary gamma-rays and neutrinos due to proton energy loss processes will be predicted.

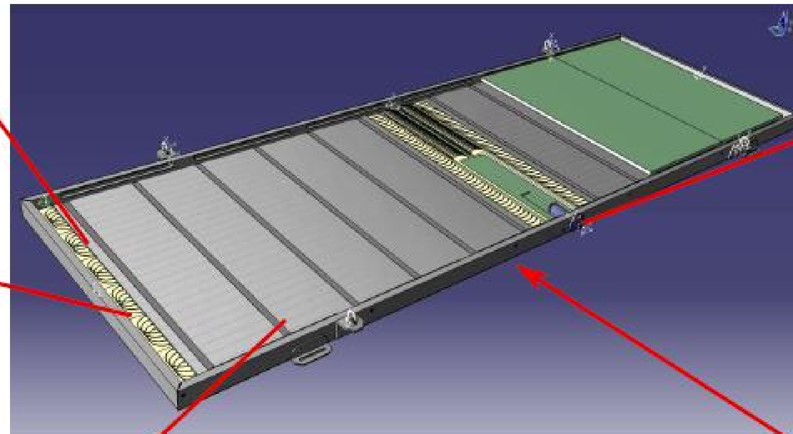
- **Exploration of fundamental particle physics at energies beyond those accessible at man-made accelerators.**
  - Understanding extensive air showers and hadronic interactions (muon deficit in simulation results).
  - Derivation of constraints on new physics phenomena.

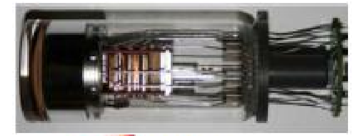


Surface Scintillator Detector (SSD)

side view of a
scintillator bar

SSD





PMT

WLS fibers and
fiber routers

Scintillator bars
160x5x1cm

Al Enclosure