Pierre Auger Observatory: latest results and prospects

Ruben Conceição

on behalf of the Pierre Auger Observatory

30th Rencontres de Blois, June 6th 2018

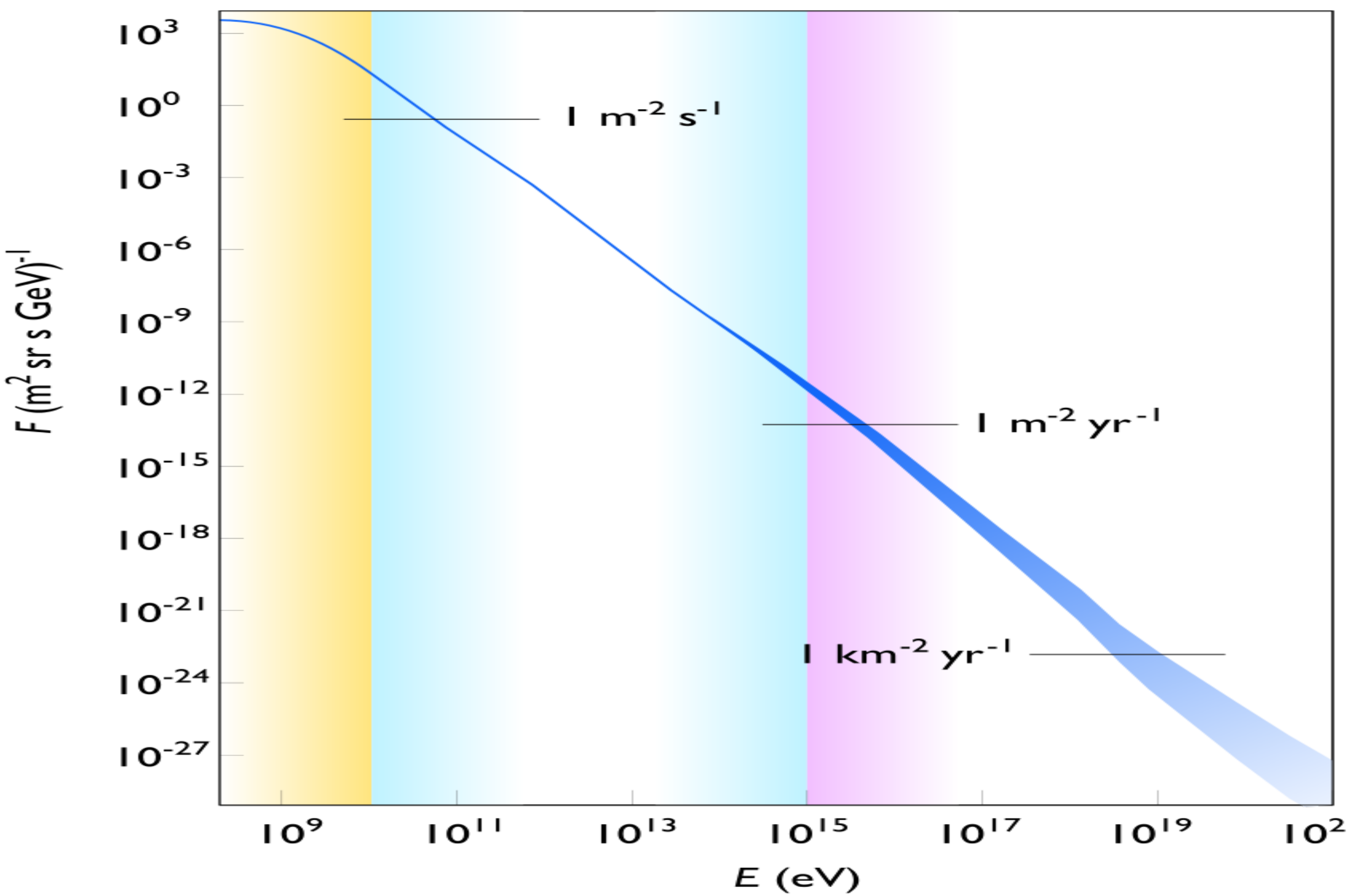
Pierre Auger Observatory

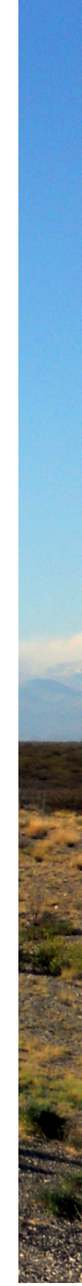
The road so far….

30th Rencontres de Blois, June 6th 2018

Ultra High Energy Cosmic Rays

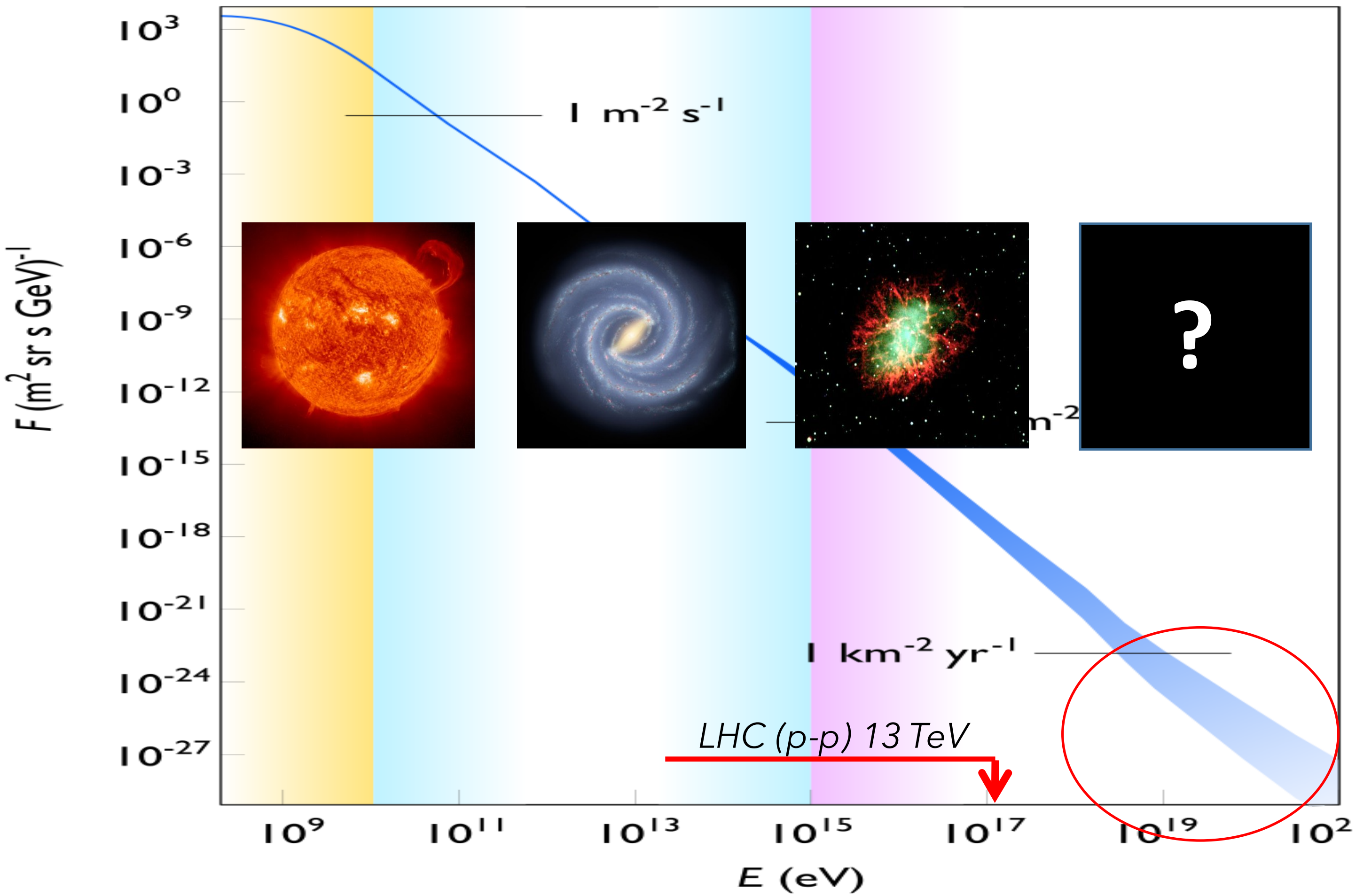
Cosmic ray energy spectrum





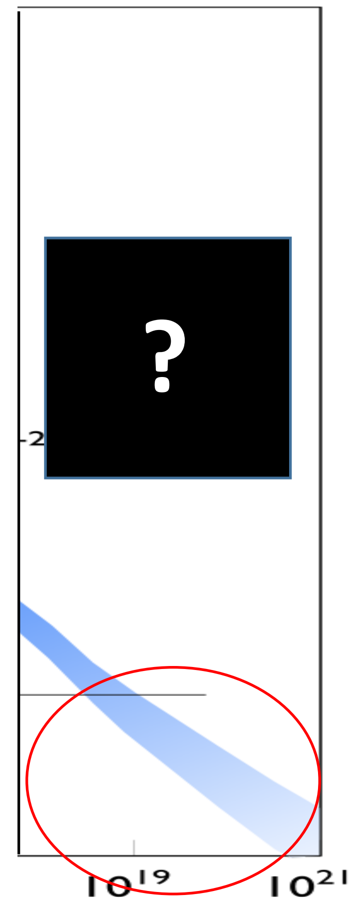
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum

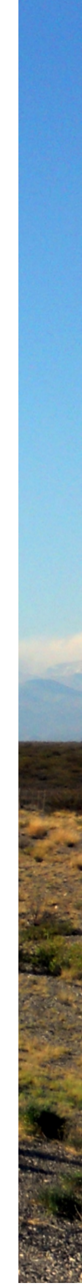


Ultra High Energy Cosmic Rays

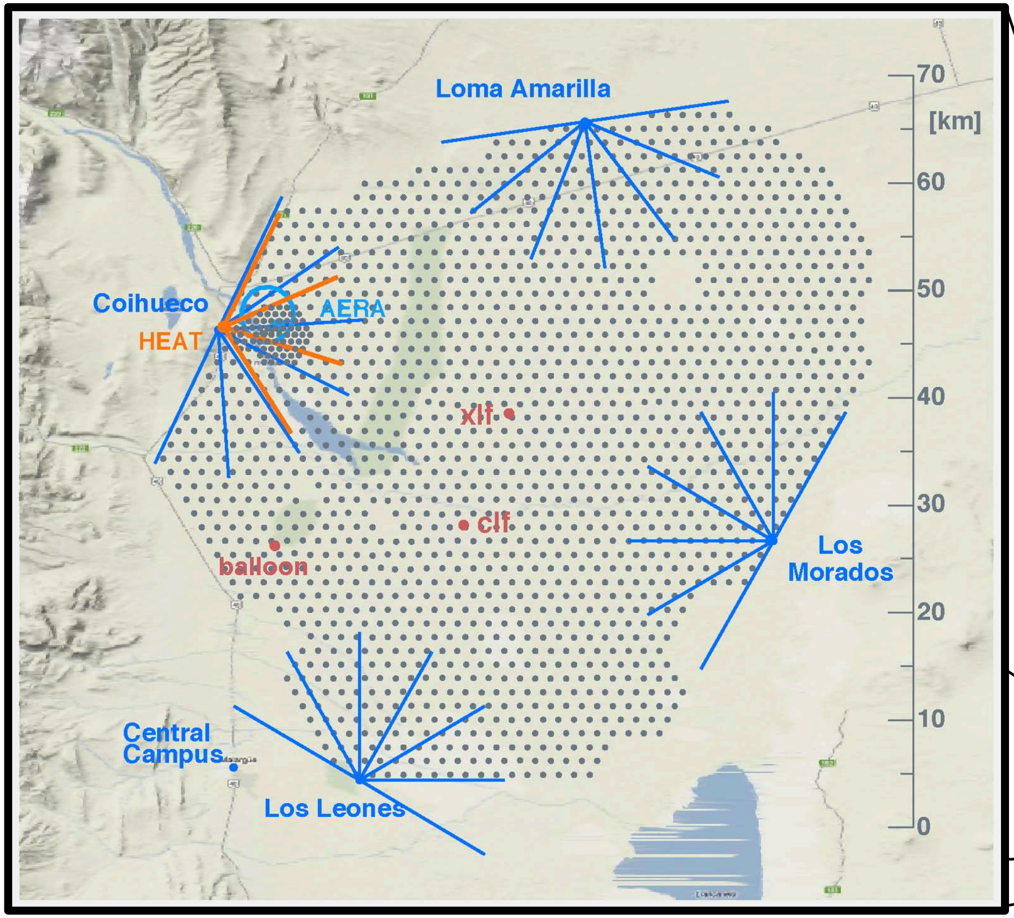
- Opportunity to understand high-energy Universe
  - Production (sources; acceleration mechanisms…)
  - Propagation (Magnetic fields…)
- Opportunity to have a glimpse of particle physics at energies above the LHC
  - High-energy interactions
    - E = 10^{19} eV => sqrt(s) ~ 130 TeV
  - Different kinematic regimes
    - E_{beam} up to 10^8 TeV



1 km^{-2} century^{-1}



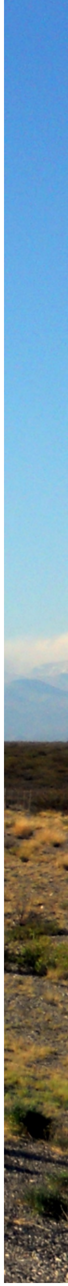
Pierre Auger Observatory



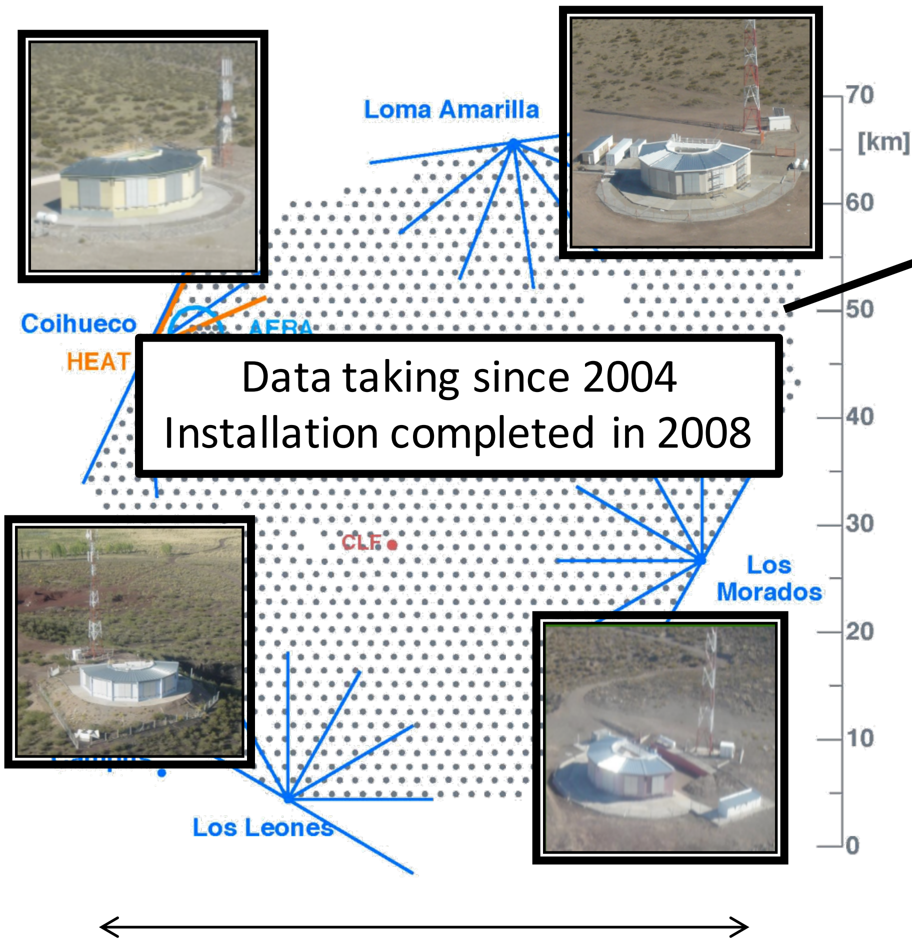
Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

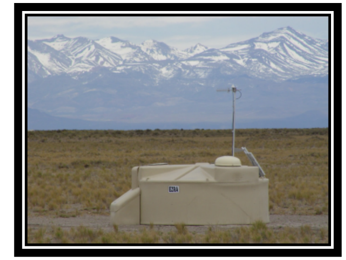


Pierre Auger Observatory



~ 60 km

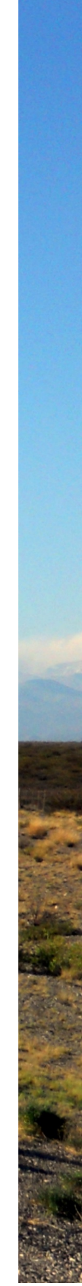
- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes



- ~ 1600 Surface Detector (SD) Stations
- 1.5 km spacing
- 3000 km^2

Low energy extension

- ✧ Aim to E ≈ 10^{17} eV
- ✧ AMIGA
  - ✧ Denser array plus muon detectors
- ✧ HEAT
  - ✧ 3 additional FD telescopes with a high elevation FoV

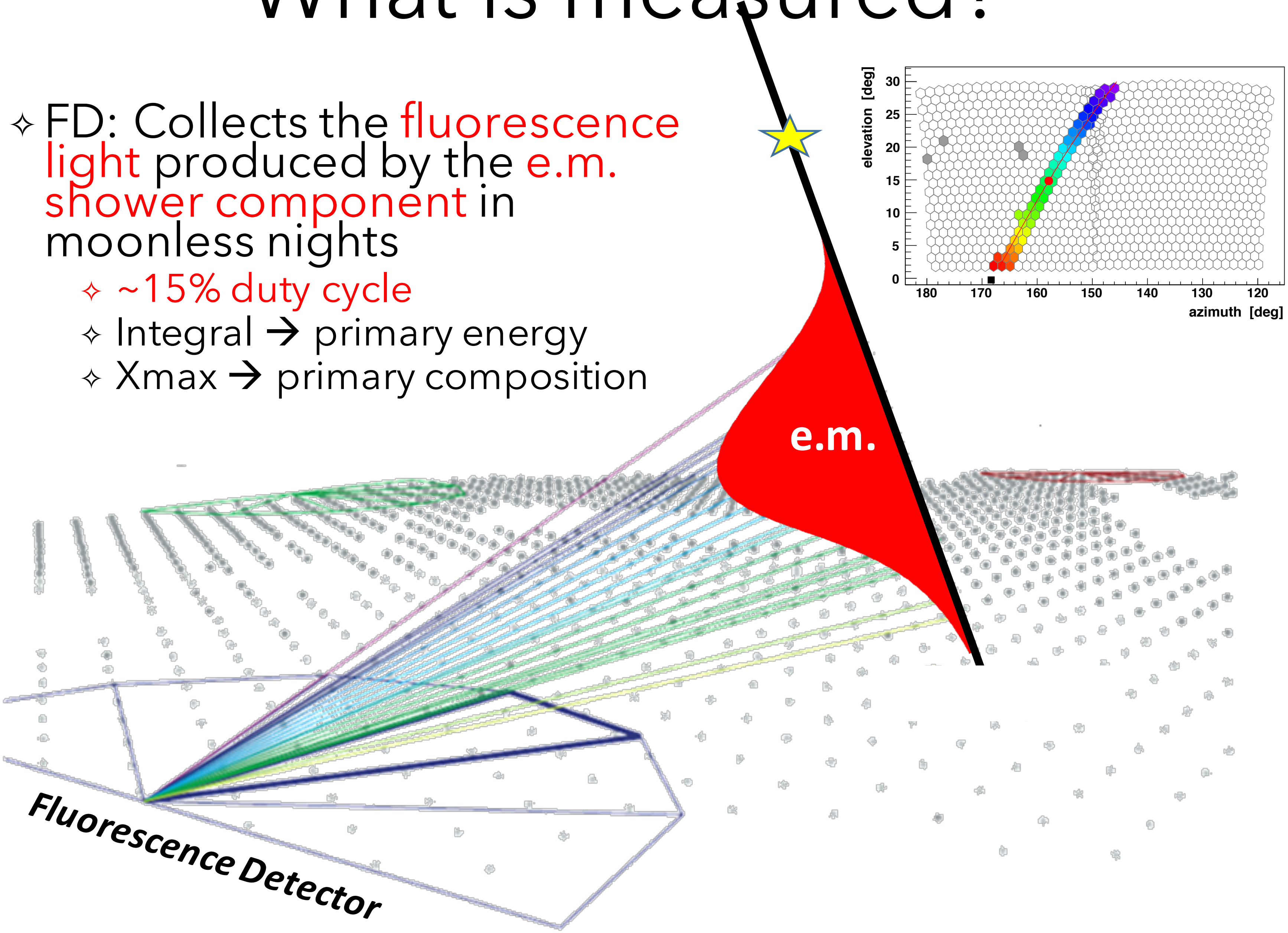


Surface detector

WCD + Fluorescence Detector

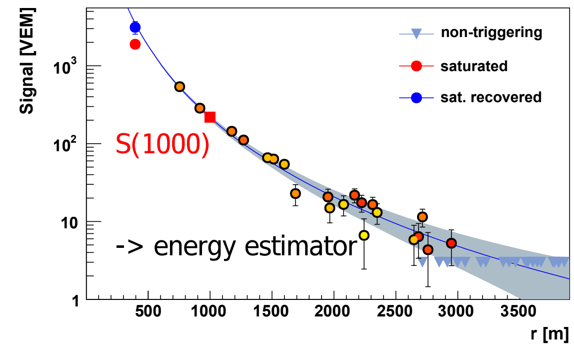
What is measured?

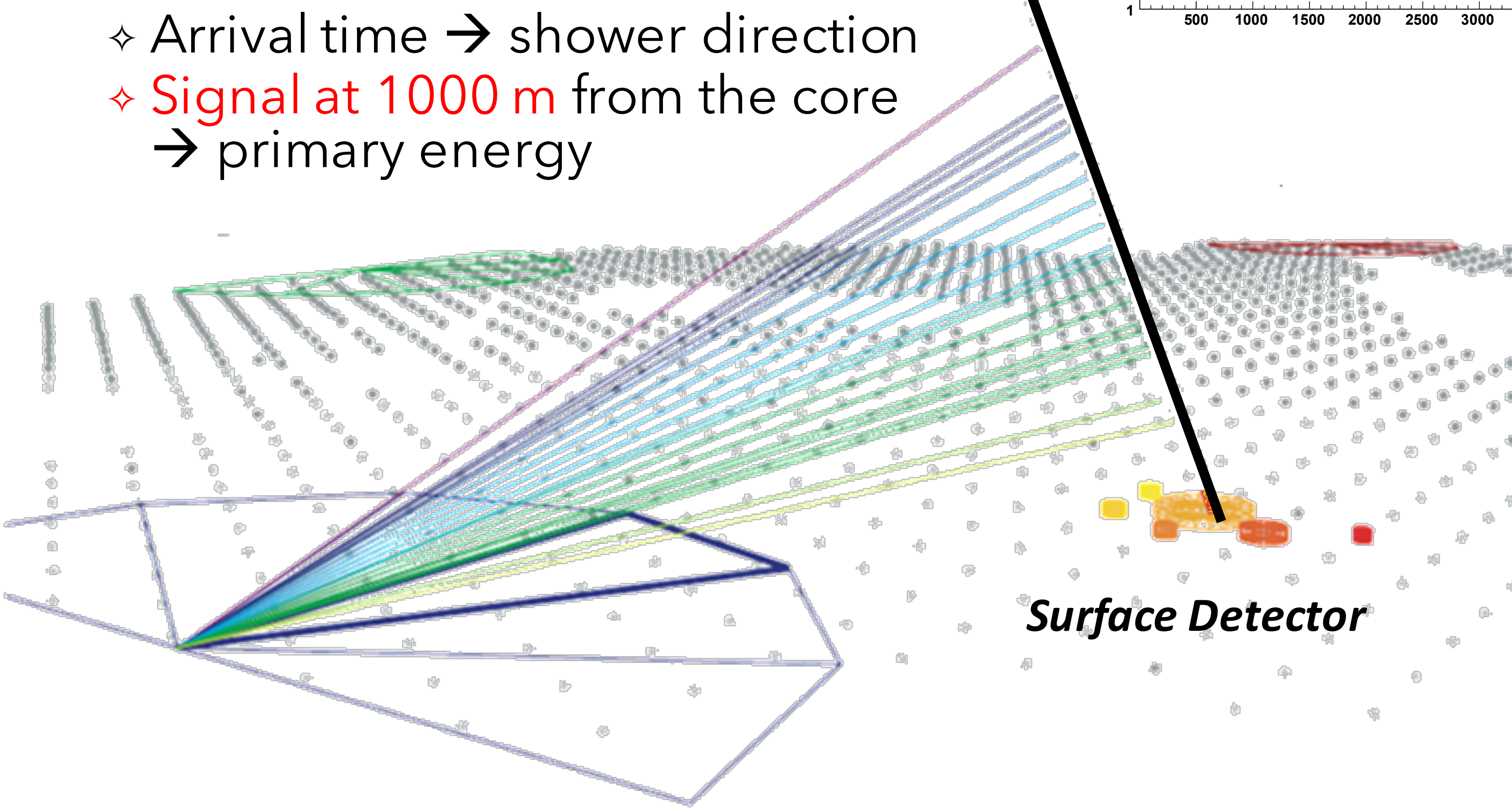
- FD: Collects the fluorescence light produced by the e.m. shower component in moonless nights
  - ~15% duty cycle
  - Integral → primary energy
  - Xmax → primary composition



What is measured?

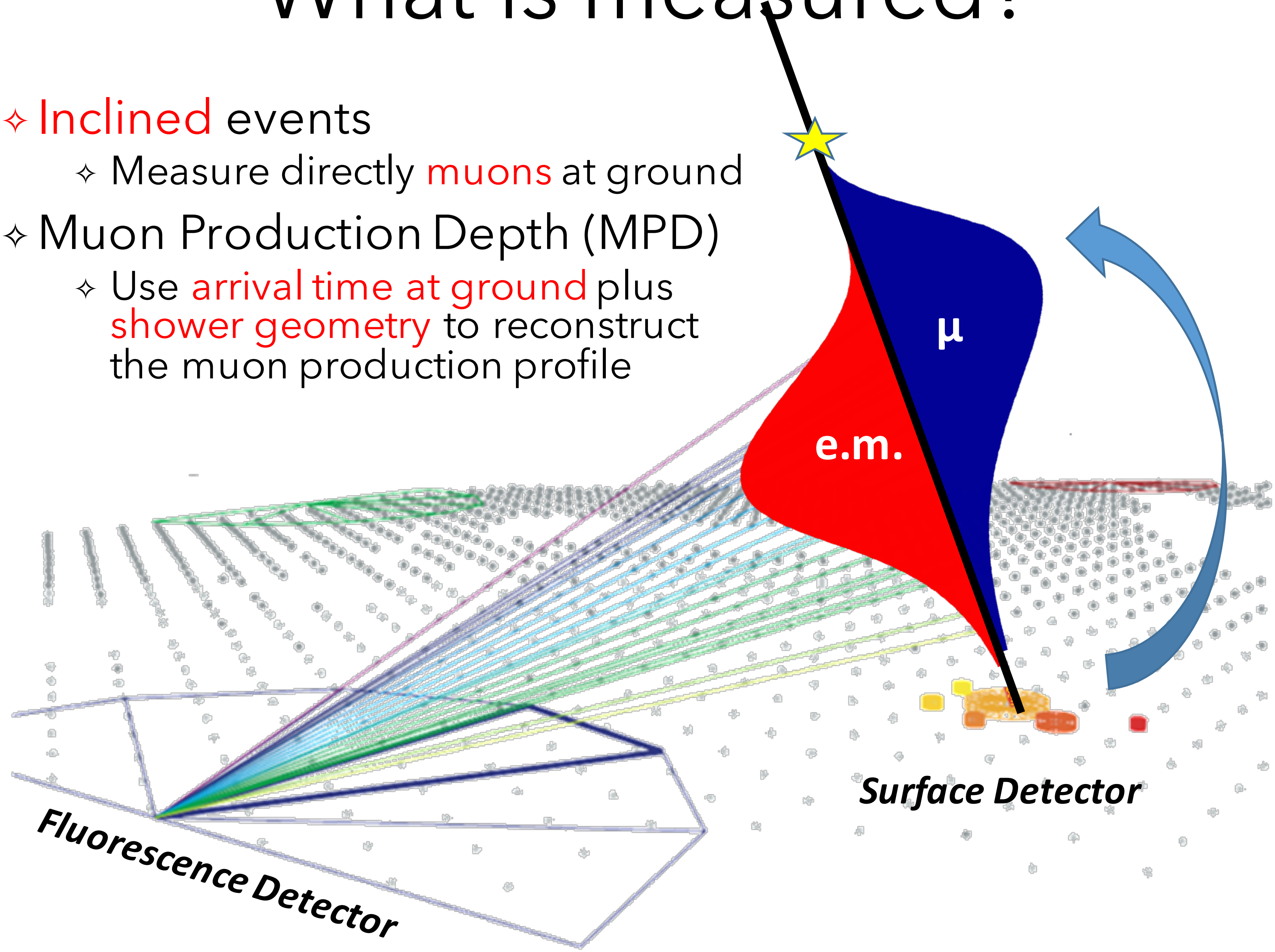
- ✧ SD: Sample the charged secondary particles that arrive at ground
  - ✧ 100% duty cycle
  - ✧ Arrival time → shower direction
  - ✧ Signal at 1000 m from the core → primary energy





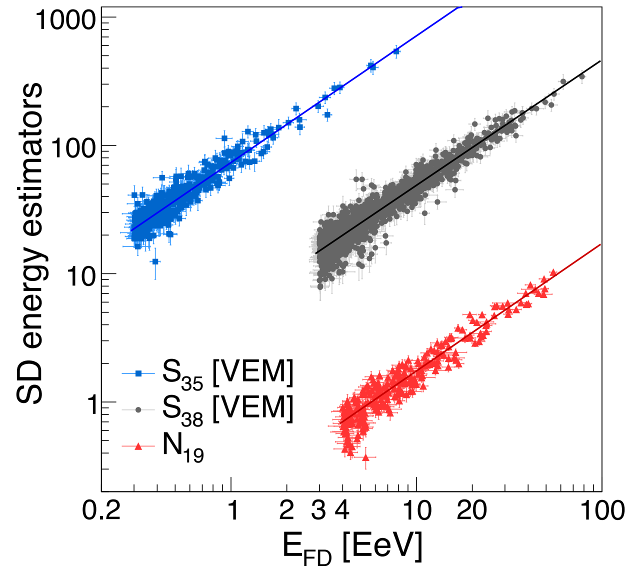
What is measured?

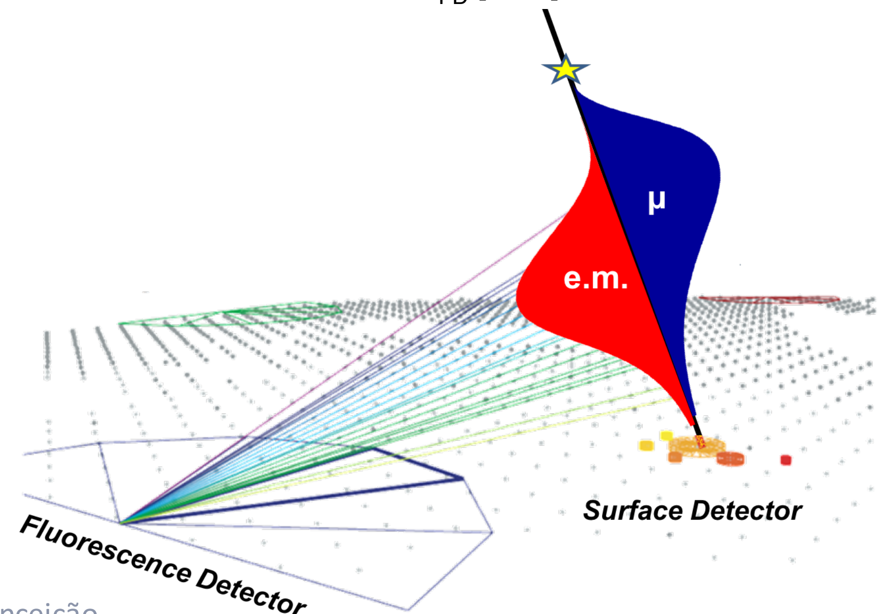
- Inclined events
  - Measure directly muons at ground
- Muon Production Depth (MPD)
  - Use arrival time at ground plus shower geometry to reconstruct the muon production profile



Hybrid technique

- Calibration of SD with FD
  - FD provides a quasi-calorimetric energy measurement
- Improve geometry reconstruction
  - For hybrid events
- Better assess/control systematic uncertainties
- Different insights of the shower
  - Access different shower components
  - Test shower consistency



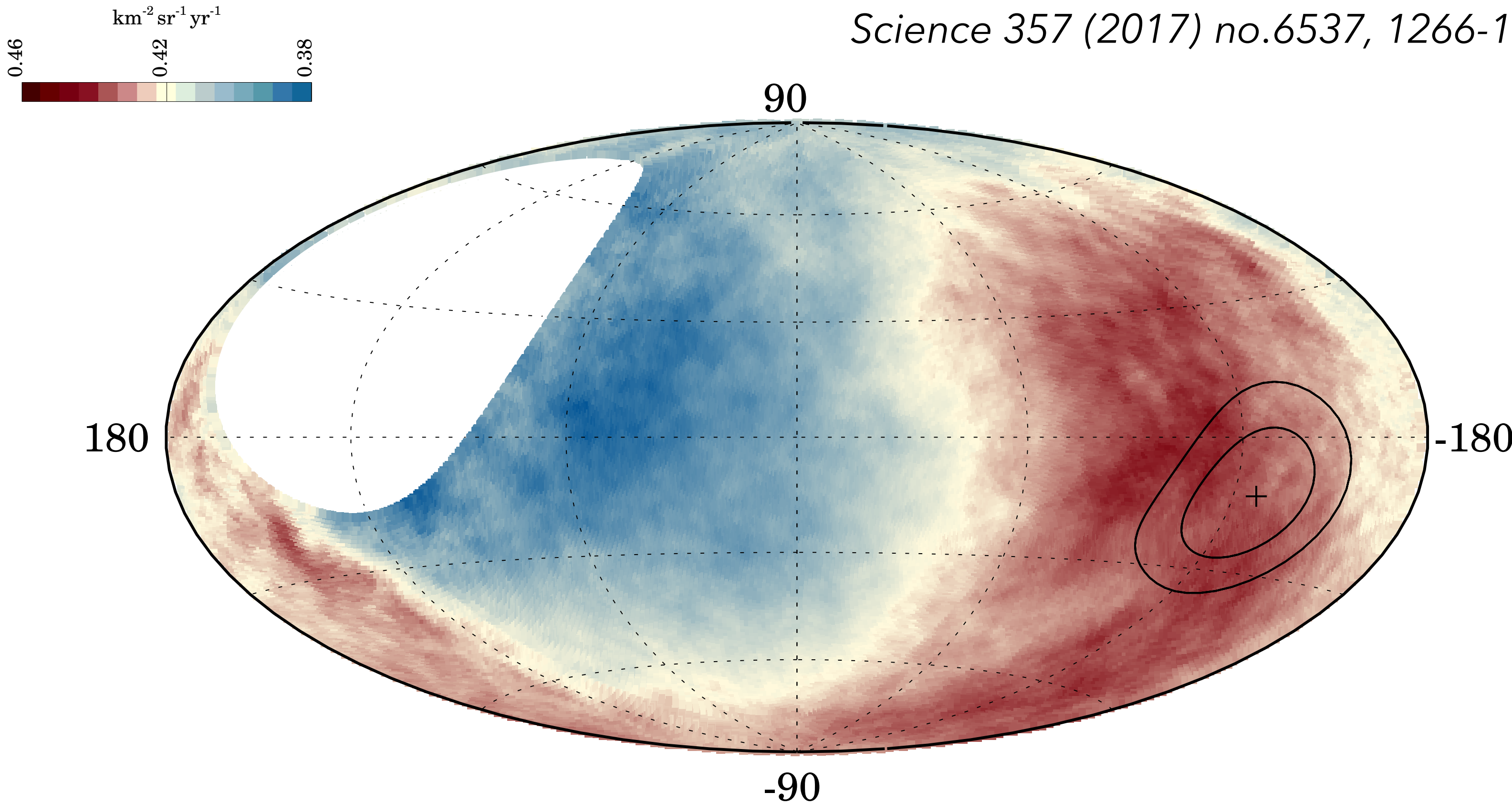


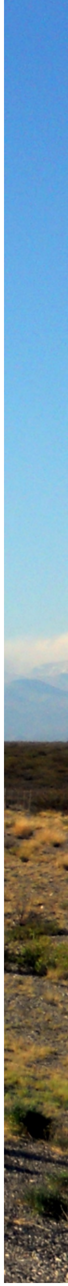
What have we learned so far about UHECRs….

A small selection of the results of the Pierre Auger Observatory

Observation of dipolar anisotropy

Science 357 (2017) no.6537, 1266-1270





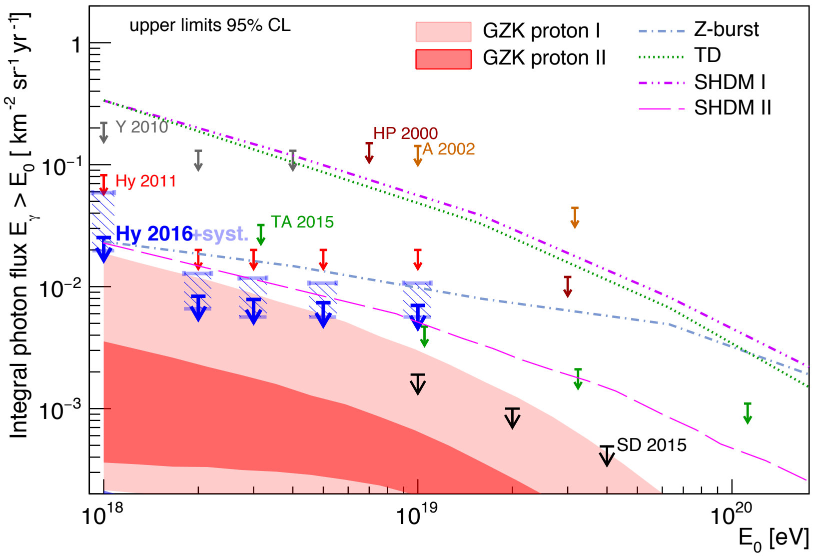
- Harmonic analysis shows a dipole for energies above 8 EeV
  - Significance: 5.2 σ (post-trial ; with penalization for energy bins exploration)
- Evidence for UHECRs origin outside the galaxy

UHE Photons/Neutrinos

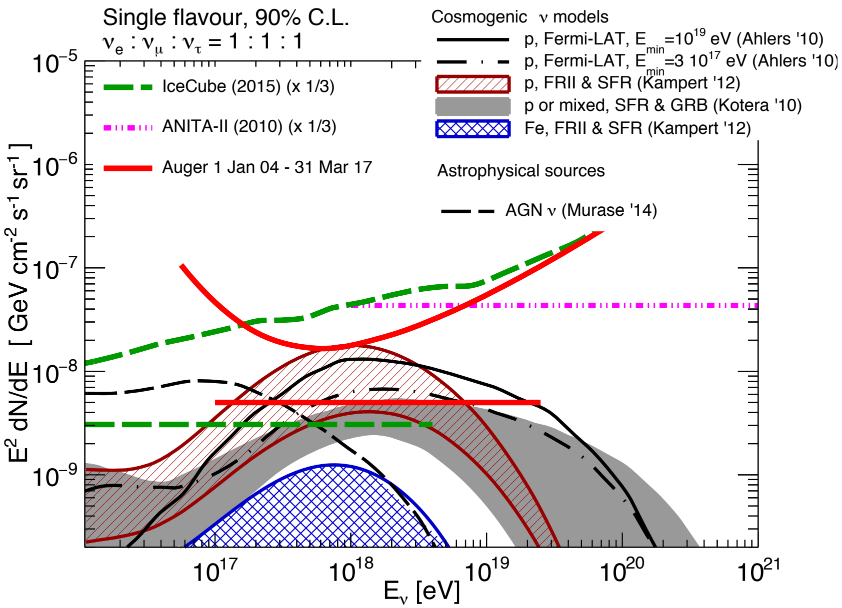
35th ICRC, PoS (2017) 517

35th ICRC, PoS (2017) 972

Photons

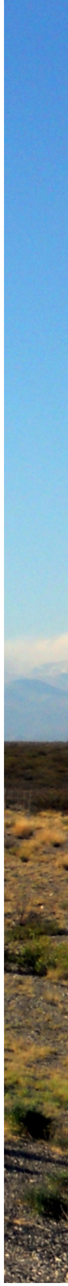


Neutrinos

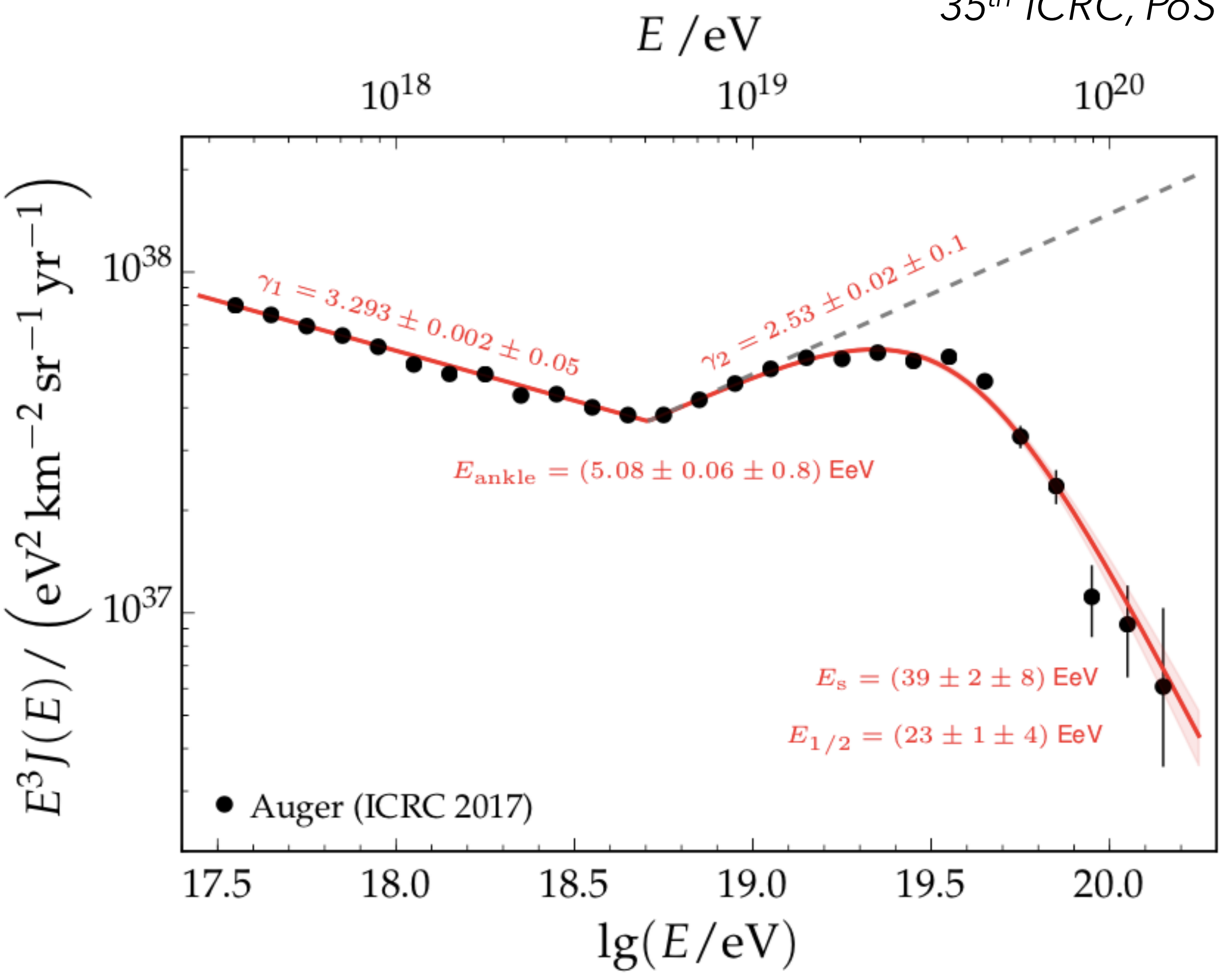


- ✧ The absence of photons and neutrinos strongly disfavors top-down acceleration models

UHECRs energy spectrum



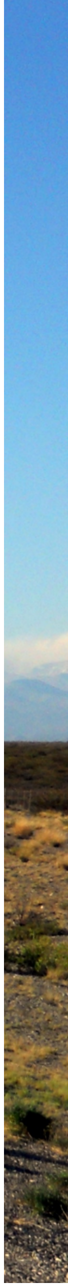
35th ICRC, PoS (2017) 486



- Suppression at highest energy unequivocally established
  - Propagation effect (GZK) or source exhaustion?

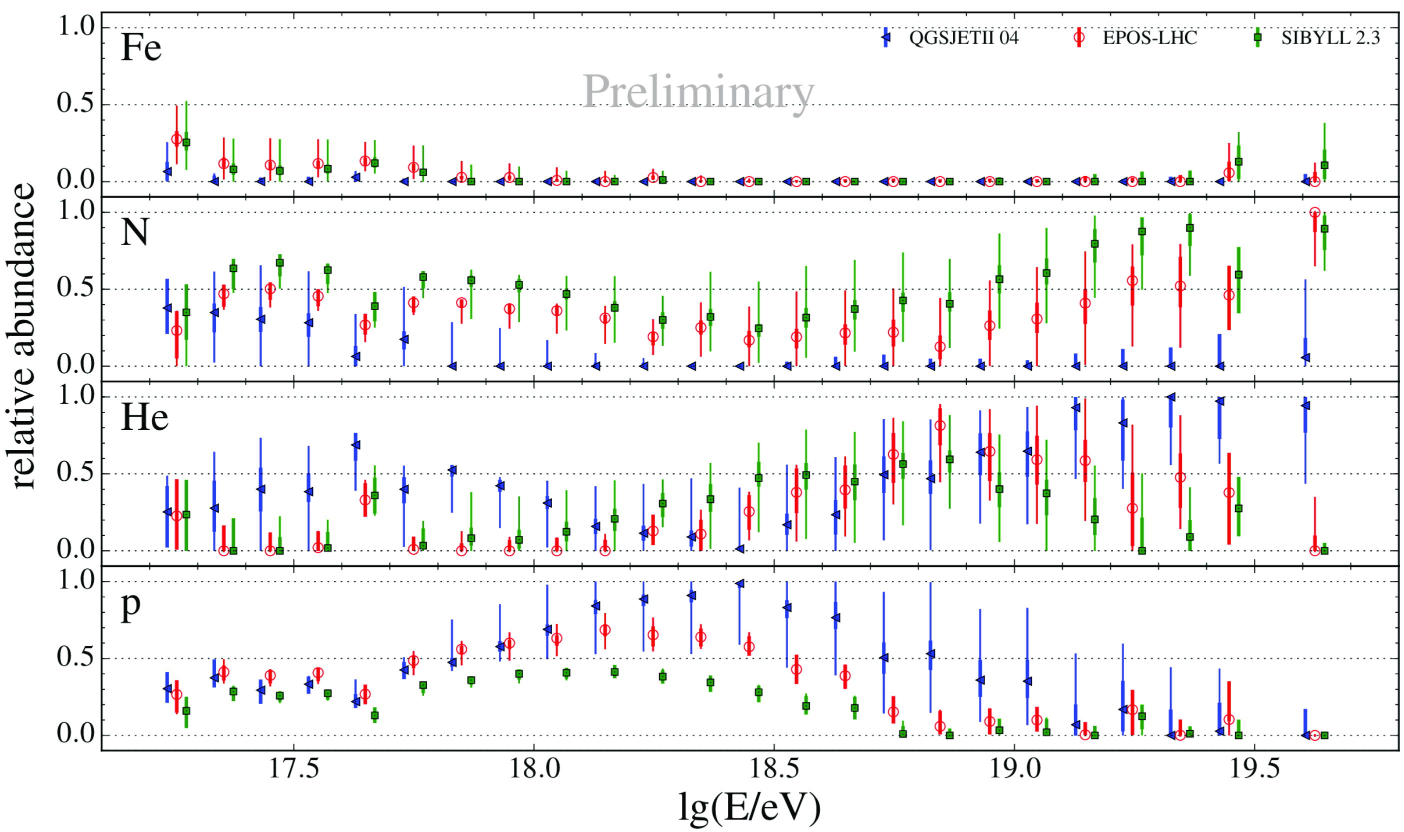
Nature of UHECRS

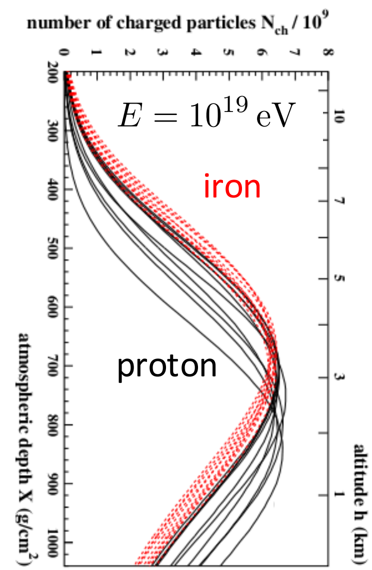
Determination of the composition of UHECRs is essential to understand its origin

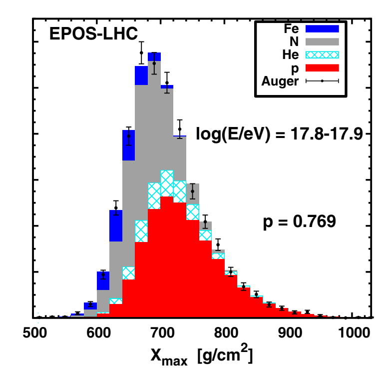


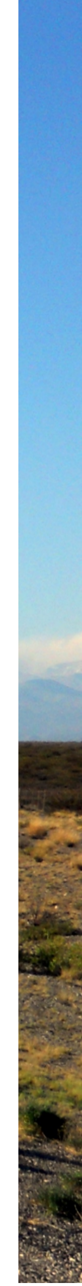
Composition fits to X_{max}

35th ICRC, PoS (2017) 506









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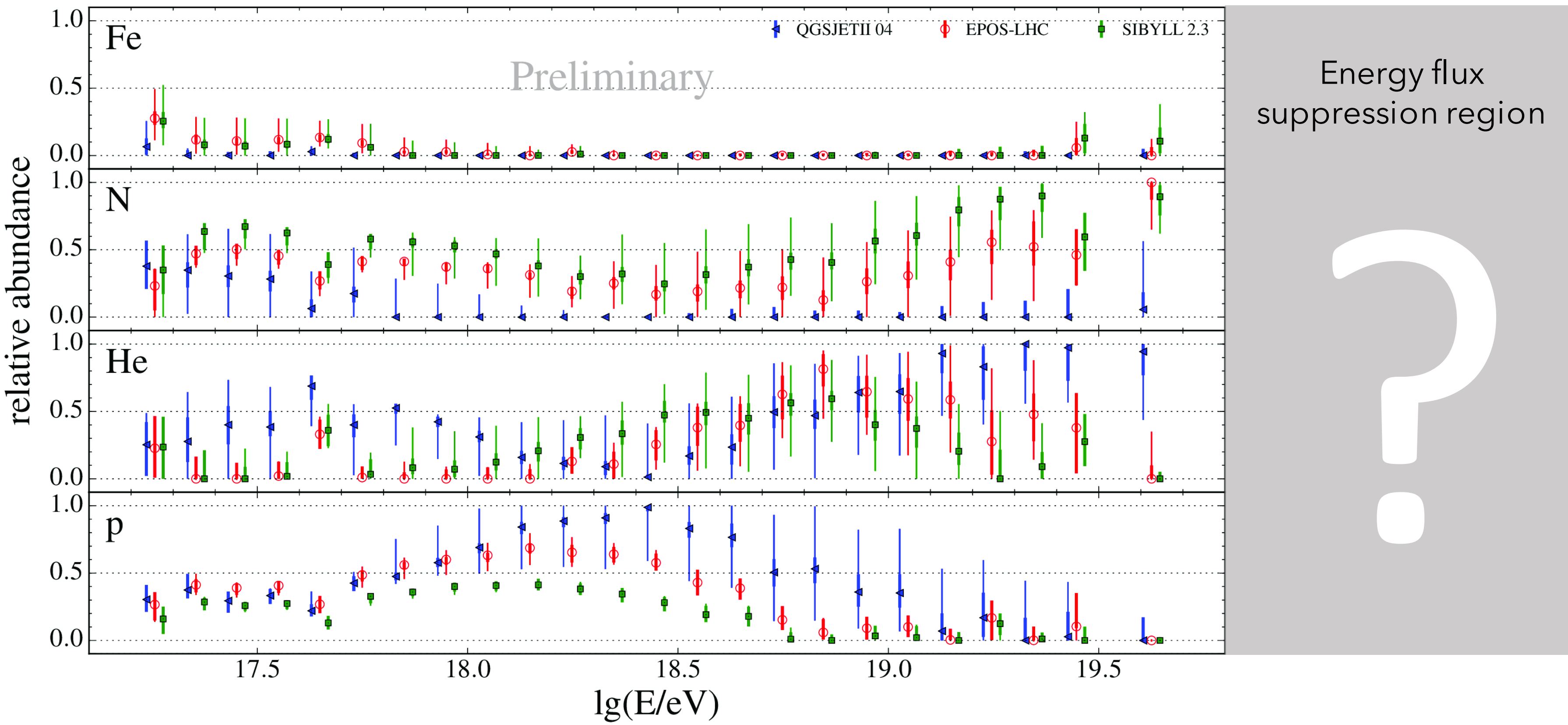
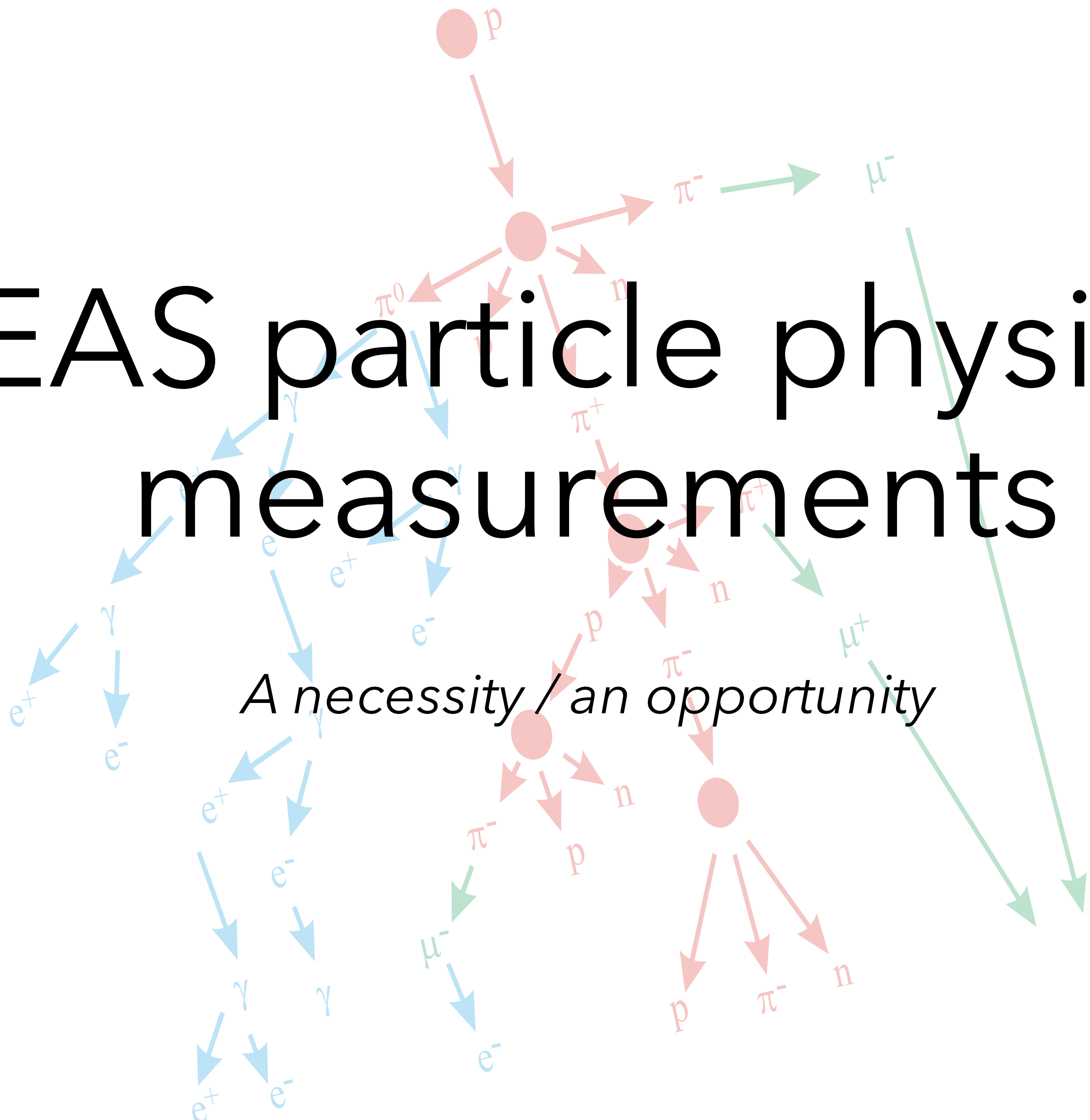


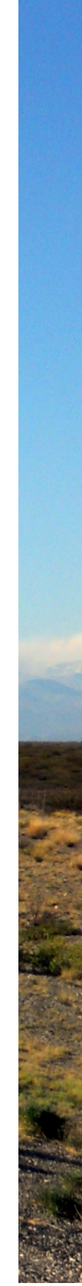
These results depend on the description of the shower, i.e., hadronic interaction models



EAS particle physics measurements

A necessity / an opportunity

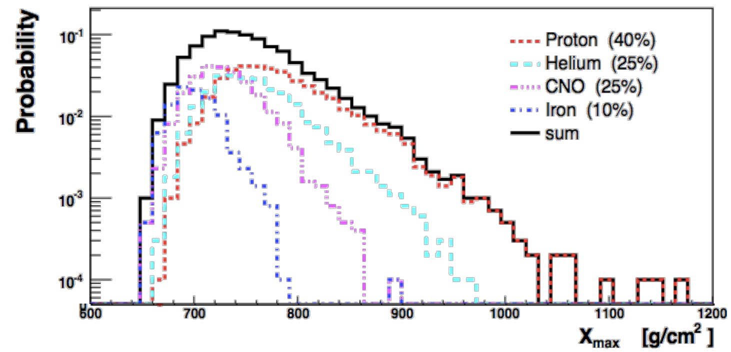
Ruben Conceição

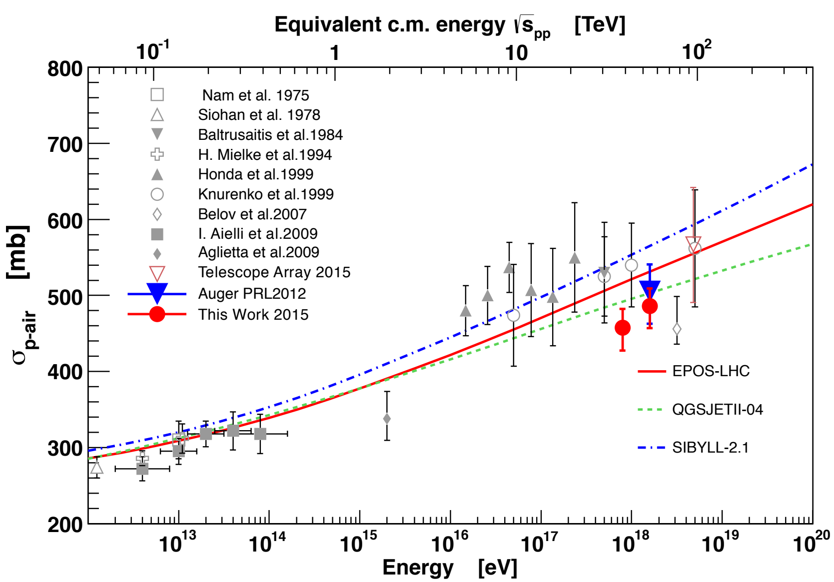


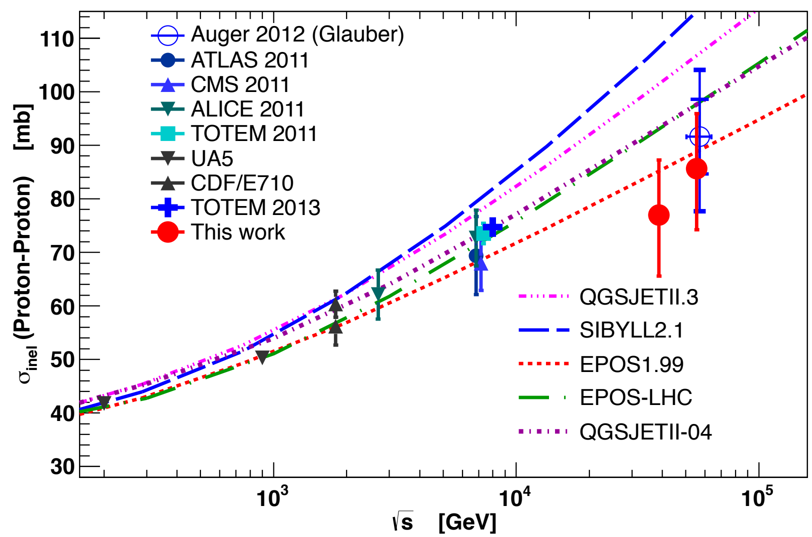
Proton-air cross-section

34th ICRC, PoS (2015) 401

- p-Air cross-section can be extracted from the X_{max} distribution tail
  - If there is a large fraction of protons



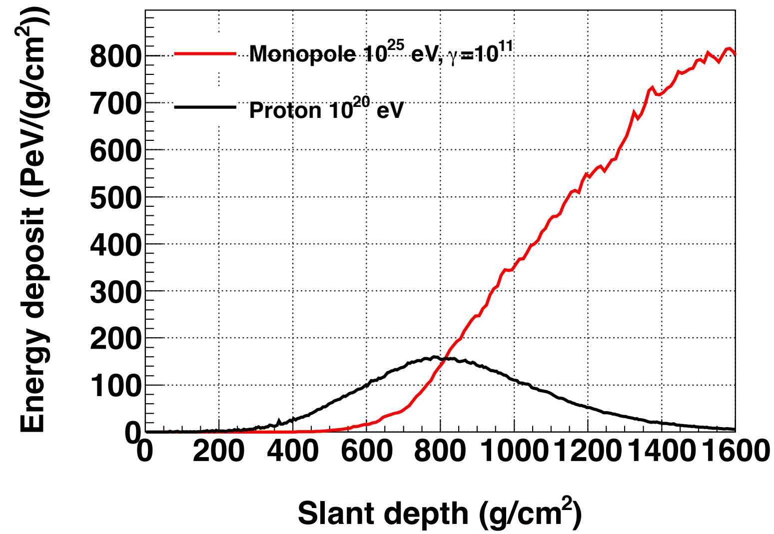


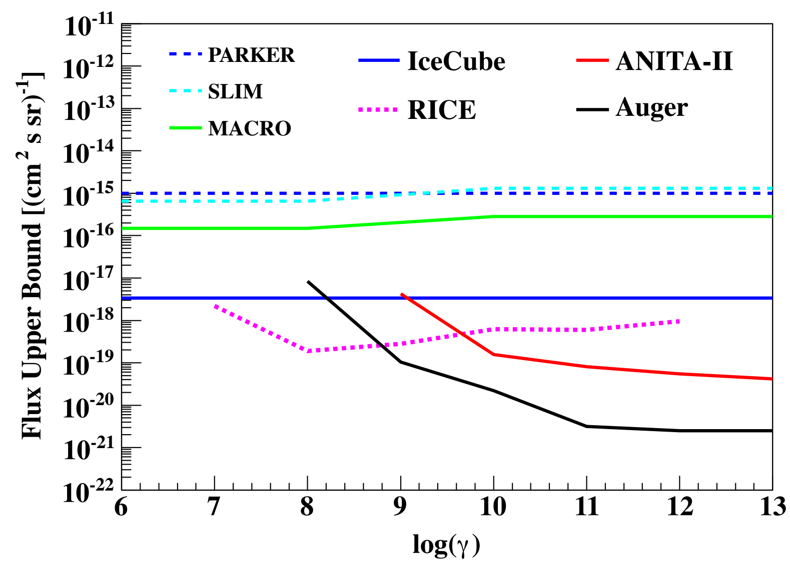


Testing exotic scenarios

Phys.Rev. D94 (2016) no.8, 082002

- Put the strongest limit on the existence of ultra-relativistic magnetic monopoles (MM)
  - Test on fundamental particle physics exotic scenarios
    - Relics of phase transitions in the early universe
  - MM produce air showers with a distinct signature from standard ones
    - $E_{mon} \approx 10^{25}\,\mathrm{eV}$
    - $M_{mon} \in [10^{11}; 10^{16}]\,\mathrm{eV/c^2}$

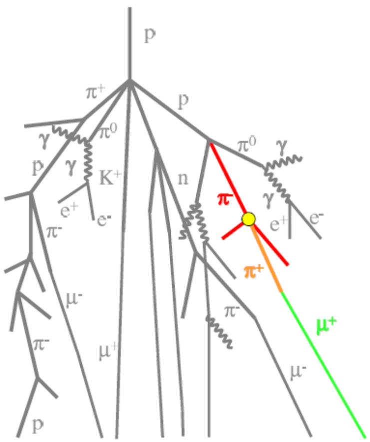




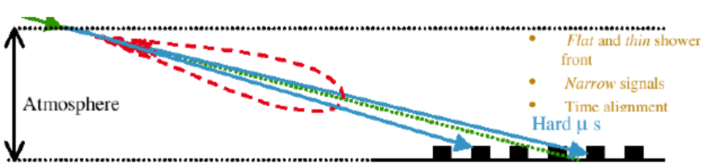
Muon content in air showers

Phys.Rev. D91 (2015) 3, 032003

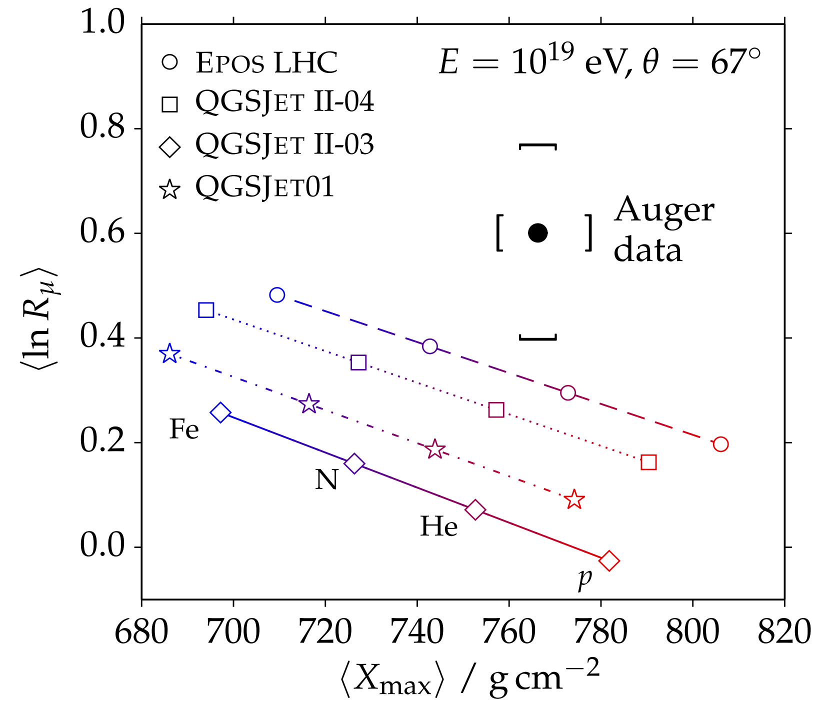
- Muons → Assess Hadronic interaction models (HIM)



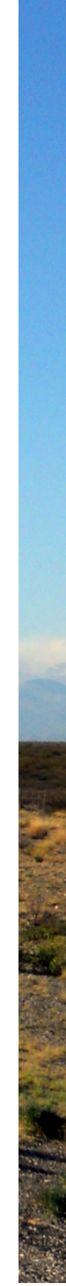
- Inclined shower → Muons



Surface Detector



Fluorescence Detector

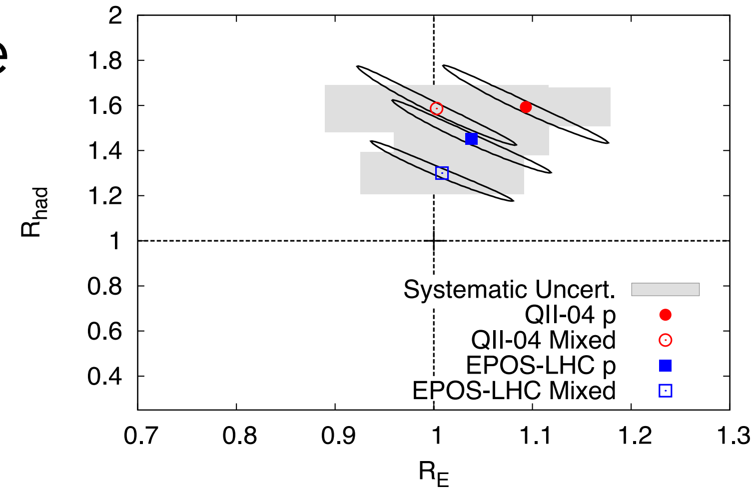


- Combination of the R_μ (number of muons) with X_{max} shows tension between data and all hadronic interaction models

More trouble for Hadronic Interaction Models…

Phys.Rev.Lett. 117 (2016) no.19, 192001

- Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had}) [Hybrid: SD + FD]
- Depth of maximum of muon production depth ($X^{*\mu}_{max}$)



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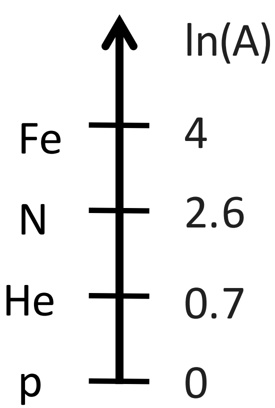
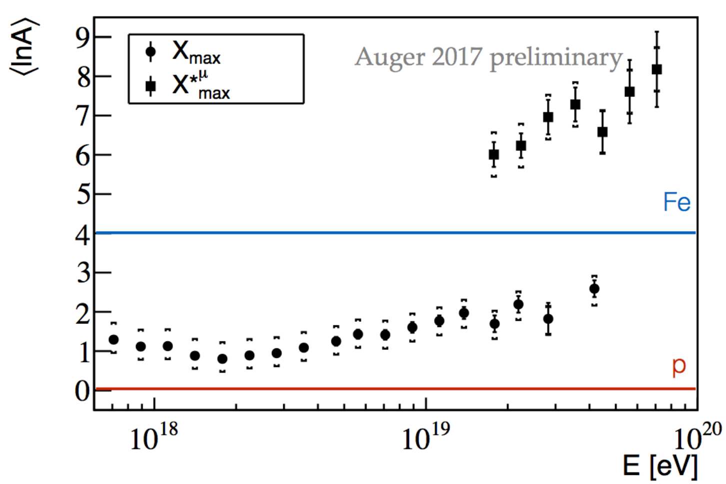
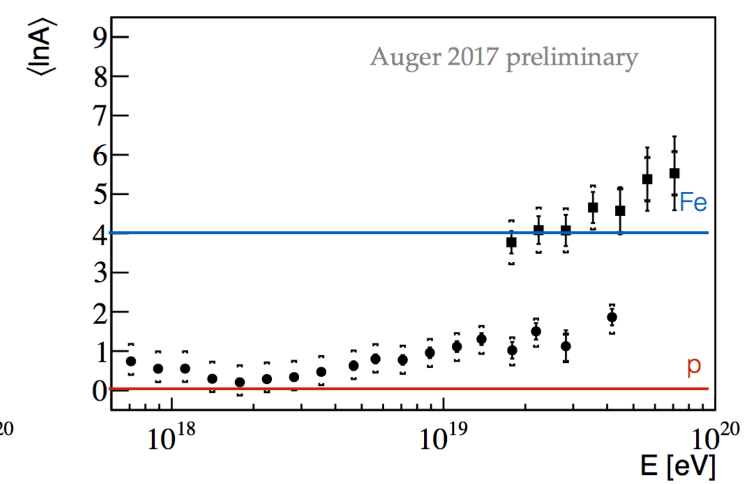
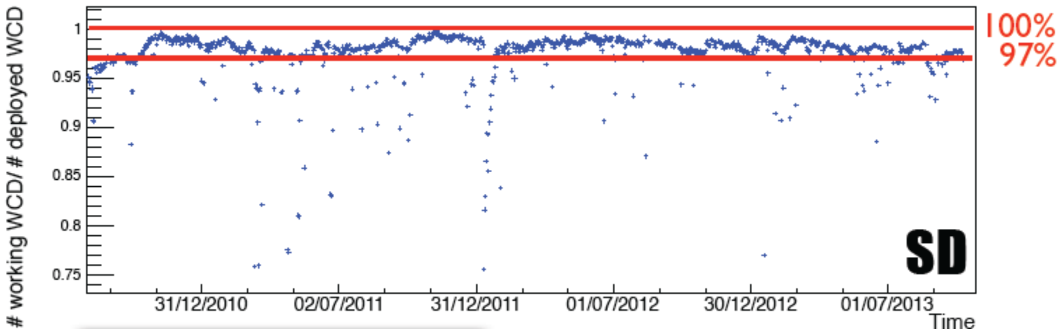


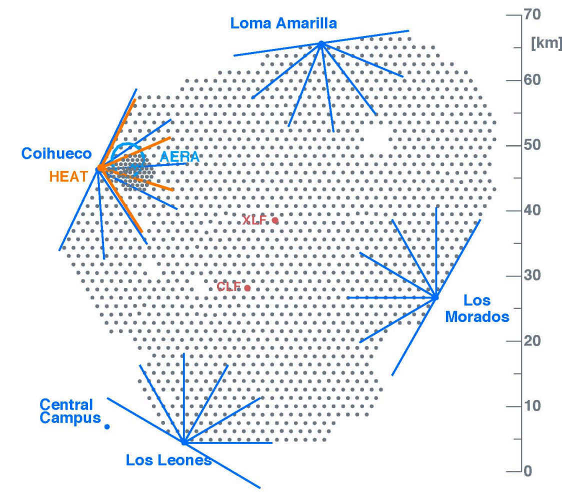




The future: AugerPrime

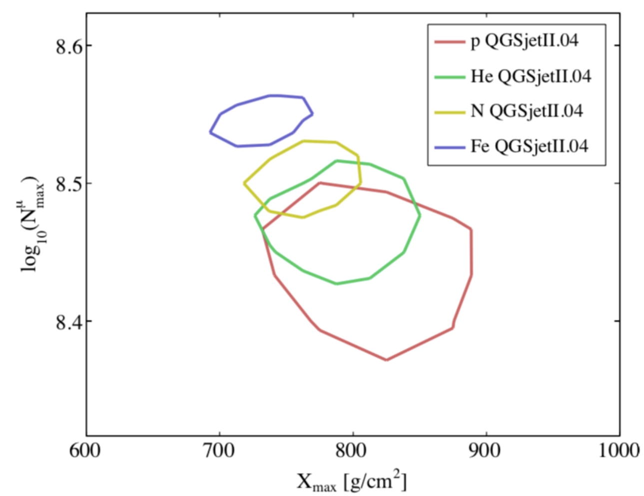
Fraction of Cherenkov tanks in operation





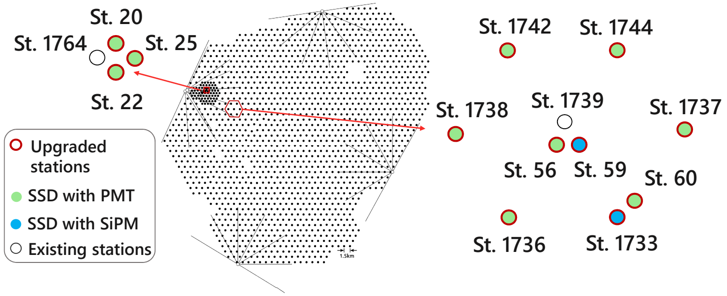
- Observatory is running smoothly and will operate until 2025
- Many interesting R&D projects: Radio, GigaHz, SiPM, RPCs, …
- Upgrade to measure separately the e.m. and muonic shower component at the ground

AugerPrime TDR, arXiv:1604.03637



The future: AugerPrime

- "Primary cosmic Ray Identification through Muons and Electrons"
- Two complementary detectors:
  - Scintillator on top of the tank: signal dominated by e.m. component
  - WCD sensitive to e.m. + muon
- The goal:
  - Enhance primary identification
  - Improve shower description
  - Reduce systematic uncertainties
- Engineering array taking data



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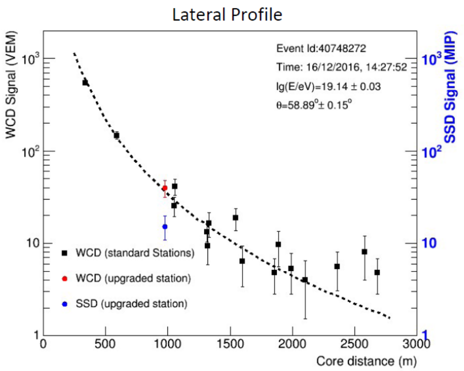
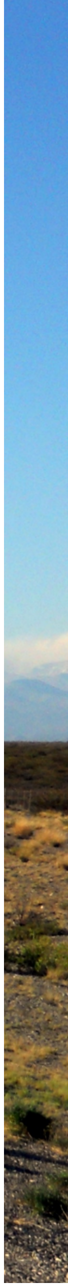
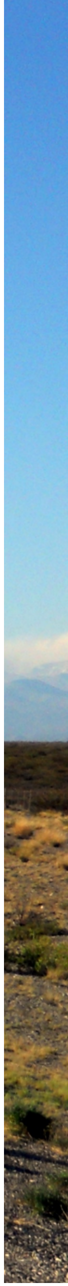




Summary

- UHECRs measured at Pierre Auger Observatory
  - Opportunity to study the high-energy Universe and Particle Physics at the highest energies
- Pierre Auger Observatory has delivered many important results
  - GZK-like suppression established
  - Complex primary mass composition scenarios
  - Current hadronic interaction models not able to describe consistently the air shower observables
- Upgrade: AugerPrime
  - Measure independently the e.m. and muonic component at ground (data taking until 2025)



Acknowledgements

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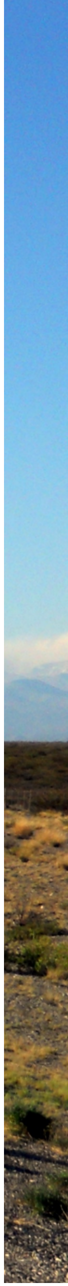
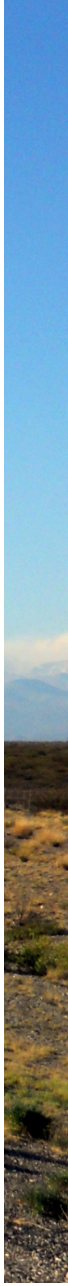
REPÚBLICA PORTUGUESA

LIP

TÉCNICO LISBOA



Backup slides

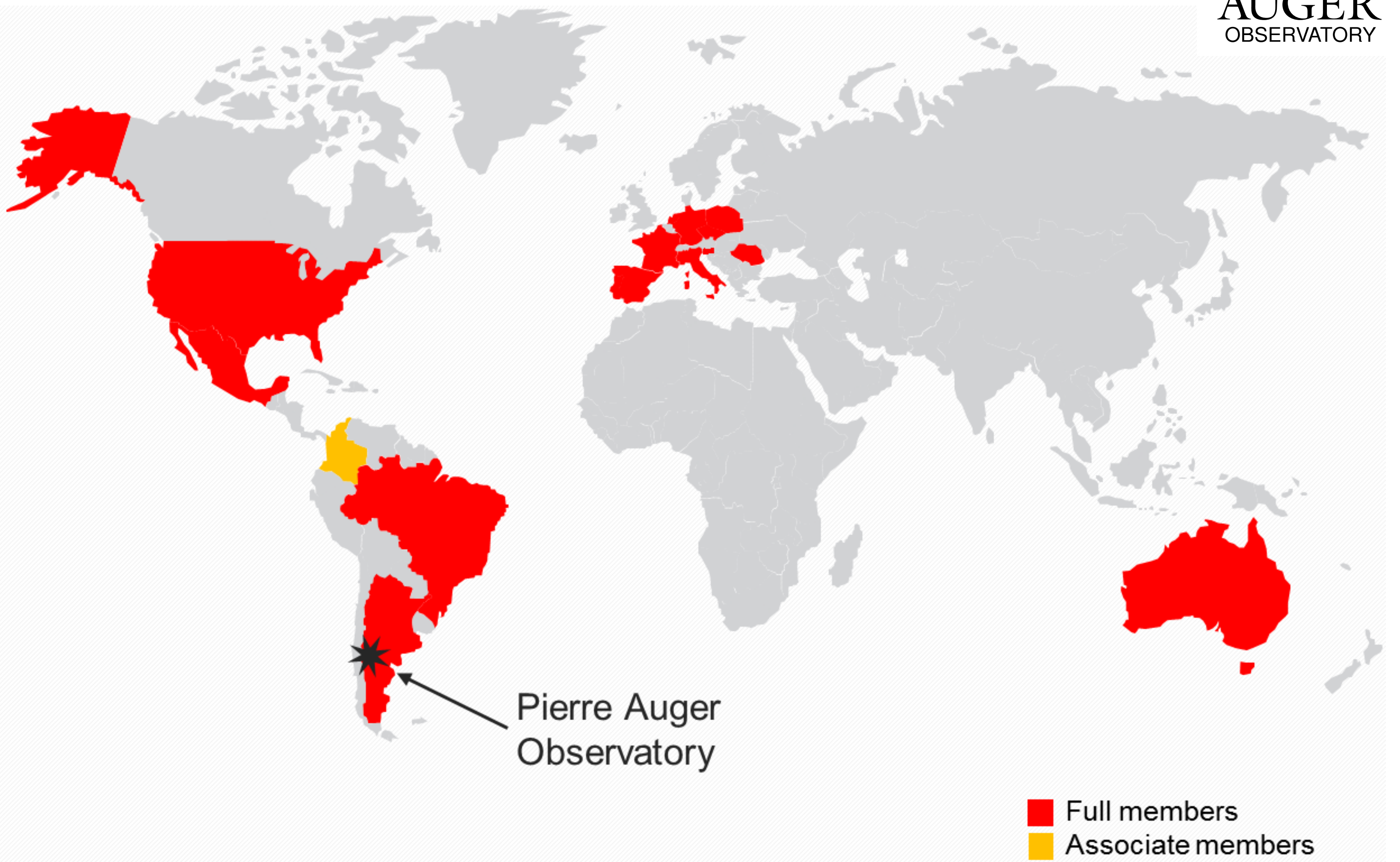


Pierre Auger Collaboration

16 countries, ≈ 90 institutions, ≈ 500 authors

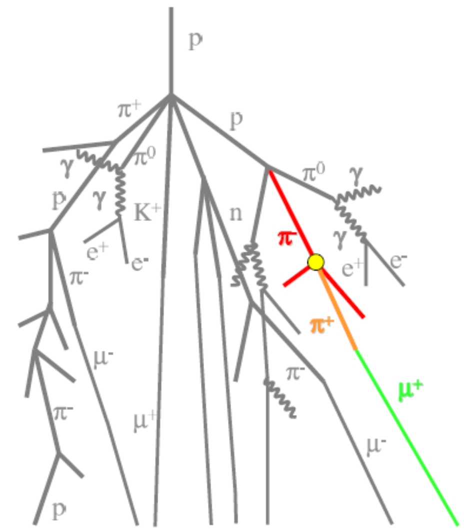
Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

*associated

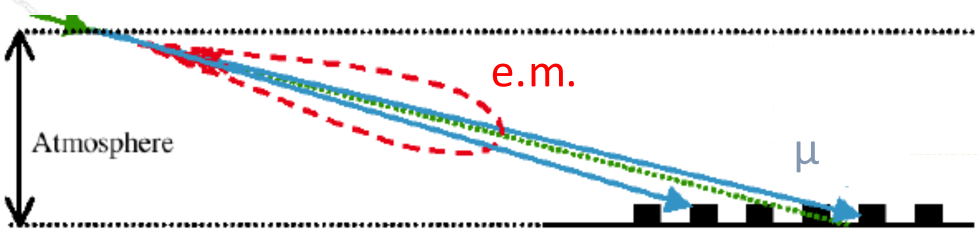


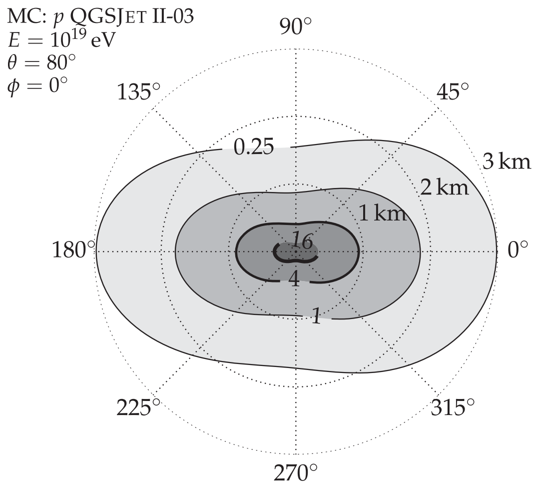
Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component



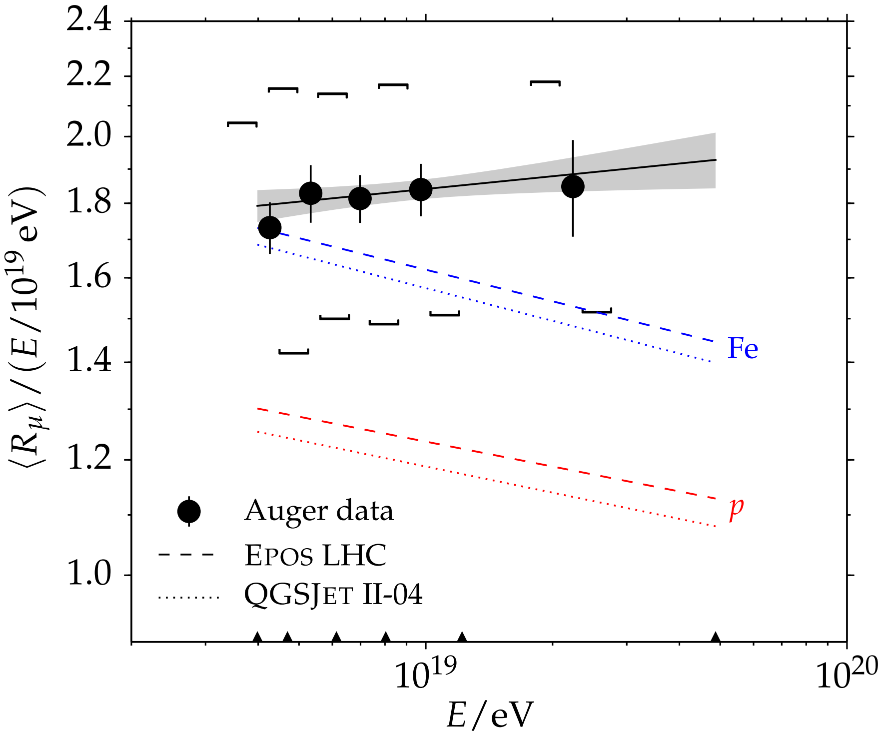
- Through inclined showers is possible to measure directly the muon content (R_μ) in the SD
  - Electromagnetic shower component gets attenuated

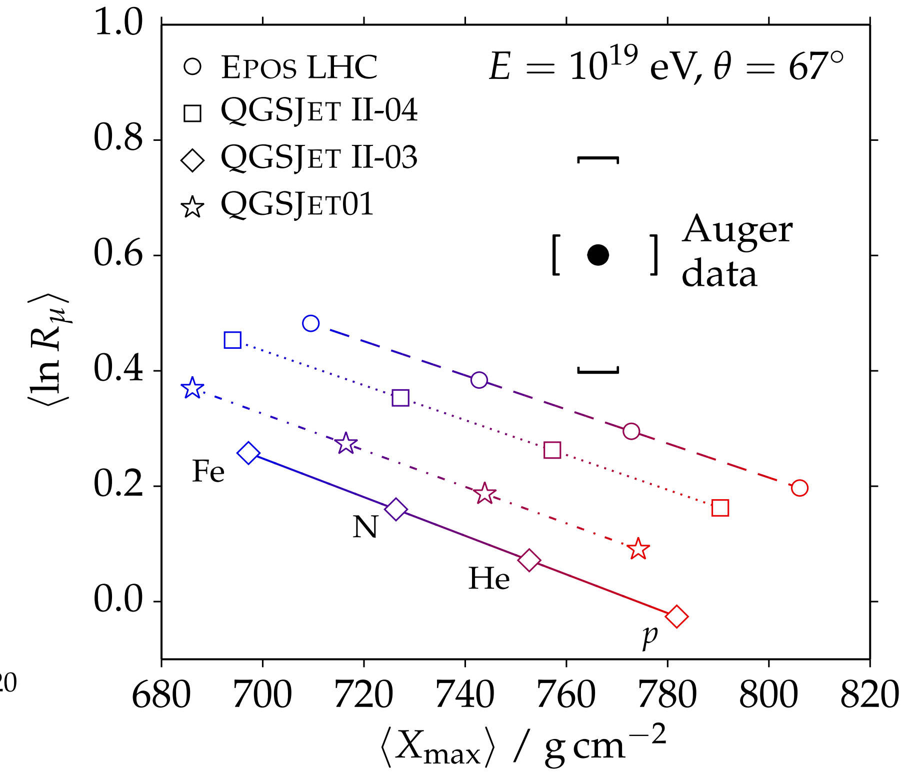


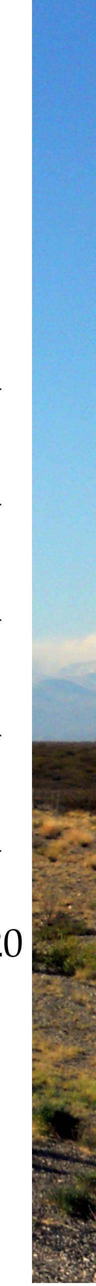


Muon content in air showers

Phys.Rev. D91 (2015) 3, 032003







- ✧ Mean muon number compatible with iron showers within systematic uncertainties
- ✧ Combination of the R_μ with X_{max} shows tension between data and all hadronic interaction models

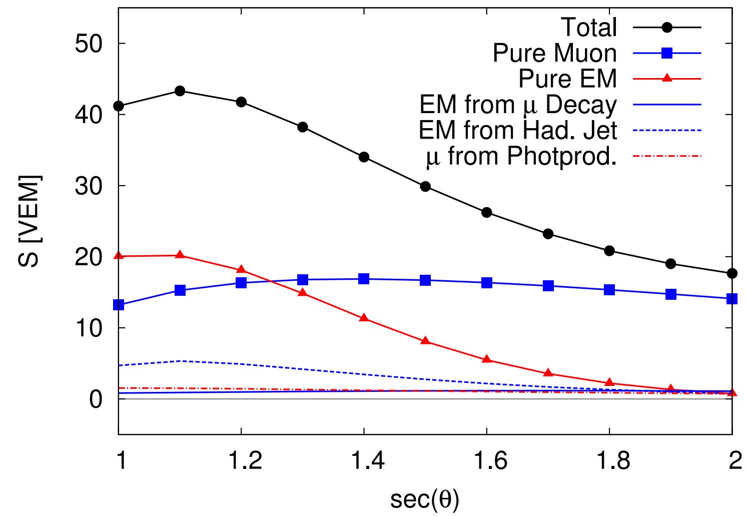
Explore hybrid events

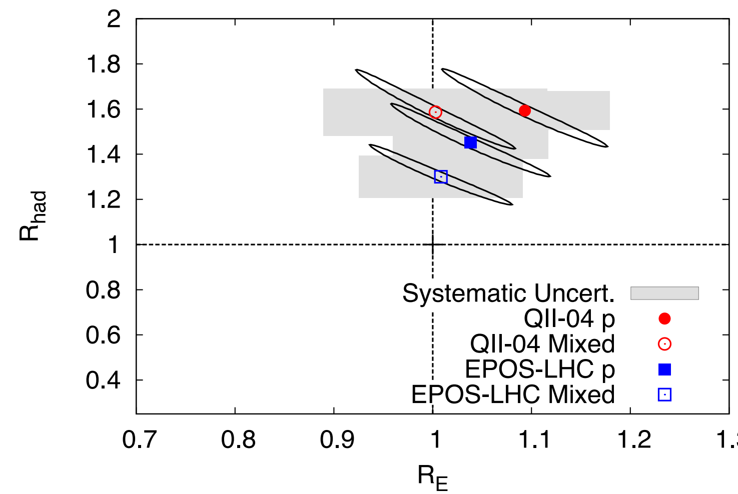
- Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had})

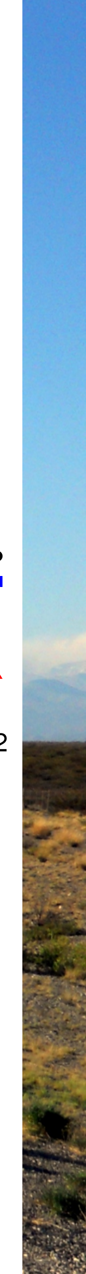
$$S_{\rm resc}(R_E, R_{\rm had})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\rm had}\, R_E^{\alpha}\, S_{{\rm had},i,j}$$

- Findings:
  - No need for an energy rescaling
  - Hadronic signal in data is significantly larger with respect to simulations

Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$







Muon Production Depth

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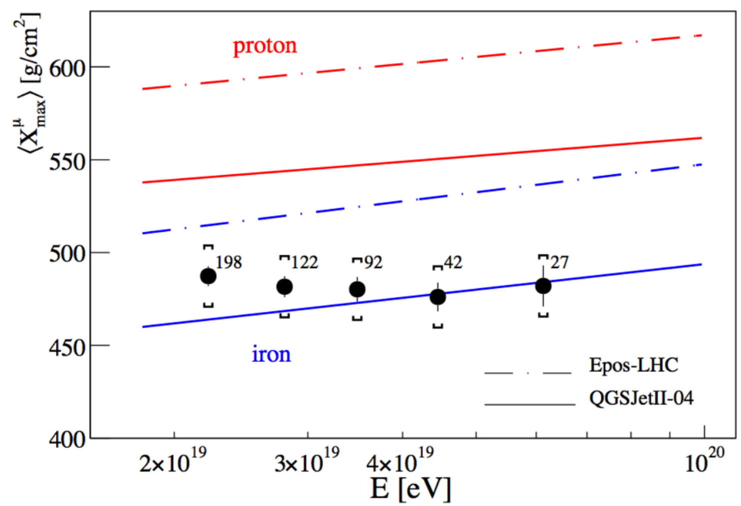
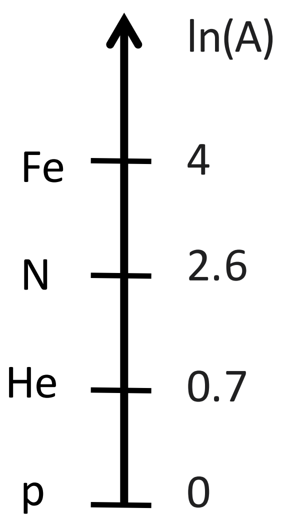
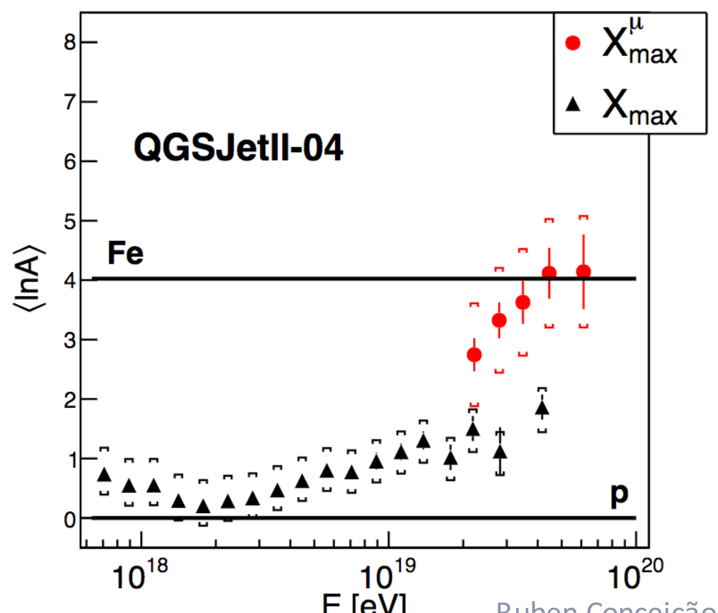
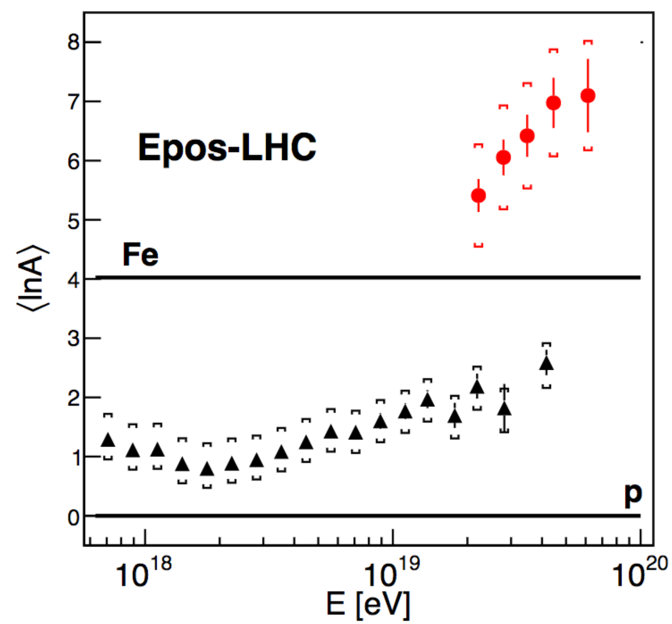
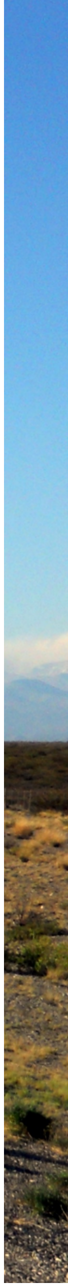
- Muon Production Depth
  - Sensitive to composition
- Mean X_{max} and X^{μ}_{max} should give the same average mass composition
  - EPOS-LHC fails to provide a consistent solution



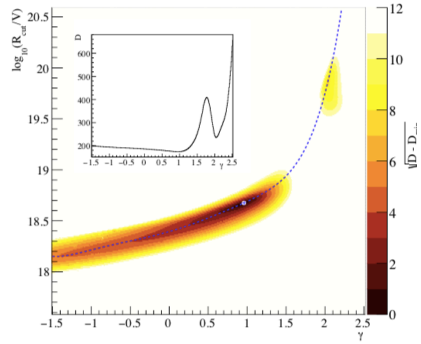








Combined spectrum + comp fits



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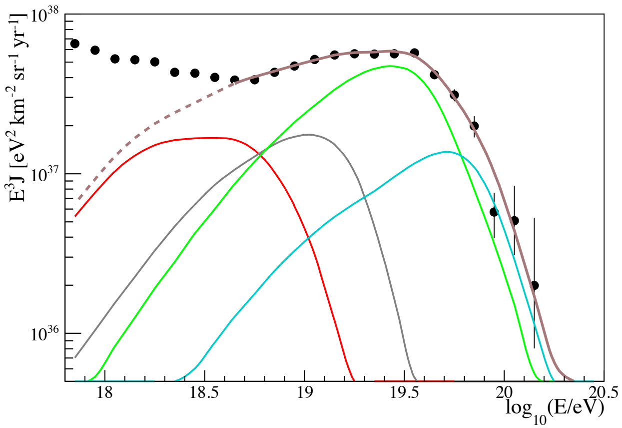
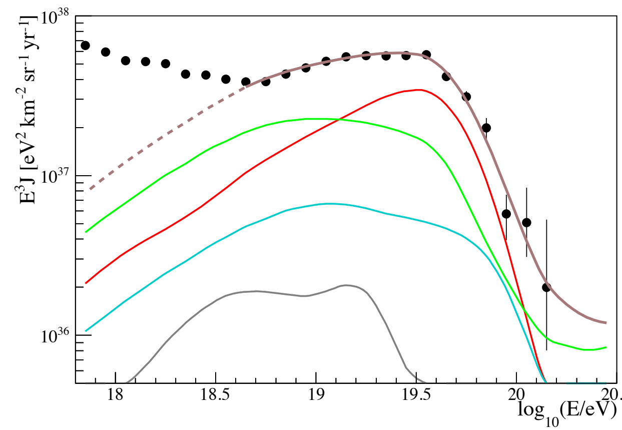
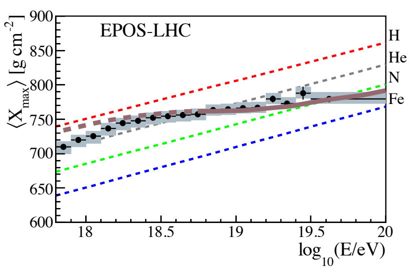
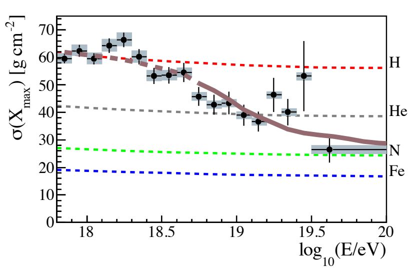
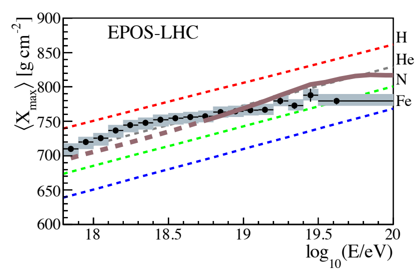
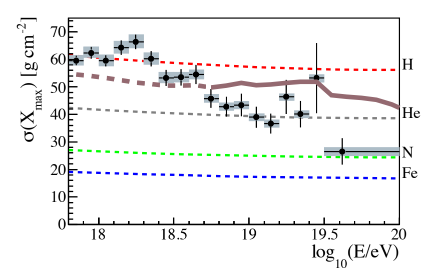


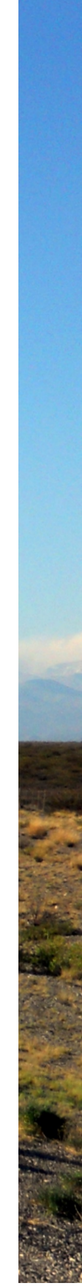










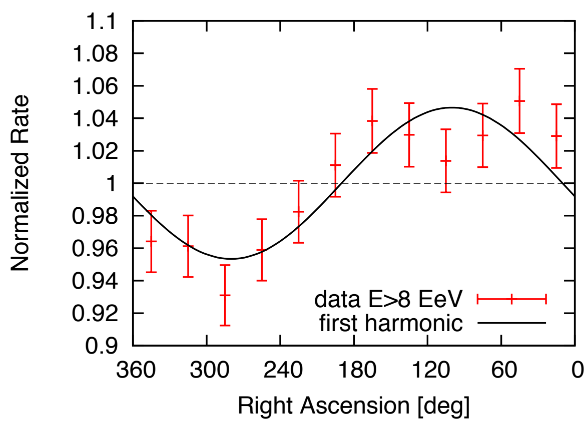


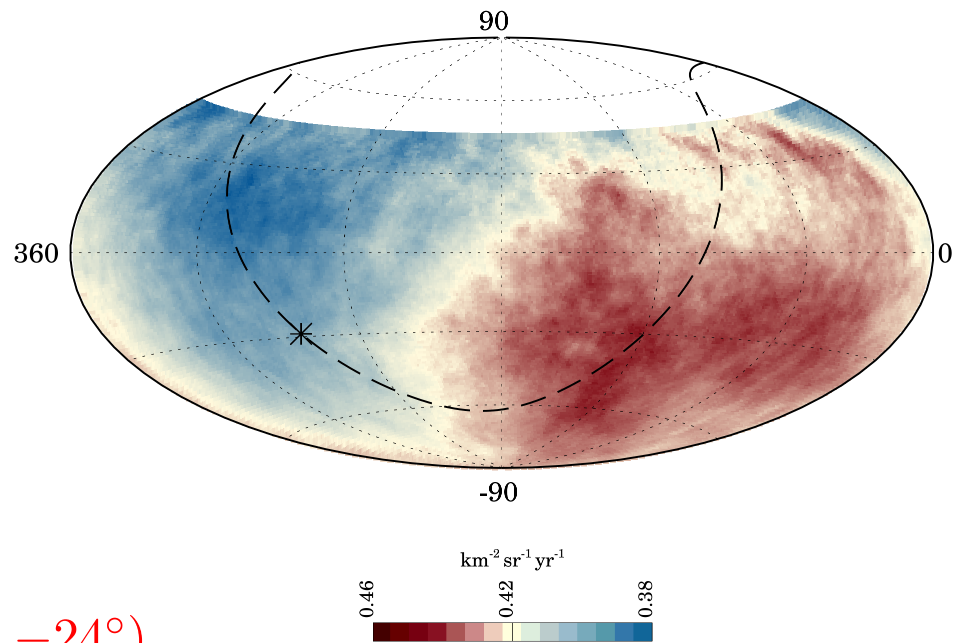
UHECRs dipole

Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

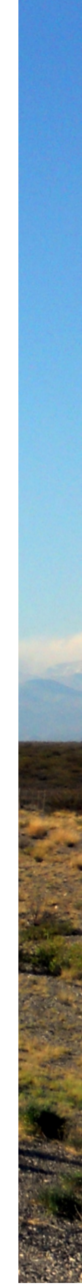
significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)





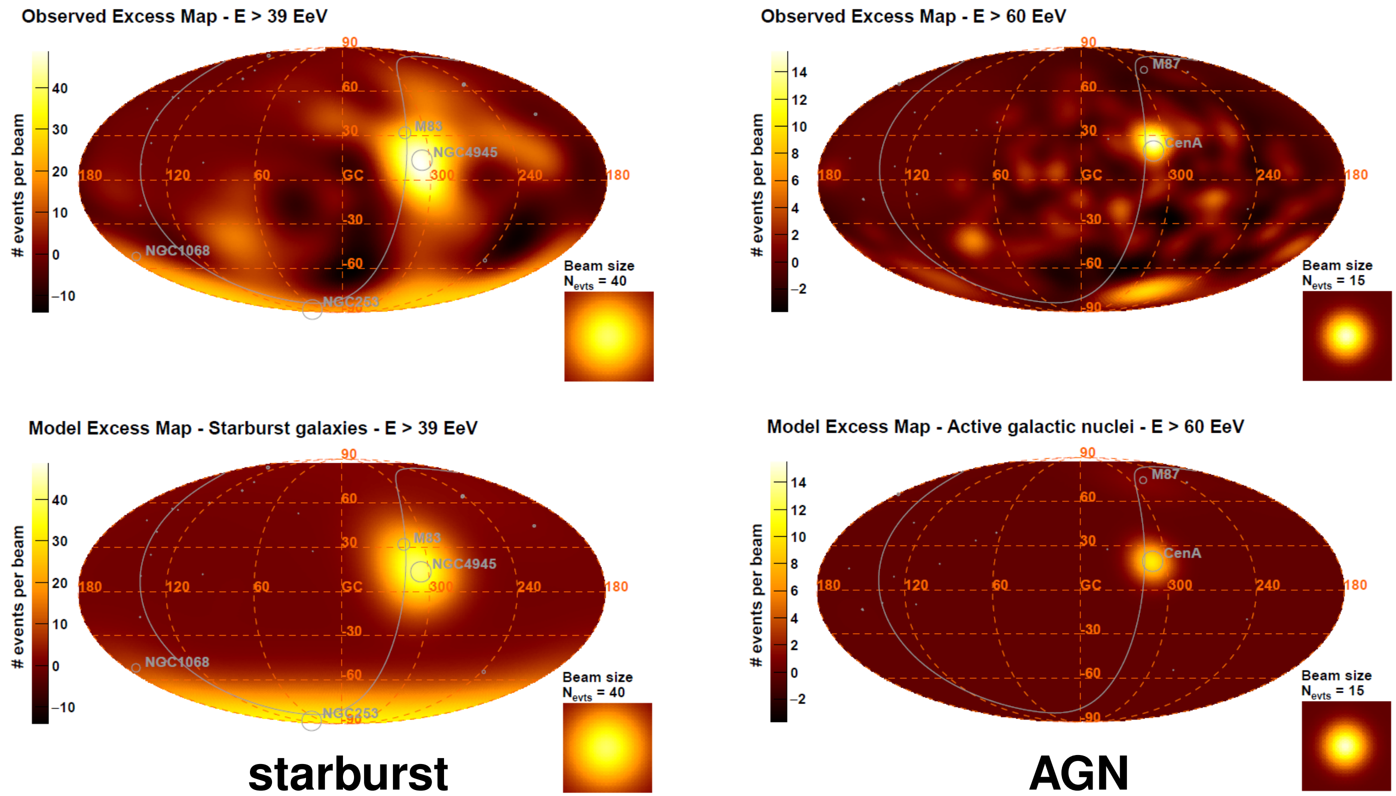
3-d dipole above 8 EeV:

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



Search for intermediate scale anisotropy

preliminary

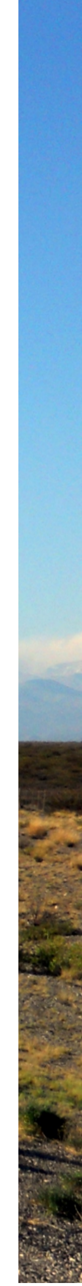


starburst

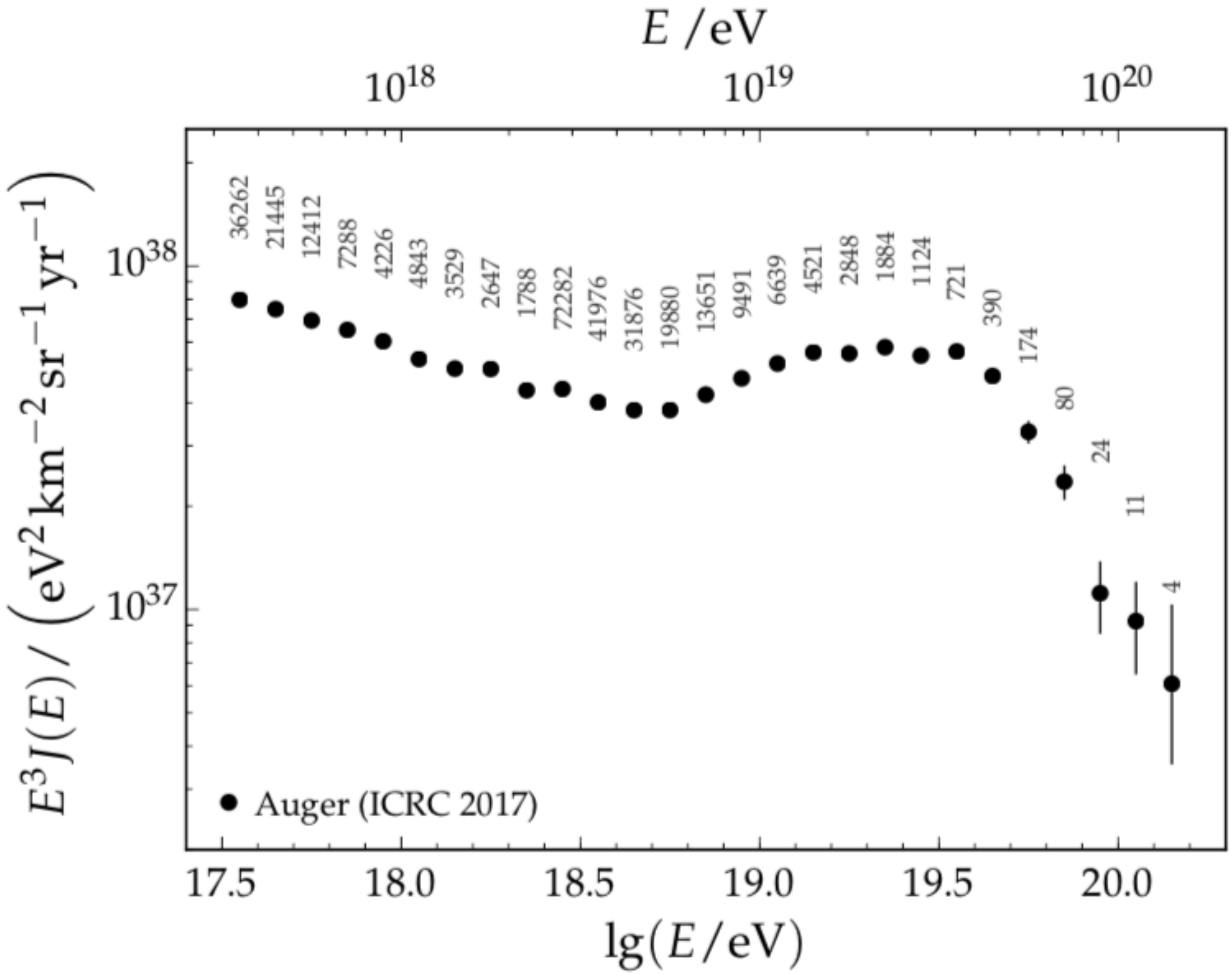
$f = 10\%,\ \psi = 13°$
pre-trial* p-value: 4×10^{-6}
post-trial** p-value: 4×10^{-5}
post-trial** significance: $3.9\,\sigma$

AGN

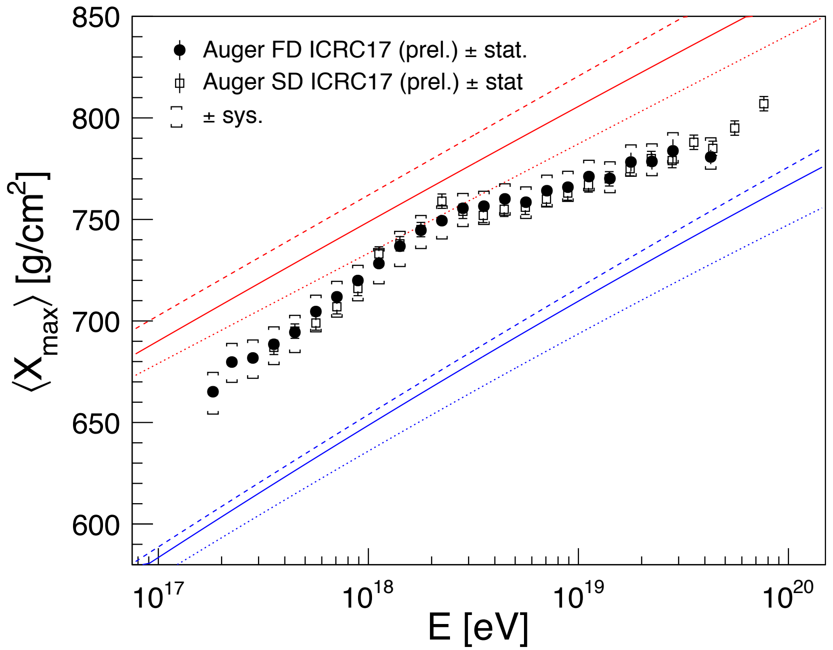
$f = 7\%,\ \psi = 7°$
pre-trial* p-value: 5×10^{-4}
post-trial** p-value: 3×10^{-3}
post-trial** significance: $2.7\,\sigma$

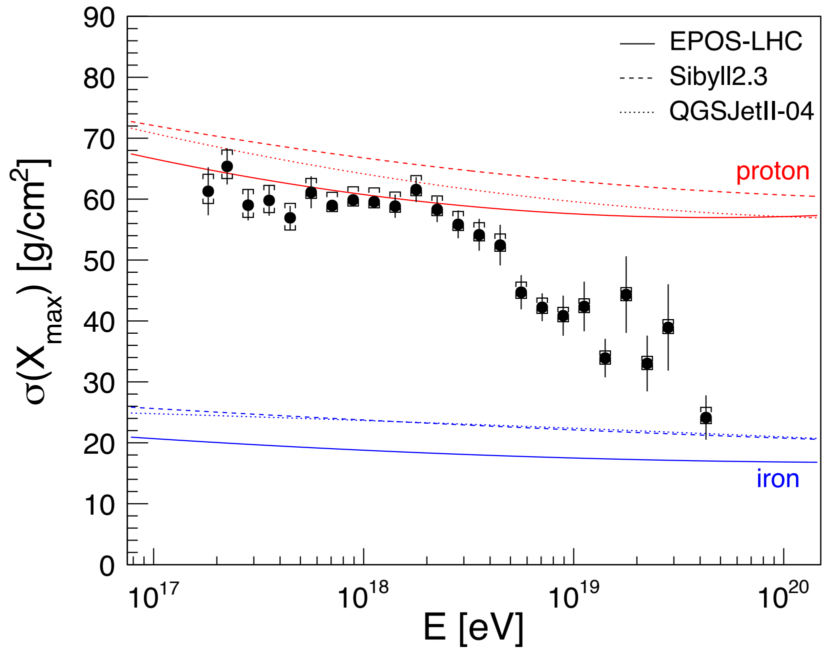


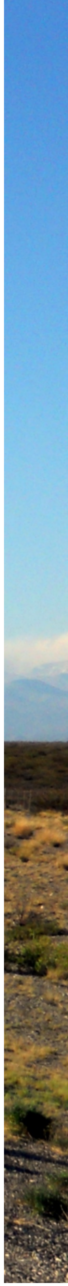
UHECRs energy spectrum



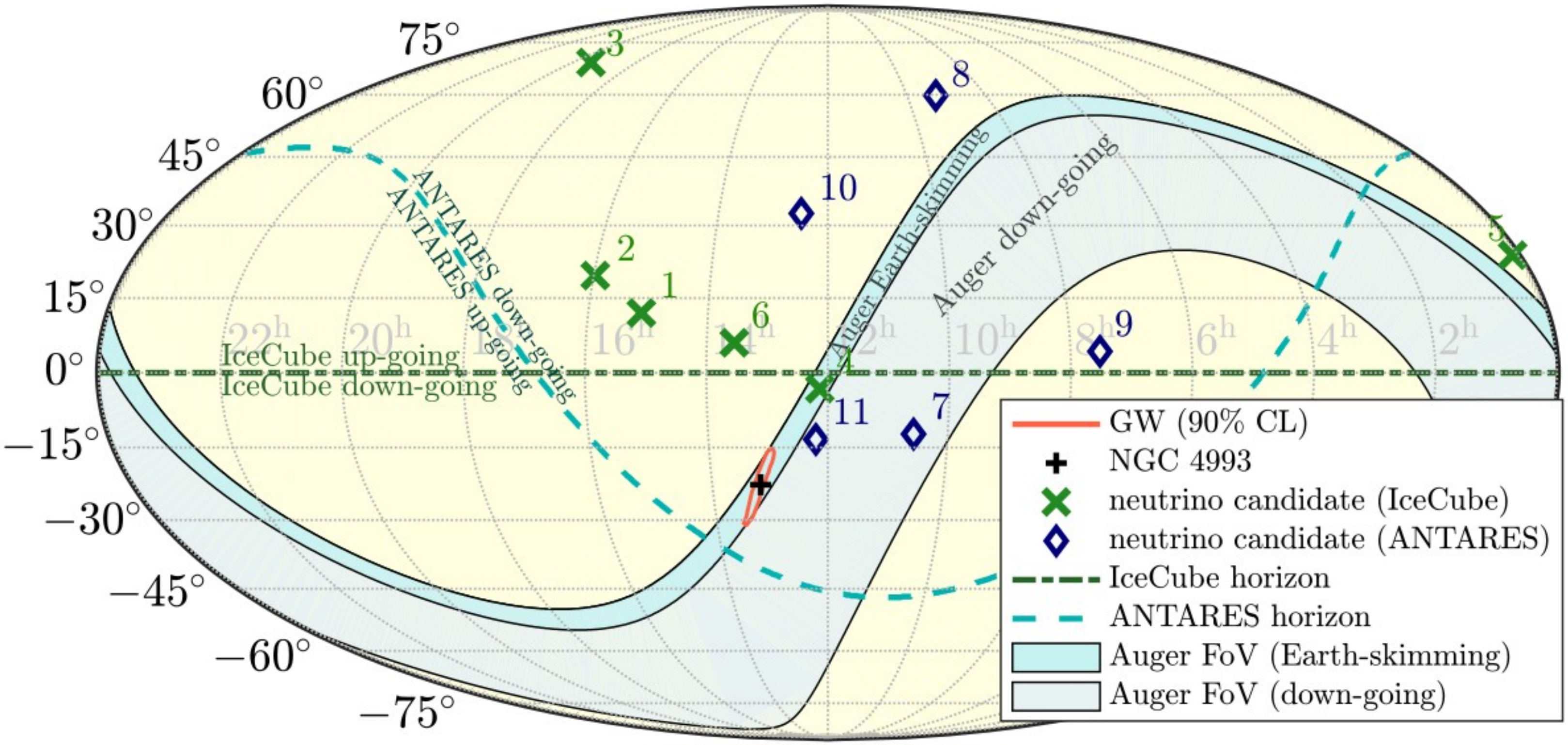
Xmax moments



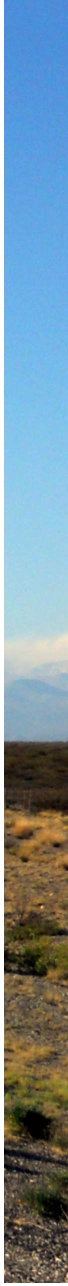




GWs and neutrinos



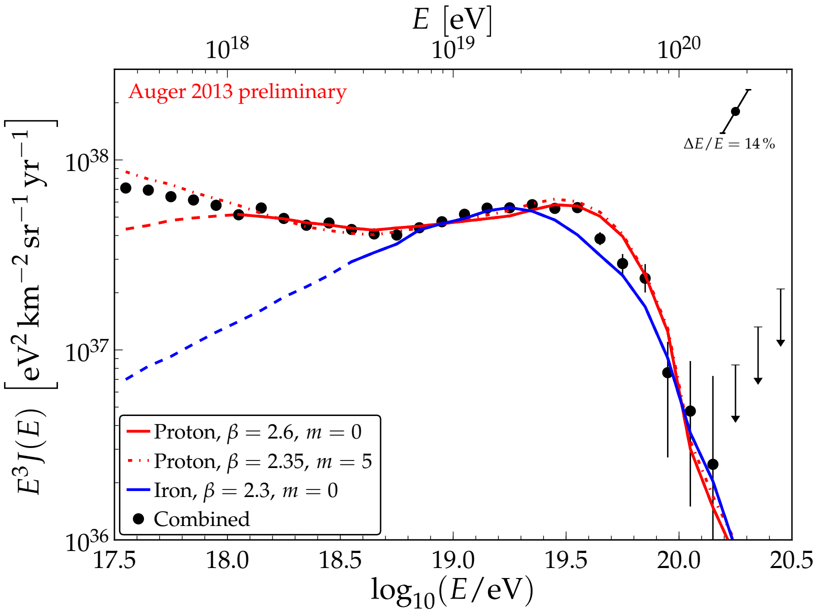
✧ Sky Map GW170817



Two possible scenarios

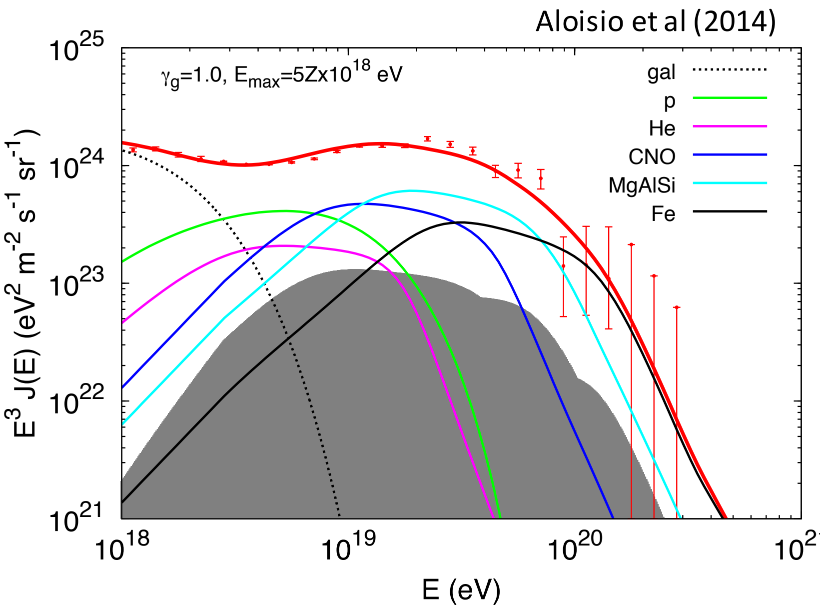
Pure proton or Fe nuclei at source

Cutoff caused by **GZK or photo-disintegration**



Mixed composition at source

Cutoff caused by **source energy exhaustion**



The UHECR composition is essential to understand the spectrum features cause

Pierre Auger Observatory: latest results and prospects

Ruben Conceição

on behalf of the Pierre Auger Observatory

30^{th} Rencontres de Blois, June 6^{th} 2018