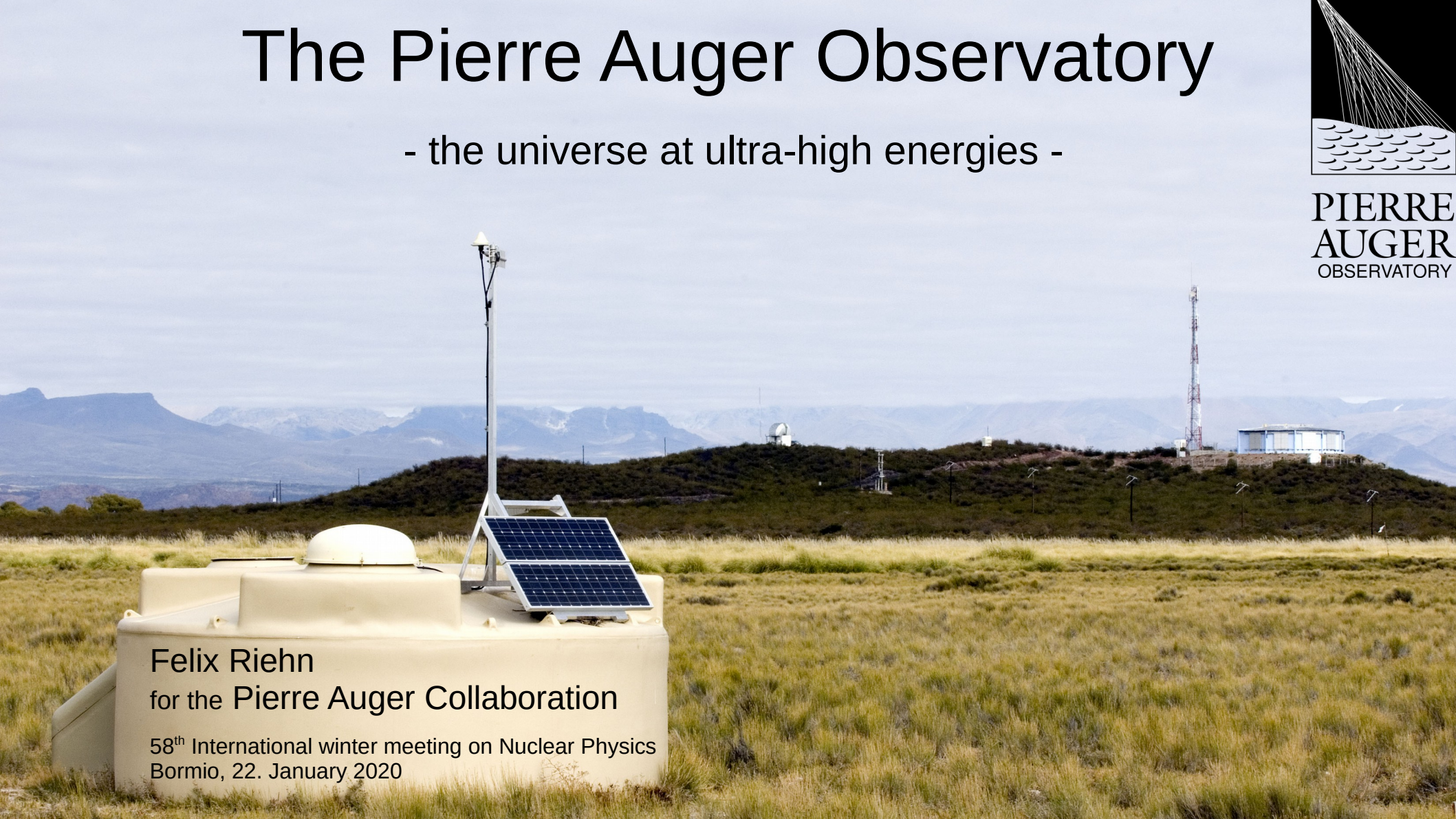
The Pierre Auger Observatory

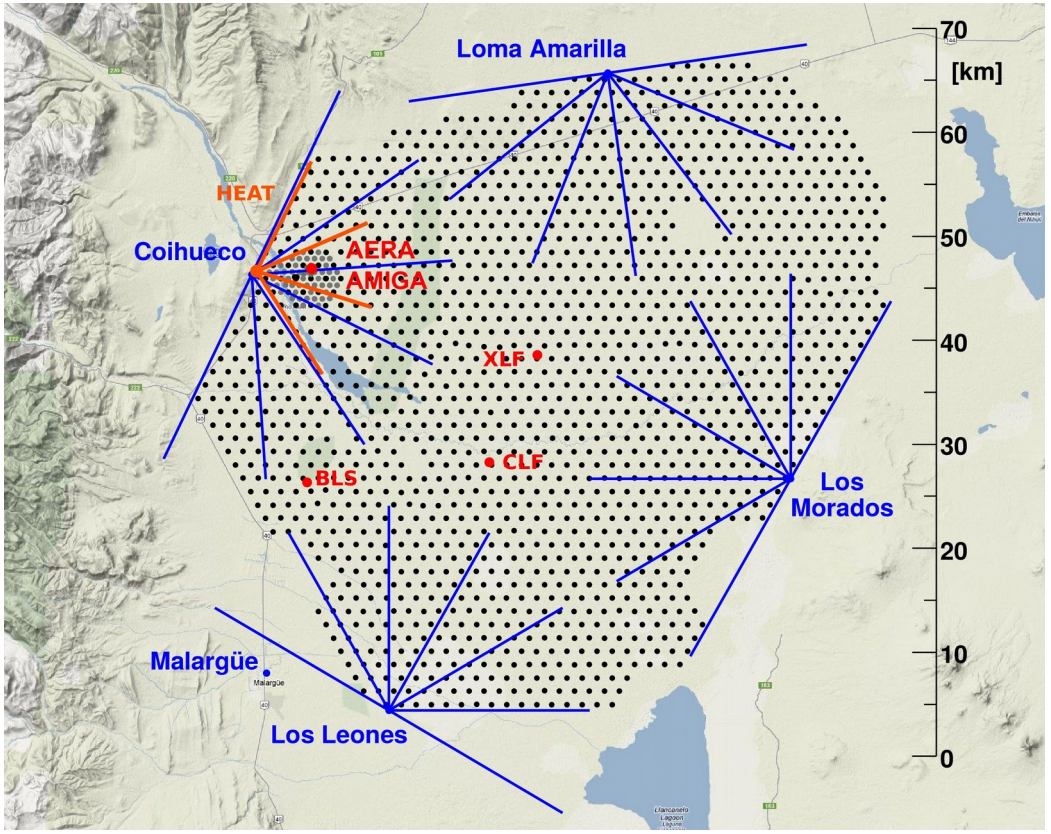
- the universe at ultra-high energies -



Felix Riehn
for the Pierre Auger Collaboration

58th International winter meeting on Nuclear Physics
Bormio, 22. January 2020

Pierre Auger Observatory



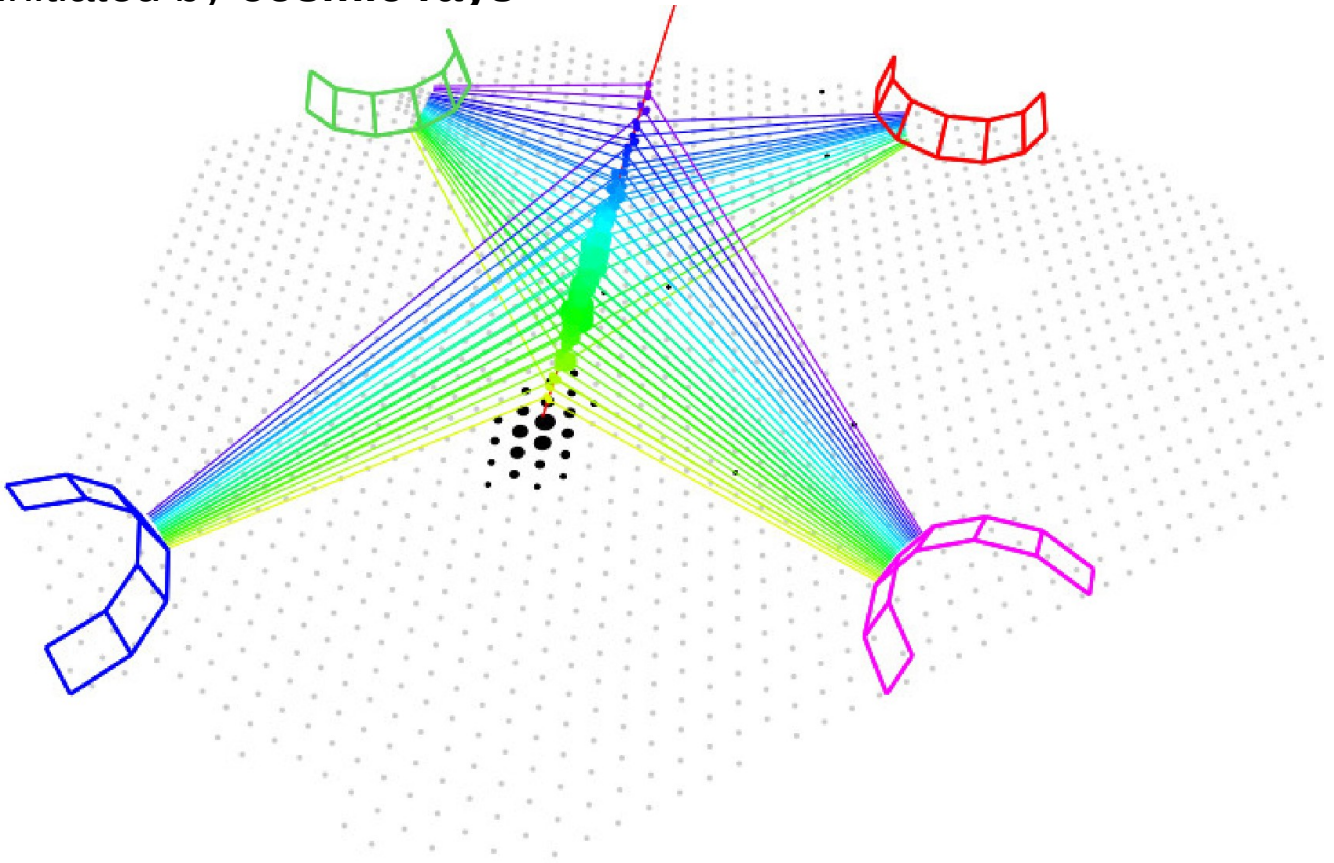
Surface detector array
1600 stations, 1.5km grid, 3000km^2
61 stations, 0.75km grid, 25km^2
~100% duty-cycle

Fluorescence detector
4 sites,
24 Telescopes with 1-30deg field-of-view,
3 Telescopes with 30-60deg field-of-view
~15% duty-cycle

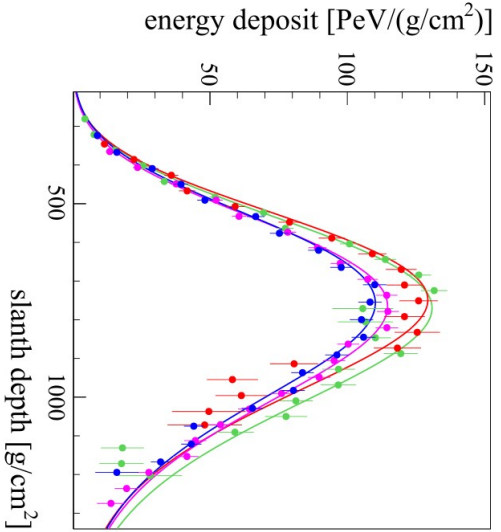
Plus: Engineering radio array, underground muon detectors, atmospheric monitoring, ..

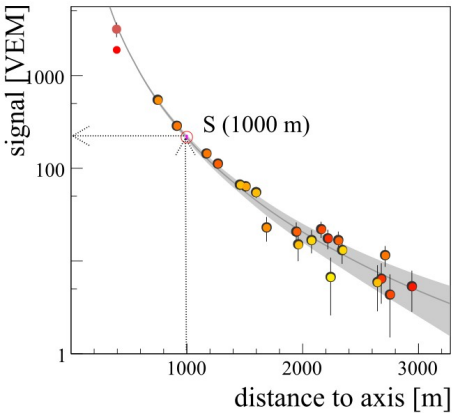
What do we measure ?

Extensive air showers
initiated by **cosmic rays**



Hybrid measurement





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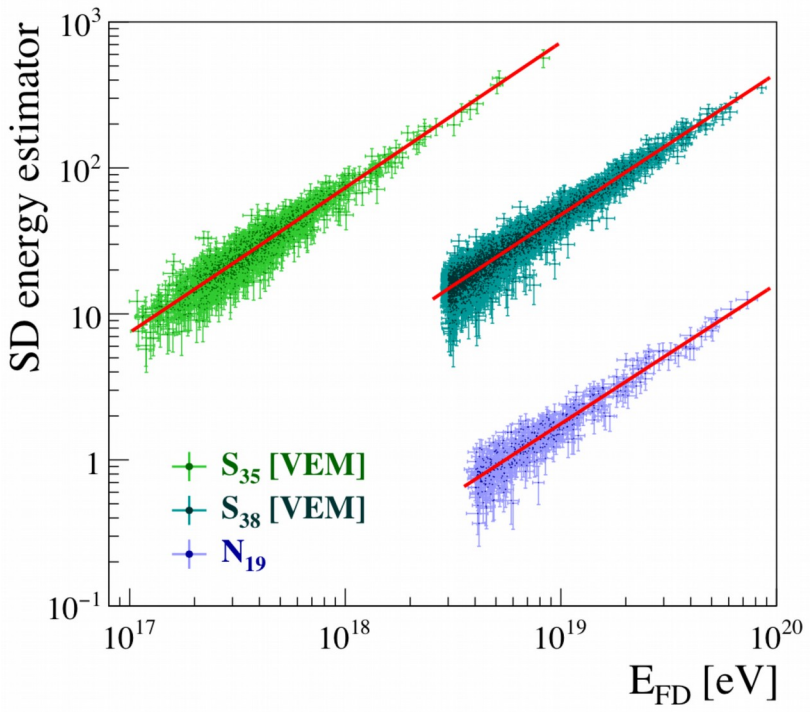
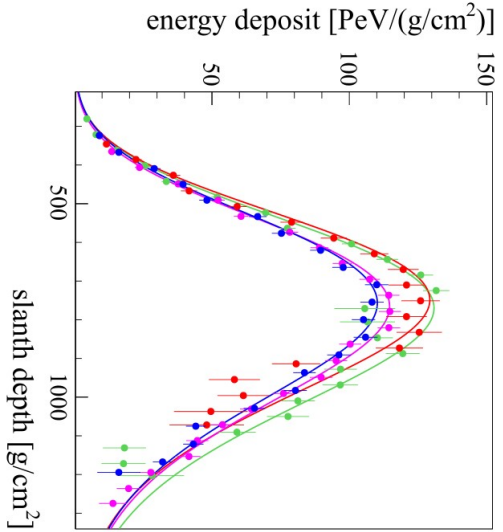
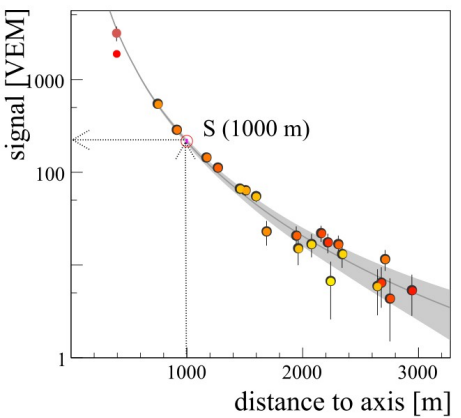
Hybrid measurement



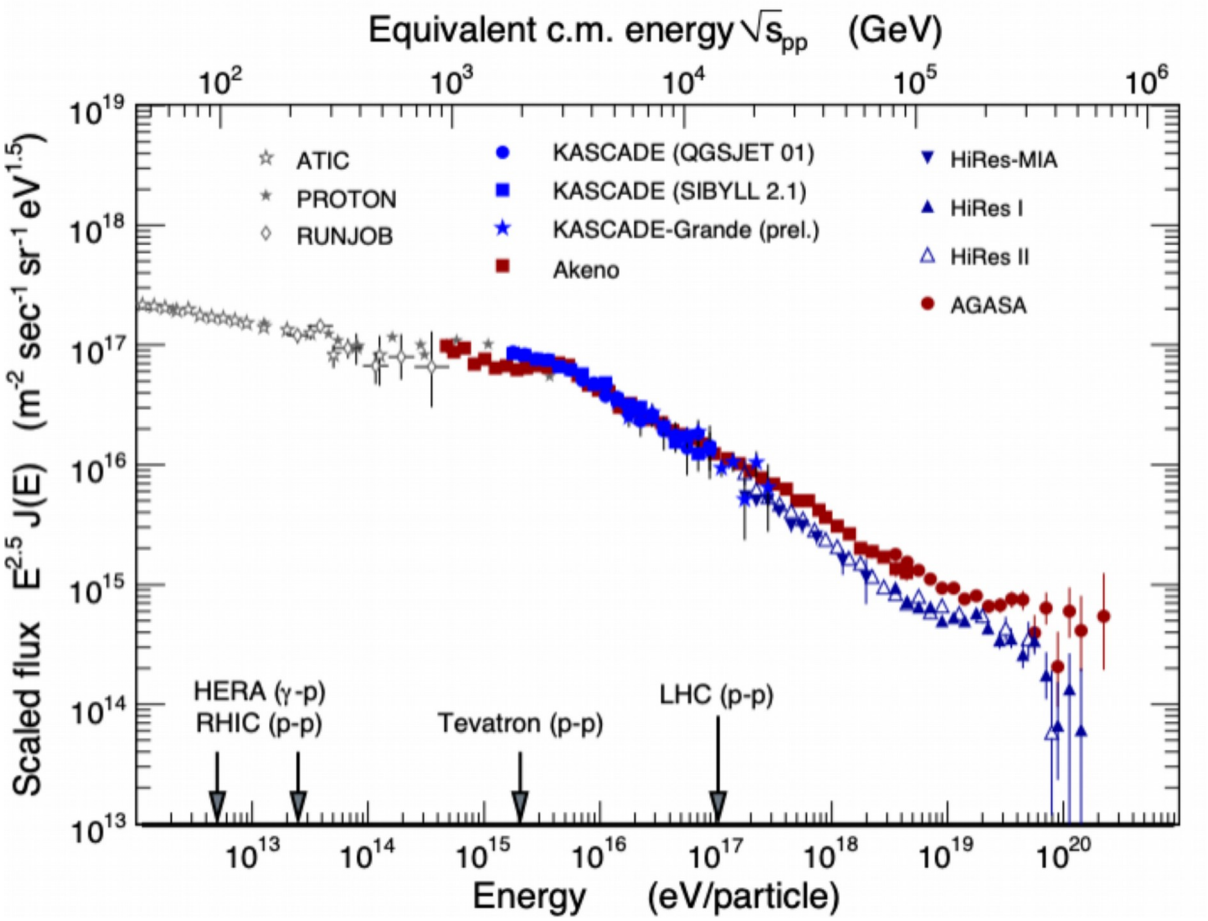




$$\sigma(E_{\mathrm{FD}})/E_{\mathrm{FD}} \;=\; 8\%$$

Absolute energy scale: 14%

Spectrum of cosmic rays



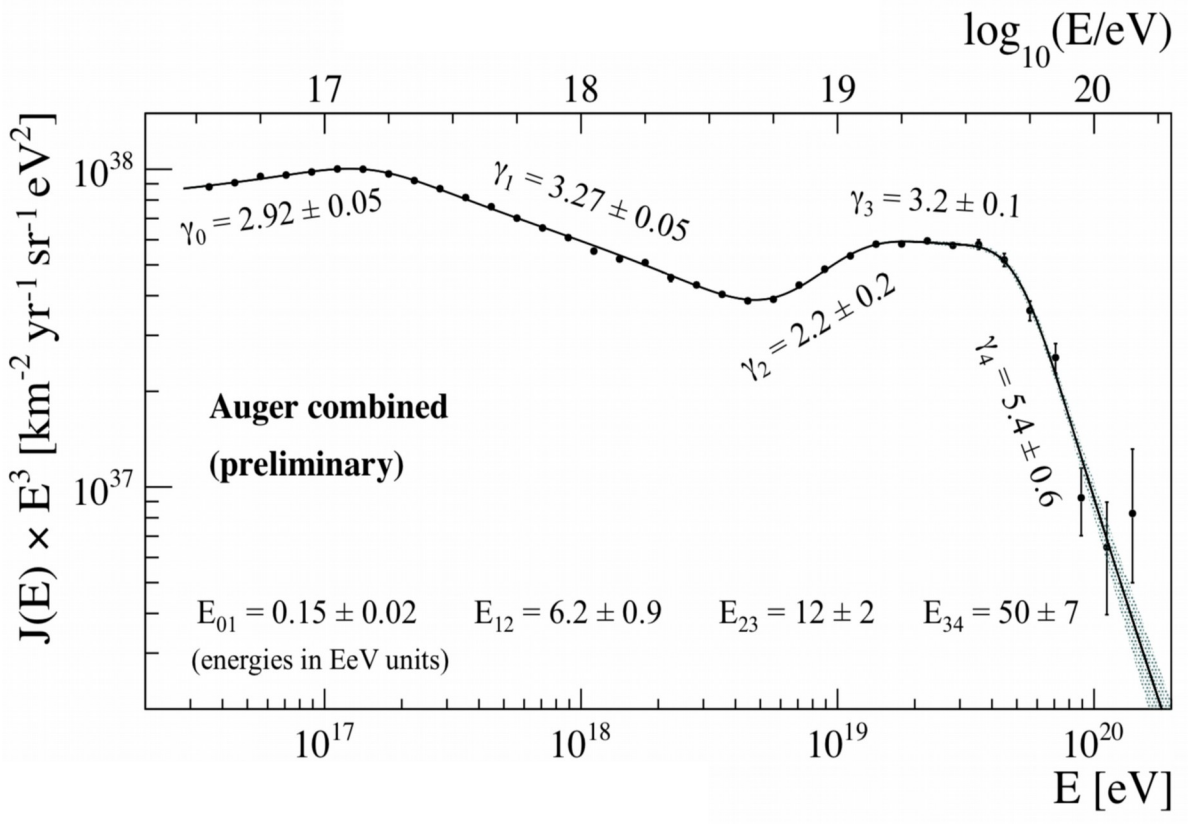
The spectrum of CRs
before
the Pierre Auger Observatory

Structures in the spectrum?

What are the primaries?
What are the sources?

End to the spectrum?

Spectrum of cosmic rays



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Why?

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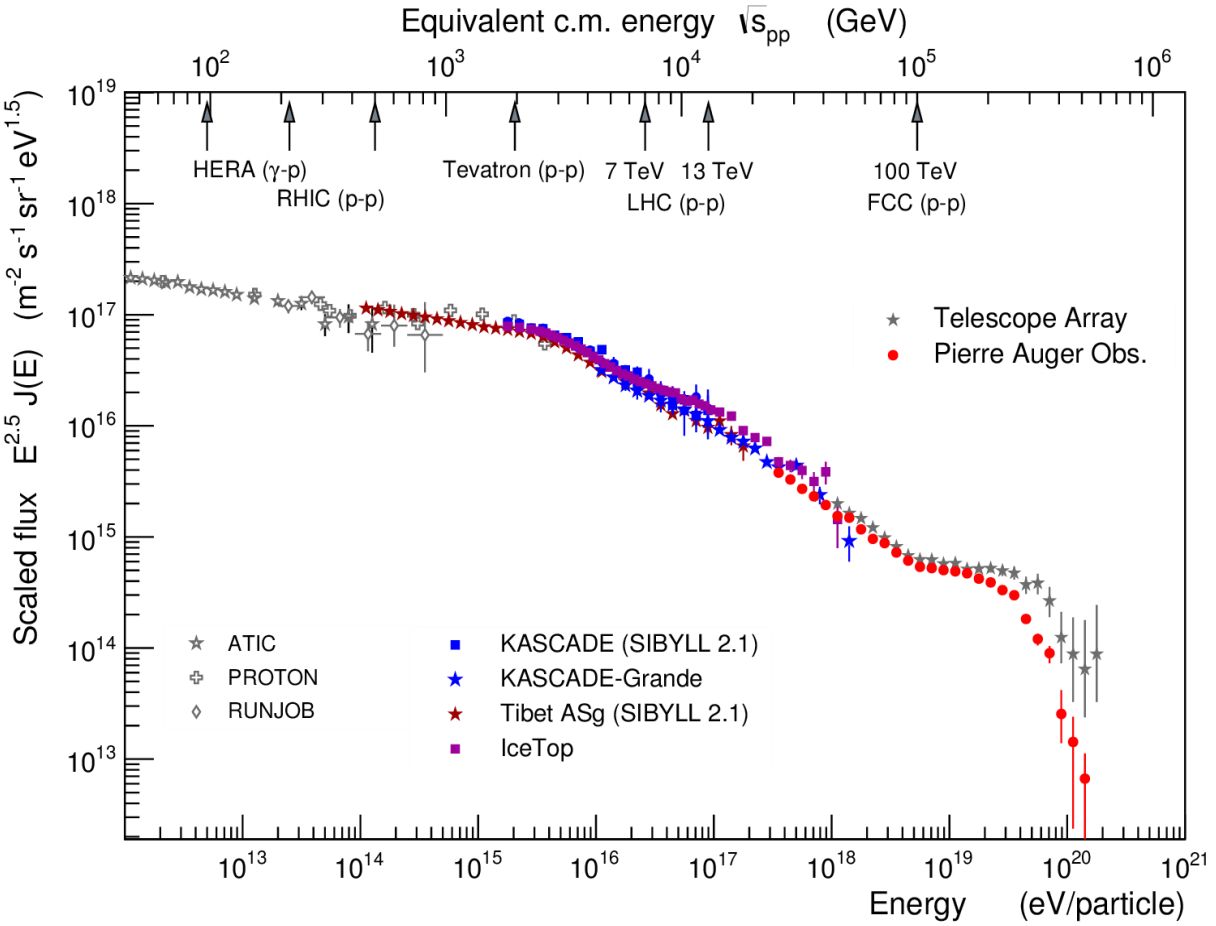

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End to the spectrum!
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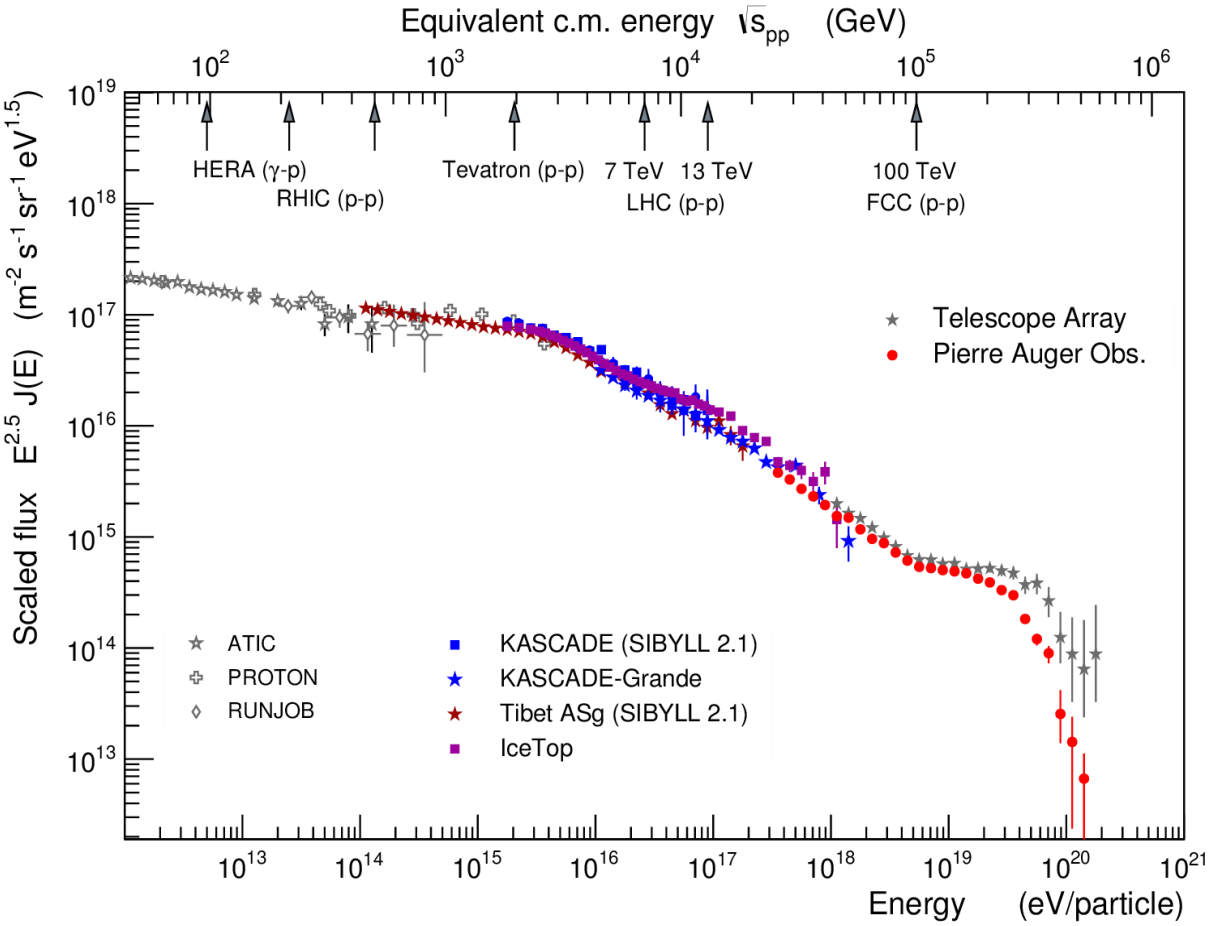
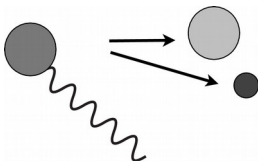
End of the spectrum: propagation



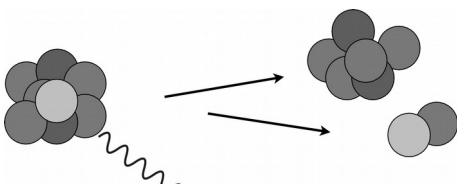
Greisen-Zatsepin-Kuzmin effect (GZK)

Proton



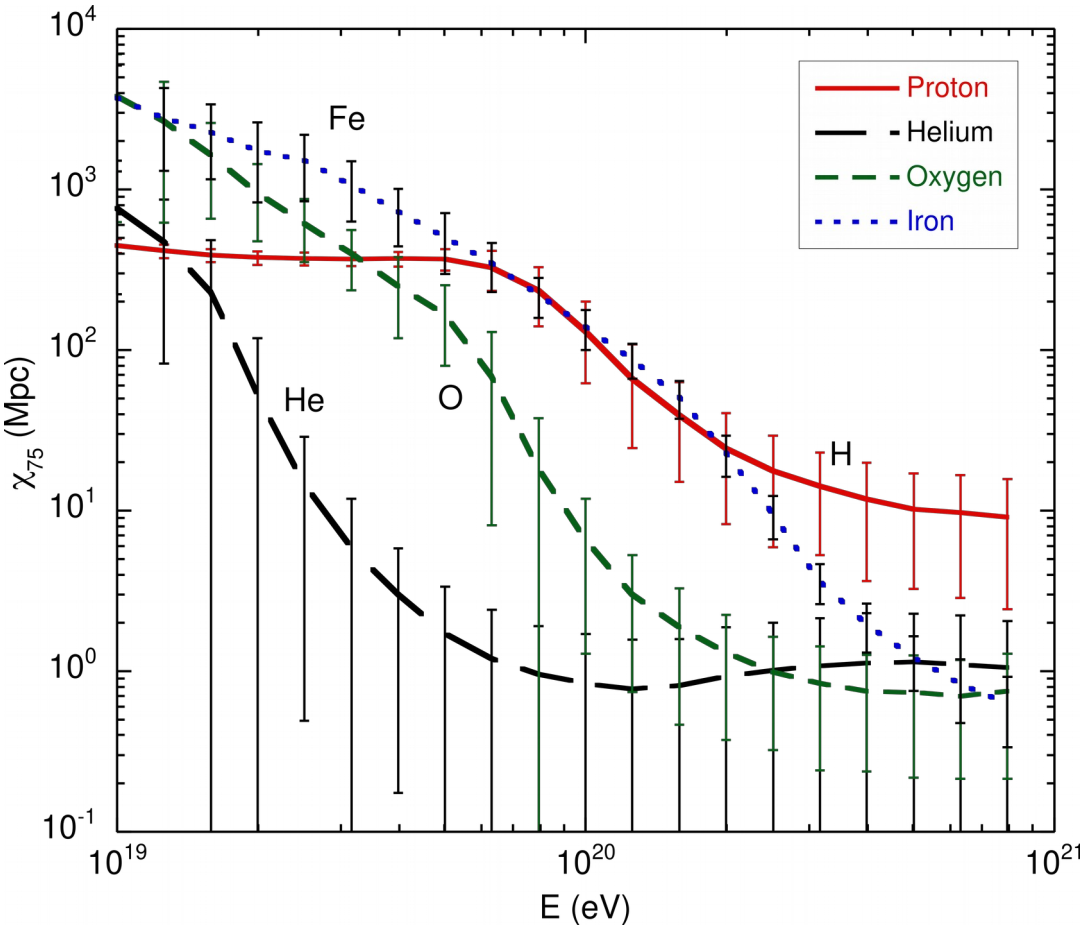
γ (CMB)

Photo-dissociation of nuclei



γ (CMB)

End of the spectrum: propagation



Greisen-Zasepin-Kuzmin effect

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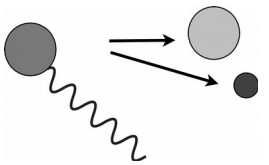

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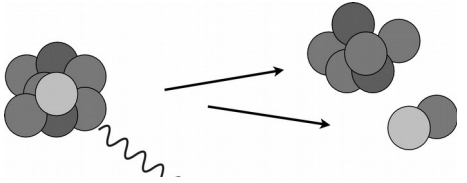

γ (CMB)

Possible sources

Sources? $E_{\max} \sim \beta_s Z B R$

Hillas (1984)

(Unger, 2006)

With LHC technology need accelerator the size of mercury orbit to achieve 10**20eV

Possible sources

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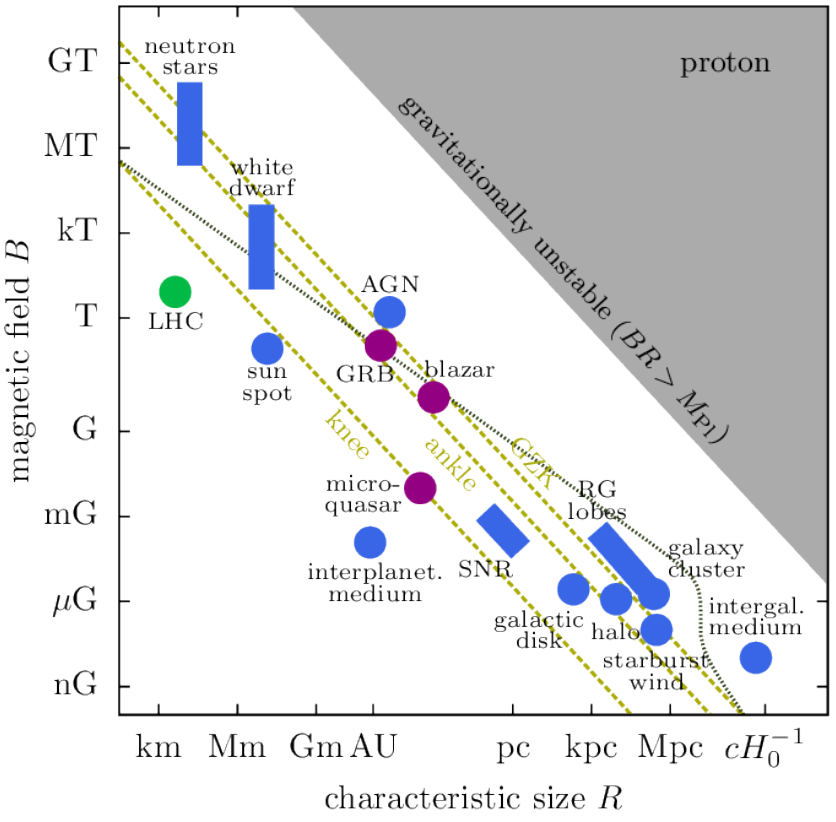

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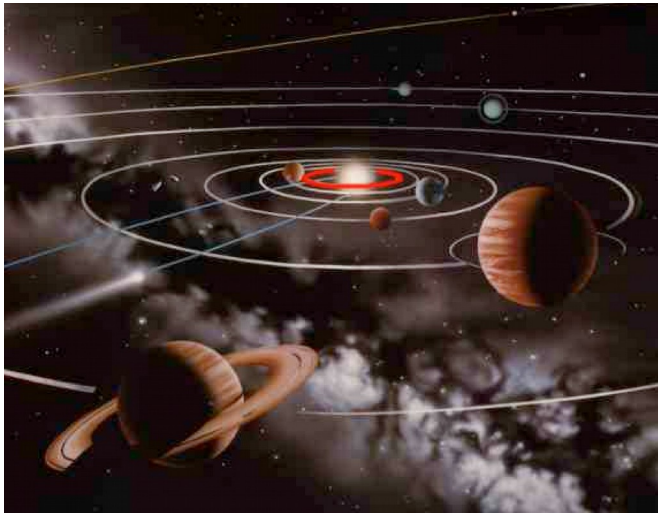
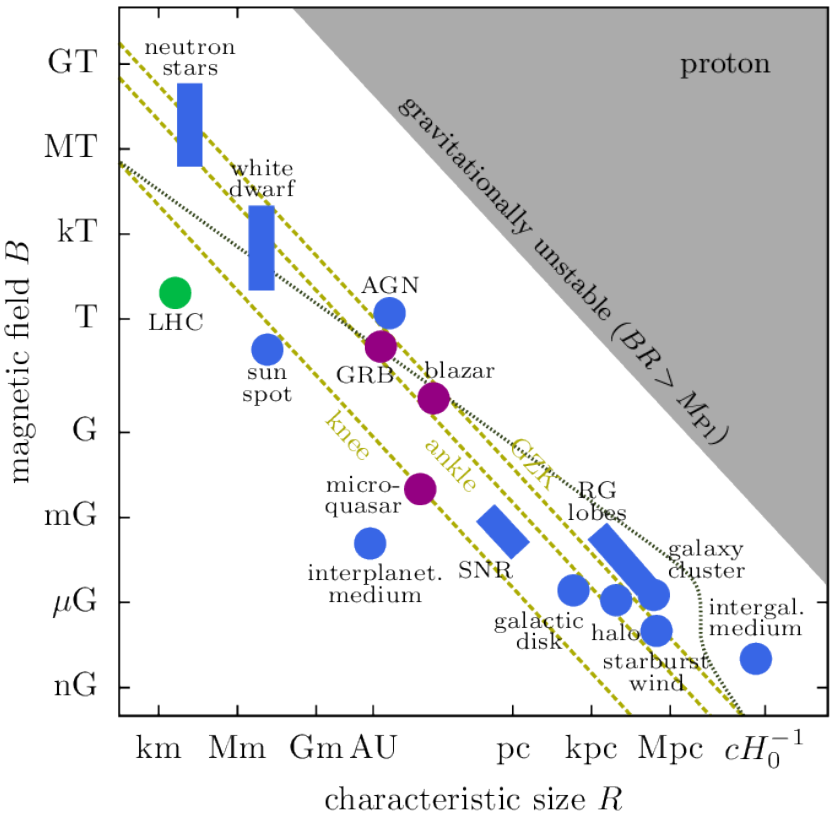
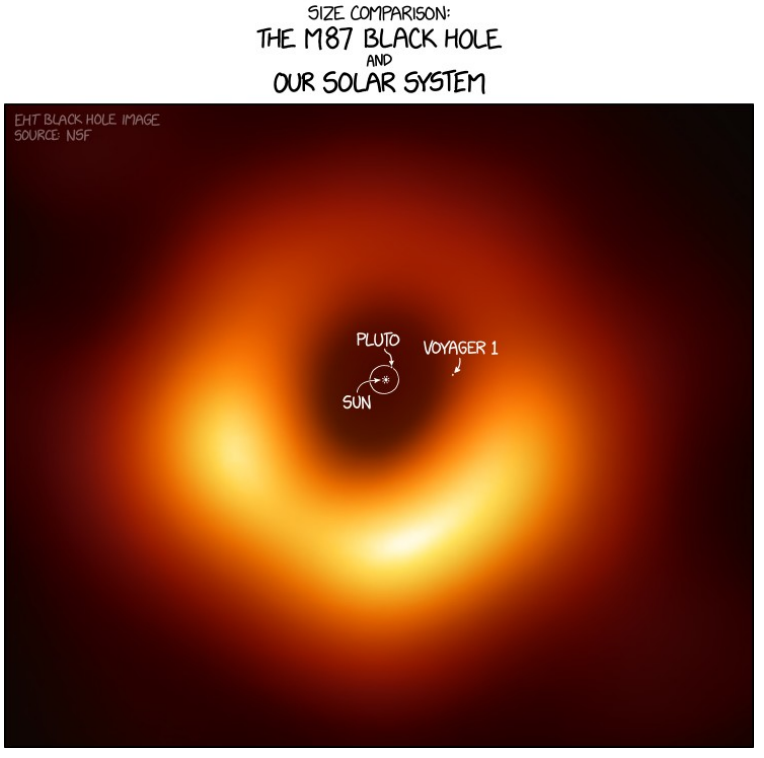


With LHC technology need accelerator the size of mercury orbit to achieve 10**20eV

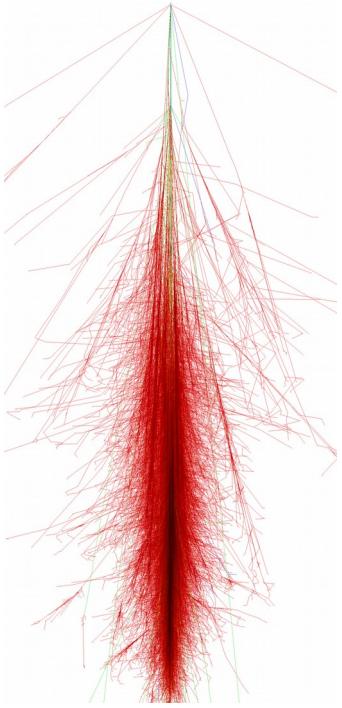
Possible sources

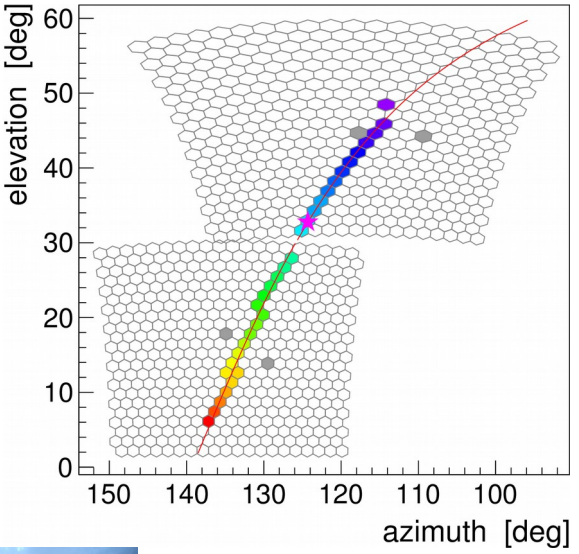


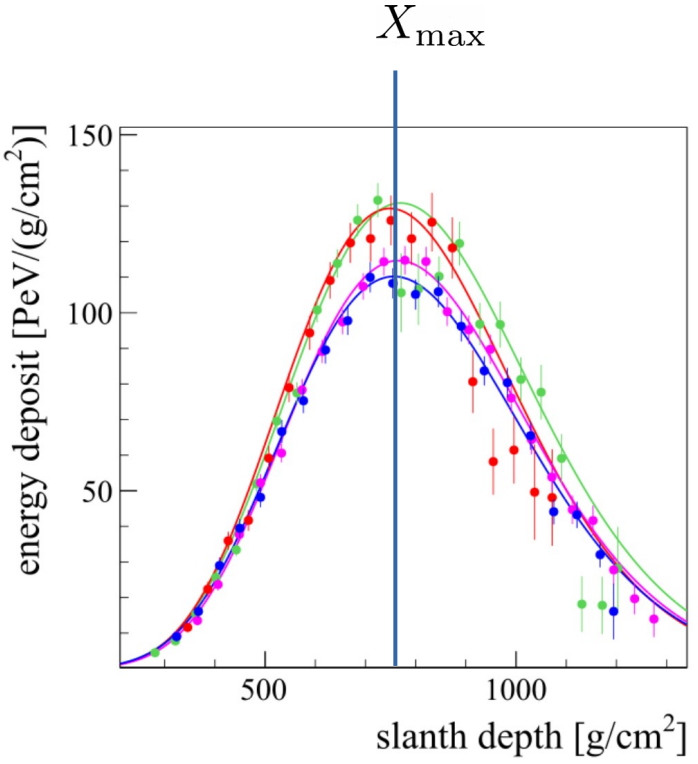


https://xkcd.com/2135/

Distinguish primaries

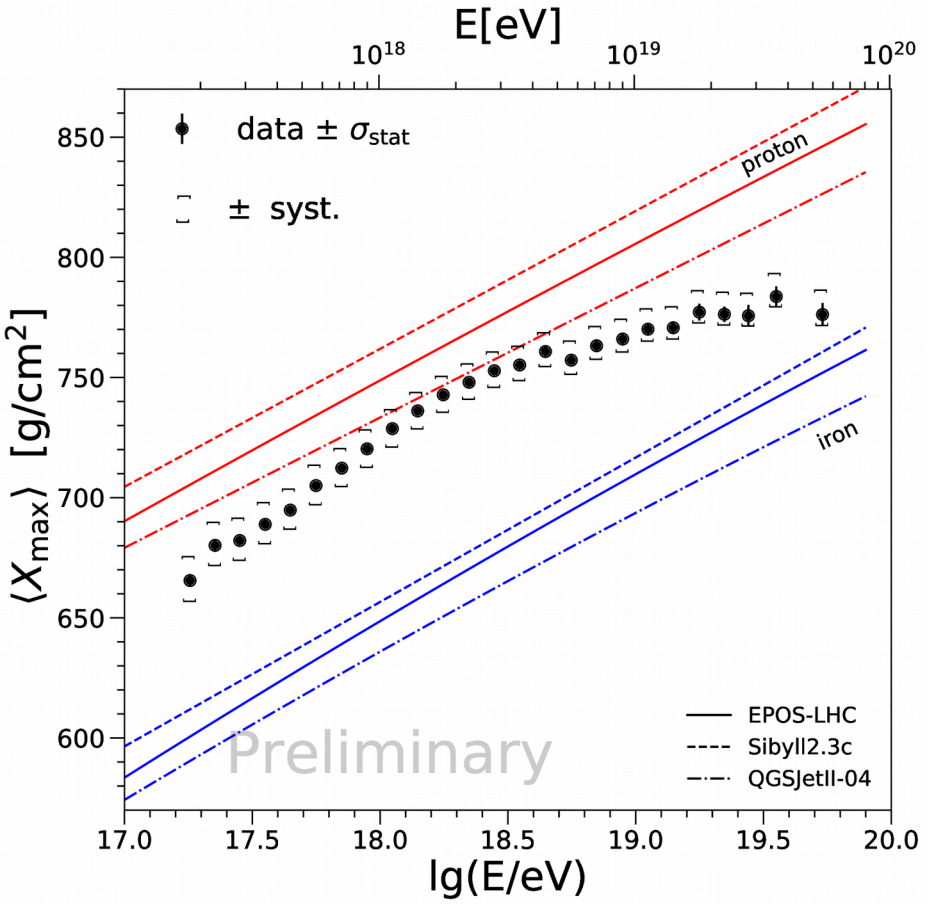


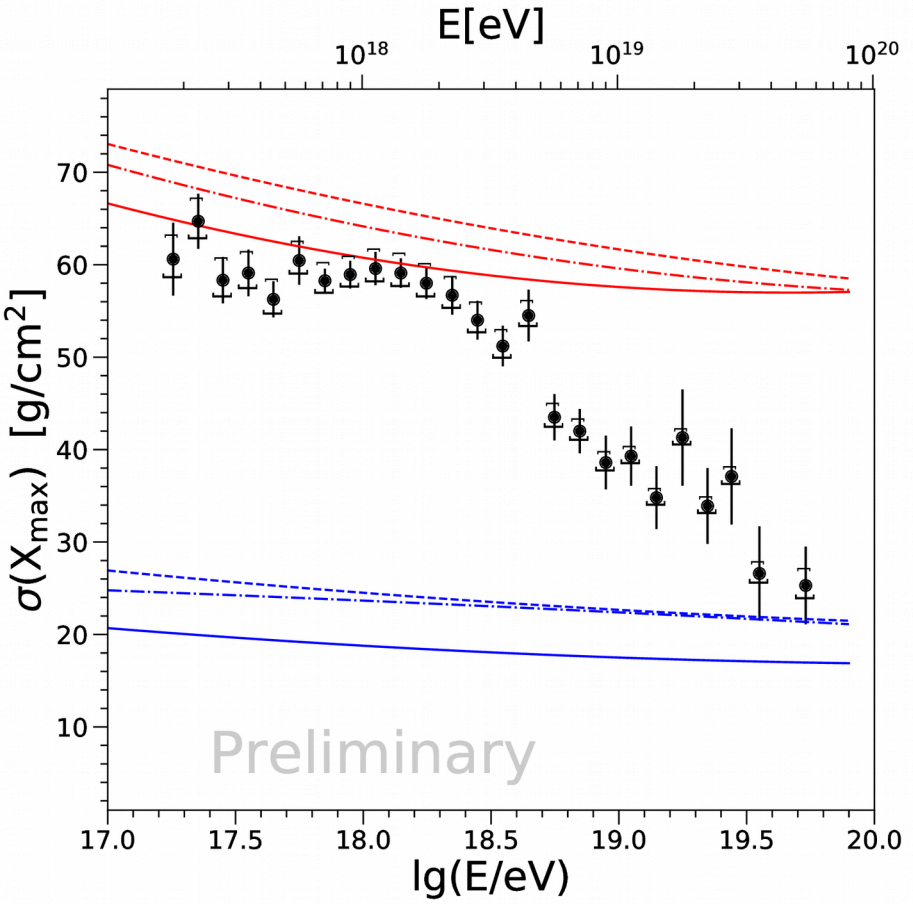




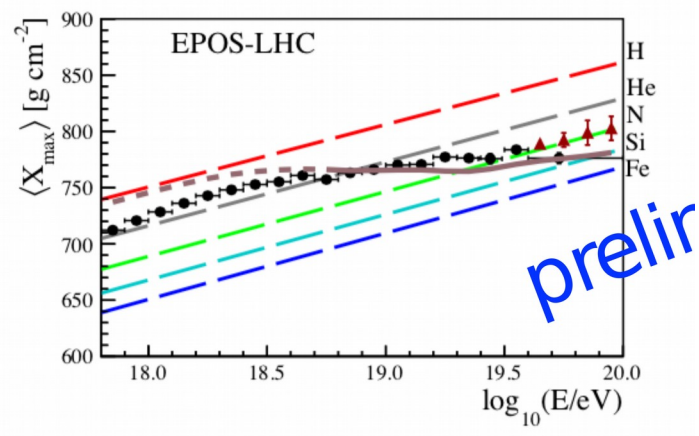
$$X_{\max} = X_0 + \Delta X$$

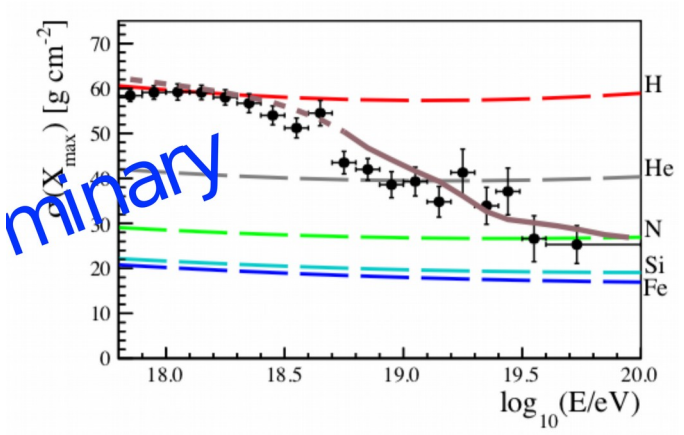
Measurement of average composition

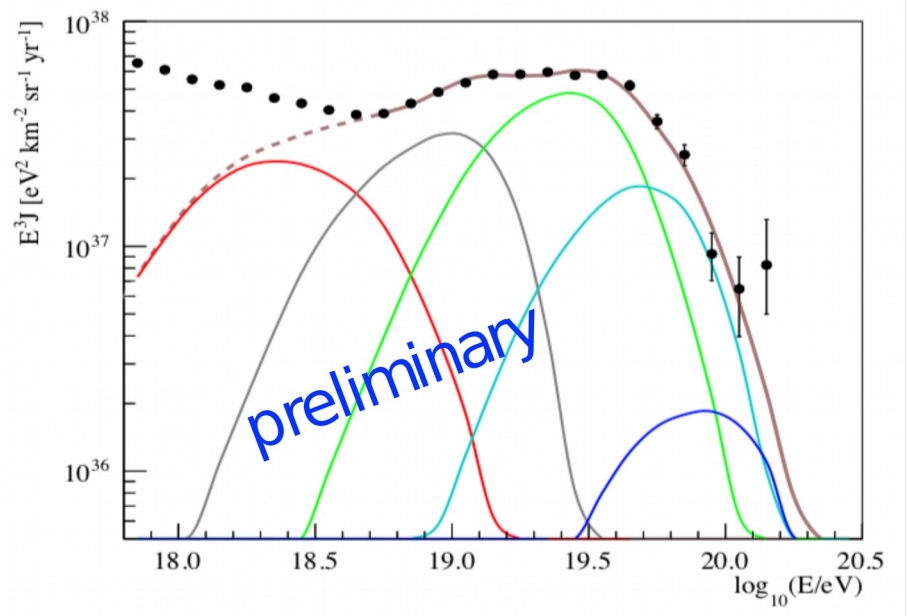




Putting it all together

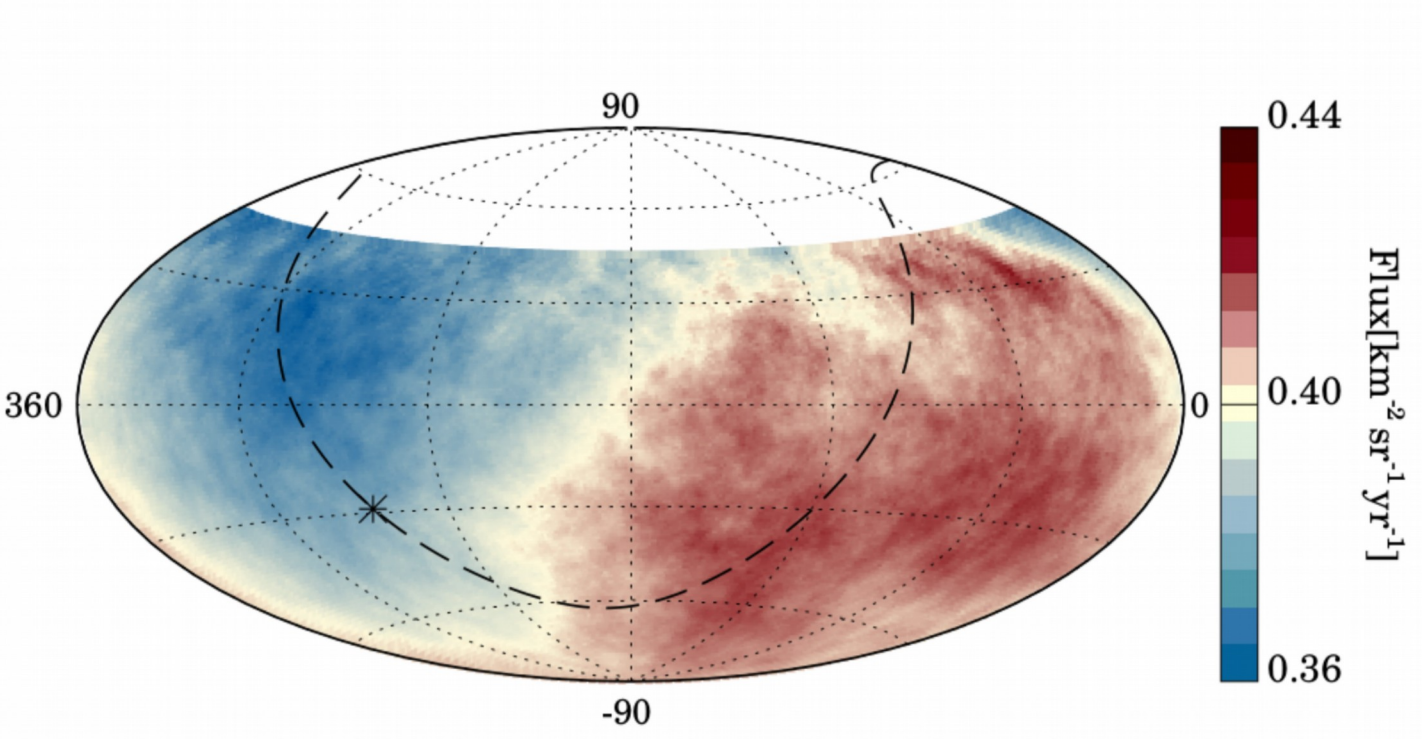






Heavy primaries at the highest energies. Where from?

Large scale anisotropy

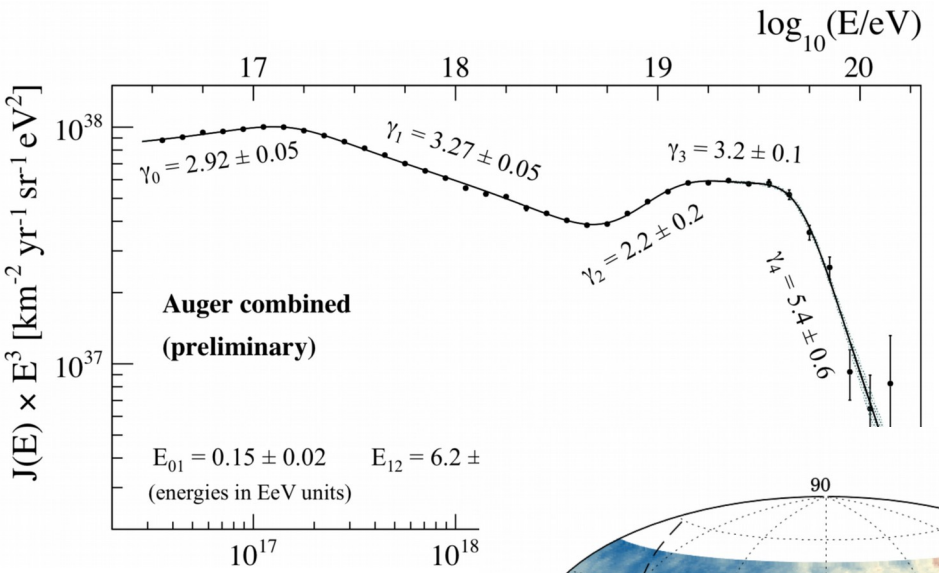


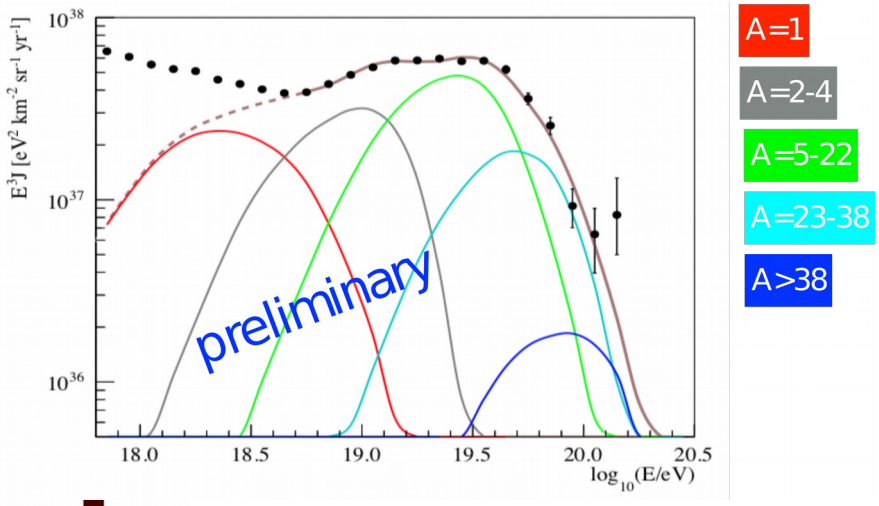
$E > 8\,\mathrm{EeV}$

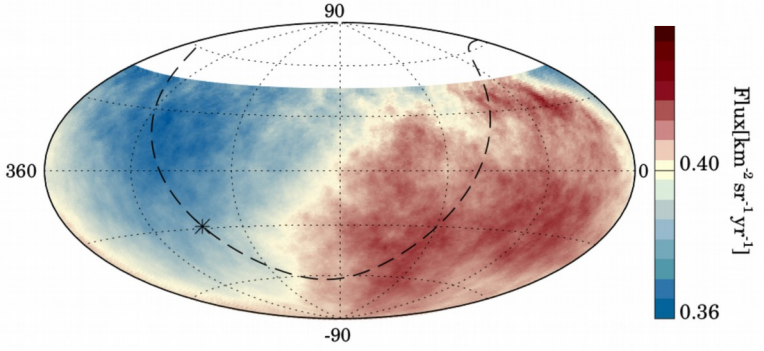
Amp: $6.6^{+1.2}_{-0.8}\%$

$\alpha, \delta = (98^\circ, 25^\circ)$

Where do we stand

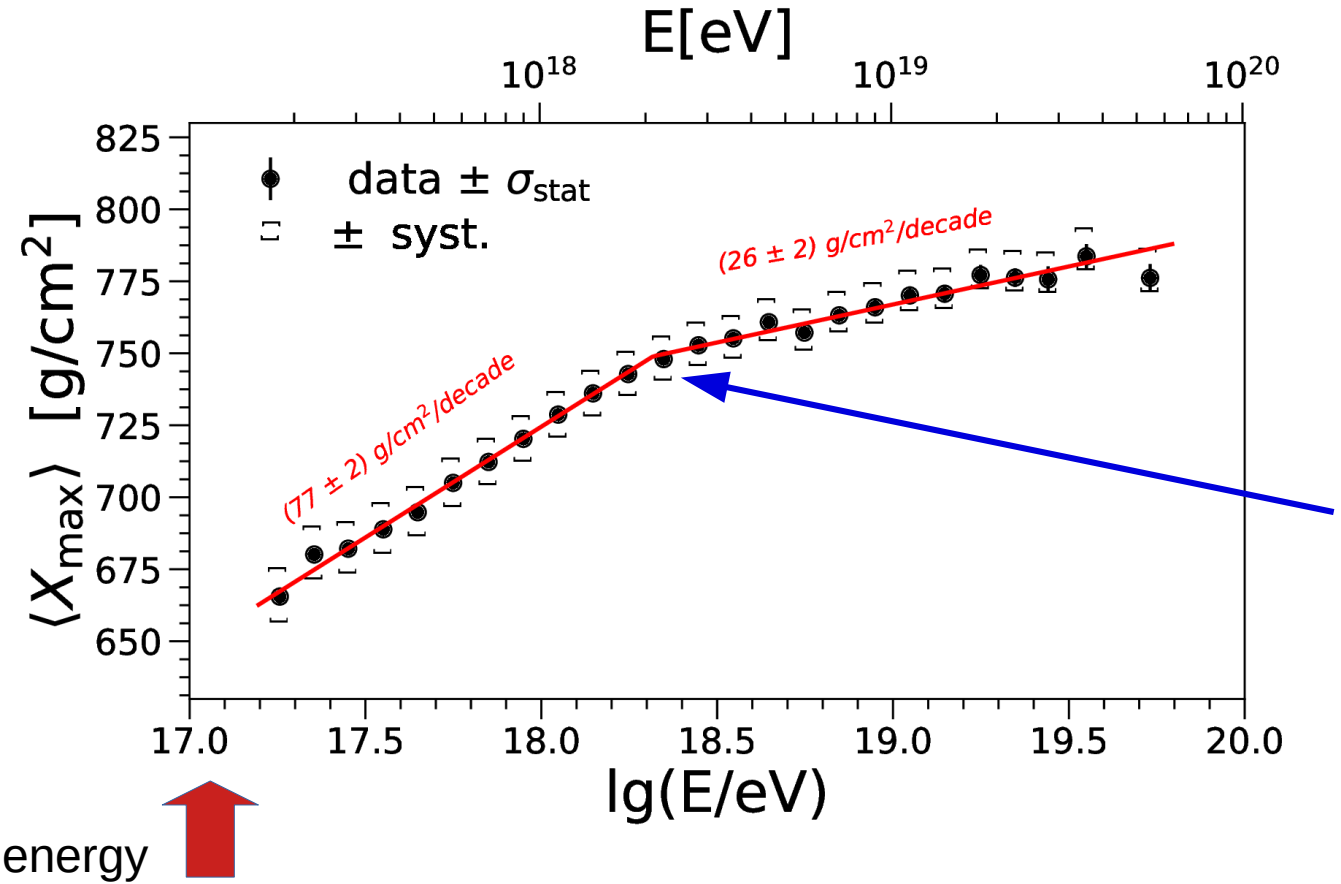






1) Complex spectrum
   (4 breaks!)
2) Non-trivial, heavy composition
3) Dipole anisotropy

What if only a trick of nature?

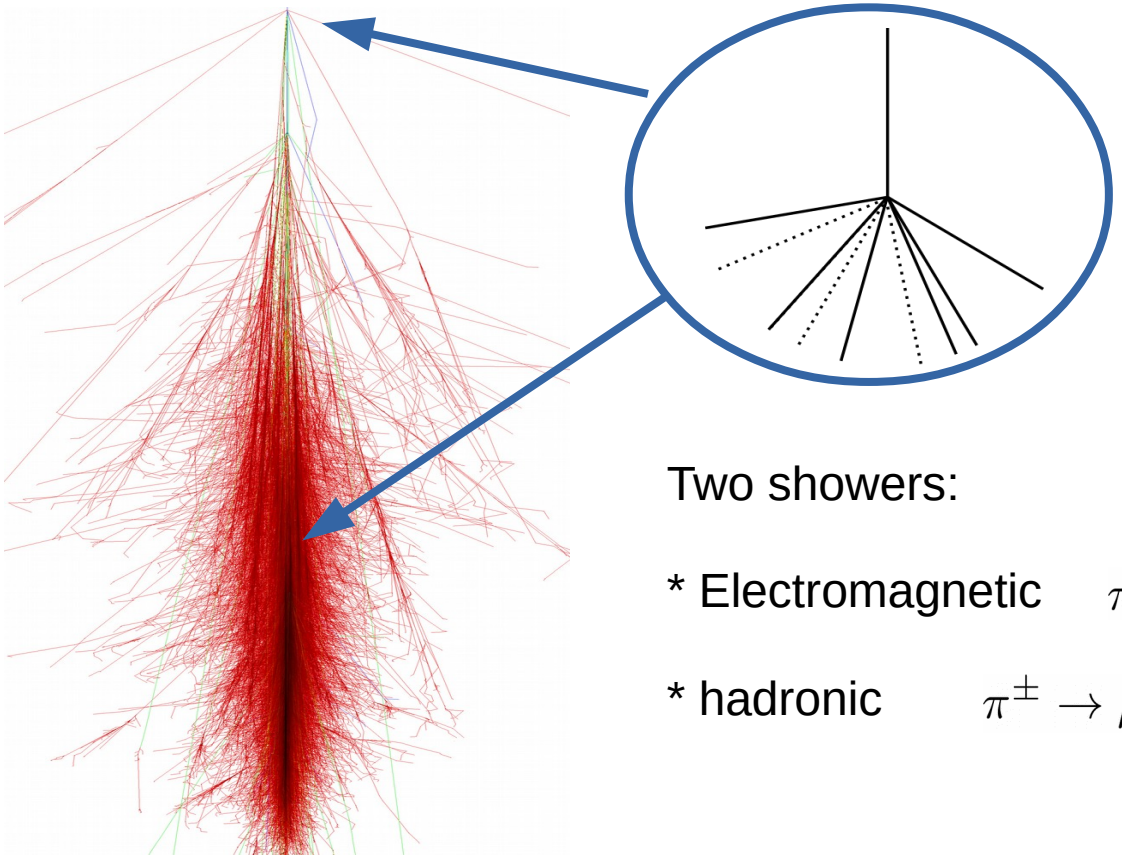


LHC energy

Not a change in Composition
What if Change in **interaction**?

Do we see other **Strange** things?

Interlude: shower physics



Many particles
many interactions !

can't see first
interaction

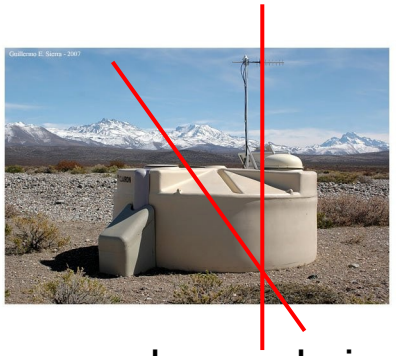
Two showers:

* Electromagnetic $\pi^0 \rightarrow \gamma\gamma$

* hadronic $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$

How to measure the muon content

Inclined air showers!

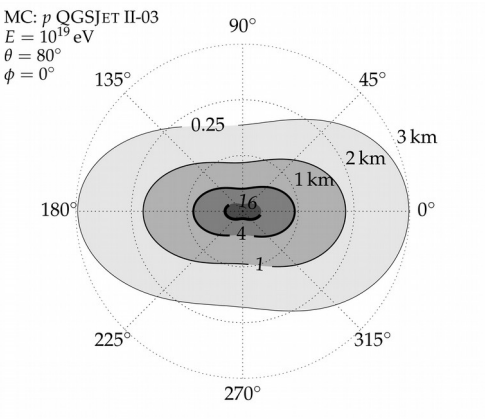


Muons → enhanced signal
EM → absorbed in atmosphere

BUT!

Geomagnetic field
+ extended path

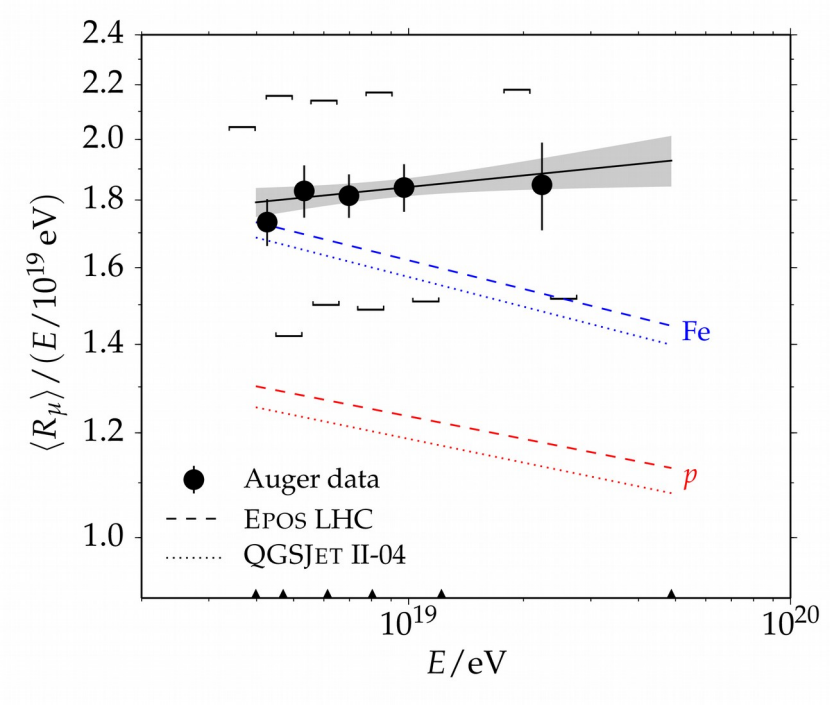
→ density at ground
not symmetric!

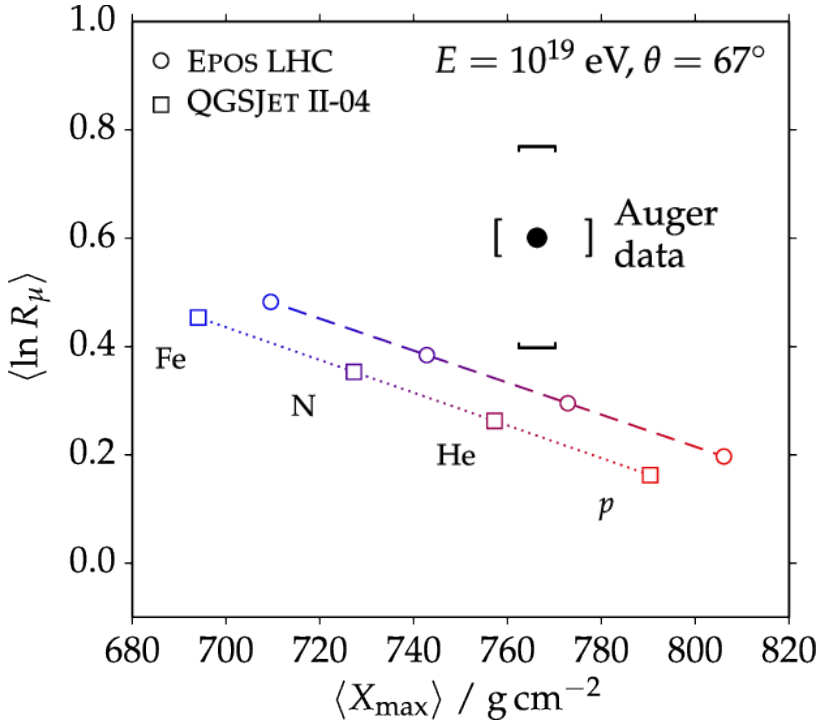


$$\rho_\mu(E,\theta,x,y) \;=\; R_\mu(E)\rho_\mu^{\mathrm{ref}}(\theta,x,y)$$

Measure scale relative to reference model

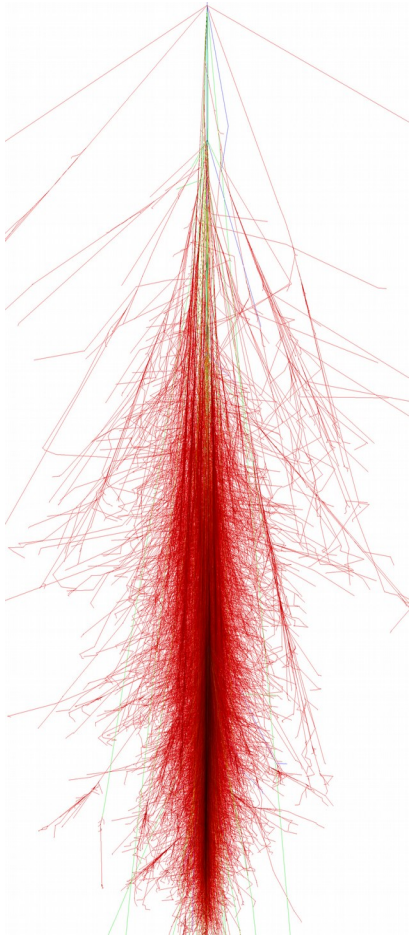
Muon content of ultra-high energy air showers

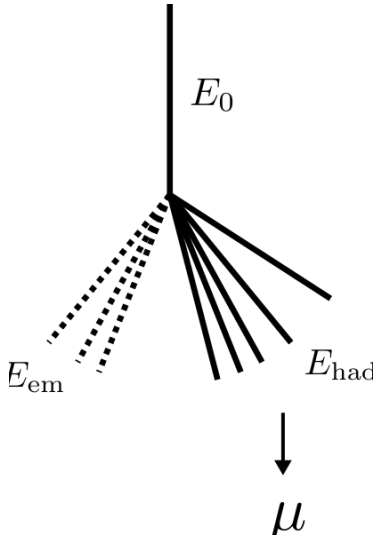




Also observed in many other observables related to muons/hadronic interactions

Two scenarios





1) New physics scenario
First (UHE) interaction modified,
Process missing in interaction models

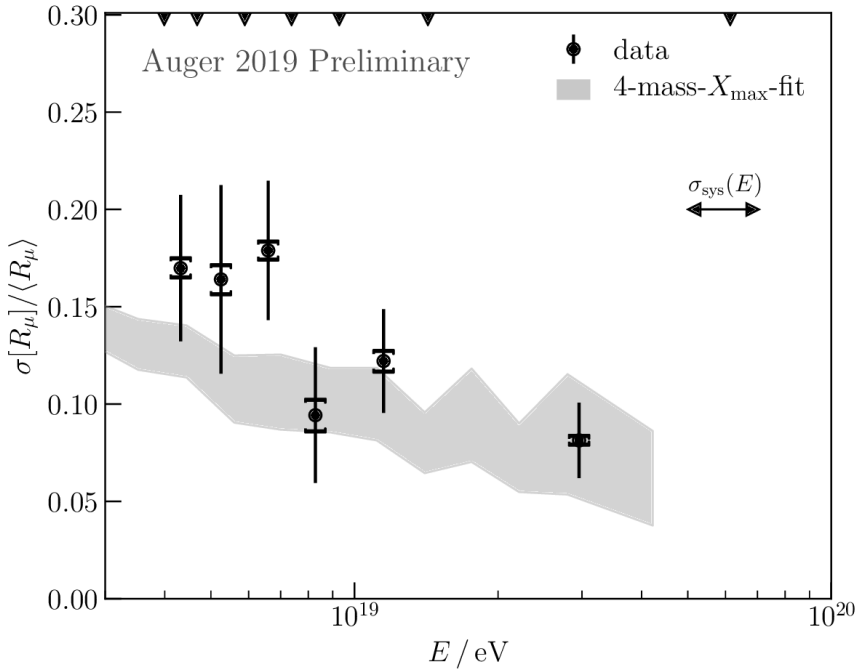
- exhibit Lorentz Invariance Violation?
- CSR
- severe enhancement of strangeness?
  (fireball, string-percolation)

=> all increase $E_{\rm had}$
=> increase μ

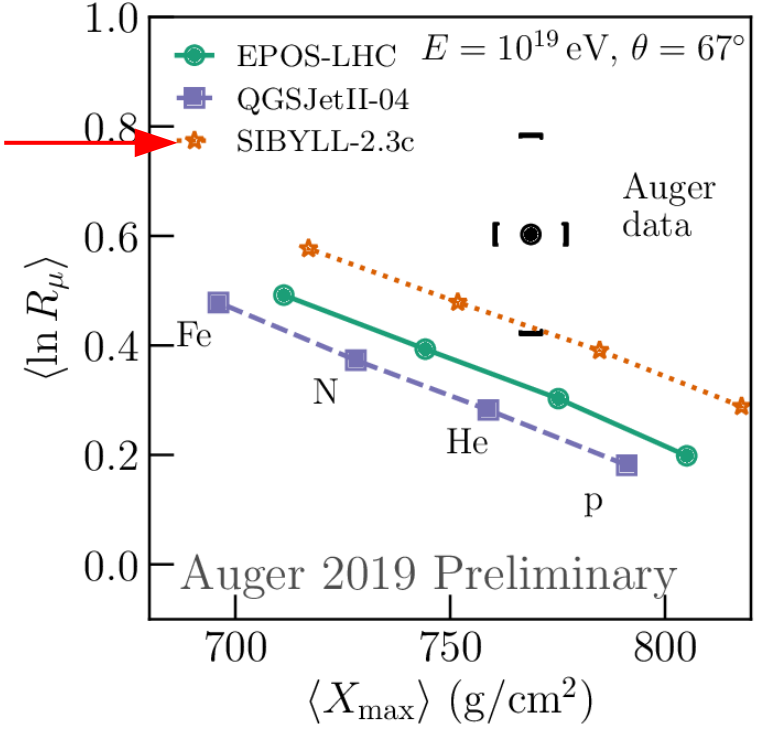
2) Standard physics scenario
all interactions modified, by a small amount
But interaction models essentially correct

Muon fluctuations

Fluctuations described by standard interaction models



Using scenario 2, average number of muons can be increased sufficiently

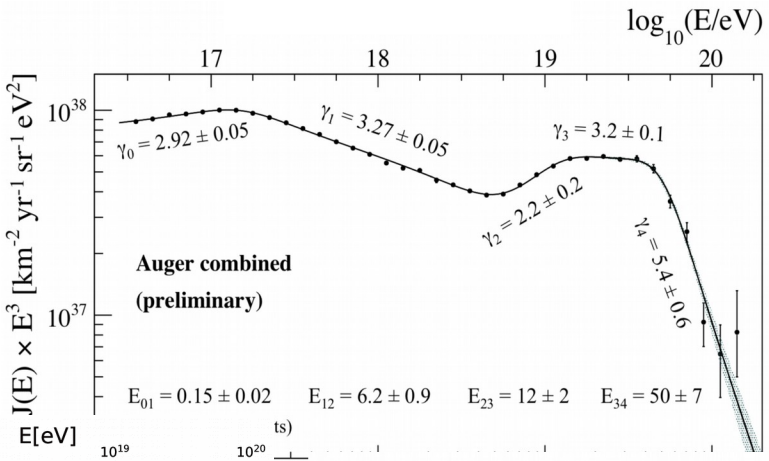


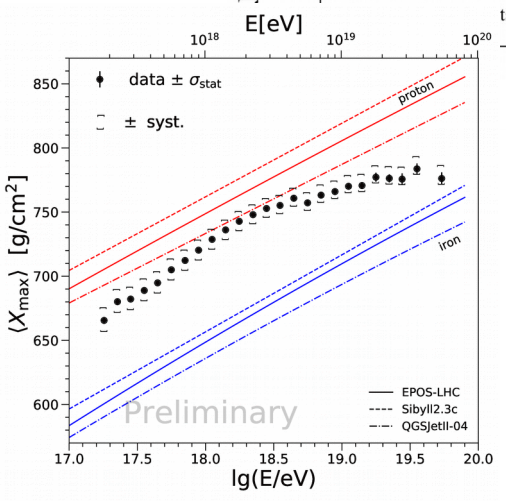
Summary

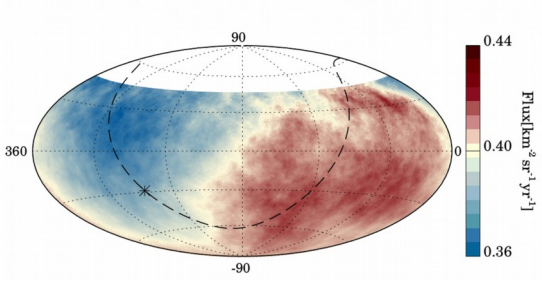
* complex spectrum, strong suppression
* heavy composition
* large-scale dipole anisotropy
* miss match in average muon content, but fluctuations well described

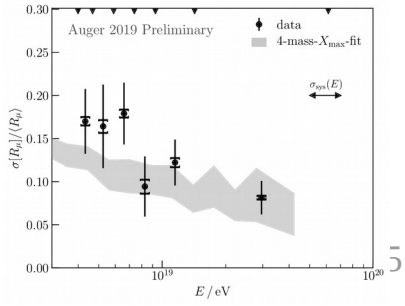
Not shown:
* intermediate-scale anisotropy
* p-Air cross section
* multi-messenger
* UHE neutrino & photon searches

Future: AugerPrime

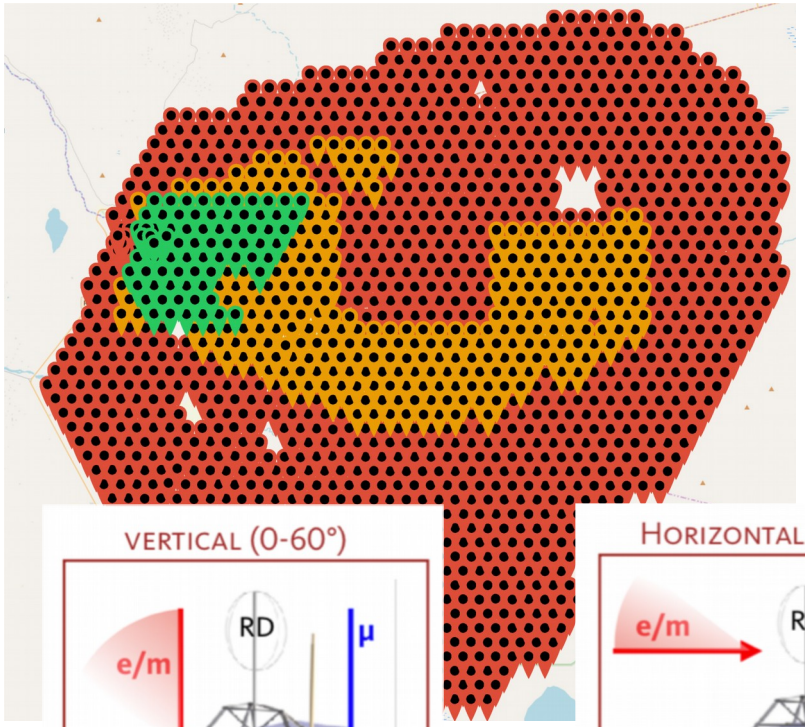


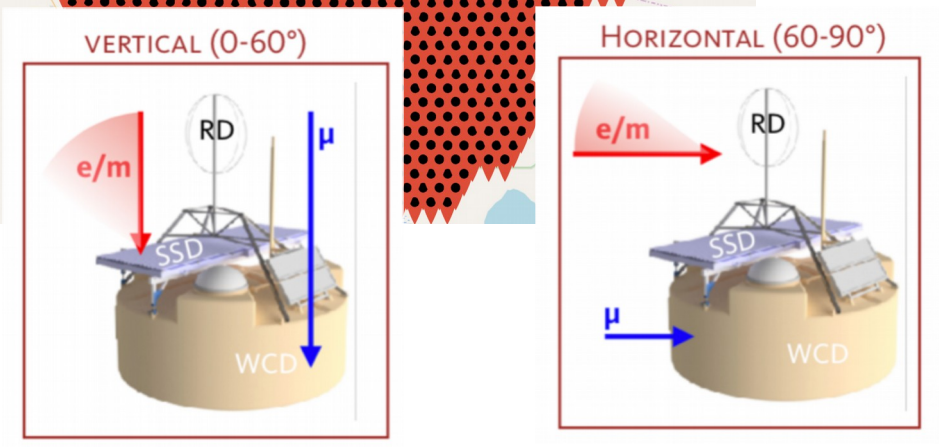


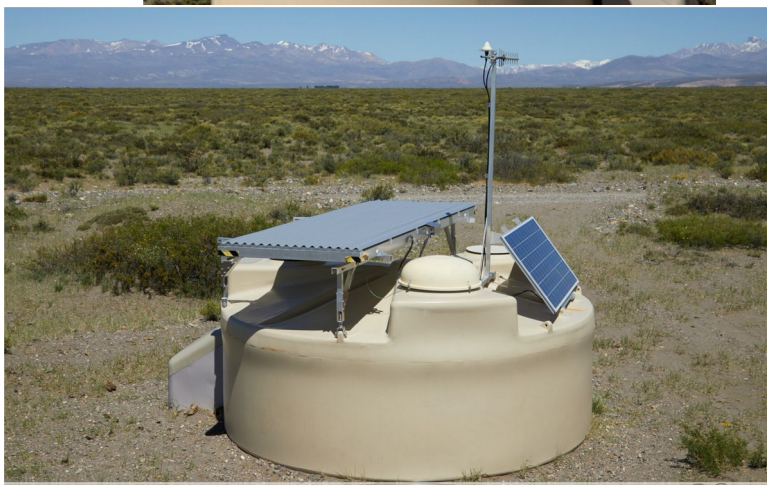




The upgrade







Large-scale anisotropy