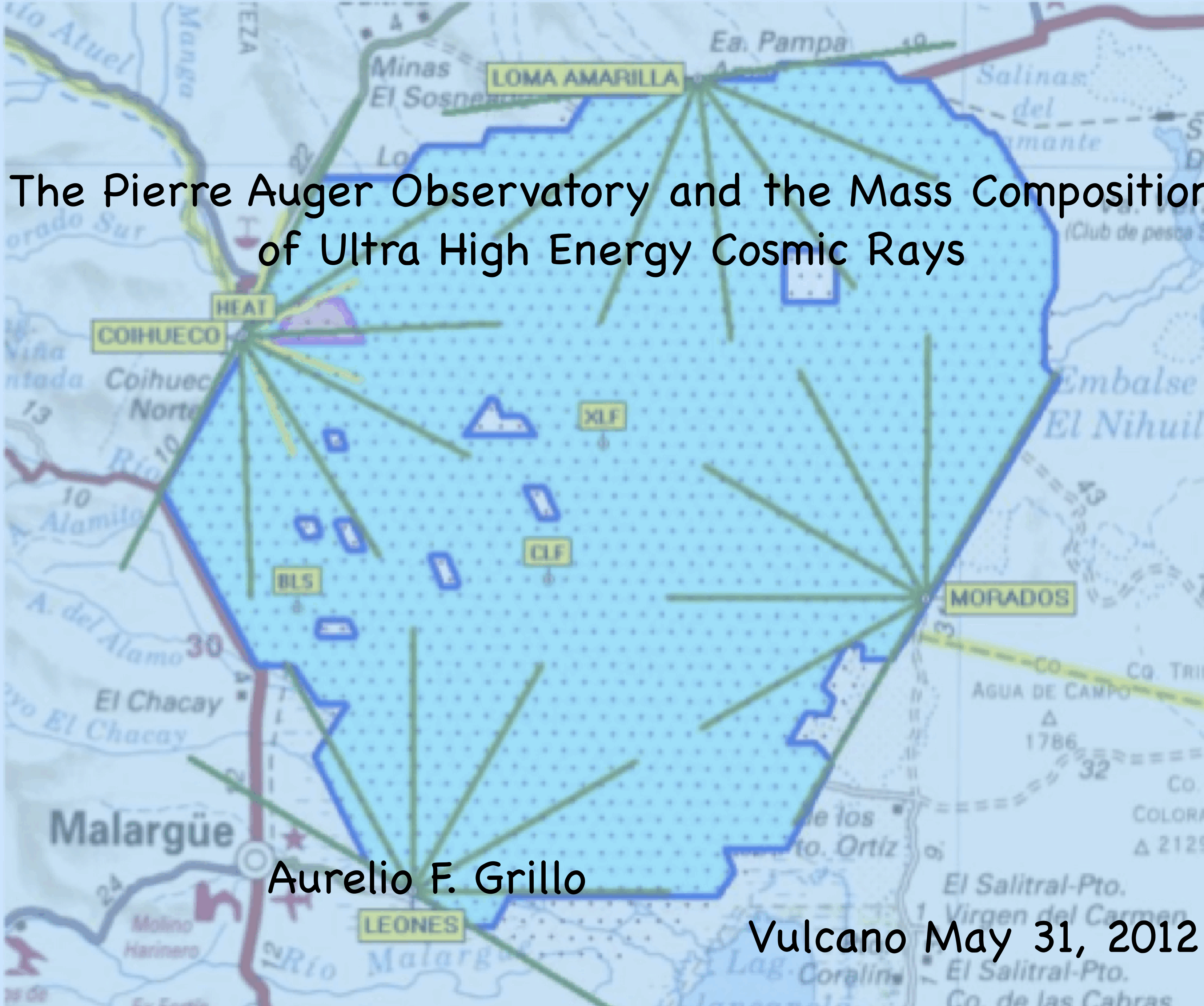
The Pierre Auger Observatory and the Mass Composition of Ultra High Energy Cosmic Rays

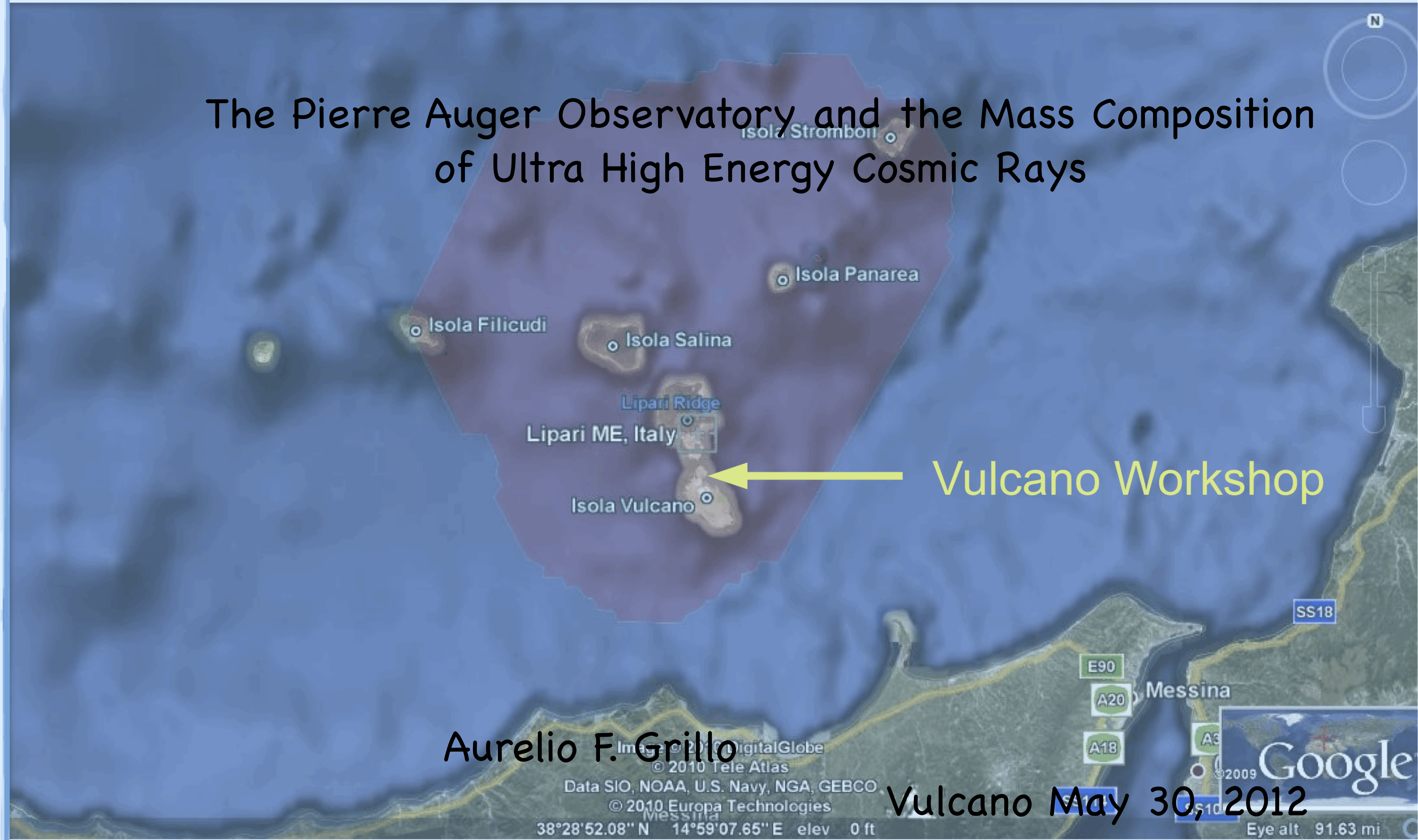


Aurelio F. Grillo

Vulcano May 31, 2012

3000 km^2 area

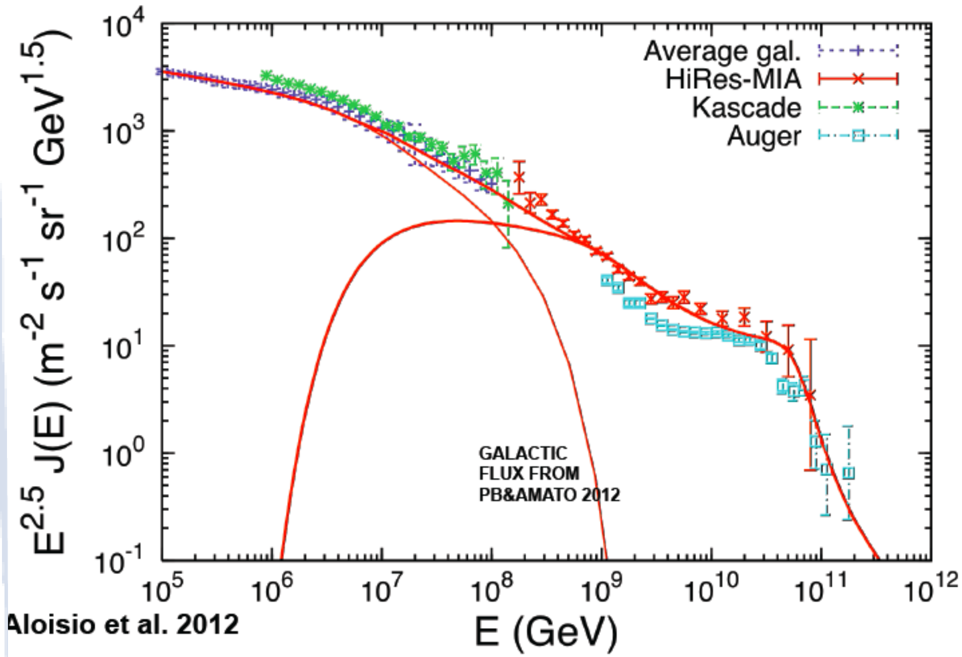
The Pierre Auger Observatory and the Mass Composition of Ultra High Energy Cosmic Rays

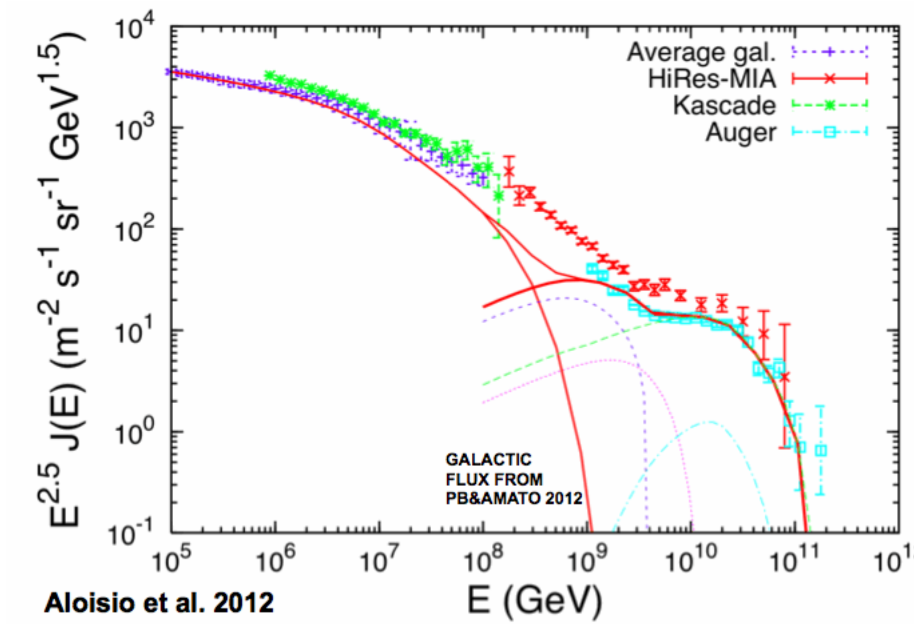


Aurelio F. Grillo

Vulcano May 30, 2012

At E> 5 EeV (5 10^{18} eV) UHECR sources are plausibly Extra-galactic.





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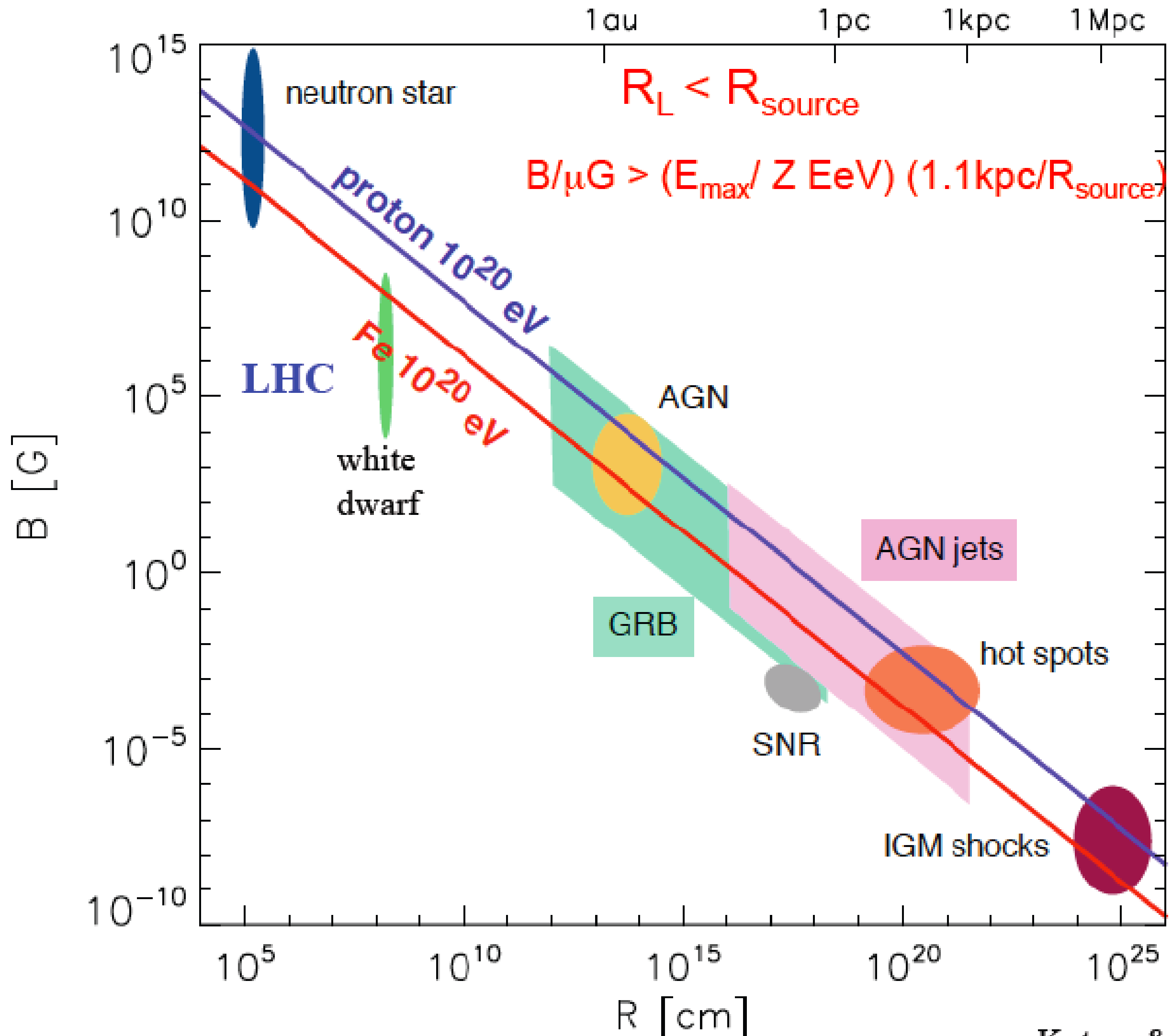
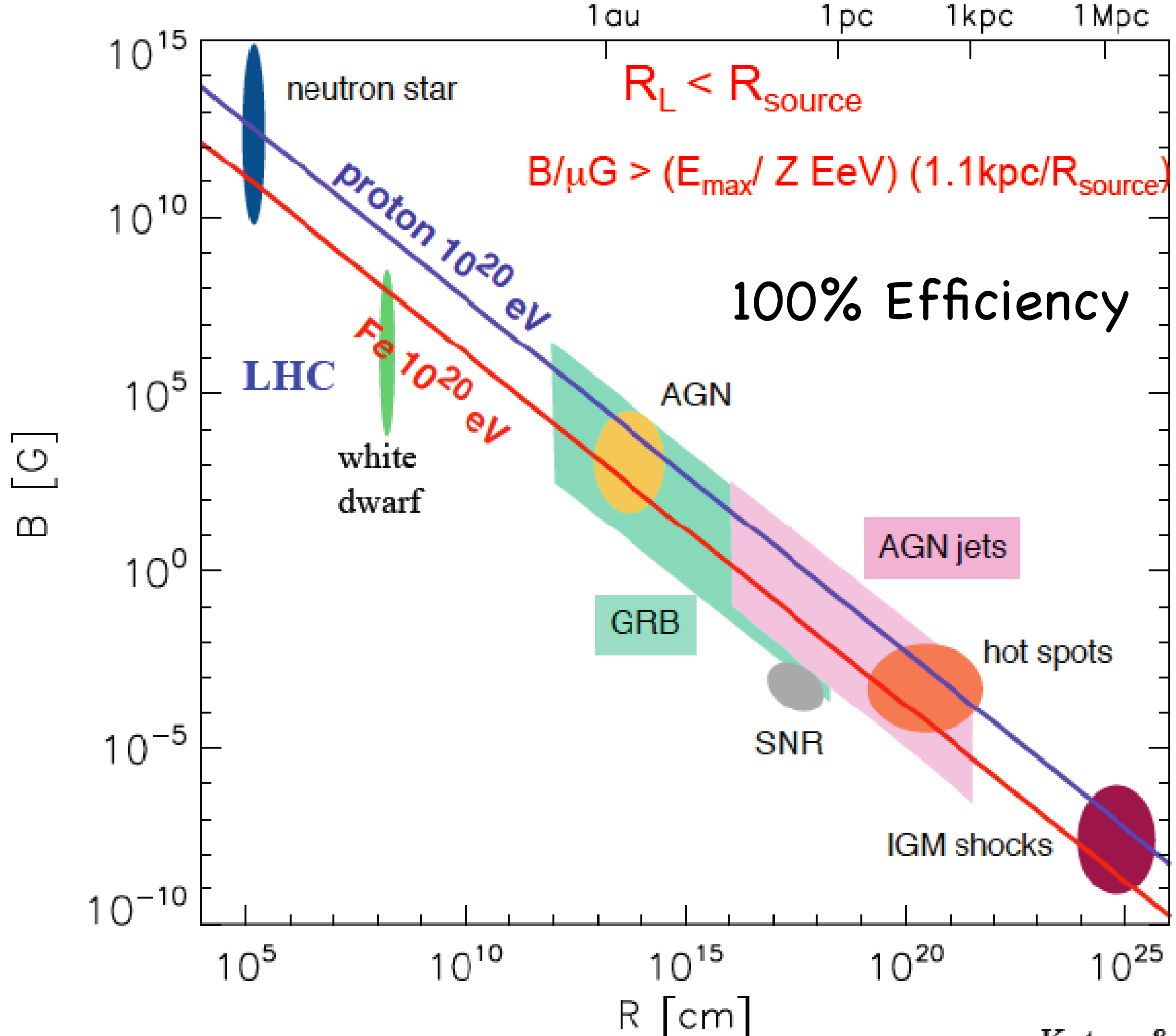


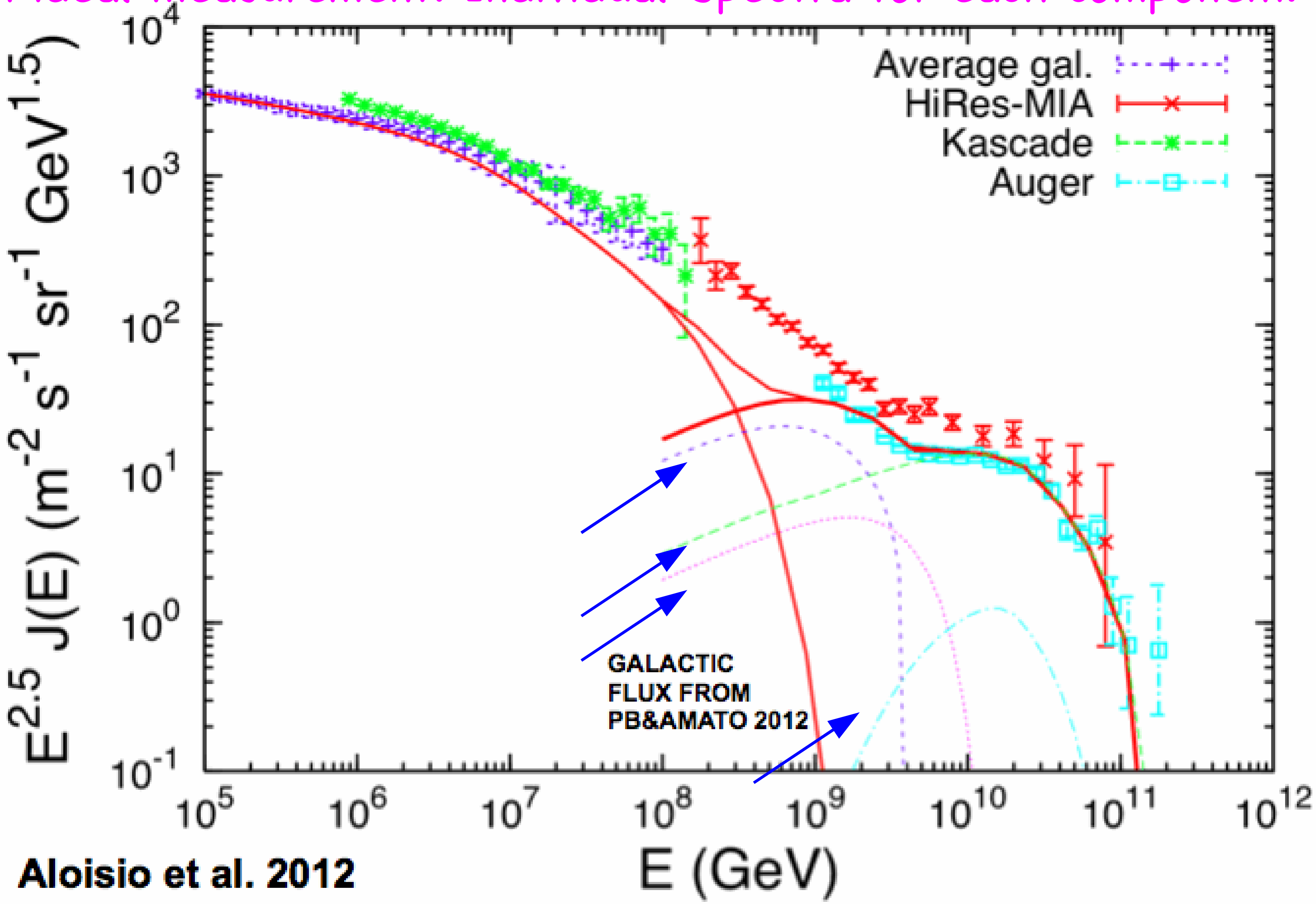
Kotera & AO'11

At E> 5 EeV (5 10^{18} eV) sources are plausibly extra-galactic.



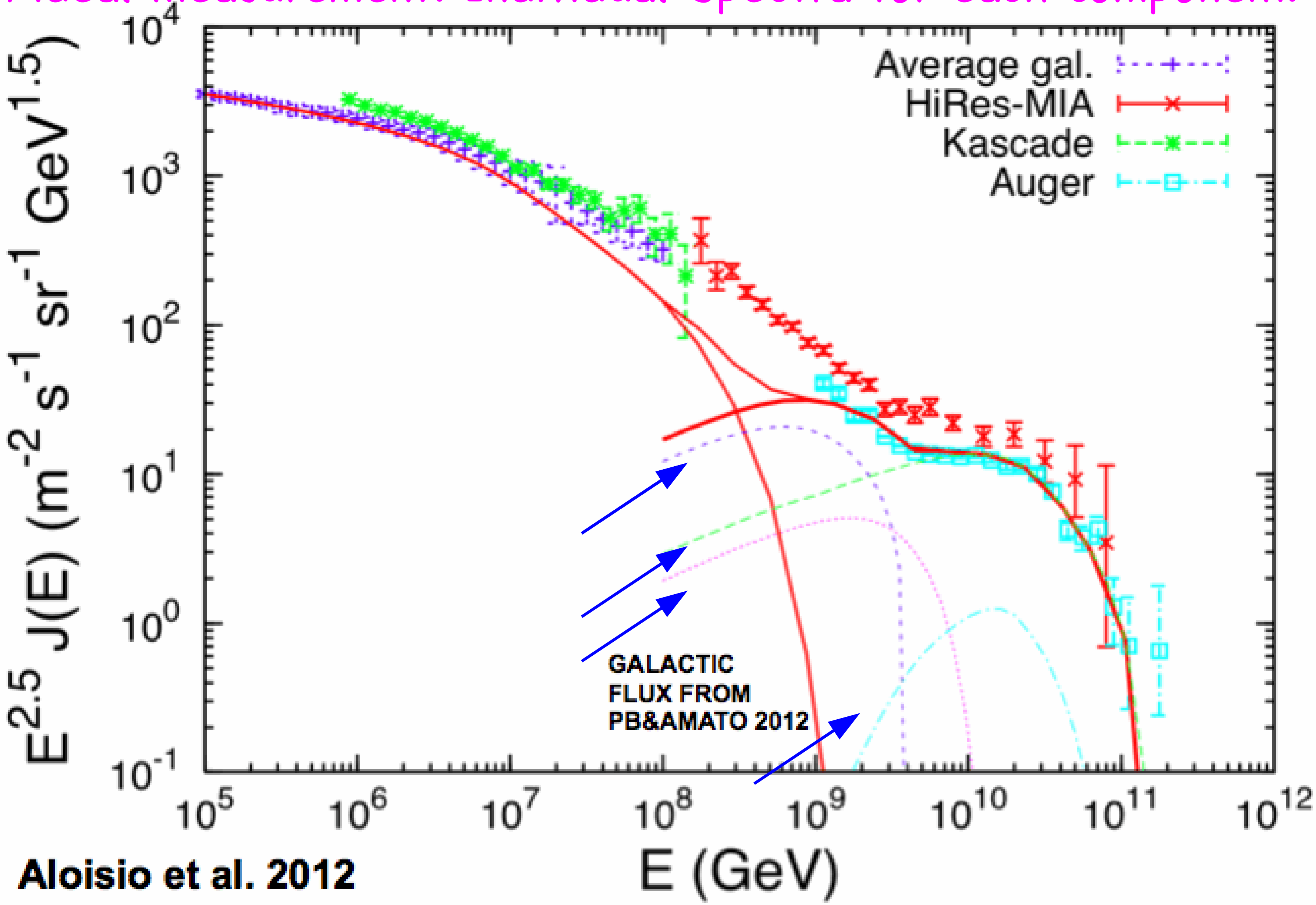
Kotera & AO'11

An ideal measurement: Individual Spectra for each component.



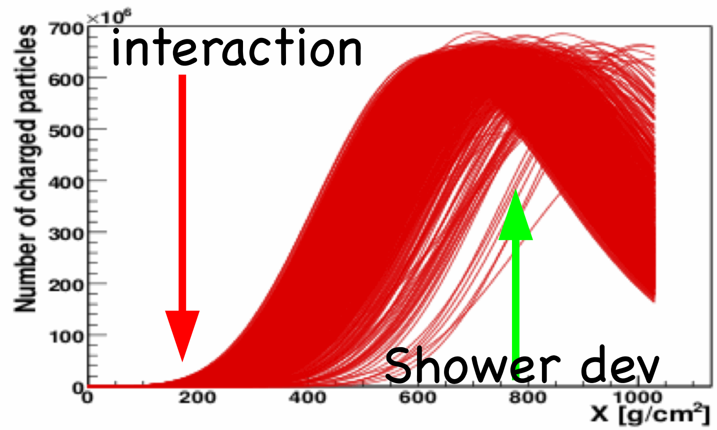
Aloisio et al. 2012

An ideal measurement: Individual Spectra for each component.

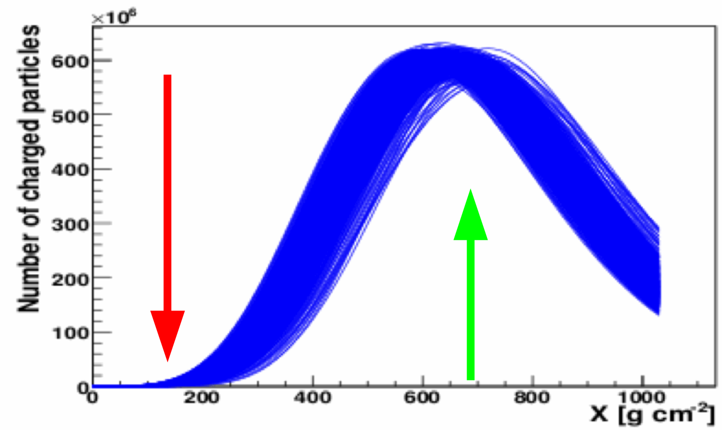


Even in such case must disentangle production/propagation

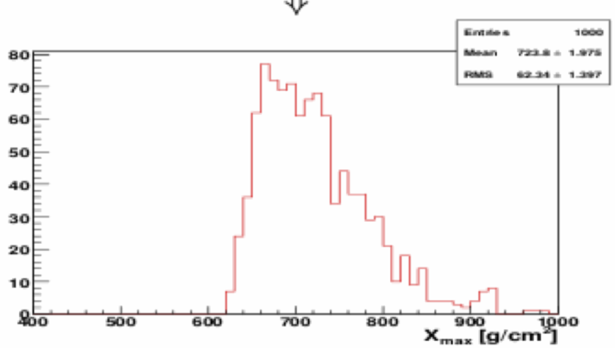
Only practical measurements, at highest energies are momenta of mass distribution: all particle spectra (0th) and higher momenta of mass related observables



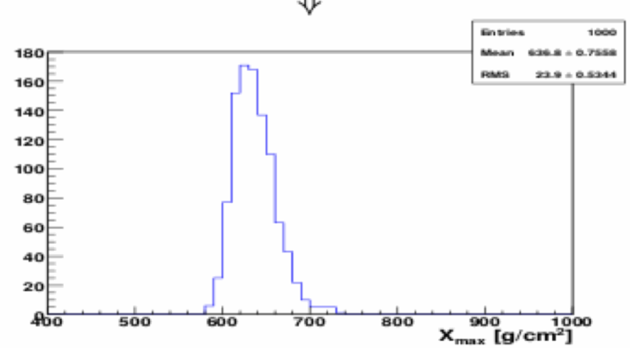
proton MC longitudinal profile ($E=10^{18}$ eV, $N_{ev}=1000$)



iron MC longitudinal profile ($E=10^{18}$ eV, $N_{ev}=1000$)

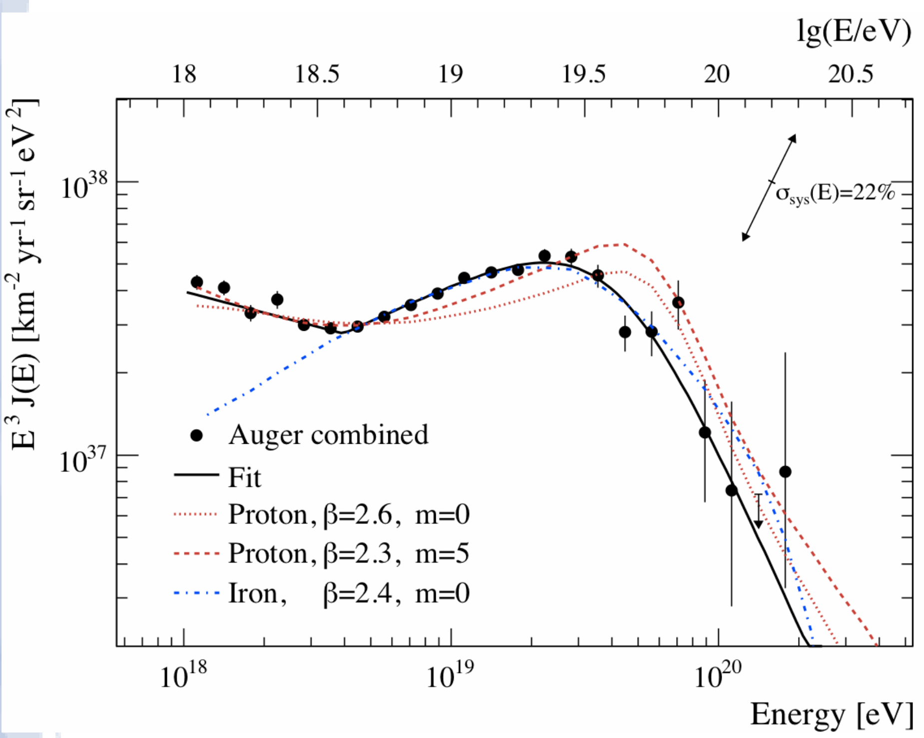


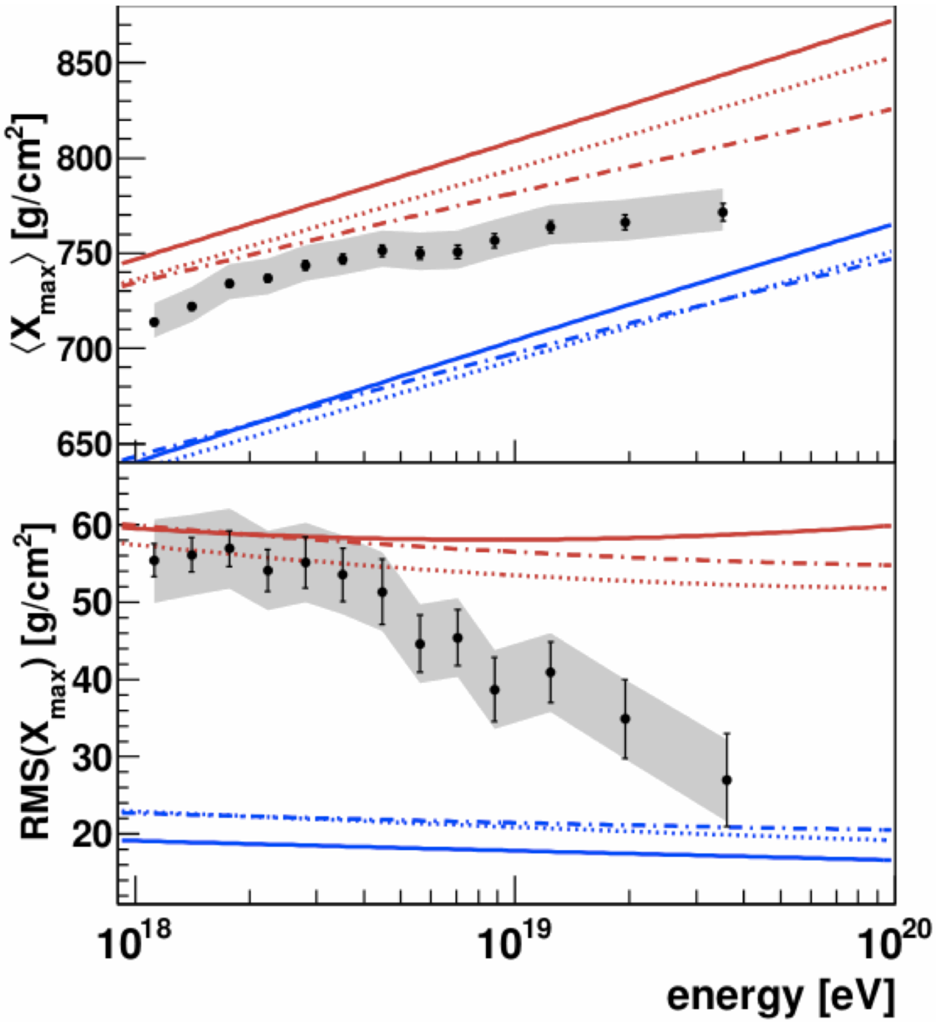
proton MC X_{max} distribution



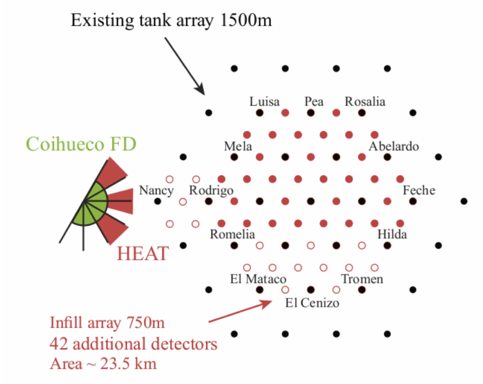
iron MC X_{max} distribution

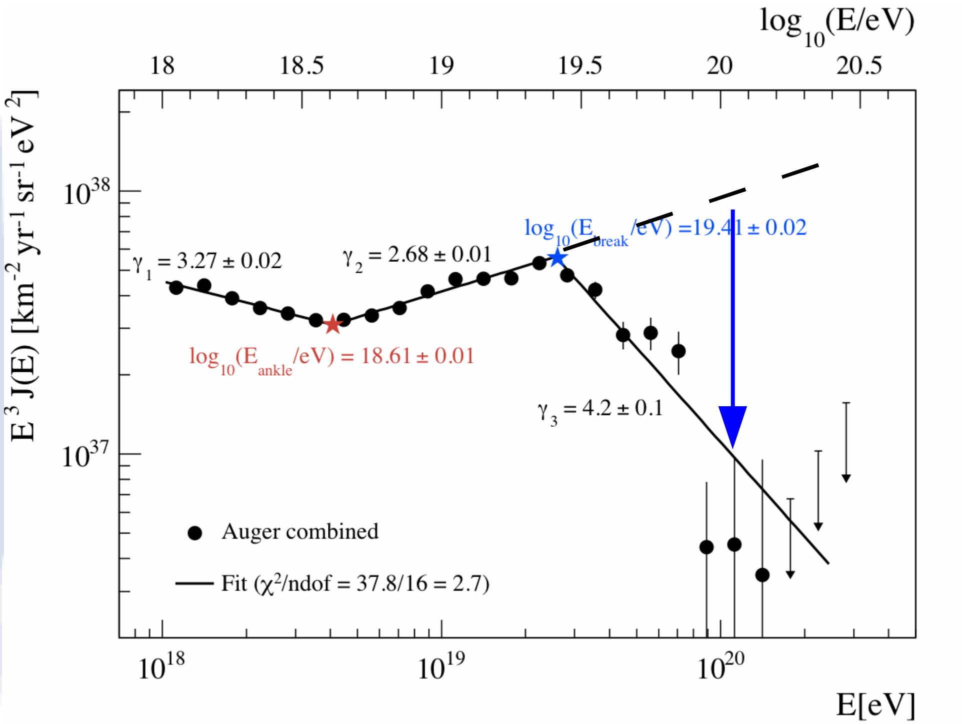
at highest energies:
all particle spectra and mass related observables

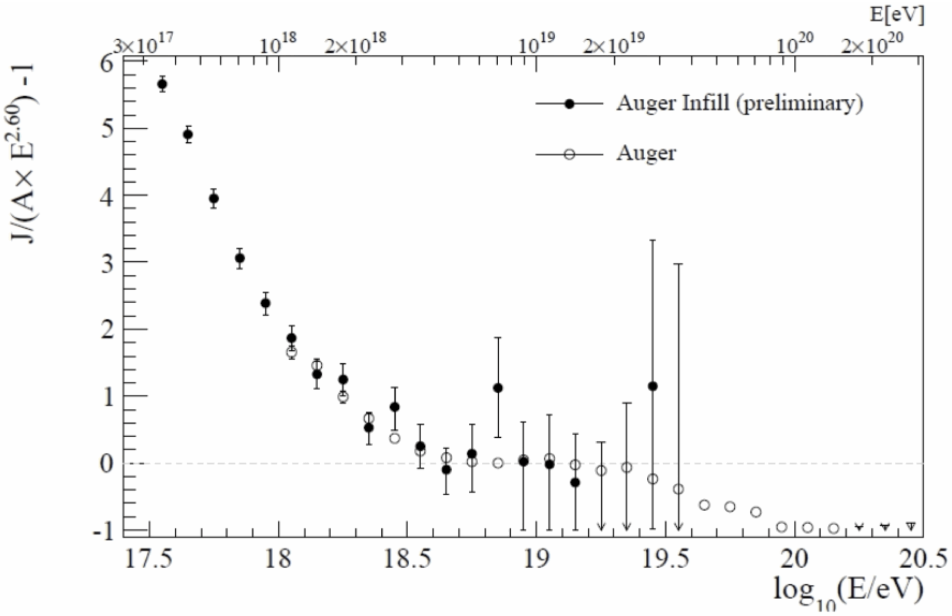




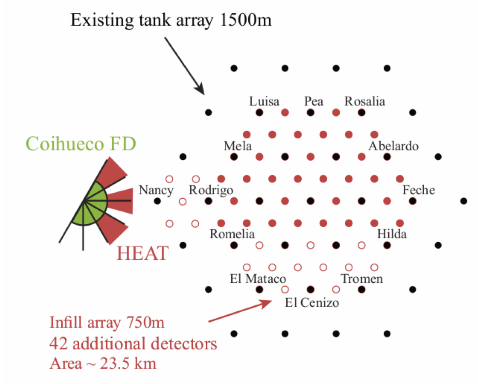
The Spectrum

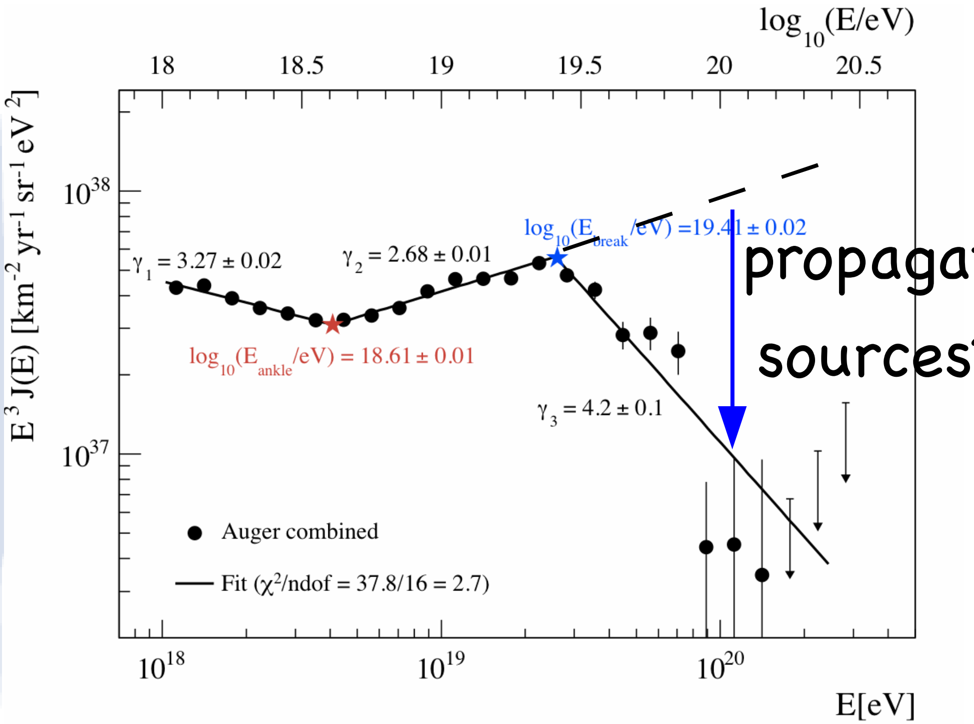






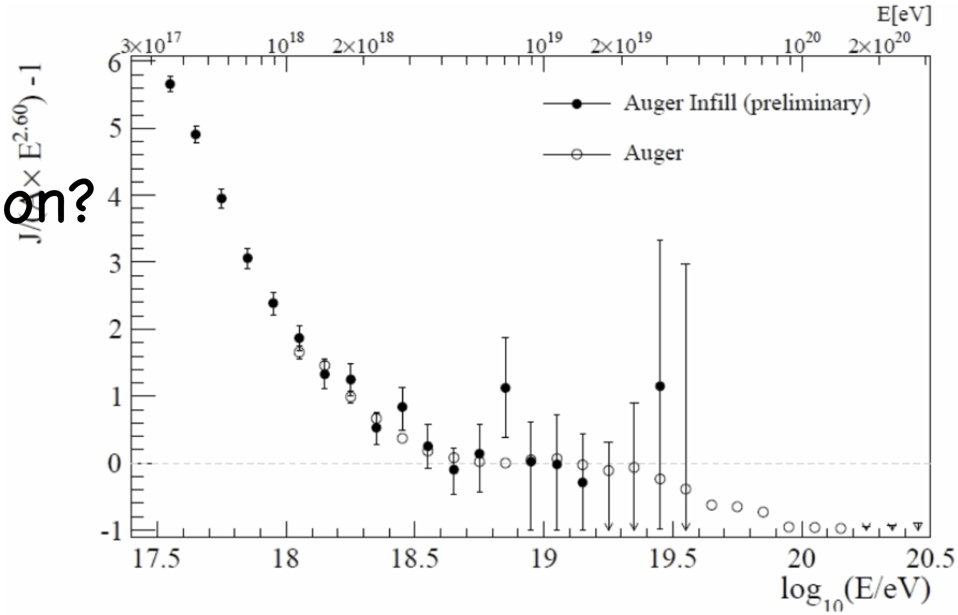
The Spectrum





propagation?

sources?



Correlation with sources

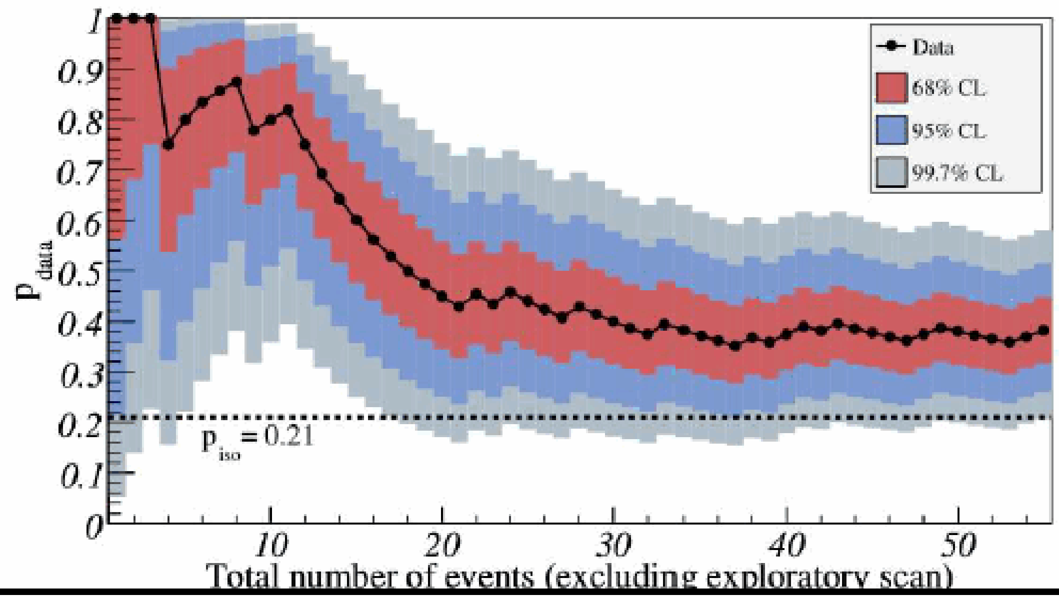
- Search for correlations between Auger high energy events and objects of the VCV catalogue of quasars and active nuclei

→ Correlation signal: 69% ($\theta = 3.2°$, $z = 0.017$, $E_{thr} = 57$ EeV)
→ to be compared with 21% expected from isotropic cosmic rays.

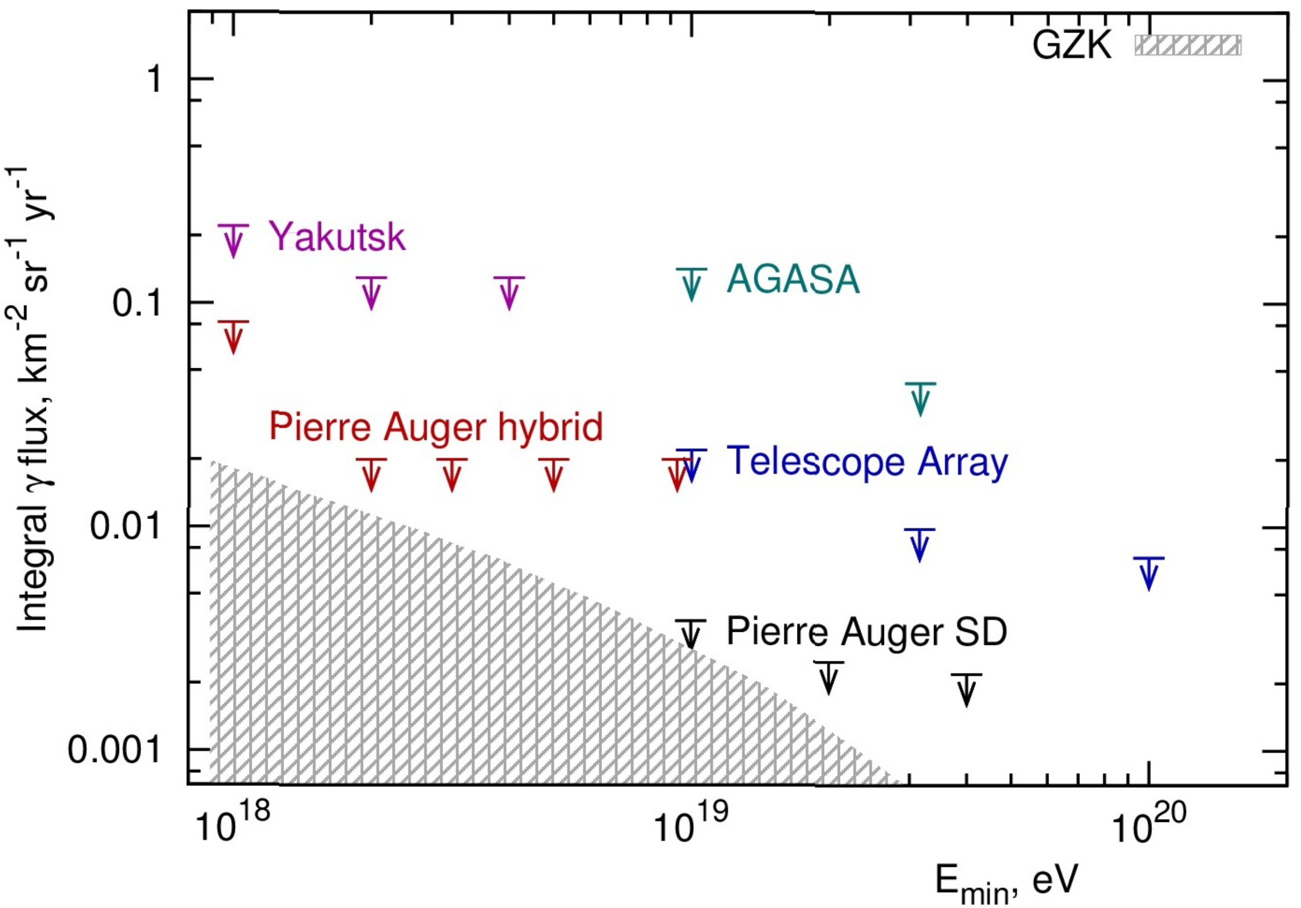
The Auger Col, Science 318:938-943,2007 - The Auger Col, Astropart.Phys.29:188-204,2008

Update in 2010: reduced correlation signal 69% → 39%

The Auger Col, Astropart.Phys. 34 (2010) 314-326



Photons

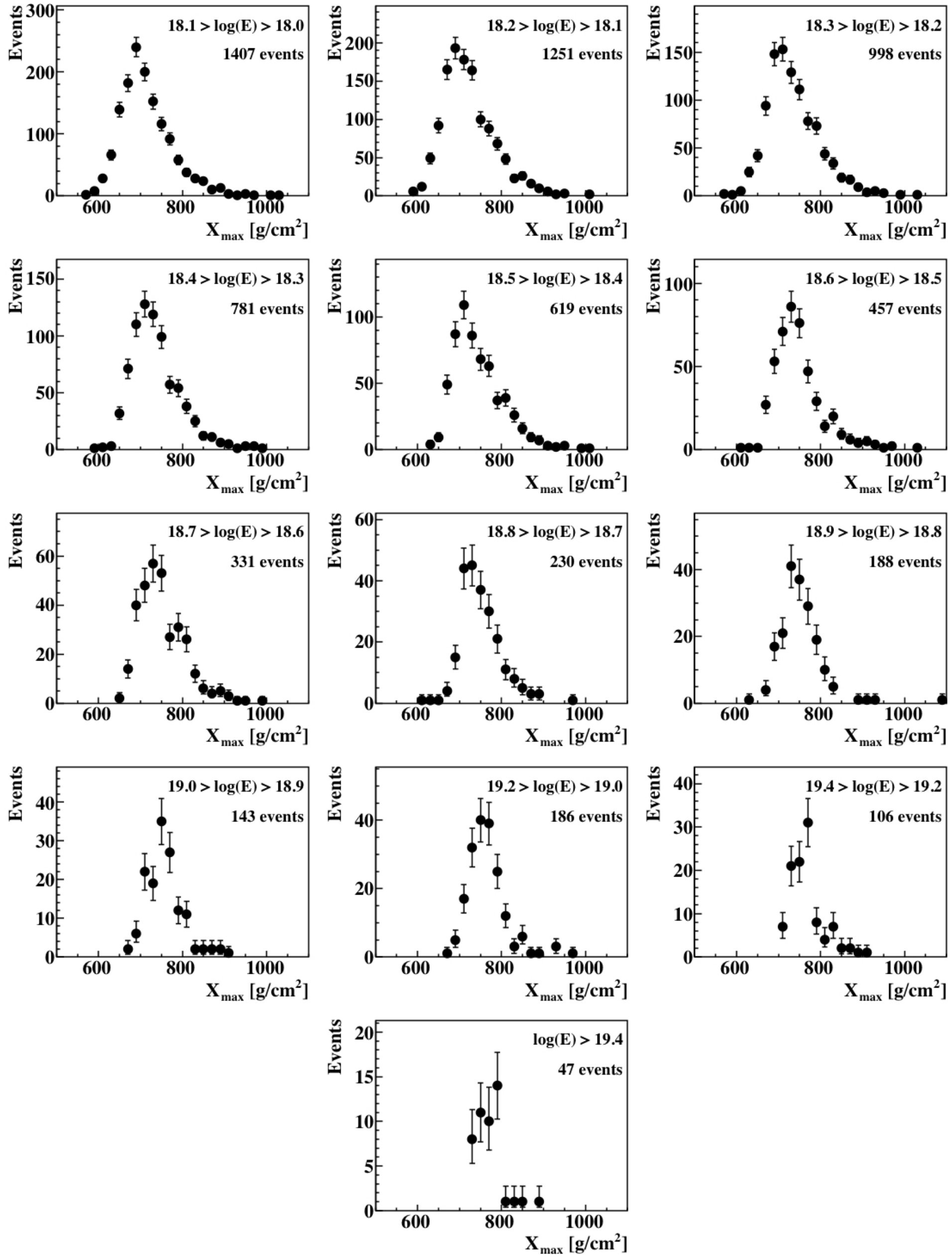


GZK
1
0.1
0.01
0.001
Integral γ flux, km^{-2} sr^{-1} yr^{-1}
Yakutsk
AGASA
Pierre Auger hybrid
Telescope Array
Pierre Auger SD
10^{18}
10^{19}
10^{20}
E_{min}, eV

mass composition measurement in Auger

What is measured in detail: the distribution of atmospheric depth, in *hybrid events* with at least one surface station active. The reconstructed maxima X_{max} are binned in reconstructed energy and the variance $RMS(X_{max})$ measured

The experimental measurement



$$\langle X_{max} \rangle = X_0 + X_1 \langle \ln A \rangle$$

$$RMS \Rightarrow \sigma^2(X_{max}) = Y_1 \sigma^2_{\ln A} + \langle \sigma^2_{sh} \rangle$$

Pure & mixed

mixed

X_0, X_1, Y_1 in general depend logarithmically on energy and depend on CR interactions in the atmosphere and shower development.

With further assumptions the coefficient can be computed and experimental measurement inverted.

$$\langle X_{max} \rangle = X_0 + X_1 \langle \ln A \rangle$$

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$$\langle X_{max} \rangle = X_0 + X_1 \langle \ln A \rangle$$ → Pure & mixed

$$\sigma^2(X_{max}) = Y_1 \sigma^2_{\ln A} + \langle \sigma^2_{sh} \rangle$$ → Pure & mixed

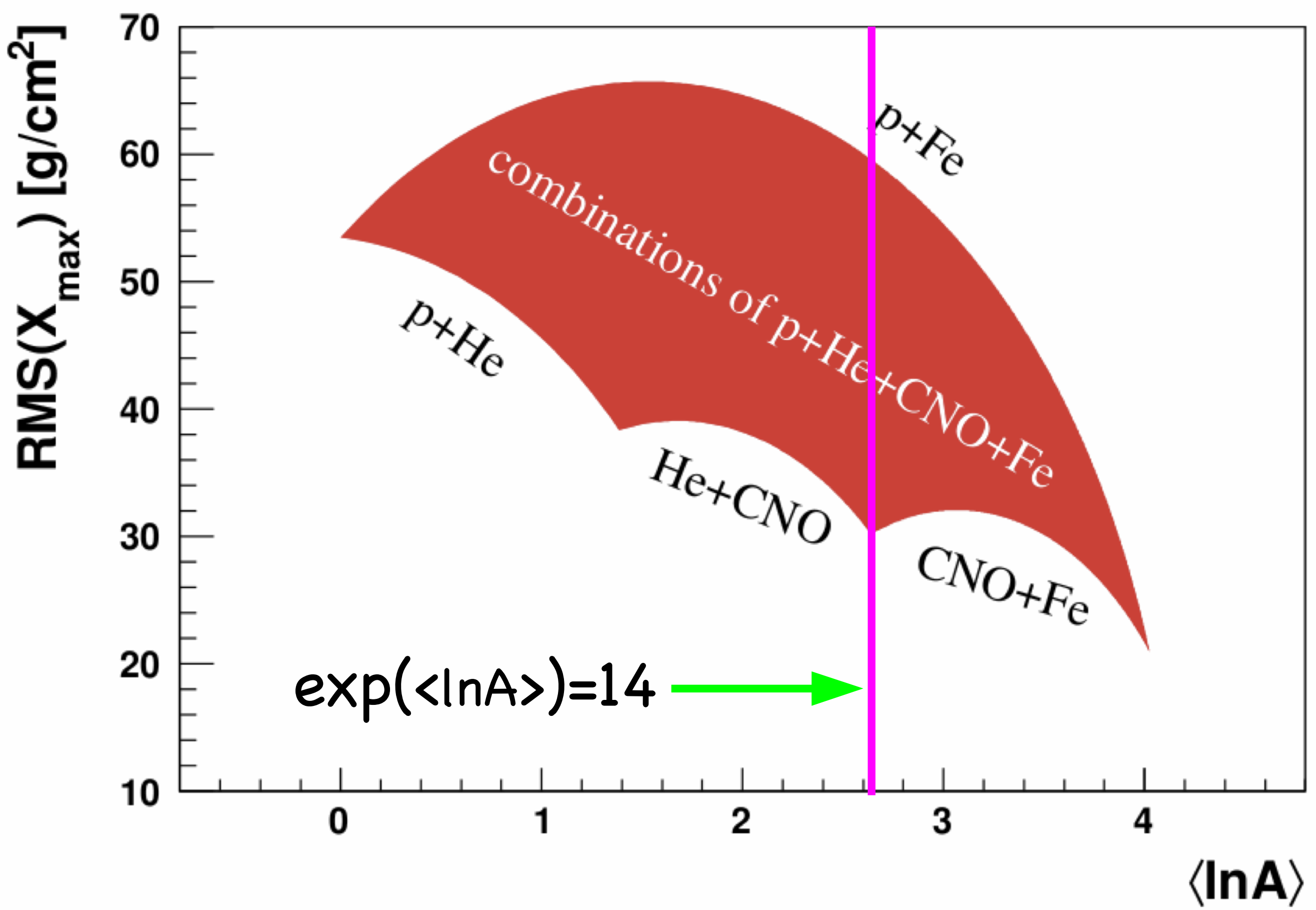
$\sigma^2_{\ln A}$ → mixed

In case of mixed composition give information on sources as well as propagation in IG space (Aloisio)

Notice: Pure composition other than protons is somewhat unnatural at Earth: Nuclei interact in photon fields and generate secondaries

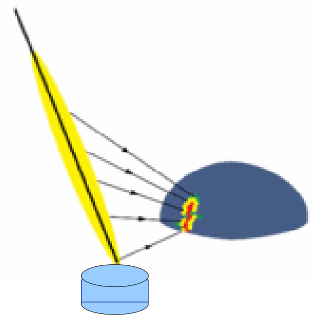
The different meaning of $\langle X_{max} \rangle$, $\sigma^2(X_{max})$ can be represented in a combined plot (Linsley)

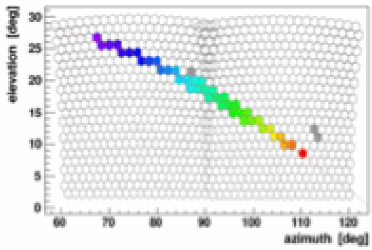
$$\langle X_{max} \rangle = X_0 + X_1 \langle \ln A \rangle \qquad \sigma^2(X_{max}) = Y_1 \sigma^2_{\ln A} + \langle \sigma^2_{sh} \rangle$$



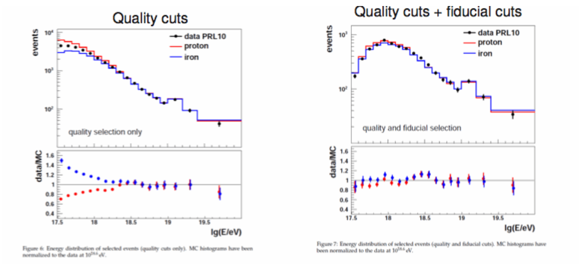
The experimental measurement

- High quality Hybrid events
  15979 events





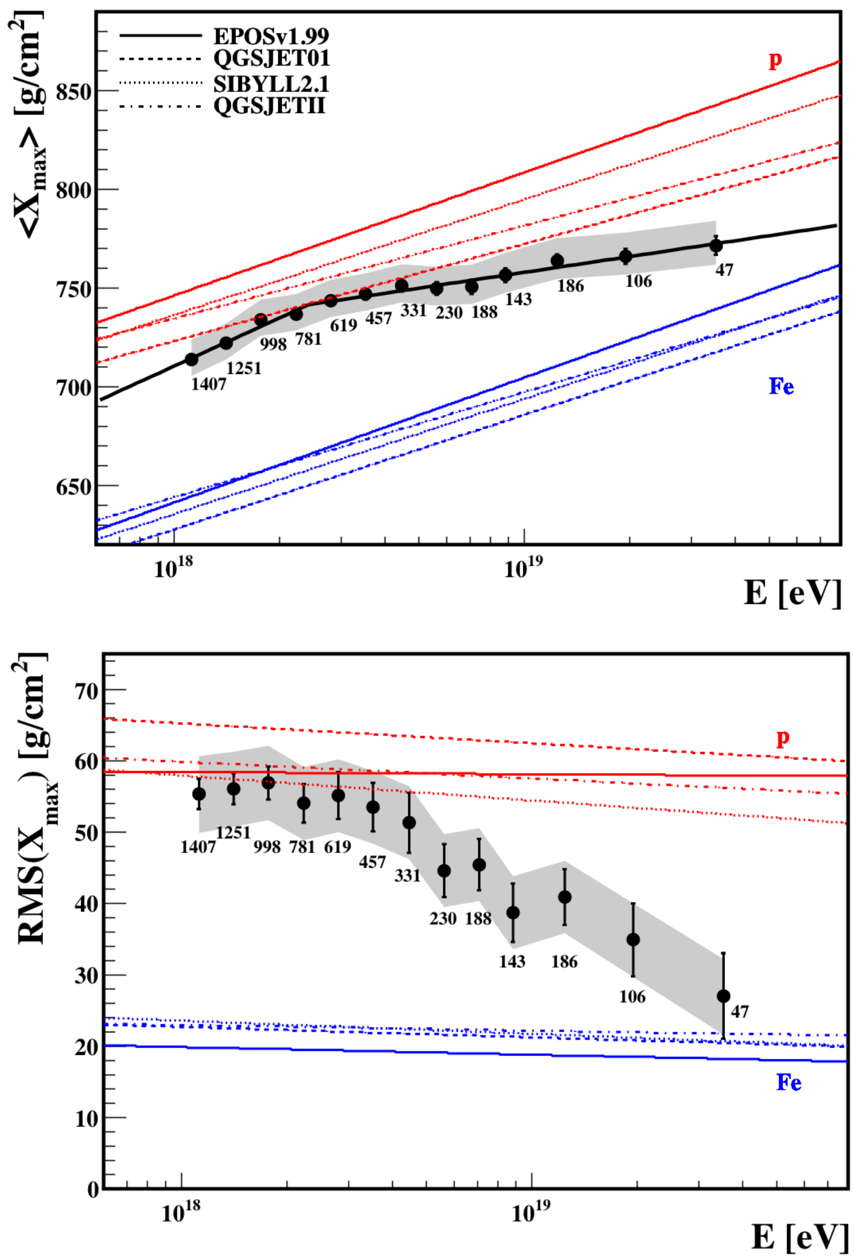
- Fiducial volume: no geometrical bias on X_{max}
  6558 events



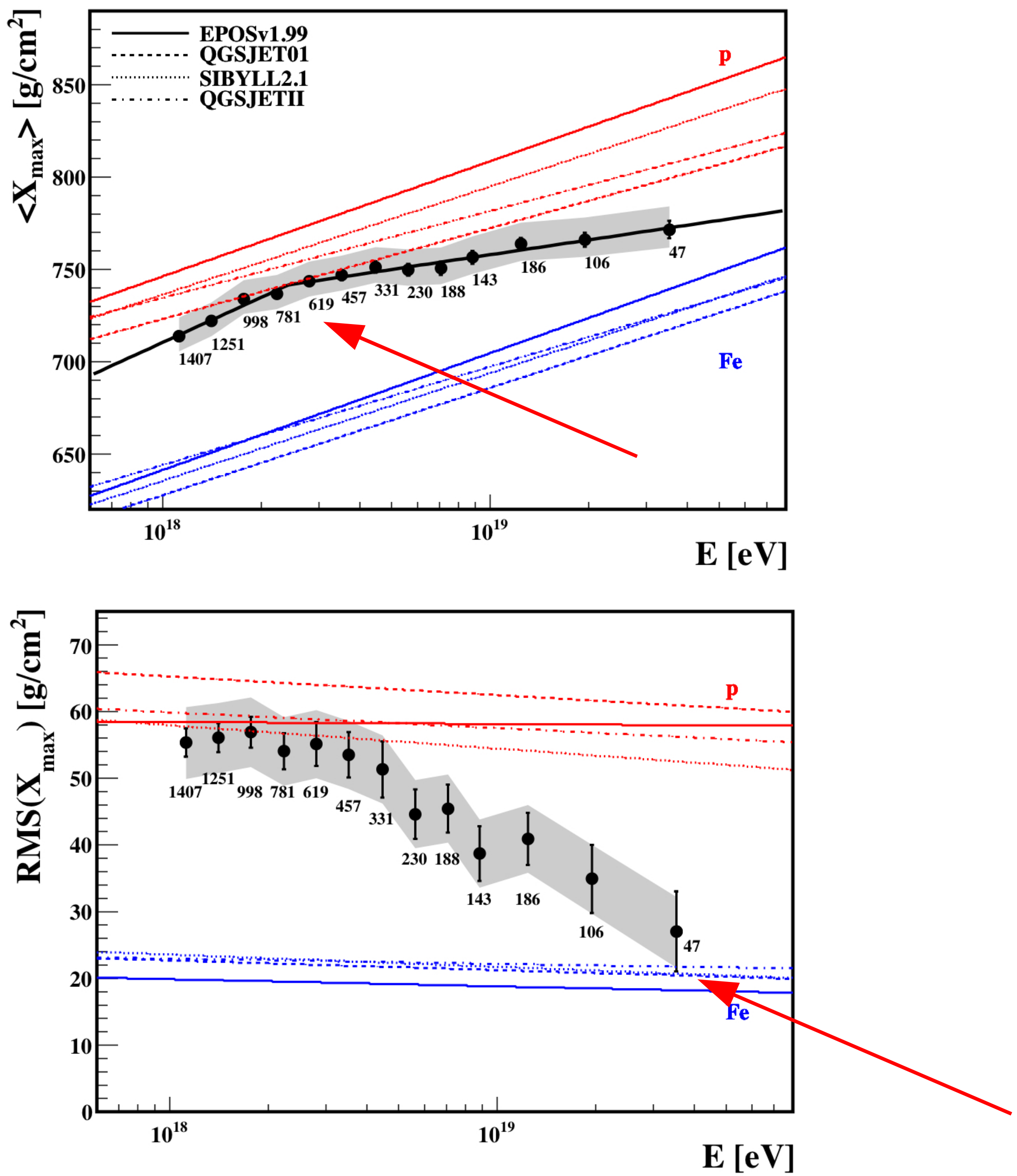
- Detection efficiency corrected

The generated distributions are independent from detection details.

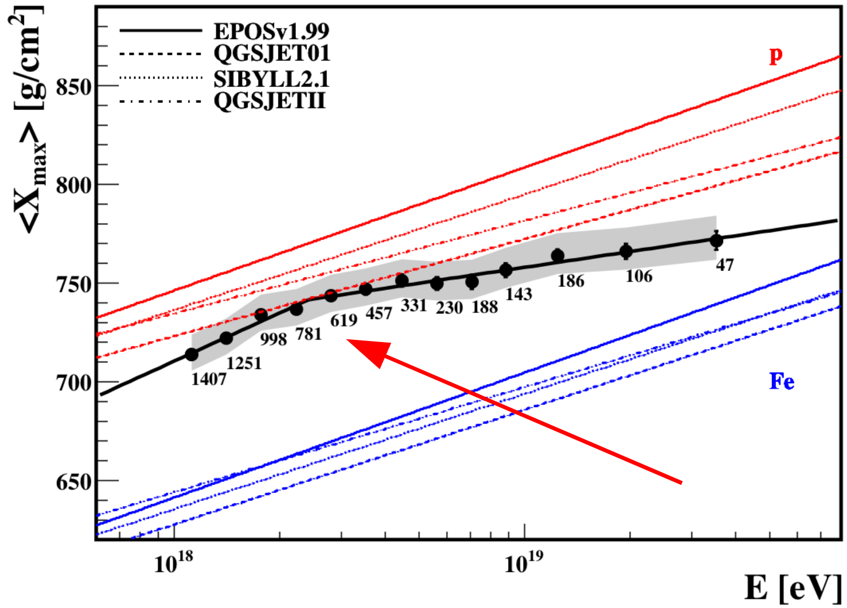
X_{max} resolution 20 g cm^{-2}


EPOSv1.99
QGSJET01
SIBYLL2.1
QGSJETII
p
Fe
<Xmax> [g/cm2]
E [eV]
RMS(Xmax) [g/cm2]
1407
1251
998
781
619
457
331
230
188
143
186
106
47

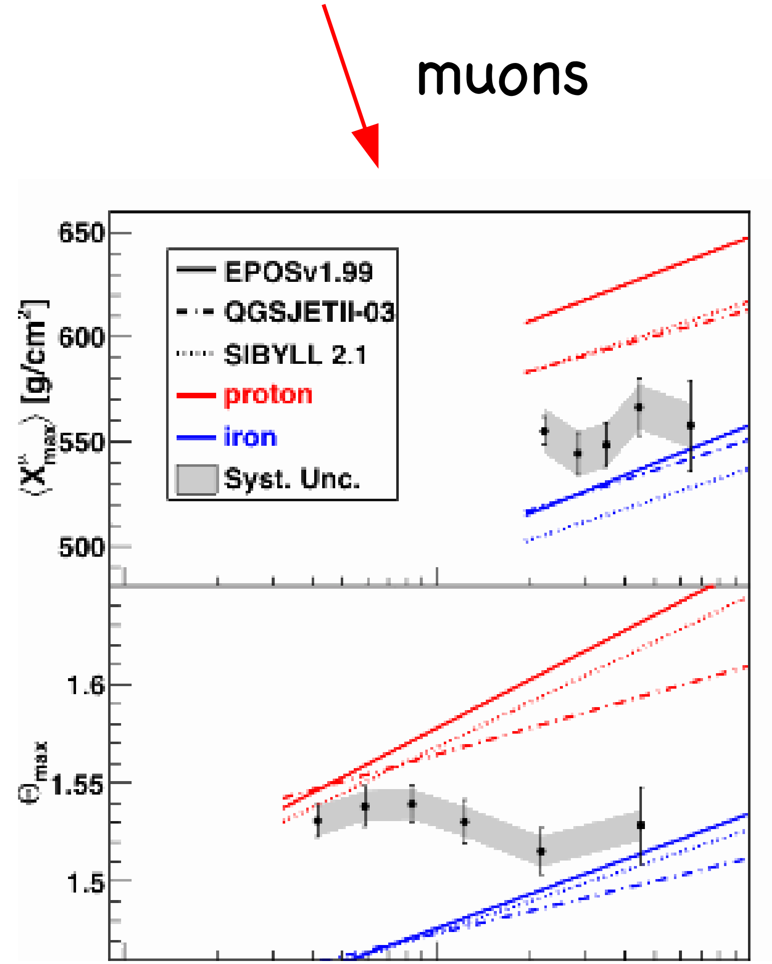
The experimental measurement

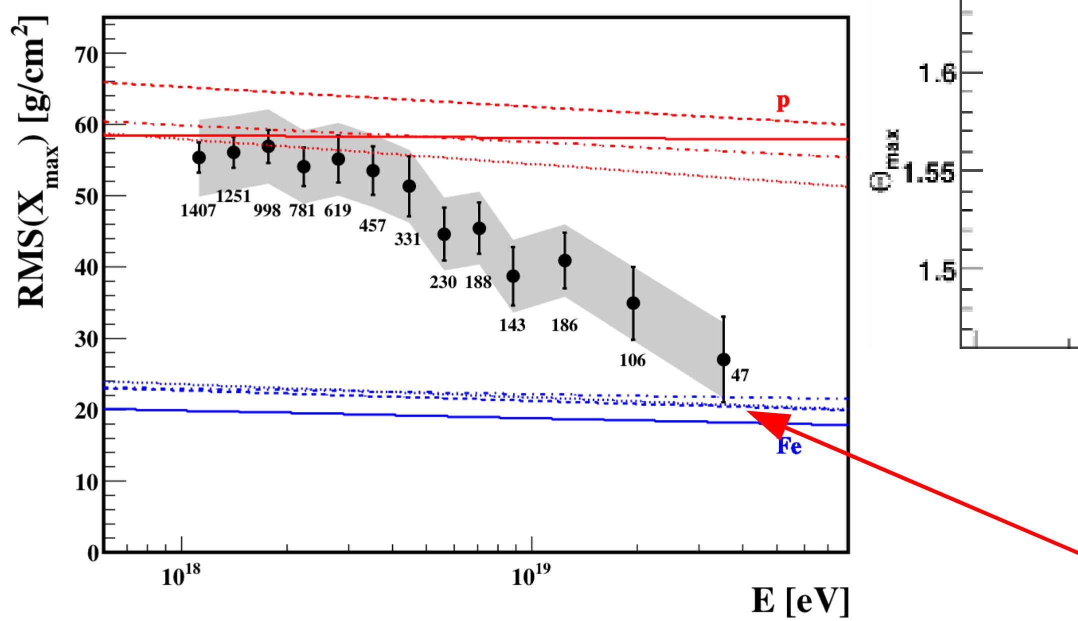


The experimental measurement

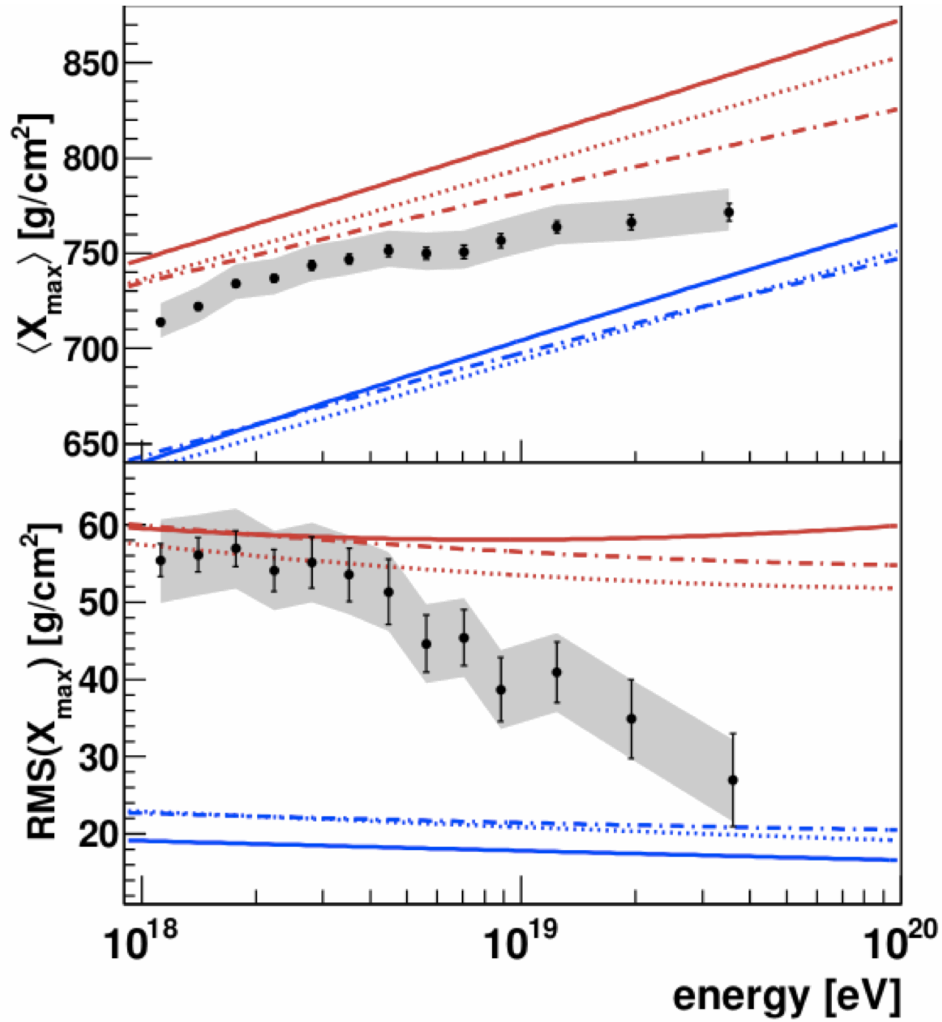


muons



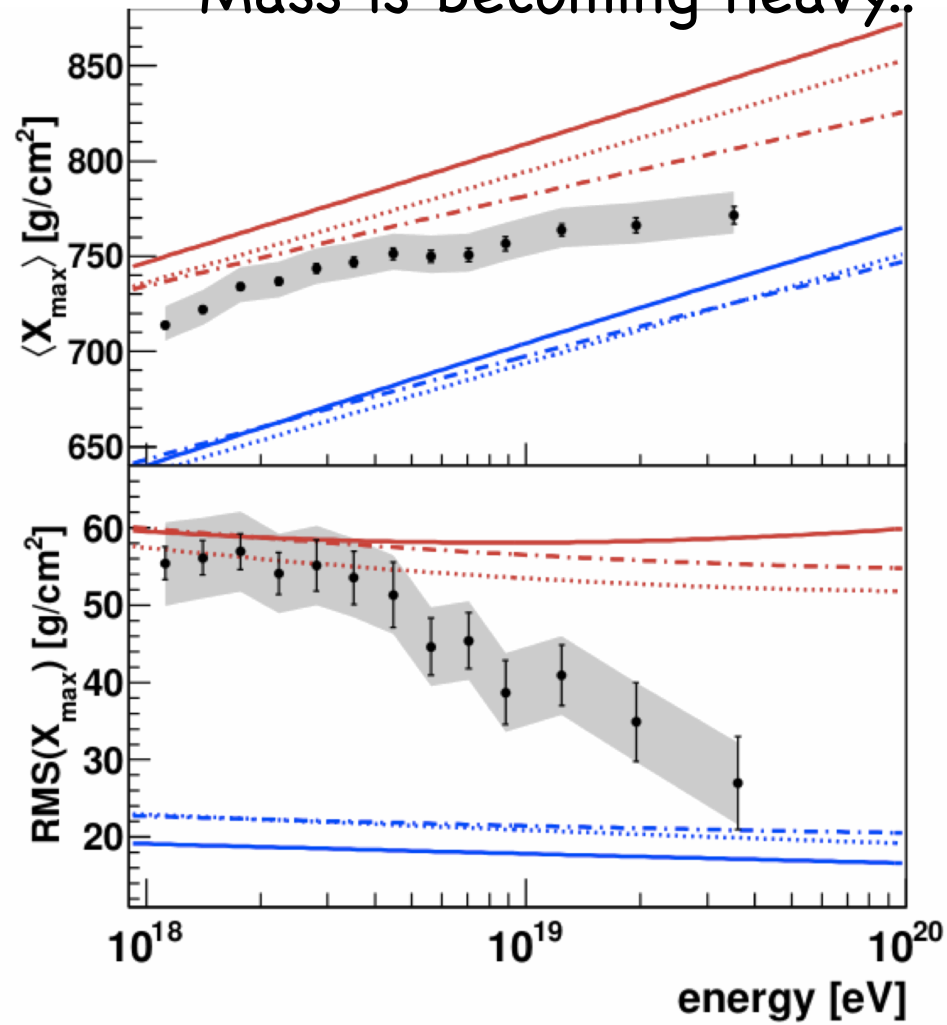


What these results are trying to say us?



What these results are trying to say us?

Mass is becoming heavy..



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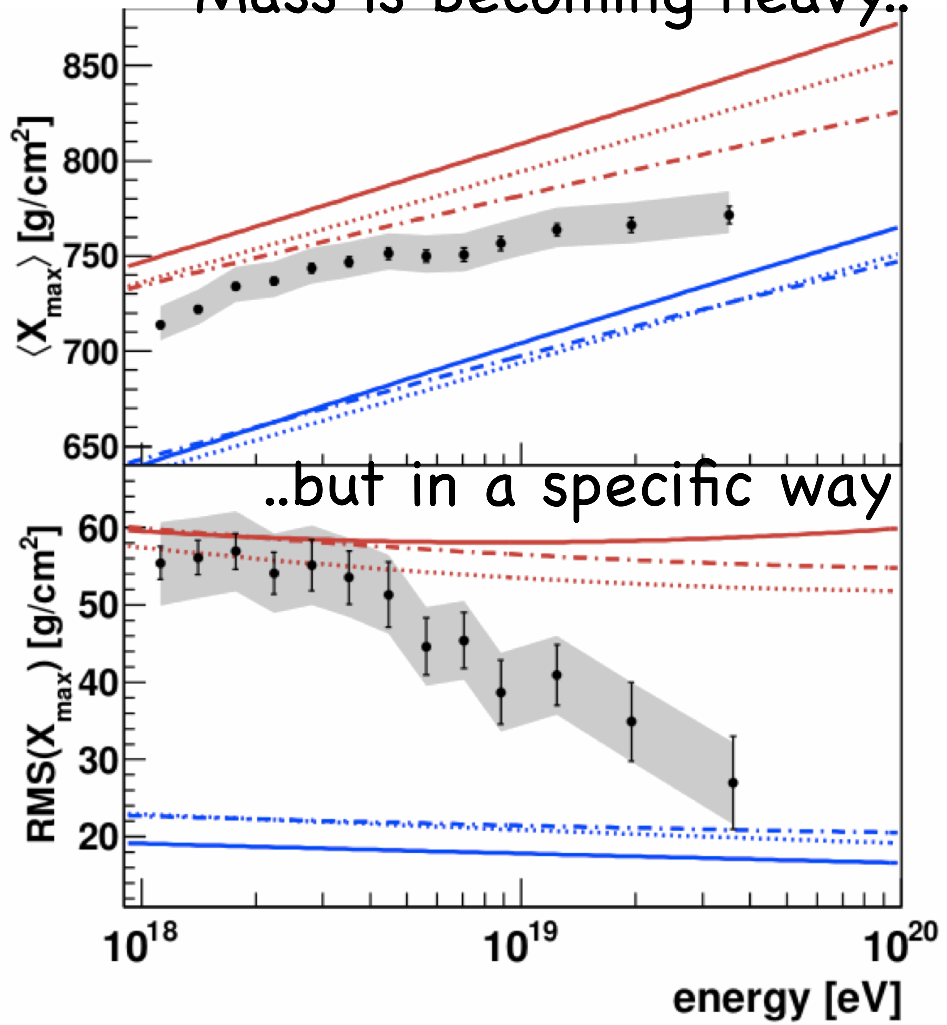

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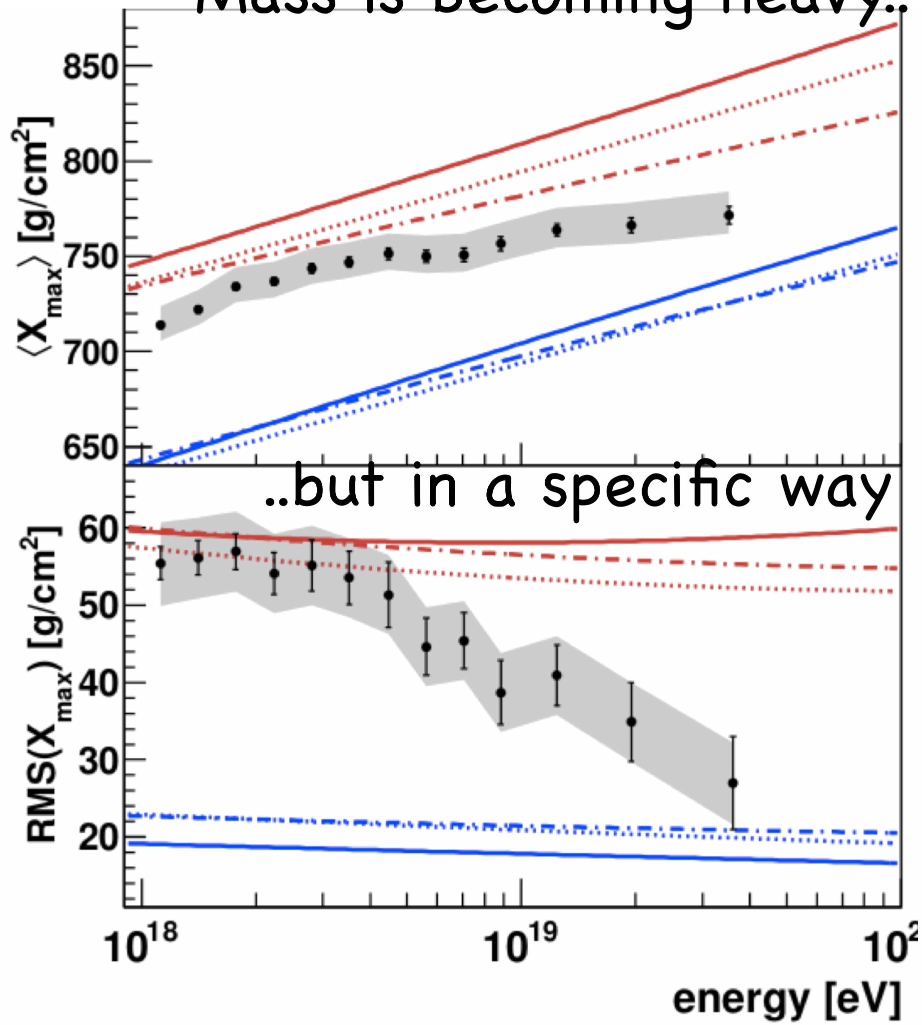
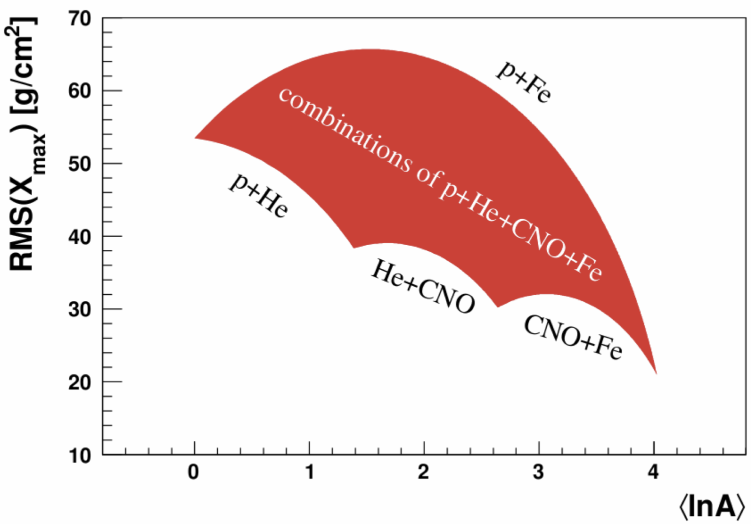
..but in a specific way





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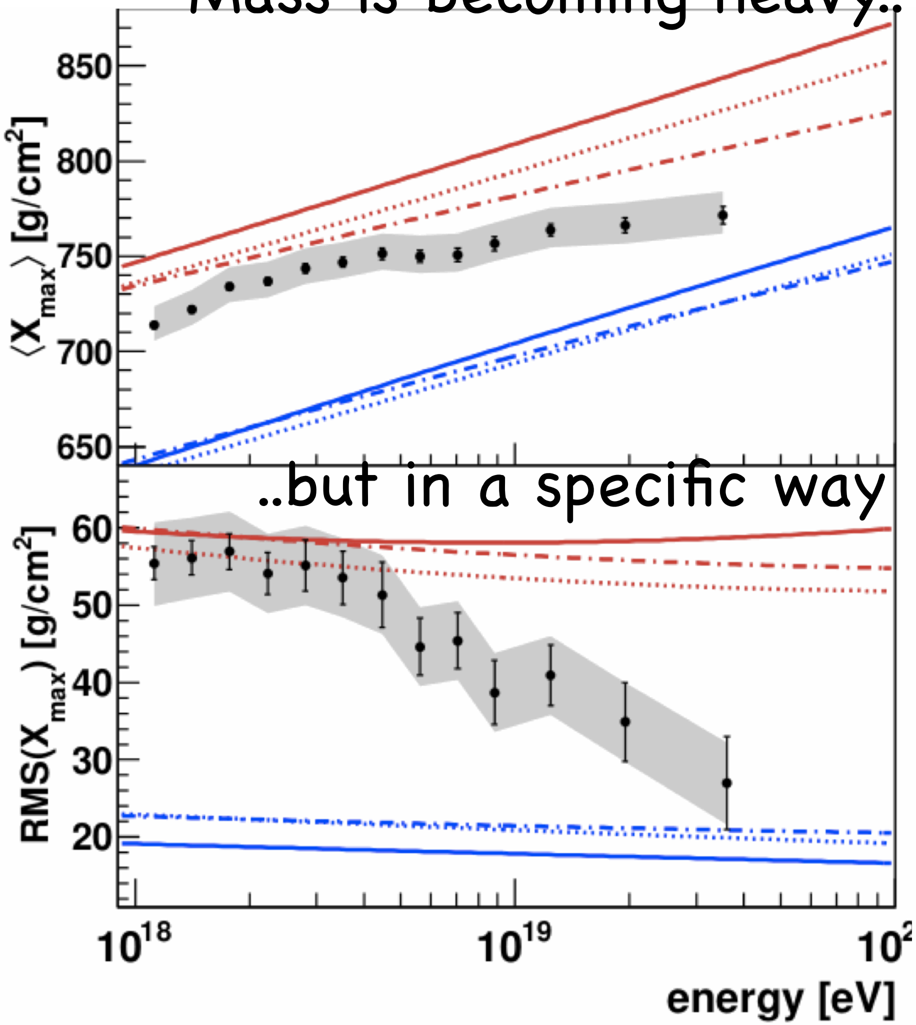

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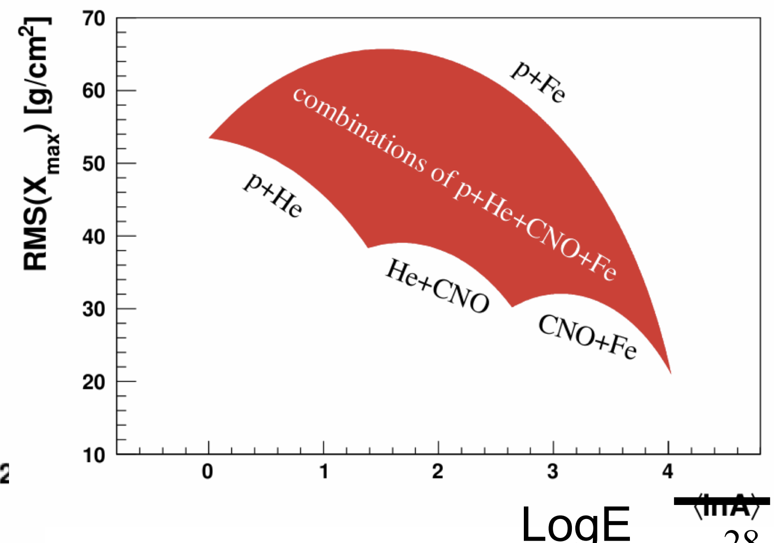
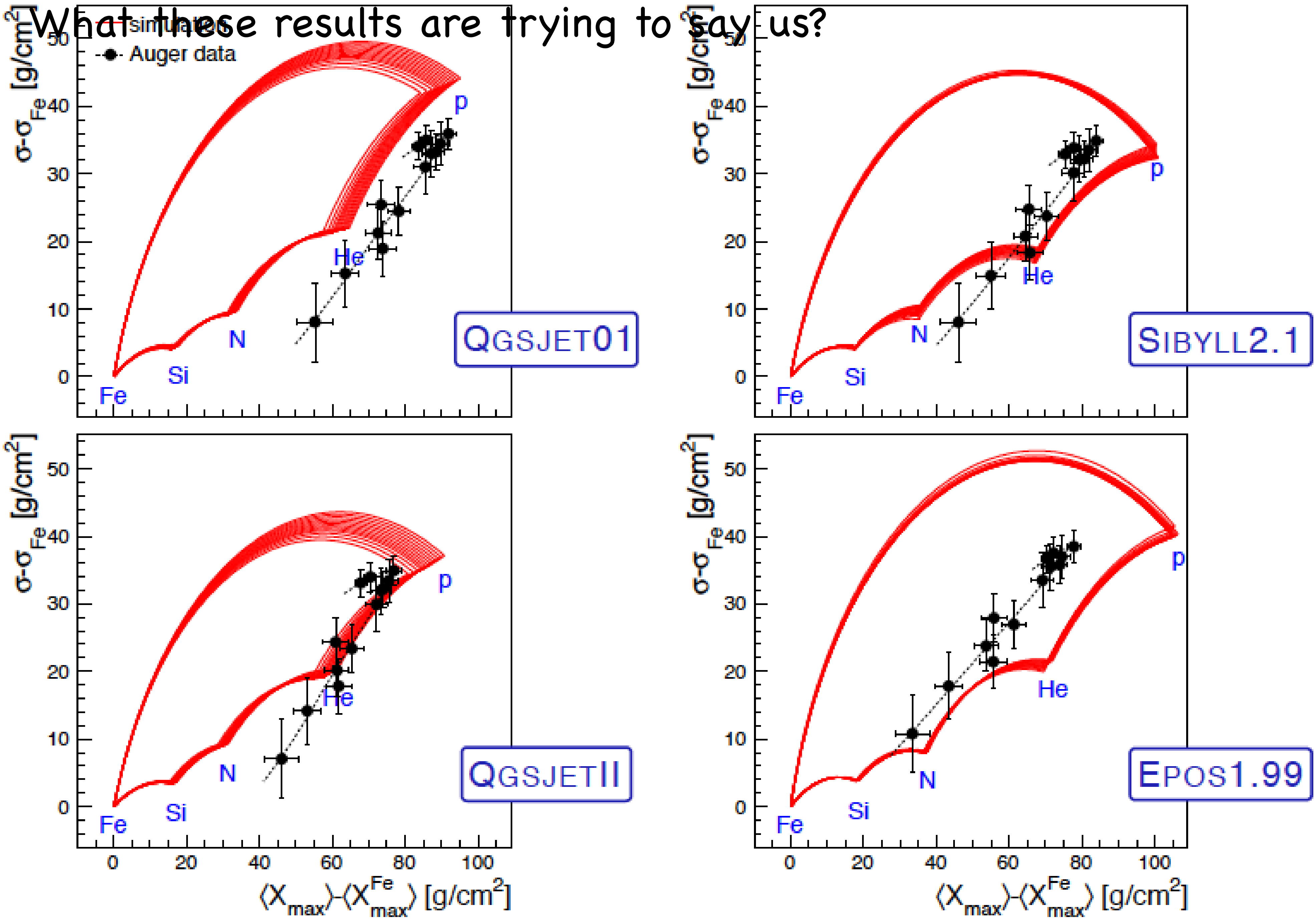


$\langle X_{max} \rangle$ vs. RMS

arXiv:1201.0018

What these results are trying to say us?



New Physics? Cannot say

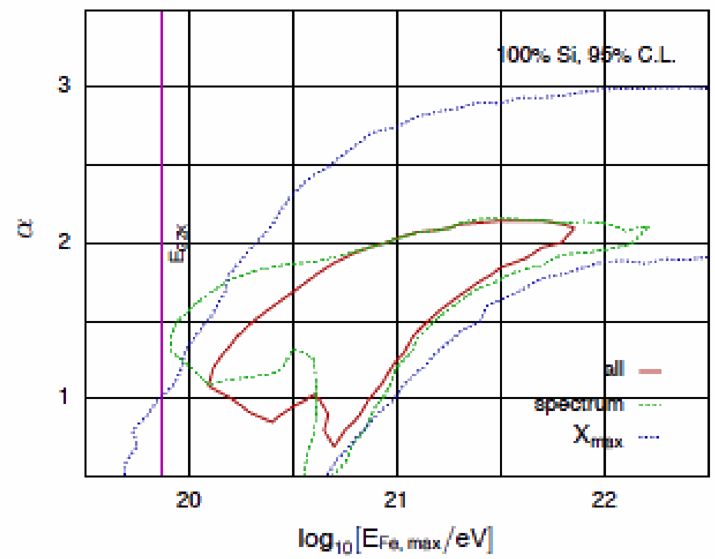
New Physics? Cannot say

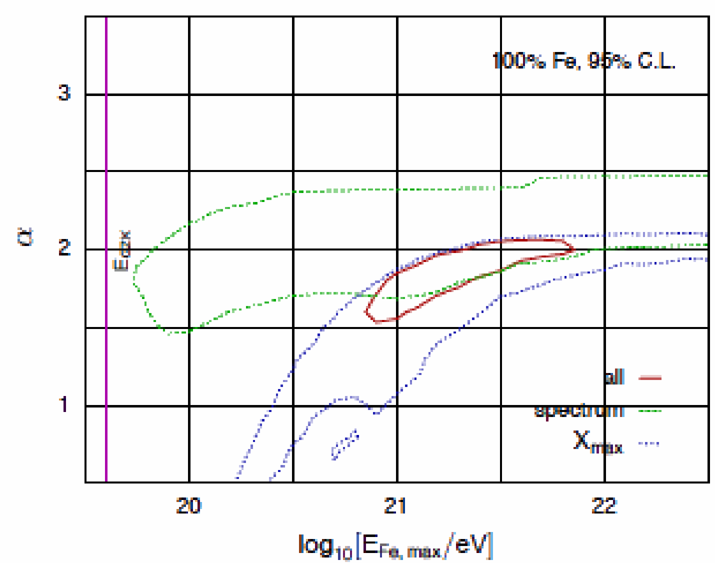
If data (spectrum, Xmax, RMS) taken literally they suggest interesting conclusions

- source parameters

The need for a local source of UHE CR nuclei

Andrew M. Taylor,[1] Markus Ahlers,[2] and Felix A. Aharonian[3,4]





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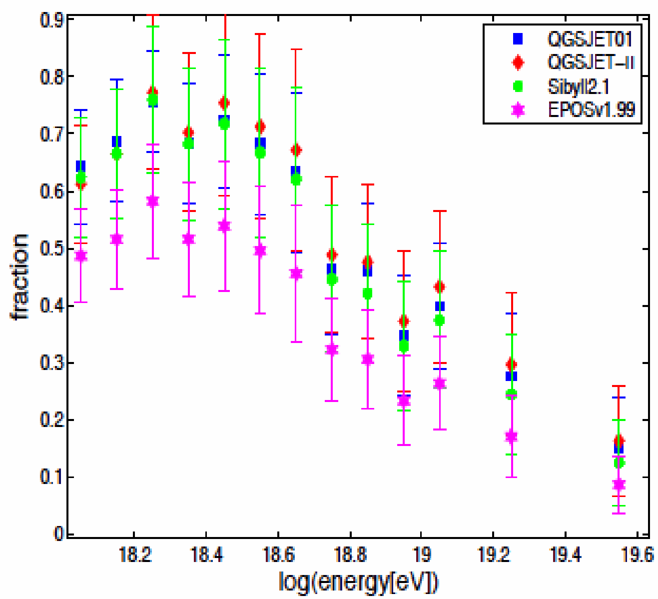


FIG. 1. An upper bound for the proton fraction of the observed flux as a function of energy, calculated using the most recent PAO data and various models of extensive air showers simulations: QGSJET01 [2], QGSJET-II [1], Sibyll2.1 [4] and EPOSv1.99 [3].

The UHECRs Composition Problem: Evidence for a New Physics at 100 TeV?

Nimrod Shaham[1] and Tsvi Piran[1]

New Physics? Cannot say

If data (spectrum, Xmax, RMS) taken literally they suggest interesting conclusions

- particle physics

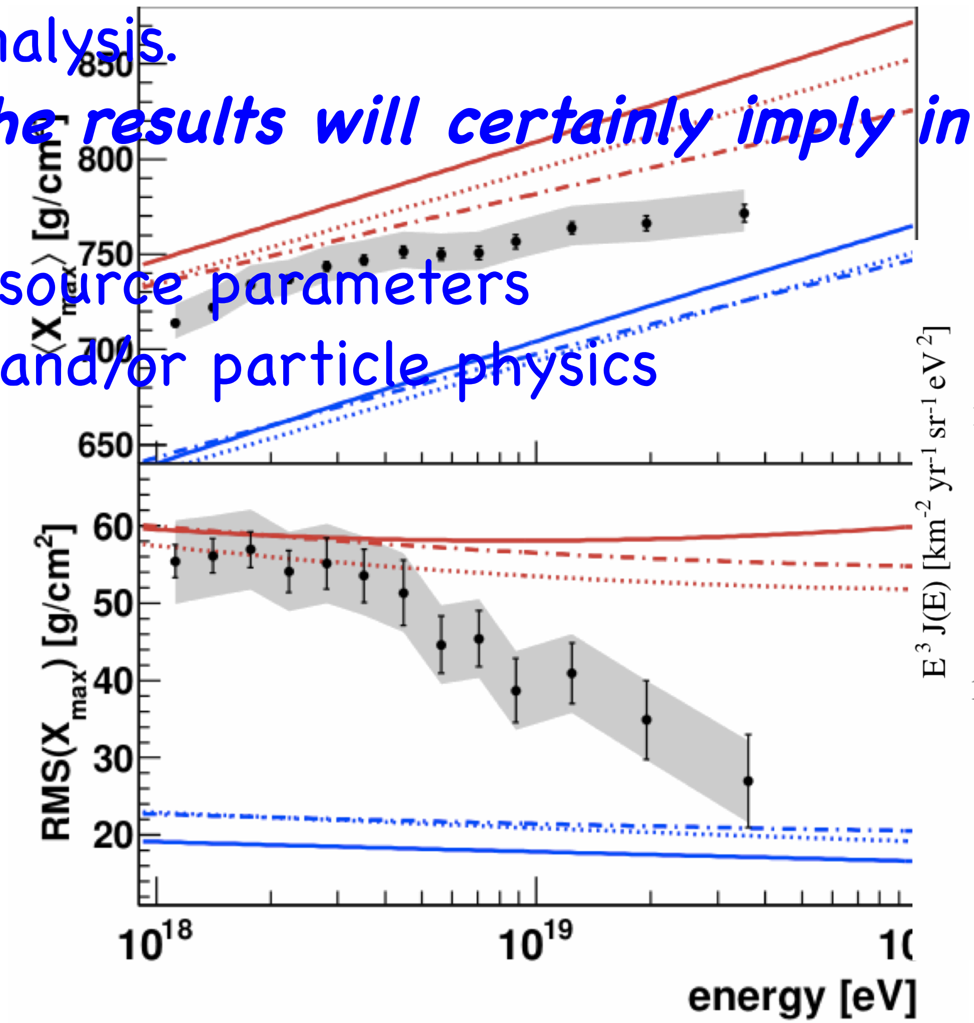
effects and estimate the source's spectral index and composition. We show that the observations requires a Fe to protons number ratio of 1:50 at the source, as well as a very hard spectrum. The lack of natural sources with such a metallicity combined with the hard spectral index and the overall incompatibility of the full data set with the simulations reveal a serious problem. Assuming that the observations and simulations are correct we conclude that the input physics is wrong and that the results points towards new physics that modifies the baryonic interactions at CM energy of a few dozens TeV, at which UHECRs collisions take place.

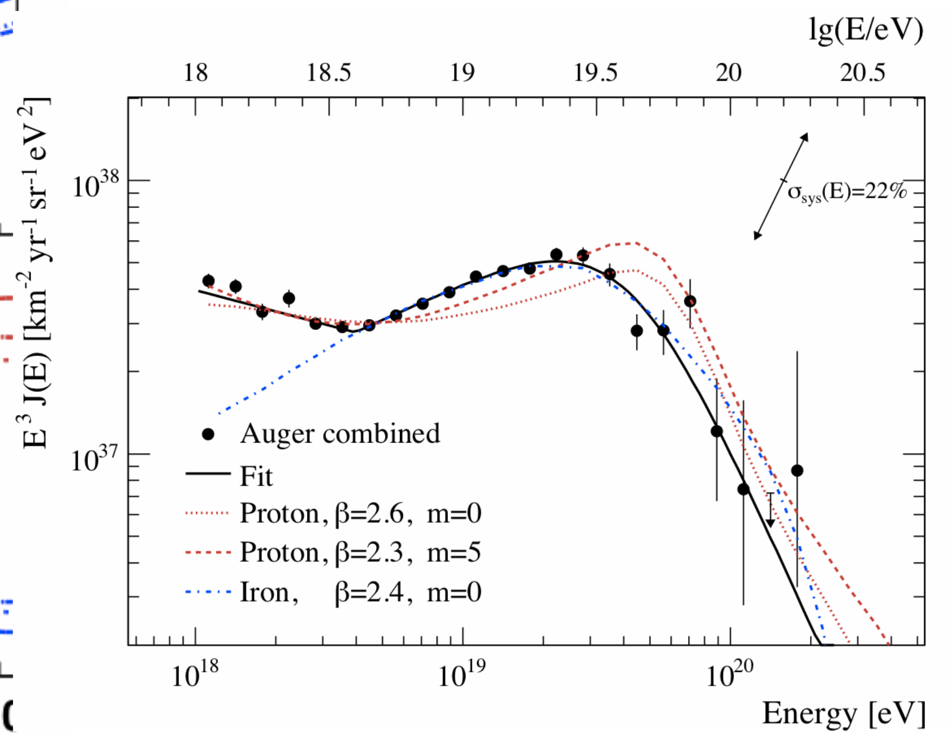
New Physics? Cannot say, ***work in progress***

Needed a combined data (spectrum, Xmax, RMS, ?correlations?) analysis.

The results will certainly imply interesting conclusions

- source parameters
- and/or particle physics





New Physics? Cannot say, ***work in progress***

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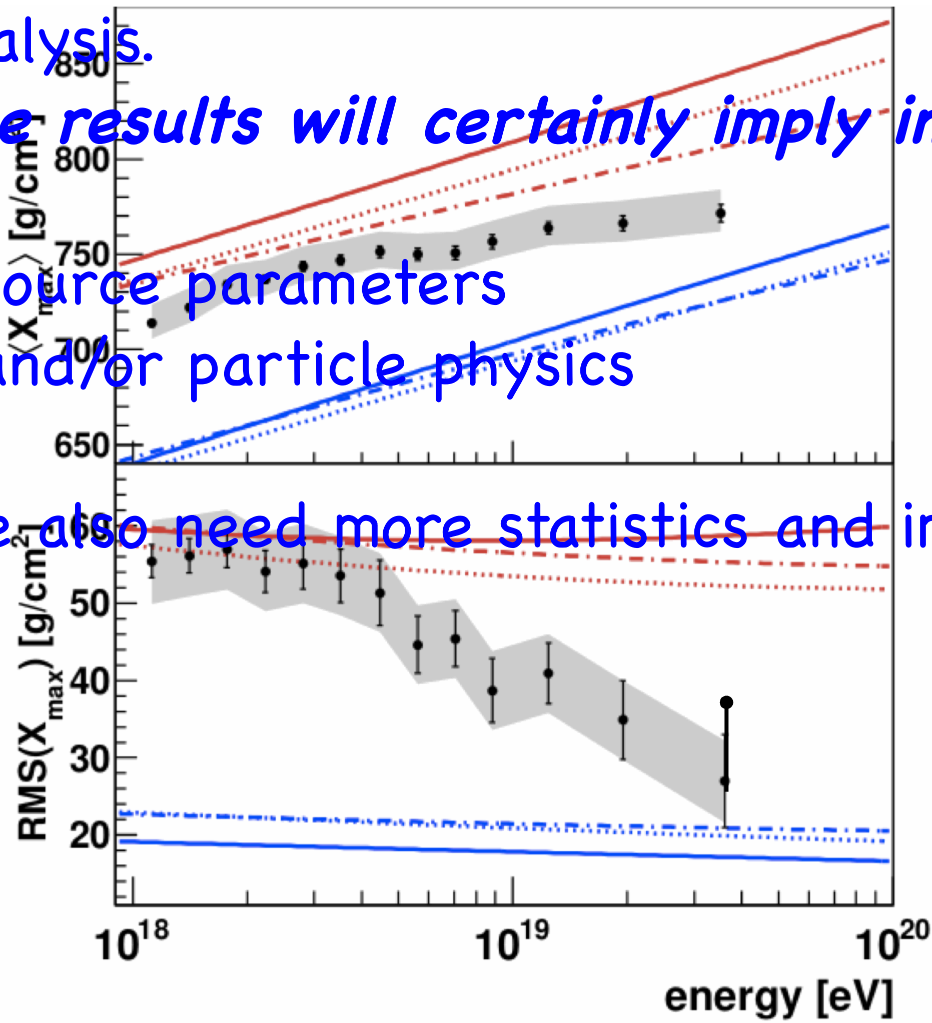
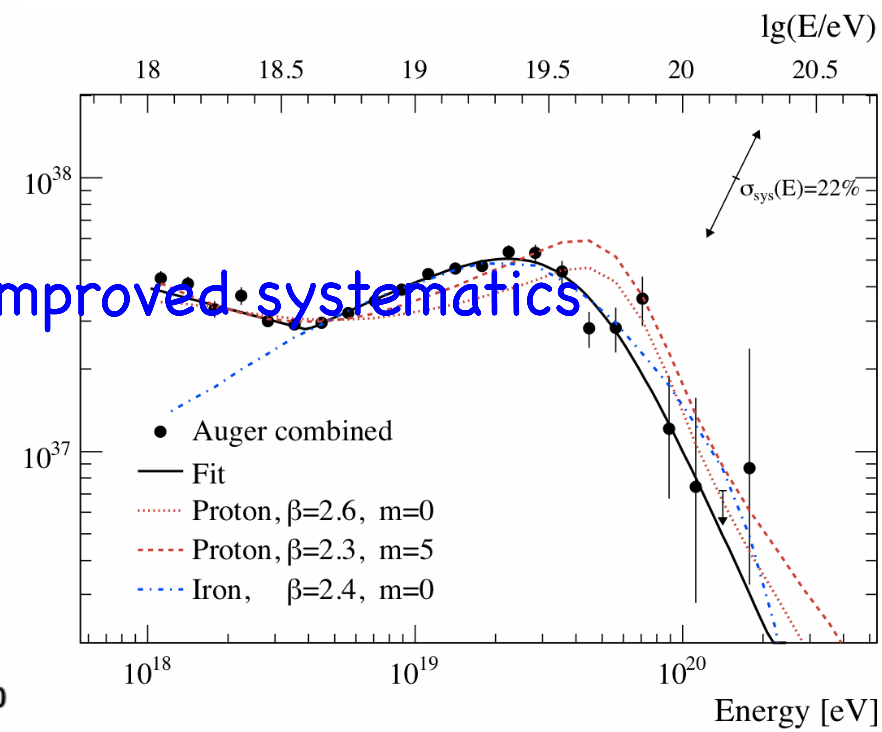
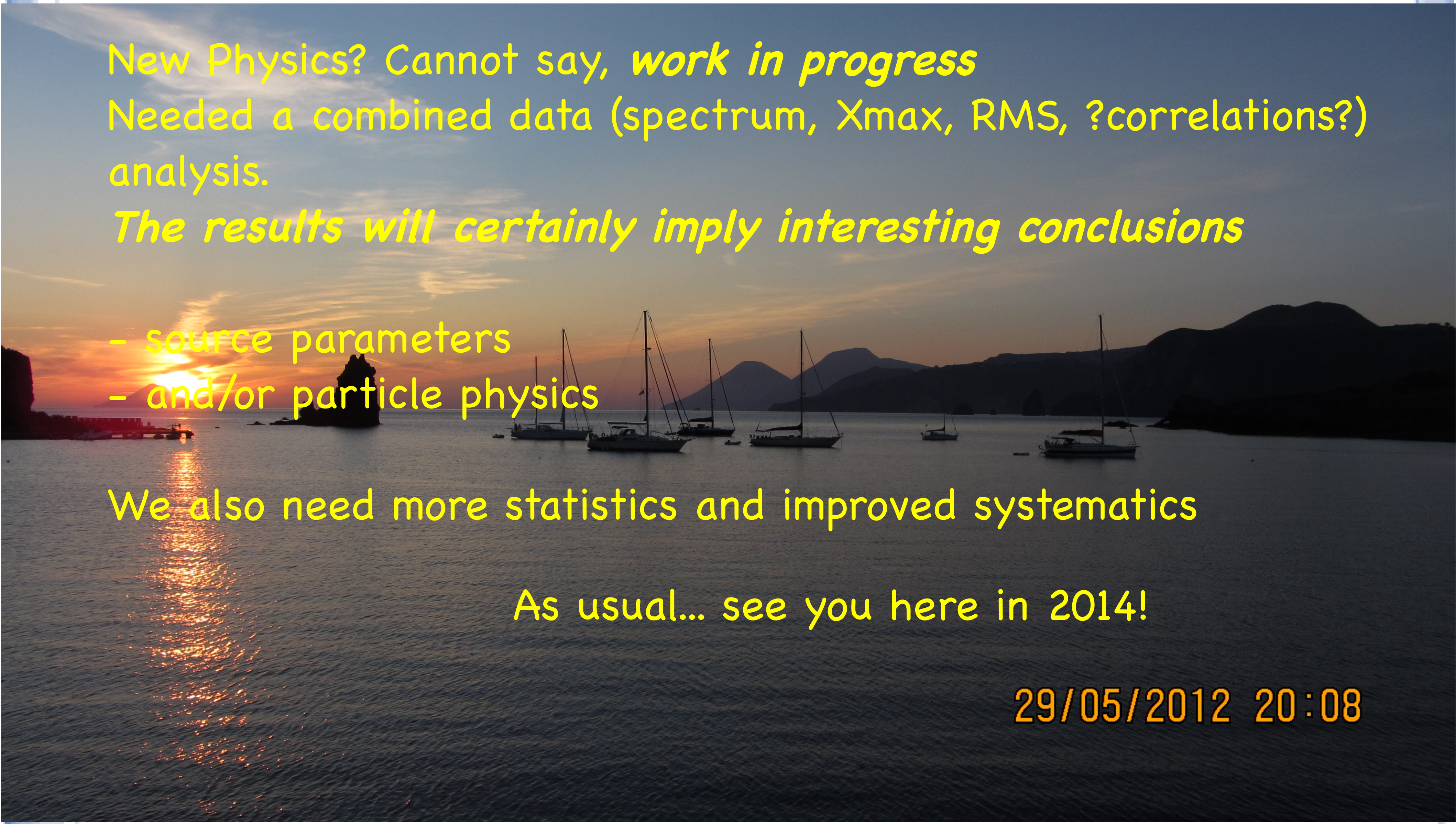
- source parameters
- and/or particle physics

We also need more statistics and improved systematics







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- and/or particle physics

We also need more statistics and improved systematics

As usual… see you here in 2014!

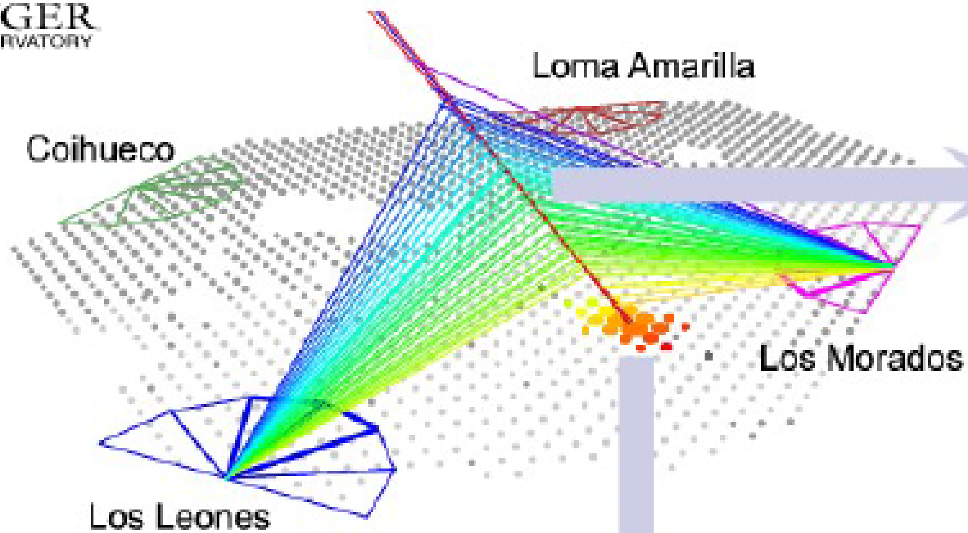
Backup

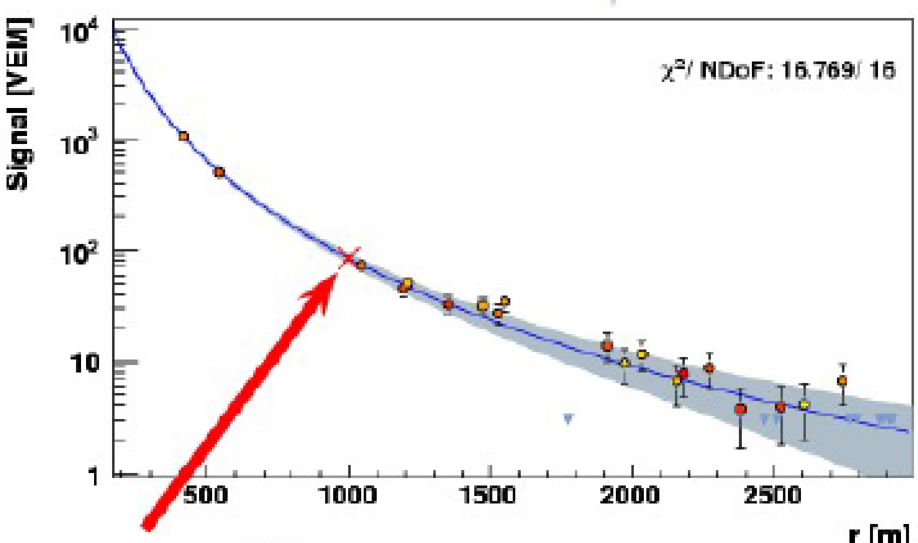
Draft version May 29, 2012
Preprint typeset using LaTeX style emulateapj v. 5/2/11

SEARCH FOR ANISOTROPY OF ULTRA-HIGH ENERGY COSMIC RAYS WITH THE TELESCOPE ARRAY EXPERIMENT

From the analysis presented, one concludes that there is no apparent deviation from isotropy in the present TA data. At high energies, this may be merely due to an insufficient number of events. However, if this tendency persists at several times larger statistics, it will be difficult to reconcile with the proton composition of UHECR

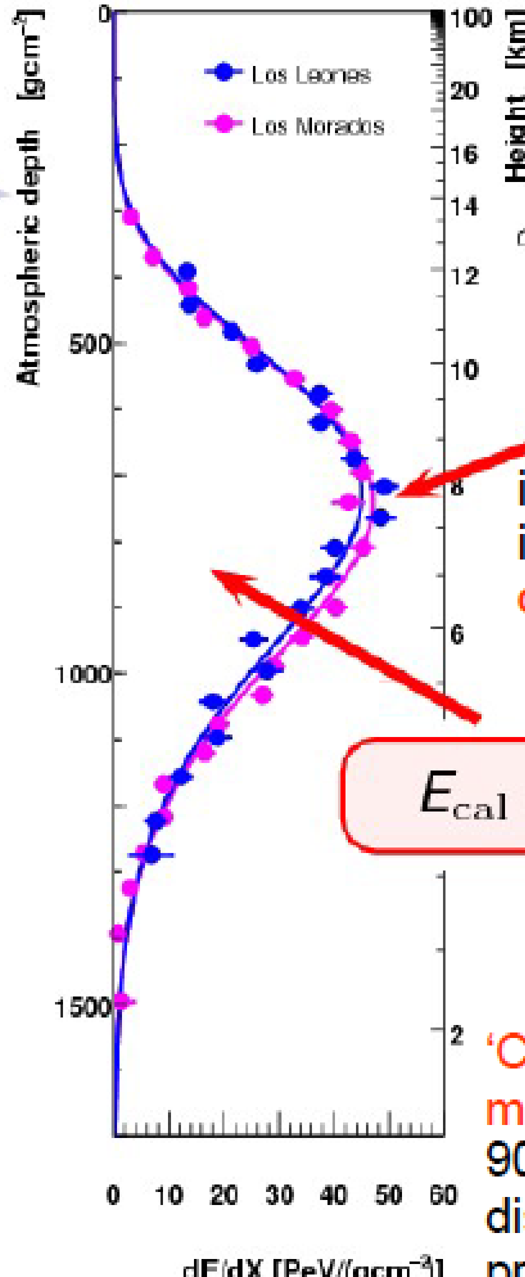
‘Hybrid’ detector





S_{1000}

Calibrated by FD



$\sigma_{X_{\rm max}} < 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \approx 15\,{\rm g/cm^2}$

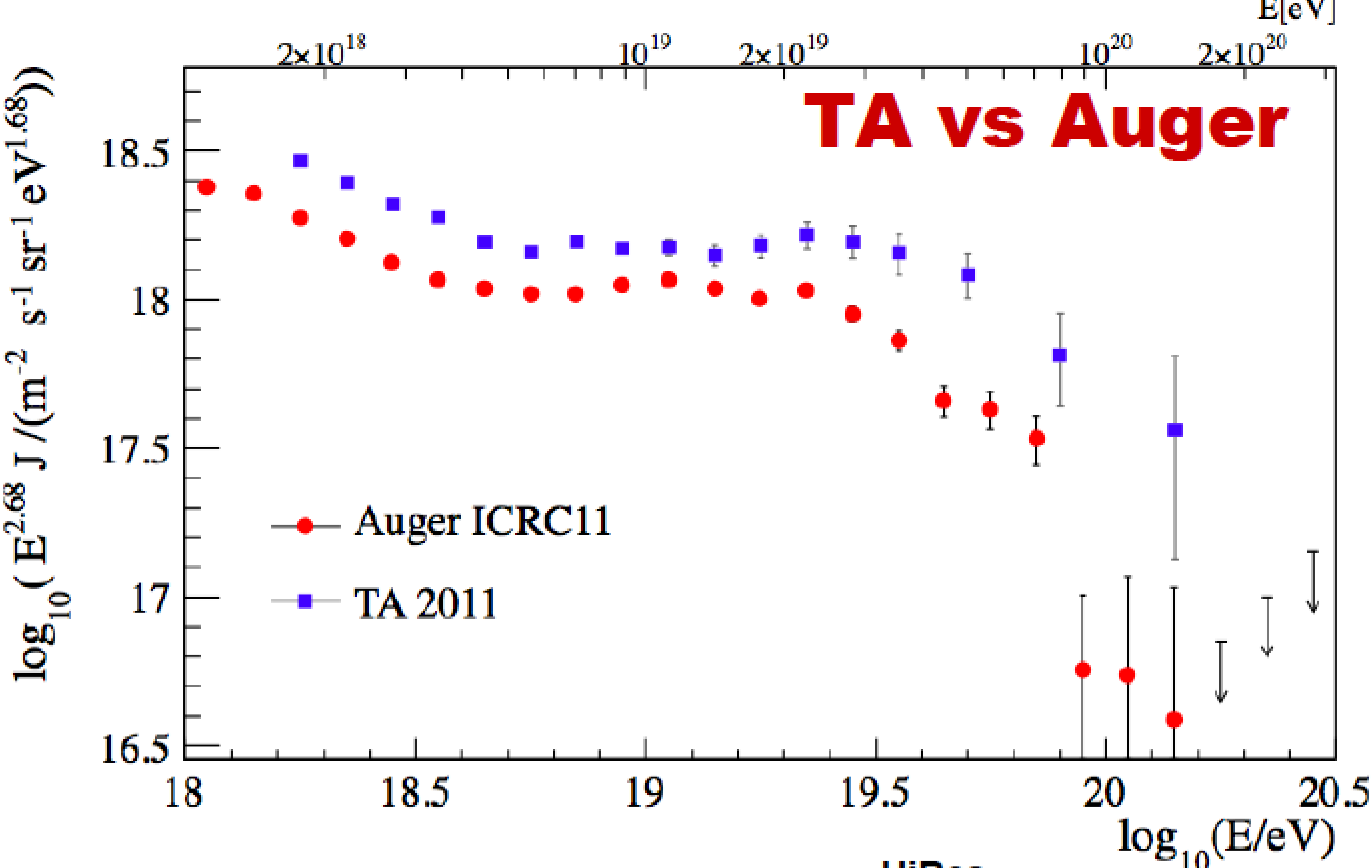
$X_{\rm max}$

its mean and r.m.s. is sensitive to composition

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

$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 22\,\%$

‘Calorimetric’ energy measurement,
90% of primary energy dissipated through e.m. processes
(Air 25 X_0 15λ)

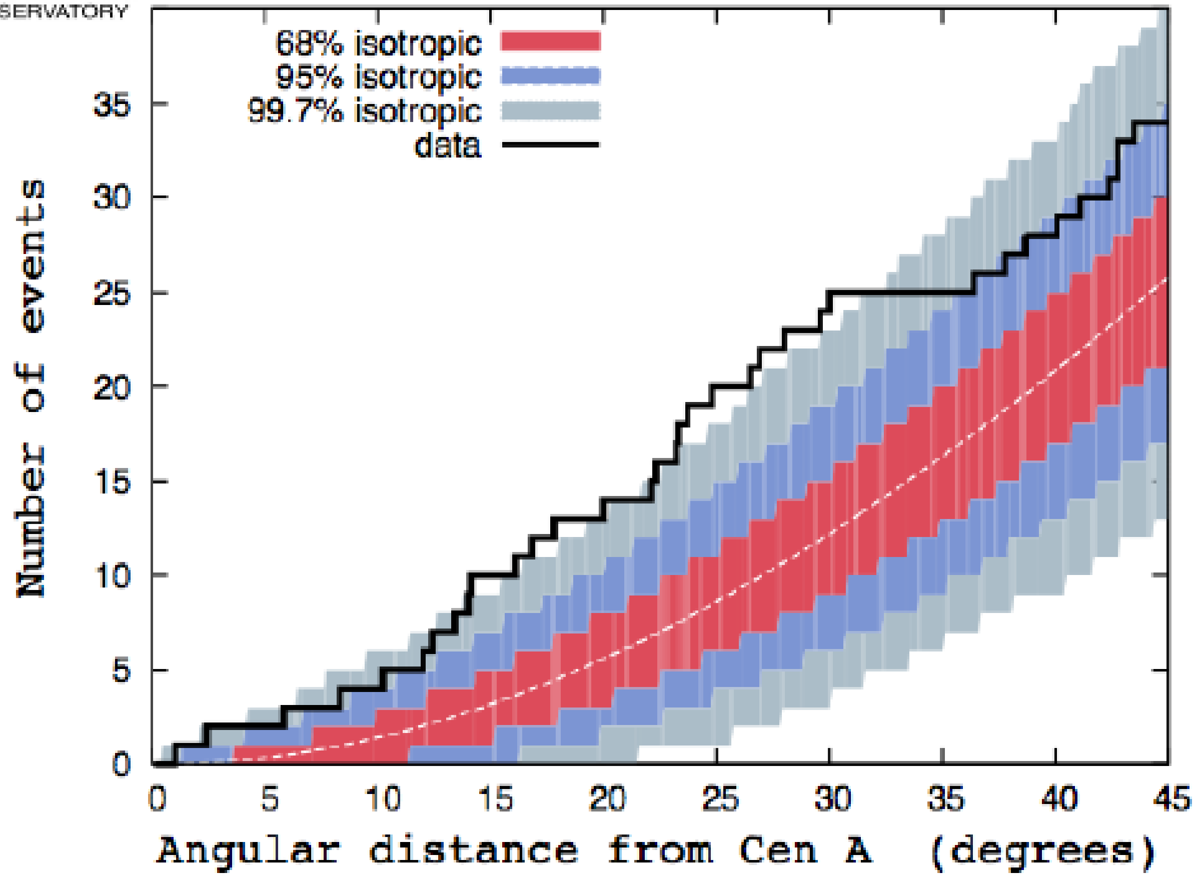


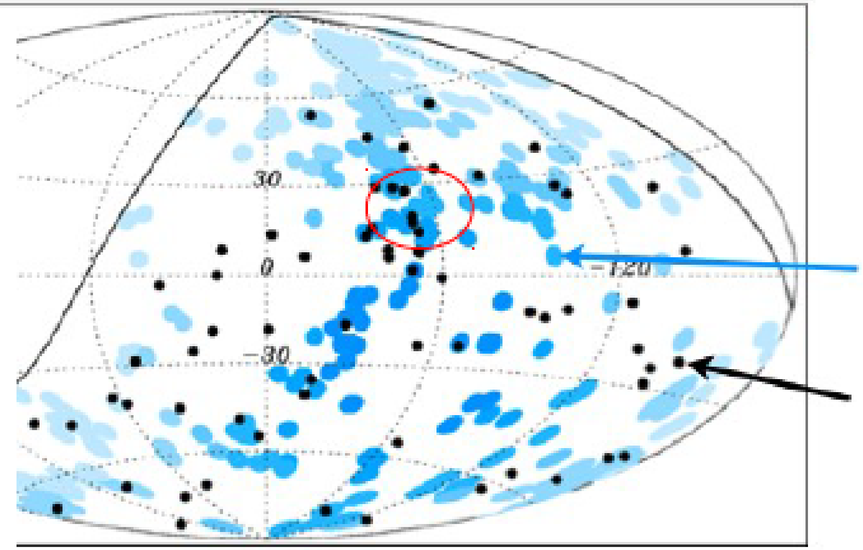
	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\mathrm{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\mathrm{eV})$	19.68 ± 0.09	19.41 ± 0.02

HiRes

Mono spectra	Stereo spectrum
-3.25 ± 0.01	-3.31 ± 0.11
-2.81 ± 0.03	-2.74 ± 0.05
-5.1 ± 0.7	-5.5 ± 1.8
18.65 ± 0.05	18.56 ± 0.06
19.75 ± 0.04	19.76 ± 0.11

CEN A?



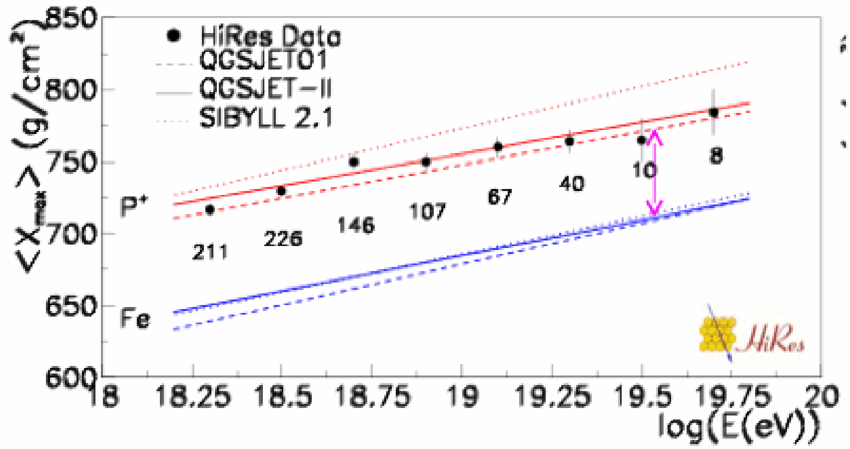


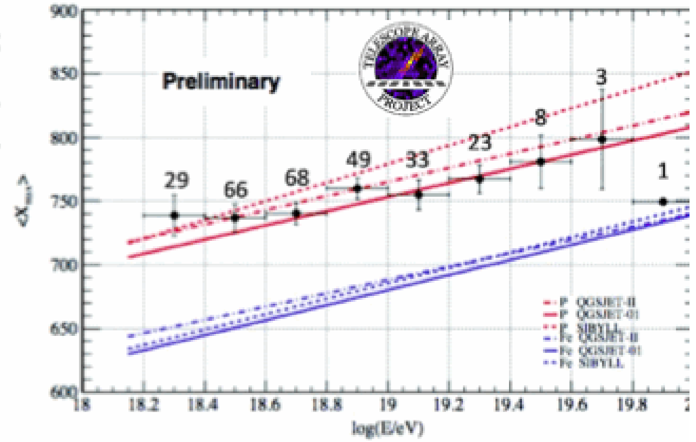
ICRC 2011

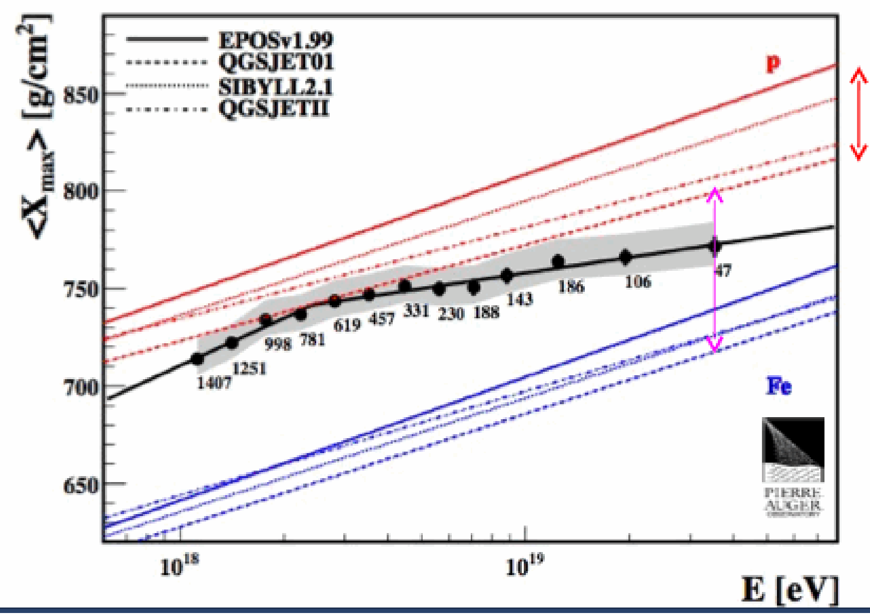
Closest radio-galaxy (3.8 Mpc)
in the southern emisphere

KS test yields 4% isotropic probability

UHECR Symposium, Feb. 2012







$<X_{max}>$

- Different analyses: X_{max} acceptance bias in data and model MC for HiRes and TA, no bias for Auger
- Auger presents evidence for a change in the slope
- Given limited statistics, no strong incompatibility

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Conclusions

•Are the differences due to issues in any of the analysis?

Apparently no.

• Are the differences within systematic uncertainties?

Auger and HiRes are not consistent within the **quoted** systematic uncertainties.

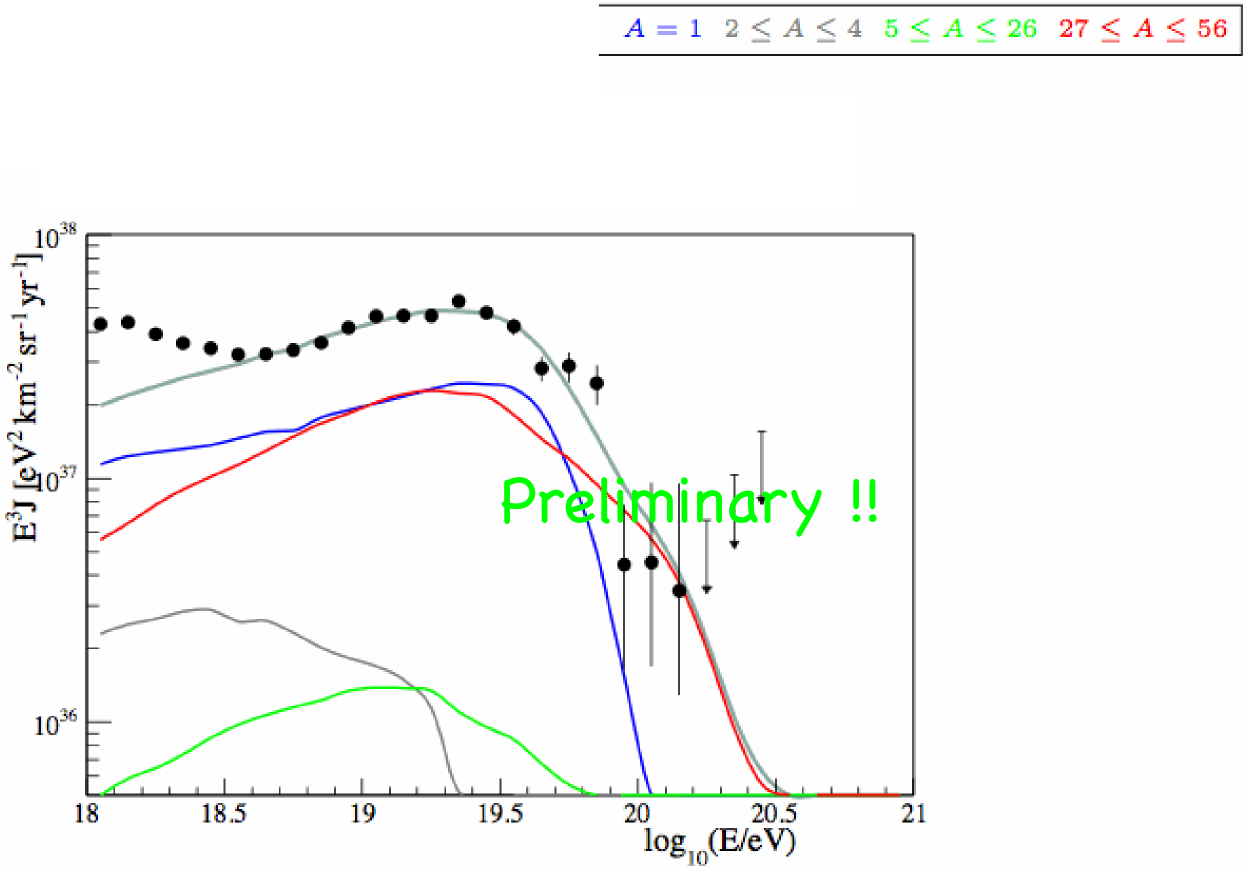
• Are the Southern and Northern sky different in terms of composition?

We need more statistics in the Northern hemisphere (about 4 times the current statistics) to give a conclusive answer. The current statistics in the northern hemisphere do not allow to discriminate between a constant composition or a changing composition as suggested by Auger. More statistics is also necessary to establish whether there is a systematic difference in the RMS(Xmax) at higher energies.

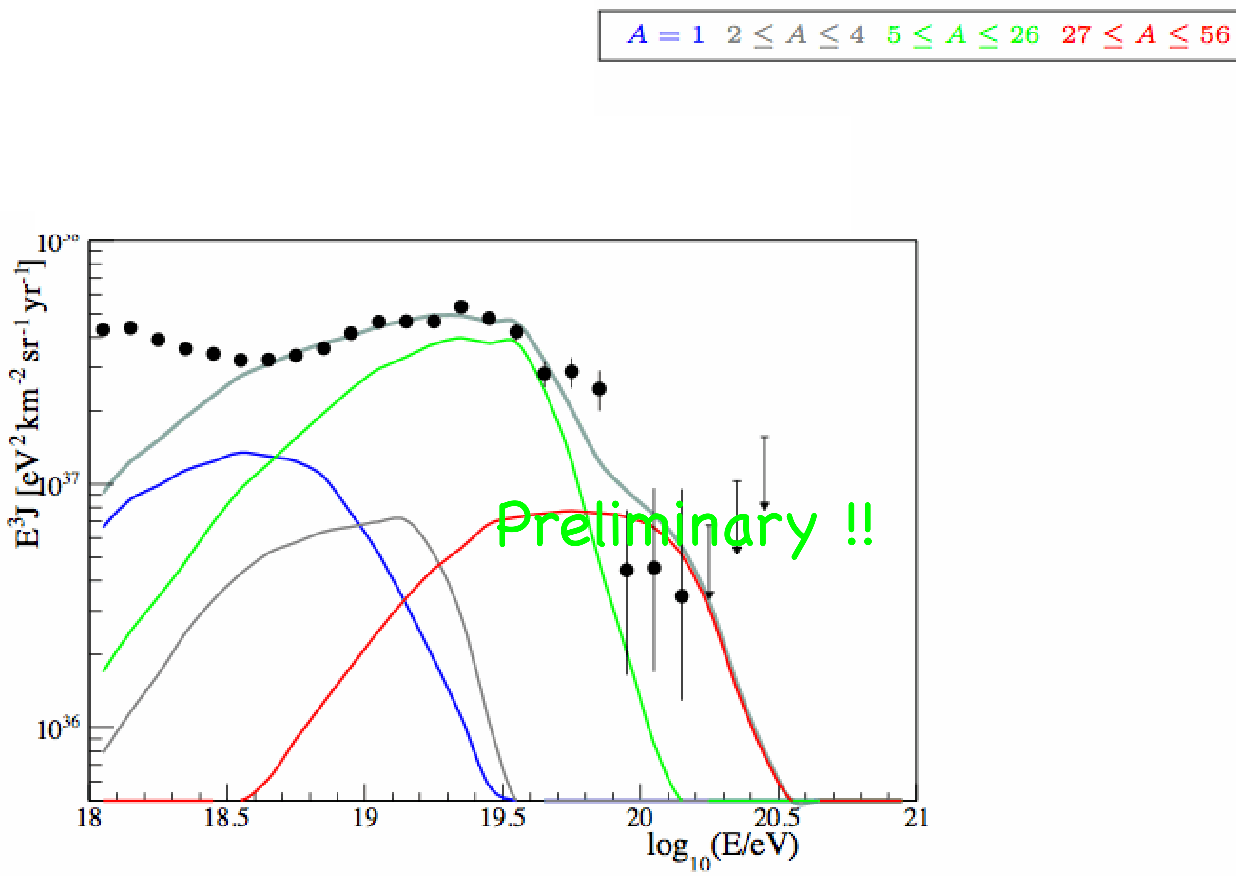
• It is interesting to point out that all three experiments (Yakutsk, HiRes and TA) are consistent (within ~5g/cm^2). But, there is a large systematic difference in <lnA> equivalent to about 30 g/cm^2 between Auger and the other experiments.

Photons: comparison of observables / techniqu

Experiment	Technique	Observables	Ref
Haverah Park	SD: water Cherenkov	attenuation of inclined showers	[2]
AGASA	SD: scintillator & muon	muon density	[3, 6]
Yakutsk	SD: scintillator & muon	muon density	[4, 5, 7]
Pierre Auger	SD: water Cherenkov	front curvature, rise time	[9]
	hybrid: fluorescence + SD	X_{max}, particle density far from the core	[8, 10]
Telescope Array	SD: scintillator	front curvature	[11]



$A=1$ $2 \leq A \leq 4$ $5 \leq A \leq 26$ $27 \leq A \leq 56$
10^{38}
10^{37}
10^{36}
E^3J [eV^2 km^{-2} sr^{-1} yr^{-1}]
18
18.5
19
19.5
20
20.5
21
$\log_{10}(E/eV)$
Preliminary !!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