

Highlights from the Pierre Auger Observatory: Composition and Anisotropy

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Solvay Workshop, SuGAR 2018, Brussels



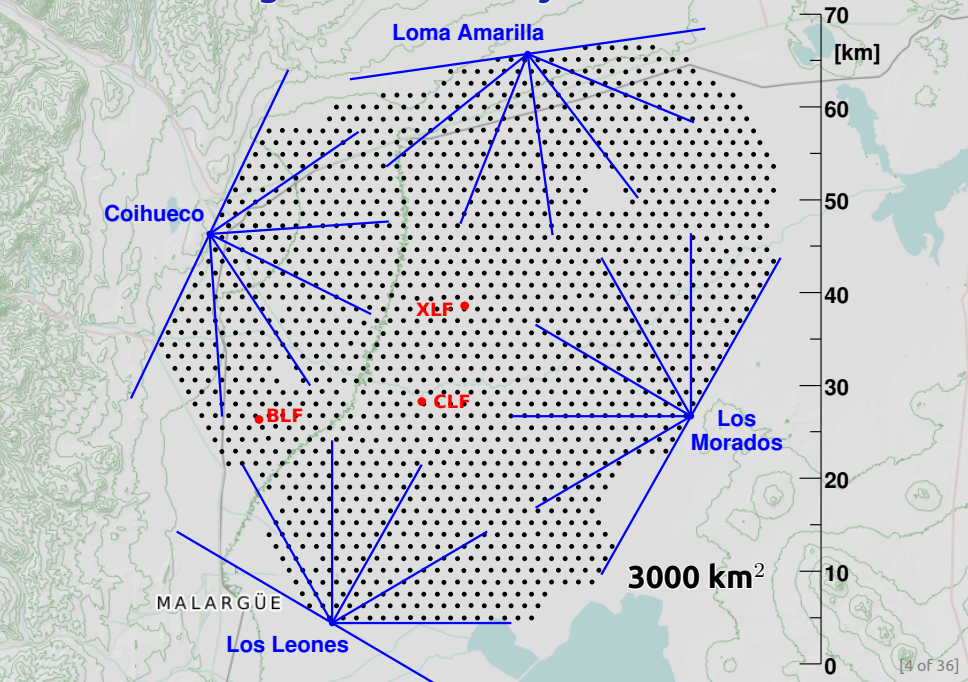
Introduction



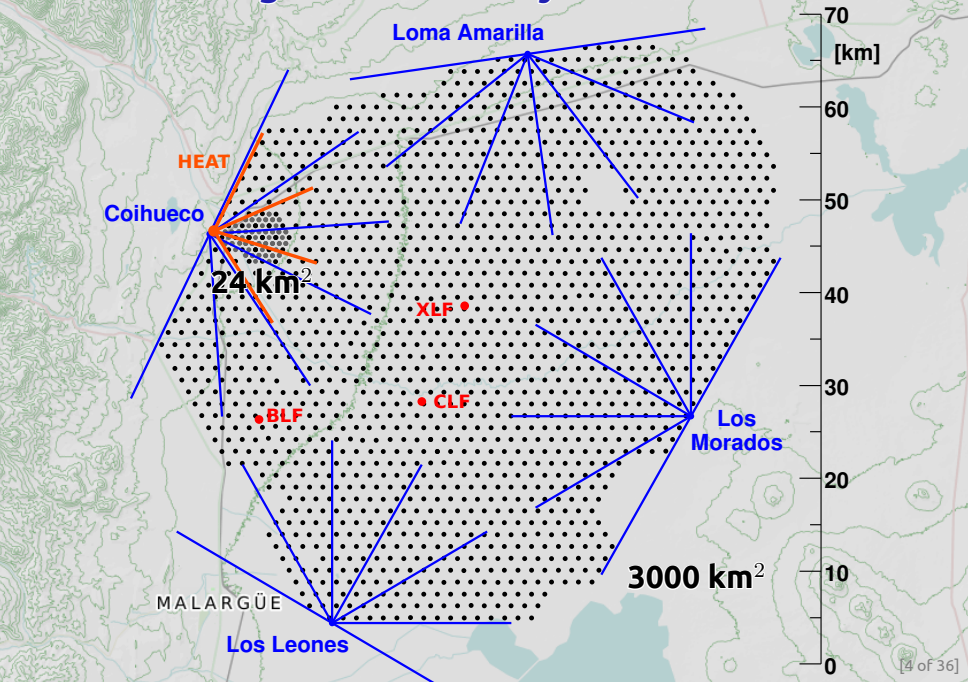
The Pierre Auger Observatory



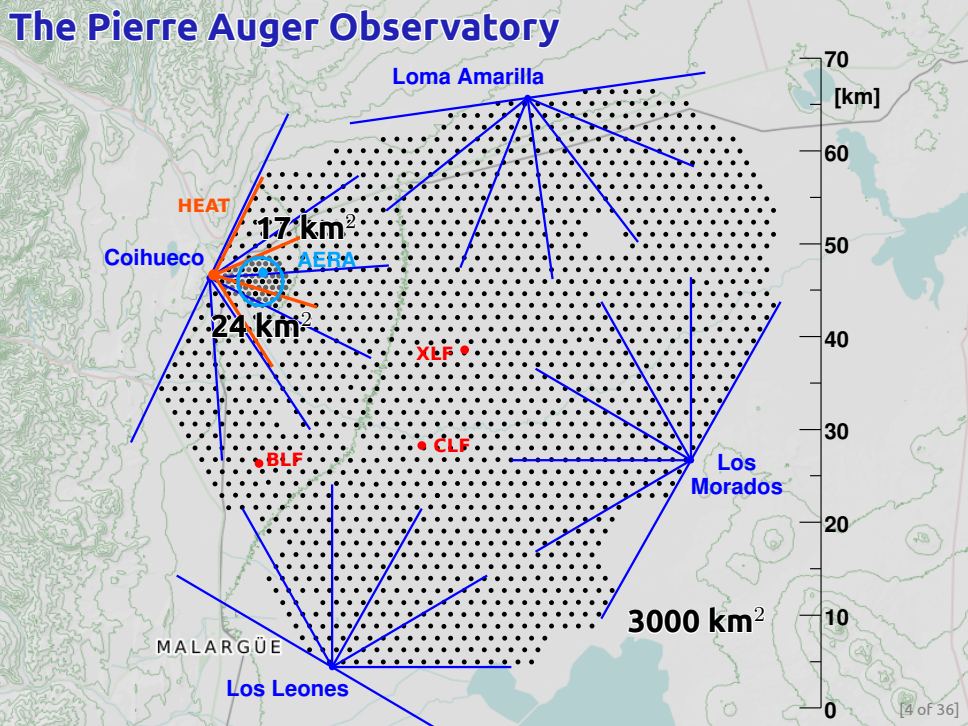
The Pierre Auger Observatory



The Pierre Auger Observatory



The Pierre Auger Observatory



UHE Exposure

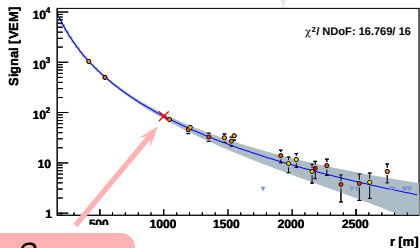
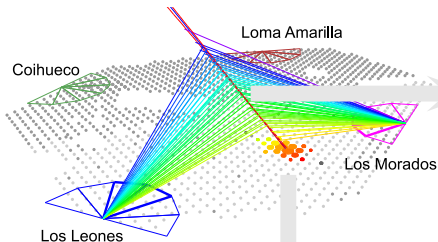
Auger Anisotropy ICRC17: $9.0 \times 10^4 \text{ km}^2 \text{ sr yr}$

Auger Spectrum ICRC17: $6.7 \times 10^4 \text{ km}^2 \text{ sr yr}$

TA Spectrum ICRC17:
 $0.8 \times 10^4 \text{ km}^2 \text{ sr yr}$

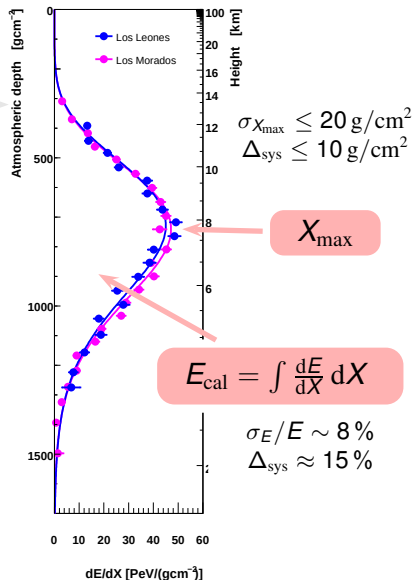
AGASA

Hybrid Detection of Air Showers

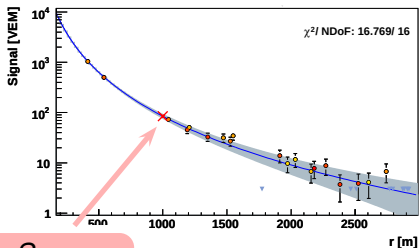
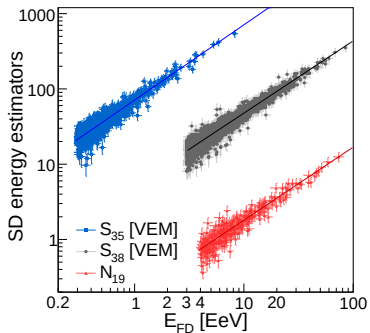


S_{1000}

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

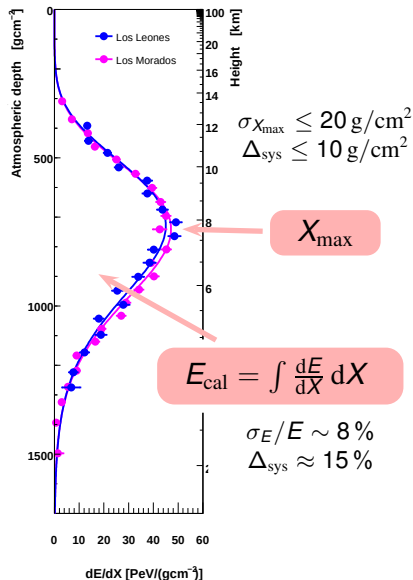


Energy Calibration

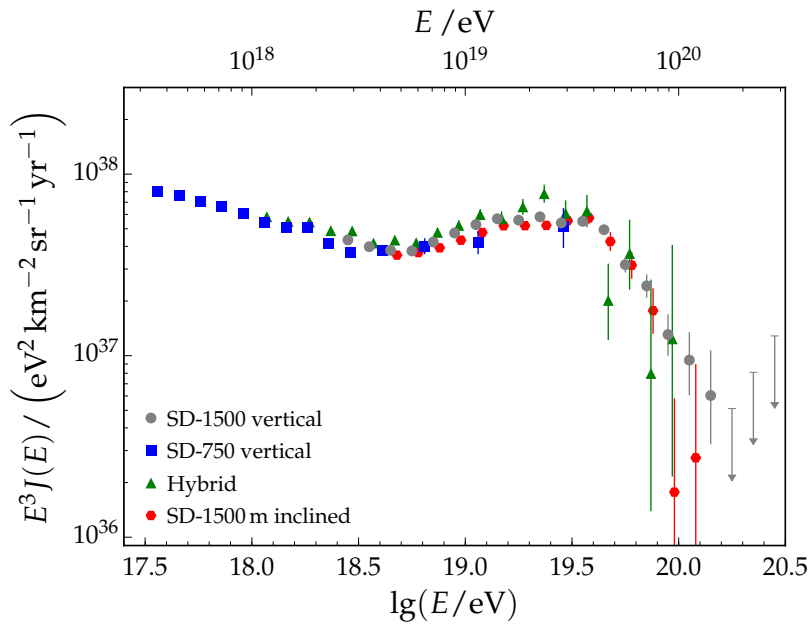


S_{1000}

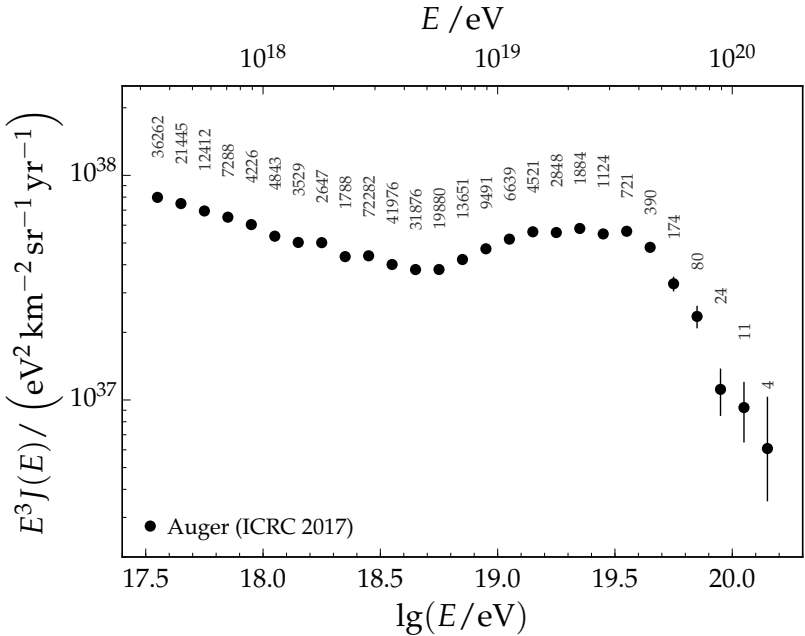
$$E_{\text{surface}} = f(S_{1000}, \theta)$$



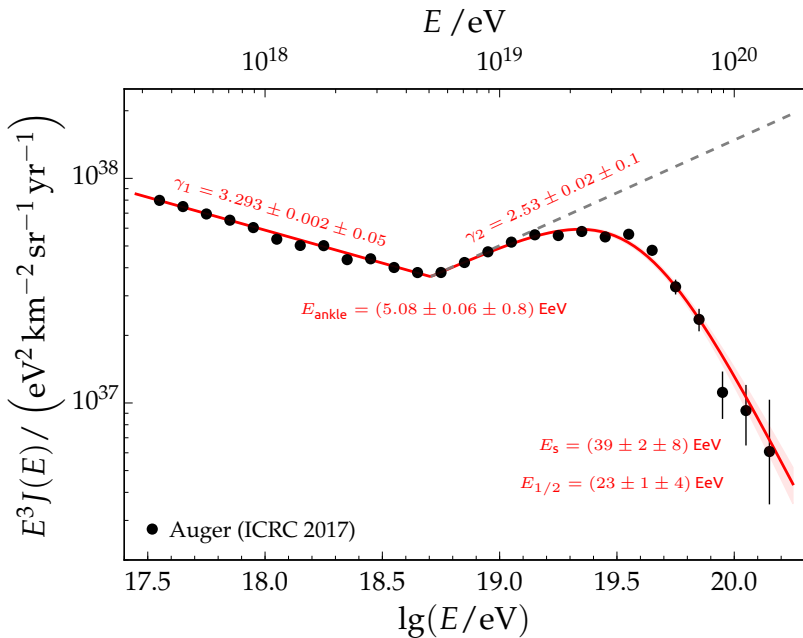
Energy Spectrum



Combined Energy Spectrum

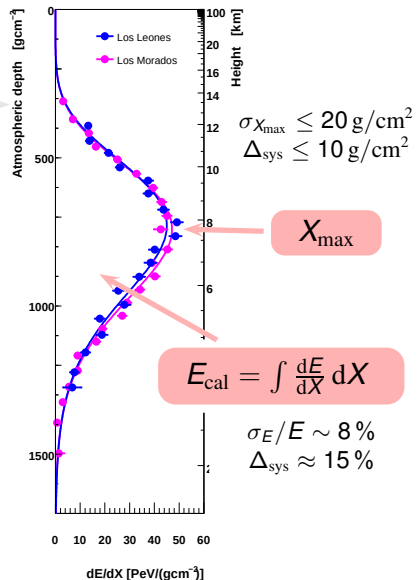
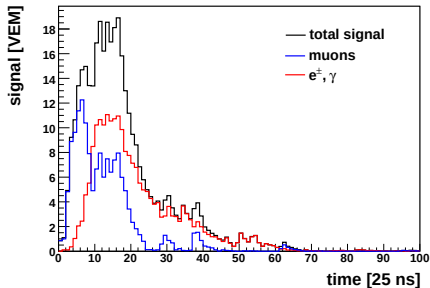
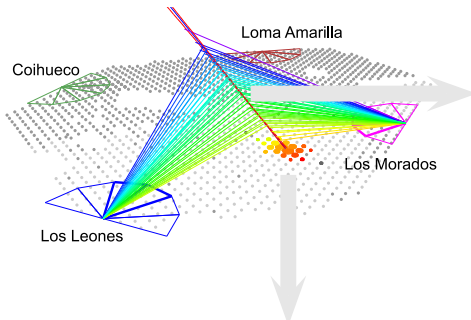


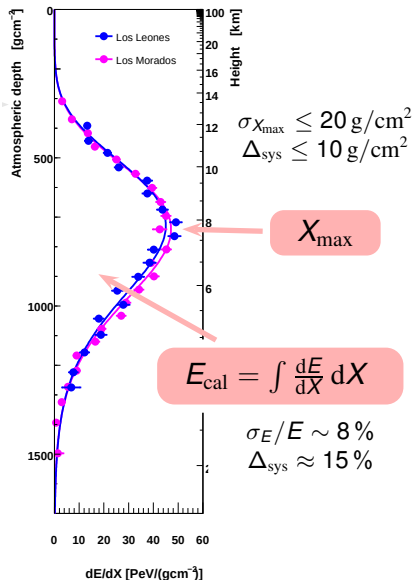
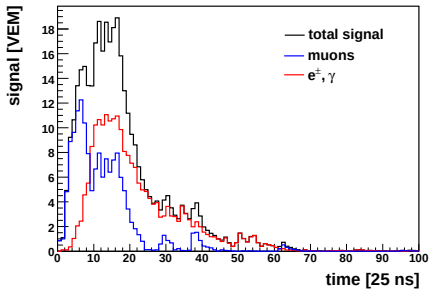
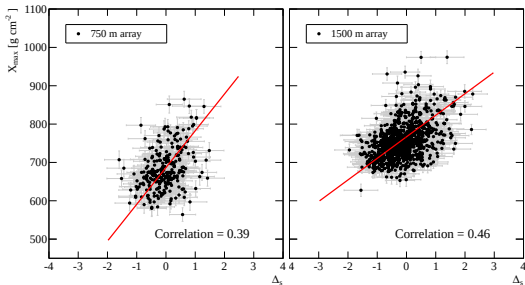
Combined Energy Spectrum



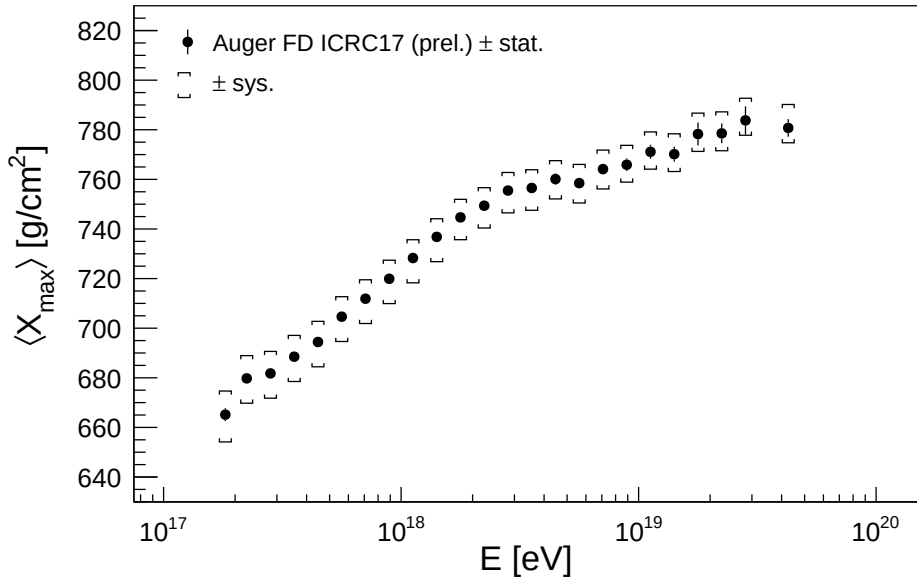
Mass Composition



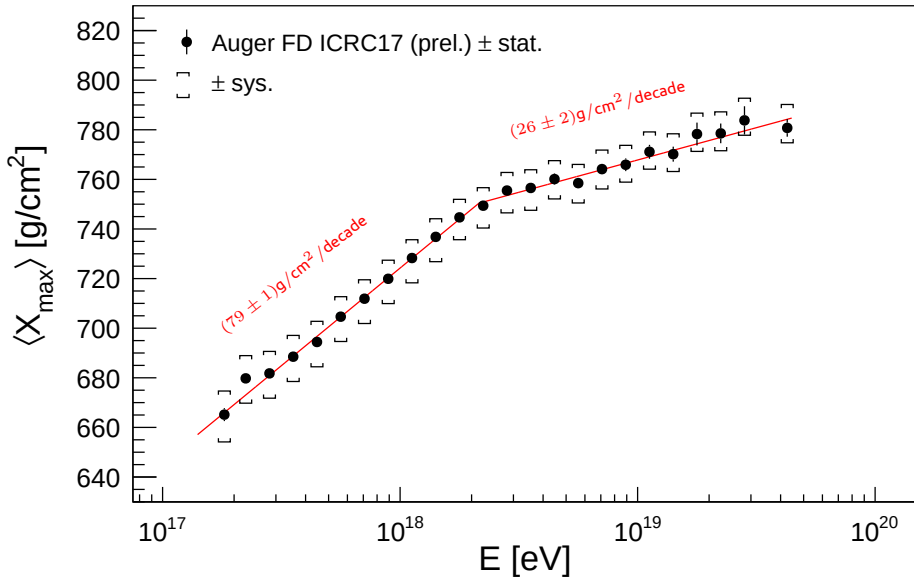




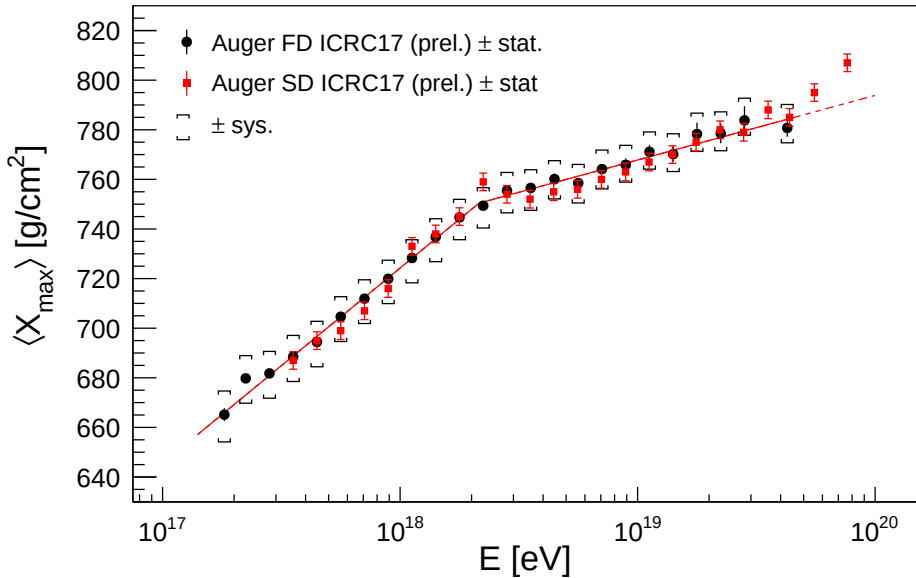
Average $X_{\max}$ Fluorescence Detector



Average $X_{\max}$ Fluorescence Detector

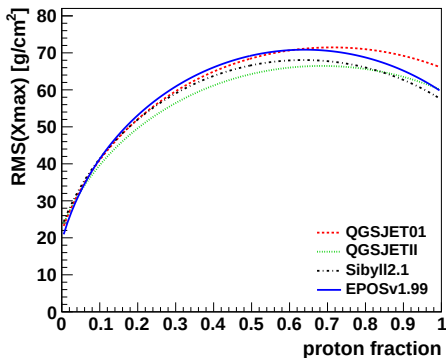
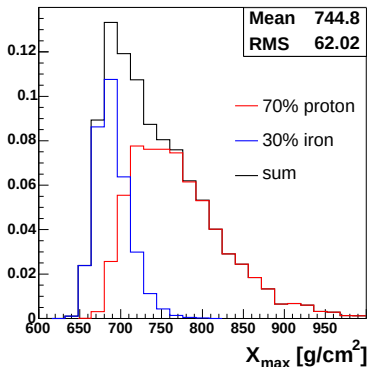


Average $X_{\max}$ Fluorescence and Surface Detector

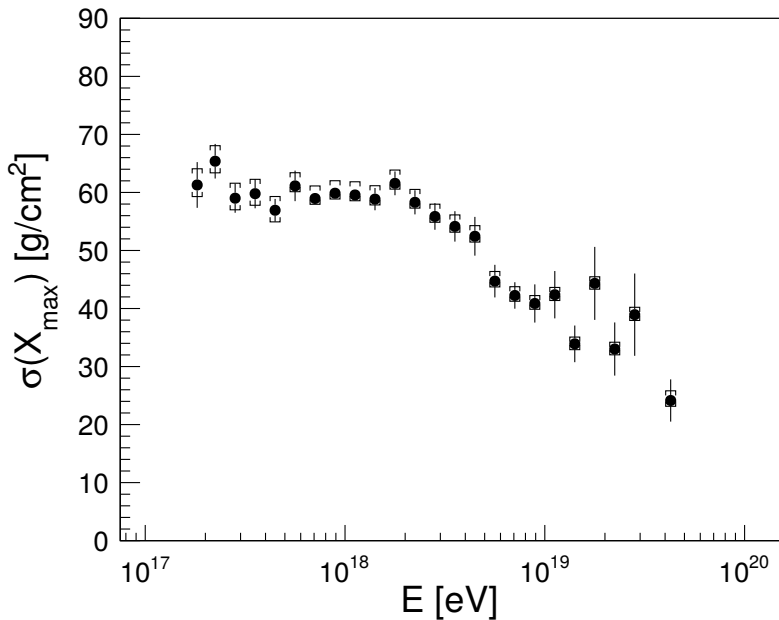


Standard Deviation of $X_{\max}$ Distribution

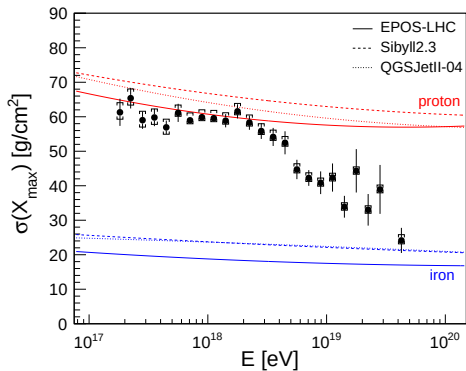
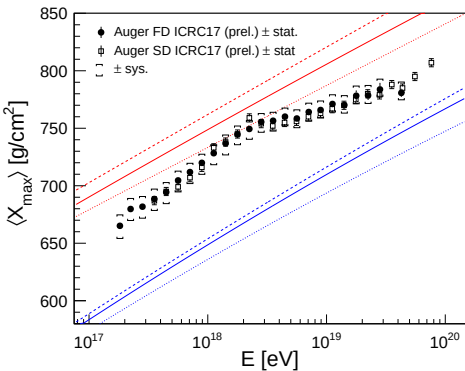
- ▶ $\sigma(X_{\max})_A^2 = \lambda_A^2 + \sigma(X_{\max} - X_{\text{first}})_A^2$
- ▶ $\sigma(X_{\max})_p > \sigma(X_{\max})_A > \sigma(X_{\max})_p / \sqrt{A}$
- ▶ mixed composition:
$$\sigma(X_{\max})^2 = \langle \sigma_i^2 \rangle + \left(\langle \langle X_{\max} \rangle_i^2 \rangle - \langle X_{\max} \rangle^2 \right)$$



Standard Deviation of $X_{\max}$ Distribution (FD)



$X_{\max}$ Moments vs. Air Shower Simulations

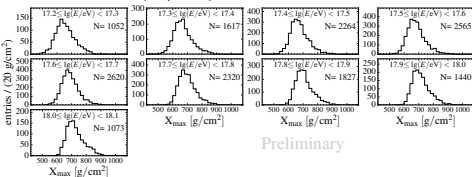


lines: air shower simulations using post-LHC hadronic interaction models

(p-He-N-Fe)-fit of $X_{\max}$ Distributions

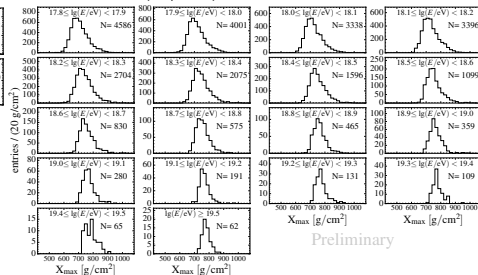
FD data:

$\lg(E/\text{eV}) = 17.2 \dots 18.1$



Preliminary

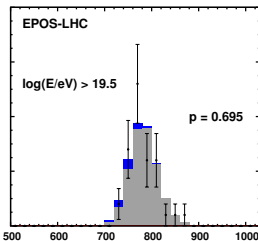
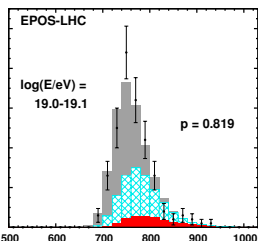
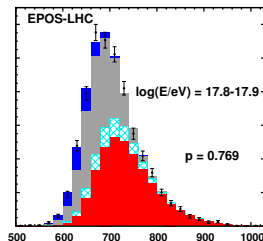
$\lg(E/\text{eV}) = 17.8 \dots > 19.5$



Preliminary

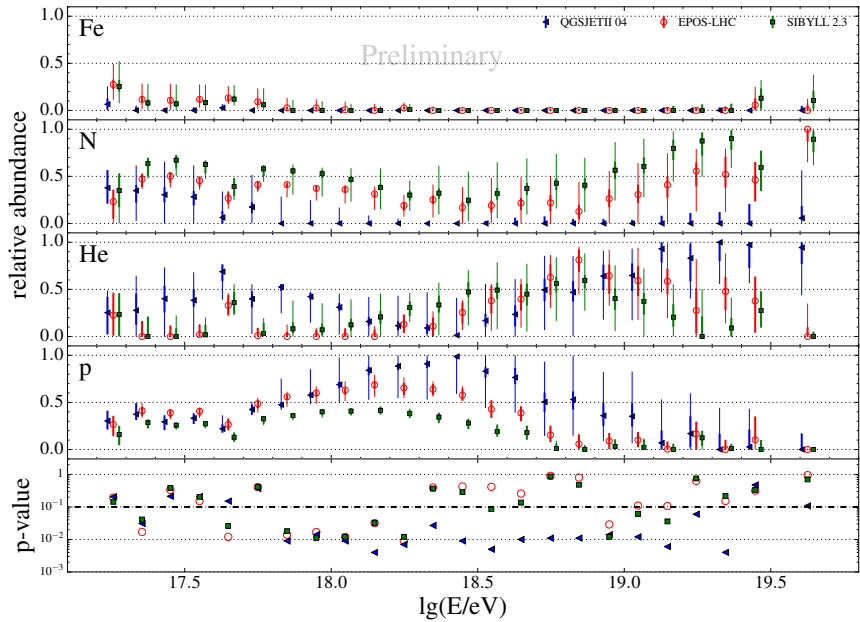
Examples of 4-component fit:

p He N Fe



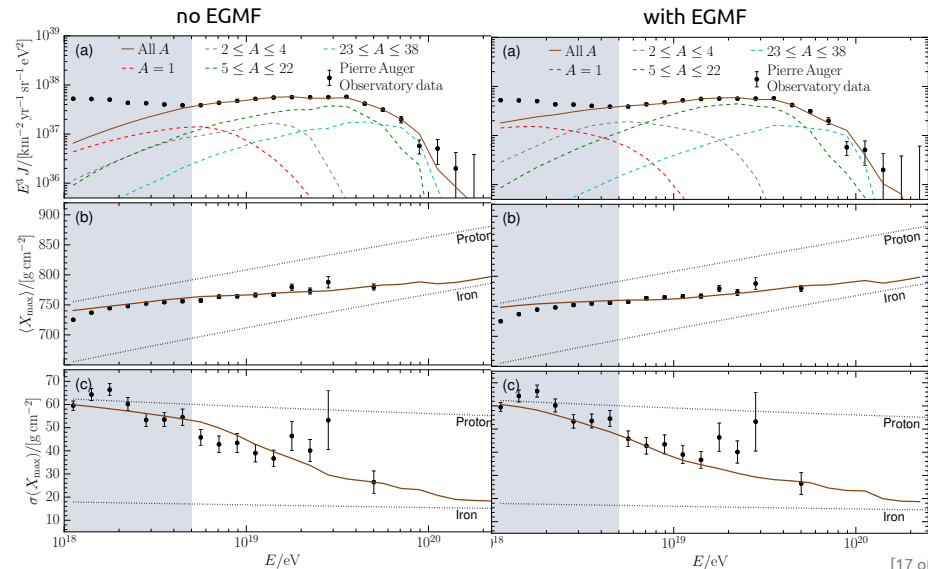
$X_{\max} [\text{g/cm}^2]$

Composition Fractions



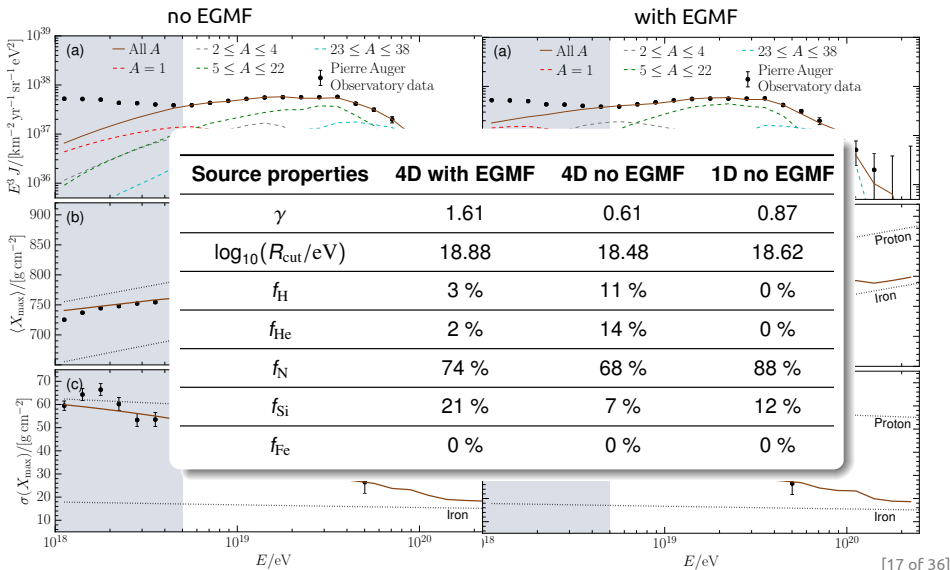
Combined Fit of Spectrum and $X_{\max}$ Distributions

rigidity-dependent cutoff at source: $E_{\max} = R_{\text{cut}} Z$, power law injection $E^{-\gamma}$,
propagation with CRPropa3, Gilmore12 EBL, Dolag12 LSS



Combined Fit of Spectrum and $X_{\max}$ Distributions

rigidity-dependent cutoff at source: $E_{\max} = R_{\text{cut}} Z$, power law injection $E^{-\gamma}$, propagation with CRPropa3, Gilmore12 EBL, Dolag12 LSS



Arrival Directions

- ▶ **Indication for Intermediate-scale Anisotropy**

accepted by ApJ. Lett., arXiv:1801.06160

- ▶ **Observation of Large-scale Anisotropy**

Science 357 (2017) 1266



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Search for Intermediate-scale Anisotropies

Analysis Strategy:

- ▶ arrival directions of data, D

- ▶ sky model from source candidates, M_i

$$M_i = (\text{flux model}) \times (\text{attenuation model}) \times (\text{angular smearing}) \times (\text{exposure})$$

- ▶ null hypothesis: isotropy M_0

- ▶ single population signal model:

$$M = (1 - \alpha) M_0 + \alpha M_i$$

- ▶ test statistics:

- ▶ ratio of likelihoods of model-data comparison

$$TS = 2 \log(P(D|M)/P(D|M_0))$$

think $\Delta\chi^2$ of (isotropy + signal) vs. isotropy

- ▶ p -value from Wilk's theorem: $p(TS) = p_{\chi^2}(TS, \Delta\text{ndf})$

- ▶ of large TS

- ▶ M describes D much better than M_0
 - ▶ M_0 excluded at p (**not**: M "proven" at p)

UHECR Source Suspects

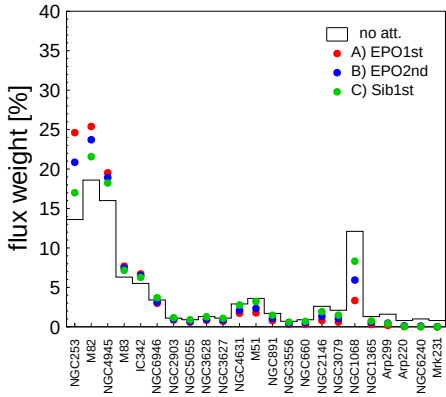


- ▶ *Swift*-BAT X-ray-selected galaxies, $D < 250$ Mpc, $\Phi > 1.3 \cdot 10^{-11} \frac{\text{erg}}{\text{cm}^2 \text{s}}$, w : 14-195 keV
- ▶ 2MRS IR-selected galaxies, $D > 1$ Mpc, w : K-band
- ▶ SBG: 23 nearby starburst galaxies, $\Phi > 0.3$ Jy, w : radio at 1.4 GHz
- ▶ γ AGN: 17 2FHL blazars and radio galaxies, $D < 250$ Mpc, w : γ -ray 50 GeV-2 TeV.

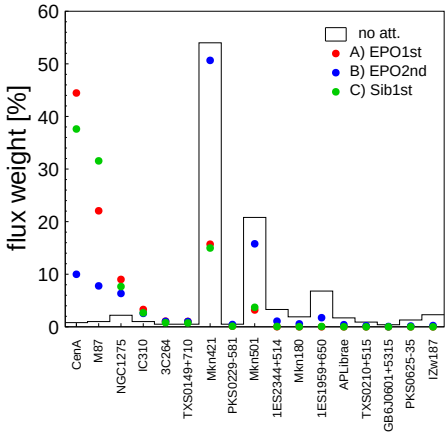
w : UHECR flux proxy, *Swift*-BAT and 2MRS previously tested (ApJ **804** (2015) 172), extragal. γ -ray sources γ AGN and SBG.

Flux Attenuation (top: SBG, bottom: γ AGN)

starburst



γ AGN

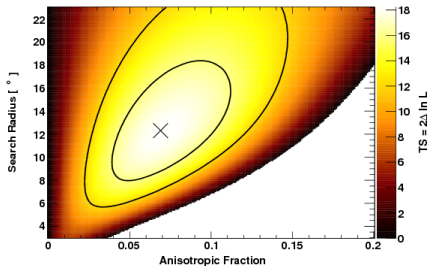


composition scenarios from Pierre Auger Coll., JCAP **1704** (2017) 038 + CRPropa3

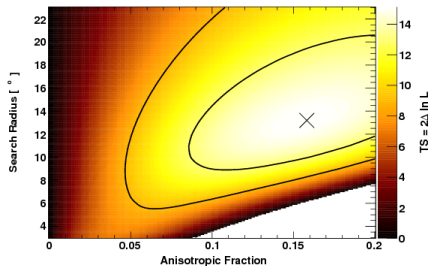
name	$\lg(R_{\max}/V)$	f_p	f_{He}	f_N	f_{Si}	γ
EPO1st	18.68	0.000	0.673	0.281	0.046	0.96
EPO2nd	19.88	0.000	0.000	0.798	0.202	2.04
Sib1st	18.28	0.702	0.295	0.003	0.000	-1.50

Optimization: Signal Fraction and Angular Smearing

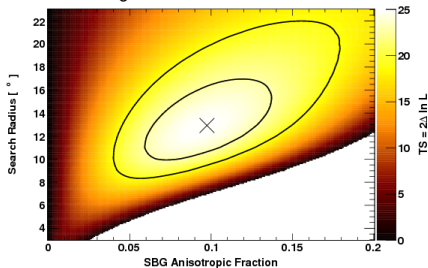
Swift-BAT - $E > 39$ EeV - Sc. A



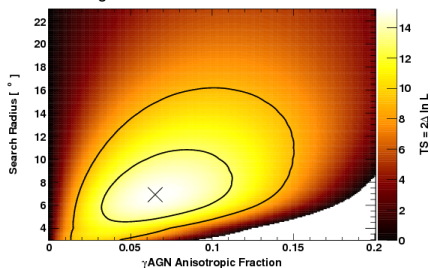
2MRS > 1 Mpc - $E > 38$ EeV - Sc. A



Starburst galaxies - $E > 39$ EeV - Sc. A

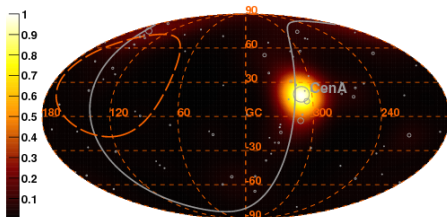


Active galactic nuclei - $E > 60$ EeV - Sc. A

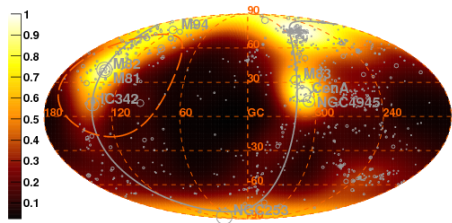


Sky Model $(\text{flux}) \times (\text{attenuation model})_A \times (\text{angular smearing}), \text{ gal. coord.}$

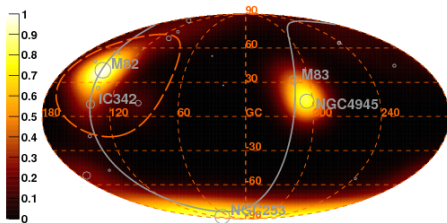
Model Flux Map - *Swift*-BAT - $E > 39 \text{ EeV}$ - Sc. A



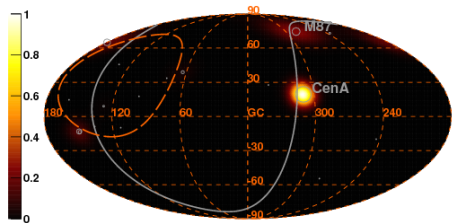
Model Flux Map - 2MRS $> 1 \text{ Mpc}$ - $E > 38 \text{ EeV}$ - Sc. A



Model Flux Map - Starburst galaxies - $E > 39 \text{ EeV}$ - Sc. A

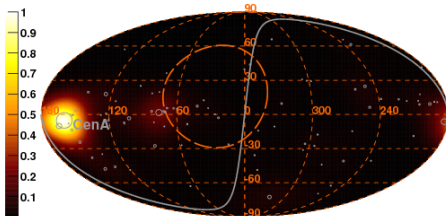


Model Flux Map - Active galactic nuclei - $E > 60 \text{ EeV}$ - Sc. A

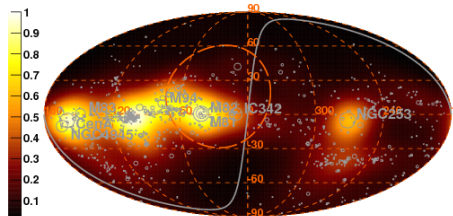


Sky Model $(\text{flux}) \times (\text{attenuation model})_A \times (\text{angular smearing}), \text{ super-gal. coord.}$

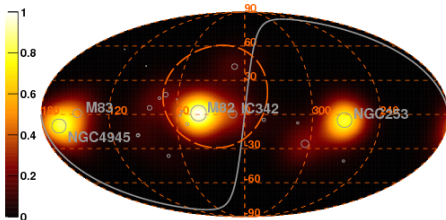
Model Flux Map - *Swift*-BAT - $E > 39 \text{ EeV}$ - Sc. A



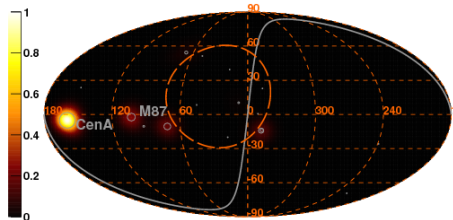
Model Flux Map - 2MRS $> 1 \text{ Mpc}$ - $E > 38 \text{ EeV}$ - Sc. A



Model Flux Map - Starburst galaxies - $E > 39 \text{ EeV}$ - Sc. A

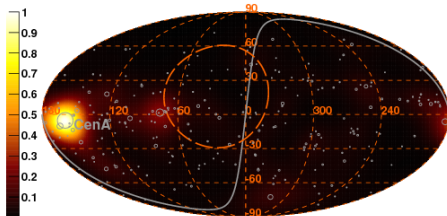


Model Flux Map - Active galactic nuclei - $E > 60 \text{ EeV}$ - Sc. A

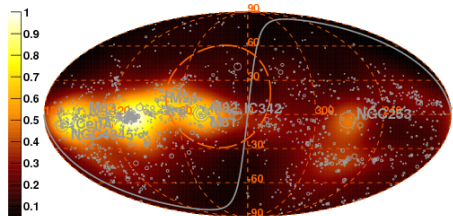


Sky Model $(\text{flux}) \times (\text{attenuation model})_{\text{B}} \times (\text{angular smearing}), \text{ super-gal. coord.}$

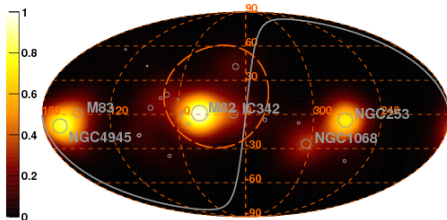
Model Flux Map - *Swift*-BAT - $E > 39 \text{ EeV}$ - Sc. B



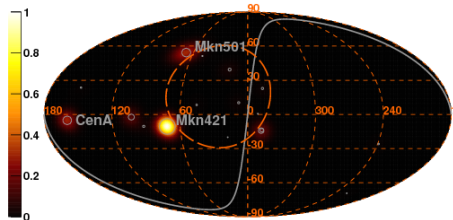
Model Flux Map - 2MRS $> 1 \text{ Mpc}$ - $E > 38 \text{ EeV}$ - Sc. B



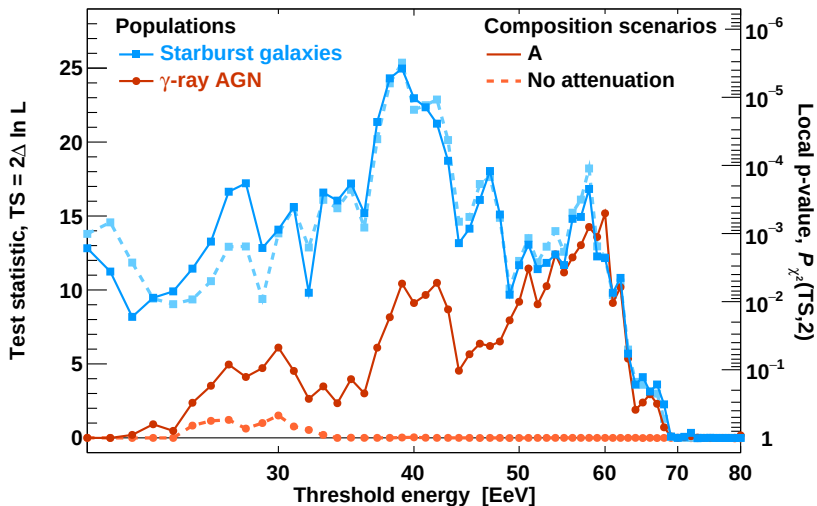
Model Flux Map - Starburst galaxies - $E > 39 \text{ EeV}$ - Sc. B



Model Flux Map - Active galactic nuclei - $E > 60 \text{ EeV}$ - Sc. B



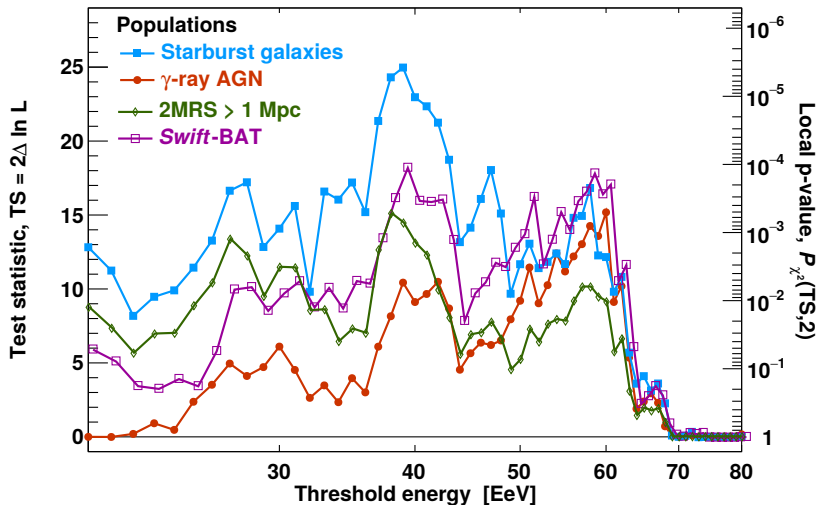
Test Statistics vs. Energy



starburst model fits data better than isotropy, significance of $4\sigma^*$.

* $P_{\chi^2}(TS, 2)$ penalized for energy scan

Test Statistics vs. Energy



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* $P_{\chi^2}(TS, 2)$ penalized for energy scan

Detailed View of Sky Models

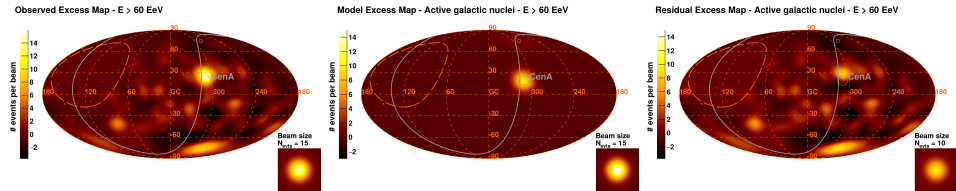
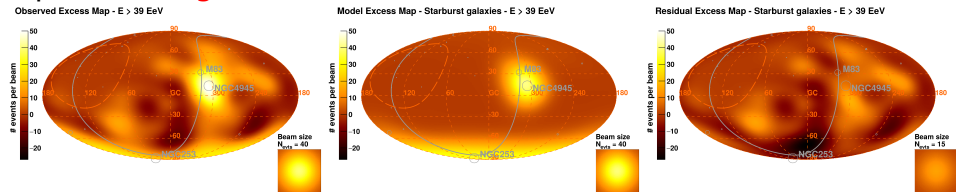
Test hypothesis	Null hypothesis	Threshold energy ^a	TS	Local p-value $\mathcal{P}_{\chi^2}(\text{TS}, 2)$	Post-trial p-value	1-sided significance	AGN/other fraction	SBG fraction	Search radius
SBG + ISO	ISO	39 EeV	24.9	3.8×10^{-6}	3.6×10^{-5}	4.0σ	N/A	9.7 %	12.9 °
γ AGN + SBG + ISO	γ AGN + ISO	39 EeV	14.7	N/A	1.3×10^{-4}	3.7σ	0.7 %	8.7 %	12.5 °
γ AGN + ISO	ISO	60 EeV	15.2	5.1×10^{-4}	3.1×10^{-3}	2.7σ	6.7 %	N/A	6.9 °
γ AGN + SBG + ISO	SBG + ISO	60 EeV	3.0	N/A	0.08	1.4σ	6.8 %	0.0 % ^b	7.0 °
<i>Swift</i> -BAT + ISO	ISO	39 EeV	18.2	1.1×10^{-4}	8.0×10^{-4}	3.2σ	6.9 %	N/A	12.3 °
<i>Swift</i> -BAT + SBG + ISO	<i>Swift</i> -BAT + ISO	39 EeV	7.8	N/A	5.1×10^{-3}	2.6σ	2.8 %	7.1 %	12.6 °
2MRS + ISO	ISO	38 EeV	15.1	5.2×10^{-4}	3.3×10^{-3}	2.7σ	15.8 %	N/A	13.2 °
2MRS + SBG + ISO	2MRS + ISO	39 EeV	10.4	N/A	1.3×10^{-3}	3.0σ	1.1 %	8.9 %	12.6 °

^aFor composite model studies, no scan over the threshold energy is performed.

^bMaximum TS reached at the boundary of the parameter space.
ISO: isotropic model.

Data vs. Model, SBG and γ AGN (gal. coord.)

top: starburst galaxies



bottom: γ AGN

Arrival Directions

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accepted by ApJ. Lett., arXiv:1801.06160

- **Observation of Large-scale Anisotropy**

Science 357 (2017) 1266

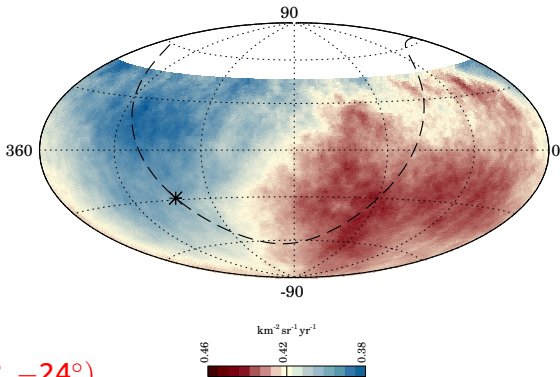
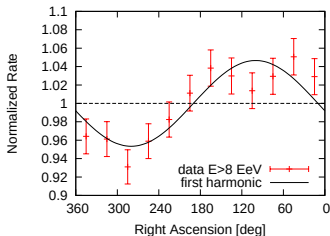


Observation of Dipolar anisotropy above 8 EeV

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}

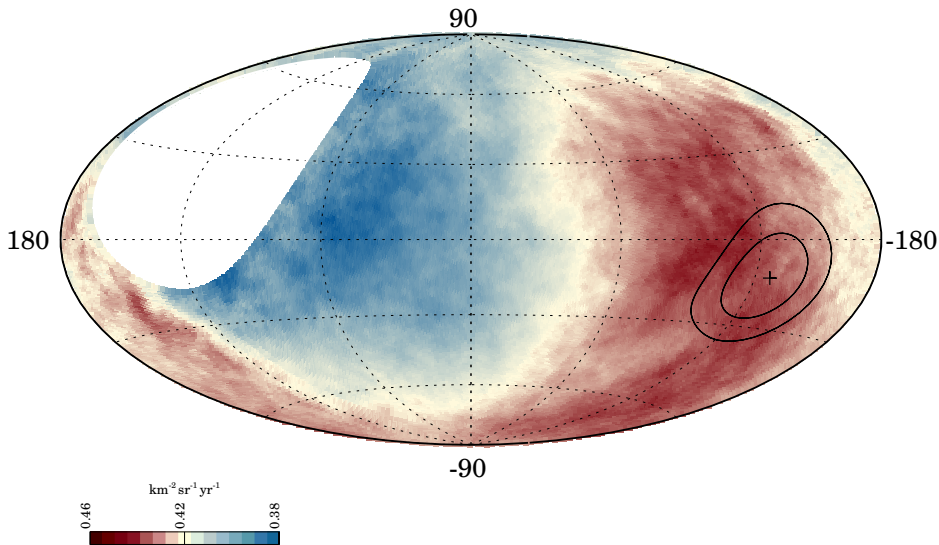
significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)



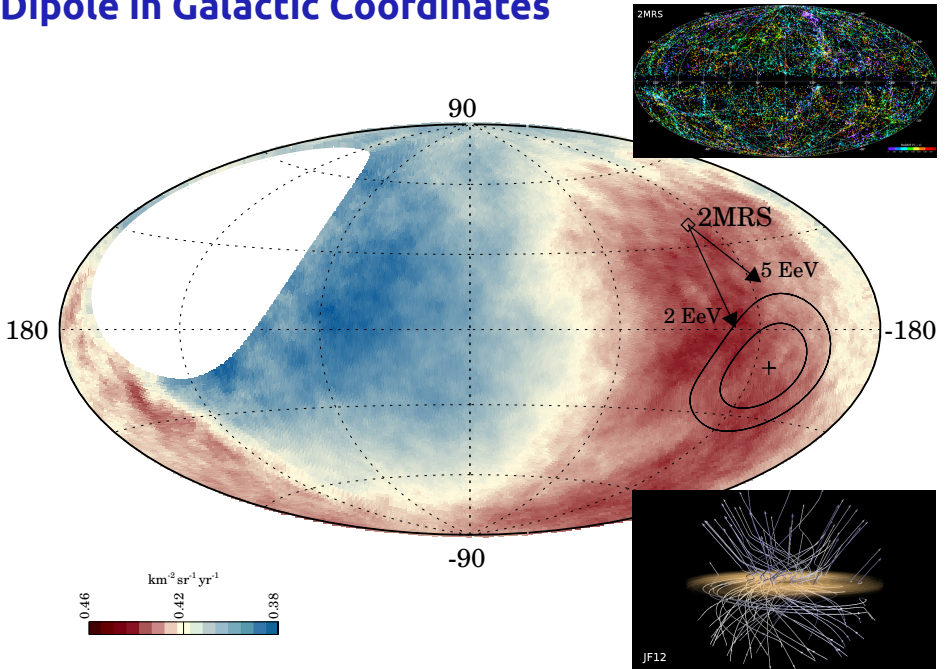
3-d dipole above 8 EeV:

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

Dipole in Galactic Coordinates



Dipole in Galactic Coordinates



Summary and Outlook



Results

spectrum, composition, secondaries:

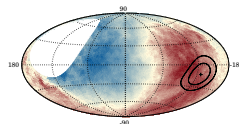
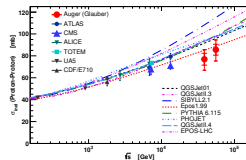
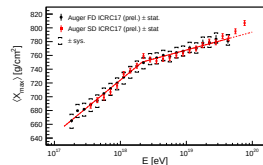
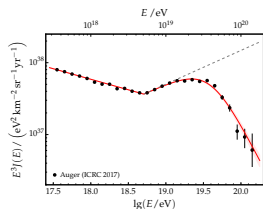
- ▶ high-exposure study of UHE flux
→ strong flux suppression
- ▶ FD/SD composition studies
→ light composition at ankle
→ mixed composition at UHE
→ Galactic Fe around $10^{17.2}$ eV?
- ▶ constraints on p-dominated sources via ν/γ
- ▶ compatible with rigidity-dependent $E_{\max}$

hadronic interactions:

- ▶ standard UHE cross section
- ▶ muon deficit in models

arrival directions:

- ▶ indication for intermediate-scale anisotropy
- ▶ observation of dipolar anisotropy



Open Questions

- ▶ Origin of the flux suppression?
- ▶ Proton fraction at UHE?
- ▶ Rigidity-dependence of anisotropies?
- ▶ Hadronic physics above $\sqrt{s} = 140$ TeV?

need large-exposure detector with
composition sensitivity!

arXiv:1604.03637v1 [astro-ph.IM] 13 Apr 2016

The Pierre Auger Observatory Upgrade "AugerPrime"

Preliminary Design Report



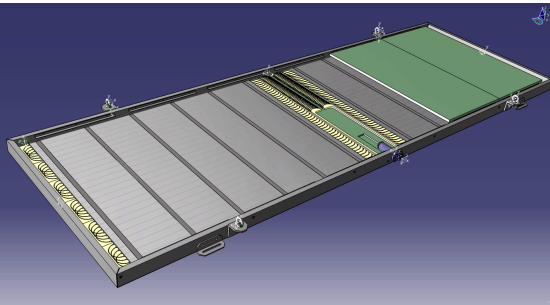
The Pierre Auger Collaboration
April, 2015



Observatorio Pierre Auger,
Av. San Martín Norte 304,
5613 Malargüe, Argentina

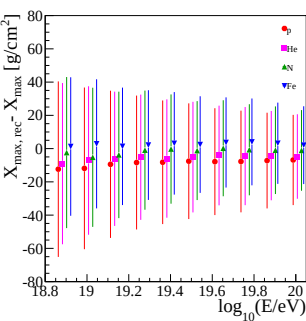
Detector Upgrades for AugerPrime

- ▶ 3.8 m² scintillators (SSD) on each 1500-m array station
- ▶ upgrade of station electronics
- ▶ additional small PMT to increase dynamic range
- ▶ buried muon counters in 750-m array (AMIGA)
- ▶ increased FD uptime

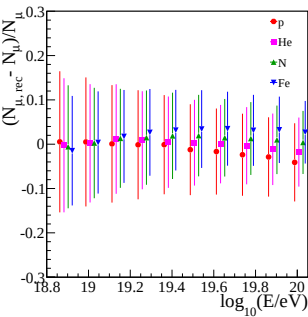


Expected Performance of AugerPrime

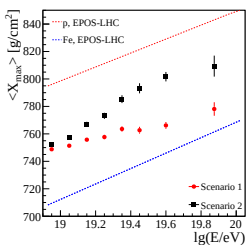
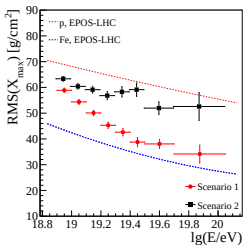
X_{max} determination:



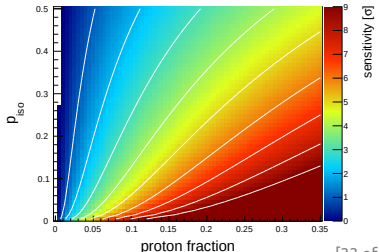
muon determination:



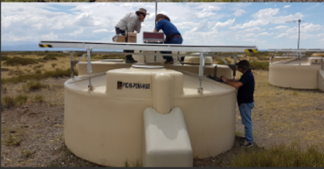
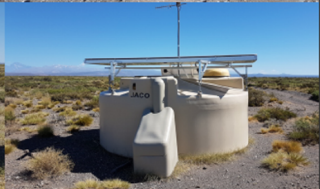
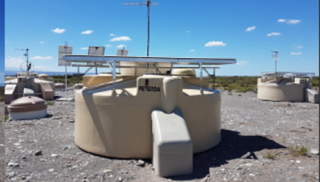
high- vs. low- R_{cut} scenario:



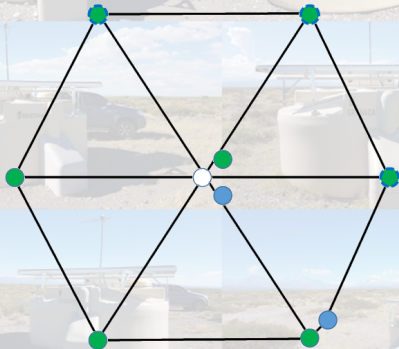
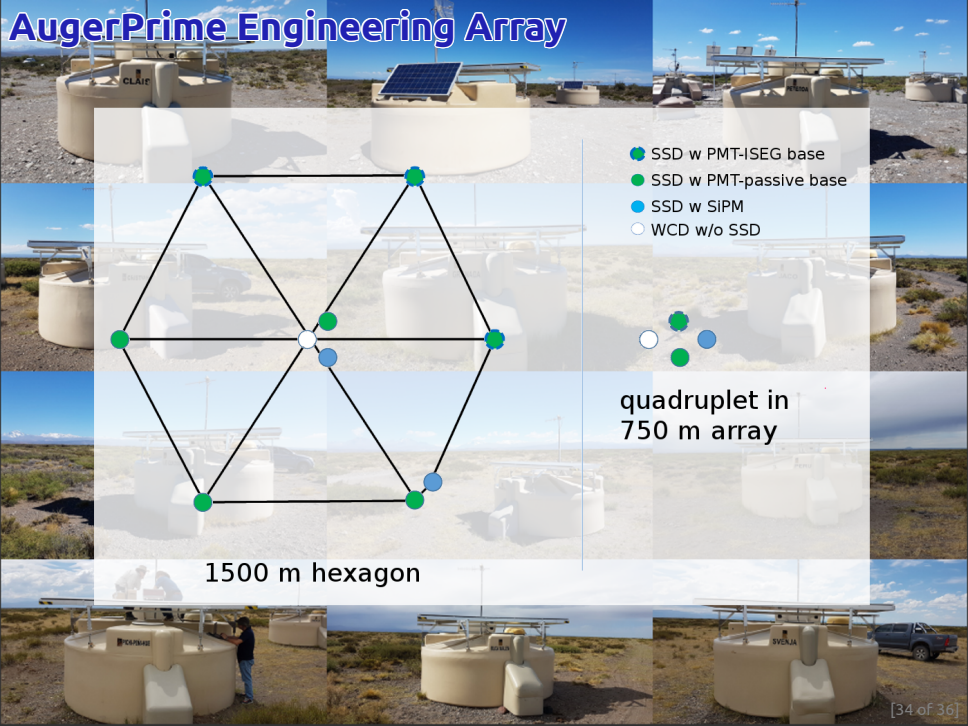
low- Z particle astronomy:



AugerPrime Engineering Array



AugerPrime Engineering Array



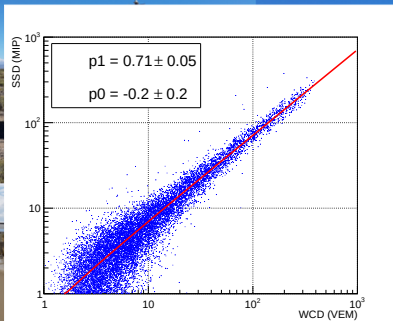
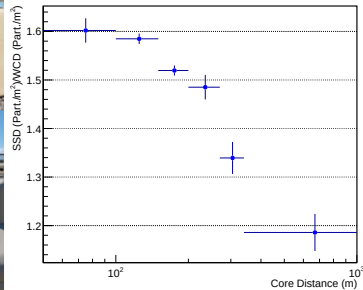
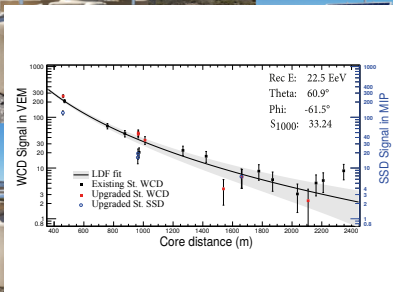
1500 m hexagon

- SSD w PMT-ISEG base
- SSD w PMT-passive base
- SSD w SIPM
- WCD w/o SSD



quadruplet in
750 m array

AugerPrime Engineering Array



- ▶ design finalized and tested
- ▶ 70% of funding secured
- ▶ finish construction by 2019
- ▶ data taking $\gtrsim$ 2025

Thanks!

