Ultrahigh Energy Cosmic Rays

What Do We Know and What's Next?

M. Unger (NYU&KIT)

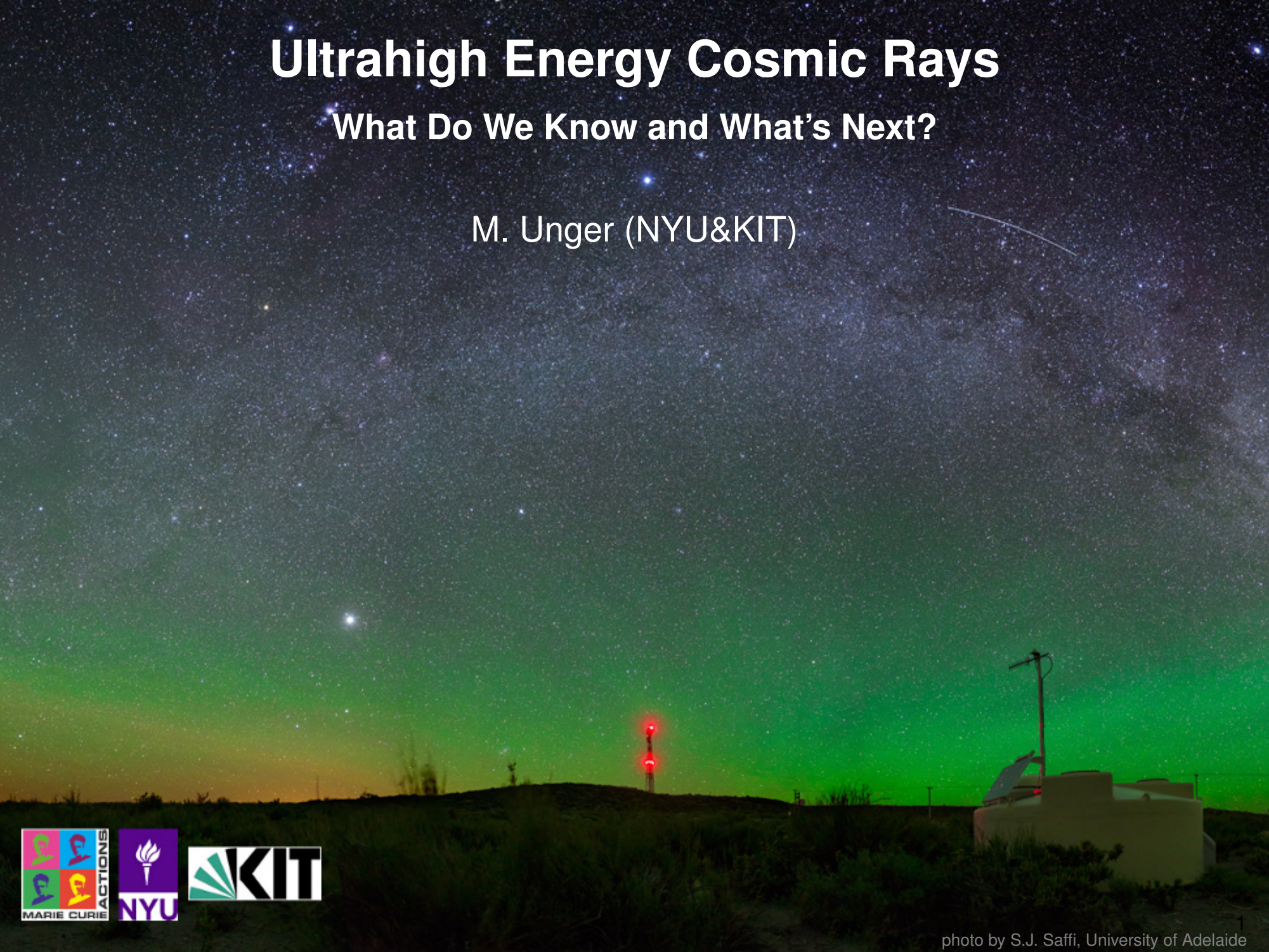
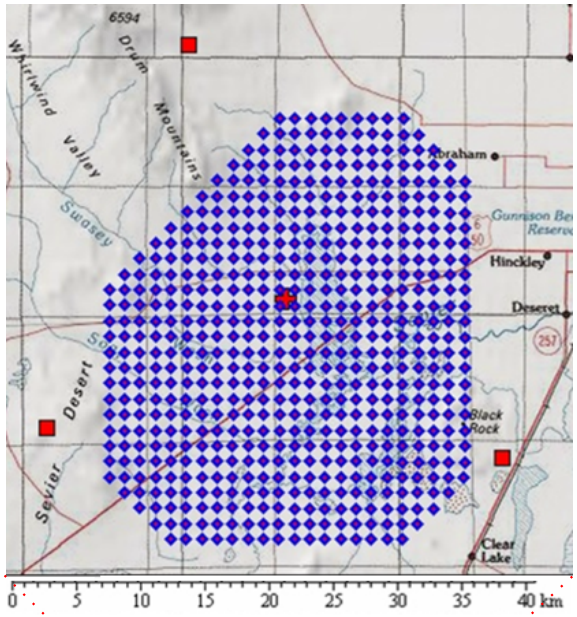
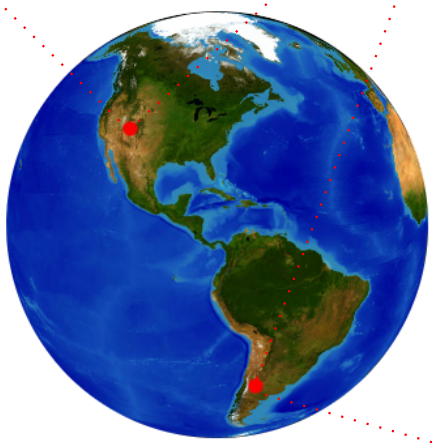


photo by S.J. Saffi, University of Adelaide

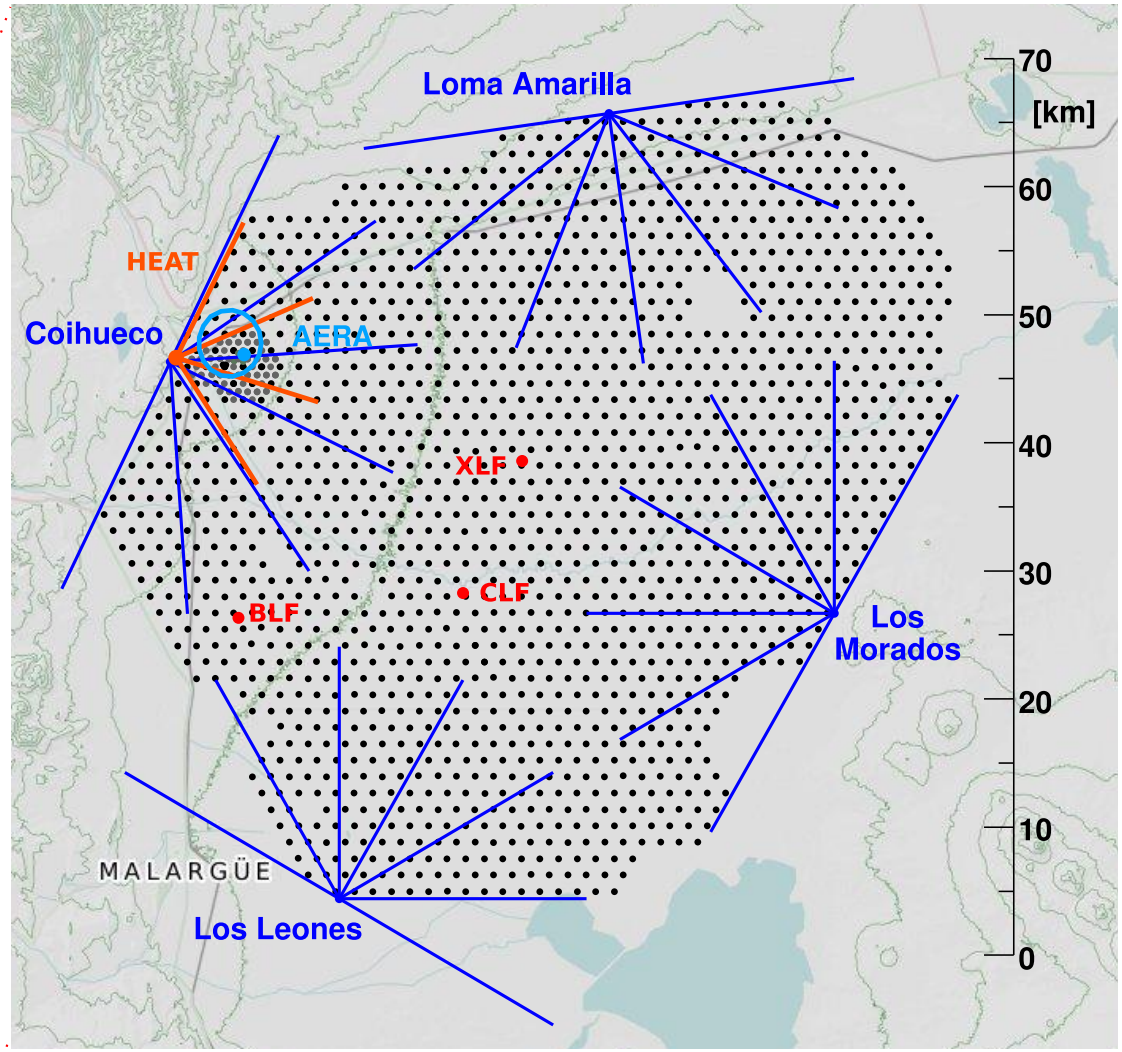
UHECR Observatories

Telescope Array





Pierre Auger Observatory

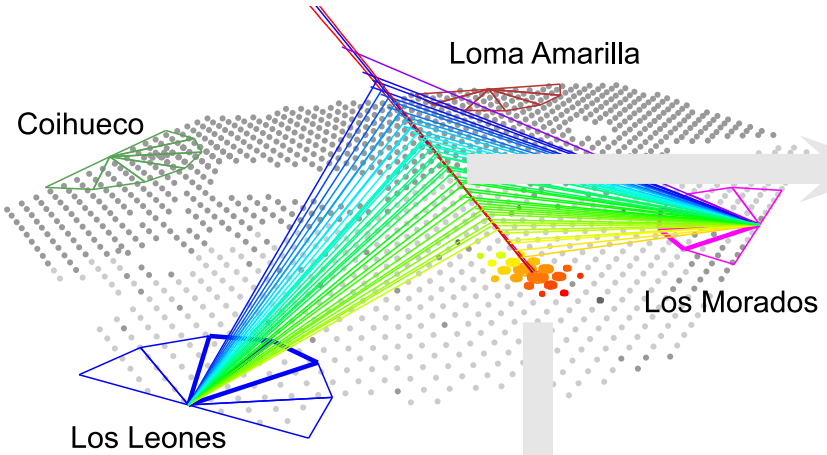


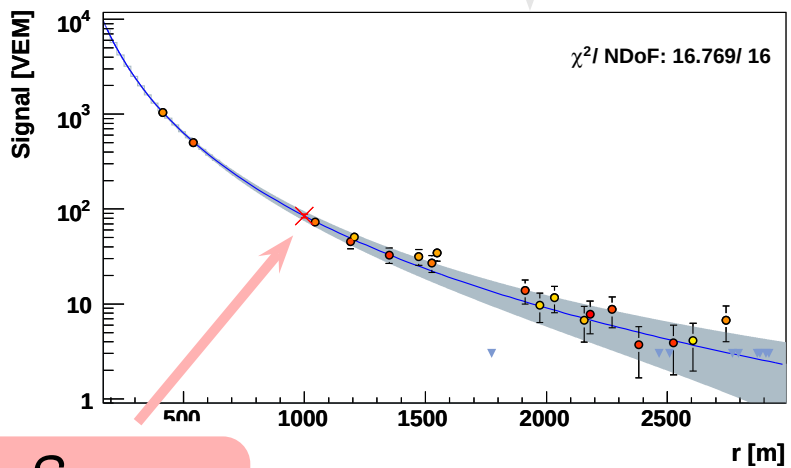
UHECR Observatories

Telescope Array

Pierre Auger Observatory

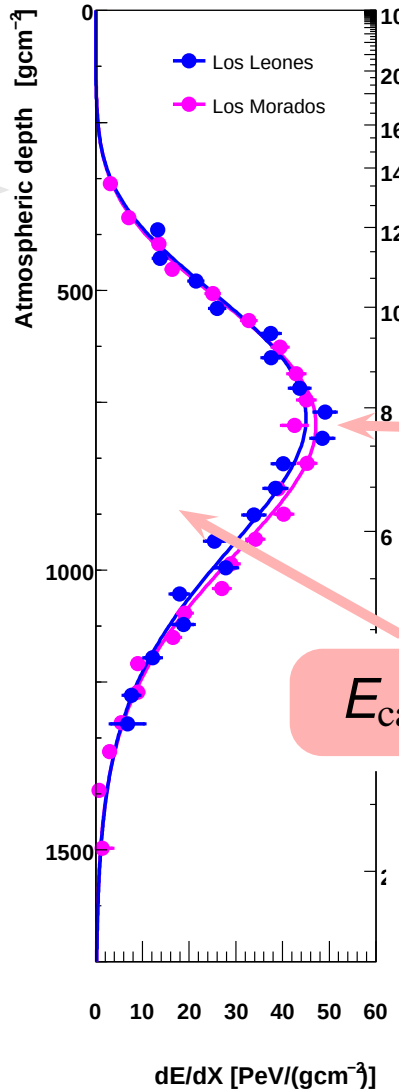
Hybrid Detection of Air Showers





S_{1000}

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



$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\text{sys}} \leq 10\,\mathrm{g/cm^2}$

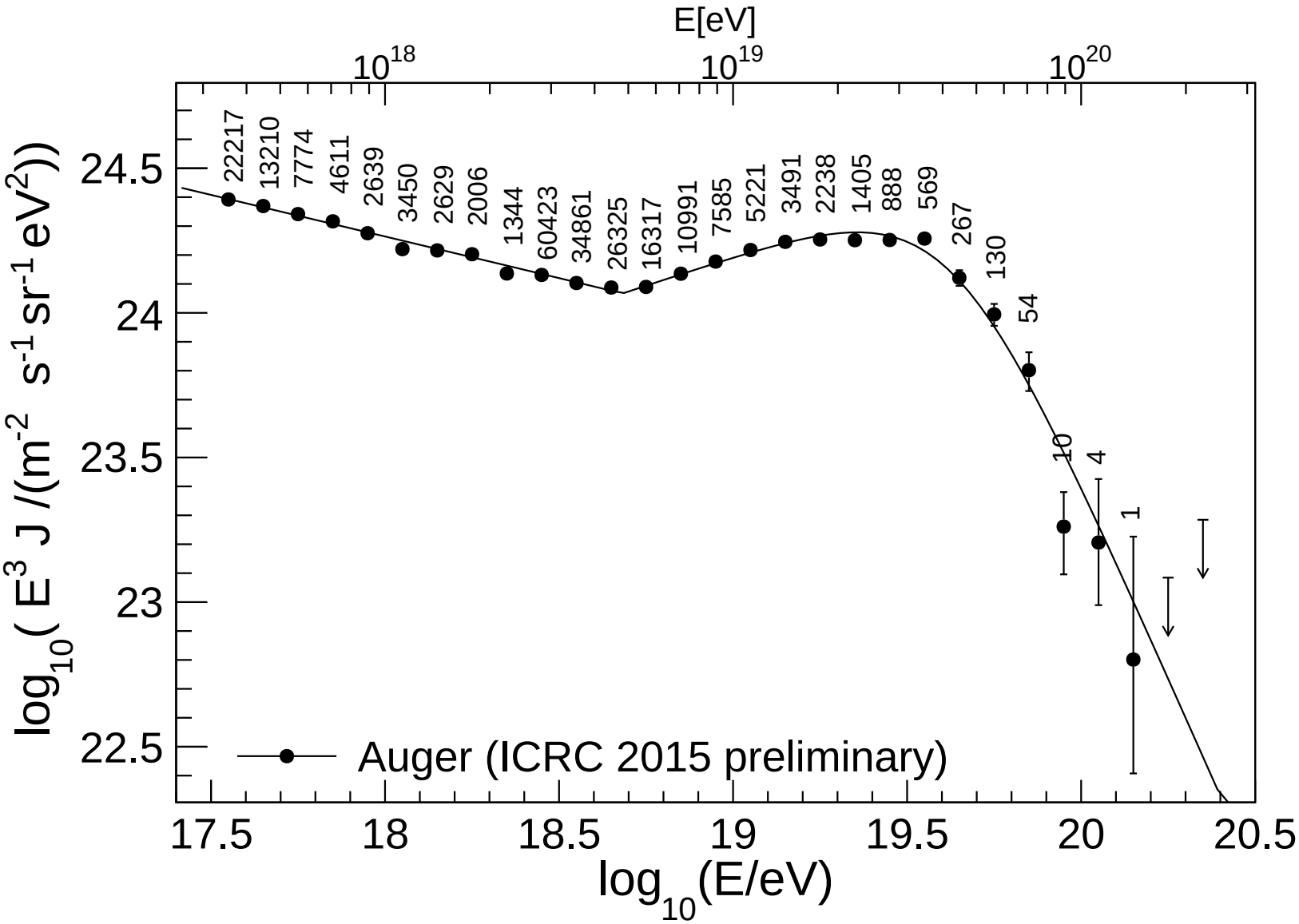
$X_{\max}$

$E_{\text{cal}} = \int \frac{dE}{dX}\, dX$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 15\,\%$

Auger Event Display, Event 3332245

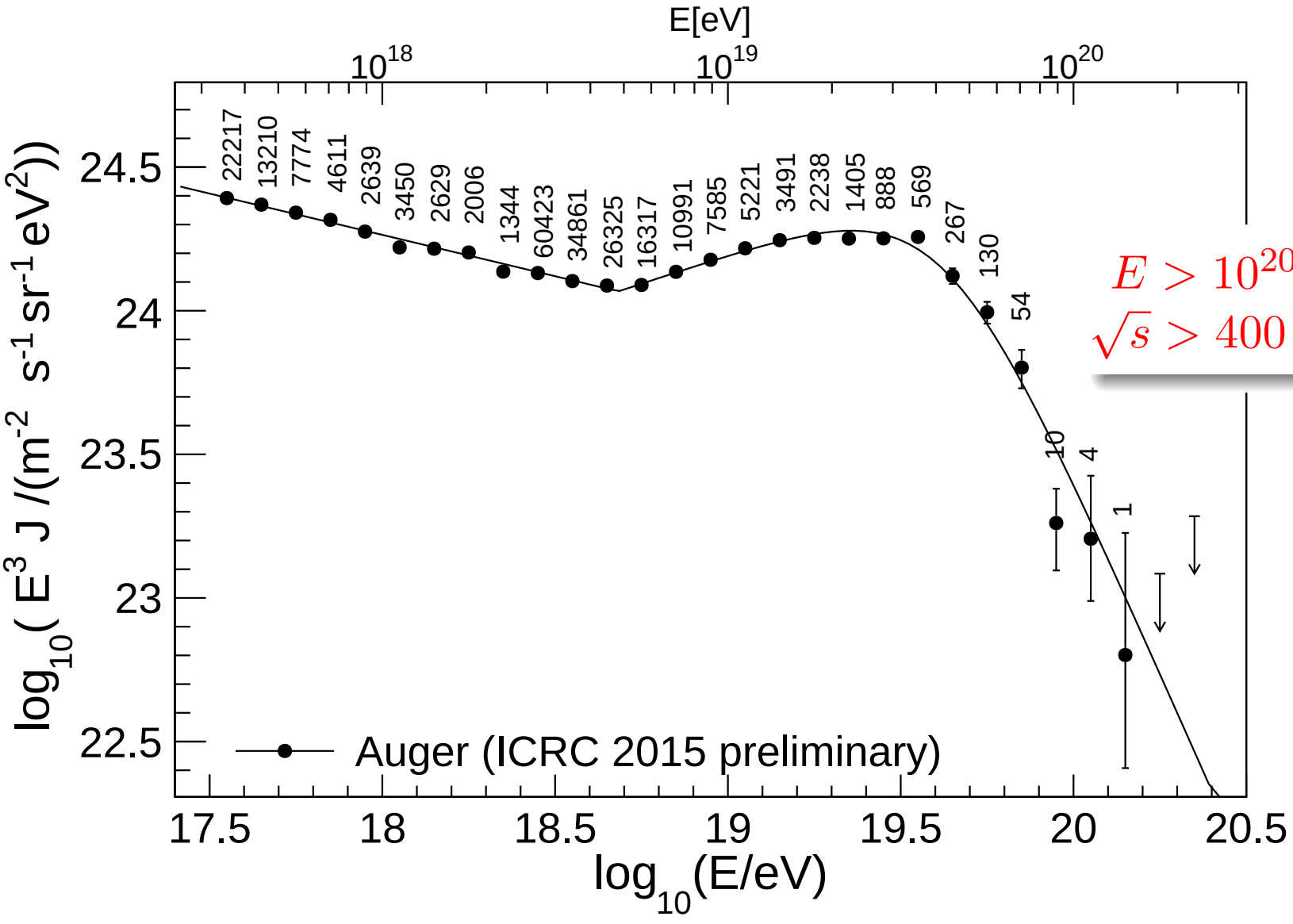
Energy Spectrum of UHECRs



exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Energy Spectrum of UHECRs



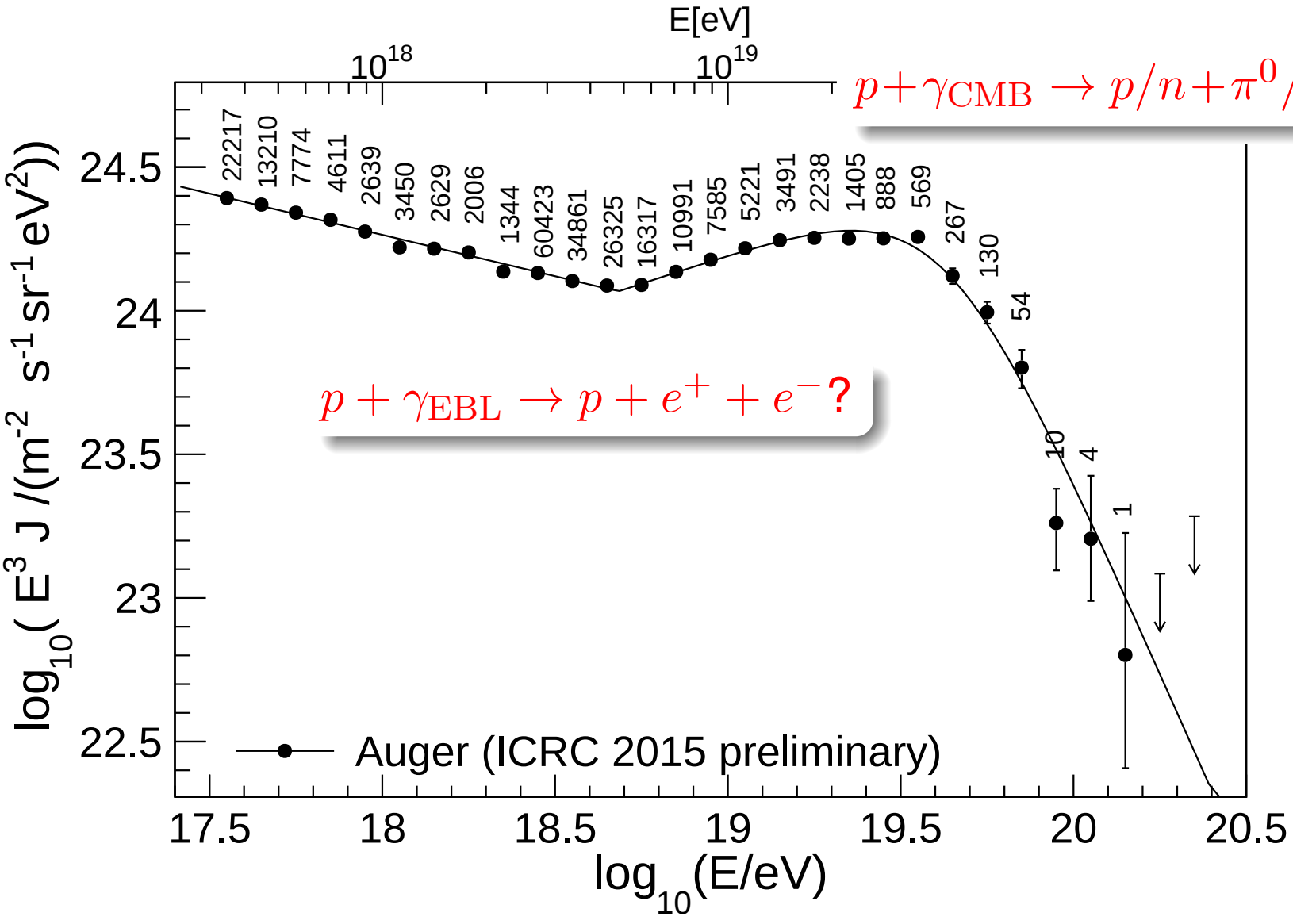
$E > 10^{20}$ eV

$\sqrt{s} > 400$ TeV

exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

(I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732)

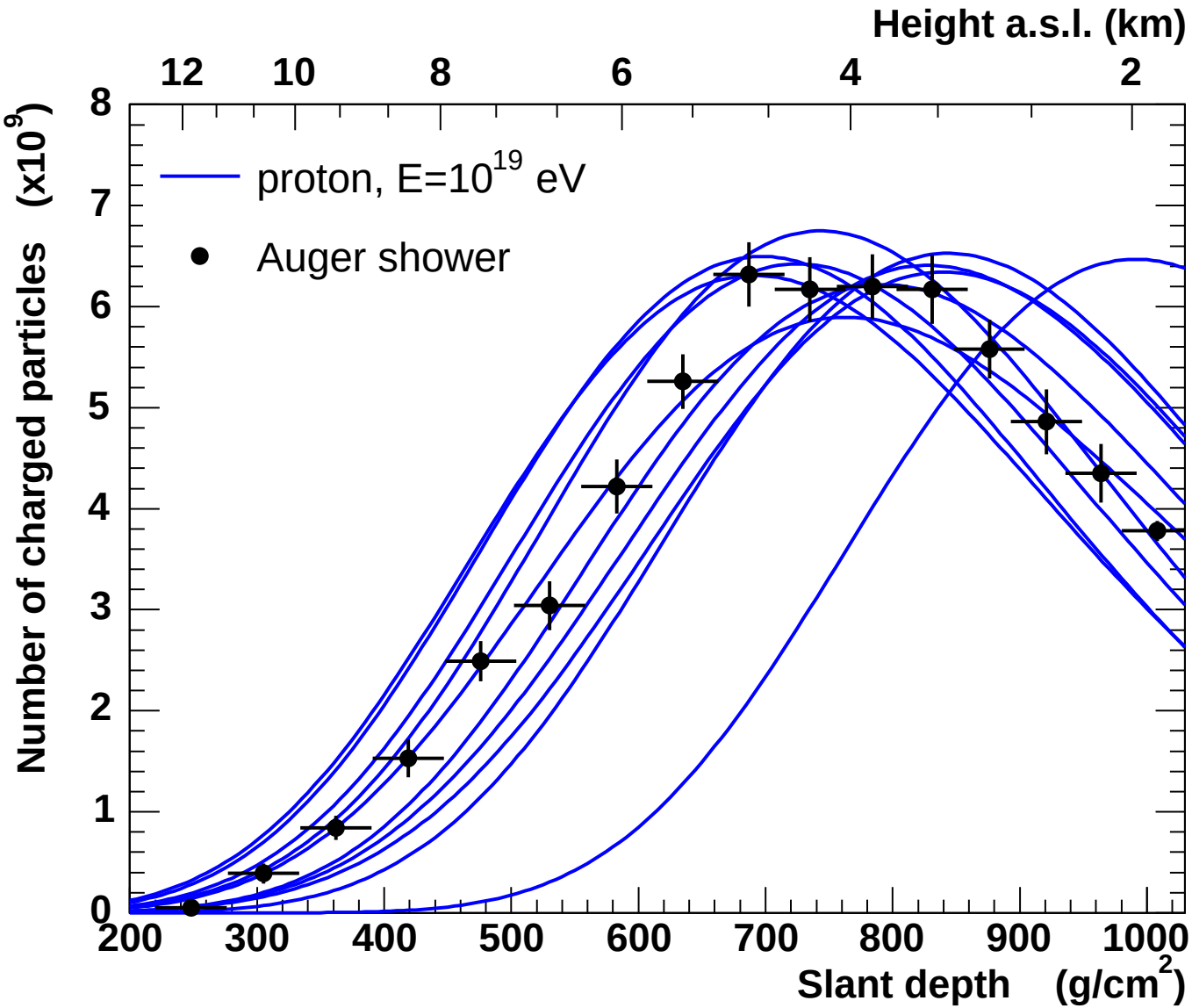
Energy Spectrum of UHECRs



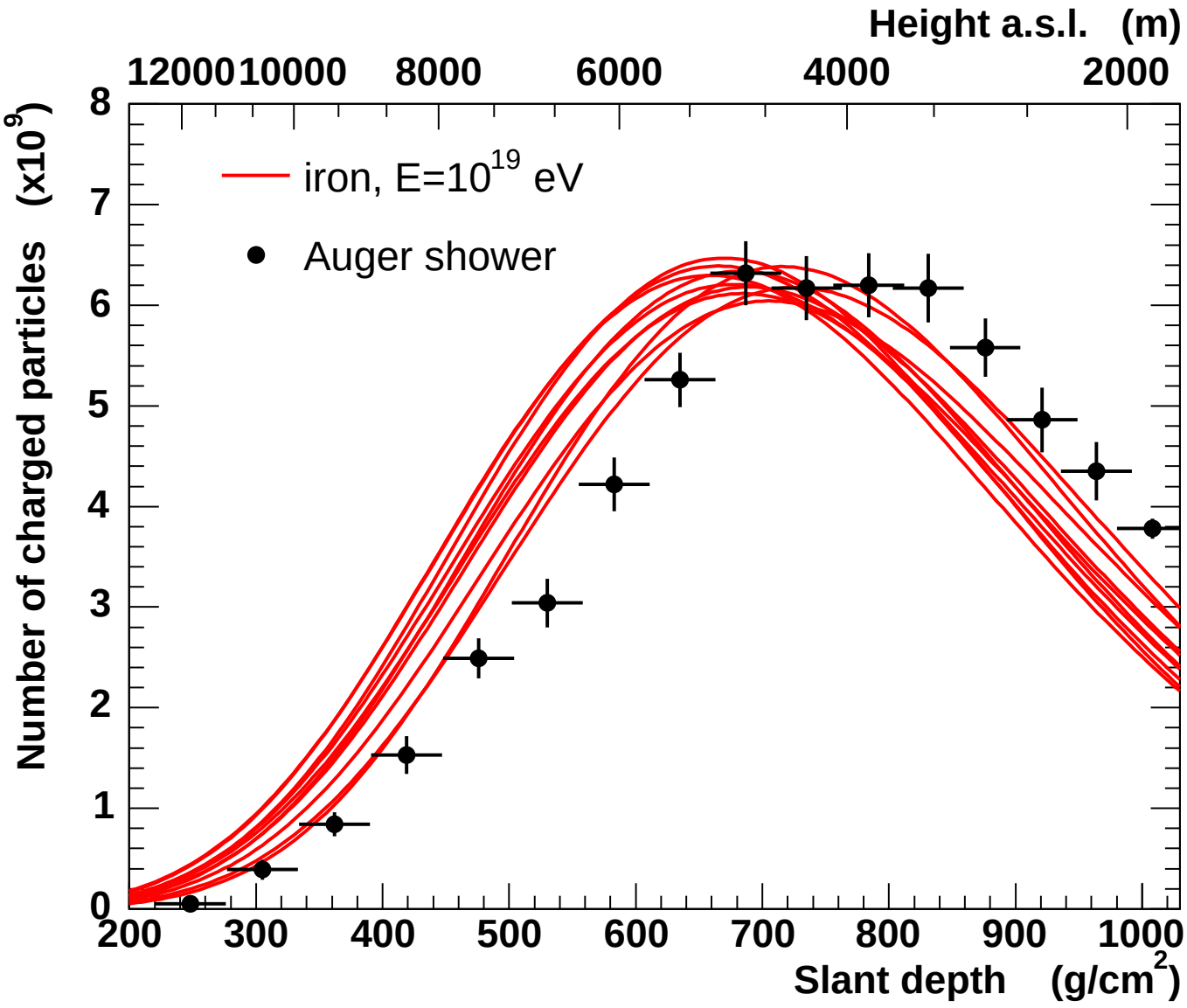
exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

(I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732)

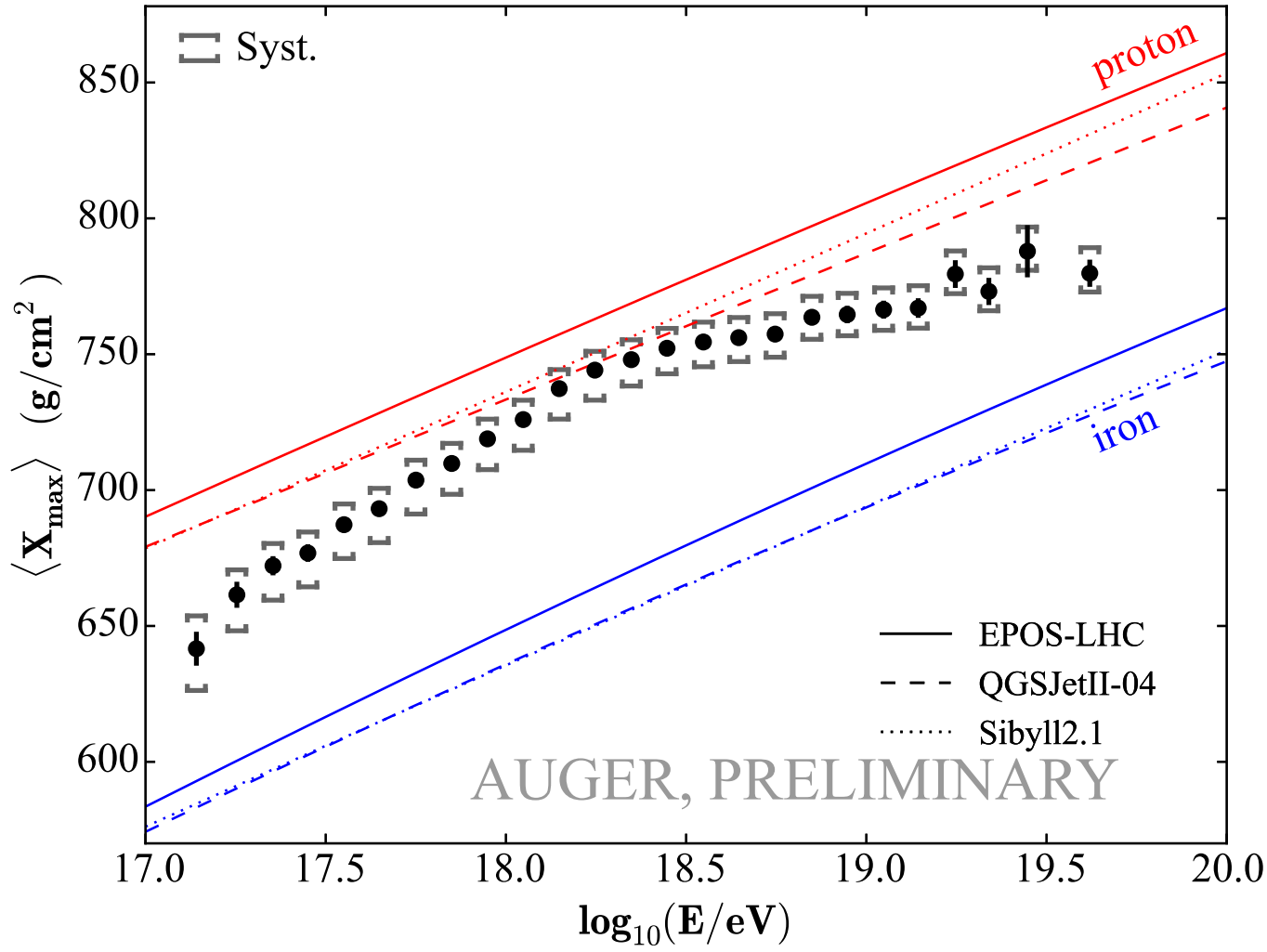
Primary Mass and Longitudinal Shower Profiles



Primary Mass and Longitudinal Shower Profiles

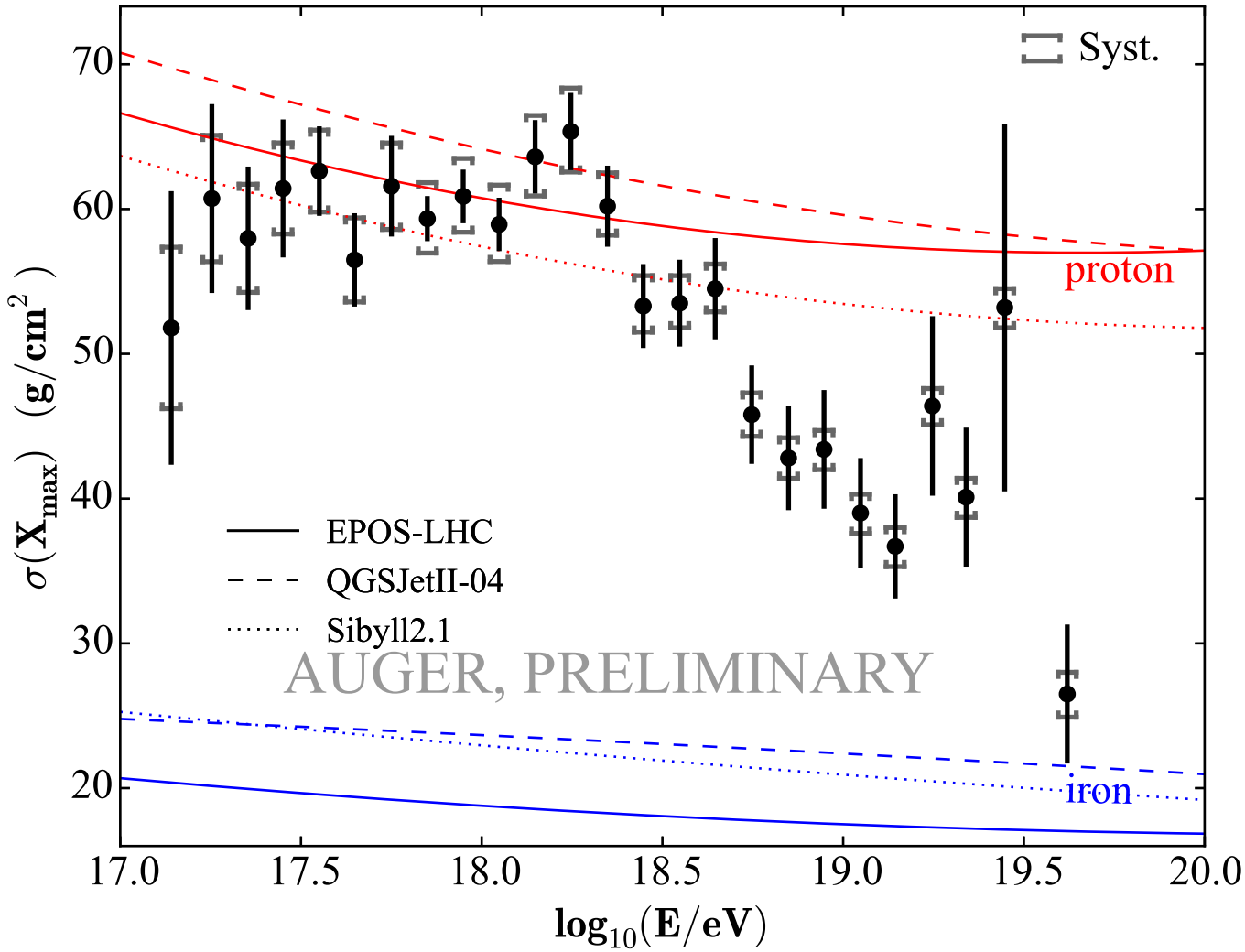


Measured $\langle X_{max} \rangle$



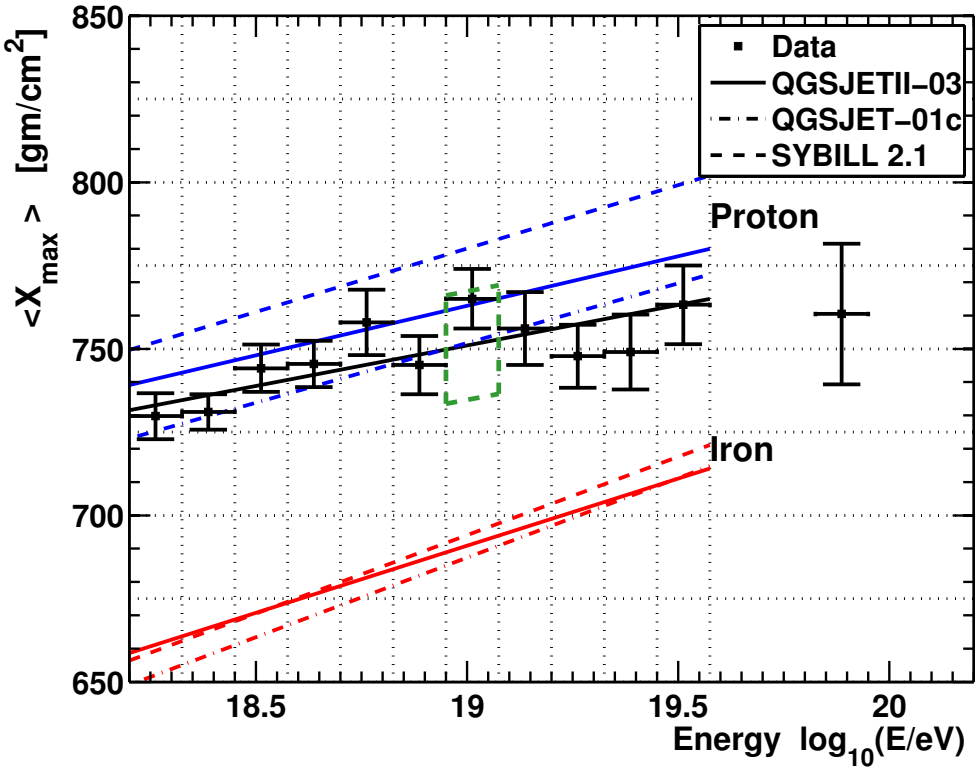
A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Measured $\sigma(\mathrm{X_{max}})$

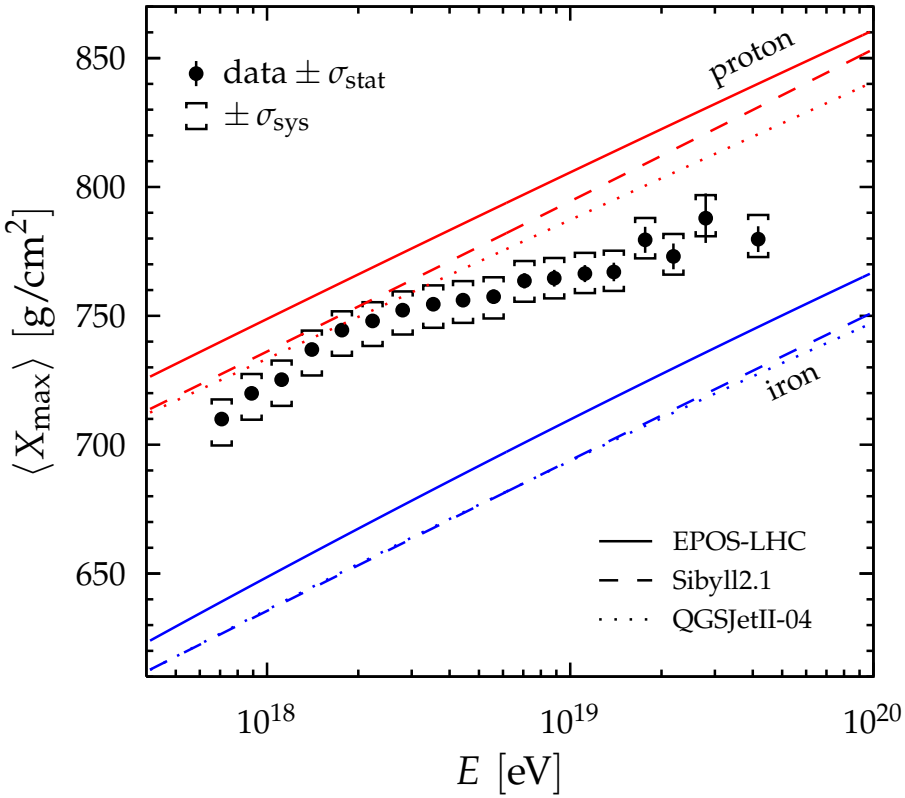


A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Average Shower Maximum: Comparison to TA

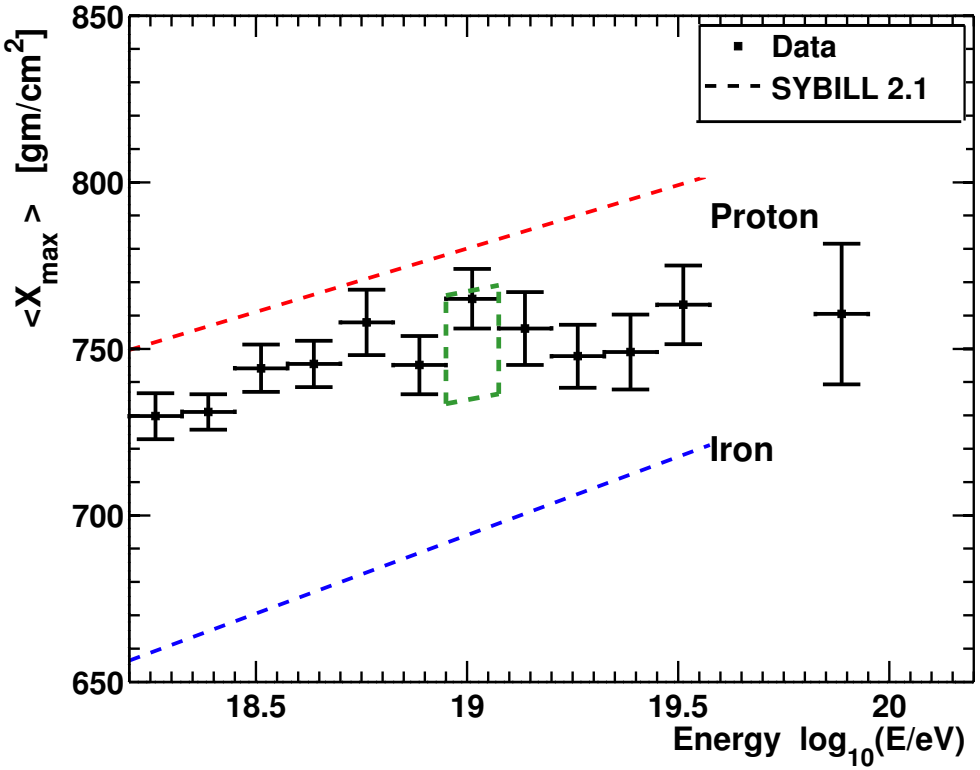


Telescope Array Coll., APP **64** (2014) 49

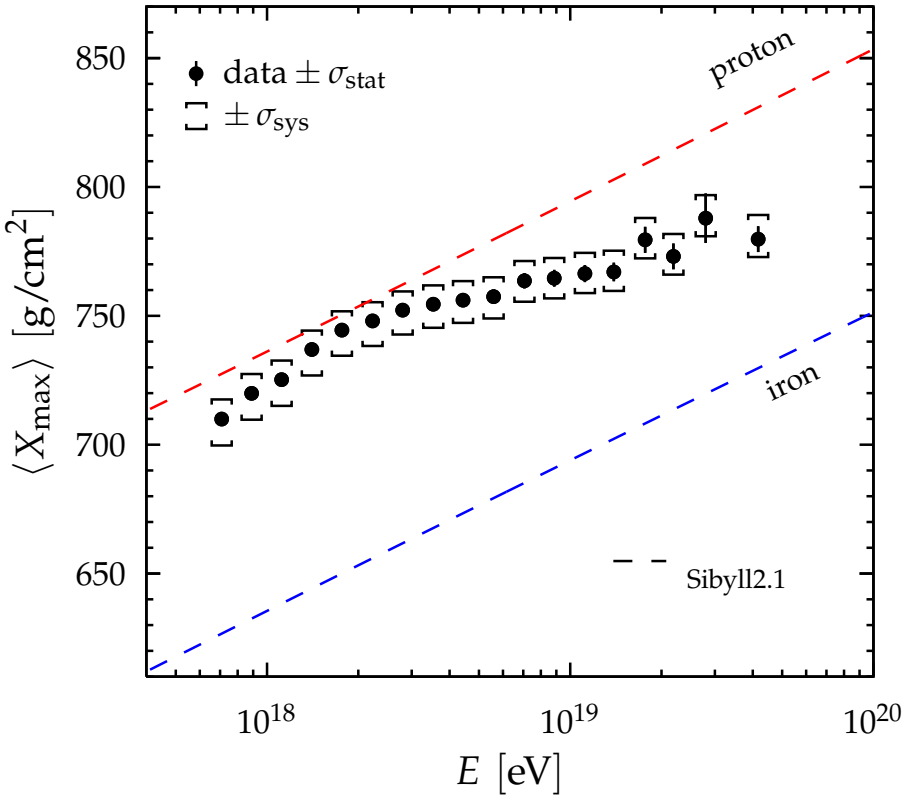


Pierre Auger Coll., PRD **90** (2014) 12, 122005

Average Shower Maximum: Comparison to TA

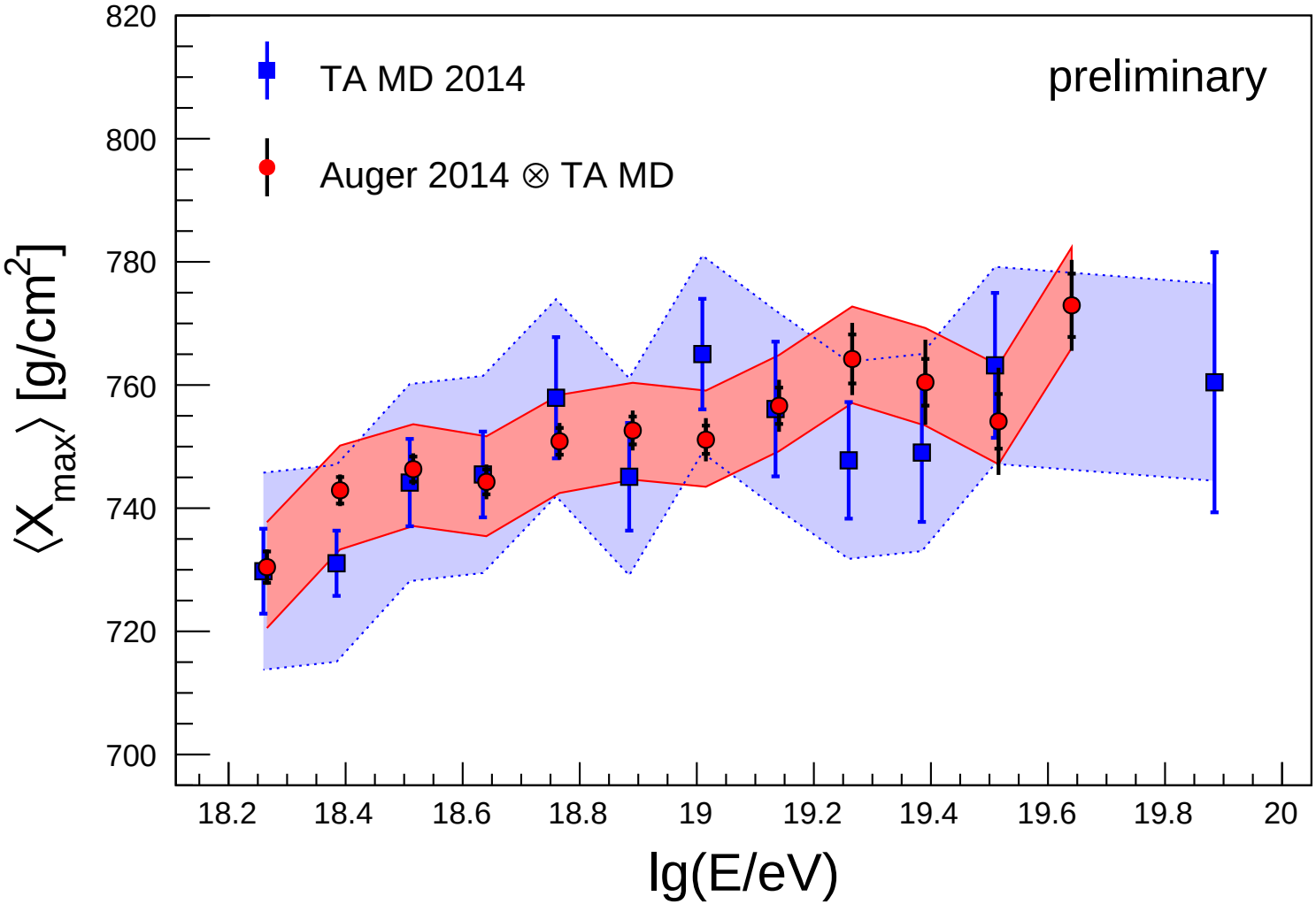


Telescope Array Coll., APP **64** (2014) 49



Pierre Auger Coll., PRD **90** (2014) 12, 122005

Average Shower Maximum: Comparison to TA

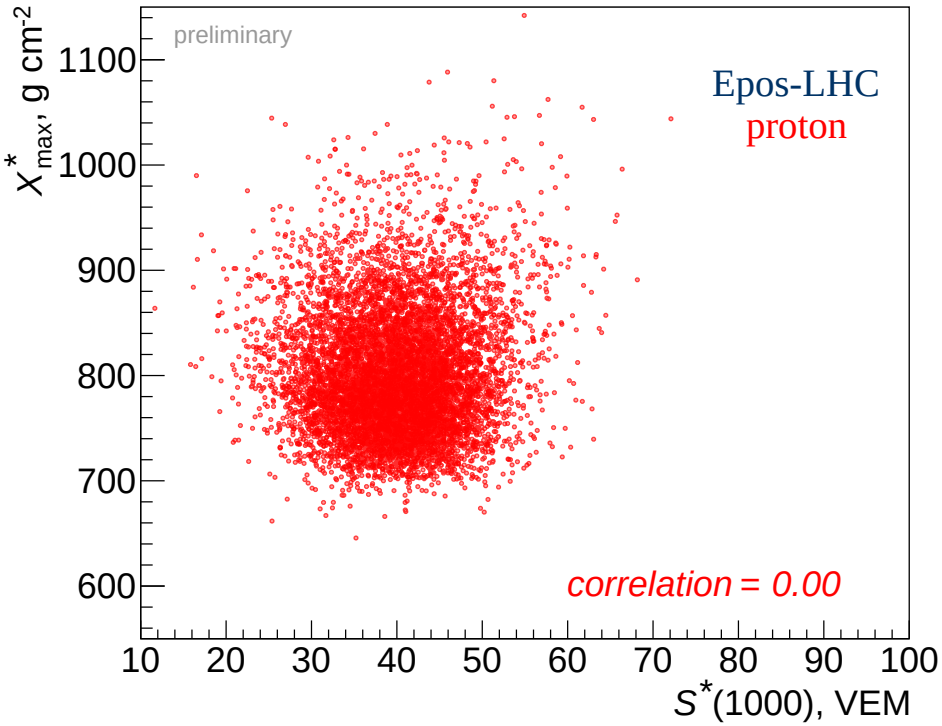


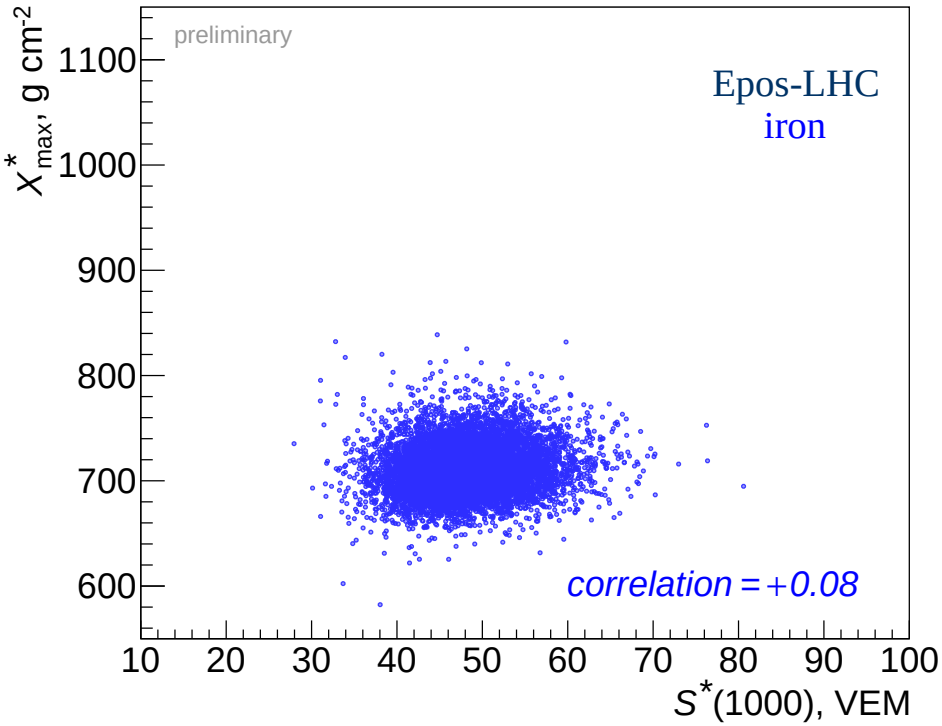
$$\langle \Delta \rangle = (2.9 \pm 2.7\ (\text{stat.}) \pm 18\ (\text{syst.}))\ \text{g/cm}^2$$

MU for the Pierre Auger and TA Collaborations, Proc. 34th ICRC, arXiv:1511.02103

Correlation between X_{max} and SD Signal

$18.5 < \lg(E/eV) < 19.0$, $X^*_{max}/S^*(1000)$: scaled to 10^{19} eV





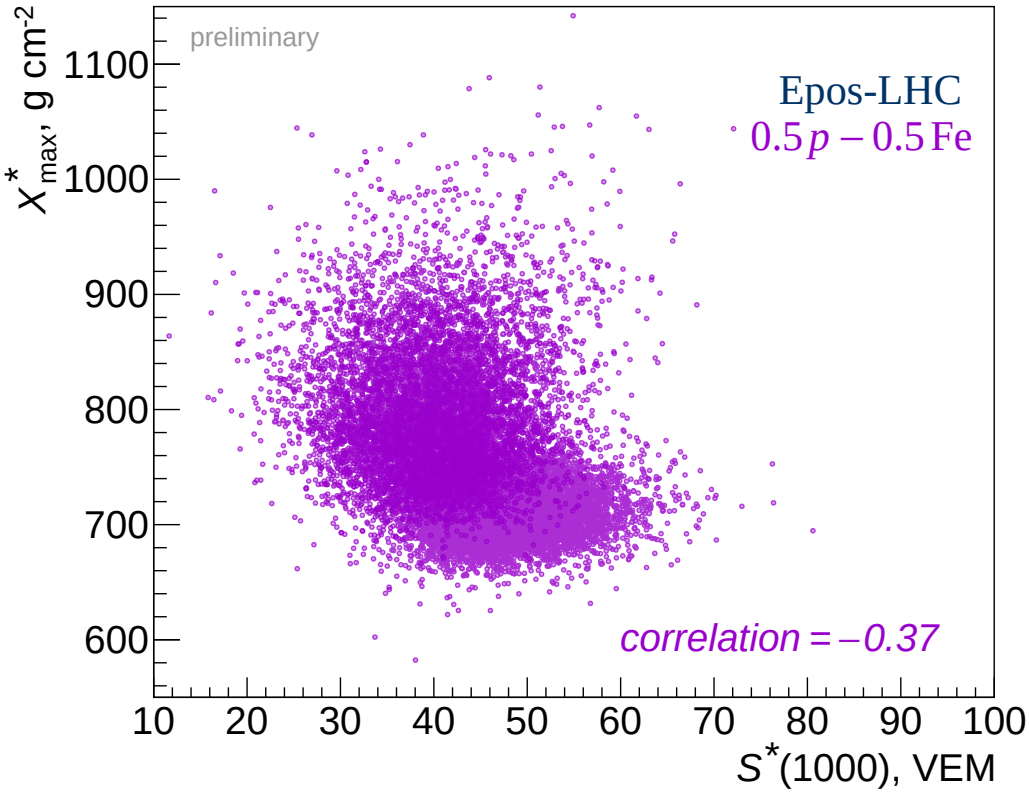
Pure compositions $\Rightarrow$ correlation $\gtrsim 0$

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Correlation between X_{max} and SD Signal

heavier nuclei produce shallower showers with larger signal (more muons)

general characteristics of air showers / minor model dependence

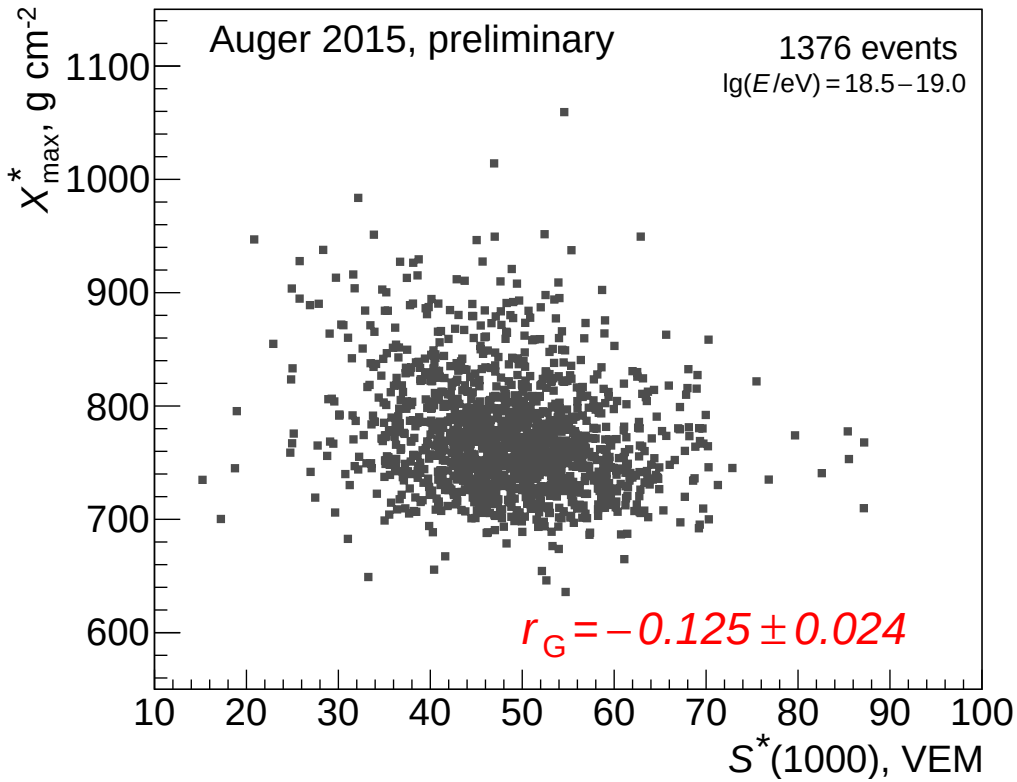


More negative correlation ⇒ more mixed composition

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Correlation between X_{max} and SD Signal

Data:



$r_G(X^*_{max}, S^*(1000))$ for protons

Epos-LHC	QGSJetII-04	Sibyll 2.1
0.00	$+0.08$	$+0.07$

difference to data

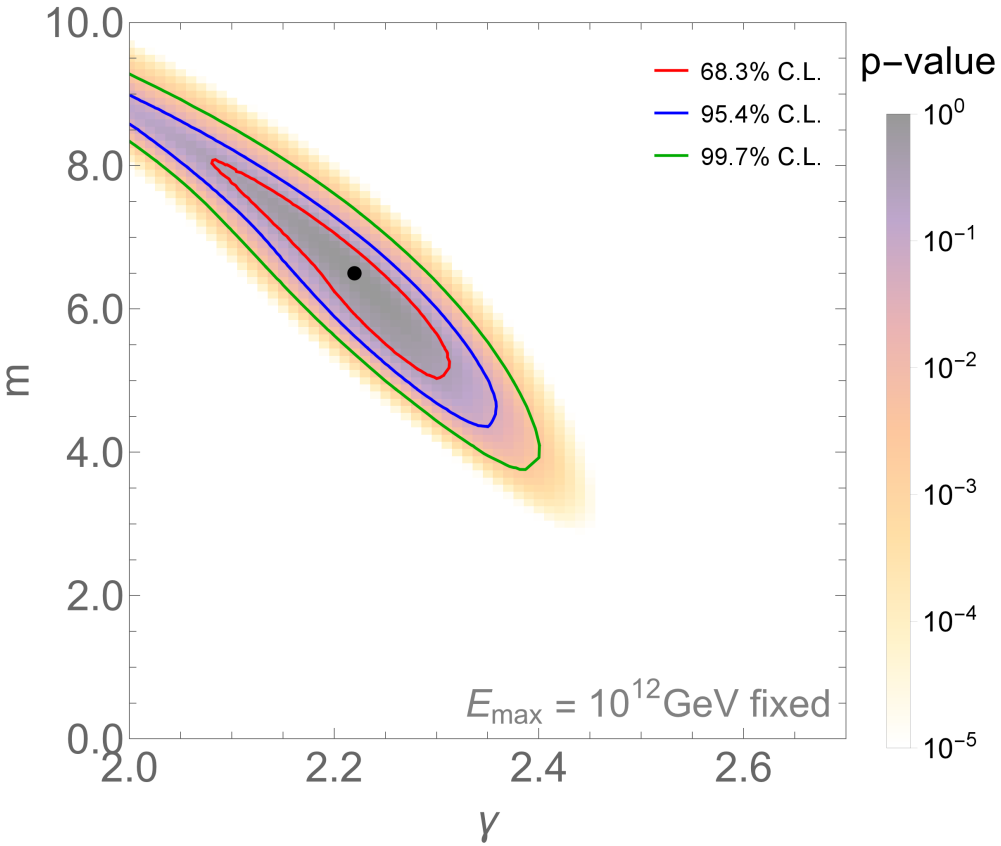
$\approx 5\sigma$	$\approx 8\sigma$	$\approx 7.5\sigma$

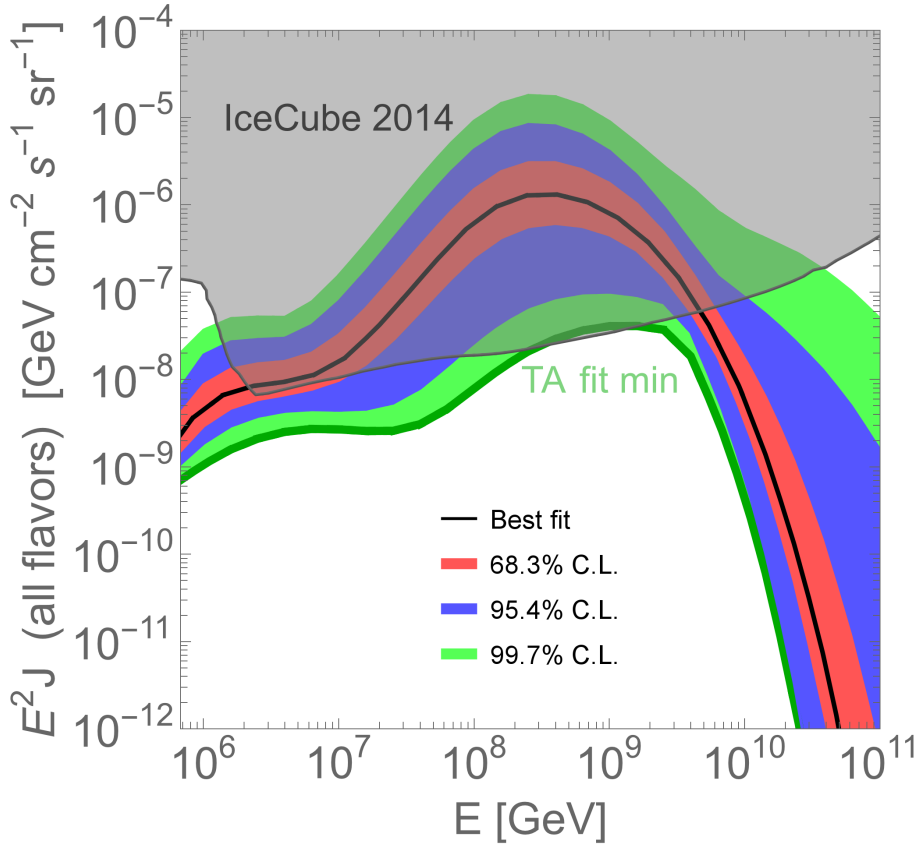
difference is larger for other pure beams

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Self-Consistent CR+ν Analysis (TA Spectrum, p)

spectral index at source γ and source evolution $(1+z)^m$



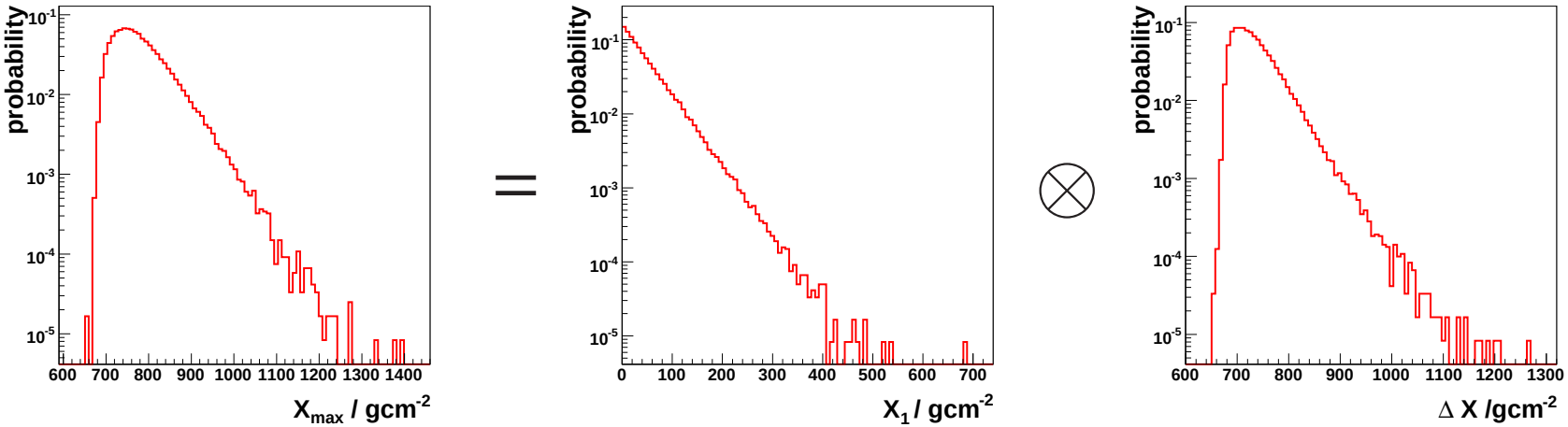


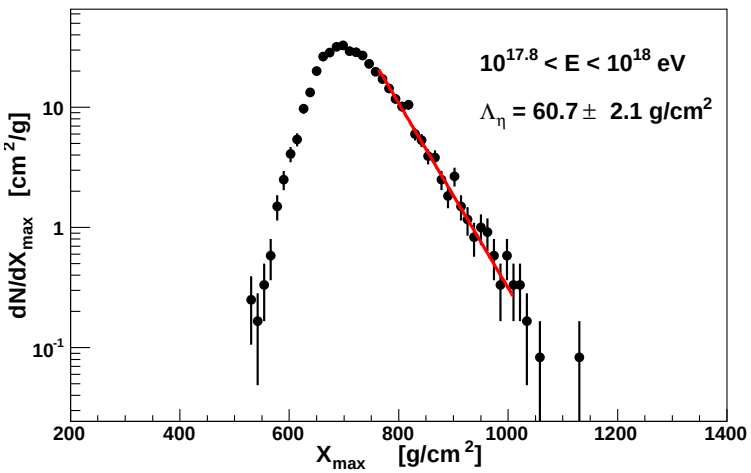
... similar results for three-parameter fit $(m, \gamma, E_{\max})$

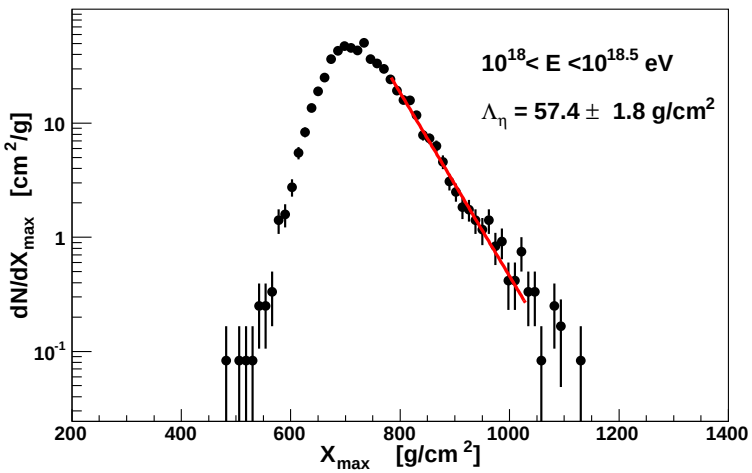
J. Heinze, D. Boncioli, M. Bustamante, W. Winter, arXiv:1512.05988

Measurement of the UHE p+Air Cross Section

tail of $X_{\max}$ distribution:







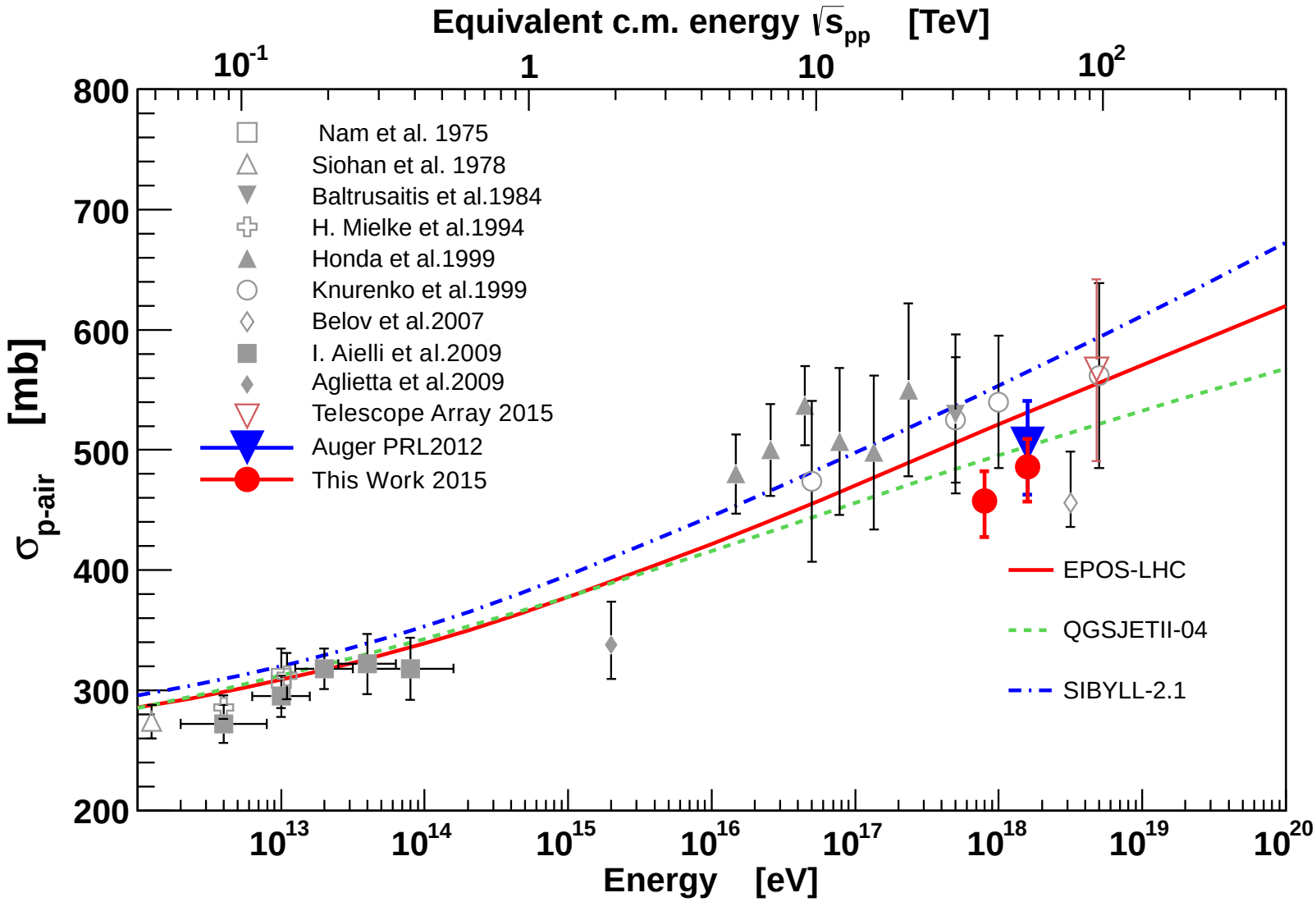
$\langle E \rangle = 10^{17.90}$ eV

$\Lambda_\eta = 60.7 \pm 2.1(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$

$\langle E \rangle = 10^{18.22}$ eV

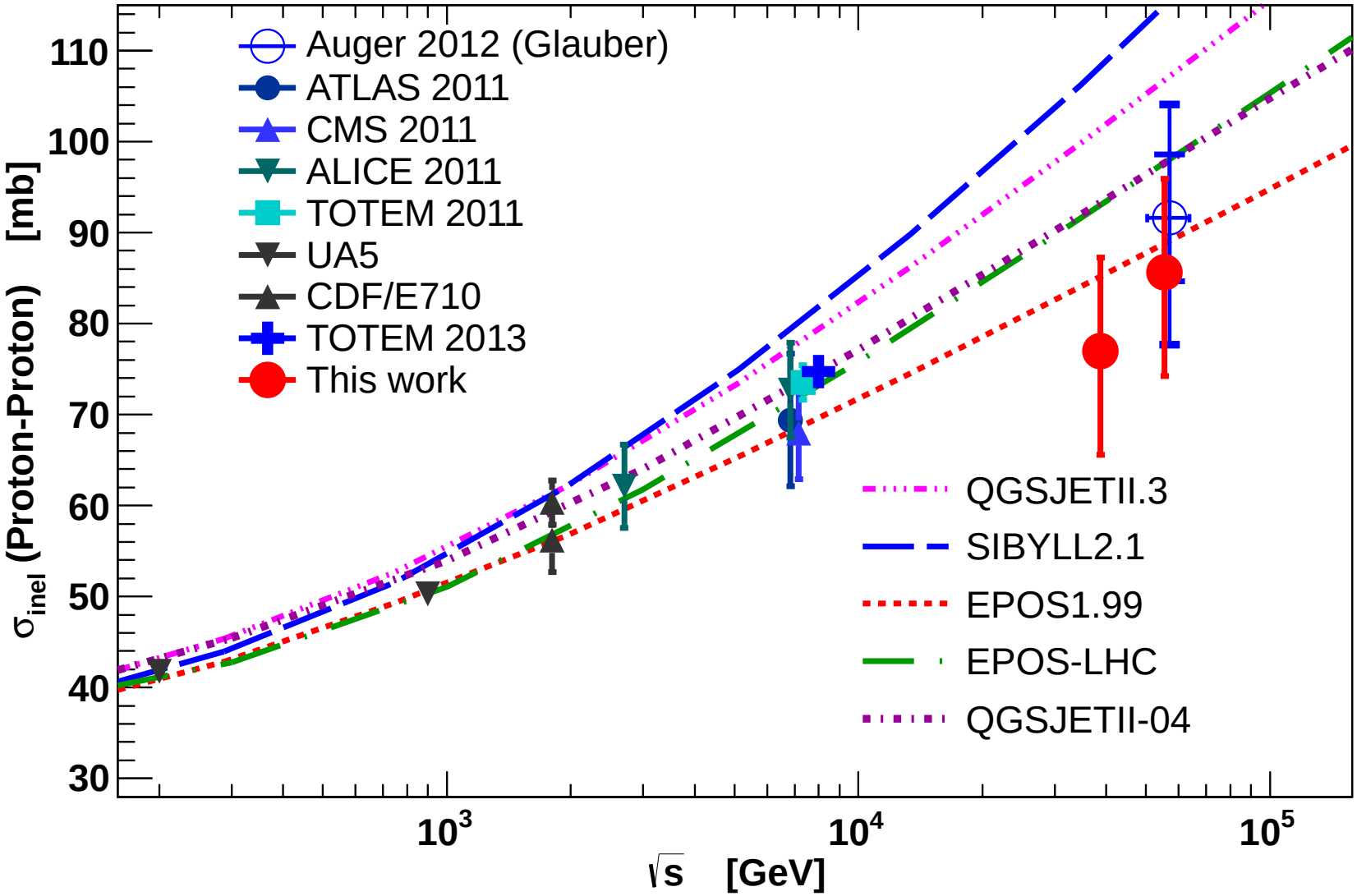
$\Lambda_\eta = 57.4 \pm 1.8(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$

Measurement of the UHE p+Air Cross Section



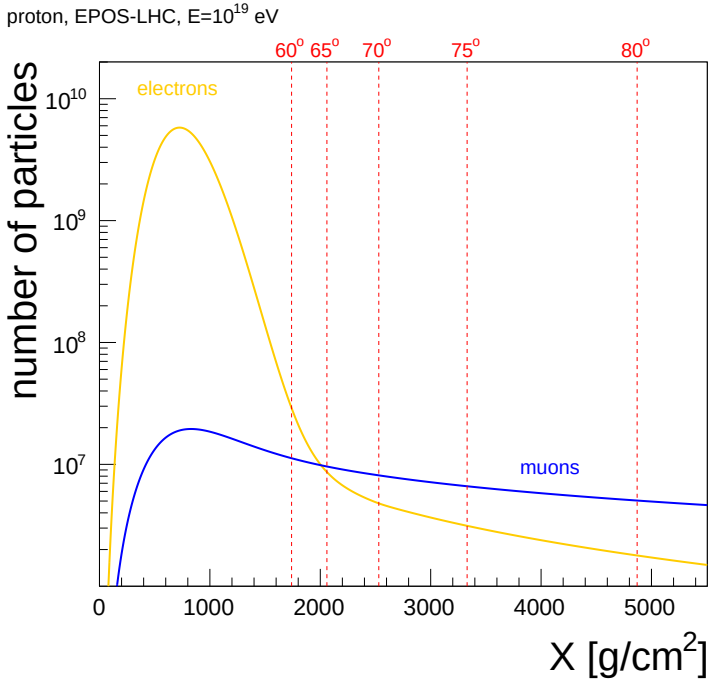
R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

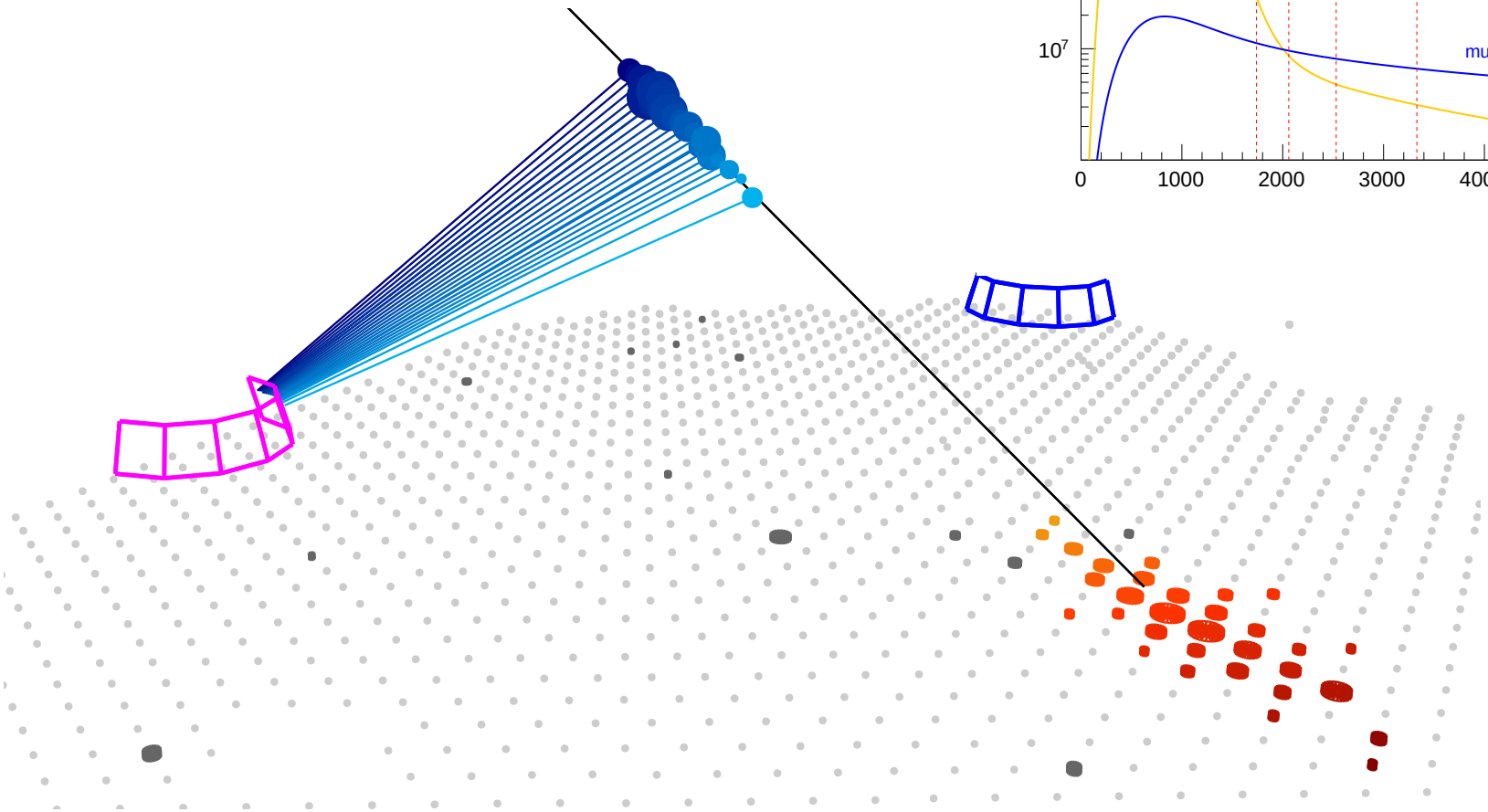
Derived UHE Proton+Proton Cross Section



R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

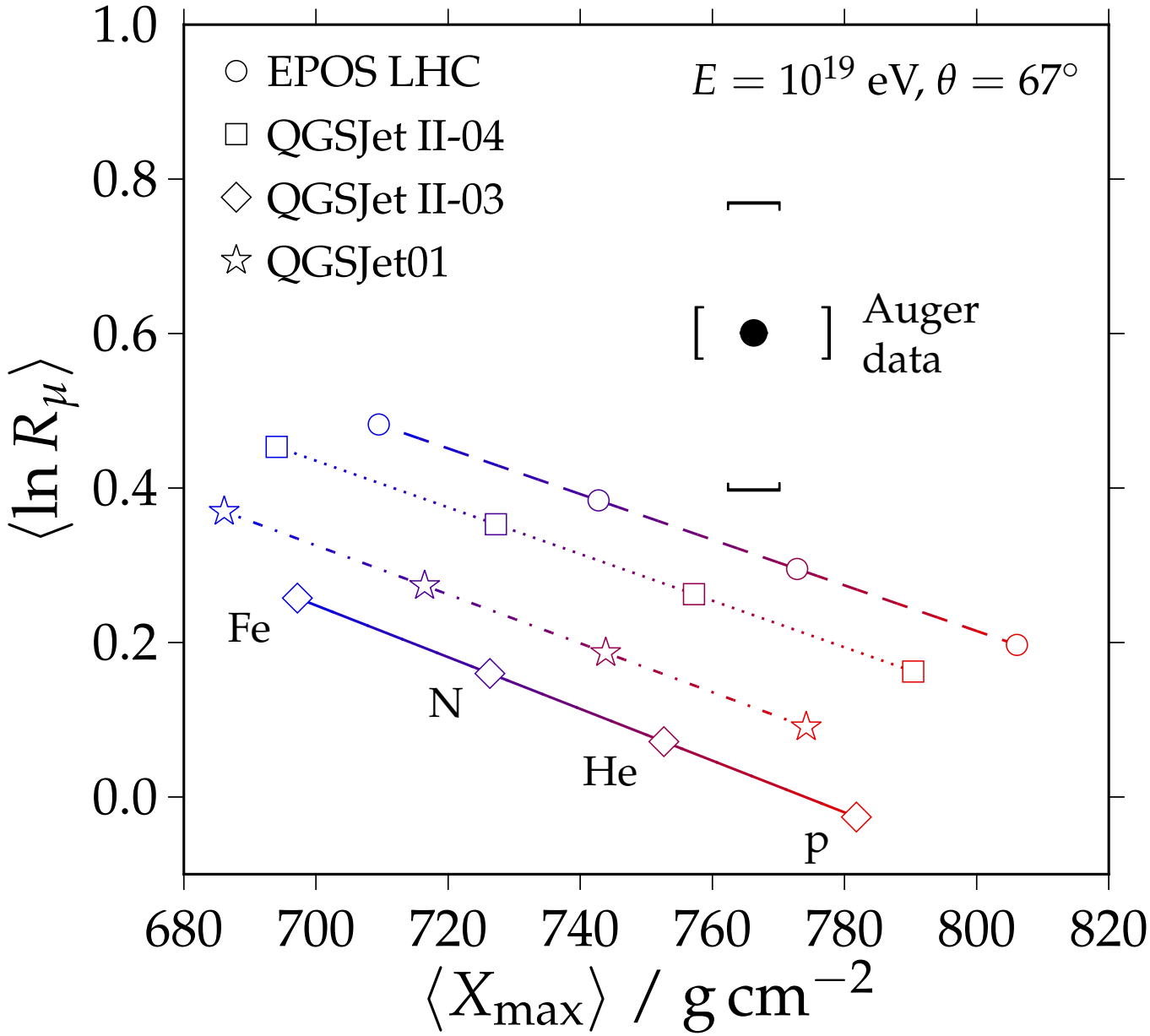
Muon Content of Air Showers





event 201114505353, $\theta = 75.6°$, $E = 15.5$ EeV

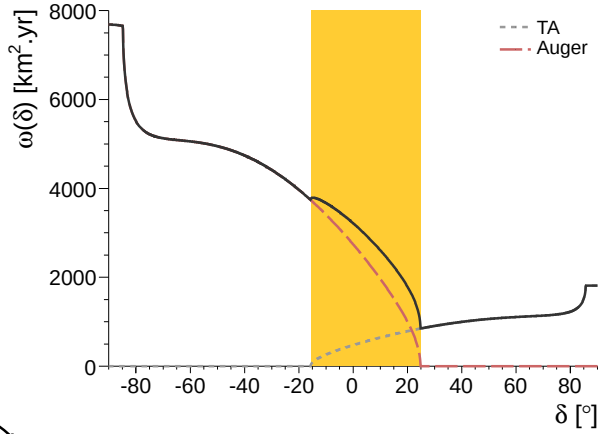
Muon Number vs. X_{max} (FD)

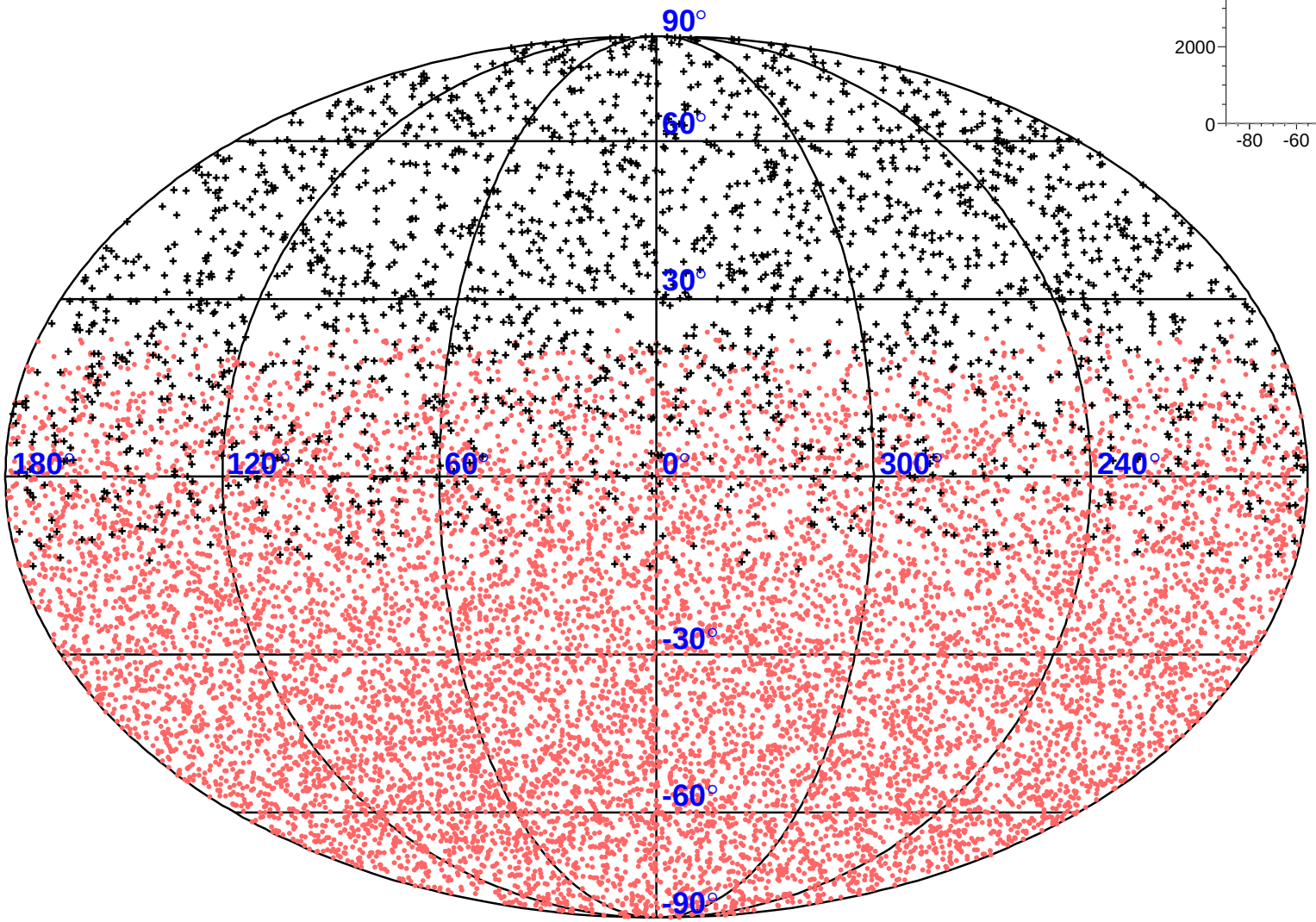


N.B.: $R_\mu = 1 \leftrightarrow N_\mu = 1.455 \times 10^7$

Pierre Auger Coll., PRD **D91** (2015) 3, 032003

The UHECR Sky above 10 EeV

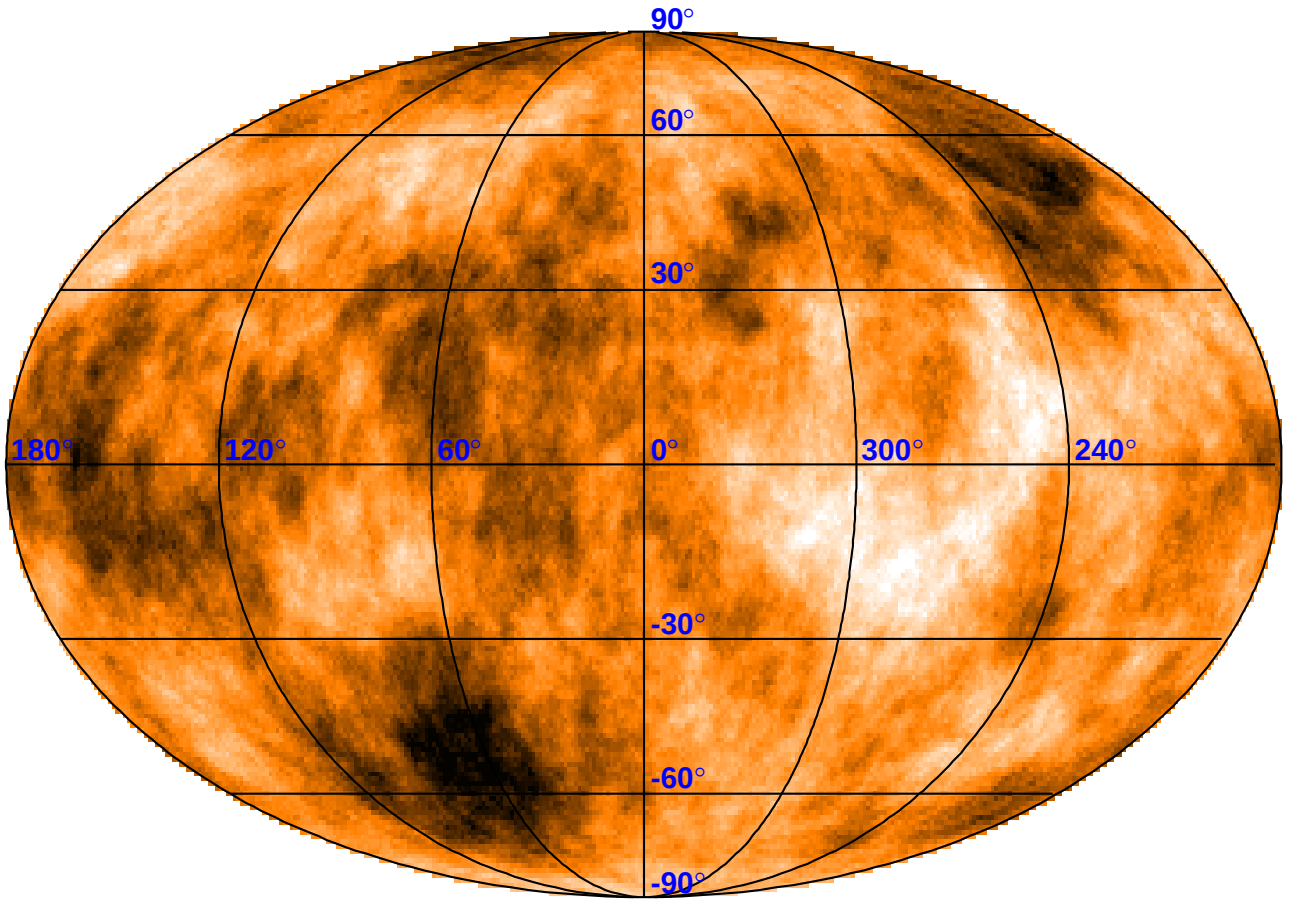


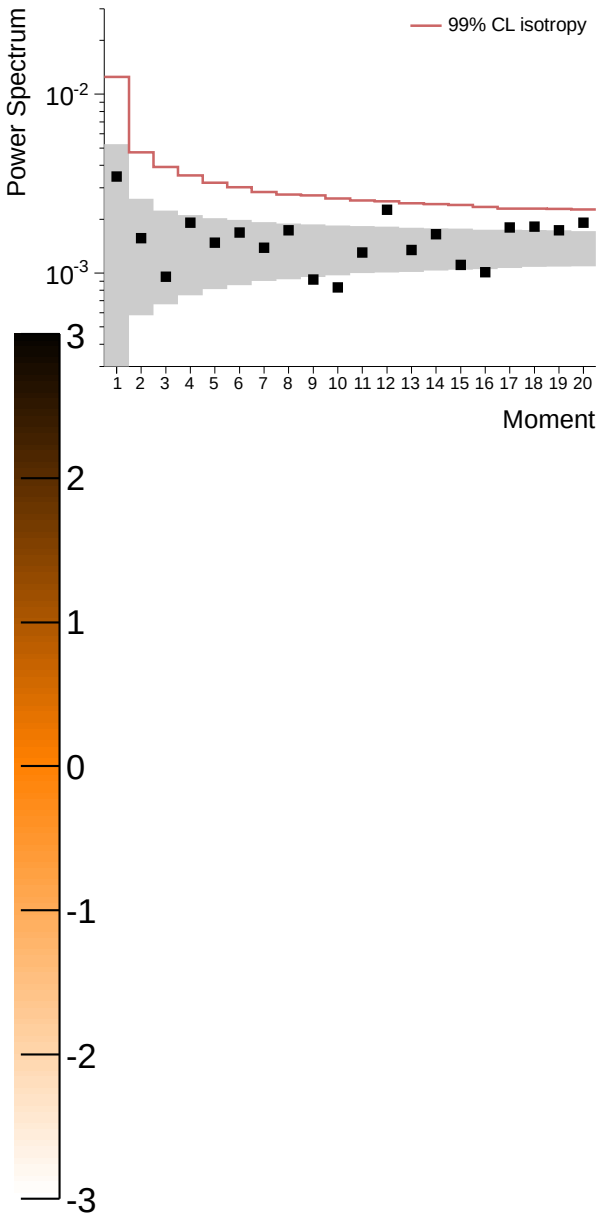


Pierre Auger and TA Collaborations, APJ **794** (2014) 2, 172

The UHECR Sky above 10 EeV

significance map:



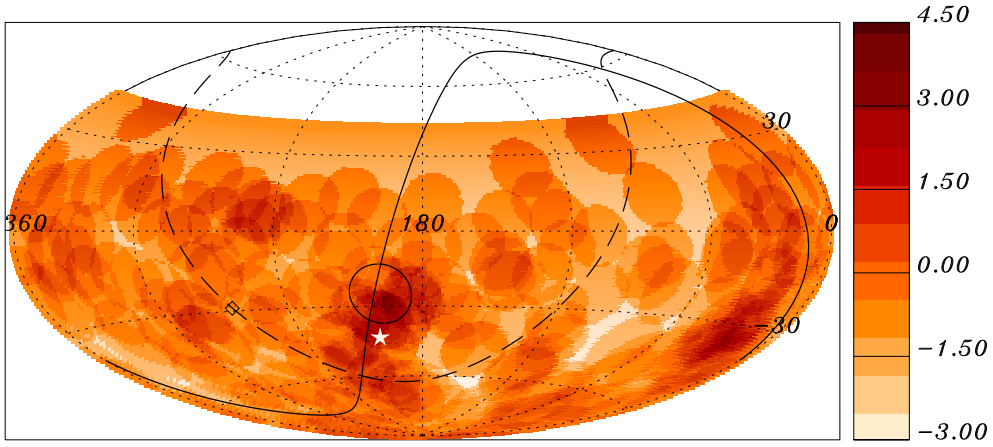


Pierre Auger and TA Collaborations, APJ **794** (2014) 2, 172

Searches for a Localized Excess of UHECRs

Auger:

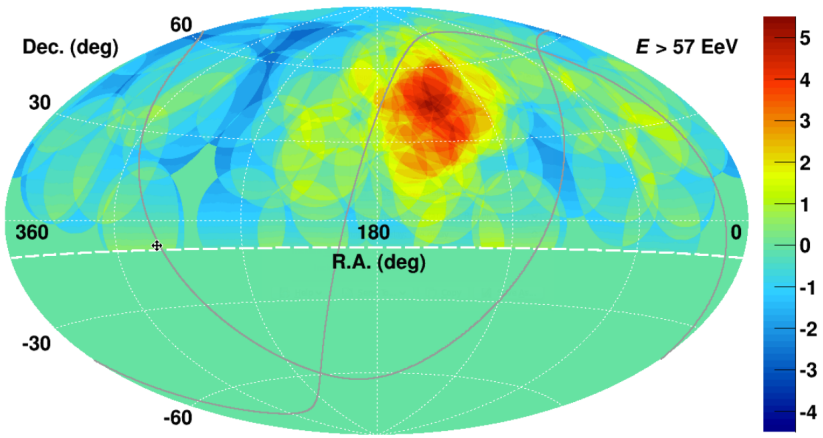
- $r = 1^\circ - 30^\circ$, $\Delta r = 1^\circ$
- $E = 40 - 80$ EeV, $\Delta E = 1$ EeV



- $r = 12^\circ$, $E = 54$ EeV
- $n_{\rm obs}/n_{\rm exp}$ = 14/3.23
- pre-trial: 4.3 σ
- post-trial: $P = 69\%$

TA:

- $r = 15^\circ - 35^\circ$, $\Delta r = 5^\circ$
- $E = 57$ EeV



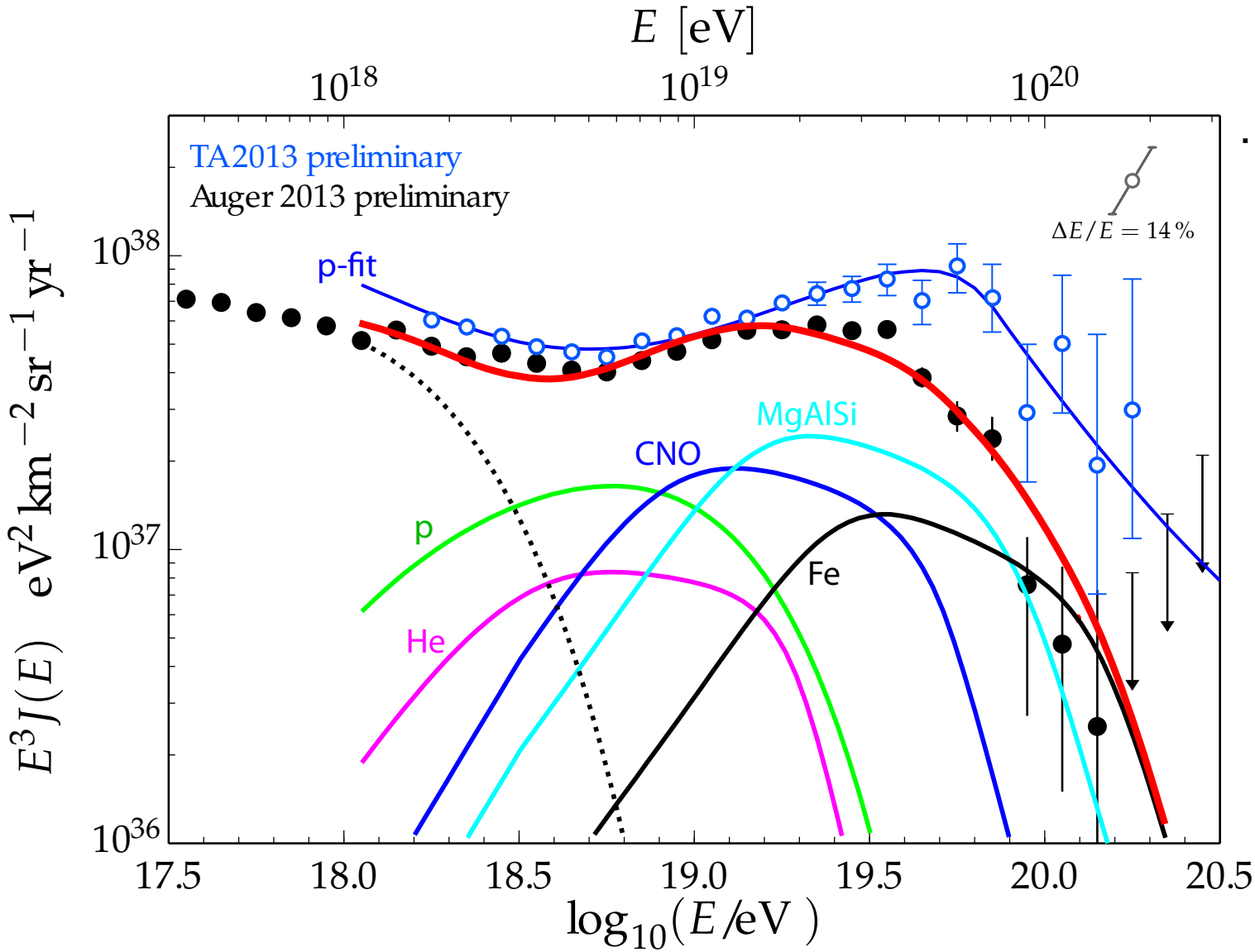
- $r = 20^\circ$, $E = 57$ EeV
- $n_{\rm obs}/n_{\rm exp}$ = 24/6.88
- pre-trial: 5.1 σ
- post-trial: 3.4 σ

Auger Coll., APJ **804** (2015) 1, 15; TA Coll., APJ **790** (2014) L21, 7-year update at ICRC15.

Summary of Observations

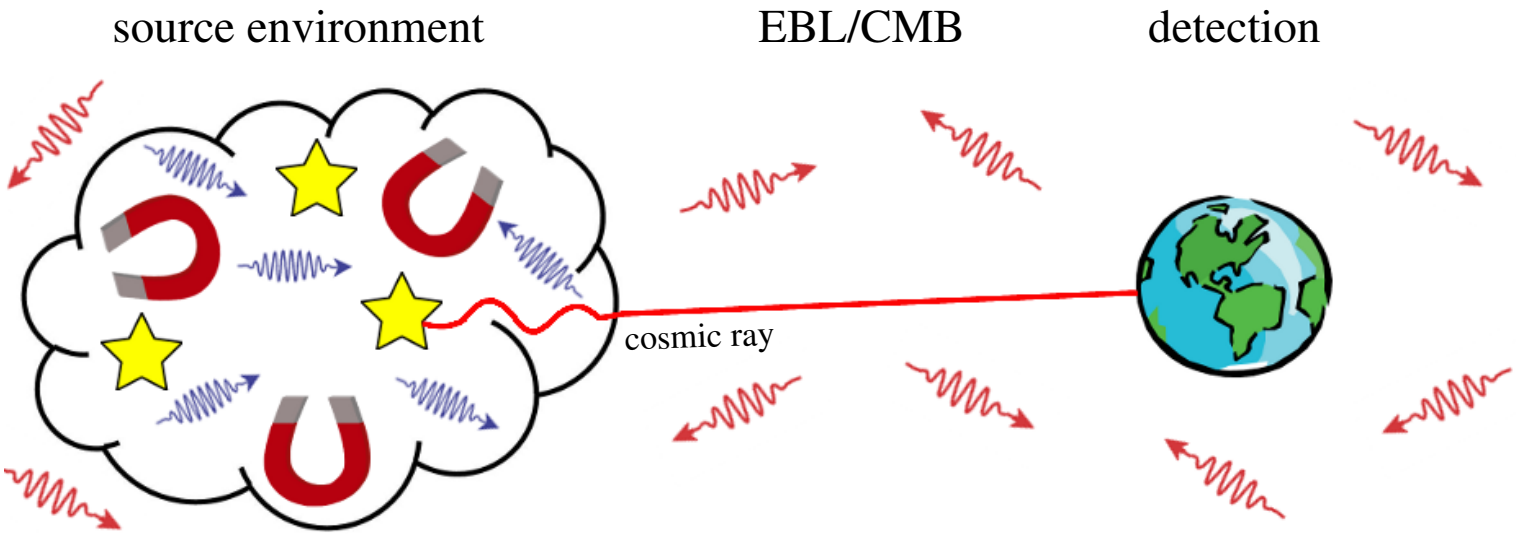
- spectrum
  $\rightarrow$ flux suppression at $E \gtrsim 5 \times 10^{19}$ eV
- elongation rate, $\langle X_{\rm max} \rangle$, $\sigma(X_{\rm max})$, $r_G(X^*_{\rm max}/S^*(1000))$
  $\rightarrow$ mixed composition around and above the ankle
  (if LHC-inspired extrapolations of hadronic interactions are ok)
- neutrinos and photons $\rightarrow$ see Carla's talk!
  $\rightarrow$ start probing cosmogenic fluxes from 100% p
- p+air cross section
  $\rightarrow$ compatible with model extrapolations
- arrival directions
  $\rightarrow$ isotropic in the South, some hints for anisotropy in the North
- muons content of air showers
  $\rightarrow$ at odds with predictions for mixed composition

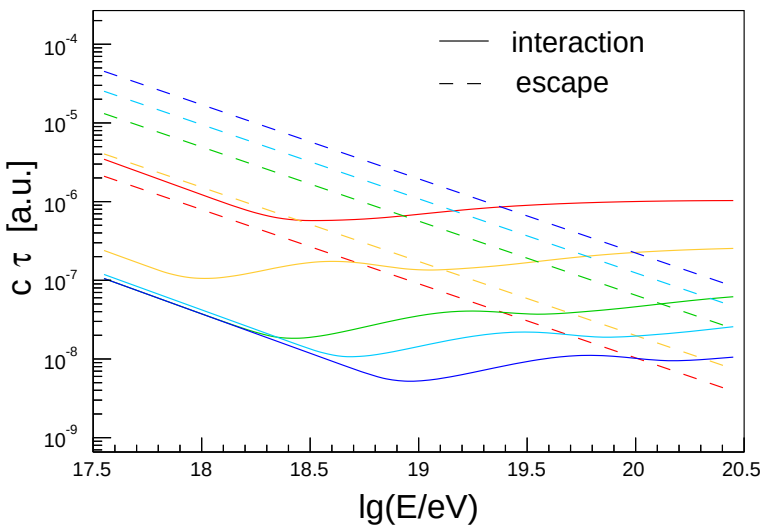
Origin of Ankle and Flux Suppression?

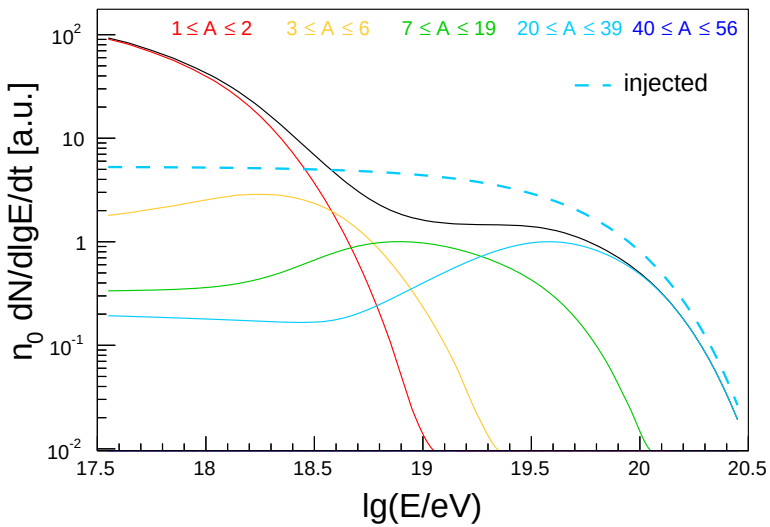


Kampert&Tinyakov, CRP **15** (2014) 318; Aloisio, Berezinsky & Blasi, JCAP 1410 (2014) 10, 02

Ankle from Interactions in Source Environment?

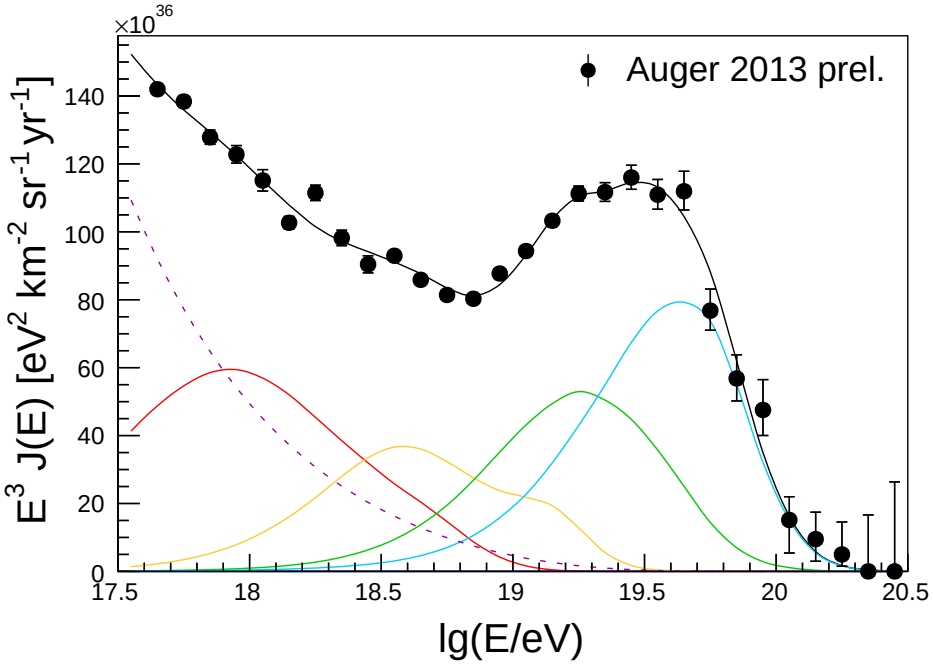


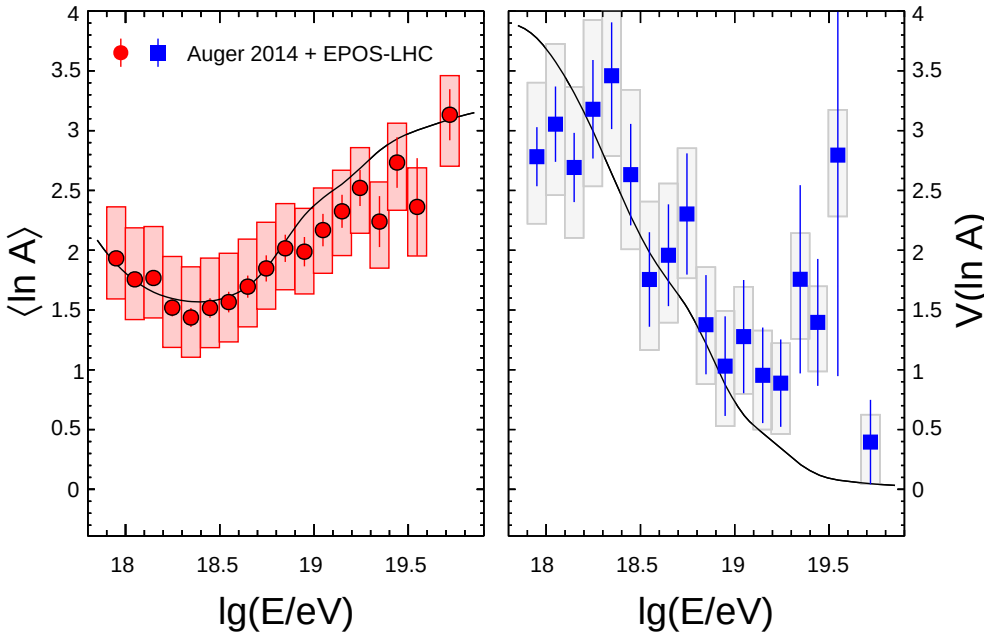




MU, Farrar & Anchordoqui, PRD **92** (2015) 123001

Ankle from Interactions in Source Environment?

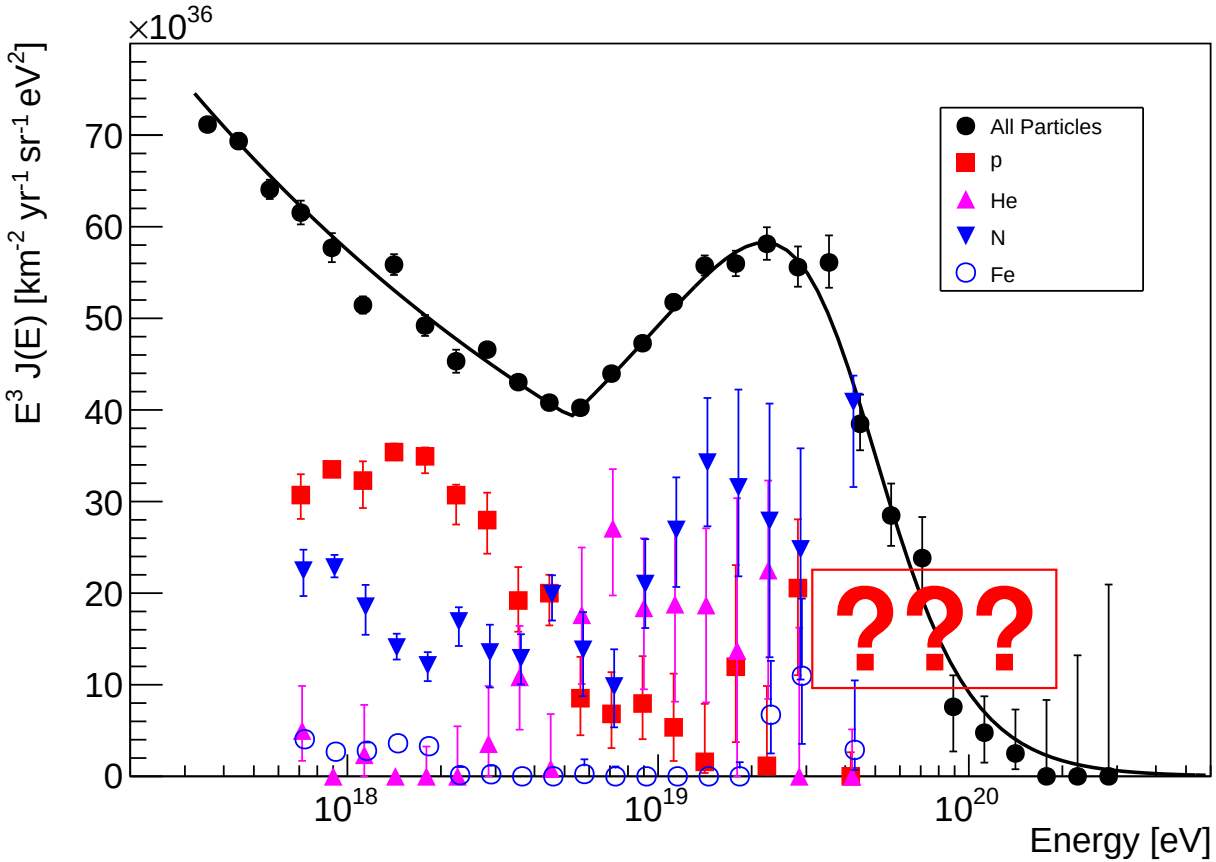




MU, Farrar & Anchordoqui, PRD **92** (2015) 123001

Upgrade of the Pierre Auger Observatory

- origin of flux suppression?
- proton fraction at UHE?
- hadronic physics above $\sqrt{s} = 140$ TeV



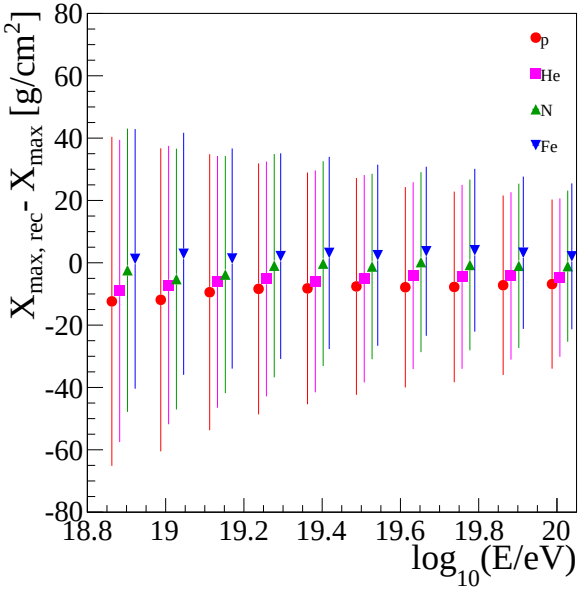
V. de Souza for the Pierre Auger Collaboration, Proc. UHECR14

Upgrade of the Pierre Auger Observatory

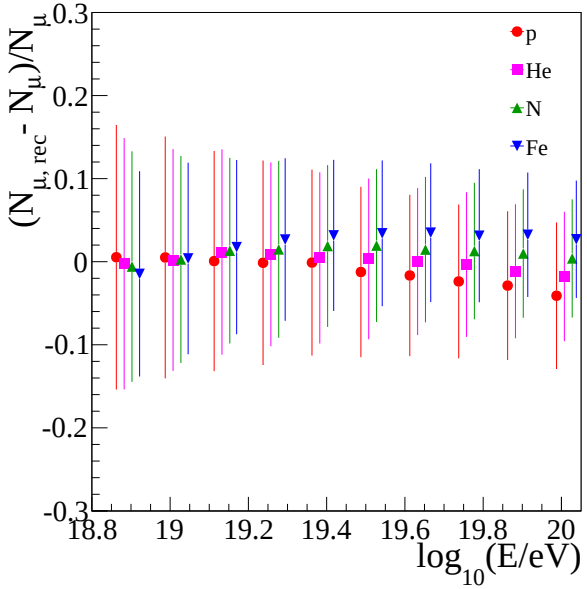
additional scintillators (4 m^2)

→ event-by-event mass estimate with 100% duty cycle

$X_{\max}$ determination:



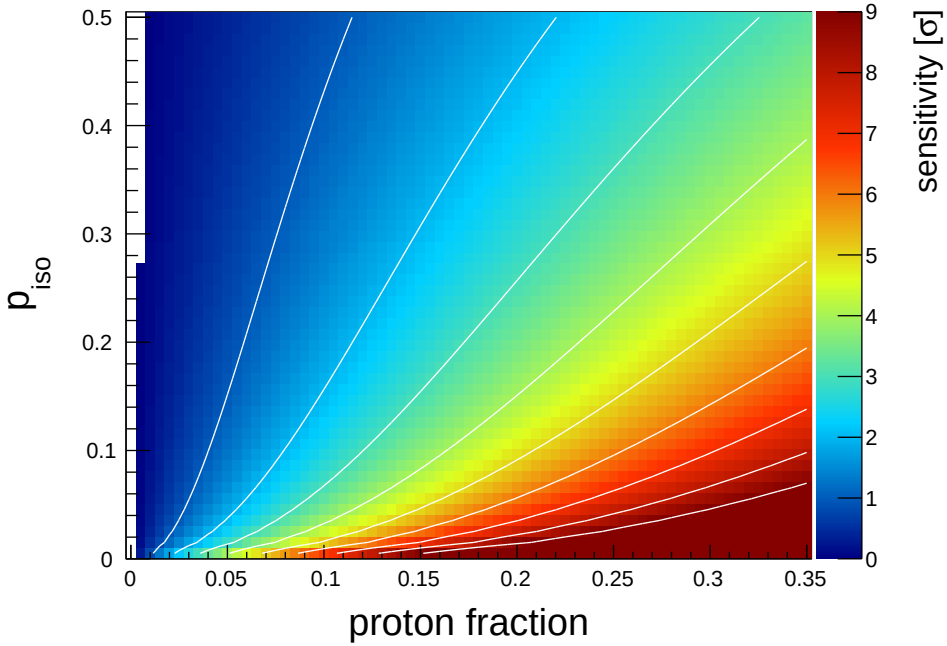
muon determination:



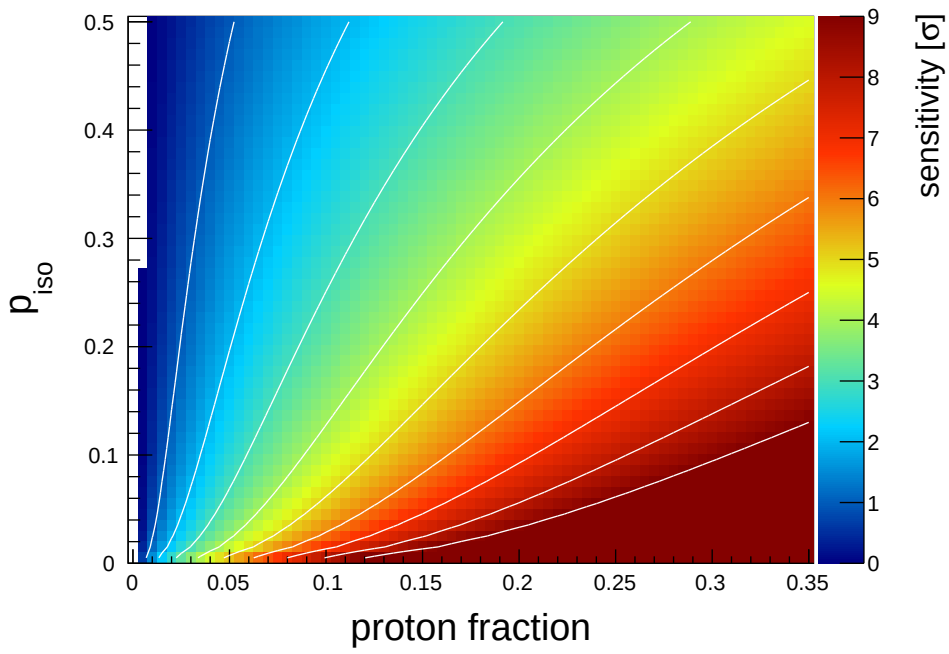
Upgrade of the Pierre Auger Observatory

low-Z particle astronomy

no mass determination:

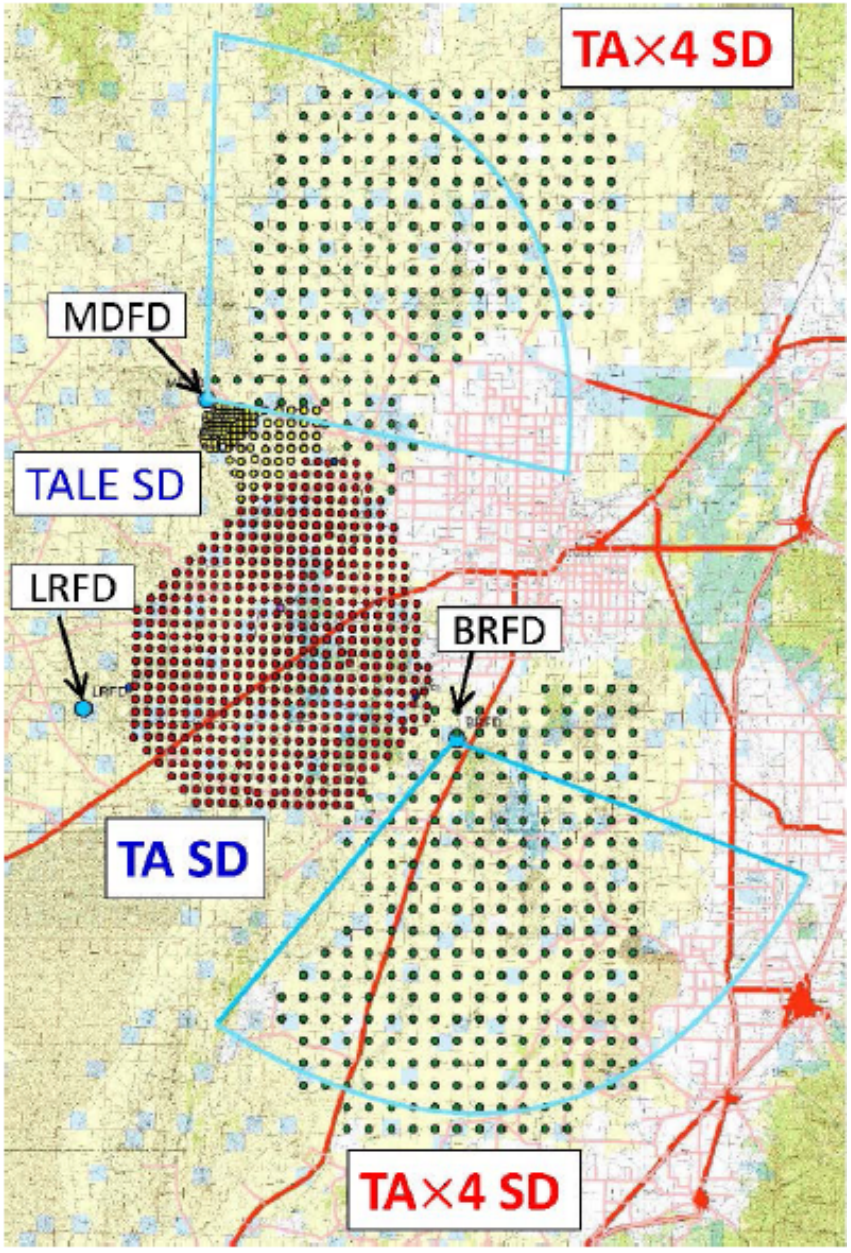


p-Fe separation merit factor: 1.5



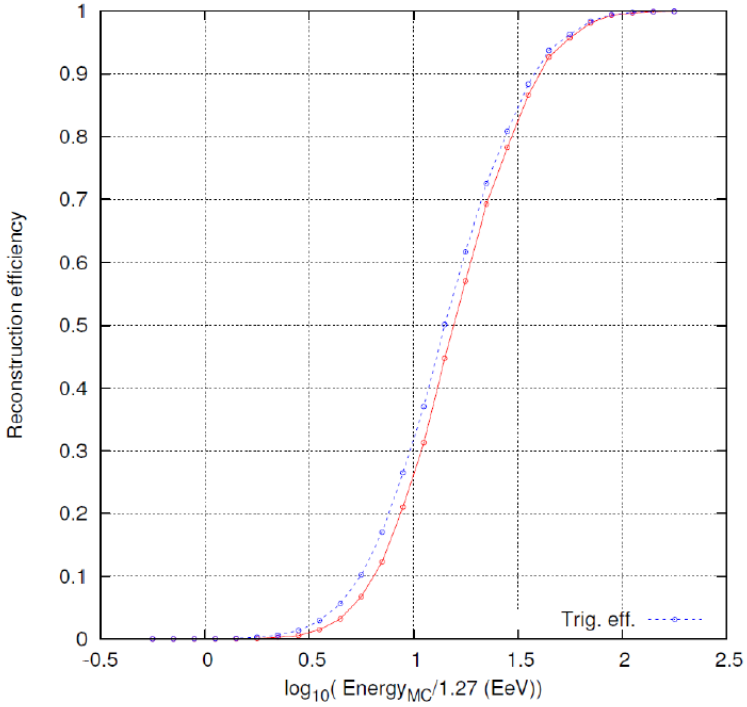
(isotropic background: 25%)

TAx4



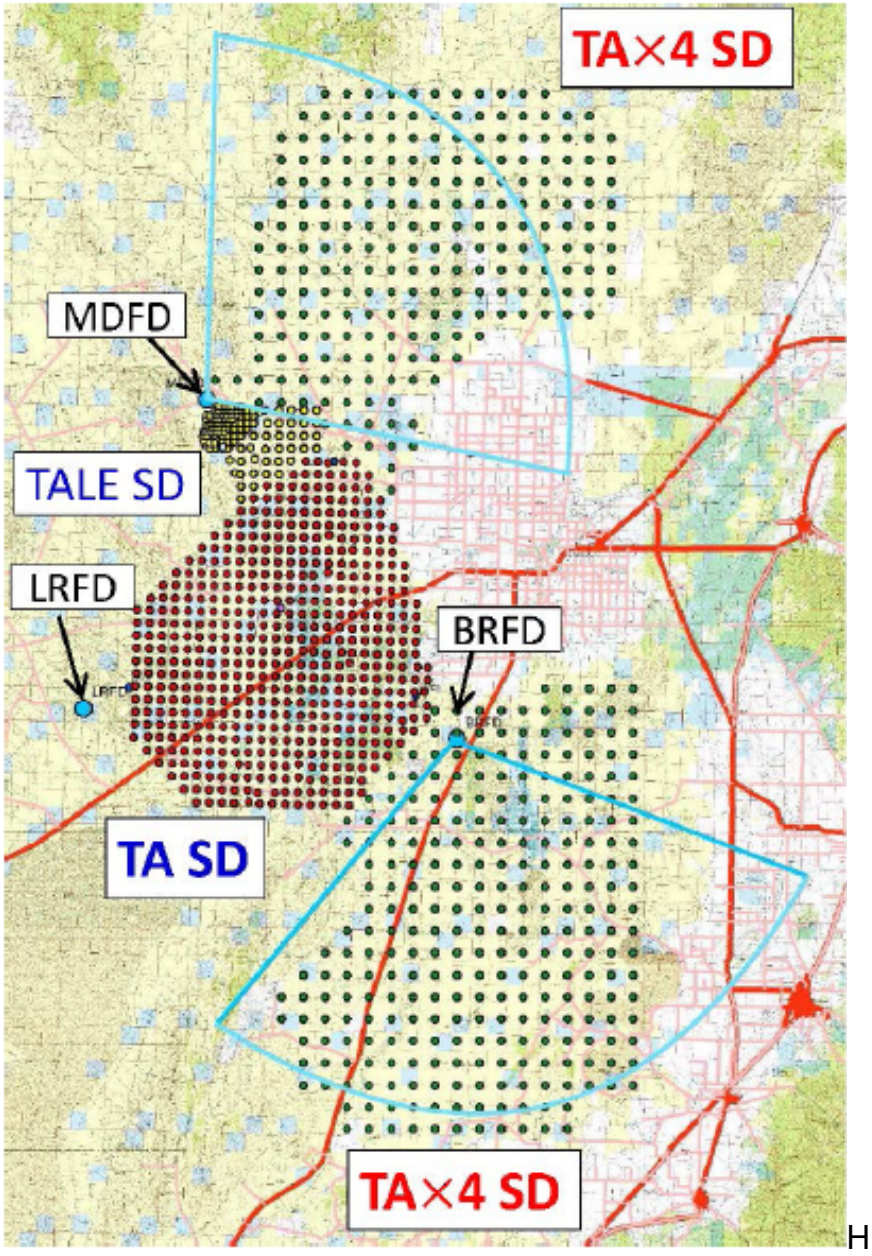
quadruple acceptance:

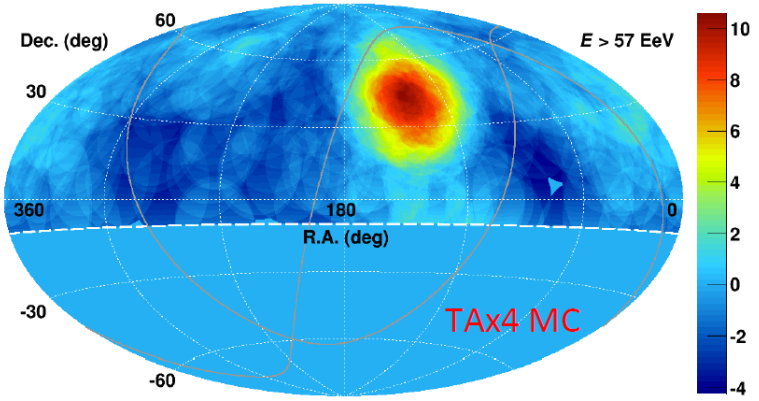
- 500 add. SDs
- 2.08 km spacing
- 2 add. FD stations

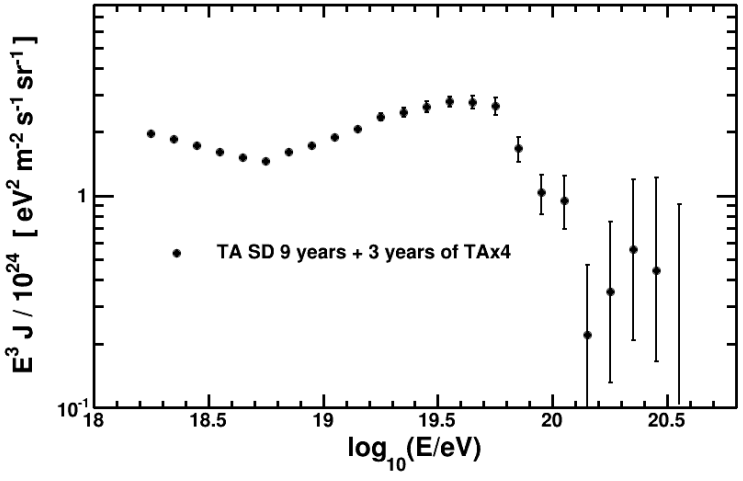


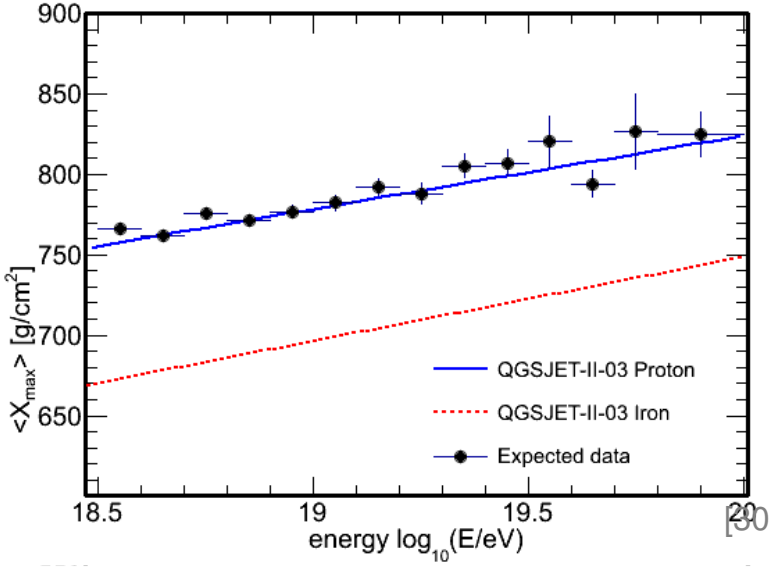
H. Sagawa for TA, UHECR14.

TAx4









H. Sagawa for TA, UHECR14.

Outlook

- TA & Auger Upgrades:
  - study nature of flux suppression
  - prospects for particle astronomy
  - R&D for Next Generation Observatory
- fluorescence detection from space
  - KLYPVE, Mini-EUSO (K-EUSO), EUSO
- radio detection of air showers
  - ground-based hybrid detectors (radio&surface)
  - high-altitude antennas
- LHC run II
  - $\sqrt{s} = 14$ TeV ($E_{\rm CR} = 10^{17}$ eV), p+O collisions?