The 7th International Workshop on Very High Energy Particle Astronomy
- Next Generation Explorer for Cosmic Ray Origin -

Auger Results on CR Origin – Status and Plans –

PIERRE AUGER OBSERVATORY

Karl-Heinz Kampert
University Wuppertal

BERGISCHE UNIVERSITÄT WUPPERTAL

Kashiwa (Japan), March 19-20, 2014

Photo by Steven Saffi

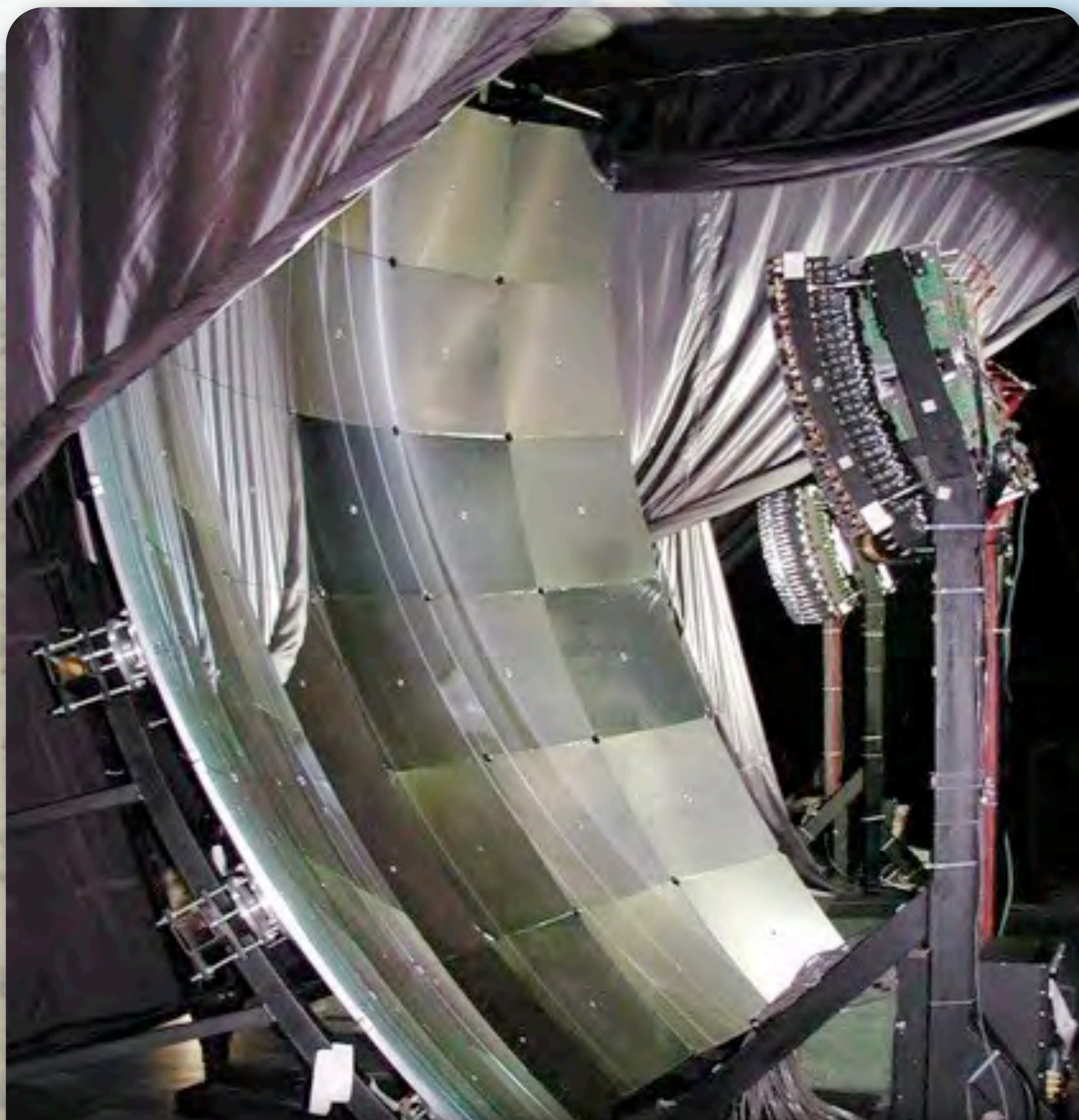
Pierre Auger Observatory

1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

130 radio antennas

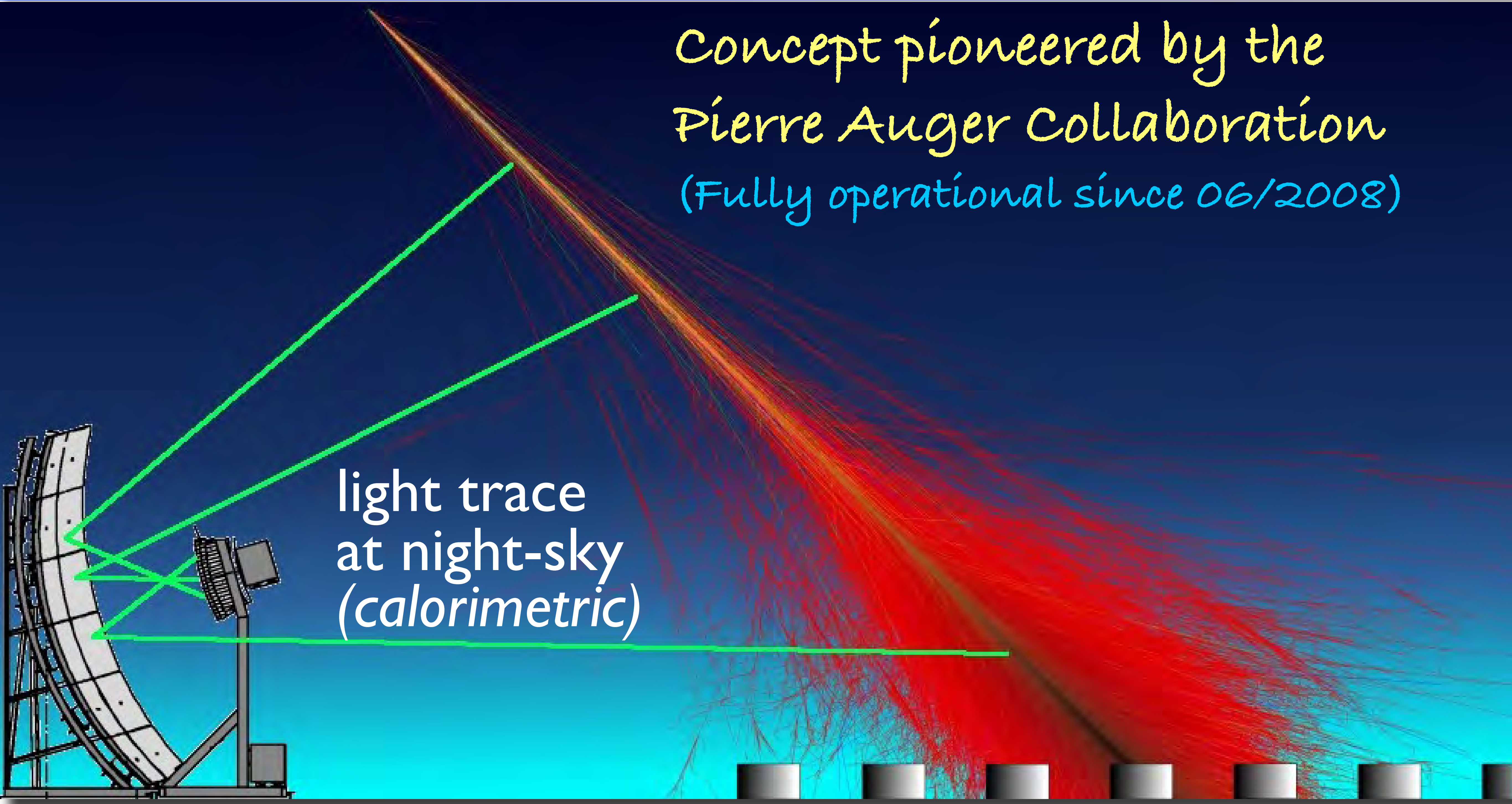
Province Mendoza, Argentina



Auger Hybrid Observatory

3000 km^2 area, Argentina
27 fluorescence telescopes plus
...1660 Water Cherenkov tanks

A New Generation: Hybrid Observation of EAS

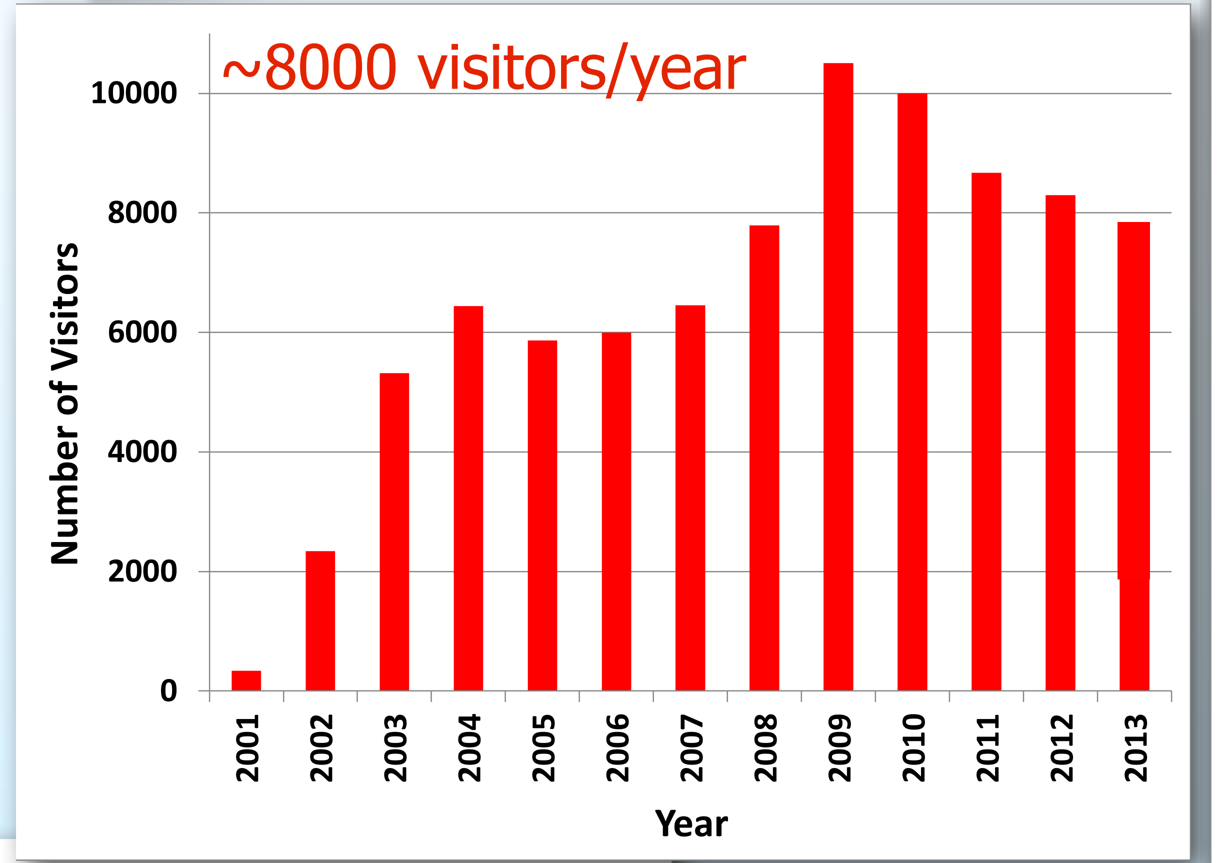


Fluorescence light

Particle-density and
-composition at ground

Also:
Detection of Radio- & Microwave-Signals

>85,000 visitors at the Observatory



80,000st visitor
in March 2013

annual
parade

Science Fair 2012
organizers and
participants

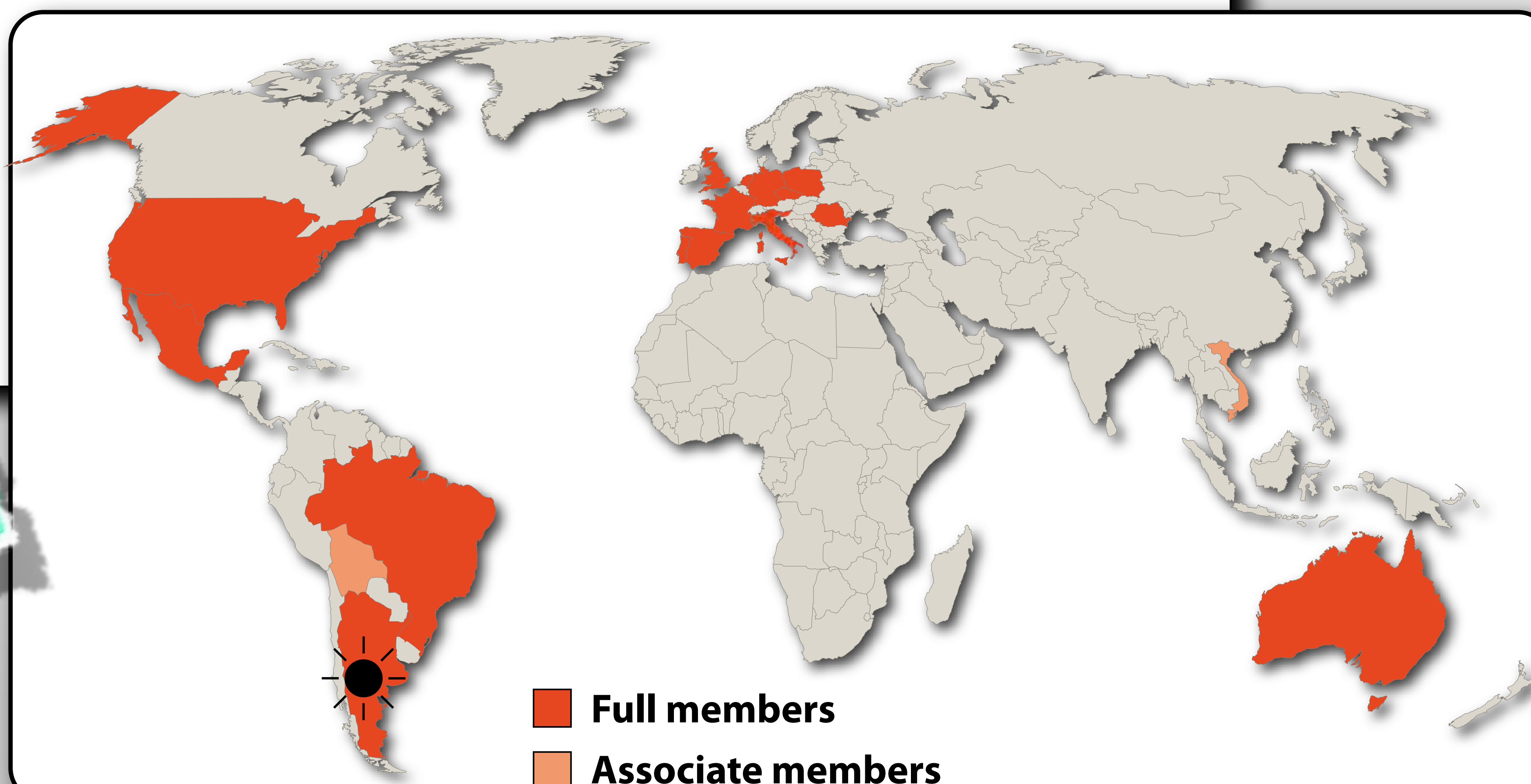
Pierre Auger Collaboration

~500 Collaborators; 90 Institutions, 18 Countries:

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

*Associated

currently 163 PhD students



Outline

1. Brief Overview of Recent Results

- energy spectrum
- mass composition
- anisotropies
- photons
- neutrinos → *J. Alvarez-Muniz*
- particle & fundamental physics
- interdisciplinary science, ...

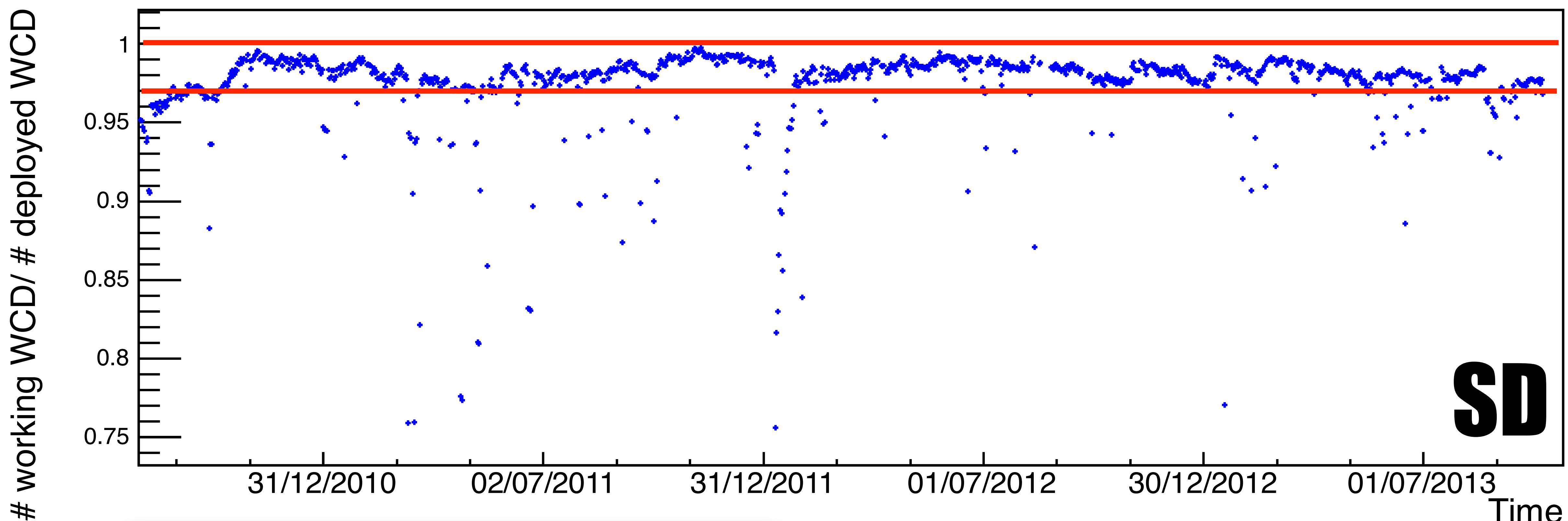
2. Puzzles to be solved; Rational of Upgrade

- origin of the flux suppression
- proton astronomy at the highest energies
- features of hadronic interaction @ $\sqrt{s}$~100 TeV

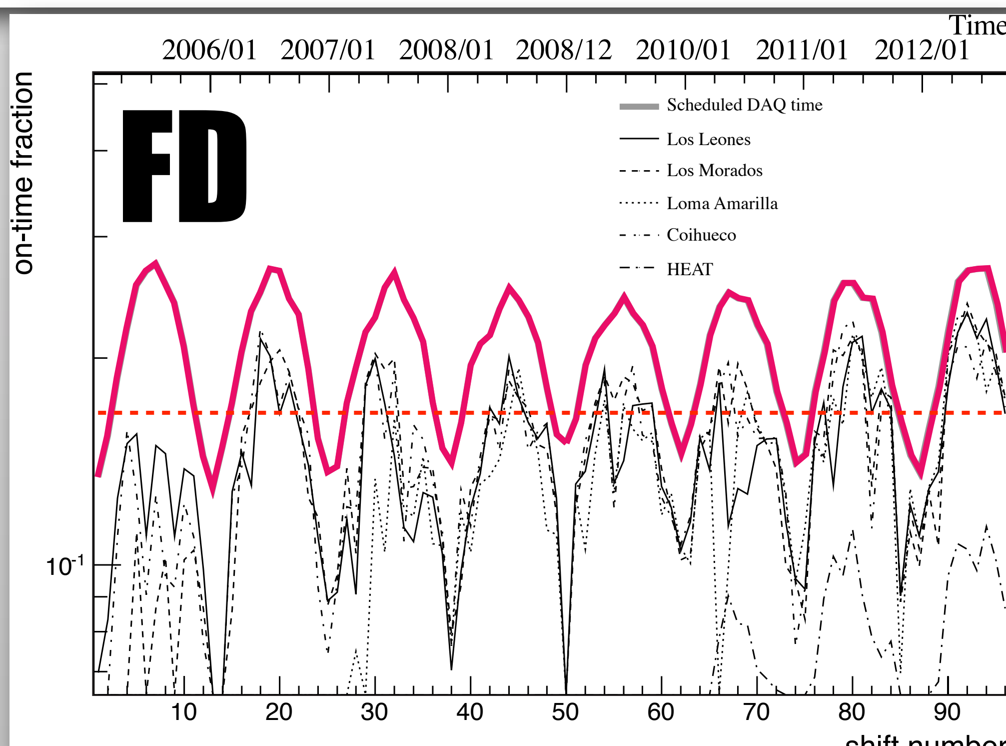
3. Cost Estimate, Timeline

The „Swiss Clock“

Fraction of Water Cherenkov Tanks in operation



100%
97%



scheduled shifts since start of Auger

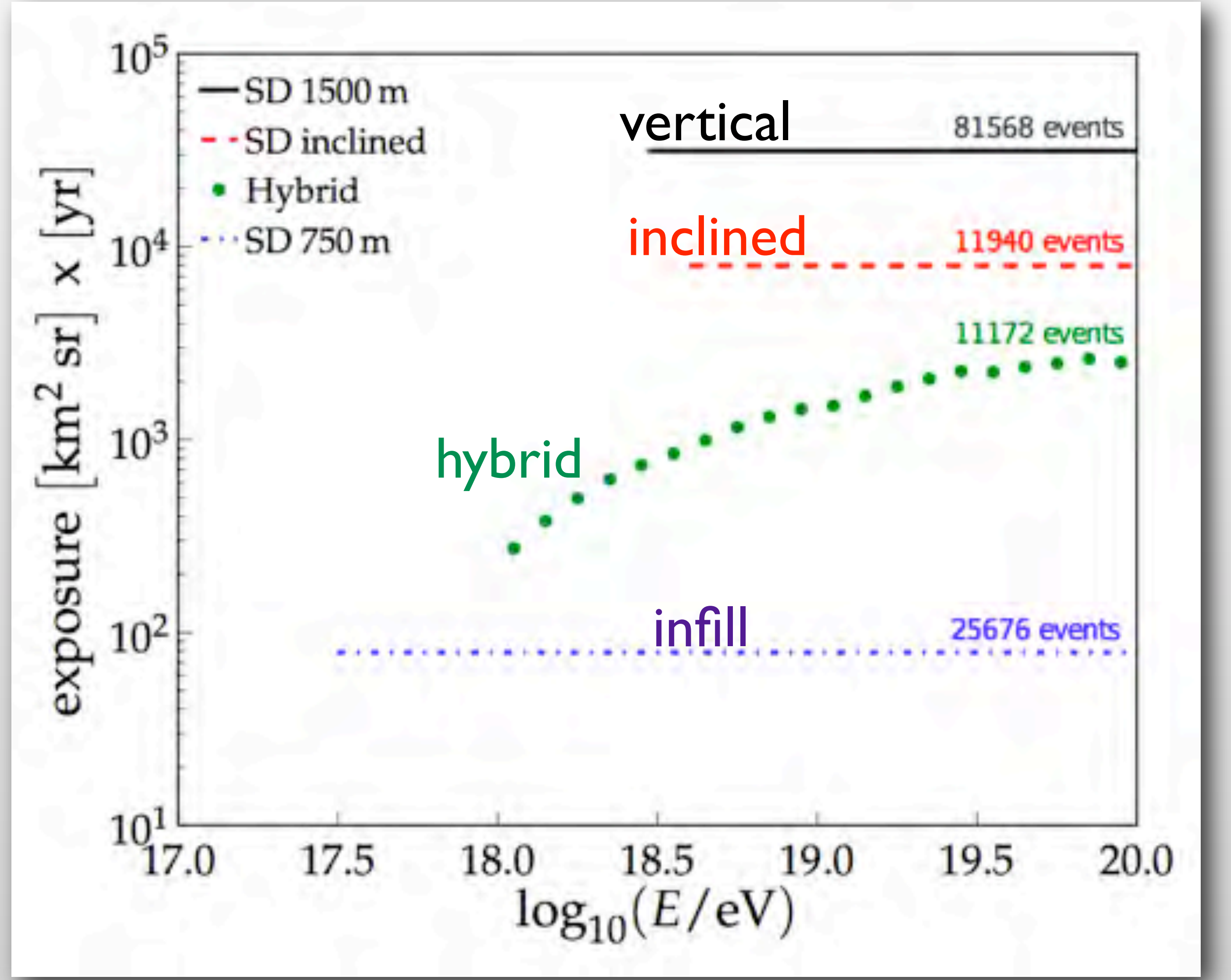
15% duty cycle

very effective atmospheric monitoring

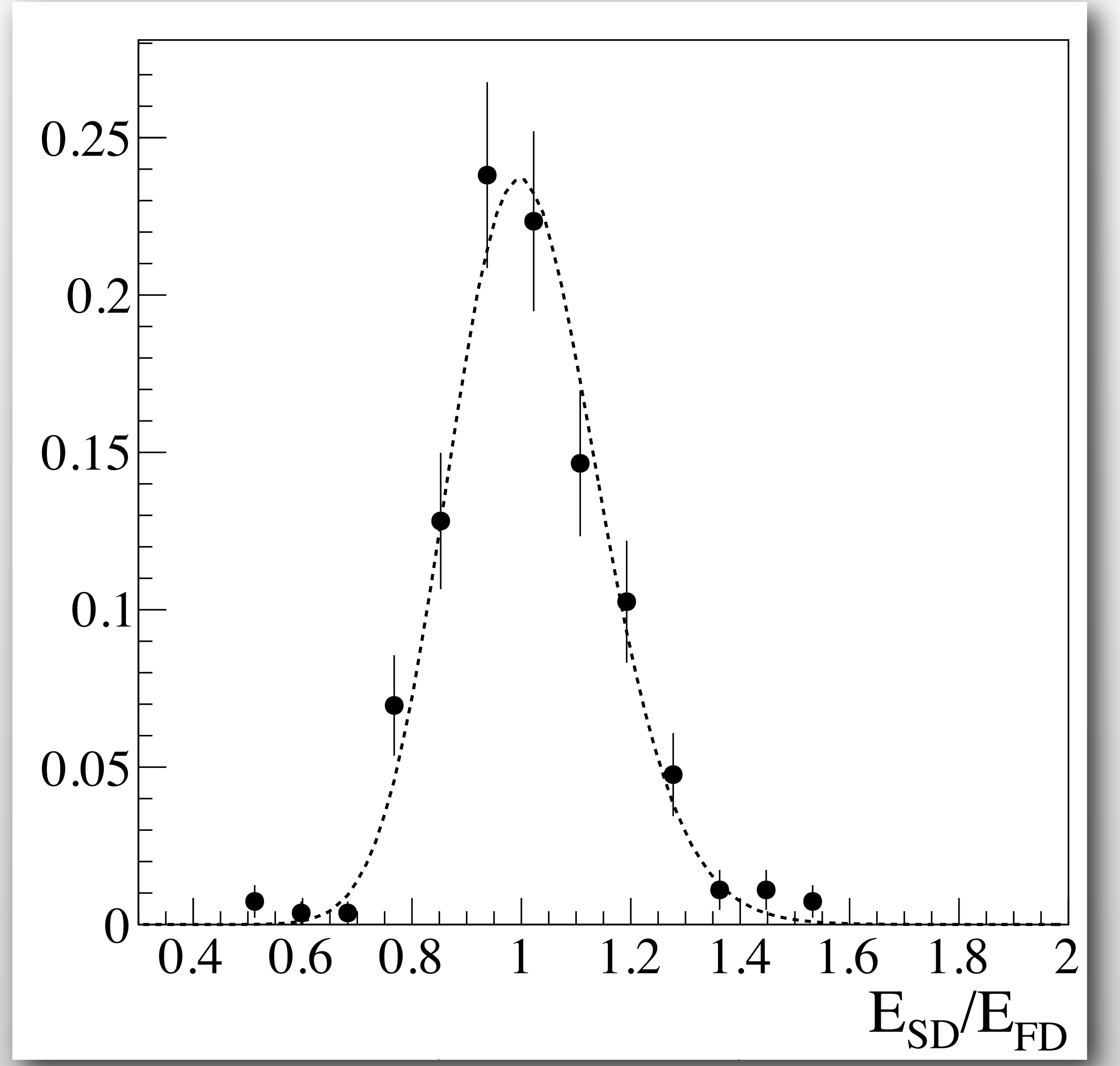
ALMA, LOFAR, ... make use of in our tools

Exposure and Performance

32 000 km^2 sr yr and about an additional 6 500 km^2 sr each year

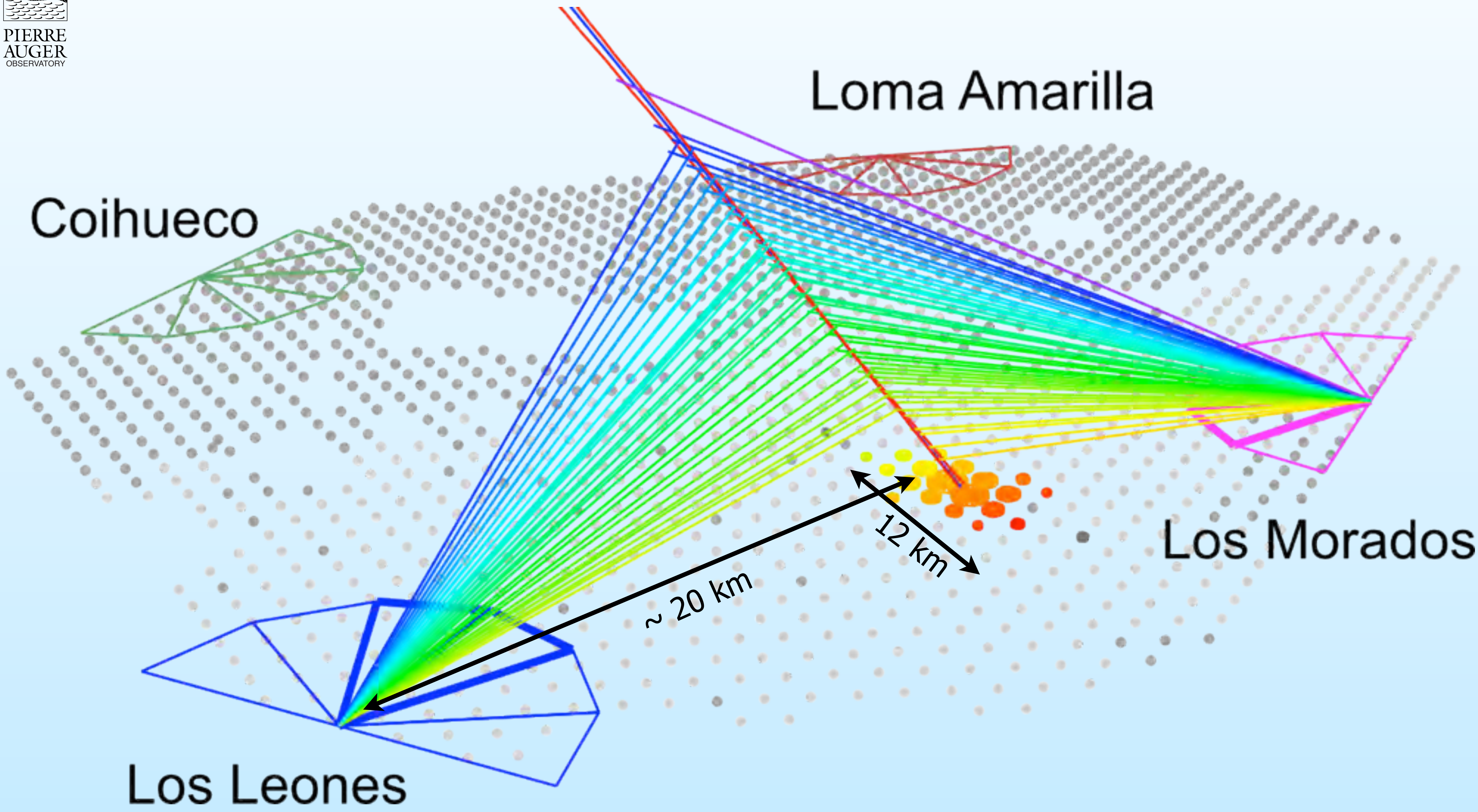


infill and standard array
aperture up to 80° zenith angle

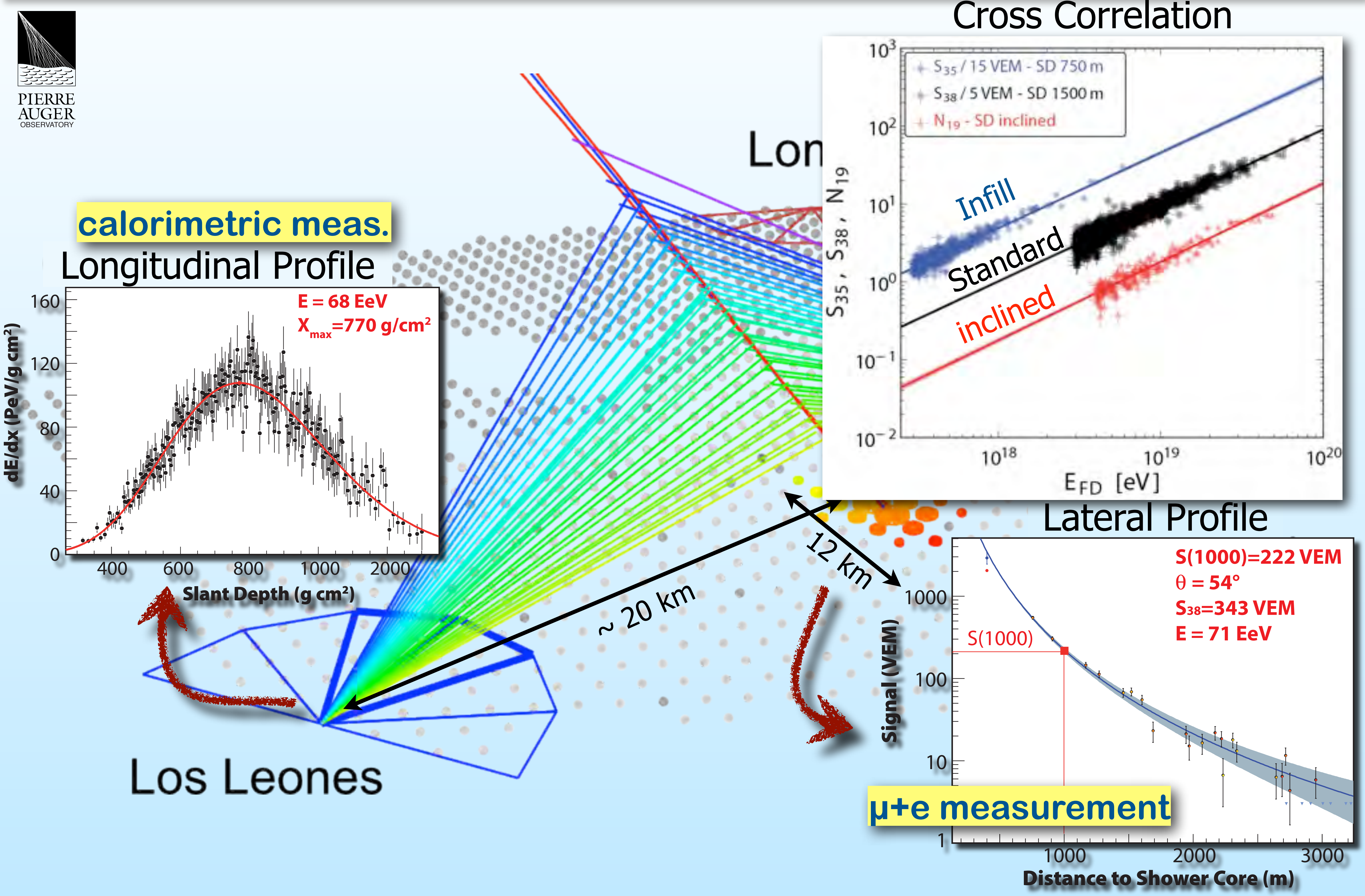


SD energy (angular) resolution
<12% (<1°) above 10 EeV

Event Example in Auger Observatory



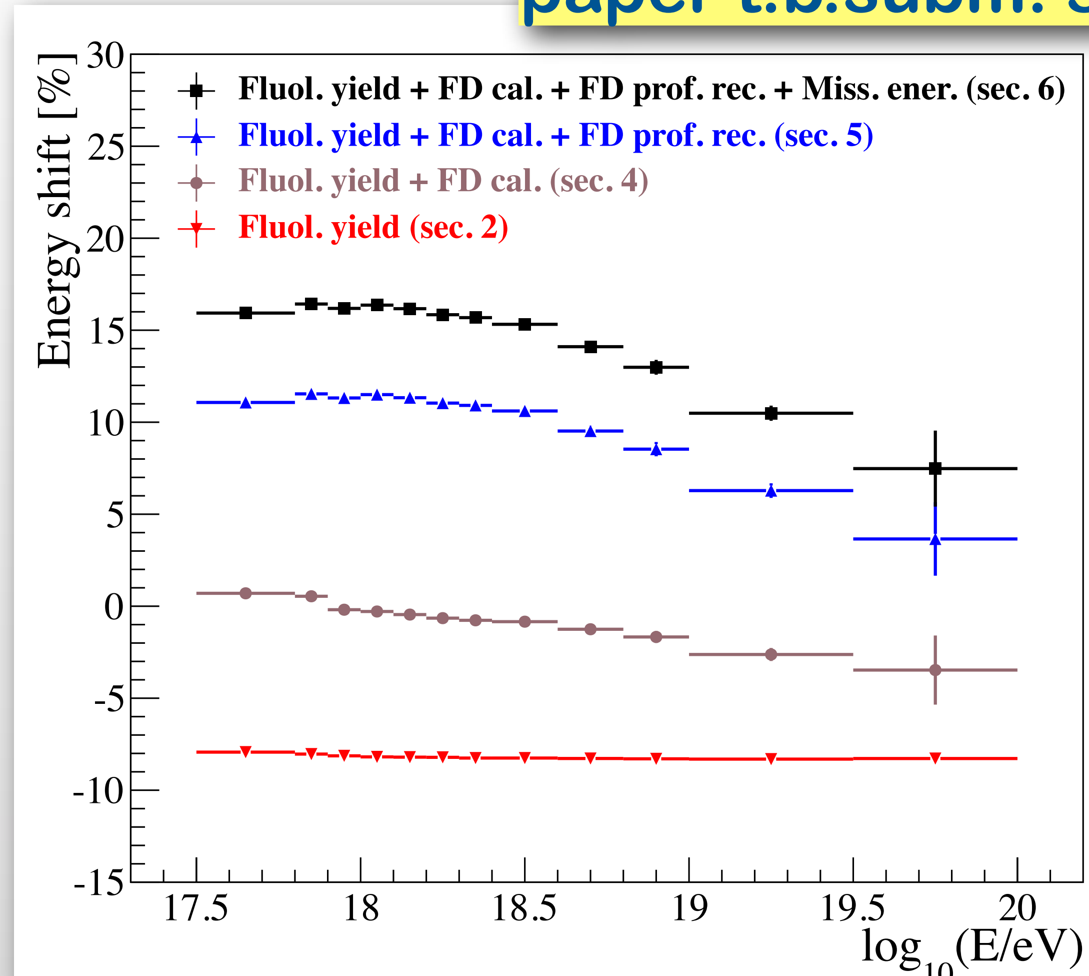
Event Example in Auger Observatory

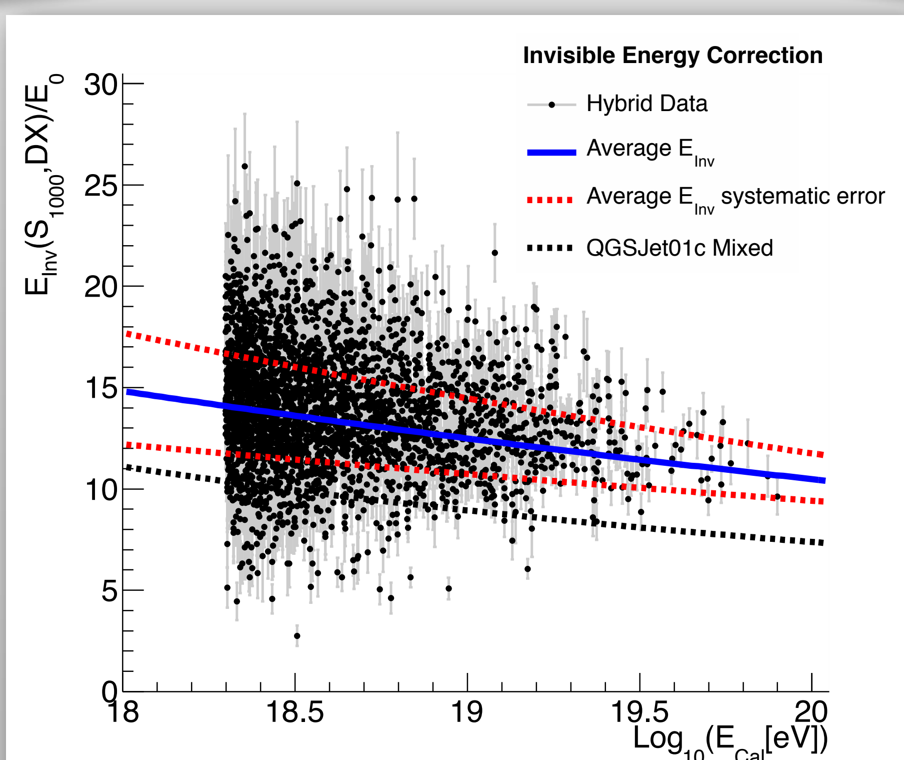


Update of Energy Scale in 2013

paper t.b.subm. soon

Lightsource flown on octocopter
– also used for X-calibration with TA –





Changes in FD energies at 10^{19} eV	
Airfly fluorescence yield (sec. 2)	**-8.3%**
New optical efficiency	3.7%
Calibr. database update with opt. halo corr.	3.2%
Sub total (FD calibration - sec. 4)	**6.9%**
Likelihood fit of the profile	2.2%
Folding with the point spread function	7.6%
Sub total (FD profile reconstruc. - sec. 5)	**9.8%**
New missing energy (sec. 6)	**4.1%**
Total	**12.5%**

New Systematics of Energy Scale

paper t.b.subm. soon

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

Based on AirFly data

Based on Atmosph. Monitoring data

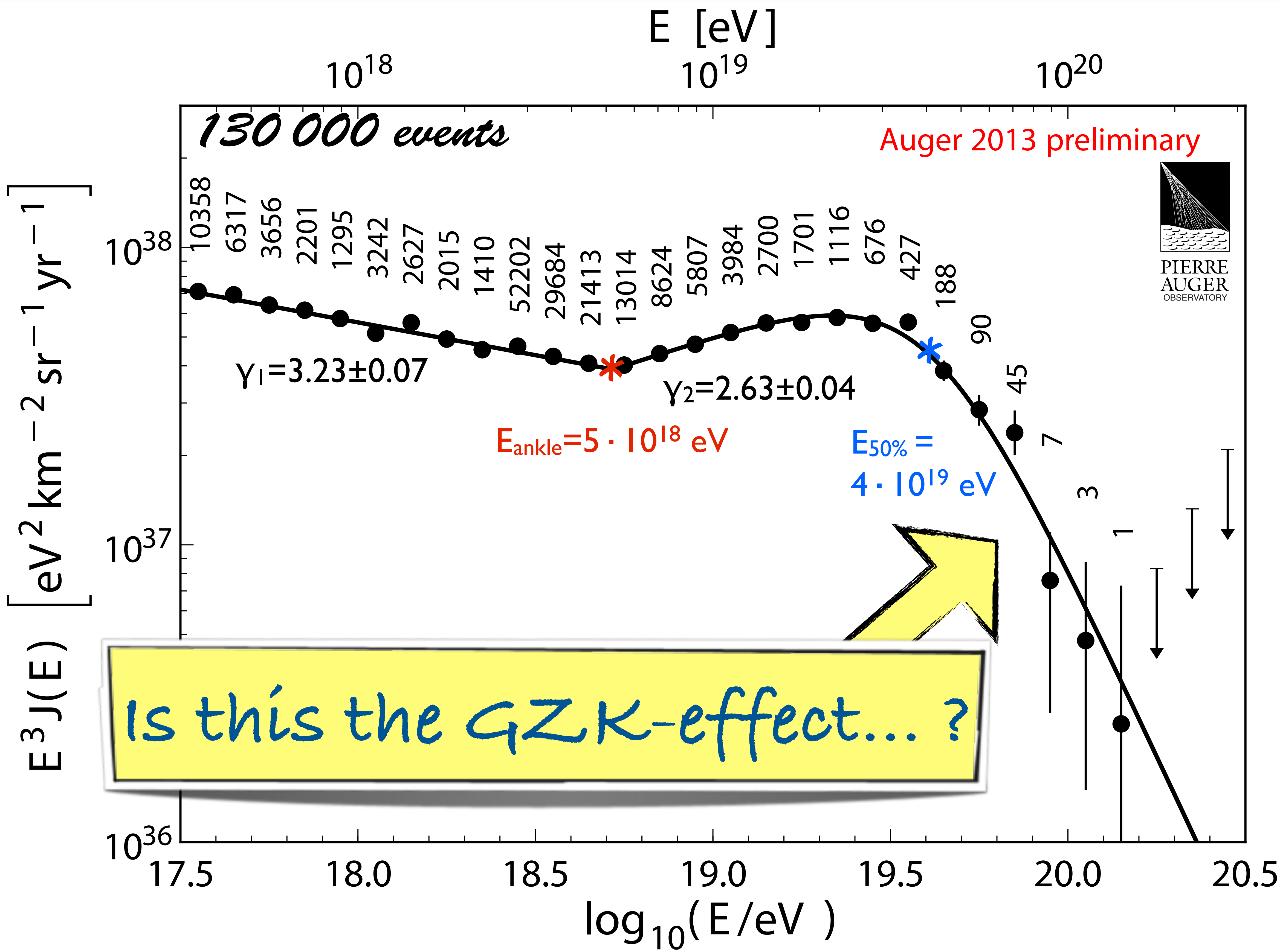
Better optical tools

Better understanding of FD data

Based on golden hybrid

down from 22% before

Auger Combined E-Spectrum (0°-80°)



Is this the GZK-effect… ?

GZK-Effect: Energy losses in CMB

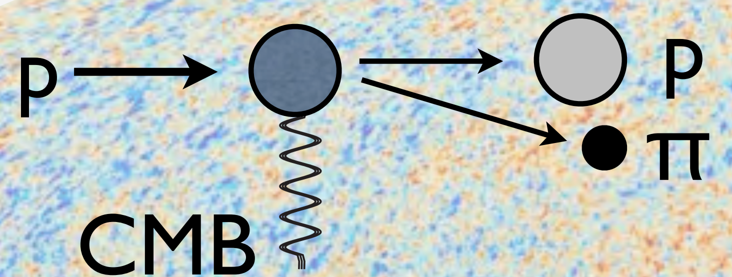


photo-pion production

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow p + \pi^0$$

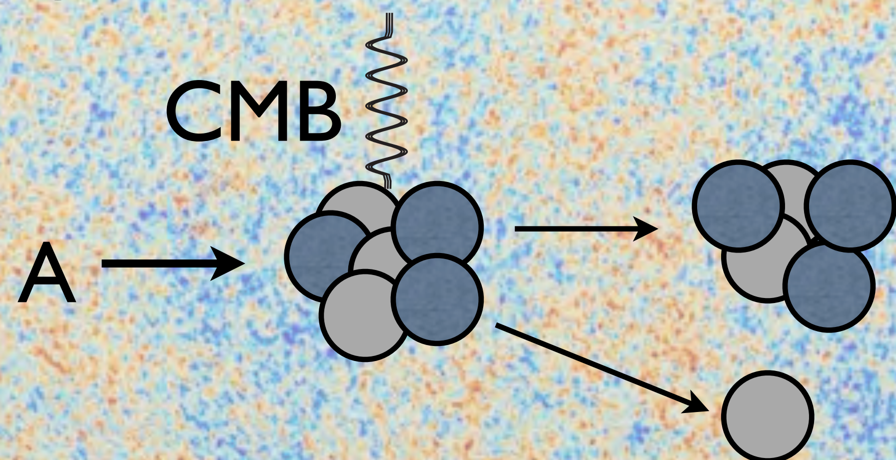


photo disintegration

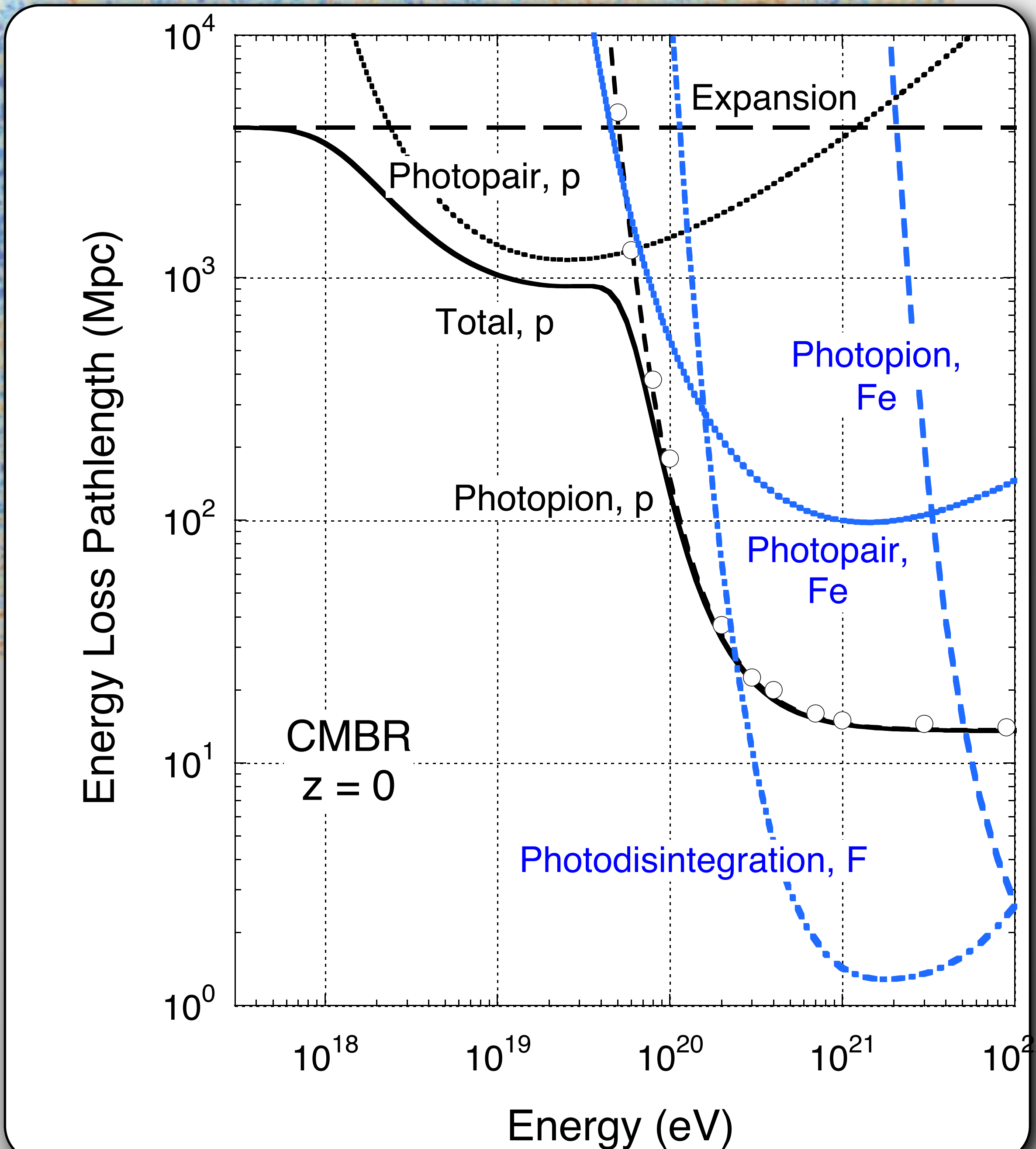
$$A + \gamma_{\mathrm{CMB}} \rightarrow (A-1) + n \ldots$$

Greisen-**Z**atsepin-**K**uz'min (1966)

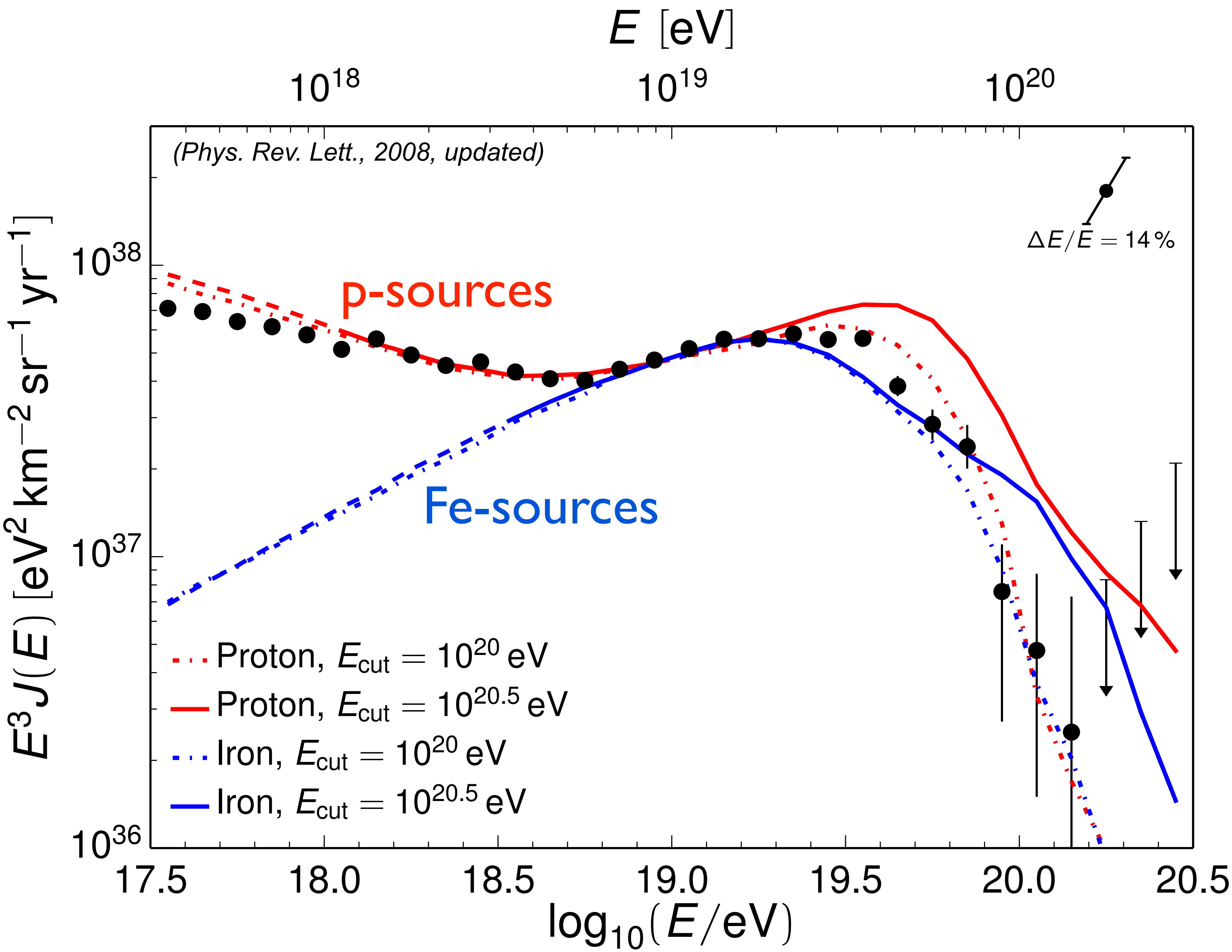
threshold: $E_p E_\gamma > (m_\Delta{}^2 - m_p{}^2)$

$\Rightarrow E_{\mathrm{GZK}} \approx 6 \cdot 10^{19}$ eV

➞ **GZK-Horizon ~ 60 Mpc**



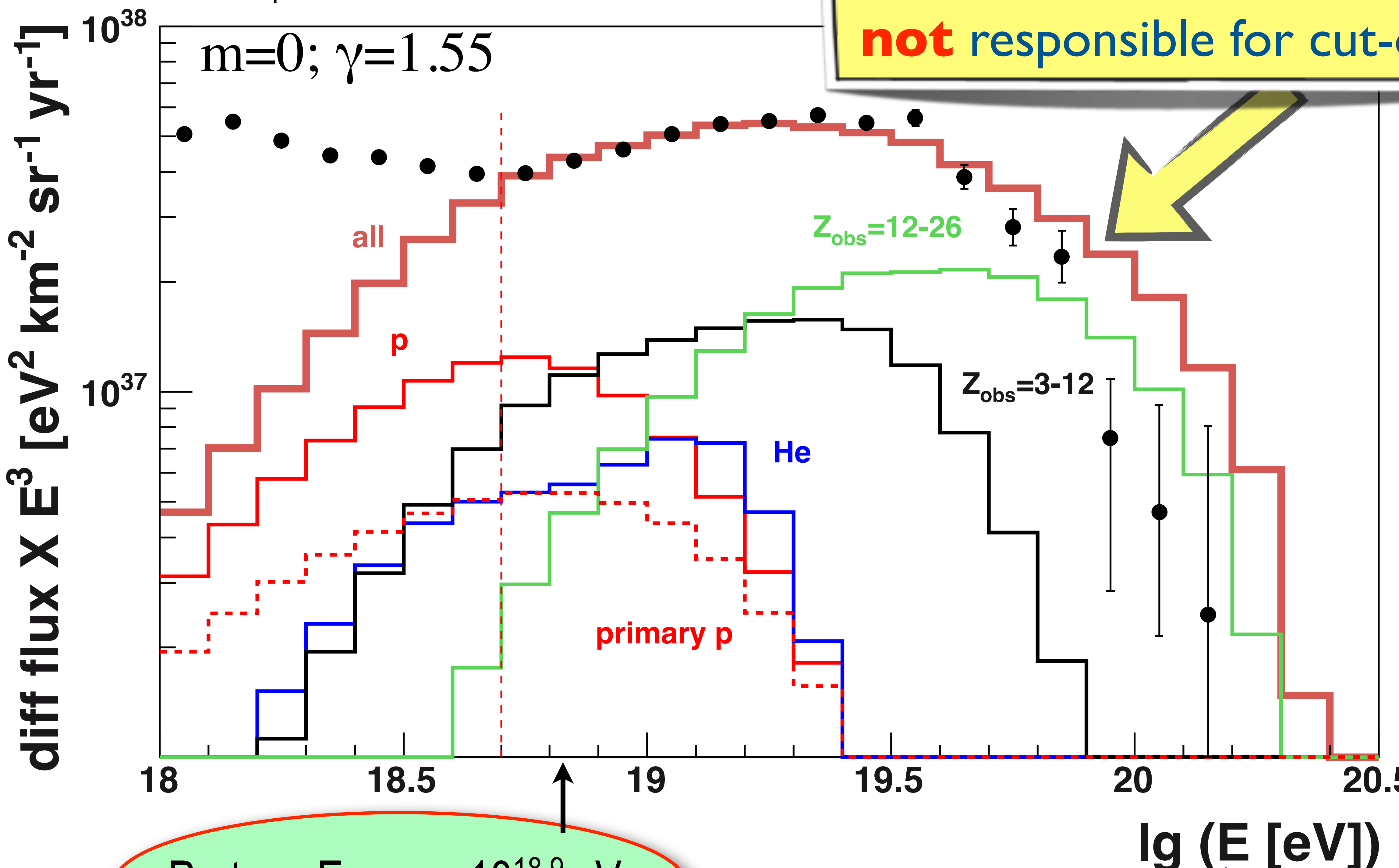
Data compared to GZK-effect



Limiting Energy of Sources (E_{max}~Z) + GZK

Model inspired by Allard, Astropart. Phys. 39-40, 2012

Simulations done with CRPropa 2.0



In this case GZK-effect is **not** responsible for cut-off!

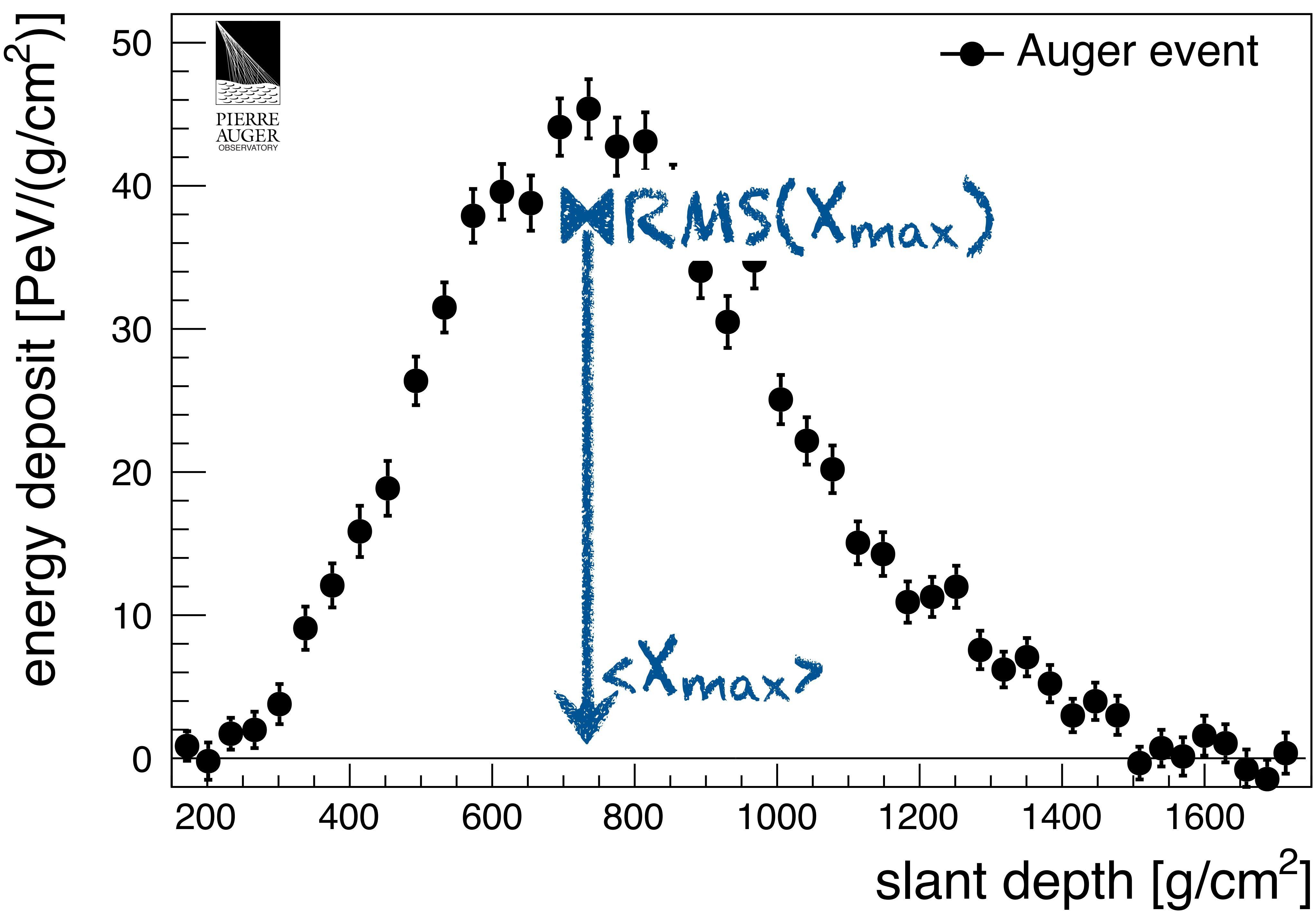
Protons $E_{max,p} = 10^{18.9}$ eV

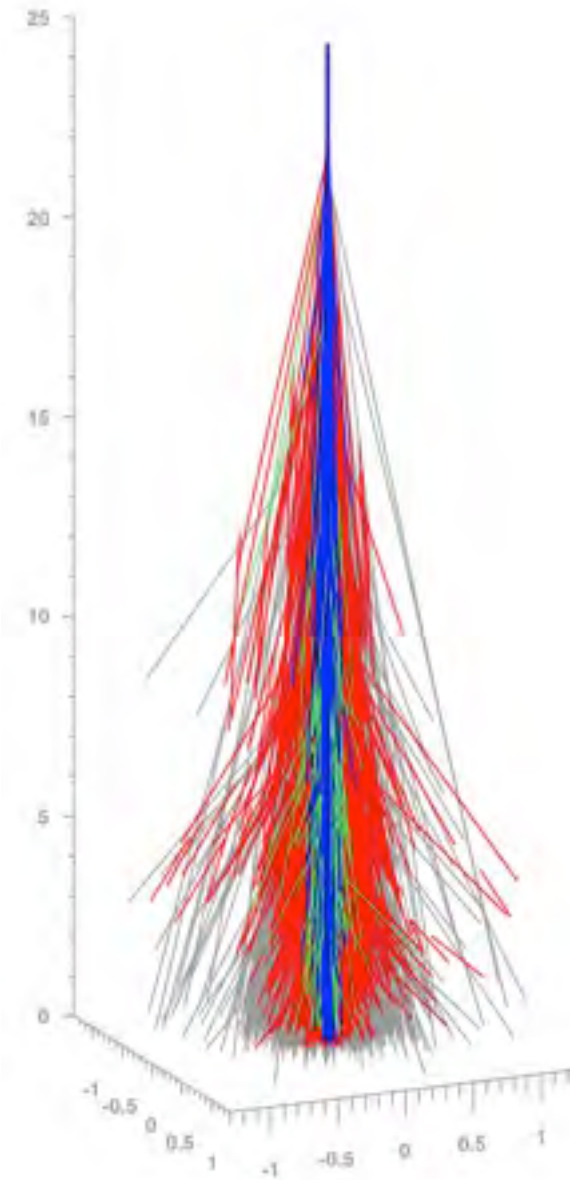
Iron $E_{max,\,Fe} = 26\ E_{max,p} = 10^{20.3}$ eV

Longitudinal Shower Development → Primary Mass

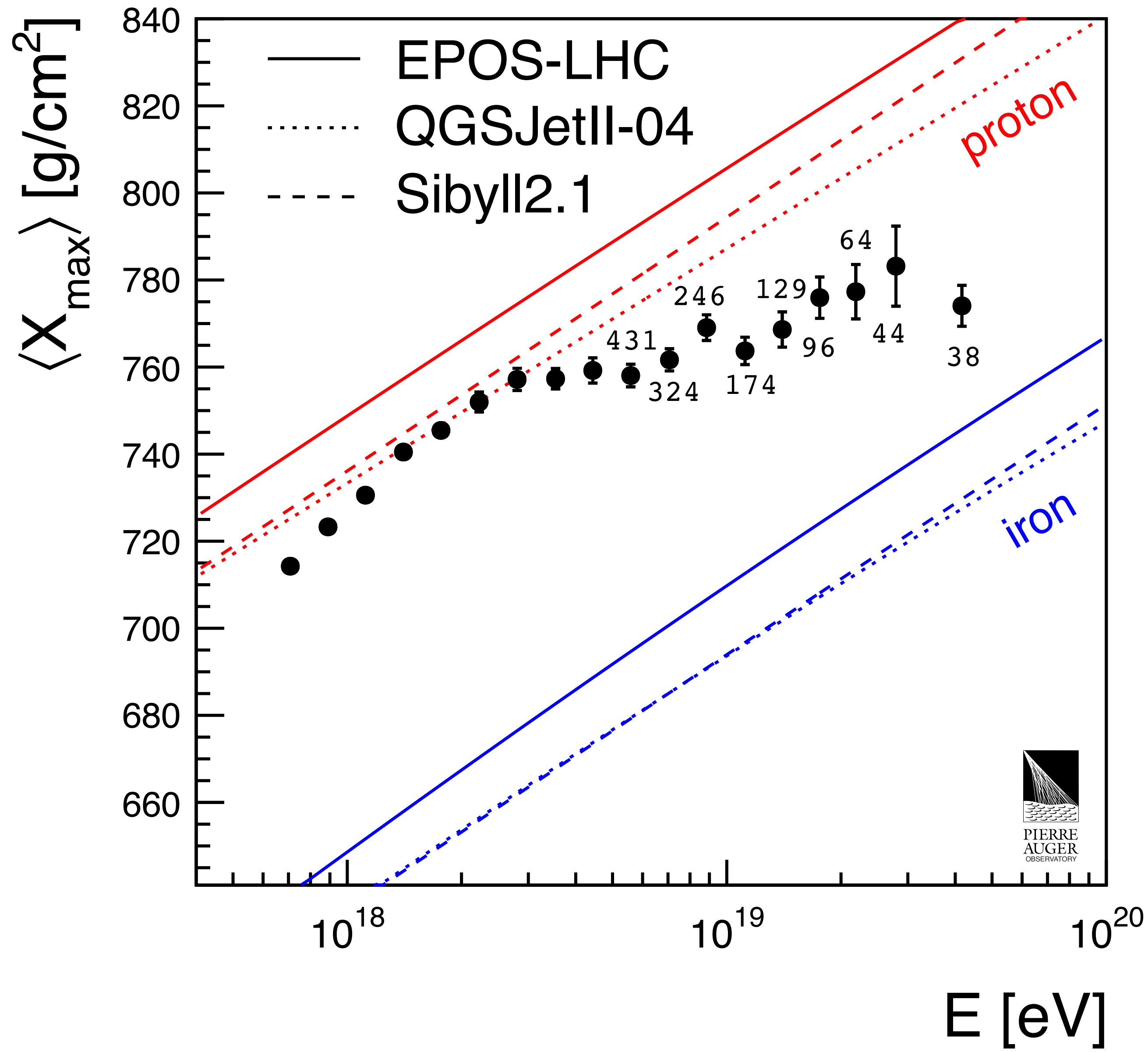
KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

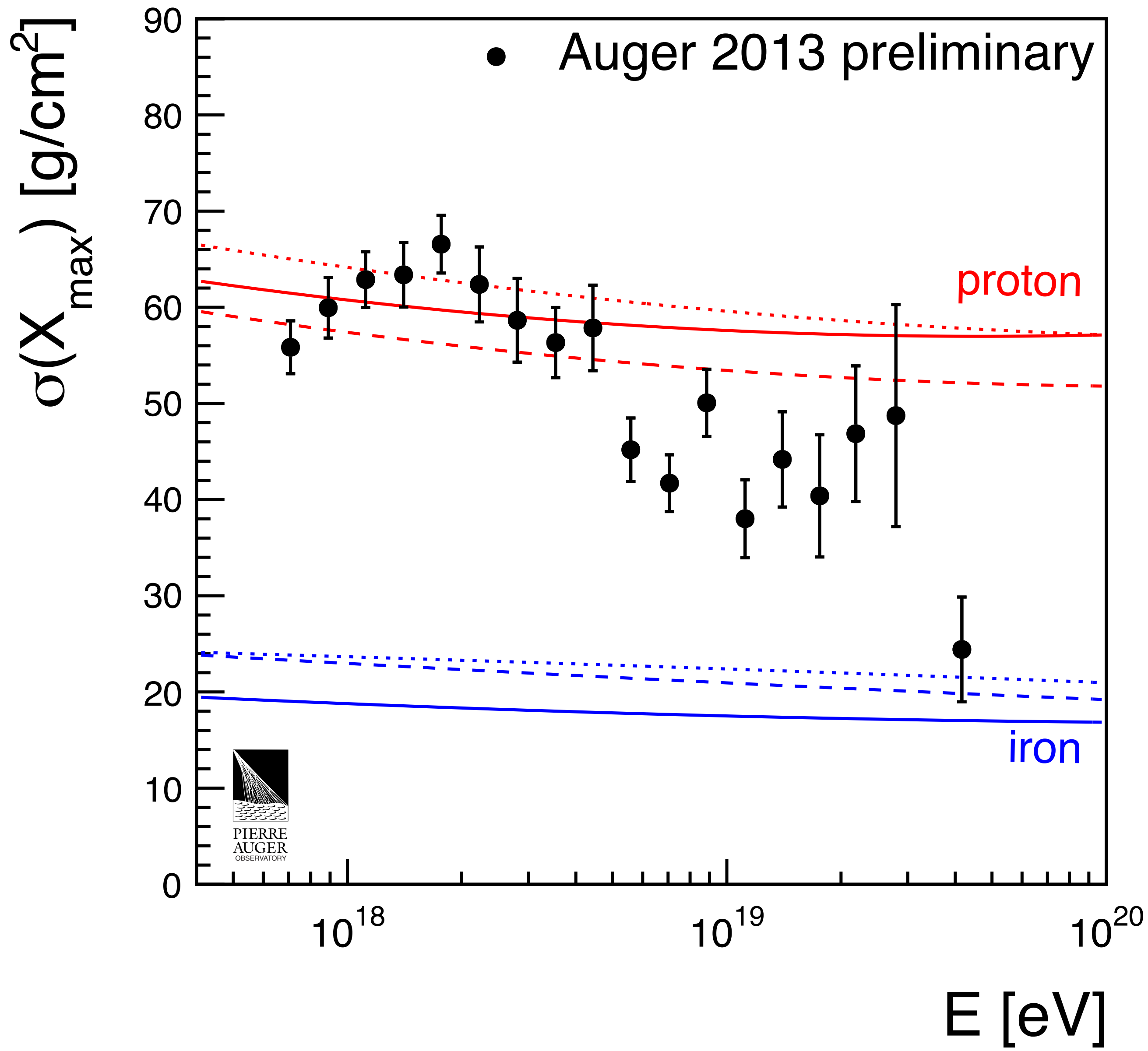
Example of a $3 \cdot 10^{19}$ eV EAS event in FD





X_{max} and RMS(X_{max}) as a fct of E

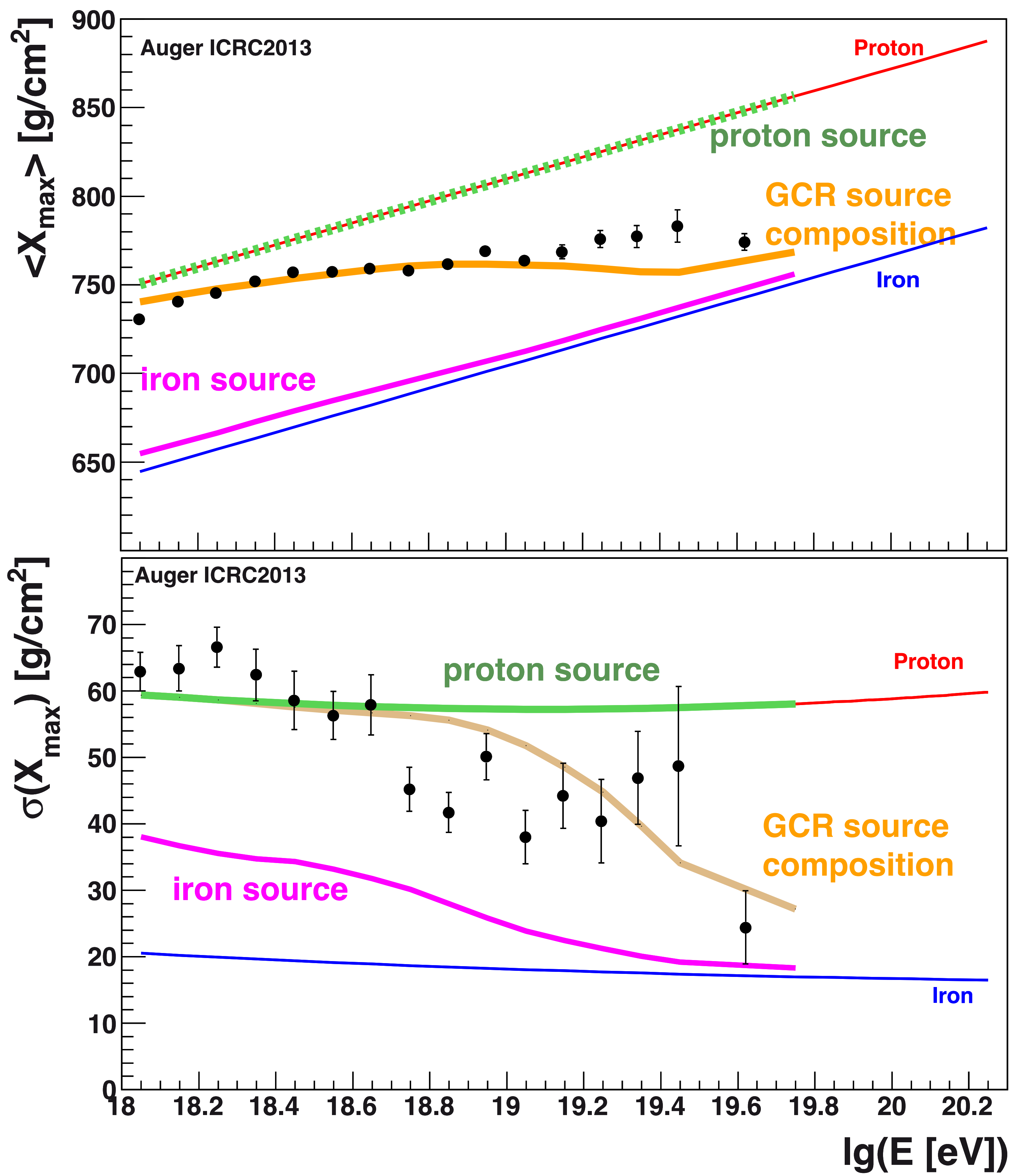


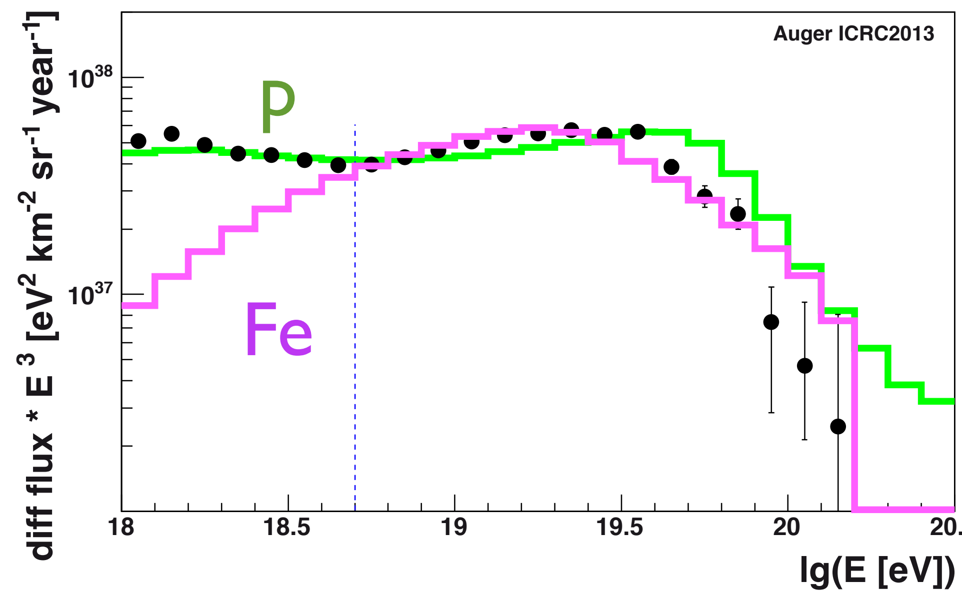


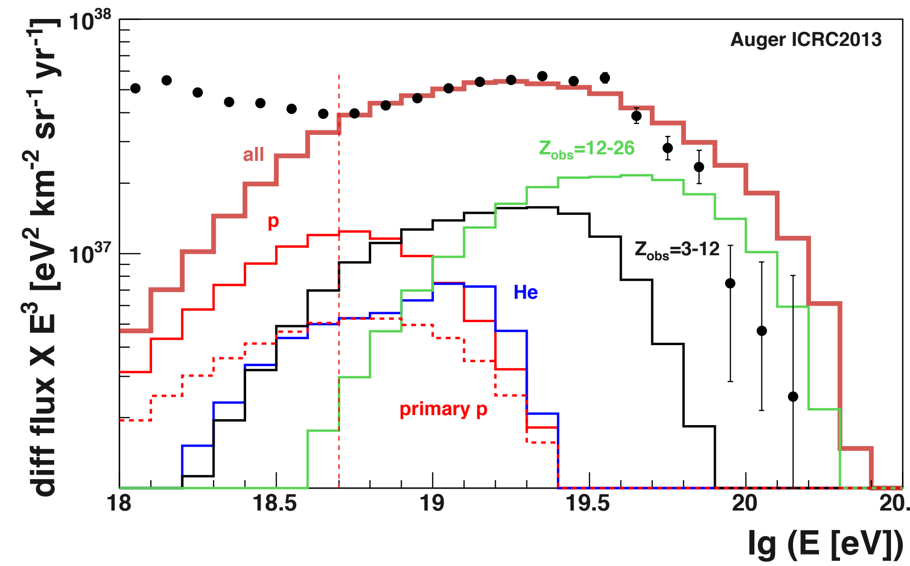
using post LHC interaction models:

Auger data show a smooth change to a heavier composition above 5 EeV

Composition compared with astrophys. scenarios







Limiting energy of sources combined with GZK describes composition data best

Implications of a heavy composition

Astroparticle Physics 39-40 (2012) 33-43
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

Extragalactic propagation of ultrahigh energy cosmic-rays ☆

Denis Allard
Laboratoire Astroparticule et Cosmologie (APC), Université Paris 7/CNRS, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France

Astroparticle Physics 54, 48 (2014)
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

UHECR composition models

Andrew M. Taylor*

...and many more papers of this type

all require very hard injection spectra unless a nearby source (population) is assumed

December 2013, volume 8, Issue 6, pp 748-758

Cosmic ray energy spectrum from measurements of air showers

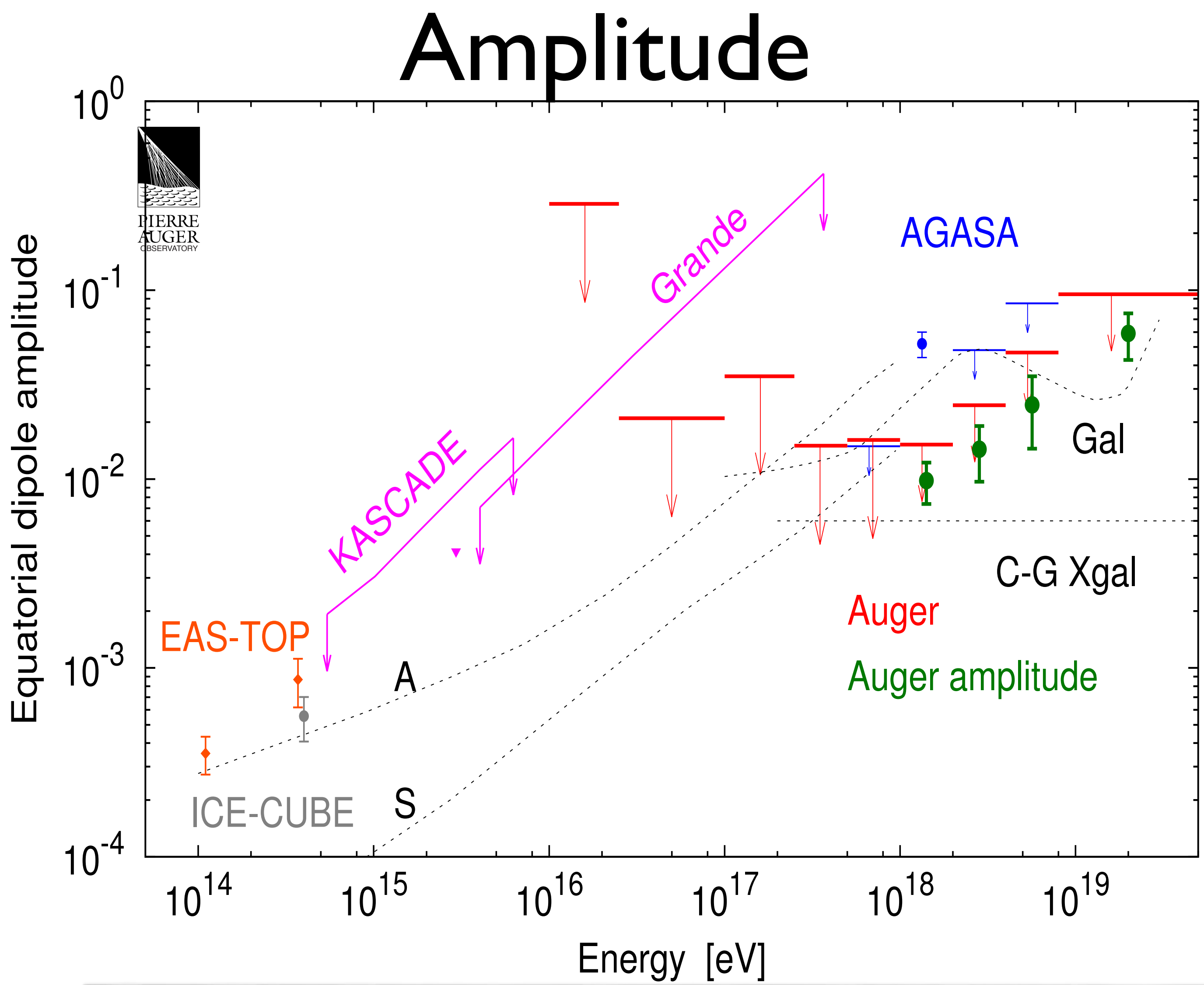
T. K. Gaisser, T. Stanev, S. Tilav

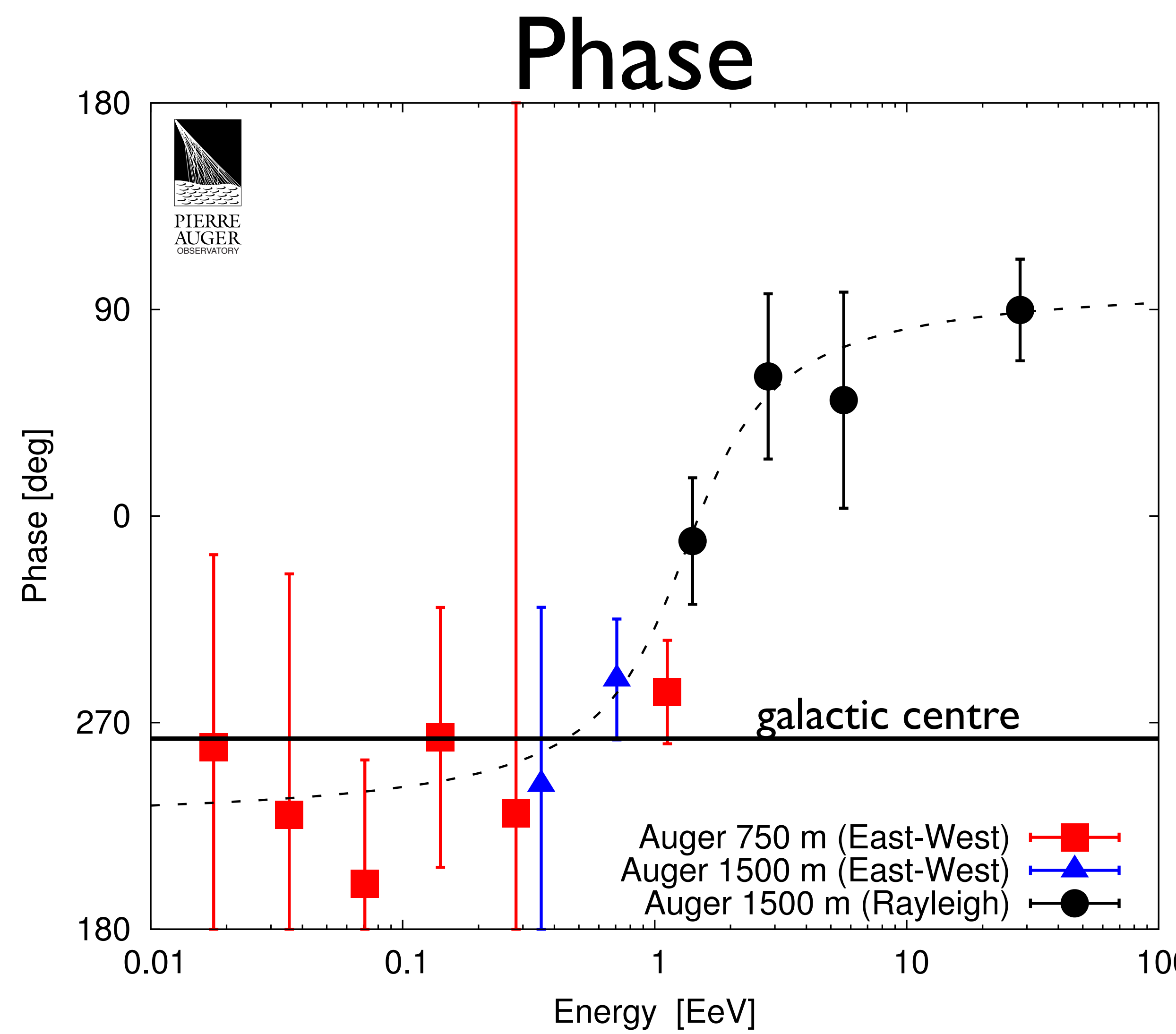
cosmic rays: implications of Auger data for source spectra and chemical composition

Subm. to JCAP 2013

R. Aloisio[1,2], V. Berezinsky[2,3] and P. Blasi[1,2]

Large Scale Anisotropies



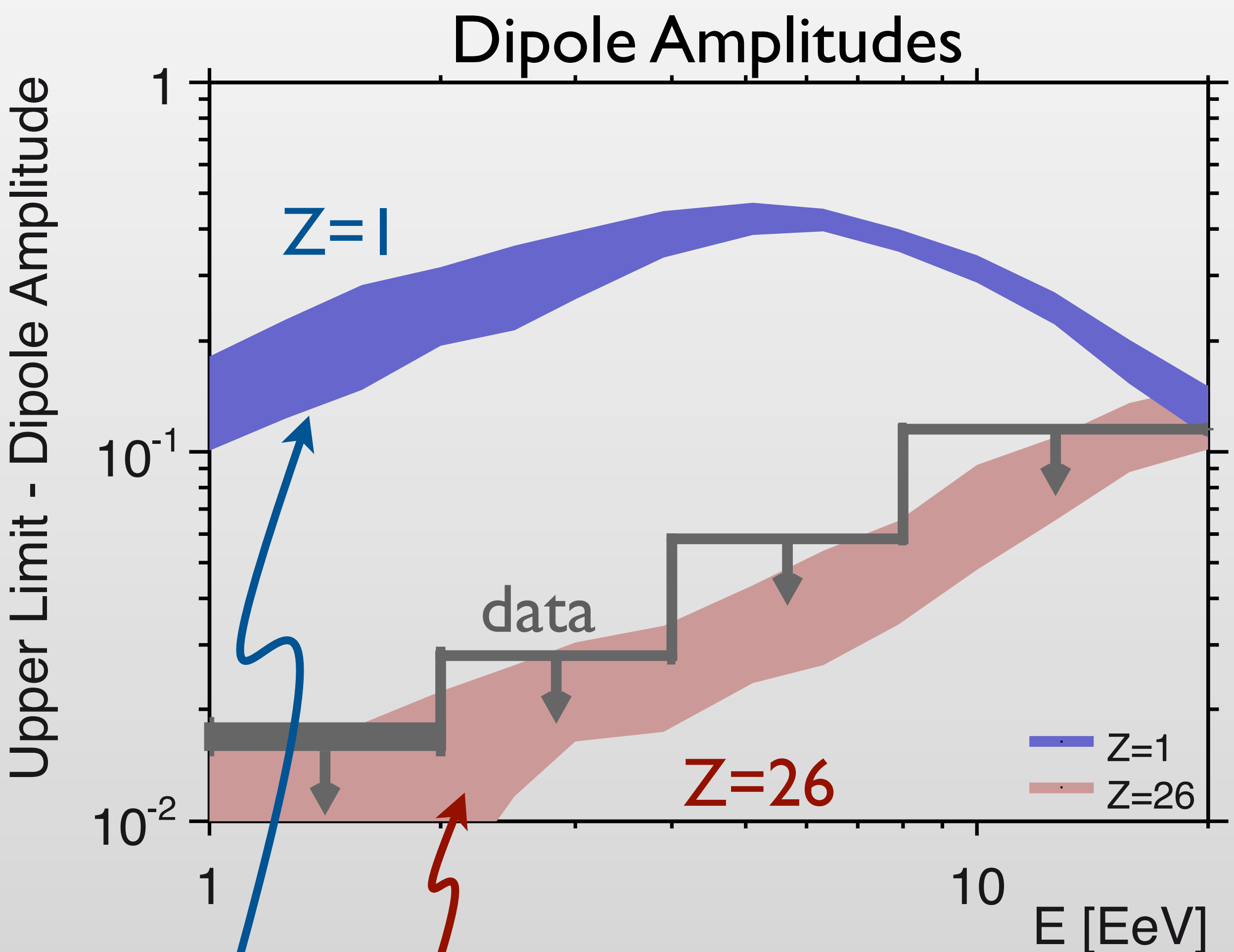


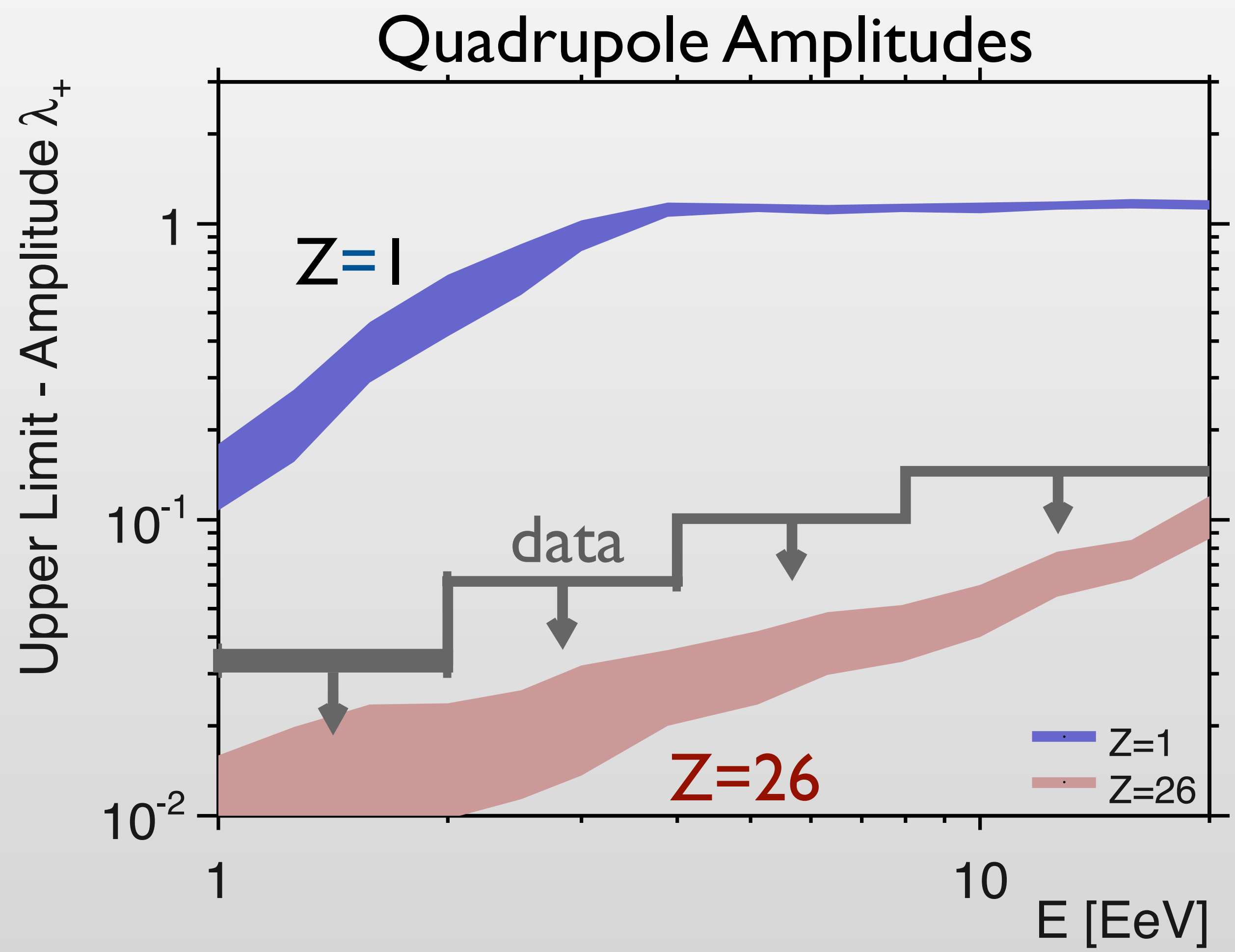
Amplitudes at E>1 EeV: P($d_\perp$)≲ 1% isotropic
→ suggests EeV protons to be of extragalactic nature

Smooth change of phase away from GC at E > 1 EeV

Large Scale Anisotropies

Auger Collaboration: ApJL, 762, L13 (2012), ApJS 203,34 (2012)

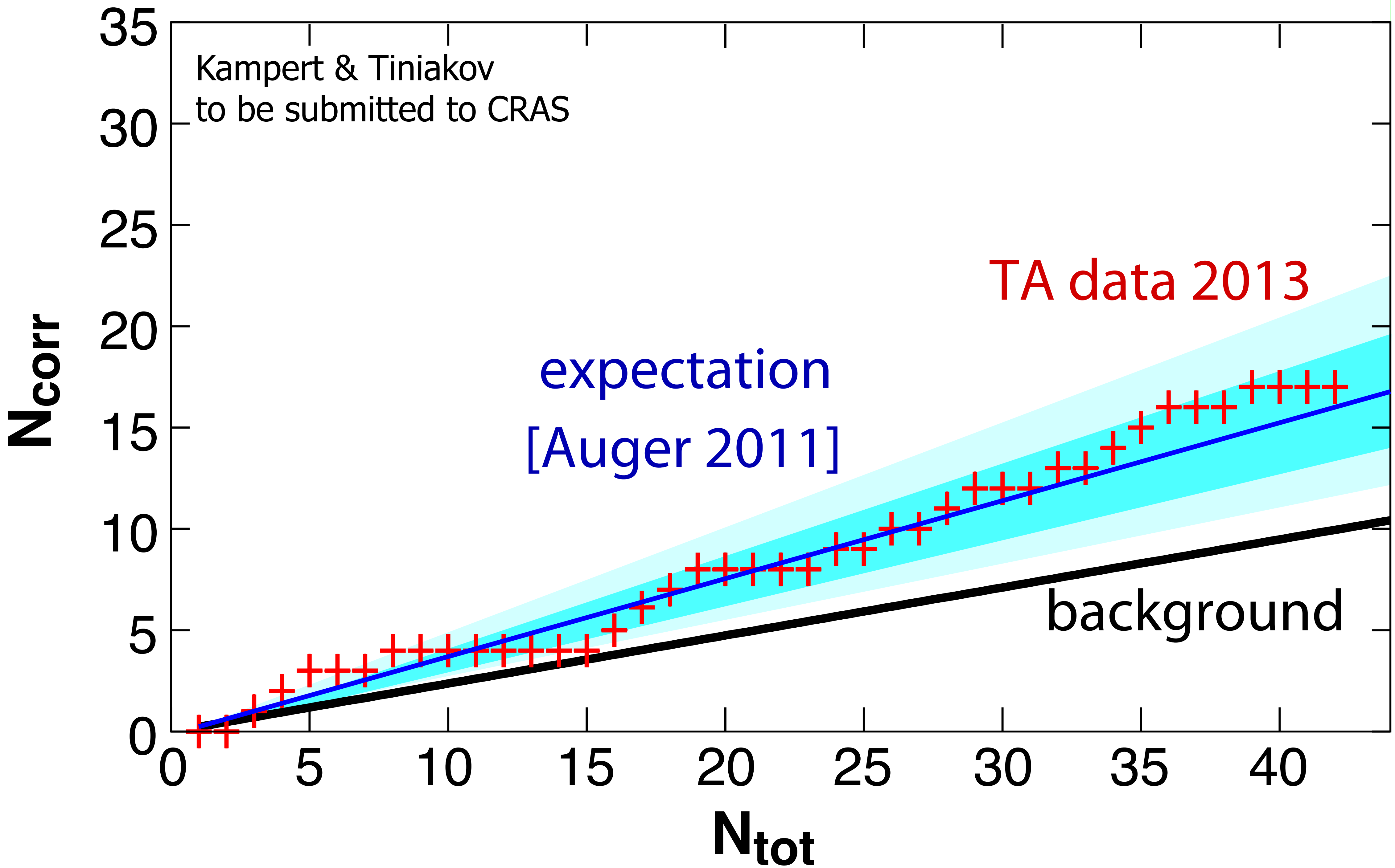




expectations from stationary galactic sources distributed in the disk

light CR component seen at 10^{18} eV cannot originate from stationary sources in the galactic disk

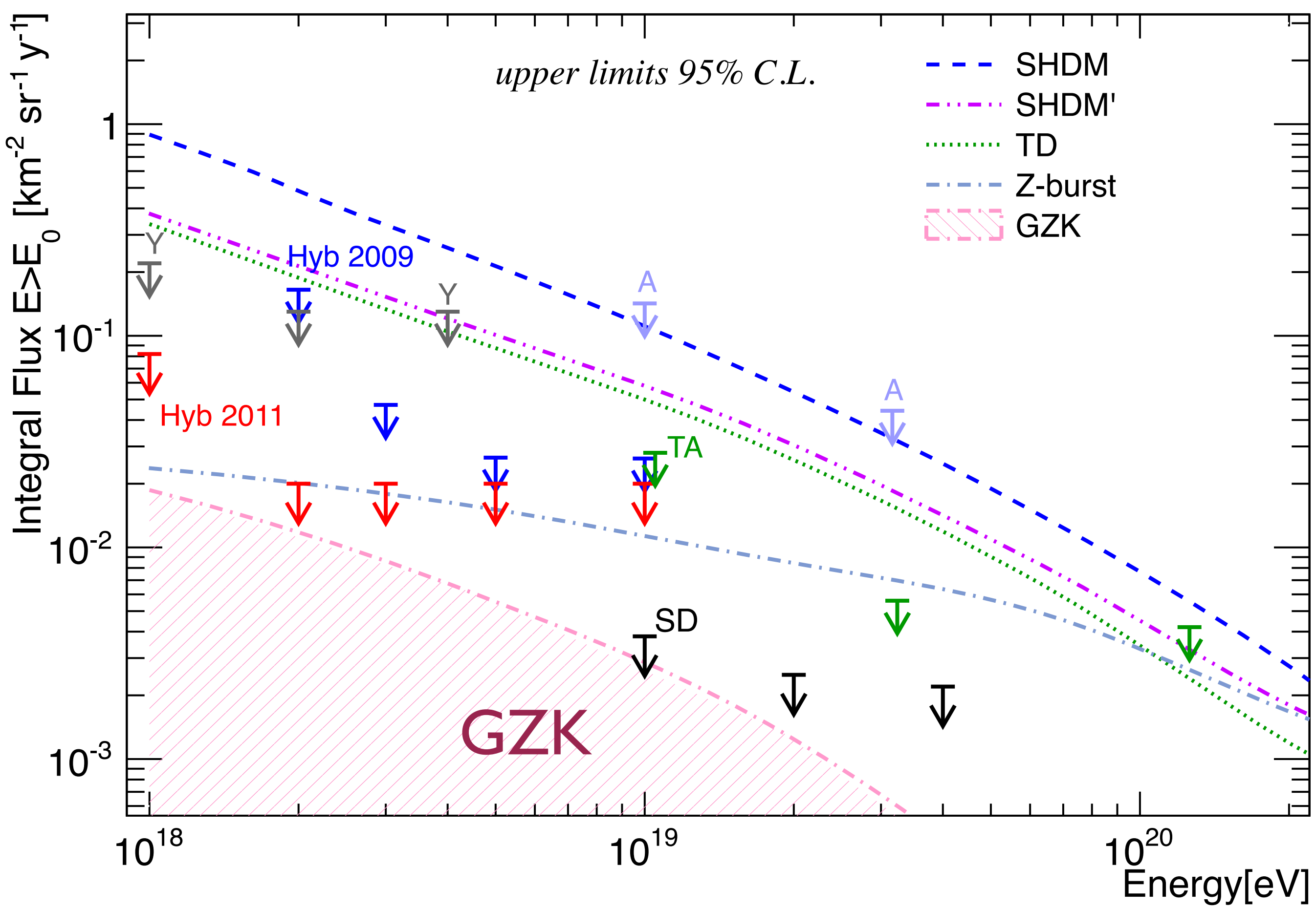
AGN Correlation: TA vs Auger



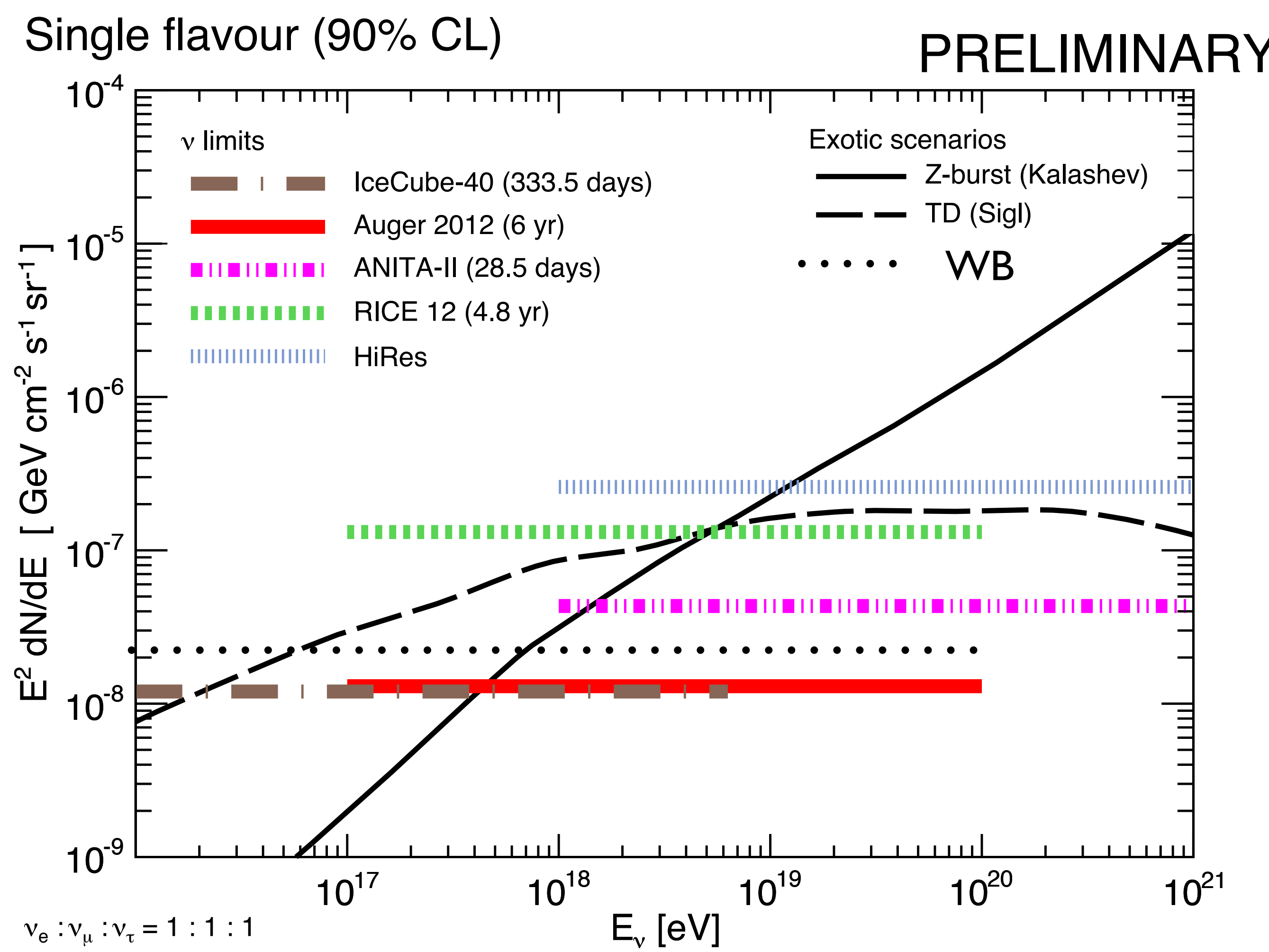
Perfect agreement between Auger & TA

Diffuse Photon and Neutrinos Limits

Photons



Neutrinos → see J. Alavarez-Muniz



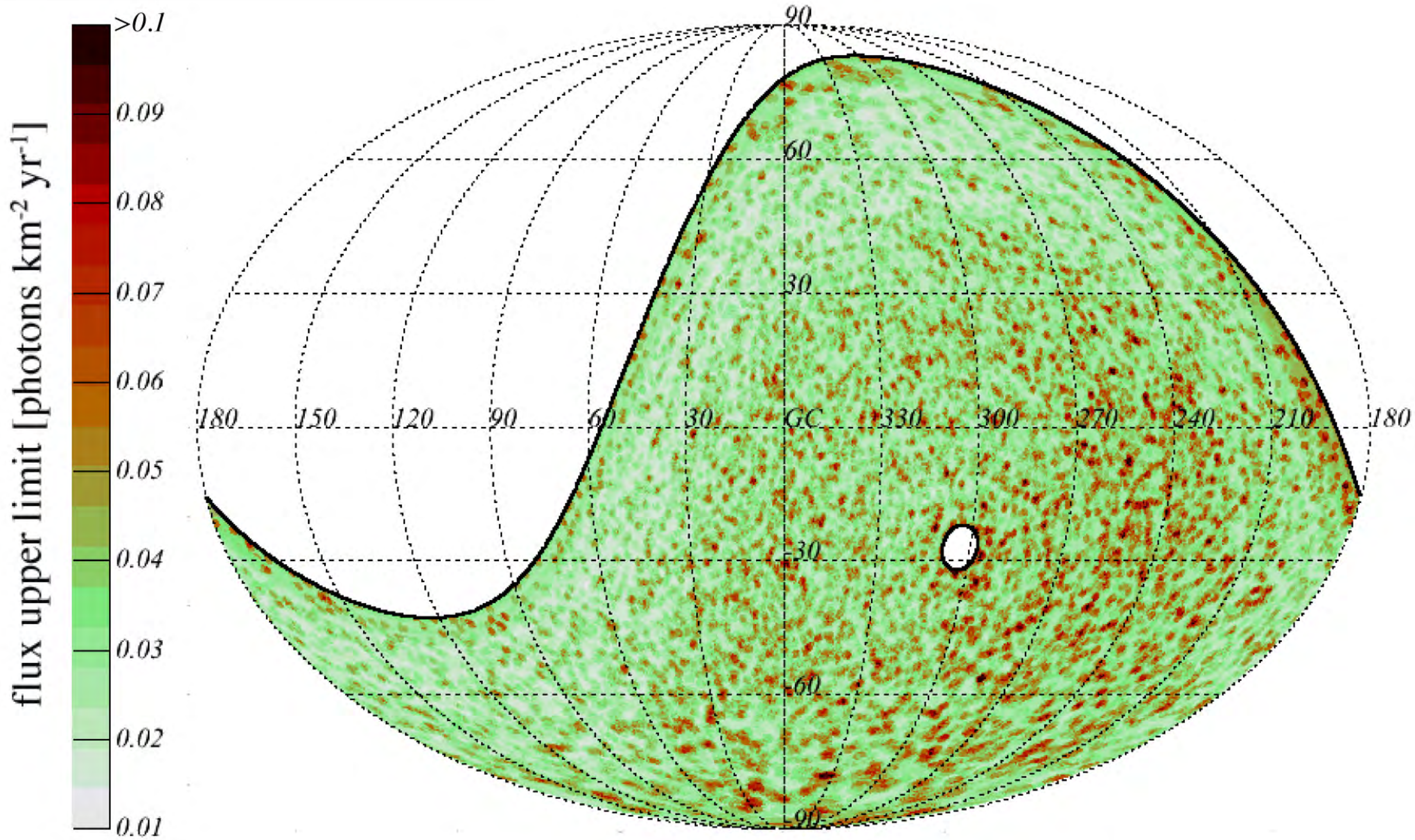
Top-Down Models ruled out

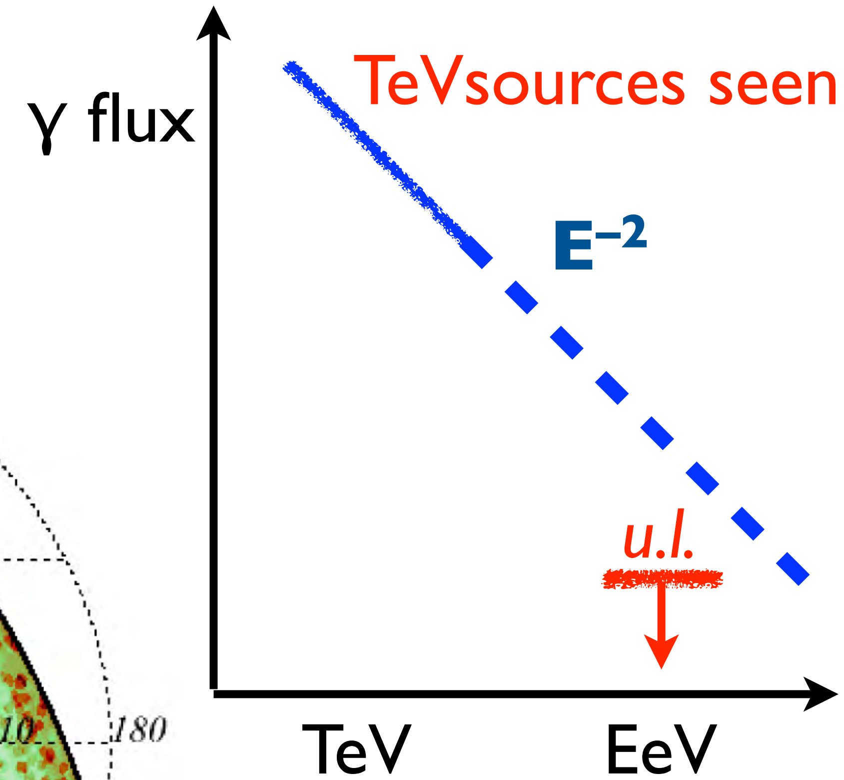
ν's now below Waxman-Bahcall flux

Becoming sensitive to GZK-ν and γ

Directional Limits of EeV Photons

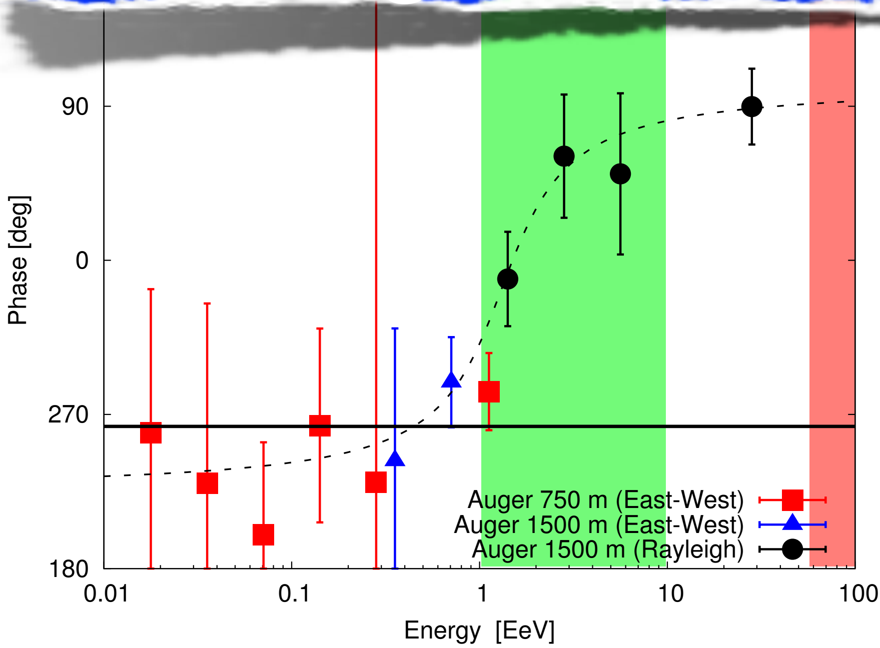
paper subm. to A&A

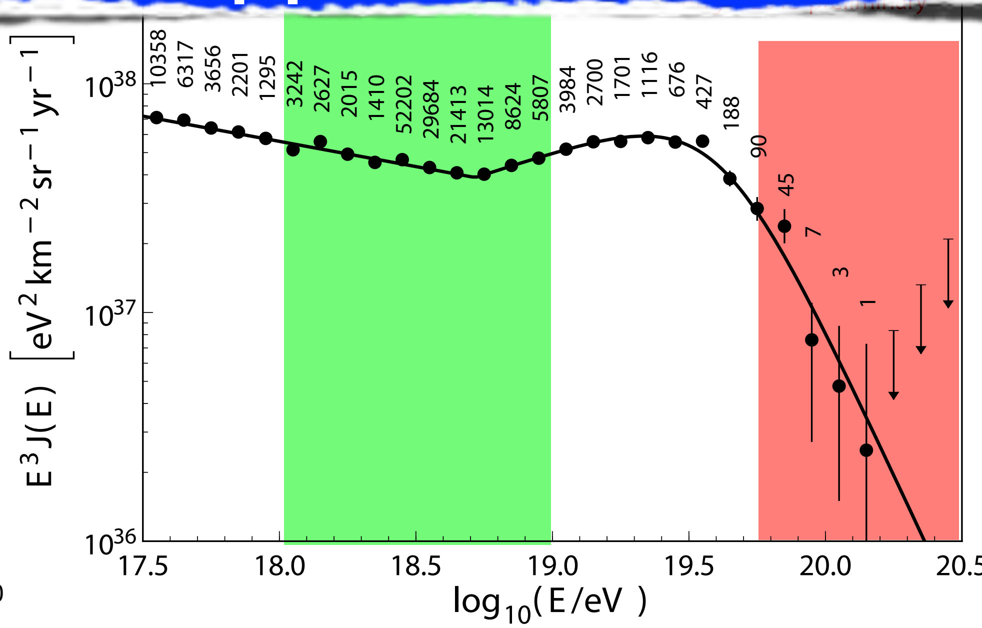


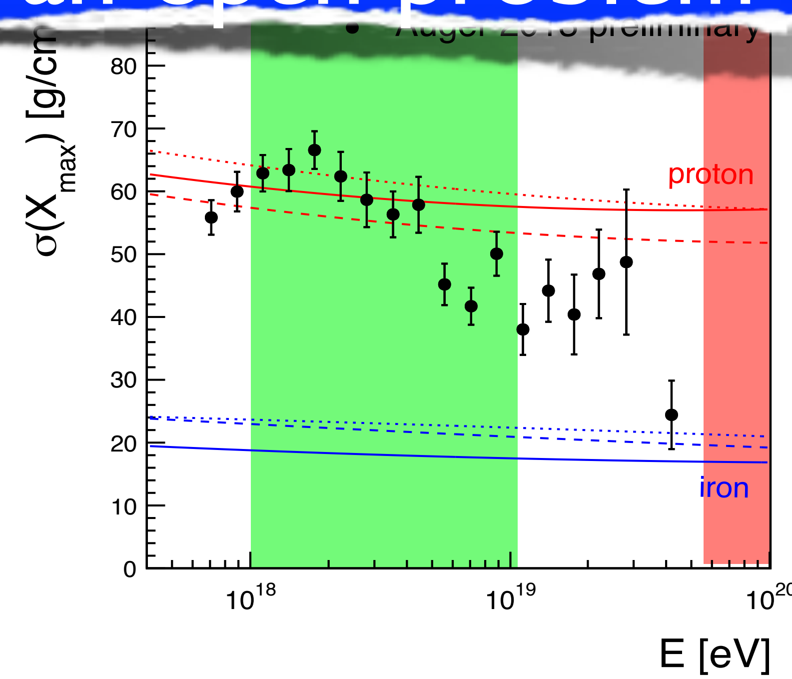


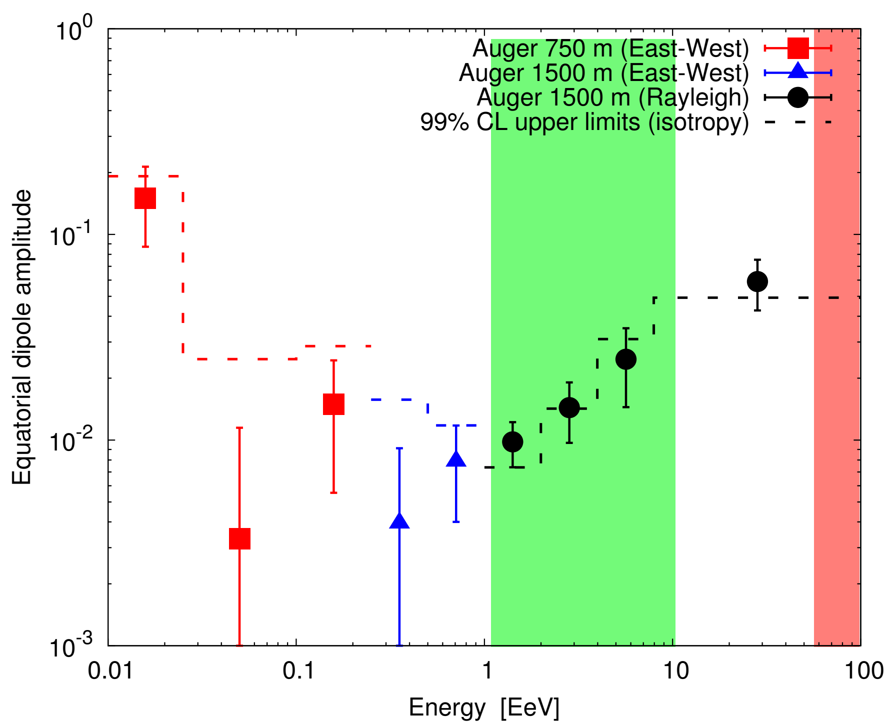
Energy flux of 0.25 eV/cm^{2}s would yield a 5σ excess (assuming E^{-2} spectr.)
Note, some Galactic TeV sources exceed 1 eV/cm^{2}s !

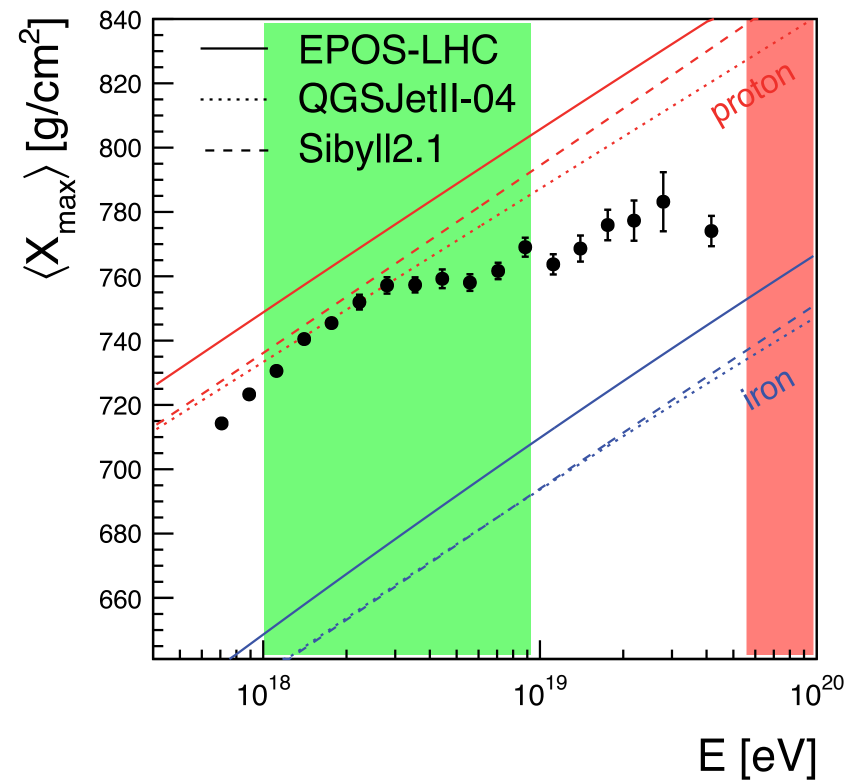
- Auger provides a wealth of high quality data
- We observe a coherent bahavior of observables
- The origin of the flux suppression remains an open problem

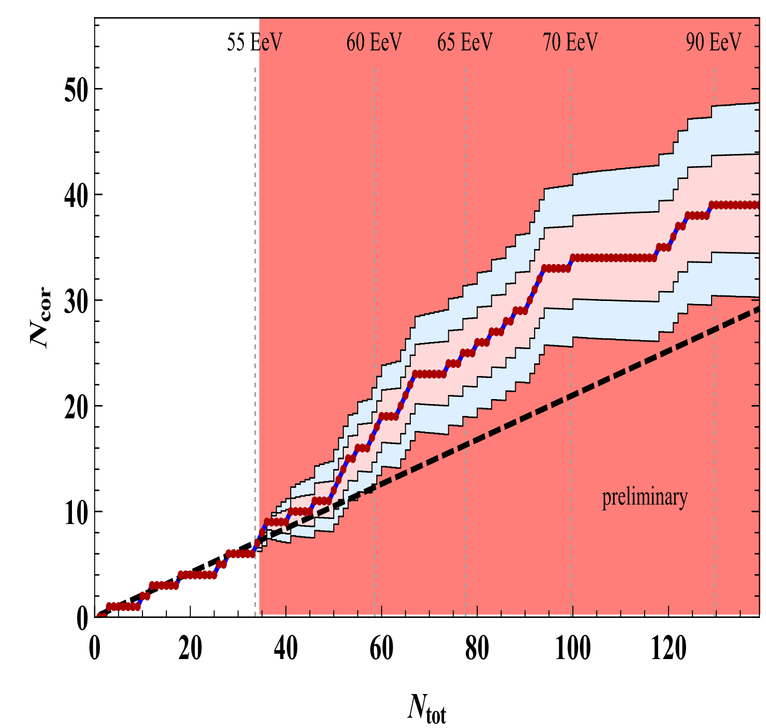






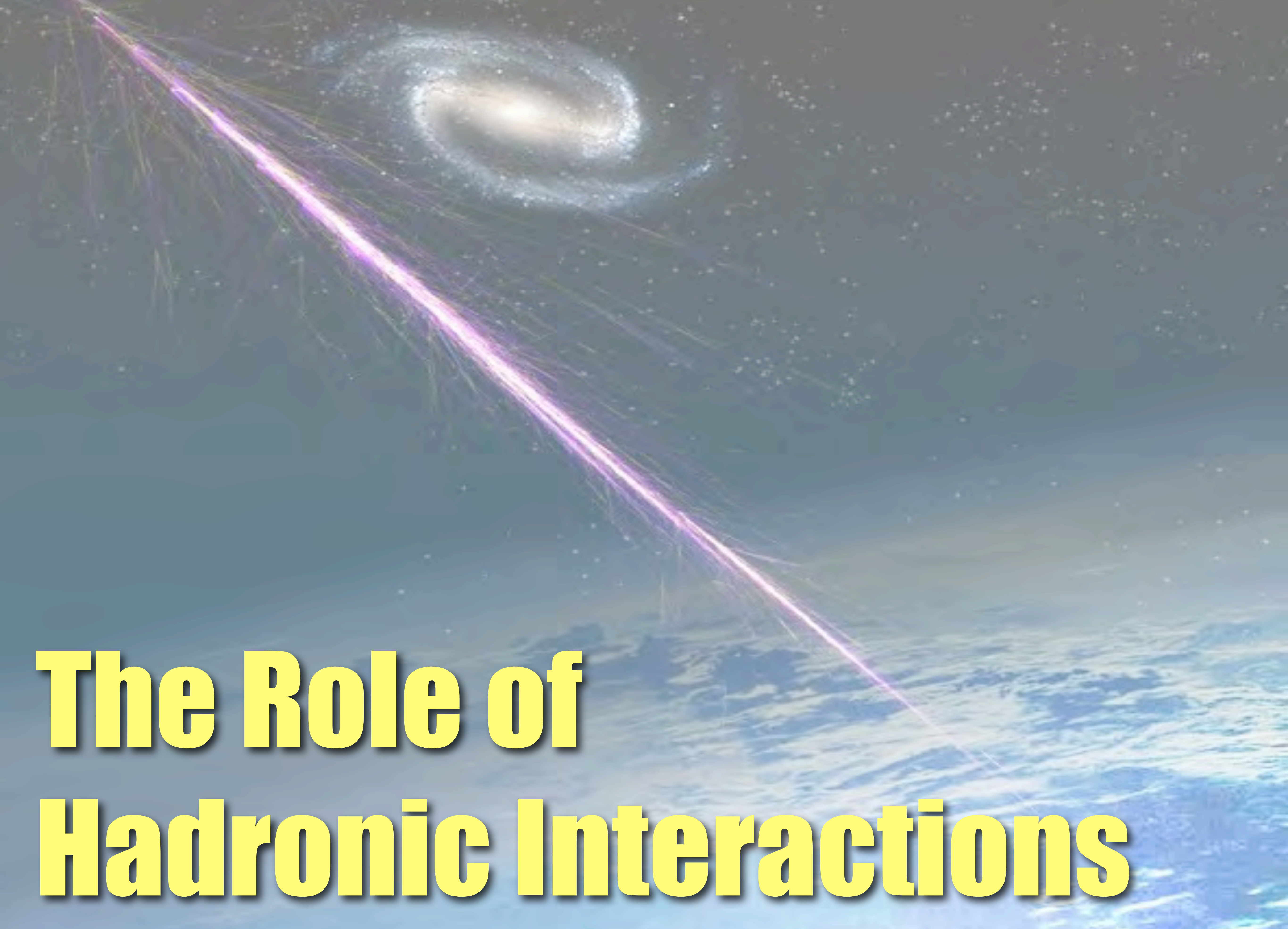






Ankle-Region

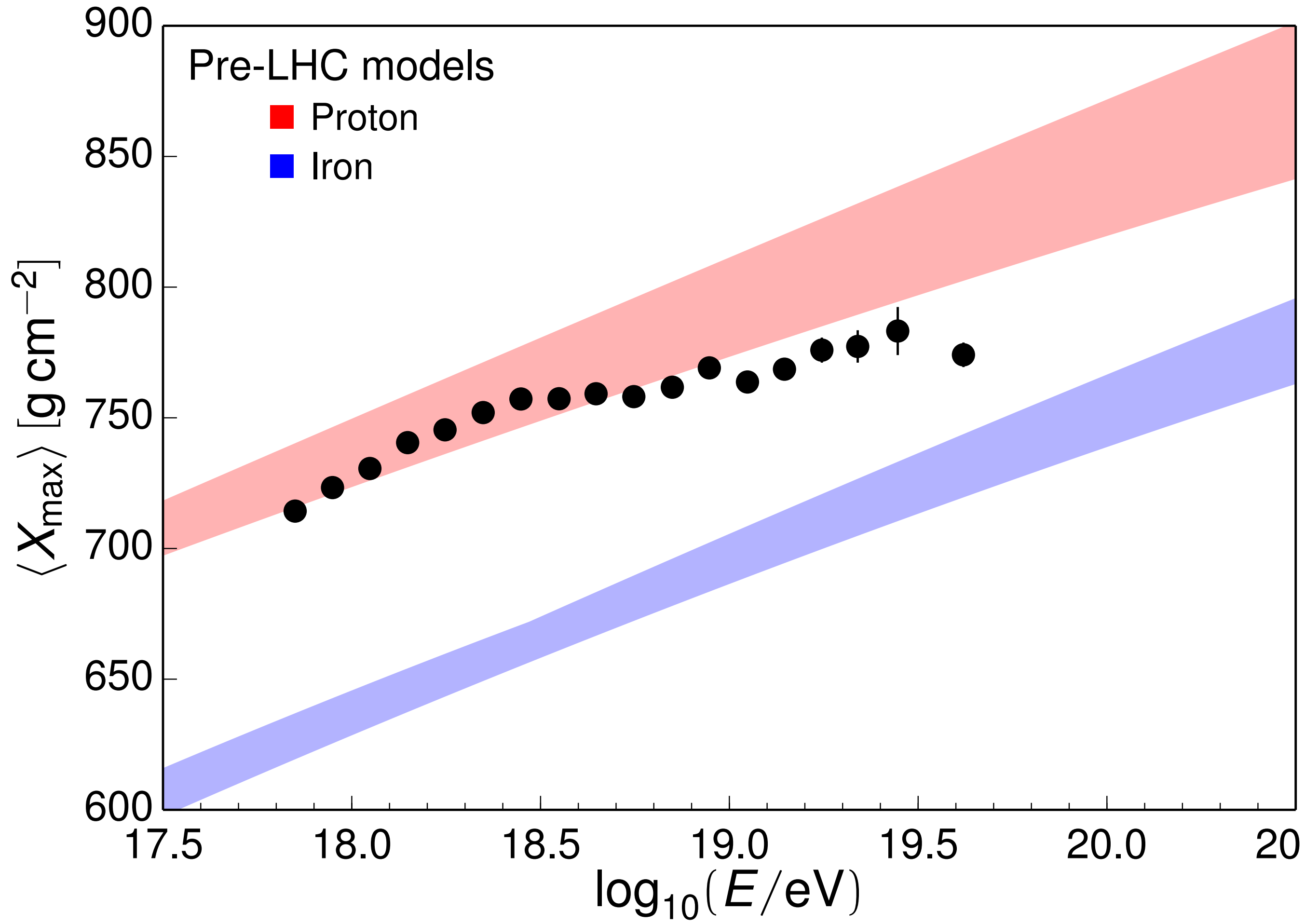
Suppression-Region



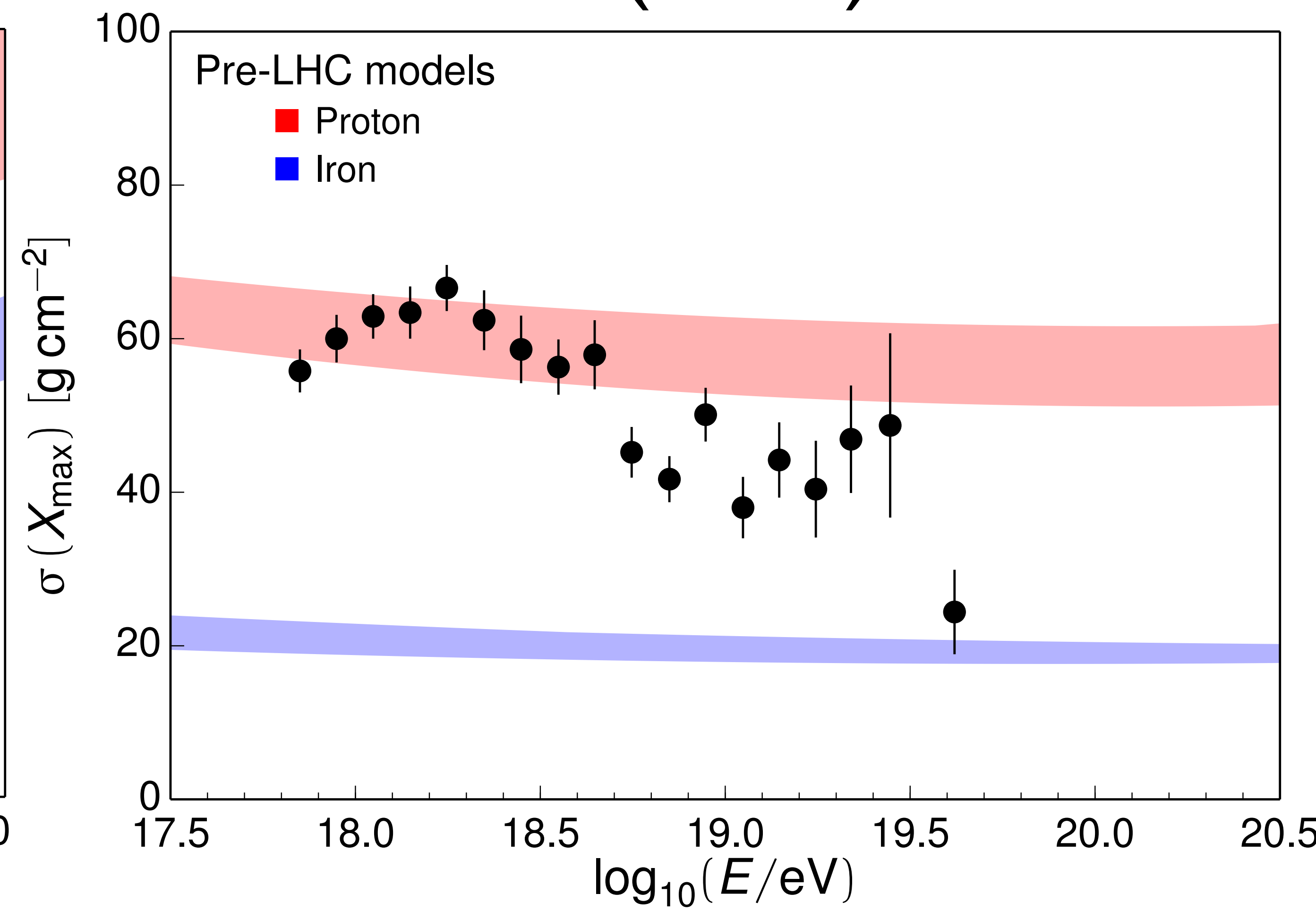
The Role of Hadronic Interactions

Xmax compared to Pre-LHC models

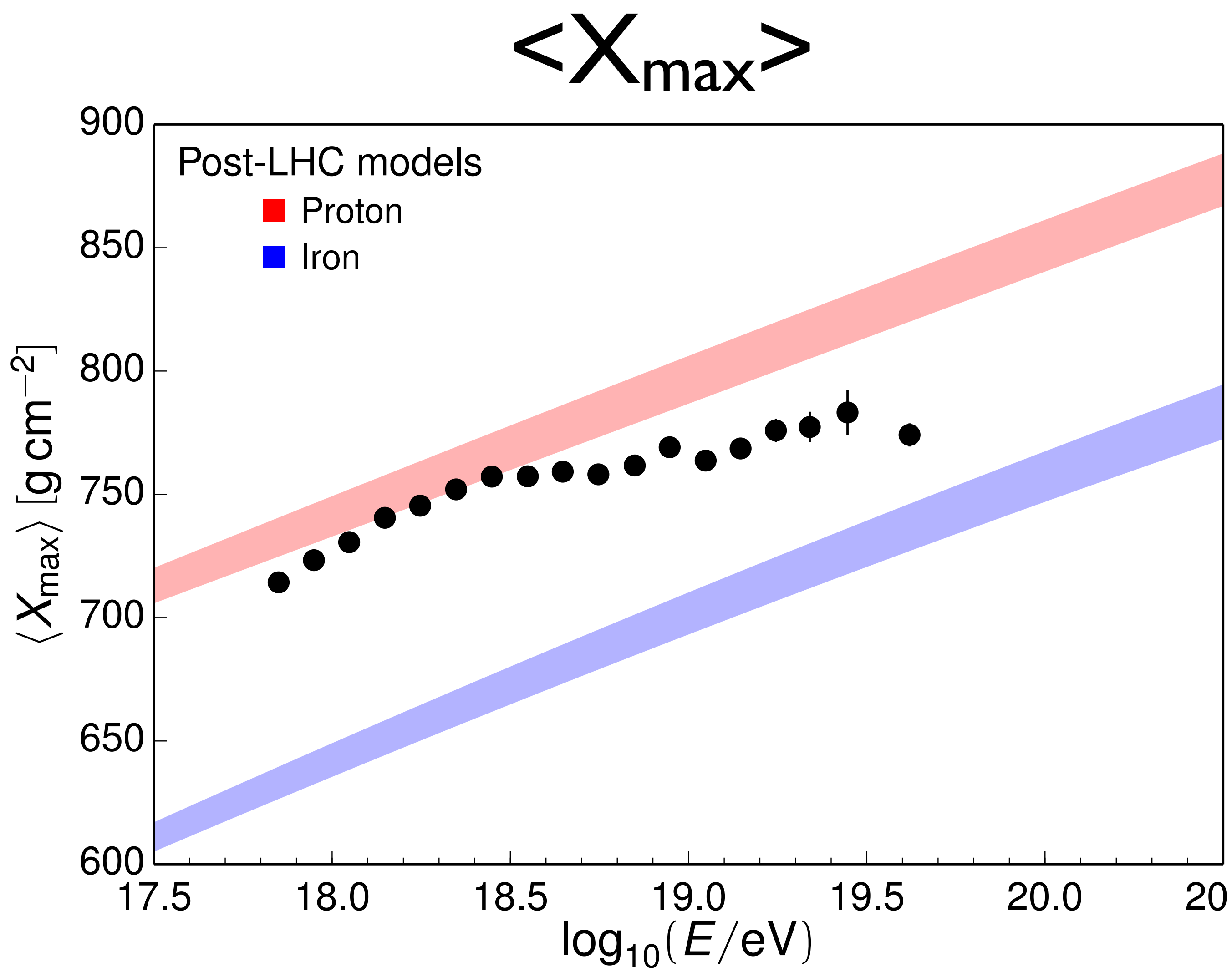
<X$_{max}$>

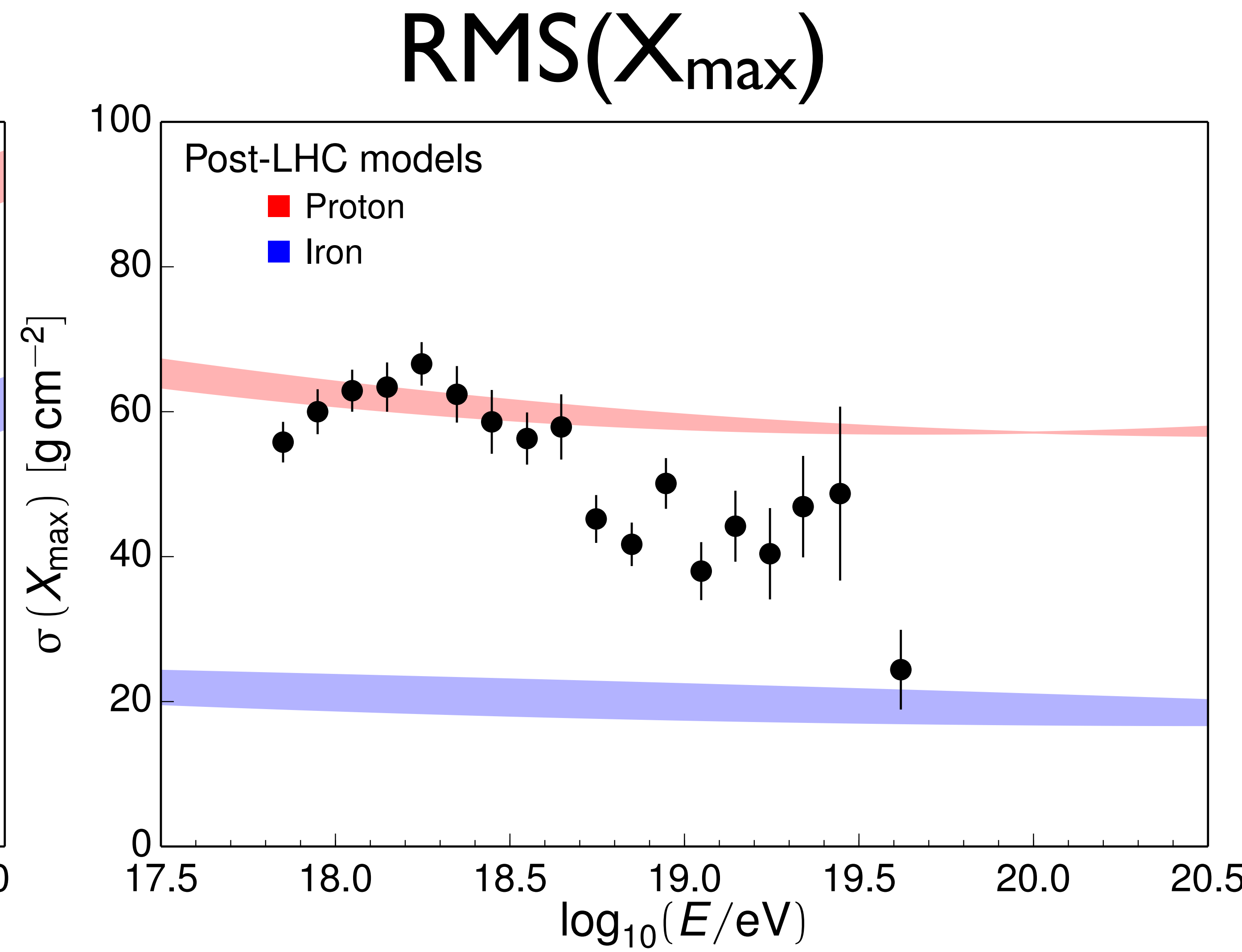


RMS(X$_{max}$)



Xmax compared to Post-LHC models

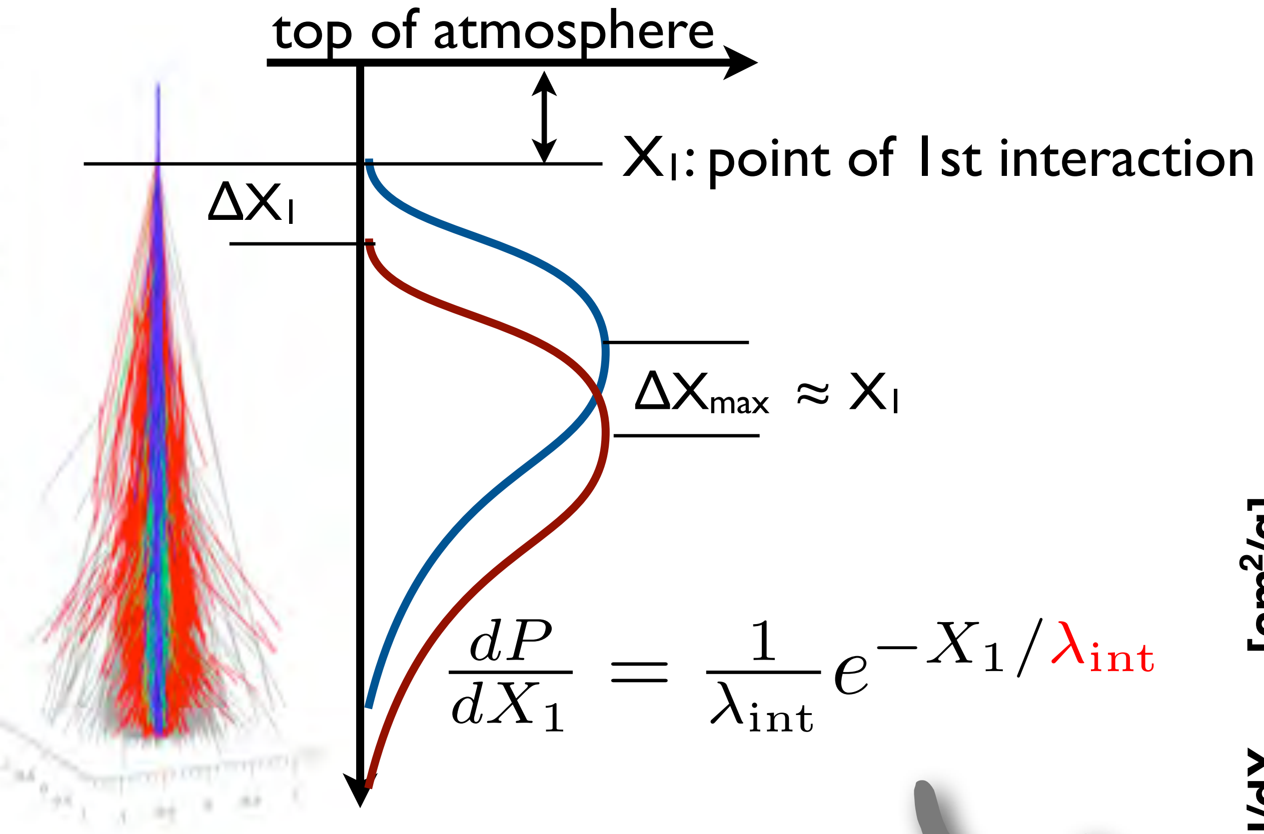


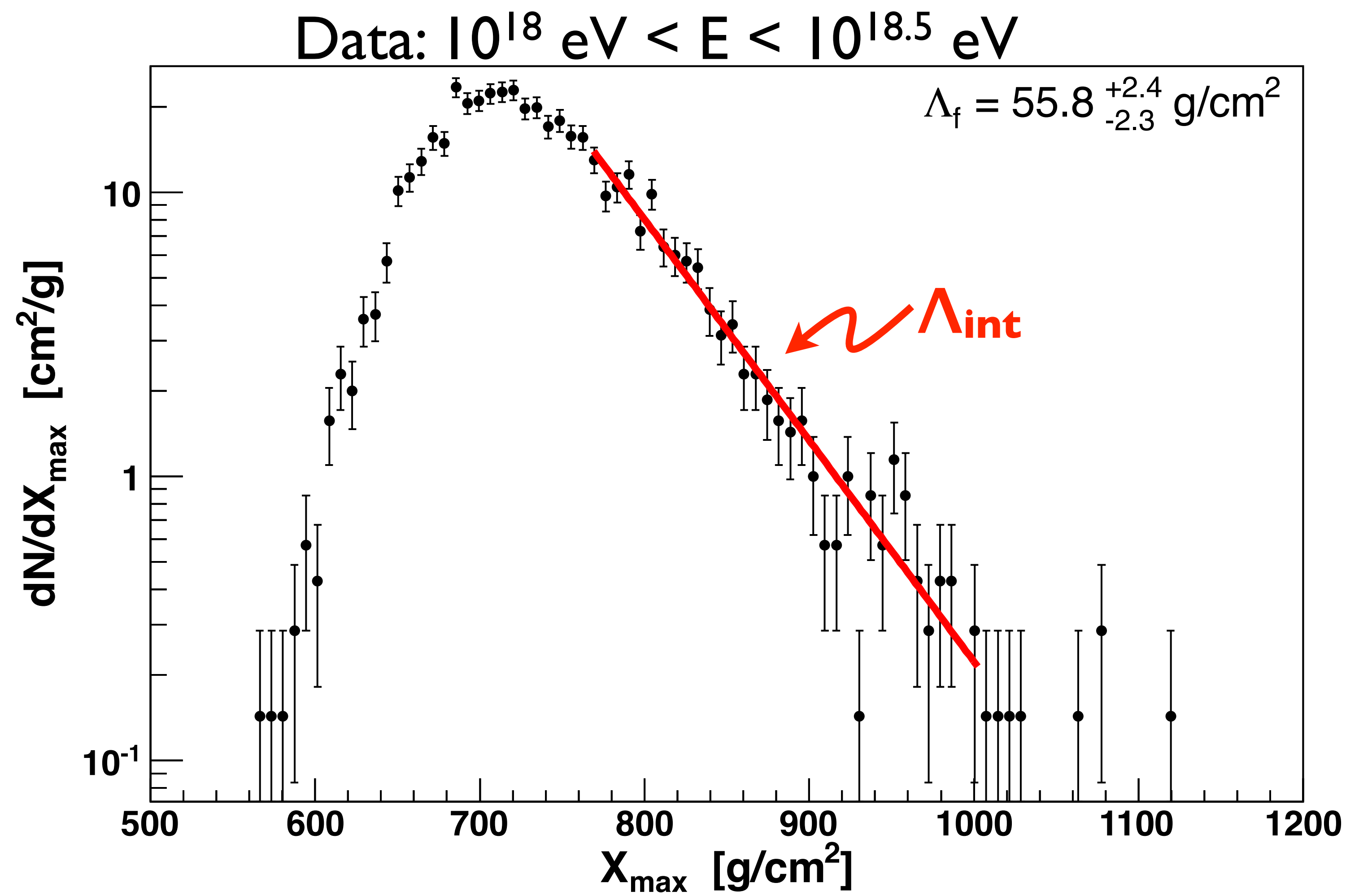


LHC data have been very useful for tuning of interaction models

see talk by H. Menjo this morning

p-Air Cross-Section from X_{max} distribution





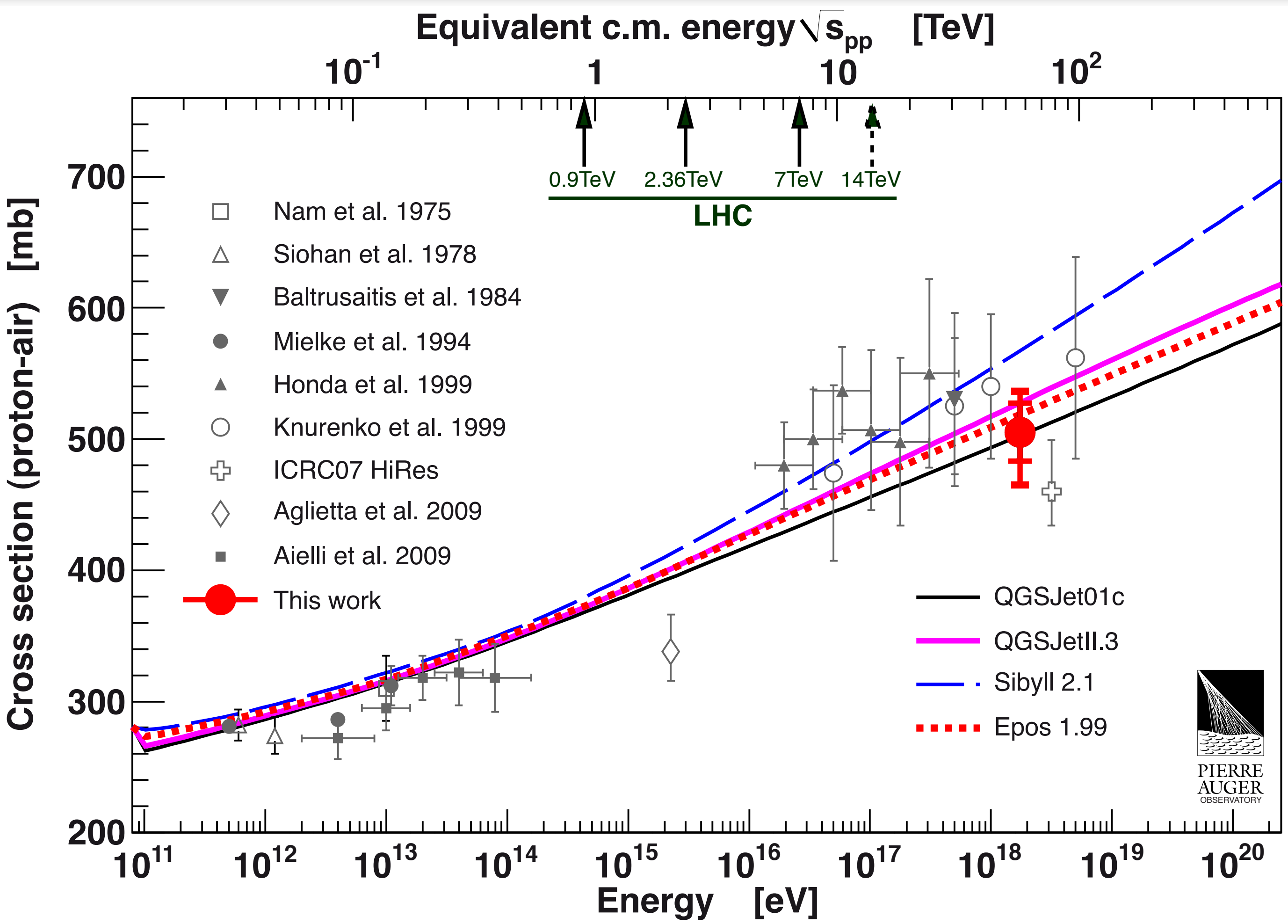
Difficulties:

- mass composition can alter Λ
- fluctuations in X_{max}
- experimental resolution ~ 20 g/cm^2

$$\sigma_{p-Air} = \frac{\langle m_{Air} \rangle}{\lambda_{int}}$$

In practice: $\sigma_{p\text{-}Air}$ by tuning models to describe Λ seen in data

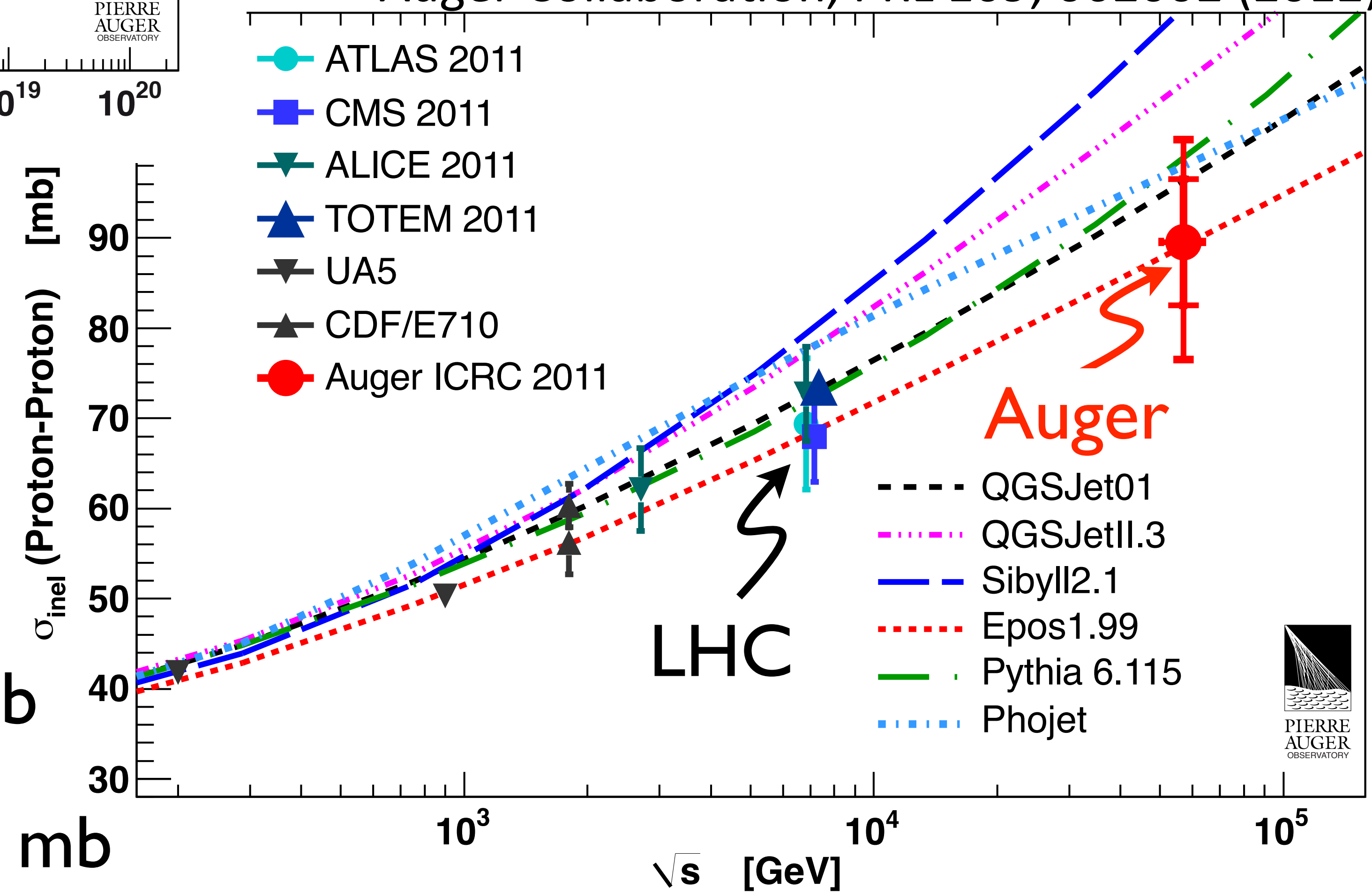
p-Air and pp Cross section @ √s=57 TeV



Conversion from p-air to p-p cross section by Glauber-approach

$$\sigma^{\mathrm{prod}}_{\mathrm{p\text{-}Air}} = (505 \pm 22_{\mathrm{stat}}\, ({}^{+26}_{-34})_{\mathrm{sys}})\ \mathrm{mb}$$

Auger Collaboration, PRL 109, 062002 (2012)

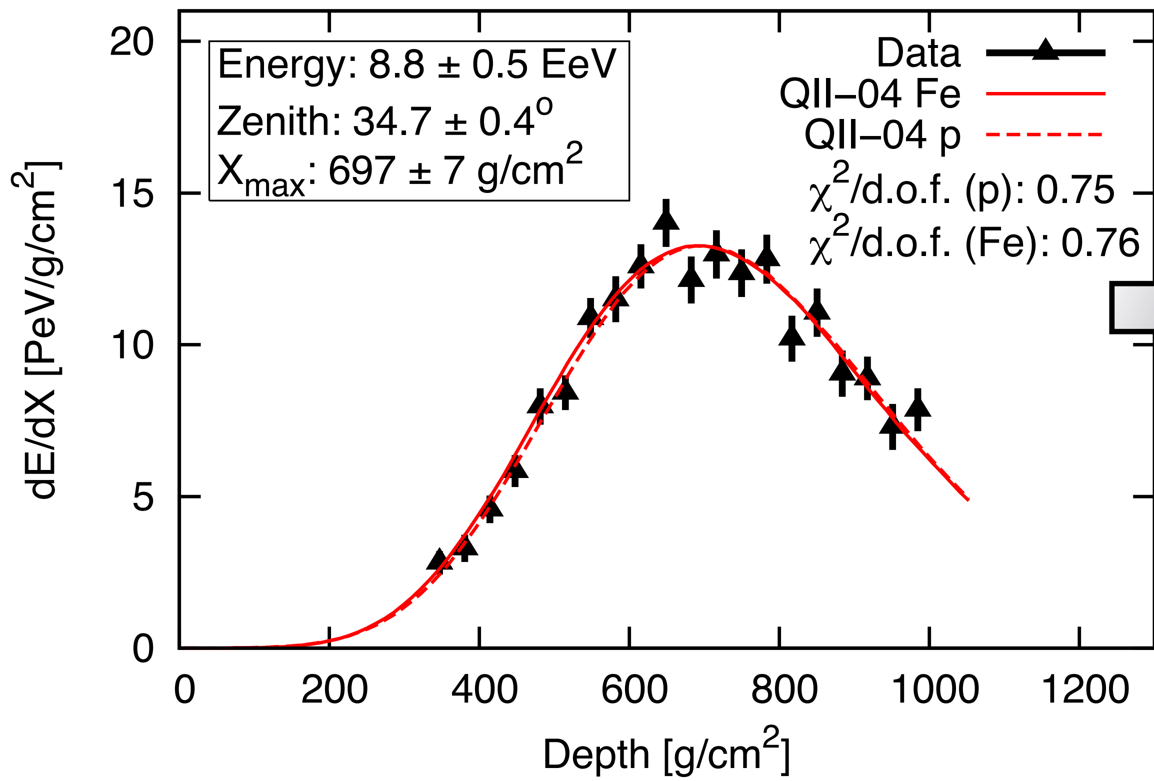


$$\sigma^{\mathrm{inel}}_{\mathrm{pp}} = [92 \pm 7_{\mathrm{stat}}\, ({}^{+9}_{-11})_{\mathrm{sys}} \pm 7.0_{\mathrm{Glauber}}]\ \mathrm{mb}$$

$$\sigma^{\mathrm{tot}}_{\mathrm{pp}} = [133 \pm 13_{\mathrm{stat}}\, ({}^{+17}_{-20})_{\mathrm{sys}} \pm 16_{\mathrm{Glauber}}]\ \mathrm{mb}$$

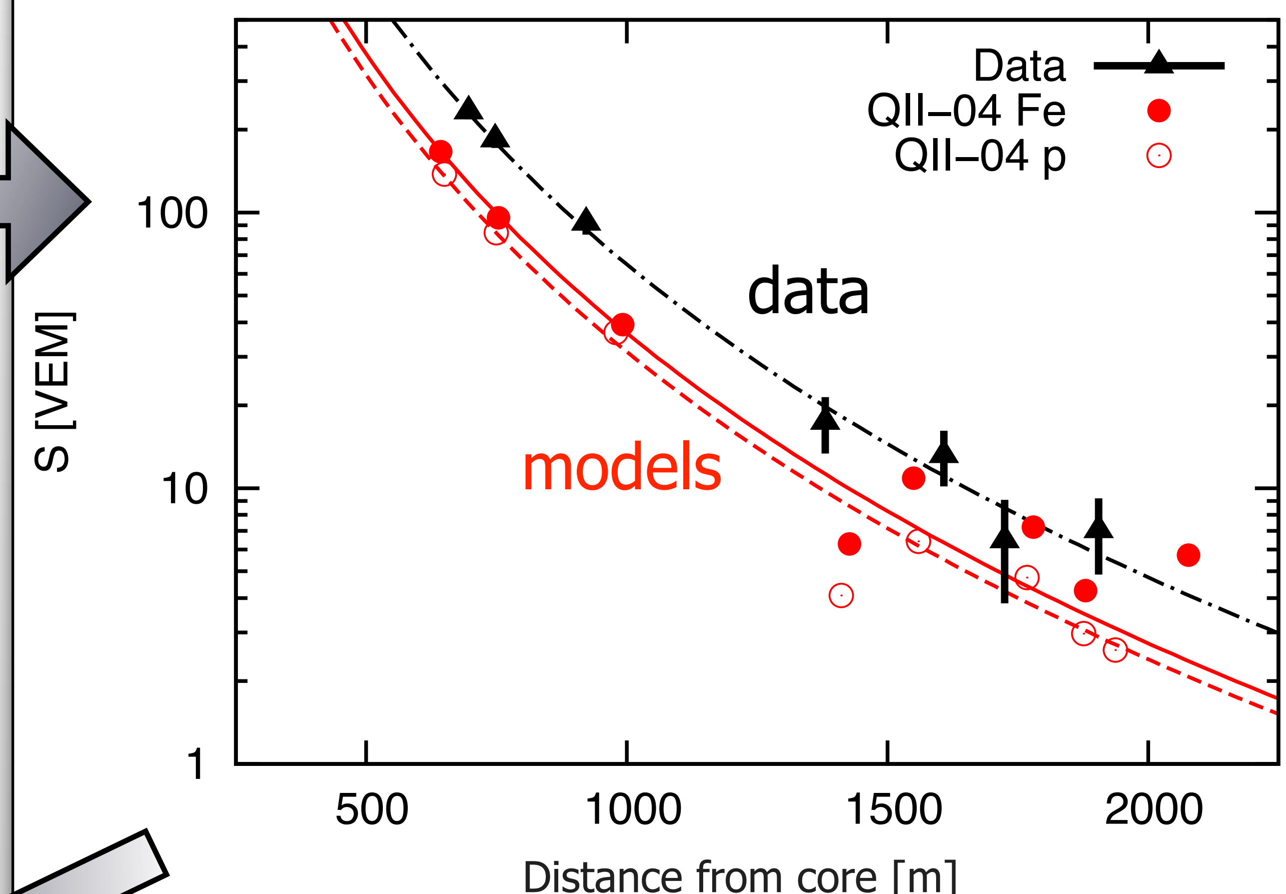
Interaction Models underestimate Muon-numbers

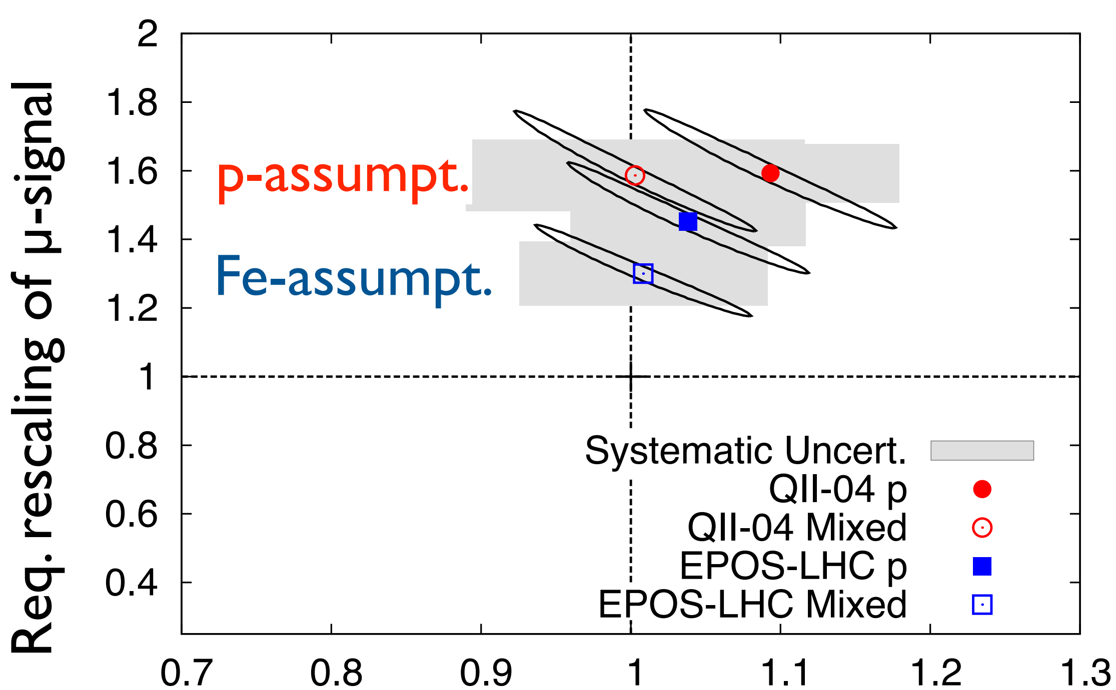
Measured event
with **matching p and Fe-simulations**



Ready to be submitted

Same measured Event
with **predicted signals for p and Fe**





Models underestimate μ-content of EAS by 30-60%

independent tests e.g. using shower universality yield the same results

Major Achievements in the first 6 years of operation

- Clear observation of flux suppression
- Strongest existing bounds on EeV ν and γ
- Strongest existing bounds on large scale anisotropies
- First hints on directional correlations to nearby matter
- Increasingly heavier composition above ankle
- pp cross section at ~10*E_{LHC}, LIV-bounds, ...
- muon deficit in models at highest energies
- geophysics (elfes, solar physics, aerosols...)

Science Goals of Auger Upgrade

1. **Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario**
   - fundamental constraints on UHECR sources
   - galactic vs extragalactic origin
   - reliable prediction of GZK ν- and -γ fluxes

2. **Search for a flux contribution of protons up to the highest energies at a level of ~ 10%**
   - proton astronomy up to highest energies
   - prospects of future UHECR experiments

3. **Study of extensive air showers and hadronic multiparticle production above $\sqrt{s}$=70 TeV**
   - particle physics beyond man-made accelerators
   - derivation of constraints on new physics phenomena

Submitted to International Science Advisory Committee

-Positively Reviewed -

PIERRE AUGER OBSERVATORY

Plans for a Proposal to Upgrade the Pierre Auger Observatory

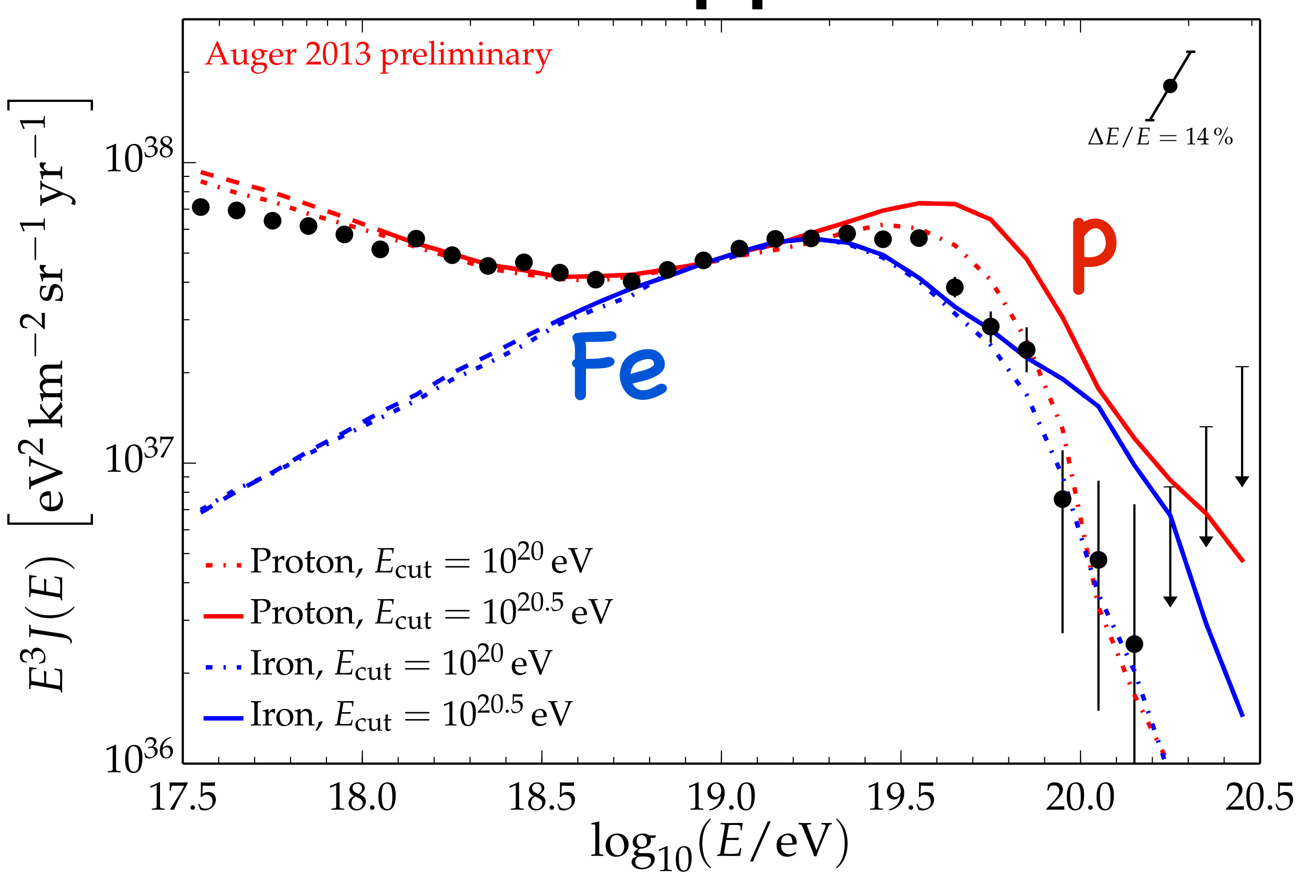
Pierre Auger Collaboration

September 29, 2013

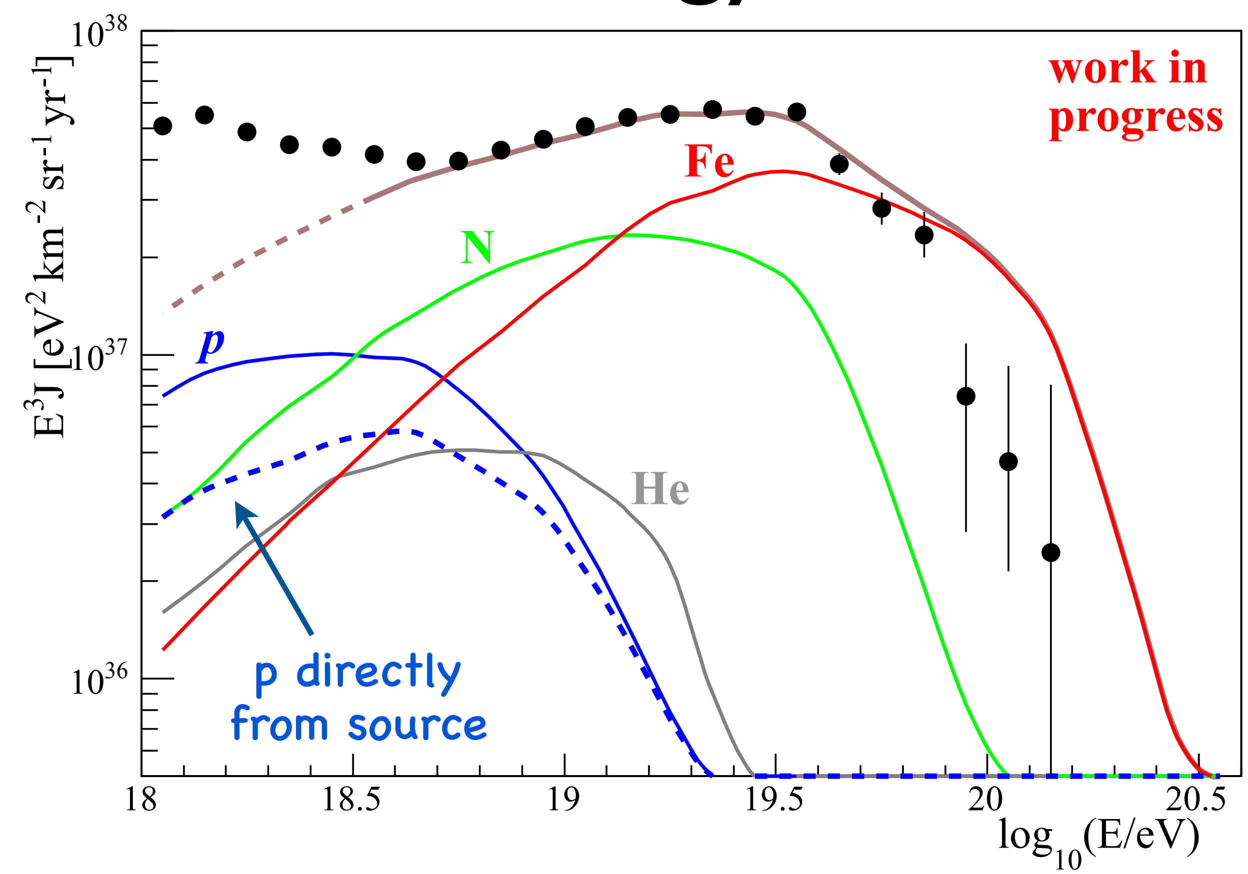
Submitter: Pierre Auger Collaboration
Observatorio Pierre Auger,
Av. San Martin Norte 304,
5613 Malargüe,
Argentina

Q1: GZK effect or Exhausted Sources ?

GZK suppression



maxium energy scenario

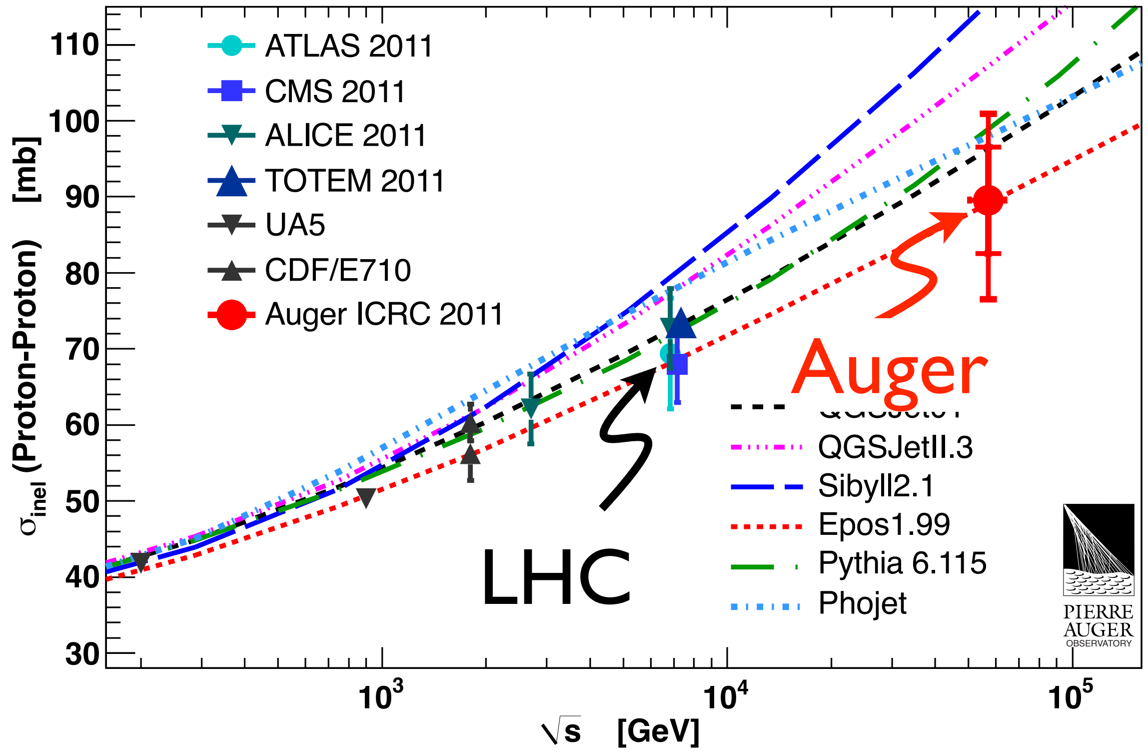


$E_{max}{}^{p} \sim 10^{18.6}$ eV →

$E_{max}{}^{Fe} \sim 10^{20}$ eV

Of fundamental astrophysical importance:
E_{max} of sources ? Standard Fermi acceleration ?

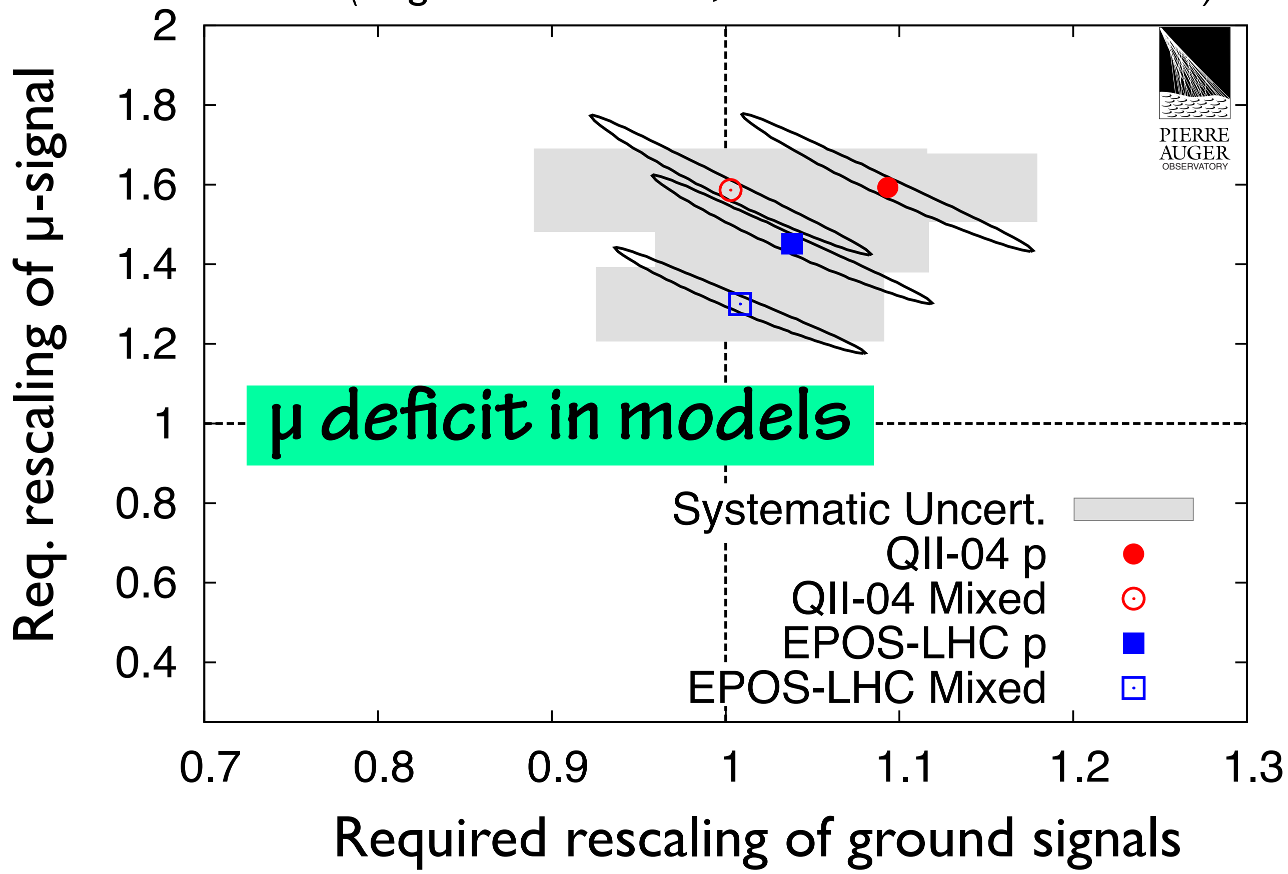
Q3: Hadronic Interactions (10^{19} eV)



Auger Collaboration, PRL 109, 062002 (2012)

pp cross section @ 57 TeV

(Auger Collaboration, ICRC 2013 & 1307.5059)



μ-Problem requires reduced e-flow into em-EAS component

but need to reproduce correlation with X_{max}

➙ separate composition from interaction features

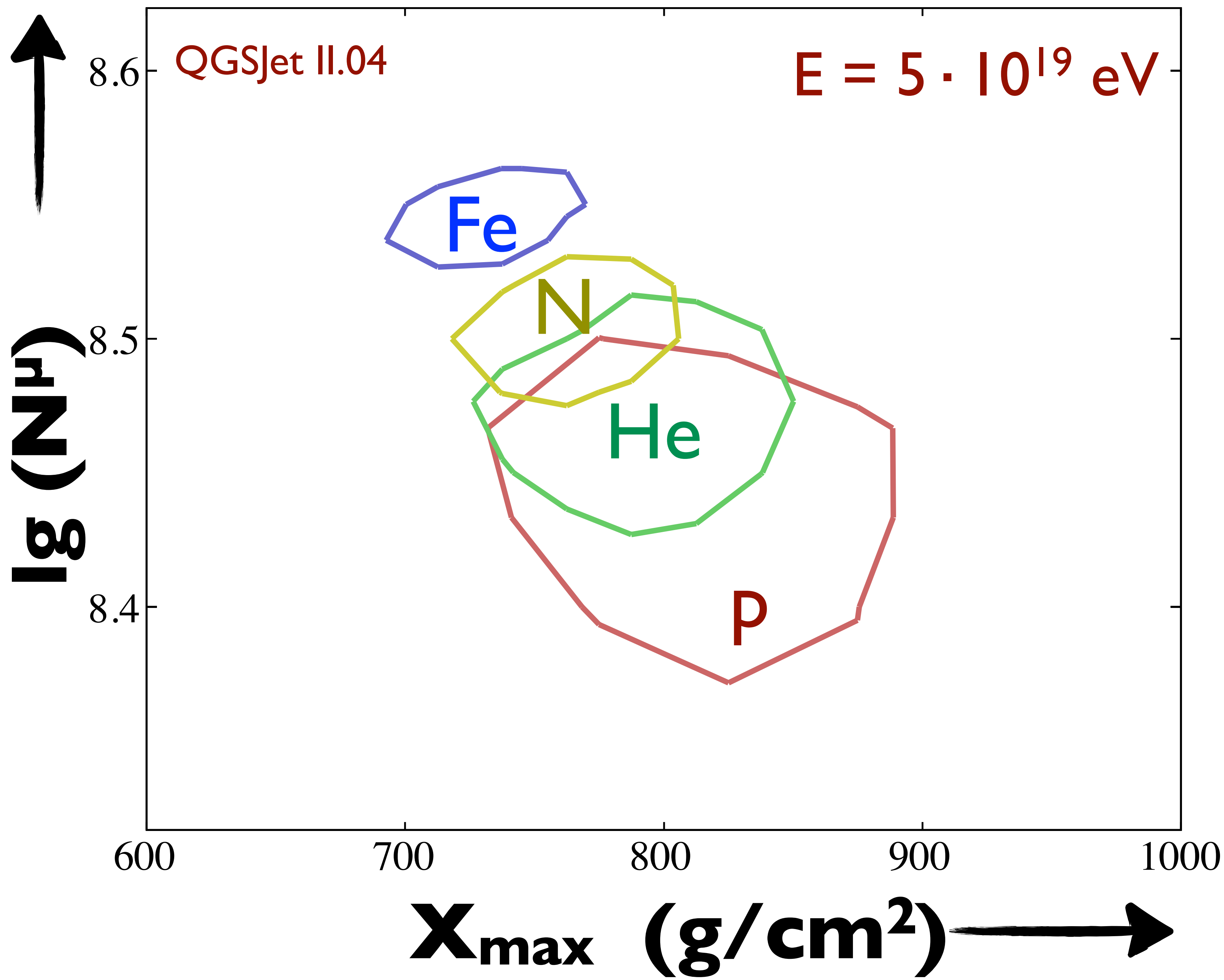
Answering the science questions requires **composition sensitivity event-by-event into the flux suppression region**

Up to know, composition based solely on Fluorescence Telescopes, duty cycle ~10-15%
(different operation modus planned to yield factor ~2)

➙ most effectively achieved by upgrade of surface detectors (duty cycle 100%)
➙ immediate boost in statistics by a factor of ~10 !

classical approach:
enhance electromagnetic/muonic separation of stations
(and time resolution)

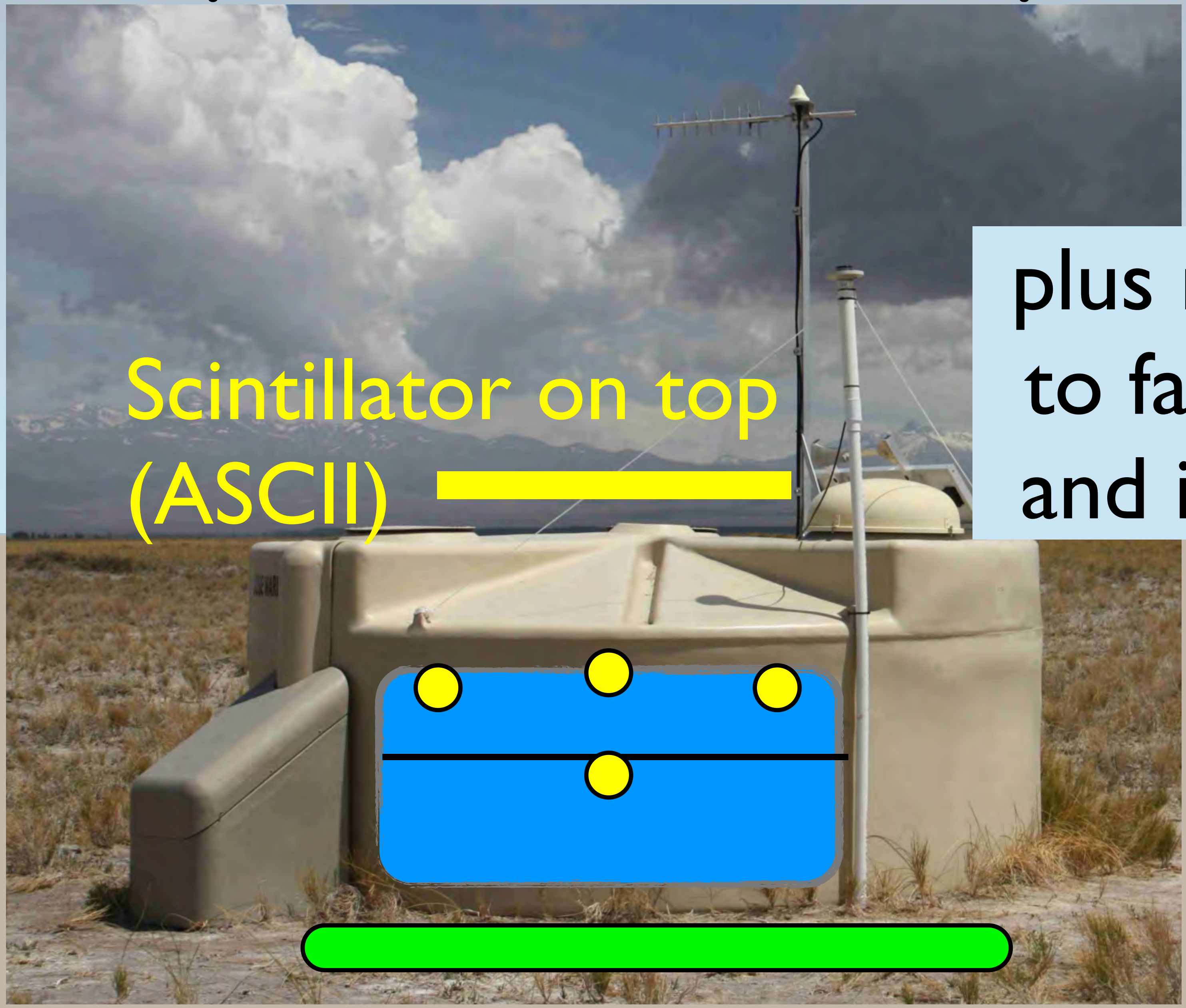
N^{μ}_{max} vs X_{max}



Muons may even outperform X_{max} at highest energies !

Different Upgrade Options under Study

Need to improve on em/mu separation in EAS



plus new electronics to facilitate readout and improve WCDs

segmented tank (LSD)

RPCs below (Marta)

Scintillators in ground (AMIGA-Grande, TOSCA)

ASCII (Scintillator on Top)

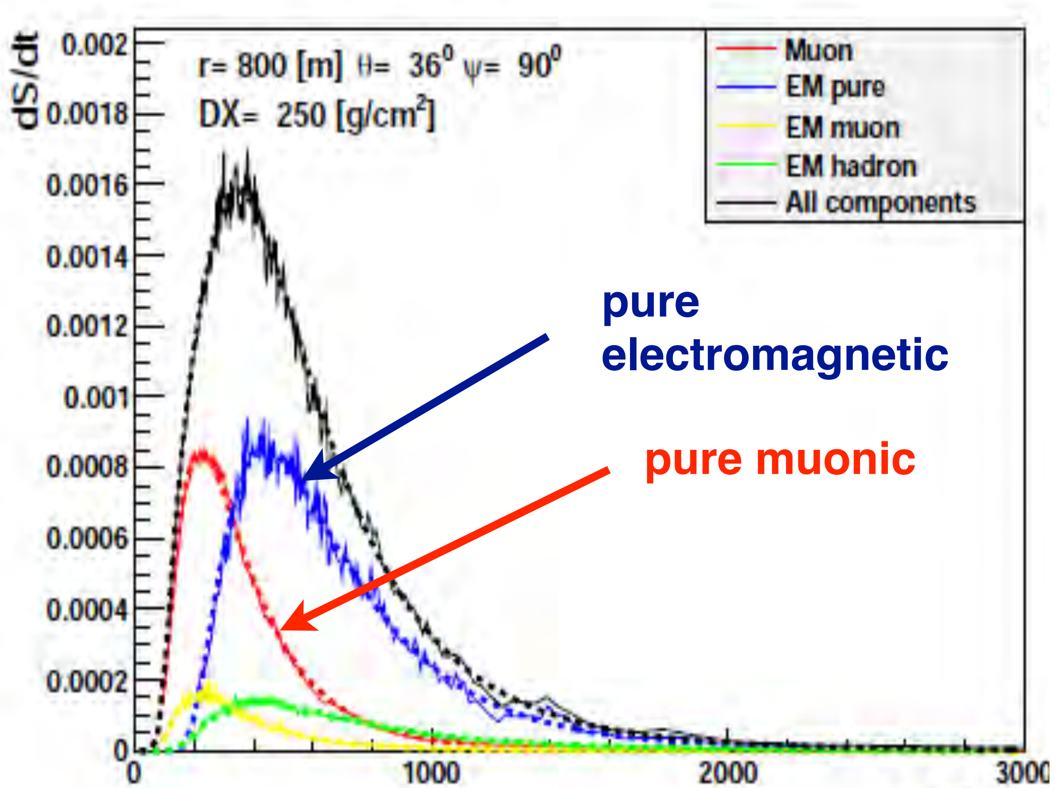
ASC-II: Auger Scintillators for Composition II

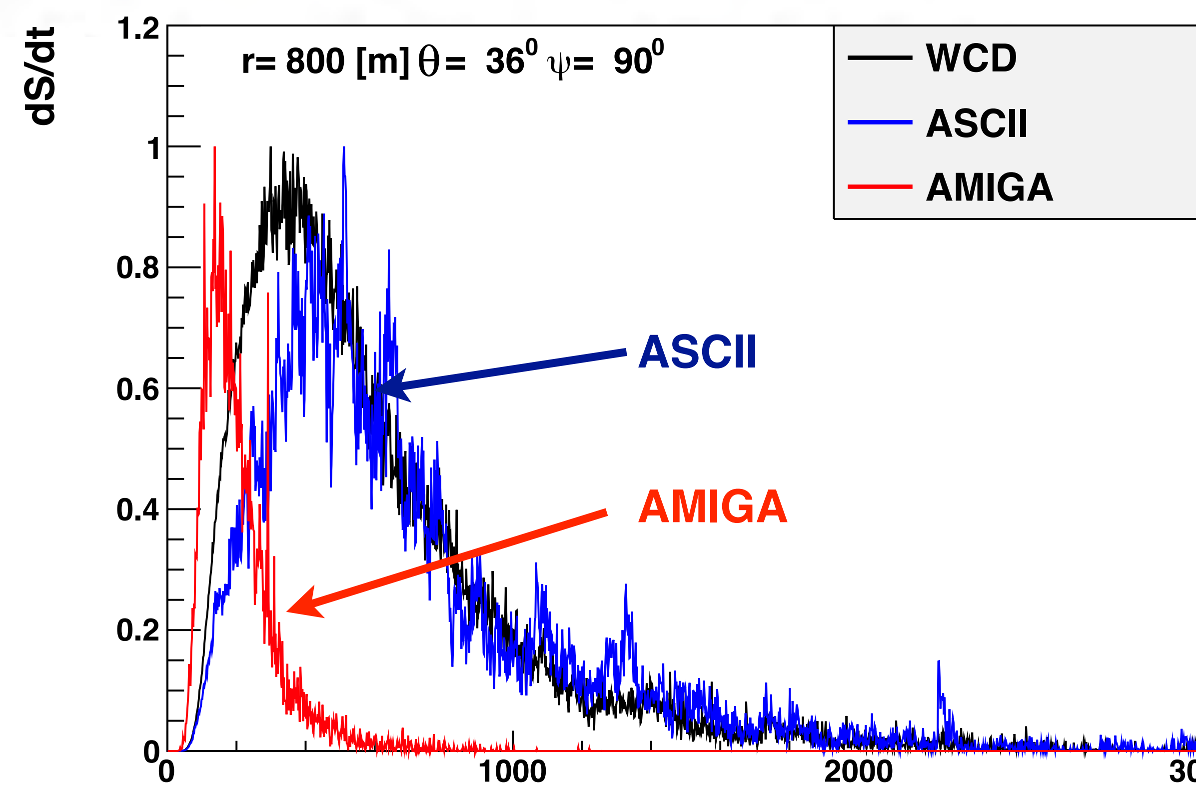
Scintillation detector of 2 m^2

27 strips of 1.8 m x 4cm x 1cm with WLS optics fibers and a 1/2 " PMT

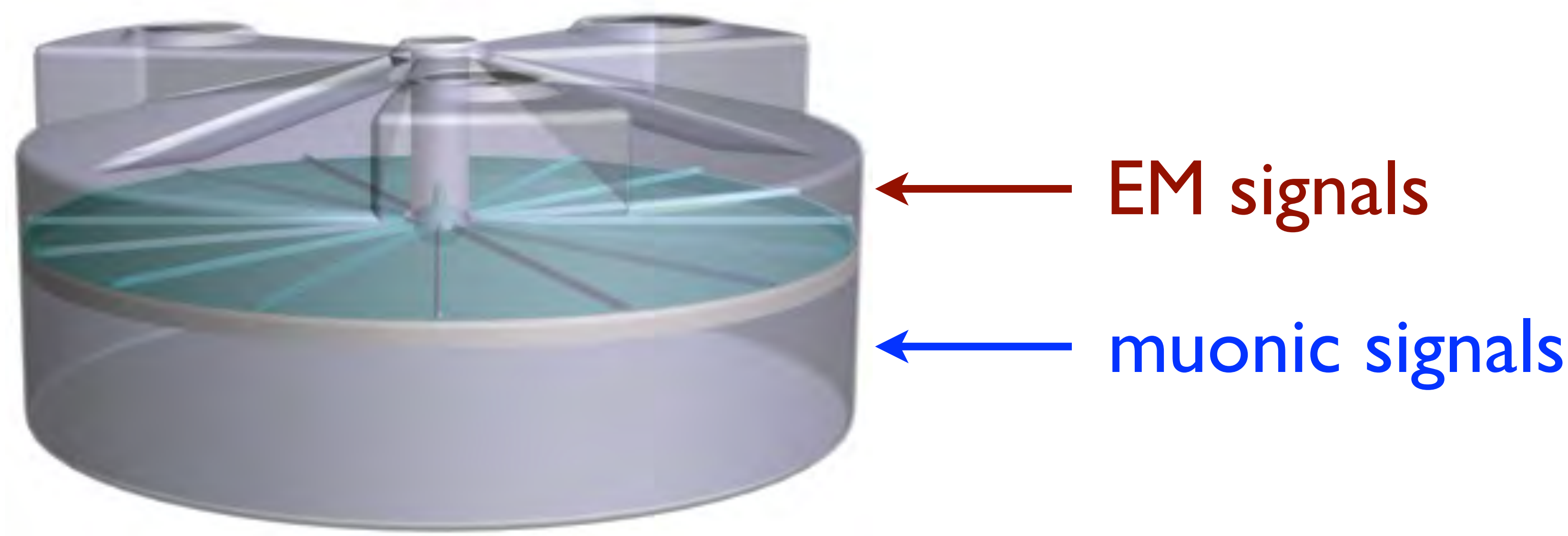
600-800m from core and E > 10^{19} eV

WCD: muon, electrons and gammas.
ASCII sensible to muons and electrons
AMIGA: muons of high energy
Universality: Xmax, E, Nmu + geometría

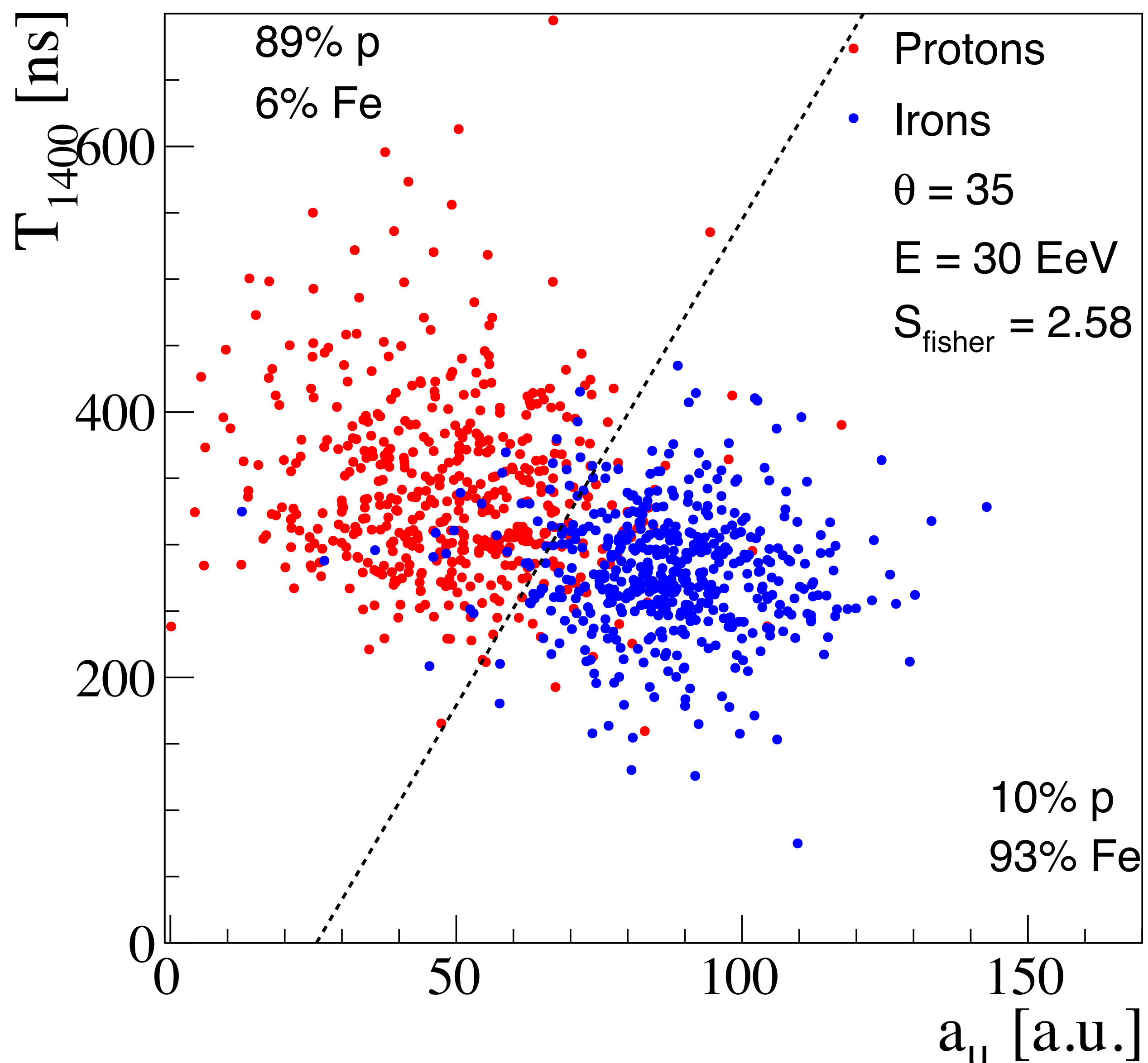




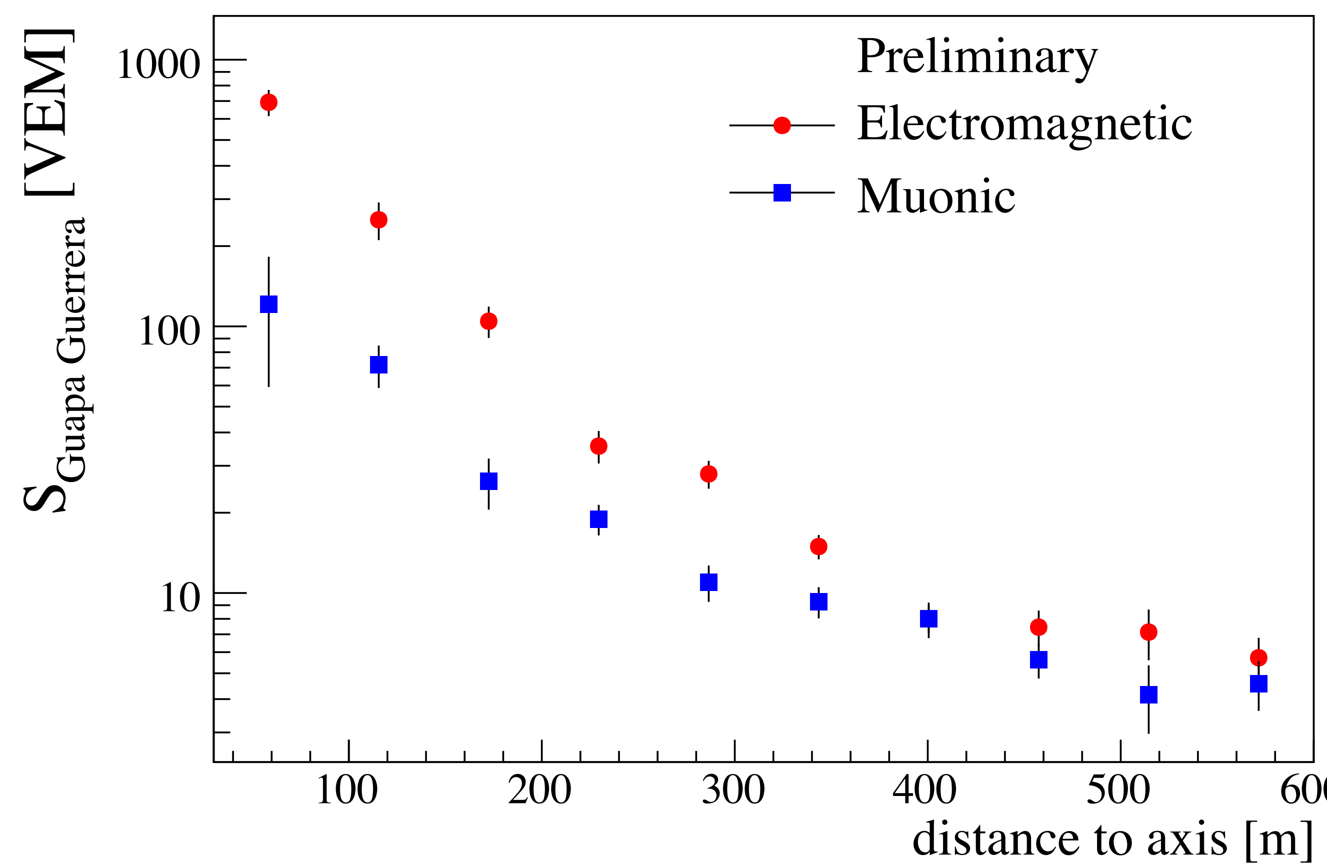
LSD (segmented tanks)



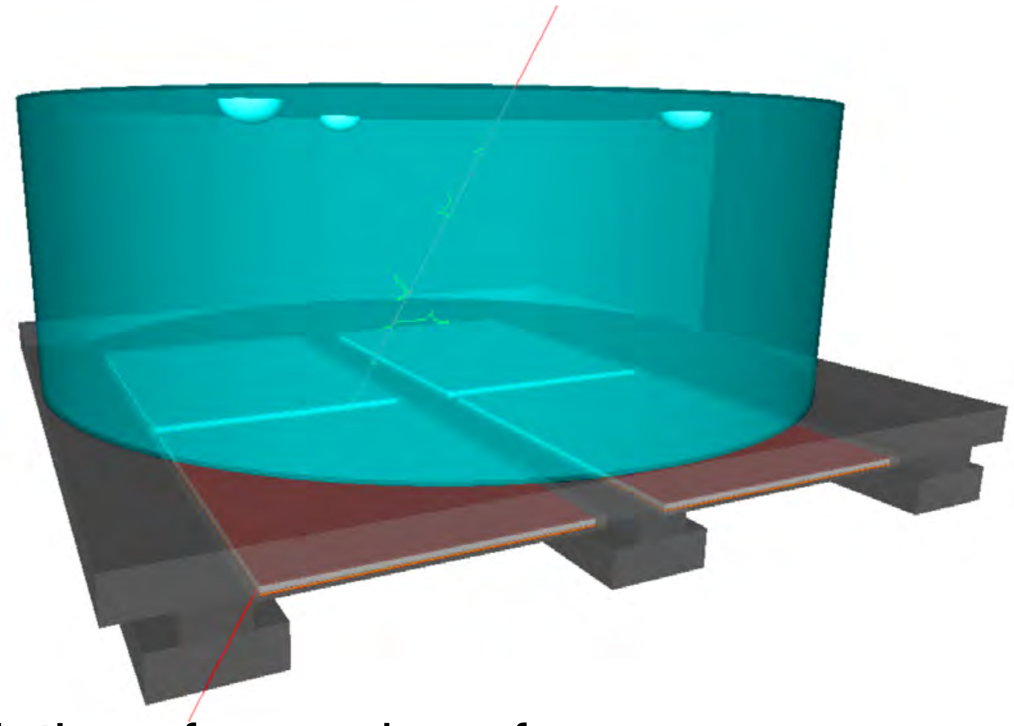
Simulation

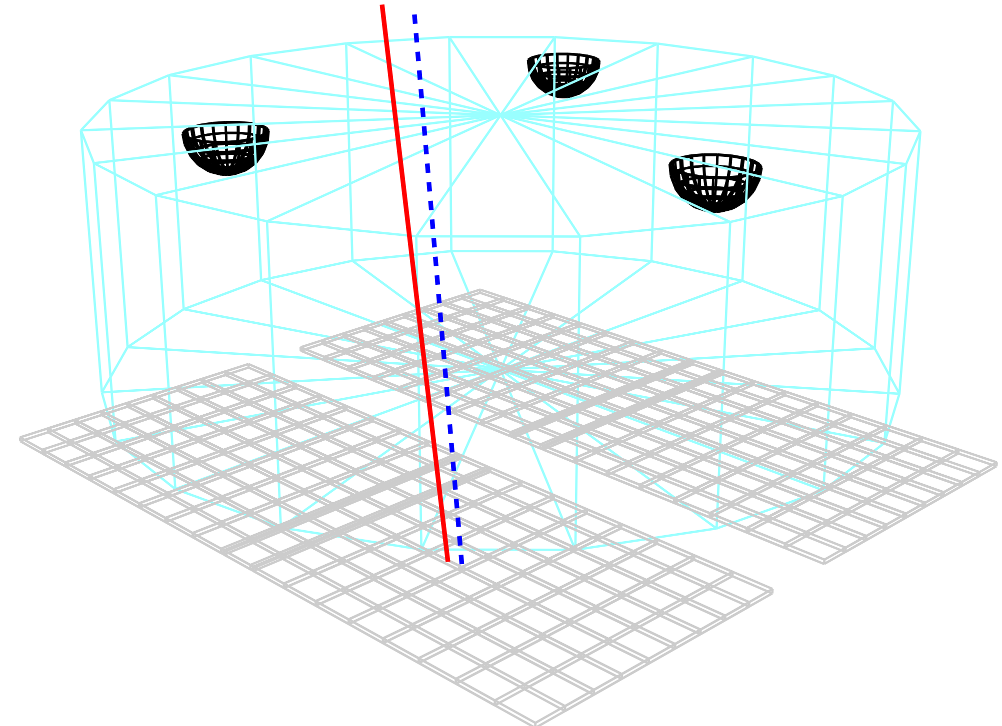


Data

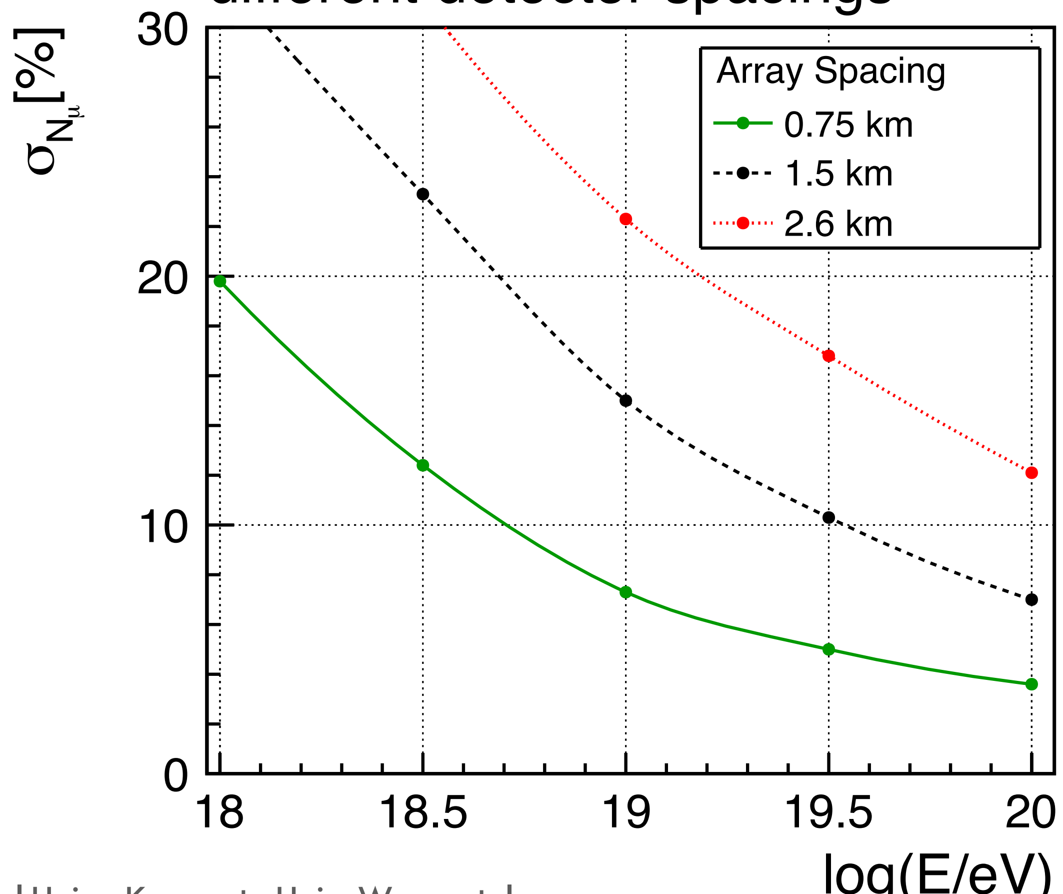


MARTA (RPCs below)

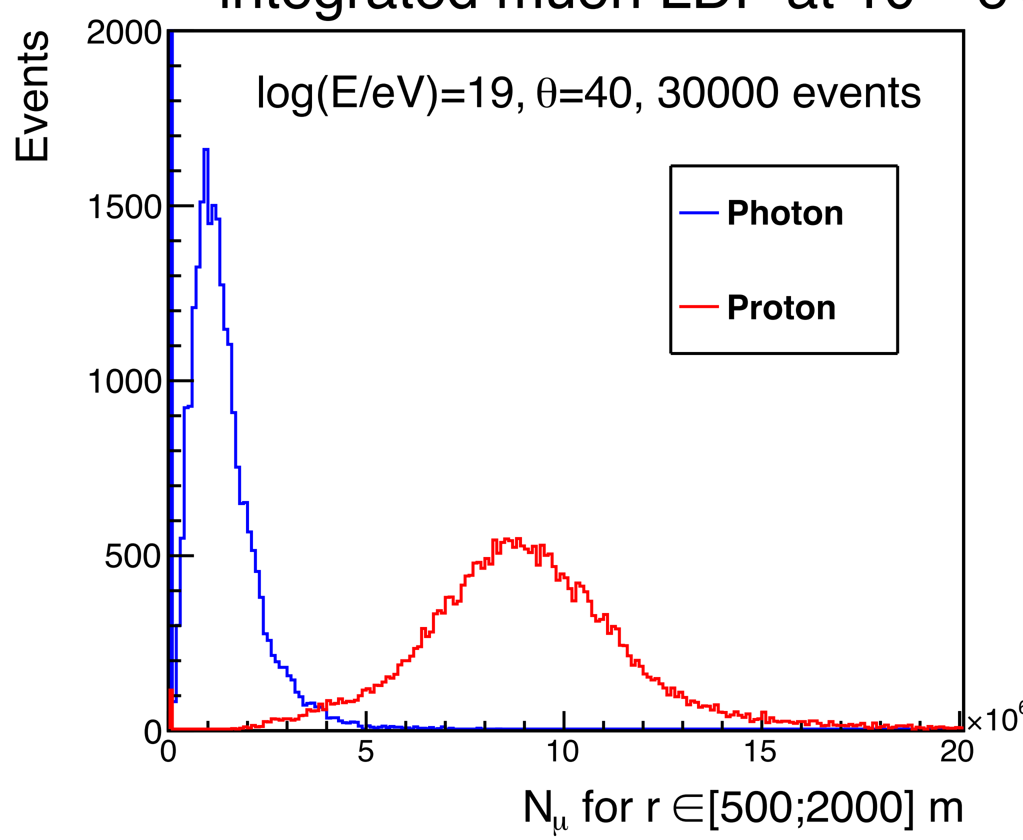




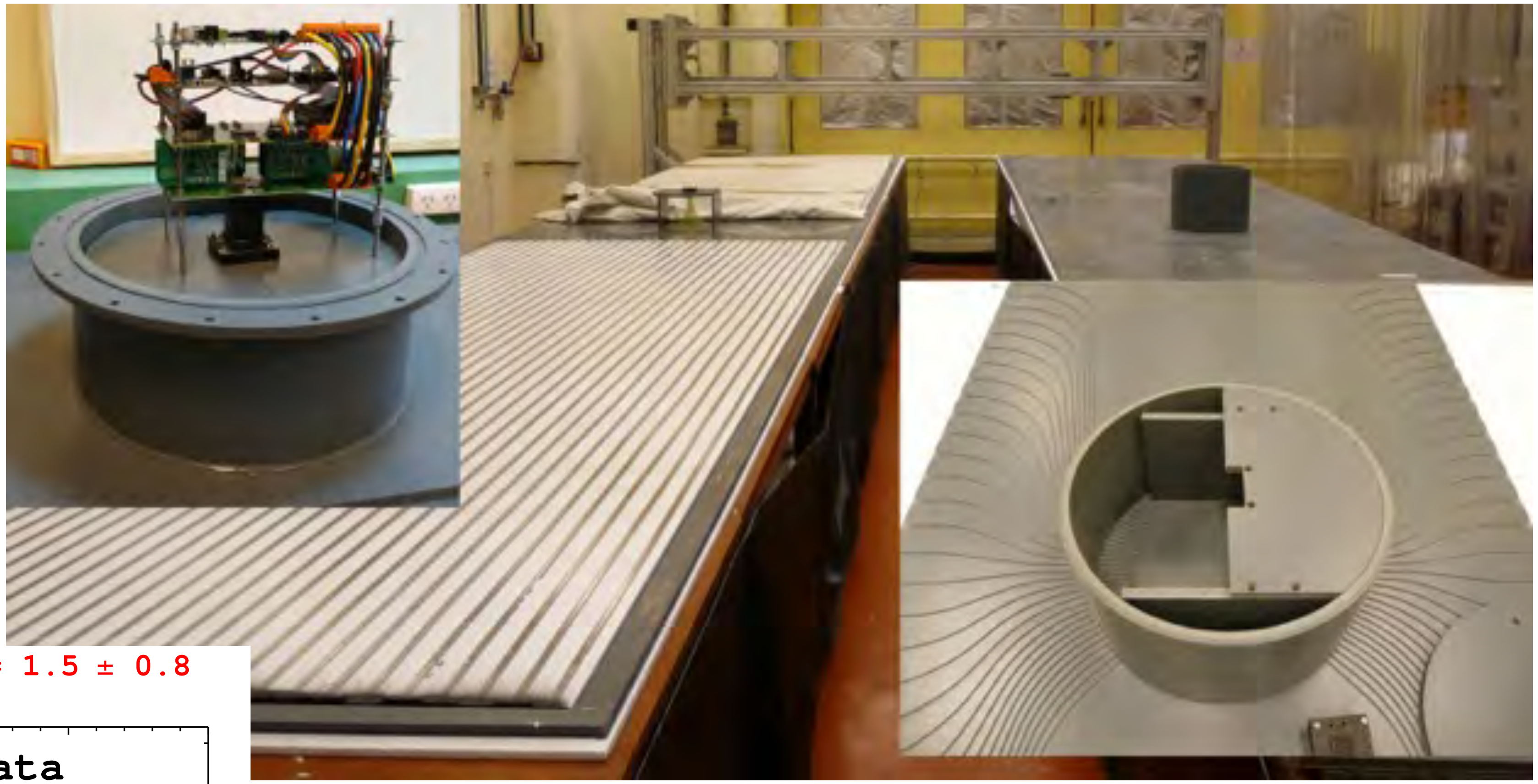
resolution of μ-numbers for different detector spacings

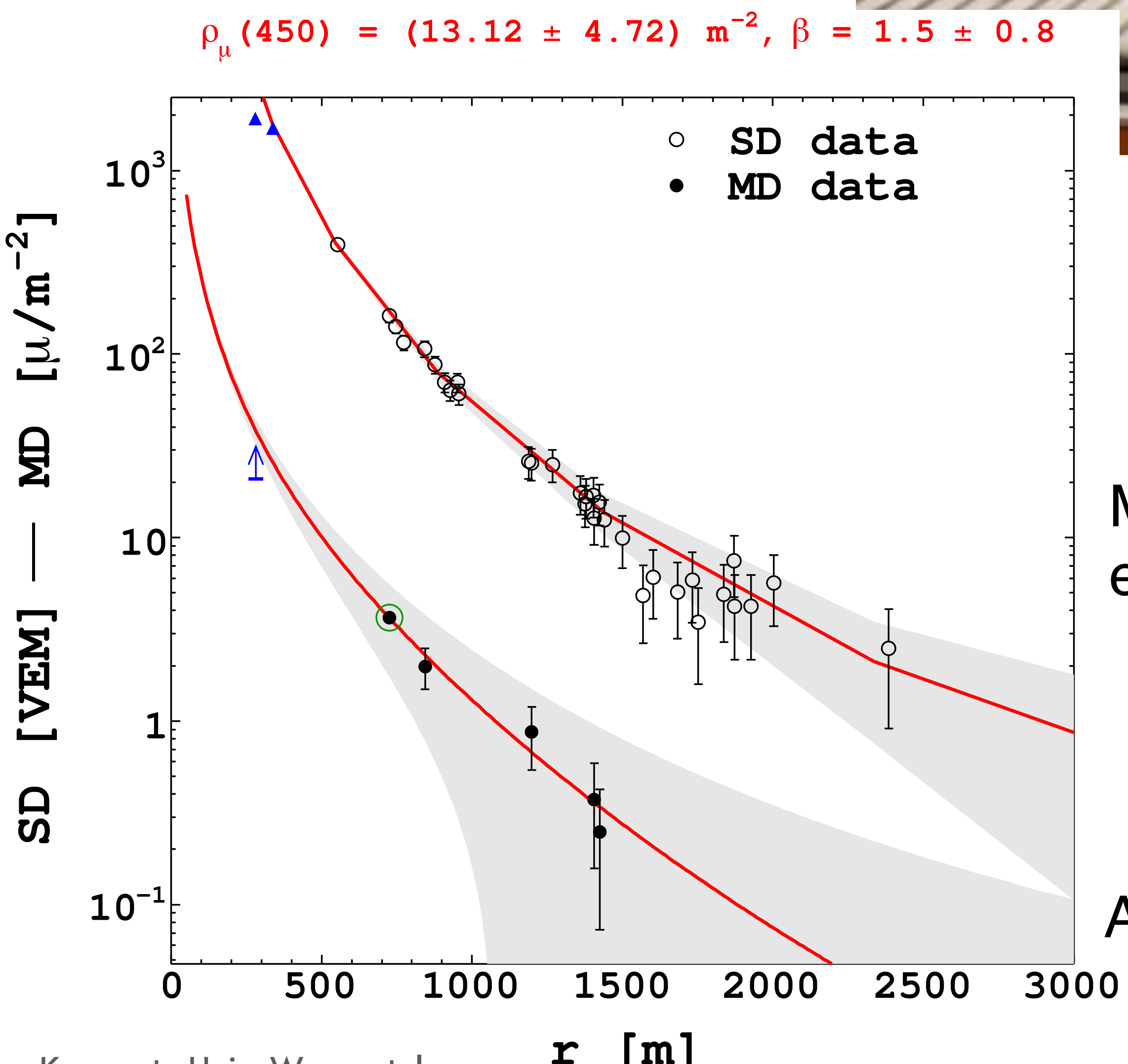


discrimination power of the integrated muon LDF at 10^{19} eV



AMIGA-Grande (Scintillators in ground)



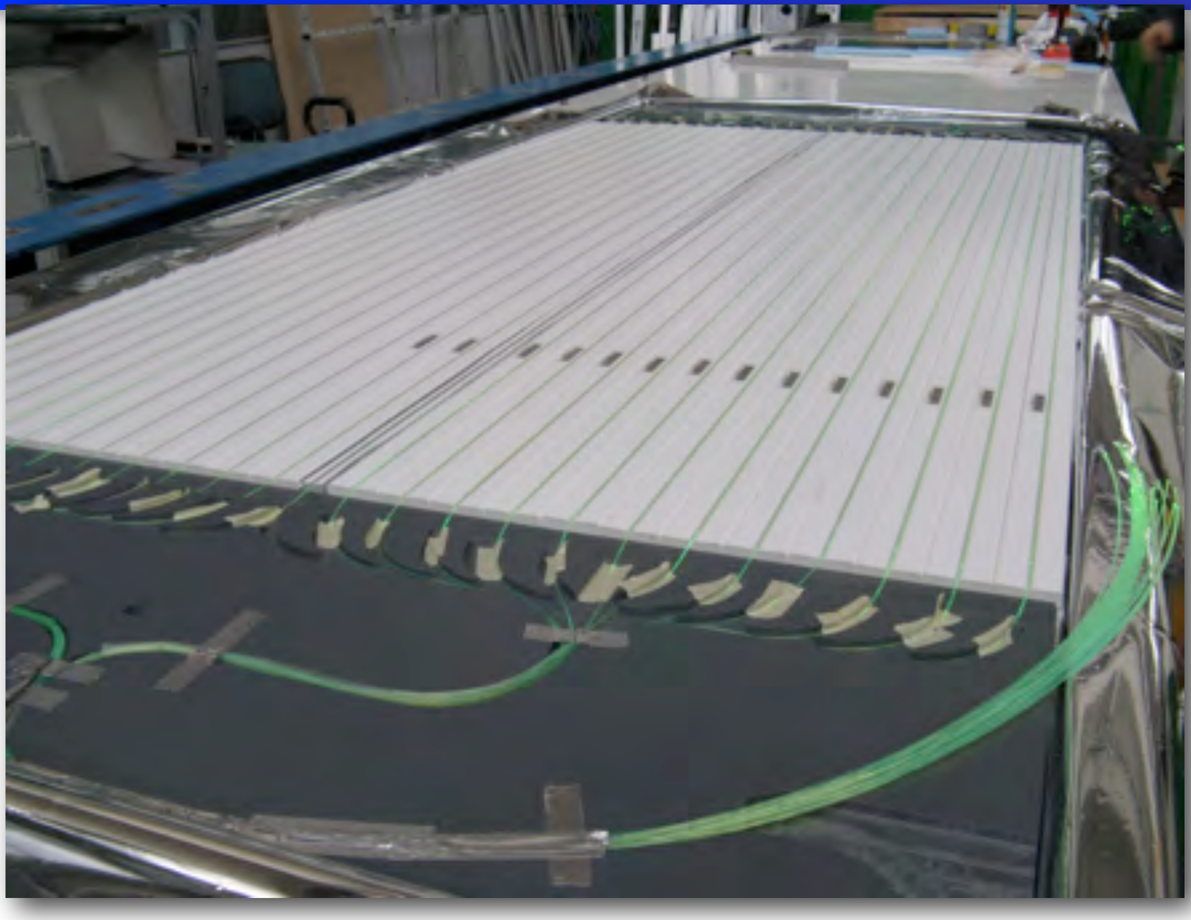


Measured LDF for a shower with reconstructed energy of $1.1 \cdot 10^{19}$ eV

WCD

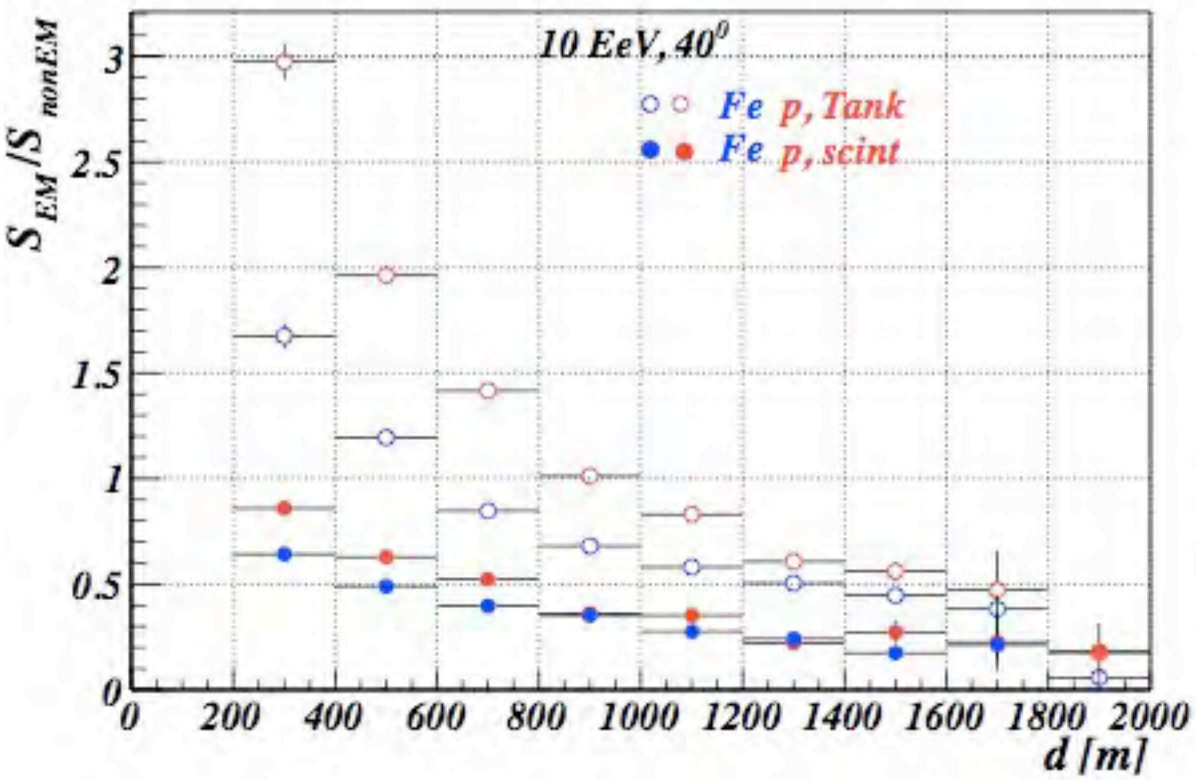
AMIGA

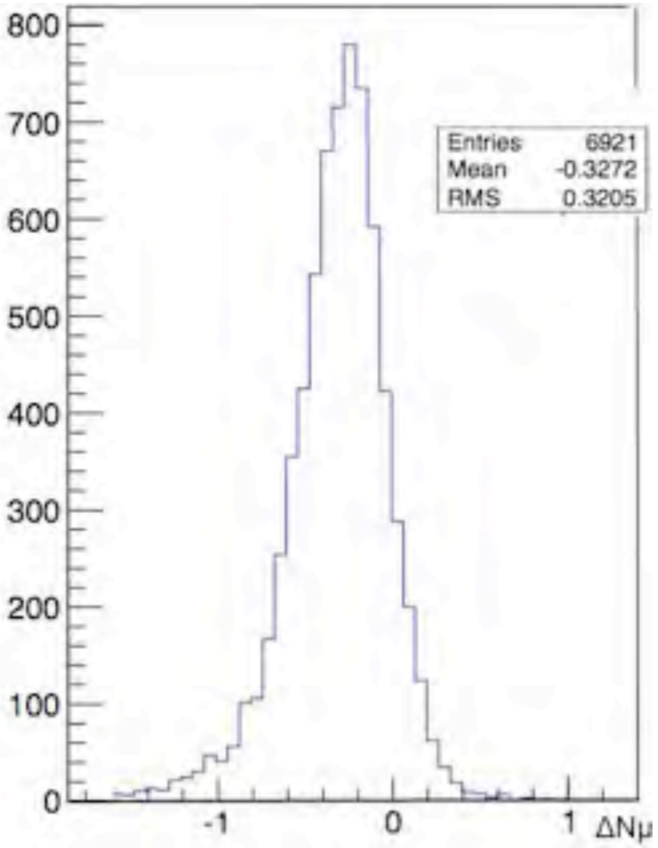
TOSCA (Scintillators in ground)



AMIGA like scintillator bars

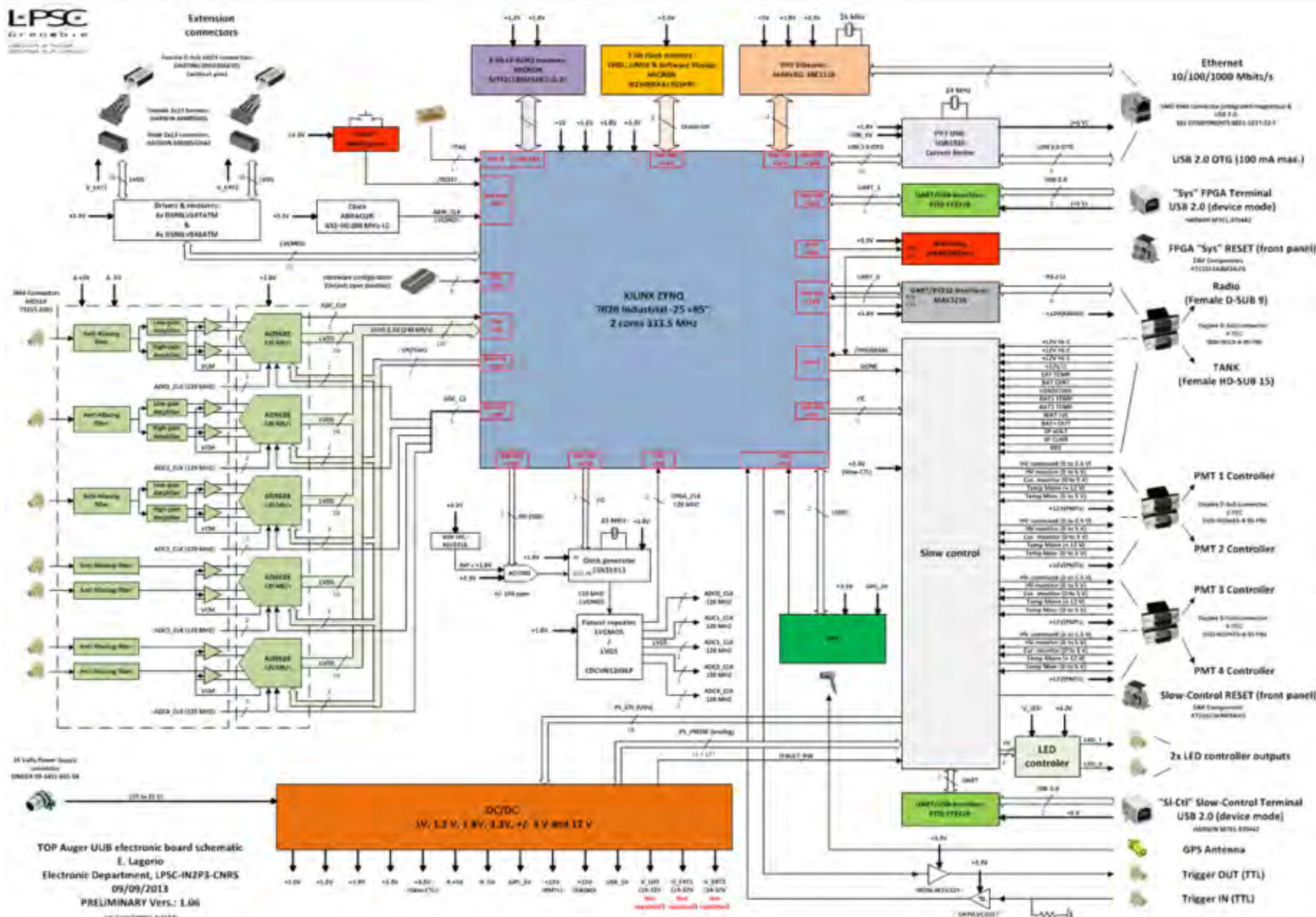
Prototype working in field





expected μ-resolution for 4 m^2 muon coverage

Electronics



Time Line and Plans of Upgrade

Planned Cost Target:

~ 20 % of initial investment → 10-12 MUSD (**~8-10 M€**)

prelim. positive report to FB by SAC in 11/2013

Time Line:

detailed review last week

	2013				2014				2015				2016				2017				2018			
Science Proposal subm			●																					
Review of Science Proposal					●																			
Prototyping in field				X	X	X	X																	
Selection of Prototype							●																	
Submission of TDR							●																	
Final Evaluation							X	X																
Seeking funds / **construction**								●	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**						
take data												X	X	X	X	X	X	X	X	X	X	X	X	→
upgrade finished																					●			

now

data taking into 2023 will double the statistics
of all data up to 2015

Conclusions

Enhancing the surface detector array for better em/mu separation will boost the science of Auger

➙ factor of ~10 in statistics for composition measurements
➙ GZK vs maximum energy
➙ allow p-astronomy (composition enhanced anisotropy)
➙ learn about global features of hadronic interactions at $\sqrt{s} > 70$ TeV
➙ decisive prediction of UHE (cosmogenic) ν-fluxes
➙ decisive for next generation UHECR Experiments

Auger is well in place to address these questions for the next decade

Thank you for your attention!