Pierre Auger Observatory: recent achievements and future plans

PIERRE AUGER OBSERVATORY

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Fermilab

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photo: Steven Saffi

Major Auger achievements

- **Clear observation of flux suppression;**
- Strongest existing bounds on EeV photons and neutrinos, rule out top-down models;
- p-air and p-p cross sections at E_{CM} = 57 TeV;
- **Increasingly heavier composition above ankle;**
- Muon deficit in hadronic interaction models at high energies;
- Strongest existing bounds on large scale anisotropies;
- First hints on directional correlations to nearby matter;
- Successful and extraordinary outreach programs;
- Solar and geophysics, unique contribution to atmospheric physics.

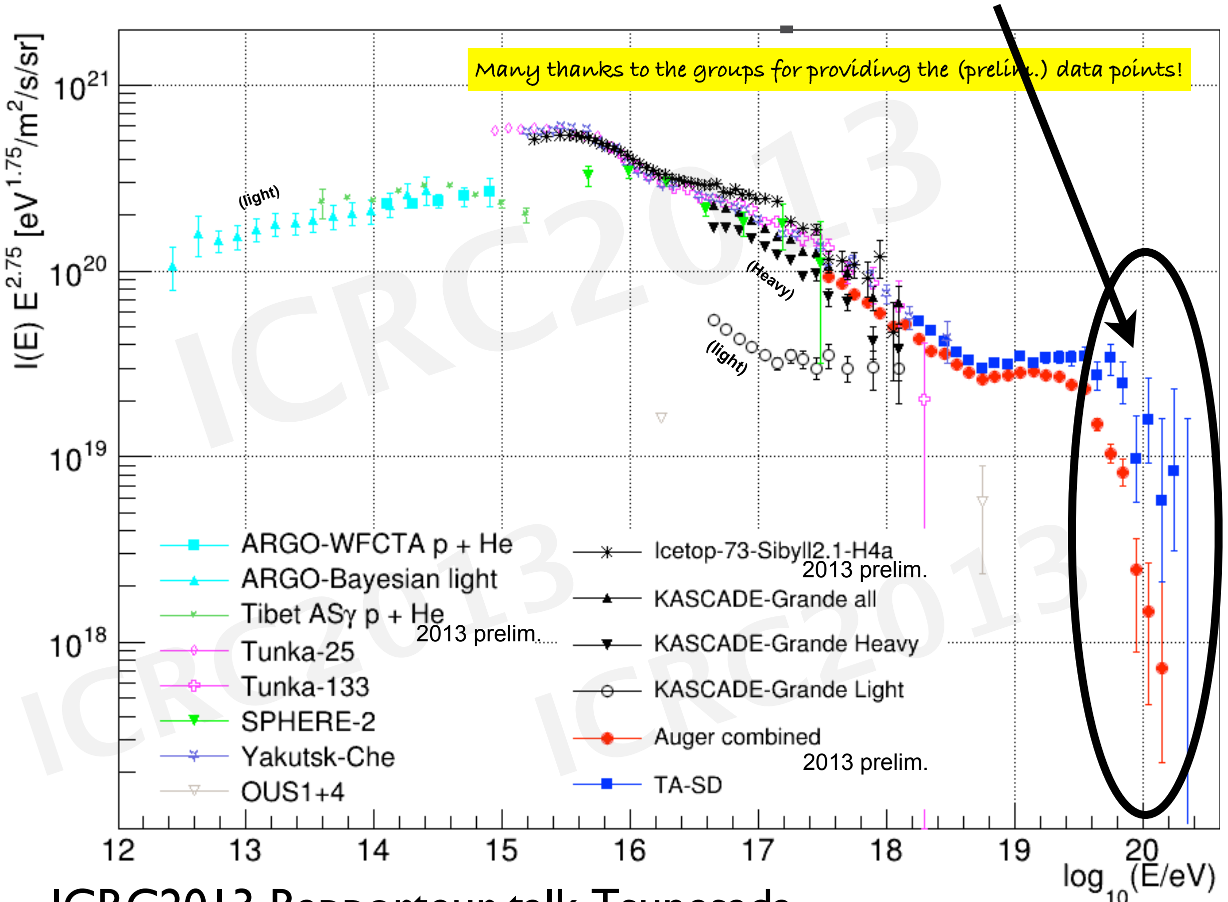
47 publications, 218 PhDs

Truly international collaboration

~500 collaborators, 90 institutions, 18 countries

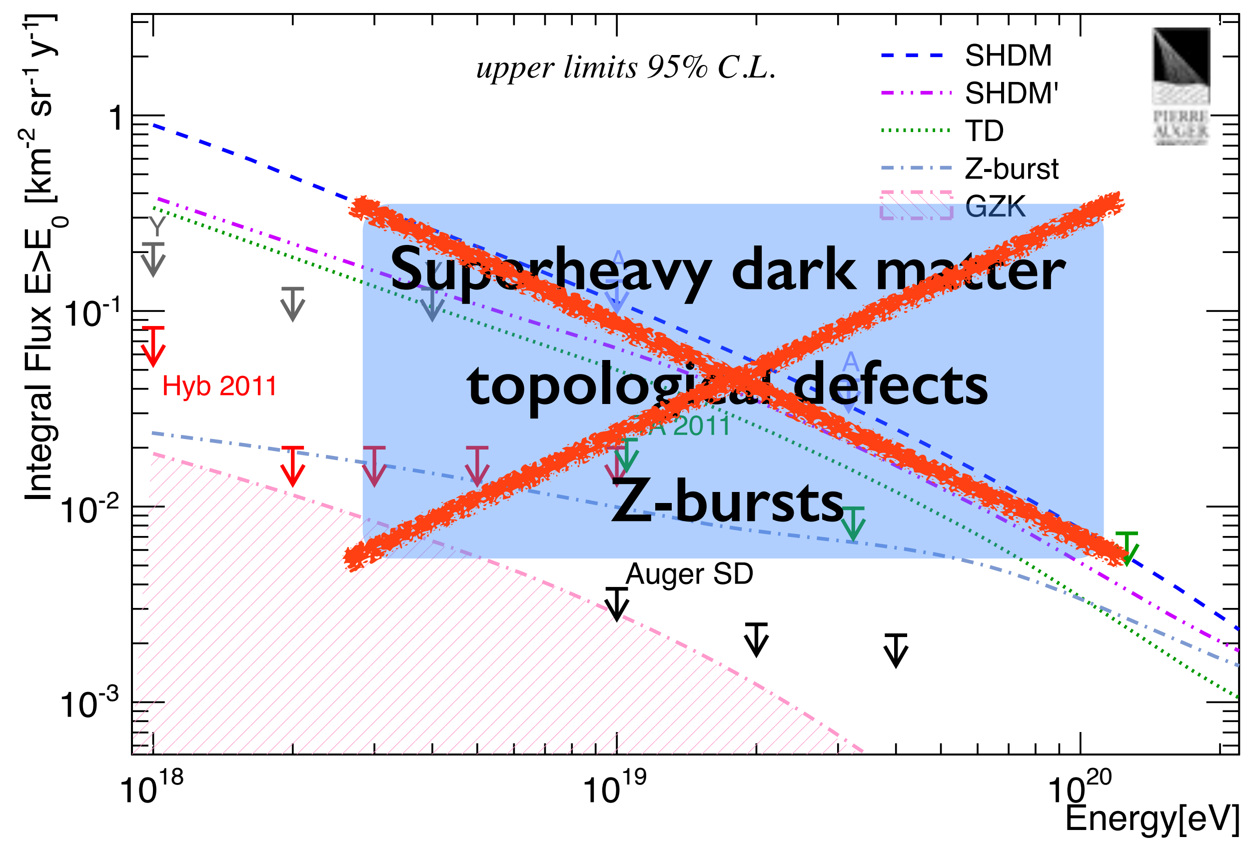
❖ State of ultra high energy cosmic rays today

Suppression of CR flux around 5x10^{19} eV confirmed



ICRC2013 Rapporteur talk, Tsunesada

Photon limits ruled out "top-down" scenarios



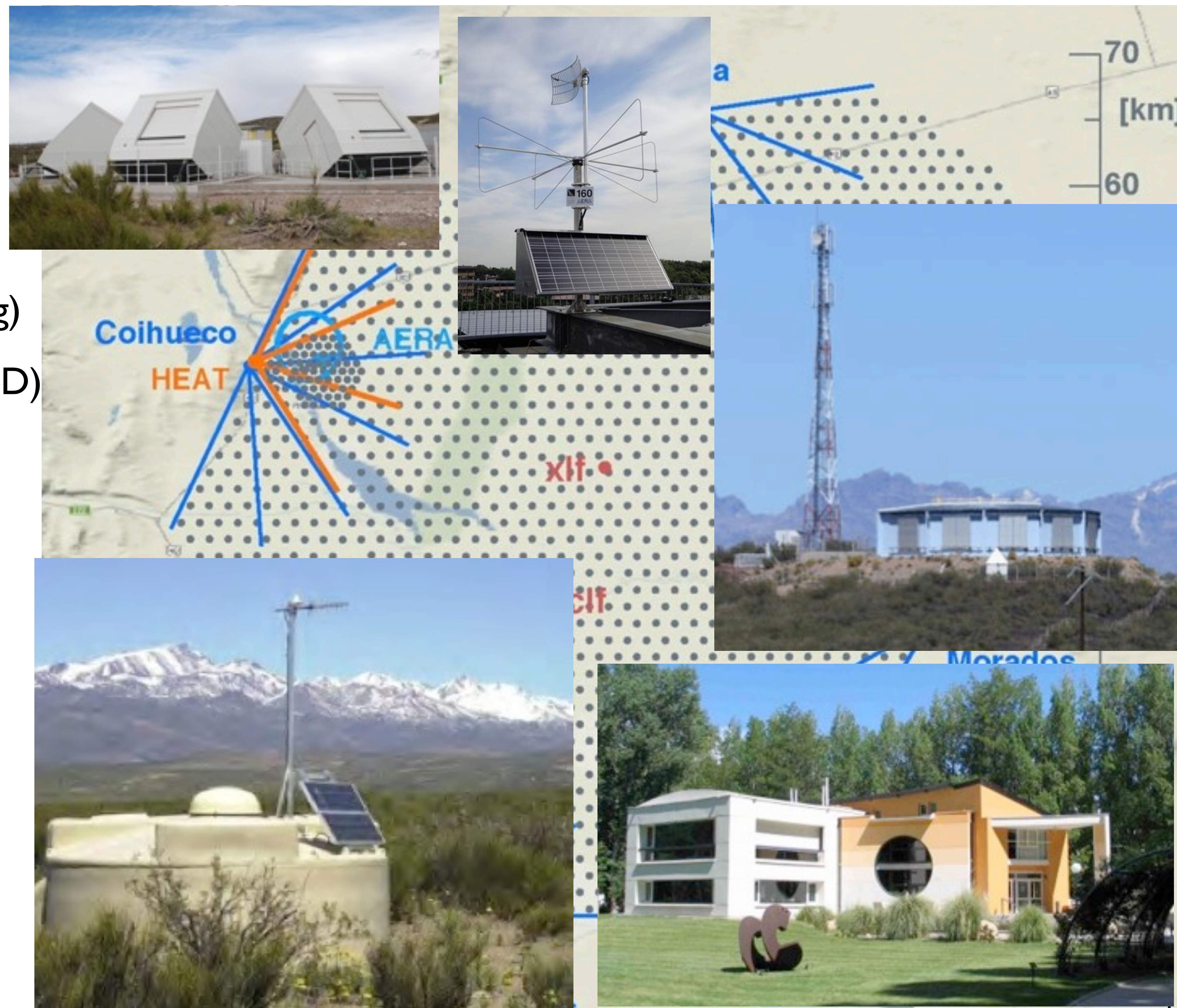
"Classic" models of UHECR typically assume:

1. particles accelerated at extra-galactic astrophysical sources
   - these sites are distributed similarly to matter distribution in the universe
2. mainly protons (some heavier nuclei also possible - model dependence)
3. flux suppression due to GZK process and/or photo disintegration during propagation to Earth
4. some degree of anisotropy expected in arrival direction distribution above certain energy

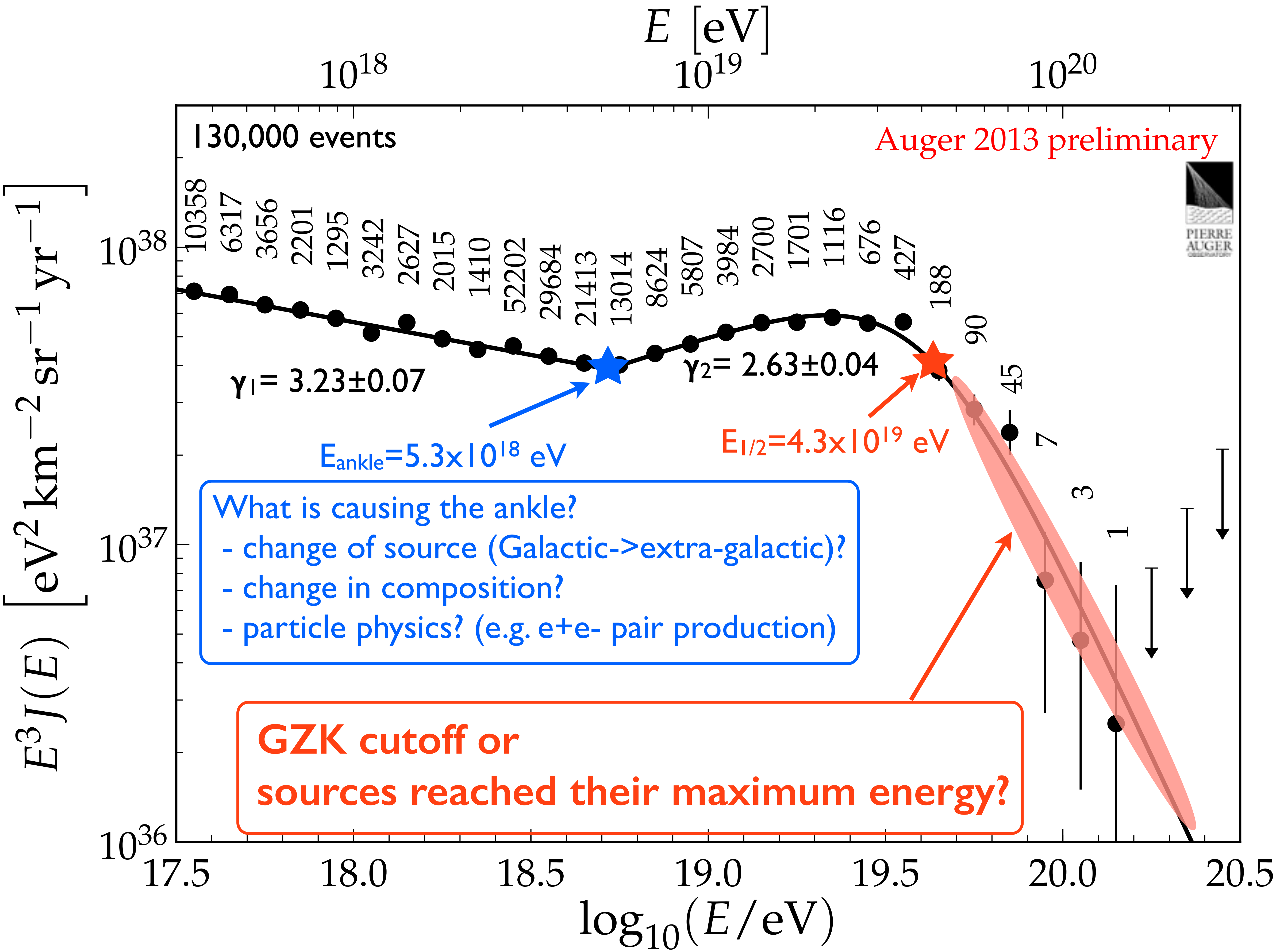
Pierre Auger Observatory

Observe, understand, characterize the ultra high energy cosmic rays and probe particle interactions at the highest energies

- Malargüe, Argentina
  $\sim$ 3000 km^2
- Surface detectors (SDs)
  - 1660 water Cherenkov detectors (WCDs) (12 tonnes, 1.5 km spacing)
- Fluorescence detectors (FD)
  - 27 air fluorescence telescopes in periphery
- Energy range
  - main array: >10^{18} eV
  - enhancements: >10^{17} eV
- 130 radio array
  - AERA (MHz), 6 km^2
- ongoing R&D activities
  - microwave (GHz), single-pixel telescope



- Updated energy spectrum: SD + infill + hybrid (zenith angle 0° - 80°)



What is the reason for the flux suppression?

Are UHECRs

1. Extra-galactic origin of mixed composition, suppression due to limited maximum energy of particles accelerated at source, $E_{max} \propto$ charge ? (can account for protons at ankle)

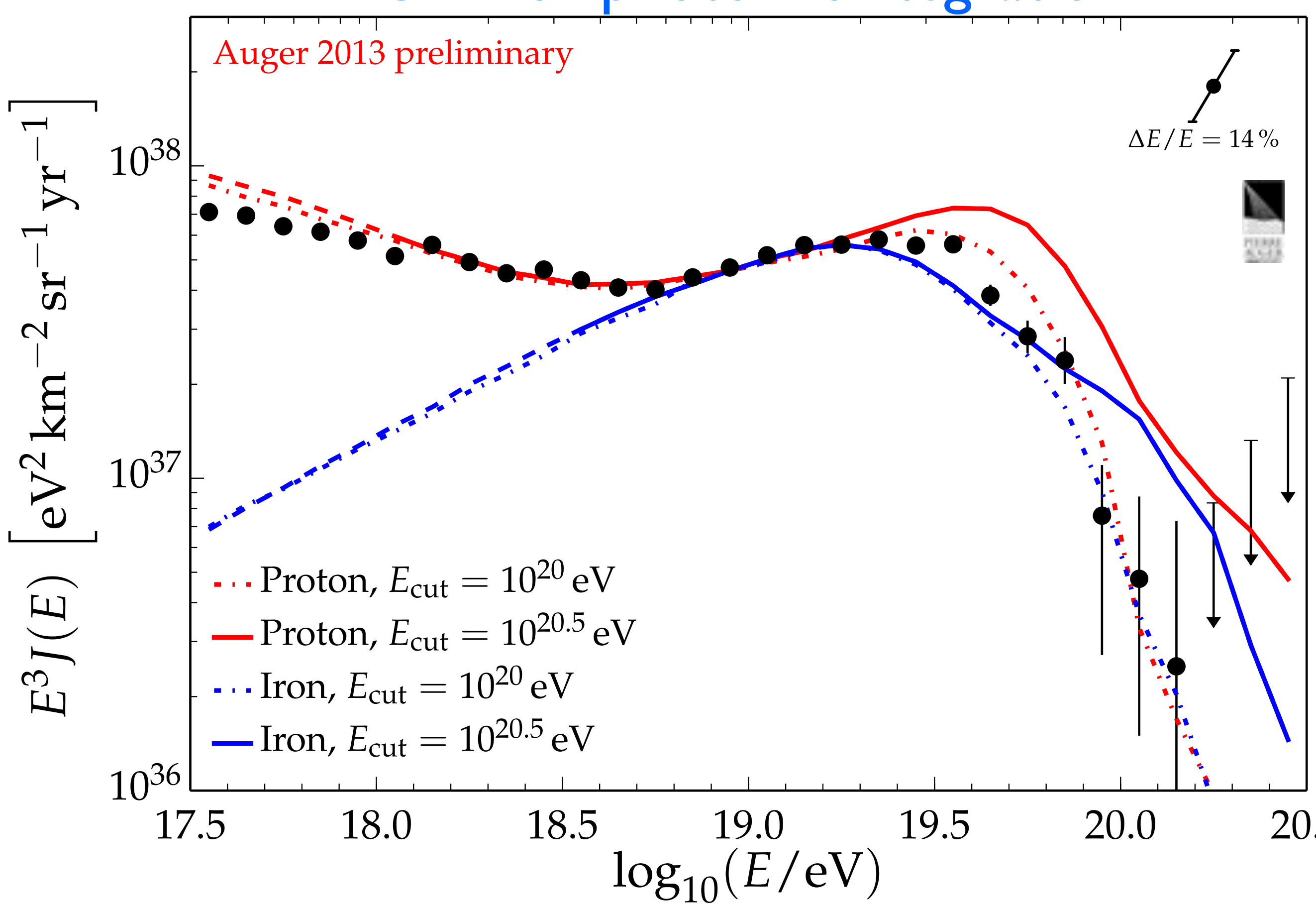
or

2. Similar to above but particles accelerated to higher energies, suppression due to photo-disintegration of heavy nuclei?

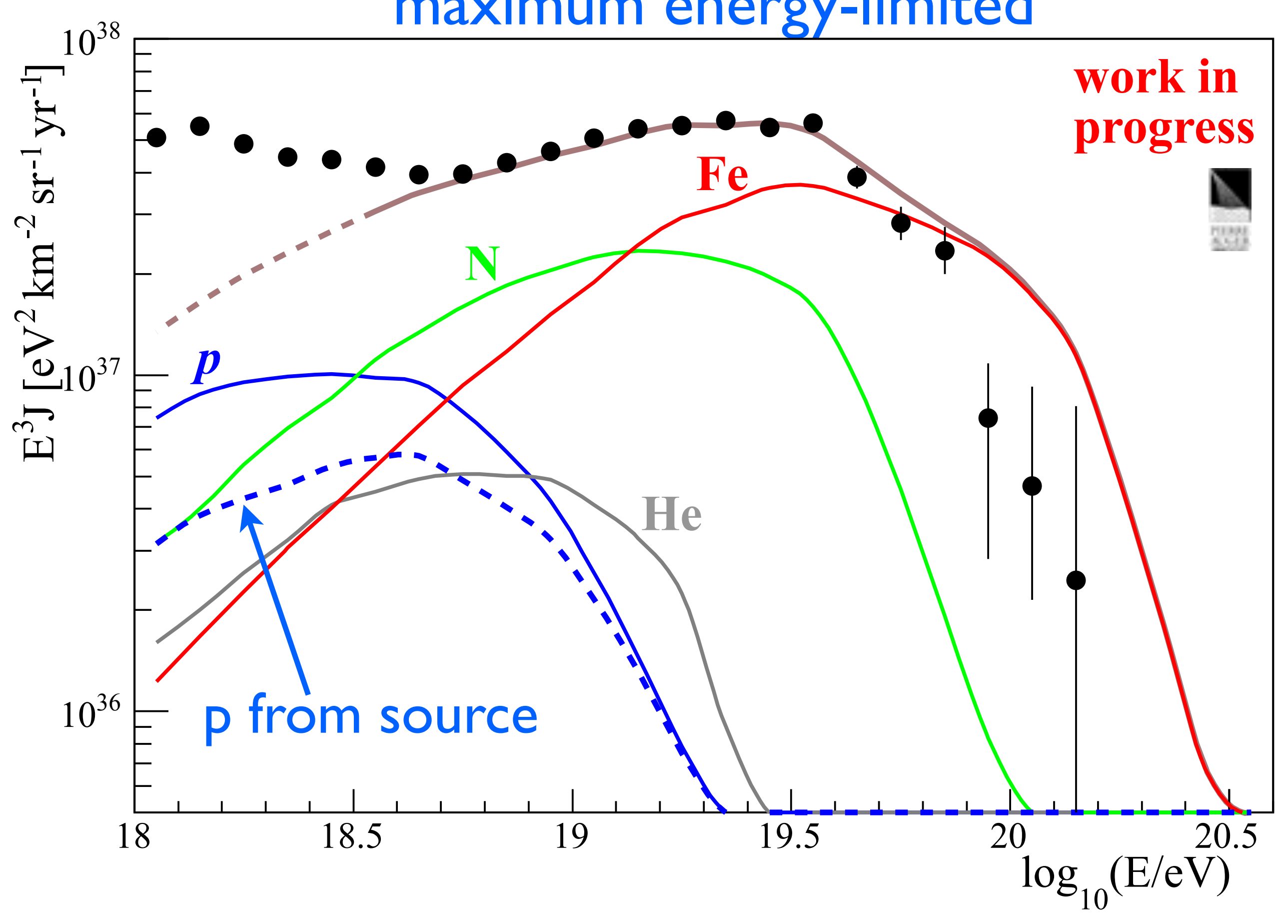
or

3. Mainly extra-galactic protons, suppression due to GZK cutoff? (ankle accountable by e^+e^- pair production.)

pure proton or Fe nuclei at source
GZK or photo-disintegration

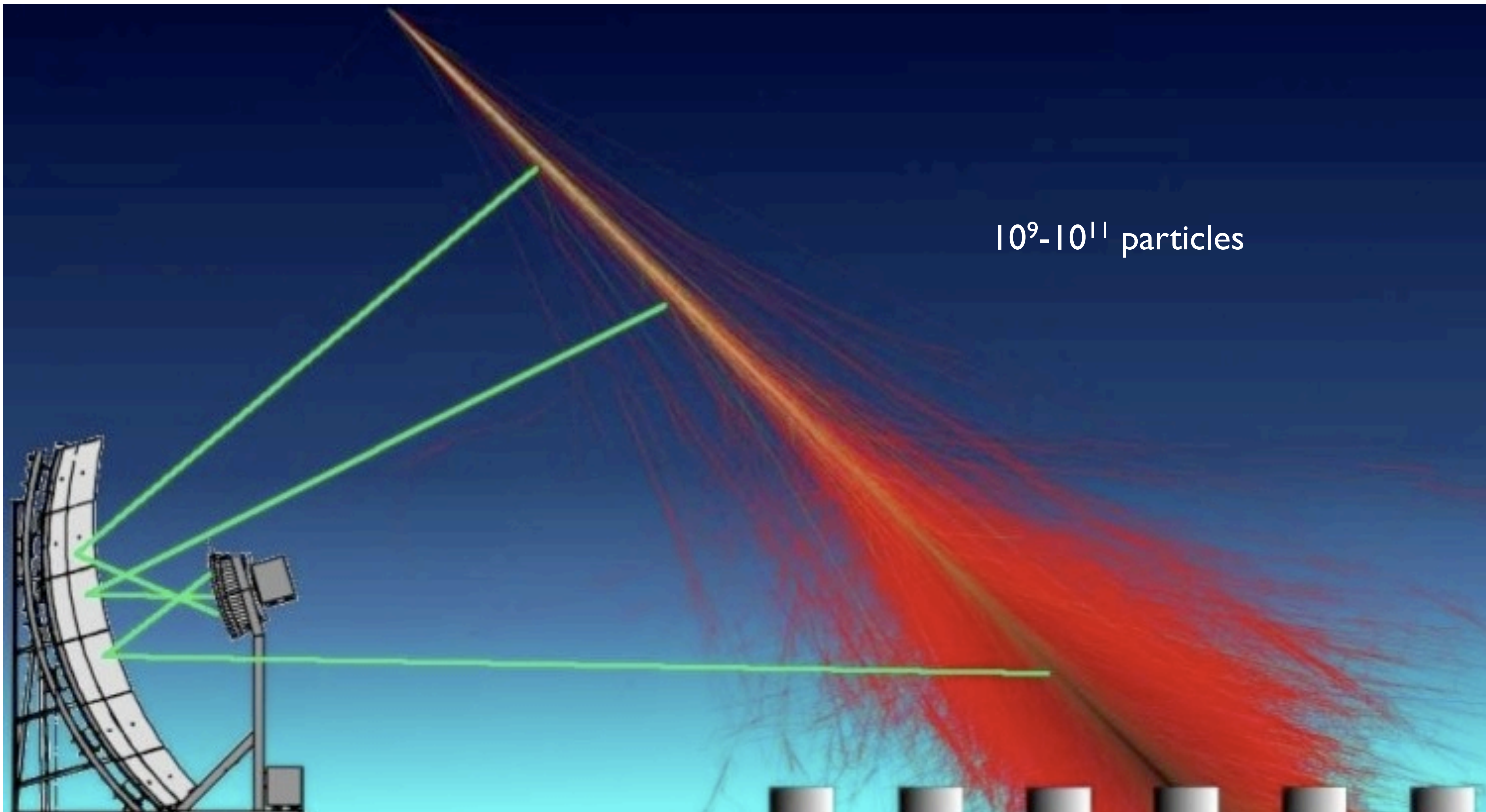


mixed composition at source,
maximum energy-limited

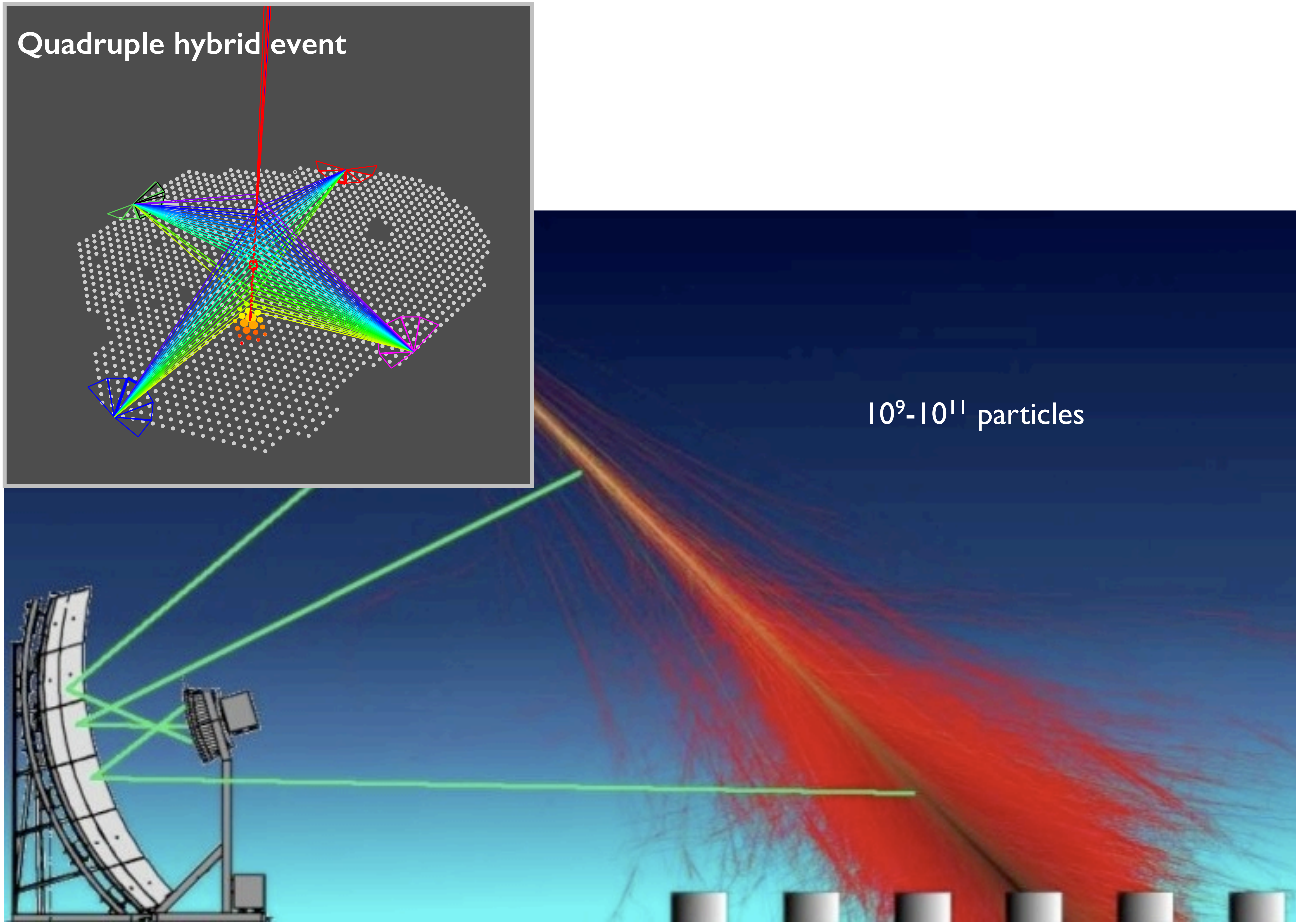


➡ Knowing composition is the key to understanding the flux suppression

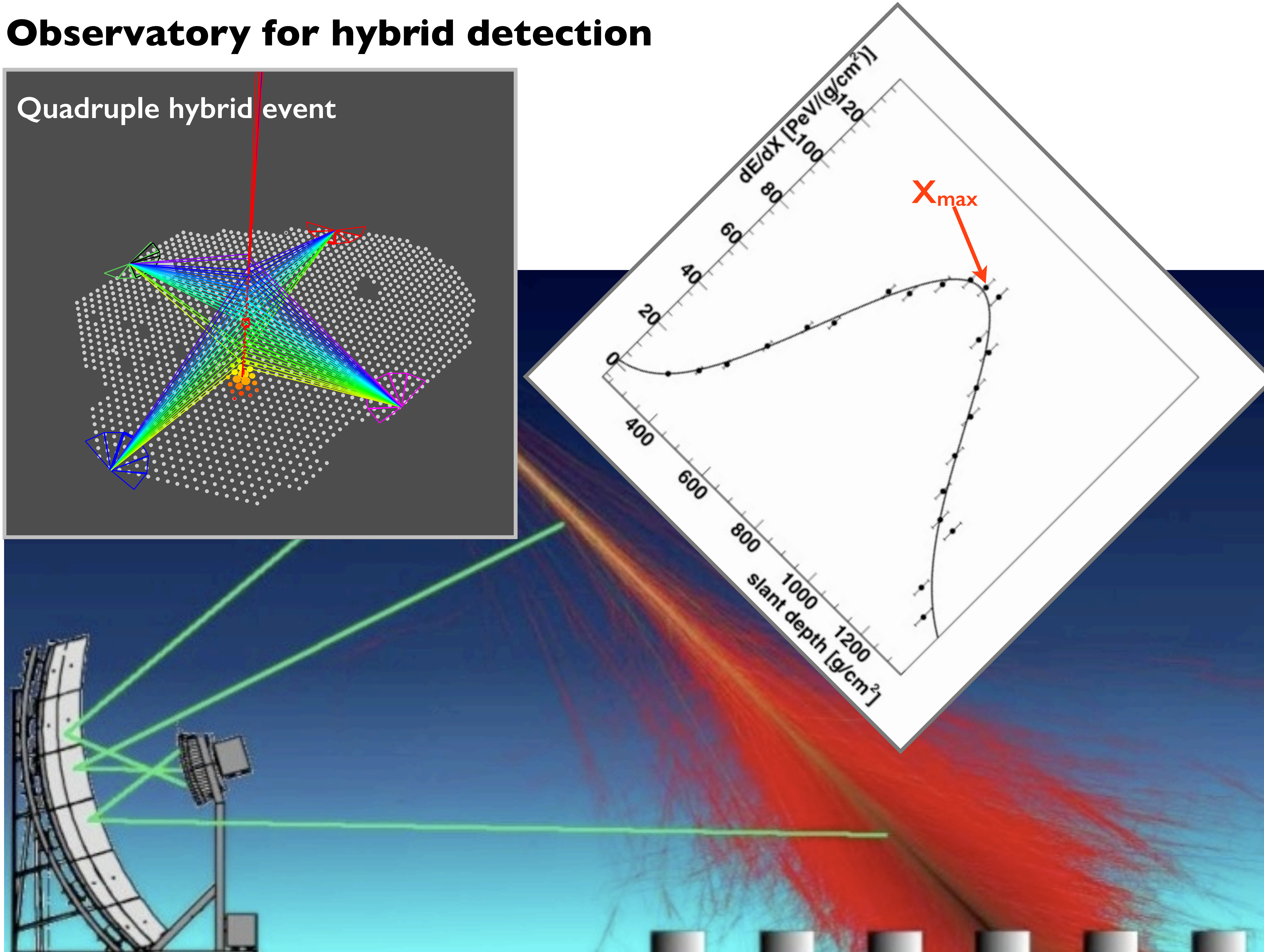
Observatory for hybrid detection



Observatory for hybrid detection



Observatory for hybrid detection



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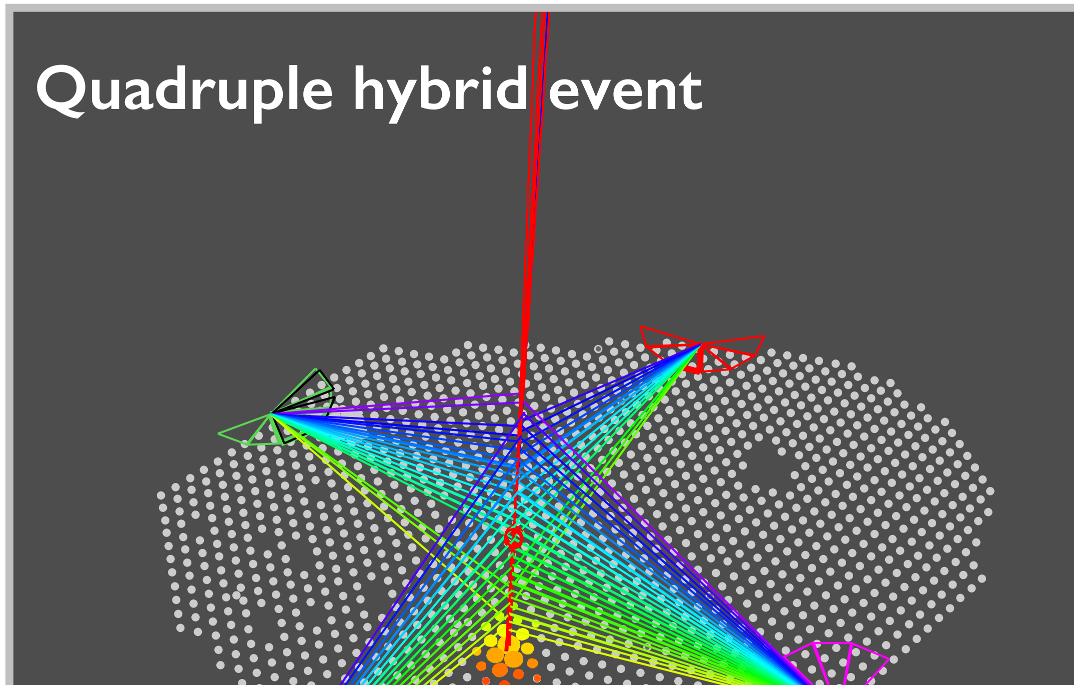
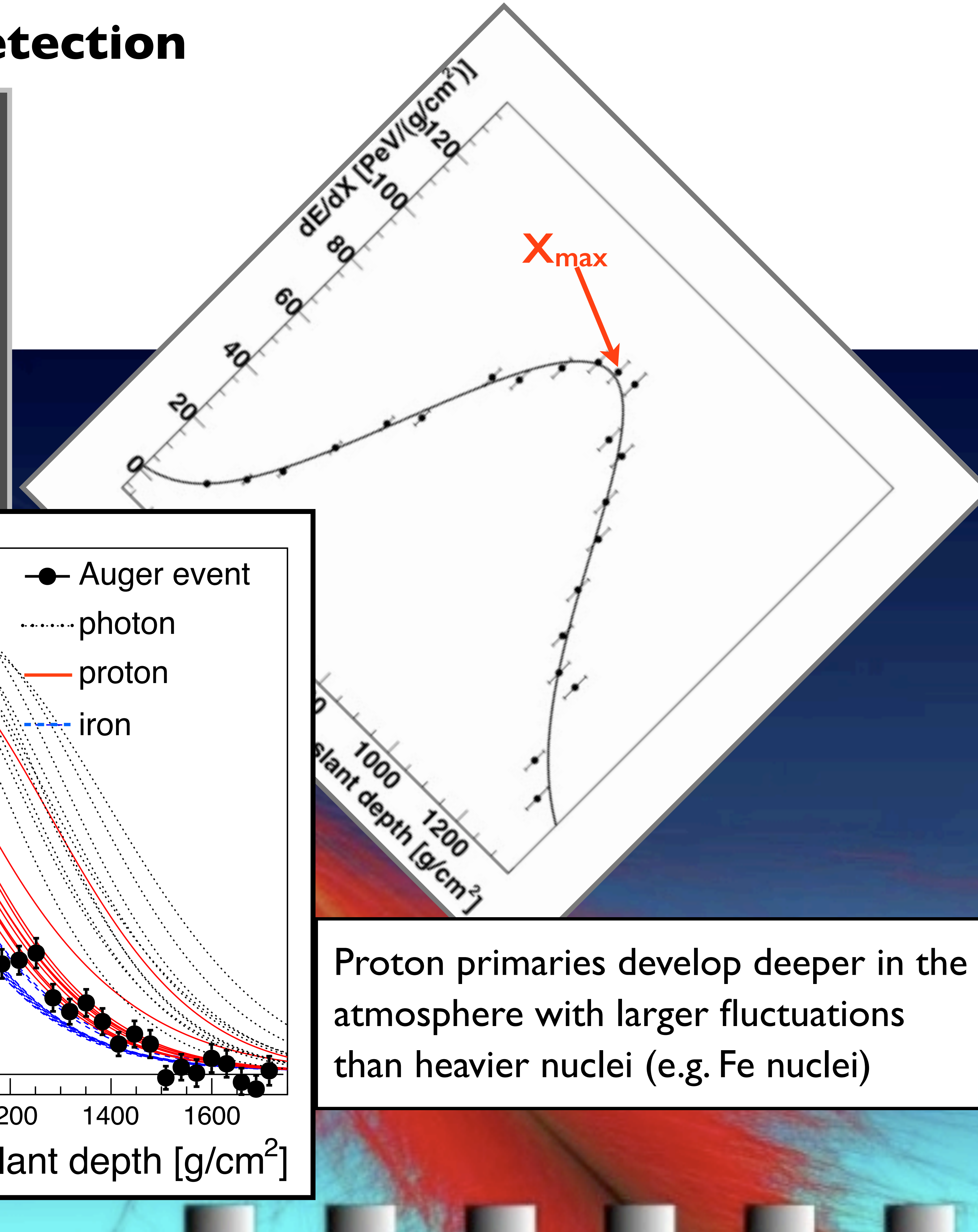
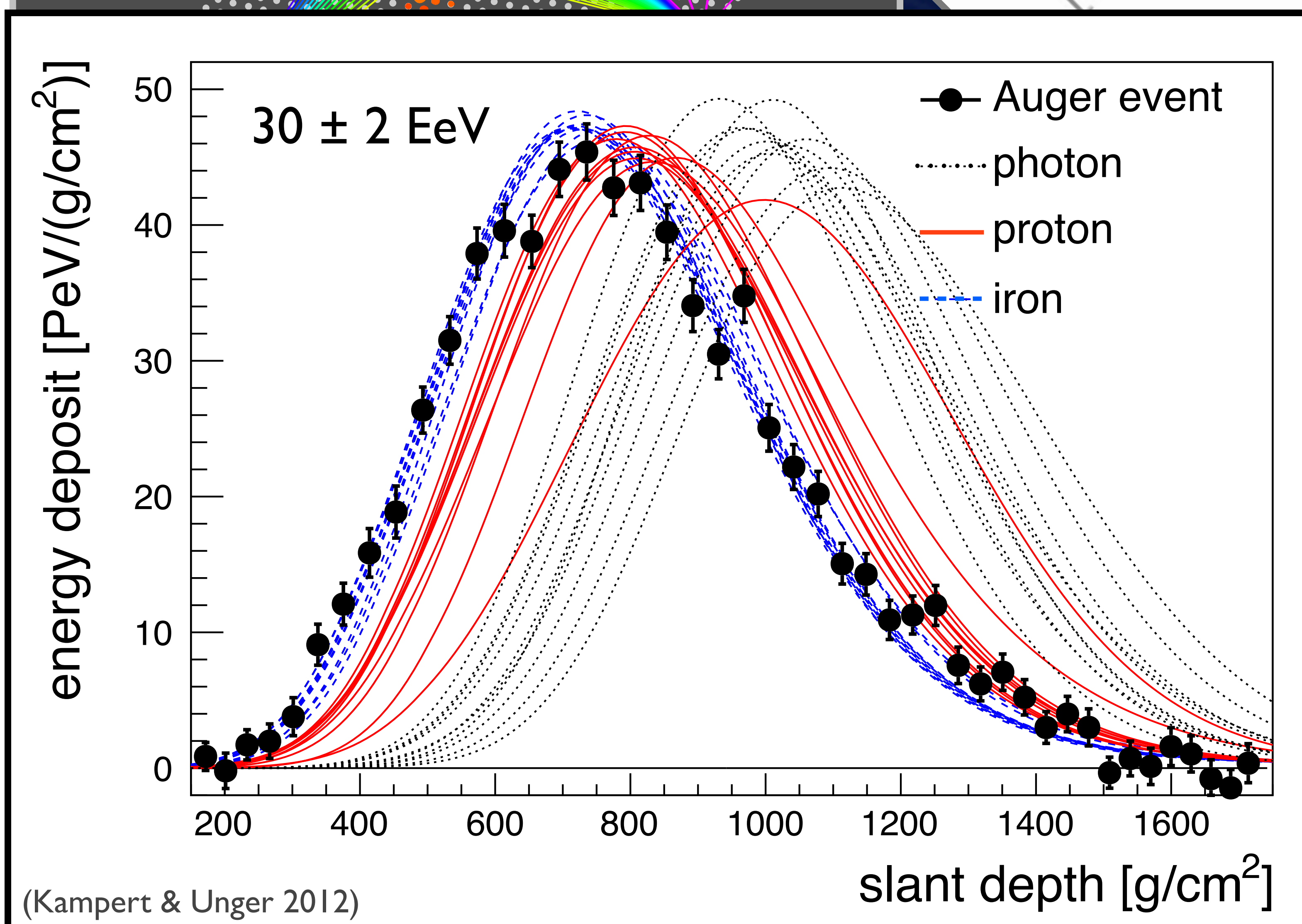


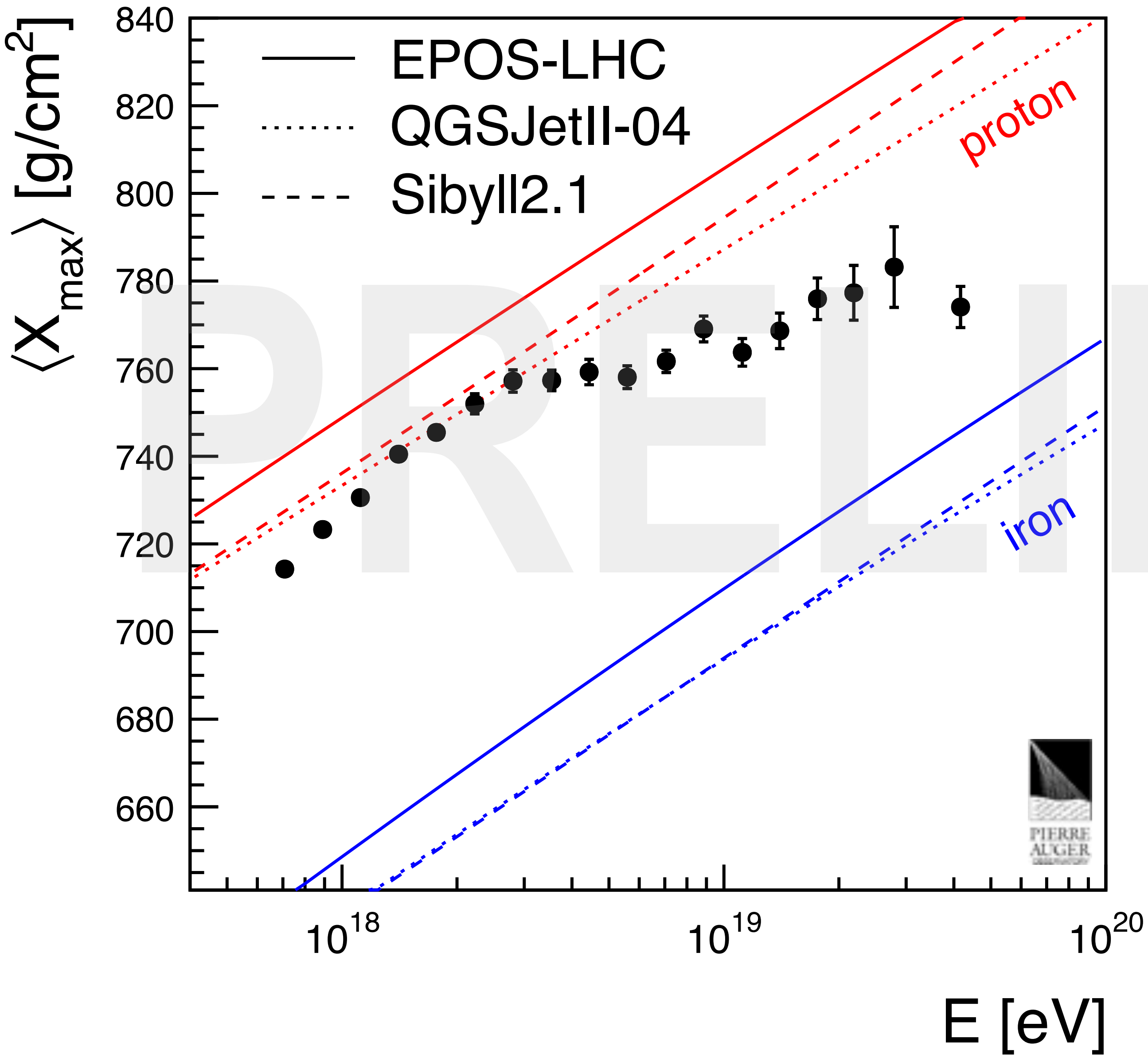


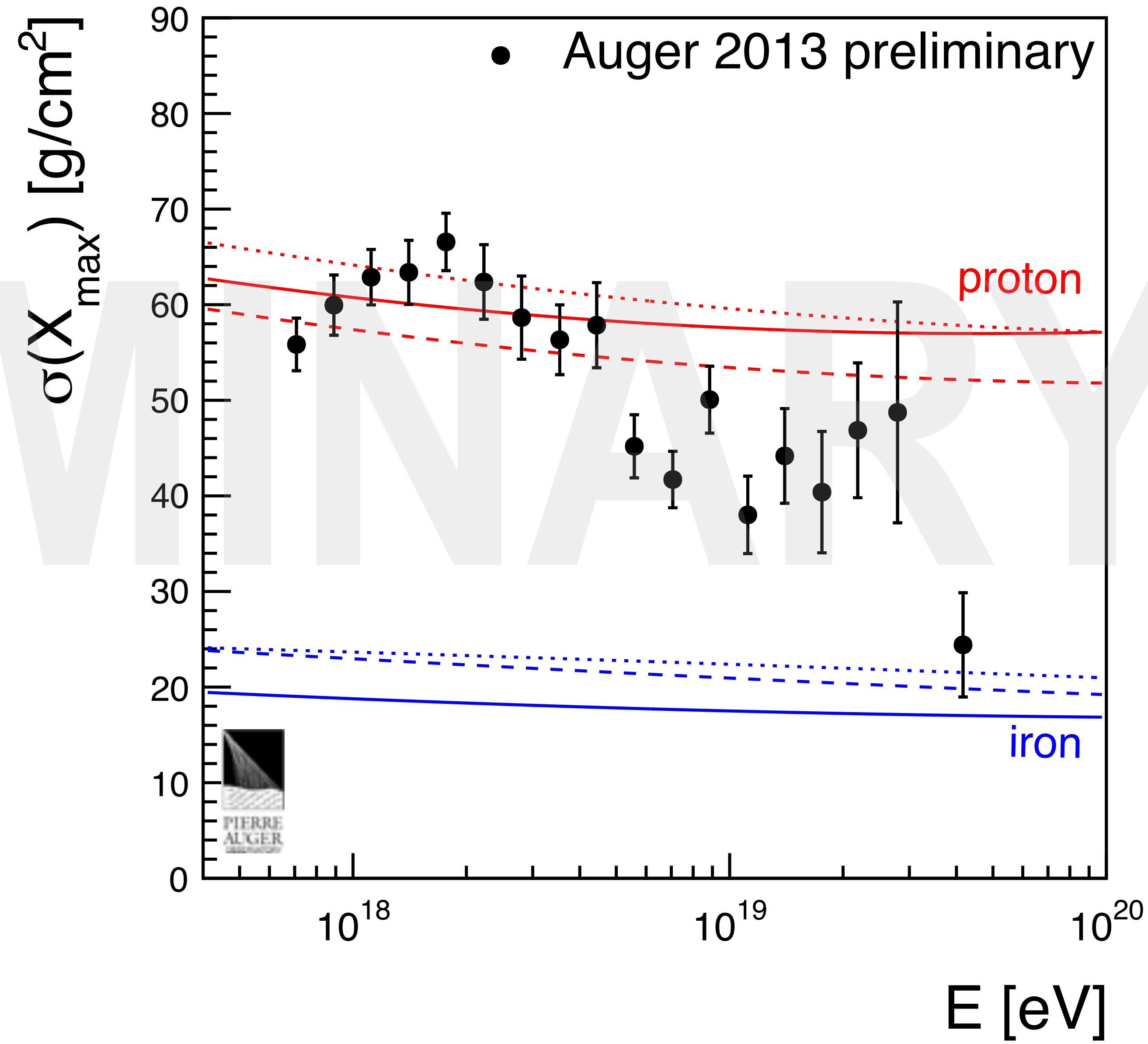


Proton primaries develop deeper in the atmosphere with larger fluctuations than heavier nuclei (e.g. Fe nuclei)

❖ X_{max} - updated mean and RMS

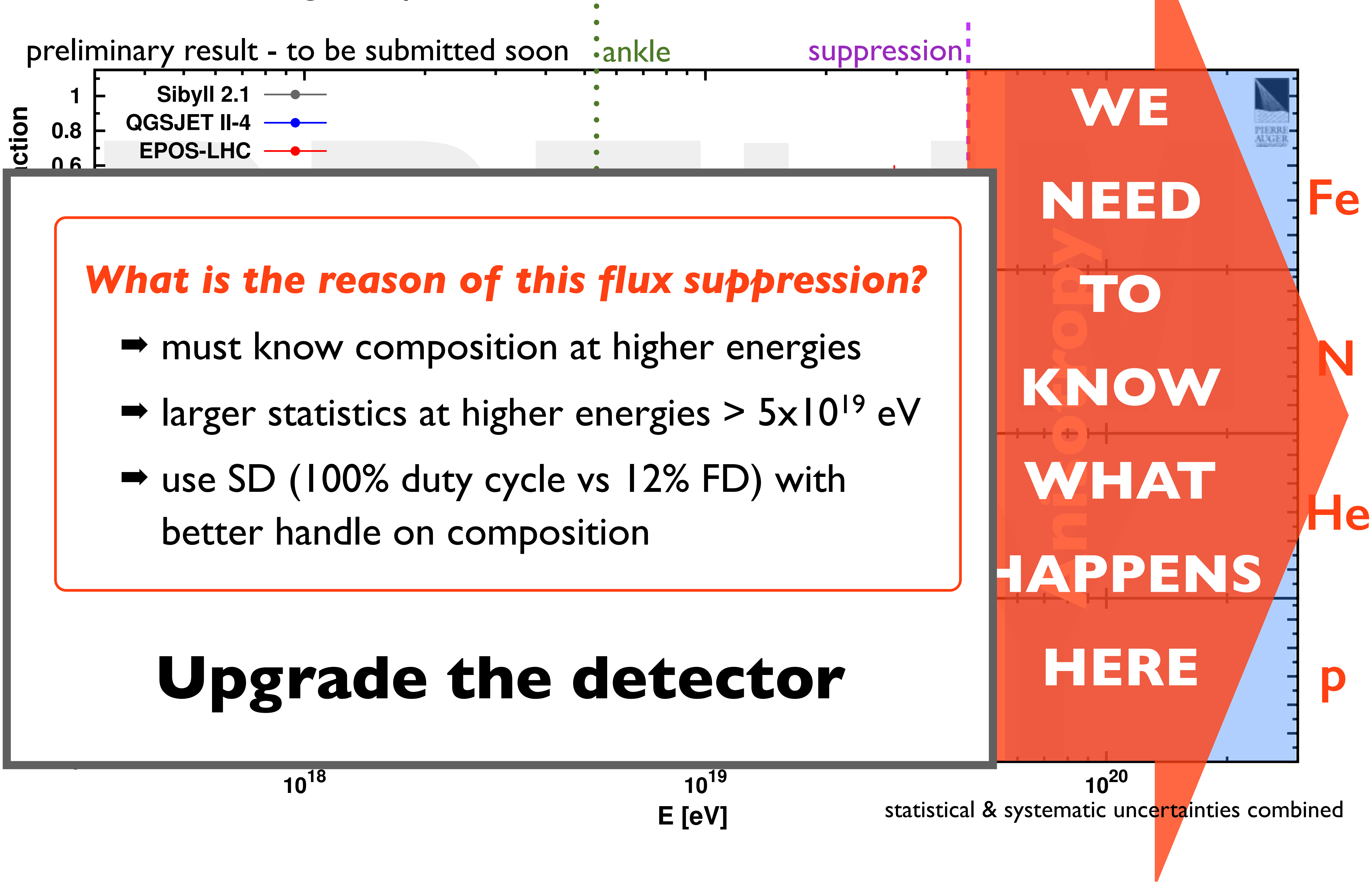
- 8 years of hybrid data (December 2004 - December 2012)
- lower energy threshold to $10^{17.8}$ eV, improved reconstruction
- 19,872 events selected (38 above $10^{19.5}$ eV)





❖ X_{max} - deducing composition

preliminary result - to be submitted soon



statistical & systematic uncertainties combined

What is the reason of this flux suppression?

- ➡ must know composition at higher energies
- ➡ larger statistics at higher energies > 5×10^{19} eV
- ➡ use SD (100% duty cycle vs 12% FD) with better handle on composition

Upgrade the detector

Science goals of the Auger upgrade

1. Elucidate origin of flux suppression and mass composition;

- differentiate between the energy loss due to propagation (e.g. GZK suppression) and the maximum energy of particles at source
- Galactic or extragalactic origin?
- reliable estimates of propagation-induced neutrino and gamma ray fluxes

2. Study hadronic interactions and extensive air showers above E_{CM} > 70 TeV

- particle physics beyond man-made colliders (e.g. cross sections)
- derivation of constraints on new physics phenomena (e.g. extra dimensions)

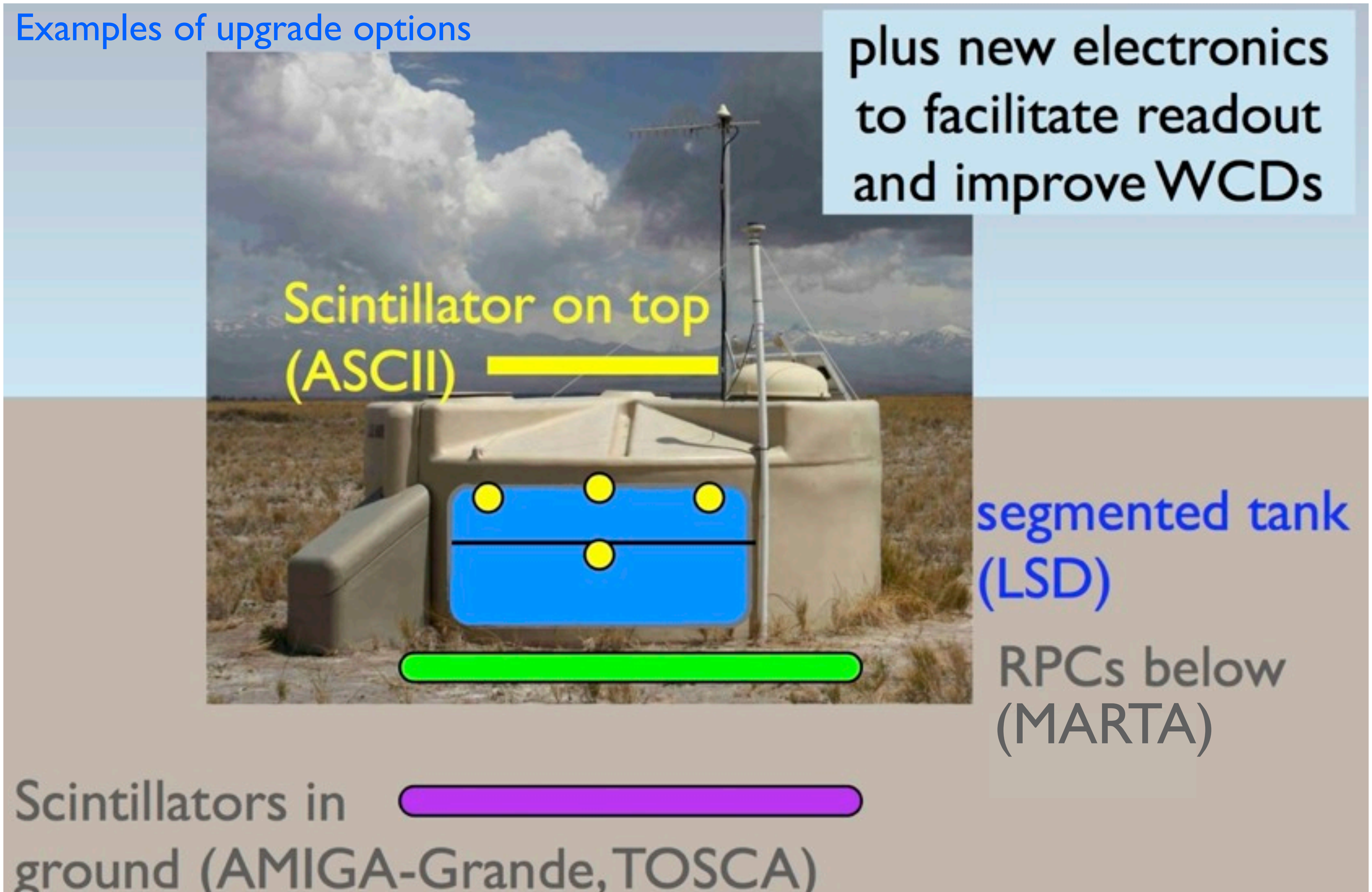
3. Search for contribution of protons at the highest energy

- estimate physics potential of existing and future CR, neutrino, gamma-ray detectors
- determine prospect for proton astronomy (open a new window or not?)
- predict propagation-induced neutrino and gamma ray fluxes

Proposed Auger upgrade for beyond 2015

1) Upgrade aging SD electronics for faster sampling and better event reconstruction;

2) Install new detector on SDs for better muon-to-electromagnetic signal discrimination
   - several options in consideration



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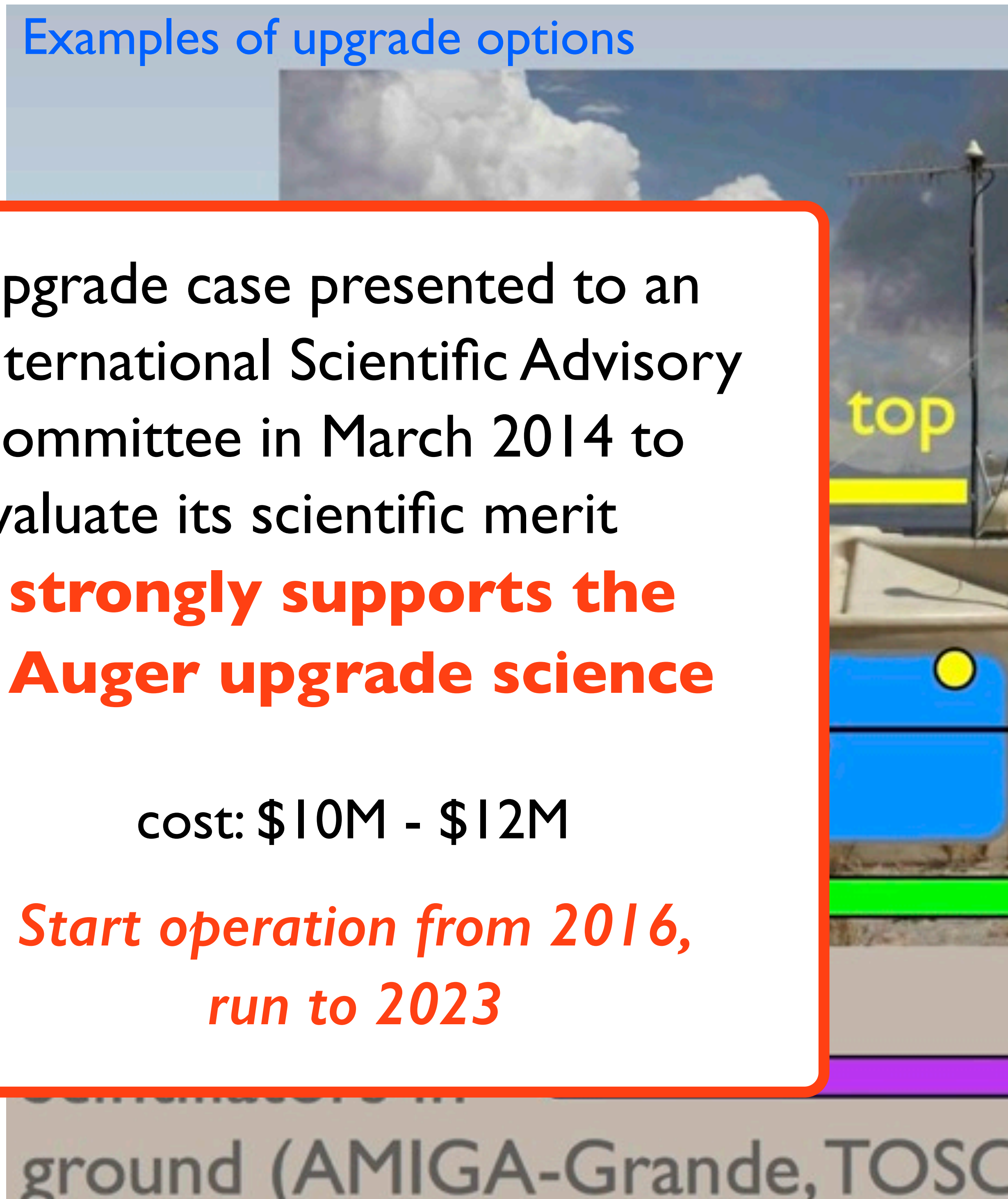
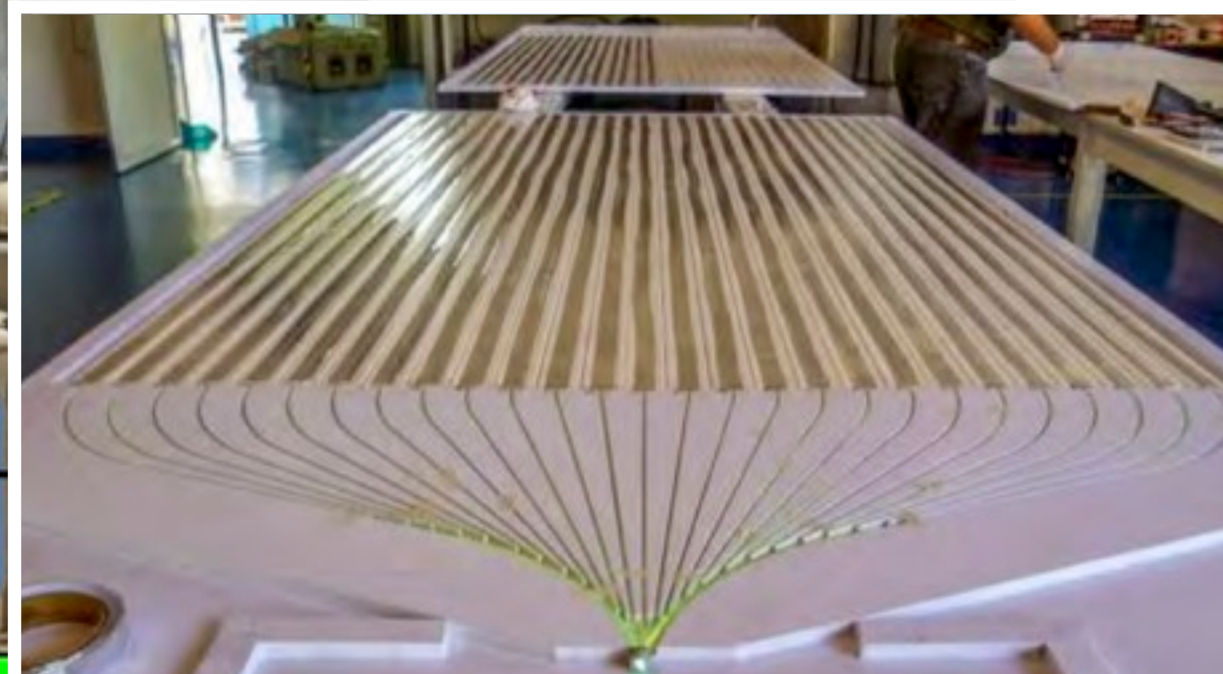
Examples of upgrade options



- Upgrade case presented to an International Scientific Advisory Committee in March 2014 to evaluate its scientific merit
  ➡ **strongly supports the Auger upgrade science**

cost: $10M - $12M

Start operation from 2016, run to 2023



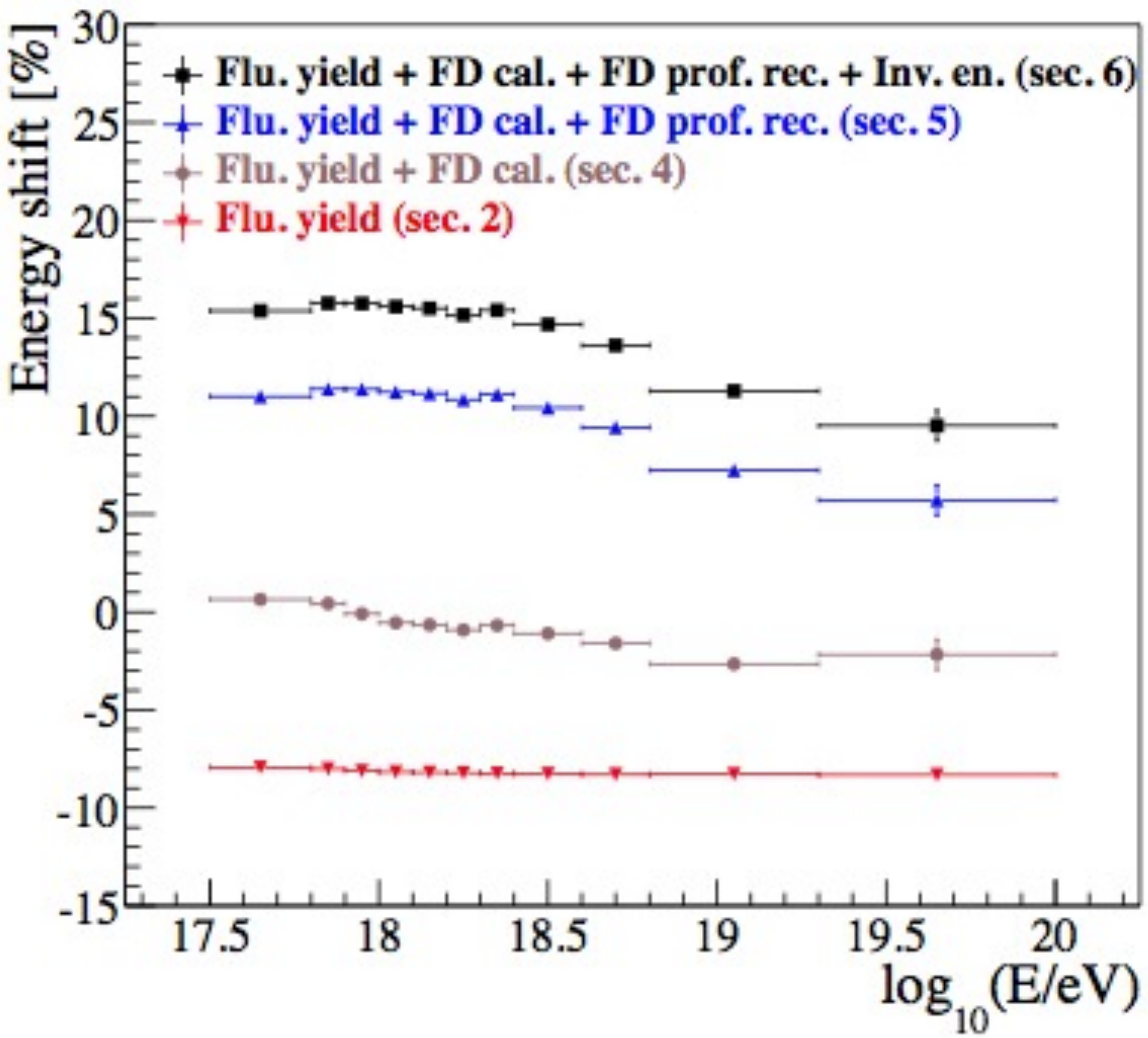
Prototype scintillator detectors (ASCII) using Fermilab's Minos scintillation bars

Summary

- Pierre Auger Observatory is currently the largest operating CR experiment;
- Spectrum extends down to $10^{17.5}$ eV, shows clear ankle and suppression features;
- Composition is more complex than previously thought;
- Upgrade of SDs to run from 2016 will be proposed by the international collaboration and several options are being considered
  - elucidate origin of the flux suppression via larger statistics on composition
  - study particle physics at E $\gg$ man-made accelerators
  - provide new gateway to future experiments in CR, gamma-rays, neutrinos
- Pierre Auger Observatory will continue to be a truly international collaboration.

backups

- Auger energy scale has changed

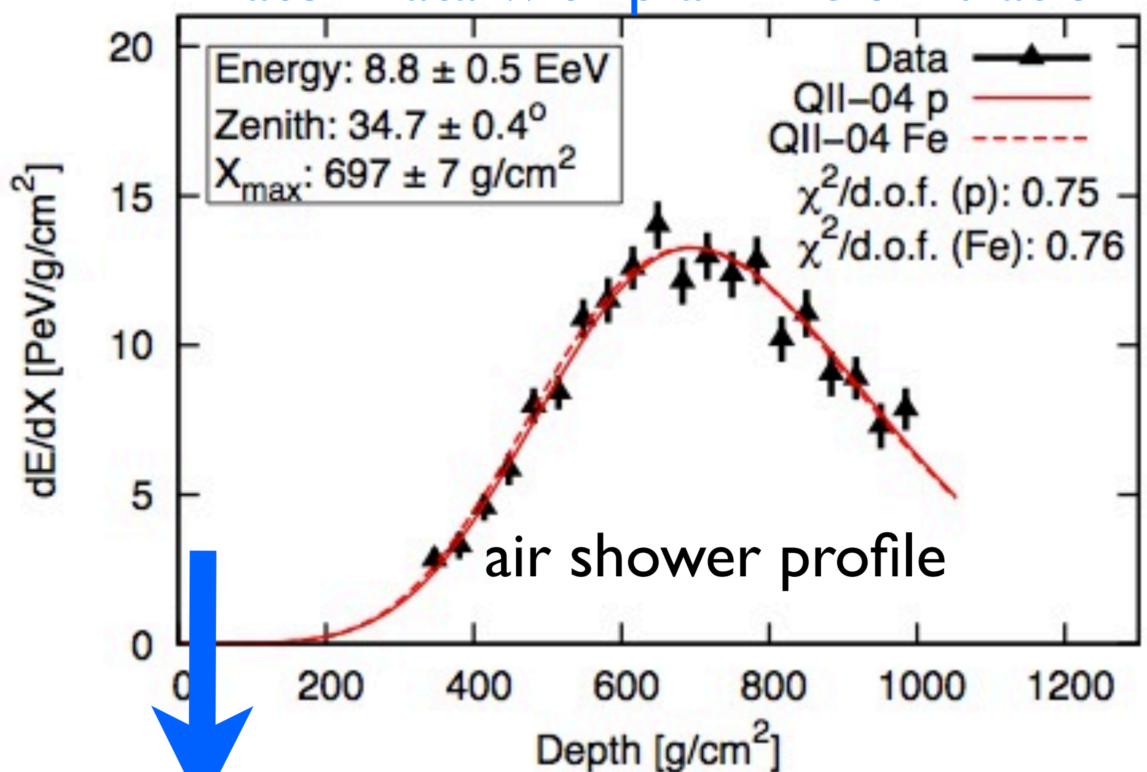


Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub 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%**

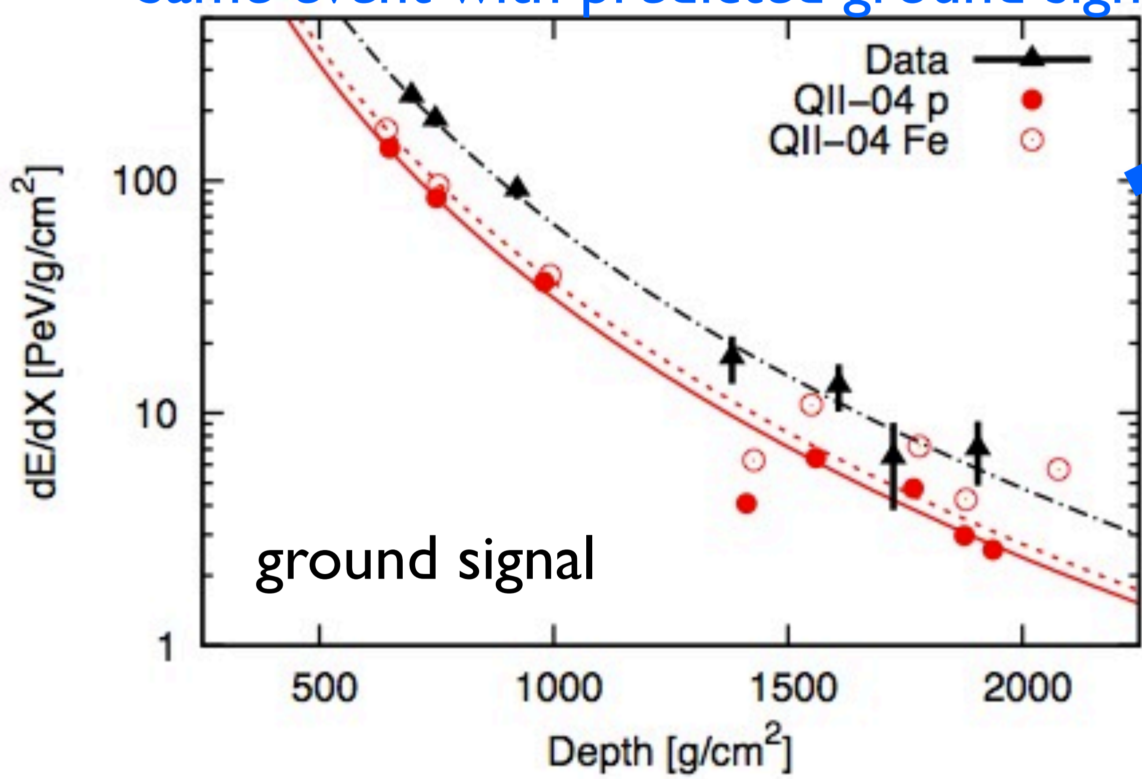
•Muon estimation

Golden hybrid event

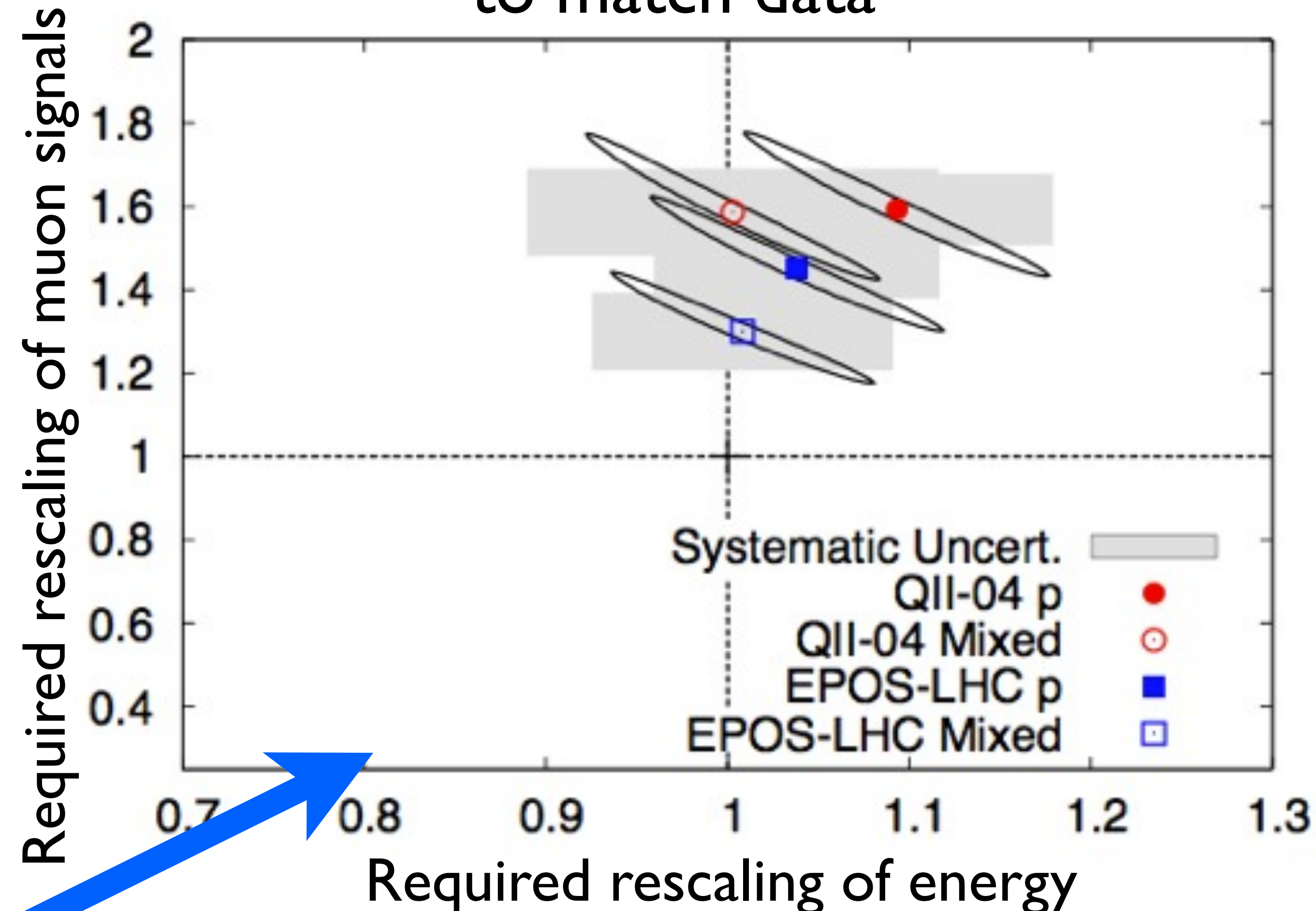
Match data with p and Fe simulation



Same event with predicted ground signal

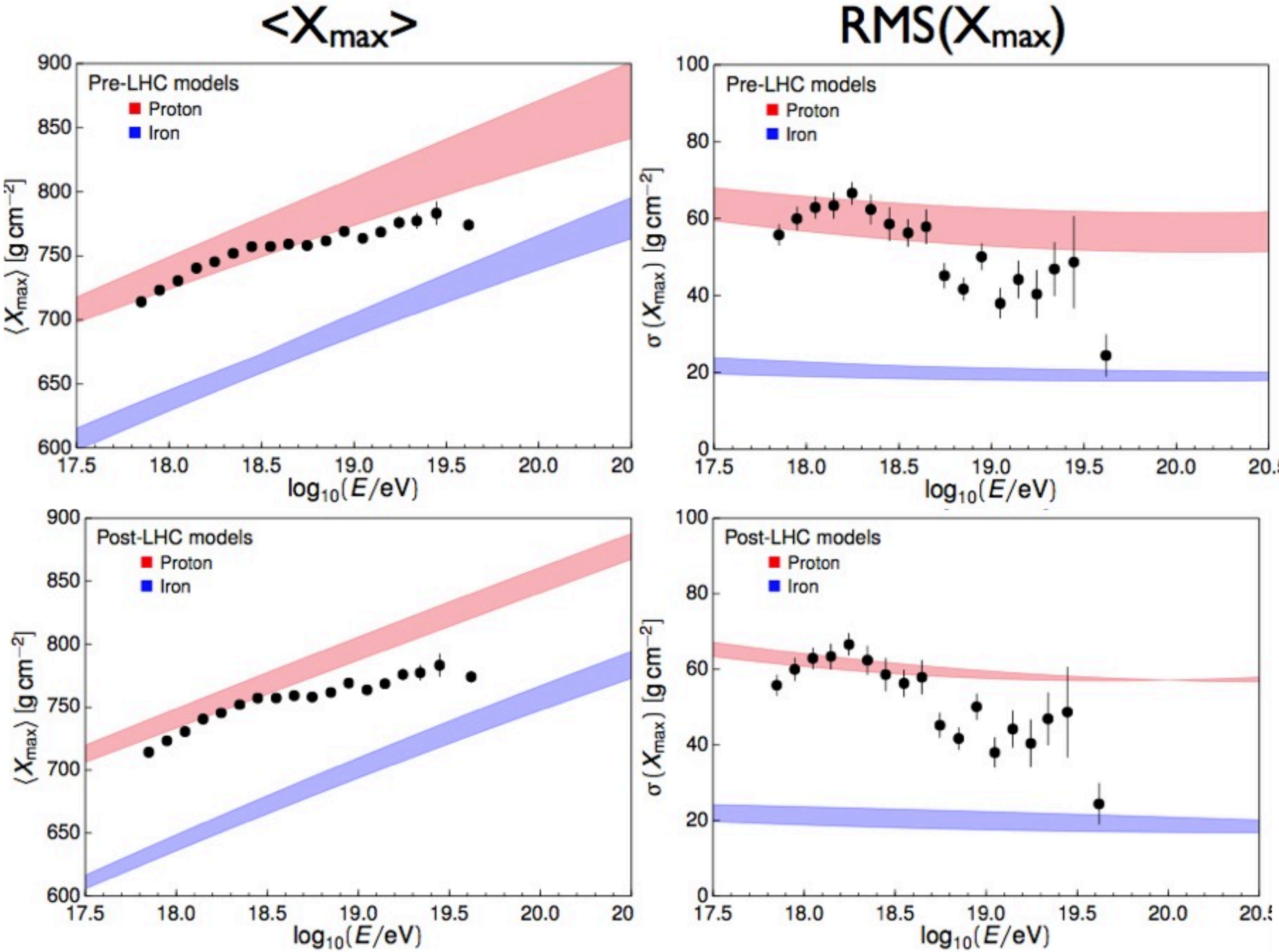


Rescale energy and muon signals to match data

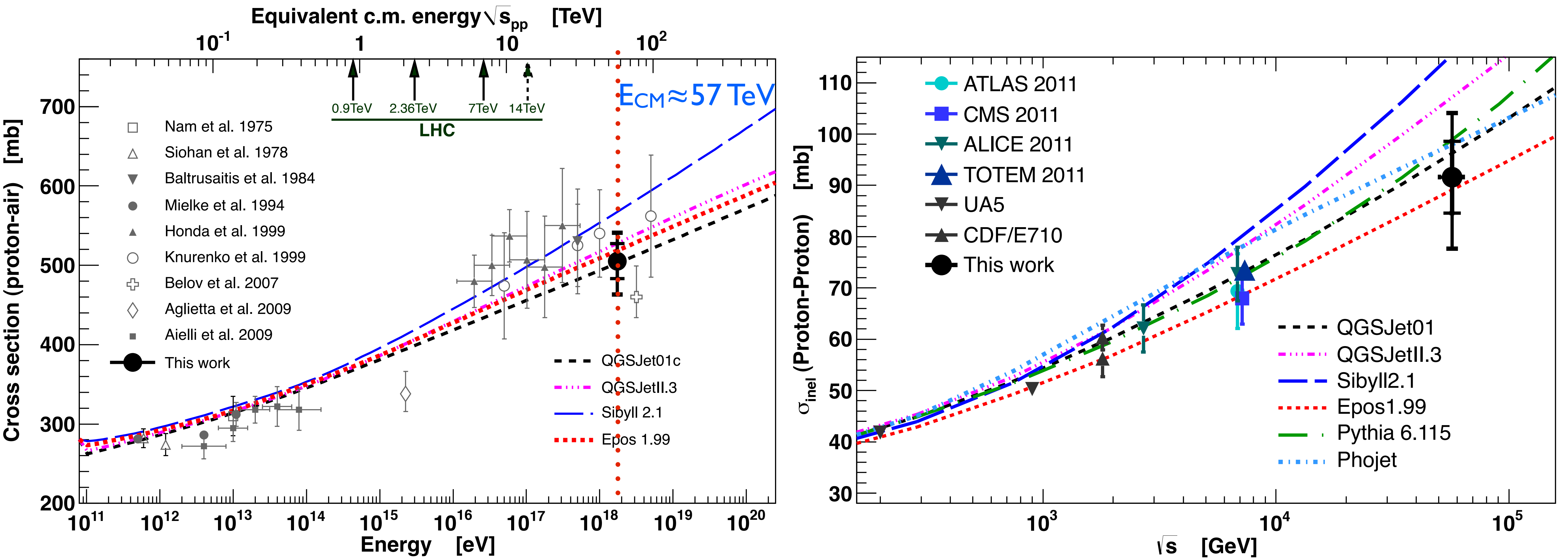


- hadronic interaction models need more muons
  - underestimate muon signals by 30-60%
- independent tests yield same results
- or are muon counts contaminated by electromagnetic signals? ➔ better muon-EM discrimination

• Hadronic interaction model - LHC is useful



Proton-air production cross section



$$\sigma^{prod}_{p\text{-}air} = 505 \pm 22_{stat}\ (+28/\text{-}36)_{sys}\ \text{mb}$$

$$\sigma^{inel}_{p\text{-}p} = 90 \pm 7_{stat}\ (+9/\text{-}11)_{syst} \pm 7_{glauber}\ \text{mb}$$

$$\sigma^{tot}_{p\text{-}p} = 133 \pm 13_{stat}\ (+17/\text{-}20)_{syst} \pm 16_{glauber}\ \text{mb}$$

Auger anisotropy