Results from the Pierre Auger Observatory: spectrum and composition

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Fermilab

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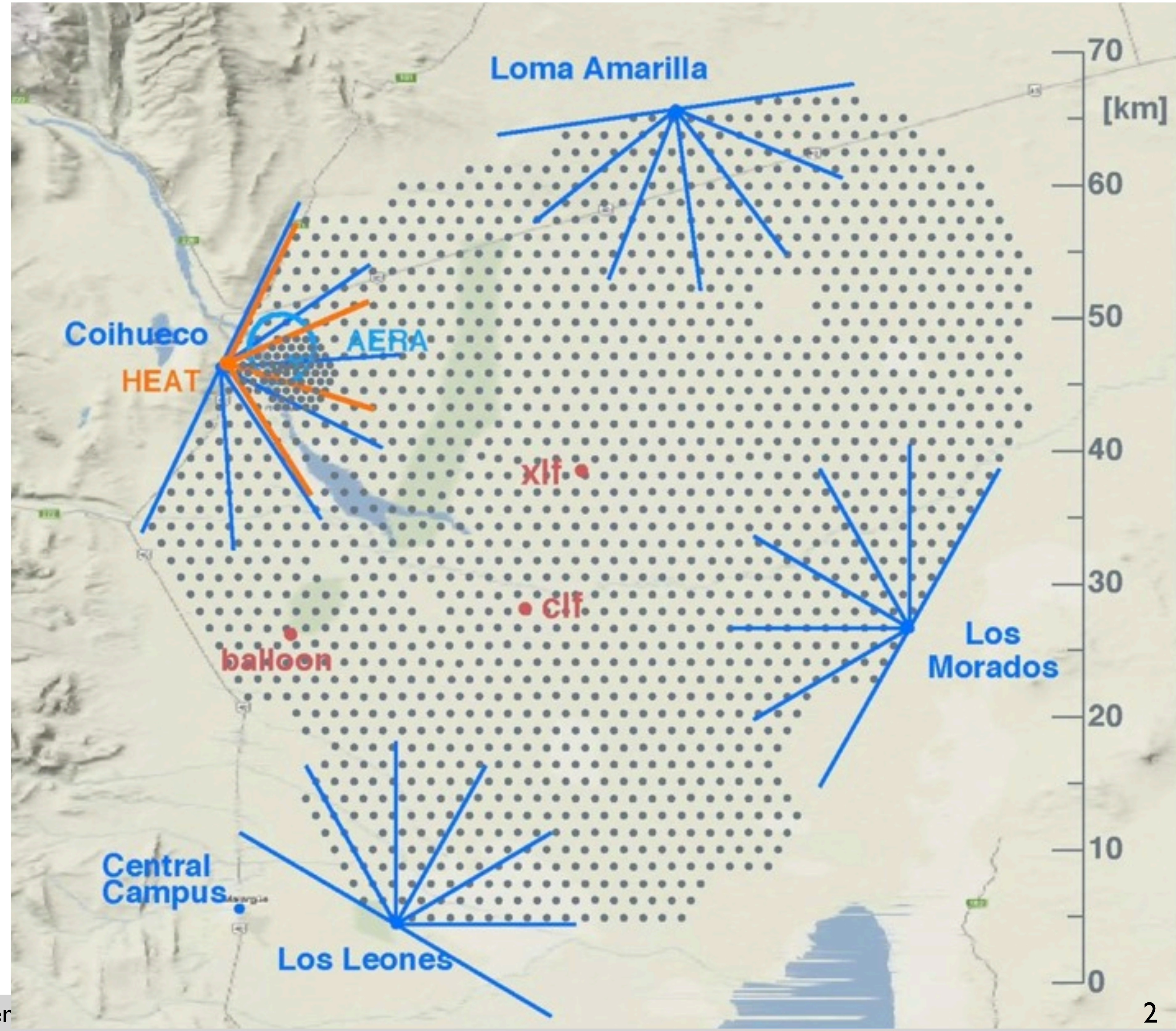
Pierre Auger Observatory

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

- Malargüe, Argentina
  $\sim$ 3000 km^2



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 (FDs)
  - 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

Pierre Auger Observatory

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

- Spectrum
- Composition
- Photon limit
- Neutrino limit

- Arrival directions - see talk by Silvia Mollerach
- AERA - see talk by Jörg Hörandel

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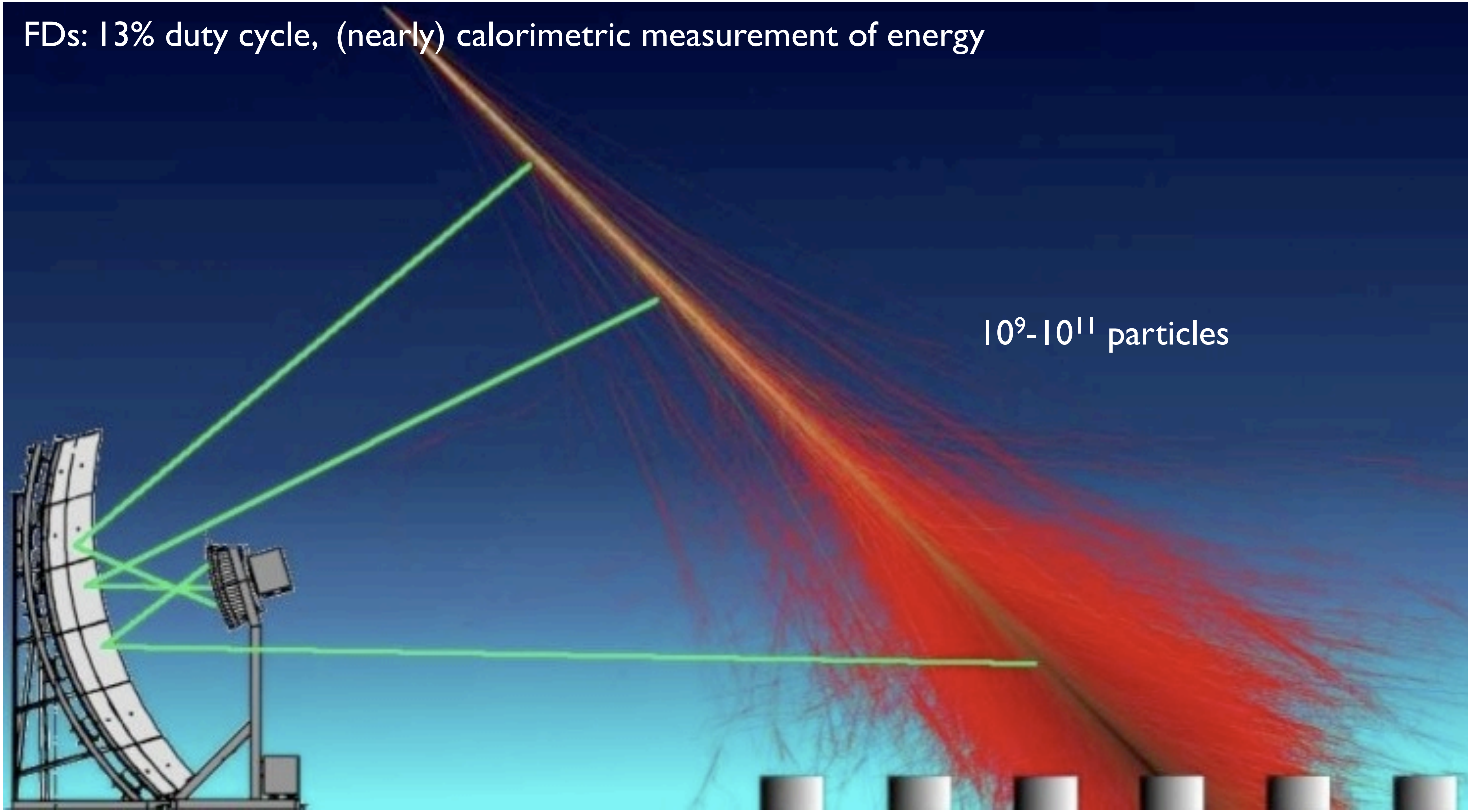
Hybrid design: thoroughly understand capabilities & systematic uncertainties of both detectors



SDs: 100% duty cycle, measure particle density

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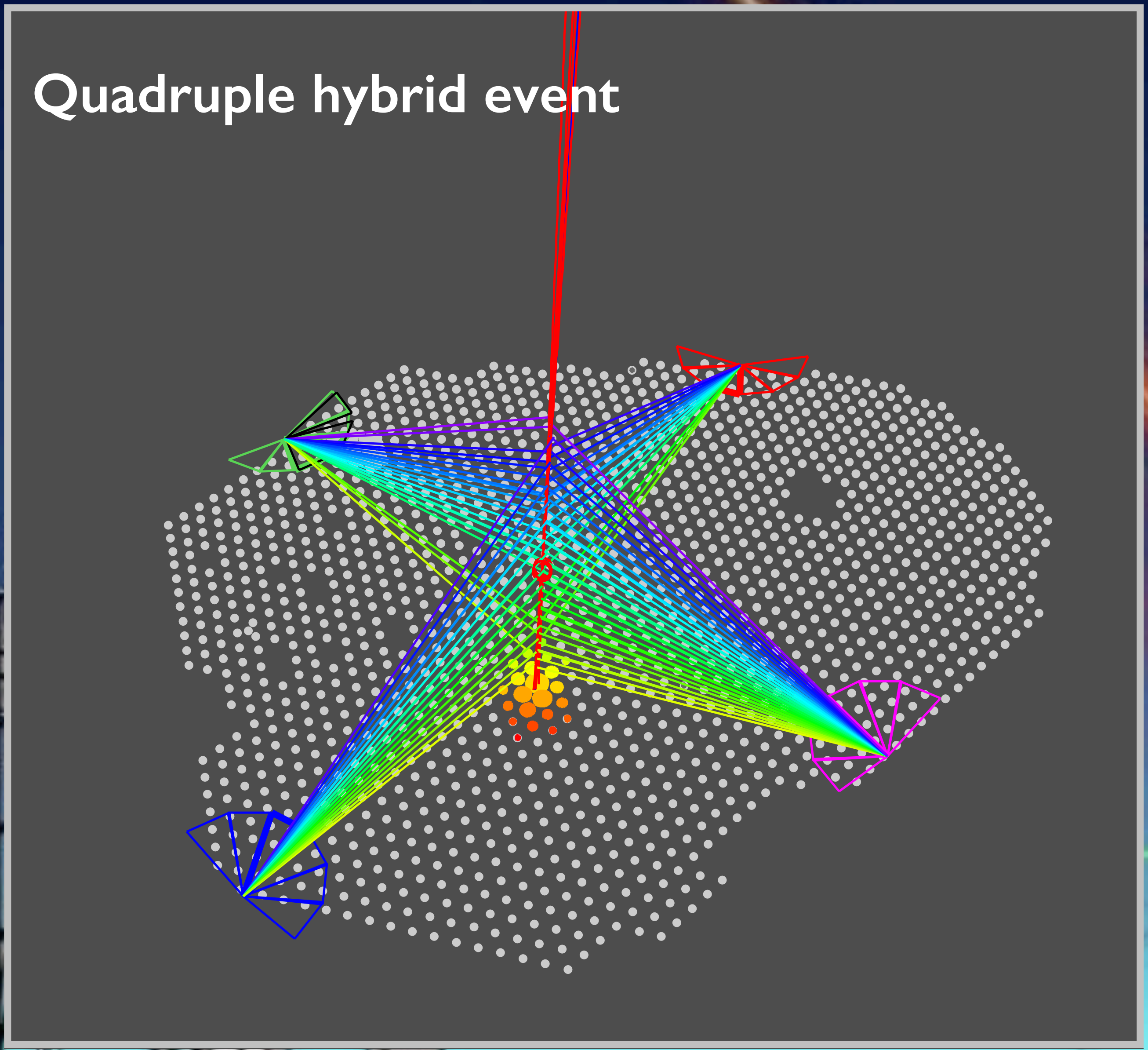
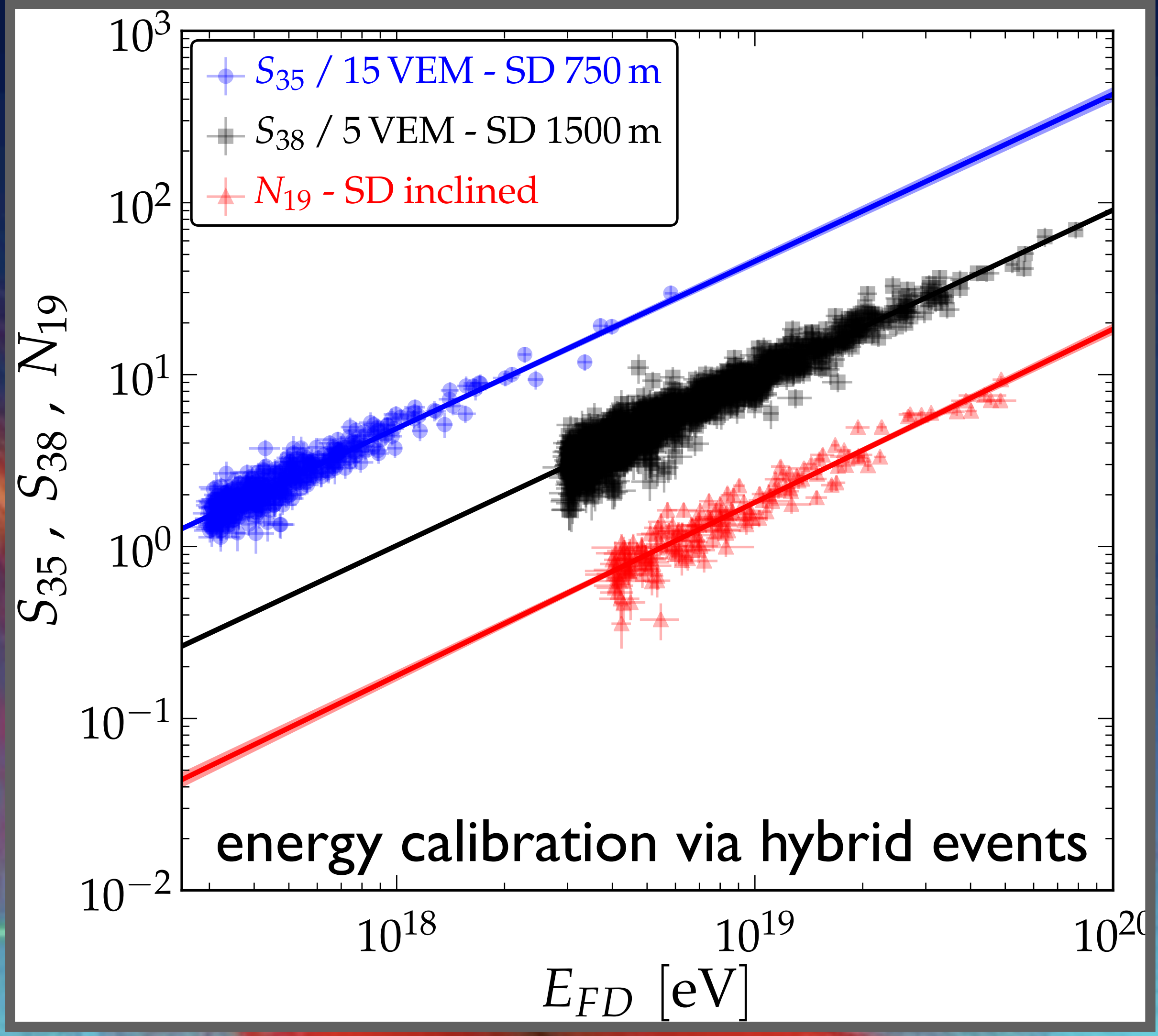
Hybrid design: thoroughly understand capabilities & systematic uncertainties of both detectors

FDs: 13% duty cycle, (nearly) calorimetric measurement of energy

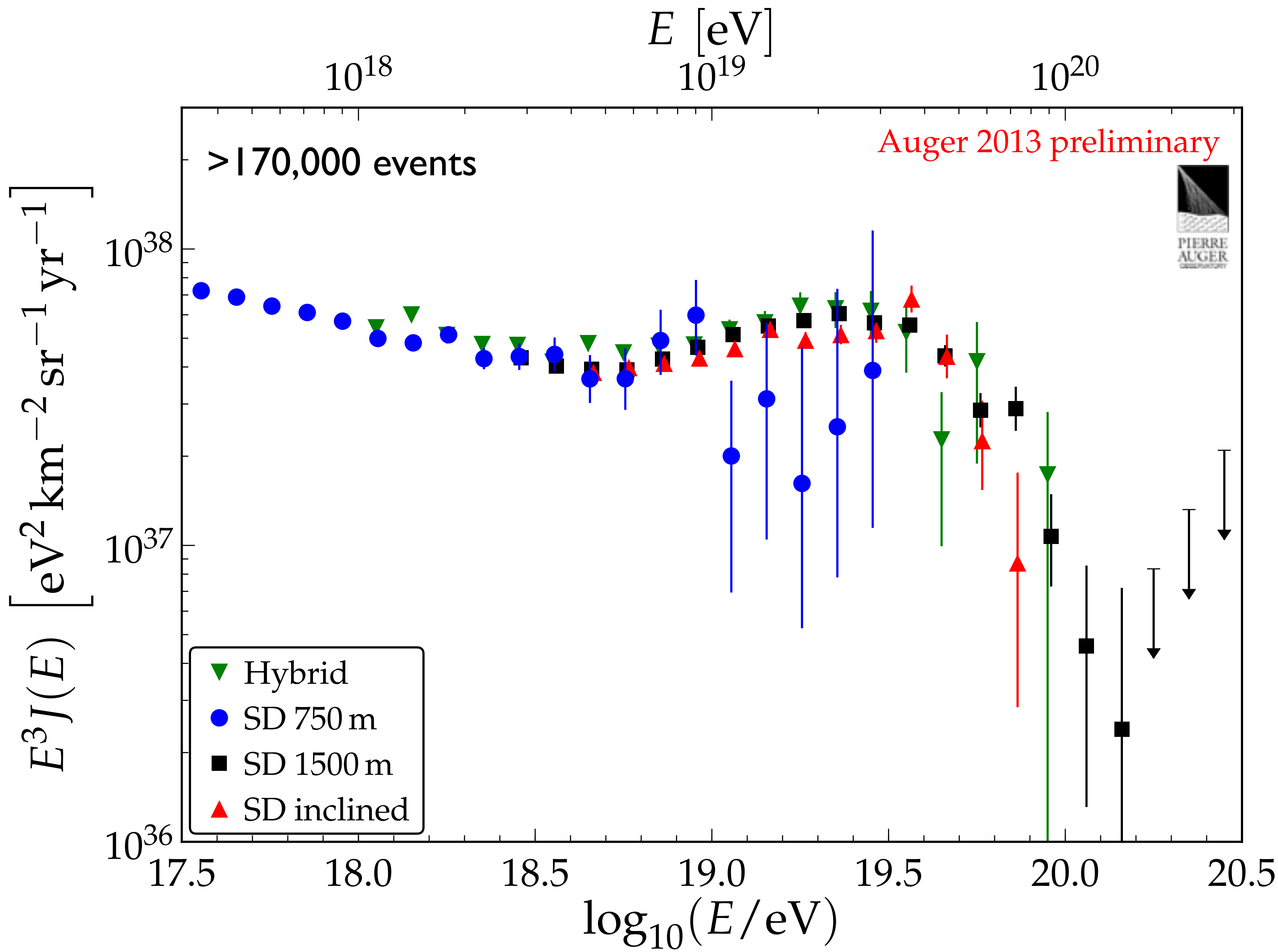




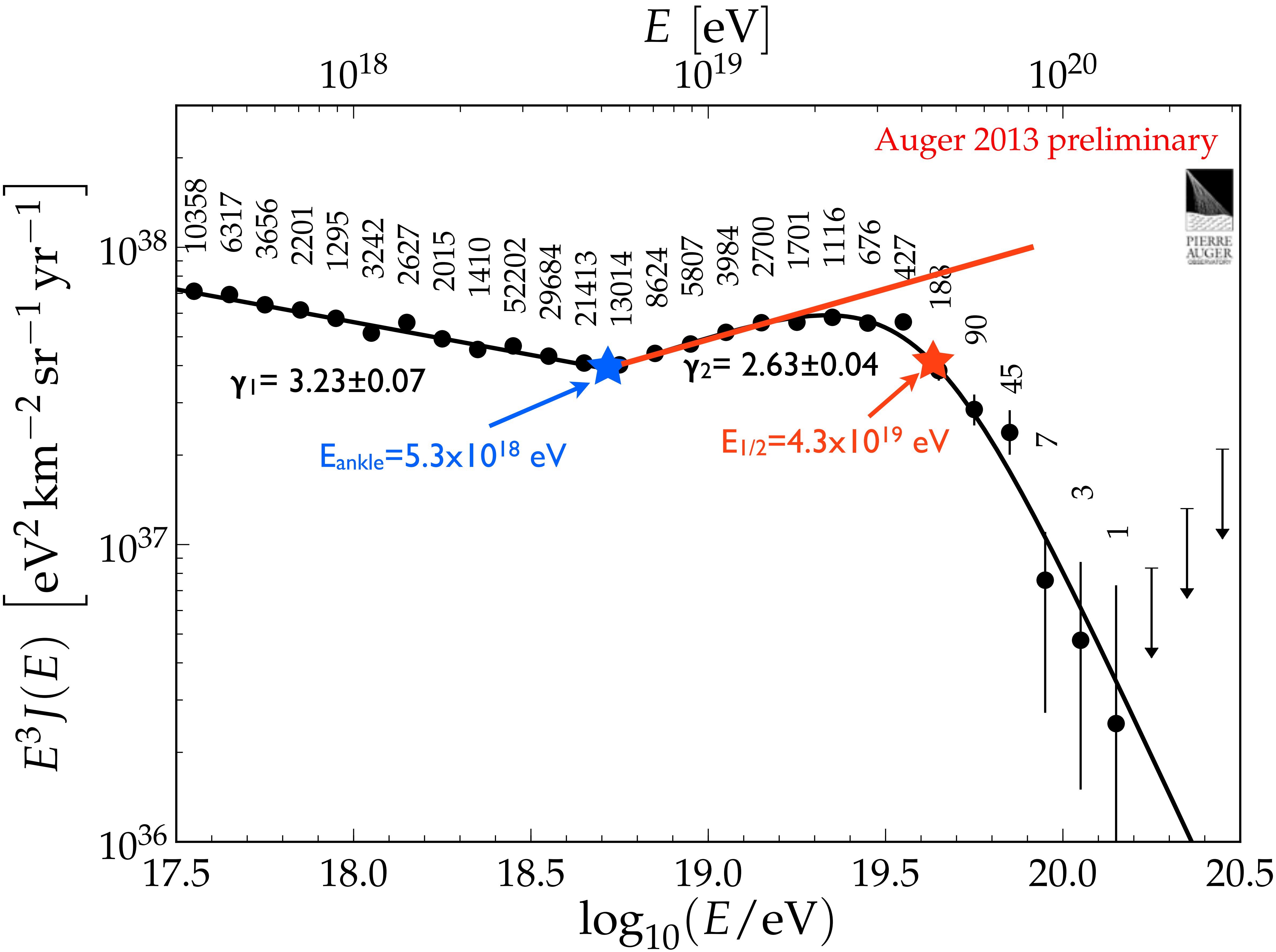
SDs: 100% duty cycle, measure particle density

❖ Energy spectrum

- SD + infill + hybrid (zenith angle 0° - 80°)
- new energy scale: change FD energies +15.6% (10^{18} eV) to +12.5% (10^{19} eV)



❖ **Energy spectrum** - combined



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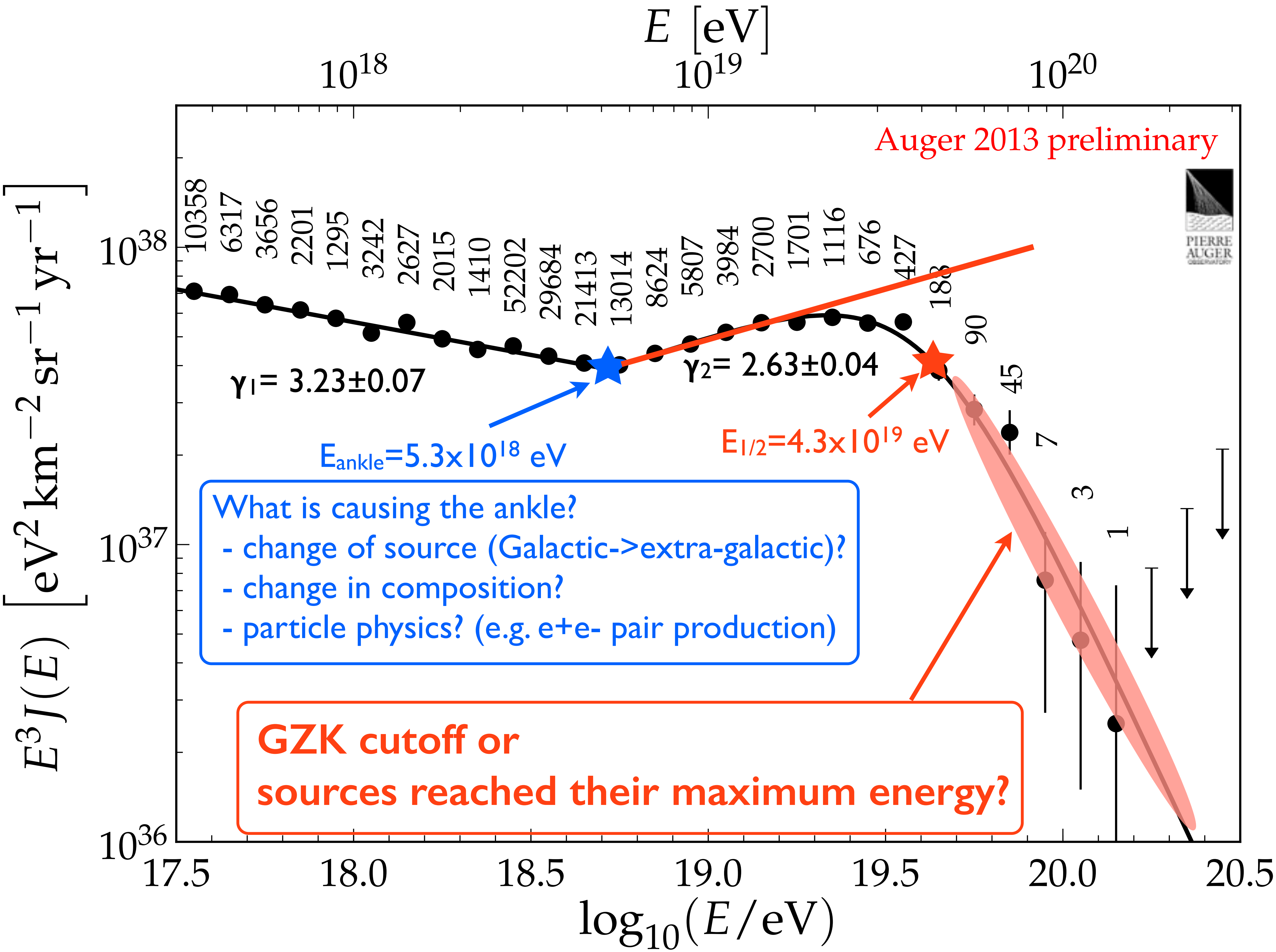
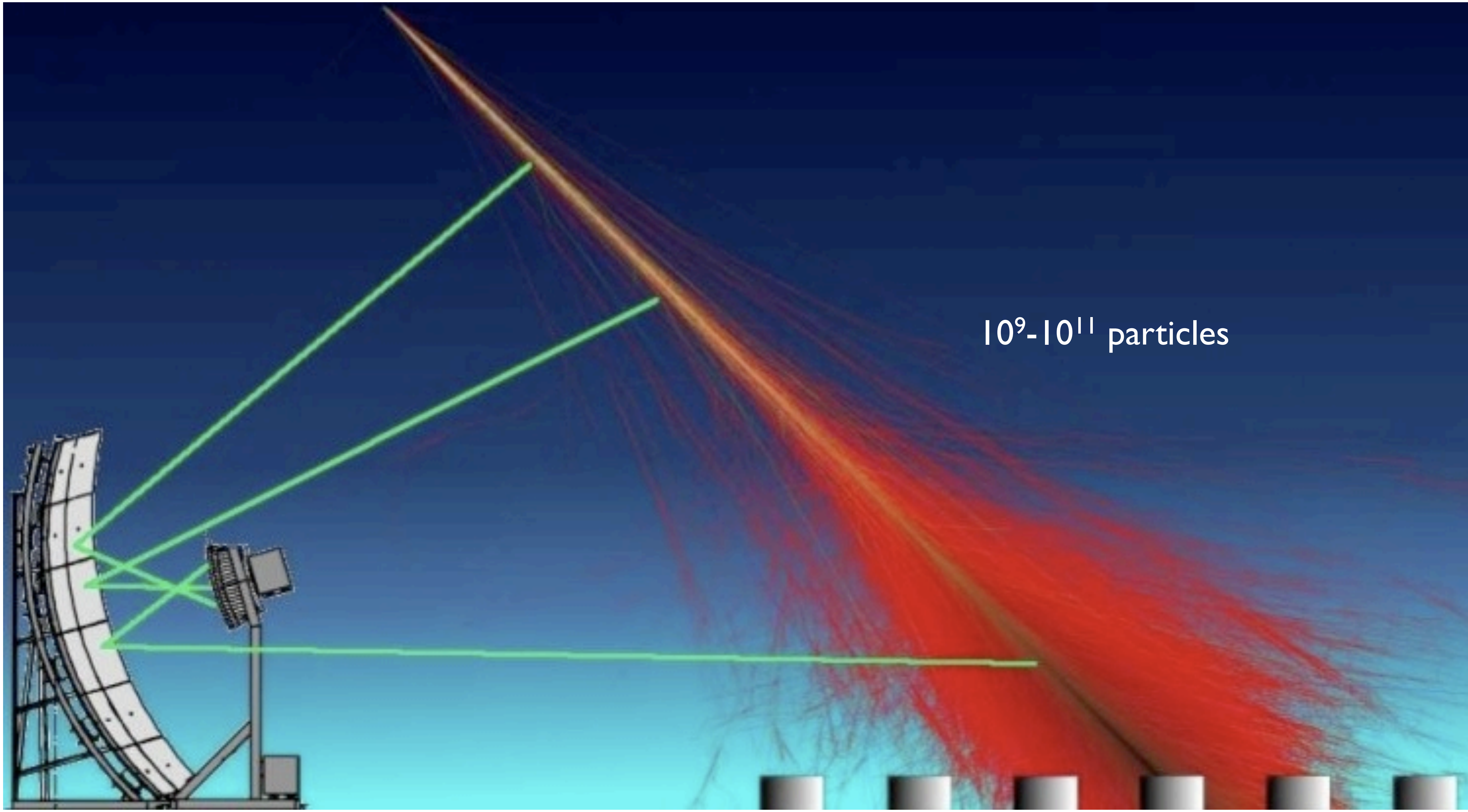


Observatory for hybrid detection

- SD constrains shower geometry → reduce uncertainty of X_{max}



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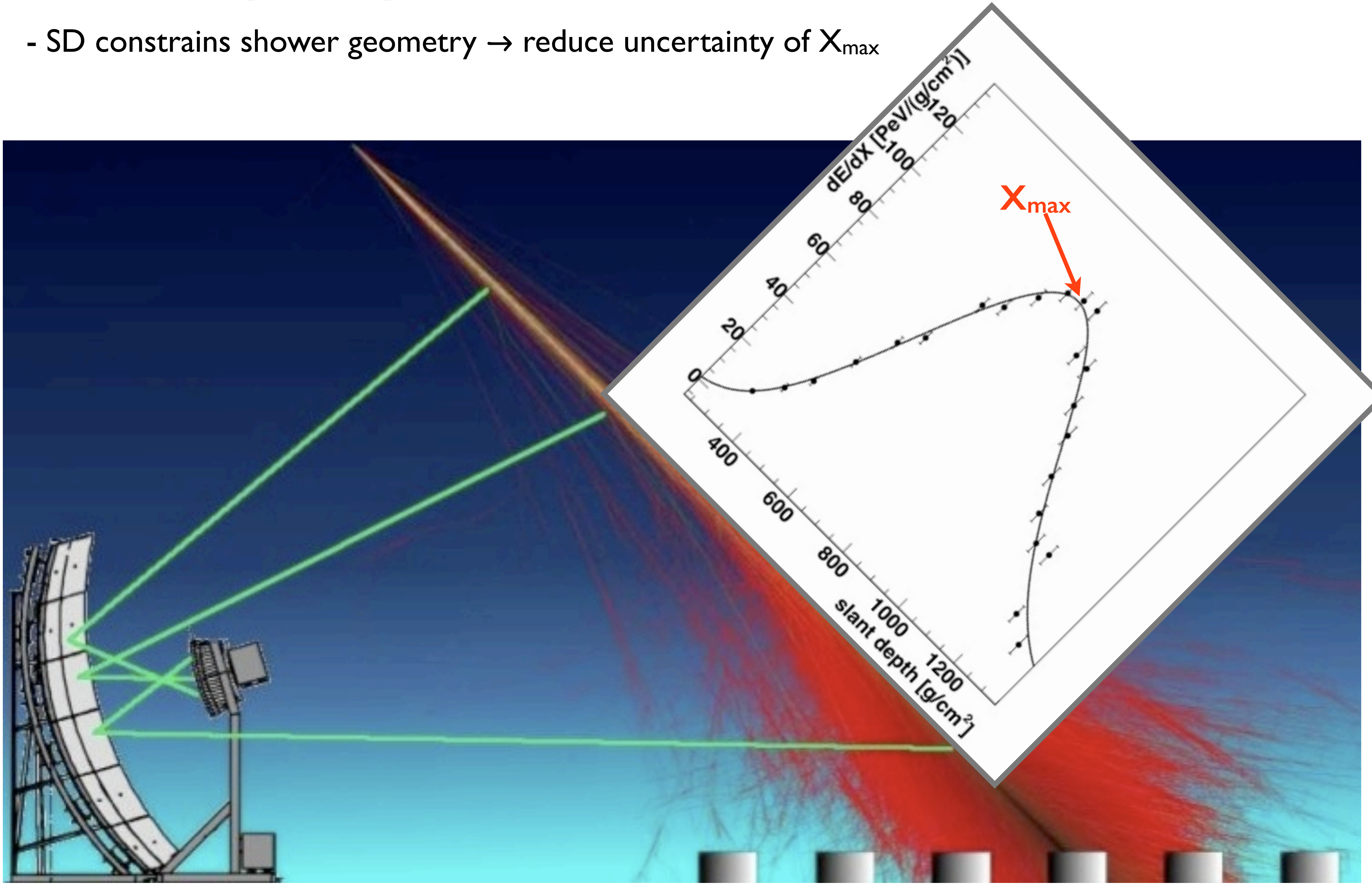

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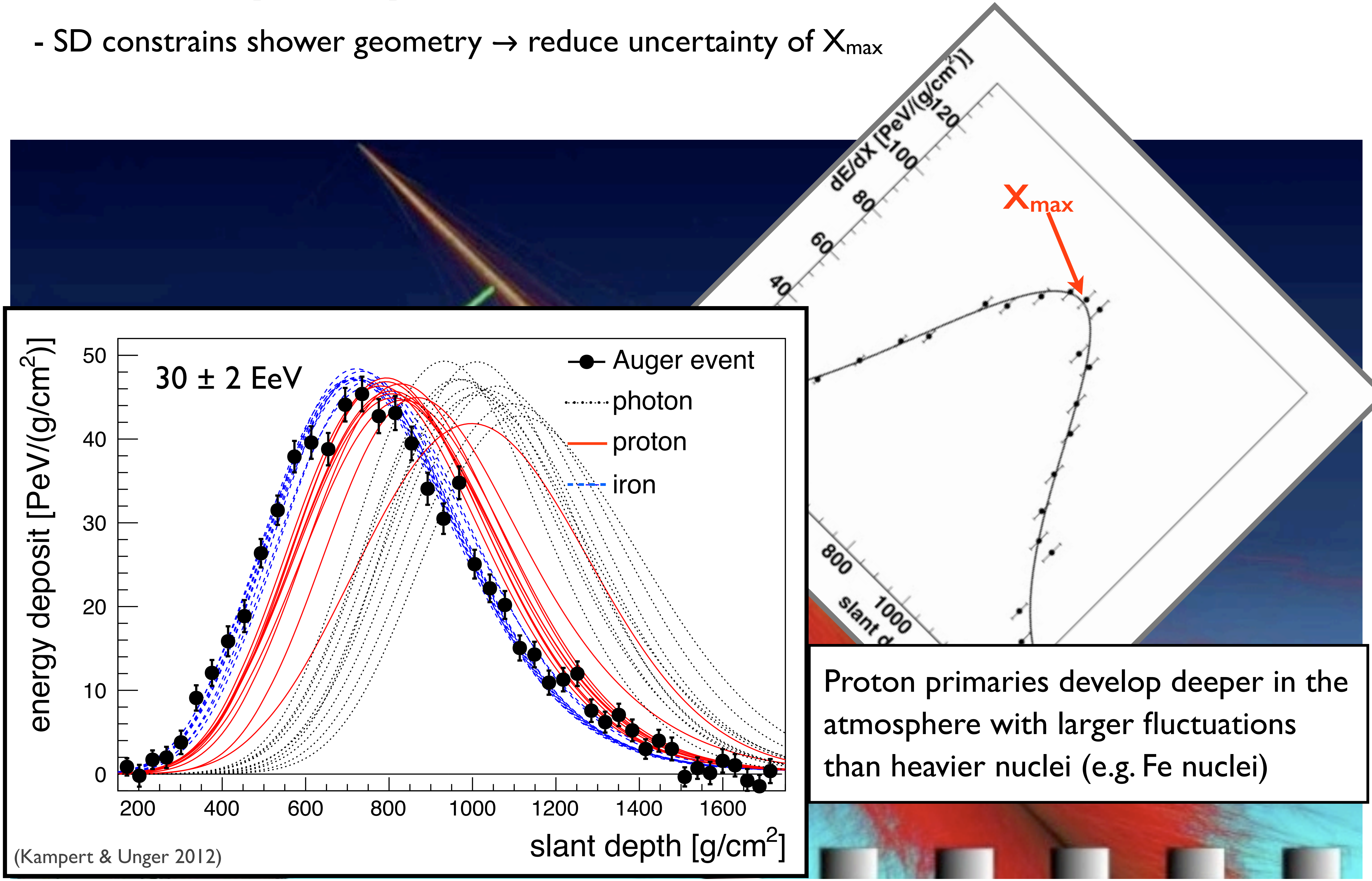
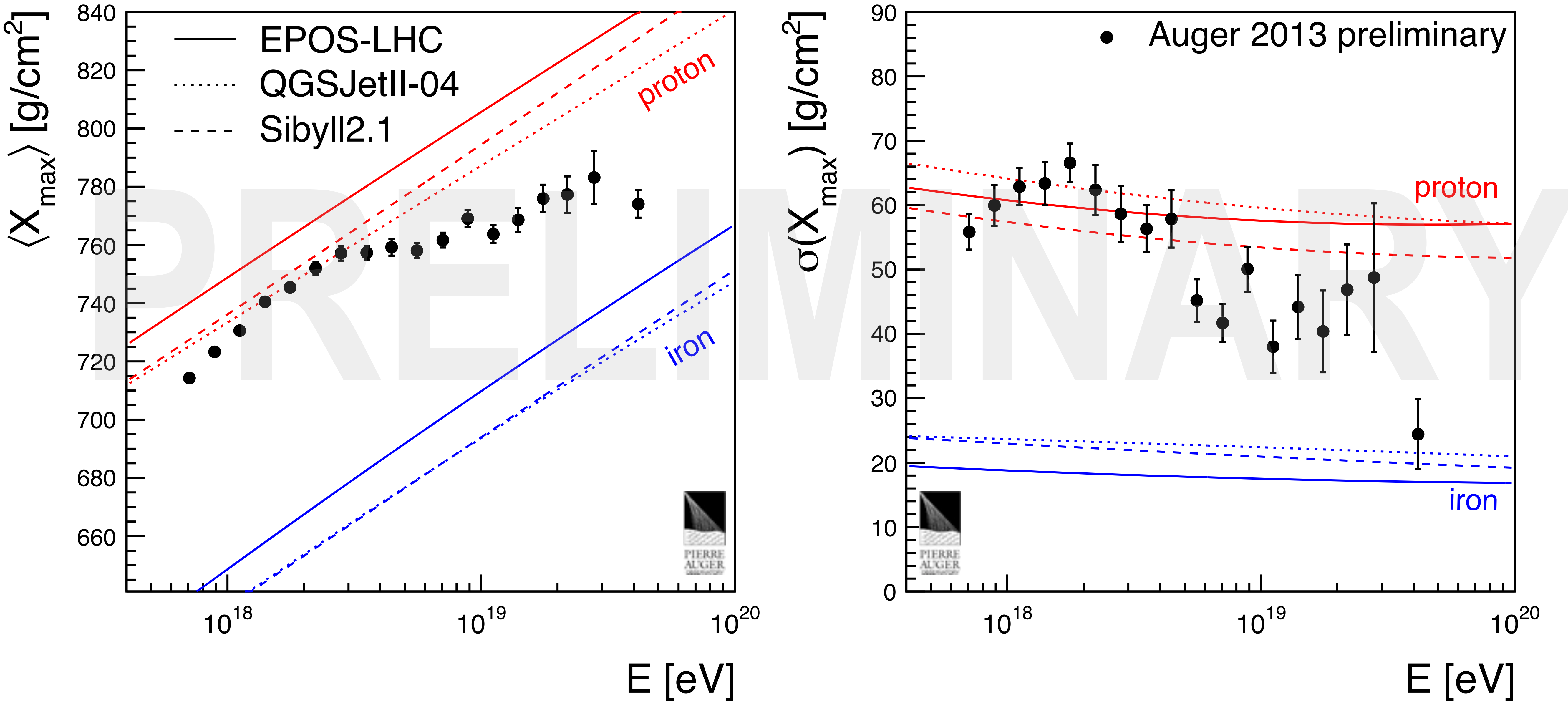


Proton primaries develop deeper in the atmosphere with larger fluctuations than heavier nuclei (e.g. Fe nuclei)

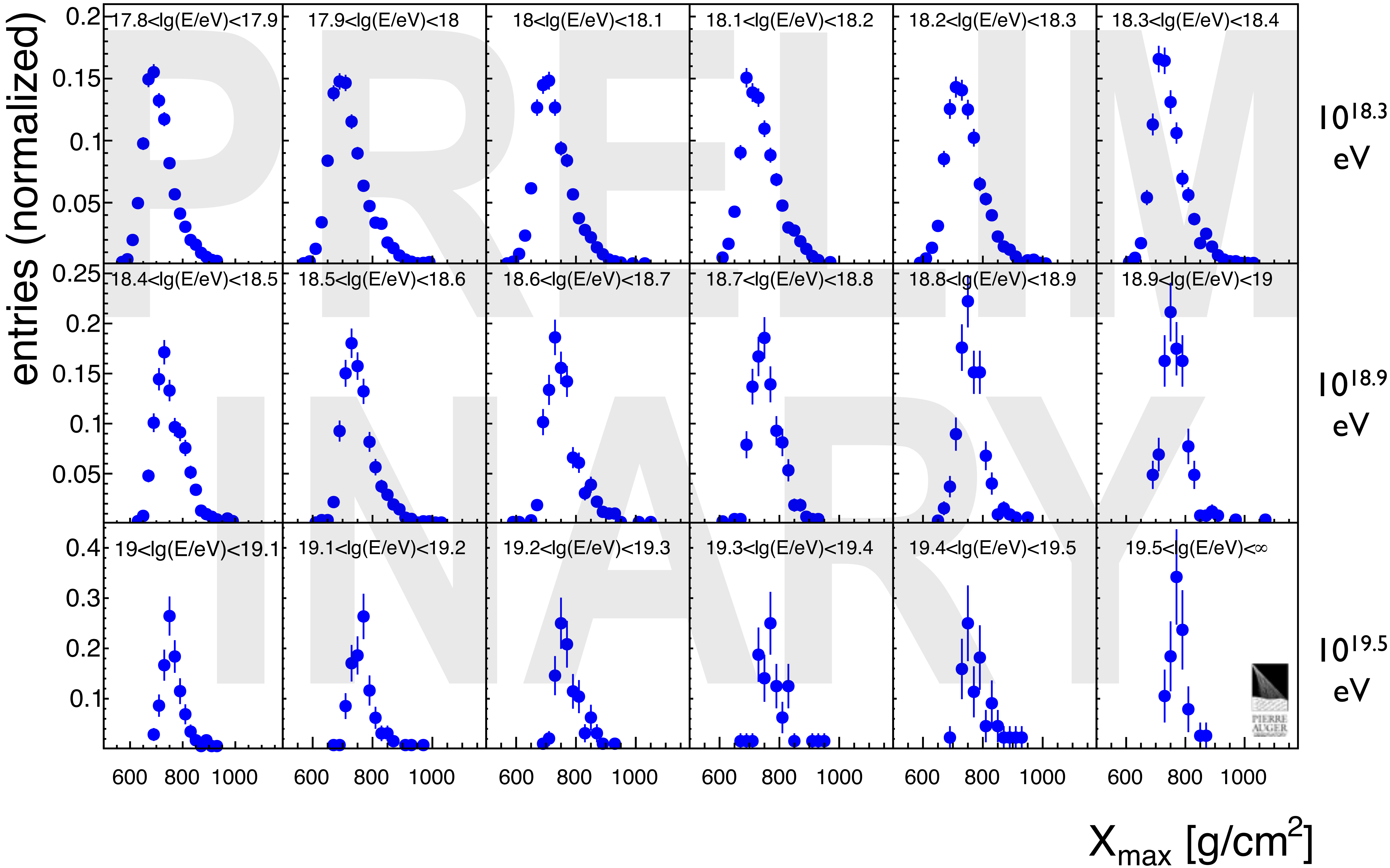
❖ X_{max} - updated mean and RMS

- hybrid data from December 2004 - December 2012
- Lower energy threshold to $10^{17.8}$ eV, improved reconstruction
- 19,759 events selected (37 above $10^{19.5}$ eV)



❖ X_{max} - distributions

- sufficient number of high quality events to study the *distribution* of X_{max}



❖ X_{max} - distributions

- sufficient number of high quality events to study the *distribution* of X_{max}

first time ever!

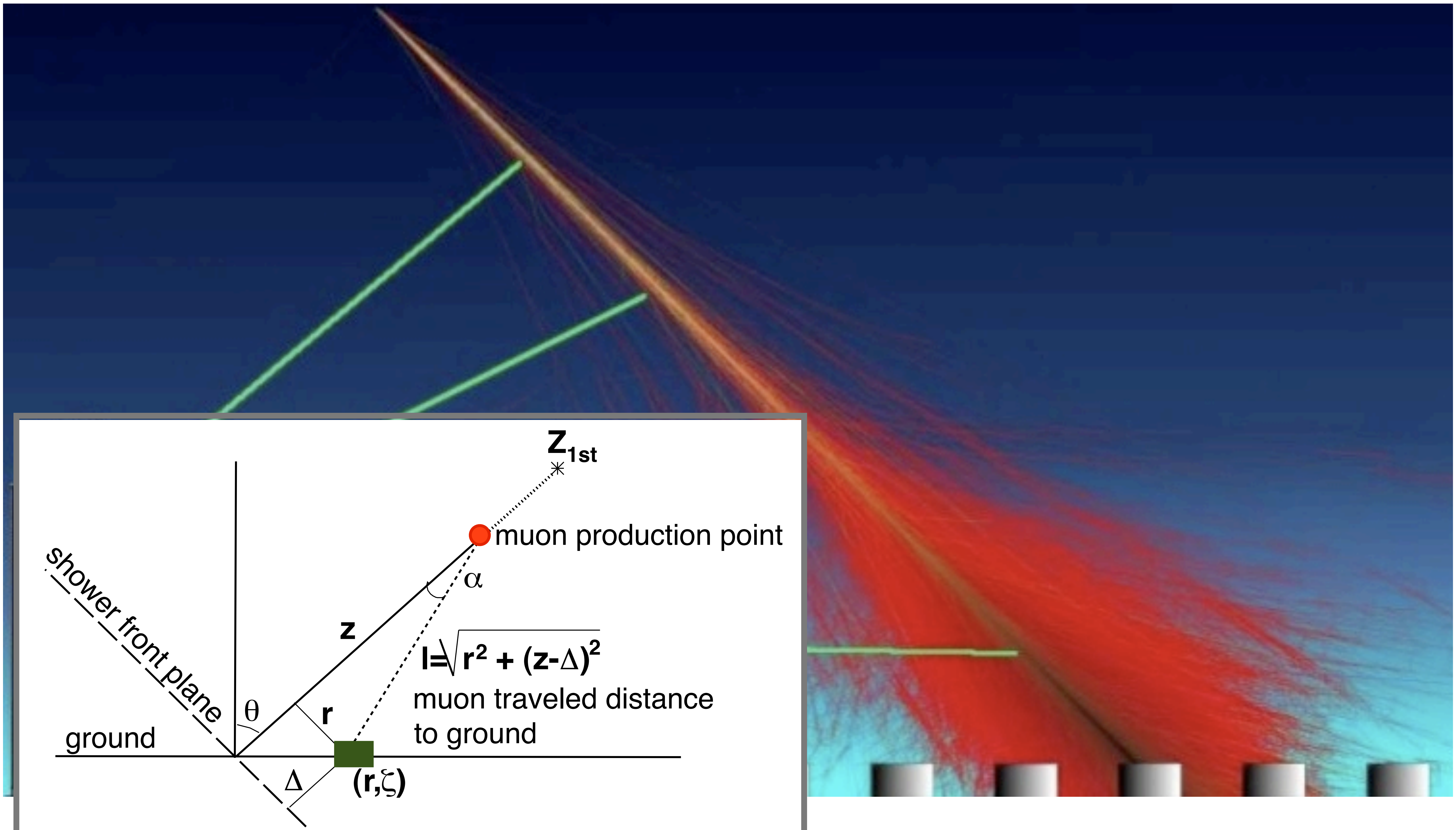
PRELIMINARY

(to be submitted in the very near future)

- No degeneracy in untangling mass combination
- Better understanding of composition
- Constrain hadronic interaction models (particle physics at $E_{CM} \gtrsim 20$ TeV)

Muons can also trace shape of shower

- Muon Production Depth: reconstruct location along shower axis where muons are produced



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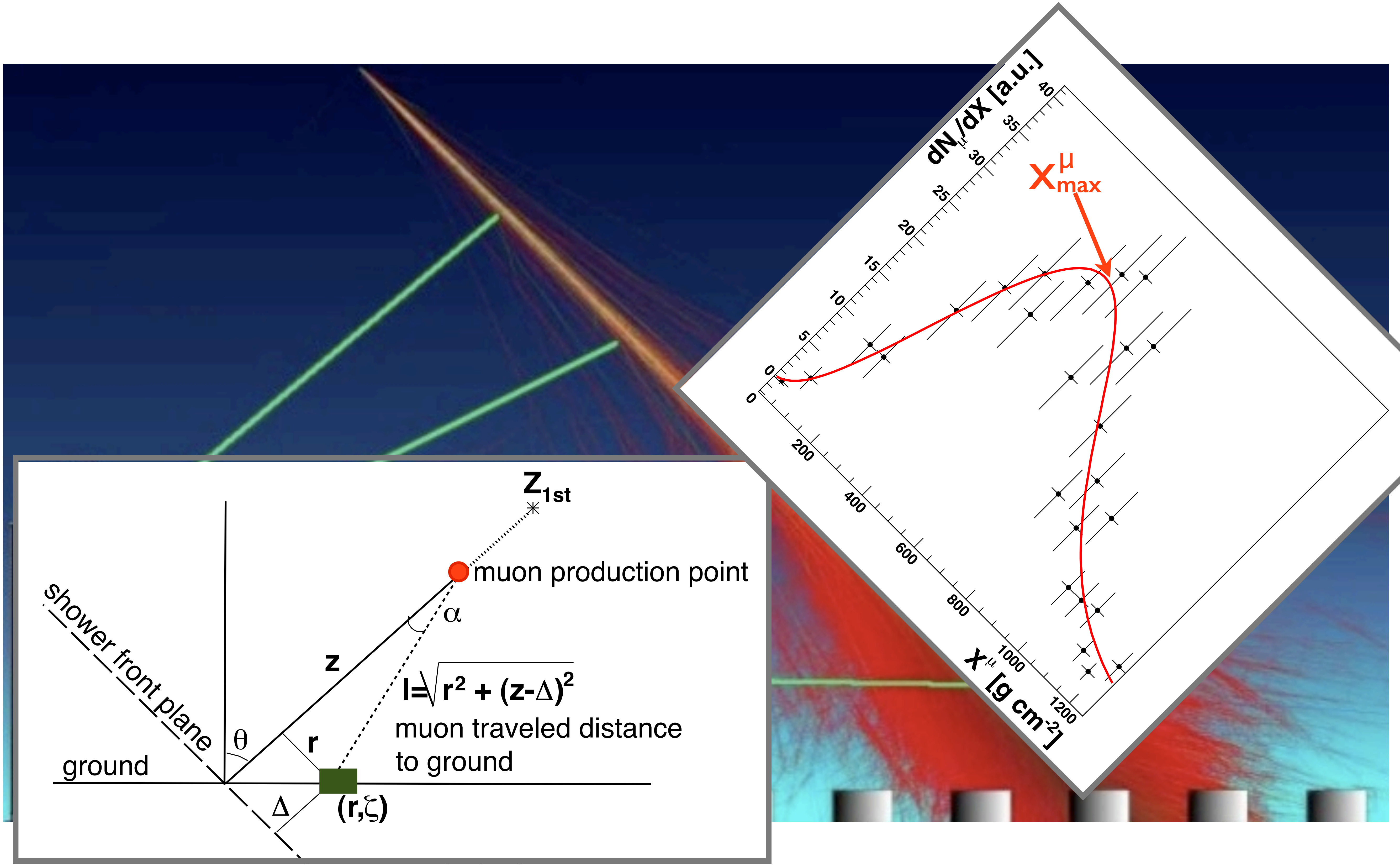

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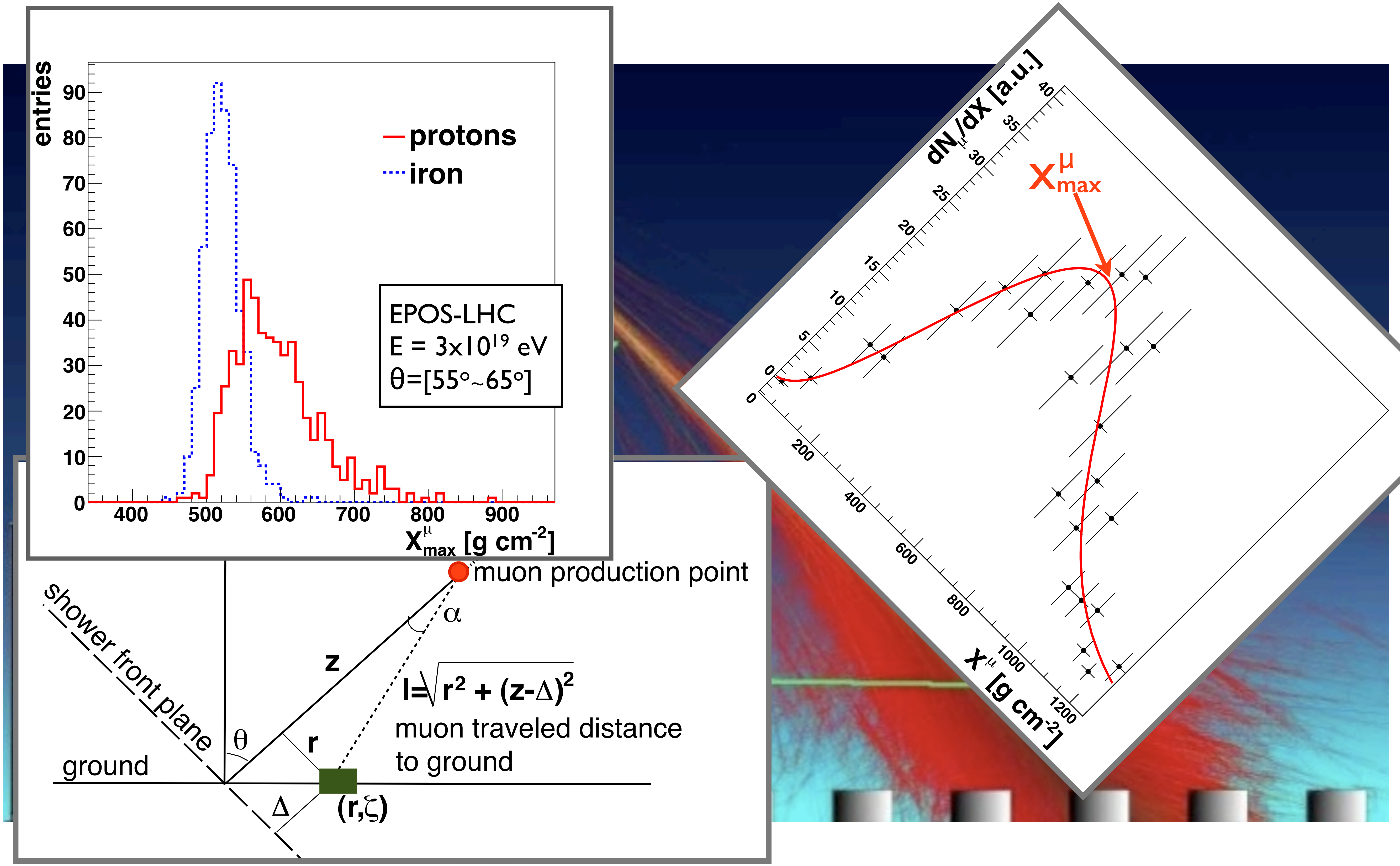
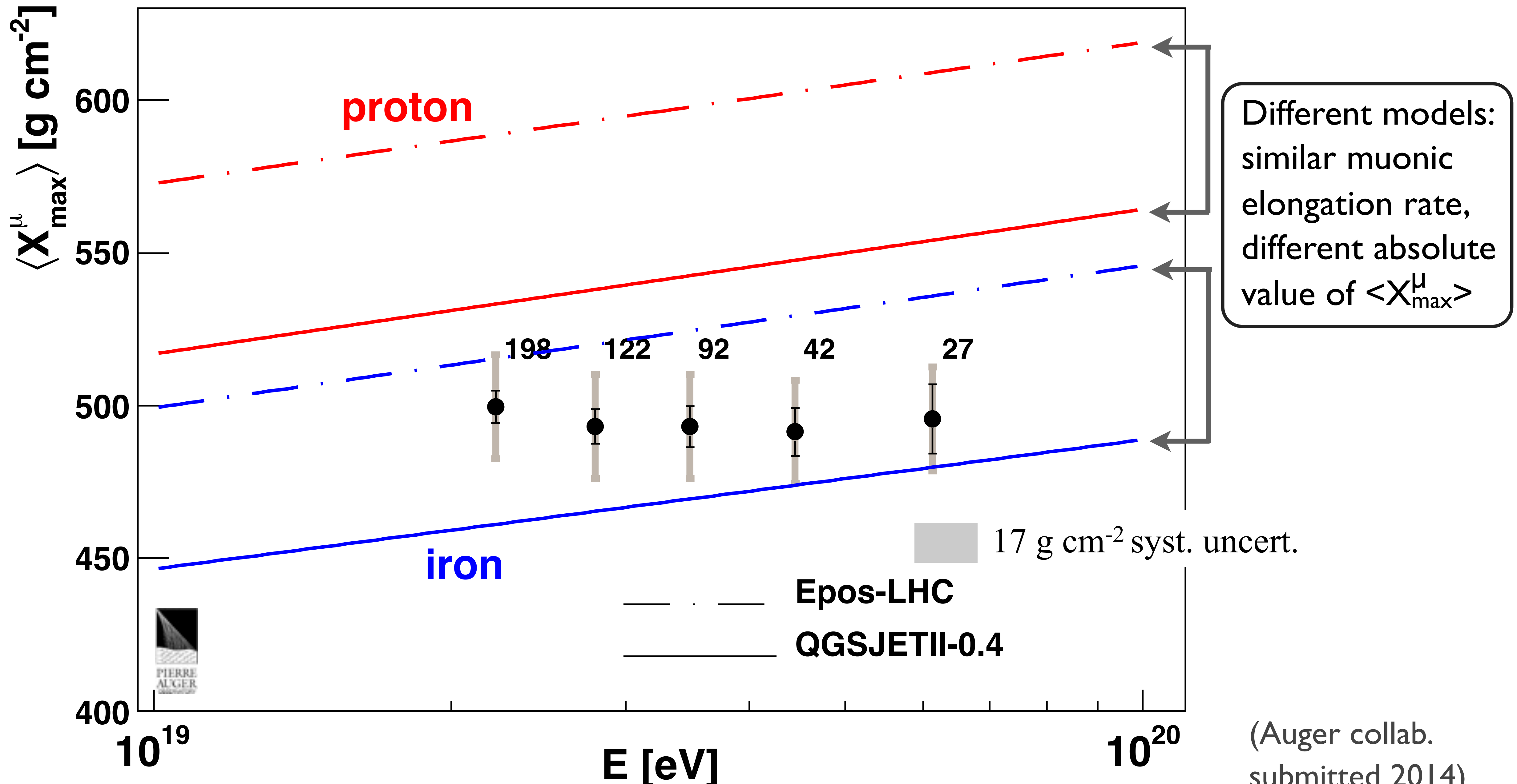


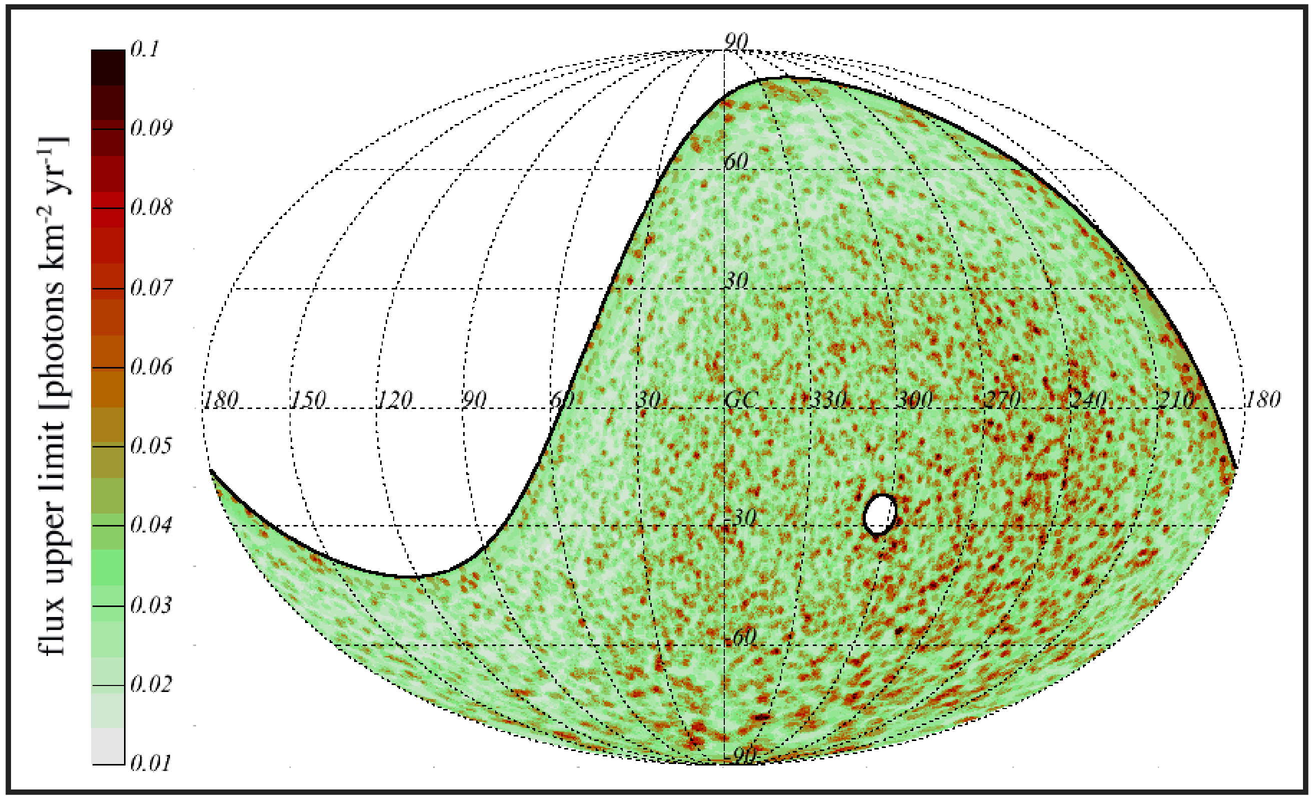
Muon Production Depth



(Auger collab. submitted 2014)

- Jan 2004 - Dec 2012; E > 2×10^{19} eV, θ > 55°, stations far from core; 481 events after cut
- Novel approach to study composition and hadronic interactions
- Currently has large systematics, will benefit from better EM-muon separation

❖ Photon limits



Directional photon limit

- Hybrid events, E = $10^{17.3}$ eV - $10^{18.5}$ eV
- No photon point source
- Regularly emitting non-beamed photon source in Galaxy < 0.25 eV cm^{-2} s^{-1}
- Constrain models for acceleration of Galactic EeV protons

(Auger collab. accepted ApJ 2014)

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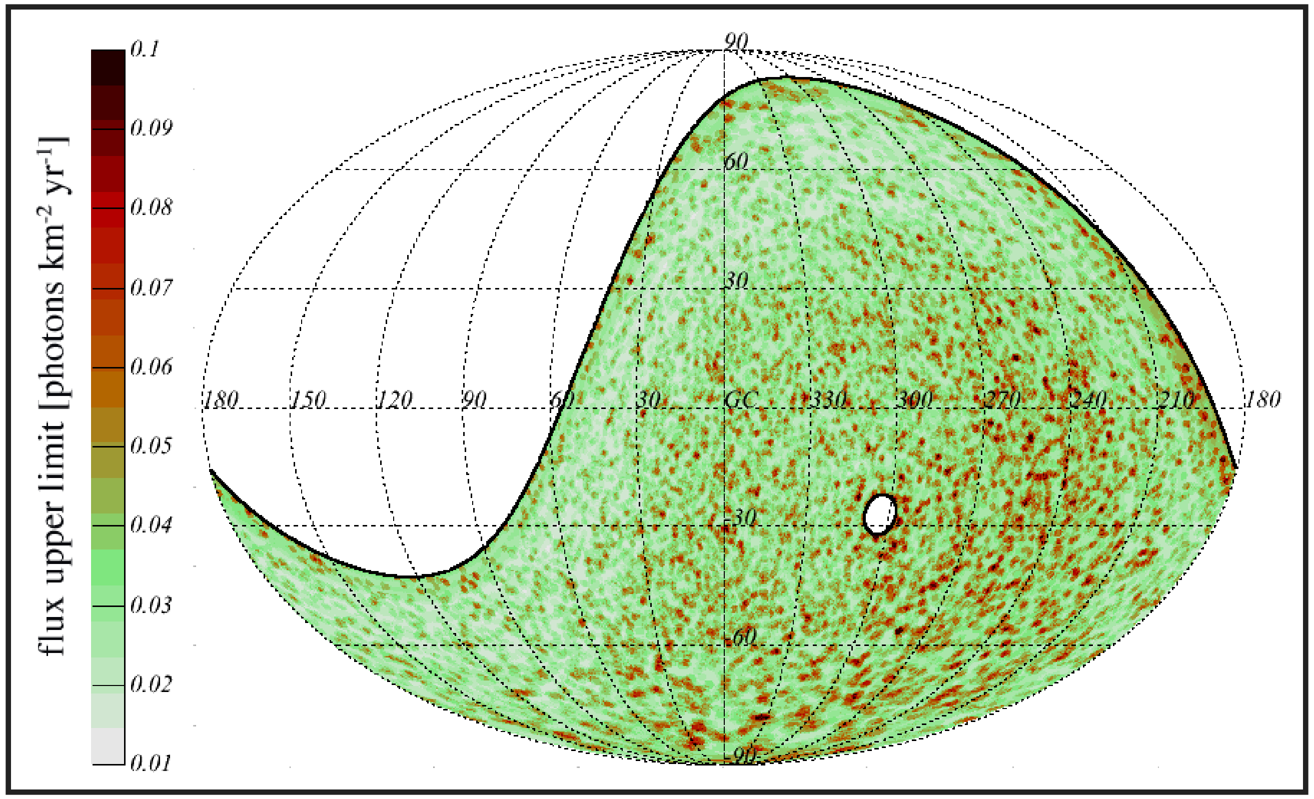

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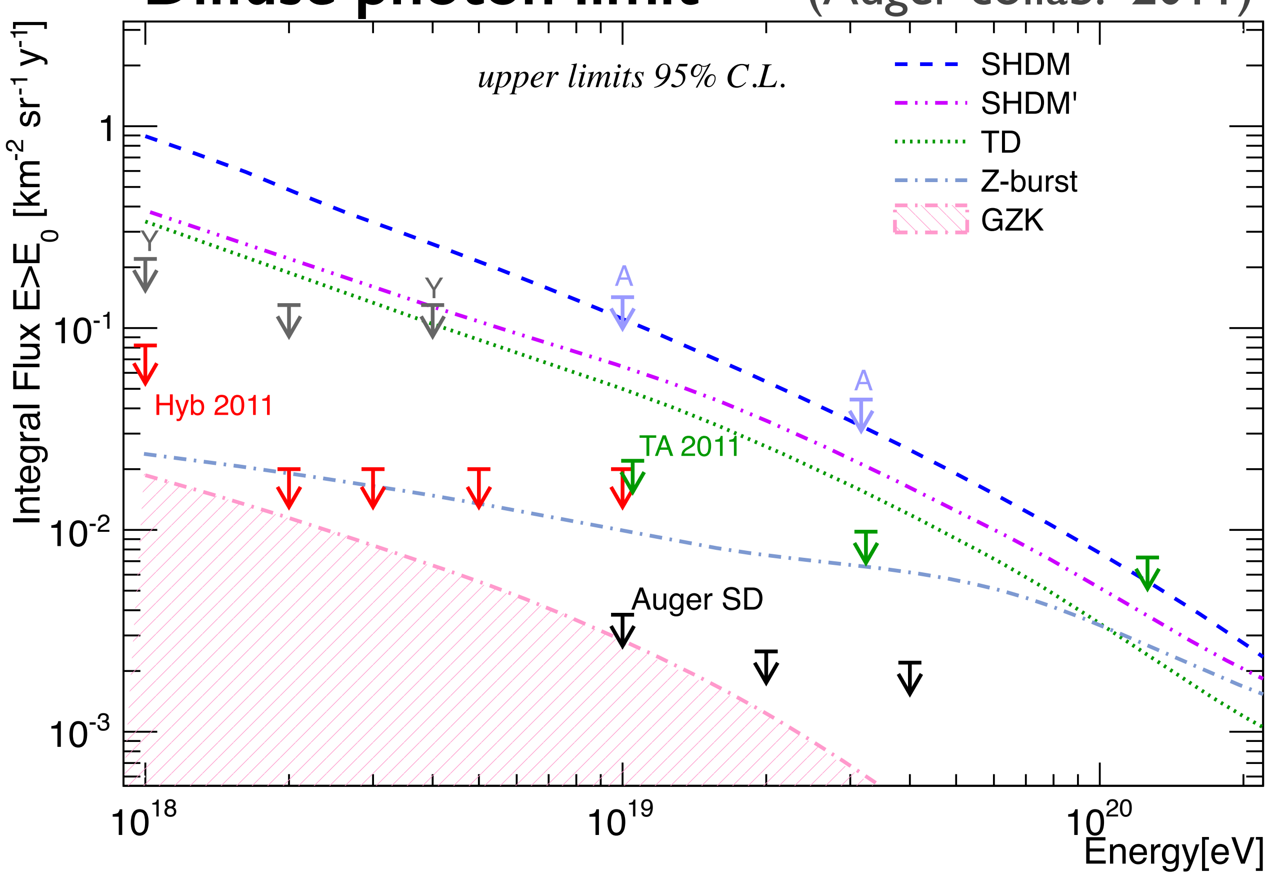
Diffuse photon limit (Auger collab. 2011)



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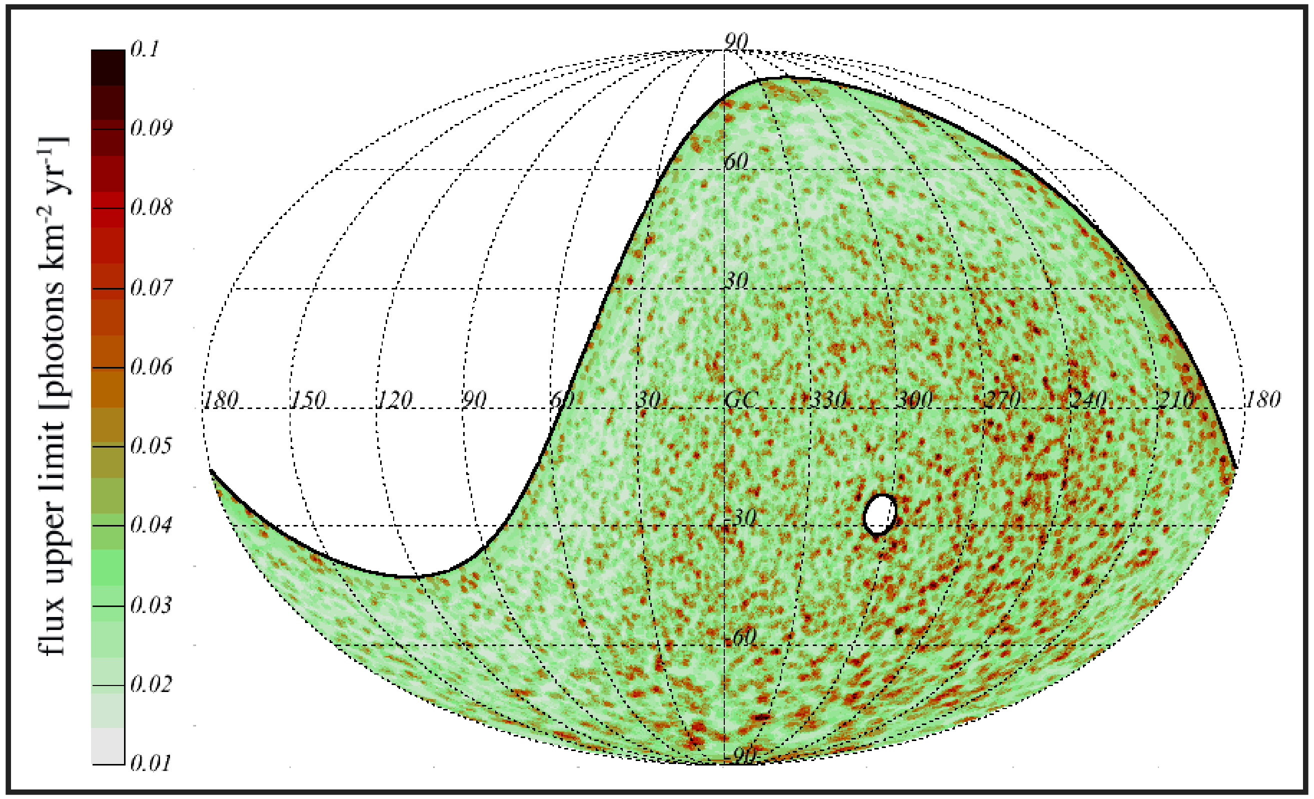

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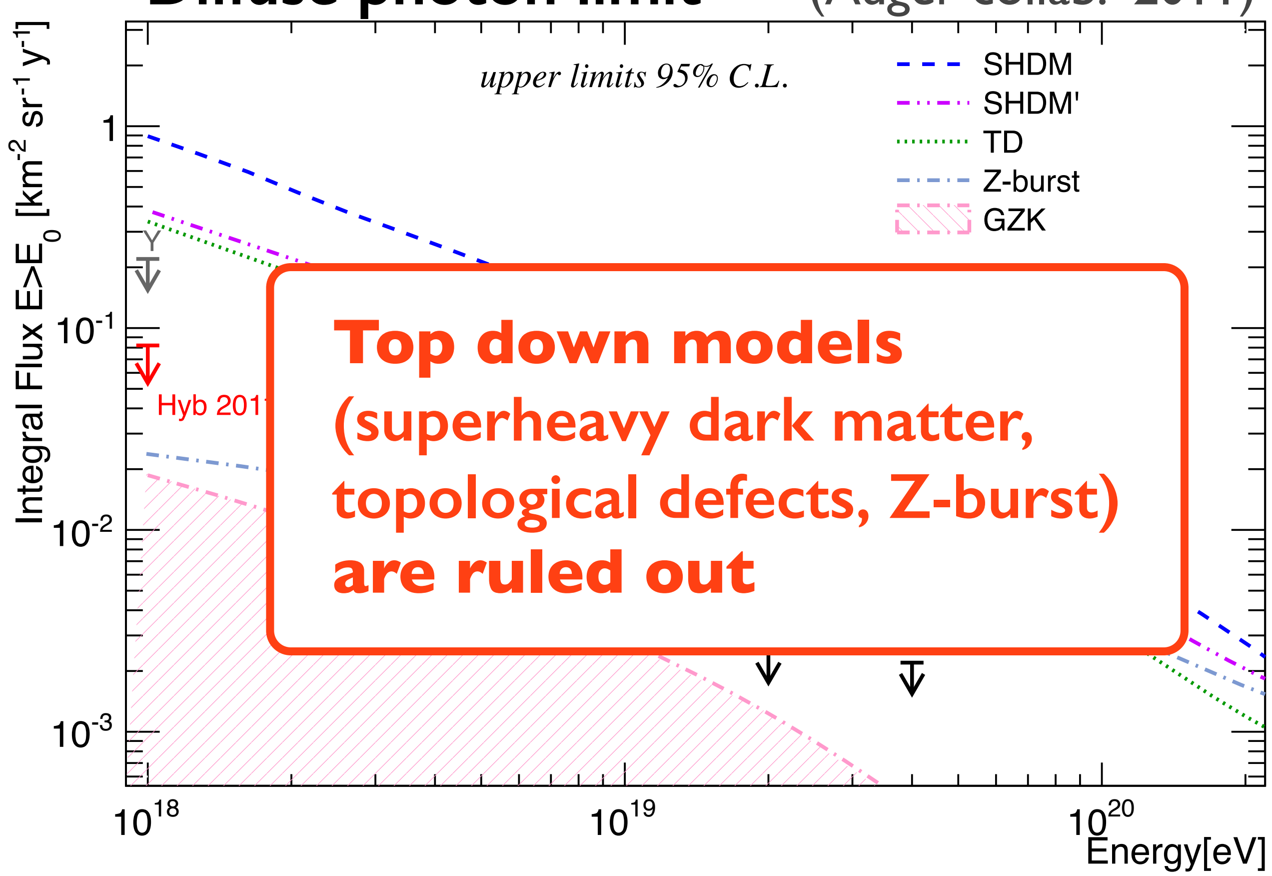

Top down models (superheavy dark matter, topological defects, Z-burst) are ruled out

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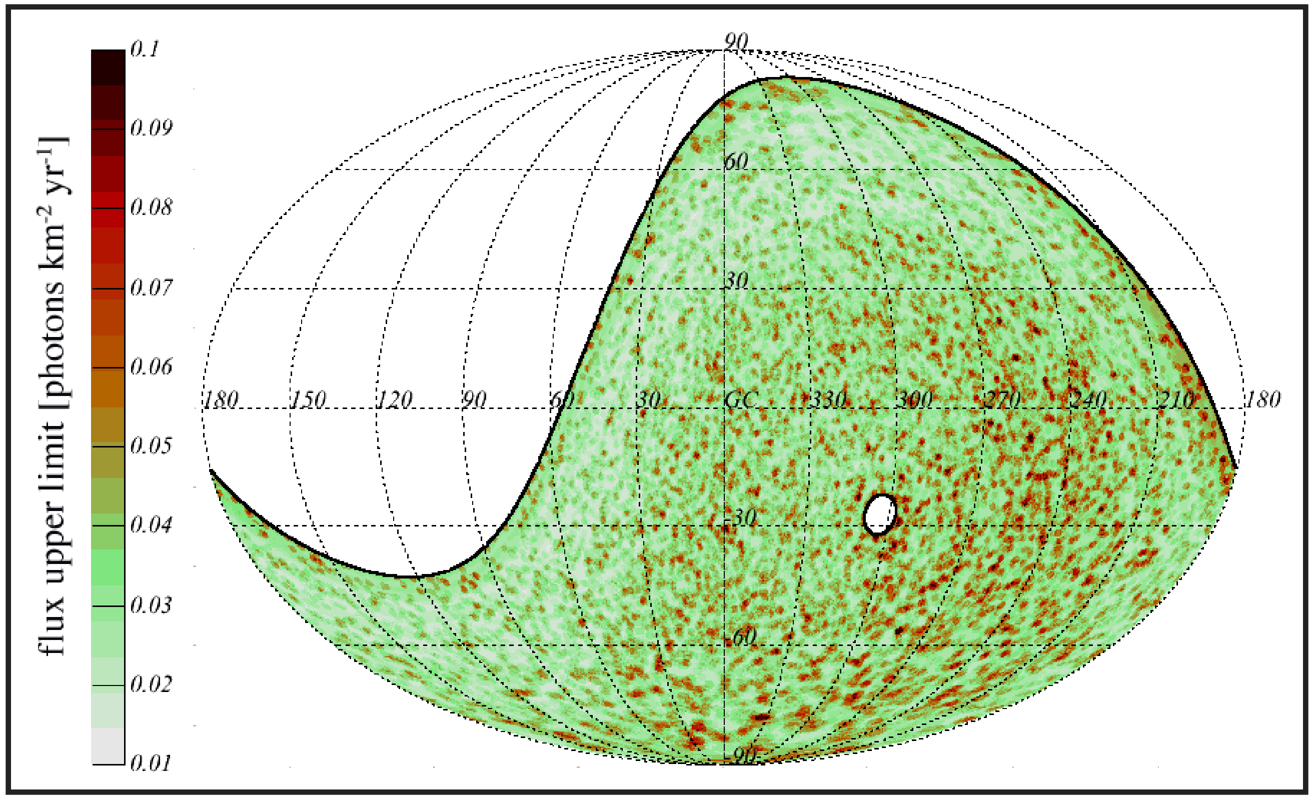

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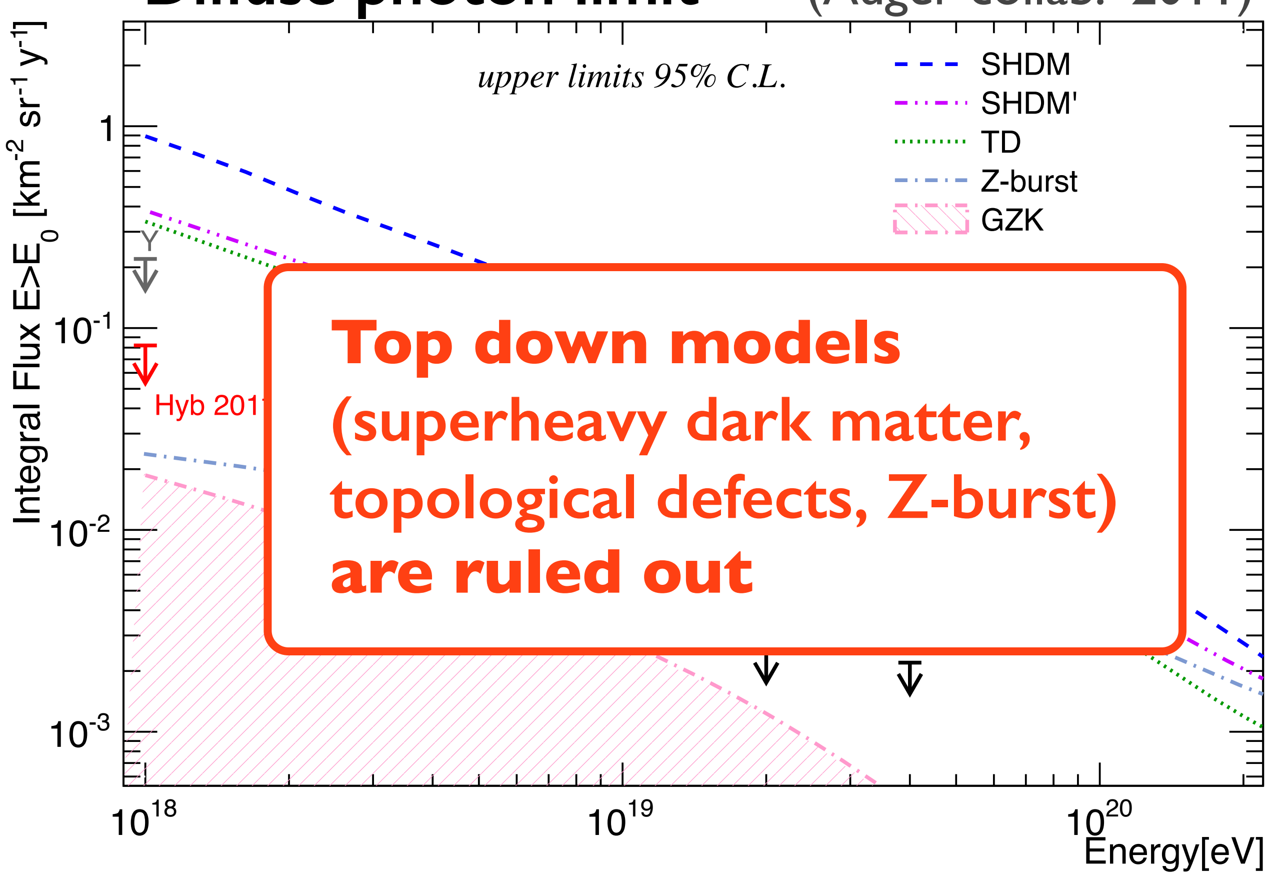

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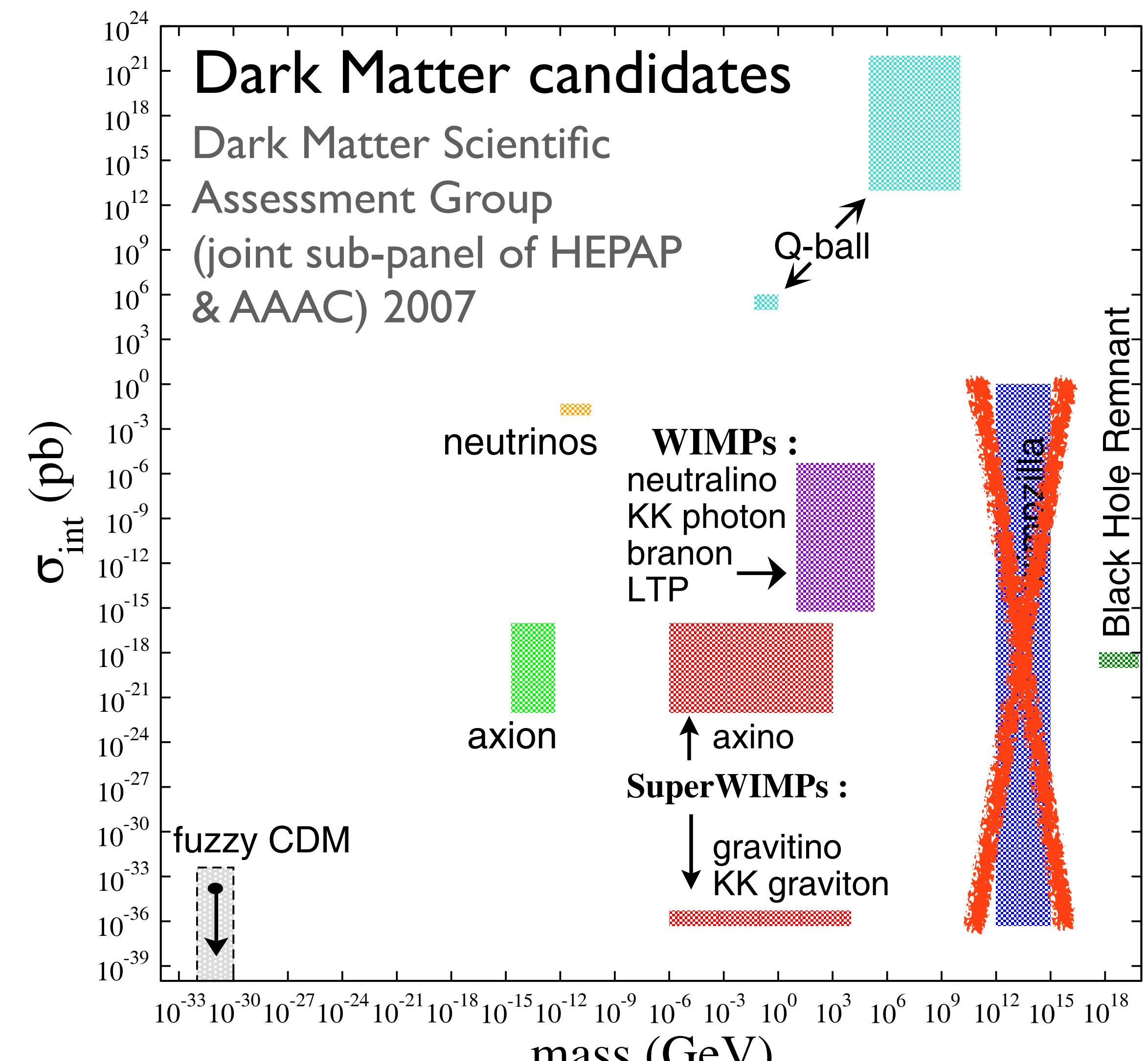
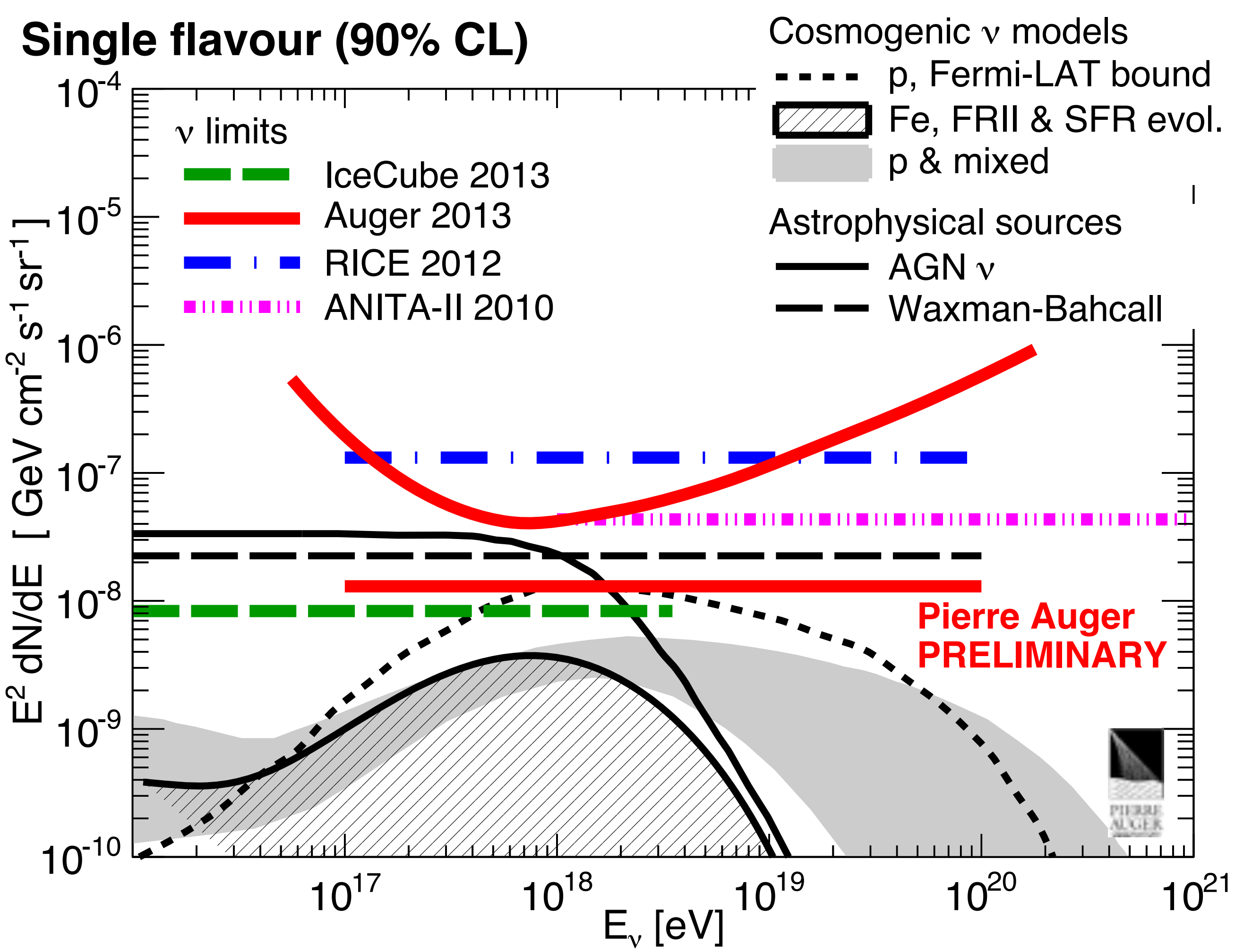
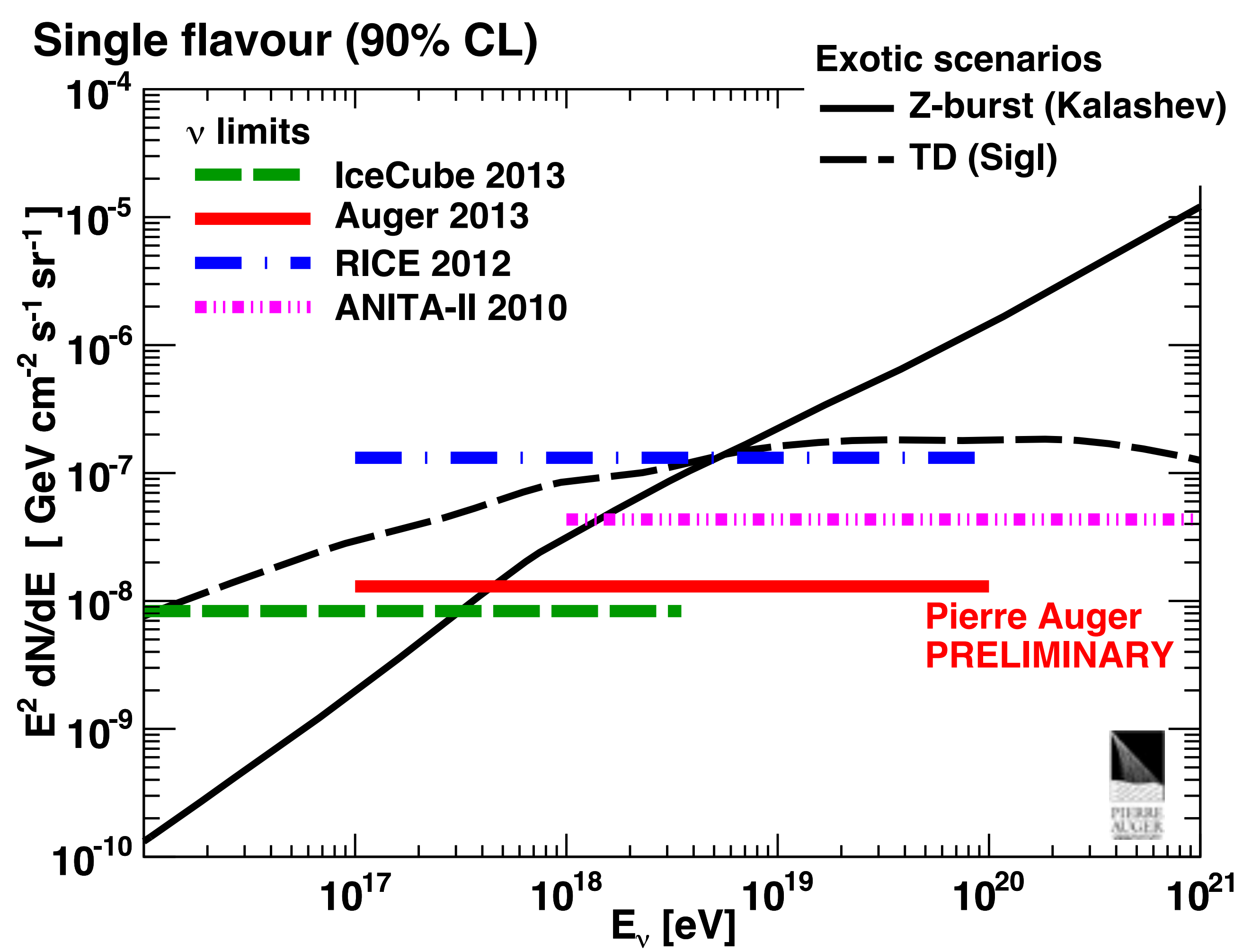


❖ Neutrino limits





- Jan 2004 - Dec 2012
- Inclined showers with broad front (young showers)
- Earth skimming 73%; down-going[75°-90°] 23%; down-going[65°-75°] 4%
- No candidates
  - ➡ limits below Waxman-Bahcall landmark, approaching cosmological models
  - ➡ strongly disfavour / rule out top-down models

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 ? (Allard et al. 2008 etc.)

or

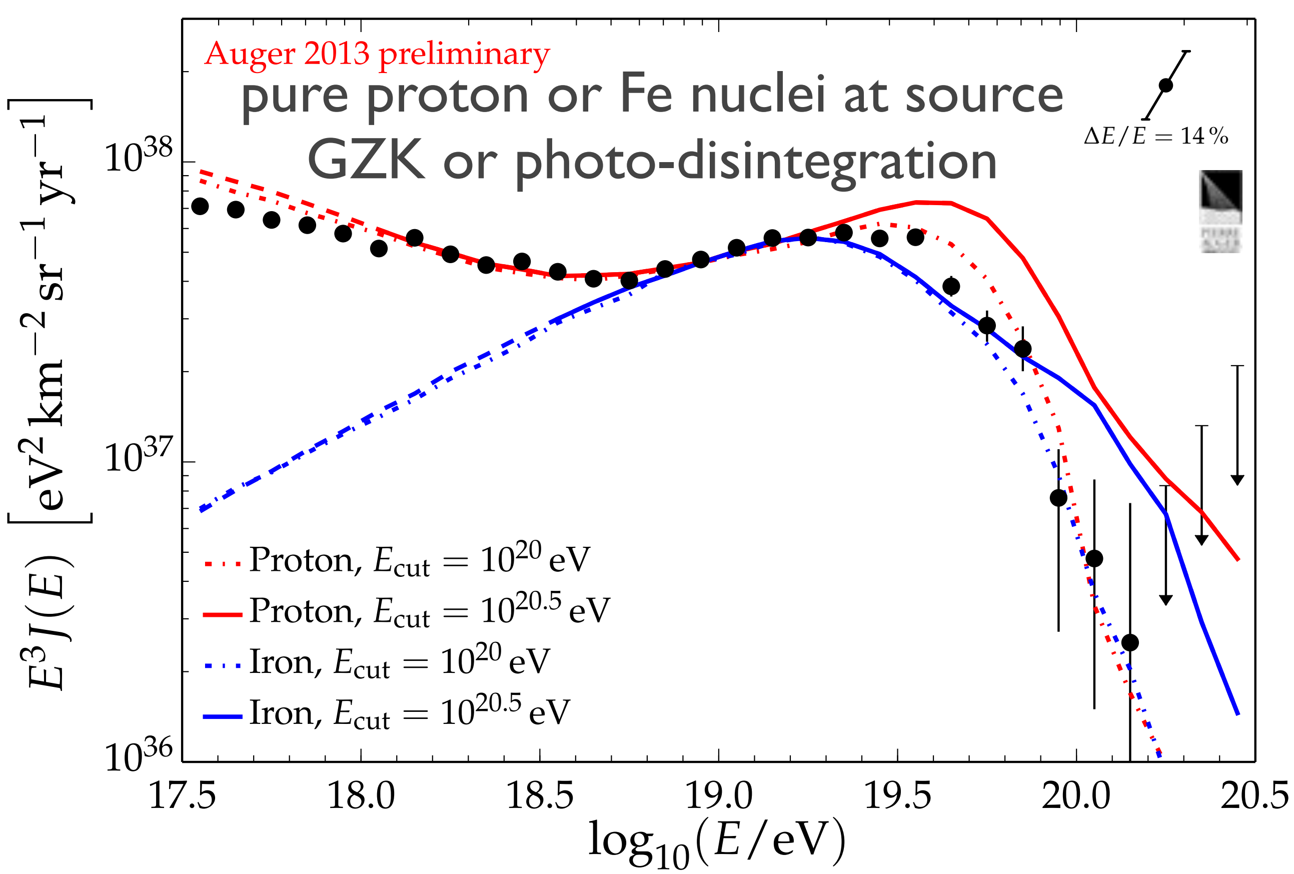
2. Similar to above but particles accelerated to higher energies, suppression due to photo-disintegration of heavy nuclei? (Taylor, Ahlers, Aharonian 2011 etc.)

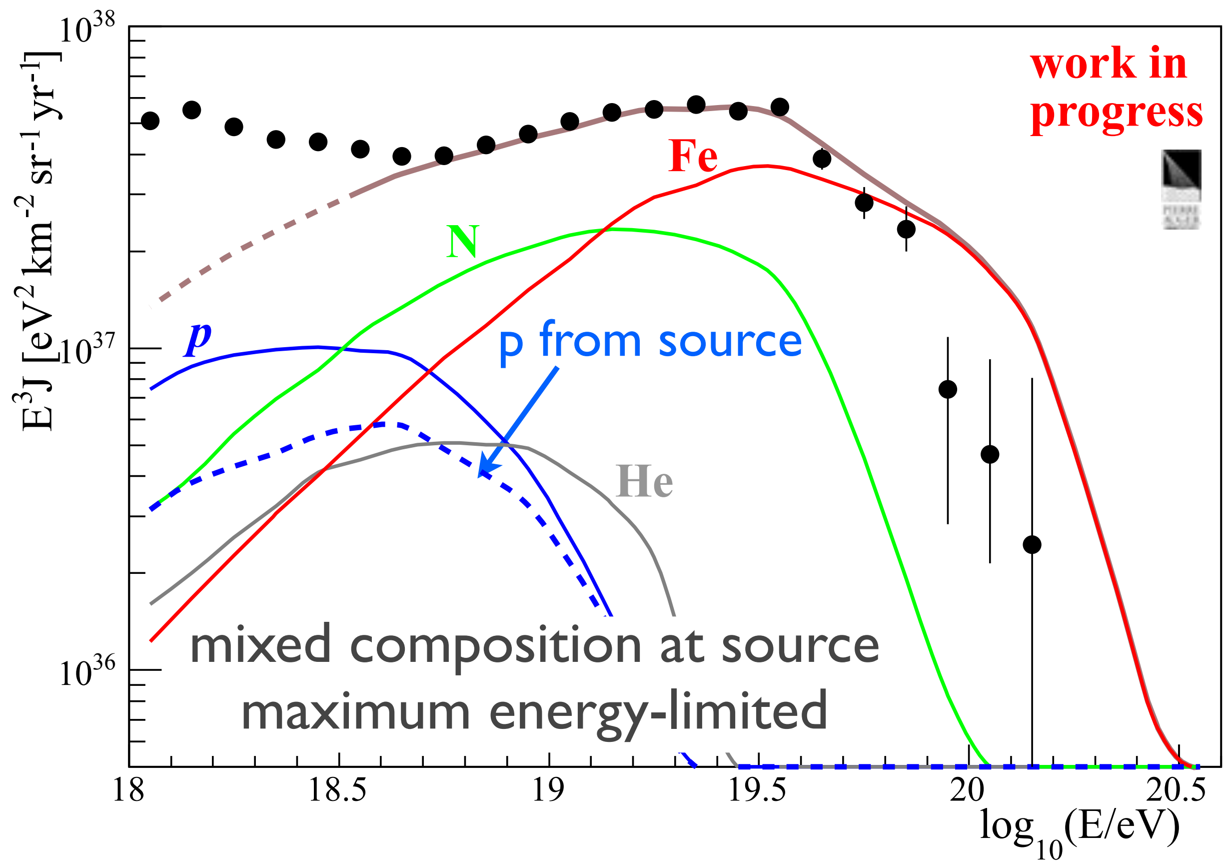
or

3. Mainly extra-galactic protons, suppression due to GZK cutoff? (ankle accountable by e^+e^- pair production.) (Berezinsky & Grigoreva 1988 etc.)

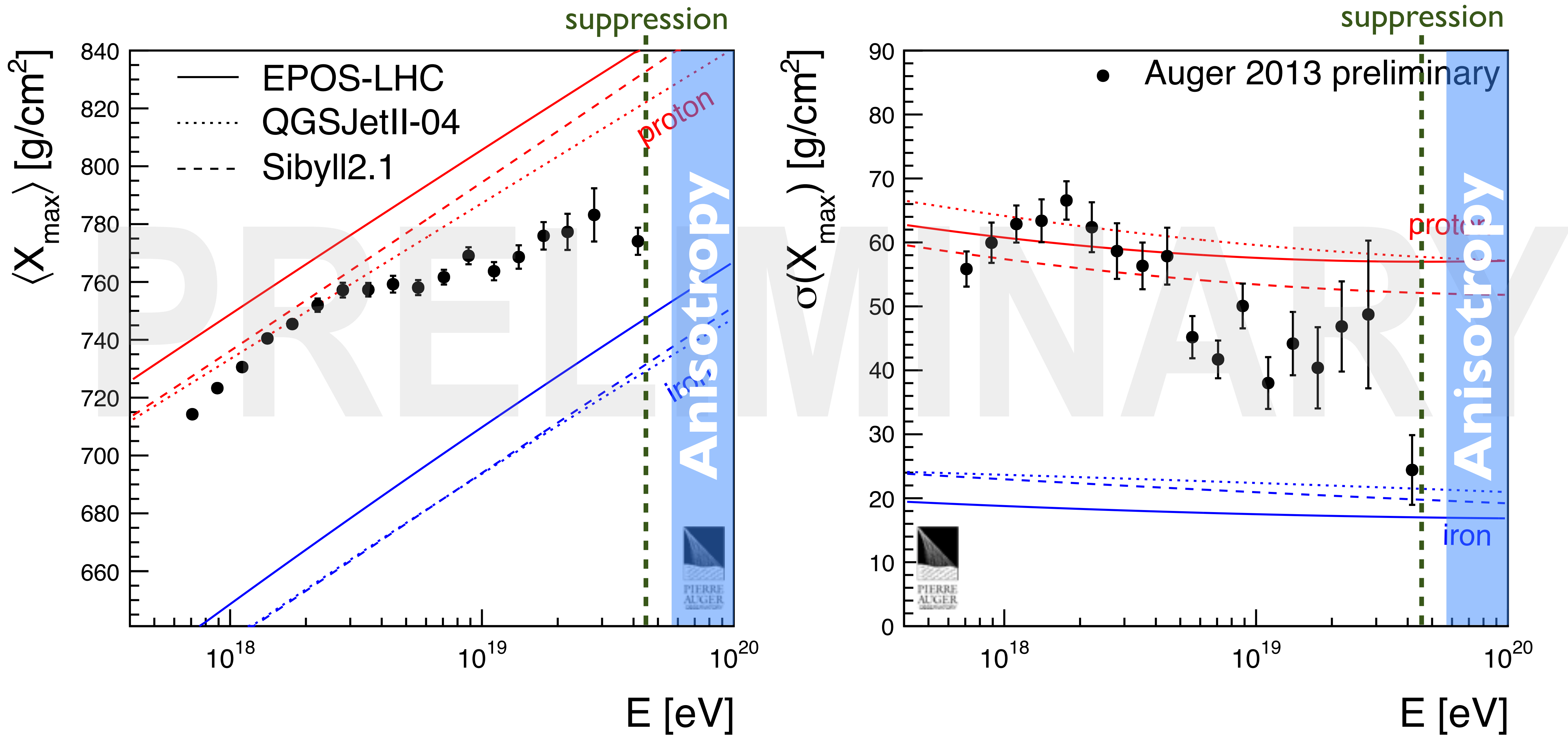
or

4. Mainly heavier nuclei produced by Galactic & extra-galactic compact objects? (Hillas 1984; Fang, Kotera, Olinto. 2013 etc.)





➡ **Knowing composition is the key to understanding the flux suppression**


suppression
840
820
800
780
760
740
720
700
680
660
⟨X_max⟩ [g/cm²]
EPOS-LHC
QGSJetII-04
Sibyll2.1
proton
iron
Anisotropy
PRELIMINARY
10^18
10^19
10^20
E [eV]
PIERRE AUGER
suppression
90
80
70
60
50
40
30
20
10
0
σ(X_max) [g/cm²]
Auger 2013 preliminary
proton
iron
Anisotropy
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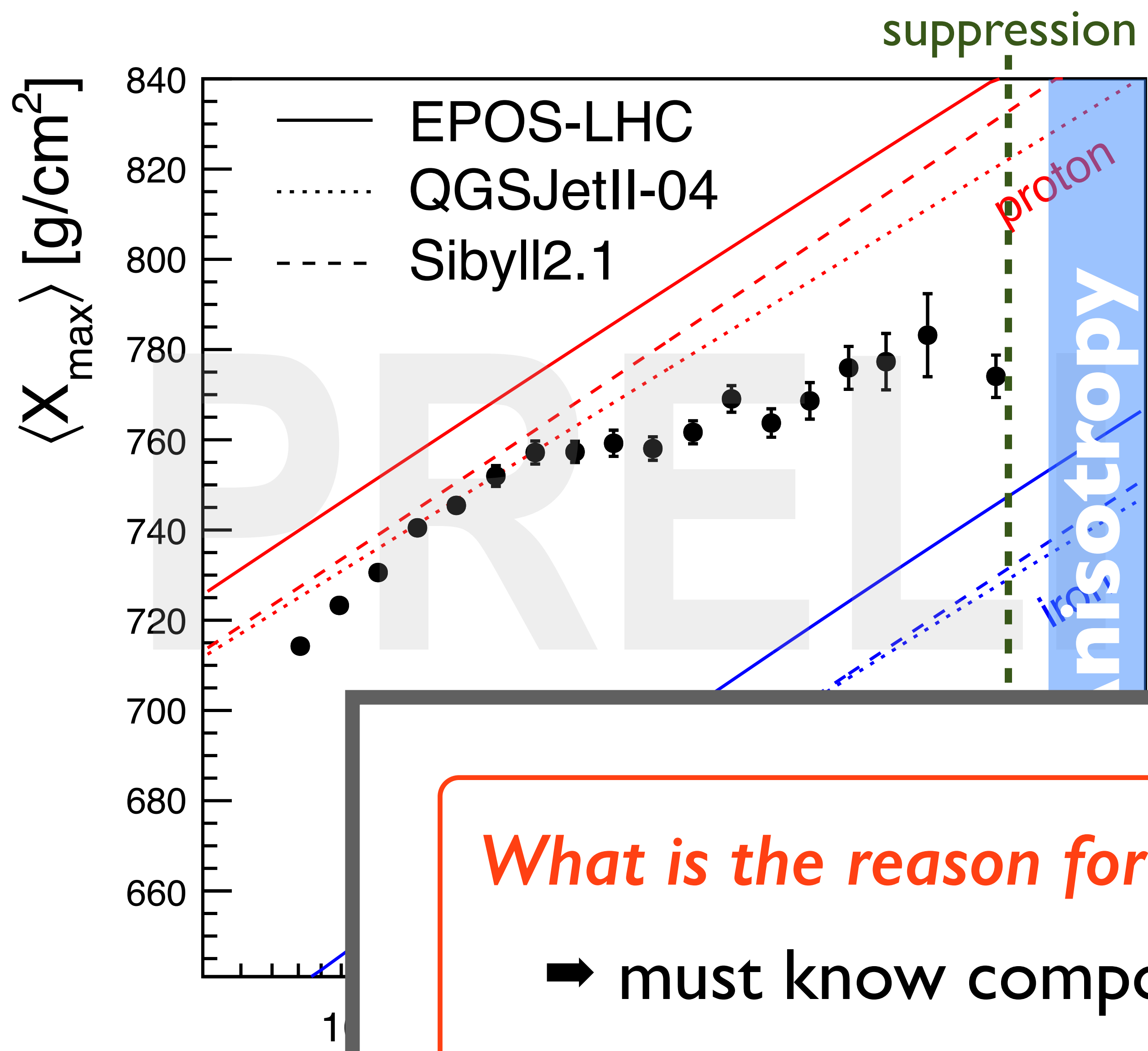
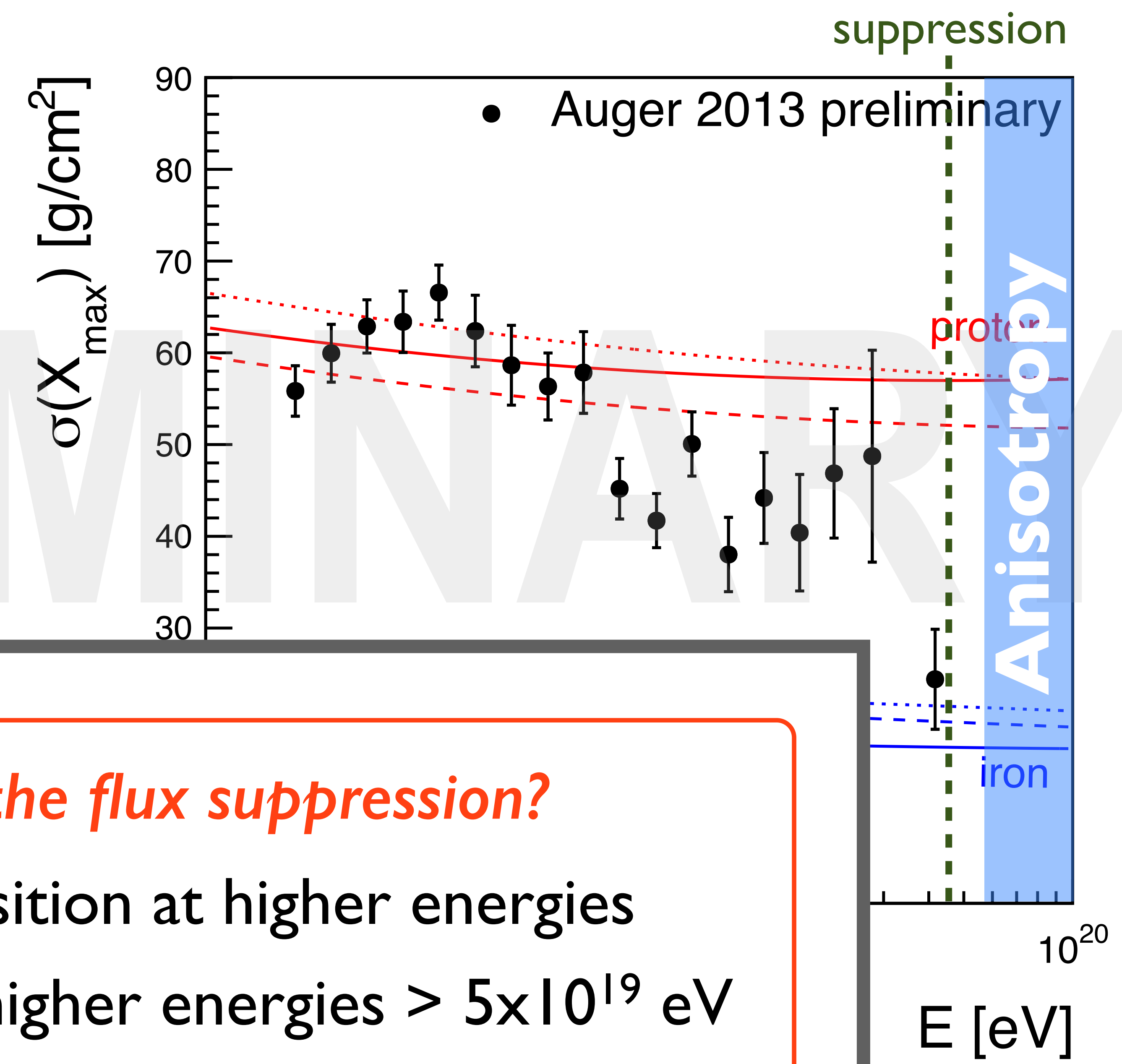
PIERRE AUGER





What is the reason for the flux suppression?

➡ must know composition at higher energies

➡ larger statistics at higher energies > 5×10^{19} eV

➡ use SD (100% duty cycle vs 13% 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 flux

2. 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

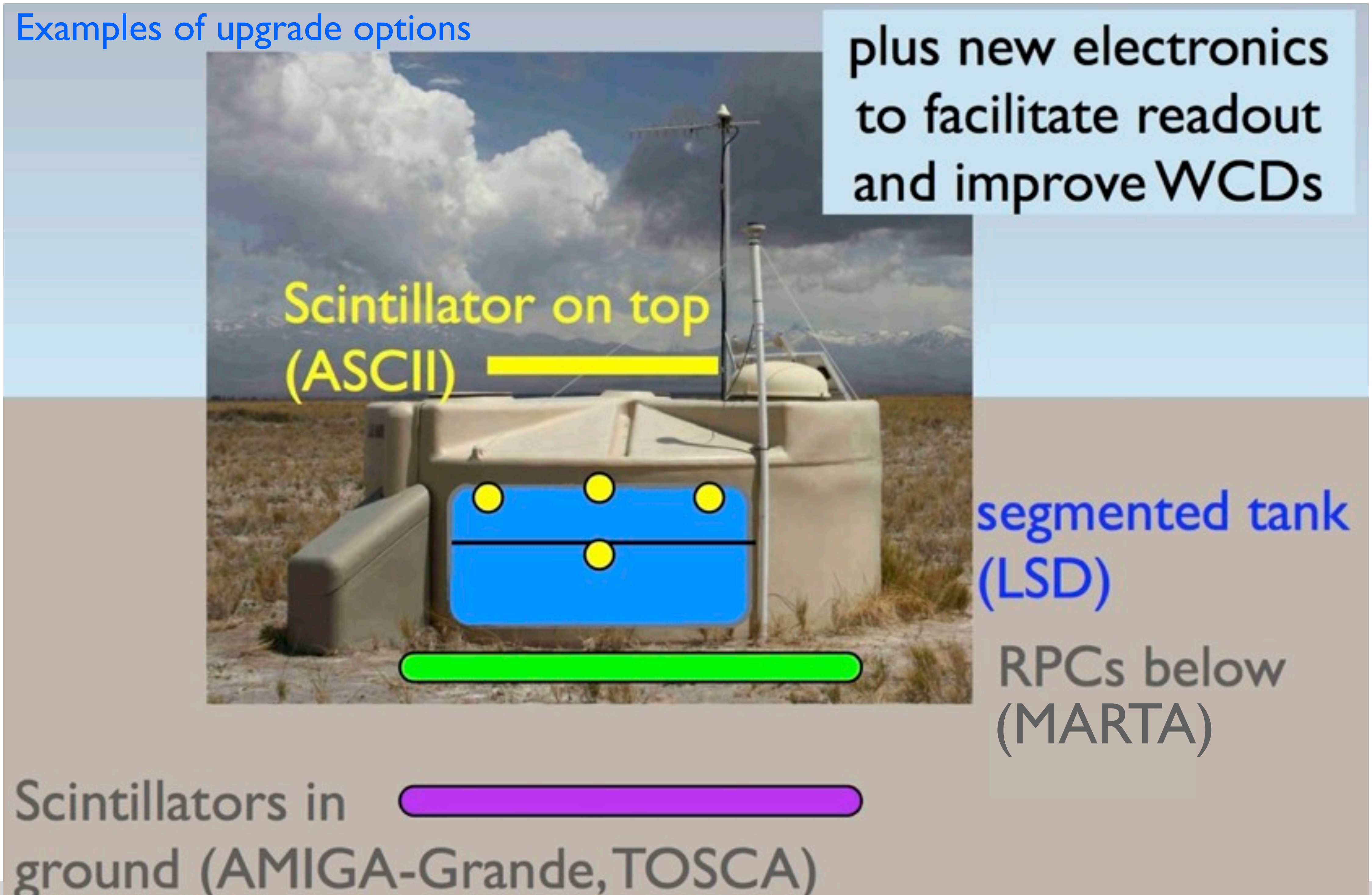
3. Study hadronic interactions and extensive air showers above $E_{CM} > 70$ TeV

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

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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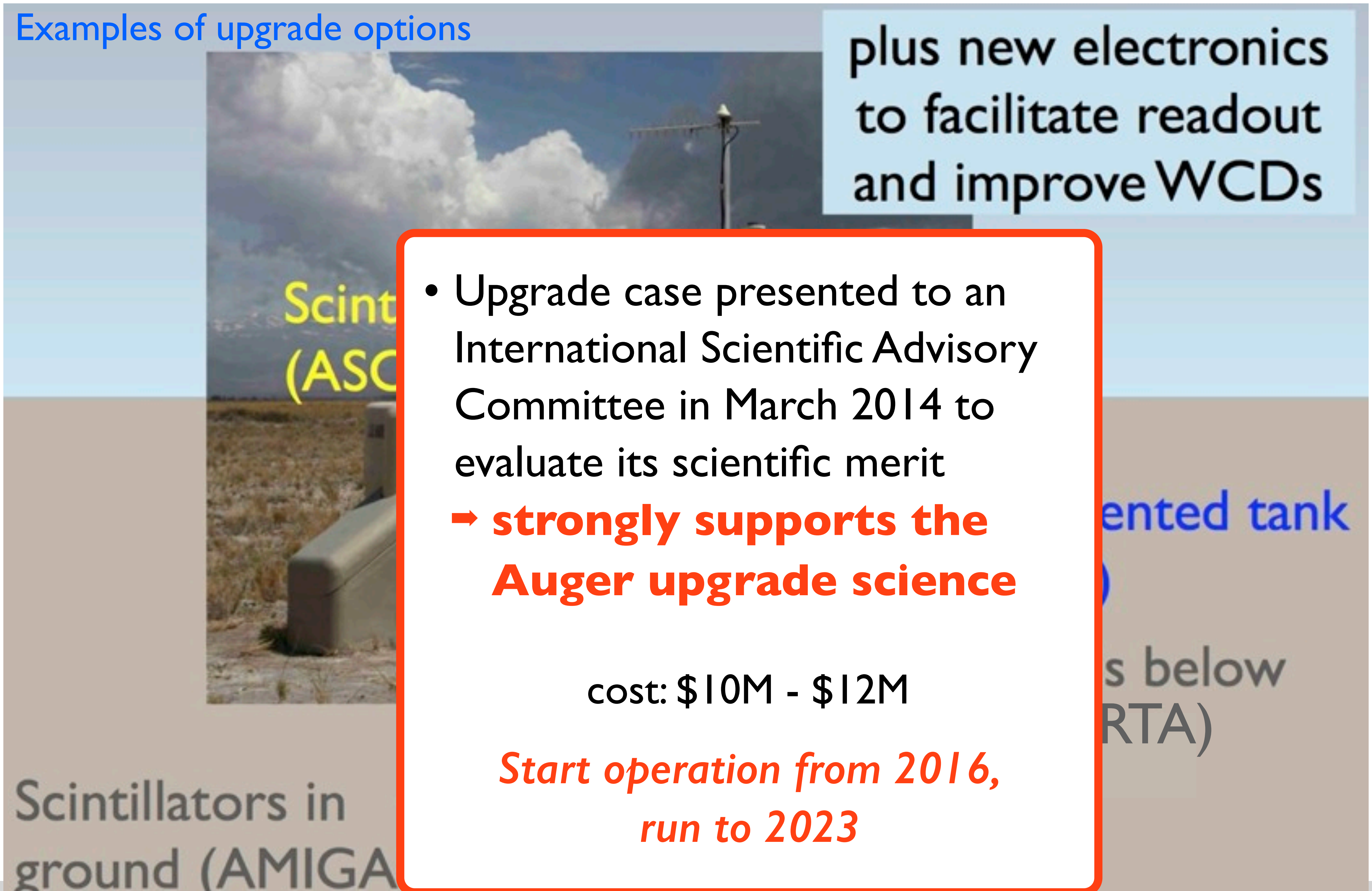


- Upgrade case presented to an International Scientific Advisory Committee in March 2014 to evaluate its scientific merit
  ➡ **strongly supports the Auger upgrade science**

cost: $10M - $12M

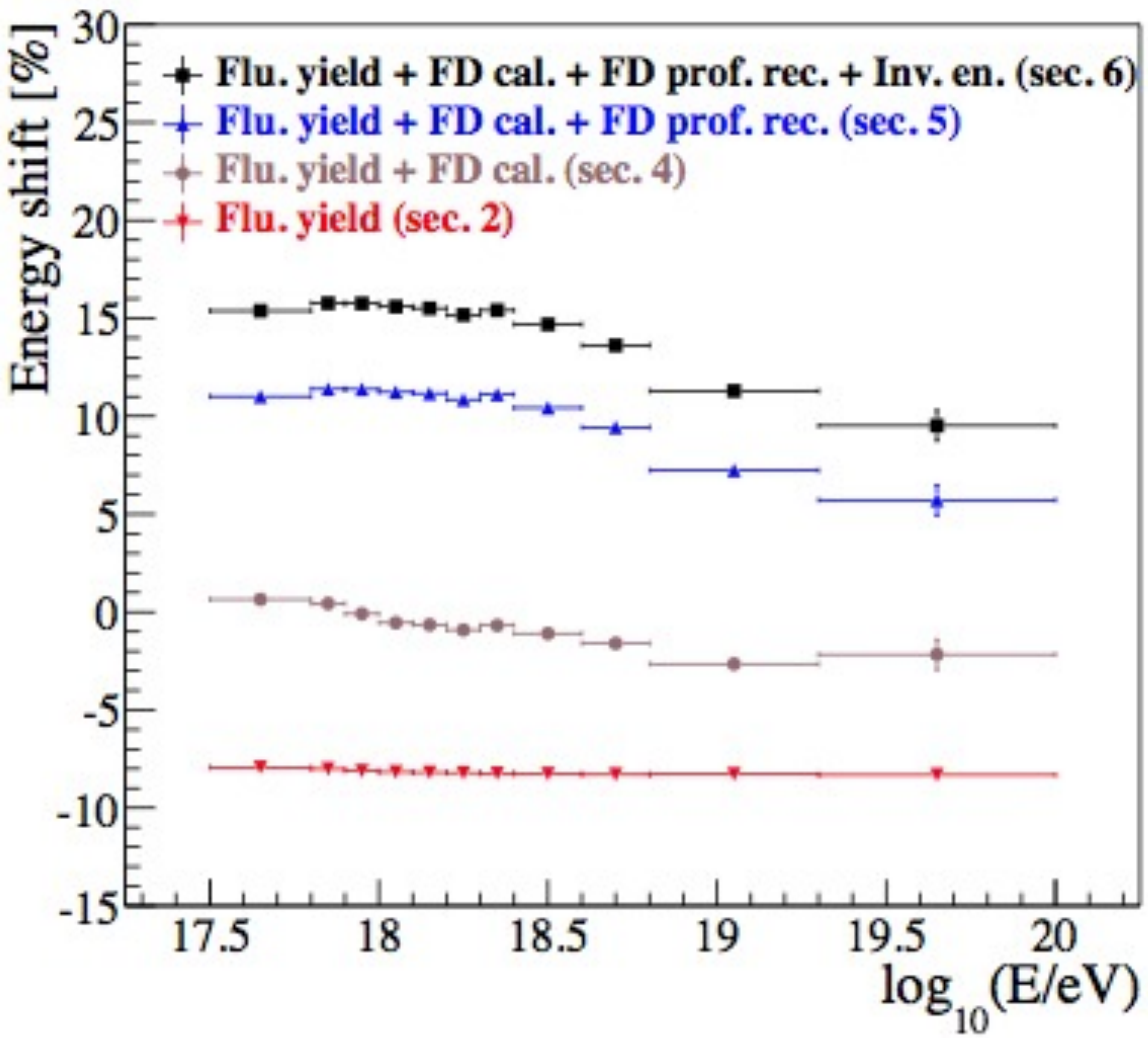
Start operation from 2016, run to 2023

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
  - do not know the cause of the suppression;
- Sufficient number of high quality X_{max} data to analyse their distribution;
- Muon Production Depth - new handle on composition and hadronic interactions;
- Photon limits - no directional photon candidate, top-down models ruled out;
- Neutrino limits - no candidate, approaching cosmological limits, top-down models strongly disfavoured or ruled out;
- Upgrade of SDs to run from 2016 will be proposed by the international collaboration and several options are being considered.

backups

• Auger energy scale has changed

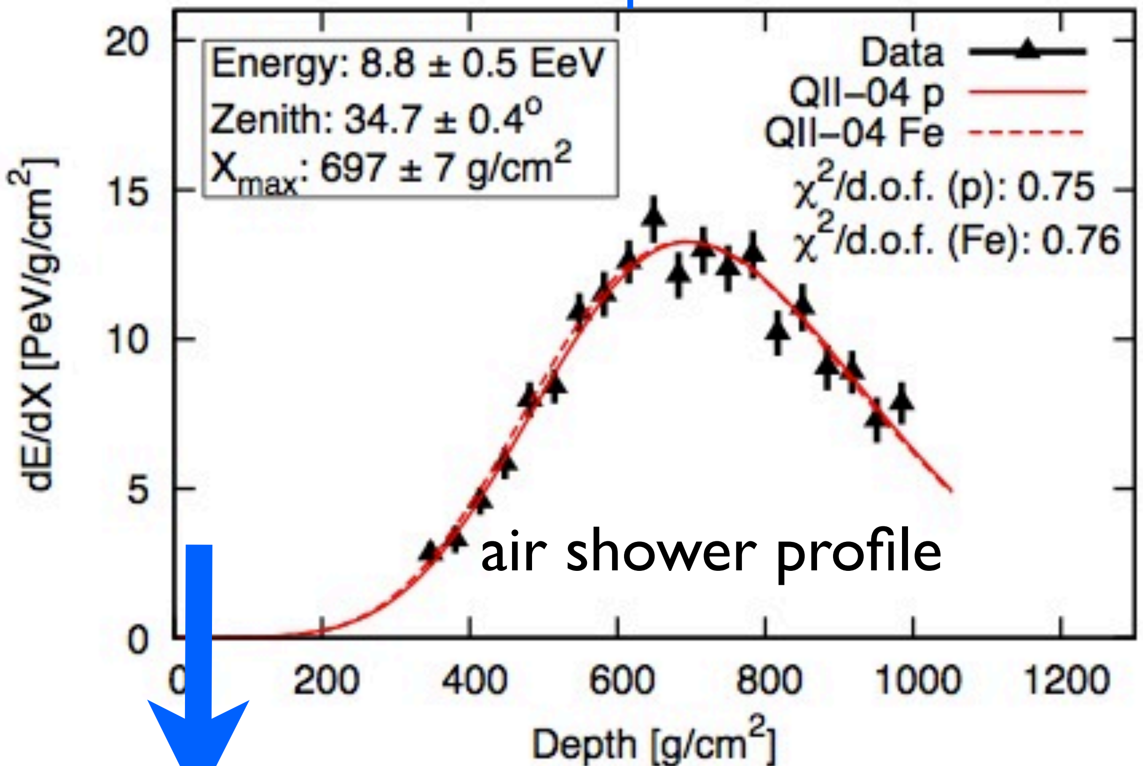


Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub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

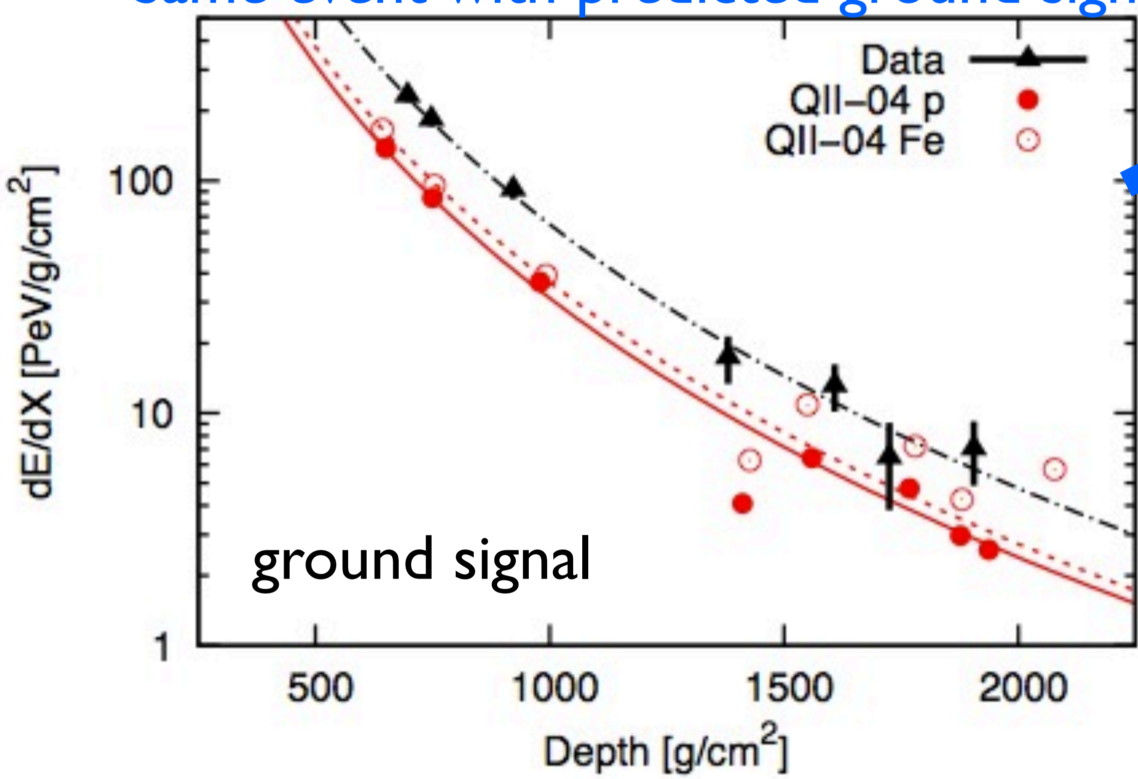
•Muon estimation

Golden hybrid event

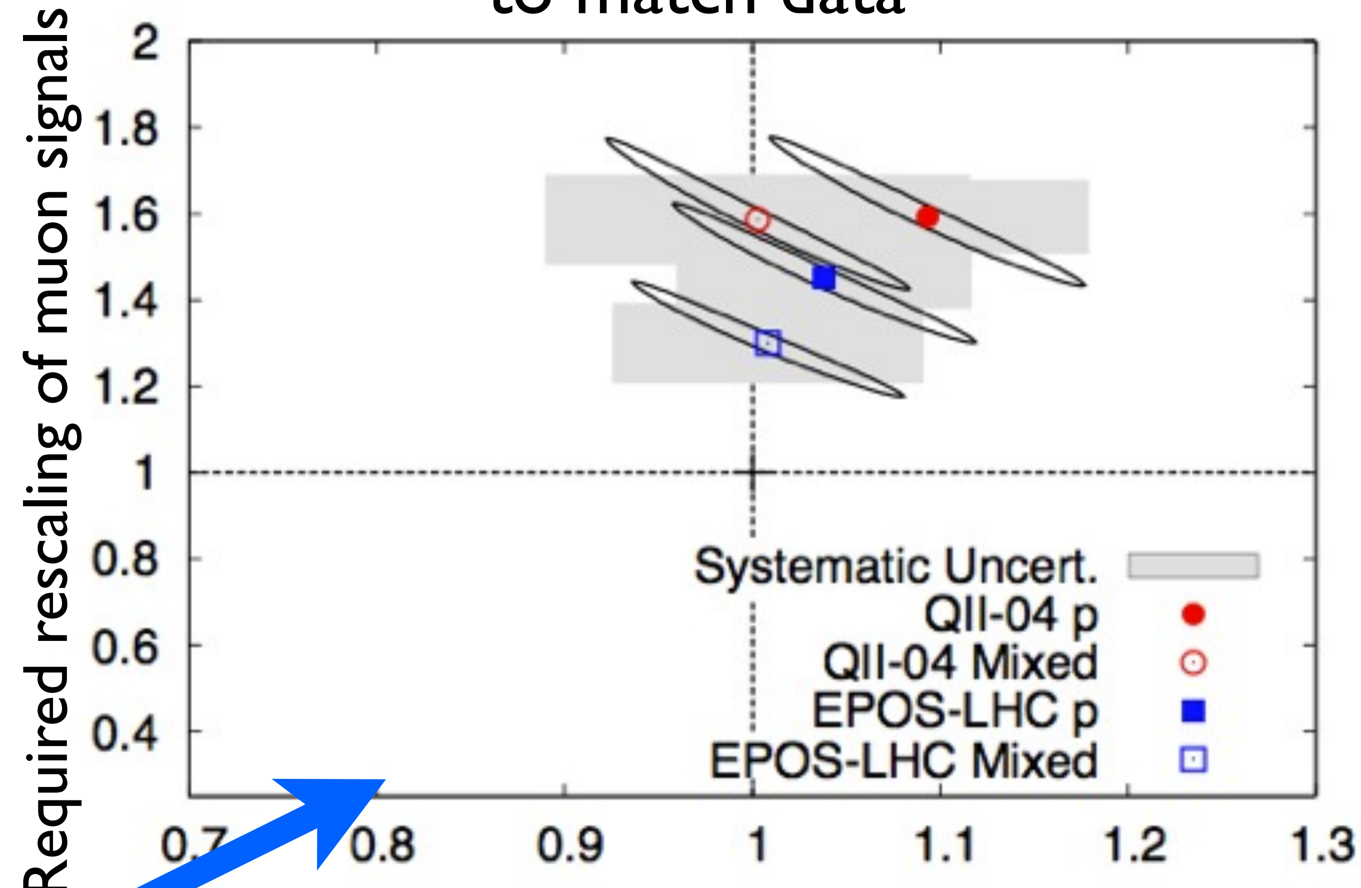
Match data with p and Fe simulation



Same event with predicted ground signal

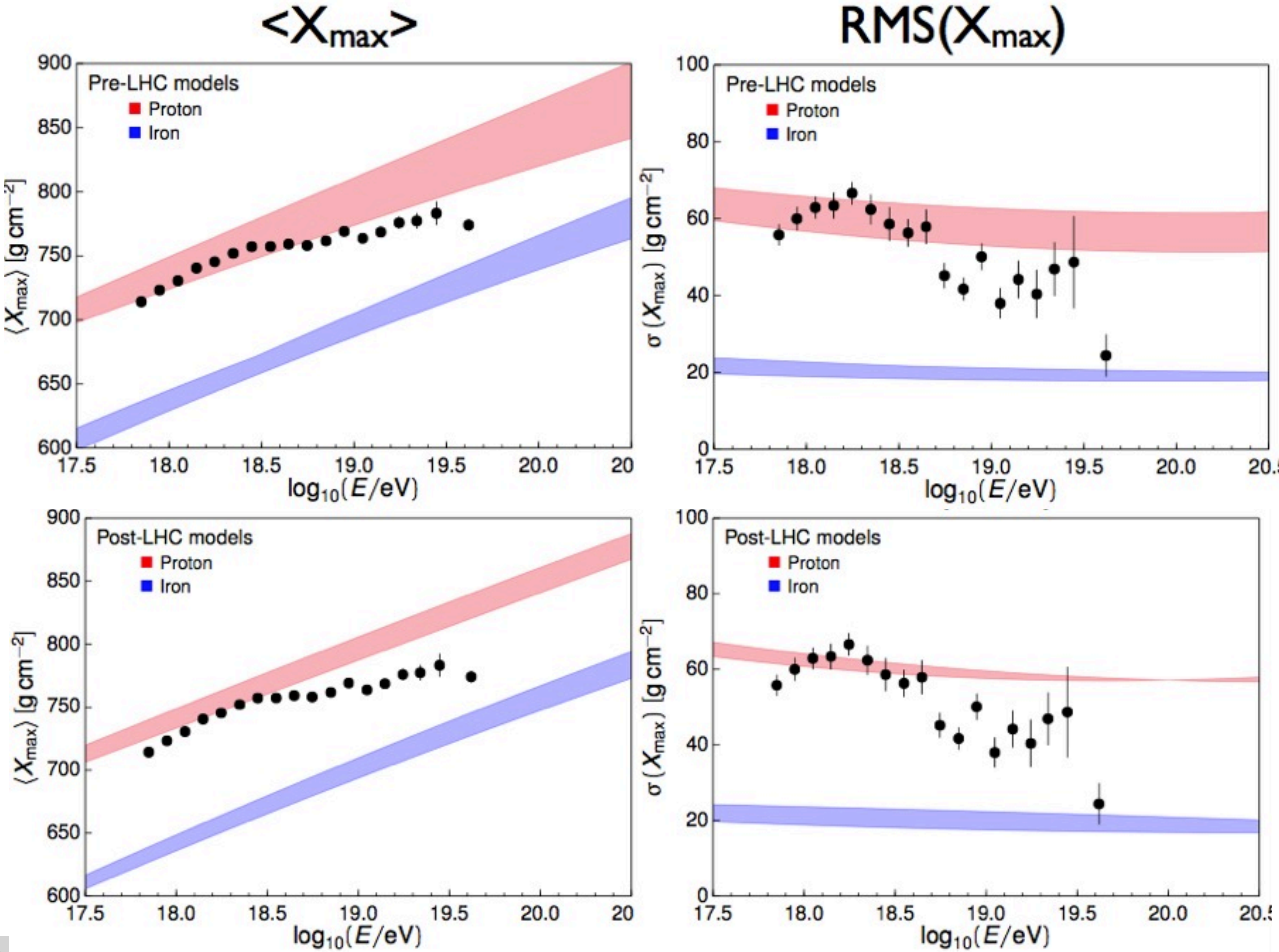


Rescale energy and muon signals to match data

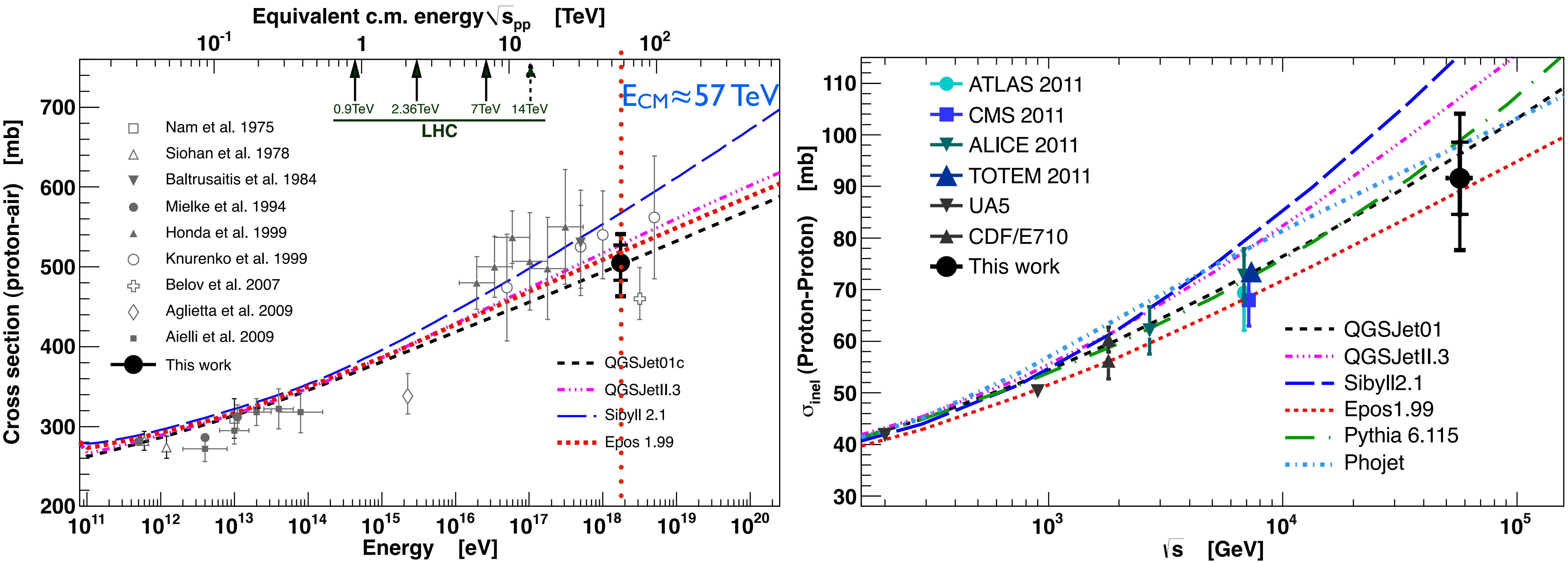


- hadronic interaction models need more muons
  - underestimate muon signals by 30-60%
- independent tests yield same results
- or are muon counts contaminated by electromagnetic signals? ➔ better muon-EM discrimination

• Hadronic interaction models - LHC is useful



Proton-air production cross section



(Auger collab. PRL 2012)

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

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

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