X_{max} from Auger and its interpretation

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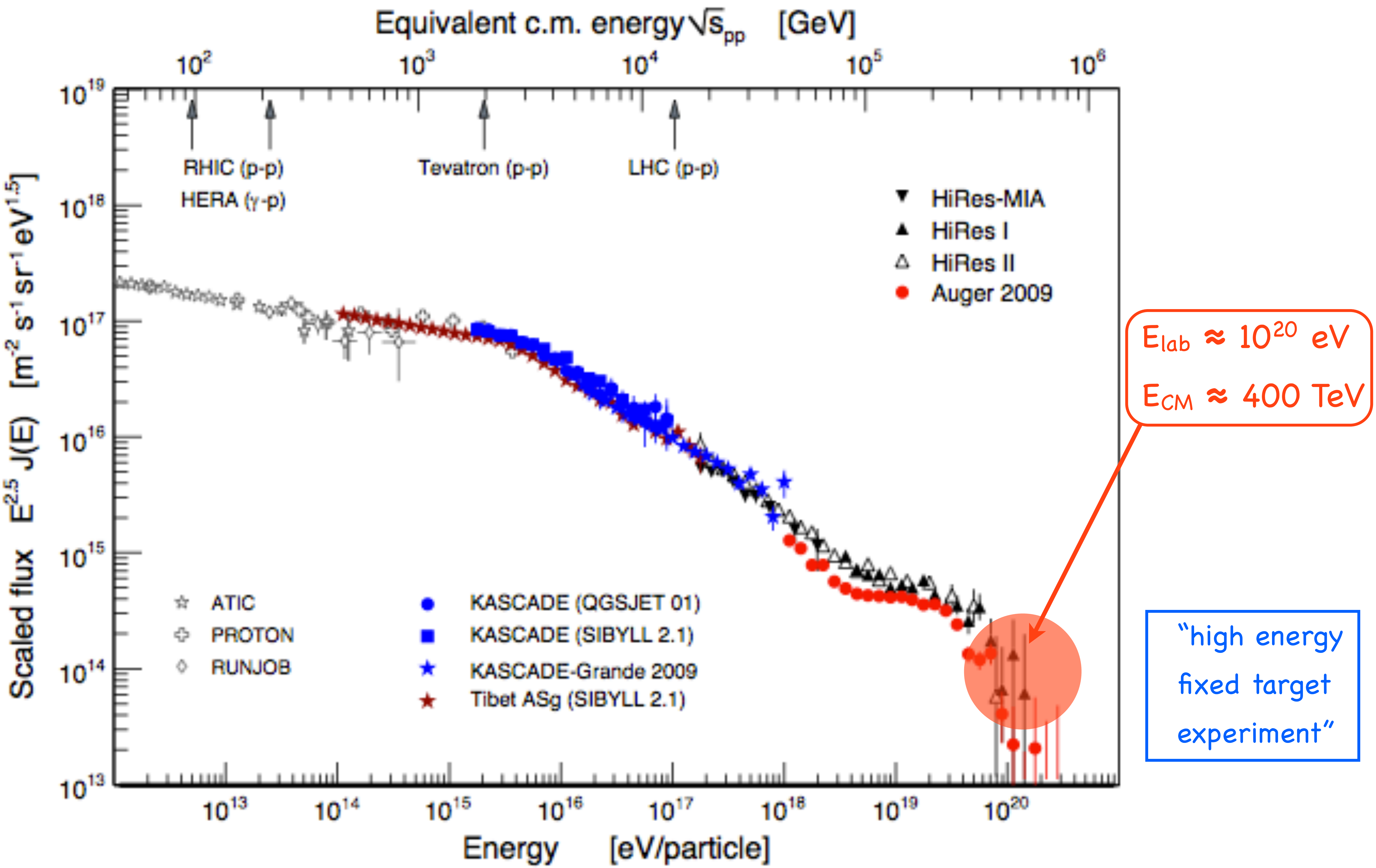
Joint Experimental-Theoretical Physics Seminar July 2nd 2010

Ultra high energy cosmic rays



"high energy fixed target experiment"

- ✦ **What** are they?

- ✦ **Where** are they coming from?

- ✦ **How do they interact?**

$E_{lab} = 10^{20}$ eV

$E_{CM} = 400$ TeV

With present accelerator technology:

LHC: 27 km circumference, $E_{CM} = 14$ TeV

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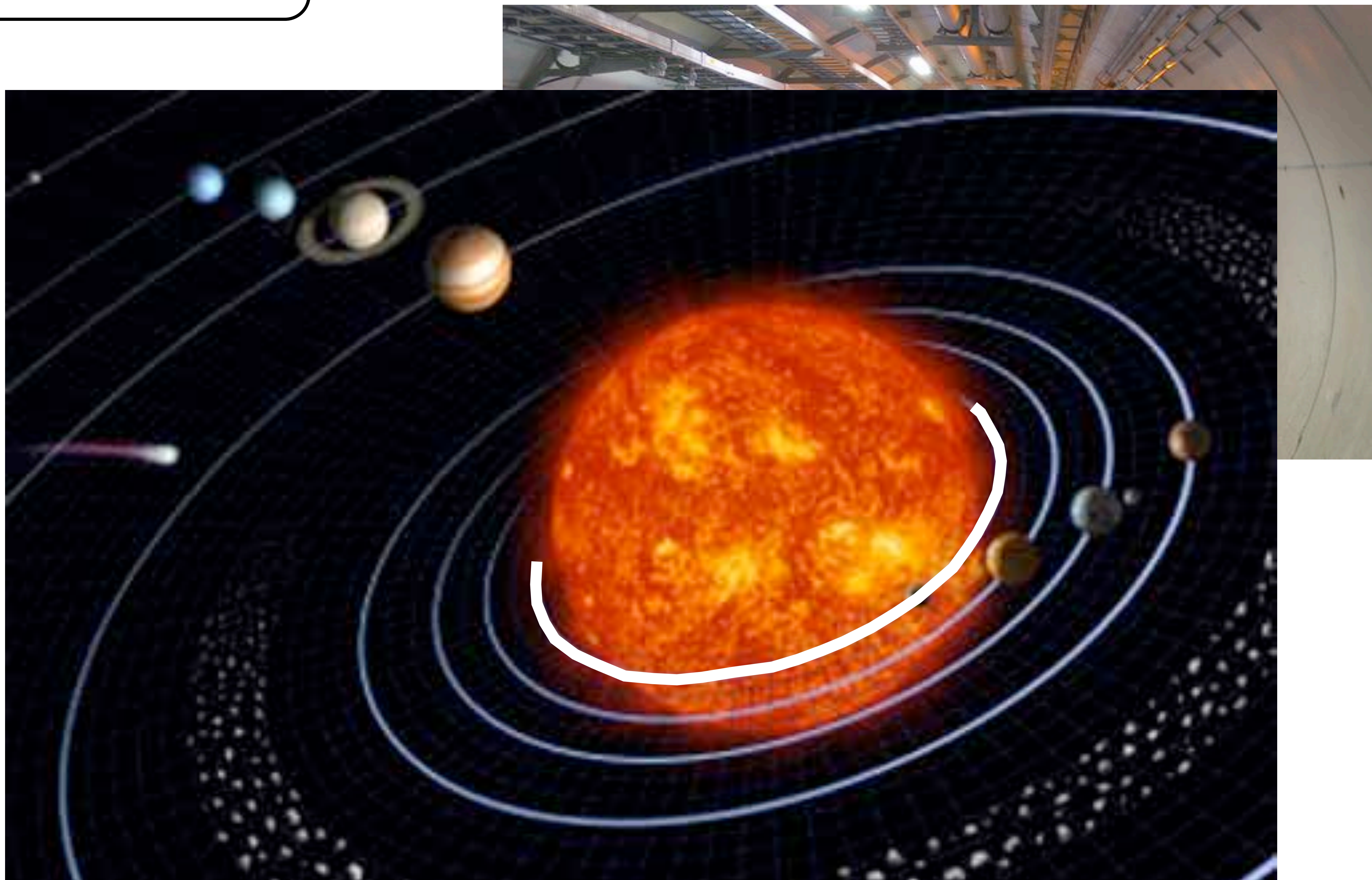


orbit of Mercury (3.6×10^8 km), LHC acceleration time of 815 years

UHECR candidates

1. Top-down

massive/high energy object decays/interacts -> lesser energy particles

monopoles; topological defects; superheavy relics ; UHECRONS ; z-bursts; etc.

(Schramm & Hill 1983; Hill 1983; Weiler 1982; Bhattacharjee & Sigl 1995; Berezinsky et al. 1997; Kolb et al. 1998; Chung et al. 1998; Albuquerque et al 1999 etc.)

disfavoured by photon & neutrino limits

2. Bottom-up

"ordinary" energy particle gets accelerated up to higher energies

AGN hot spot, jets, central BH; cluster shocks; colliding galaxies; gamma ray bursts; neutron stars; etc.

(Hillas 1984; Thorne et al. 1986; Biermann & Strittmatter 1987; Vietri 1995; Waxman 1995; Kang et al 1996; Olinto et al. 1999 etc.)

Astrophysical sources : diffuse shock acceleration? Hillas 1984

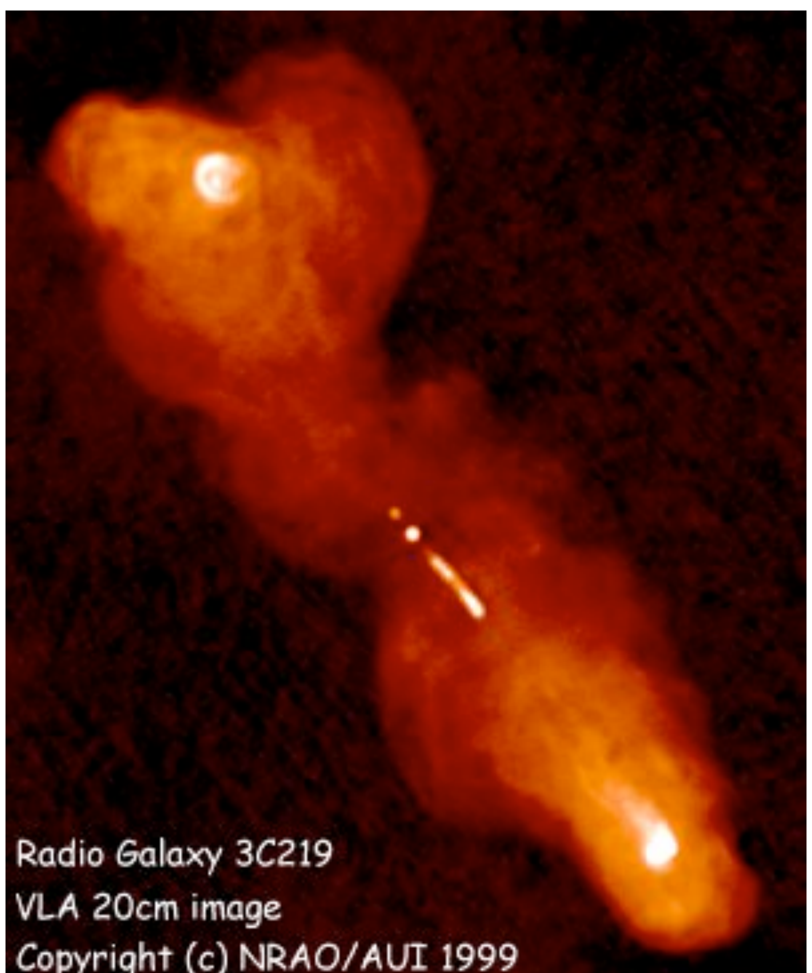
$$E_{\max} \approx Z\, v \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu G}\right) \times 10^{18}\mathrm{eV}$$

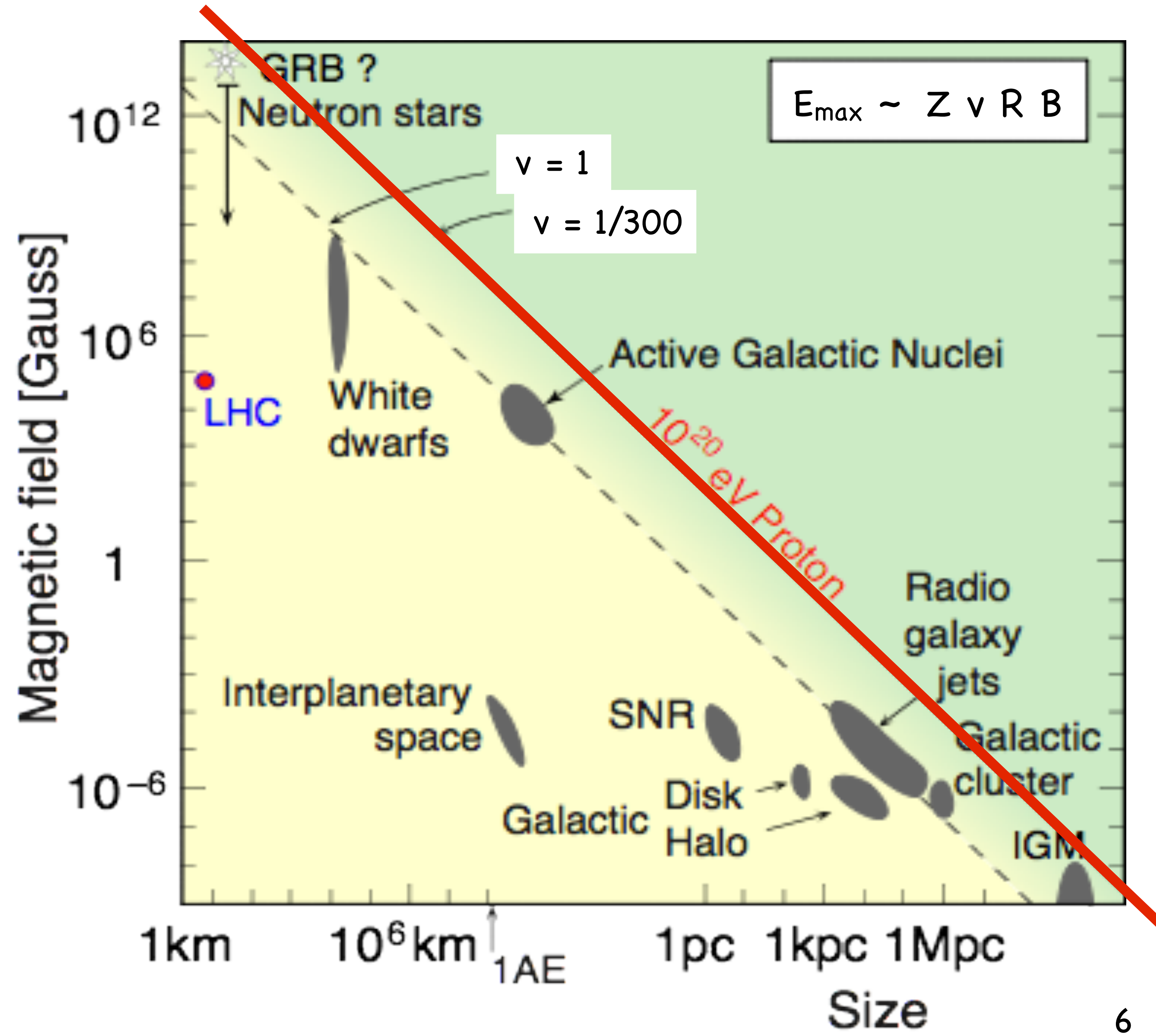
charge

shock velocity

acceleration region

magnetic field





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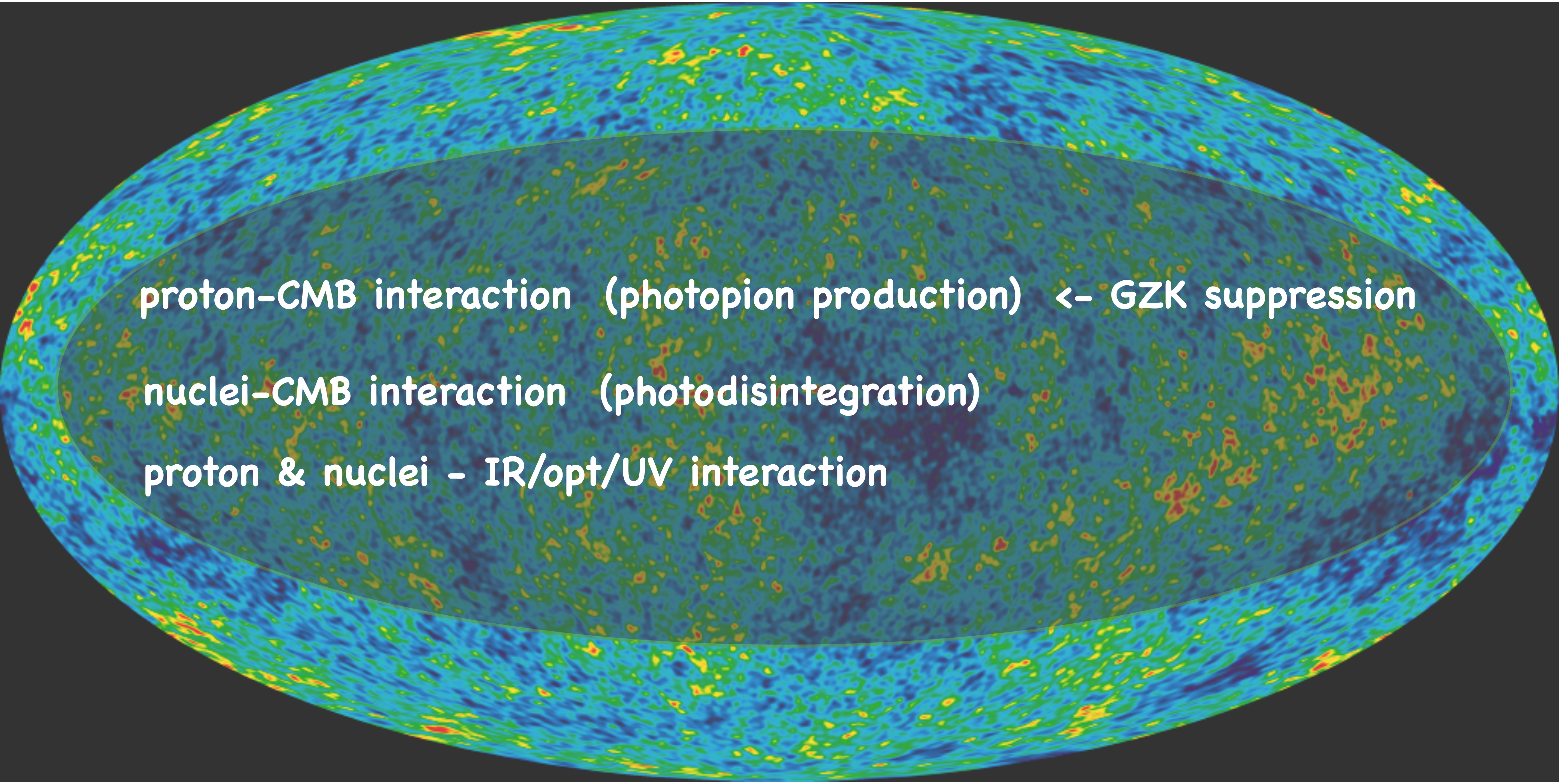
difficult to accelerate / far away

max energy ~ 10^{20} eV

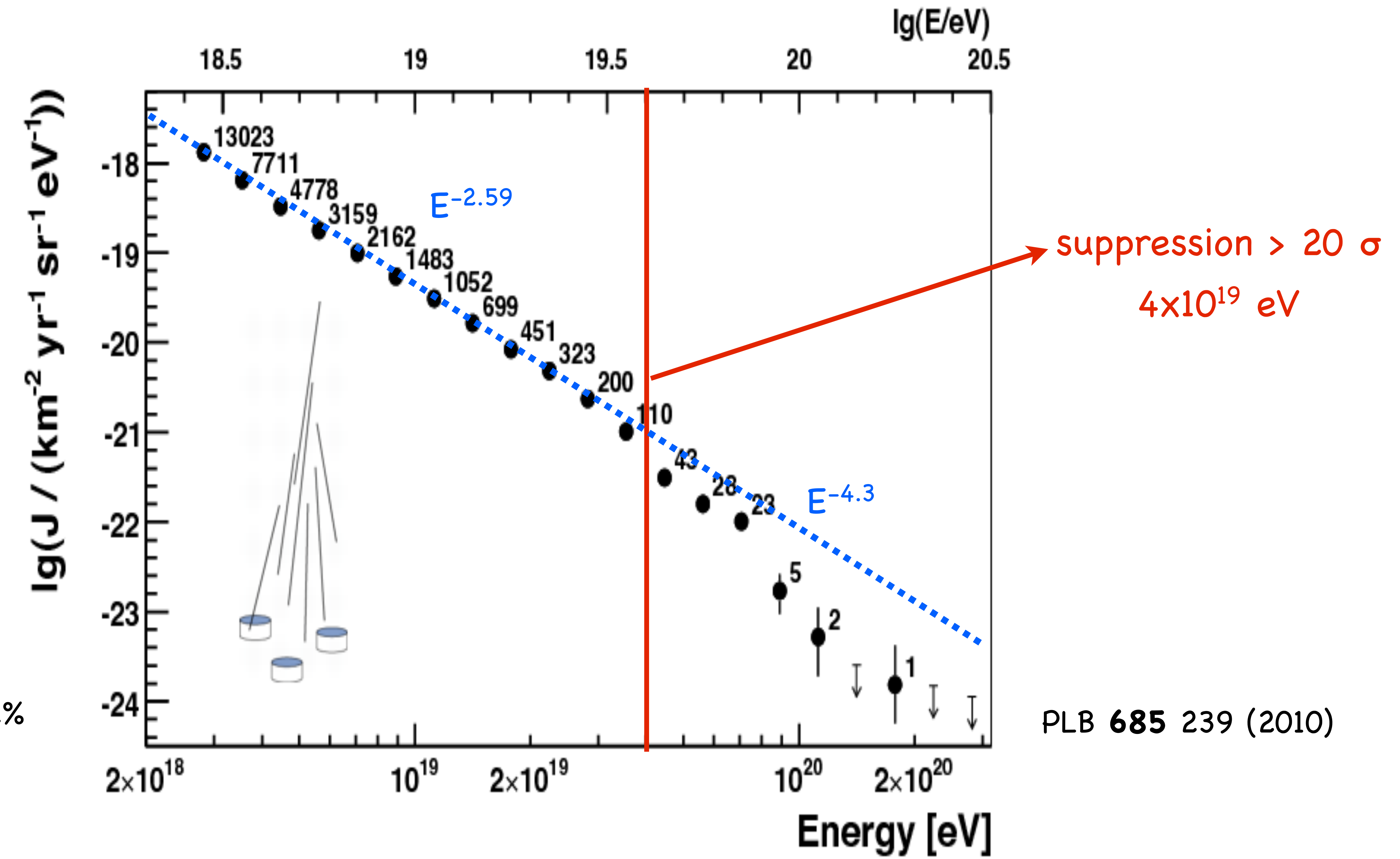
UHECRs $\gtrsim 5\times10^{19}$ eV need to come from nearby



-> flux suppression

UHECR spectrum

Auger observes a suppression



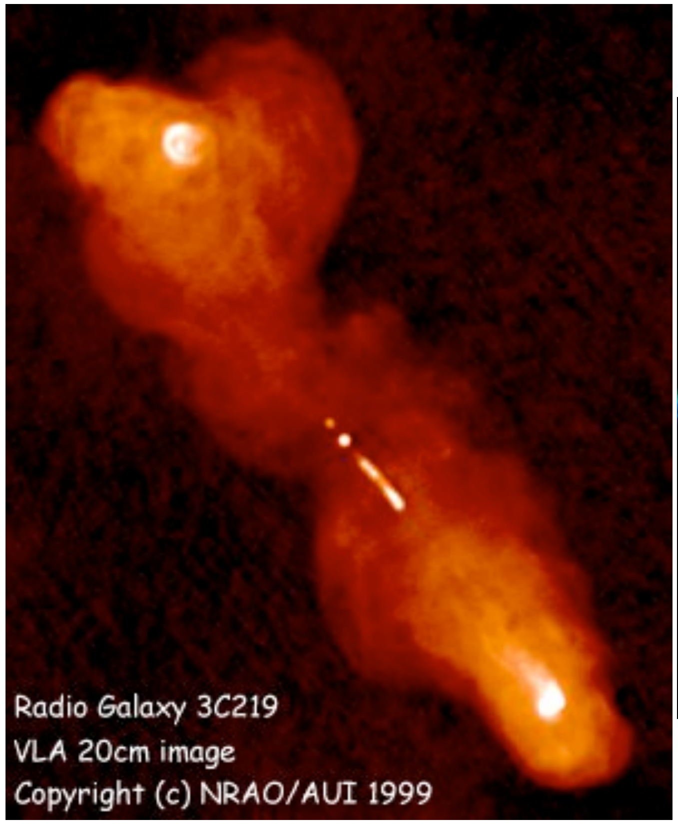
syst. energy uncertainty 22%

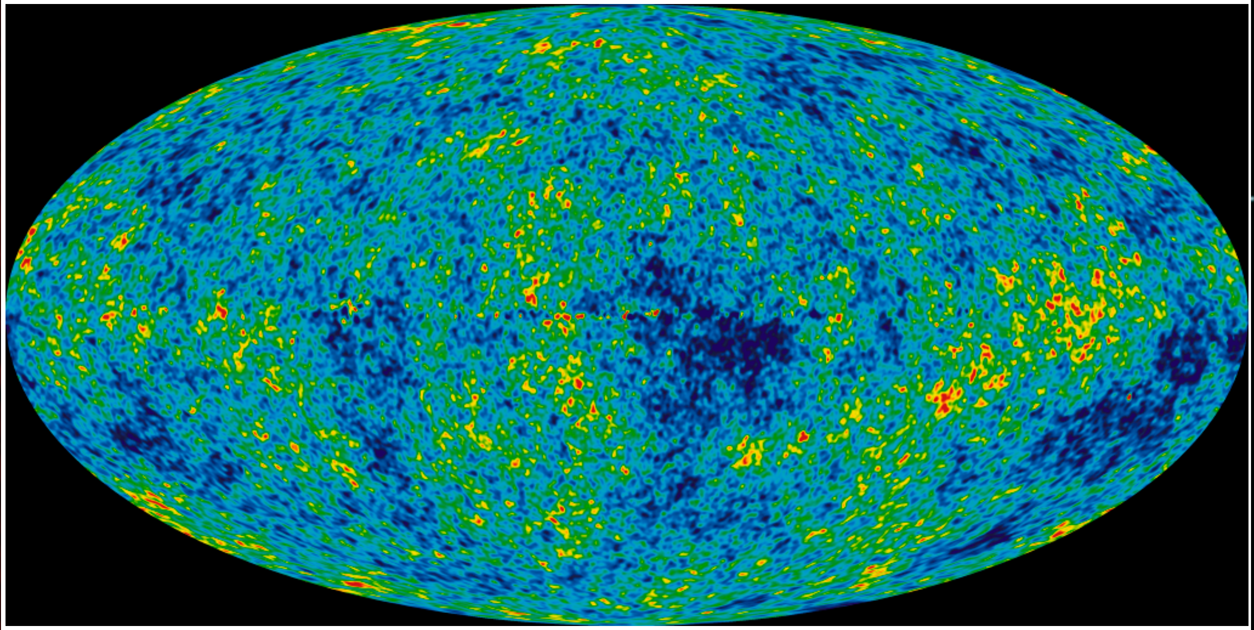
PLB **685** 239 (2010)

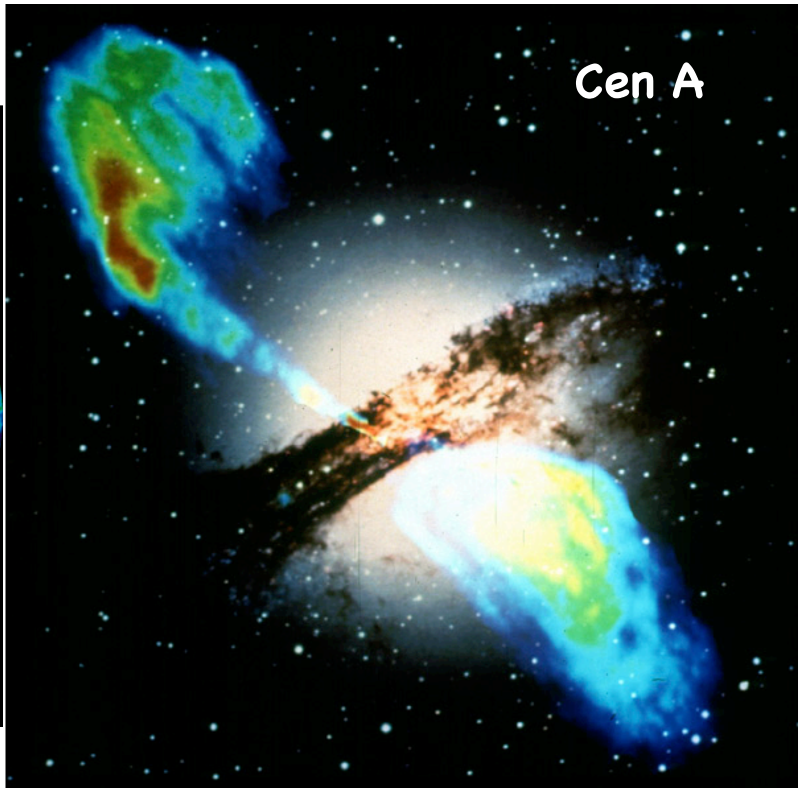
- updated spectrum for the surface detector
- data taken: Jan 2004 - Dec 2008,   12 790 km^2 sr yr

- Flux suppression observed at highest energy (> 4×10^{19} eV)

- Highest energy cosmic rays (> 5.5×10^{19} eV) have correlation with nearby AGNs







- protons can escape accelerator without much energy loss

- protons are abundant and stable

- heavier nuclei disintegrate in the source (& during propagation)

Physics Today May 2010

The highest-energy cosmic rays may be iron nuclei

Or perhaps, at energies far beyond what terrestrial accelerators can produce, protons just look fat.

Previously most observations and arguments seemed to support proton dominance at the highest energies.

So a straightforward reading of the new Auger shower data would be that the most energetic nuclei arriving from AGNs are mostly Fe nuclei.

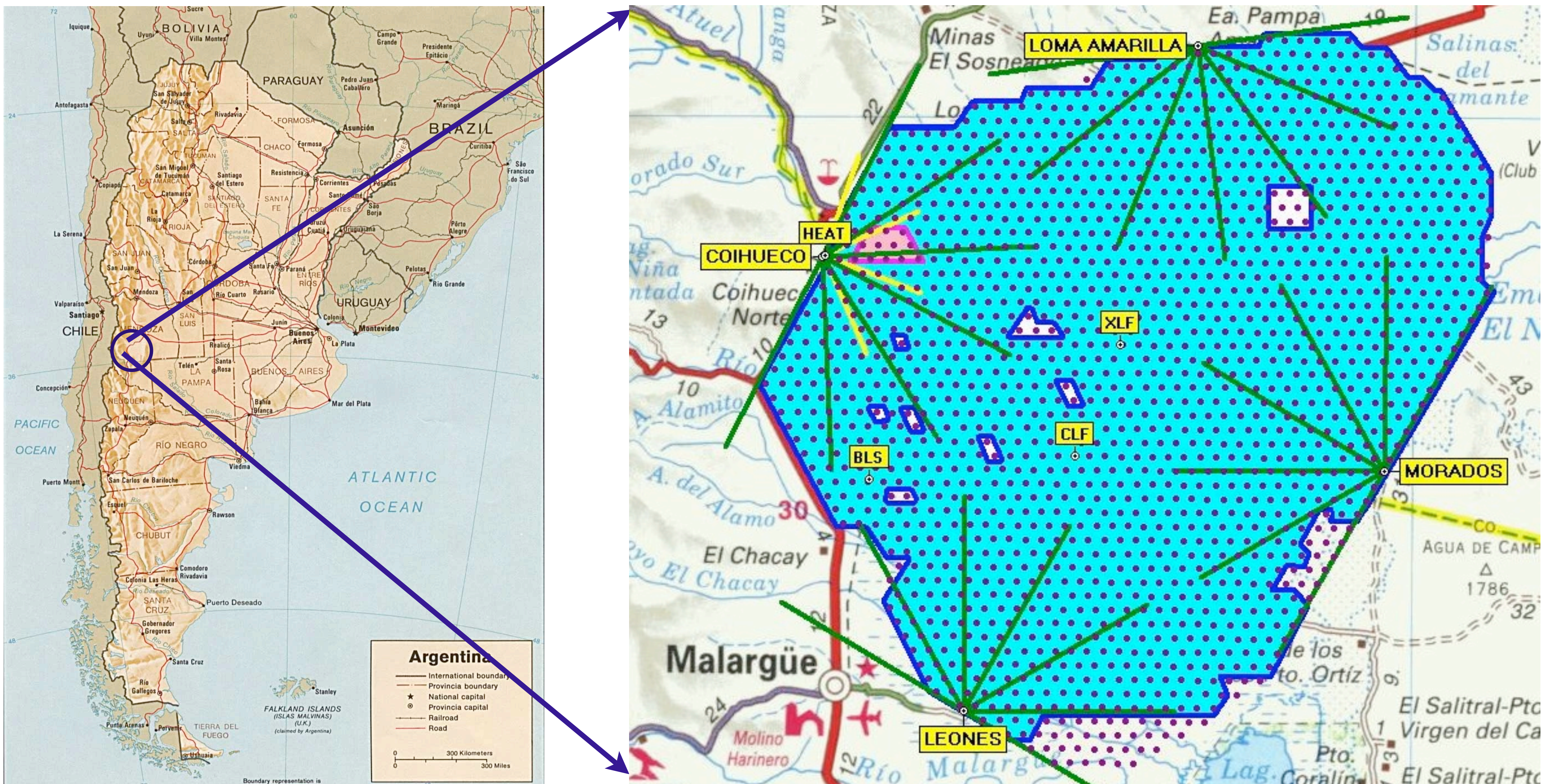
There's considerable wiggle room in extrapolating the standard model of hadronic interactions to that terra incognita.

Protons or iron nuclei? Other elements? Exotic particles? New physics?

The Pierre Auger Observatory

http://www.auger.org

- South: Malargüe, Mendoza, Argentina $\sim$ 3000 km^2, completed
  - Hybrid: 4 air fluorescence telescopes & 1600 water Cherenkov detectors
- North: planned in SE Colorado, USA $\sim$ 20 000 km^2



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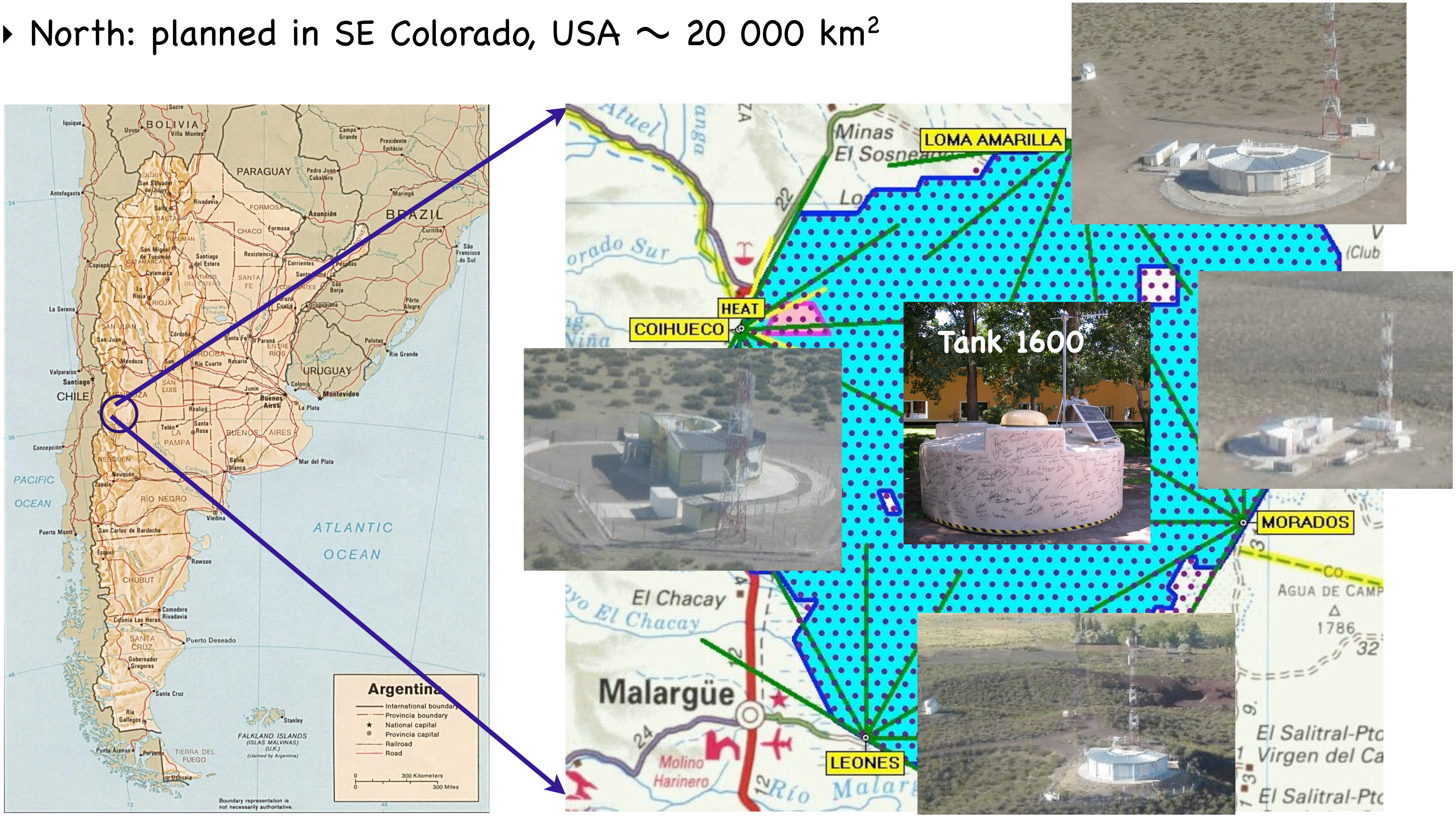
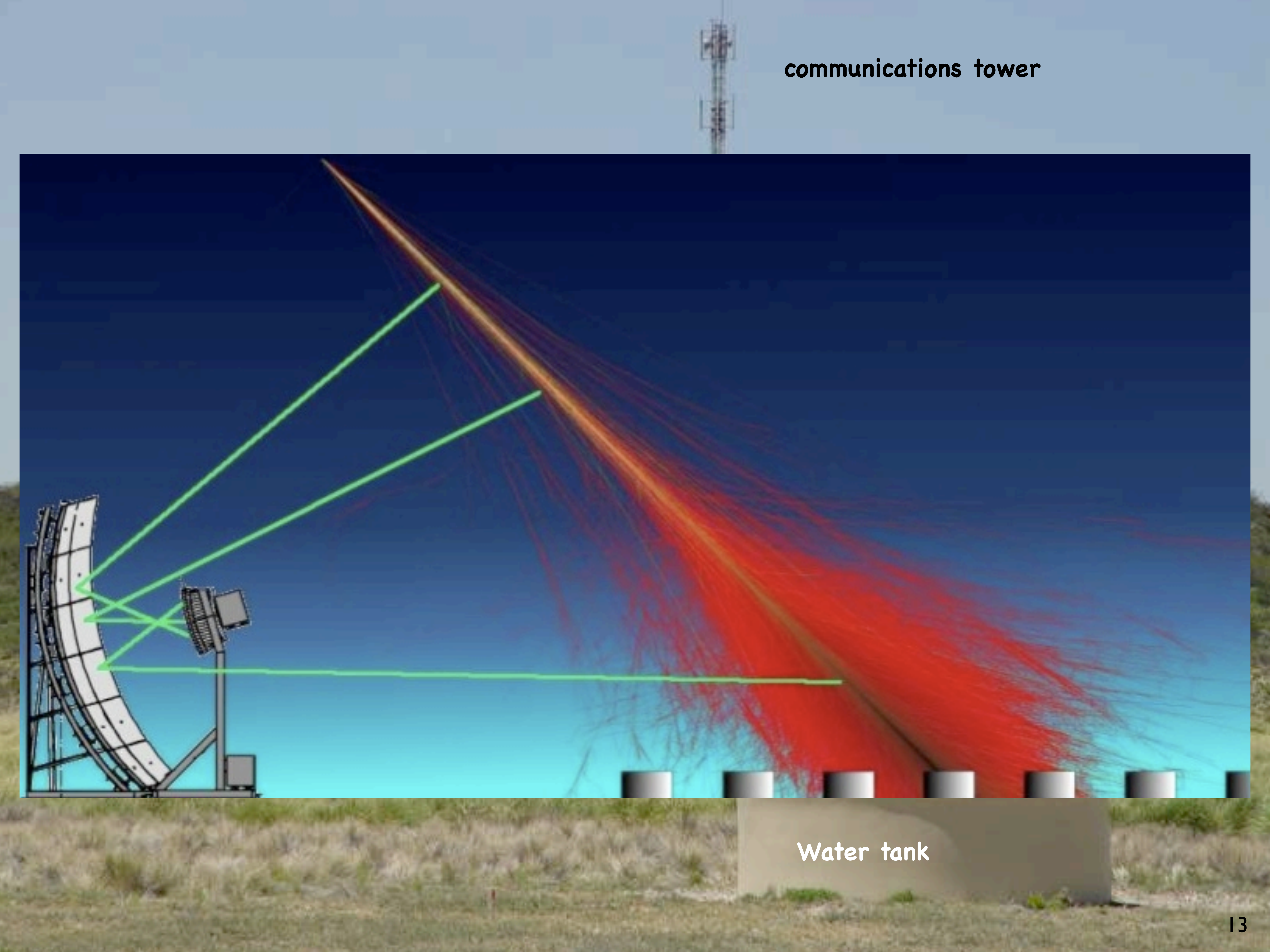
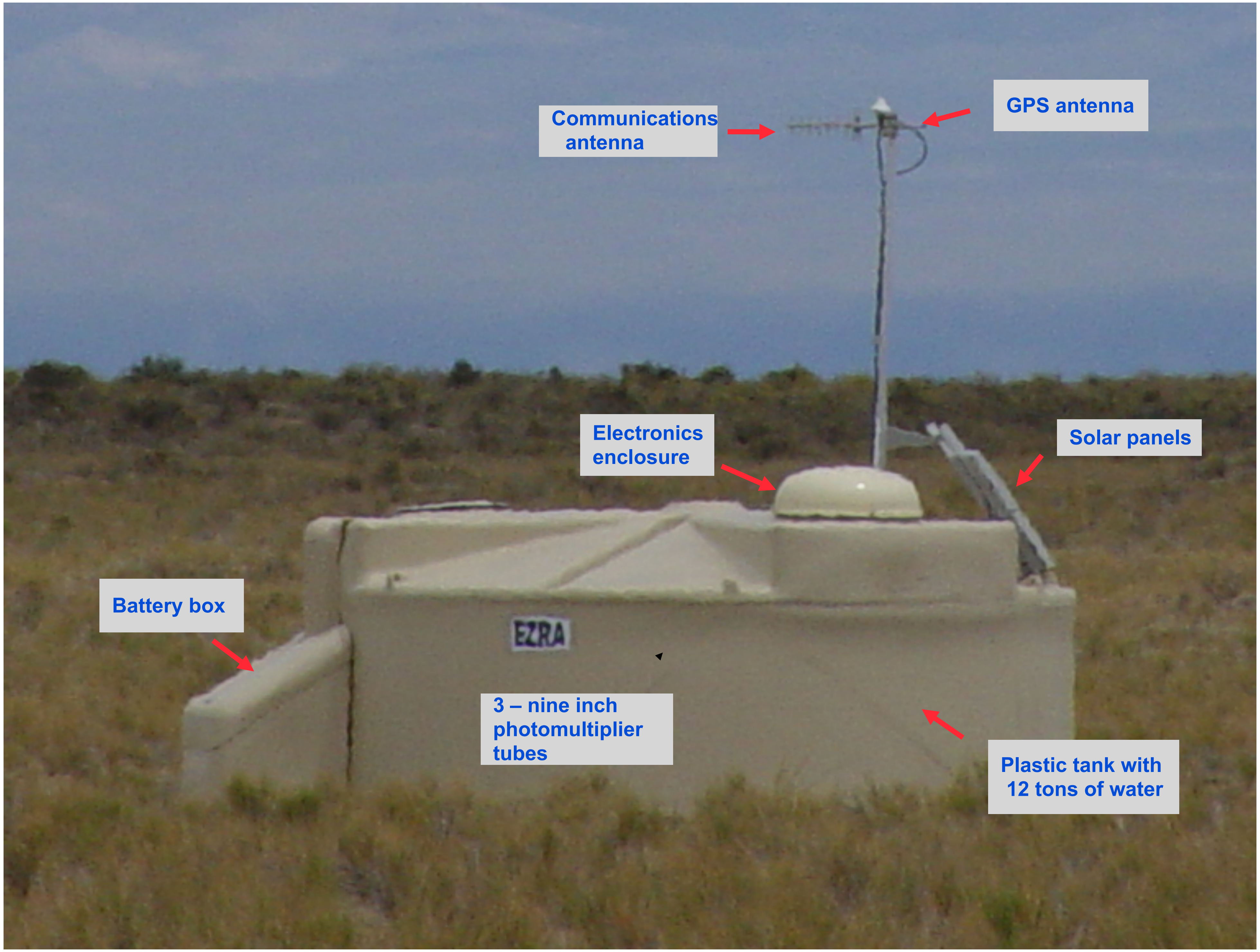



communications tower
Fluorescence telescope
Water tank


communications tower
Water tank

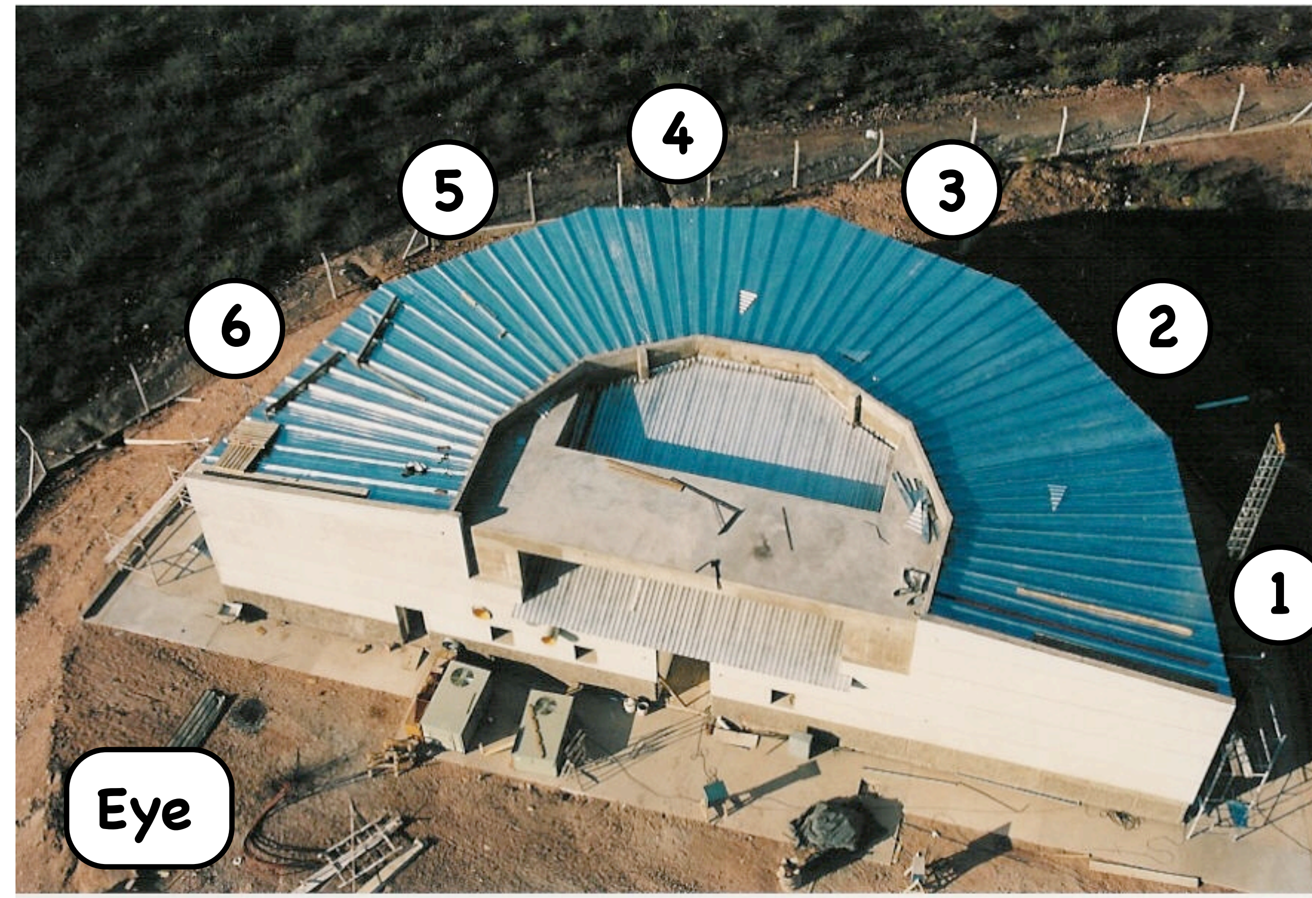
Surface detector



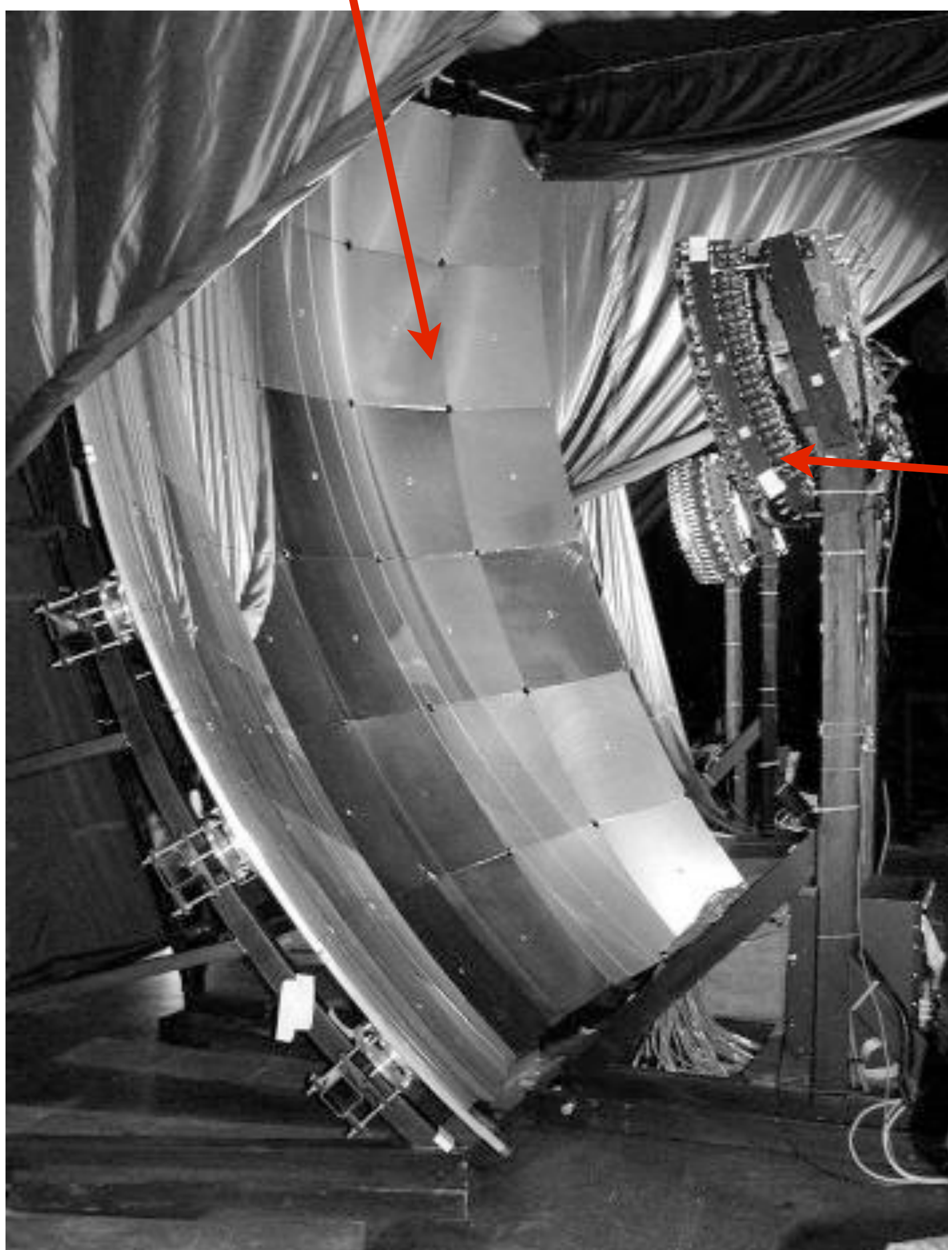
1.5 km triangular spacing

Fluorescence detector:

- 4 "eyes"
- each eye has 6 telescopes $(1.5^{\circ}-30^{\circ})$
- 10% duty cycle: dark nights only

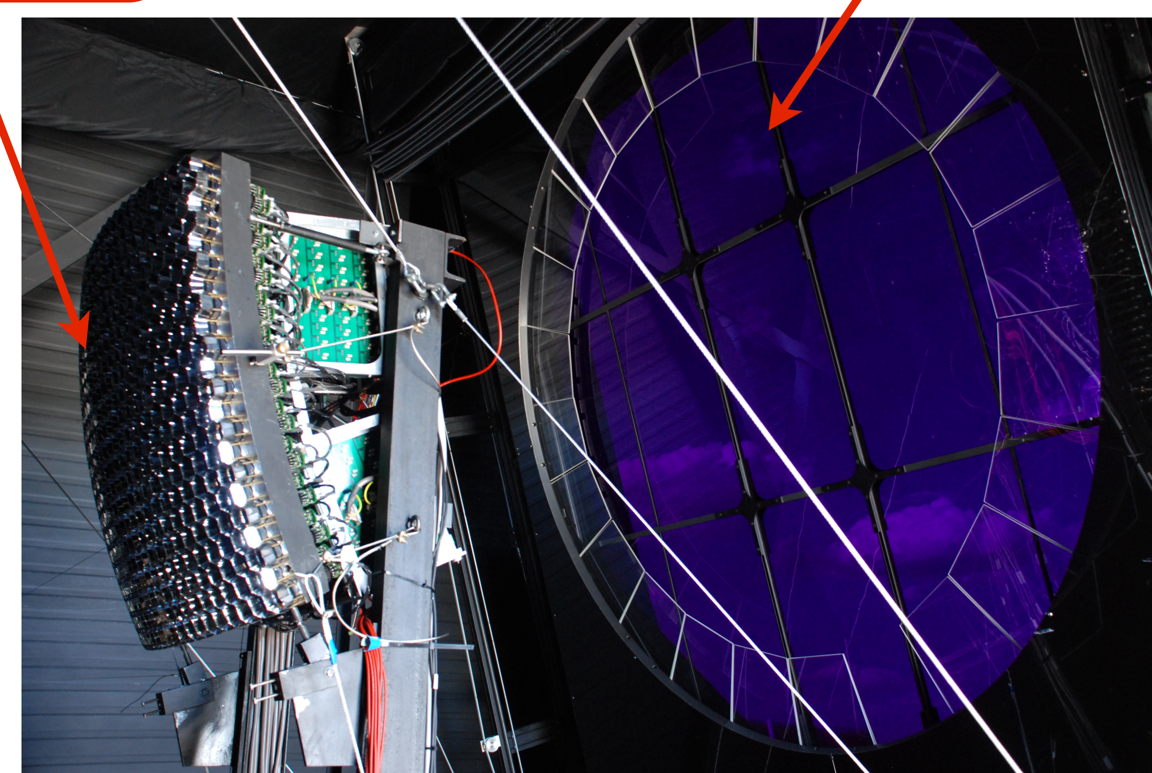


mirror



camera (PMTs)

UV filtre



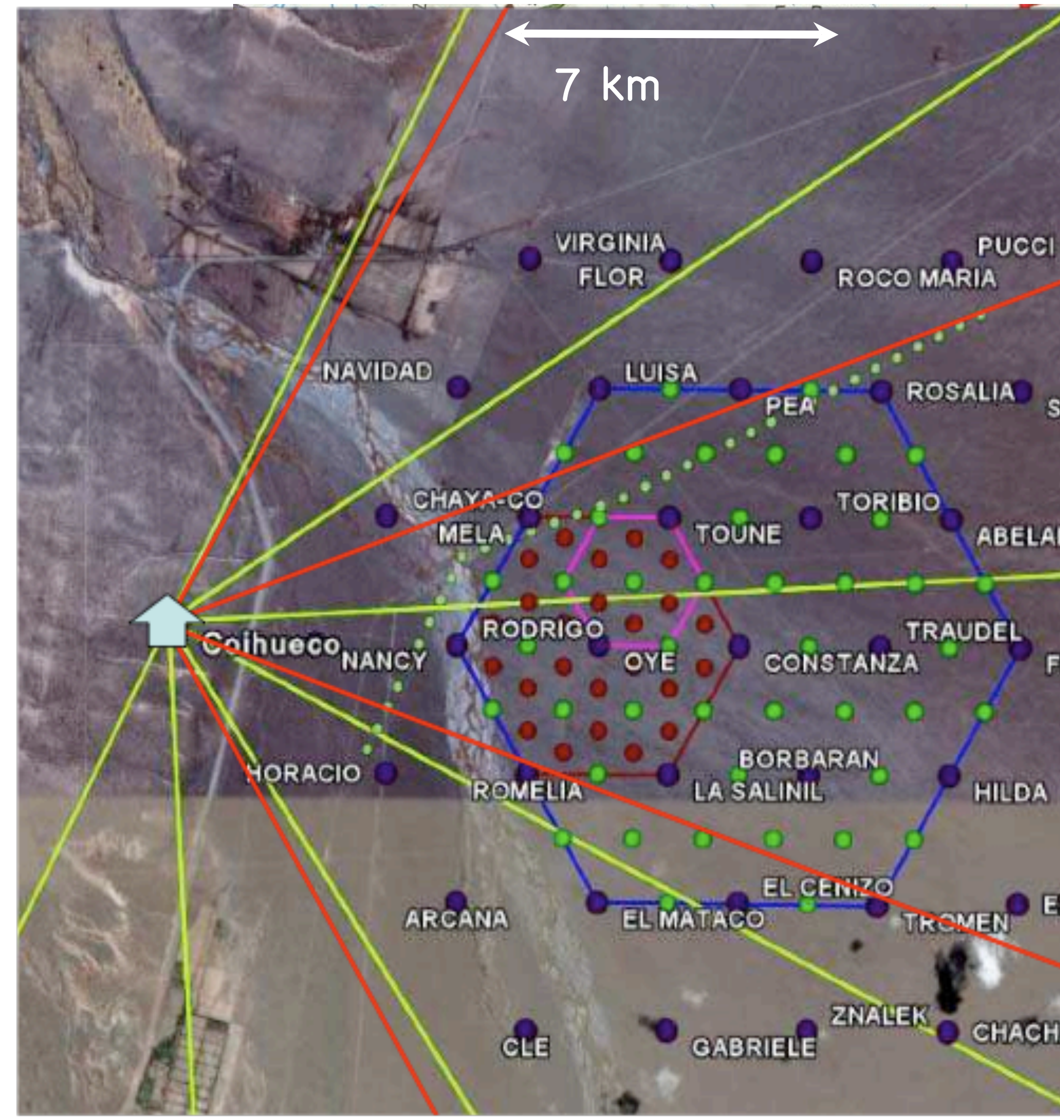
Enhancements

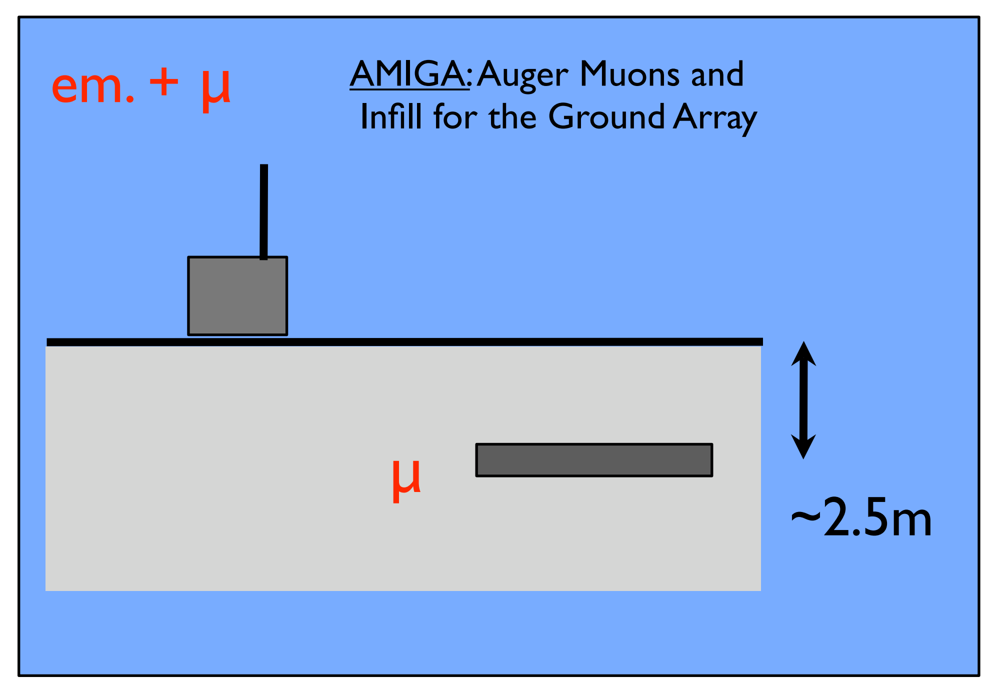
1. High Elevation Auger Telescope (HEAT)
2. Muons and Infill (AMIGA)

Objective:

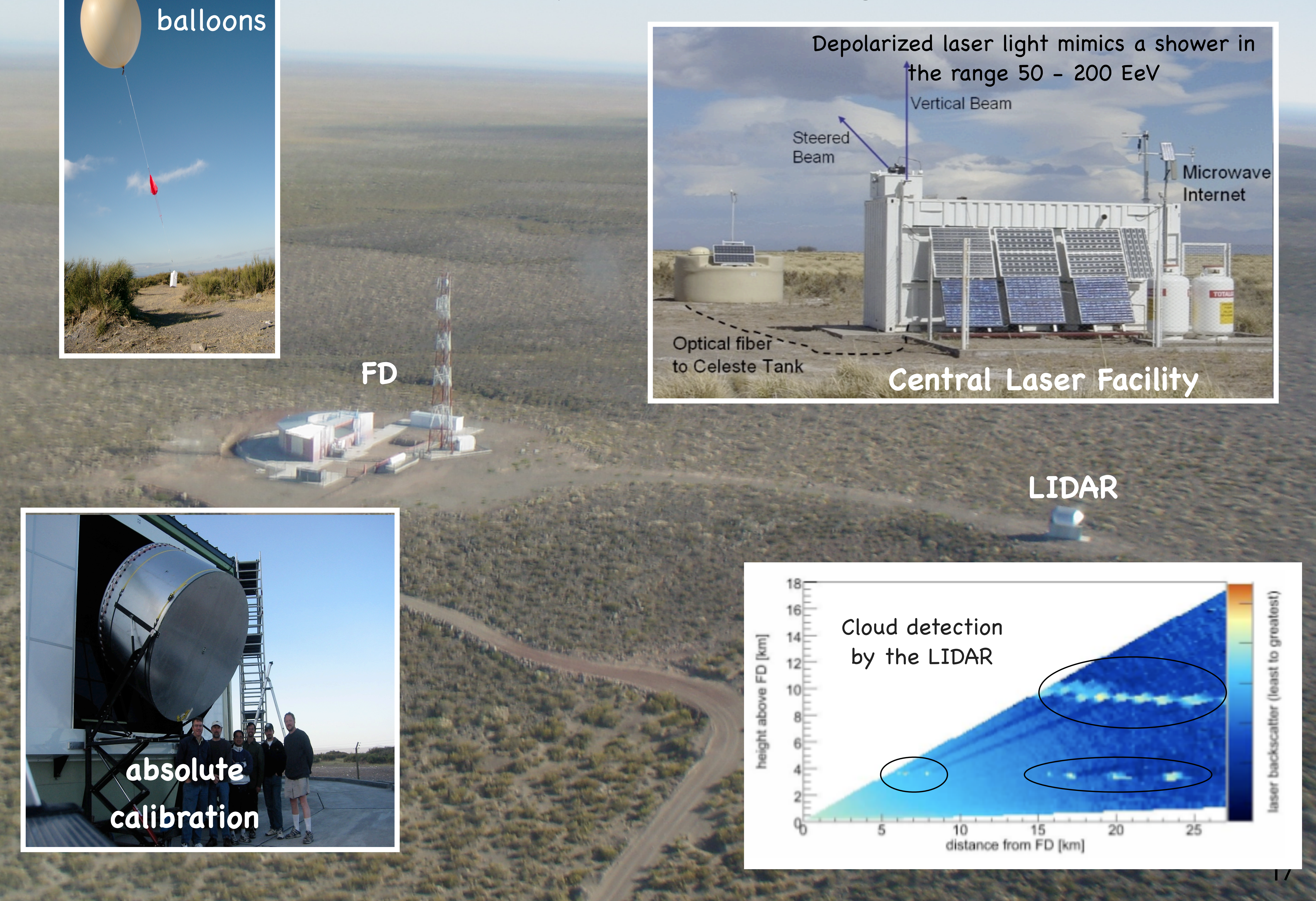
- extend down to lower energy ~ 10^{17} eV
- obtain better composition information

Infill + HEAT -> low energy hybrid trigger

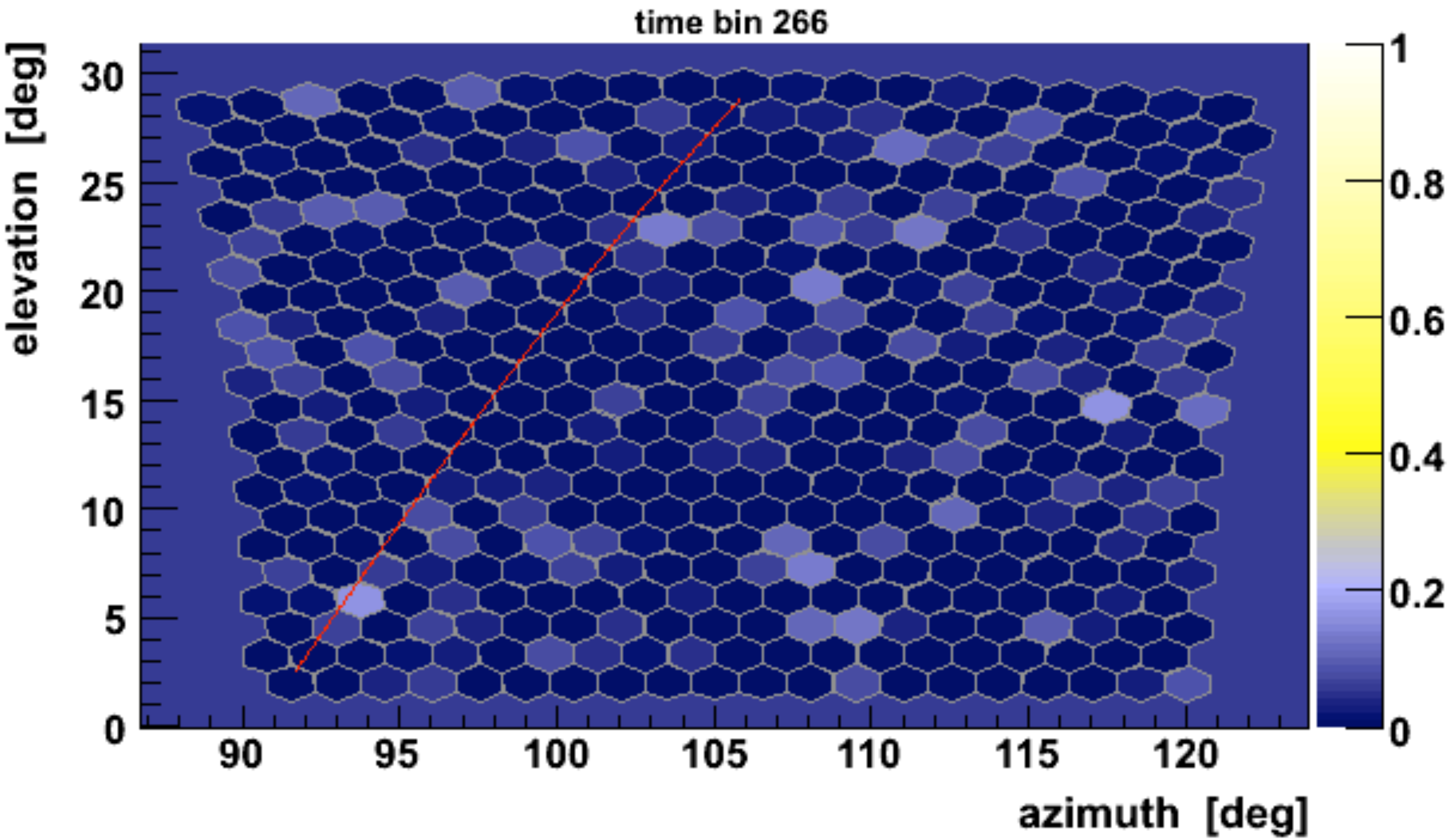




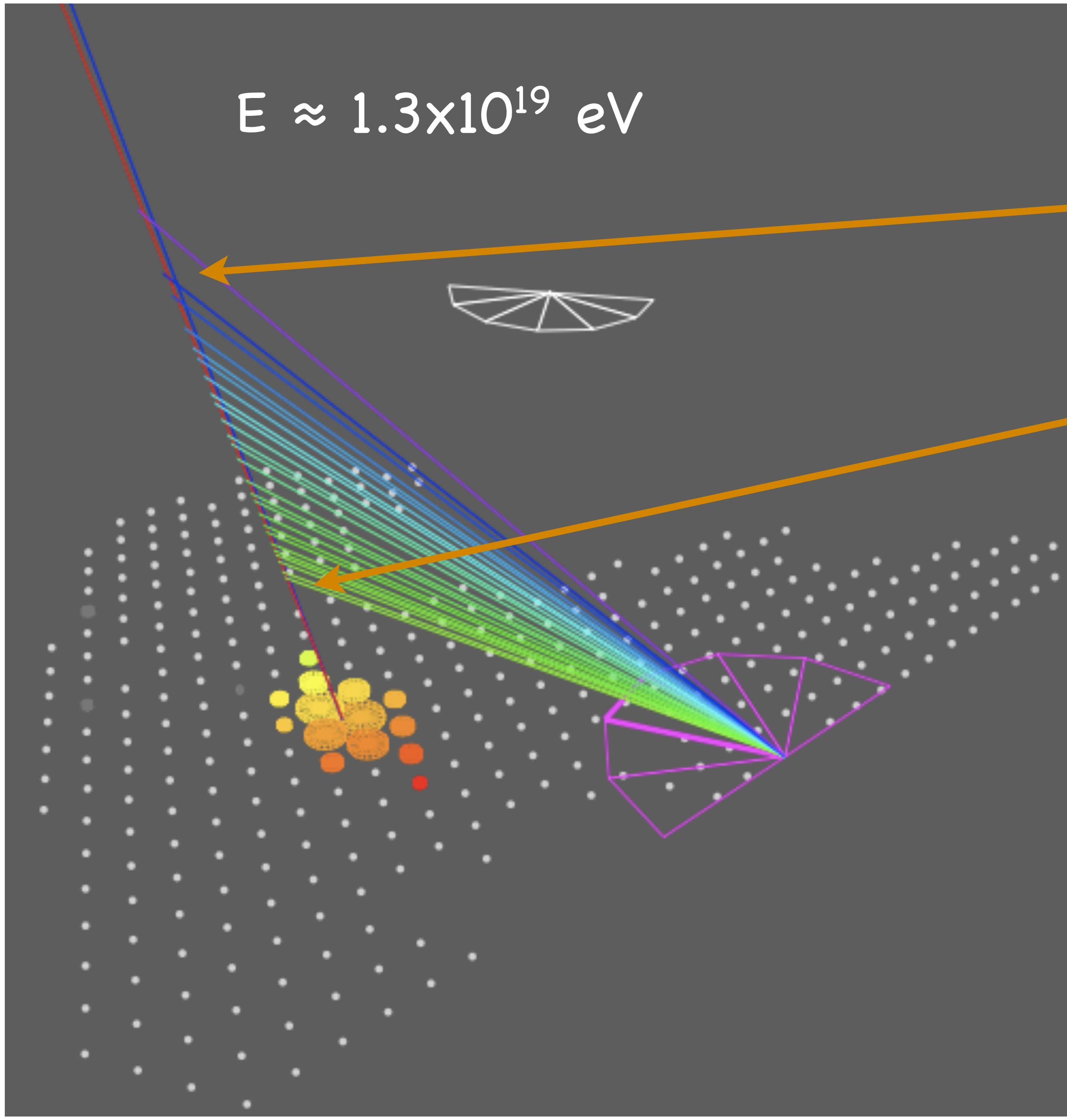
Atmospheric monitoring

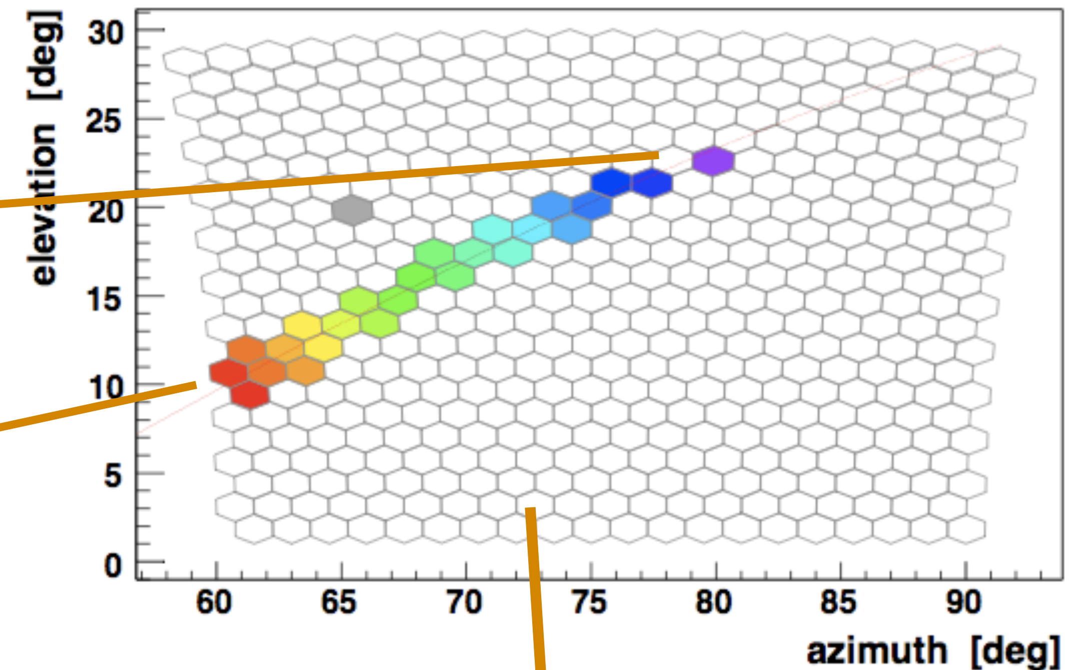


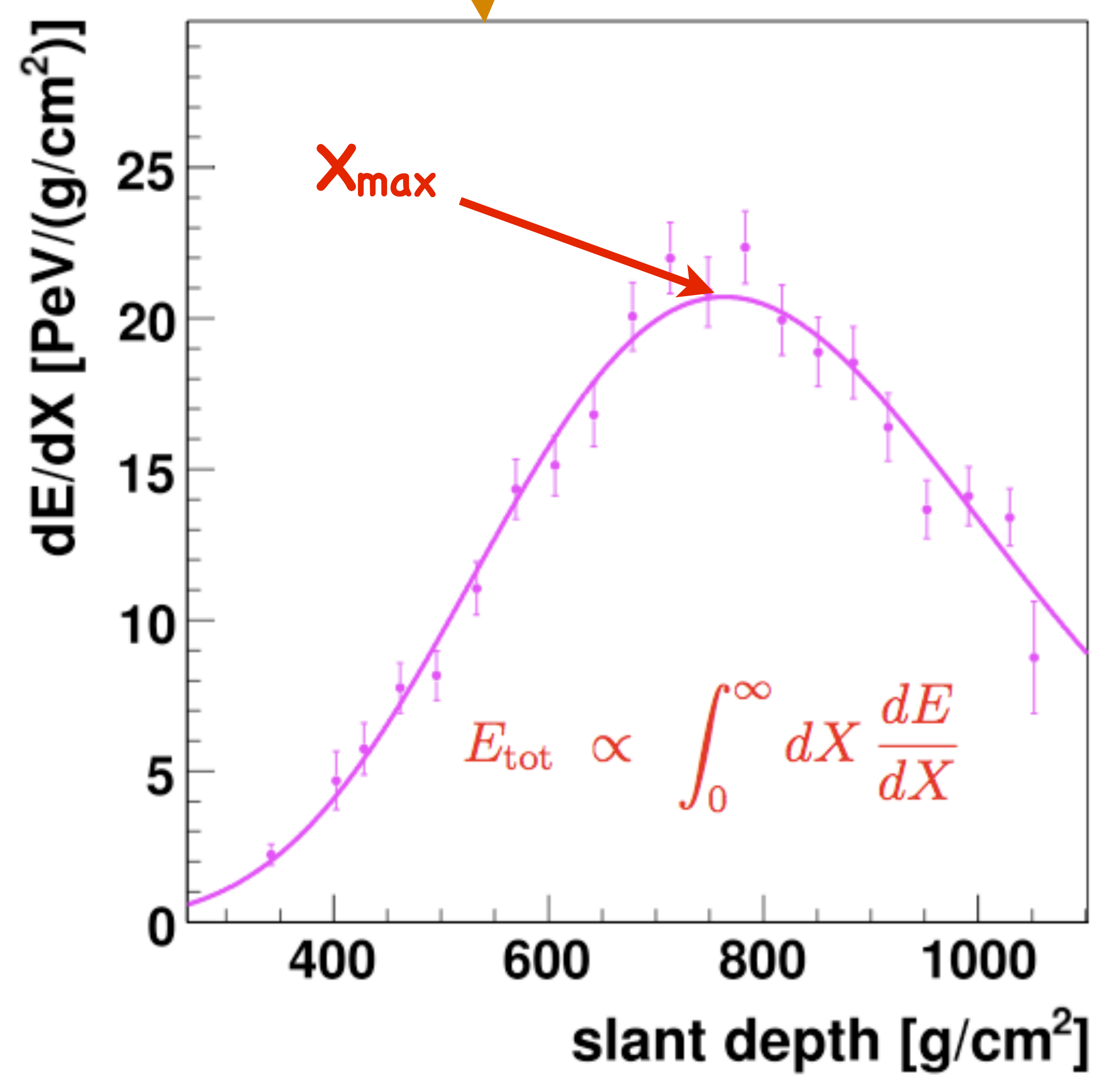
Observation with the fluorescence detector



Data from the fluorescence detector







- Energy : integrate shower profile
- X_{max} : maximal point in shower profile

(slant depth: air mass along cosmic ray trajectory)

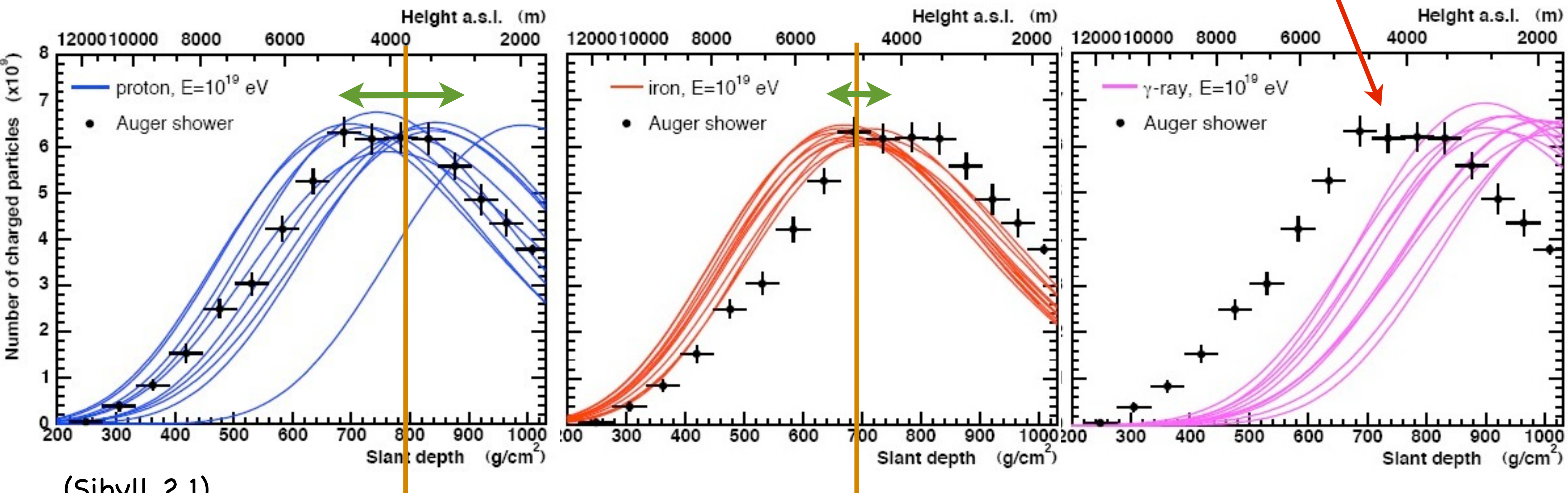
Behaviour of X_{max} tells about the composition:

photon primary severely limited by Auger

- different particles develop different profiles;

mean

fluctuation (RMS)



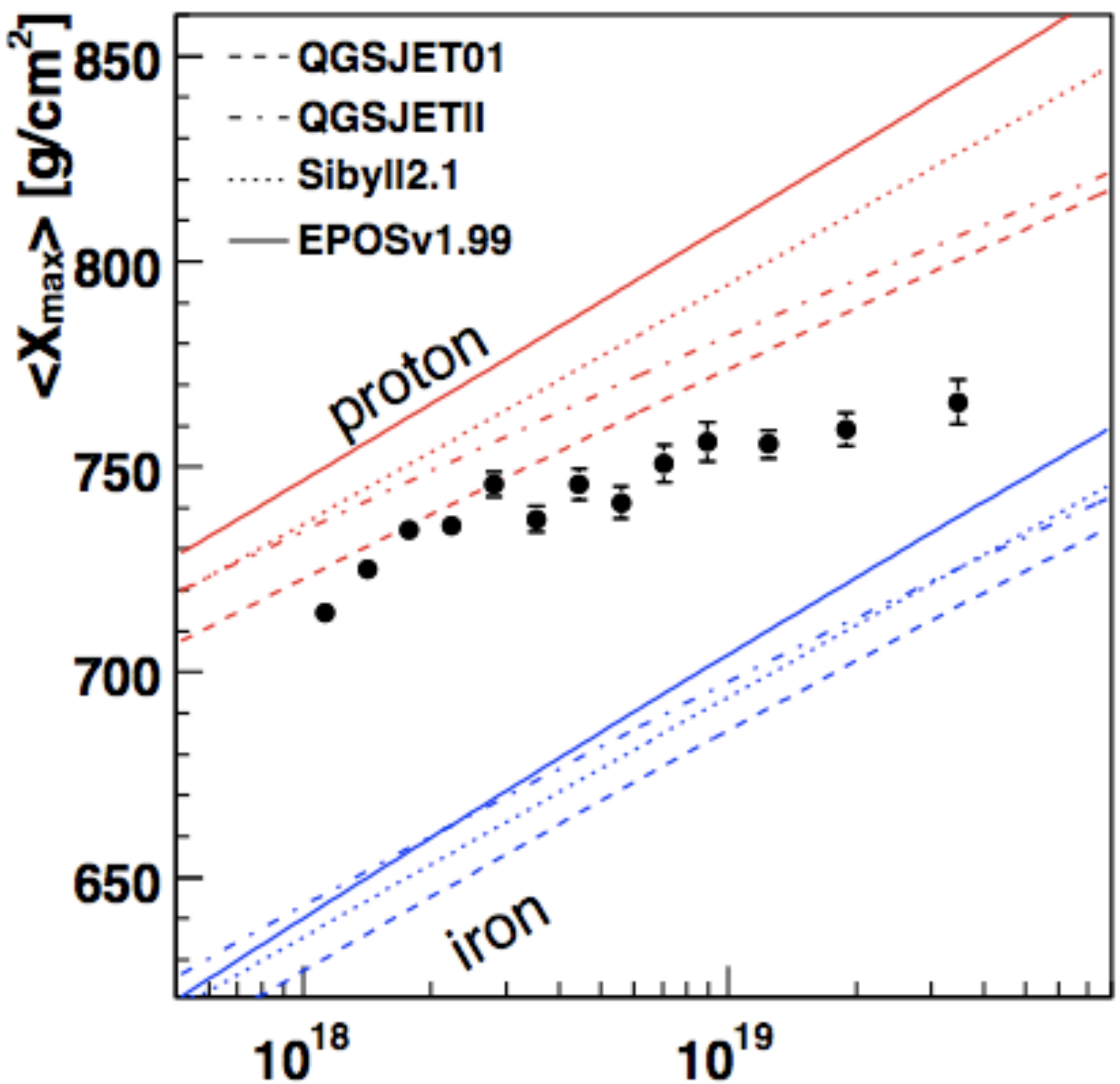
(Sibyll 2.1)

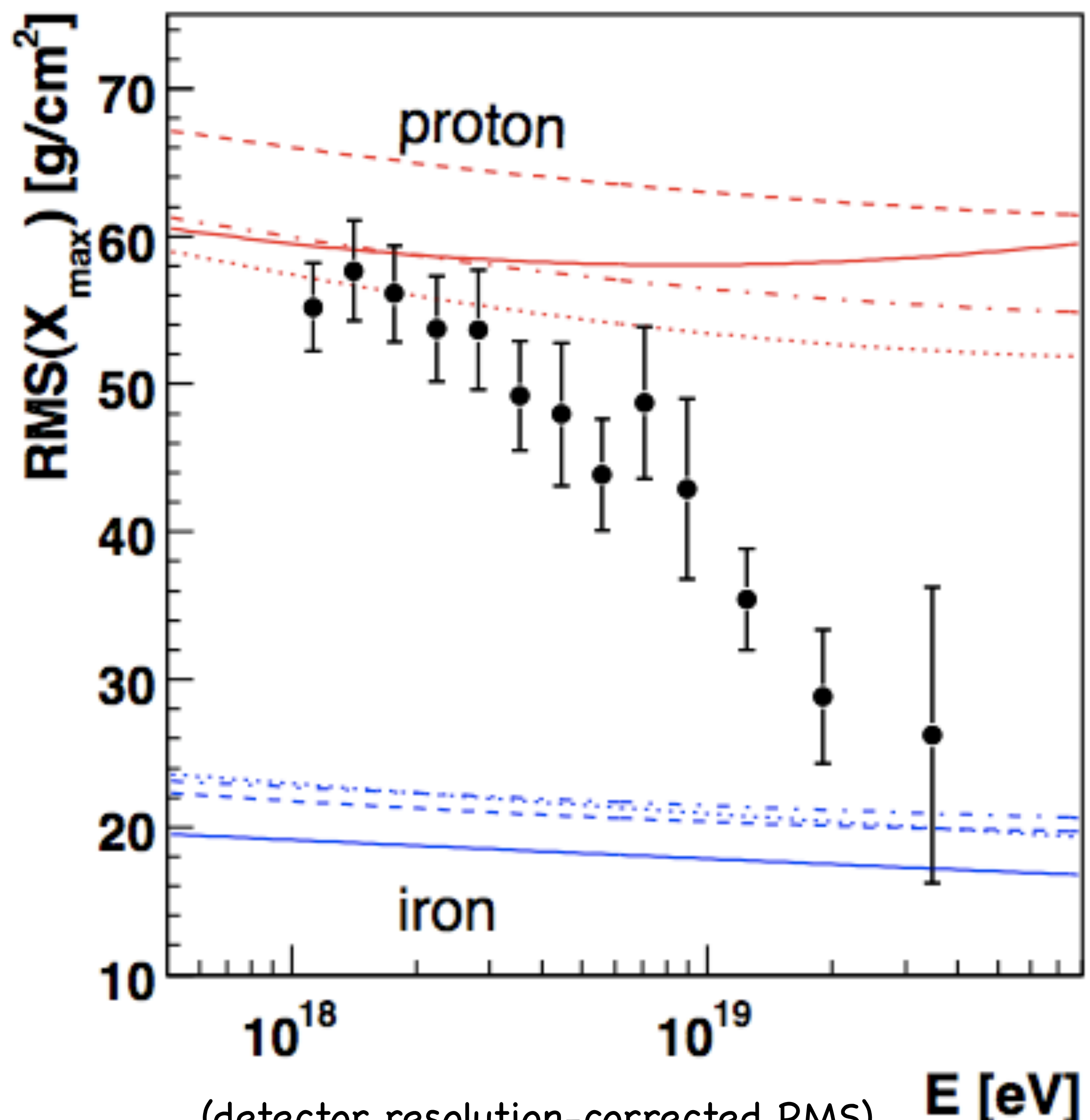
- protons develops deeper & larger fluctuations than iron nuclei
- photons develop very deep

- indirect inference from air shower - simulation require

- electromagnetic interactions: EGS4 <- stable, understood
- hadronic interactions: DPMJET, EPOS, QGSJET, Sibyll <- varies, not understood

X_{max}'s behaviour: mean and fluctuation (RMS)

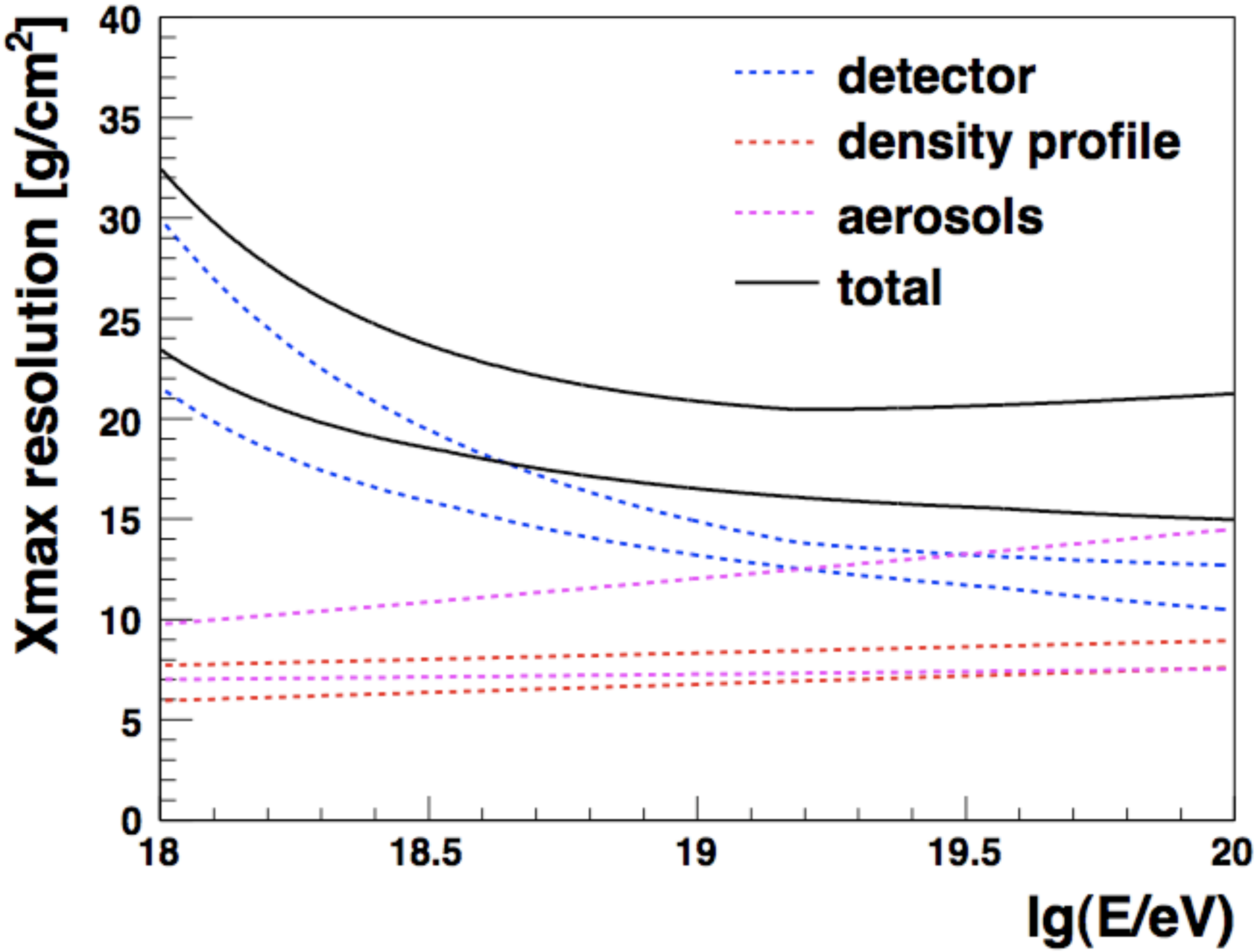




PRL **104** 091101 (2010)

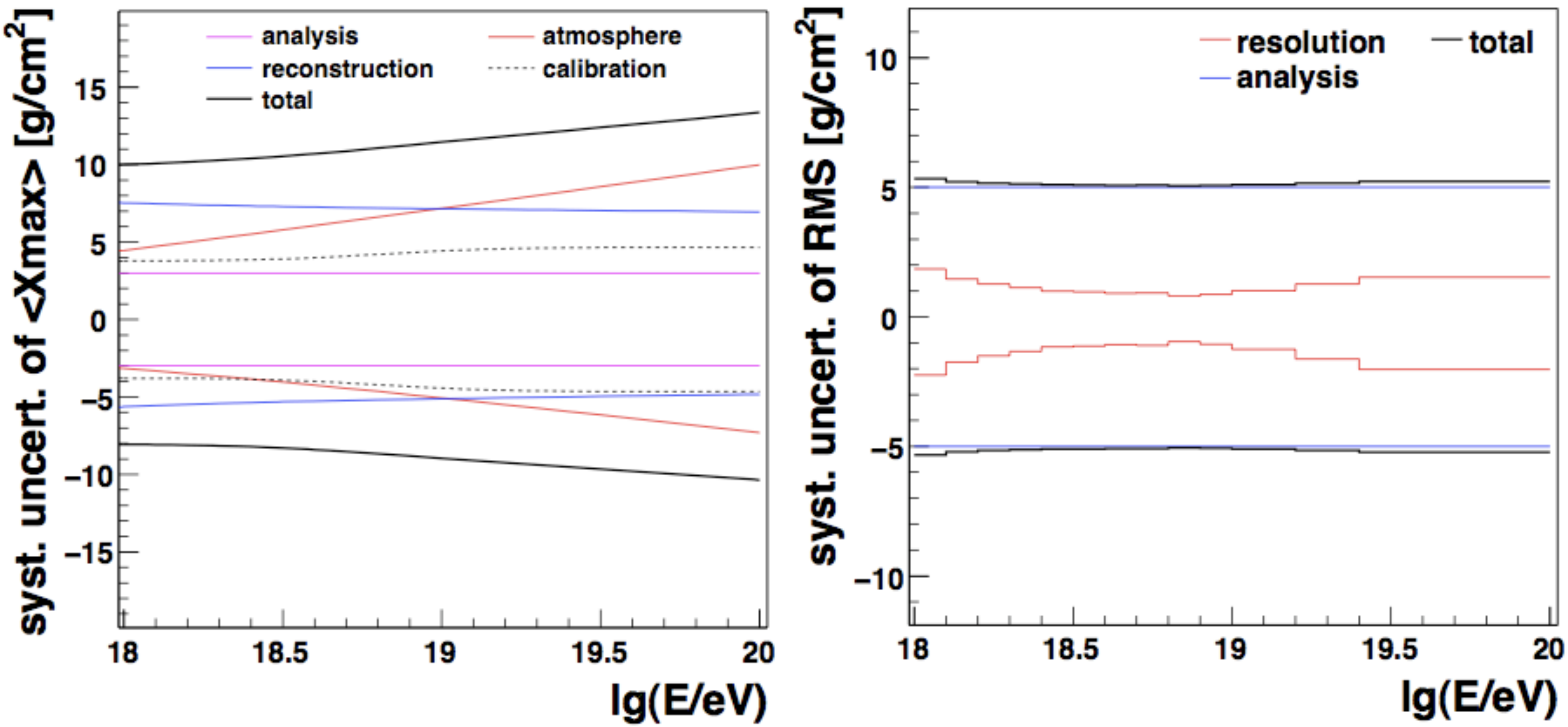
(detector resolution-corrected RMS)

X_{max} resolution



- detector: check with MC
- density profile: seasonal variation of atmosphere & fluorescence yield
- aerosol: cleanliness of atmosphere

Systematic uncertainties

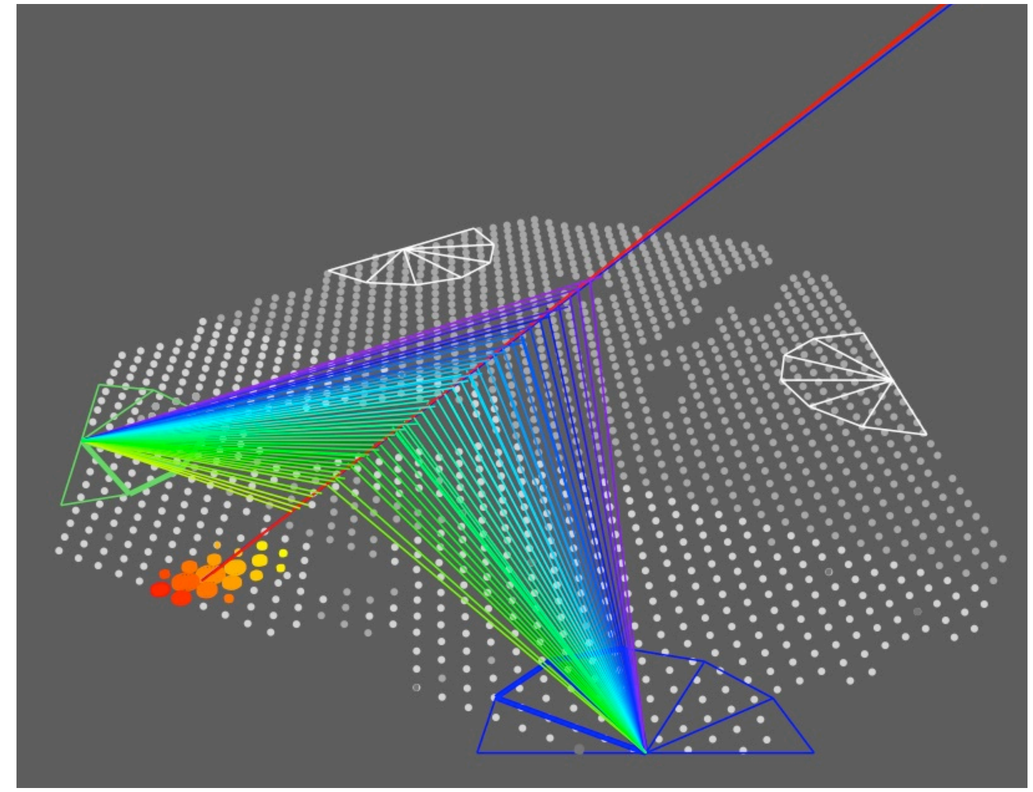


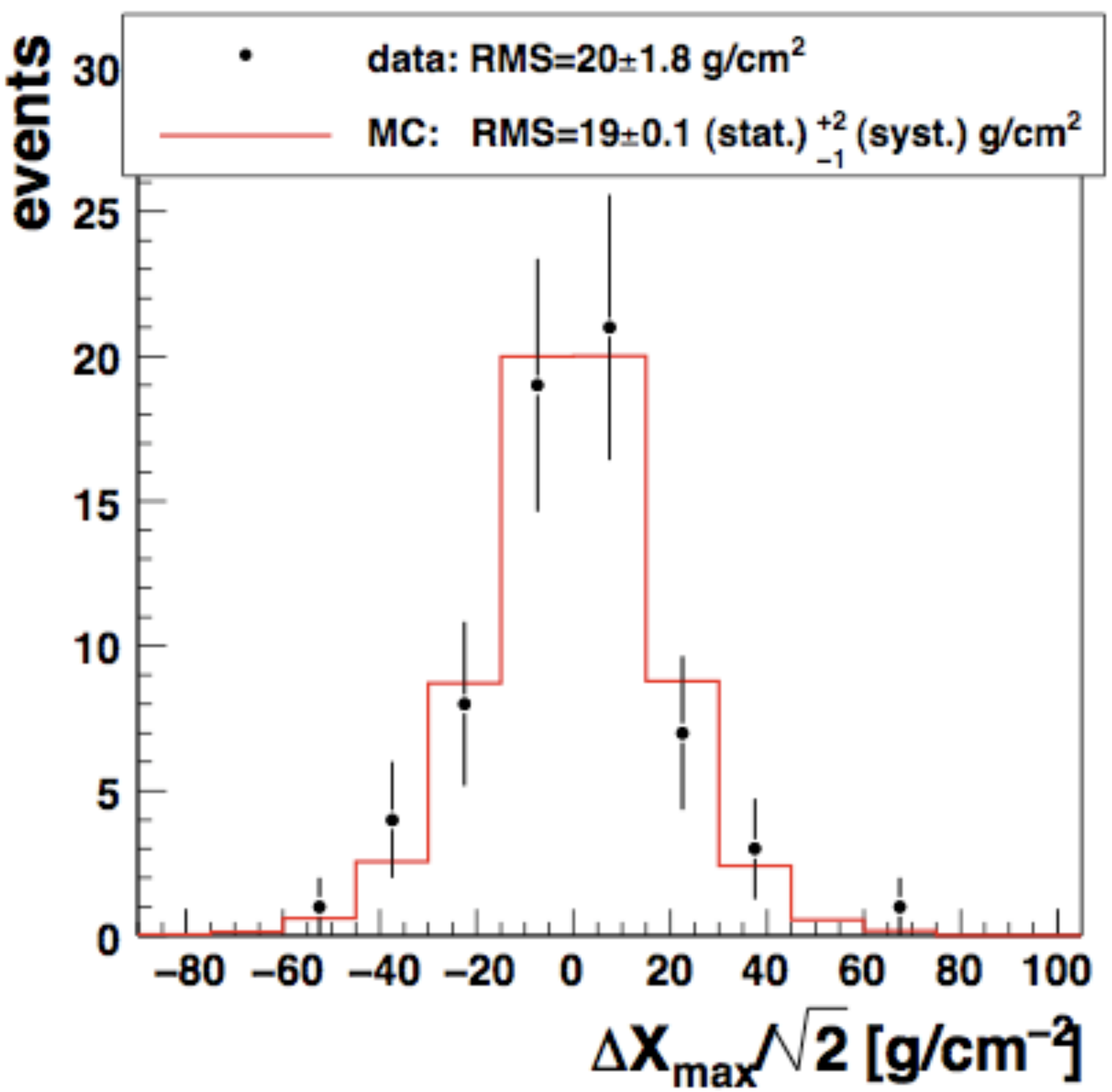
- mean: +10/-8 g/cm^2 (10^{18} eV) ~ +12/-10 g/cm^2 (10^{20} eV)
- RMS: ±5 g/cm^2

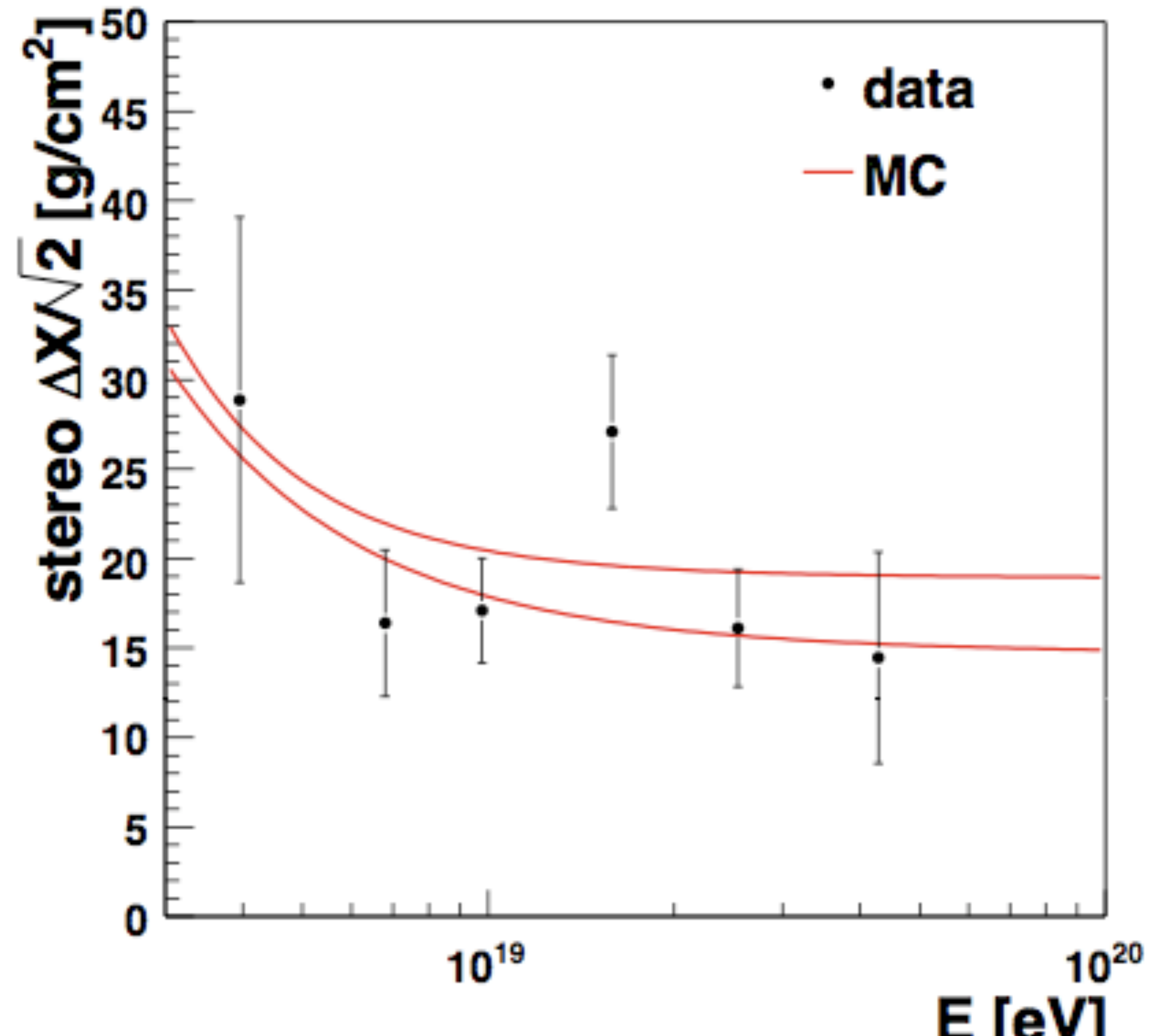
Cross check I: with stereo

Check with multiple-eye events :

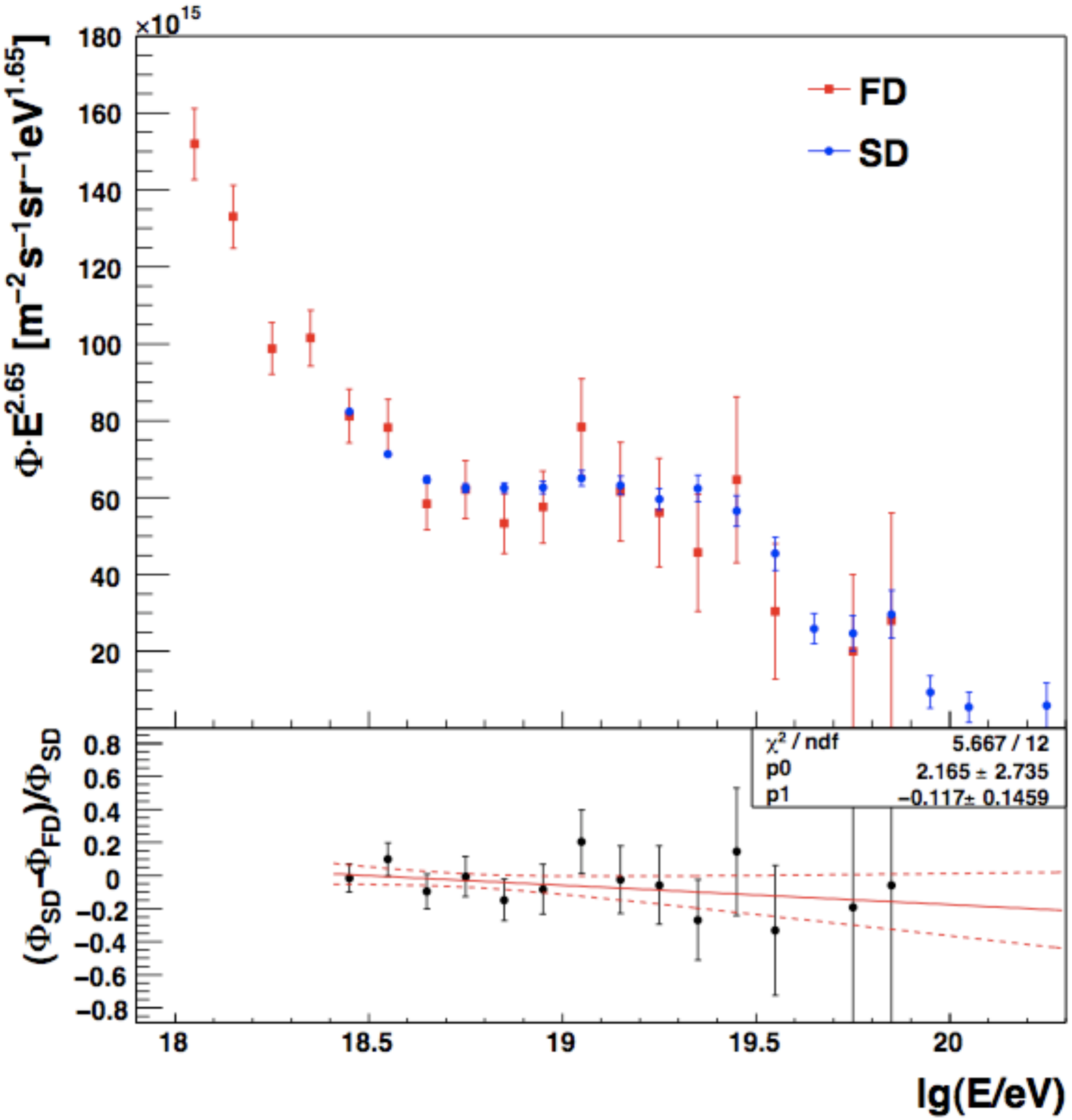
- independent measurement by > 2 eyes
- difference of X_{max} distribution
  $\propto$ detector resolution
- agree with simulation by ± 2 g/cm^2





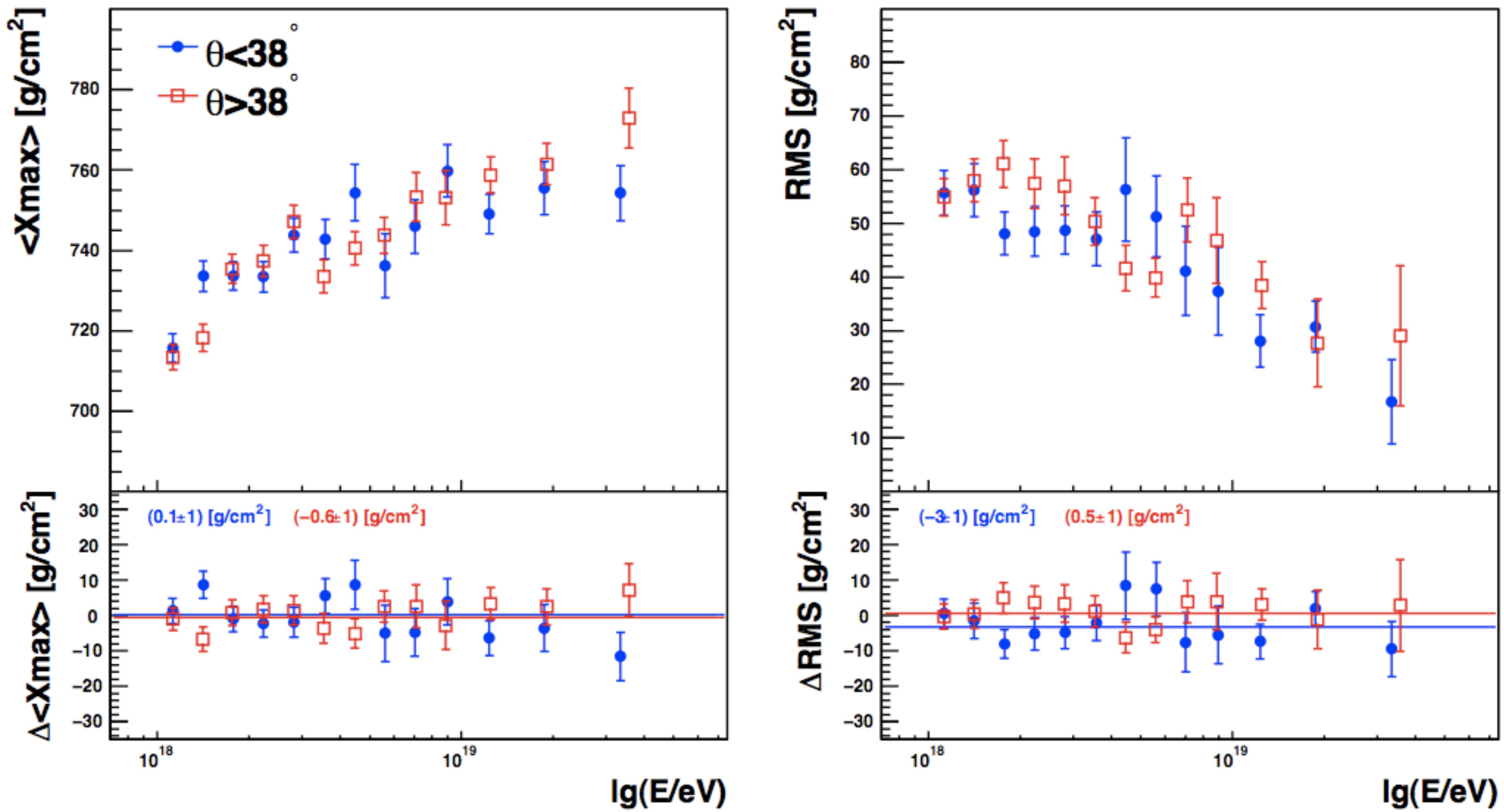


Cross check II: spectrum comparison of fluorescence with surface detector events



- High energy showers develop deeper (larger X_{max}) in atmosphere
- FD is not missing events at high energies

Cross check III: vertical vs inclined events



- Vertical (<38°) : small height, lower FOV, larger effect from aerosol
- Inclined (>38°) : large height, upper FOV, smaller effect from aerosol
- no difference between the two

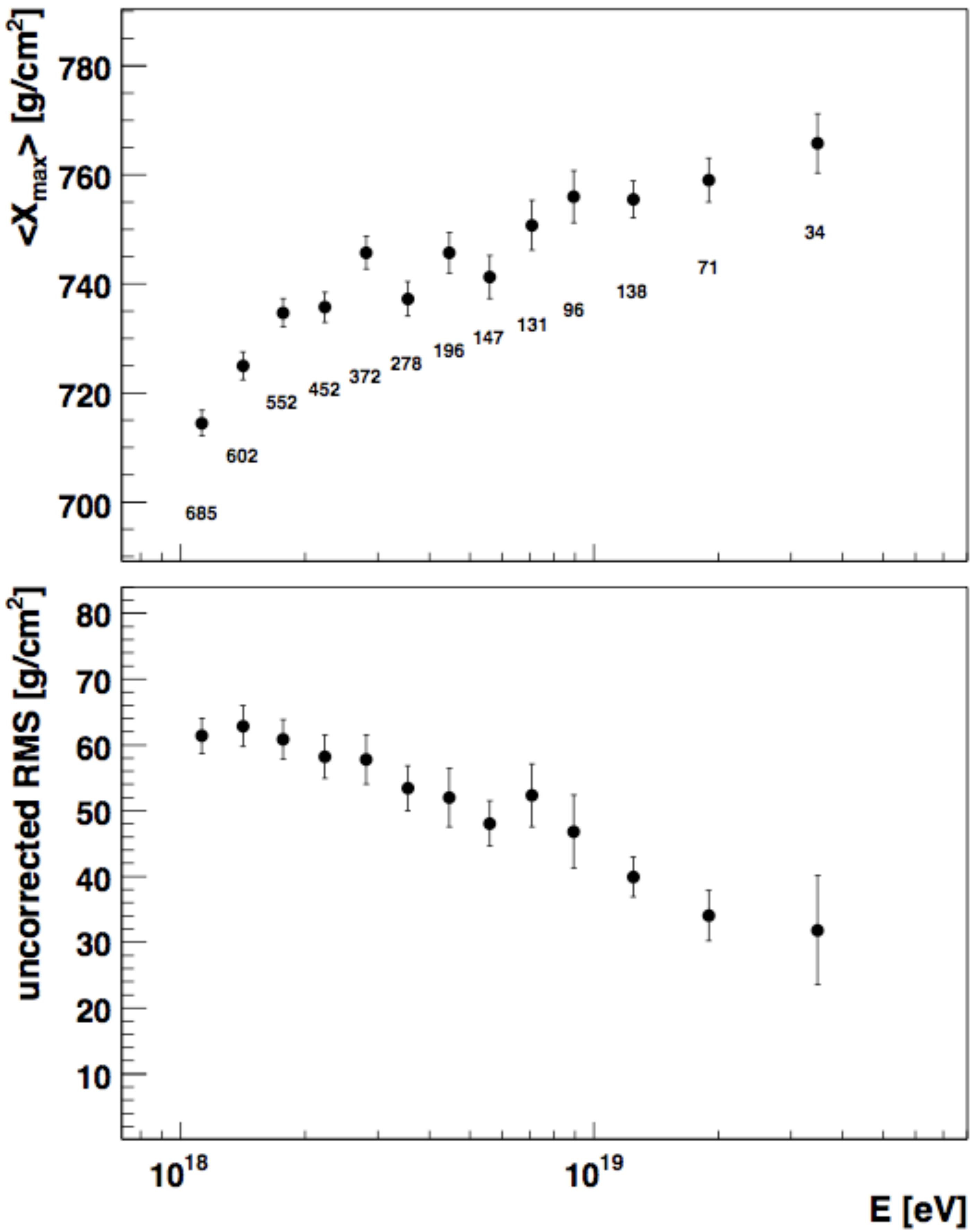
Final data selection

- Hybrid trigger: fluorescence + 1 surface station
- Atmosphere & calibration
  - good camera calibration
  - measured aerosol profile
  - good atmospheric condition
  - cloud fraction < 25%
- Fiducial volume cuts
  - distance to tank, zenith angle (energy dependent) <- minimise bias
  - field of view
- Quality cuts
  - X_{max} observed
  - low expected reconstruction uncertainty
  - reduced χ^2 of profile fit < 2.5

-> Excellent reconstruction, good resolution for accurate studies

3754 events

Data of X_{max} : mean and fluctuation (RMS)



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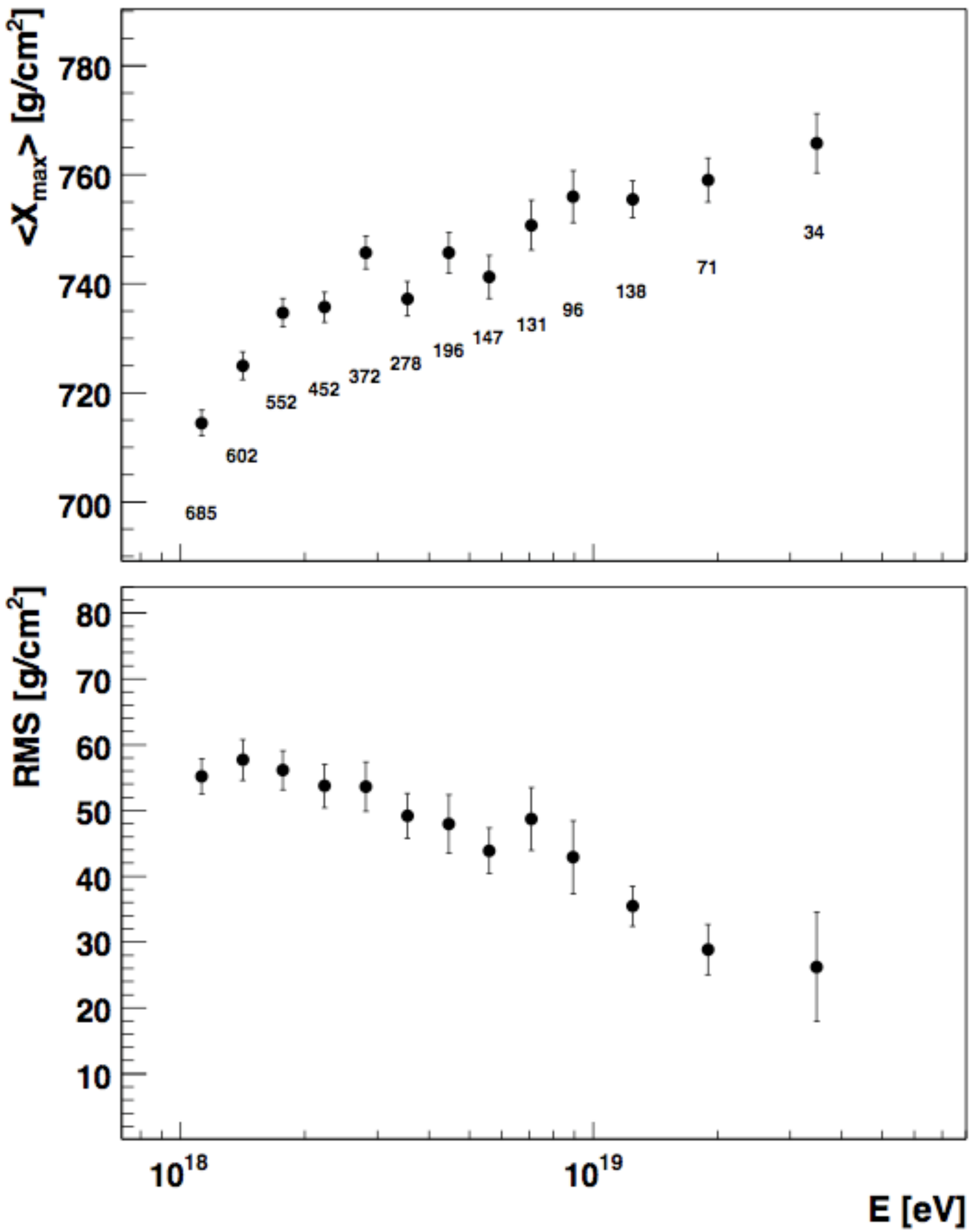

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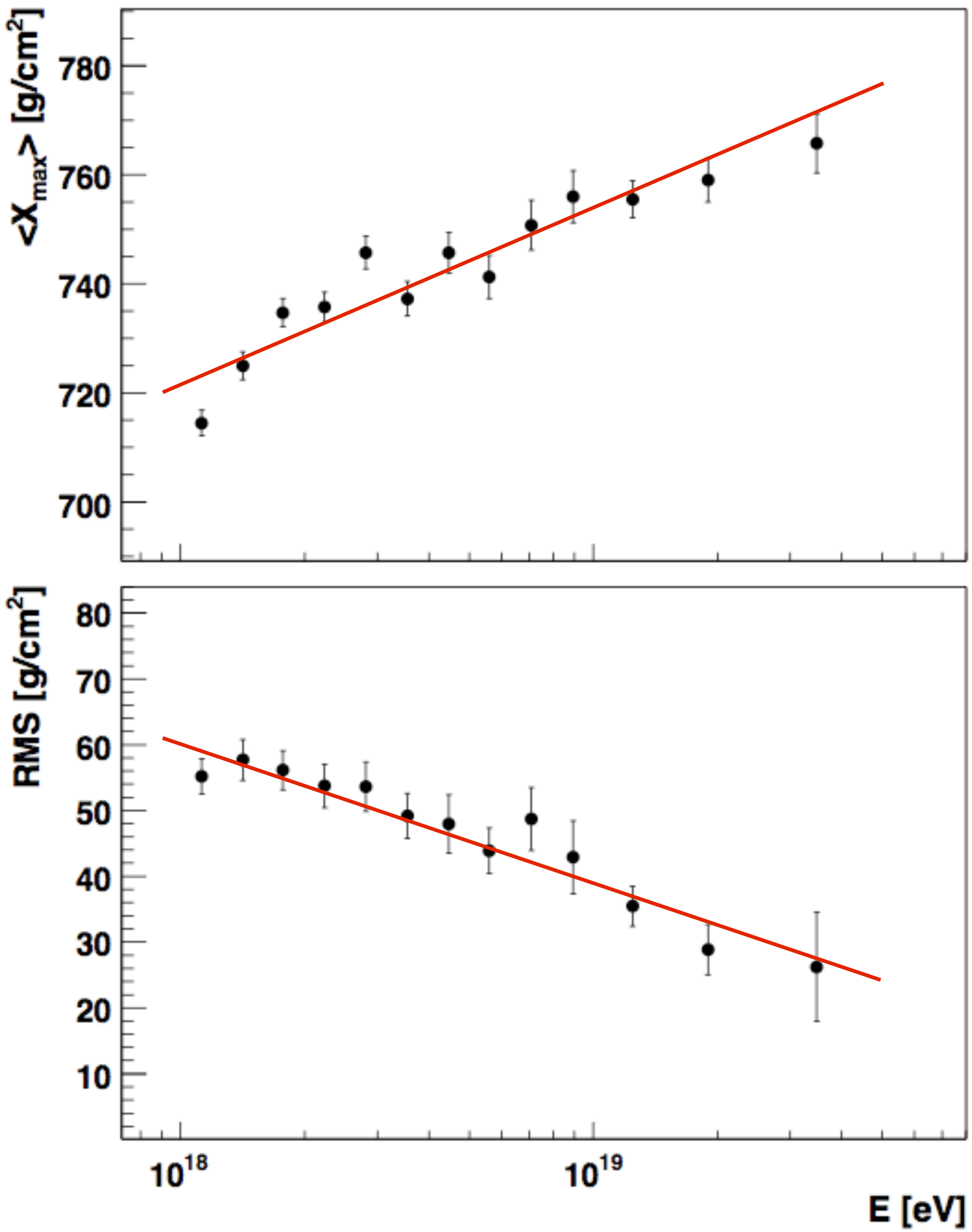
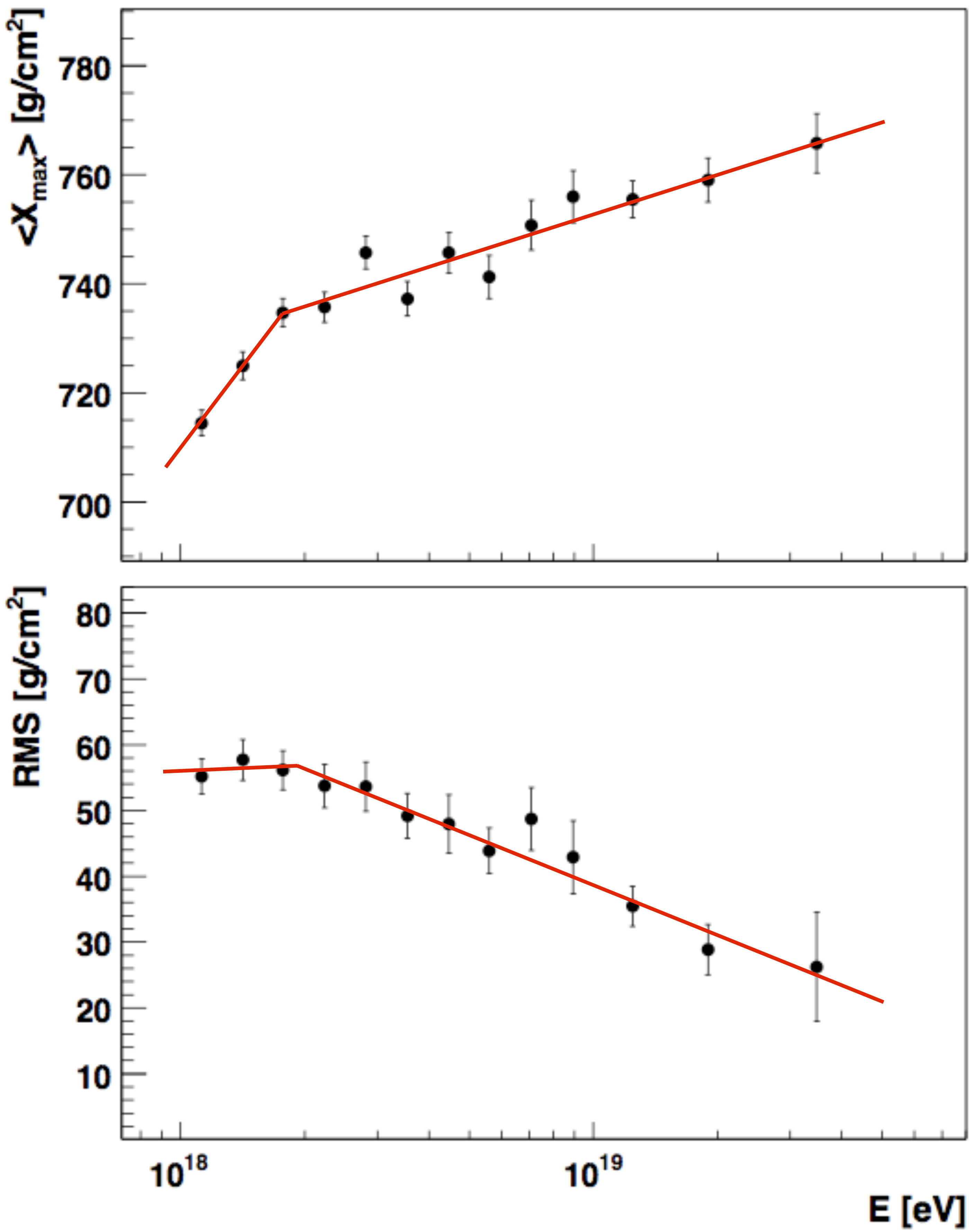


log(E)-X_{max} linear fit

- $<X_{max}>$:
  - slope = 33 ± 2 g/cm^2
  - χ^2/N_{dof} = 35/11

- RMS :
  - slope = -21 ± 3 g/cm^2
  - χ^2/N_{dof} = 5.6/11

Data of X_{max} : mean and fluctuation (RMS)

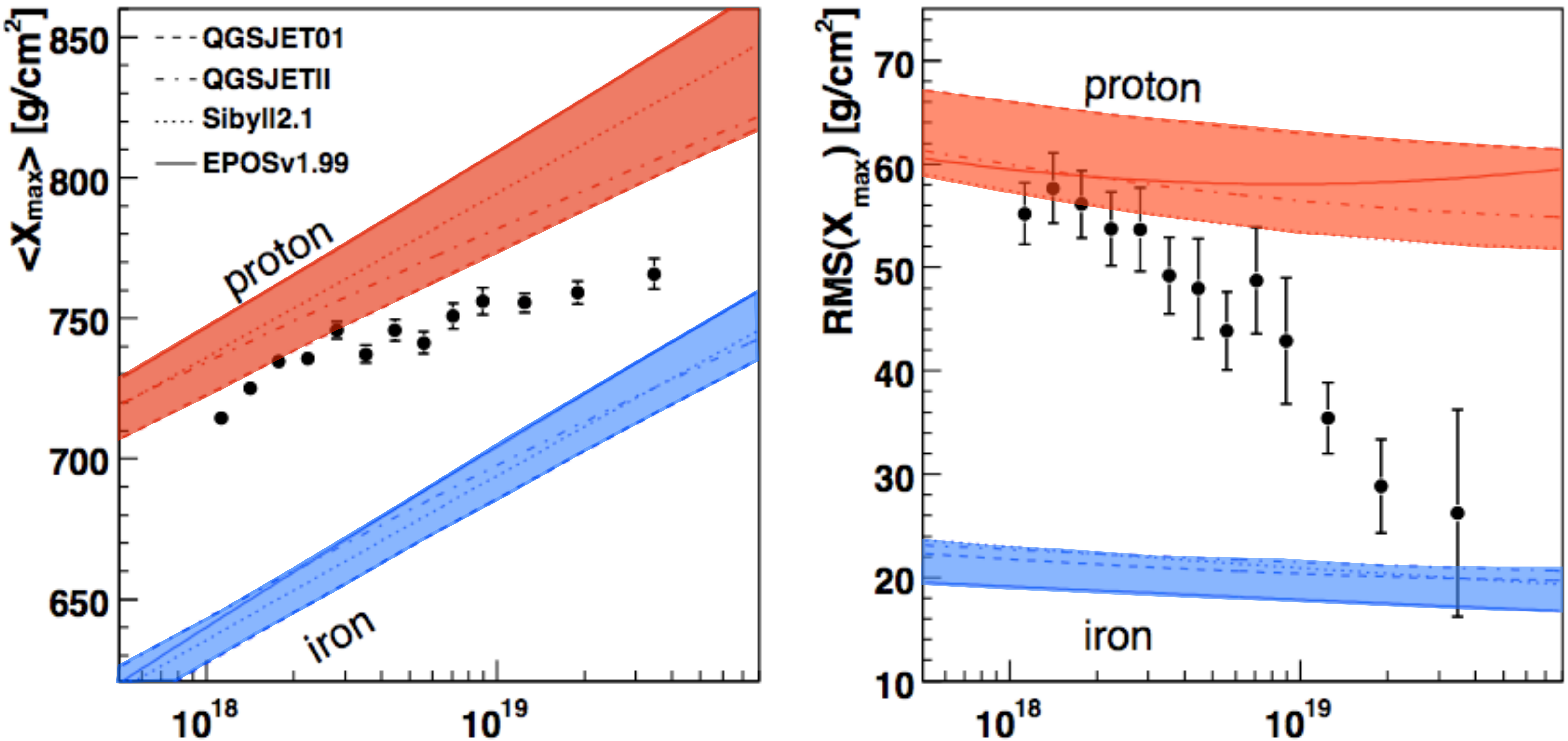


log(E)-X_{max} linear broken line fit

- <X_{max}> :
  - slope1 = 106 ± 35 g/cm^2
  - slope2 = 24 ± 3 g/cm^2
  - log(E_{break}/[eV]) = 18.2 ± 0.1
  - χ^2/N_{dof} = 9.7/9
- RMS :
  - slope1 = 5 ± 20 g/cm^2
  - slope2 = -26 ± 4 g/cm^2
  - log(E_{break}/[eV]) = 18.3 ± 0.1
  - χ^2/N_{dof} = 2.2/9

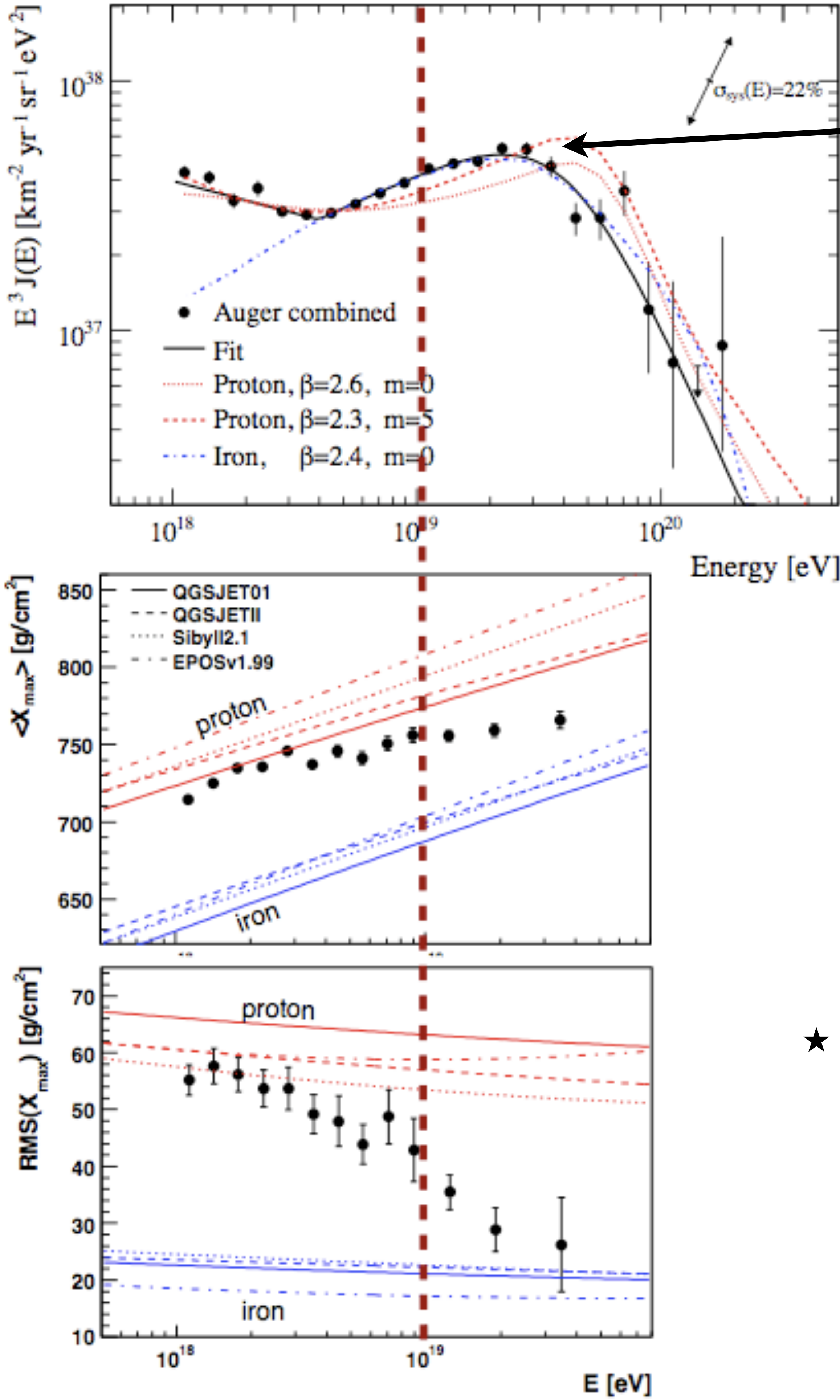
change of slope
-> change in composition?

Data of X_{max} : mean and fluctuation (RMS)



(detector resolution-corrected RMS)

- Models give different predictions
- Need more data : max E bin < 4×10^{19} eV



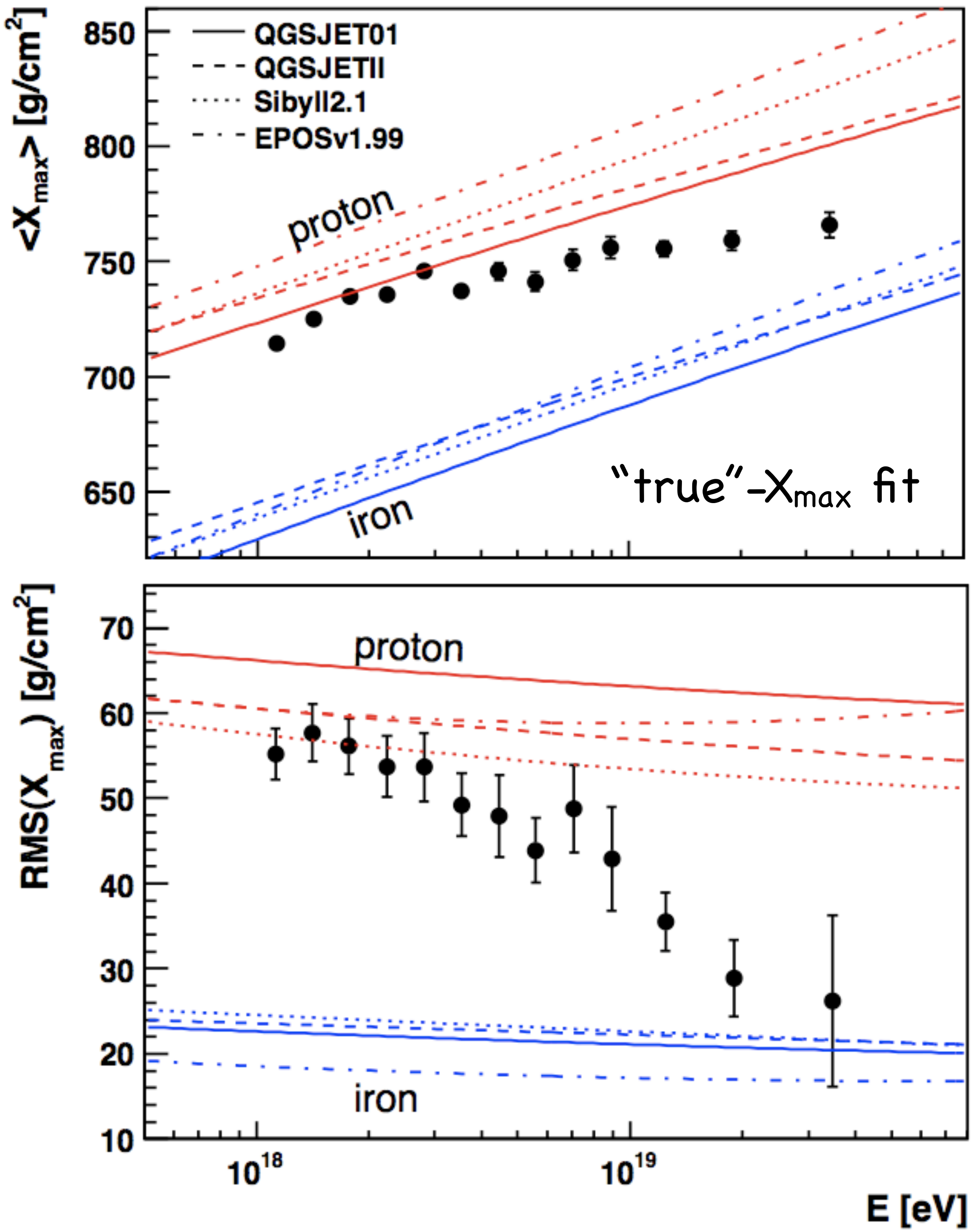
Cutoff observed at 4×10^{19} eV

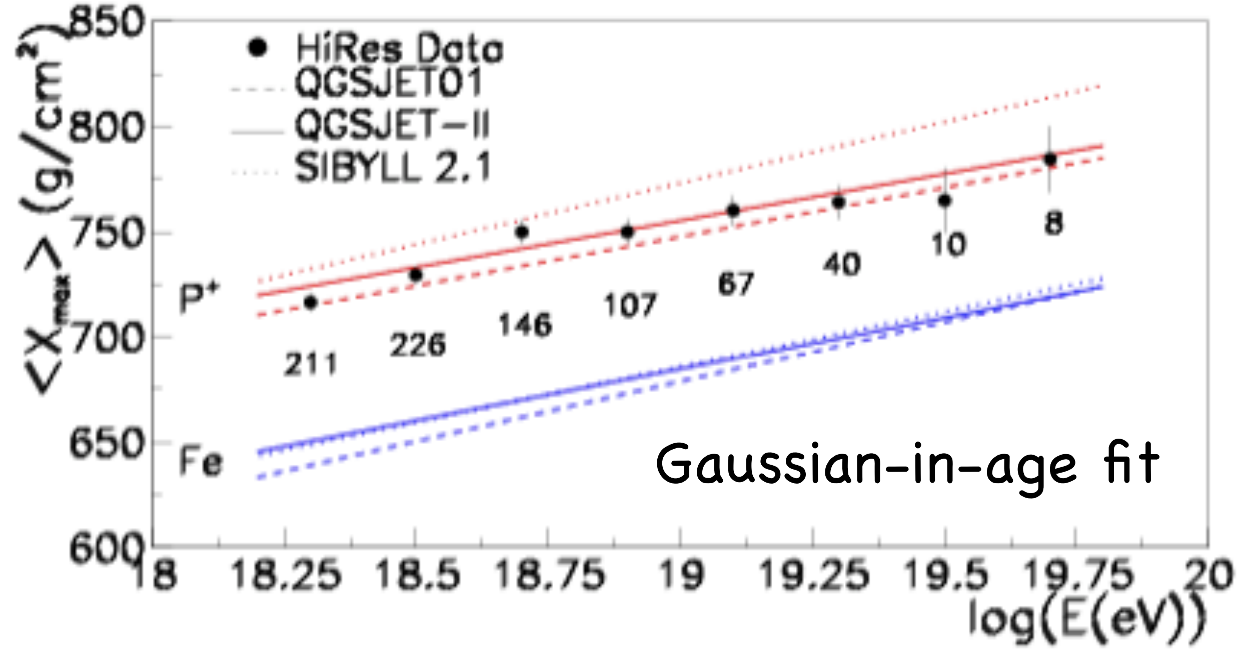
- correlation $E > 5.5 \times 10^{19}$ eV
- X_{max} highest $E < 4 \times 10^{19}$ eV

★ Aim: composition & particle characteristics,

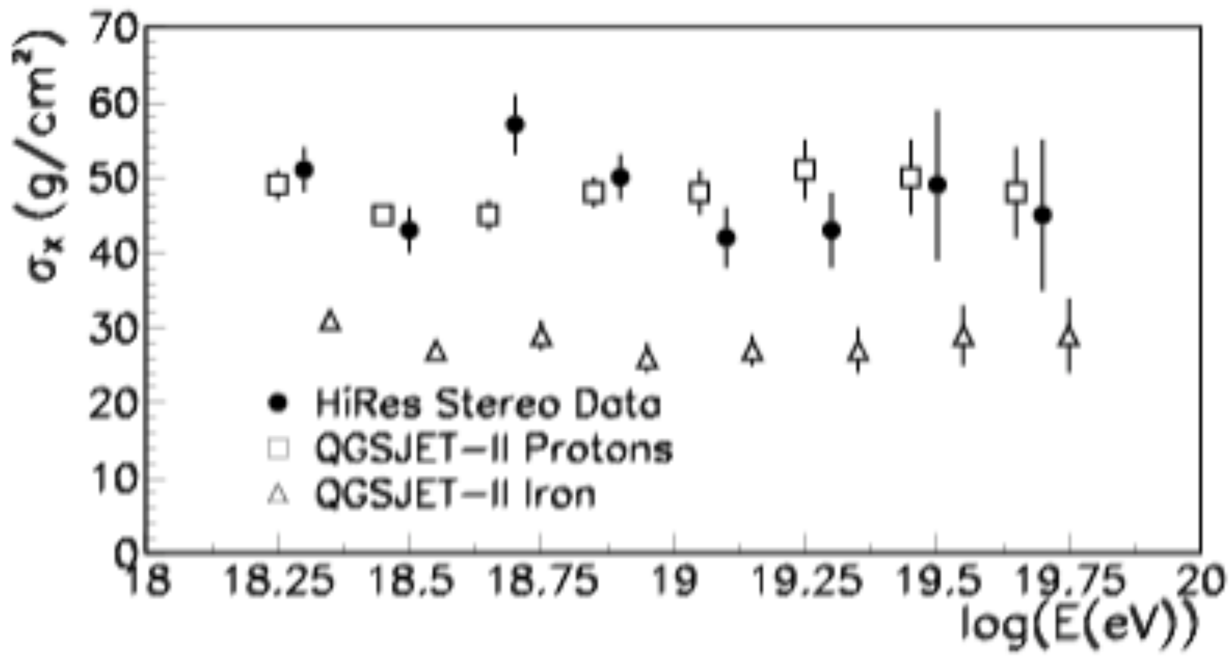
e.g. cross sections at Auger energies

Comparing X_{max} of Auger and HiRes





Gaussian fit to distribution truncated at 2xRMS



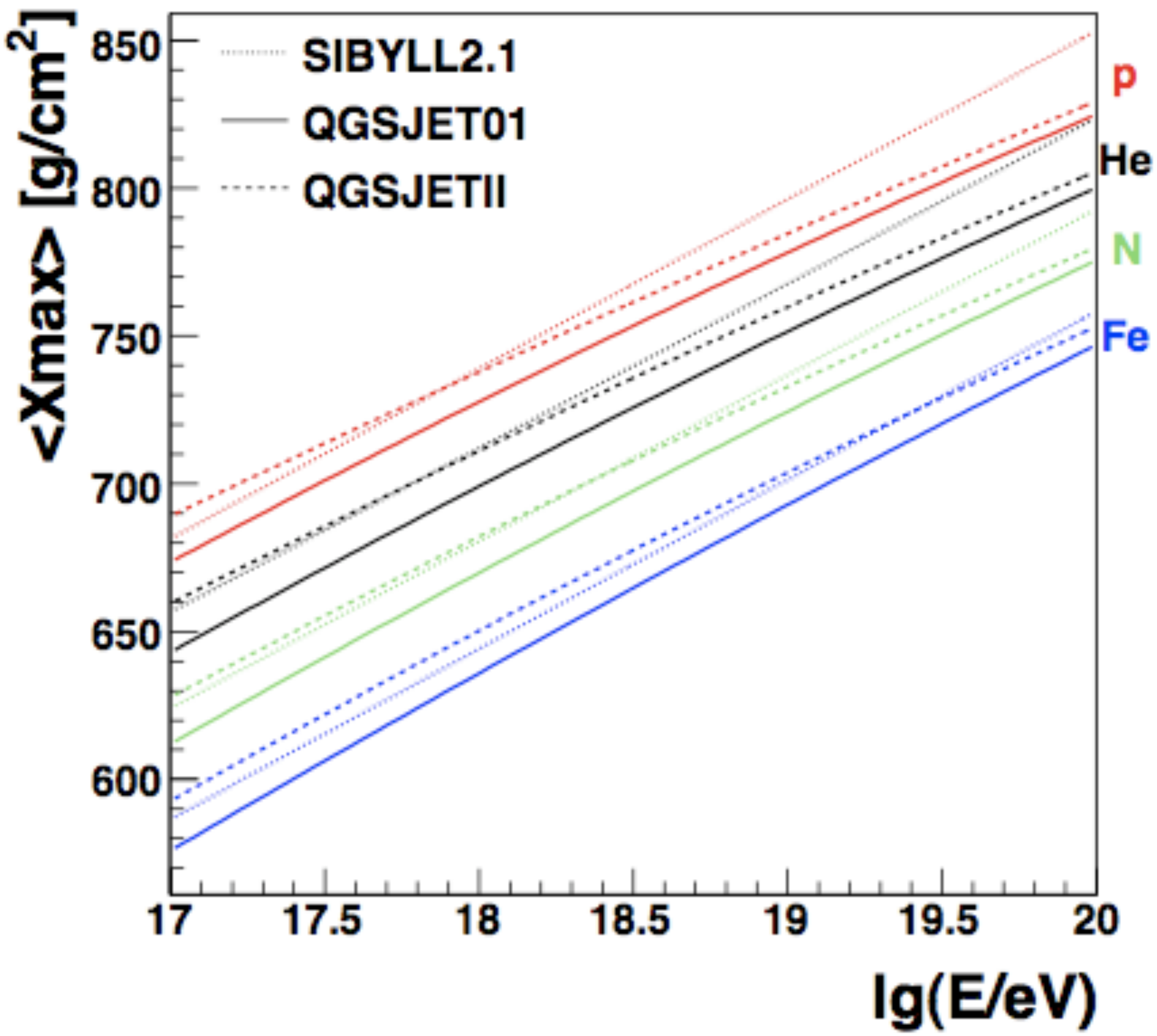
N(Auger) = 3754

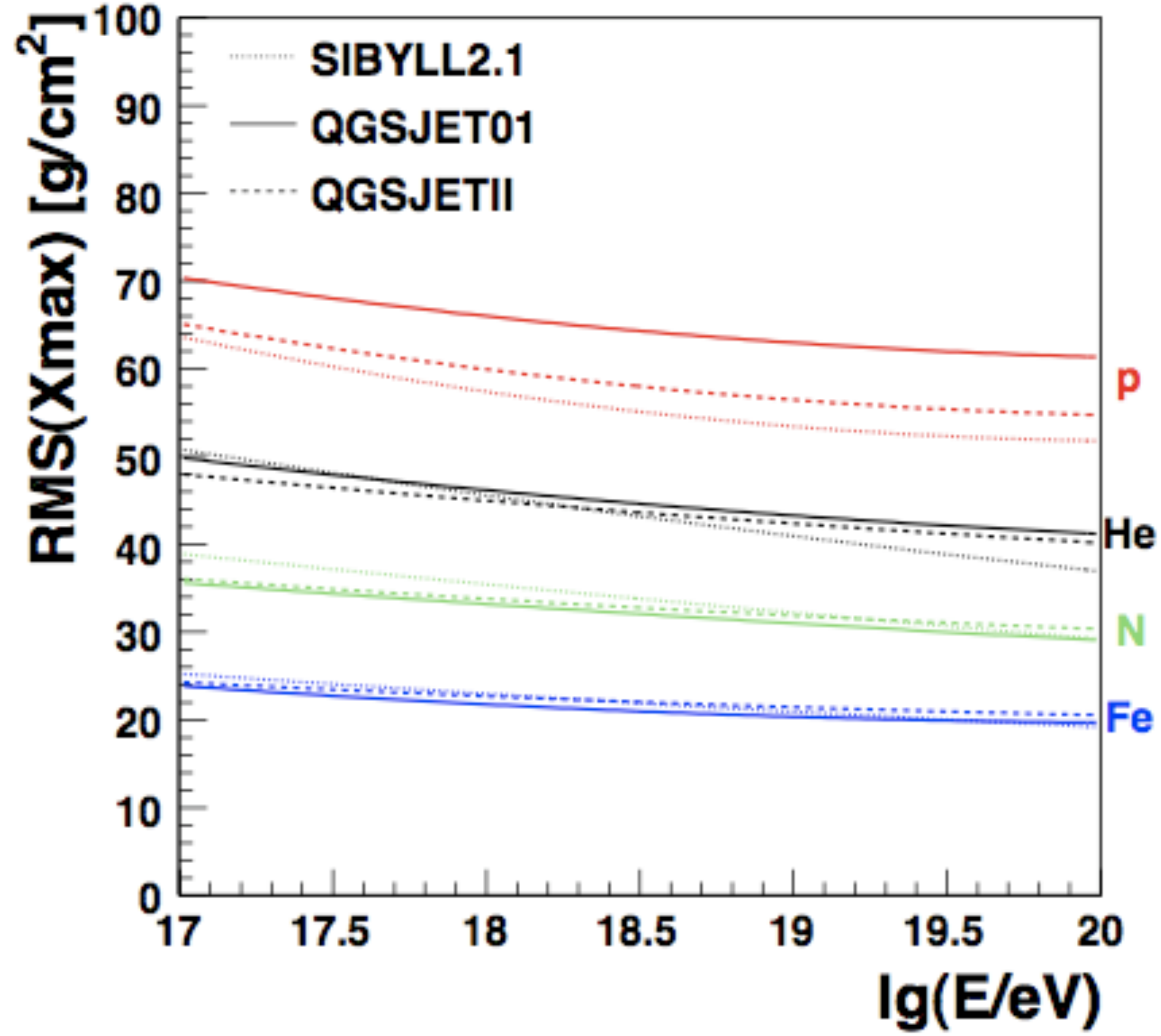
PRL **104** 091101 (2010)

N(HiRes) = 815

PRL **104** 161101 (2010)

Assuming various compositions





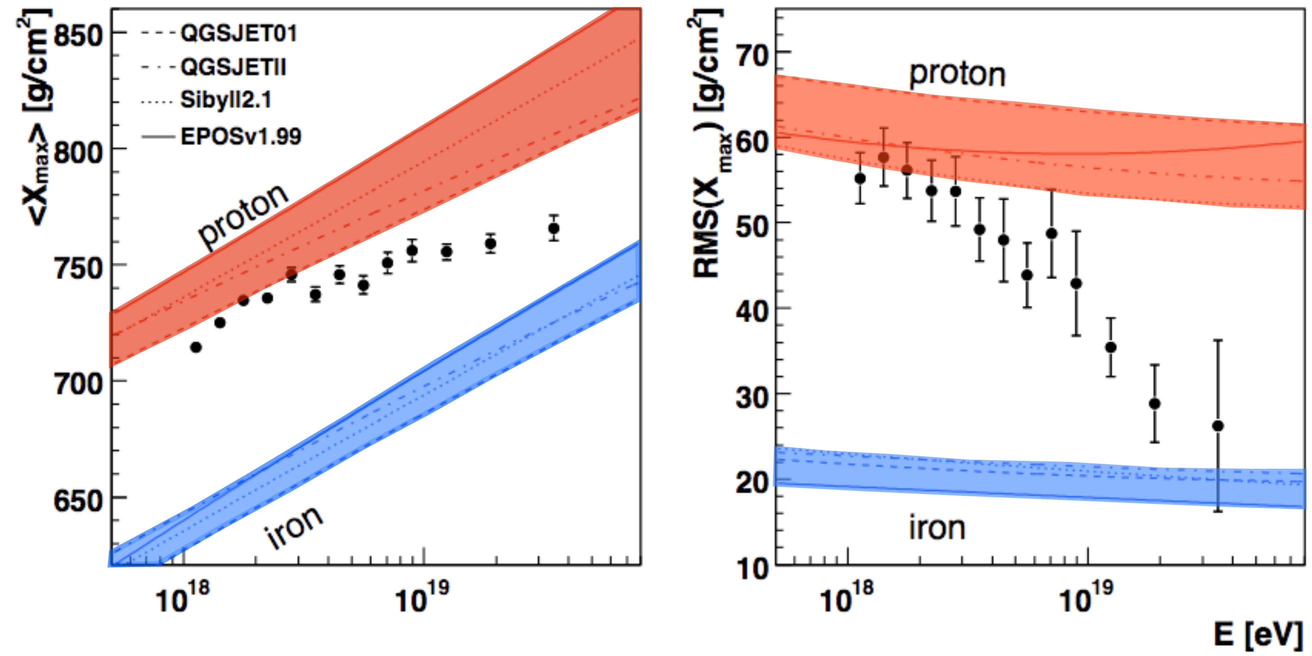
p : most stable

He : disintegrate during propagation

N (CNO) : disintegrate during propagation

Fe : heaviest abundant element, survive long-distance propagation

‣ Models give different prediction



❖ Hadronic interaction model required for data interpretation

- EPOS, QGSJET, Sibyll ...
  ➡ phenomenology-based: dual parton, minijets, pomerons, strings etc.

- “low energy” accelerator data
  ➡ cross section, particle distribution

- extrapolate to higher energies

‣ Tevatron -> LHC : $E_{lab} \approx 10^{15}$ eV -> 10^{17} eV

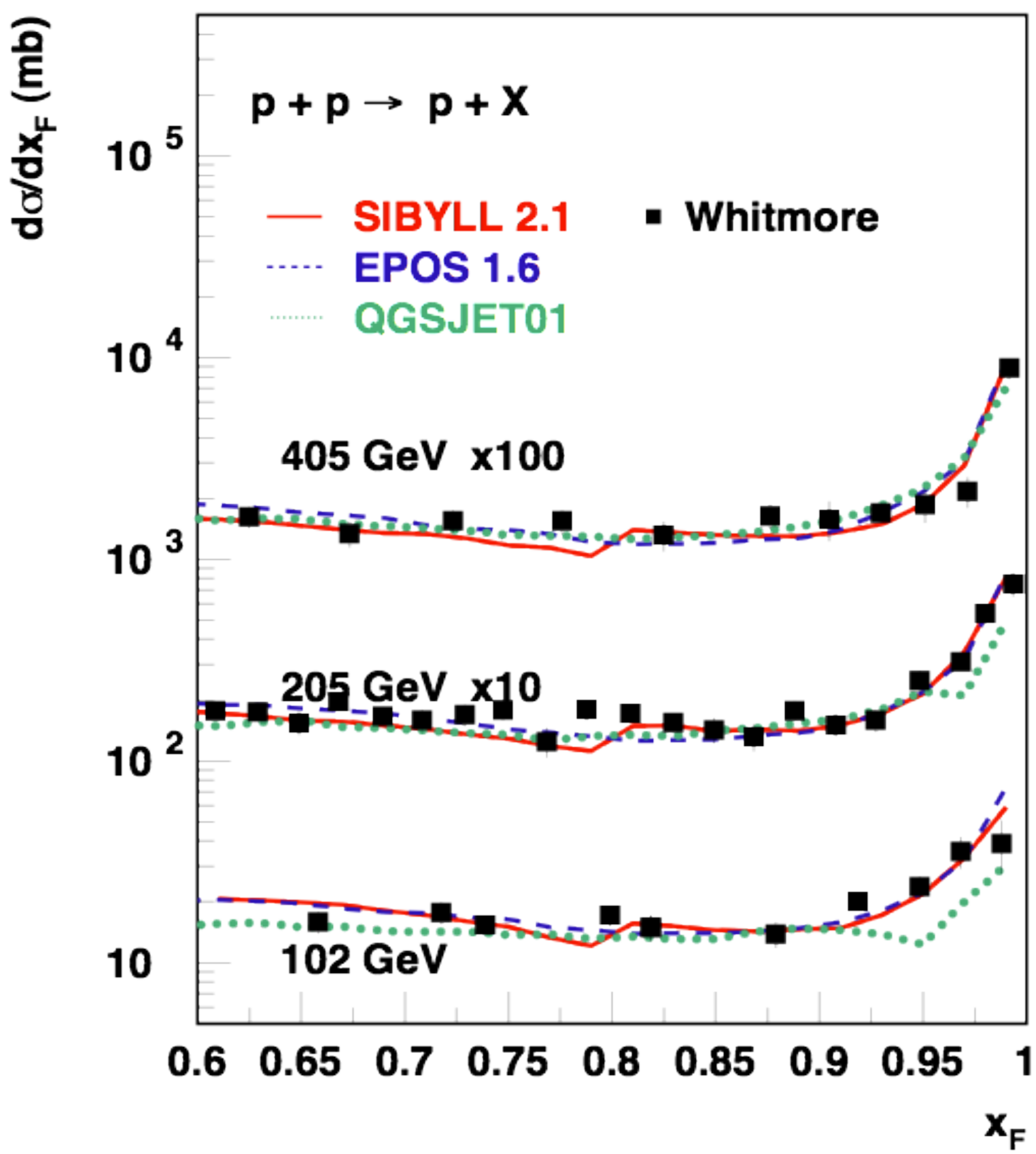
‣ Auger’s enhancements : $E \approx 10^{17}$ eV

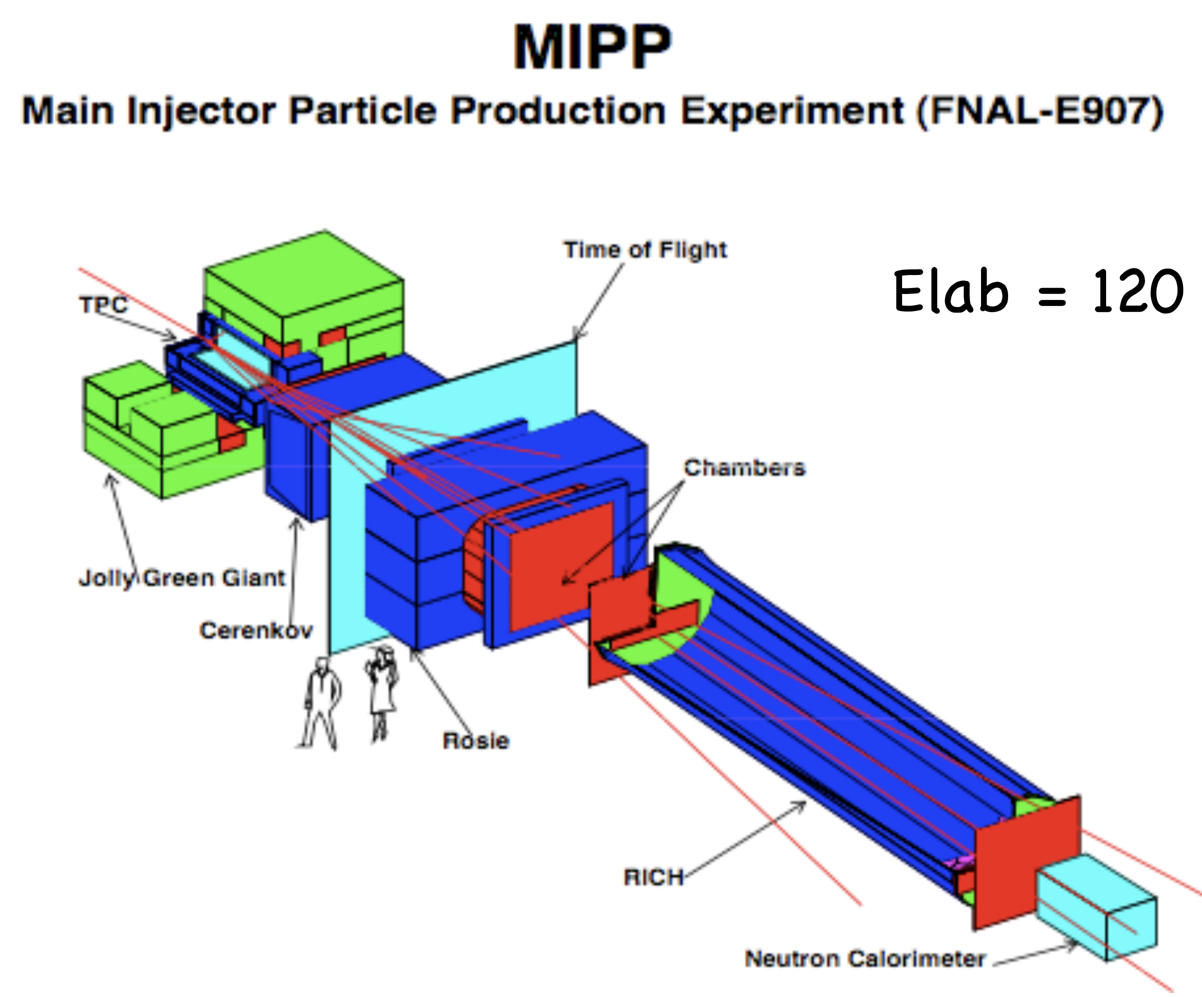
-> gap is decreasing

Data from accelerator -> used in cosmic ray hadronic interaction models

- Fixed target experiments - larger phase space, lower energy (E_{lab} < 800 GeV)
  - nuclei targets

NAL 30" Bubble chamber

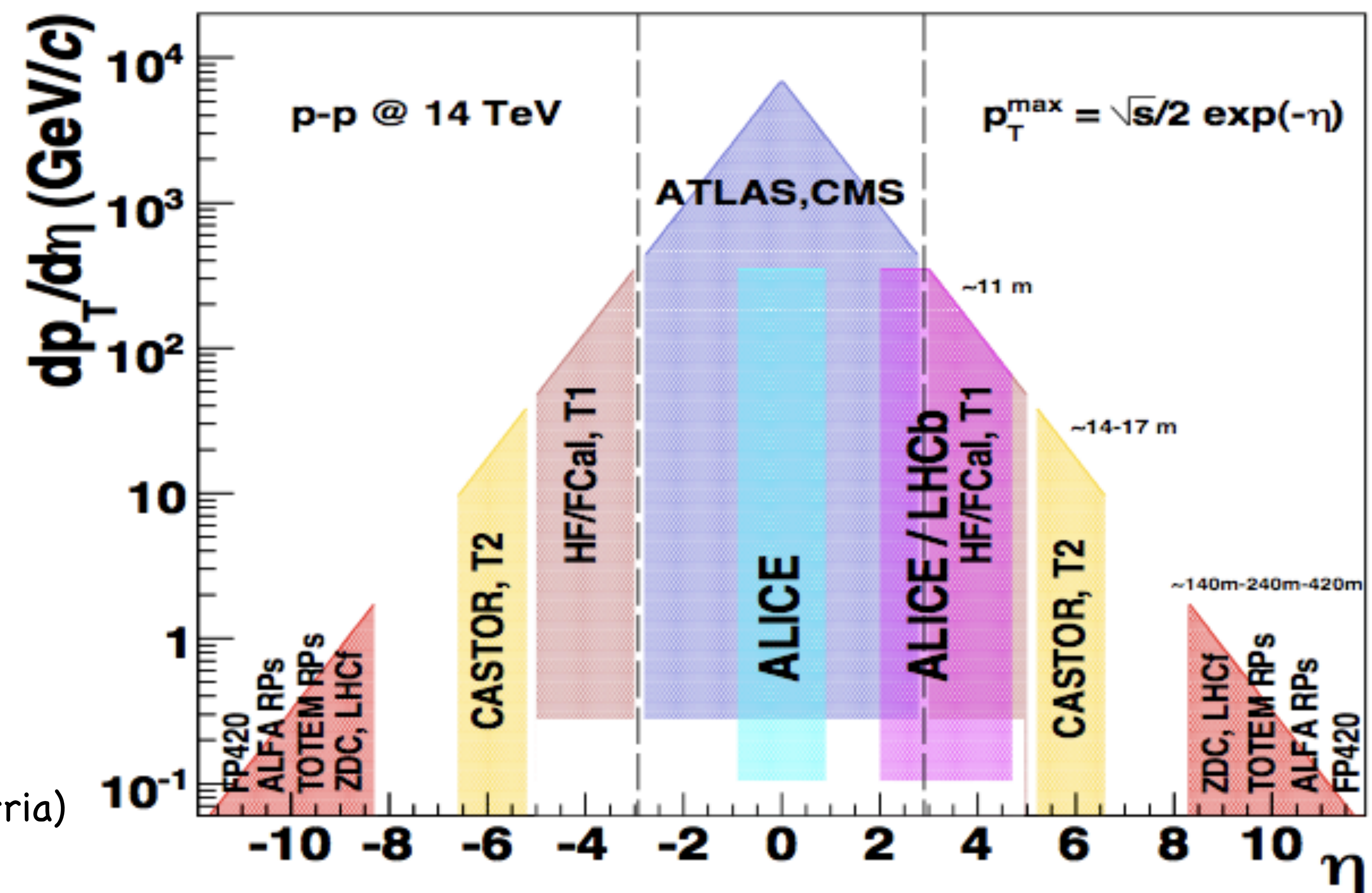




Elab = 120 GeV

Data from accelerator -> used in cosmic ray hadronic interaction models

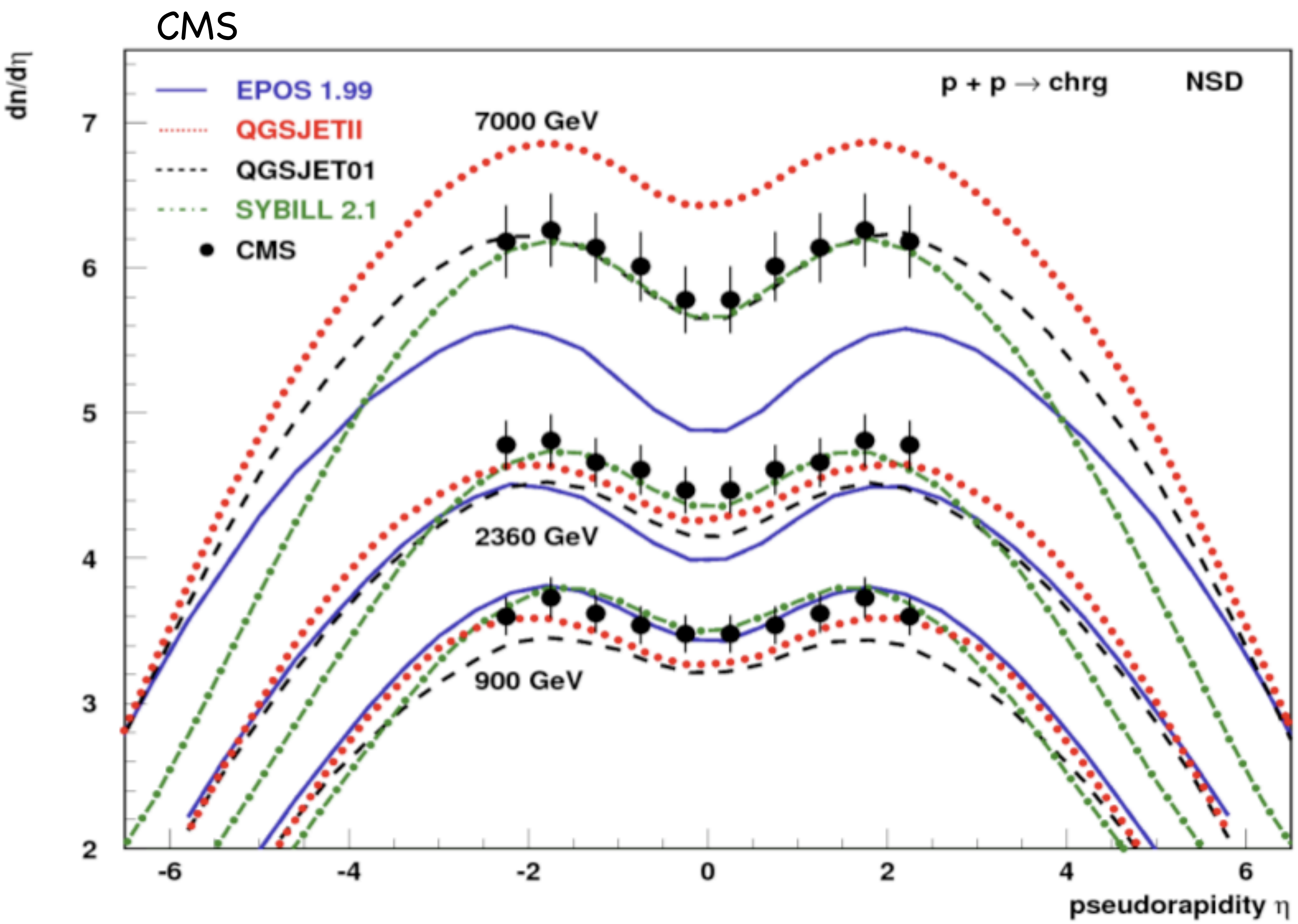
- Fixed target experiments - larger phase space, lower energy (E_{lab} < 800 GeV)
  - nuclei targets
- Colliders - smaller phase space, higher energy ($E_{lab} < 10^{15}$ eV -> 10^{17} eV)
  - p-p or heavy ion collision (N/O/Ar - N/O/Ar collision?)

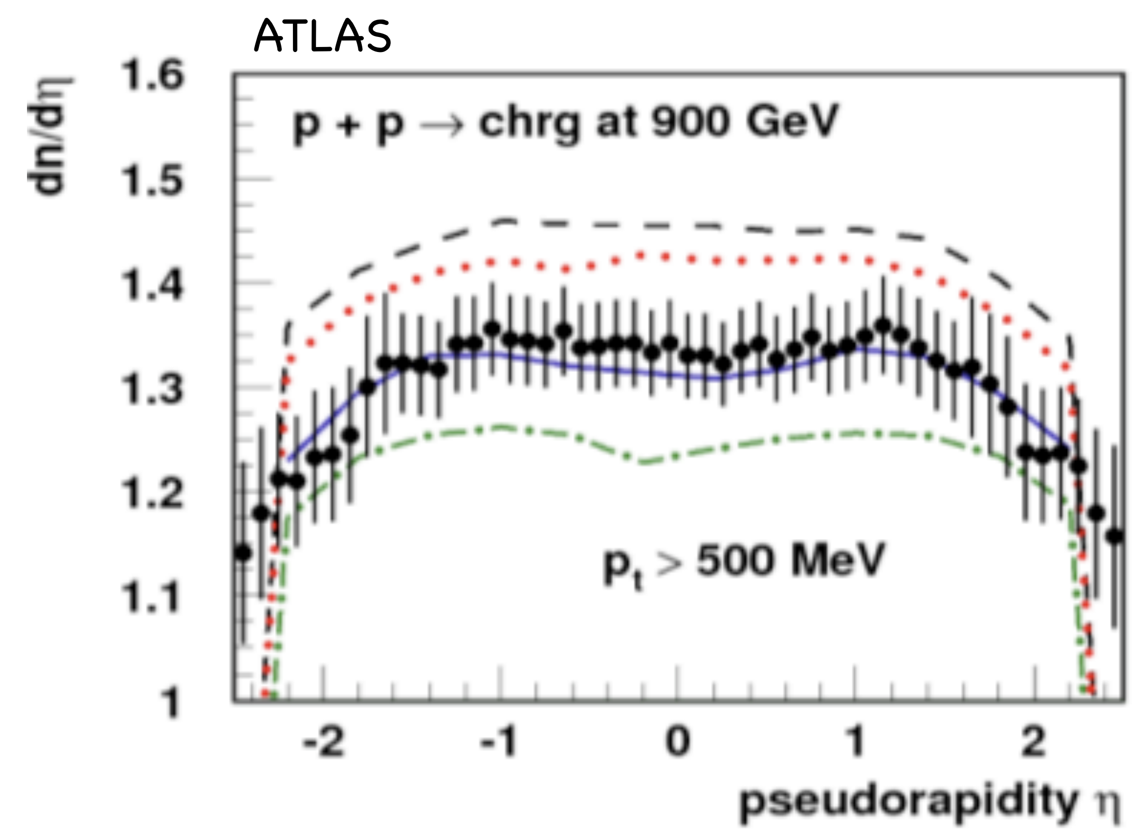


(D. d'Enterria)

Cosmic ray hadronic interaction models at LHC

1. Pseudorapidity distribution





- multiplicites are NOT underestimated (in central region)

- very good at 900 GeV (EPOS) ; good overall average (Sibyll & QGSJET01)

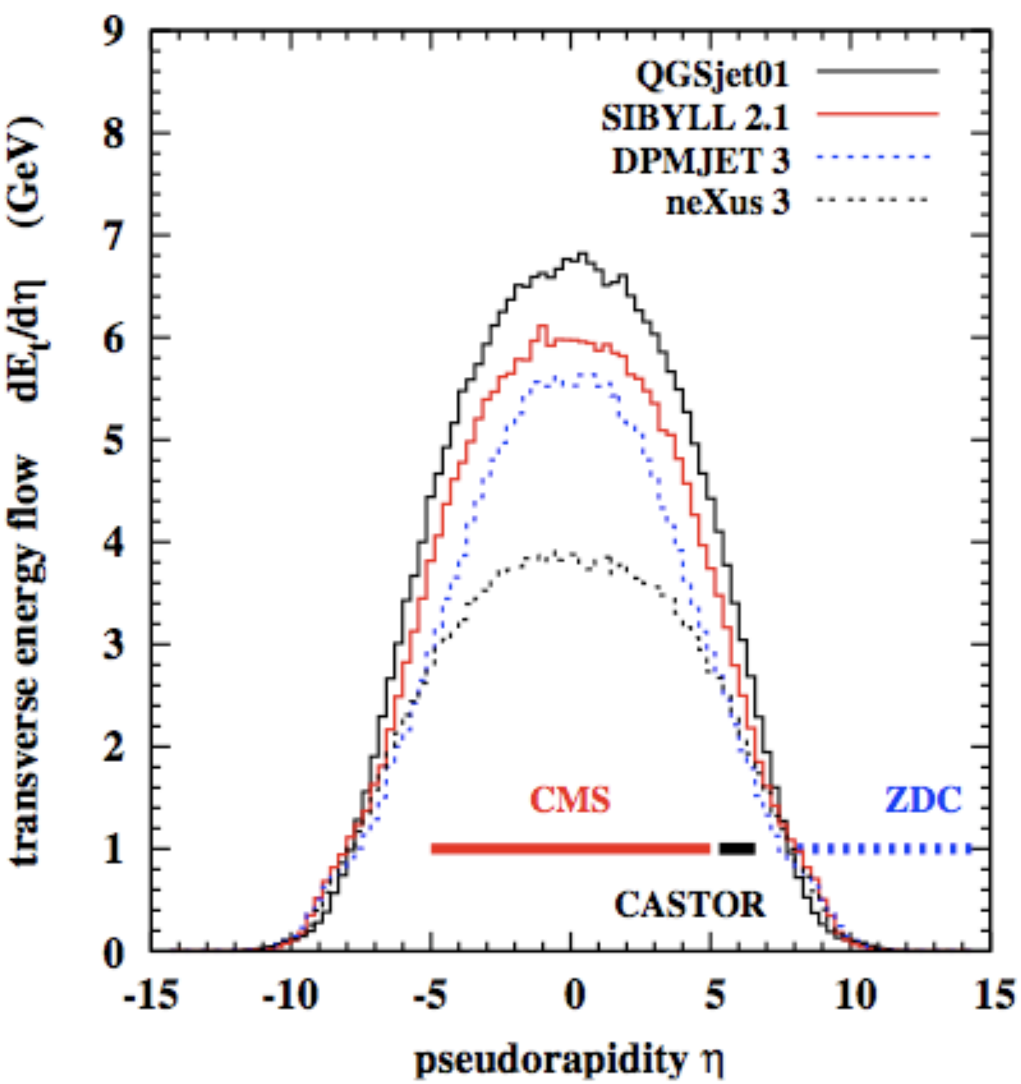
What cosmic ray physicists need

- Forward region - charged particle distribution
  - neutral particle distribution

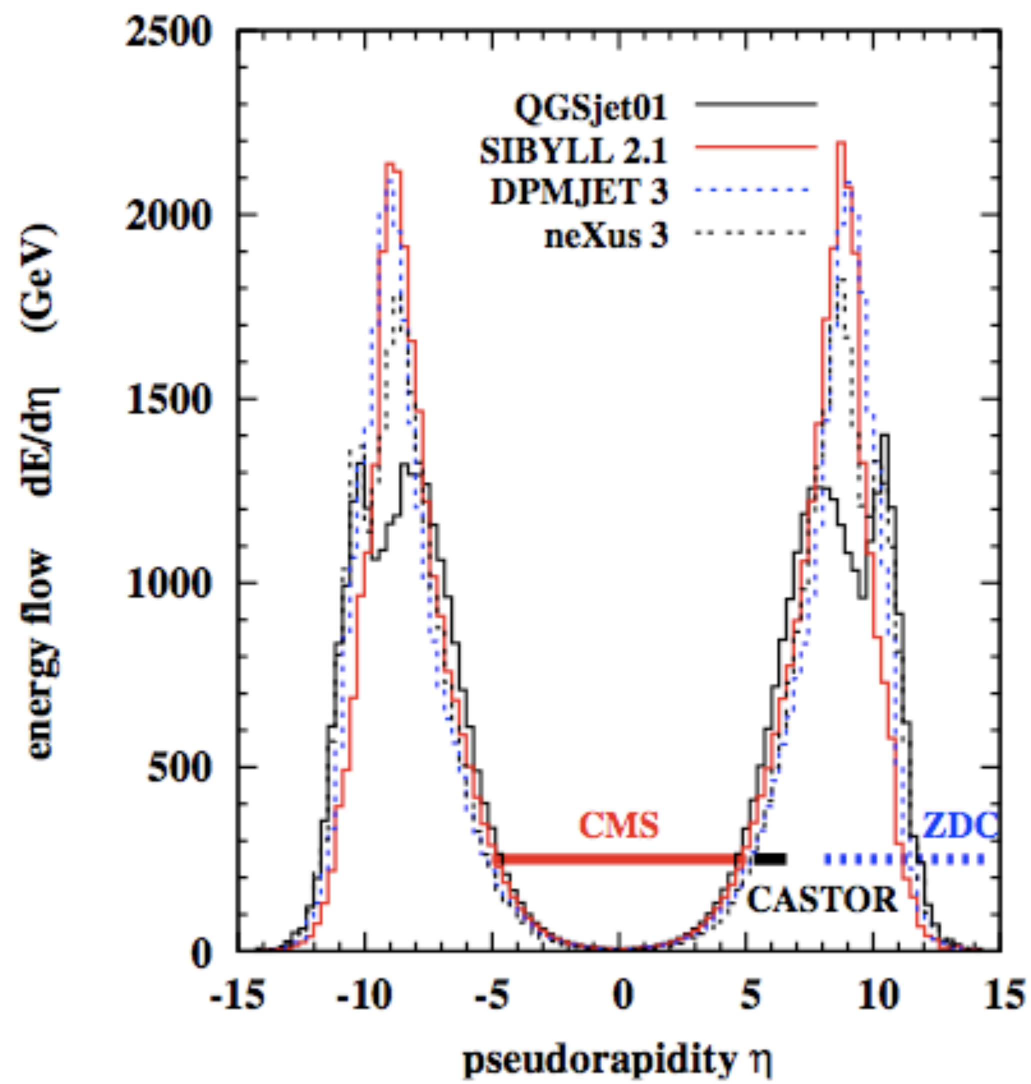
- hadron-nuclei collision (p π K beams) (N, O, Ar)

- nuclei-nuclei collision (N, O, Ar)

Transverse energy flow



Total energy flow



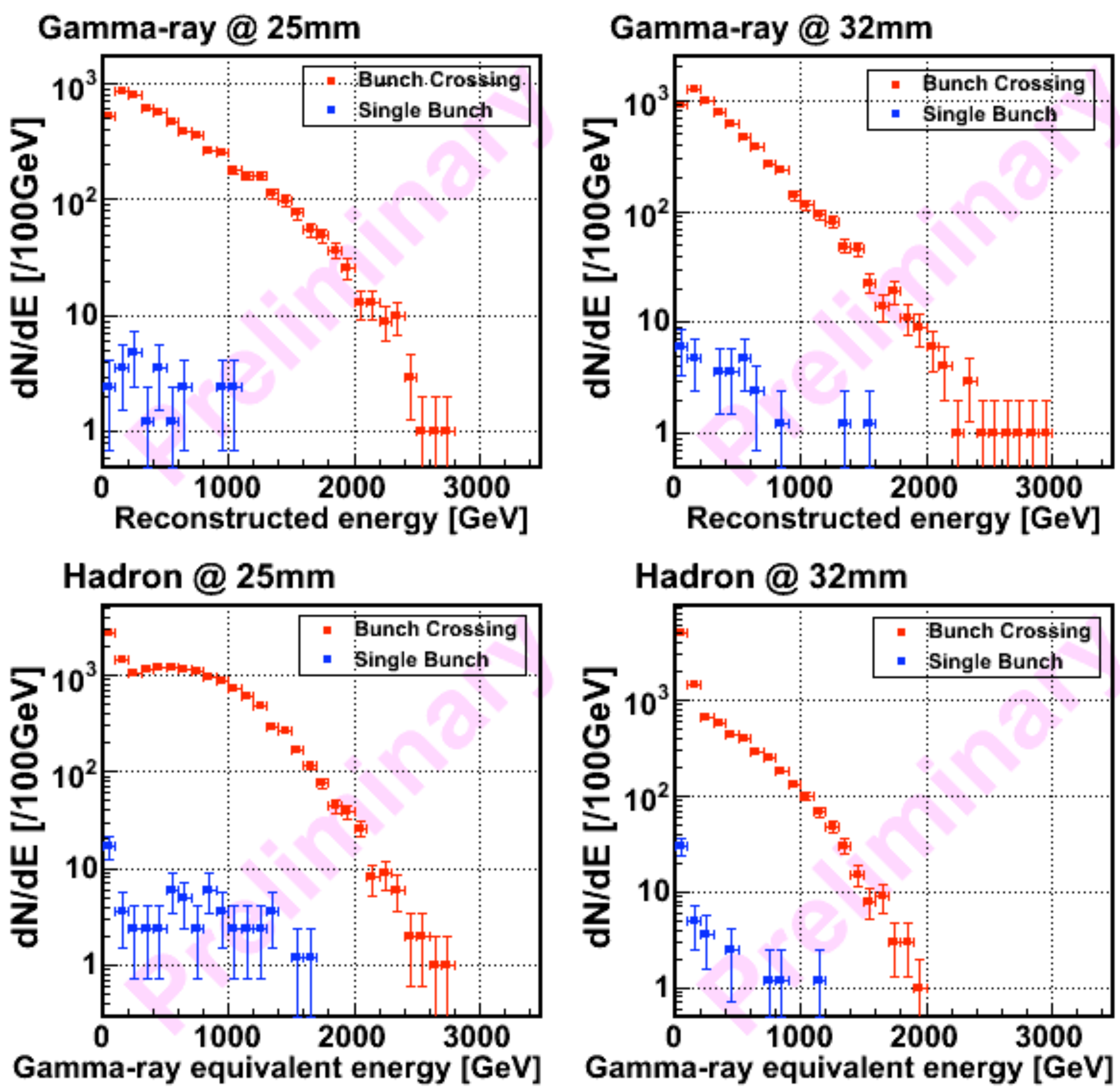
What cosmic ray physicists need

- Forward region - charged particle distribution
  - neutral particle distribution <- LHCf

- hadron-nuclei collision (p π K beams) (N, O, Ar)

- nuclei-nuclei collision (N, O, Ar)

|η| > 8.4, 0-deg

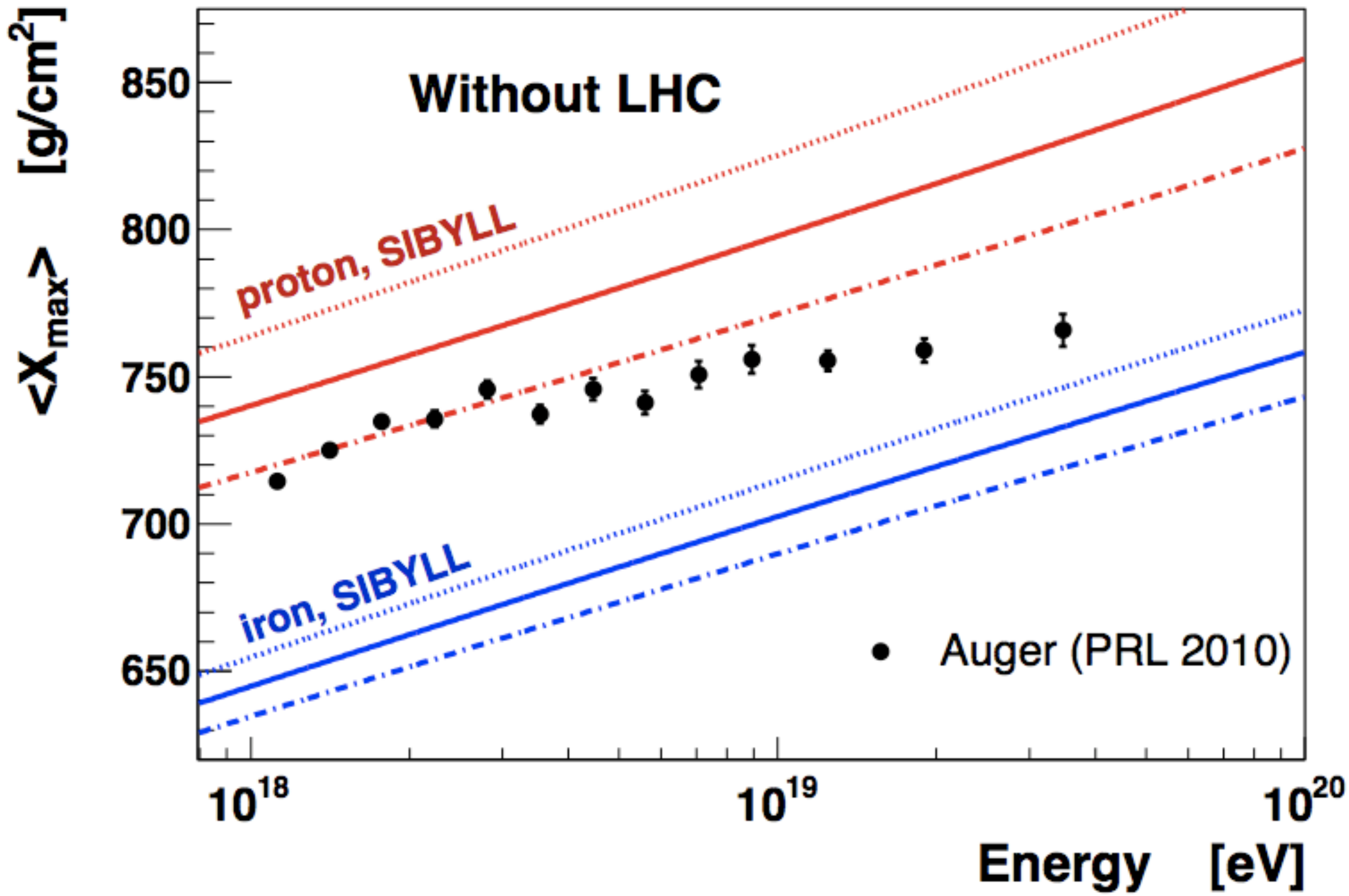


First data from

LHCf at 7 TeV

(T. Sako @ ISVHECRI 2010)

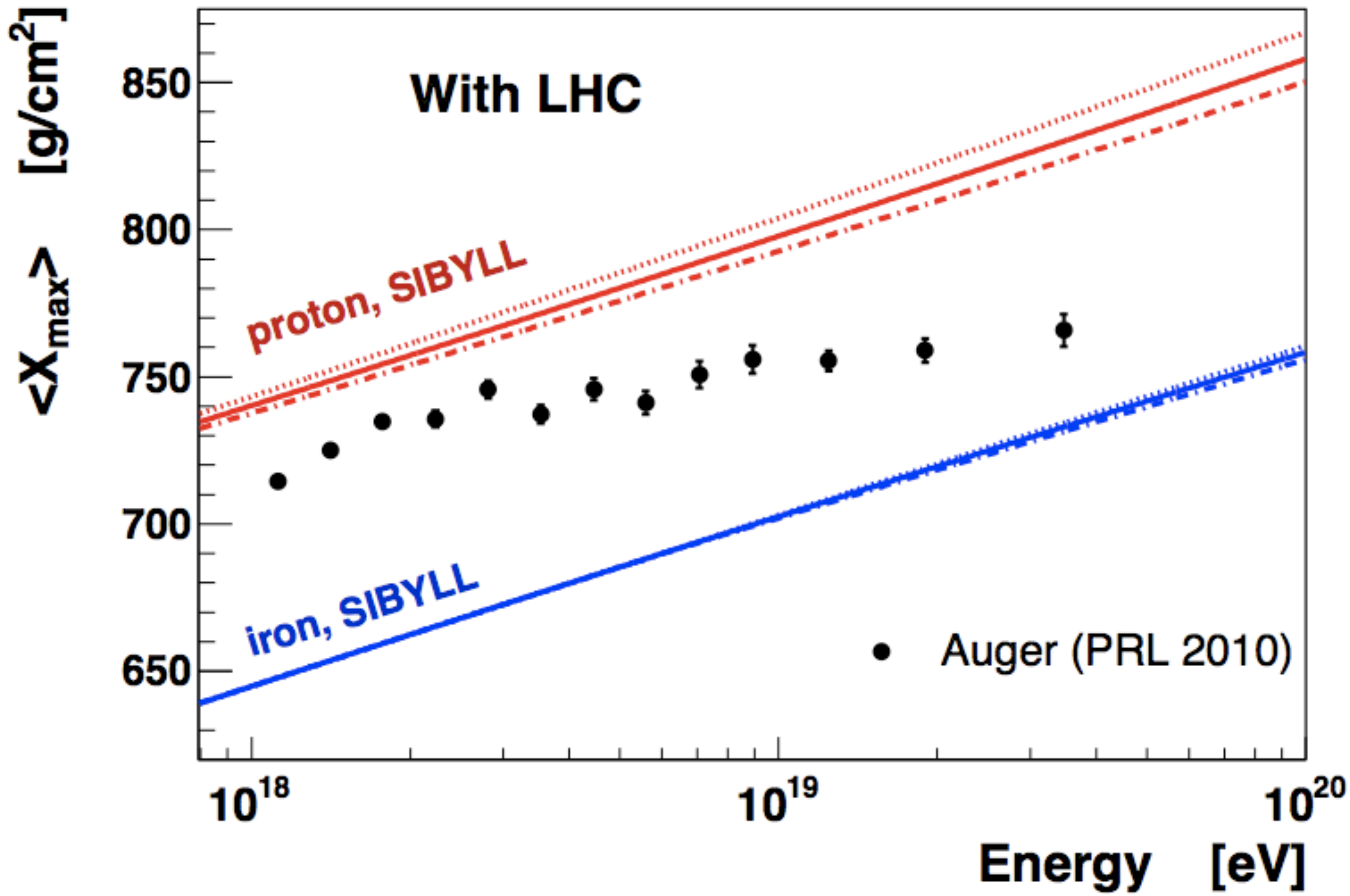
Example of what LHC could do for cosmic rays : elasticity



(R. Ulrich
@ ISVHECRI 2010)

- assuming everything is known until 300 GeV,
- extrapolate with 10% uncertainty per energy decade
- forward region information required.

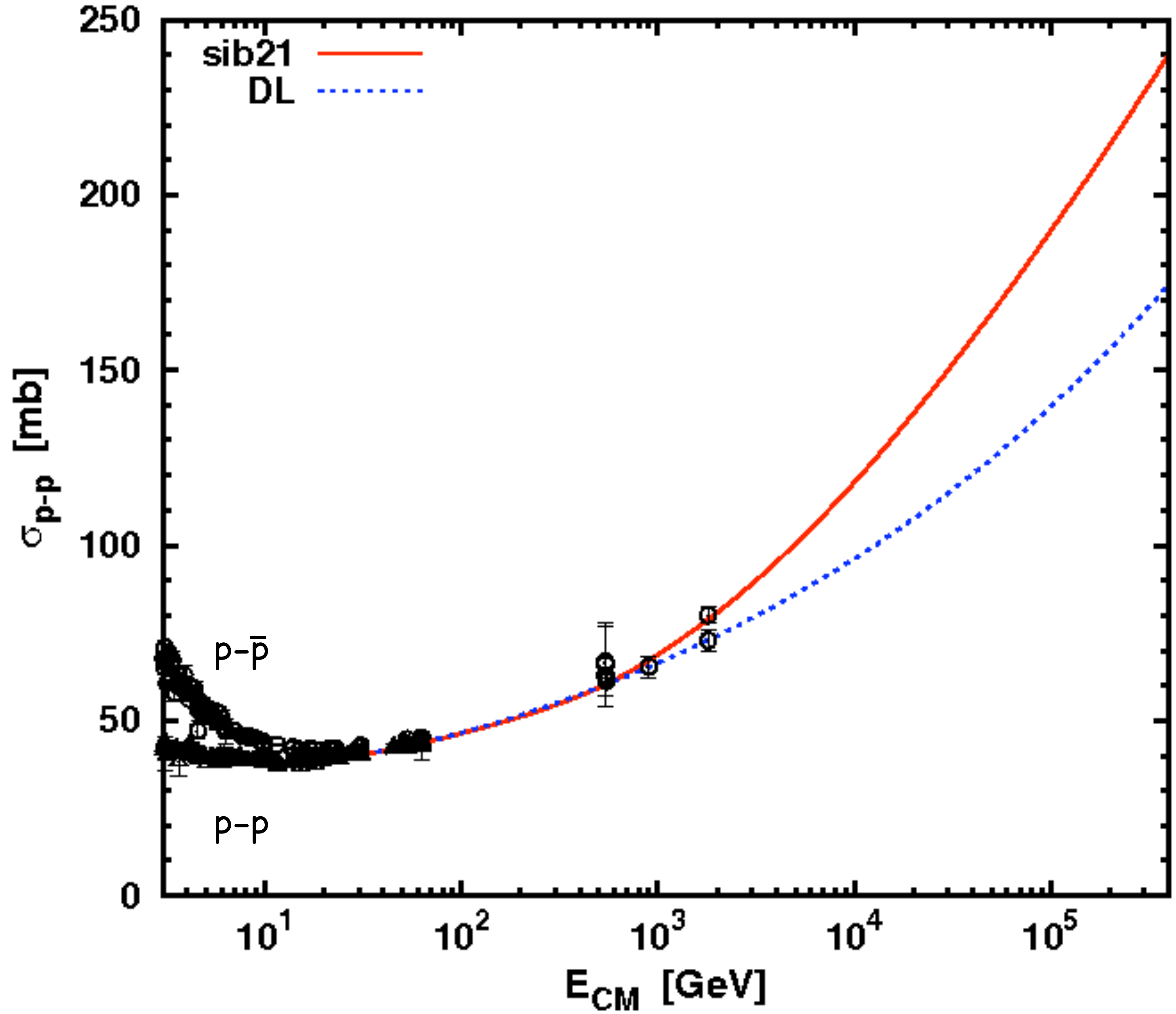
Example of what LHC could do for cosmic rays : elasticity



(R. Ulrich @ ISVHECRI 2010)

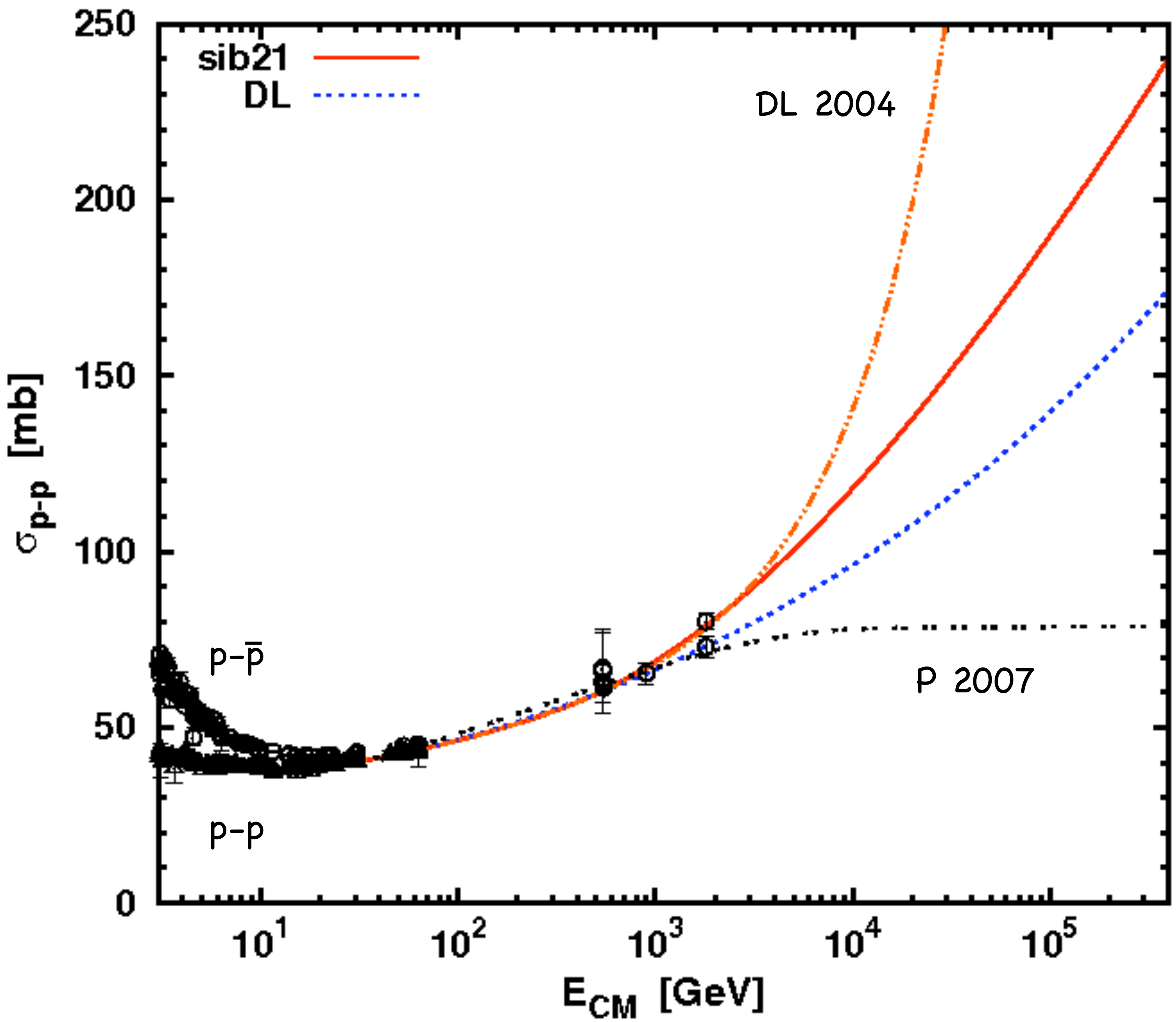
- assuming everything is known until 14 TeV,
- extrapolate with 10% uncertainty per energy decade
- forward region information required

Testing cases of σ_{p-p} for effect on X_{max}



- Sibyll 2.1 - highest for cosmic ray MCs
- Donnachie & Landshoff 1992 - good prediction for Tevatron

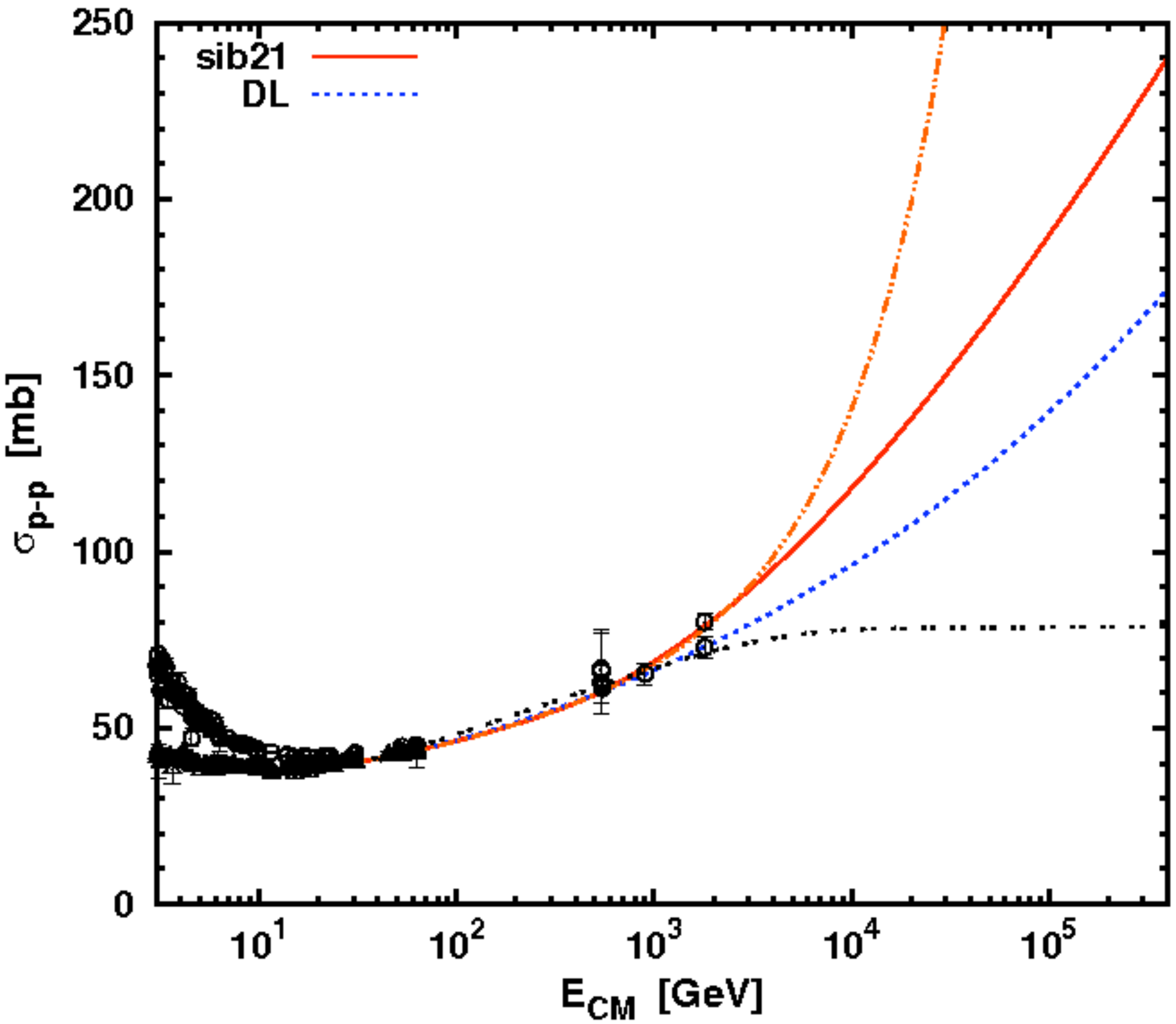
Testing cases of $\sigma_{p\text{-}p}$ for effect on X_{max} : extreme values

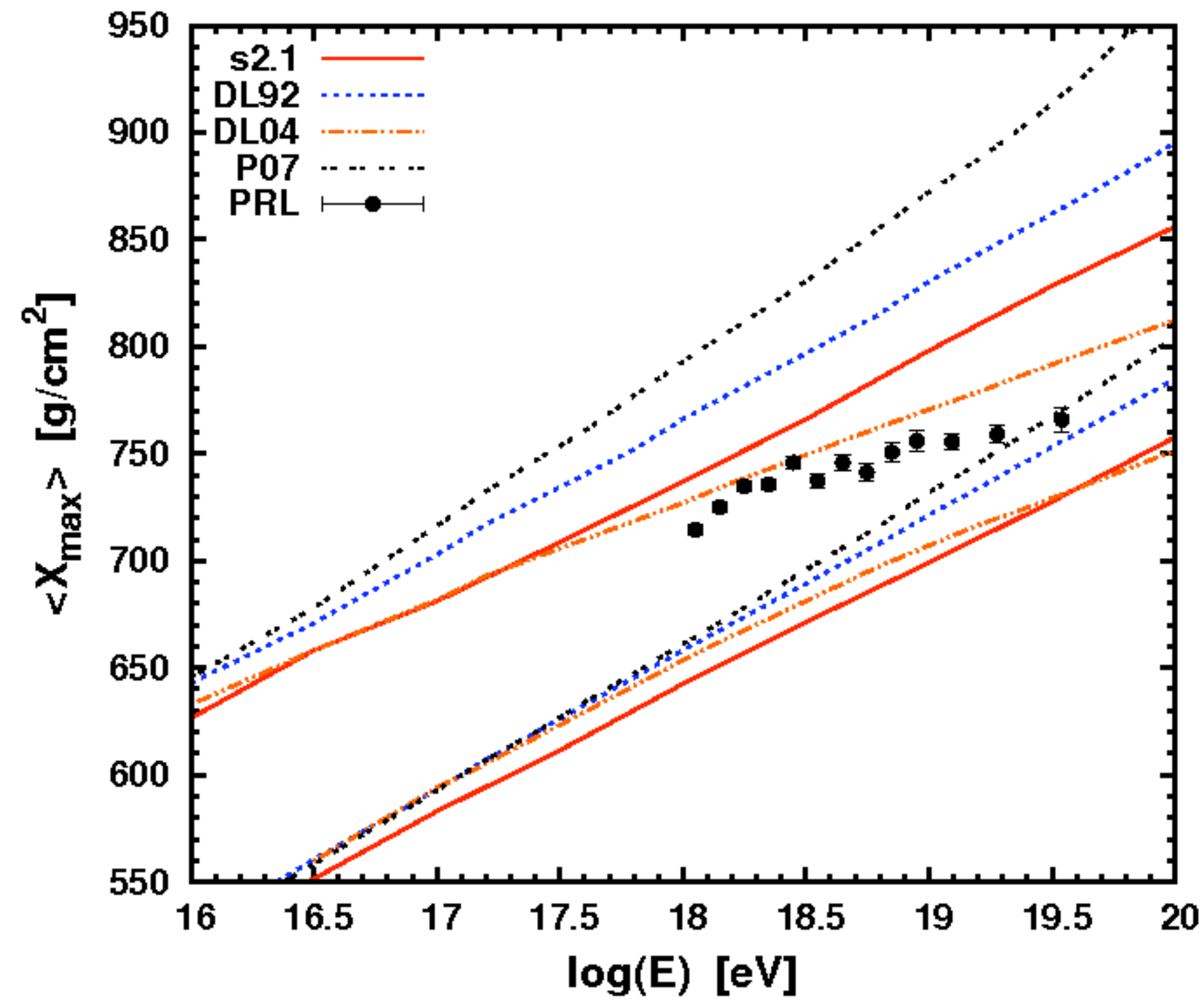


- Donnachie & Landshoff (2004) : hard pomeron term added <- highest

- Pancheri et al (2007) : soft gluon resummation (CTEQ) <- lowest

Testing cases of σ_{p-p} for effect on X_{max} : extreme values



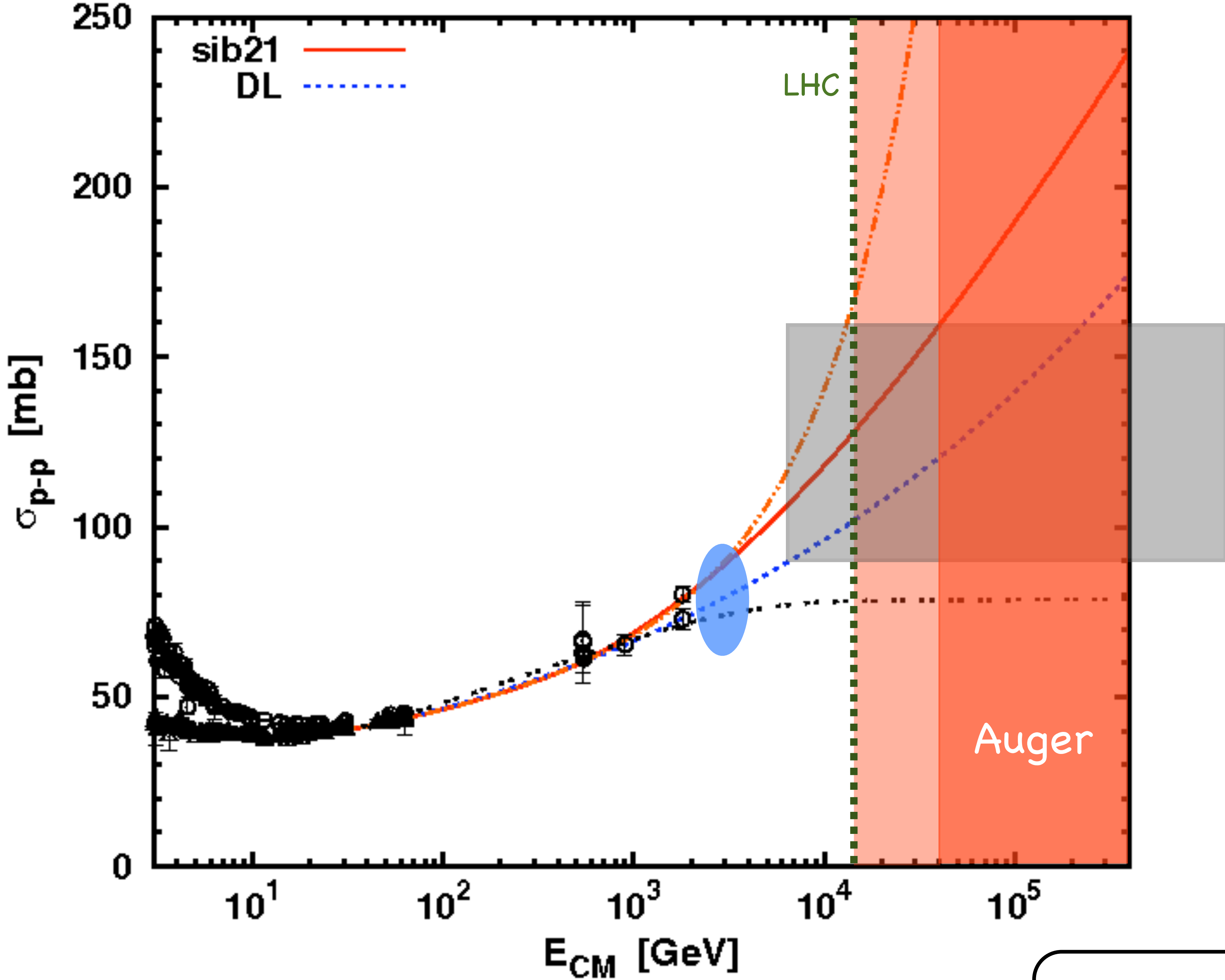


(simulation thanks to S. Timm & FermiGrid team)

- range of X_{max} depends on the cross section model

- composition can vary p <-> Fe depending on cross cross section

Data and prediction of $\sigma_{p\text{-}p}$



125 ± 35 mb?
(P. Landshoff)

107.3 ± 1.2mb?
(M. Block)

e.g. $\sigma_{p\text{-}air}$ (40 TeV) ≈ 800 mb
if CRs are protons

★ LHC can tell us which theory is better

★ Auger can tell us which theory is better, **up to a higher energy**

Summary

- Auger measured 3754 high quality hybrid events for X_{max} :
  - change in composition suggested,
  - fluctuation decreases at high energies
  - heavy nuclei with increasing energy

    OR

  - hadronic interaction model needs substantial modifying

- Particle accelerator data useful and crucial to understand cosmic rays;

- LHC bridges gap between manmade and natural particle accelerators;

  based on this,

- Auger can probe particle physics beyond LHC.