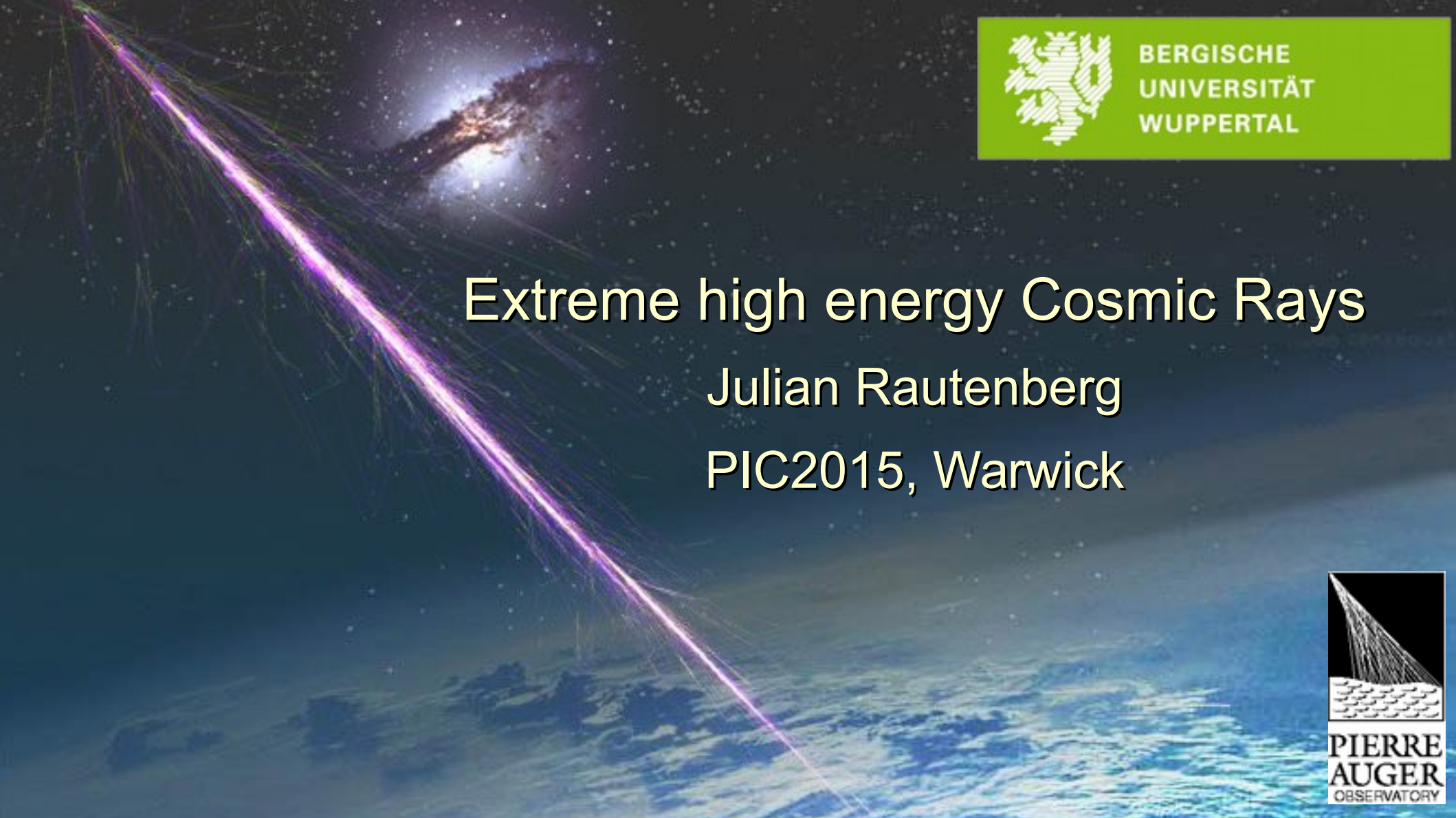
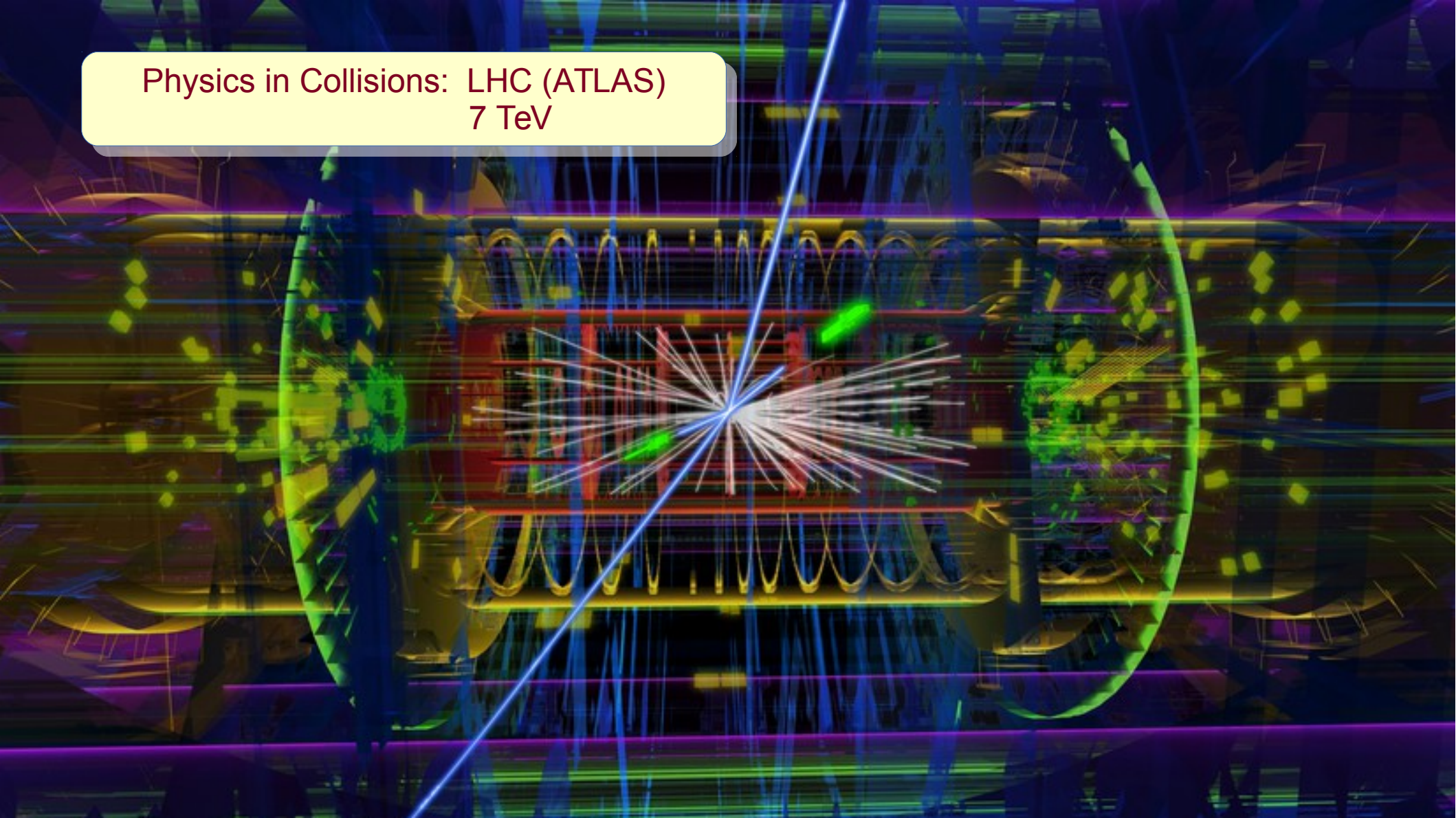
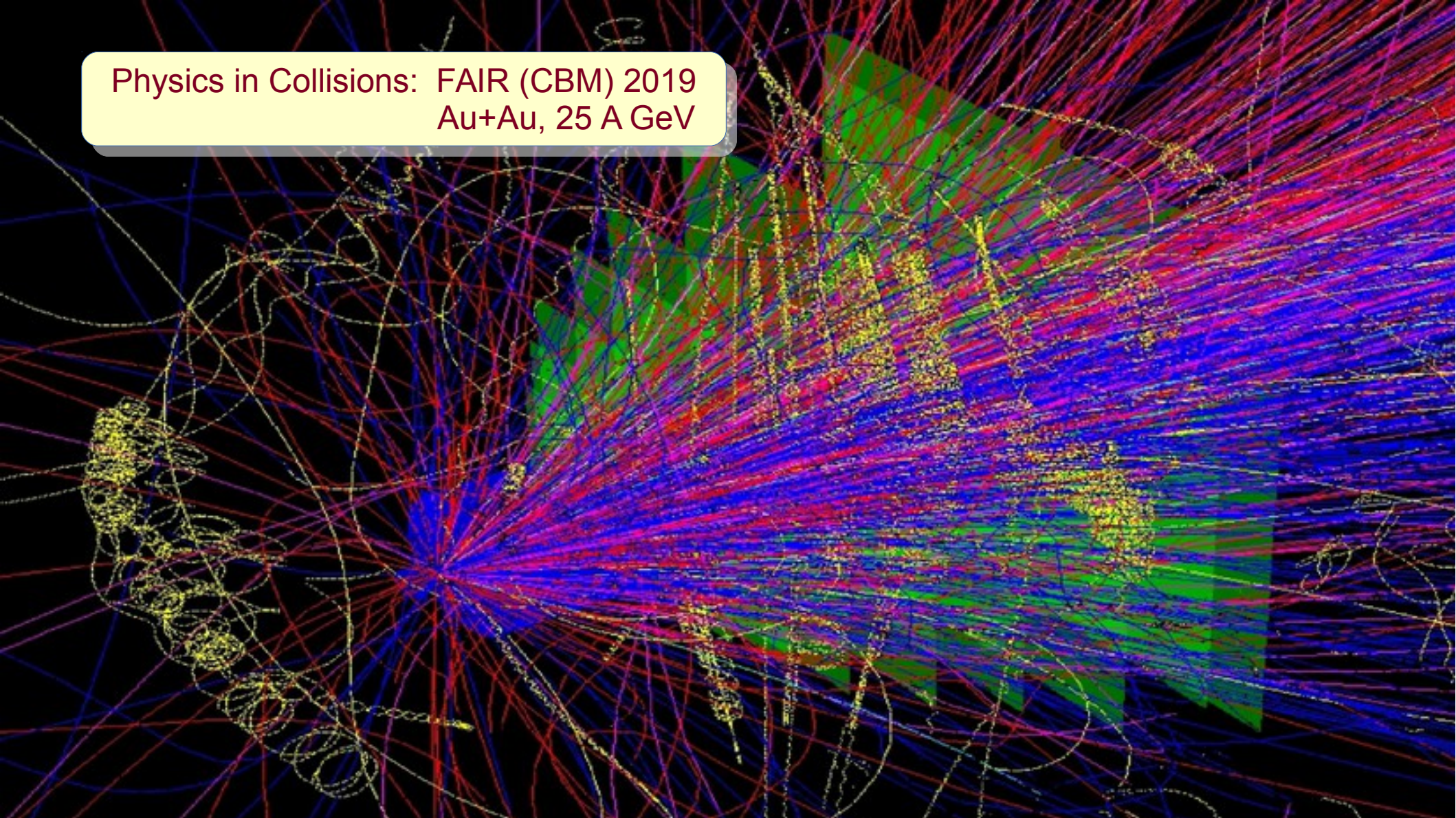


Extreme high energy Cosmic Rays

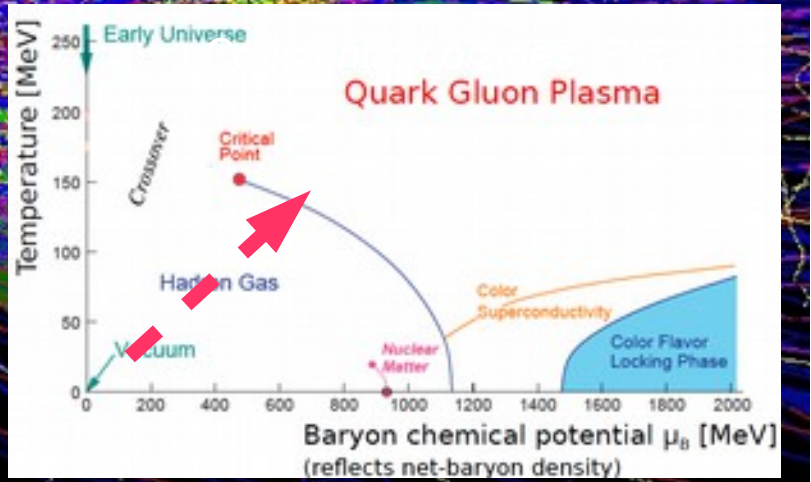
Julian Rautenberg

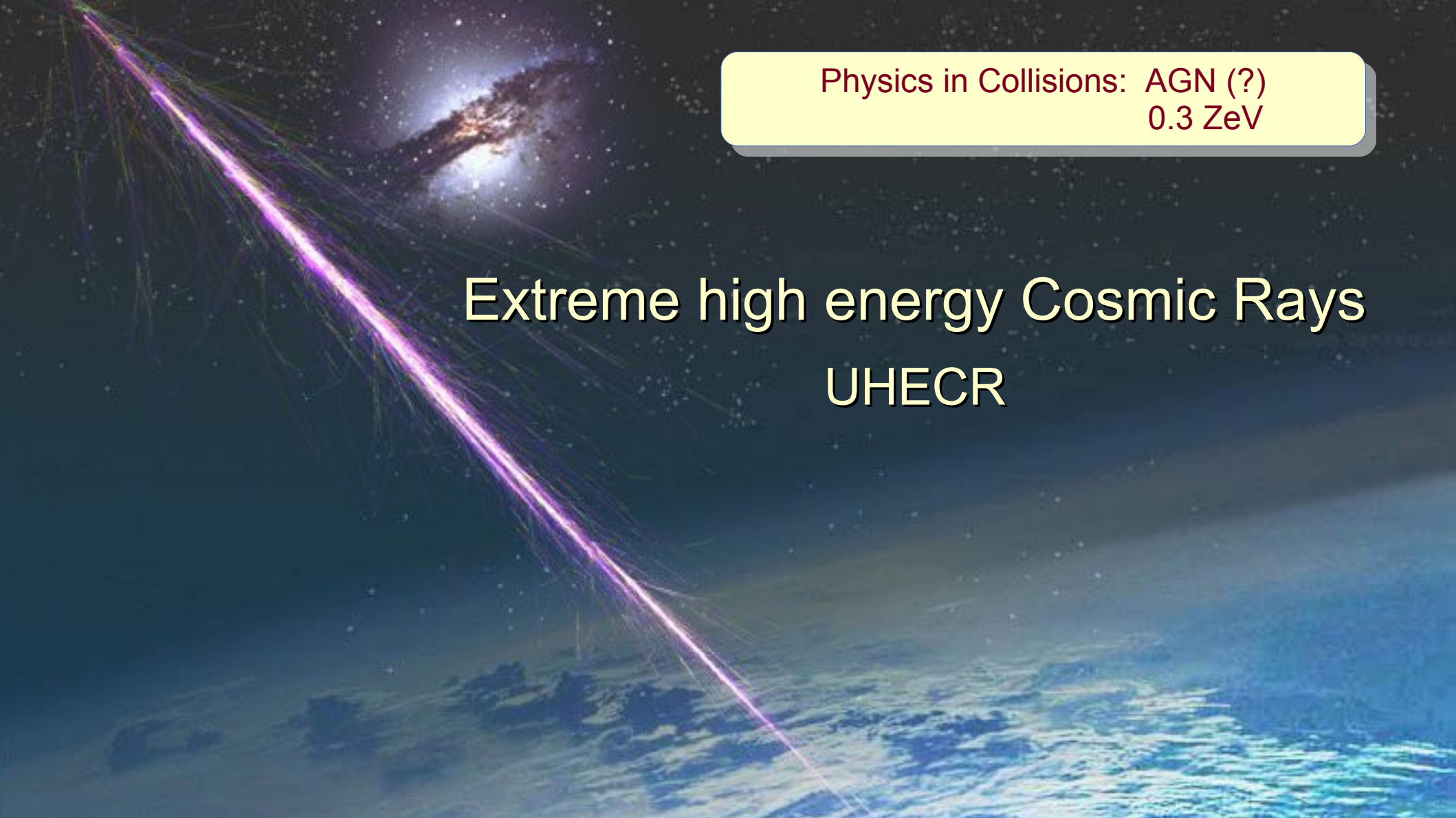
PIC2015, Warwick


Physics in Collisions: LHC (ATLAS)
7 TeV


Physics in Collisions: FAIR (CBM) 2019
Au+Au, 25 A GeV

Physics in Collisions: FAIR (CBM) 2019
Au+Au, 25 A GeV



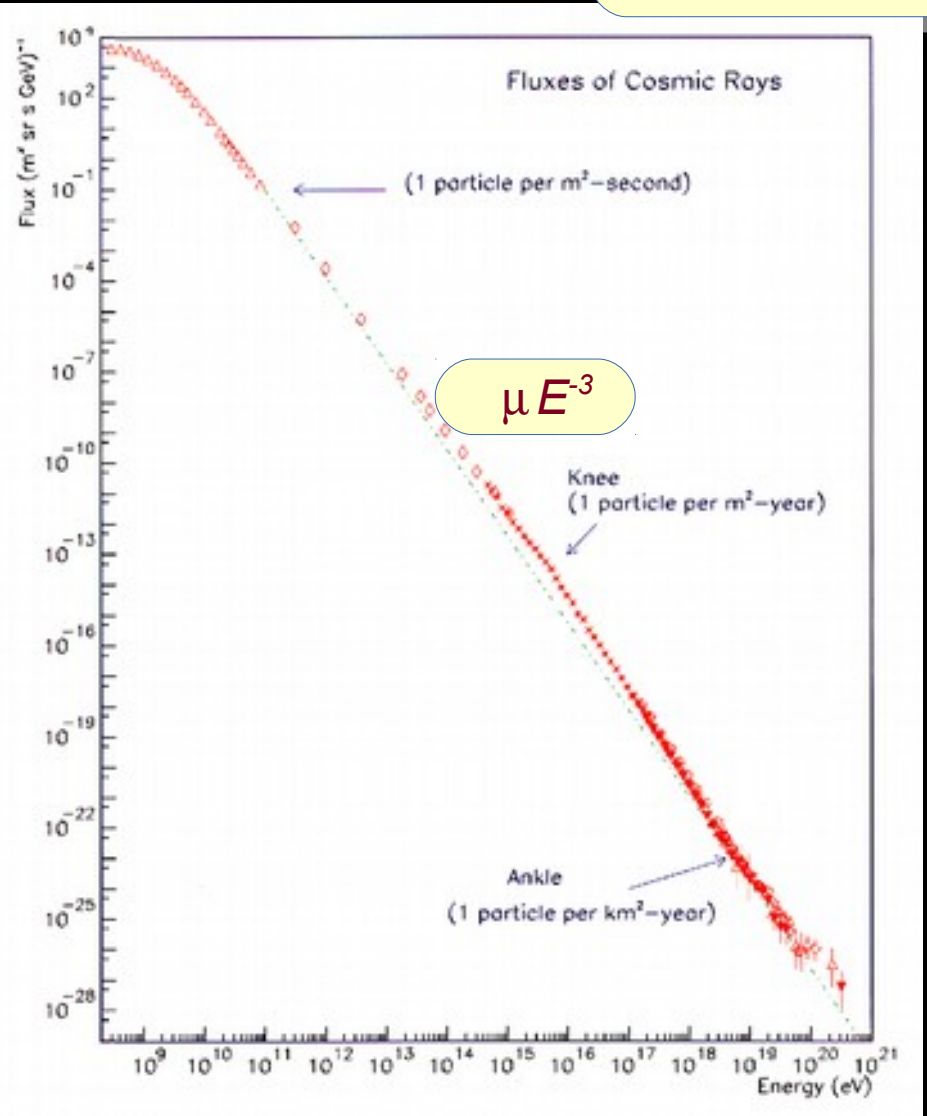


Physics in Collisions: AGN (?)
0.3 ZeV

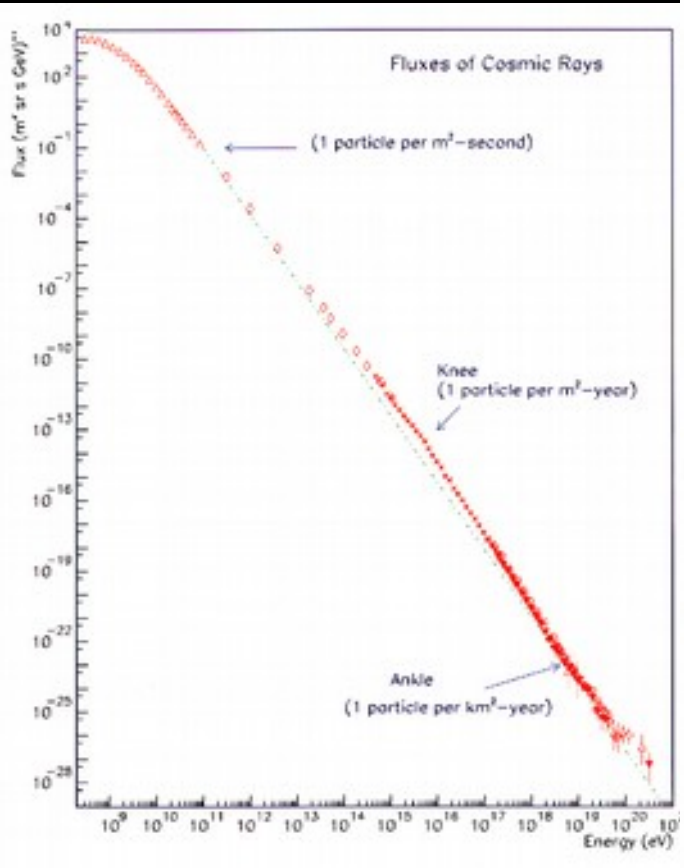
Extreme high energy Cosmic Rays

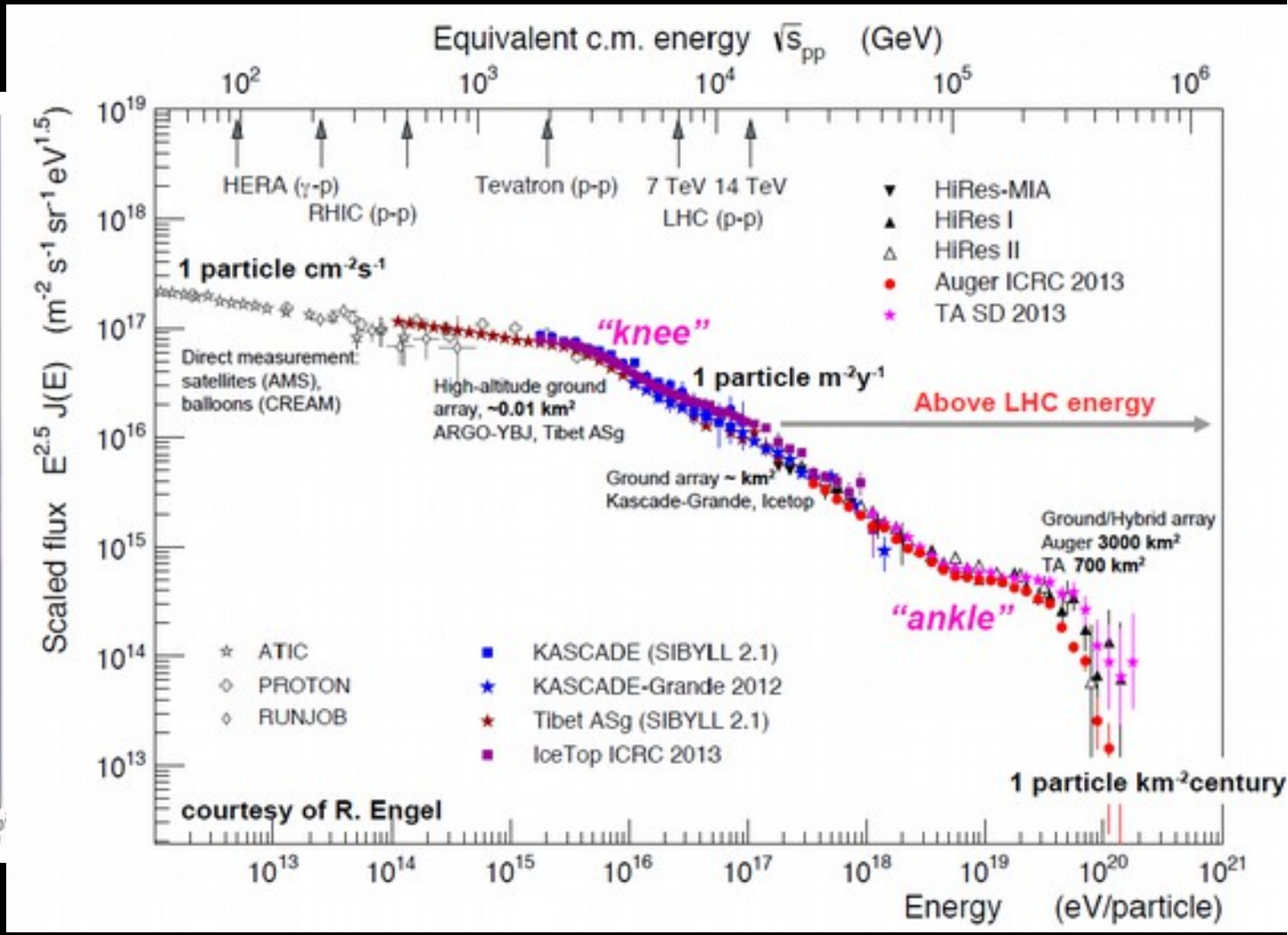
UHECR

The Flux of the Cosmic Rays

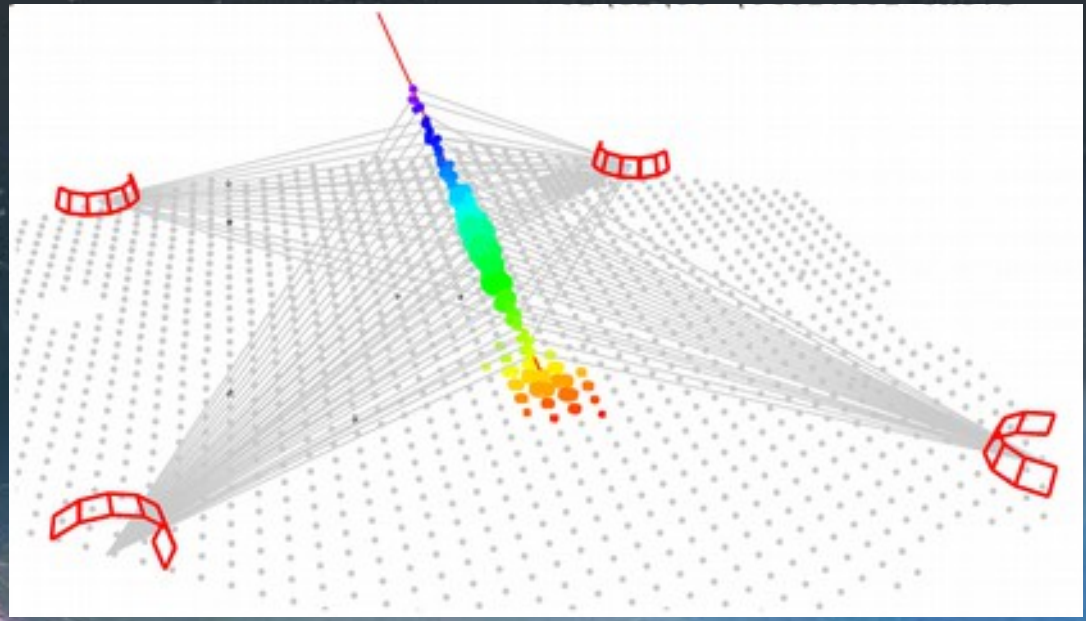


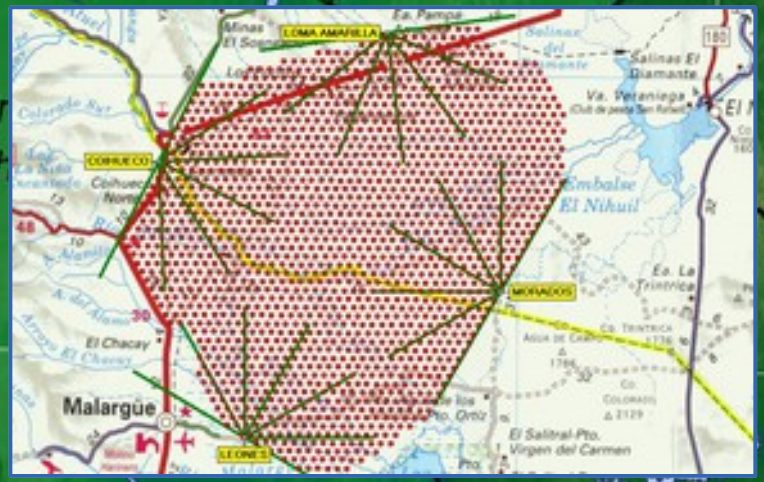
The Flux of the Cosmic Rays





EAS: 15 km shower development





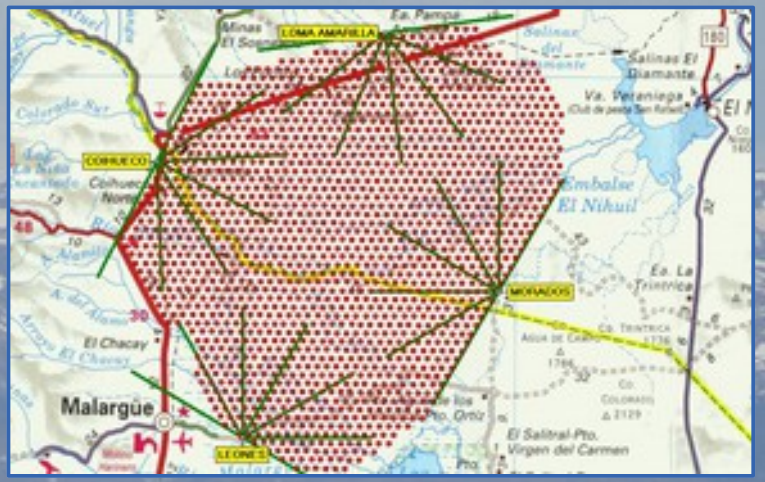
Pampa Amarilla
Province of Mendoza
1400 m a.s.l.
35° South, 69° West
3000 km²

Pierre Auger Collaboration:
>490 scientists
from 17 countries

PIERRE AUGER OBSERVATORY

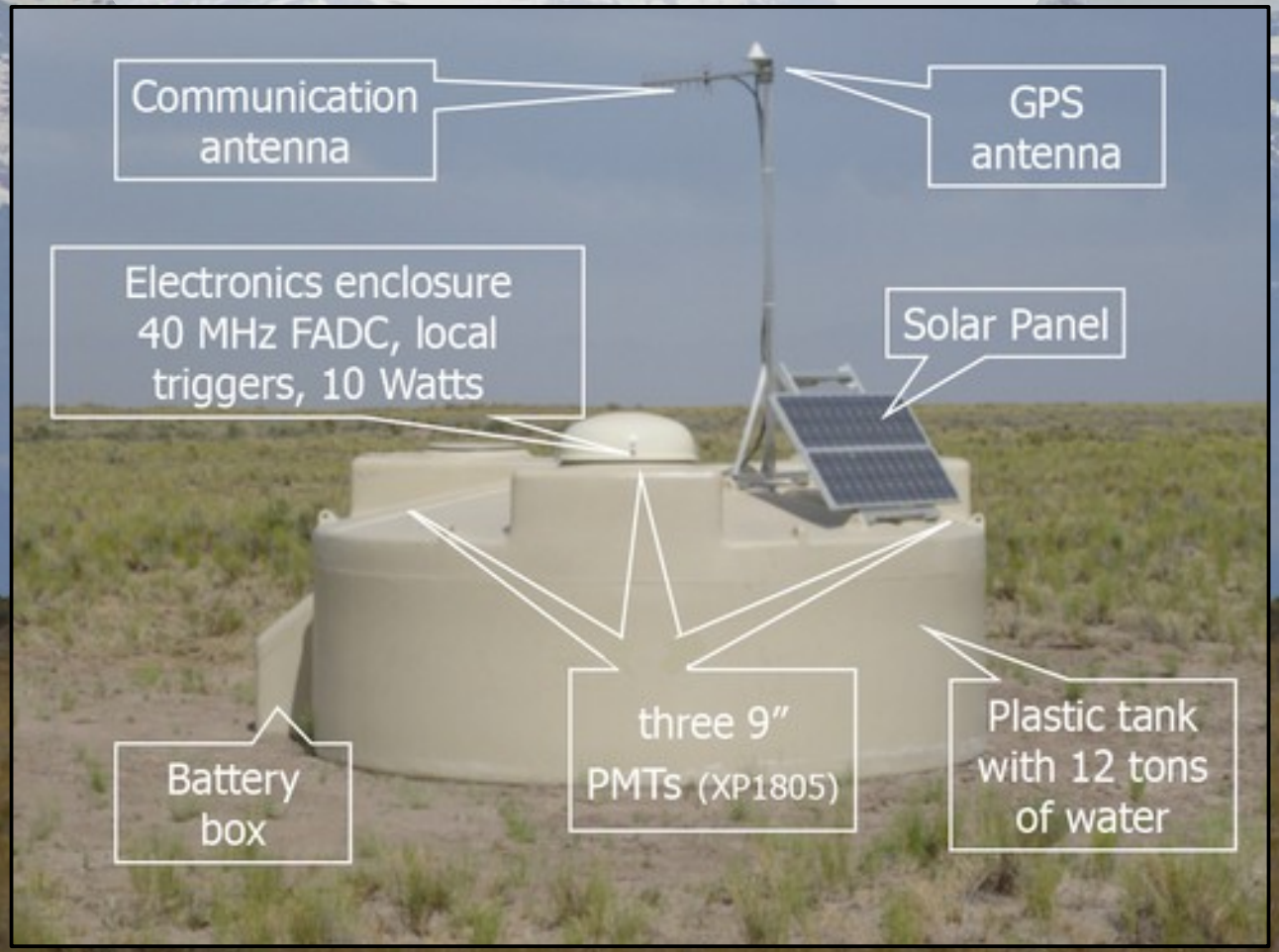
Córdoba
Mercedario
Aconcagua
Mendoza
Tupungato
BUENOS AIRES
Río de la Plata
Uruguay
Chile

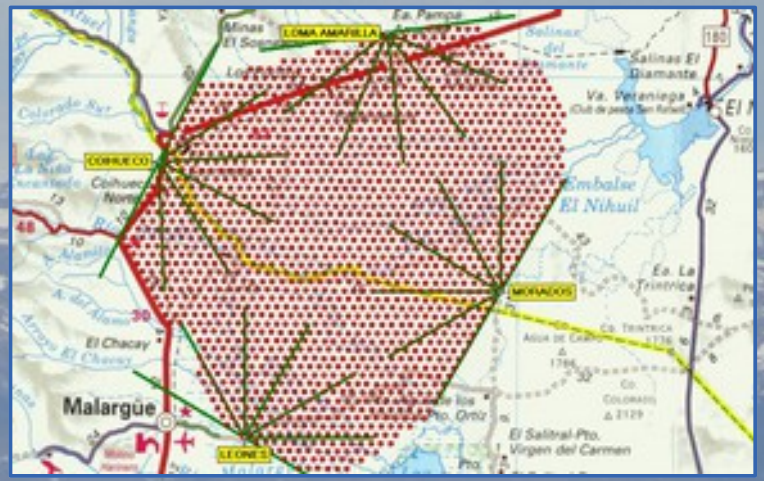
Surface Detector (SD)



1660 Detectors
1.5 km spacing
Triangular grid
Continuous data-taking
Infill on half gridsize

Surface Detector (SD)



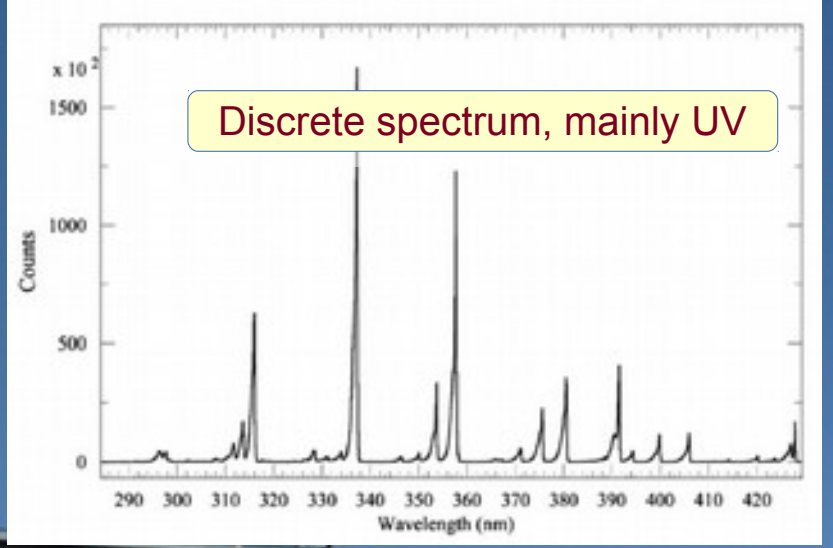


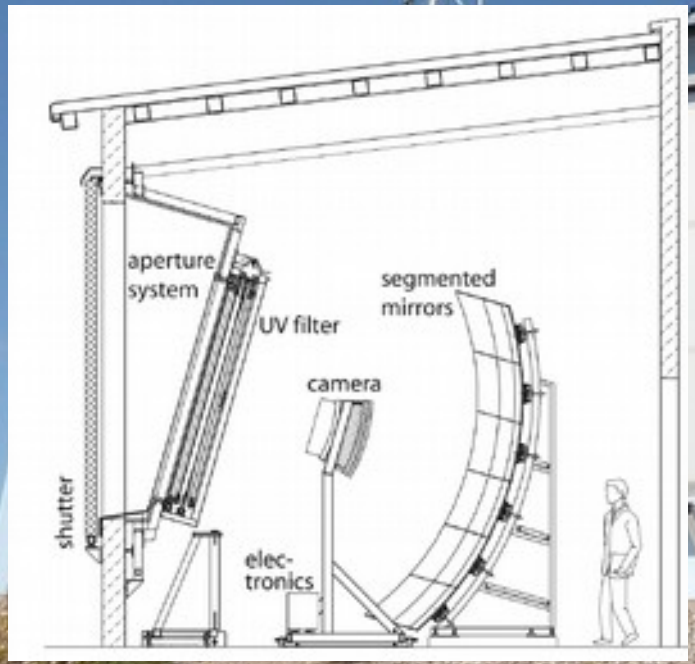
1660 Detectors
1.5 km spacing
Triangular grid
Continuous data-taking
Infill on half gridsize

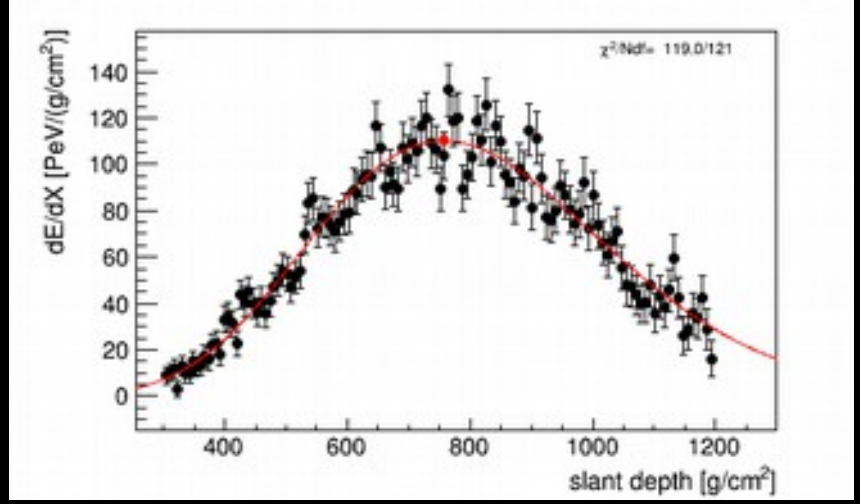
Fluorescence Detector (FD)

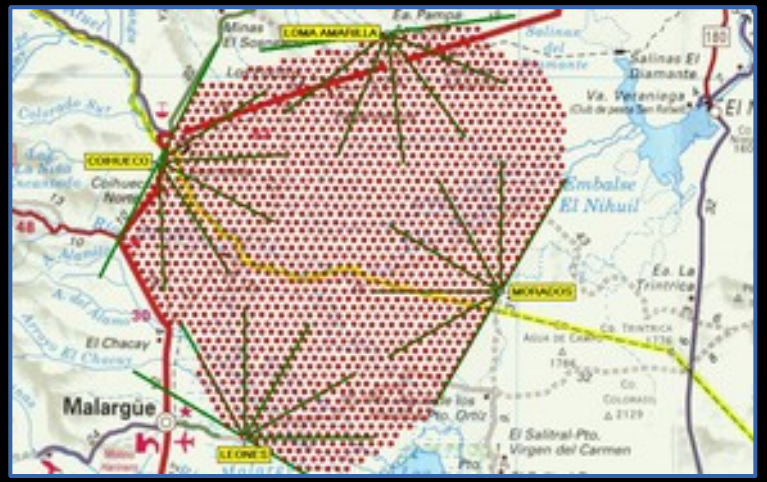
Fluorescence Detector (FD)

4x6 Telescopes (+3)
440 PMT camera
Uptime ca. 15%



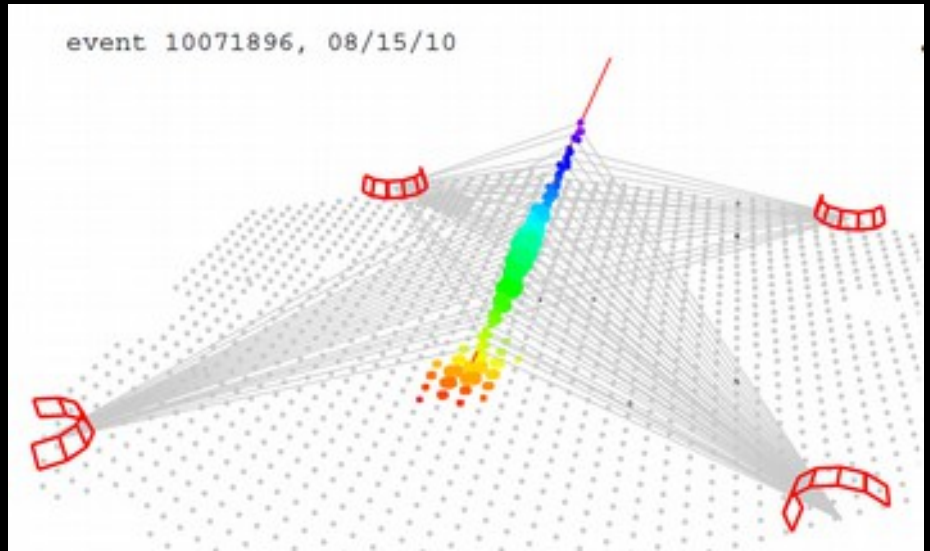


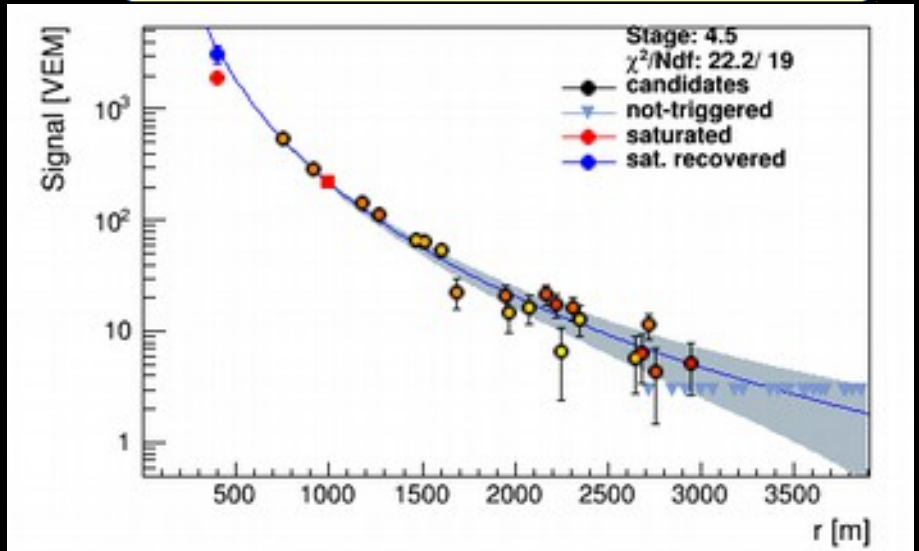




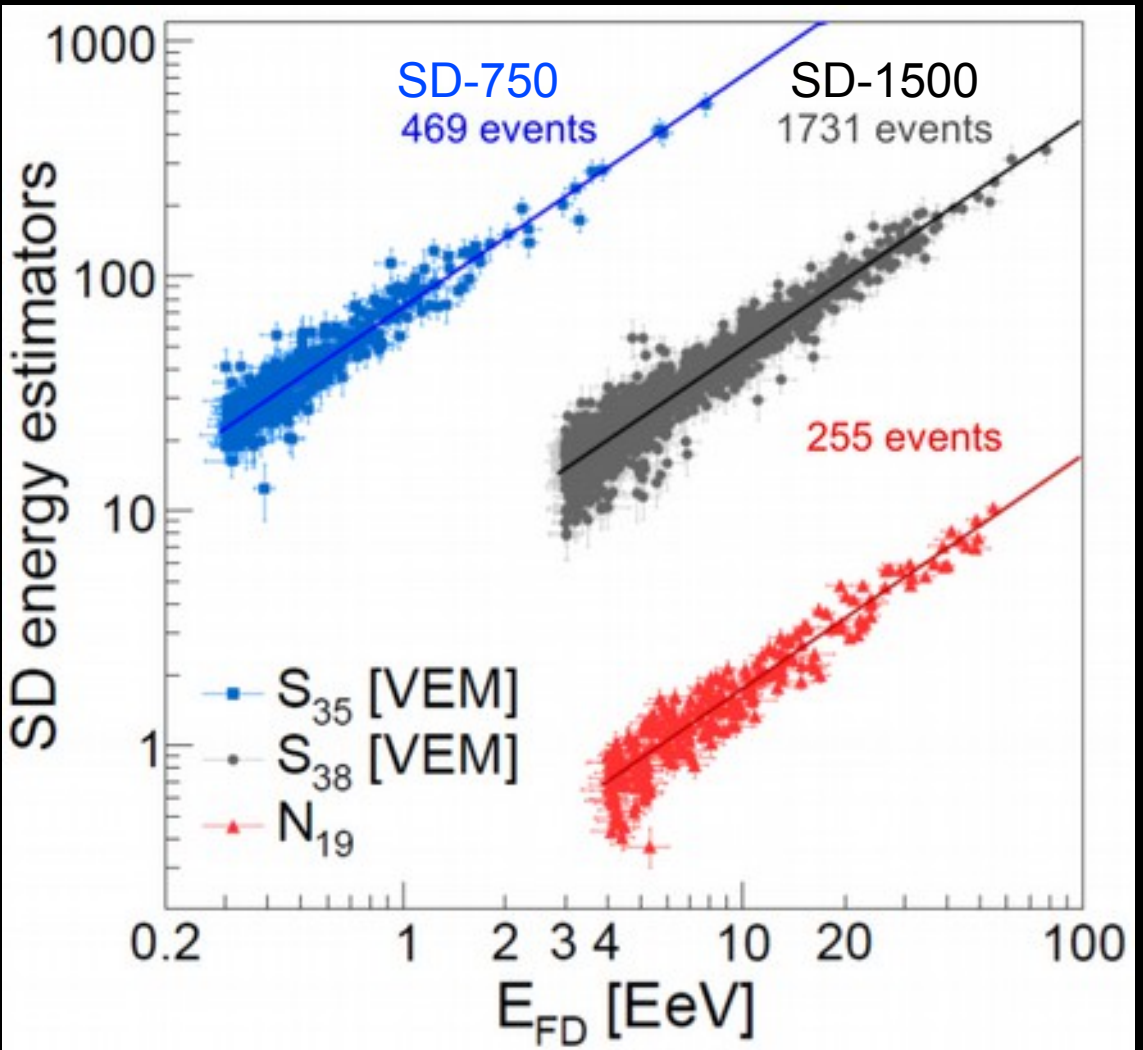
FD: longitudinal development

SD: lateral distribution





Energy Calibration Pierre Auger Observatory



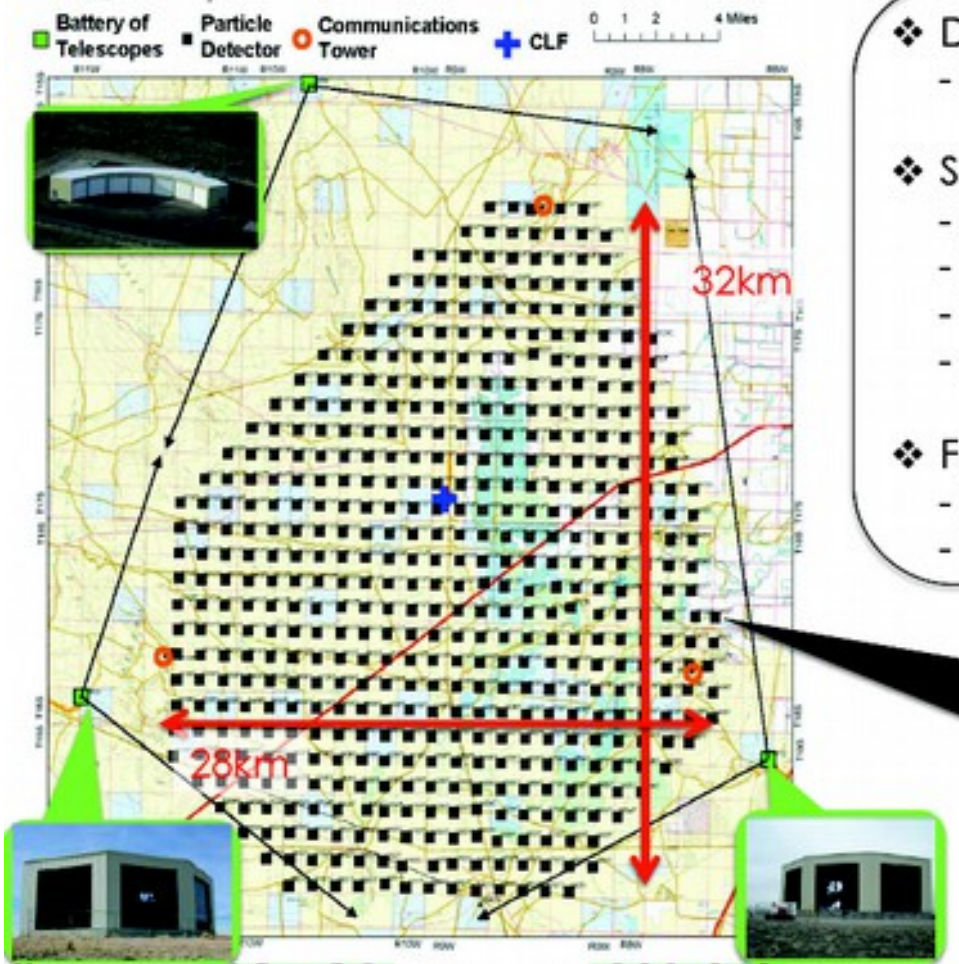
FD: dE/dx (EM)
- ++ well understood,
- –– but attenuation in atmosphere needs proper monitoring

SD: particles from hadronic interactions
- –– large uncertainties

Use Fluorescence Detector
to calibrate Surface Detector

Result: 15% energy uncertainty

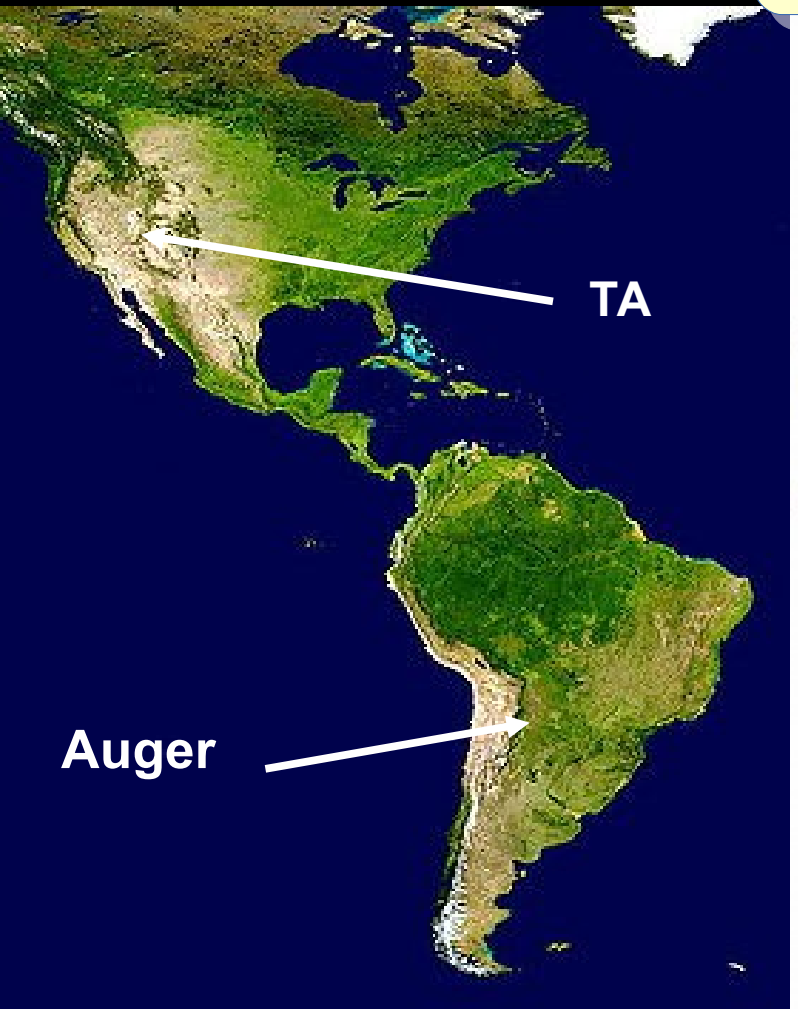
Telescope Array Experiment

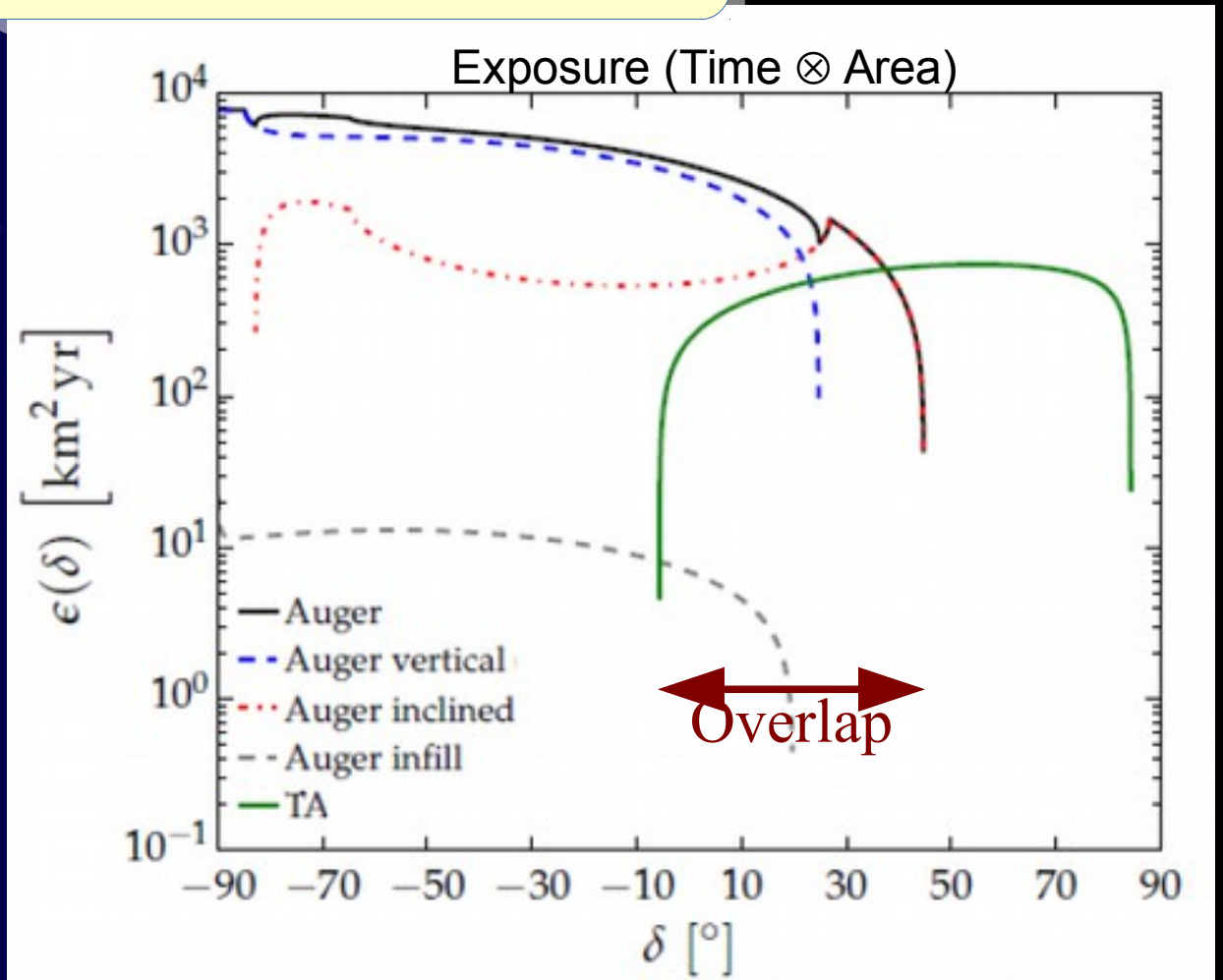


- Desert in Utah, USA
  - 39.30°N, 112.91°W, 1400m a.s.l.
- Surface Detector (SD)
  - 3m^2 Scintillation Detector
  - 507 det. with 1.2km spacing
  - Distributed across 700km^2
  - Operating since 2008
- Fluorescence Detector (FD)
  - 3 stations
  - 12 telescopes / station

K. Kawata
ICRC 2015

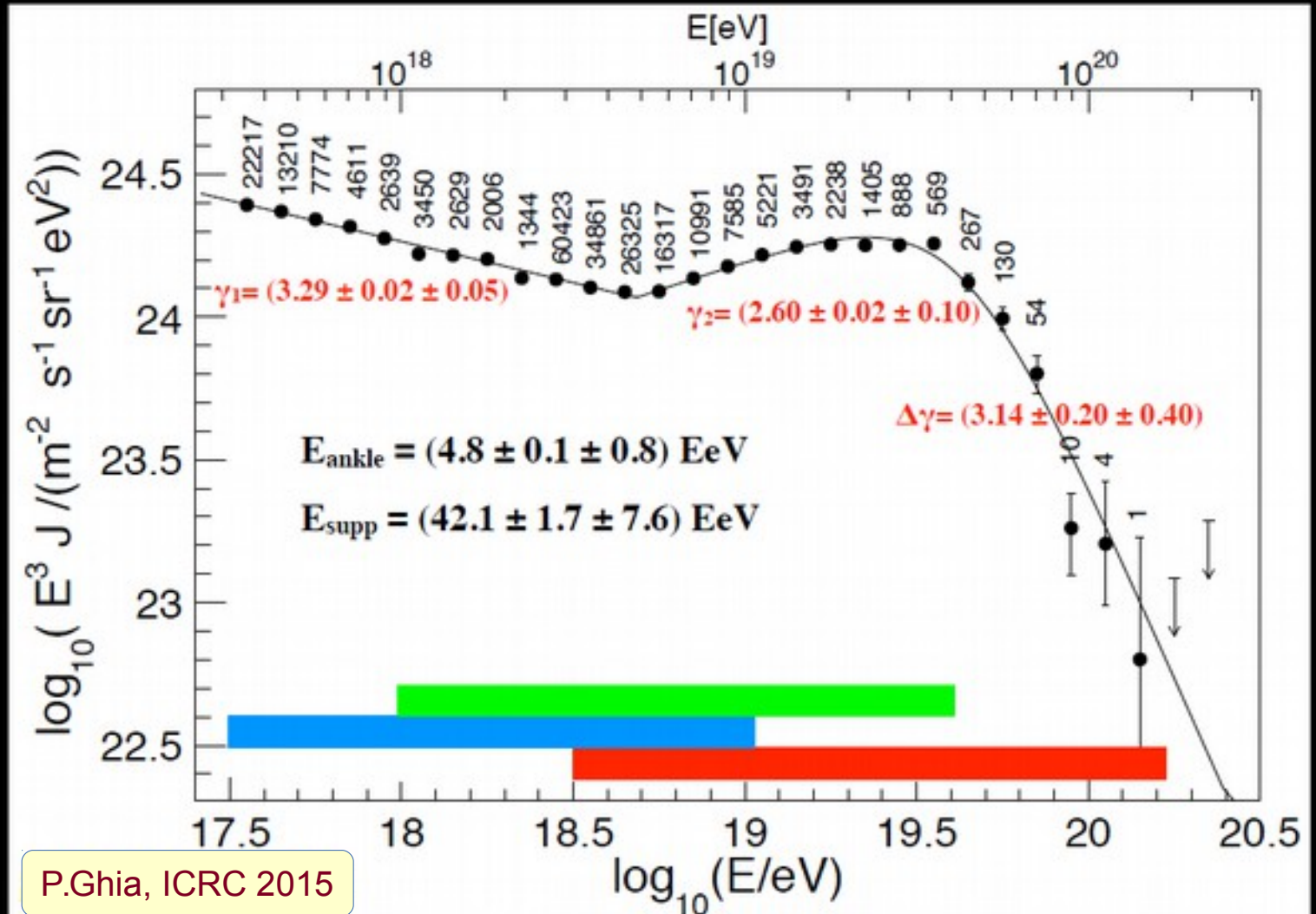
Complementary in declination
Exposure: Auger ca. 8x TA





4 data sets combined: SD 750 m, FD (hybrid), SD 1500 m (0-60˚), SD 1500 m (60-80˚)

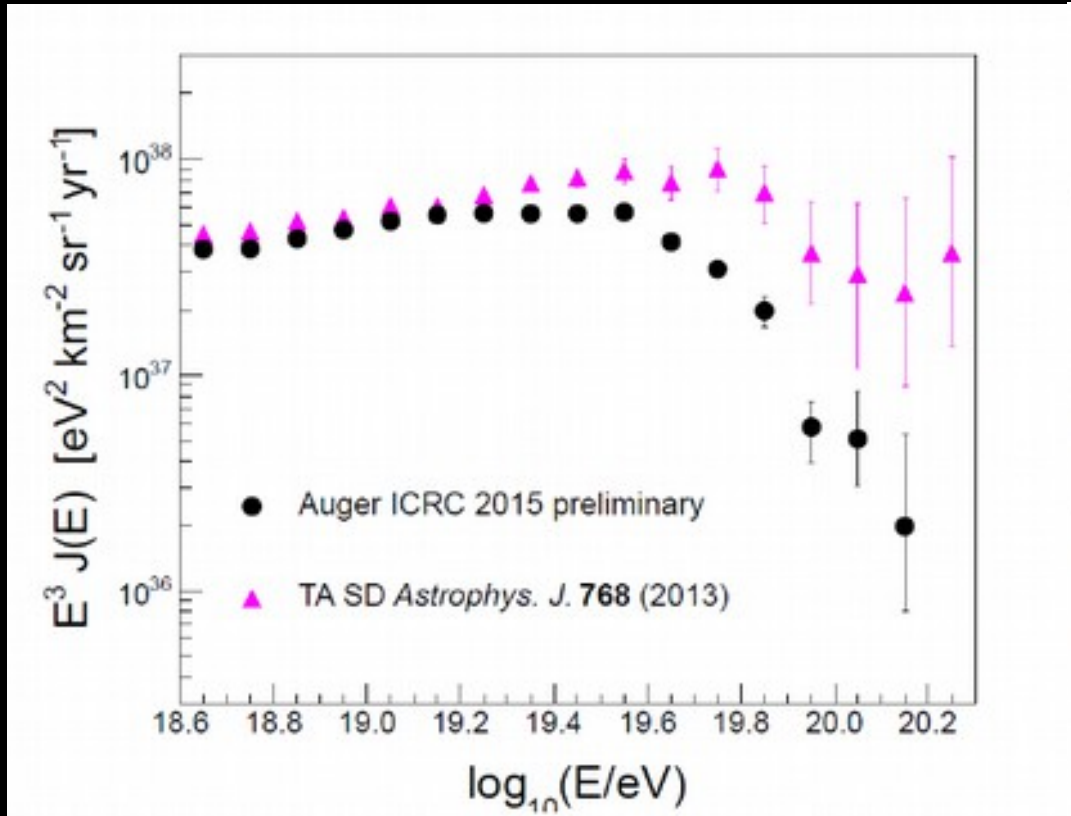
≈ 200 000 events, ≈ 50000 km² sr yr exposure, FOV: -90˚, +25 in δ

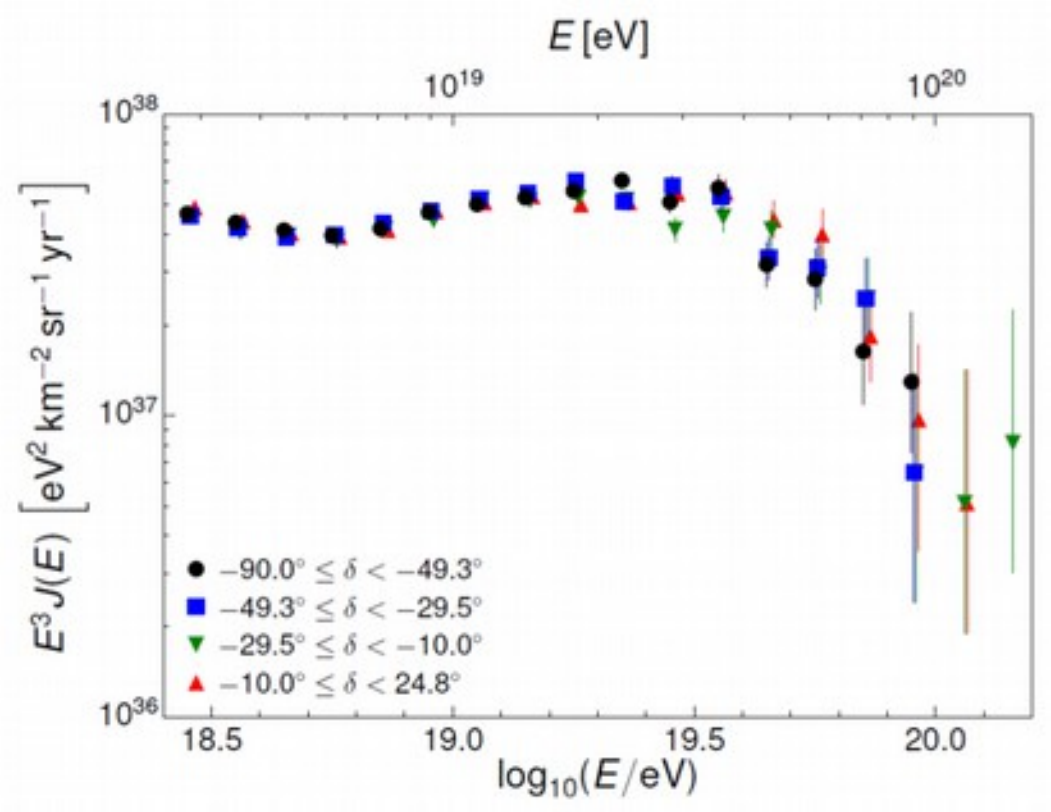


P.Ghia, ICRC 2015

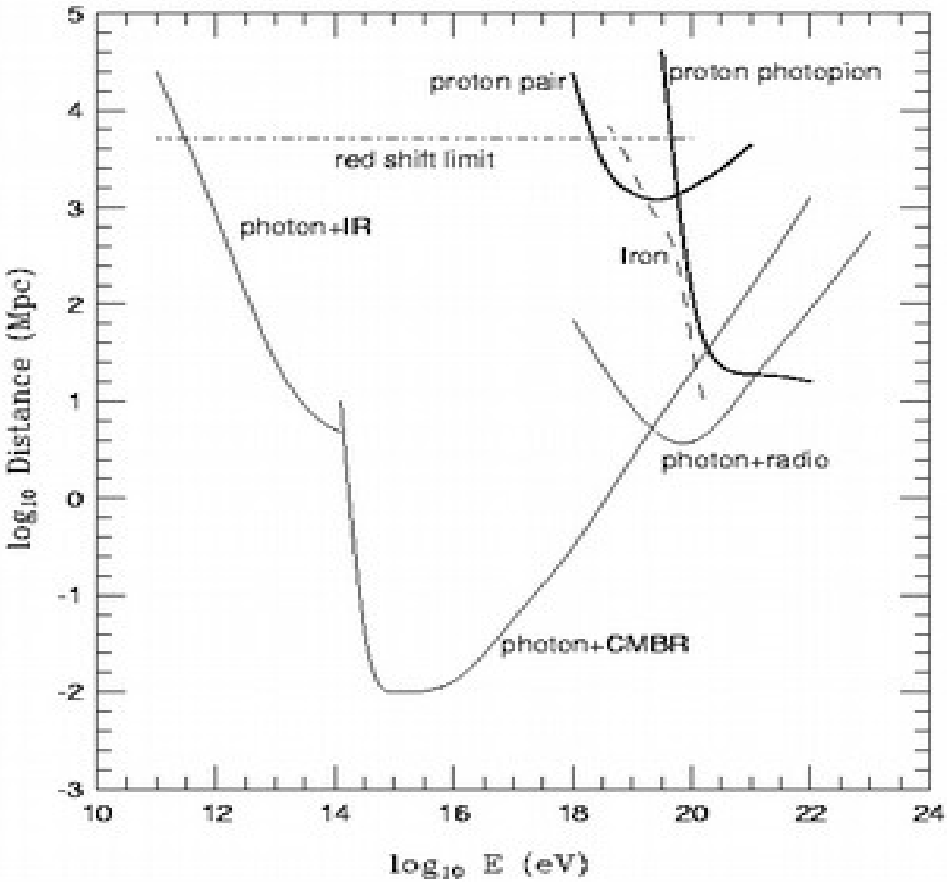
Discrepancy between Auger and TA
Energy-scale? Fluorescence yield?

Auger: desclination independant !
ICRC2015#271





End of the spectrum?



Greisen Zatsepin Kuz'min effect (1966):
Interaction with the cosmic microwave background (CMB)

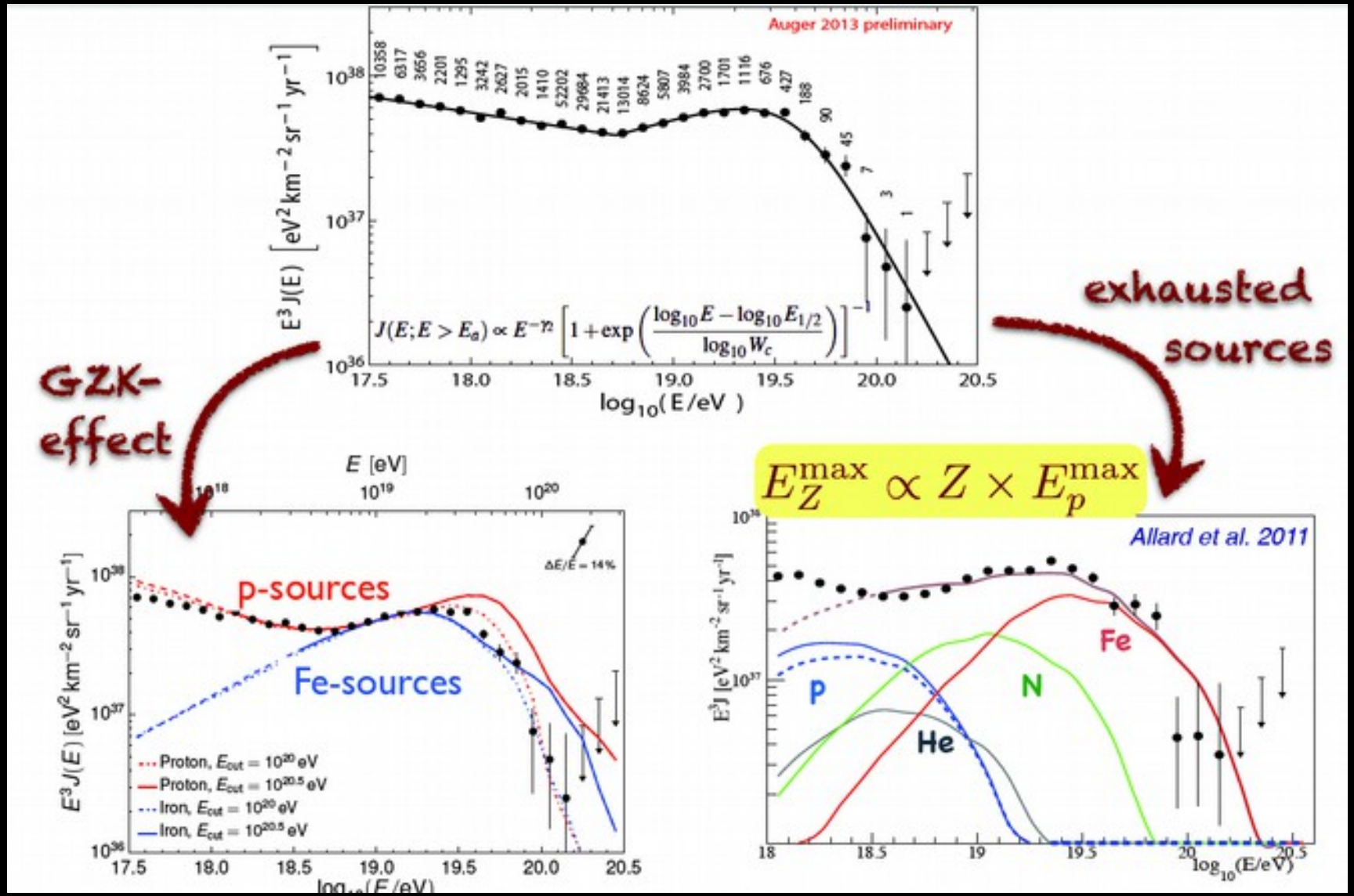
protons:

$$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$$
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

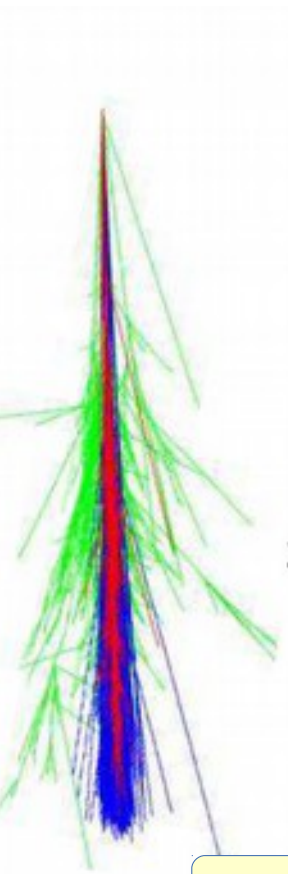
E ≥ 7 10^{19} eV

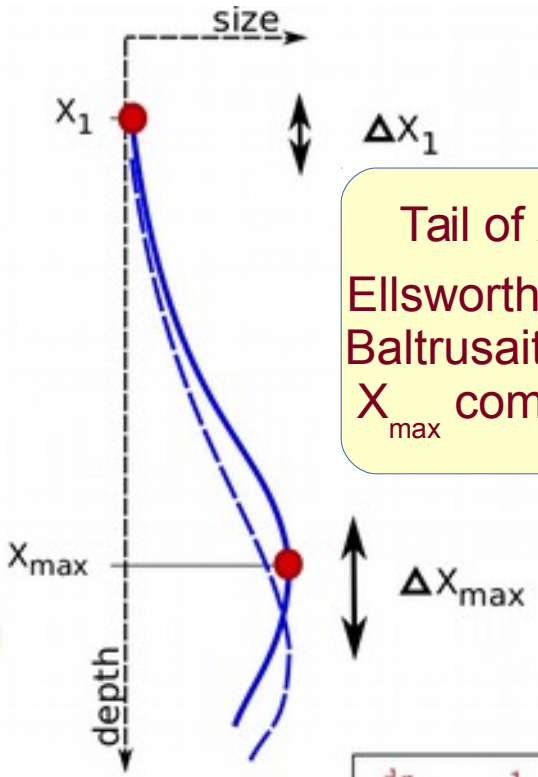
nuclei: photo-disintegration and pair production on CMB (RB IR)

"horizon" (p and nuclei) ~ 100 Mpc (~10^{20} eV)


Auger 2013 preliminary
$E^3 J(E)$ $\left[\mathrm{eV^2\,km^{-2}\,sr^{-1}\,yr^{-1}}\right]$
$J(E;E>E_a) \propto E^{-\gamma_2}\left[1+\exp\left(\frac{\log_{10}E-\log_{10}E_{1/2}}{\log_{10}W_c}\right)\right]^{-1}$
$\log_{10}(E/\mathrm{eV})$
GZK-effect
exhausted sources
$E_Z^{\max} \propto Z \times E_p^{\max}$
Allard et al. 2011
p-sources
Fe-sources
Proton, $E_{cut} = 10^{20}$ eV
Proton, $E_{cut} = 10^{20.5}$ eV
Iron, $E_{cut} = 10^{20}$ eV
Iron, $E_{cut} = 10^{20.5}$ eV
$\Delta E/E = 14\%$
P
He
N
Fe

p-Air cross-section at EeV



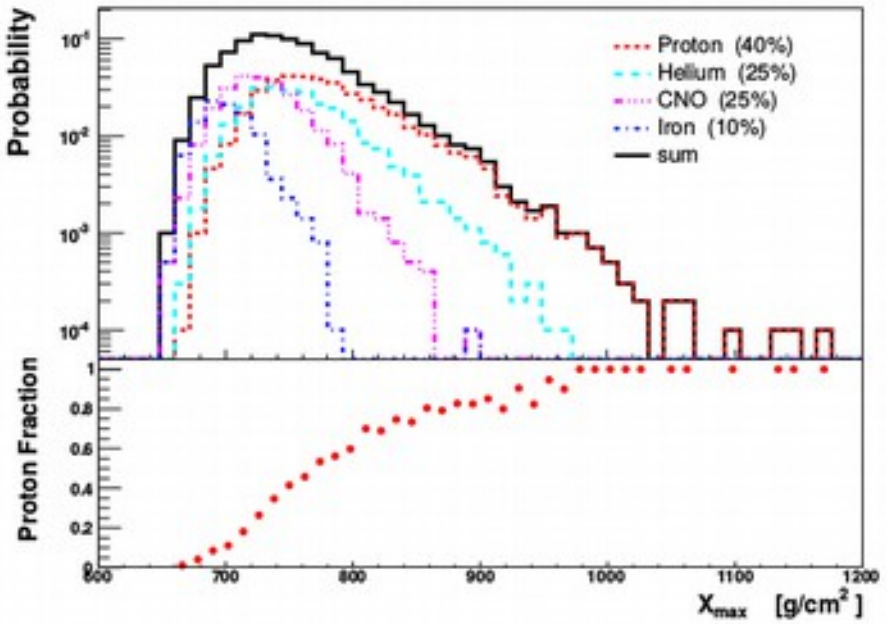


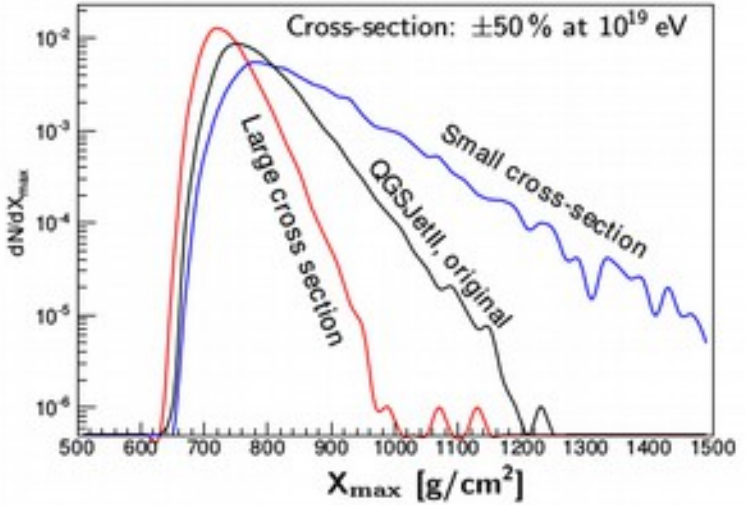
Tail of X_{max} distribution
Ellsworth et al. PRD 1982,
Baltrusaitis et al. PRL 1984
X_{max} composition sensitive

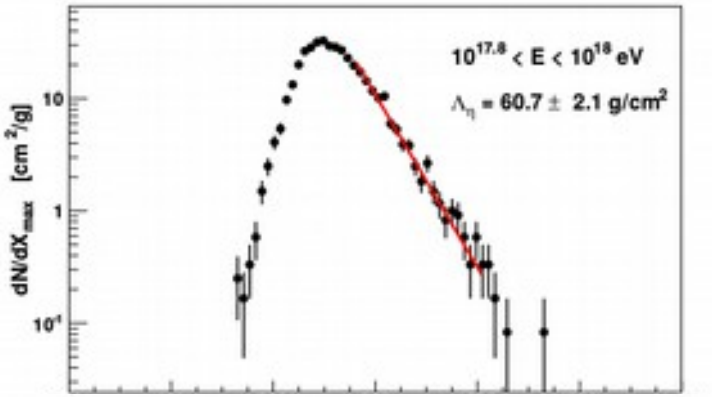
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

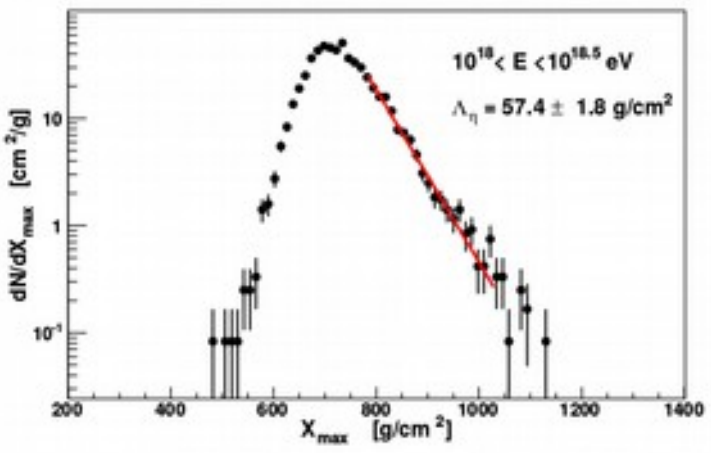
$$\sigma_{int} = \frac{<m_{air}>}{\lambda_{int}}$$

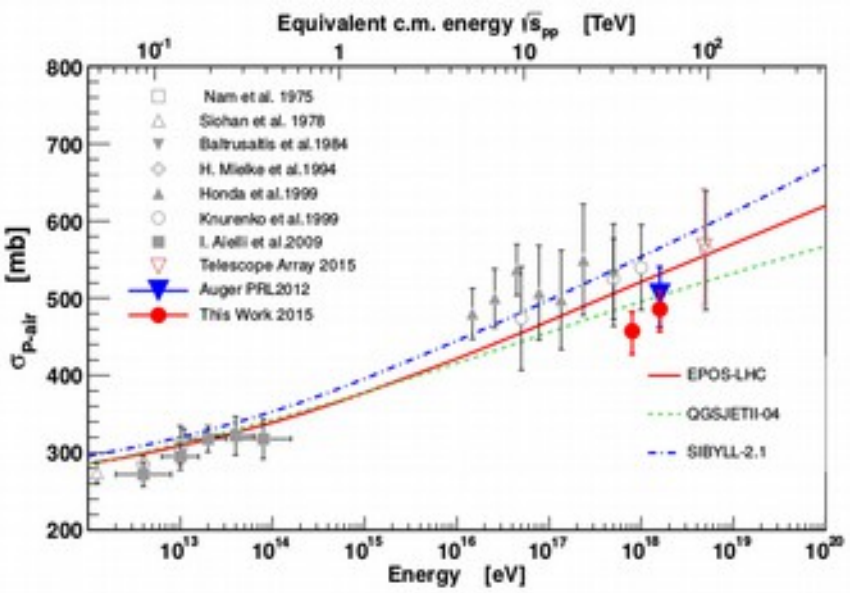
ICRC 2015 #401

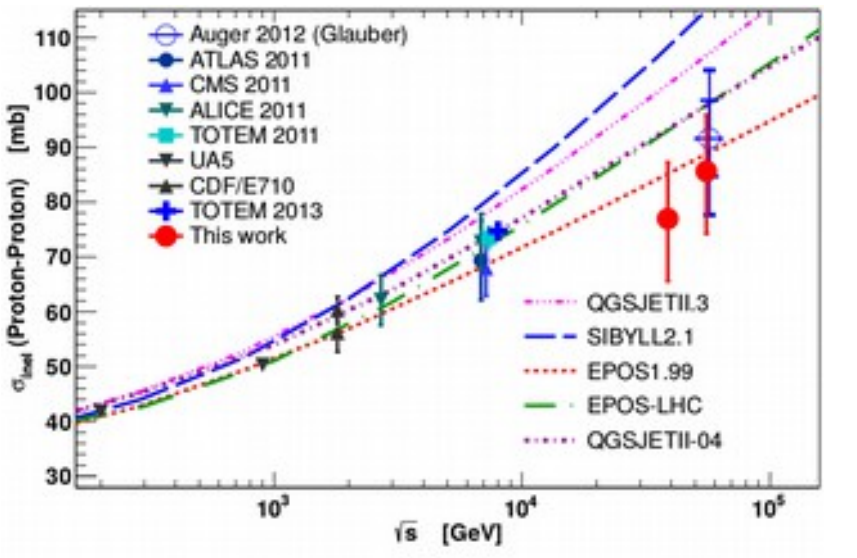












σ_{pp} [38.7±5.2 TeV] = [76.9±5.4(stat)+5/-7(syst) ± 7(glauber)] mb

σ_{pp} [55.5±3.6 TeV] = [85.6±5.0(stat)+5/-7(syst) ± 7(glauber)] mb

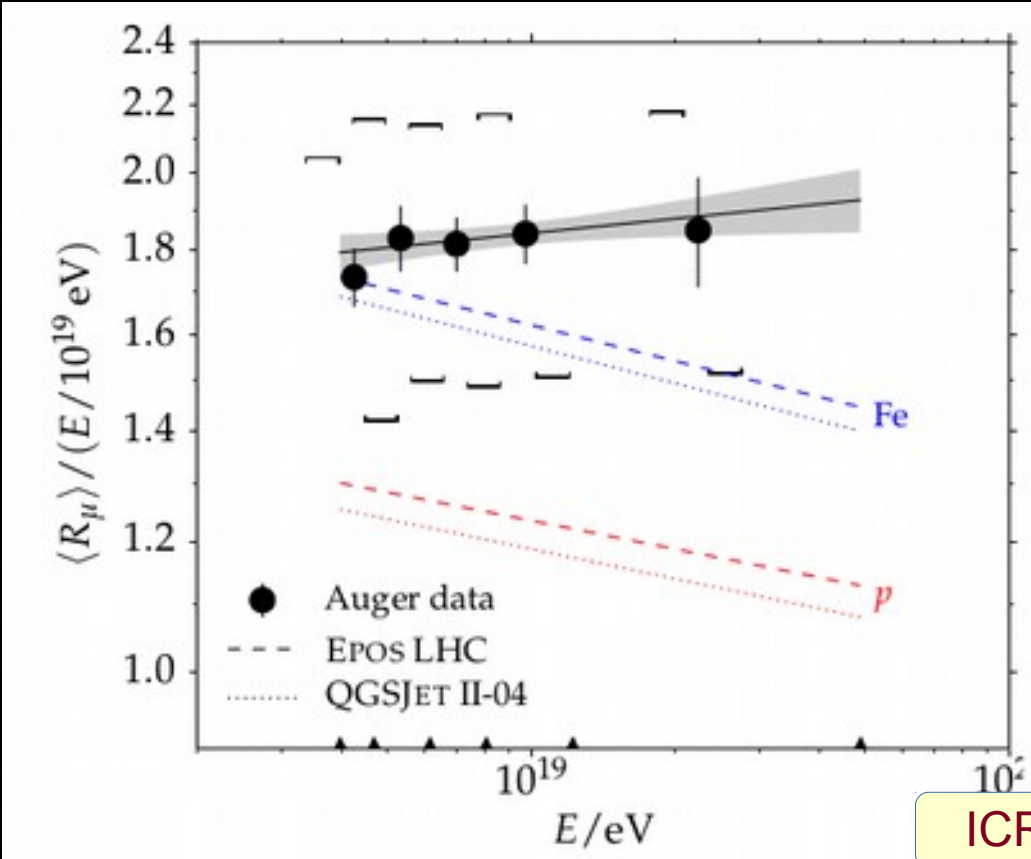
ICRC 2015 #401

Testing the hadronic models

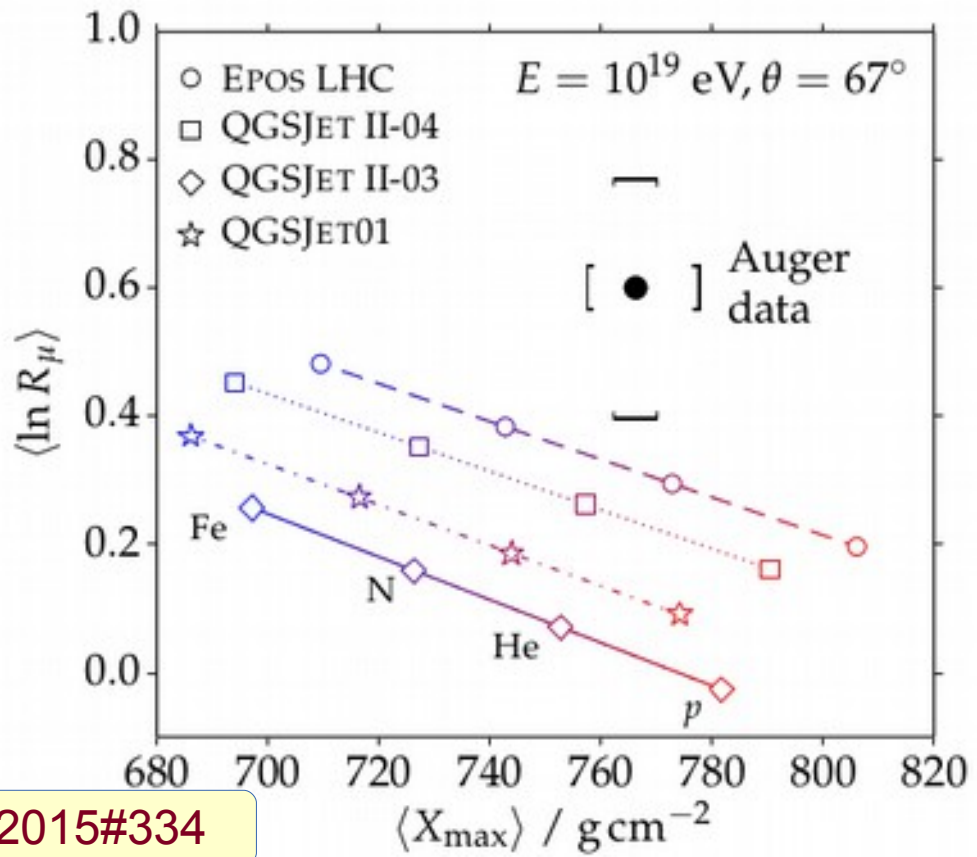
For hybrid inclined shower (em absorbed) measure nuber of muons

Too many muons and tension with $\langle X_{max} \rangle$

<#muons> vs energy

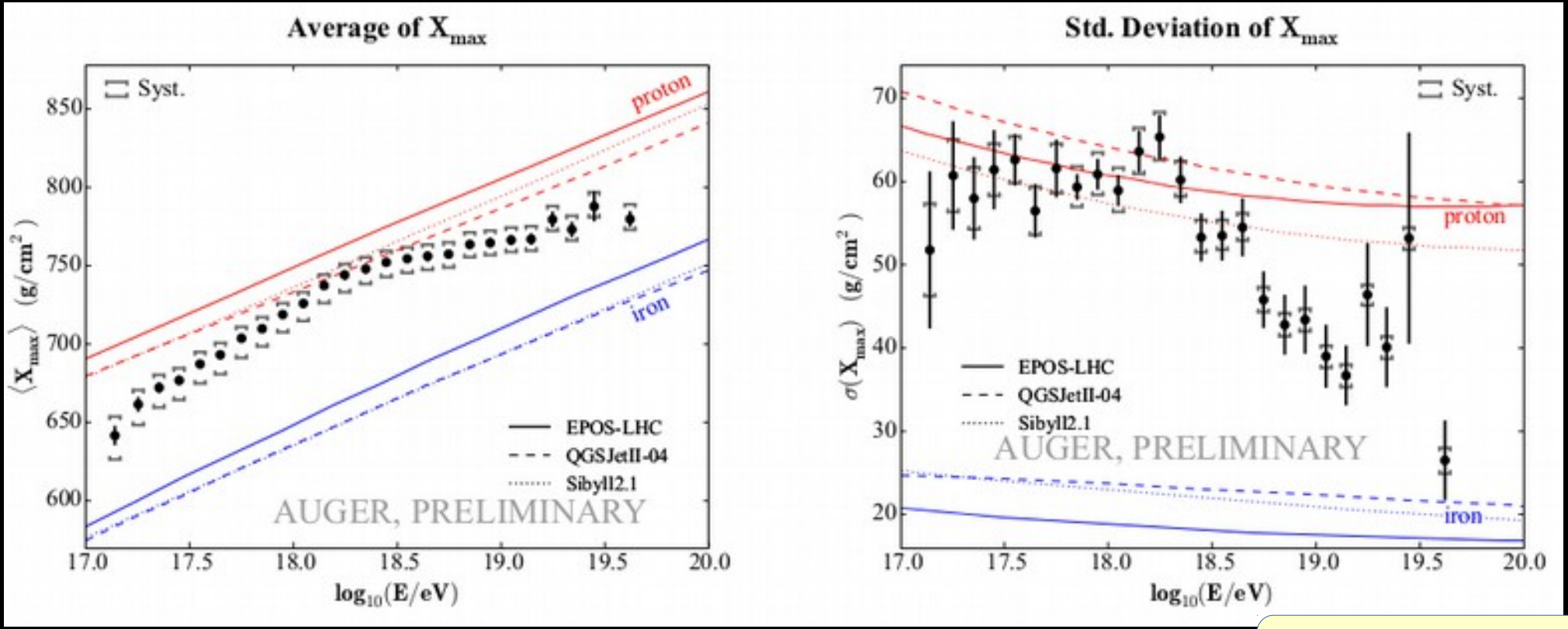


<#muons> vs $\langle X_{max} \rangle$ at 10 EeV



ICRC2015#334

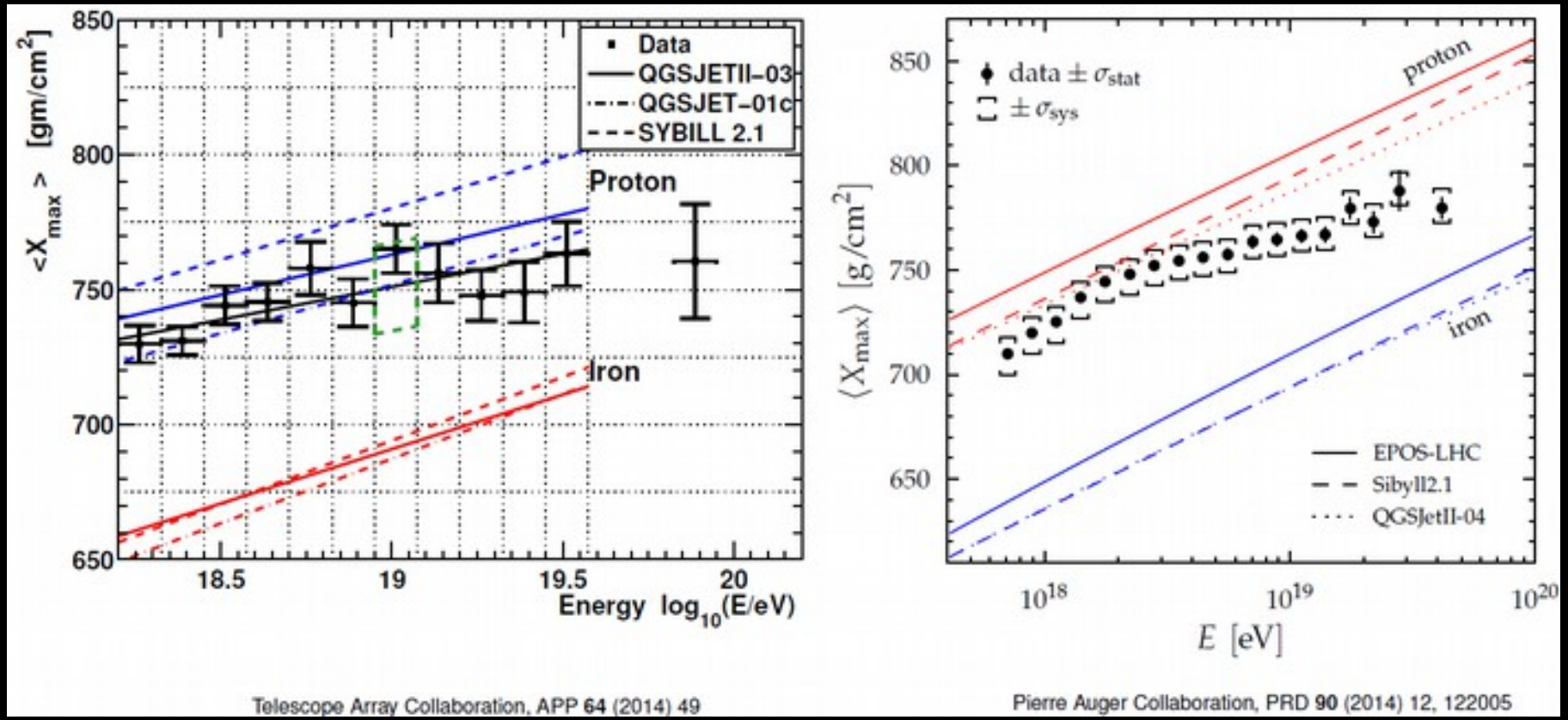
Composition: <X_{max}>



Heavy (2×10^{17}eV) to Light (2×10^{18}eV) to Heavy (2×10^{19}eV)
Data up to 40 EeV
Conclusion independent of EPOS-LHC / QGSJETII-04

ICRC2015#420

Composition: $\langle X_{max} \rangle$

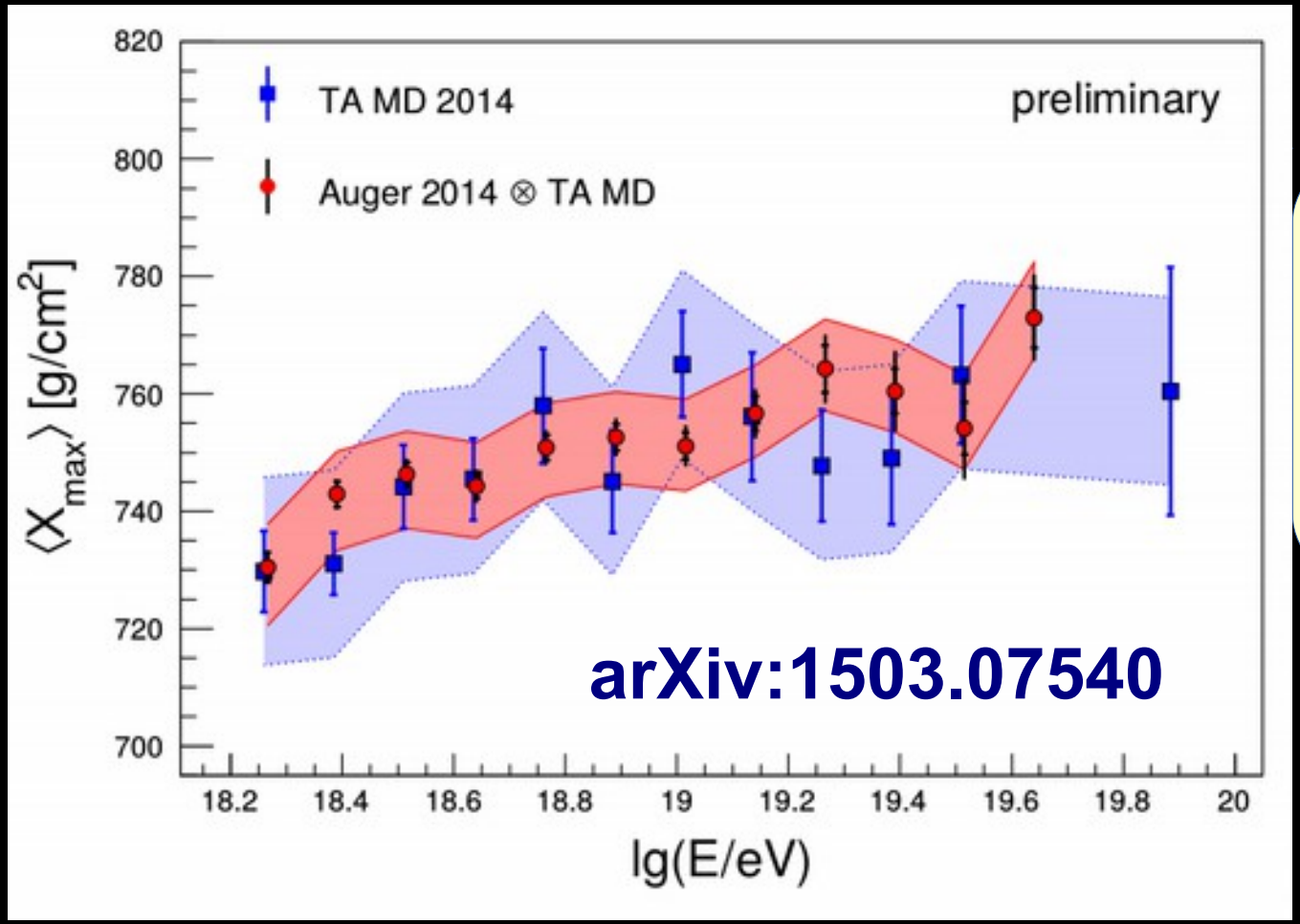


Maximize statistics ↔ Minimize bias

Measured $\langle X_{max} \rangle$ ↔ Unfolded $\langle X_{max} \rangle$

Simulation incl. Detector ↔ Simulation as generated

Composition: $\langle X_{max} \rangle$



UHECR Working-Group resolved discrepancy between TA and Auger:

Auger data folded with TA Detector accepance agrees well

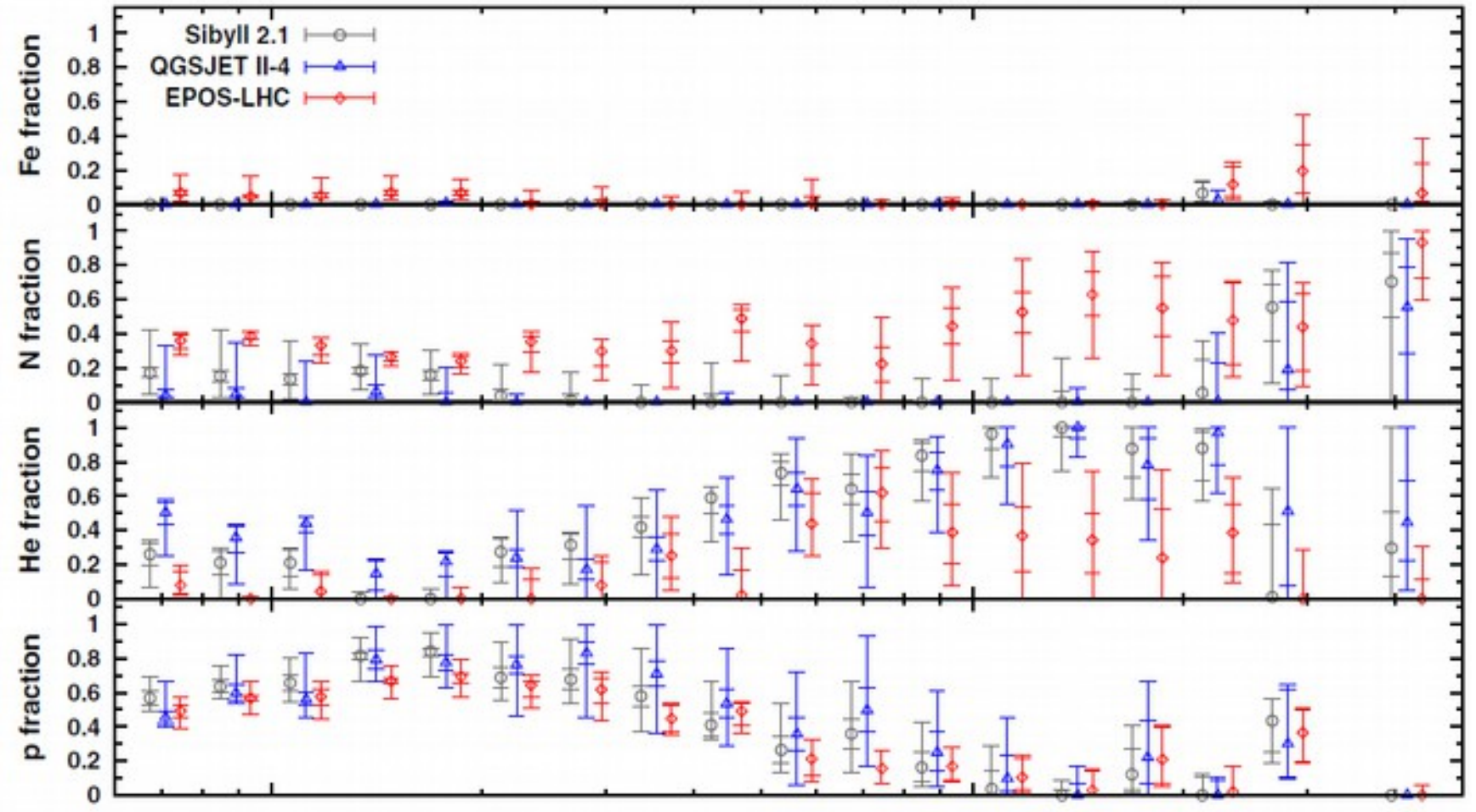
Auger: PHYSICAL REVIEW D 90, 122006 (2014)

Fe

N

He

p

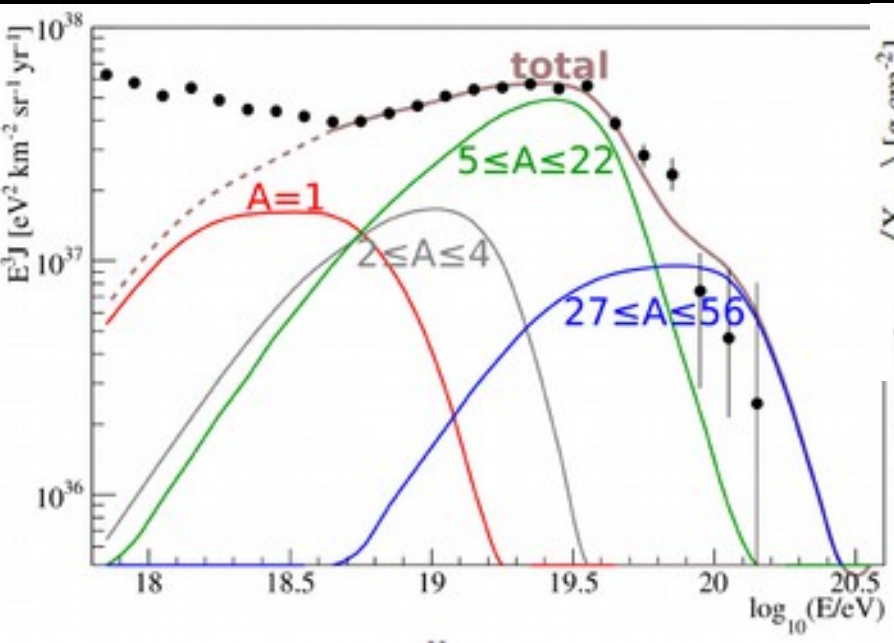


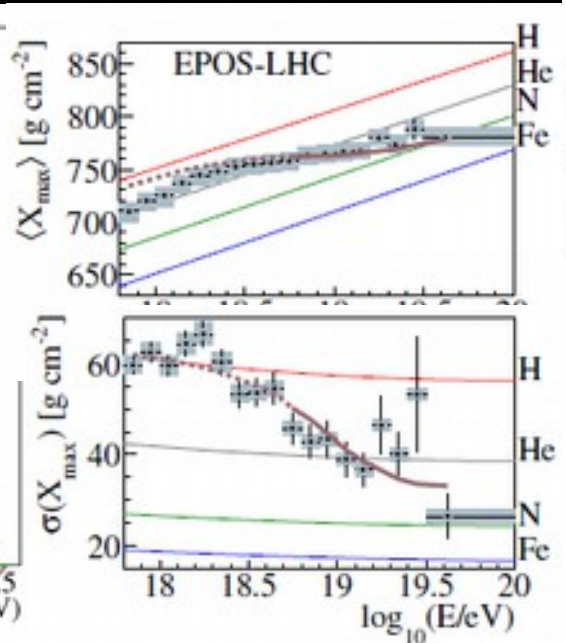
Propagation simulation

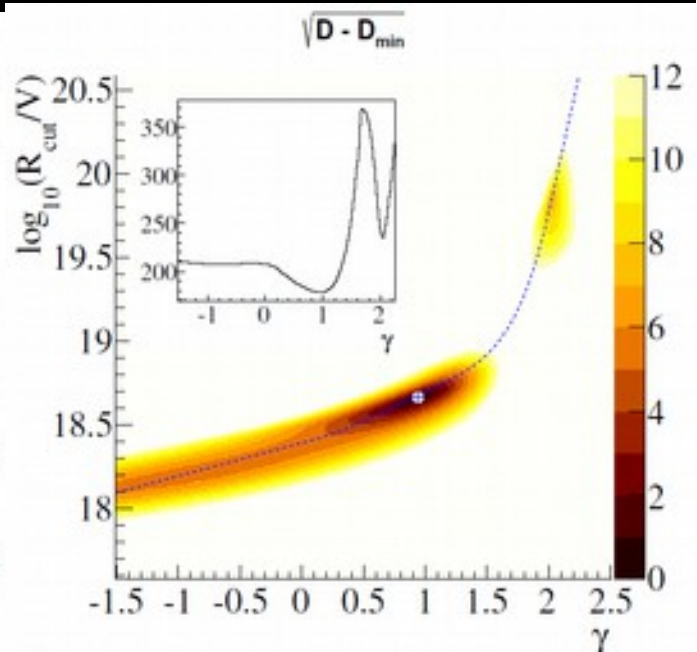
Fit results of propagation simulations (**SimProp**, **CRPropa**) to Auger measurements (Spectrum, $\langle X_{max} \rangle$, $\sigma(X_{max})$)

Varying spectral index and cut-off energy of source while

Assuming source distribution and extra galactic magnetic field model

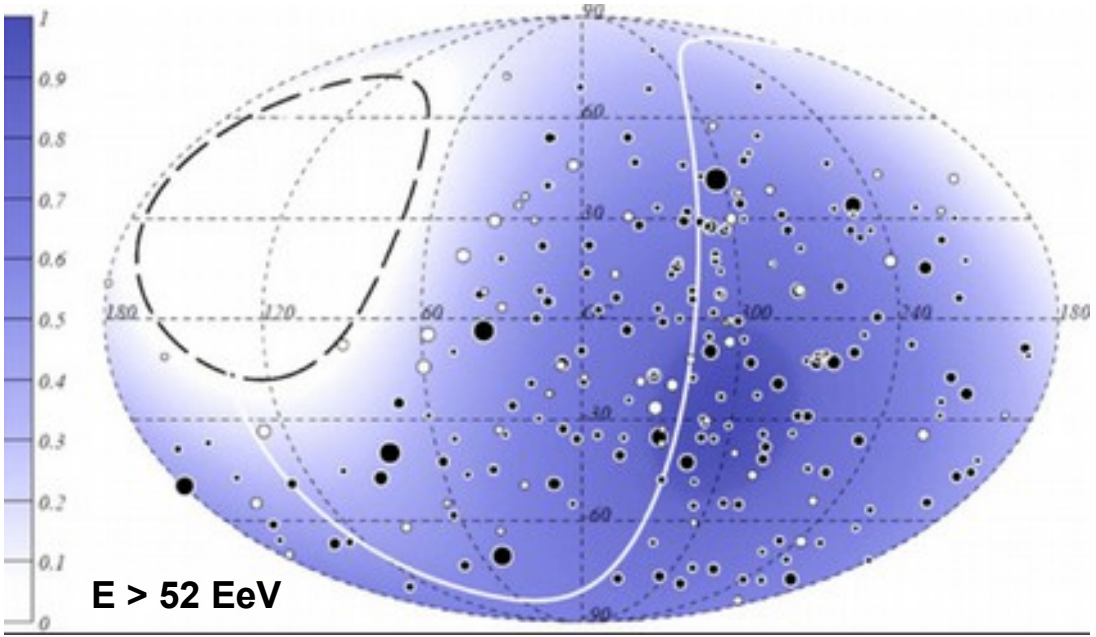






Anisotropy

Astrophysical Journal, 804:15, 2015



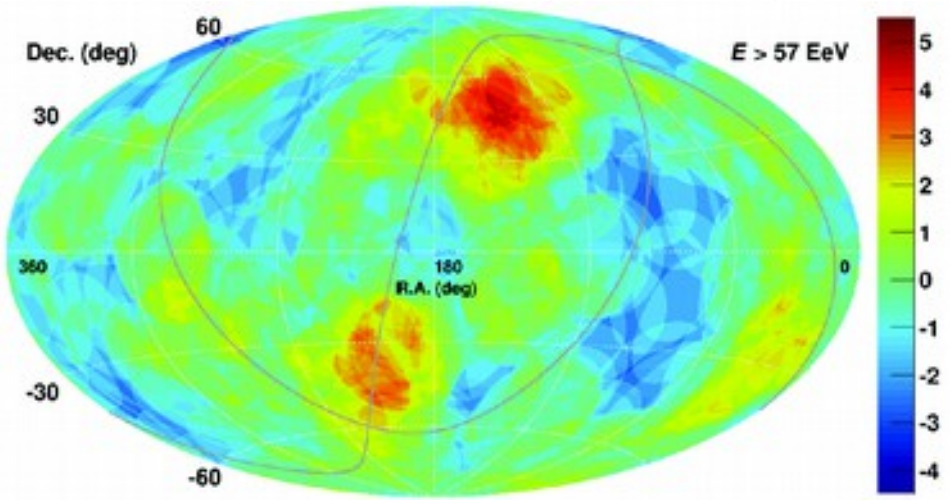
1/1/2004 - 31/3/2014

231 events, zenith < 80°
black(white) vertical (inclined)

No significant excesses were found around the Galactic Center, the Galactic Plane, or the Super-Galactic Plane.

No significant correlations with source from several catalogs

Sky survey with Auger and TA



Auger and TA, **ICRC 2015**

TA

7 years, 109 Events (> 57 EeV)

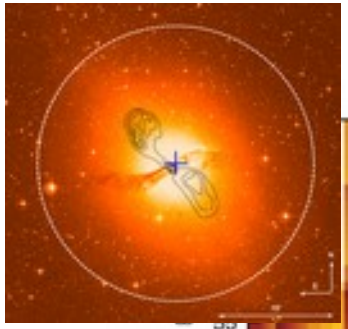
Northern Hemisphere: hot spot seen by TA (3.4 σ) near the Ursa Major cluster

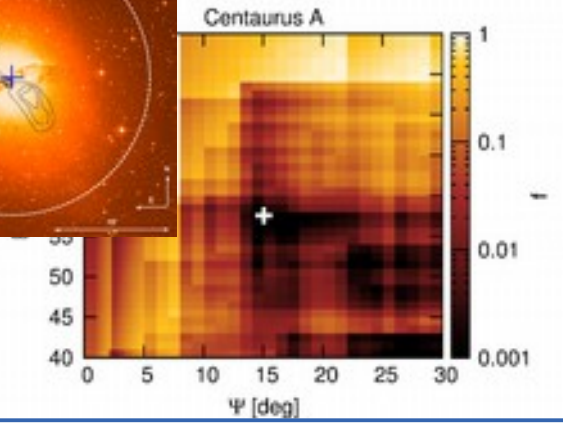
Auger

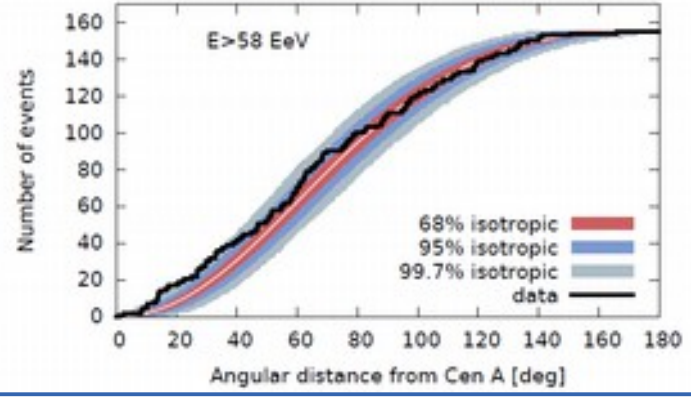
10 years 157 events (> 57 EeV)

Southern Hemisphere: hot spot seen by Auger (post-trial prob 1.4%) near to Cen A

The sky around Cen A





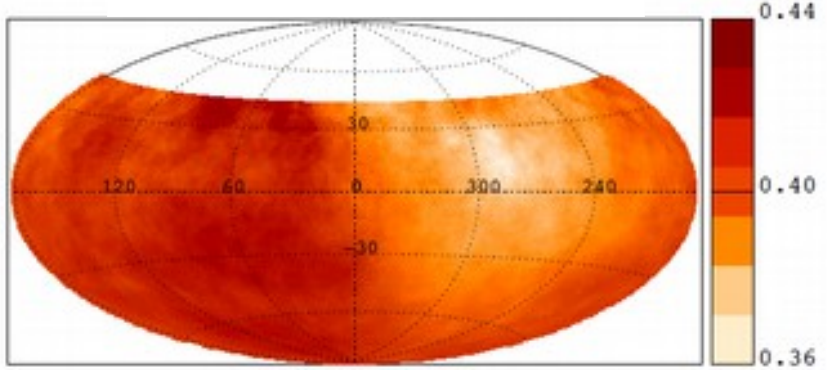


Large Scale anisotropy at the highest energies

Rayleigh analysis in right ascension and azimuth

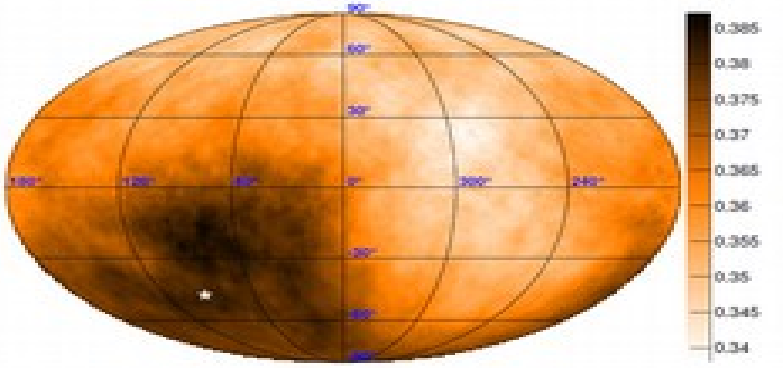
Auger and TA, **ICRC 2015**

Sky map of the CR flux **E > 8 EeV**



Auger (7.3 ± 1.5)% (p=6.4 10^{-5})

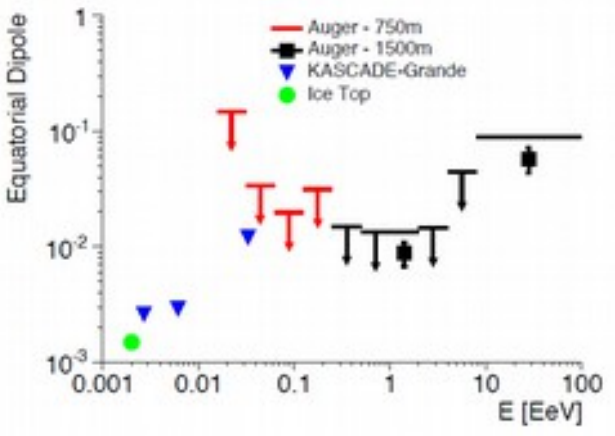
Sky map of the CR flux **E > 10 EeV**



Auger and TA (6.5 ± 1.9)% (p=5 10^{-3})

Indication of transition from galactic to extragalactic cosmic rays

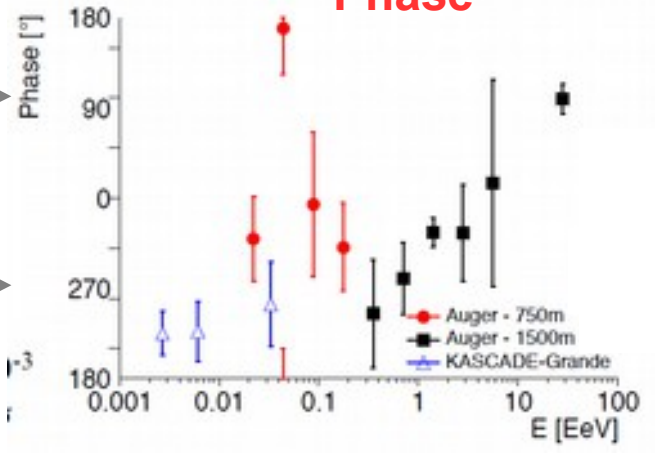
Dipole Amplitude



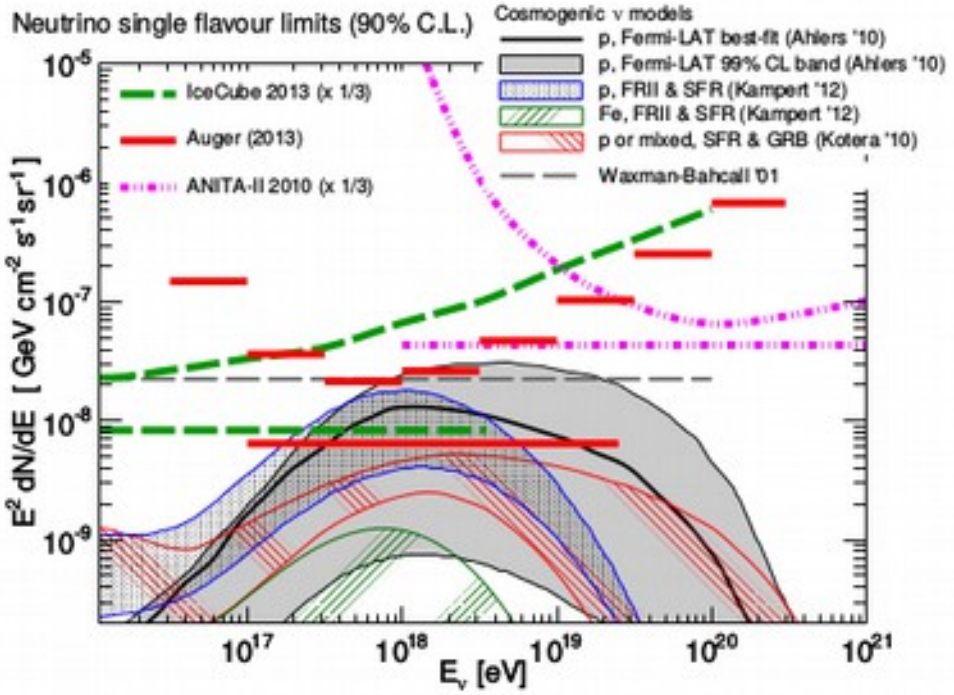
dipole points outwards gal. center →

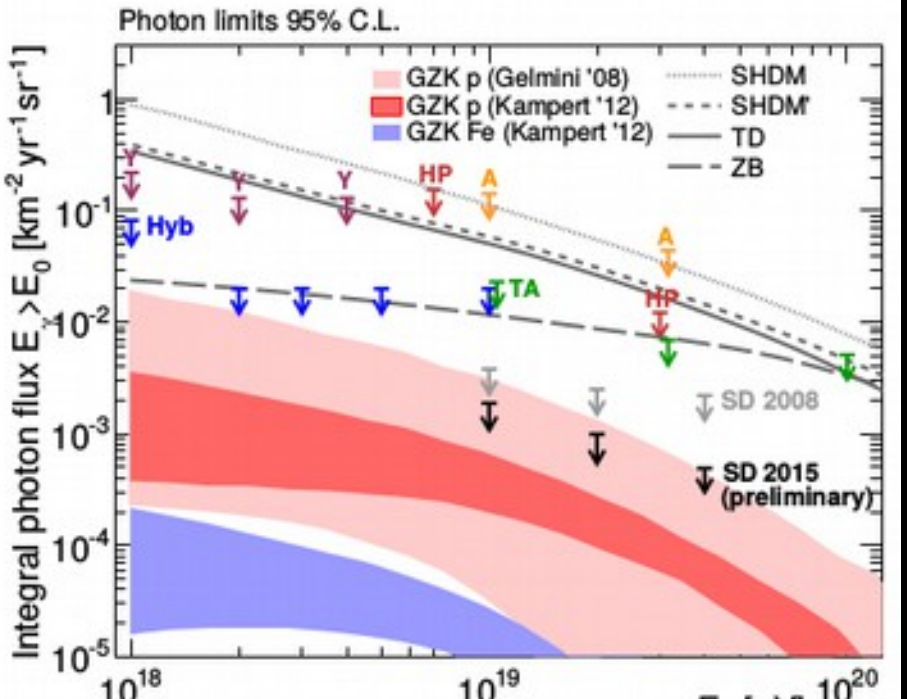
dipole points to gal. center →

Phase



Neutrino and Photon limits





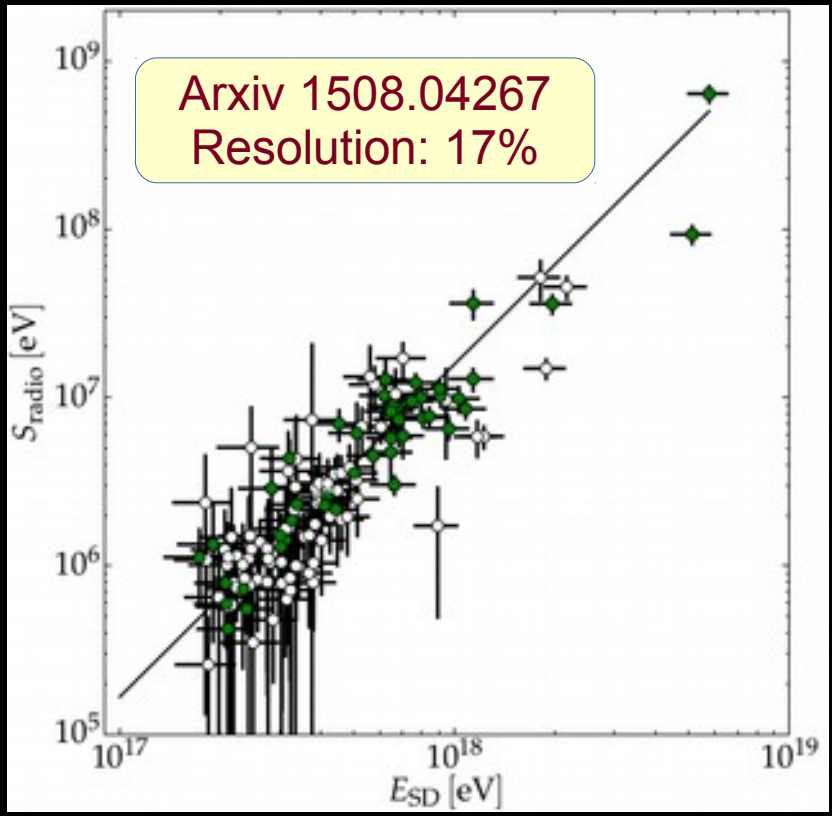
Select „young“ showers in inclined or earth-skimming events
First limits from EAS into WB-bound

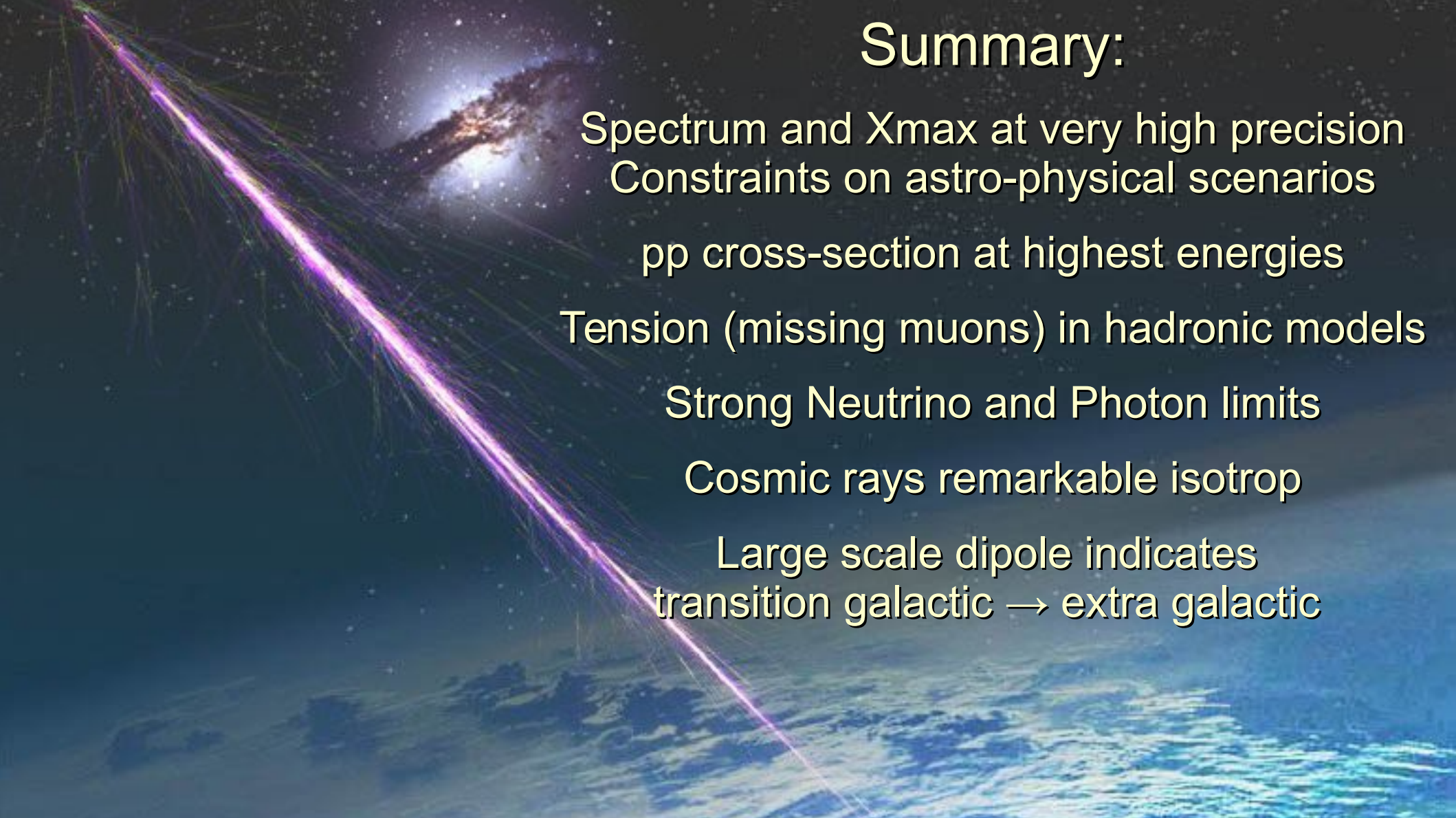
Select photons by timing characteristics and lateral distribution
Strongly disfavours Top-Down models

ICRC2015#1103

EAS radio-detection at the Pierre Auger Observatory

- Emission well understood
- Optimal EM detector for inclined shower
- No attenuation in atmosphere
- Coposition sensitivity promissing
- High potential for absolute e-scale





Summary:

Spectrum and Xmax at very high precision
Constraints on astro-physical scenarios

pp cross-section at highest energies

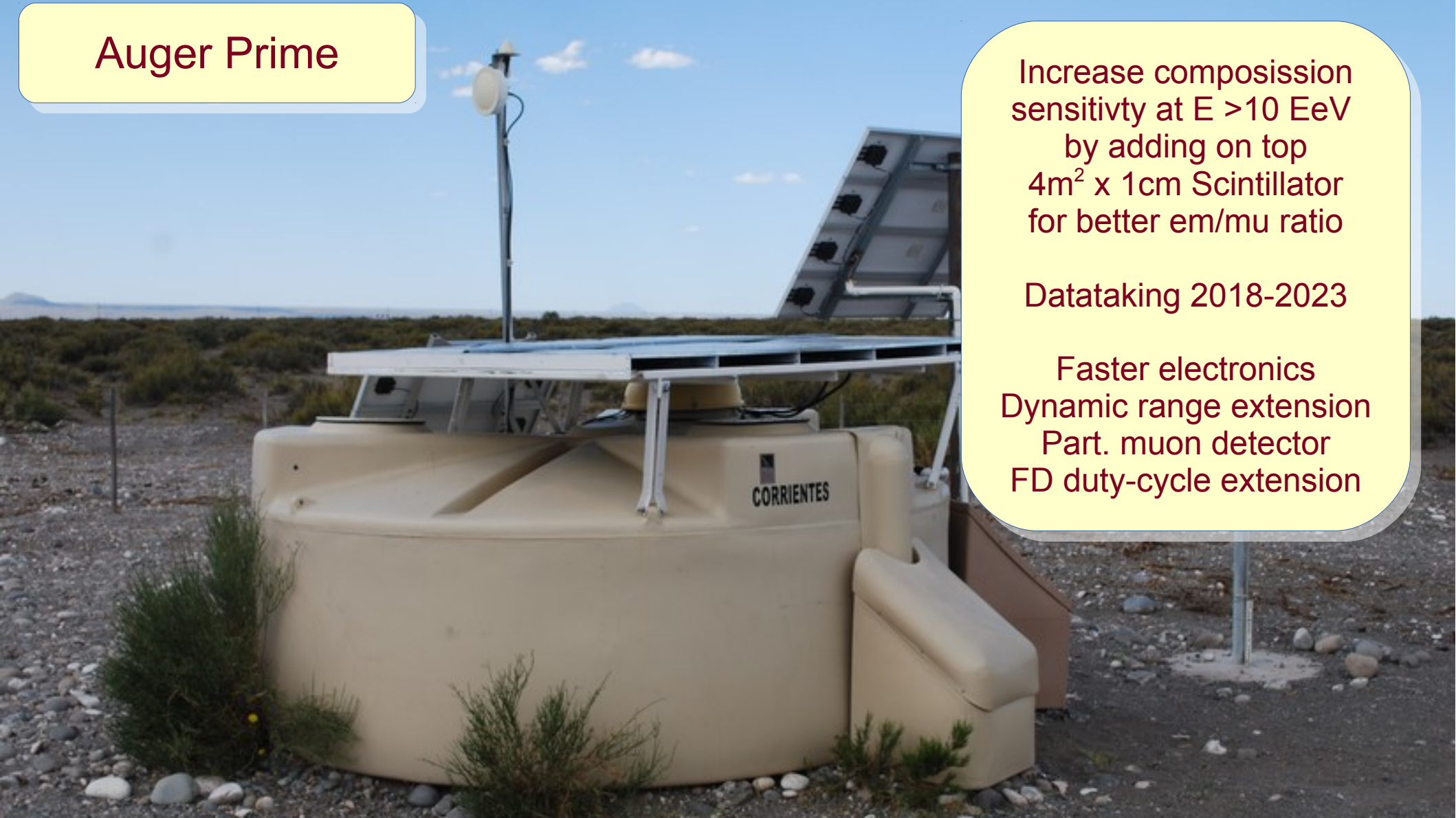
Tension (missing muons) in hadronic models

Strong Neutrino and Photon limits

Cosmic rays remarkable isotrop

Large scale dipole indicates
transition galactic → extra galactic

Auger Prime



Increase composission sensitivty at E >10 EeV by adding on top $4m^2$ x 1cm Scintillator for better em/mu ratio

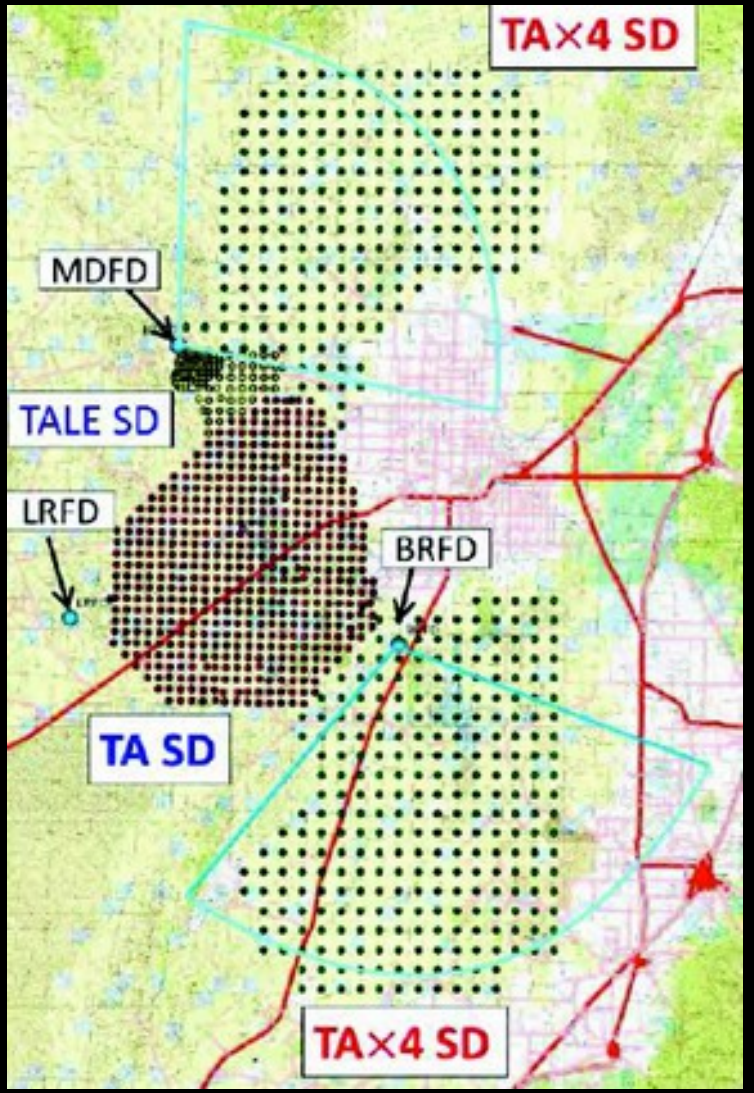
Datataking 2018-2023

Faster electronics
Dynamic range extension
Part. muon detector
FD duty-cycle extension

TA upgrade

Extend the SD area by a factor 4
700 → 2800 km^2

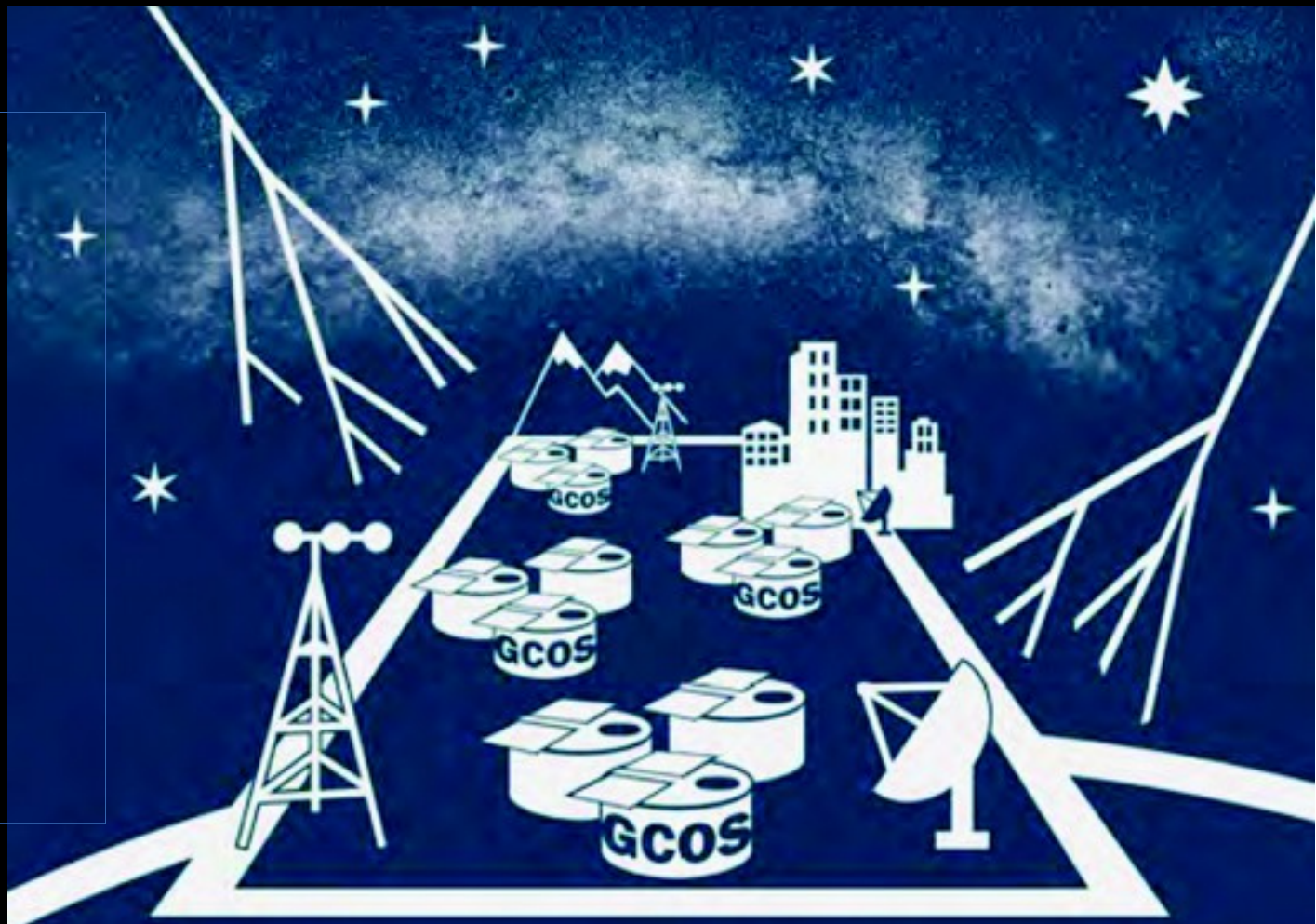
Additional few-PMT FDs?



Far-Future: GCOS

p-astronomy with sources

- Global, few sites, N+S
- ca. 90,000 km^2 (x30 Auger)
- FD with SiPMs?
- No FD at all?
- Optimal detector for composition-sensitivity?




… some way ahead to understand
the sources of the higest energetic particles