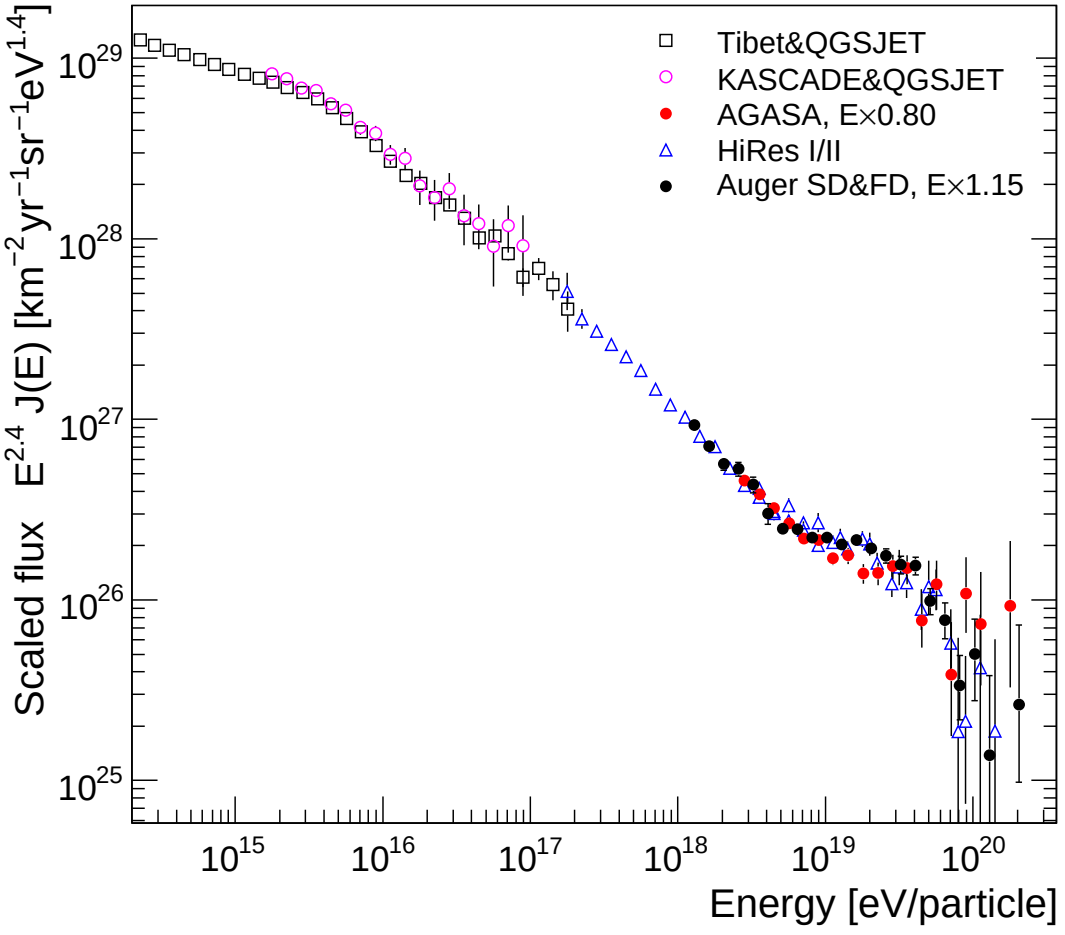
Extragalaktische Kosmische Strahlung

Michael Unger
(KIT)

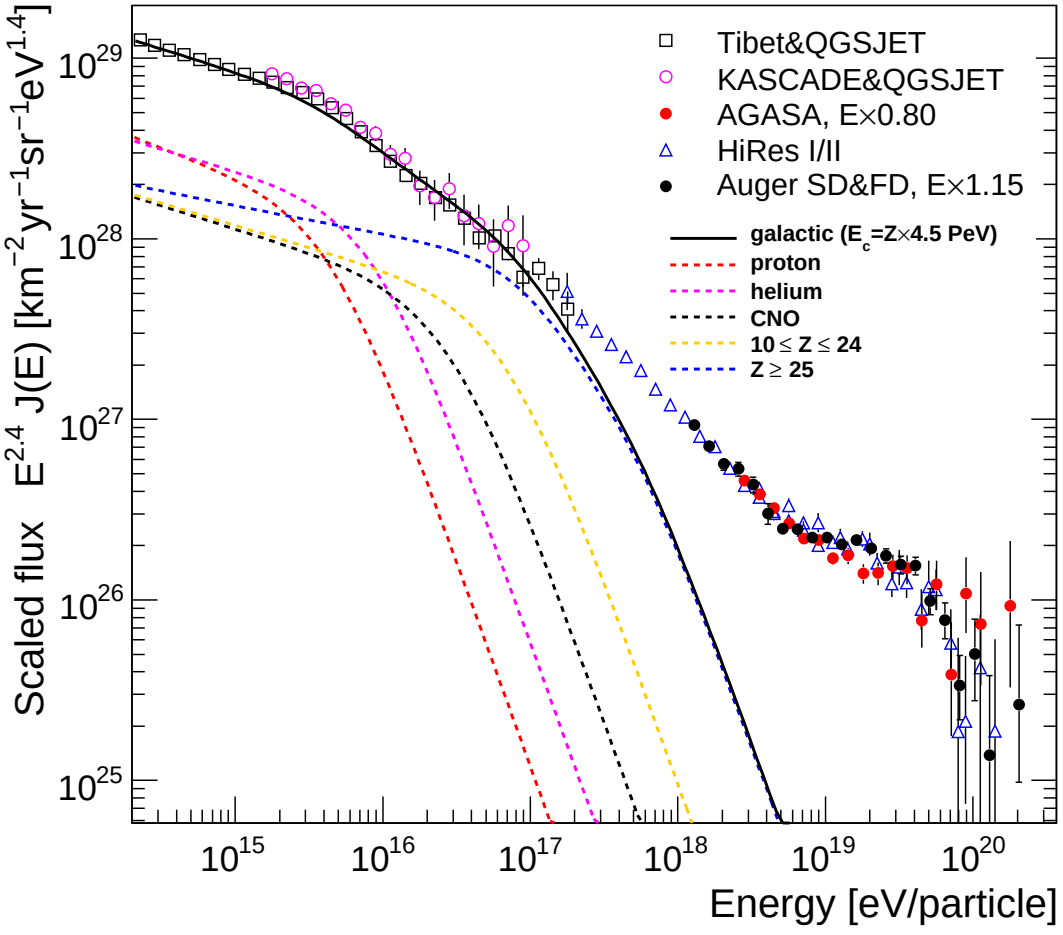
Energy Spectrum



'standard model' of knee:

- maximum energy:
  $\propto Z \cdot E$
- gyro-radius in gal. B-field
  $\propto Z \cdot E$

Energy Spectrum



(example: 'polygonato' model, Hörandel, APP (2003))

'standard model' of knee:

- maximum energy: $\propto Z \cdot E$
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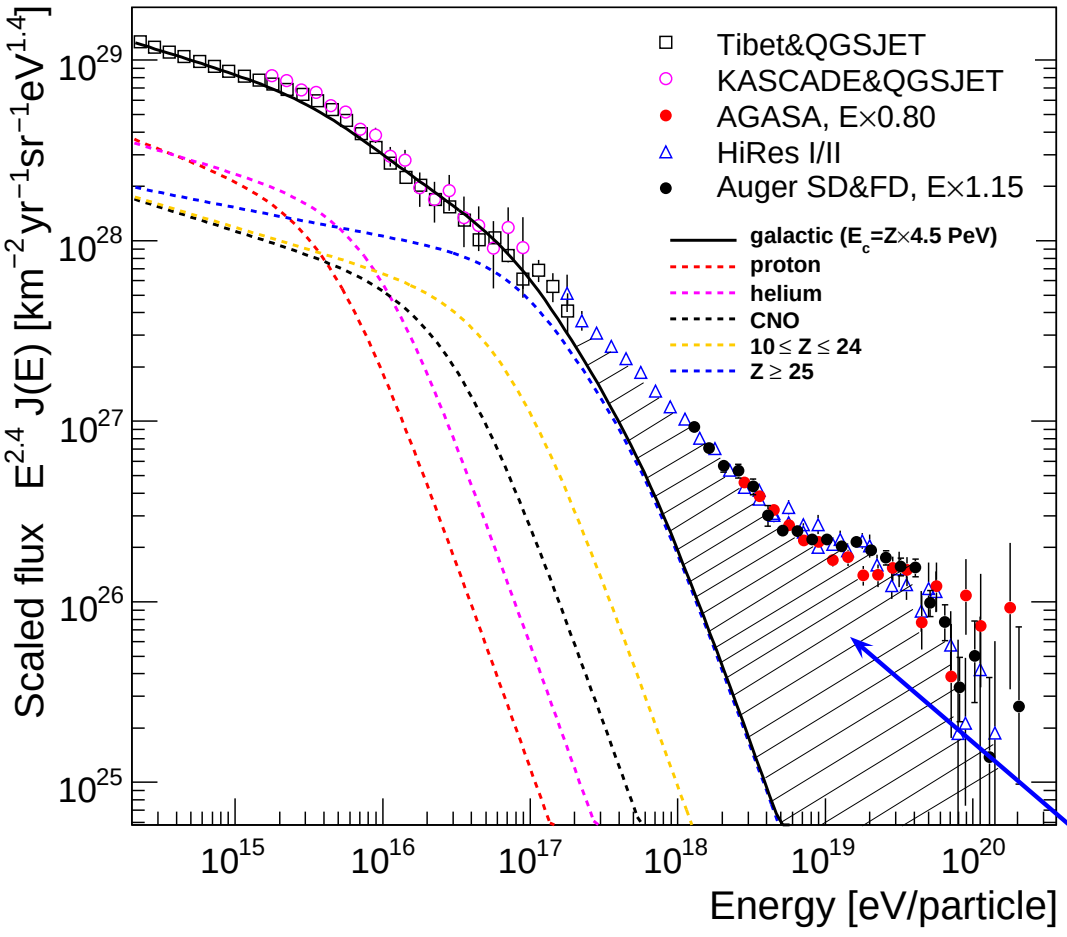
$\longrightarrow$ between 10^{17} and 10^{19} eV:

transition galactic $\rightarrow$ extragalactic CR

Energy Spectrum



(example: 'polygonato' model, Hörandel, APP (2003))

'standard model' of knee:

- maximum energy: $\propto Z \cdot E$
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$\longrightarrow$ between 10^{17} and 10^{19} eV:

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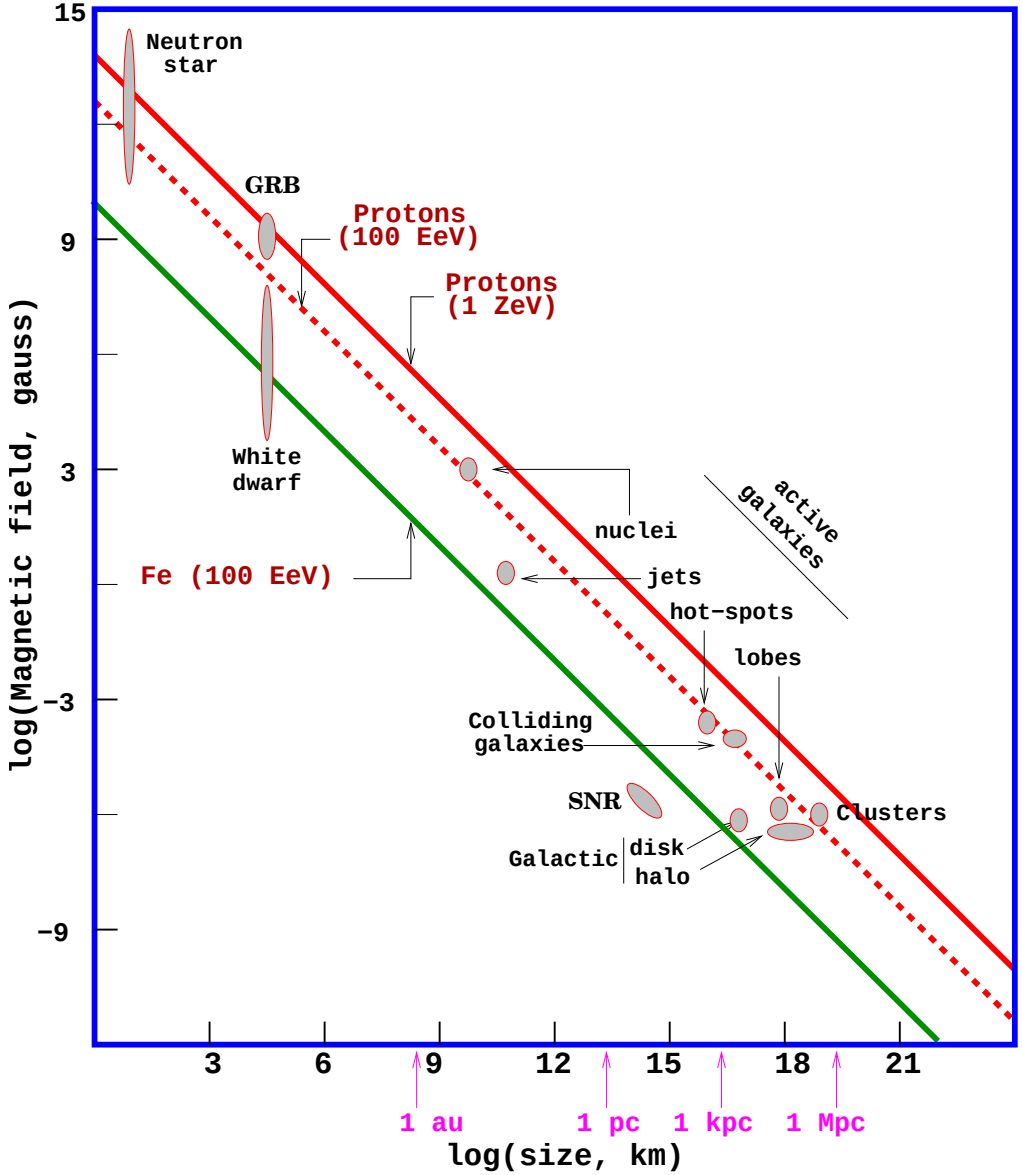
extragalactic stuff

Zevatrons?

LHC:

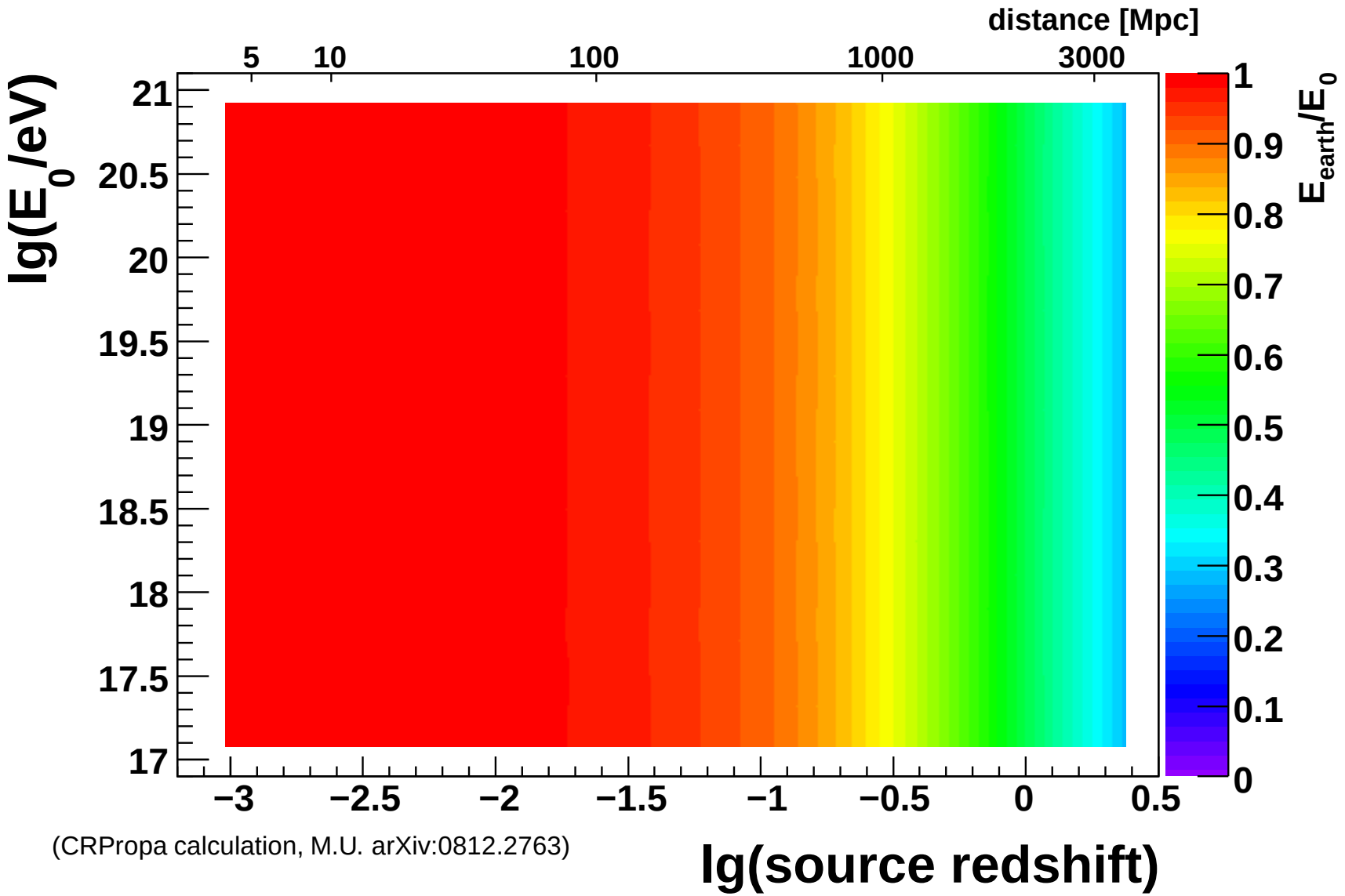
ILC:

Hillas-plot (necessary but not sufficient!)



Propagation of extragalactic protons

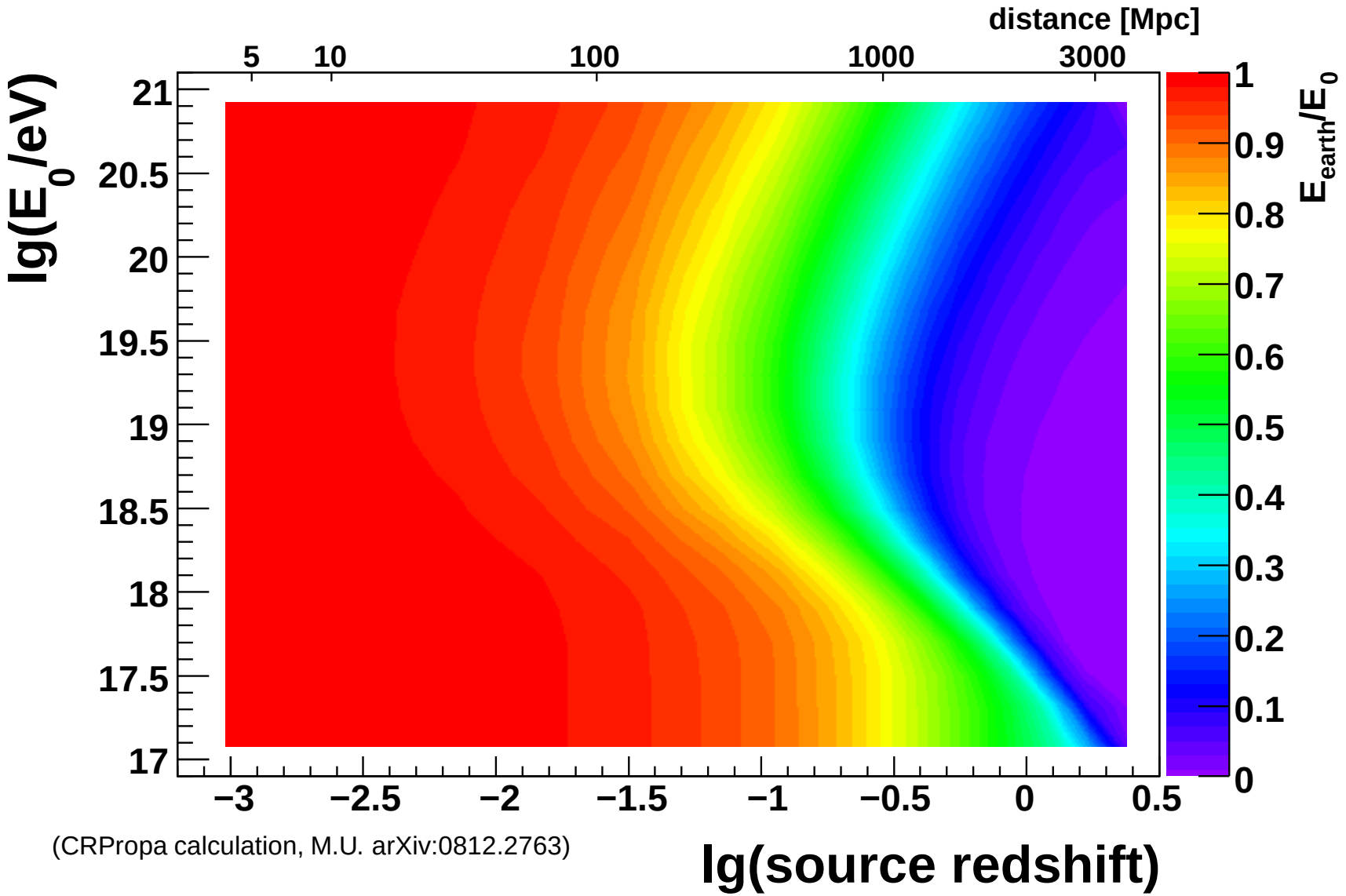
redshift



(CRPropa calculation, M.U. arXiv:0812.2763)

Propagation of extragalactic protons

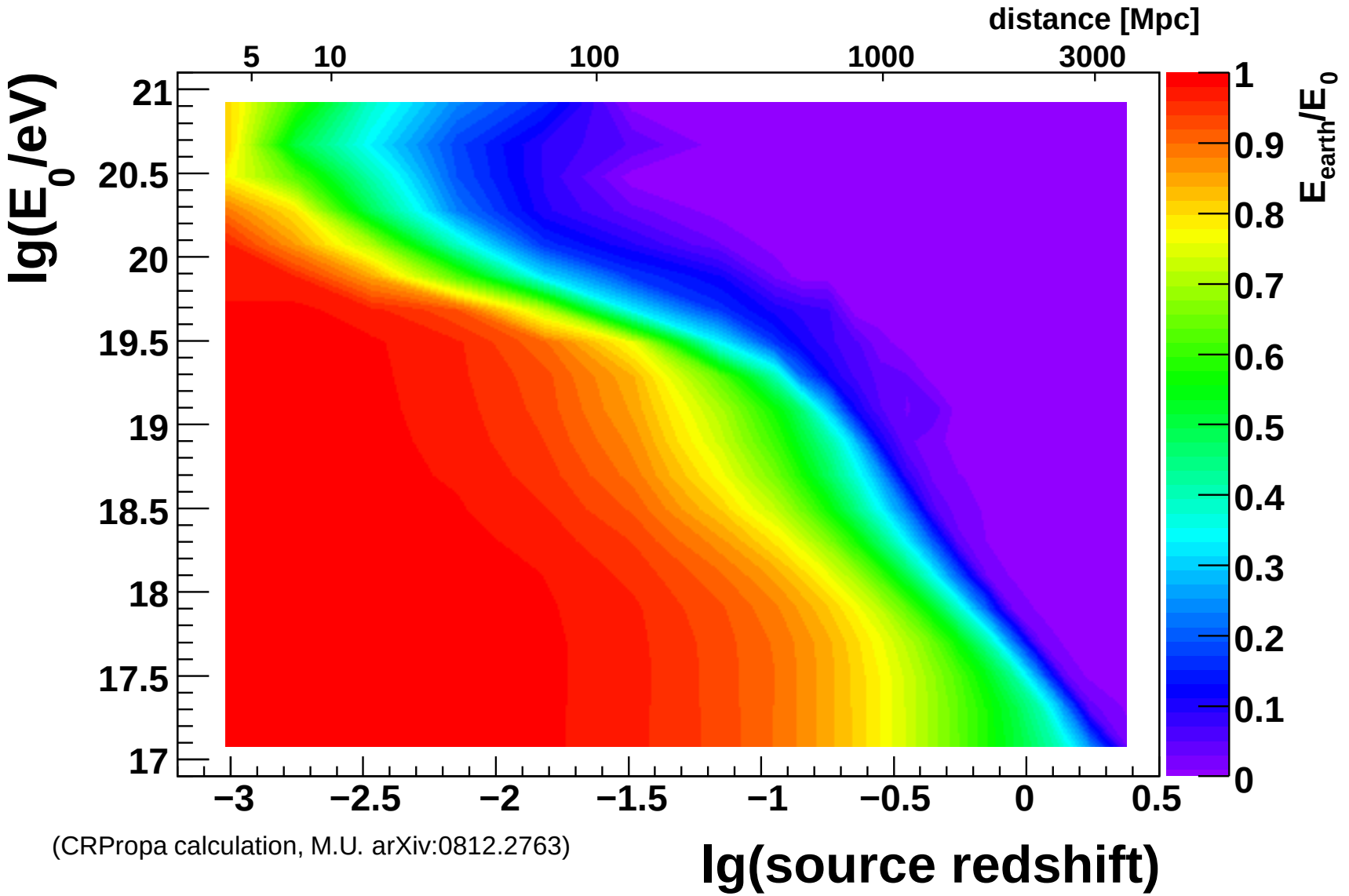
redshift + $p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-}$



(CRPropa calculation, M.U. arXiv:0812.2763)

Propagation of extragalactic protons

redshift + $p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-}$ + $p + \gamma_{\mathrm{CMB}} \rightarrow p + \pi^{0}$



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Propagation of extragalactic protons

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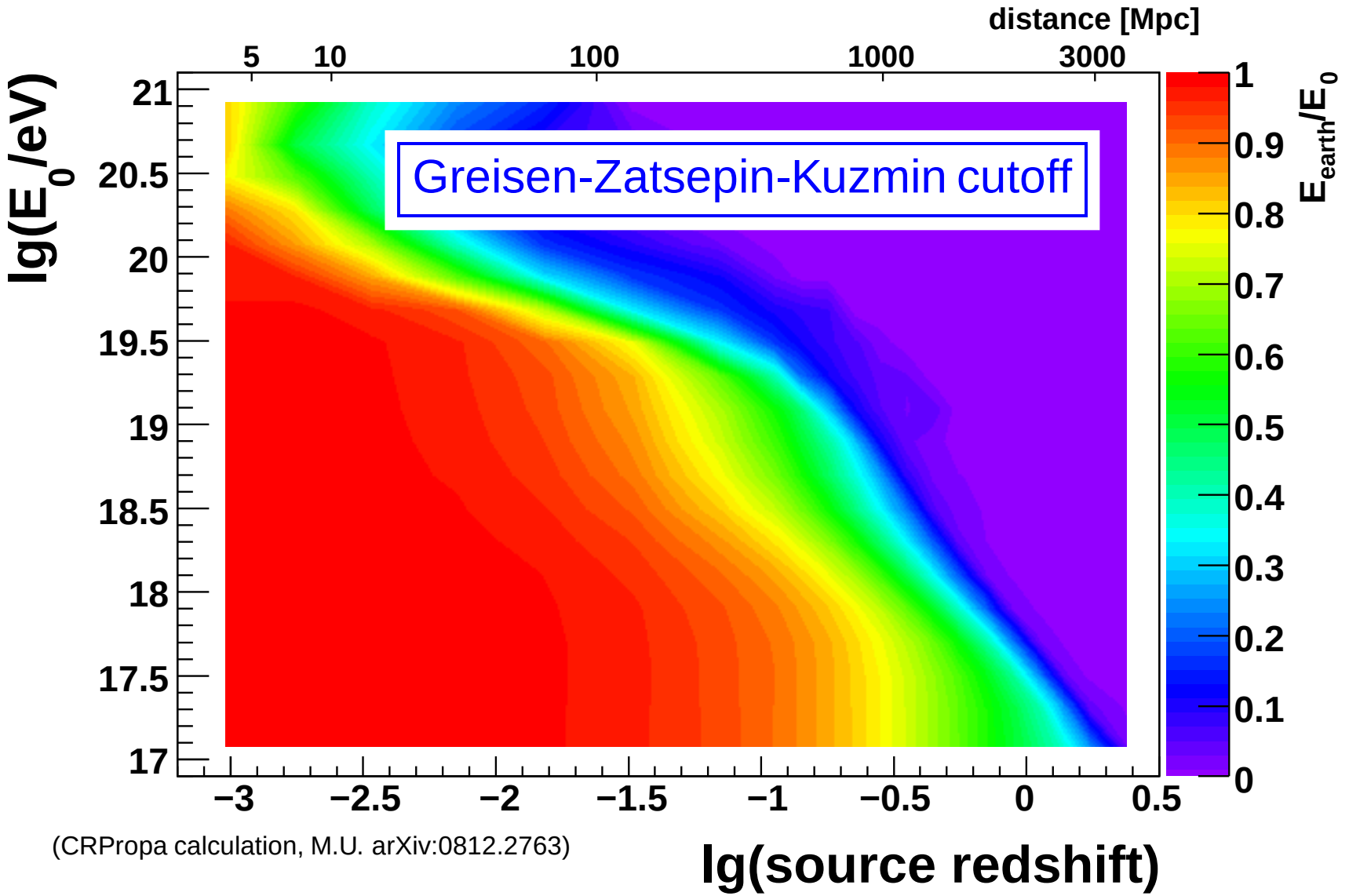
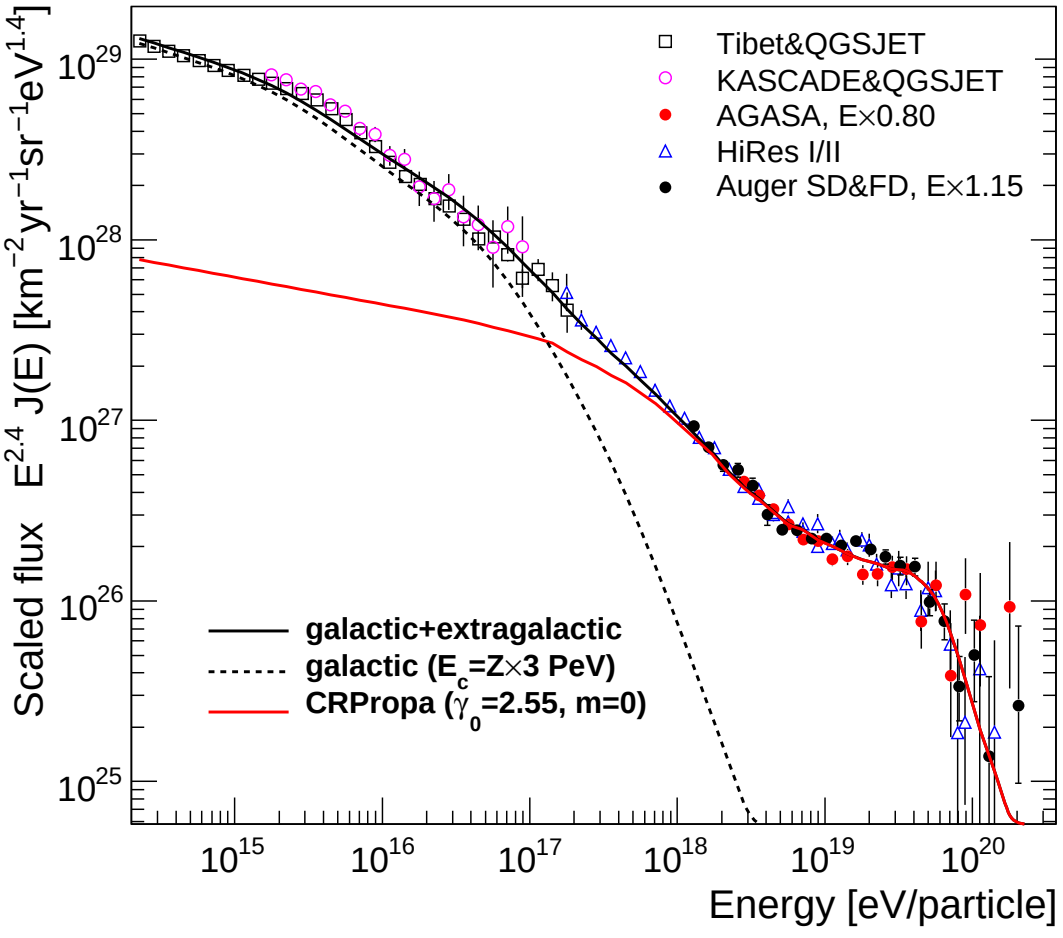


(CRPropa calculation, M.U. arXiv:0812.2763)

'Dip' Model

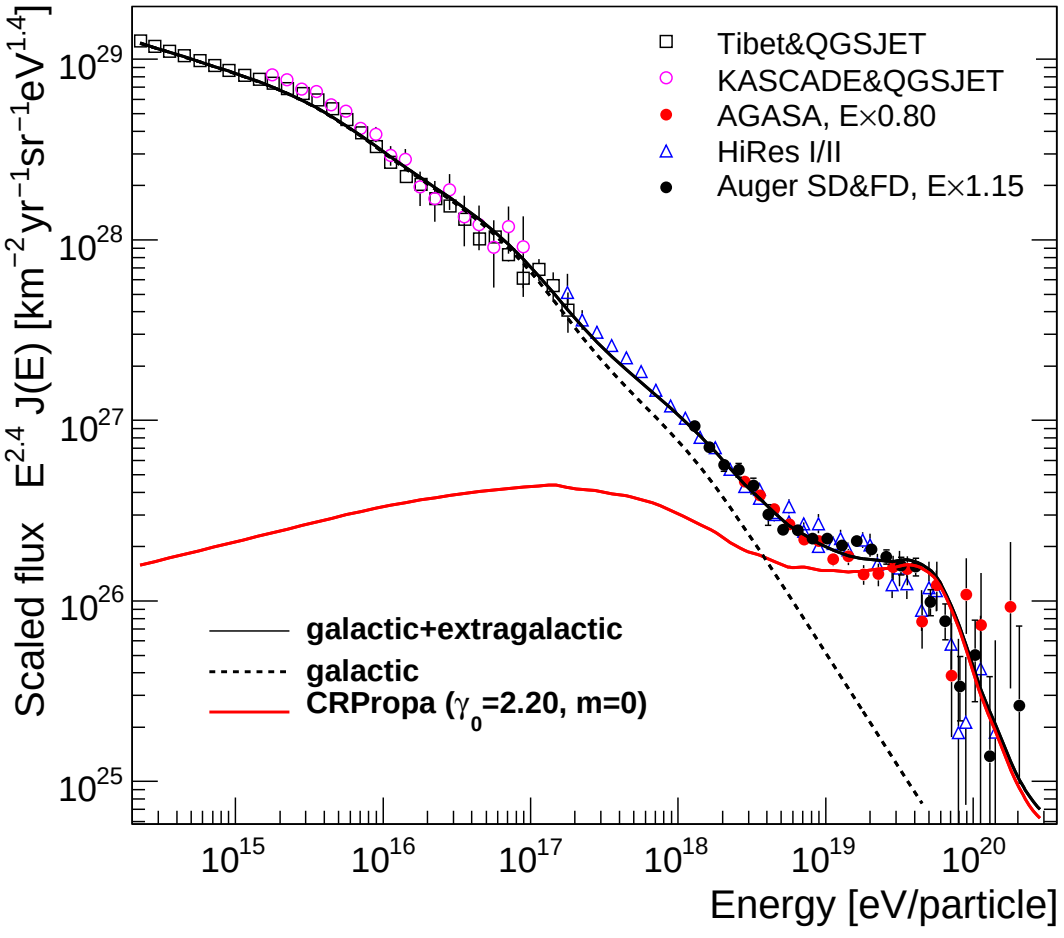
(Berezinsky et al.)



- transition Gal-EGal at '2nd Knee' $\sim 10^{17}$ eV
- 'standard' galactic component
- spectral feature from energy loss
- steep source spectrum (energy crisis?)
- postulates EGal p ($\lesssim$ 10% He)

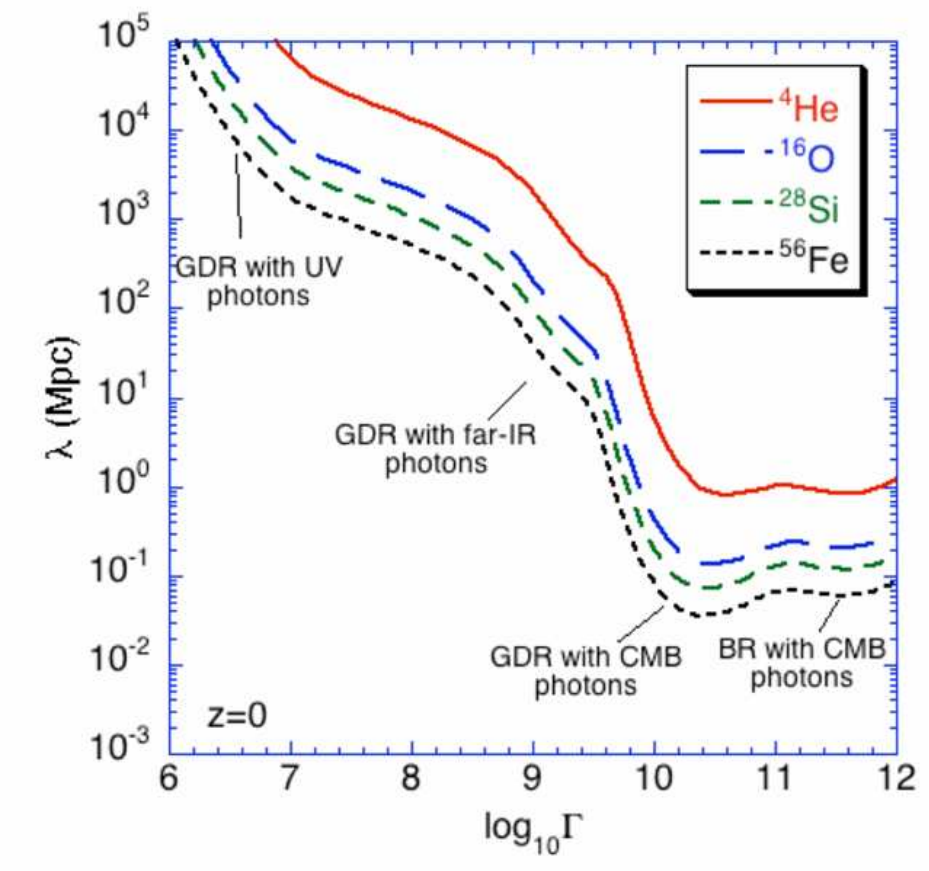
'Ankle' Model

(z.B. Bahcall&Waxman 2002, Hillas 2005, Wibig&Wolfendale 2007)



- transition Gal-EGal at several EeV
- UHE galactic sources??
- flat source spectrum

Propagation of extragalactic Nuclei

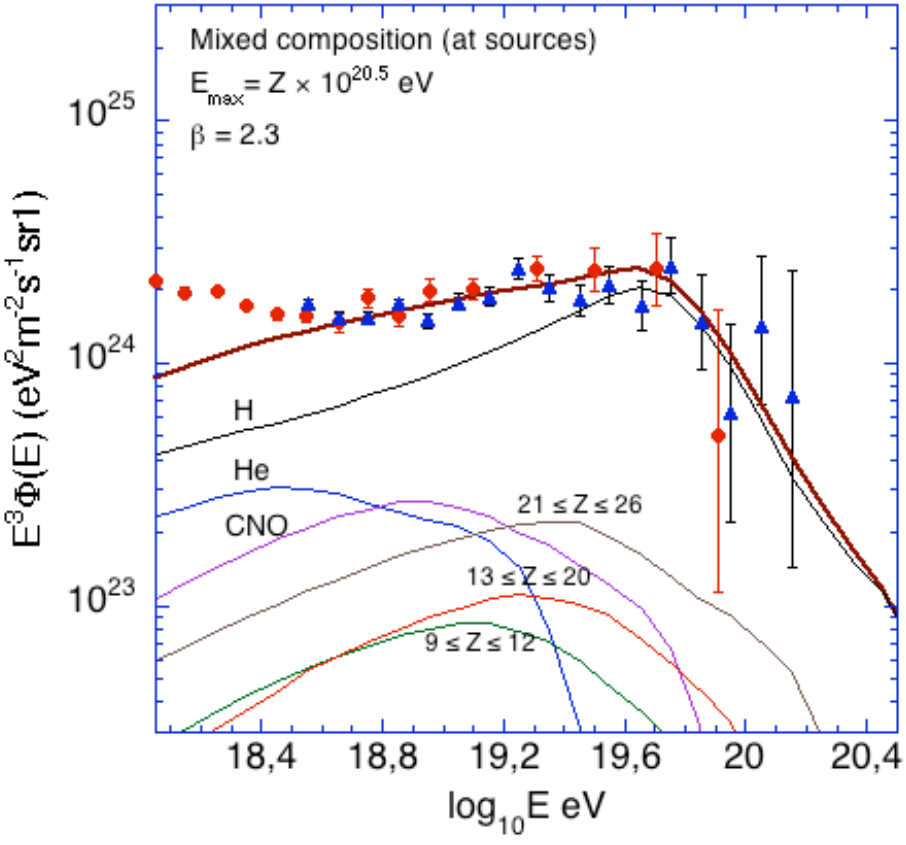


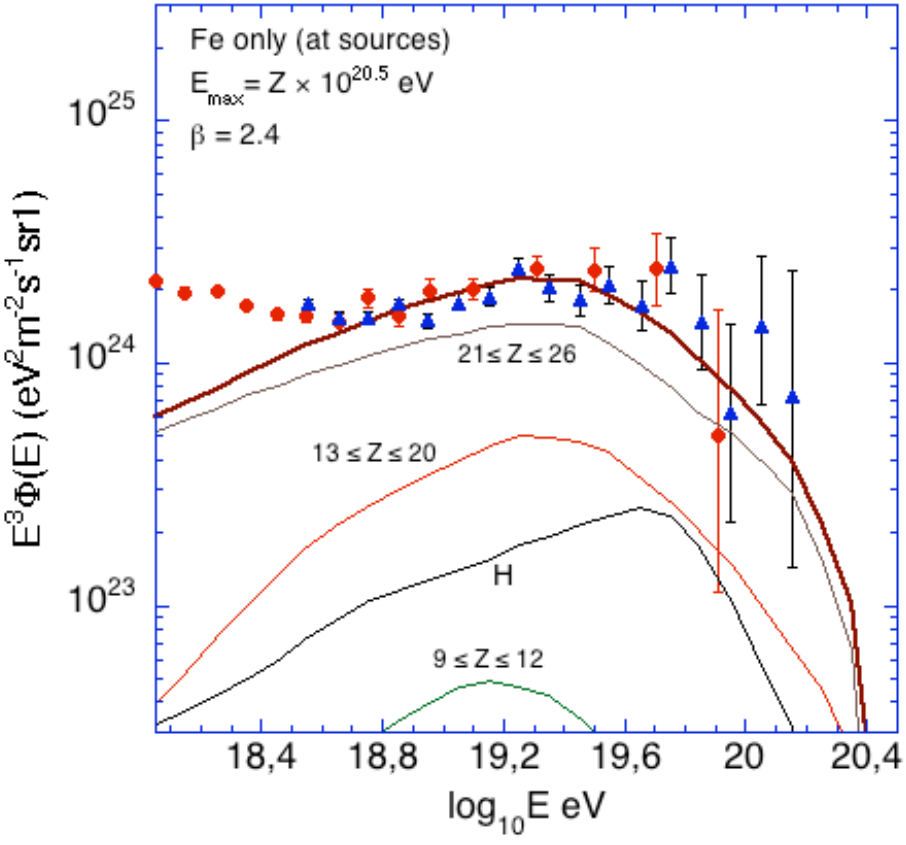
- photo-dissociation, z.B. $A + \gamma \rightarrow A - 1 + n/p$
- change of beam composition during propagation!

(Allard et al. JCAP 0810:033,2008)

'Mixed Composition' Model

(Allard et al. 2005, 2008)

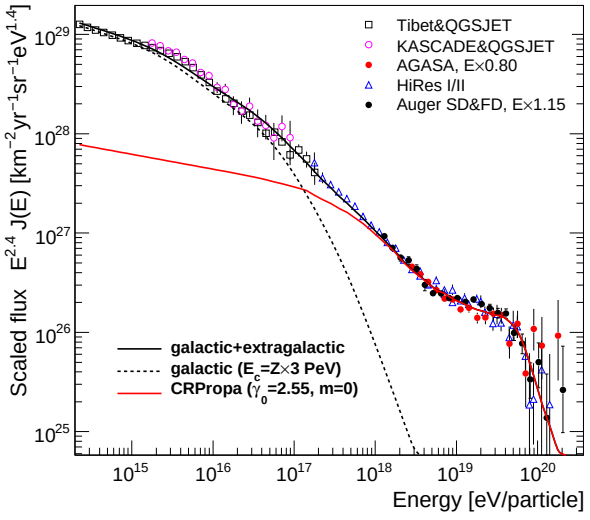




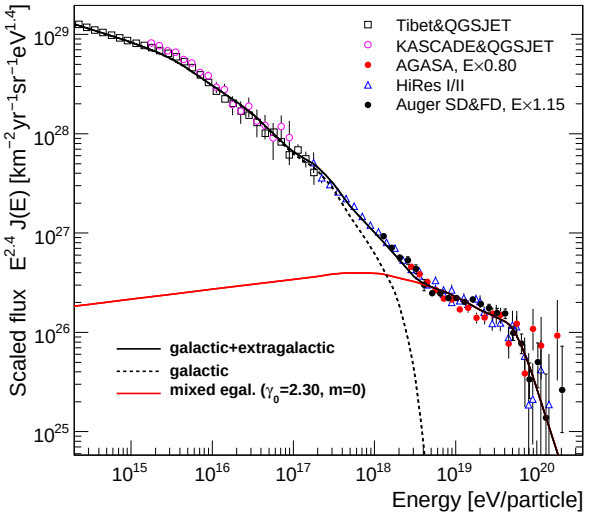
- transition Gal-EGal around EeV

Comparison of models

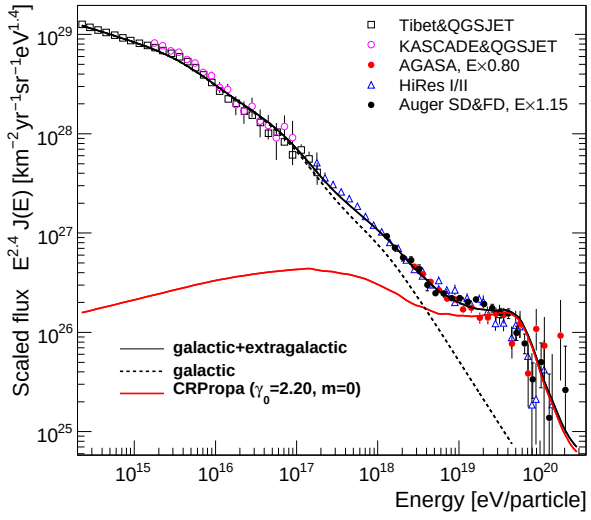
dip



mixed



ankle



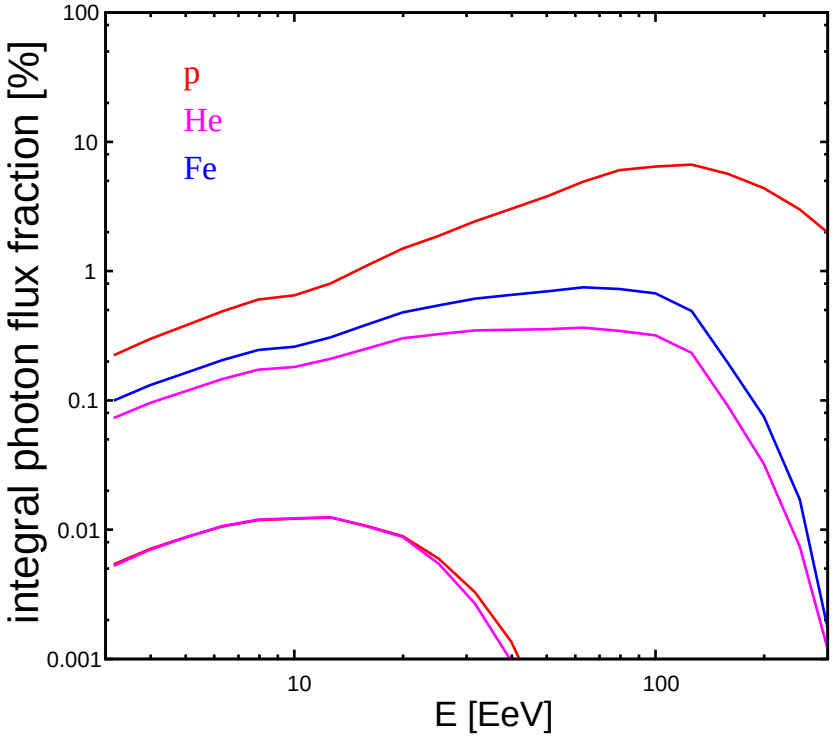
→ combined measurement of flux, composition and anisotropy

Photons and Neutrinos

in sources or during propagation (cosmogenic):

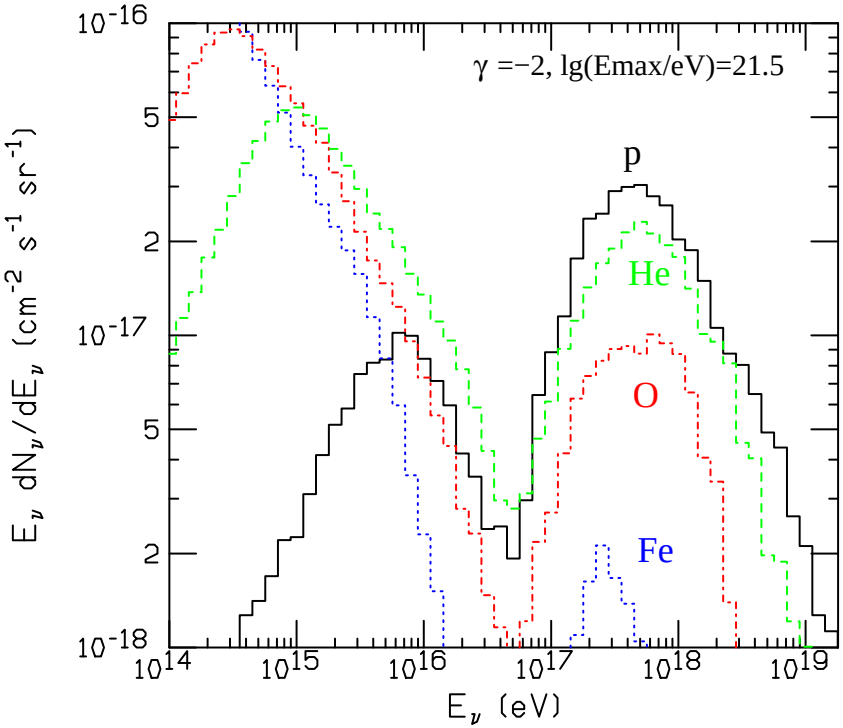
$$ {}^{A}_{Z} + N, \gamma \rightarrow X + \begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{0} \rightarrow \text{photons} \end{matrix} $$

cosmogenic photons



(Gelmini et al., JCAP (2007) 0711:002)

cosmogenic neutrinos

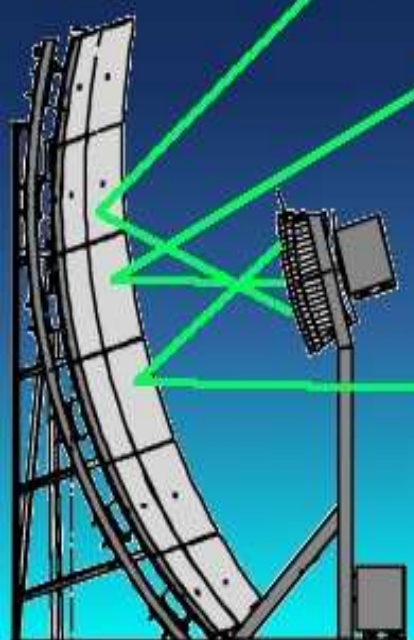


(Hooper et al., APP23 (2005) 11)

Airshower measurements

fluorescence telescopes:
- longitudinal development
- calorimetric
- $\tau \approx 13\%$

surface detectors
- lateral distributions
- particle densities
- $\tau \approx 100\%$



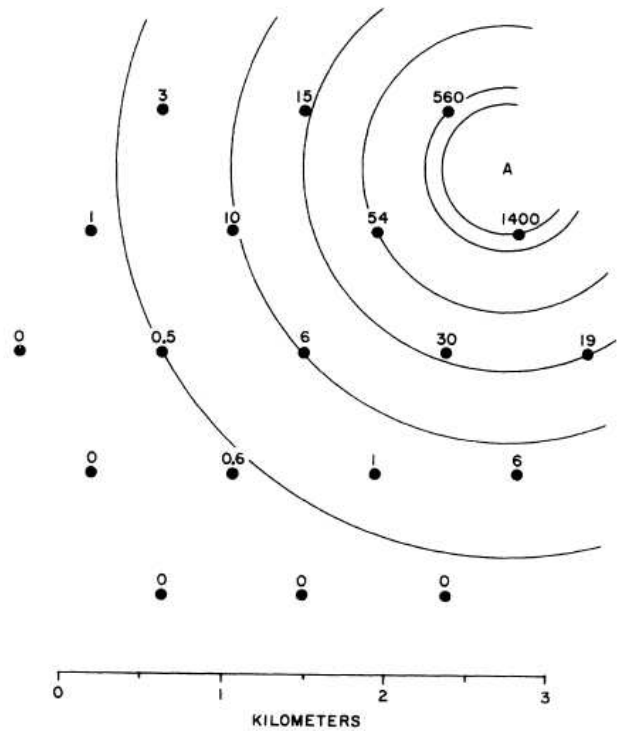
VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

Analysis of a cosmic-ray air shower recorded at the MIT Volcano Ranch station in February

point marked "*A*," assuming only (1) that shower particles are distributed symmetrically about an



scintillator array Volcano Ranch, $E \approx 1.0 \cdot 10^{20}$ eV

THE ASTROPHYSICAL JOURNAL, 441:144–150, 1995 March 1

DETECTION OF A COSMIC RAY WITH MEASURED ENERGY WELL BEYOND THE EXPECTED SPECTRAL CUTOFF DUE TO COSMIC MICROWAVE RADIATION

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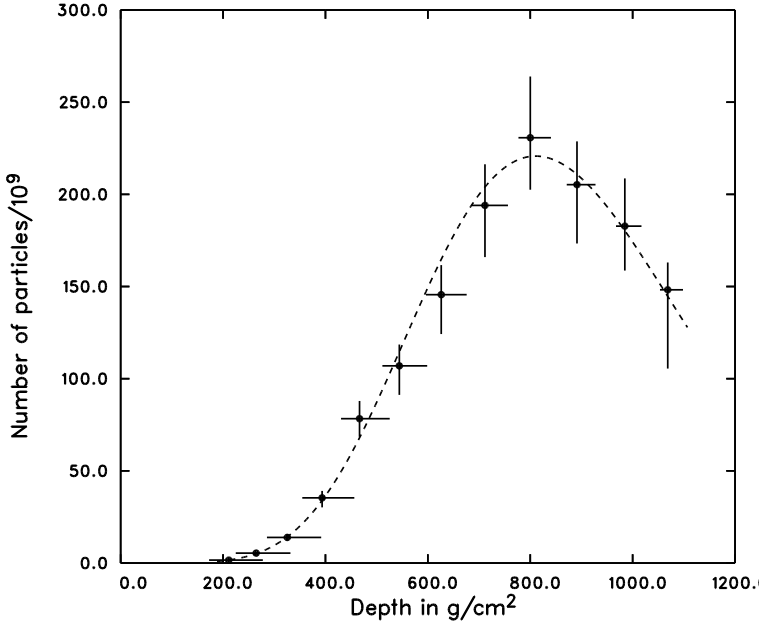
D. B. KIEDA,[2] S. KO,[2] C. G. LARSEN,[2] E. C. LOH,[2] M. Z. LUO,[5] M. H. SALAMON,[2]
J. D. SMITH,[2] P. SOKOLSKY,[2] P. SOMMERS,[2] J. K. K. TANG,[2] AND S. B. THOMAS[2]

Received 1994 May 31; accepted 1994 September 13

ABSTRACT

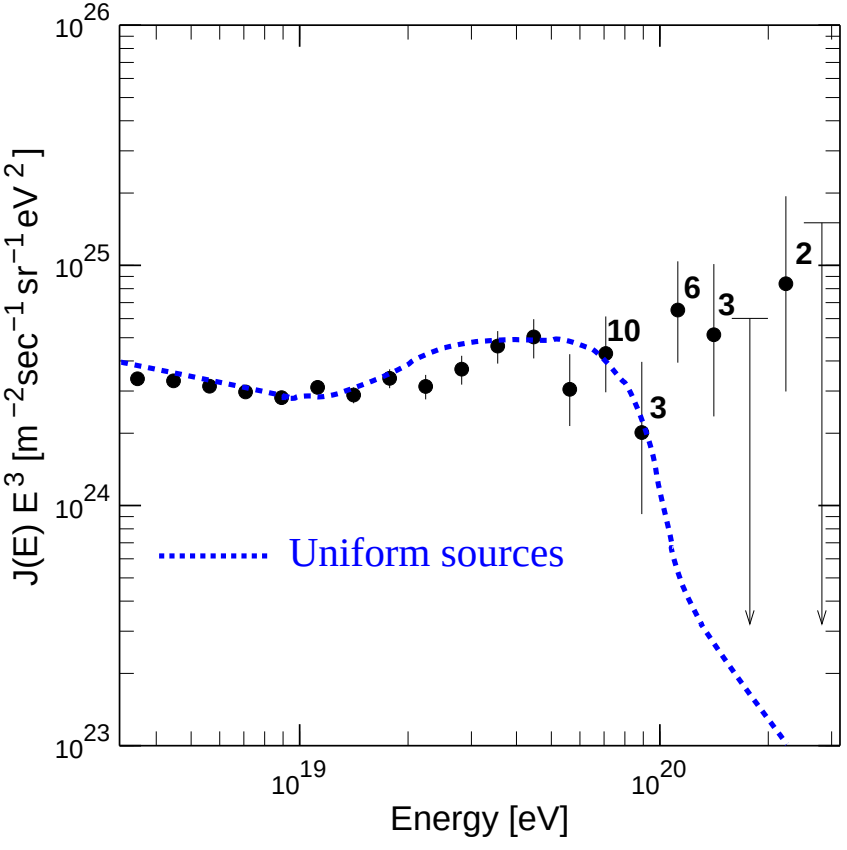
We report the detection of a 51 Joule ($3.2 \pm 0.9 \times 10^{20}$ eV) cosmic ray by the Fly's Eye air shower detector in Utah. This is substantially greater than the energy of any previously reported cosmic ray. A Greisen-Zatsepin-Kuz'min cutoff of the energy spectrum (due to pion photoproduction energy losses) should occur



fluorescence detector Fly's Eye, $E = 3.2 \pm 0.9 \cdot 10^{20}$ eV

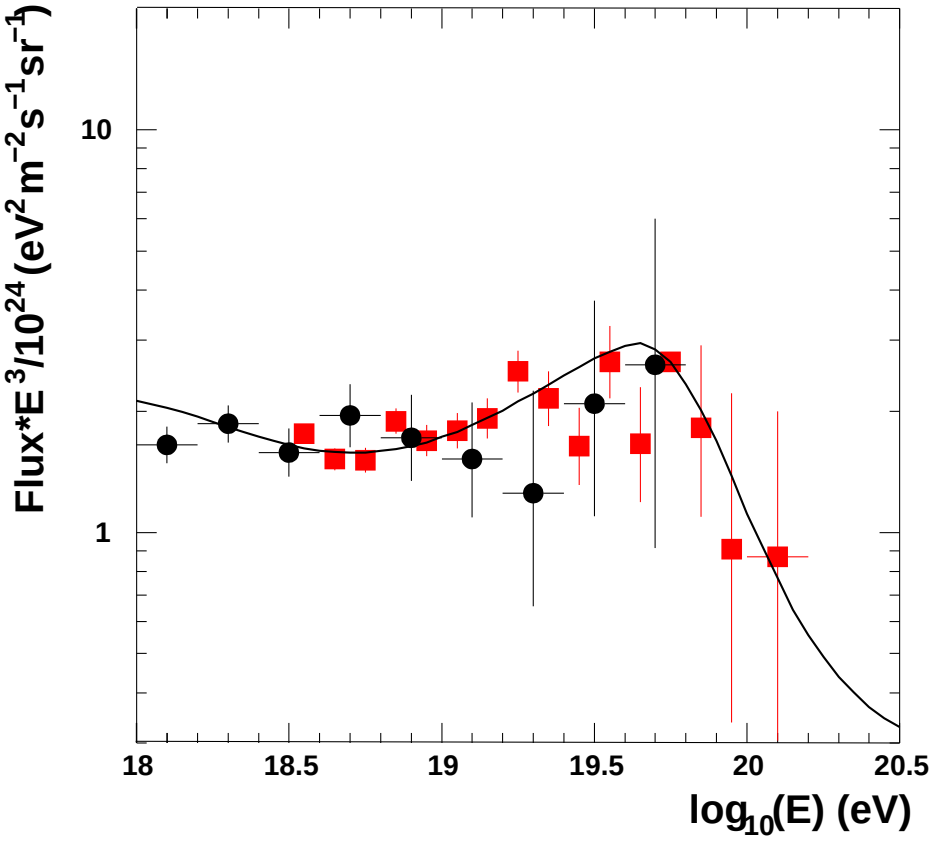
The GZK puzzle

AGASA (scintillator)



(M. Takeda et al., APP **19** (2003), 447)

HiRes (fluorescence)



(T. Abu-Zayyad, APP **23** (2005) 157)

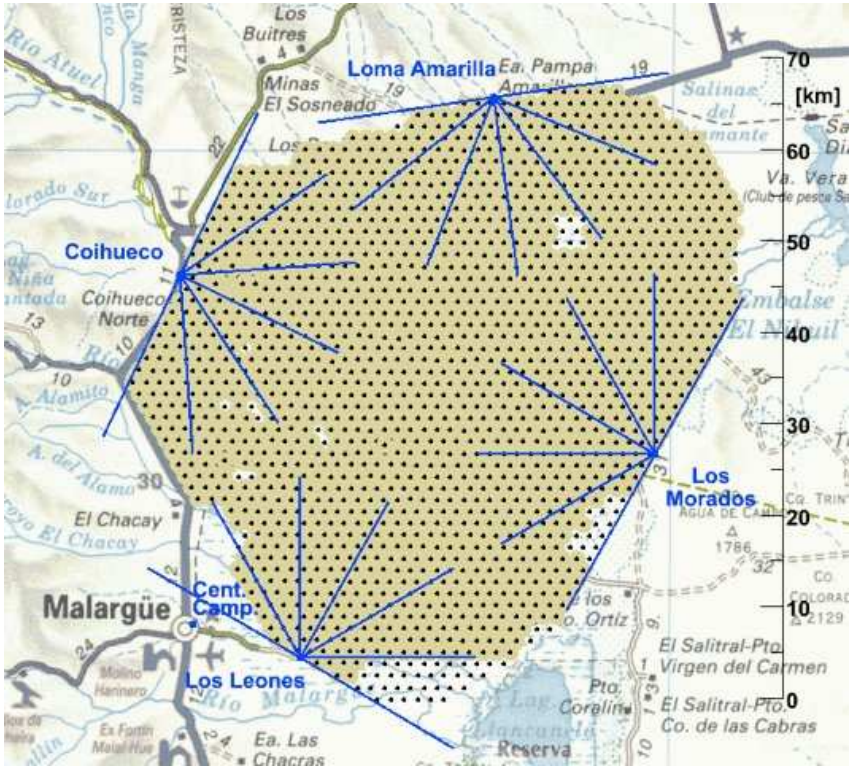
The Pierre Auger Observatory

Colorado, USA
(in planning)

Mendoza, Argentina
(Auger South)

- 18 countries, 476 scientists
- 6 institutes and 80 scientist from Germany
  (RWTH Aachen, MPI Bonn, Uni Hamburg, 3×KIT,
  Uni Siegen, Uni Wuppertal)

The Pierre Auger Observatory



- area: 3000 km^2
- 4 fluorescence detectors (30° $\times$ 180°)
- 1663 water Cherenkov detectors, spacing 1.5 km
- data taking since 2004, completed in 2008

The Pierre Auger Observatory

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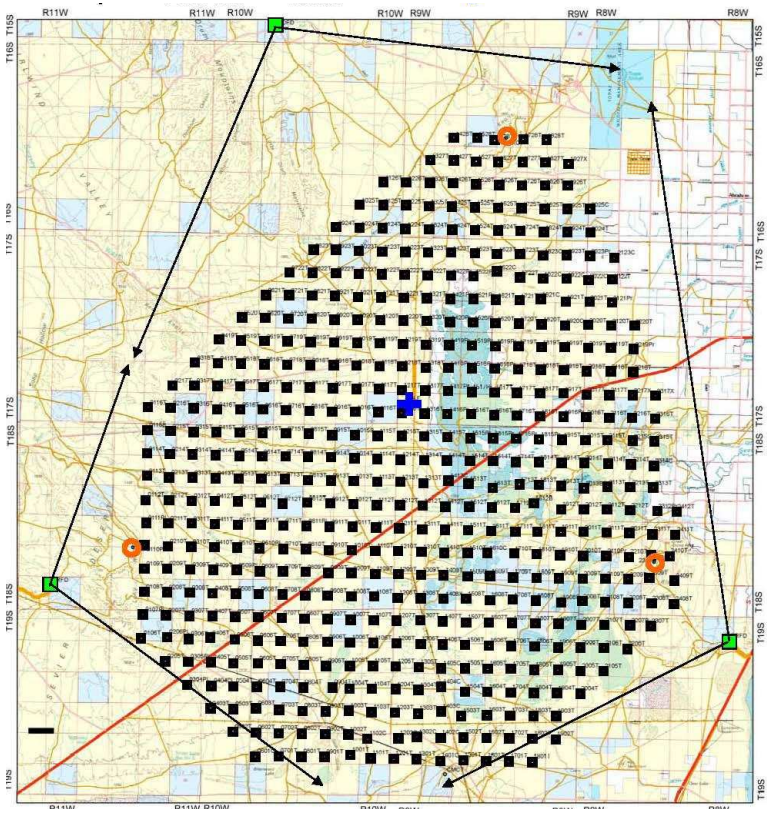
Telescope Array (Utah, USA)



- area: 750 km^2 ($\sim$ 0.25 Auger)
- 3 fluorescence detectors (30° $\times$ 120°)
- 507 scintillators, spacing 1.2 km
- completed in 2008

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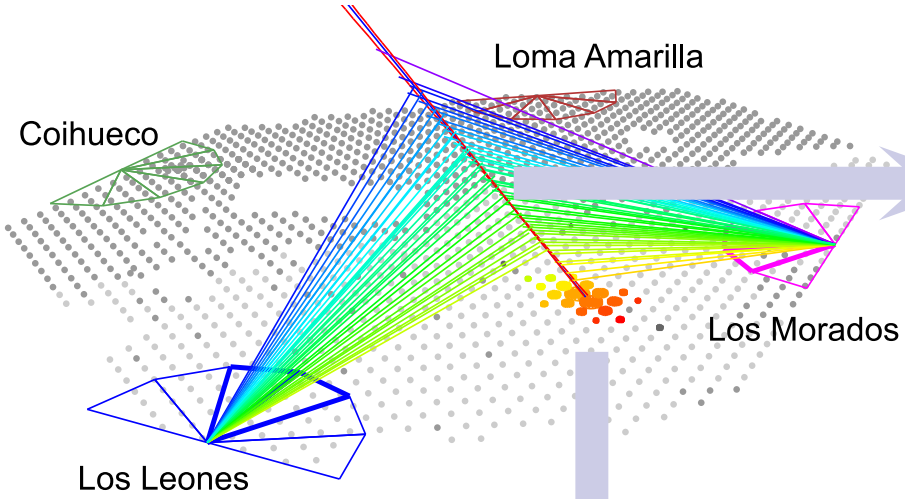
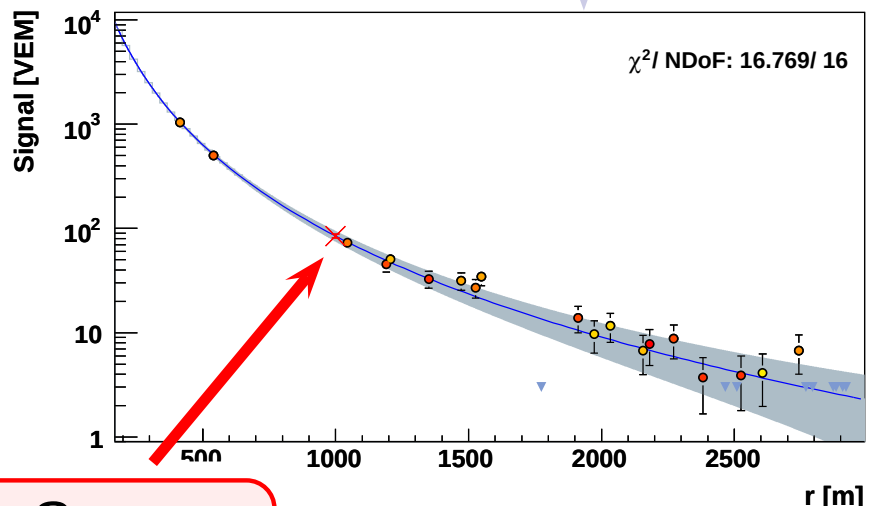
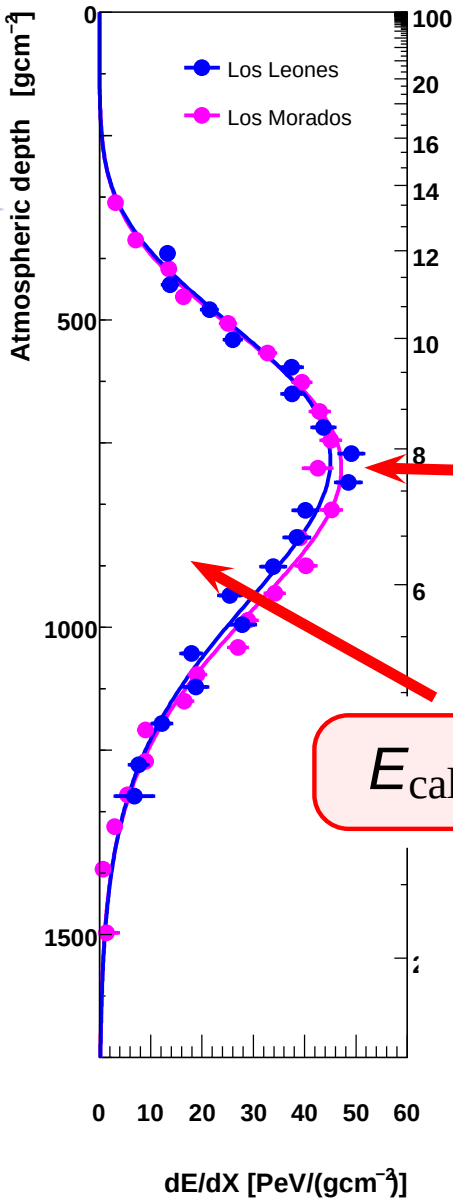
Hybrid Measurement of Air Showers in Auger





S_{1000}

$E_{\text{surface}} = f(S_{1000}, \theta)$



$\sigma_{X_{\max}} < 20\,\text{g/cm}^2$

$\Delta_{\text{sys}} \approx 15\,\text{g/cm}^2$

$X_{\max}$

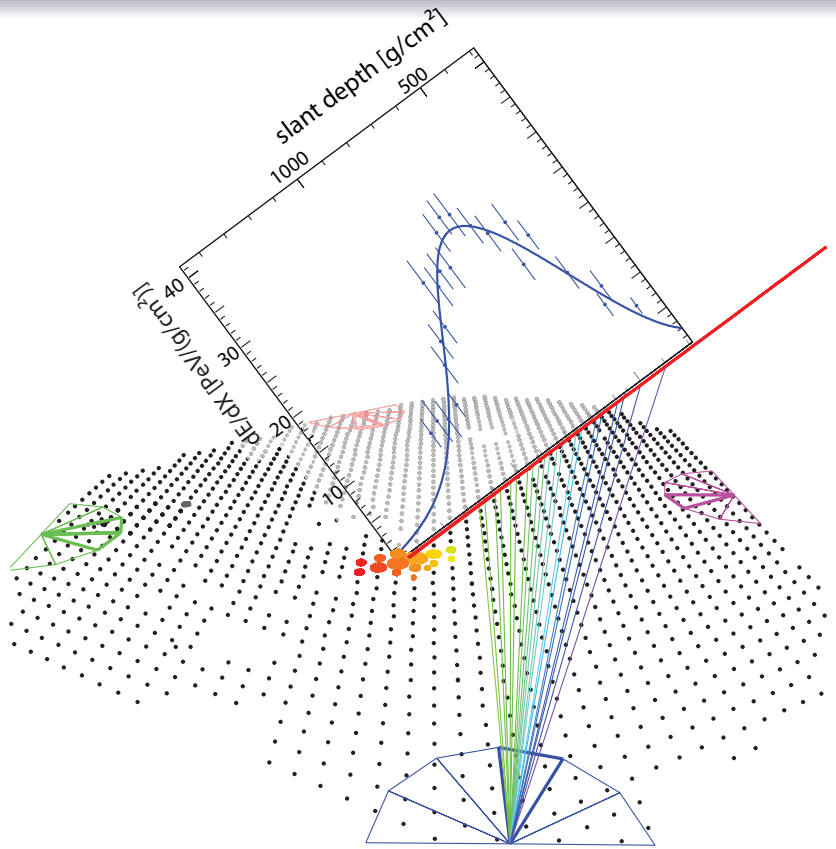
$E_{\text{cal}} = \int \frac{dE}{dX}\, dX$

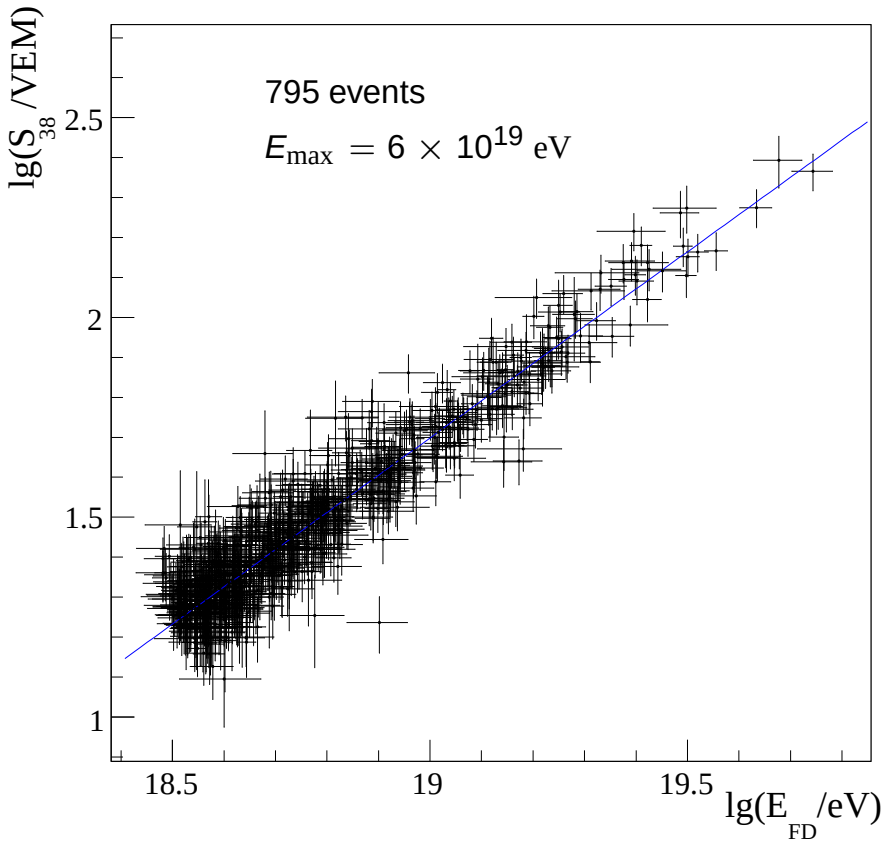
$\sigma_E / E \sim 8\,\%$

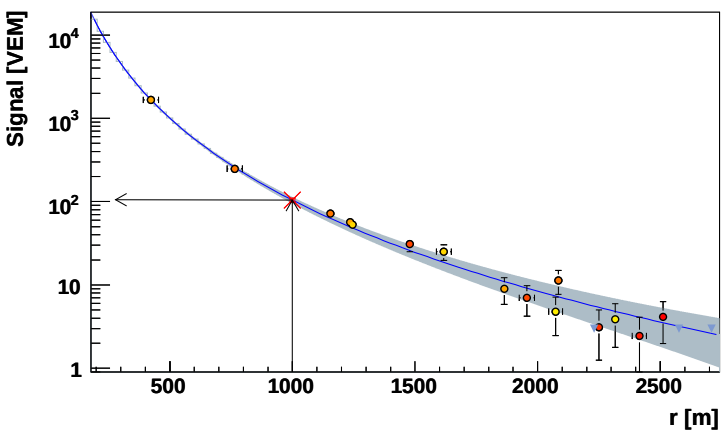
$\Delta_{\text{sys}} \approx 22\,\%$

(R. Ulrich, APS meeting 2010)

Calibration of Surface Detector Energy

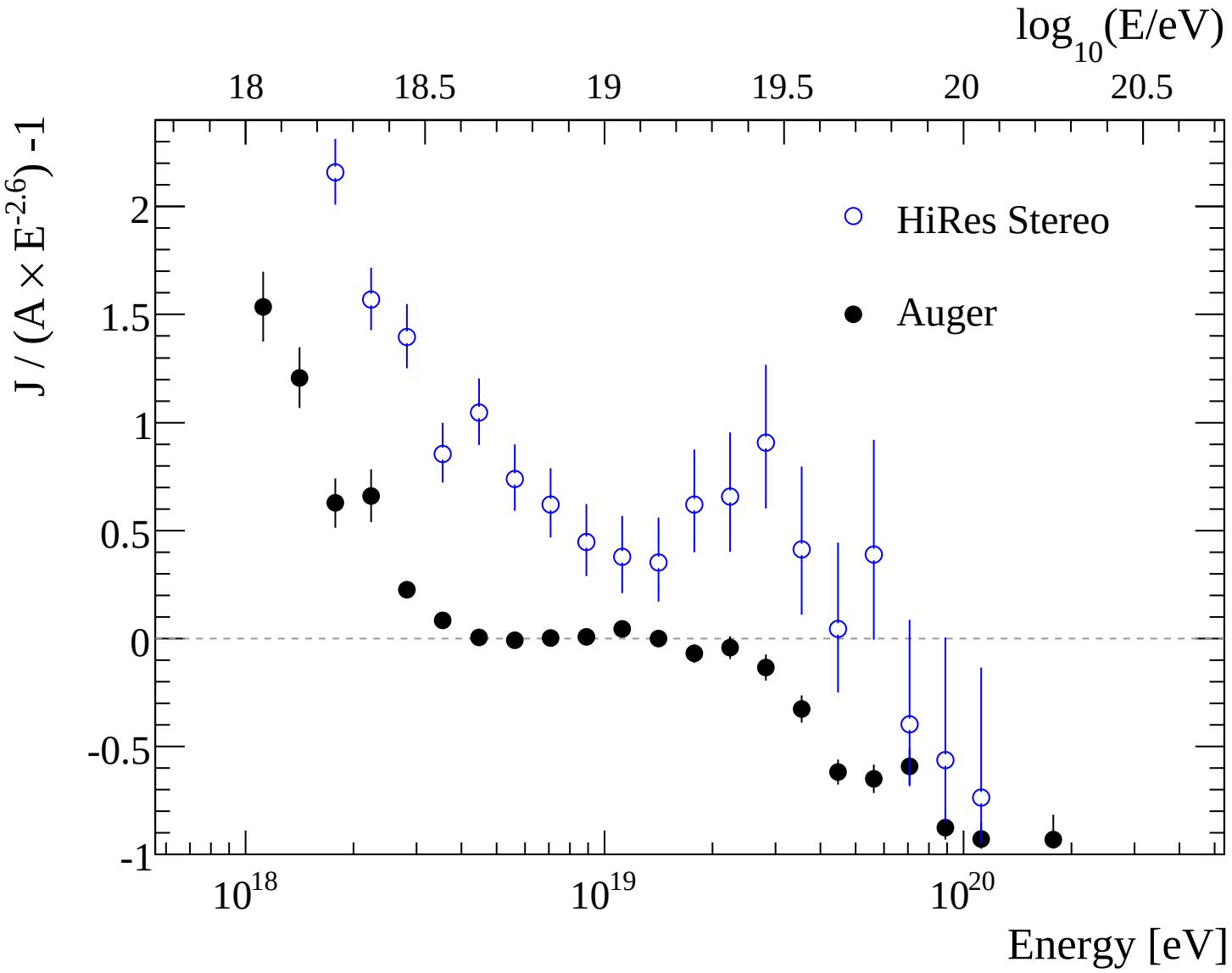






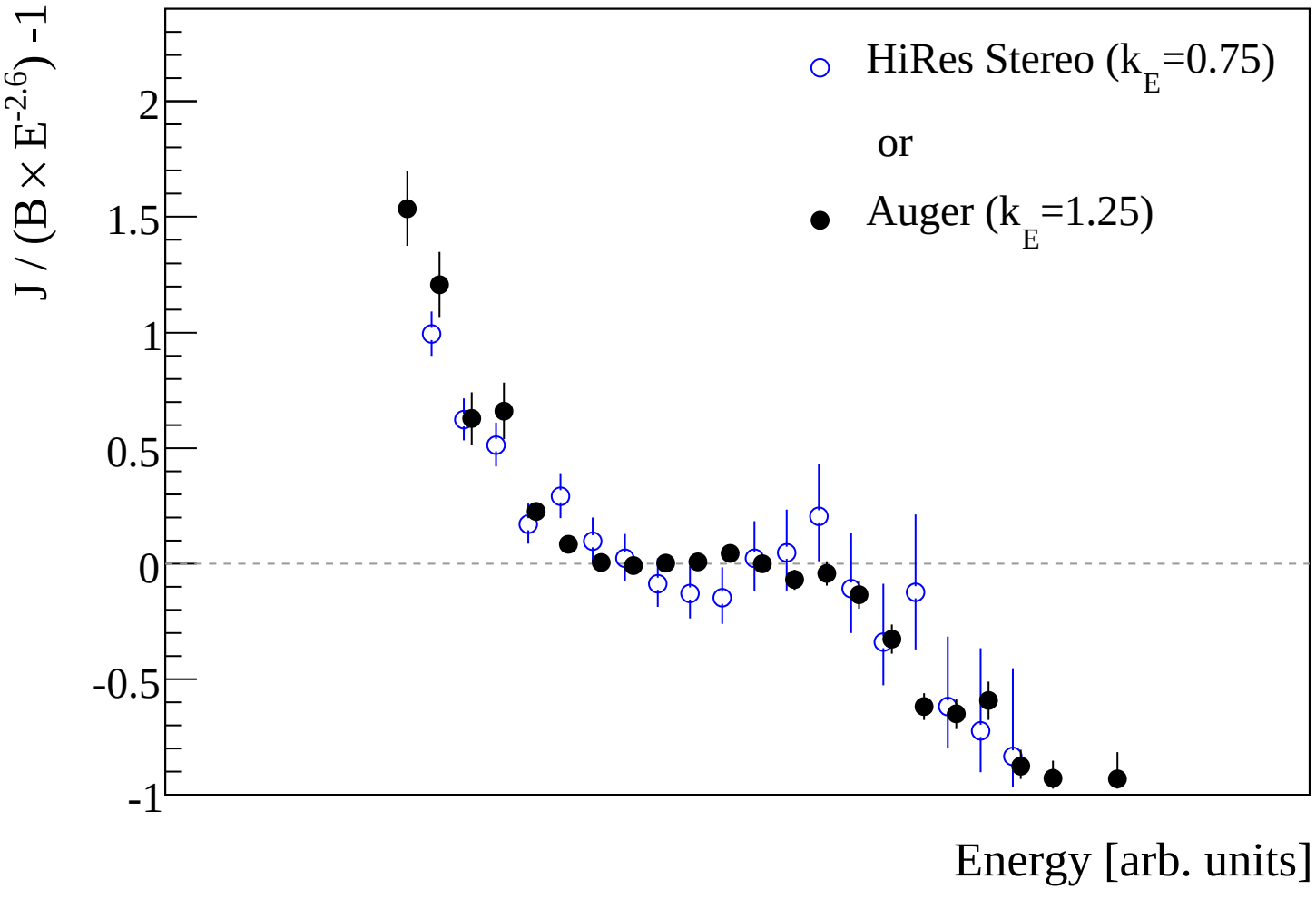
(F. Schüssler, ICRC2009)

Auger and HiRes Energy Spectrum



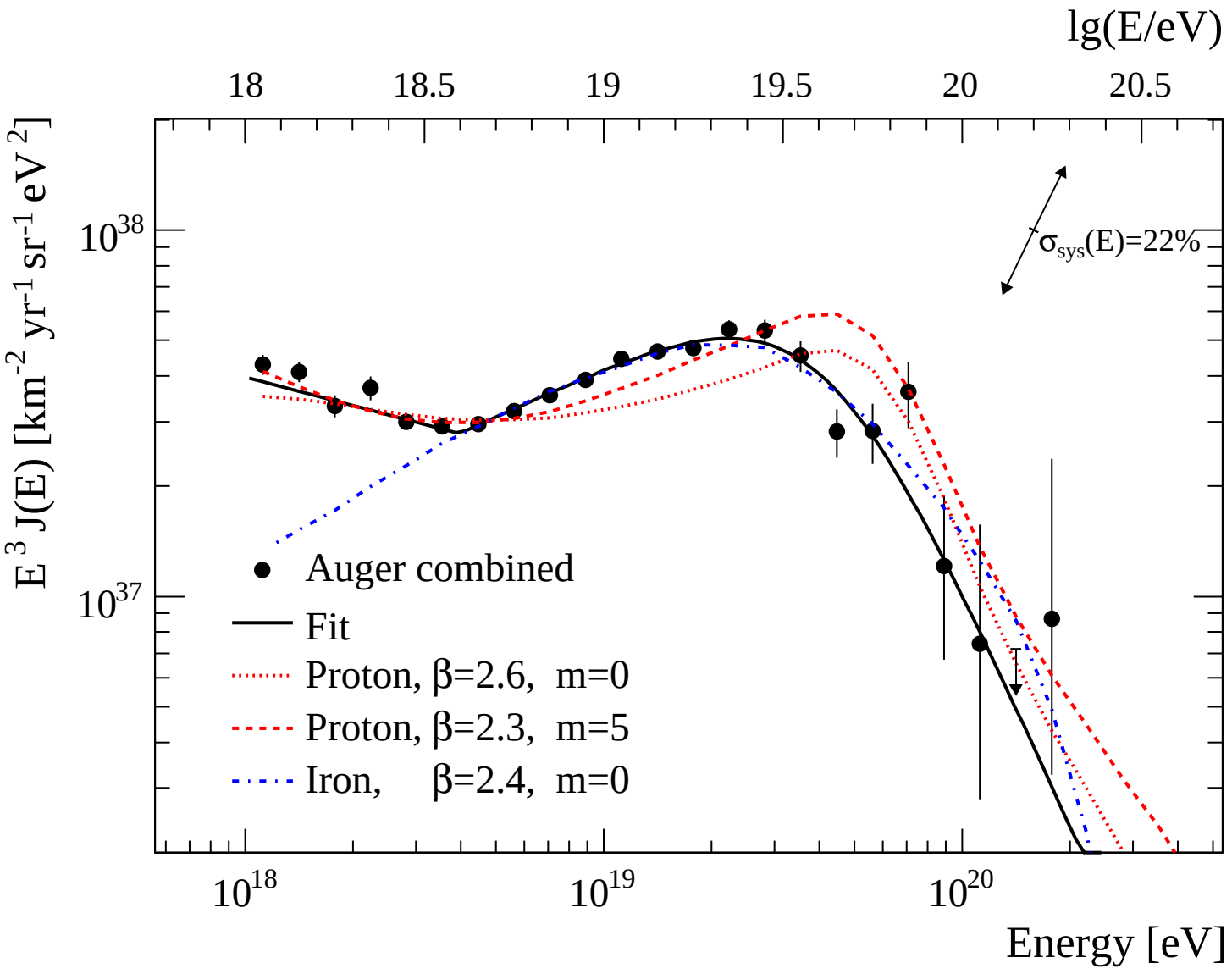
(Auger PRL **101** (2008) 61101, PLB (2010); HiRes APP **32** (2009) 53)

Auger and HiRes Energy Spectrum

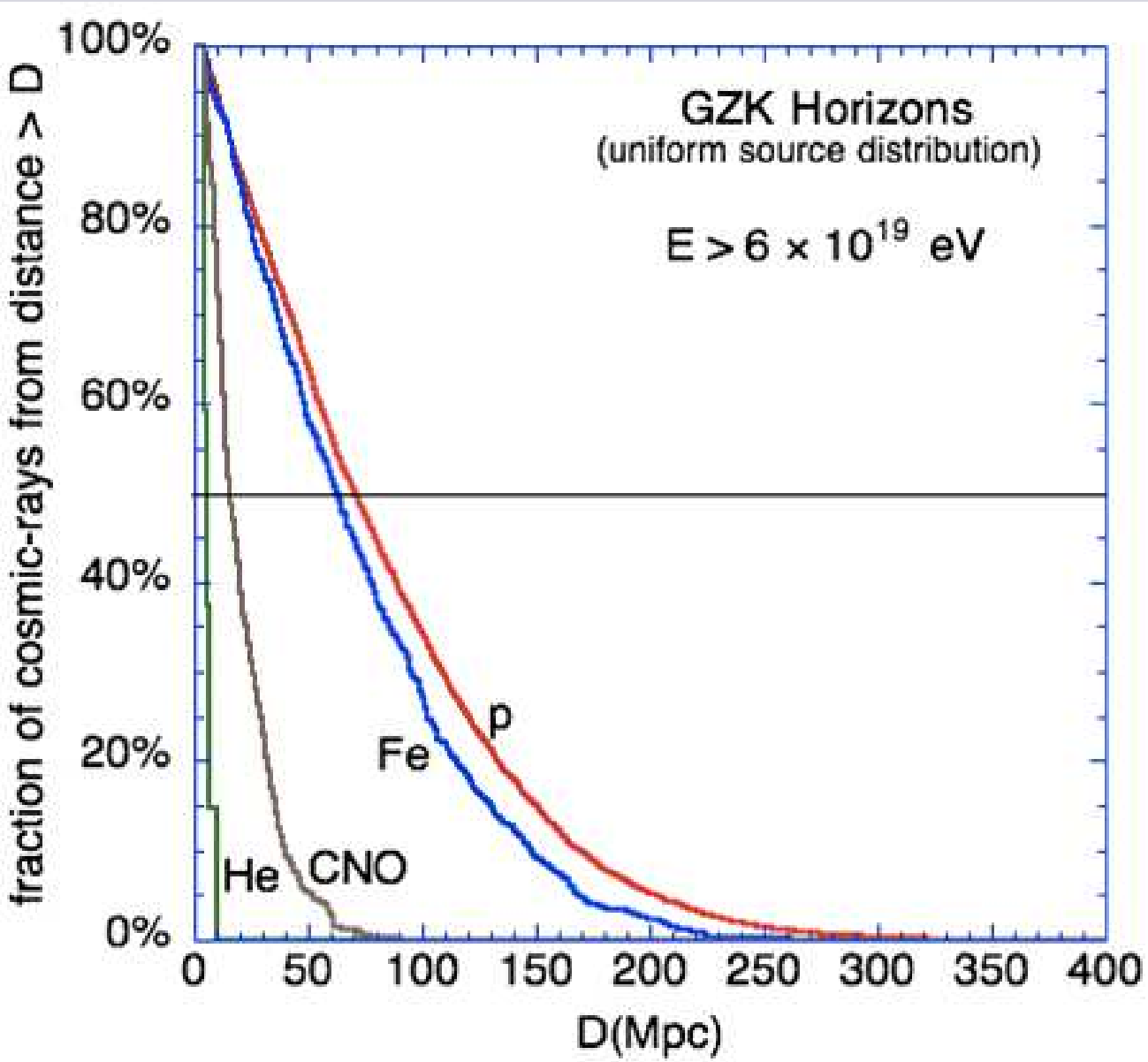


(Auger PRL **101** (2008) 61101, PLB (2010); HiRes APP **32** (2009) 53)

Comparison to UHECR Propagation

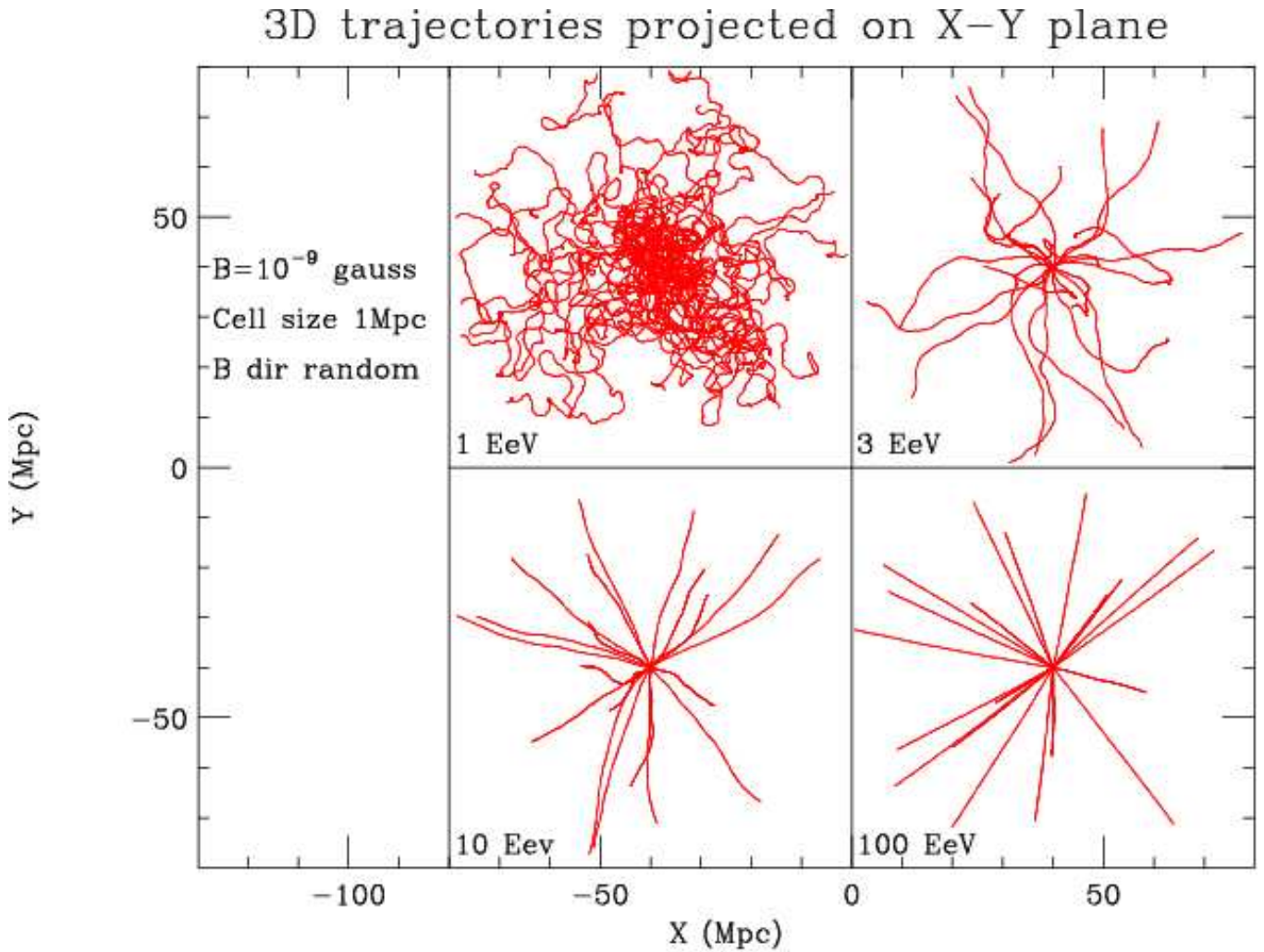


GZK-Sphere


GZK Horizons
(uniform source distribution)
E > 6 x 10^19 eV
fraction of cosmic-rays from distance > D
100%
80%
60%
40%
20%
0%
0
50
100
150
200
250
300
350
400
D(Mpc)
p
Fe
He
CNO

Particle Astronomy?

intergalactic B-Fields

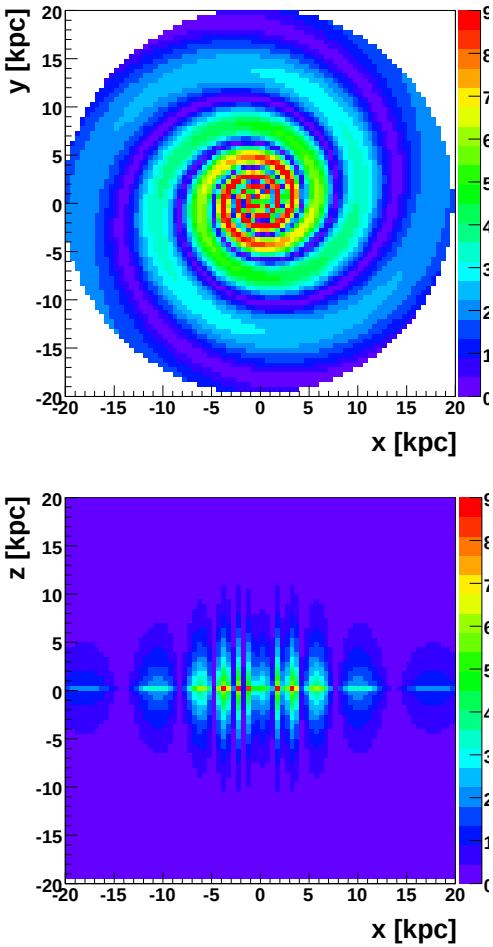


(J. Cronin, TAUP 2003)

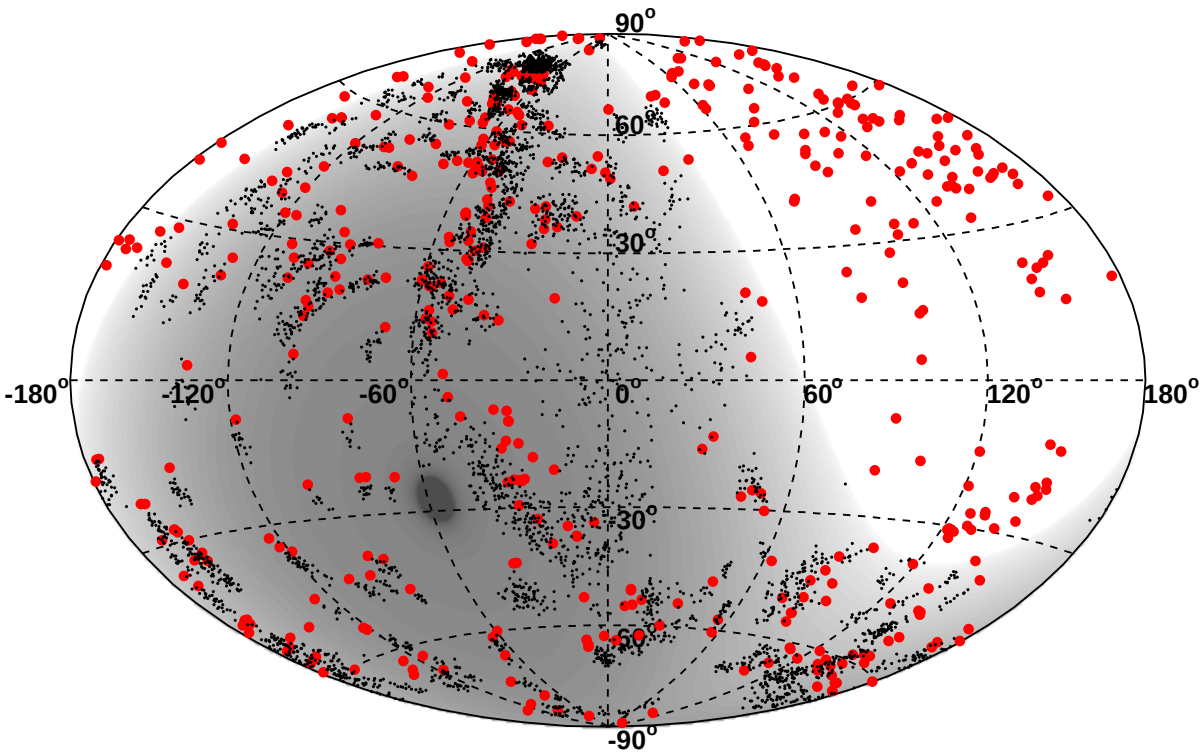
Particle Astronomy?

galactic B-field

BSS model



deflections of protons $E > 50$ EeV



(colors: B-field [μG])

(gray scale: Auger South acceptance)

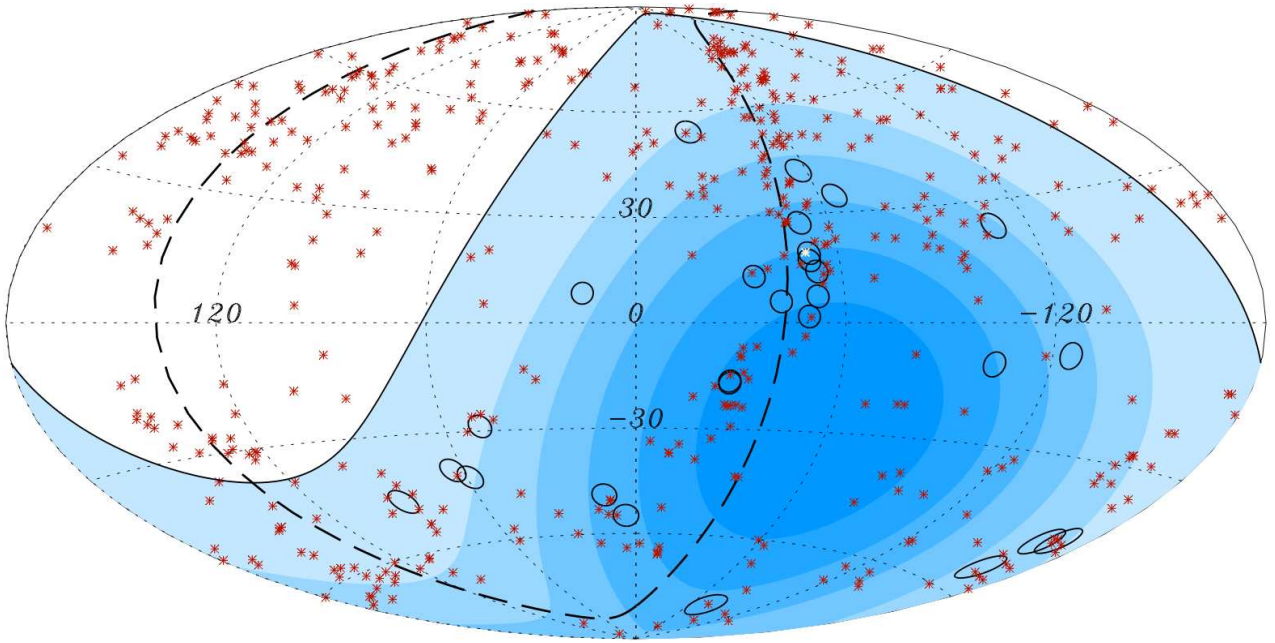
Anisotropy Studies

- $E > 55$ EeV
- correlation with VCV AGNs
  $\delta < 3.1°$, $D < 75$ Mpc
- isotropy excluded at 99% C.L.

  (Auger, Science **318** (2007) 938)

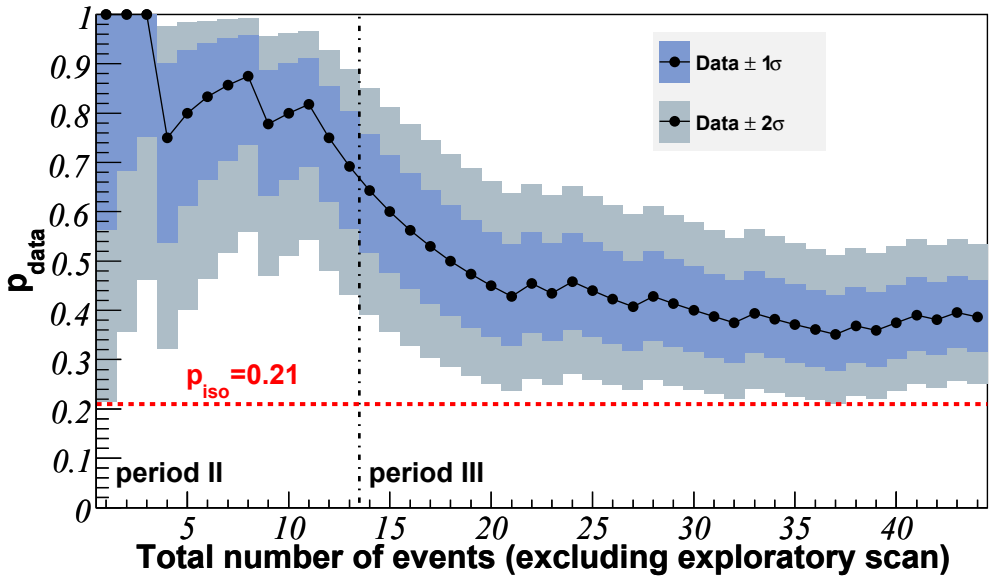
- exploratory scan: 9 of 14 correlate
- independent test sample: 9 of 13 correlate
- not confirmed by HiRes

  (APP **30** (2008), 175)



Anisotropy Studies - Update

data up to 31 March 2009

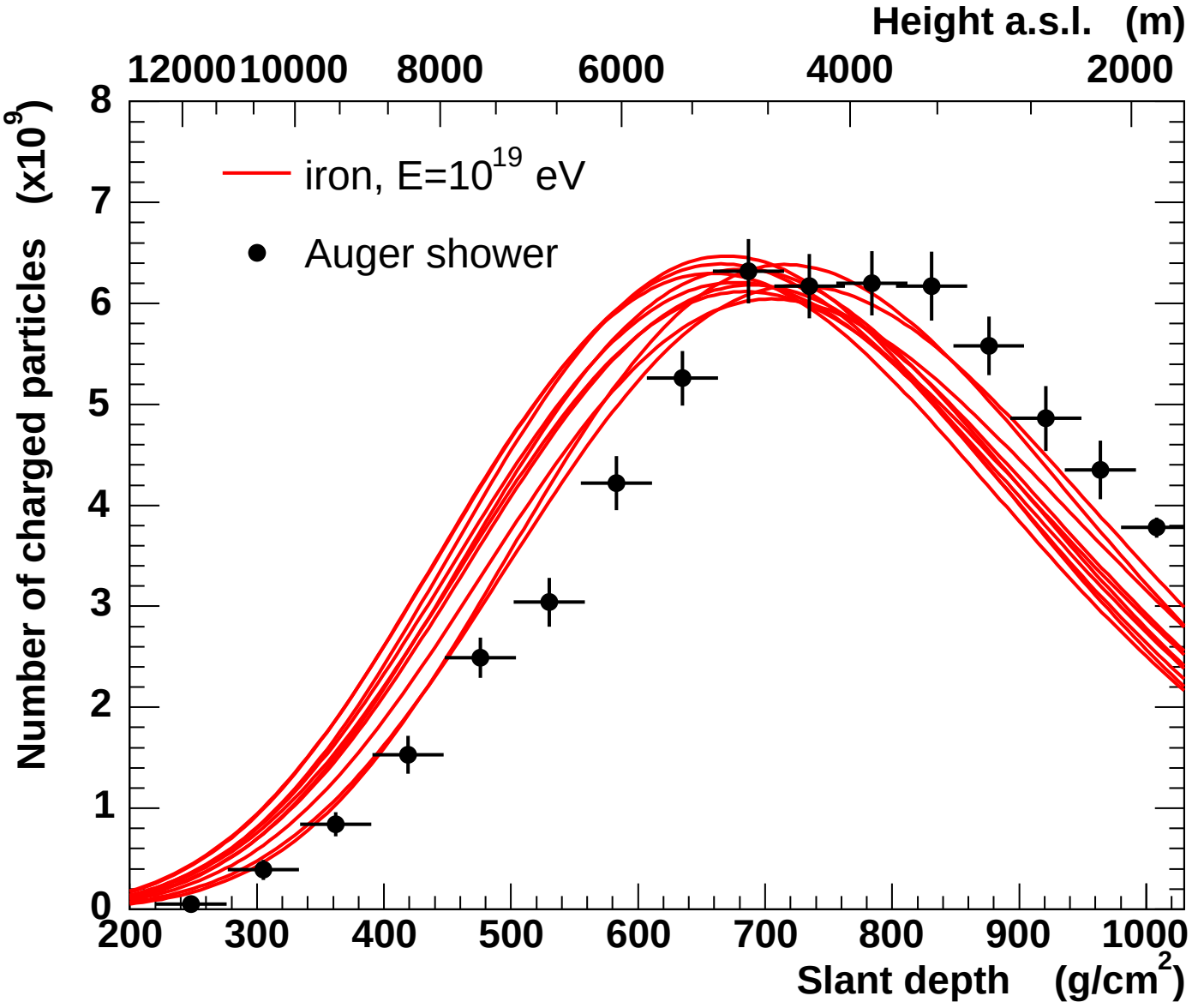


binomial probability for isotropy:

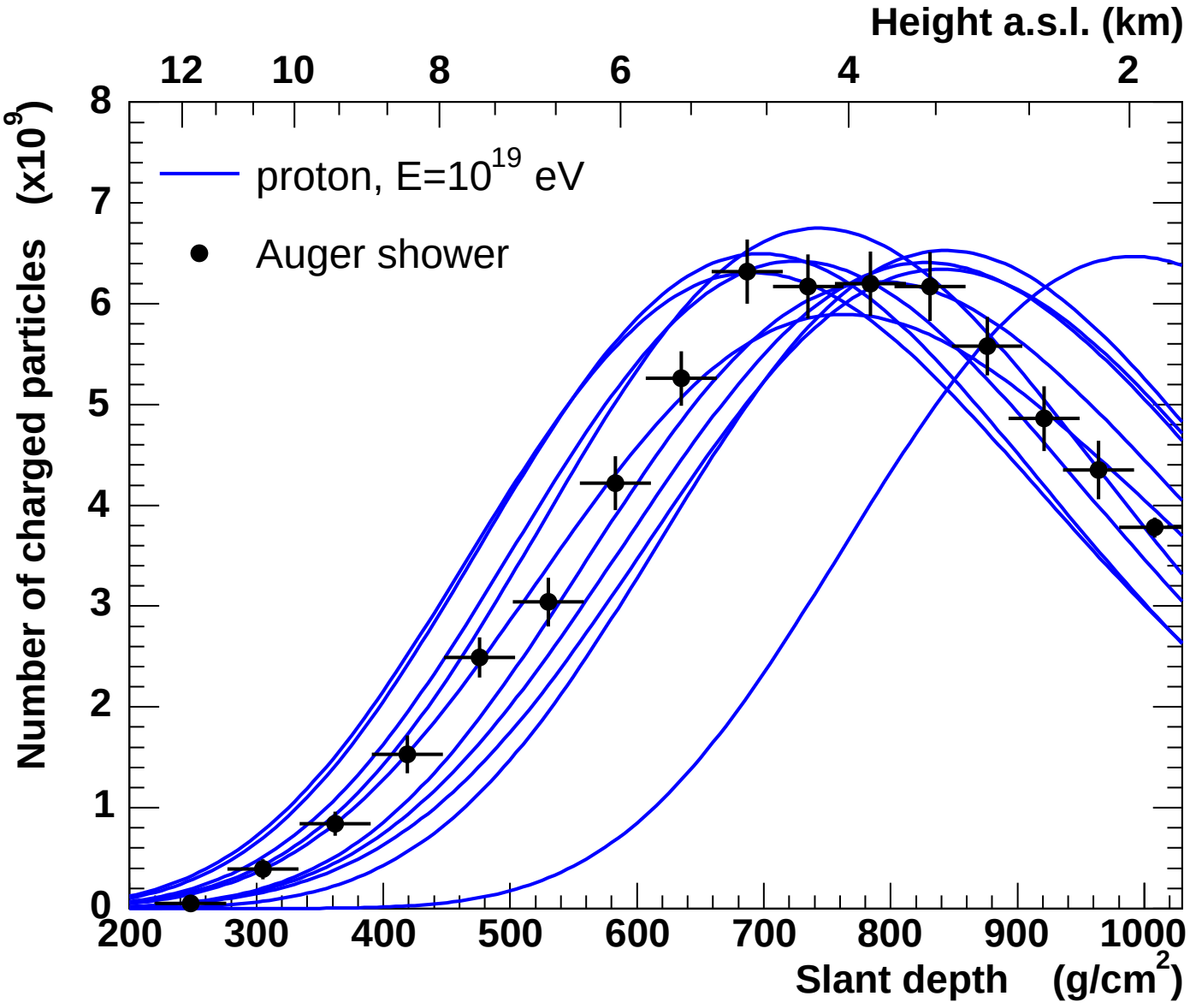
$$P(k=17, N=44, p=0.21) = \sum_{r=k}^{N} \binom{N}{r} p^r (1-p)^{N-r} = 0.006$$

(paper in preparation)

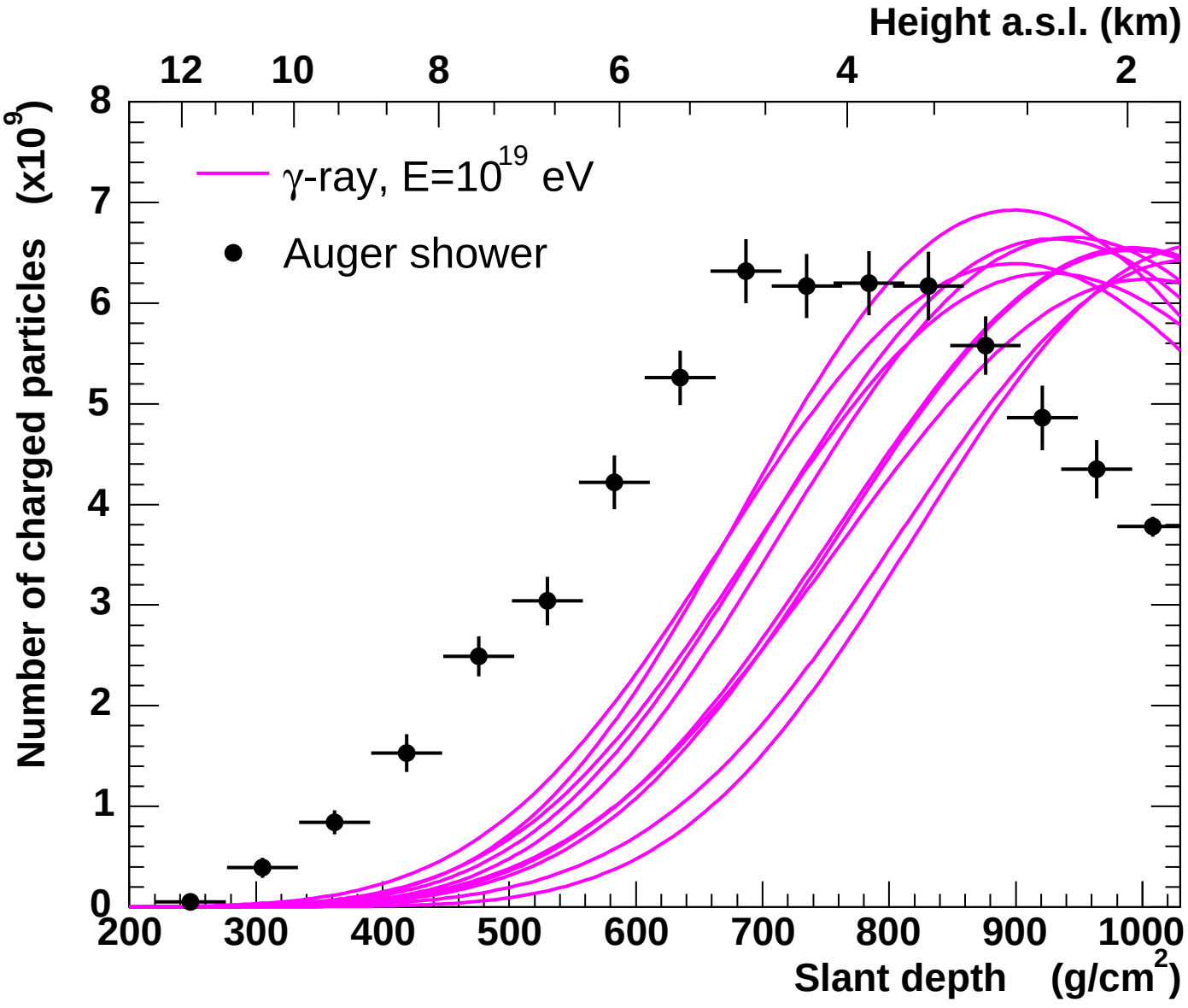
Composition and Longitudinal Profiles



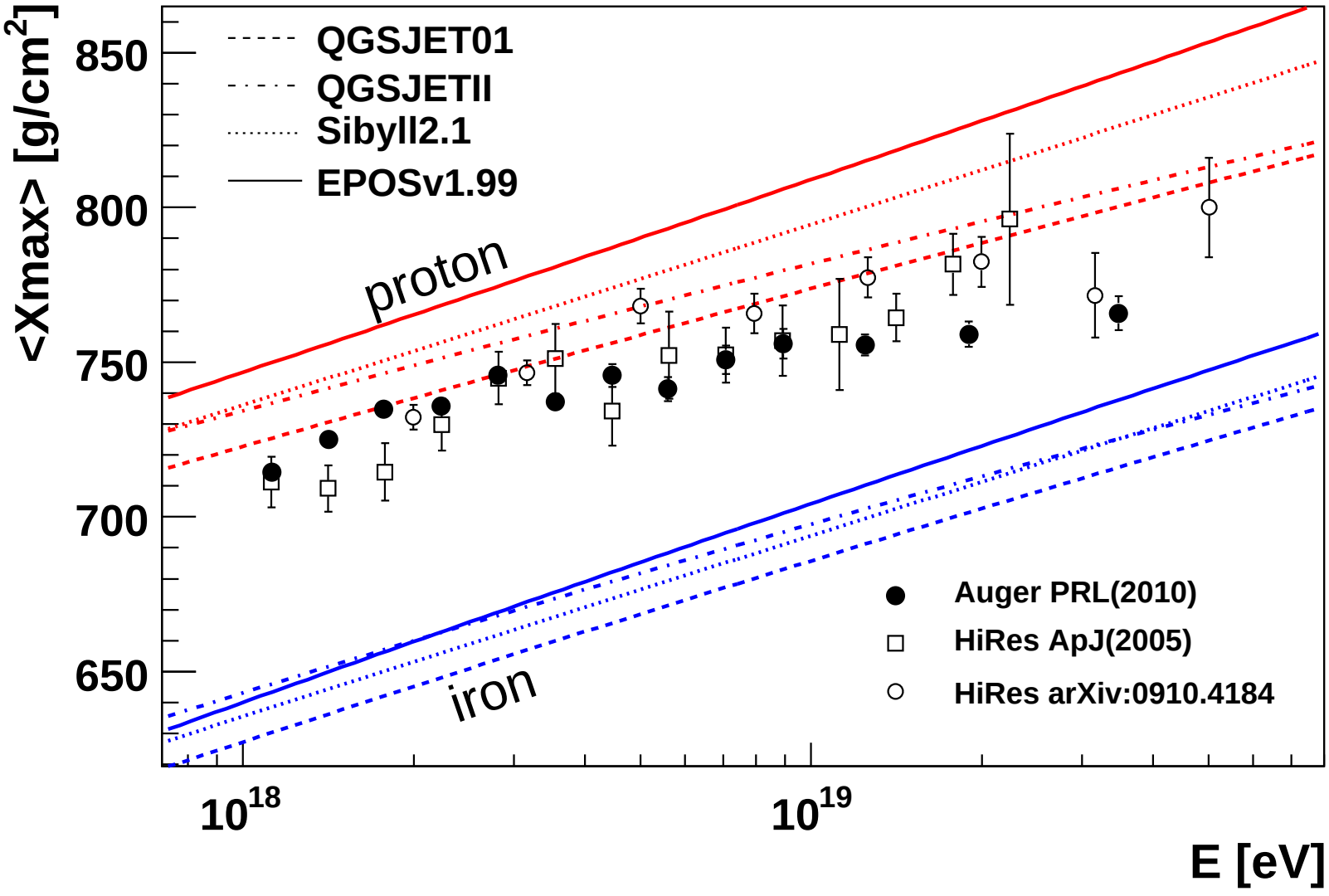
Composition and Longitudinal Profiles



Composition and Longitudinal Profiles

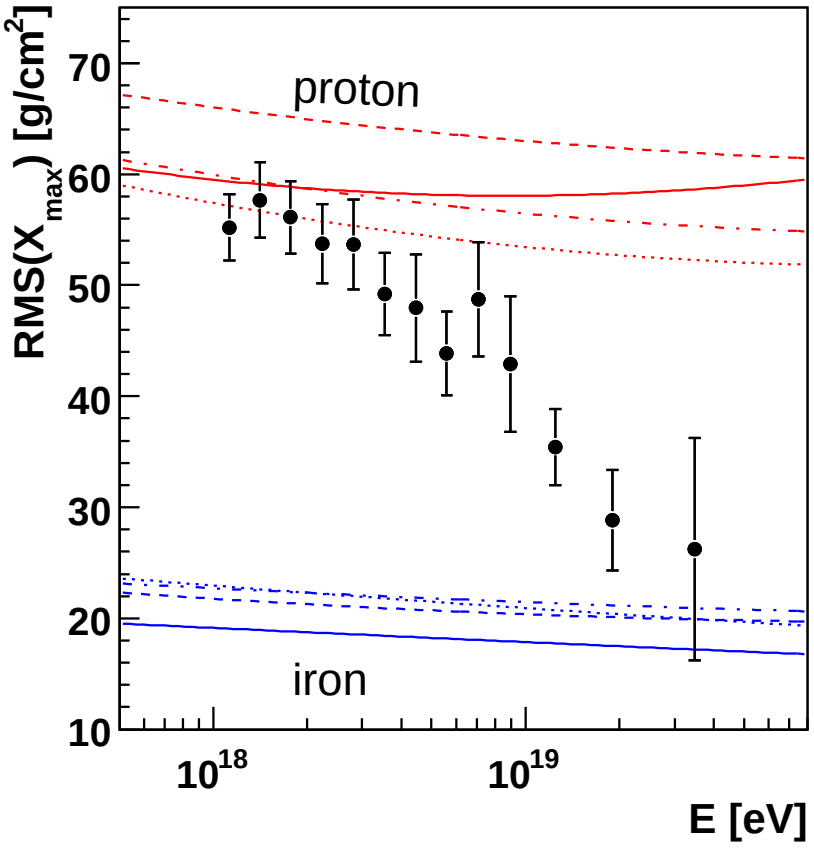


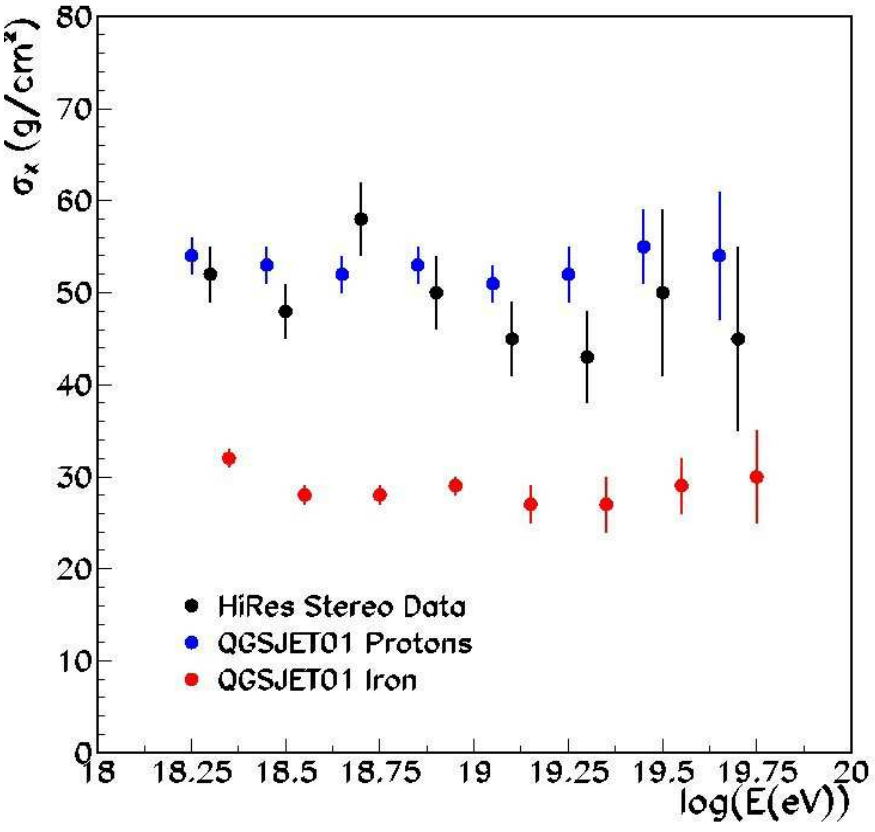
Composition Studies with Xmax



(Auger PRL (2010), HiRes ApJ **622** (2005) 910, HiRes arXiv:0910.4184)

Composition Studies with Xmax

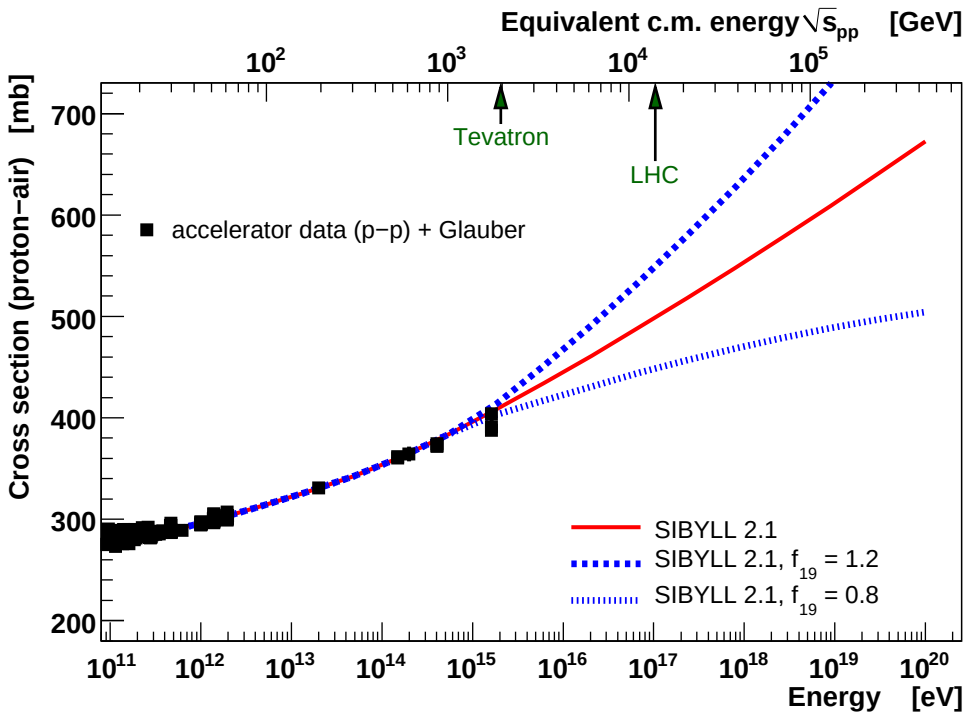


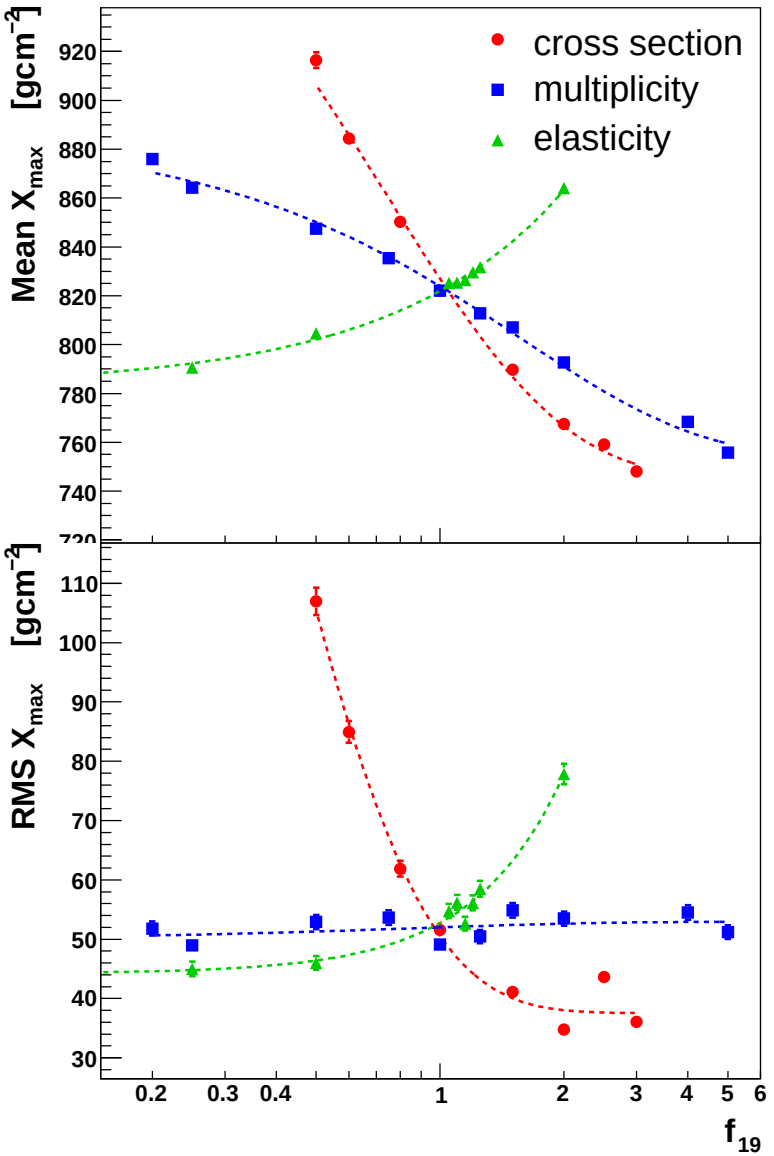


Auger: RMS(Xmax), corrected for resolution

HiRes: σ_X =Gaussian-fit-truncated-at-two-times-RMS
not corrected for resolution

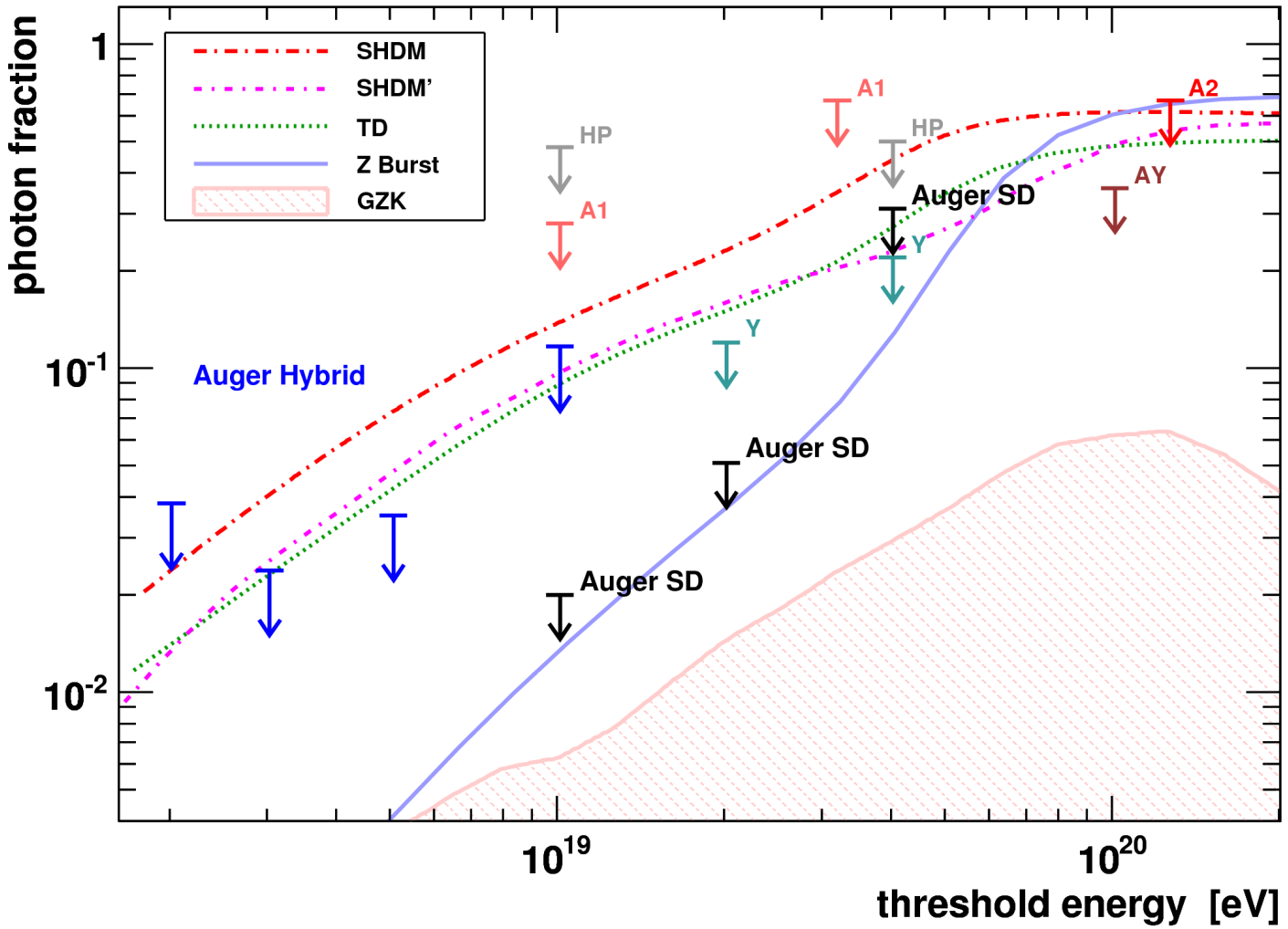
Caveat: Hadronic interactions





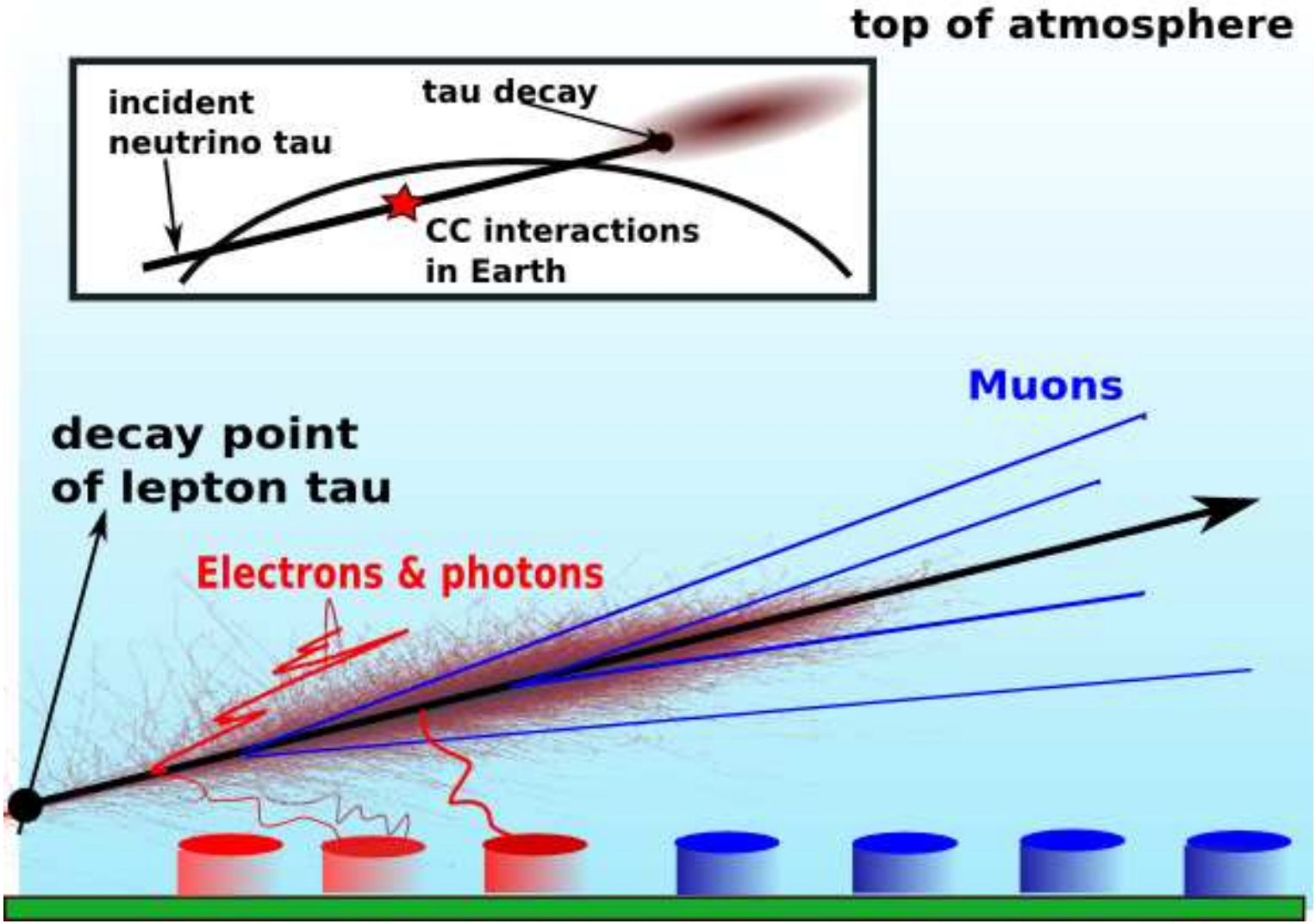
(R. Ulrich et al., ICRC09, arXiv:0906.0418)

Search for Photons



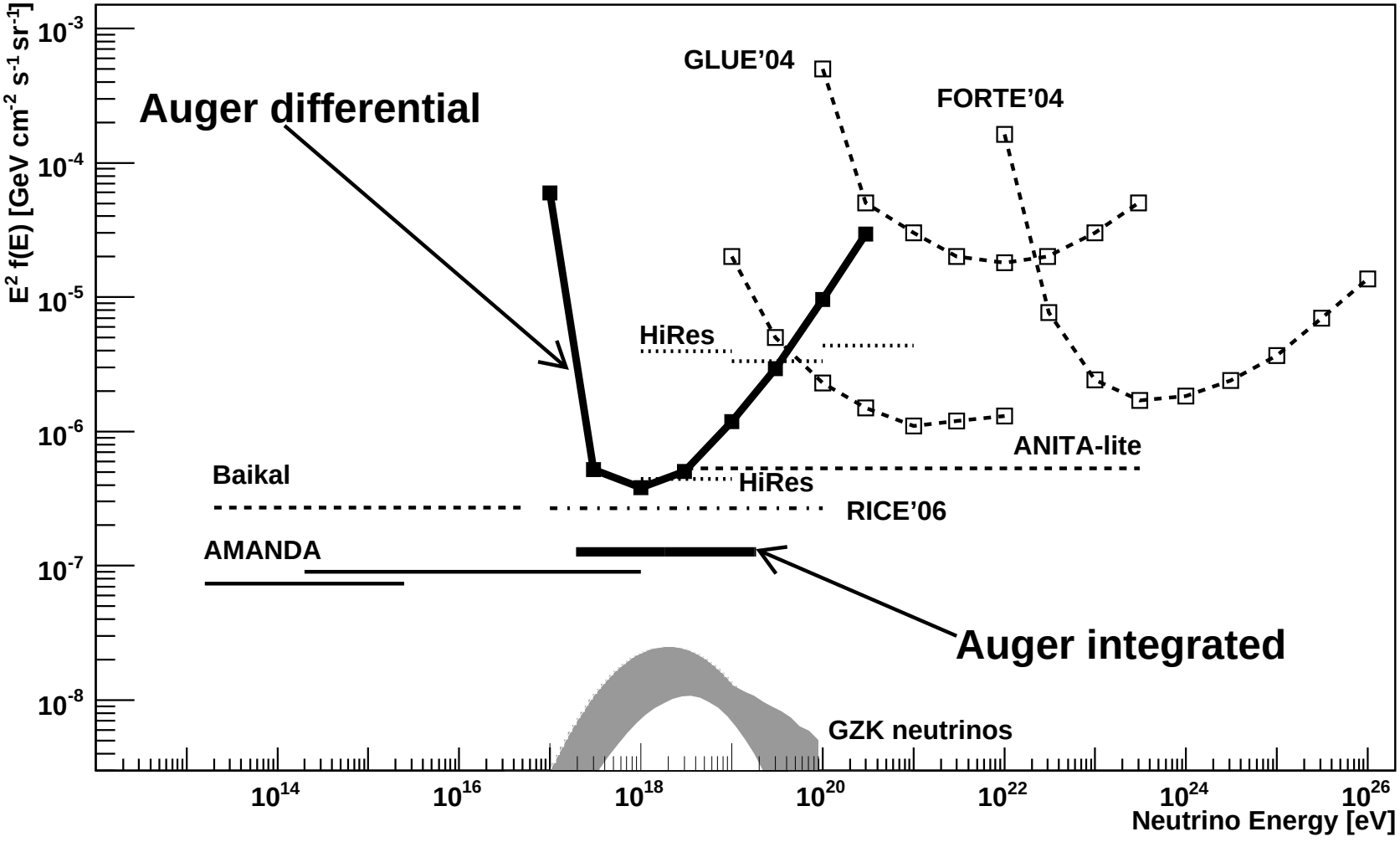
(Auger Astropart.Phys **31** (2009) 399 and Astropart.Phys. **29** (2008) 243)

Search for Neutrinos



(D. Gora et al., ICRC09)

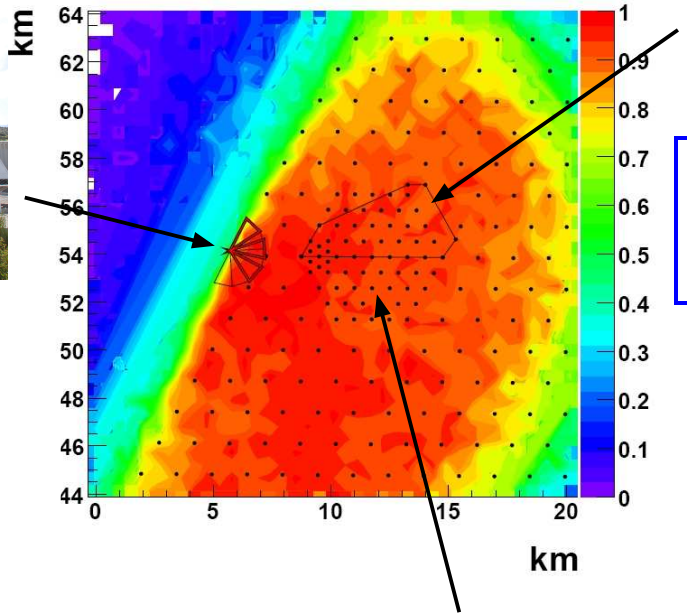
Search for Neutrinos



(Auger, Phys.Rev. **D79** (2009) 102001)

'Super-Hybrid' measurements at Auger South

High Elevation Auger Telescopes (HEAT)

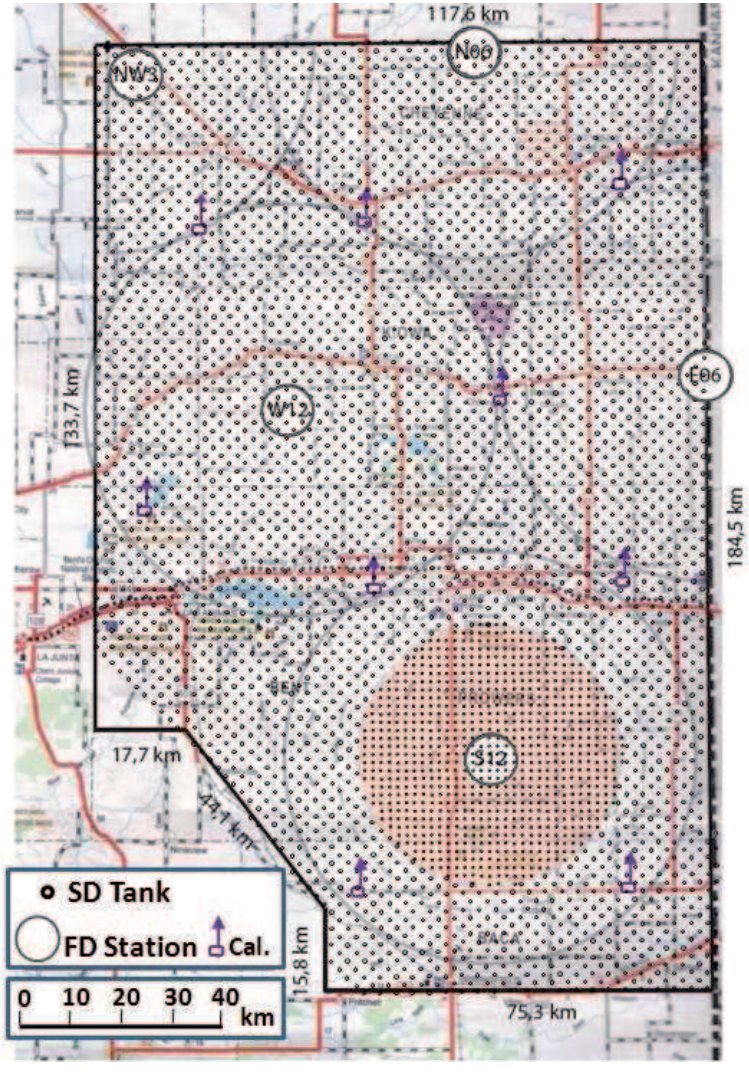


Auger Engineering Radio Array (AERA)

- fluorescence
- water cherenkov
- 30 m^2 muon counters (3 m under ground)
- radio antennas
- area 24 km^2

Auger Muons and Infill for the Ground (AMIGA)

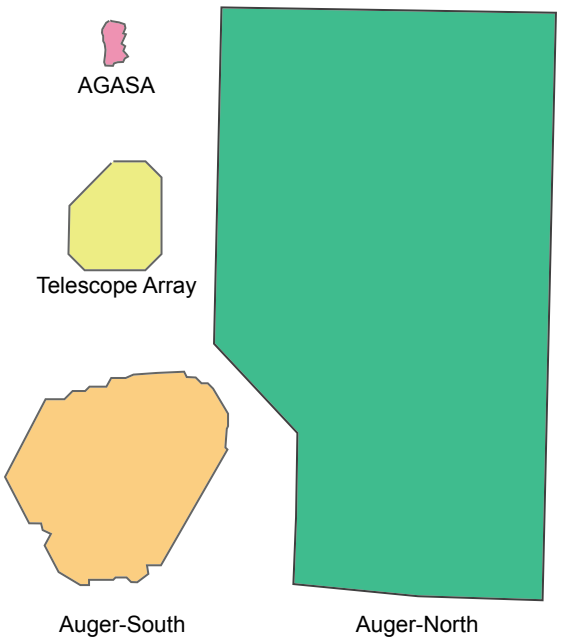
Northern Site of the Pierre Auger Observatory

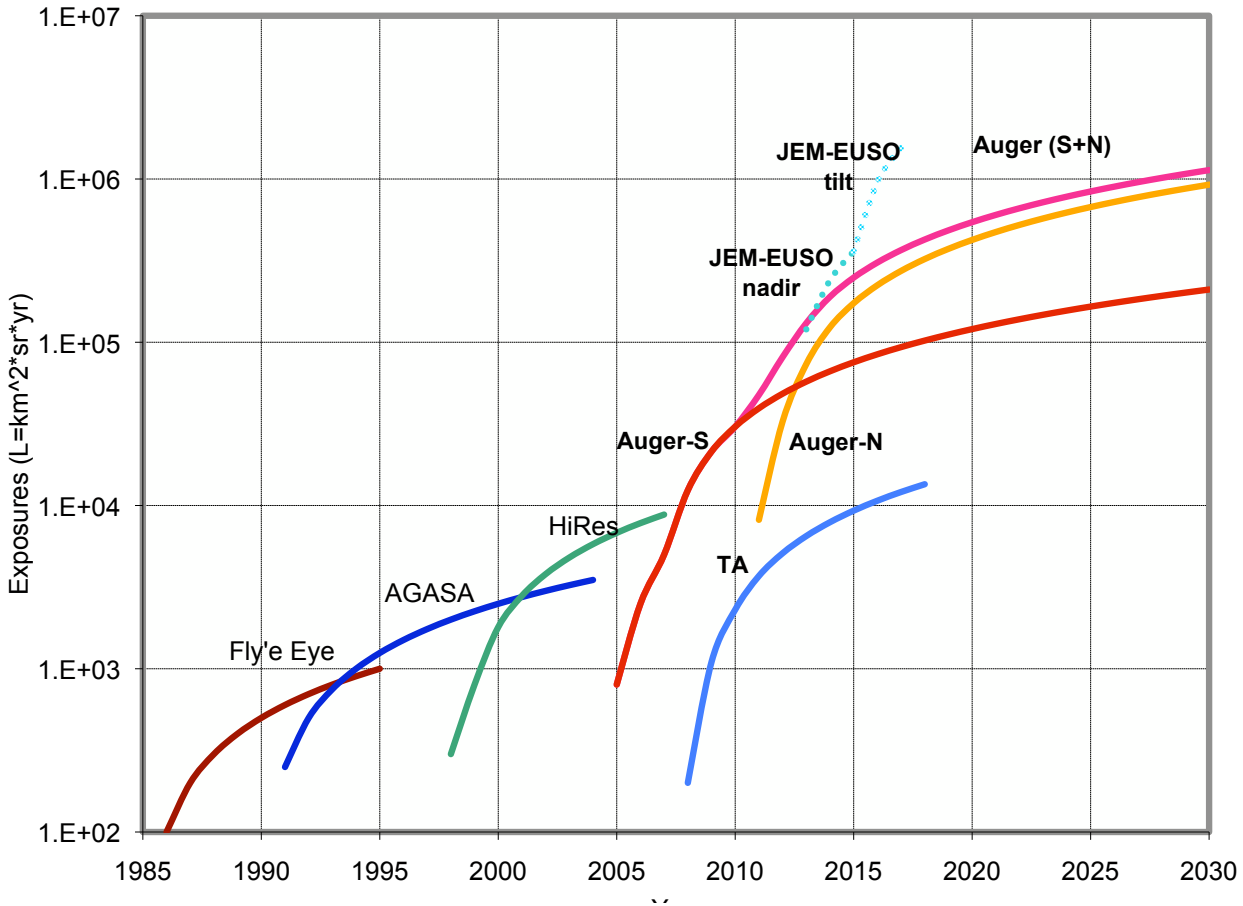


- Size: 20,000 km^2
- 4400 tanks
- 2300m tank-spacing
- 39 telescopes

(Auger North Design Report at www.auger.org/admin)

Comparison of Exposures

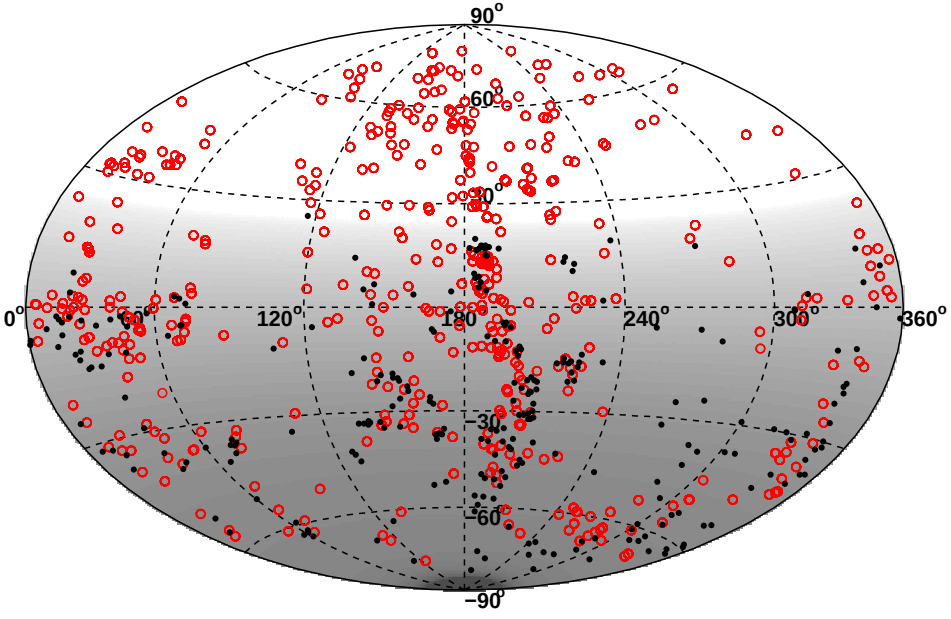




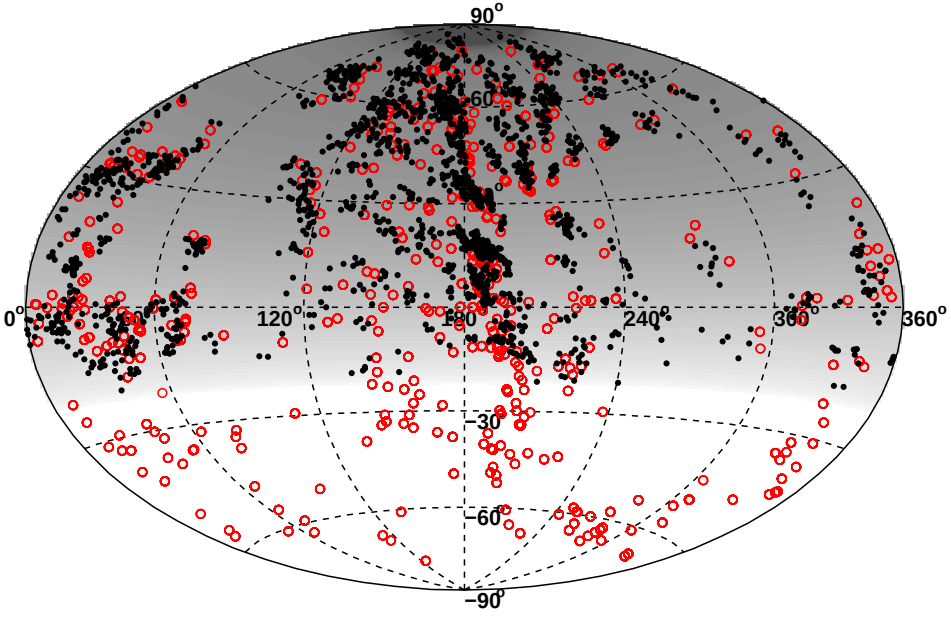
(J. Blümer et al., to appear NJP 2010)

Example: Events E>55 EeV, t=10 years

Auger South, N=270



Auger North, N=1890



simulation with sources $\sim$ VCV, BSS and protons

- full FD coverage, $t = 10$ years, $\tau = 13\%$
  $\rightarrow$South: 35 events above 55 EeV
  $\rightarrow$North: 246 events above 55 EeV

Conclusions

Major progress in the last years:

- unambiguous observation of flux suppression at UHE
- photon limits $\rightarrow$ top-down models disfavored
- evidence for anisotropy within the GZK sphere
- evidence for mixed particle composition

Questions for the next decade:

- maximum energy of sources?
- distribution of sources?
- galactic and extragalactic magnetic fields?
- hadronic interactions at ultrahigh energies?