# Recent Results and New Puzzles from the Pierre Auger Observatory

Ralph Engel, for the Pierre Auger Collaboration

# The first extremely high energy event

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## 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)

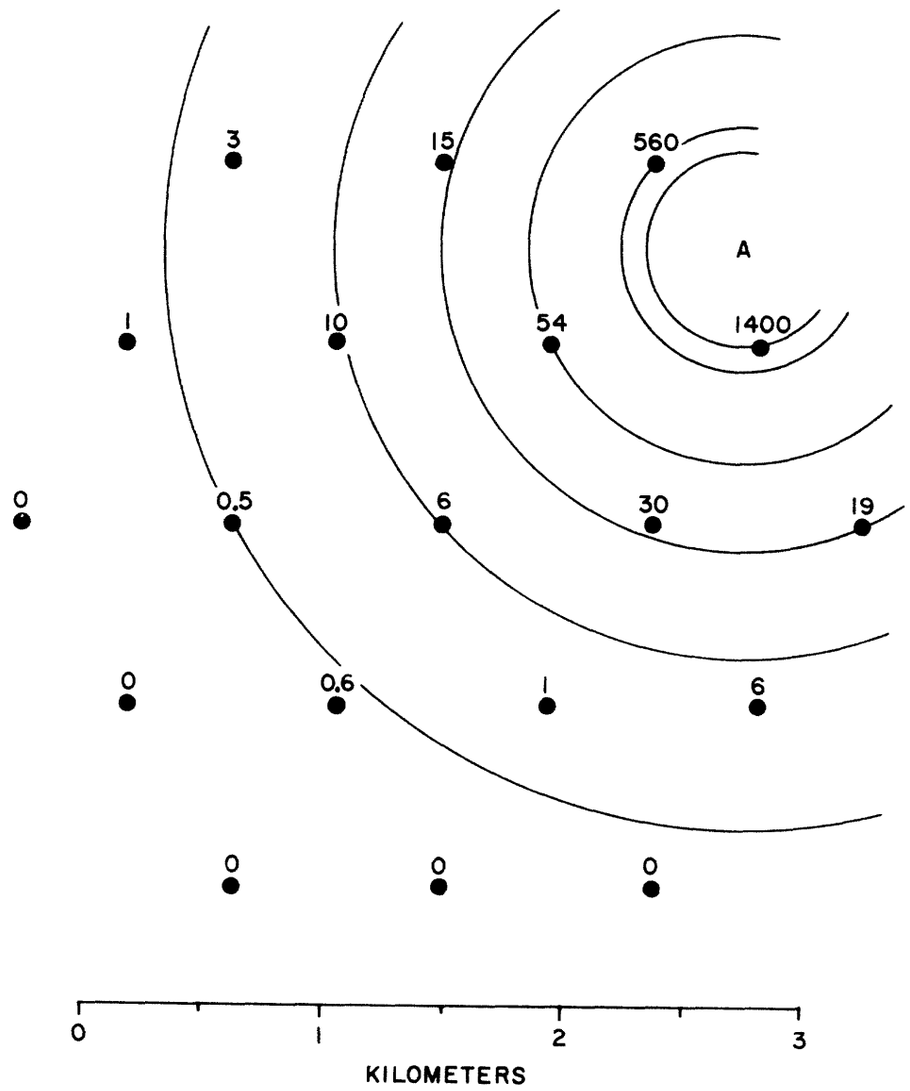
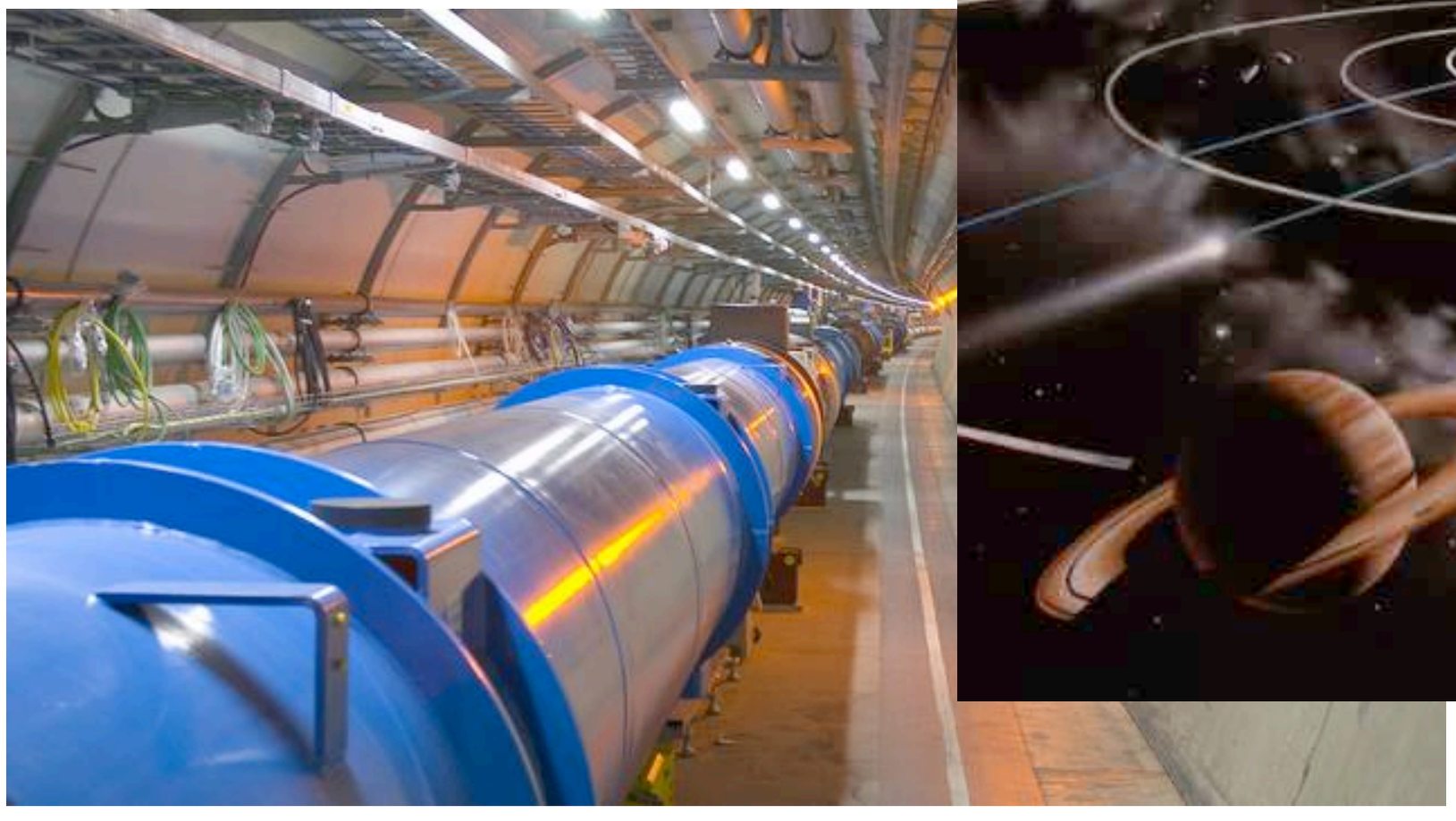



FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-$m^2$ scintillation detectors. The numbers near the circles are the shower densities (particles/$m^2$) registered in this event, No. 2-4834. Point "*A*" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

# Ultra-high energy: $10^{20}$ eV

Need accelerator of size of Mecury´s orbit
to reach $10^{20}$ eV with current technology

Large Hadron Collider (LHC),
27 km circumference,
superconducting magnets



*(M. Unger, 2006)*

Acceleration time for LHC: 815 years

# Source: diffuse shock acceleration?

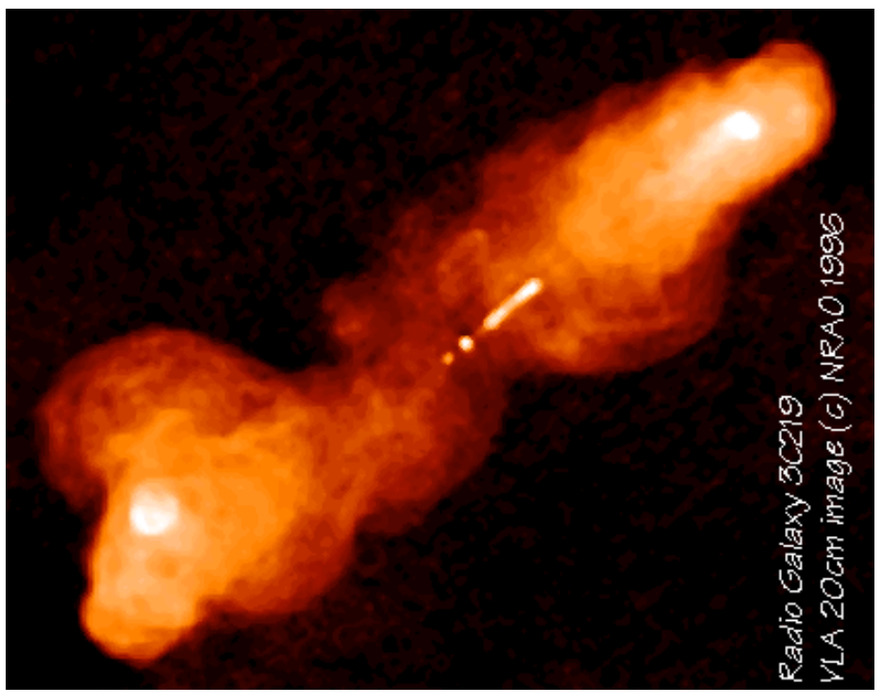
*Hillas 1984:*

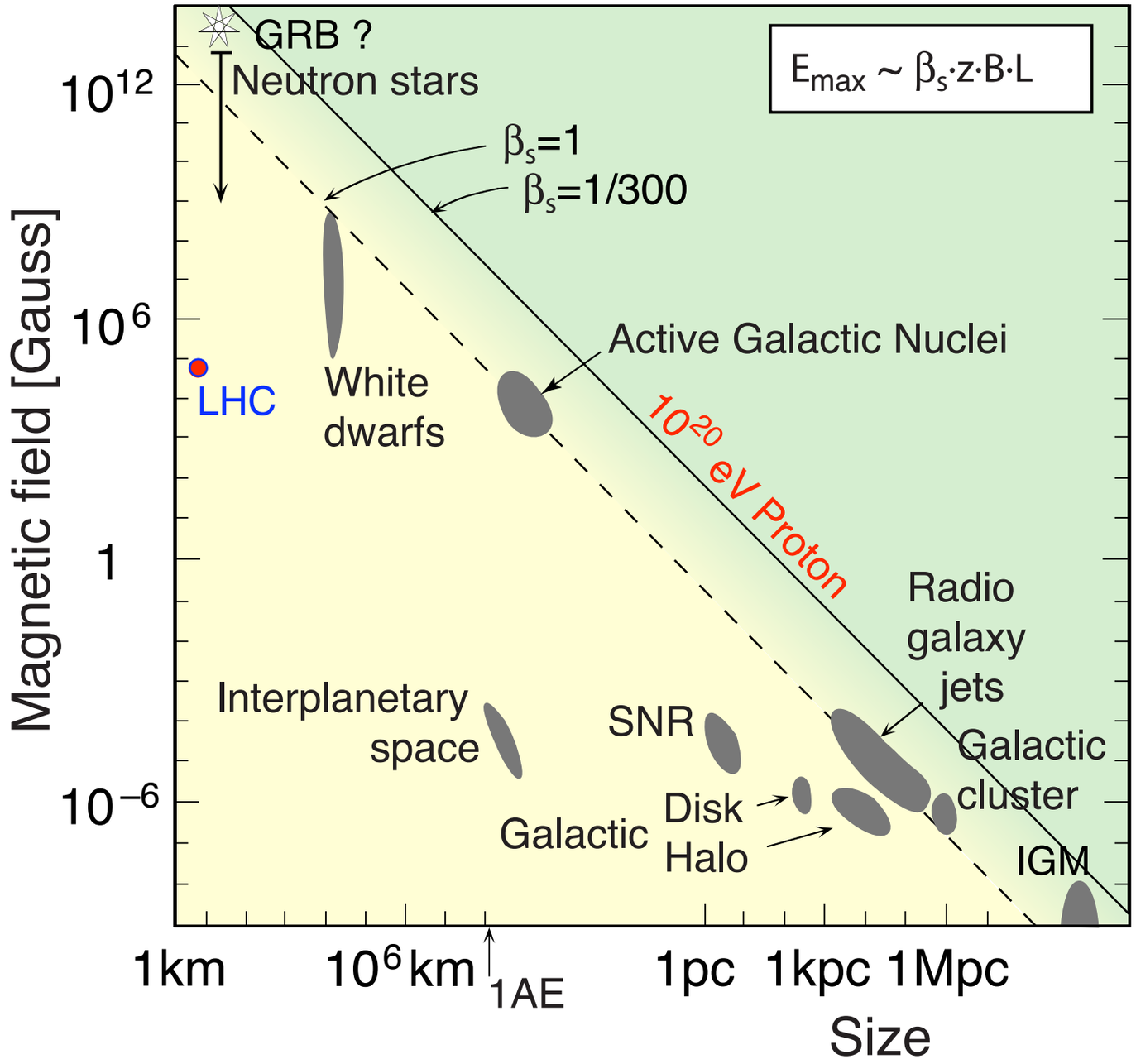
$$E_{\max} \simeq 10^{18}\,\mathrm{eV}\, Z\, \beta \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)$$

shock velocity

size of acc. region

mag. field strength



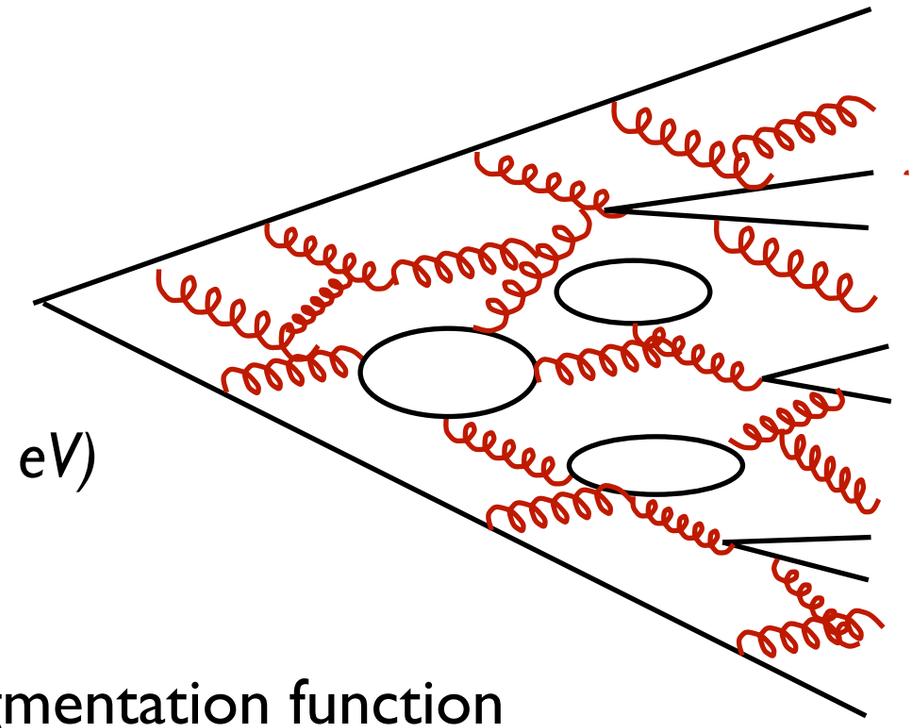
# Sources: exotic scenarios

**X particles from:**

- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....

X particle

($M_X \sim 10^{23}$ - $10^{24}$ eV)



Fragmentation function

$$\frac{dN_h}{dx} \sim x^{-3/2}(1-x)^2$$

QCD: ~ $E^{-1.5}$ energy spectrum

QCD+SUSY: ~ $E^{-1.9}$ spectrum

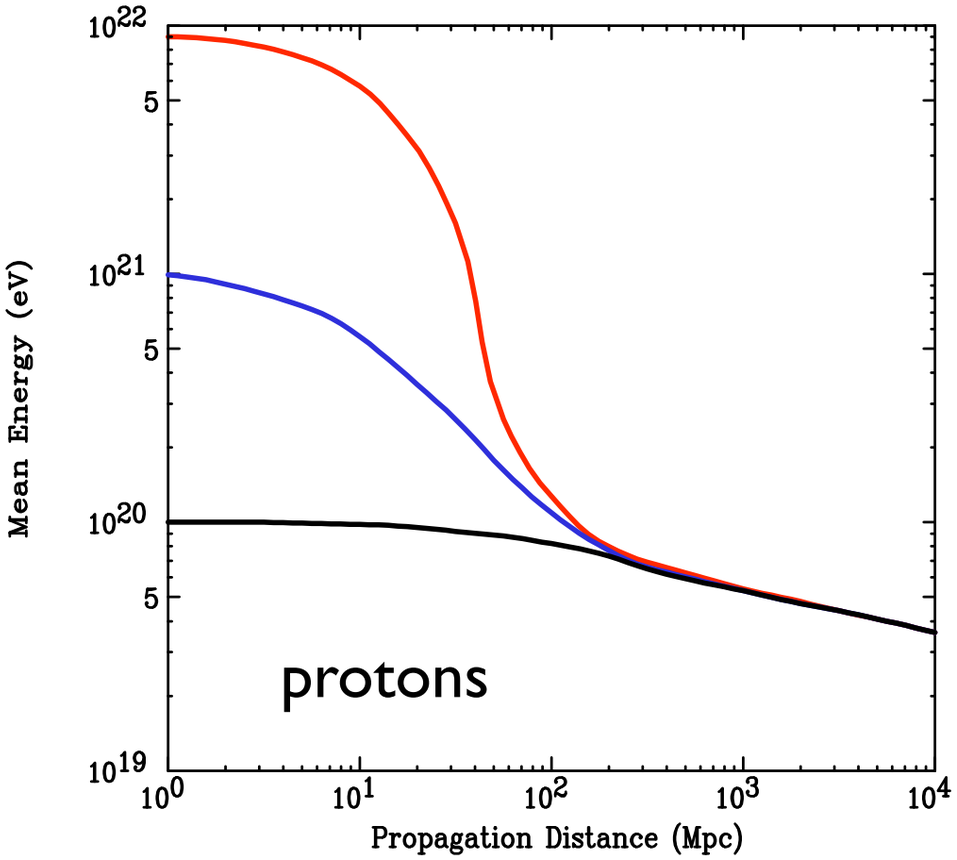
Injected particles: Gamma-ray/nucleon ~ 1.5 - 3

# Fact sheet of some source scenarios

| | Process | Distribution | Injection flux |
|---|---|---|---|
| AGNs, GRBs, ... ( ☆ ) | Diffuse shock acceleration | Cosmological | p ... Fe |
| Young pulsars ( ☆☆ ) | EM acceleration | Galaxy & halo | mainly Fe |
| X particles ( ☆☆☆ ) | Decay & particle cascade | (a) Halo (SHDM)<br>(b) Cosmological | ν, γ-rays and p |
| Z-bursts ( ☆☆☆☆ ) | $Z^0$ decay & particle cascade | Cosmological & clusters | ν, γ-rays and p |

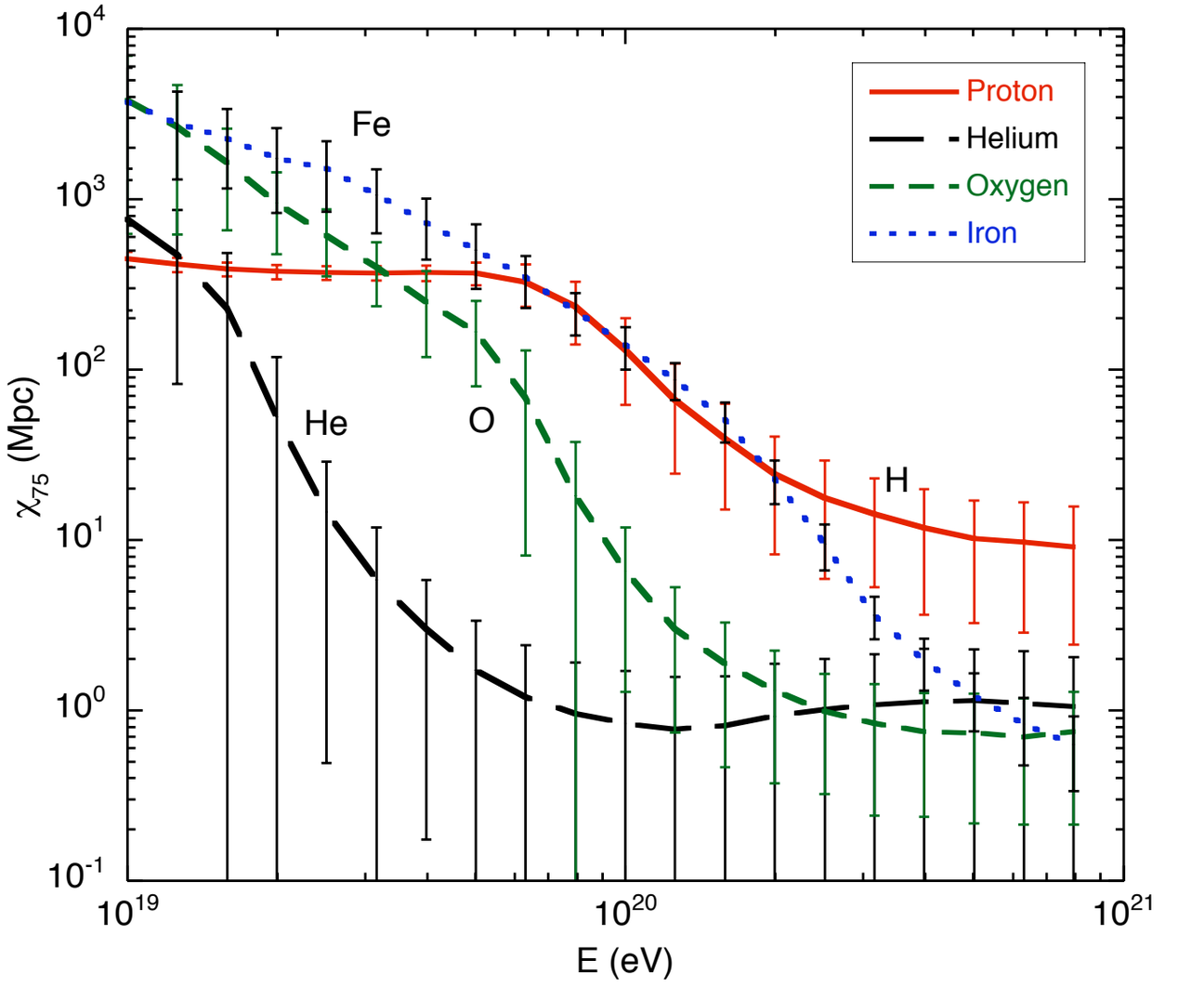
# Greisen-Zatsepin-Kuzmin (GZK) suppression

*(Cronin, TAUP 2003)*




$$
\begin{aligned}
p\,\gamma &\rightarrow p\,\pi^0 \\
p\,\gamma &\rightarrow n\,\pi^+ \\
A\,\gamma &\rightarrow (A-1)\,n \\
A\,\gamma &\rightarrow (A-2)\,(pn)
\end{aligned}
$$

Energy loss distance E ds/dE

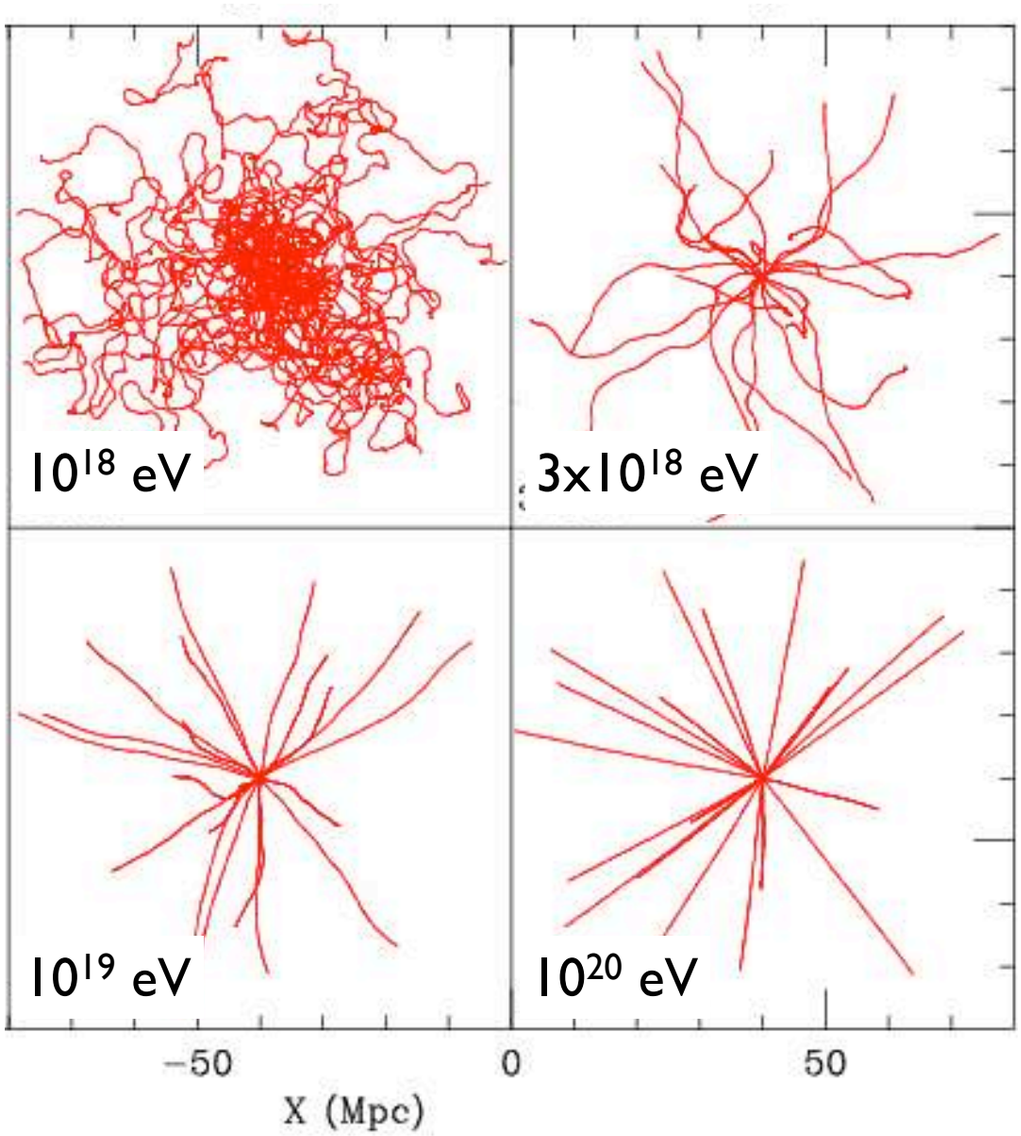



*(Allard et al., 2005)*

Gamma-rays even more suppressed

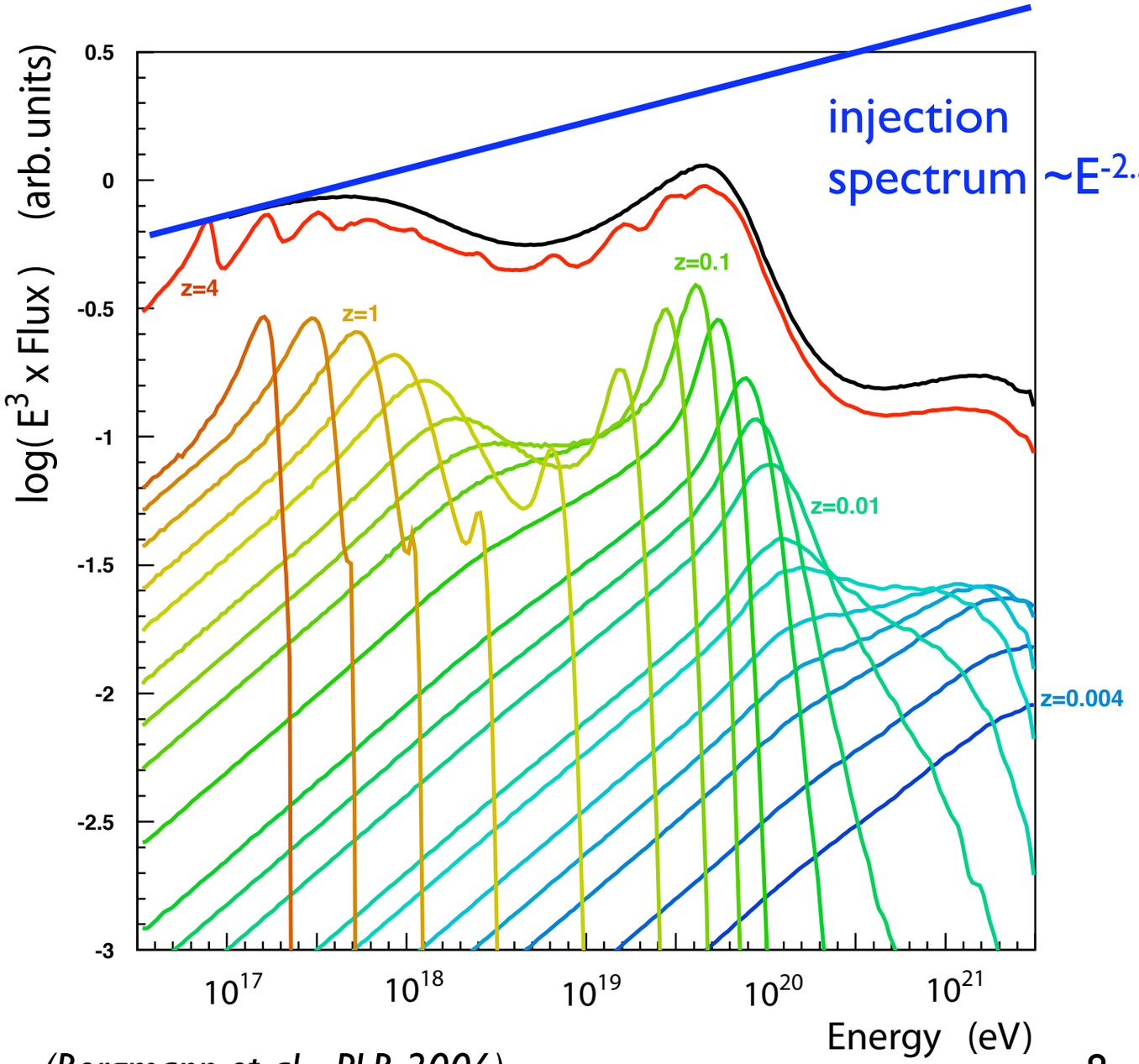
# GZK suppression and magnetic field deflection

## Extragalactic magnetic field deflection



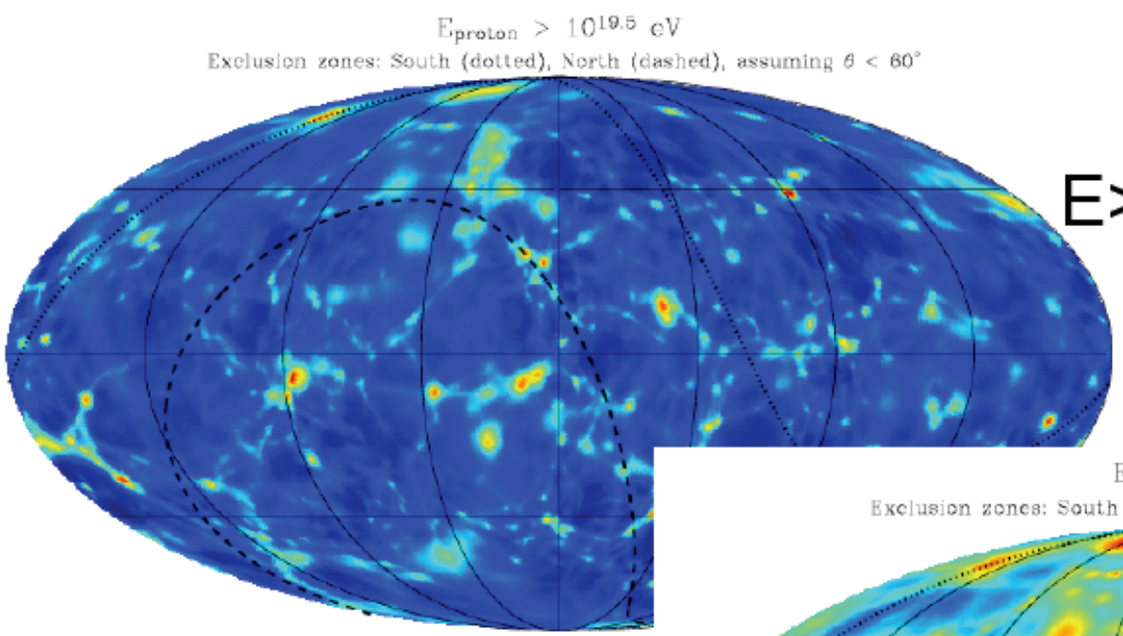

| Redshift | Lum.Distance |
|---|---|
| 0.004 | 16 Mpc |
| 0.01 | 40 Mpc |
| 0.05 | 200 Mpc |
| 0.1 | 415 Mpc |

## GZK horizon: energy-source relation



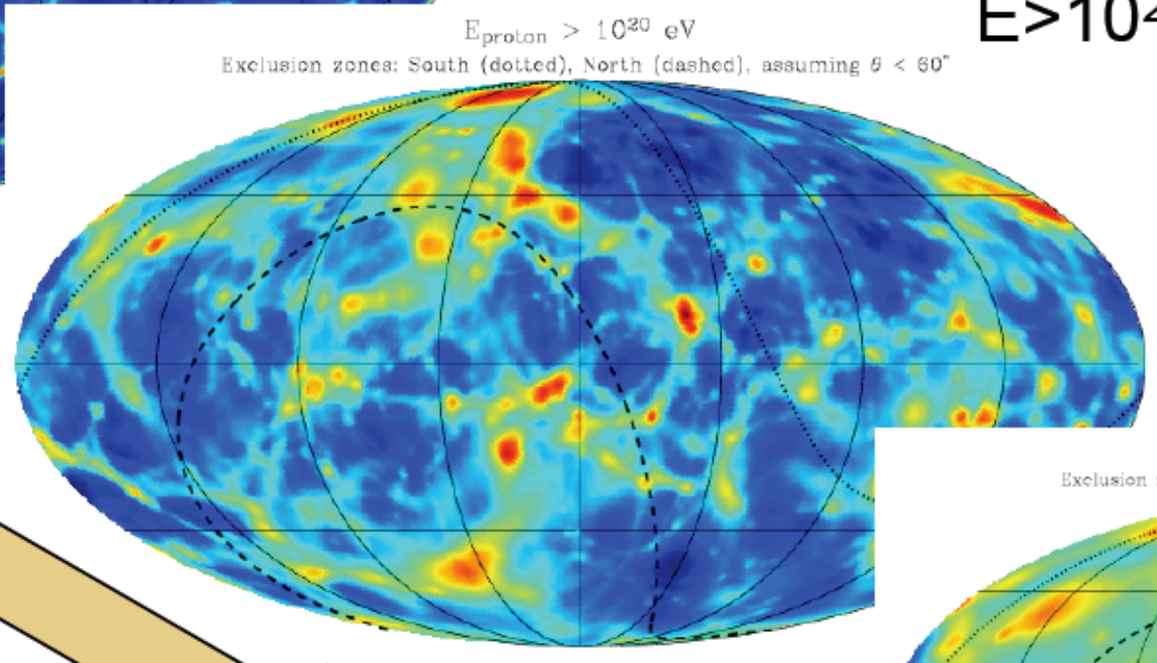

*(Bergmann et al., PLB 2006)*

# Expected anisotropy based on matter distribution




$E>10^{19.5}$ eV

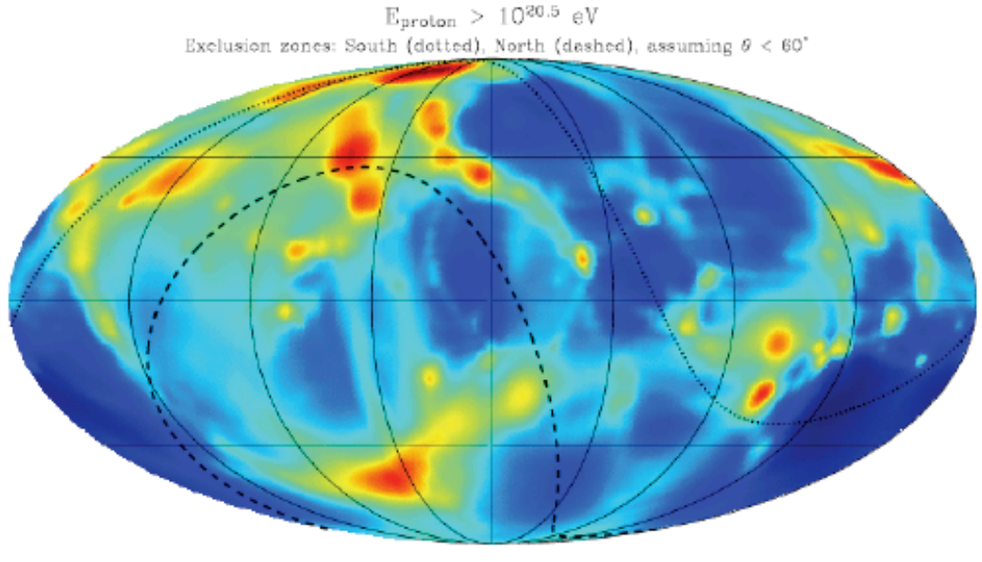
Full sky coverage: northern observatory




$E>10^{20}$ eV

GZK suppression

$E>10^{20.5}$ eV




*(Armengaud et al., 2006)*

# Exotic propagation scenarios

## Violation of Lorentz invariance (space time fluctuations)

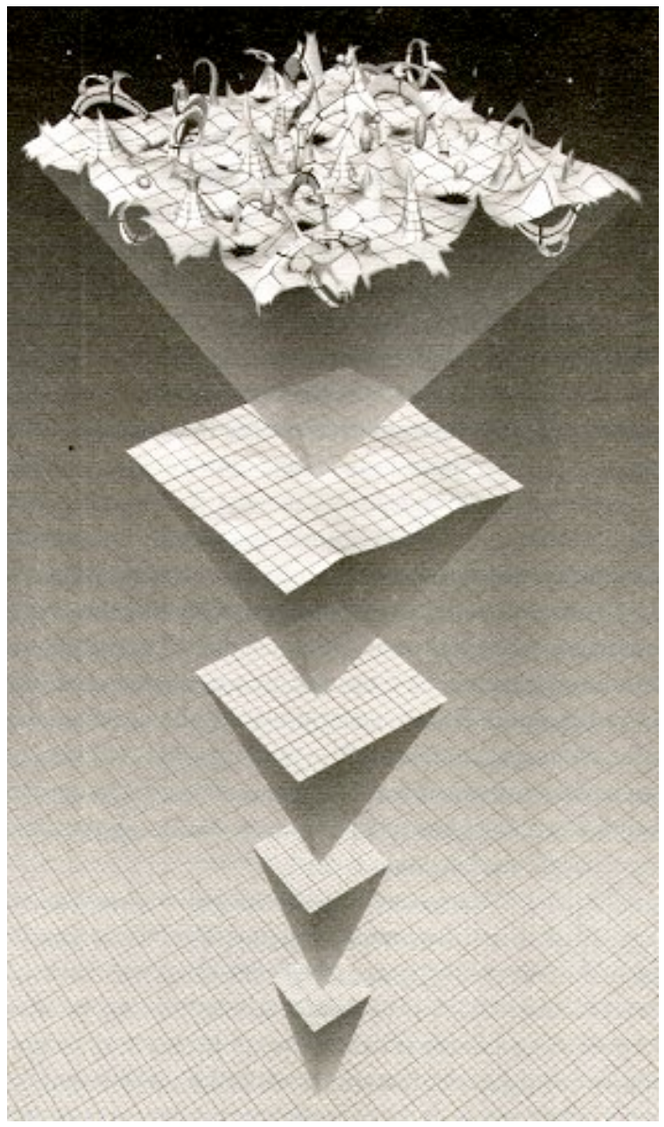
$$4E_{CMB}E_{\rm th} = (m_p + m_\pi)^2 - m_p^2 + \epsilon \frac{E_{\rm th}^{2+a}}{M_P^a} \left[1 - \frac{m_p^{1+a} + m_\pi^{1+a}}{(m_p + m_\pi)^{1+a}}\right]$$

*(Coleman & Glashow PRD59 1999,*
*Jankiewicz et al., 2004)*

## Light supersymmetric baryons

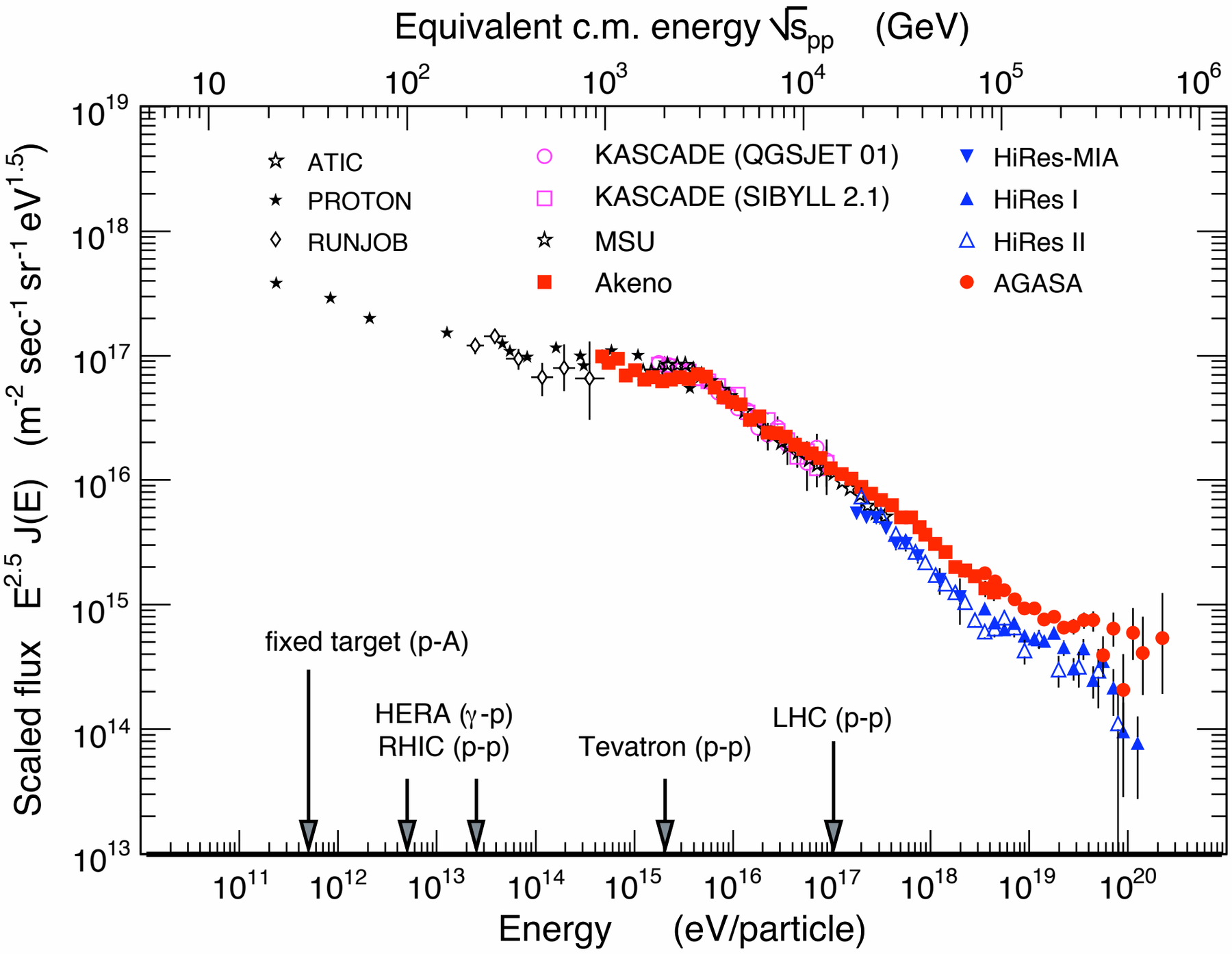
Threshold for GZK process increased
But: extensive air showers different

*(Farrar et al., 1998 )*



# Observations ?

# Situation before Auger Observatory: flux




**Situation unclear**

- Flux suppression, GZK effect?
- Energy of ankle
- Flux normalization

**Energy reconstruction uncertainty:**

| | |
|---|---|
| AGASA | ~18% |
| HiRes | ~17% |

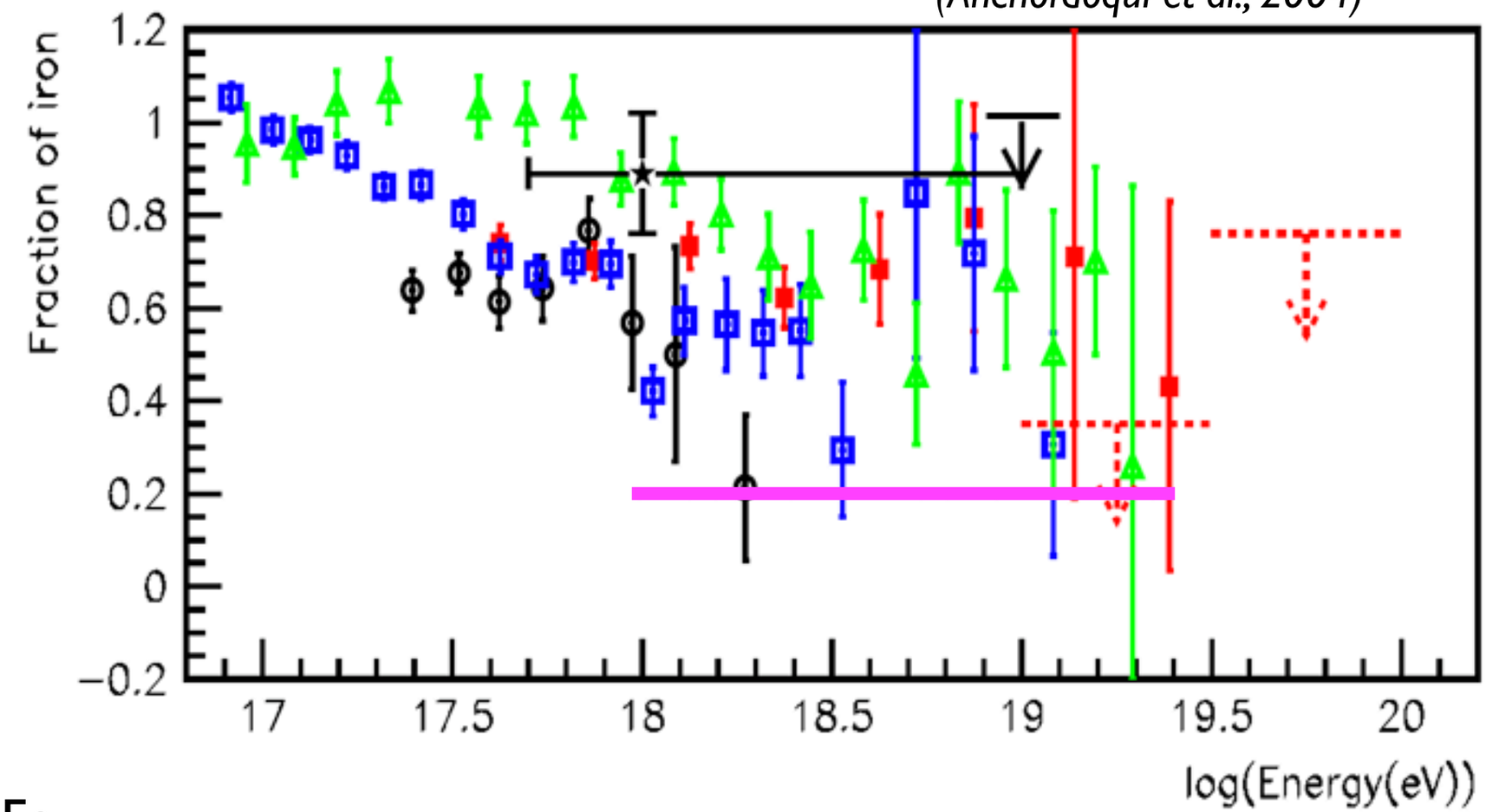
Events above $10^{20}$ eV: 11 (AGASA), 4 (HiRes)

# Situation before Auger Observatory: composition

***SIBYLL 1.6***

Fly's Eye
AGASA A100
AGASA A1

*(Anchordoqui et al., 2004)*




***QGSJET 98/01***

Haverah Park
AGASA
HiRes

HiRes: 80% p and 20% Fe

# Situation before Auger Observatory: composition

***SIBYLL 1.6***

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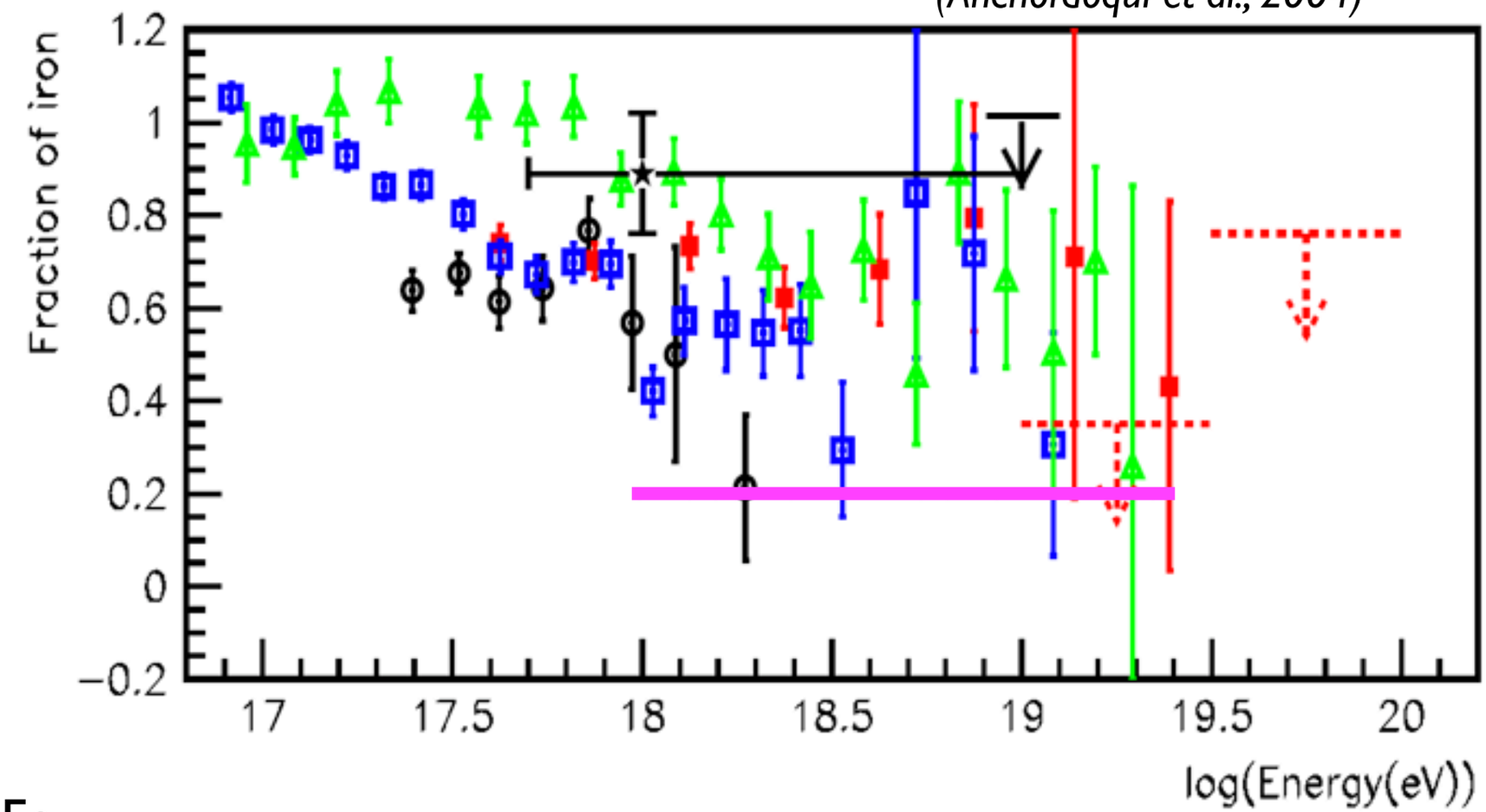



***QGSJET 98/01***

Haverah Park
AGASA
HiRes

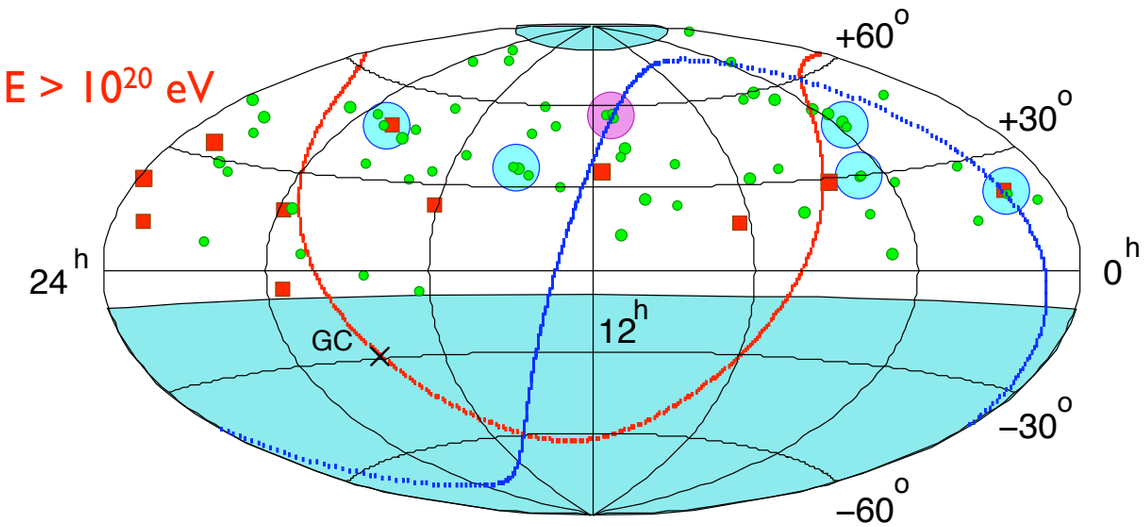
HiRes: 80% p and 20% Fe

**Caveats:**

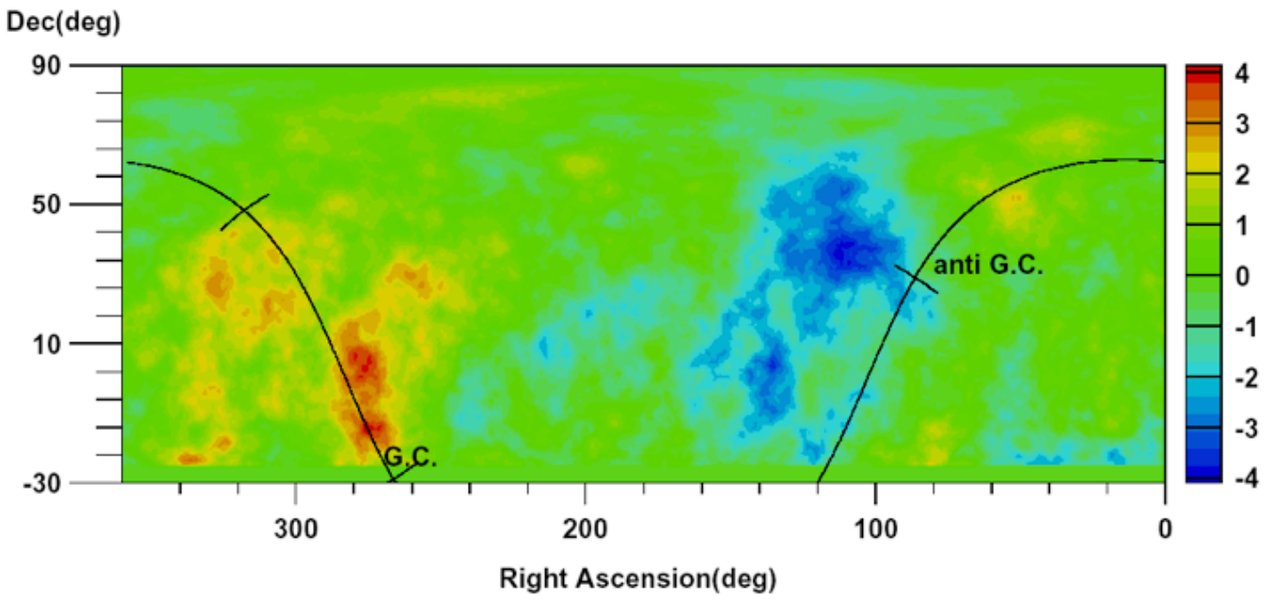
- low statistics
- interaction model dependence
- muon and Xmax information consistent?

# Situation before Auger Observatory: anisotropy

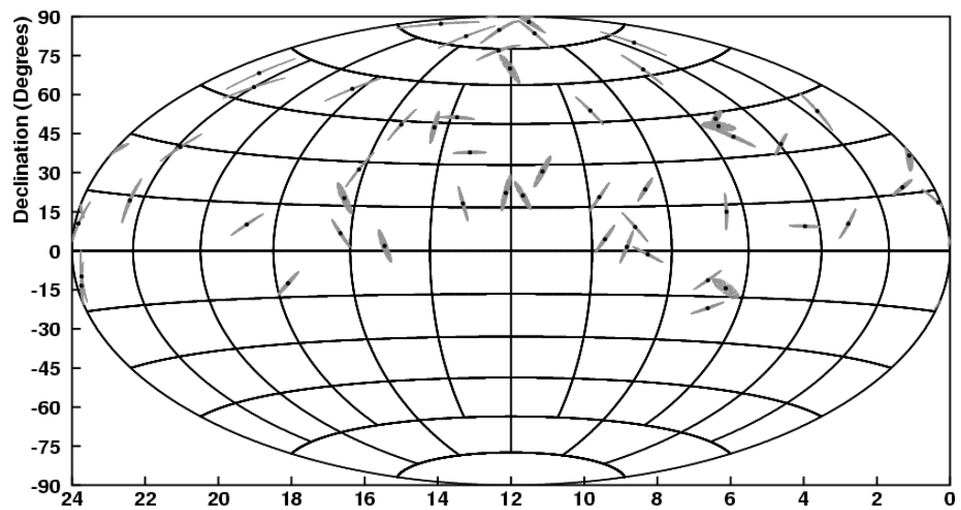
## AGASA




E > 4x10[19] eV, 5 doublets, 1 triplet




## HiRes

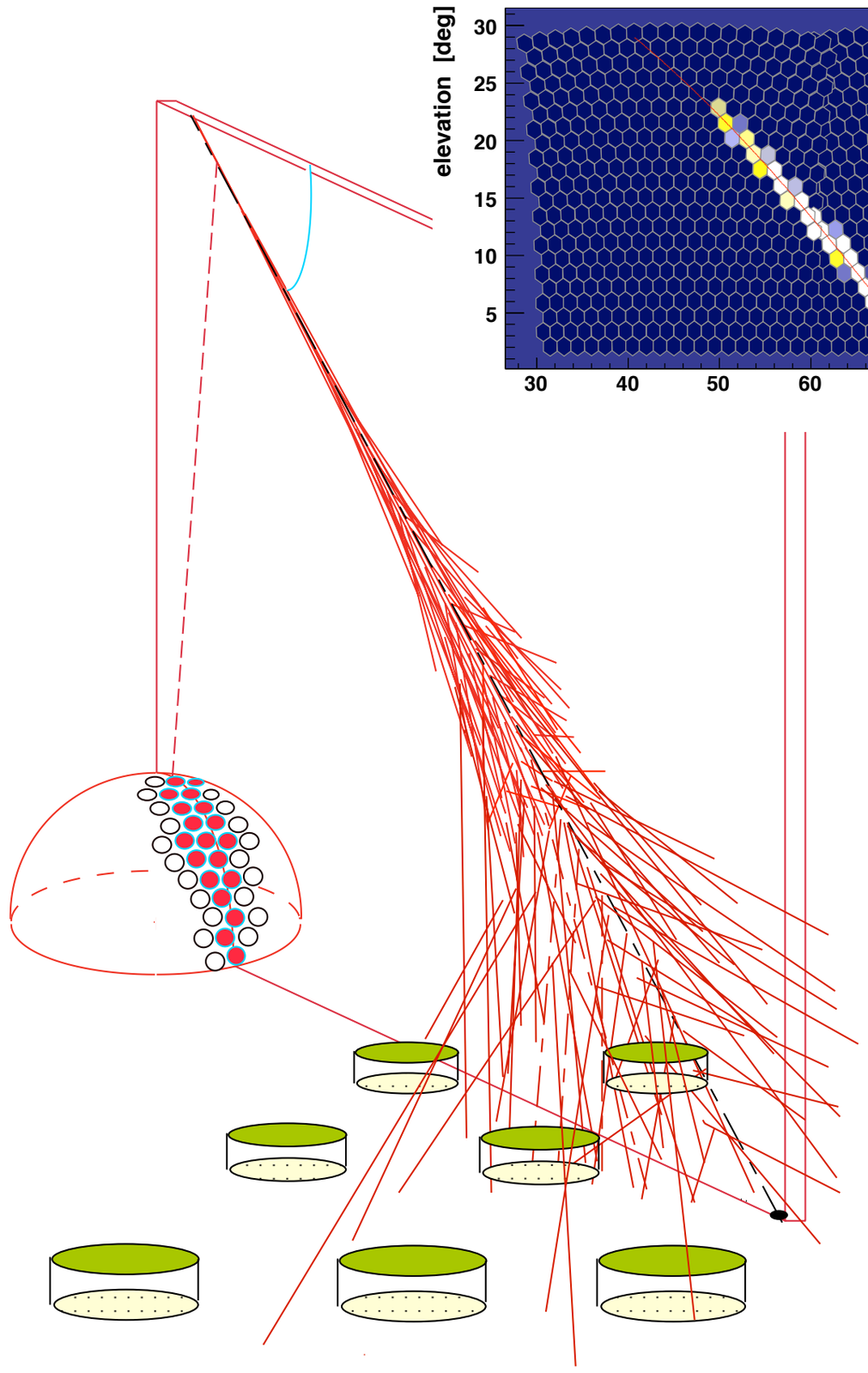



Monocular: 52 evts, stereo: 27 evts
no small scale clustering found

Correlation with Bl Lacs?
Medium range ~25° correlation?

E > 10[18] eV, dipole anisotropy, excess from GC region *(Excess in similar region also found in SUGAR)*

# Different measurement techniques





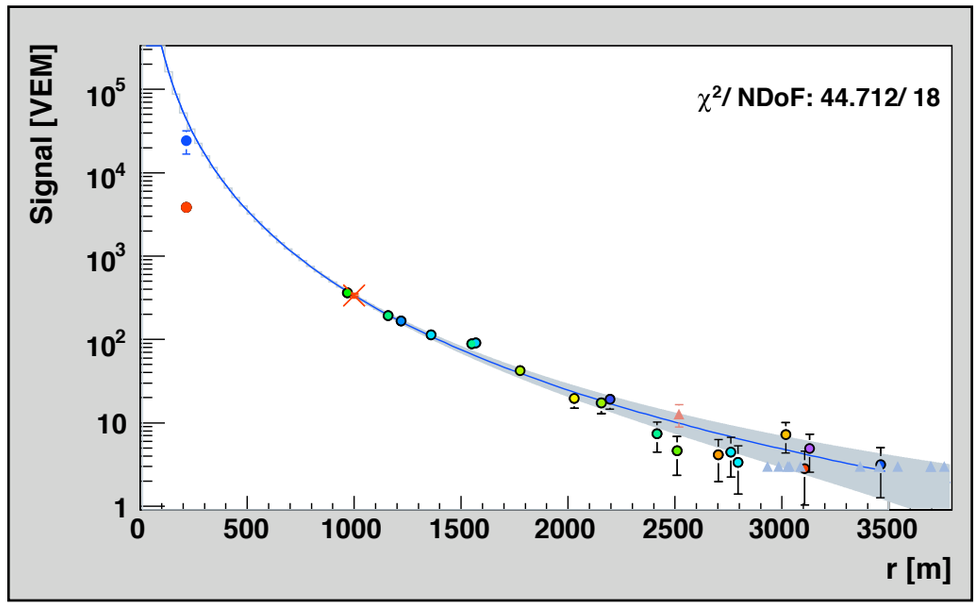

**AGASA:** surface array
**HiRes:** fluorescence telescopes

Fluorescence telescopes:

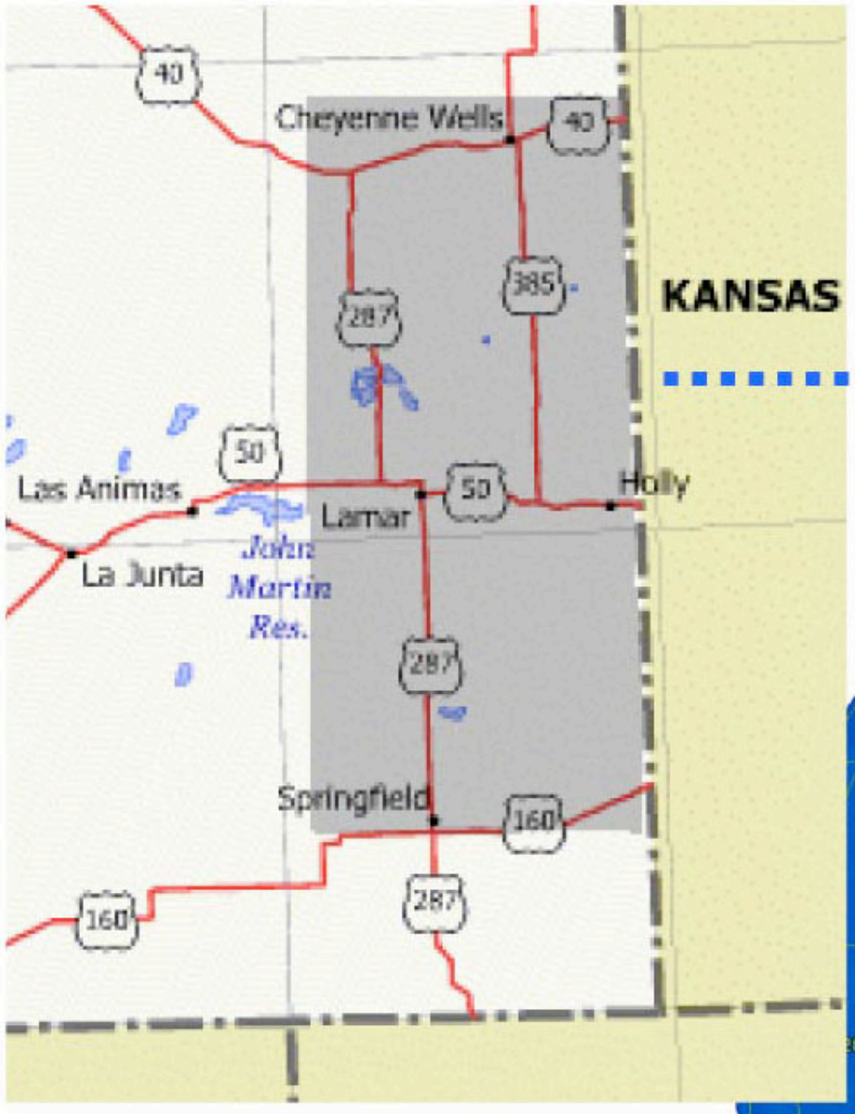
- Calorimetric energy measurement
- Aperture energy-dependent
- Duty cycle ~15%

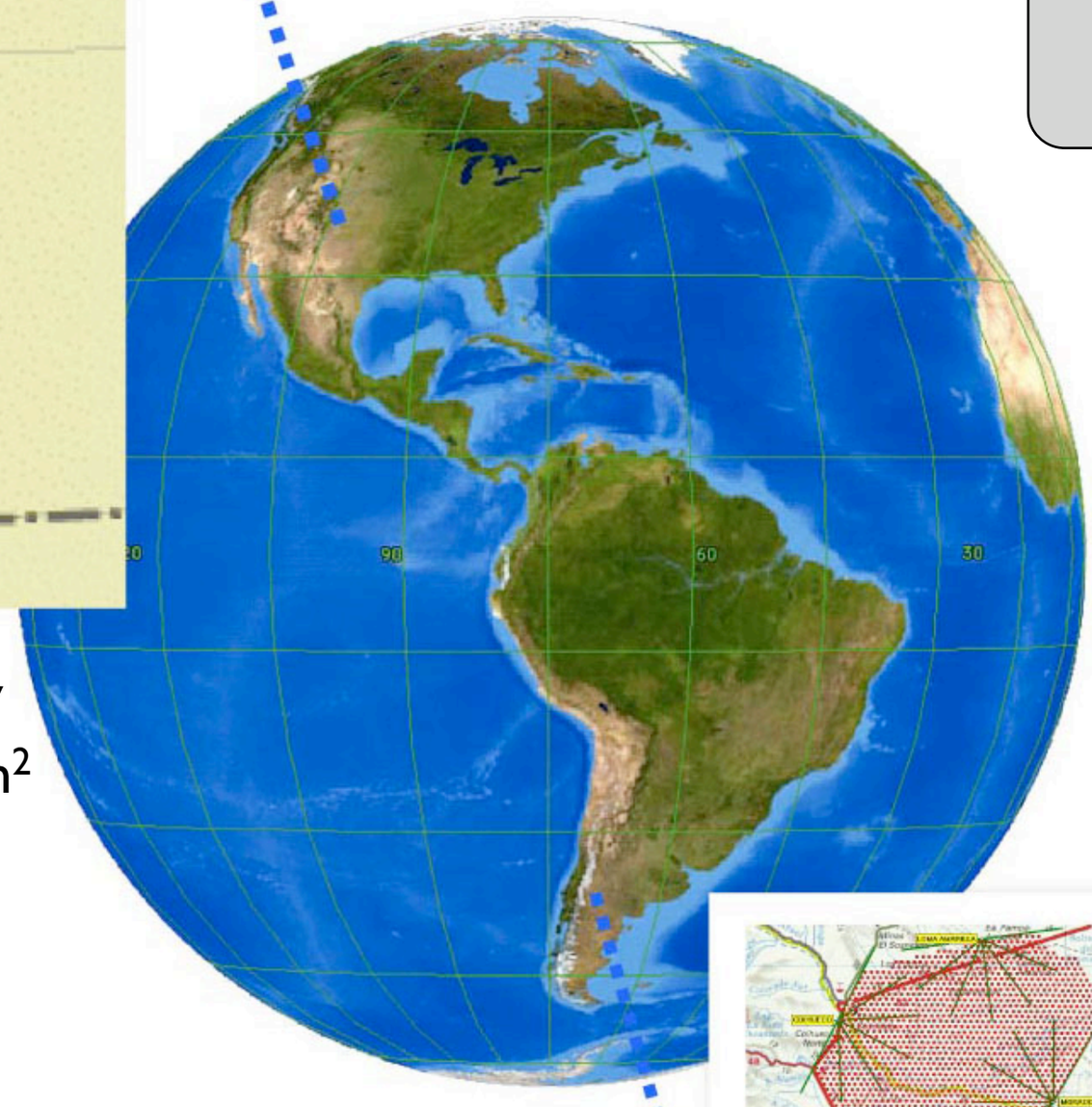
Surface detector array:

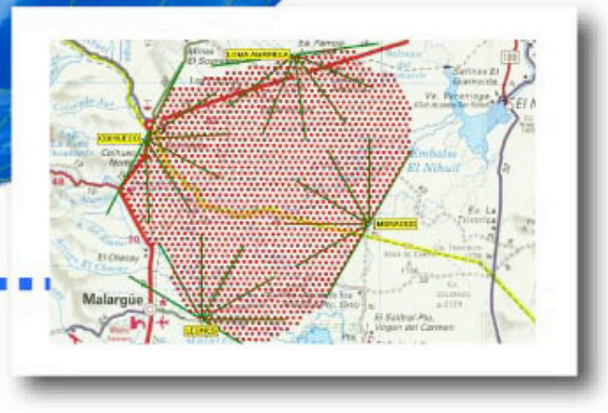
- Shower size at ground
- Aperture energy-independent
- Duty cycle ~100%



# The Pierre Auger Project




High statistics
Hybrid detection
Full sky coverage

**Northern Observatory**

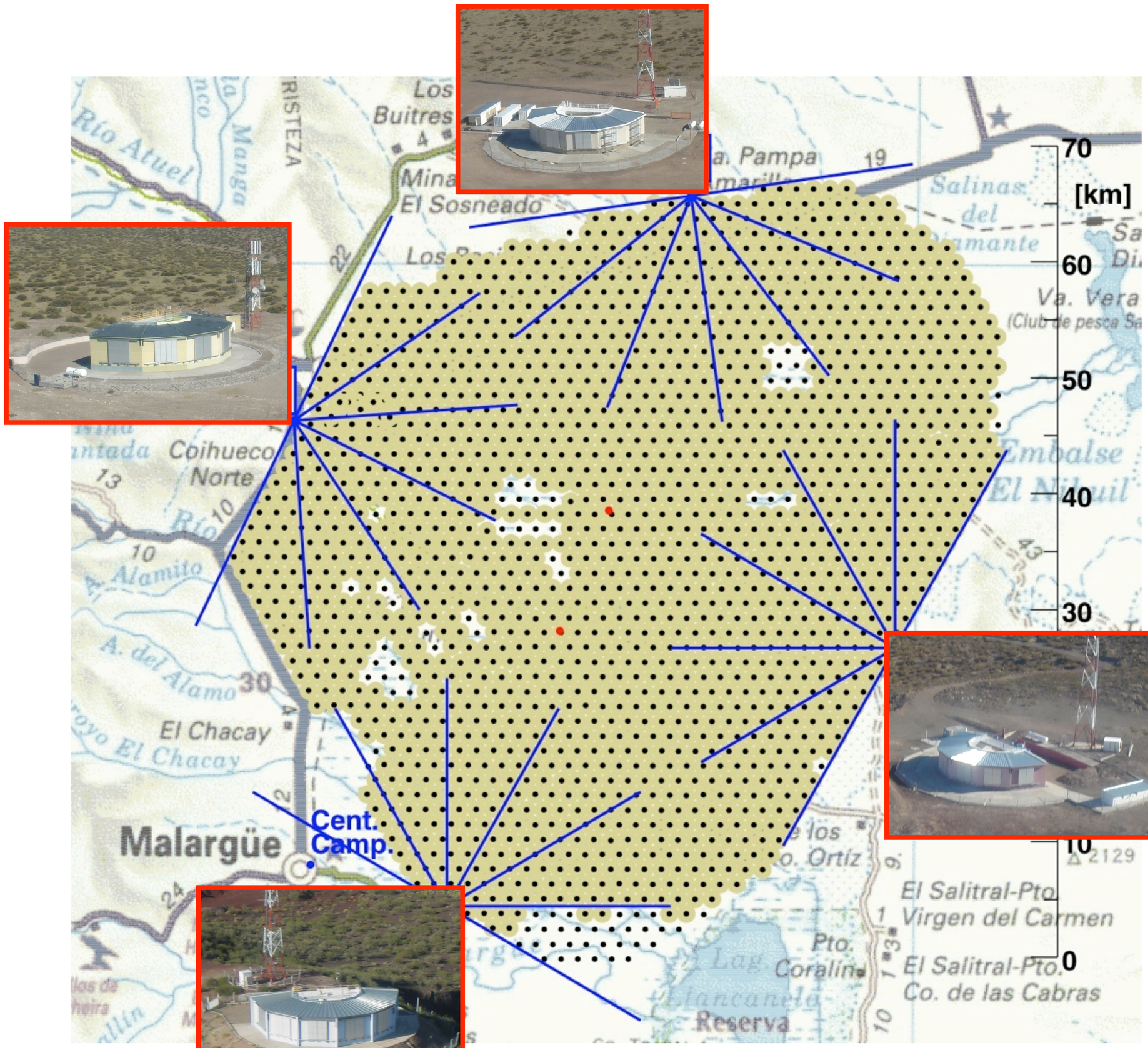
4000 detectors 20,000 km$^2$

**Southern Observatory**

1600 detectors 3,000 km$^2$

*1992 Paris workshop*
*1996 Design report*
*1999 Ground breaking*
*2001 Engineering array*
*2003 Construction phase*
*2008 Completion*

# Southern Pierre Auger Observatory

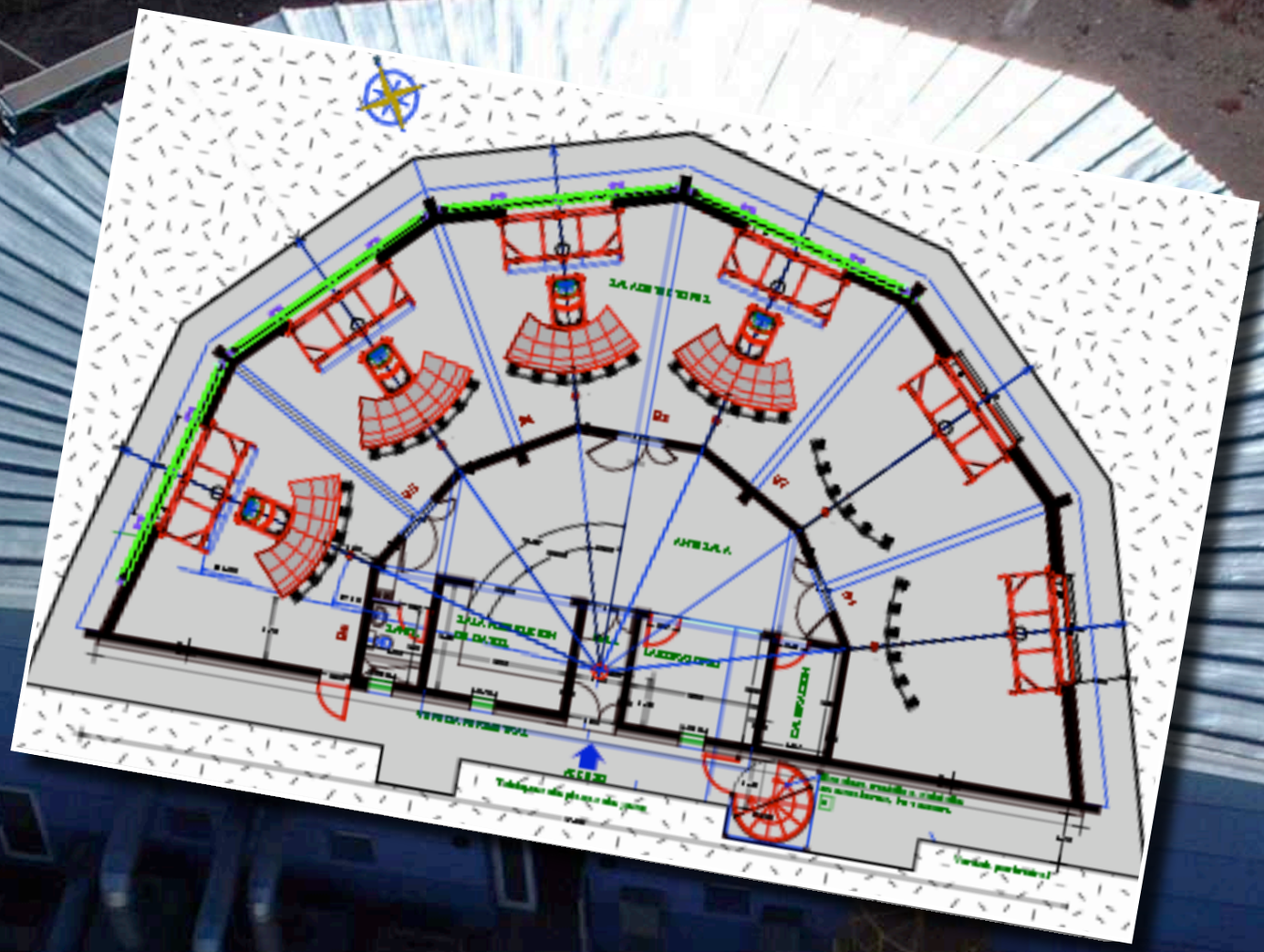



1600 surface detectors: water-Cherenkov tanks (triang. grid of 1.5 km)

4 fluorescence detectors (24 telescopes in total)

# Auger South on a cloudy day ...

six telescopes each viewing 30° by 30°



six telescopes each viewing 30° by 30°

# One of 24 fluorescence telescopes

PMT camera with 440 pixels,
1.5° FoV per pixel, 10 MHz

UV transmitting filter, corrector lens, safety curtain

3.4 m segmented mirror (aluminum alloy, glass)

# Southern Pierre Auger Observatory

Laser facilities




1600 surface detectors:
water-Cherenkov tanks
(triang. grid of 1.5 km)

Balloon station

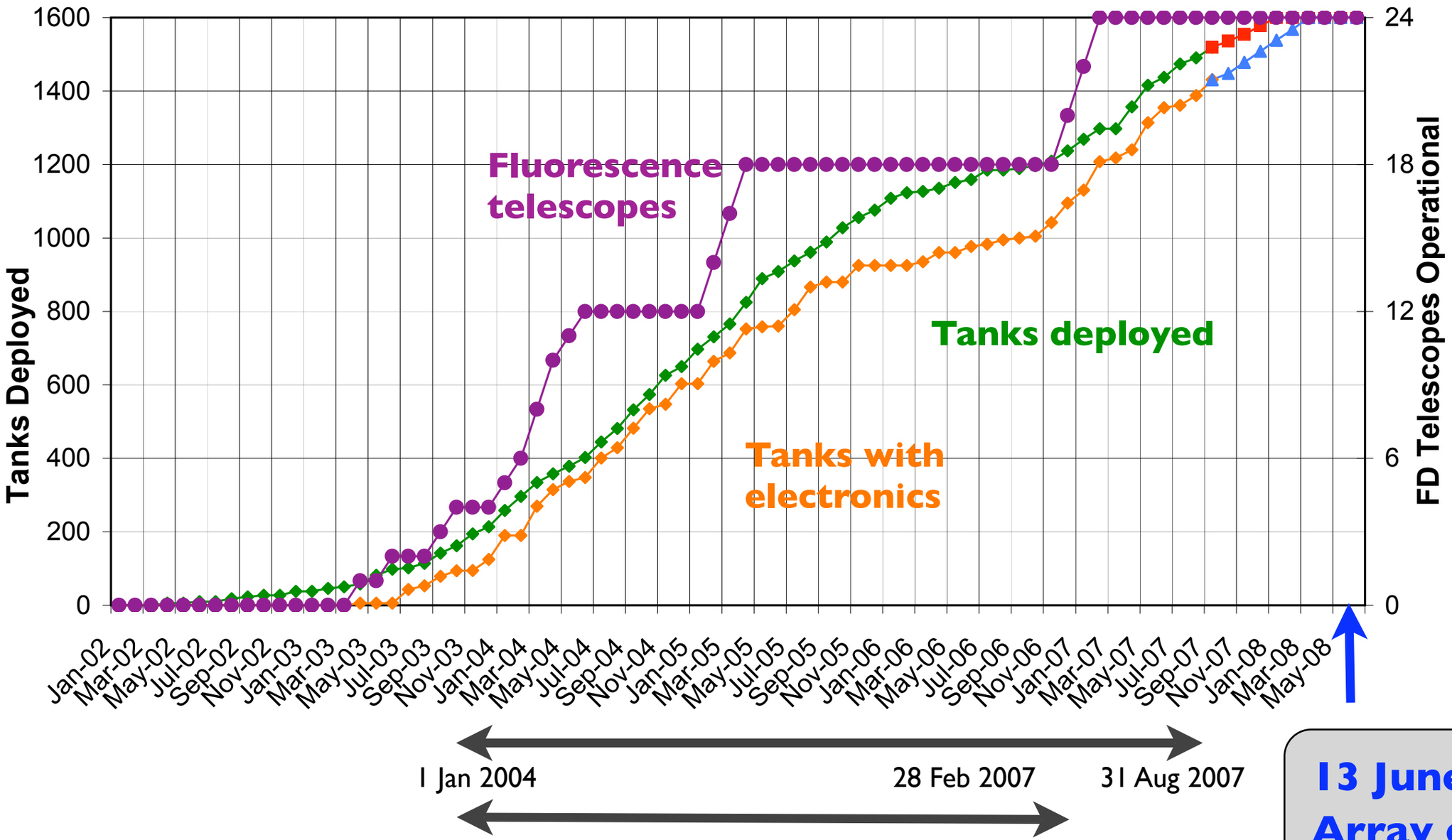




4 fluorescence detectors
(24 telescopes in total)

# Central data acquisition building

# Integrated aperture used for data analysis



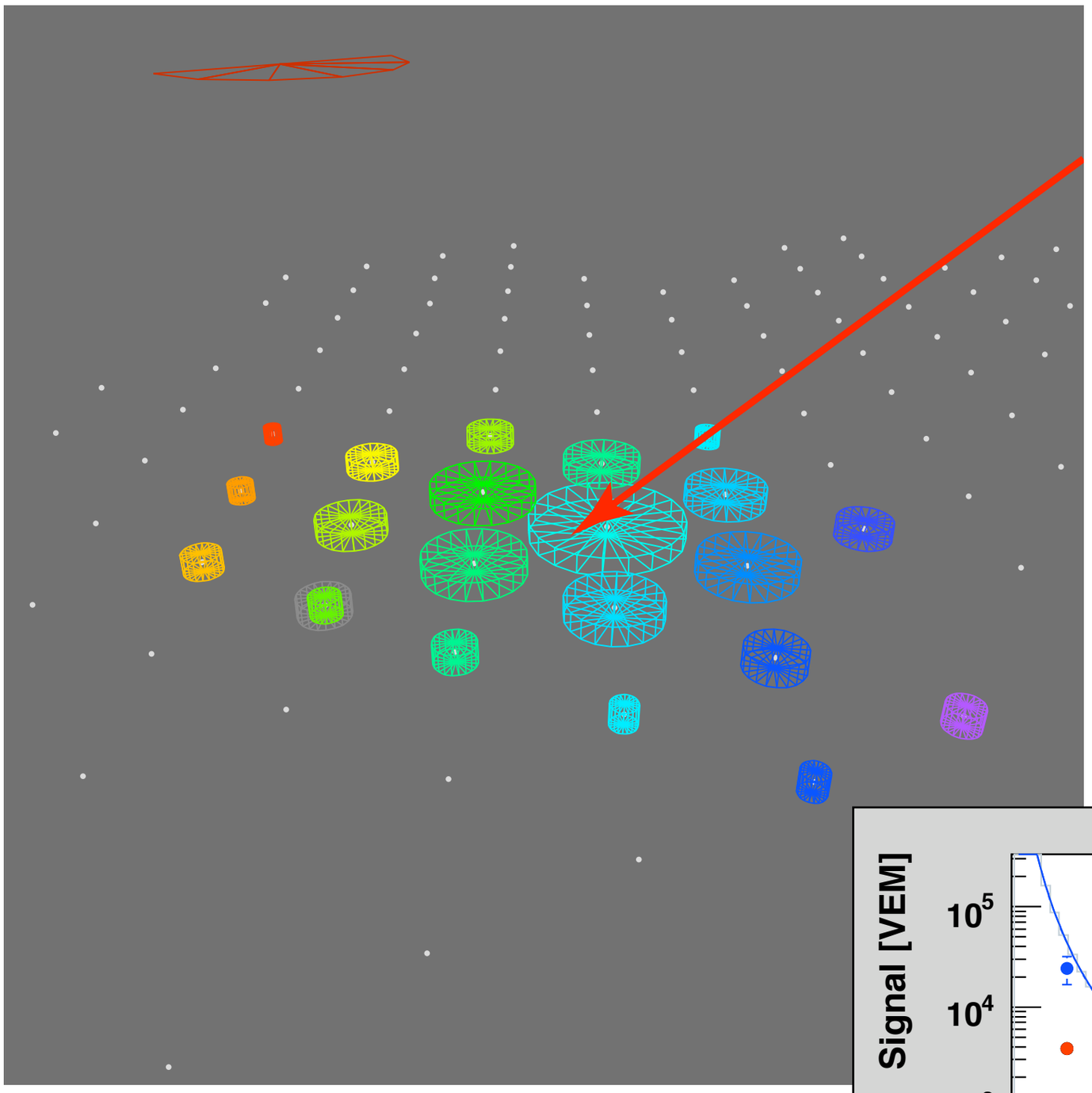

Data presented in talk:
5165 km$^2$ sr yr ~ 0.8 full Auger year
9000 km$^2$ sr yr  anisotropy studies

**13 June 2008:**
**Array completed!**
1660 tanks deployed
1603 with electronics
24 telescopes

*AGASA: 1600 km$^2$ sr yr*  *HiRes I (mono) ~ 5000 km$^2$ sr yr @ 10$^{20}$ eV*

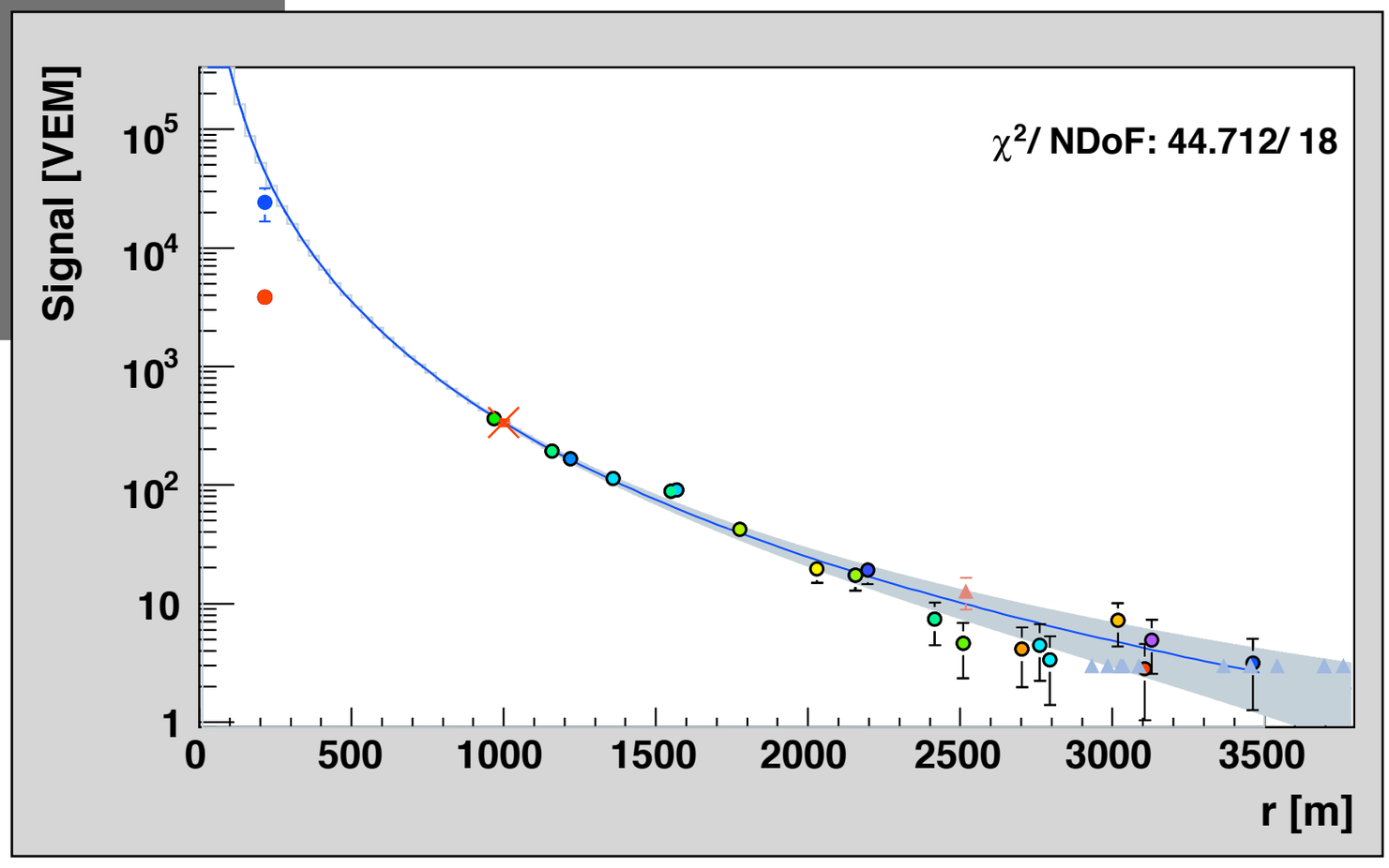
“Last Friday, June 13th, at 13:00 hs, the "last" surface detector (the one with signatures from the whole Collaboration) was filled with water. It was put to work immediately afterwards.”

# Surface detector events



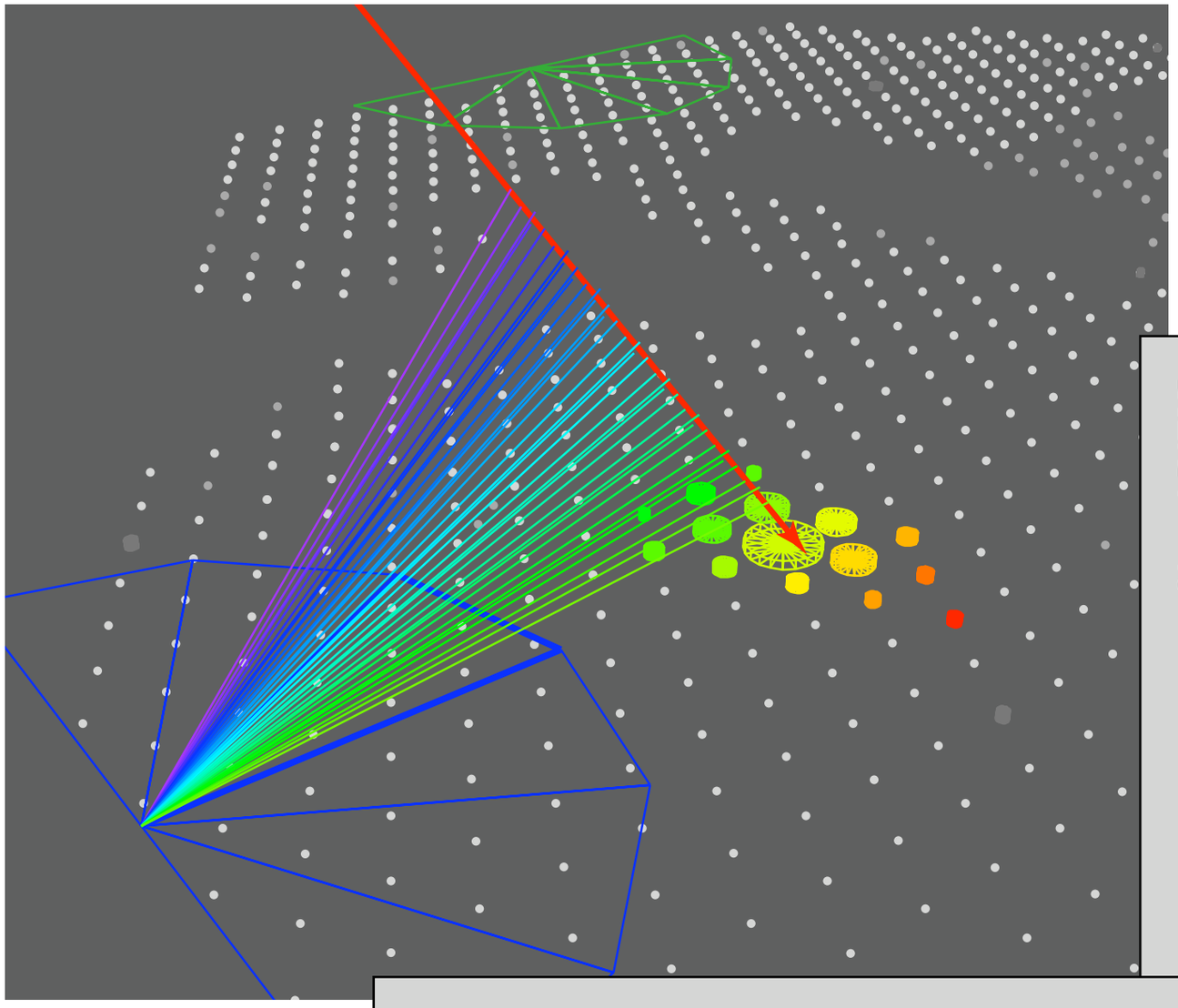
More than 650,000 events
(T5 trigger, used in analysis)

Example: $E > 10^{20}$ eV, $\theta \approx 45°$

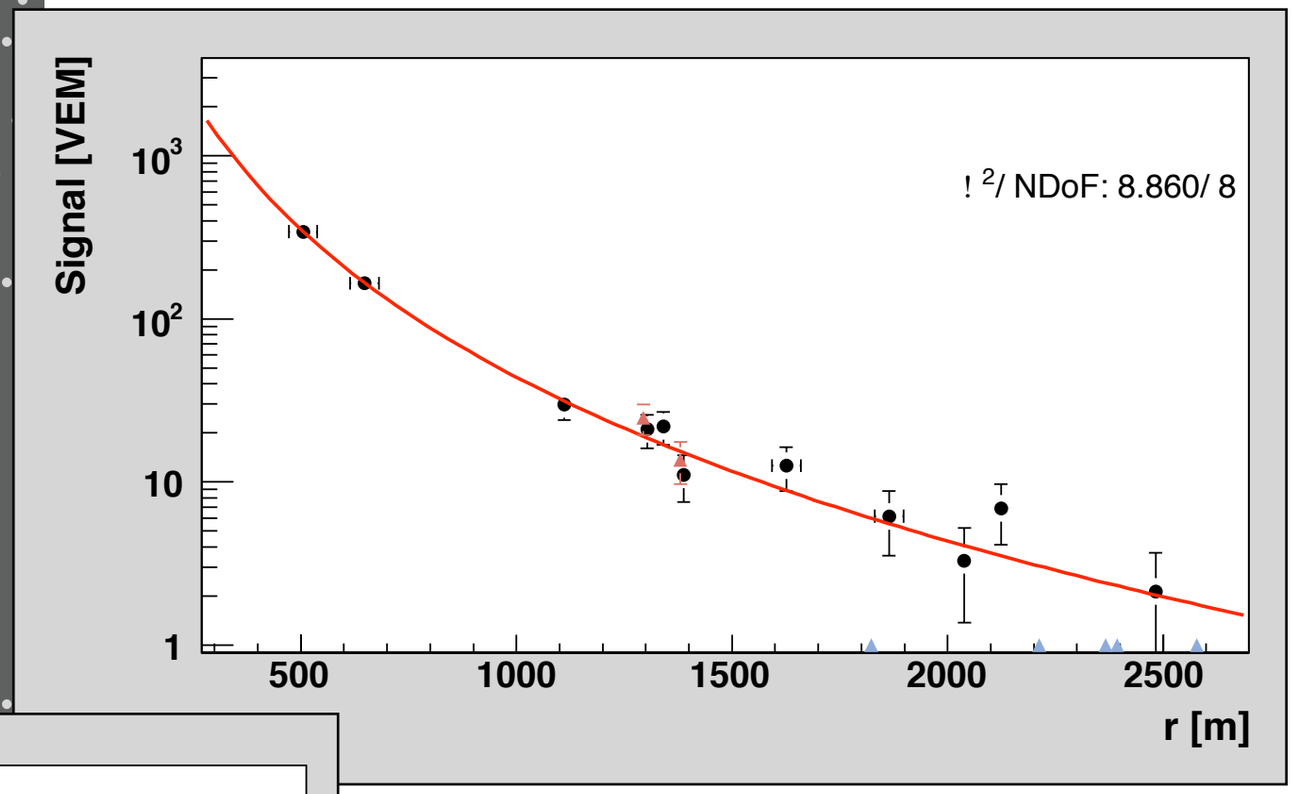



Tank signal in units
of the signal of
a vertical muon

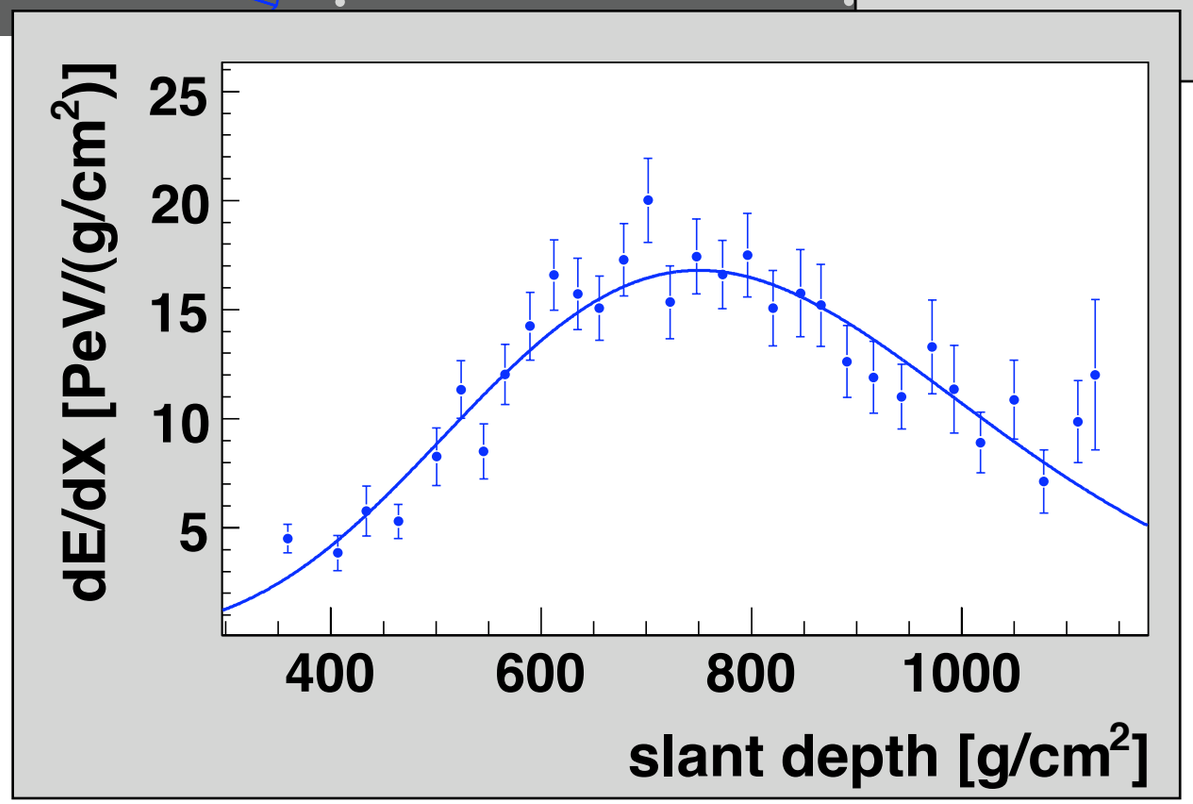
# Golden hybrid events



## Lateral distribution

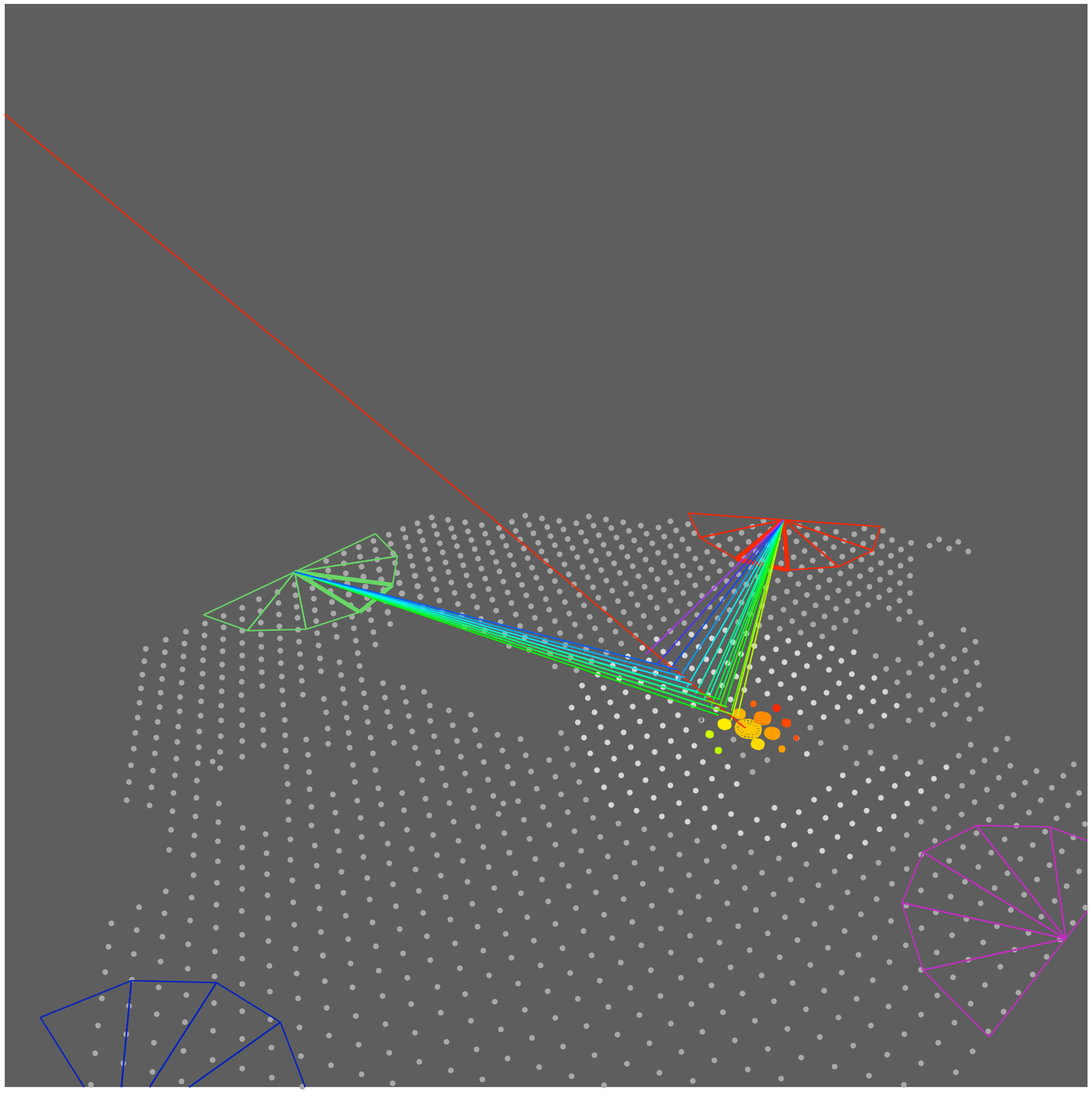



Shower longitudinal profile



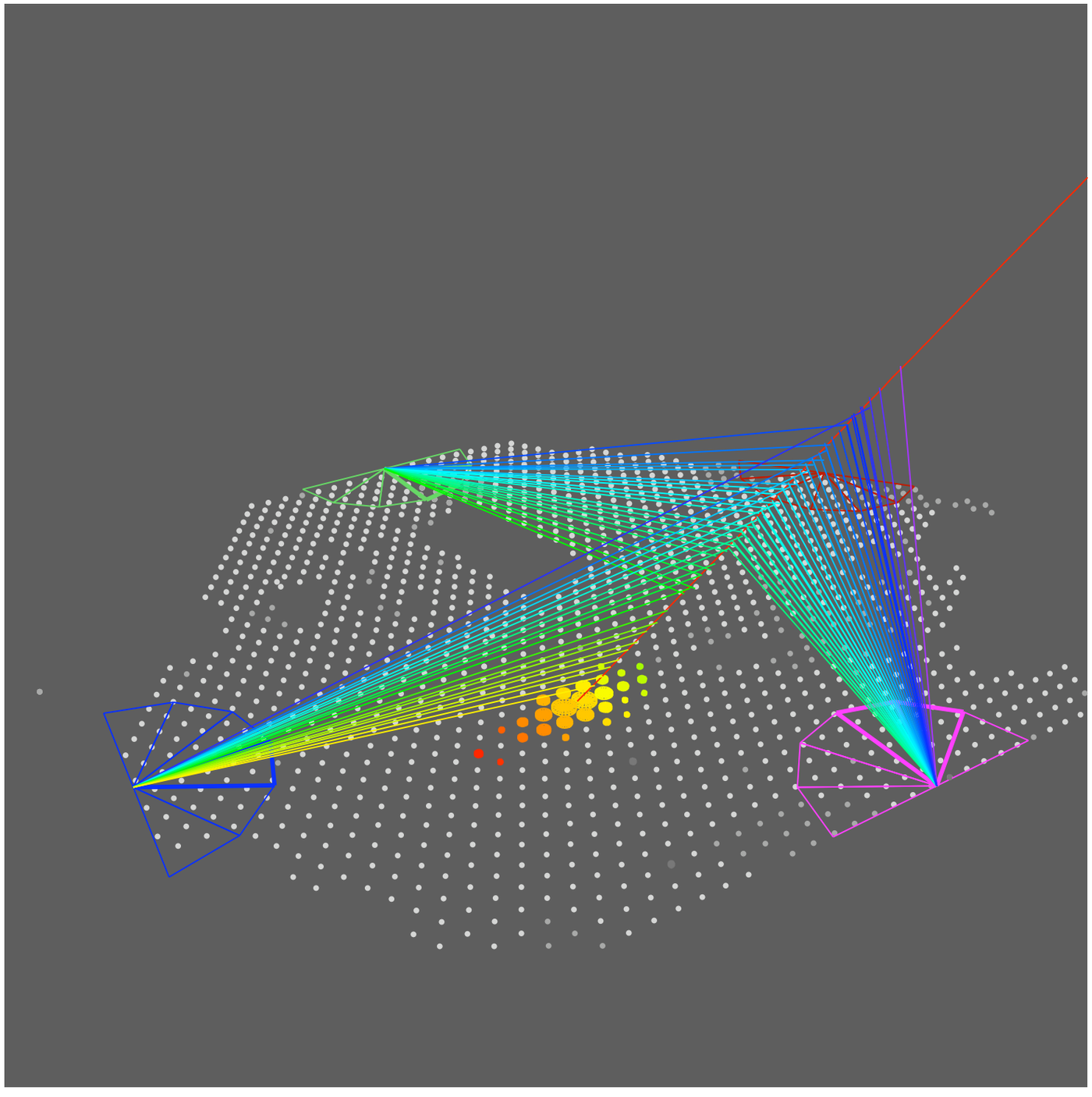

Hybrid events ~ 80,000
Golden hybrid events ~ 10,000

# Other types of Auger events



Event 200718905882 (9.7.2007)

# Other types of Auger events

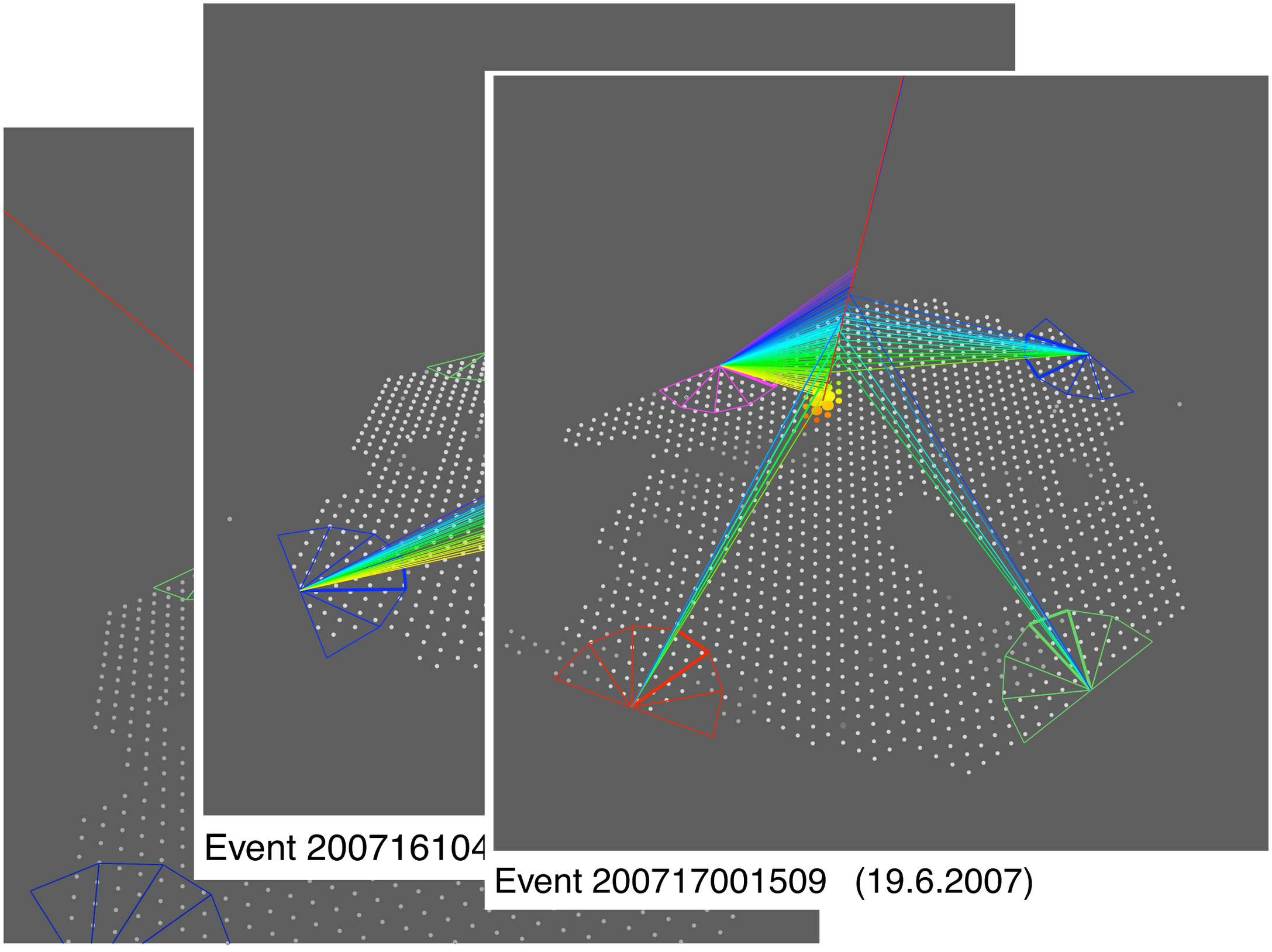


Event 200716104390 (11.6.2007)



Event 200718905882 (9.7.2007)

# Other types of Auger events

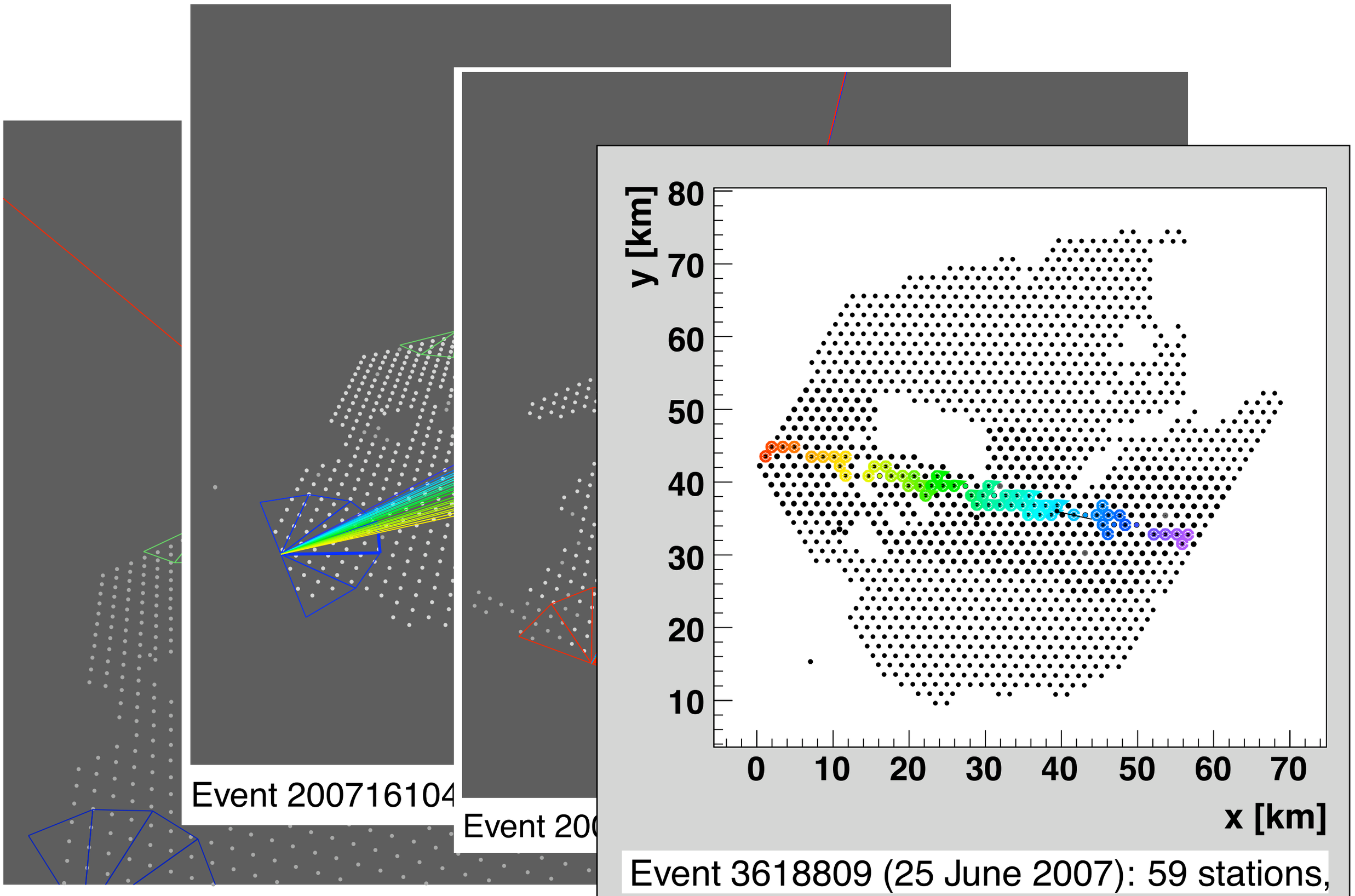


Event 200716104

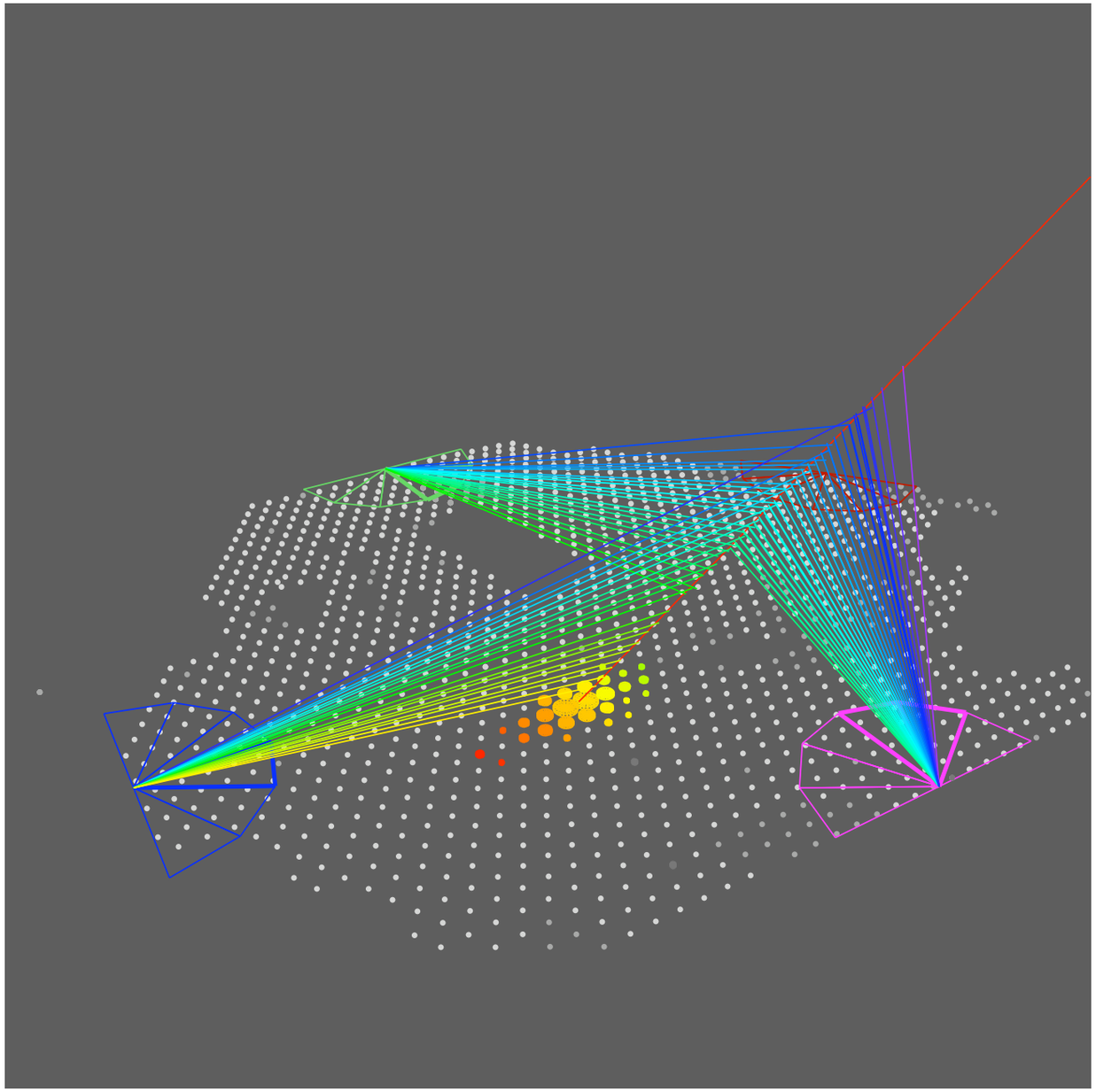
Event 200717001509 (19.6.2007)

Event 200718905882 (9.7.2007)

# Other types of Auger events

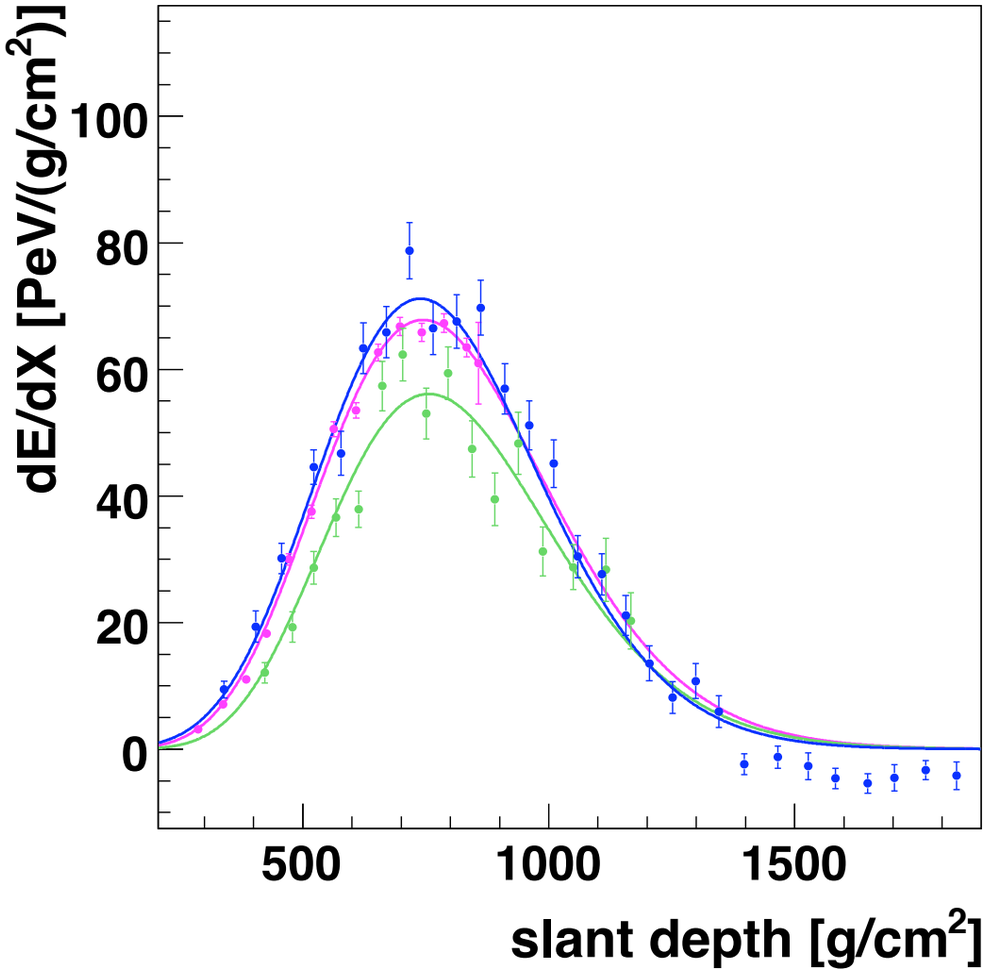


# Golden hybrid events: many cross checks possible



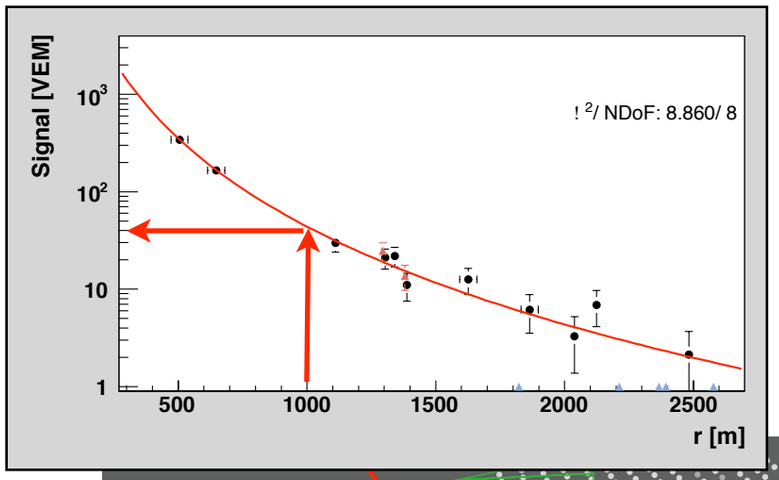
Event 200716104390 (11.6.2007)

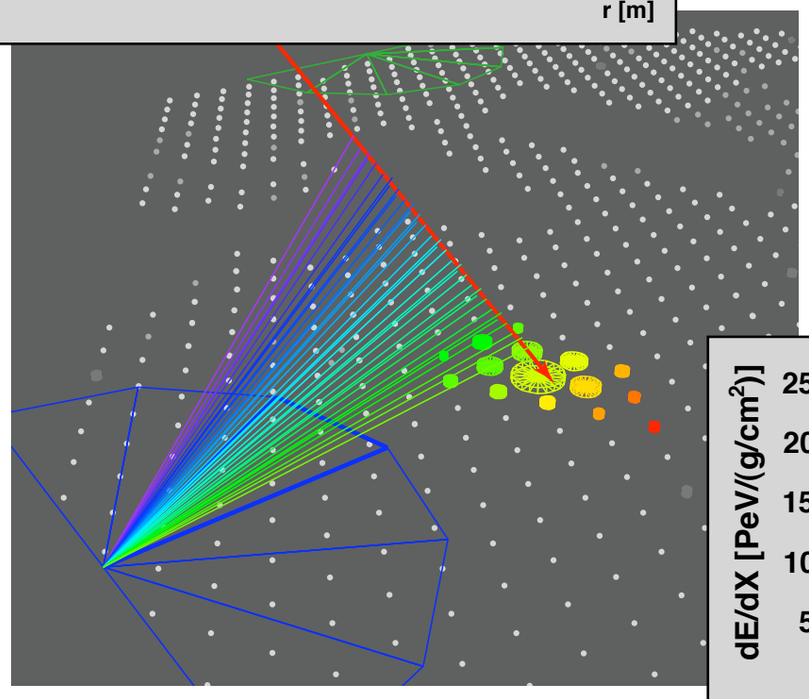
Independent profile reconstuctions

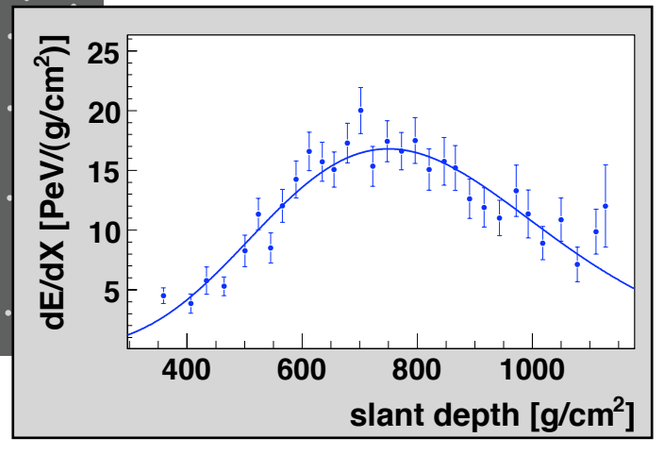


# Cosmic Ray Flux

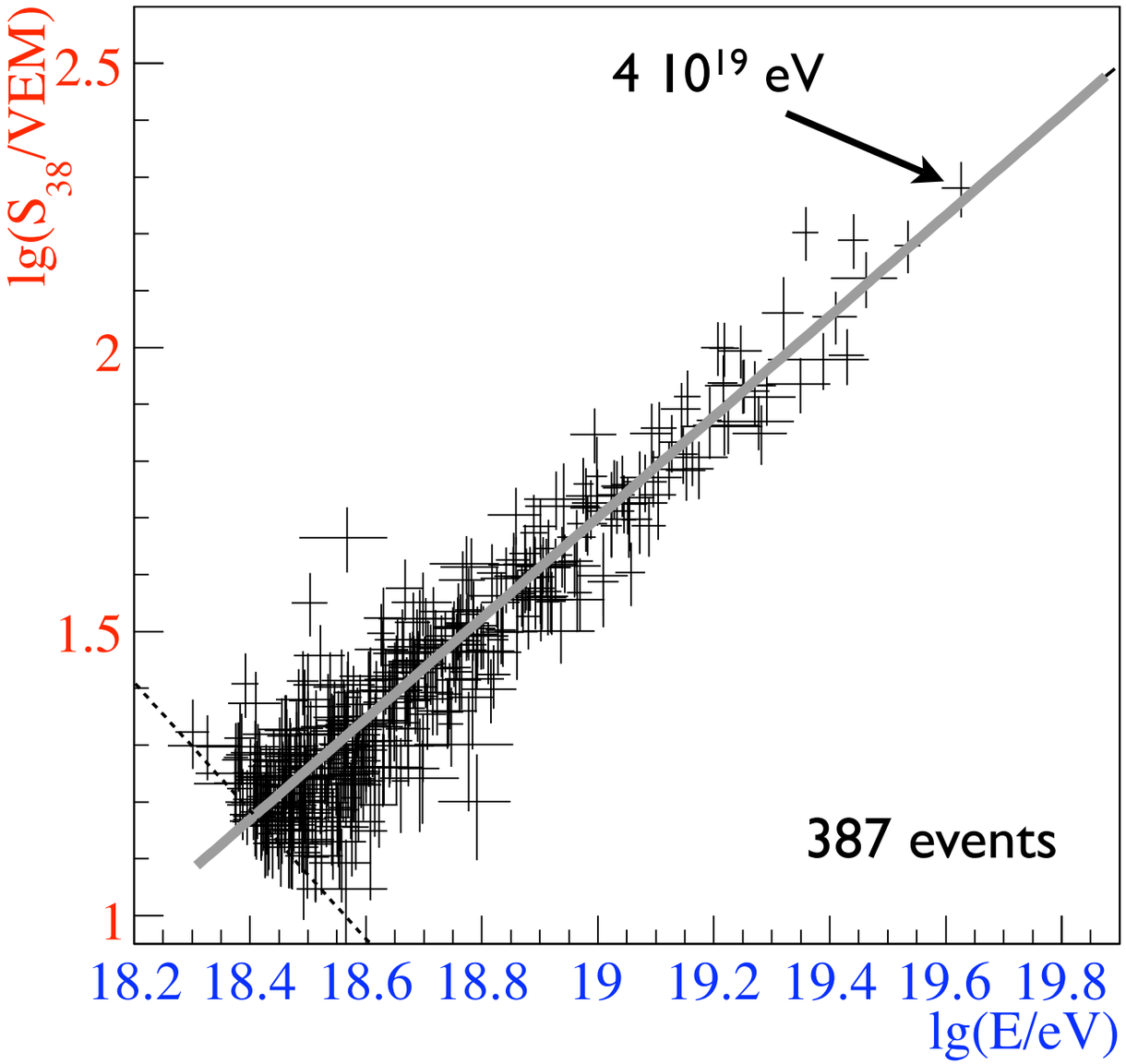
# Energy calibration of surface detector






Shower size at 1000m and θ=38°

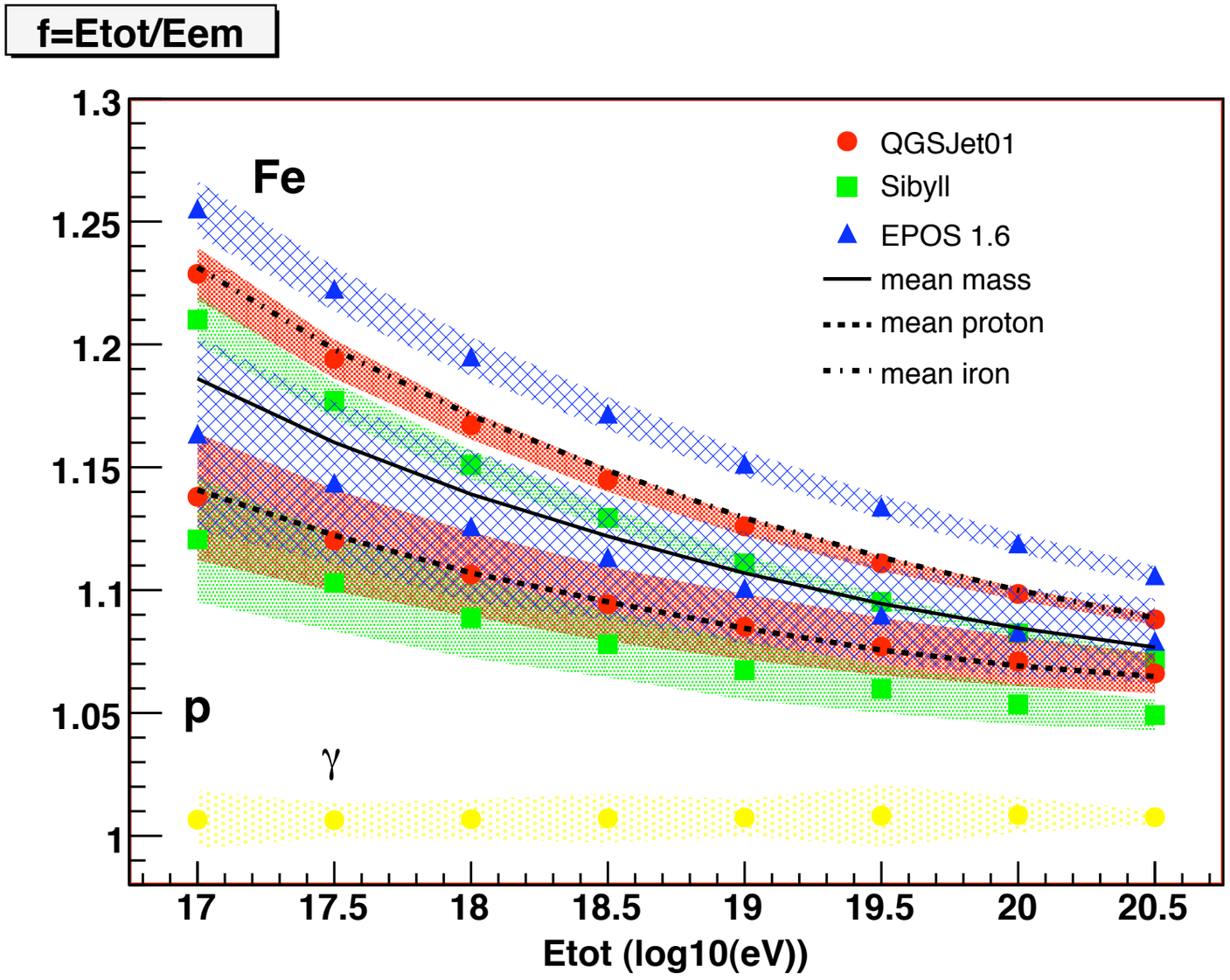



## Fluorescence detector energy

$$E_{\mathrm{prim}} = f_{\mathrm{corr}} \cdot \int \frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{dX}}\,\mathrm{d}X$$

*(Fluorescence yield uncertainty)*

# Systematic uncertainties of energy assignment

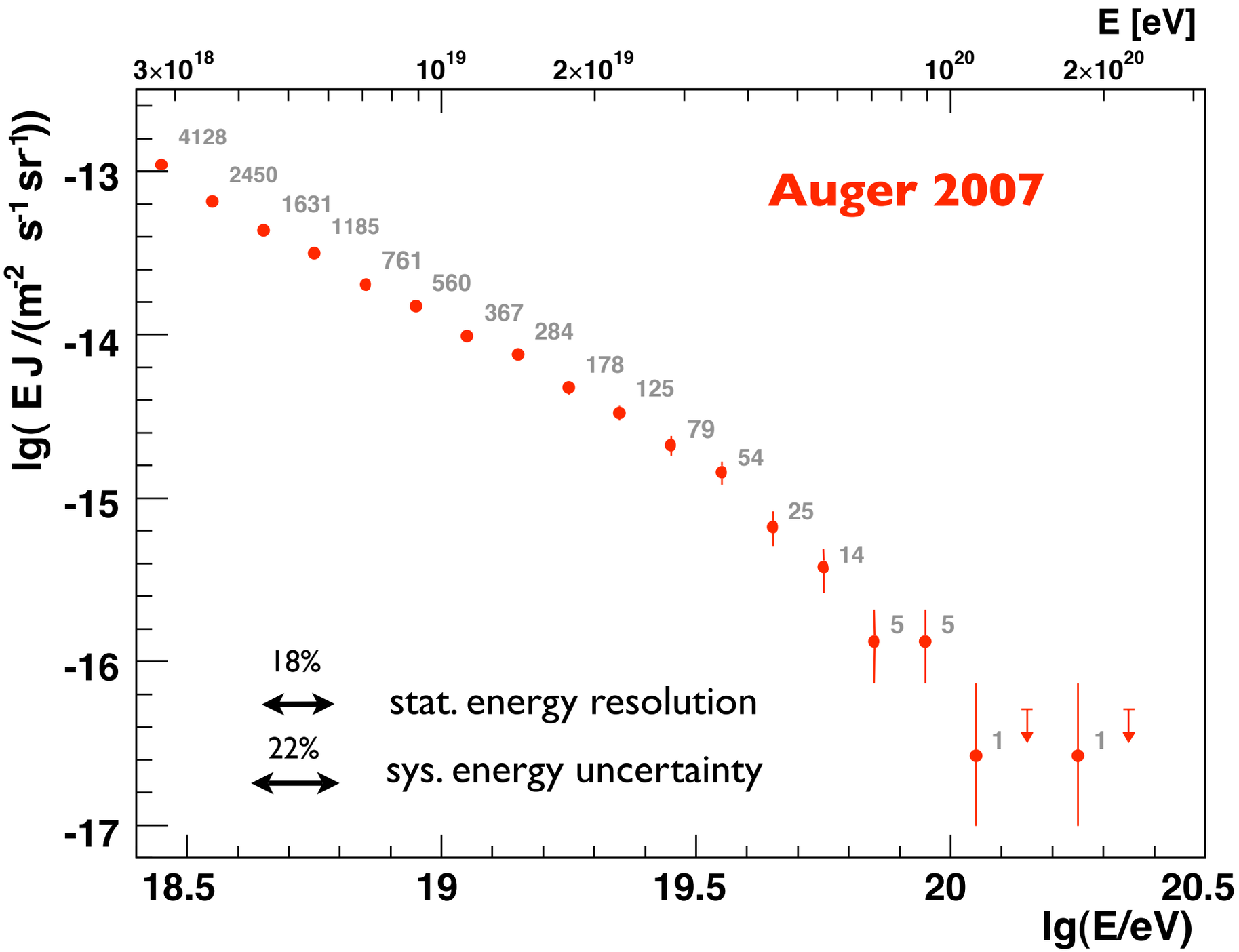



*(T. Pierog et al., ICRC 2007)*

Model dependence of energy correction small

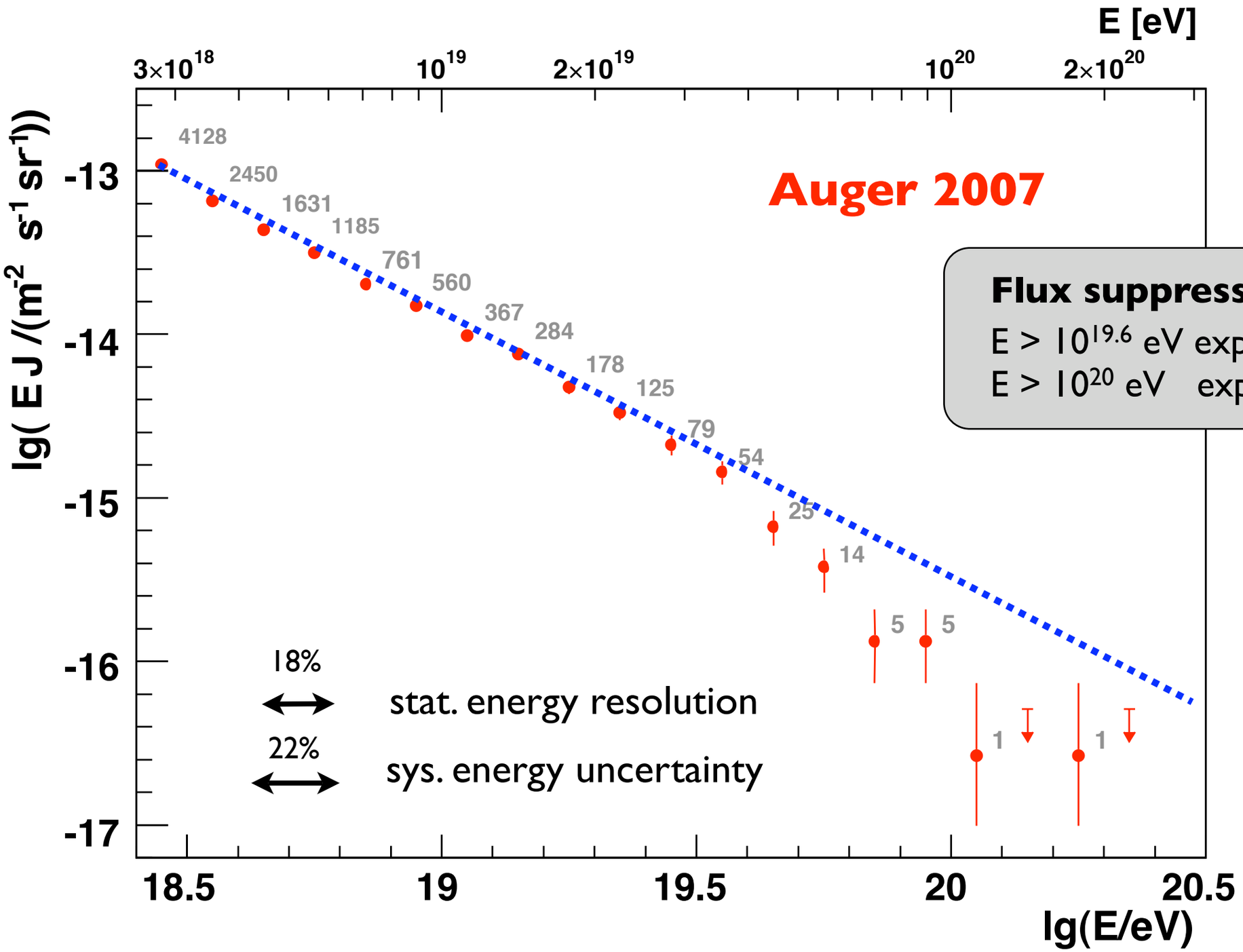
| | |
|---|---|
| fluorescence yield | 14% |
| telescope calibration | 10% |
| reconstruction | 10% |
| aerosols | 5% |
| humidity | 5% |
| overall | 22% |

# Auger surface detector energy spectrum




Data: 1 Jan 2004 - 28 Feb 2007, 5165 km$^2$ sr yr

# Auger surface detector energy spectrum



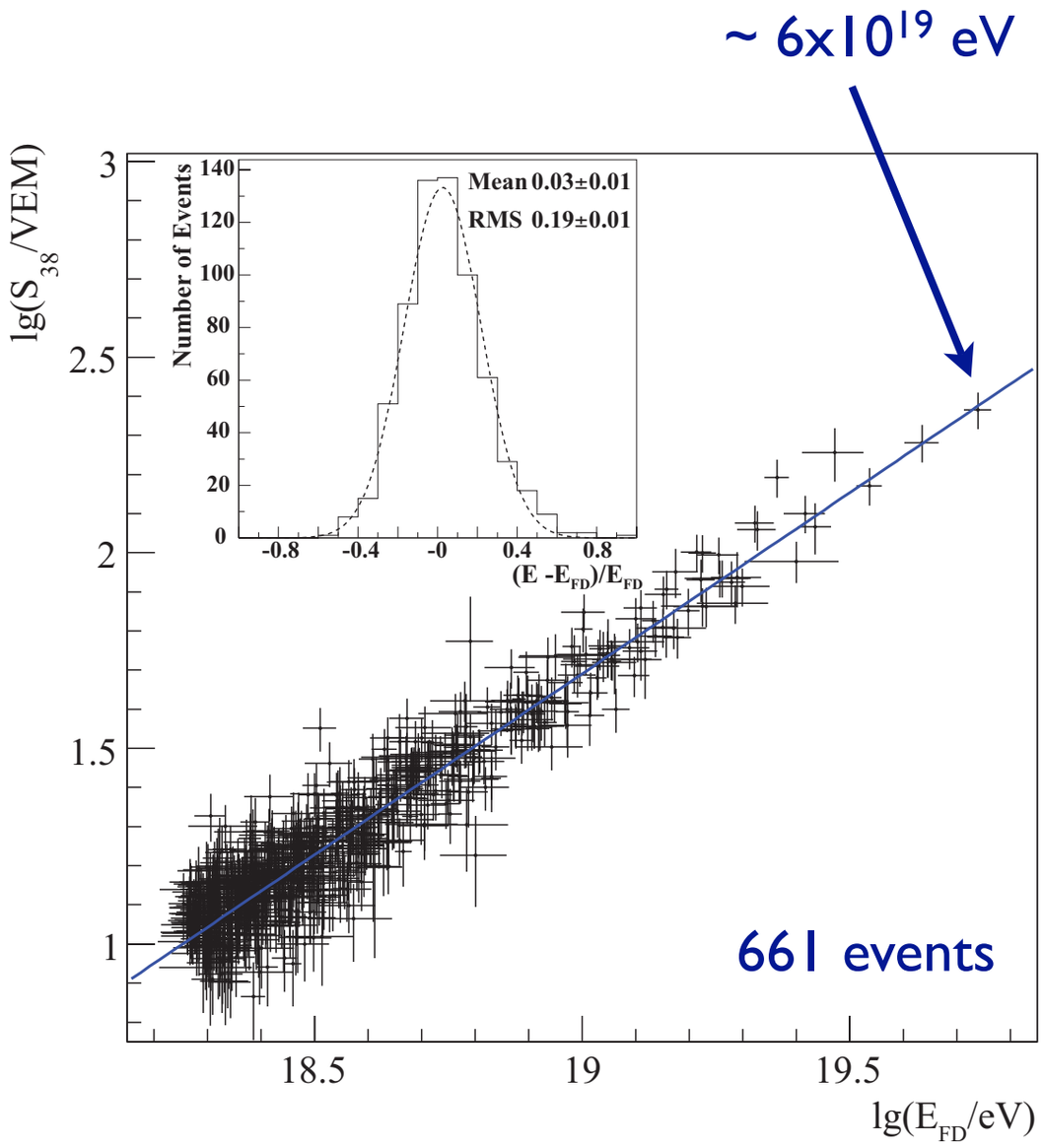

**Flux suppression ~ 6σ**

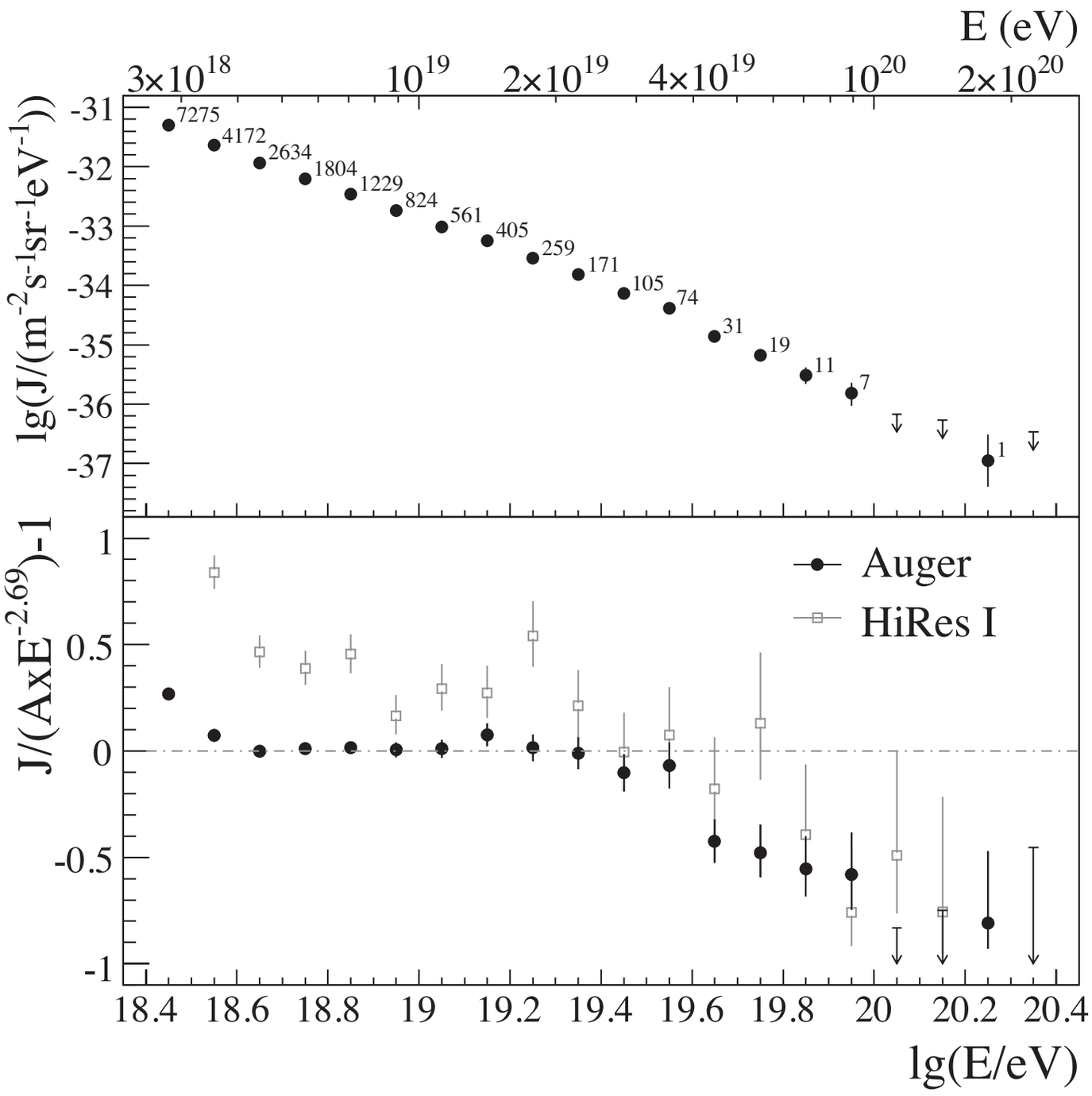
E > $10^{19.6}$ eV exp: 132 det: 51

E > $10^{20}$ eV exp: 30 det: 2

Data: 1 Jan 2004 - 28 Feb 2007, 5165 km$^2$ sr yr

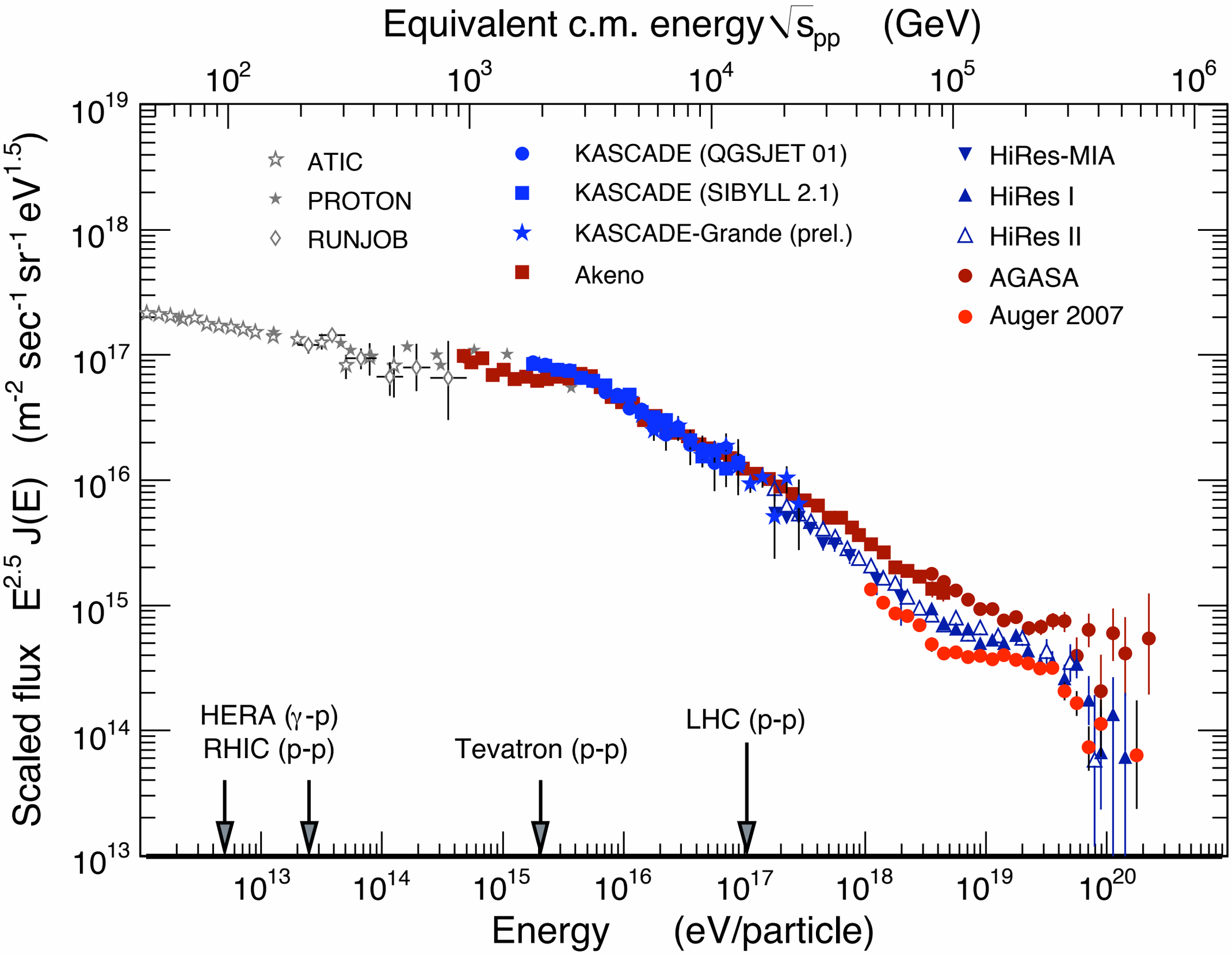
# Update: spectrum published in PRL 2008



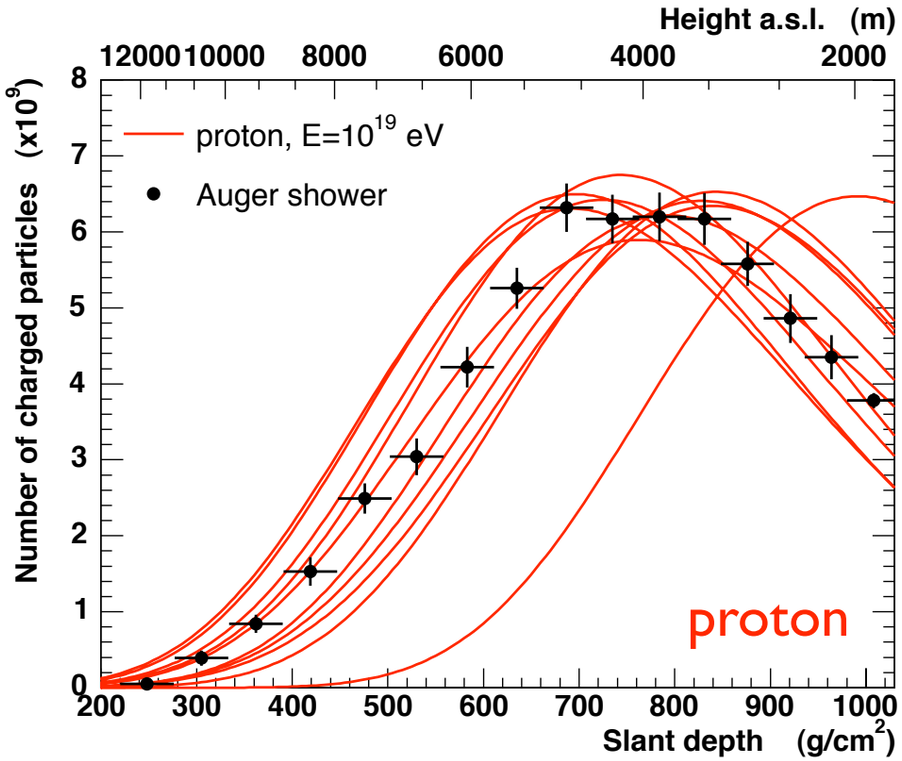

Data: 1 Jan 2004 - 31 Aug 2007

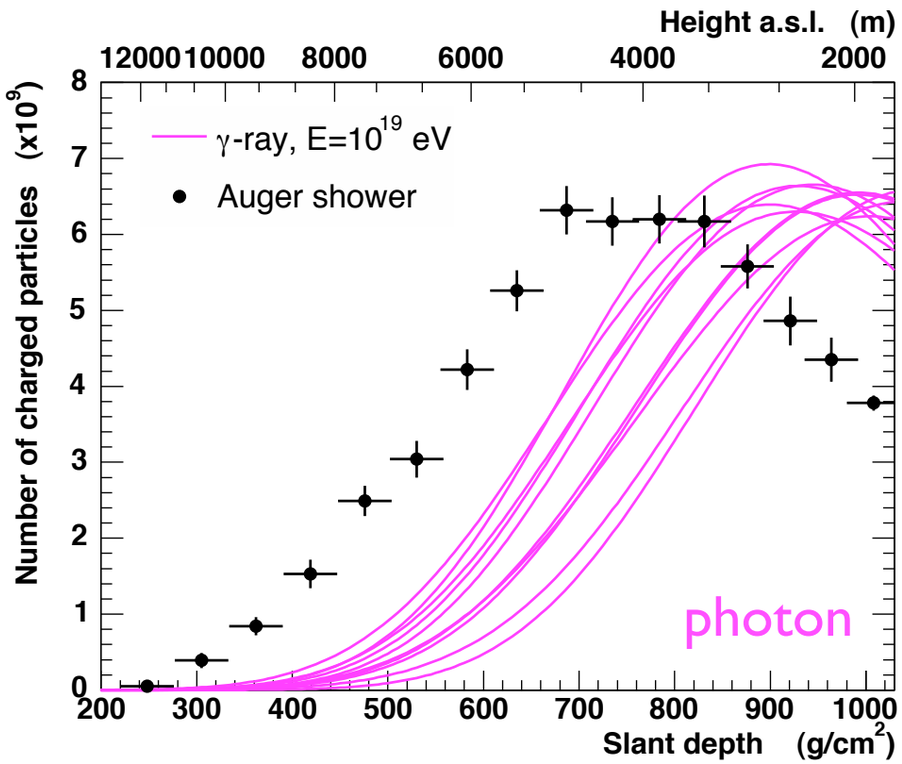
*Phys. Rev. Lett. 101 (2008) 061101*

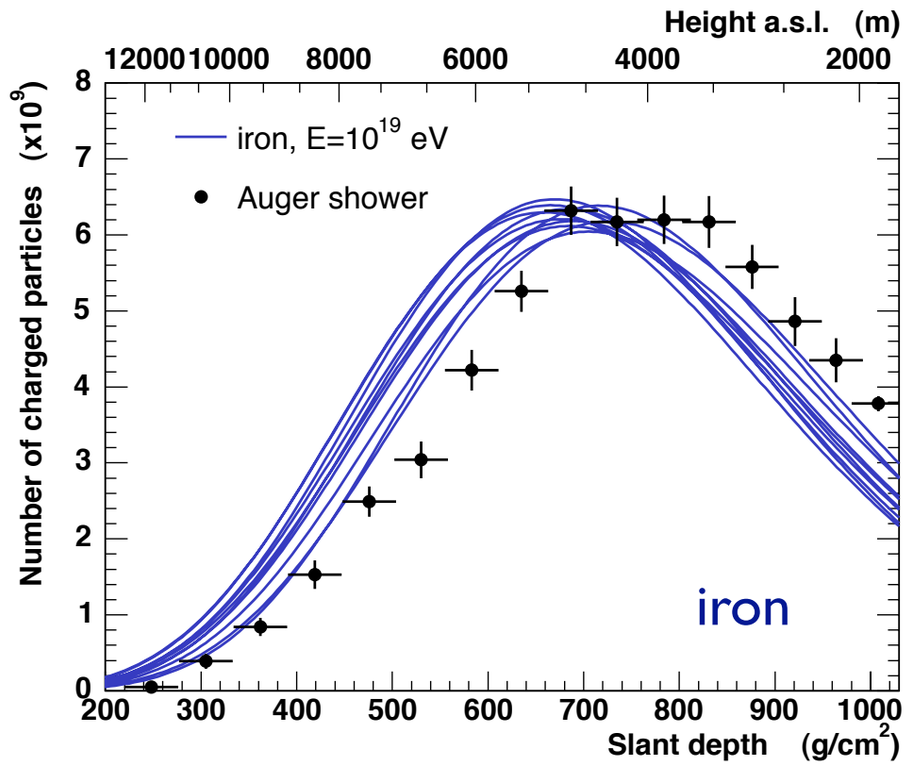

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
Scaled flux $E^{2.5}$ J(E) ($m^{-2}$ $sec^{-1}$ $sr^{-1}$ $eV^{1.5}$)
$10^{19}$
$10^{18}$
$10^{17}$
$10^{16}$
$10^{15}$
$10^{14}$
$10^{13}$
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2007
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
$10^{13}$
$10^{14}$
$10^{15}$
$10^{16}$
$10^{17}$
$10^{18}$
$10^{19}$
$10^{20}$
Energy (eV/particle)

# Elemental Composition, Photons, Neutrinos

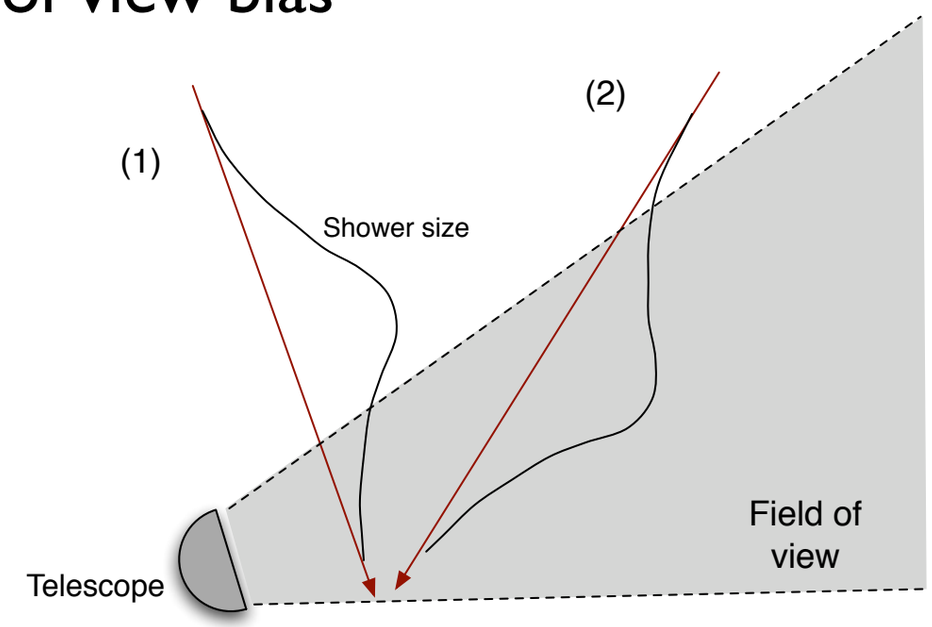
# Composition: measurement of longitudinal profile



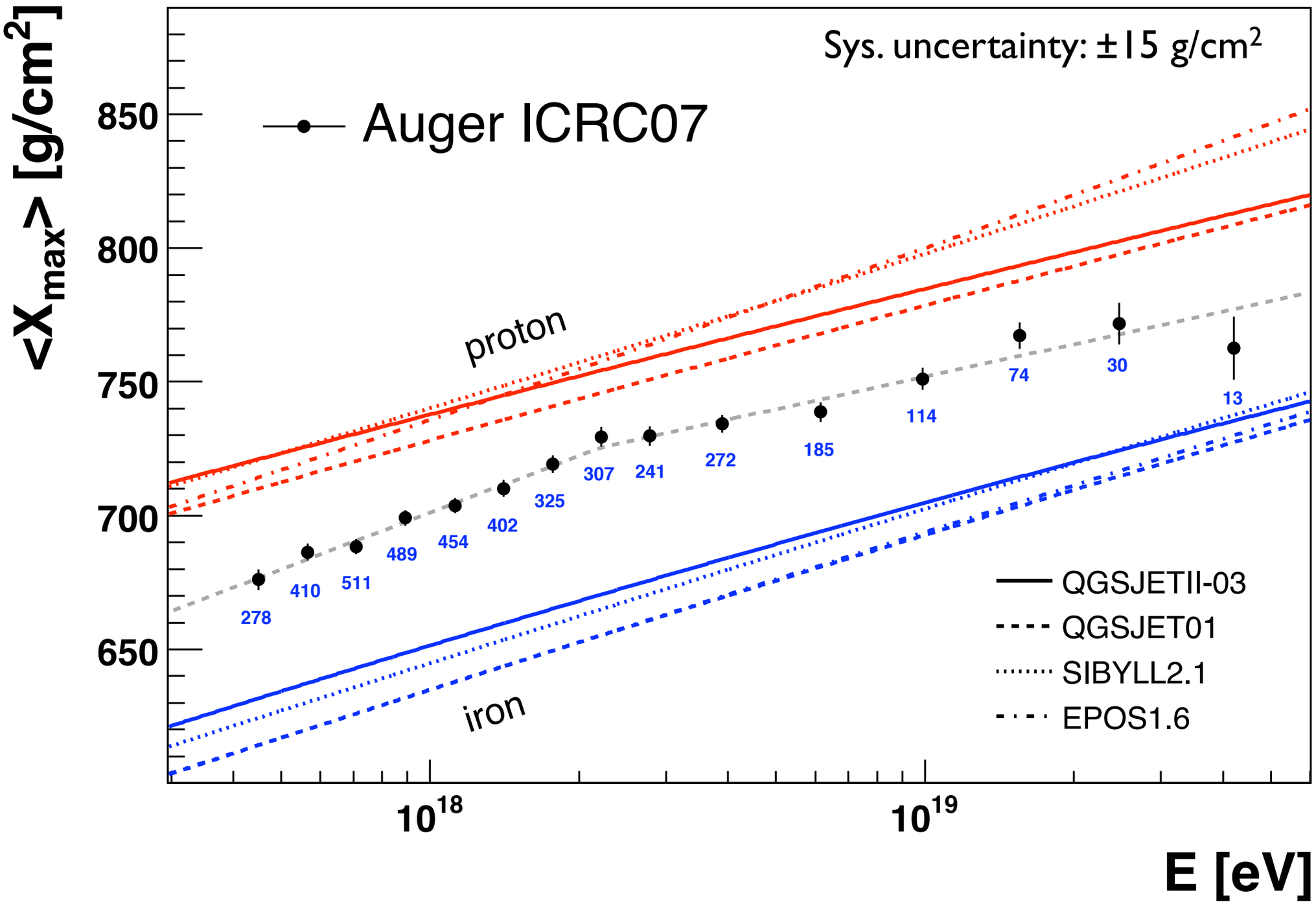




## Field of view bias

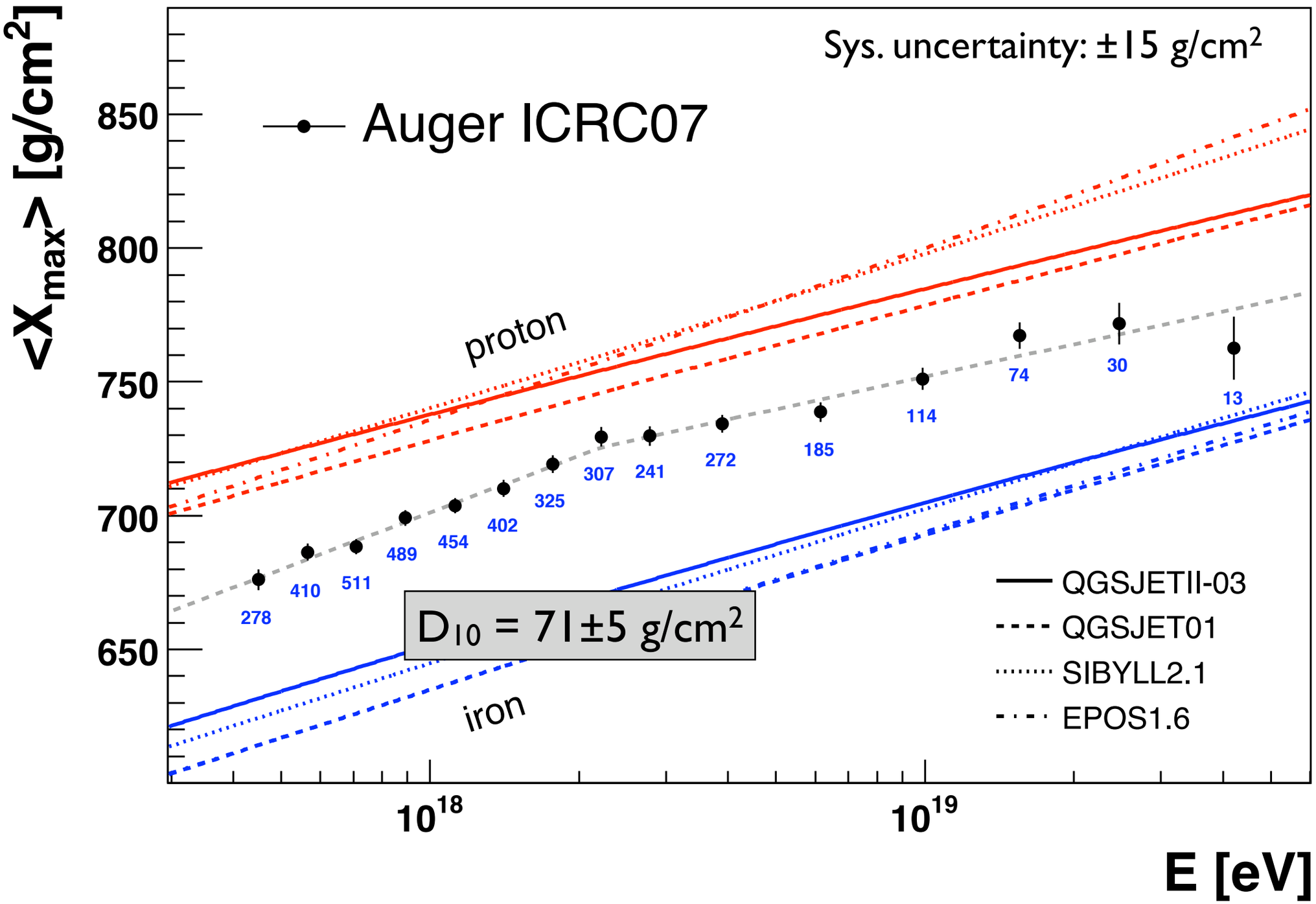


# Composition: mean depth of shower maximum



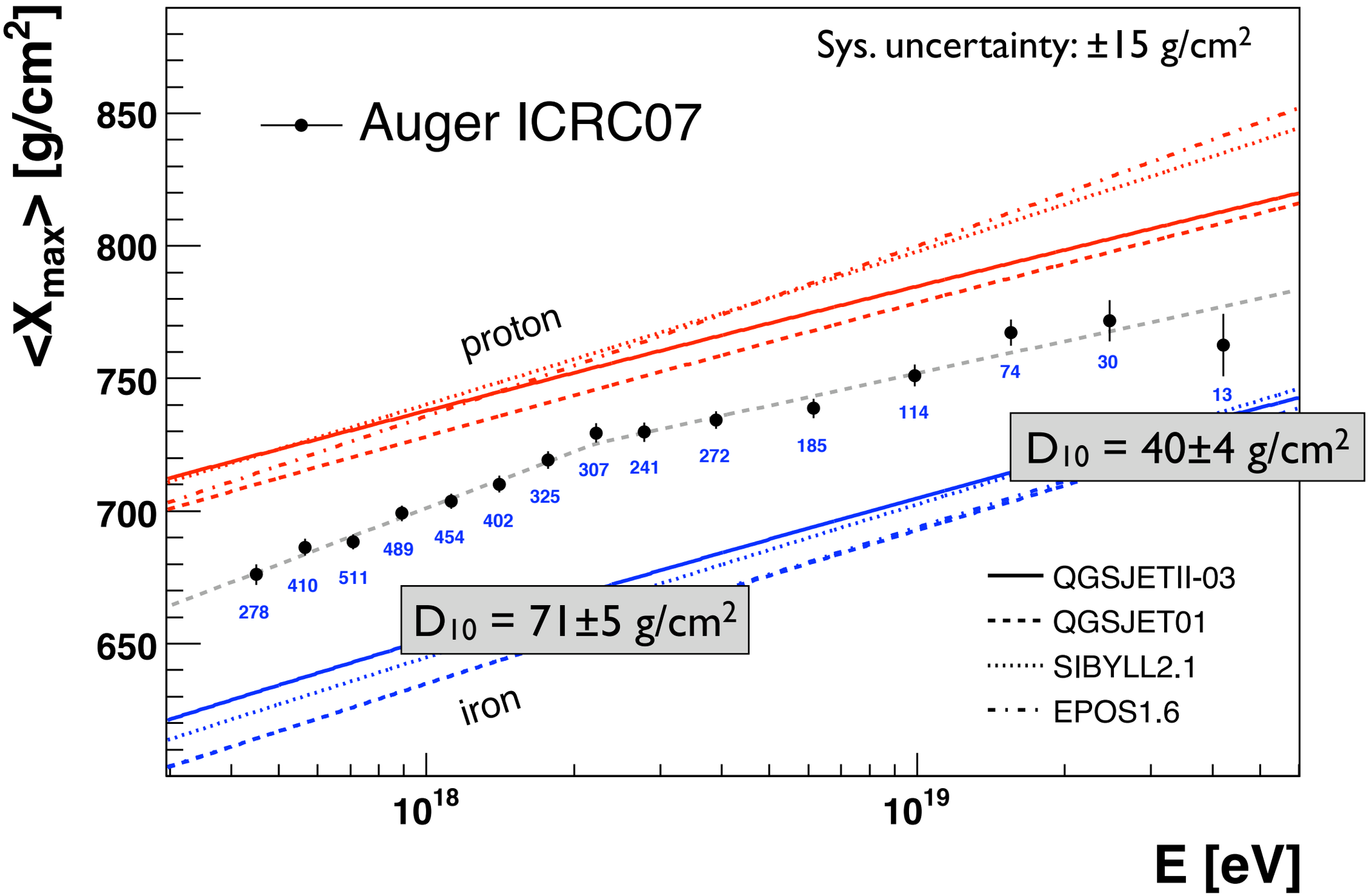

(Note: not consistent with muon data and current interaction models)

# Composition: mean depth of shower maximum




(Note: not consistent with muon data and current interaction models)

# Composition: mean depth of shower maximum



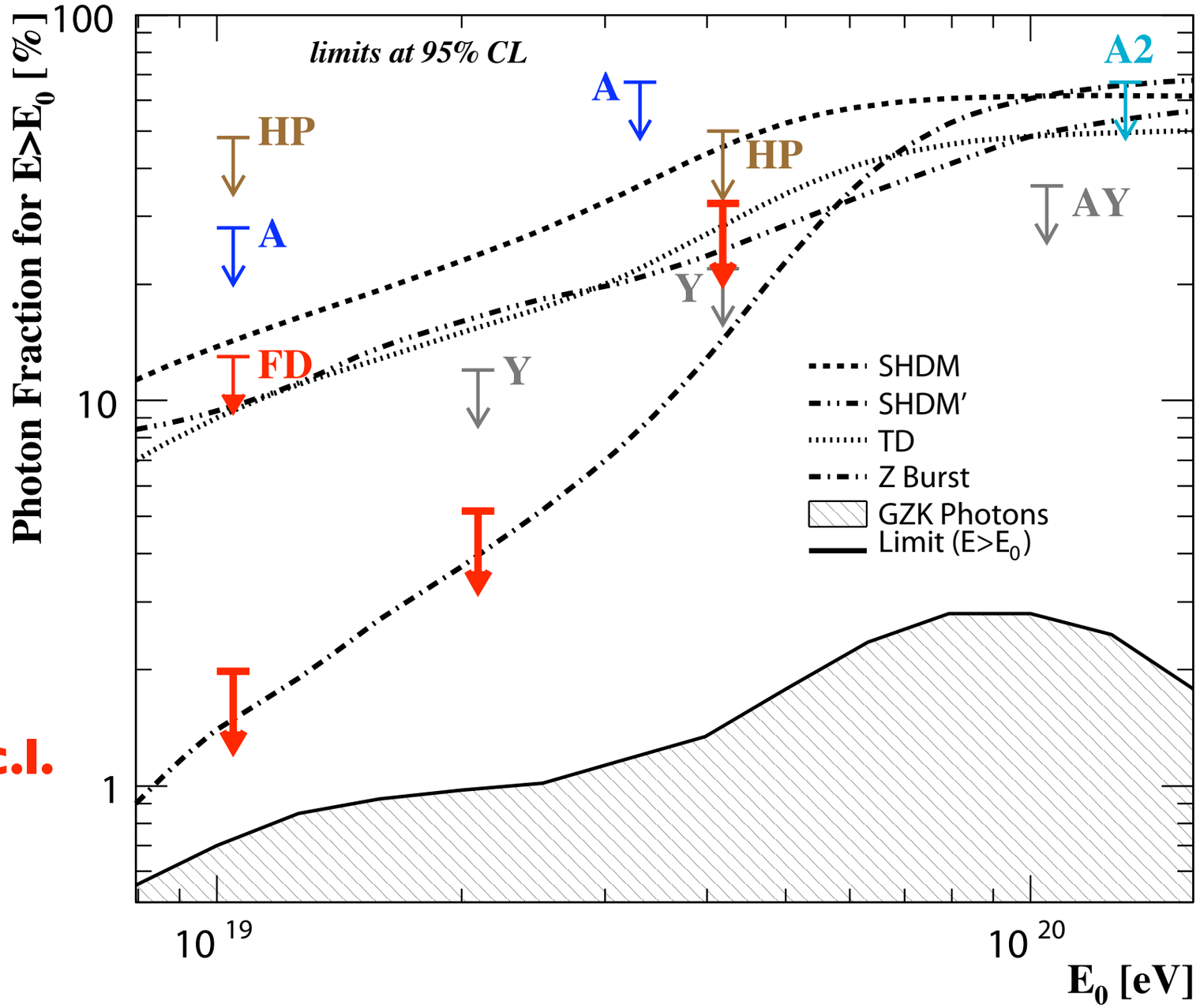

(Note: not consistent with muon data and current interaction models)

# Limit on fraction of photons in UHECR flux

Many exotic source scenarios excluded

**Auger, 95% c.l.**

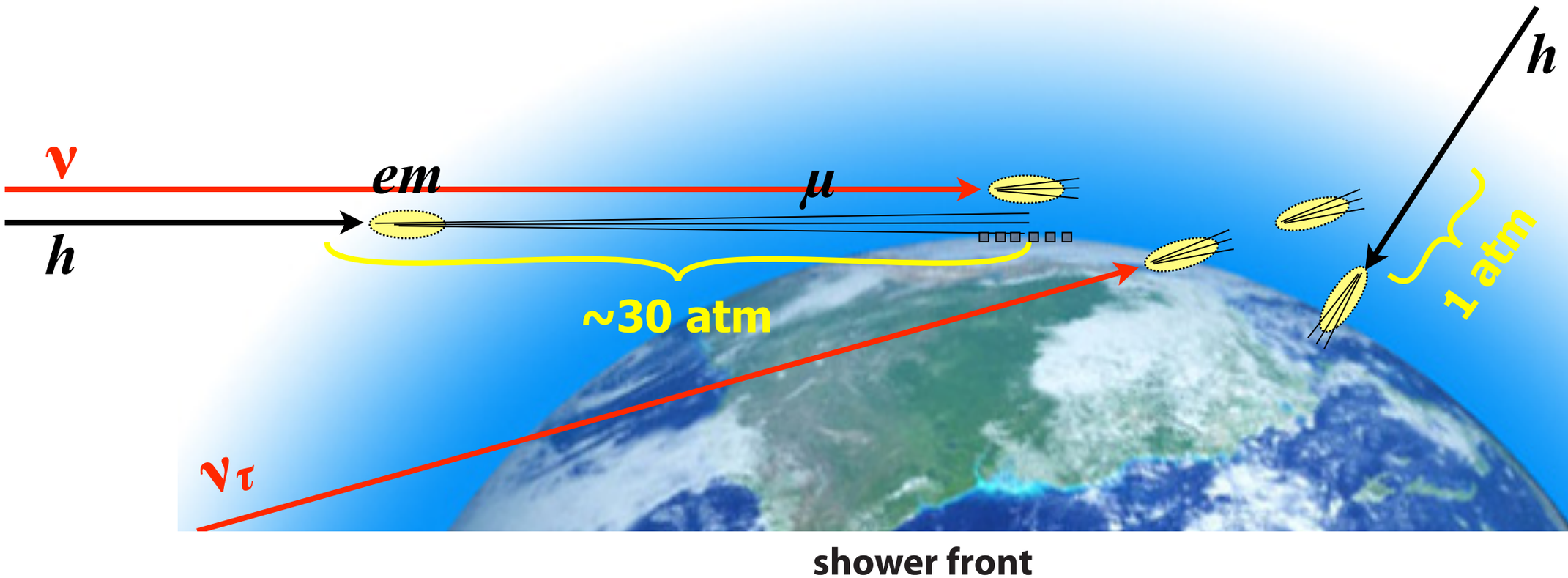
Integral photon flux limit

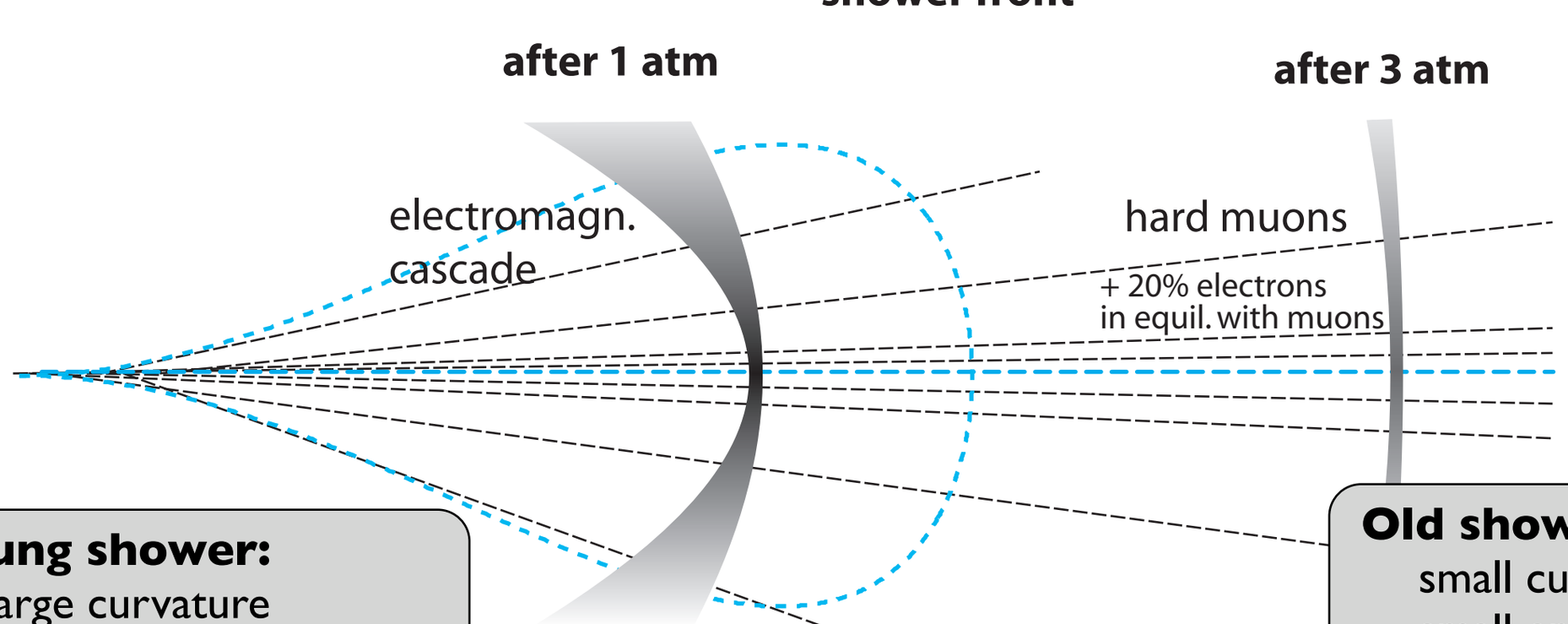



*Astropart. Phys. 29 (2008) 243*

Data: 1 Jan 2004 - 31 Dec 2006

# Neutrino-induced shower sensitivity

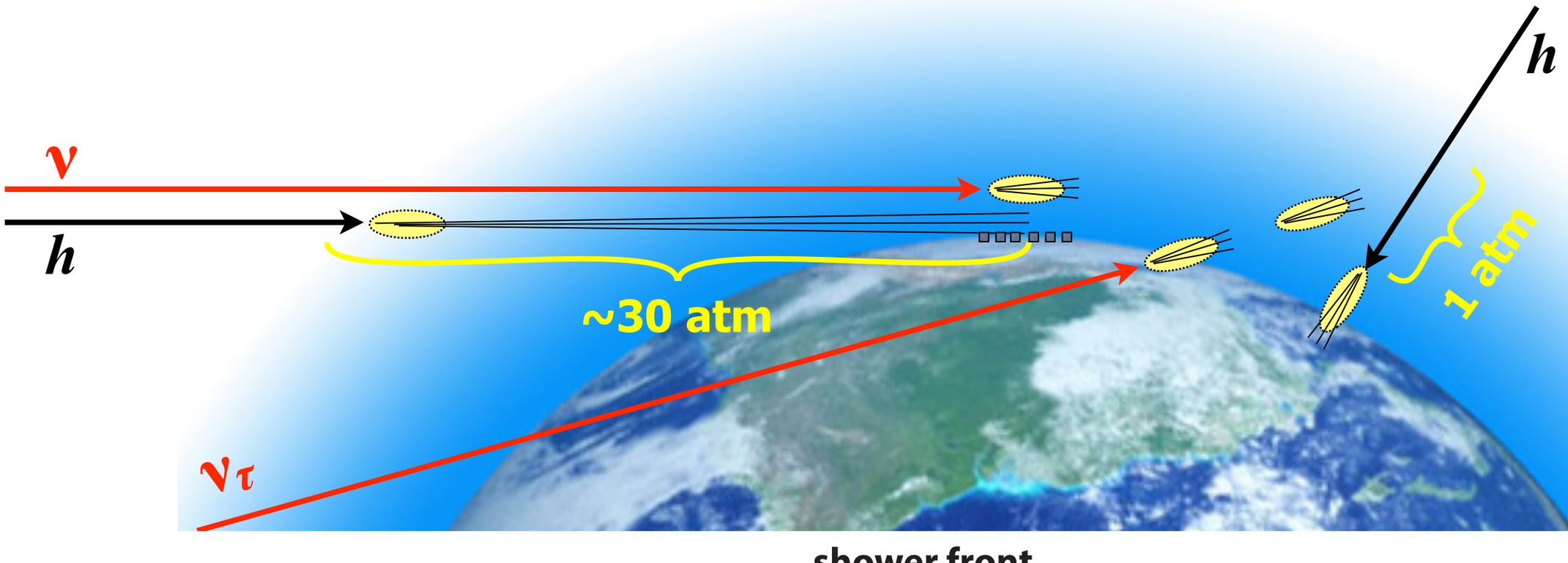


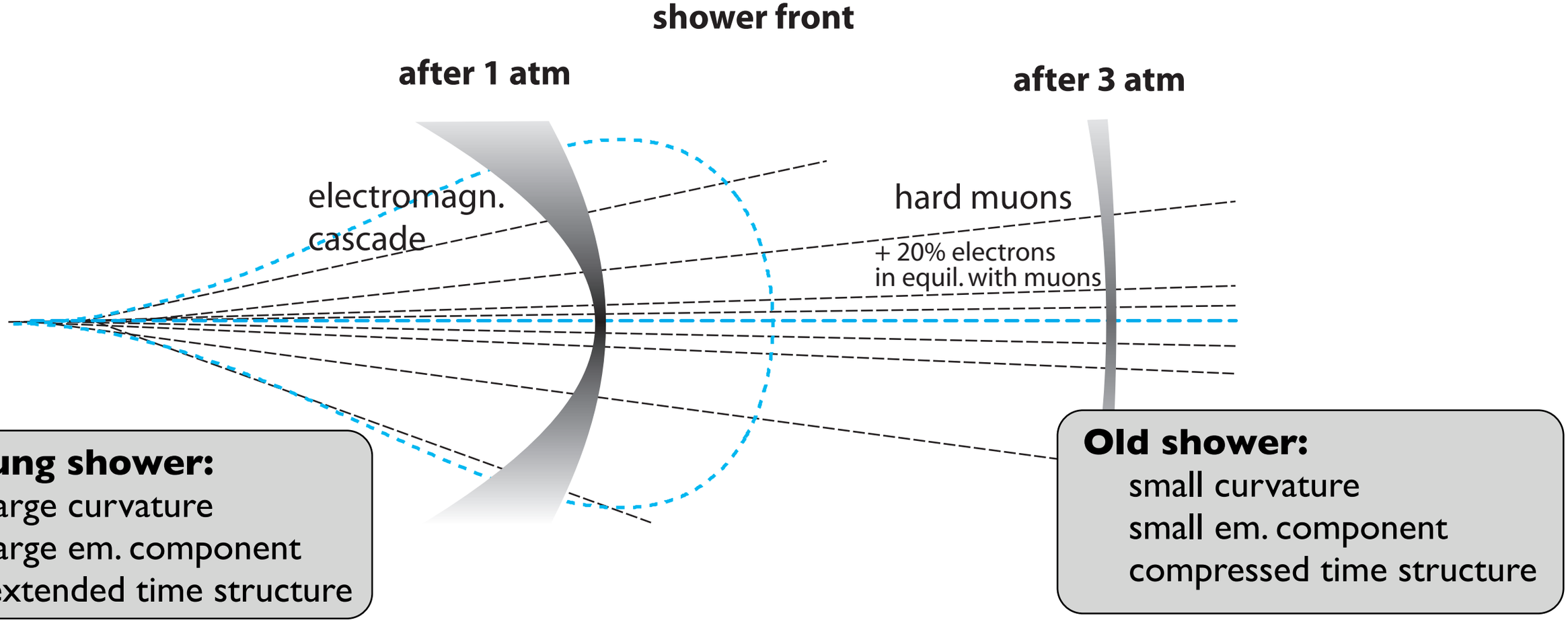




**Young shower:**
large curvature
large em. component
extended time structure

**Old shower:**
small curvature
small em. component
compressed time structure

# Neutrino-induced shower sensitivity

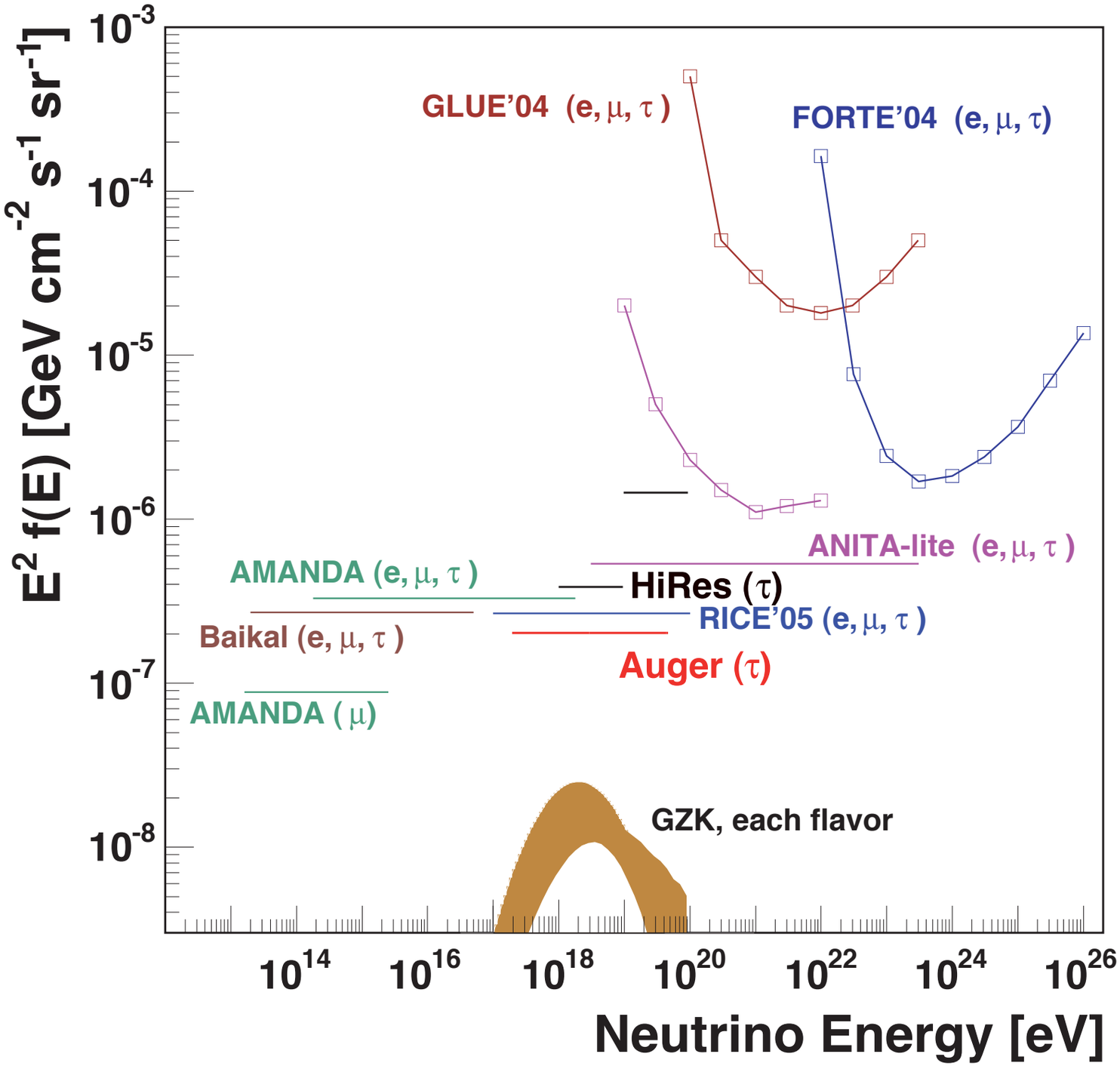



**Young shower:**
large curvature
large em. component
extended time structure

**Old shower:**
small curvature
small em. component
compressed time structure

# Neutrino flux limit at ultra-high energy



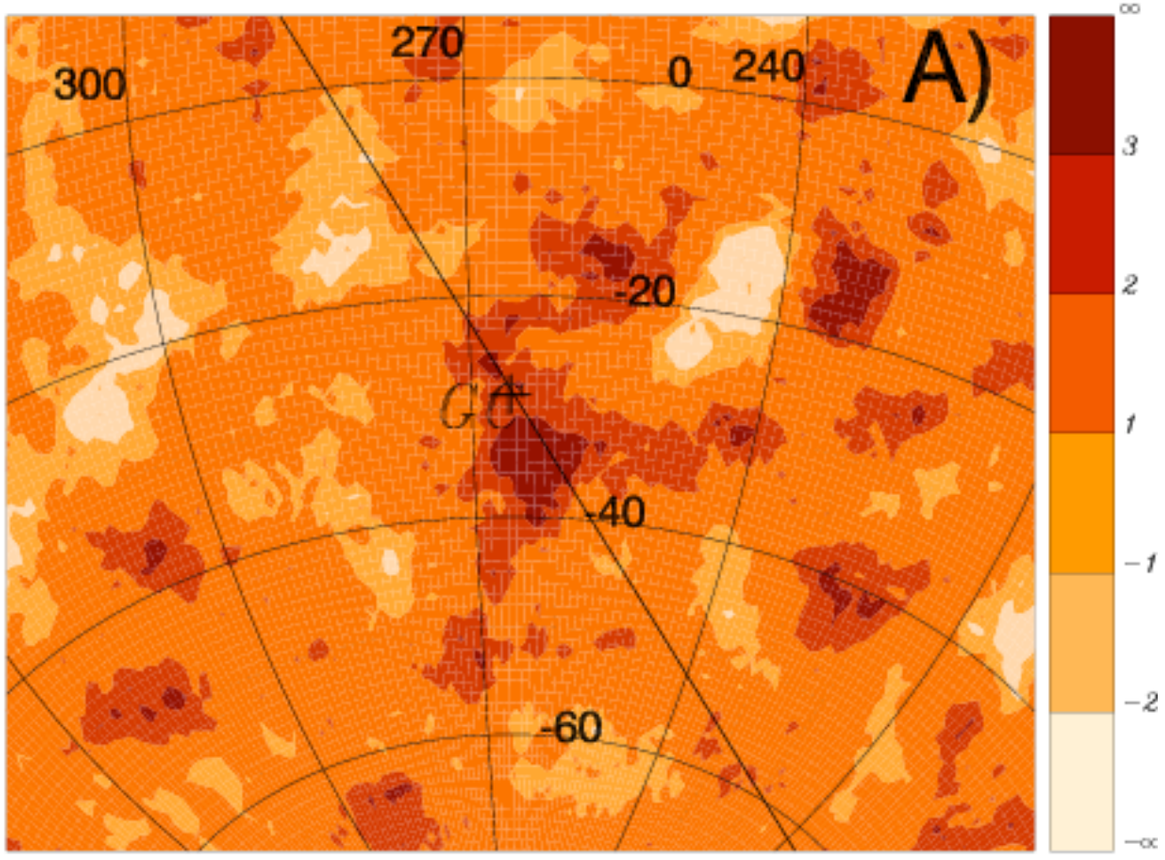

**Auger 2007:**
Horizontal showers with surface detector

*(PRL 100 (2008) 211101)*

# Arrival direction distribution

# Galactic center point source search

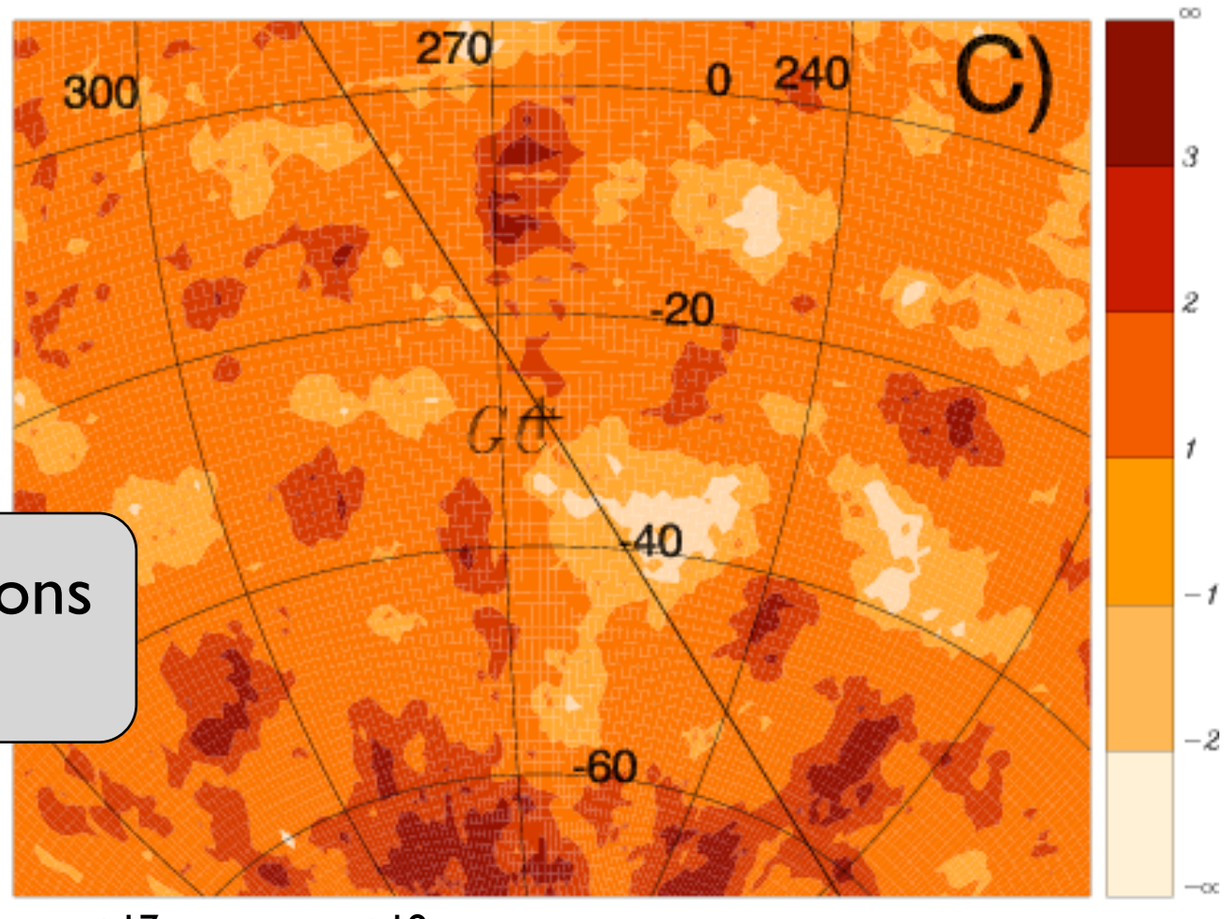
Significance plots




$10^{18} < E < 10^{19}$ eV

Dark red: *more events than expected*
Light red: *fewer events than expected*

**Auger, ICRC 2007**



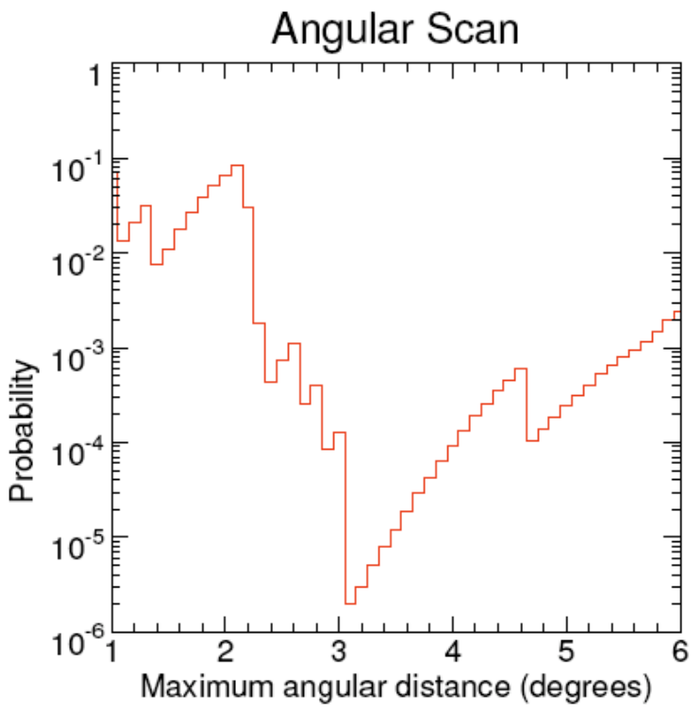

$10^{17} < E < 10^{18}$ eV

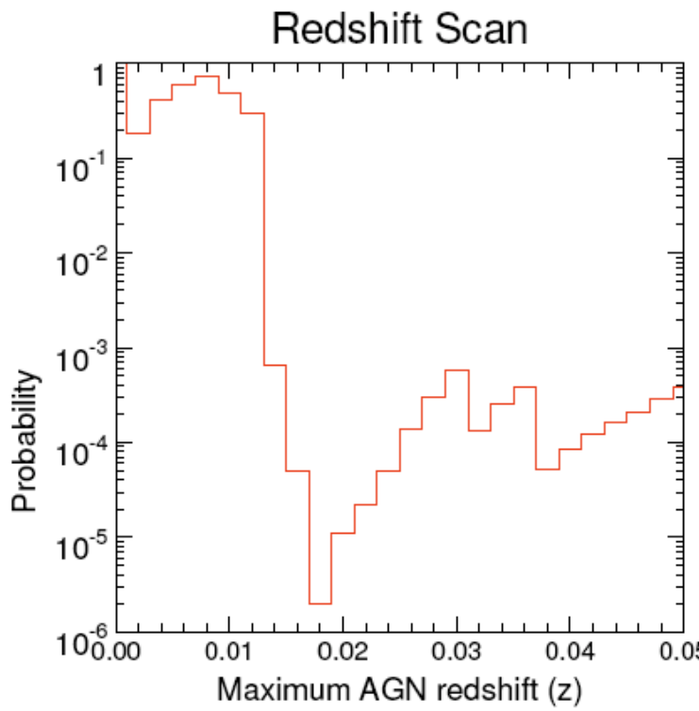
No confirmation of previous indications for excess from GC region

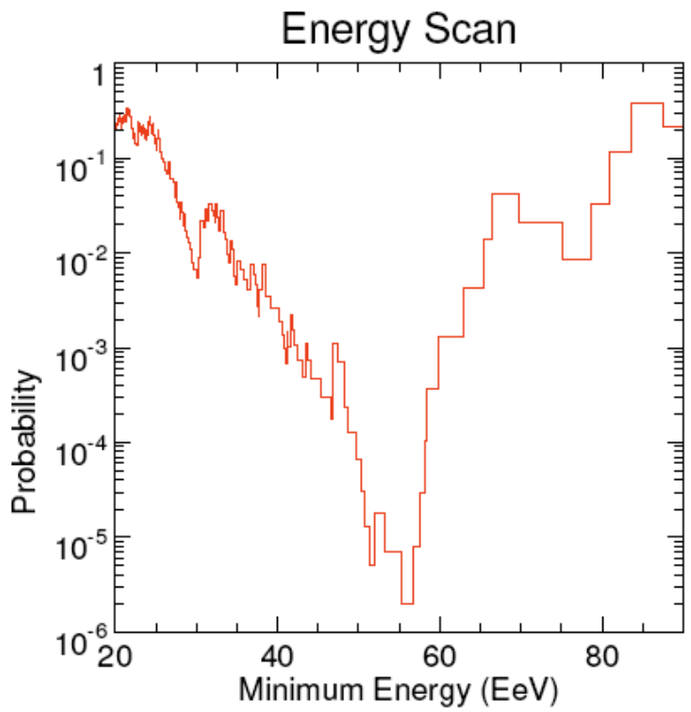
*AGASA: would have* ***16σ***
*SUGAR: would have* ***30σ*** *in Auger*

# Possible correlation with nearby objects ?

- 12th Veron-Cetty & Veron catalogue of AGN
- Data set: Jan 1st, 2004 to May 27th, 2006, well-contained events
- Scan over angular distance, maximum redshift, energy threshold




Minimum: 12 out of 15 correlated with nearby AGNs (3.2 expected)

$\Delta\alpha = 3.1°$, $E_{min} = 5.6 \times 10^{19}$ eV, $z_{max} = 0.018$ (75 Mpc)

Uncorrected chance probability: $P \sim 2 \times 10^{-6}$

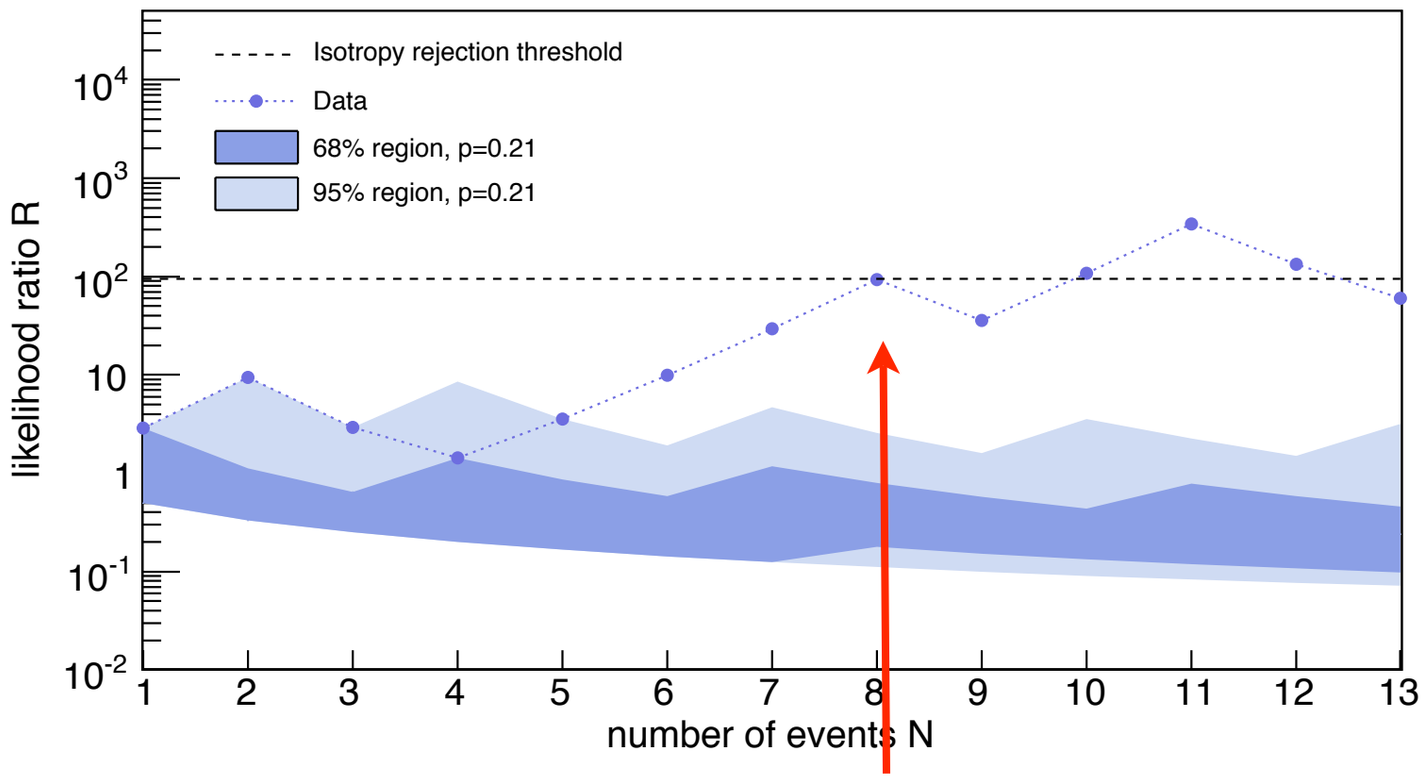
**Correction for trials needed!**

# Auger analysis: running prescription

***Standard prescription*:** pre-define

- number of events or period of time
- data selection criteria and correlation parameters
- nominal chance probability threshold for publishing a claim
- perform test once if event number reached

***Running prescription:*** test prescription for each **new** event
(penalty factor for many tests has to be included)




1% chance probability

| $N$ | $k_{min}$ | Threshold (percent) |
|---|---|---|
| 4 | 4 | 0.19 |
| 6 | 5 | 0.32 |
| 8 | 6 | 0.40 |
| 10 | 7 | 0.44 |
| 12 | 8 | 0.47 |
| 13 | 8 | 0.55 |
| 15 | 9 | 0.58 |
| 16 | 9 | 0.67 |
| 18 | 10 | 0.70 |
| 20 | 11 | 0.71 |
| 21 | 11 | 0.75 |
| 23 | 12 | 0.77 |
| 24 | 12 | 0.81 |
| 26 | 13 | 0.82 |
| 27 | 13 | 0.86 |
| 29 | 14 | 0.87 |
| 30 | 14 | 0.91 |
| 31 | 14 | 0.99 |
| 33 | 15 | 1.00 |
| 34 | 15 | 1.05 |

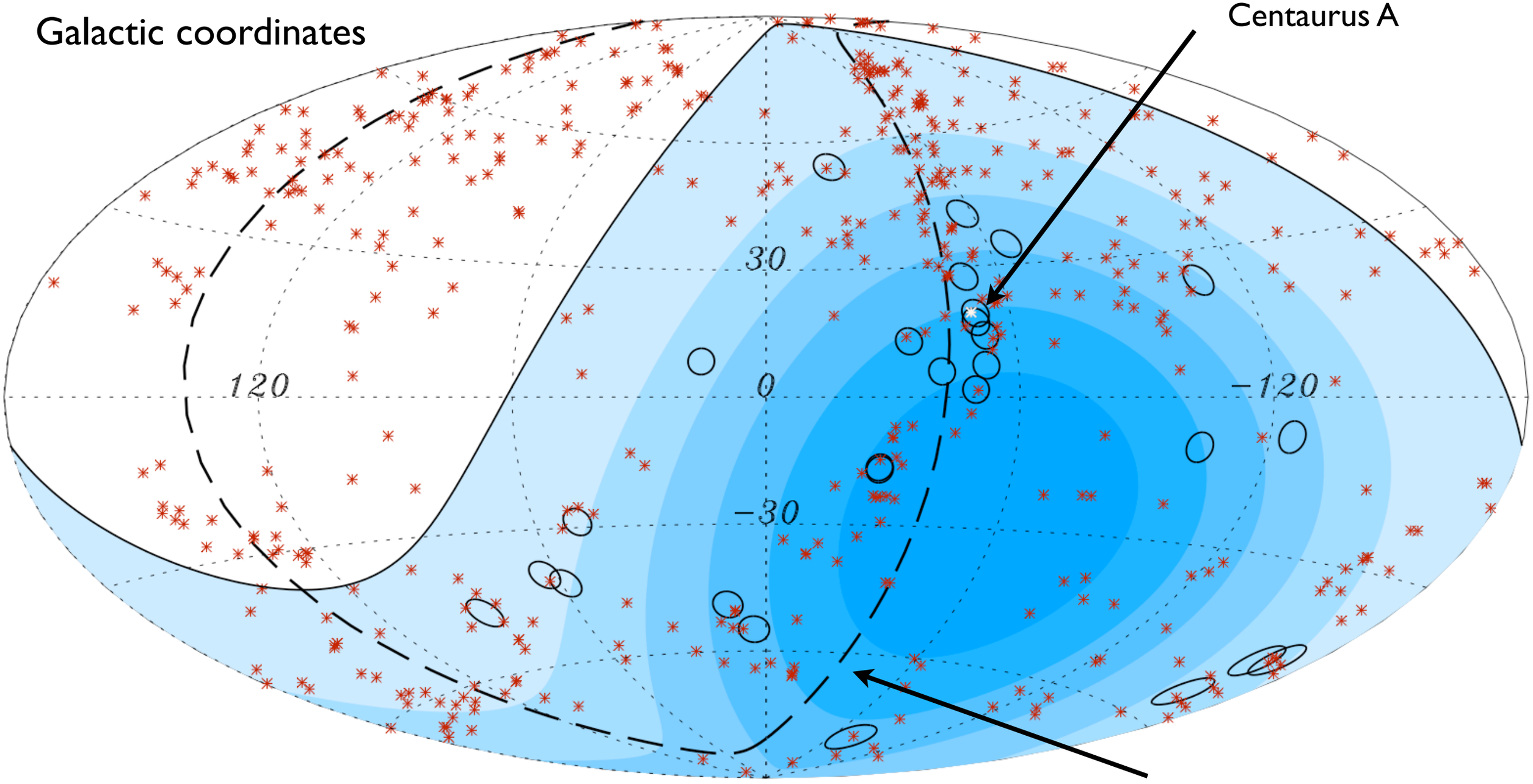
*May 27, 2006*

*May 25, 2007 (6 out of 8 new events)*

Gala


Verc

# Anisotropy of utra-high energy cosmic rays



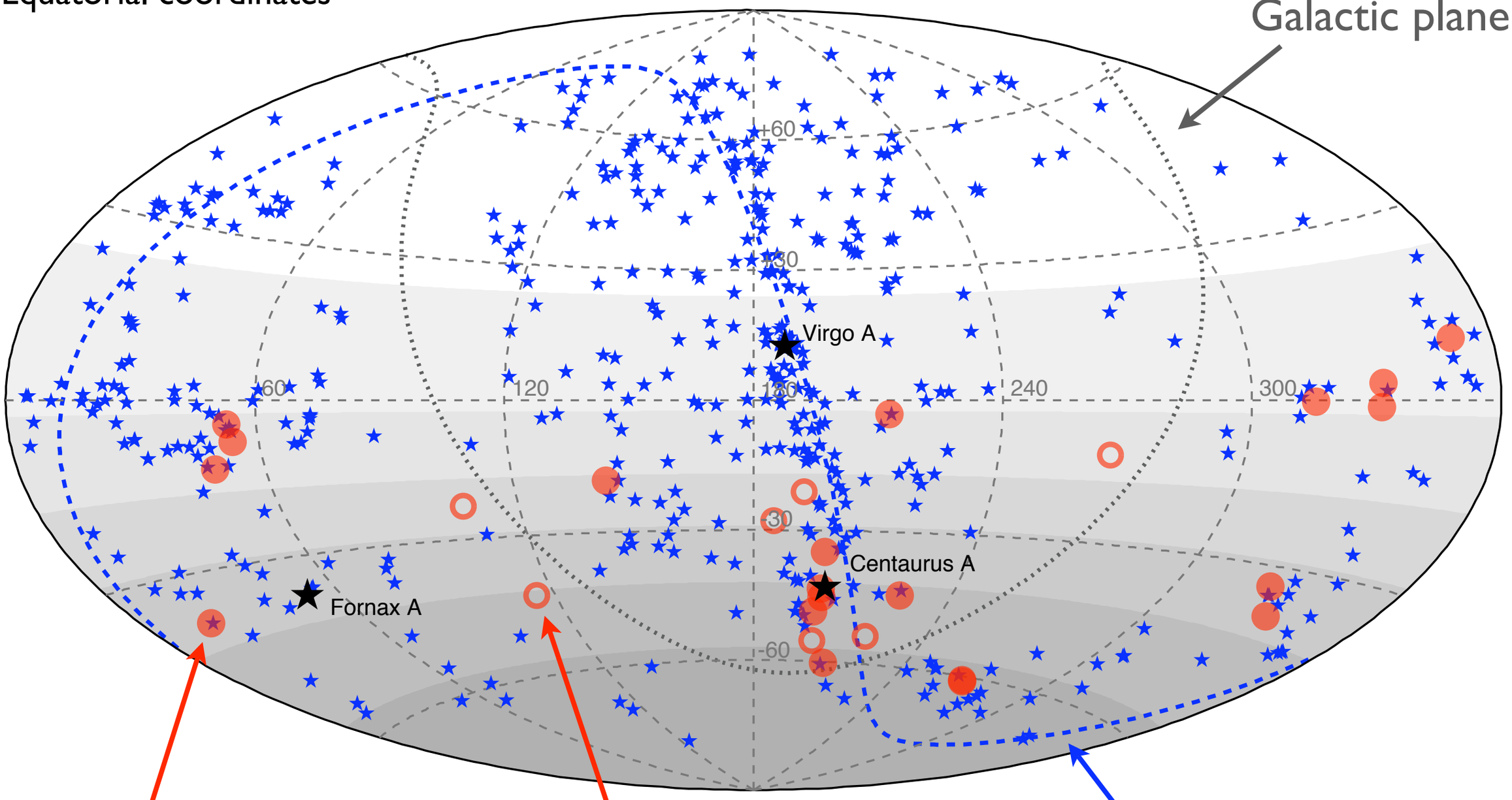

**Veron-Cetty:** 472 AGN (z< 0.018, ~75 Mpc)
318 in field of view of Auger

Scan-corrected probability ~$10^{-5}$

**Auger:** 27 events above 5.7 $10^{19}$ eV,
20 correlated within 3.1°

# Exposure of southern Auger Observatory

Hammer-Aitoff projection,
Equatorial coordinates




correlated events (20)

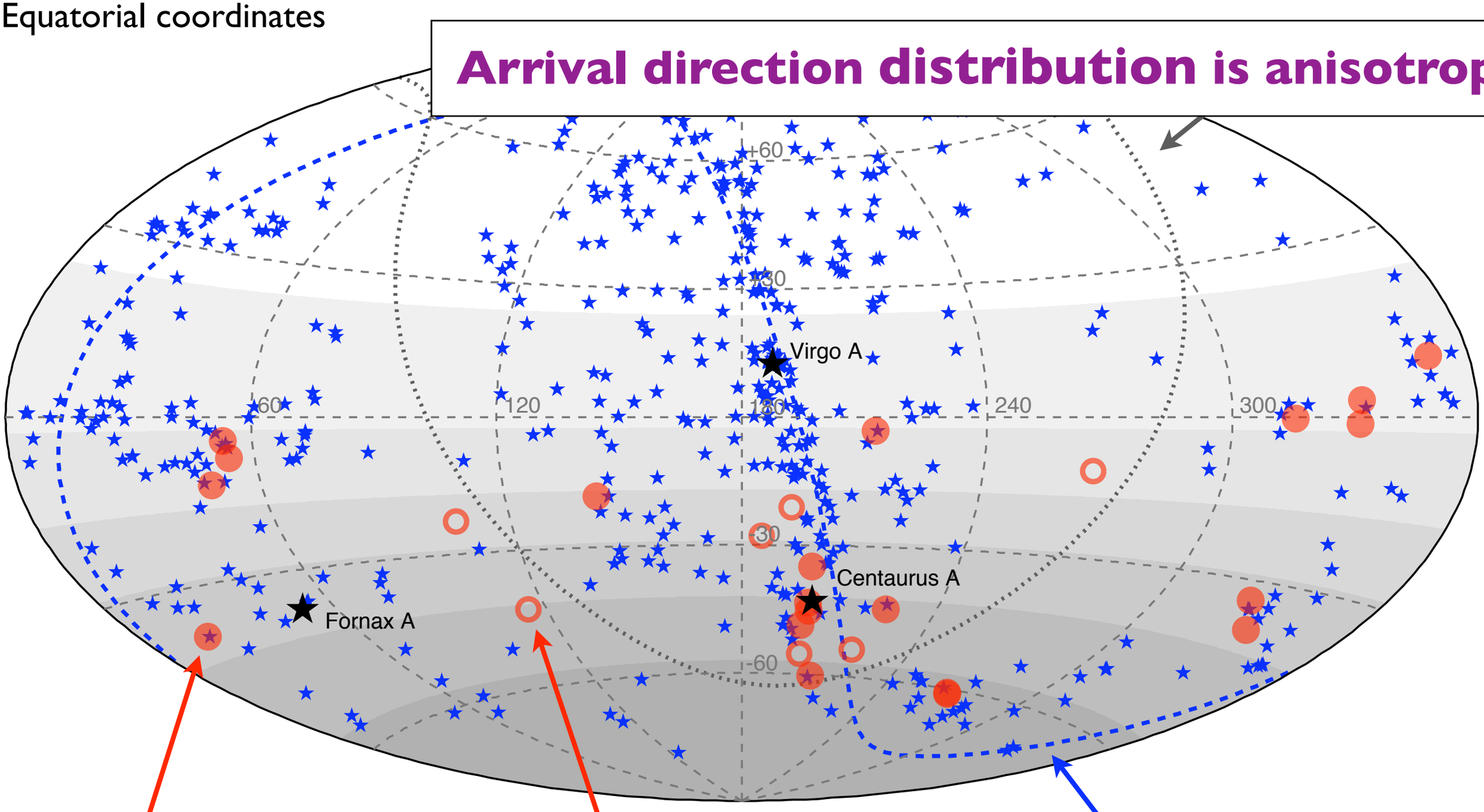
uncorrelated events (7)

supergalactic plane

# Exposure of southern Auger Observatory

Hammer-Aitoff projection,
Equatorial coordinates

**Arrival direction distribution is anisotropic**




correlated events (20)

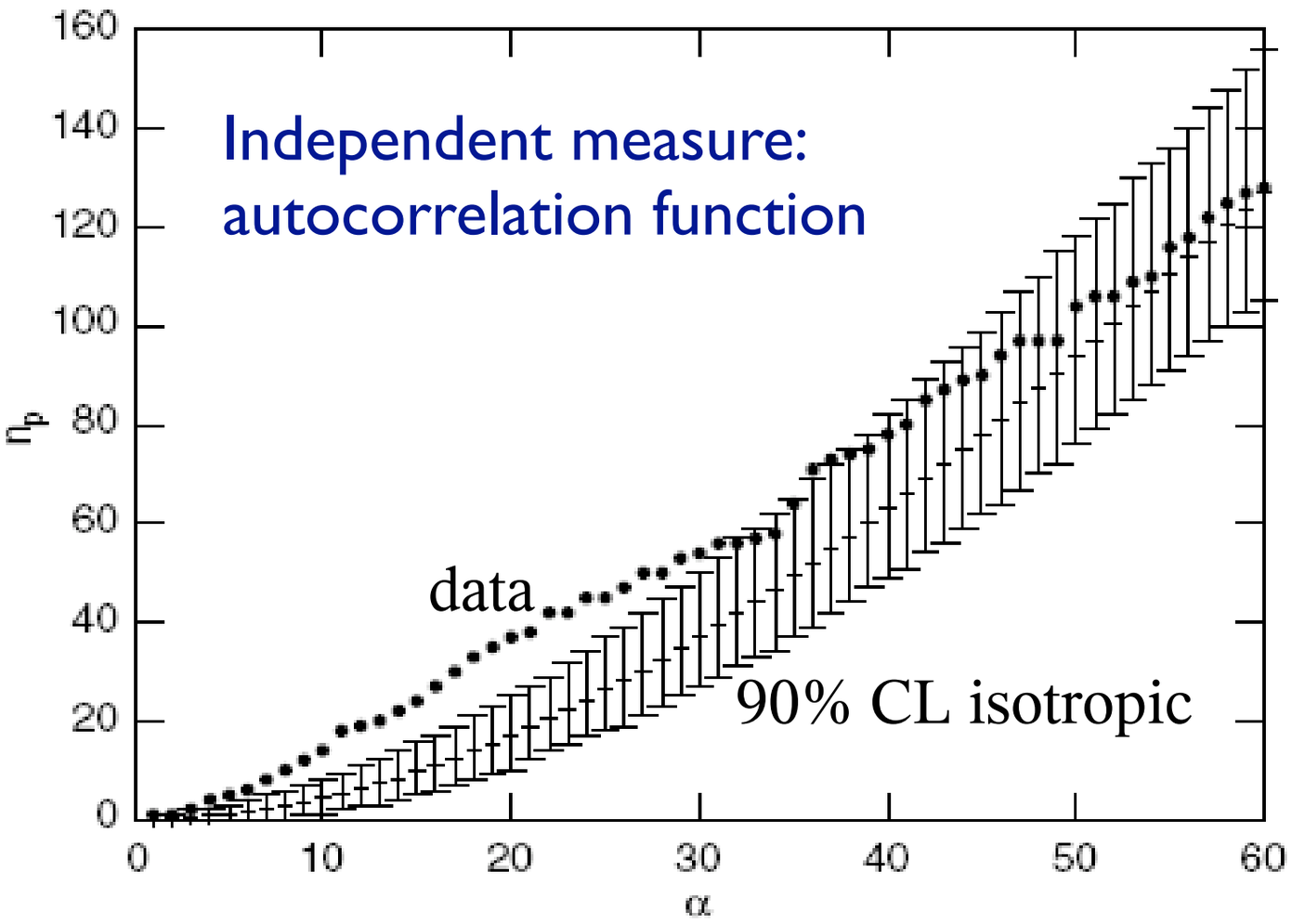
uncorrelated events (7)

supergalactic plane

# Exposure of southern Auger Observatory

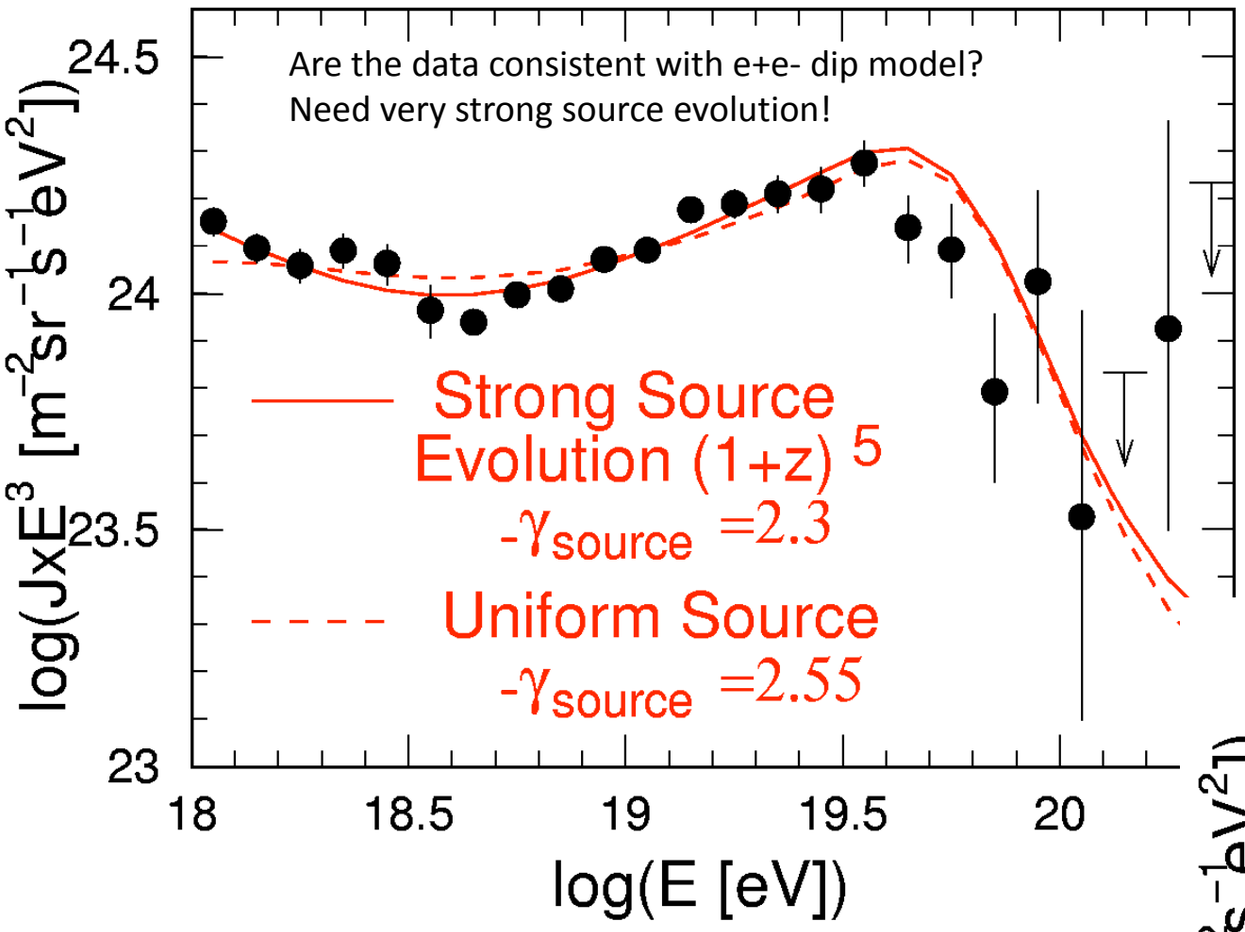
Hammer-Aitoff projection,
Equatorial coordinates

**Arrival direction distribution is anisotropic**

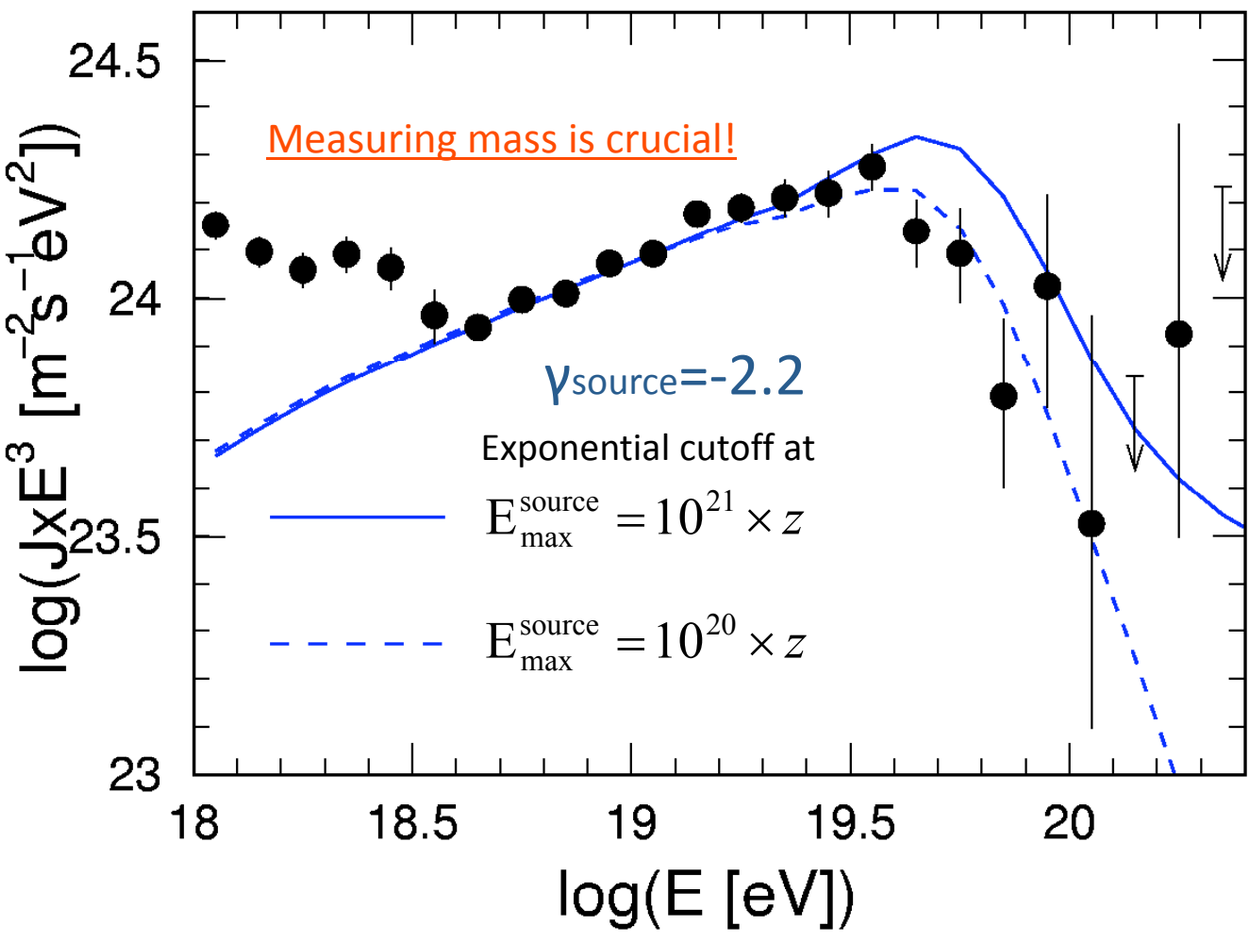


# Astrophysical Interpretation

# Comparison with GZK suppression models




**Pure proton model**
(Berezinsky et al.)

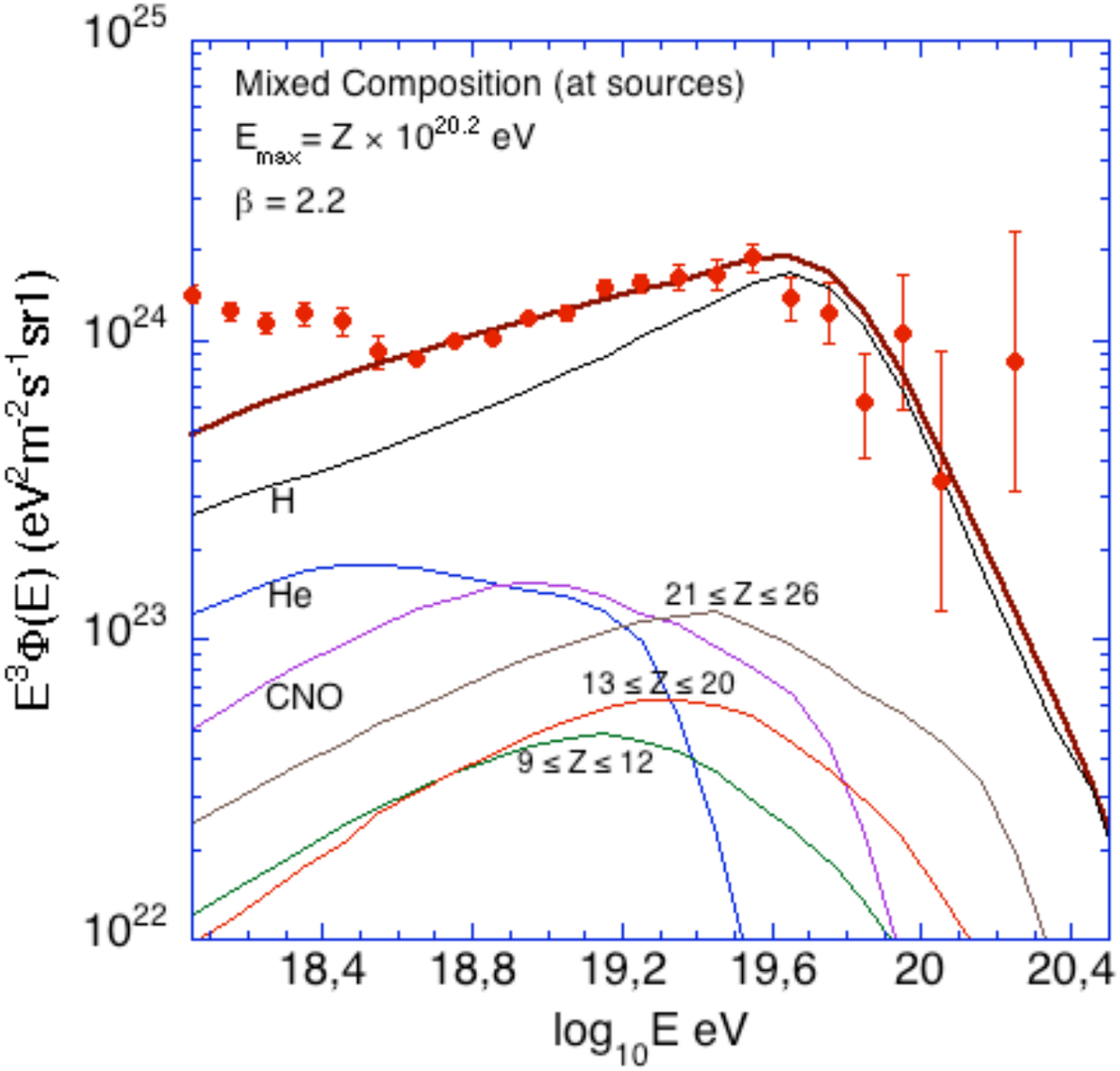


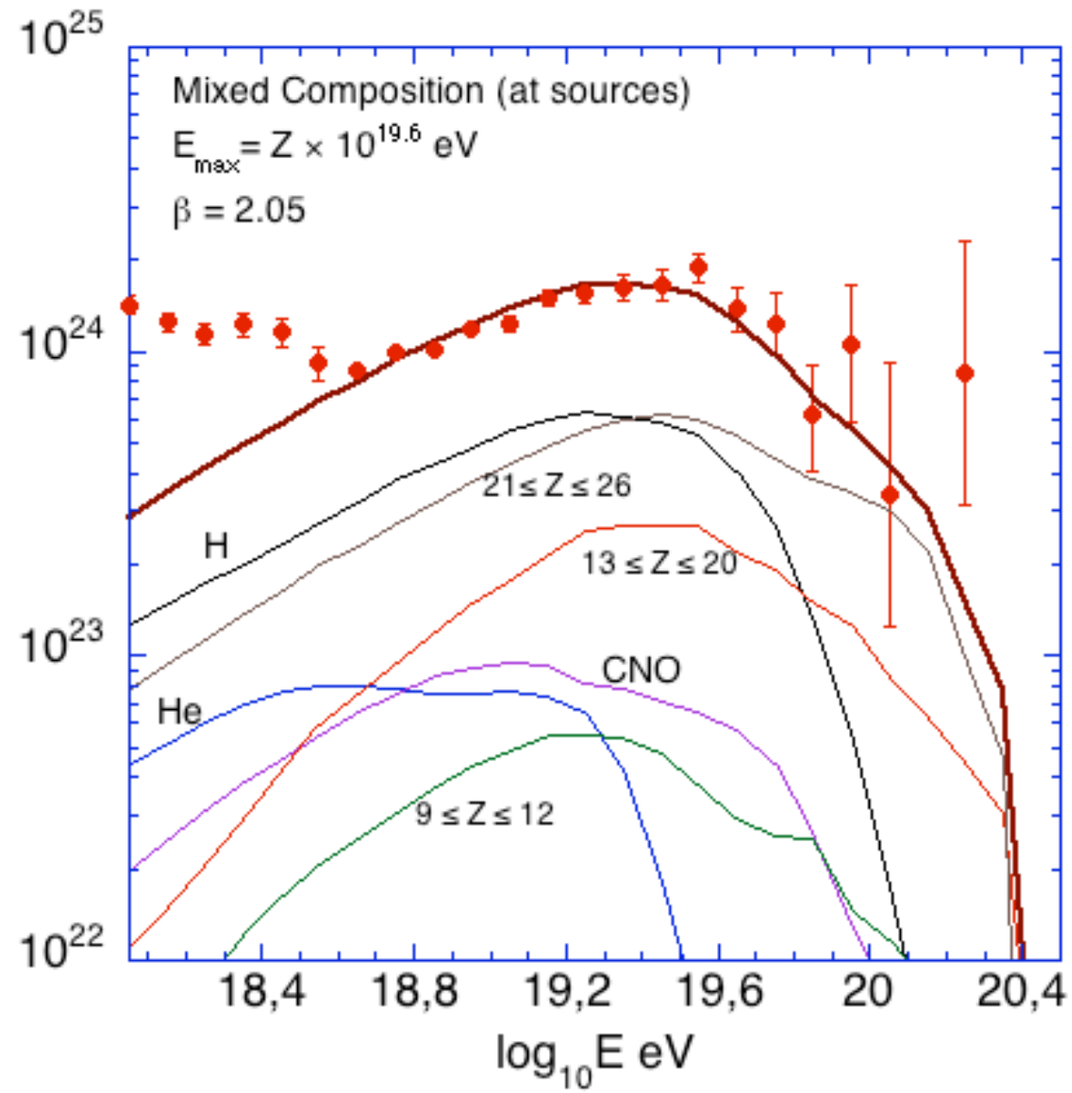

**Mixed composition model**
(Allard et al., Hillas)

# Particle physics with air showers

(a) Correlation with sources allow identification of particles

(b) Propagation leads to either light or heavy composition



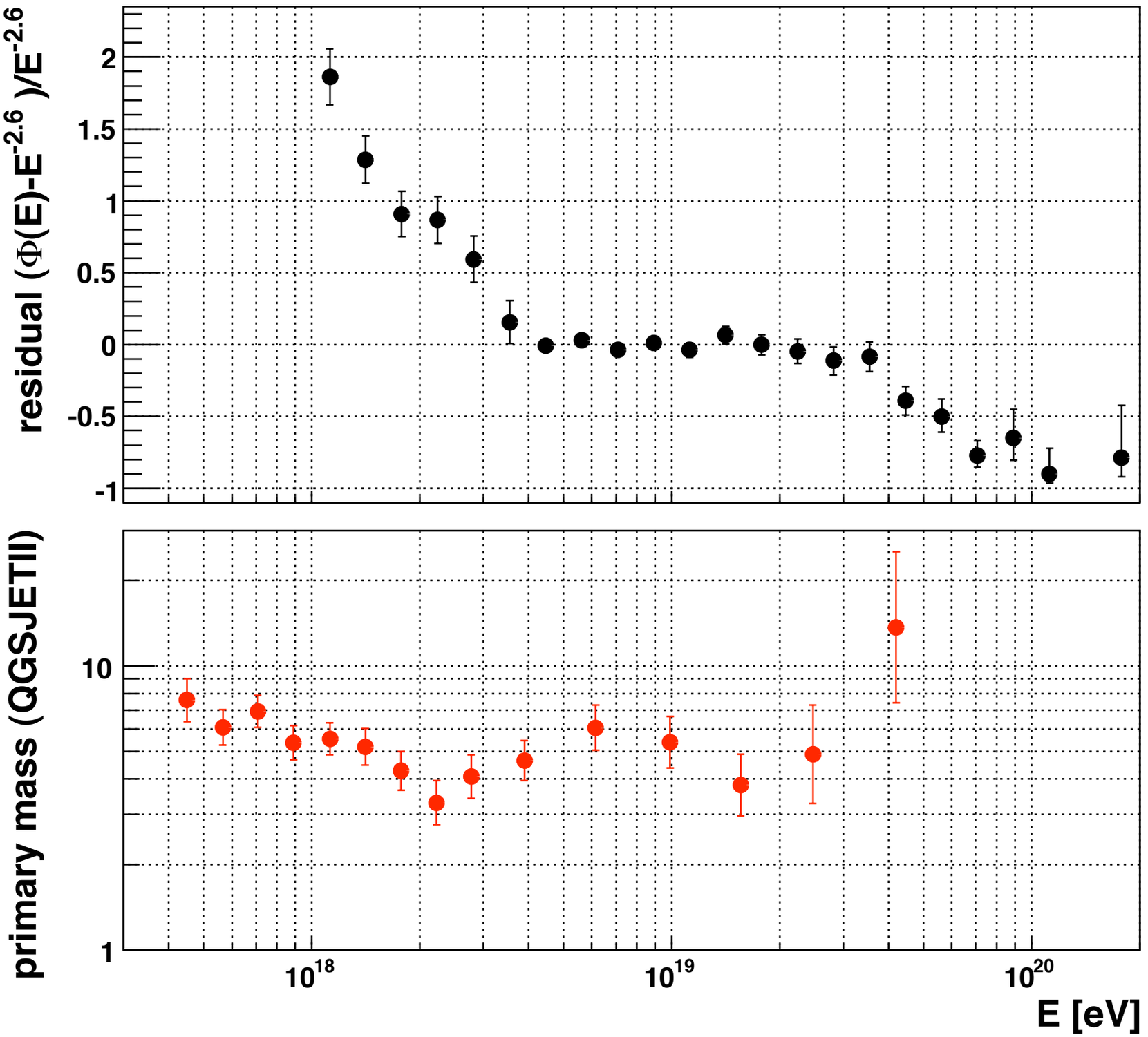




*Allard et al., arXiv:0805.4779 [astro-ph]*

# Comparison of composition and flux features

Deviation from $E^{-2.6}$ flux

Mean mass number



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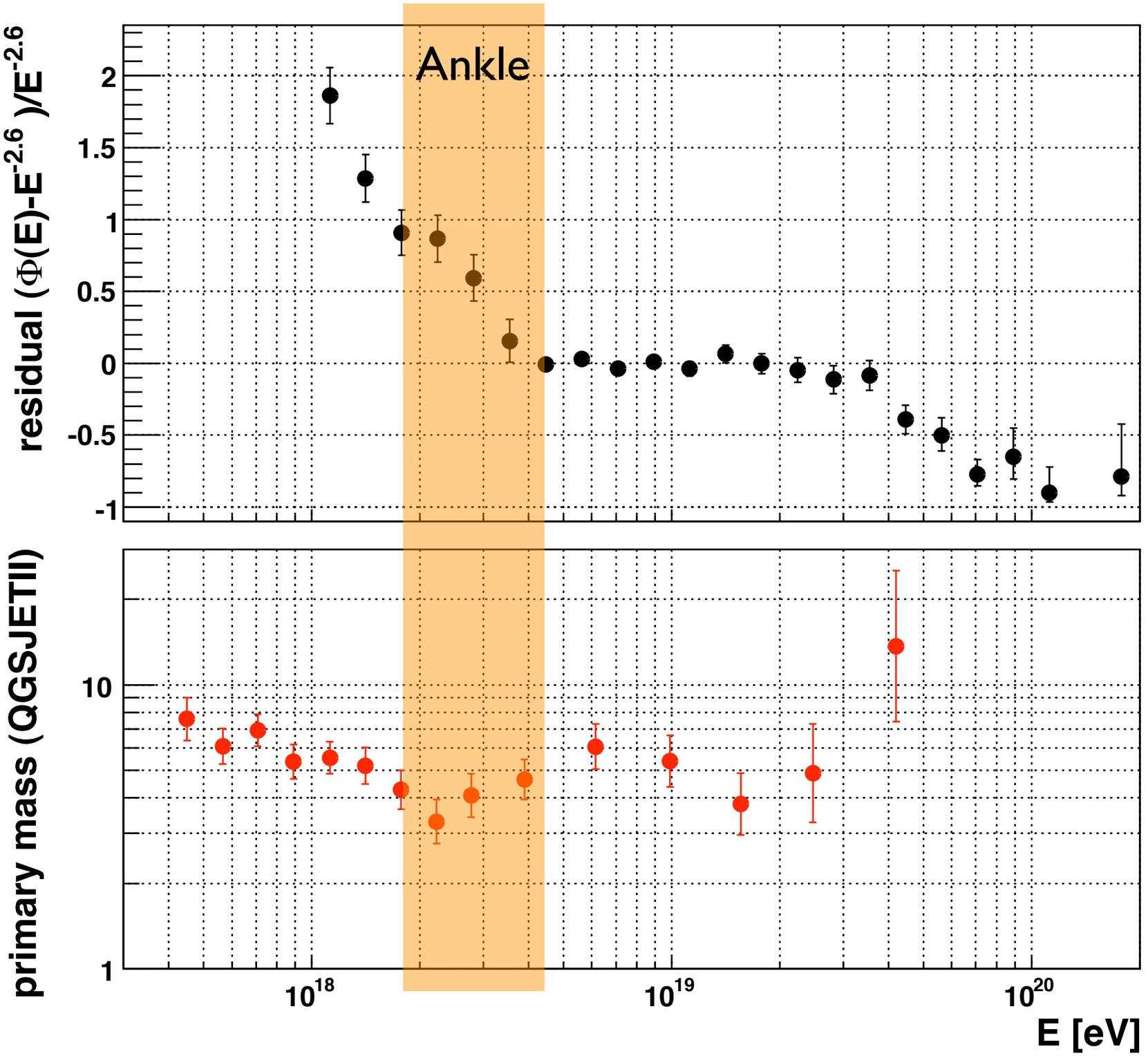
Deviation from $E^{-2.6}$ flux

Mean mass number



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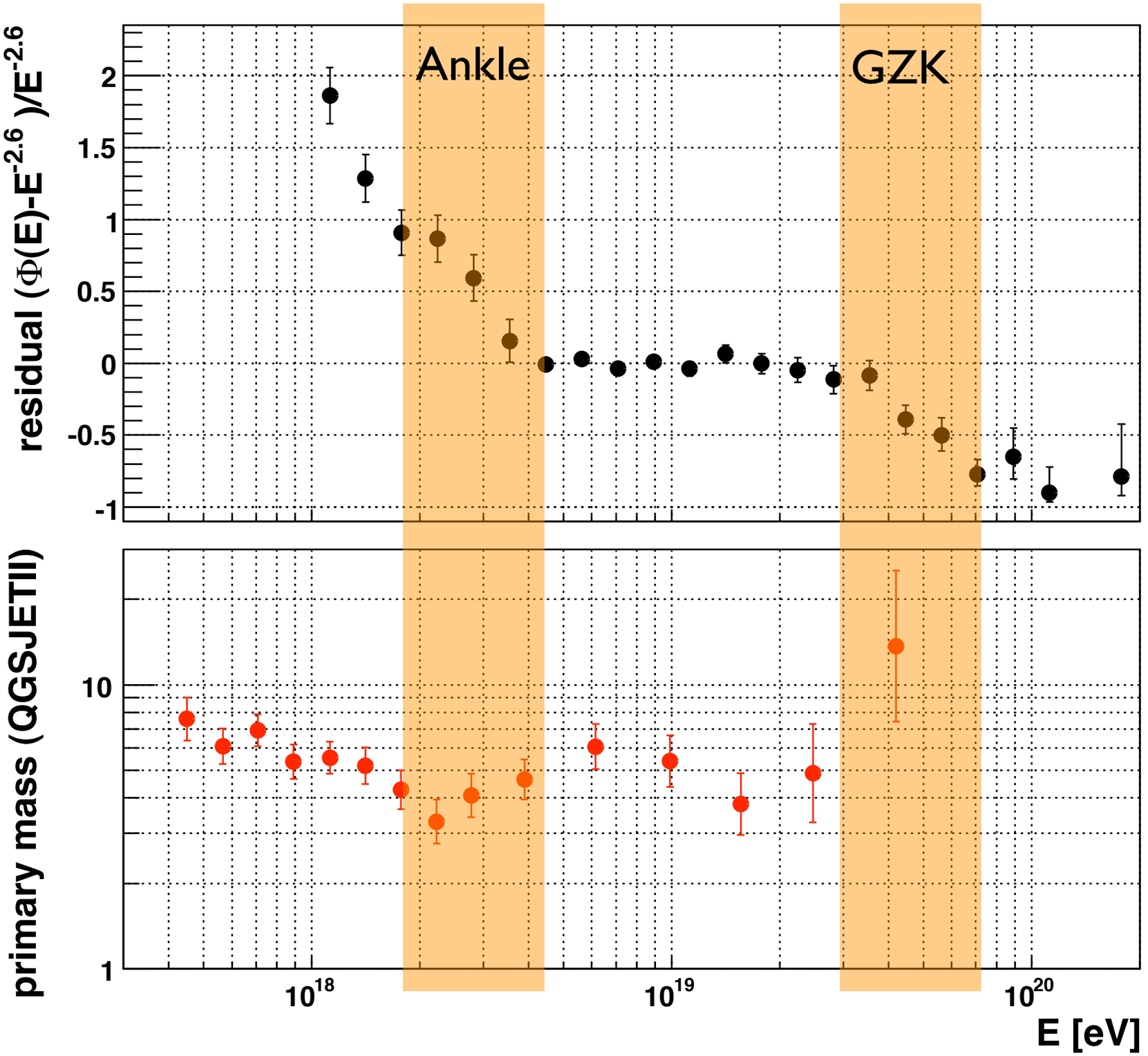
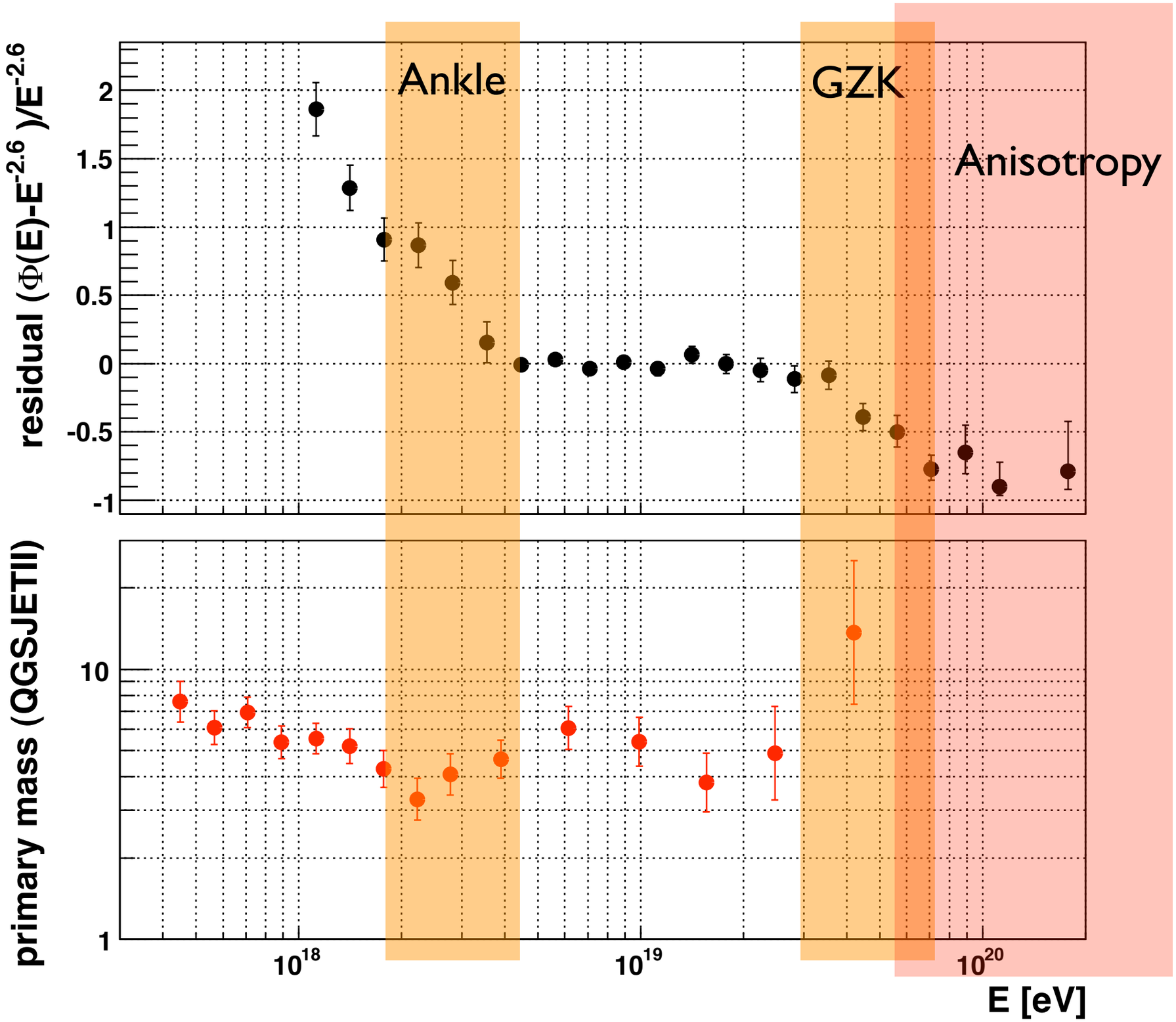


# Comparison of composition and flux features

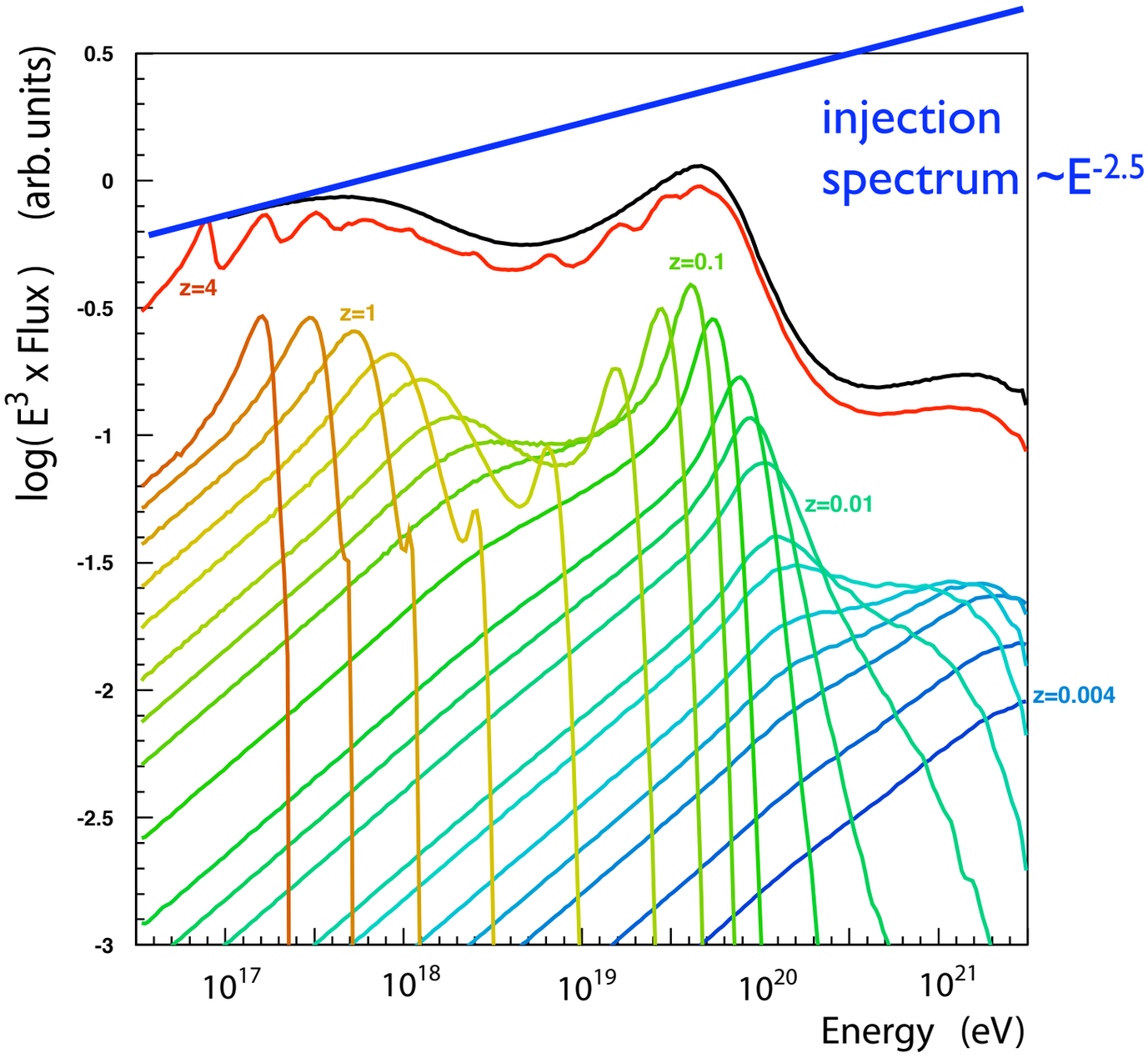
Deviation from $E^{-2.6}$ flux

Mean mass number



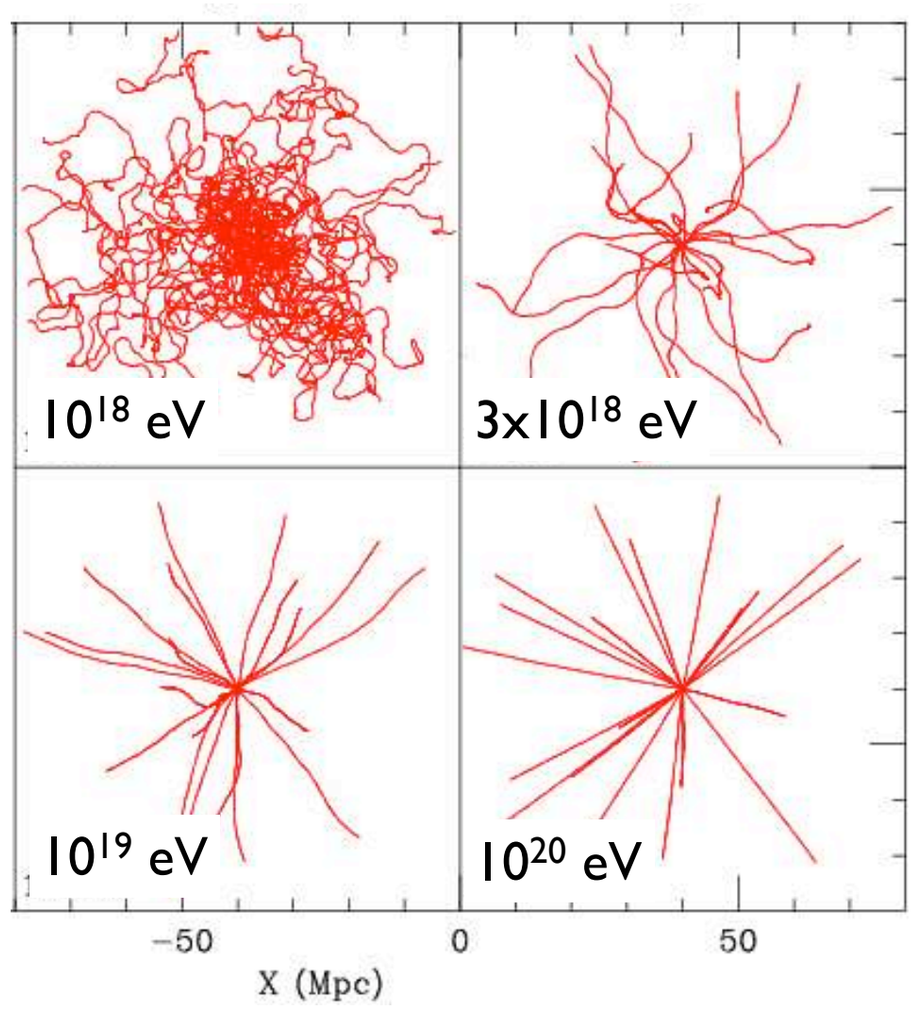
# GZK suppression and anisotropy

## GZK horizon: energy-source relation




*(Bergmann et al., PLB 2006)*

## Extragalactic magnetic field deflection




| Redshift | Lum.Distance |
|---|---|
| 0.004 | 16 Mpc |
| 0.01 | 40 Mpc |
| 0.05 | 200 Mpc |
| 0.1 | 415 Mpc |

# New Puzzles

# Could it be that AGNs are indeed the sources?

**Assumption:** all AGNs of the VC catalogue have same injection power

**Expectation:** ~6 events from Virgo cluster, none observed
(excluded at 99% level for complete distribution)

*(Gorbunov et al., arXiv:0711.4060 [astro-ph])*

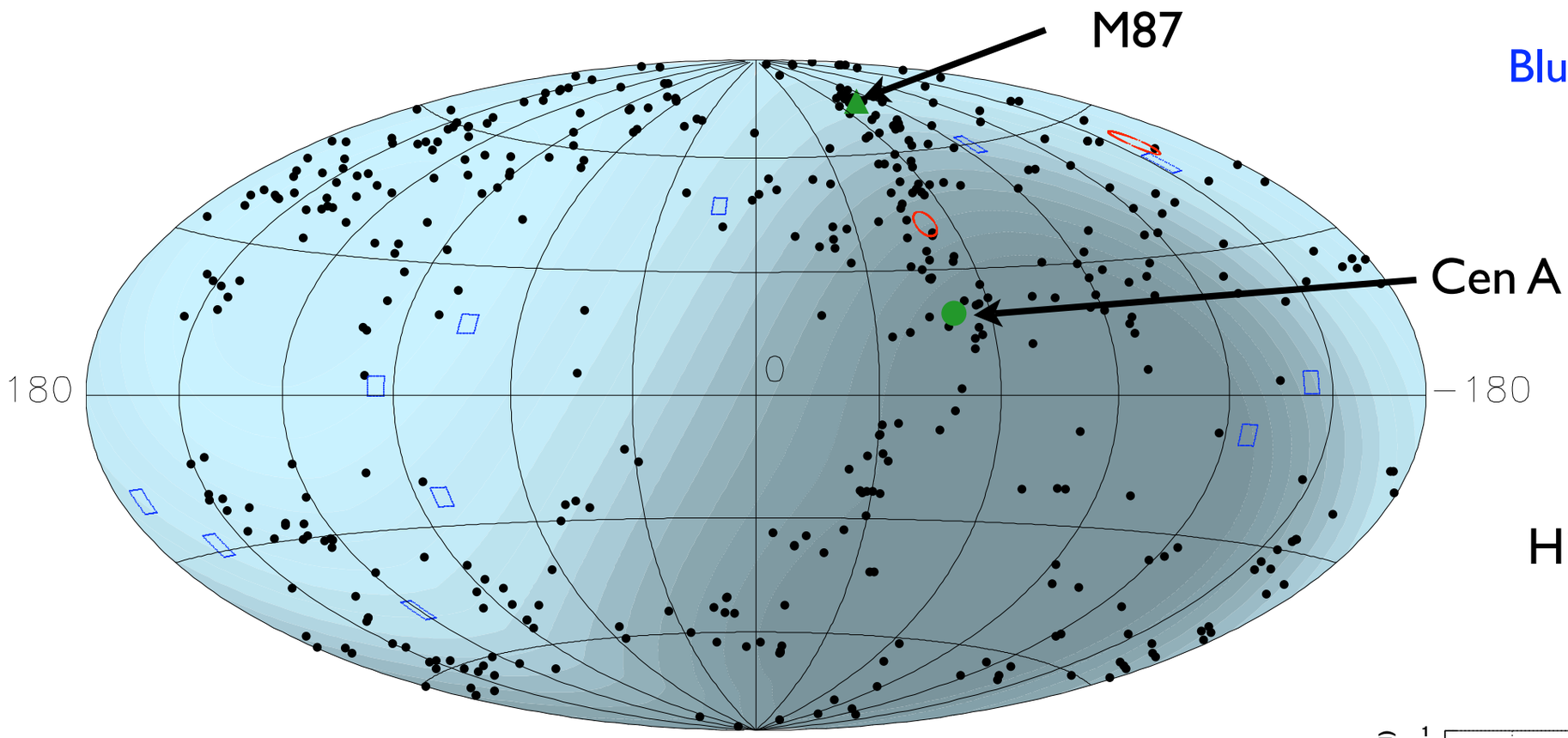
**Possible interpretations:**

- AGNs have different injection power (predicted by Biermann, Falcke et al.)
- Sub-class of AGNs are sources
- AGNs are not sources, sources are distributed similar to AGNs
- Anisotropy of distribution independent of source catalogue

- AGNs correlated with UHECRs are standard Seyfert galaxies, not very powerful

*See discussion in Auger Collab., arXiv0712.2843 [astro-ph] and forthcoming paper*

# Why does HiRes not see a signal?



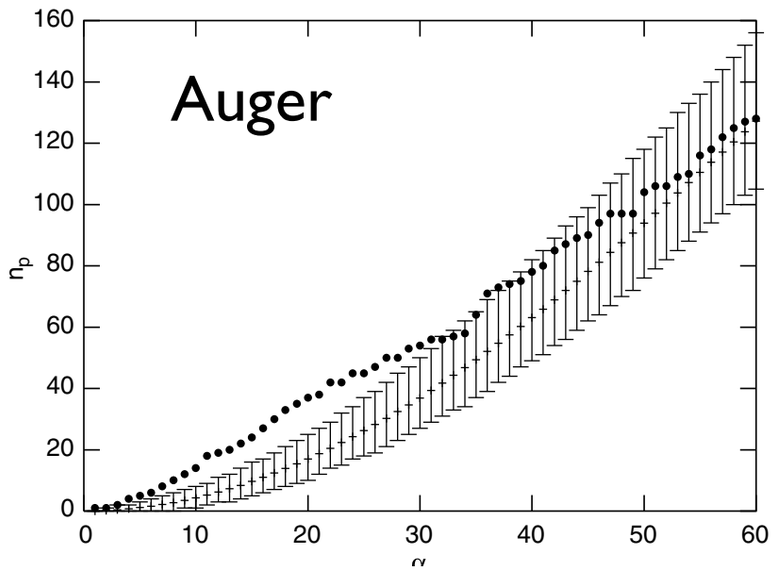

Blue: not correlated

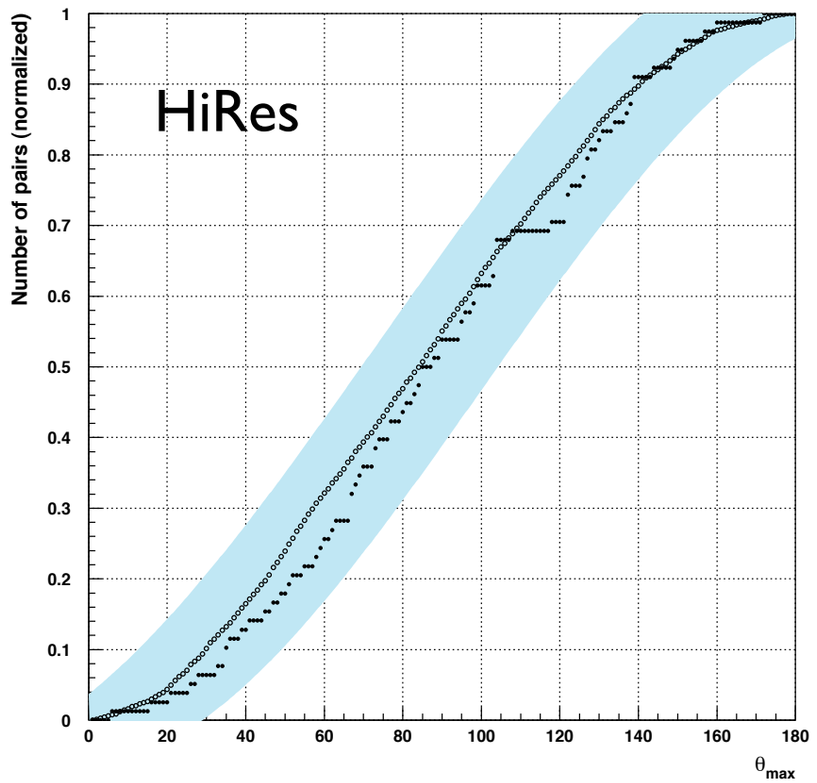
Red: correlated

HiRes stereo data:
13 events (2 correlated)

*(HiRes Collab., astro-ph/0804.0382)*

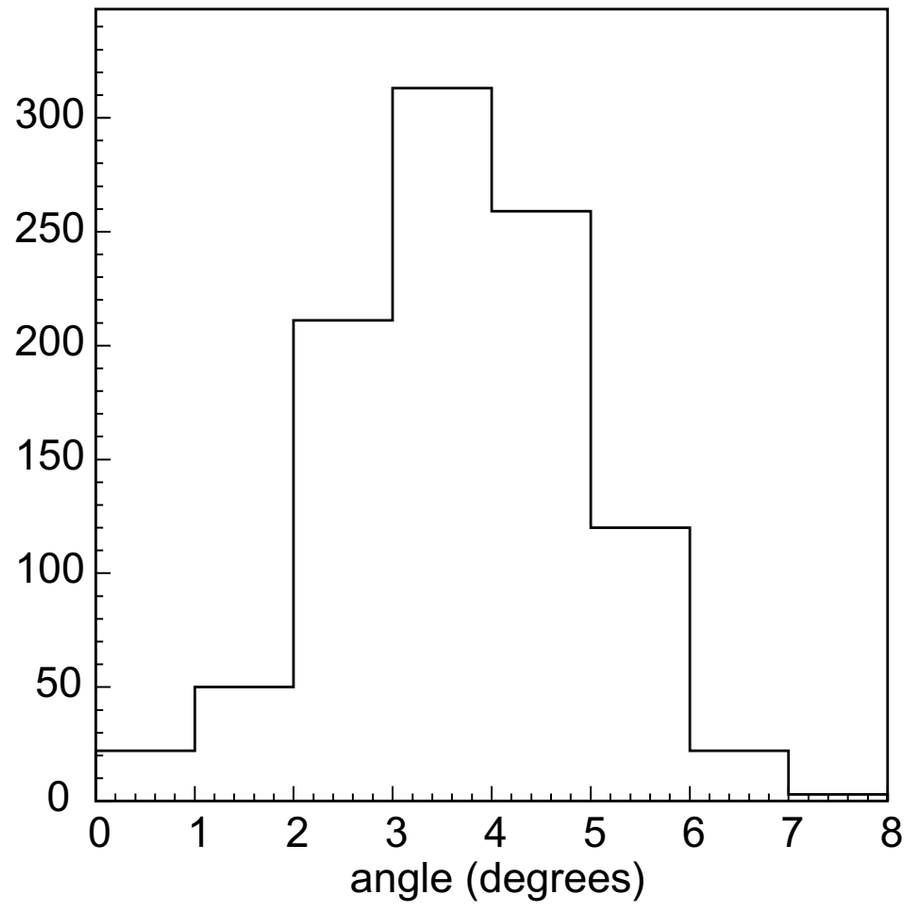
Autocorrelation
(independet test)



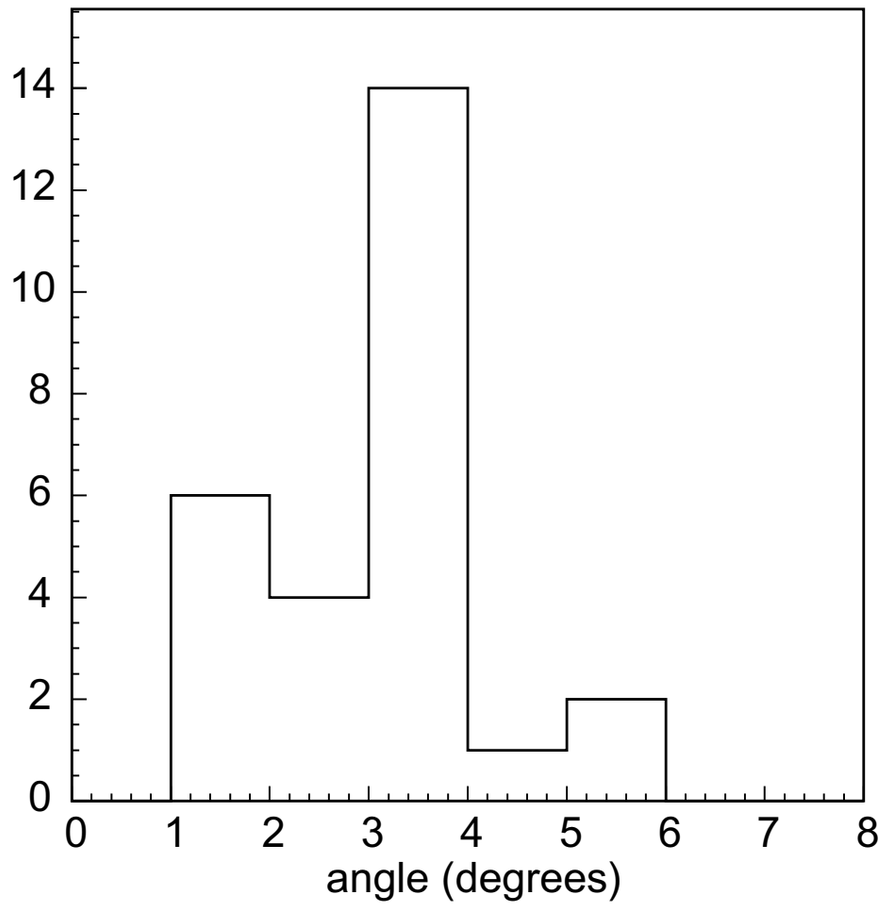



# Does the correlation imply protons as UHECRs?

Deflection of protons if only regular field of spiral is used




1000 events with isotropic arrival distribution



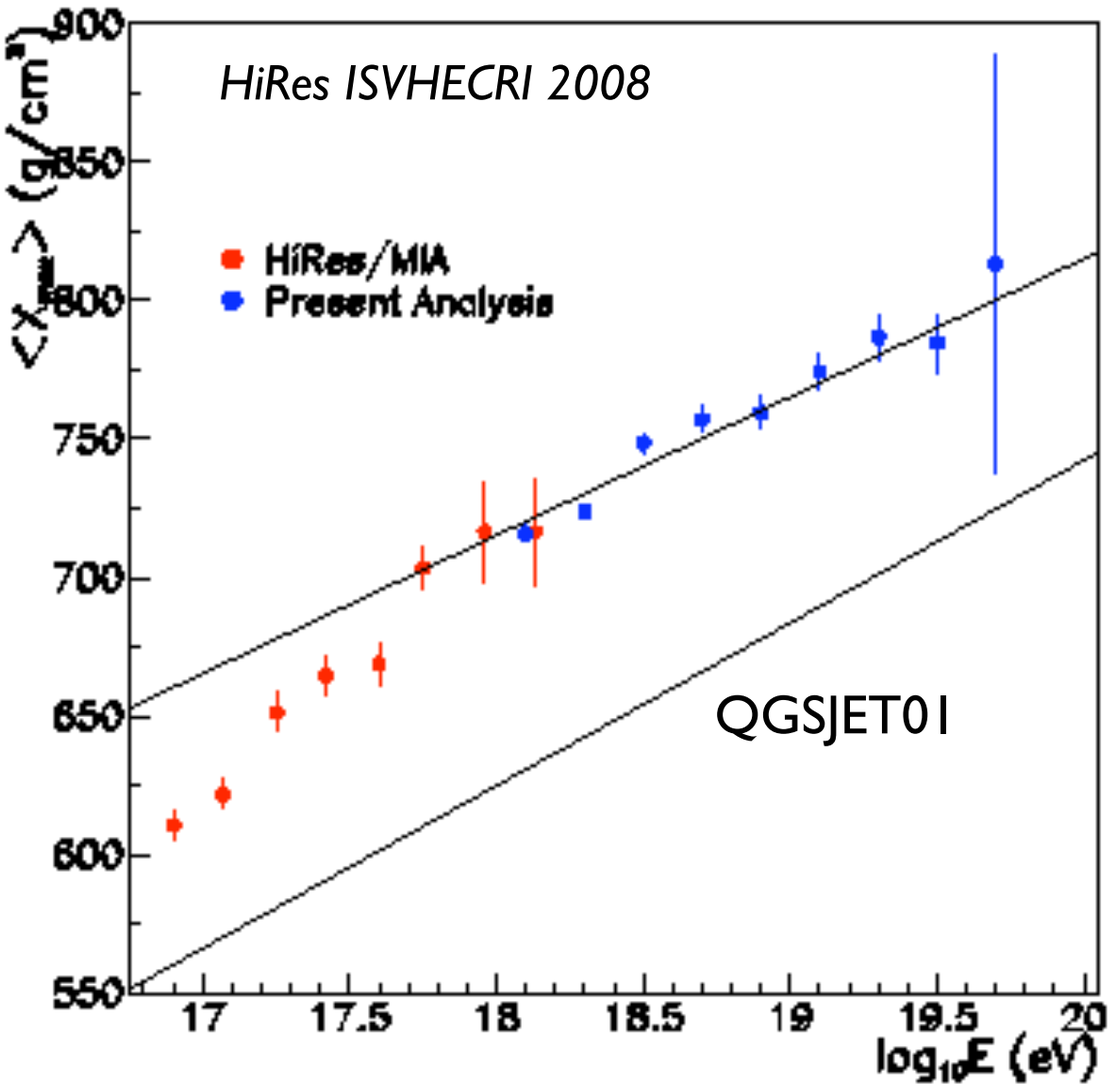

Directions of 27 Auger events

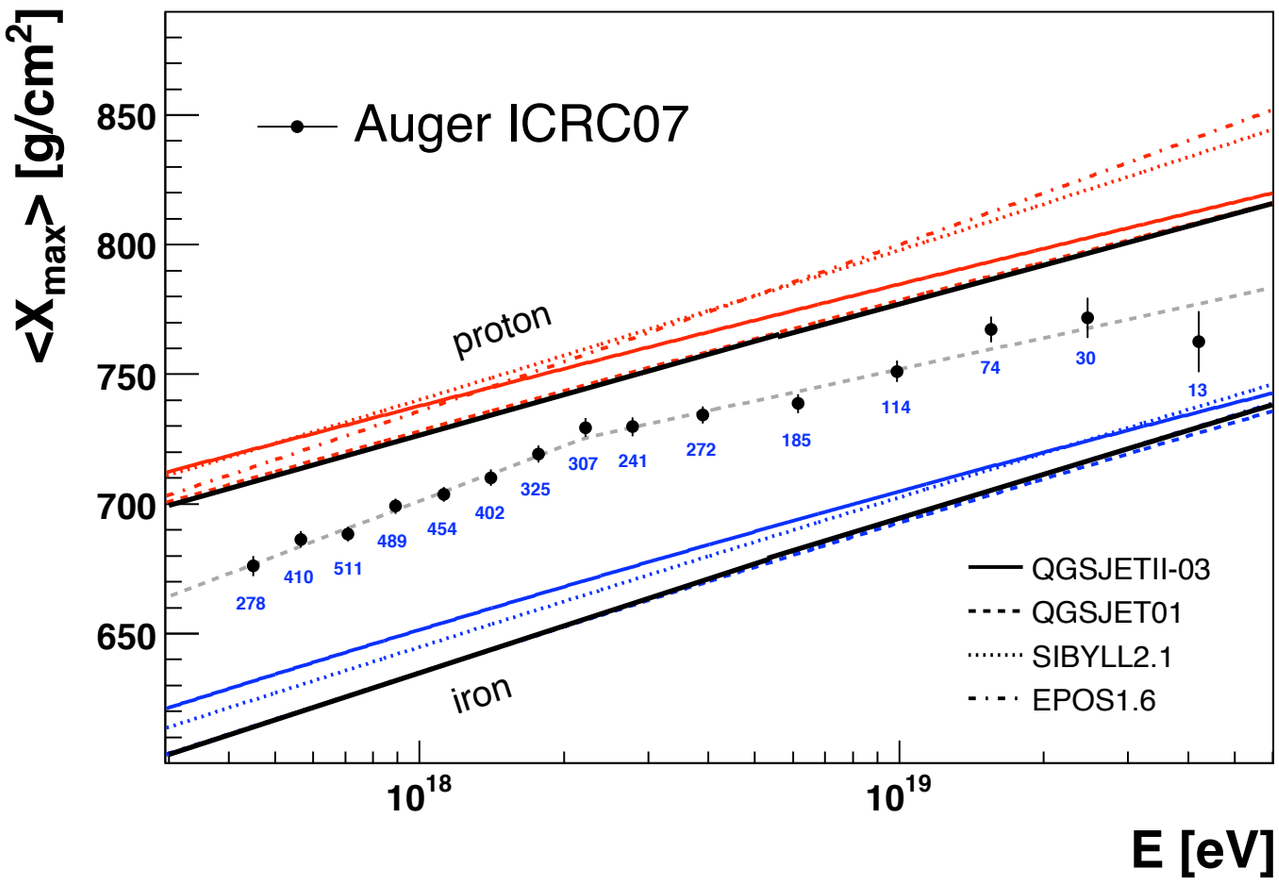
*Auger, arXiv:0712.2843 [astro-ph]*

# Latest (preliminary) HiRes stereo data

HiRes: different method to determine Xmax from shower profiles,

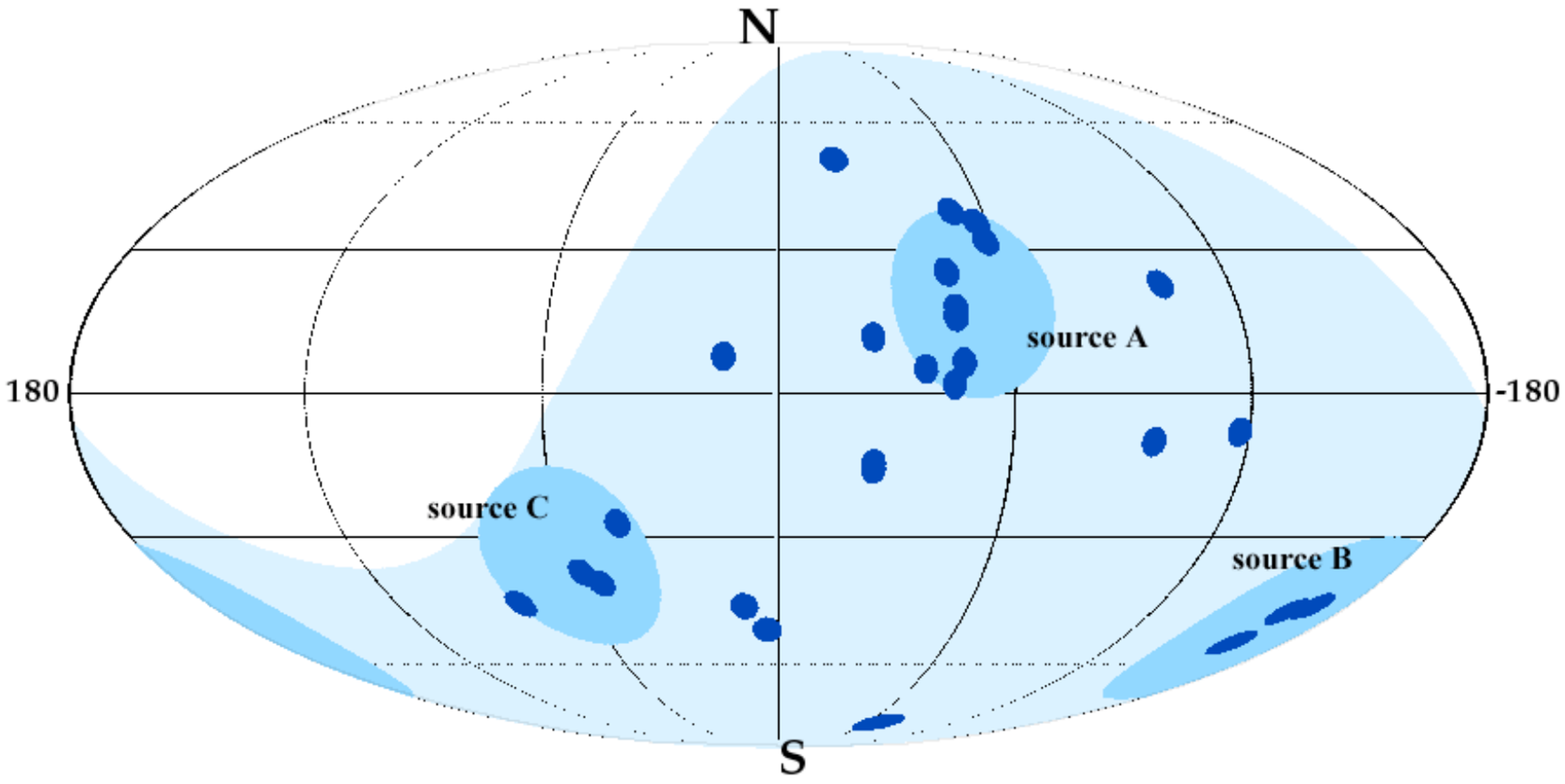
Absolute numbers not comparable, relation to model predictions comparable




*Auger: sys. uncertainty ~15 g/cm²*

# Only three sources and mid-mass primaries?




*Wibig & Wolfendale, astro-ph/0712.3403*

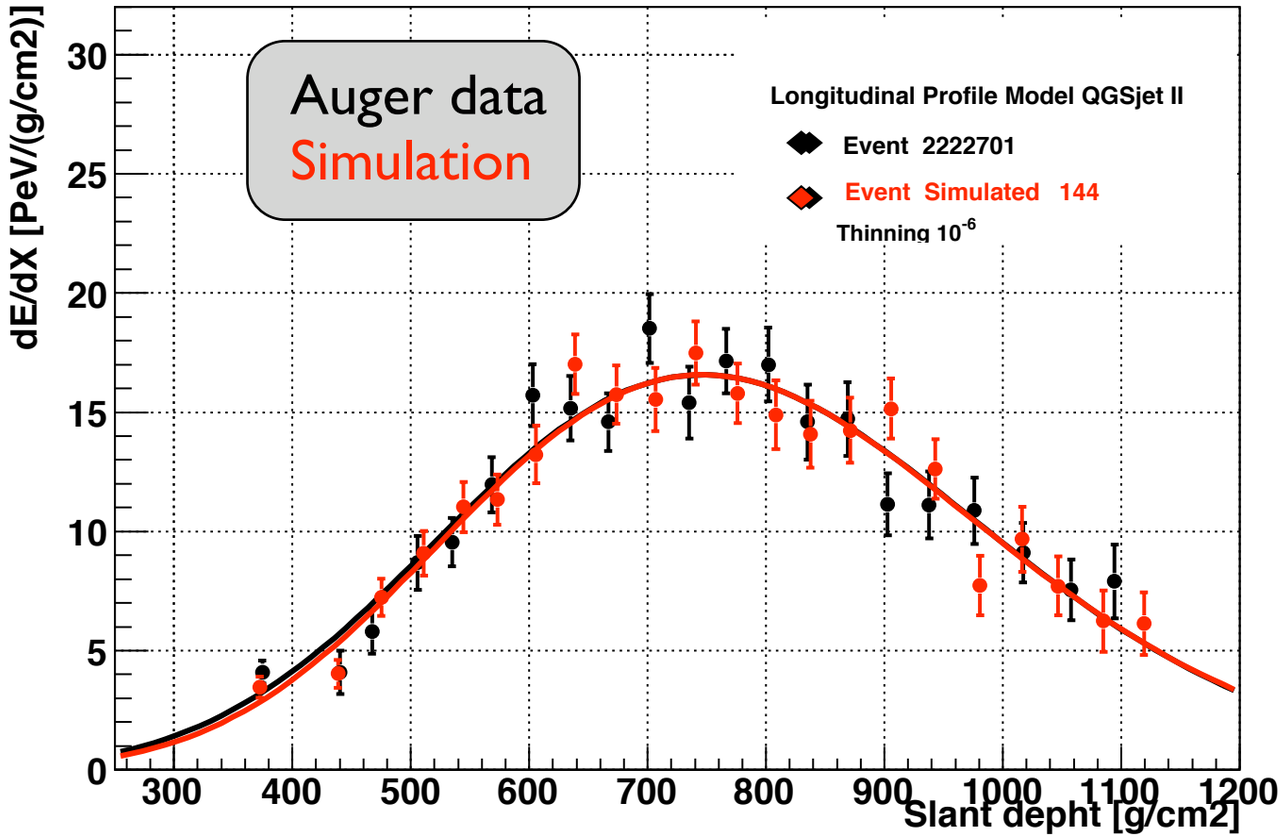
| Source | Distance (Mpc) | Galaxy | IGM | Total | Median displacement observed | $Z$ |
|---|---|---|---|---|---|---|
| CEN–A | 5 | 0.7 | 1.1 | 1.3 | 10 | 7.7 |
| Source B | 20 | 0.46 | 2.2 | 2.2 | 6 | 2.7 |
| Source C | 33 | 0.48 | 2.8 | 2.8 | 10 | 3.6 |

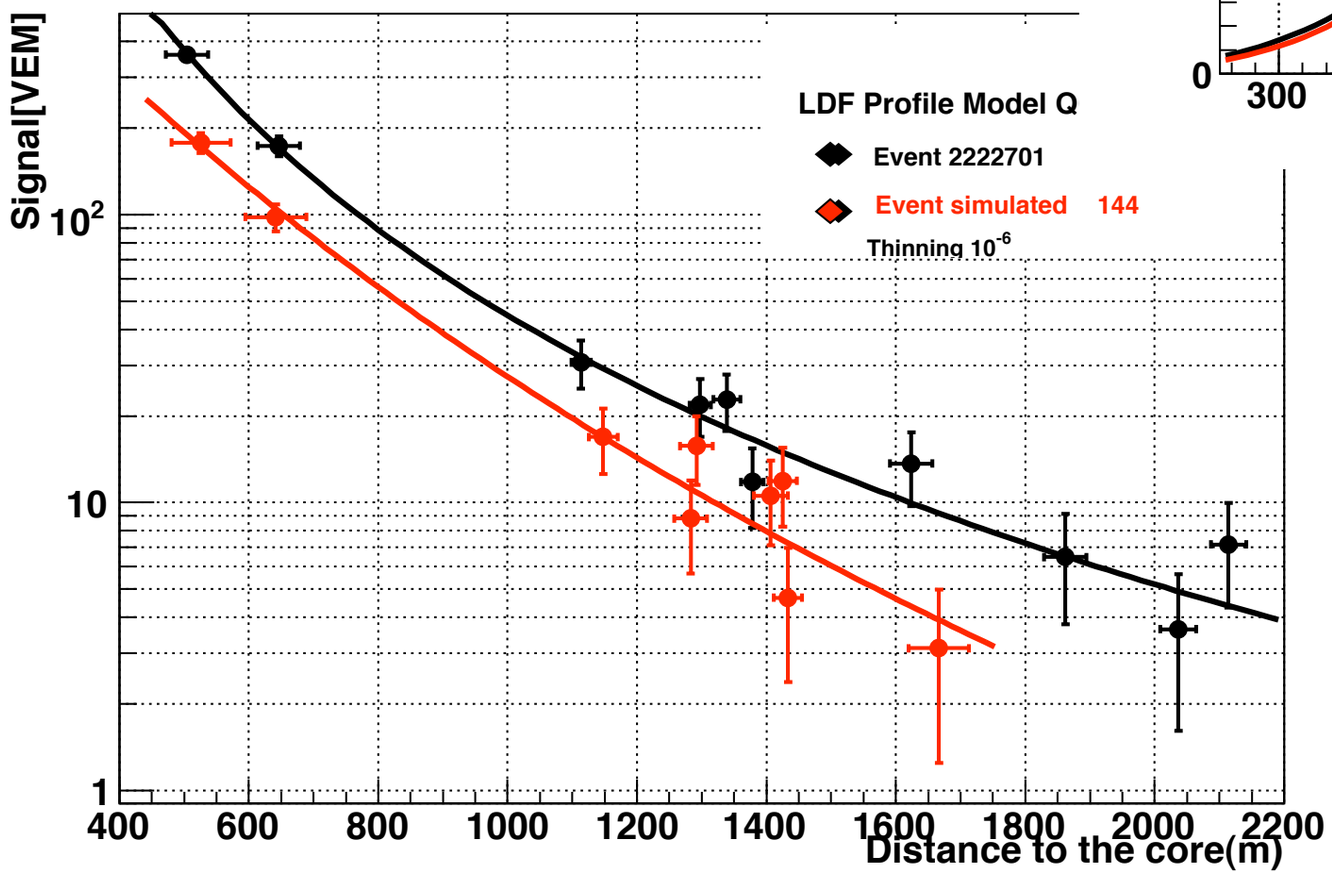
But: no detailed simulation yet available

# Comparison of longitudinal and lateral distributions

**Auger data:**
Event ID 2222701
$\theta = 48°$, $E = 1.1 \times 10^{19}$ eV

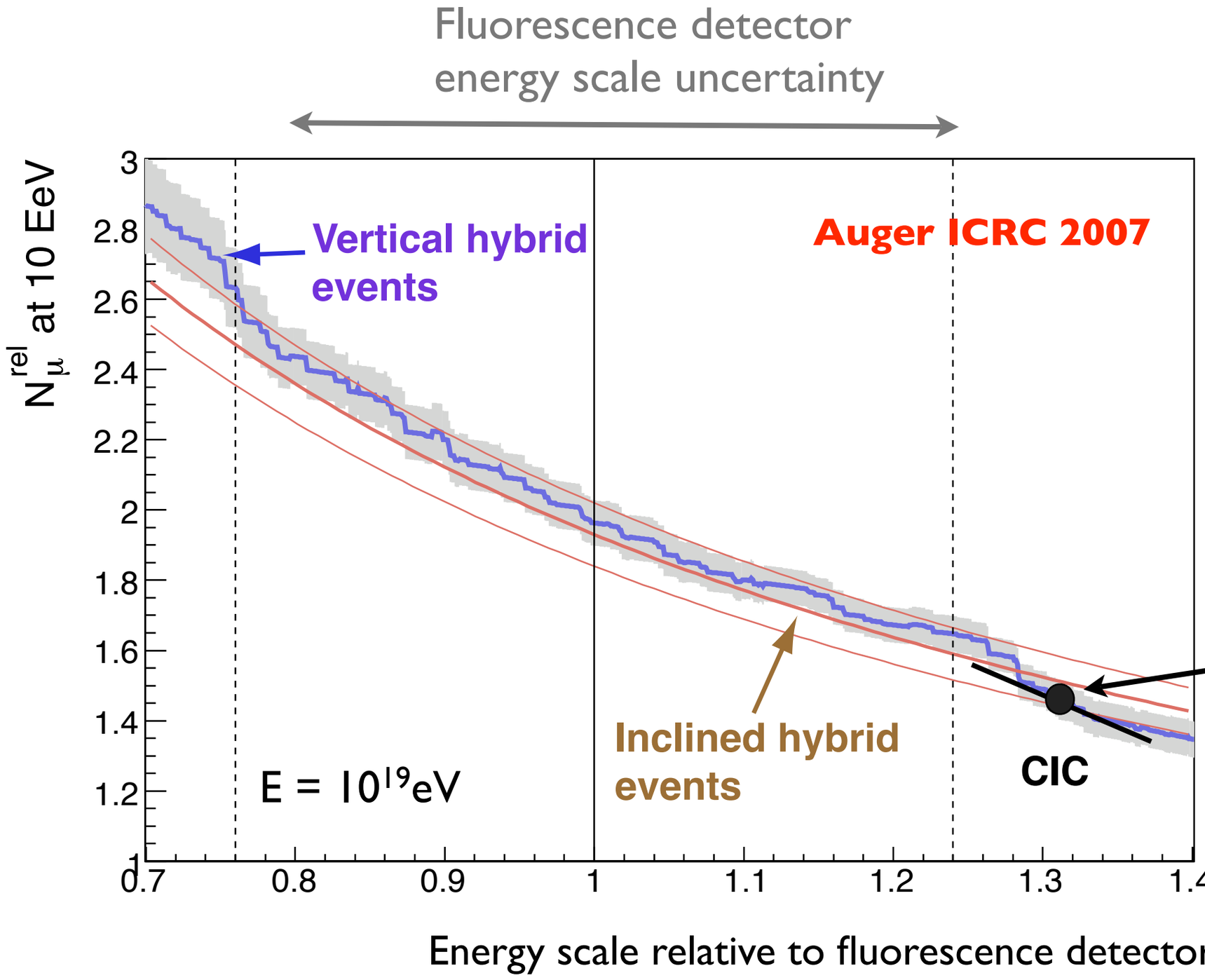
**Simulation:**
CORSIKA, QGSJET II,
proton primary




Systematic difference of lateral distributions found:
(a) Energy calibration problem?
(b) Muon deficit in simulation?

# Systematic study of differences: muon excess?

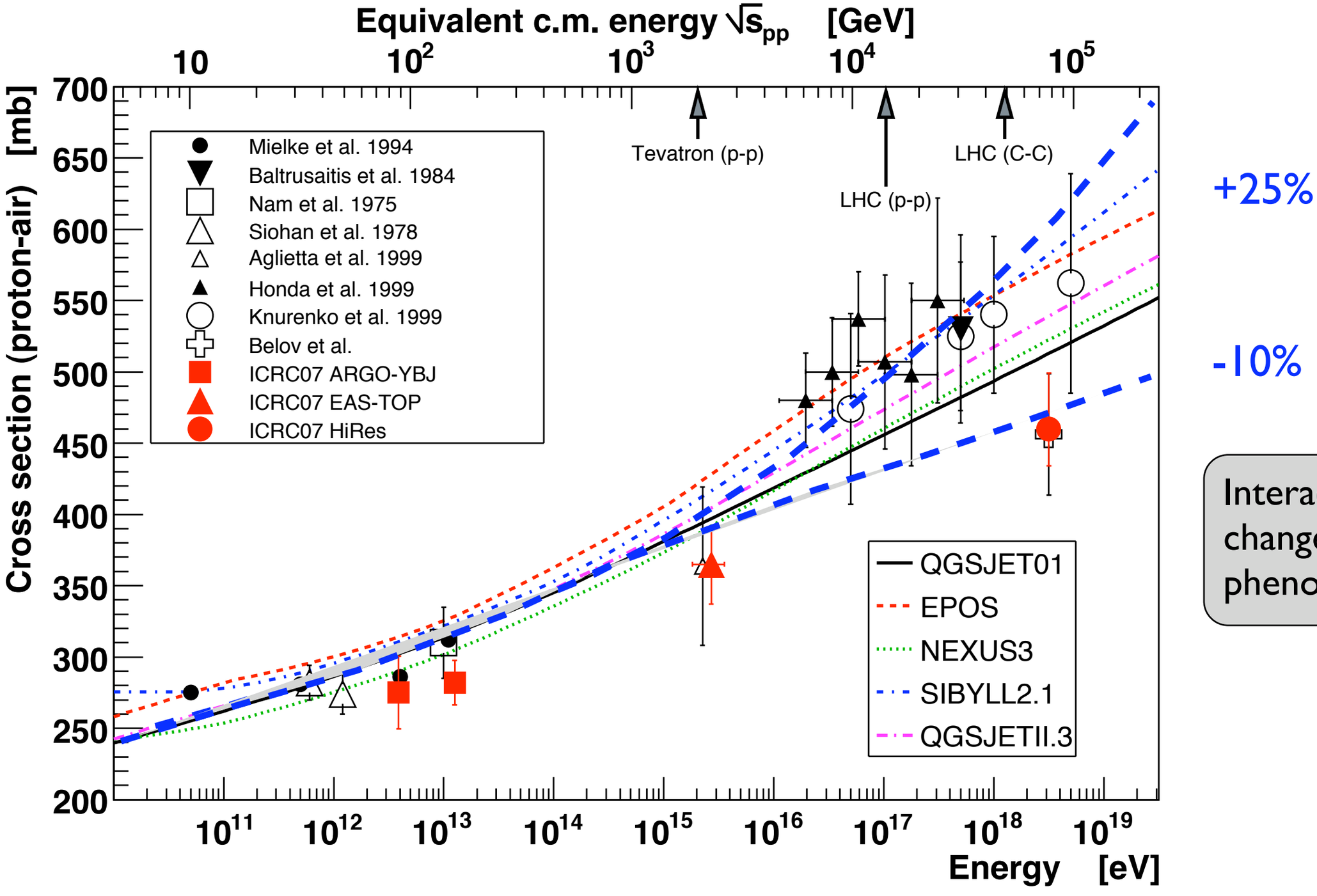



QGSJET II (p) = 1.0
(Fe) = 1.39

SIBYLL 2.1 (p) = 0.87
(Fe) = 1.27

*(Method: Schmidt et al., astro-ph/0712.3750)*

# Change hadronic interaction models ?



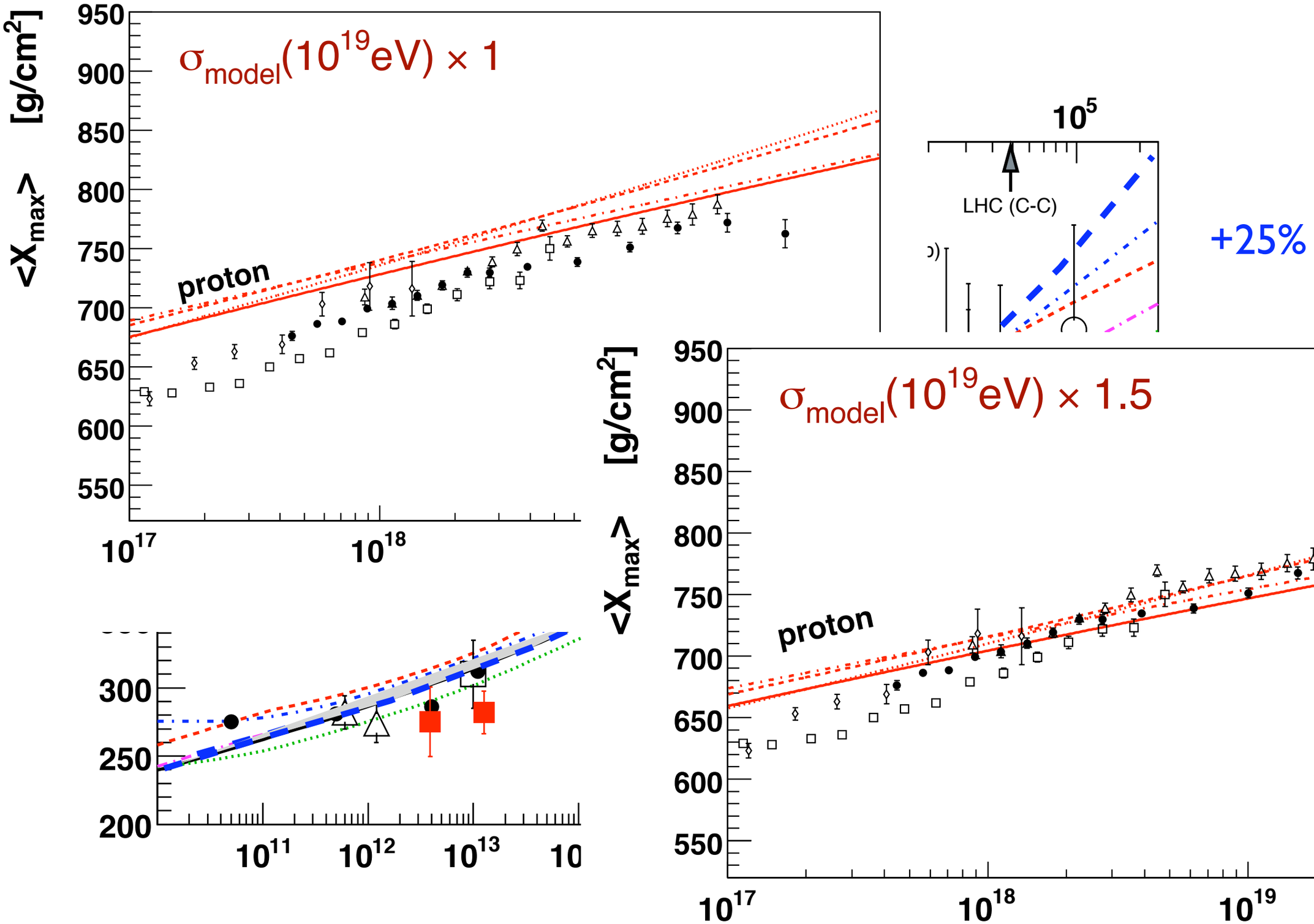

+25%

-10%

Interaction model changed phenomenologically

*(R. Ulrich et al., ISVHECRI 2008)*

# Change hadronic interaction models ?




*(R. Ulrich et al., ISVHECRI 2008)*

# Conclusions and outlook

## Excellent performance Southern Pierre Auger Observatory

## First physics results

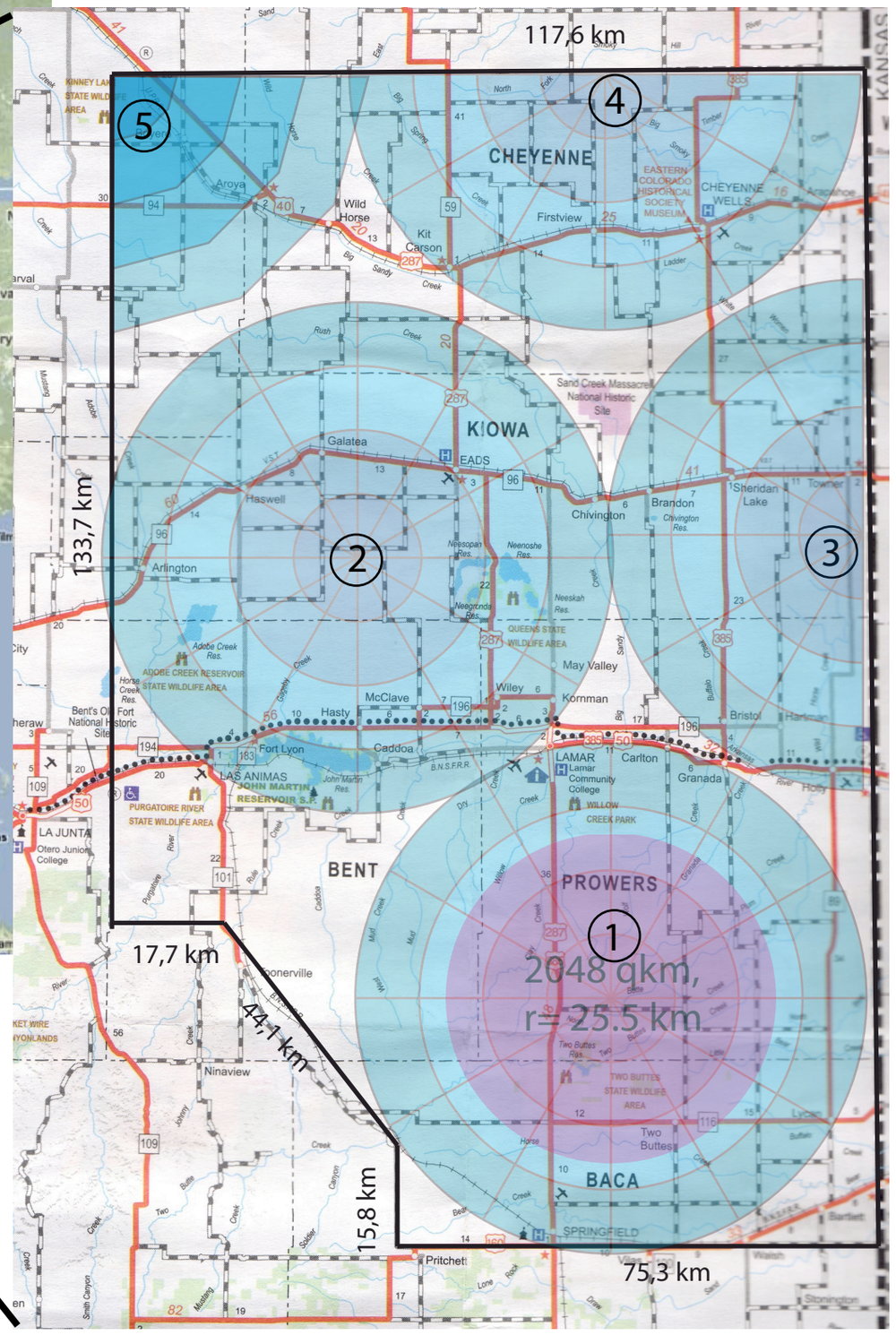
- Primary cosmic ray flux: suppression, most likely GZK effect
- Composition:
  - hadronic mixed ($<A_{eff}>$ ~ 4 ... 10), correlated with flux
  - low limits on photon fraction (~2% @ 95% c.l.)
- Ultra-high energy cosmic rays are not isotropically distributed
- **Not yet consistent picture**

## Outlook:

- More statistics to come
- Enhancements of Southern Observatory to extend range to lower energy
- Design studies and R&D for Northern Observatory

# Detector location and layout

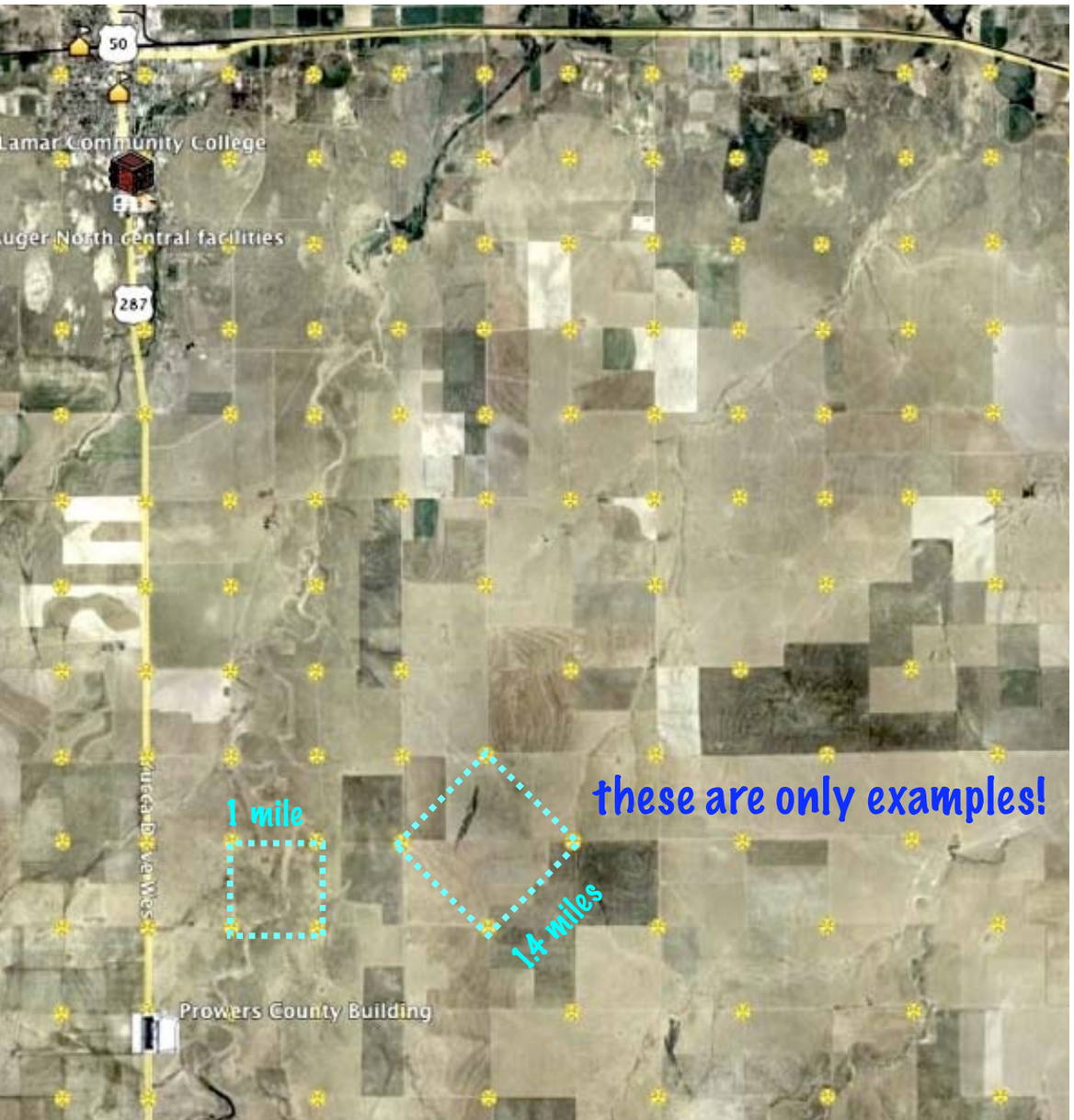

Lamar, Colorado

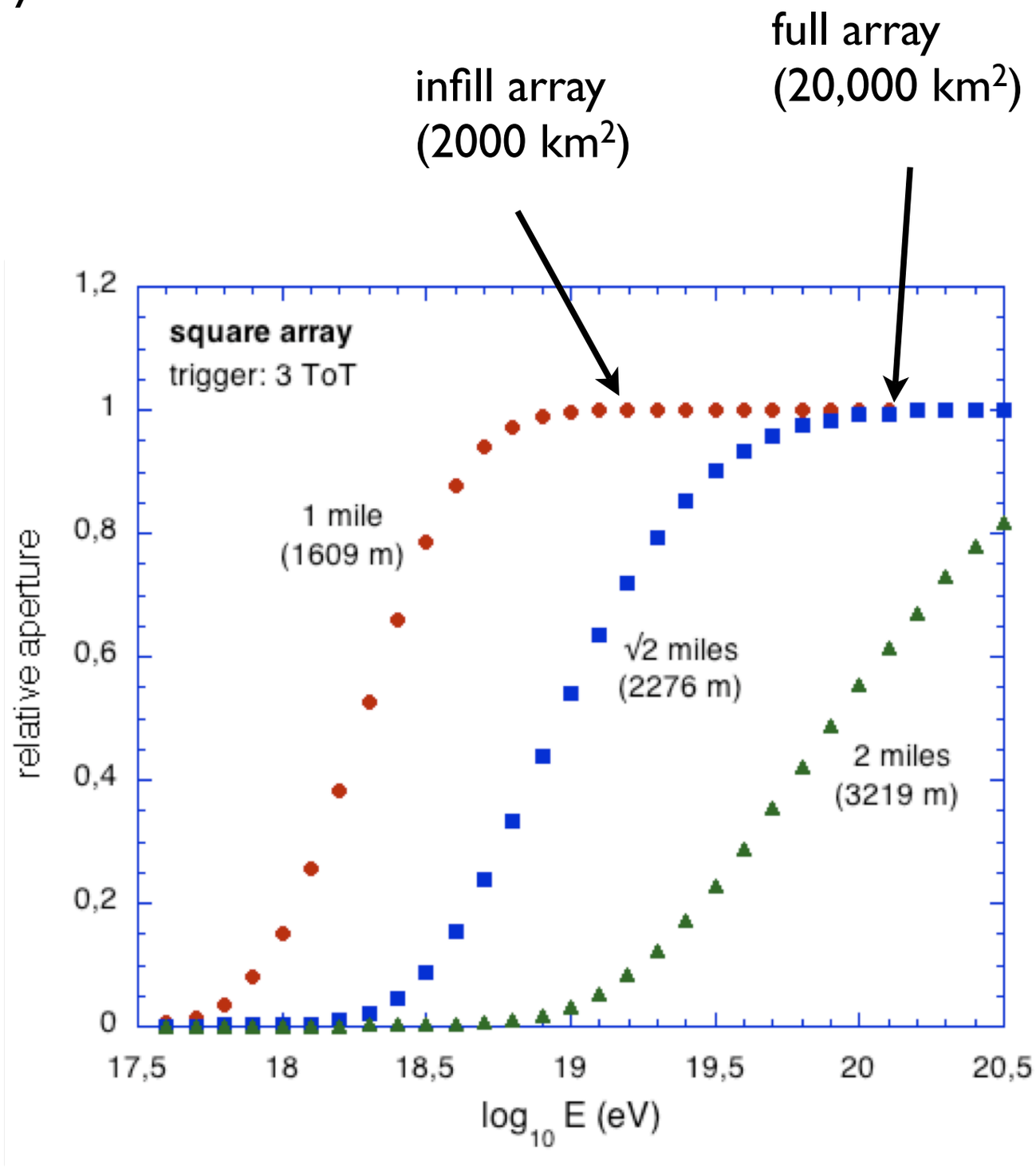



- 20,000 km$^2$ with $\sqrt{2}$ mi grid
- 4000 surface detector stations
- infill array with 400 stations (2000 km$^2$)
- 39 fluorescence telescopes

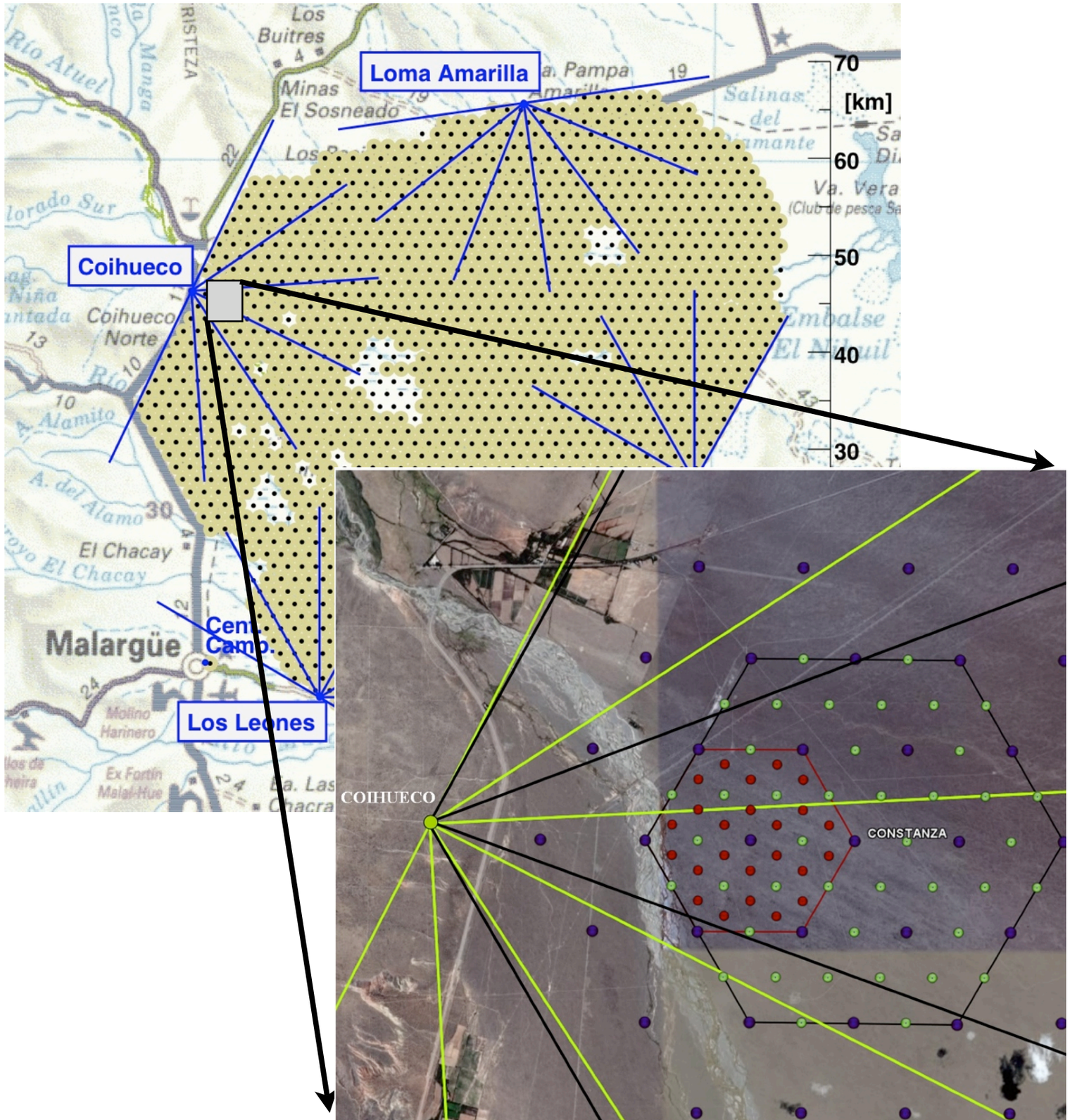
# Surface detectors and trigger thresholds

- Water-Cherenkov tanks with one PMT only
- Use of existing 1 mi grid of roads
- Tank-to-tank commuication

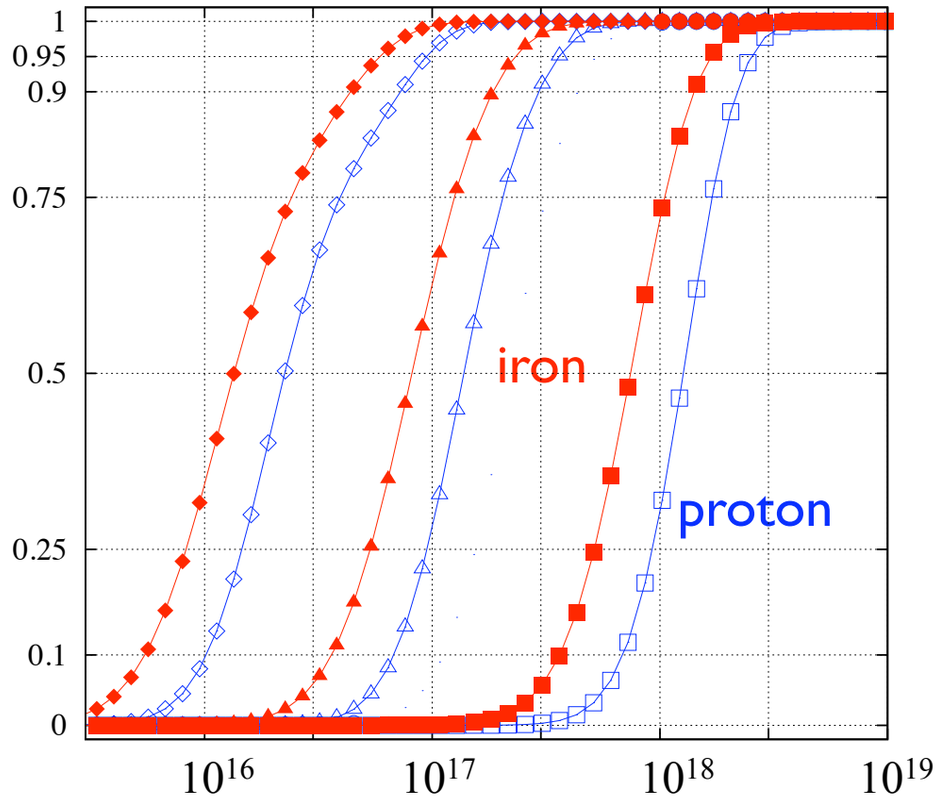


# Infill array of water Cherenkov detectors



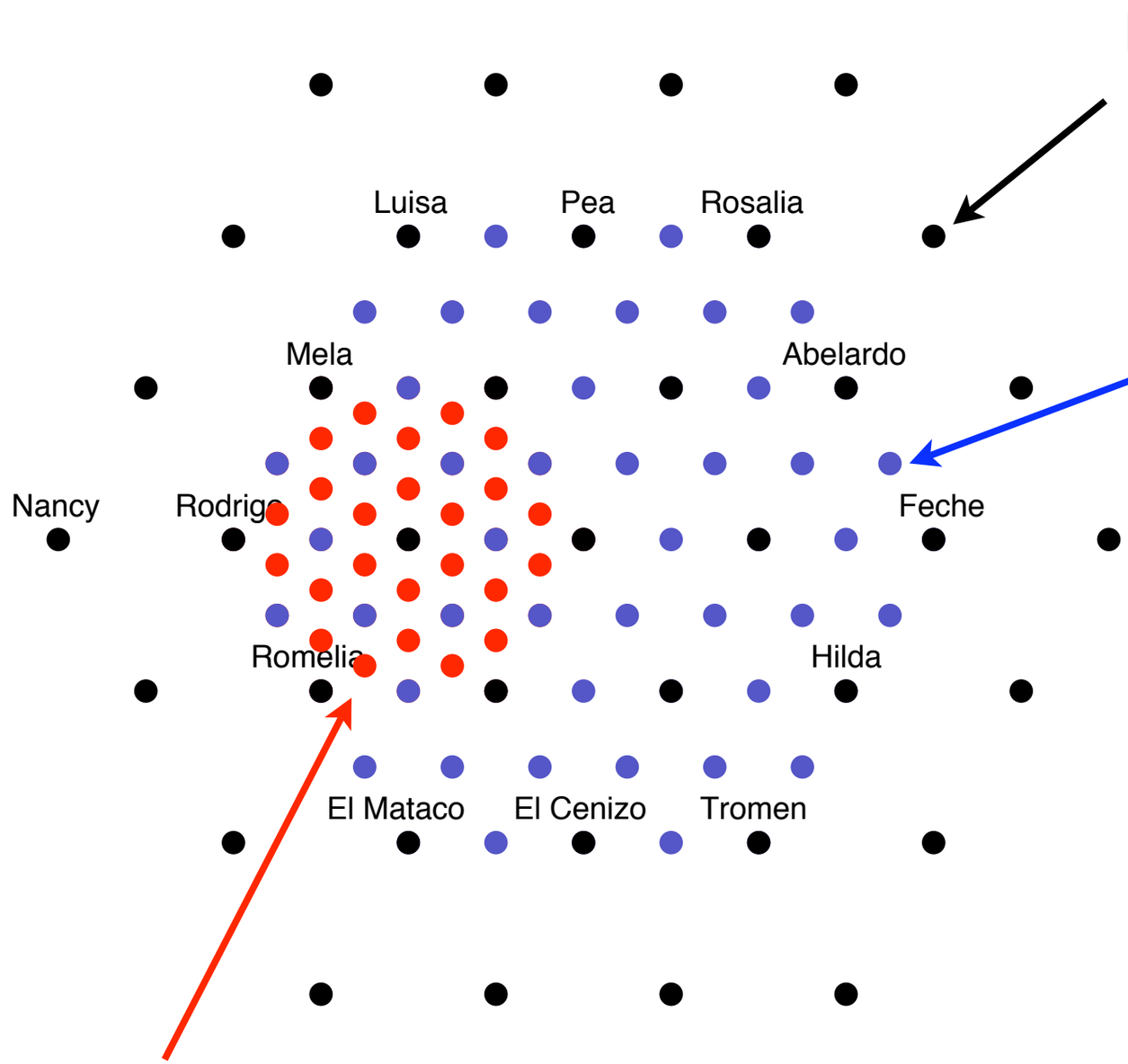

## Simulated acceptance



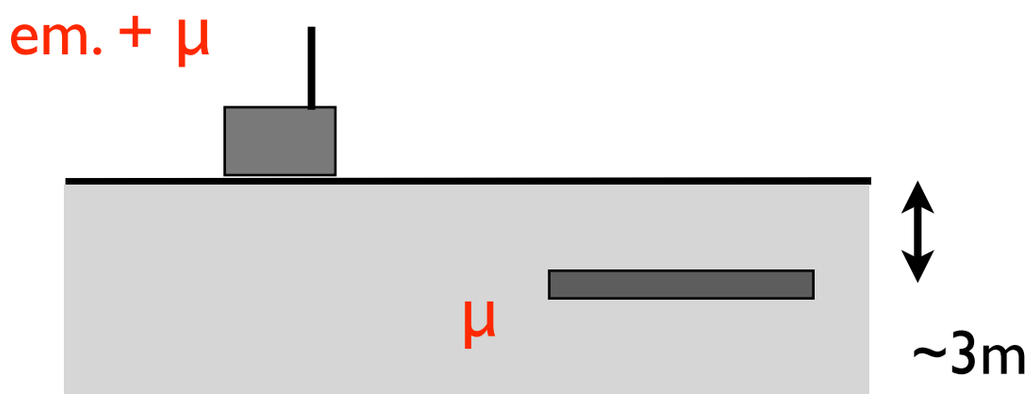

433m 750m 1500m

Threshold for infill array ~$10^{17}$ eV

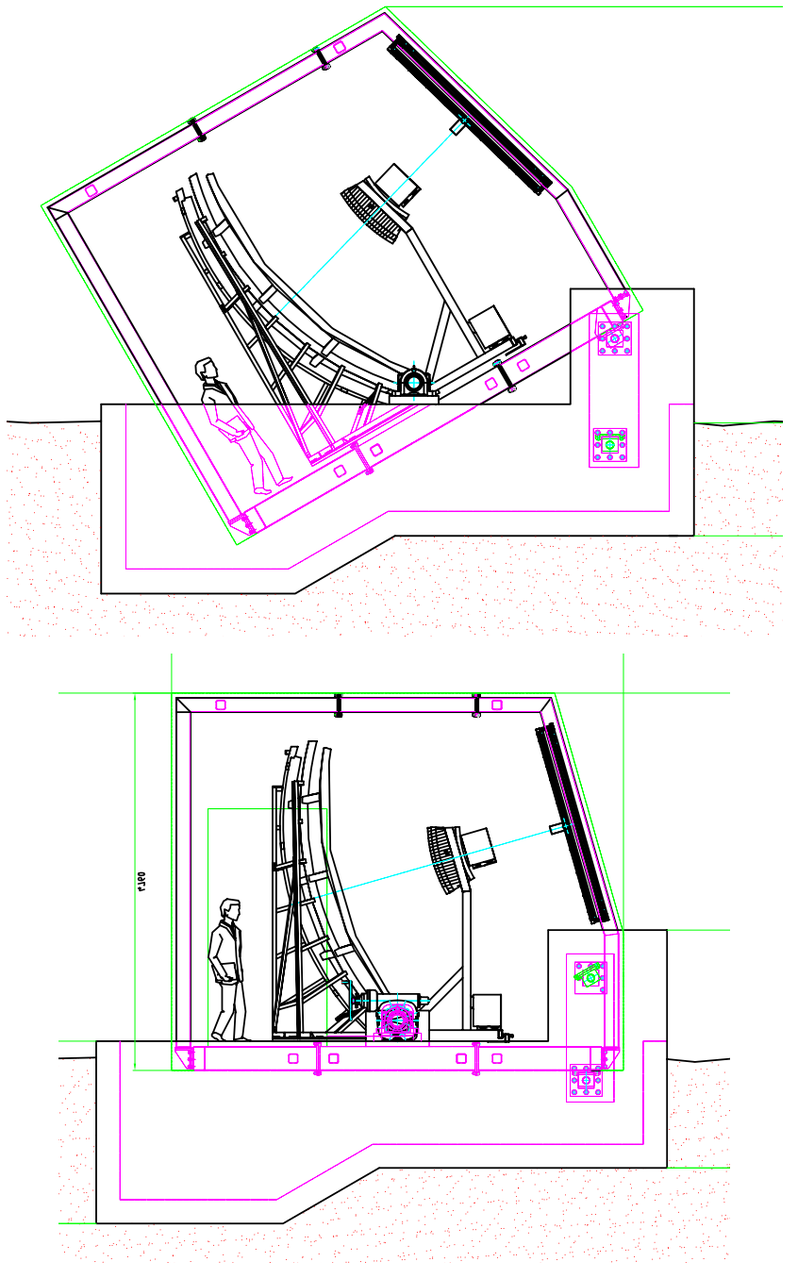
# AMIGA: Auger Muons and Infill for the Ground Array

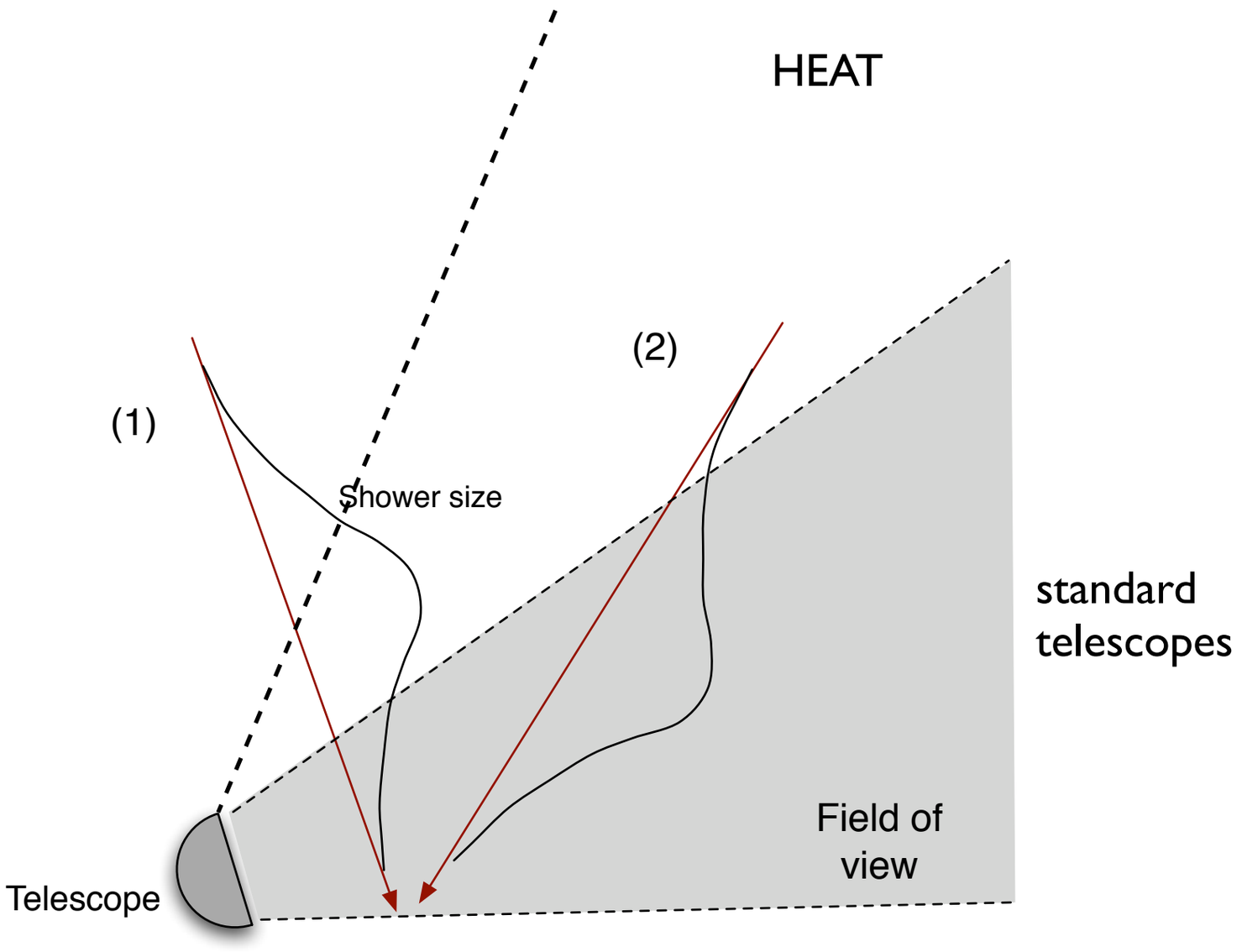



Each of the 85 detectors:
pair of Cherenkov tank
and muon counter

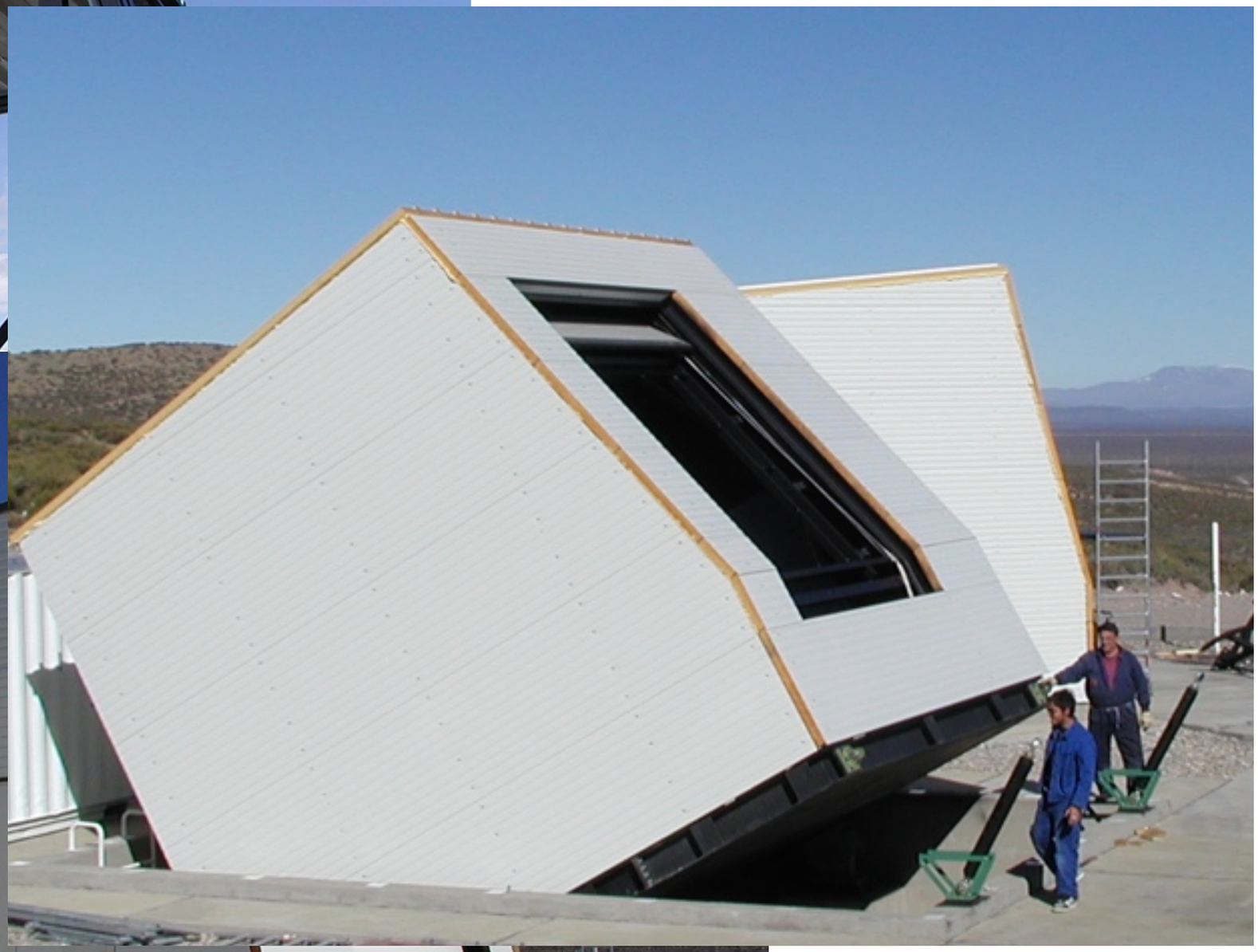


# HEAT: High Elevation Auger Telescopes






- 3 ``standard´´ Auger telescopes tilted to cover 30 - 60° elevation
- Custom-made metal enclosures
- Also prototype study for northern Auger Observatory



Auger 2007

KASCADE

-Grande

IceTop/IceCube

Tower

Stereo

TA

AMIGA/HEAT

Auger

Scaled flux $E^{2.5}$ J(E) ($m^{-2}$ sec$^{-1}$

$10^{14}$ $10^{15}$ $10^{16}$ $10^{17}$

$10^{17}$ $10^{18}$ $10^{19}$ $10^{20}$

(eV/particle)

Hexagon
(7 x 60 m$^2$)

Existing tank array 1500m

Infill array 750m

Muon detectors:
54 (30m$^2$) + 7 (60m$^2$)
Cherenkov tanks: 61
Area ~ 23 km$^2$

Luisa Pea Rosalia Mela Abelardo Nancy Rodrigo Feche Romelia Hilda El Mataco El Cenizo Tromen

Infill array 433m
Area ~ 5.9 km$^2$

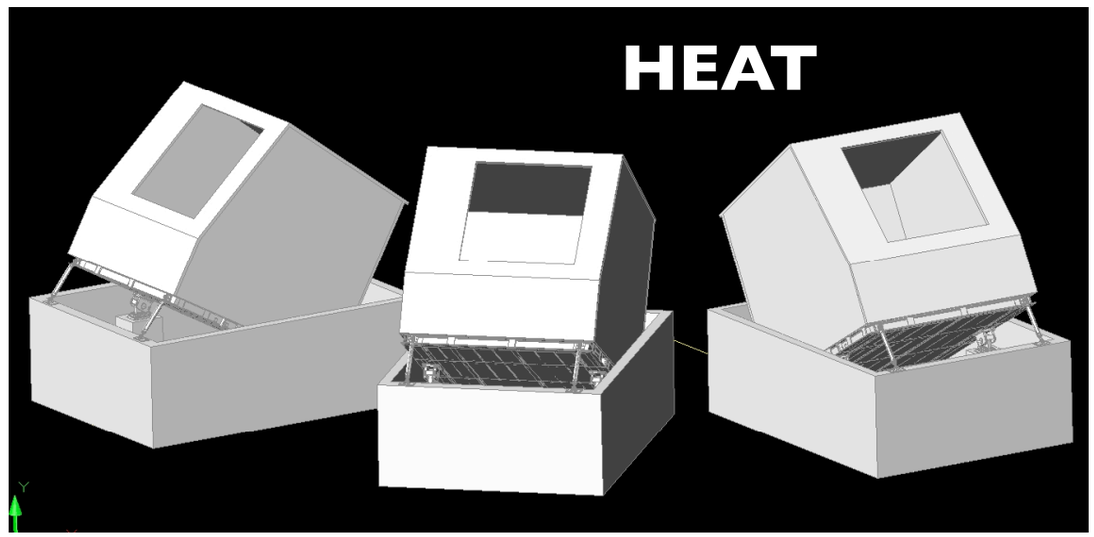
AMIGA

em. + μ

μ

~2.5m

Detector pairs



# Pierre Auger

Malargüe, Argentina
March 15-19, 2006

PIERRE AUGER OBSERVATORY

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