Cosmic rays at highest energies – Spectrum and composition of UHE cosmic rays

Outline

- Energy spectrum
- Composition
  - neutrinos/photons
  - charged particles
- (Anisotropy: See talk by O. Deligny)

Recontre Blois
June 2011

Markus Roth
Karlsruhe Institute of Technology

Astroparticles: particles from astrophysical sources

...The highest energy particles in the universe.

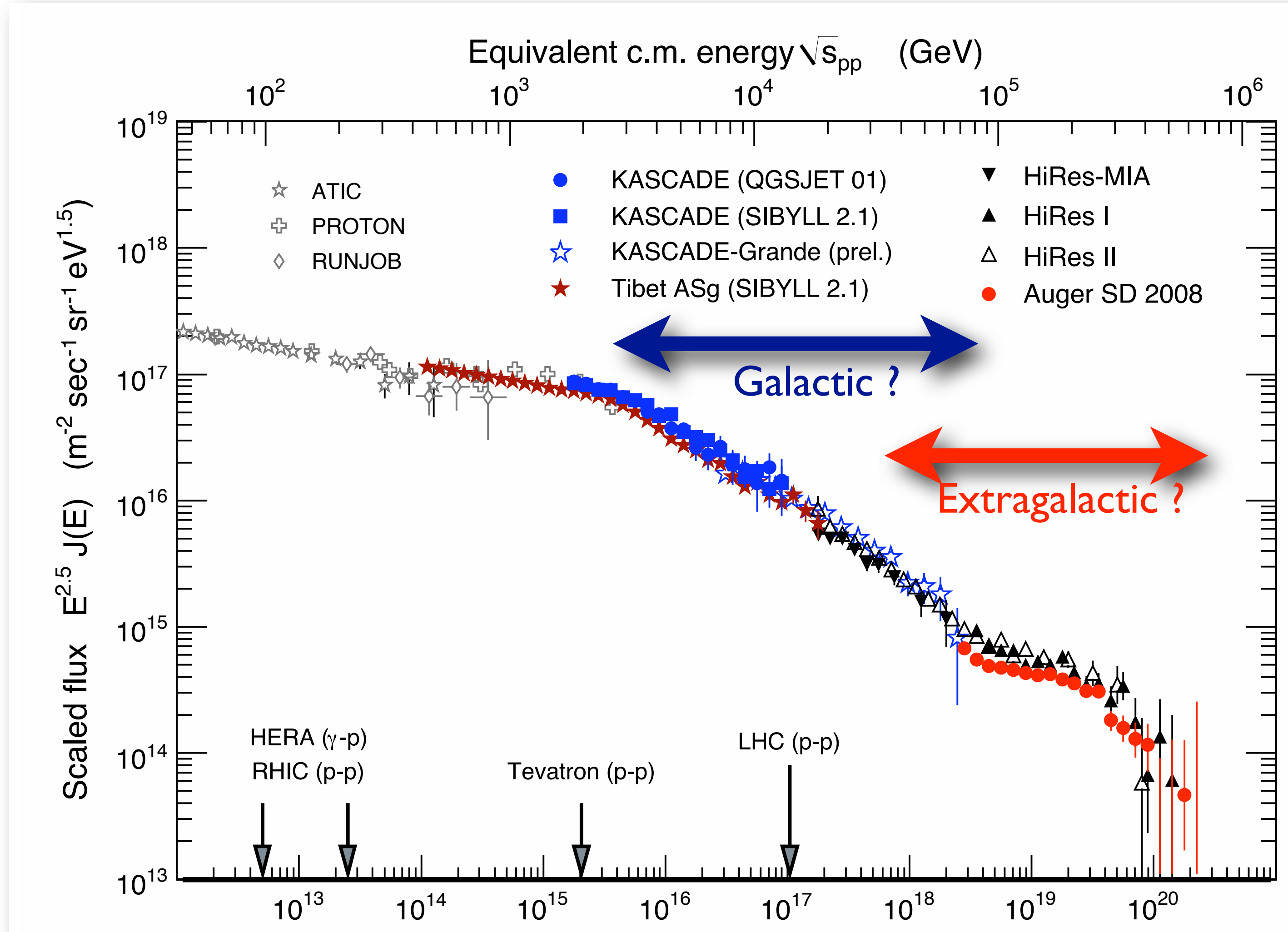
There are Cosmic Particle Accelerators out there that go up to > 10^{20} eV !!

What/where are the accelerators?
What is the nature of the CRs?

We need to determine:

- Features in the energy spectrum
    - Ankle
    - Suppression
- Abundance of particle species
  (known as mass composition)
- Distribution of arrival directions
  (see Olivier Deligny's talk)

Details of nuclear and hadronic interactions unknown at high energies

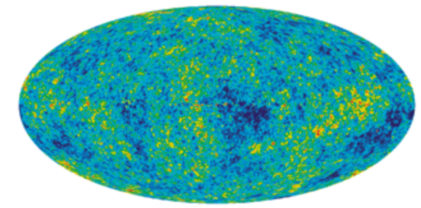


Courtesy Ralph Engel

(UHECRs: E>10^{19}eV)

Particle horizon: Greisen-Zatsepin-Kuzmin effect

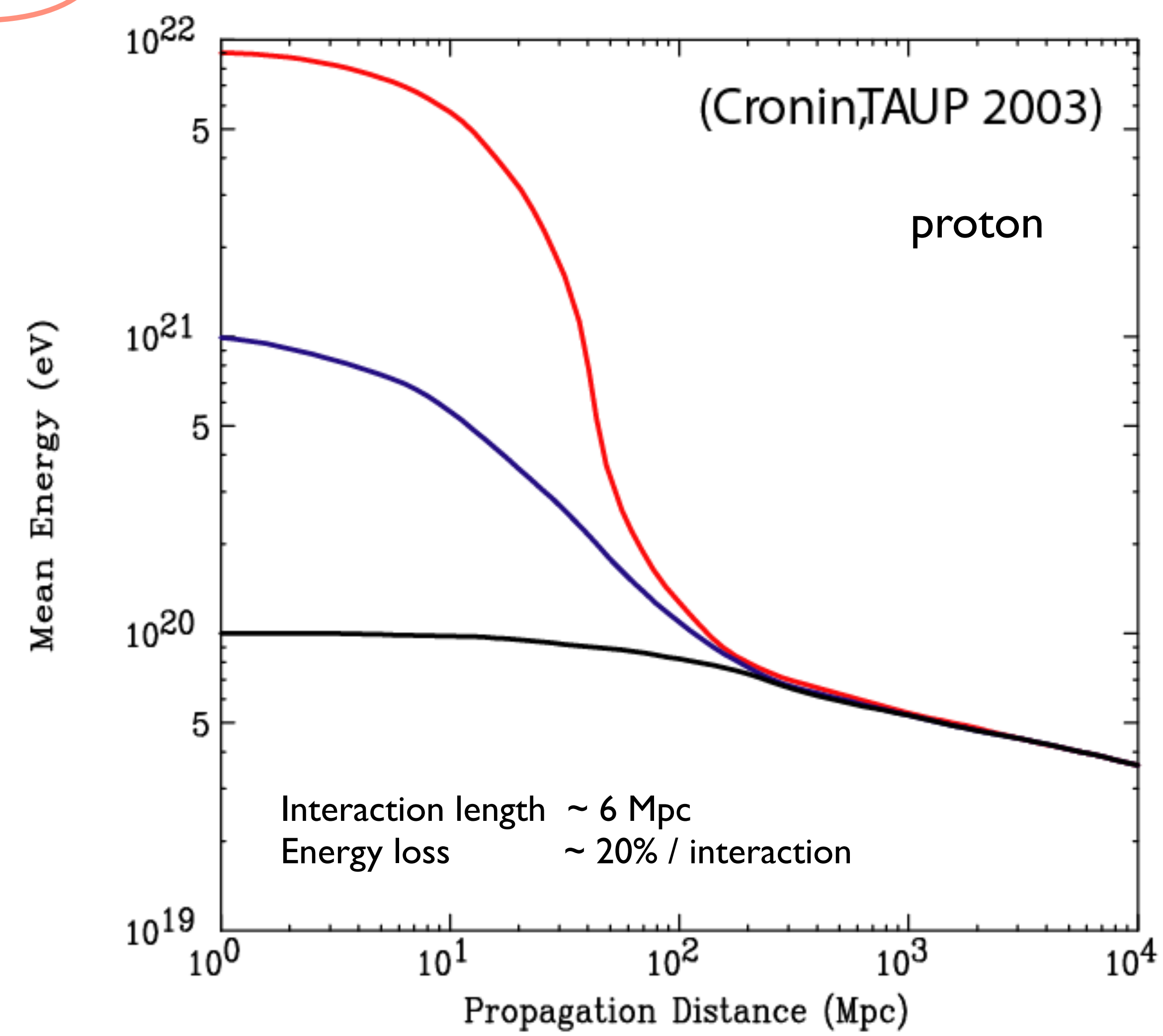
Photo pion production (E_p > 5x10^{19}eV due to CMB) :



$$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \ldots + 2\,\gamma$$
$$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \ldots + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

Photo dissociation

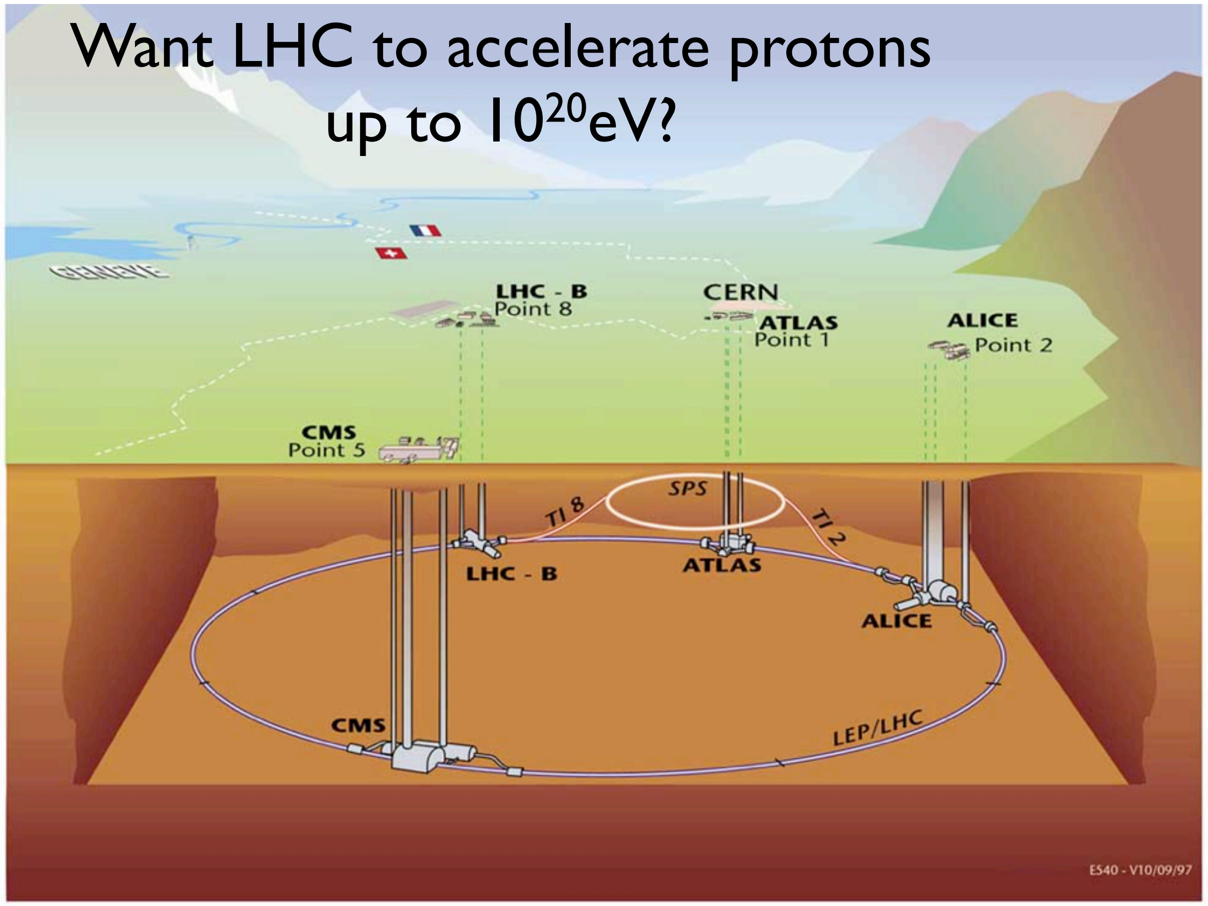
$$^{56}\mathrm{Fe} + \gamma_{3K} \rightarrow {}^{55}\mathrm{Fe} + n$$



Universe becomes opaque
for E>6 10^{19}eV
Sources must be close (<100Mpc)!
If sources are universal:
Cut-off in CR spectrum

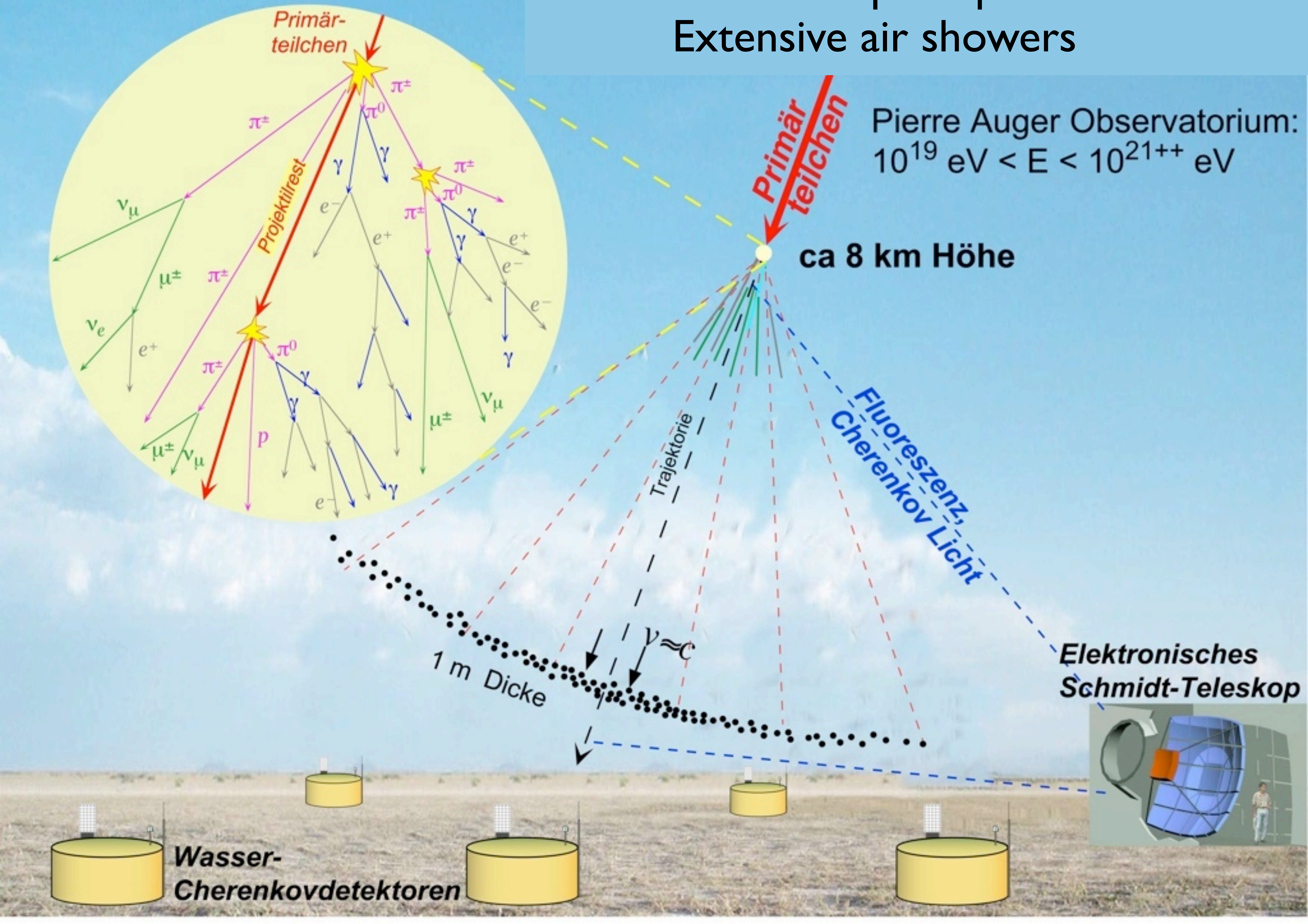
1 lyr = 9.46 × 10^{15} m
1 pc = 3.26 lyr ~ π lyr

Accelerators for 10^{20}eV protons



$r_{Merkur} = 58 \times 10^6$ km = 0.387 au

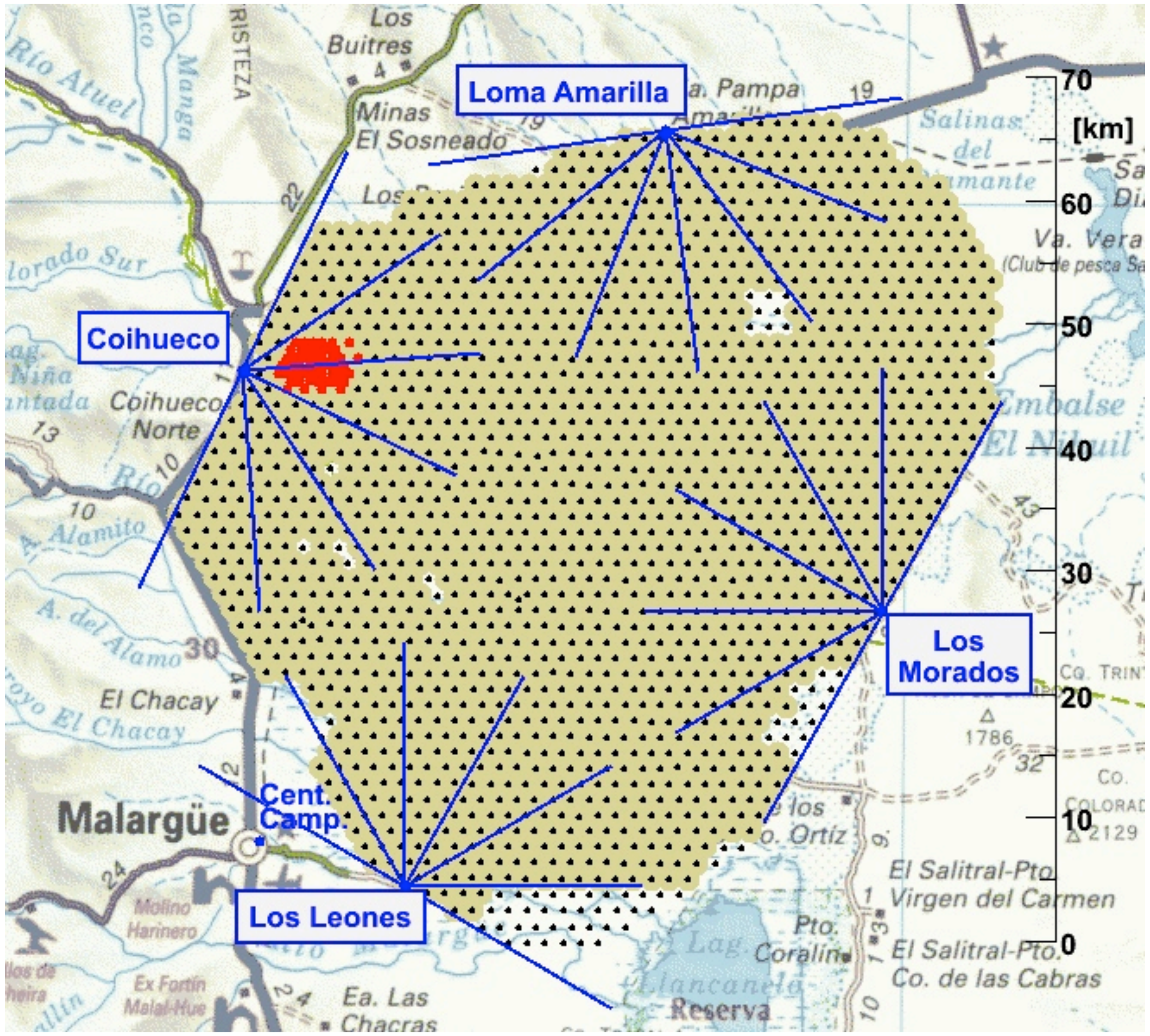
Detection principle: Extensive air showers



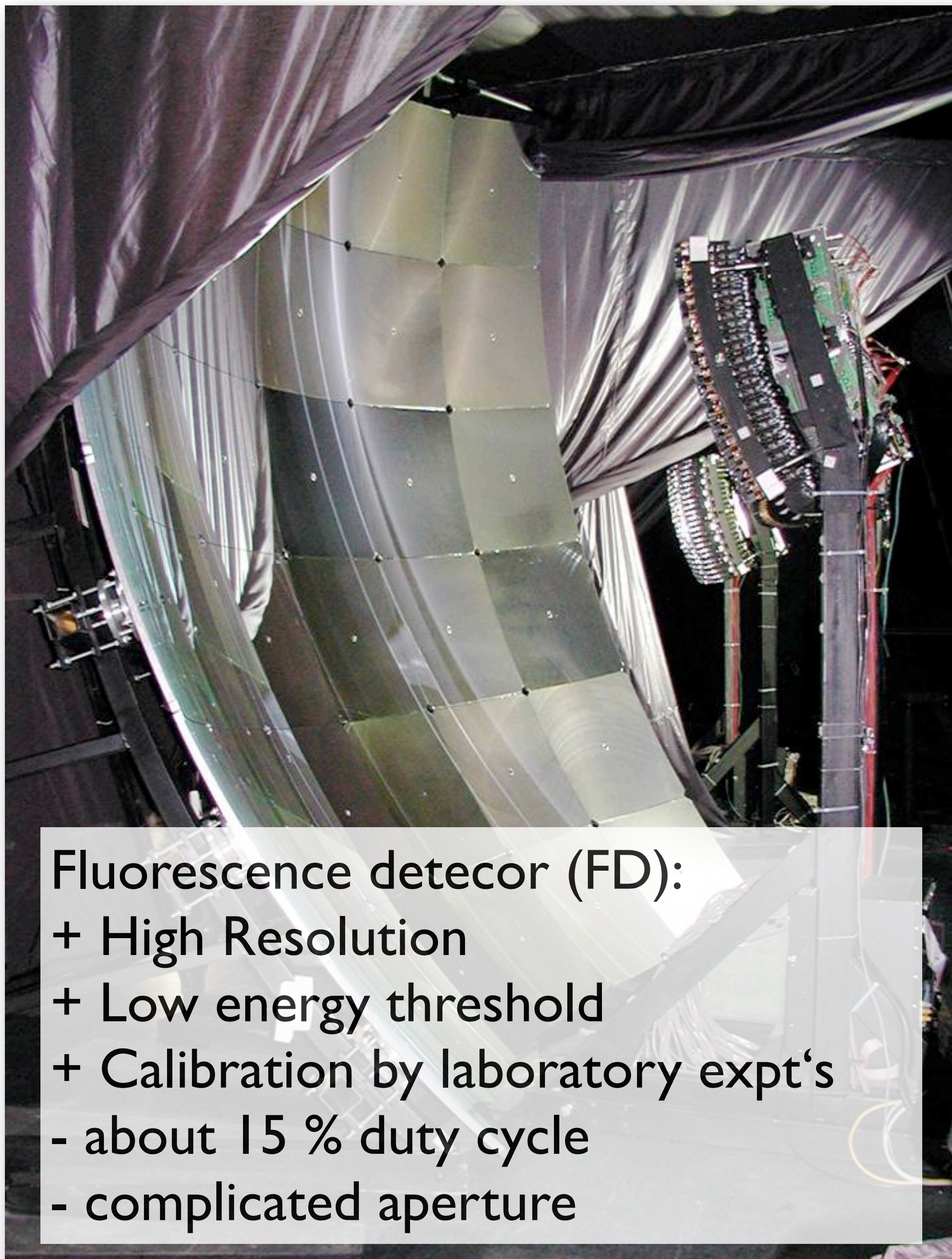
The Pierre Auger Observatory

- Auger: >400 authors from 17 countries
- Hybrid detector near Malargüe/Argentina
- Surface detector (SD): 1660 tanks deployed

- All 4 fluorescence buildings (FD) complete each with 6 telescopes
  (plus 3 additional at higher elevation; low energies)
- 1st 4-fold on May 20th 2007

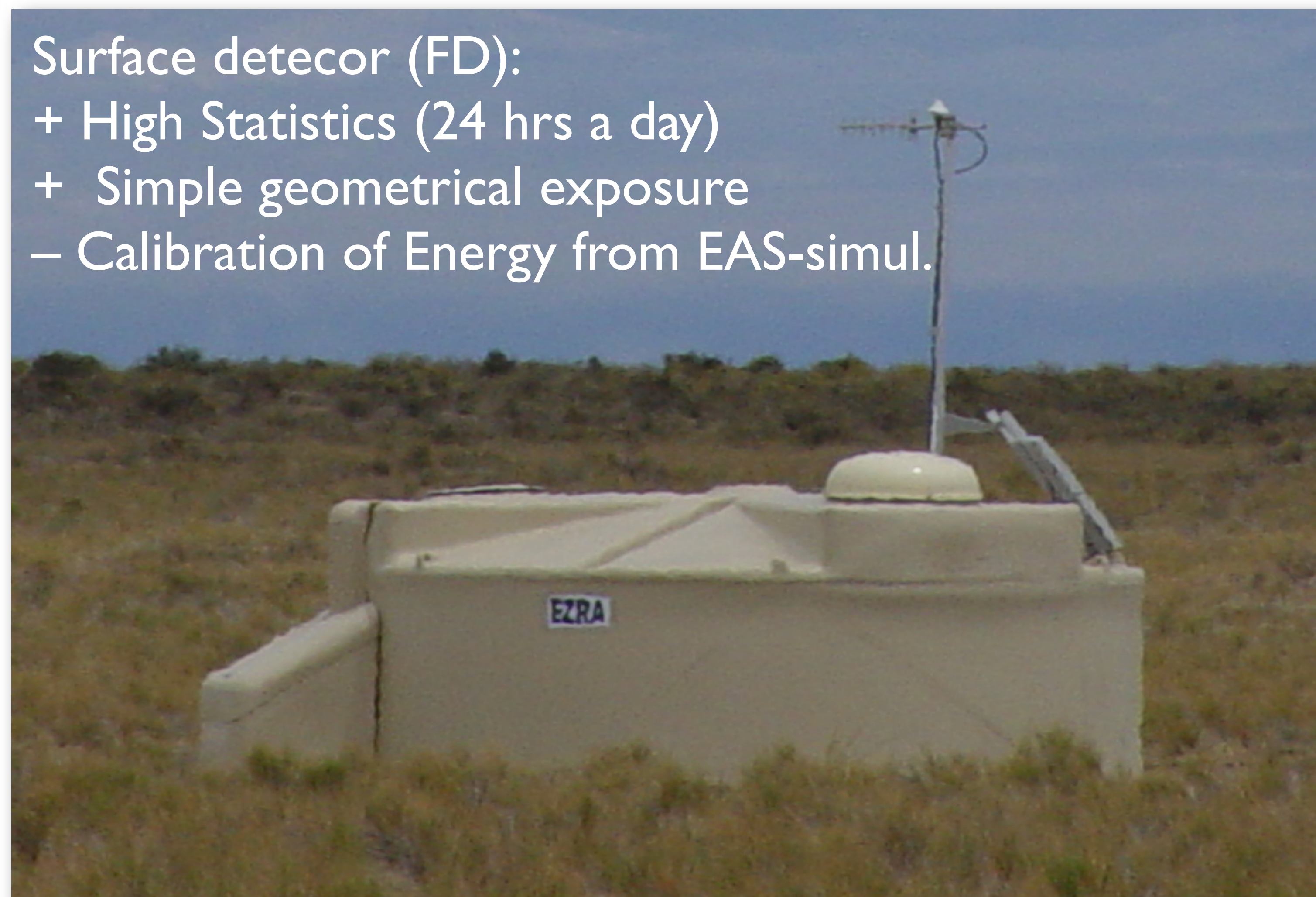


A telescope and a water cherenkov station



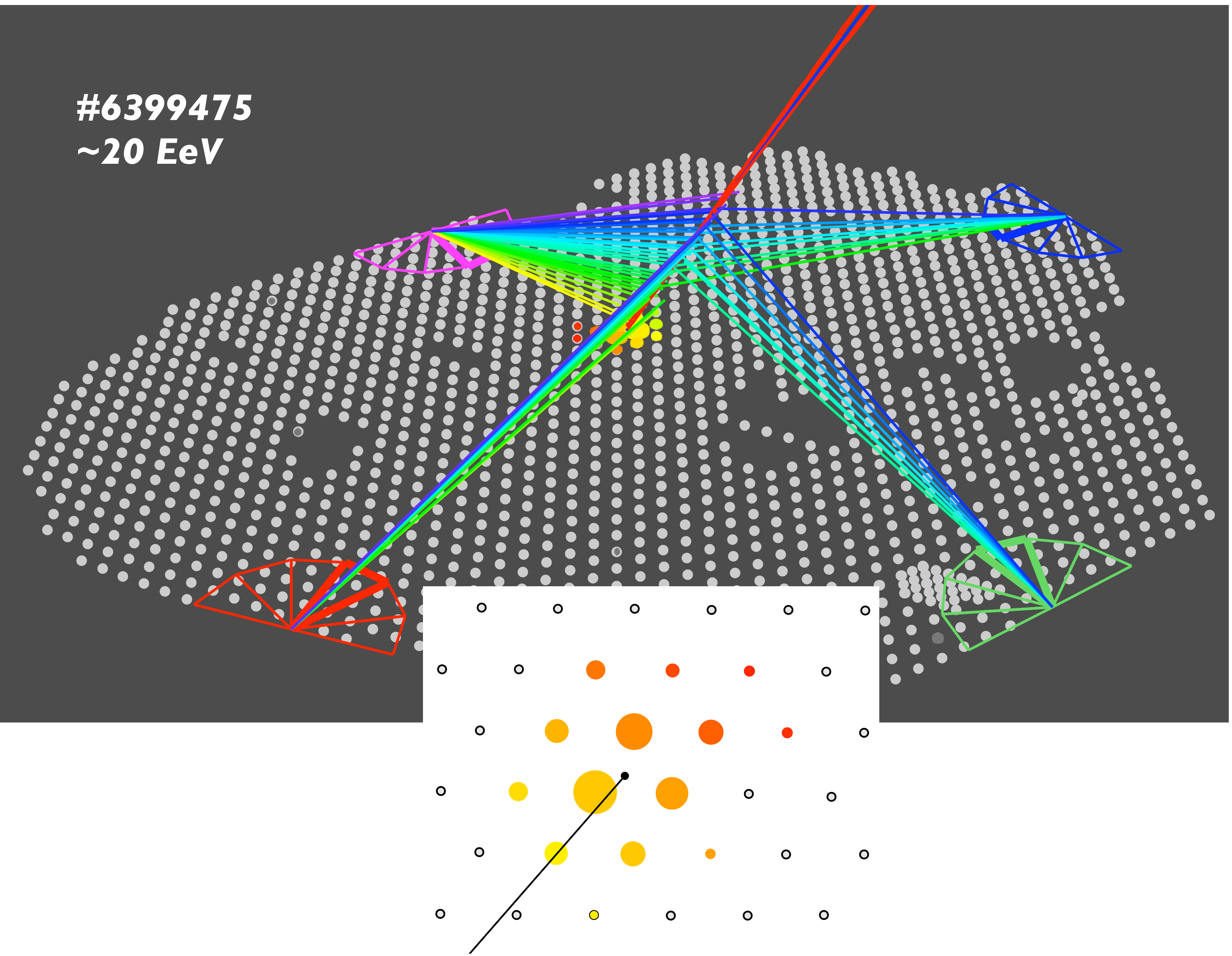
27 fluorescence (Schmidt) telescopes ...

...1660 Water Cherenkov tanks

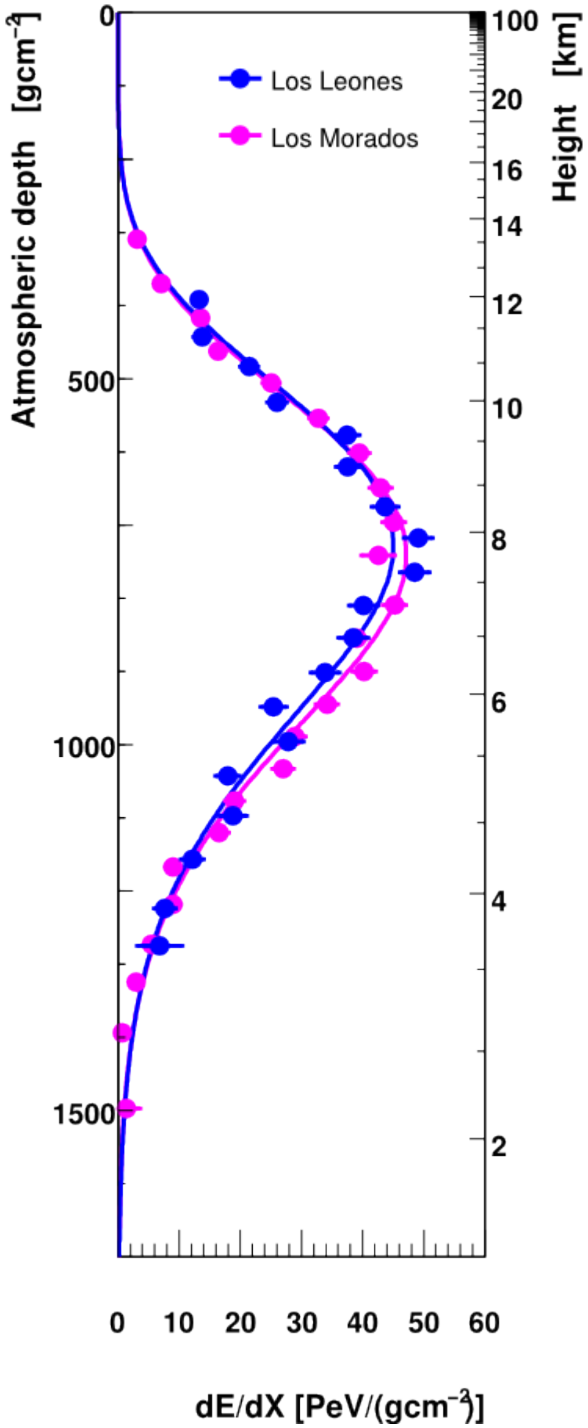


The hybrid nature of Auger

4-fold event

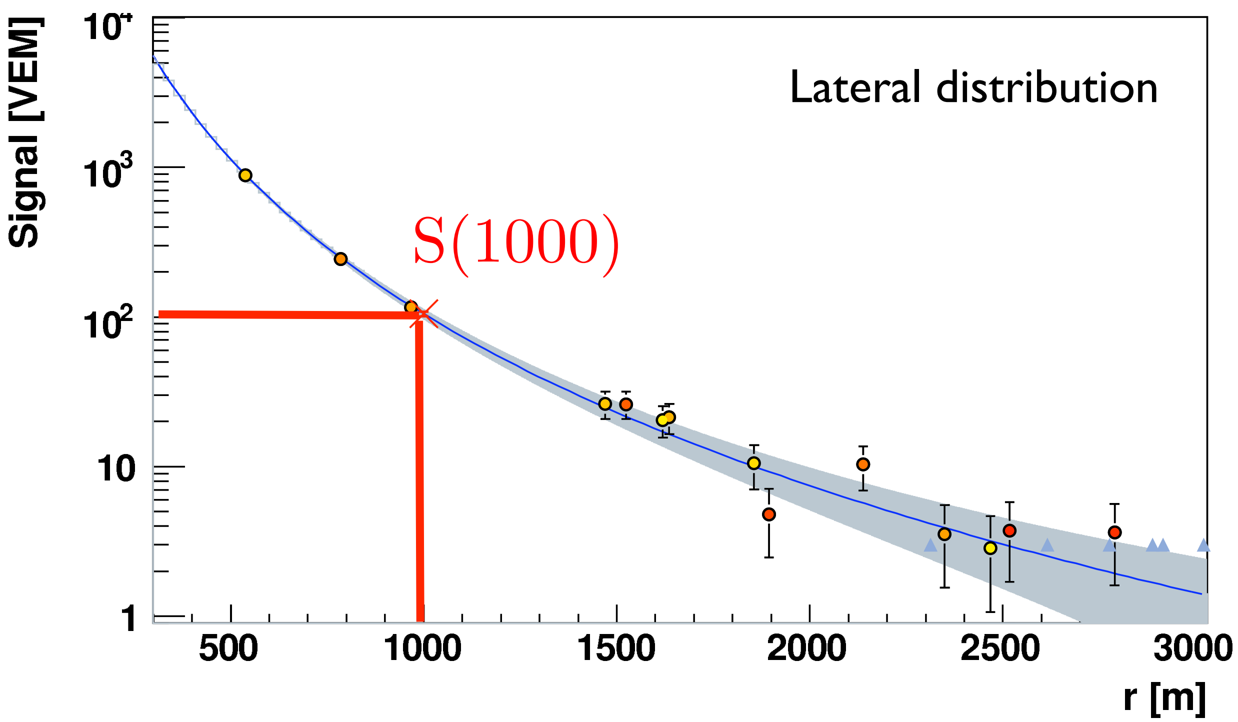


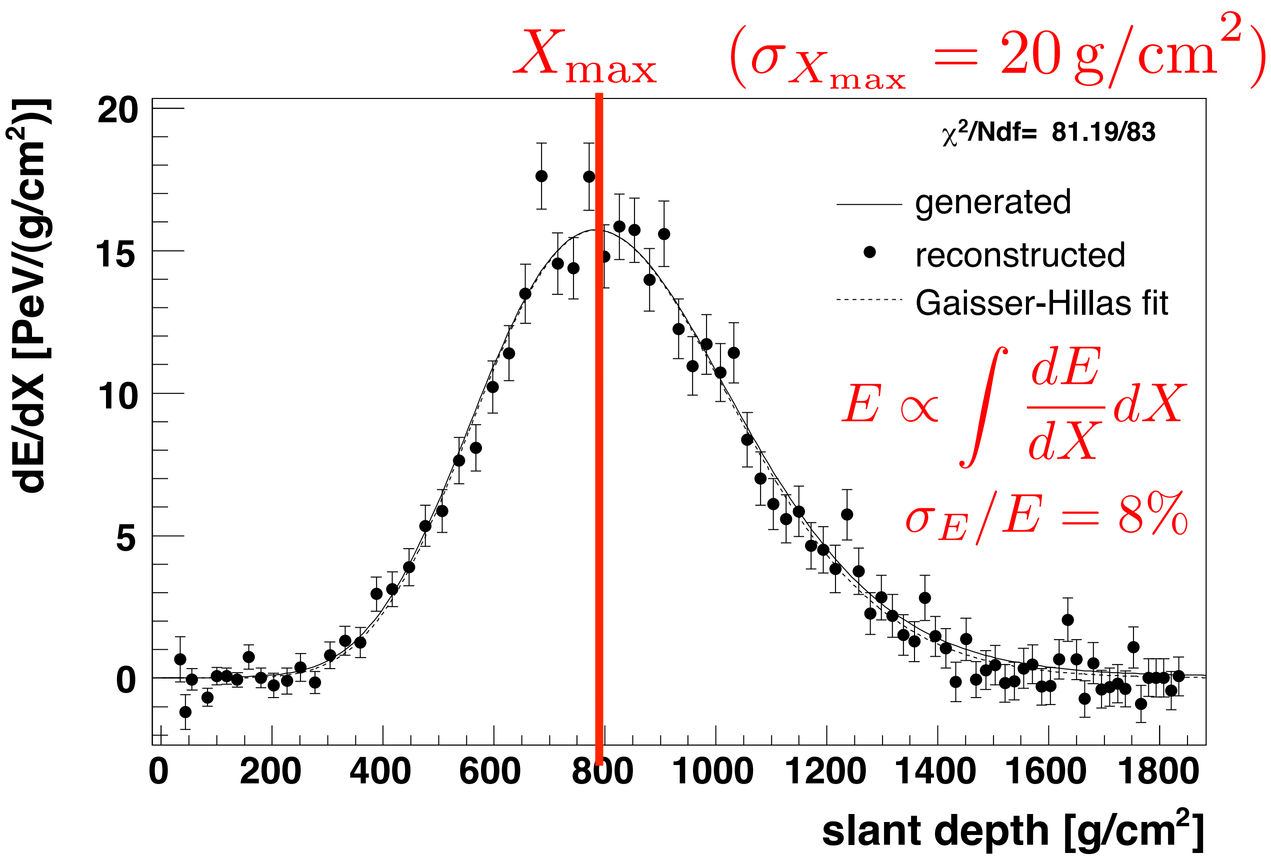
#6399475
~20 EeV

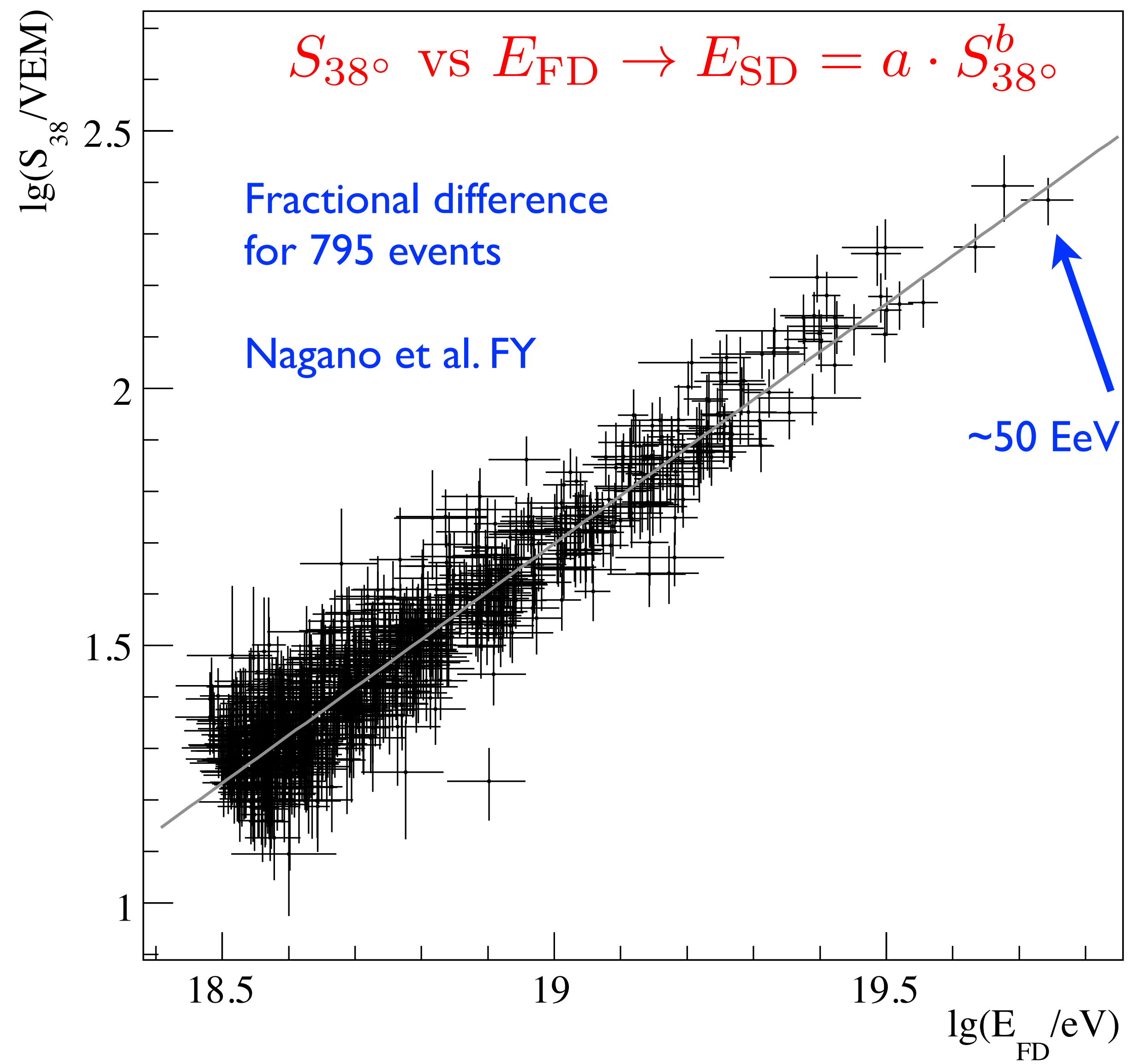


Los Leones
Los Morados
Atmospheric depth [gcm^{-2}]
Height [km]
dE/dX [PeV/(gcm^{-2})]
0
500
1000
1500
100
20
16
14
12
10
8
6
4
2
0 10 20 30 40 50 60

SD spectrum:
Energy calibration with the fluorescence detector







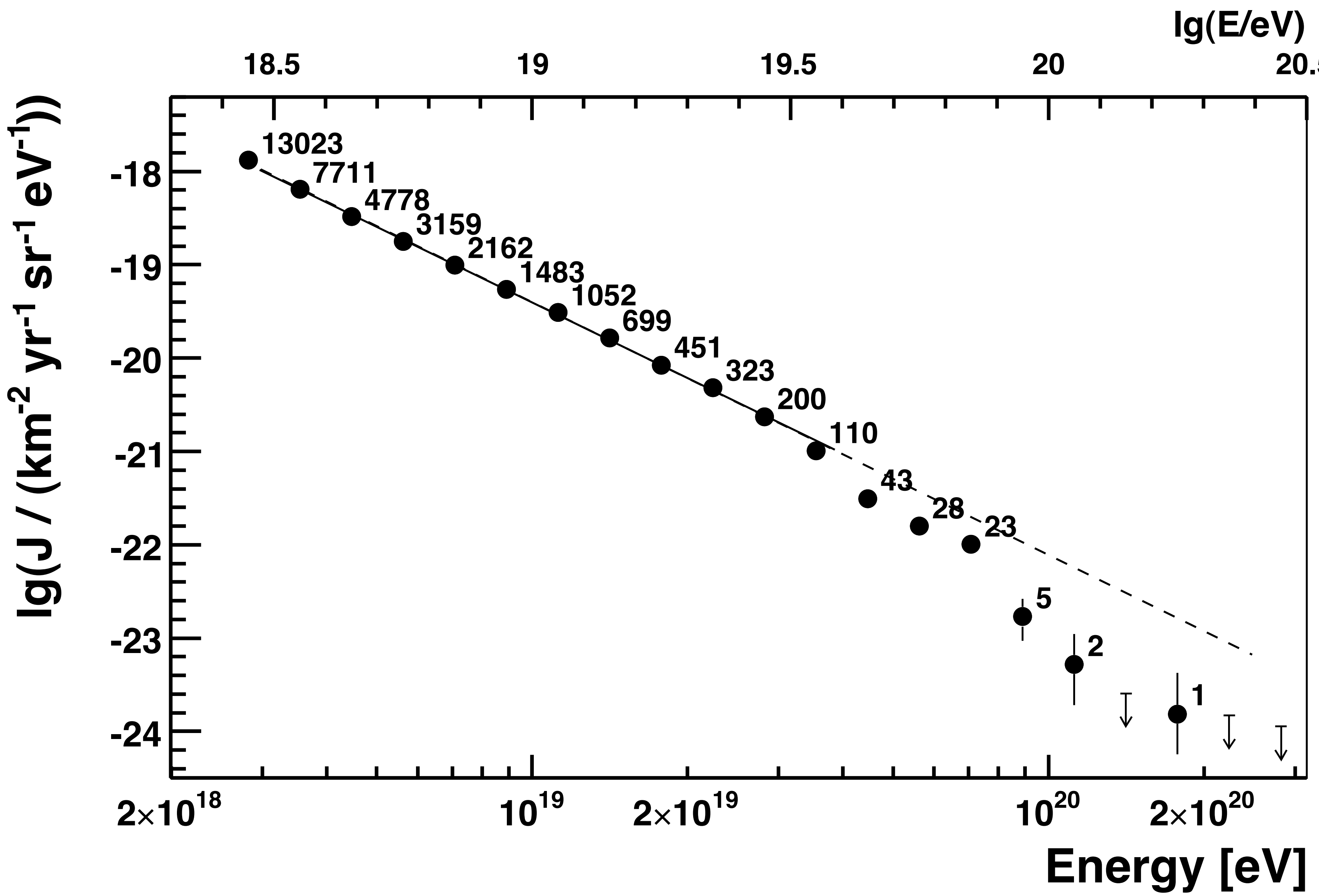
Note:
Both S_{38° and E_{SD} are determined experimentally.
We do not rely on shower simulation.

SD energy spectrum

35,250 SD events
with E > 3 · 10^{18} eV

Corrected for energy resolution
- energy dependent
- less than 20% over the full range

Energy scale Uncertainty: 22%
(Fluorescence yield, Calibration, reconstr.)

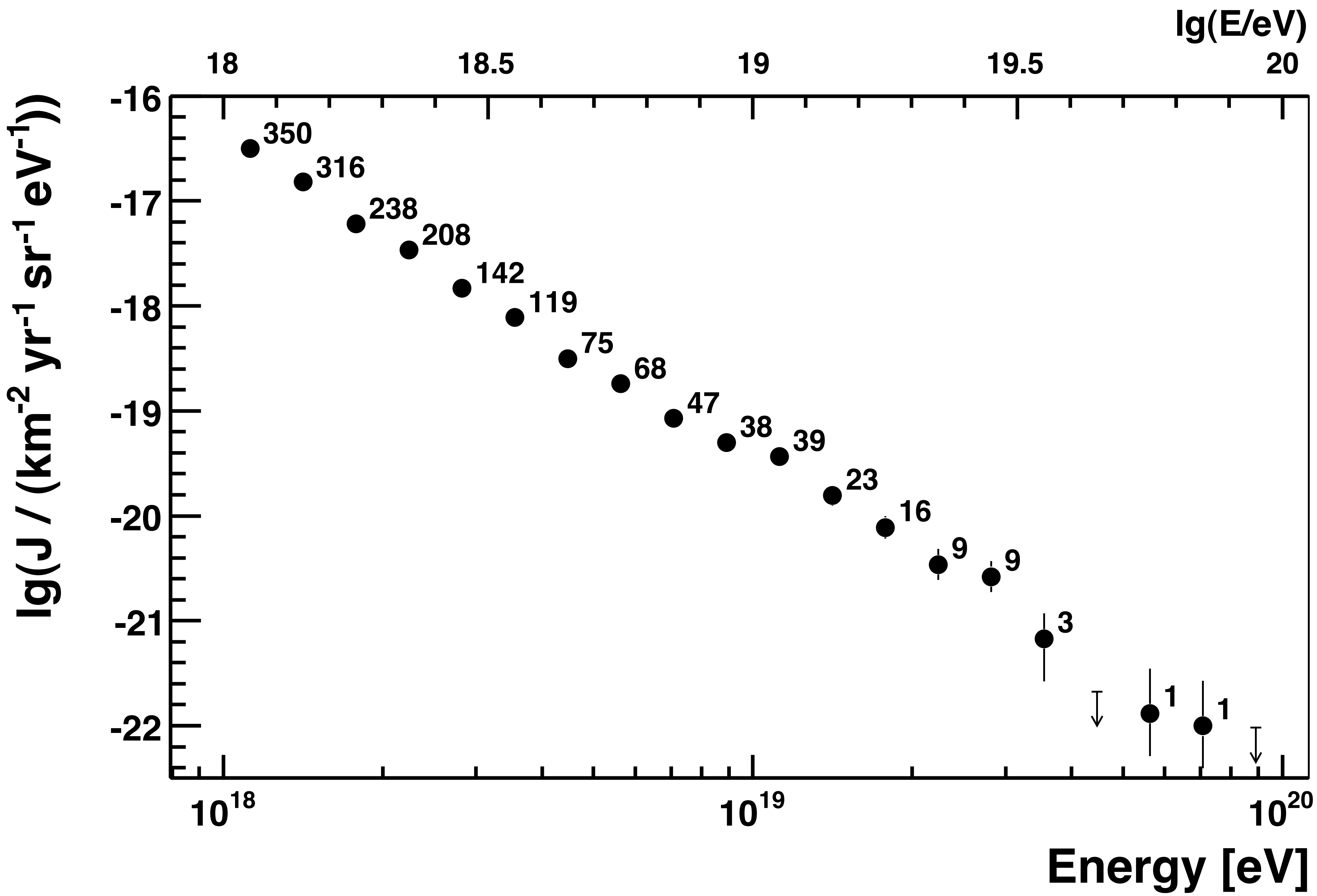


Update of PRL 101, 061101 (2008)

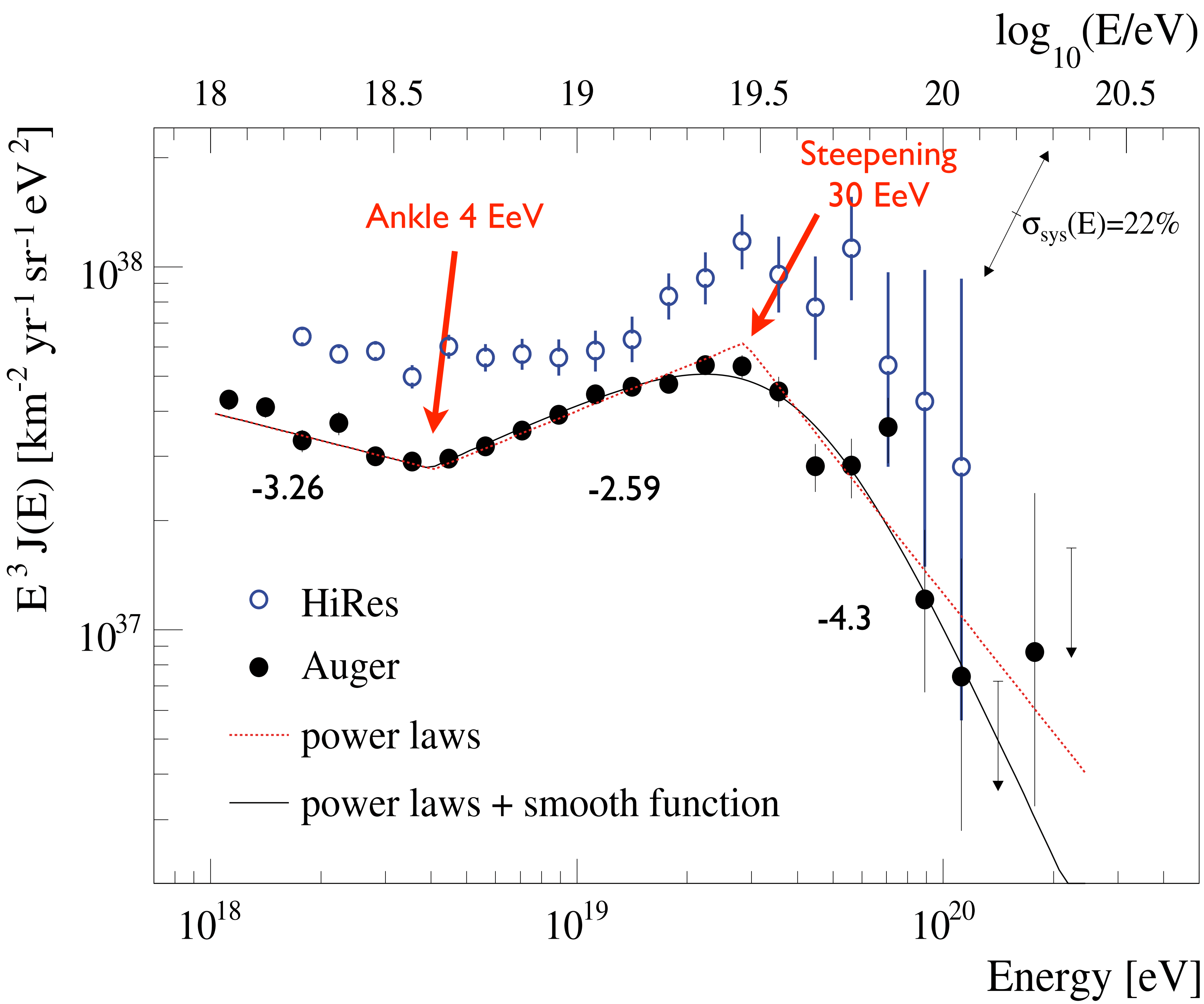
Hybrid spectrum

Energy resolution<6%
Overall syst. uncert. (exposure):
- 10% @ 10^{18}eV
- 6% @ 10^{19}eV

Energy scale uncertainty: 22%
- Fluorescence yield 14%
- Reconstruction 10%
- Calibration 9.5%



The Auger spectrum



22% syst. uncertainty on FD energy scale

Ankle at 4 EeV:
Transition from galactic to extra-galactic CRs?
Steepening at 30 EeV:
Max. energy of accel. or propagation?

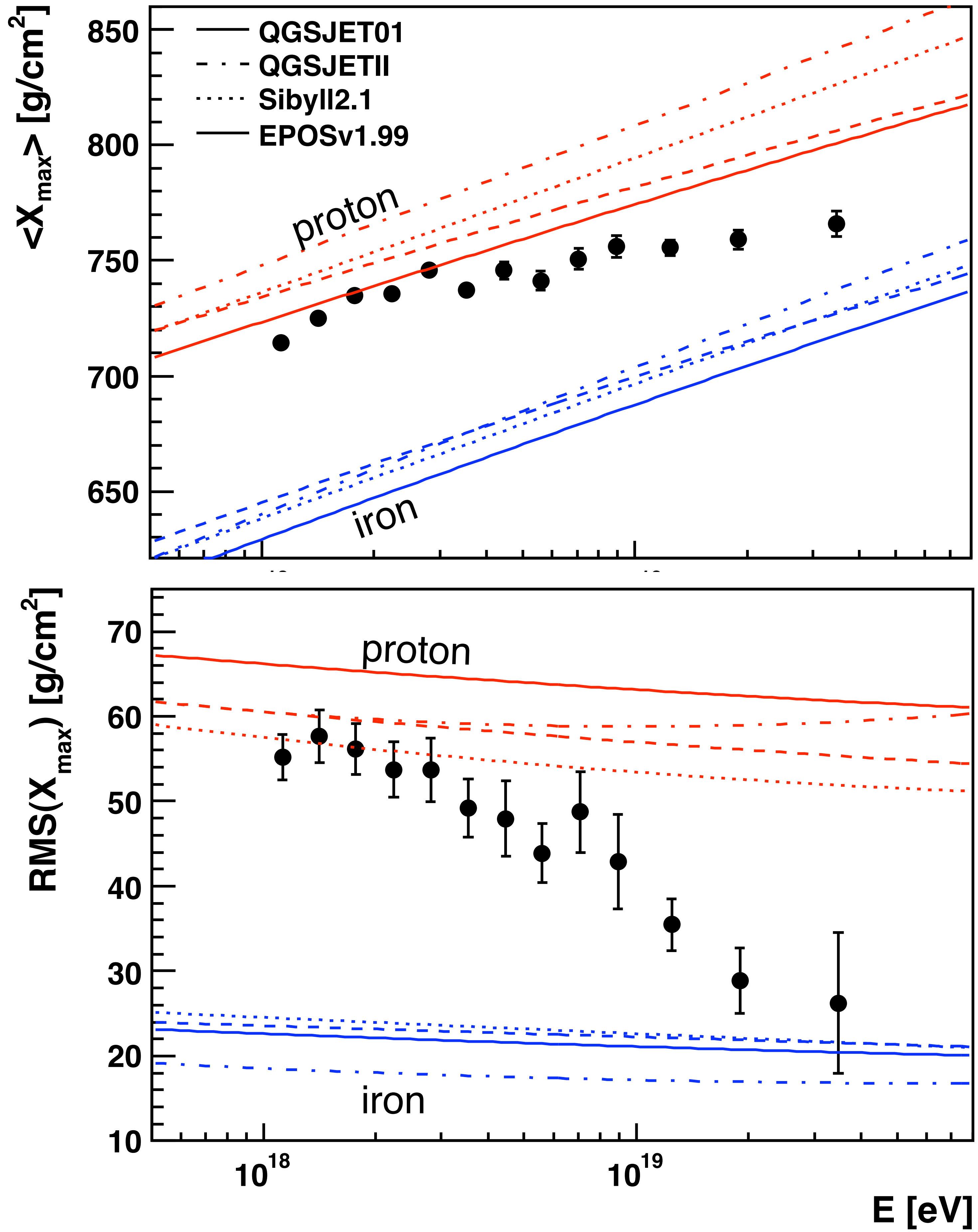
Physics Letters B 685 (2010) 239–246

Elemental composition: FD

$\langle X_{max} \rangle$ and RMS vs E

- vs simulations

Clear trend to heavier elements



Physical Review Letters 104 (2010) 091101

Elemental composition: FD

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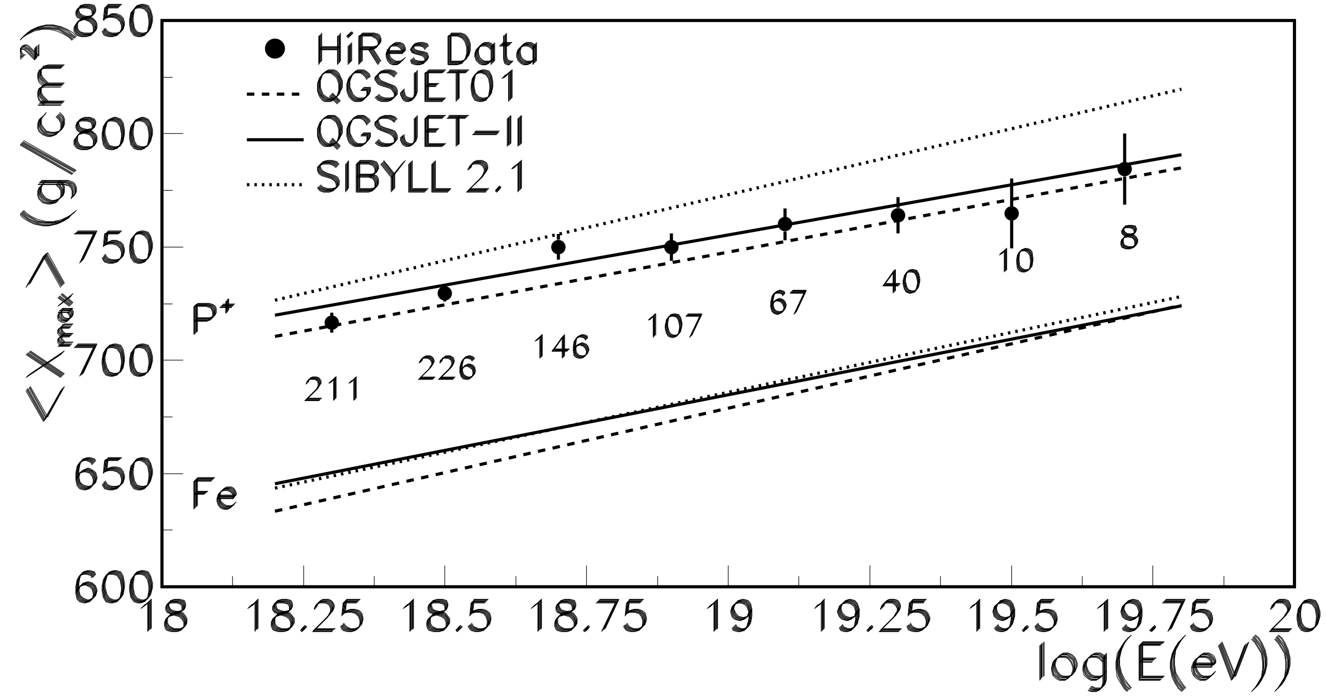
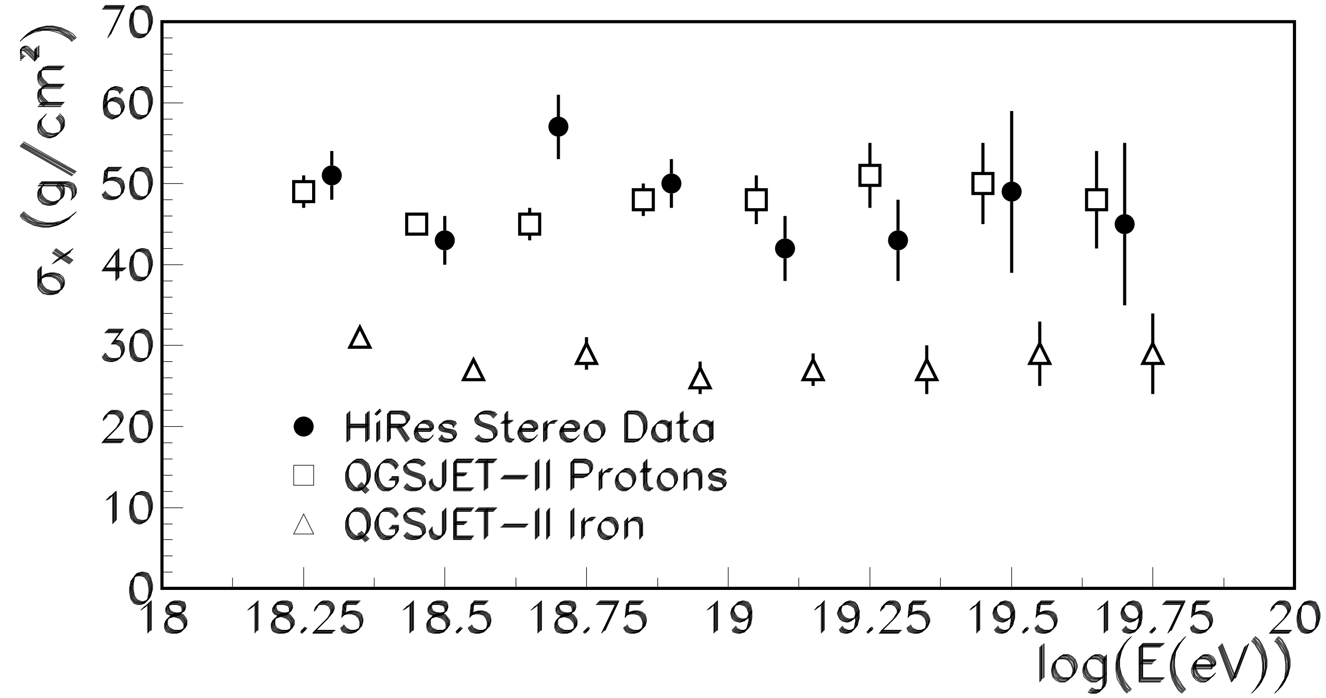




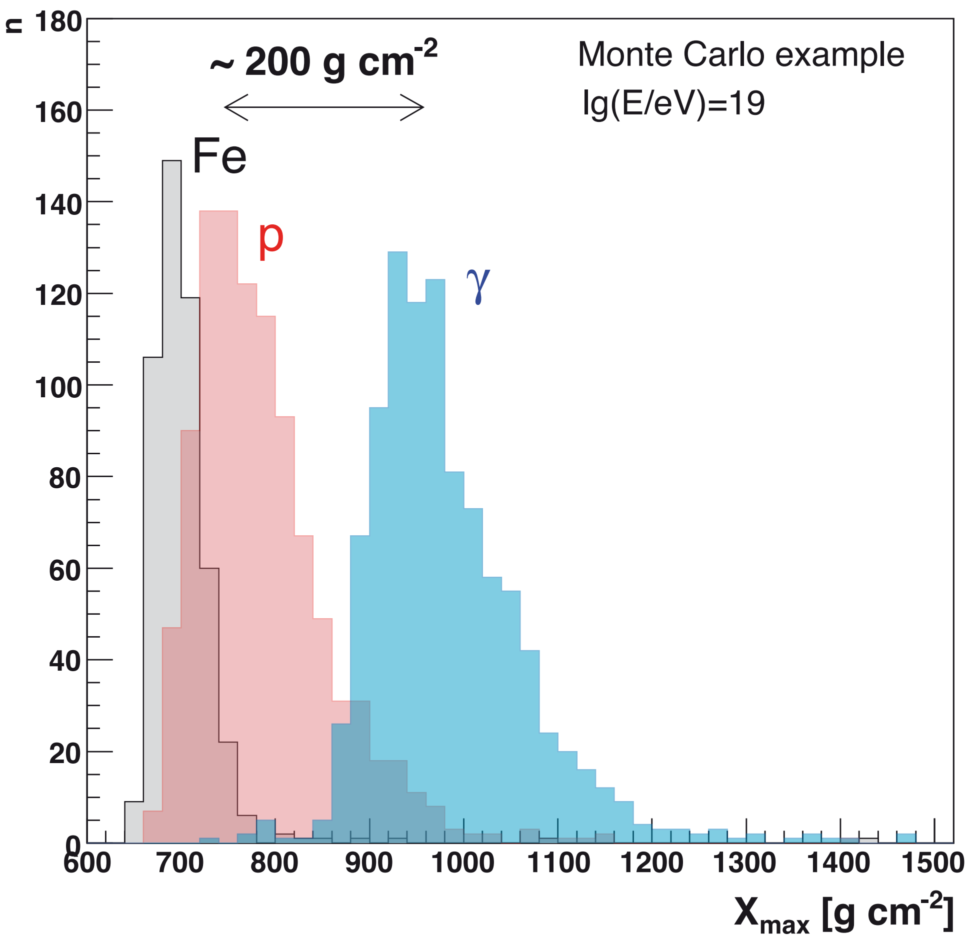
Clear trend to heavier elements ?

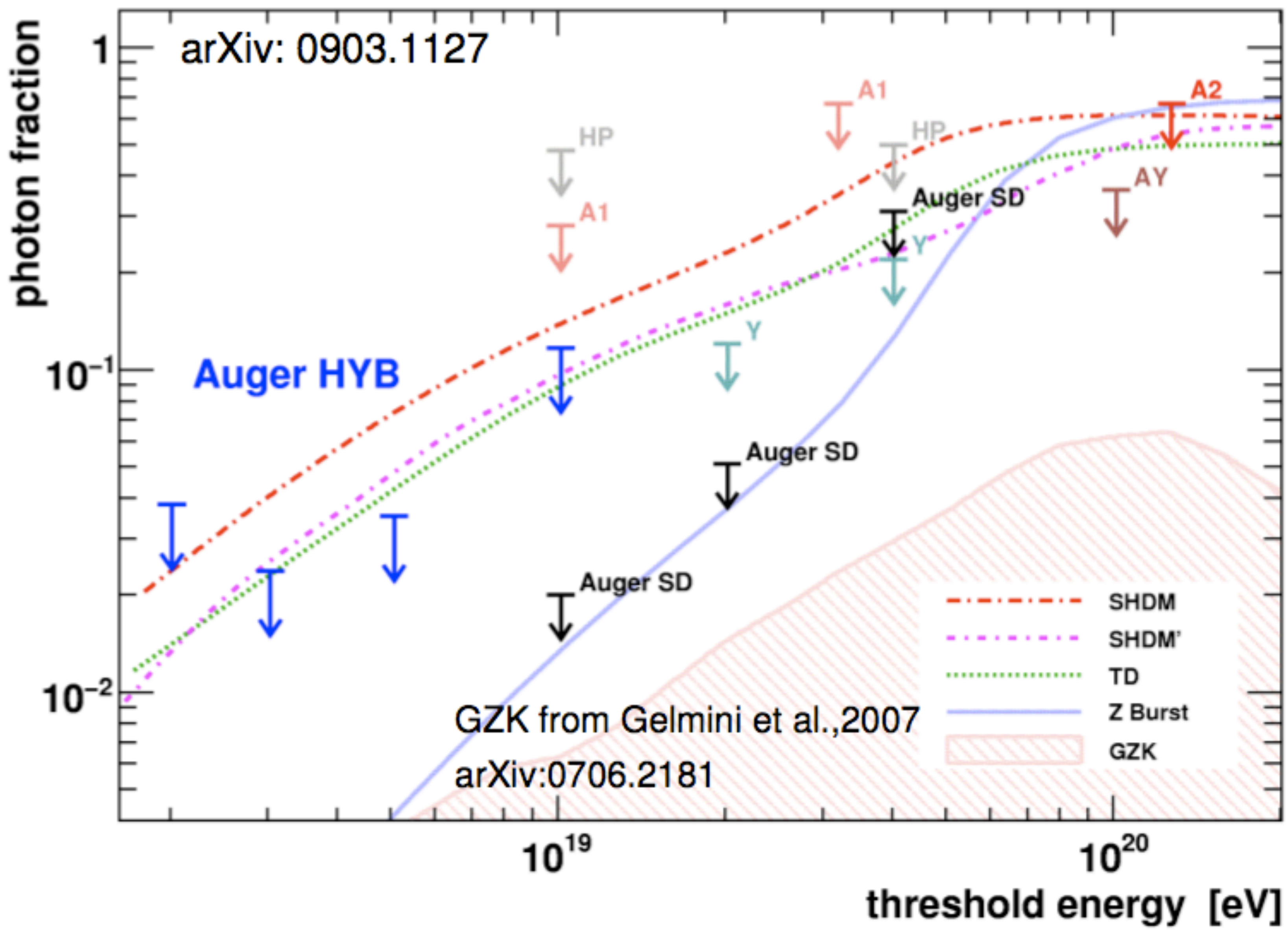
Telescope array (TA) may sheed light on HiRes results
(HiRes + 3 add. Telescopes
+ scint. Array of 600km^2)

Indications of Proton-Dominated Cosmic Ray Composition above 1.6 EeV

HiRes Collab. Phys.Rev.Lett.104:161101,2010

Photon flux limit

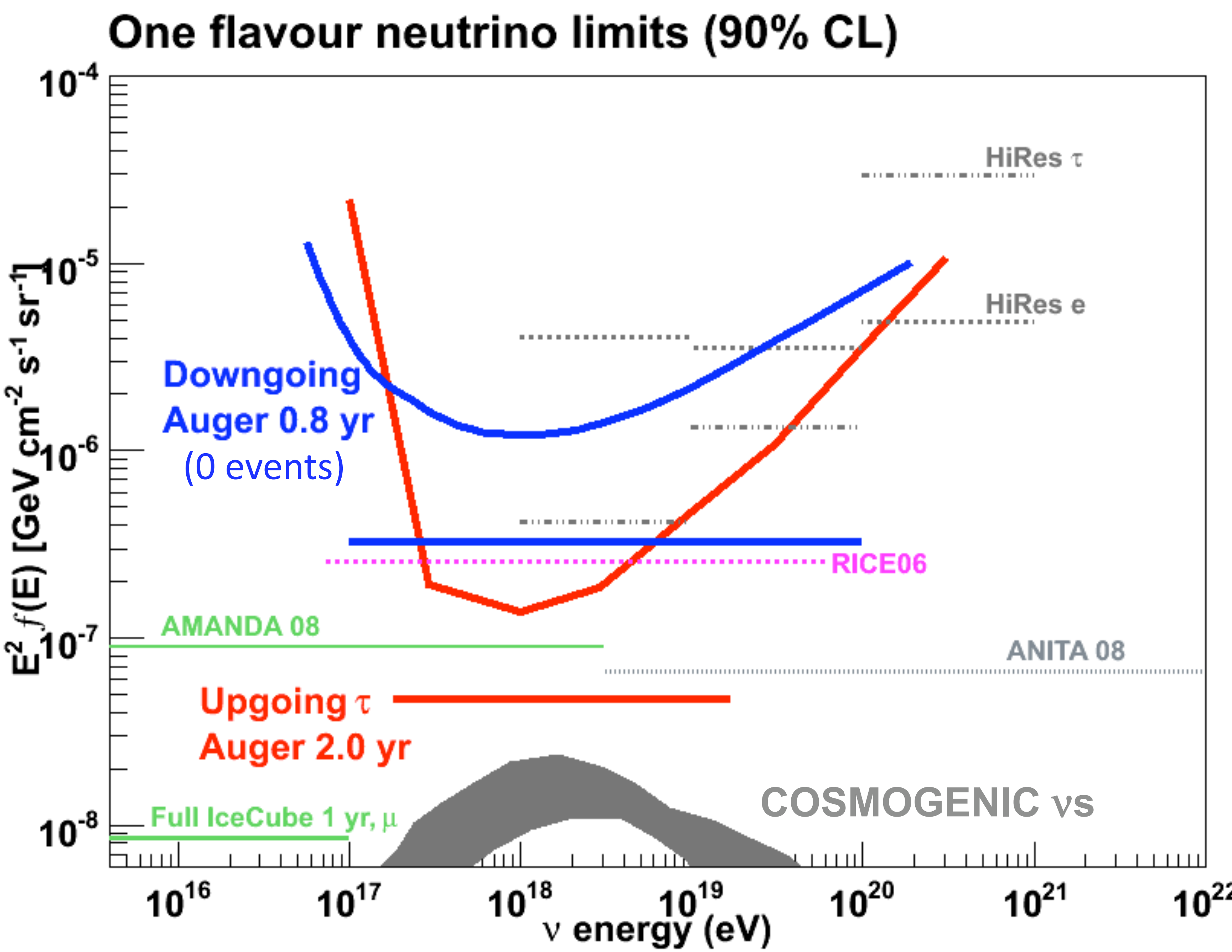




V. Scherini et al., arXiv:0903.1127 [astro-ph]

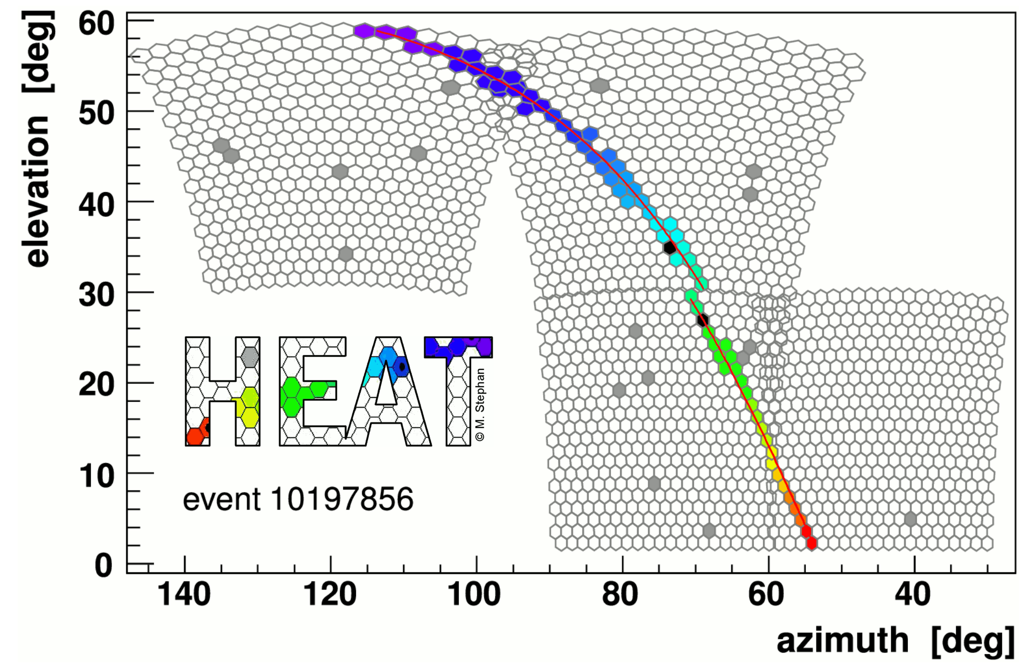
- All top-down production models strongly constrained
- GZK photons: 0.1% (95% C.L.) accessible after 20 years of Auger SD?
  If Auger North built, can be reached in 10 years (arXiv:0906.2347)

Neutrino flux limits



J. Tiffenberg, ICRC 2009, arXiv:0906.2347 [astro-ph]

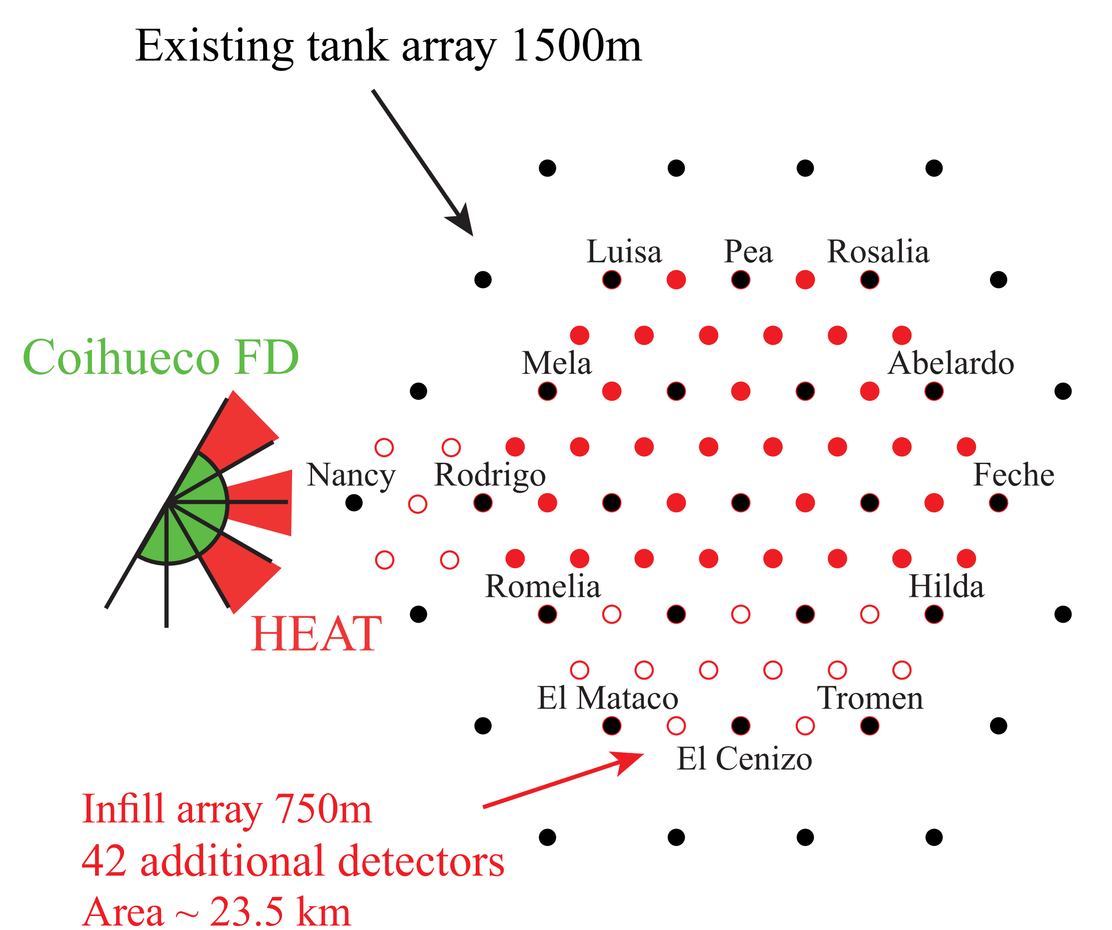
New developments



HEAT (FD):
- 3 telescopes at 30-60° in elevation
- Lower energy threshold
- Composition study at the transition region

AMIGA
(nested SD & additional muon counters):
- 750m spacing
- Infill SD stations
- 35qm muon counter

Radio:
- Establishing the selftriggering radio technique (MHz range)



Summary

Auger collects data with an annual exposure of 7000 km^2 sr yr
Largest statistics and highest quality ever

Spectrum:

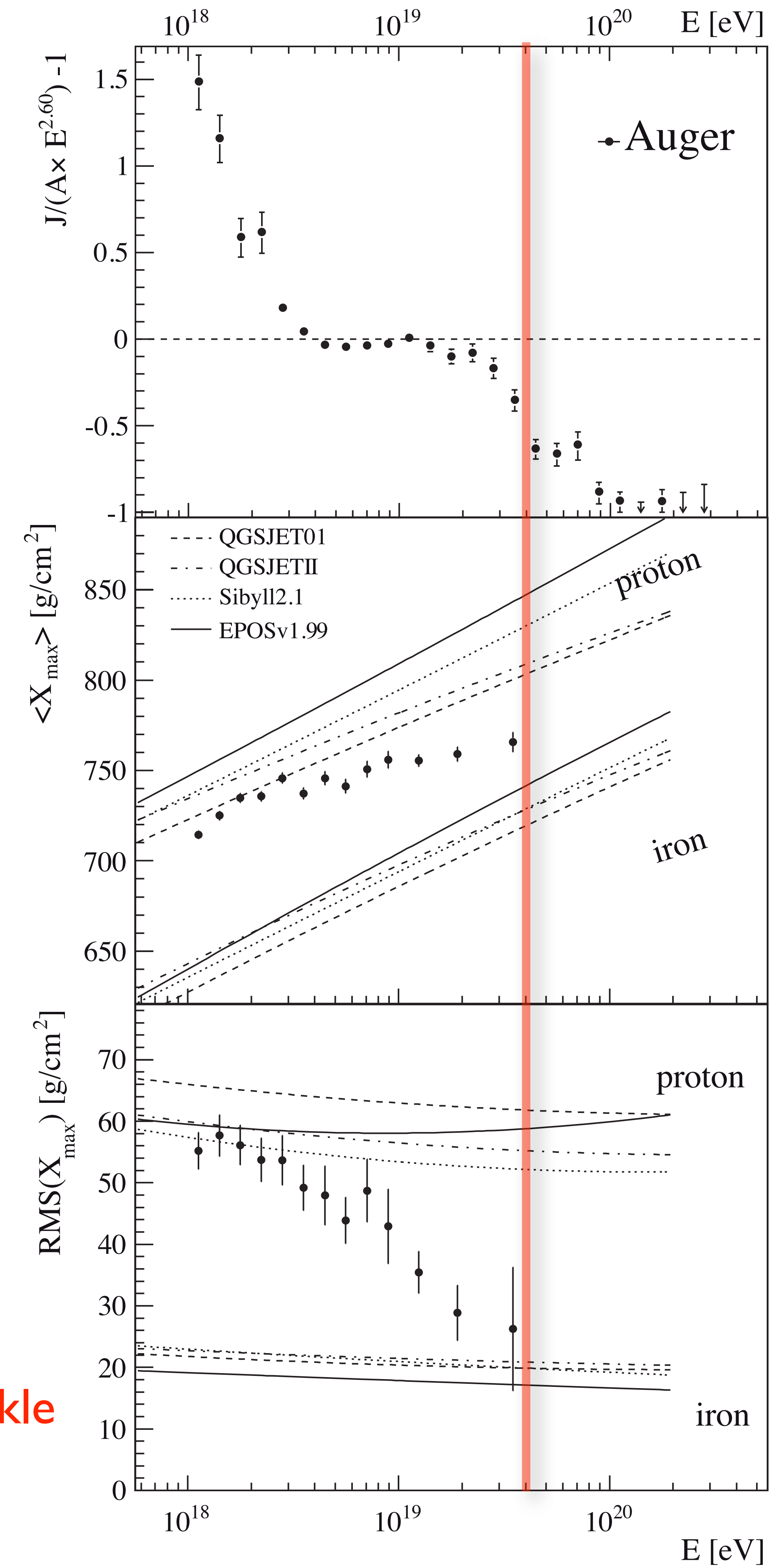
- ankle and steepening seen
  at ≈ 4.1×10^{18} and ≈ 3.9×10^{19} eV
  with model-independent measurement and analysis.

ankle: transition galactic to extra-galactic? (HEAT, infill SD)
cut-off: likely GZK cut-off, hint that UHECRs are protons?

Mass composition:

- upper limits on photons and neutrinos,
  i.e. most top-down scenarios of CR origin rejected
- hint at mixed / heavy nuclear composition
  at high energies
  (Suffering from X_{max} statistics in GZK-energy range)

Outlook:
The Observatory is being extended to a multi-hybrid observatory allowing high quality measurements also below ankle



END

Astroparticles: particles from astrophysical sources

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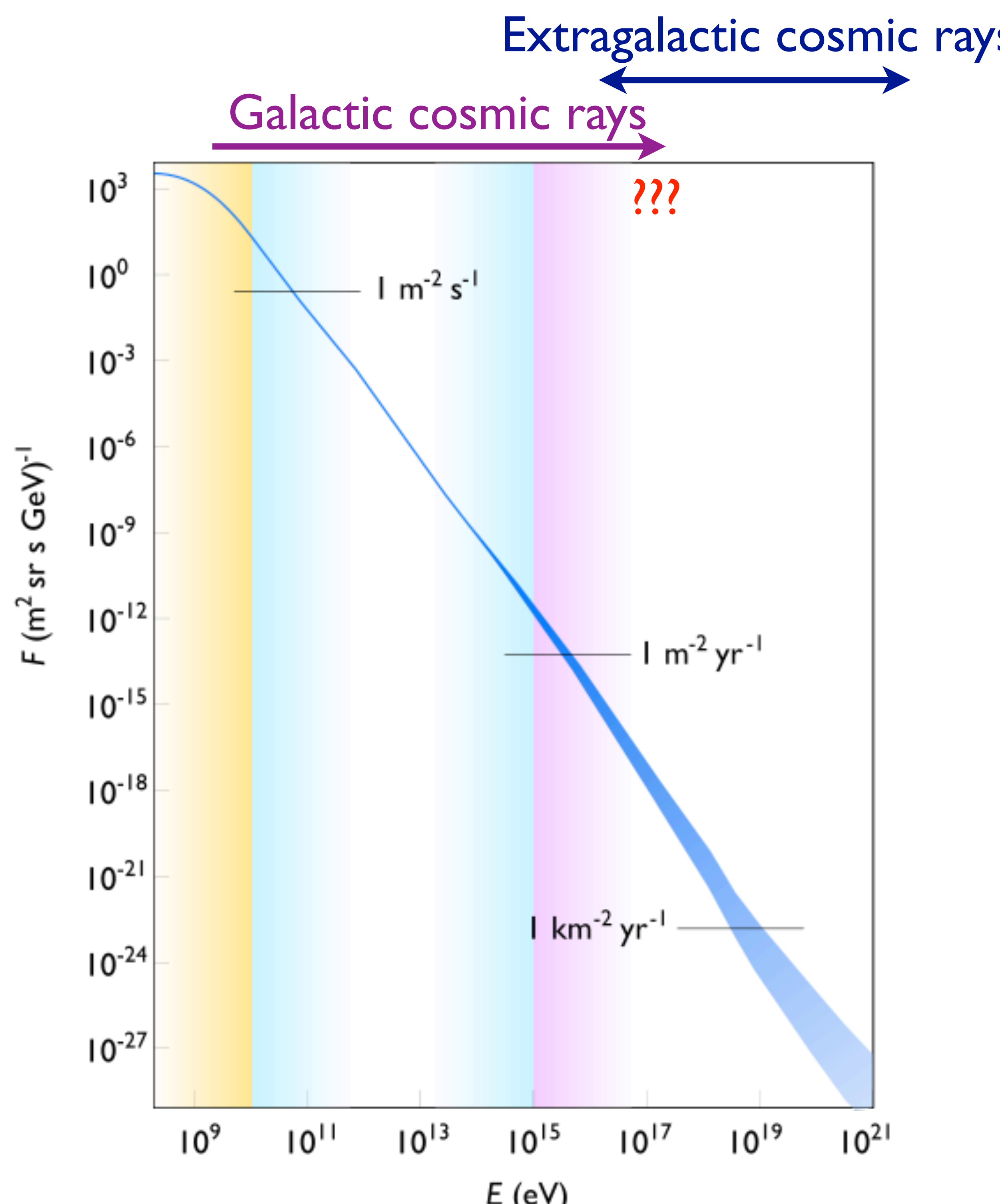


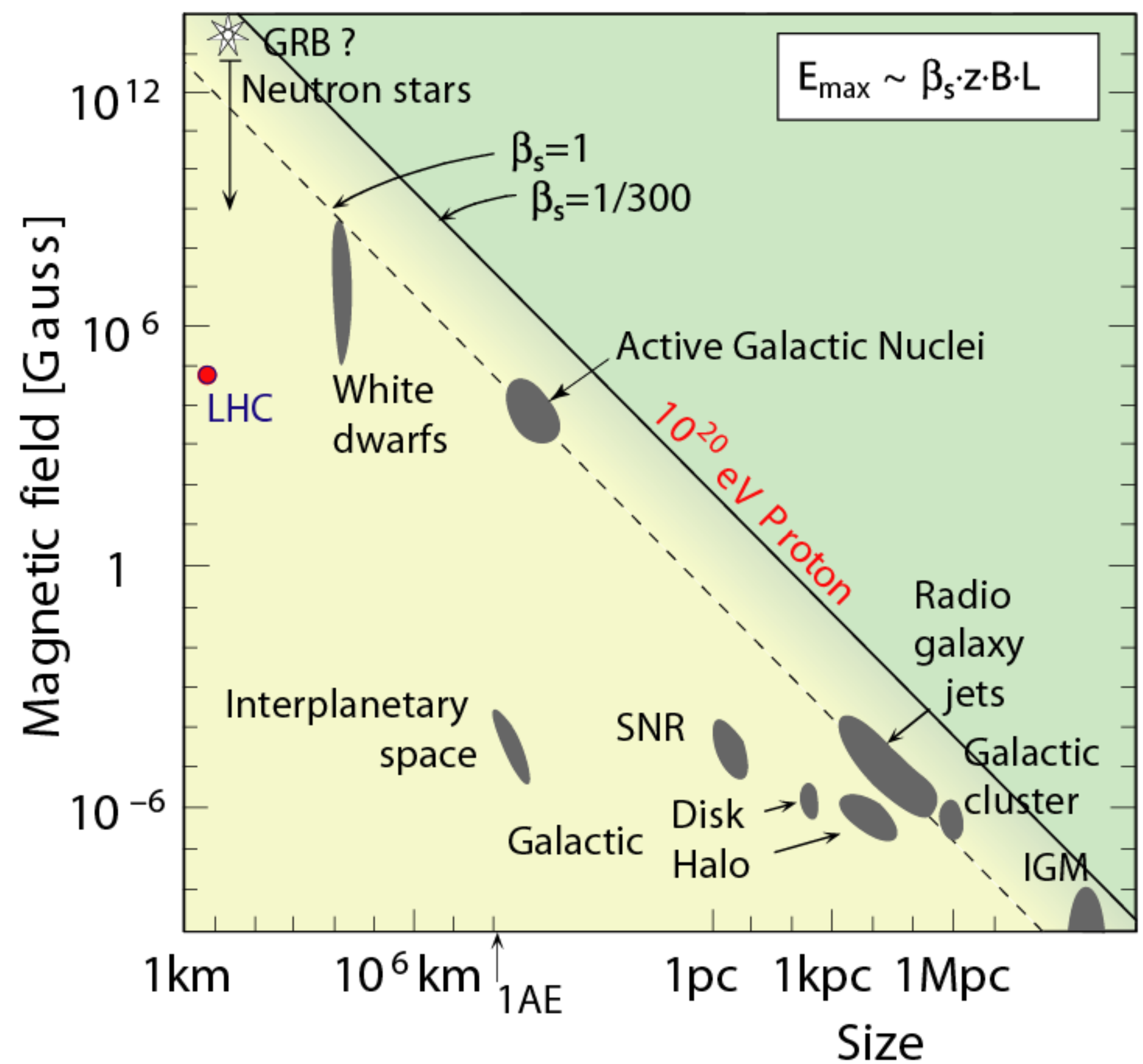
(UHECRs: $E>10^{19}$eV)

Astrophysical candidates

$$E_{\max} \propto Z\beta_s BL$$

Z: charge of the CR
ß: shock velocity
B: magnetic field strength
L: size of the accel. region

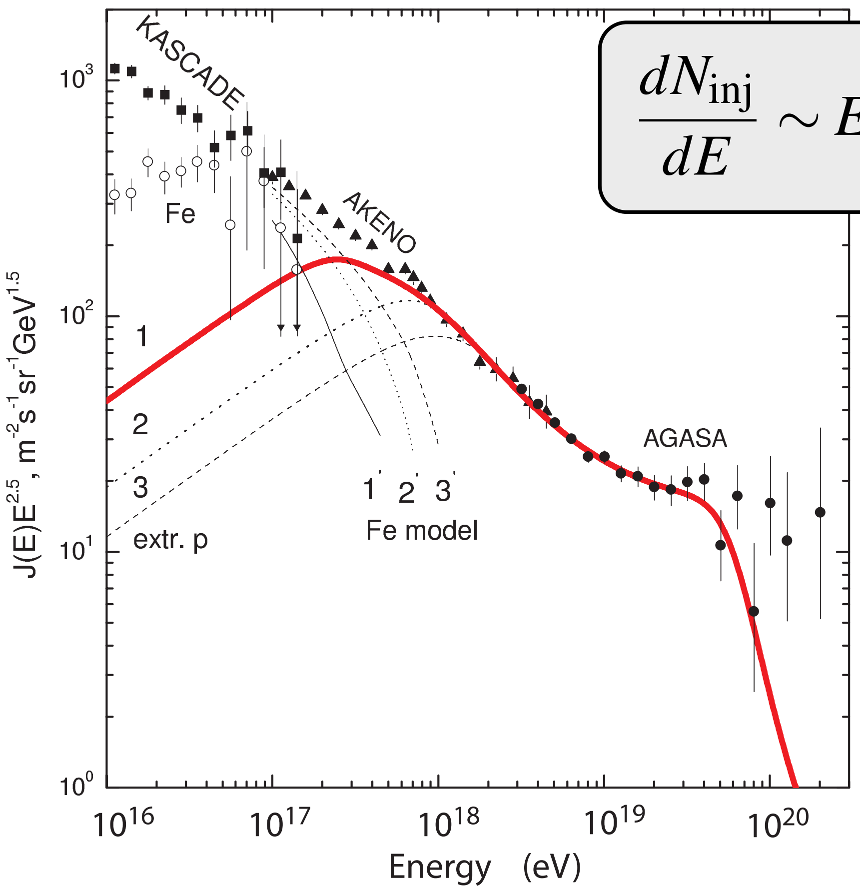
... Or top down
mechanims



Hillas diagram (Blümer 2000)

Modelling ankle and suppression

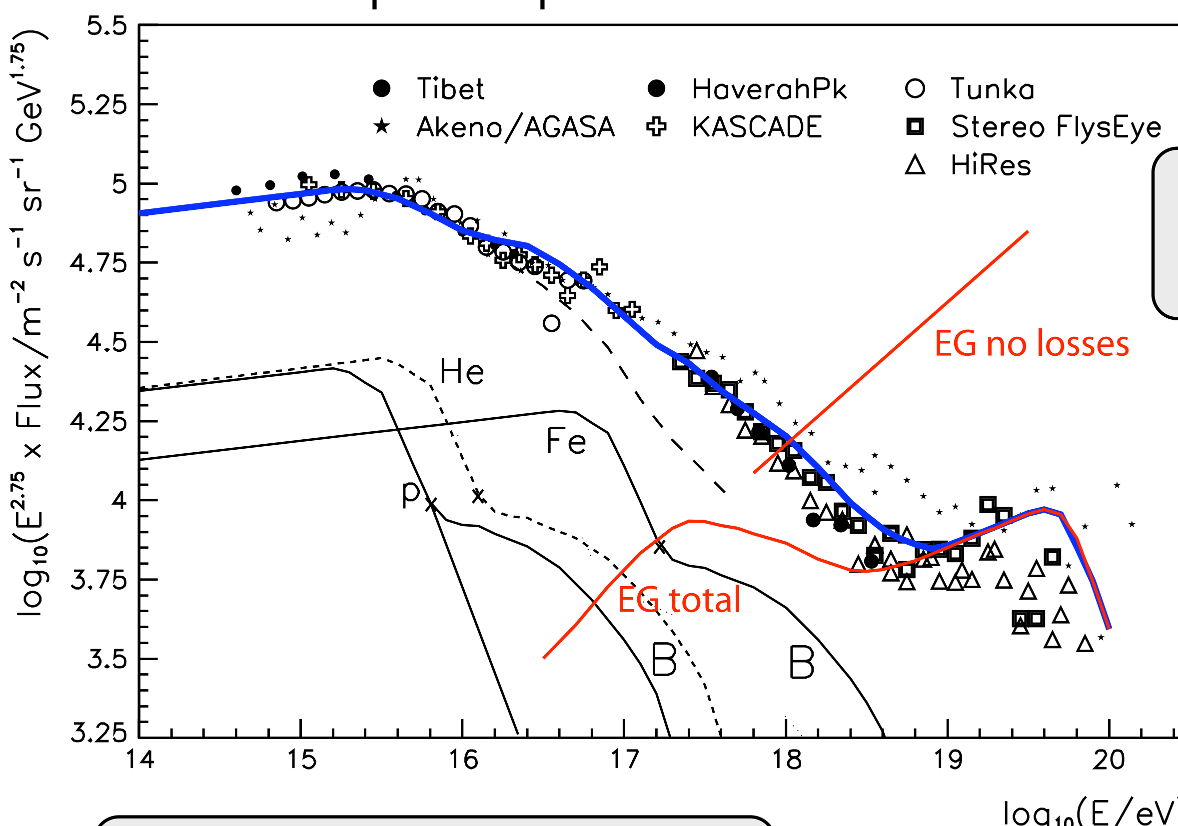
Steep injection spectrum



$$\frac{dN_{\rm inj}}{dE} \sim E^{-2.7}$$

(Aloisio, Berezinsky et al., 2004)

Scaled all-particle spectrum



$$\frac{dN_{\rm inj}}{dE} \sim E^{-2.3}$$

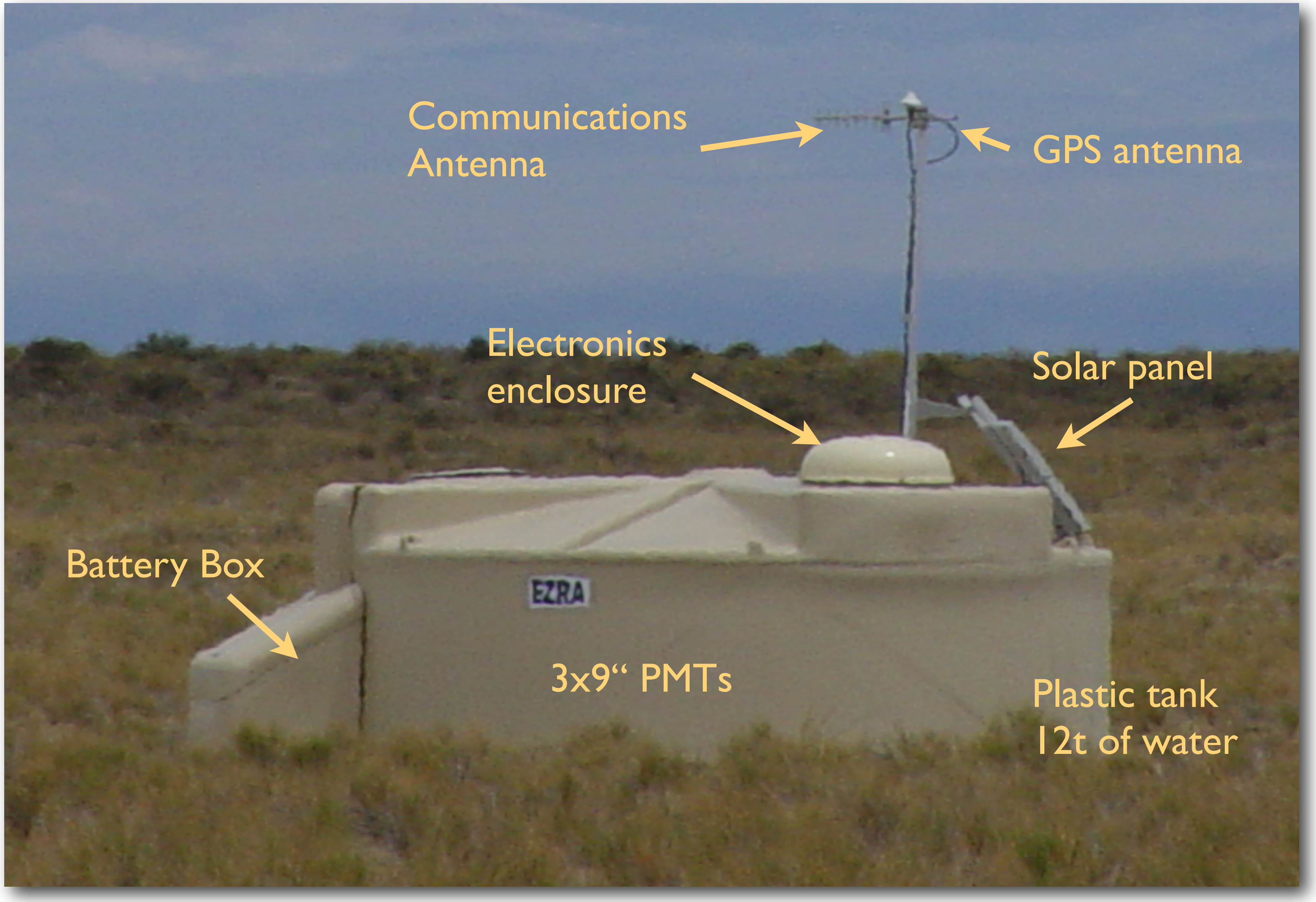
p ... Fe as UHECR

Need additional ``component B´´

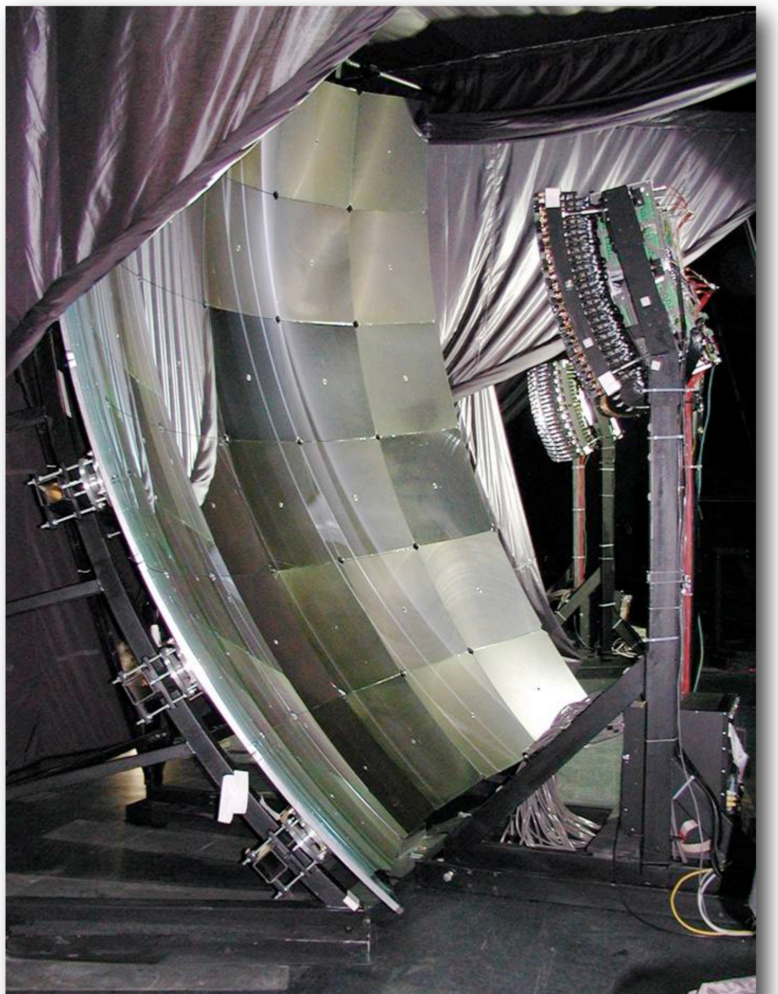
(Hillas J. Phys. G31, 2005)

The surface detector

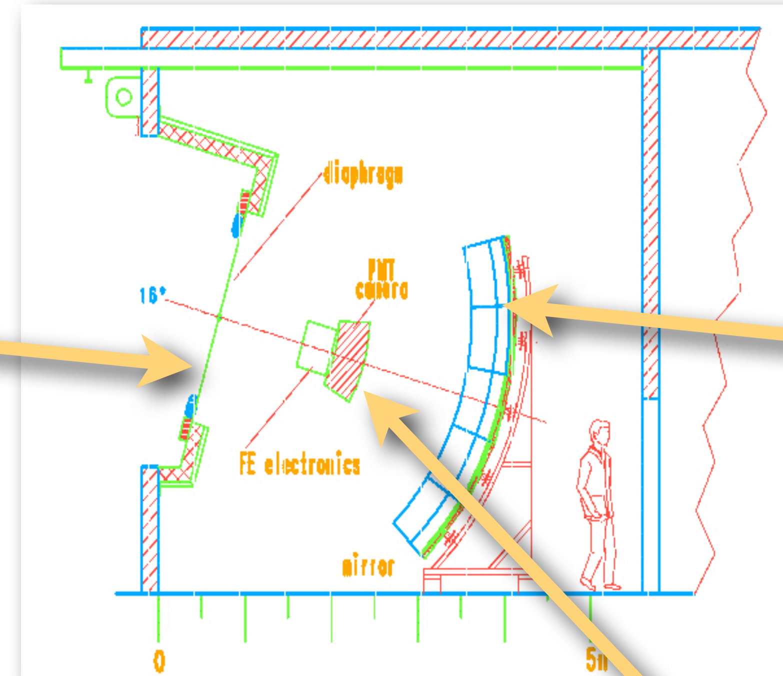
- 1600 Water Cherenkov tanks (1.2 m height, 10 m^2 area)
- 12,000 ltrs of purified Water
- Three 9“ PMTs
- 40 MHz FADCs
- solar powered
- GPS based timing
- micro-wave communication



The fluorescence detector

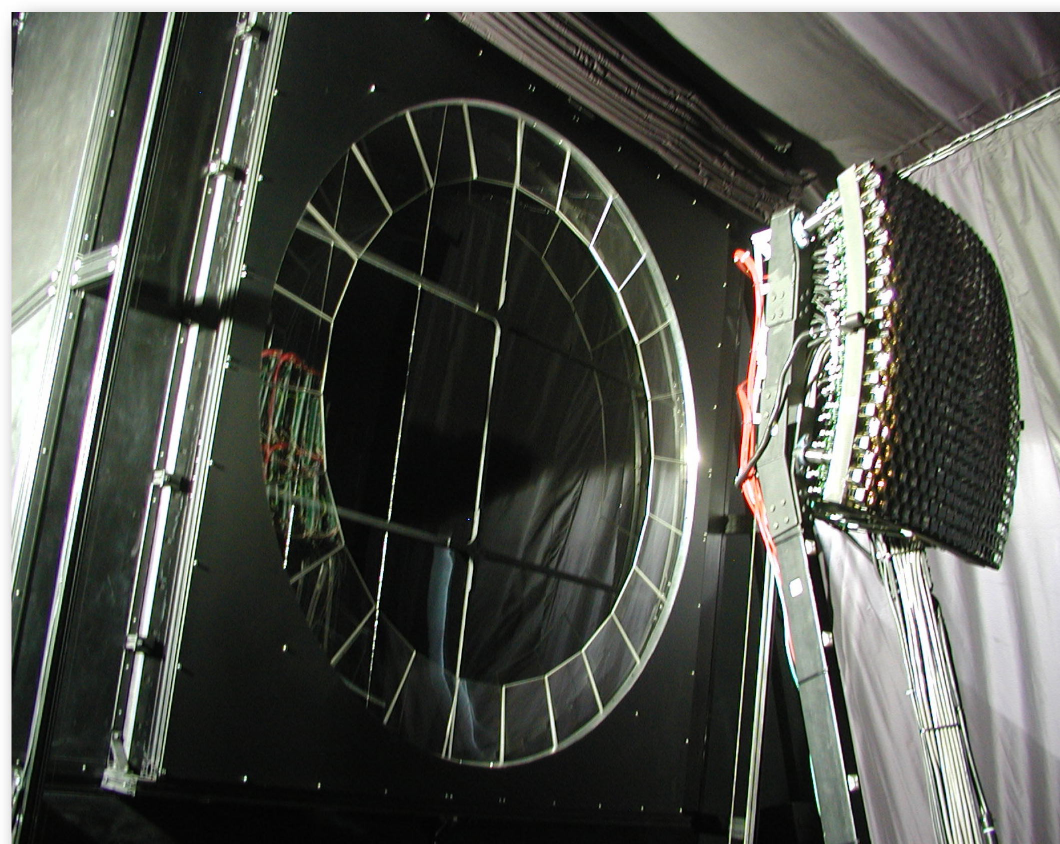


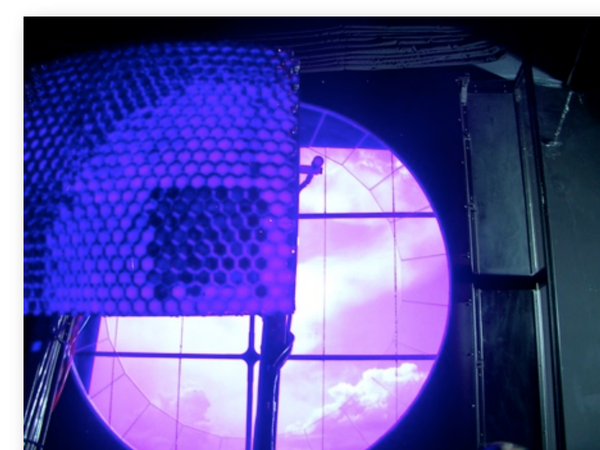
Aperture stop
and optical filter



3.4 meter radius
segmented mirror

440 pixels
camera

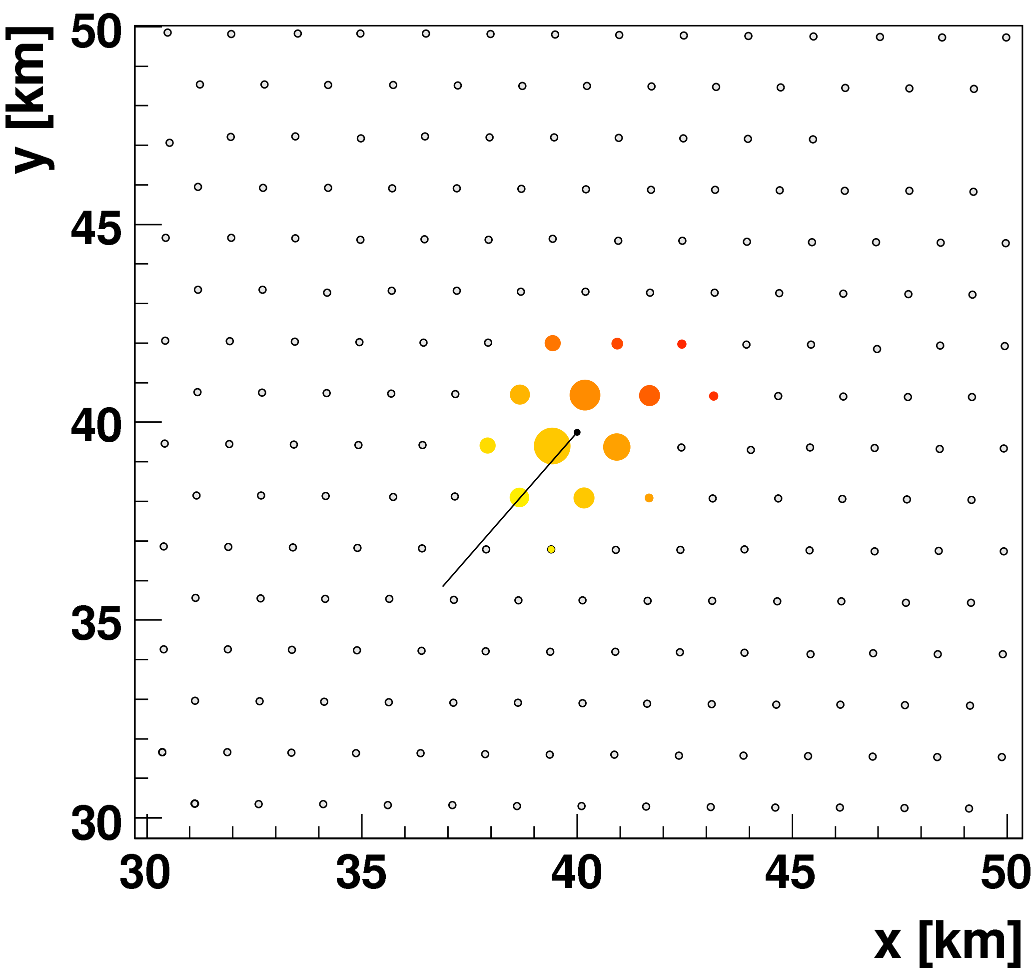


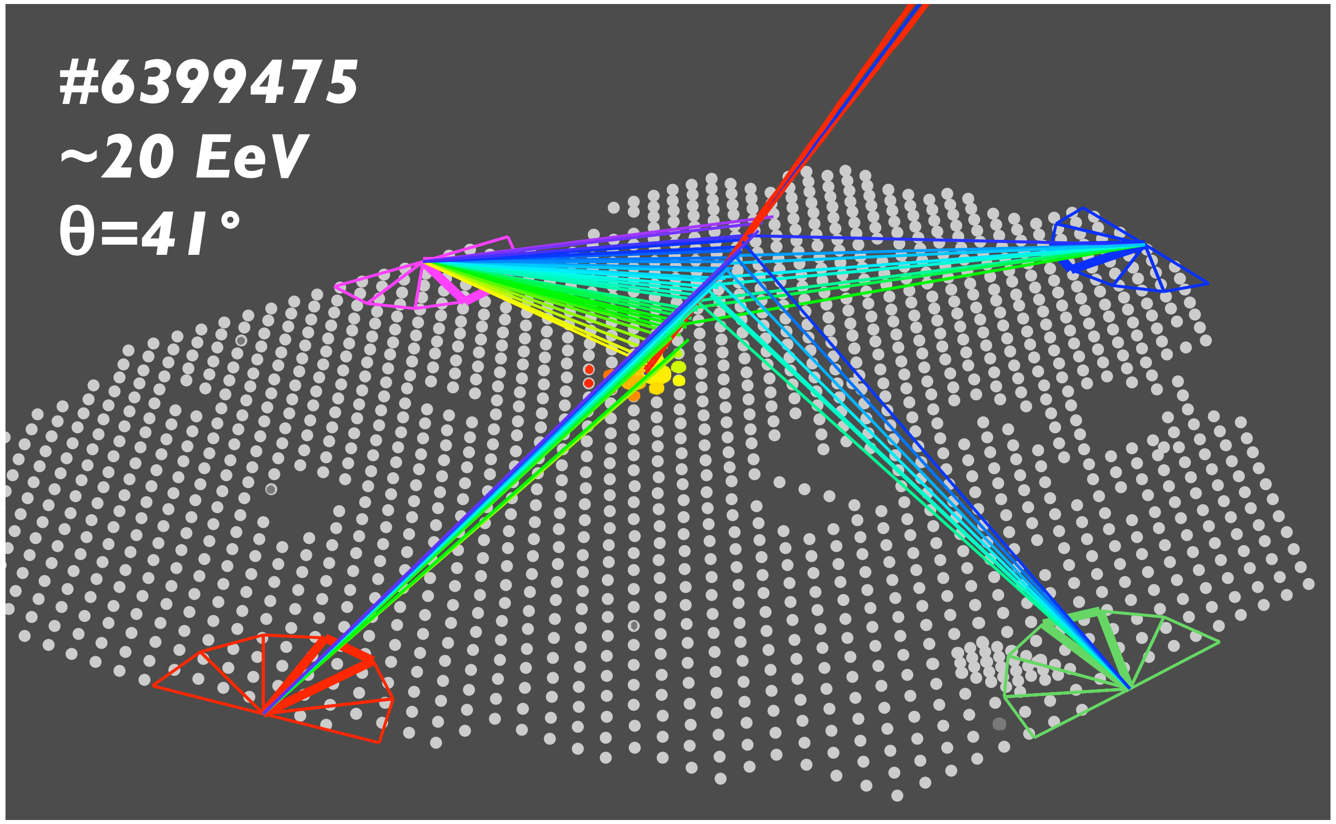


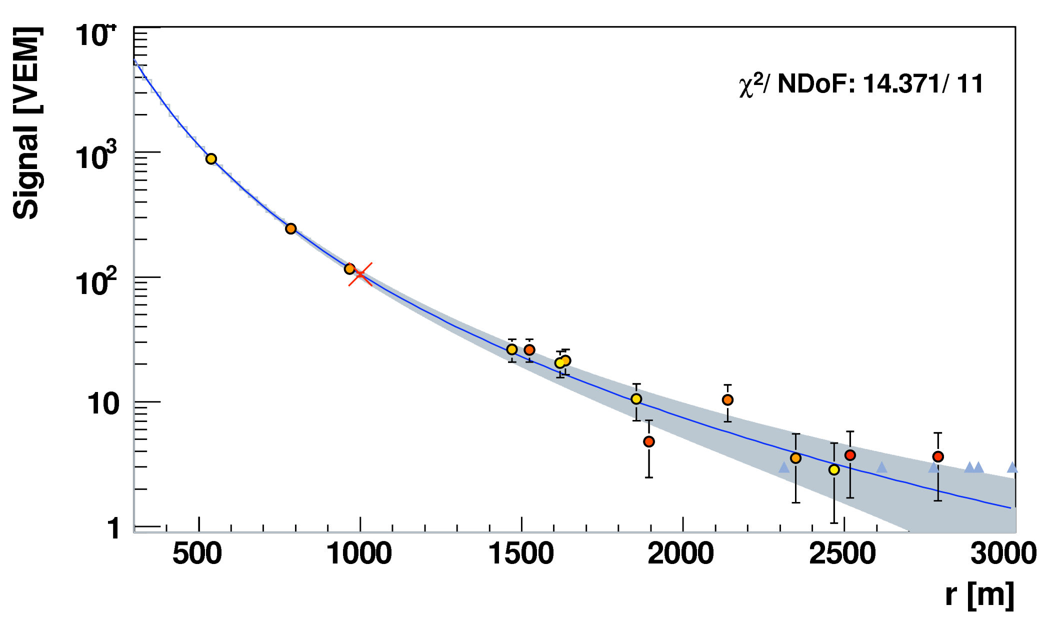
The hybrid era

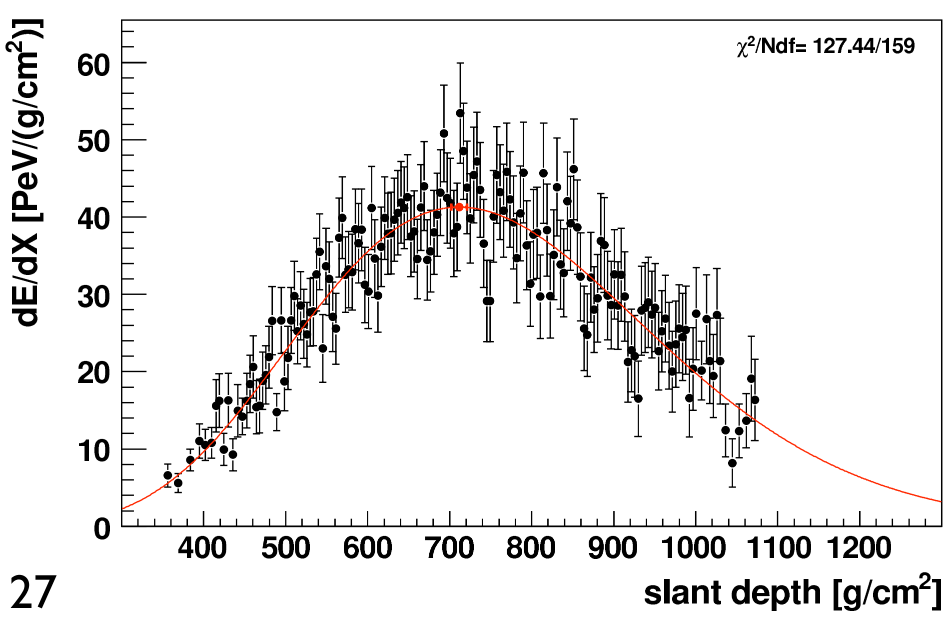
	FD-mono	SD-only	FD+SD (Hybrid)	SD (Hyb calib)
Angular resolution	~3-5°	~1-2°	~0.5°	~1-2°
Aperture	dependent on detector MC and atmosph. cond.	purely geometric, A and model free	dependent on detector MC and atmosph. cond.	purely geometric, A and model free
Energy	approx. A and model free	A and model dependent	approx. A and model free	approx. A and model free
Duty cycle	~13%	~100%	~13%	100%
Experiment	Fly's Eye, HiRes I, Hires II	AGASA, Haverah Park	Auger	Auger

4-fold event

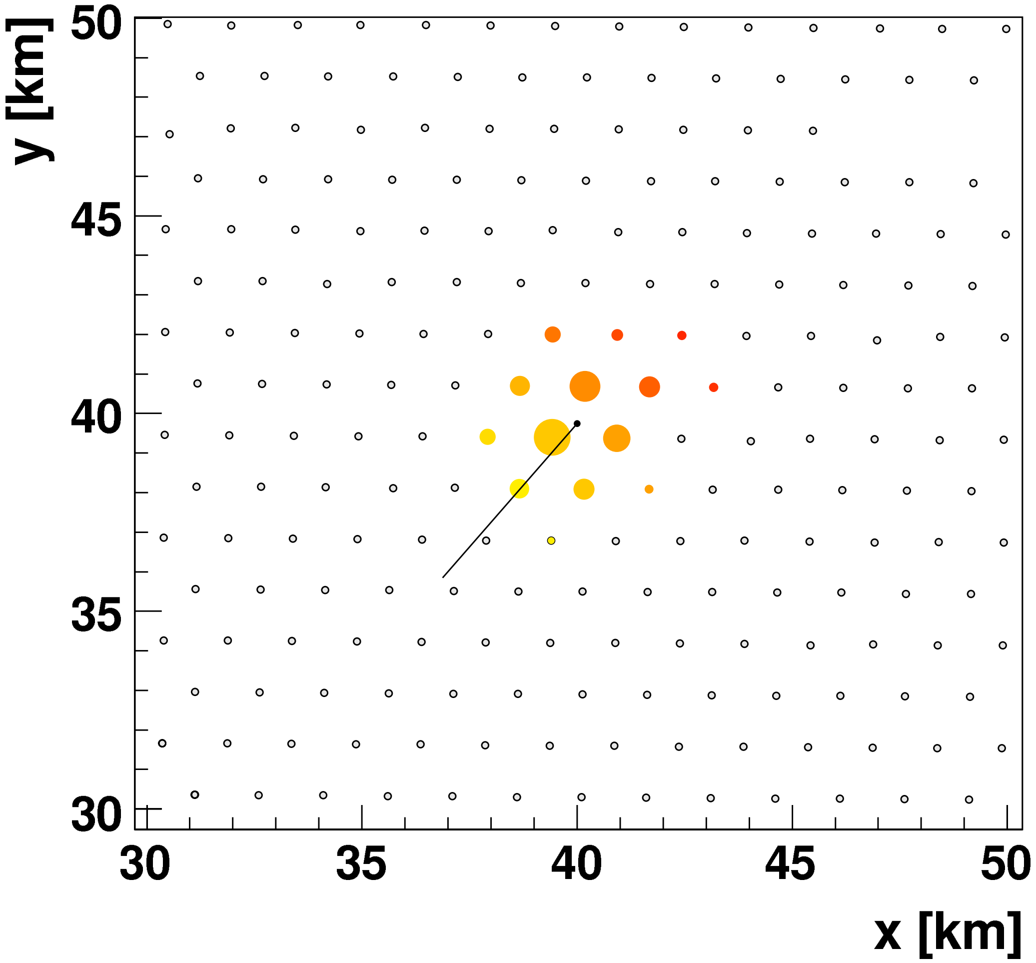

y [km]
x [km]
30
35
40
45
50

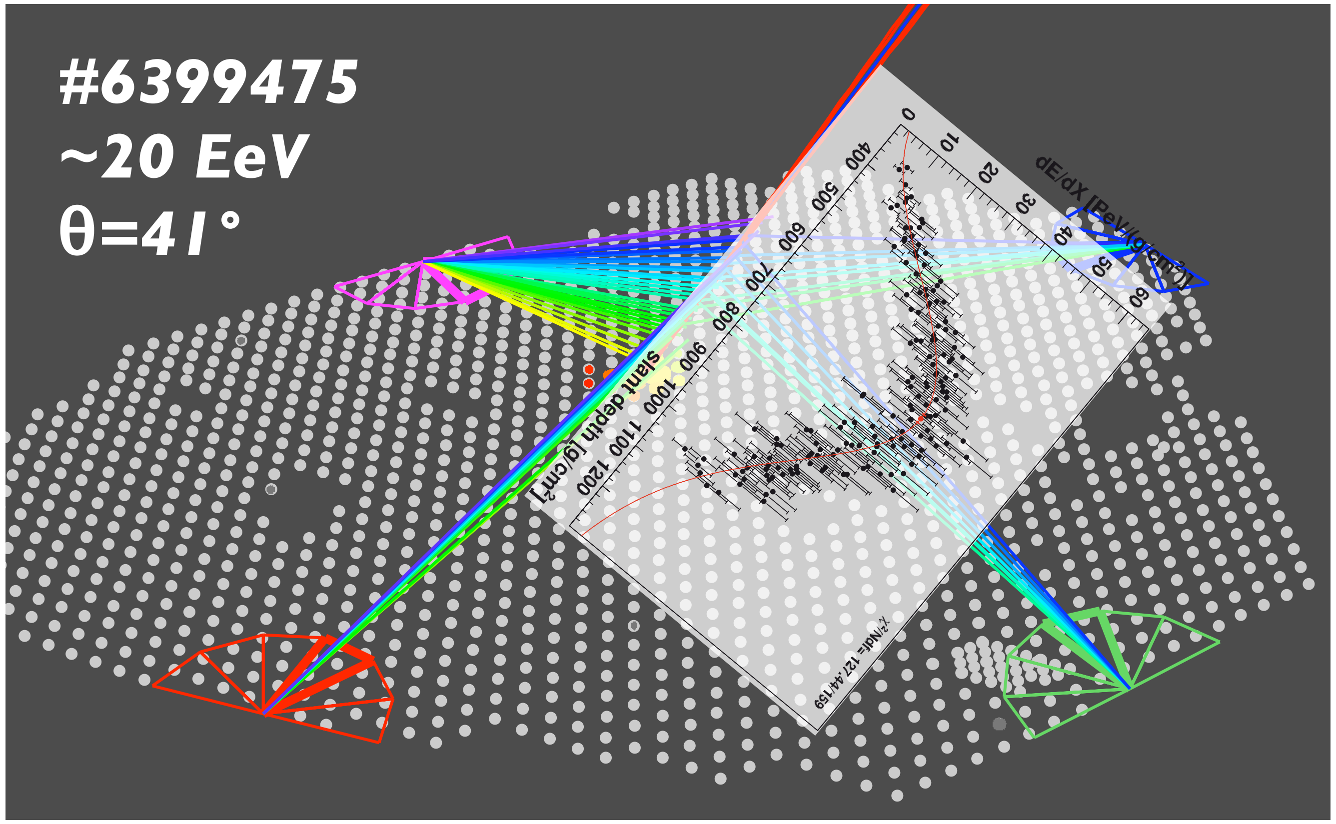

#6399475
~20 EeV
θ=41°


Signal [VEM]
χ^2/ NDoF: 14.371/ 11
r [m]
500
1000
1500
2000
2500
3000


dE/dX [PeV/(g/cm^2)]
χ^2/Ndf= 127.44/159
slant depth [g/cm^2]

4-fold event


y [km]
x [km]
30
35
40
45
50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~20 EeV
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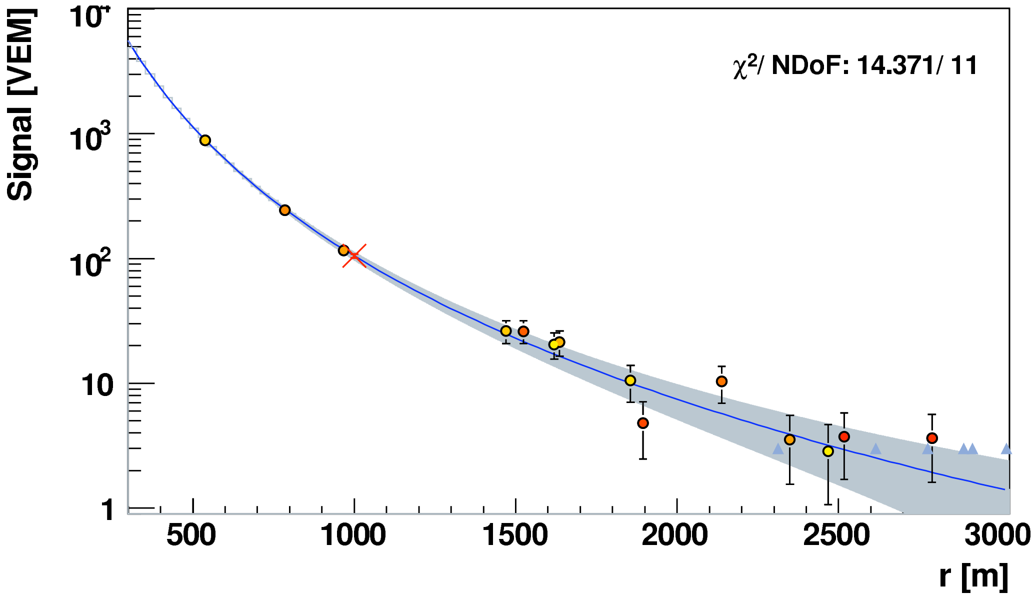
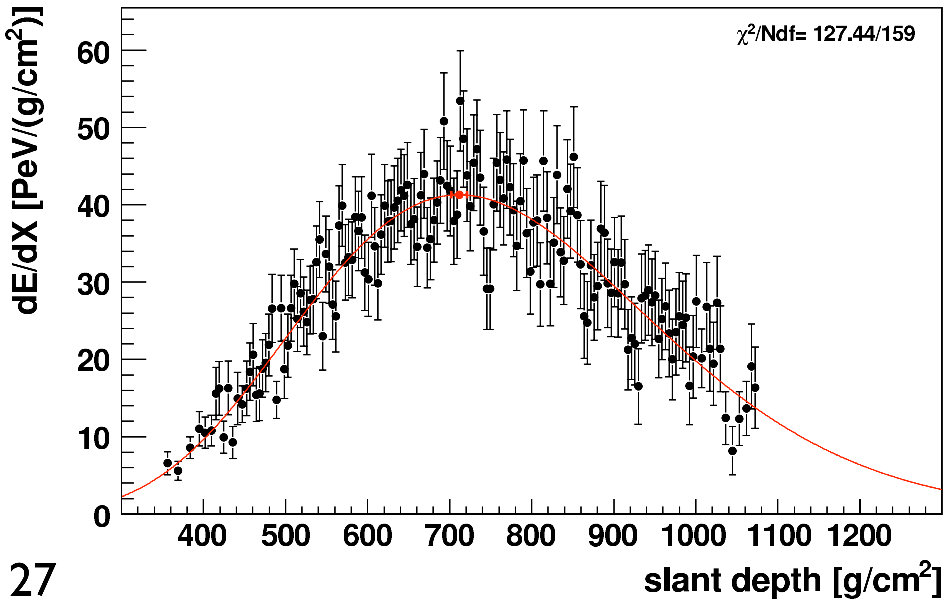
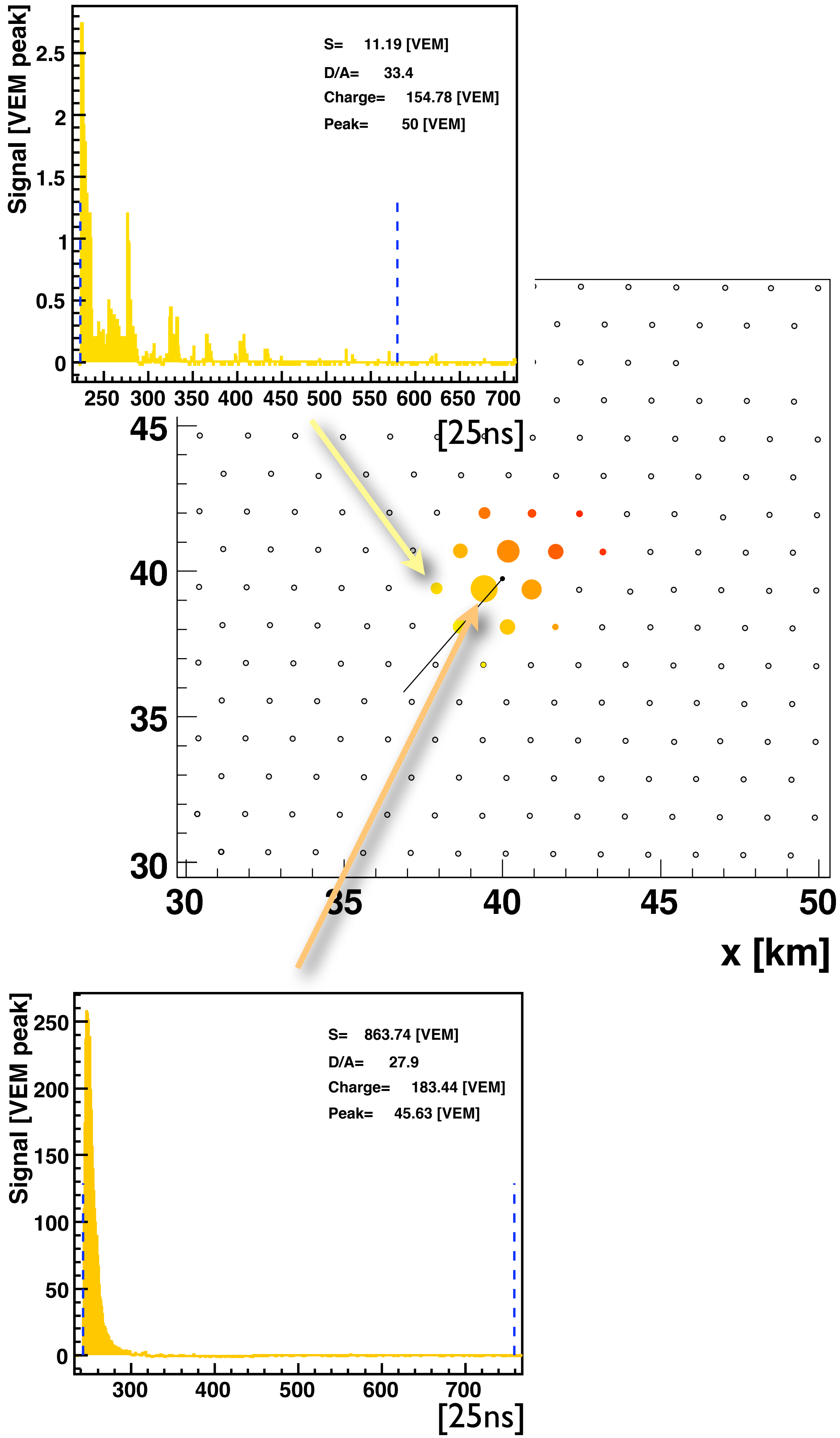
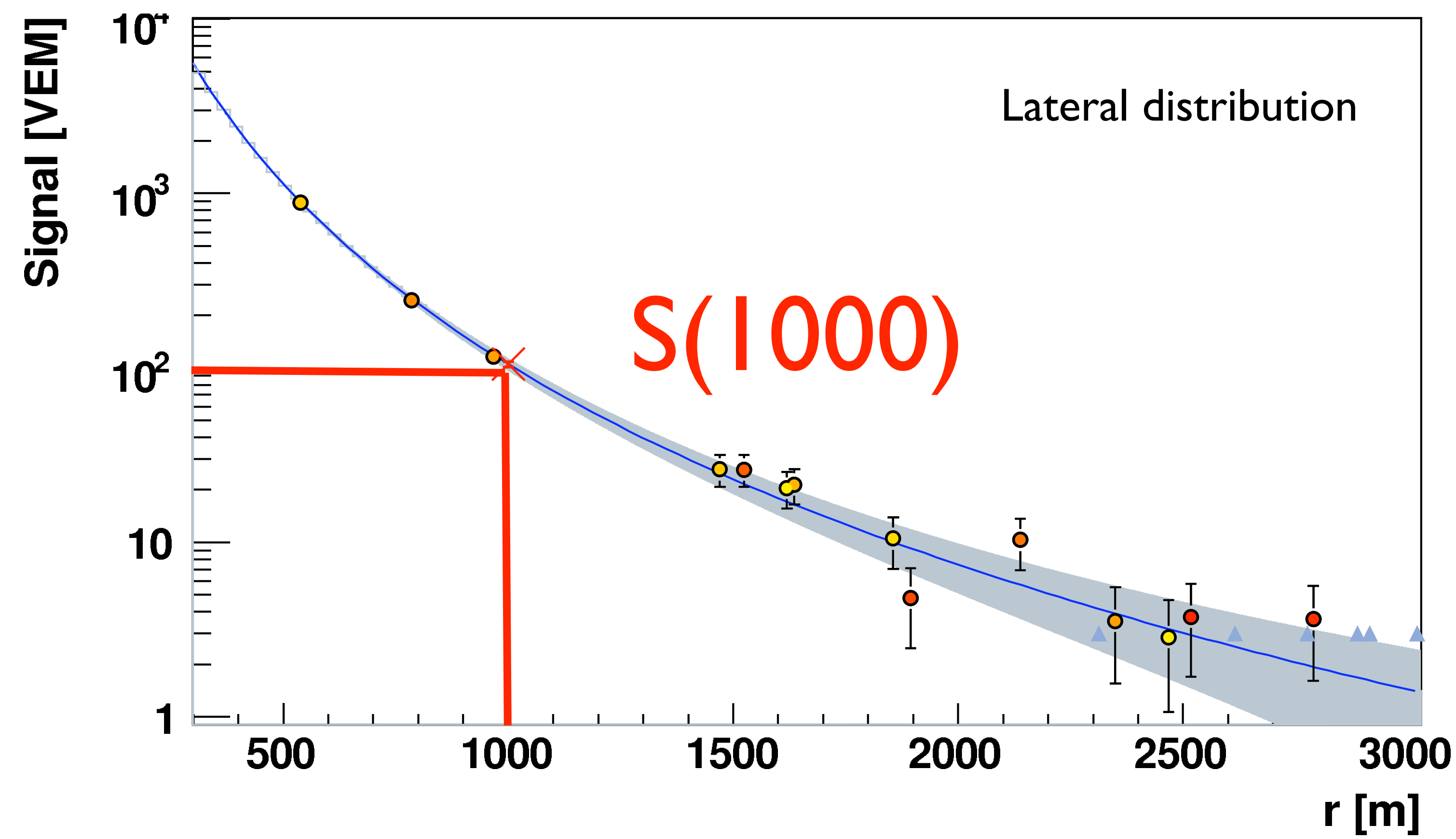

Signal [VEM]
χ^2/ NDoF: 14.371/ 11
r [m]


dE/dX [PeV/(g/cm^2)]
χ^2/Ndf= 127.44/159
slant depth [g/cm^2]

SD reconstruction



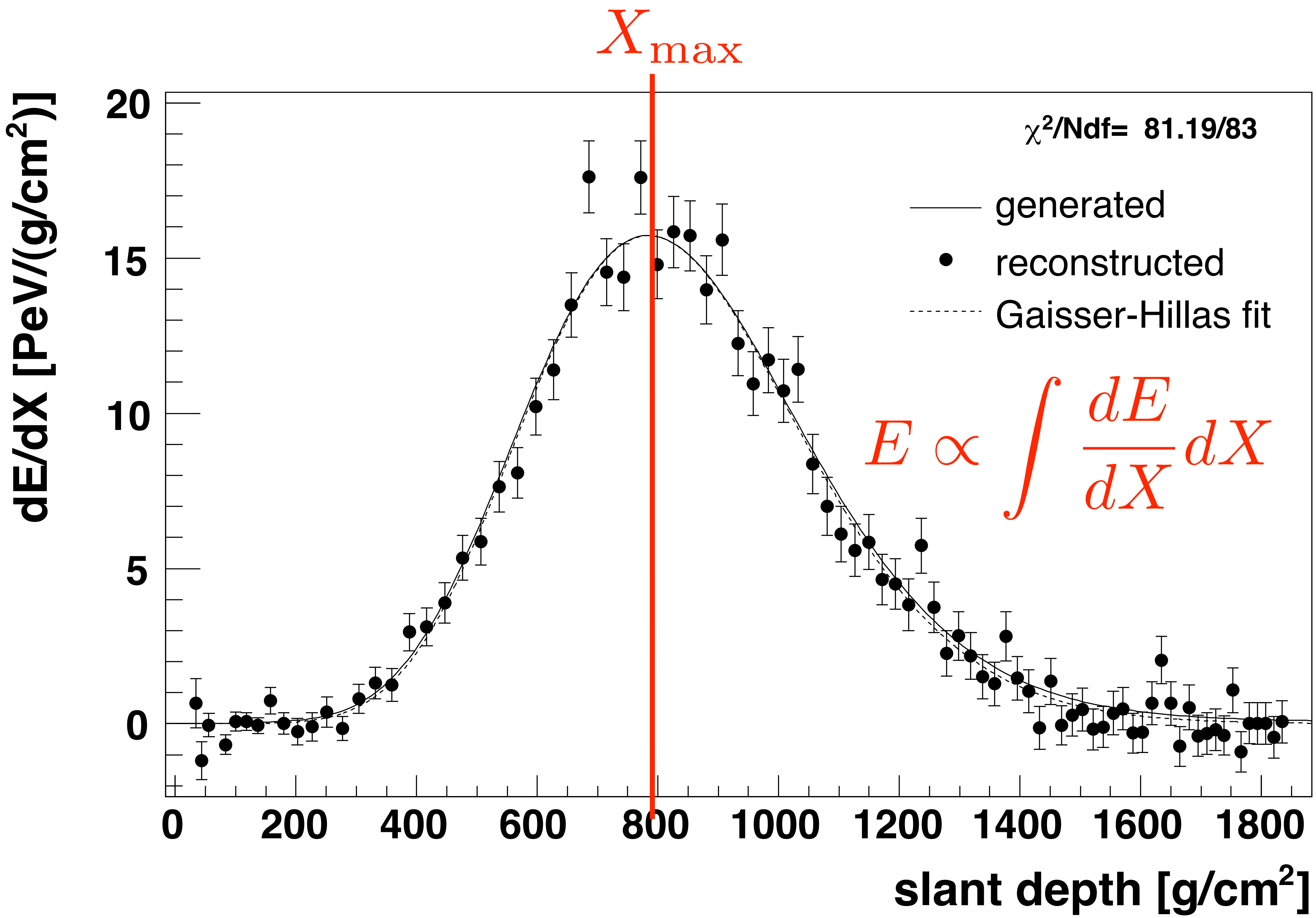


Detector signal at 1000 m from shower core

- S(1000)
- determined for each surface detector event

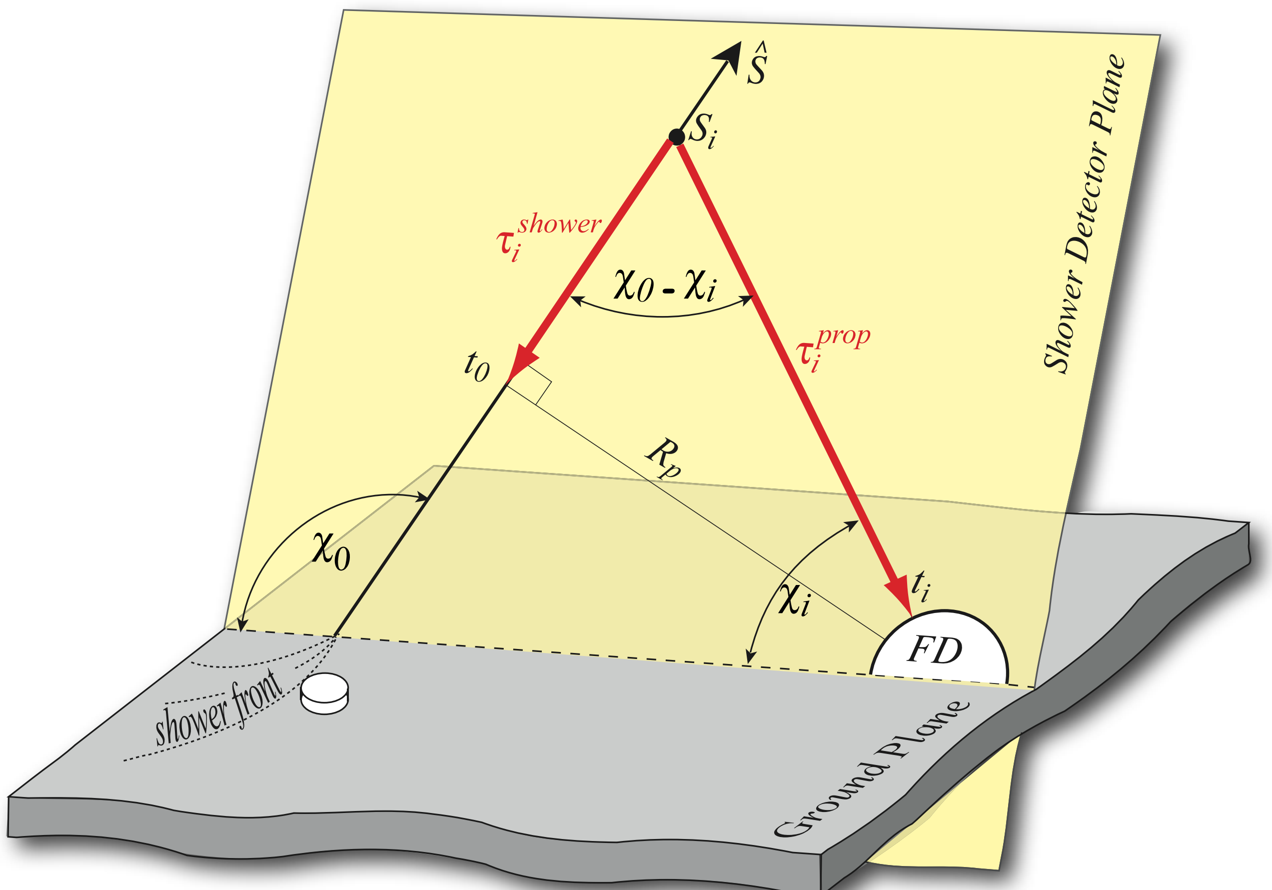
S(1000) ~ E

FD reconstruction



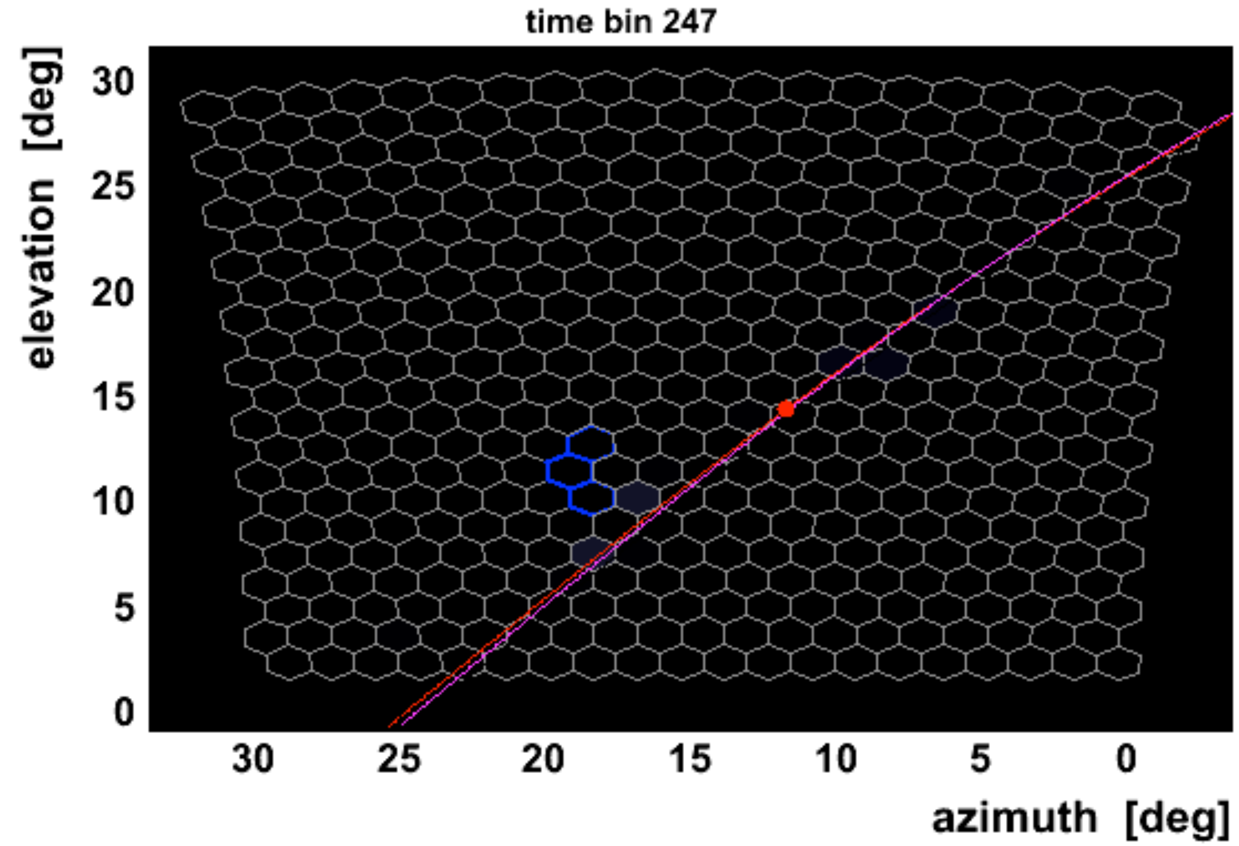
Geometrical reconstruction

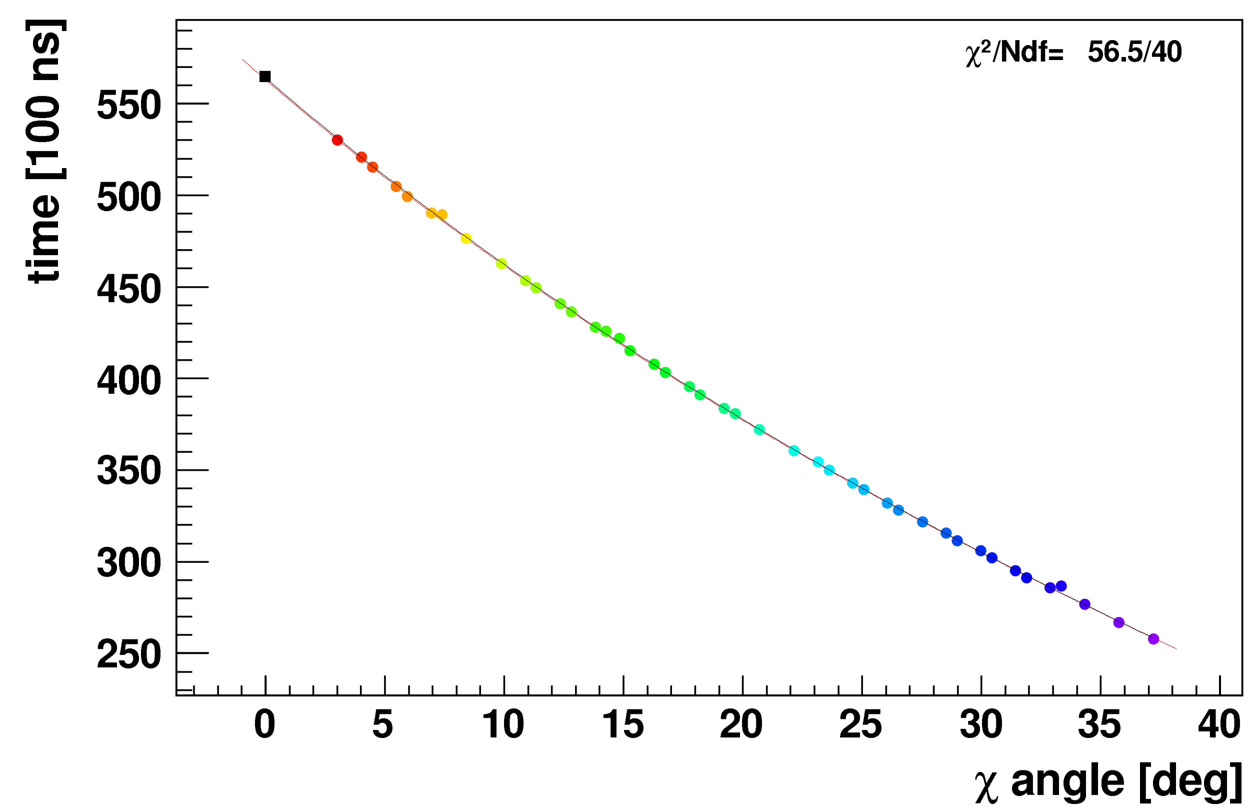
Precise shower geometry
from breaking degeneracy using SD timing



times, t_i, at angles χ_i, are key to finding R_p

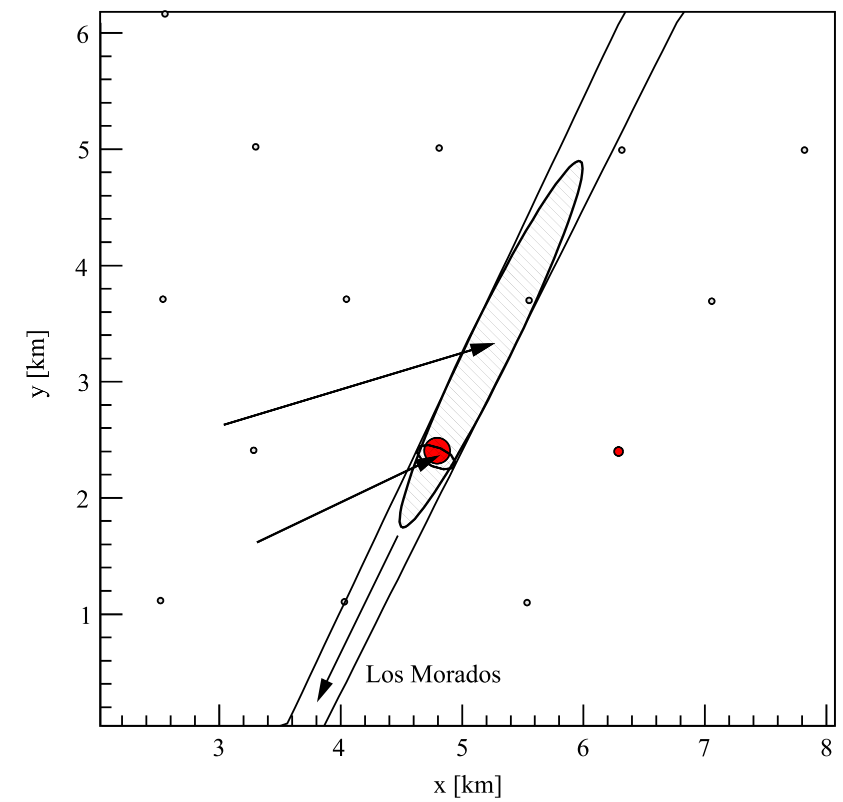
$$t_i = t_0 + \frac{R_p}{c} \cdot \tan\left(\frac{\chi_0 - \chi_i}{2}\right)$$

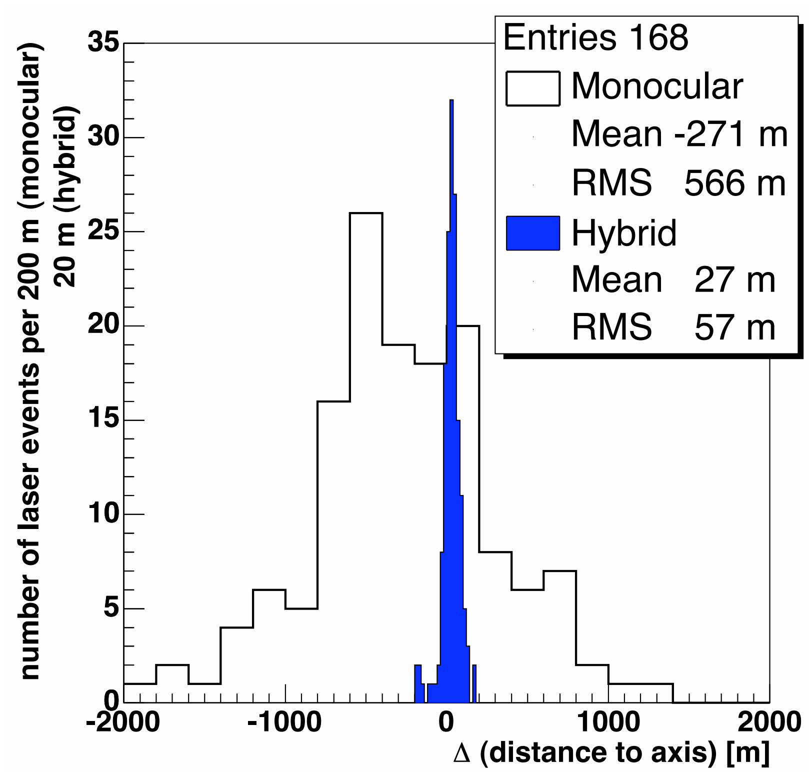


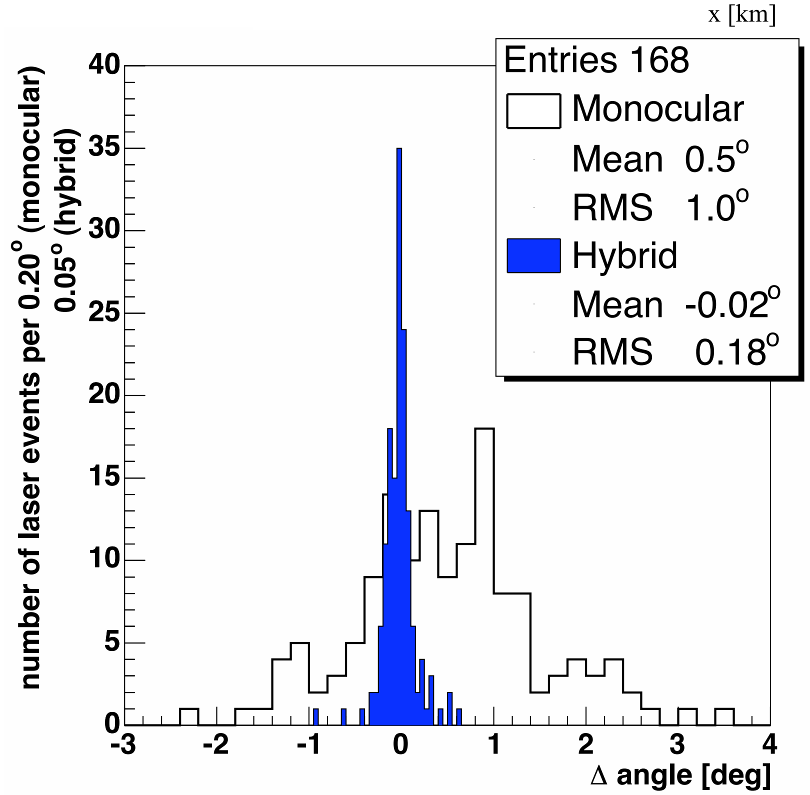


Hybrid resolution

FD only	~ 500 m
FD + 1 station	~ 50 m
Hybrid energy resolution	~ 8% above 10 EeV
Hybrid X_{max} resolution	~20 g/cm^2







How to determine the spectrum

Flux measurement $$J(E) = \frac{d^4N(E)}{dE\, dA\, d\Omega\, dt} \simeq \frac{1}{\Delta E}\frac{\Delta N(E)}{\mathcal{E}(E)}$$

E: straight forward from FD,
but FD only active for 10% of time

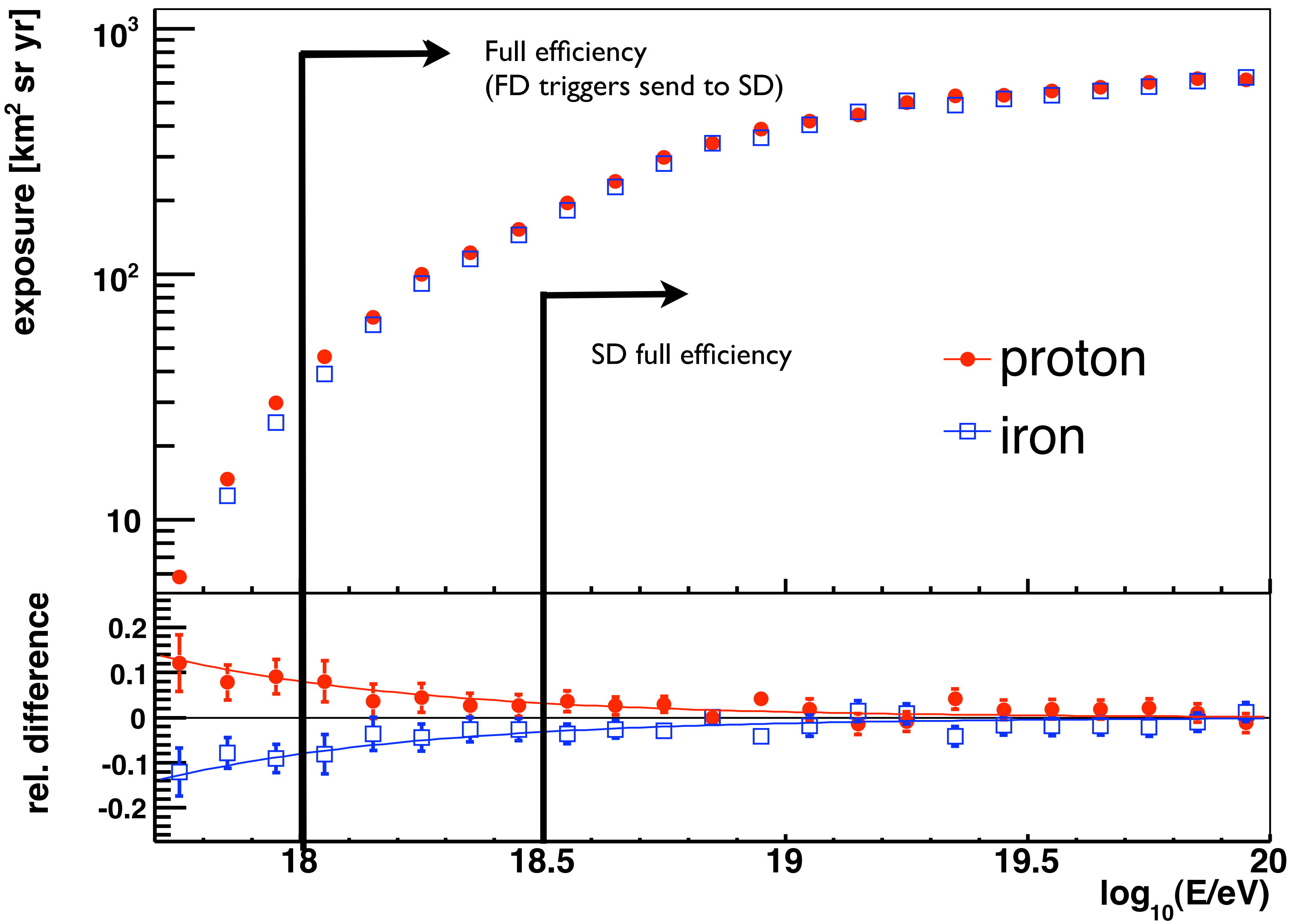
model dependent from SD,
SD active for 100% of time

get energy calibration from FD
for high statistics from SD

A, $\mathcal{E}$: directly from size of SD
above 3×10^{18} eV

Hybrid exposure

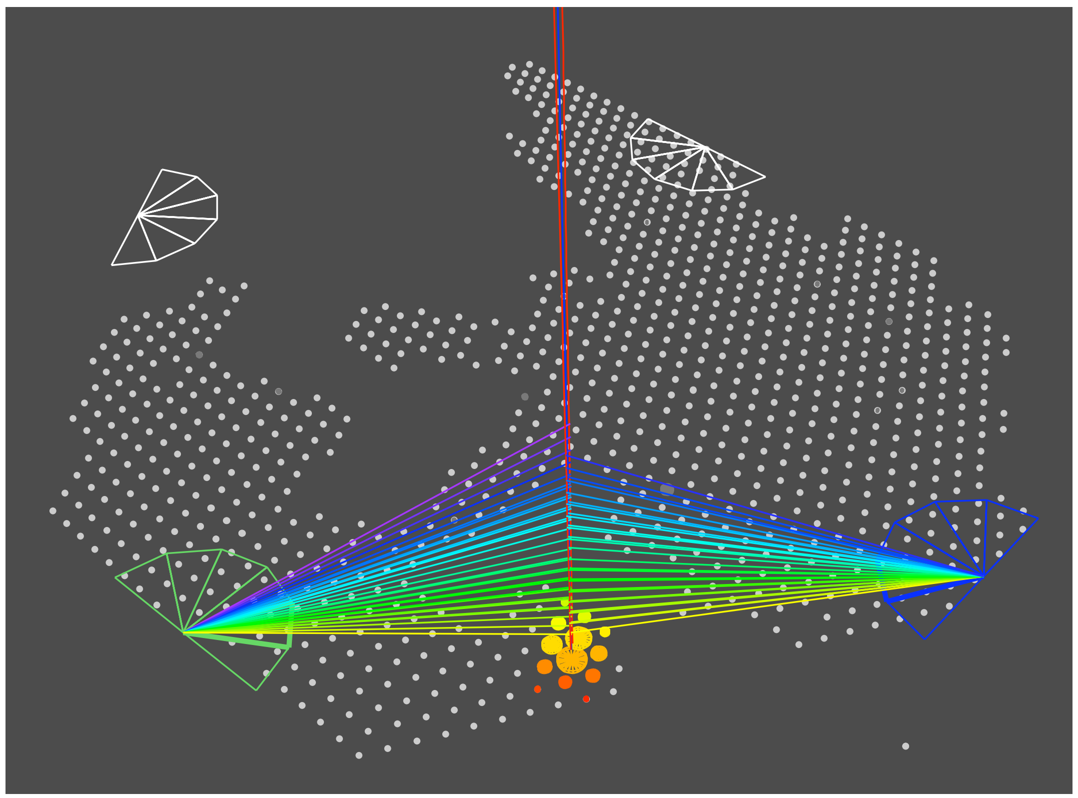
(Hybrid=FD+SD information)



Sys. uncert. <8% @ 10^{18}eV
Negligible at higher energies

$$J(E) = \frac{d^4N(E)}{dE\,dA\,d\Omega\,dt} \simeq \frac{1}{\Delta E}\frac{\Delta N(E)}{\mathcal{E}(E)}$$

Energy determination with FD



Source	Systematic uncertainty	Comment
Fluorescence yield	14%	Nagano + AIRFLY
P,T and humidity effects on yield	7%	
Calibration	9.5%	Calib. source, laser
Atmosphere	4%	
Reconstruction	10%	Optical spot, Lat. Ch. dist.
Invisible energy	4%	Model dependence
Total	22%	

FD energy: statistical uncertainty <6%
determined with

- detector simulation
- validated by stereo events

FD energy: systematic uncertainty ~22%

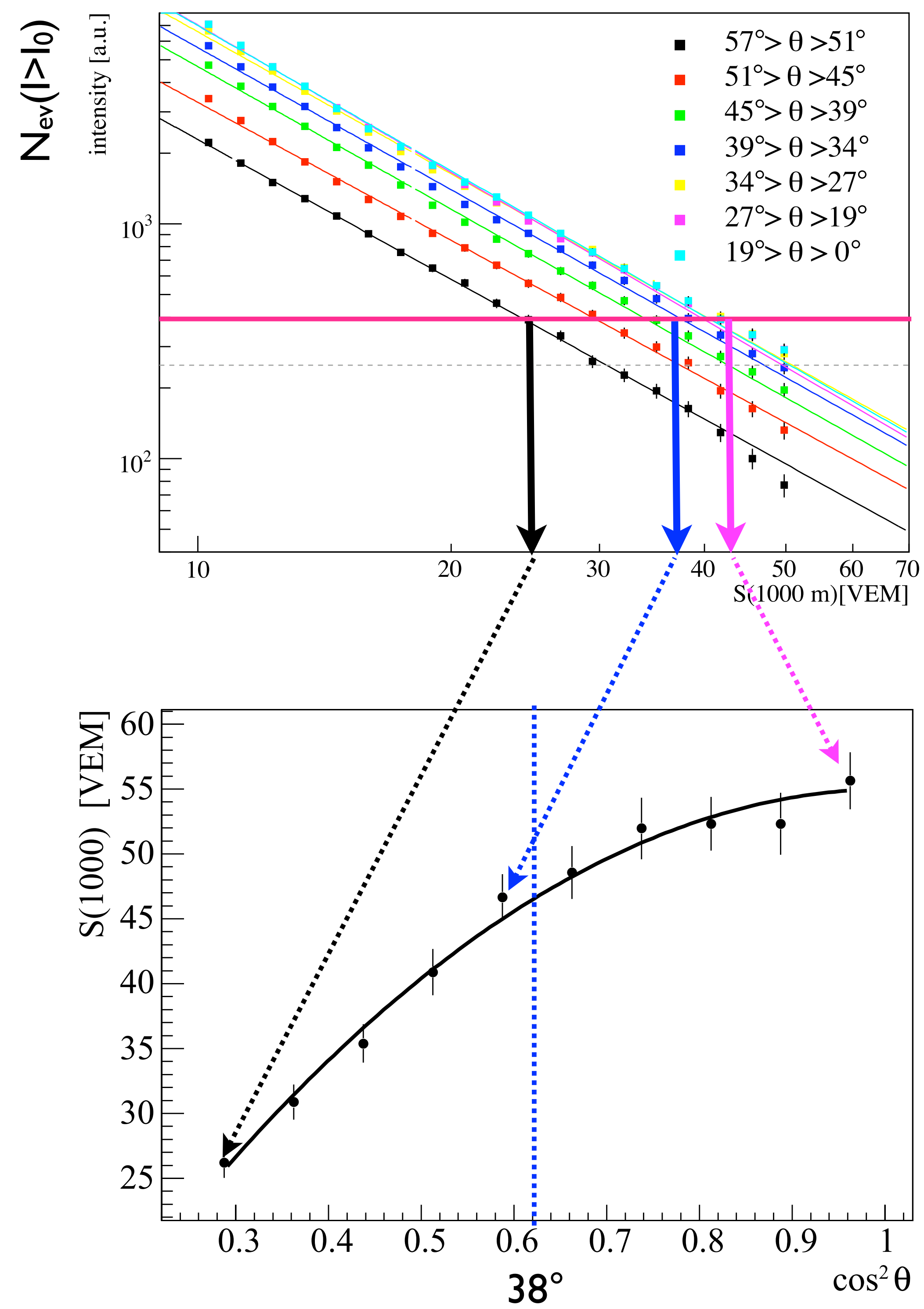
S(1000) attenuation with zenith angle

Isotropy of cosmic rays
Integral Constant Intensity Cut
Constant Intensity ≡ Fixed energy

Given a measured S(1000)(θ)

$S_{38°}$

38° is the average zenith of high-quality events



SD spectrum: Energy calibration with the fluorescence detector

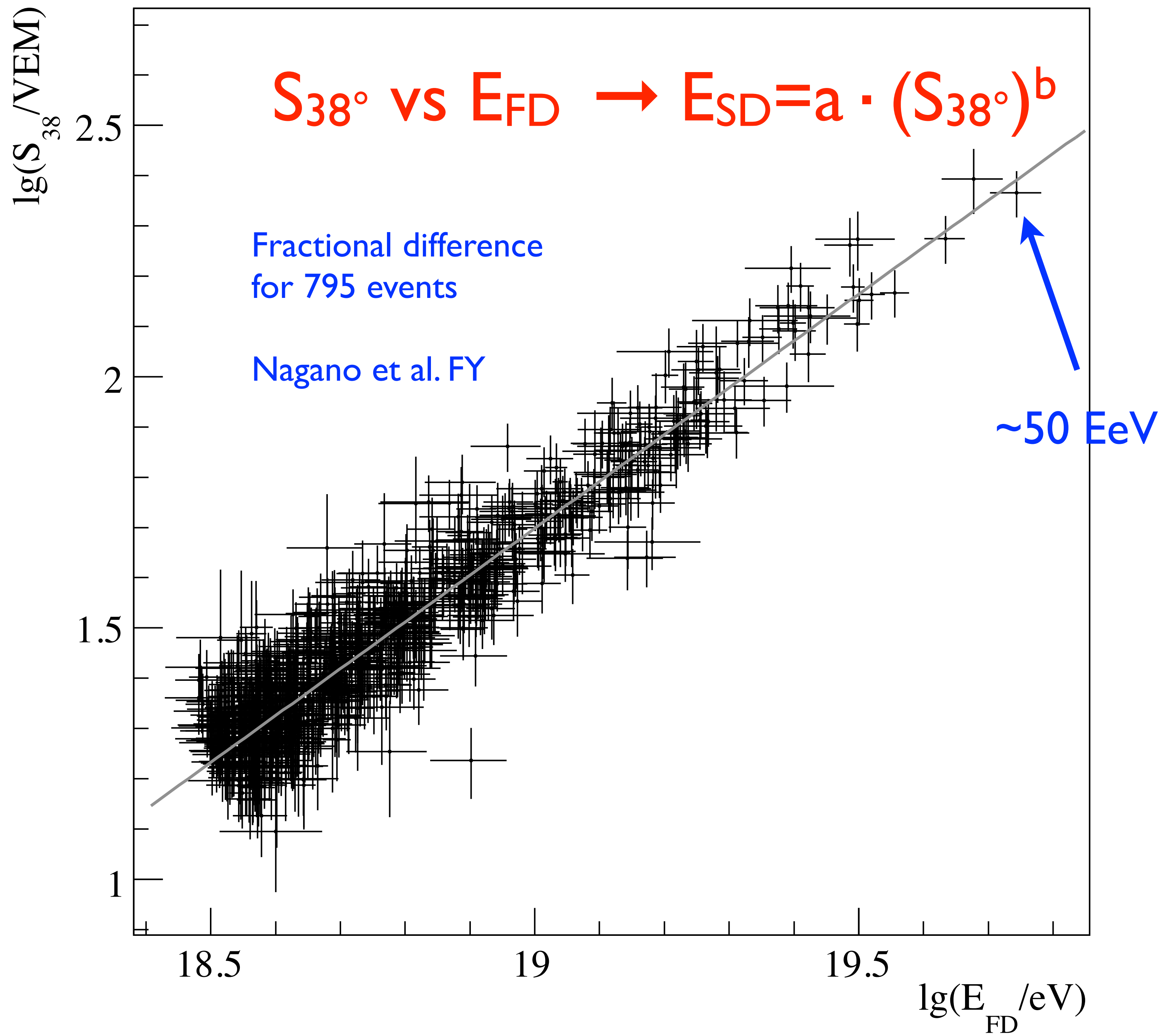
$S_{38°} \propto$ S1000 corrected for zenith dependency

Energy uncertainty from calibration curve:

- 7% at 10 EeV
- 15% at 100 EeV

Improves with increasing hybrid statistics

Note:
Both $S_{38°}$ and E_{SD} are determined experimentally. We do not rely on shower simulation.



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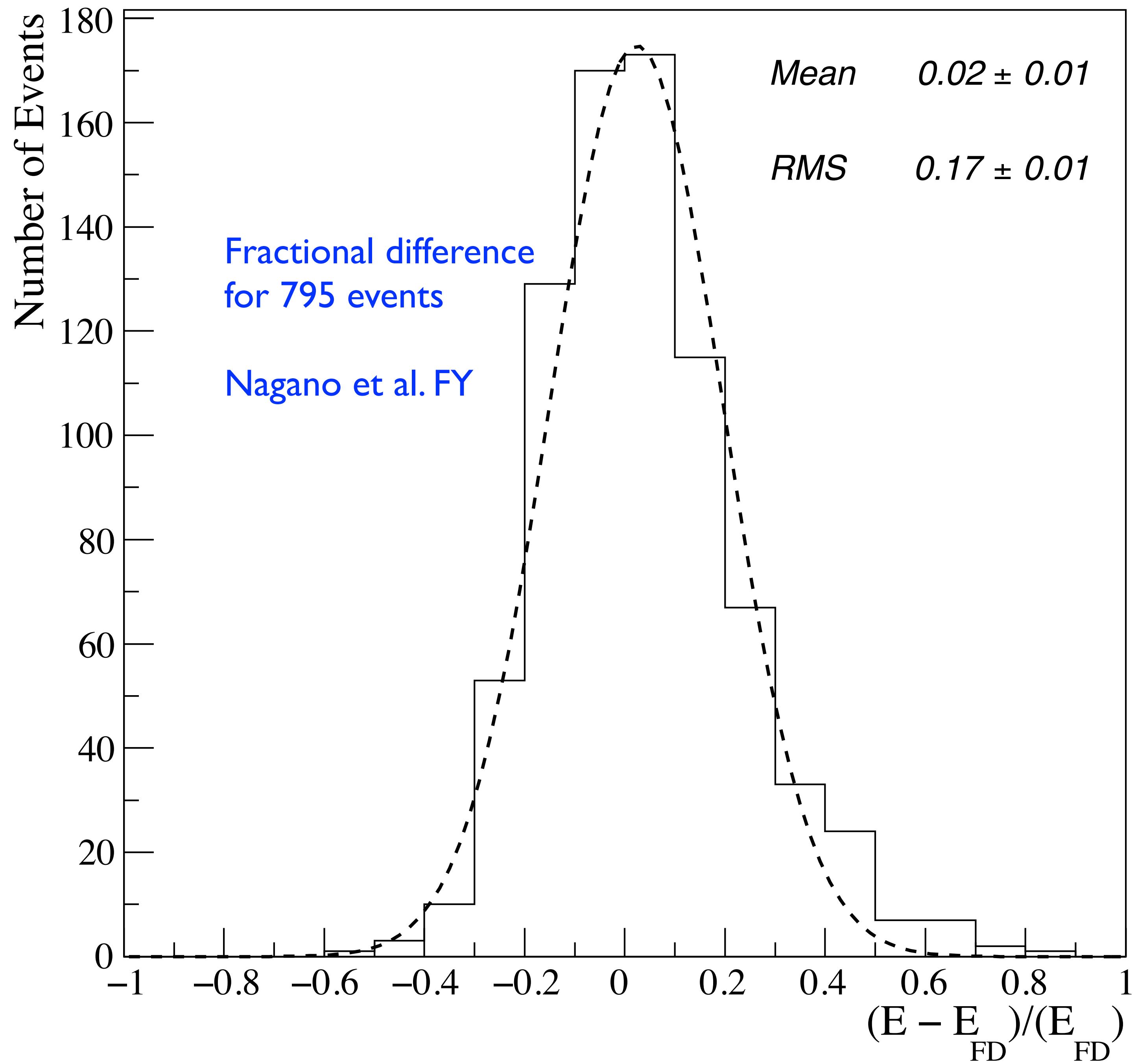
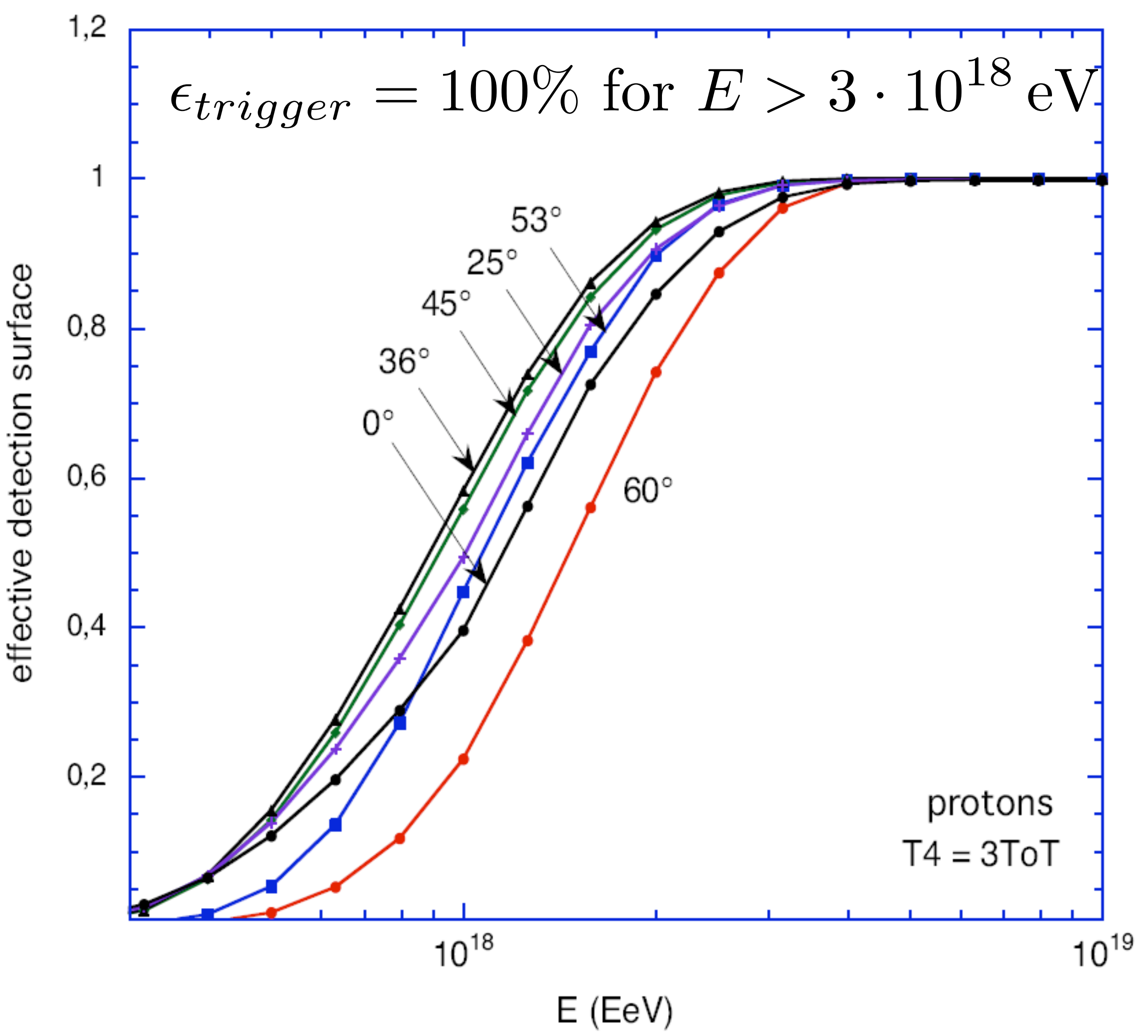
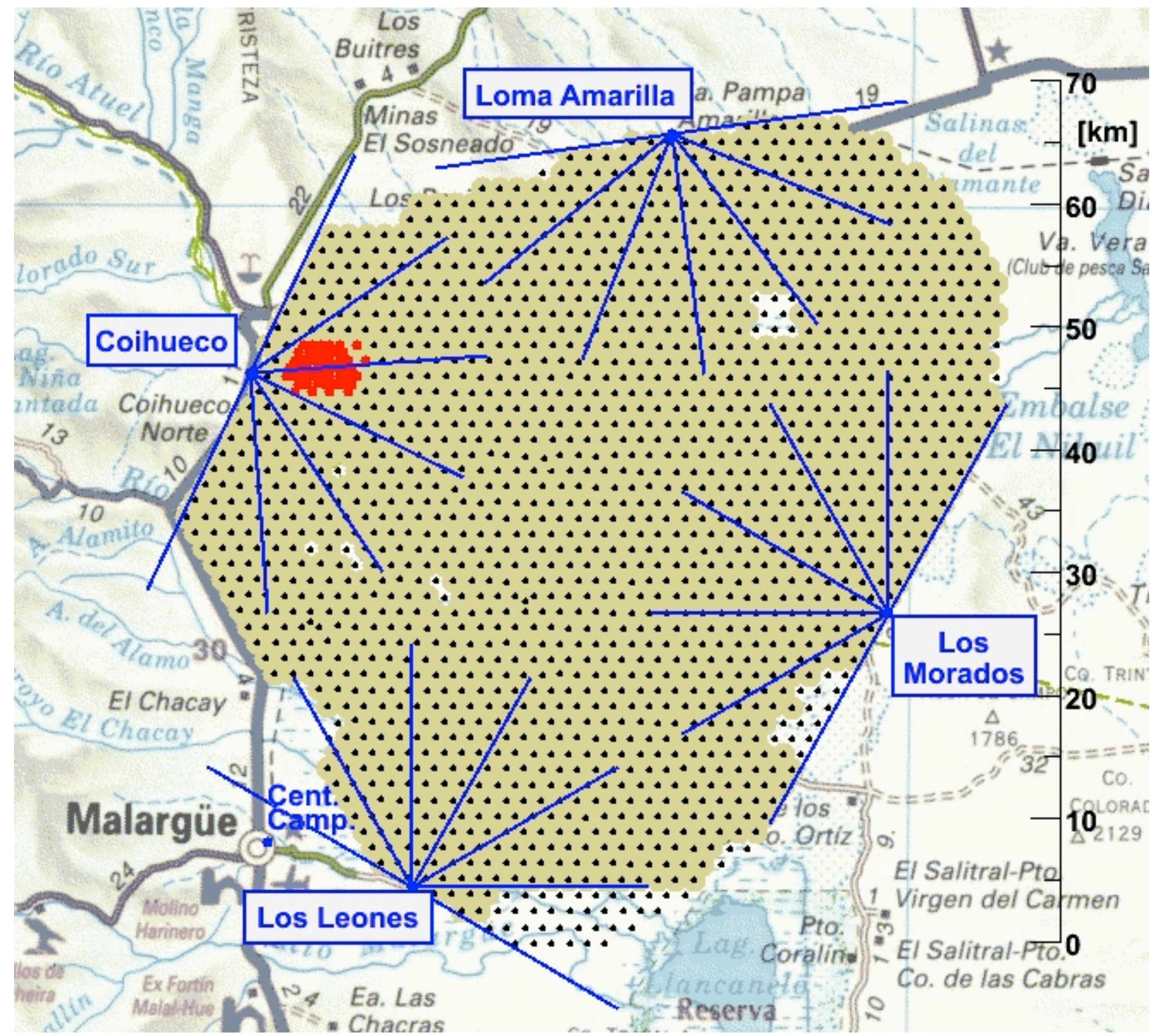


SD Exposure

Data period:
1 Jan 2004 - 31 Mar 2009
154 Tanks - >1600 Tanks

Zenith range:
0-60°

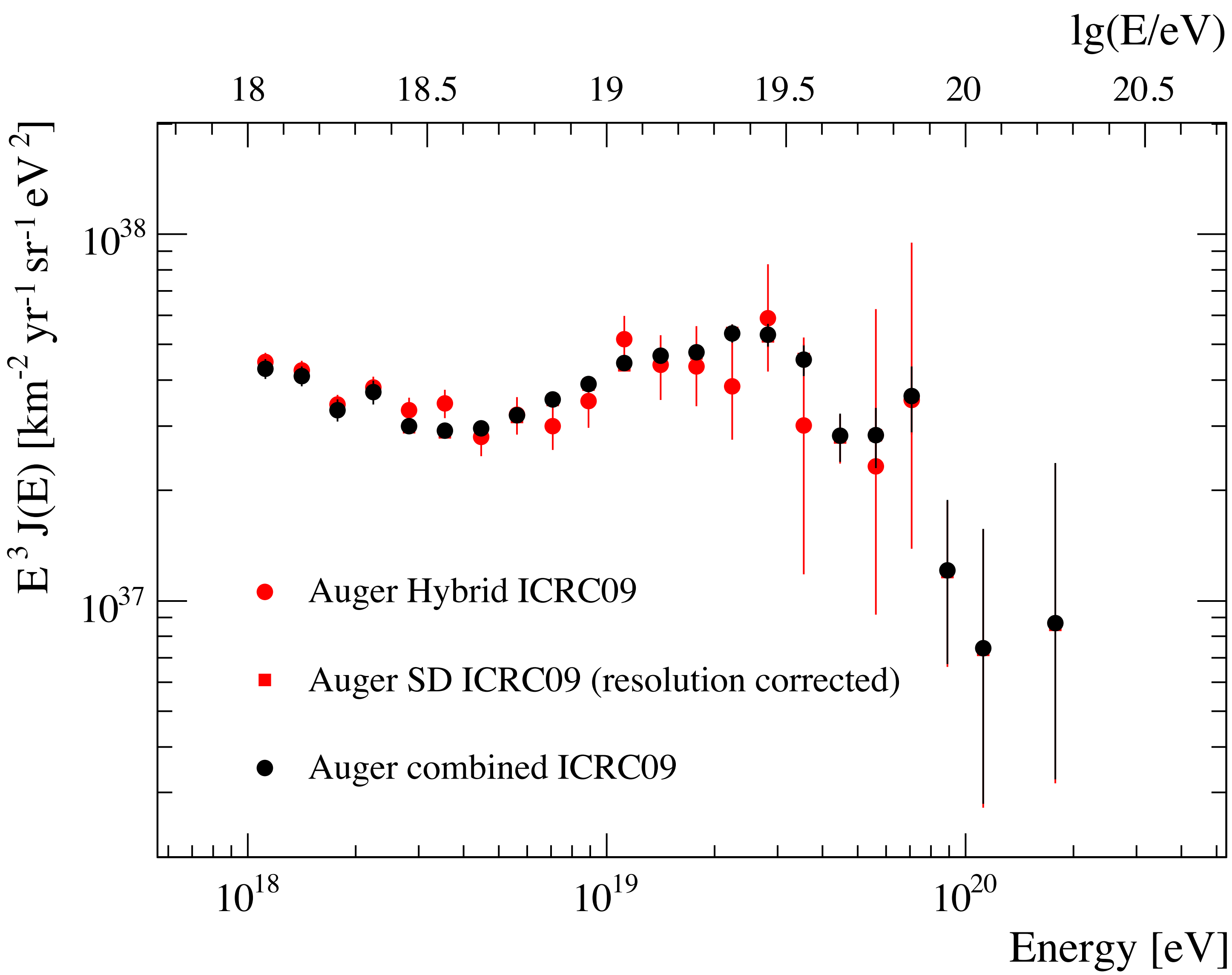




Integrated exposure: 12,790 km² sr year

The Auger spectrum

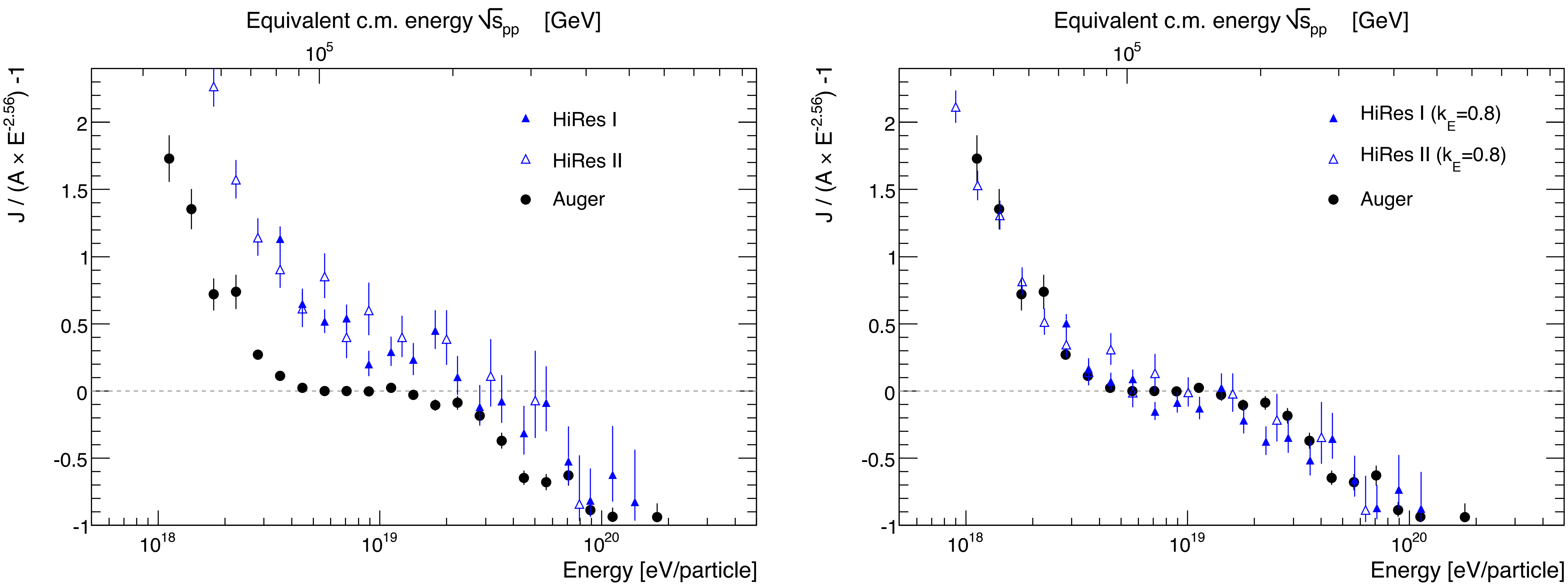
Syst. uncertainty on flux <4%



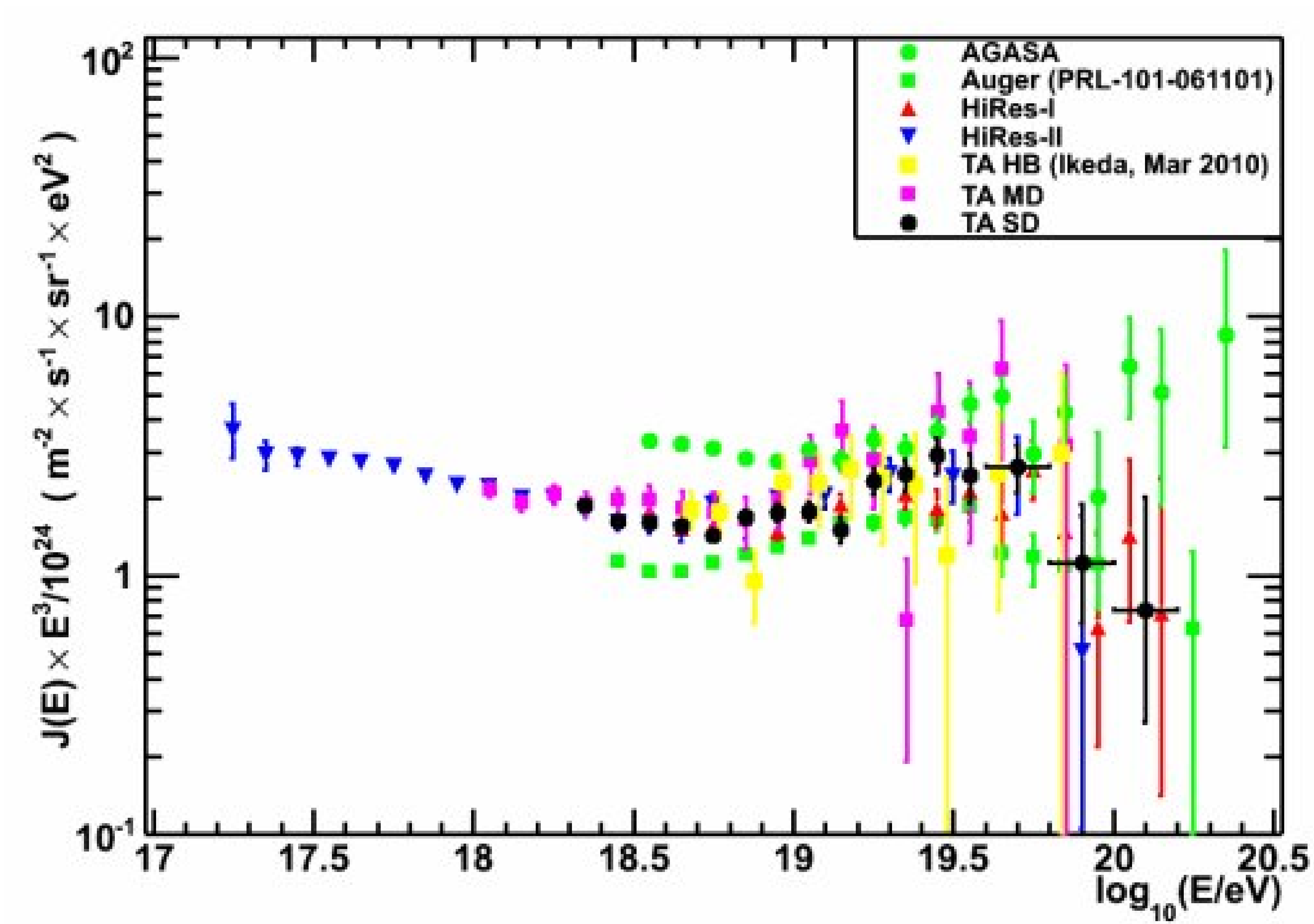
Physics Letters B 685 (2010) 239.

Likelihood method to combine the spectra incl. stat. and syst. uncertainties

The Auger spectrum



22% system. Uncertainty
on FD energy scale



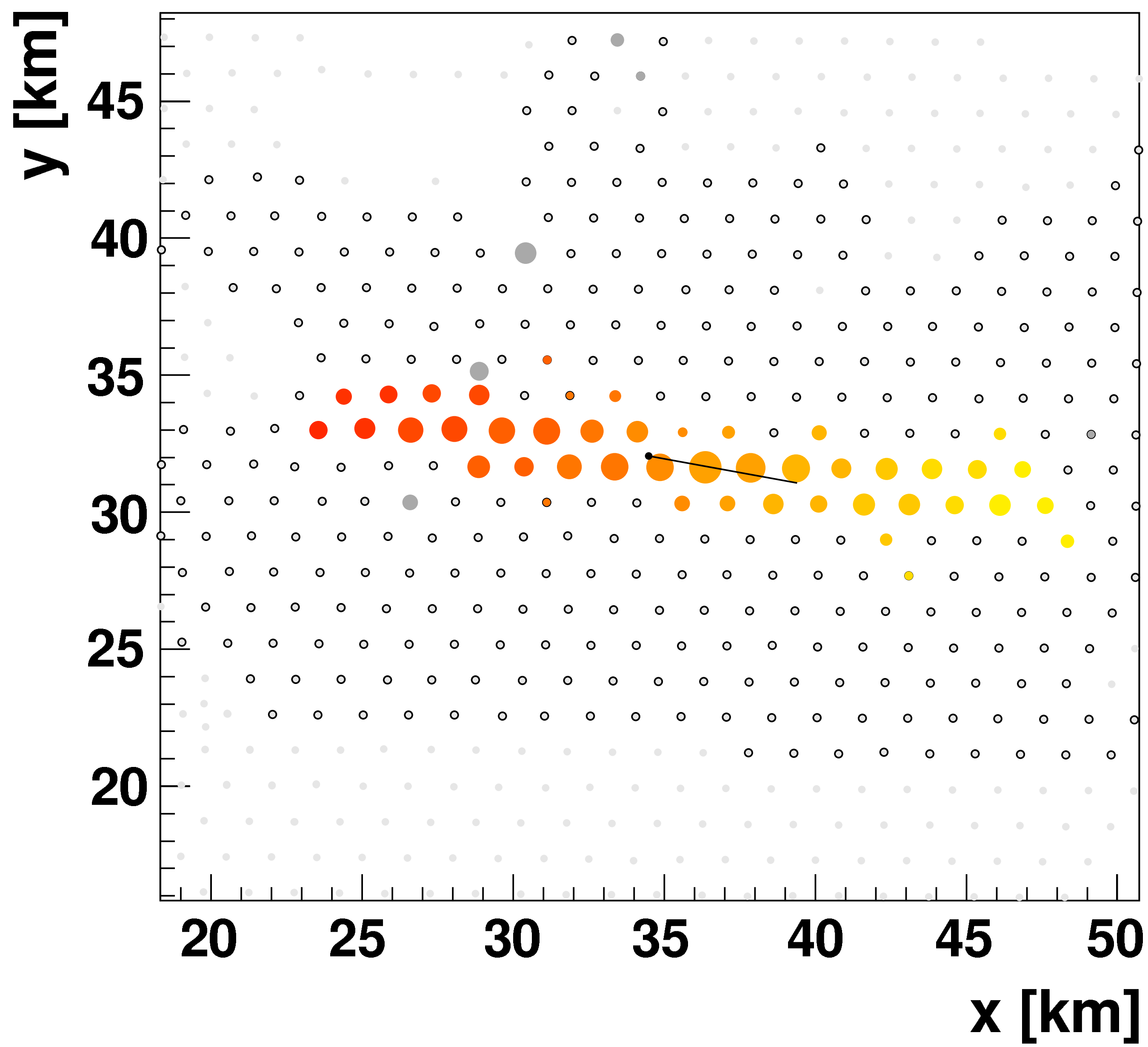
AGASA
Auger
HiRes-I
HiRes-II
TA Hybrid
TA MD
TA SD

B. Stokes Nagoya 2010

Horizontal air showers (HAS)

- Zenith angles > 60°
- Increase the aperture by 30%
- complex modeling and reconstruction

Event 3085995
45 signal stations
$\theta \approx 78°$



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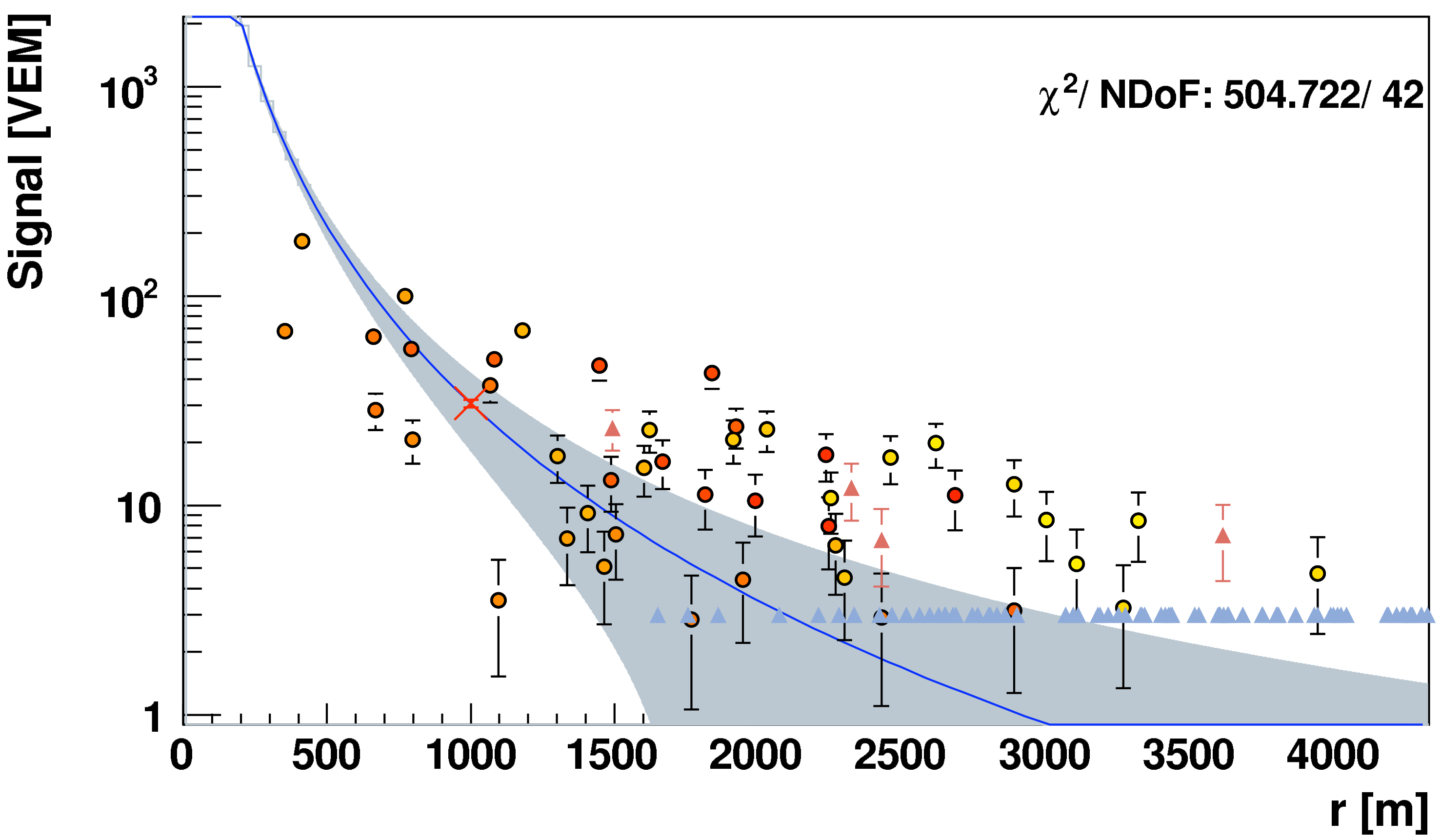

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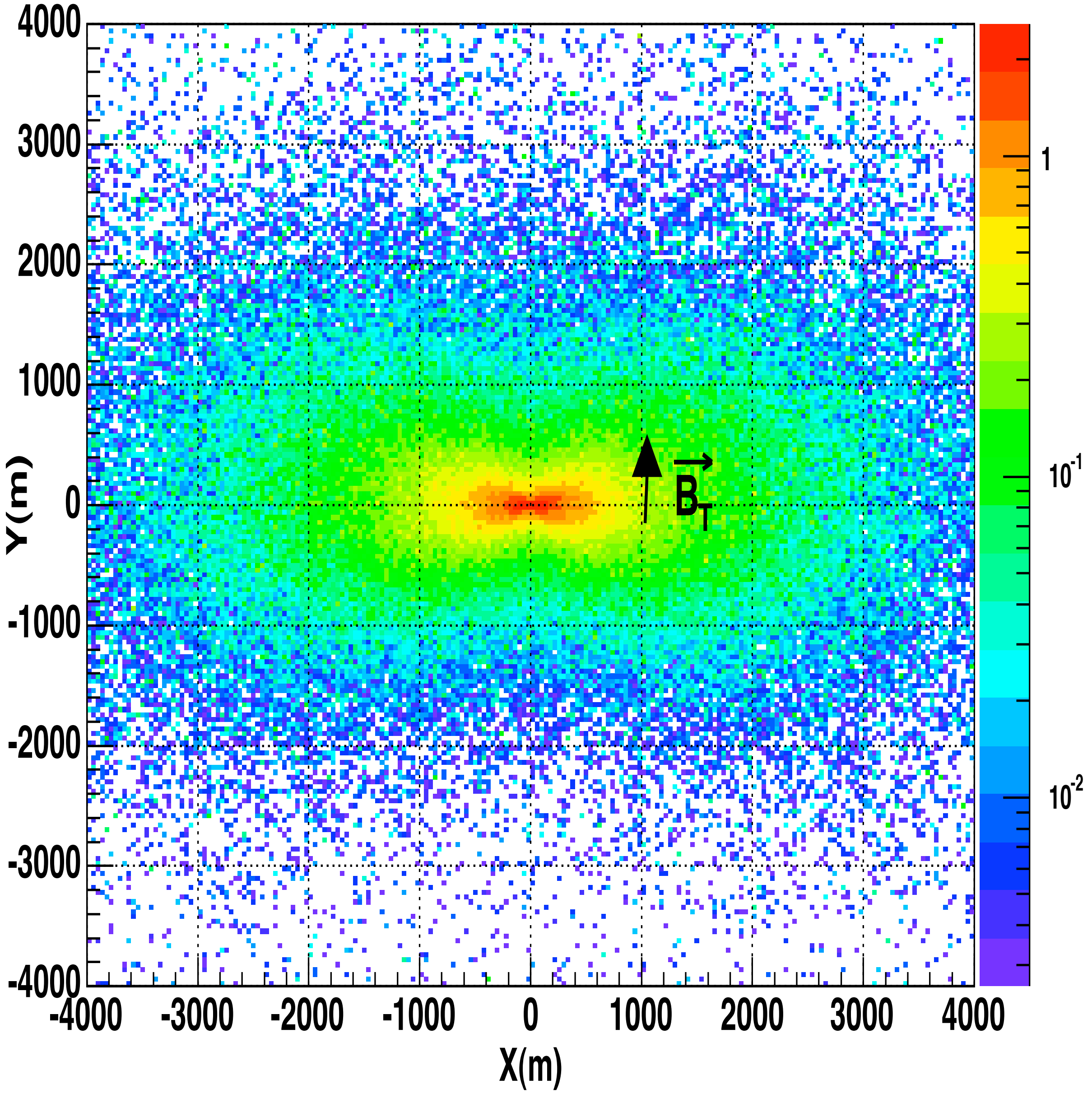
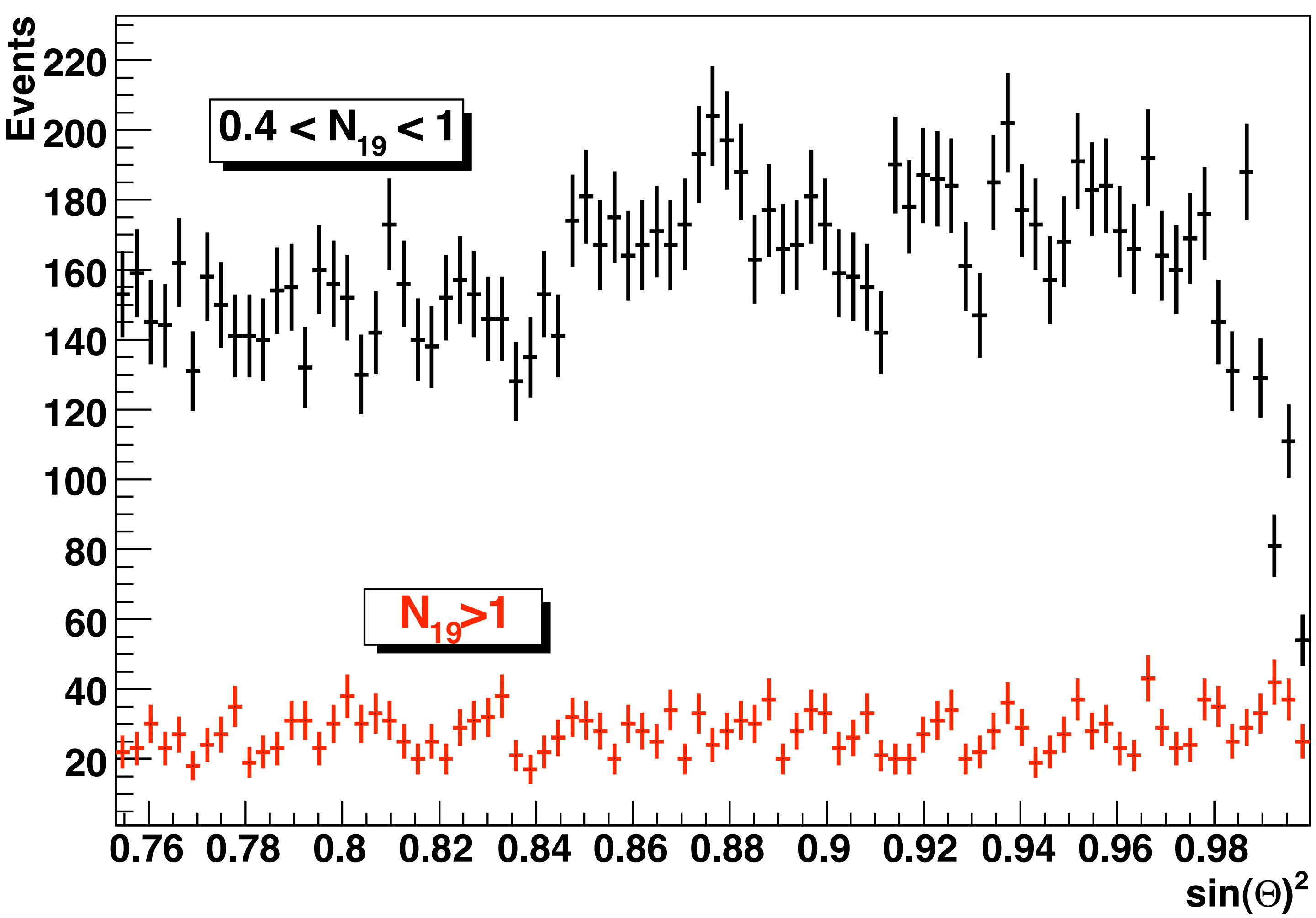
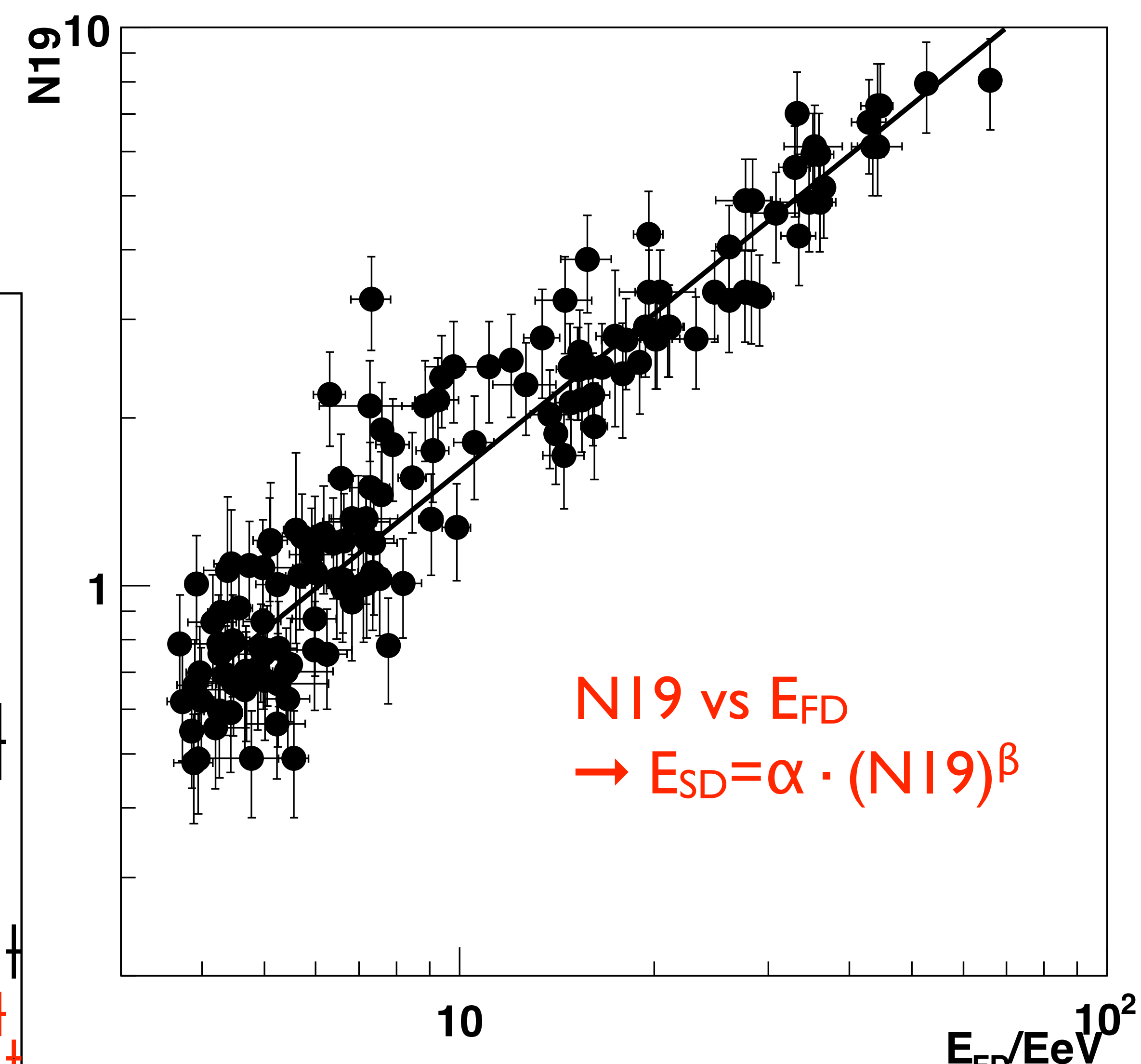


HAS energy calibration

- N19 zenith independent measure of the muon content
- Energy resolution of 22%



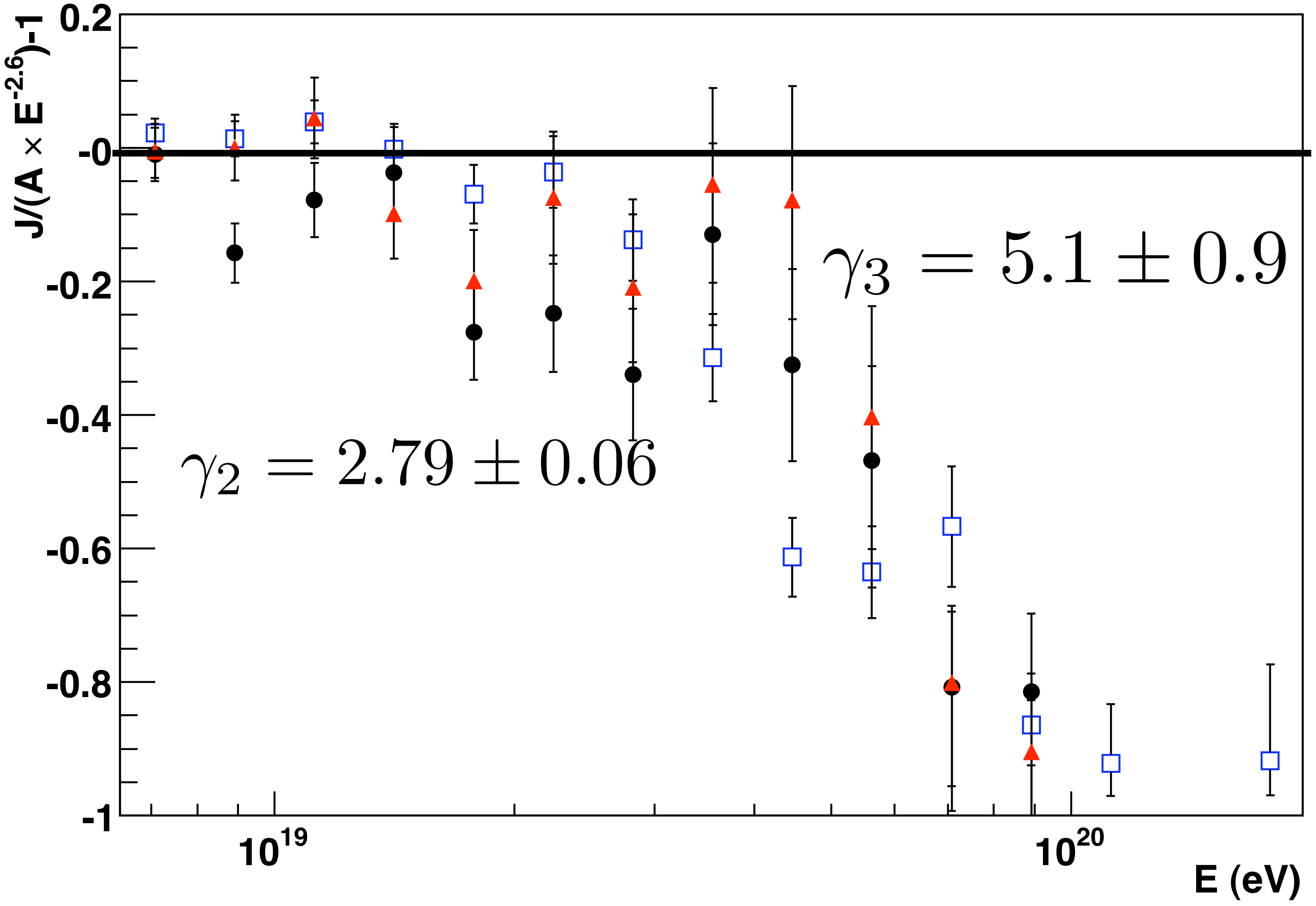


R.Vasquez et al., ICRC 2009

HAS energy spectrum

$60° < \theta < 80°$
$E > 6 \cdot 10^{18}$ eV
1750 events
1 Jan 2004 - 31 Dec 2008

3850 km^2 sr year



Vertical spectrum
Reconstruction A
Reconstruction B

Auger collab. ICRC09
H. Dembinski PhD thesis, 2009
T. Schmidt PhD thesis, 2010

Generation & Detection

Pion decay at source a/o propa.:

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_\mu$$
$$\hookrightarrow \quad \mu^{\pm} \longrightarrow e^{\pm} + \nu_e + \nu_\mu$$

Flavour counting $2\nu_\mu + \nu_e$

Neutrino oscillation $1\nu_e + 1\nu_\mu + 1\nu_\tau$

$$\tau \longrightarrow \mu + \nu_\mu + \nu_\tau$$

→ track ☹

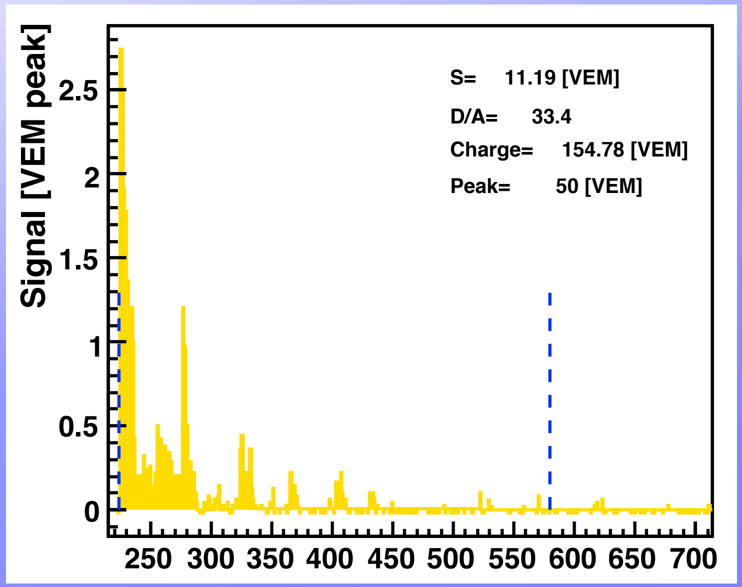
$$\tau \longrightarrow e + \nu_e + \nu_\tau$$

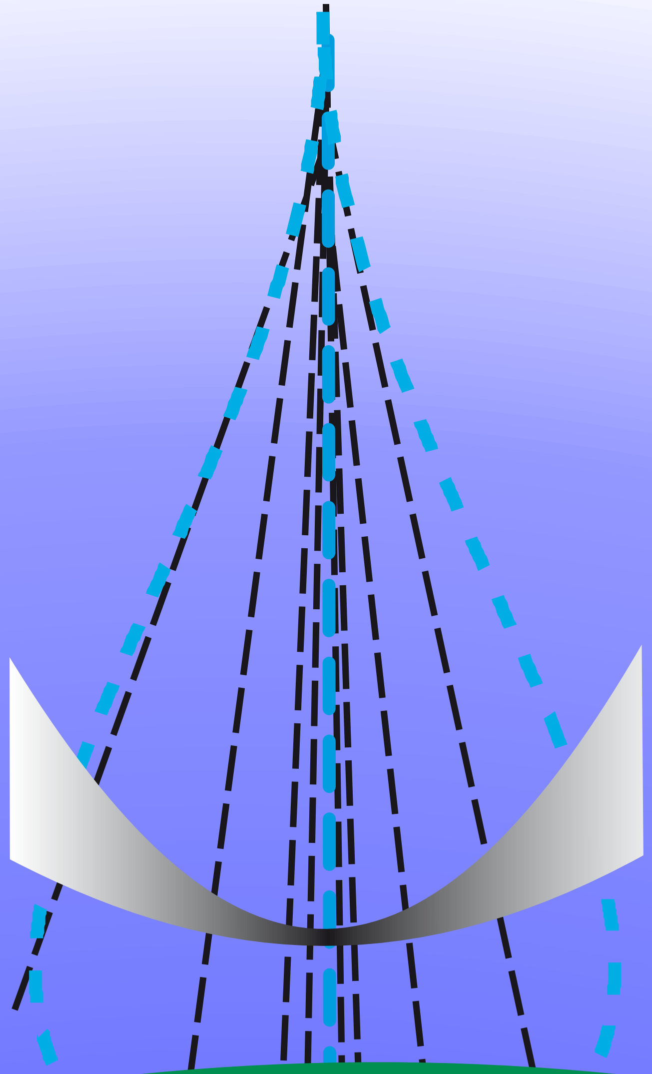
→ shower ☺

$$\tau \longrightarrow hh + \nu_\tau$$

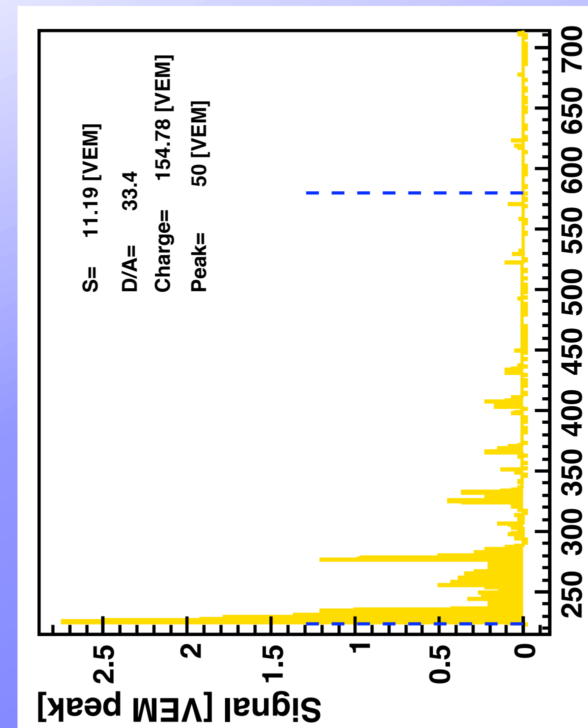
→ shower ☺

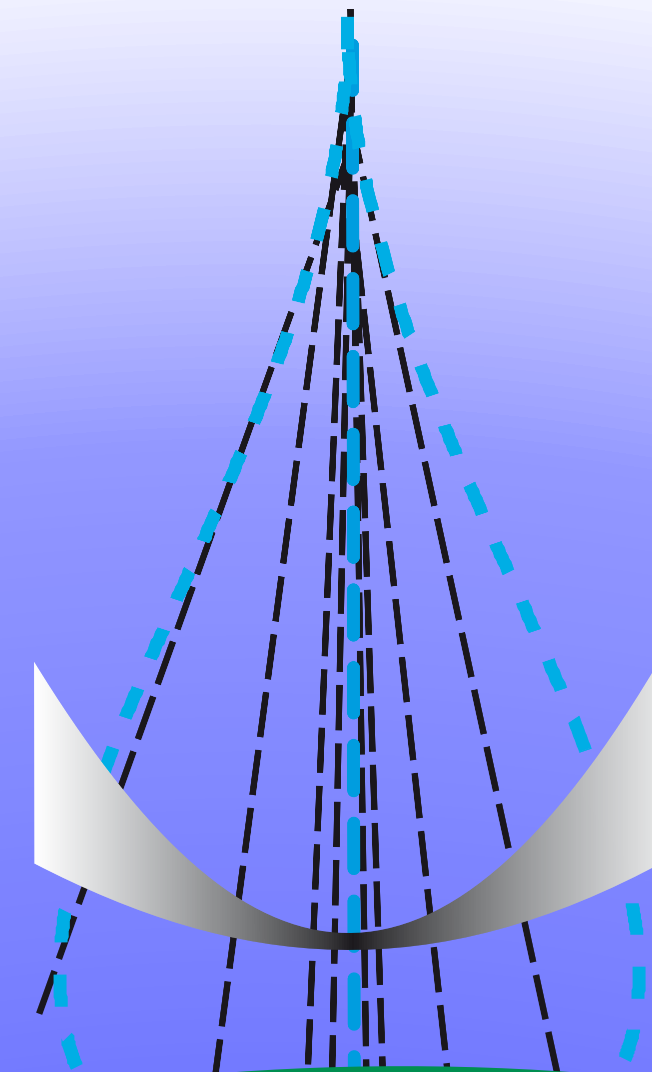
A vertical shower





A vertical shower

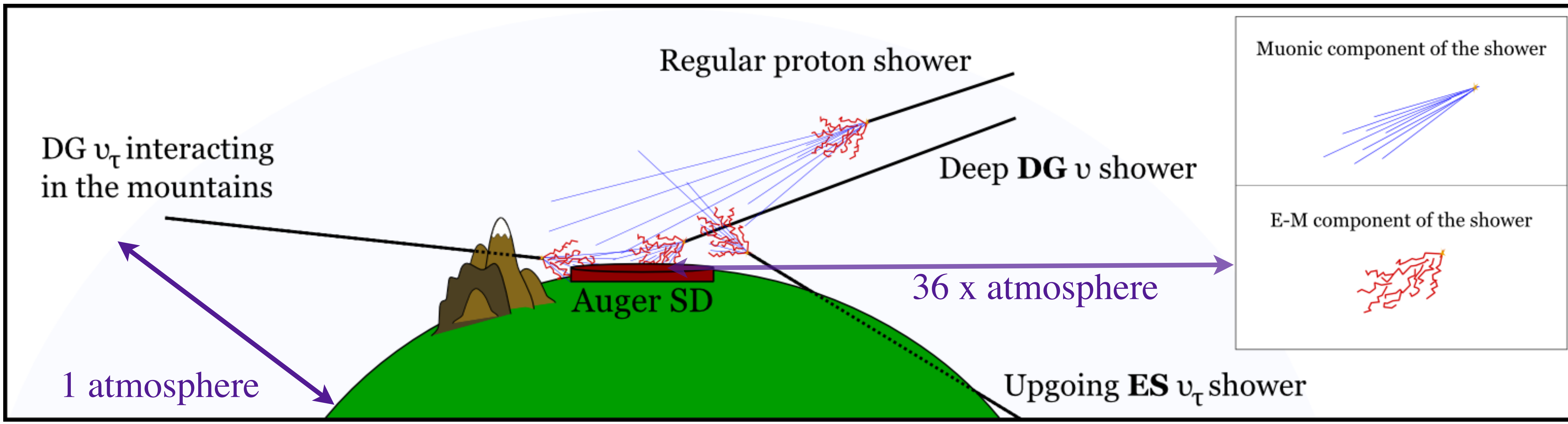




Elemental composition: neutrinos

Only a neutrino can induce a young horizontal shower:

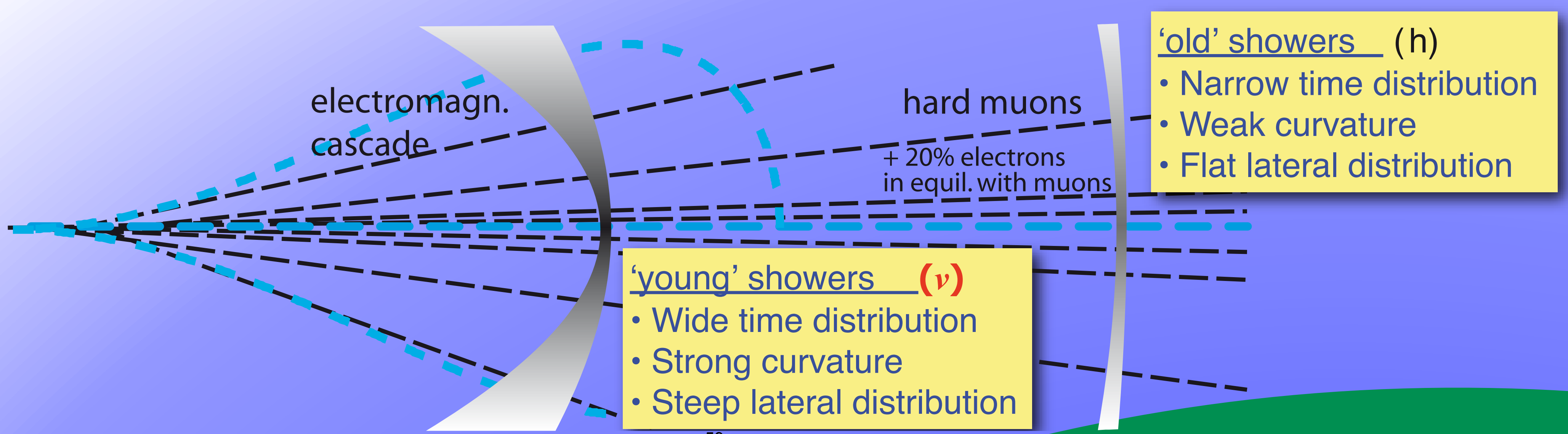
- DG: Down-going neutrino (ν_e, ν_μ, ν_τ; CC and NC interactions)
- ES: Earth skimming shower (CC in earth; τ decay above ground)



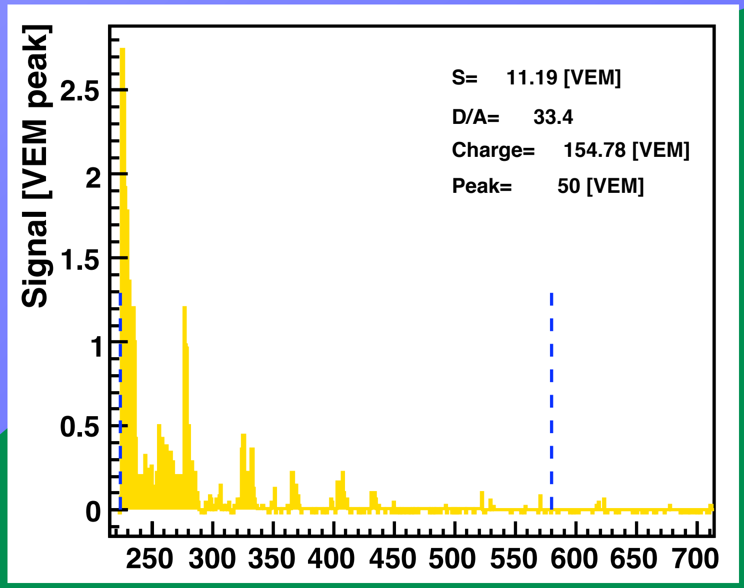
Neutrino Showers:

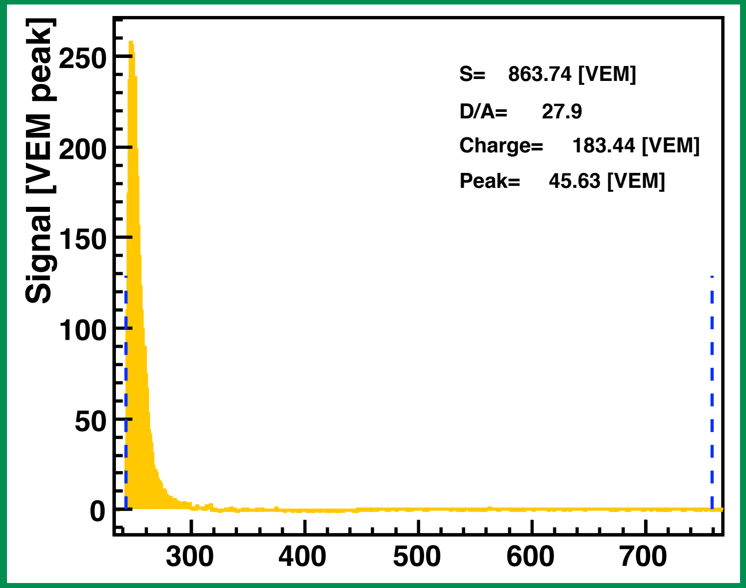
- Deep, very inclined (36,000 g cm^{-2}): elongated shower footprint
- Start as broad signals, narrowing as EM particles range out

«Young» vs «old» showers

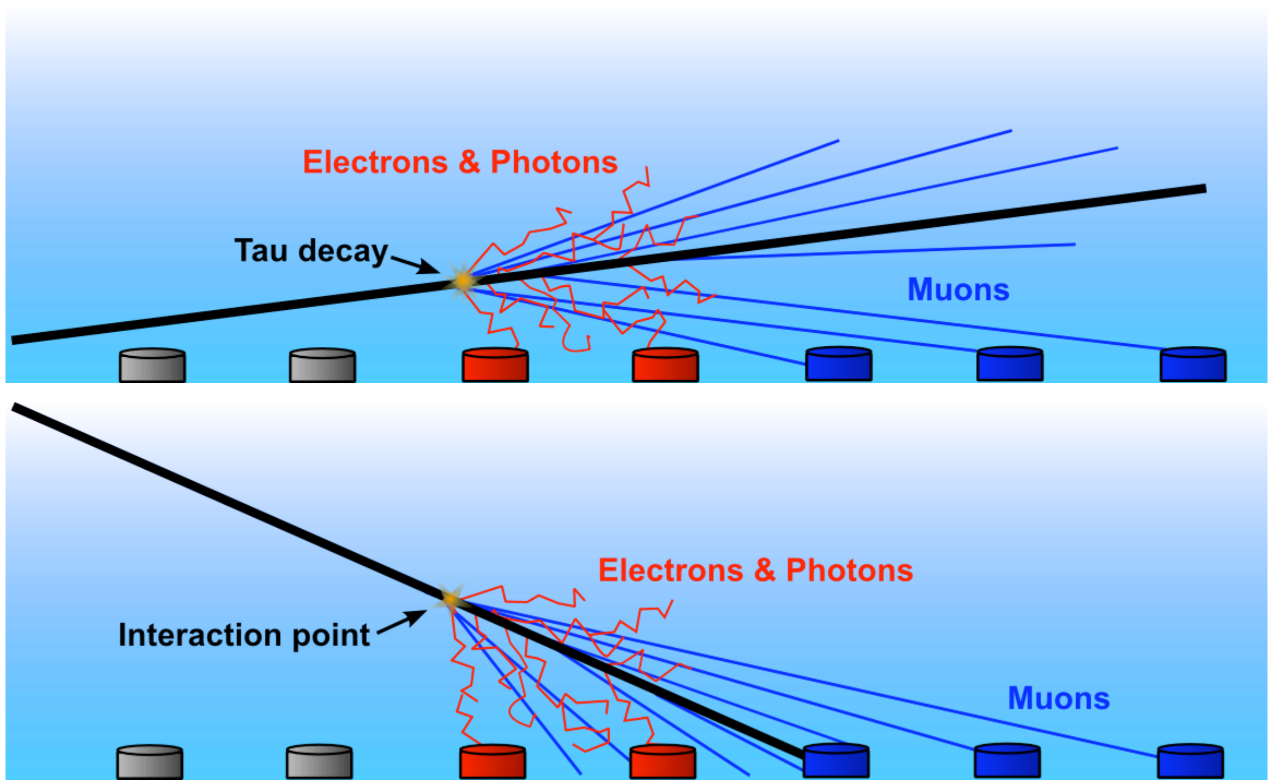


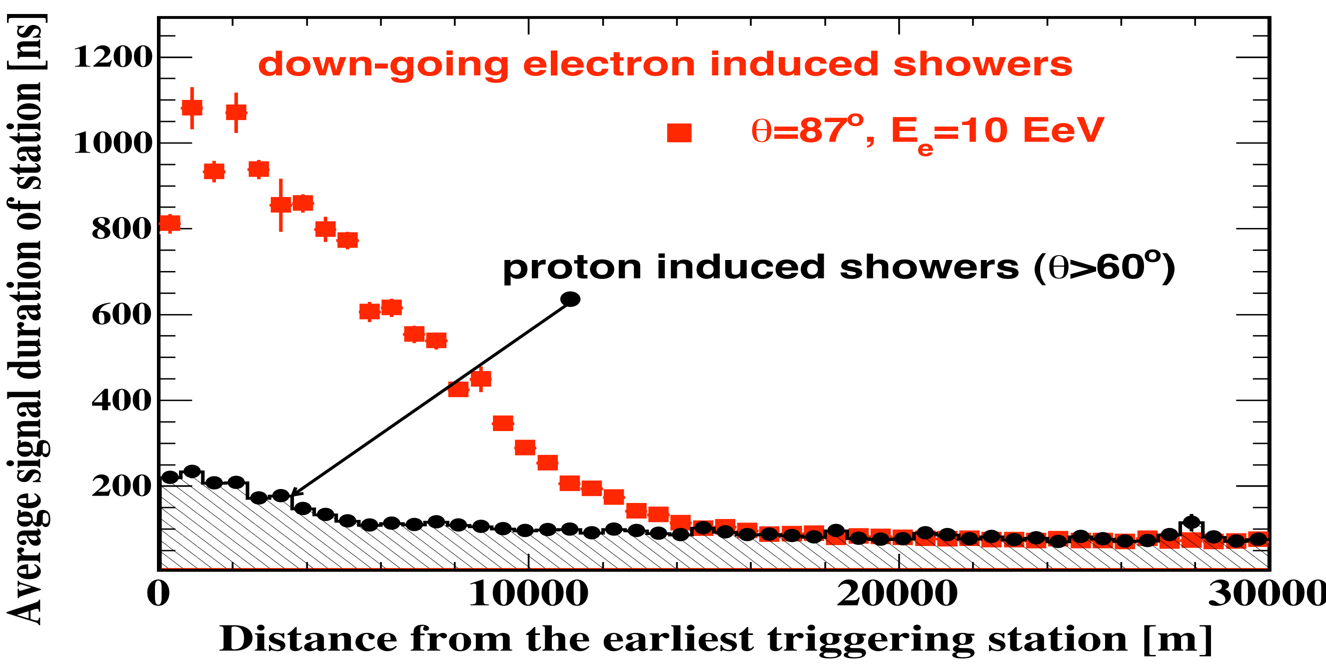
59





SD event tagging: Neutrinos

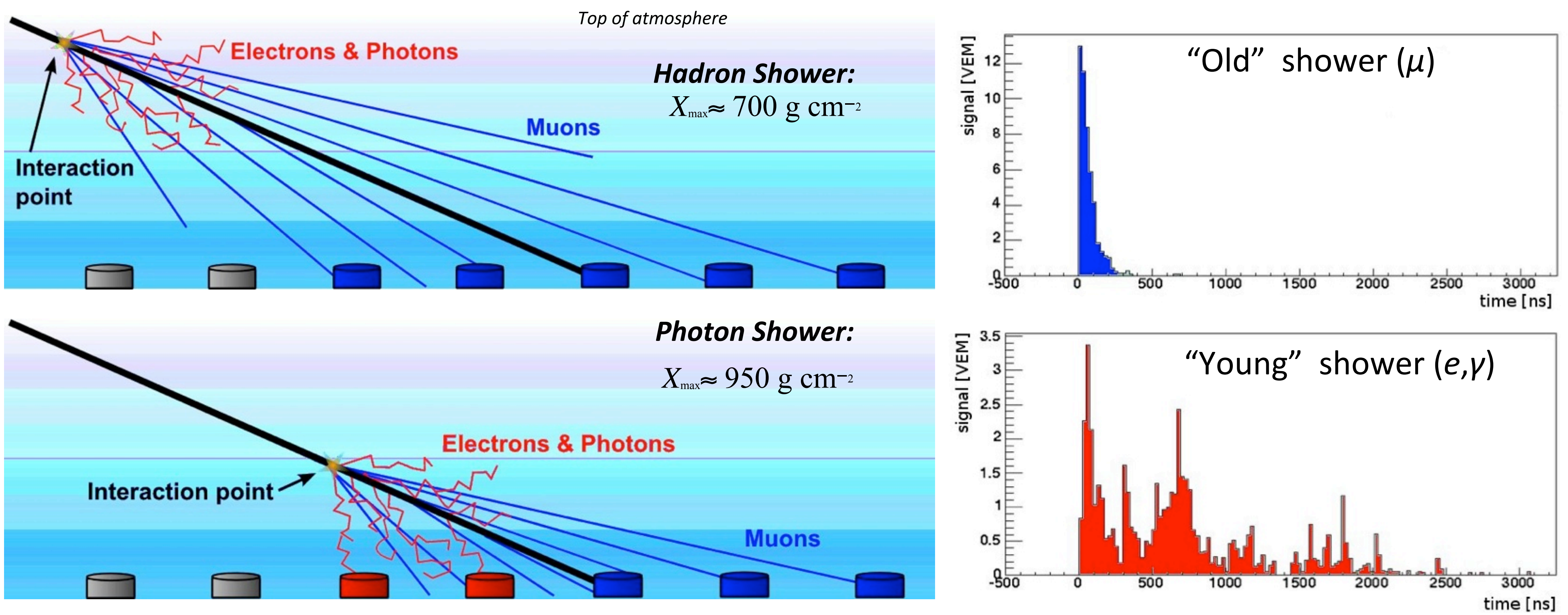




Neutrino Showers:

- Deep, very inclined (36,000 g cm^{-2}):
  elongated shower footprint
- Start as broad signals, narrowing as EM particles range out
- Upgoing events: earth-skimming ν_τ
- Downgoing events: all flavors, CC + NC interactions

SD event tagging: photons



- γ showers develop deep in atmosphere (+200 g cm^{-2} w.r.t. hadrons)
- EM particles in shower do not have time to range out before reaching ground level. Showers look "young":
  - Moderately inclined
  - Large scatter in particle arrival times; large *risetime* in signal trace
  - Shower front has smaller radius of curvature w.r.t. "old" hadronic shower

Astropart. Phys. 29 (2008) 243

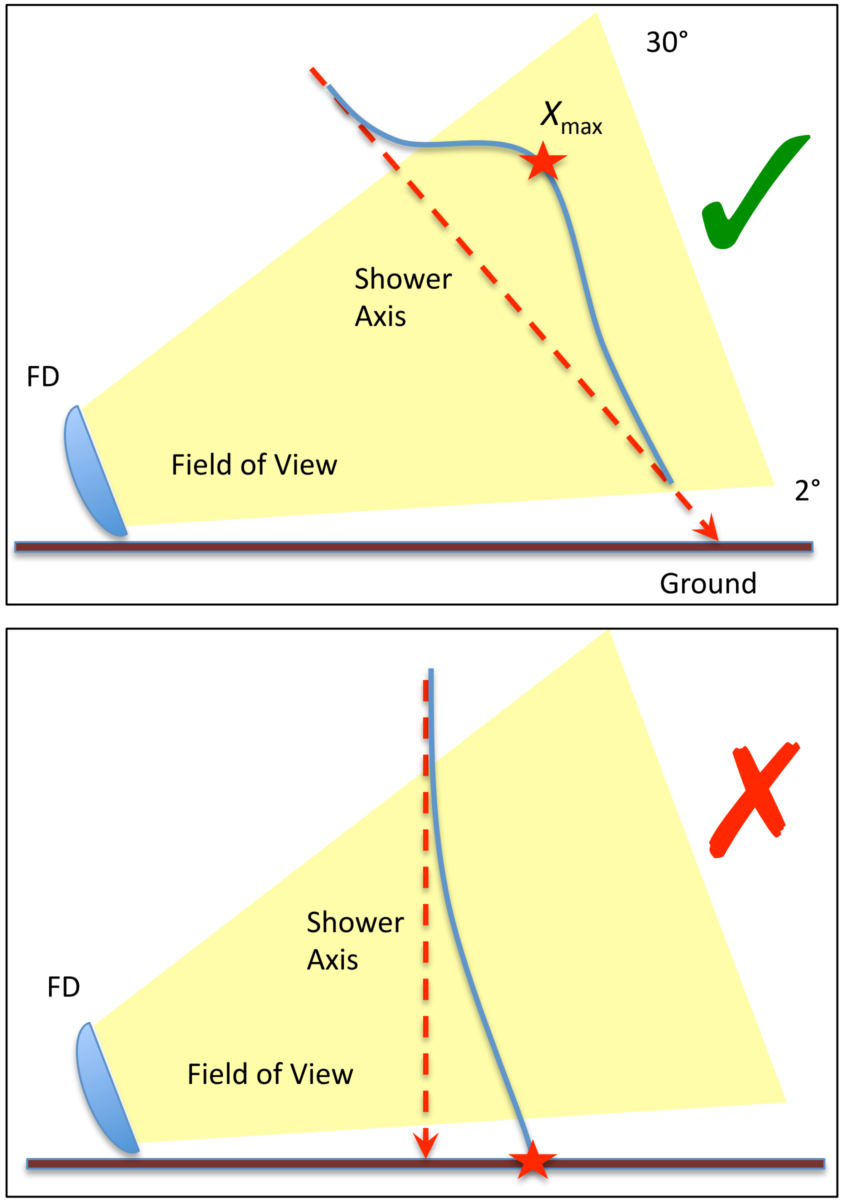
Hybrid event tagging: photons

- Hybrid mode: search for showers with unusually deep X_{max} using FD telescopes

- Strong geometry cuts: X_{max} contained in field of view

- Strong profile/fiducial volume cuts: vertical and distant showers rejected to remove trigger and reconstruction biases

- Strong atmospheric cuts to remove distorted profiles (cloud removal)



Astropart. Phys. **31** (2009), 399-406

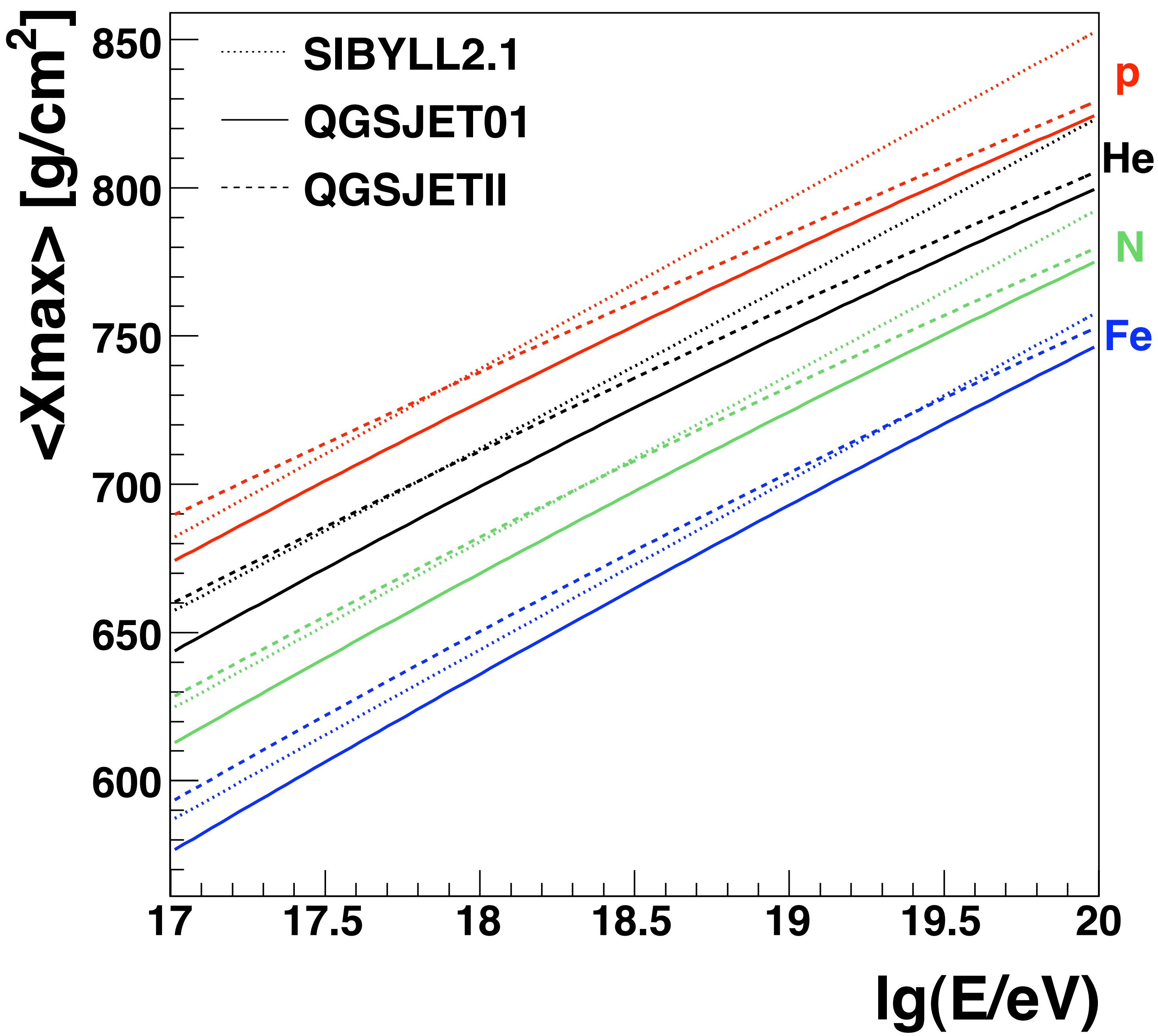
Average shower maximum X_{max}

Primary protons:

$$\langle X_{max} \rangle = D_{10} \lg(E) + const$$

Superposition model:

$$\langle X_{max} \rangle = D_{10} \lg(E/A) + const$$

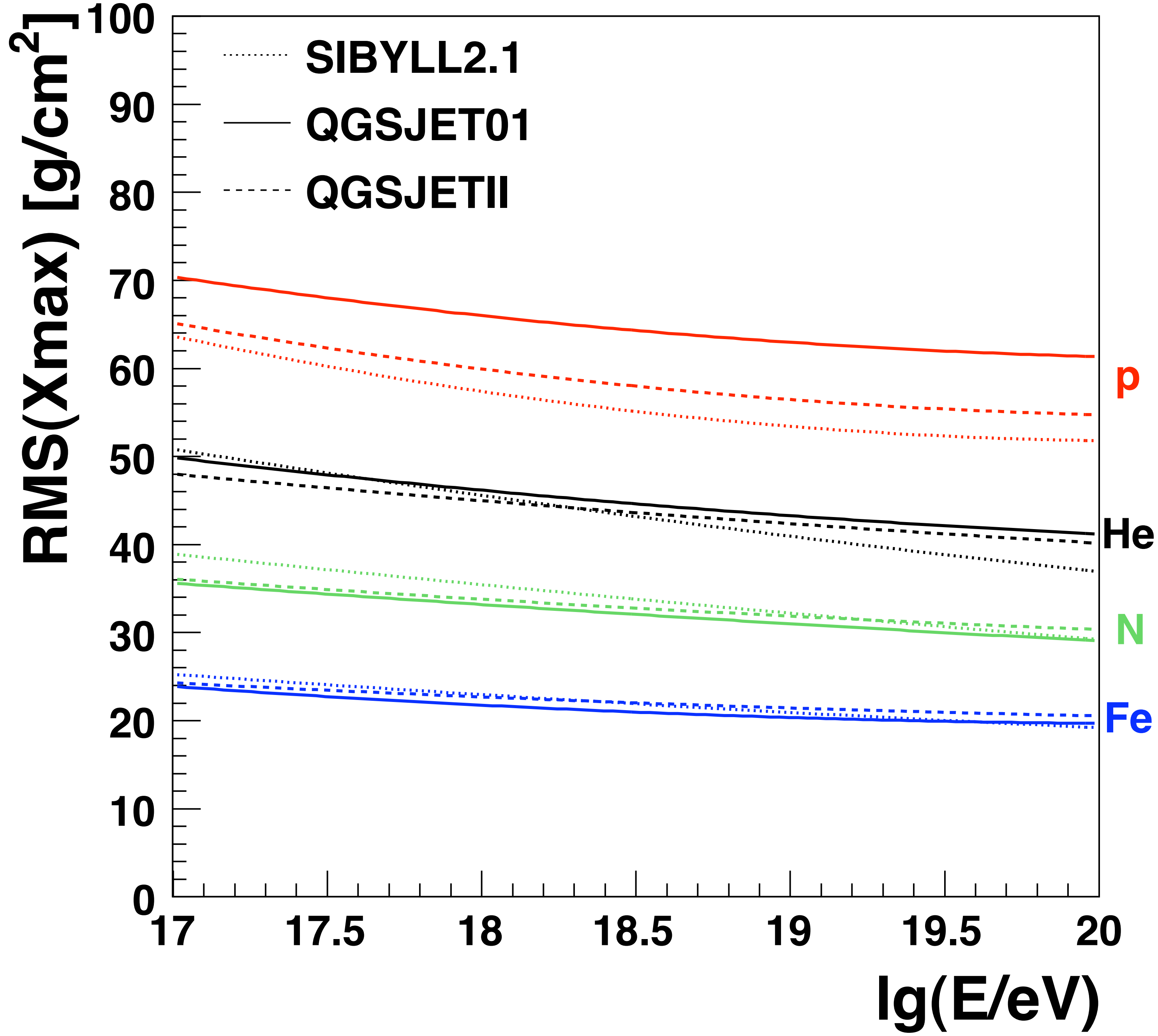


Shower to shower fluctuations

Qualitatively

RMS(A_1) < RMS(A_2)

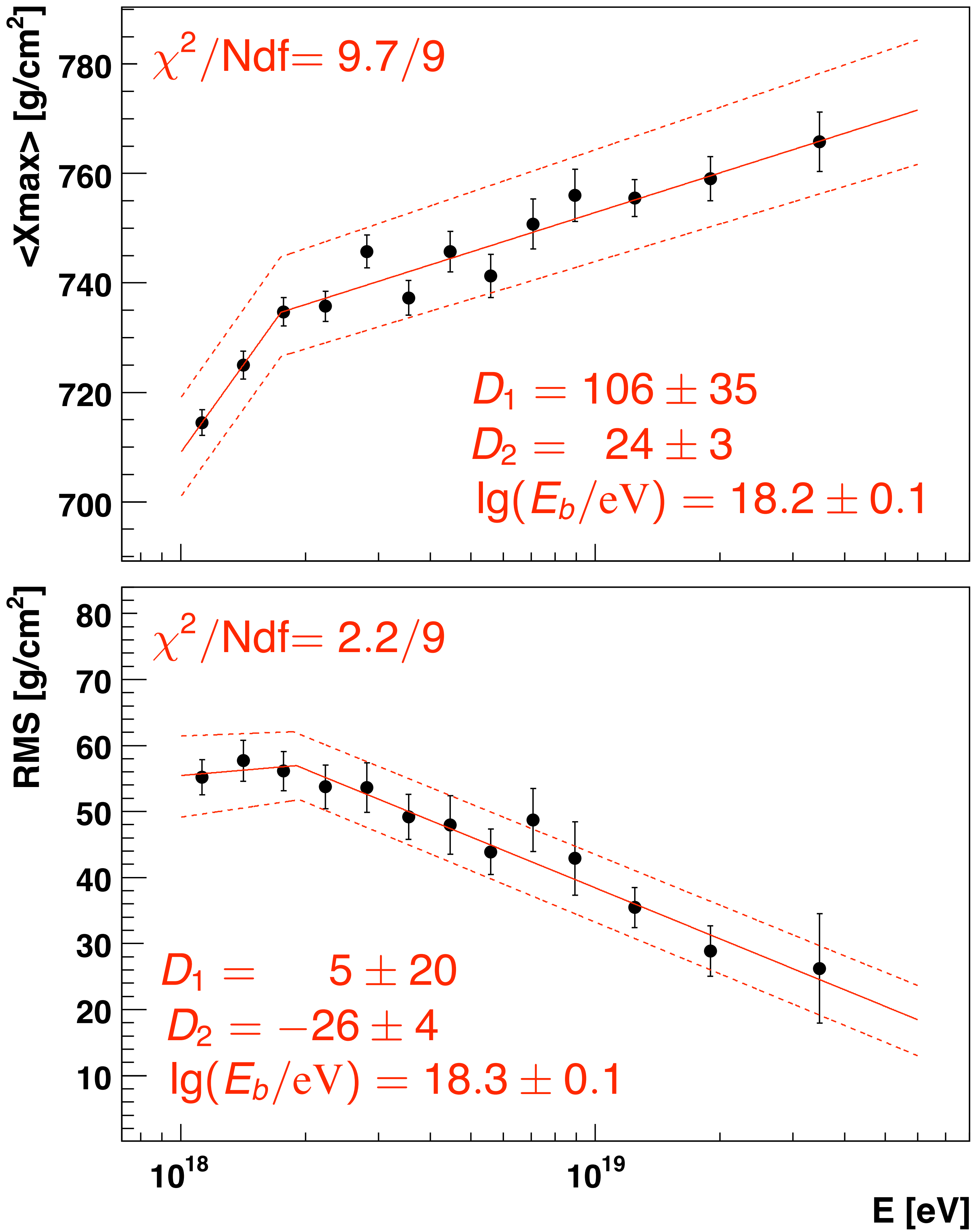
for A_1 > A_2



FD results

$\langle X_{max} \rangle$ and RMS vs E

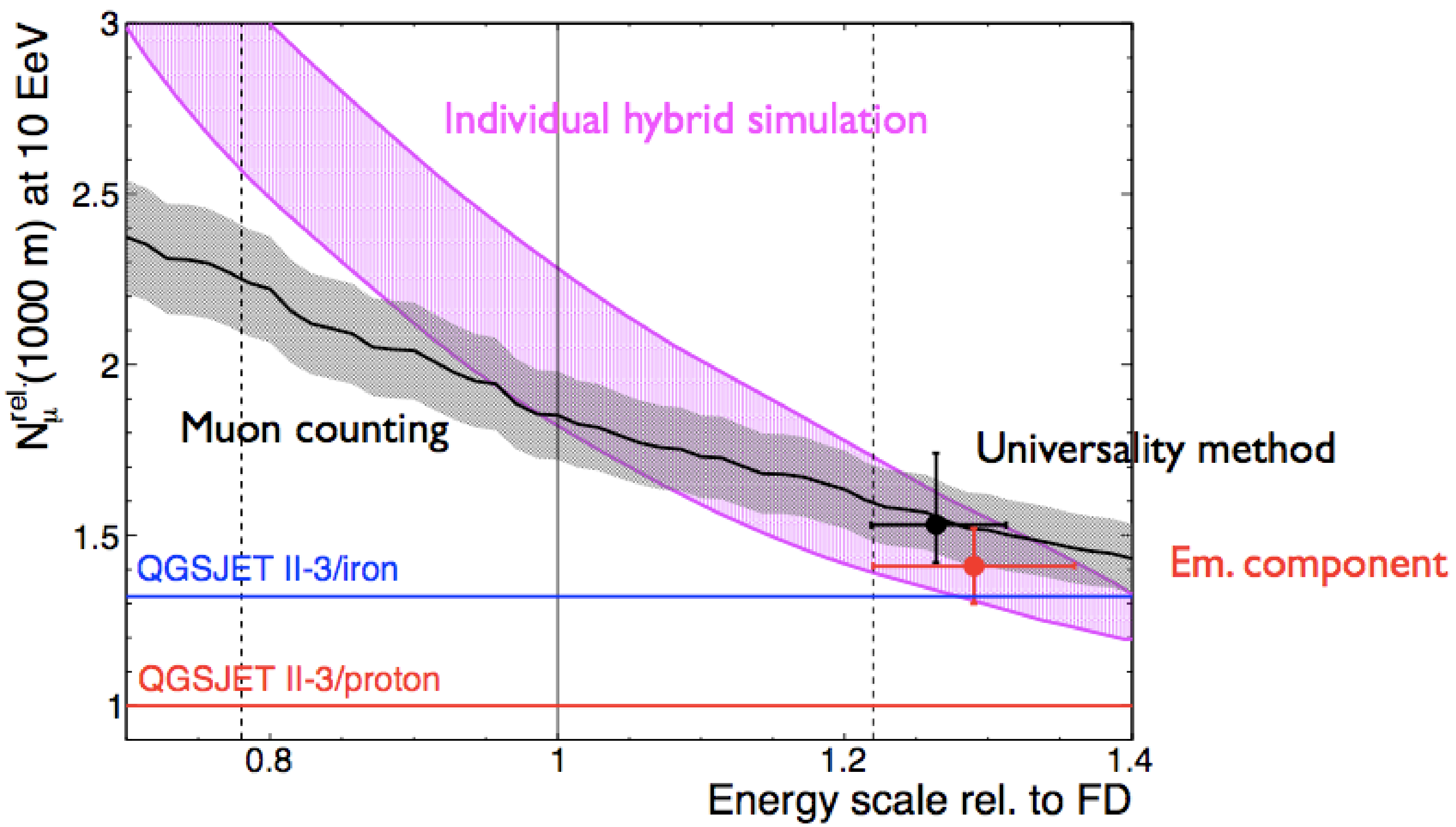
Broken line fit:
Slopes D [g/cm^2/decade]



Particle physics:
Validation of hadronic interaction models

Self consistent description of Auger data is obtained only with a number of muons 1.3 to 1.7 times higher predicted by QGSJET-II for protons at an energy 25-30% higher than that from FD calibration

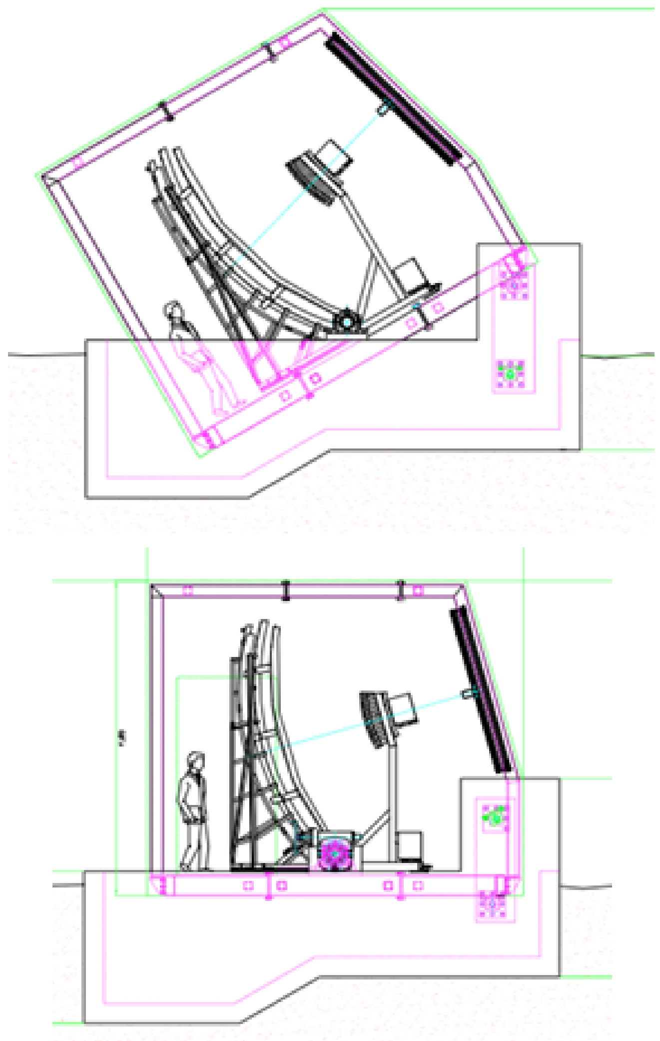
The results are marginally compatible with the predictions of QGSJET-II for Iron primaries

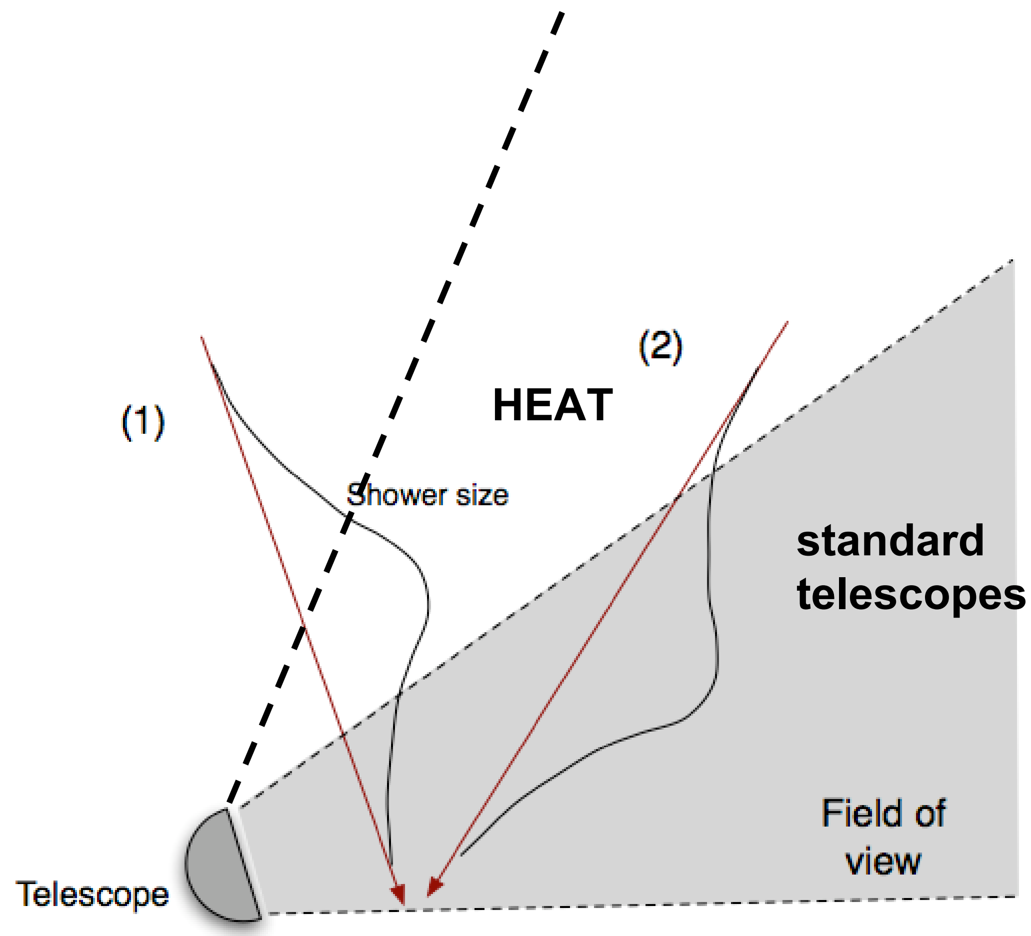


See recent talk by Ralph Engel here at same occasion (modified x-sections, ...)

Enhancements

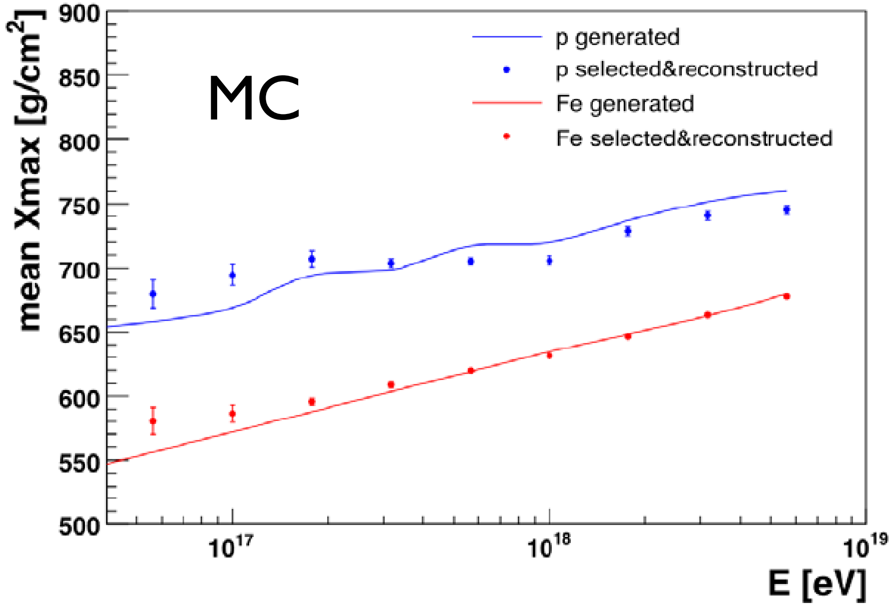
HEAT: High Elevation Auger Telescopes

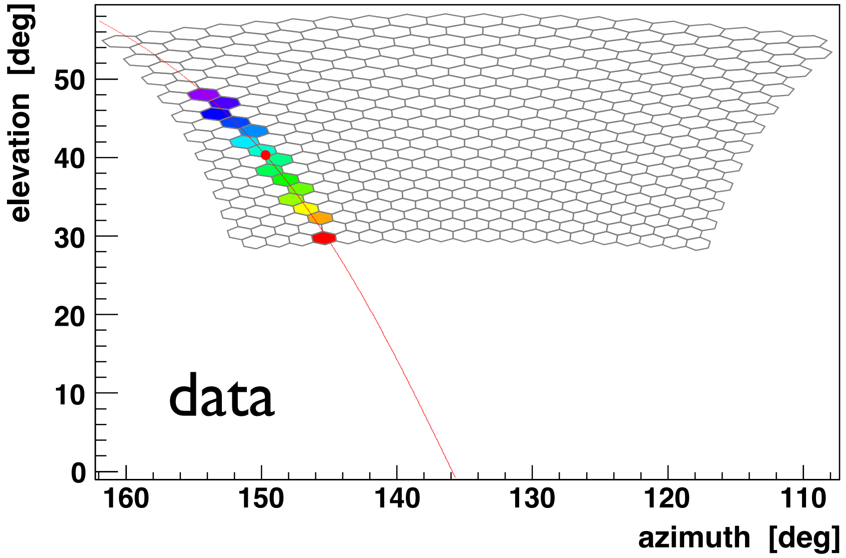


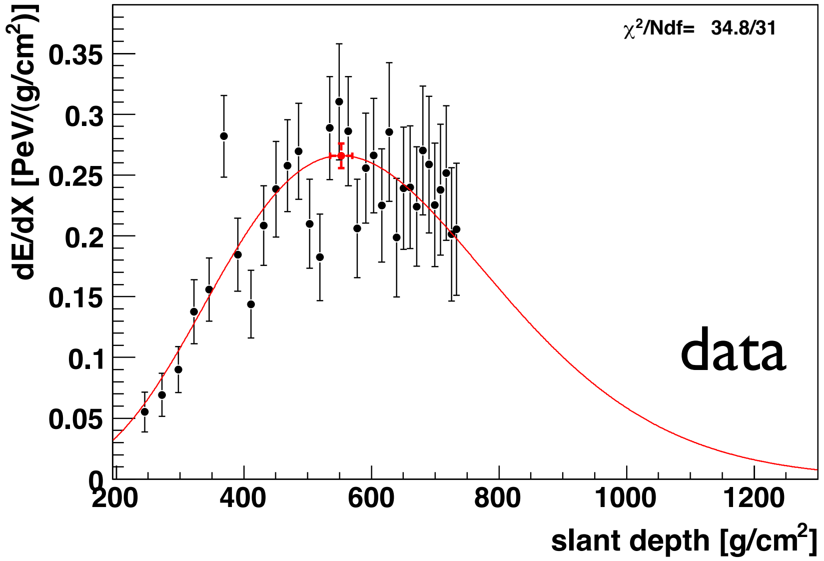


- 3 *standard* Auger telescopes tilted to cover 30 - 60° elevation
- Custom-made metal enclosures
- Also prototype study for northern Auger Observatory

HEAT: High Elevation Auger Telescopes

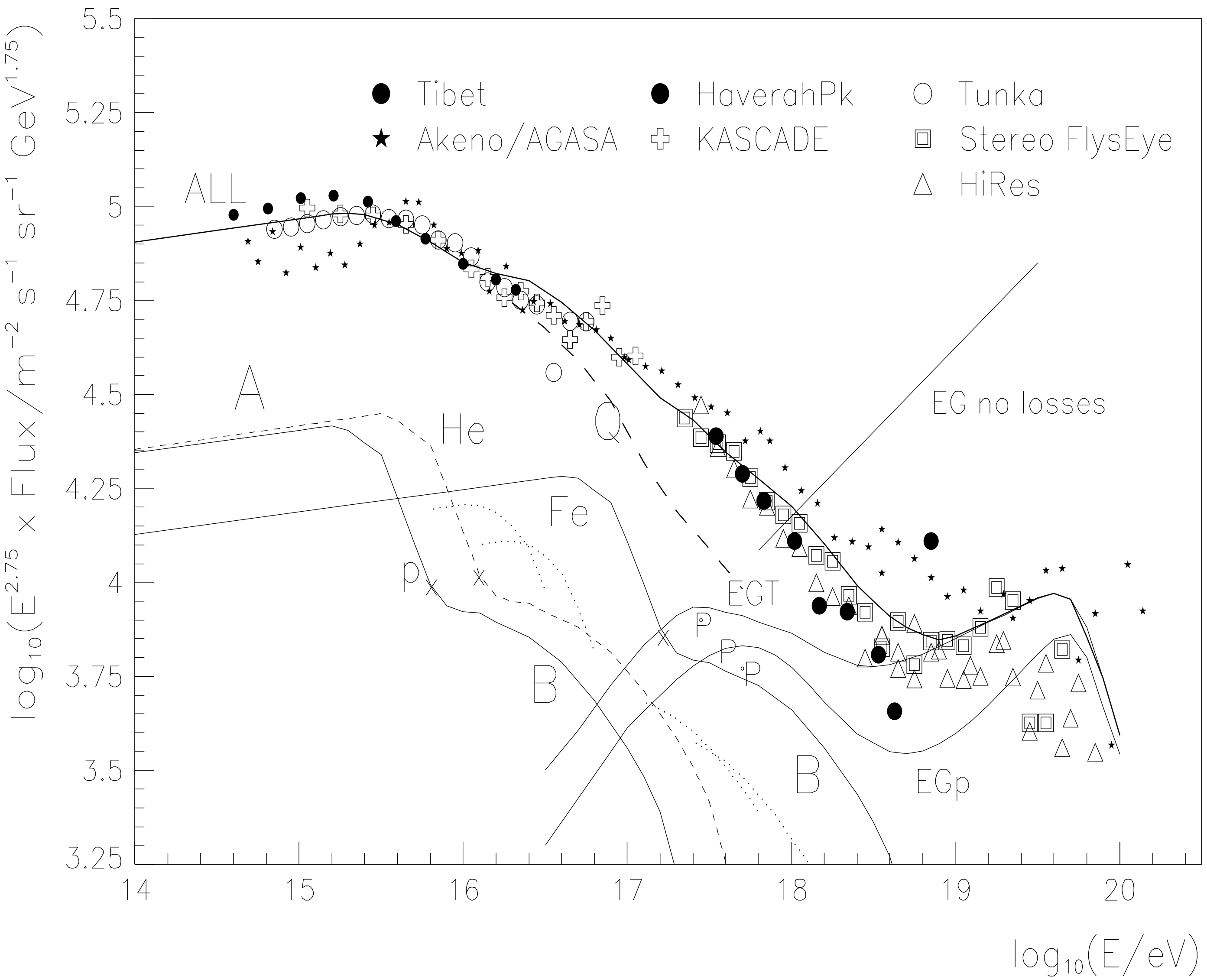




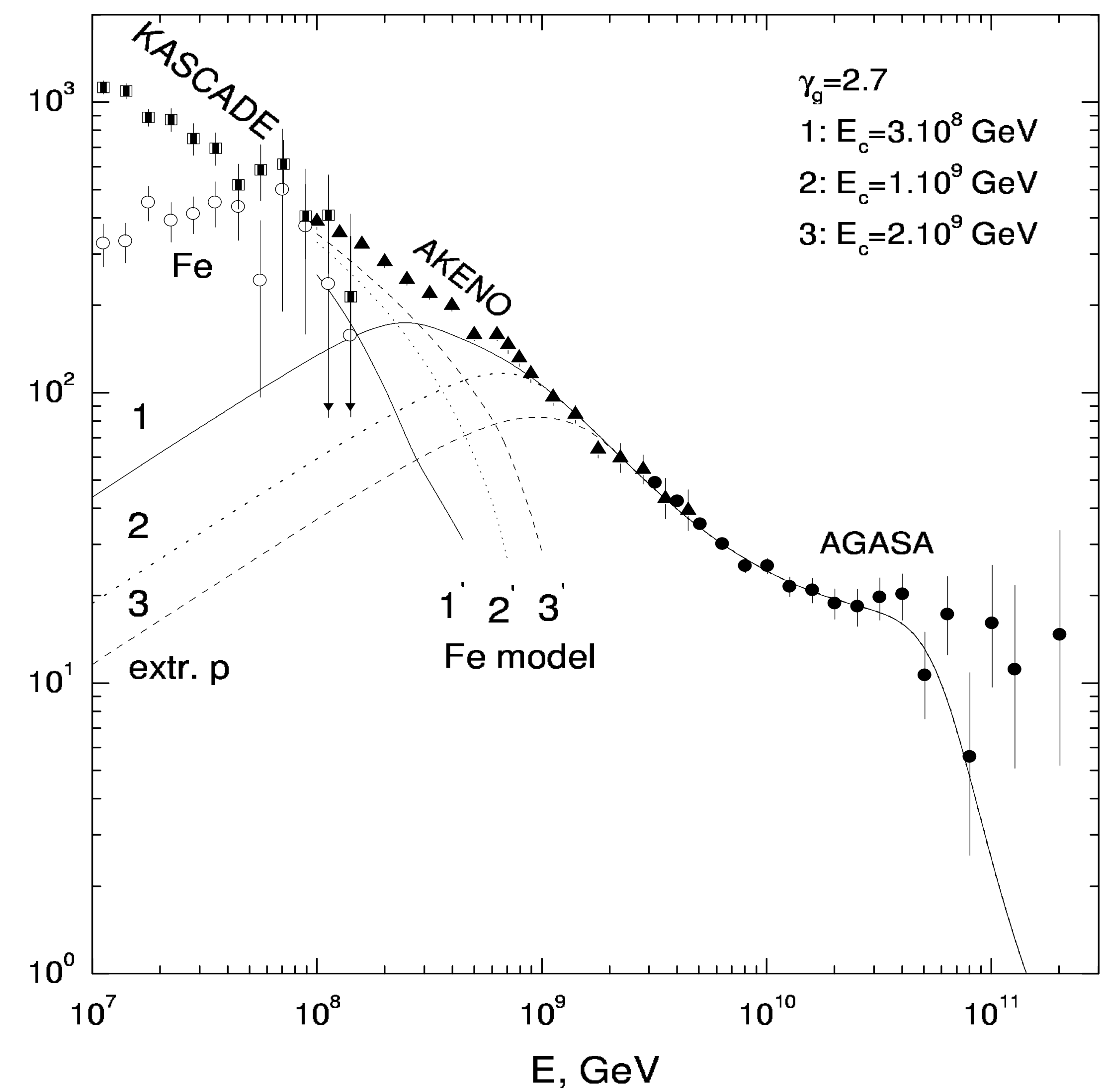


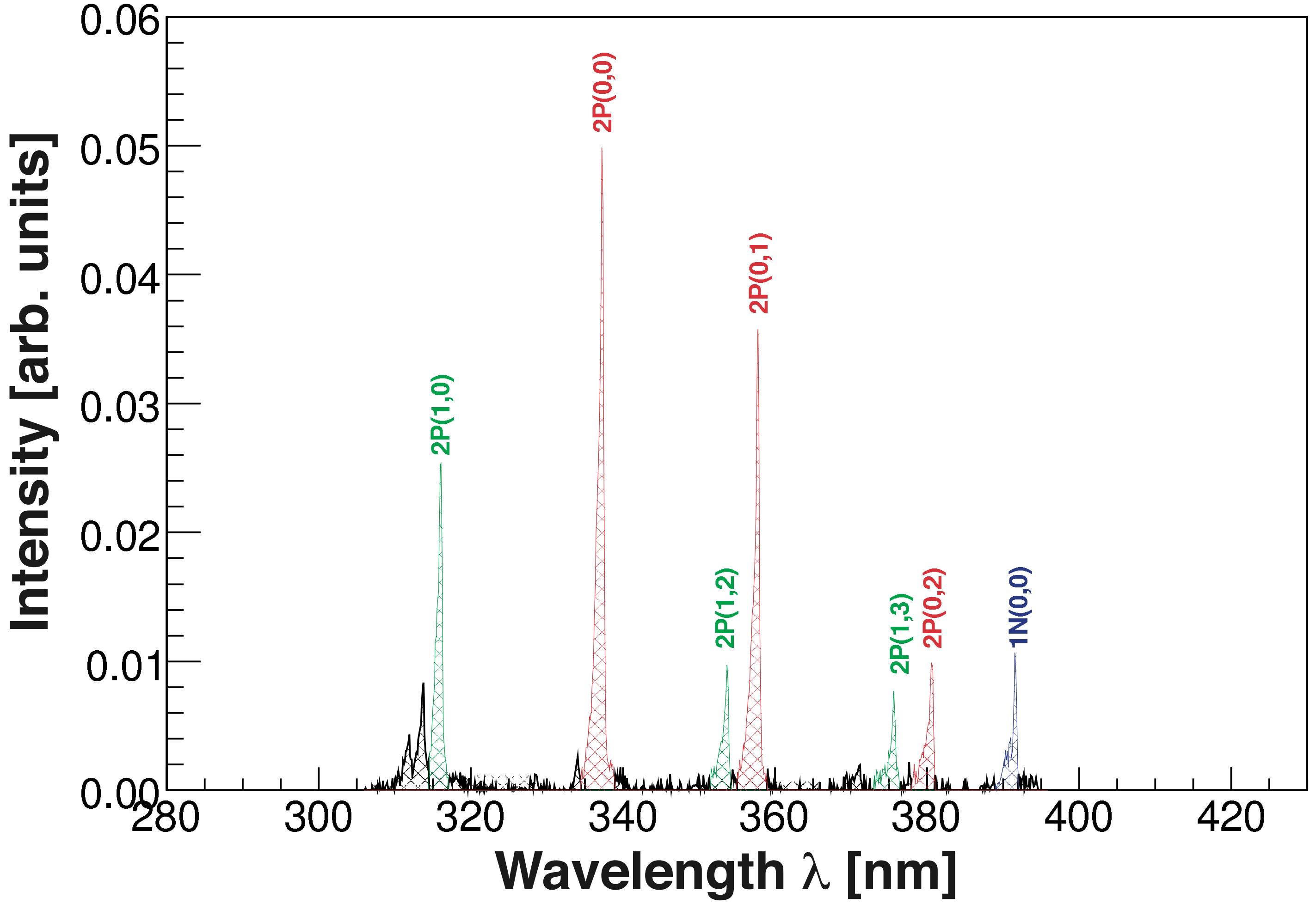
Energy: $(1.68 \pm 0.11) \times 10^{17}\,\mathrm{eV},\ \mathrm{X_{max}} : 553 \pm 17\,\mathrm{g/cm^2}$

Hillas model



Bereszinsky model




Intensity [arb. units]
Wavelength λ [nm]
2P(0,0)
2P(0,1)
2P(1,0)
2P(1,2)
2P(1,3)
2P(0,2)
1N(0,0)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
280
300
320
340
360
380
400
420

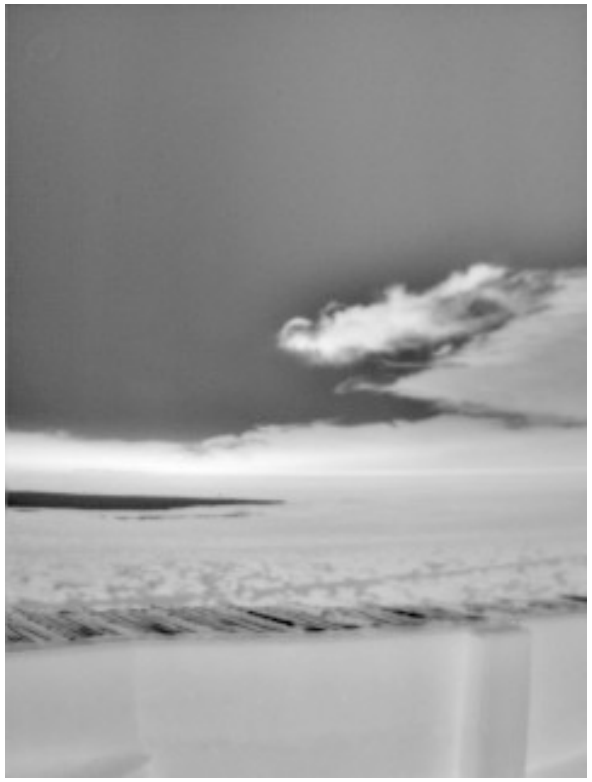
Monitoring the atmosphere (Auger)

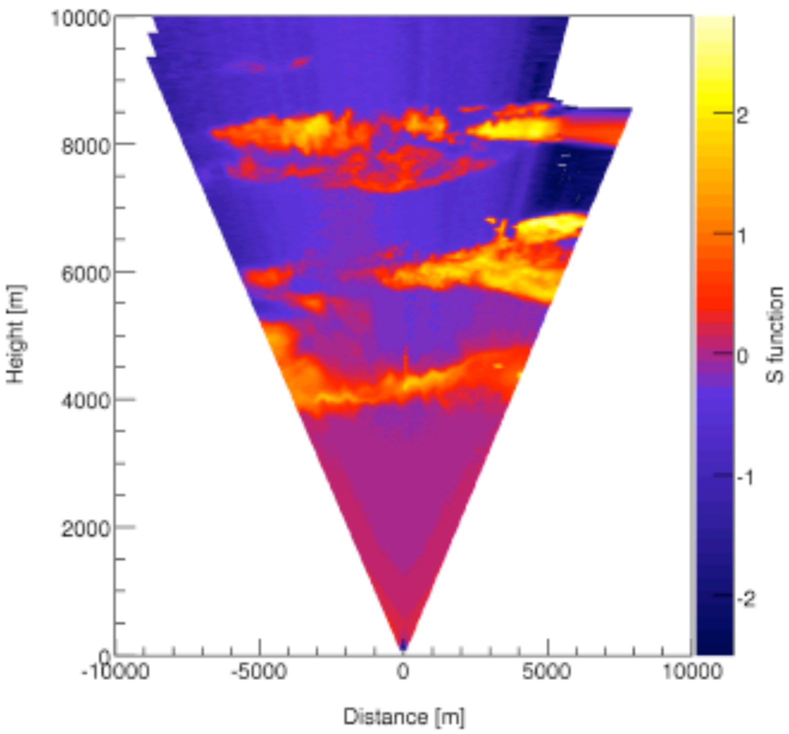
Monitor the state of
- the molecular atmosphere
- aerosol distribution and scattering properties
- night-time cloud

lidars

UV lasers

cloud detection





infra-red cameras and lidar

radiosondes