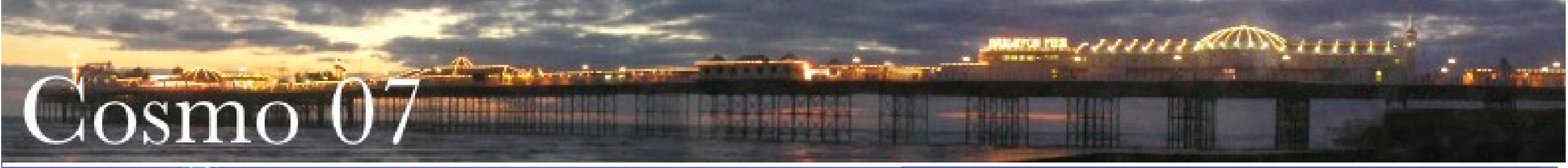


Catching cosmic rays

Ultra-High Energy

J Knapp, U of Leeds
for the
Pierre Auger Collaboration

Contents:

- UHE Cosmic Rays
- The Pierre Auger Observatory
- Results

UHECRs

Cosmic Ray Flux:

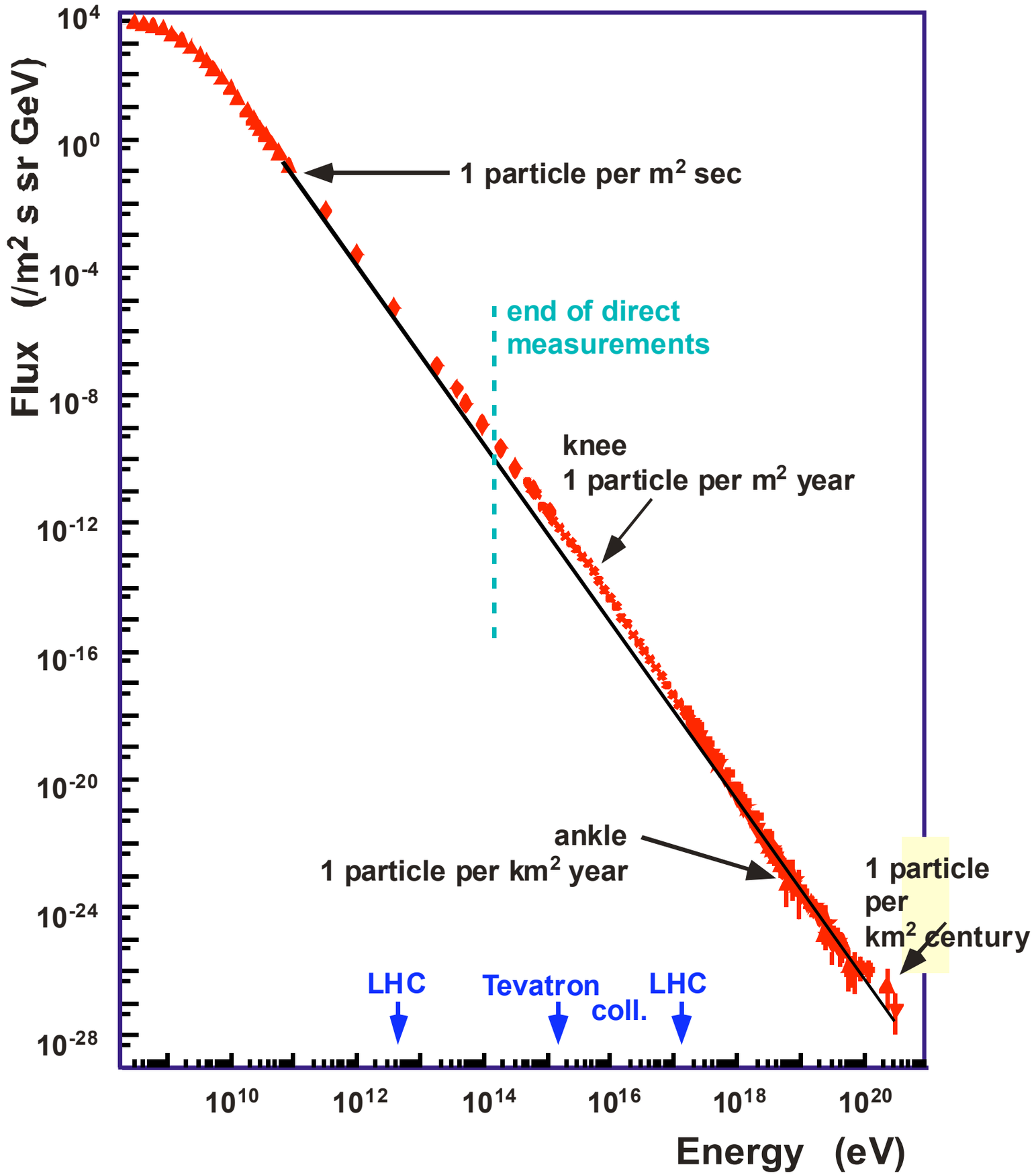
steeply falling:

x 10 up in energy

1/500 down in flux

no upper end (so far)

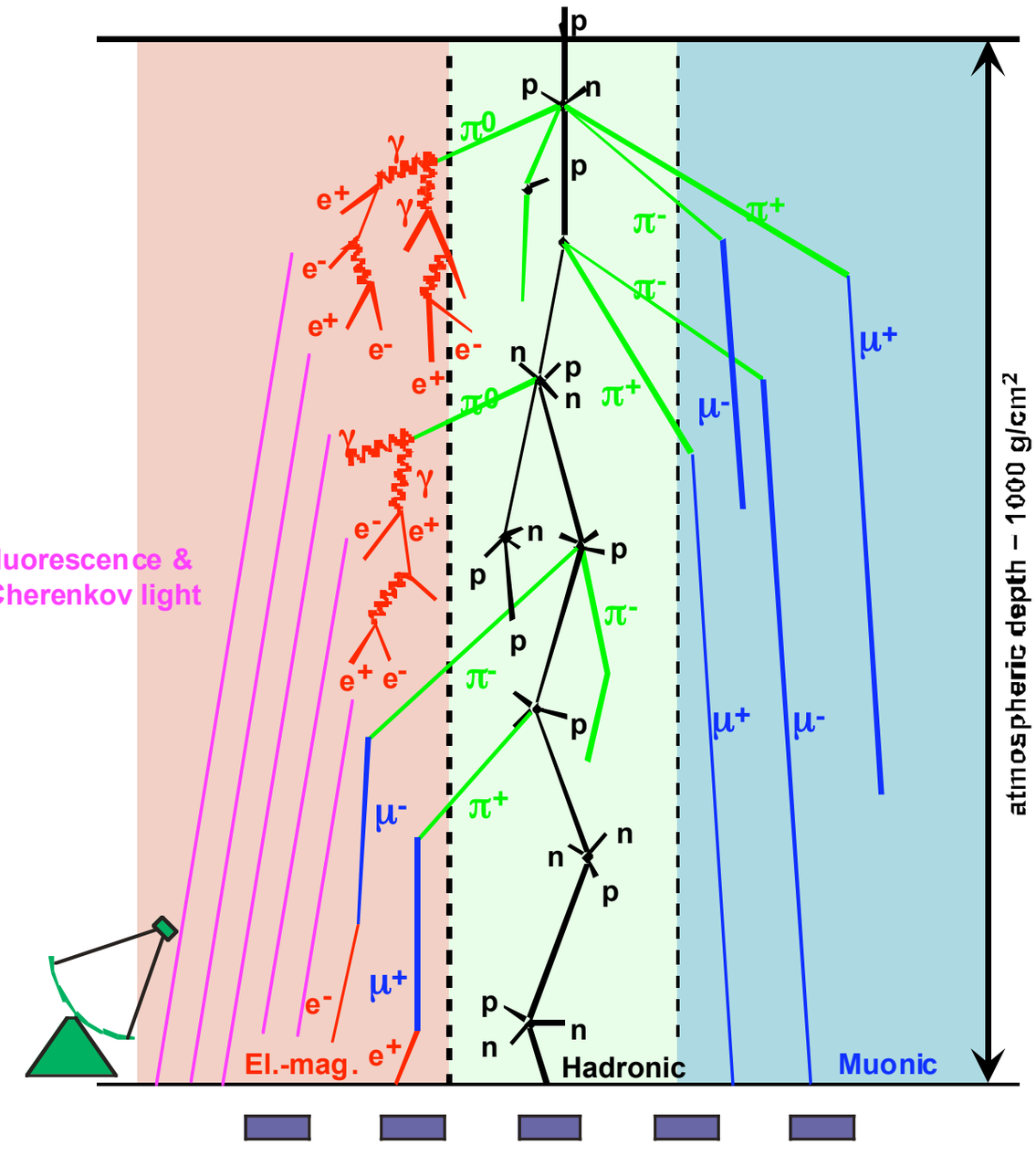
real high-energy physics!



Schematic Shower Development

energy
particle type
direction

???



detector response: energy deposits, times, efficiencies, thresholds, ...

Shower development depends on:

- hadronic interactions,
- electromagnetic interactions,
- particle production,
- decays,
- transport, ...

Complex interplay of many effects:

- no analytic solution possible
- no test beam for calibration available

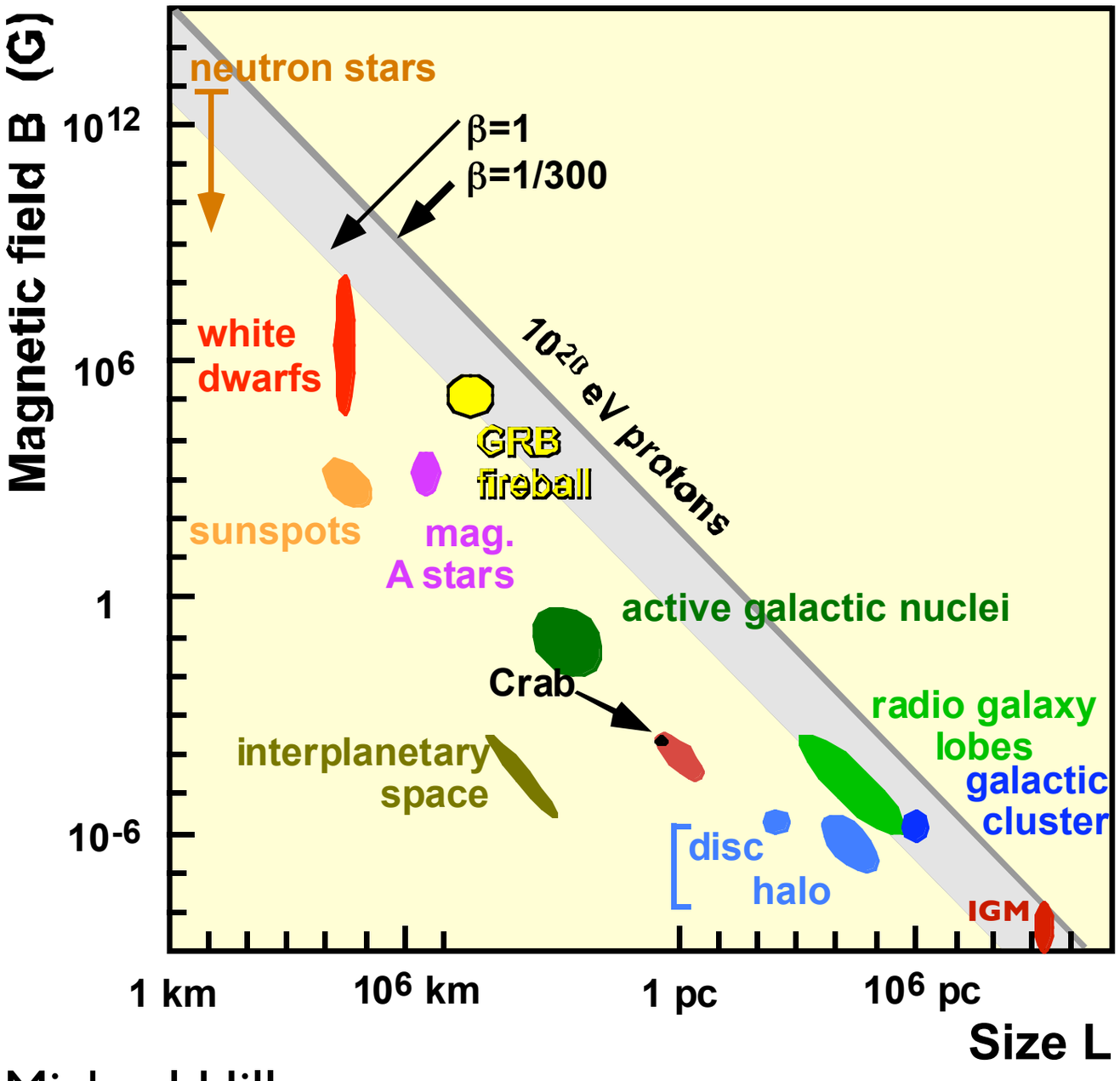
(at least for really high energies)

Need an air shower model:

- simulate showers for specific primaries
- get realistic detector responses
- find algorithms for reconstruction of primary shower parameters

Forward particles carry energy into the atmosphere & drive shower development

Possible Acceleration Sites to 10^{20} eV



Michael Hillas

$B_{\mu G} \times L_{kpc} > 2\, E_{EeV} / Z$

$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

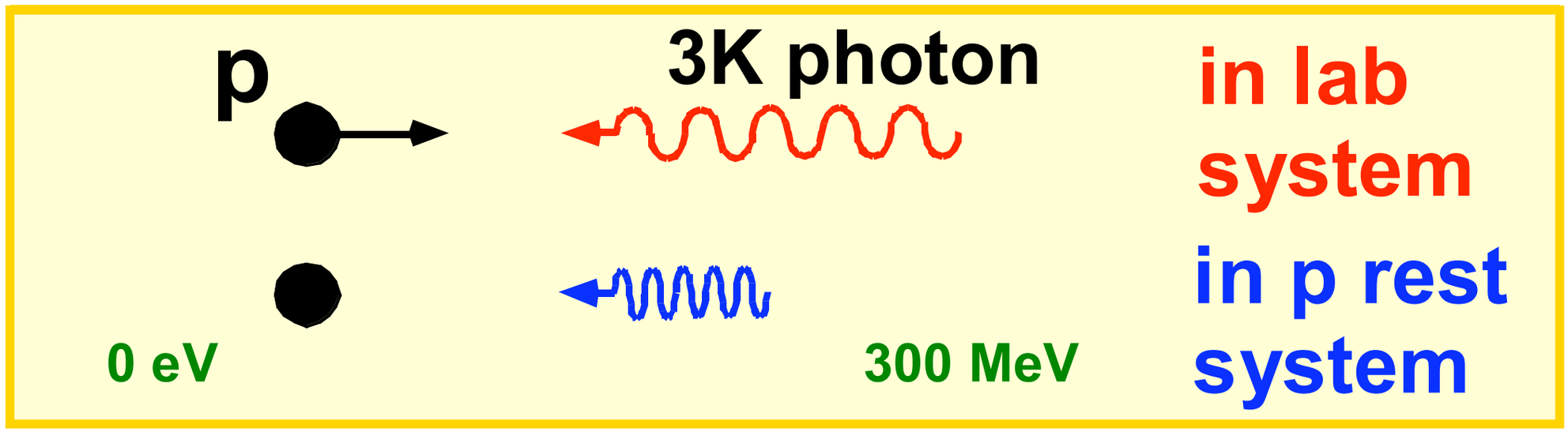
to fit gyroradius within L and to allow particle to wander during energy gain

But also:
gain should be more rapid than losses due to magnetic field (synchrotron radiation) and photo-reactions.

No obvious candidates ....

GZK Cut-Off

Greisen Zatsepin Kuzmin



$p + \gamma_{3K} \longrightarrow \Delta^{+} \longrightarrow p + \pi^{0}$ (γ) Photopion production

$\longrightarrow n + \pi^{+}$ (ν)

$^{56}Fe + \gamma_{3K} \longrightarrow {}^{55}Fe + n$ Photo dissociation

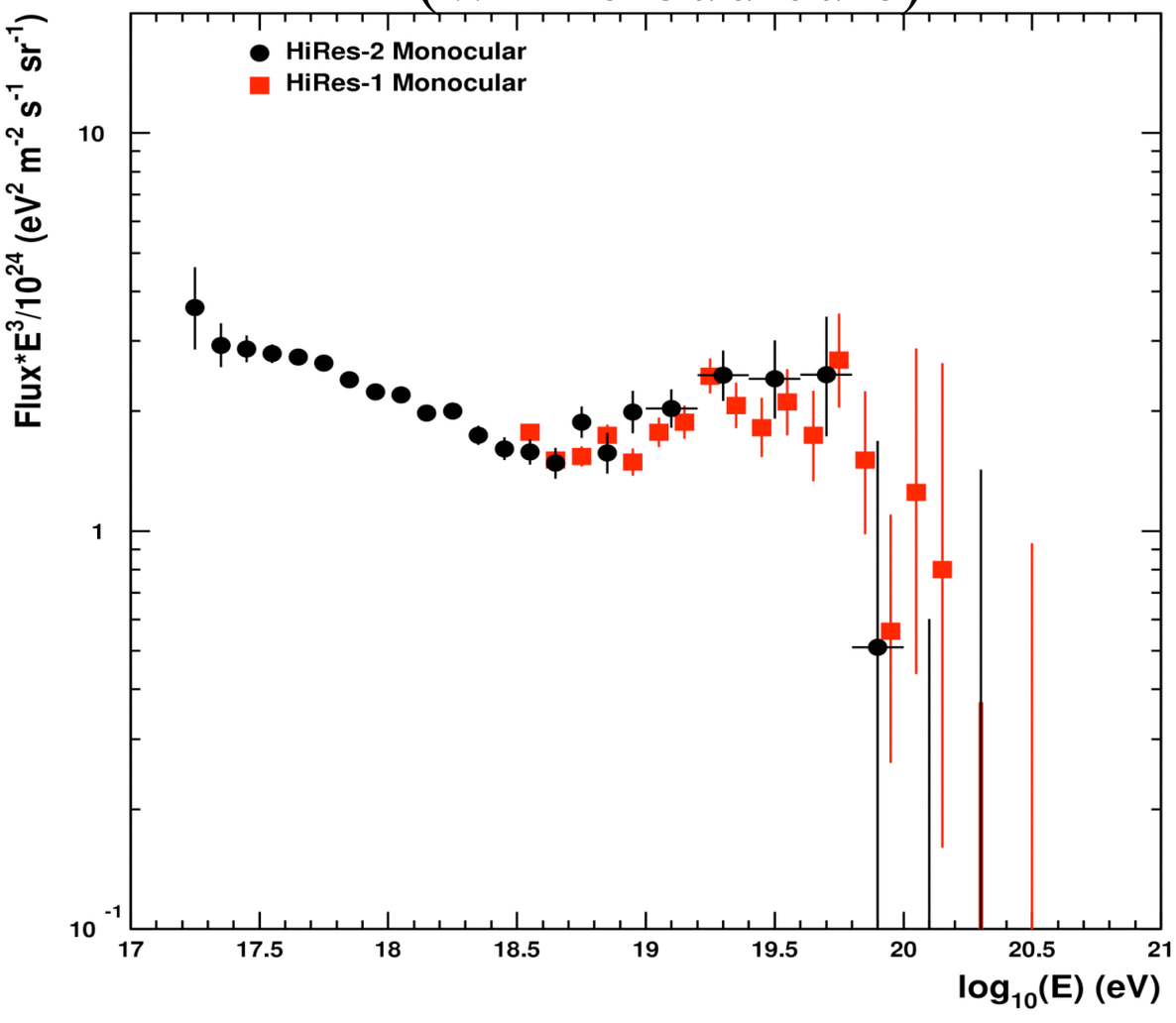
Universe is opaque for $E > 4 \cdot 10^{19}$ eV

Are CRs protons? Does Lorentz invariance hold?

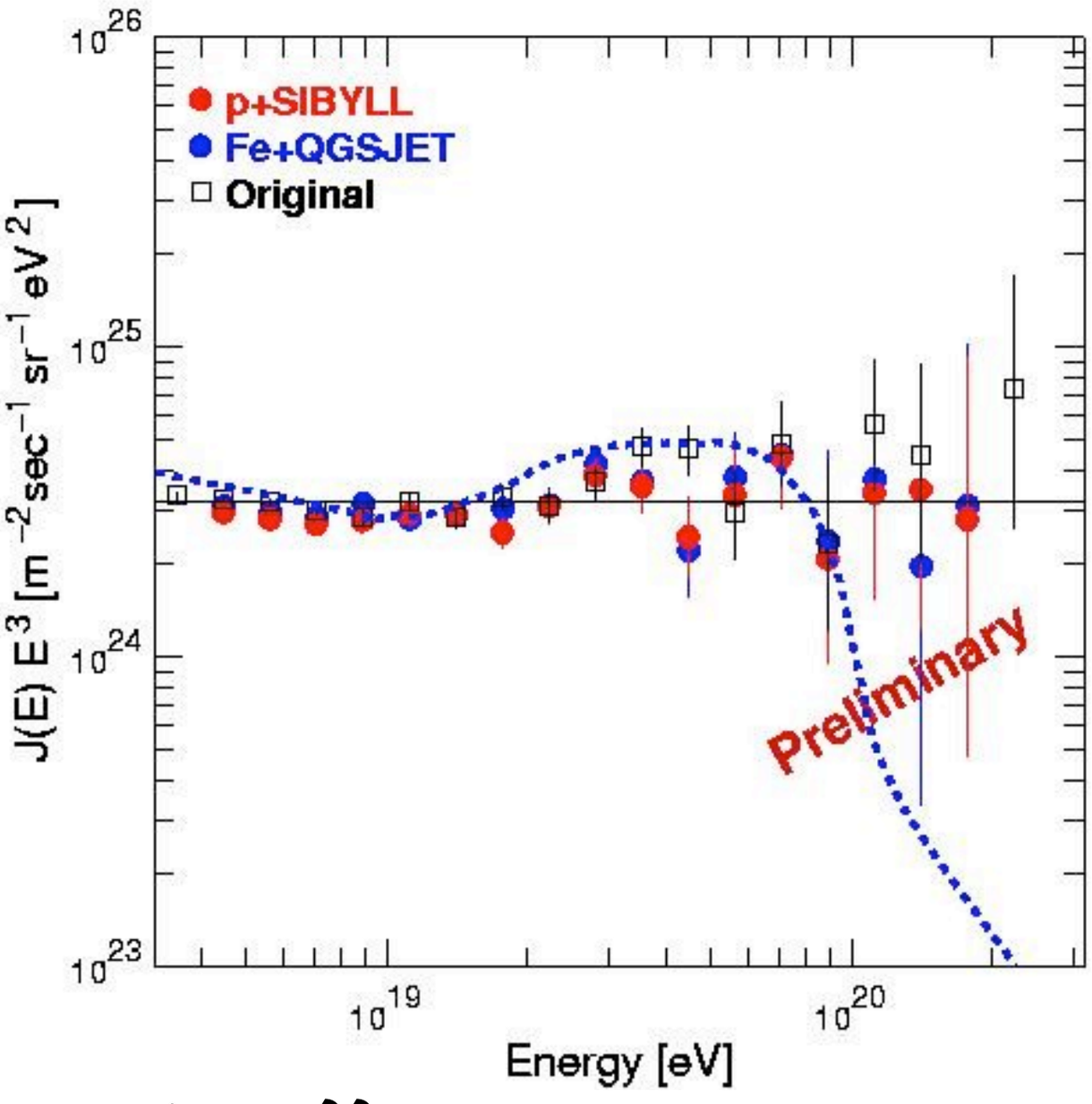
Cut-off or no cut-off ???

HiRes 2006

Most recent Mono spectrum
(with cloud cuts)

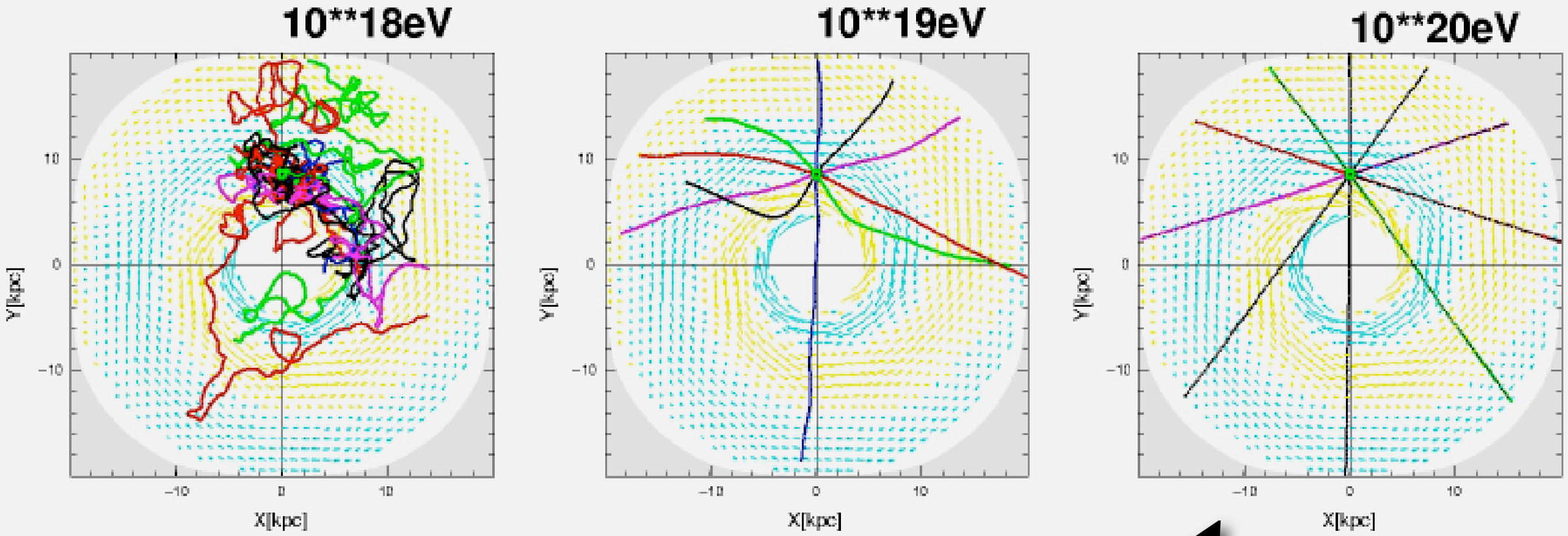


AGASA 2006

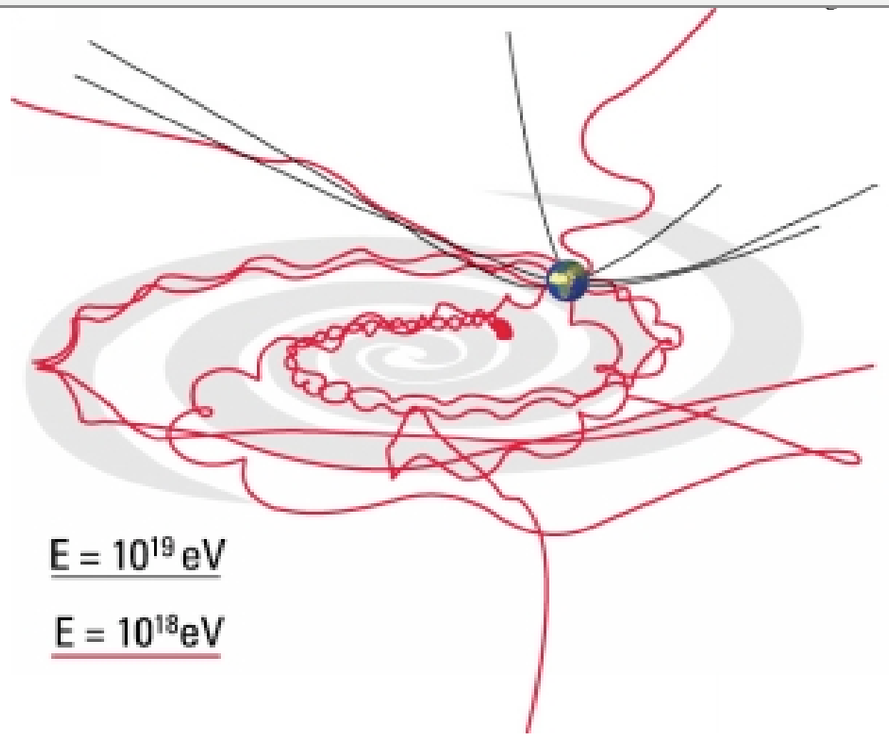


low statistics, systematics ??

Highest energy particles must be extragalactic



deflection < 1°



Astronomy with charged particles ?

needed:

much more statistics,
good energy resolution,
control of systematics,
mass composition

Auger

>300 PhD physicists / 70 institutions from

Argentina, Australia, Brazil, Bolivia, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, USA, Vietnam

Auger: unprecedented statistics and precision

~30 evts/yr with $E > 10^{20}$ eV

(based on AGASA flux)

Hybrid Detector:

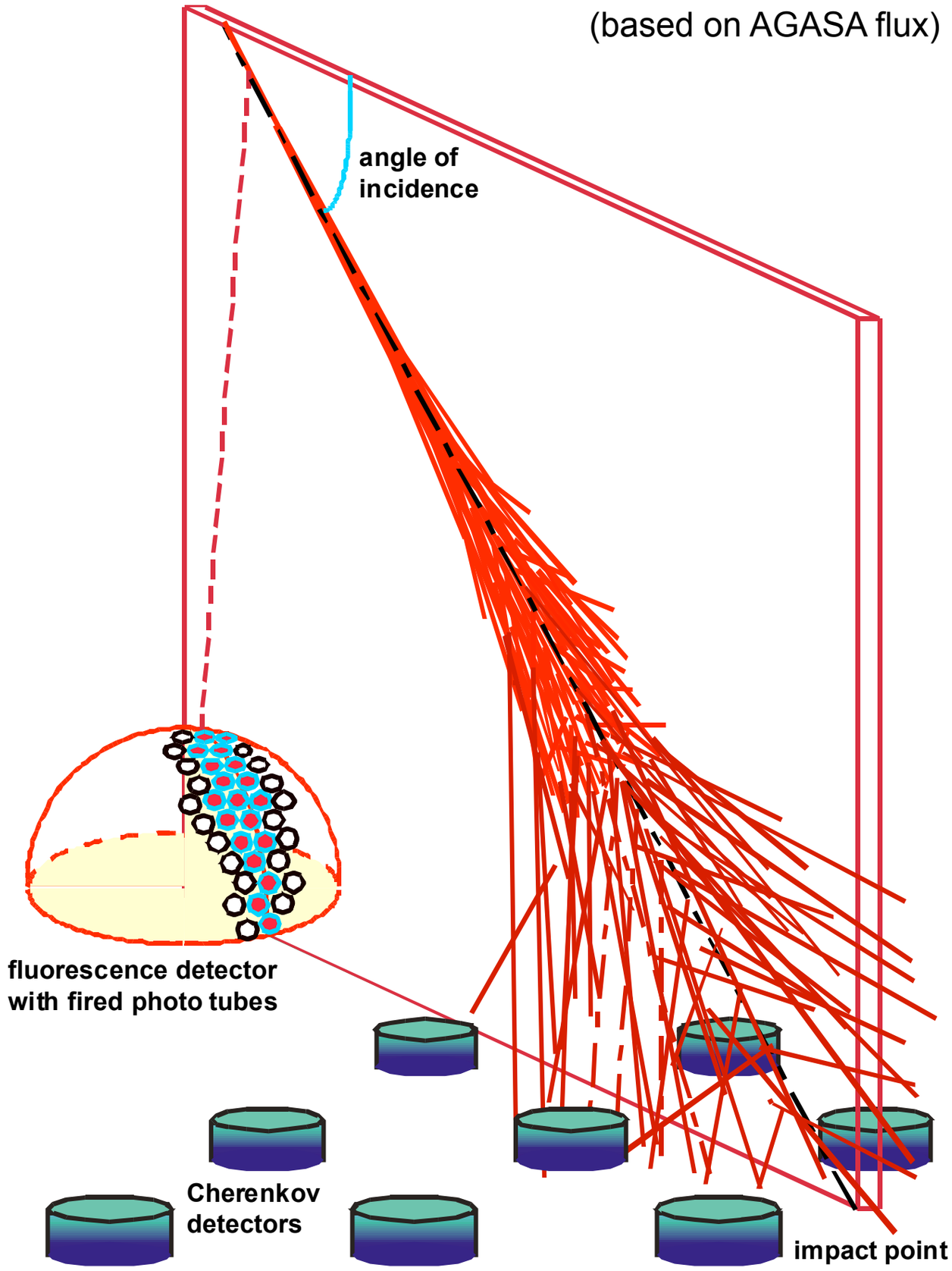
Array of 1600 water Cherenkov detectors
- covering 3000 km^2
- duty cycle: 100%

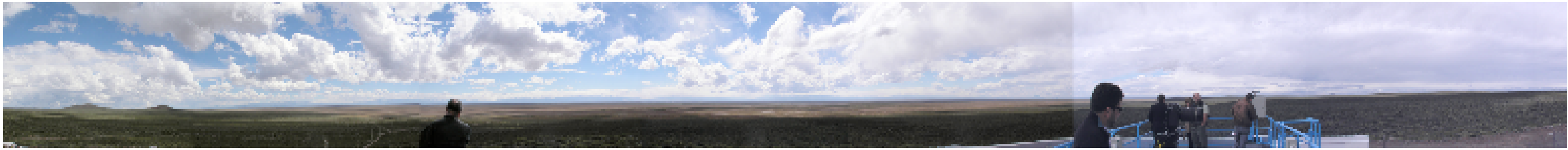
Fluorescence telescopes
- 24 FDs (30^{o}x30^o each)
- duty cycle: 10%

Better geometric reconstruction, cross-calibration, control of systematics.

Full-sky coverage with 2 observatories in northern and southern hemisphere.

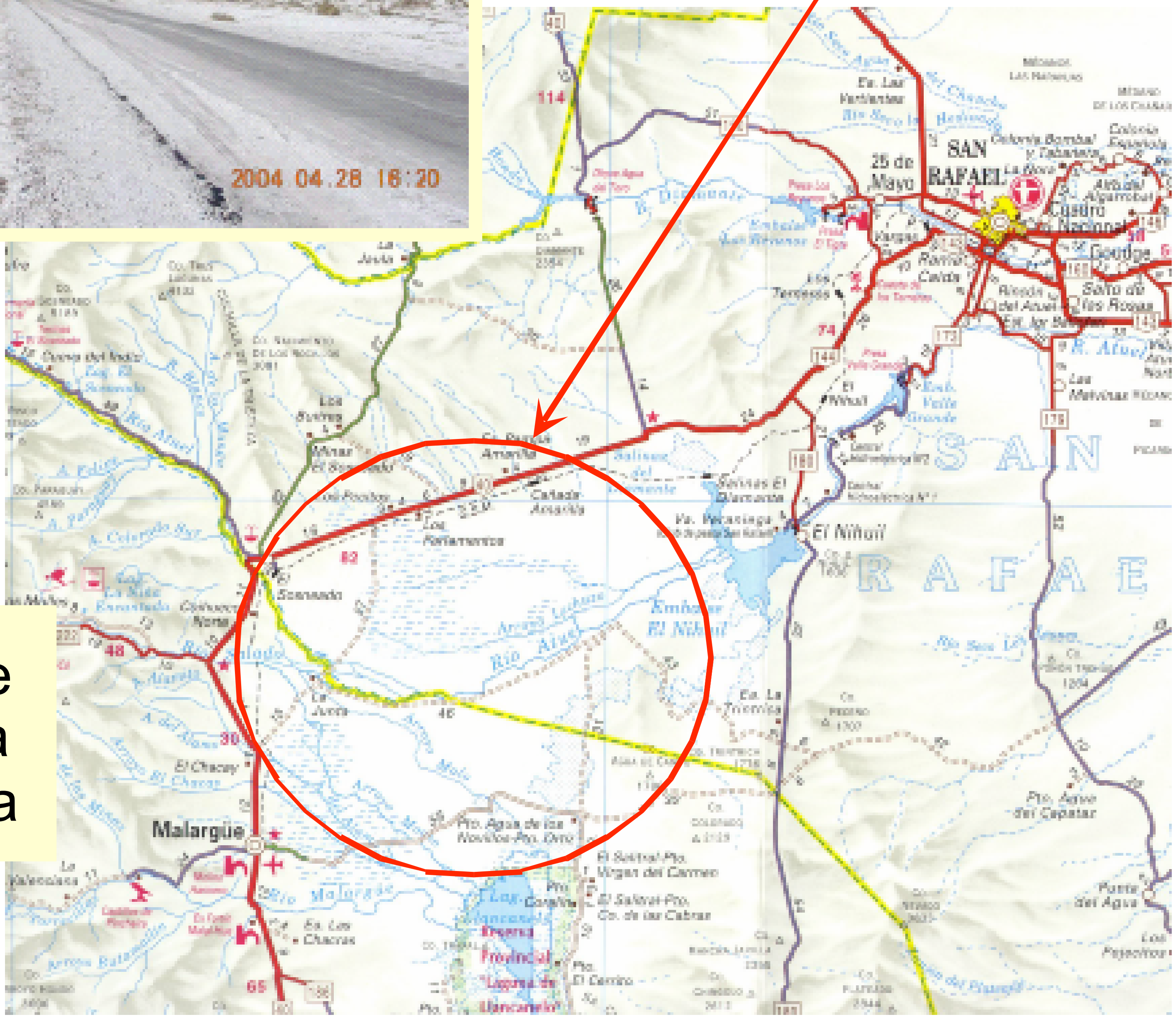
Shape of the spectrum? Cut-off?
Anisotropy in arrival directions?
Mass composition ?



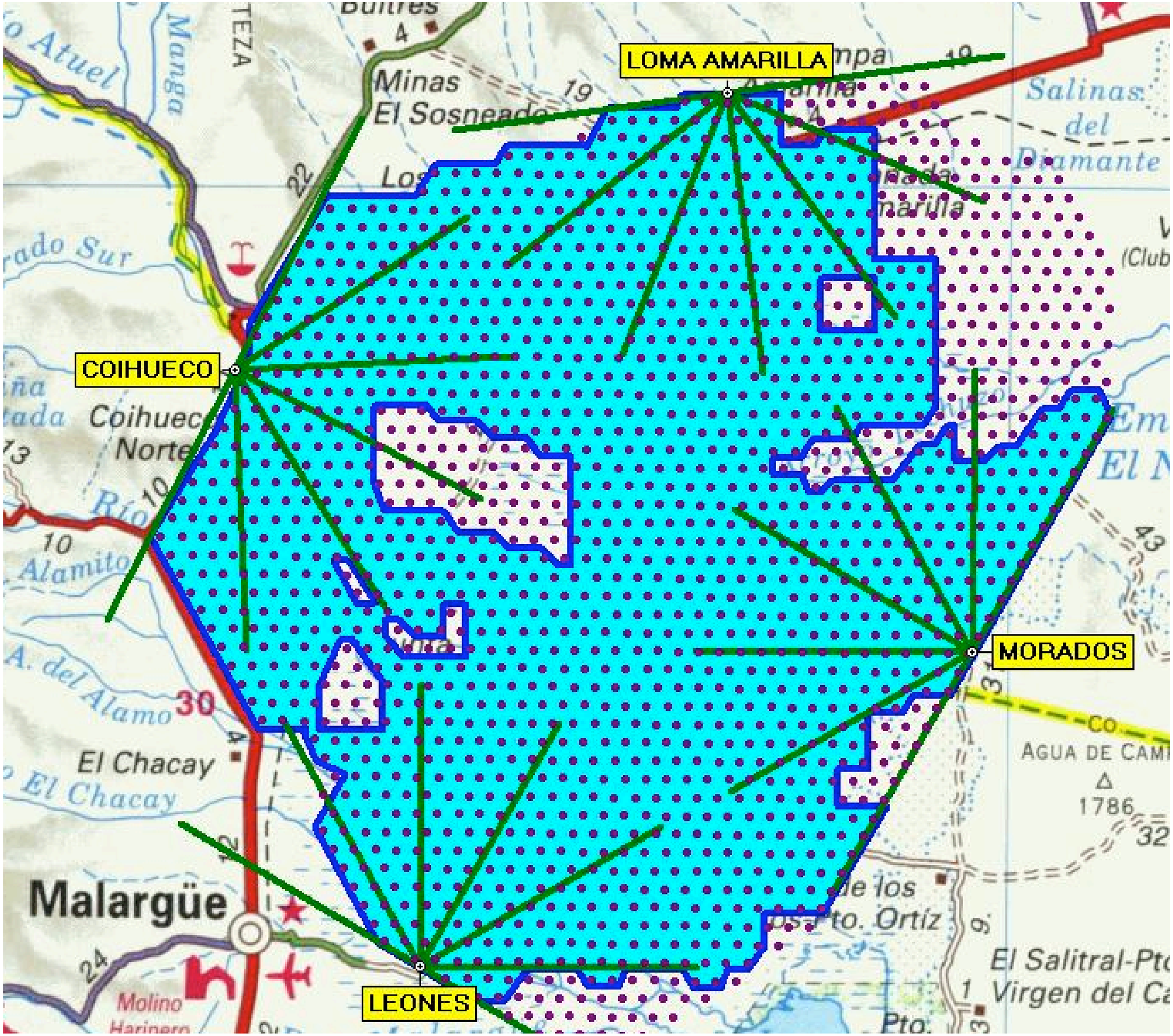


Auger South

(1400 m a.s.l., 35.2° S, 69.2° W)



Malargüe
Mendoza
Argentina



Status:
July 2007

1438 deployed
1400 filled
1364 taking data

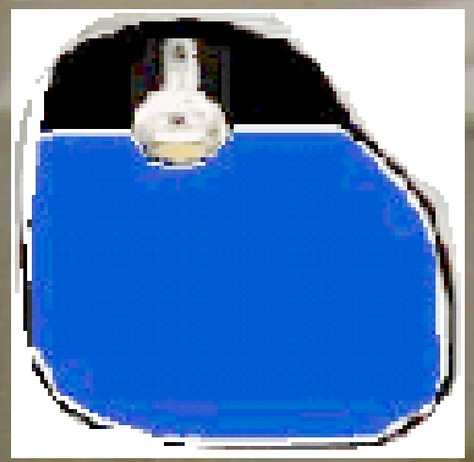
all 24 FD complete

Communications antenna

GPS antenna

Electronics enclosure

Solar Panels



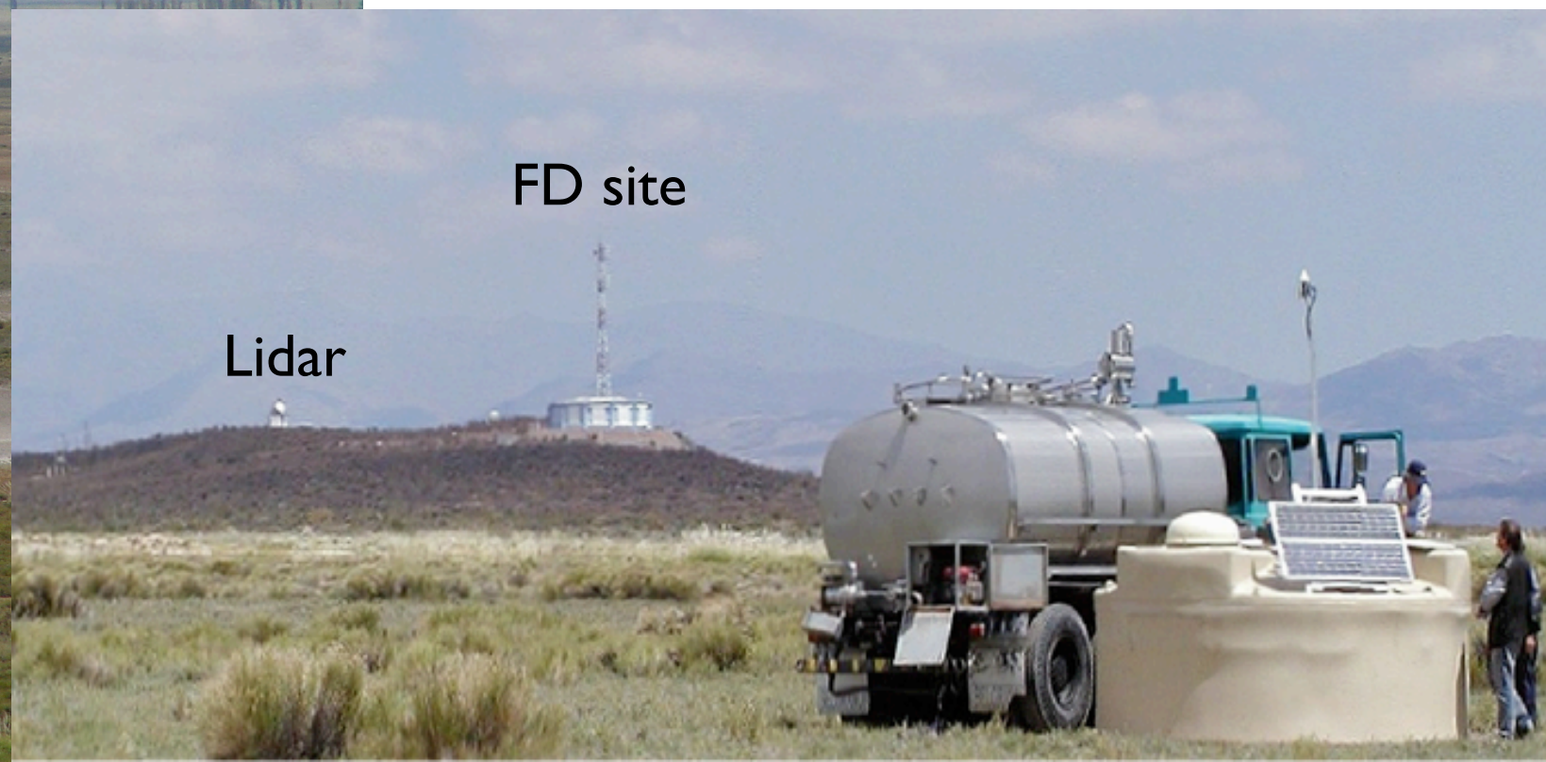
3 x 9" PMTs

Plastic tank
12 m^3 water

Battery box

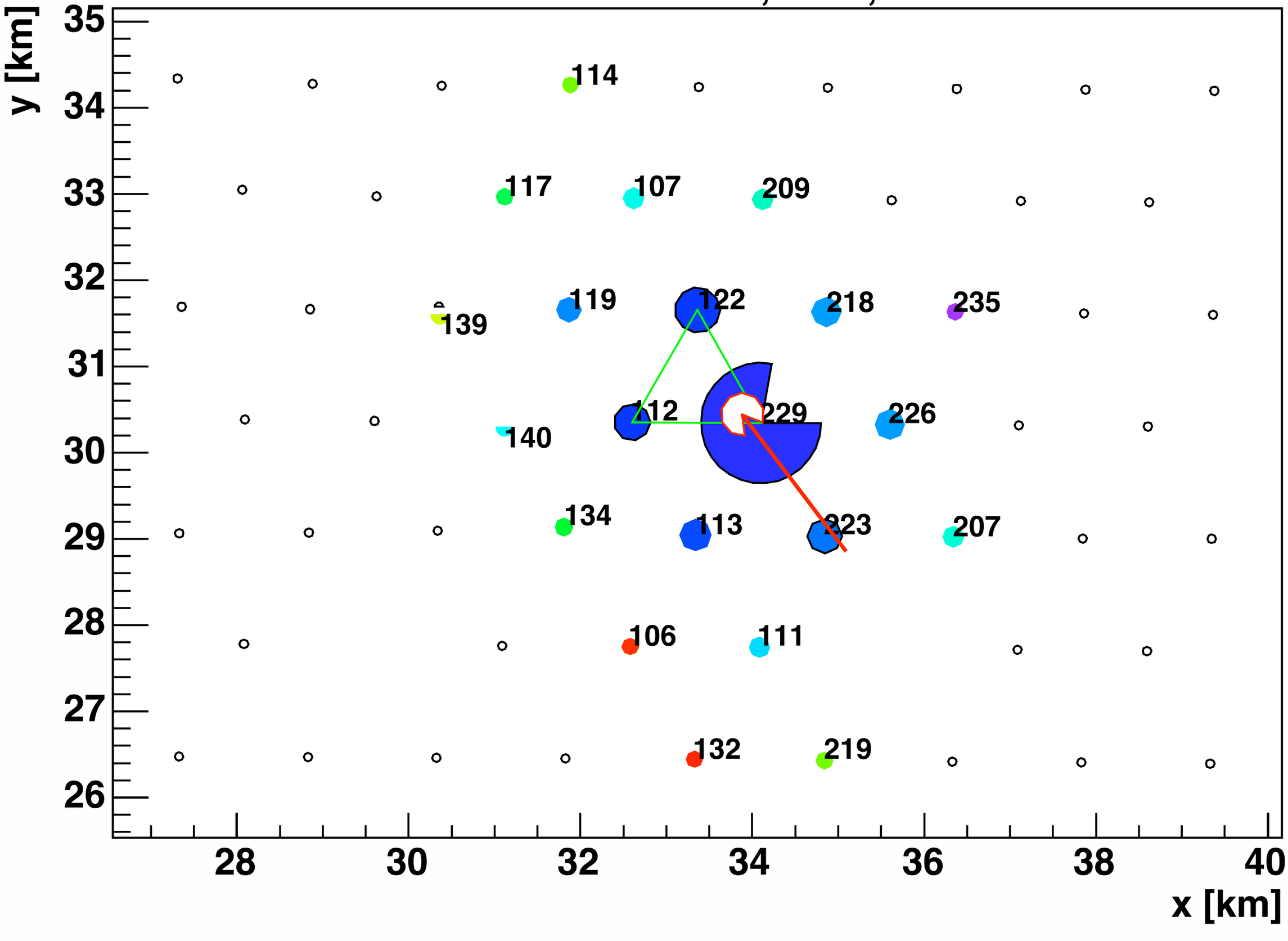
1600 water Cherenkov detectors over 3000 km^2

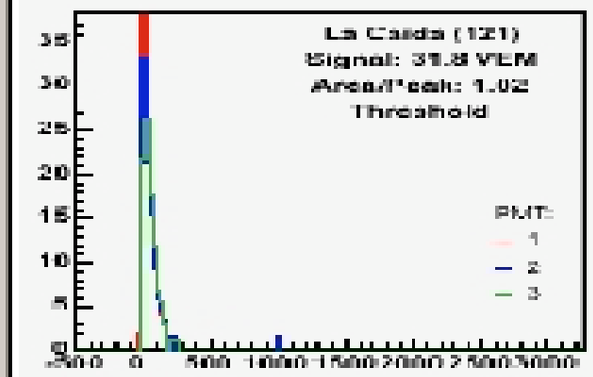
SD tanks in the field

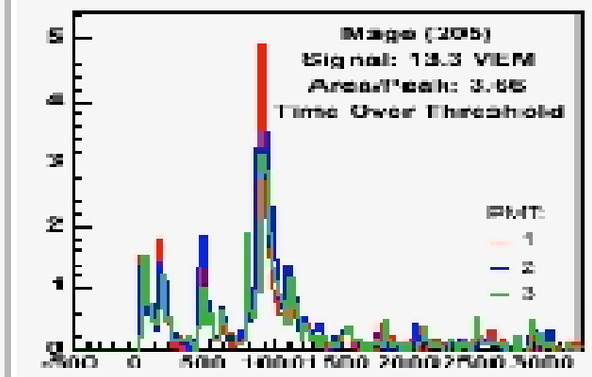


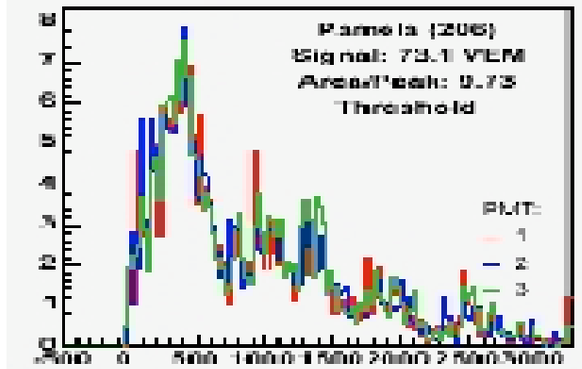
Event 1096757

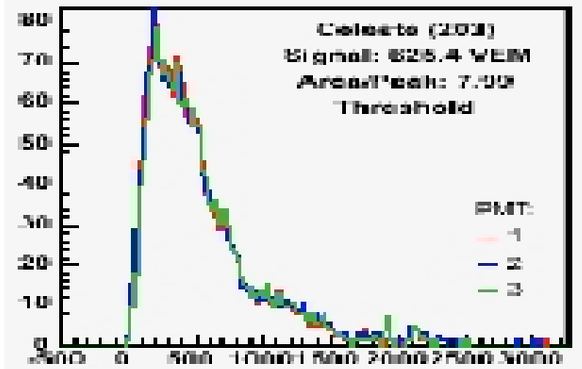
21 tanks, 45°, 86 x 10^{18} eV

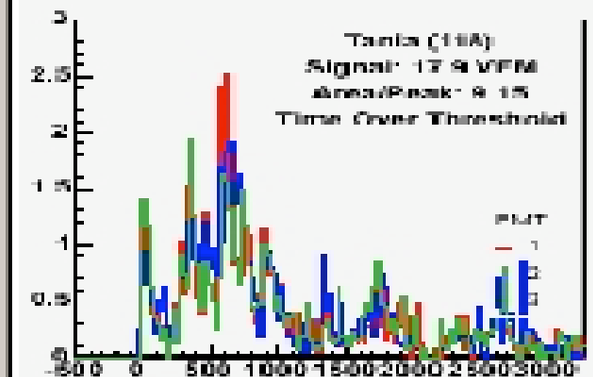


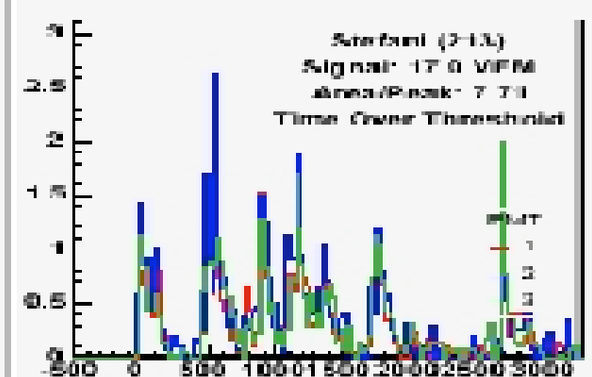


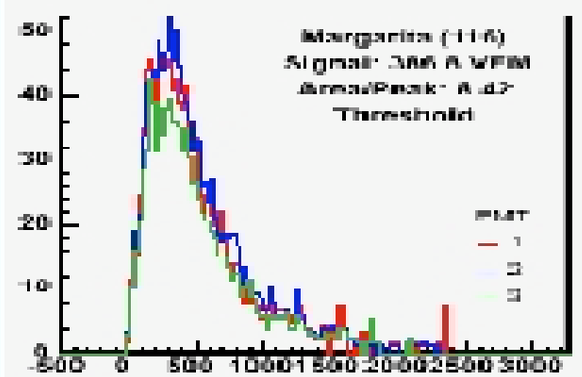


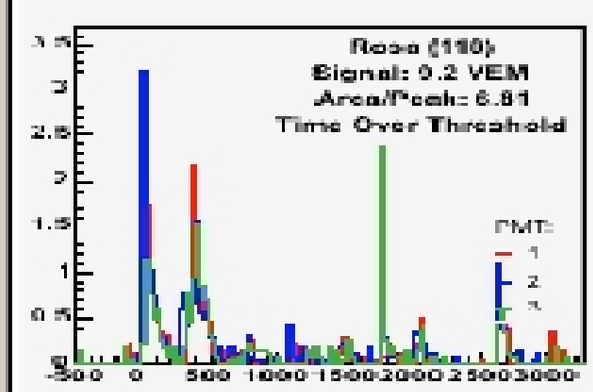


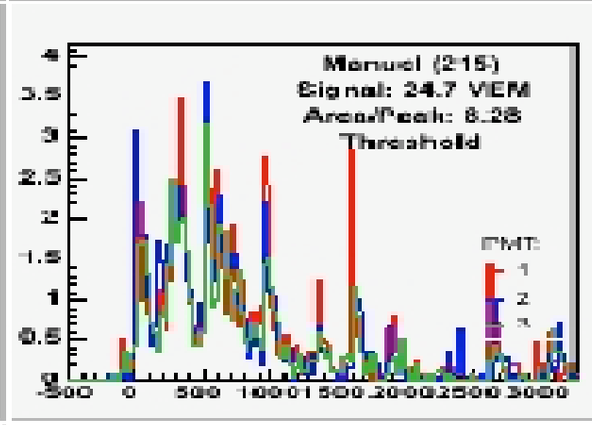


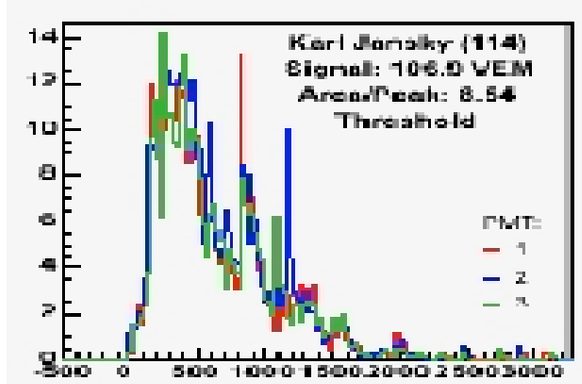


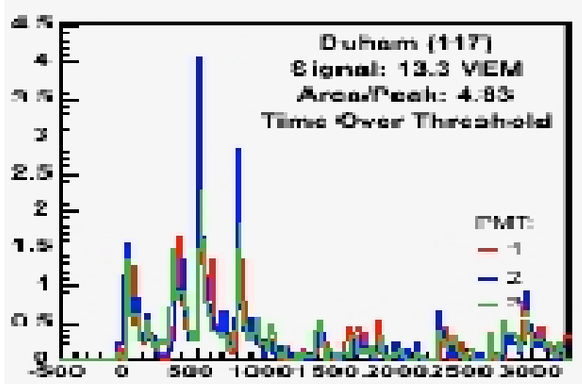


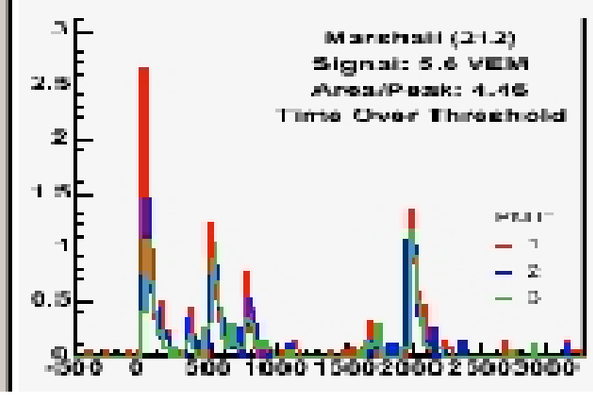


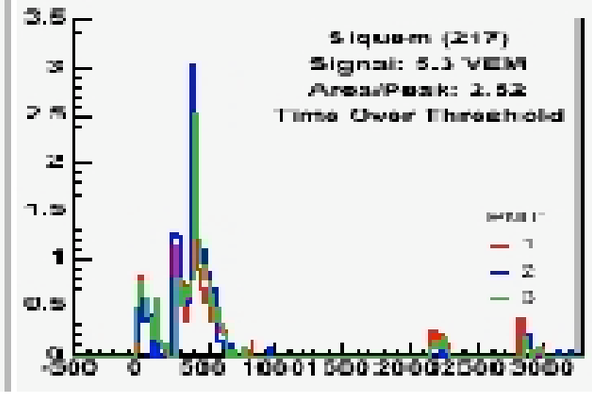


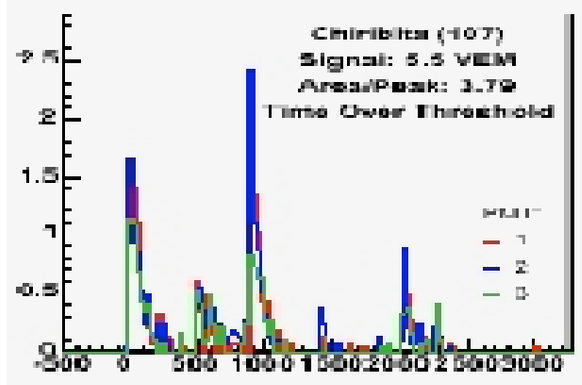


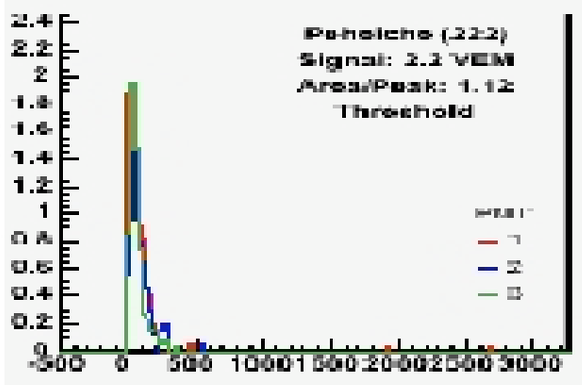






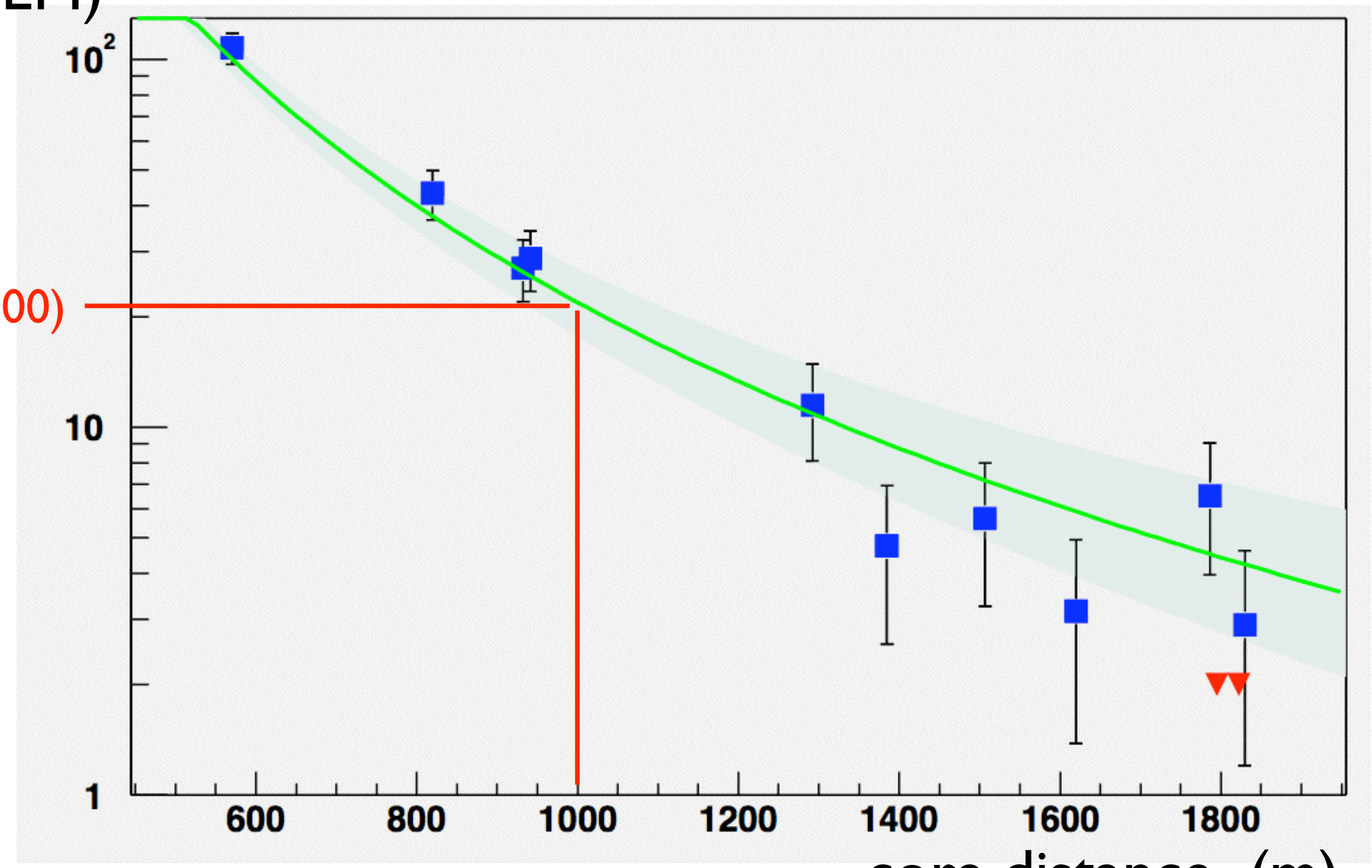






High & smooth pulses close to shower core, low & spiky pulses far away.

S (VEM)

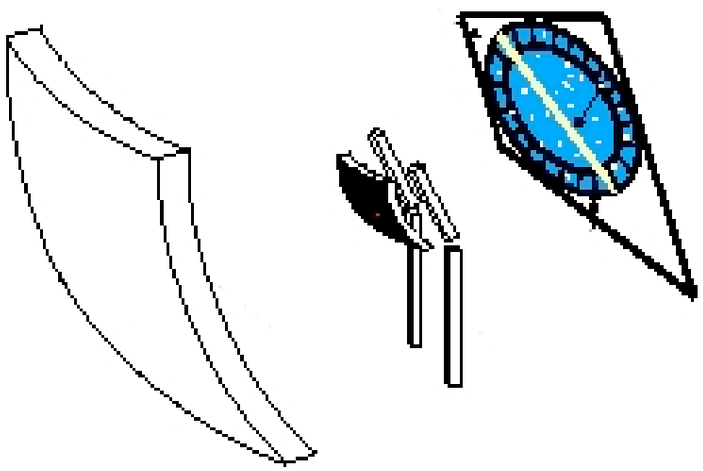


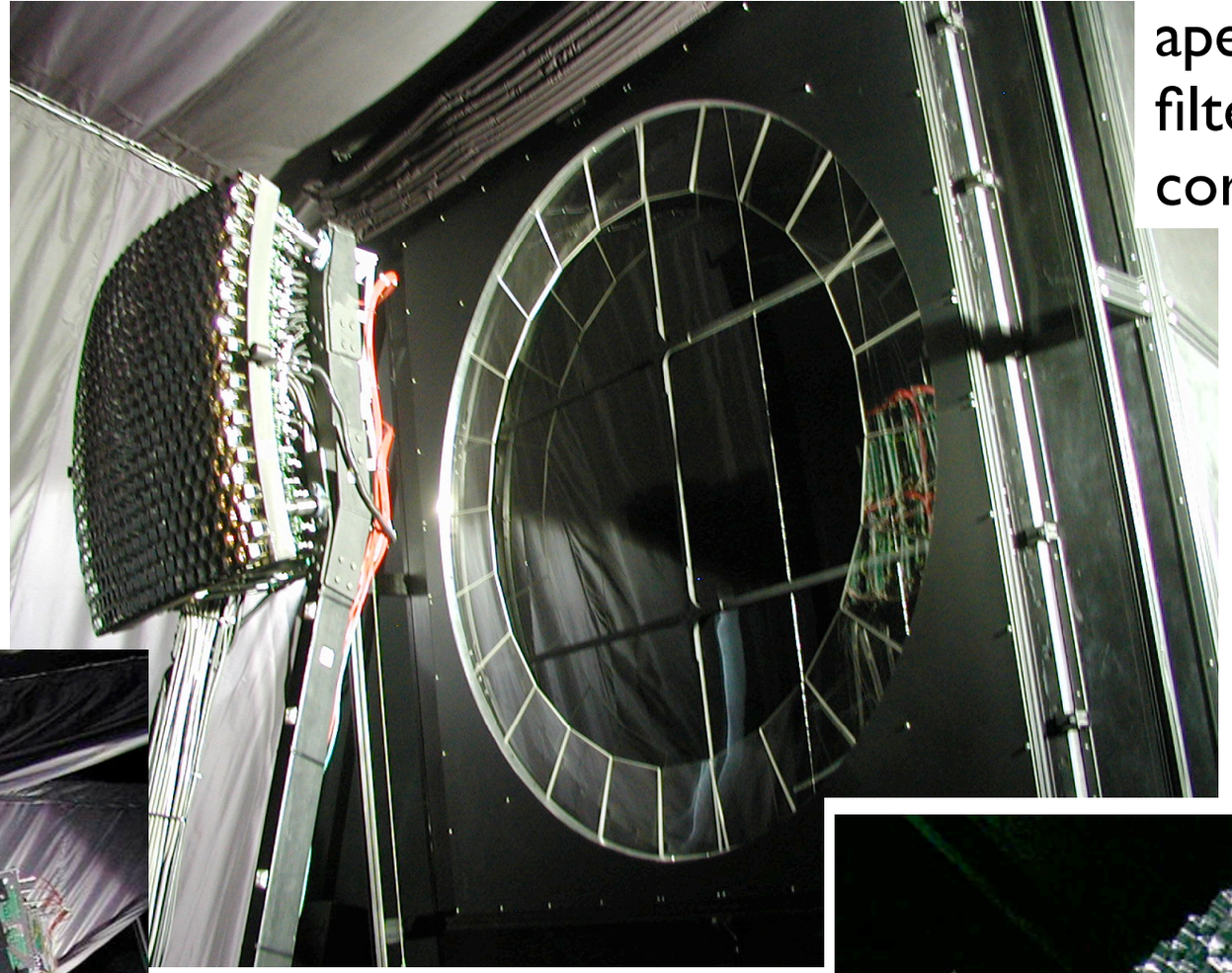
core distance (m)

S(1000) is good SD-only parameter to estimate the energy

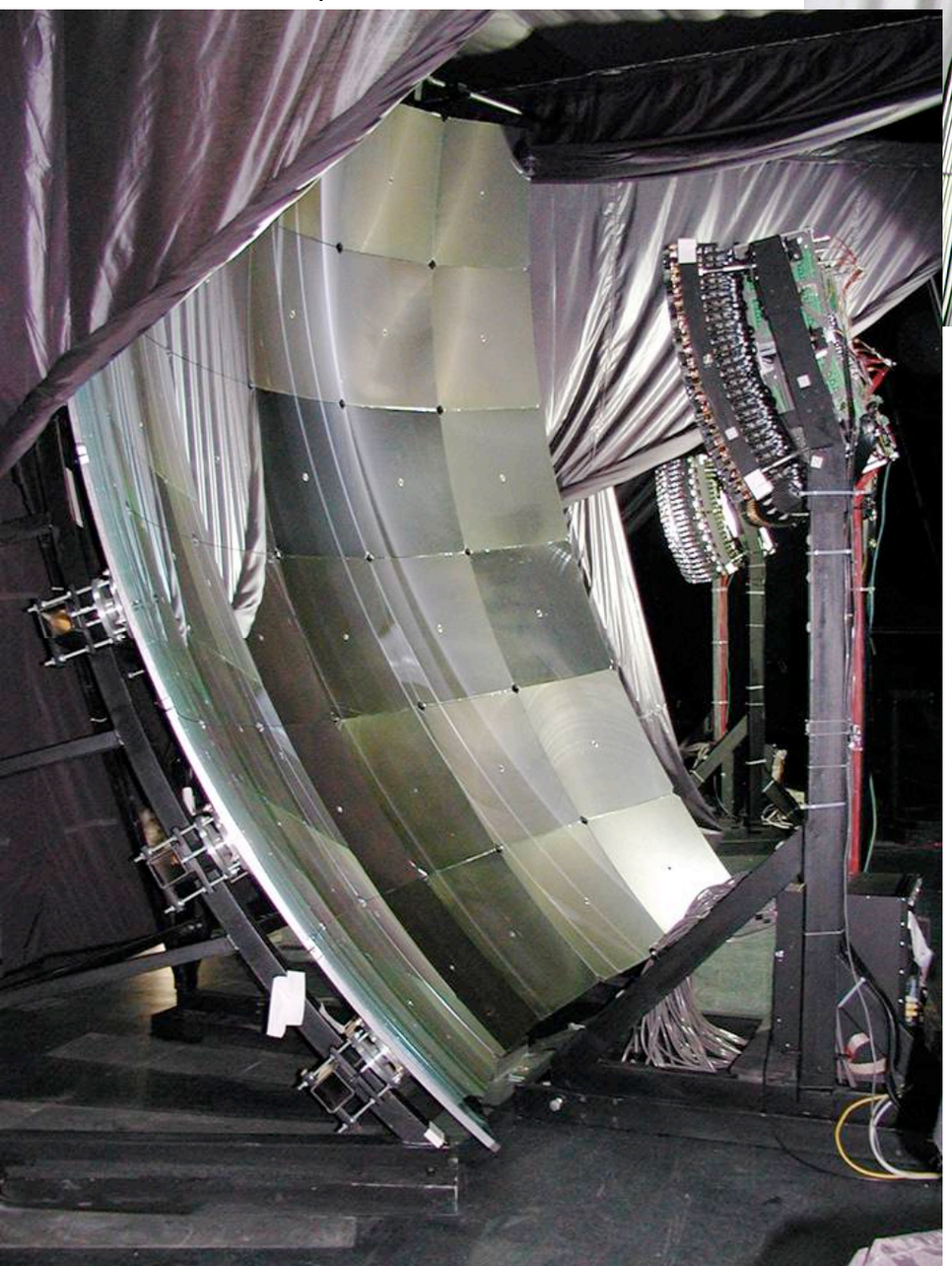
E as function of S(1000) either from cross-calibration with FD or from MC.

FD telescope:





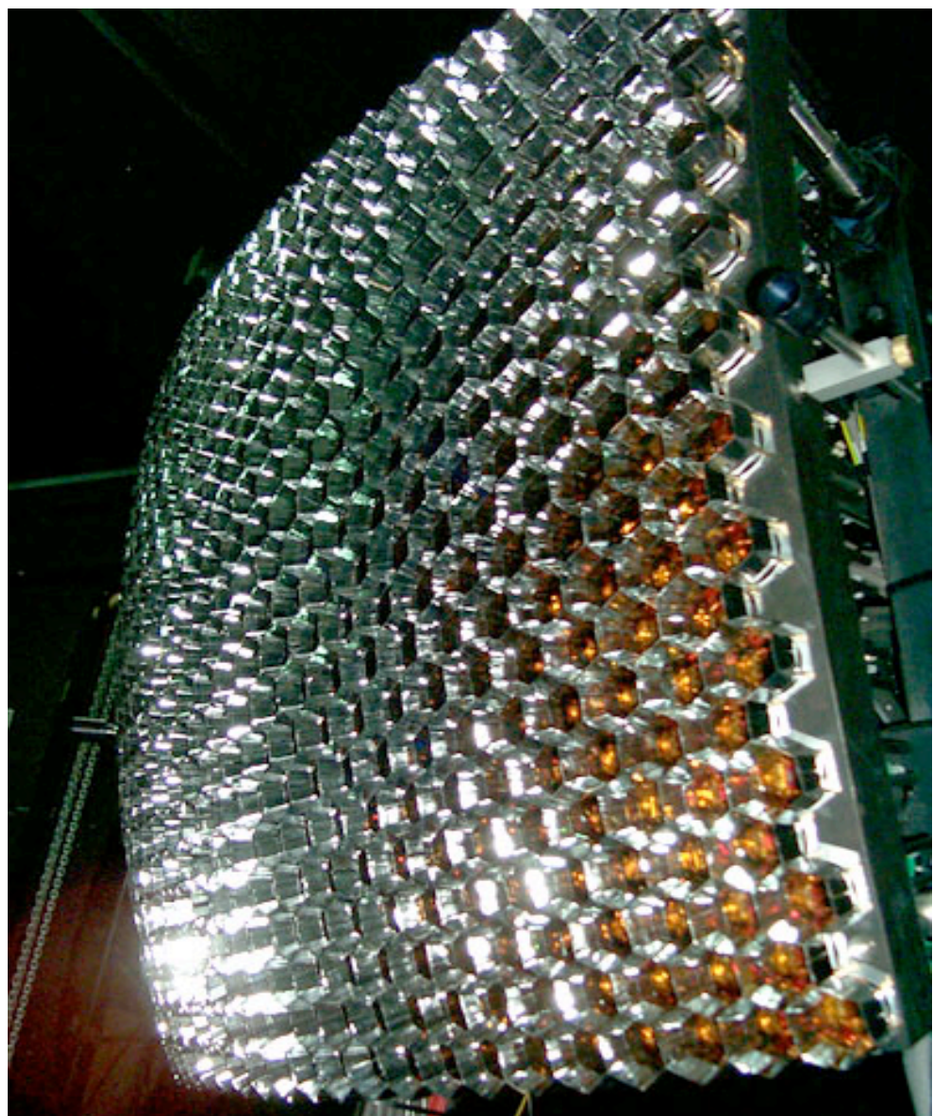
aperture with shutter, filter and Schmidt corrector lenses



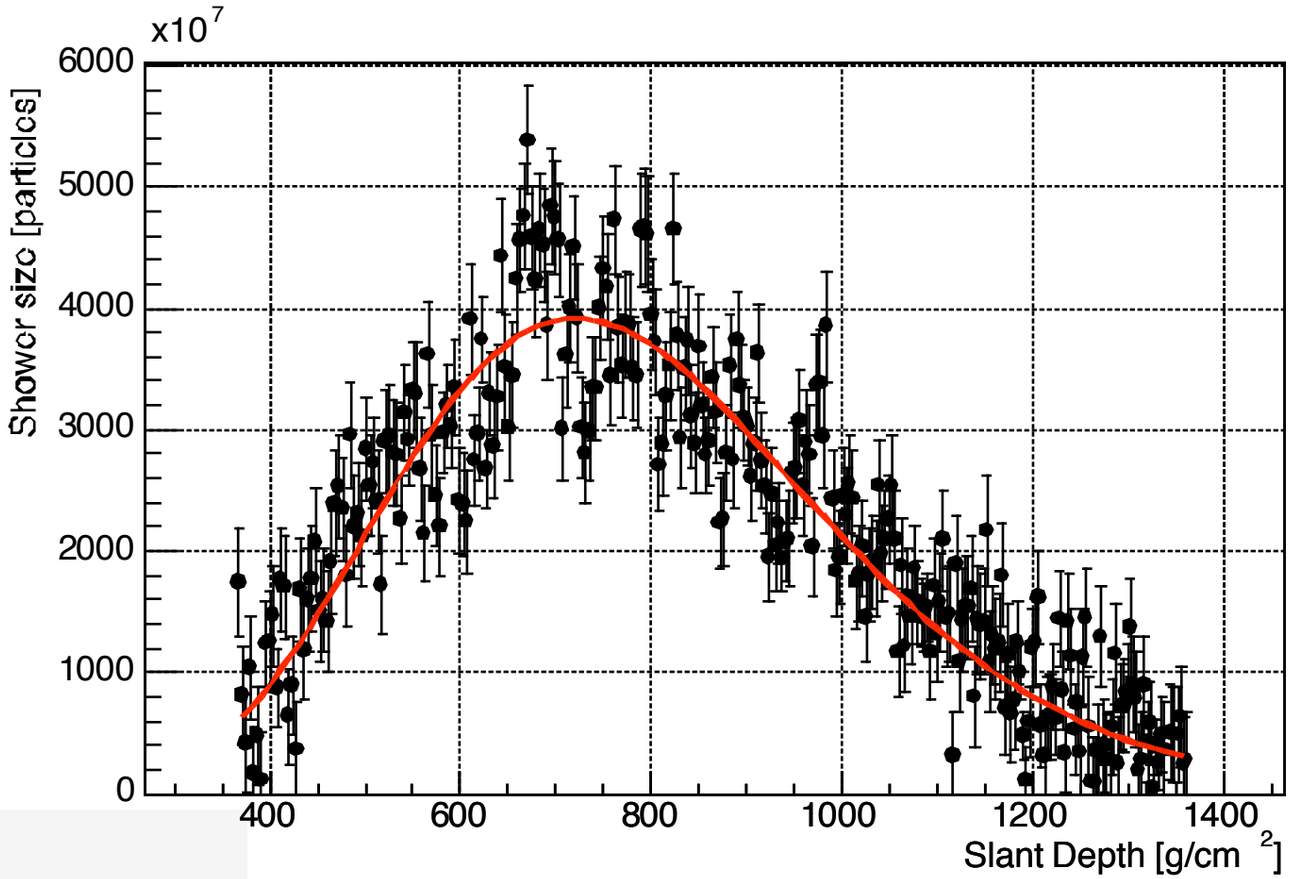
11 m^2 mirror (Aluminium)

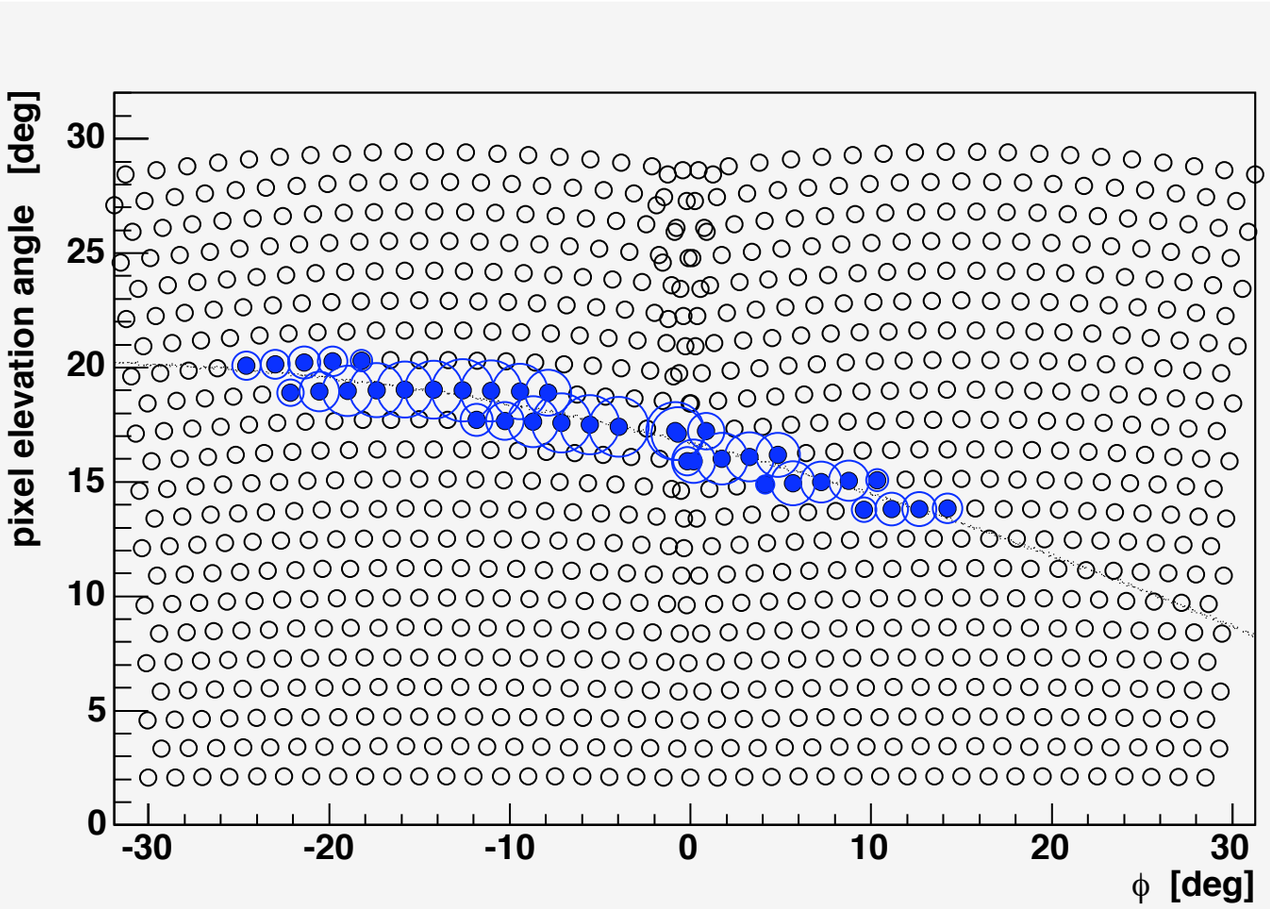
440 PMT camera

24 telescopes at 4 sites
30°x30° FOV, each



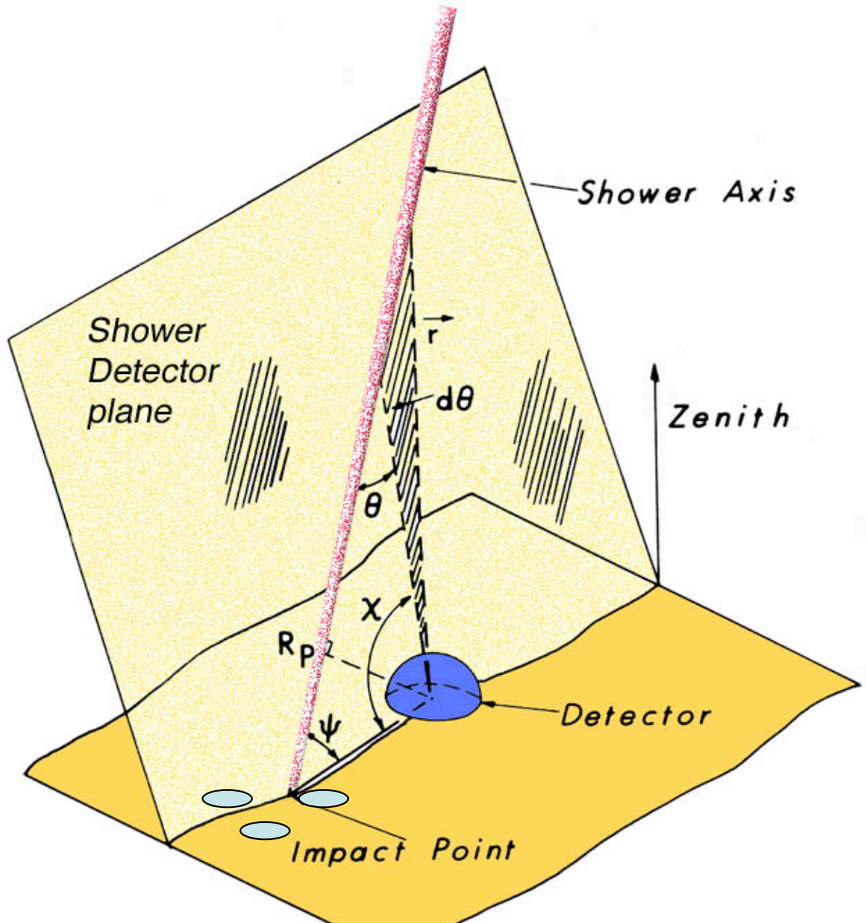
FD: longitudinal profile
calorimetric energy
X_{max} for mass comp.

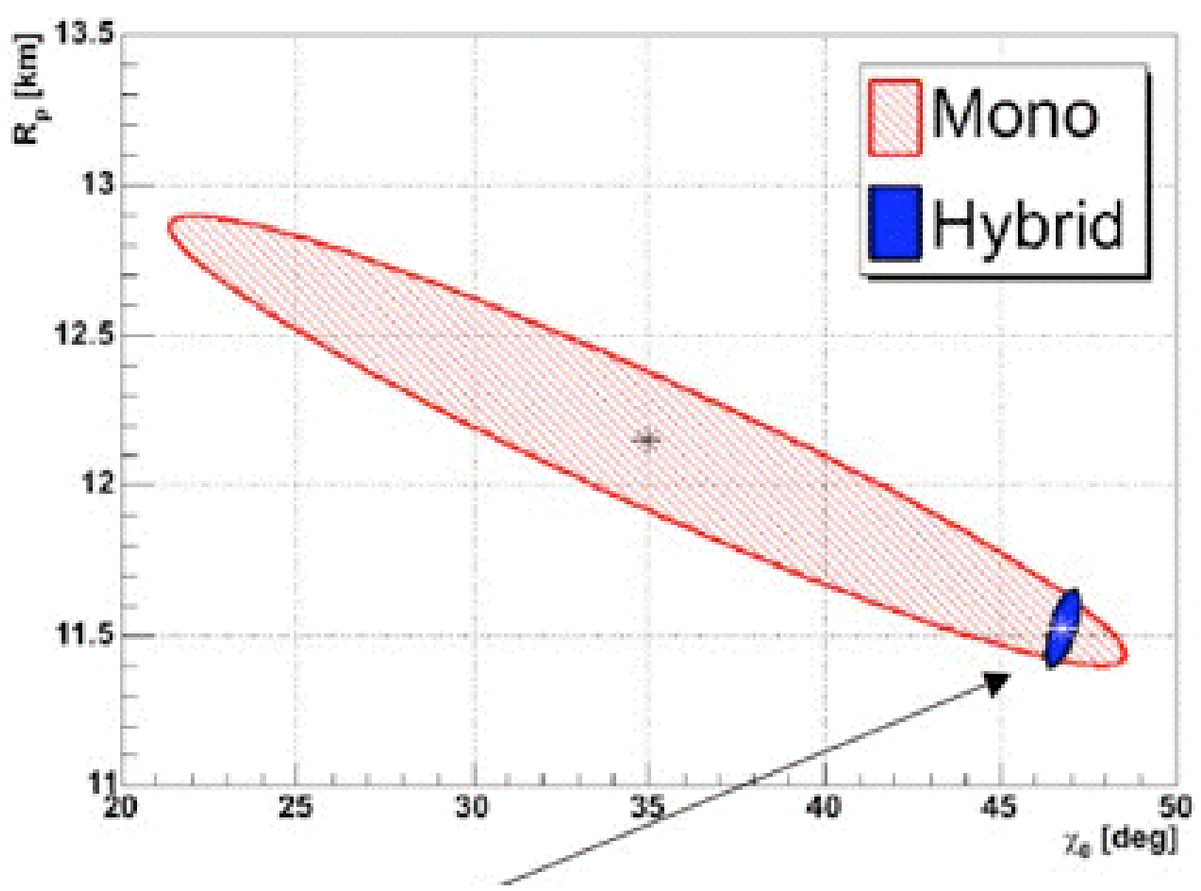




SD &FD: hybrid,
very good geometry
cross-calibration

	hybrid	SD only	FD only
angular resolution	0.2°	1-2°	3-5°
aperture	independent of E, mass, models	independent of E, mass, models	dependent of E, mass, models and spectral slope
energy	independent of mass, models	dependent of mass, models	independent of mass, models





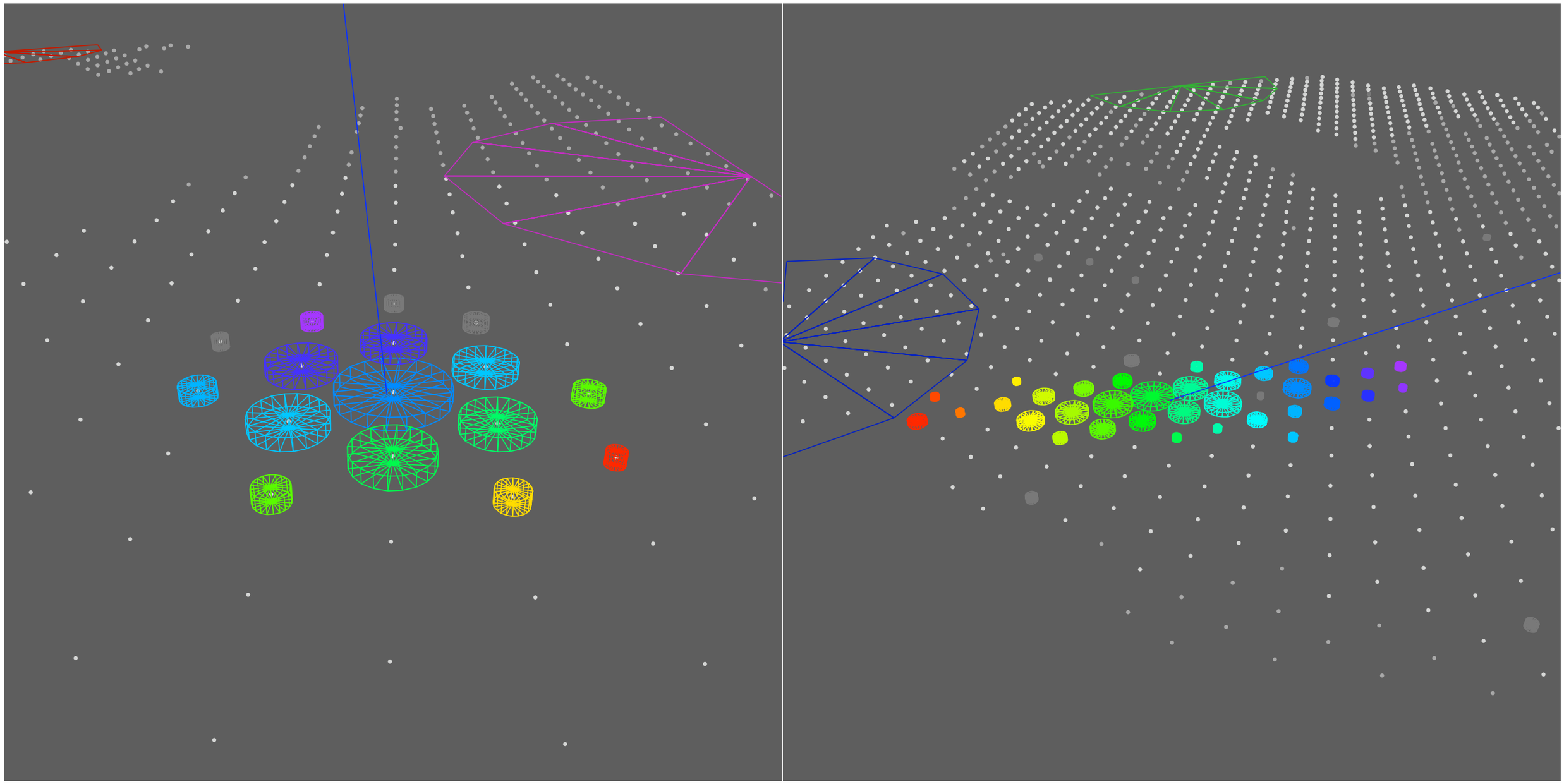
highest energy events so far:

near vertical

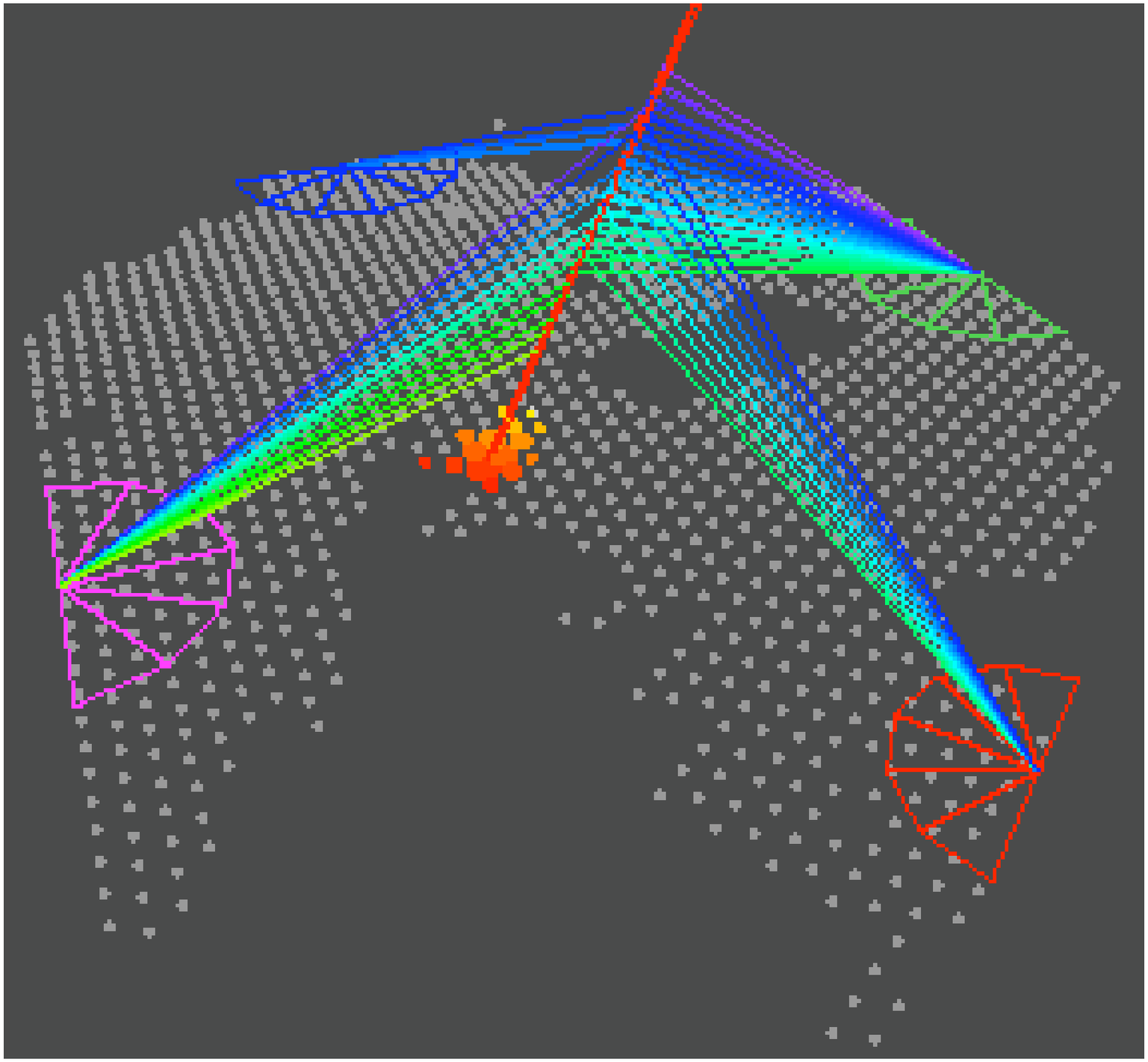
$E = 1.67 \times 10^{20}$ eV $\theta = 14°$

inclined

$E = 0.37 \times 10^{20}$ eV $\theta = 74°$



20 May 2007 E ~ 10^{19} eV
Shower seen by array and all 4 FDs



Spectrum

- SD near vertical
- SD inclined
- Hybrid

Energy: 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

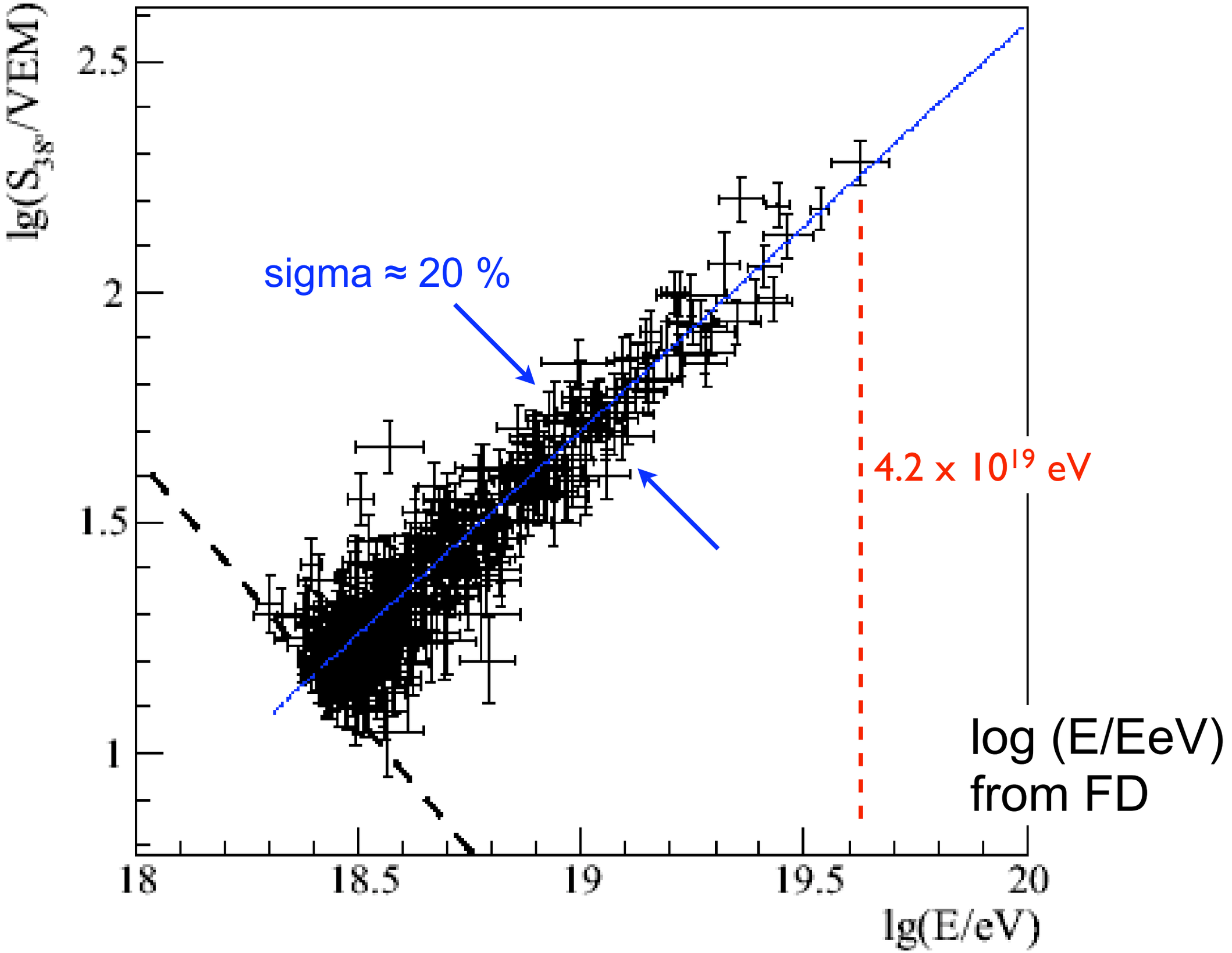
for high statistics from SD

Aperture: directly from size of SD

(above 3×10^{18} eV)

log (S1000) from SD

387 hybrid events



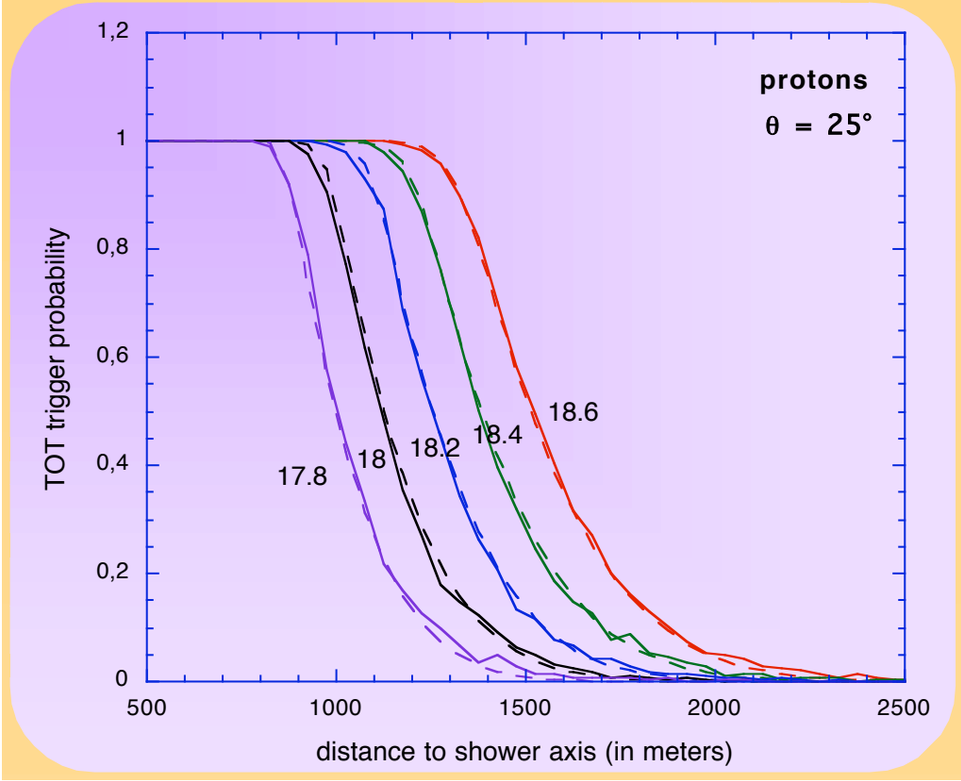
model independent; error on S(1000) decreases with energy

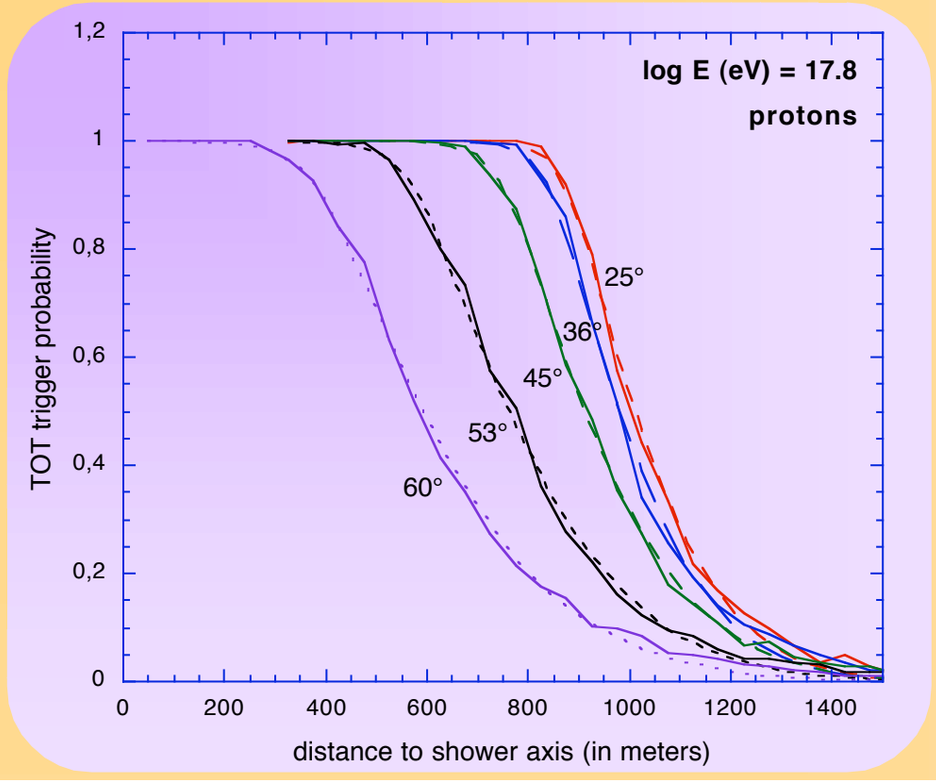
Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

model dependent

Efforts to decrease these uncertainties

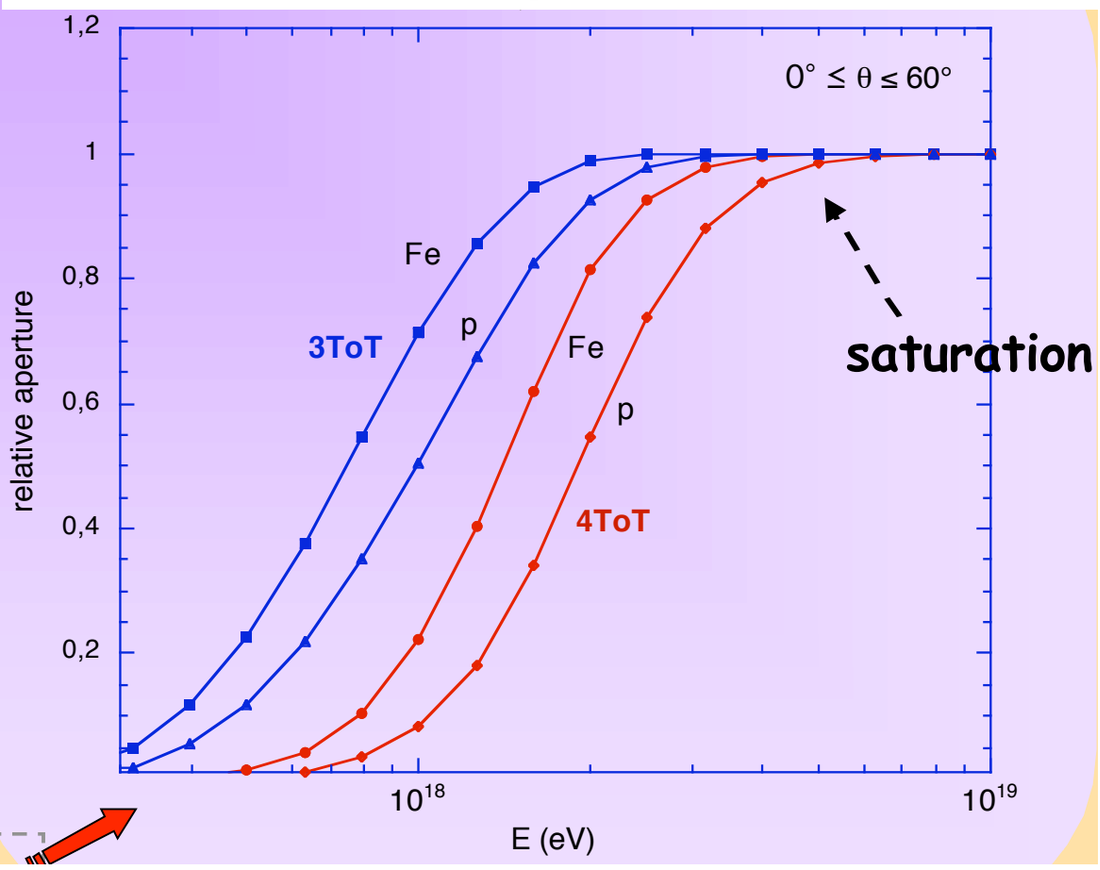
Aperture Calculation

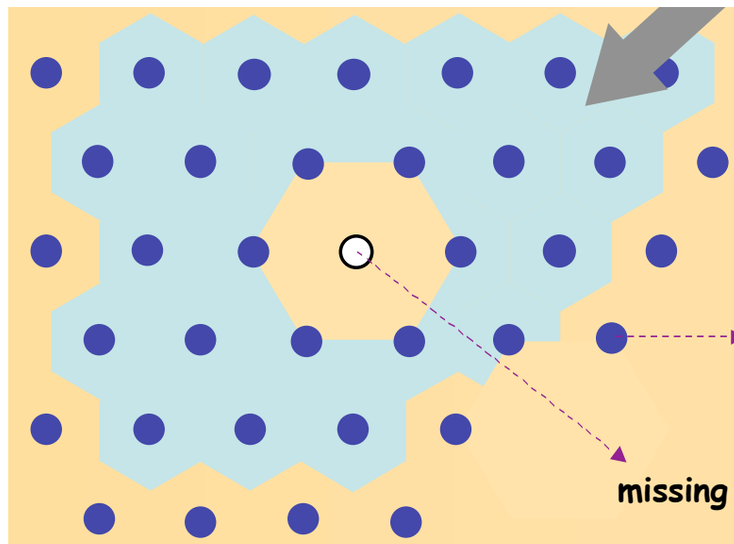


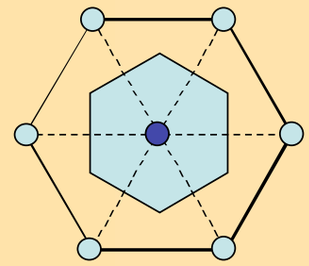


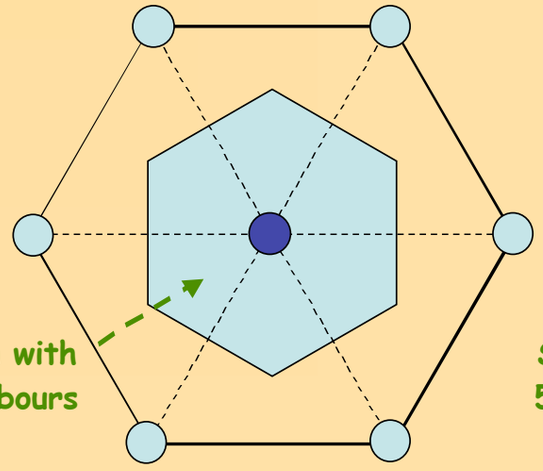
lateral trigger probability

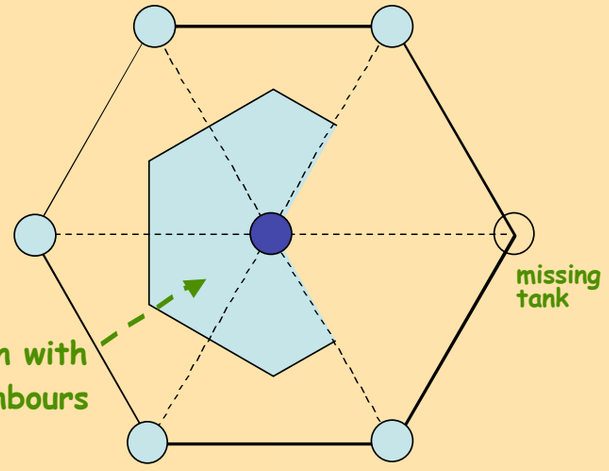
relative aperture



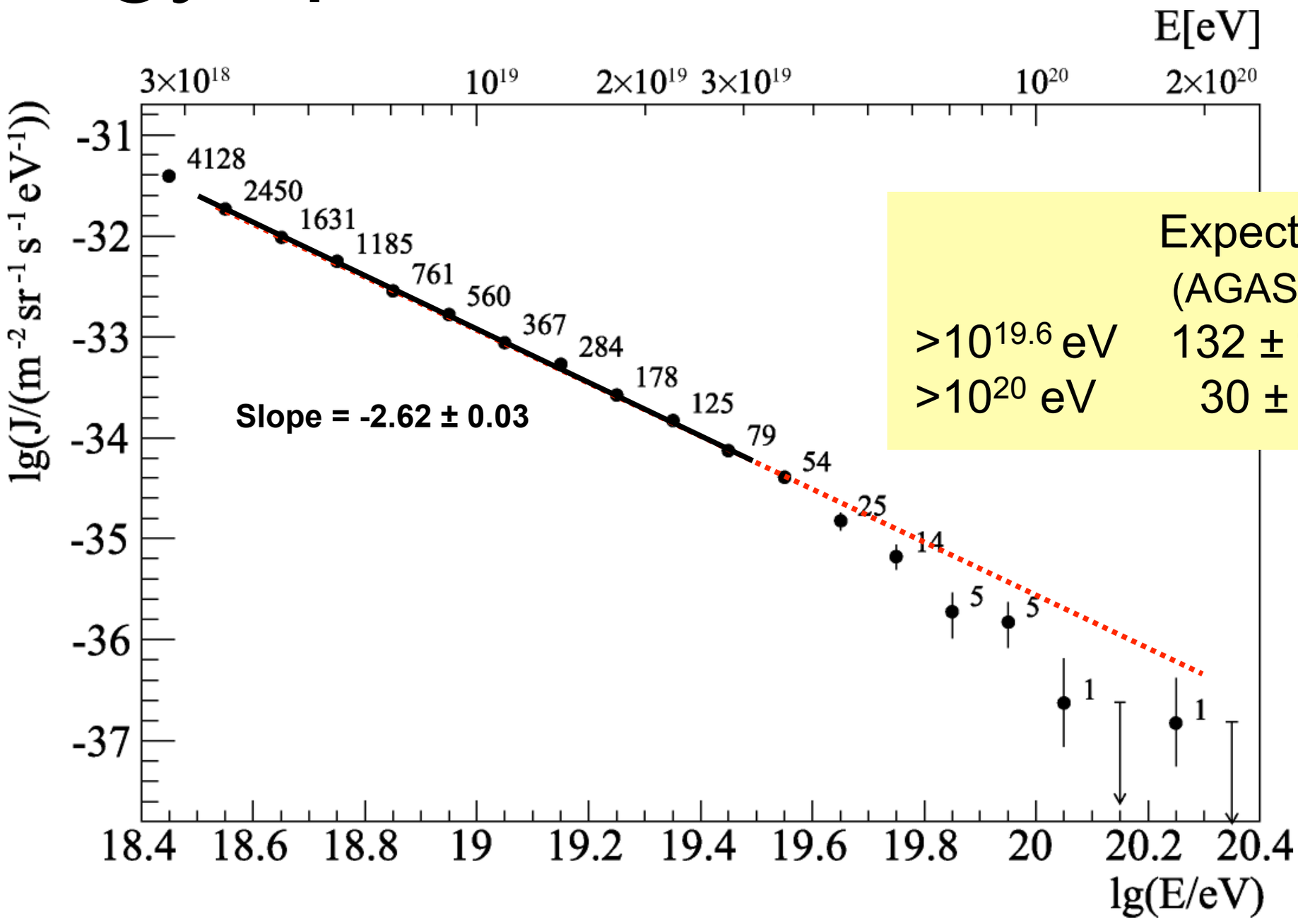








Energy spectrum from SD

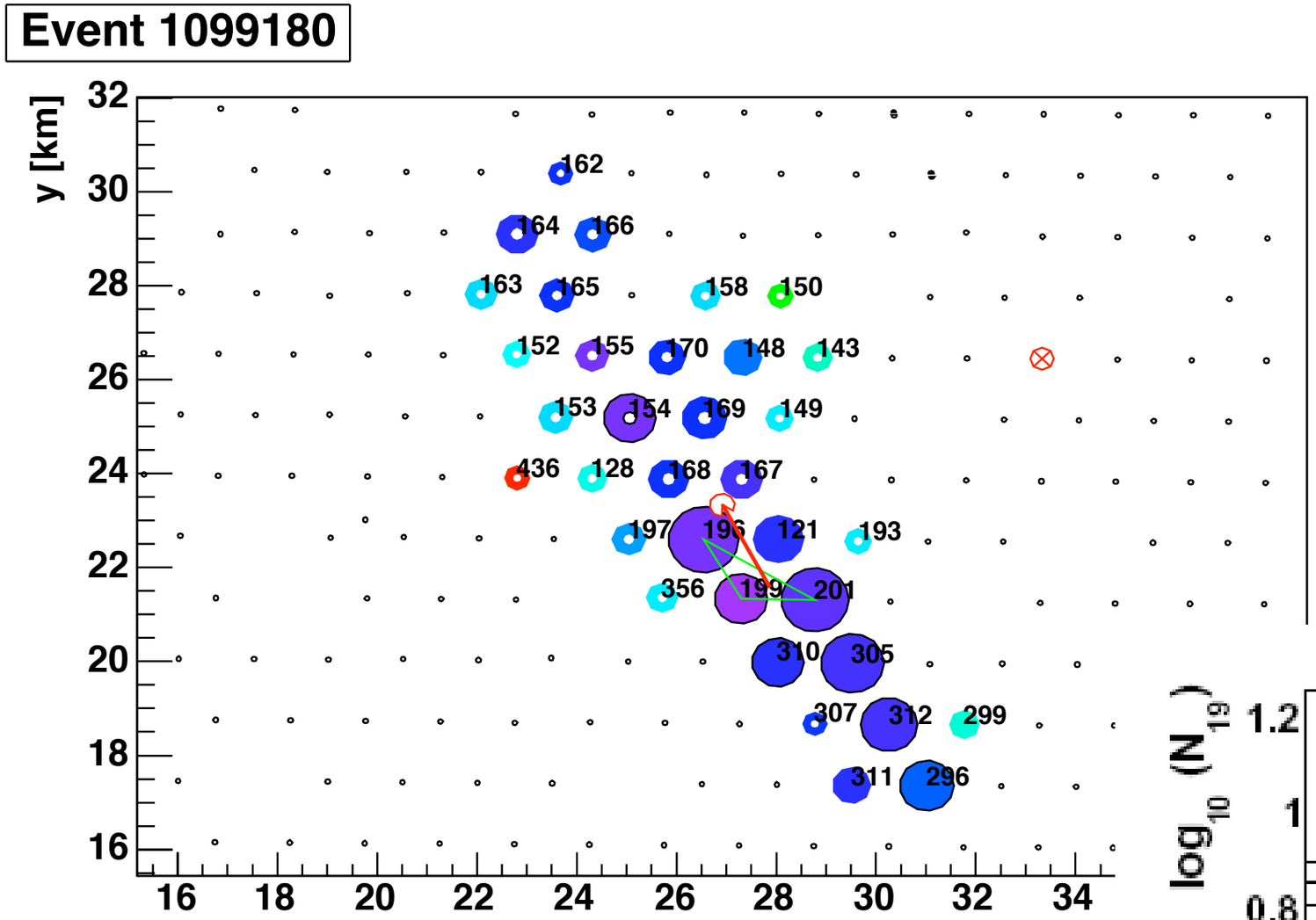


	Expected (AGASA)	Observed
$>10^{19.6}$ eV	132 ± 9	51
$>10^{20}$ eV	30 ± 2.5	2

5165 km^2 sr yr ≈ 0.85 full-Auger years

zenith angle: 0-60°

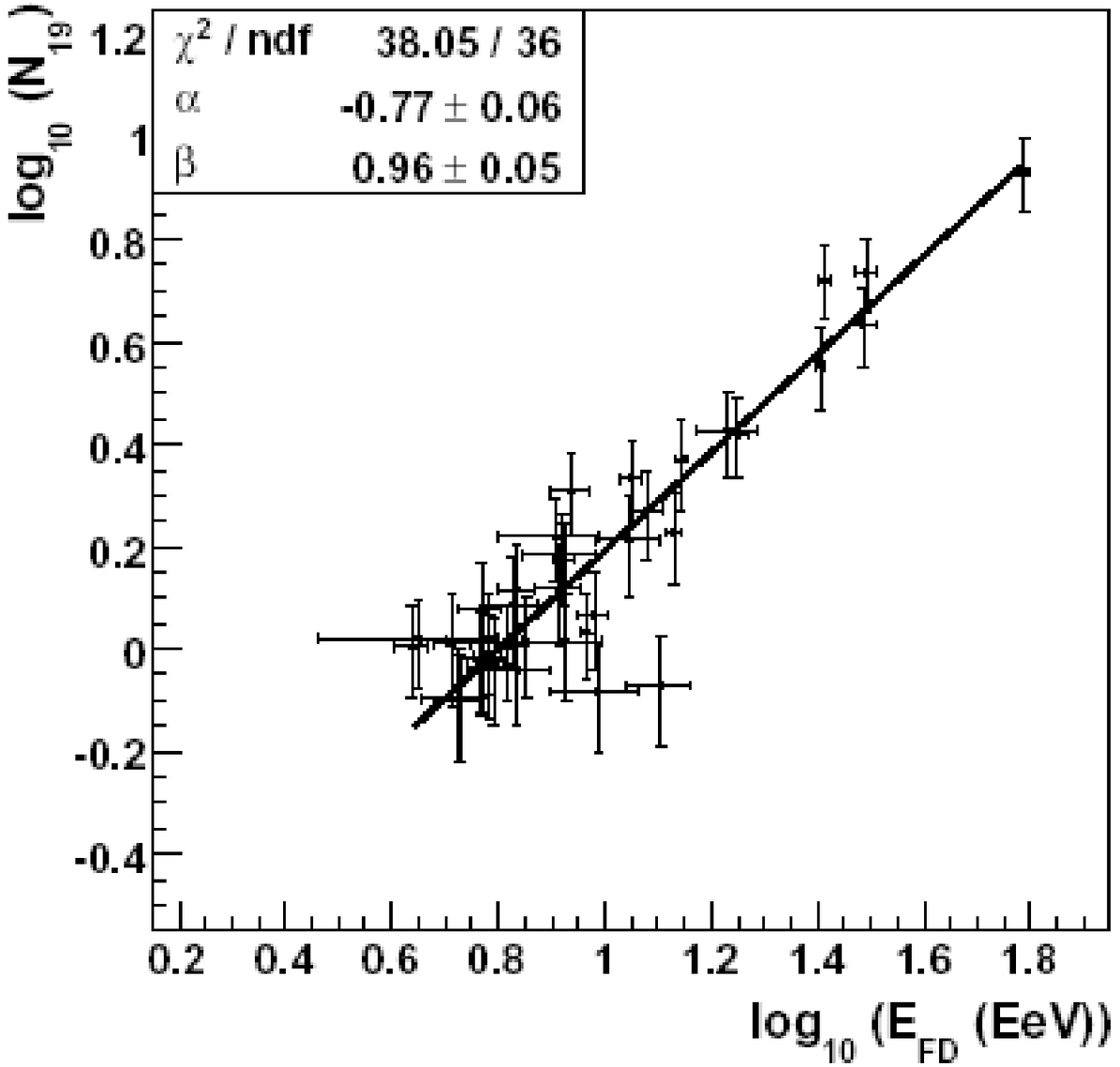
7725 events > $10^{18.5}$ eV



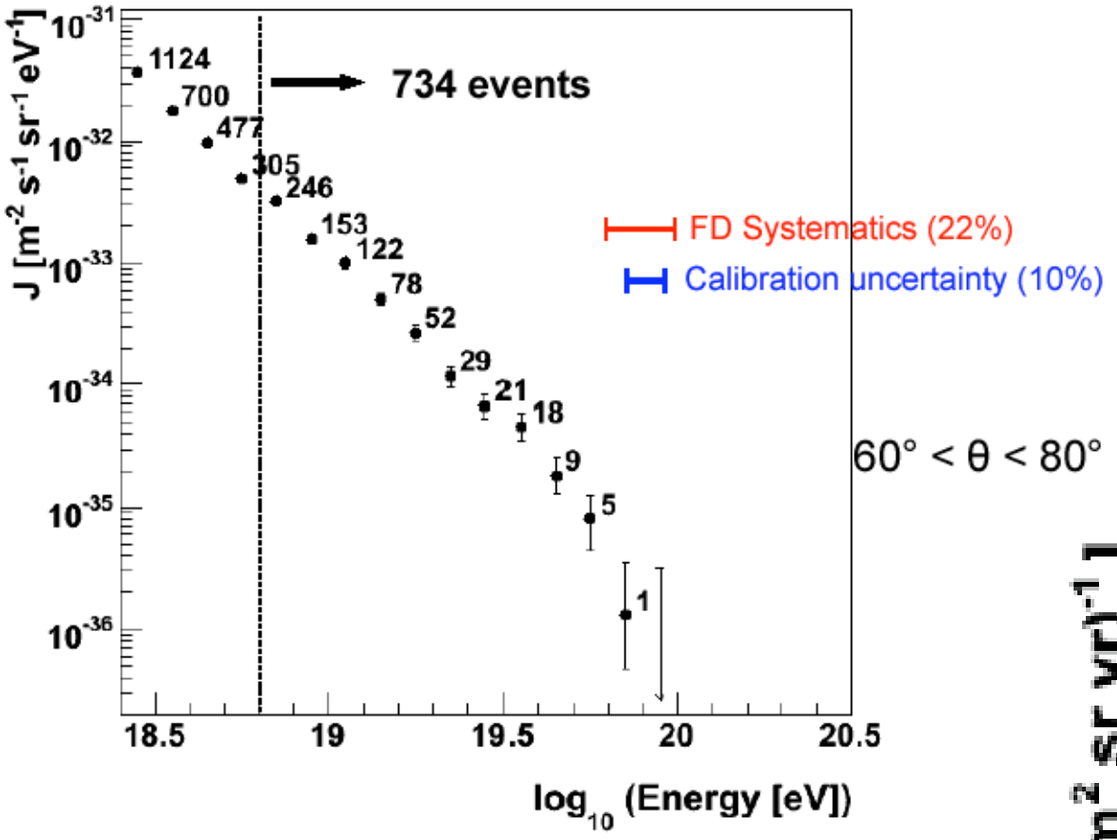
34 tanks, 82°,
$E \approx 10^{19}$ eV

inclined showers add to aperture,
only muons survive at ground;

N_{19} is suitable energy parameter

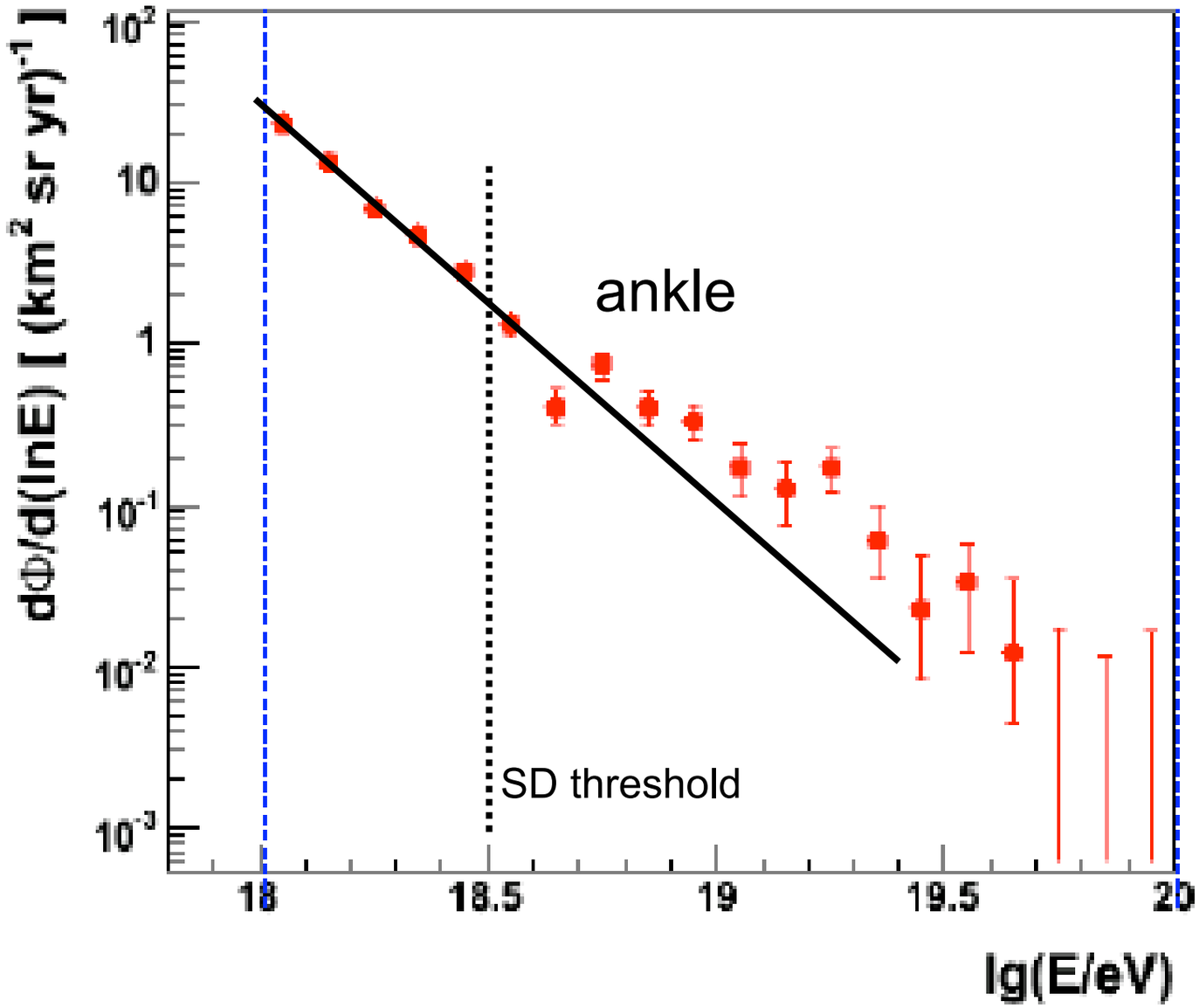


Inclined shower spectrum

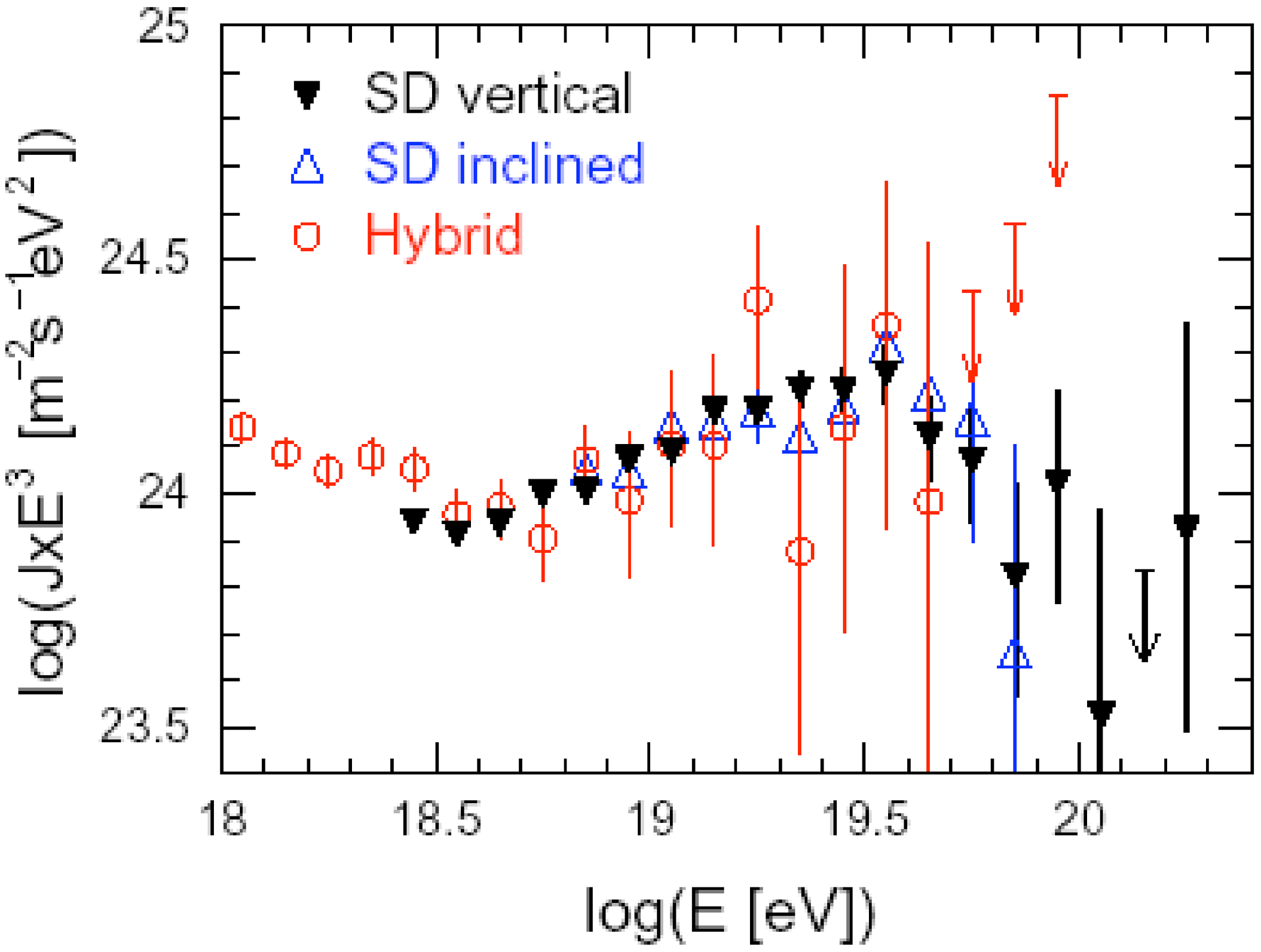


Exposure 1510 km^2 yr sr (29% of θ<60°)

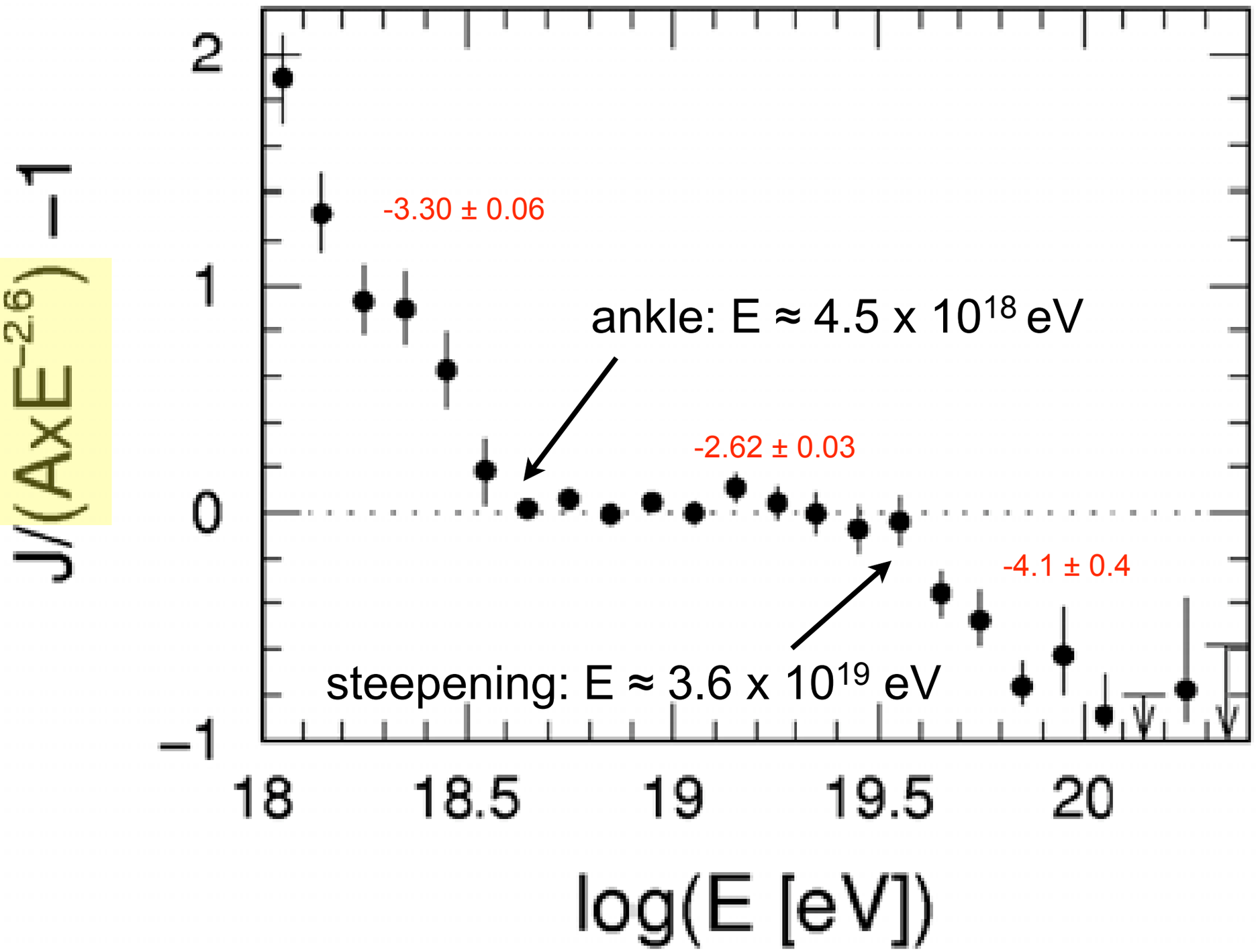
Hybrid spectrum



Auger Spectra:

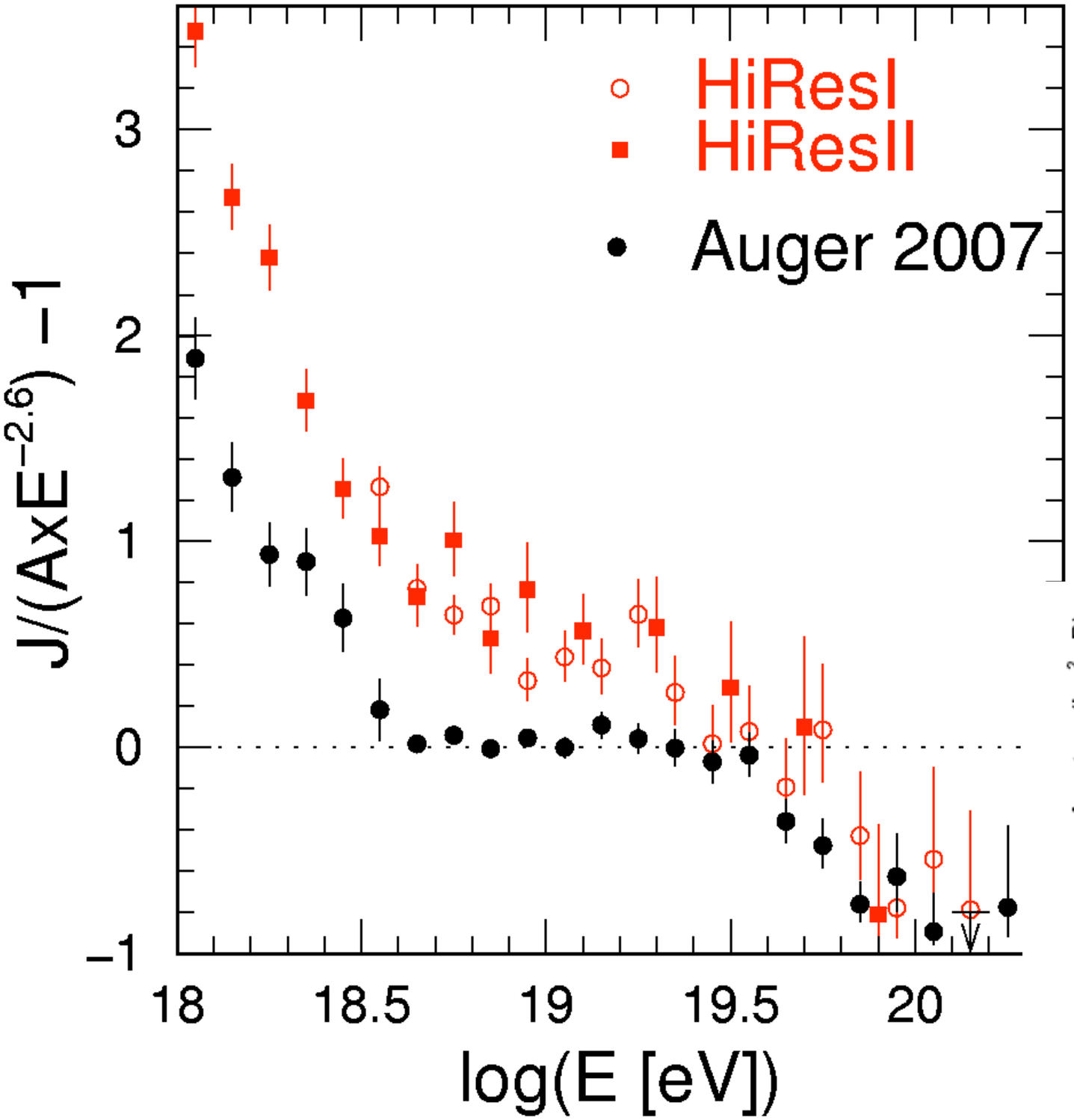


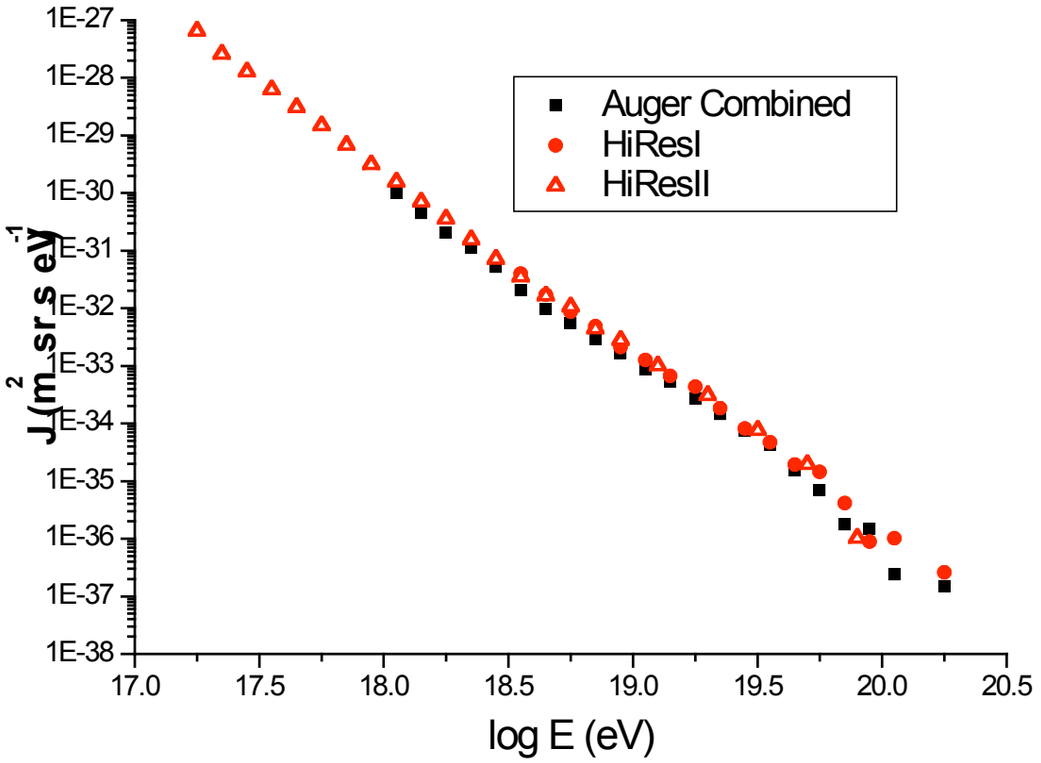
Residuals (combined spectrum)

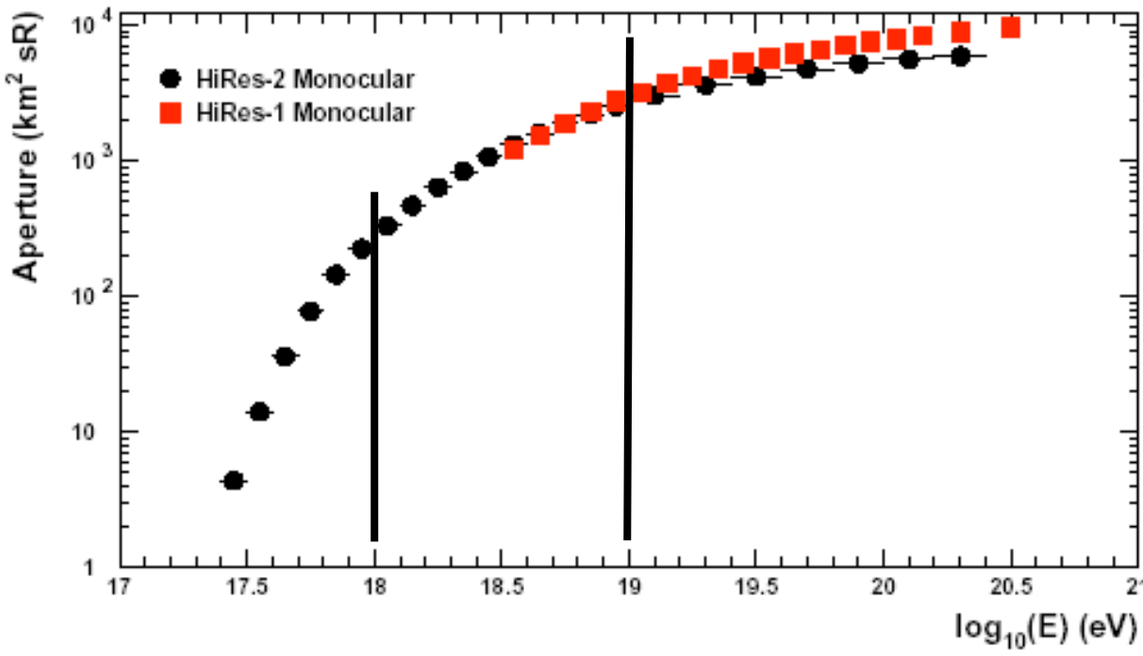


independent of models and mass

Auger finds a ankle at E ≈ 4.5 x 10^{18} eV and spectral steepening at E ≈ 3.6 x 10^{19} eV.







Is HiRes aperture known well enough ???

changes by 10x from 1 to 10 EeV,

depends on mass composition, models, spectral slope

Does Auger see the GZK cut-off ?

GZK cut-off: if CRs are protons with source spectrum »10^{20} eV
sources are universally distributed
depression by about a decade at ≈ 5 x 10^{19} eV

Also nuclear primaries would be absorbed/destroyed, but not quite in the same way (propagation).

Alternatives:

maximum energy of accelerator ?
effect of a local source ?

Is ankle the transition point between galactic and extragalactic CRs ?

... need more info on composition ...

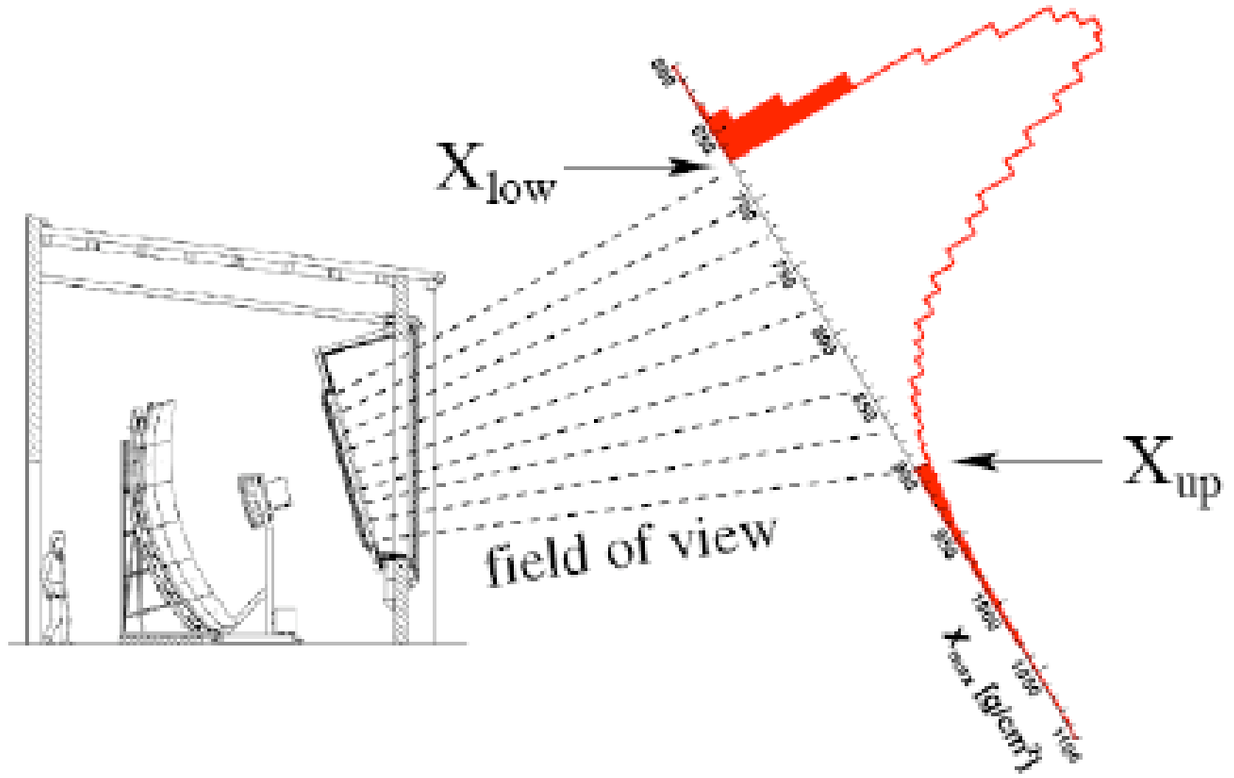
Composition

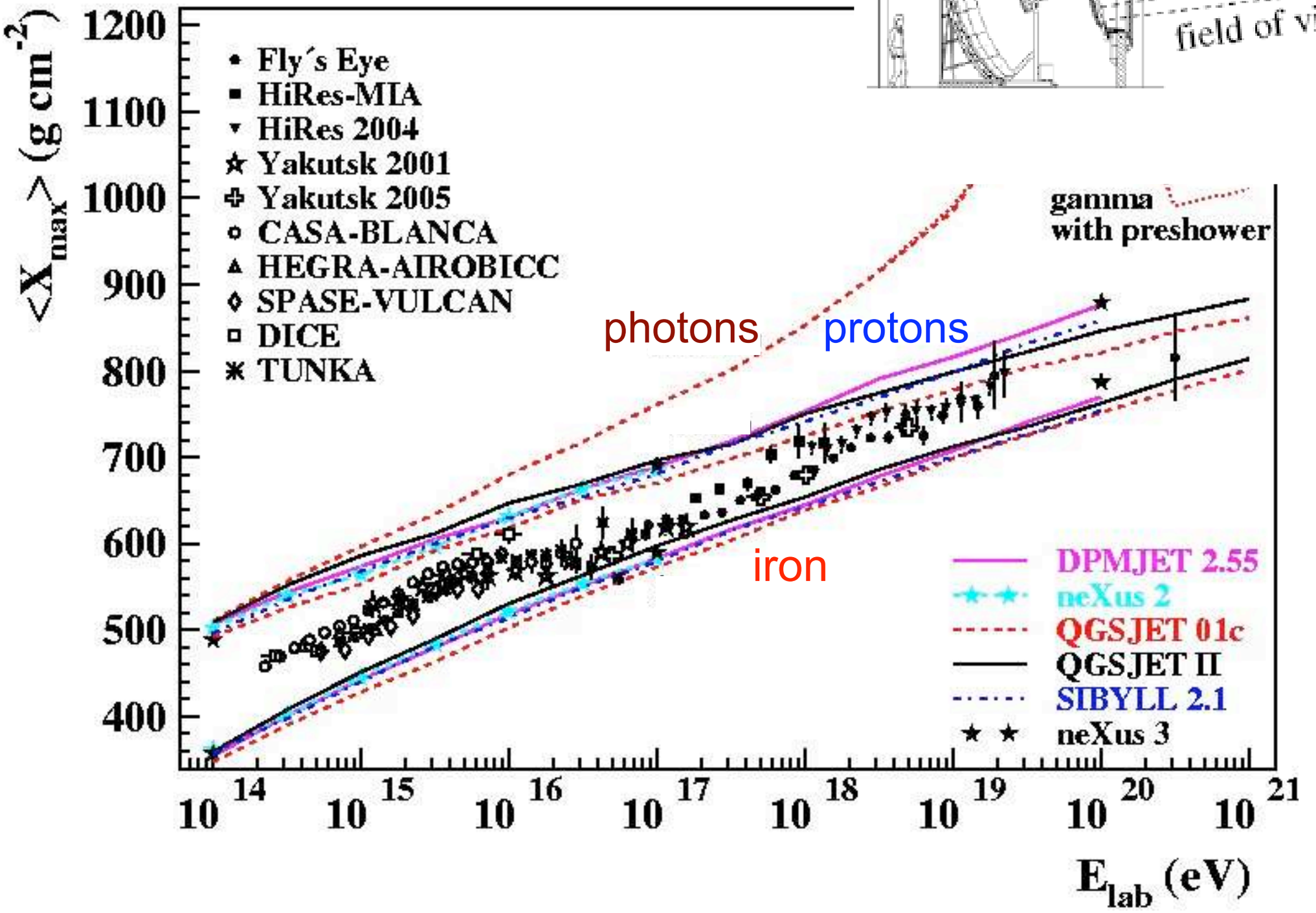
- photons
- neutrinos
- nuclei

FD: measure X_{max}

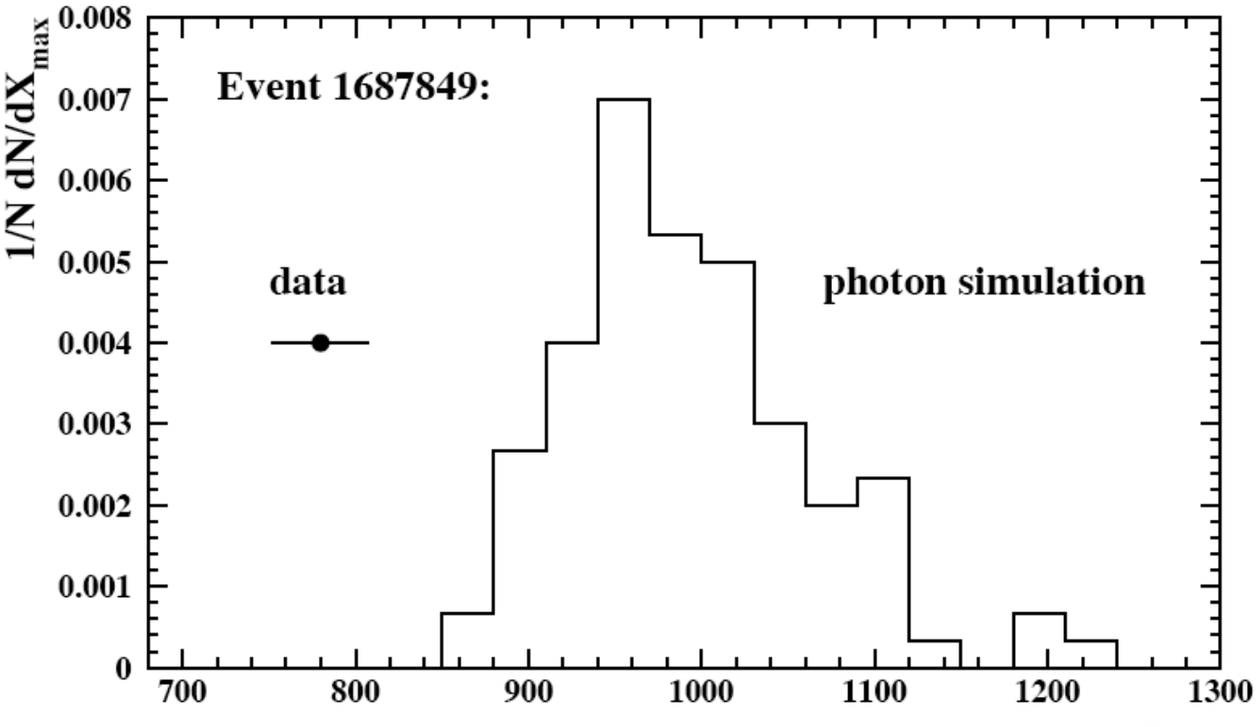
photons maximise deeper than nuclei

protons maximise deeper than iron



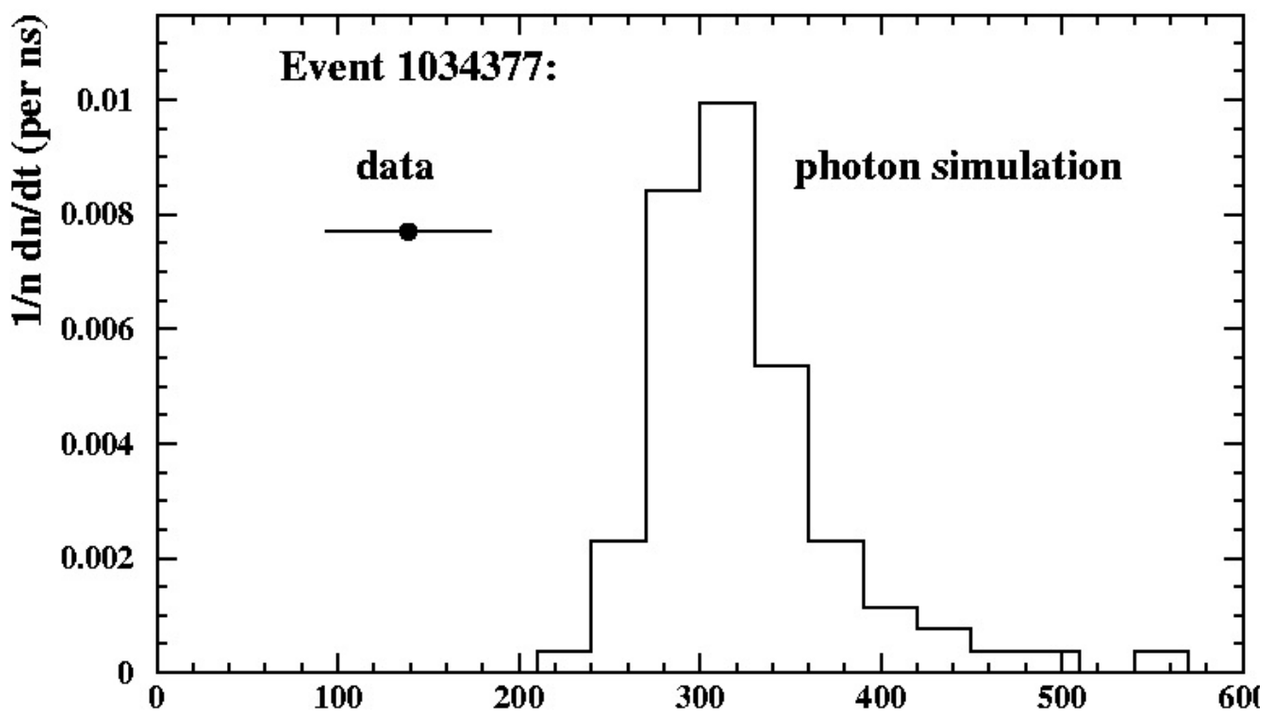


Hybrid events



Xmax (g/cm^2)

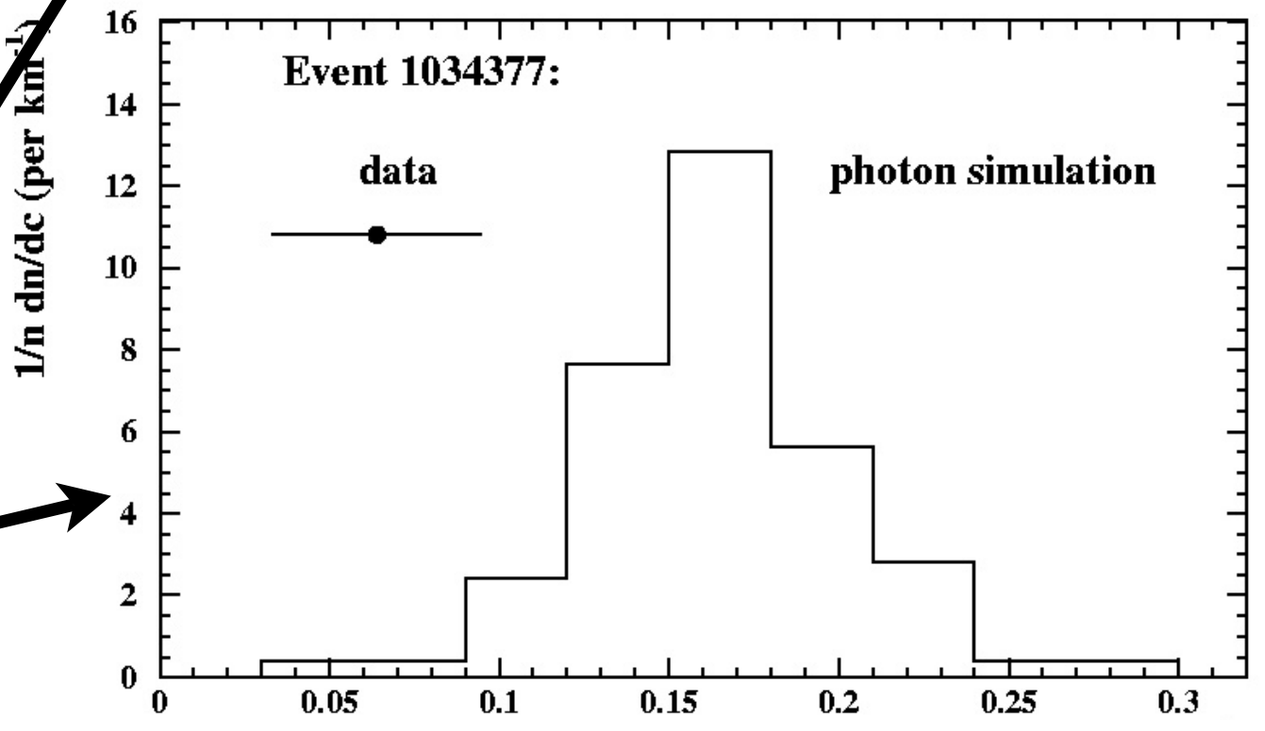
SD events



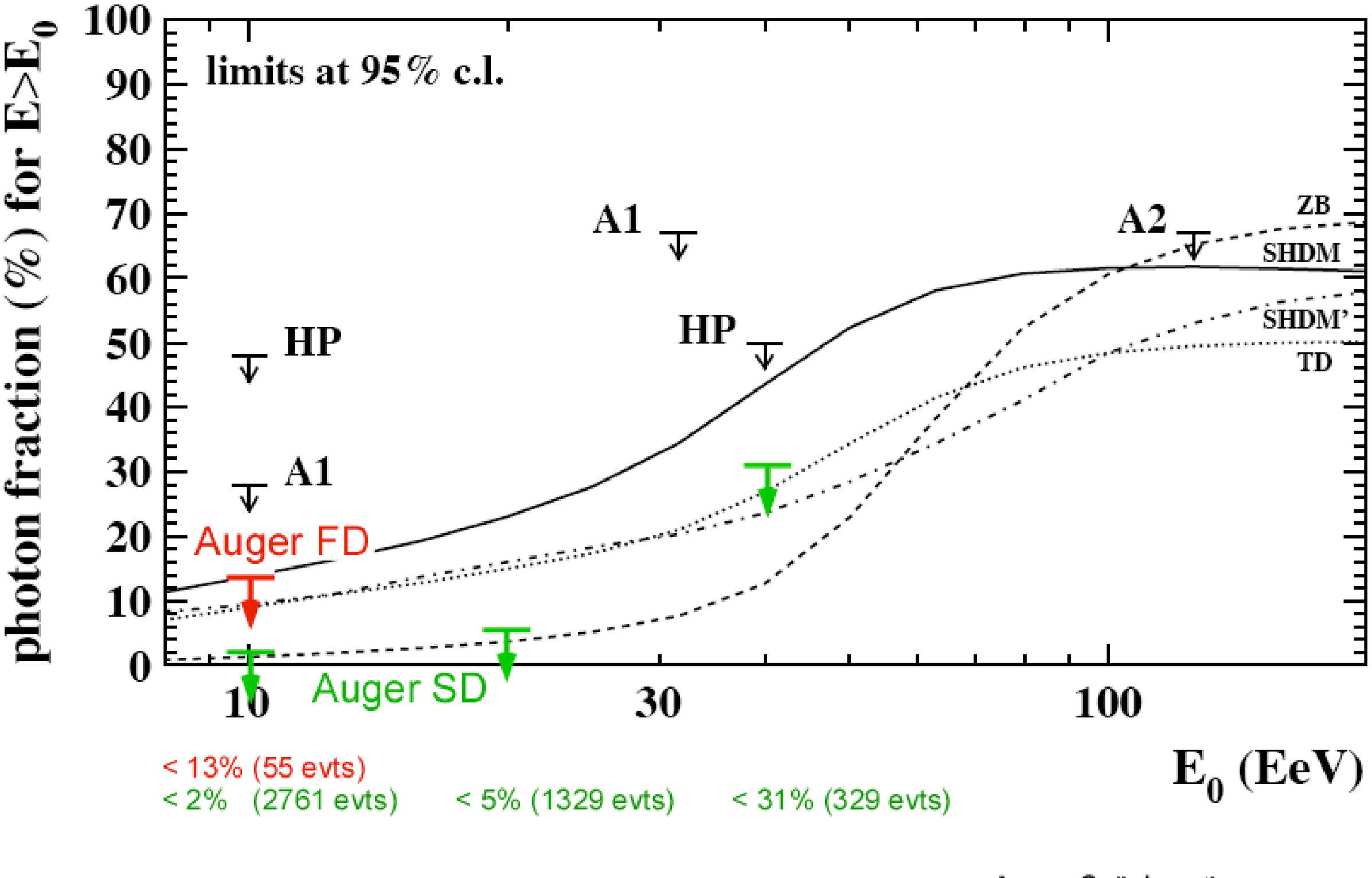
signal rise time (ns)

Compare each event with photon MCs,
Combine probabilities for all events

SD: much larger statistics, but reconstruction not mass independent



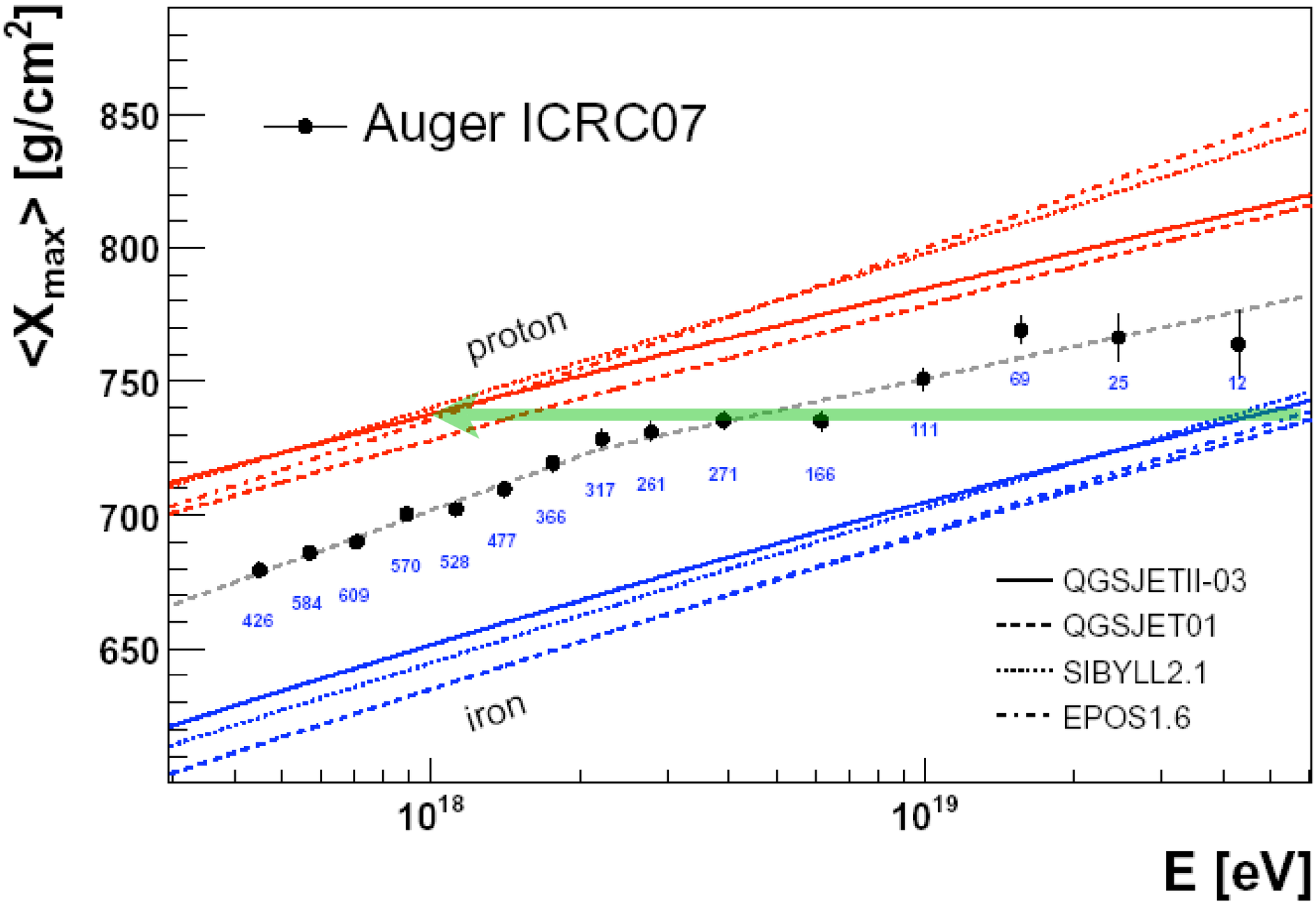
curvature of shower front (1/km)



most top-down models are ruled out

Auger Collaboration
Astrop. Phys. 27 (2007) 155
to be submitted to Astrop. Phys.

Hadronic composition from $X_{max}(E)$



X_{max} ~ lg(E/A)

same E/A

Mixed composition up to highest energies ? not expected

(Results strongly model dependent)

more work: fluctuations in X_{max} , SD variables, ...

Residual

<ln(A)>

Spectrum Residuals vs. < ln A >

Spectrum

Mass

Fe

O

He

H

2

1

0

-1

4

2

0

17.5

18.0

18.5

19.0

19.5

20.0

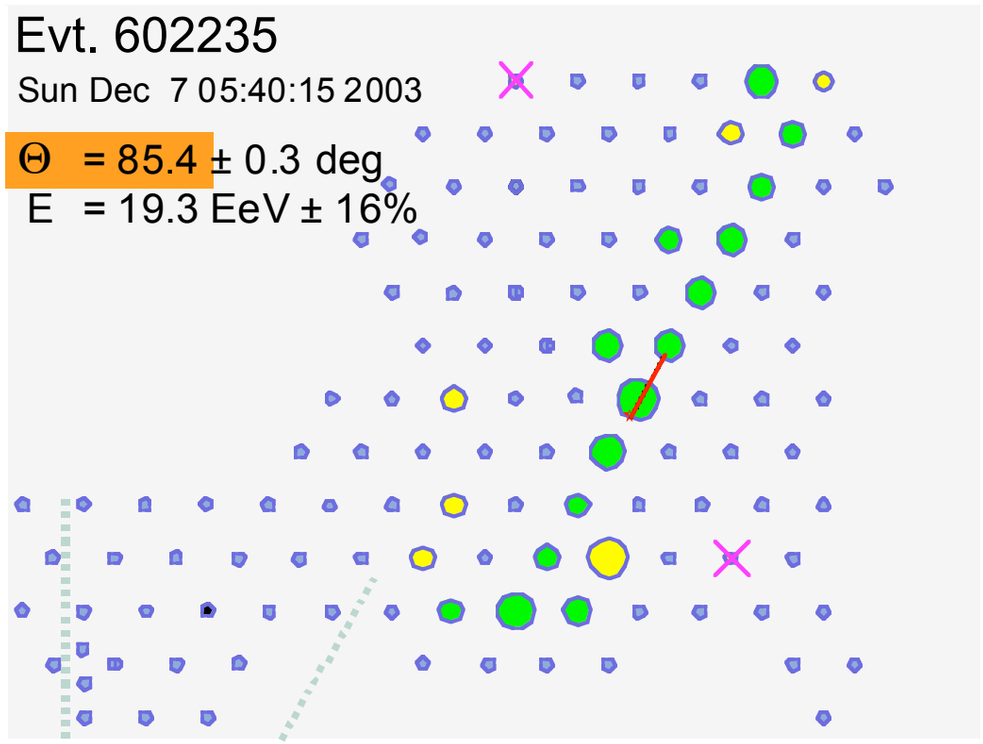
log E (eV)

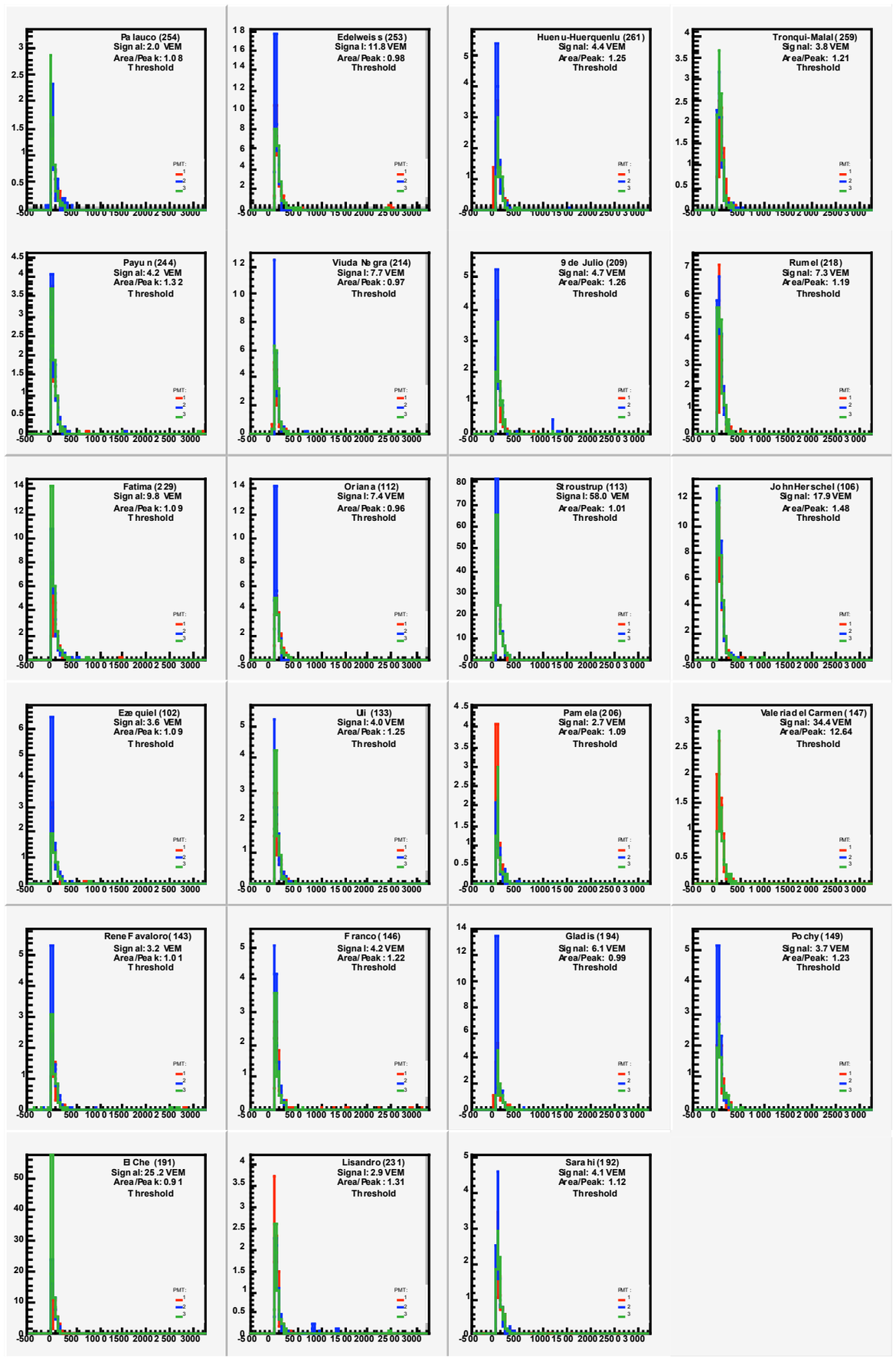
Horizontal showers

Due to water tanks (1.2 m high) the Auger SD has sensitivity for nearly-horizontal showers ($\Theta > 60^o$)

Special event reconstruction techniques
(by Ave, Watson, Zas et al.)
first applied to Haverah Park data

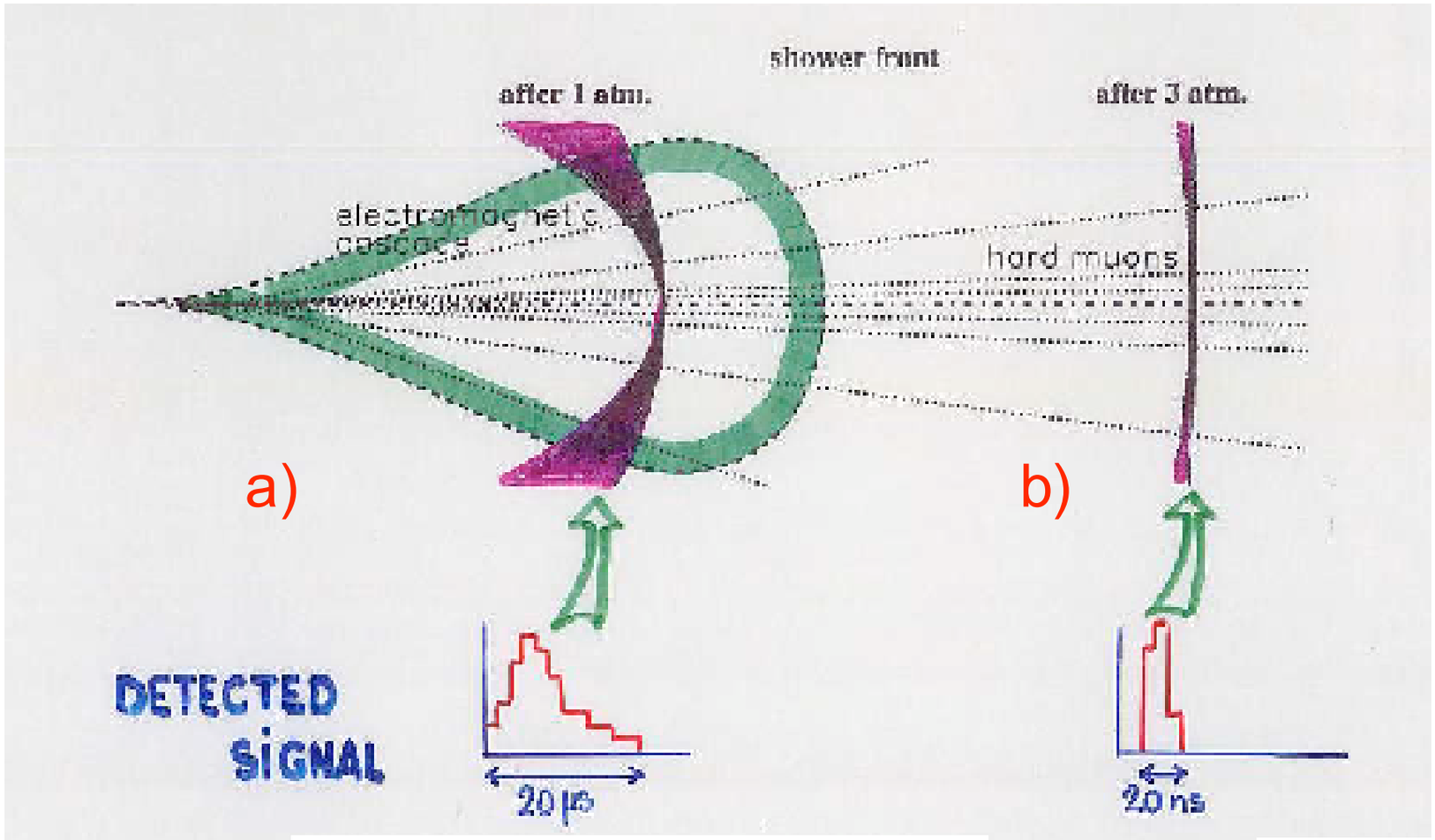
~ doubles aperture for CR events
increases sky coverage
sensitivity also to neutrinos





Neutrino detection with Auger

horizontal showers from hadrons: el.mag. component absorbed, muons only

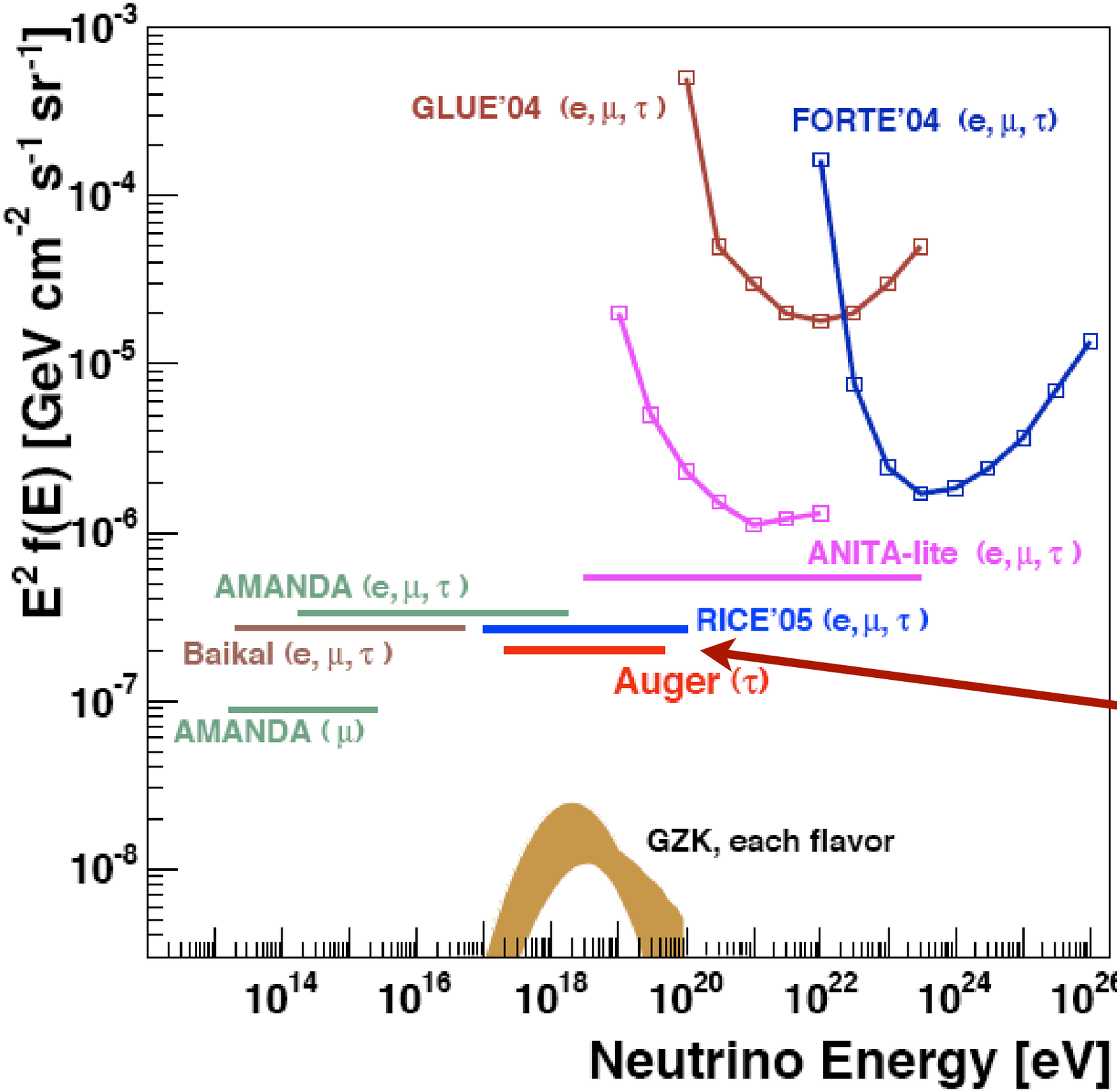


full el.mag. component,
curved shower front,
broad arrival time distribution

no el.mag. component,
plane shower front,
sharp arrival times

horizontal showers from neutrinos: look like a) after > 3 atmospheres

Auger: no neutrino candidate

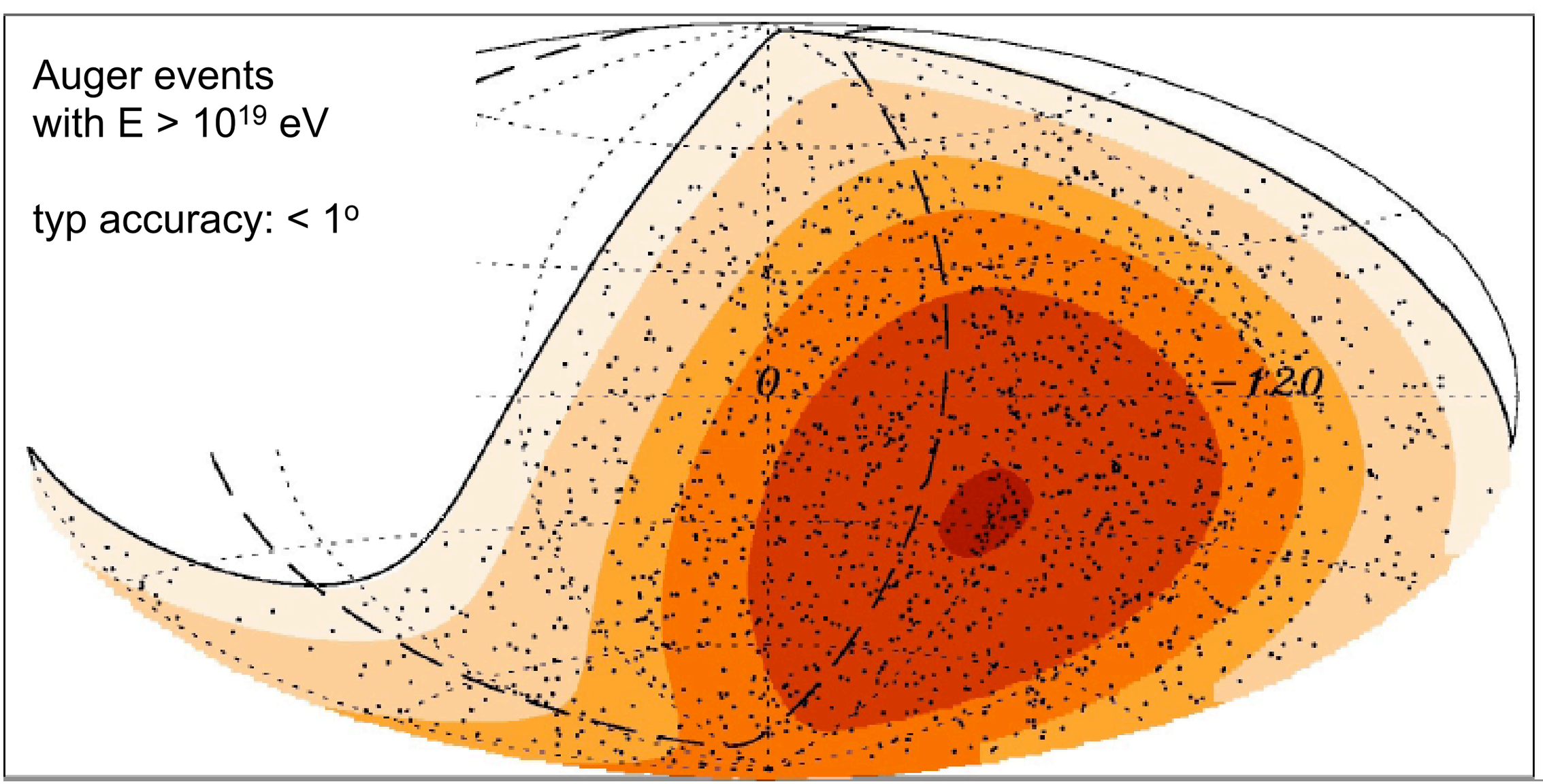


neutrino limit
ICRC 2007,
published soon

Anisotropy

Auger events
with E > 10^{19} eV

typ accuracy: < 1°



Clusters, point sources ? (AGASA)

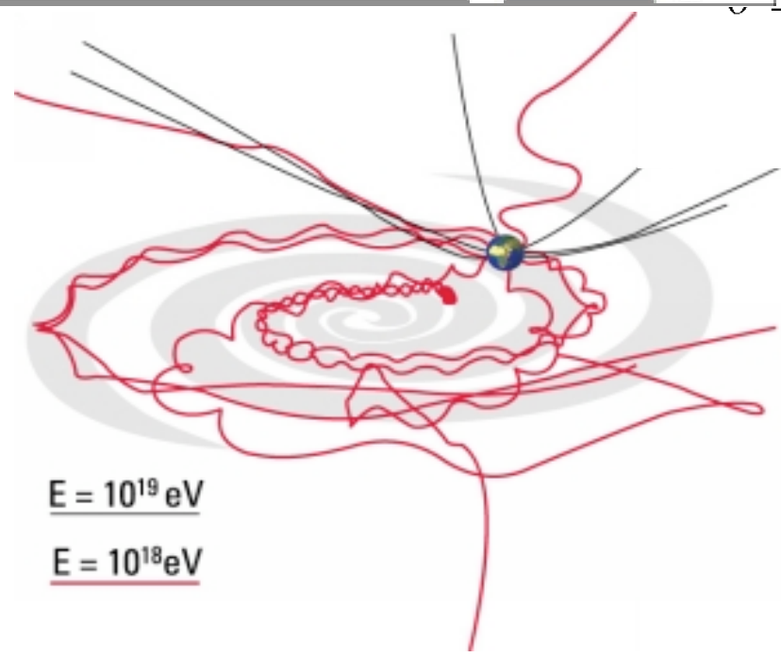
Large-scale anisotropies ? (AGASA, Sugar)

Correlations with potential source populations ?

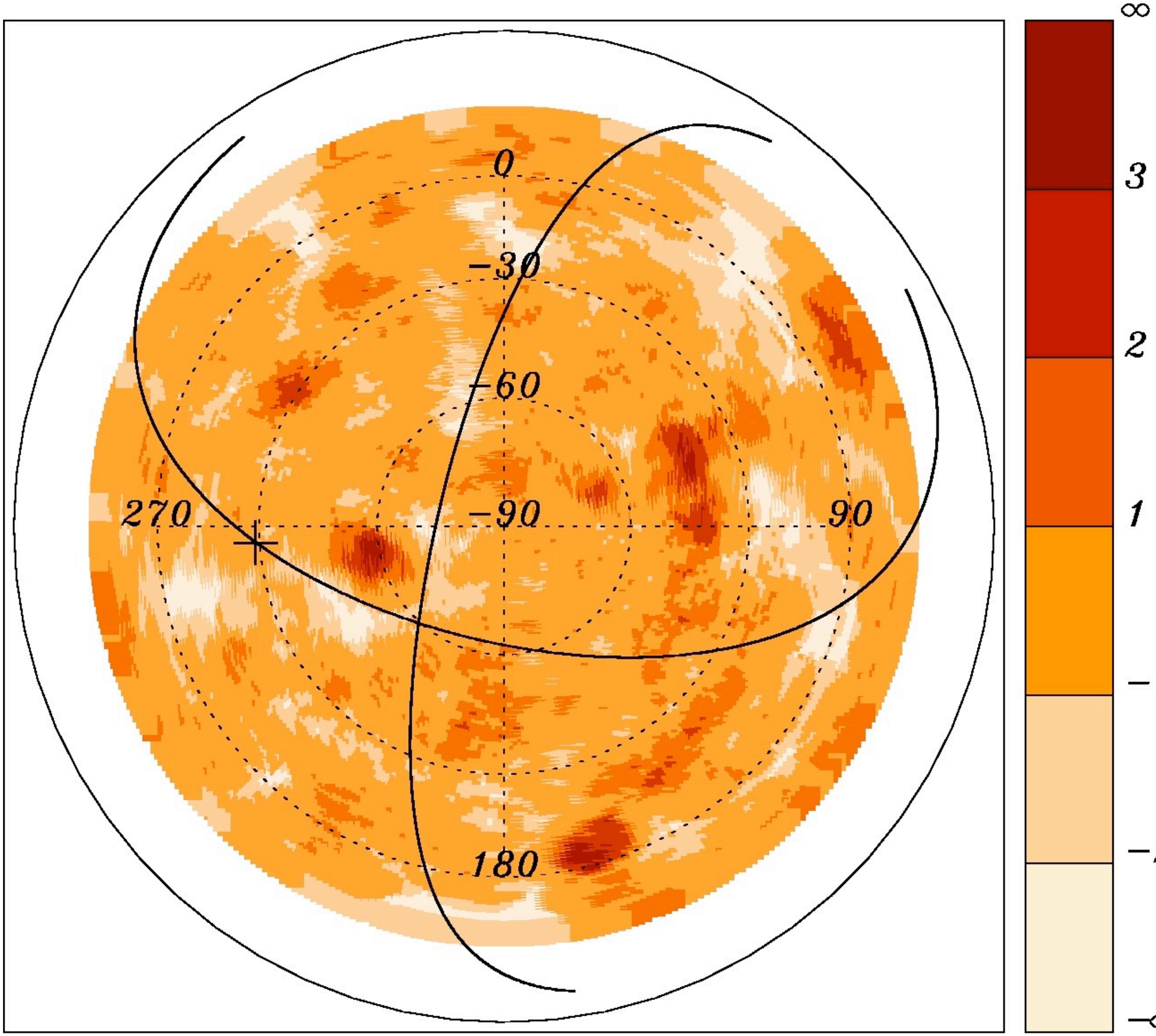
e.g. AGNs, Blazars, ... (HiRes)

Alignment & ordering in energy ?

- expected for real cosmic ray sources
- "spectroscopy" in cosmic magnetic fields

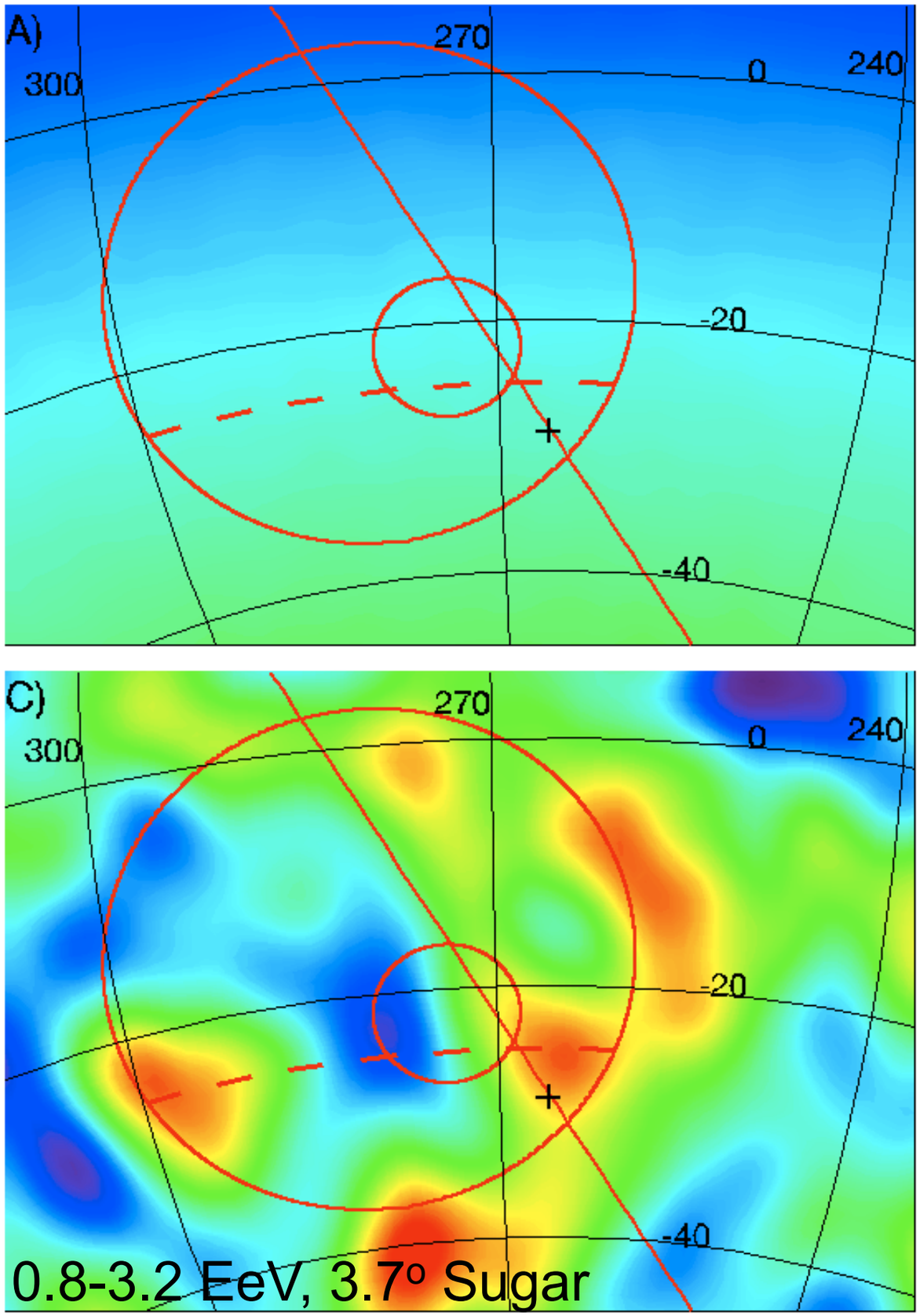


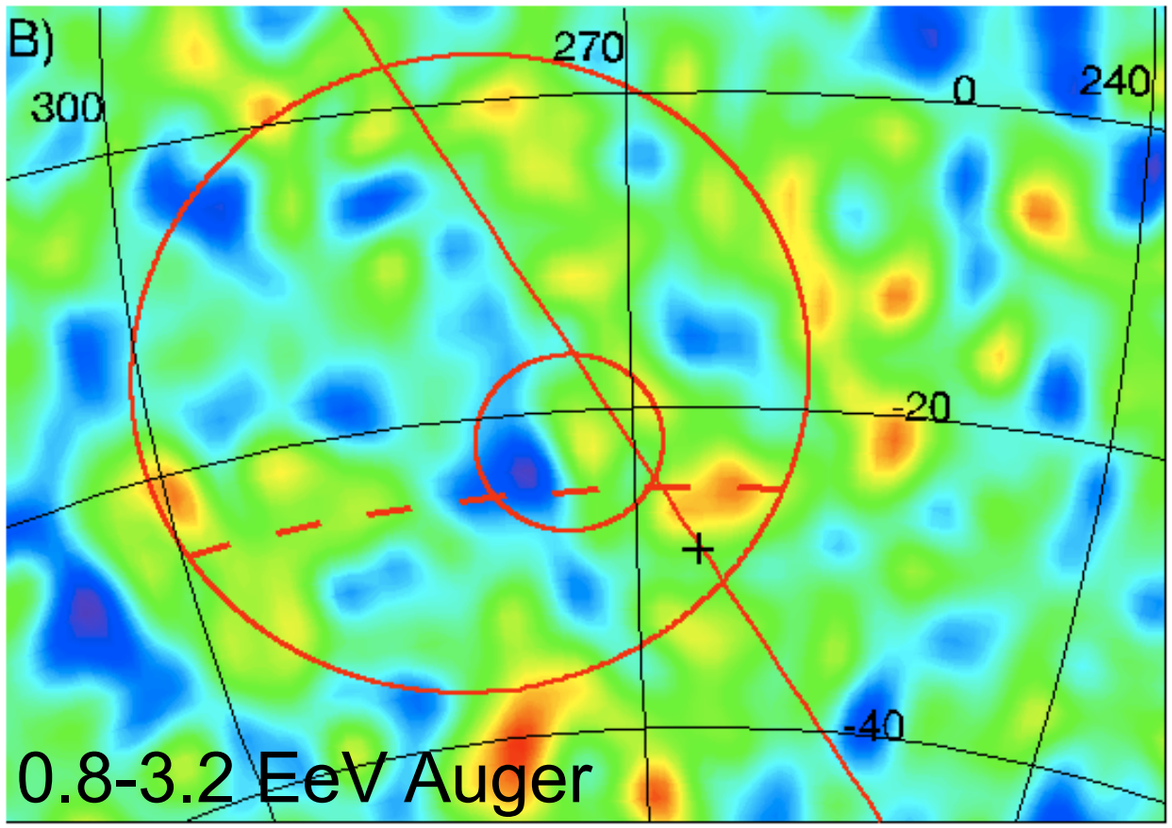
No large over-densities or dipoles

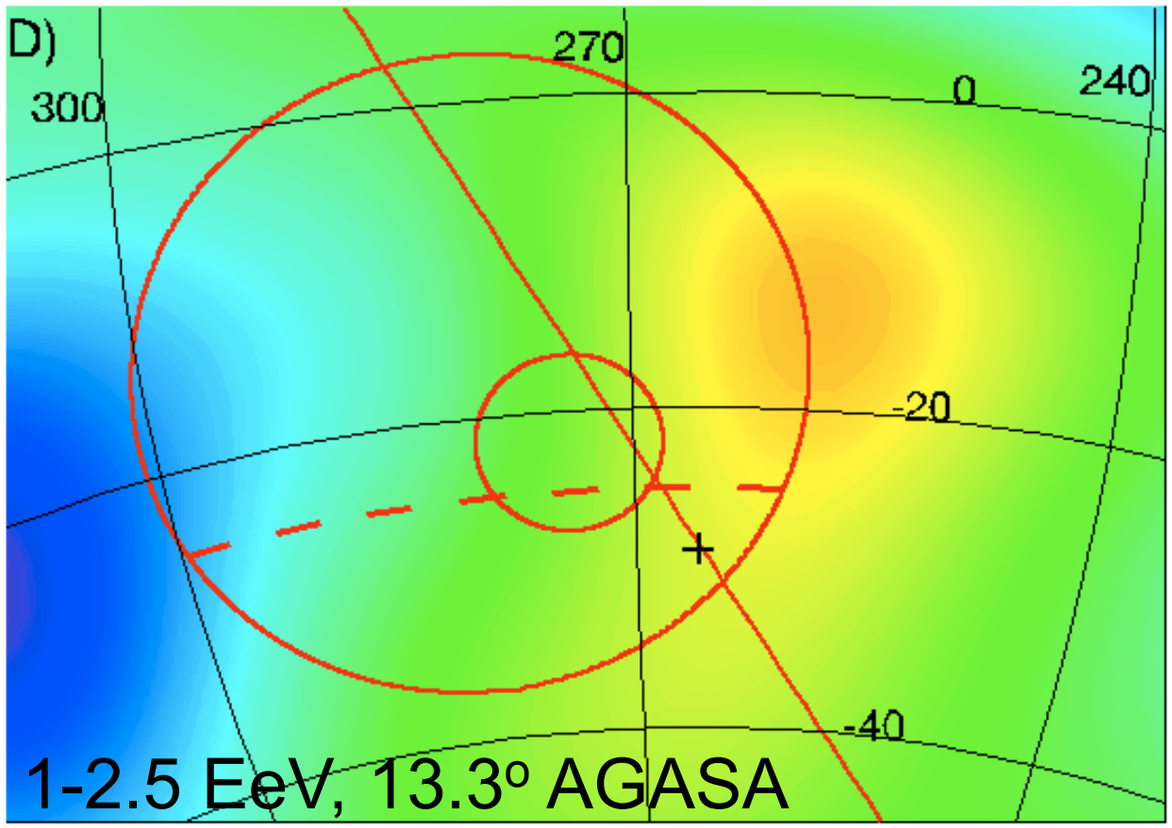


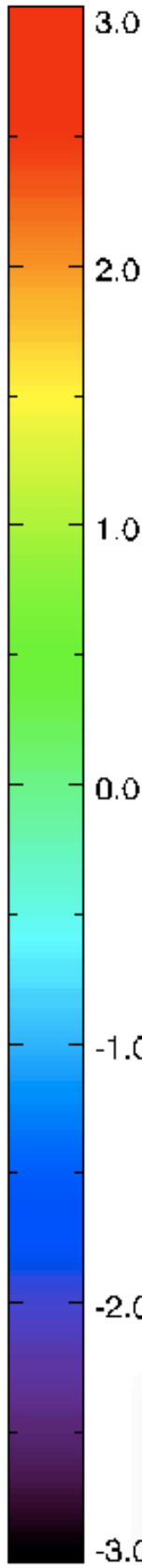
Auger: Galactic Centre

see Astrop. Phys. 27 (2007) 244









1.0-2.5 EeV AGASA:

506/414

+4.5σ or +22%

Auger:

1155/1160

(22% excess would give +1415 evts. or +7.5σ)

0.8-3.2 EeV Sugar:

22/12

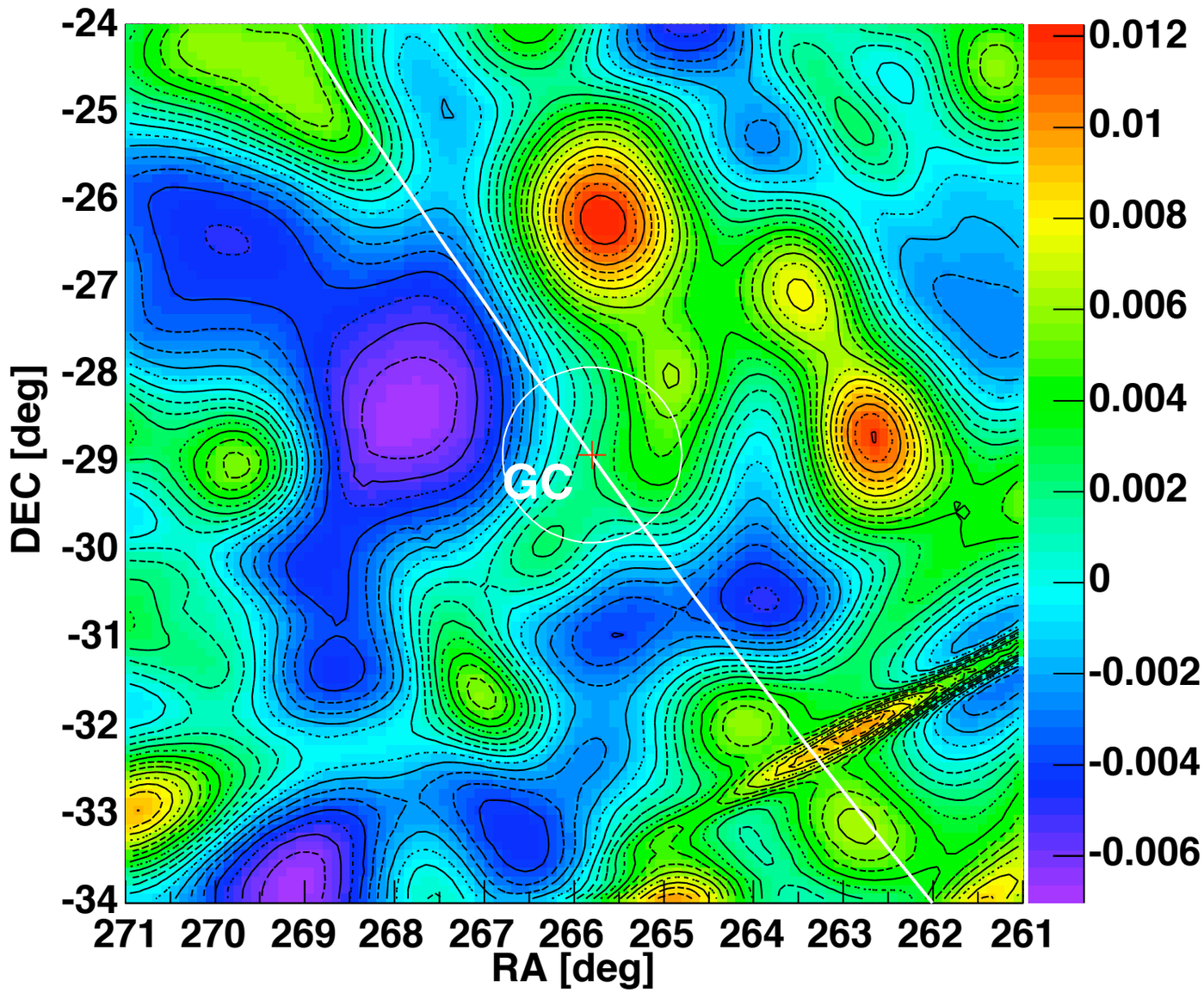
+2.9σ or +85%

Auger:

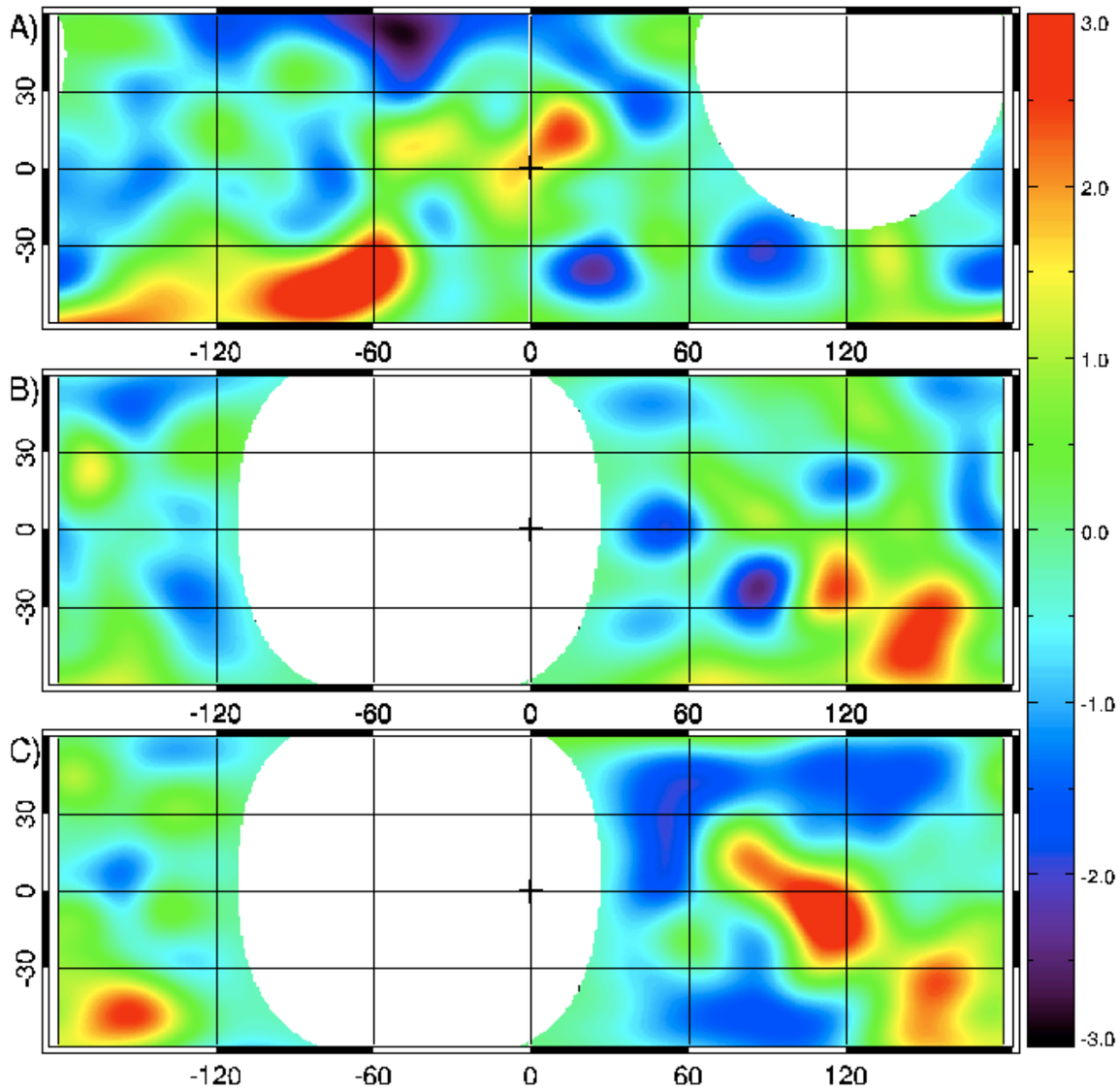
144/151

(85% excess would give +279 evts. or +10.5σ)

no point source



no correlation with galactic or super galactic plane



No dipoles or large-scale excesses

No significant emission from Galactic Centre
as claimed by AGASA and Sugar

No small-scale clustering as claimed by AGASA

No signal from BL Lacs as claimed by HiRes

but:

Some hints for anisotropy at are seen:

2 prescriptions are set up
to be tested with independent data sample
(answer very soon)

...and
Auger will increase event number 5-10x in next few years

Summary:

Auger South is almost compete (>85%) and is taking high-quality data:
Event sample (>10^{19} eV) already larger than that of AGASA and HiRes,
with superior energy and angular resolution
Auger statistics is growing fast

Spectrum: ankle at ≈ 4.5 x 10^{18} eV and steepening at ≈ 3.6 x 10^{19} eV
with model-independent measurement and analysis
But what is the interpretation?
ankle: transition galactic to extra-galactic ?
cut-off: GZK cut-off ? a local effect ? maximum energy of accelerators ???

Mass composition is crucial:
upper limits on photons and neutrinos
mixed nuclear composition at highest energy ???
are hadronic models right ? higher cross section ? more muons ?
(needs more work)

Arrival directions: no point sources (yet), several earlier claims falsified,
but first hints at anisotropies (2 prescriptions running)

Outlook:

Auger-South complete in a few months.
Reliable experimental data for many years to come
(& solid basis for theoretical work)

After last tank is deployed: begin construction of
high elevation FD (to 60°), denser SD sub-array, muon detectors
for hybrid work down to 10^{17} eV
(designed and fully funded)

Auger North: 10000 km^2, Colorado, US
submit proposal within a year