The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1842-18

International Workshop on QCD at Cosmic Energies III

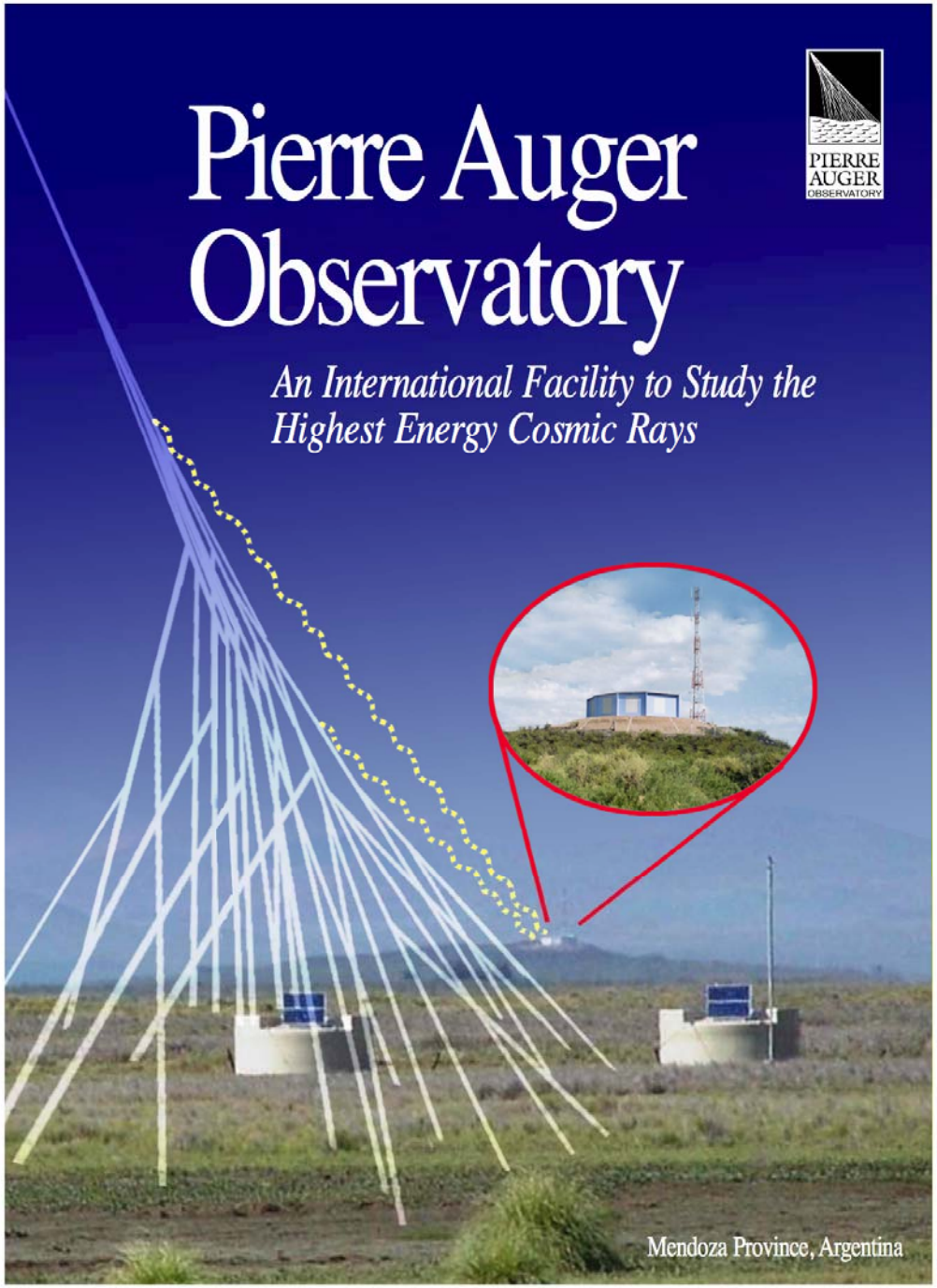
28 May - 1 June, 2007

Lecture Notes

J. Matthews

Louisiana State University
Baton Rouge, USA

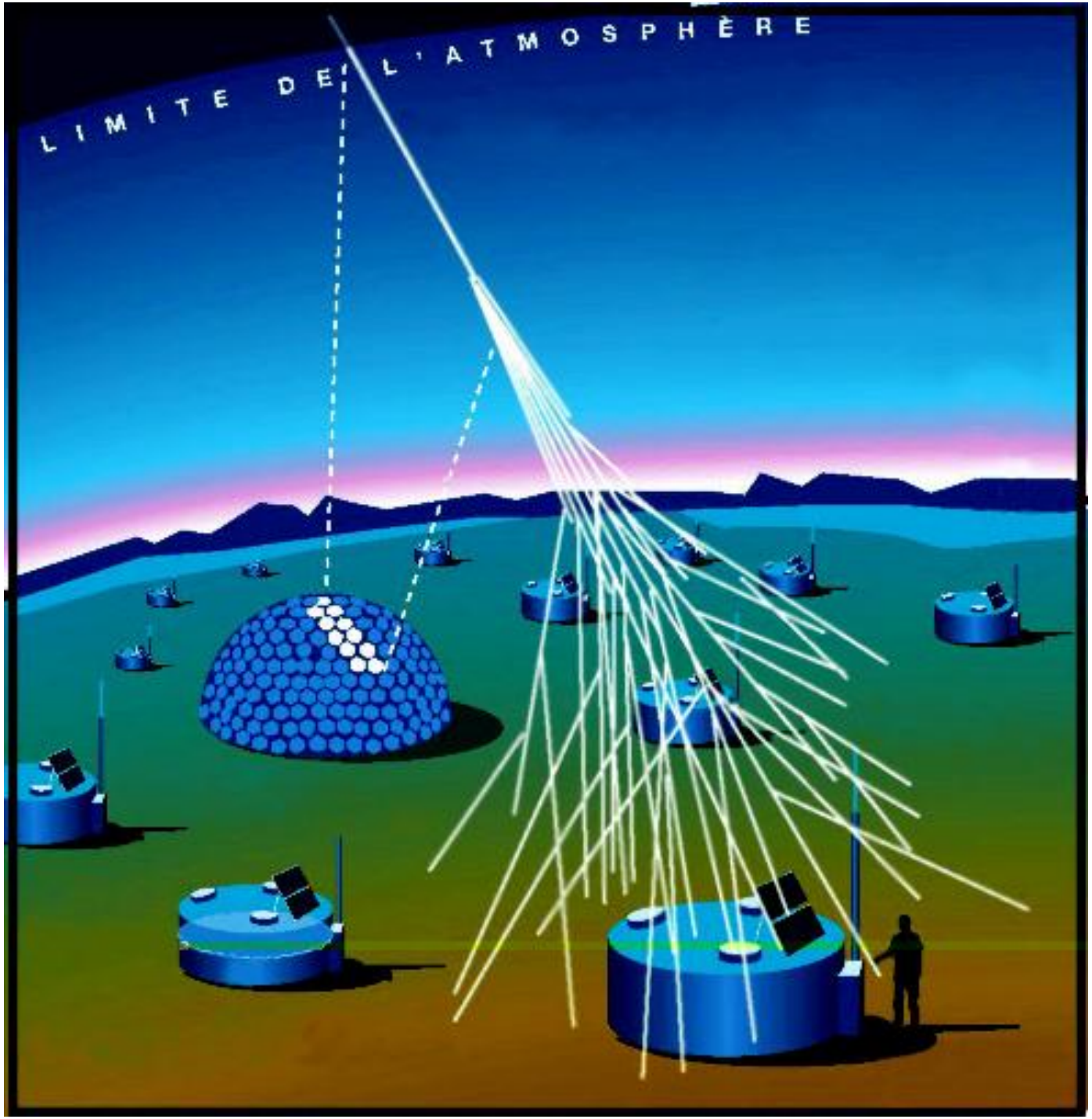
Argentina
Australia
Bolivia*
Brasil
Czech Republic
France
Germany
Holland
Italy
Poland
Mexico
Slovenia
Spain
United Kingdom
USA
Vietnam*

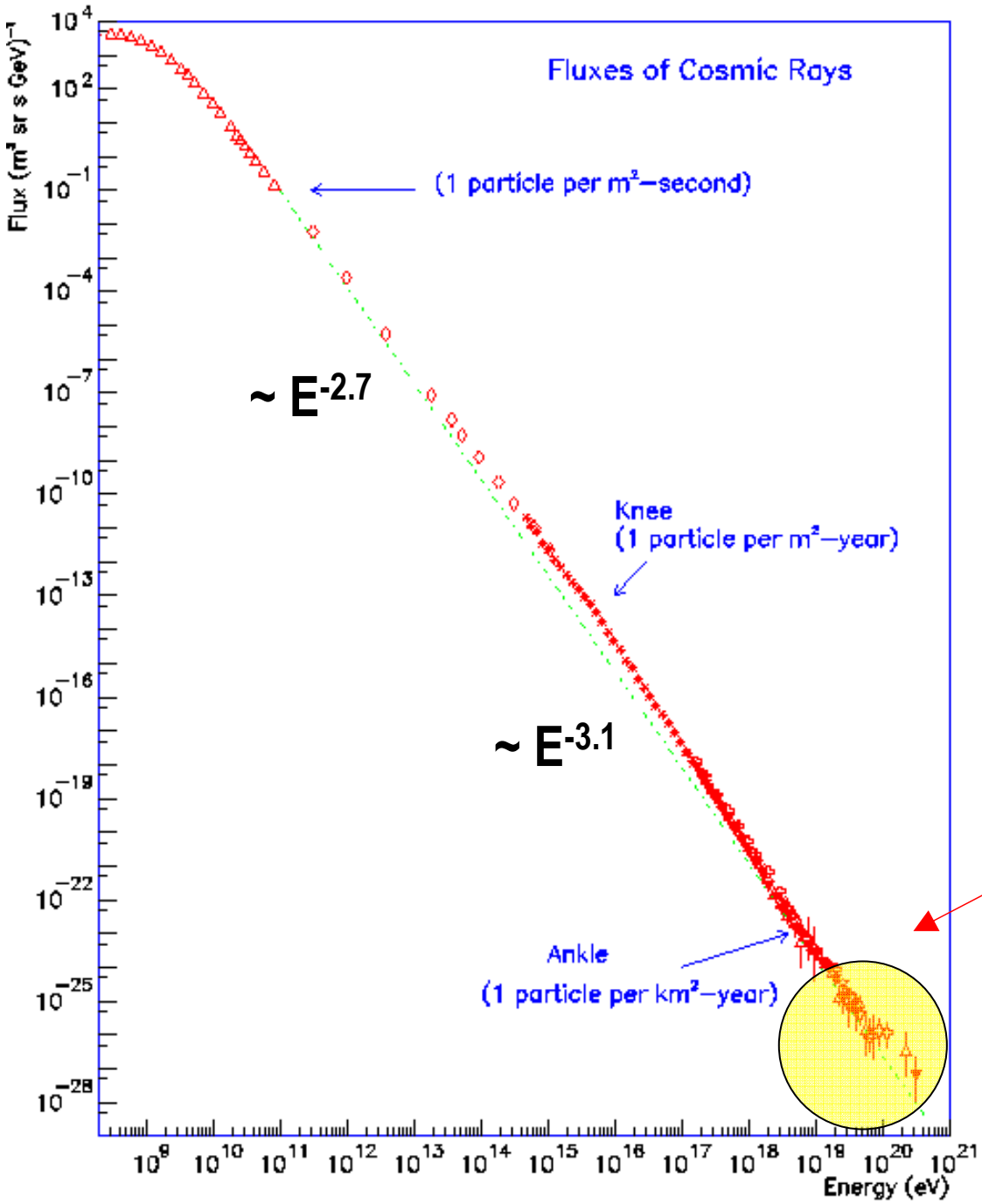


Jim Matthews

Louisiana State University

Southern University

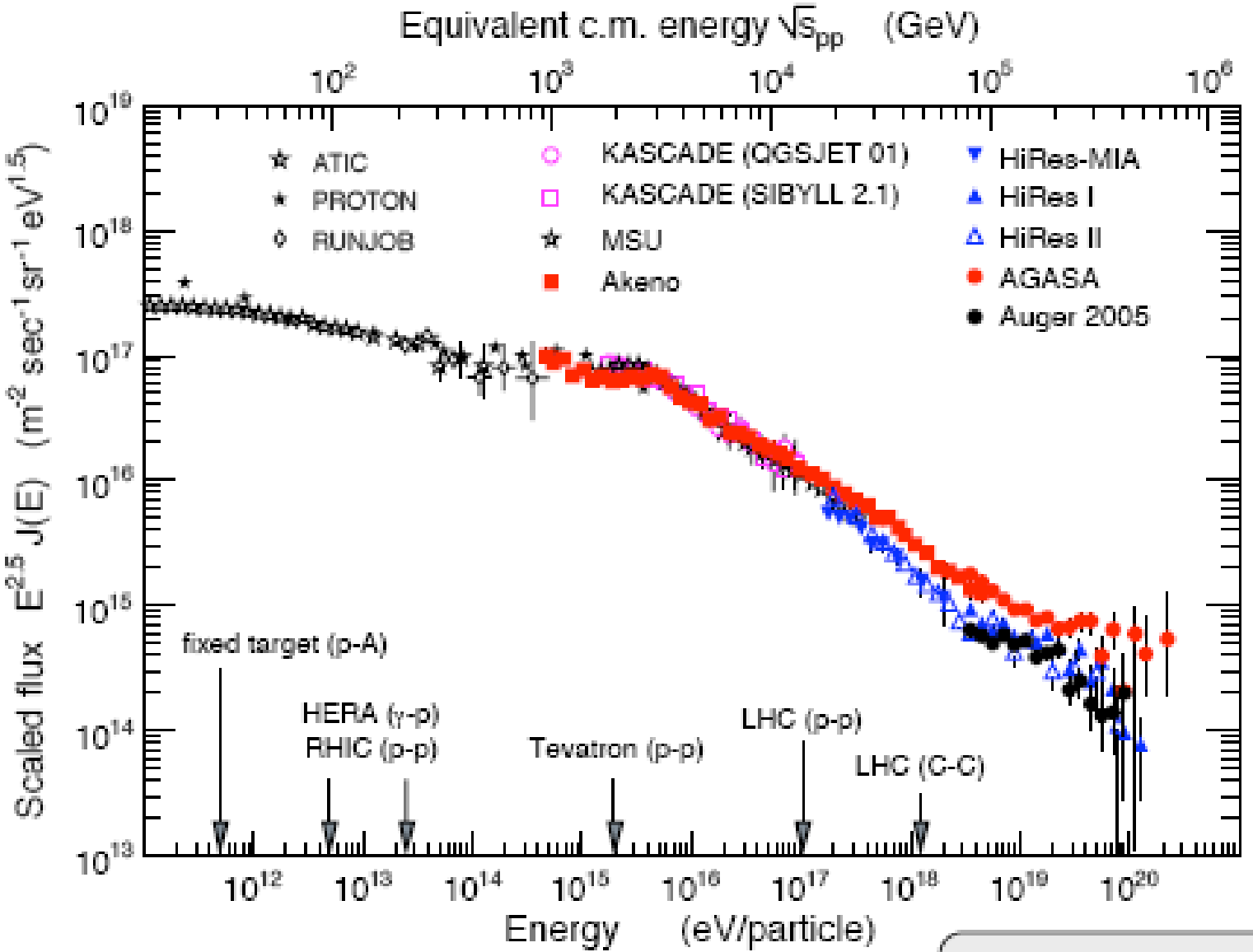

LIMITE DE L'ATMOSPHÈRE



Above 10^{20} eV (50 Joules!):

$\Phi \approx 1$ per km^2 per century

Flux x $E^{2.5}$



Statistical errors only!

The purpose of Auger is:

Identify the origin and the identity of the highest energy cosmic rays

How?

1. **Measure the shape of the energy spectrum**
2. **Measure the particle type**
3. **Locate the sources**

And then?

Astrophysics: **what is the acceleration mechanism?**

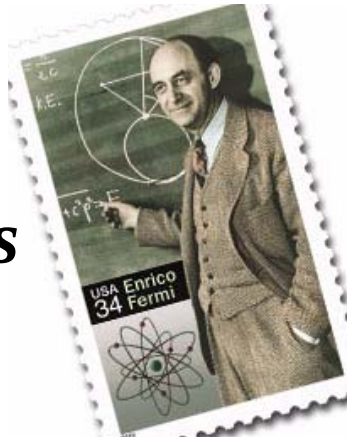
Particle Physics: **what are interactions like at such energy?**

How to get particles to extreme energy

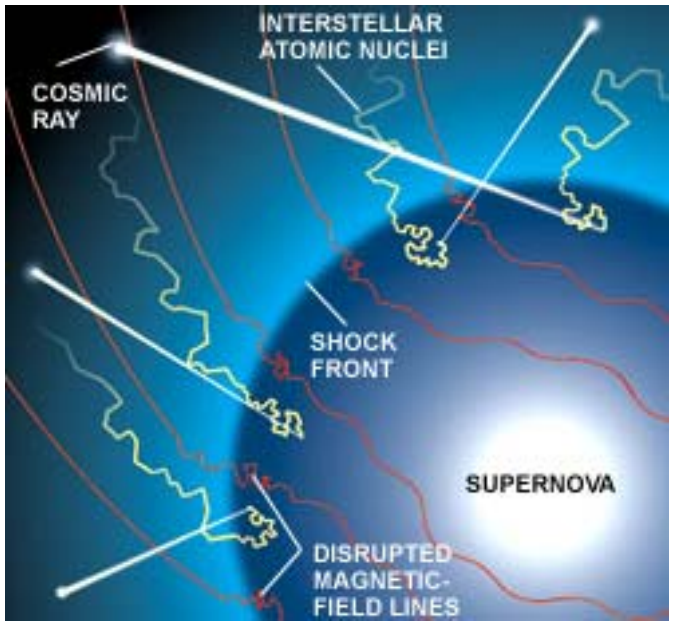
- **Fermi Acceleration (Bottom-Up)**
  - **repeated encounters with strong plasma shocks**
  - **naturally produces power-law with correct index**
  - **maximum energy can be extremely large**
  - **observed in nature**

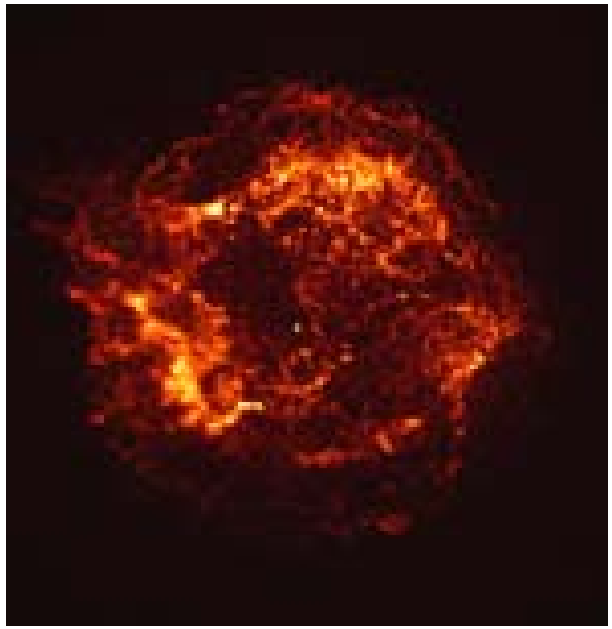
- **"Exotic" (Top-Down)**
  - **decay of massive relic particles**
  - **interaction of Z's with cosmic background neutrinos**
  - **topological defects, other things ???**
  - *Signature: protons, photons, neutrinos*

Galactic Cosmic Ray Origin?



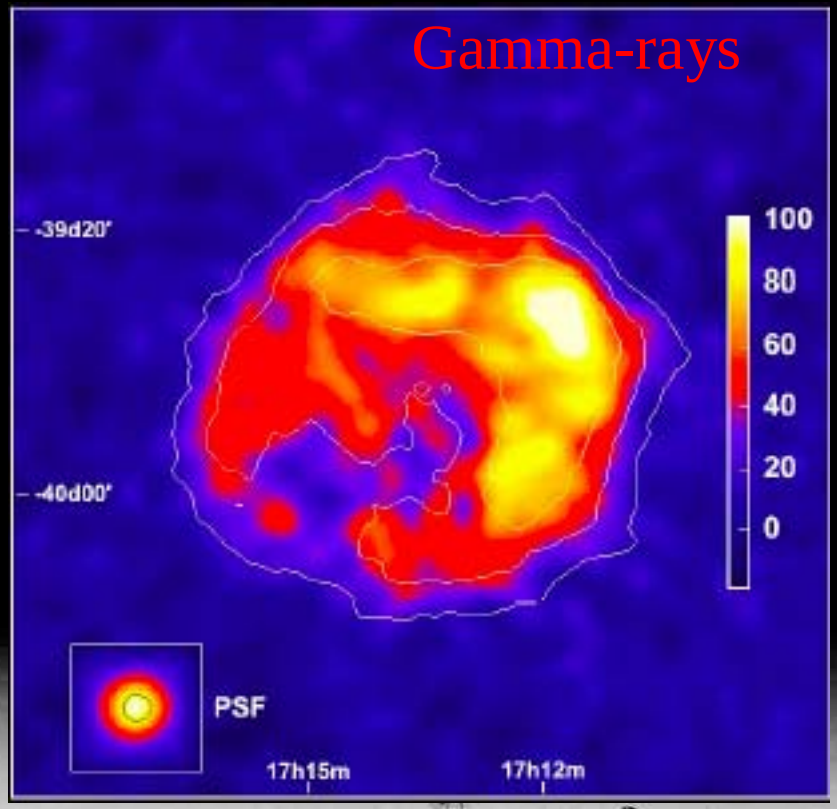
Fermi Acceleration in Supernova Shocks
up to ~ 10^{15} eV - 10^{17} eV?

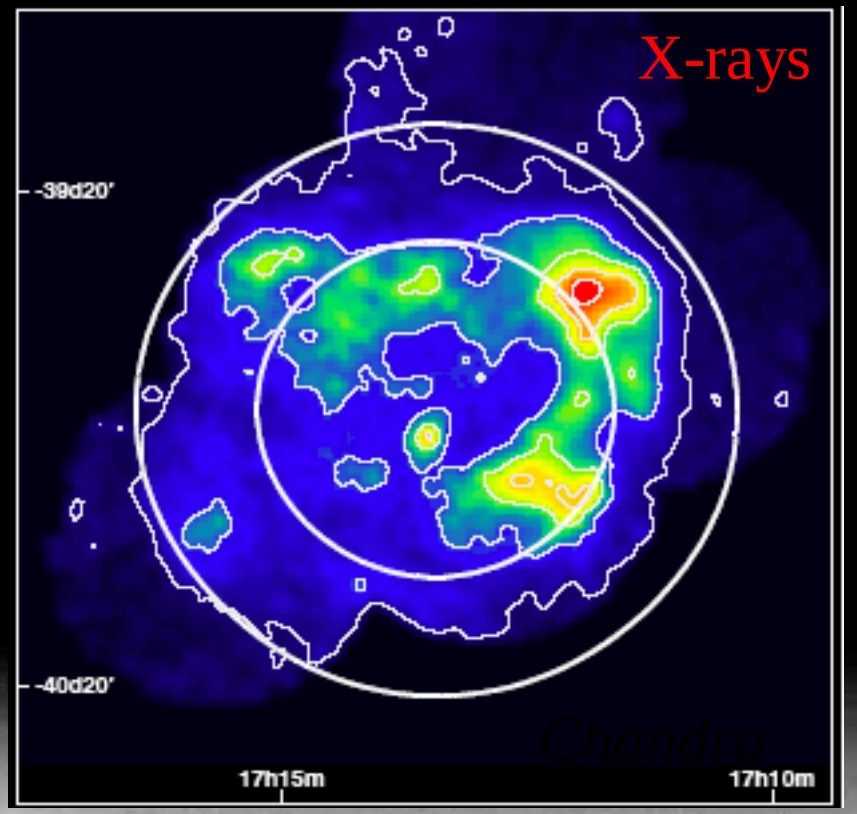


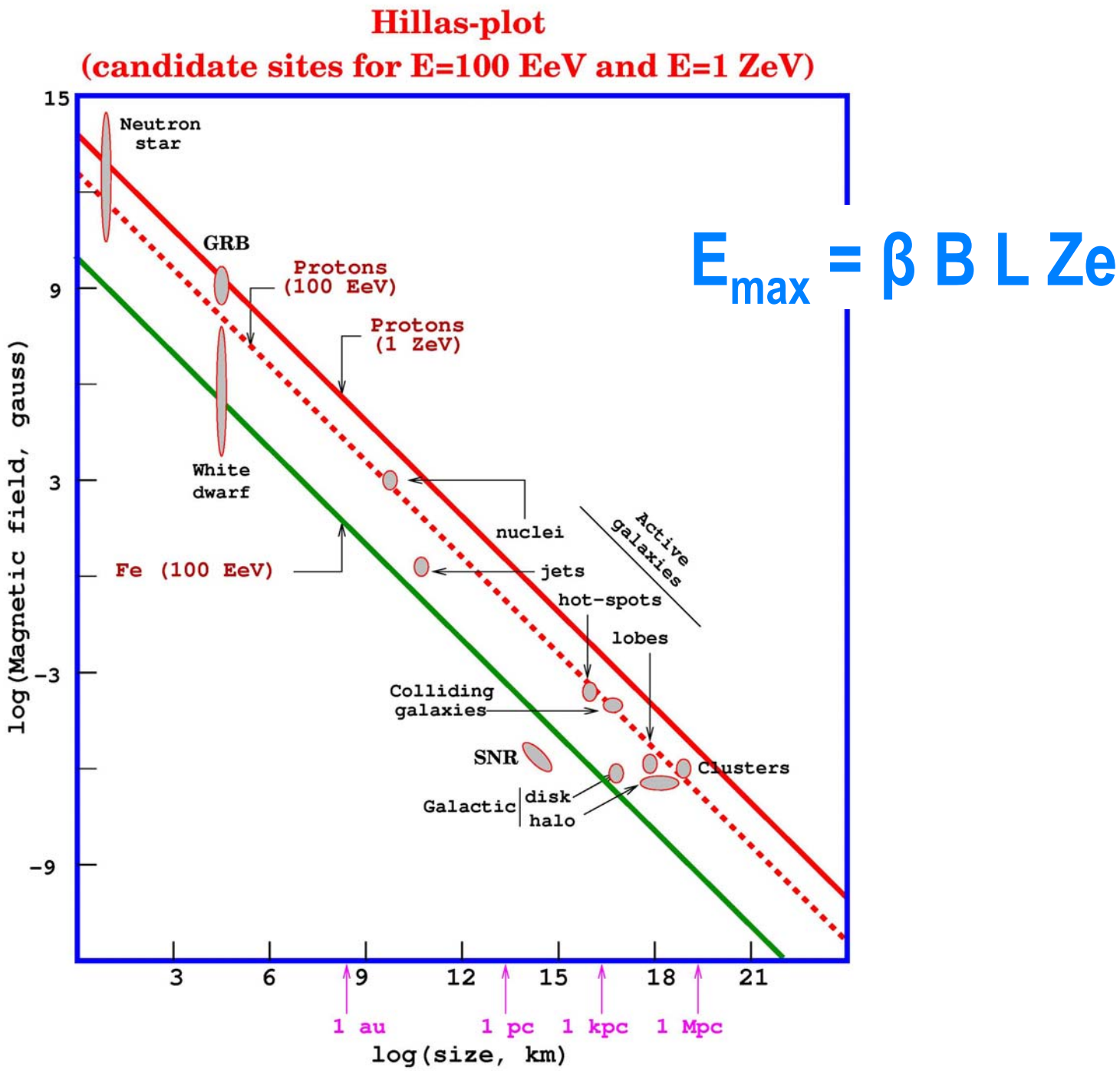


HESS - smoking guns in TeV γ's ?

RX J1713 - 20 σ



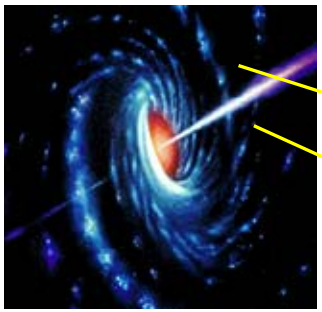




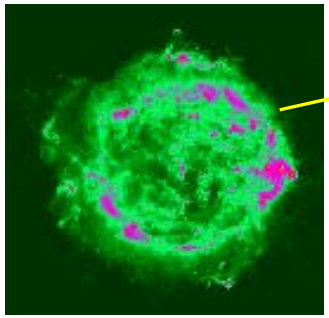
$$E_{max} = \beta B L Ze$$

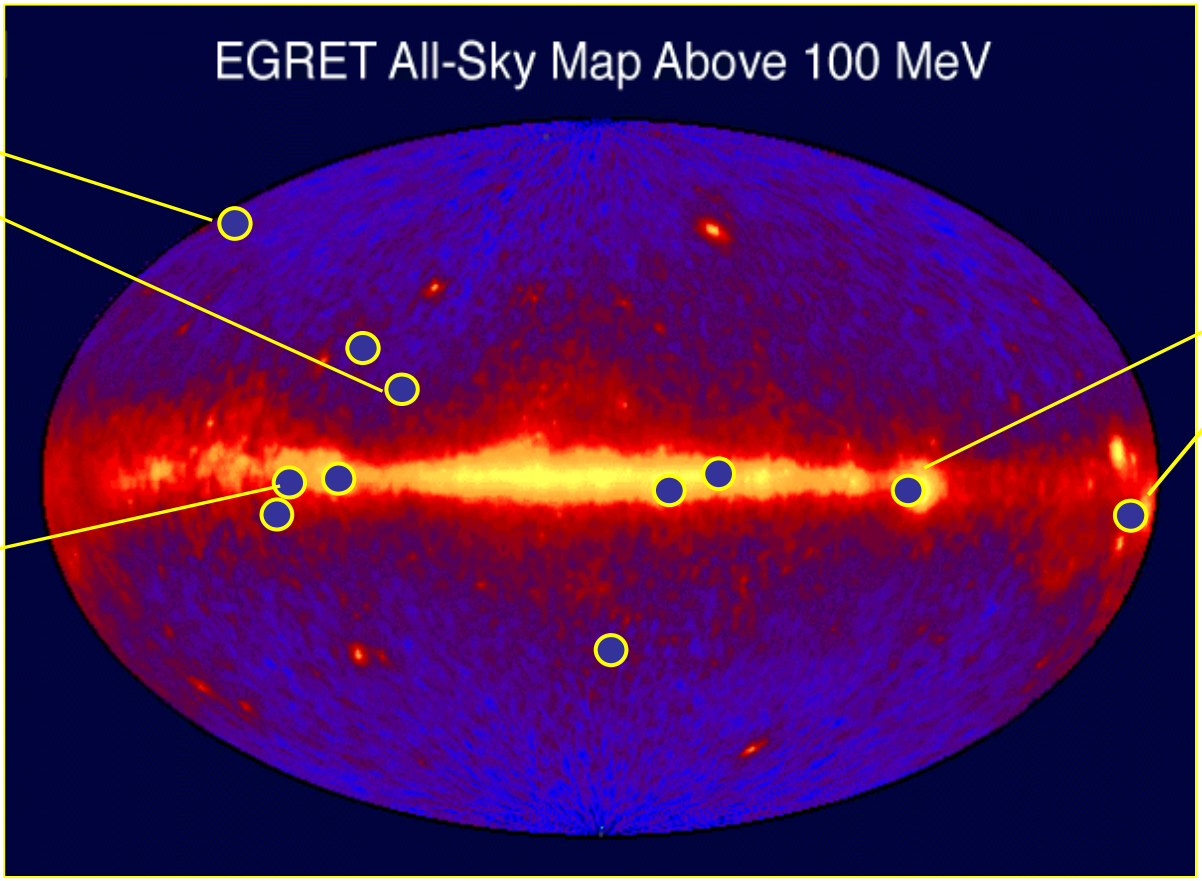
The Extreme Universe

AGN

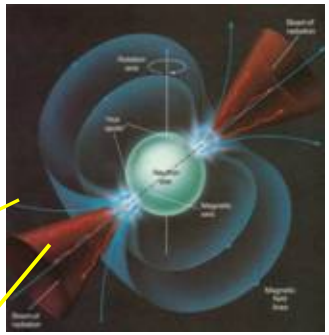


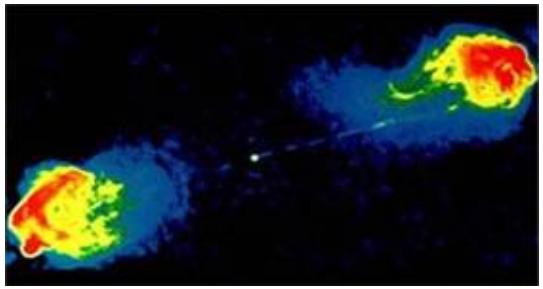
SNR





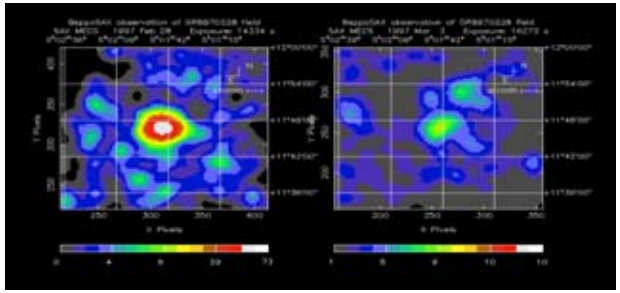
Pulsar





Radio Galaxy

GRB

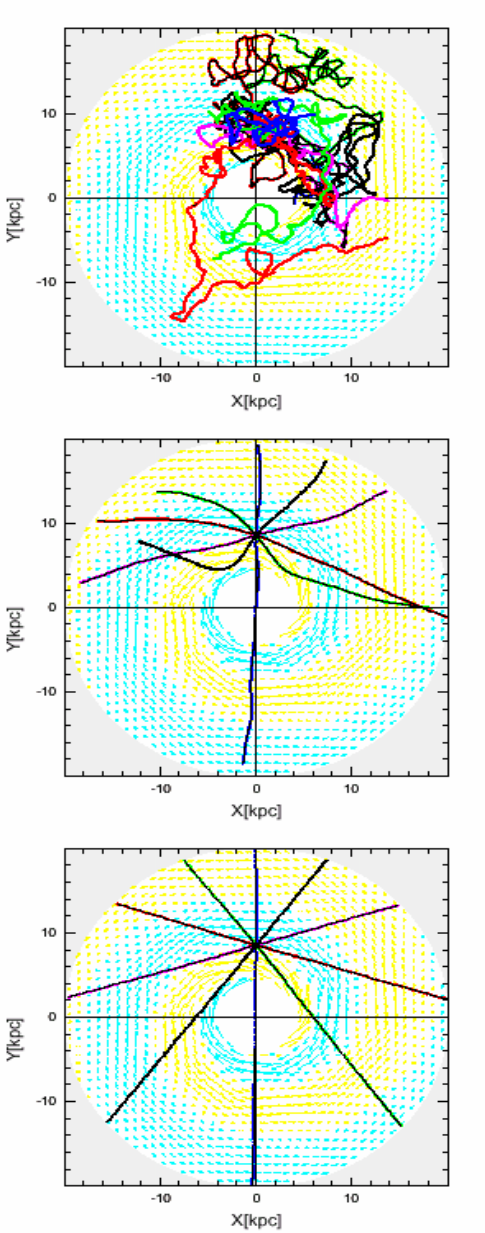


Trajectories of Cosmic Ray Protons in the Galaxy

- **Protons are trapped in our Galaxy up to ~10^{18}eV**
- **Protons can travel straight above ~10^{20}eV**

↓

- **Charged-Particle Astronomy**



E=10^{18}eV

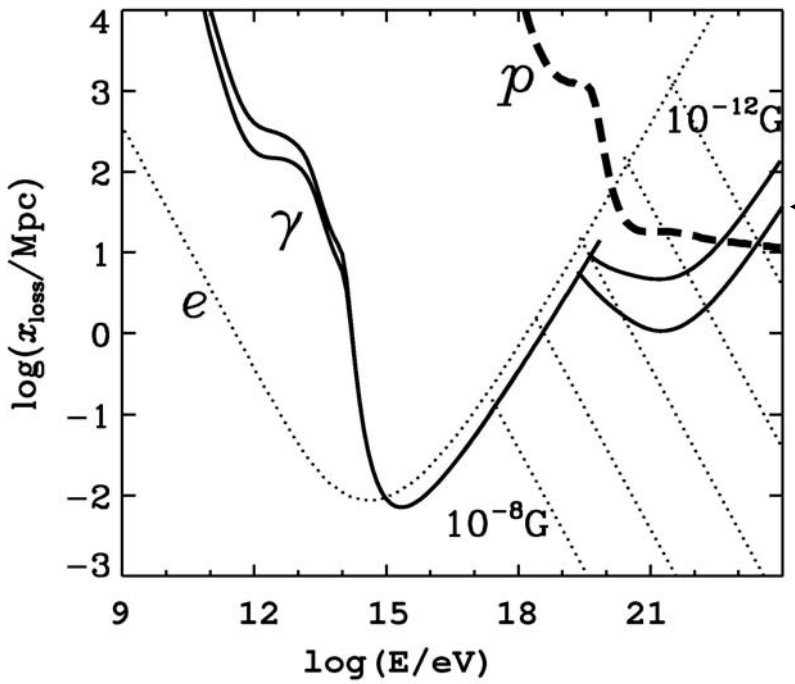
E=10^{19}eV

E=10^{20}eV

Propagation through cosmic radiation

(from R.J.Protheroe)

$x_{loss} = x_{int}$ /mean inelasticity



Included processes:

Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)

Gammas: pair-production through IR, CMB, and radio backgrounds

Protons: Bethe-Heitler pair production, pion photoproduction

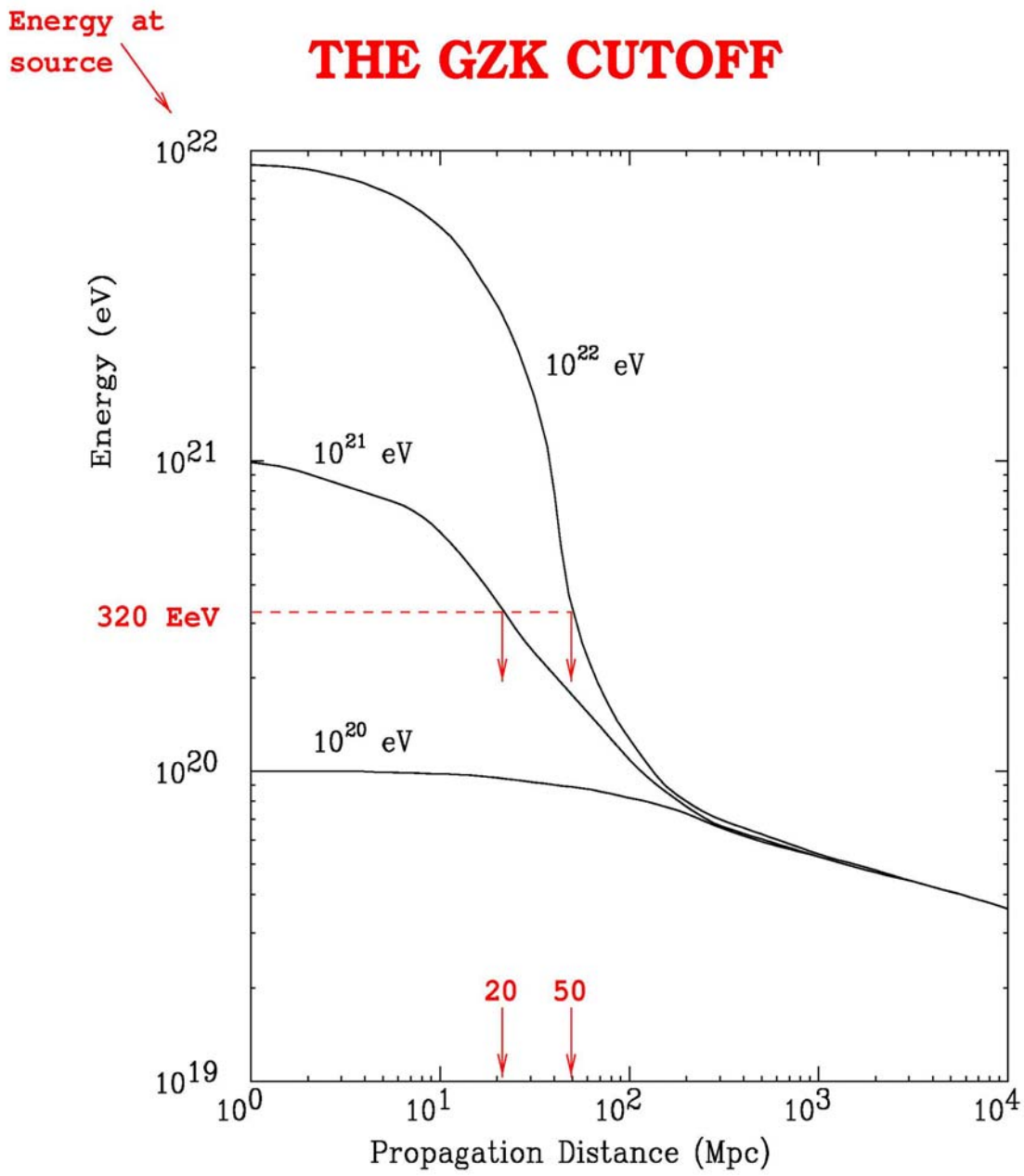
30 Mpc – distance to center of local group (Virgo Cluster)

p + γ (2.7°K)

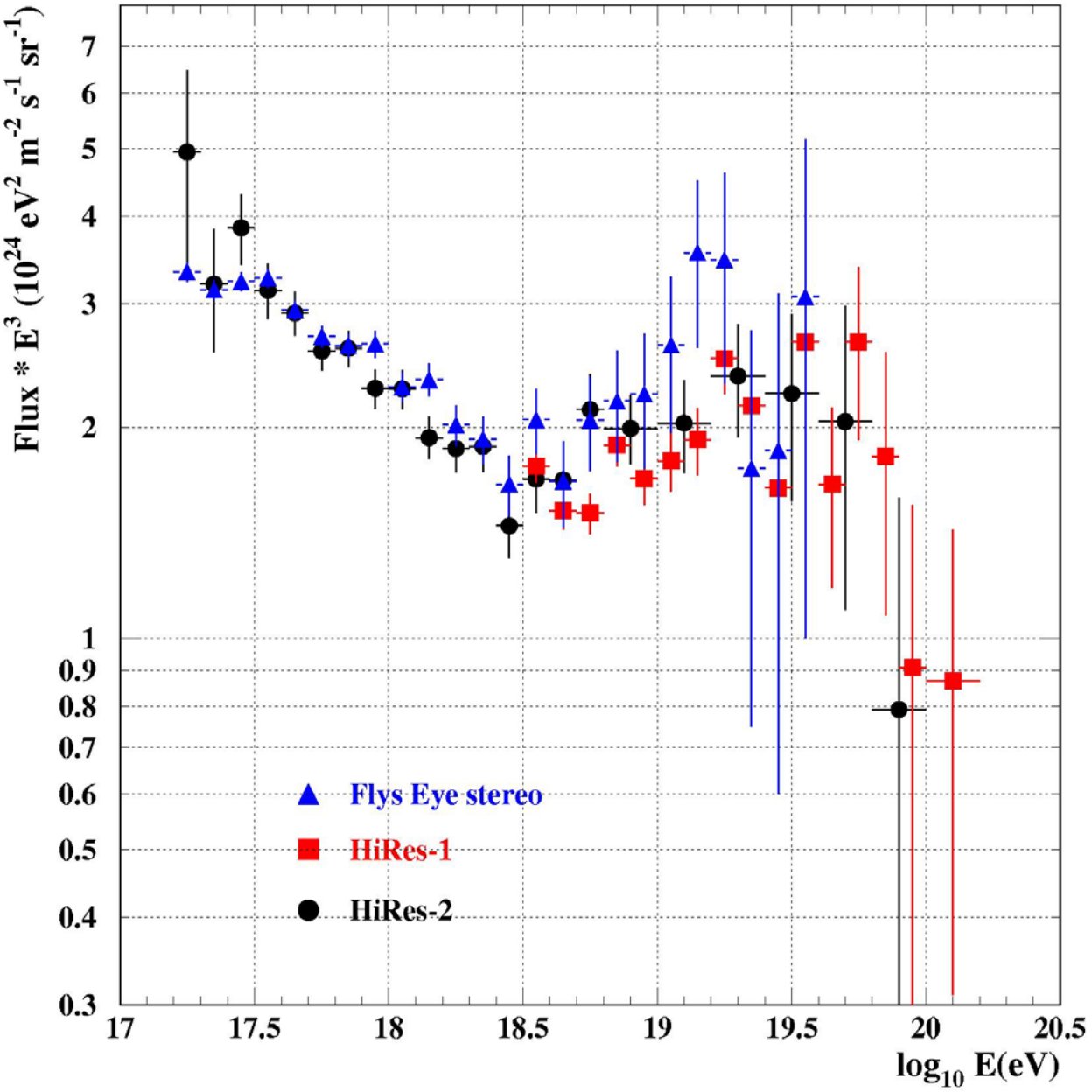
→ Δ

→ p + π's

THE GZK CUTOFF



Hi-Res Energy Spectrum

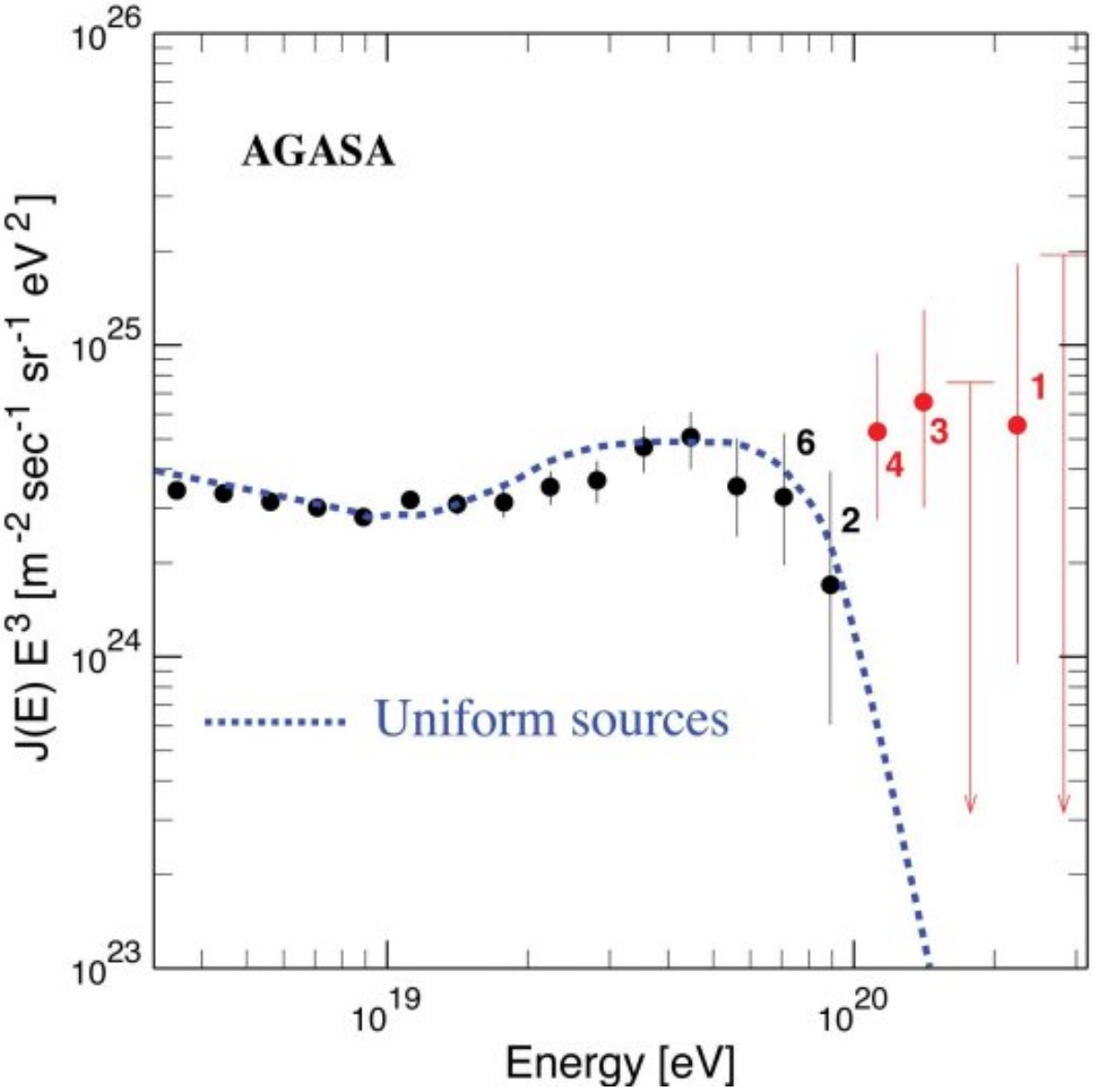


astro-ph / 0409140

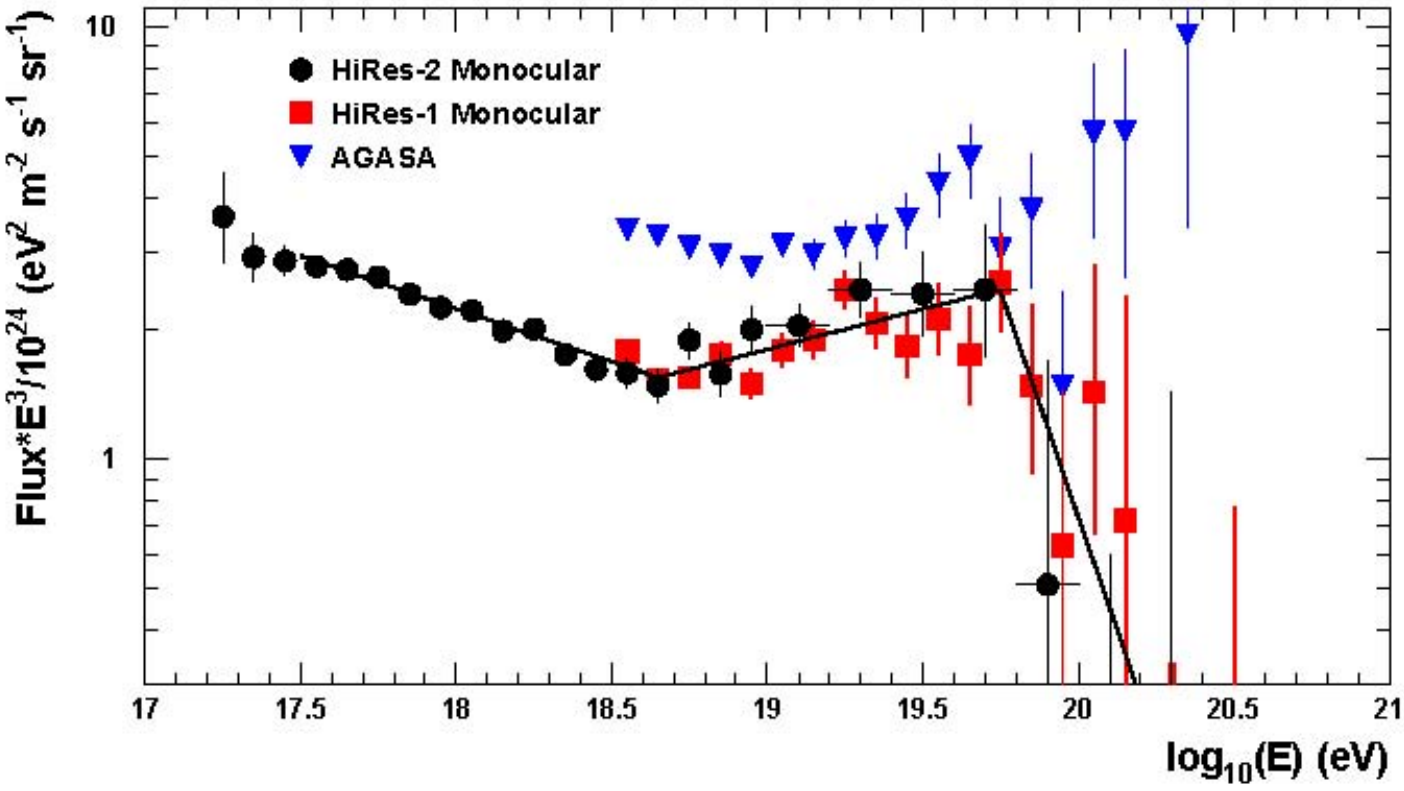
Sep '04

AGASA Energy Spectrum

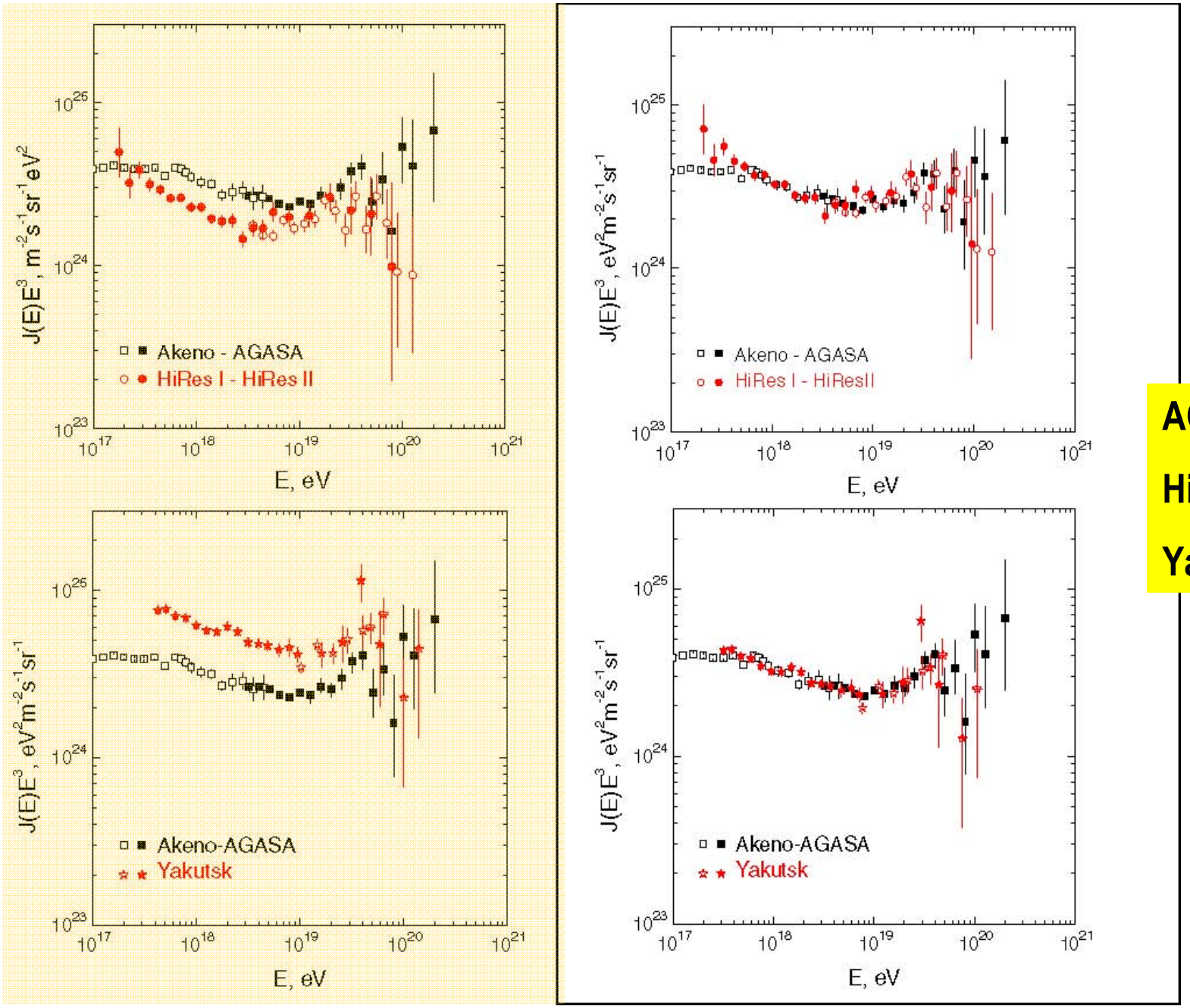
- **After 10 years of operation, AGASA observed ~10 events above GZK cutoff.**
- **Can not be explained by cosmologically uniform source distribution.**



HiRes astro-ph/070399 6 Mar 2007



Modest systematic energy shifts for either could bring much better agreement (except at the end ? ...)



AGASA x 0.9

HiRes x 1.2

Yakutsk x 0.75

V.Berezinsky, A. Gazizov, S. Grigorieva, Phys. Rev. **D74**, 043005 (2006)

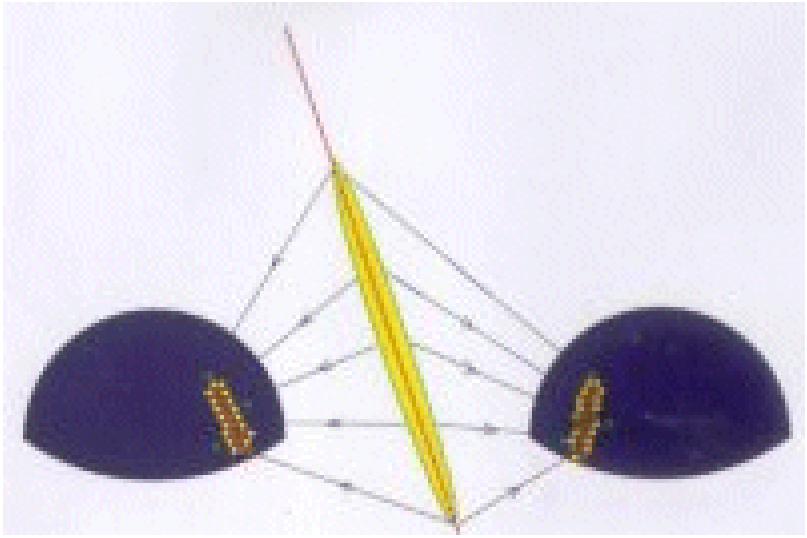
(Speculations)

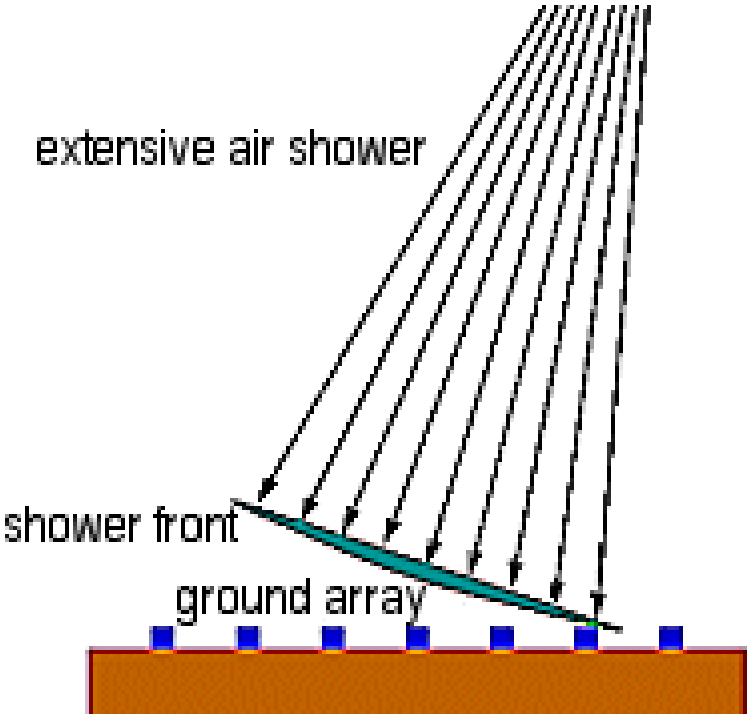
There has been a new measurement of atmospheric fluorescence efficiency by "AirFly" (not yet published)

It may systematically raise the energy of HiRes events

EPOS-based simulation generates singnificantly more muons in EAS.

This could systematically lower AGASA energy. (small effect on Auger spectrum)





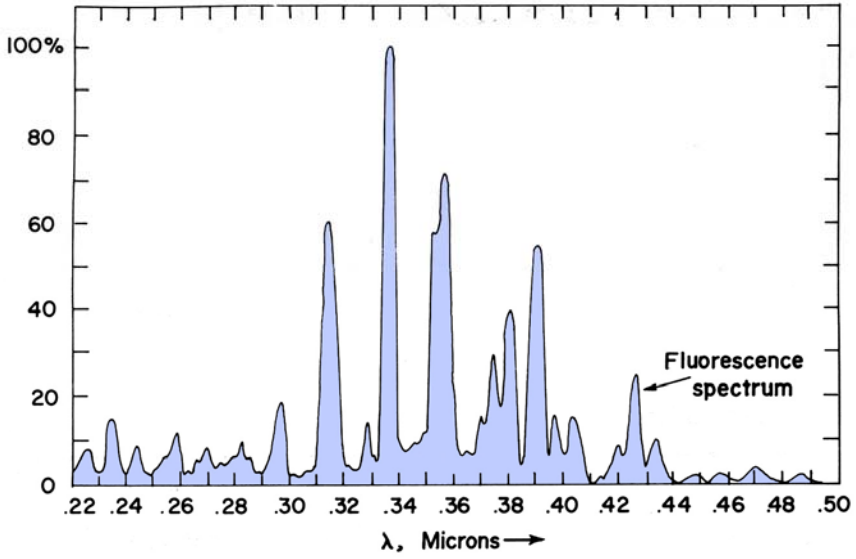
The Auger Observatory uses both techniques, with:

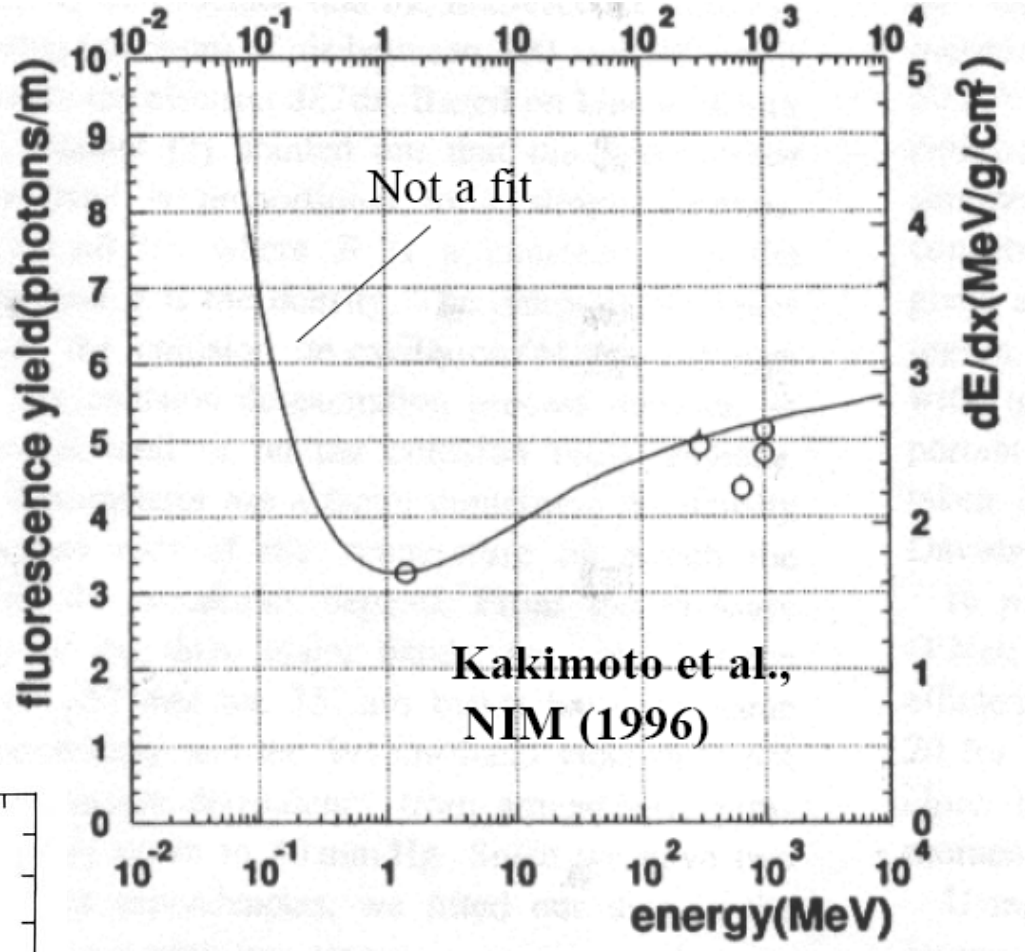
- Very large size (statistics)

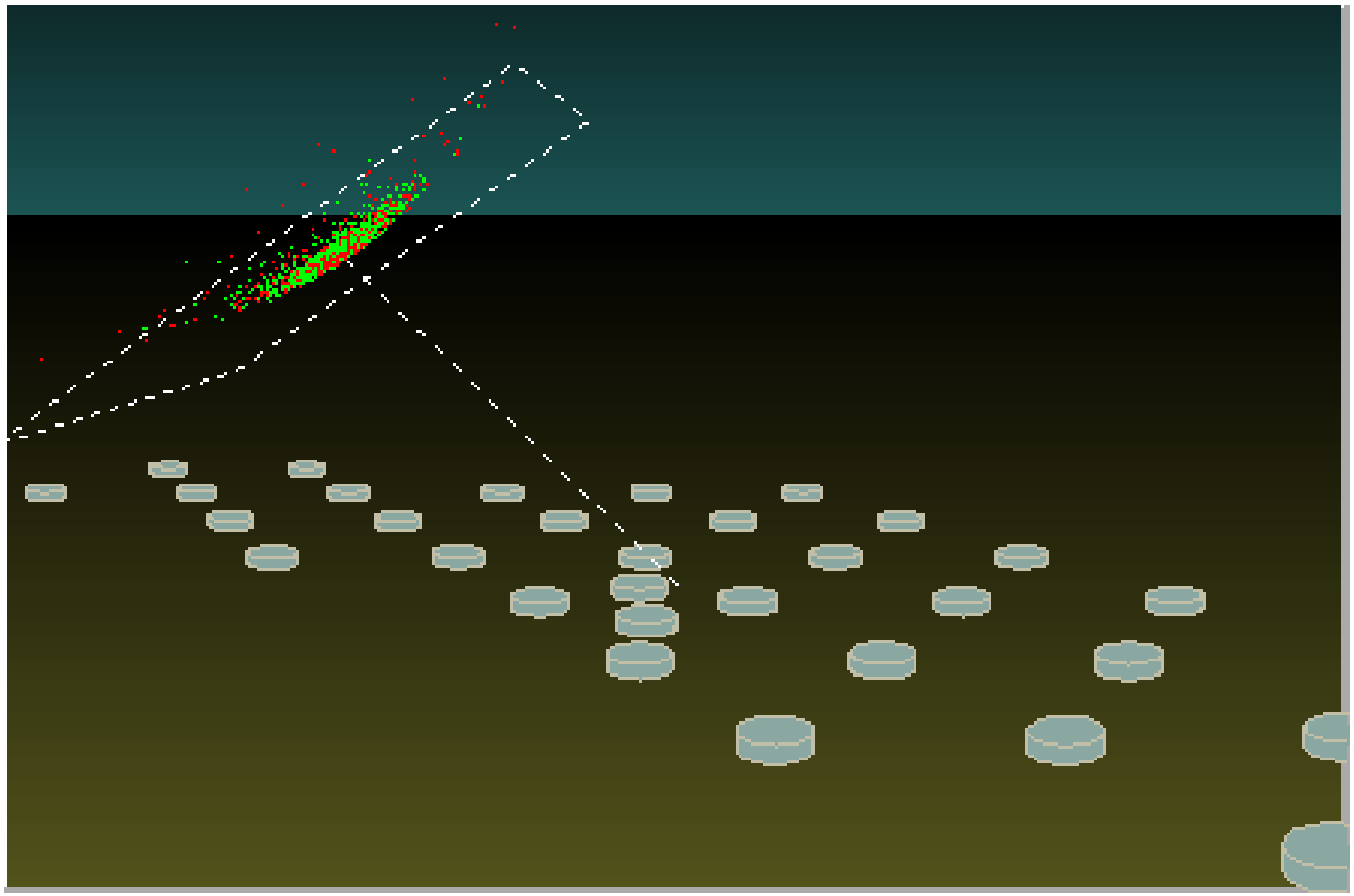
- *Good energy (spectrum) and angular resolution (astronomy)*

Air Fluorescence –

Excitation of atmospheric nitrogen by electrons in air showers



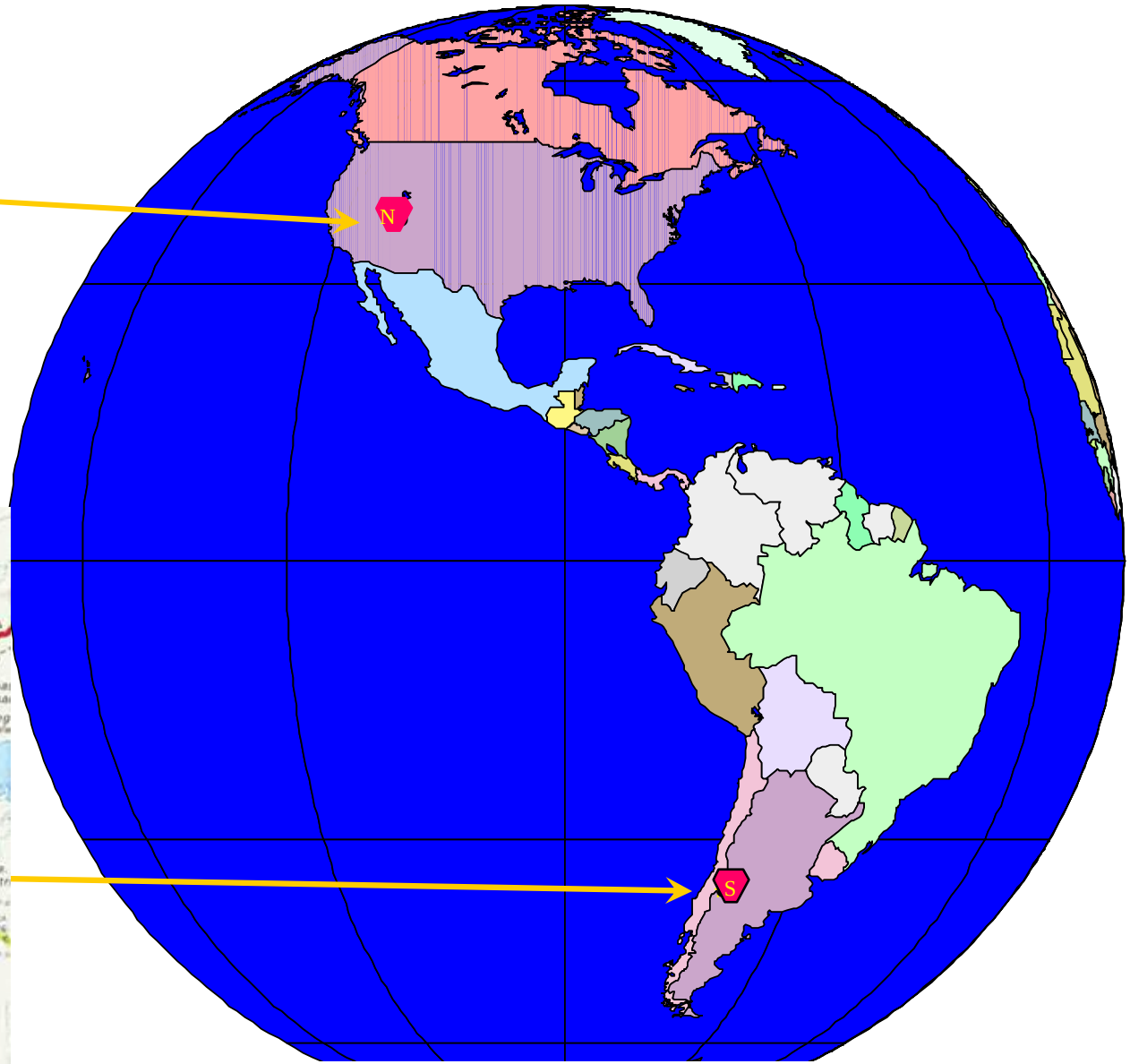


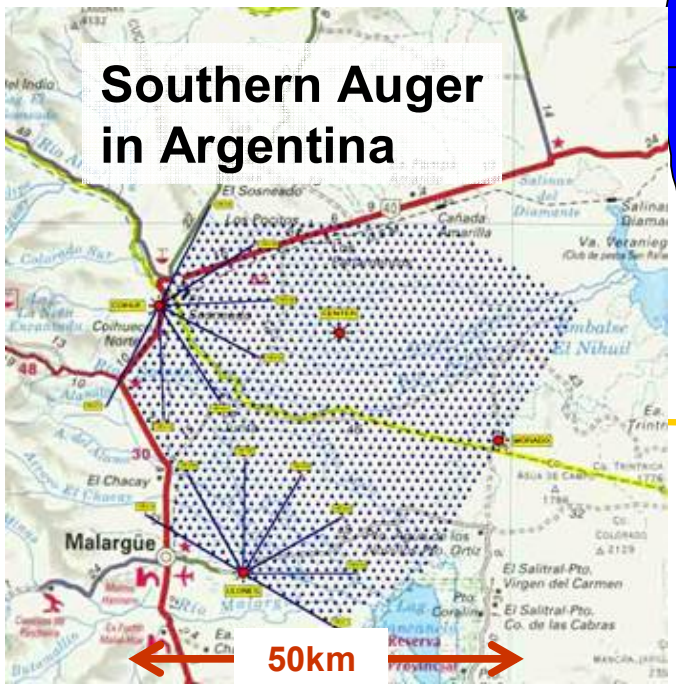


Surface detector array - measurement of EAS particles

Pierre Auger Observatory

Northern Auger in Colorado

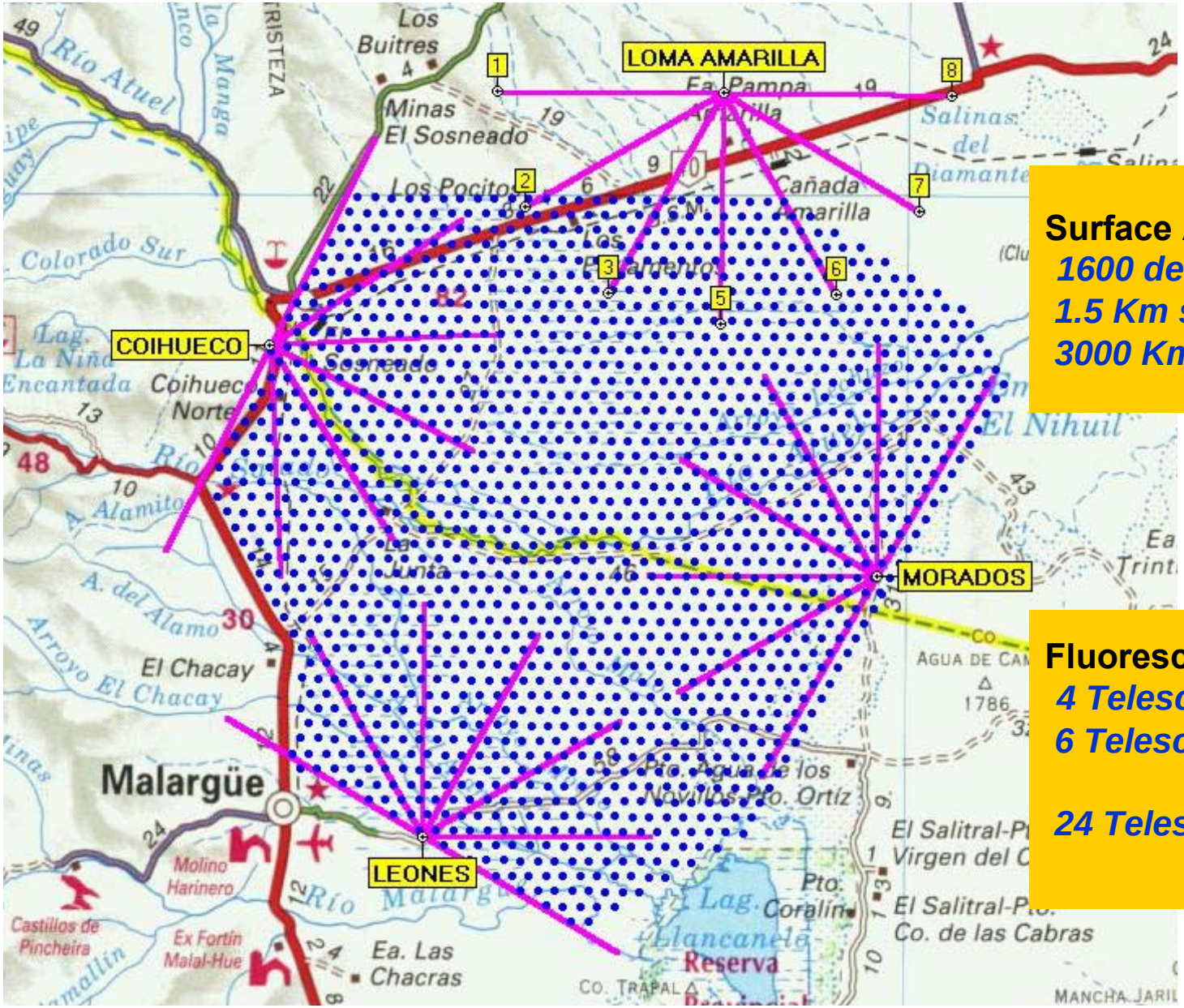




38° South, near Malargue, Mendoza, Argentina

PIERRE AUGER OBSERVATORY


Santiago
Malargue, Argentina
Image © 2005 EarthSat
Image © 2005 DigitalGlobe
© 2005 Google
Pointer 35°17'37.72" S 69°27'49.48" W elev 4607 ft
Streaming 100%
Eye alt 22.33 mi



Surface Array

1600 detector stations

1.5 Km spacing

3000 Km^2

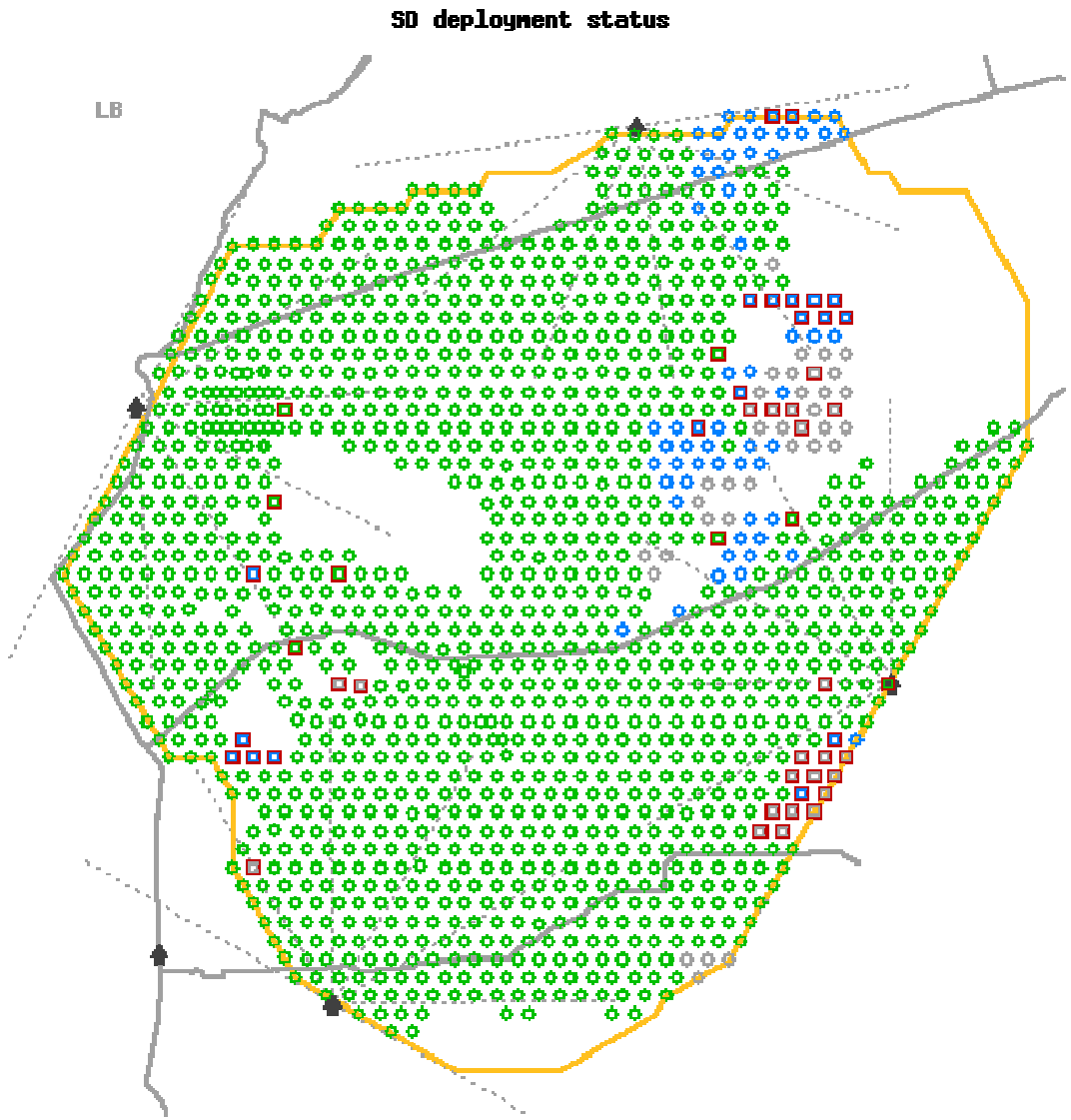
Fluorescence Detectors

4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

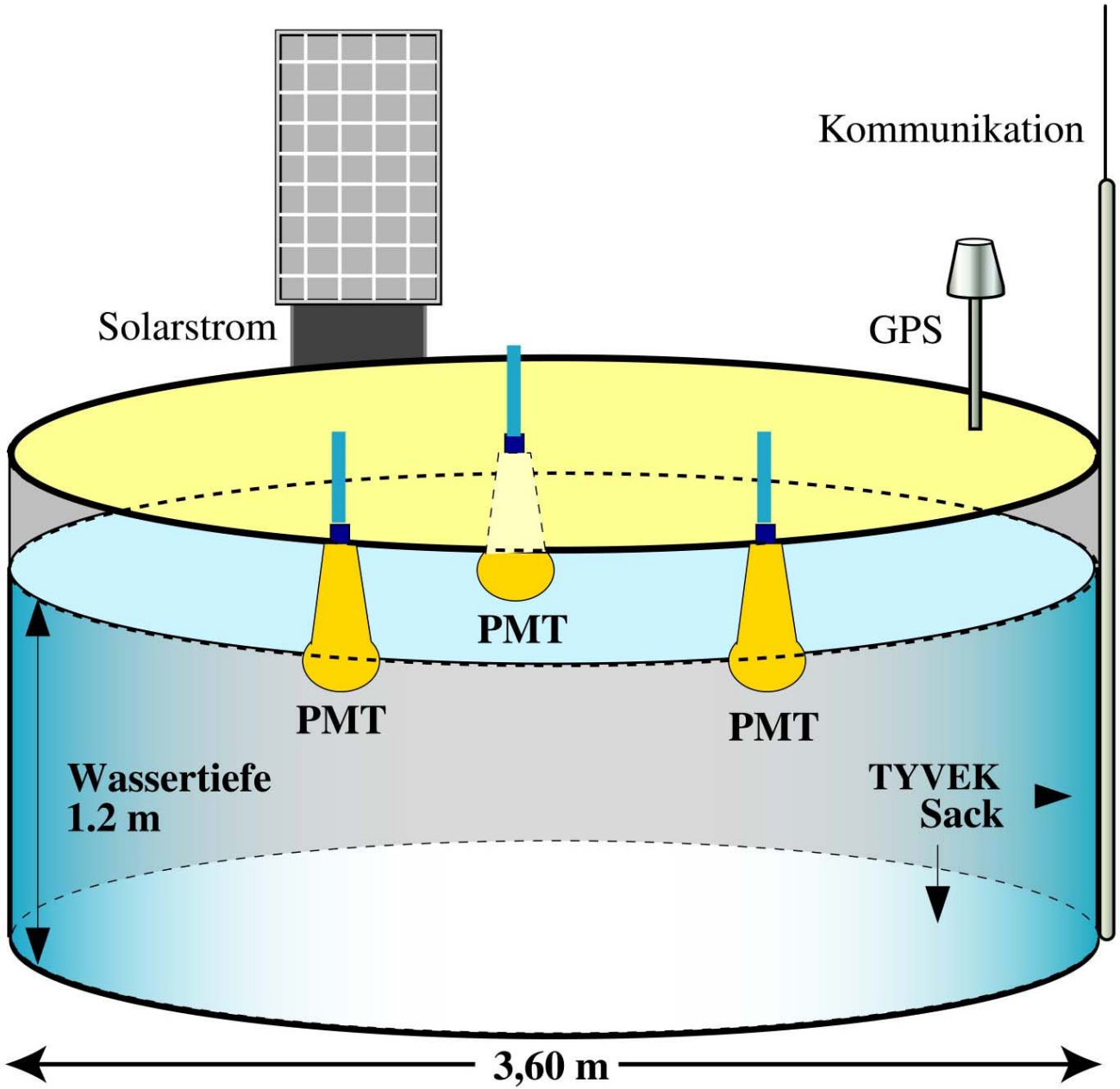
AGASA spectrum >> 100 events/yr above 10^{20} eV

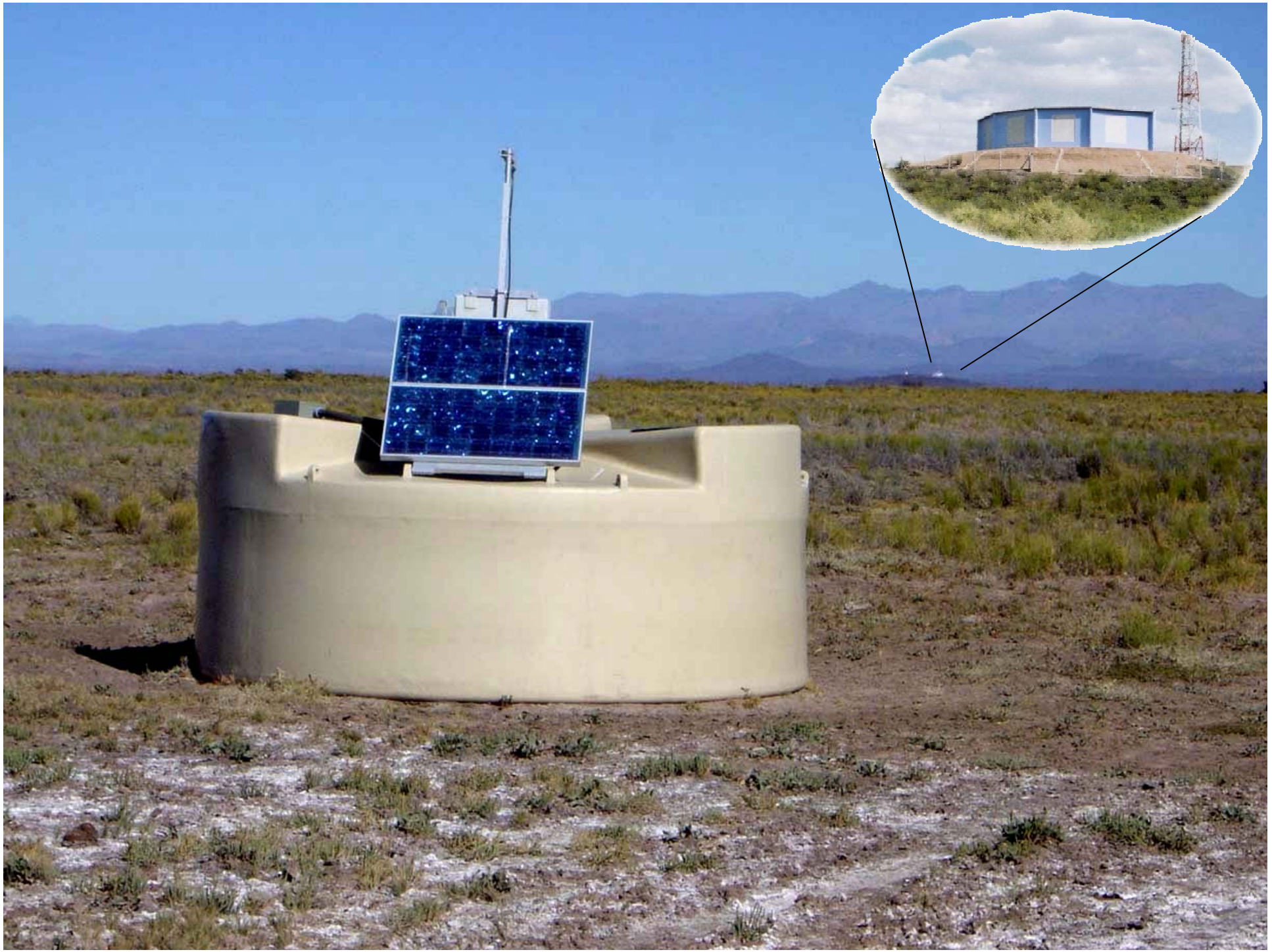


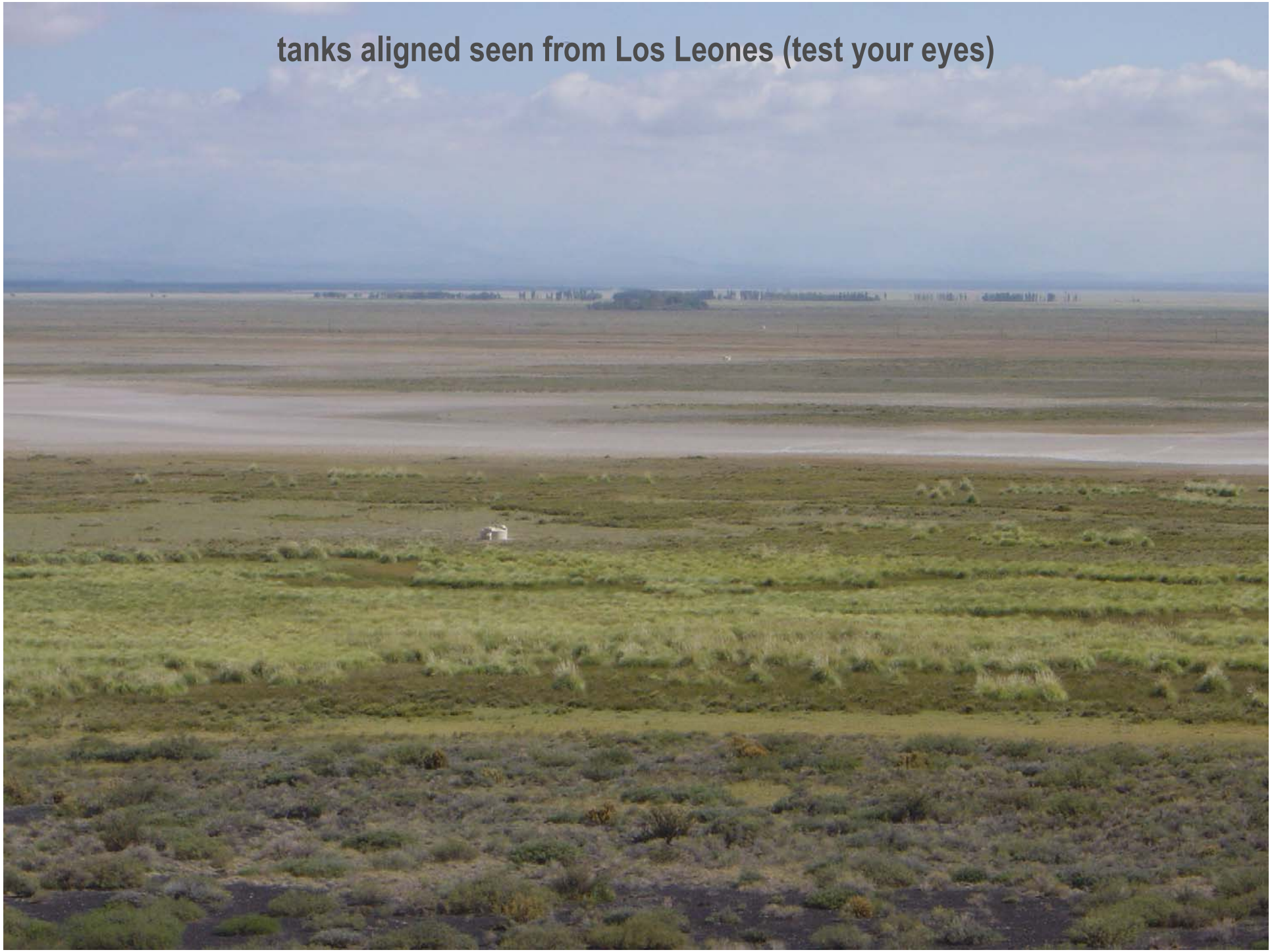
27 May 07

1408 tanks deployed, 1354 with water and 1279 with electronics

1600 water Cherenkov tanks make a surface array of >3000 km^2

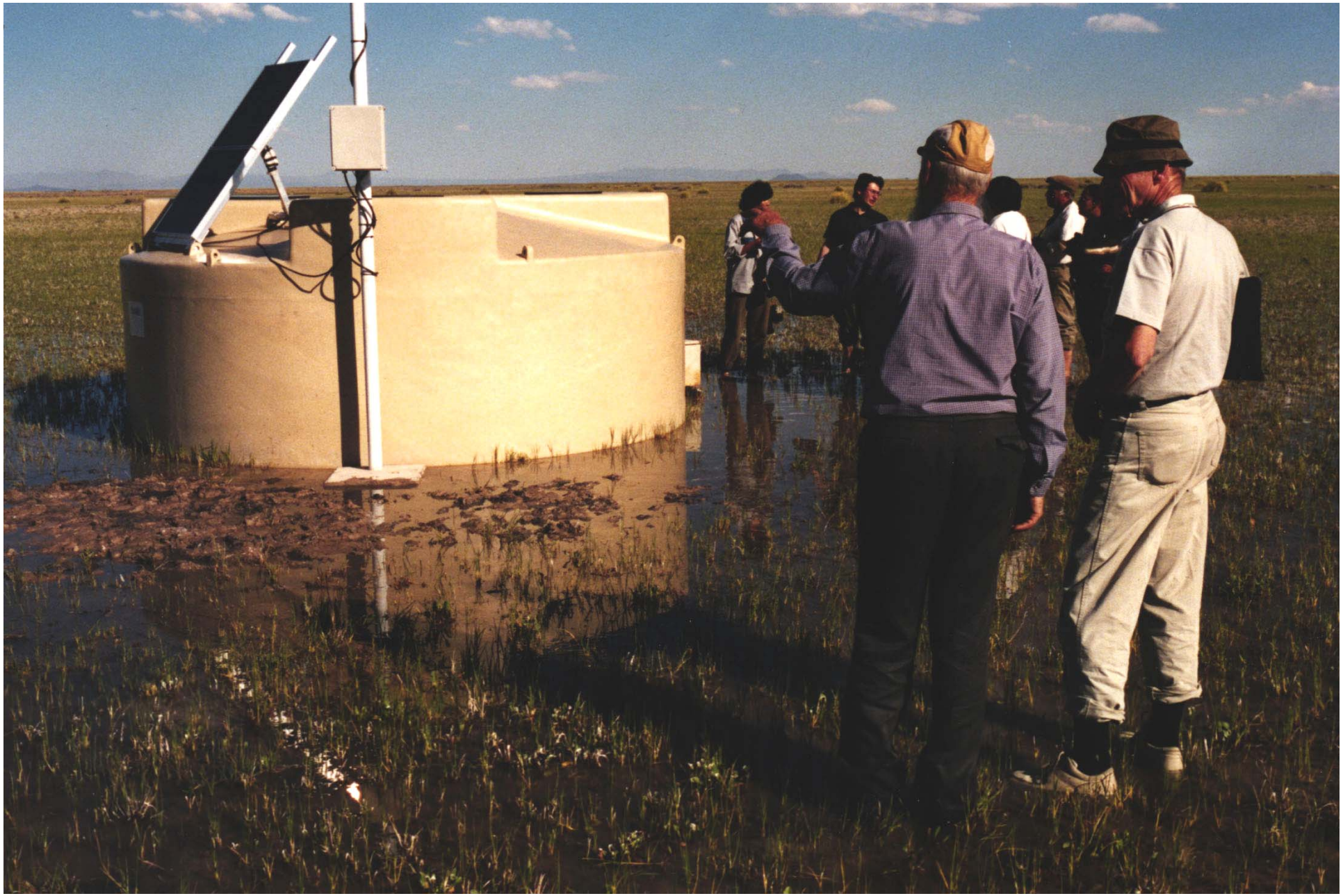





tanks aligned seen from Los Leones (test your eyes)


tanks aligned seen from Los Leones (zoomed)

the Pampa is wet without Auger tanks...

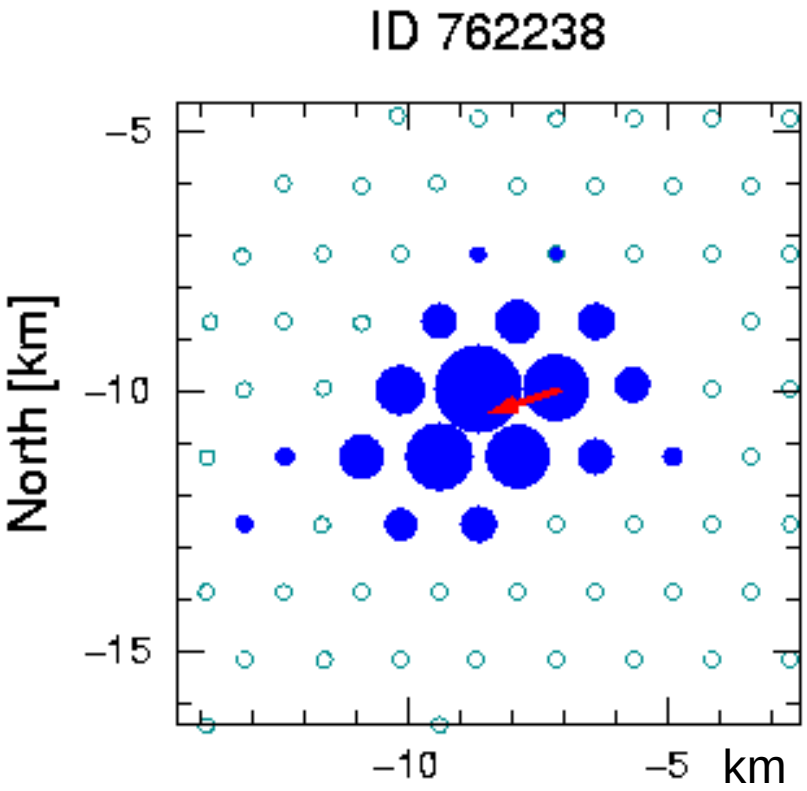



DAD

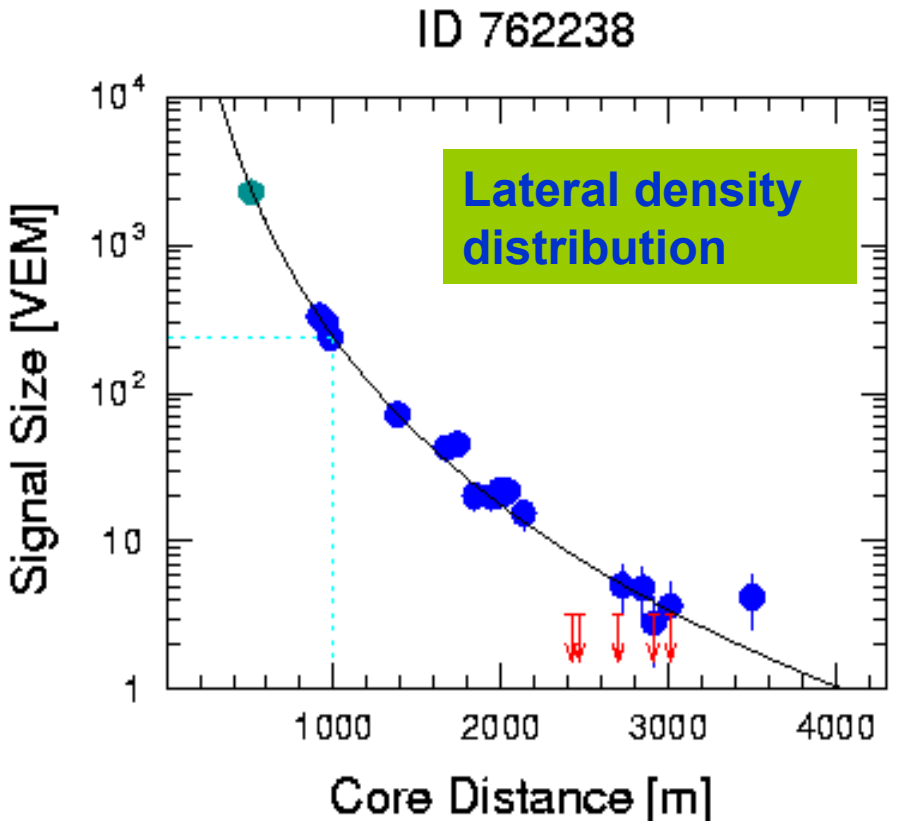
Auger webcam in the backyard: more tanks to go

- 15-20 tanks/week from 3 manufacturers
- assembly: more than four per day
- Water transport is up to four tanks per day.

θ~ 48º, ~ 70 EeV (7 x 10^{19} eV)



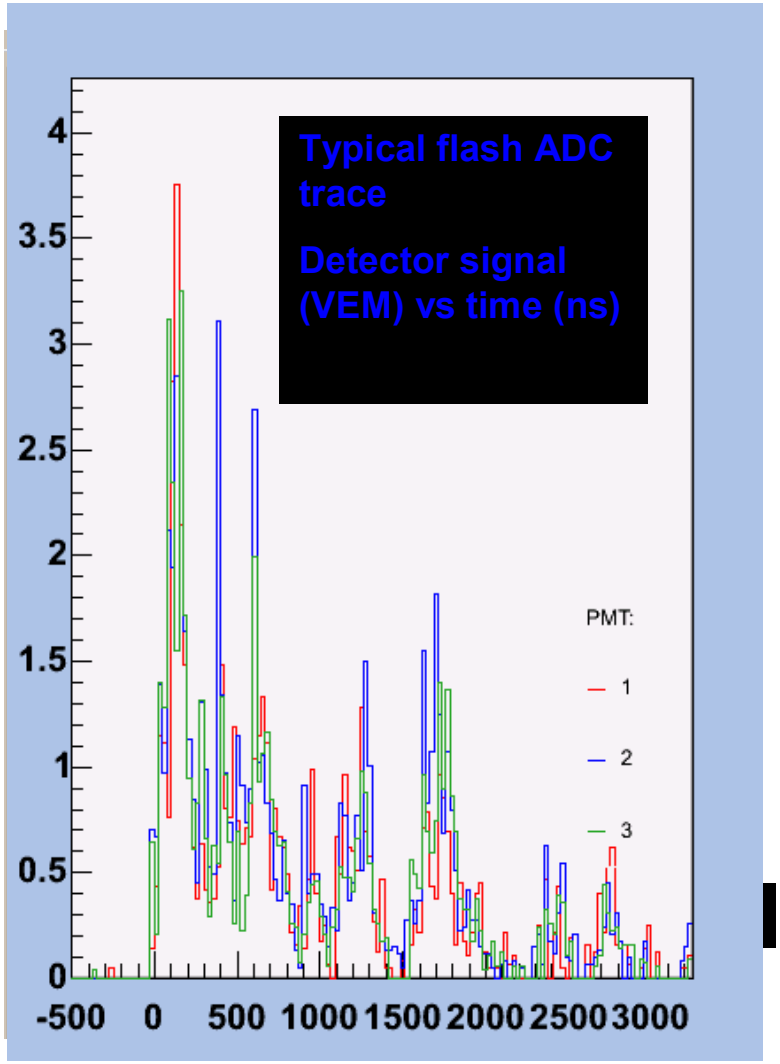
18 detectors triggered

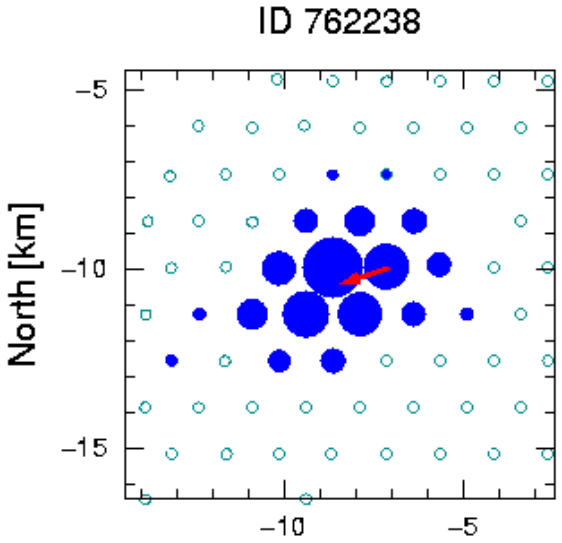


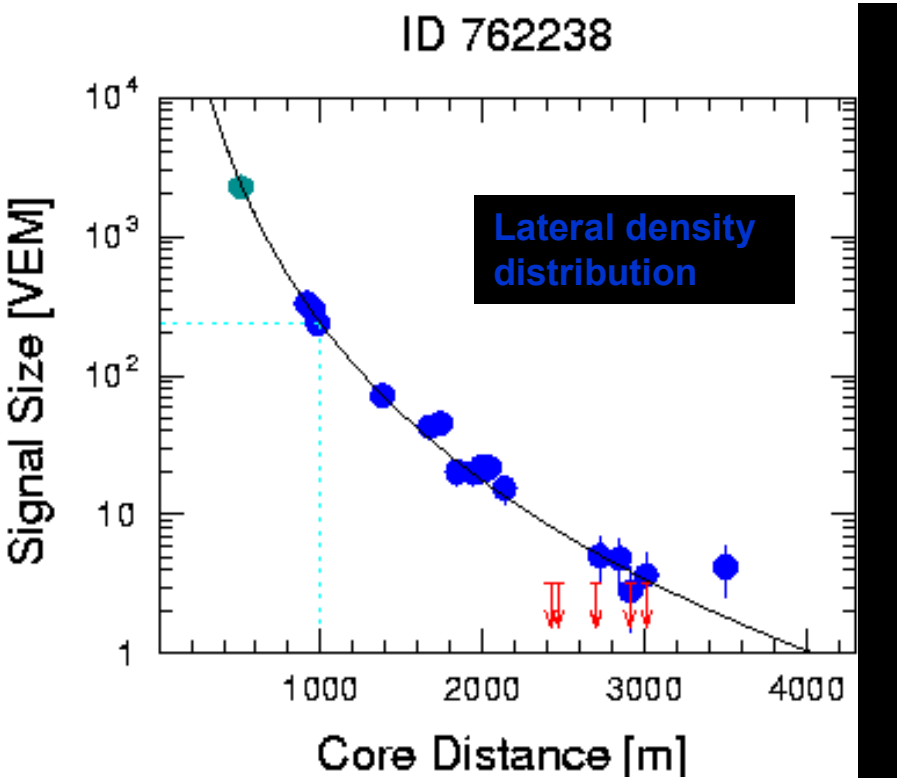
Example Event 1

A moderate angle event 762238

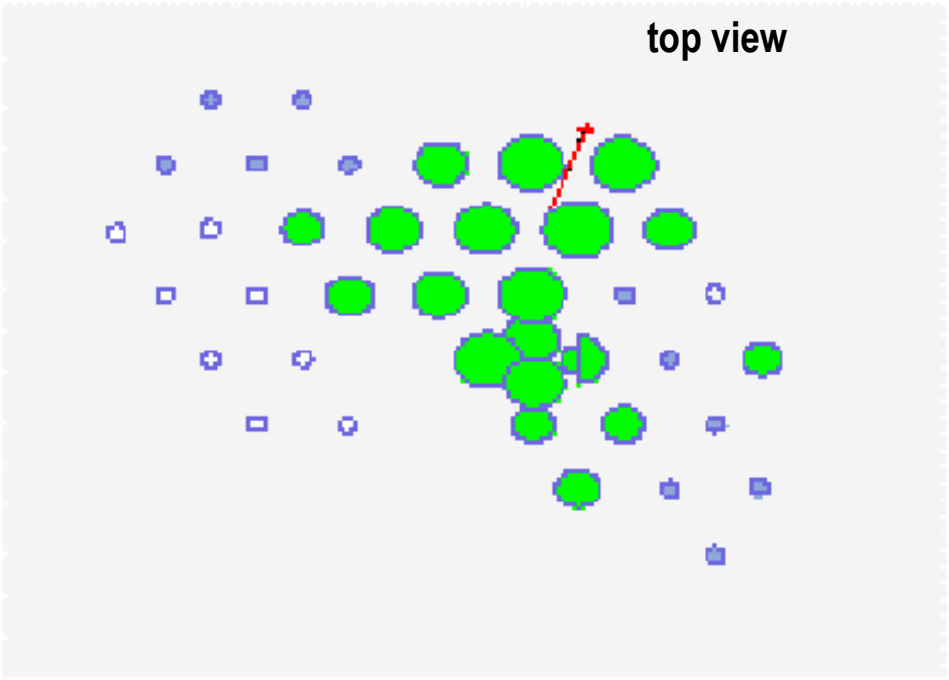
Zenith angle ~ 48º, Energy ~ 70 EeV

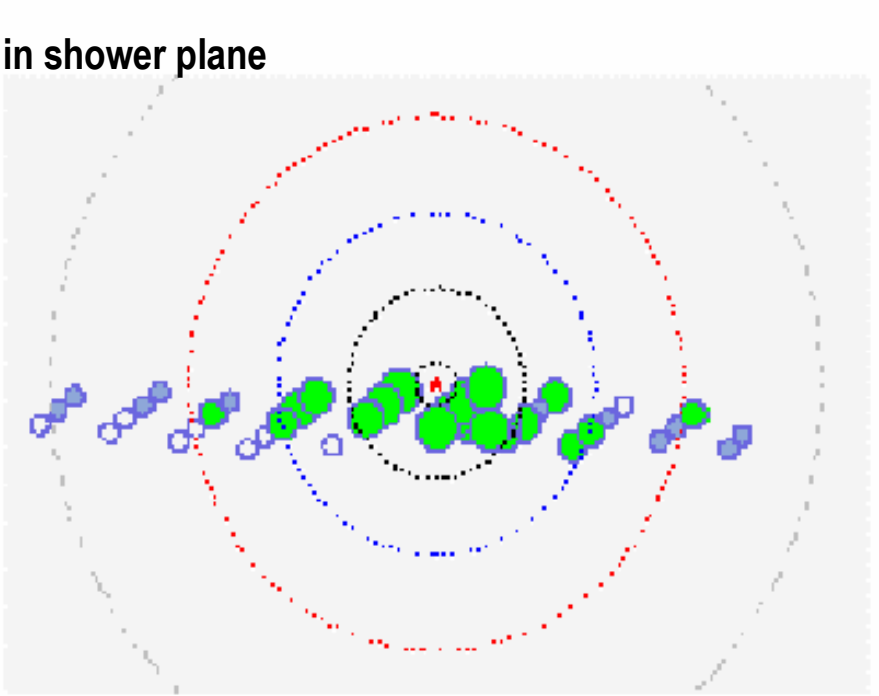




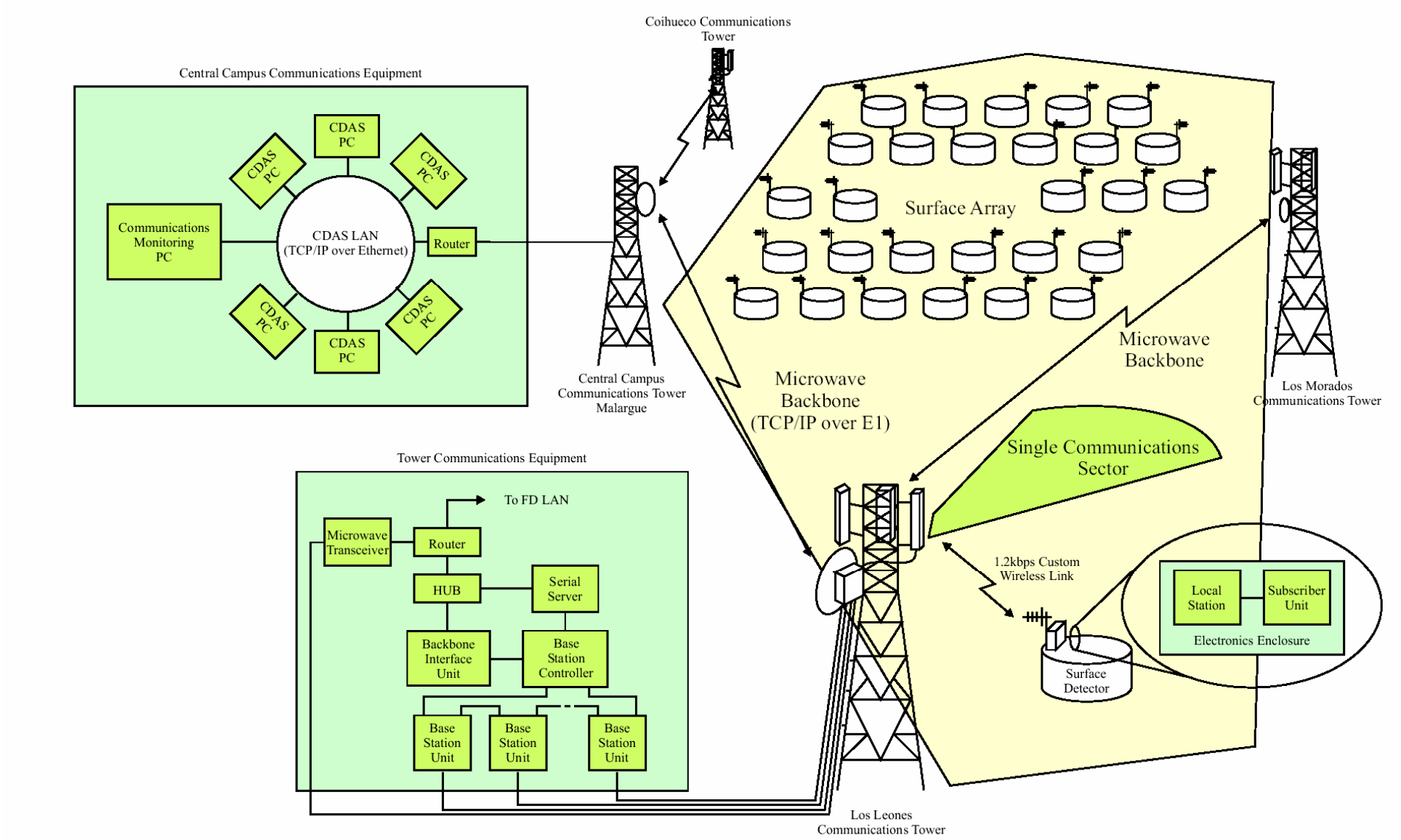


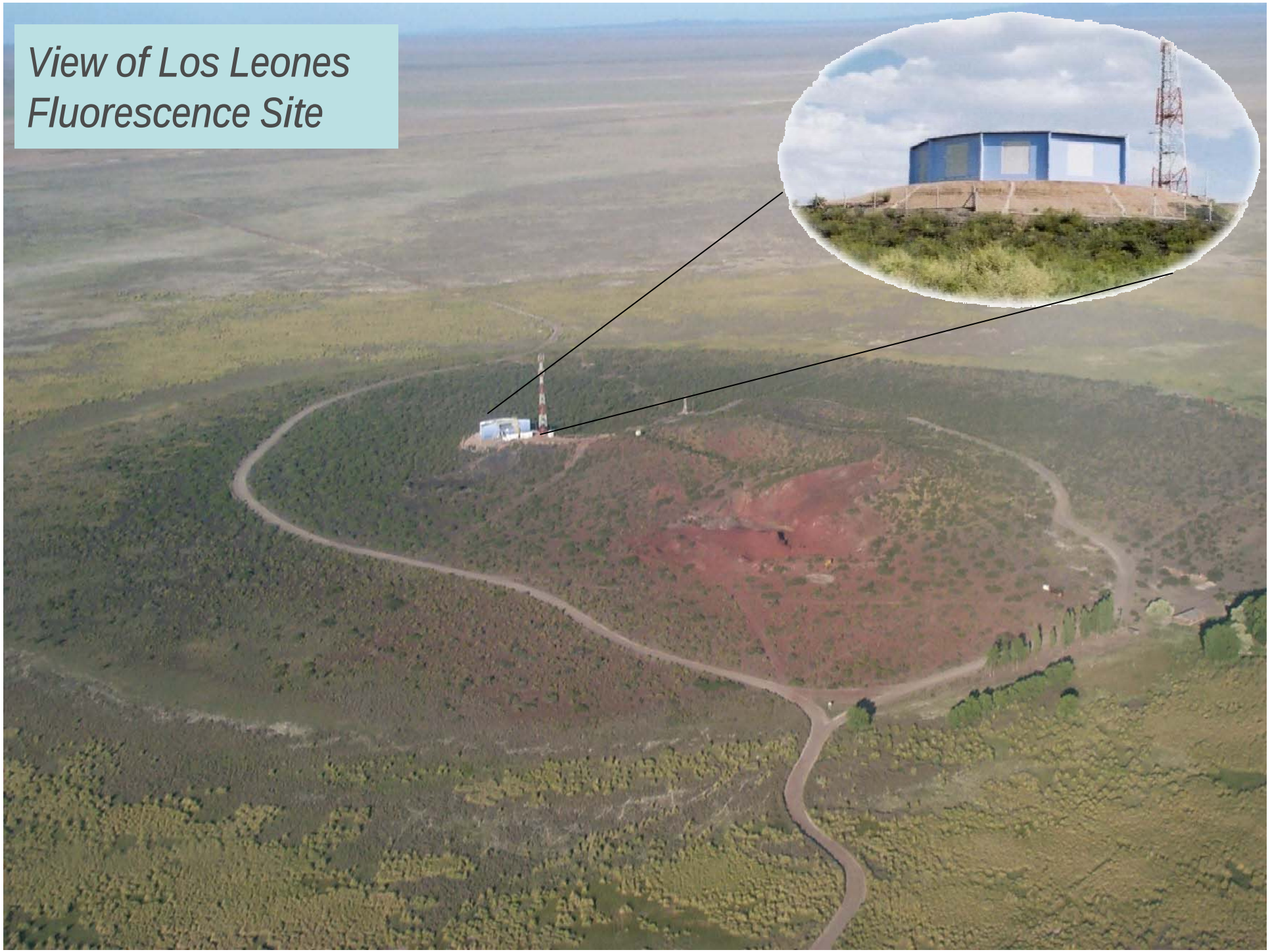
very inclined 20-tank event with 82° zenith angle...

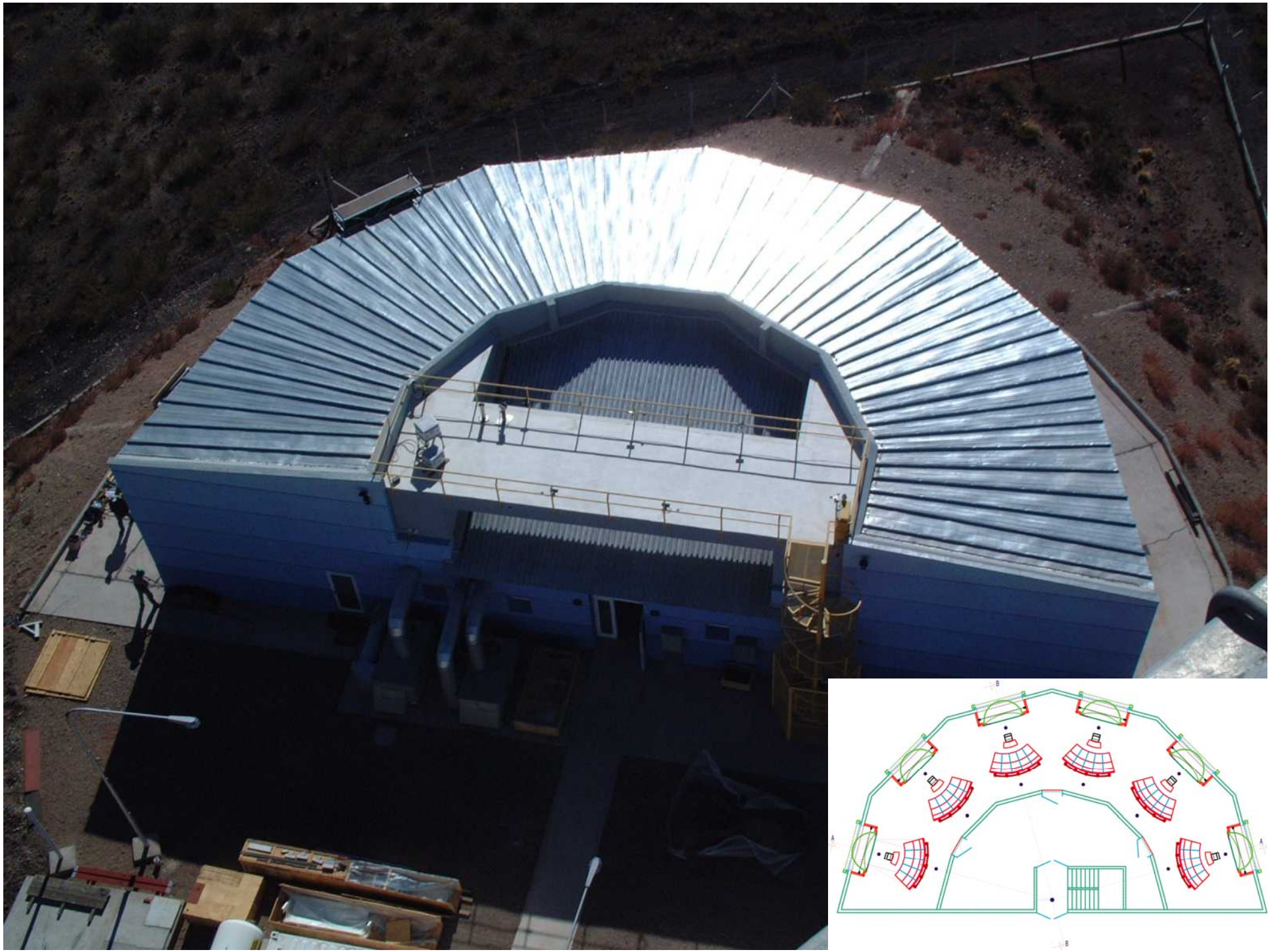


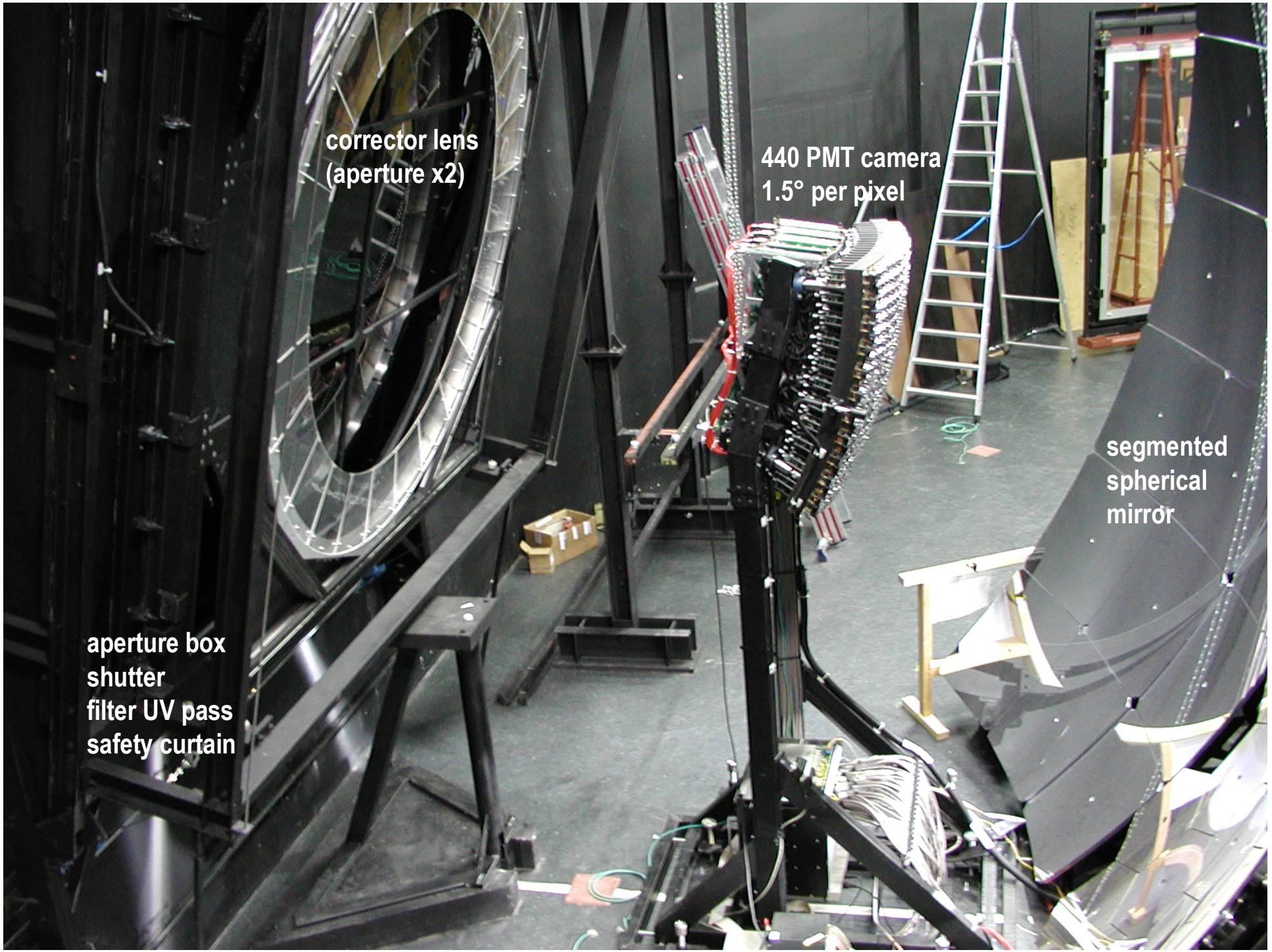


Telecommunication system

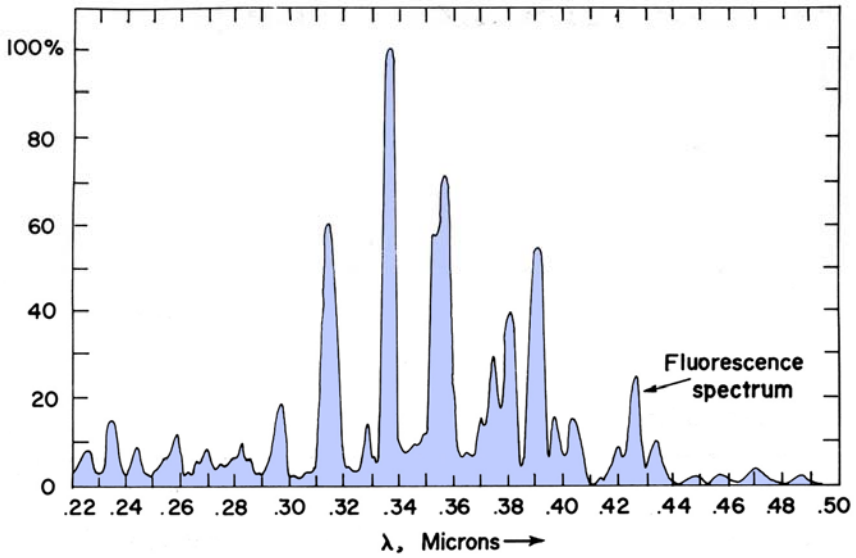



View of Los Leones
Fluorescence Site

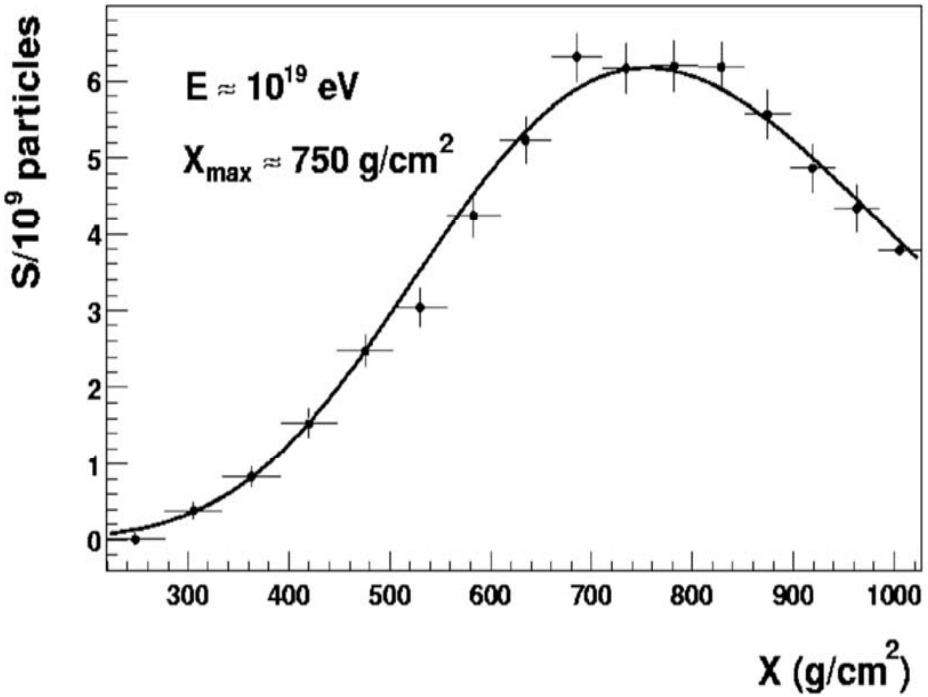


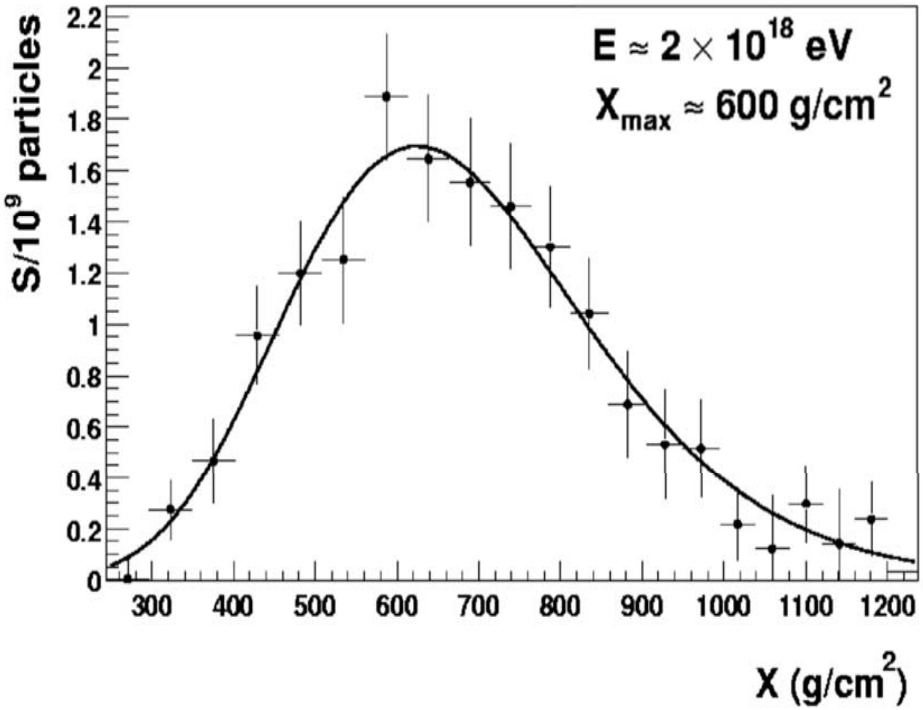

corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror
aperture box
shutter
filter UV pass
safety curtain

telescope calibration includes the atmosphere



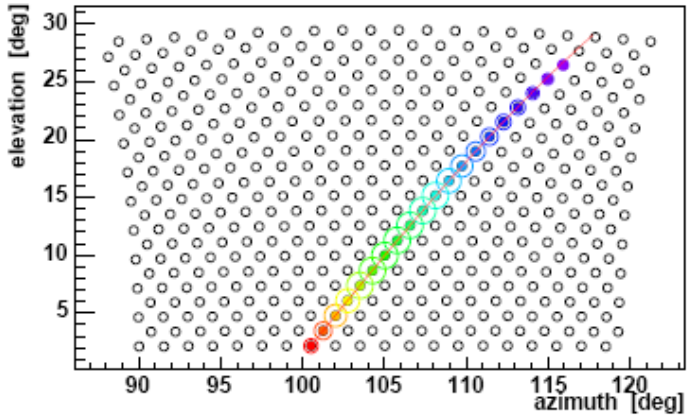
two sample profiles from the engineering array



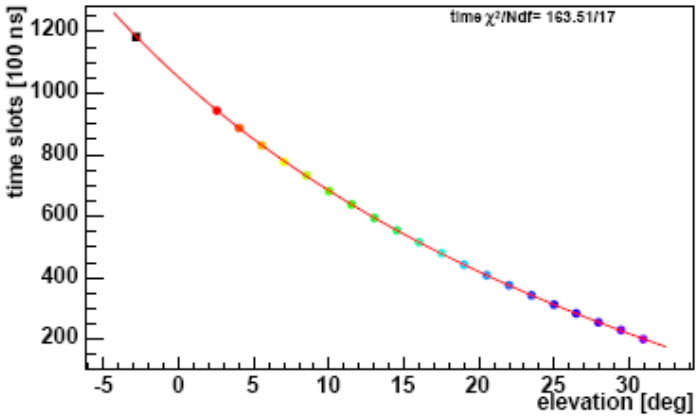


Coihueco Run 1187 Event 564

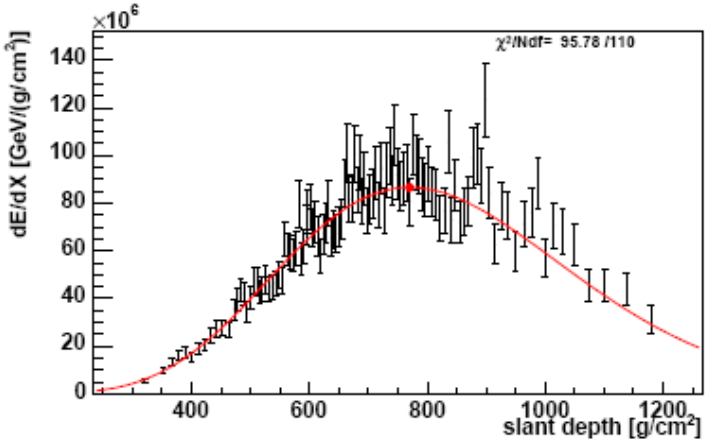
SDP fit



Axis fit



energy deposit



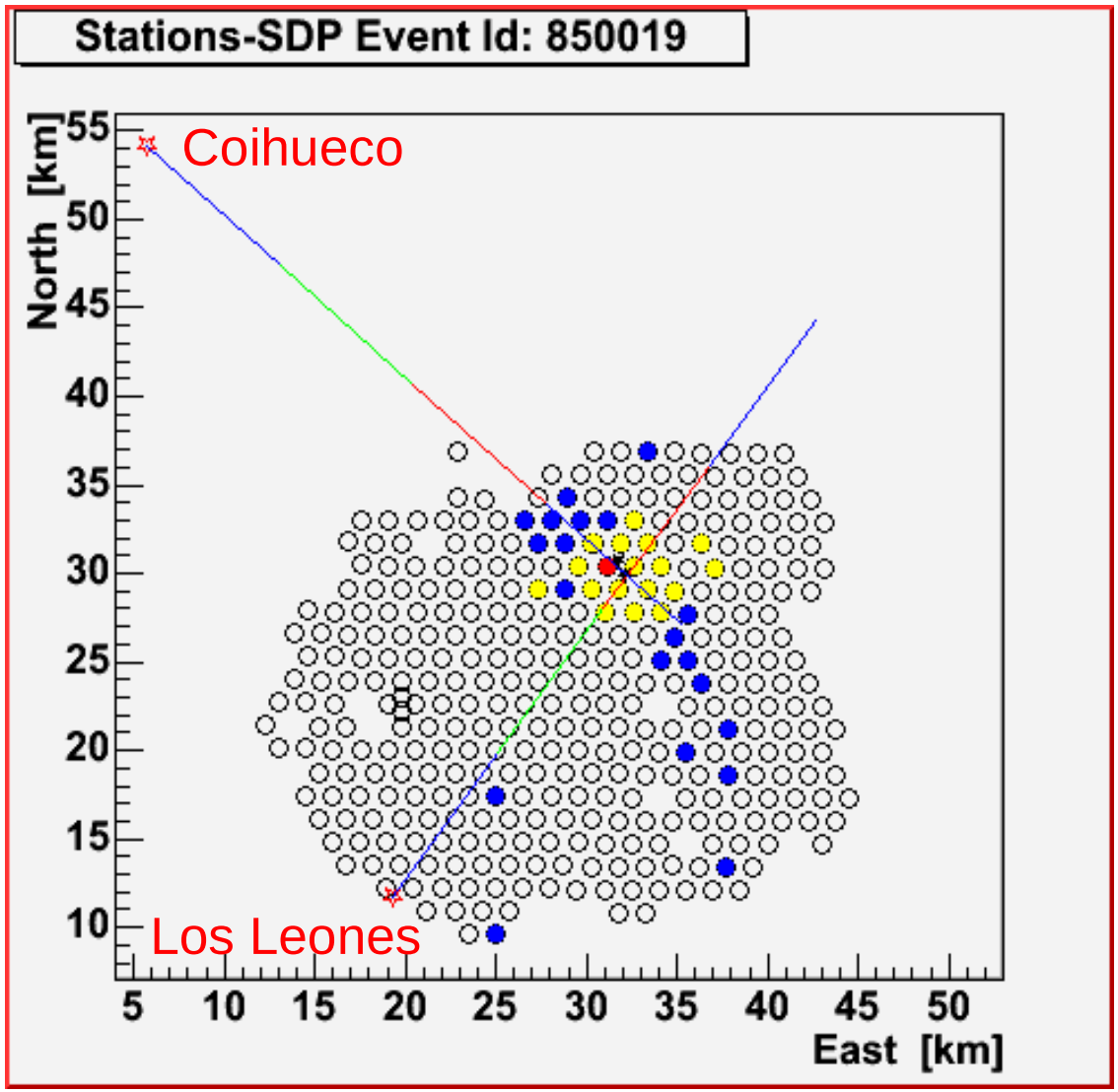
Run 1187 Event 564
time stamp: 807699612 s 735072804 ns
UTC date: 2005-08-10 08:59:59
in Coiheco mirror 4 (in DAQ: 1 2 3 4 5 6)
T3 Id 4164
Event type: 'Physics - Int or L/R trigger'
Event class: 'Shower Candidate'

lg(E/eV)=19.76 ± 0.01
Xmax =769.82 ± 5.40 g/cm^2
X0 =-113.23 ± 57.59 g/cm^2
λ =67.29 ± 6.21 g/cm^2
dEdXmax =86.57 ± 1.30 PeV/g/cm^2

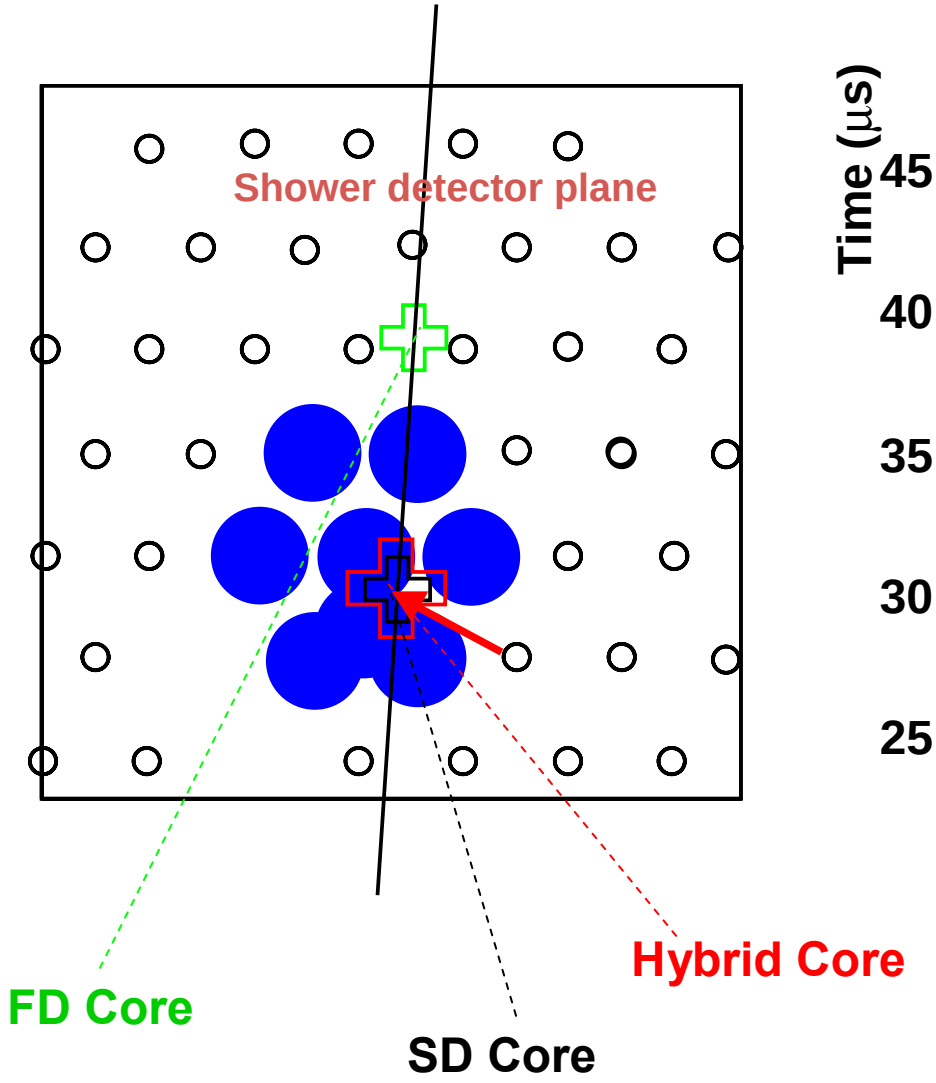
(θ,φ)=(51.58, 134.68) deg.
(x,y)=(36.45, 44.29) km
dca to Eye=23.25 ± 0.03 km

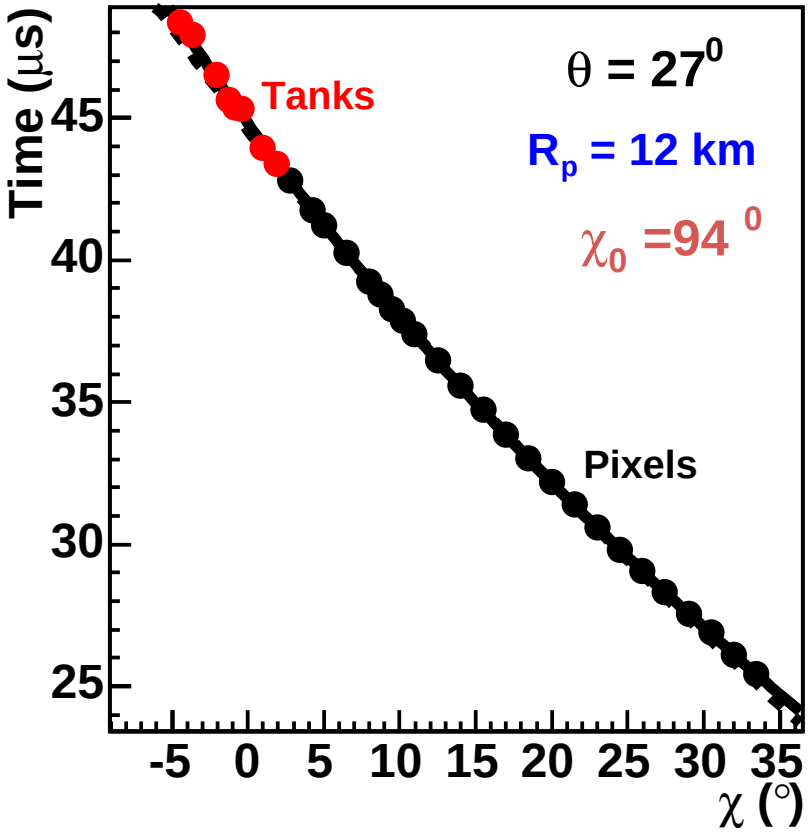
A stereo-hybrid event

- An example of an event seen by Los Leones and Coihueco FD eyes, and the SD
- June 26 2004
- by definition high energy (to be seen by Coihueco)

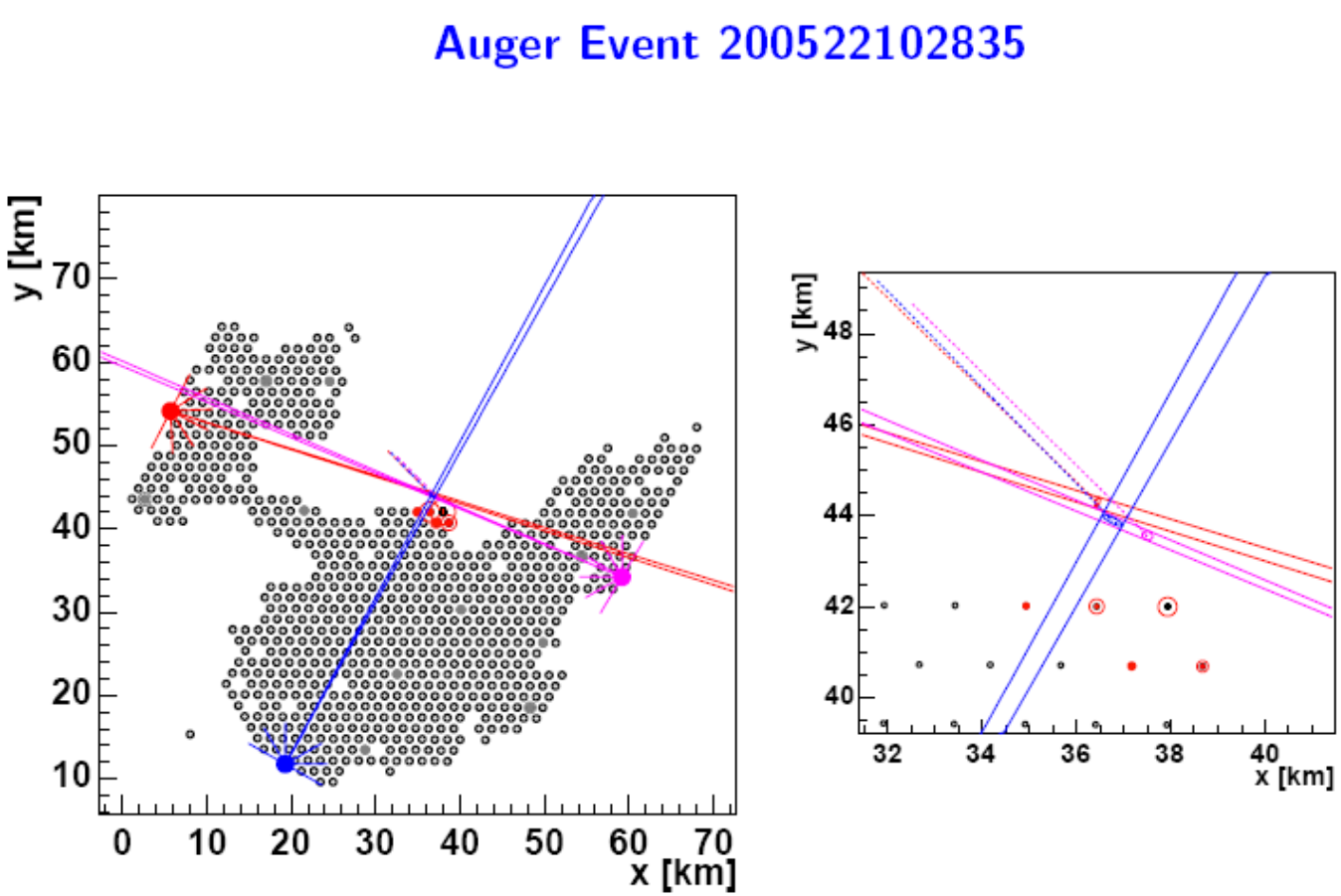


10.2 EeV Hybrid event





An event seen by three fluorescence telescopes (10 August 2005)



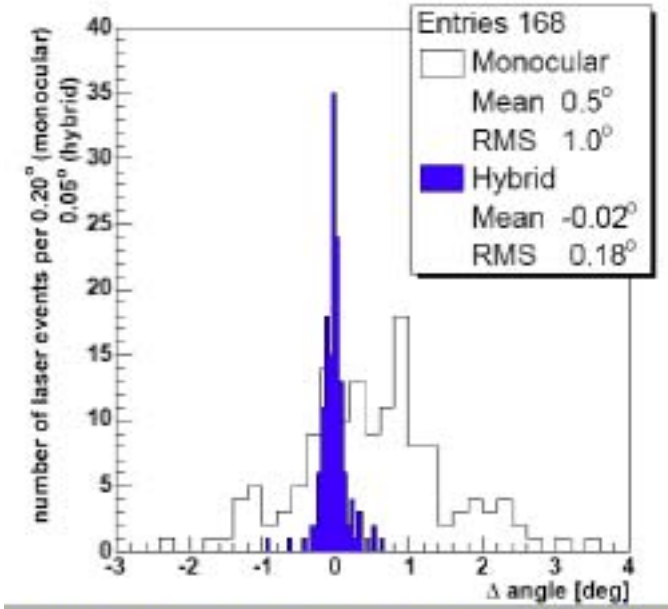
Angular Resolution

Surface Detectors

determined by timing uncertainties (~ 12 ns)

< 1° E > 10EeV

A.R. (68% CL)	# of tanks	Typical if
< 2.2°	3	E < 3 EeV
< 1.7°	4	3 EeV < E < 8 EeV
< 1.4°	5 or more	E > 8 EeV

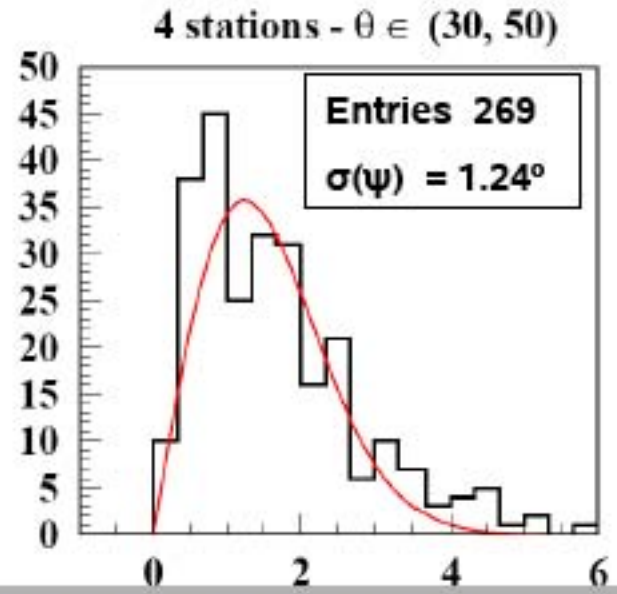


Angle in laser beam /FD detector plane

Hybrid events

0.6° (mean)

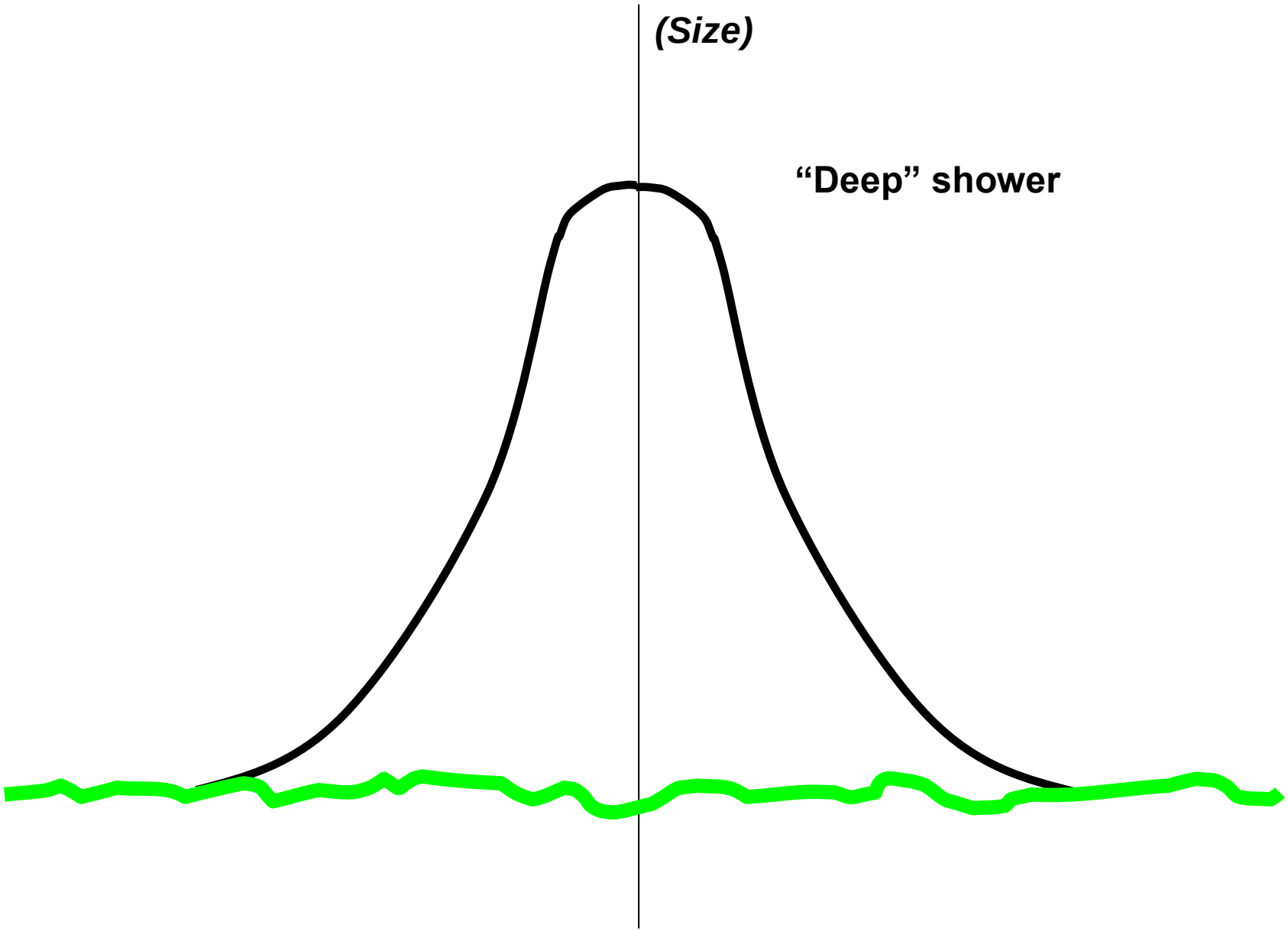
Consistency →

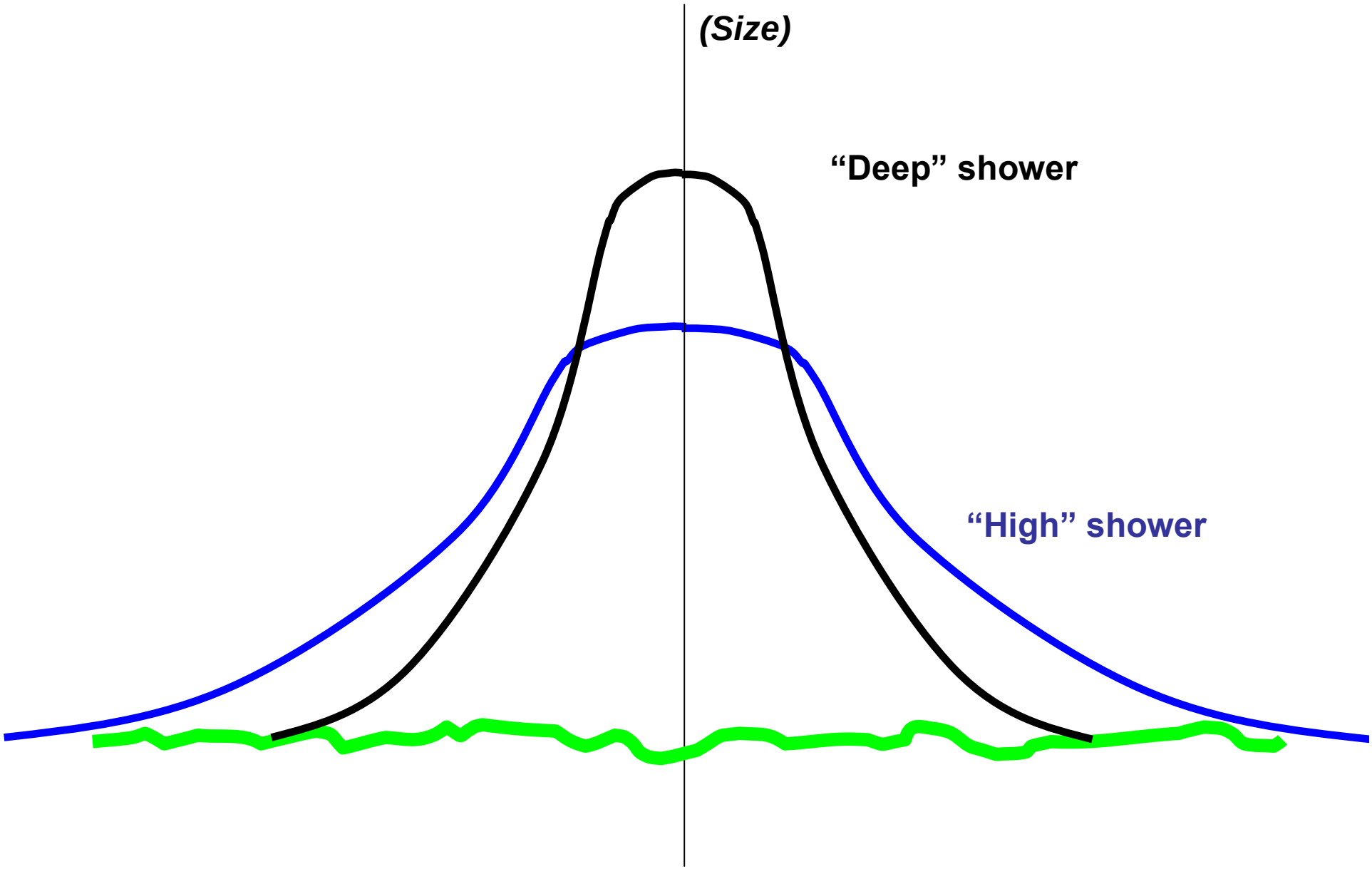


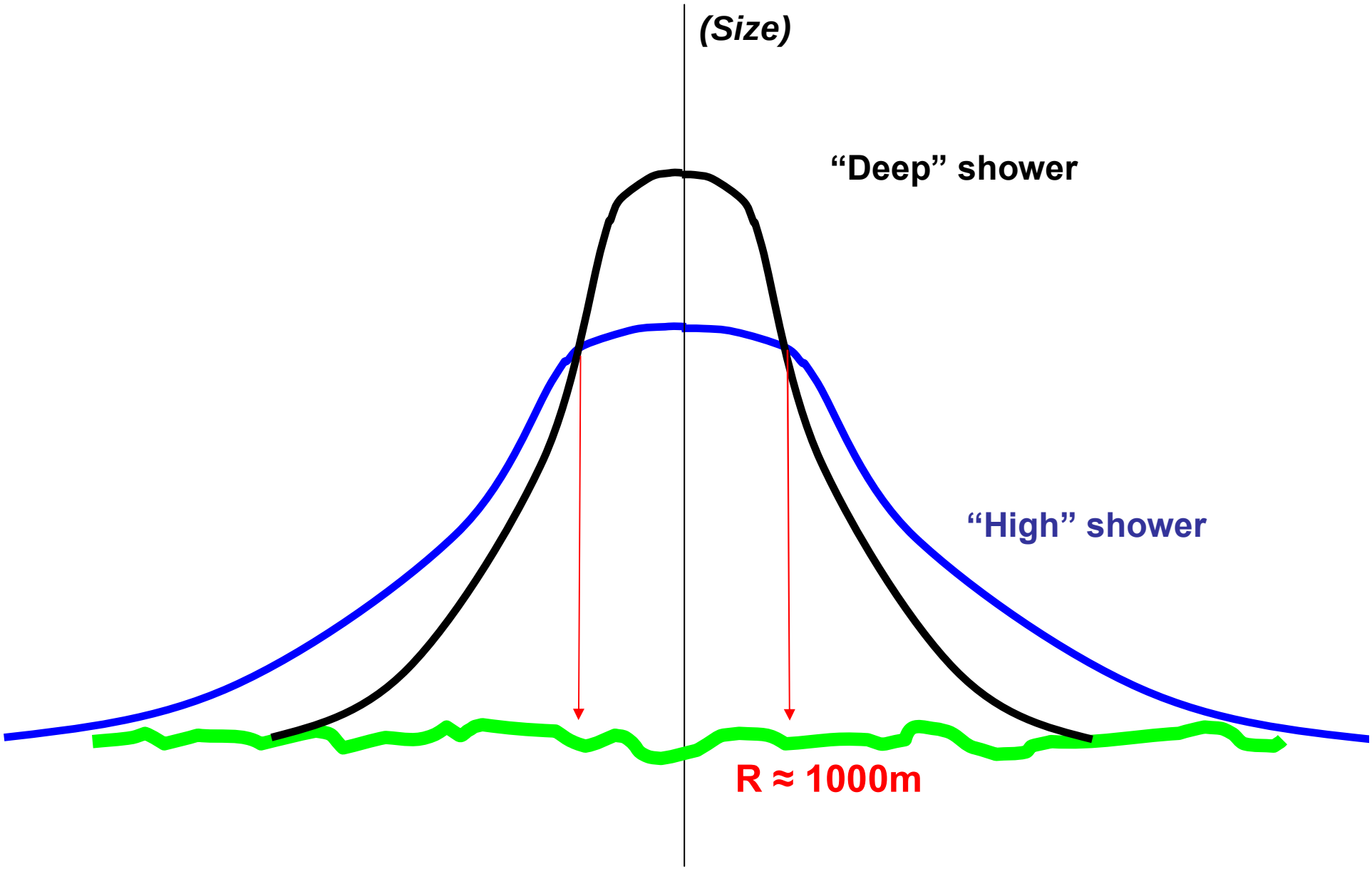
Hybrid-SD only space angle difference

There are two ways to obtain the energy of an event:

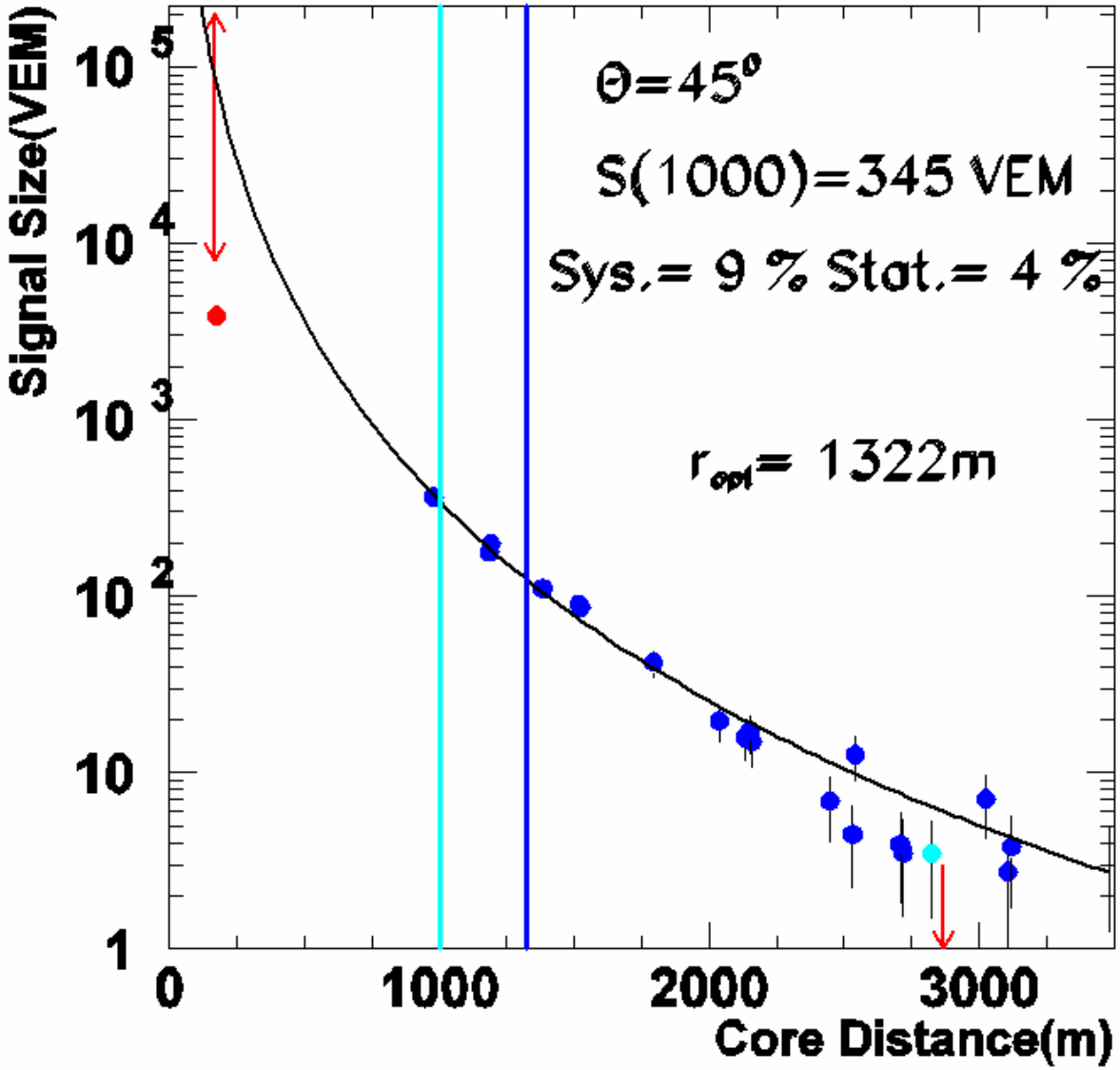
1. **By simulation of air showers and surface detectors**. *Needs careful Monte Carlo, including particle physics beyond where accelerator data give guidance.*
2. **By connecting Fluorescence energy with Surface size**. *Very nearly "model independent", since FD gives a calorimetric determination of energy. But note that only about 10% of events are measured by both SD and FD*

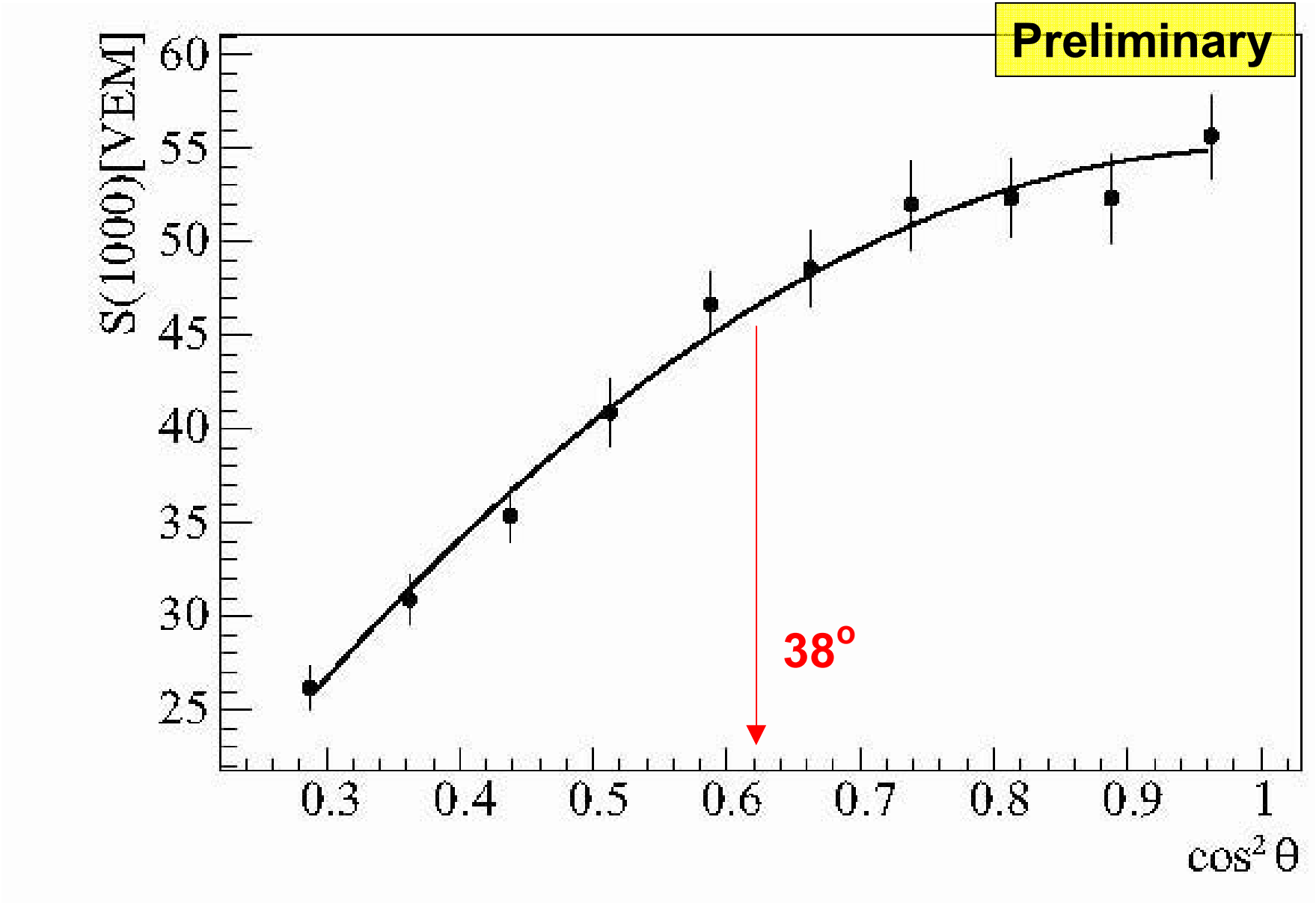

(Size)
“Deep” shower

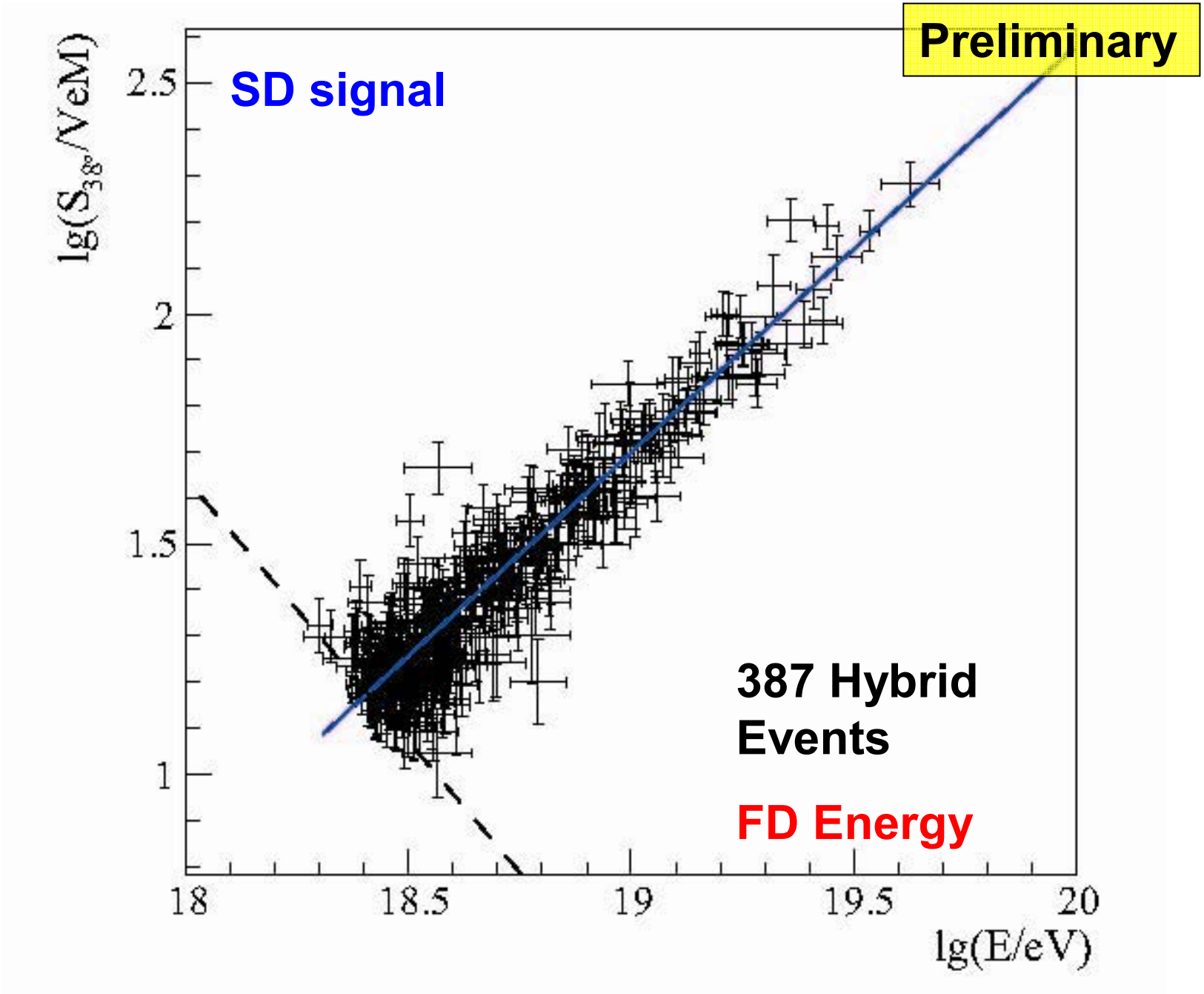

(Size)
“Deep” shower
“High” shower


(Size)
“Deep” shower
“High” shower
R ≈ 1000m

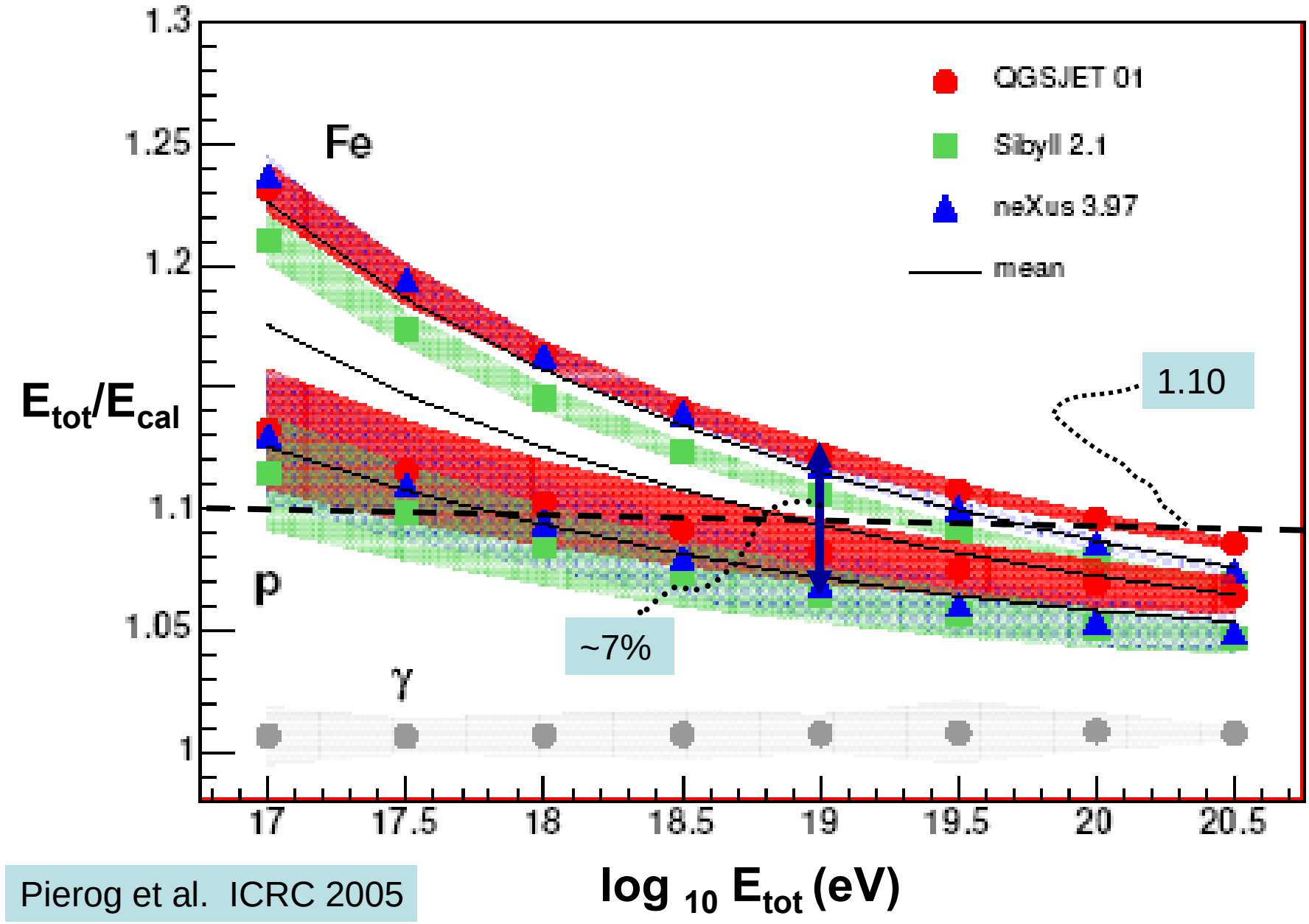
1096757-- 86 EeV




Preliminary
S(1000)[VEM]
60
55
50
45
40
35
30
25
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
cos² θ
38°


Preliminary
SD signal
lg(S38°/VeM)
2.5
2
1.5
1
18
18.5
19
19.5
20
lg(E/eV)
387 Hybrid Events
FD Energy

Ratio of total energy to electromagnetic energy for fluorescence detector

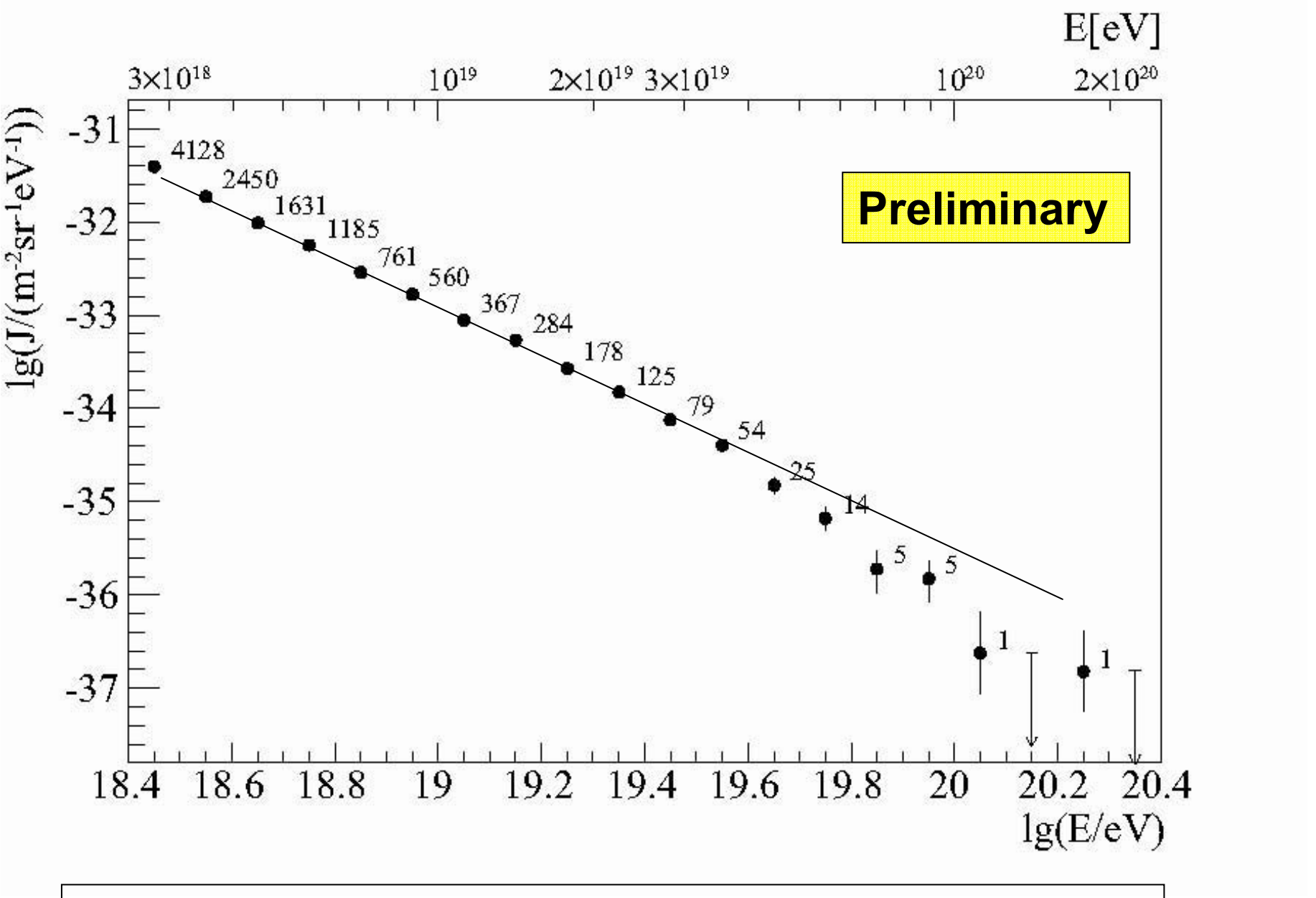


Pierog et al. ICRC 2005

Spectrum data set: 1 January 2004 through 28 February 2007.

Integrated exposure: 5165 km^2 sr year

(~ 3 x AGASA or our 2005 Pune ICRC Report)



Statistical uncertainty shown (systematic ~ 22%)

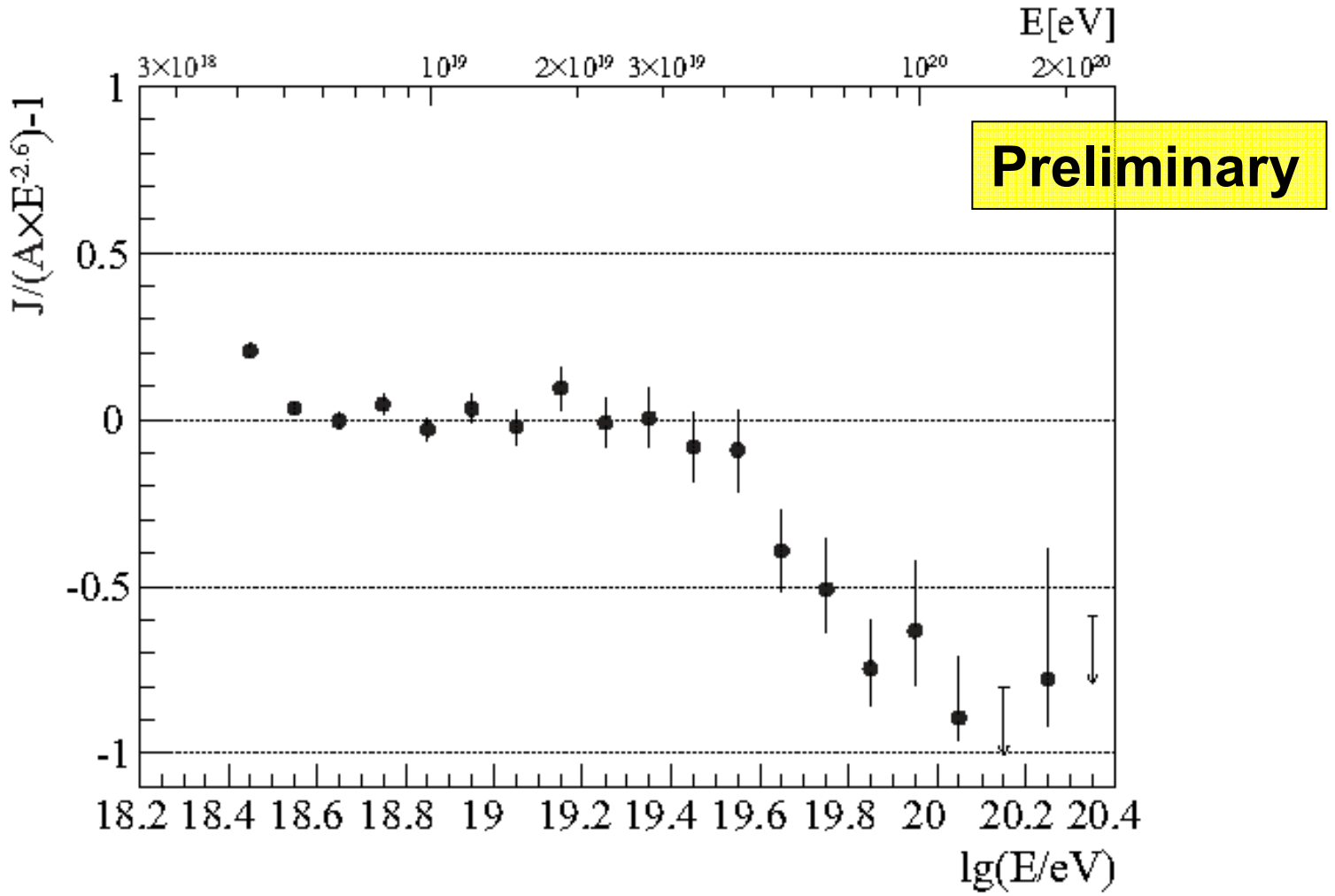
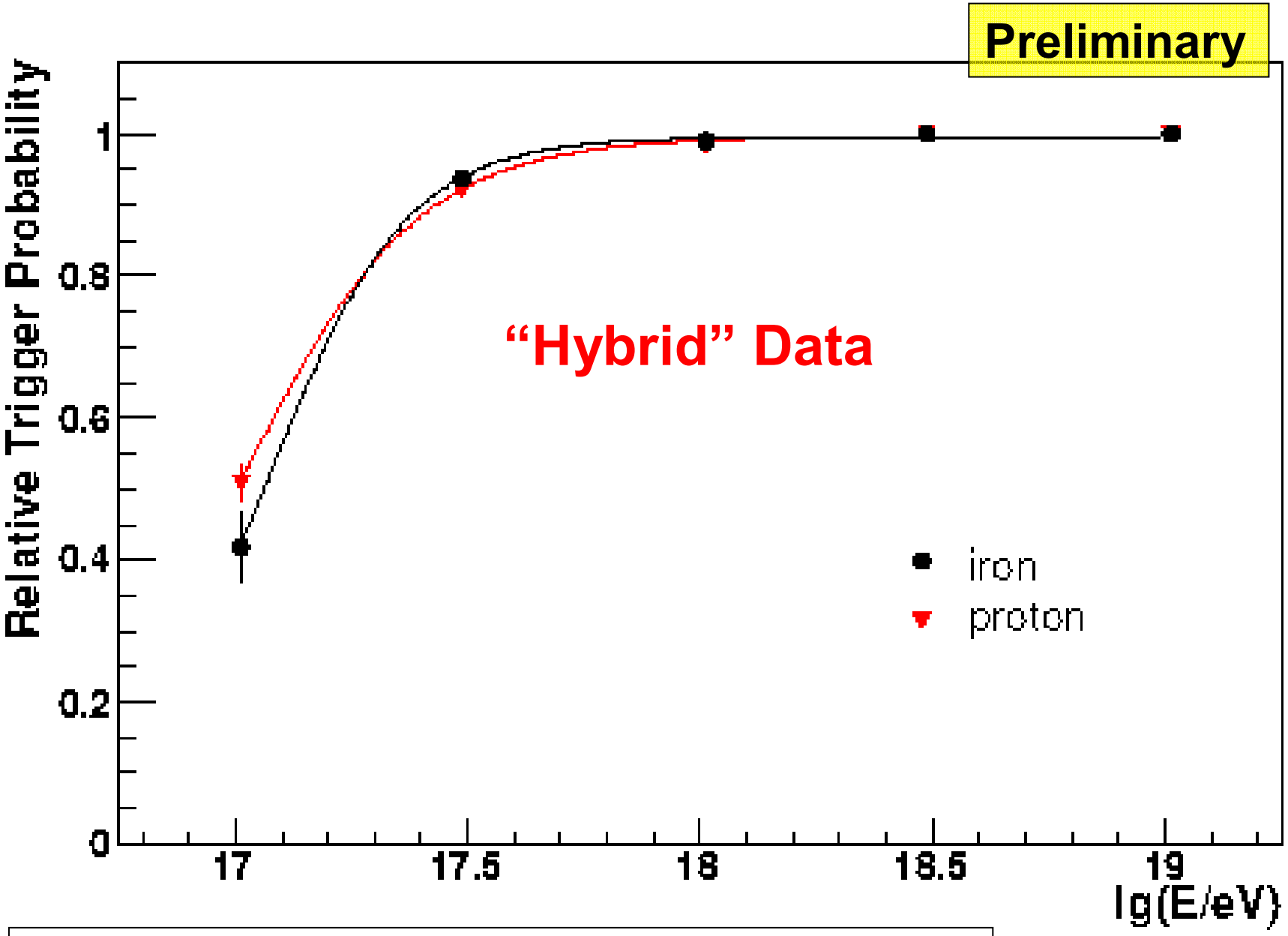


Figure 6: Fractional difference between the derived spectrum and an assumed flux $\propto E^{-2.6}$ as a function of energy.

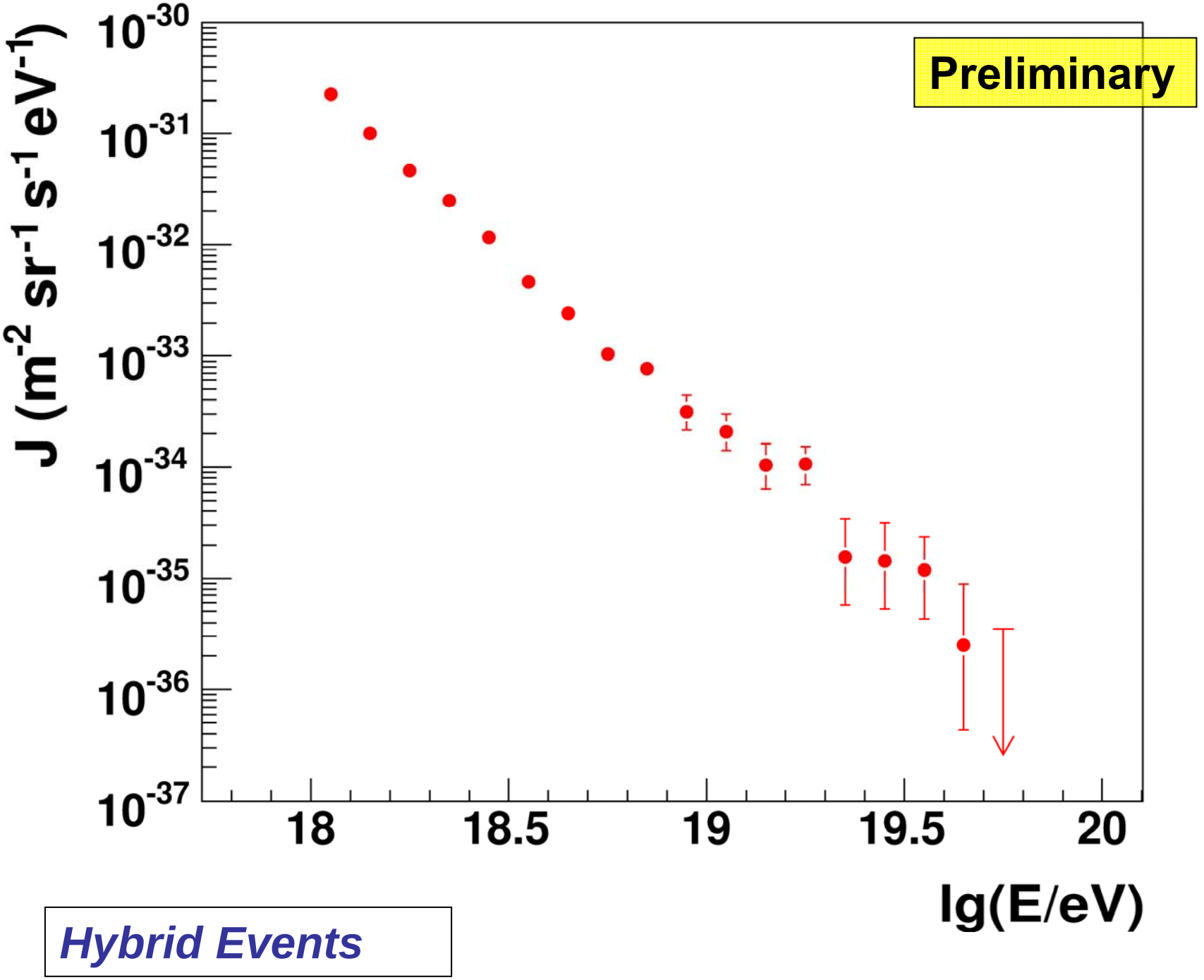
Systematic Energy uncertainty of 22% dominated by

Fluorescence Yield (~14%)

S(1000) vs. E fit (~10%)



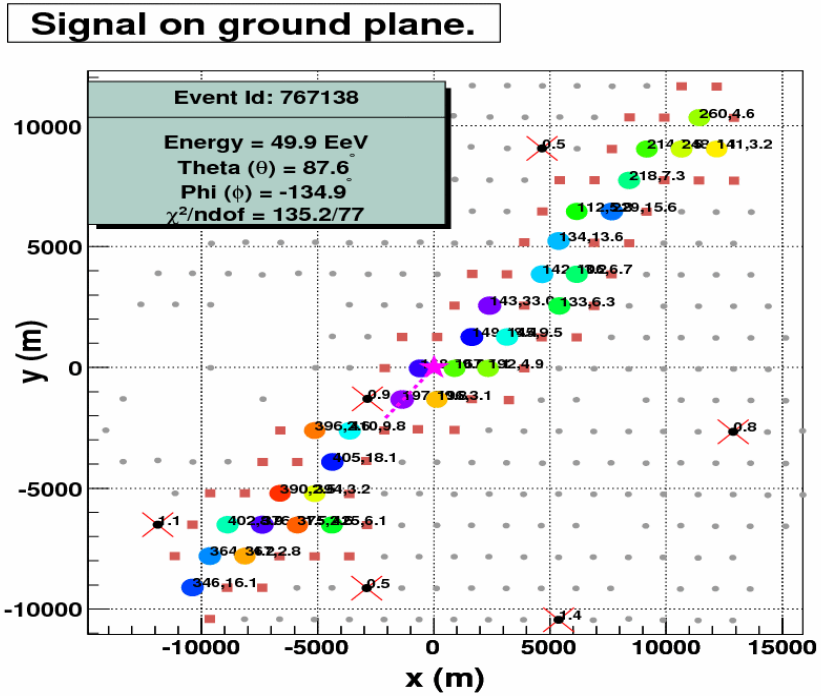
FD Triggers with one or more SD tanks

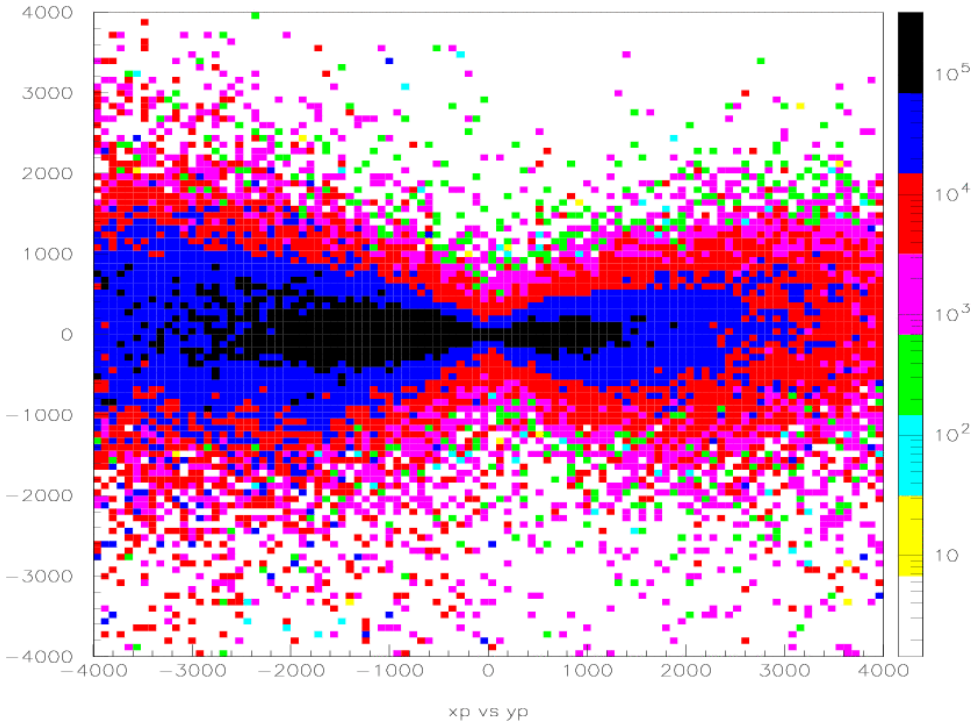


Hybrid Events

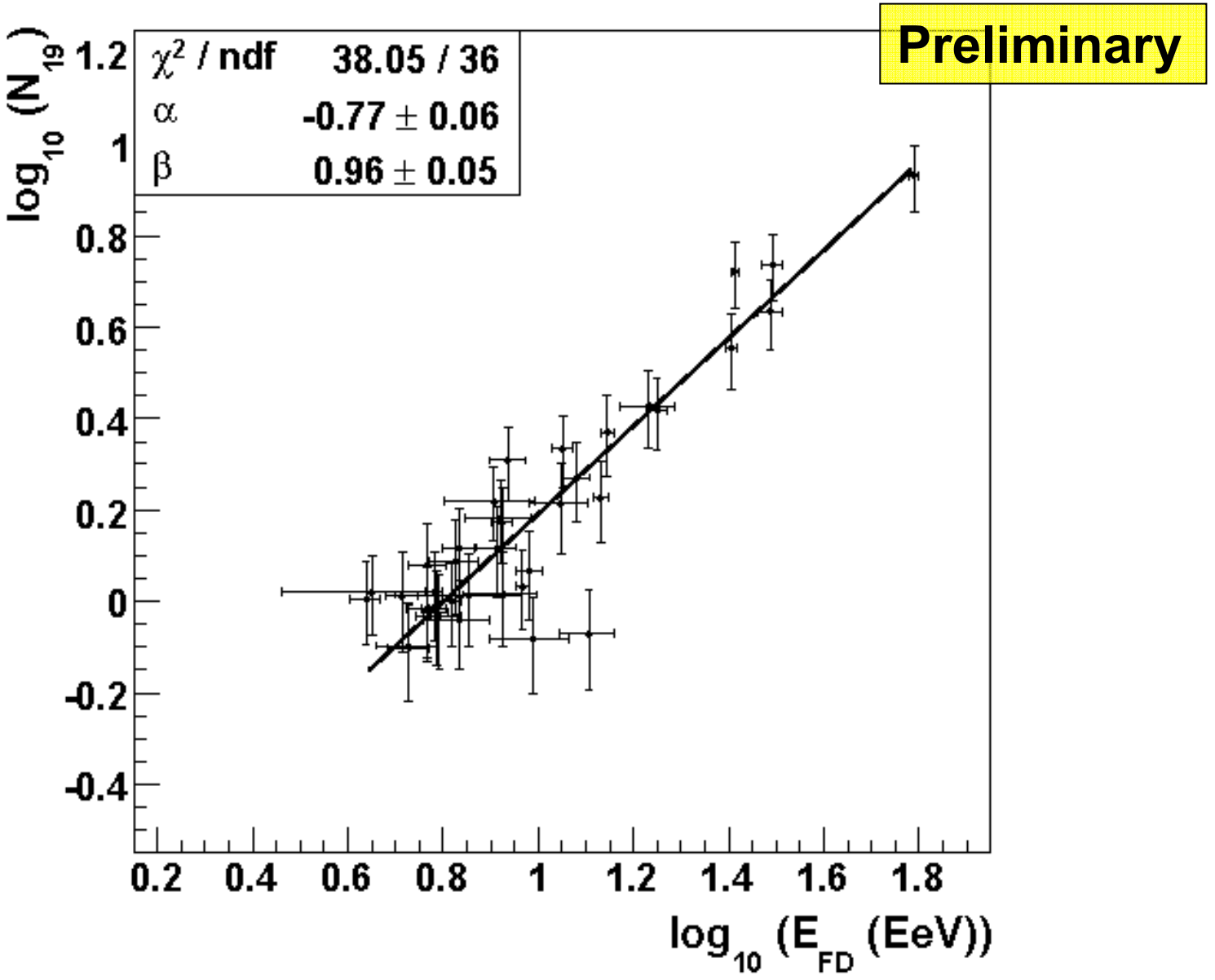
Highly inclined events (> 60^o) ... mostly muons

Event 767138

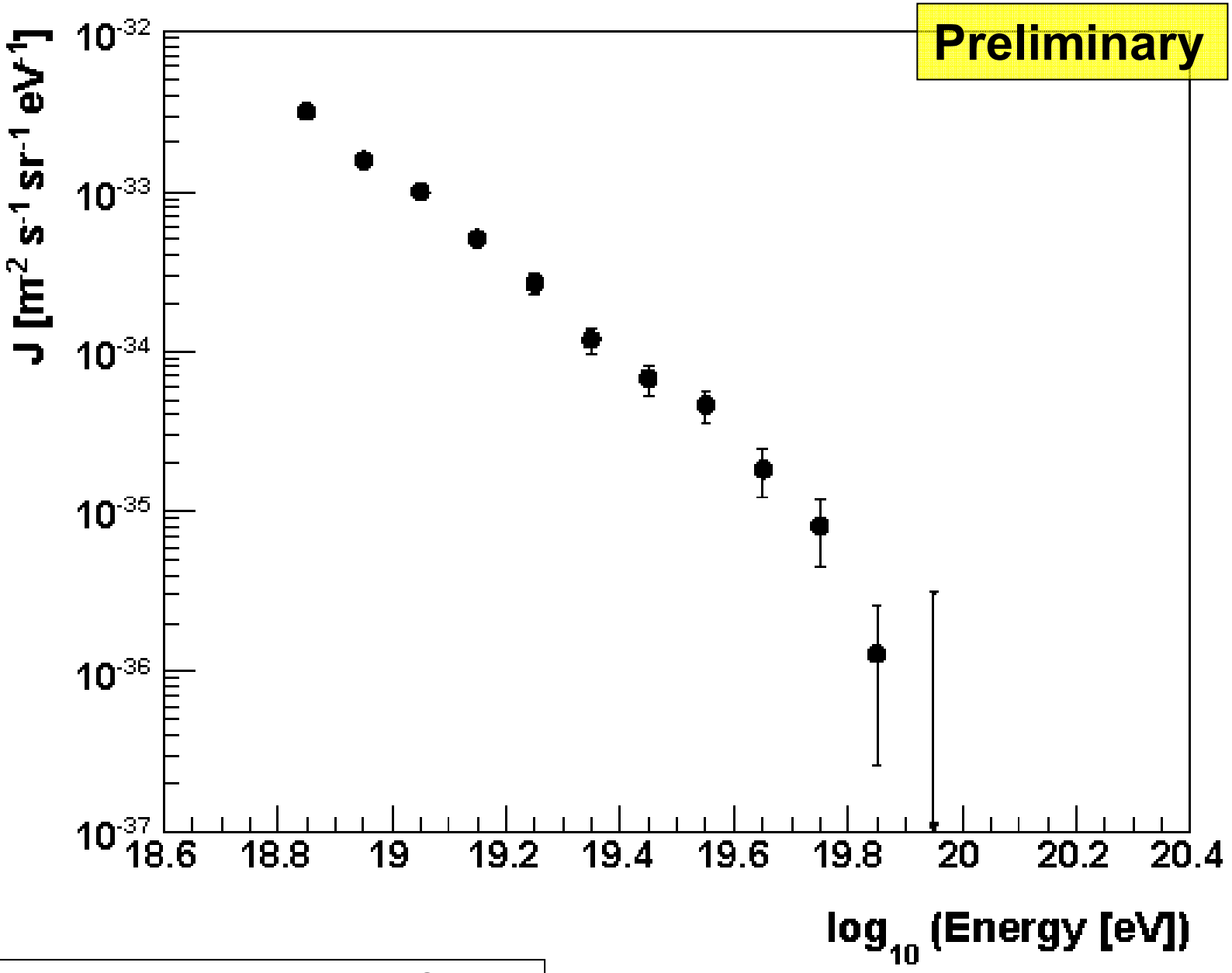




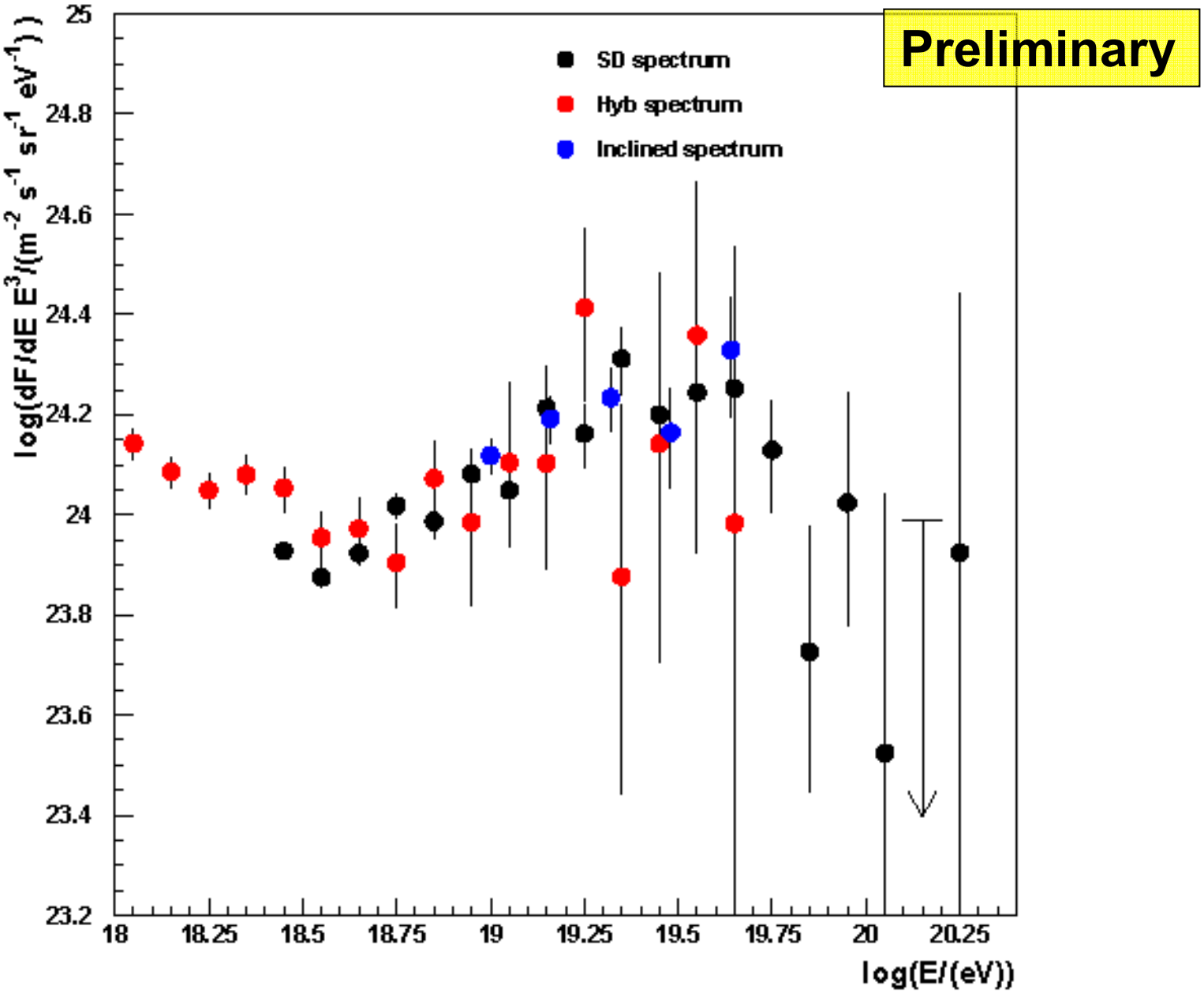
Θ = 87.6
ϕ = -134.9
E = 49.2
R= 19 km
χ/dof =1.7
NTanks = 37



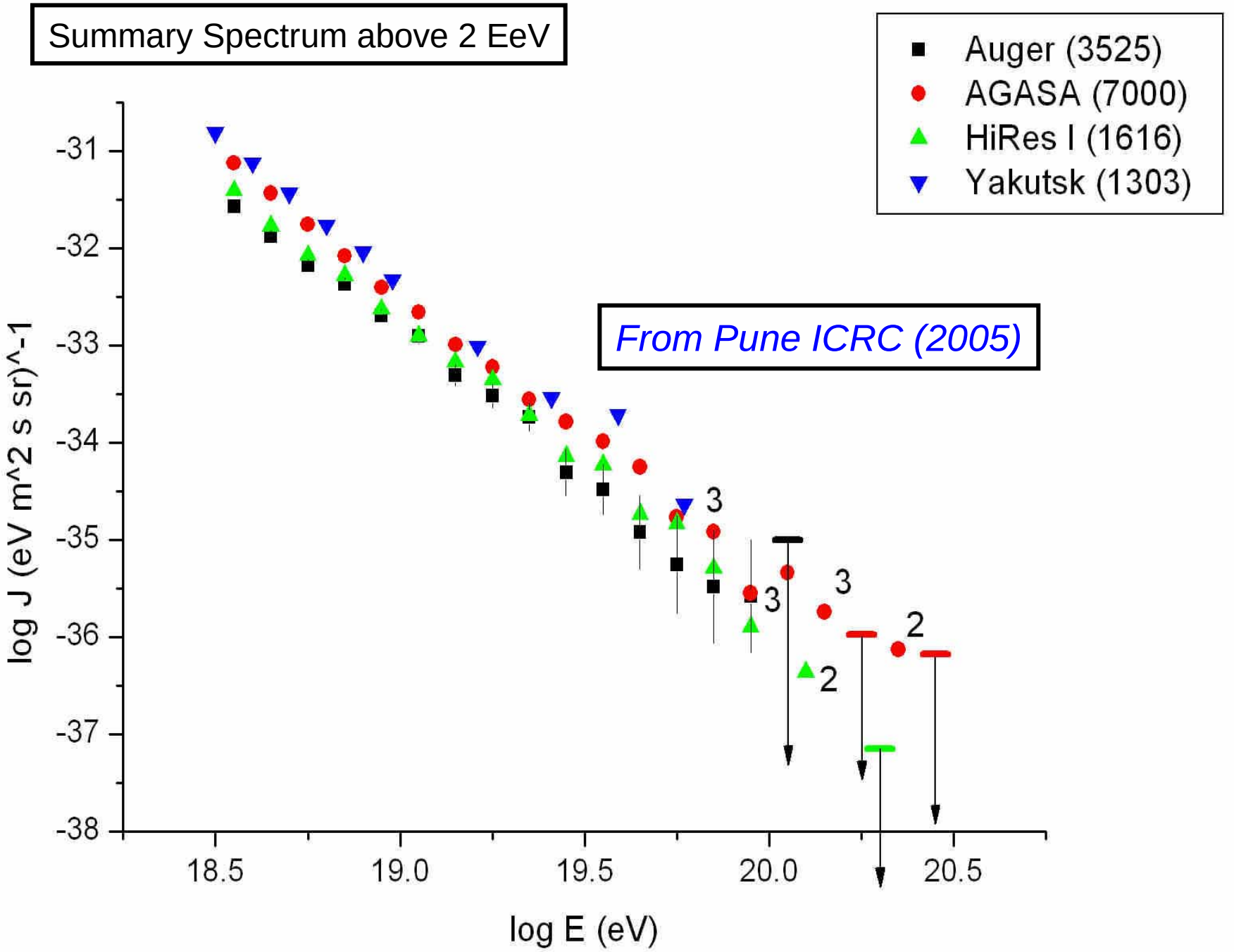
Highly inclined events (> 60^o) ... mostly muons



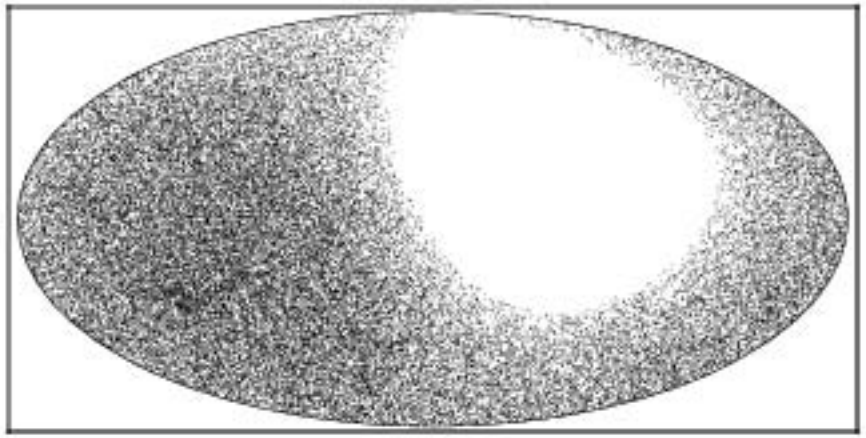
Inclined events (> 60^o)



Combined spectra ... three independent methods


Summary Spectrum above 2 EeV
Auger (3525)
AGASA (7000)
HiRes I (1616)
Yakutsk (1303)
From Pune ICRC (2005)
log J (eV m^2 s sr)^-1
-31
-32
-33
-34
-35
-36
-37
-38
18.5
19.0
19.5
20.0
20.5
log E (eV)
3
3
3
2
2

Events map

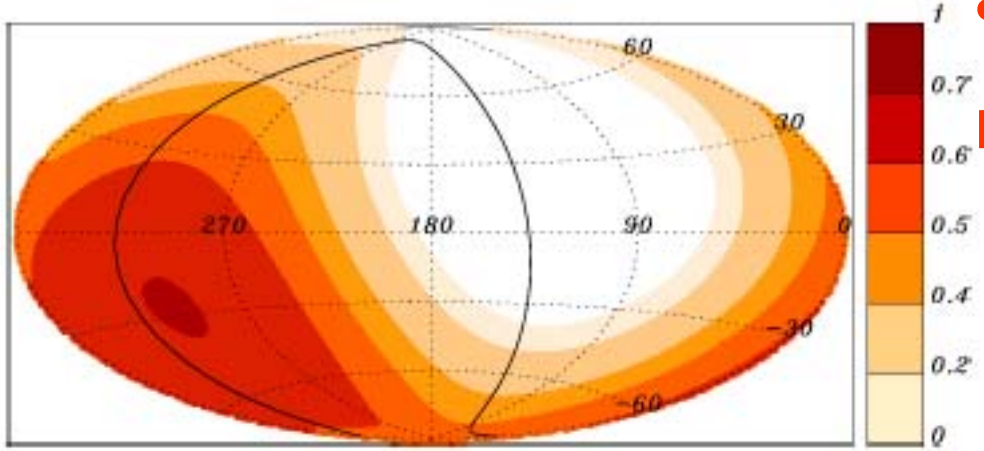


Galactic coordinates (l,b)

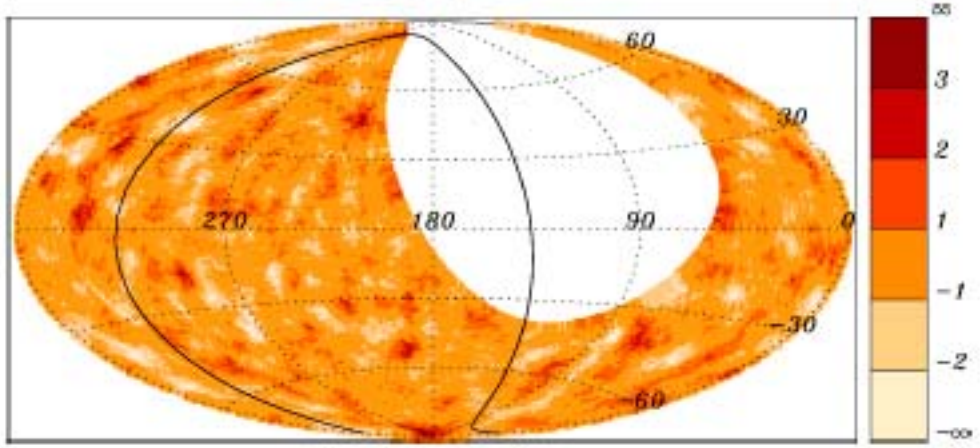
80,000 evts

Energy > 17.9 eV

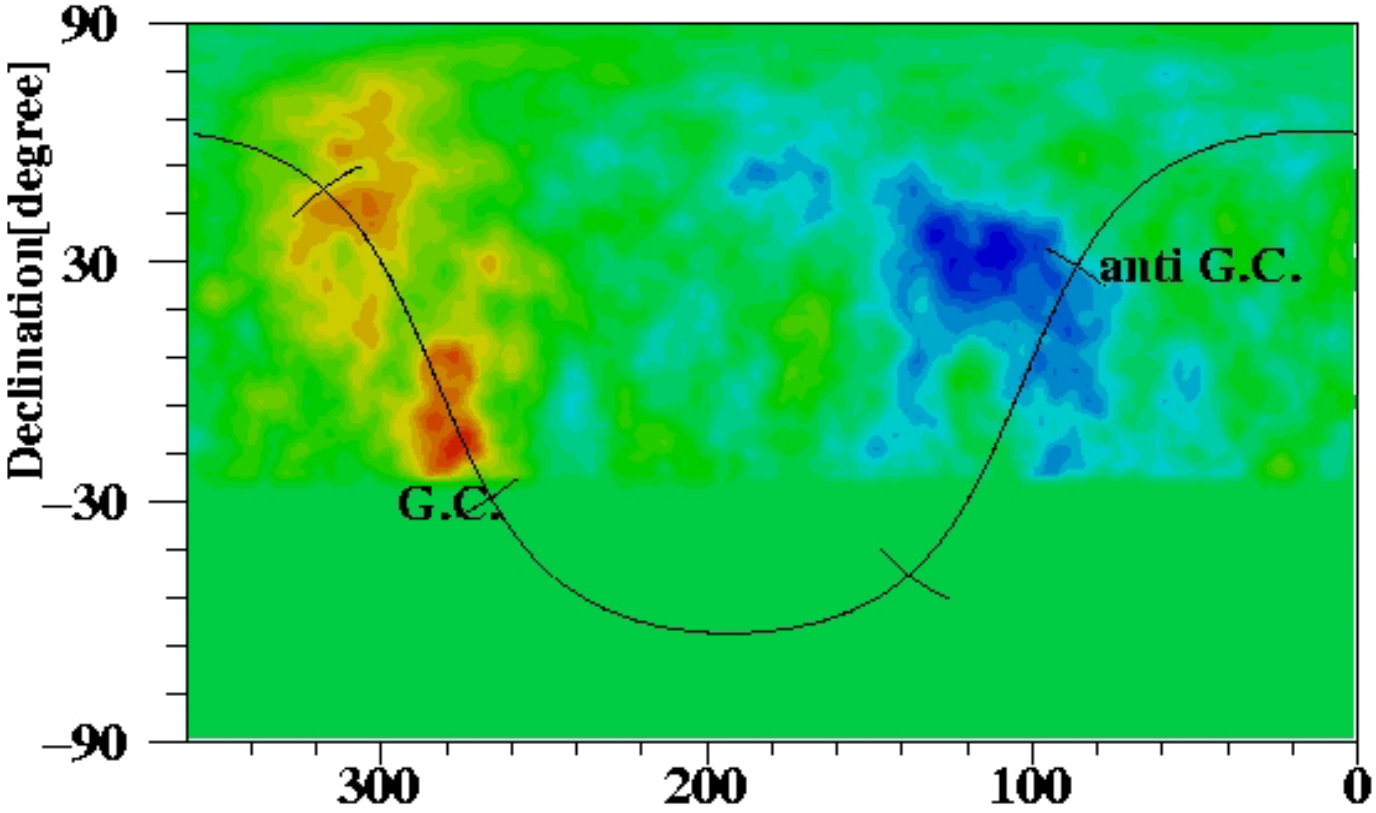
Exposure map
(5⁰ radius windows)



Excesses/defects significance map



Anisotropy : UHECR Sky



AGASA (2003) – excess near GC around 1 EeV

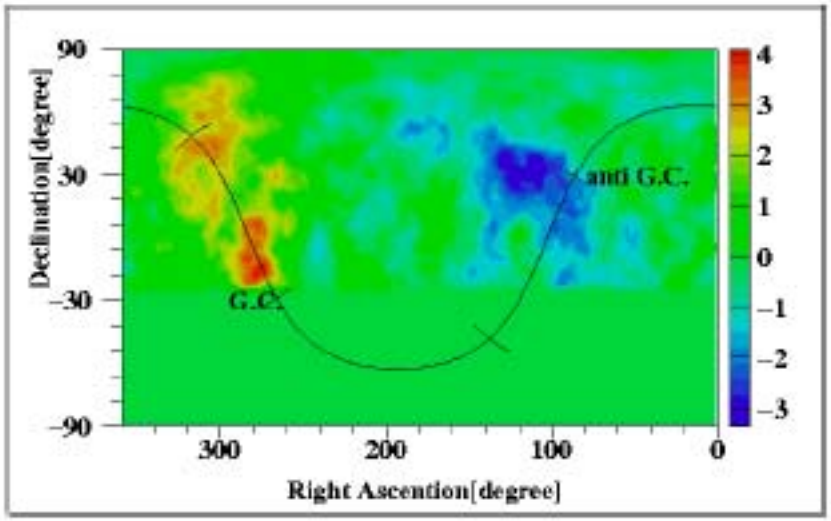
Testing previous reports of excesses

AGASA: 506/413.6 (22% excess)

10^{18} eV < E < $10^{18.4}$ eV

20° radius window around (280°,-17°)

(Hayashida et al 1999)

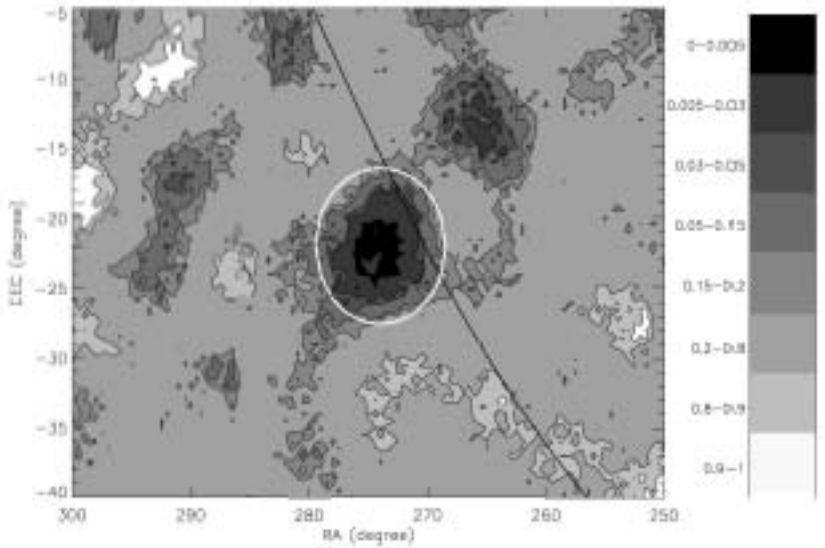


SUGAR: 21.8/11.8 (85% excess)

$10^{17.9}$ eV < E < $10^{18.5}$ EeV

5.5° radius window around (274°,-22°)

(Bellido et al 2001)



AUGER: 2116 / 2159.5

= 0.98 ± 0.02

22% excess would have been 2634 events (10 σ)

AUGER: 286 / 289.7

= 0.98 ± 0.06

Preliminary

No excess from the Galactic Center region

astro-phy/0607382

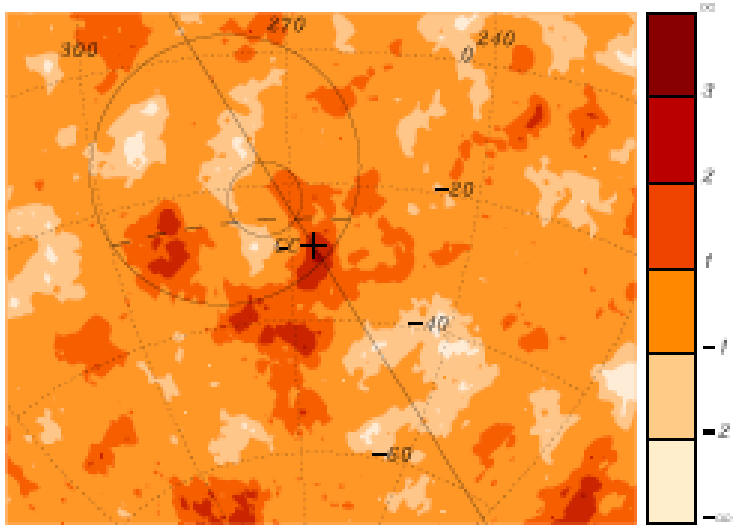
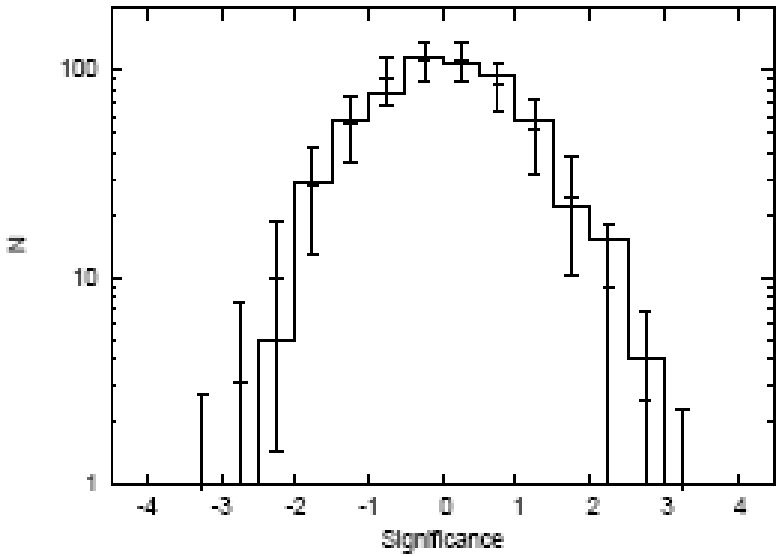
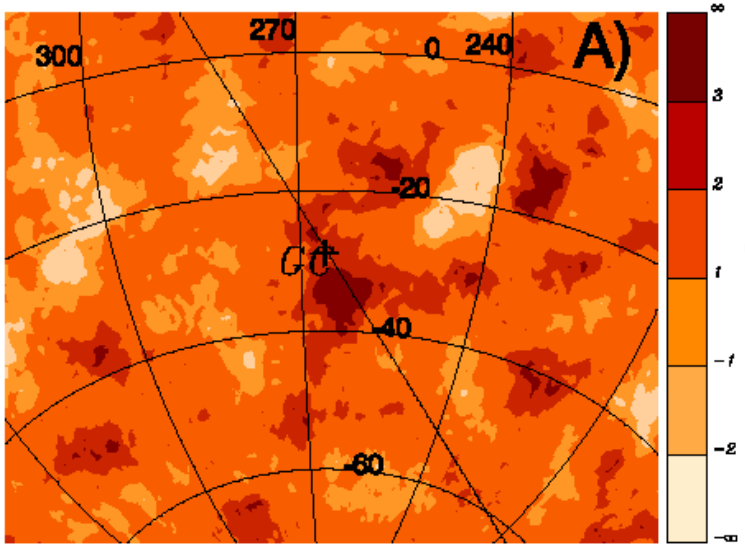


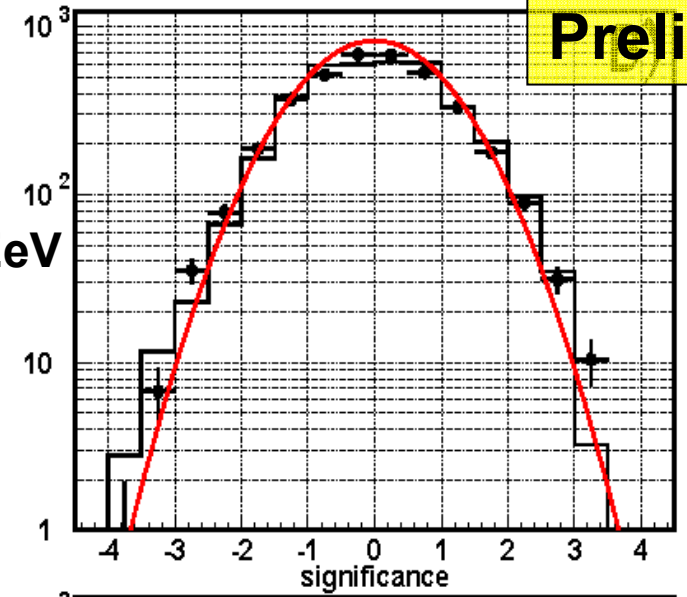
Fig. 1. Map of CR overdensity significances near the GC region on top-hat windows of 5° radius. The GC location is indicated with a cross, lying along the galactic plane (solid line). Also the regions where the AGASA experiment found their largest excess as well as the region of the SUGAR excess are indicated.

"Anisotropy studies around the Galactic centre at EeV with the Auger Observatory" Pierre Auger Collaboration (J. Abraham et al.)
Astropart. Phys. 27 (2007) 244

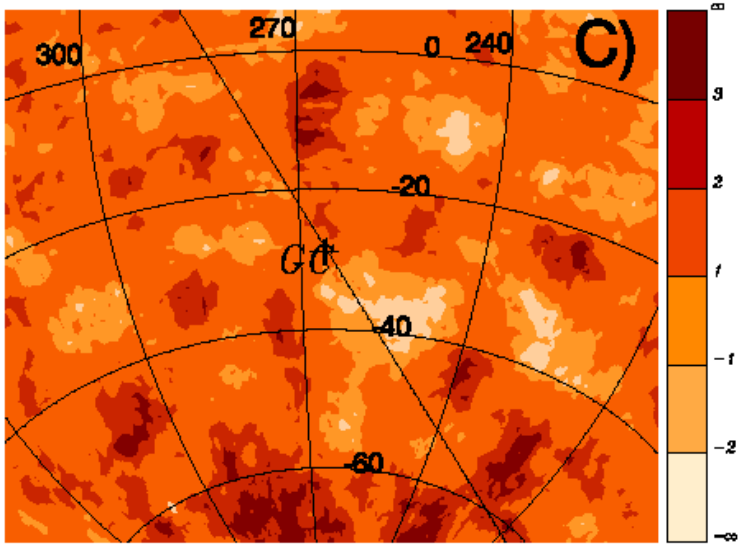




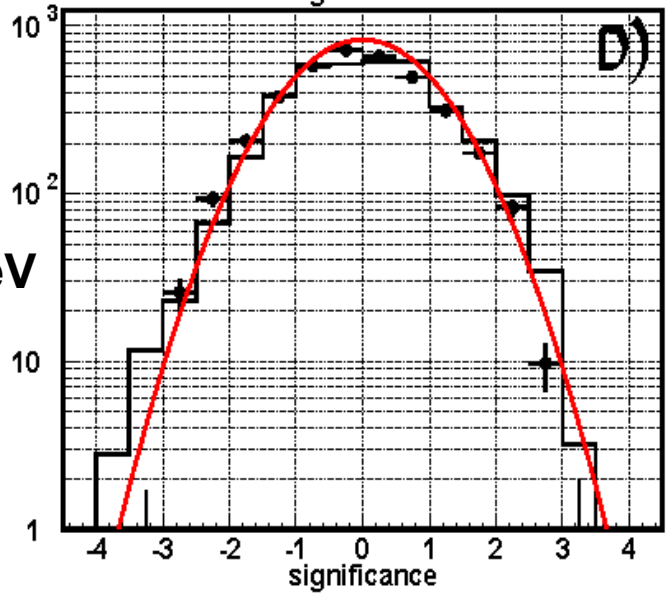
0.1 – 1 EeV



Preliminary



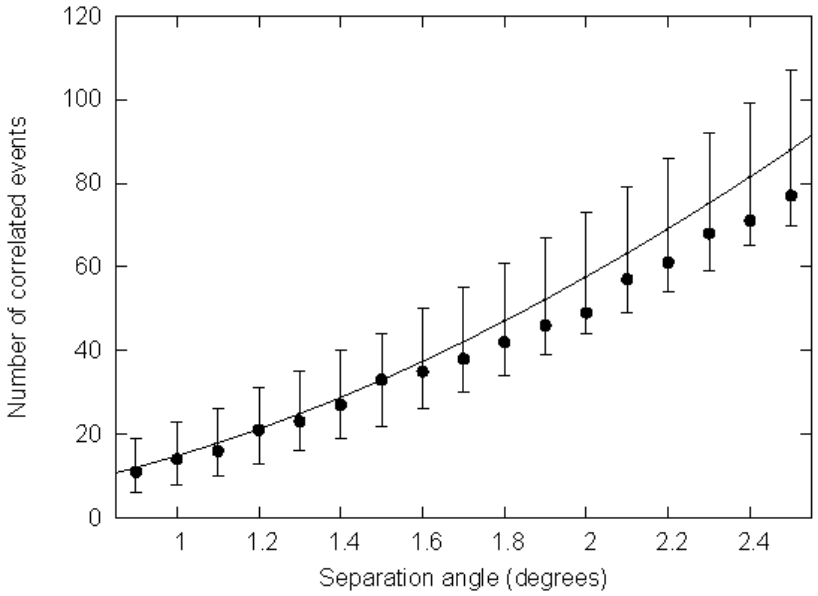
1 – 10 EeV

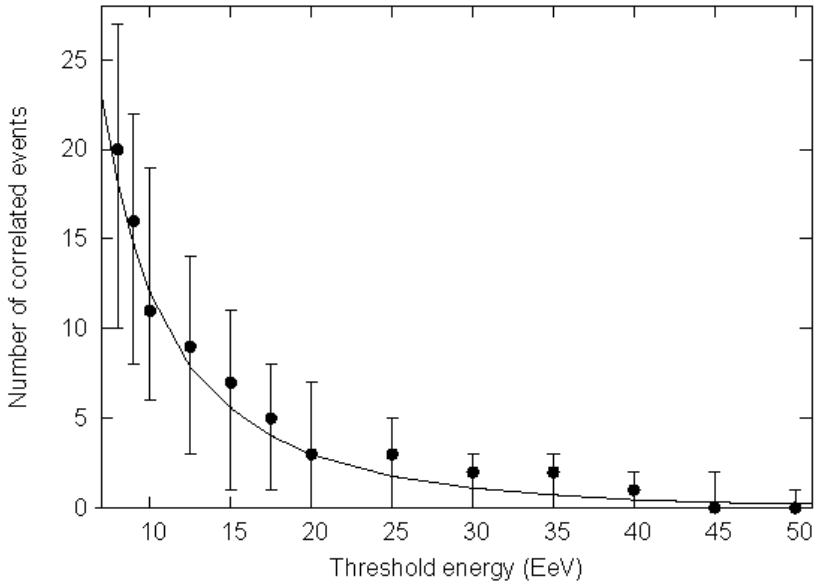


2007 ICRC data set: twice as large as previous publication

BL Lacs ?

Preliminary





Events at fixed energy ~10 EeV

Events within < 0.9 deg.

Number of events correlated with BL Lacs (m < 18, Veron-Cetty 10th catalog)

Line: expectation for an uncorrelated isotropic flux

Bars: 95% dispersion of simulated isotropic sets.

Several object- or pattern-oriented searches underway

How to look and understand your chance probabilities:

1. **Look for "interesting" things, a priori. Establish criteria to maximize any interesting consequence.**

2. **Publish the "prescription" and wait a while to test with new independent data**

Ordinary EAS at large zenith angles have little left but muons bunched tightly in time.

If an event does not, then it is a neutrino candidate

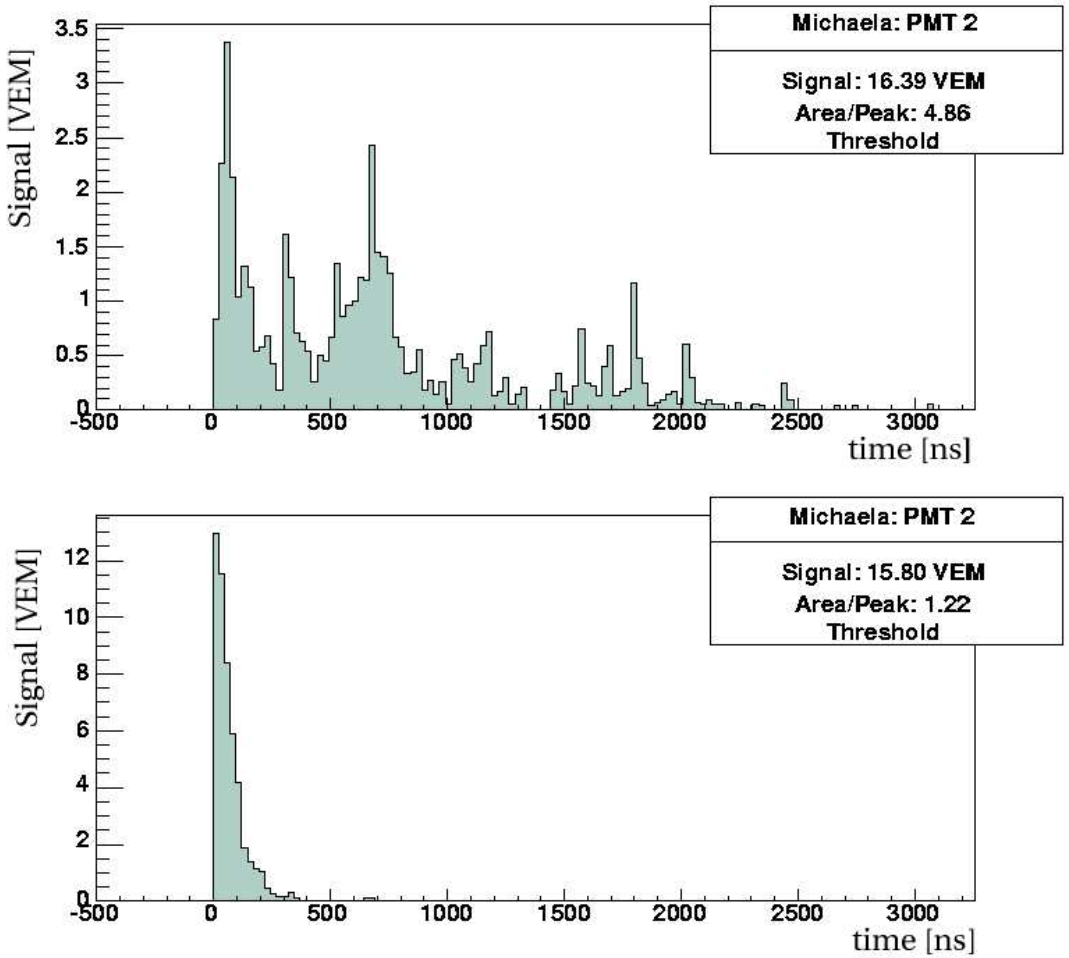
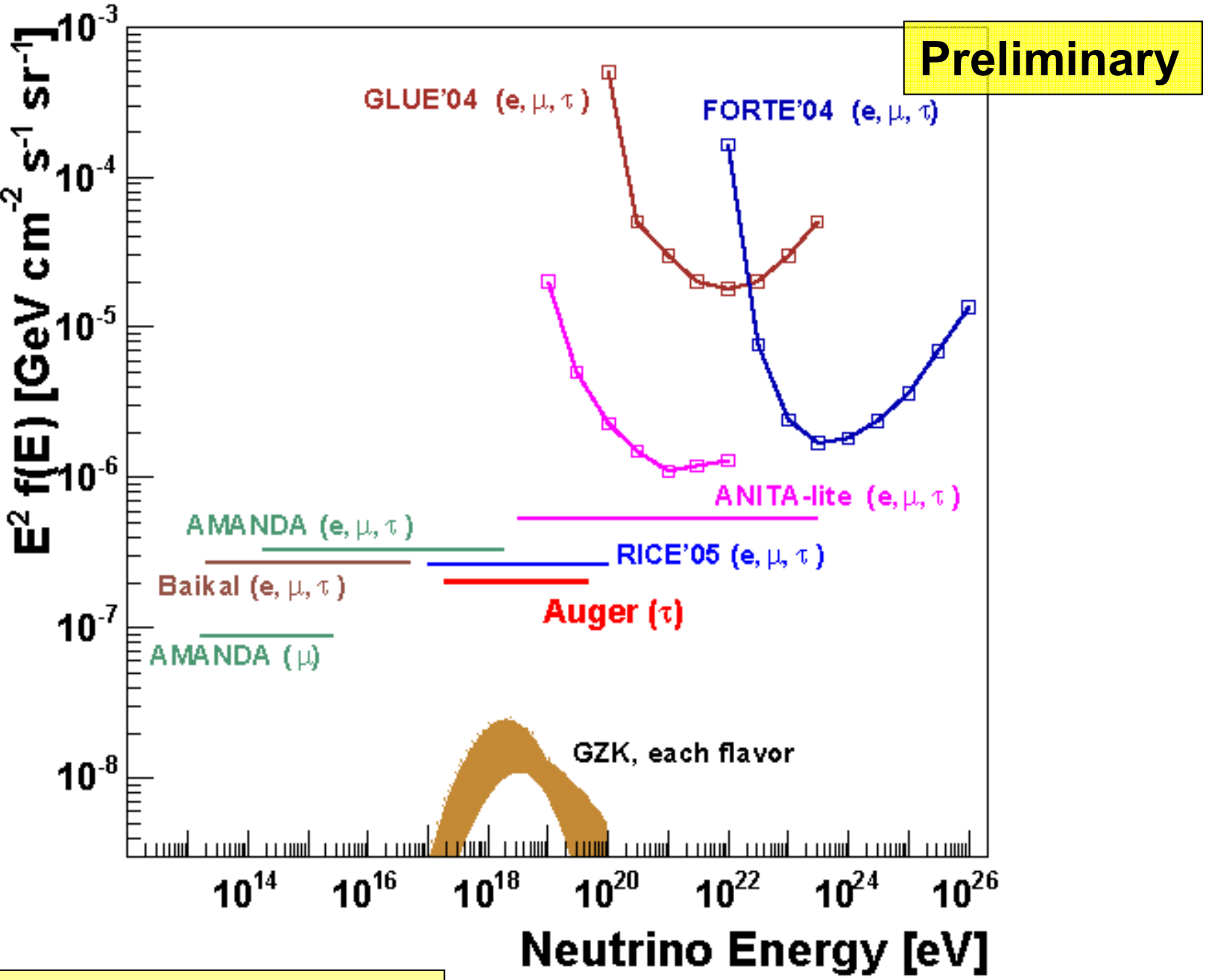


Figure 1: FADC traces from a station of two different real showers after subtraction of baseline and calibration. Top: moderately inclined (40°); bottom: quasi-horizontal (80°).



"earth-skimming" tau events

Summary

- Auger is performing very well.

- The highest energy events look “normal” and have been reconstructed well.

Published:

- Do not confirm Galactic-Center excess

- Gamma rays < ~16% of total flux.

Work underway (ICRC 2007 and beyond):

- "Model-independent" energy spectra suggests GZK, "ankle".
- Angle-energy patterns?
- Correlation with objects (AGNs, ...) ?
- Composition changes at highest E ?
- Highly inclined showers – neutrinos ?

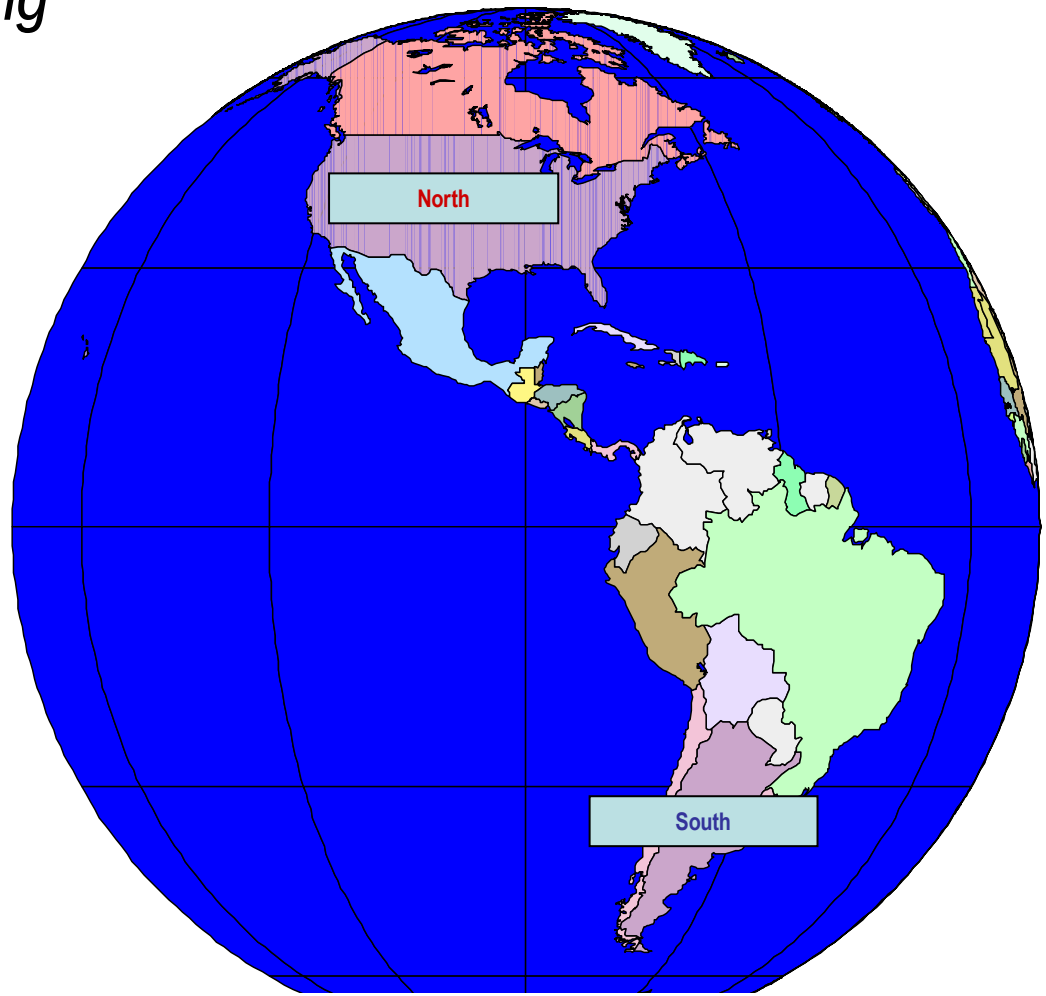
The Future

- Complete Auger-South: end of 2007
- Start Auger-North (10^4 km^2) in SE Colorado around 2009
- Enhancements at Auger-South
  - Radio detection of showers
  - Measurement of muons
  - Exploration to lower energies both with denser array of water-tanks and Fluorescence detector pointing to higher elevations

What's Next: science and full-sky coverage

- *consolidation of understanding*
  - **data quality, monitoring, operation procedures**
  - **analysis methods**
  - **calibration**

- *we're very satisfied with what we built...*
- *The Northern Site*
  - **scientific case**
    - **N/S astrophysical sources**
    - **isotropy: new physics**
  - **site: Colorado**
  - **seamless data integration**
  - **improvements**

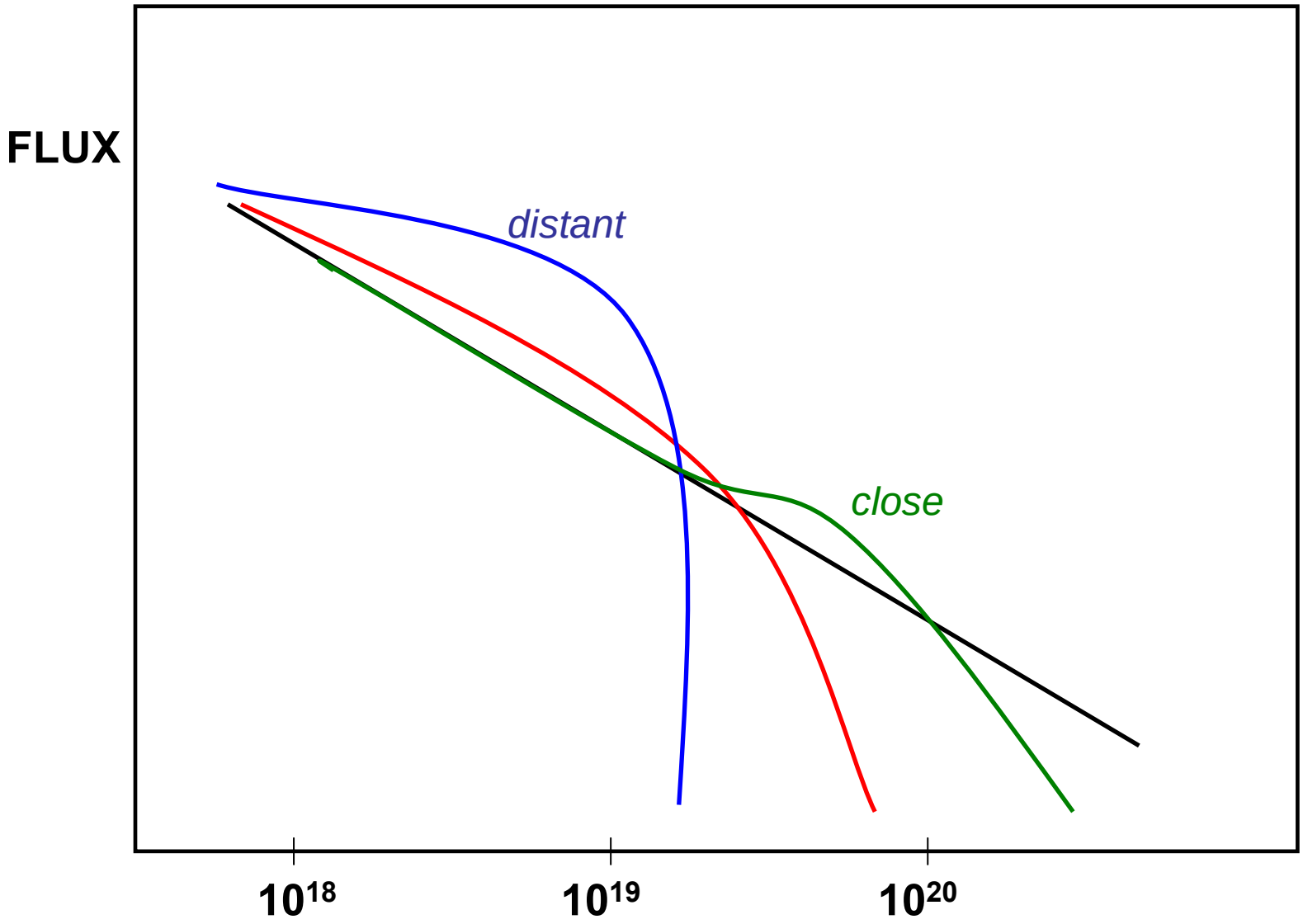


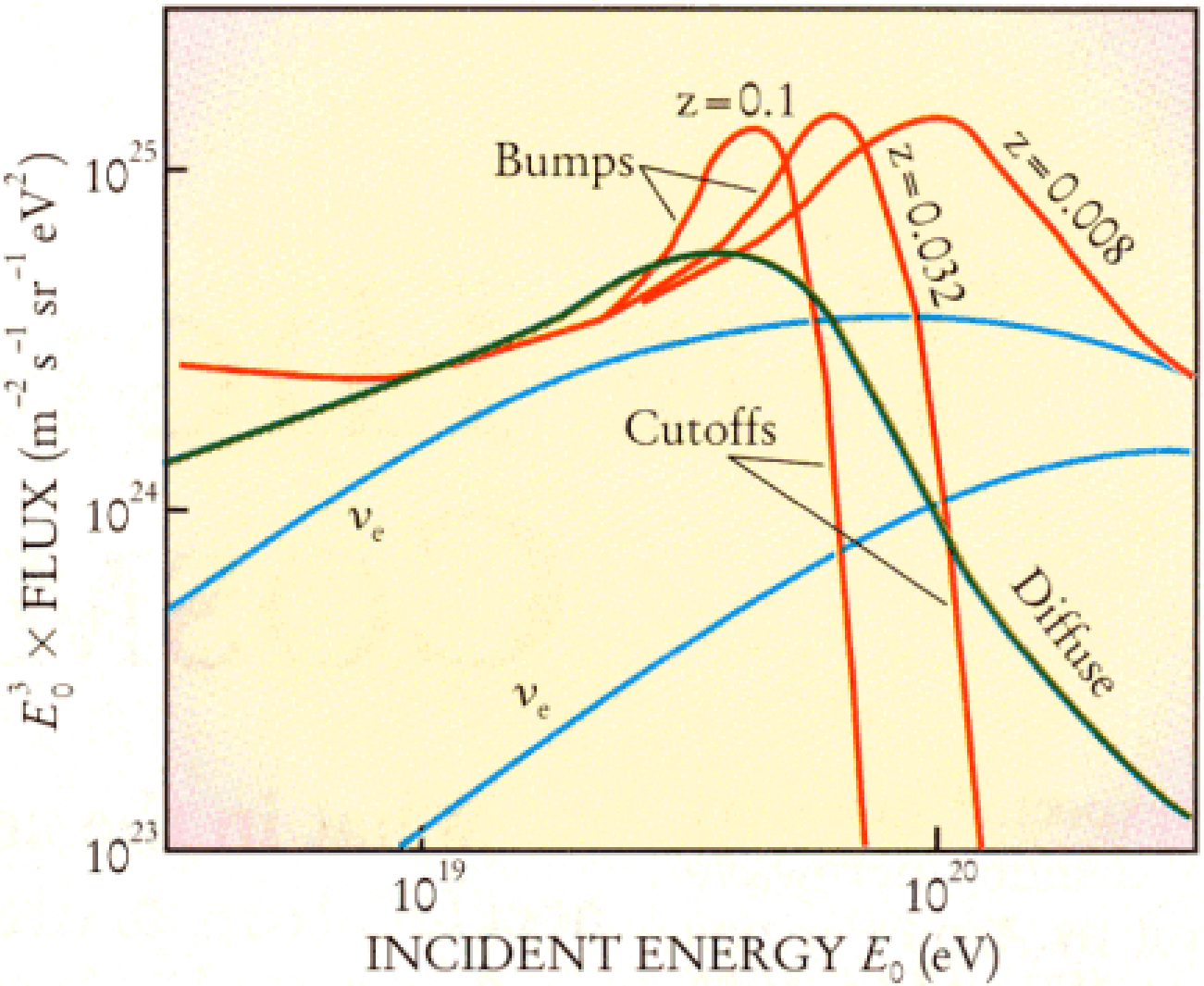
Auger North:

View the Northern Sky

3 x larger array than Auger South: statistics

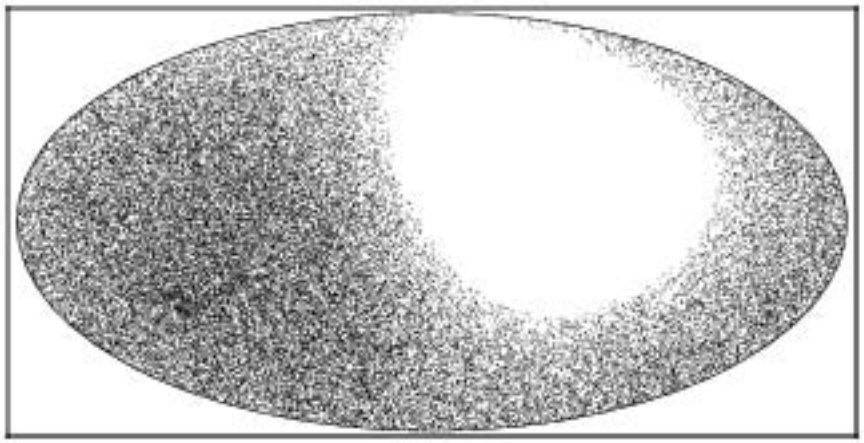
GZK Alteration of observed flux




z=0.1
Bumps
z=0.032
z=0.008
Cutoffs
ν_e
ν_e
Diffuse
10^{25}
10^{24}
10^{23}
10^{19}
10^{20}
$E_0^3 \times$ FLUX (m^{-2} s^{-1} sr^{-1} eV^2)
INCIDENT ENERGY E_0 (eV)

The sources visible in the Southern sky may be quite different than those seen from the Northern sky

Events map



Galactic coordinates (l,b)

Source map:

???

SPECIALS
COMMENTARY
REWARDS
CONTACT US
BANKING METHODS
RESPONSIBLE GAMBLING
FEATURES
SPECIALS
Science Specials

POLITICS
UK General Election
US Presidential Election

AWARDS
Booker Prize

MUSIC
Mercury Music Prize

FEATURES

SPECIALS

Specials | Politics | Awards | Music

Specials - Science Specials

Physics Breakthroughs

SELECTION Click here or on ODDS to change view order	ODDS	BET NOW OR ADD TO MULTIPLE
Understanding the origin of cosmic rays by 2010	4/1	Bet
The ATLAS experiment at CERN finding the Higgs Boson by 2010	6/1	Bet
The Laser Interferometer Gravitational Wave Observatory (LIGO) detecting gravitational waves by 2010	10/1	Bet
Building a fusion power station by 2010	100/1	Bet

2004-08-30 17:00:00

Bet Help Bet Calculator

Information about Ladbrokes, Affiliates, Jobs and the Hilton Group here