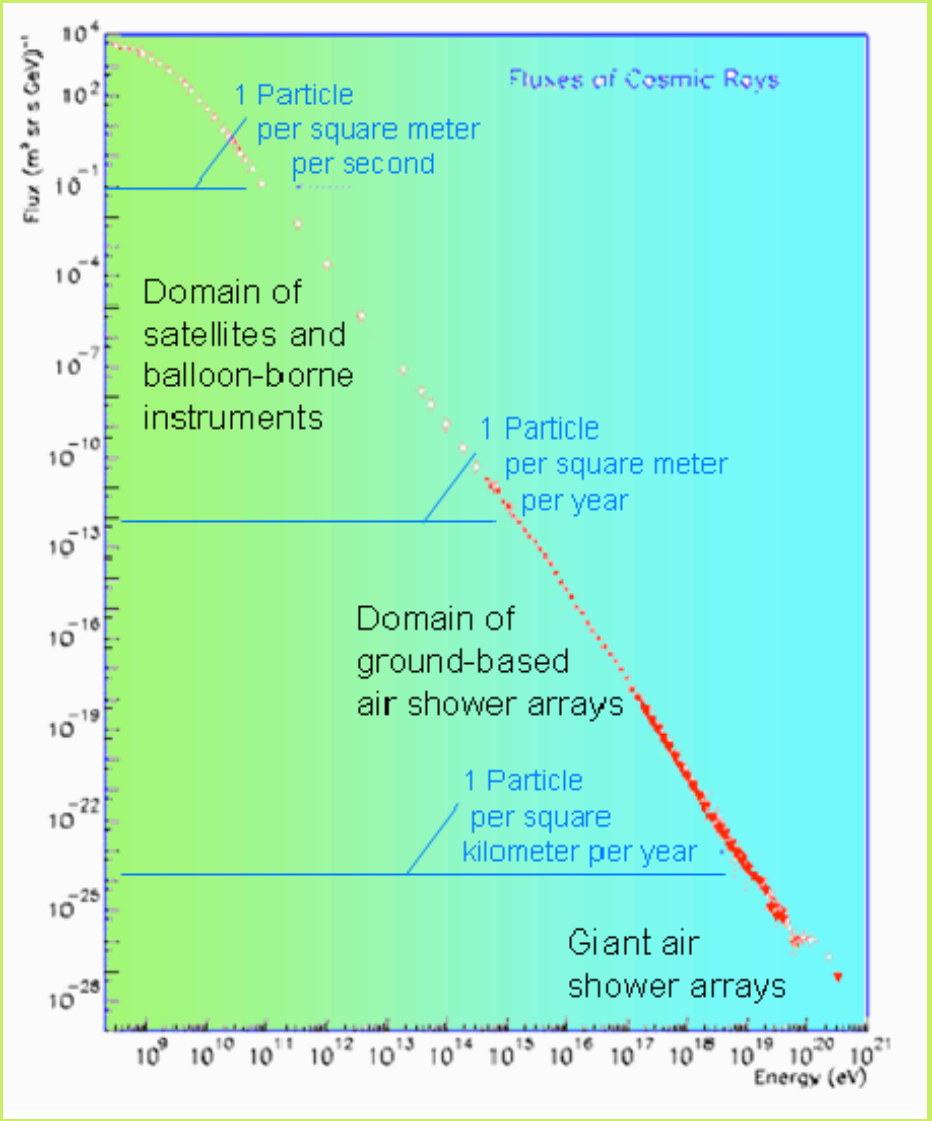
Hunting for cosmic particles

G. Navarra
INFN-University Torino (Italy)

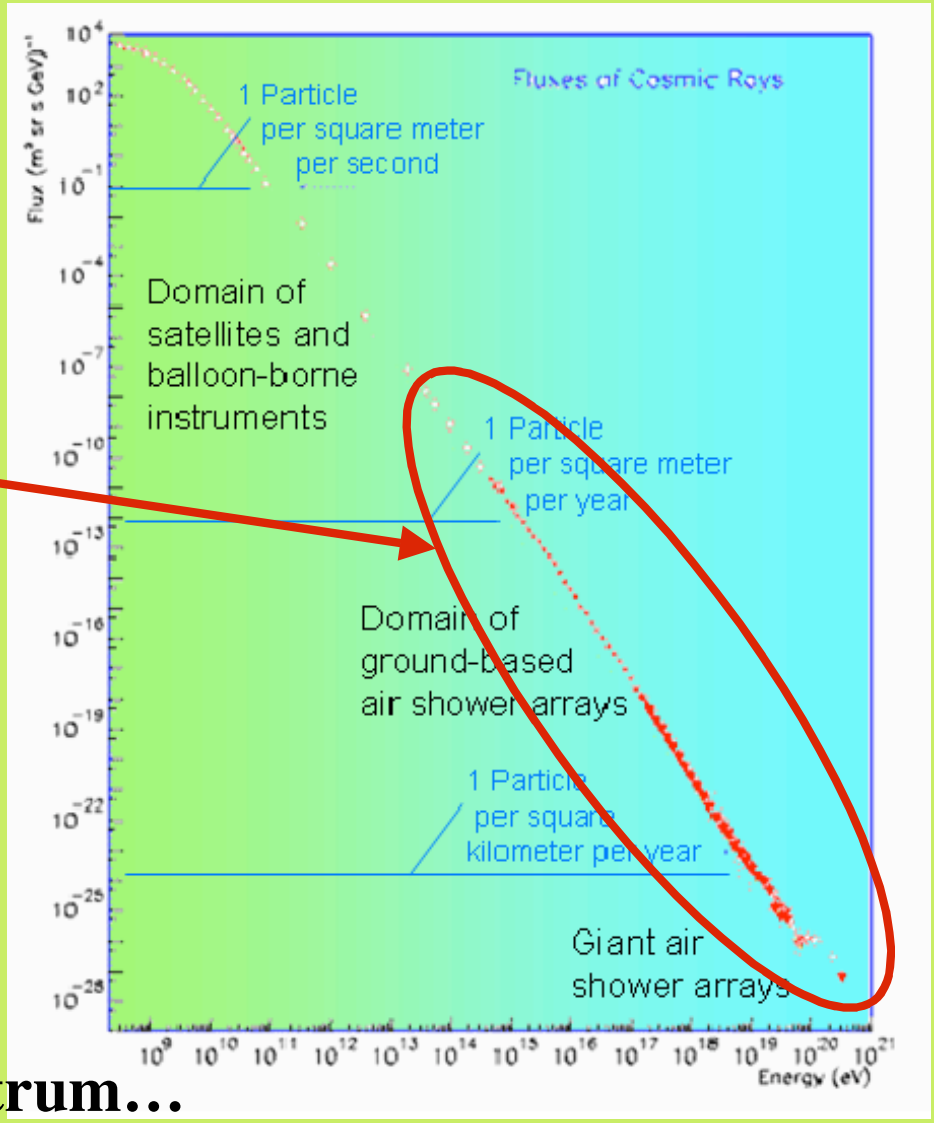
XII International Workshop on Neutrino Telescopes
Venice, March 6-9 2007

The cosmic ray energy spectrum:



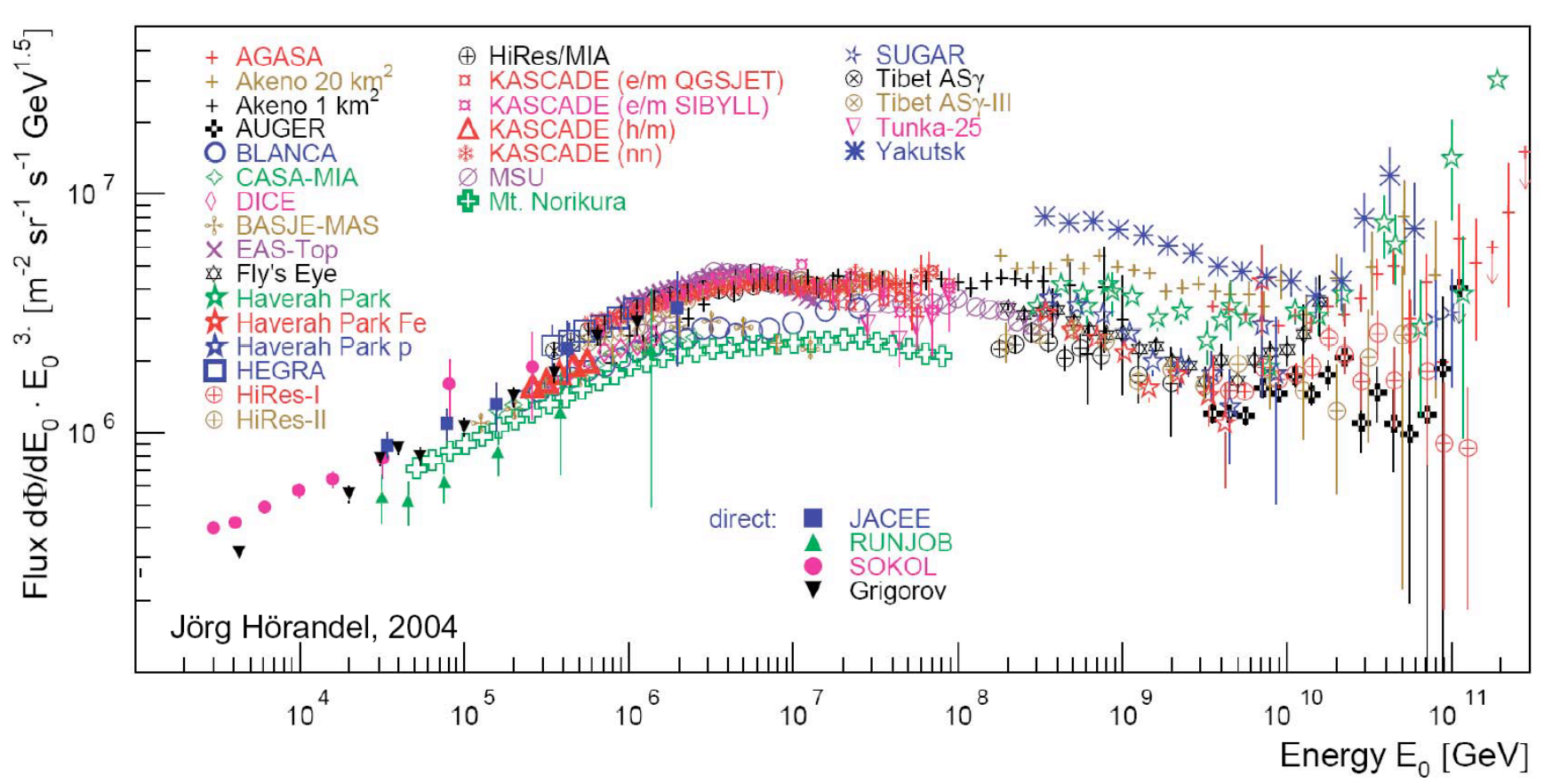
The cosmic ray energy spectrum:

High energies: ground based arrays

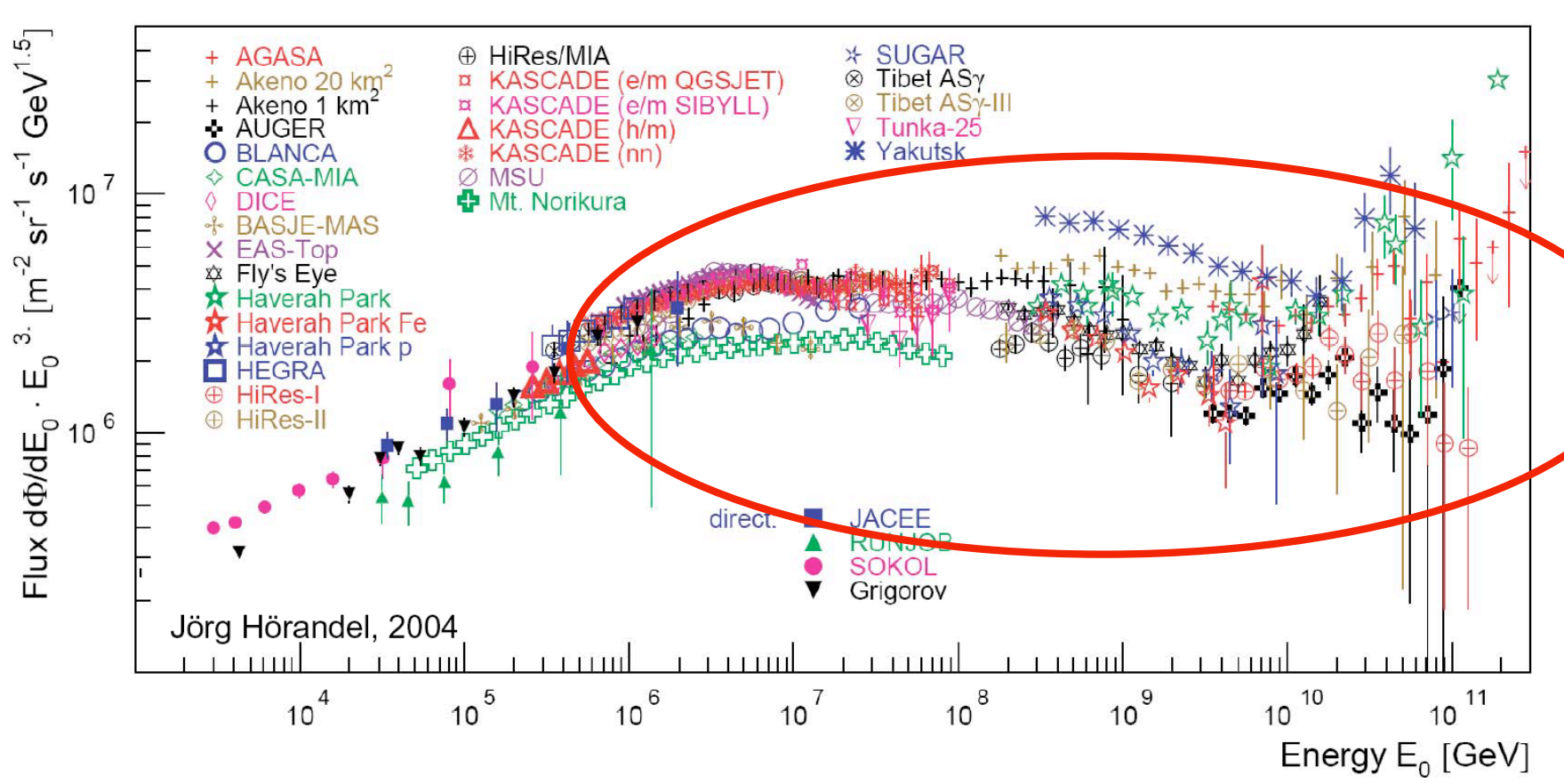


The quasi power spectrum…

Physics and problems: $S(E_0)*E_0^3$

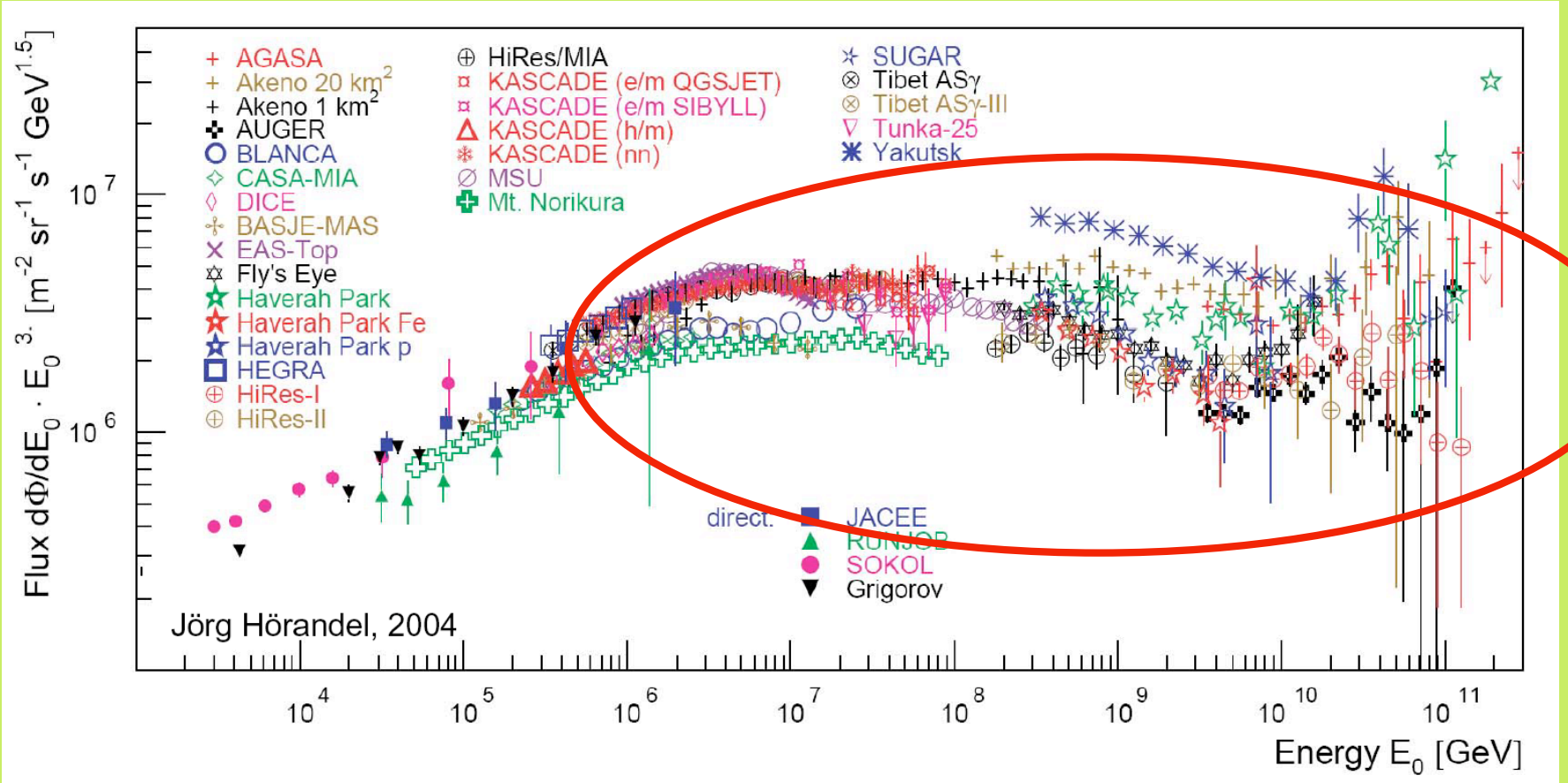


Physics and problems: $S(E_0)*E_0^3$



Physics and problems: $S(E_0)*E_0^3$

"knee"….. end-galactic…extragalactic…end-spectrum…



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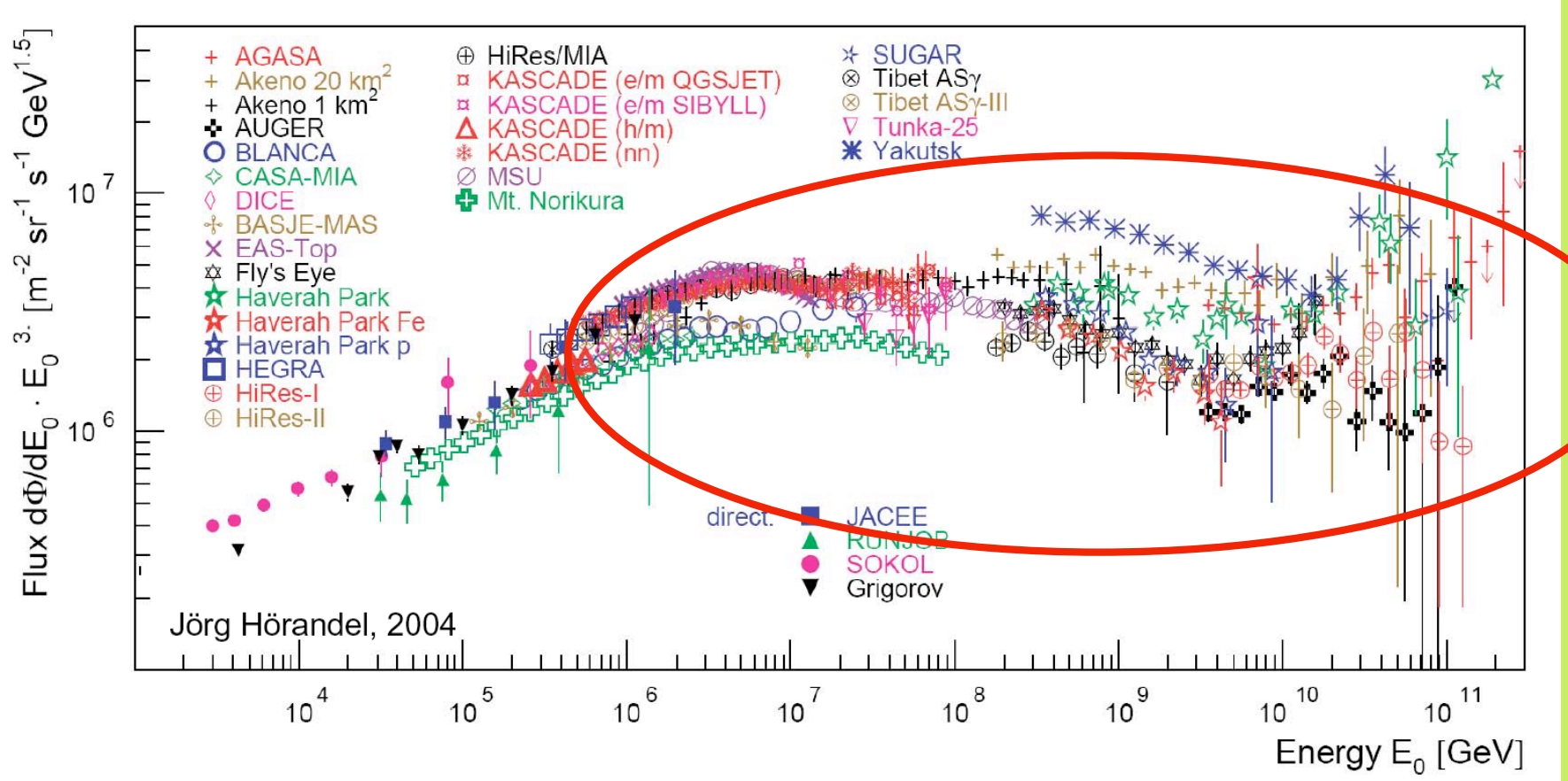


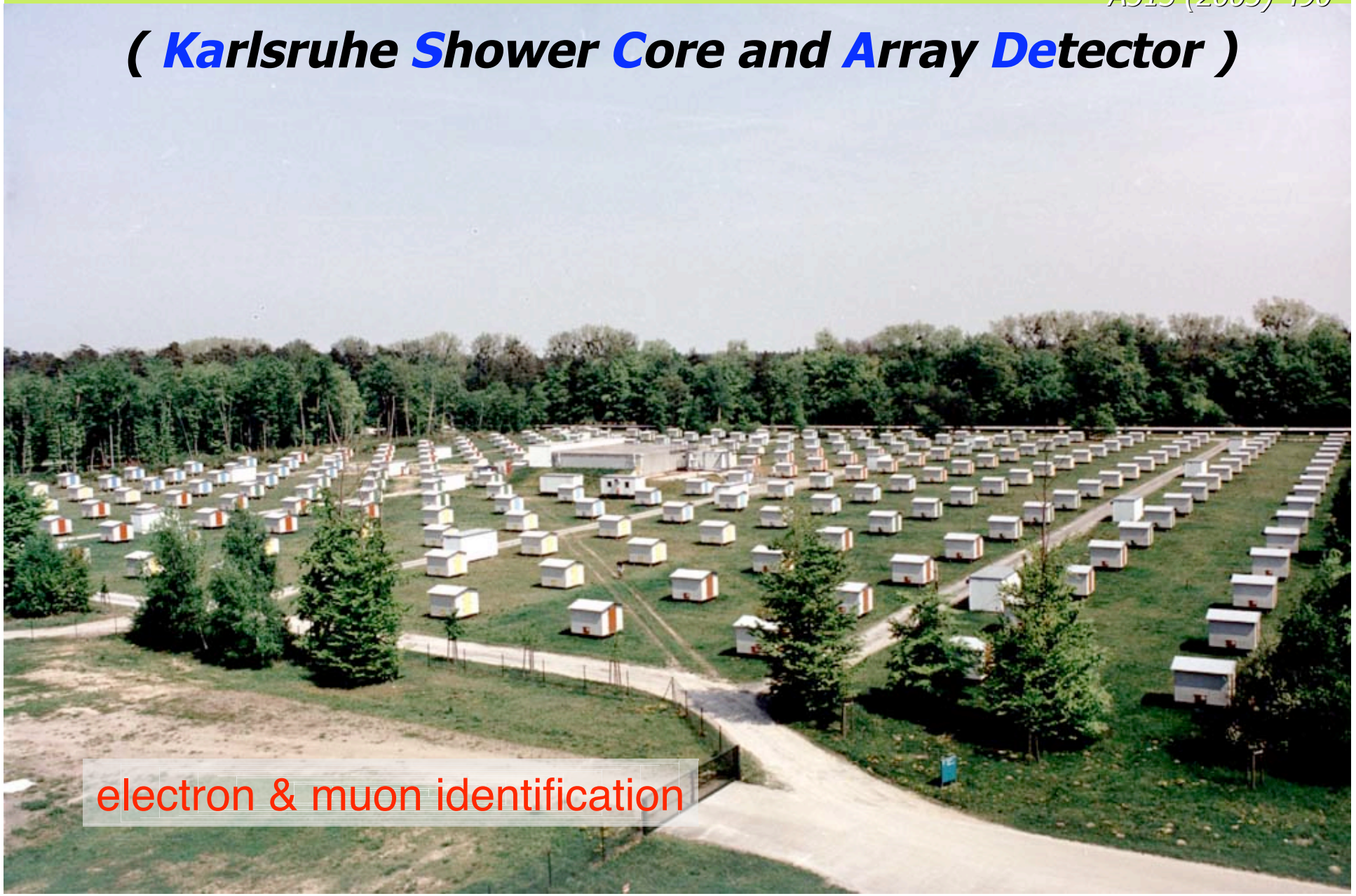
energy spectrum..composition…anisotropies…interactions…

EAS-TOP
(LNGS)
+ underground μ-det.

KASCADE

Nucl. Instr. Meth. A513 (2003) 490

(Karlsruhe Shower Core and Array Detector)



The “knee”

SOVIET PHYSICS JETP VOLUME 35 (8), NUMBER 3 MARCH, 1959

ON THE SIZE SPECTRUM OF EXTENSIVE AIR SHOWERS

G. V. KULIKOV and G. B. KHRISTIANSEN

Moscow State University

Submitted to JETP editor April 22, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 635-640 (September, 1958)

Experimental data are presented on the size spectrum of extensive air showers in the region 10^5 to 2×10^6 particles. An analysis of these and other data available in the literature indicates that there is, very probably, an irregularity in the shower size distribution curve in the region between 10^6 and 10^7 particles. This is considered to constitute an argument in favor of the metagalactic origin of cosmic rays with energies above 10^{16} ev.

f ~ 0.01 m^{-2} d^{-1}

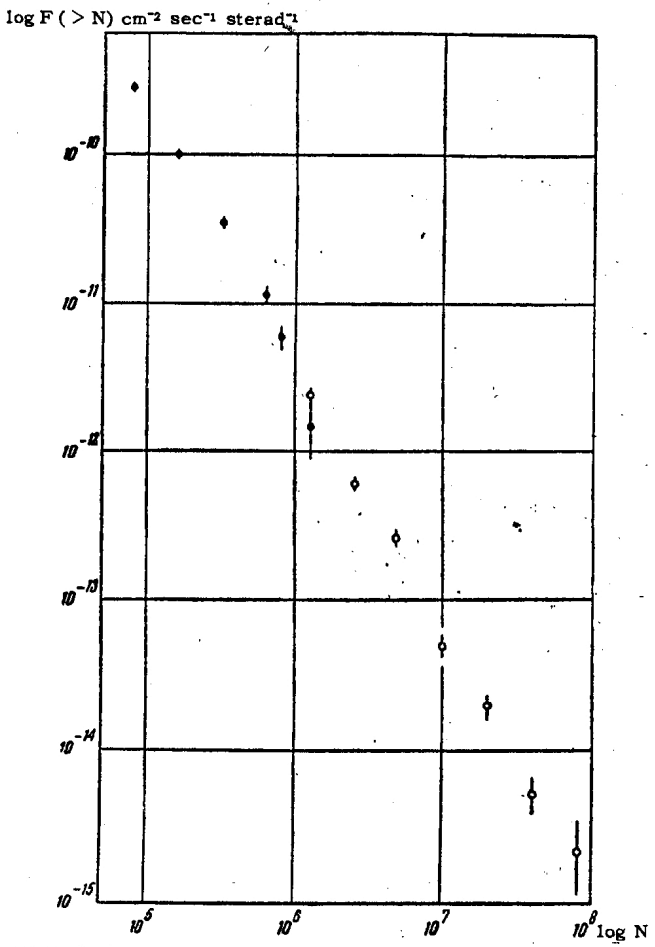


FIG. 2. Integral size spectrum of EAS. ● – measurements of the present experiment, ○ – measurements of reference 7.

The “knee”

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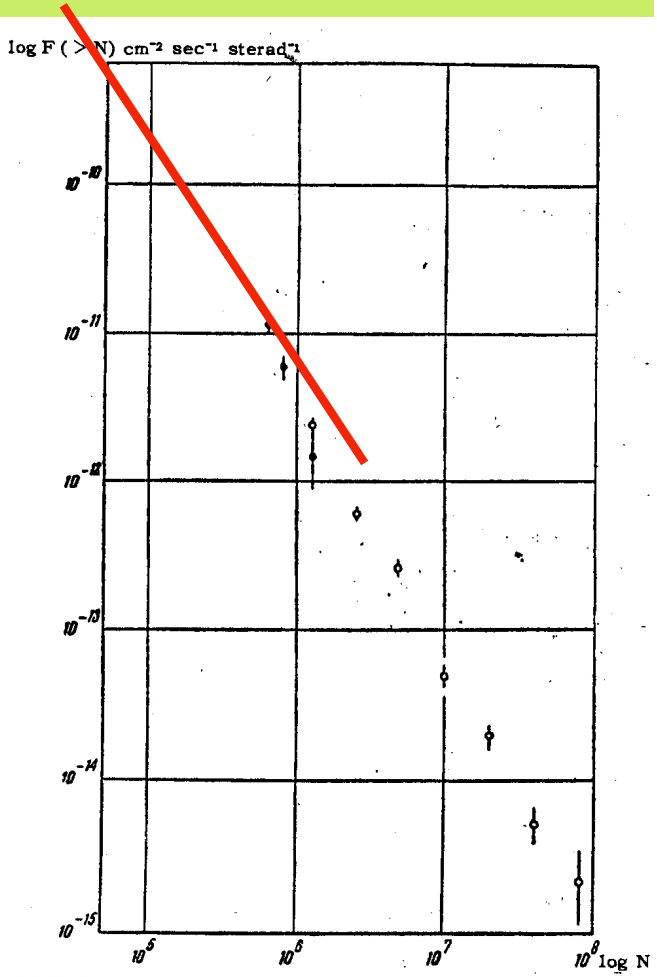

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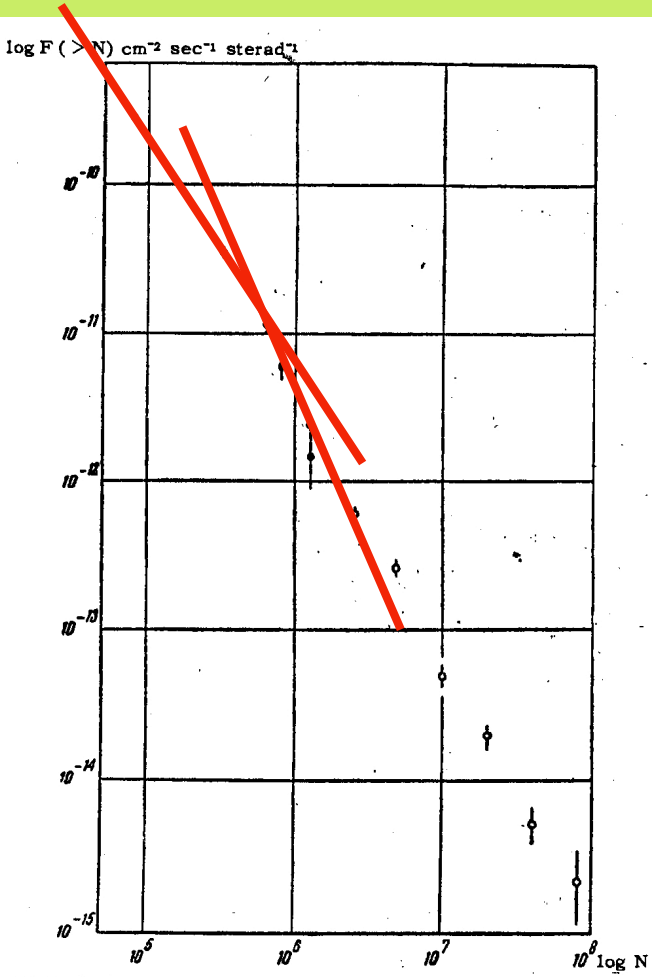
B. Peters & G. T. Zatsepin:
R ~ E/Z



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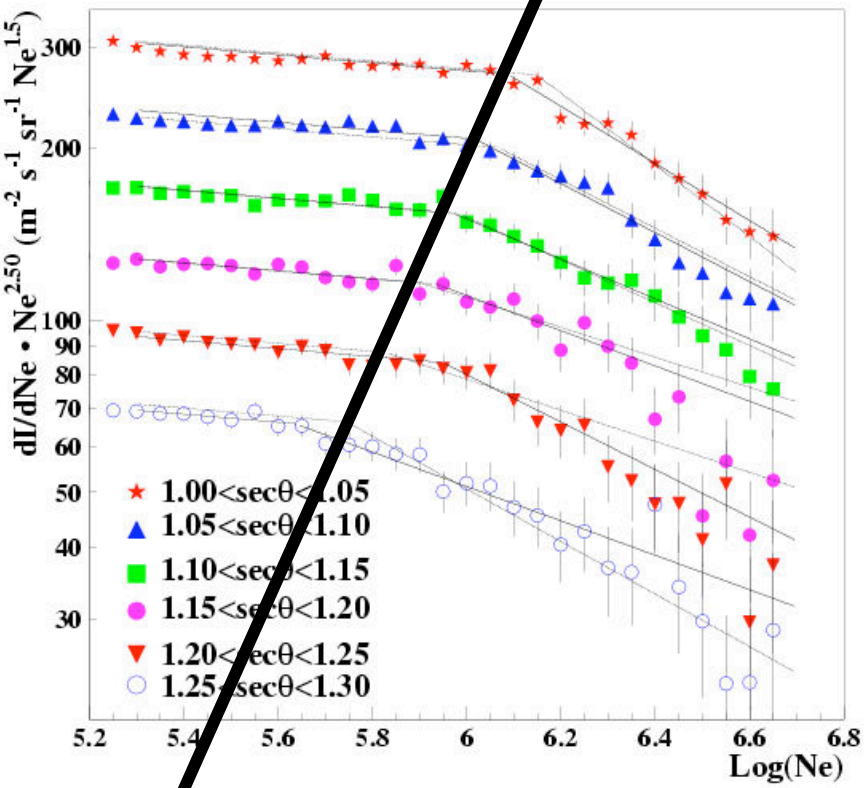
The "knee"

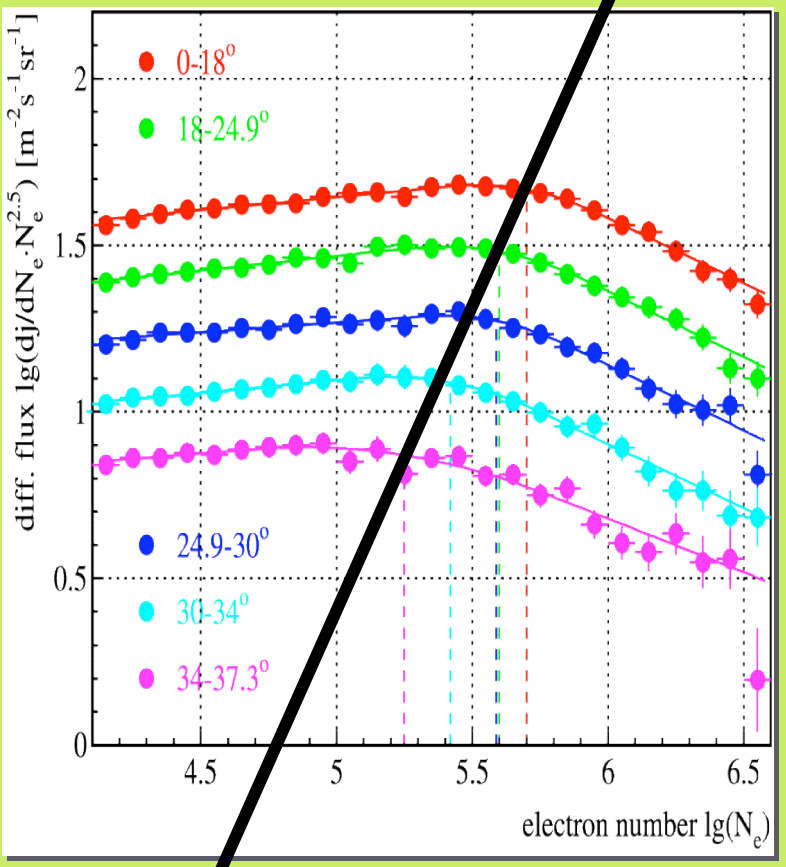
E.M. DETECTORS:
Ne spectra in the knee region

EAS-TOP



2000 m a.s.l.

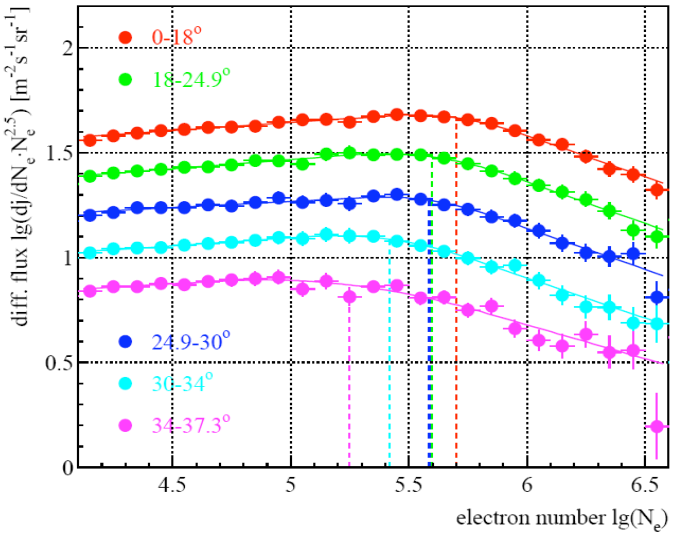
KASCADE



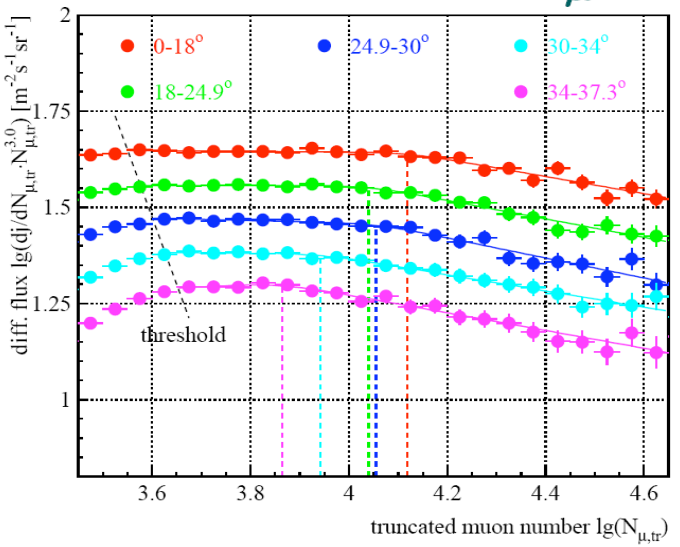
100 m a.s.l.

KASCADE size spectra

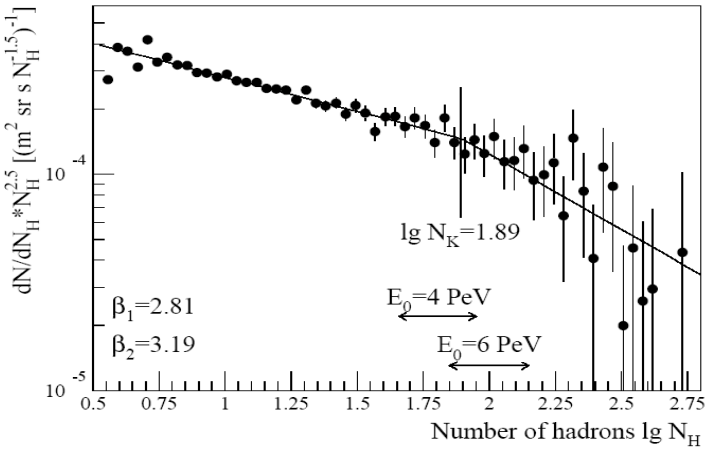
Electron Size Spectra N_e



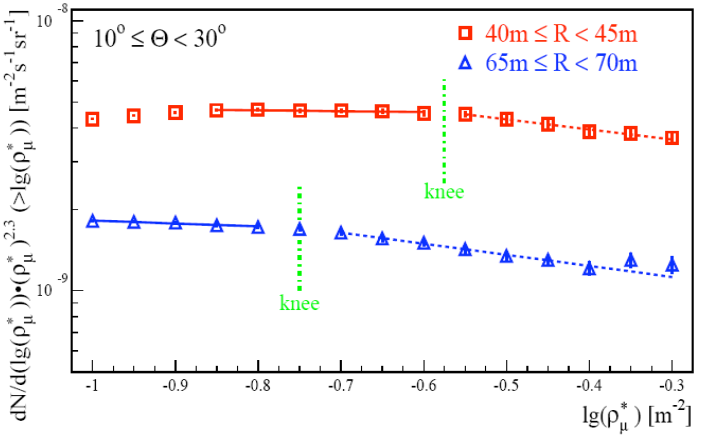
Muon Size Spectra N_μ^{tr}



Hadron Size Spectra N_h

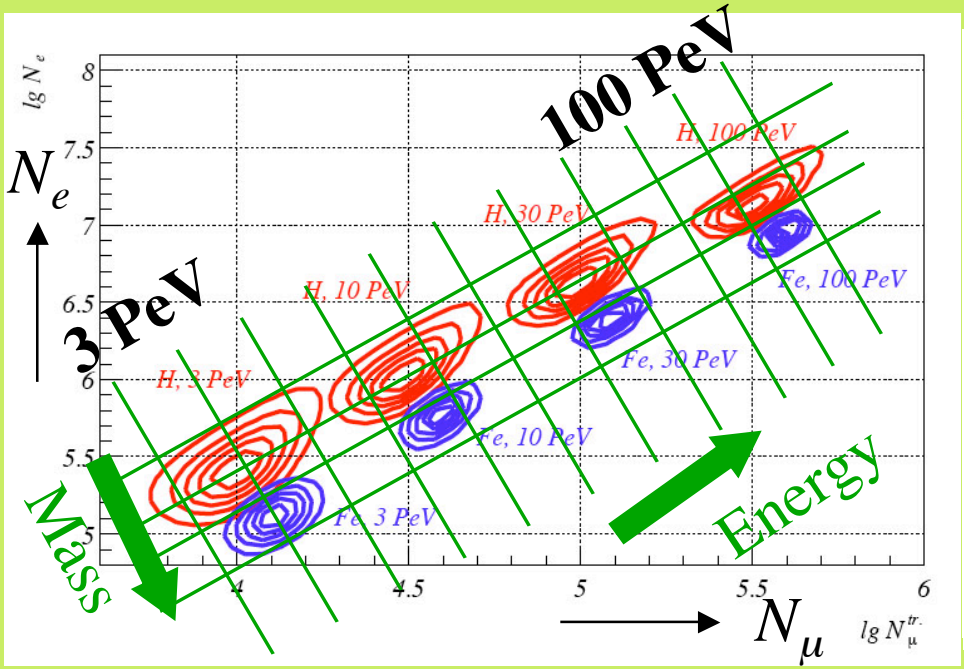


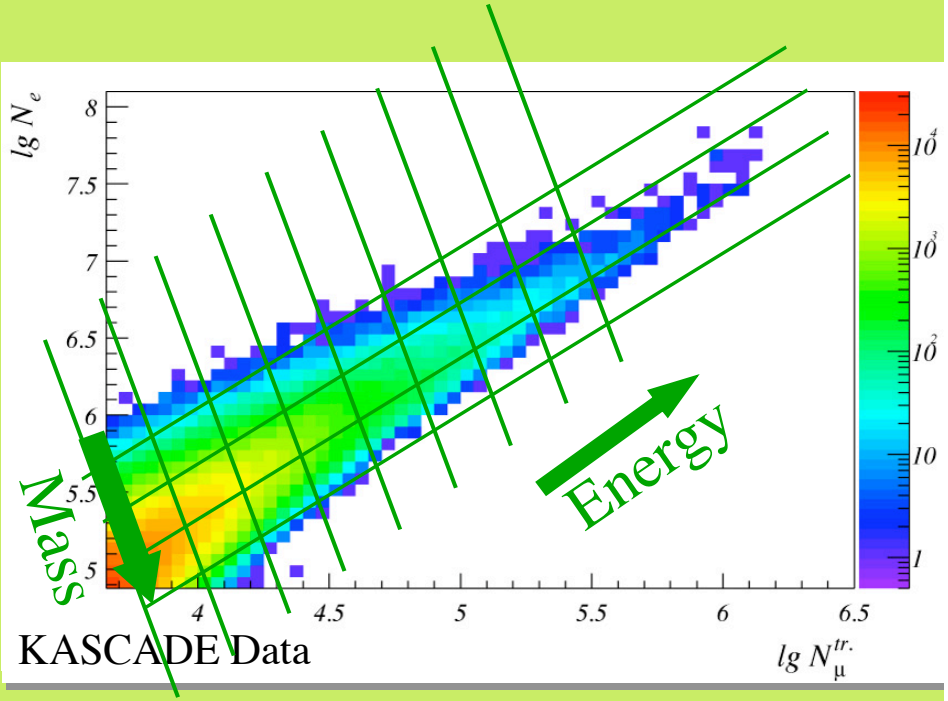
Muon Density Spectra $\rho_\mu^\star$



A.Haungs

(N_e , N_μ) ⇔ (Energy , Mass)





CORSIKA SIMULATIONS **DATA**

P + He + CNO + Si + Fe

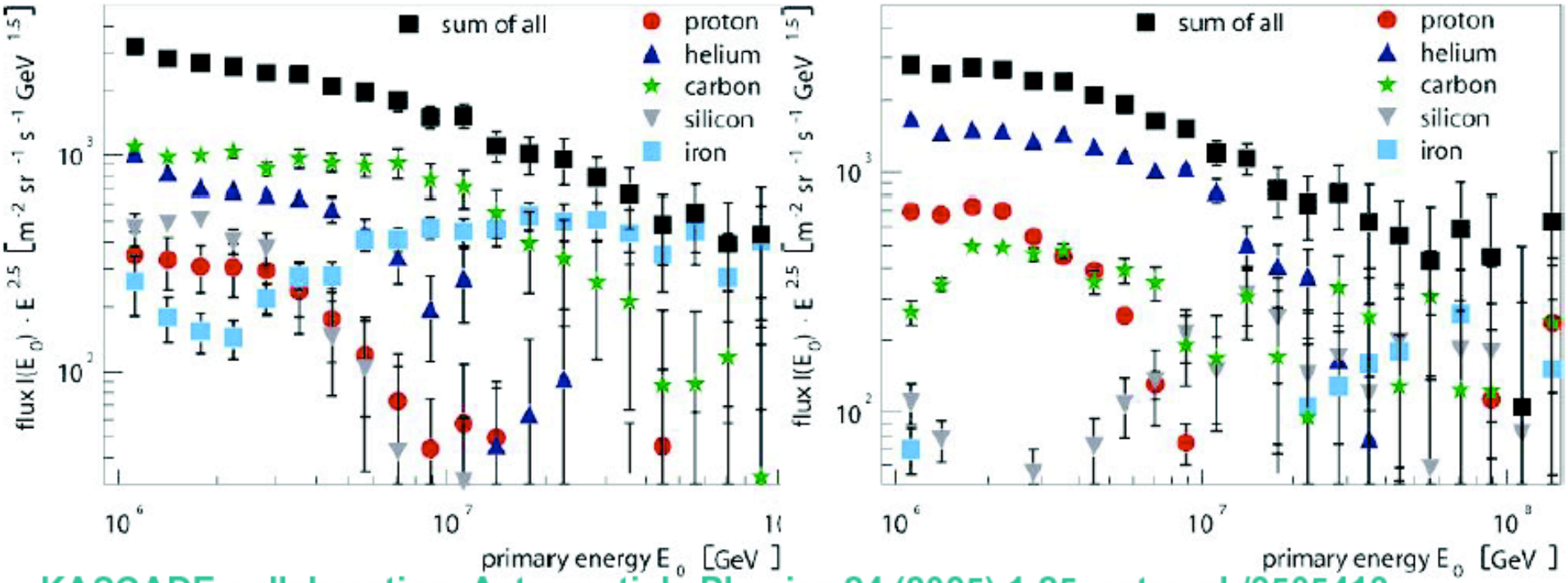
KASCADE results

Steepening of the lightest components $(E_\mu < GeV)$

- same unfolding but based on two different interaction models:
- SIBYLL 2.1 and QGSJET01 (both with GHEISHA 2002) all embedded in CORSIKA

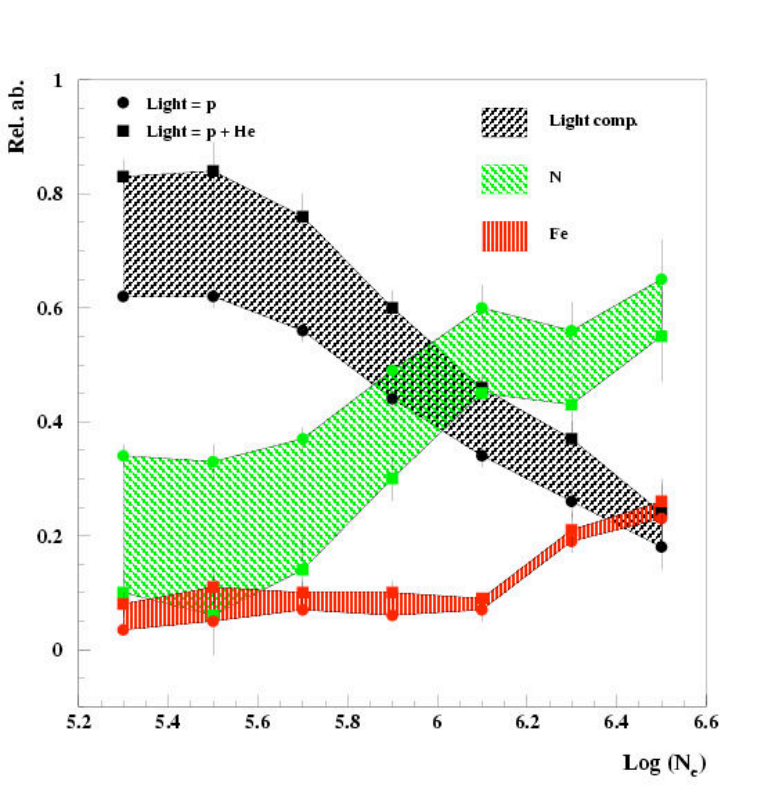
…model dependences, but not of general result

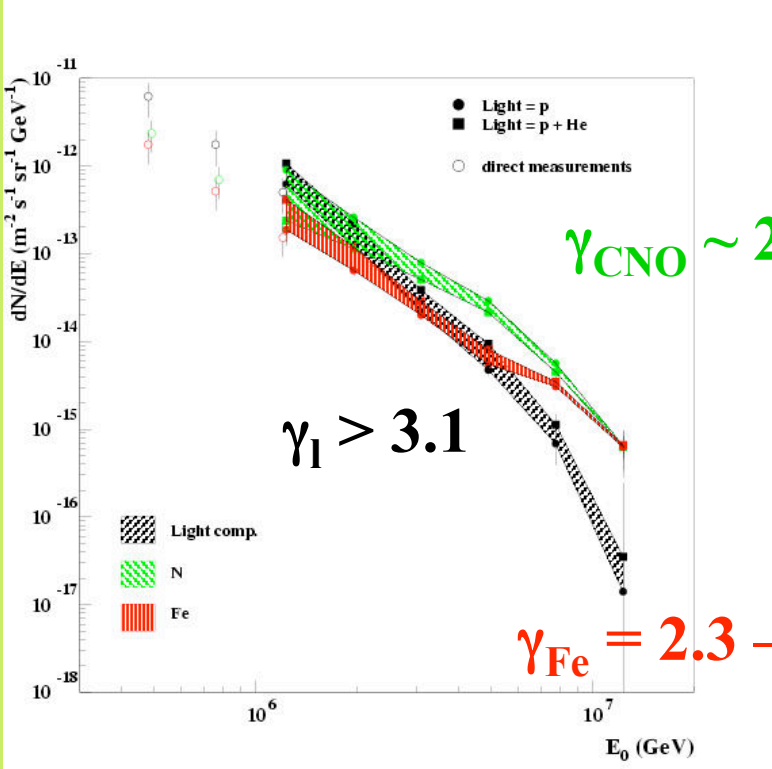
SIBYLL **QGSJet**



KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25, astro-ph/0505413

The composition in the ‘knee’ region
EAS-TOP





$\gamma_{CNO} \sim 2.75$

$\gamma_l > 3.1$

$\gamma_{Fe} = 2.3 - 2.7$

Mass group $\bar{\gamma}$
Heavier primary spectra harder ➔ $E_k \propto Z$?

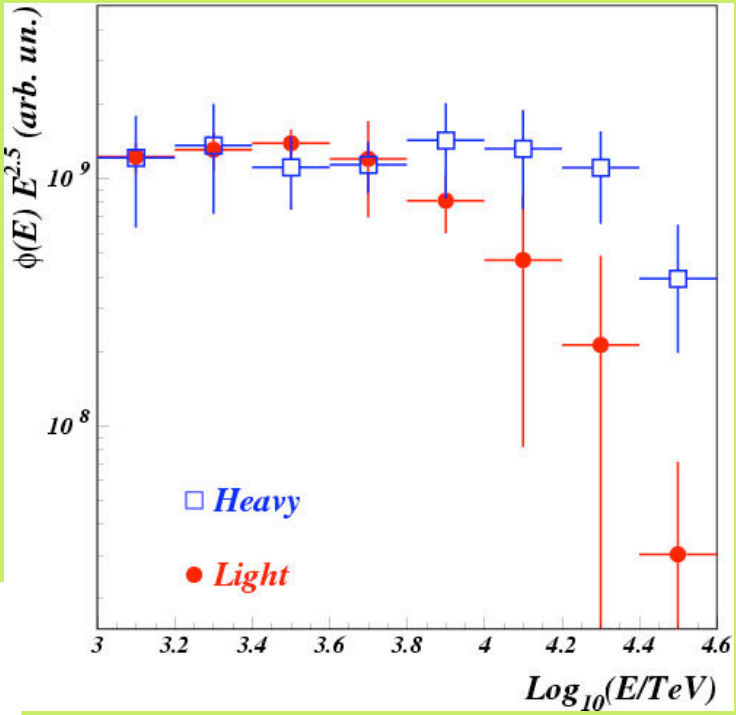
EAS-TOP & MACRO (TeV μ)
Composition at the knee

L = p + He H = Mg + Fe

5.92–6.15	0.50 ± 0.17	0.50 ± 0.24	12.2/9
6.15–6.35	0.30 ± 0.20	0.70 ± 0.32	4.7/10
6.35–6.70	0.24 ± 0.32	0.76 ± 0.45	8.4/8

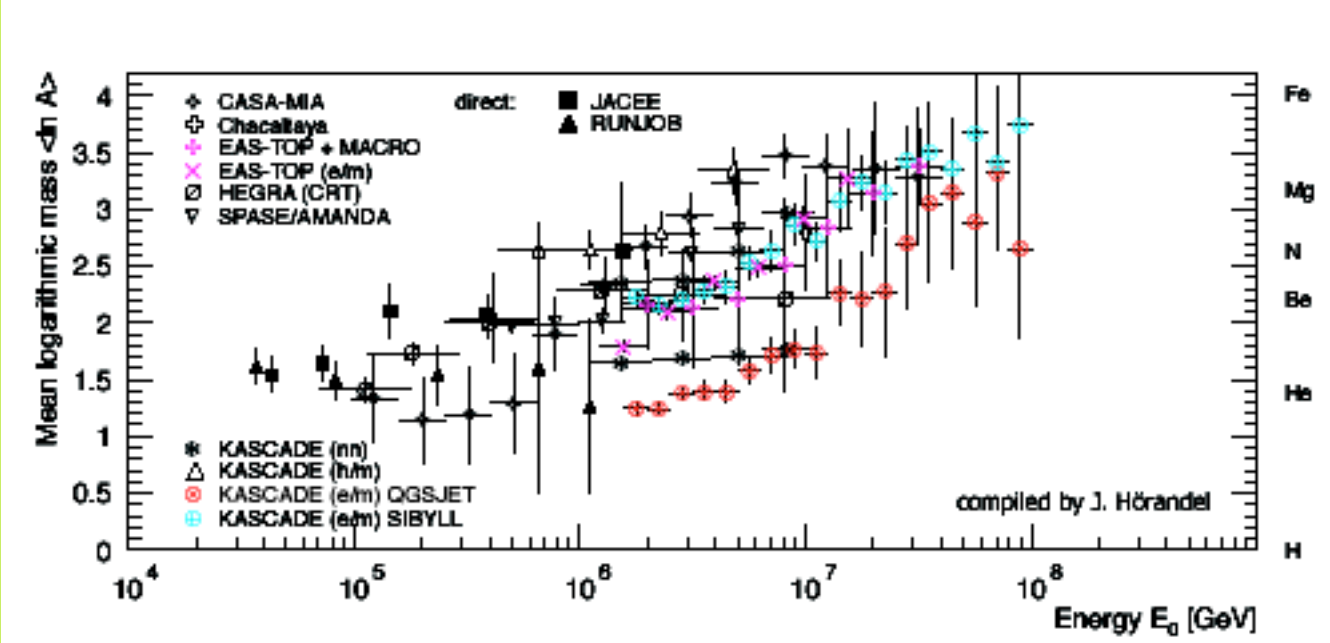
normalizations for the two components (L, H) as a function of s
vo parameters are correlated, so that errors are not independen

lering only two components in the primary beam. We ha
: a combination of p and Fe components, and a combinati
es: a "Light" (L) and "Heavy" (H) one, built with equal



Astrop. Phys., 20 (2004) 641

Evolution of composition from direct exp. and EAS Ne-Nμ data

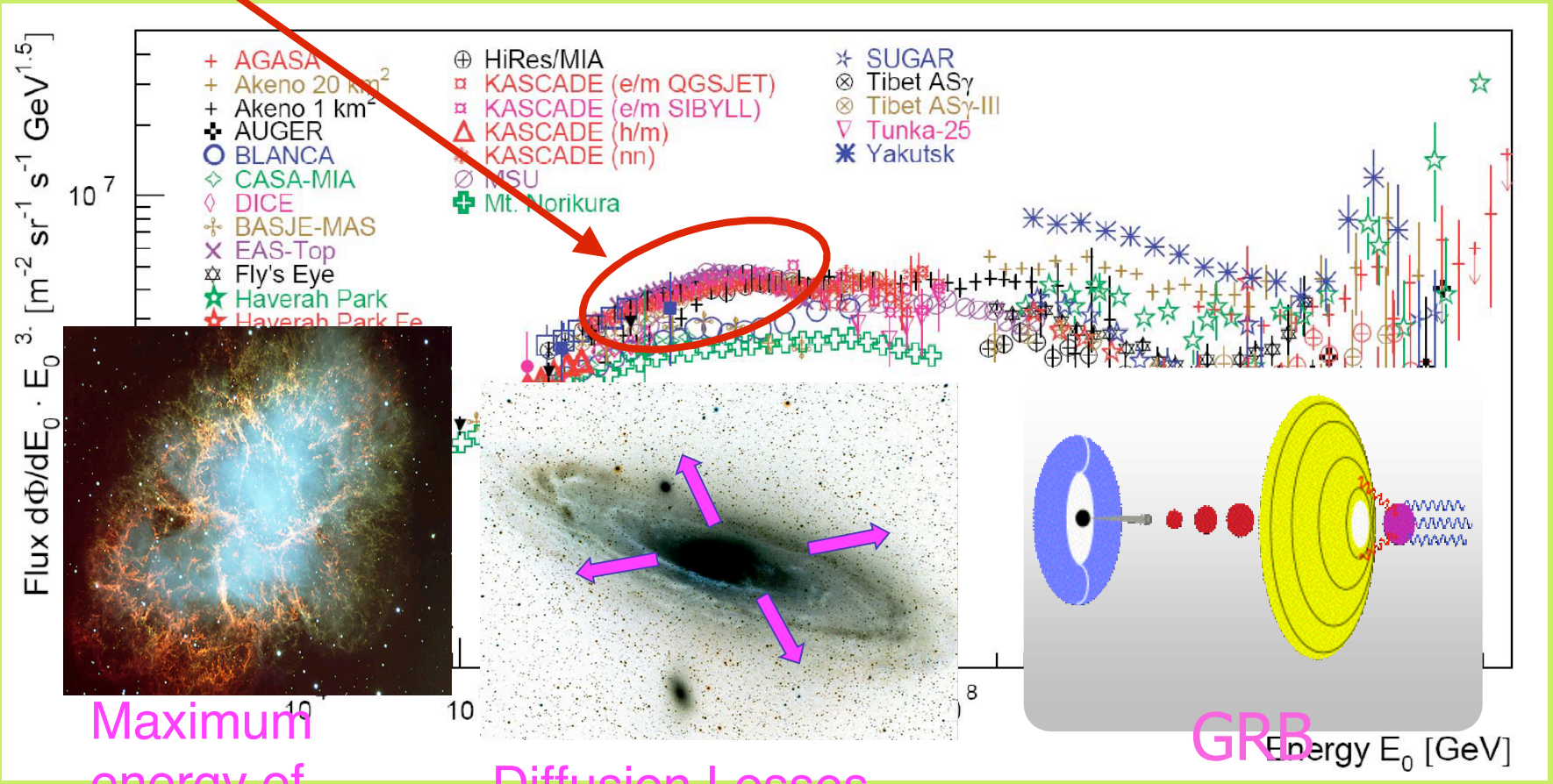


consistent with other observables

Features and problems: $S(E_0)*E_0^3$

"knee": source limit? Galactic containment? Cannoonball? HE?

$E_k(N) \sim Z \cdot E_k(p)$ **$E_k(N) \sim A \cdot E_k(p)$**

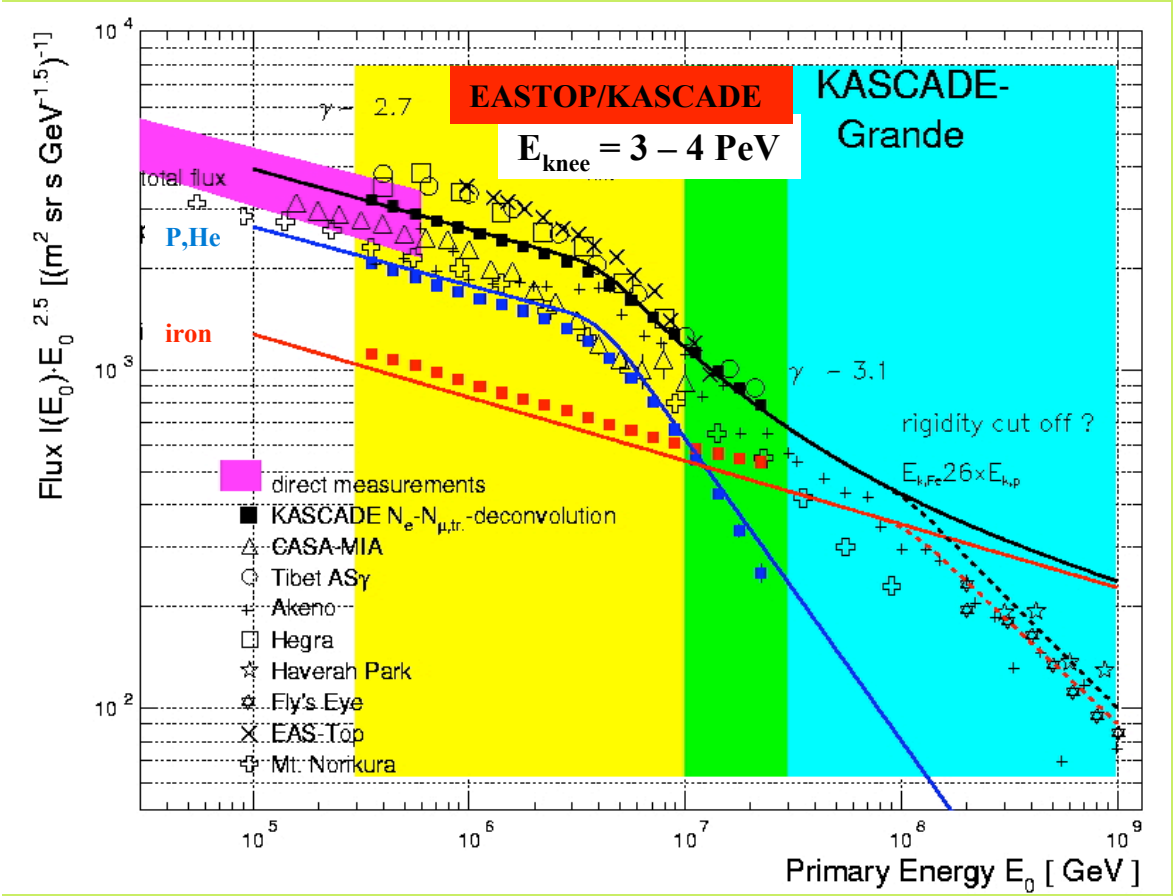


Maximum energy of accelerators ?

Diffusion Losses from Galaxy ?

GRB Cannon Ball Model

KASCADE-Grande: 0.5 km^2



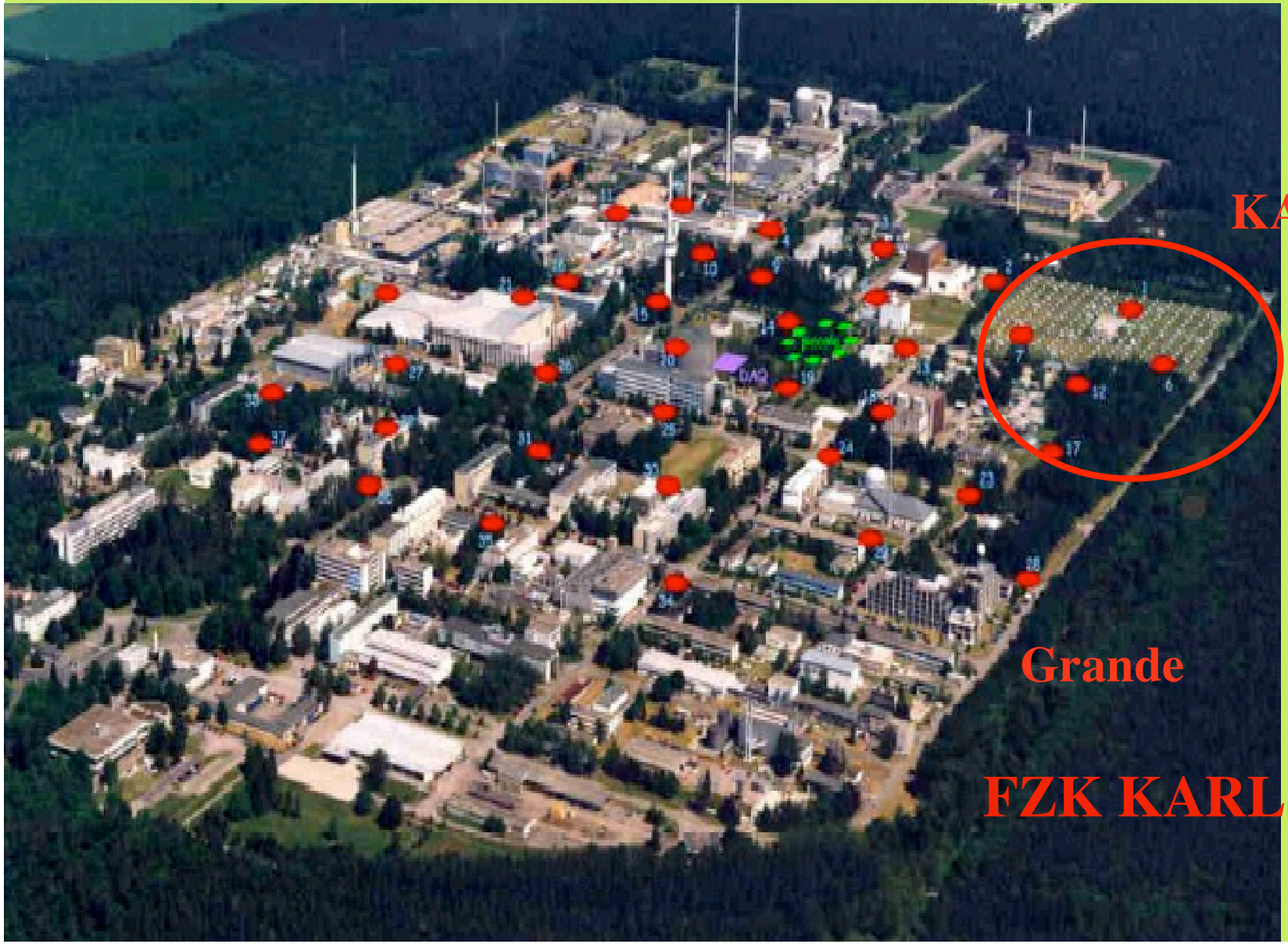
"Fe knee" ?

HE models ?

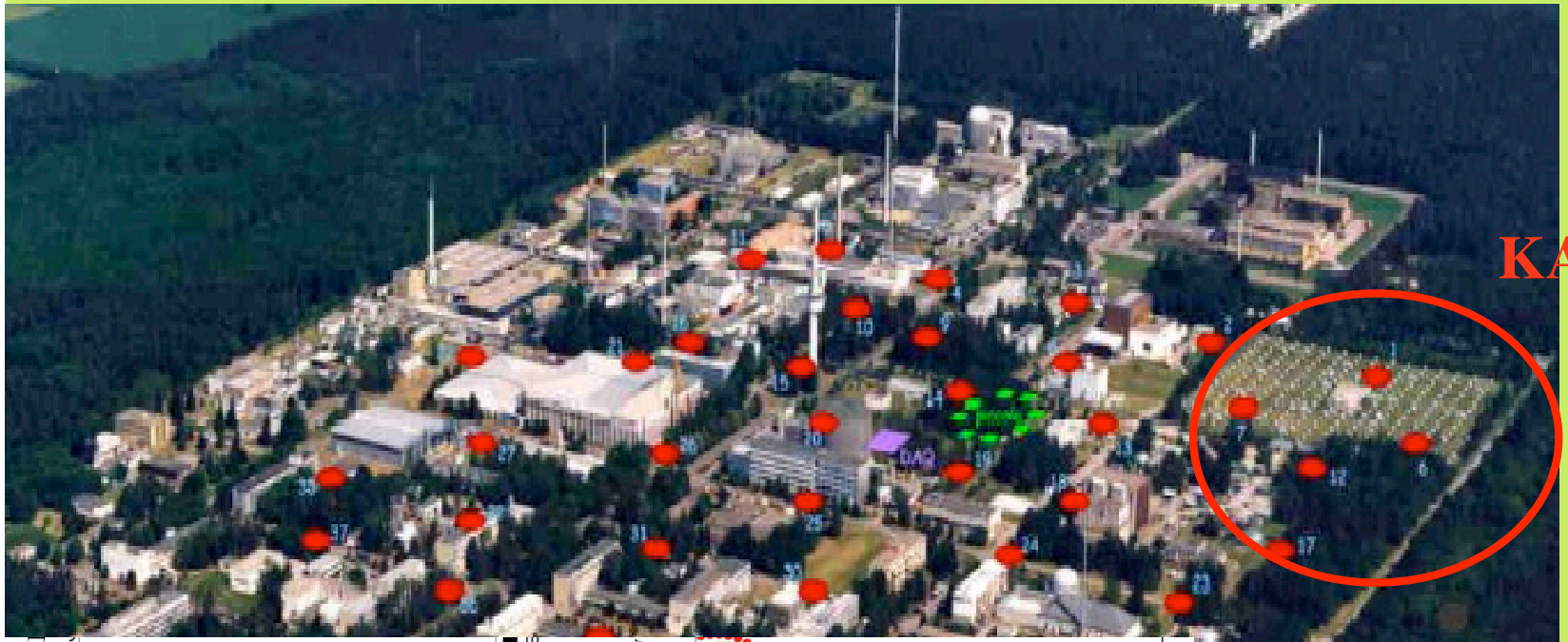
Energy det. & Flux?

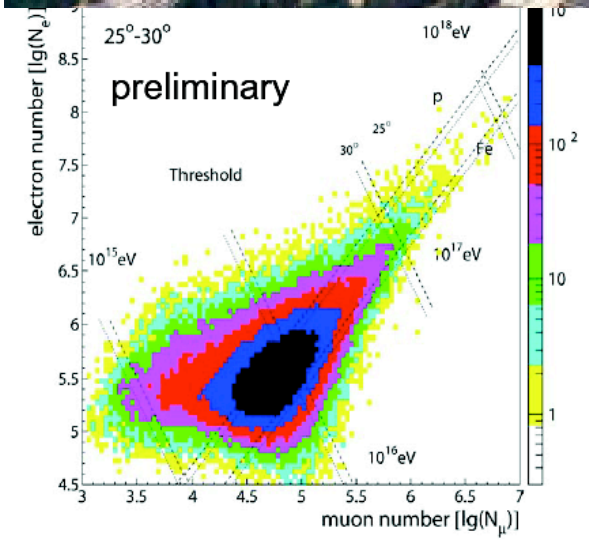
Extension of KASCADE acceptance without significant loss in accuracy

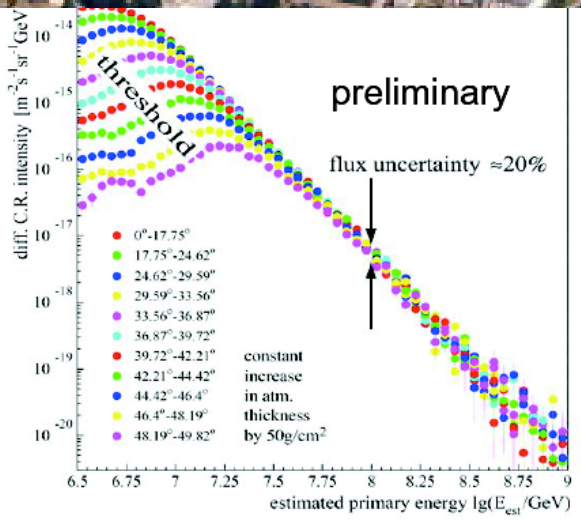
KASCADE-Grande 10^{16} - 10^{18} eV



KASCADE-Grande 10^{16} - 10^{18} eV



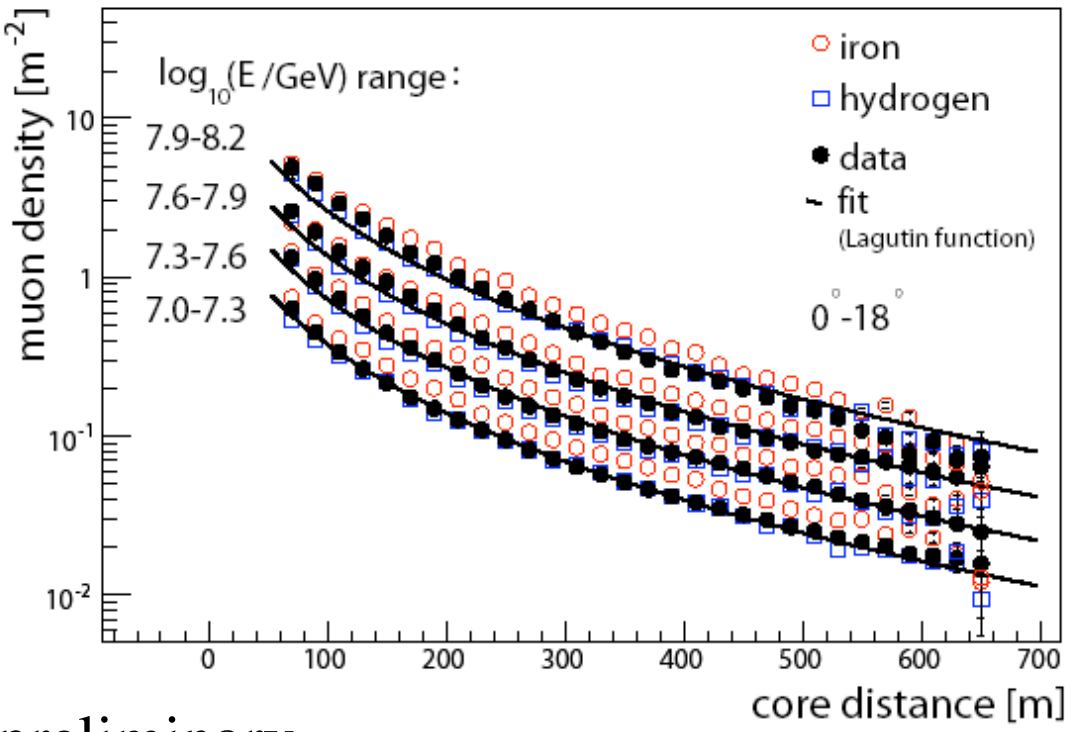




FZK KARLSRUHE

KASCADE-Grande muon LDF

Test of high energy hadronic interaction models at
$E_0 = 10^{16} - 10^{17}$ eV

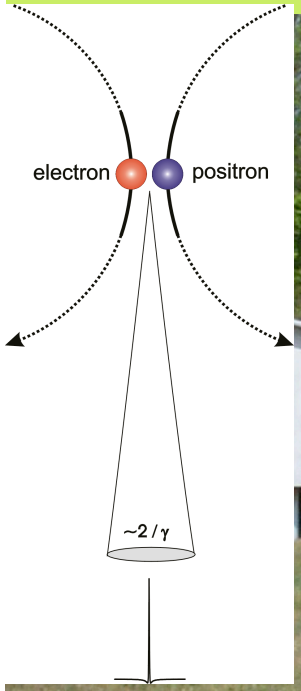


preliminary

Figure 3. Lateral density distributions of muons measured with KASCADE-Grande compared with simulated distributions.

LOPES radio detection

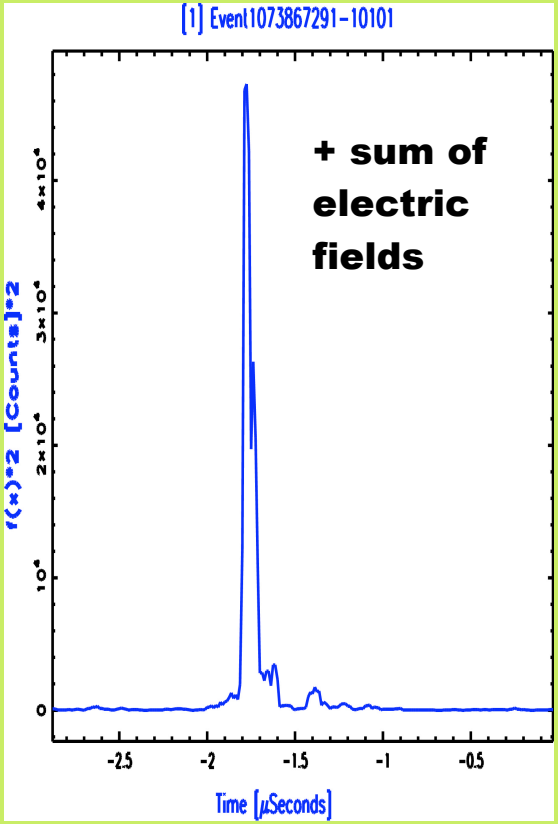
LOPES radio detection



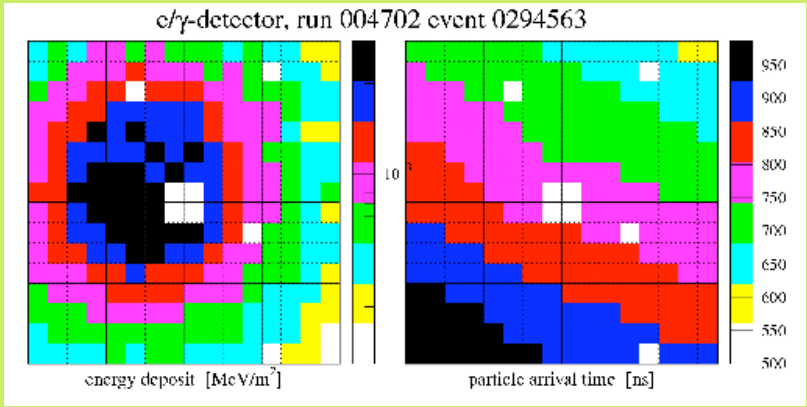
- deflection of electron-positron pairs in the Earth's magnetic field
  → coherent emission at low frequencies

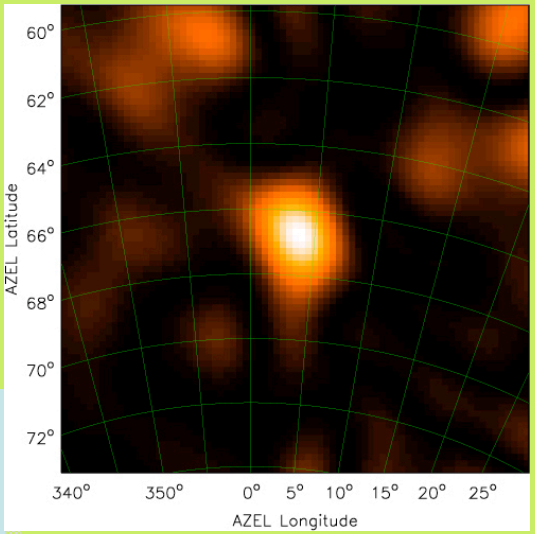
- with radio detection
  → see shower development
  → observe 24 hrs/day

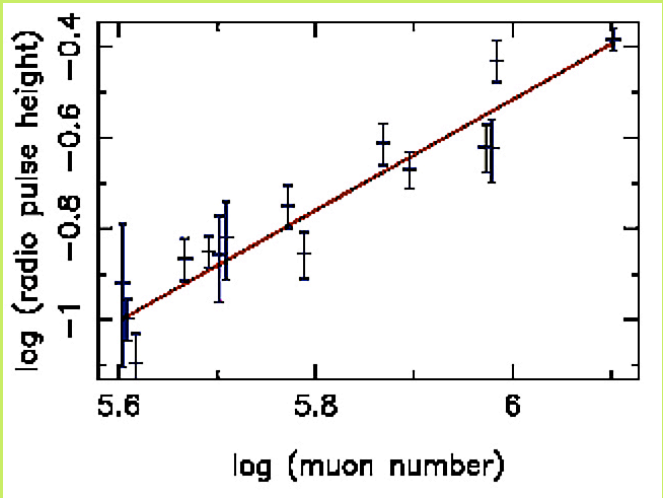
LOPES 10 Analysis



- energy ≈ 10^{17} eV
- EAS core inside antennas
- Θ = 25.5°, Φ = 42.5°
- signal is coherent







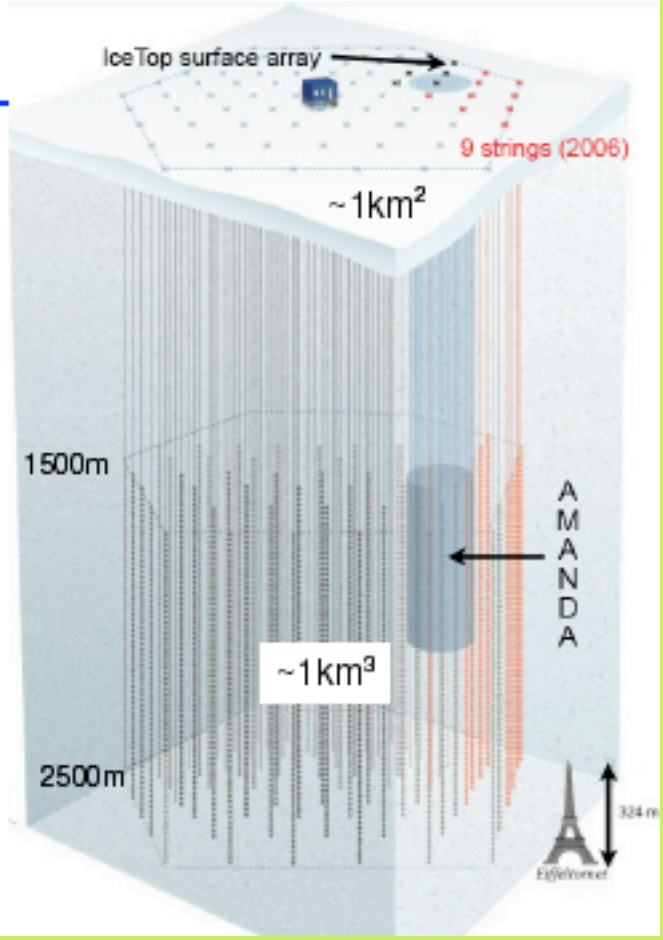
data analyses:
- EAS analyses KASCADE
- radio signal analyses
- sky mapping

LOPES collaboration, Nature 425 (2005) 313

IceCube Detector

2006 / expected 2007 / ~2011

- Icetop: 16 (26,80) stations, 2 tanks per station with 2 DOMs each
- AMANDA: 677 OMs @ 19 strings (completed 2000)
- IceCube: 9 (21-23,70-80) strings with 60 DO 22 each
- 11th string this season



Several depths and muon energies

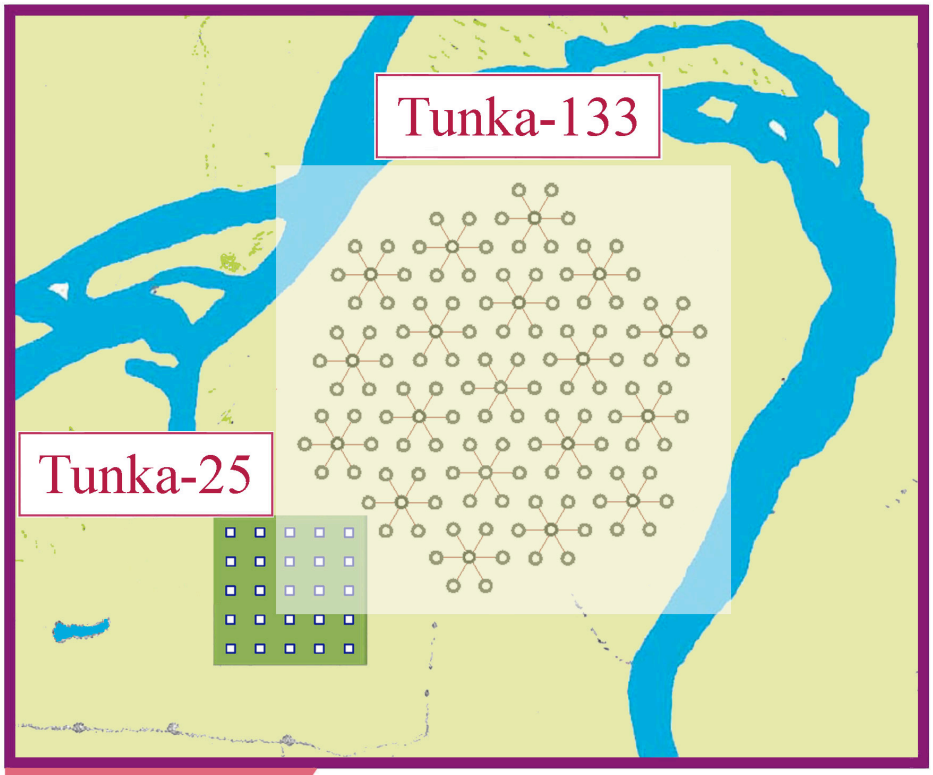
TUNKA array:

0.8 Km^2

CERENKOV LIGHT

URL:

http://dbserv.sinp.msu.ru/tunka



51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

Telescope Array

576 plastic scintillation Surface Detectors (SD)

5 communication towers

$3m^2$ 1.2cm t two layers

Atmospheric fluorescence telescope 3 stations **FD**

1.2km spacing

20km

Sensitivity of SD : ~9 x AGASA

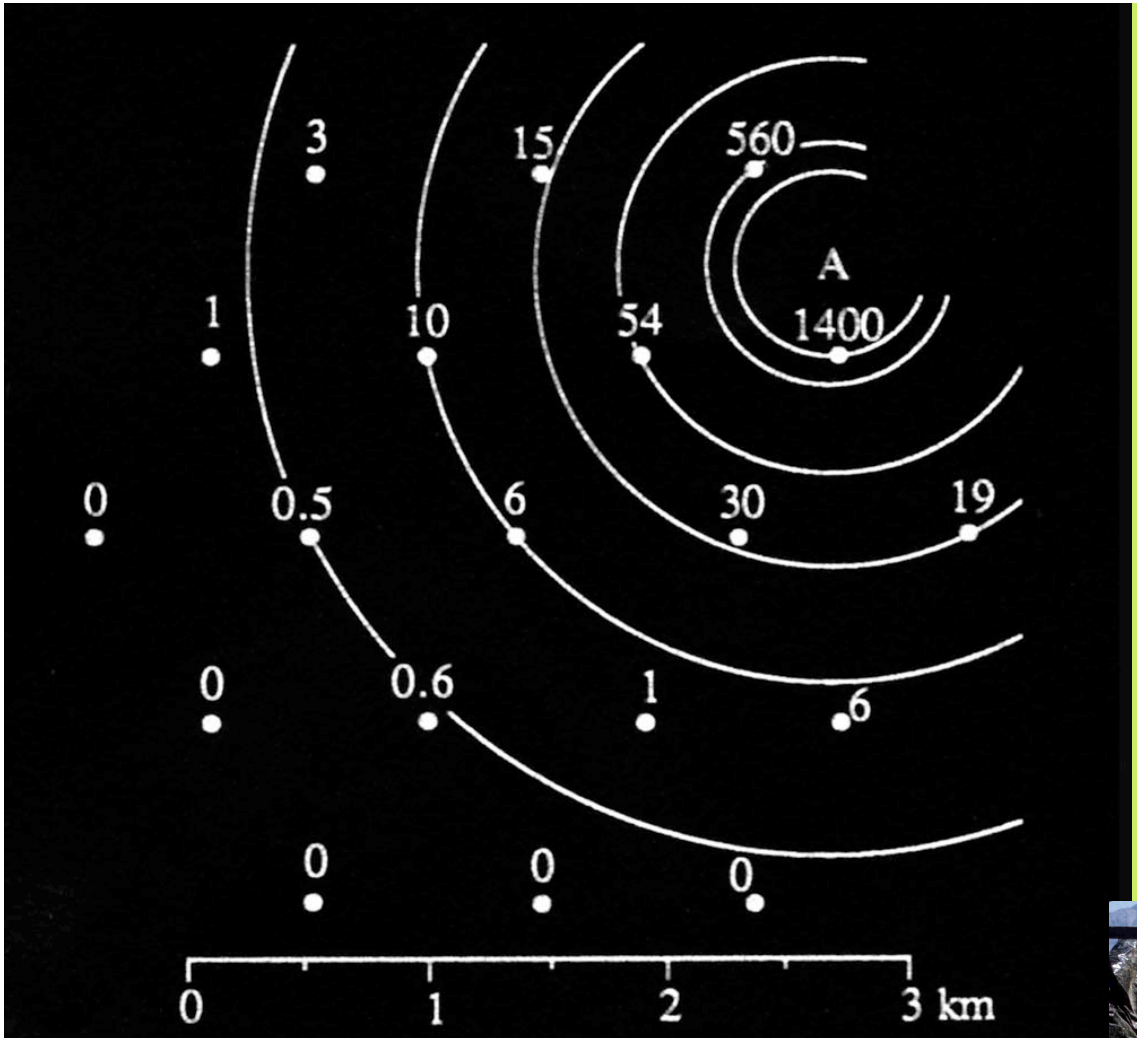


FIGURE 1

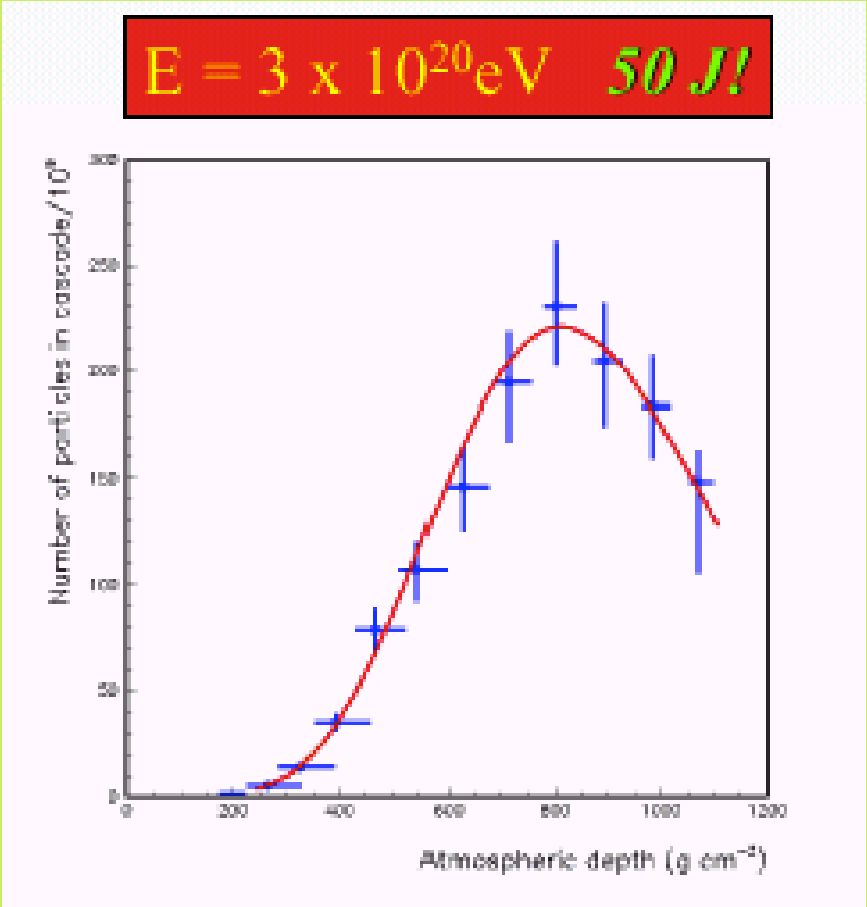
The first event[1] claimed to be due to a primary cosmic ray of 10^{20}eV. The black dots are 3.3m² detectors on a 884m grid. The circles are contours of equal density: A marks the core.

Volcano Ranch
10^{20} eV
J. Linsley
Phys. Rev. Lett.10, 146 (1963)

Particle density measurements at ground (scintillators)

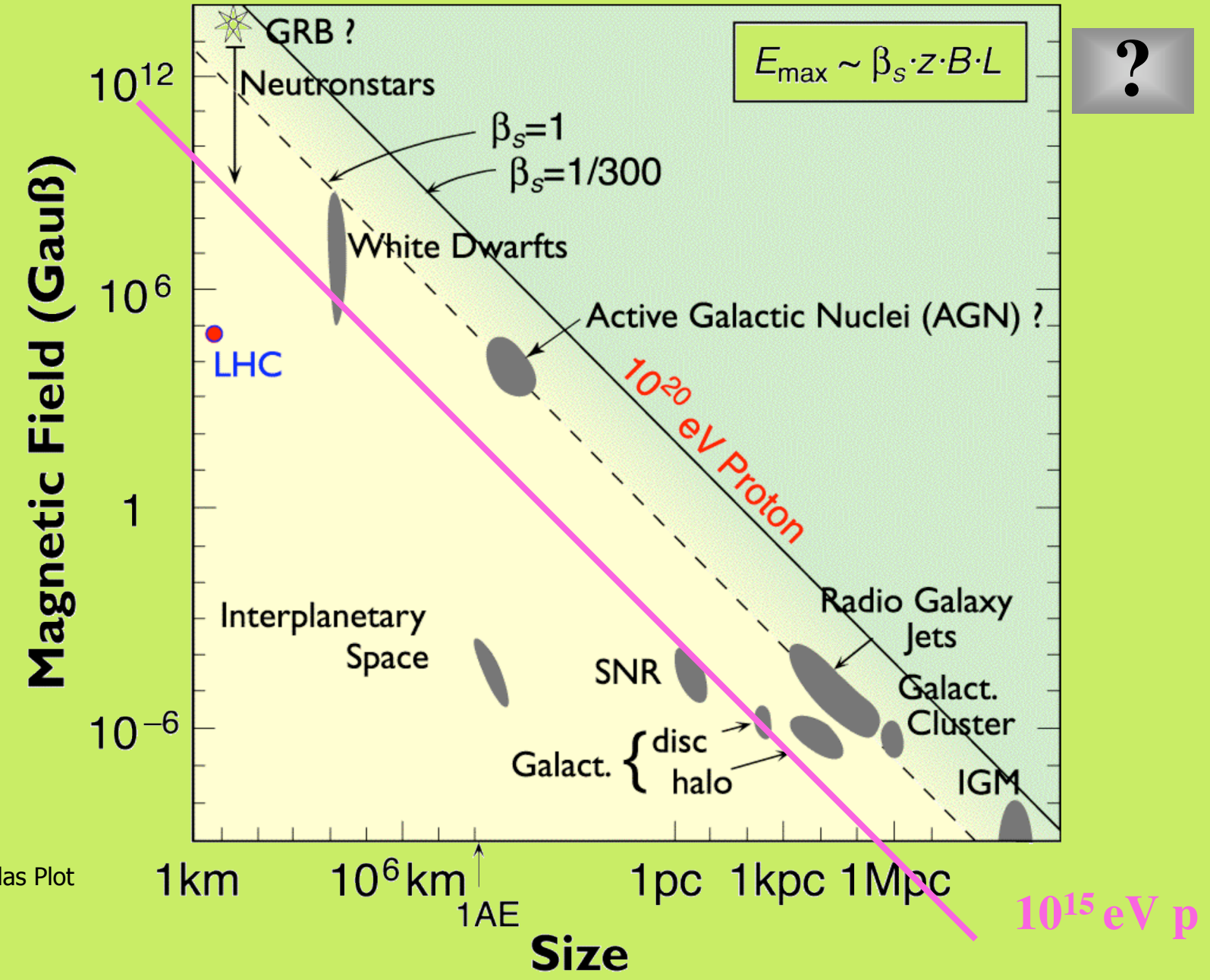
The Fly‘s Eye in UTAH

Fluorescence light in atmosphere



Bird et al, Ap.J., 441, 144 (1995)

?? SOURCE CANDIDATES ??

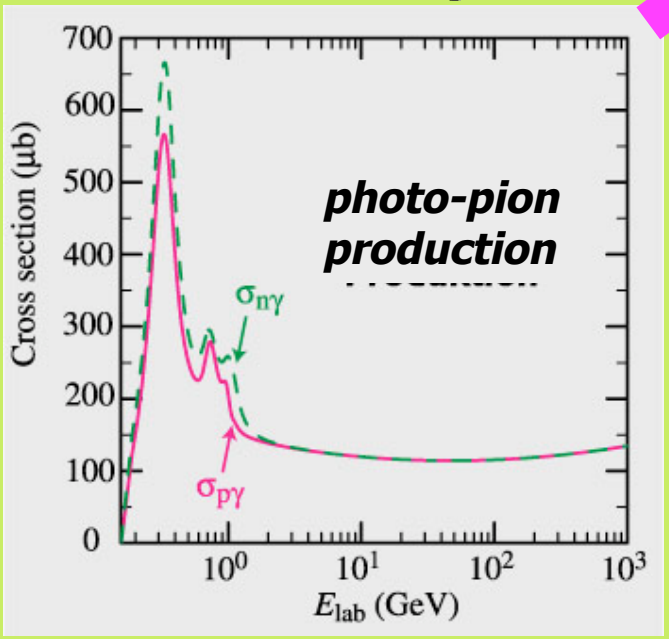


Hillas Plot

GZK-Effect

protons with $E>6\cdot10^{19}$ eV scatter with CMBR

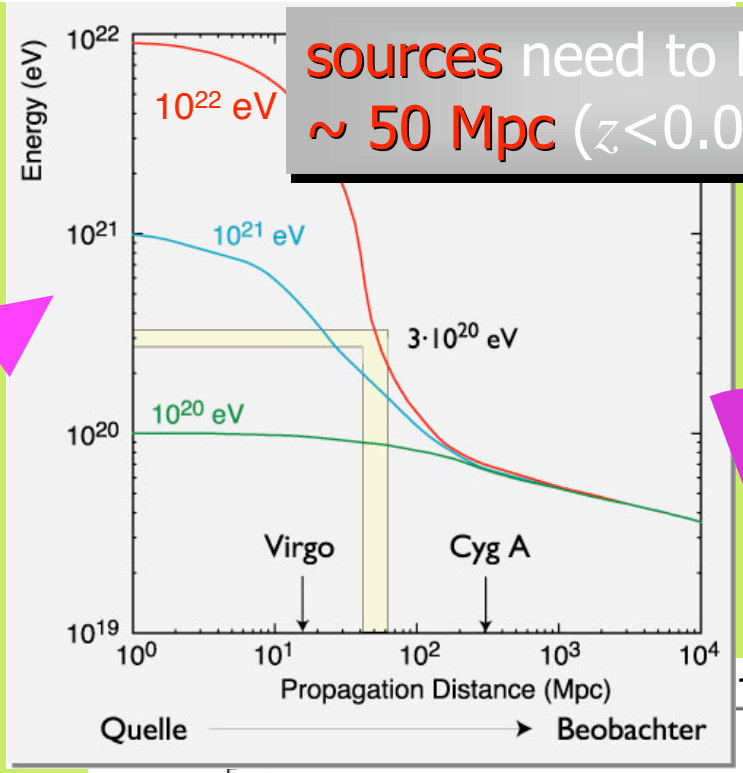
(Greisen - Zatsepin - Kuzmin)



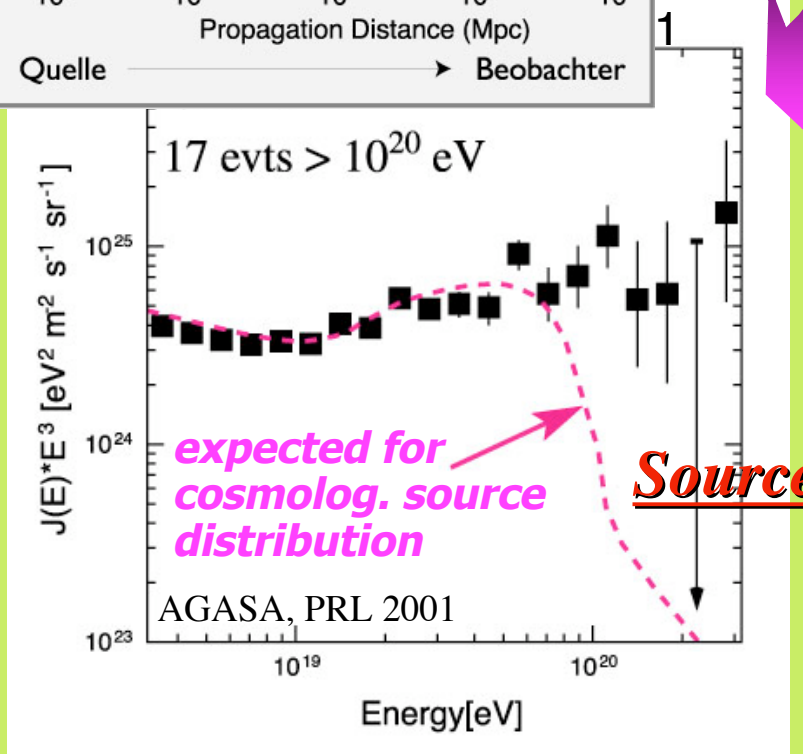
$$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0 \; ; \; n + \pi^+$$

threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

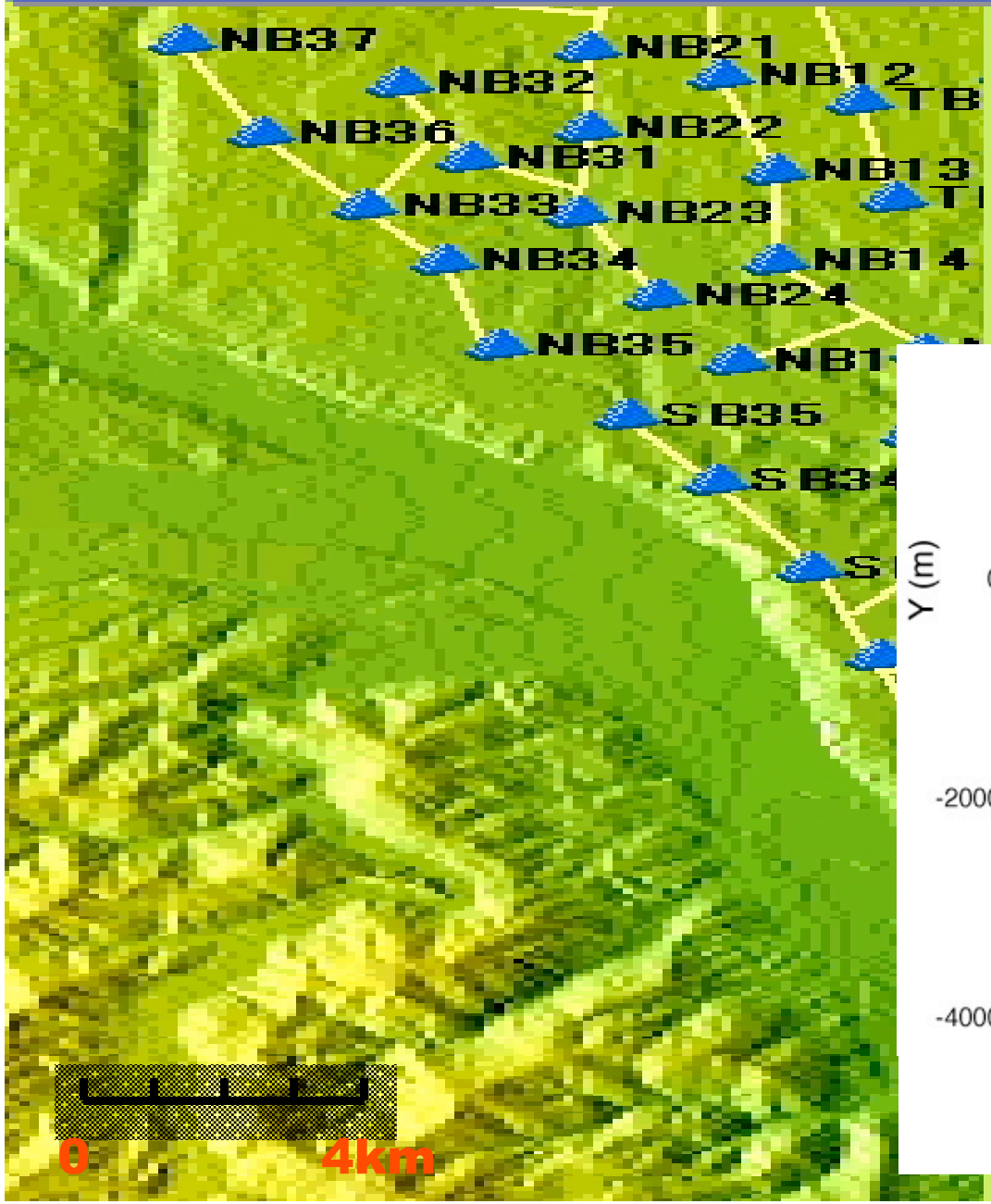
$\Rightarrow E_{GZK} \approx 6\cdot10^{19}$ eV



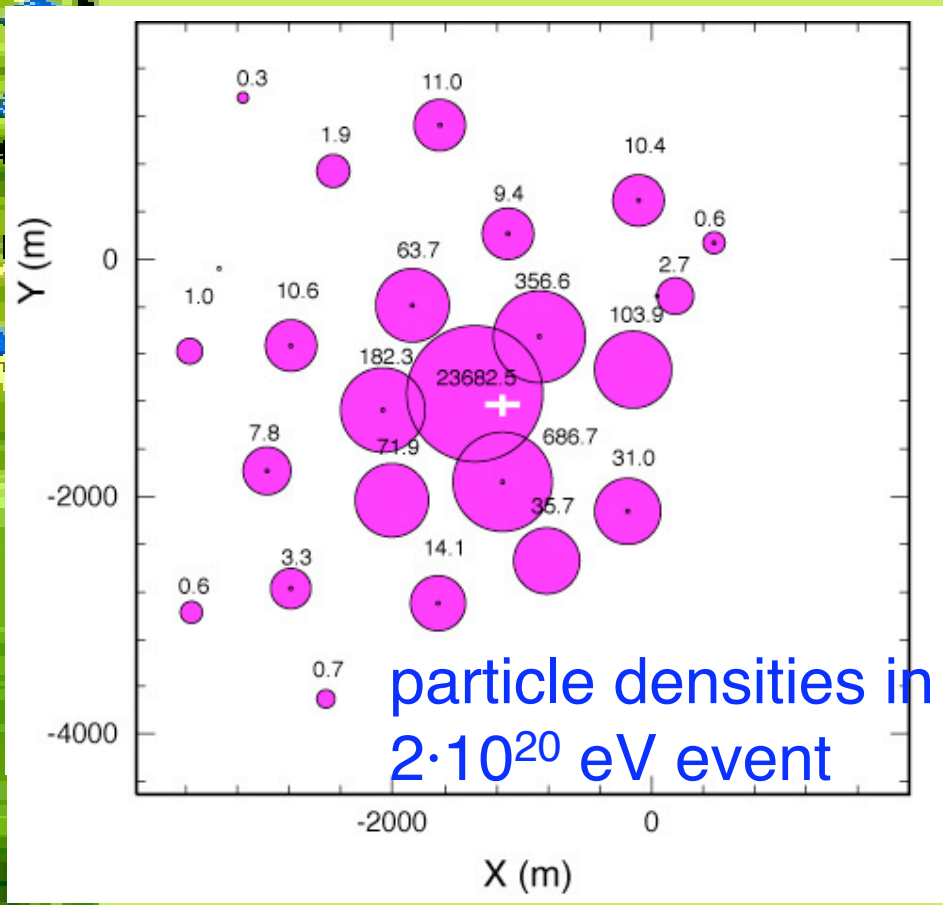
sources need to be within ~ 50 Mpc (z<0.01) !



Akeno Giant Air Shower Array



100 km^2 Area in Akeno
111 scintillation counters
á 2.2 m^2 area
closed down Jan. 04



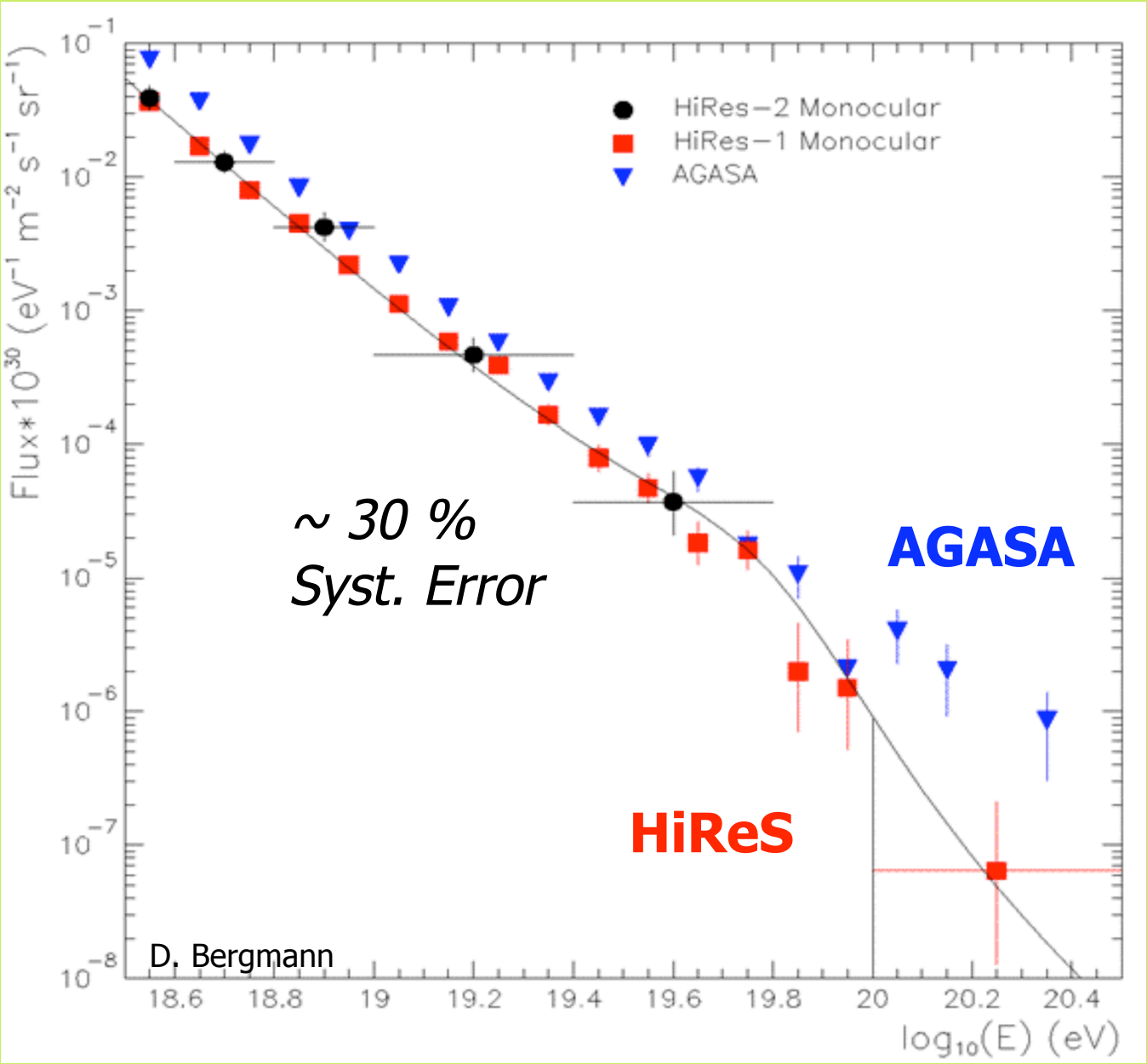
particle densities in $2 \cdot 10^{20}$ eV event

High Resolution Fly's Eye: HiRes

- 21 Mirrors
  - 360 deg in azimuth
  - 3-17 deg in elevation
- Sample & Hold DAQ
- Began observation in June 1997

- 42 Mirrors
  - 360 deg in azimuth
  - 3-33 deg in elevation
- FADC DAQ
- Began observation in October 1999

HiRes vs AGASA



?

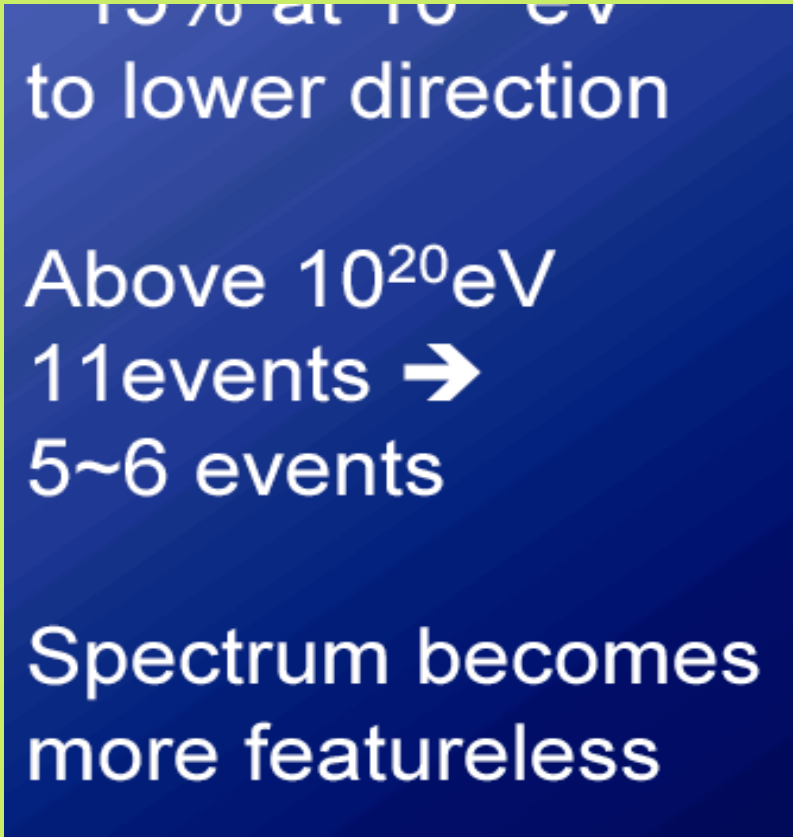
?

AGASA UNCERTAINTIES (M. Teshima)

Possible energy overestimation up to 45 deg.

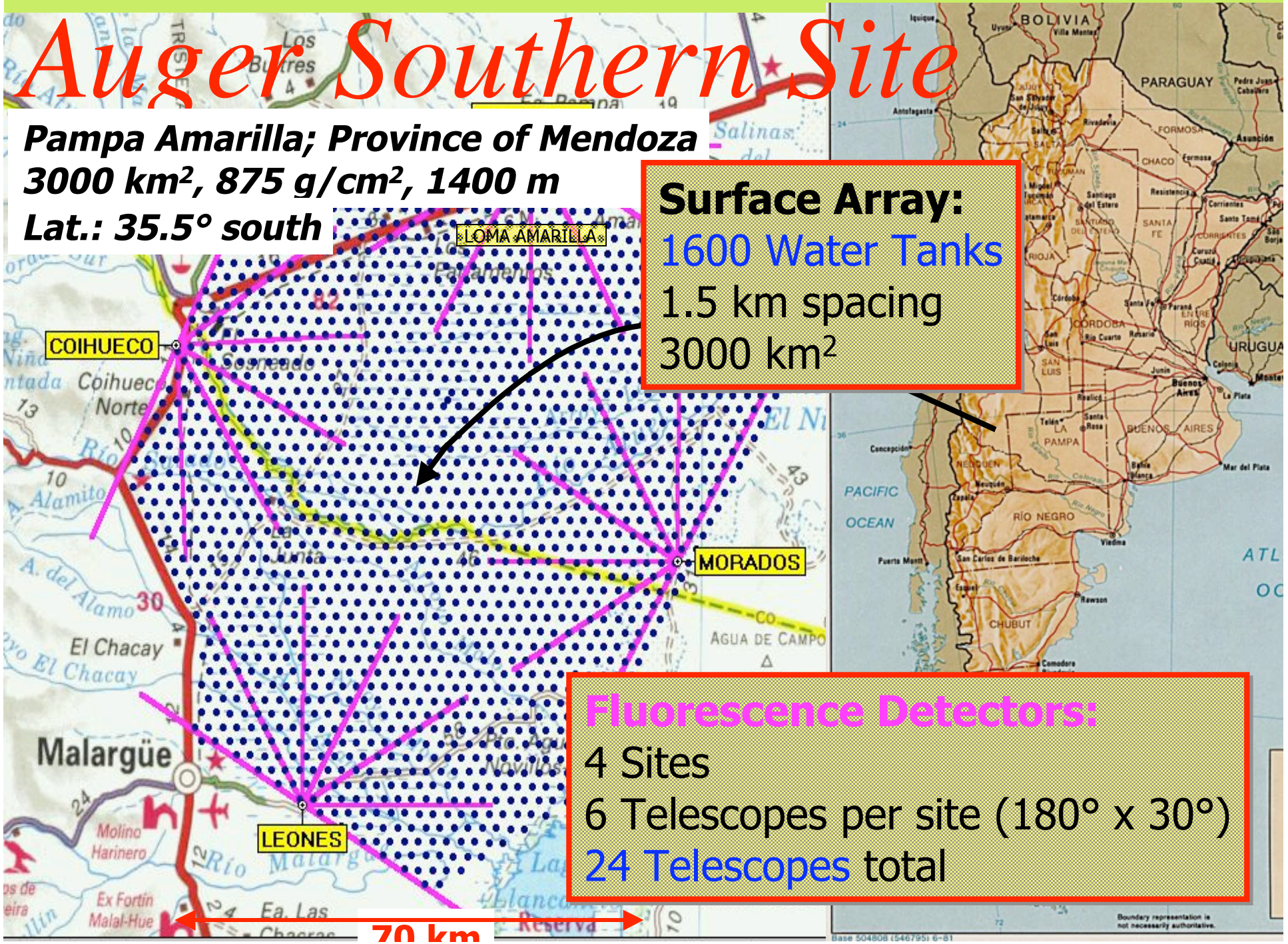
-real uncertainties on real data

- Super-GZK events still exist



Auger Southern Site

Pampa Amarilla; Province of Mendoza
3000 km², 875 g/cm², 1400 m
Lat.: 35.5° south

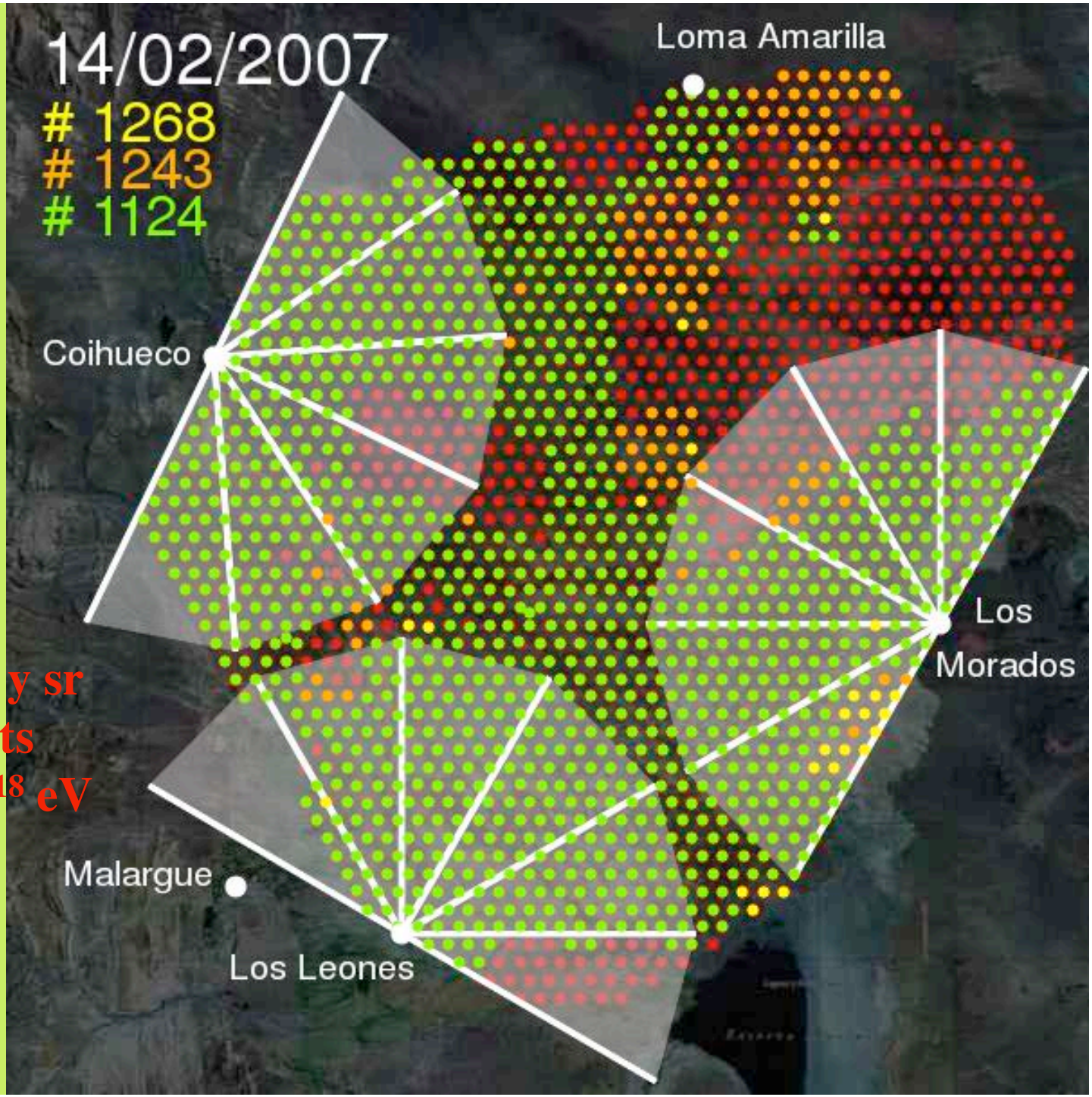


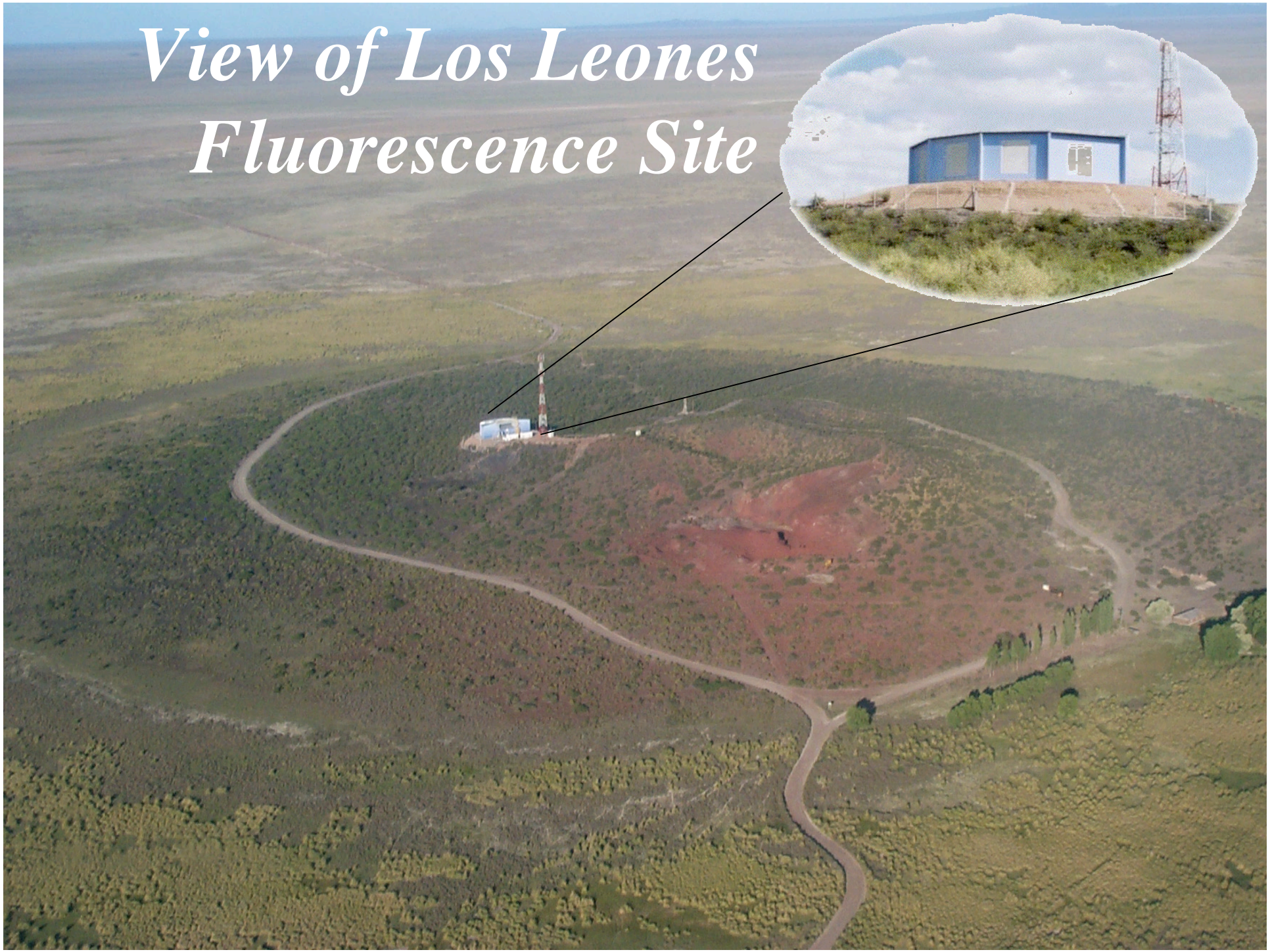
Surface Array:
1600 Water Tanks
1.5 km spacing
3000 km²

Fluorescence Detectors:
4 Sites
6 Telescopes per site (180° x 30°)
24 Telescopes total

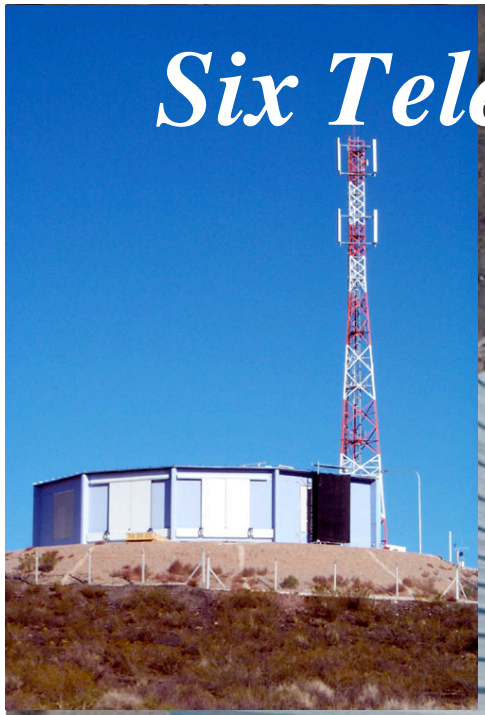
Auger today

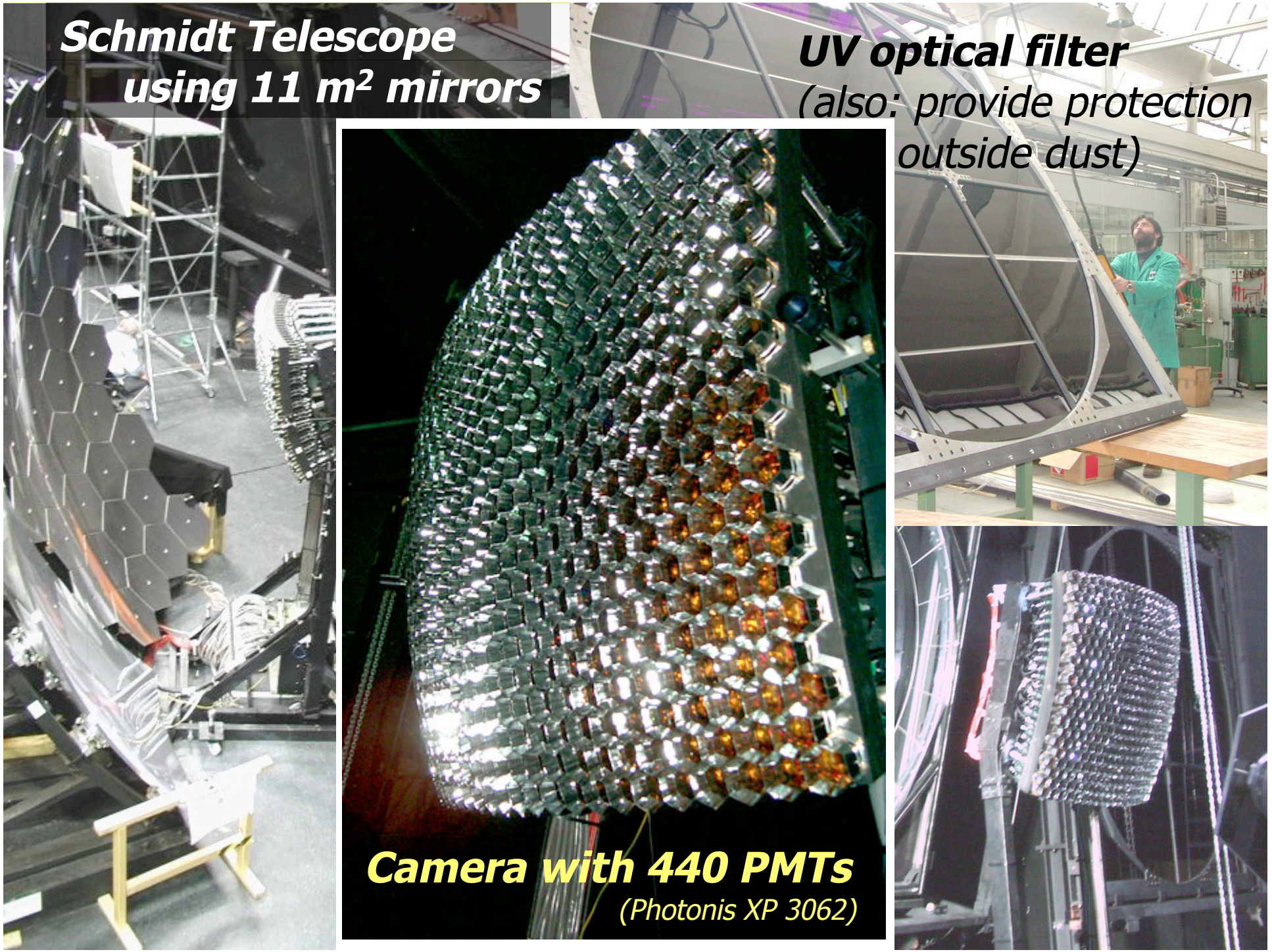
Exp ~ 5000 km^2 y sr
Tot ~ 5 10^5 events
>10^4 above 3.10^{18} eV
(full efficiency)




View of Los Leones
Fluorescence Site

Six Telescopes viewing 30°x30° each




Schmidt Telescope
using 11 m² mirrors
UV optical filter
(also: provide protection
outside dust)
Camera with 440 PMTs
(Photonis XP 3062)

Atmospheric Monitoring

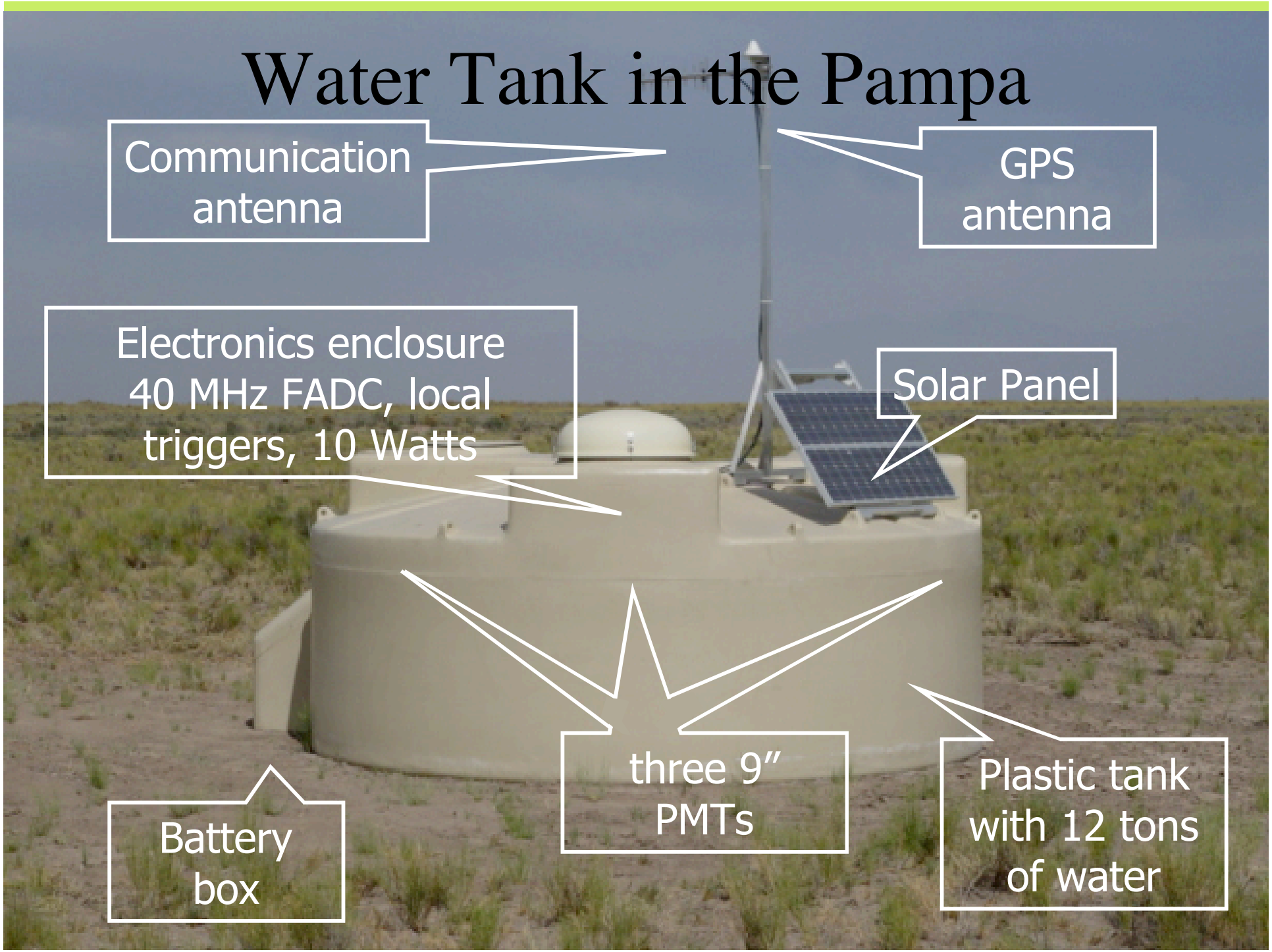
- LIDAR at each eye
- cloud monitors at each eye
- central laser facility
- regular balloon flights

↳**light attenuation length**
↳**Aerosol concentration**
(Mie scattering)

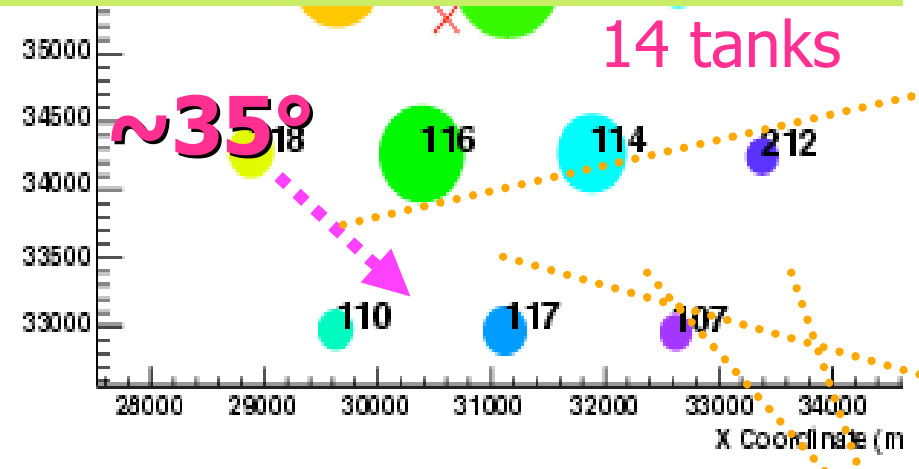
Balloon probes ↳ (*T,p*)-profiles

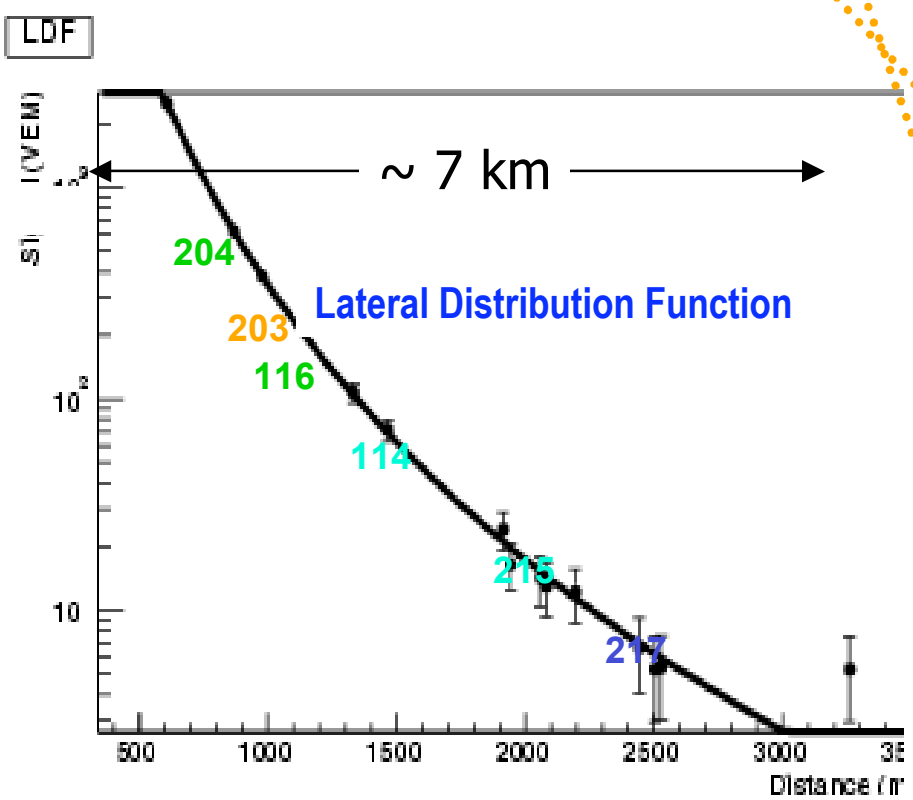
Aligned Water Tanks as seen from Los Leones

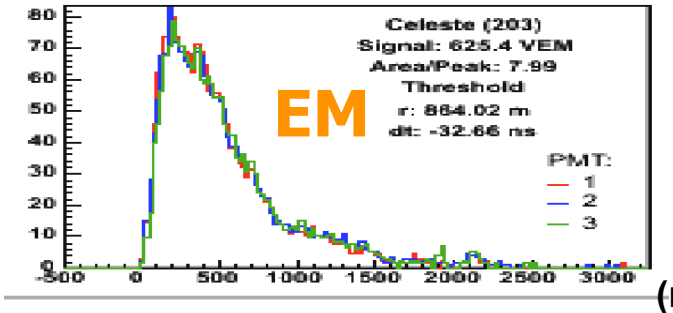
Water Tank in the Pampa



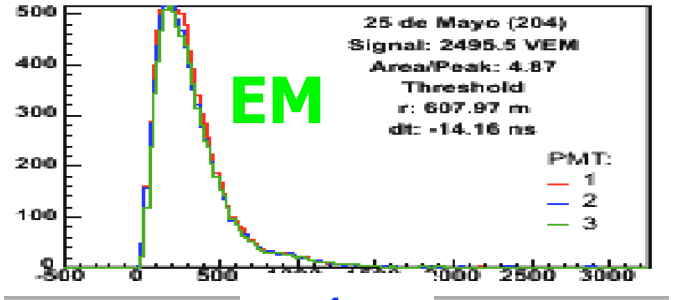
A typical ‘young’ shower (zenith~35°)





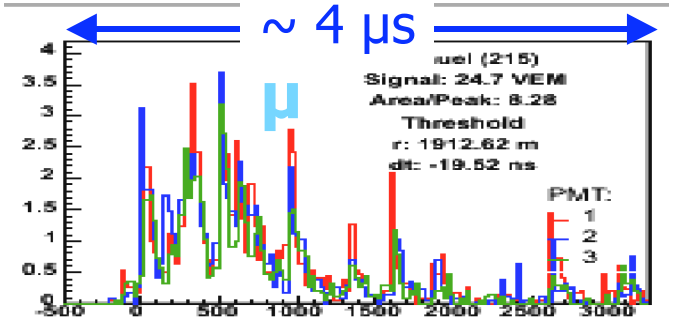


203



204

~ 4 μs



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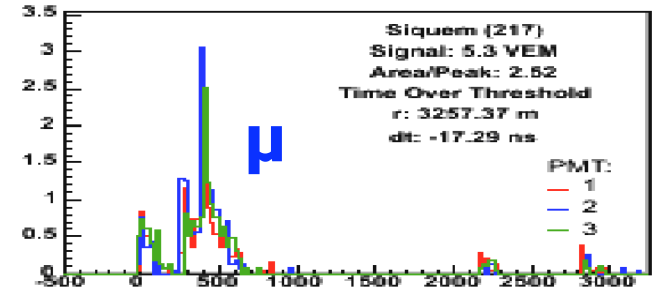
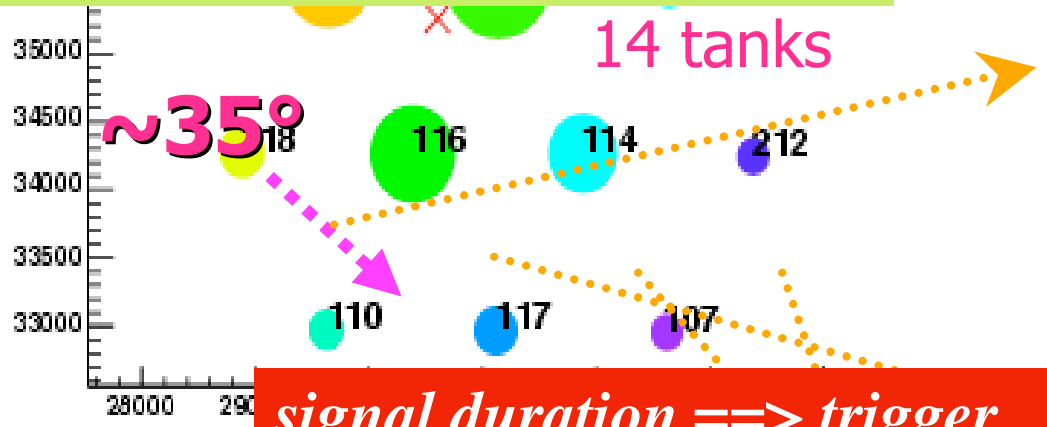
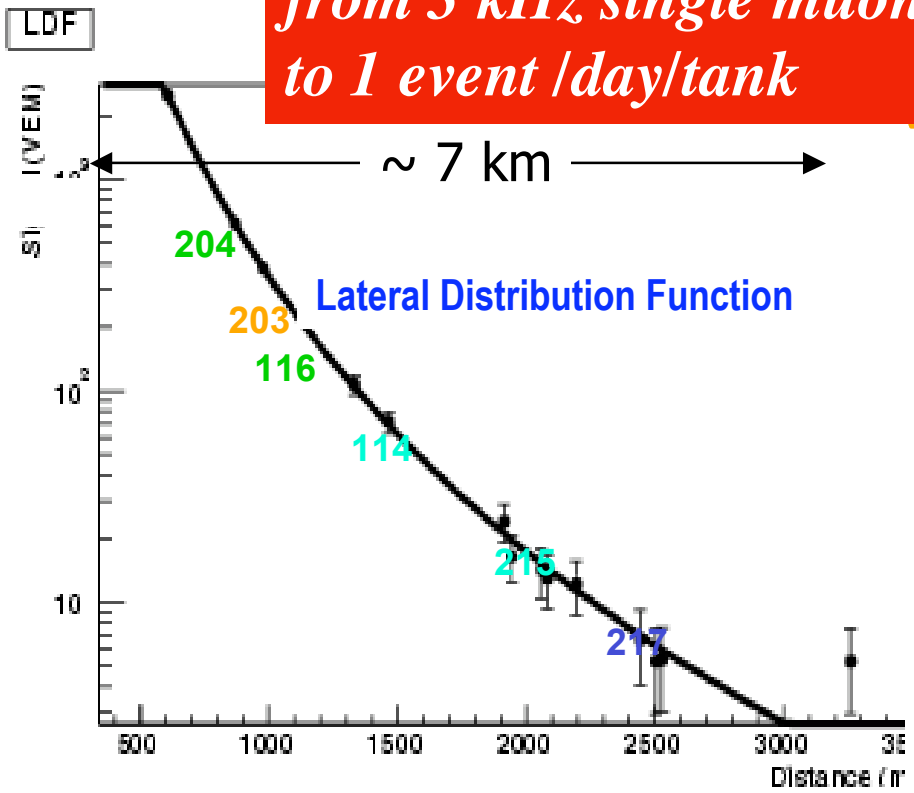


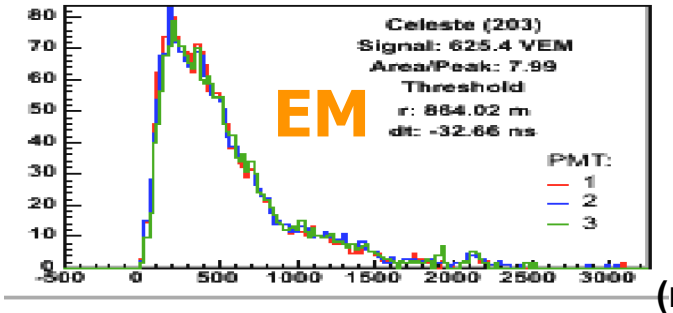
217

A typical ‘young’ shower (zenith~35°)



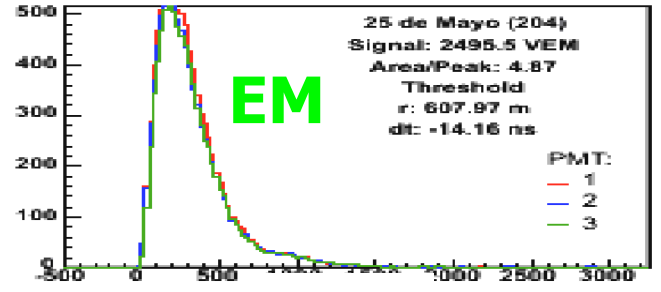
signal duration ==> trigger from 3 kHz single muon rate to 1 event /day/tank





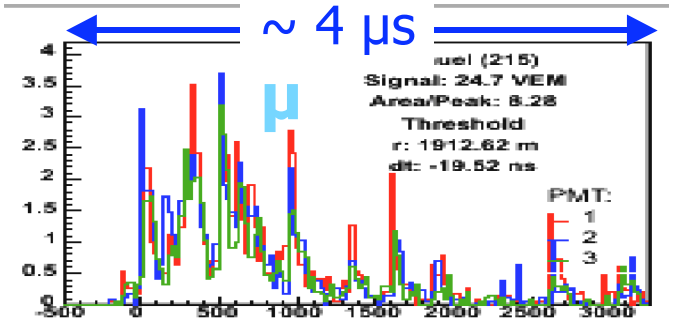
203

(nsec)



204

~ 4 μs



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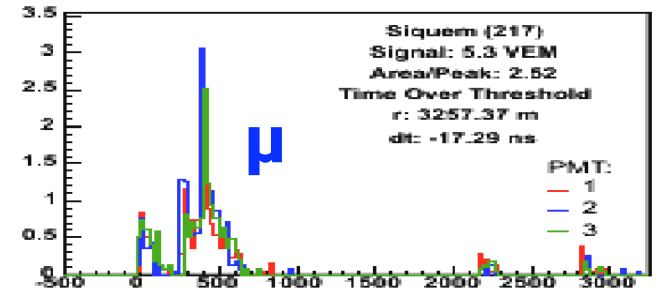
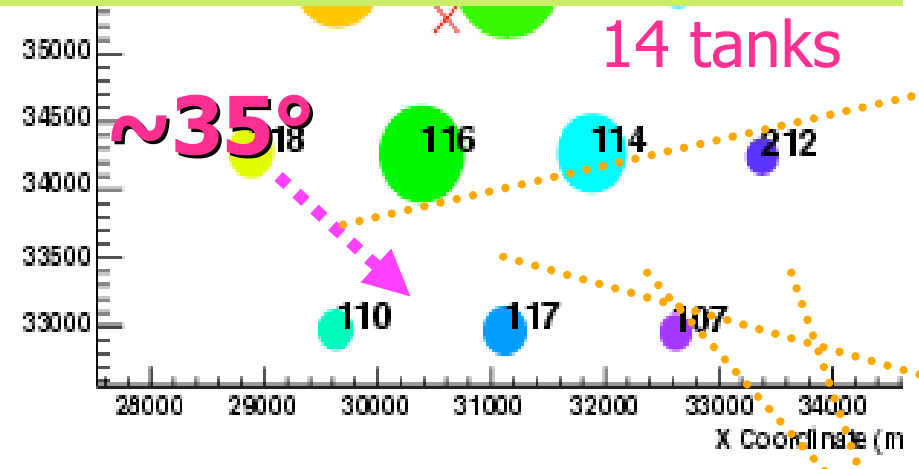
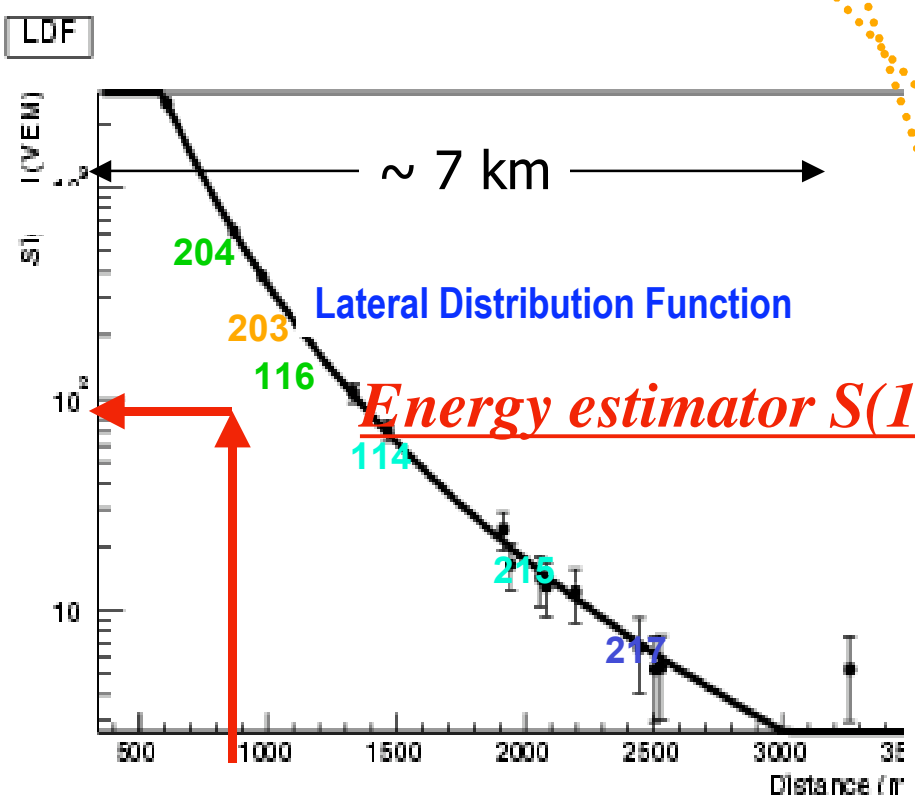
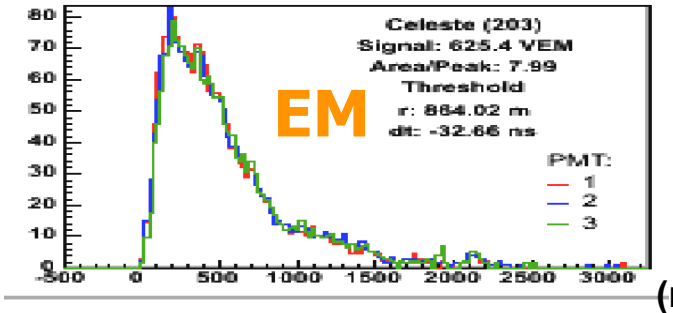


217

A typical ‘young’ shower (zenith~35°)

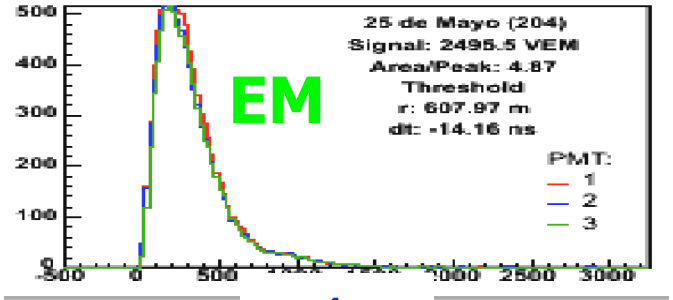






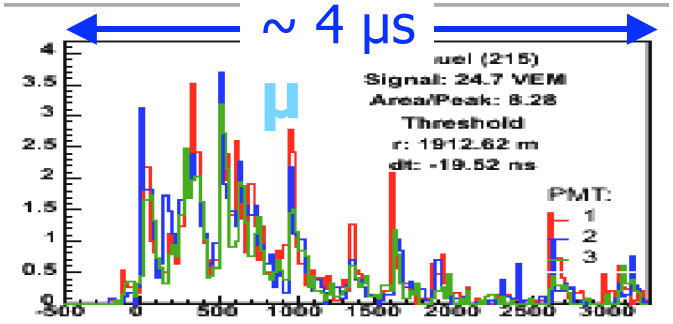
203

(nsec)



204

~ 4 μs



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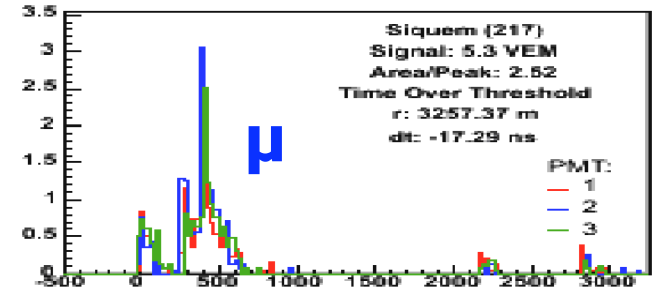
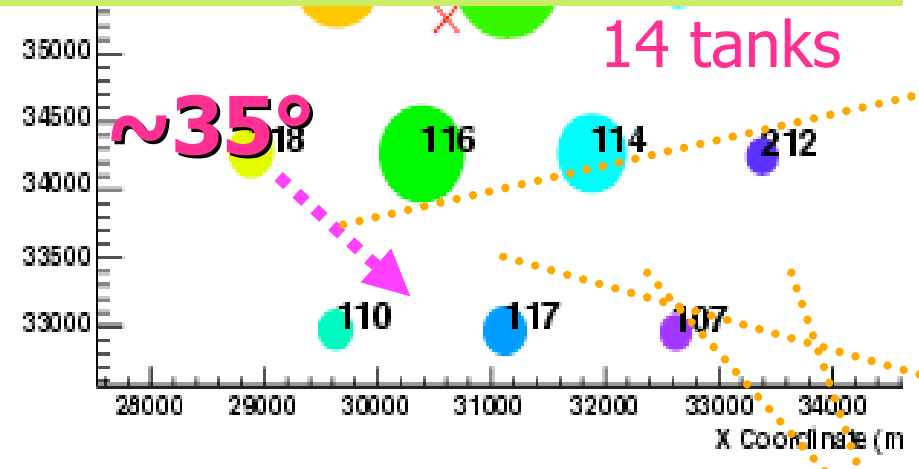
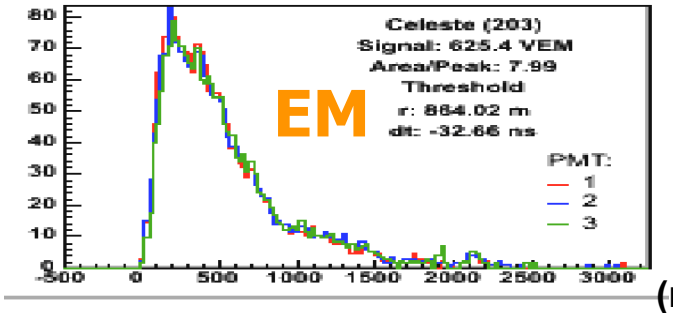


217

A typical ‘young’ shower (zenith~35°)





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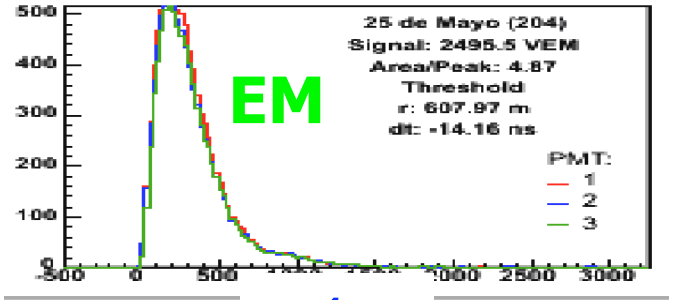

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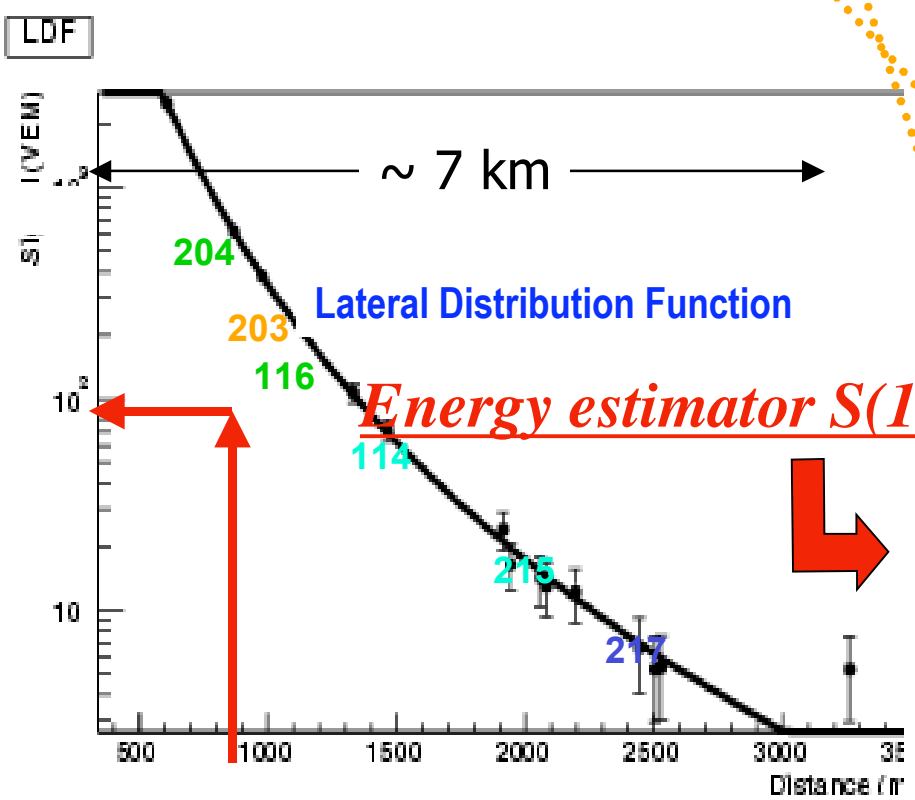
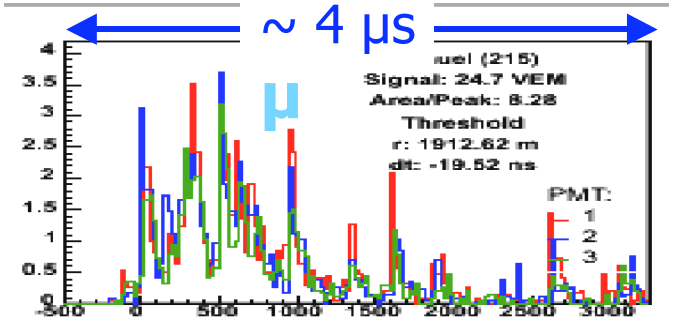
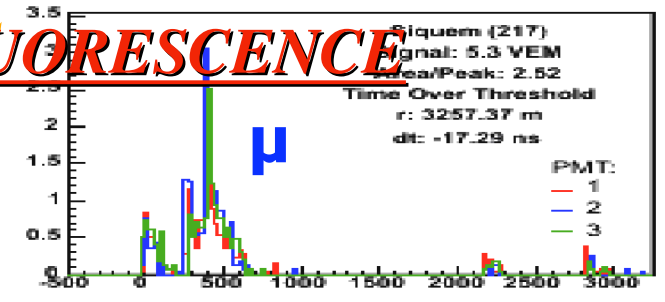




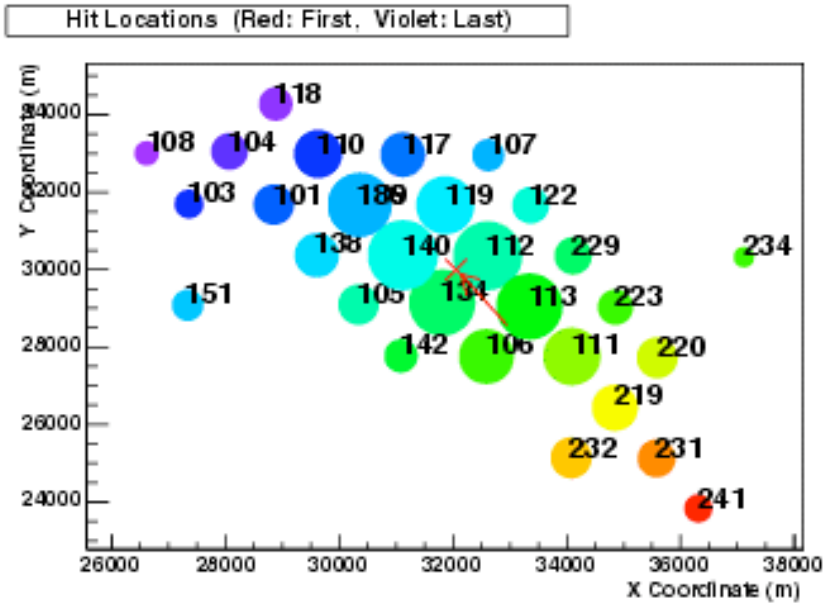
215

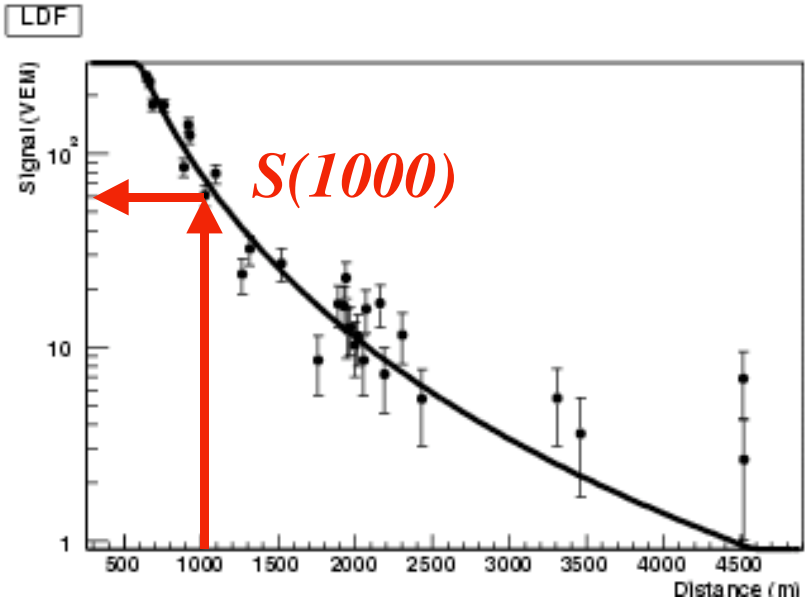
FLUORESCENCE

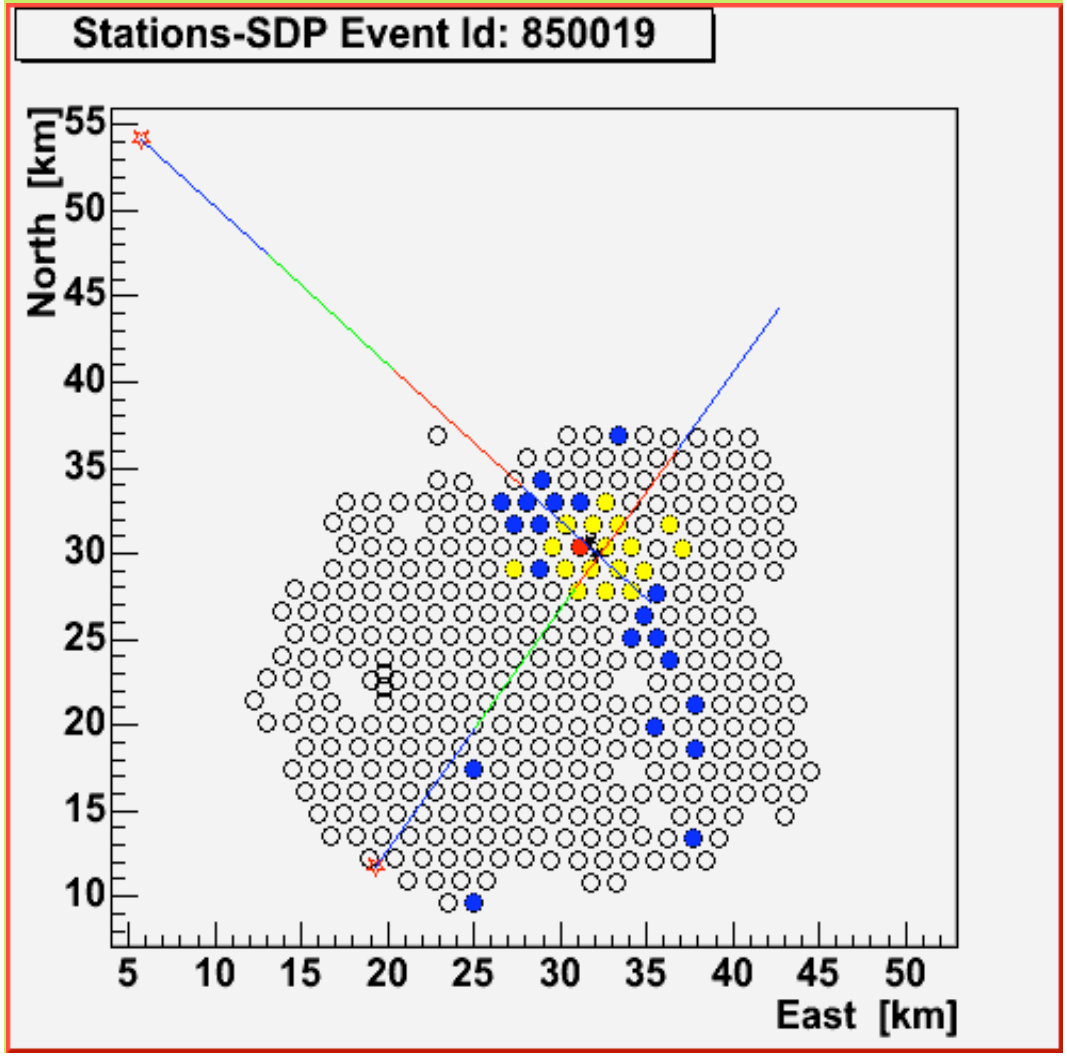


217

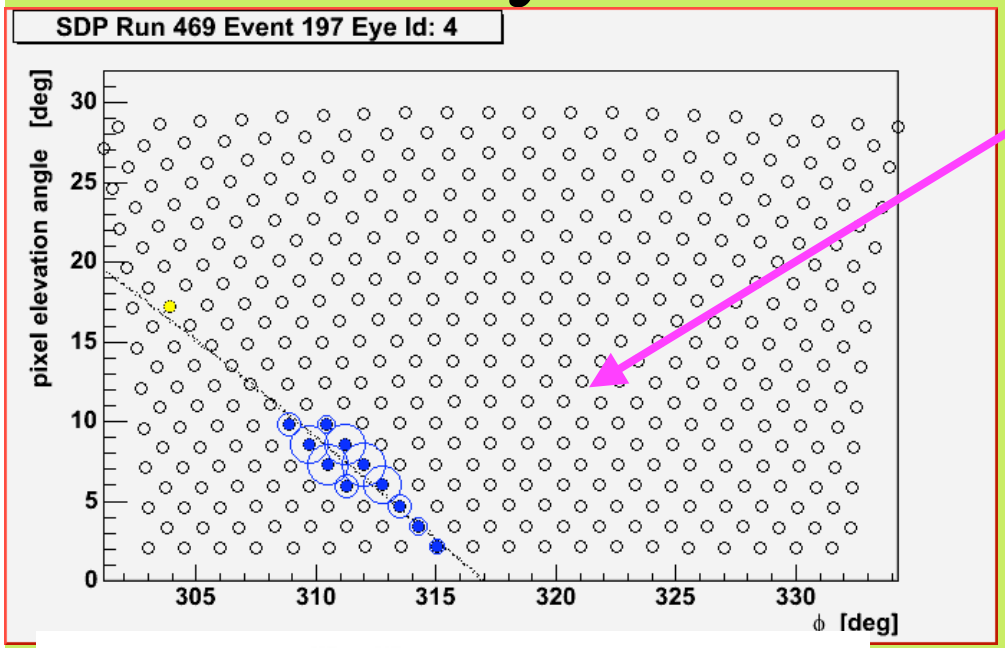
A Stereo Hybrid; θ ~70°

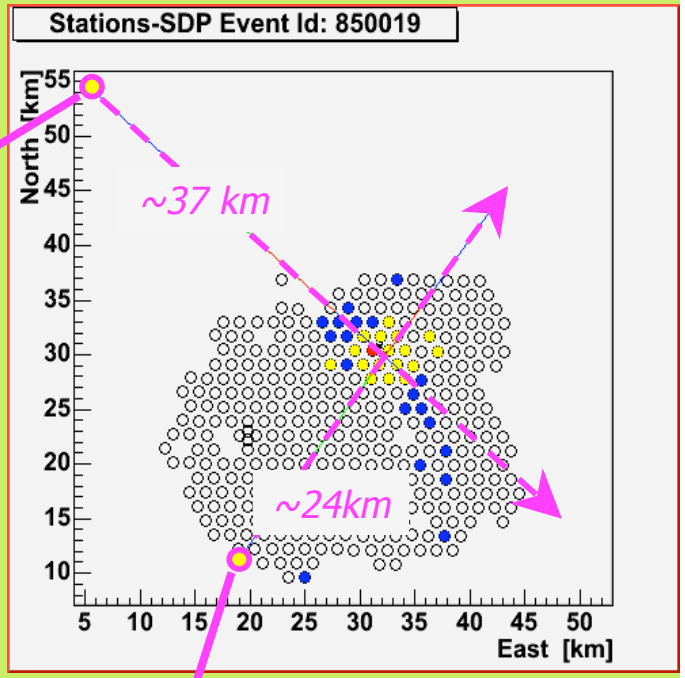


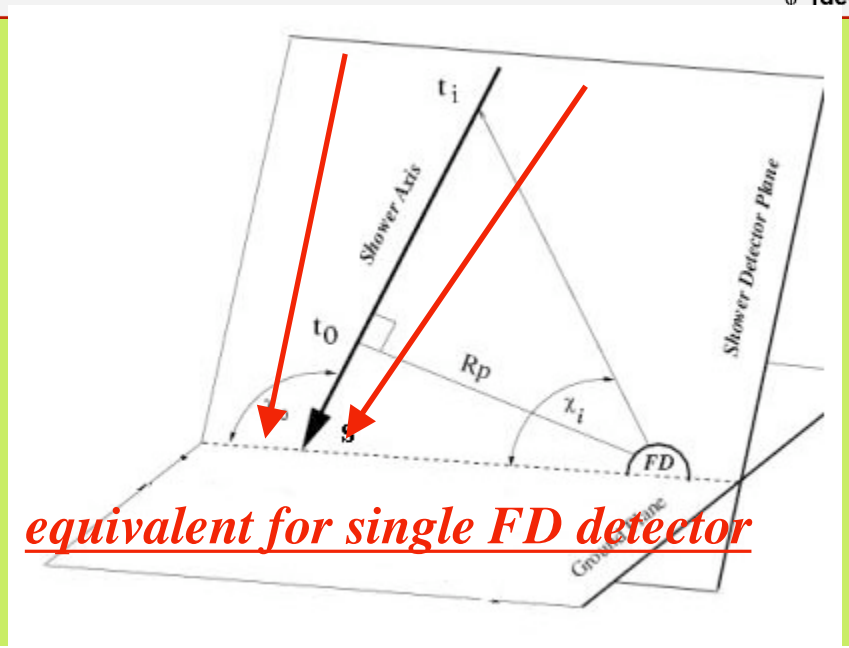




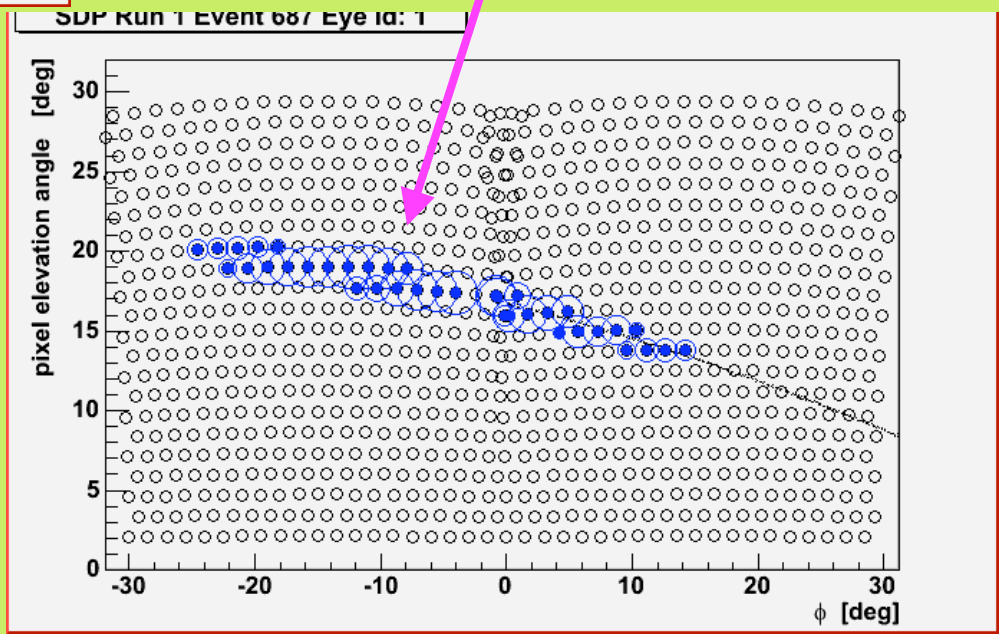
A stereo hybrid; θ ~70°



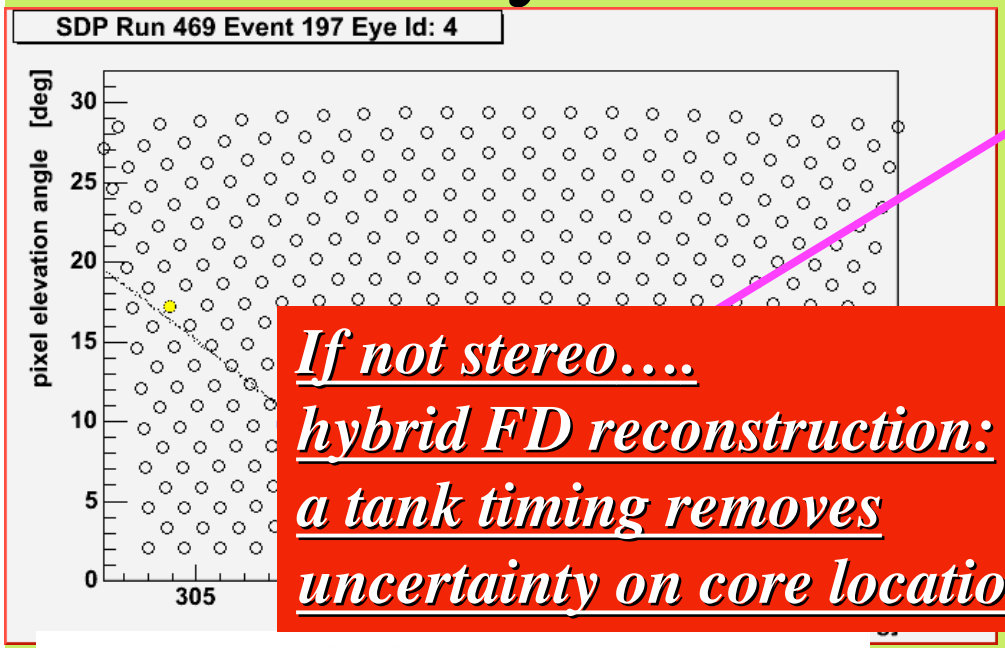


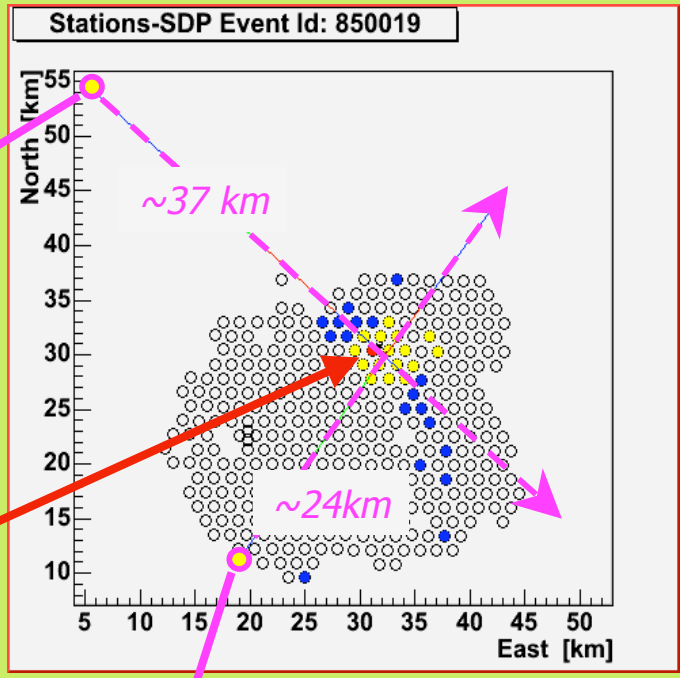


equivalent for single FD detector

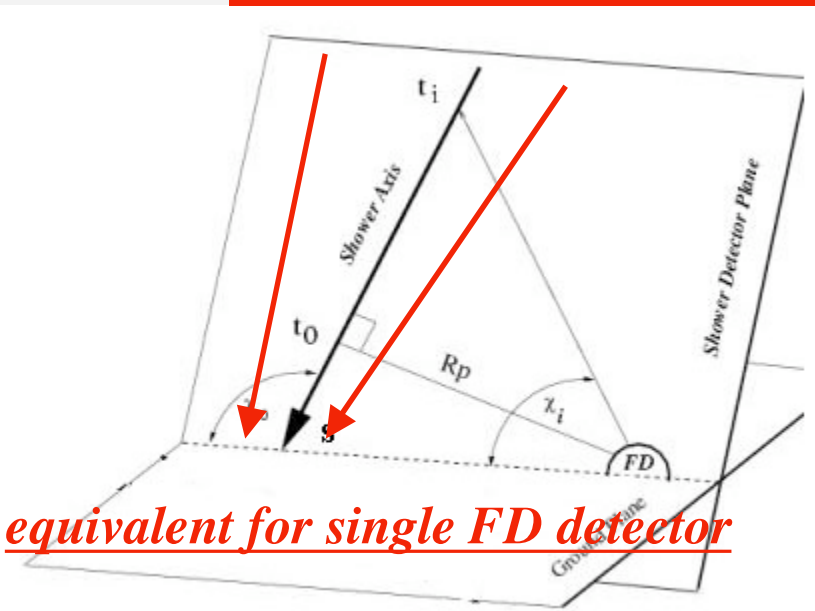


A stereo hybrid; θ ~70°

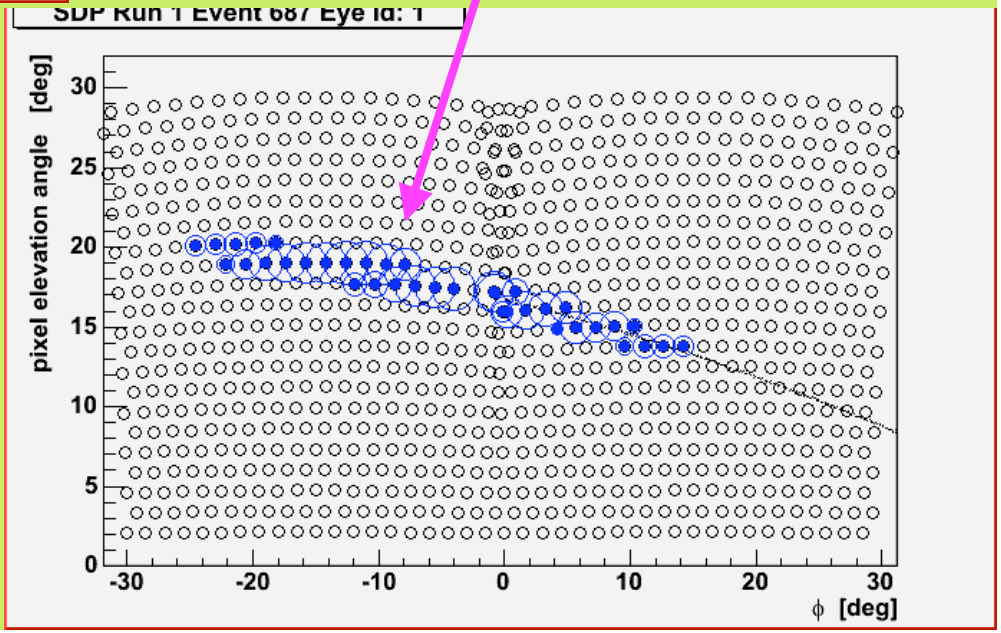




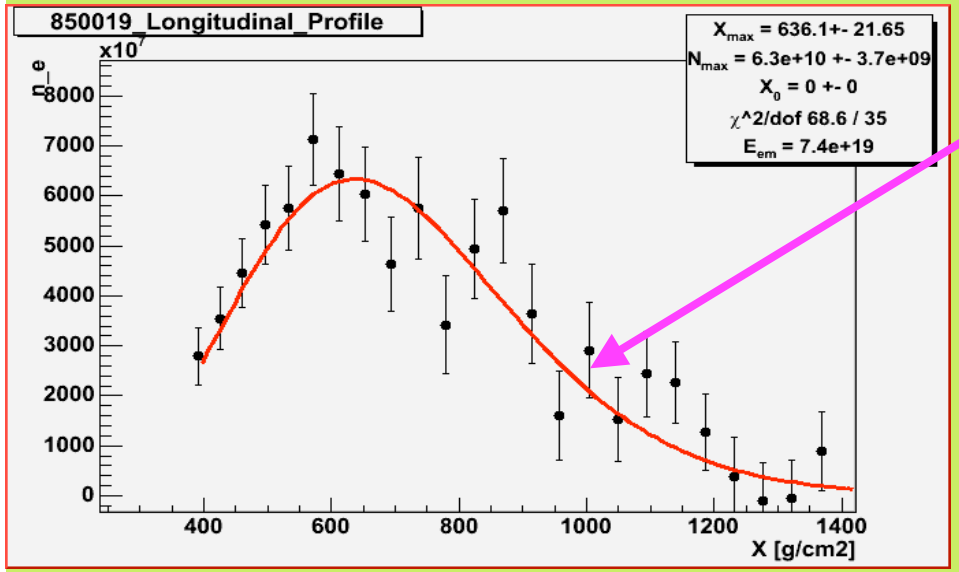
If not stereo….
hybrid FD reconstruction:
a tank timing removes
uncertainty on core location

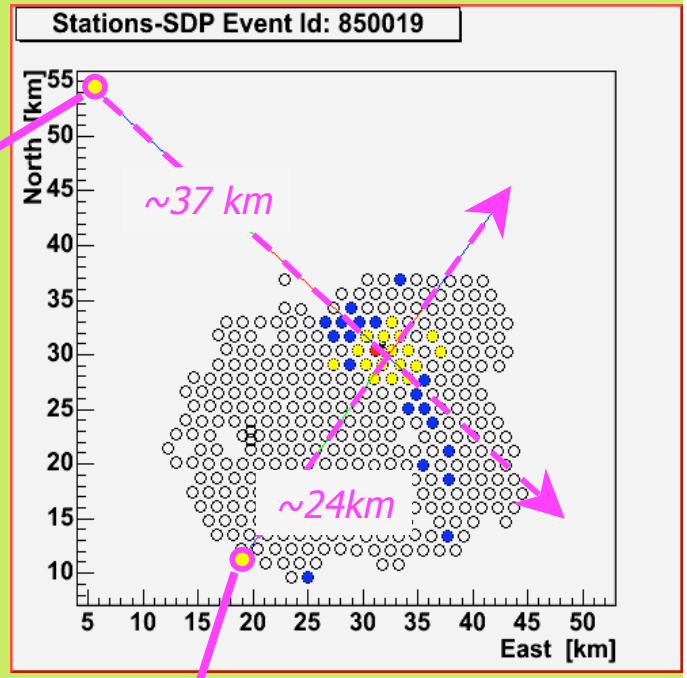


equivalent for single FD detector



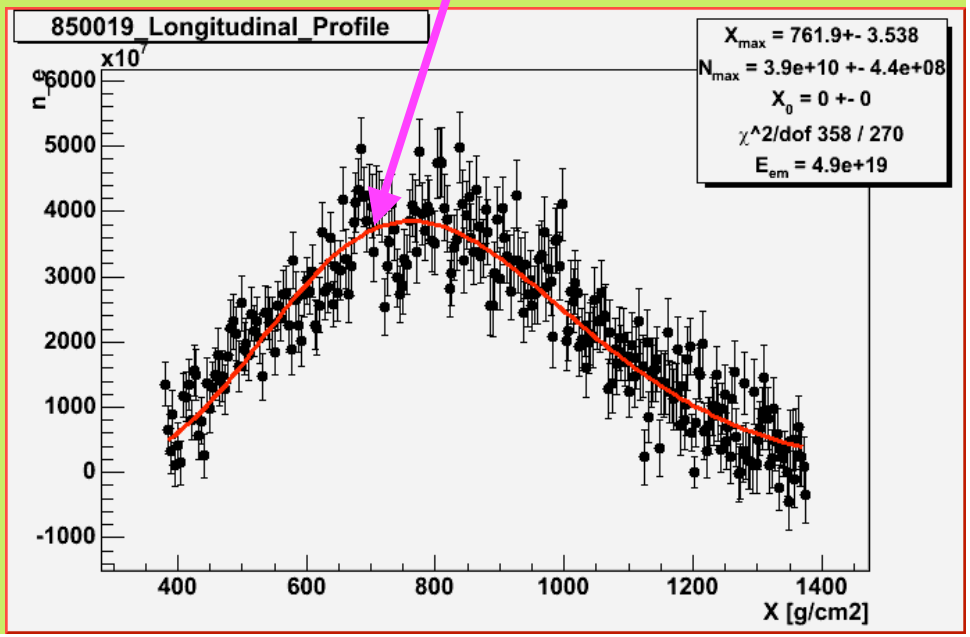
A stereo hybrid; θ ~70°



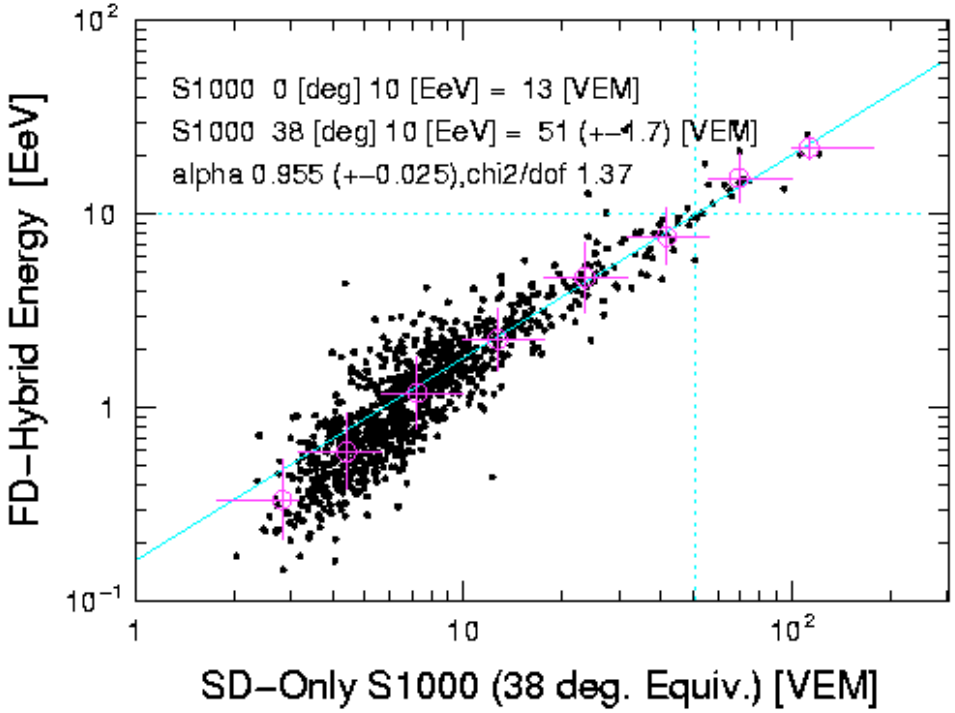


Integral of Longitudinal Shower Profile ⇒ Energy

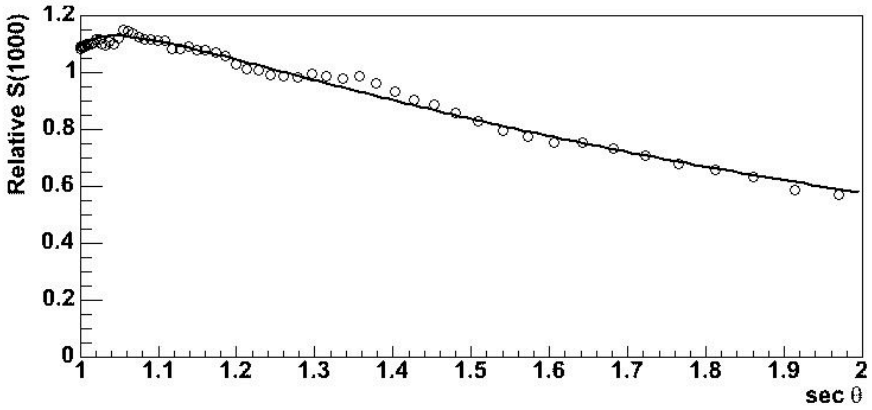
~ 4.8 Photons / m / electron
(~ 0.5 % of *dE/dx*)



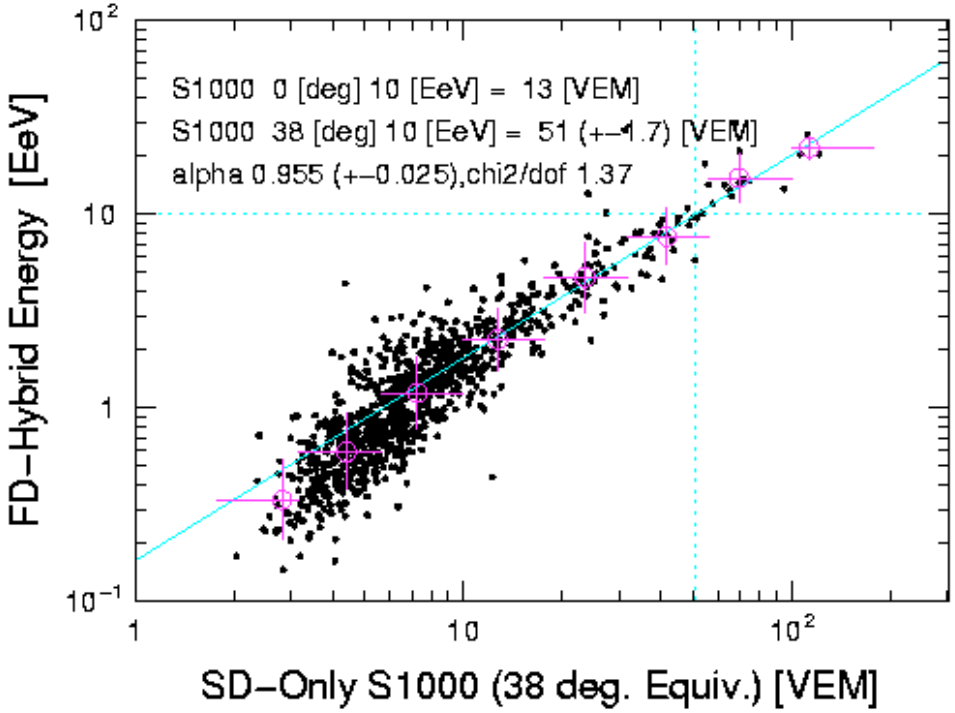
Auger Hybrid
calibration of Surface through fluorescence



Angular dependence of S(1000): "constant intensity cut"

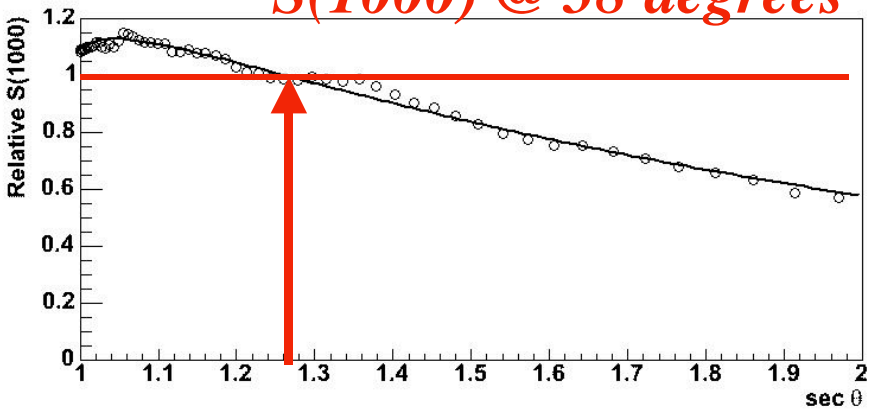


Auger Hybrid
calibration of Surface through fluorescence



Angular dependence of S(1000): "constant intensity cut"

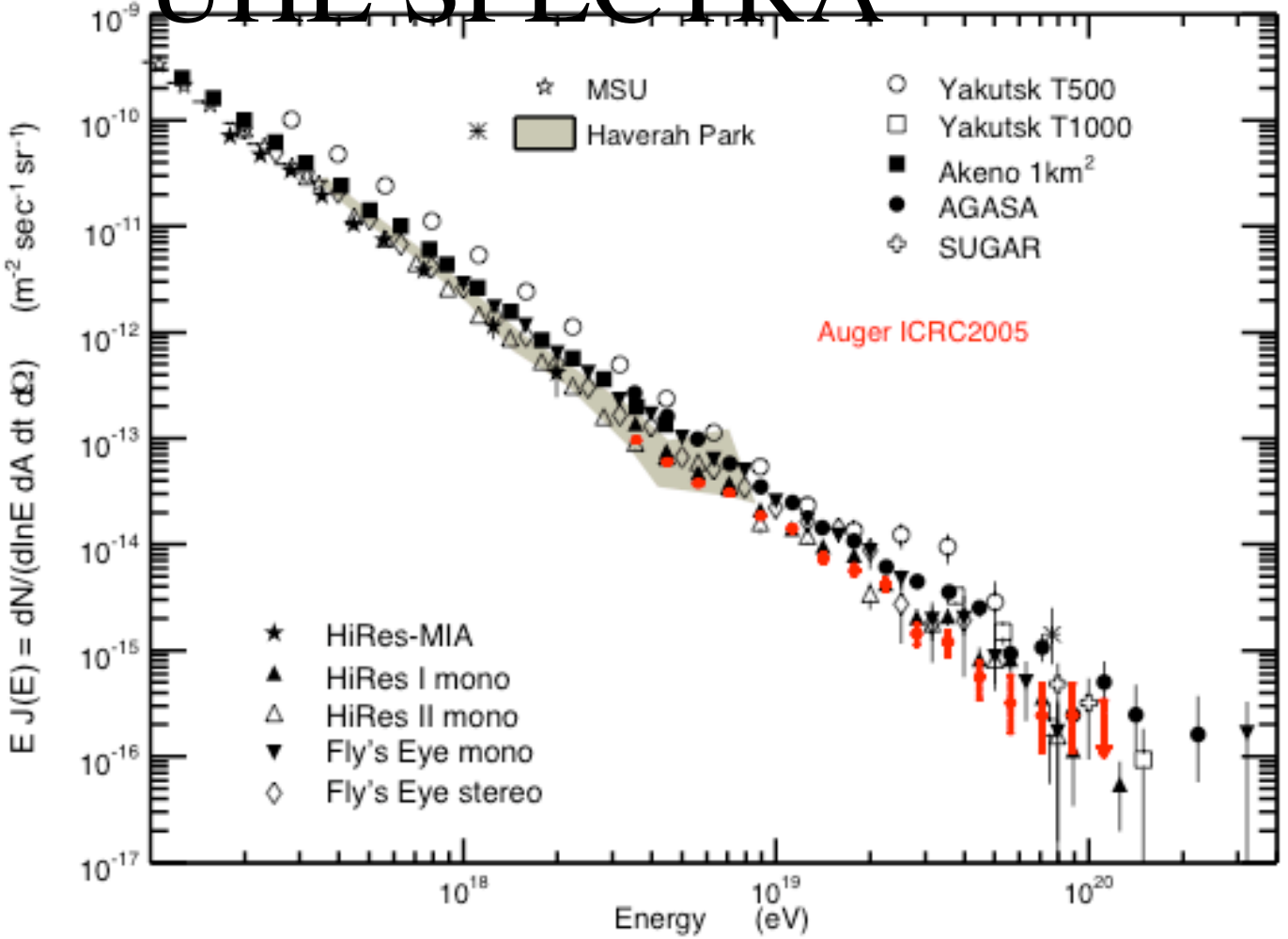
S(1000) @ 38 degrees



UNCERTAINTIES

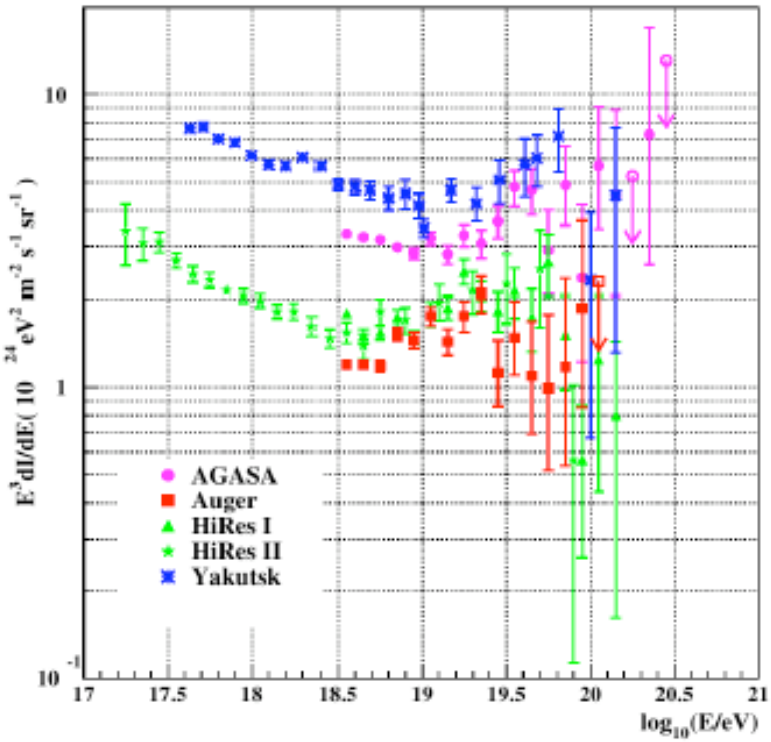
Auger Hybrid/fluorescence		
	light yield	**~ 15%**
	PMT calibration	**~ 12%**
	sky	**~ 15%**
total		**~ 25%**
Conversion to SD		**~ 15%**
Statistical SD		**~ 10%**
SD simulations		**~ 25%**

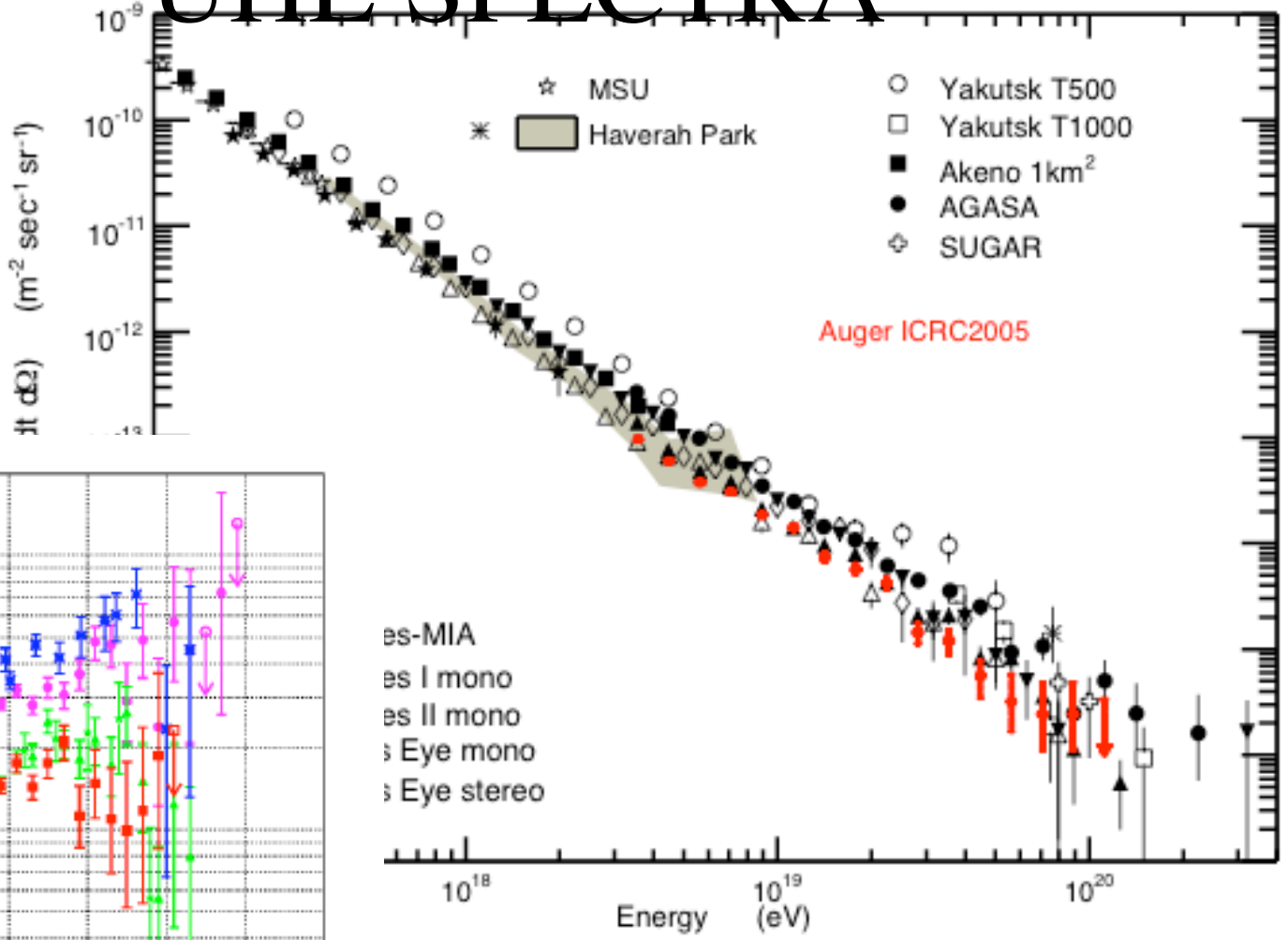
UHE SPECTRA



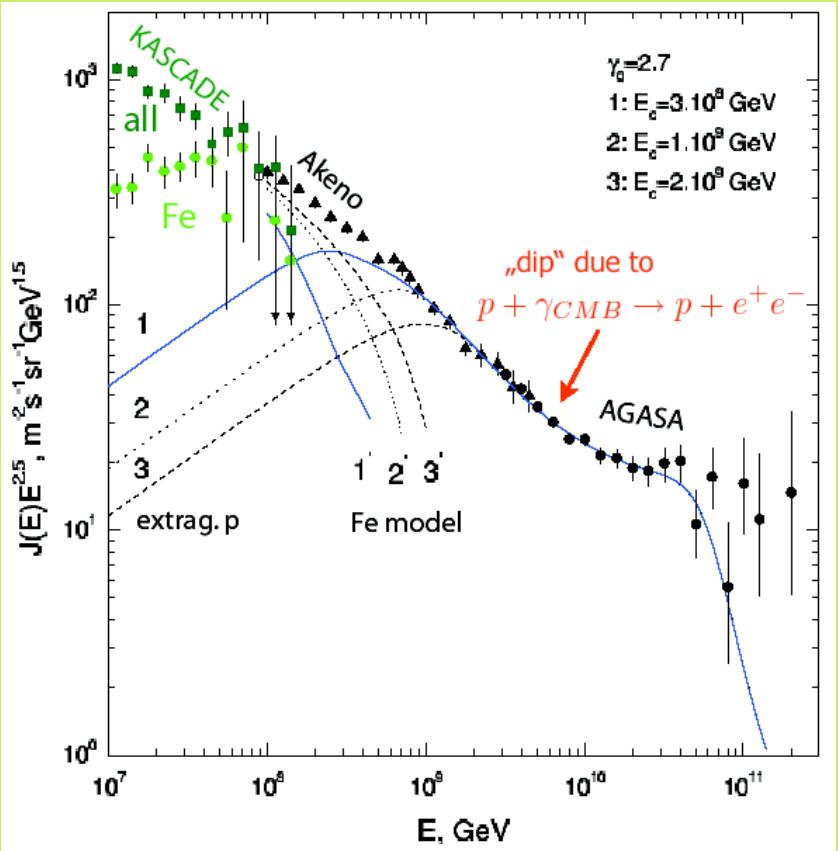
Auger ICRC 2005: syst. unc. 30% ==> 50%

UHE SPECTRA


AGASA
Auger
HiRes I
HiRes II
Yakutsk
log10(E/eV)


MSU
Haverah Park
Yakutsk T500
Yakutsk T1000
Akeno 1km2
AGASA
SUGAR
Auger ICRC2005
Energy (eV)

From galactic to extragalactic: Aloisio & Berezinsky Astro-ph/0403477

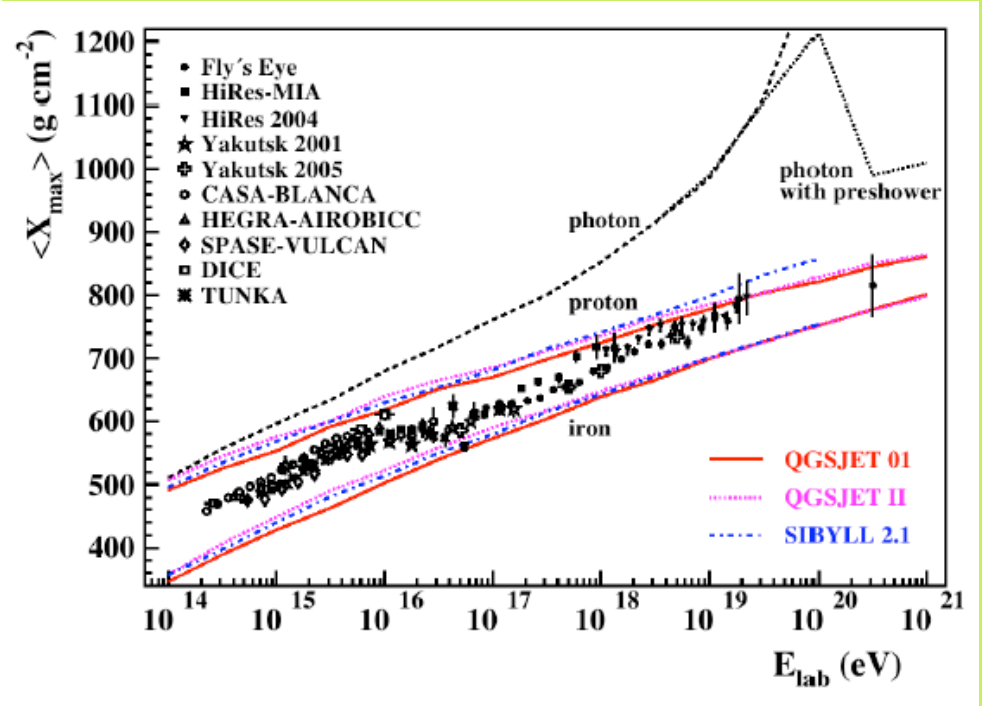


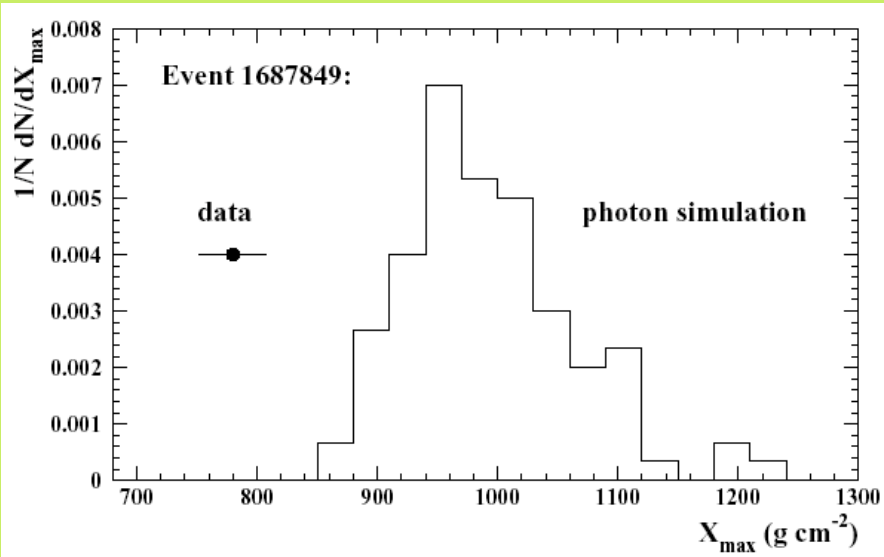
See also:
Phys. Rev. D 74, 043005 (2006)
hep-ph/02004357

See also A.M. Hillas

Cosmology, Galaxy Formation and Astroparticle Physics on the pathway to the SKA
Klöckner, H.-R., Jarvis, M. & Rawlings, S. (eds.)
April 10th-12th 2006, Oxford, United Kingdom

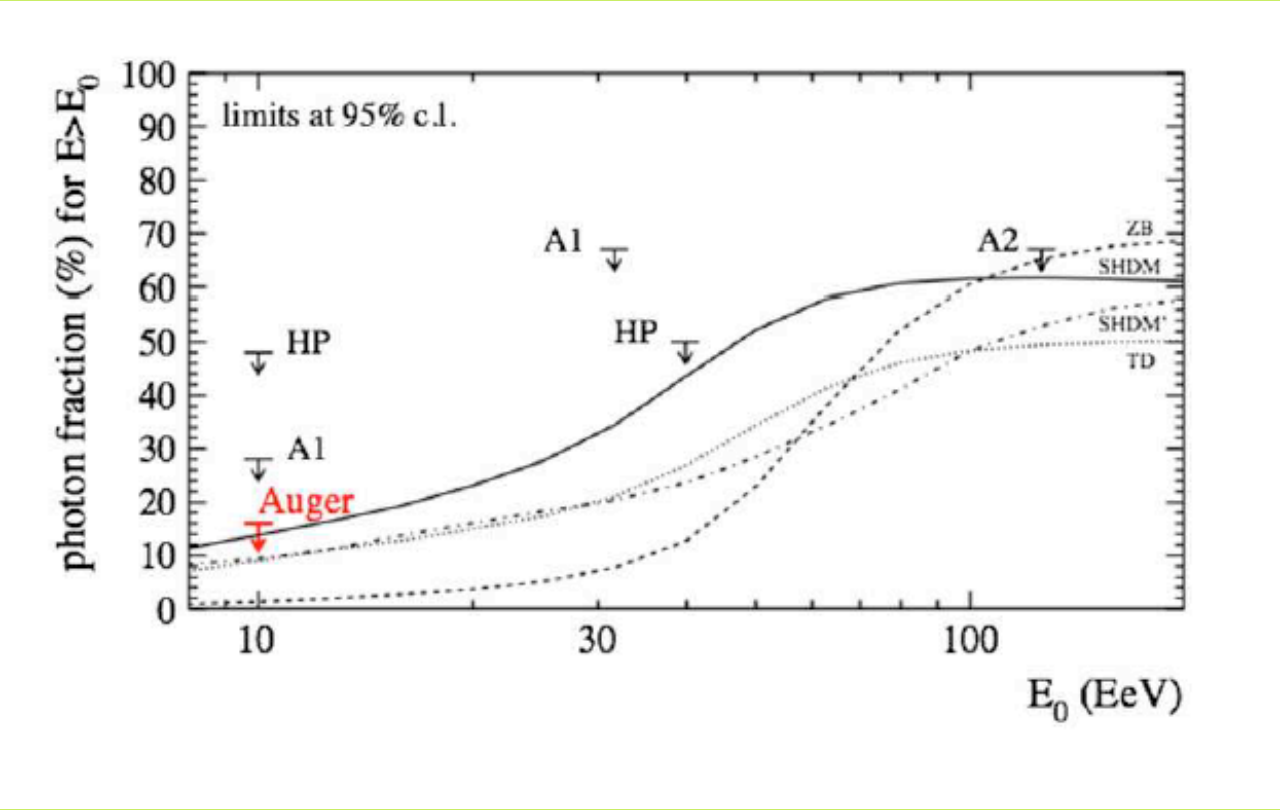
AUGER and photon primaries: depth of shower maximum





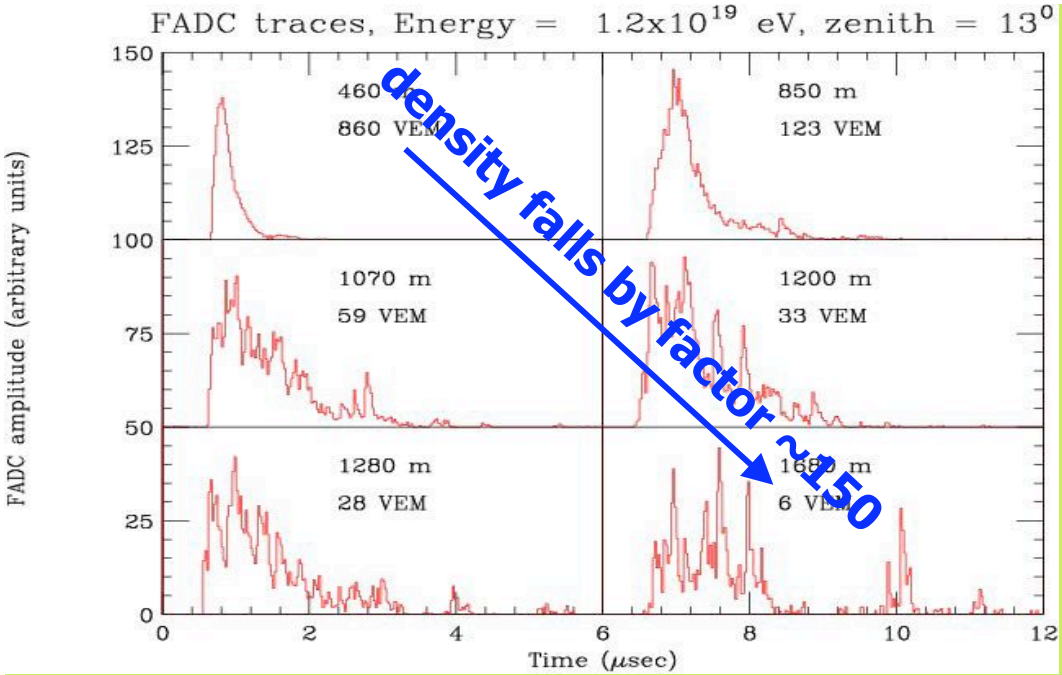
LPM effect

Photon fraction: upper limit



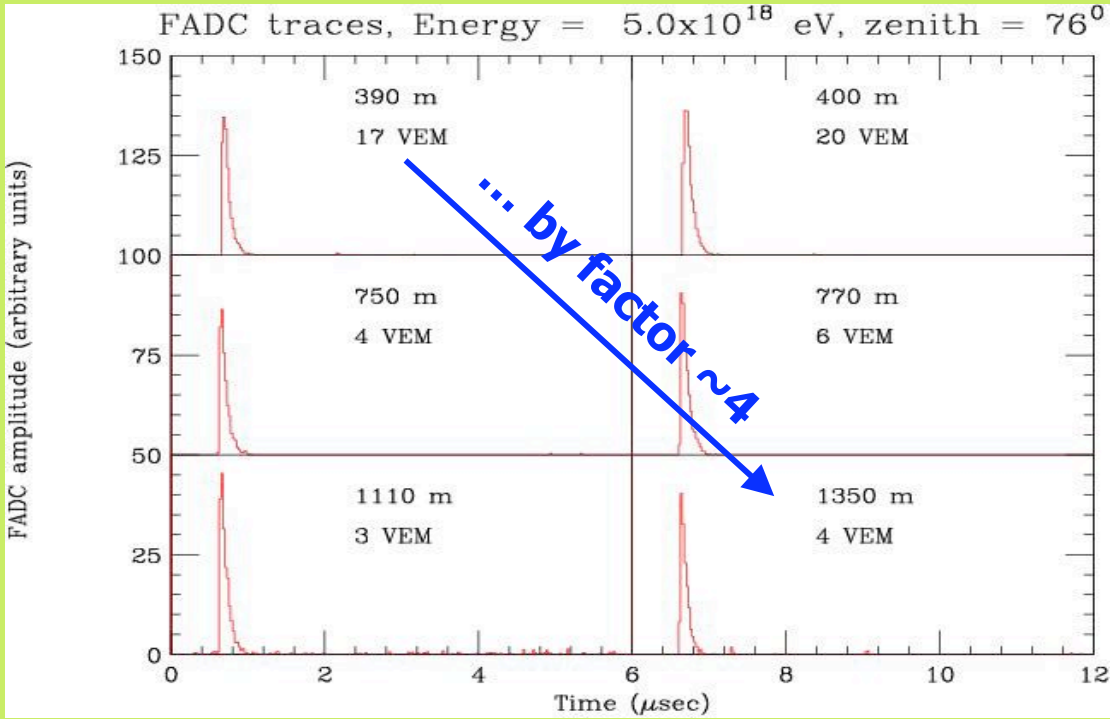
Astrop. Phys. 27 (2007) 155

Auger and ν–primaries

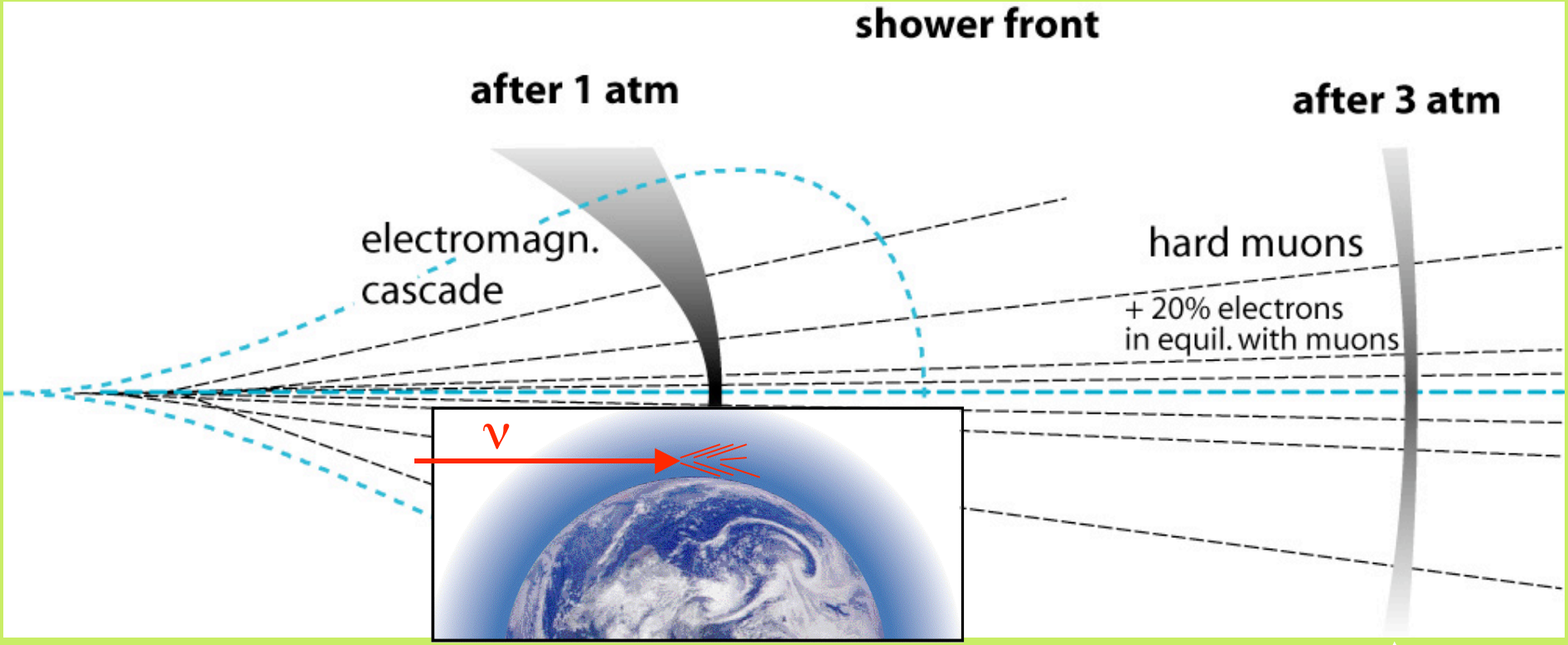


'young' shower

'old' shower



Vertical vs Horizontal Showers



'young' showers

- Wide time distribution
- Strong curvature
- Steep lateral distribution

~ 5 μs

'old' showers

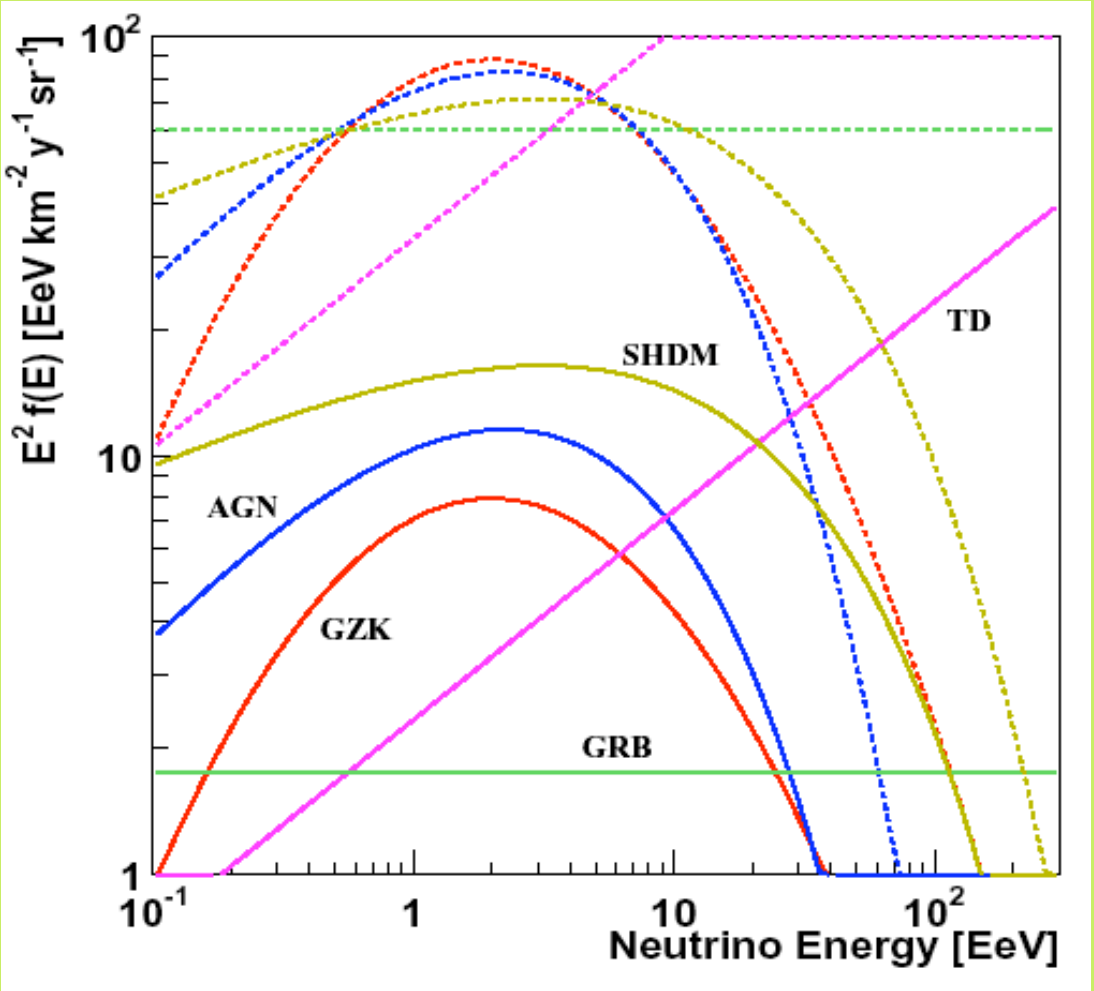
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

~ 0.2 μs

Only a neutrino can induce a young horizontal shower !

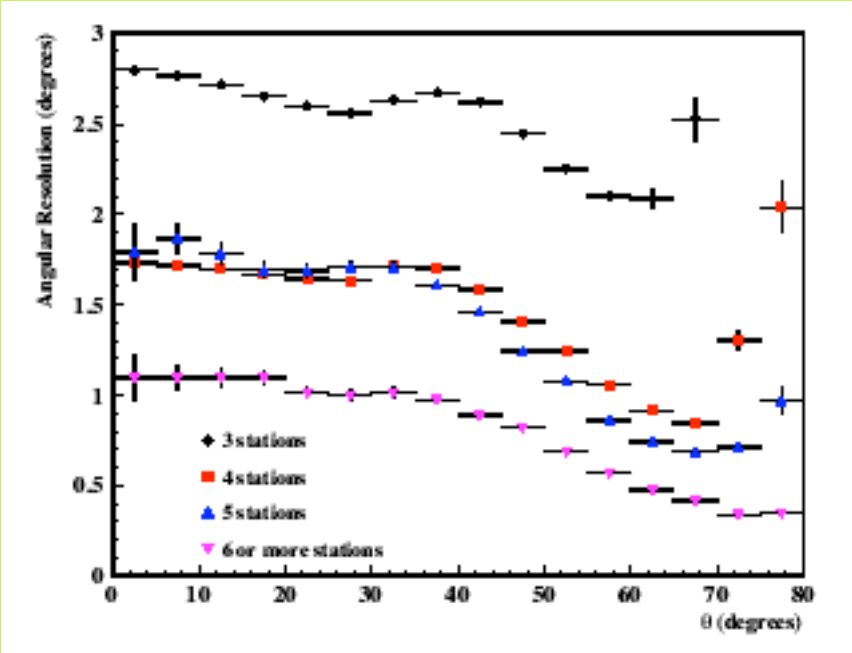
Auger and ν-primaries sensitivity

(1 year 90% limits for ν_τ "Earth-skimming" events)



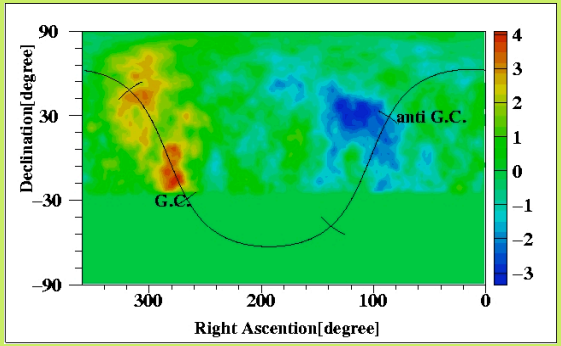
Auger and arrival directions

anisotropies and point sources: accuracies

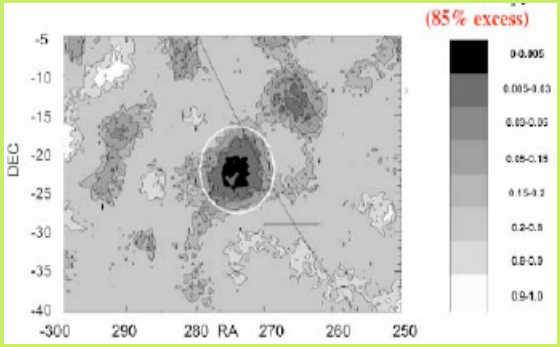


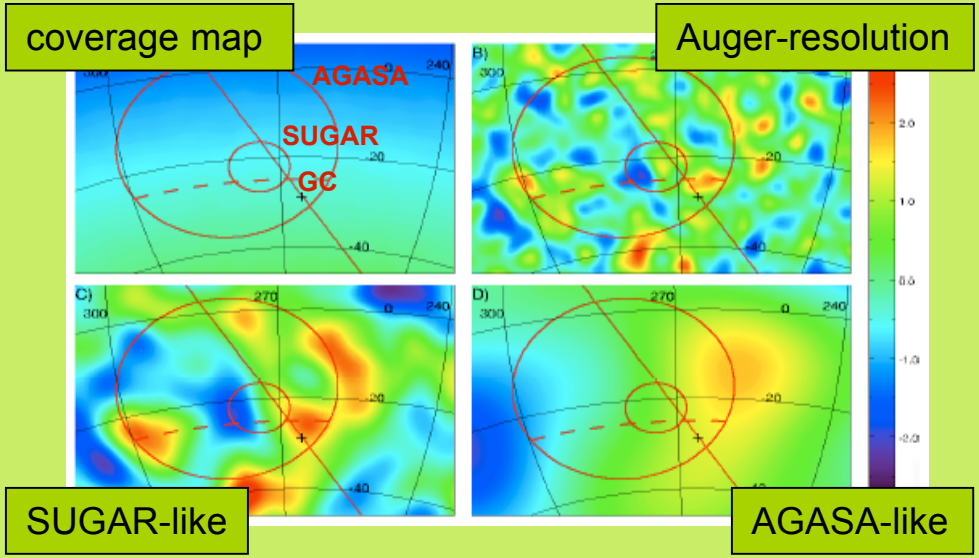
Anisotropies around the GC UHE

AGASA
- excess = 22%
- $E = 10^{18}$-$10^{18.4}$ eV
- $(\alpha,\delta) = (280°,-17°)$



SUGAR
- excess = 85%
- $E = 10^{17.9}$-$10^{18.5}$ eV
- $(\alpha,\delta) = (274°,-22°)$





AUGER: no excess

upper limit ~ 6%

Anisotropies around the GC UHE

AGASA
- excess = 22%
- $E = 10^{18}$-$10^{18.4}$ eV
- $(\alpha,\delta) = (280°,-17°)$

SUGAR
- excess = 85%
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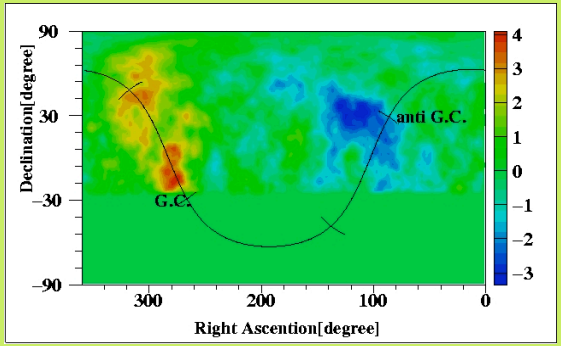
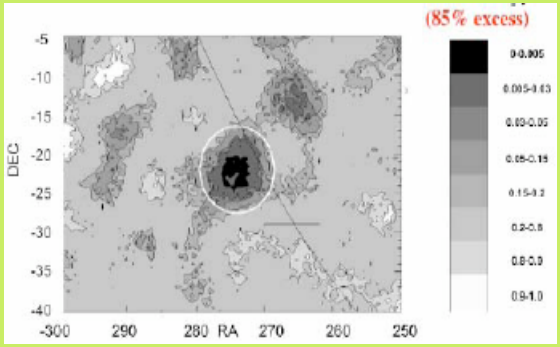
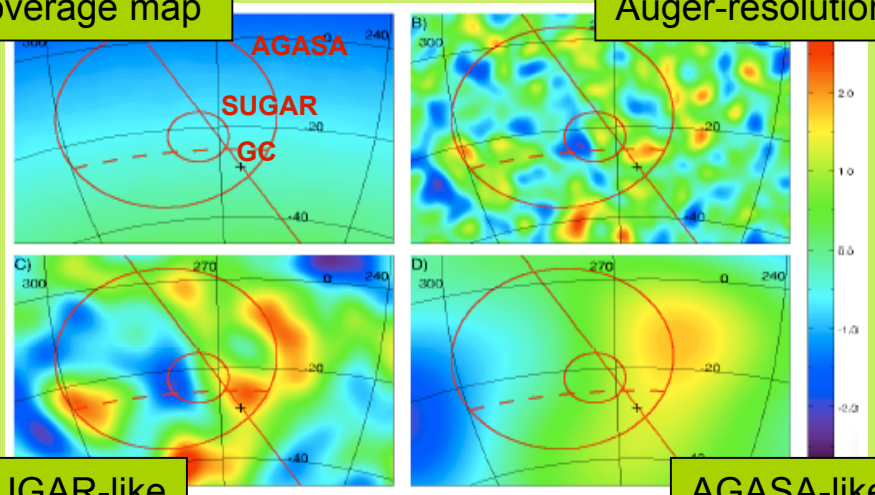




coverage map



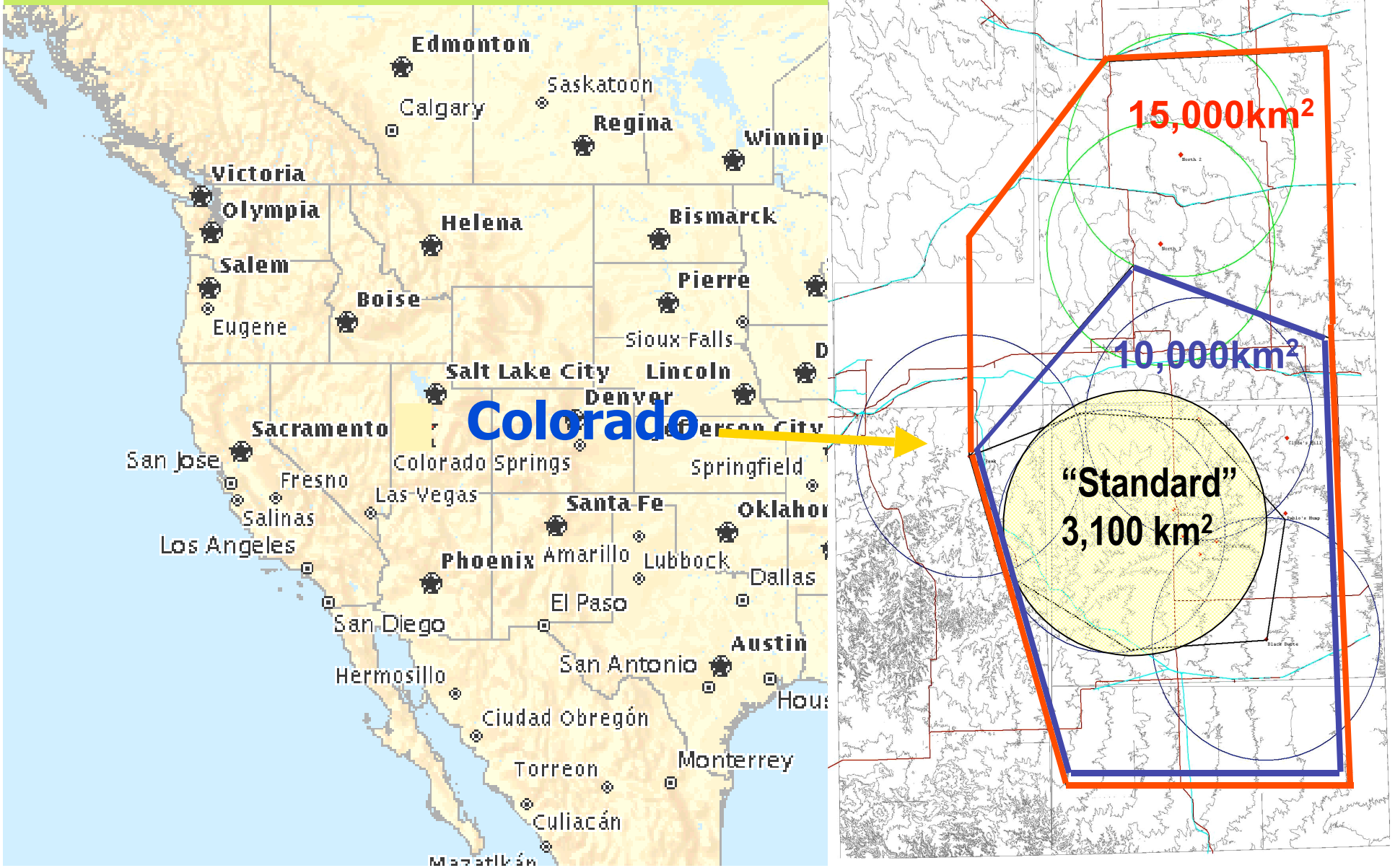
Auger-resolution

SUGAR-like

AGASA-like

Auger South large scale anisotropy (3.5 10^5 ev/y)
sens. (10 y) < 0.1%
Eo > 0.8 EeV (50% eff.)
galactic/extragalactic?

The Auger Northern Site



Auger North Science

- Clear Window of "Charged Particle Astronomy"
  - $\sim 4 \cdot 10^{19}$ eV – $\sim 10^{20}$ eV
  - Regardless of existence of the GZK feature
  - Northern sky + Southern sky

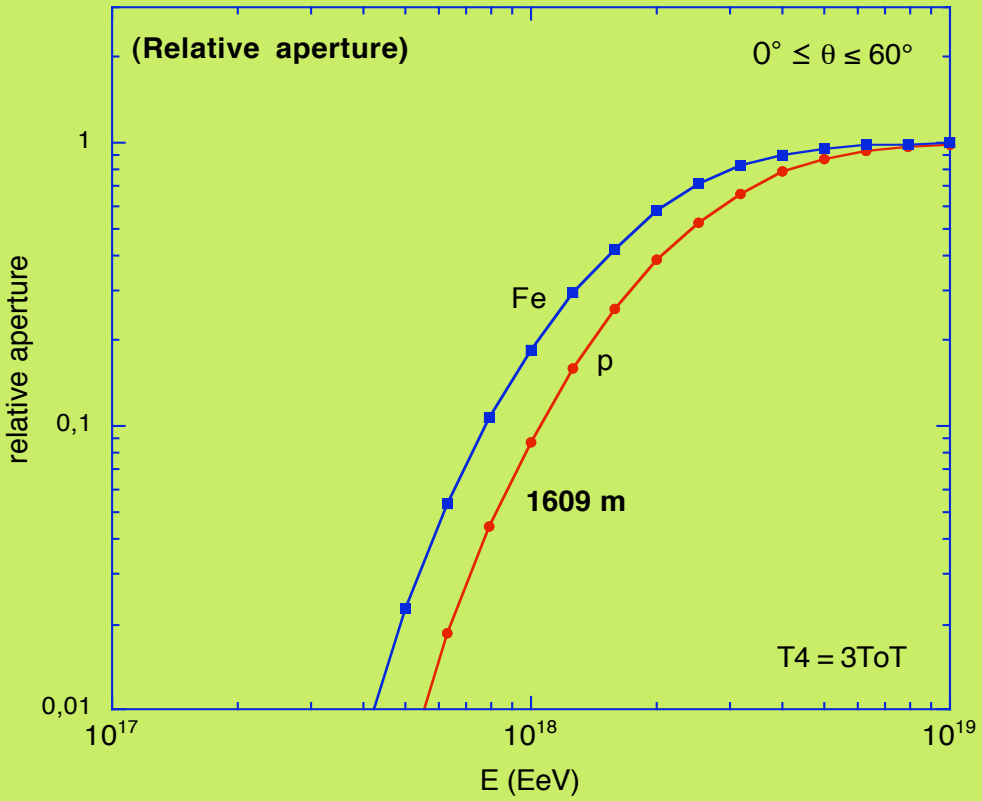
- Need for the Largest Detector beyond GZK
  - High statistics of trans-GZK events (> 1000 ev Eo>E_{GZK} in 5 y)
  - Neutrinos from Top-down Mechanism and GZK

Auger South **3,000 km² = 1,157 mile²**

Hexagonal grid – 1.5 km separation

Auger North **10,368 km² = 4,000 mile²**

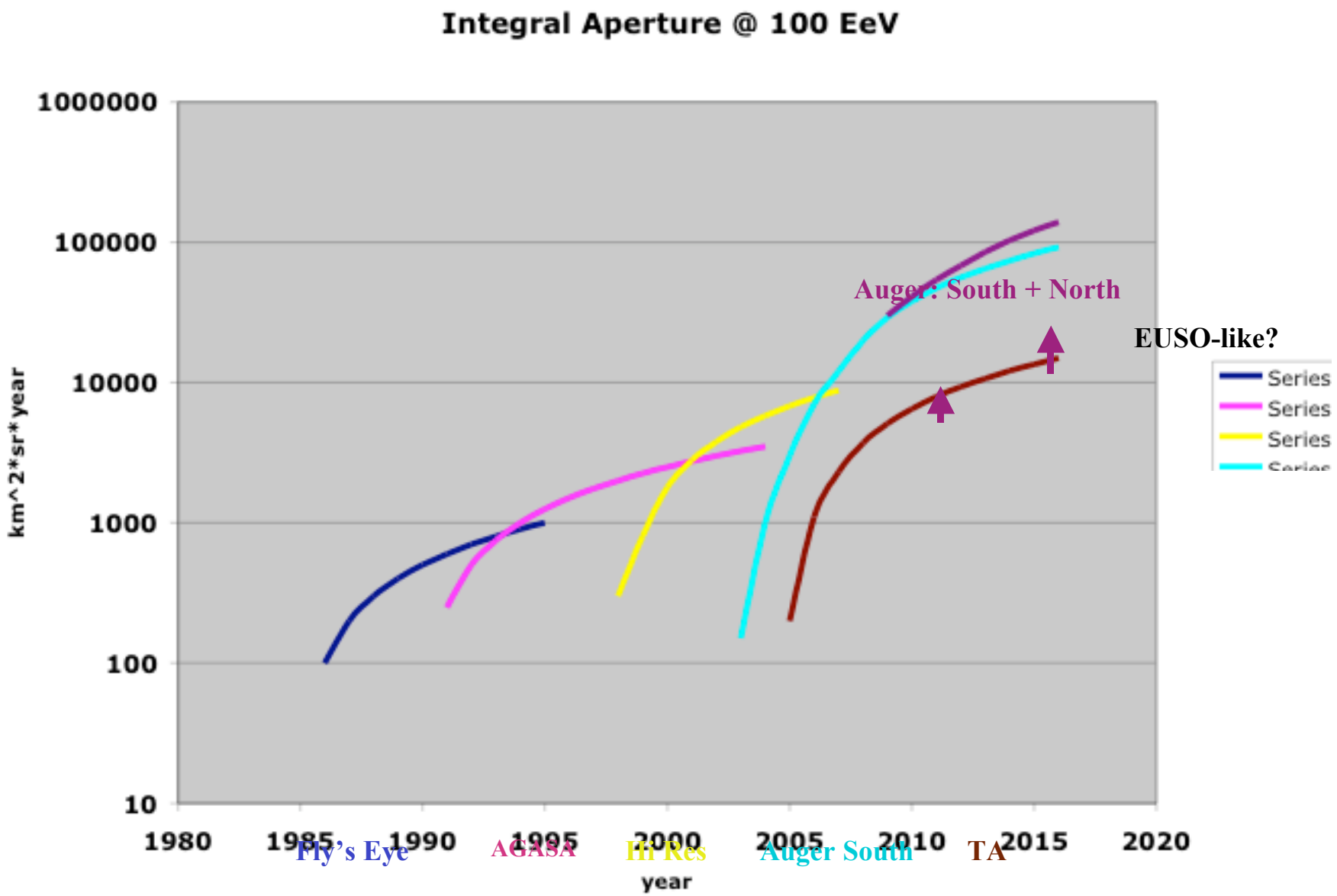
Square grid – 1 mile separation



n ~ 2.10^5 events/year
E > $2.\ 10^{18}$ eV (50% eff)

sens ~ 0.1% in 10 years

All extragalactic ?!


Integral Aperture @ 100 EeV
1000000
100000
10000
1000
100
10
km^2*sr*year
1980
1985
1990
1995
2000
2005
2010
2015
2020
year
Auger: South + North
EUSO-like?
Series
Series
Series
Fly's Eye
AGASA
Hi Res
Auger South
TA