observe coincidences in neiboring detectors

-> air shower trigger

measure the trajectory of primary particle

- position of shower axis from particle density

- direction of shower axis from arrival times

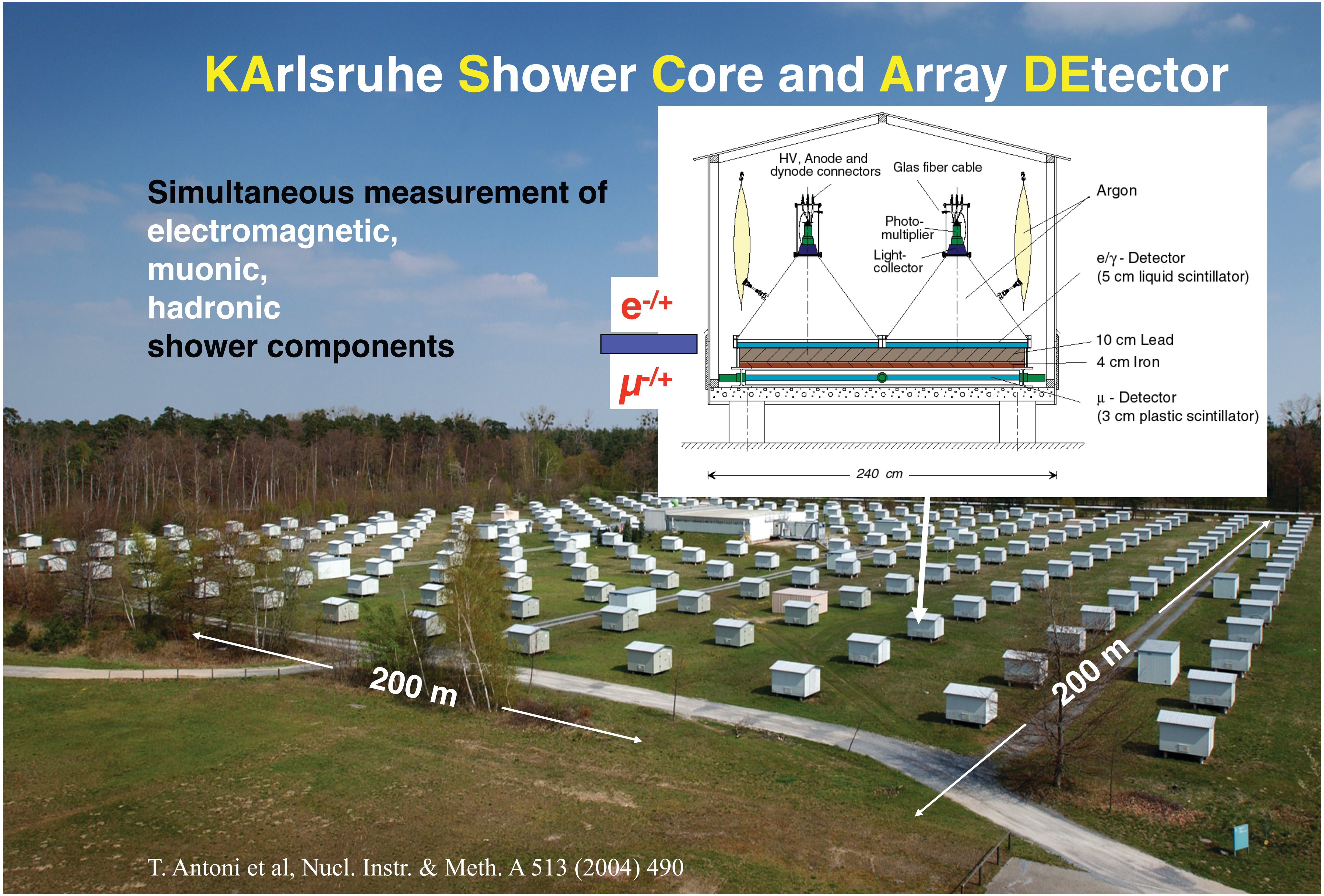
<u>measurement of muons</u>

absorber material $(\sim 20\,X_0)$ to absorb electrons & photons

μ are penetrating particles

(no losses through Bremsstrahlung

$$\left.\frac{dE}{dx}\right|_{Brems}(E) \propto \left(\frac{m_e}{m_\mu}\right)^2$$

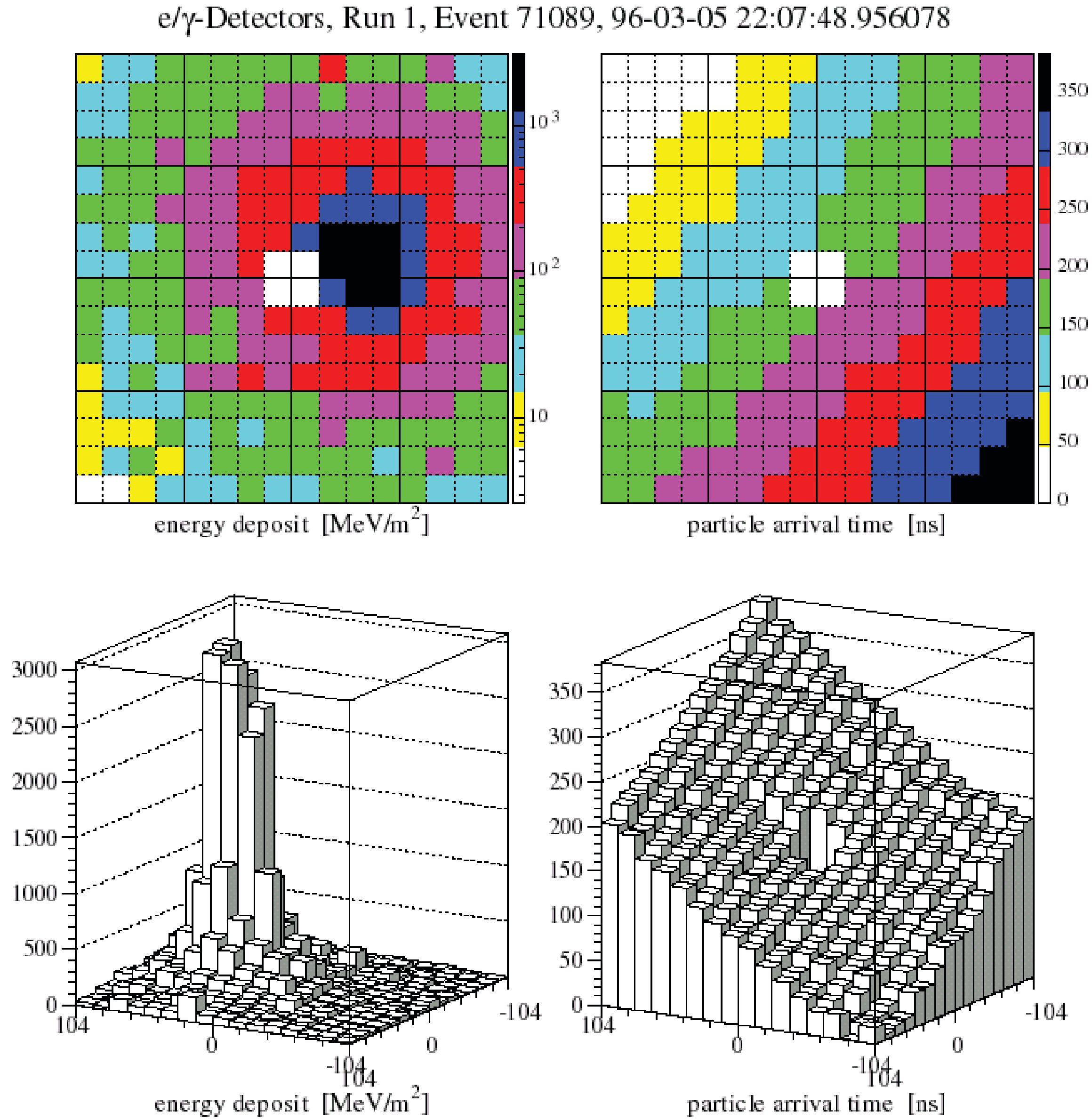


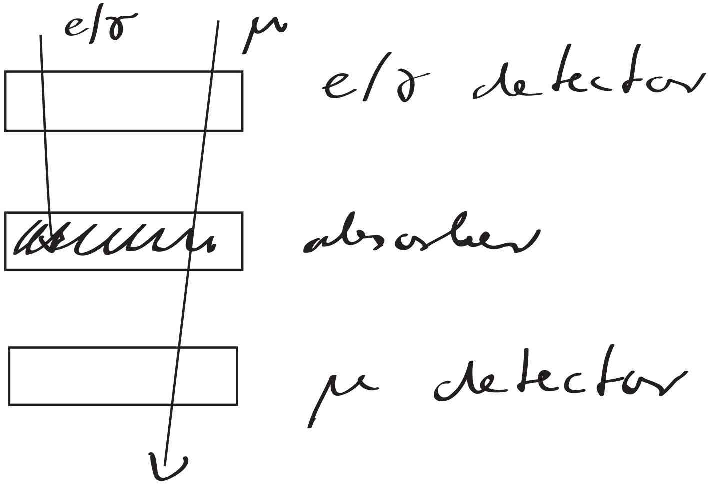
KArlsruhe Shower Core and Array DEtector
Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components
e-/+
μ-/+
HV, Anode and dynode connectors
Glas fiber cable
Argon
Photo-multiplier
Light-collector
e/γ - Detector
(5 cm liquid scintillator)
10 cm Lead
4 cm Iron
μ - Detector
(3 cm plastic scintillator)
240 cm
200 m
200 m
T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

Event reconstruction in the scintillator array

electromagnetic component

shower core	□r = 2.5 – 5.5 m
shower direction	□□ = 0.5° – 1.2°
shower size	□N_e/N_e = 6 – 12 %

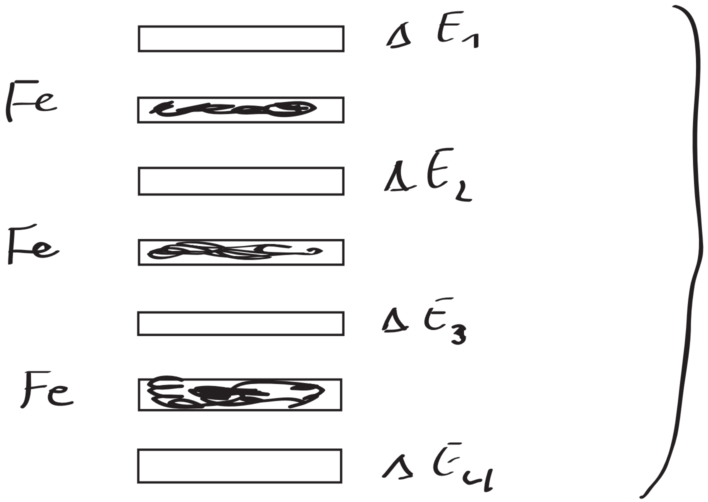




→ count number of muons

measurement of hadrons

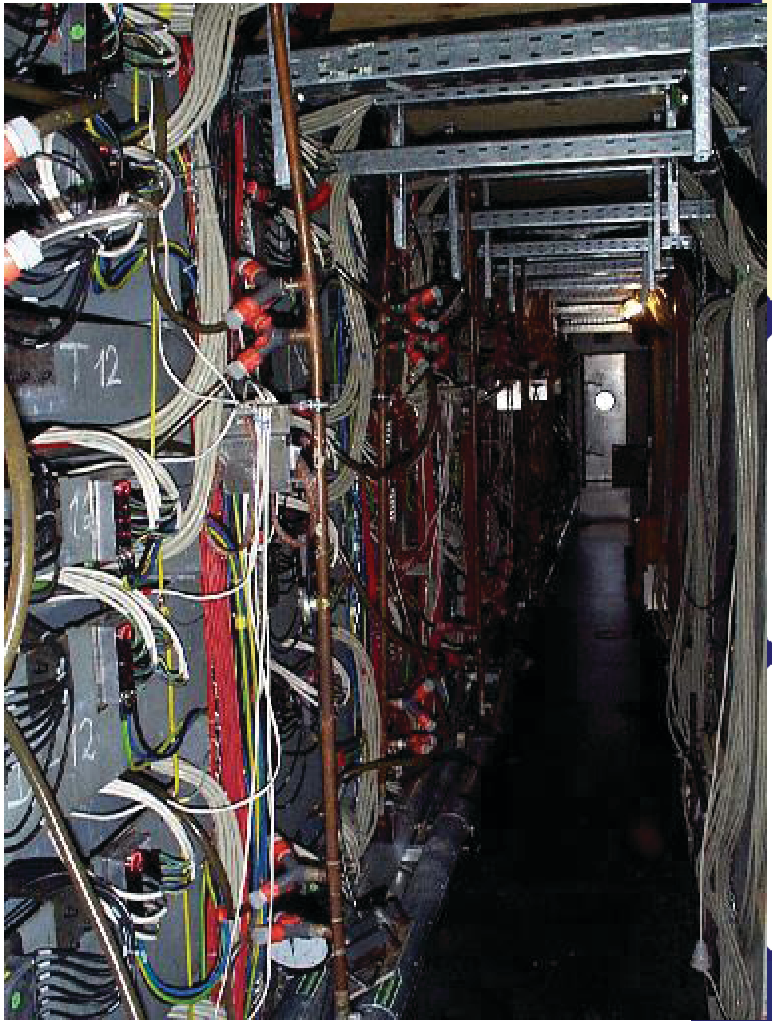
hadron calorimeter

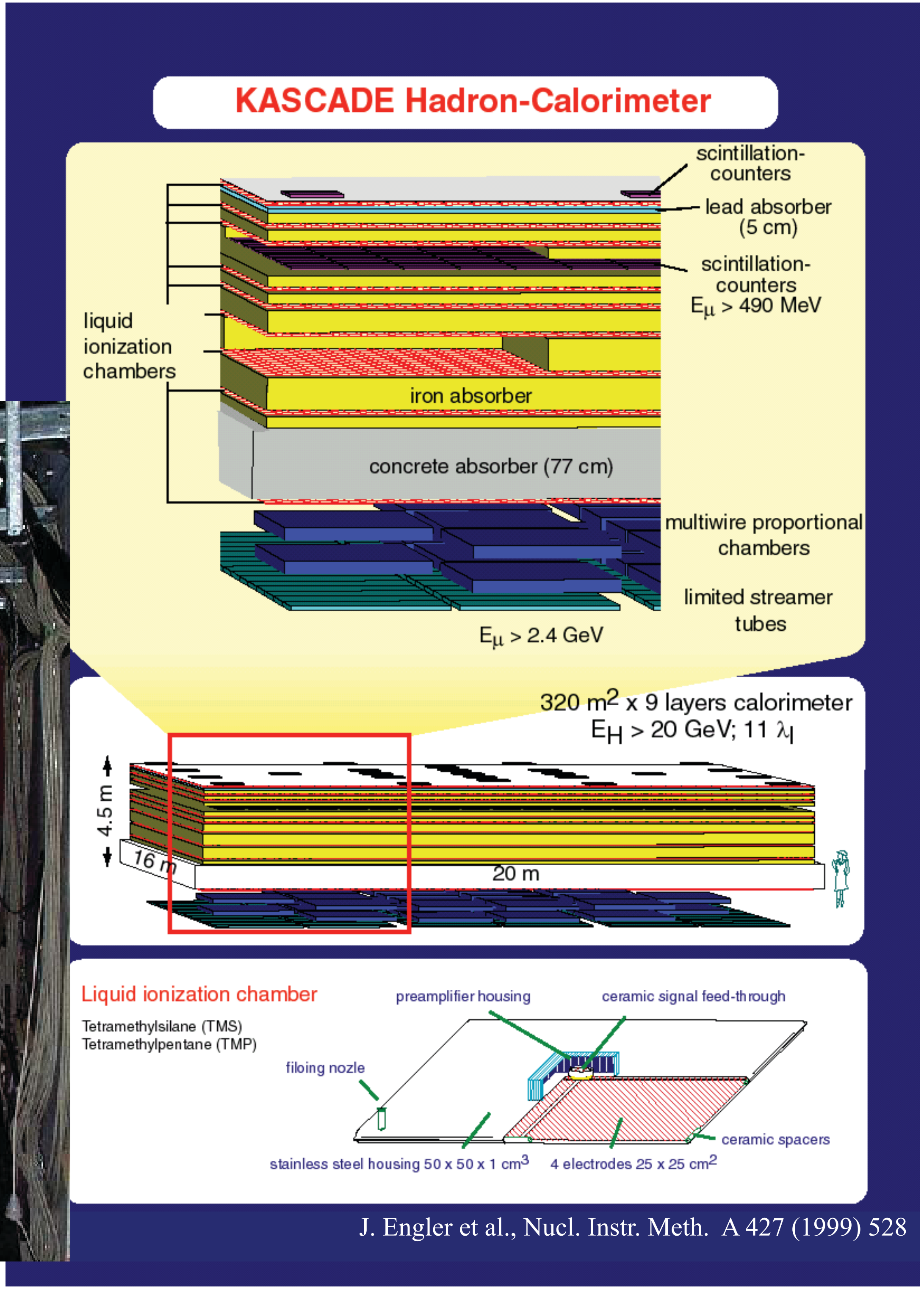


$\hat{=}\ 10\ \lambda_I$

$\lambda_I \sim \frac{1}{n\sigma} \sim 16{,}7\ \text{cm in Fe}$

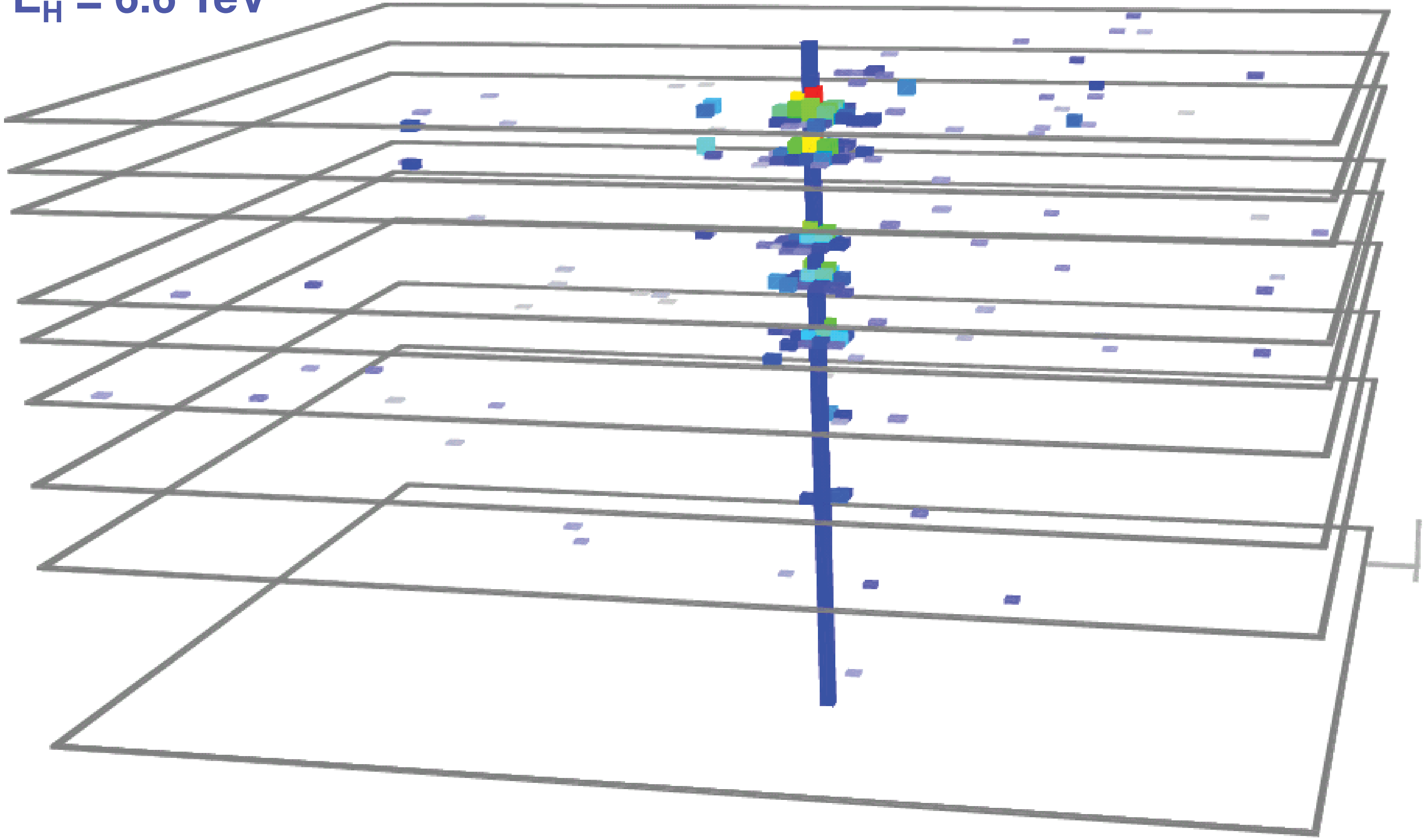
KASCADE Hadron Calorimeter





Reconstruction of hadrons

Unaccompanied hadron
E_H = 6.6 TeV



spatial resolution:
$\sigma_x \sim 10 - 12$ cm

angular resolution:
$\sigma_\theta \sim 1° - 3°$

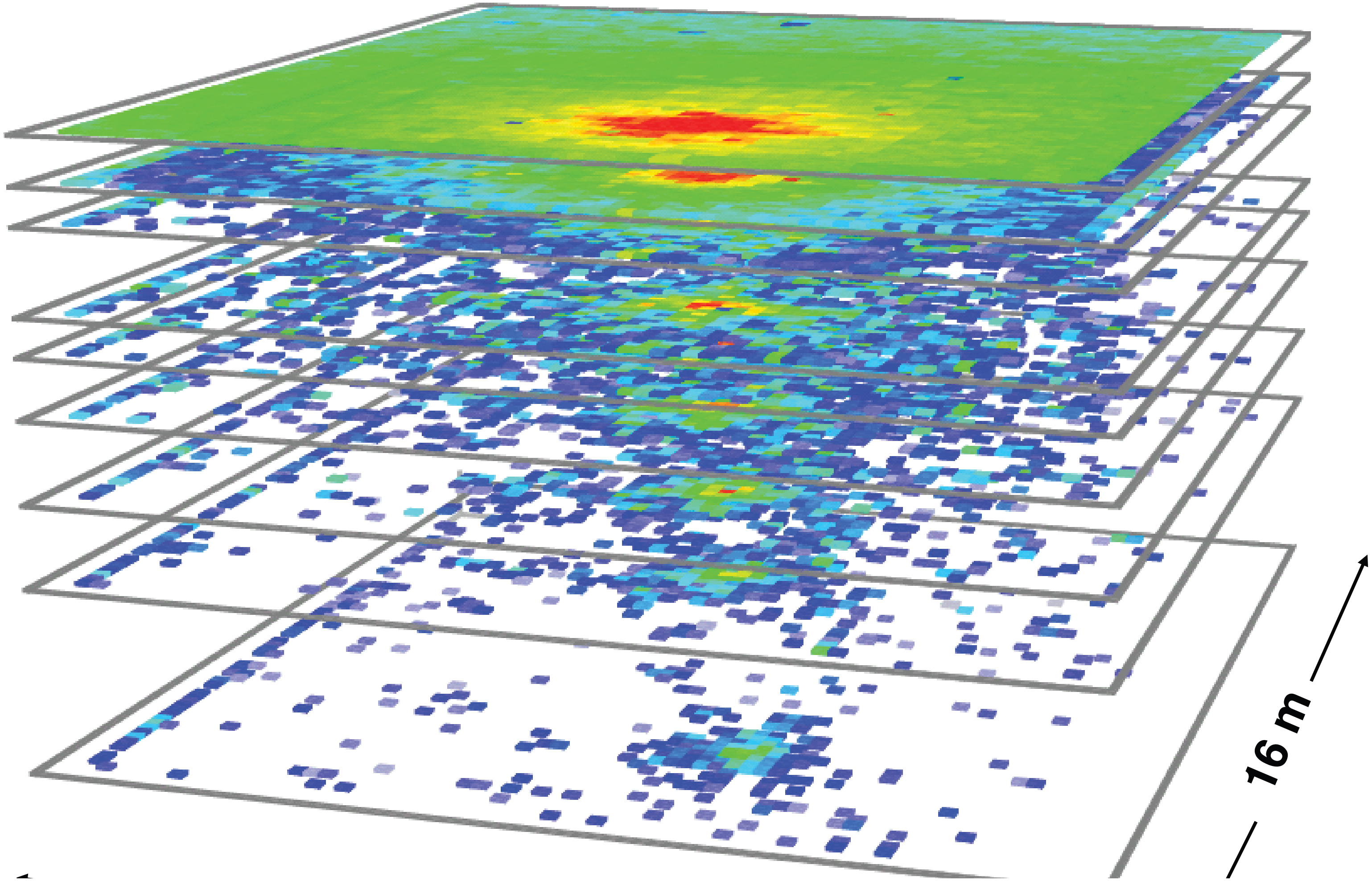
energy resolution:

$$\frac{\sigma(E)}{E}[\%] \approx \frac{250}{\sqrt{E/\,\mathrm{GeV}}}$$

Hadronic shower core

$E_0 \sim 6$ PeV

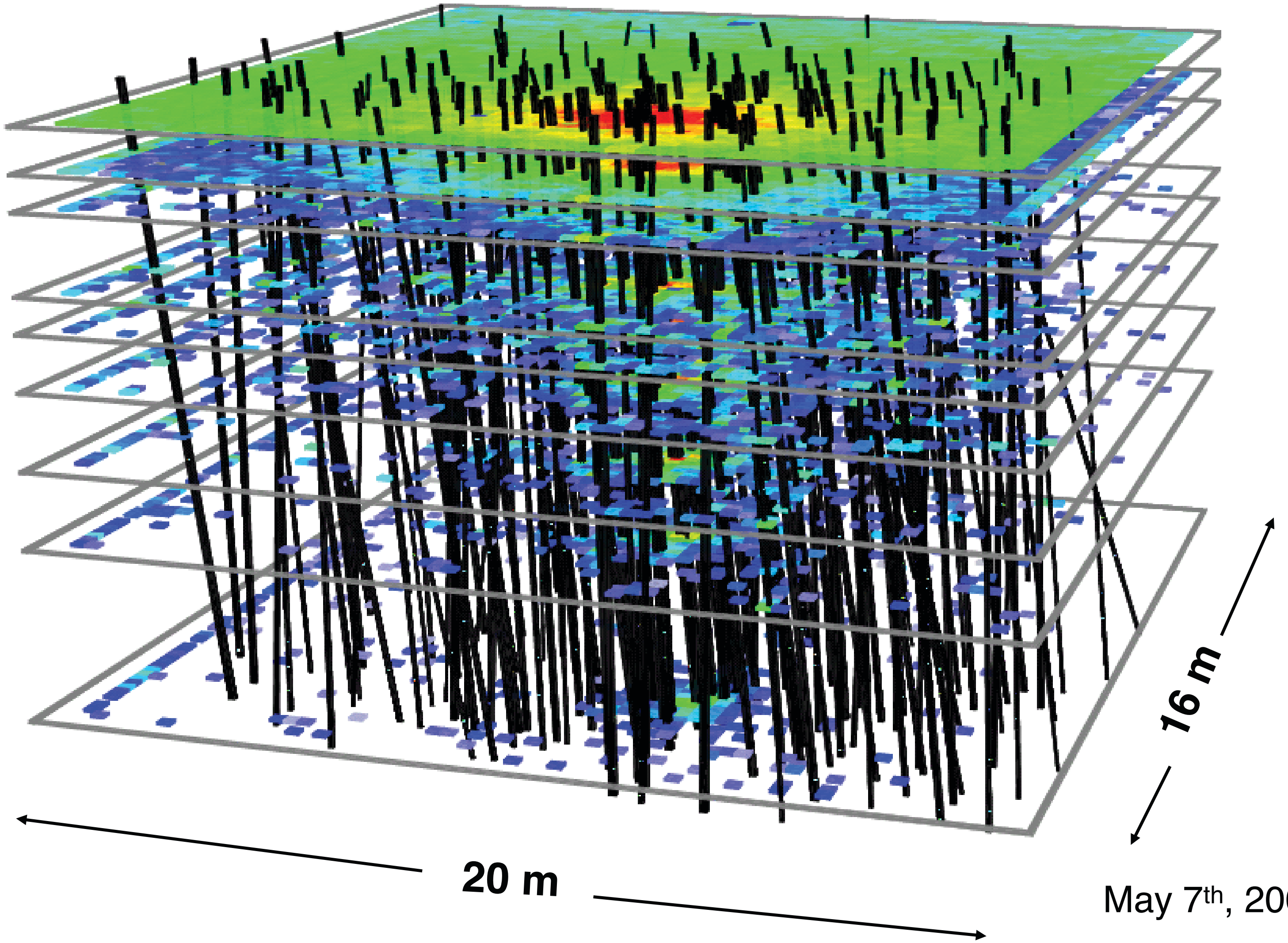
Number of reconstructed hadrons $N_h = 143$



Hadronic shower core

$E_0 \sim 6$ PeV

Number of reconstructed hadrons $N_h = 143$



May 7th, 2002 9:45

to determine the properties of the primary particle we measure the number of electrons N_e

muons N_μ

hadrons N_h

→ measure the lateral distribution $\rho_{e,\mu,h}(r)$

$$N_{e,\mu,h} = \int_0^\infty 2\pi r \, \rho_{e,\mu,h}(r) \, dr$$

we need a suitable parameterization

$$\rho(r) \propto \left(\frac{r}{r_M}\right)^{s-2} \left(1 + \frac{r}{r_M}\right)^{s-4,5}$$

r_M: Molière radius $\approx 0{,}25\, X_0$

in air ~ 80m for $e^\pm$

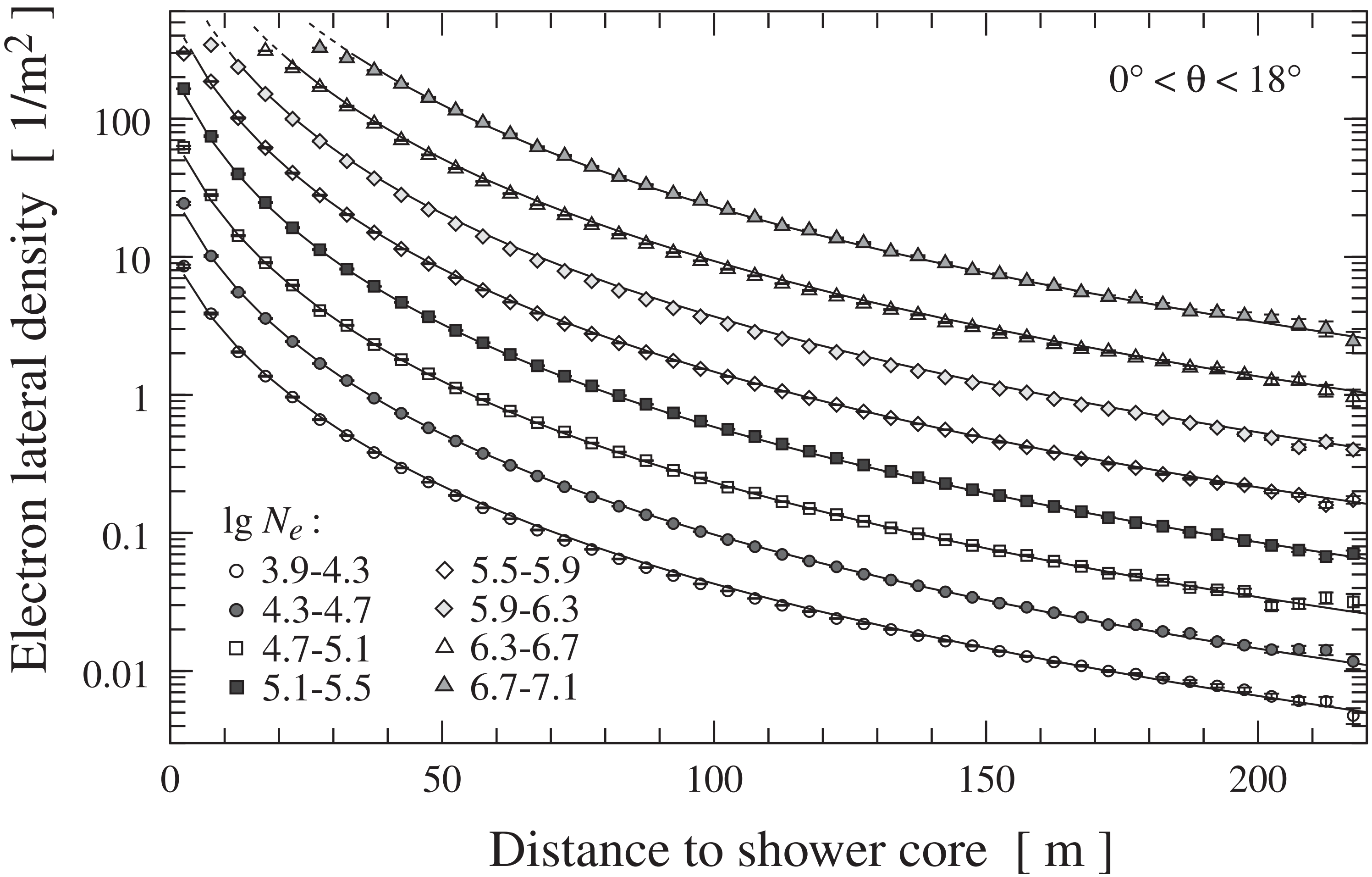
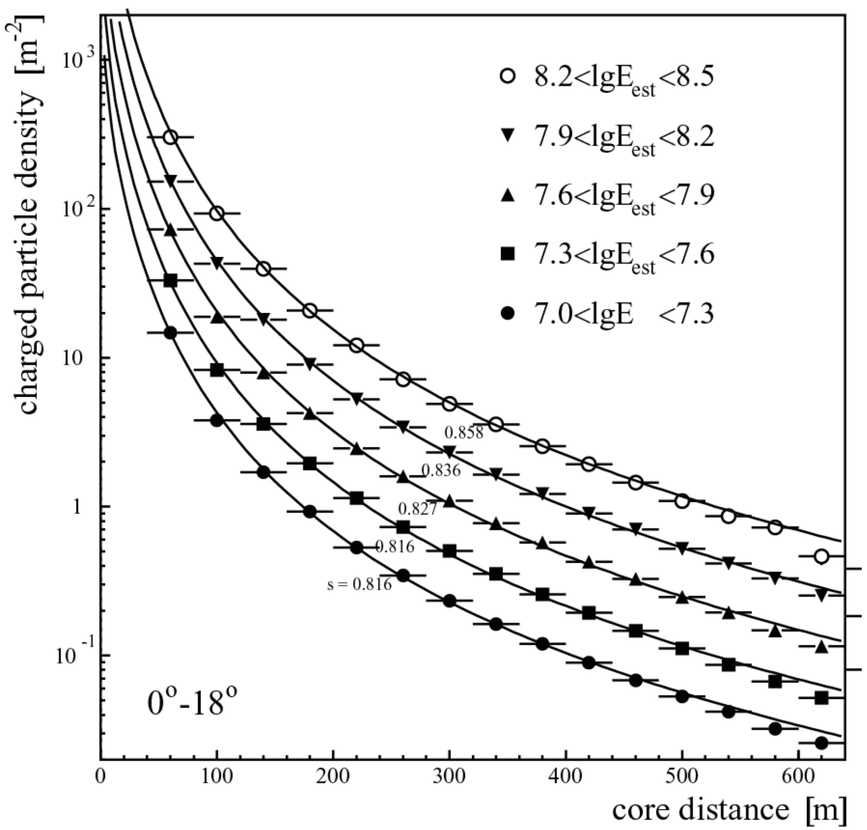


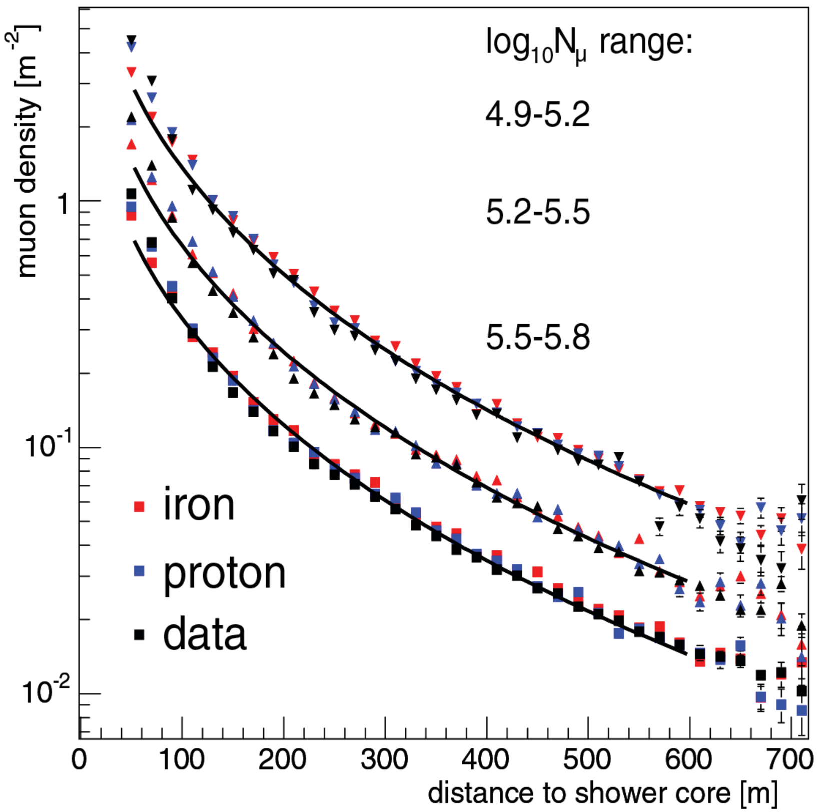
Fig. 2. Lateral distributions of electrons above a 5 MeV kinetic energy for zenith angles below 18°. The lines show NKG functions of fixed age parameter $s = 1.65$ but varying scale radius r_e (see the text).

KASCADE-Grande – Lateral distributions

NKG function

$$\rho(r,s,N_e) = \frac{N_e}{r_M^2}\,\frac{\Gamma(4.5-s)}{2\pi\Gamma(s)\Gamma(4.5-2s)}\left(\frac{r}{r_M}\right)^{s-2}\left(1+\frac{r}{r_M}\right)^{s-4.5}$$

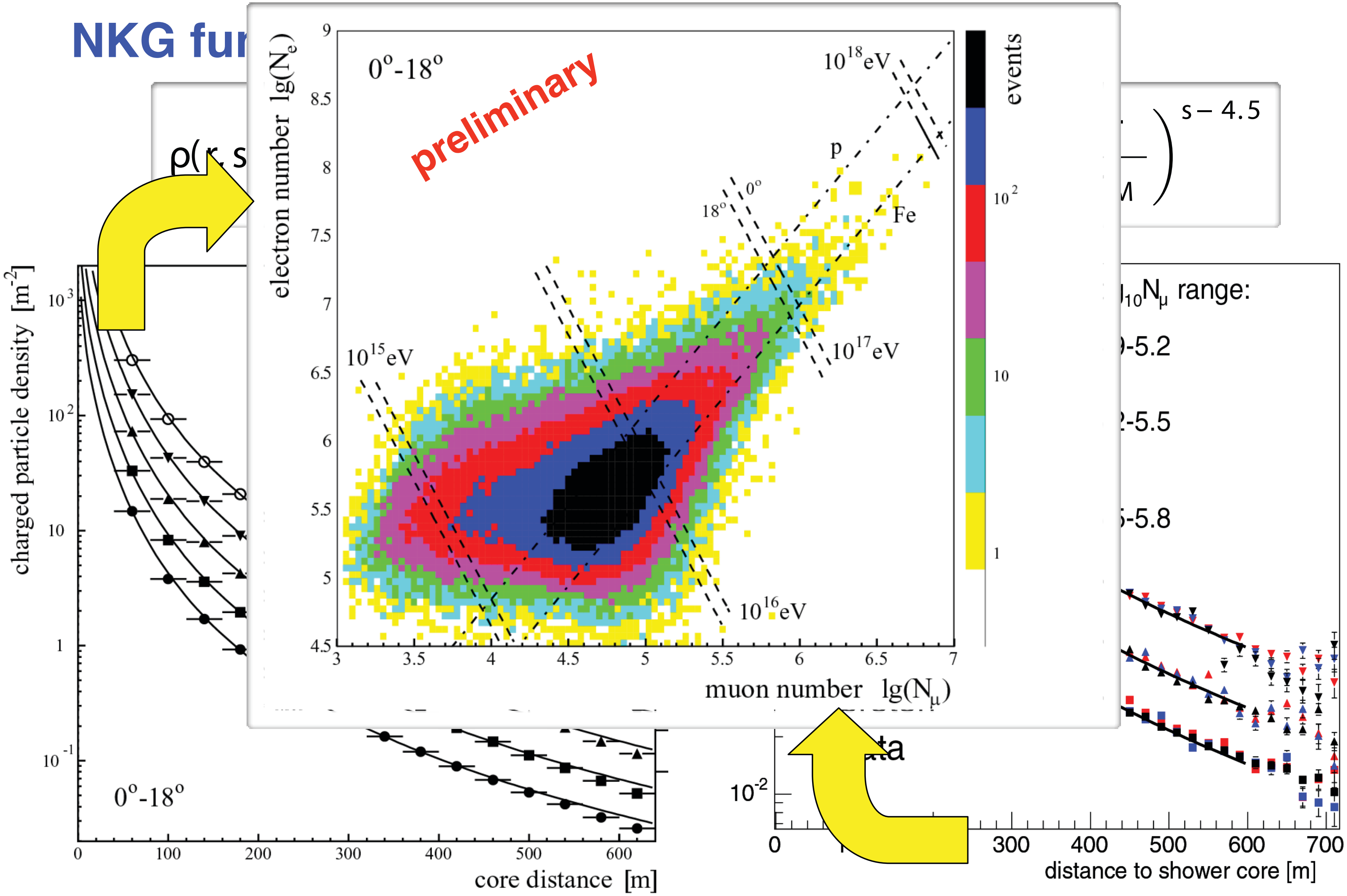




R. Glasstetter et al., Proc. 29th ICRC, Pune 6 (2005) 293

J. v. Buren et al., Proc. 29th ICRC, Pune 6 (2005) 301

KASCADE-Grande – Lateral distributions



R. Glasstetter et al., Proc. 29th ICRC, Pune 6 (2005) 293

J. v. Buren et al., Proc. 29th ICRC, Pune 6 (2005) 301

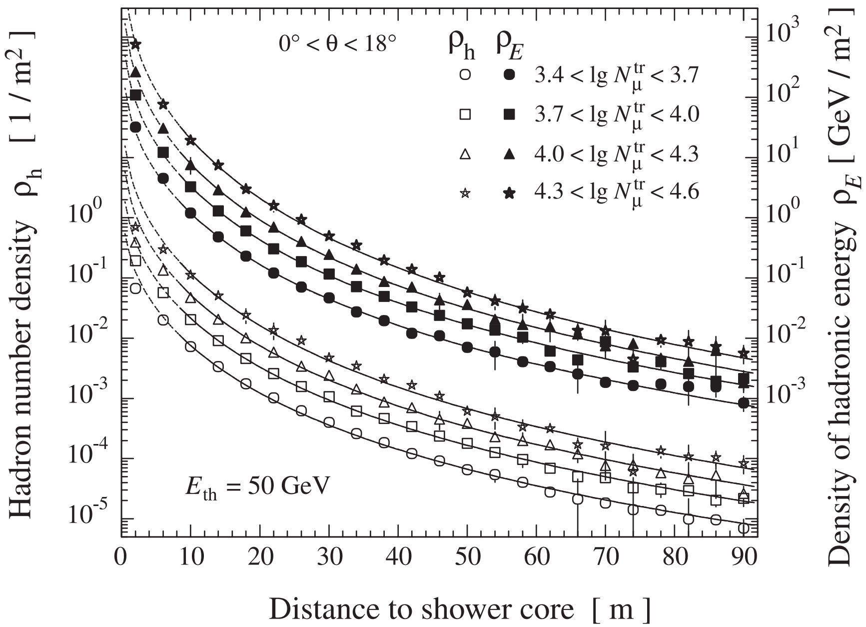


Fig. 12. Density of hadron number (left scale, open symbols) and of hadronic energy (right scale, filled symbols) versus the core distance for showers of truncated muon numbers as indicated. Threshold energy for hadrons is 50 GeV. The curves represent fits of the NKG formula to the data at $r \geqslant 8$ m with a radius fixed to $r_h = 10$ m.

T. Antoni et al. / Astroparticle Physics 14 (2001) 245–260

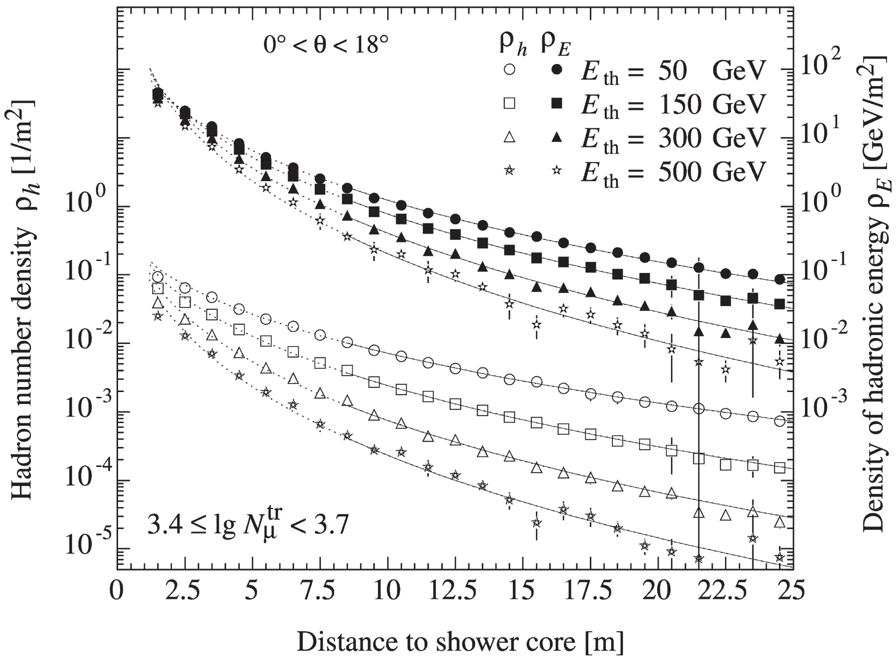


Fig. 14. Density of hadron number (left scale, open symbols) and of hadronic energy (right scale, filled symbols) versus shower core distance for various thresholds of hadron energy. The curves represent fits of the data to the NKG function as in Fig. 12.

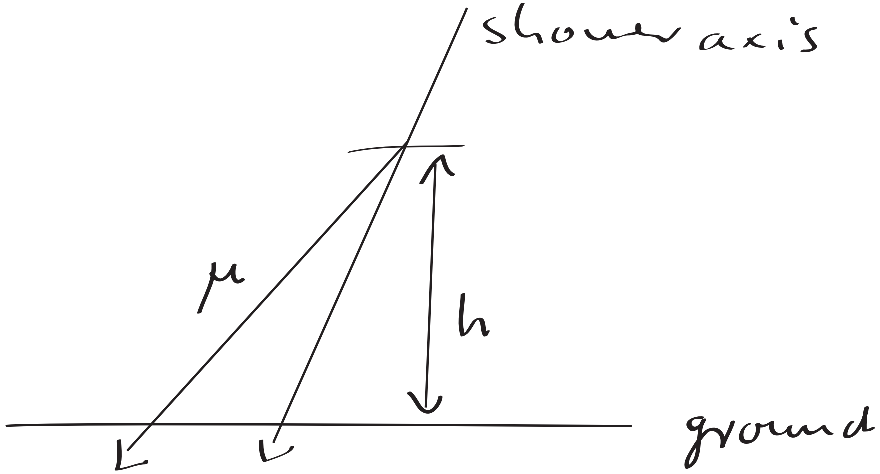
$\sim 400\,m$ for $\mu^{\pm}$

$\sim 15\,m$ for hadrons

determine the mass of the primary particle

- $\frac{e}{\mu}$ ratio or $\frac{h}{\mu}$ ratio

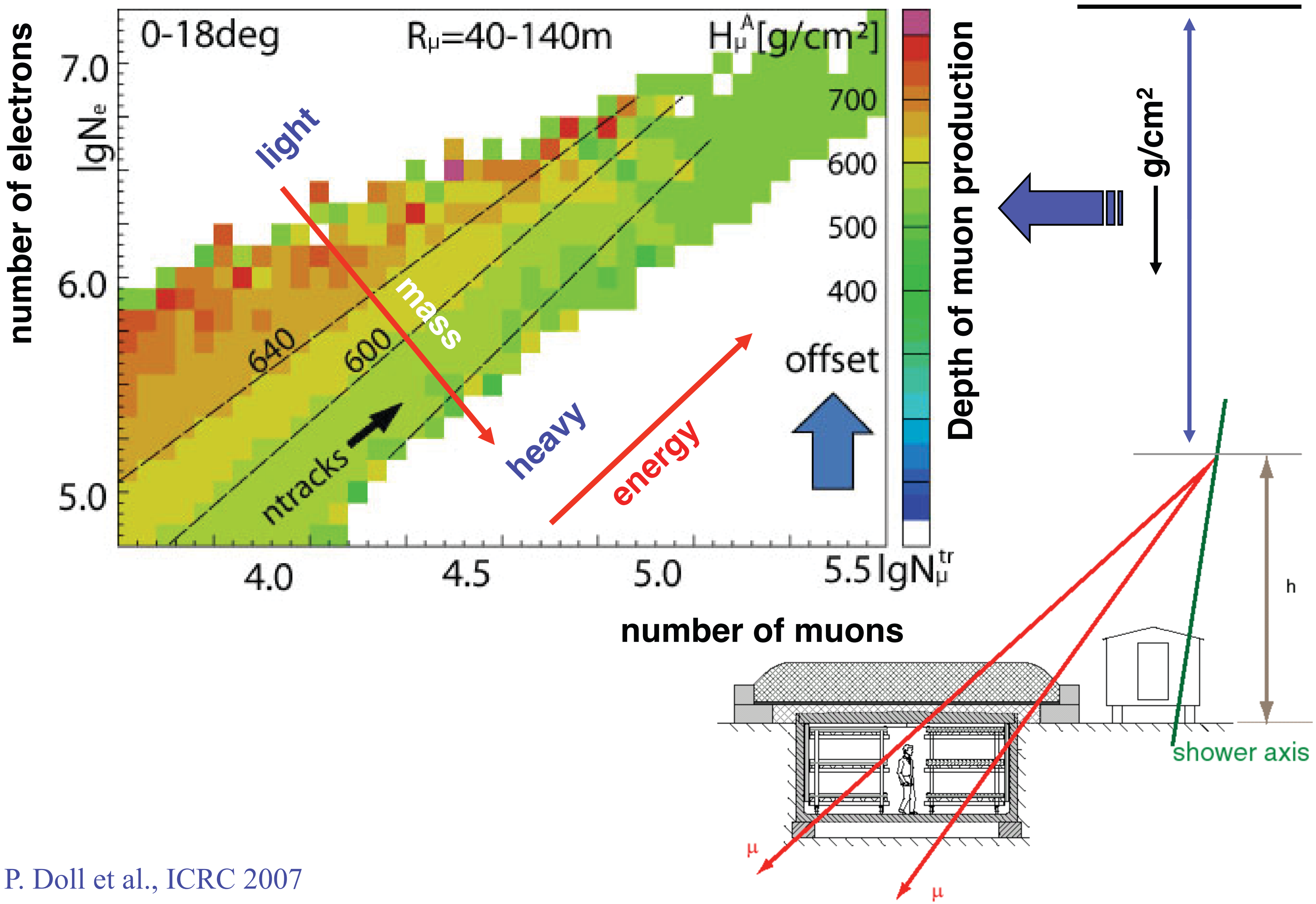
- muon production height or X_{max} (for e/γ component)



high h → heavy particle

low h → light particle

Muon production height – KASCADE muon tracking detector



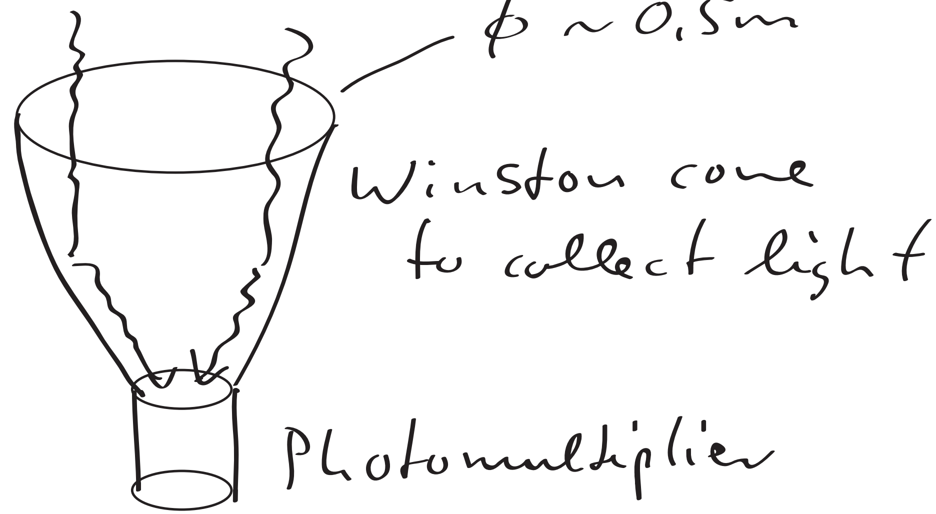
P. Doll et al., ICRC 2007

Measurement of Čerenkov light

two techniques:

1) non-imaging detectors

open Č detectors



register Č-photons as function of distance to shower axis

→ total number of photons → energy

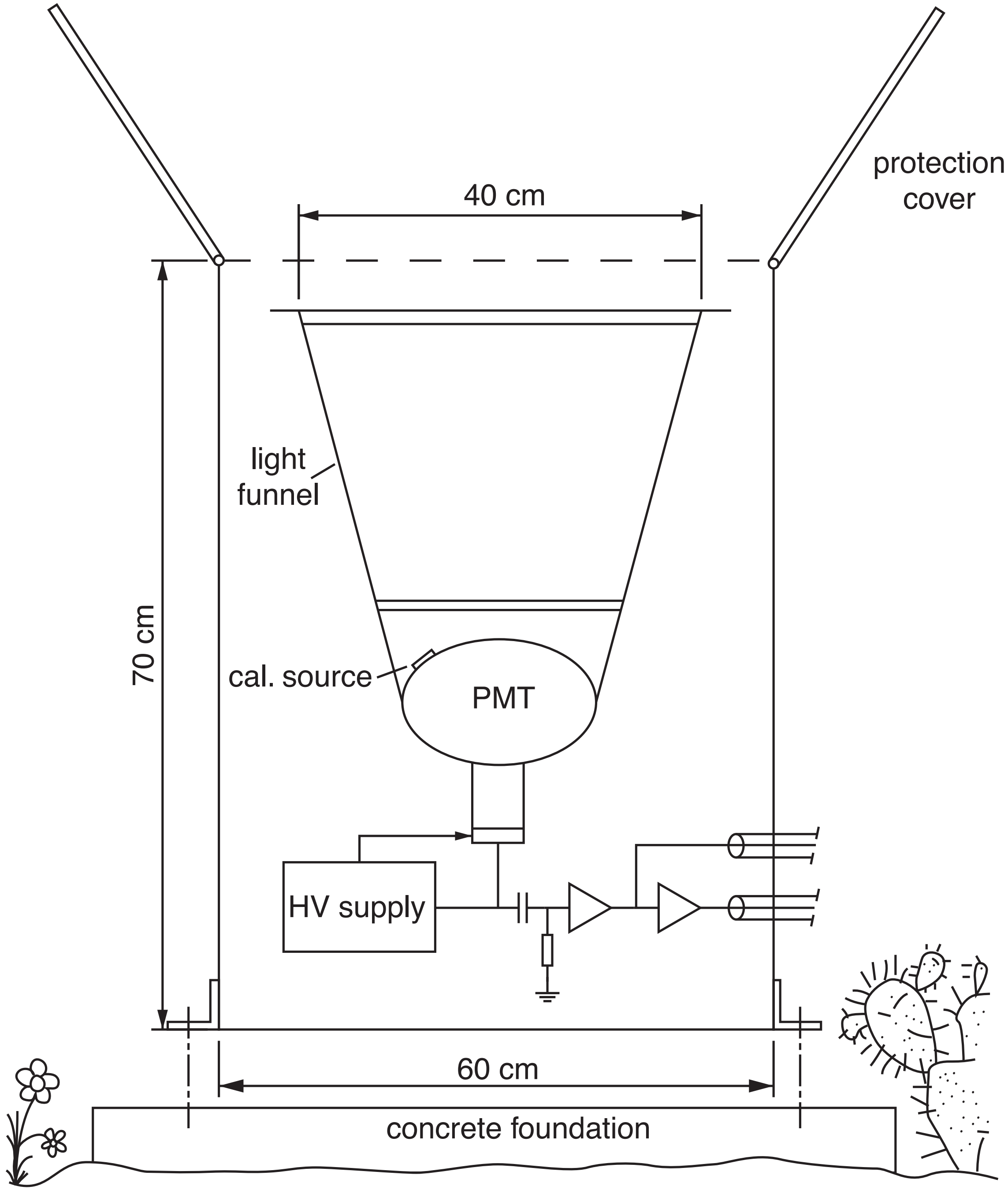


Fig. 4.19. Integrating Cherenkov cone of an AIRO-BICC station and auxiliaries. Directly above the PMT a glass filter restricted the incoming light to wavelengths smaller than 500 nm and a plexiglass cover protected against dew, white frost and dust [29]

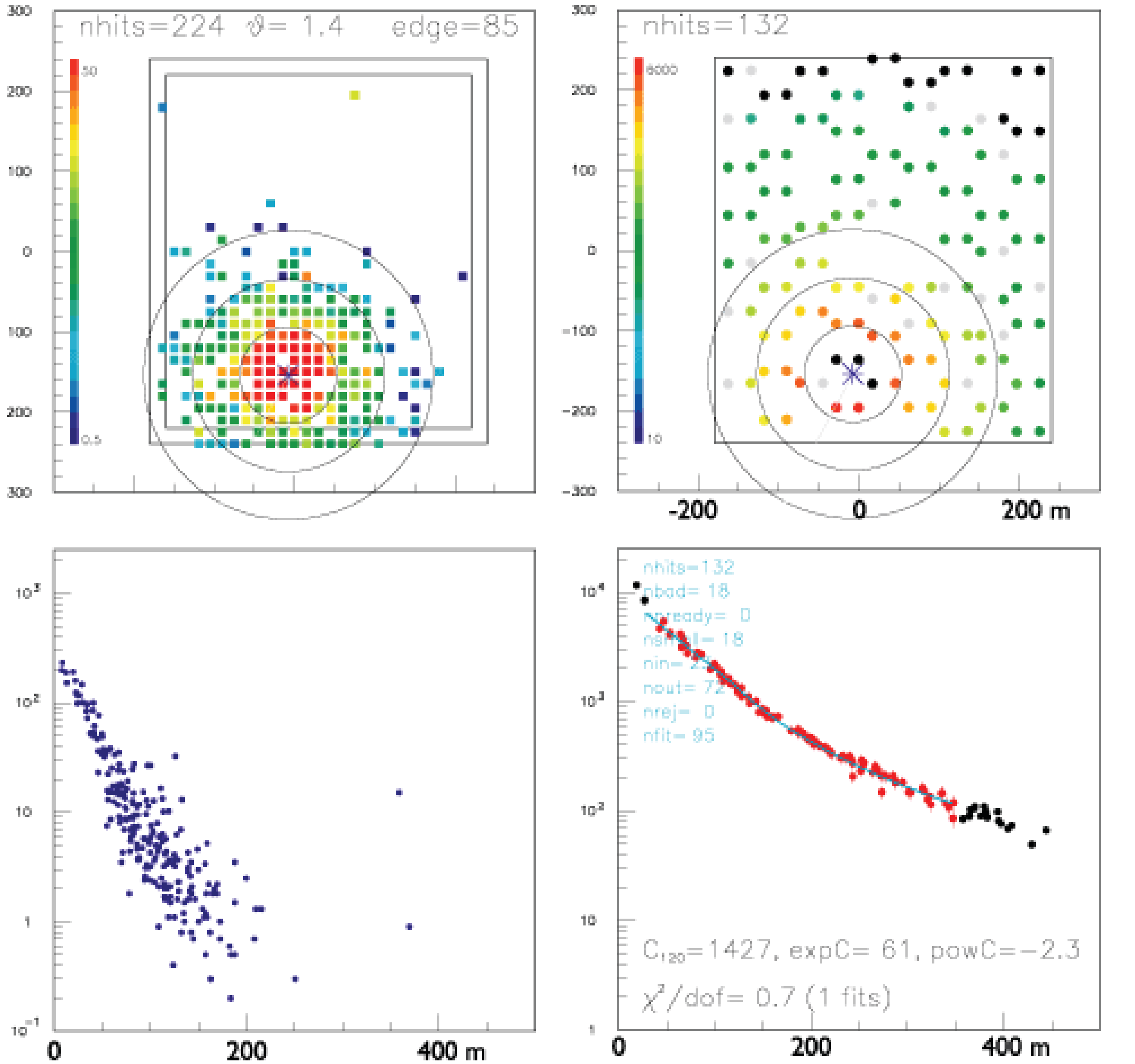
Single event in CASA-BLANCA

CASA

measures particles,
determines shower core

BLANCA

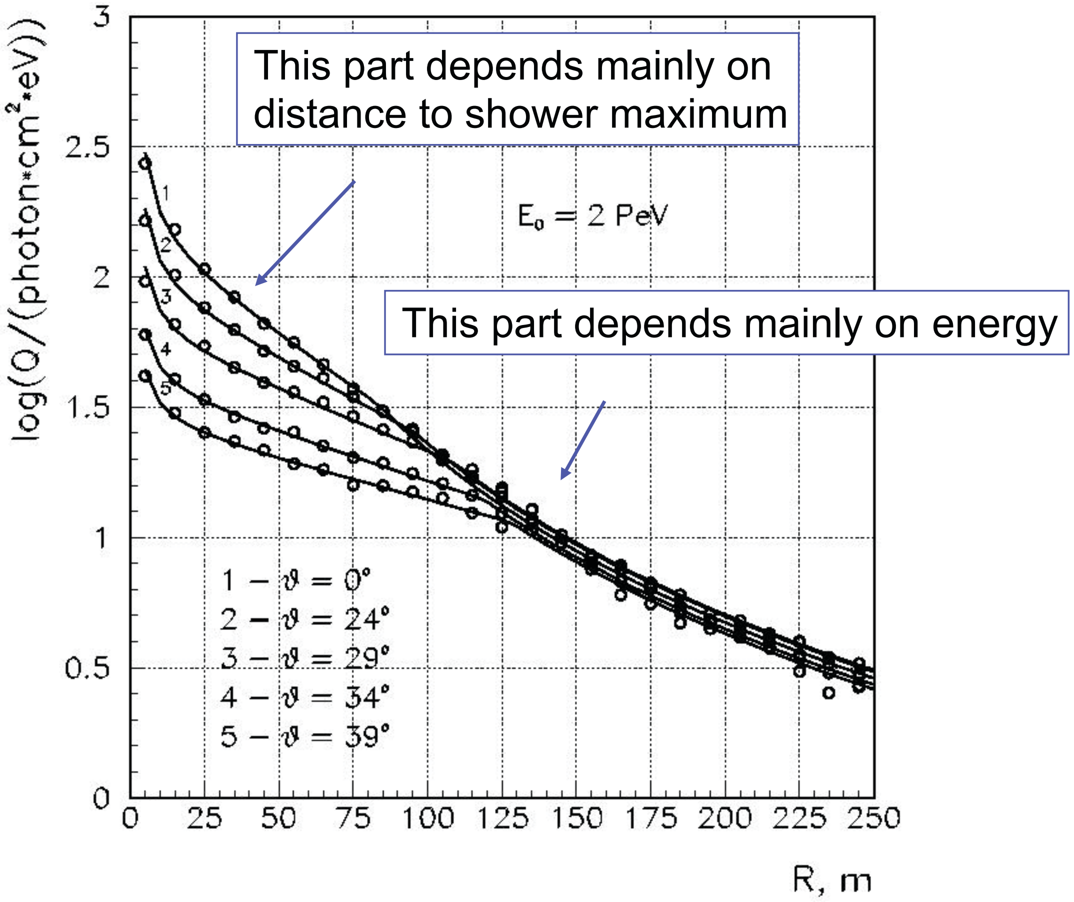
measures Cherenkov light,
determines lateral C-distribution

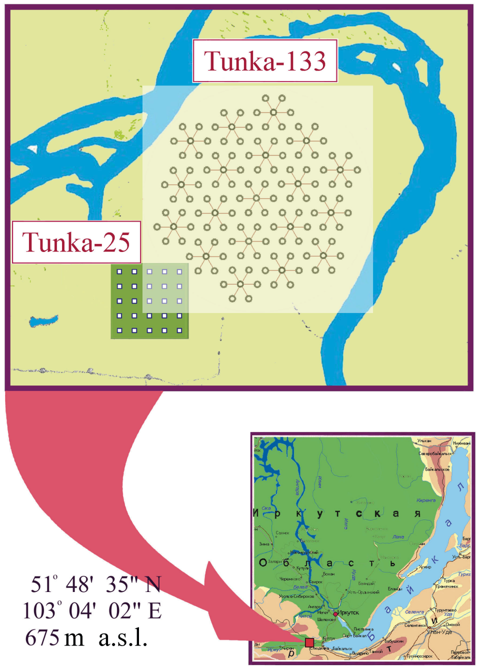


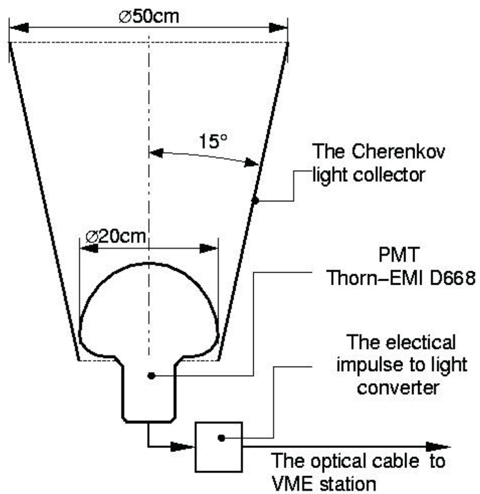
Tunka Experiment

Lateral distribution of Cerenkov light

$$C(r) = \begin{cases} C_{120} \times \exp(s[120\,m - r]) & 30\text{ m} < r < 120\text{ m} \\ C_{120} \times (r/120\,m)^{-\hat{a}} & 120\text{ m} < r < 350\text{ m} \end{cases}$$

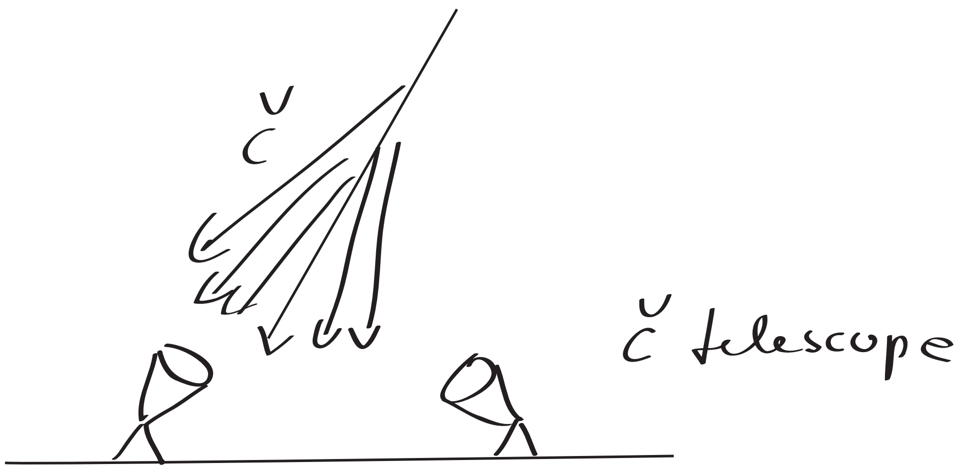






Ch. Spiering, DPG 2005

2) imaging Čerenkov telescopes → IACT



camera → image of shower

field of view ~ 4°

⇒ ideal for measurement of γ-induced showers ⇒ TeV gamma ray astronomy

Fluorescence detectors

main difference to Č light: isotropic light emission

→ showers can be observed from aside

but amount of light is small (4π emission)

simple estimate: 10^{17} eV → 0.1 Watt

10^{20} eV → 100 W light bulb

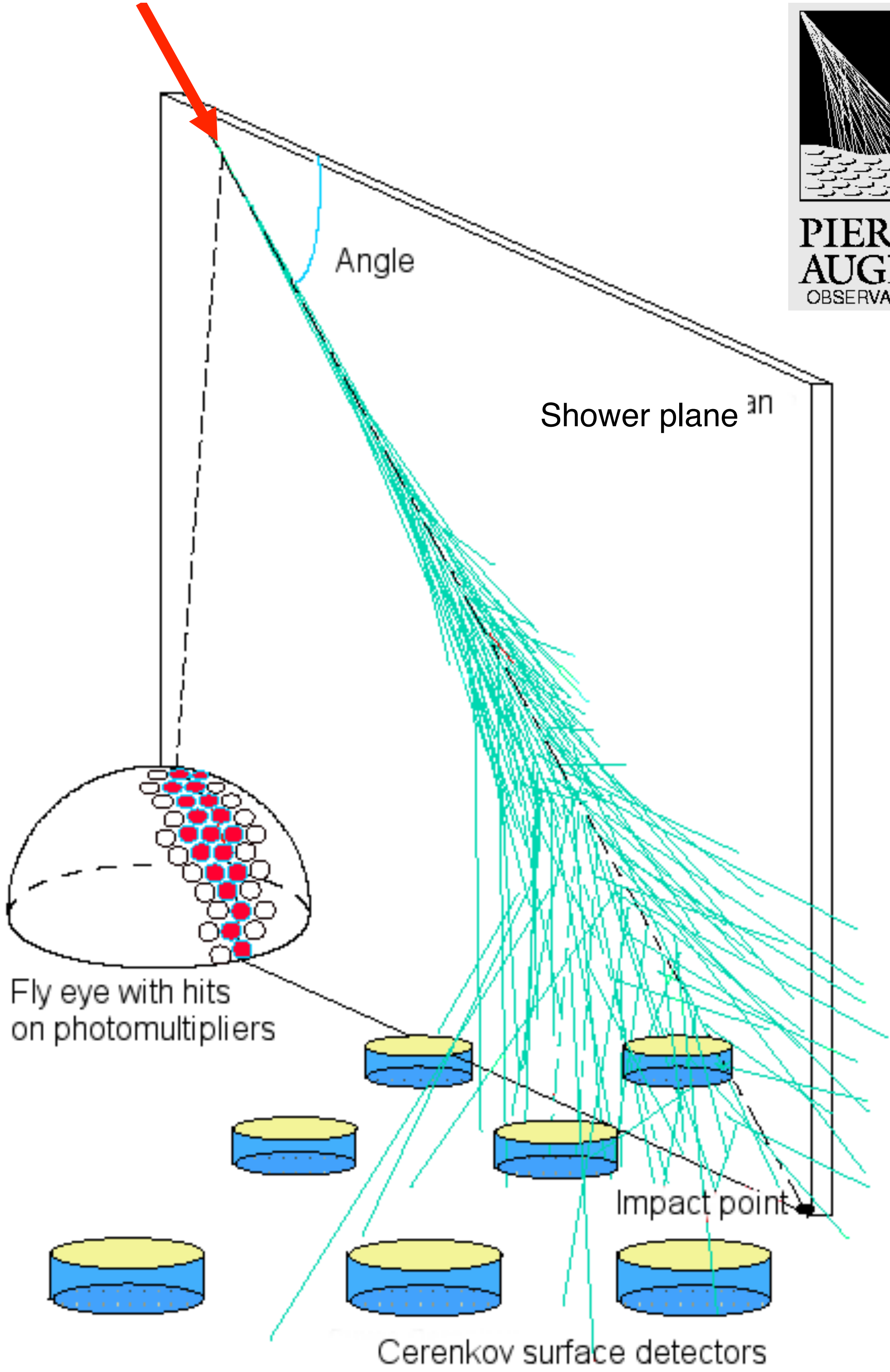
imaging telescopes with PMT camera

field of view $\sim 30^{\circ}$

Hybrid Detector

Fluorescence telescope

Surface array
(water Cherenkov detectors)



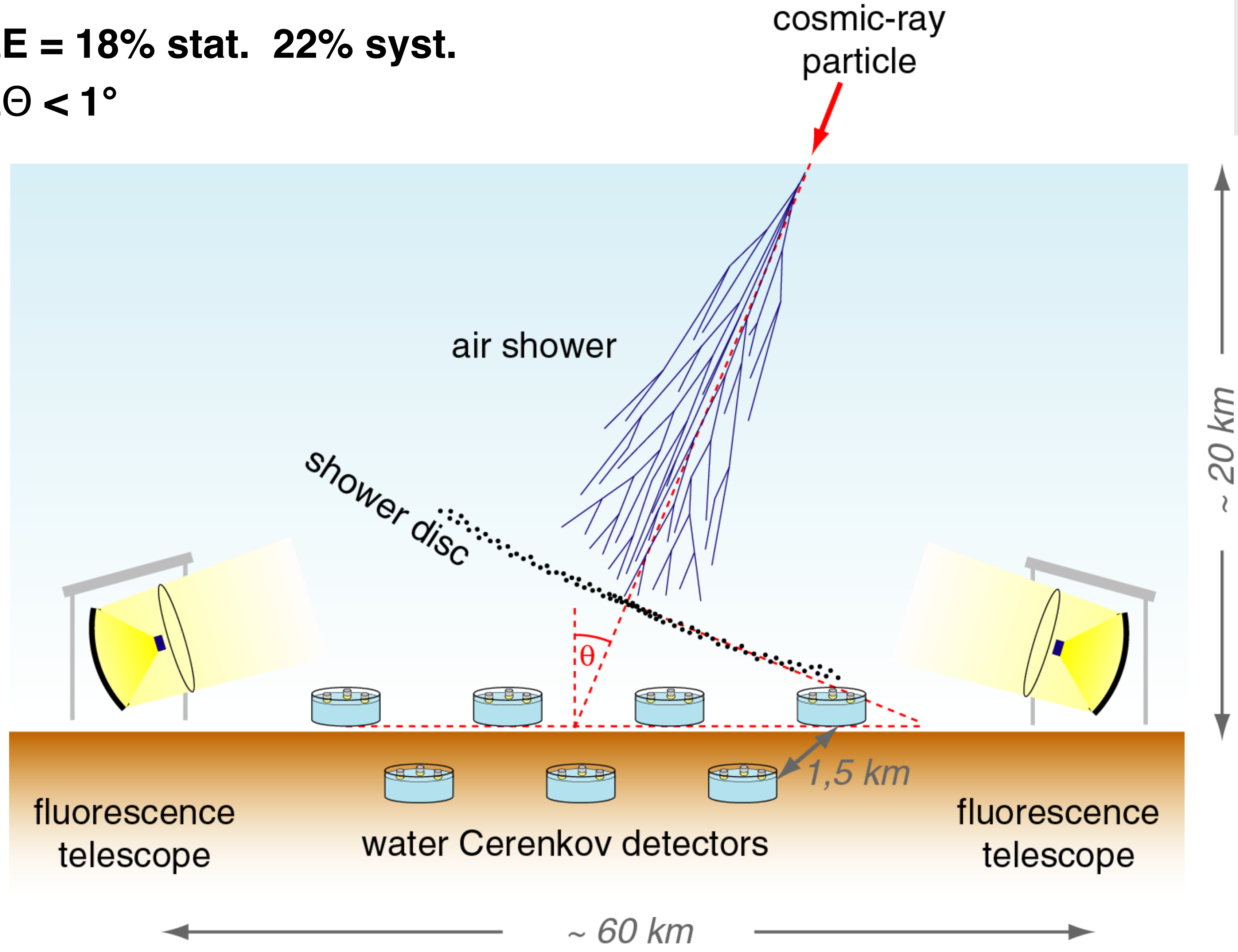
PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory

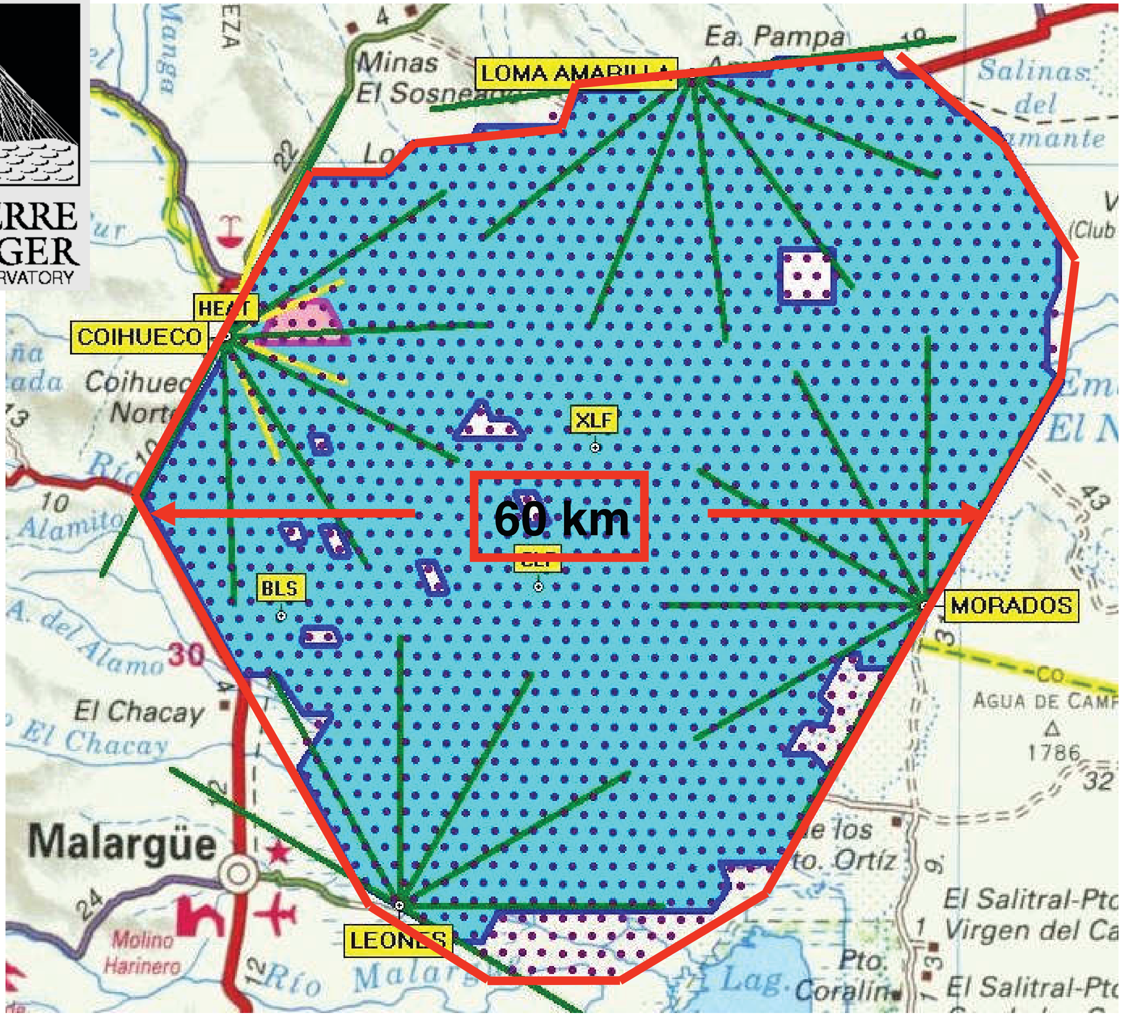
The detection principle

ΔE = 18% stat. 22% syst.

ΔΘ < 1°



PIERRE AUGER OBSERVATORY



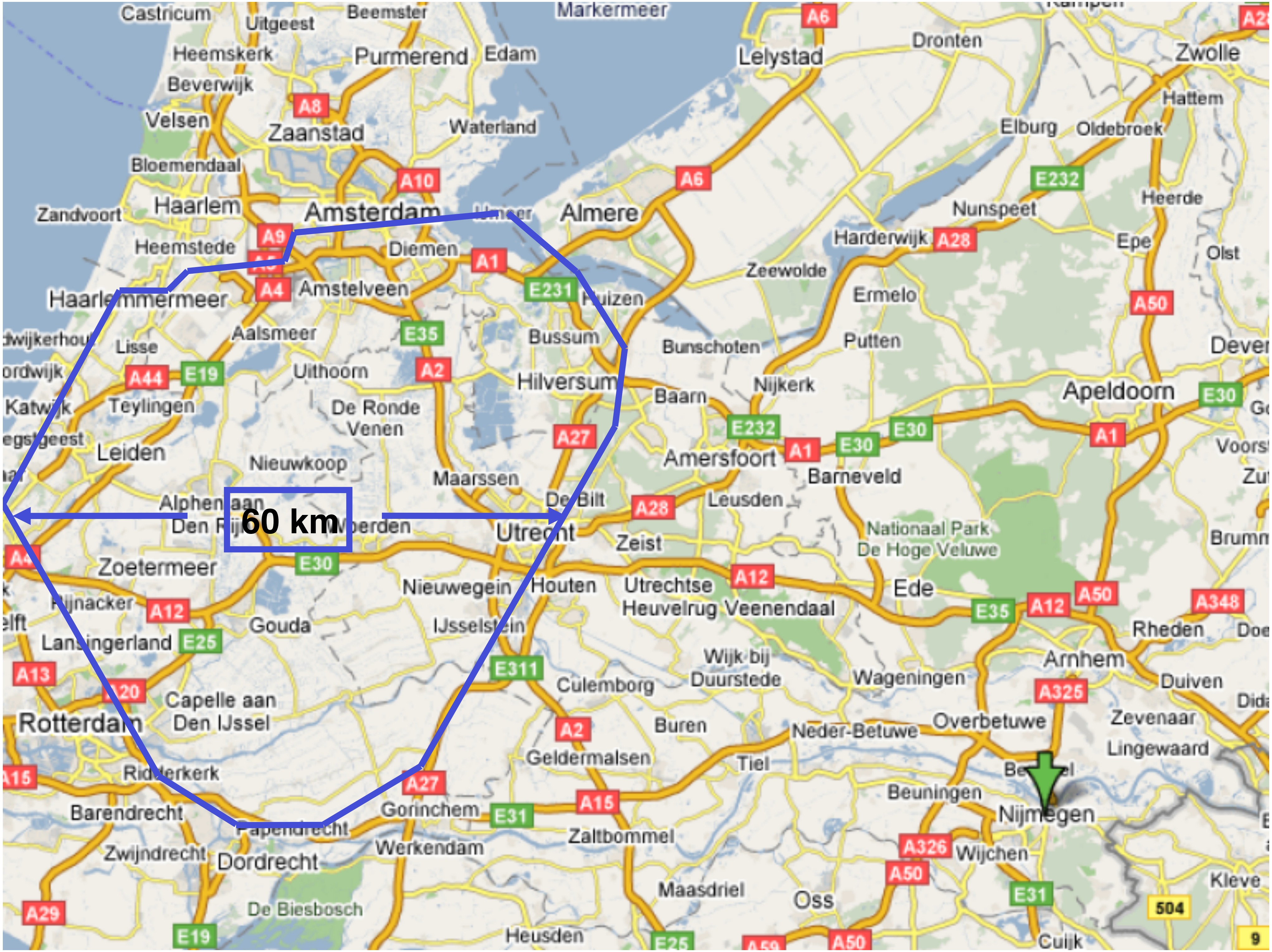
Pierre Auger Observatory

3000 km²

4 telescope buildings
6 telescopes each

Spring 2008:

water Cherenkov detector array completed
1600 tanks operating


60 km
Castricum
Uitgeest
Beemster
Markermeer
Heemskerk
Purmerend
Edam
Lelystad
Dronten
Zwolle
Beverwijk
Velsen
Zaanstad
Waterland
Hattem
Elburg
Oldebroek
Bloemendaal
Zandvoort
Haarlem
Amsterdam
Almere
Nunspeet
Heerde
Heemstede
Diemen
Harderwijk
Epe
Olst
Haarlemmermeer
Amstelveen
Zeewolde
Ermelo
Aalsmeer
Bussum
Lisse
Bunschoten
Putten
Uithoorn
Hilversum
Nijkerk
Apeldoorn
Katwijk
Teylingen
De Ronde Venen
Baarn
Leiden
Nieuwkoop
Amersfoort
Barneveld
Maarssen
De Bilt
Leusden
Alphen aan Den Rijn
Woerden
Utrecht
Zeist
Nationaal Park De Hoge Veluwe
Zoetermeer
Nieuwegein
Houten
Utrechtse Heuvelrug
Veenendaal
Ede
Gouda
IJsselstein
Rheden
Lansingerland
Arnhem
Wijk bij Duurstede
Wageningen
Culemborg
Duiven
Capelle aan Den IJssel
Rotterdam
Buren
Neder-Betuwe
Overbetuwe
Zevenaar
Geldermalsen
Lingewaard
Ridderkerk
Tiel
Beuningen
Barendrecht
Gorinchem
Nijmegen
Papendrecht
Zaltbommel
Zwijndrecht
Dordrecht
Werkendam
Wijchen
Maasdriel
Oss
Kleve
De Biesbosch
Heusden
Cuijk
A1
A2
A4
A6
A8
A9
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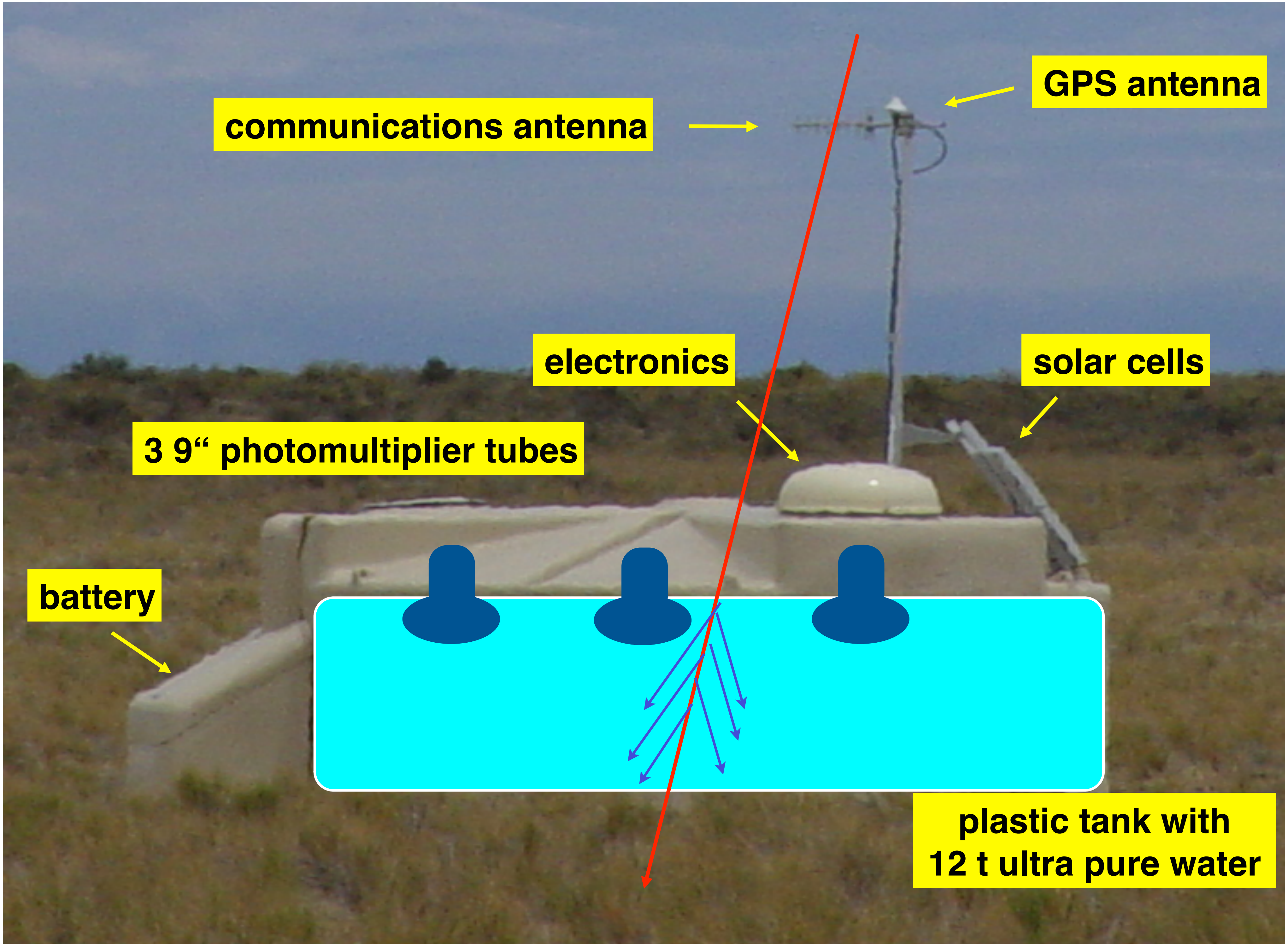
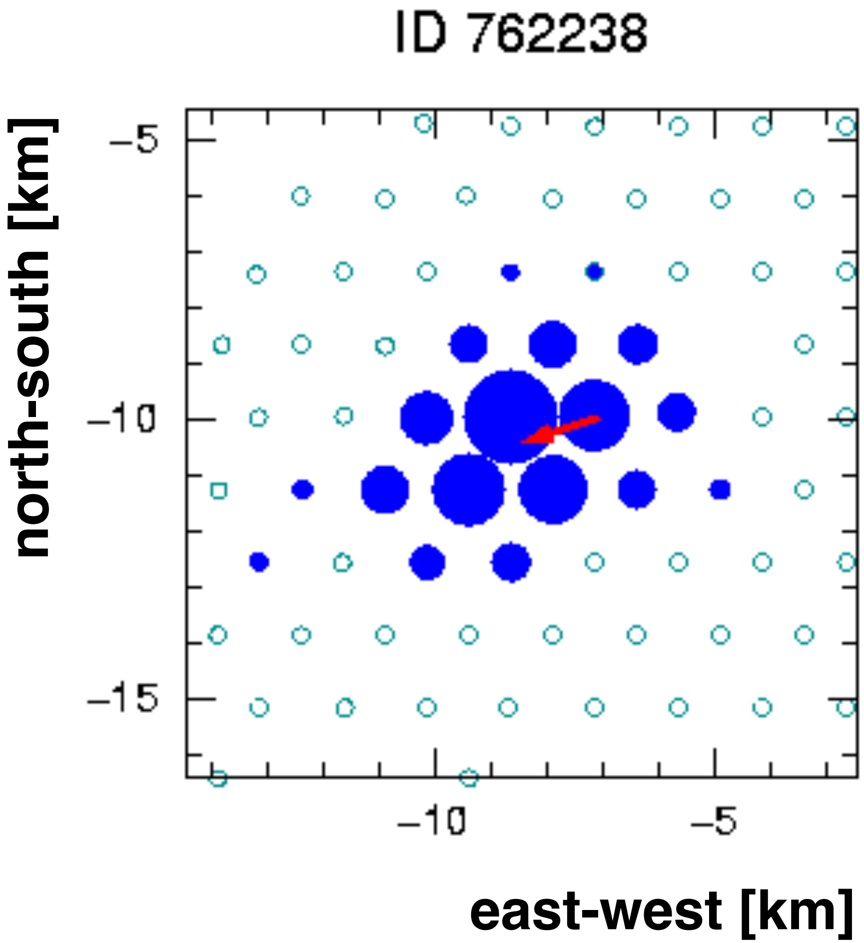
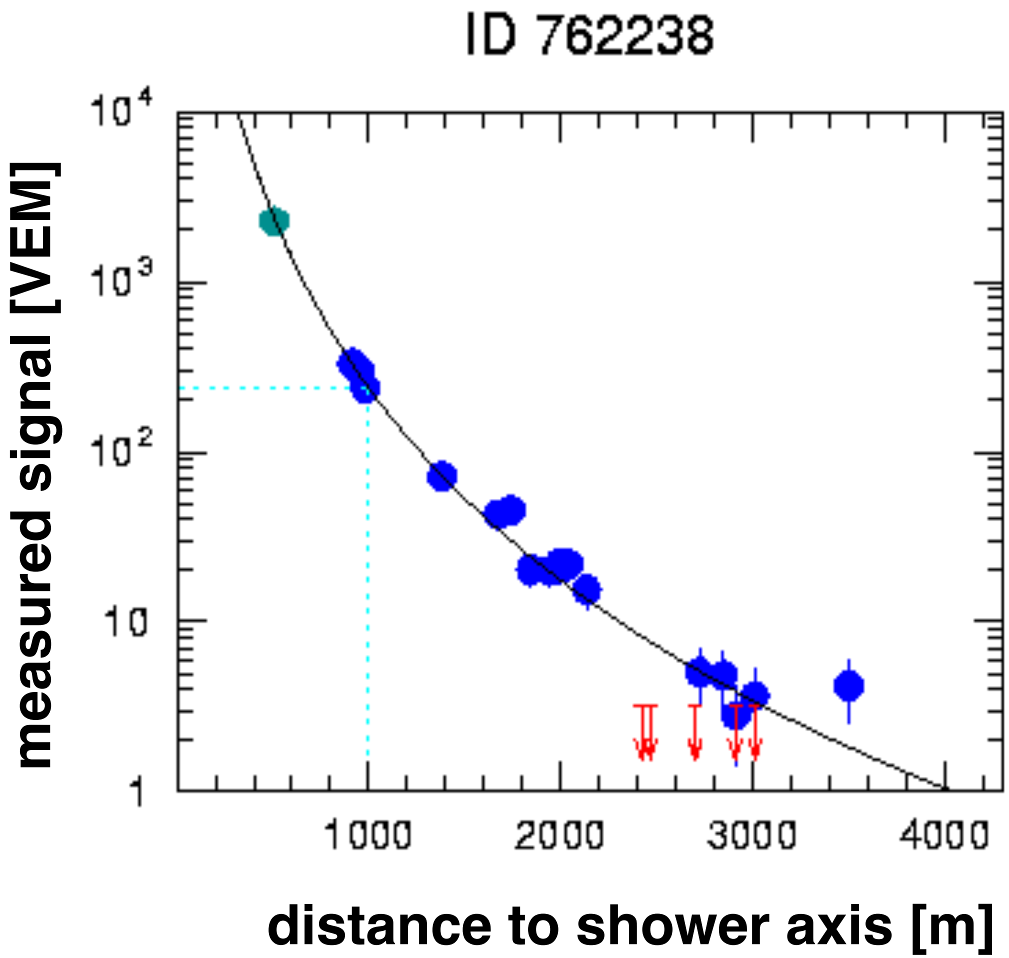
A325
A326
A348
E19
E25
E30
E31
E35
E231
E232
E311
504
9

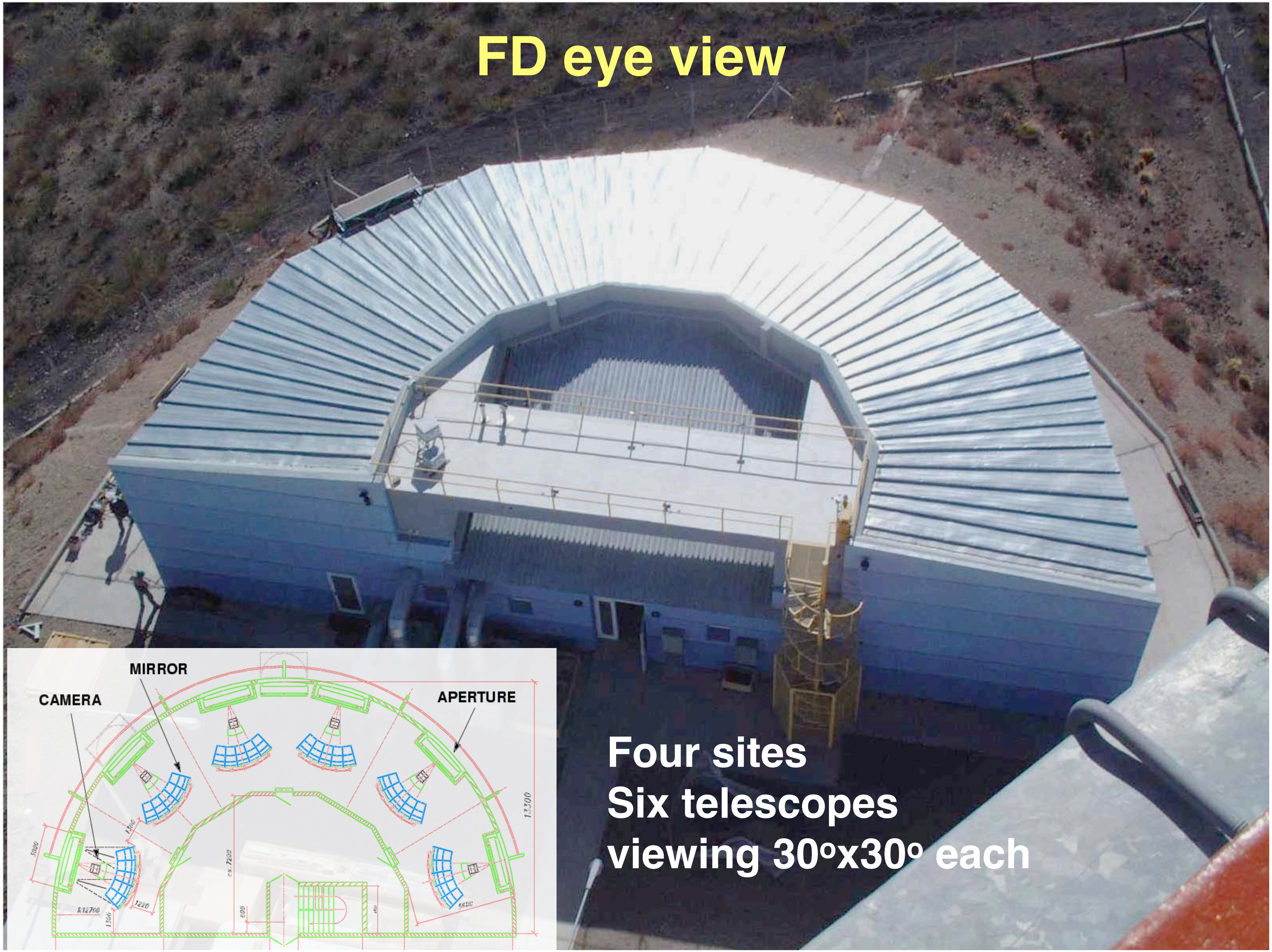

communications antenna
GPS antenna
electronics
solar cells
3 9“ photomultiplier tubes
battery
plastic tank with
12 t ultra pure water

Air shower registered with water Cherenkov detectors

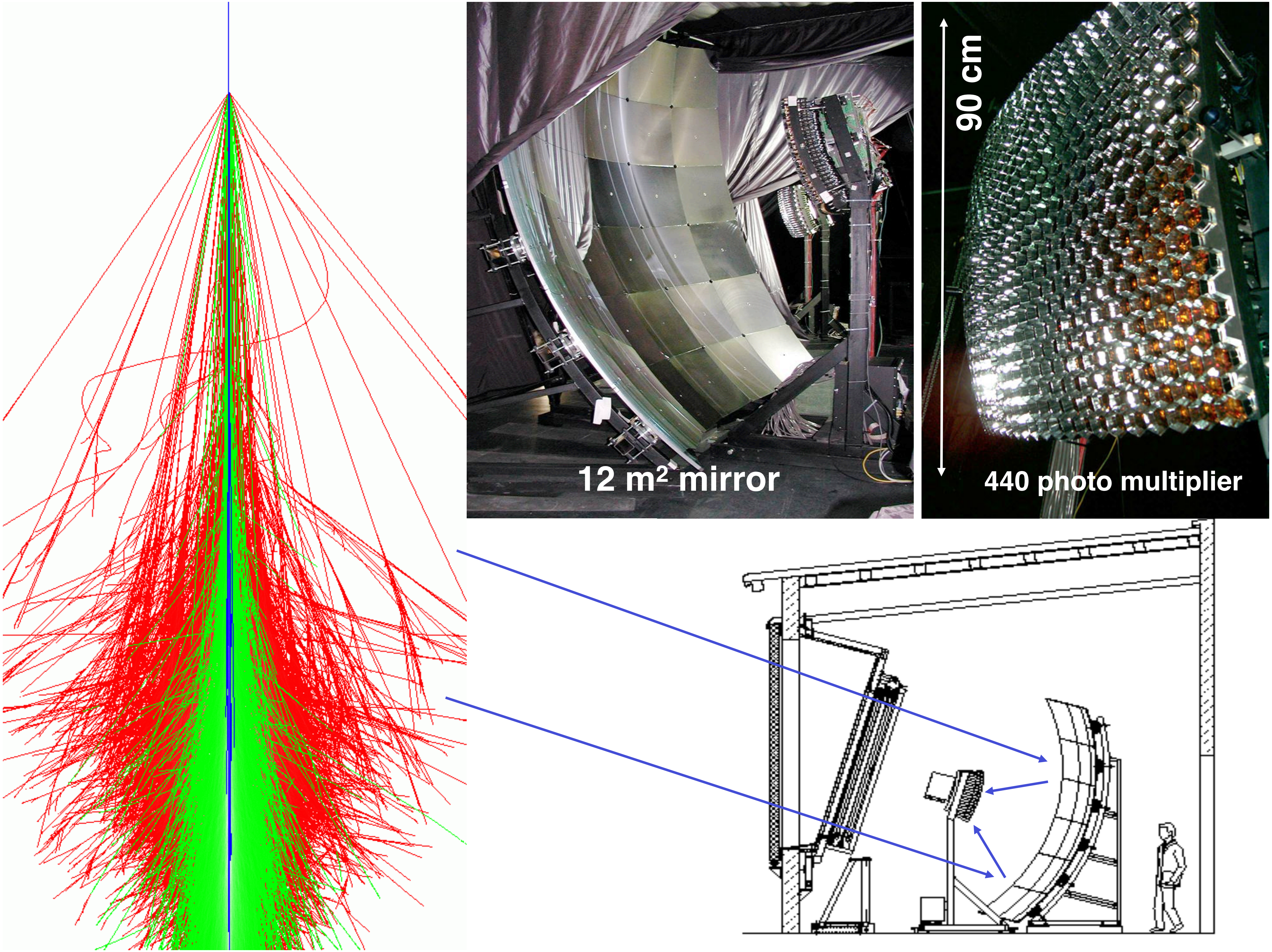


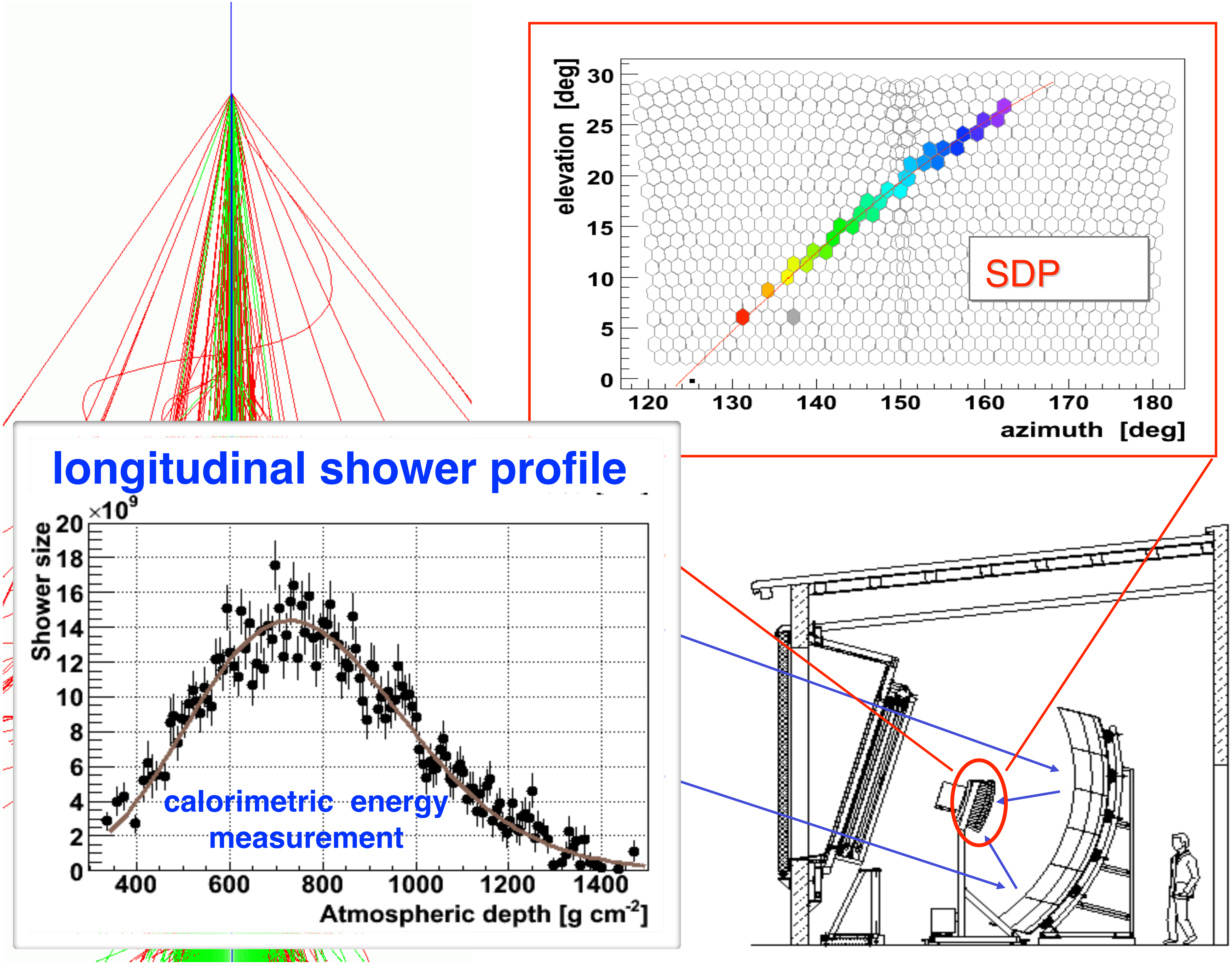


FD eye view



Four sites
Six telescopes
viewing 30°x30° each


12 m^2 mirror
90 cm
440 photo multiplier


longitudinal shower profile
Shower size
×10^9
20
18
16
14
12
10
8
6
4
2
0
400
600
800
1000
1200
1400
Atmospheric depth [g cm^-2]
calorimetric energy
measurement
elevation [deg]
30
25
20
15
10
5
0
120
130
140
150
160
170
180
azimuth [deg]
SDP

Atmospheric Monitoring & Calibration: CLF, Lidar, radiosondes, ground-based weather stations

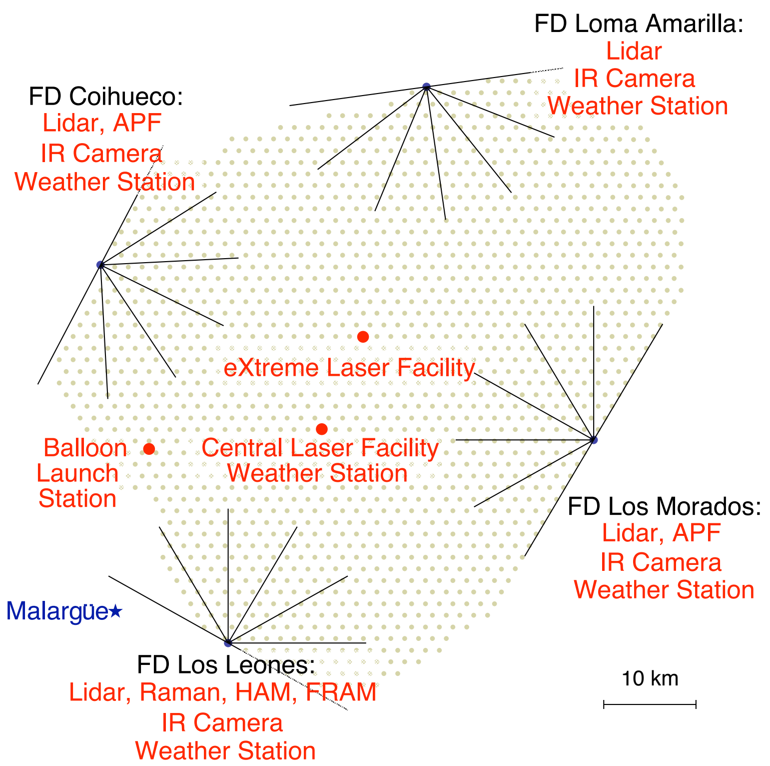
Central Laser Facility

Absolute Calibration

Drum for uniform camera illumination – end to end calibration

Lidar at each fluorescence eye

Auger atmospheric monitoring



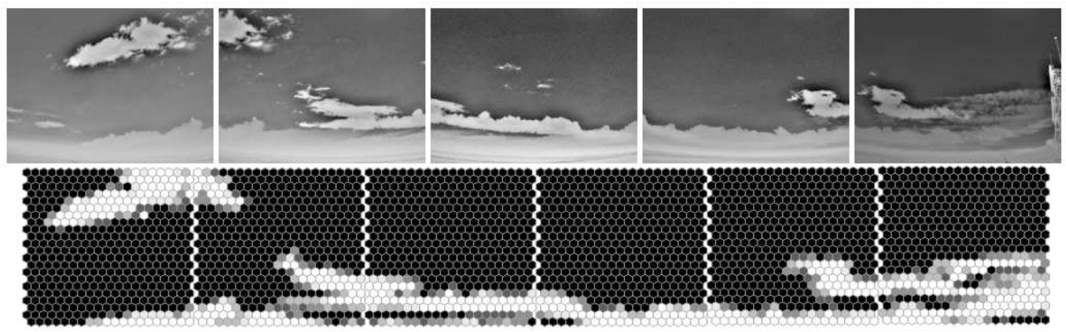


Fig. 6. Top: raw IRCC image. Bottom: FD pixels coverage mask: lighter values on the greyscale represent greater cloud coverage

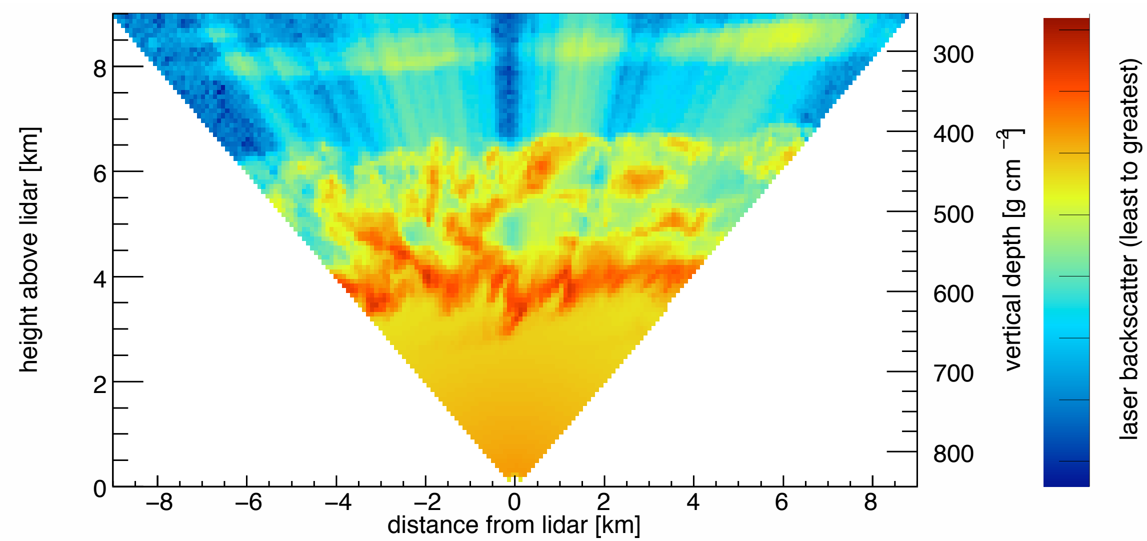
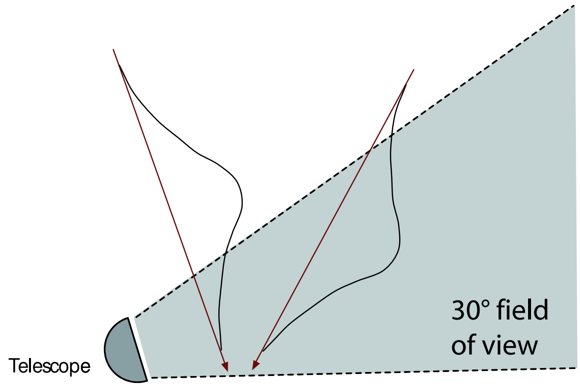


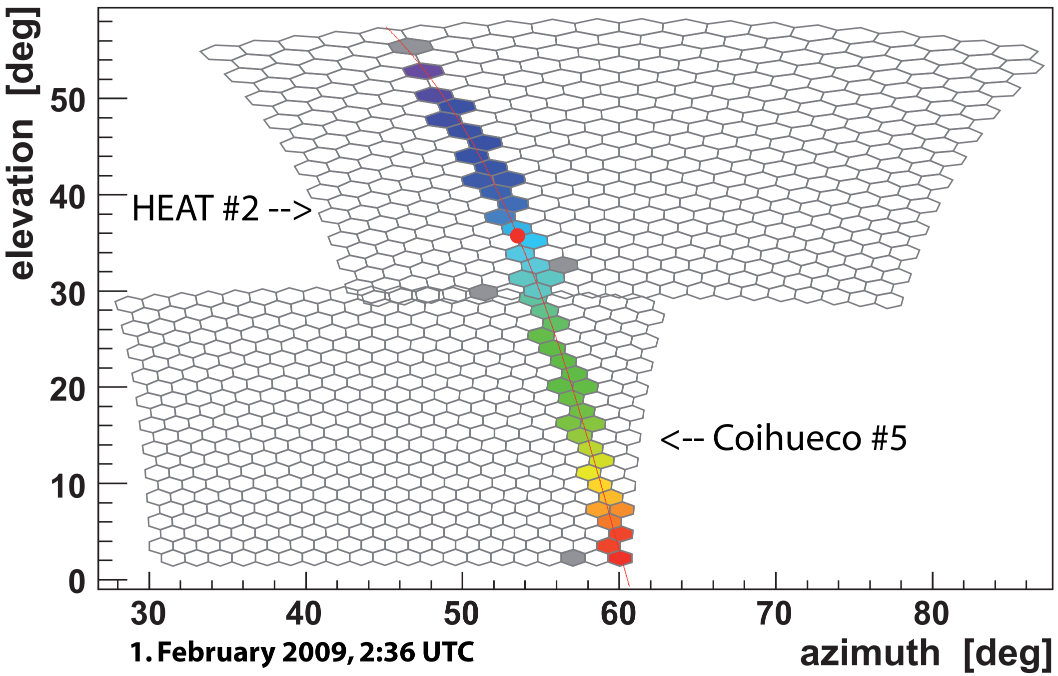
Fig. 7. A cloud layer around 3.5 km height as detected by the LIDAR

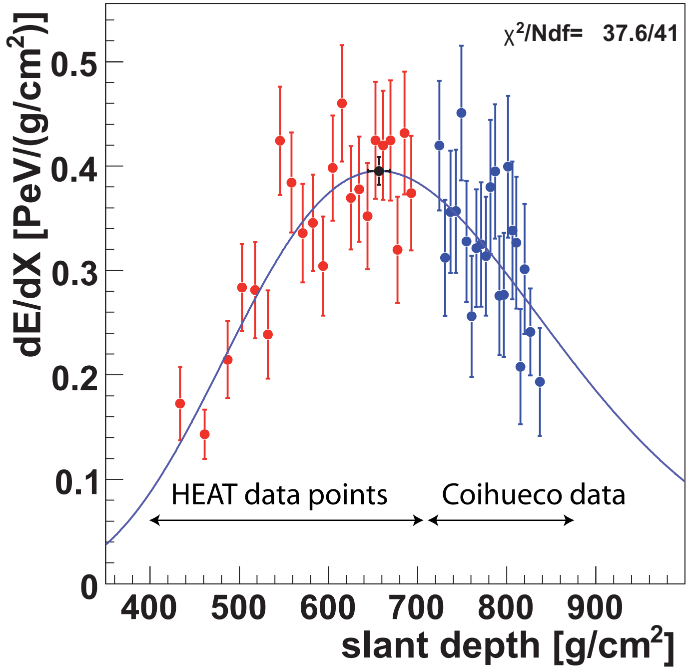
S. BenZvi et al., ICRC 2009

L. Valore et al., ICRC 2009

HEAT - High Elevation Auger Telescopes

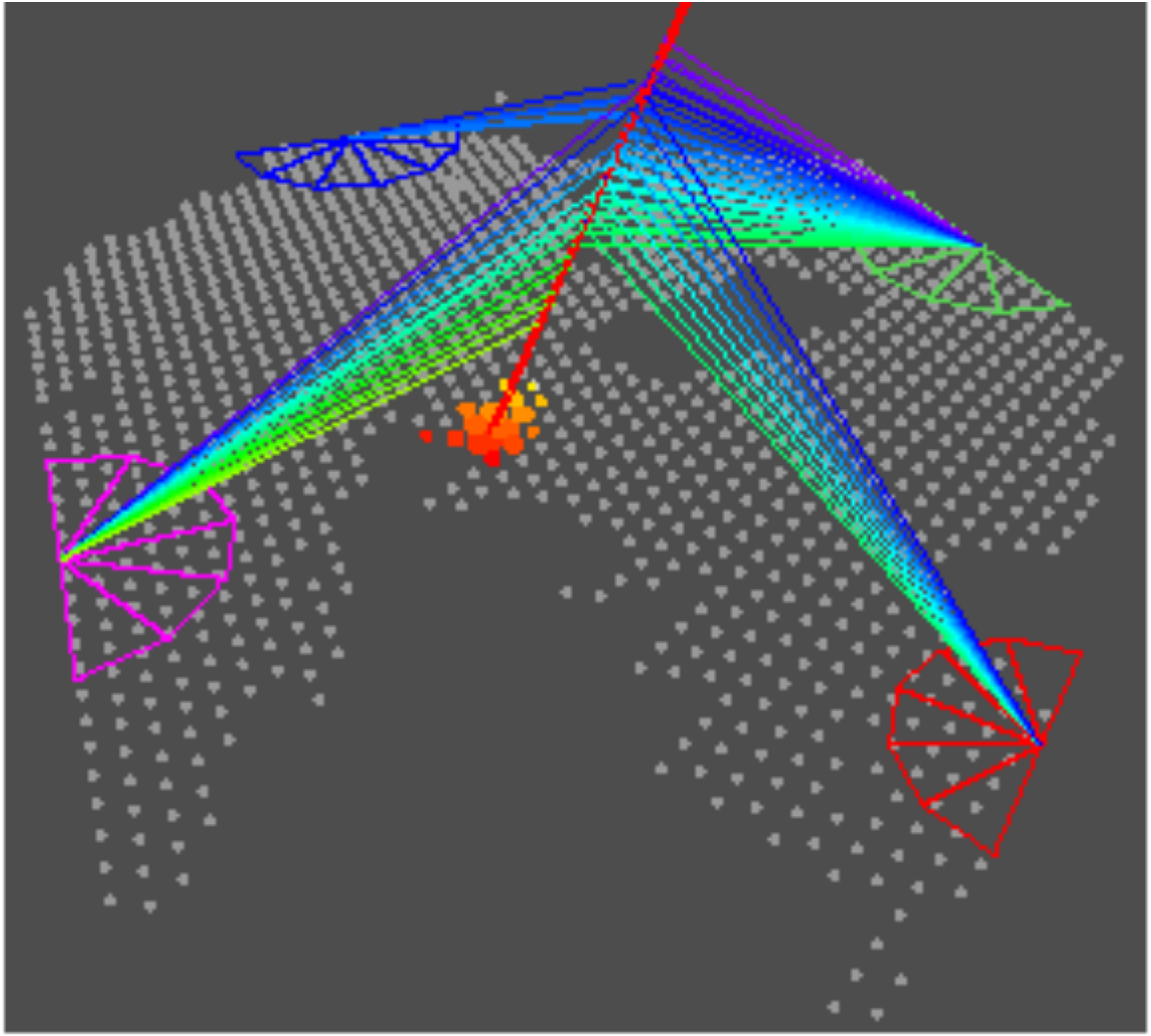






M. Kleifges et al., ICRC 2009

A Hybrid Event



20 May 2007 E ~ 10^{19} eV