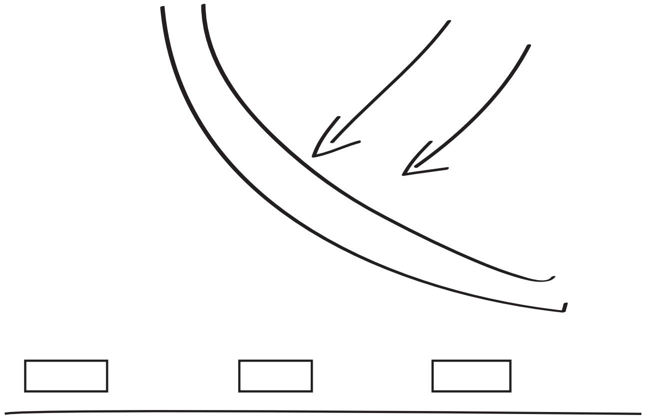
Measurement methods

Particles at ground

cascade of secondary particles allows to sample the shower at specific points



detector coverage

10^{15} eV: 1% (15m)

10^{20} eV: 10^{-8} (1.5km)

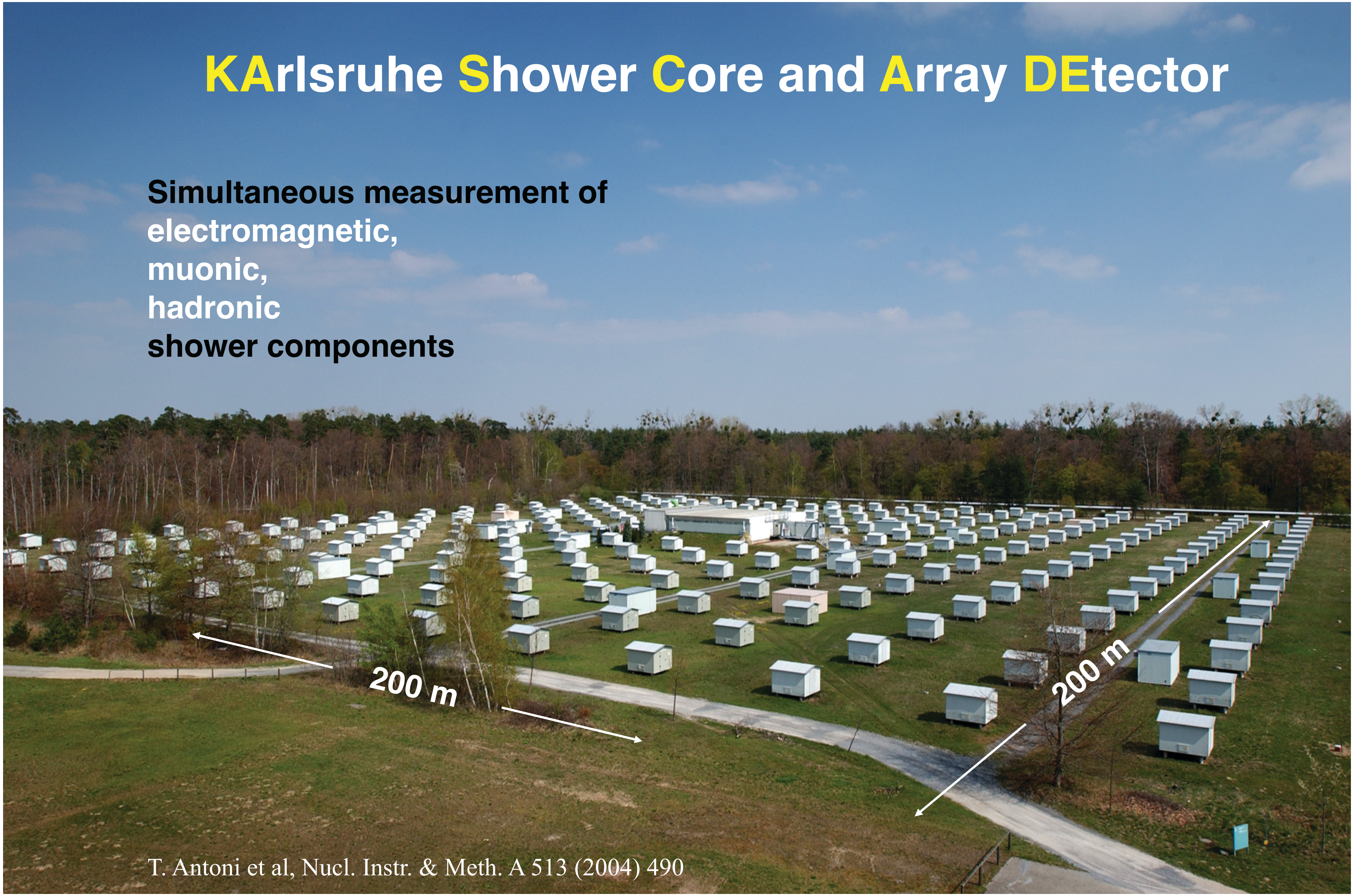
example KASCADE

40000 m^2 total area

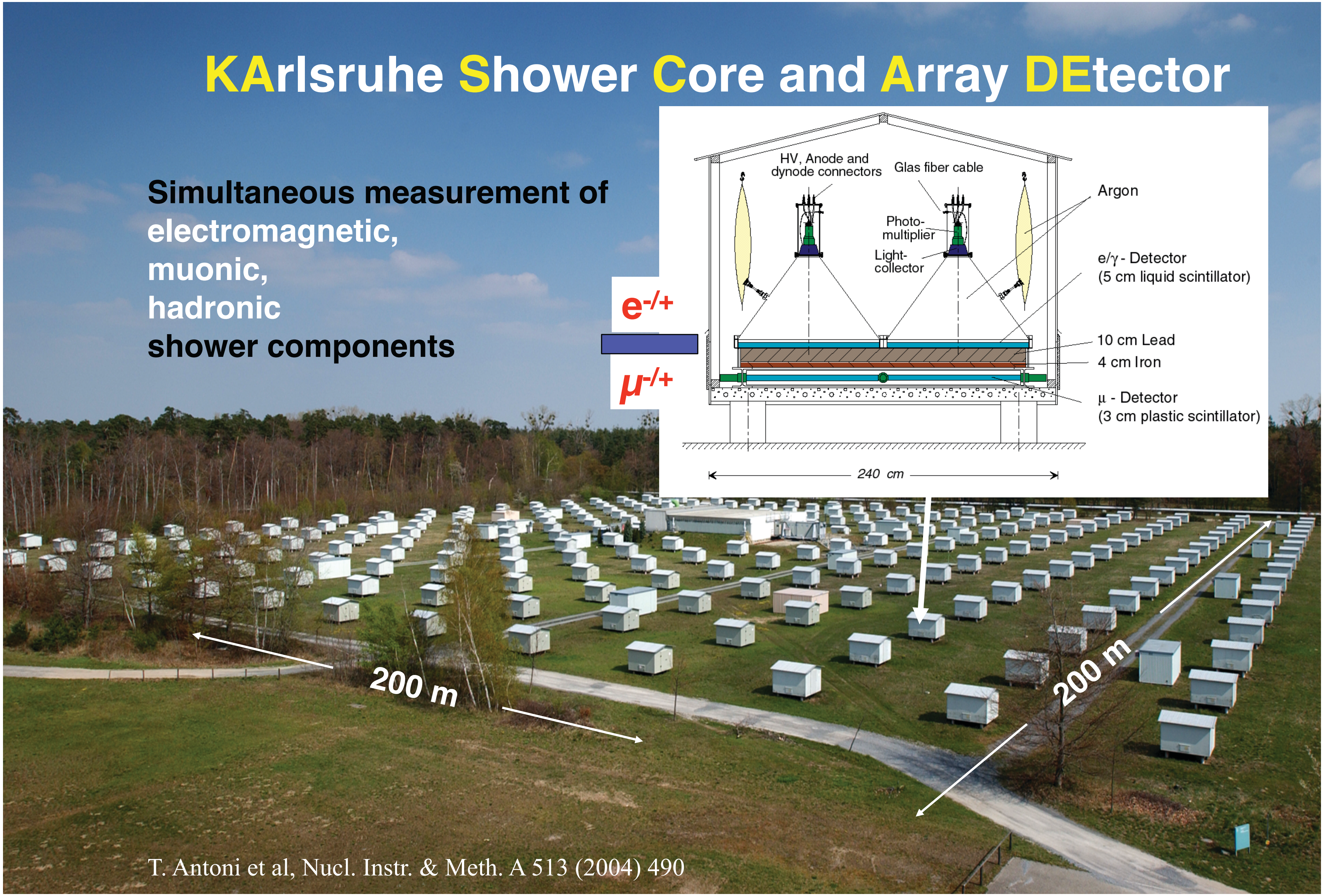
500 m^2 e/γ (≈ 1.2 %) detector distance 13m

KArlsruhe Shower Core and Array DEtector

Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components



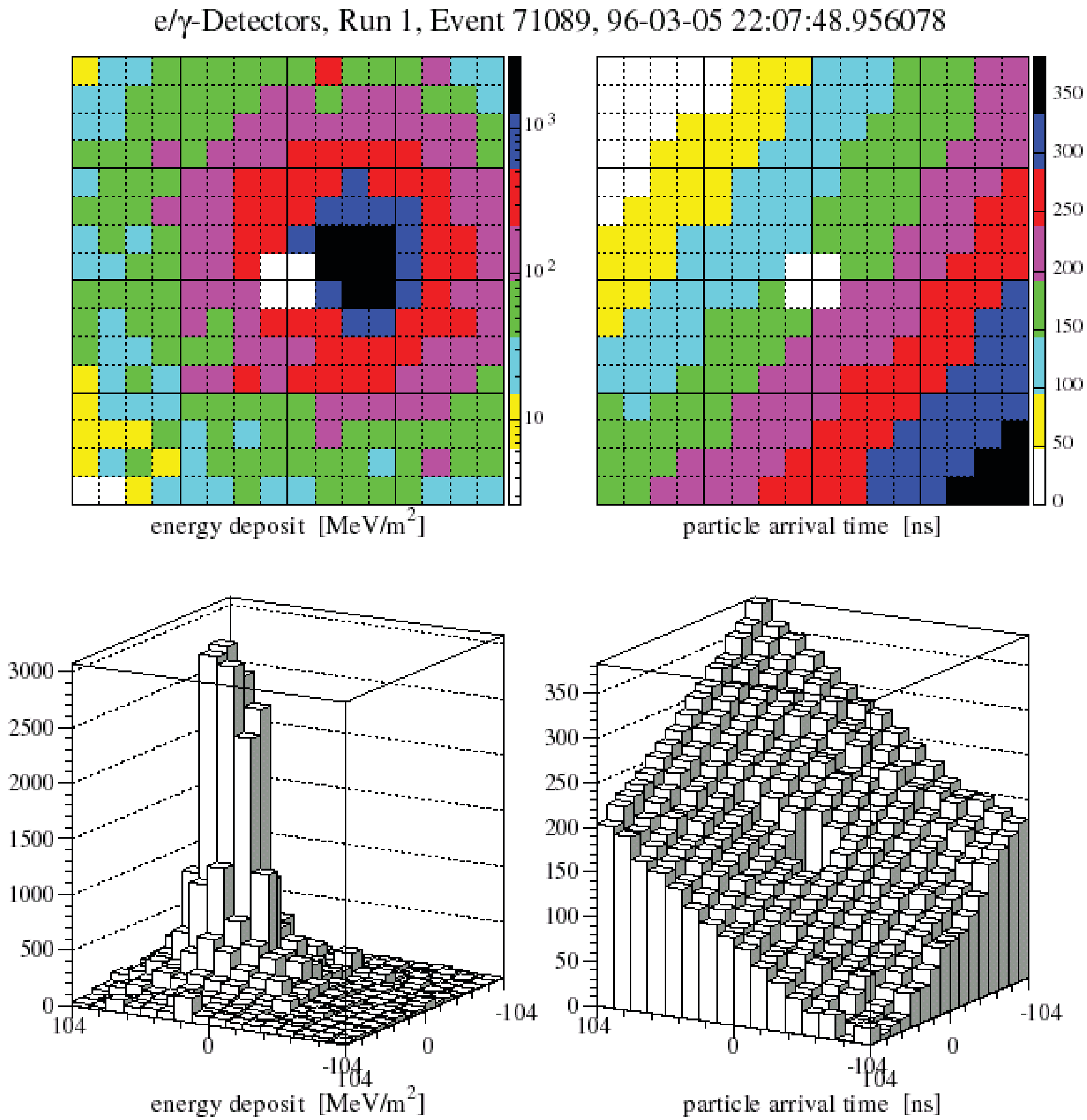
T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

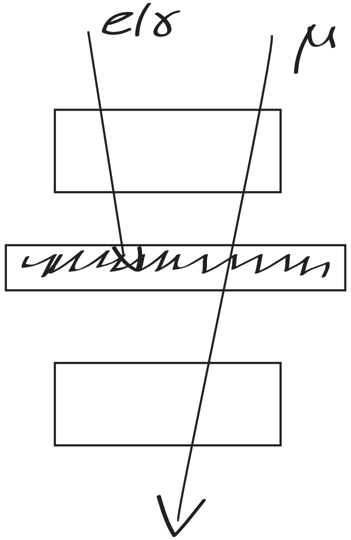

KArlsruhe Shower Core and Array DEtector
Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components
e-/+
μ-/+
HV, Anode and dynode connectors
Glas fiber cable
Argon
Photo-multiplier
Light-collector
e/γ - Detector (5 cm liquid scintillator)
10 cm Lead
4 cm Iron
μ - Detector (3 cm 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 %





e/γ detector

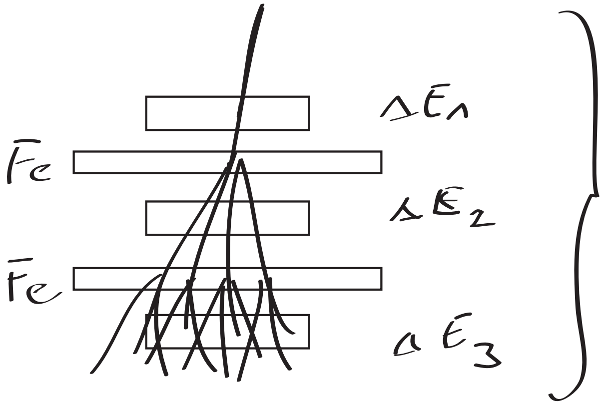
Fe + Pb absorber

μ detector

⇒ count the number of electrons and muons

measurement of hadrons

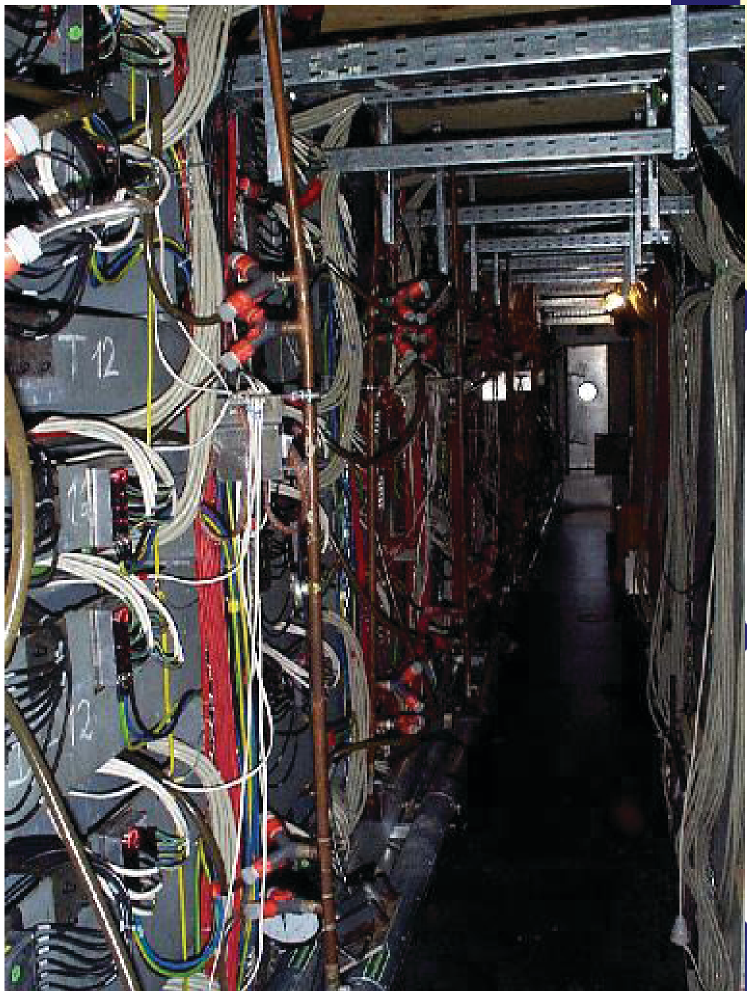
hadron calorimeter

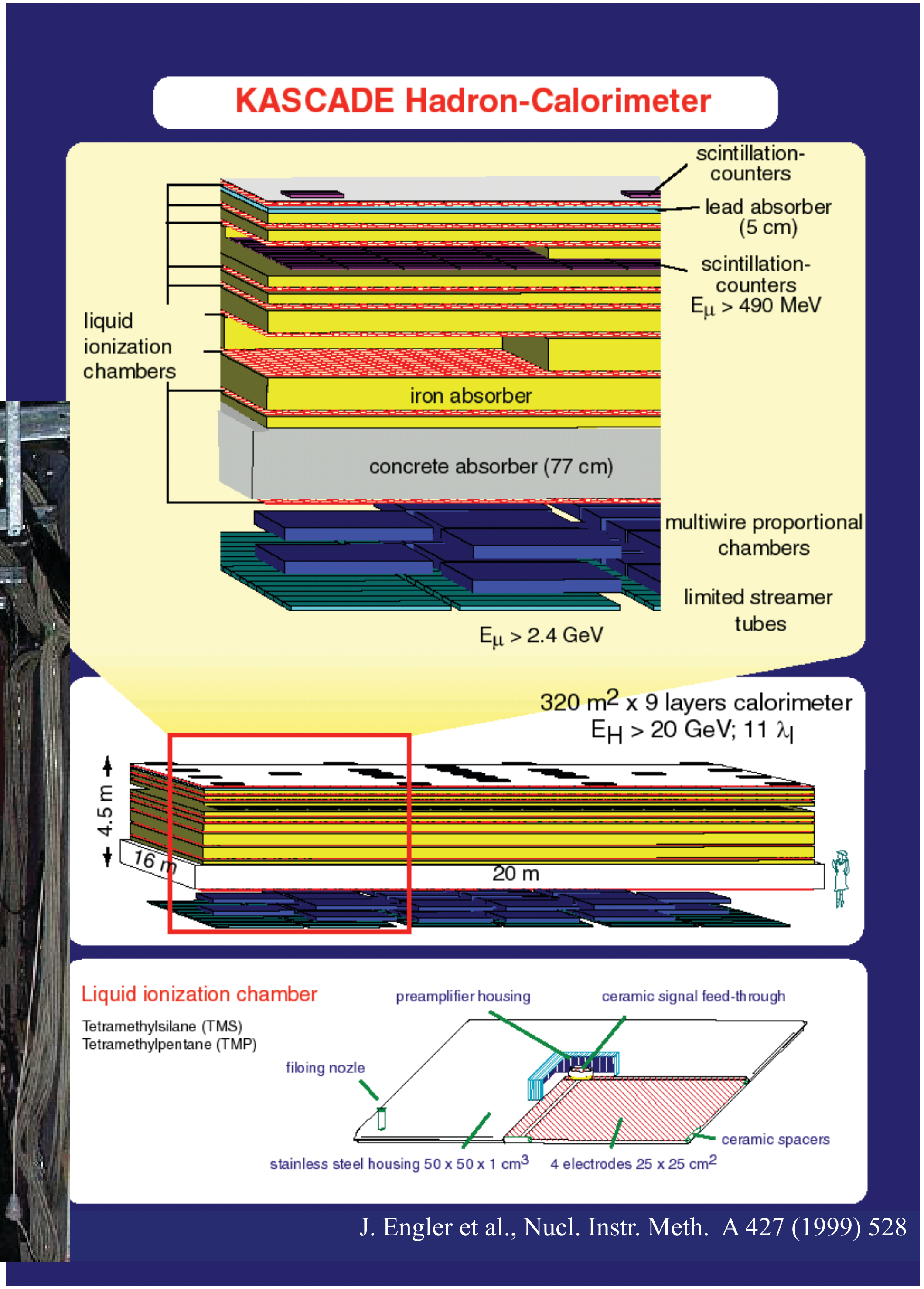


$\hat{=}\ 10\ \lambda_I$

$$\lambda_I \simeq \frac{1}{n \cdot \sigma} \approx 16.7\ \text{cm in Fe}$$

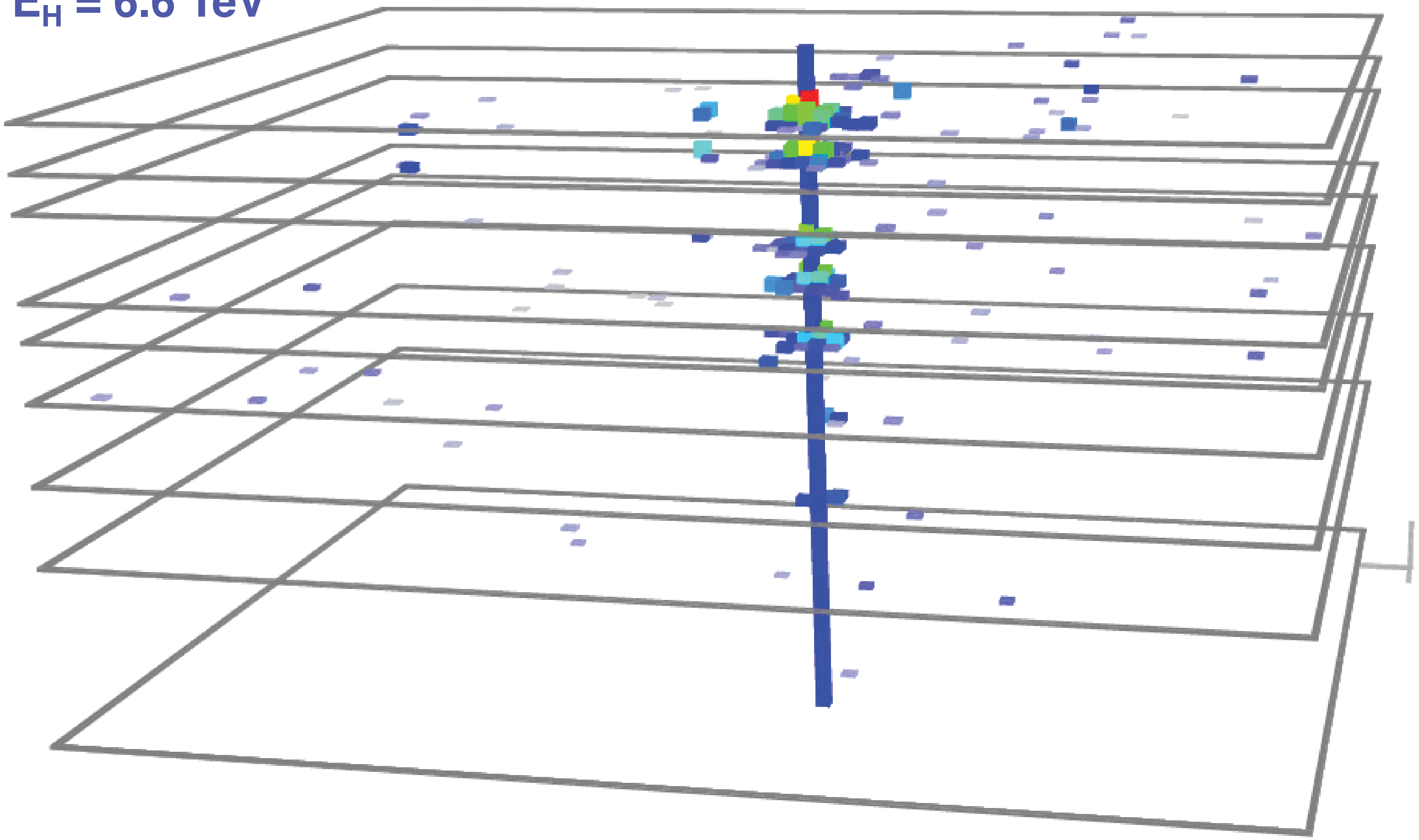
KASCADE Hadron Calorimeter





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°

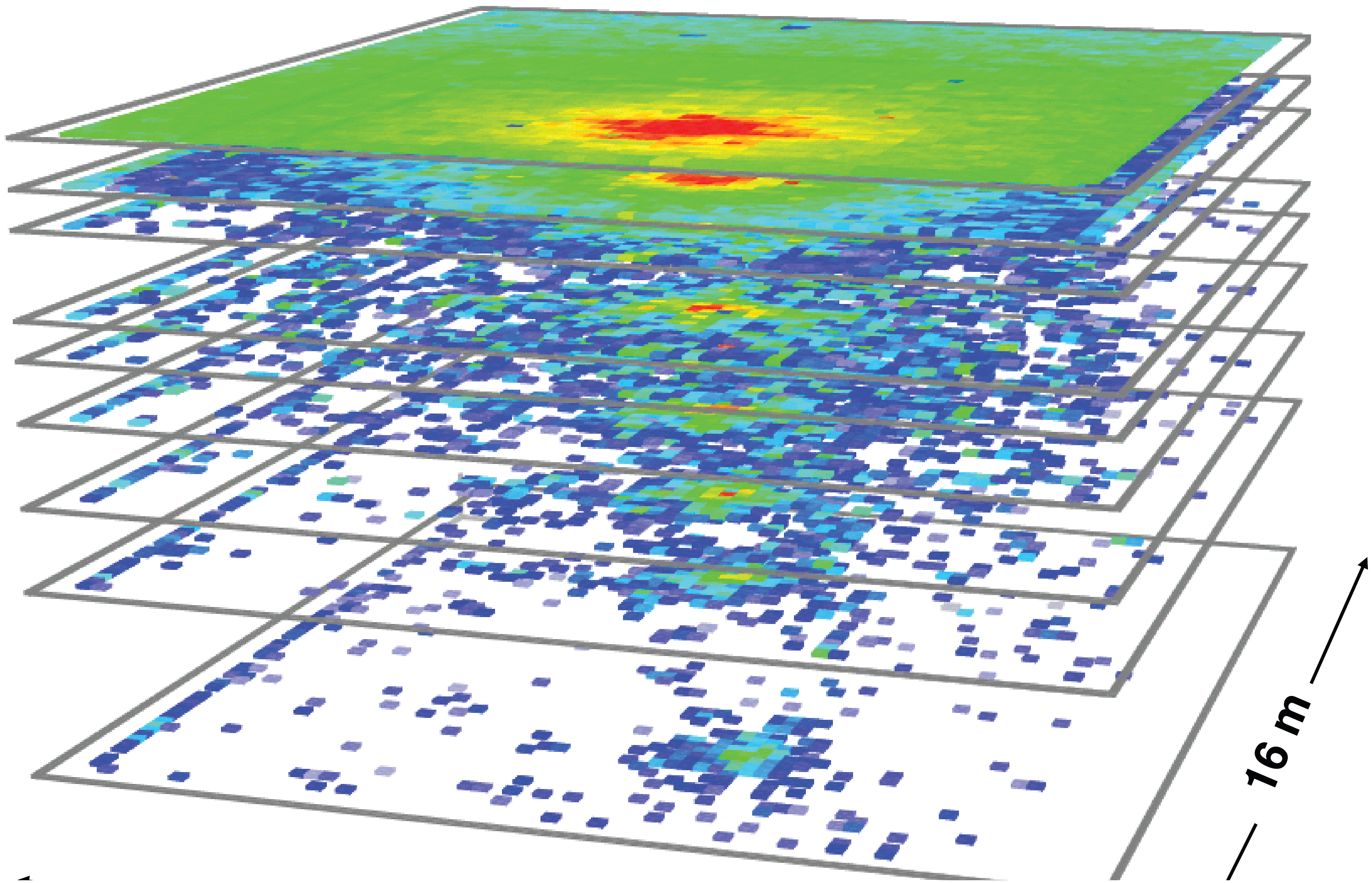
energy resolution:

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

Hadronic shower core

$E_0 \sim 6$ PeV

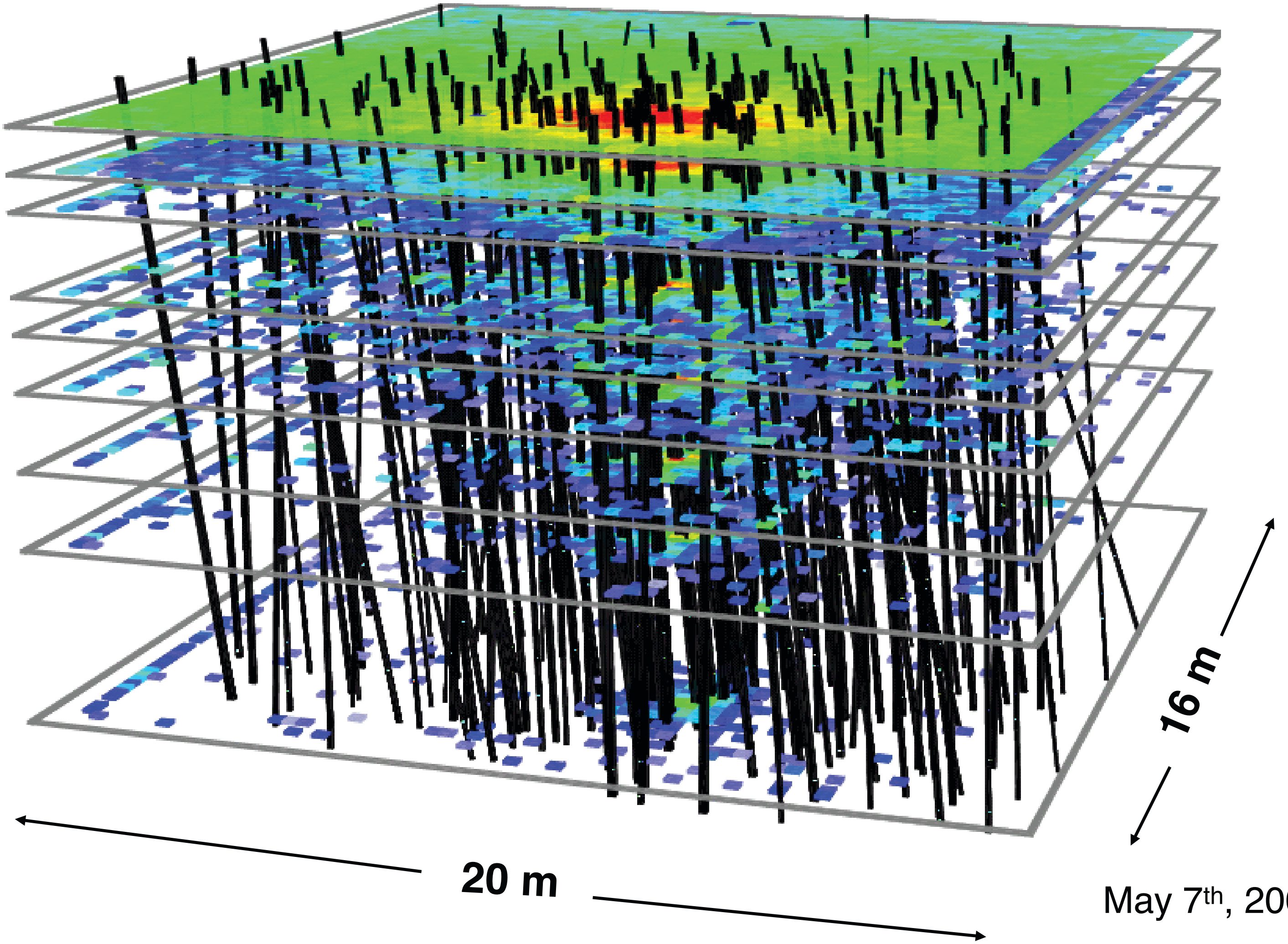
Number of reconstructed hadrons $N_h = 143$



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 density 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 parametrization

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

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

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

~ 400 m for $\mu^\pm$

~ 15 m for hadrons

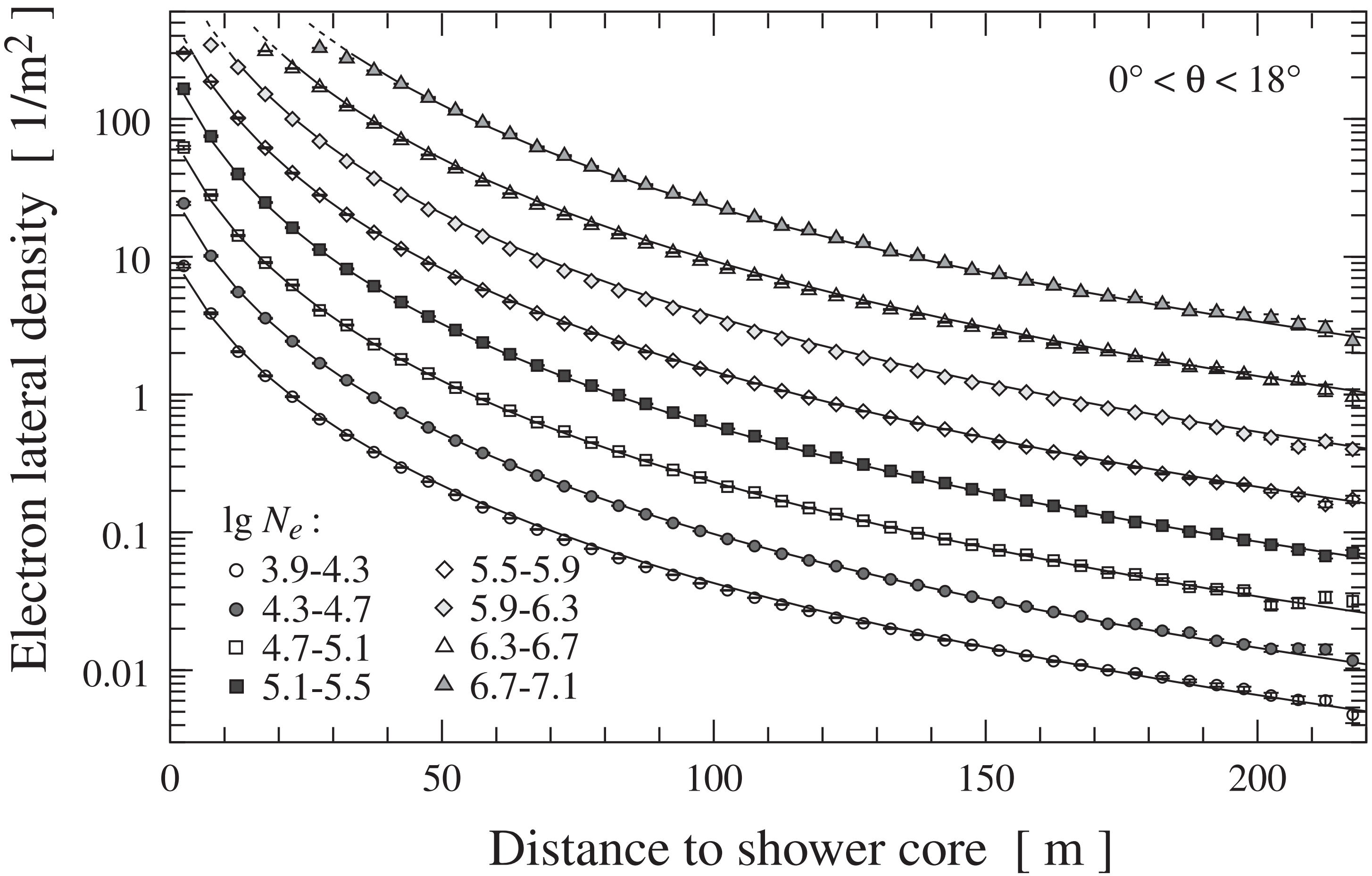
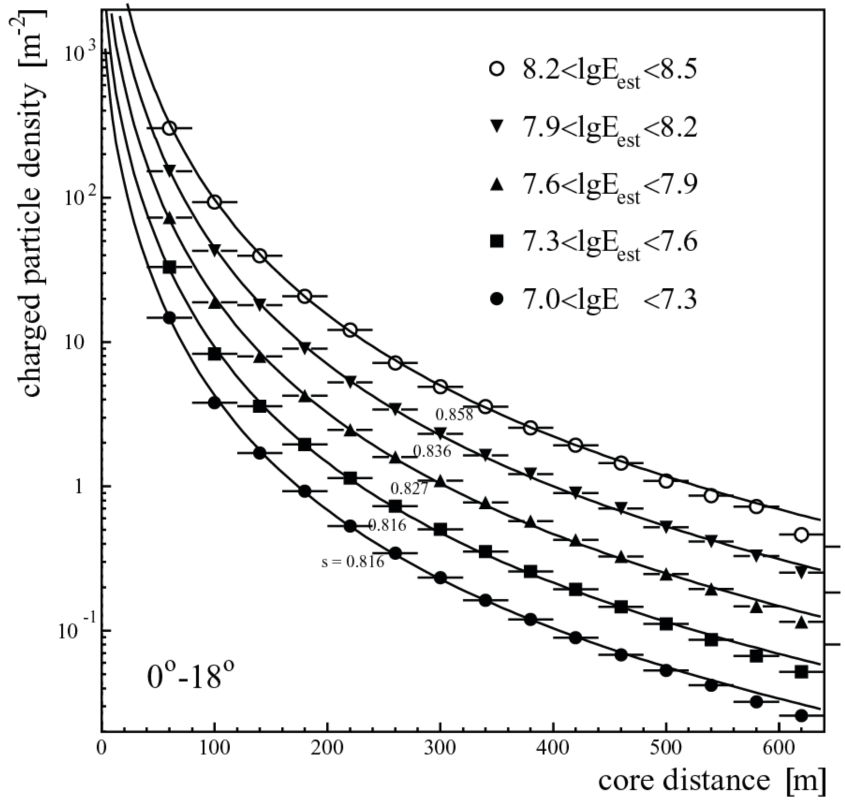


Fig. 2. Lateral distributions of electrons above a 5 MeV kinetic energy for zenith angles below 18°. The lines show NKG functions of fixed age parameter $s = 1.65$ but varying scale radius r_e (see the text).

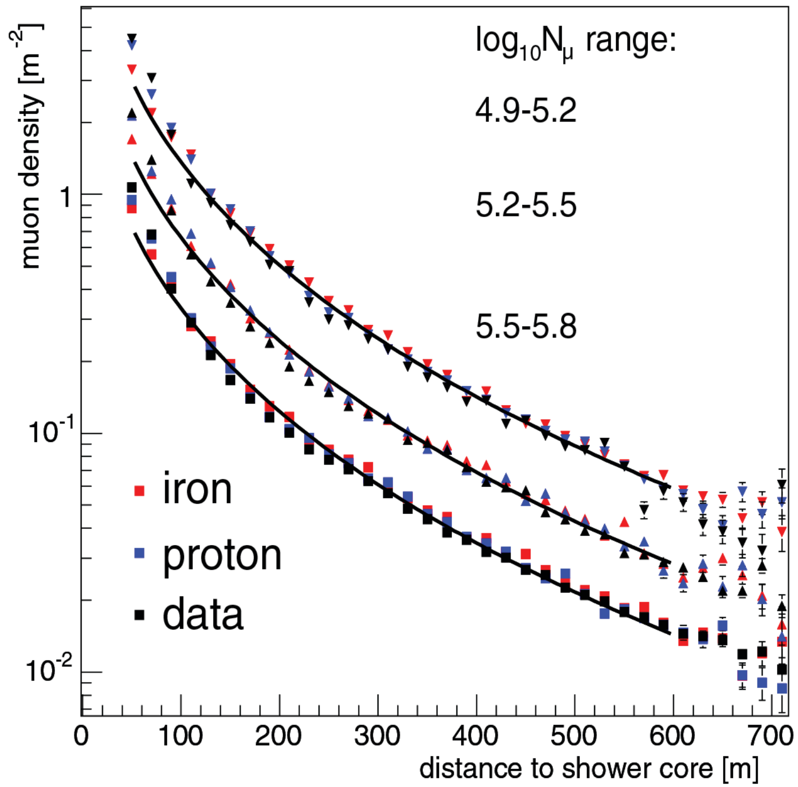
KASCADE-Grande – Lateral distributions

NKG function

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



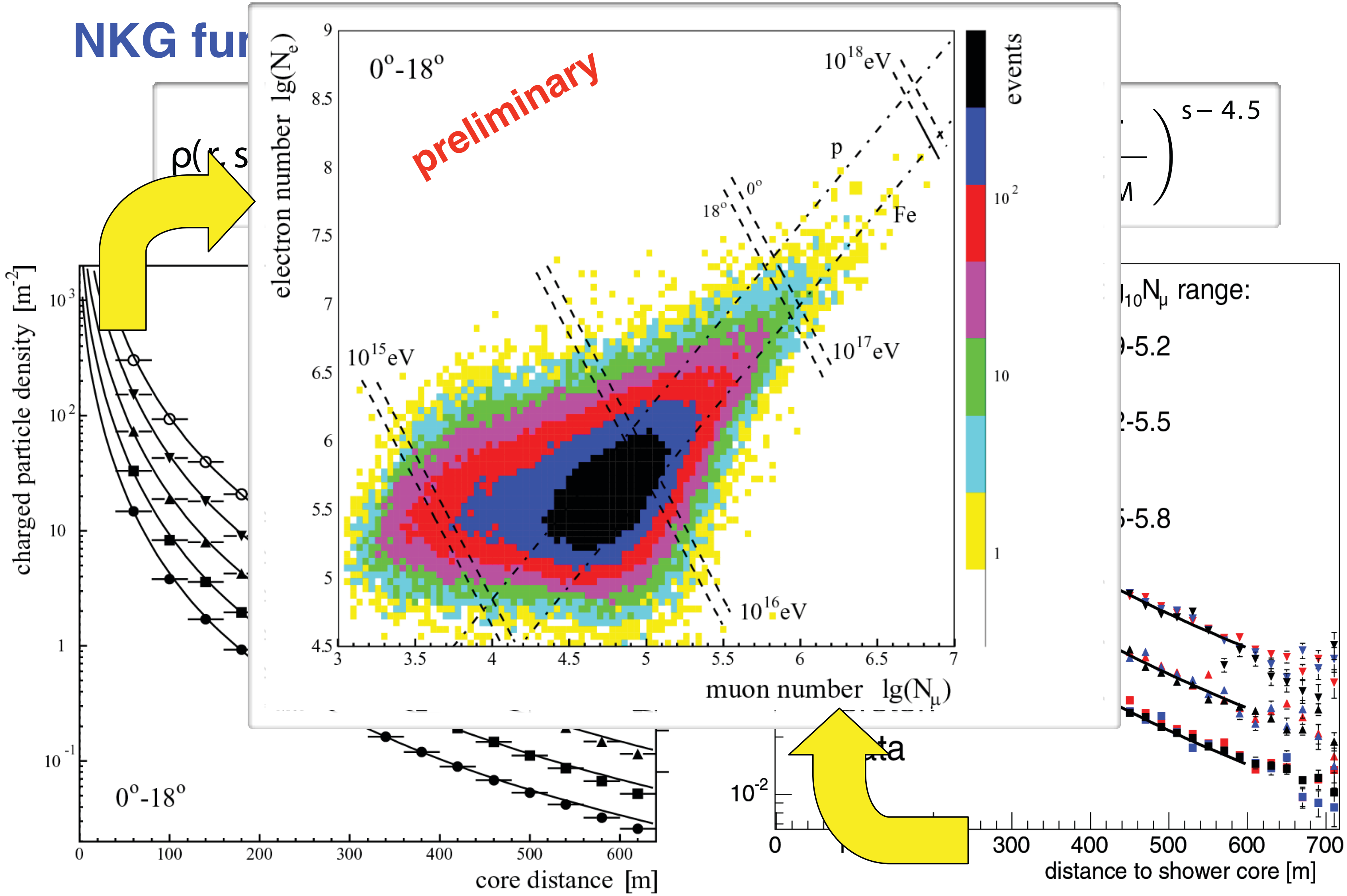
R. Glasstetter et al., Proc. 29th ICRC, Pune 6 (2005) 293



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

KASCADE-Grande – Lateral distributions

NKG fu



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

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

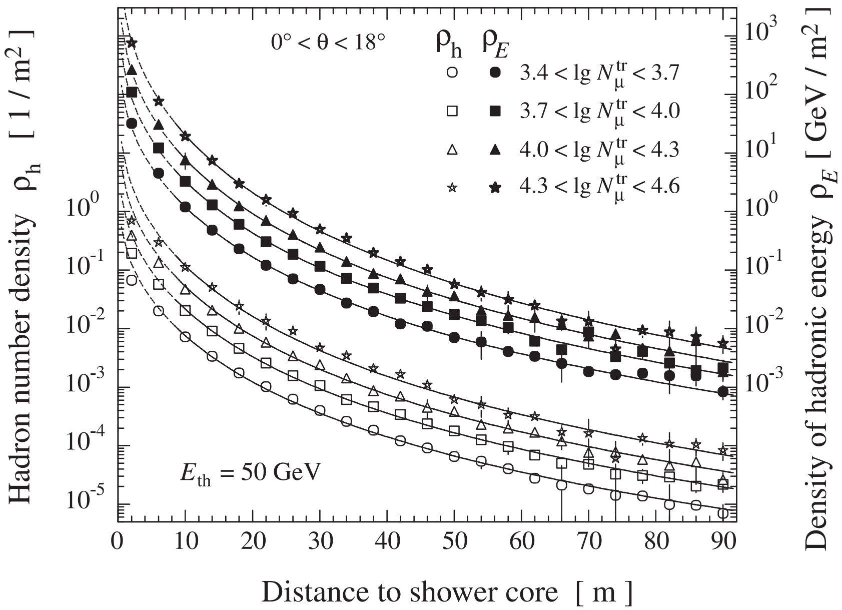


Fig. 12. Density of hadron number (left scale, open symbols) and of hadronic energy (right scale, filled symbols) versus the core distance for showers of truncated muon numbers as indicated. Threshold energy for hadrons is 50 GeV. The curves represent fits of the NKG formula to the data at $r \geqslant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

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

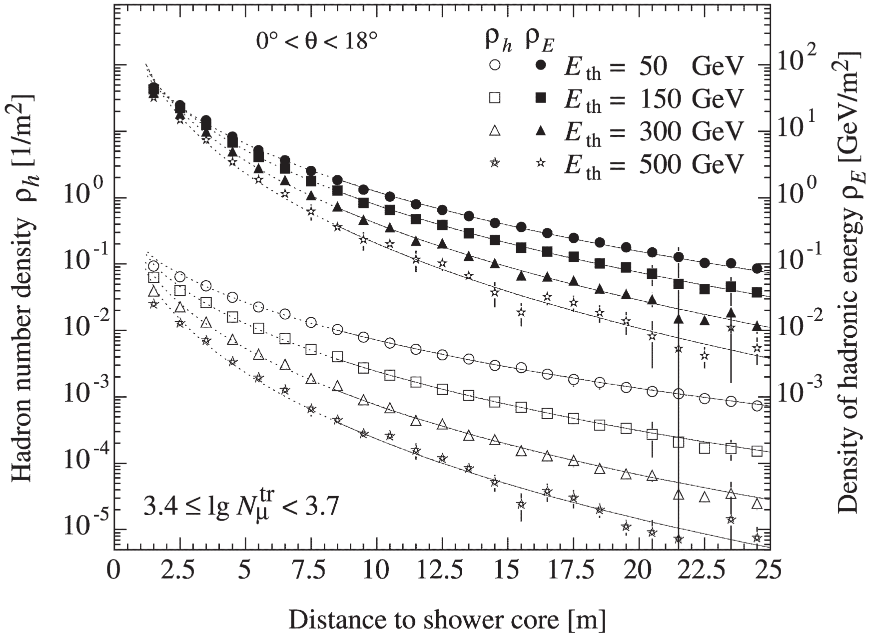
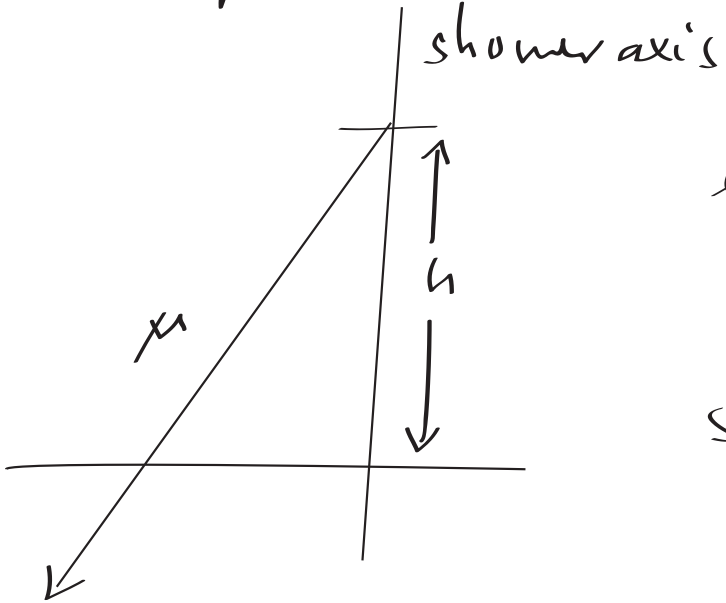


Fig. 14. Density of hadron number (left scale, open symbols) and of hadronic energy (right scale, filled symbols) versus shower core distance for various thresholds of hadron energy. The curves represent fits of the data to the NKG function as in Fig. 12.

to determine the mass of the primary particle

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

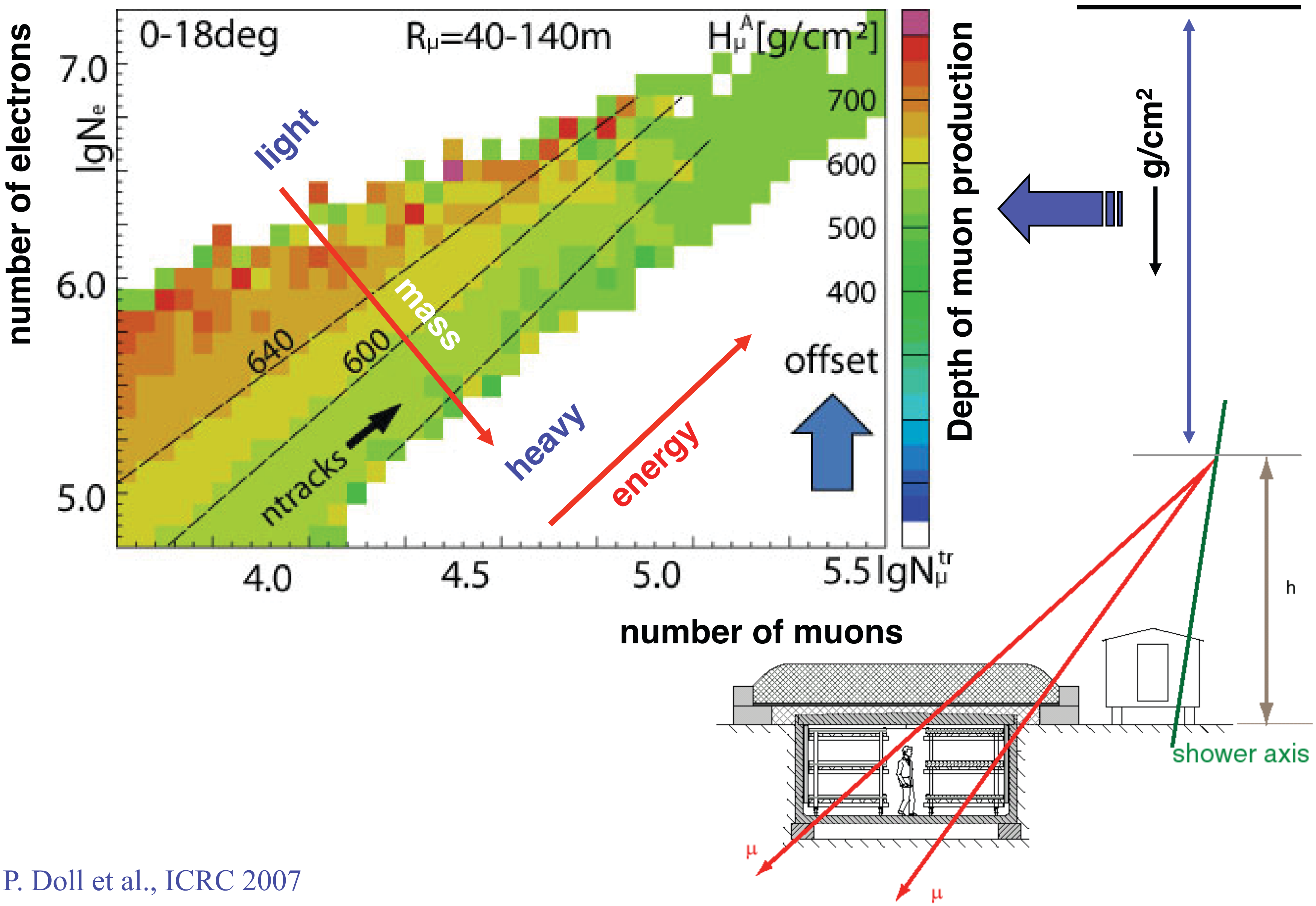
- muon production height or X_{max} for e/m comp.



large h -> heavy primary particle

small h -> light particle

Muon production height – KASCADE muon tracking detector

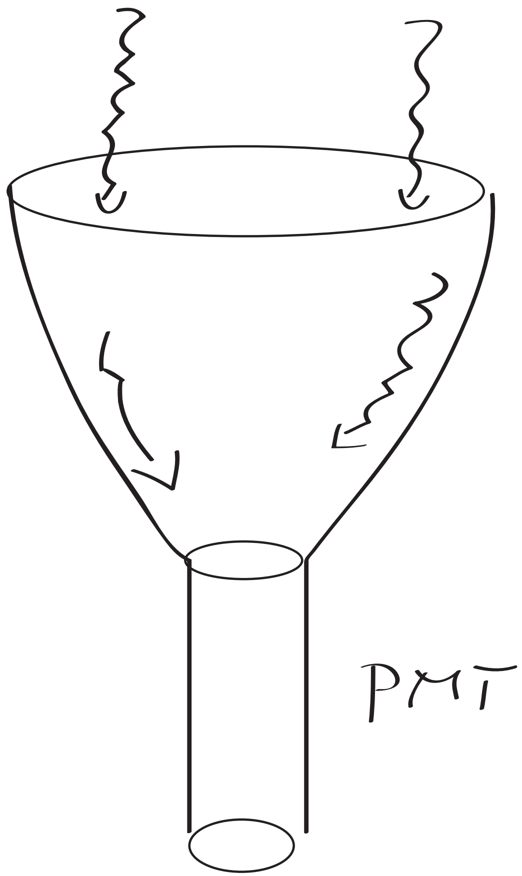


P. Doll et al., ICRC 2007

Measurement of Čerenkov light

two techniques

1) non-imaging detectors   open Č detectors



$\phi \sim 0{,}5\,m$

Winston cone
to collect light

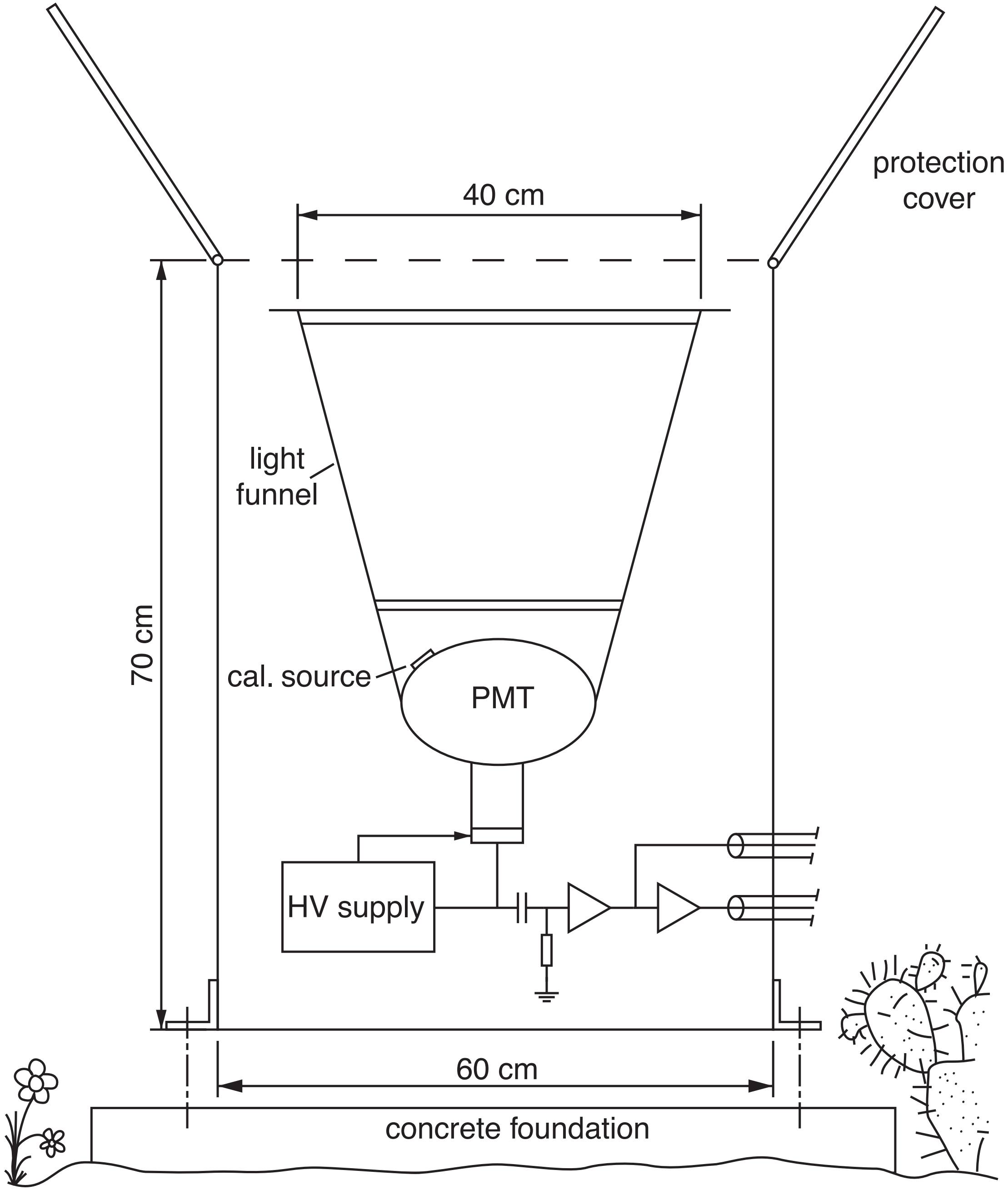
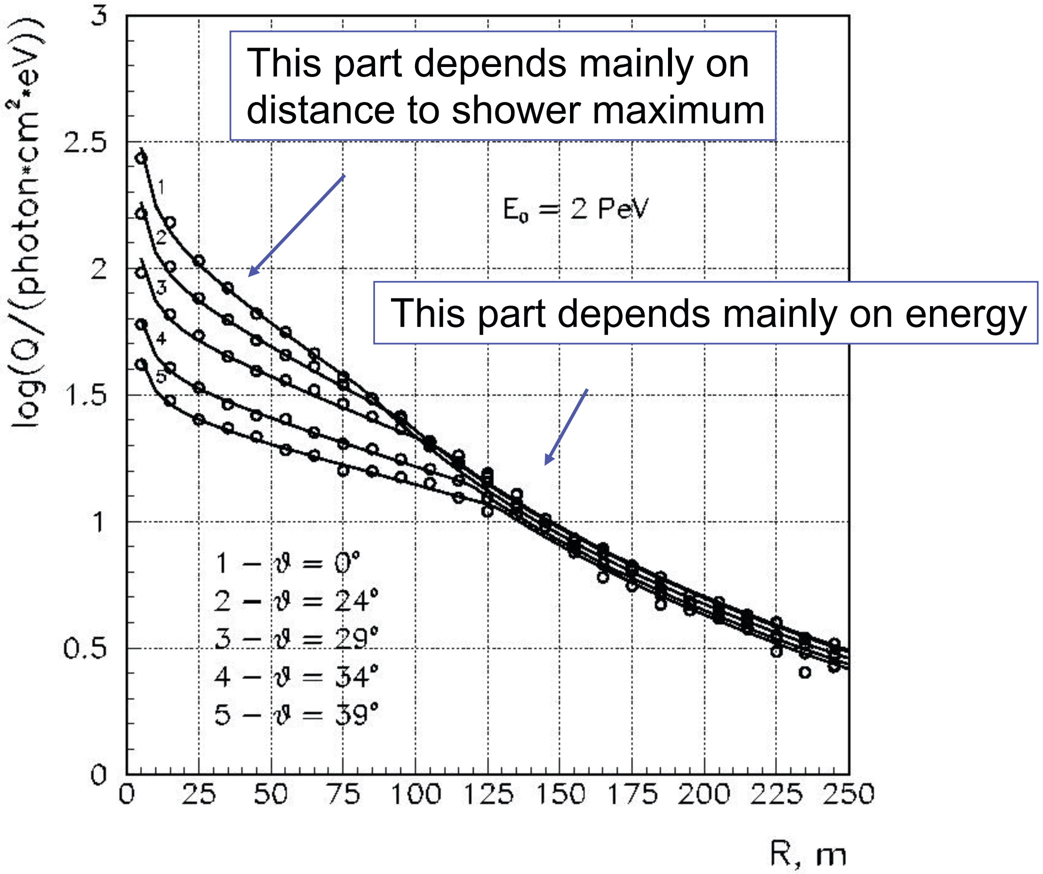


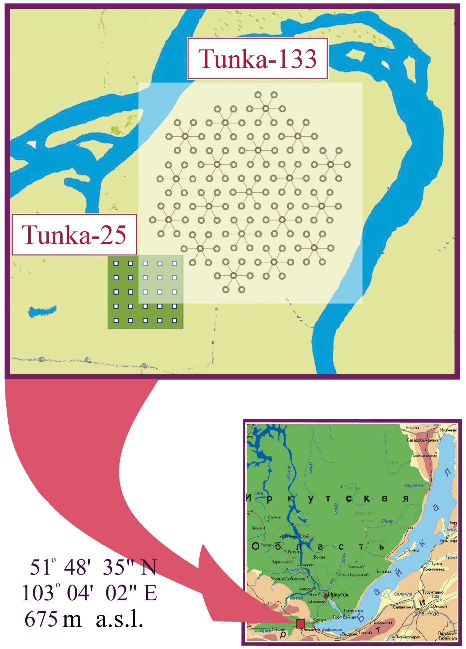
Fig. 4.19. Integrating Cherenkov cone of an AIRO-BICC station and auxiliaries. Directly above the PMT a glass filter restricted the incoming light to wavelengths smaller than 500 nm and a plexiglass cover protected against dew, white frost and dust [29]

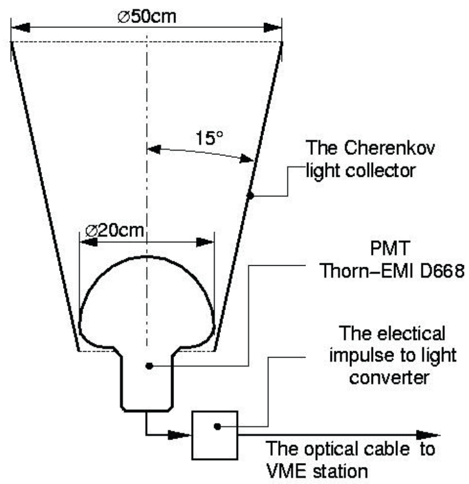
Tunka Experiment

Lateral distribution of Cerenkov light

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







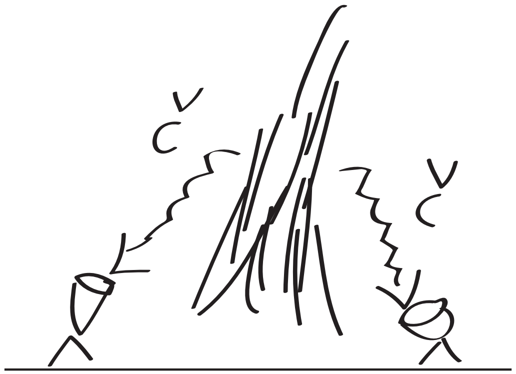
Ch. Spiering, DPG 2005

registers Č photons as a function of distance to the shower axis

—> total number of particles

—> energy

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 is isotropic light emission

→ showers can be observed from aside

but ammount of light is small

(4π emission)

imaging telescopes with PMT camera

field of view ~30°

simple estimate:

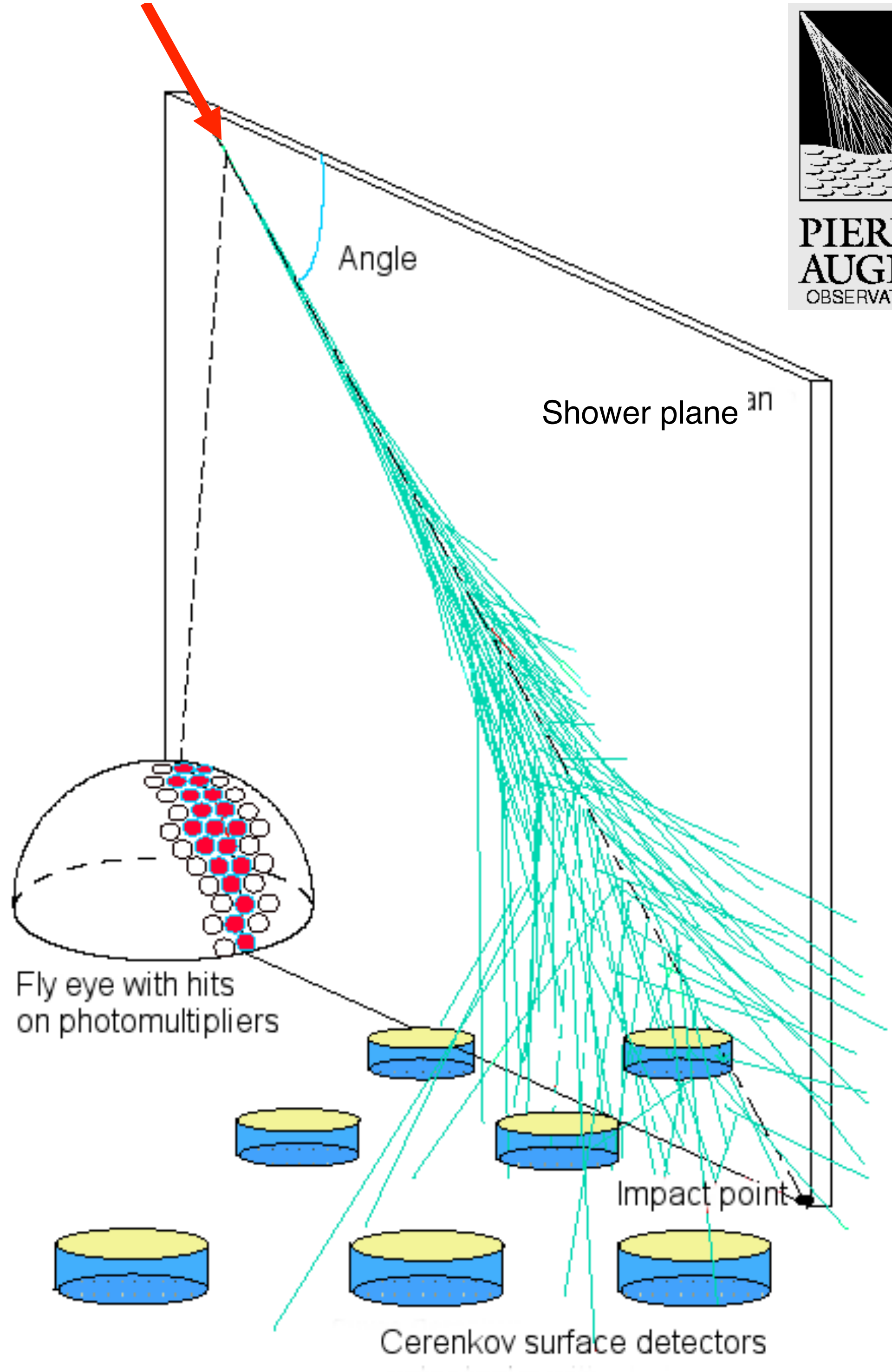
10^{17} eV → 0.1 W

10^{20} eV → 100 W

Hybrid Detector

Fluorescence telescope

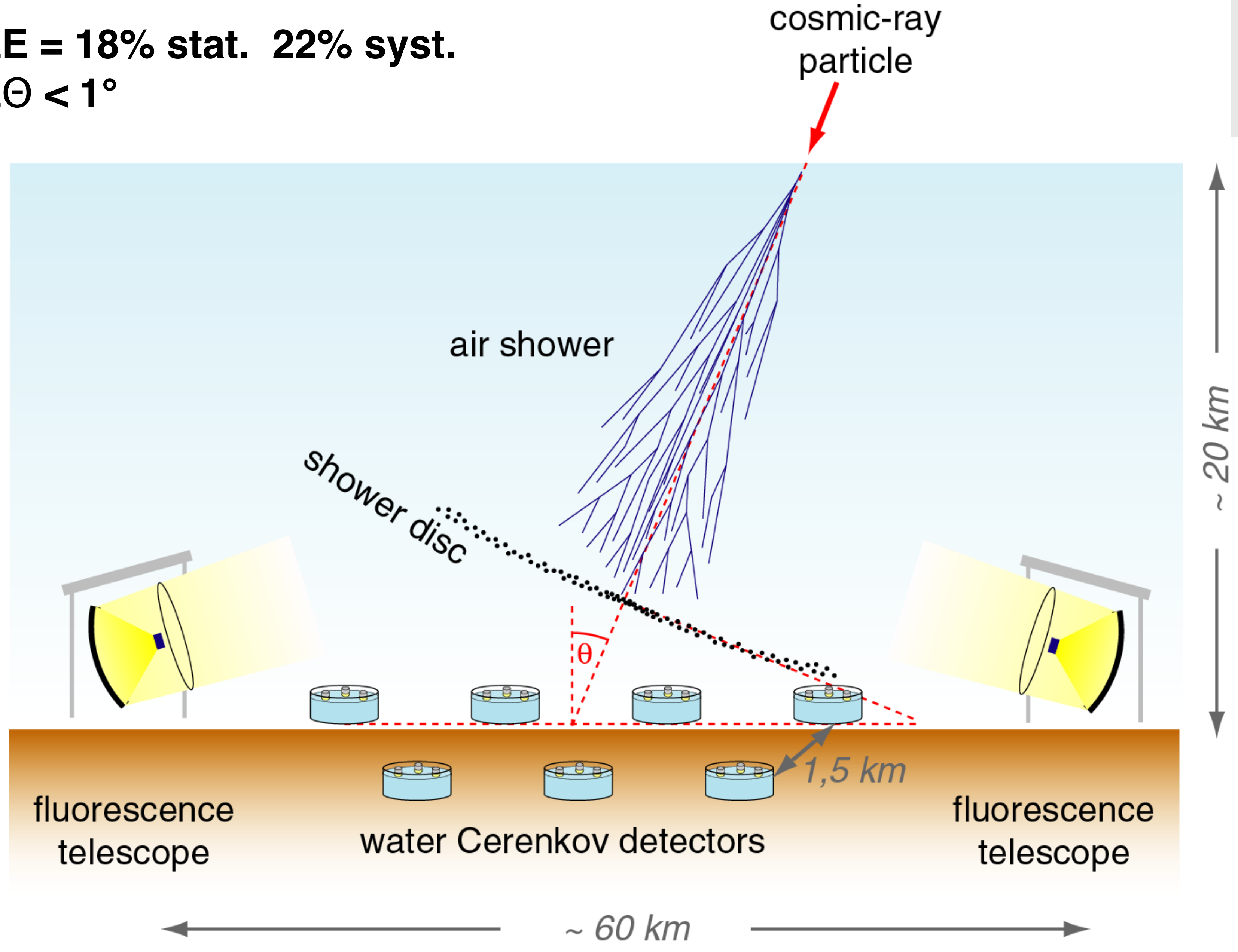
Surface array (water Cherenkov detectors)

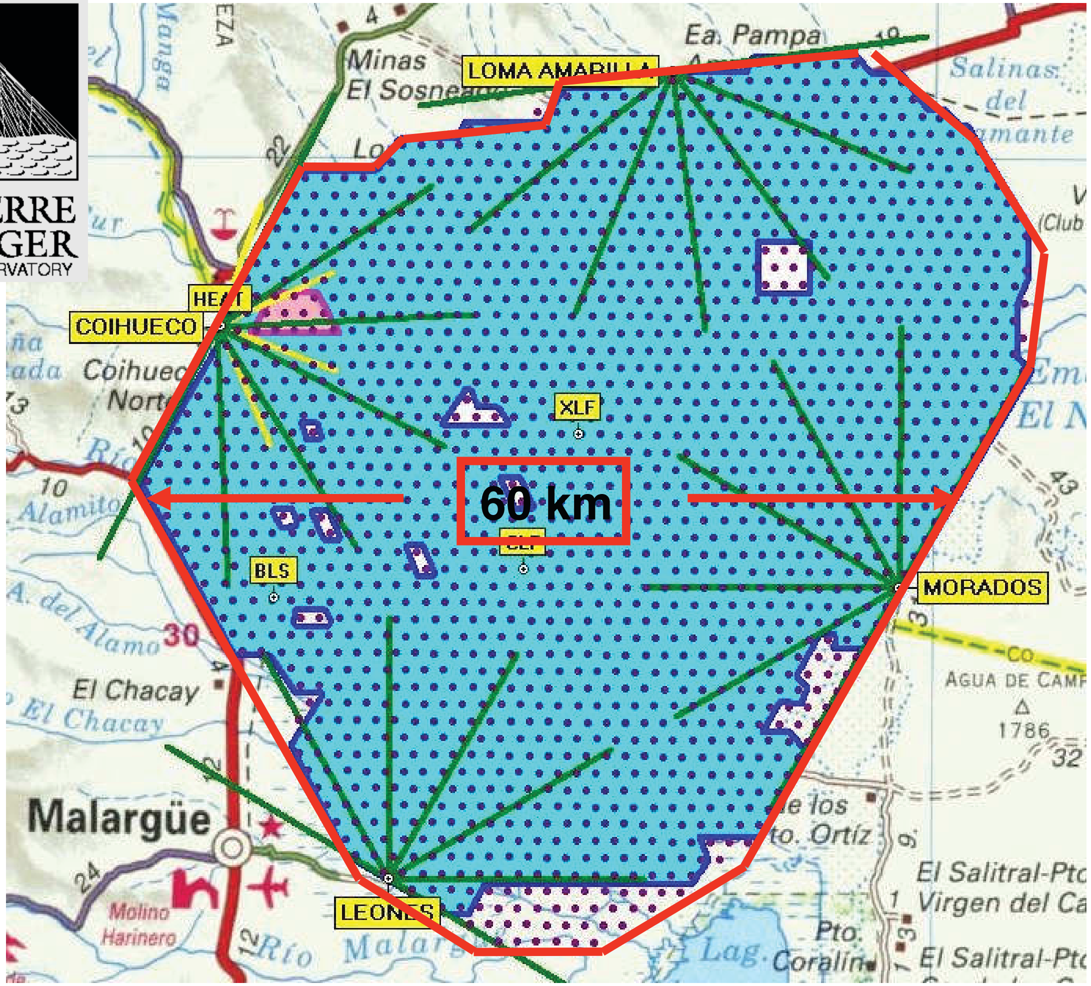


The Pierre Auger Observatory

The detection principle

ΔE = 18% stat. 22% syst.
ΔΘ < 1°



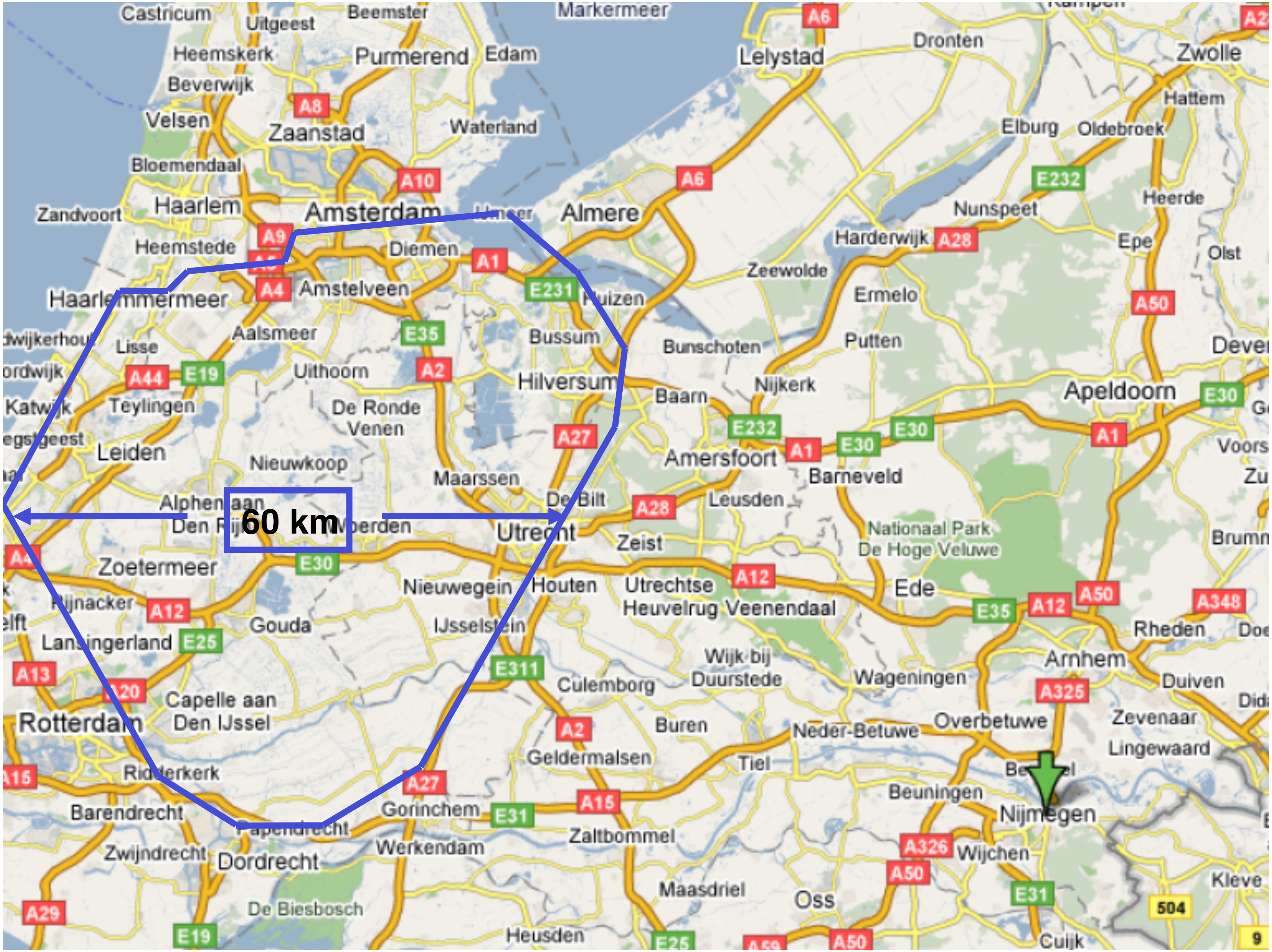


Pierre Auger Observatory

3000 km^2

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
Beverwijk
Velsen
Zaanstad
Waterland
Bloemendaal
Zandvoort
Haarlem
Amsterdam
Almere
Lelystad
Dronten
Zwolle
Hattem
Elburg
Oldebroek
Heerde
Nunspeet
Harderwijk
Epe
Olst
Heemstede
Diemen
Amstelveen
Haarlemmermeer
Aalsmeer
Zeewolde
Ermelo
Bussum
Bunschoten
Putten
Lisse
Uithoorn
Hilversum
Baarn
Nijkerk
Apeldoorn
Teylingen
De Ronde Venen
Amersfoort
Barneveld
Leiden
Nieuwkoop
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
Lansingerland
Rheden
Arnhem
Wijk bij Duurstede
Wageningen
Culemborg
Duiven
Capelle aan Den IJssel
Rotterdam
Buren
Neder-Betuwe
Overbetuwe
Zevenaar
Lingewaard
Geldermalsen
Tiel
Ridderkerk
Beuningen
Nijmegen
Barendrecht
Gorinchem
Zaltbommel
Werkendam
Zwijndrecht
Dordrecht
Wijchen
Maasdriel
Oss
Kleve
De Biesbosch
Heusden
Cuijk
A1
A2
A4
A6
A8
A9
A10
A12
A13
A15
A27
A28
A29
A44
A50
A325
A326
A348
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E25
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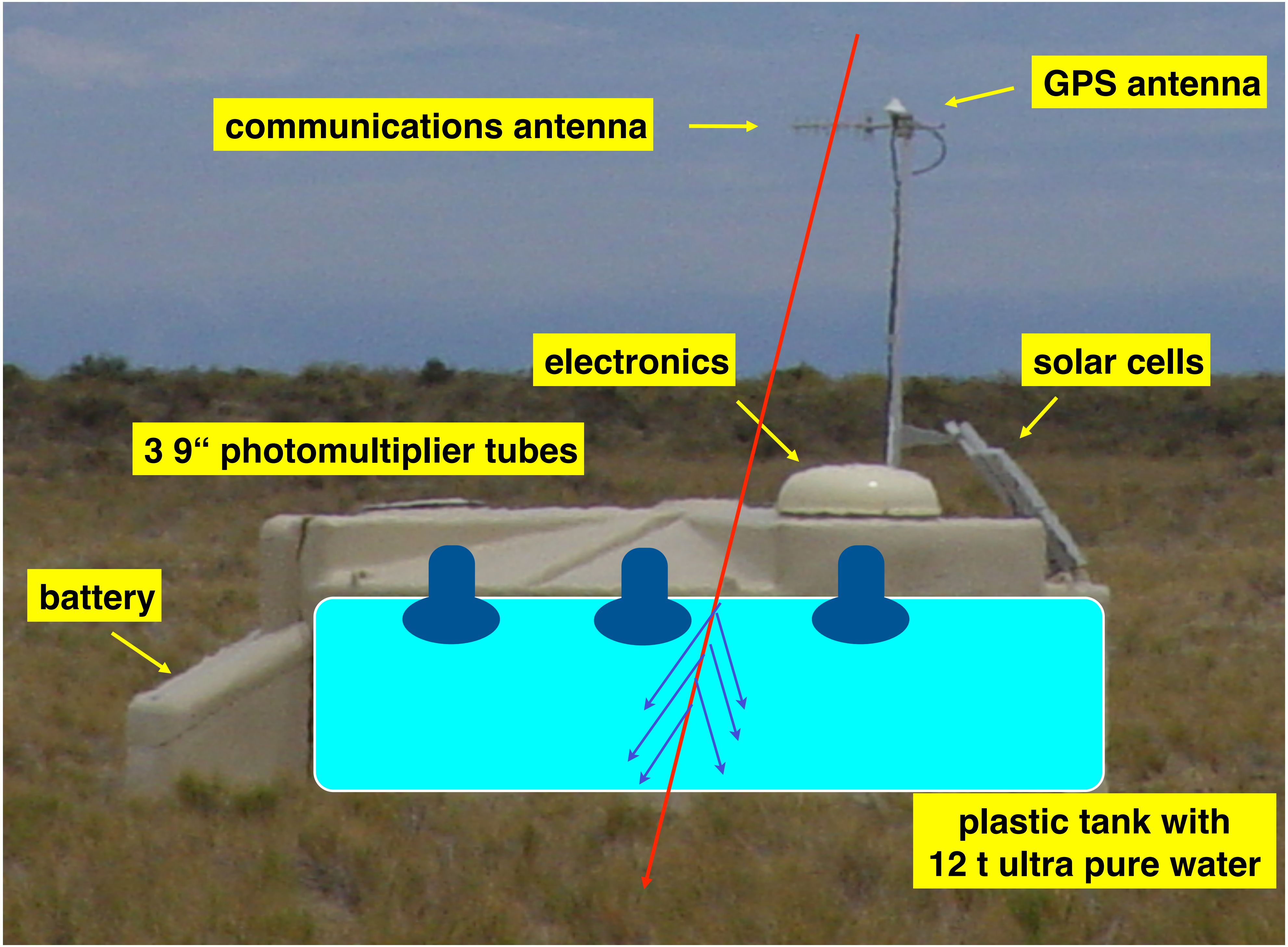
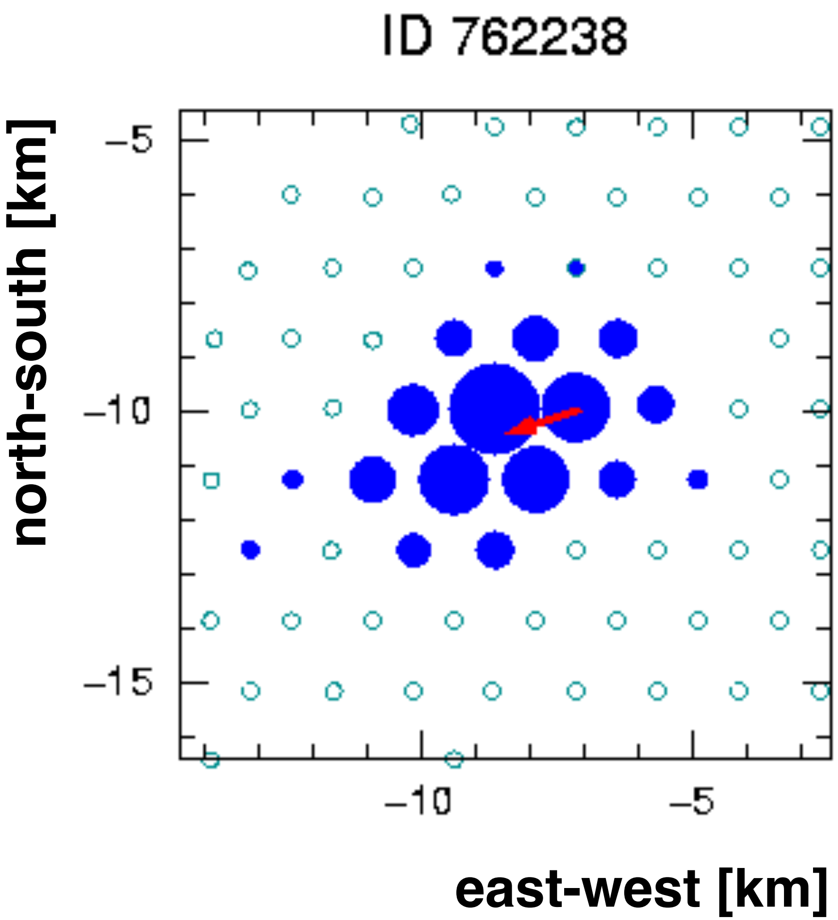
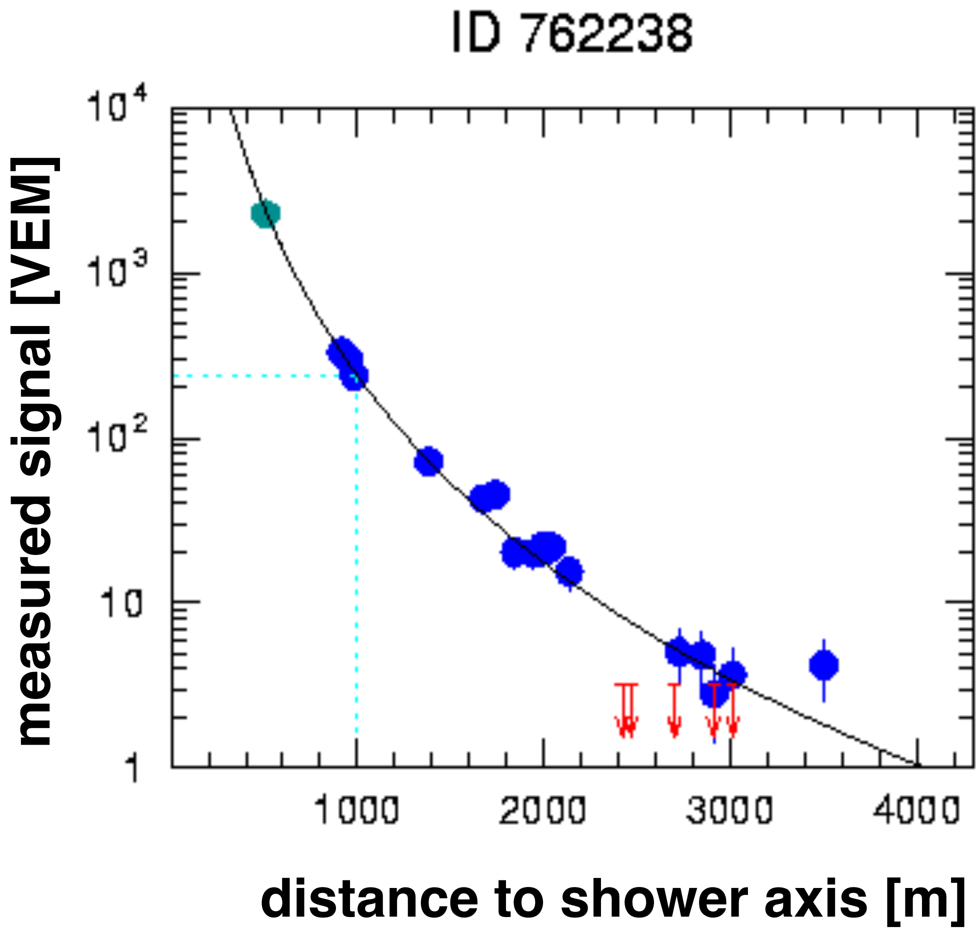
E31
E35
E231
E232
E311
504

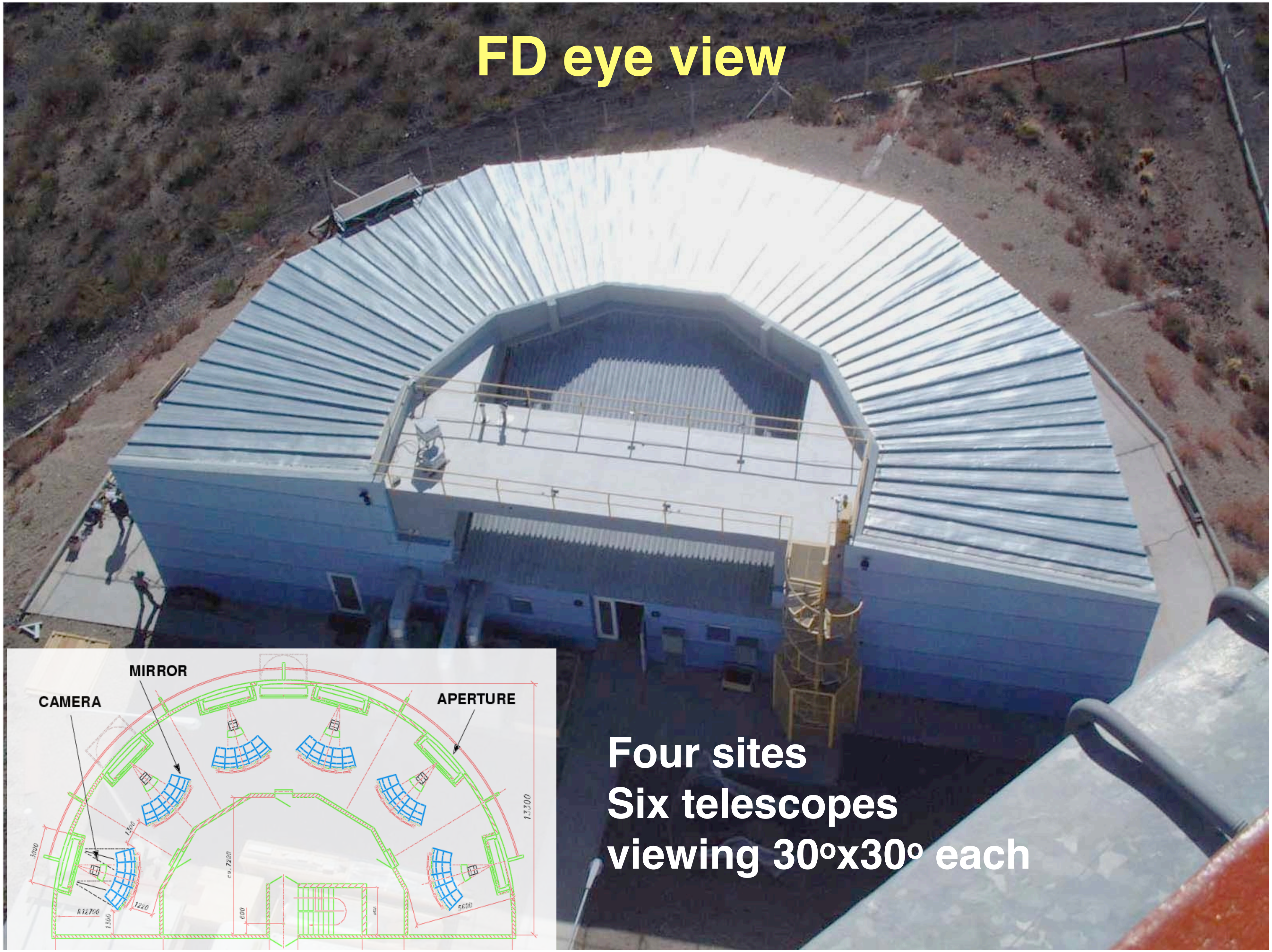

communications antenna
GPS antenna
electronics
solar cells
3 9“ photomultiplier tubes
battery
plastic tank with
12 t ultra pure water

Air shower registered with water Cherenkov detectors

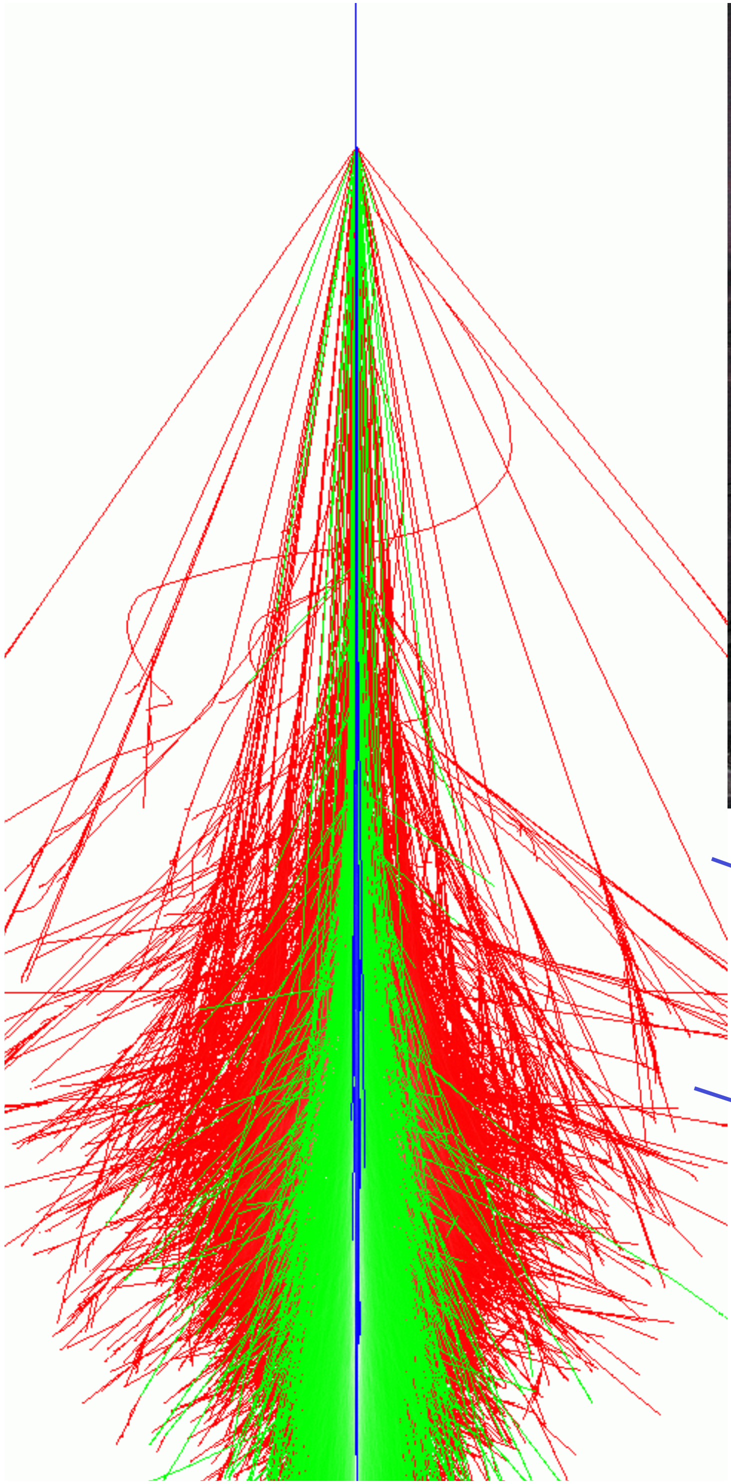


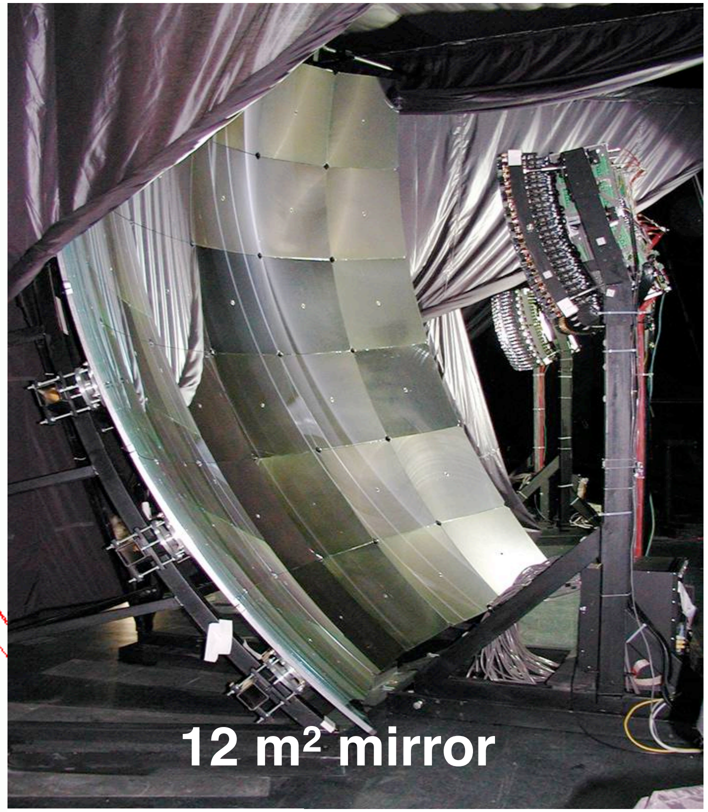


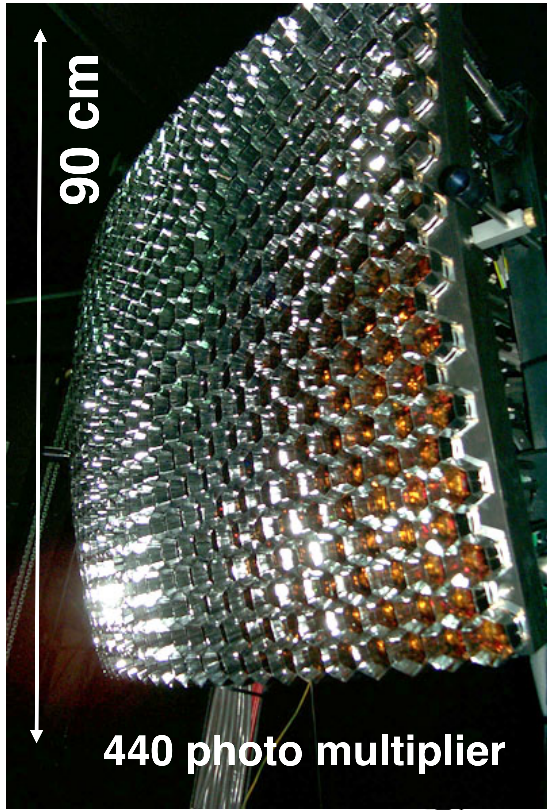
FD eye view

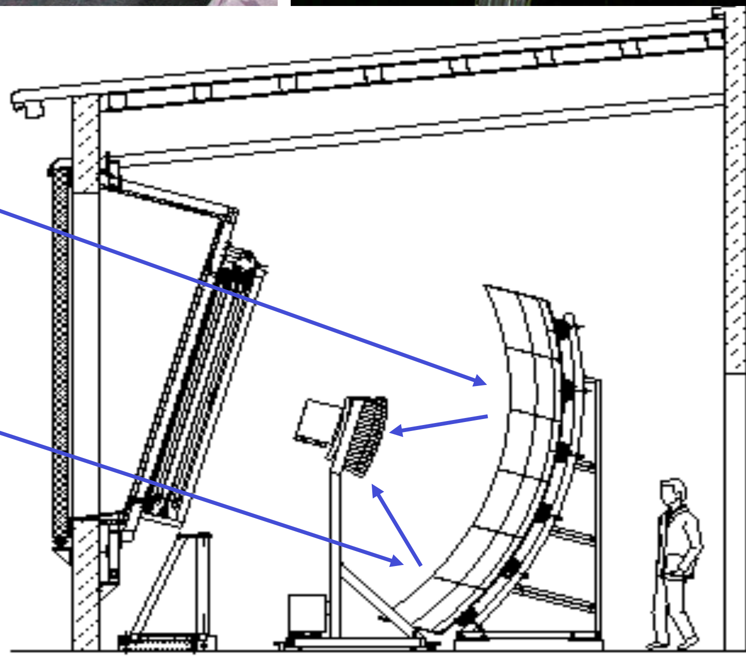


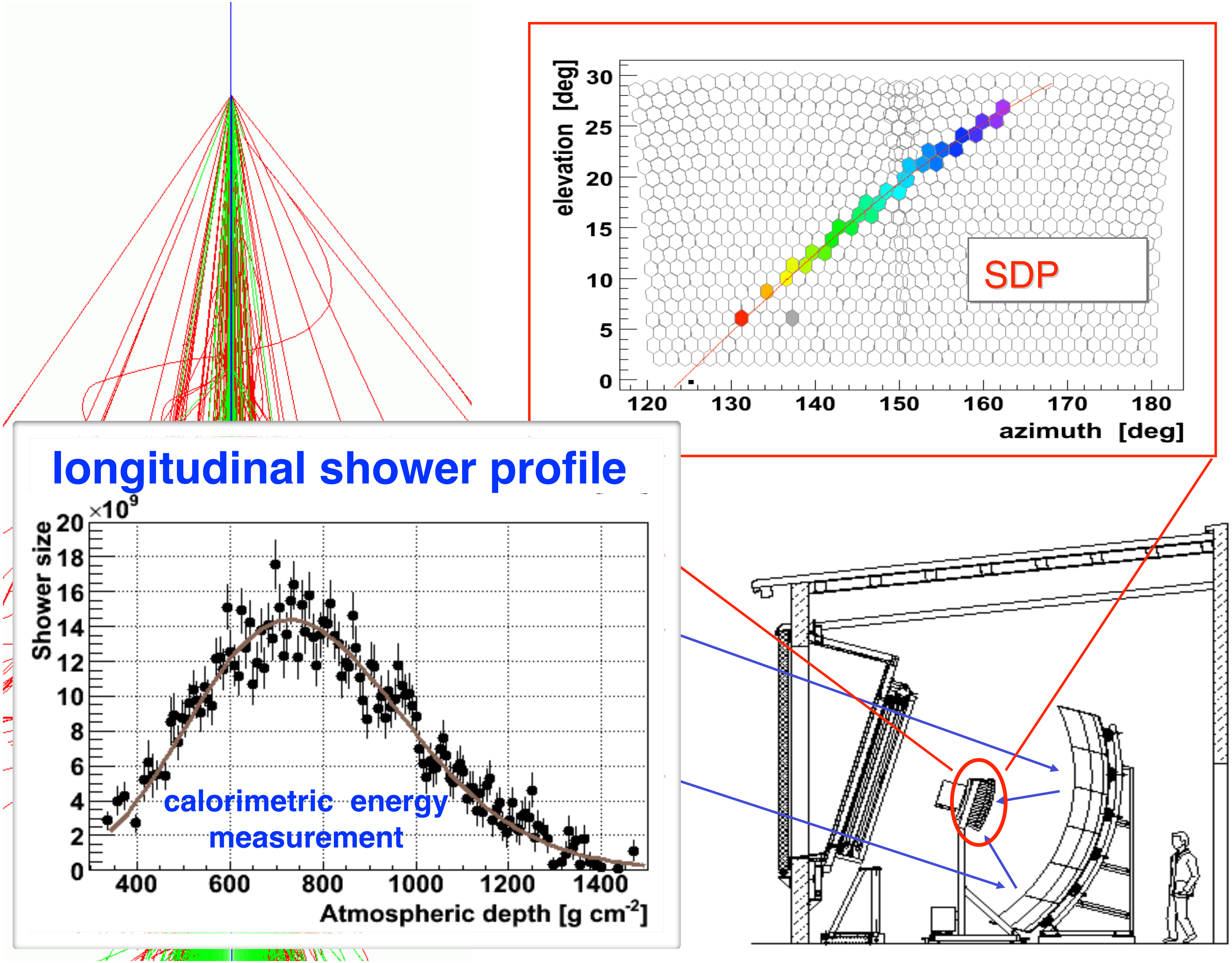
Four sites
Six telescopes
viewing 30°x30° each




12 m² mirror

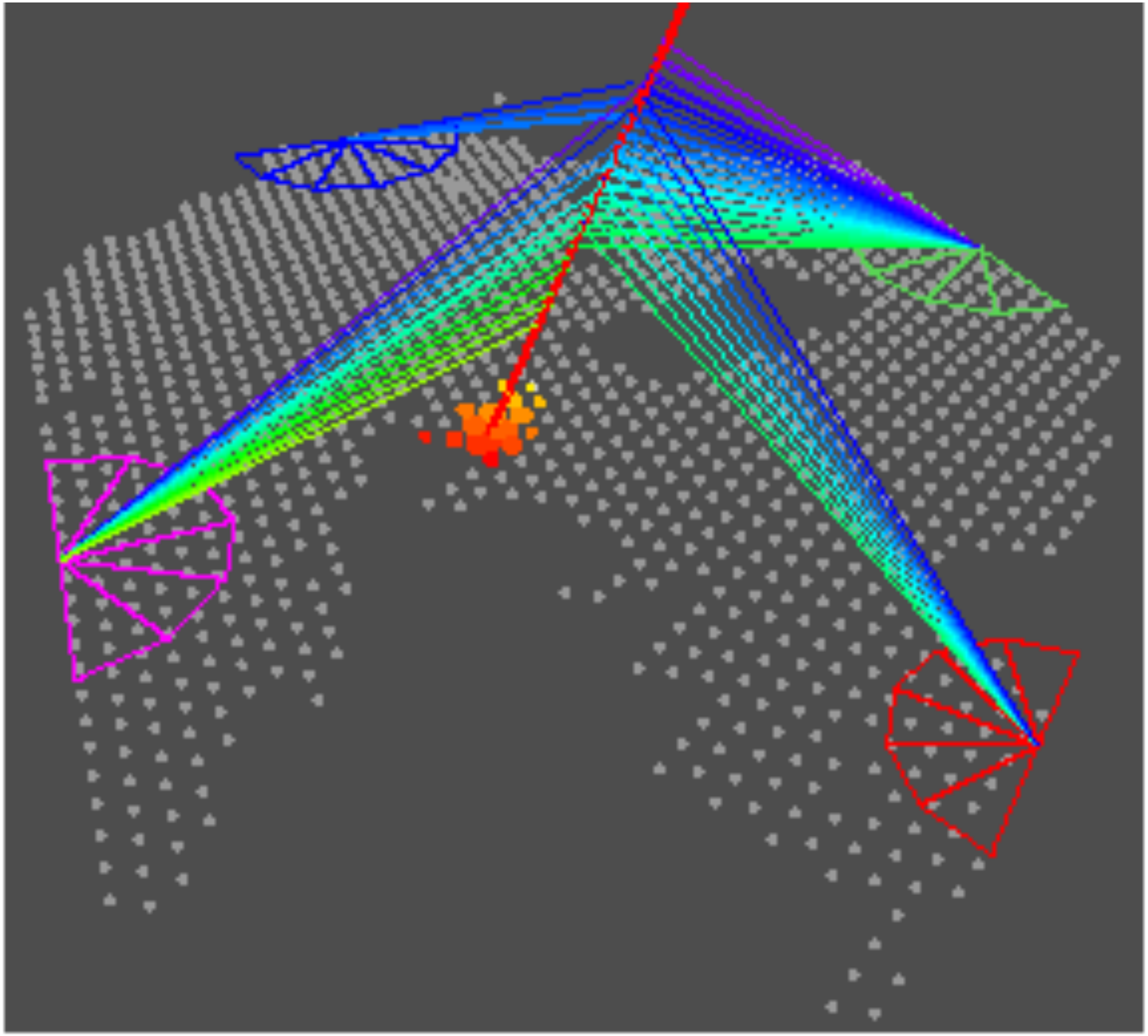

90 cm
440 photo multiplier





elevation [deg]
30
25
20
15
10
5
0
120
130
140
150
160
170
180
azimuth [deg]
SDP
longitudinal shower profile
×10^9
Shower size
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

A Hybrid Event



20 May 2007 E ~ 10^{19} eV