V: Experimental techniques

To be measured:

1 Primary direction $\equiv$ shower axis

2 Primary energy

3 Primary composition (mass)

Primary direction (Origin) :

A) With a surface detector :use the lateral distribution

1) Take at least 3 stations hit (3 times and 3 energies) and estimate the shower plane normal.

2) Suppose a symmetry around the shower axis and given a reference lateral profile get the shower impact point on ground.

3) Re-estimate the shower axis taking into account the shower plane curvature

4) Loop on 1, 2 and 3 (3 times is usually enough) to obtain the shower geometrical parameters. $\vec{A} = \{(x, y)_{core}, \theta, \phi\}$

The estimates precision increase with energy :

$\Delta\theta \sim 2^o \quad @ \quad 10^{19}eV \longrightarrow 1^o \quad @ \quad 10^{20}eV$

$\Delta X, Y \sim 80m@ \quad 10^{19}eV \longrightarrow 40m \quad @ \quad 10^{20}eV$

B) With the fluorescence :use a longitudinal profile.

In this case $\vec{A}$ is in the plane defined by the hit photo tubes and the eye's center. The lateral profile is not used and can be studied for [A]. The axis position within the plane is given by the PM times, for the shower ground impact the ground detector barycenter gives the best estimate.

Hybrid mode : $\Delta\theta \sim 0.35^o$ et $\Delta X, Y \sim 20m$

primary energy (Spectrum):

A) With a surface detector

- Extrapolation/interpolation of the measured densities $\rho(r)$ at the optimal distance. (proportionality with E_{prim} is always good).
- $\rho(r)$ is compared to Monte Carlo predictions (adapted to the specific detector, e.g. scintillators or Čerenkov)
- this estimate depends weakly on
  1) The physics of the first interactions.
  2) The primary type.

Resolution is about 20% (15% from 1 and 2, and 15% from statistical fluctuations)

B) With the fluorescence

- $N_\gamma \propto N_e$ along the longitudinal profile.
- $E_{em} = 2.2MeV\ g^{-1}cm^{-2} \times \int N_e(X)dX$ where E_{em} is the electromagnetic energy which represents 90% of the primary energy.
- Resolution of 5% for hadronic showers and 10% for photons.

Primary Mass (Composition) :

1) ρ_μ is a good estimator (also ρ_μ/ρ_{em}).

Reminder : Superposition model $E = A \times \frac{E}{A}$:

a) $\longrightarrow$ Fewer stage before reaching $e_\pi \sim 1\ GeV$

b) $\longrightarrow$ Less EM energy.

This result is common to all interaction models (realistic ones!)

2) Rise time $T_{\alpha-\beta}$

3) X_{max} position

With a reference point (e.g. 1000m from the core) and a reference energy E_0 one has 3 quantities:

$\rho_{\mu/em}(1000)$, $T_{\alpha-\beta}(1000)$

and

$\hat{X}_{max} = X_{max} - \frac{d<X_{max}>}{dlogE}(logE - logE_0)$.

For a given primary these observables are correlated (via the shower developments speed) giving distinct curves according to the primary type.

There are unknowns in the primary interaction models (in-elasticity, cross section, multiplicity).

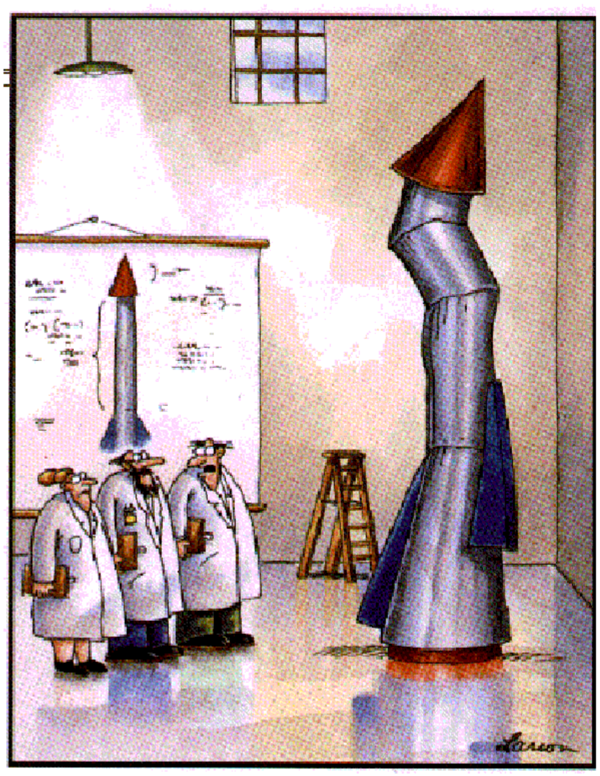
Fluorescence detector allows to study the longitudinal profiles and thus to constraint those unknown parameters.

Auger

Philosophy:

- Need high statistics (large detection surface)
- Uniform sky coverage (2 sites). [Fig 5.3 à5.9]
- Principle : Hybrid detector. [Fig 5.10]
  - Fluorescence detector [Fig 5.11 et 5.12]
  - Surface array (water Čerenkov) [Fig 5.13 à 5.16]
- Good energy and direction resolution [Fig 5.17]
- Good sensitivity to composition. [Fig 5.18]

How did it all start?



"It's time we face reality my friends: we should keep to ground detectors."

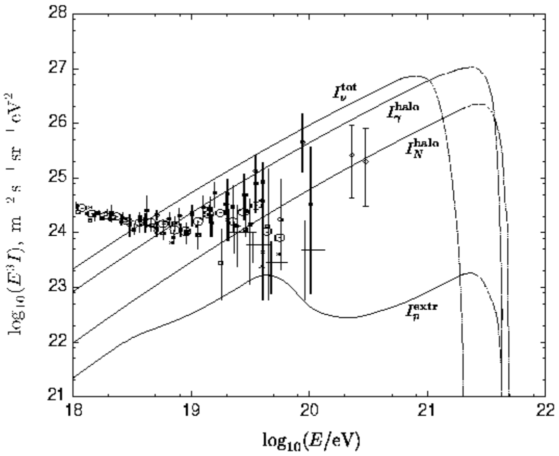
High statistics

Auger in 5 years (HiRes in 70 to 130 years):

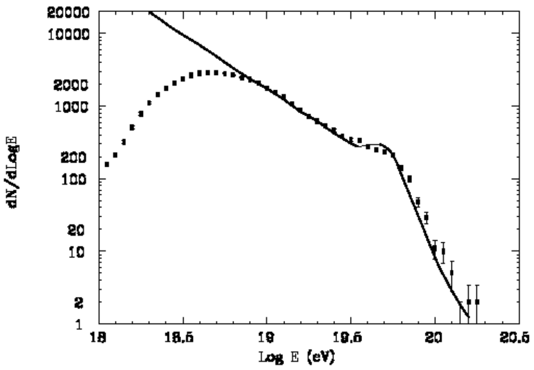
>100 EeV   >10 EeV

E > 10 EeV	30000 events
E > 30 EeV	3000 events
E > 100 EeV	300 events

ABSOLUTELY necessary



Quasi-stable X-particle model (Vilenkin)

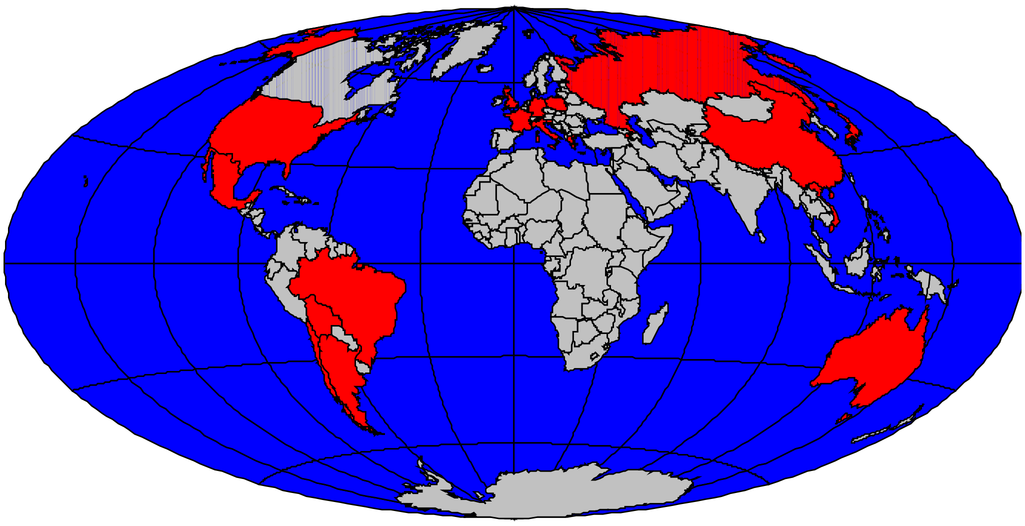


Cosmologically distributed sources with cutoff
(20 months of data with Auger)

[Fig 5.3]

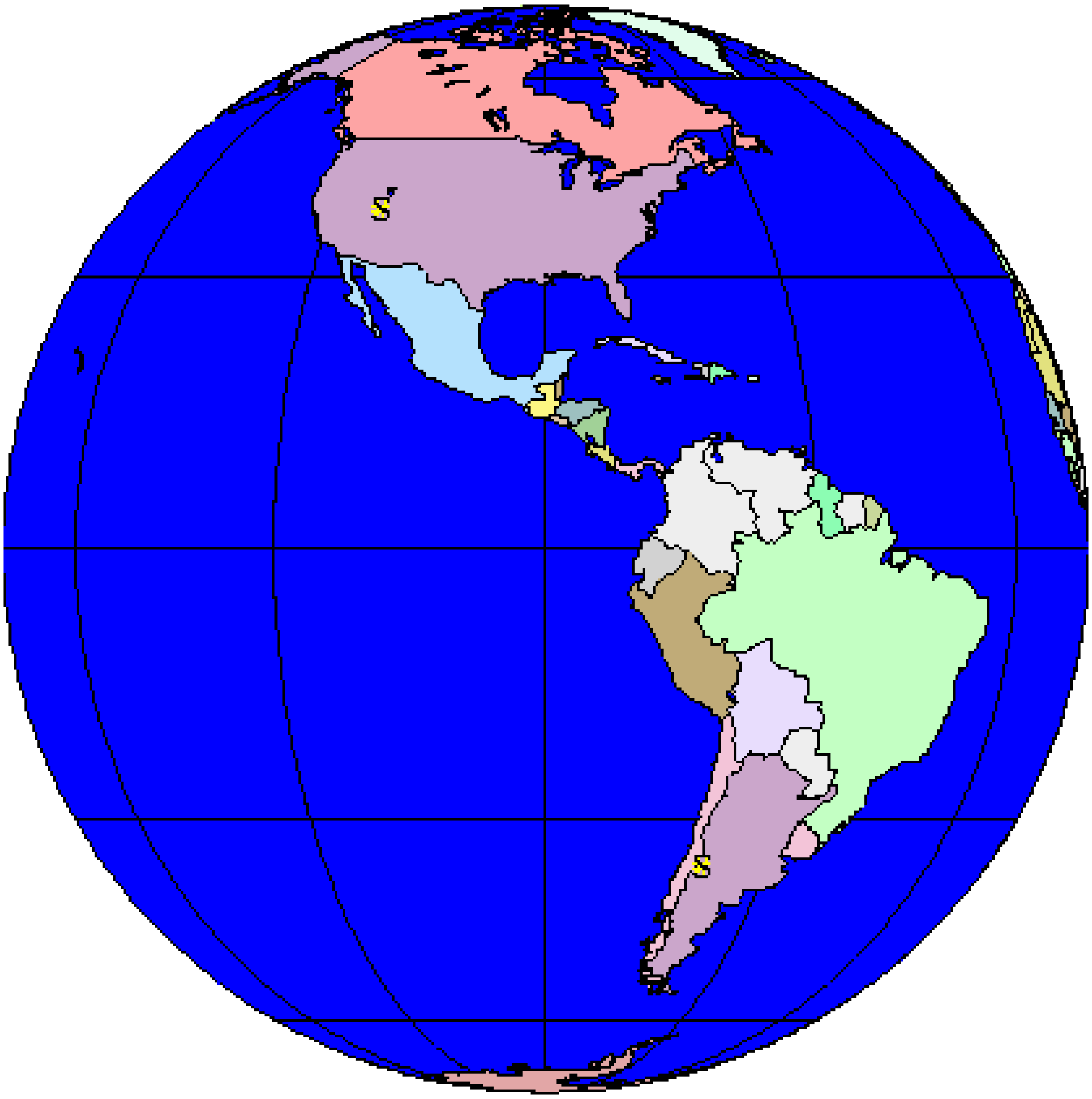
Auger Collaboration

	Country	Institutions	Phys.+Eng.
EUROPE	Armenia	1	6
	France	6	29
	Greece	1	15
	Germany Italy	1	3
	Poland	2	8
	Slovenia	1	3
	Russia	1	4
	United Kingdom	1	6
ASIA	China	1	11
	Japan	1	6
	Vietnam	2	9
	Australia	1	3
LATIN AMERICA	Argentina	6	38
	Bolivia	1	4
	Brazil	4	26
	Chile	1	3
	Mexico	4	43
	USA	11	62
	TOTAL	46	279



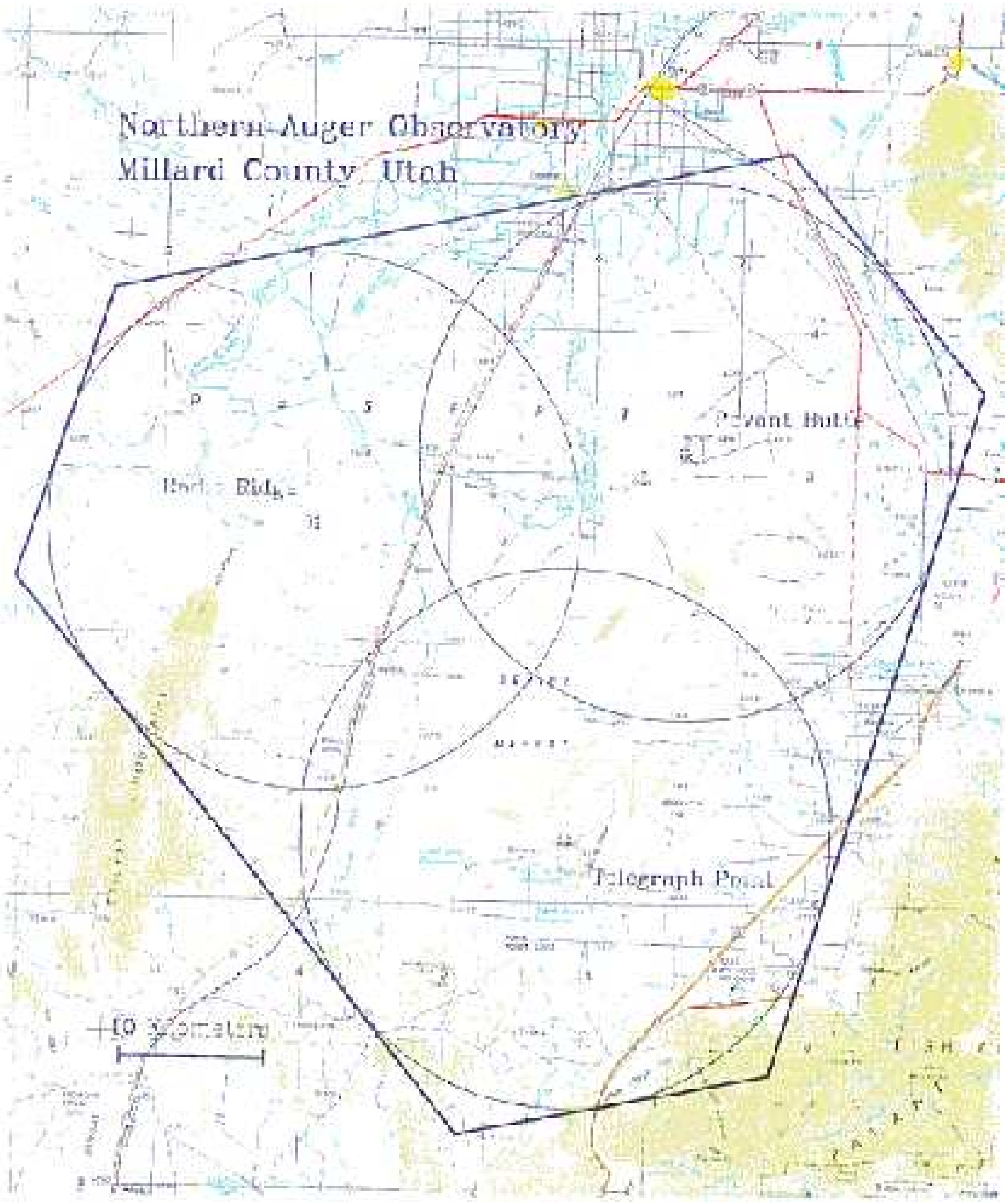
[Fig 5.4]

Sites positions



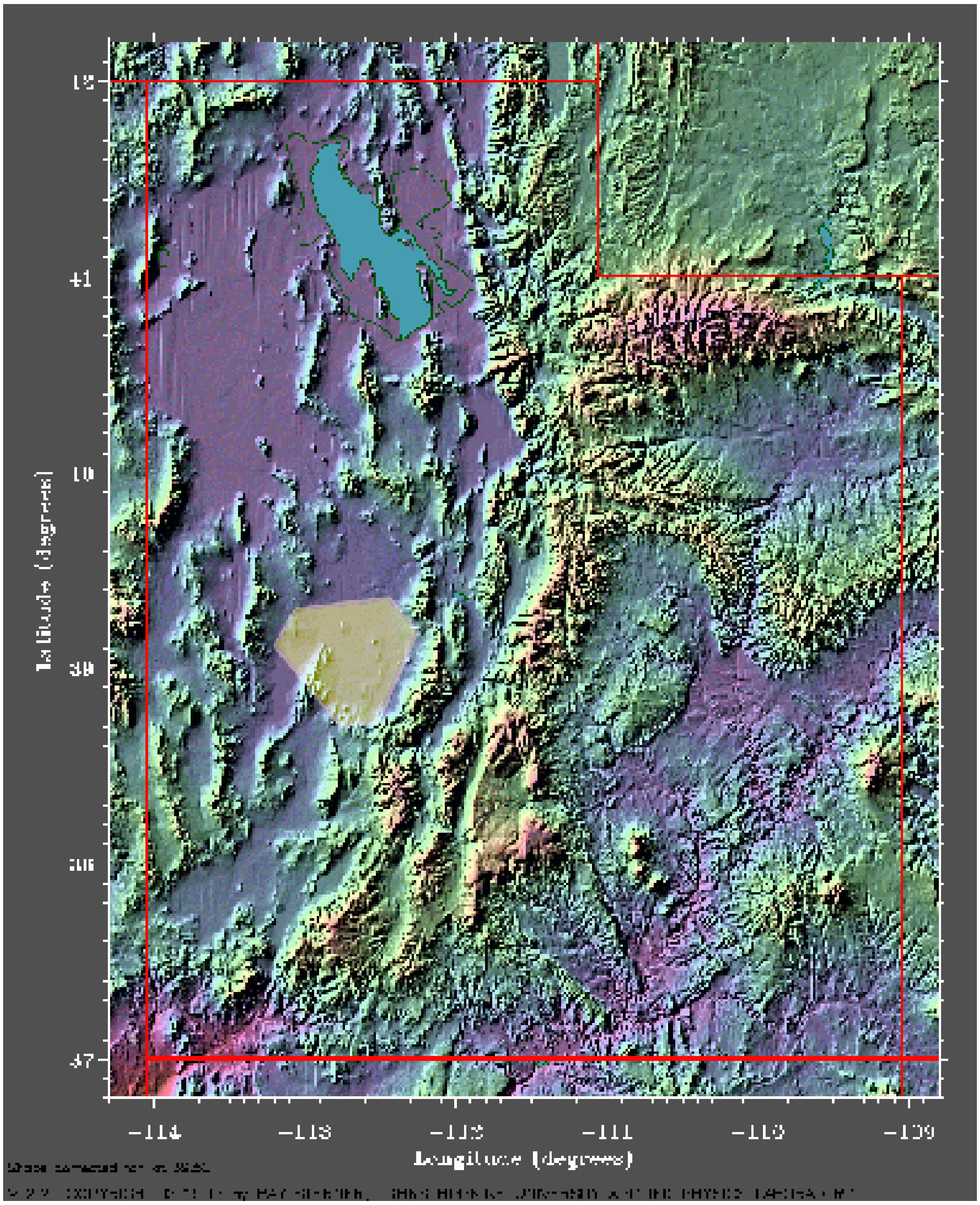
[Fig 5.5]

Northern Site



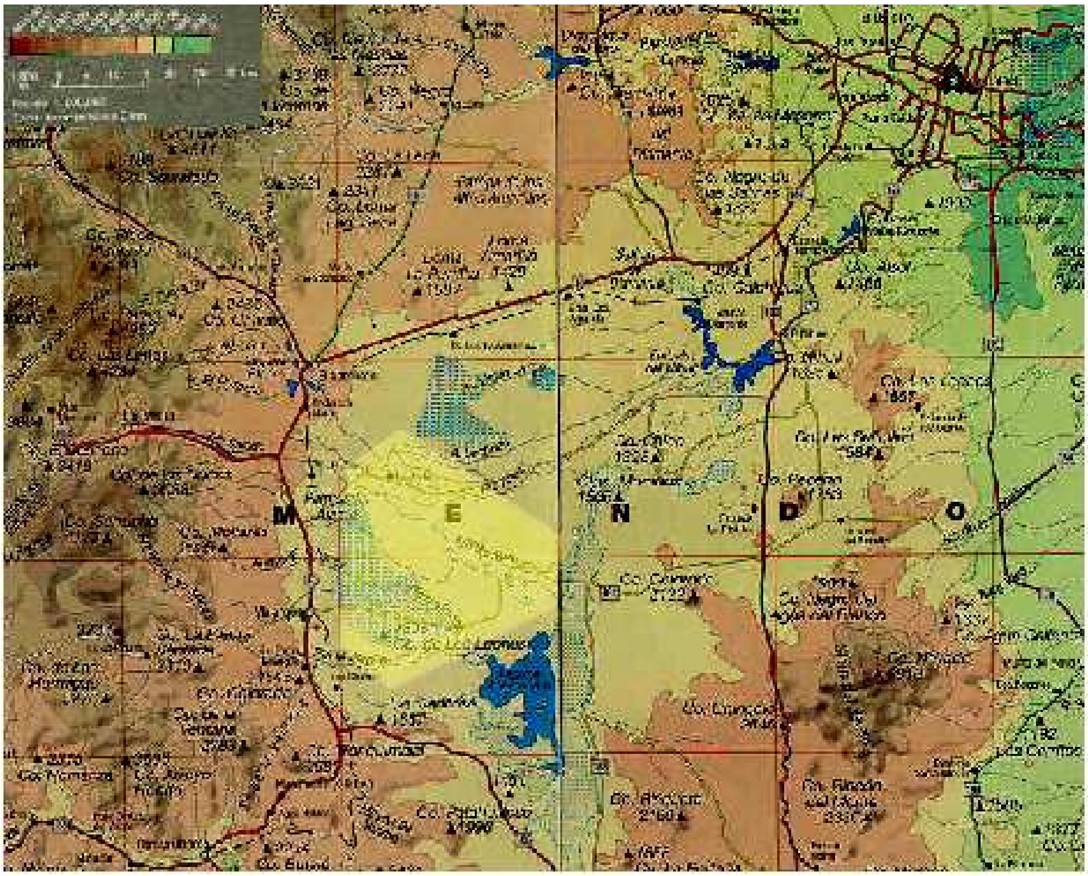
[Fig 5.6]

Northern site (satellite)



[Fig 5.7]

Southern site



[Fig 5.8]

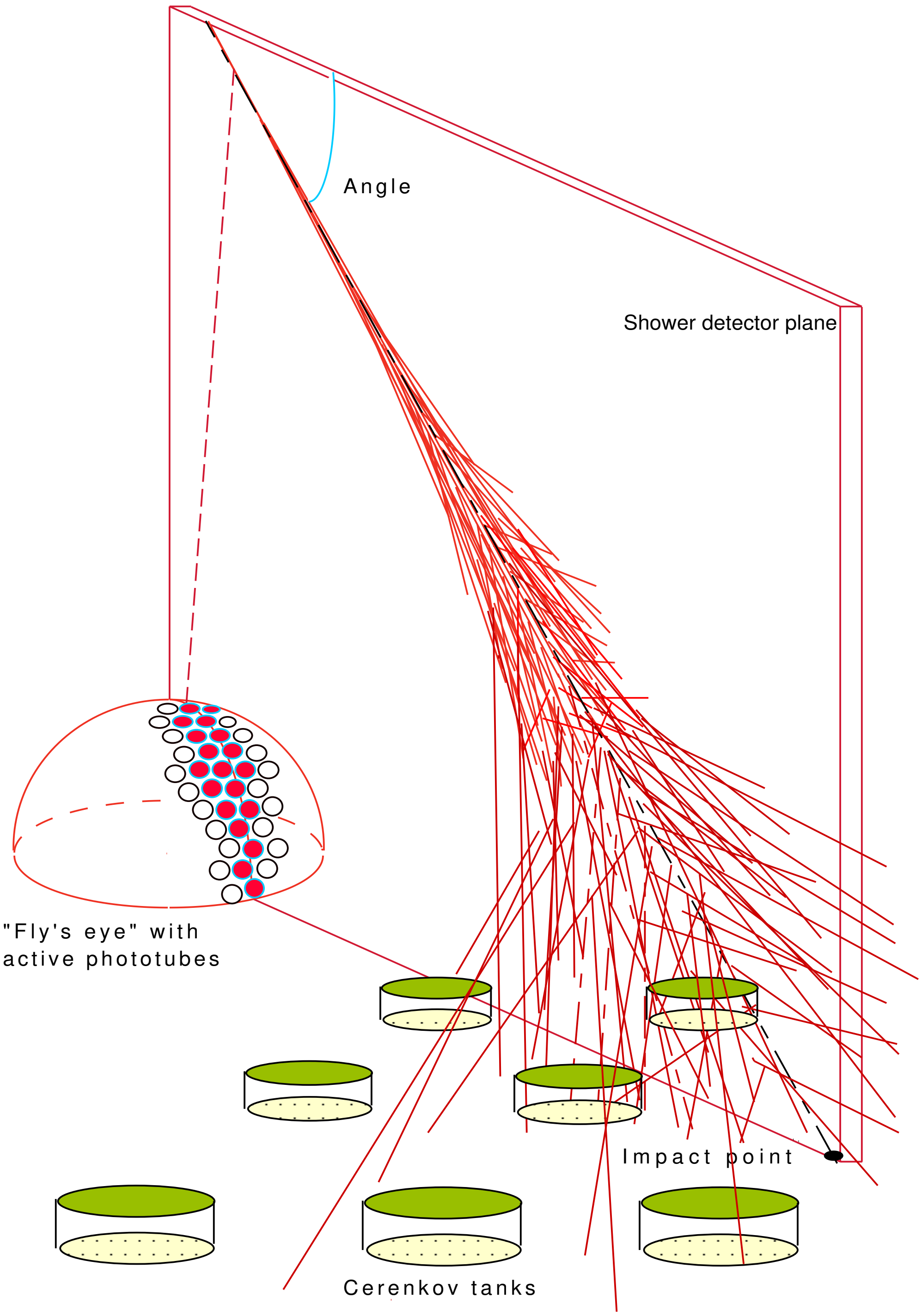
Site photos

[Fig 5.9]

Why a hybrid detector?

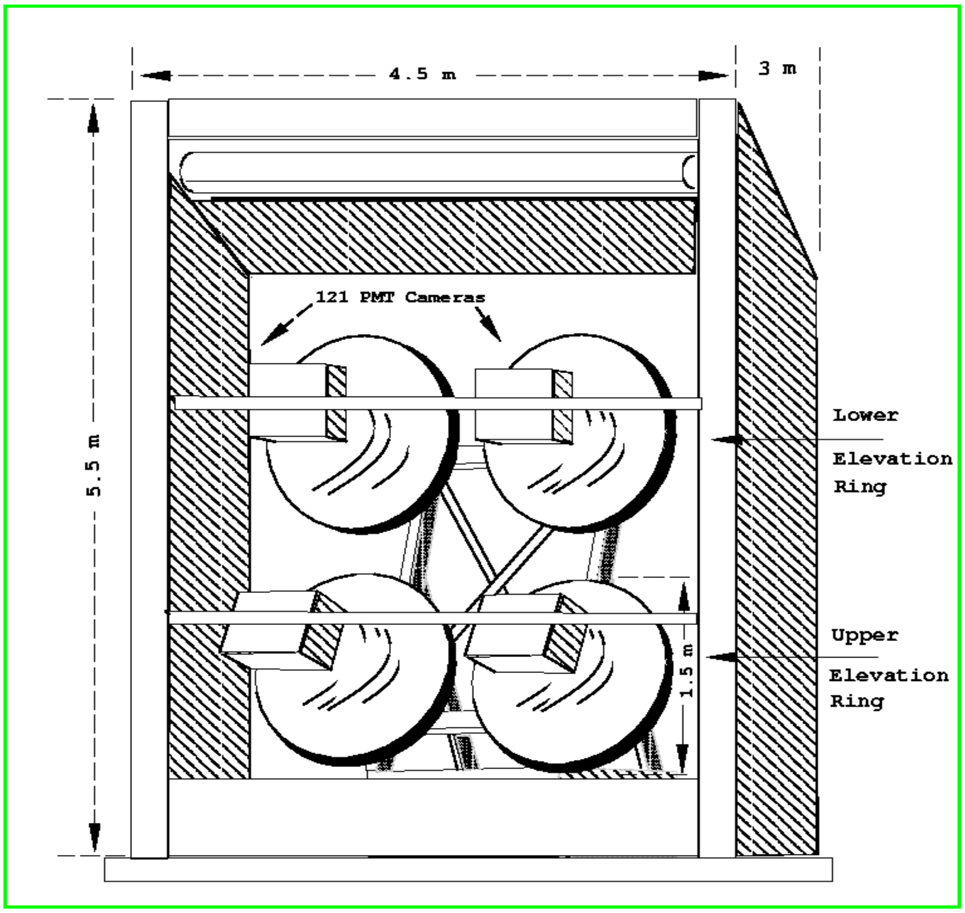
- Cross calibration
  - Complementary measure of the energy and direction of the primary.
  - Allows for redundancy checks of interesting events.
  - Allows to study (and reduce) systematics.
- Increase composition sensitivity
  - Measuring $\rho_\mu/\rho_{em}, t_{\alpha-\beta}$ and X_{max} increase significantly the mass resolution of the detector.
- Hadronic cascades
  - Muon and EM densities combined with the longitudinal profile put constraints on the hadronic interaction models.
- Uniform sky coverage
  - The surface array has a duty cycle close to 100%. With a detector in each hemisphere one obtains a uniform sky coverage.
- Cost
  - The cost per event with a surface detector is much lower than with a stereo fluorescence detector.
  - Eyes don't need a high sensitivity at large distances.
  - Hybrid events are as good as fluorescence stereo events.

Operating mode



[Fig 5.10]

Fluorescence detector elements



Two and a half eyes to cover the surface array above 10^{19}eV.

Each eye is composed of mirrors and PMT cameras.

[Fig 5.11]

Air Fluorescence

Very low yield : $\varepsilon = E_{emission}/E_{loss} \simeq 10^{-5}$.

Emission in the near UV : 300 to 400 nm.

Number of fluorescence photons produced by N_e charged particles:

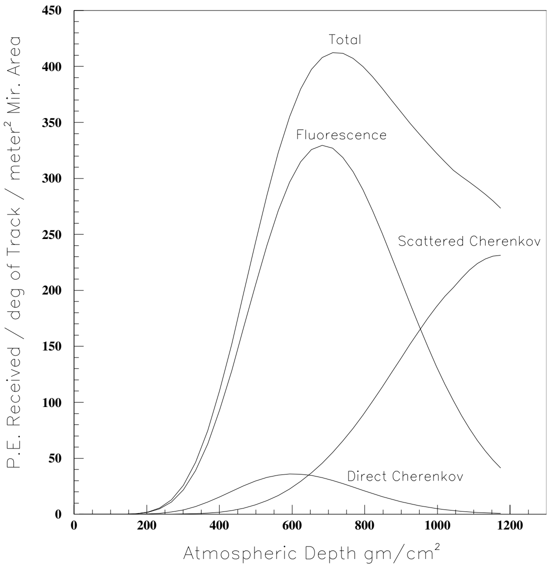
$$dN_\gamma = N_f \times N_e \times dl$$

where N_f is the photon yield per charged particle and per meter.

N_f is essentially independent of pressure and temperature.

Čerenkov photon yield by a shower element of length dl see under the solid angle $d\Omega$:

$$d^2 N_c \simeq \frac{N_0\ e^{-\theta/\theta_0}}{2\pi sin(\theta)} dl d\Omega$$

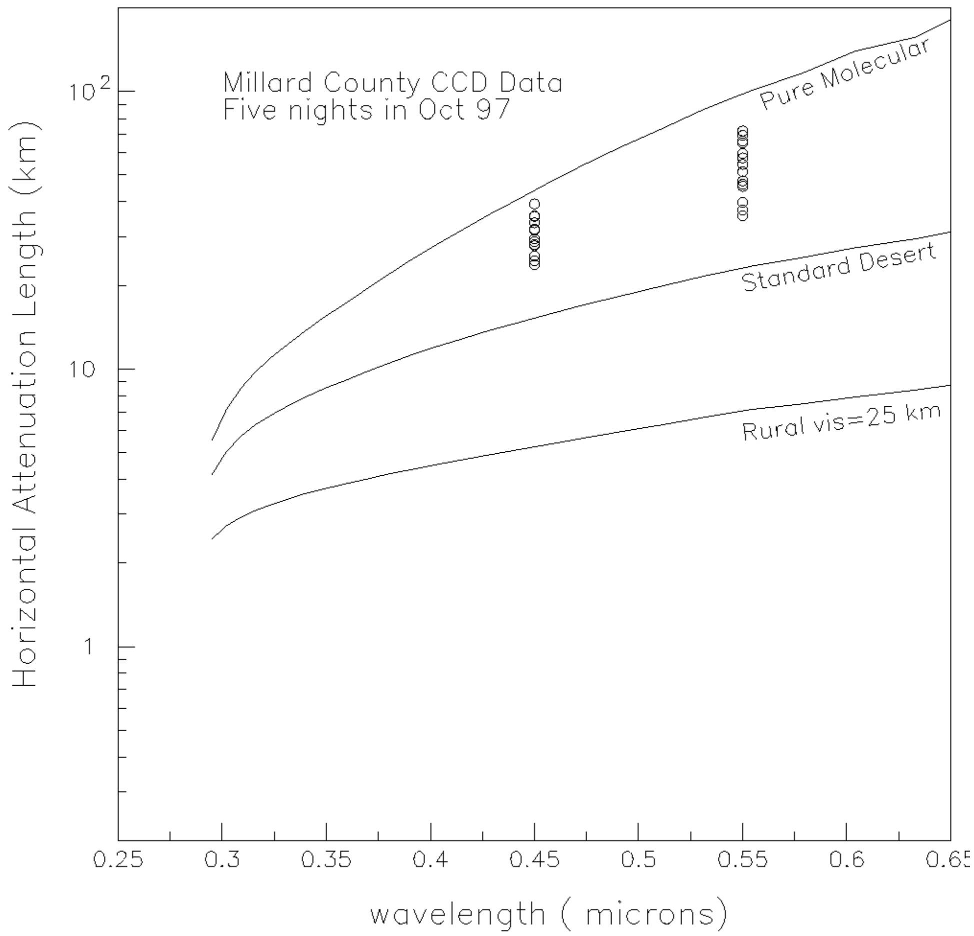


Signal as measured by a fluorescence detector as a function of the atmospheric depth. Simulation for a 10^{19}eV proton with $\theta = 45^o$ and $\phi = 0^o$ impact point 10km from the eye.

PM signal : $S \propto \frac{A\varepsilon N_e cT}{4\pi R^2}\xi(R)$. Noise : $B \propto \sqrt{A\varepsilon\Omega T}$.

Remark : Problem of the air scattering (Mie (10km) and Rayleigh (23km)).

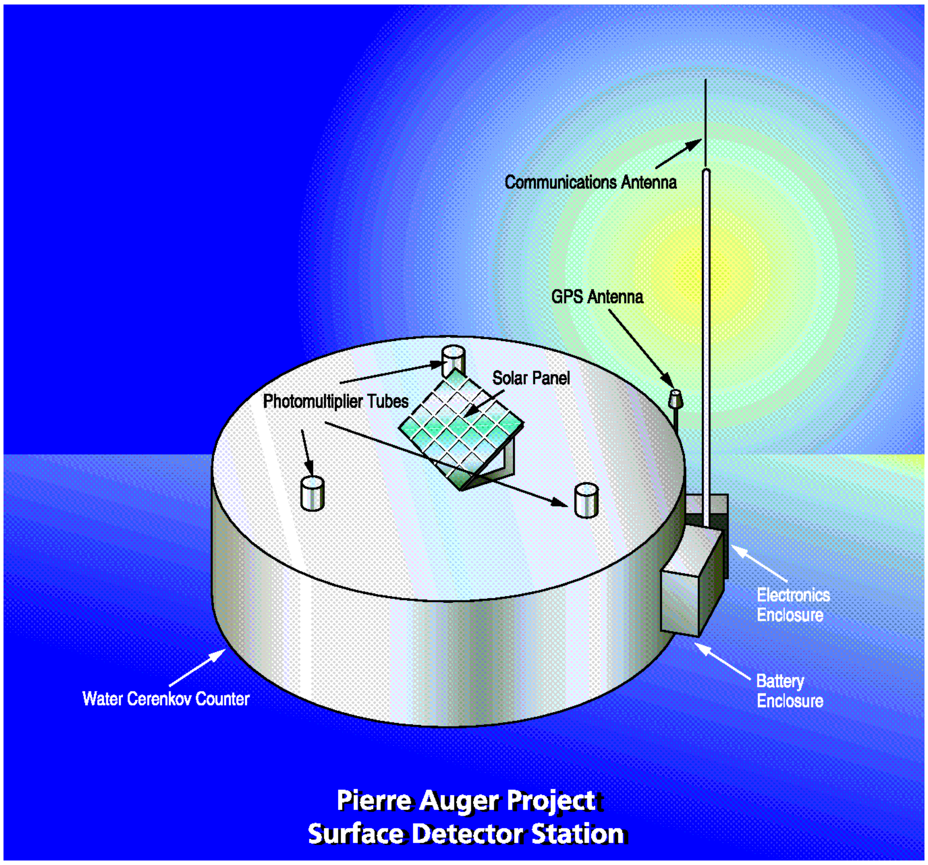
Atmospheric transparency

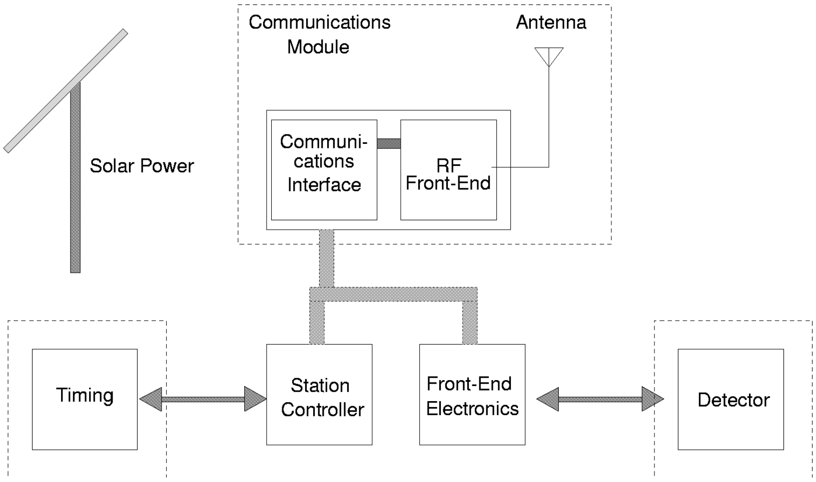


Atmospheric transparency as measured on the northern observatory site.

[Fig 5.12]

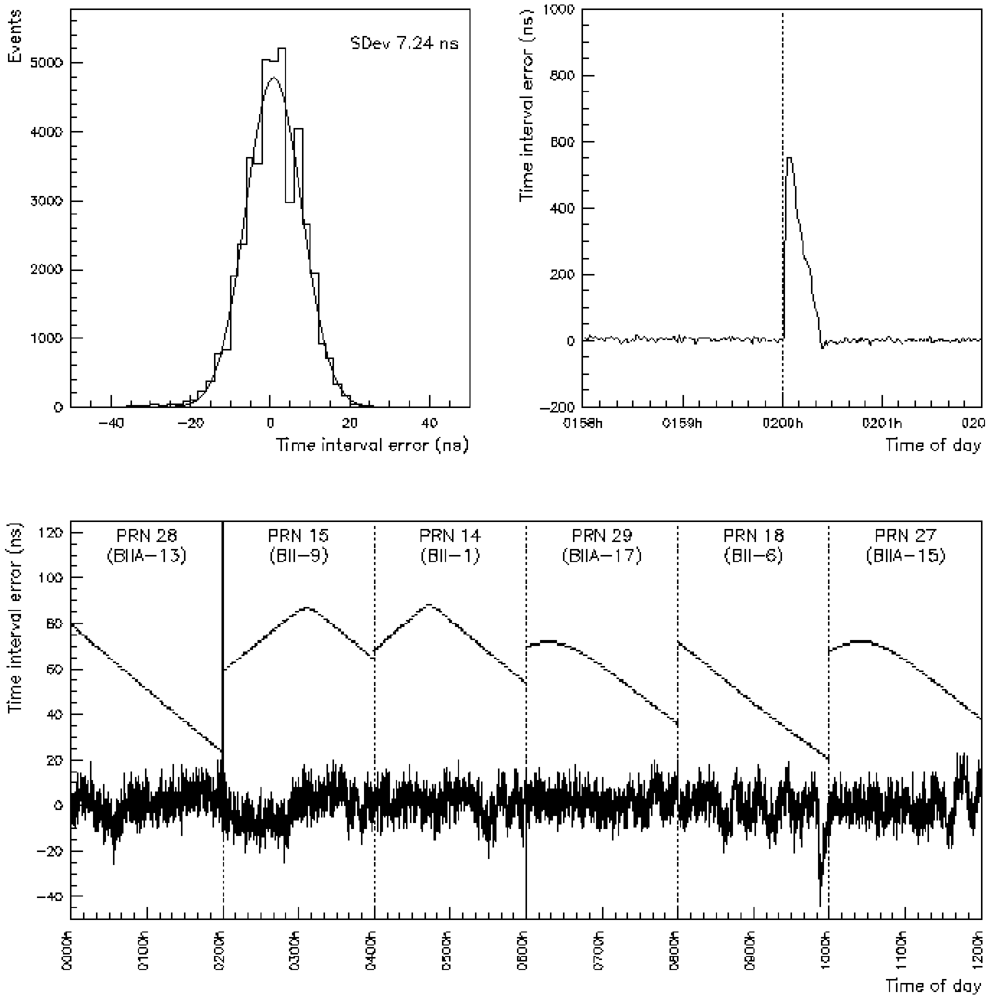
Surface detector





[Fig 5.13]

Time Synchronization



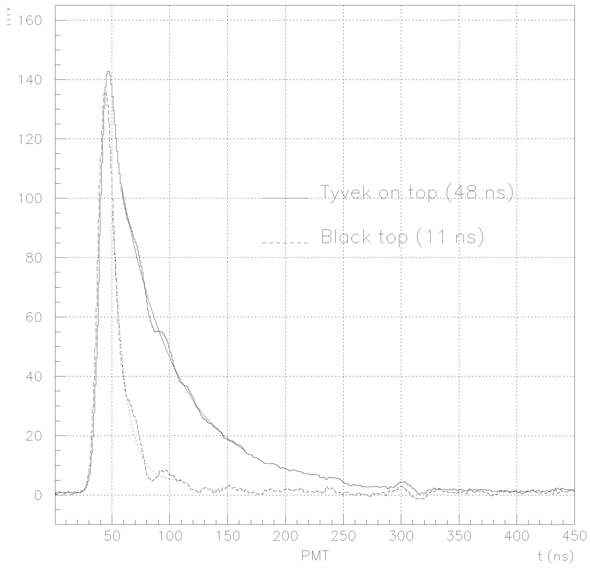
Time difference between two time stamp units separated by 11.2 km.

Bottom : The measured difference and the GPS satellite elevation angle.

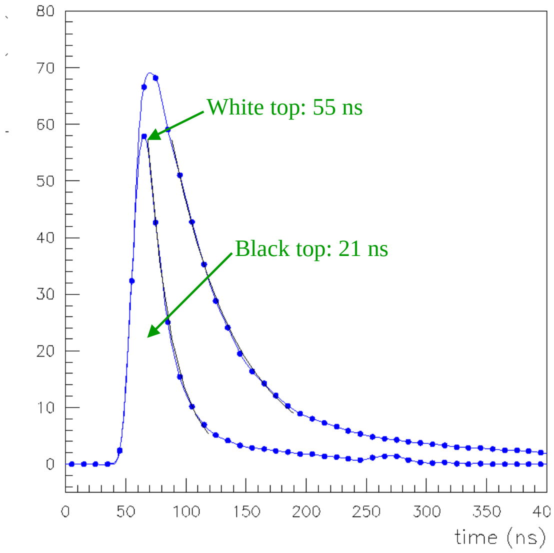
Top left : resolution, right : zoom on the transient observed at 02h00.

[Fig 5.14]

Tank prototype from Tandar (Argentina)



Data



Simulation (Pryke)

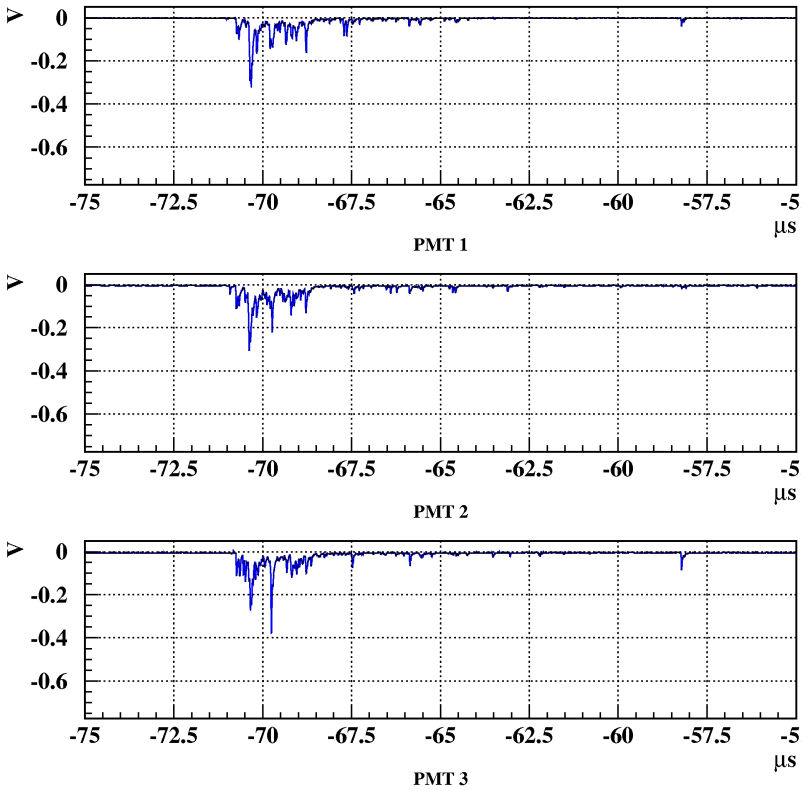
[Fig 5.15]

Tank prototype from AGASA (Japan)

10^{20} eV event

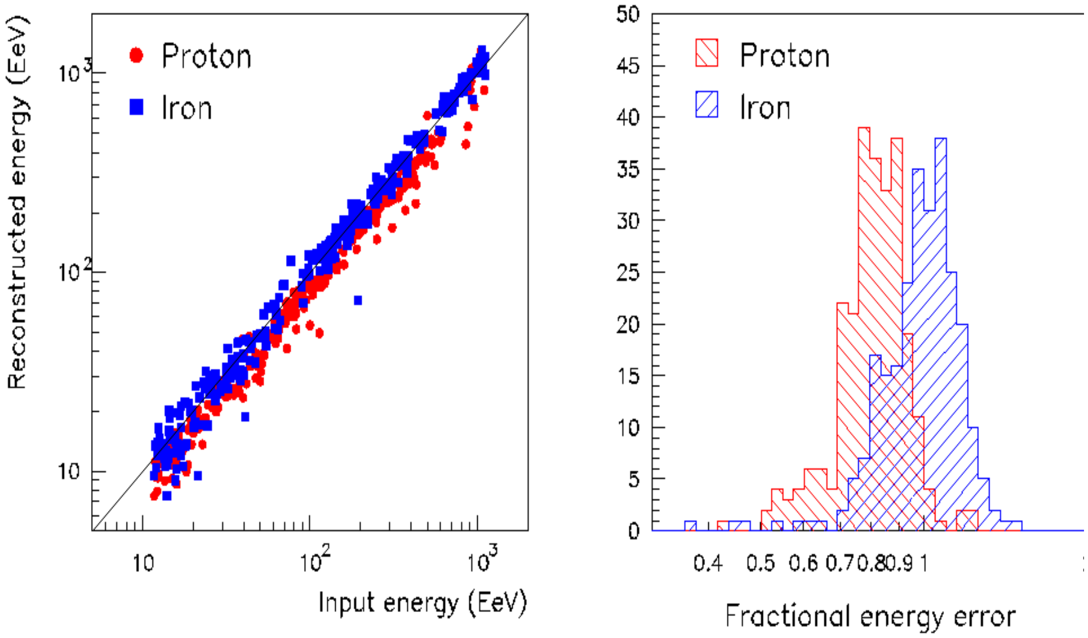
1.7 km from core

30^{o} zenith angle



[Fig 5.16]

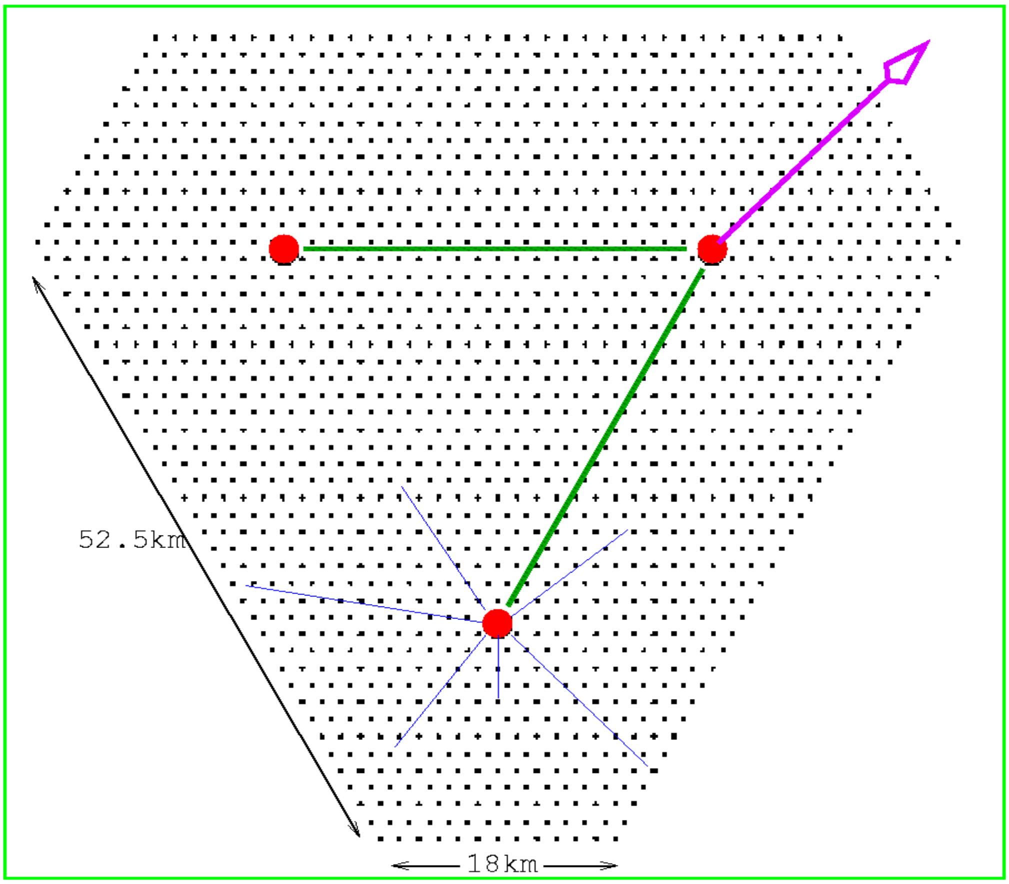
Energy reconstruction (SA)



- Energy resolution, 15% for protons and 10% for Iron. systematic offset (to be corrected) between proton and Iron : 20%.
- The angular resolution is better than a degree in both case for E > 10^{19}eV.

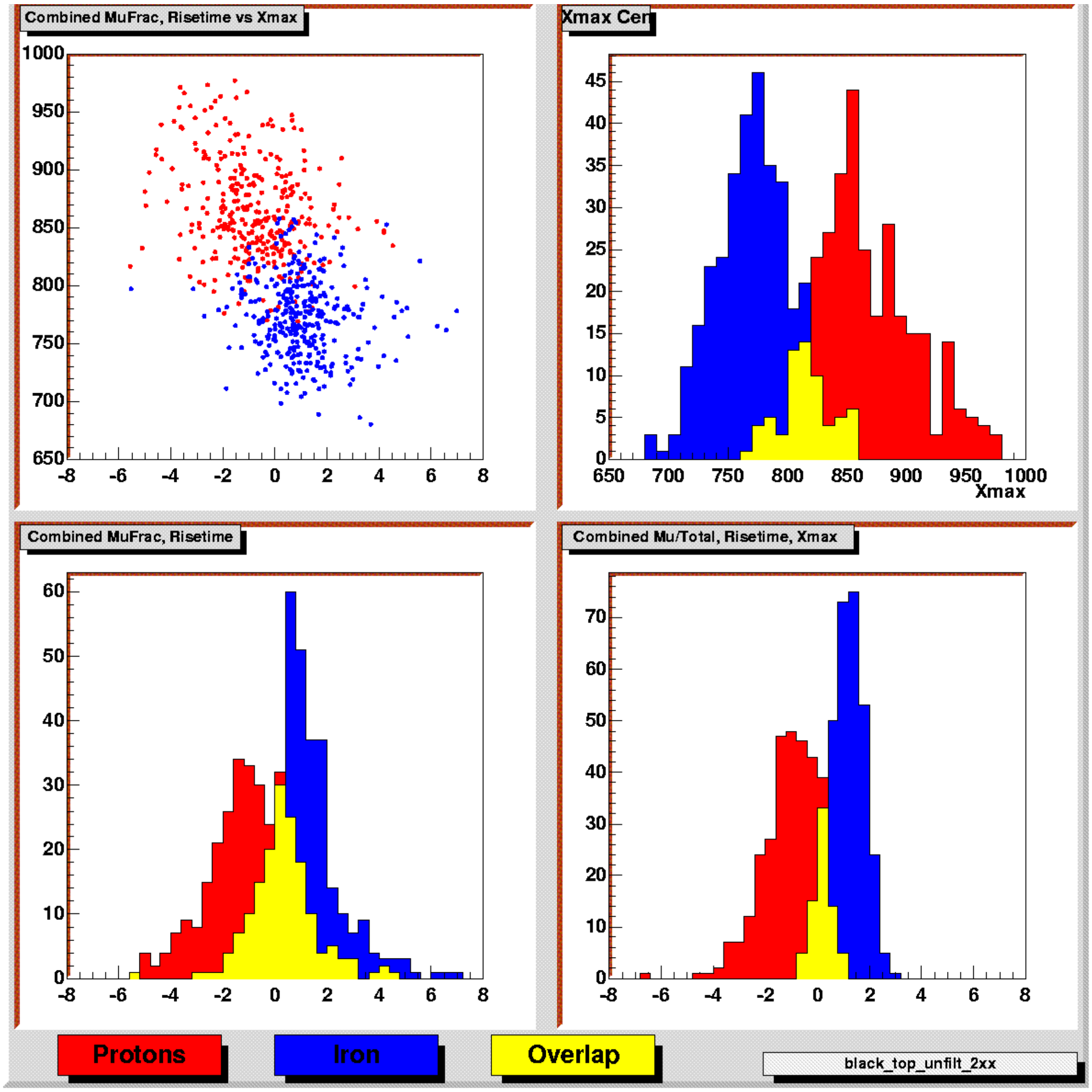
[Fig 5.17]

General layout



- Cerenkov tanks
- The three Eyes and telecom concentrators
- ISM band links *(24 bits@20Hz;4kbytes@.001Hz)*
- Internet link *(1.4 Mbits/s)*
- Microwave links *(2 Mbits/s)*

Primary mass



[Fig 5.18]

Performances

* **Duty cycle :** array 100%
  FD 10% (15% ??)

* **Efficiency** >90% @ E>10 EeV

* **Energy resolution**

	array alone	hybrid mode
100 EeV	15%	10%
10 EeV	30%	20%

* **Angular resolution**

	array alone	hybrid mode
100 EeV	1 deg	0.20 deg
10 EeV	2 deg	0.35 deg

* **Statistical power**

	Now	Auger (1 yr)
>100 EeV	9	6-120
> 40 EeV	~100	~500

* **Primary identification:** complicated but much better than now anyway!