Tecniche di rivelazione di raggi cosmici e *extended air showers*

Oscar Adriani
INFN Sezione di Firenze / Dipartimento di Fisica dell'Università di Firenze

- Region 1: 10^{9} eV – 10^{12} eV
    - Direct detection
- Region 2: 10^{12} eV - 10^{17} eV
    - Direct detection
    - EAS
        - Charged particles
        - Cherenkov
        - Fluorescence
- Region 3: 10^{17} eV - 10^{21} eV
    - *Giant array – Hybrid techniques*
- Examples used in the talk: INFN approved experiments

What are the CR?

Electromagnetic radiation:
- Radio
- IR
- Visible
- UV
- X
- γ

→ Astronomy, Astrophysics

Charged particles:
- p
- e^-
- e^+
- $\bar{p}$
- Nuclei
- Antinuclei?
- ???

Subjects of this talk

Neutral particles:
- ν
- ???

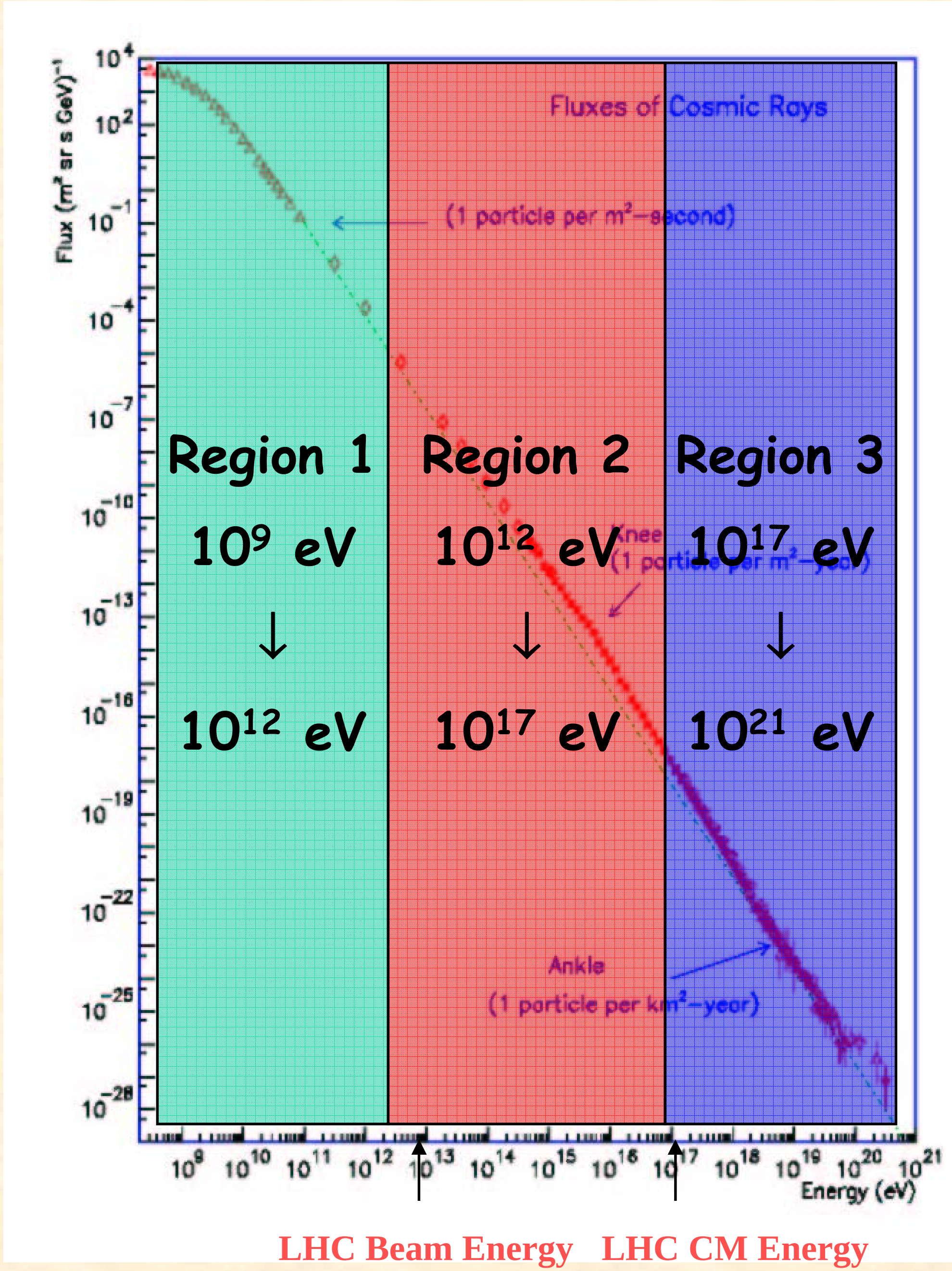
→ CR

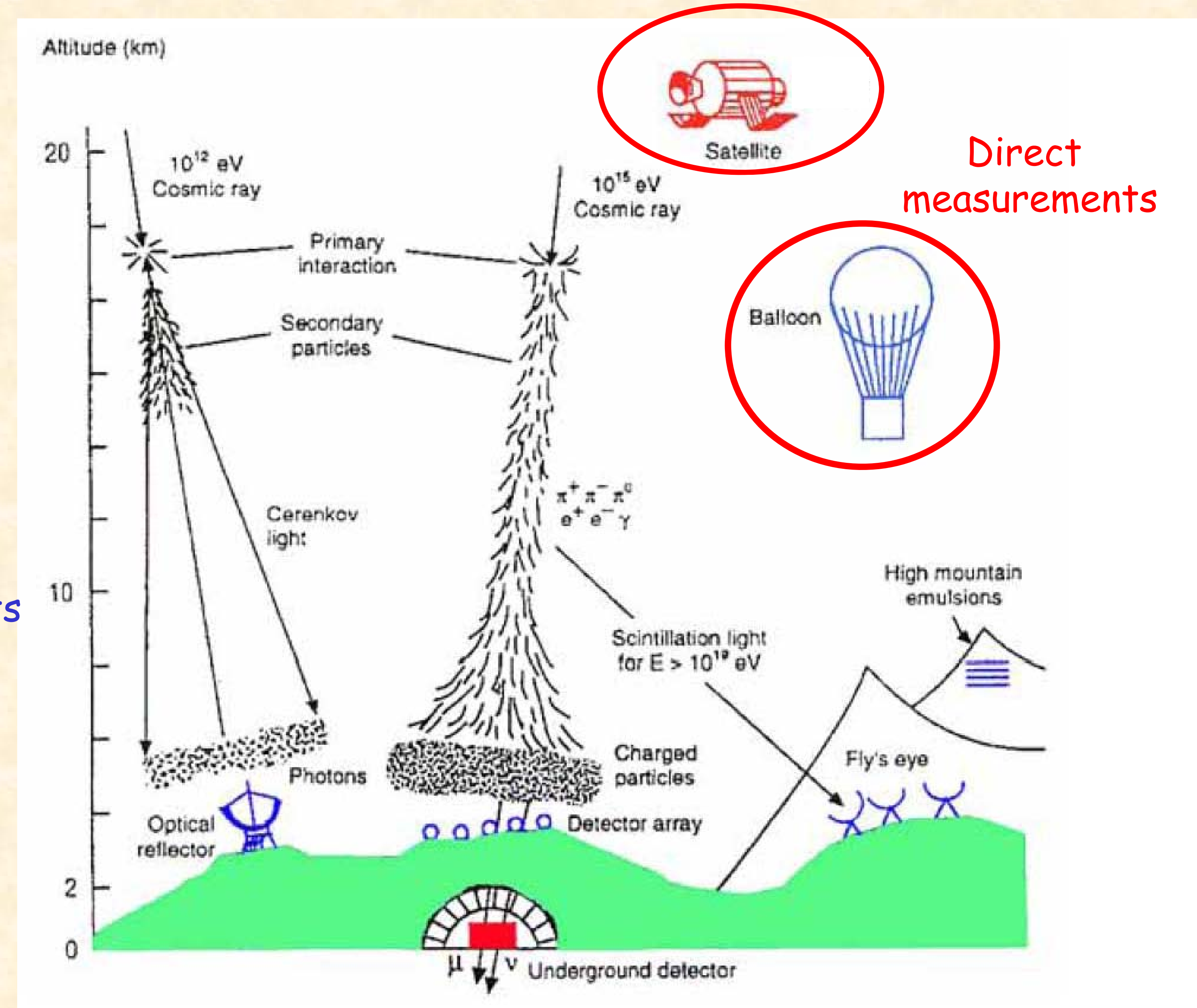
Primary cosmic rays

$$\Phi \propto E^{-2.7}$$

Deviations from this power law
- knee (4.10^{15} eV)
- ankle (5.10^{18} eV)

Very different techniques are necessary to cover these huge differences of:
- Fluxes
- Energies





Direct measurements

Indirect measurements

The INFN approved experiments that will be used as 'examples' for this talk:

- WIZARD/Pamela
- AMS2

} Region 1

- CREAM
- ARGO-YBJ

} Region 2

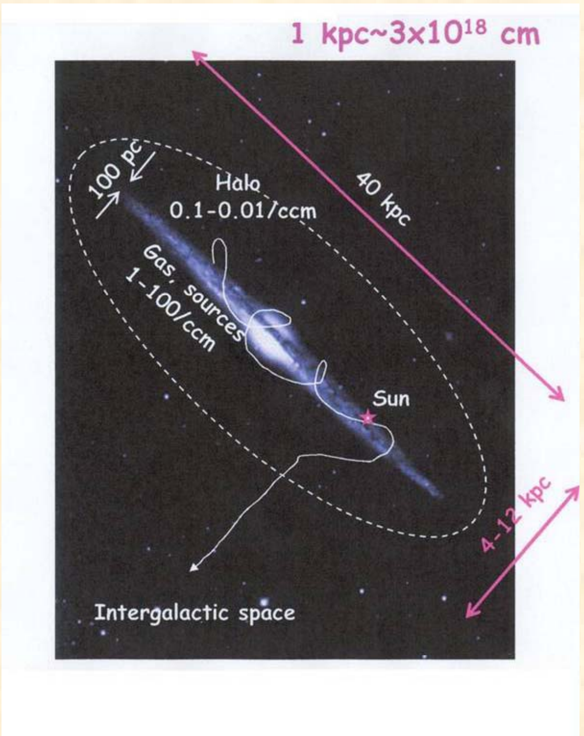
- AUGER

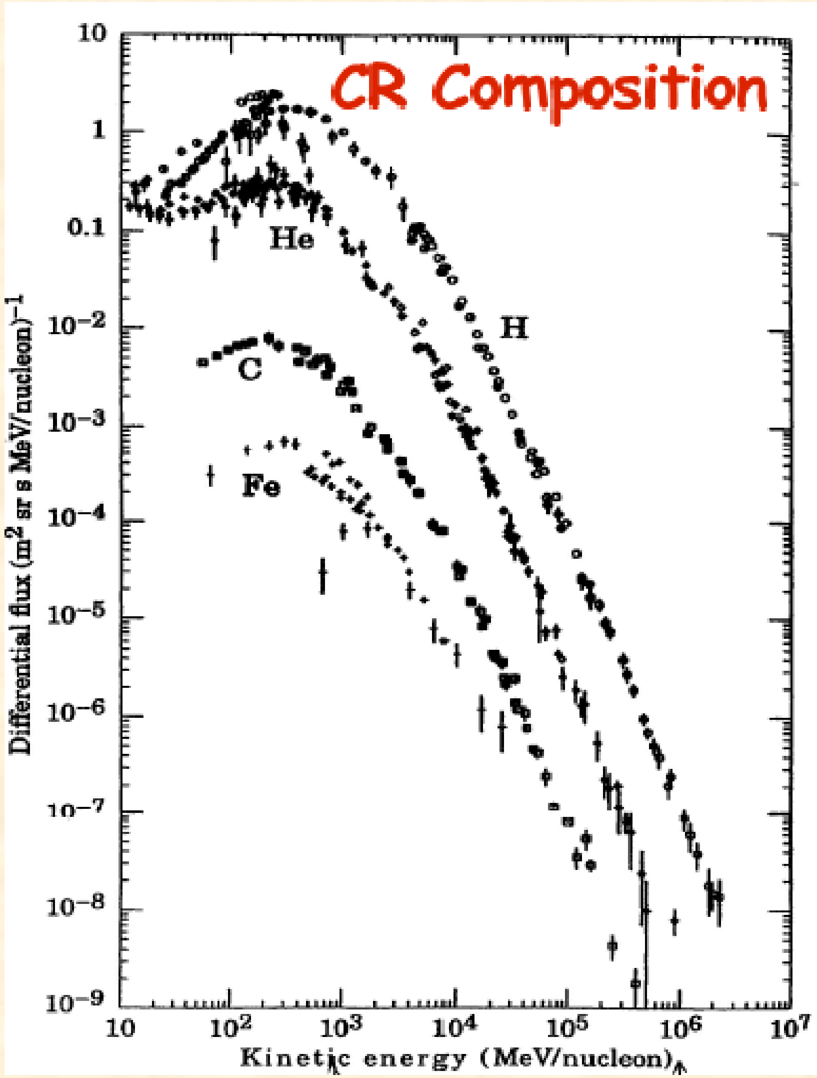
} Region 3

Only some selected topics for each experiment will be shown for time limitation!
I apologize for this.....

Region 1: 10^9 eV – 10^{12} eV

- Best known region
- Direct measurements are possible
- Effect of solar modulation up to 1 GeV
- All elements are present (up to U)
- Absolute flux important for ν physics





Experimental techniques

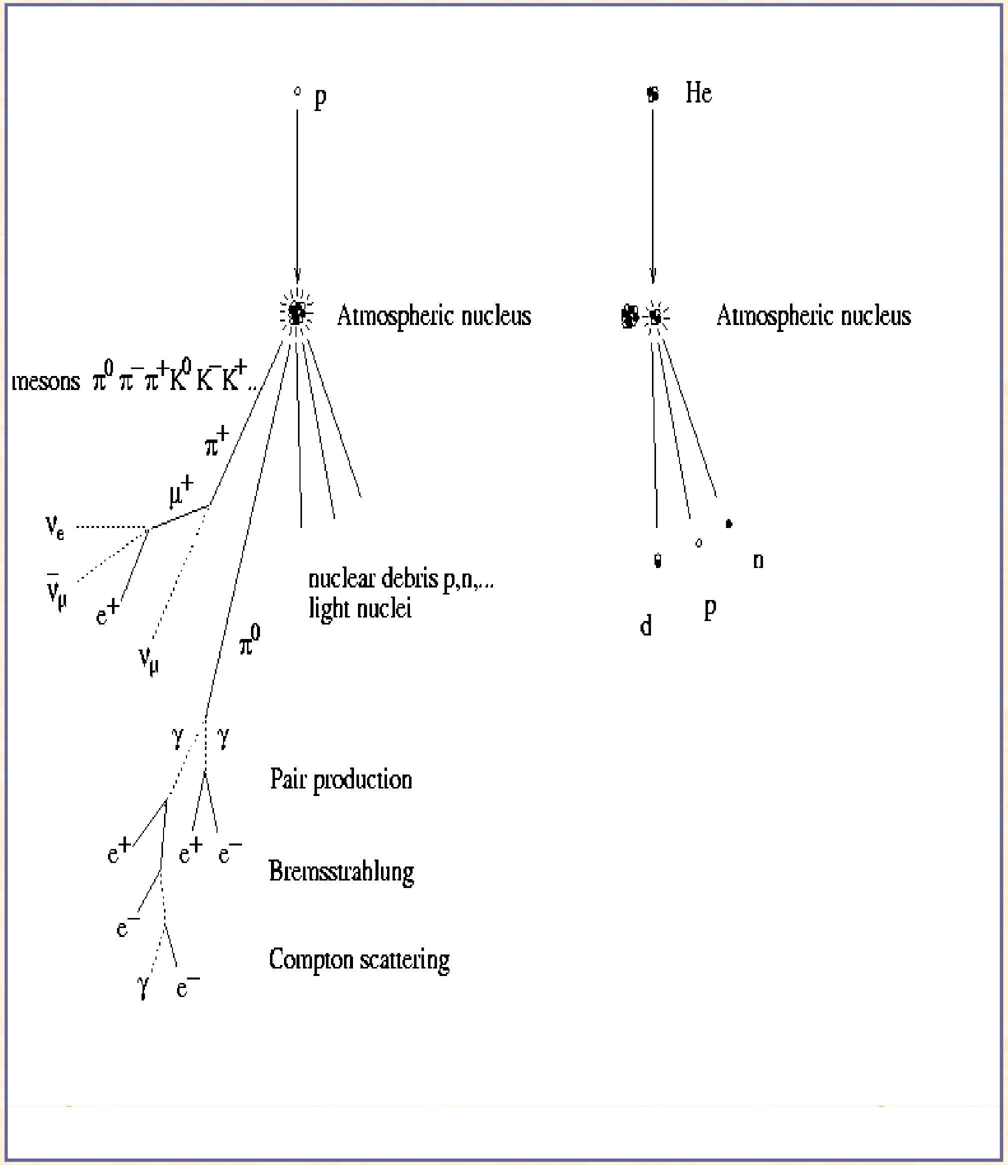
1. ~~Experiments on earth~~
2. Experiments on balloon
3. Experiments on satellite

Measurements to be done

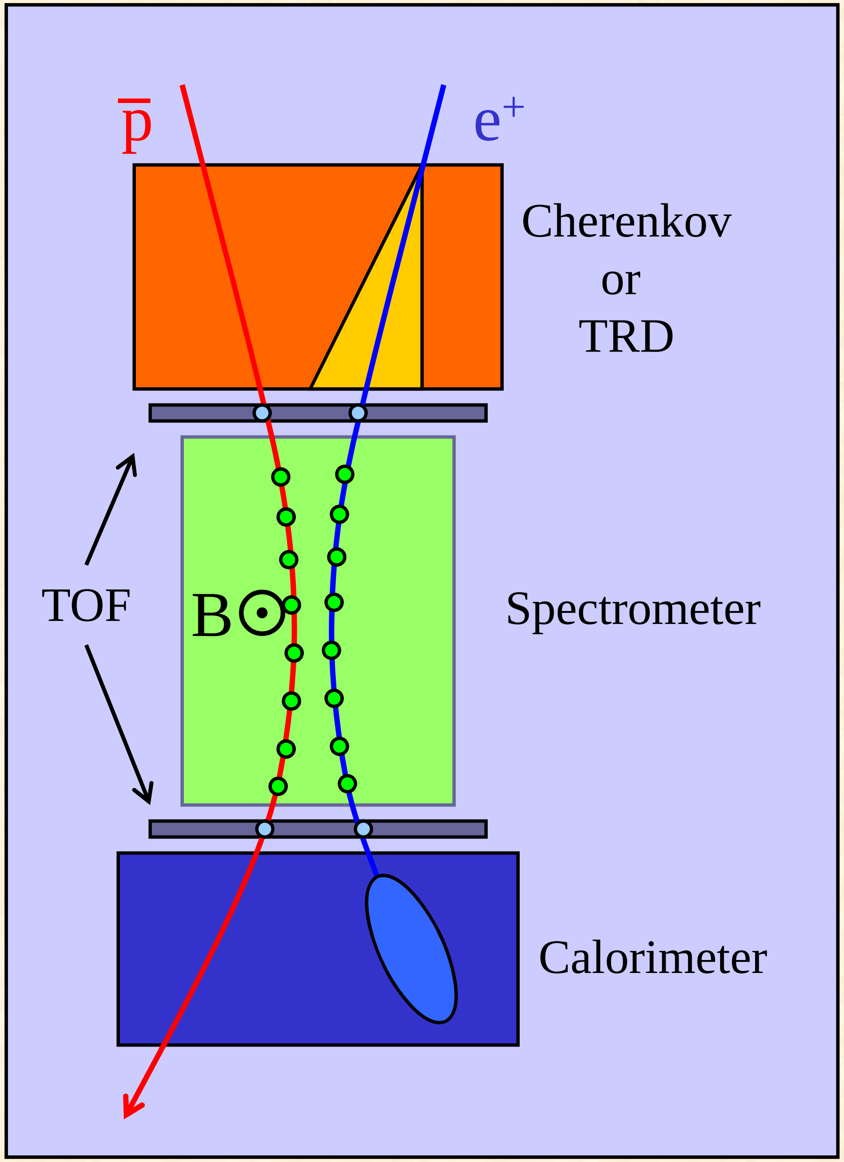
1. Momentum
2. Z
3. Identification (e^-/anti-p, e^+/p …)
4. Isotopical identification

Complex techniques are necessary (strong link with accelerator based experiments!):

1. Many subdetectors
2. Magnetic spectrometers
3. Calorimeters
4. TRD
5. Cherenkov
6. TOF
7. Trigger
8. Veto
9. …



'Ideal' experiment

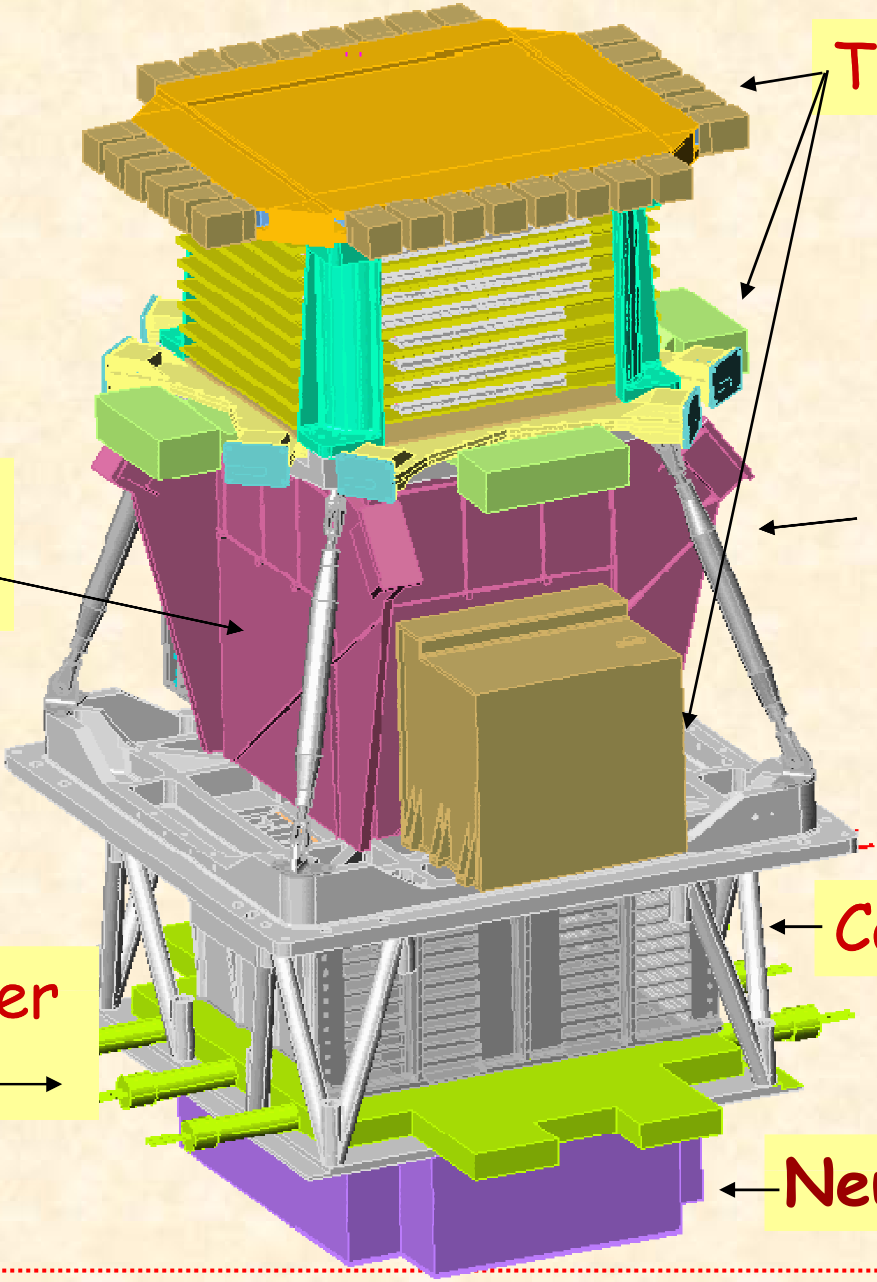


1) Measurement of energy/momentum
2) Identification of type of particle

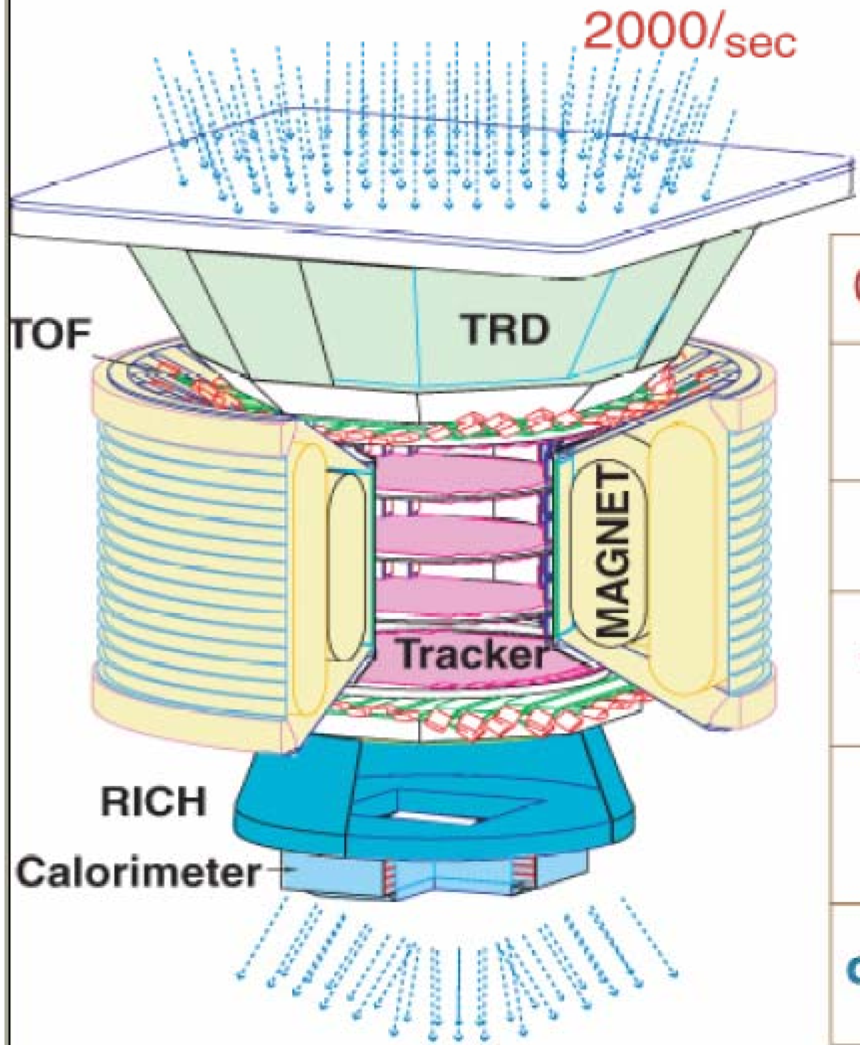
- Magnetic spectrometer
  - Sign of the charge (e^+/e^-, antip/p)
  - Magnetic rigidity R=p/Ze
- Particle identification
  - TOF (β)
    - Charge (dE/dx)
    - Identification (β vs R)
    - Albedo rejection
  - Cherenkov or TRD
    - Identification (β vs R)
  - E.m. calorimeter
    - Identification (topology of the interaction)

PAMELA

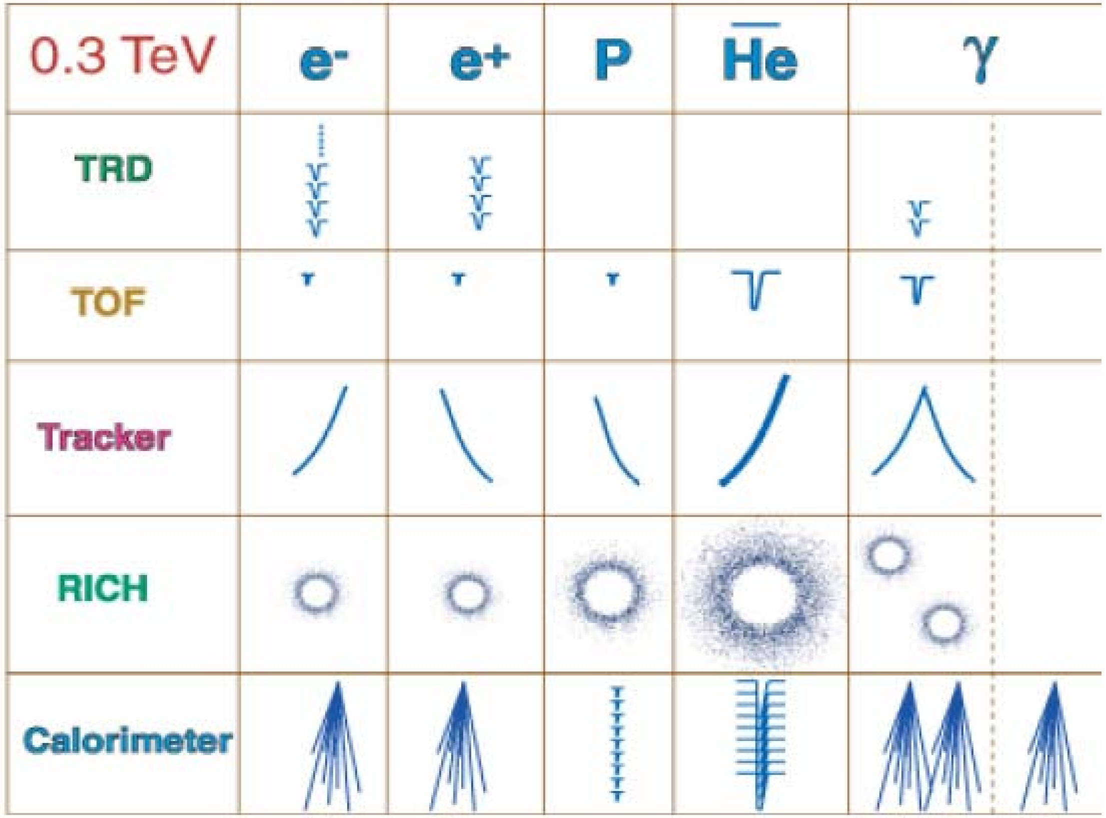
Launched on
June 15, 2006



AMS: A TeV Magnetic Spectrometer in Space



G.F. 5000 cm² sr
Exposure > 3 yrs

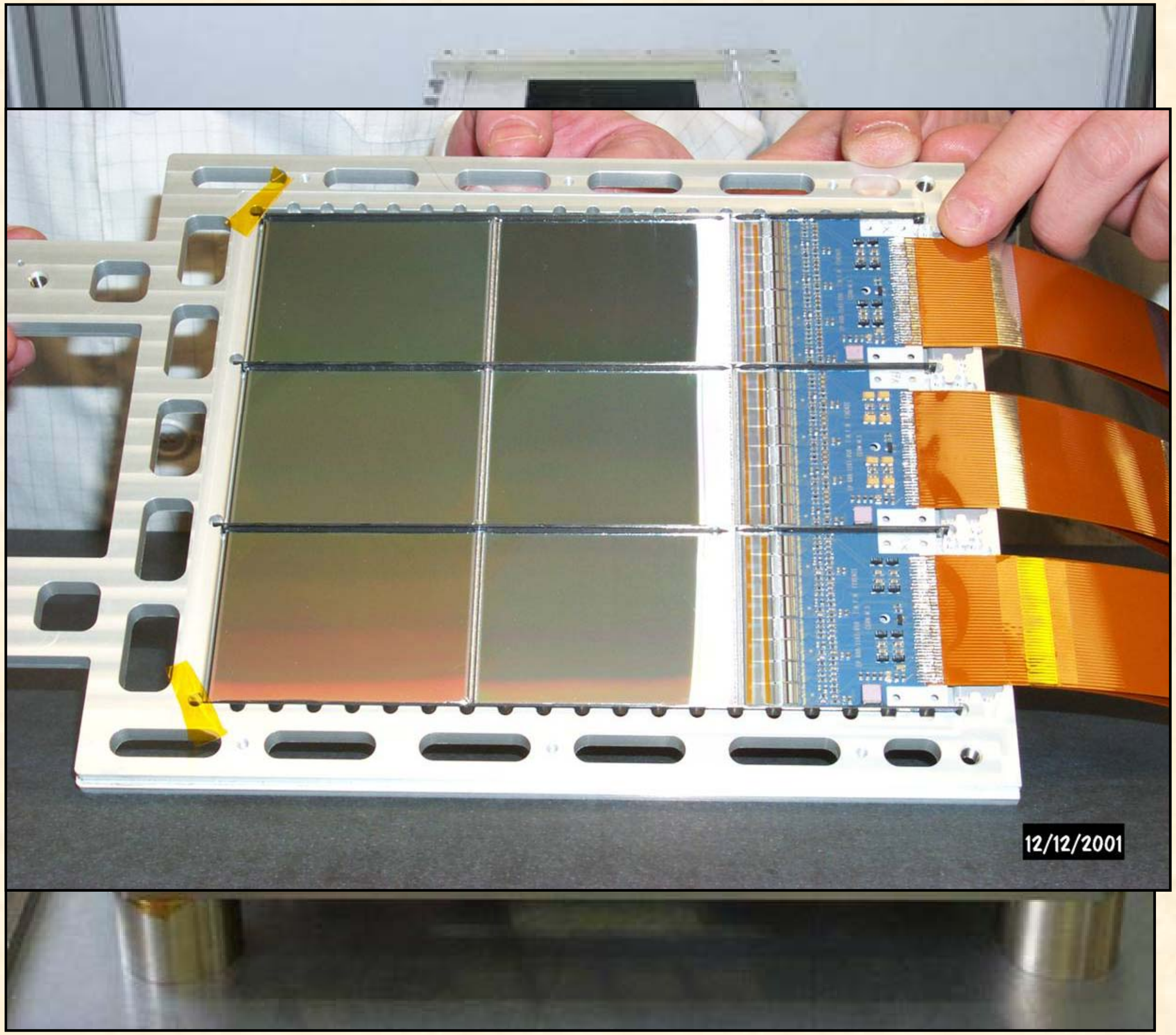


$dP/P^2 \sim 0.004$ ➔ MDR = 2.5 TV, h/e = 10^{-6} (ECAL +TRD)

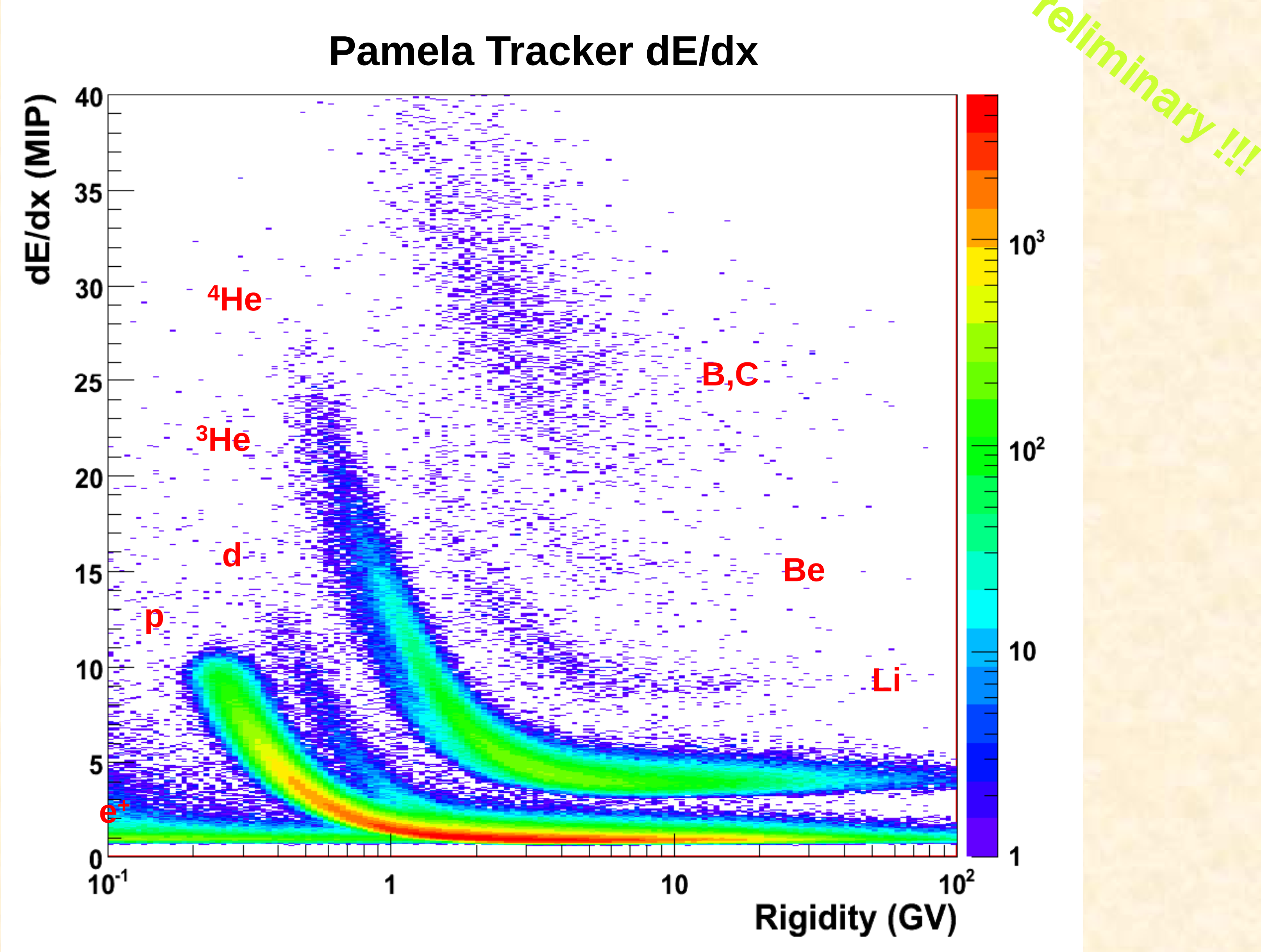
Pamela Magnetic spectrometer

Si Tracker + magnet

- Rigidity measurement
- 5 Nd-B-Fe magnet segments
- 0.48T at the centre
- (13.2 x 16.2 cm^2) x 44.5 cm high
- 6 planes of 300μm thick double sided Si detectors
- <3μm resolution in bending view
- +/-10 MIP dynamic range (VA1 chips)

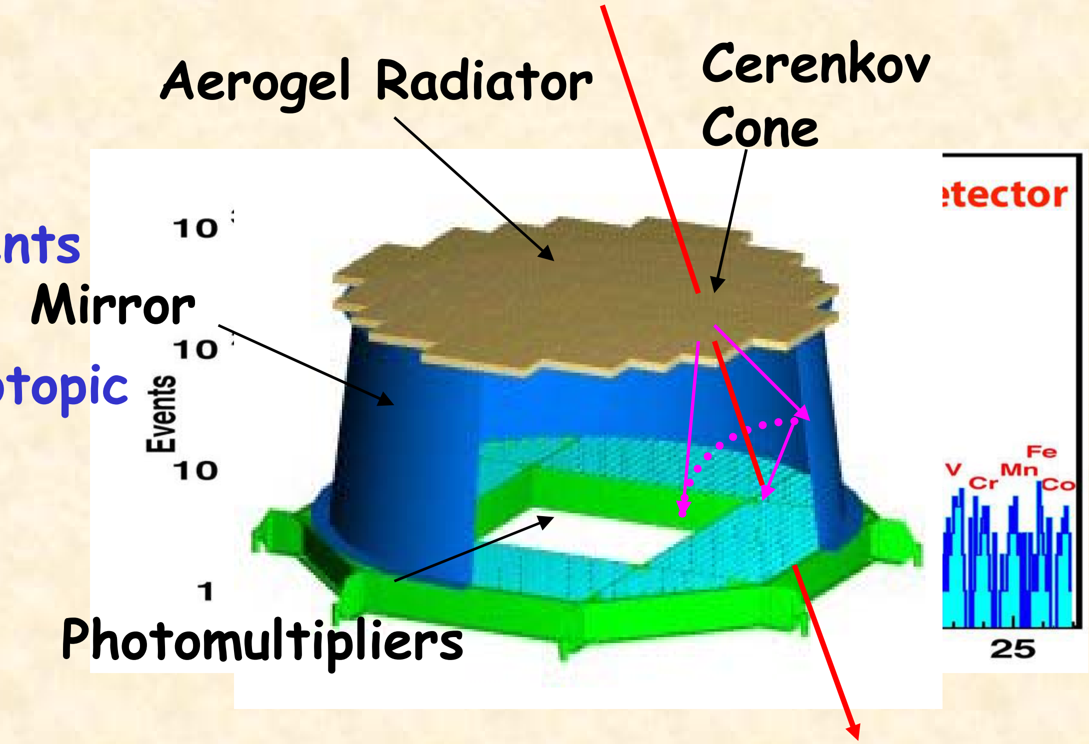


MDR ~ 1 TV/c


Pamela Tracker dE/dx
dE/dx (MIP)
Rigidity (GV)
4He
3He
d
p
e+
B,C
Be
Li
Preliminary !!!

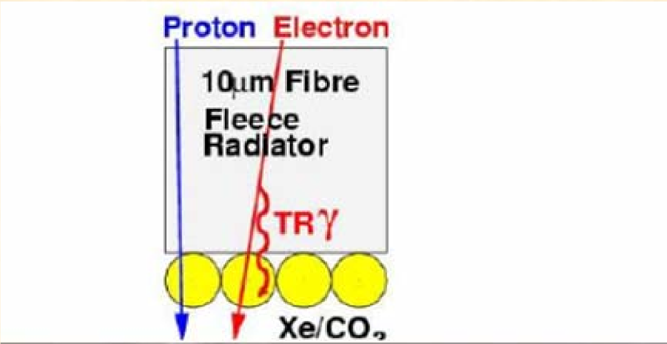
AMS02 RICH

- Proximity focus RICH
- 2 different radiators:
  - 2.7 cm Aerogel, n=1.05
  - 0.5 cm NaF, n=1.336
- Accurate Velocity Measurements via Opening Angle of Cerenkov Cone → Isotopic Separation.
- |Q| measurements up Z~ 30
- $\Delta\beta/\beta = (0.67 \pm 0.01) * 10^{-3}$ (test beam)
- Additional Particle Identification capability

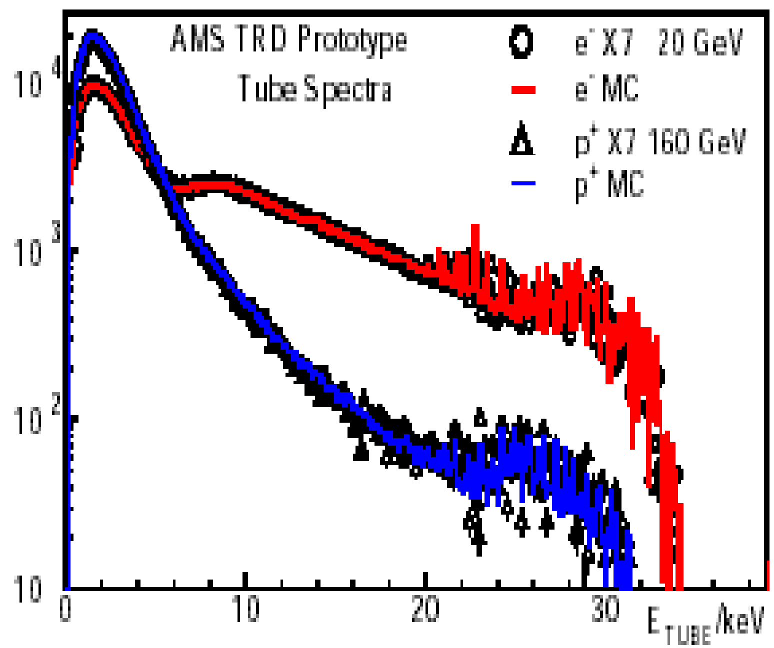


AMS02 TRD

- 20 layers,328 chambers,5248 tubes
- Mechanical Accuracy <100μm



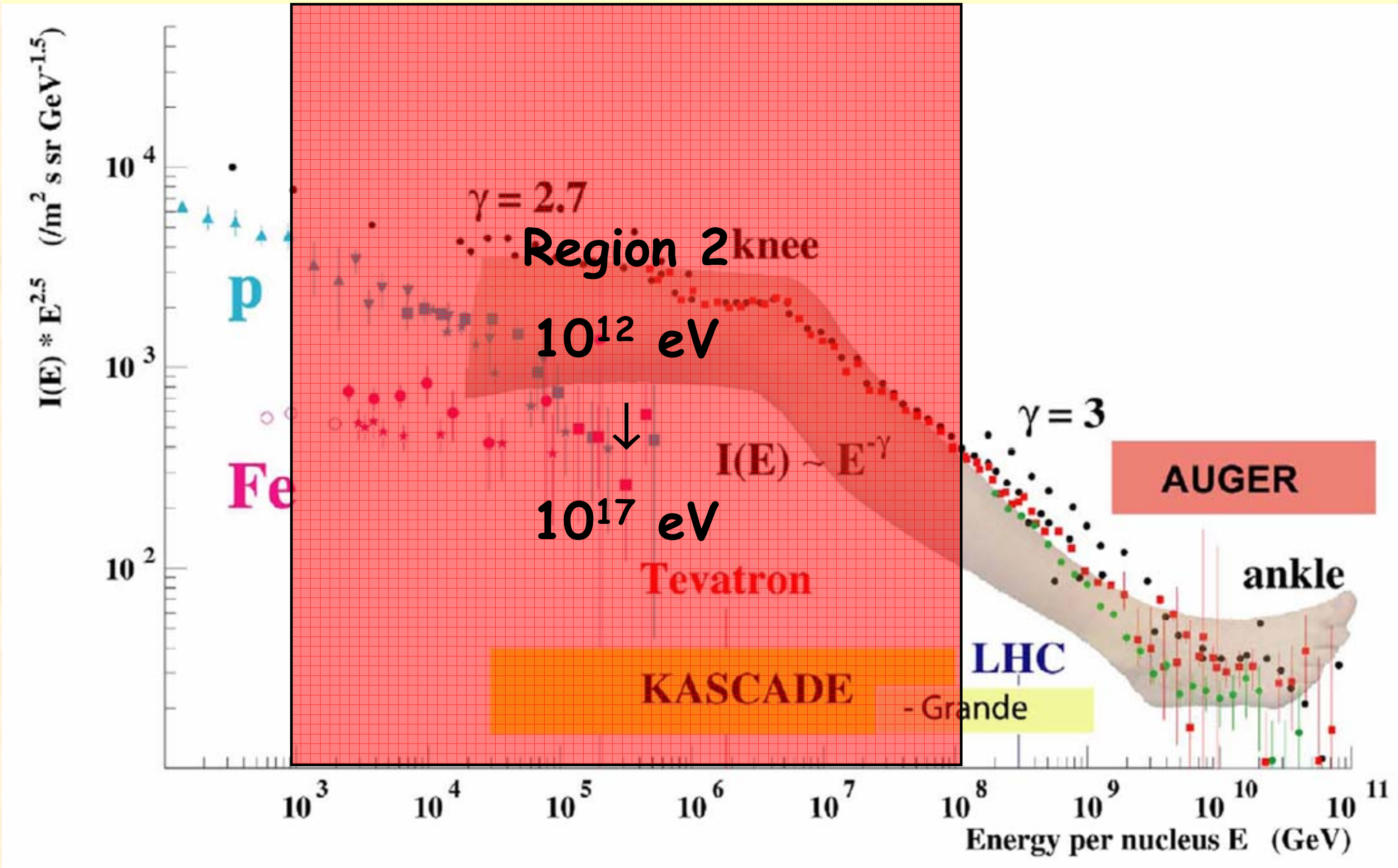
CERN beamtest with TRD prototype: proton rejection > 100 up to 250 GeV at electron efficiency 90% reached



Gas system in space!!!

Region 2: 10^{12} eV – 10^{17} eV

- Very interesting region (astrophysics!!!)
- Knee around 10^{15} – 10^{16} eV
- Transition region between direct and indirect measurements



What is the knee?

First change in slope at $4*10^{15}$ eV total energy

It should be related to some change in the propagation or acceleration of the CR

- Escape from the galaxy?
- Differents cut-off for different elements?
- Rigidity (η=p/Z) dependent cut off?

Which is the composition of the CR at the knee?

Heavy or Light CR?

Direct measurements (Balloon)

Energy and Z

Direct measurements are possible up to ≅ 10^{15} eV

Techniques similar to the 'Region 1'

Bigger acceptance, simpler detectors

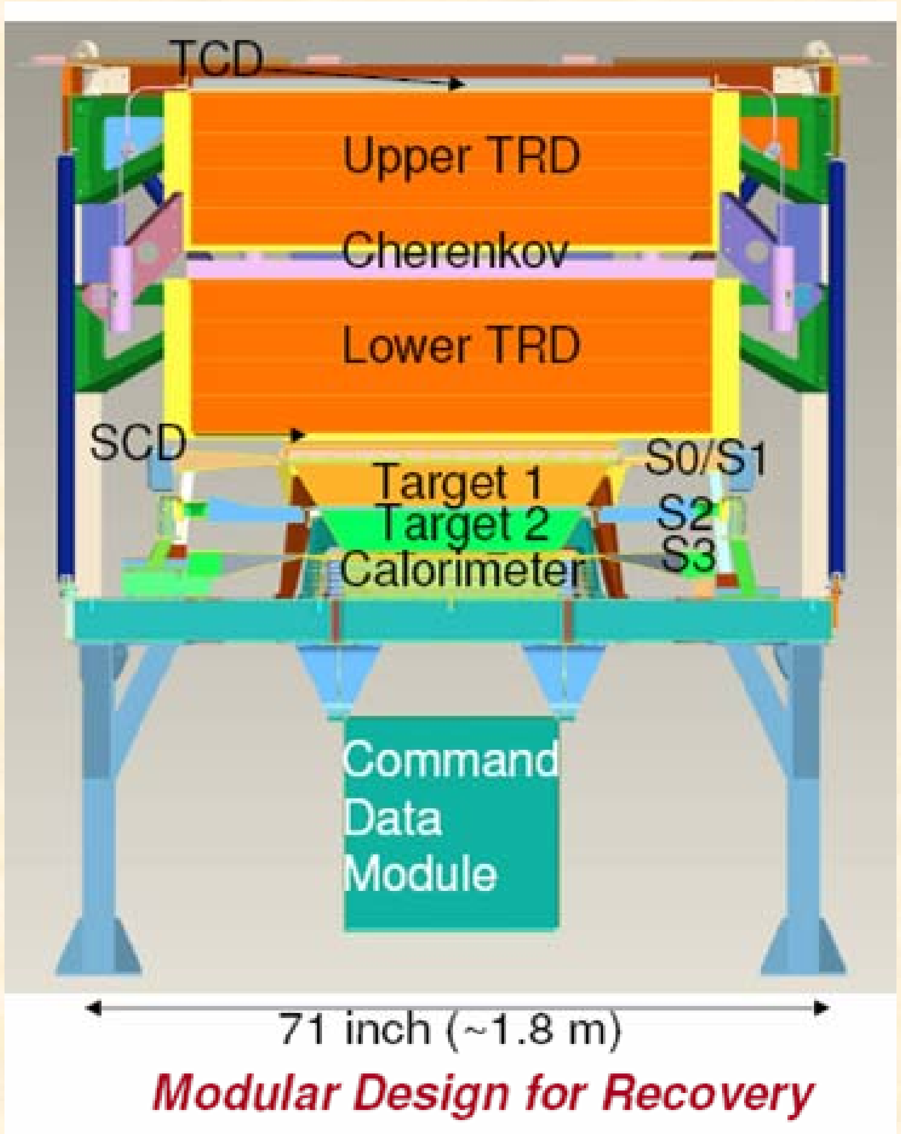
groups	observables	energy range
JACEE(1980-1995?)	p, He, …, Fe;	TeV – PeV/p
RUNJOB(1995-)	p, He, …, Fe;	TeV – PeV/p
	ultra-heavy (Z ≅ 30);	1-10 GeV/n
ATIC(2001-2002)	p, He, …, Fe;	10 GeV-100 TeV/p
TRACER(2003-2006)	B → Fe	1-1000 GeV/n

CREAM

- Complementary charge measurements:
  - Timing based Charge Detector
  - Cherenkov Counter
  - Pixellated Silicon Charge Detector
  - Scintillating Fiber hodoscopes

- Complementary energy measurements:
  - TRD (velocity for Z>2)
  - Si-W Calorimeter (energy for all Z)

- Large acceptance
  - 2.2 $m^2 sr$



Direct measurement of Energy (1 TeV→1000 TeV)
Measurement of Z (p→Fe)

70 days of flight from 2 launches

Seo et al., Proc. 29th ICRC, Pune, 10, 185-198, 2005; Seo et al. COSPAR 2006

CREAM-I

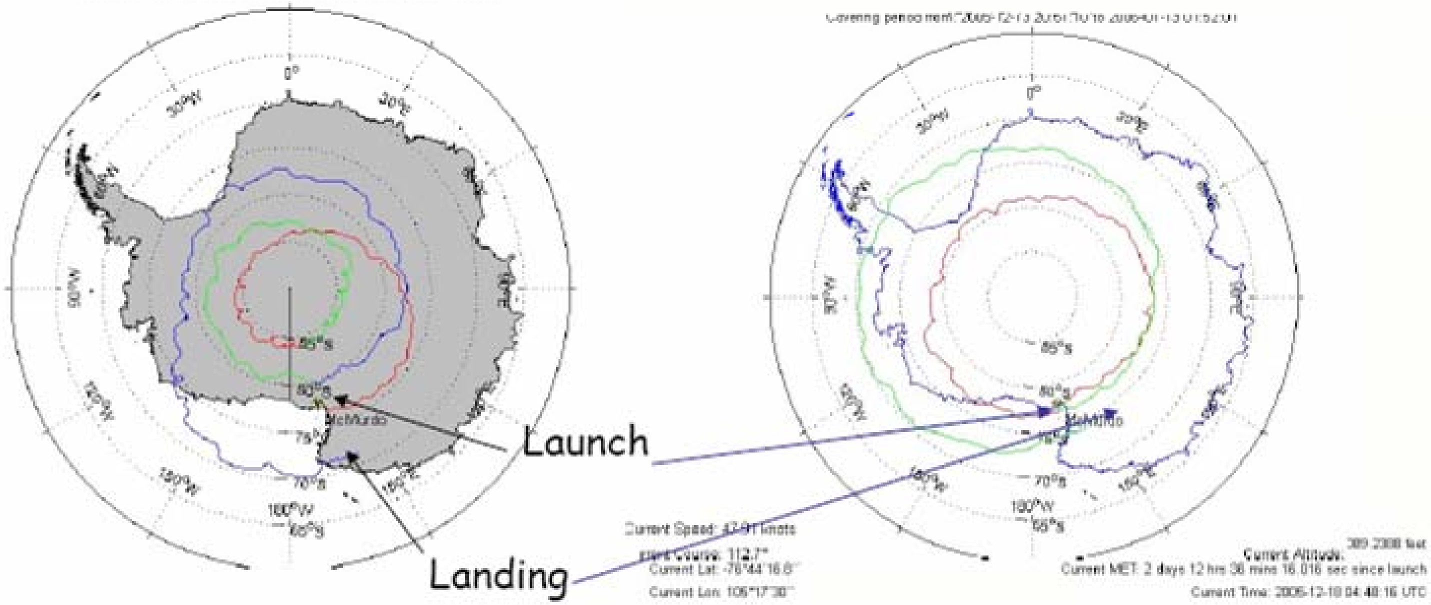
12/16/04 - 1/27/05

Record breaking 42 days

CREAM-II

12/16/05-1/13/06

28 days



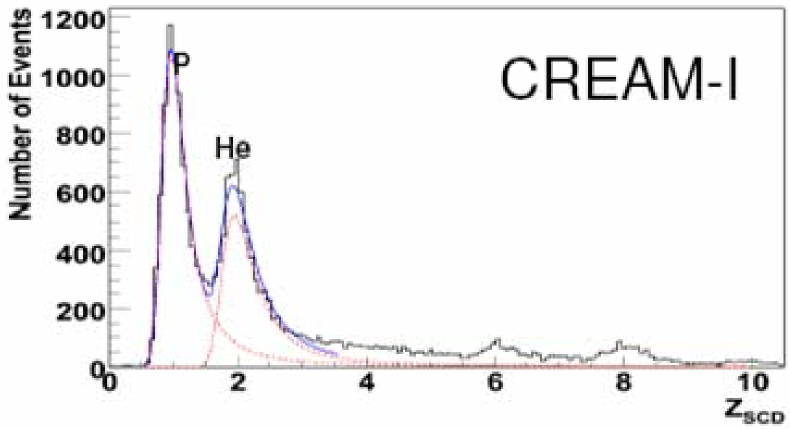
42 M science events
(60 GB data)

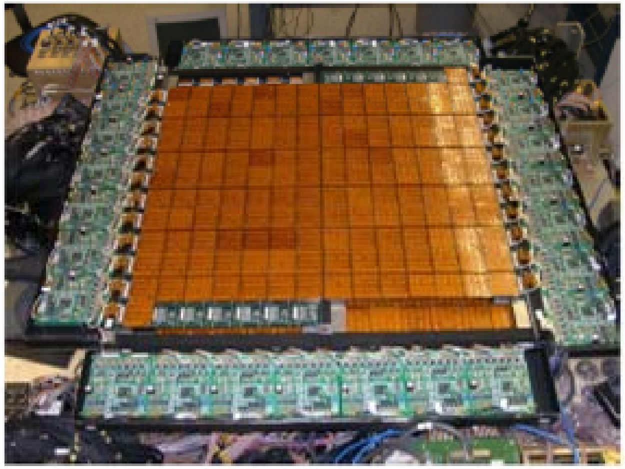
27 M science events
(57 GB data)

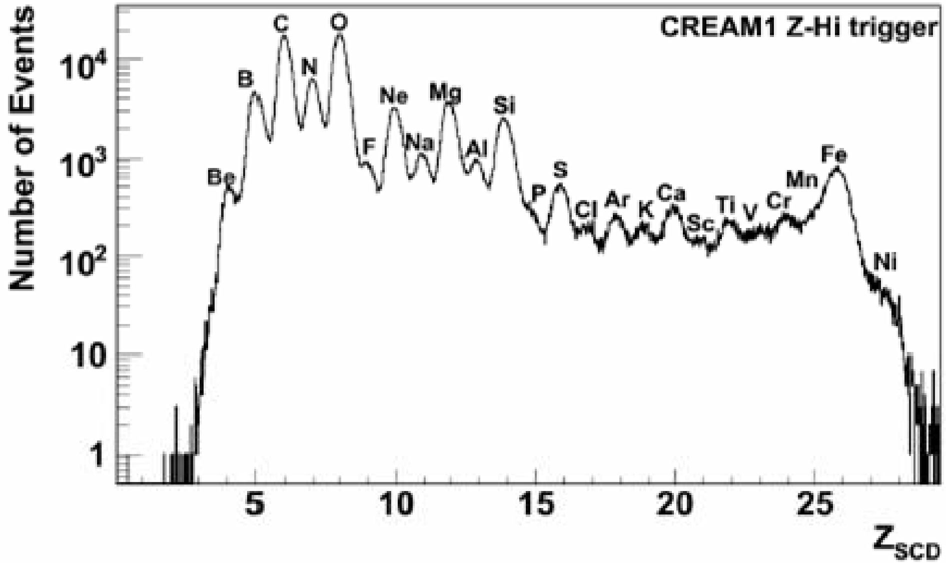
From Eun-Suk Seo, CRHEU07

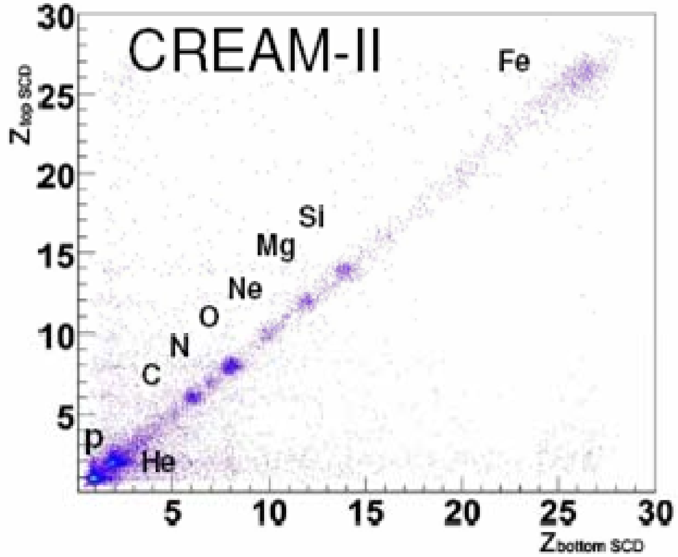
Charge Measurements: 2 layers of SCD

Park et al, Nucl. Instr. and Meth. A , 570, 286-291, 2007









From Eun-Suk Seo, CRHEU07

Indirect measurements

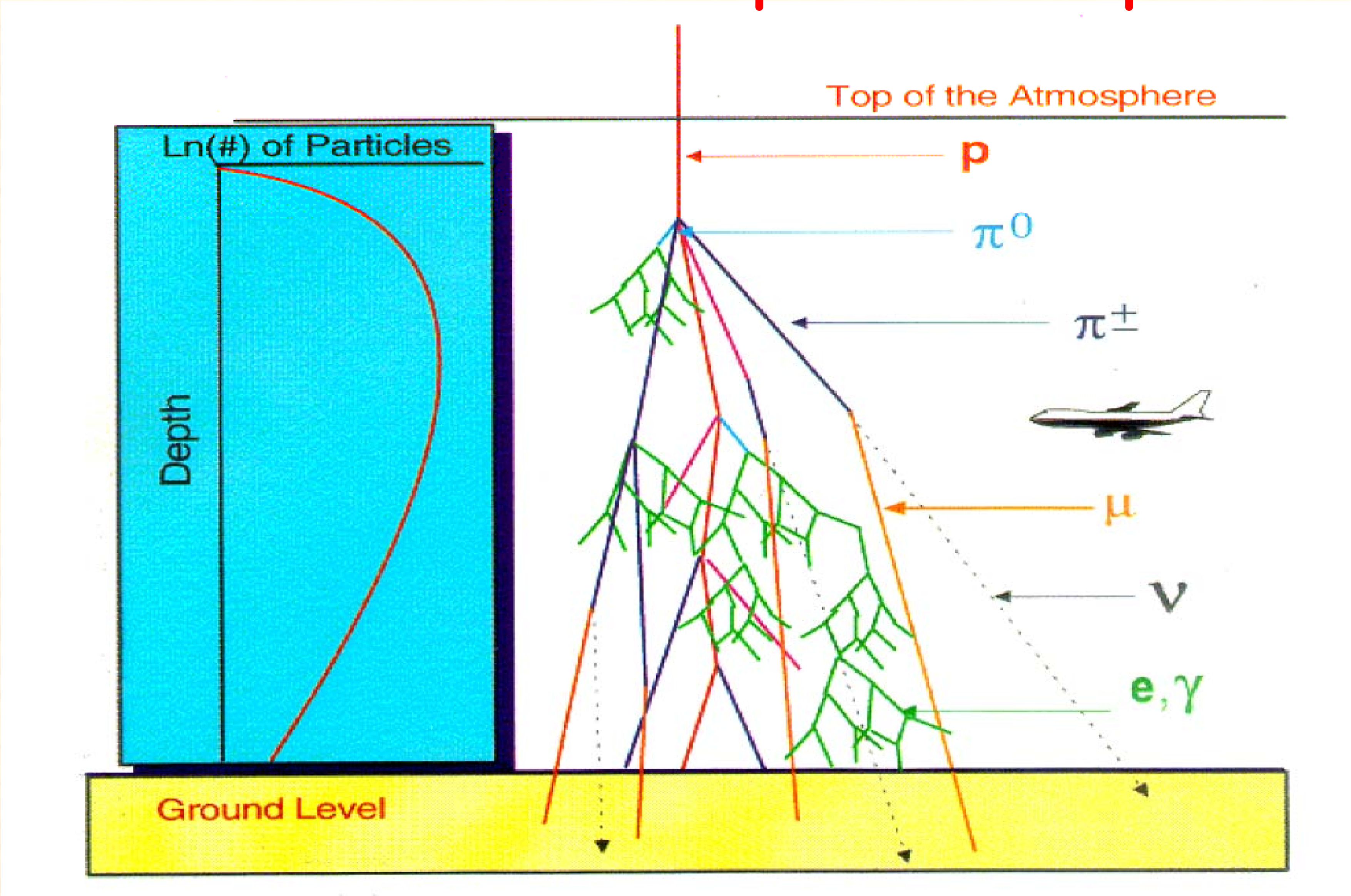
If the energy of the CR is too big to be directly measured, indirect measurements are necessary.

The atmosphere is used as 'PASSIVE CALORIMETER'

Object of the measurements:

1. Charged particles: $\mu^{\pm}$, $e^{\pm}$, p (Extended Air Shower detectors, EAS)
2. Cherenkov light
3. Fluorescence light

Charged component: EAS vs Atmospheric Depth



....

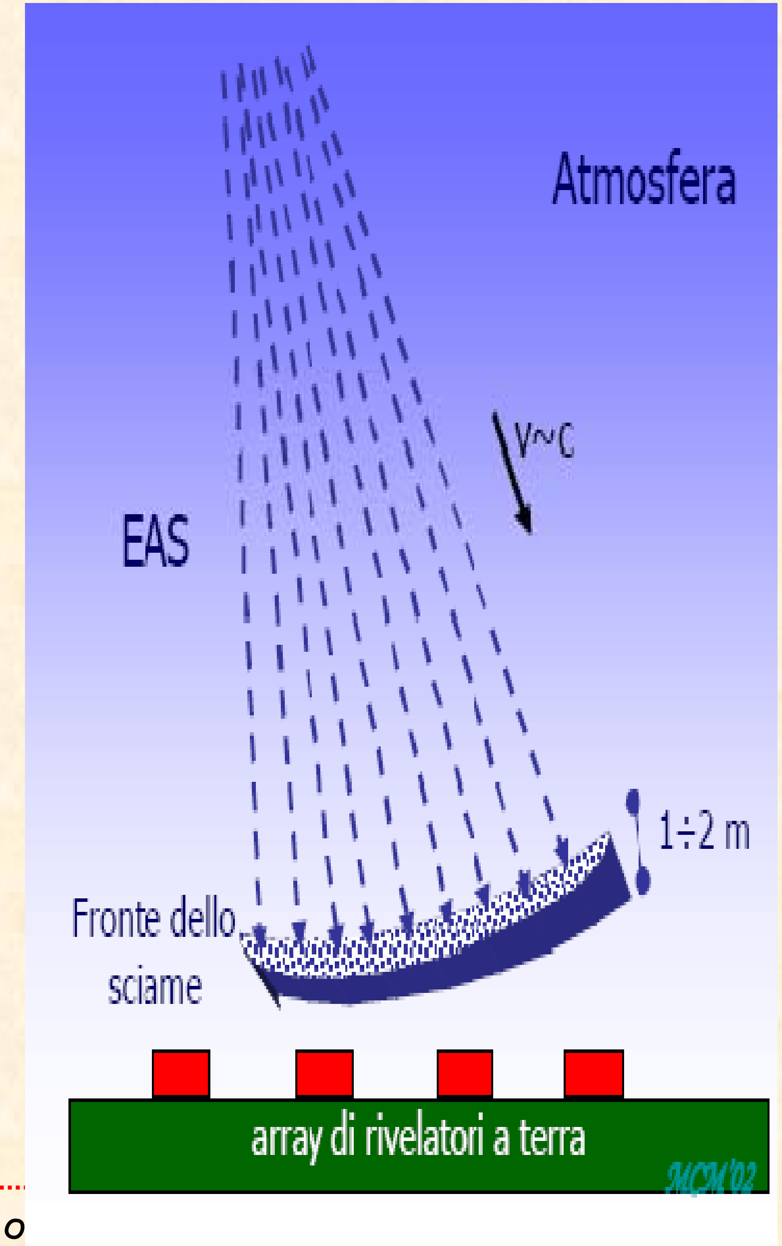
Charged component EAS Detection

Density Sampling

the particle density is observed in an array of detectors (sampling), and it is used to identify the shower core and the total number of particles in the shower → reconstruction of the energy of the primary CR

Fast Timing

the arrival direction of the primary CR (shower's axis) is obtained by measuring the different arrival times of the particles on the different detectors of the array



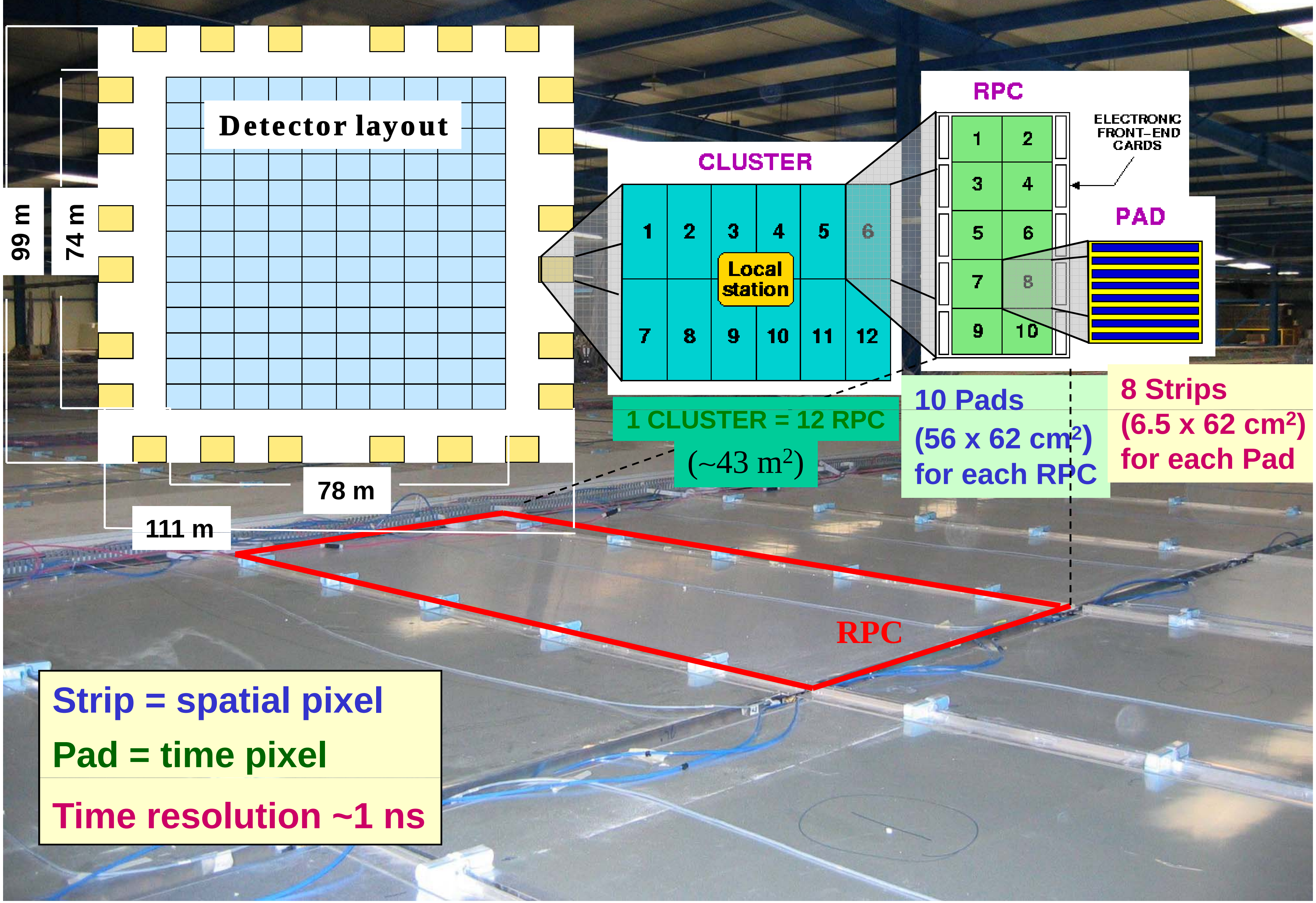
The ARGO-YBJ experiment

High Altitude Cosmic Ray Laboratory @ YangBaJing

Site Altitude: 4,300 m a.s.l. , ~ 600 g/cm^2

Site Coordinates: longitude 90° 31’ 50” E, latitude 30° 06’ 38” N

ARGO-YBJ detector Hall



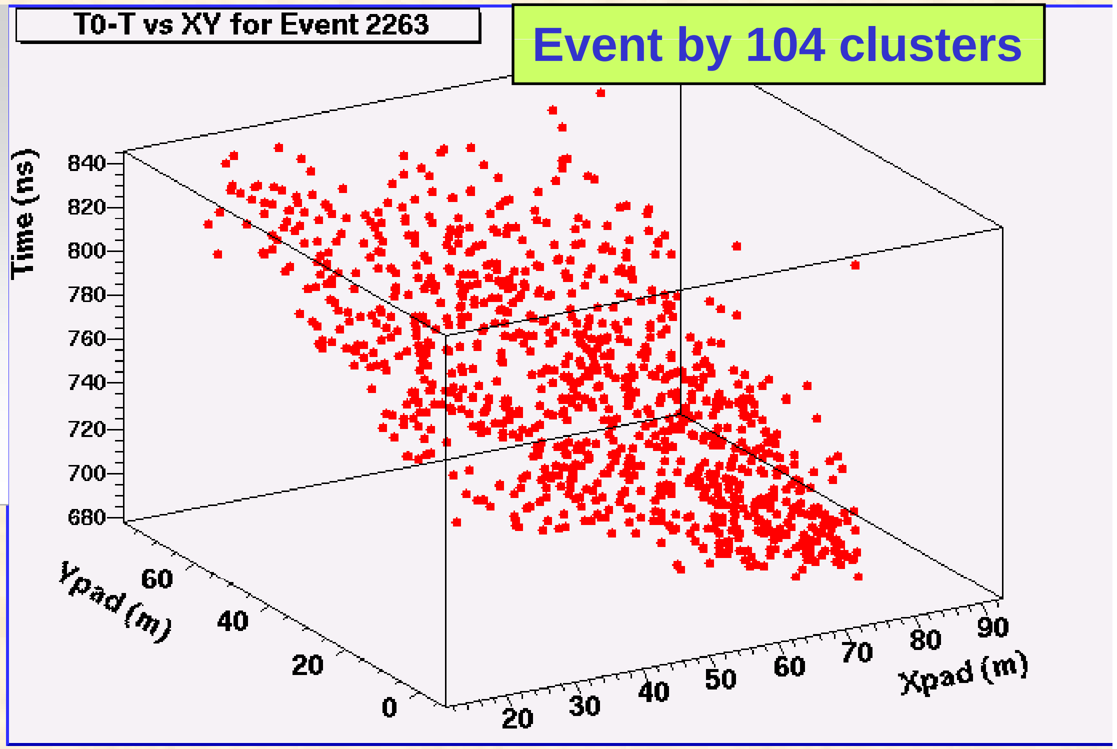
Detector performance

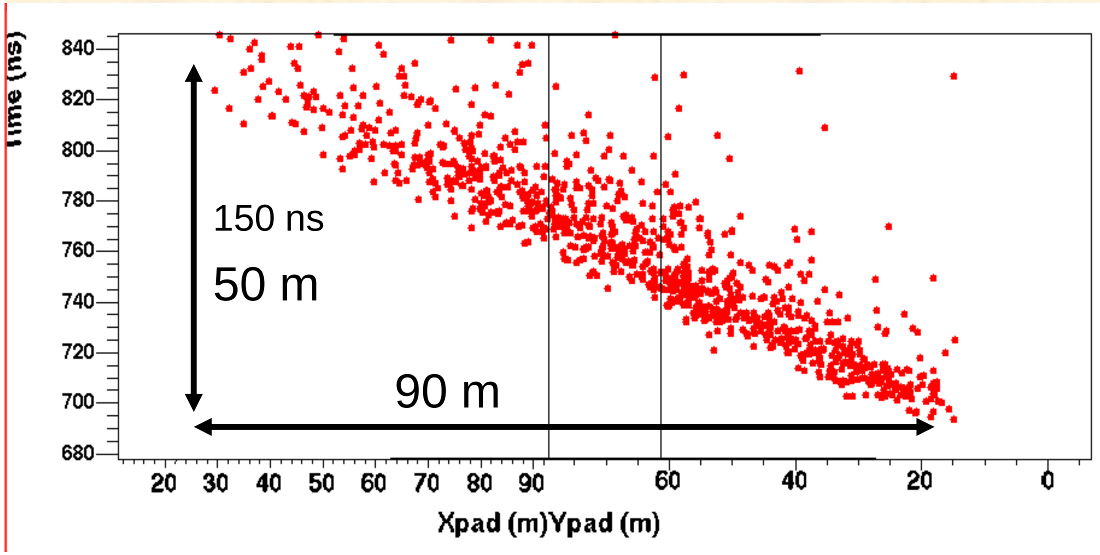
High space-time granularity
+ Full coverage technique
+ High altitude

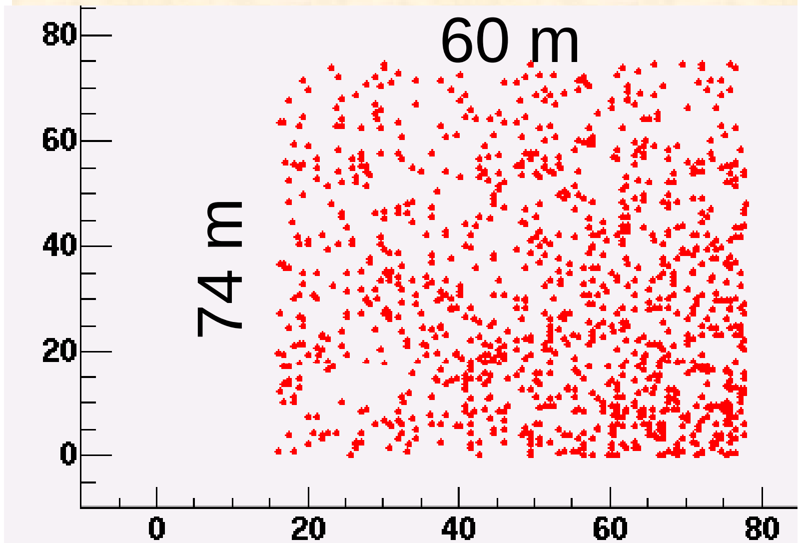
⇓

a unique way to study EAS

- Full space-time reconstruction
- Shower topology
- Structure of the shower front





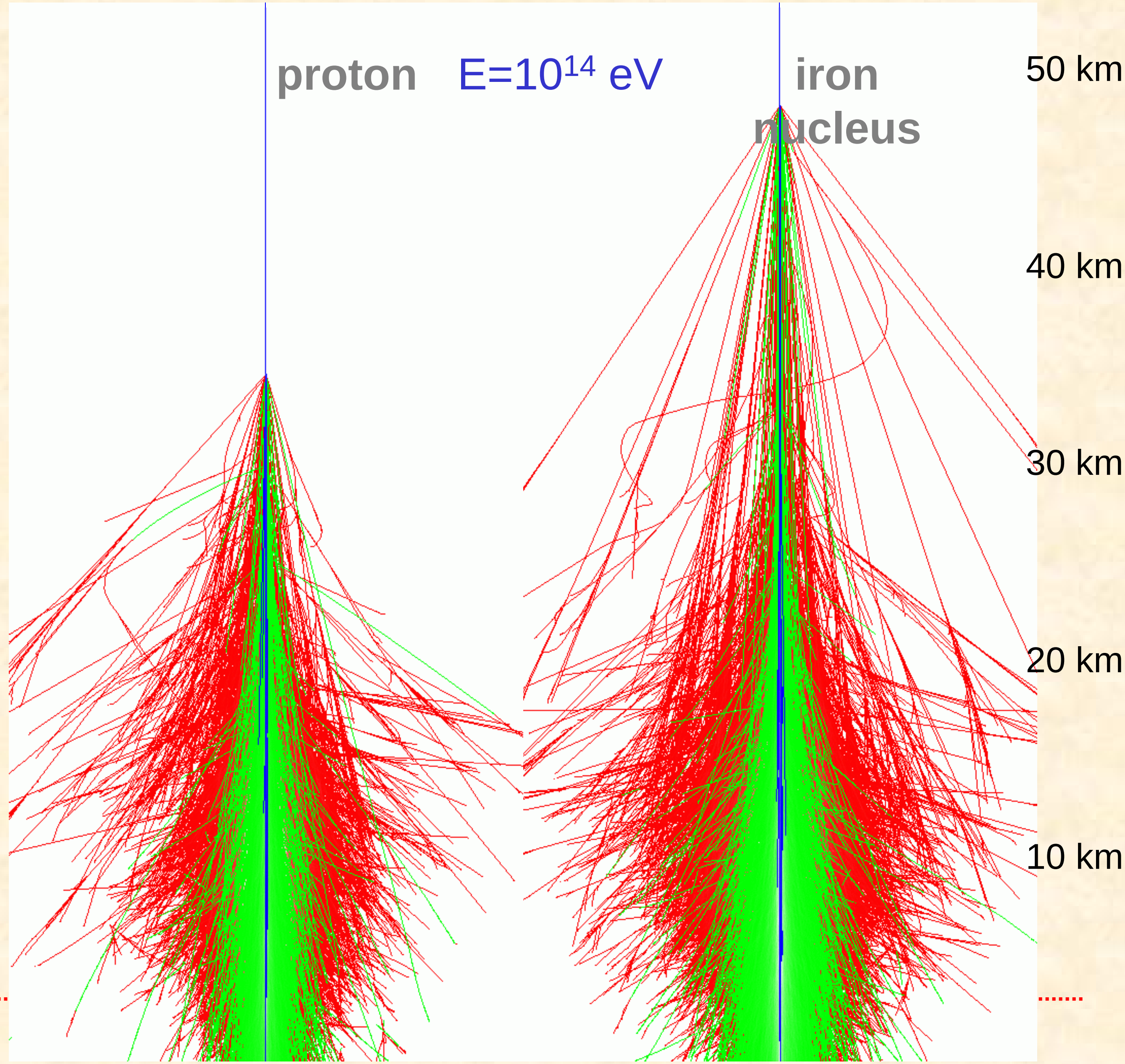


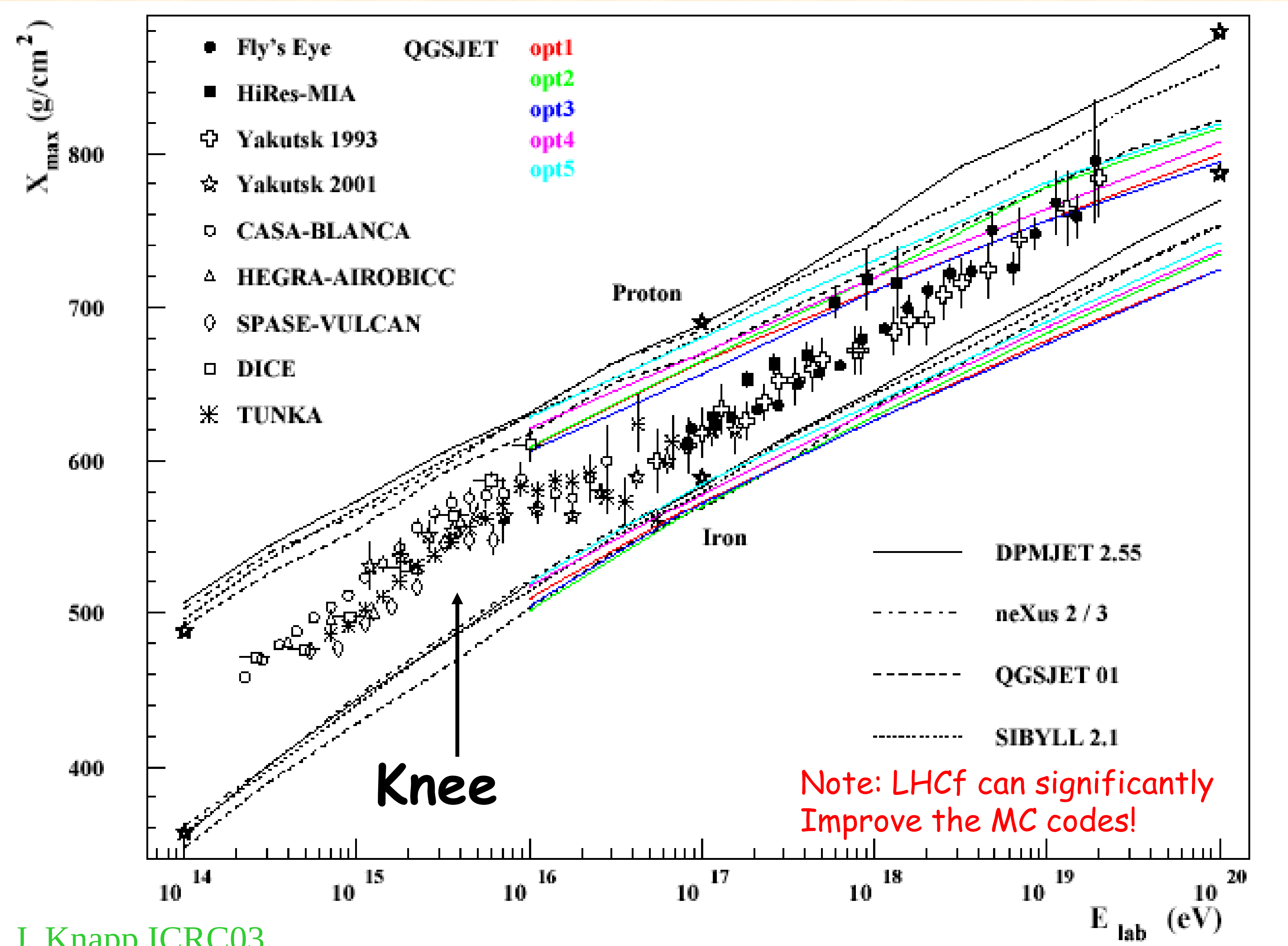
Next step: We want to identify the primary CR! Light or heavy?

CORSIKA Simulation

QGSJET/EGS4

e/γ
μ
h





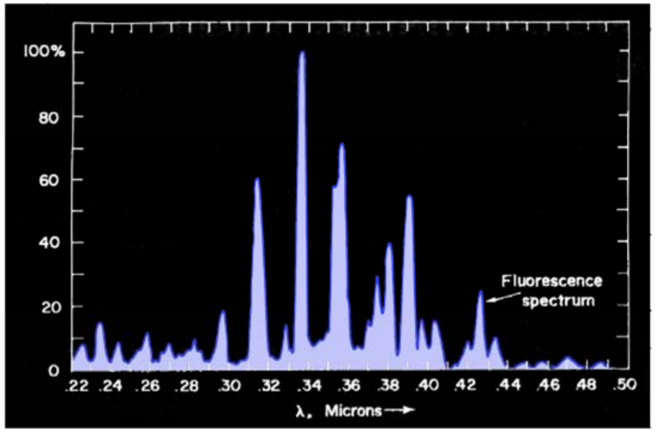
J. Knapp ICRC03

How can we measure X_{max}?

- We can profit of the different components of the shower development!
  - Charged components
  - Cherenkov component
  - Fluorescence component

- Cherenkov light produced by the ultrarelativistic component of the shower (mainly $e\pm$)
- Fluorescence light produced by the de-excitation of the N2 molecules in the air after the excitation induced by the shower.

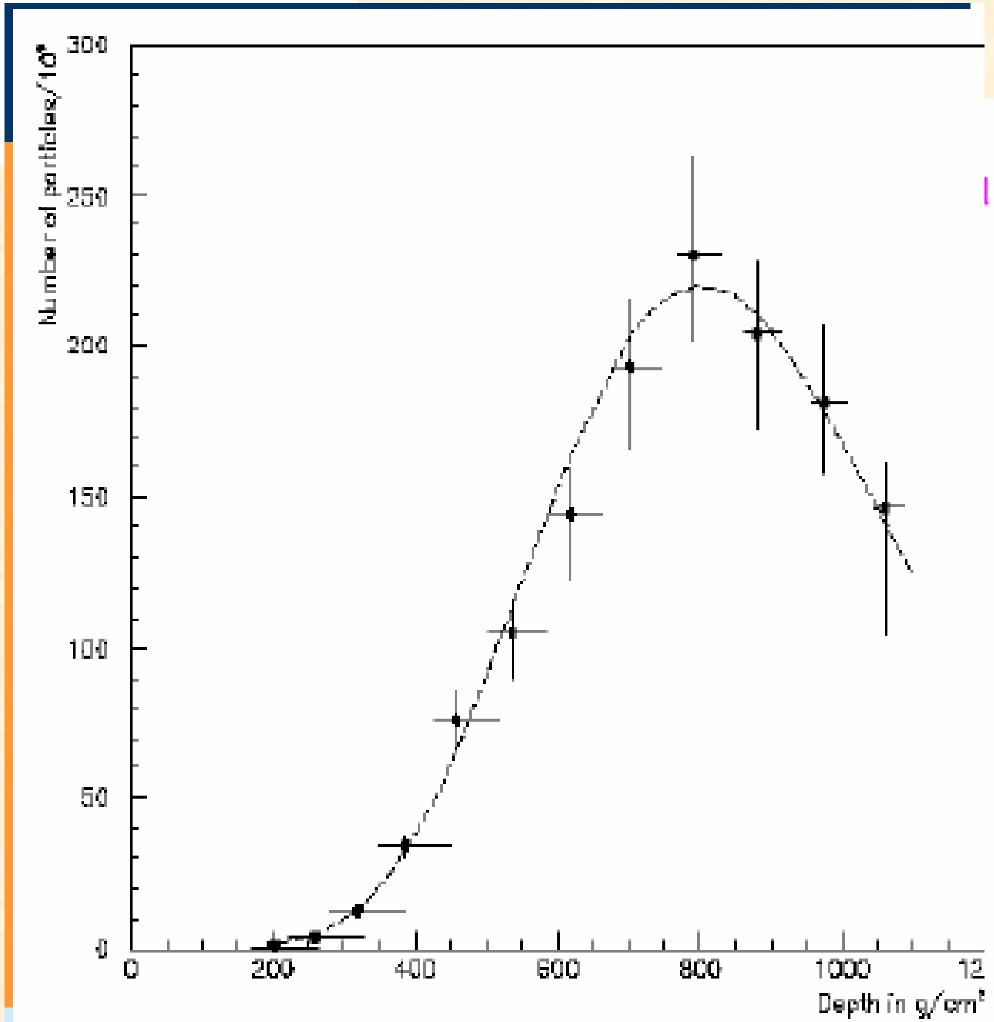
The shower can be 'followed' in it's 2d or 3d development



Fluorescence Spectrum

fluorescence yield between 300 - 400nm

approx. 4 photons per shower particle per metre of track



1. Time information
2. Amplitude information
3. Observing direction

↓

Longitudinal development of the shower

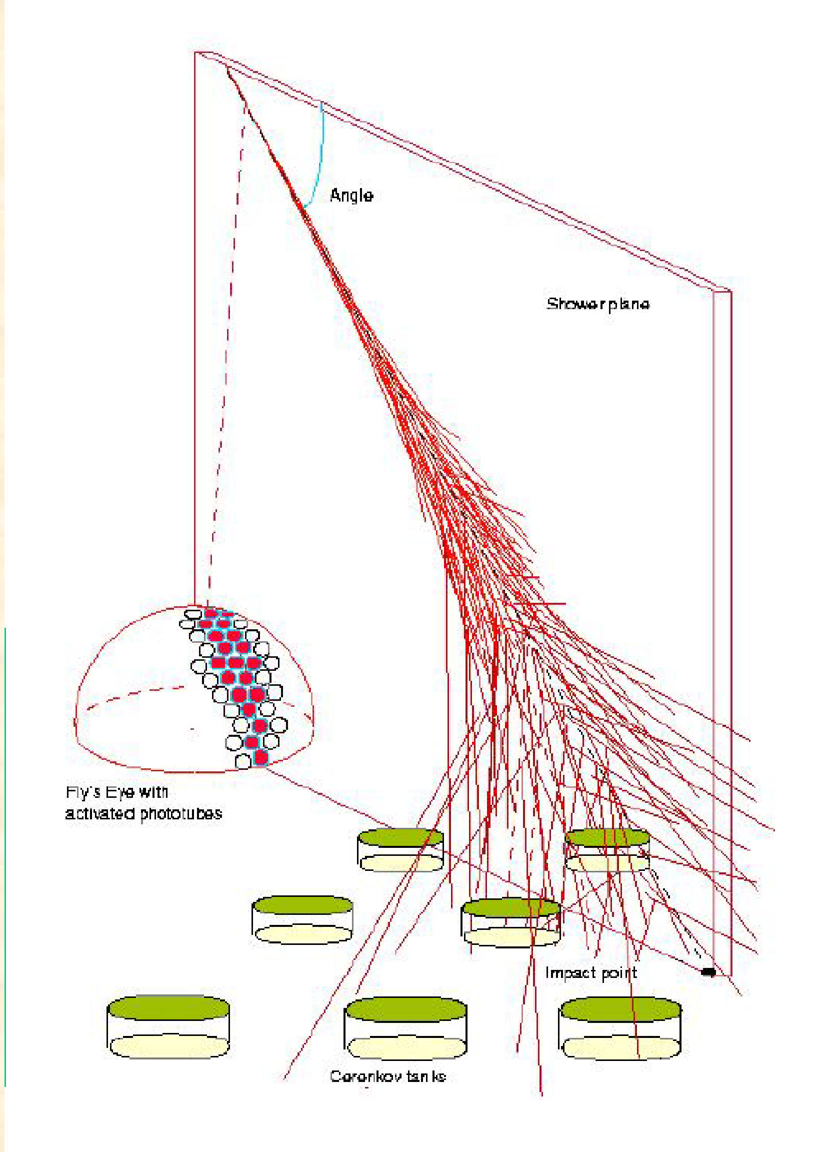
Disadvantages:
- Dark nights
  - Reduced live time
- Strong dependance on weather conditions
  - Monitoring is necessary
  - Reduced live time

'Complete' EAS detection

Fluorescence detector to reconstruct the longitudinal development

Array of Cherenkov detectors for the lateral distribution measurement ($\alpha \cong 6^0$).

Array of charged particle detectors to sample the shower



Summary of Region 2

1. The knee is not fully understood
2. Direct measurements are energy limited
3. Indirect measurements are not very precise but can profit of the different measurements that can be done (charged particles, Cherenkov, Fluorescence) to identify the primary CR

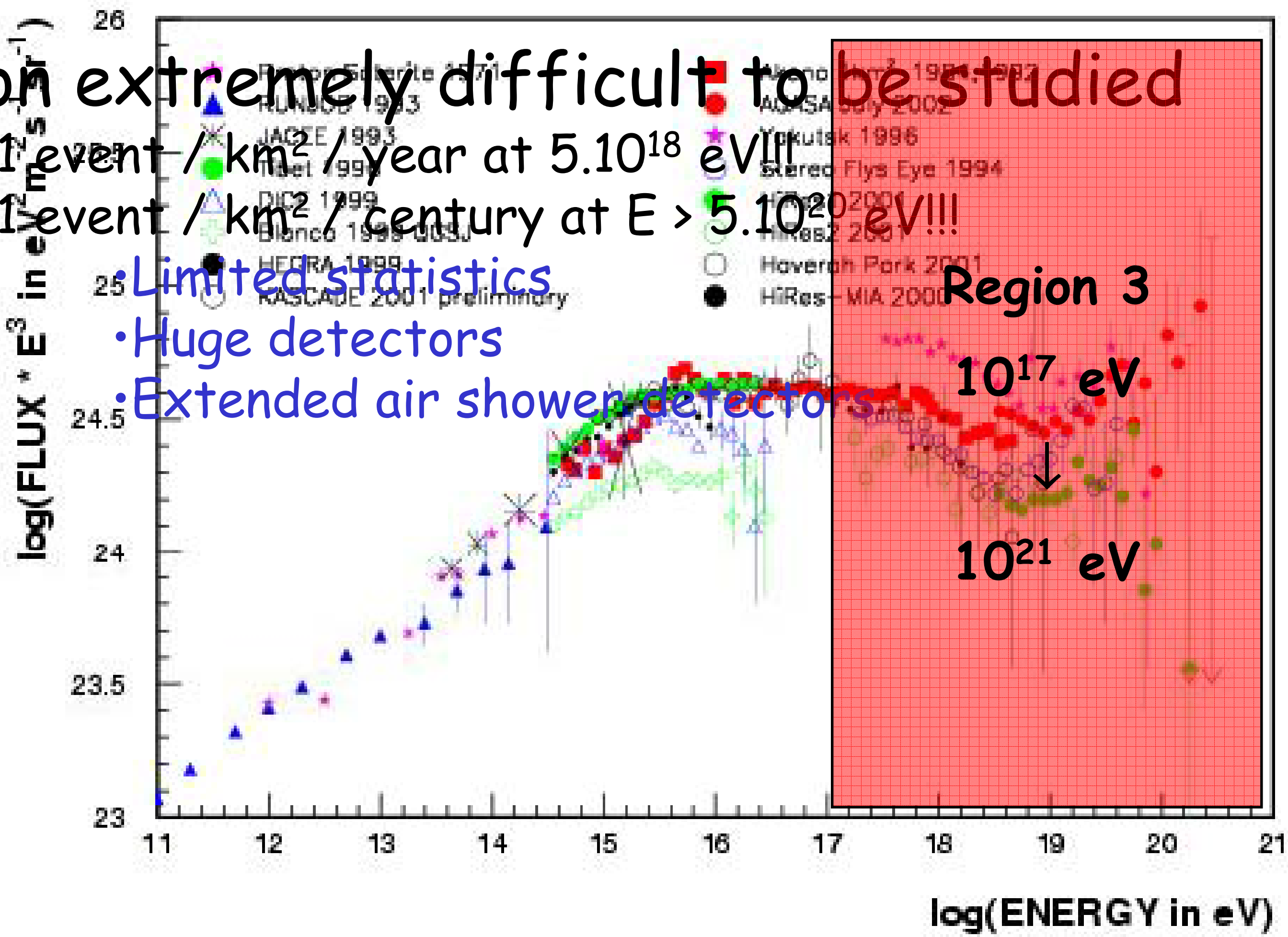
Region 3: 10^{17} eV – 10^{21} eV (UHECR)

Region extremely difficult to be studied

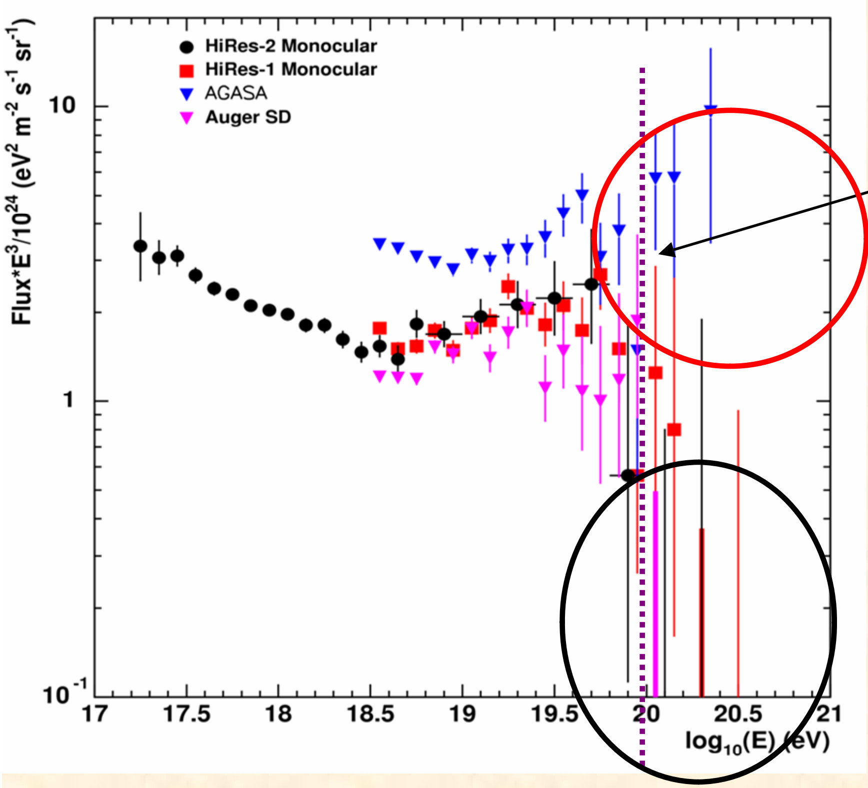
Flux ≅ 1 event / km² / year at 5.10^{18} eV!!!

Flux ≅ 1 event / km² / century at E > 5.10^{20} eV!!!

- Limited statistics
- Huge detectors
- Extended air shower detectors



GZK cut off



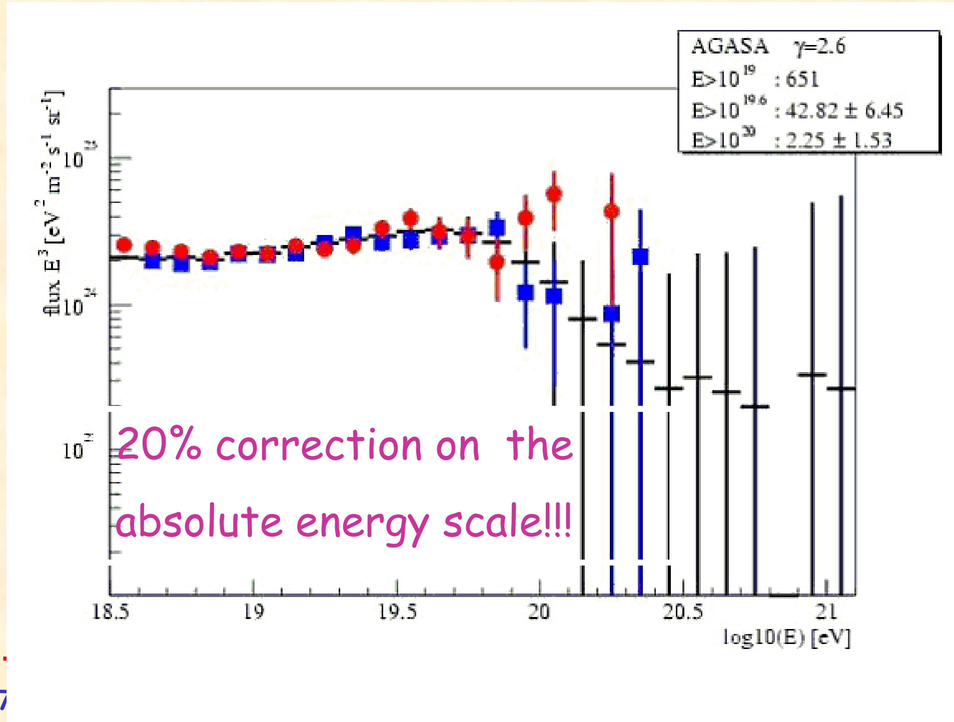
GZK cutoff: 10^{20} eV

$p\gamma(2.7K) \rightarrow \Delta \rightarrow N\pi$

super GZK events?!?

AGASA reports 18% systematic uncertainty in energy determination. 10% of systematic is due to interaction model.

Accelerator calibration is necessary: LHCf



Current experimental status

At least 5 'old' experiments observed events with $E > 10^{20}$ eV (Volcano Ranch, Haverah Park, Yakutsk, Fly's Eye/HiRes, Agasa)

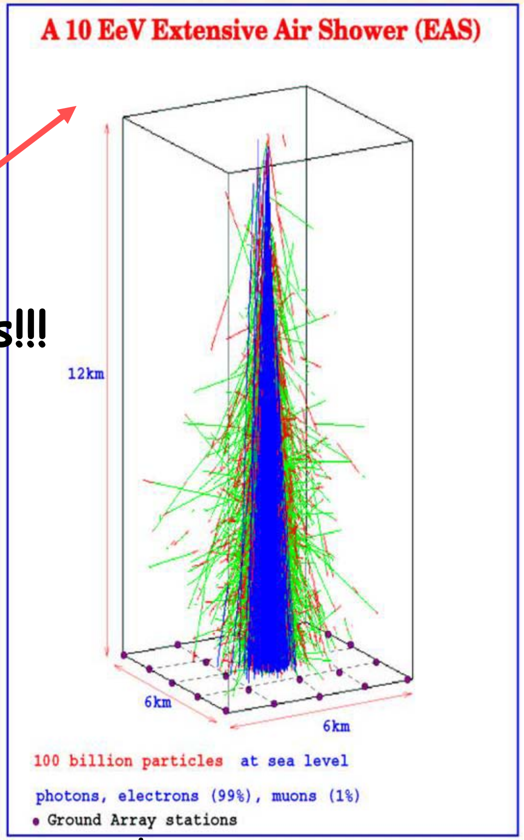
$$\int_{E=10^{19}eV}^{\infty} N(E)dE \cong 100$$

$$\int_{E=10^{20}eV}^{\infty} N(E)dE \cong 10$$

Number of events observed up to now

10^{19} eV

10^{11} particles!!!



However:

1. the energy reconstruction method critically depends on the Monte Carlo codes
2. Statistics is very limited
3. **Hybrid technique + Huge acceptance is mandatory!**

Pierre Auger Observatory

>250 researchers from 17 Countries:

Italian AUGER Groups:

Catania, L'Aquila, Lecce, Milano, Napoli, Roma, Torino

PIERRE AUGER OBSERVATORY

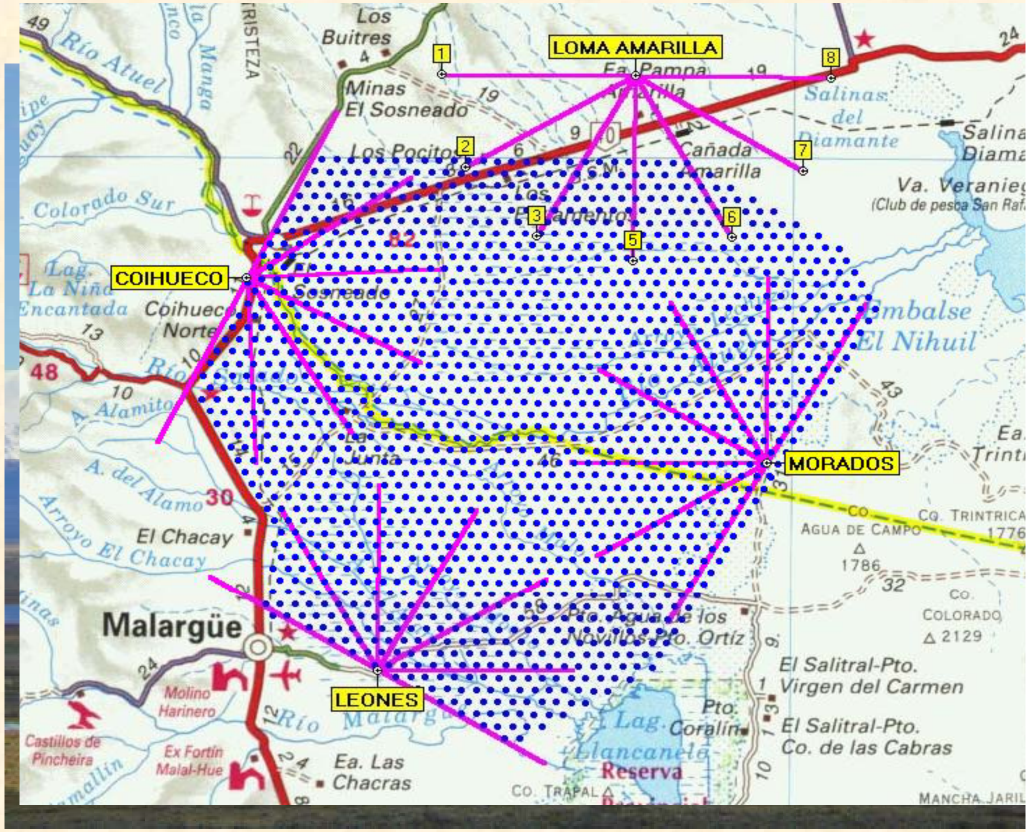
- Full sky coverage
  - South – Argentina Funded
  - North – Not Yet Funded
- Hybrid detection technique
  - 1600 particle detectors (Water Cherenkov) over 3000 km^2
  - 4 Fluorescence Detectors
- It will Measure Direction, Energy, & Composition of CR
- Very high statistics!
  - ~ 60 events/yr E > 10^{20}eV
  - ~ 6000 events/yr E > 10^{19}eV

SOUTH Observatory

- Low human activity
- Excellent climate

35° S latitude
69° W longitude
~1.4 km a.s.l..
X =875 g/cm²

Malargue, Mendoza, Argentina

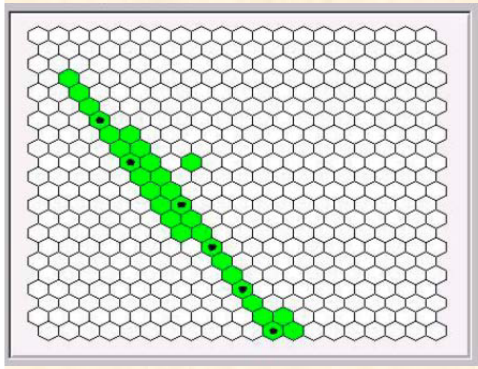


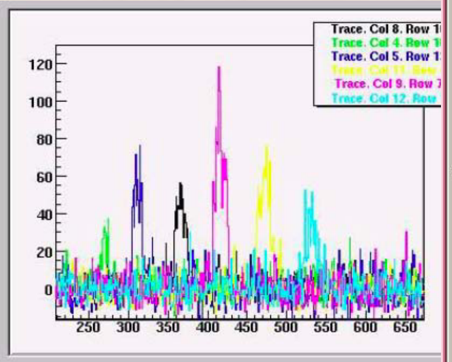
area 3000 Km²

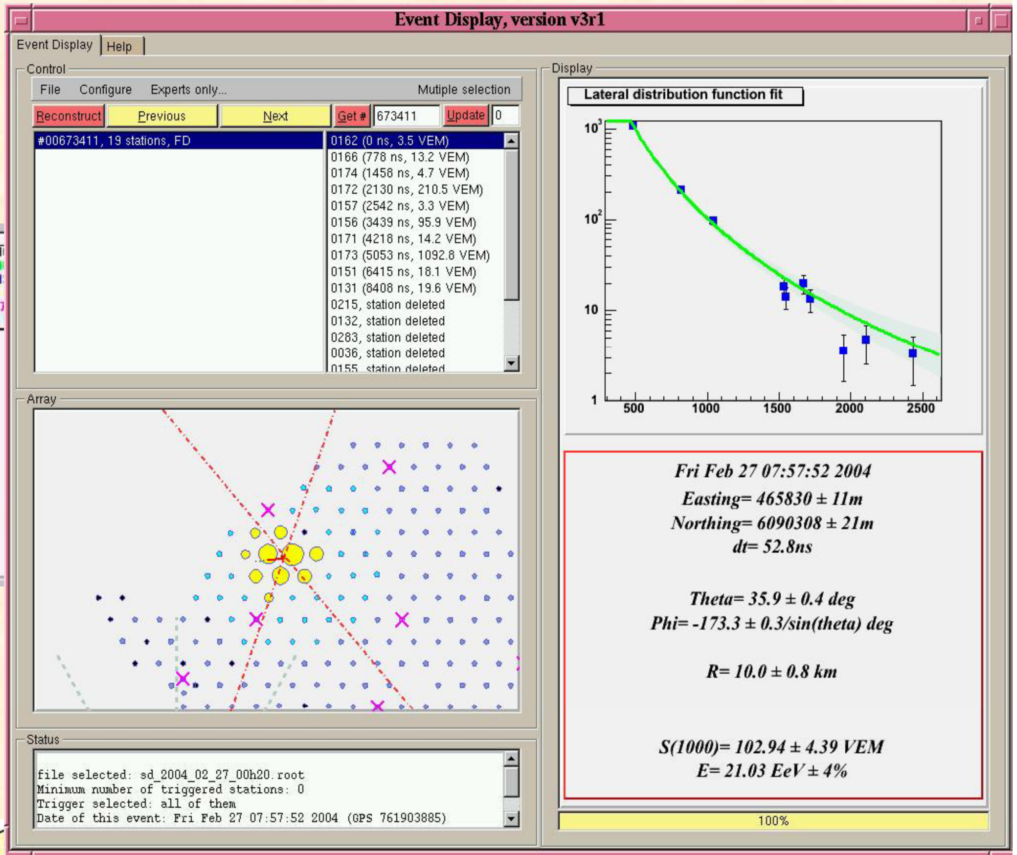
aperture 7350 Km² sr

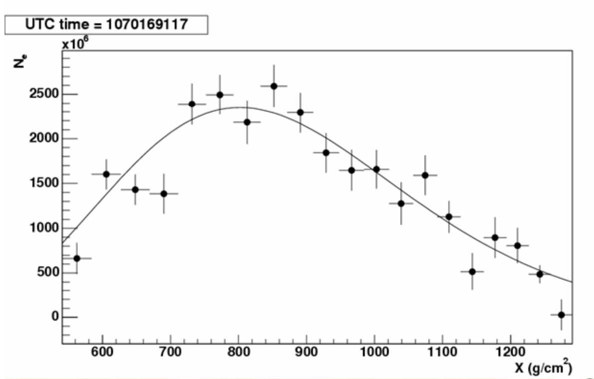
- **4 Eyes for the FD (6 telescopes)**
- **1600 Cherenkov detectors, Step: 1.5 Km**

A typical hybrid event





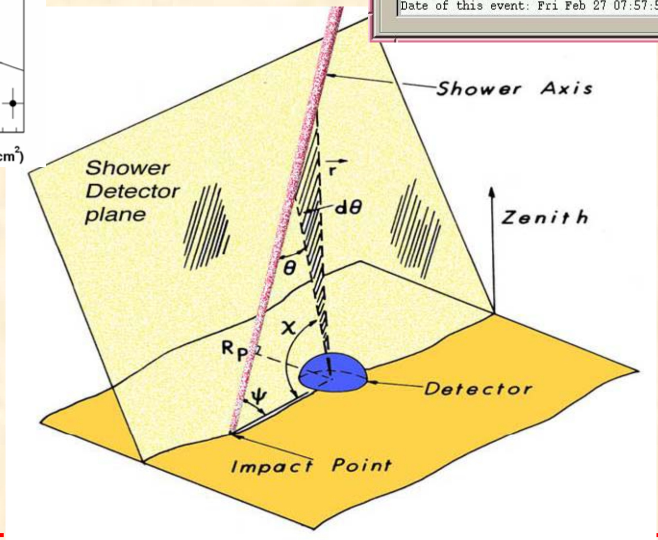




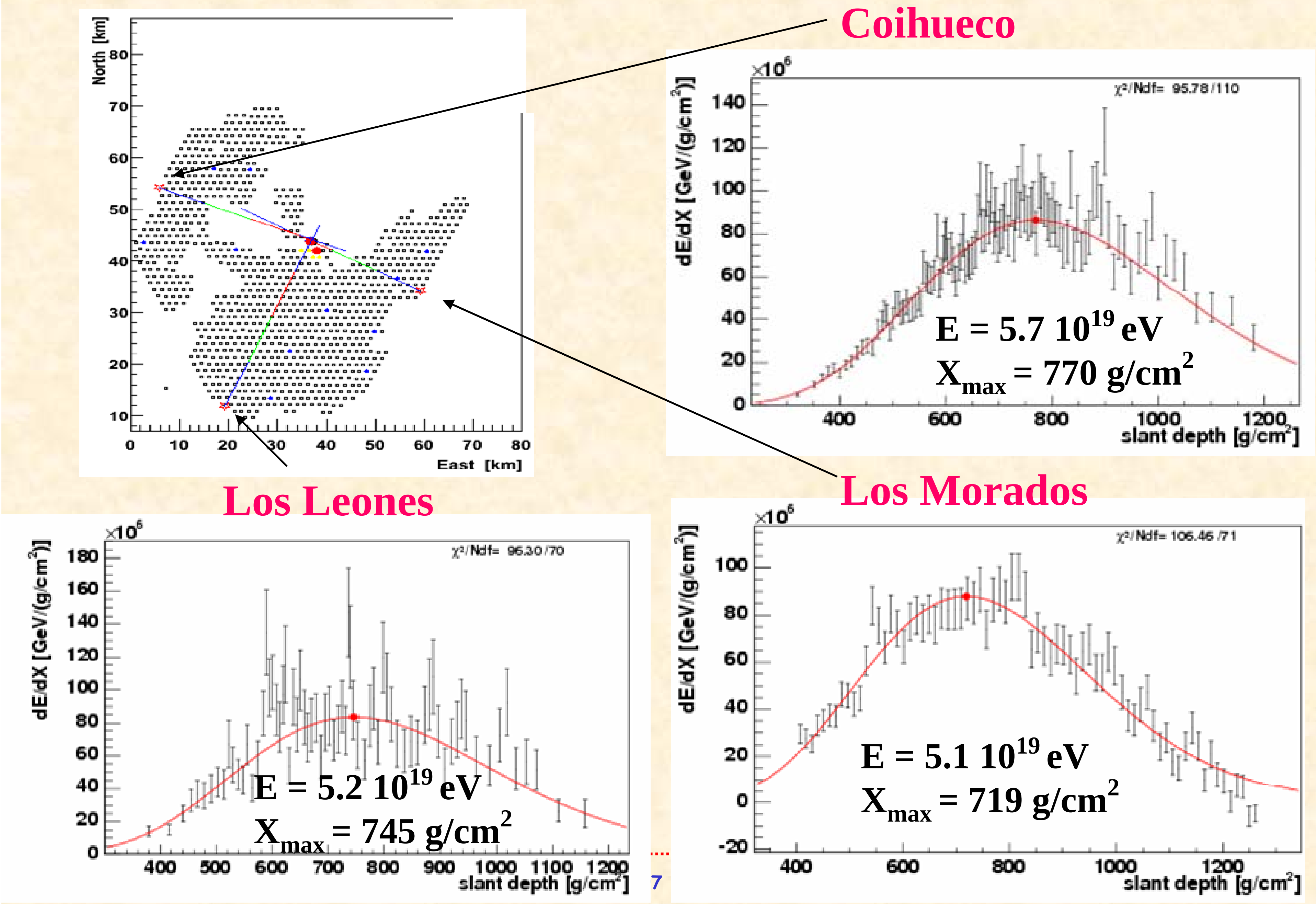
SD reconstruction

Longitudinal profile

FD reconstruction



Stereo event (tri-eyes view)



Conclusions

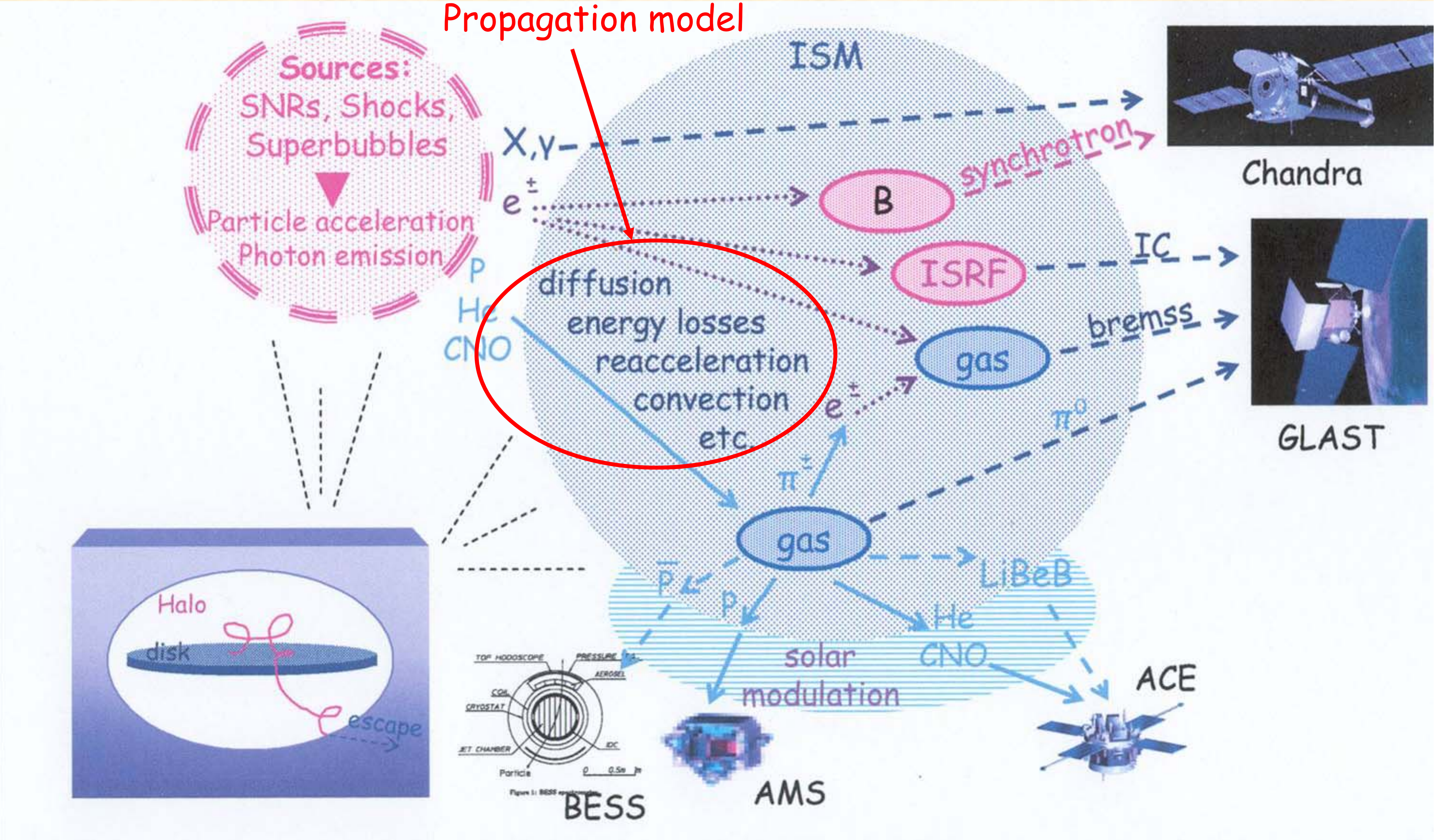
- Huge energy range and huge differences in CR fluxes requires very different techniques

- The modern detectors are very refined and precise in all the different CR regions

- CR physics is extremely interesting and challenging!!!!

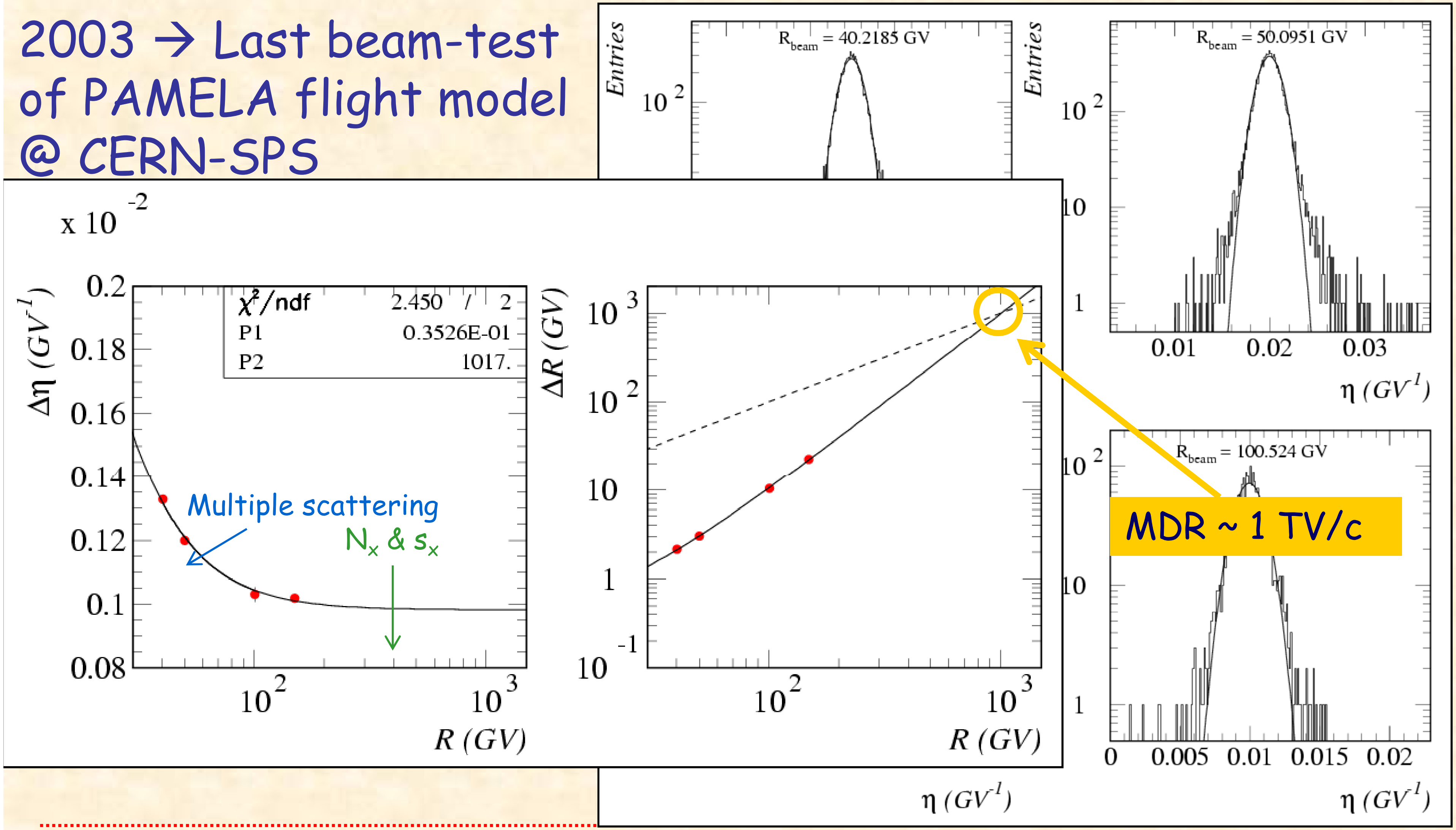
Spares Slides

Astrophysics of galactic cosmic rays



Momentum resolution

2003 → Last beam-test of PAMELA flight model @ CERN-SPS



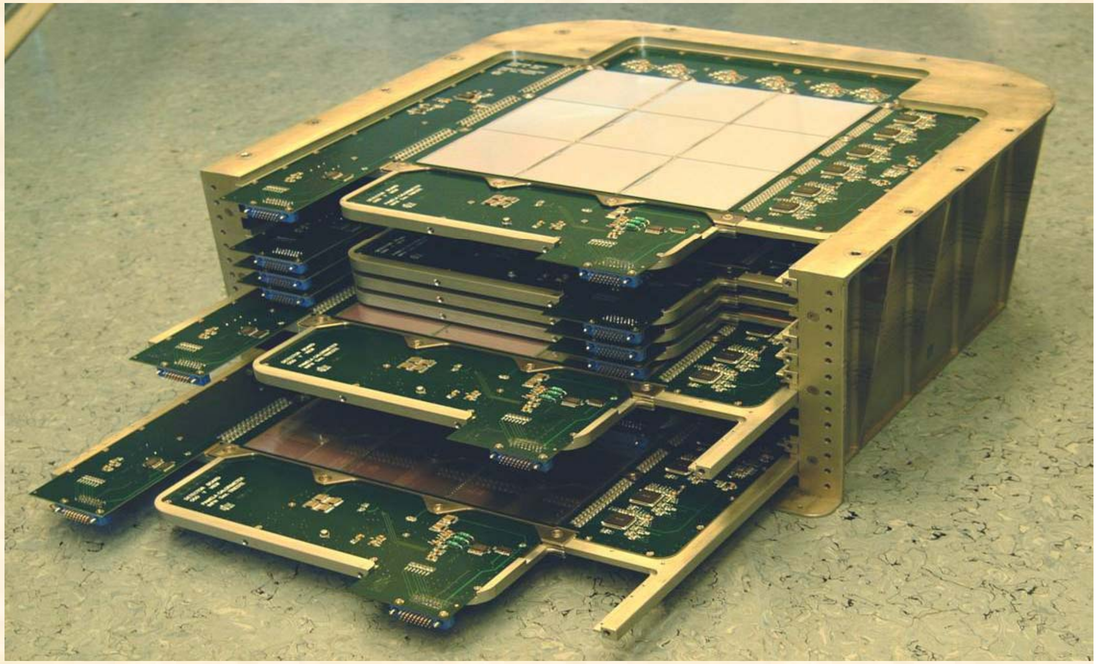
Pamela Calorimeter

Si-W Calorimeter

- Measures energies of $e^{\pm}$.

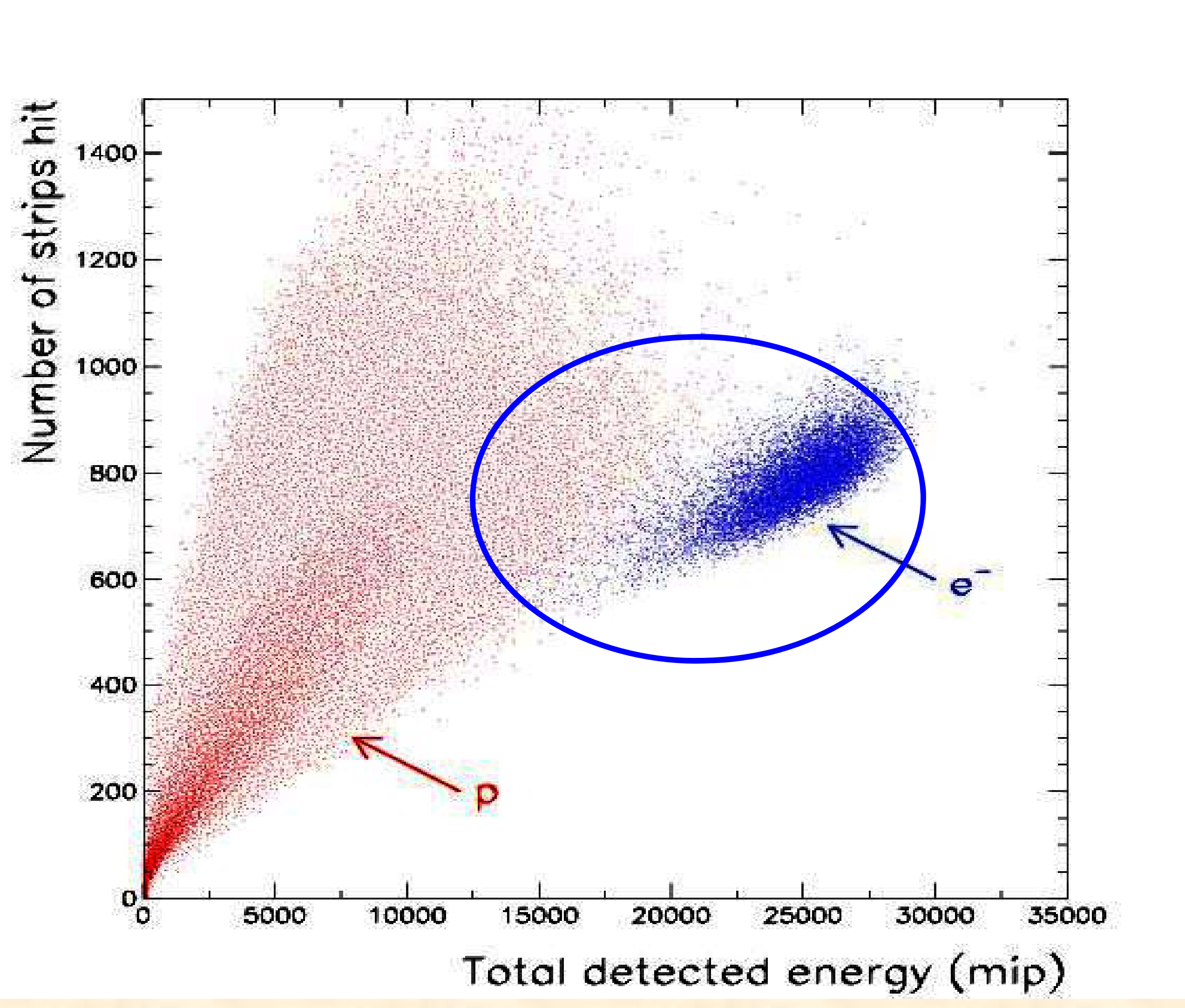
  $\Delta E/E = 15\% / E^{1/2} + 5\%$

- Si-X / W / Si-Y structure.
- 22 Si / 21 W $\Rightarrow 16X_0 / 0.9\lambda_0$
- Imaging: EM - vs- hadronic discrimination, longitudinal and transverse shower profile
- Total number of channels 4224
- Wide dynamic range $\cong$ 1 - 1000 MIP



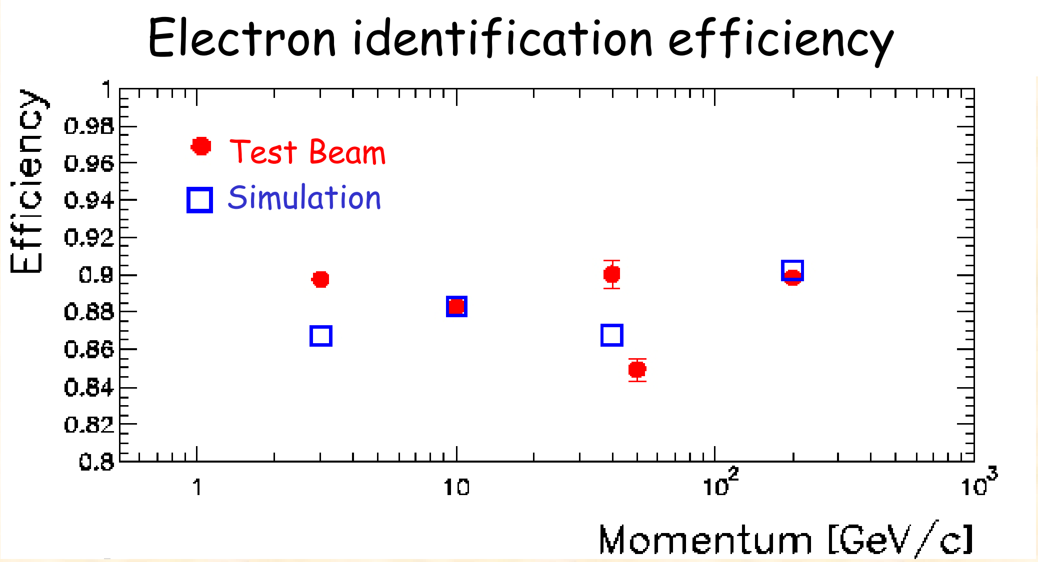
Calorimeter Requirements:
- p/e^+ selection eff. ~ 90%
- p rejection factor ~ 10^5
- e^- rejection factor > 10^4

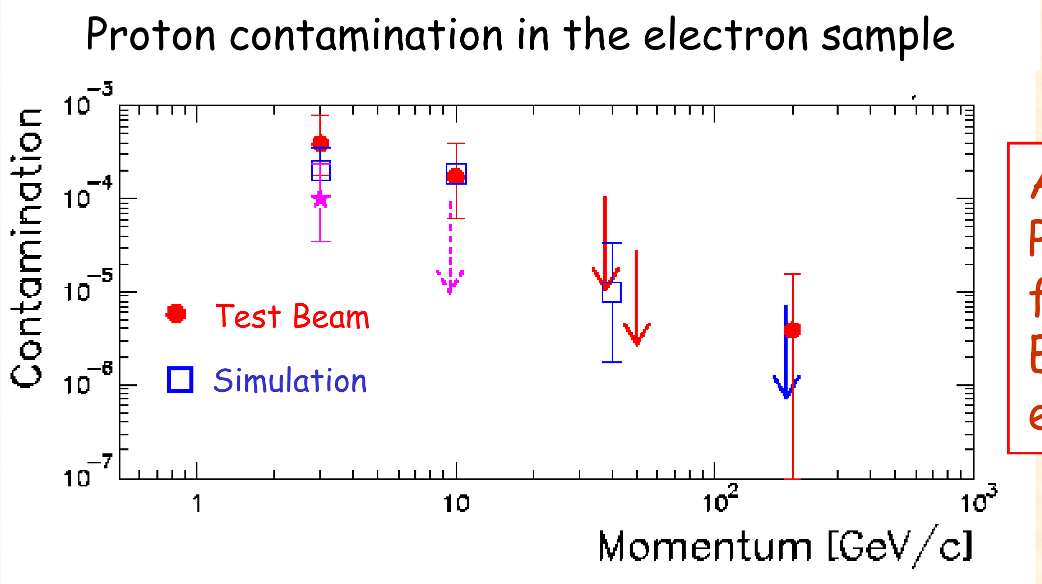
Electron-Proton Separation



SPS Test Beam Data:
p & e⁻
200 GeV/c

SPS Test Beam Data (p&e⁻ up to 200 GeV) + Simulation





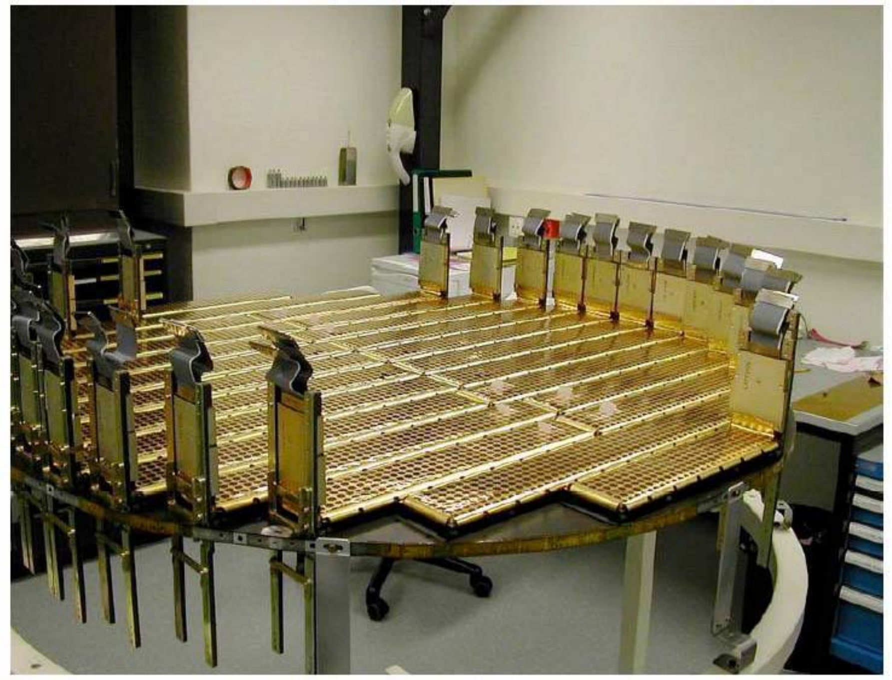
At 200 GeV:
Proton rejection factor ≅ $2.3 \cdot 10^5$
Electron selection efficiency ≅ 90%

AMS02: Tracking system

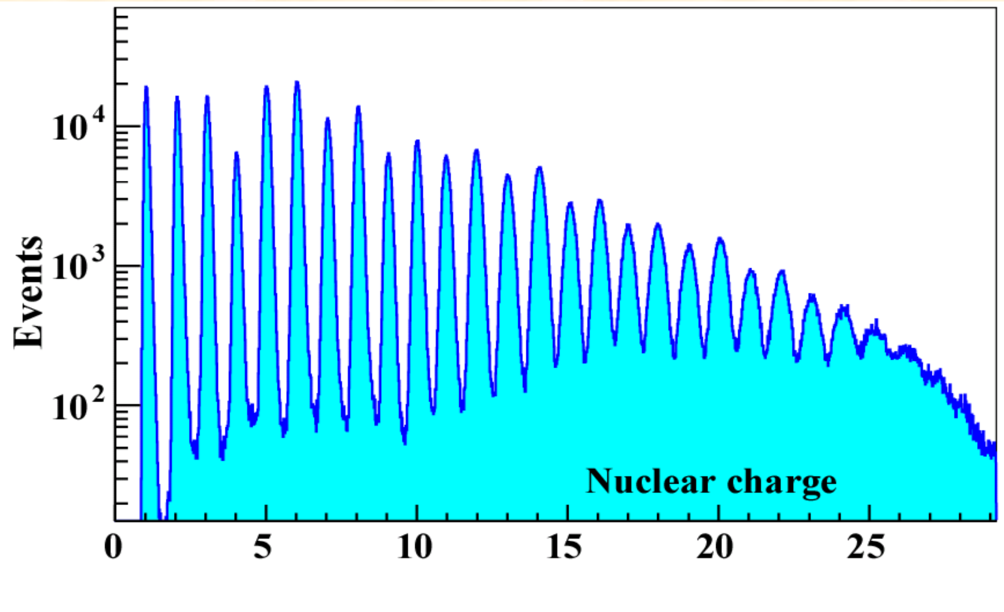
Dimensions~ 6.4 m^2

MDR ~ 2 TV/c

8 planes, 300k channels

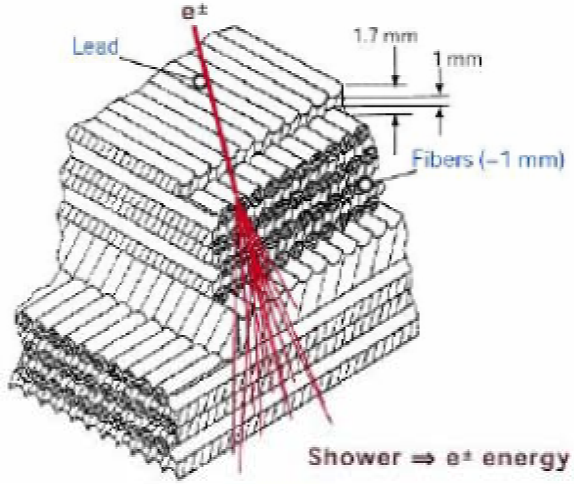


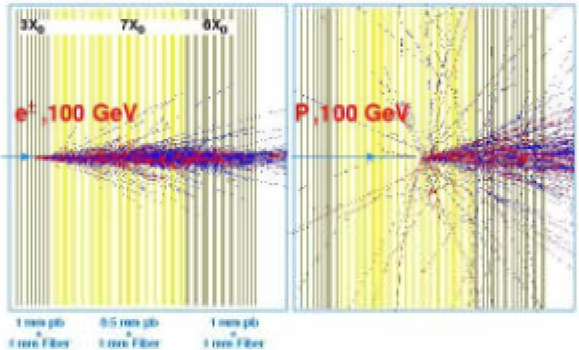
Z discrimination is possible up to Fe



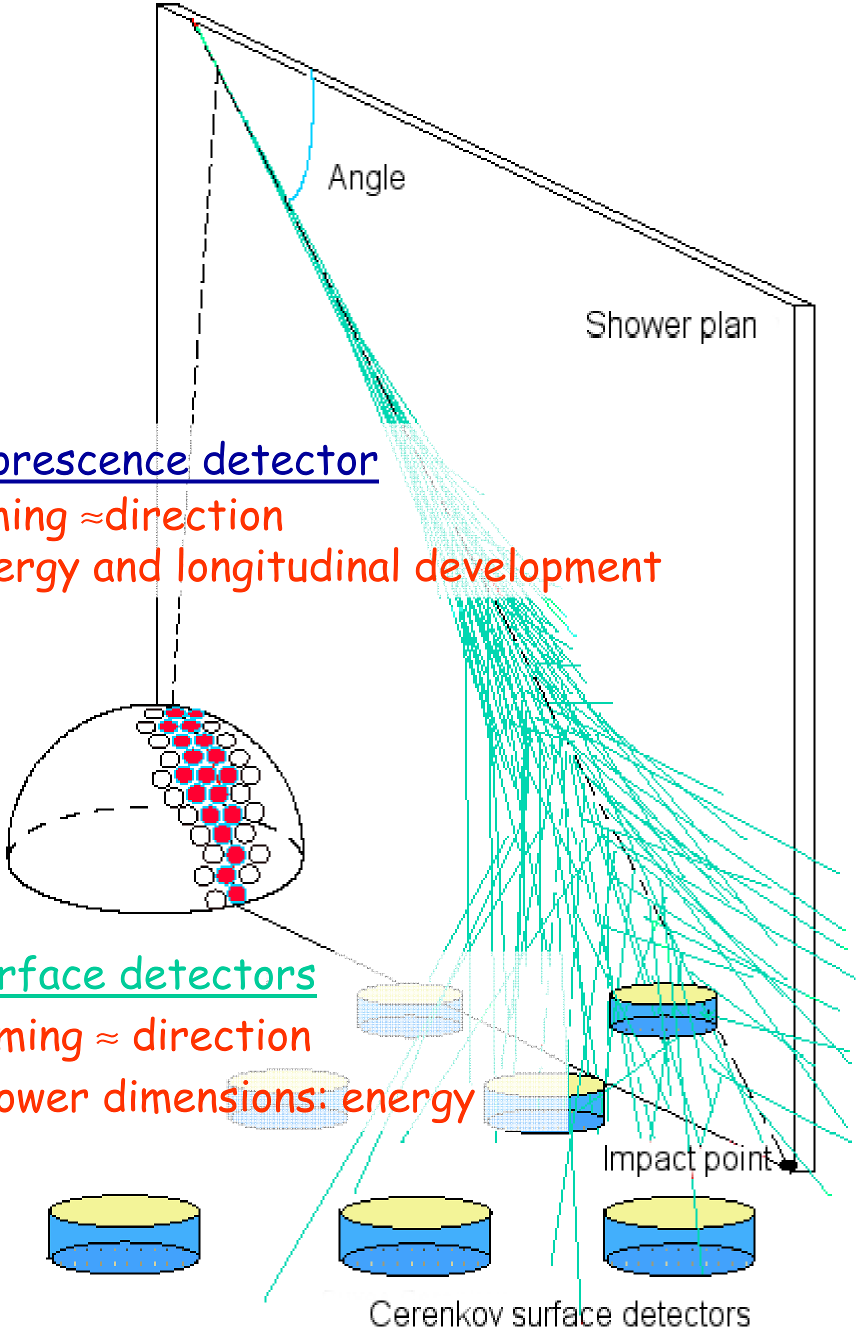
AMS-02: Electromagnetic Calorimeter

- Lead scintillating fiber sandwich (640 kg), 3D sampling by crossed layer
- $\sim 17 X_o$ radiation lenghts
- 9 superlayers piled up disposed along Y and X alternately
- Energy resolution (GeV) $\Delta E/E \simeq 10.1\%/\sqrt{E} \oplus 2.6\%$
- Distinction between hadrons and e/γ by shower shape
- Protons supressed by 10^{-4} up to 500 GeV. Together with TRD, rejection of hadrons/electrons $\geq 10^6$
- Independent γ detector, angular resolution $\sim 2^{\circ}$, γ independently triggered





Hybrid Technique



Fluorescence detector
- timing ≈direction
- energy and longitudinal development

Surface detectors
- timing ≈ direction
- shower dimensions: energy

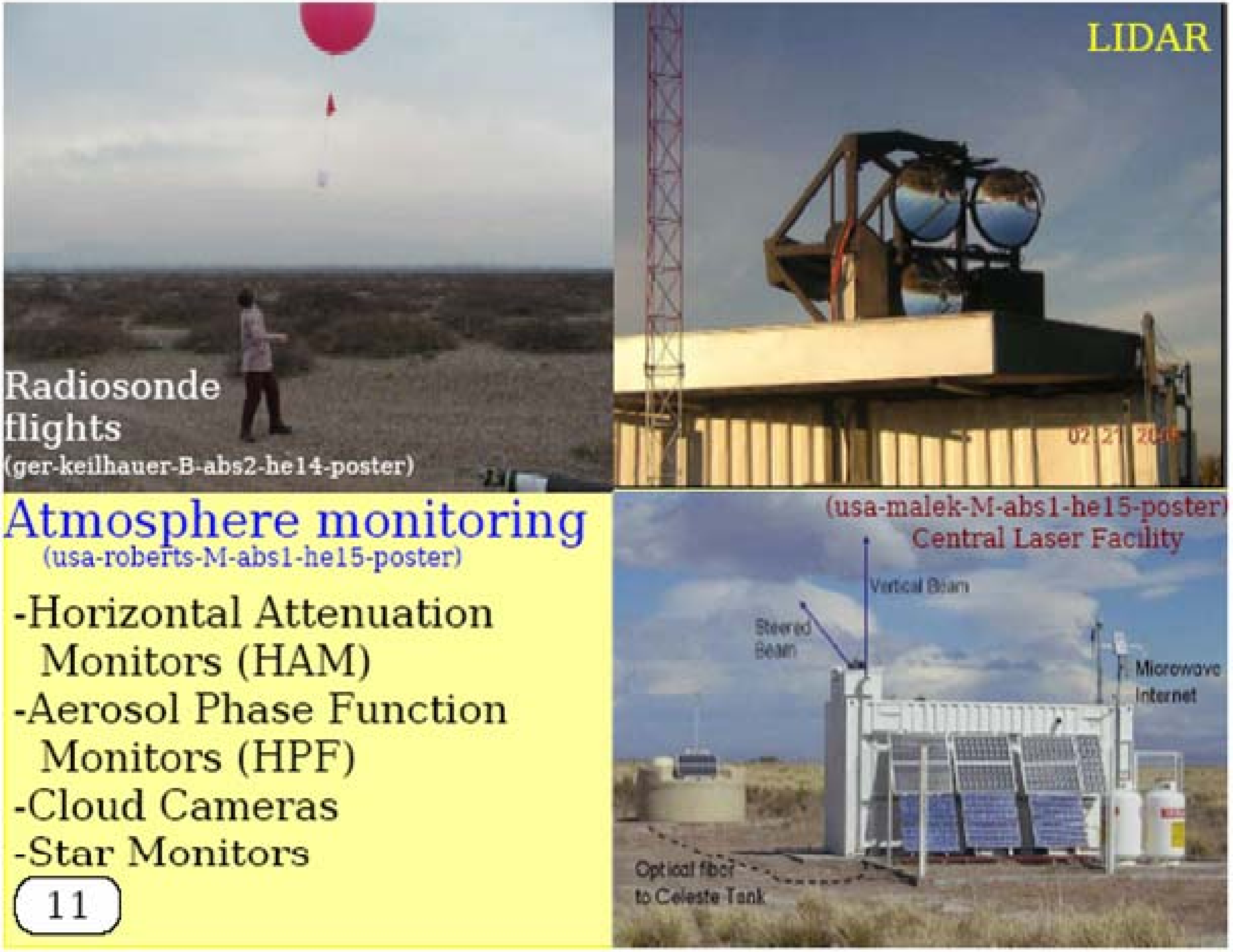
3-D image of the shower:
- ✓ Longitudinal profile from FD
- ✓ Lateral profile from SD
- ✓ Stereo detection

Cross calibration:
- ✓ Two complementary and independent methods for the EAS detection

Better data quality:
- ✓ Systematics are reduced
- ✓ Geometrical and energetic resolutions are improved
- ✓ Better determination of the shower axis (simultaneous measurement of the event with different detectors)
- ✓ Small model dependance

Uniform sky coverage:
- ✓ SD: 100% duty cycle
- ✓ FD: 10% duty cycle

Atmospheric monitoring is crucial



Balloons/Satellites

Balloons:

Altitude ~ 40 km

→ ~ 5 g/cm^2 residual atmosphere

Limited life (day/night effect)

(6-40 hours)

'Local' observations

Long duration (40 days)

Big payloads (4 ton)

Payload can be recovered

Limited cost

Satellites:

Altitude > 300 km

→ ~ 0 g/cm^2 residual atmosphere

3 years data taking

'All sky' survey

Many possible orbits

Limited payload mass

Limited power

Complexity

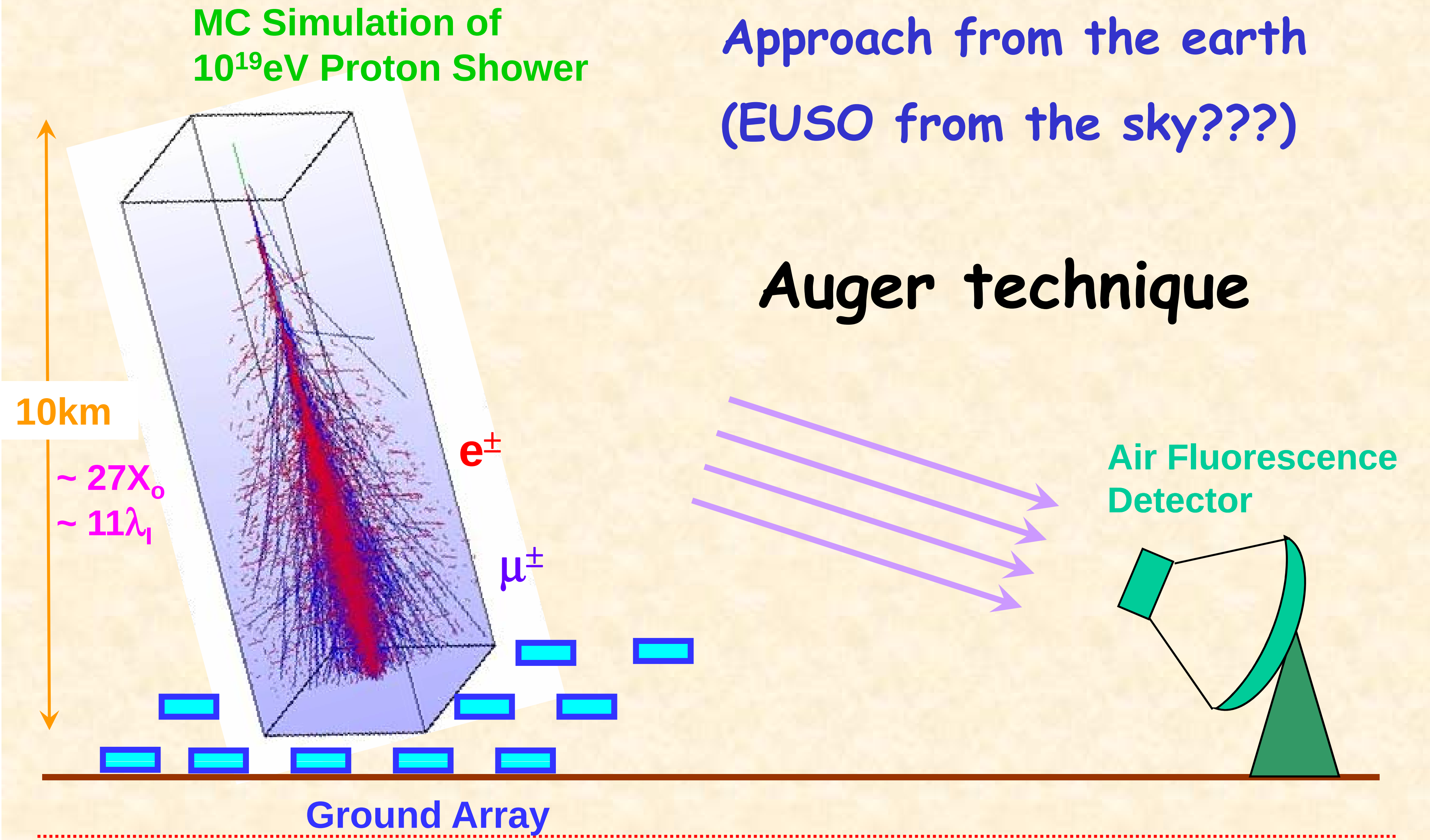
Cost!

Principle of Hybrid Detection (extremely important for UHECR)

Approach from the earth

(EUSO from the sky???)

Auger technique



Auger performances (SD + FD)

South observatory (end of 2007):

1600 SD
4 FD eyes

Duty Cycle:
SD 100%
FD 10-15% (dark and clean nights)

Efficiency:
>90% above 10^{19} eV

Energy resolution (final goal):

	SD alone	Hybrid system
10^{20} eV	15%	10 %
10^{19} EeV	30%	20%

Angular resolution :

	SD alone	Hybrid system
>3.10^{18} eV	1.4°- 2.2°	0.6°

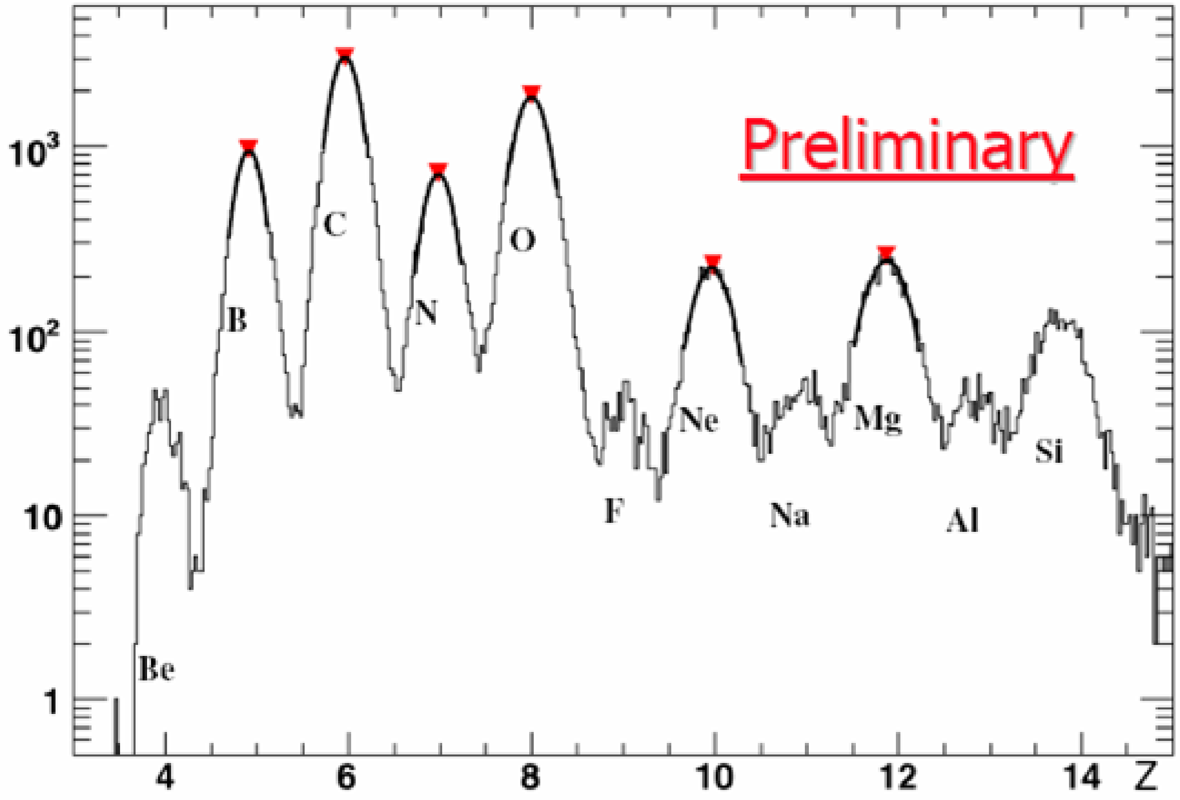
Shower core reconstruction:

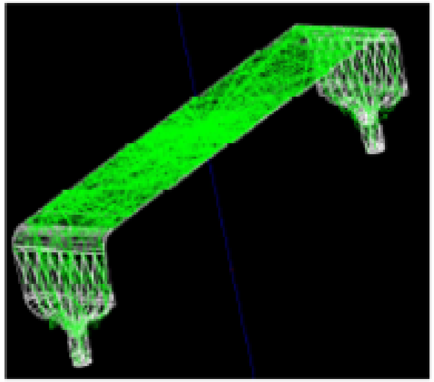
SD alone	FD Mono	Hybrid system
≈ 150 m	≈ 600 m	≈ 50 m

TCD charge measurement

Maestro, CREAM collaboration meeting Jan.11-12, 2007

Charge Resolution ~ 0.2 e for O and C

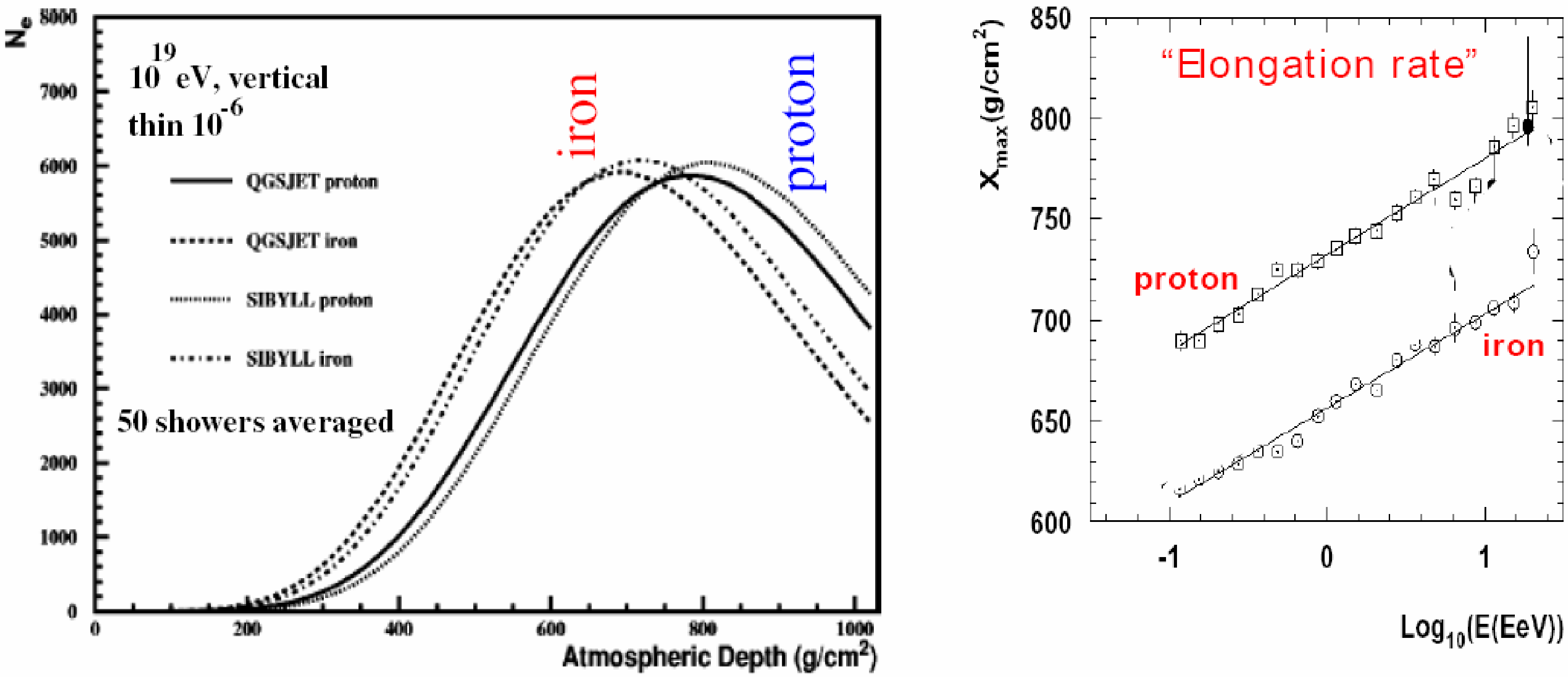




From Eun-Suk Seo, CRHEU07

Depth of Shower Maximum (Xmax)

Expected values for the mean Xmax for proton and iron primaries according to EAS simulations.



FD: Advantages and Disadvantages

Advantages:

- Calorimetric measurement of shower energy
  - Model independance
  - Reduced importance of MC
- Large collecting area
- Entire shower profile is observed
  - Good precision in X_{max}

Disadvantages:

- Dark nights
  - Reduced live time
- Strong dependance on weather conditions
  - Monitoring is necessary
  - Reduced live time