Direct measurements of Cosmic Rays

put detectors for particles above the atmosphere on satellites or balloons to directly measure the properties of CRs

challenge: mixture of different particles
with different energies
impinging on the detector from different directions

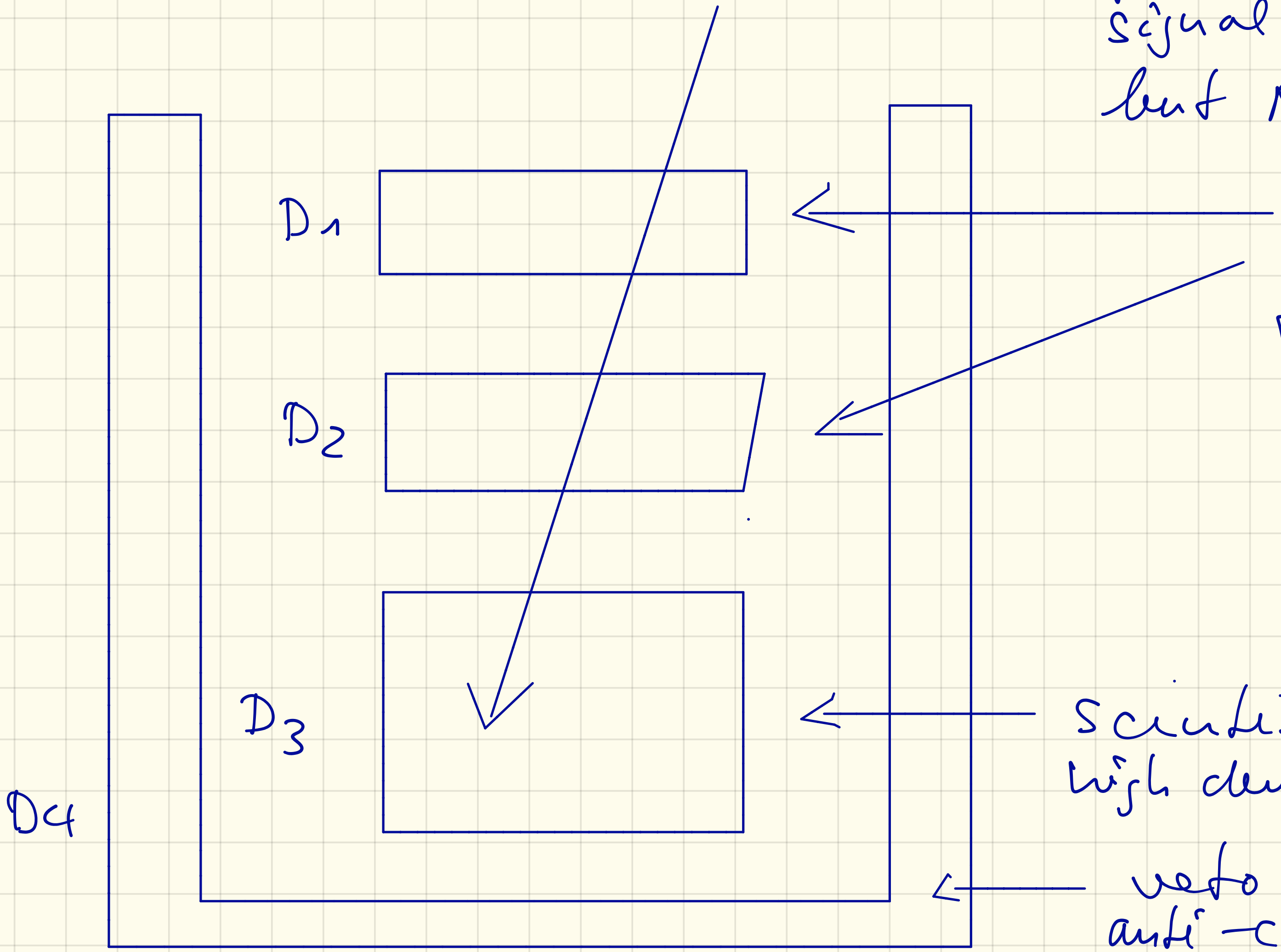
=> a combination of different detectors is required, operated in coincidence

Detectors for direct measurements of Cosmic Rays above the atmosphere

•Silicon detector	lZl, A, E	isotopes
•Magnet spectrometer	+/- Z, E	anti-particles
•Calorimeter	lZl, E	elements
•Cherencov detector	lZl, E	elements
•Transition radiation detector	lZl, E	elements

Si-detector, classical set-up

particle telescope
signal D_1 & D_2 & D_3
but NOT D_4

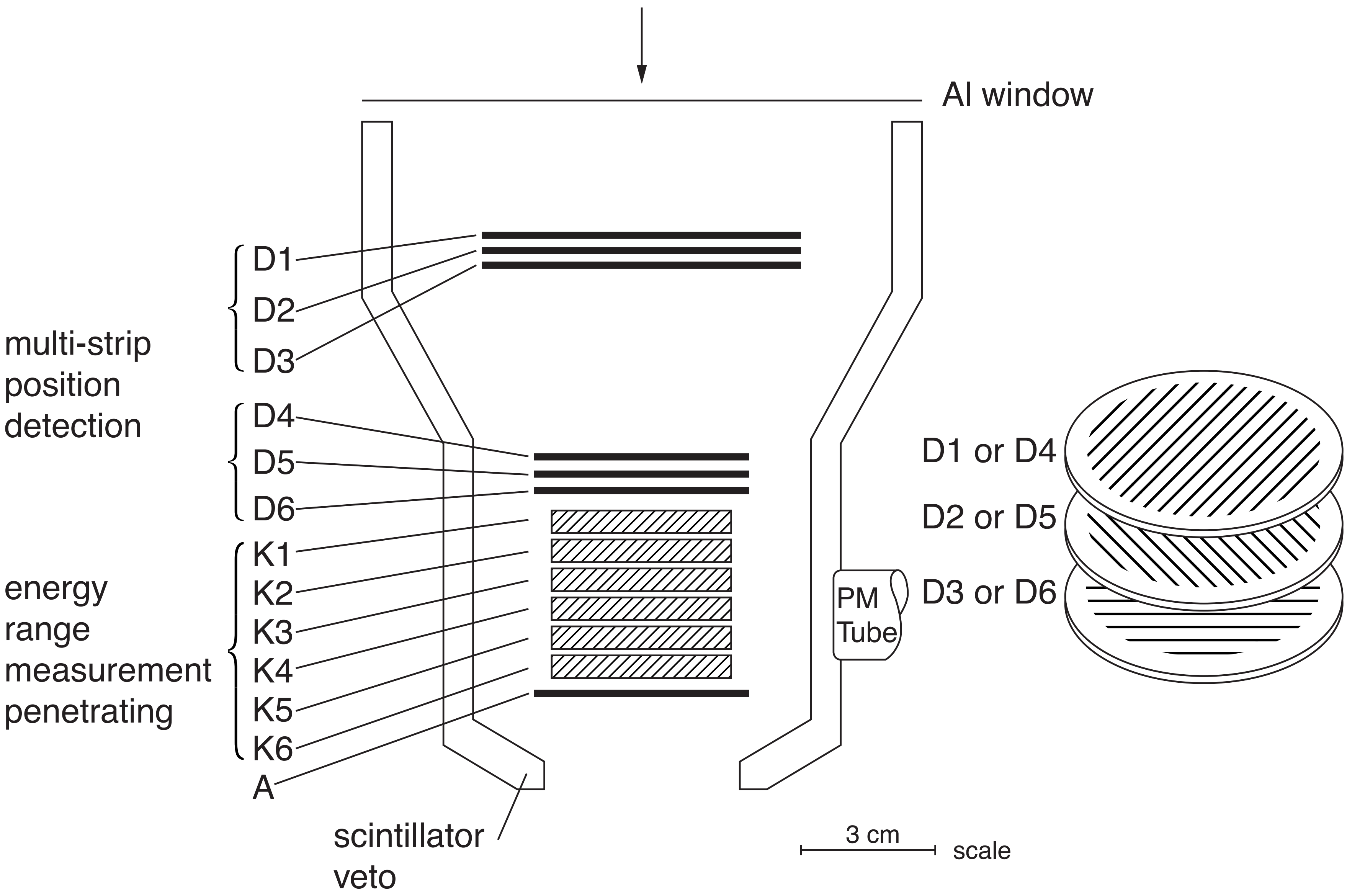


Si detectors
thin, good E resolution

Scintillator
high density

veto counter
anti-coincidence

Ulysses High Energy Telescope (HET)



in which energy range can we use such a detector?

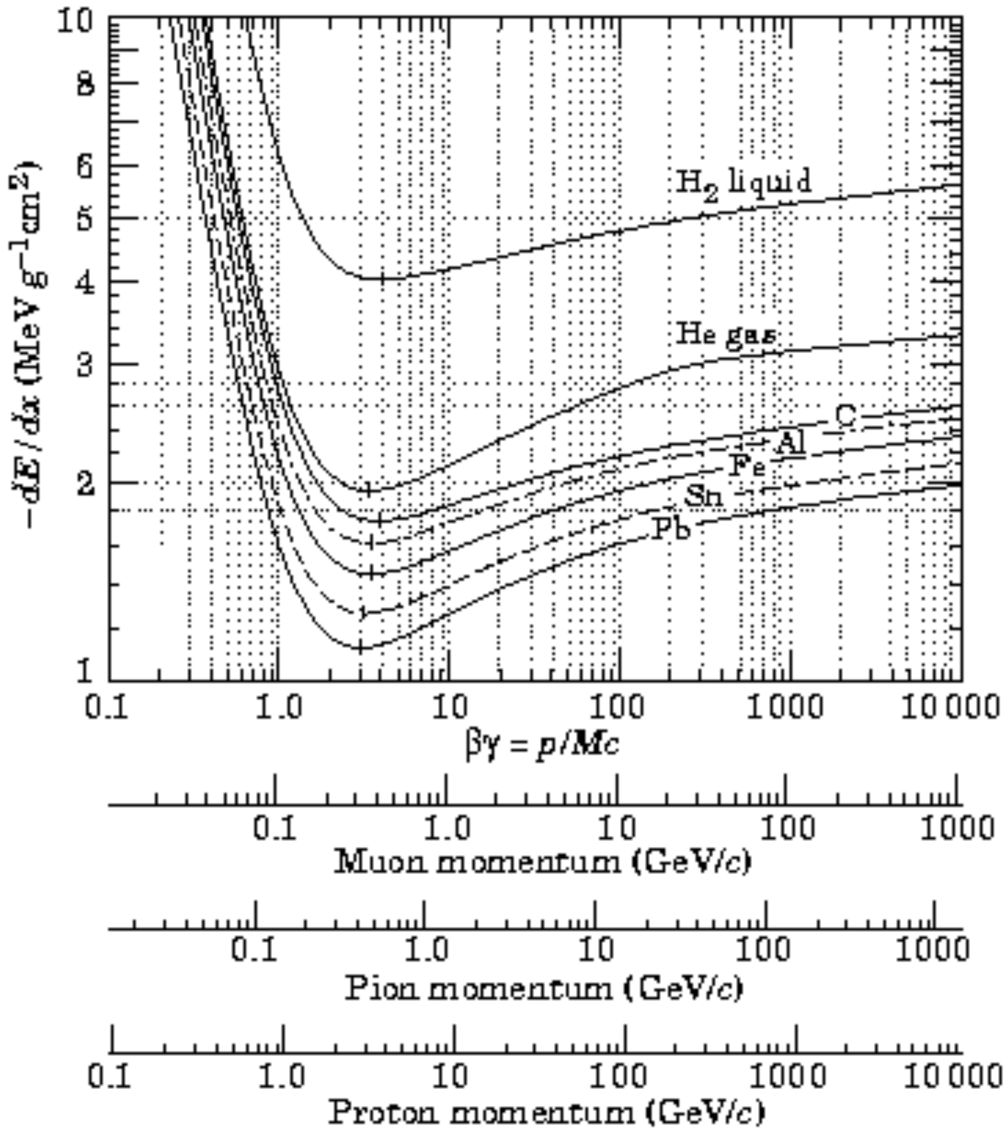
- the energy has to be large enough to cross $D_1 + D_2$ and impinge on D_3
- but low enough to be absorbed in D_3

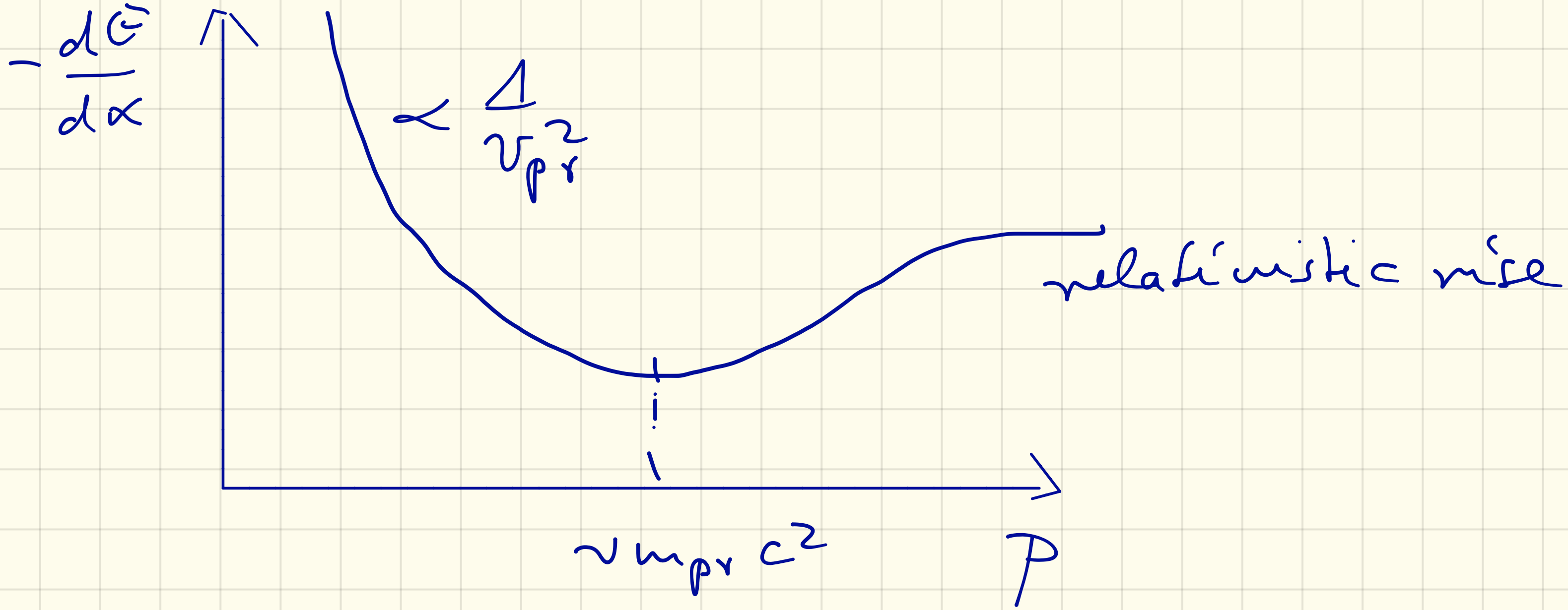
particles loose energy through ionization described by the Bethe Bloch formula

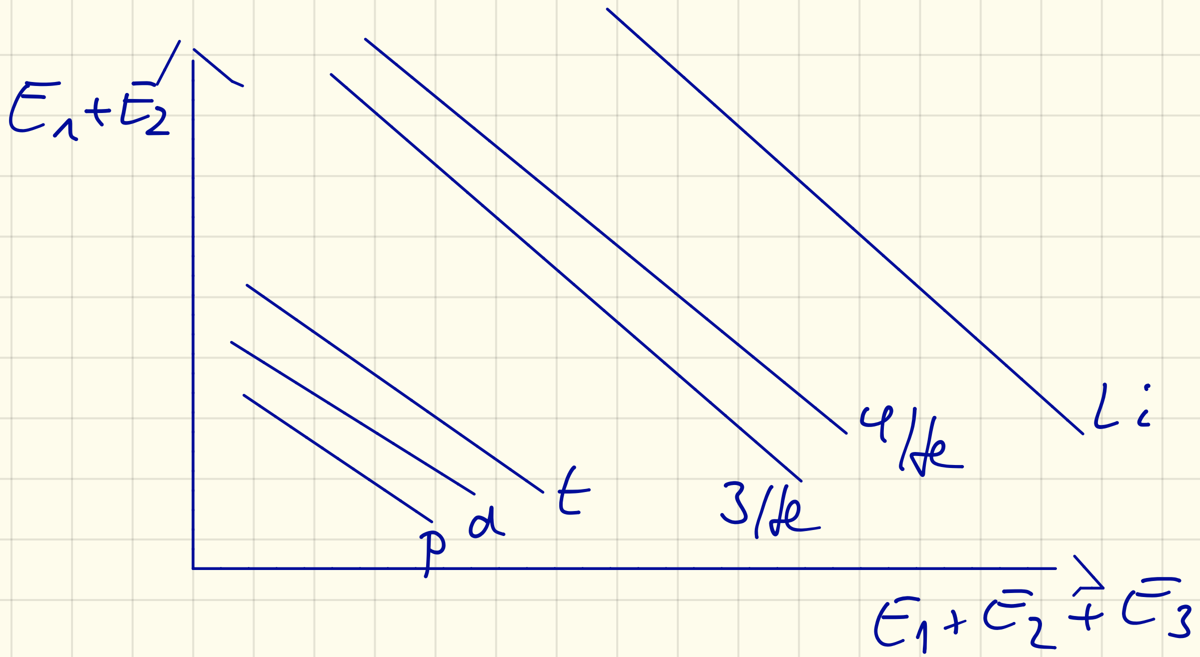
$$-\frac{dE}{dx} = \frac{z_{pr}^2 \cdot 4\pi \cdot N_A \cdot e^4 \cdot Z_{abs}}{v_{pr}^2 \cdot m_e \cdot A_{abs}} \left(\ln \frac{2 m_{pr} v_{pr}^2}{I(1-\beta_{pr}^2)} - \beta_{pr}^2 \right)$$

$$\propto \frac{z_{pr}^2}{v_{pr}^2} \qquad \propto z_{pr}^2 \frac{m_{pr}}{E_{pr}^{kin}}$$

specific energy loss
Bethe Bloch formula

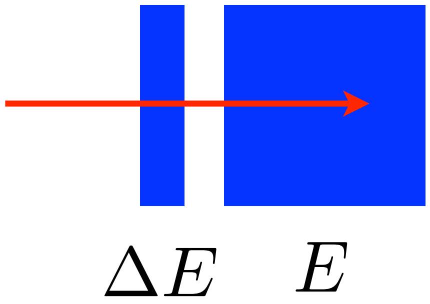


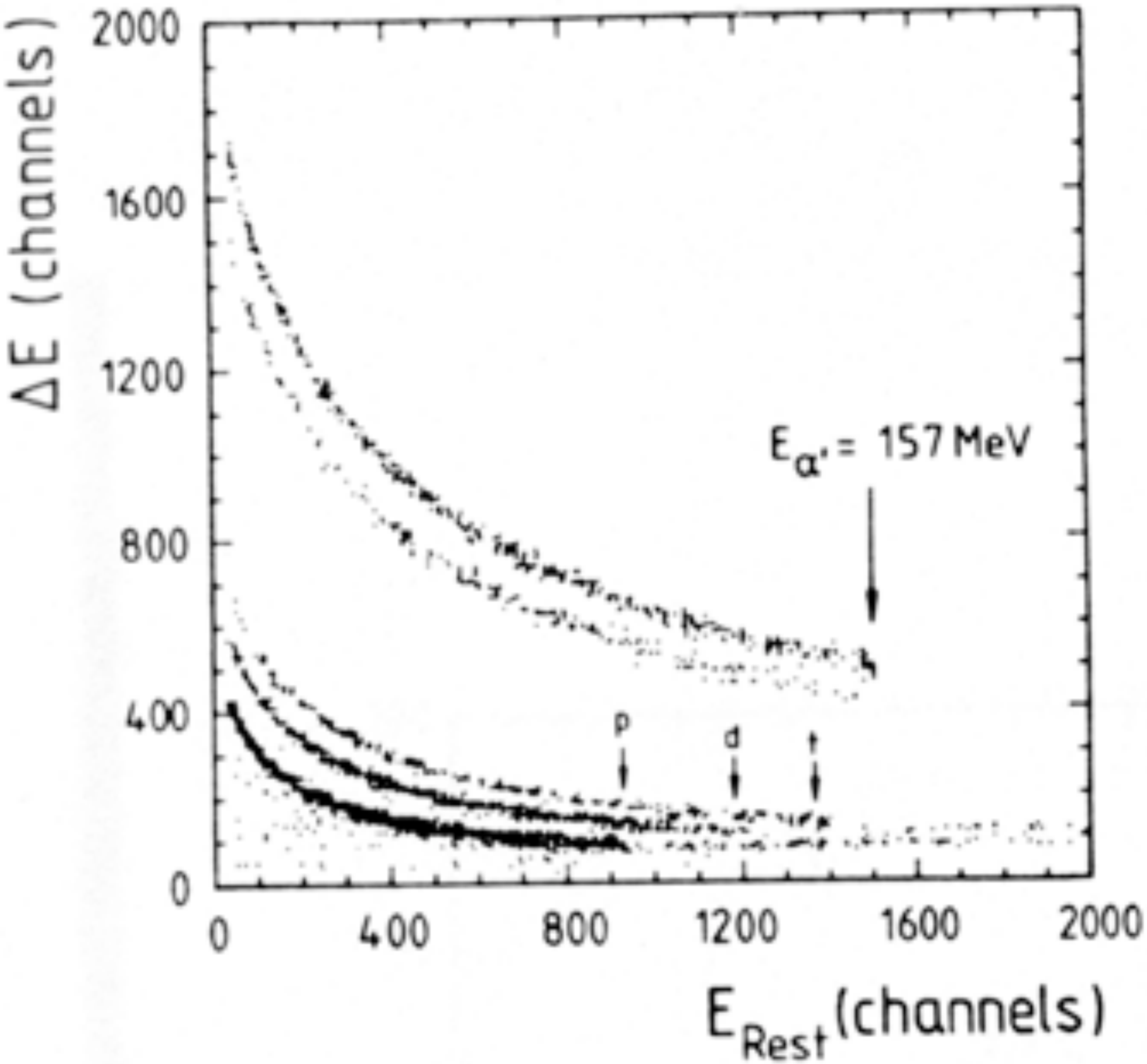




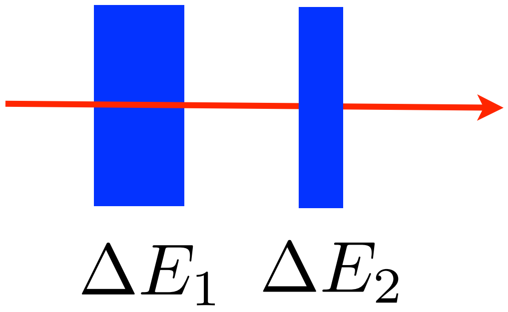
total energy
of the particle
$E_1+E_2+E_3$

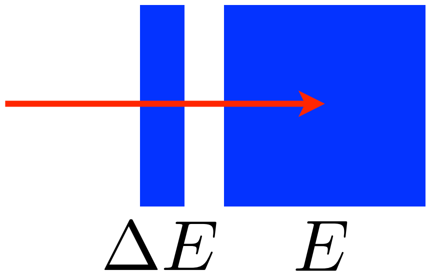
particle identification





particle identification





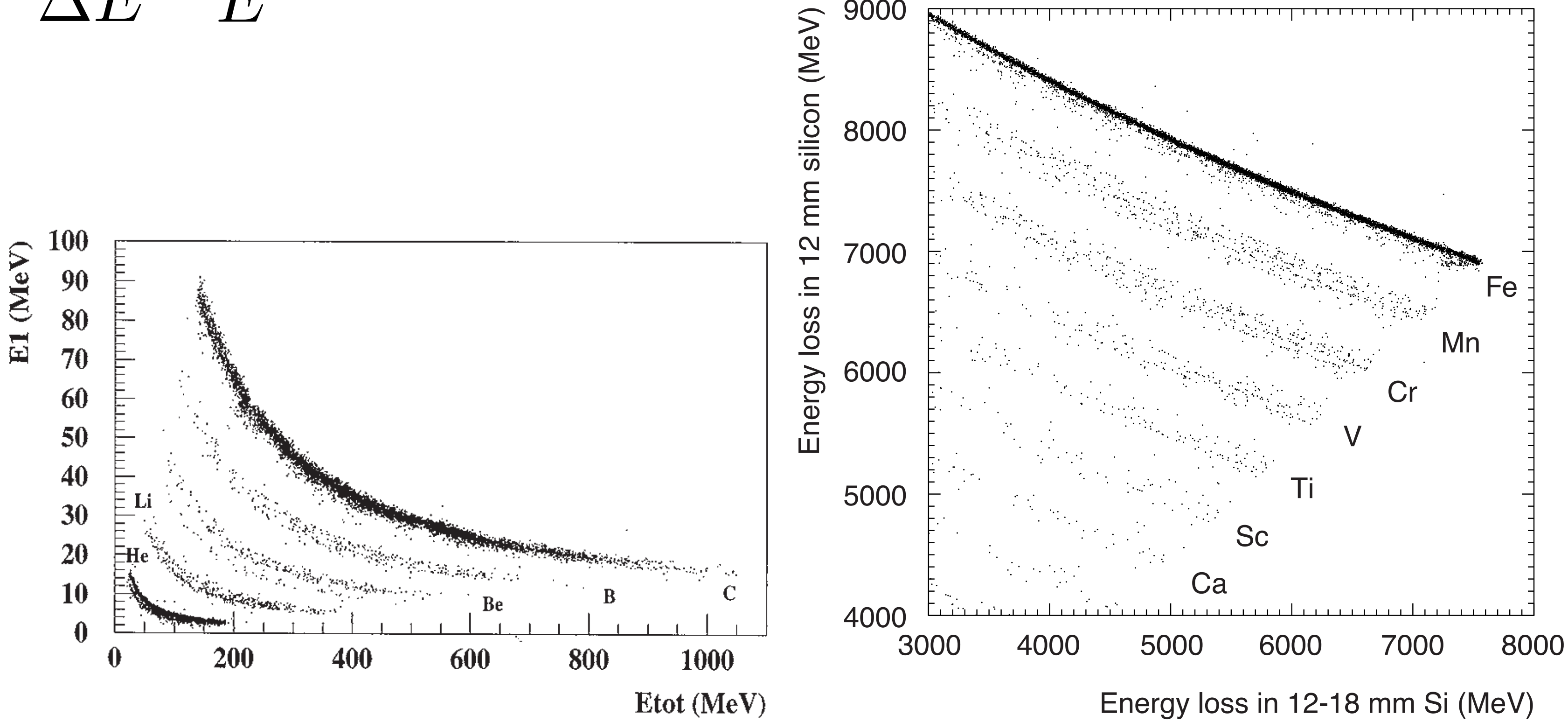
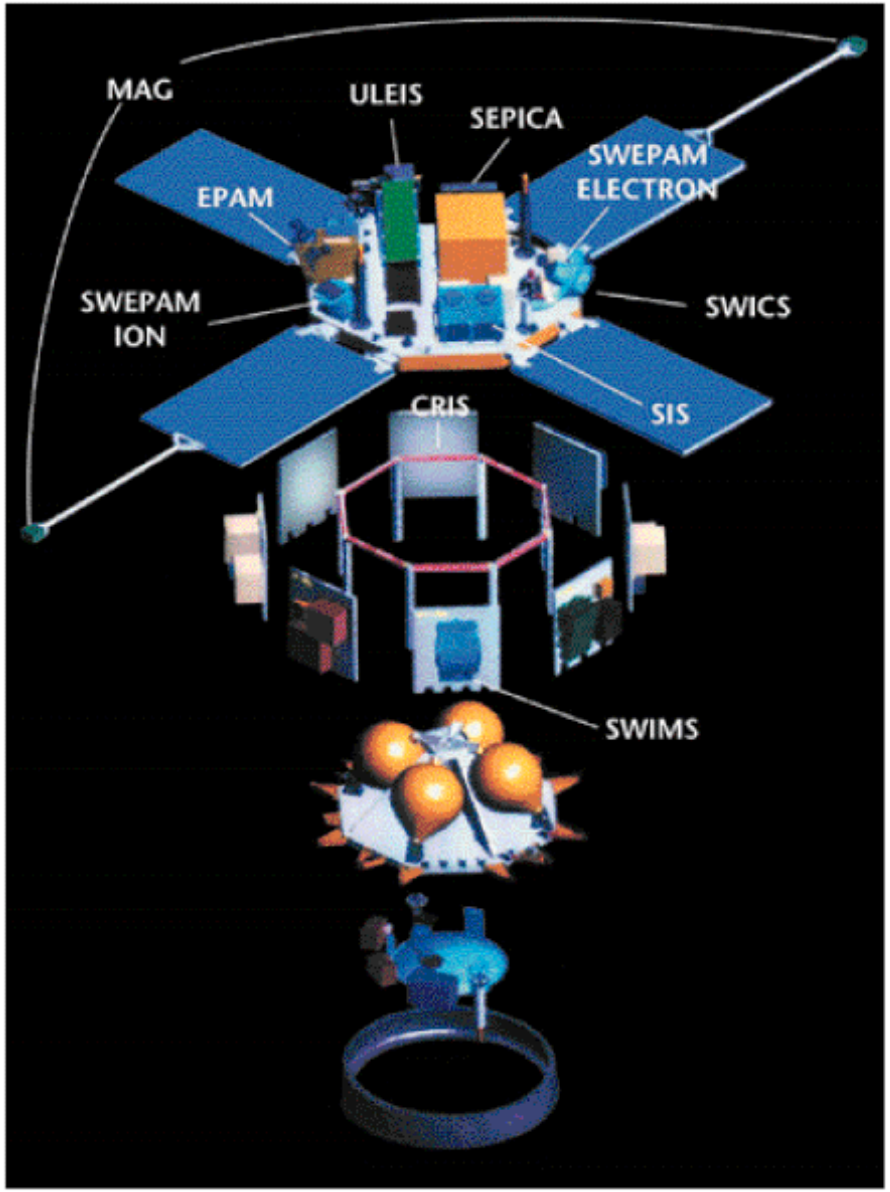


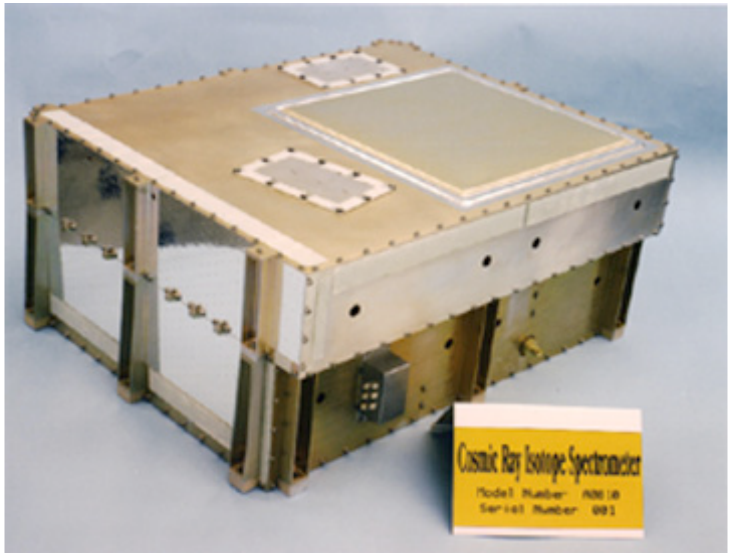
Fig. 3.4. *Left*: Energy loss in the first plane (E1) vs. total energy (E_{tot}) detected by the NINA telescope for particles fragmented from a ^{12}C test beam [8]. *Right*: Scatter plot of ΔE in 12 mm Si vs. ΔE in the following 6 mm Si from calibration of the CRIS instrument in an ^{56}Fe beam [5]

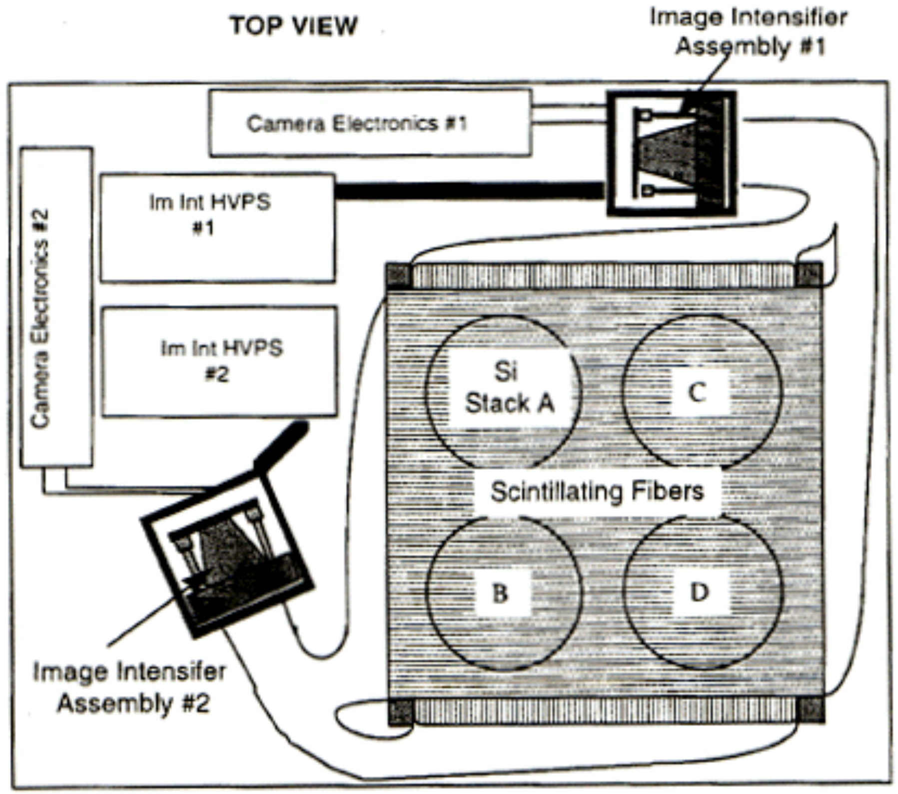
Advanced Composition Explorer (ACE)

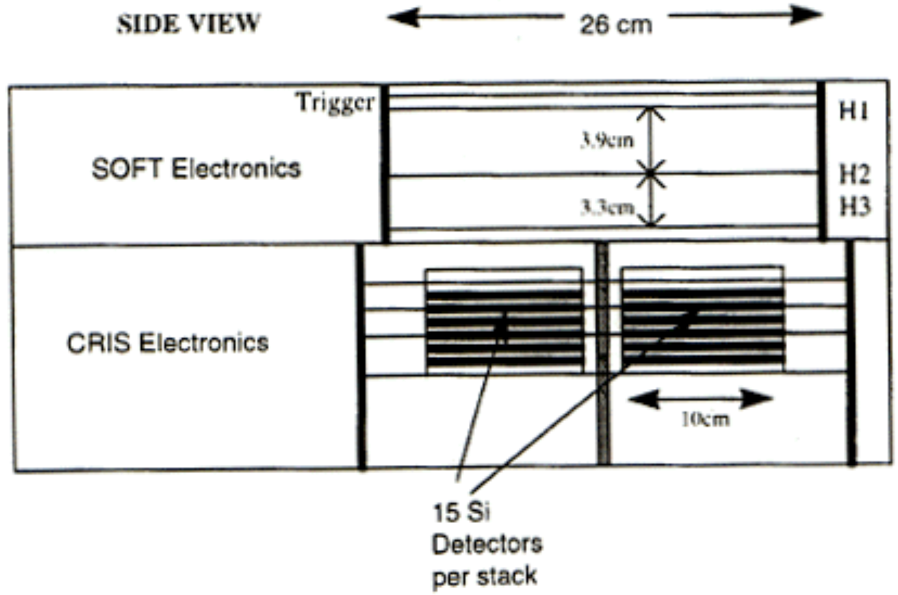


NASA / Goddard Space Flight Center; Start: 25.8.97,
9 wissensch. Instrumente (156 kg) ; 90% duty cycle
$1 \leq Z \leq 28$; 1 keV $\leq E \leq 600$ A·MeV

CRIS: The Cosmic Ray Isotope Spectrometer



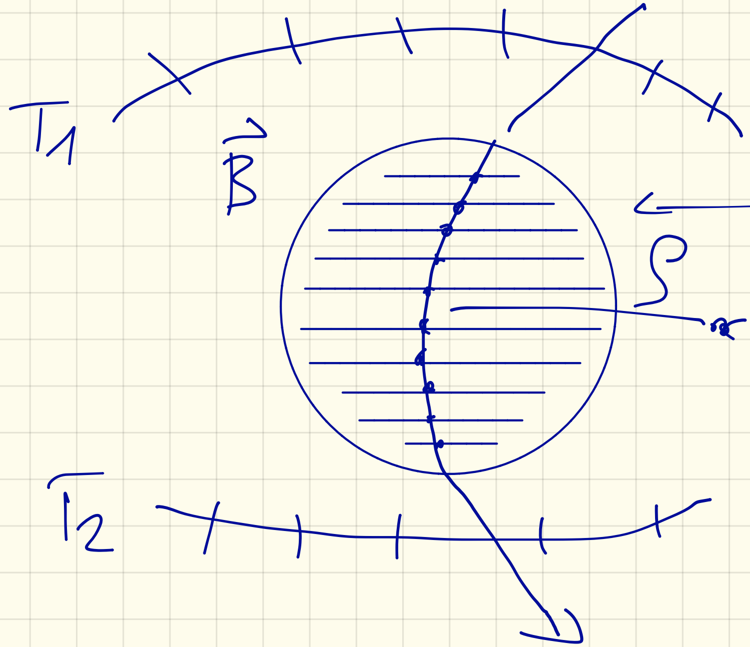




this technique works up to several 100 MeV/nucleon since particles have to be absorbed

For higher energies up to ~ 1 TeV one can use

magnet spectrometer



segmented counters (scintillator)

e.g. wire chamber
Si strip detector
high spatial resolution

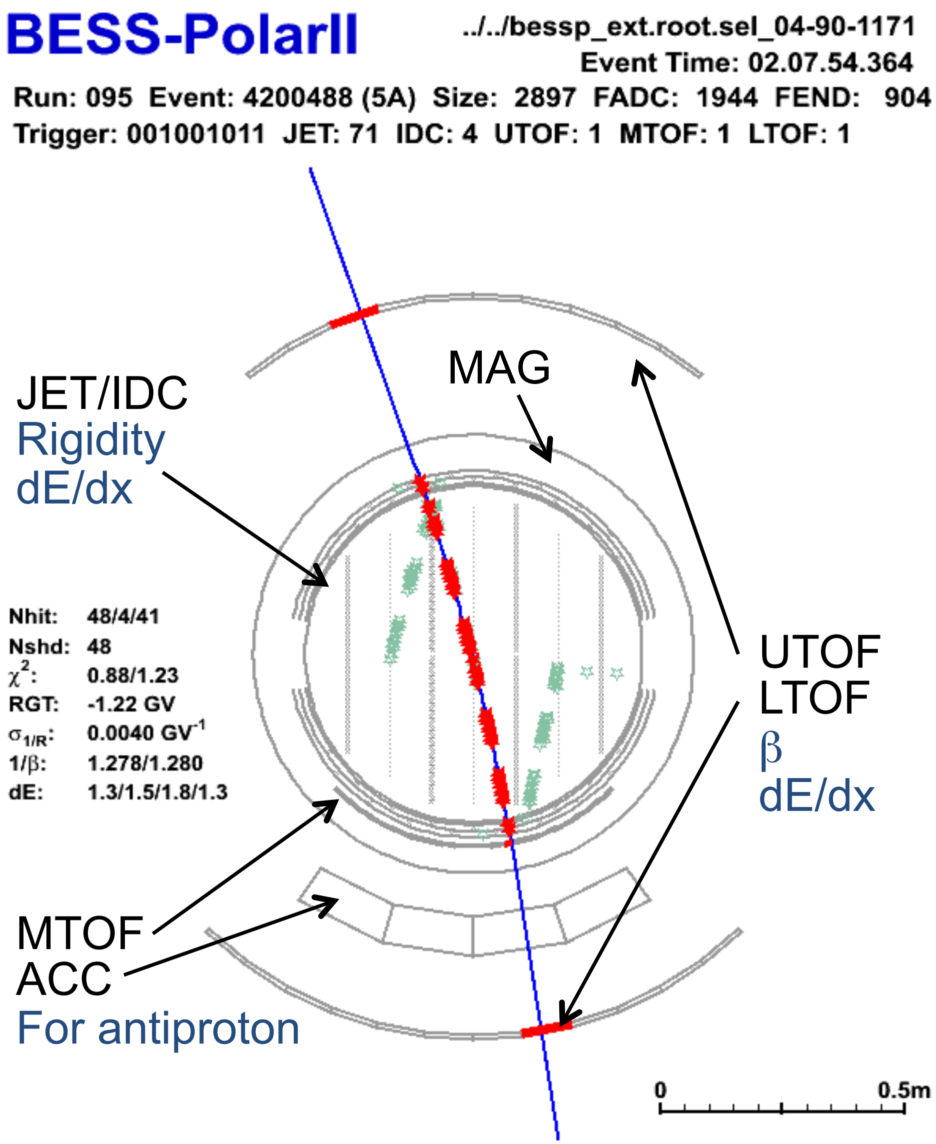
$T_1 + T_2$ time of flight (TOF) measurements
$\rightarrow$ direction

track reconstruction $\rightarrow$ curvature ρ

$$\frac{mv^2}{\rho} = v \cdot B \cdot Z \Rightarrow p = B \cdot \rho \cdot Z$$

Z is determined from signal in scintillator ($\propto Z^2$)

BESS Instrumentation



Event display with reconstructed Antiproton track is shown.

Rigidity (MDR:240GV)

Solenoid: Uniform field (ϕ=1m, B=0.8T)
Thin material (2.4 g/cm^2)

Drift chamber: Redundant hits
(σ~150μm, 32~48+4hits)

Charge, Velocity

TOF, Chamber: dE/dx measurement
(Z = 1, 2, ...)

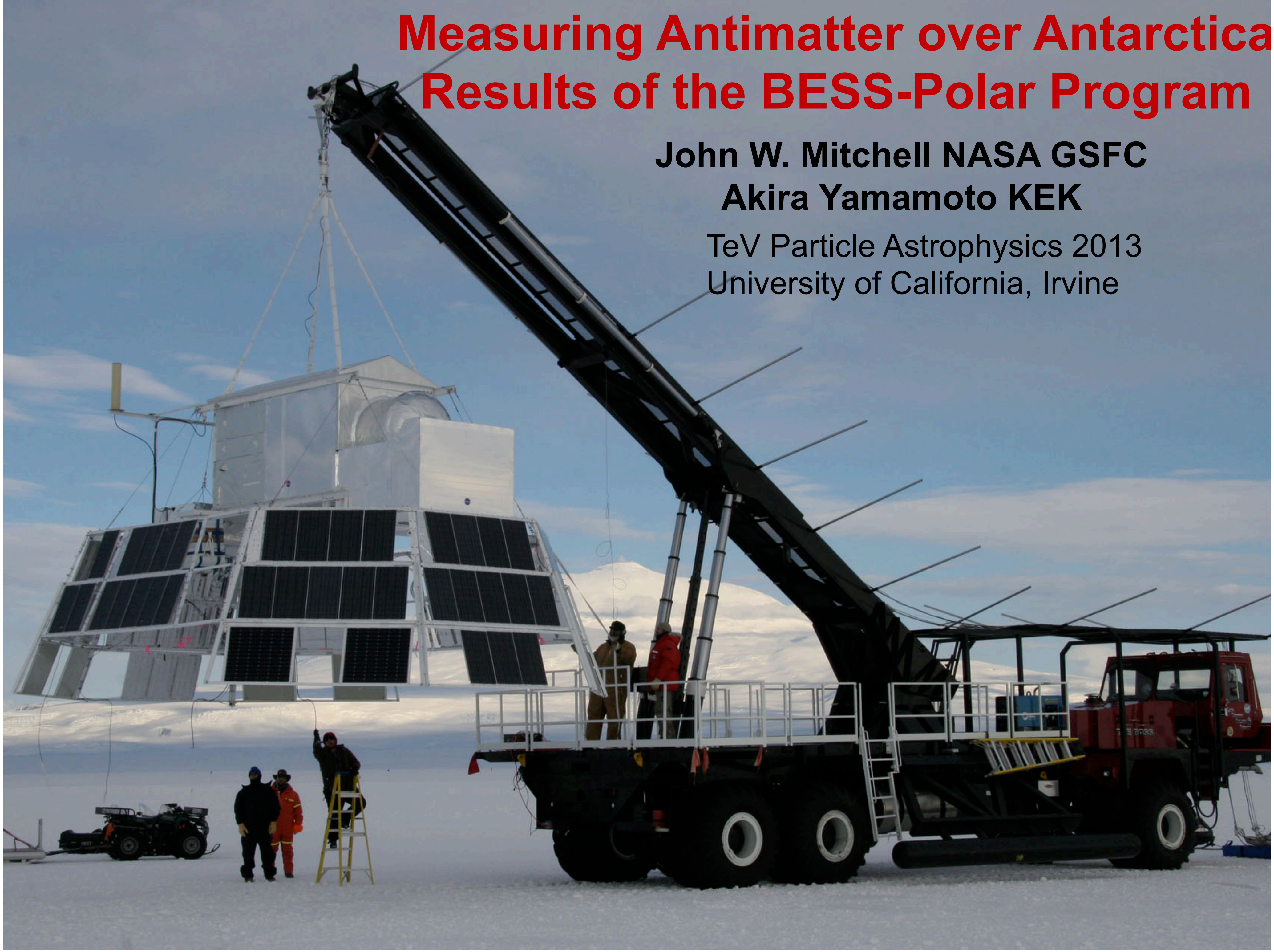
TOF: 1/β measurement (σ~1,2%)

$$m = ZeR\sqrt{1/\beta^2 - 1}$$

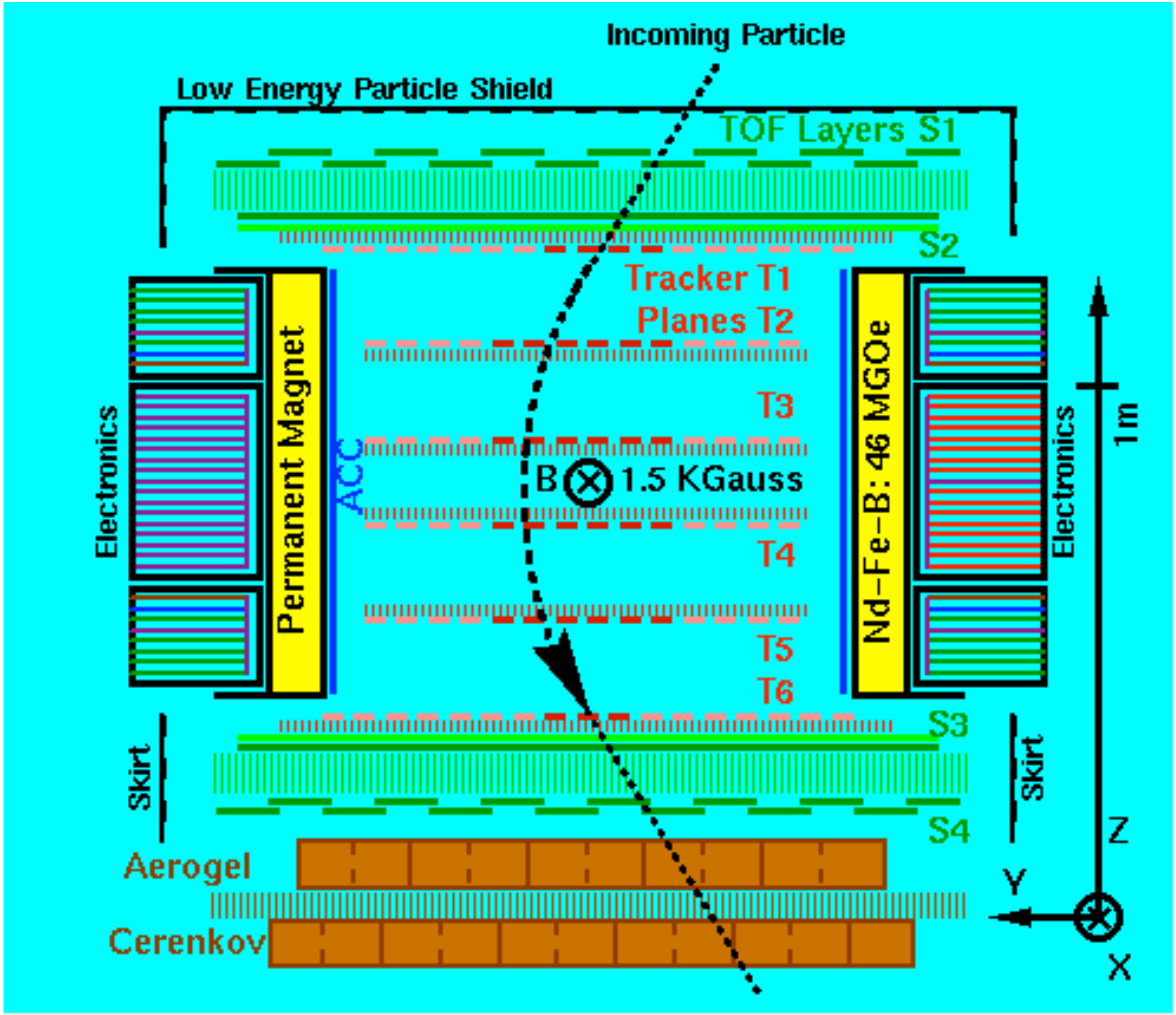
Measuring Antimatter over Antarctica
Results of the BESS-Polar Program

John W. Mitchell NASA GSFC
Akira Yamamoto KEK

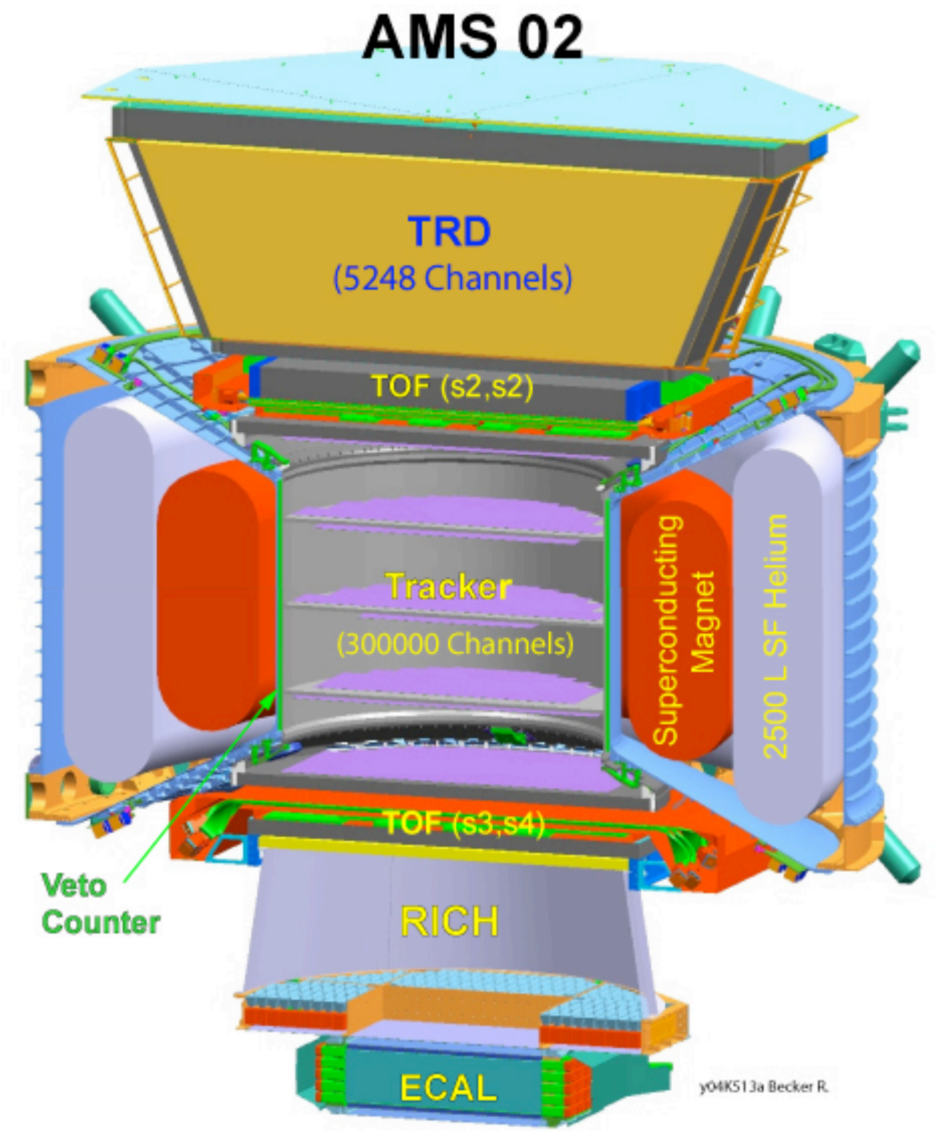
TeV Particle Astrophysics 2013
University of California, Irvine



Alpha Magnetic Spectrometer - AMS

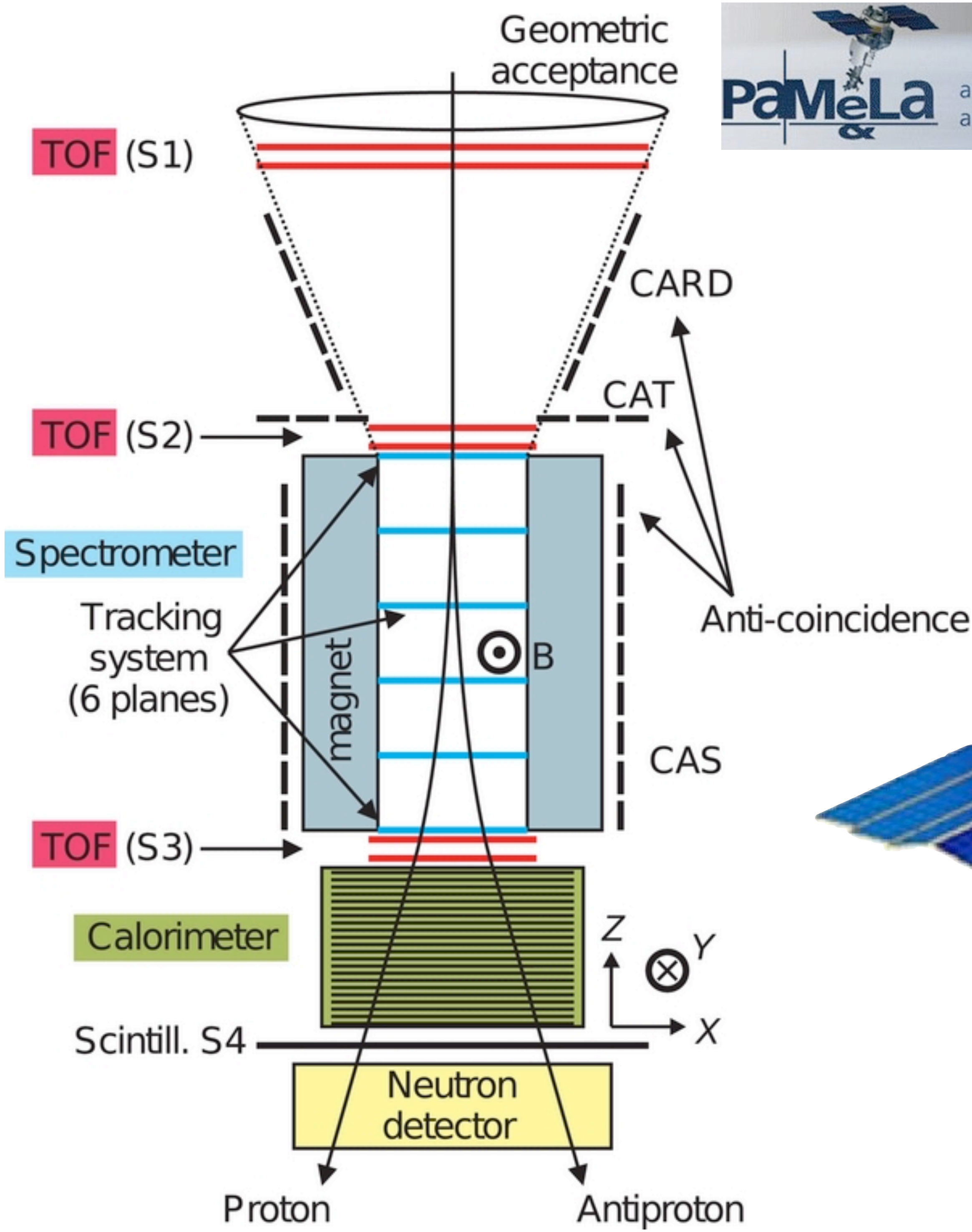


Alpha Magnetic Spectrometer - AMS



Alpha Magnetic Spectrometer - AMS

PaMeLa a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics



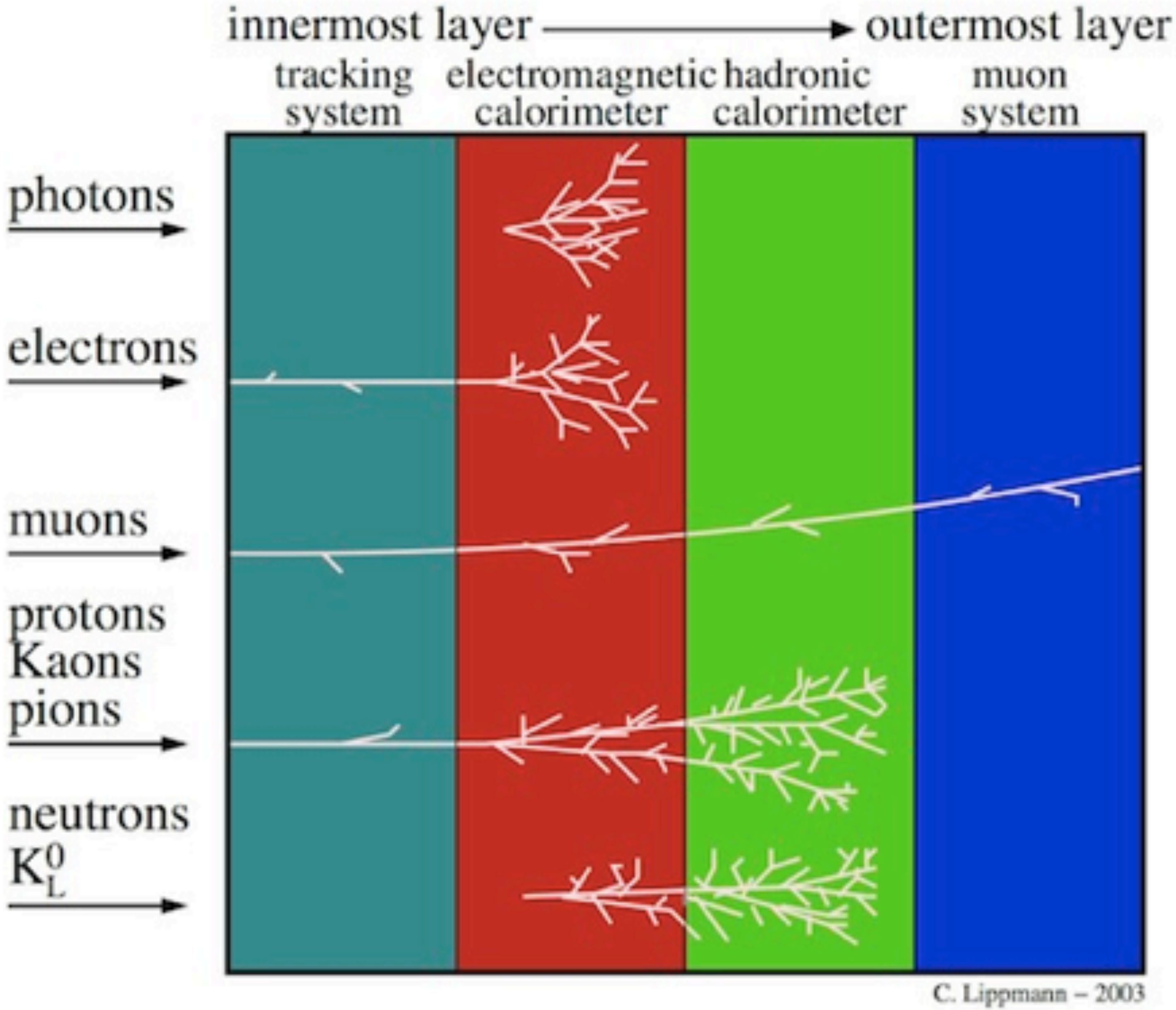


Figure 1: Components of a "traditional" particle physics experiment. Each particle type has its own signature in the detector. For example, if a particle is detected only in the electromagnetic calorimeter, it is fairly certain that it is a photon.

Electromagnetic calorimetry

Fabjan, Rev. Mod. Phys. 75 (2003) 1243

radiation length

$$X_0\ (\mathrm{g/cm^2}) \simeq \frac{716\ \mathrm{g\ cm^{-2}} A}{Z(Z+1)\ \ln(287/\sqrt{Z})} ,$$

energy of electron reduced by 1/e after traveling distance x

$$\langle E(x)\rangle = E_0\ e^{-\frac{x}{X_0}} .$$

critical energy: ionization losses and radiation losses (Bremsstrahlung) become equal

$$\epsilon = \frac{610(710)\ \mathrm{MeV}}{Z + 1.24(0.92)} .$$

longitudinal profile of e/m shower
using X_0 allows an universal description

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} , \qquad t = x/X_0$$

shower maximum
depth at which largest number of secondary particles is produced

$$t_{\max} \simeq \ln \frac{E_0}{\epsilon} + t_0 ,$$

calorimeter thickness containing 95% of energy

$$t_{95\%} \simeq t_{\max} + 0.08Z + 9.6$$

transverse size of e/m shower (Molière radius)
mainly due to multiple scattering

$$R_M\ (\mathrm{g/cm^2}) \simeq 21\ \mathrm{MeV} \frac{X_0}{\epsilon(\mathrm{MeV})} .$$

Electromagnetic calorimetry

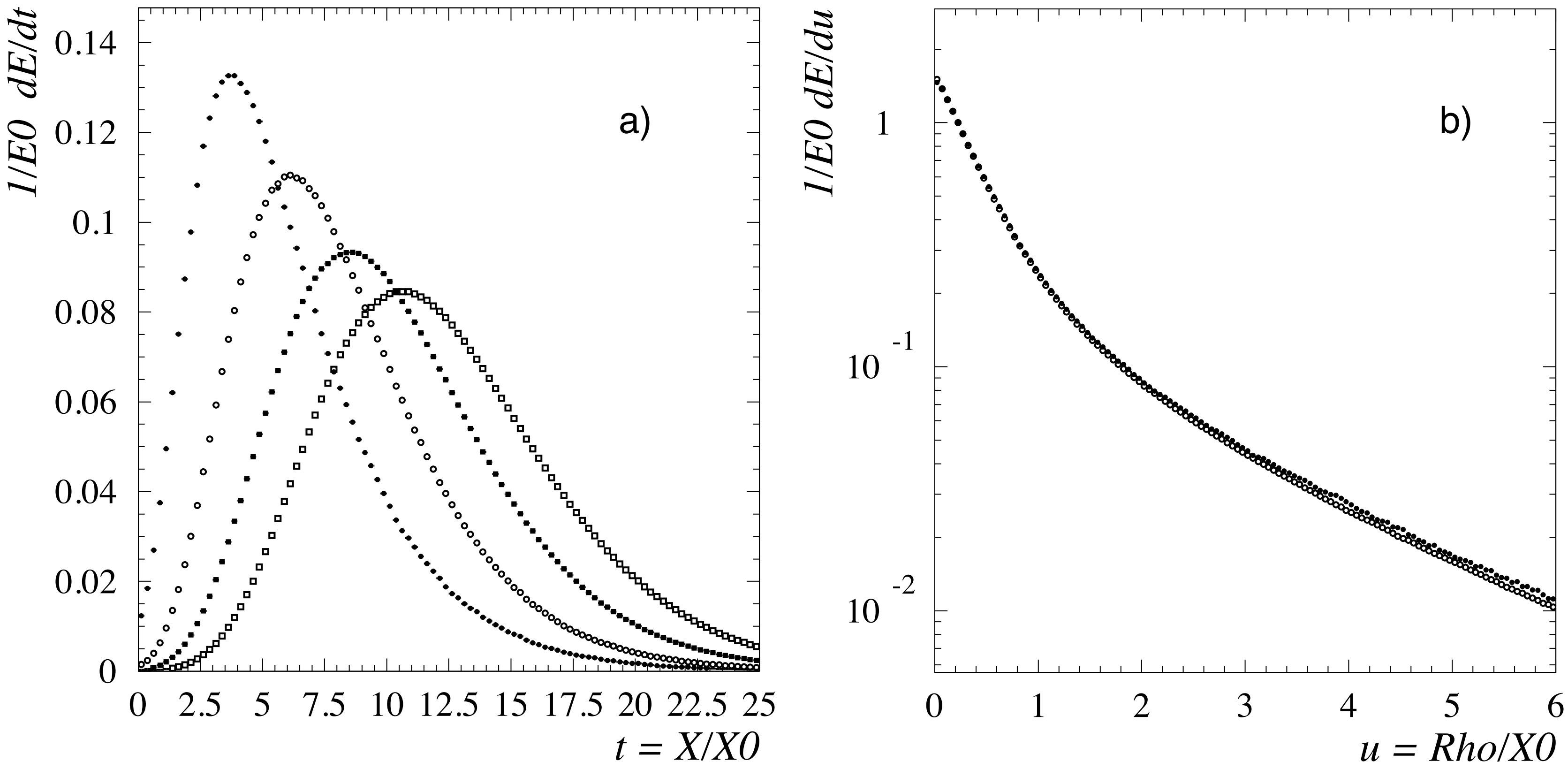
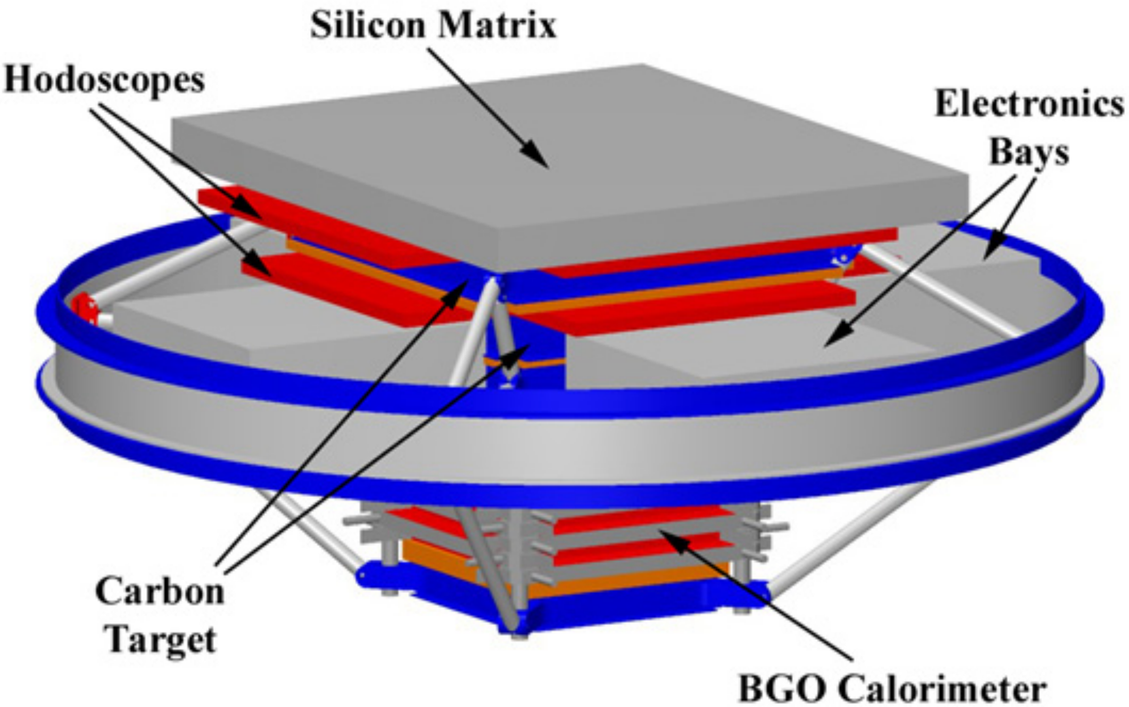
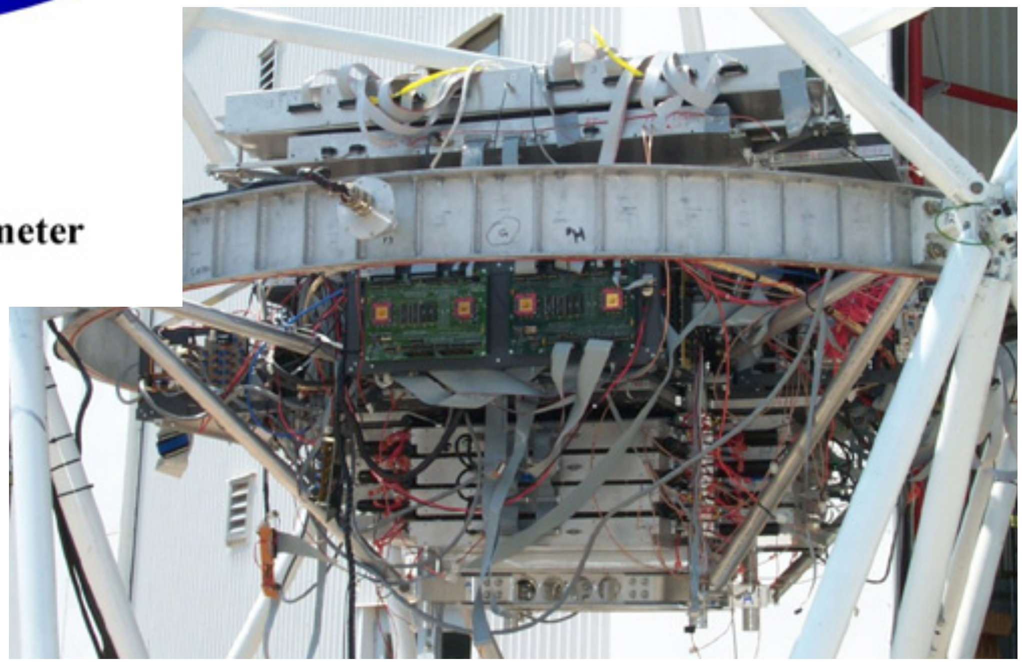


FIG. 2 (a): Simulated shower longitudinal profiles in $PbWO_4$, as a function of the material thickness (expressed in radiation lengths), for incident electrons of energy (from left to right) 1 GeV, 10 GeV, 100 GeV, 1 TeV. (b): Simulated radial shower profiles in $PbWO_4$, as a function of the radial distance from the shower axis (expressed in radiation lengths), for 1 GeV (closed circles) and 1 TeV (open circles) incident electrons. From Maire (2001).

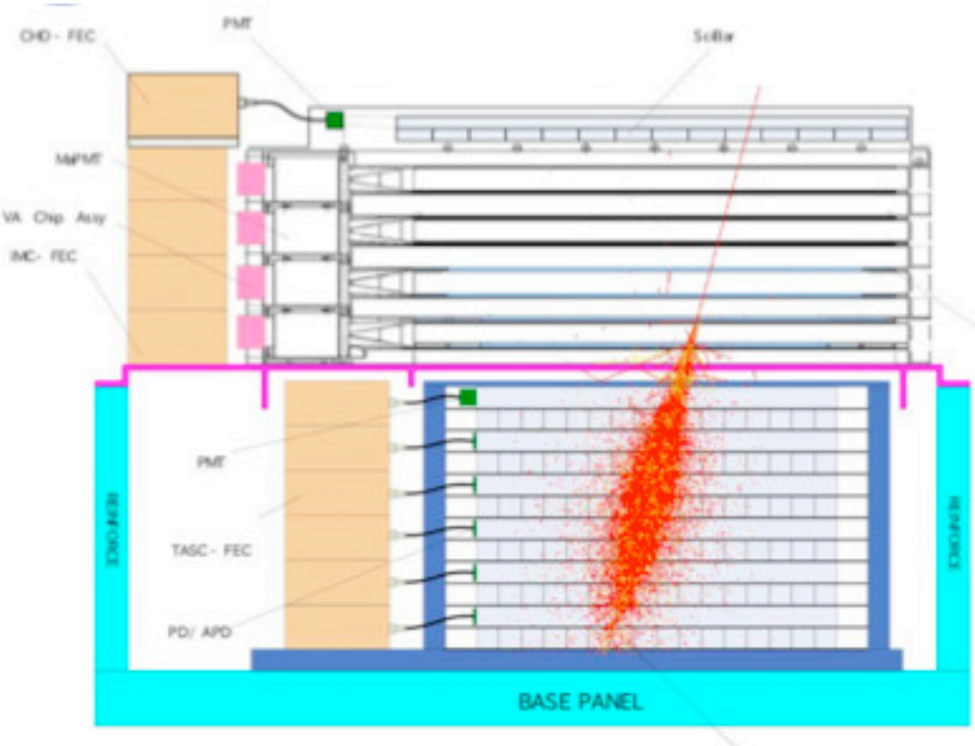
Fabjan, Rev. Mod. Phys. 75 (2003) 1243


Advanced Thin Ionization Calorimeter


Silicon Matrix
Hodoscopes
Electronics Bays
Carbon Target
BGO Calorimeter

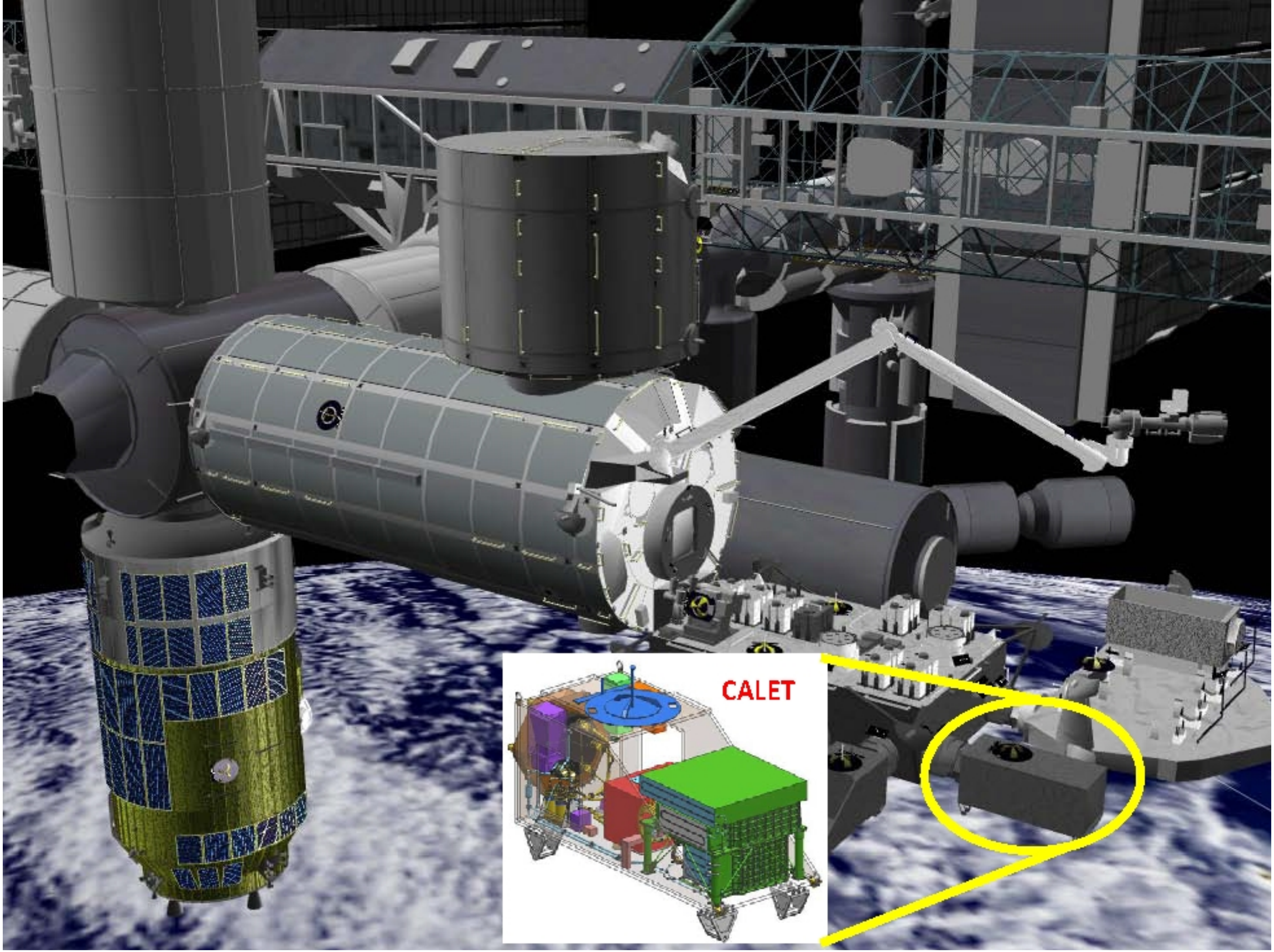


The CALorimetric Electron Telescope (CALET): High Energy Astroparticle Physics Observatory on the International Space Station



- CHarge Detector (CHD)
  (Charge Measurement in Z=1-40)
- Imaging Calorimeter (IMC)
  (Particle ID, Direction)
  Total Thickness of Tungsten (W): 3 X_0 , 0.11 λ_I
  Layer Number of Scifi Belts: 8 Layers × 2(X,Y)
- Total Absorption Calorimeter (TASC)
  (Energy Measurement, Particle ID)
  PWO 20mm x 20mm x 320mm
  Total Depth of PWO: 27 X_0 (24 cm) , 1.35 λ_I

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	**Charge Measurement (Z = 1 - 40)**	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	**Plastic Scintillator : 2 layers Unit Size: 32mm x 10mm x 450mm**	SciFi : 16 layers Unit size: 1mm^2 x 448 mm Total thickness of Tungsten: 3 X_0	PWO log: 12 layers Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: 27 X_0
Readout	**PMT+CSA**	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)

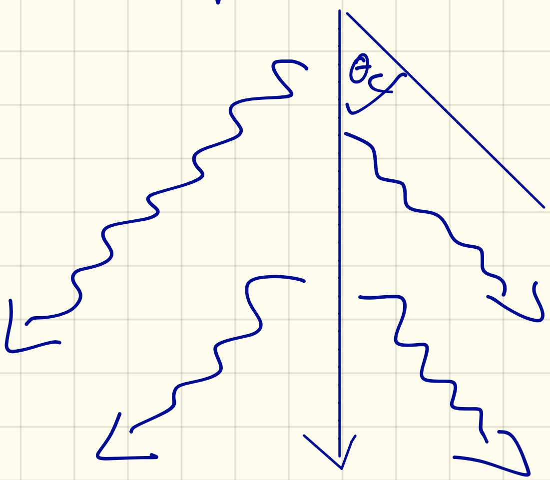

CALET

Čerenkov Detector

charged particles in a medium with refractory index n moving with a velocity $v > \frac{c}{n}$

→ Čerenkov radiation

particle



$$\cos\theta_c = \frac{c}{n \cdot \beta \cdot c} = \frac{1}{n\beta}$$

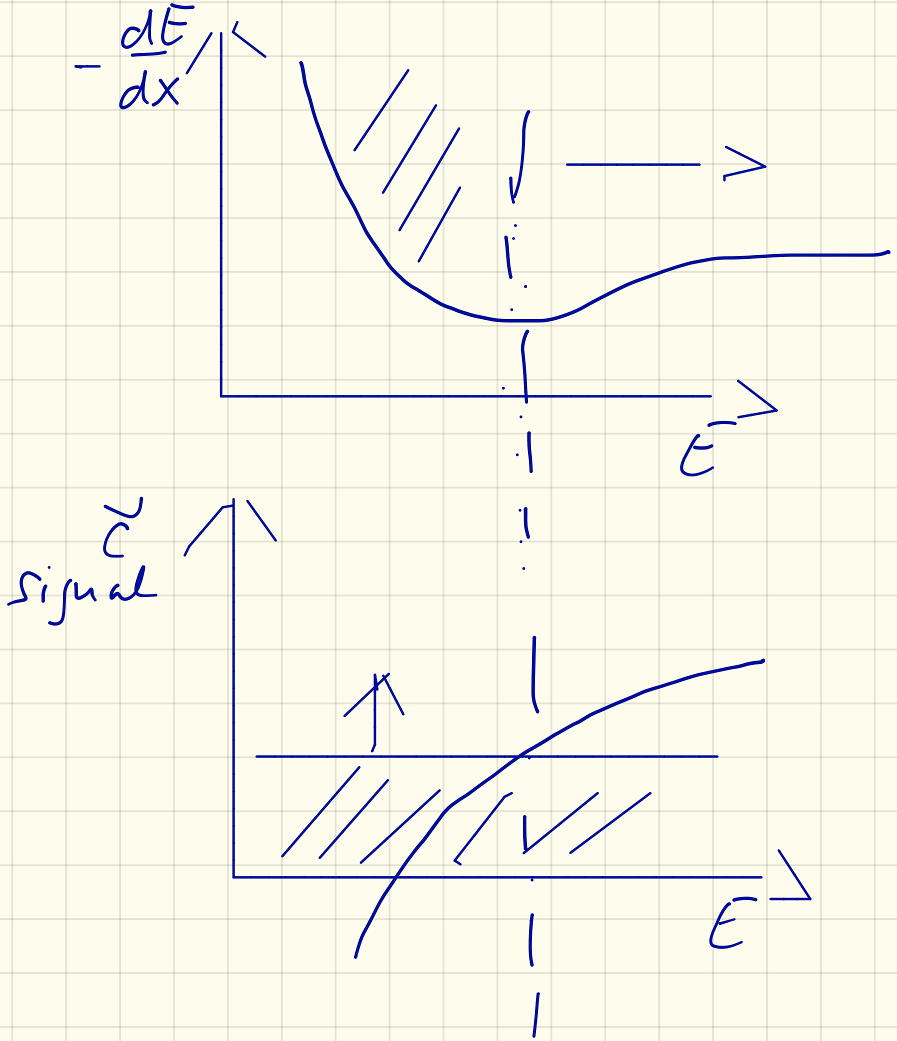
$$\Rightarrow \theta_c = \arccos\frac{1}{n}$$

$n > 1 \Rightarrow$ threshold energy

$$\gamma_{th} = \frac{1}{\sqrt{1-\beta_{th}^2}} = \frac{1}{\sqrt{1-\frac{1}{n^2}}} = \frac{E_{th}}{m_0 c^2}$$

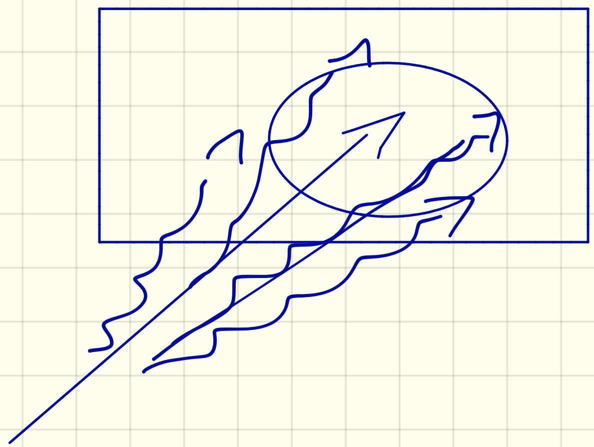
• threshold detector

with a Č detector low-E particles can be ~~identified~~ rejected



• ring imaging Č counter (RICH)

→ measure β from θ_c



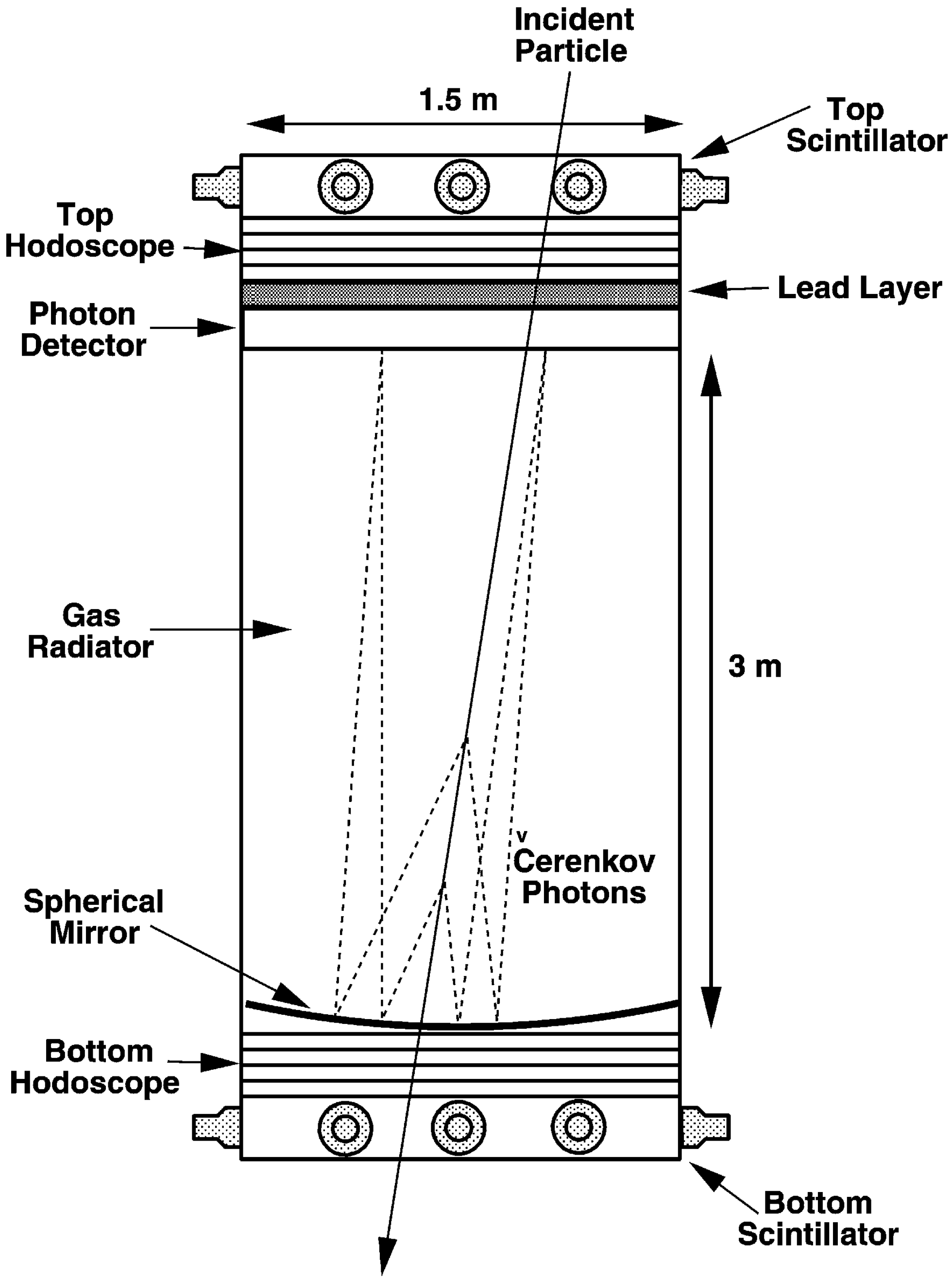


Fig. 1. Schematic cross-section of the instrument.

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Astroparticle Physics 18 (2003) 487–500

Astroparticle Physics

www.elsevier.com/locate/astropart

The energy spectrum of cosmic-ray protons and helium near 100 GeV

E. Diehl [1], D. Ellithorpe, D. Müller, S.P. Swordy *

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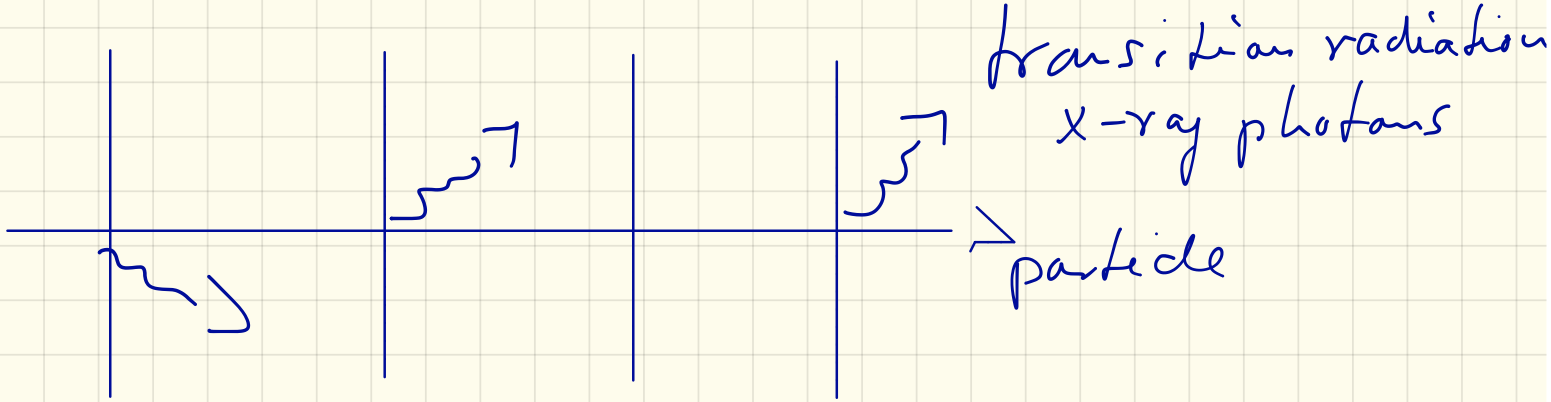
Received 15 February 2002; accepted 2 May 2002

Transition radiation detector (TRD)

below Č. threshold

charged particles traverse a border between two media with different electric properties
→ transition radiation is emitted (Ginzburg 1946)



radiated $E \propto \gamma$ Lorentz factor
→ energy measurement

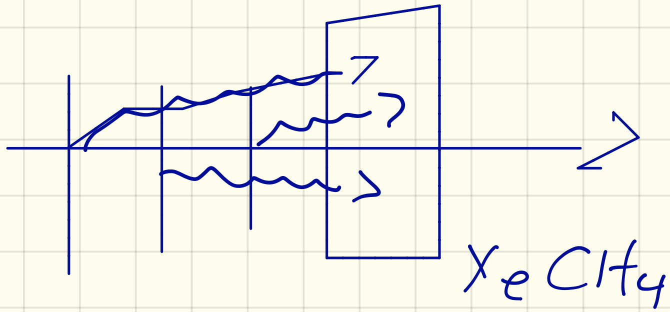
measurement of the x-ray photons

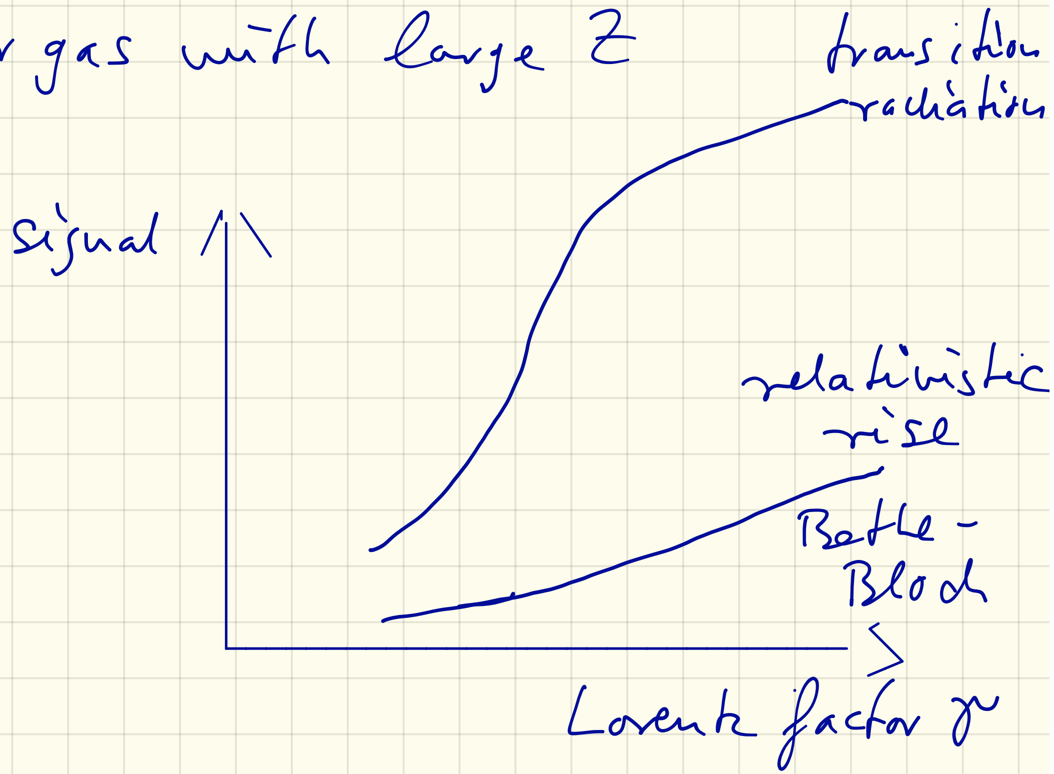
e.g. with a MWPC (multi-wire proportional chamber)

photoelectric effect $\sigma \propto Z^5$

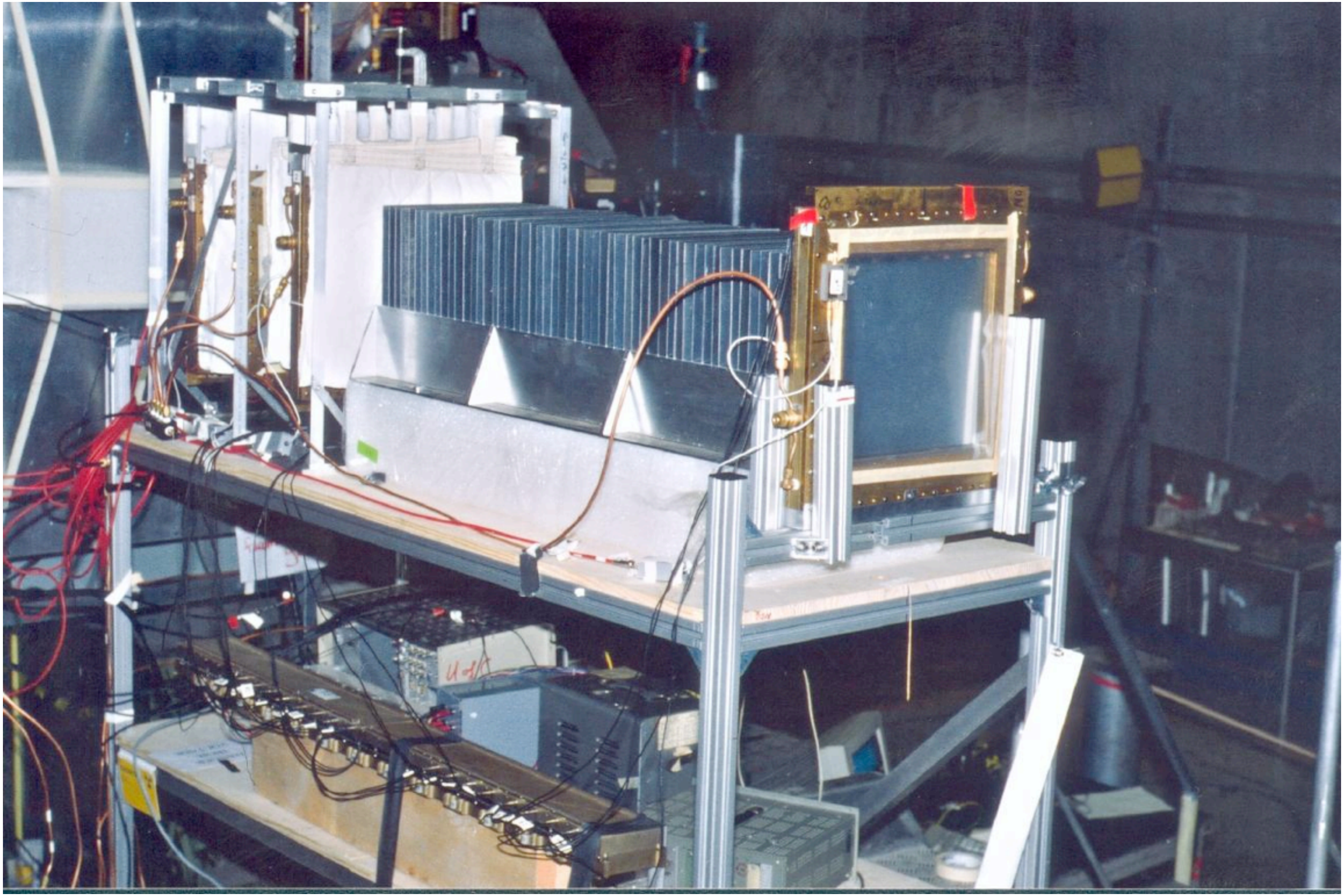
-> big cross section for gas with large Z

-> Xe





TRD test at CERN



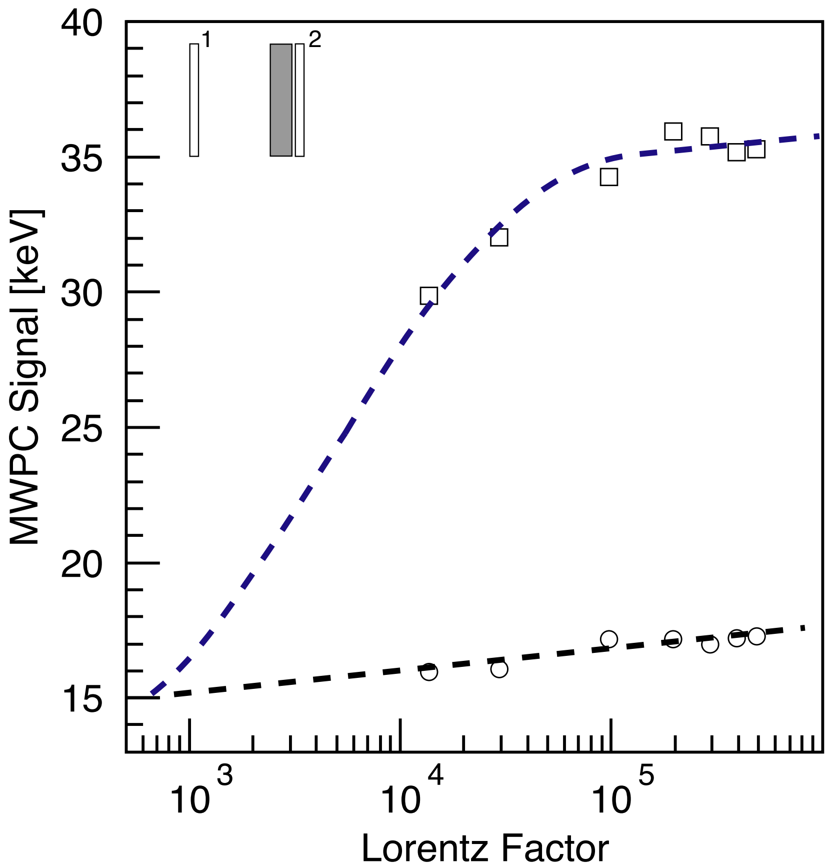
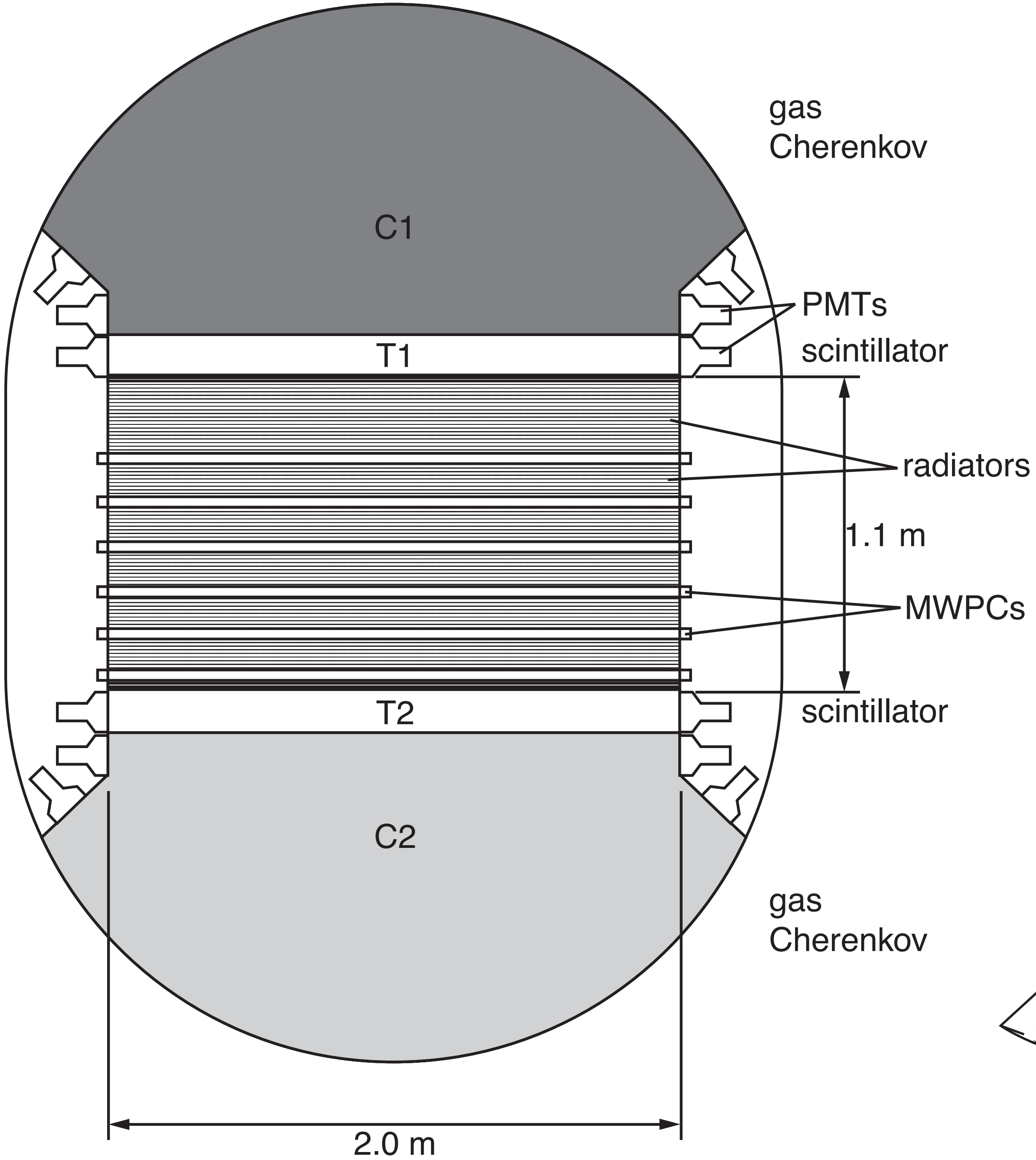
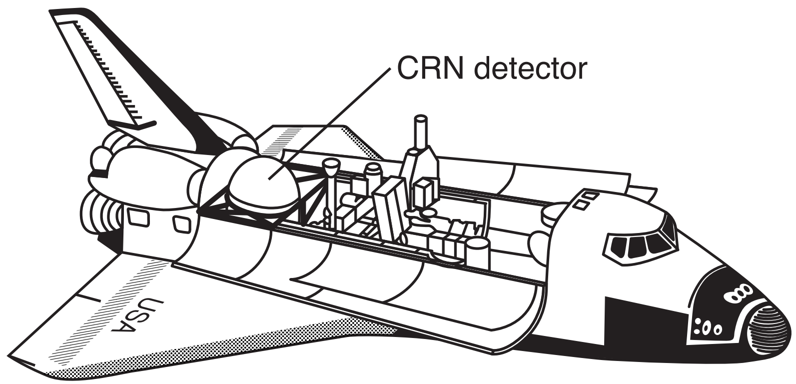


Fig. 8. Average detector signal versus Lorentz factor for a CRN-like radiator configuration. The open circles are data from MWPC 1, and the open squares are from MWPC 2, as shown in the inset schematic. The dashed lines serve to guide the eye.

Transition
Radiation
Detector

Cosmic Ray Nuclei instrument - CRN



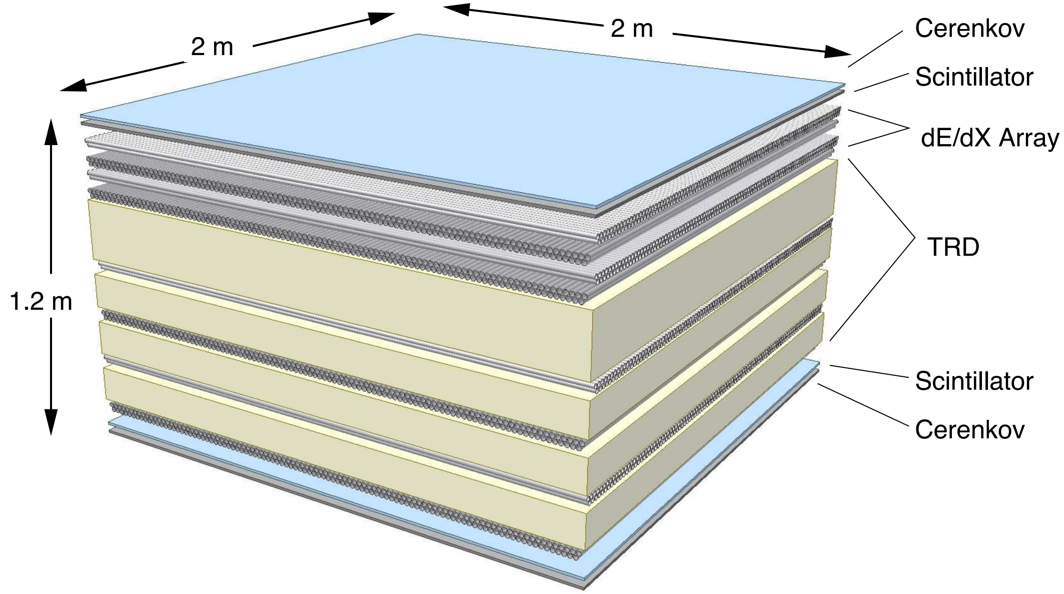


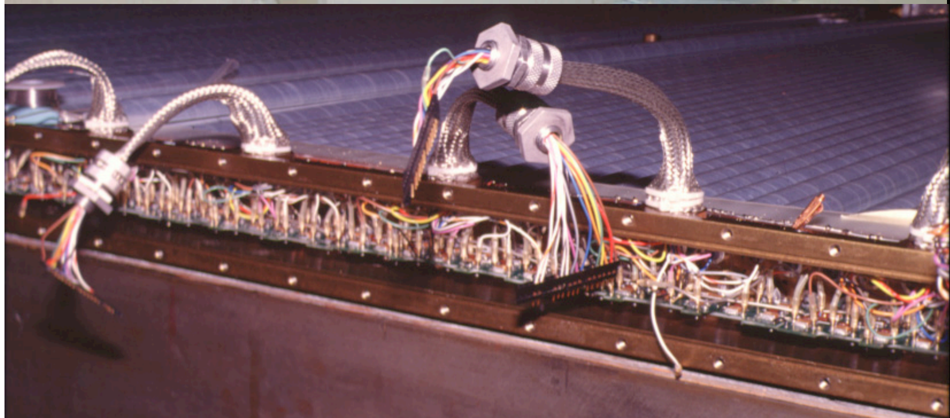
Challenger 1985

TRACER experiment

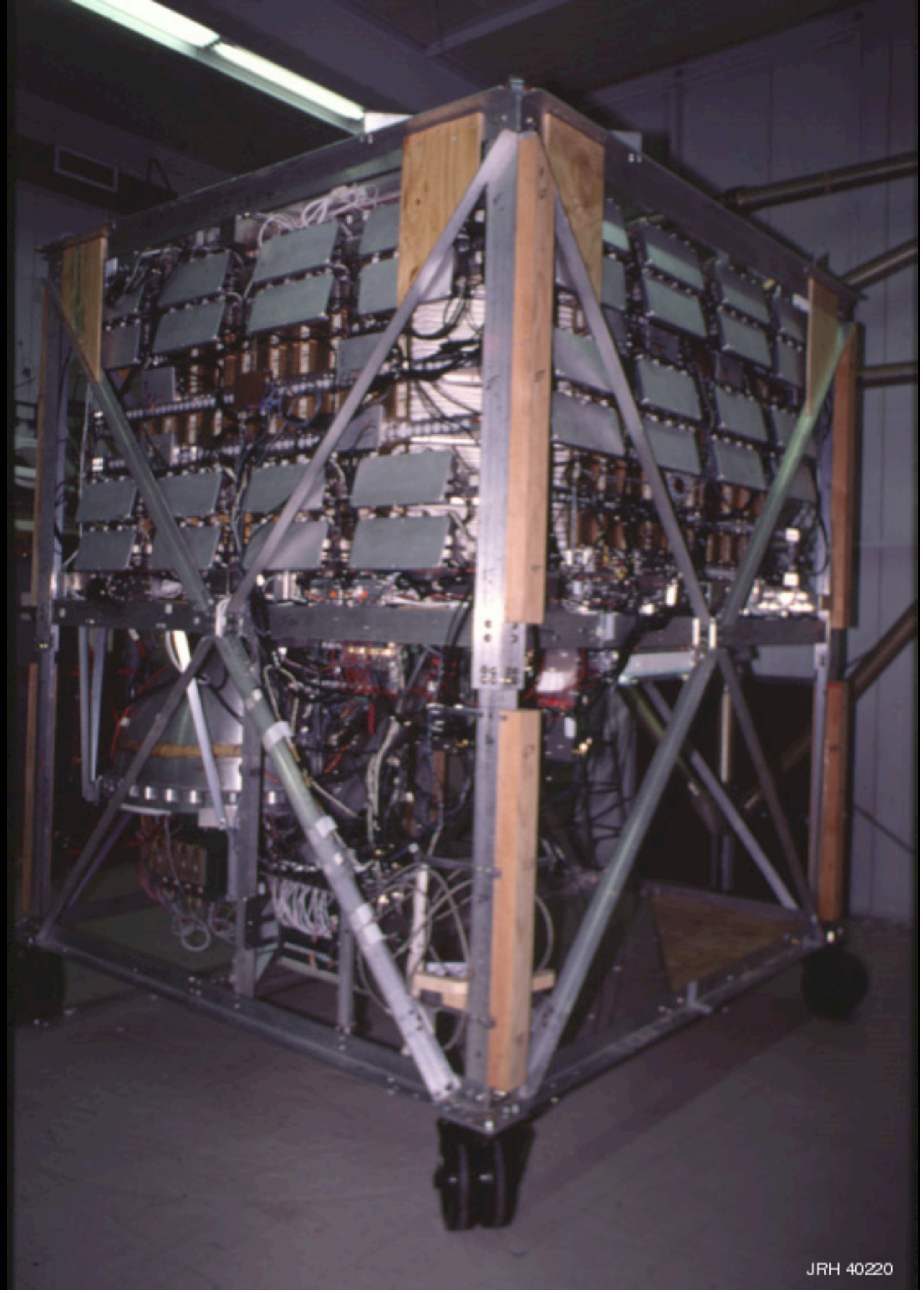
TRACER Overview

- Two pairs of Cerenkov and Scintillation Detectors
- 1600 Proportional Tubes (2cm $\times$ 2m) in 16 Layers
  - Upper 8 Layers: dE/dX in Gas (dE/dX array)
  - Lower 8 Layers: dE/dX+TR (TRD)

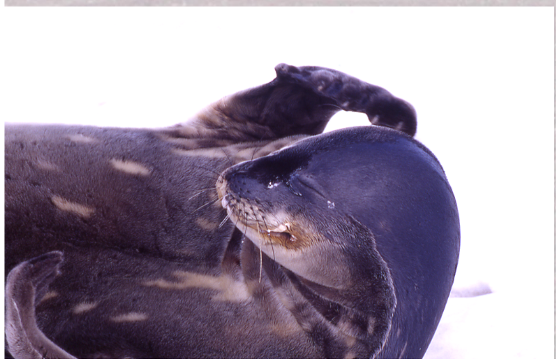




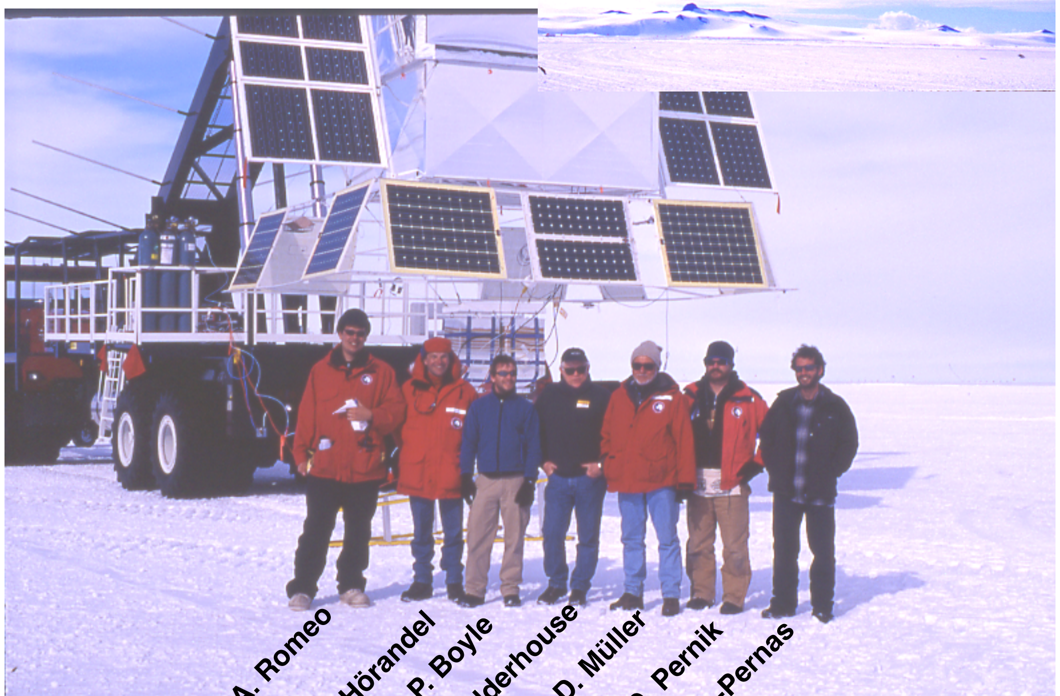

JRH 38201


JRH 40220

TRACER Experiment - Mc Murdo, Antarctica
flight: 12. – 26. December 2003 ~ 40 km (3-5 g/cm²)



TRACER Experiment



TRACER Experiment - Mc Murdo, Antarctica
flight: 12. – 26. December 2003 ~ 40 km (3-5 g/cm²)

balloon filled with $10^6\ m^3$ He

$\varnothing$ 130 m

total mass $\sim 5t$

flight altitude ~ 40 km (3–$5\ g/cm^2$)

<u>charge measurement</u>

$$\frac{dE}{dx} \propto Z^2$$

$$Z \propto \sqrt{\text{signal in scintillator}}$$

TRACER - measured charge distribution

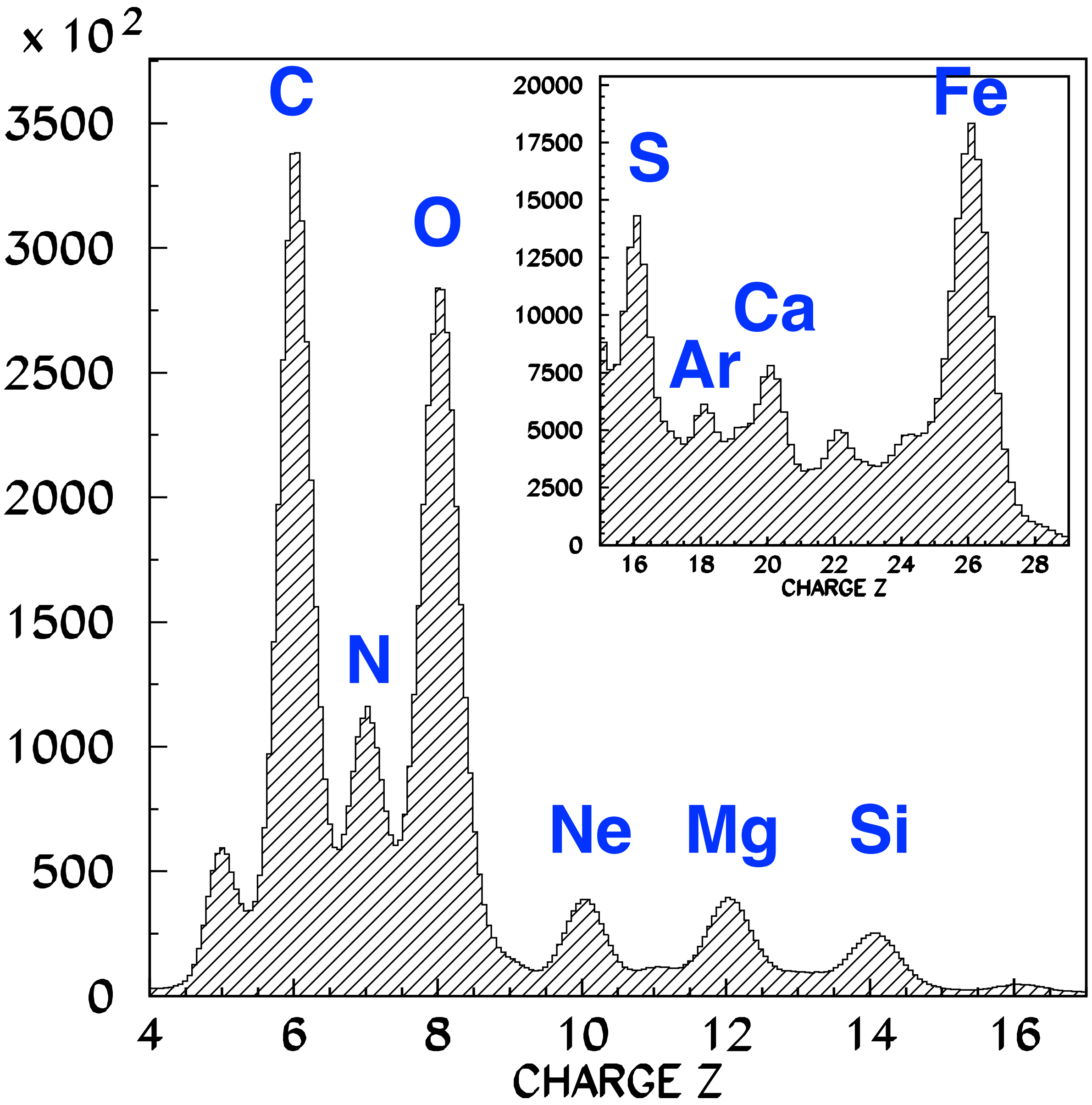


FIG. 5.—Charge histogram for all events measured in flight.