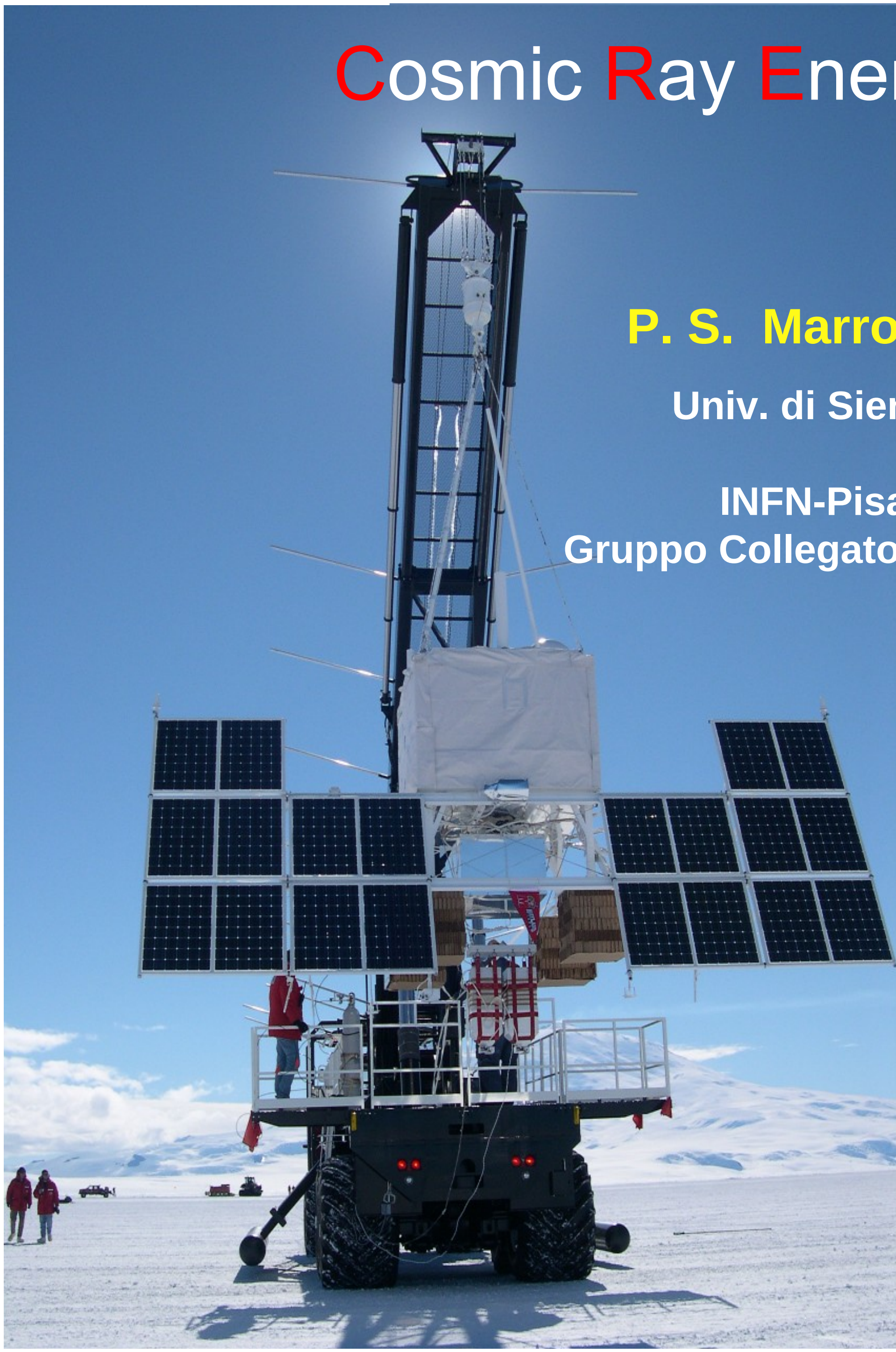
Cosmic Ray Energetics And Mass

P. S. Marrocchesi

Univ. di Siena

INFN-Pisa
Gruppo Collegato di Siena



Outline of the talk

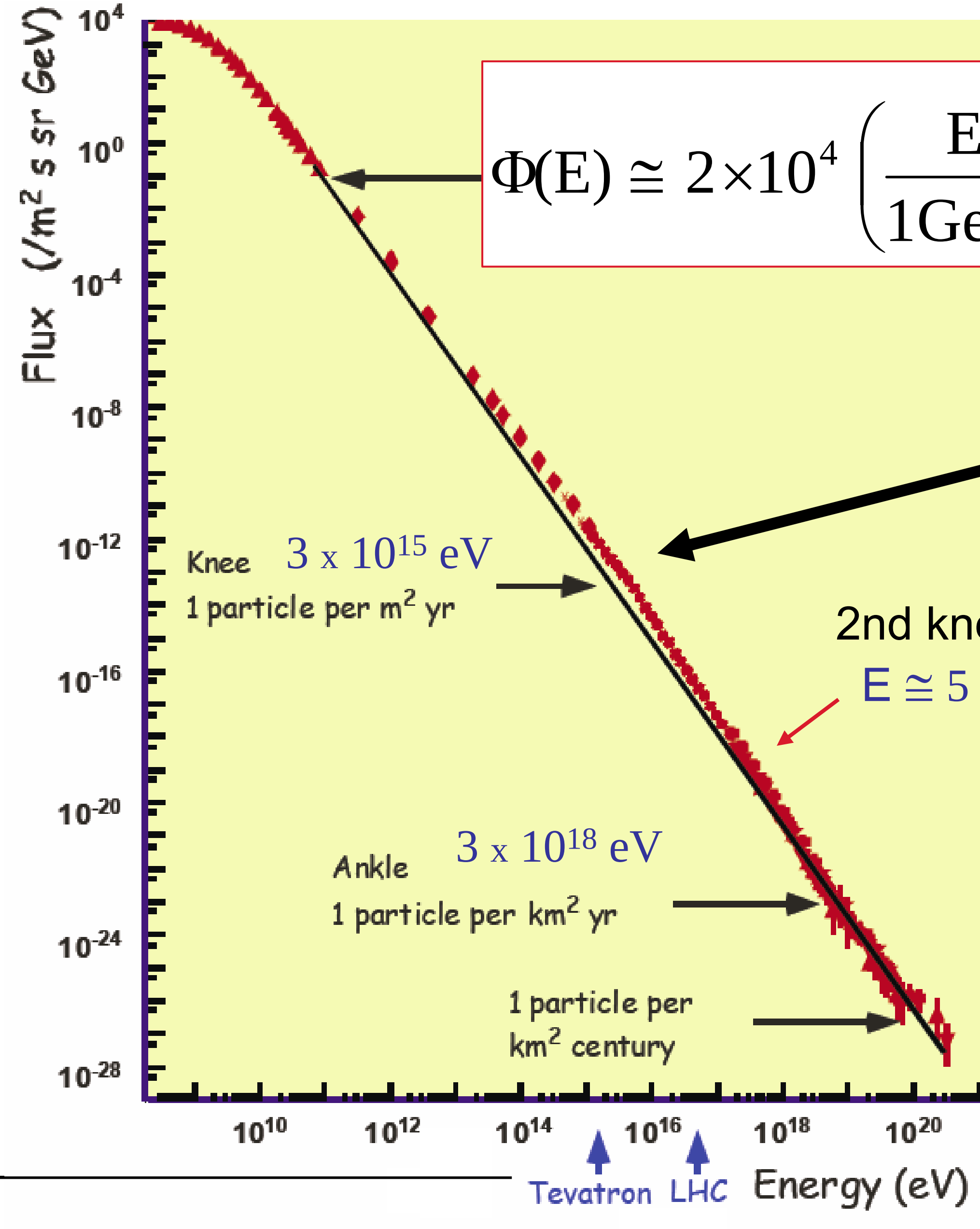
- Physics goals

- CREAM-1:
  - instrument configuration
  - results: B/C abundance ratio
    N/O abundance ratio
    H & He energy spectra

- CREAM-2
  - instrument configuration
  - data analysis
  - Heavy nuclei energy spectra

Cosmic ray spectrum

$$\Phi(E) \cong 2\times10^{4}\left(\frac{E}{1\,\mathrm{GeV}}\right)^{-2.7} \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,sr^{-1}\,\mathrm{GeV}^{-1}$$



Broken power law spectrum at the "knee"

2nd knee (dip)

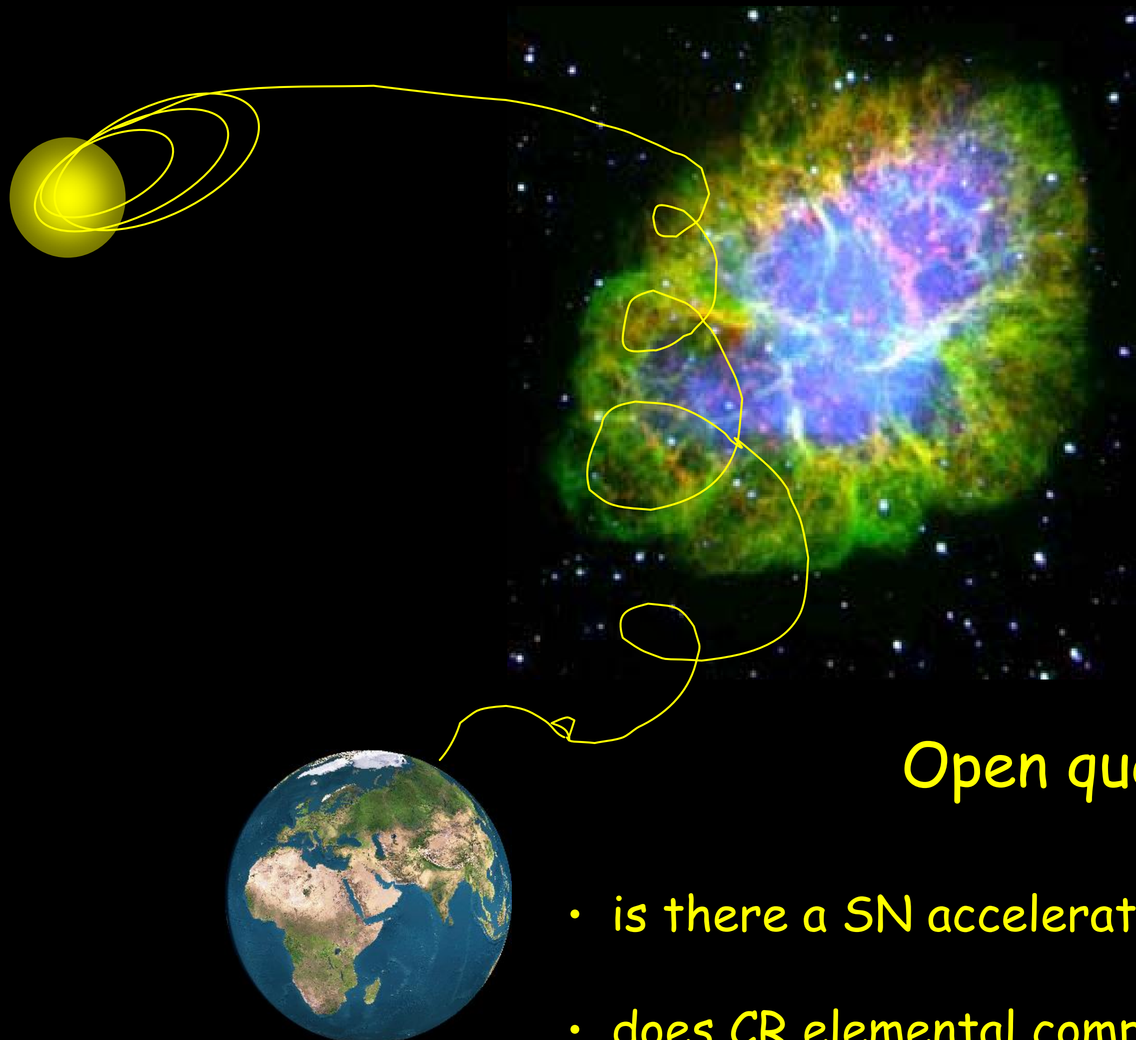
$E \cong 5 \times 10^{17}$ eV

A simple power law in the "all elements" spectrum below the knee:

$$\Phi(E) = k\,E^{-\gamma}$$

$\gamma \cong 2.7$ spectral index

Standard Model of Origin, Acceleration and Propagation of Galactic Cosmic Rays

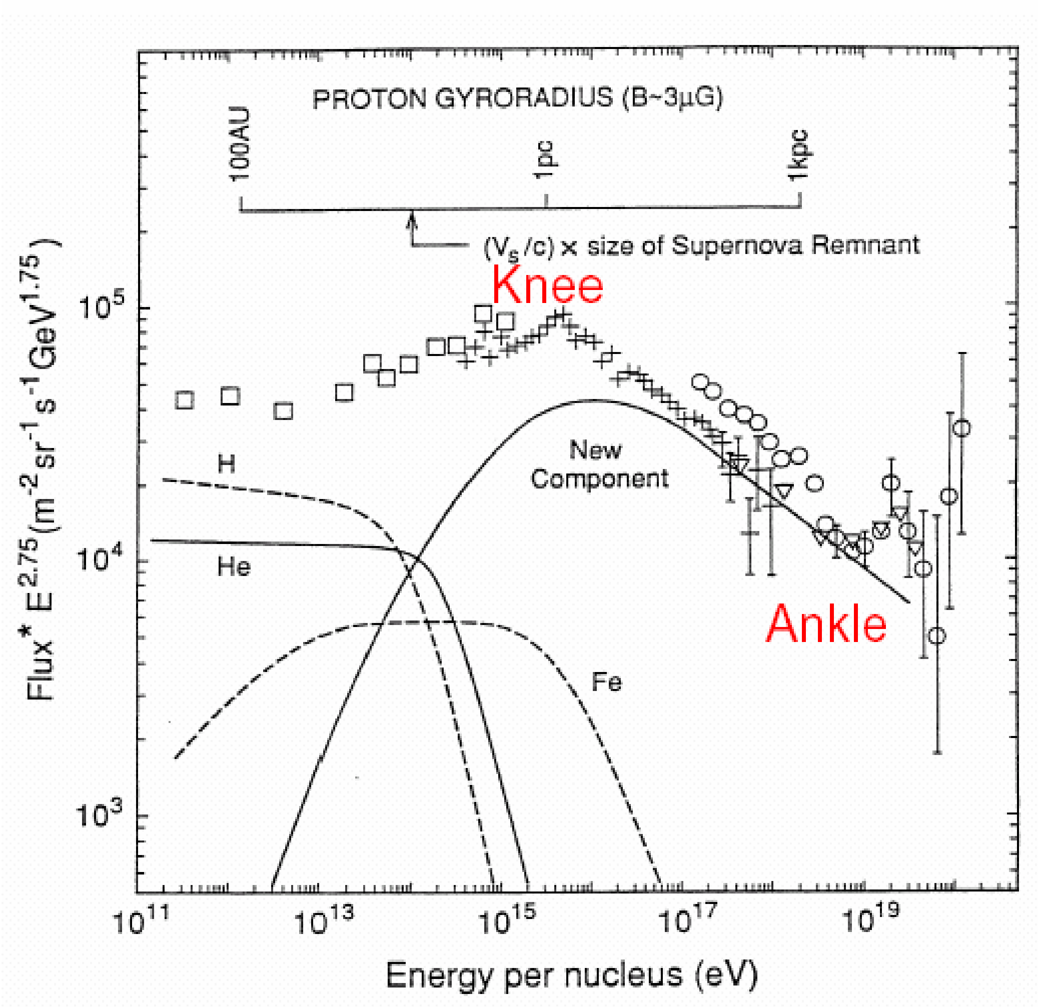


Supernova remnant

Open questions:

- is there a SN acceleration limit ?
- does CR elemental composition change with energy ?
- what is the energy dependence of the confinment time of CR in the Galaxy ?

- A **change in elemental composition** above **Z x 10^{14} eV** is predicted by a class of models (e.g.: Lagage & Cesarsky, 1983) based on supernova acceleration shock waves.
- **Direct measurements at 10^{14} eV** by **JACEE** (nuclear emulsions, balloon flights) favours light elements while heavier elements (e.g. Fe) are expected above the knee.



An <u>SNR acceleration limit</u> might imply that each chemical species has a characteristic (Z dependent) cutoff:

$$E_{max} \sim Z \times 10^{14} \text{ eV } ?$$

However, more recent models of CR acceleration predict an SN acceleration limit for protons above 10^{15} eV

Propagation of nuclei through the Galaxy

In absence of continuous energy losses (or re-acceleration) : $N_a(E_k)$ $\left[(\text{GeV/nucleon})^{-1}\ cm^{-3}\right]$

$$\frac{\partial N_a}{\partial t} - \vec{\nabla}\left(D\ \vec{\nabla} N_a\right) + nv\sigma_a N_a = q_a + \sum_{b>a} nv\sigma_{ba} N_b - \frac{1}{\tau_a^{\mathrm{dec}}} N_a$$

Diffusion in 3-dim

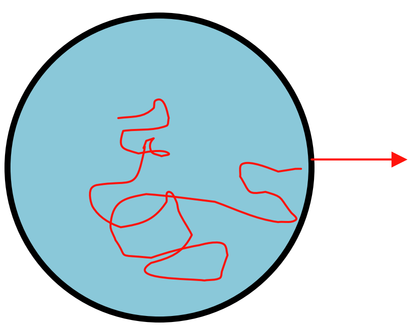
Losses due to the collisions with the ISM (total inelastic cross section: spallation on H and He)

sources

spallation b → a

decay of unstable nuclei

Leaky box model



$$\vec{\nabla}\left(D\ \vec{\nabla} N_a\right) \rightarrow \frac{N_a}{\tau^{\mathrm{esc}}}$$

confinement time
in the Galaxy ~ 10^7 y

$$\boxed{\langle\xi\rangle \equiv \langle\rho\rangle\ v\ \tau_{esc} \sim 5\ \mathrm{g\ cm^{-2}}}$$

"grammage" [g cm^{-2}]:
average thickness of ISM traversed during propagation

Dependence of τ_{esc} on energy

In the leaky-box model: $$D(E)\,\nabla^2 N \sim \frac{N}{\tau_{esc}(E)} \Rightarrow$$

where the **escape length** $<\rho>\, v\, \tau_{esc}$ **decreases with energy**: $$\boxed{\tau_{esc}(E) \propto E^{-\delta}}$$

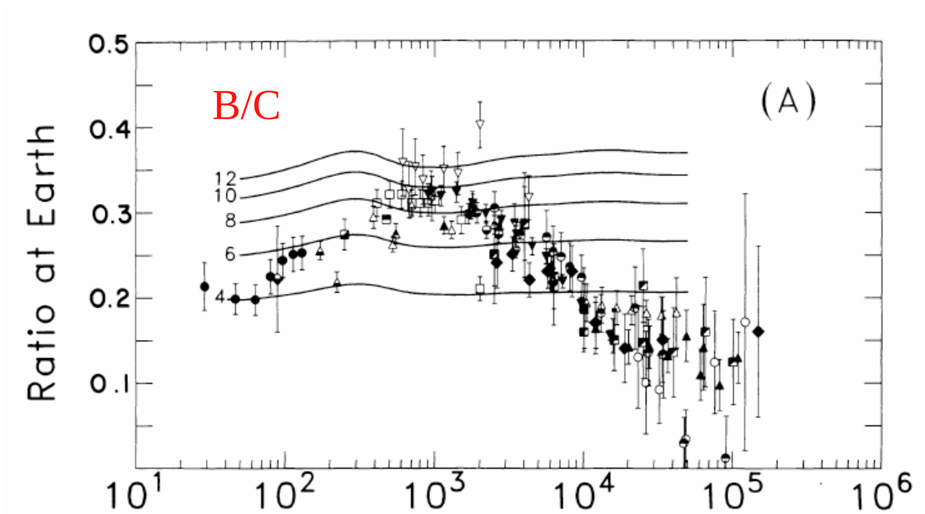
For primary nuclei: $$\frac{N(E)}{\tau_{esc}(E)} + \frac{N(E)}{\tau_{int}(E)} \cong Q(E)$$

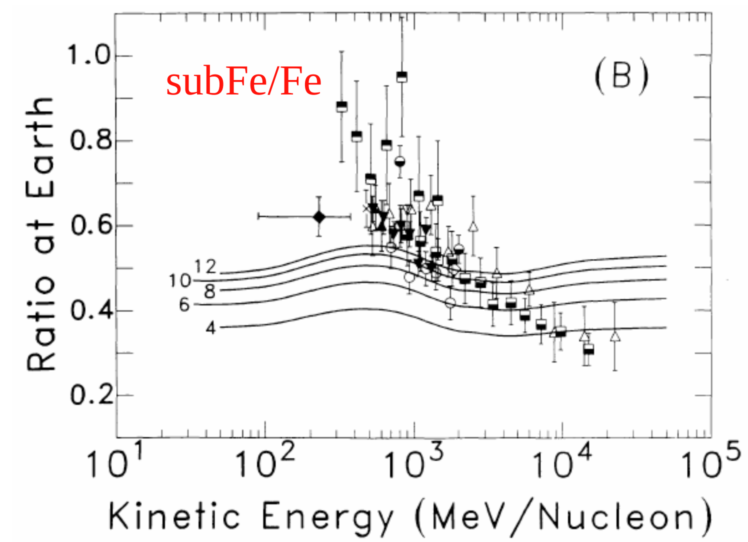
In the limit of high energy: $\tau_{esc} << \tau_{int}$ $$\boxed{N(E) \cong Q(E)\,\tau_{esc}(E)}$$

$$\boxed{N(E) \cong Q(E) \propto E^{-\alpha}}$$ source spectrum

$$\boxed{N(E) \cong Q(E)\,\tau_{esc}(E) \propto E^{-\alpha-\delta}}$$ observed spectrum

The secondary-to-primary ratio S/P



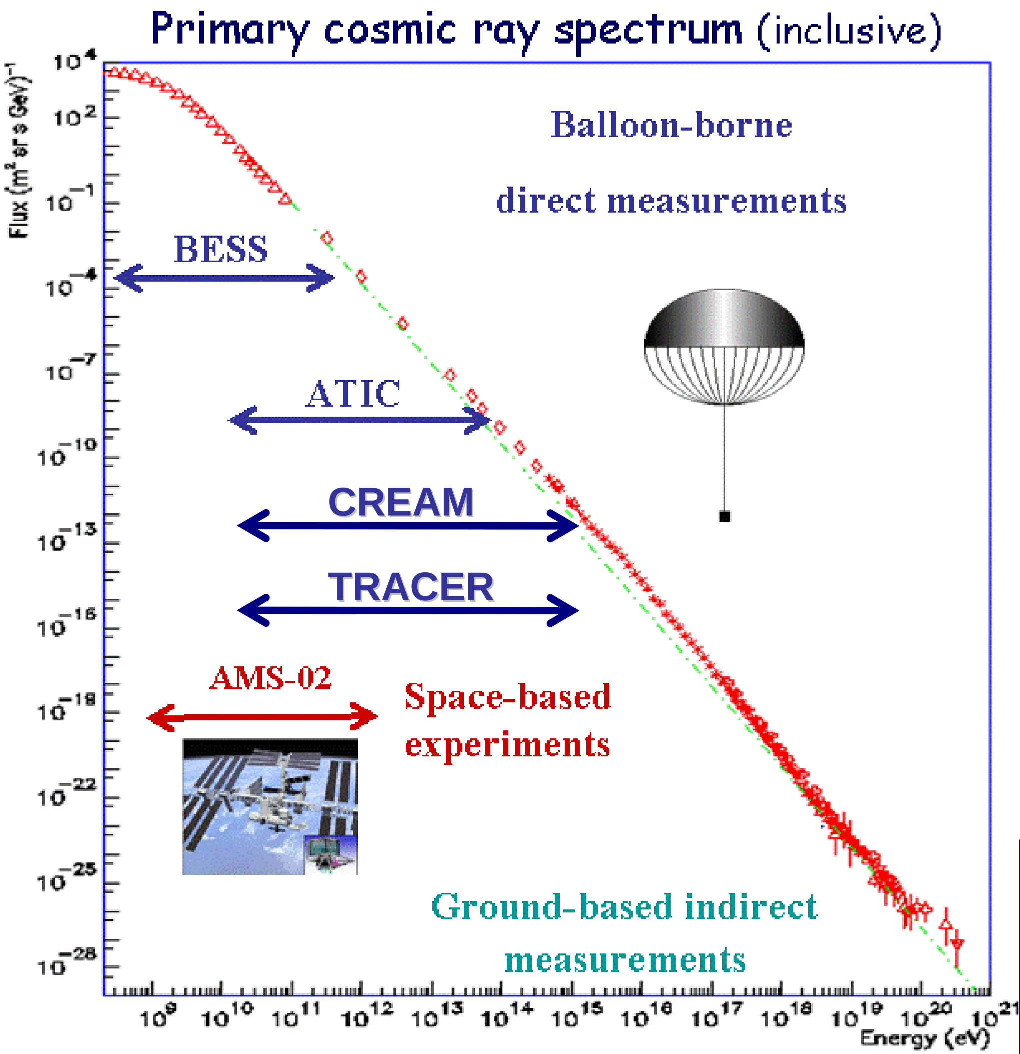


The measured secondary-to-primary ratios, as a function of E/nucleon, are incompatible with an energy independent τ_{esc}

At high energy (E > 100 GeV/n) the S/P ratios measure the **energy dependence of the escape length**:

$$\boxed{\frac{N_S}{N_P}(E) \;\cong\; P_{P\rightarrow S}\,\frac{\tau_{esc}(E)}{\tau_{int}} \rightarrow E^{-\delta}}$$

CREAM main science goals



- search for a **cutoff in the proton spectrum** at E ≥ 100 TeV
- search for a change in the **elemental composition** approaching the "knee"
- measurement of **secondary-to- primary ratios** (test of propagation models).

CREAM can measure individual energy spectra and elemental composition (from H to Fe) of cosmic rays up to 1000 TeV

CREAM 1 & 2 collaboration

University of Maryland, USA
H.S. Ahn, O. Ganel, J.H. Han, K.C. Kim, M.H. Lee, A. Malinin, E.S. Seo, R. Sina, P. Walpole, J. Wu, Y.S.Yoon, S.Y. Zinn

Ohio State University, USA
P.S. Allison, J. J. Beatty, T. J. Brandt

University of Siena and INFN, Italy
M.G. Bagliesi, G. Bigongiari, P. Maestro, P.S. Marrocchesi, R. Zei

University of Chicago, USA
P. Boyle, S.P. Swordy, S.P. Wakely

University of Minnesota, USA
J.T. Childers, M.A. Duvernois

Penn State University, USA
N.B. Conklin, S. Coutu, S.I. Mognet

Ewha Womans University, Republic of Korea
J.A. Jeon, S. Nam, I.H. Park, N.H. Park, J. Yang

Northern Kentucky University, USA
S. Nutter

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NASA

Wallops Flight Facility
Goddard Space Flight Center

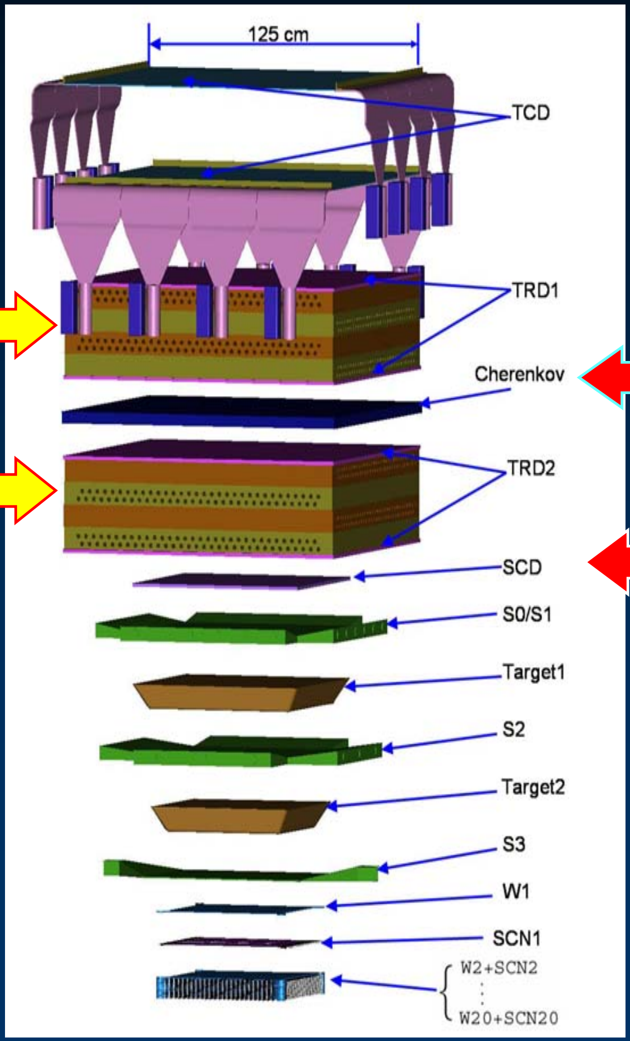
INFN
Istituto Nazionale di Fisica Nucleare

PNRA s.c.r.l.

Detector Systems in CREAM-1

- TCD: Timing Charge Detector
  - Trigger and Charge
- TRD: Transition Radiation Detector
  - Tracking
  - Lorentz Factor for Z ≥ 3

calorimeter module



CER: Cherenkov Detector
– Charge/Velocity for Z ≥ 3

SCD:

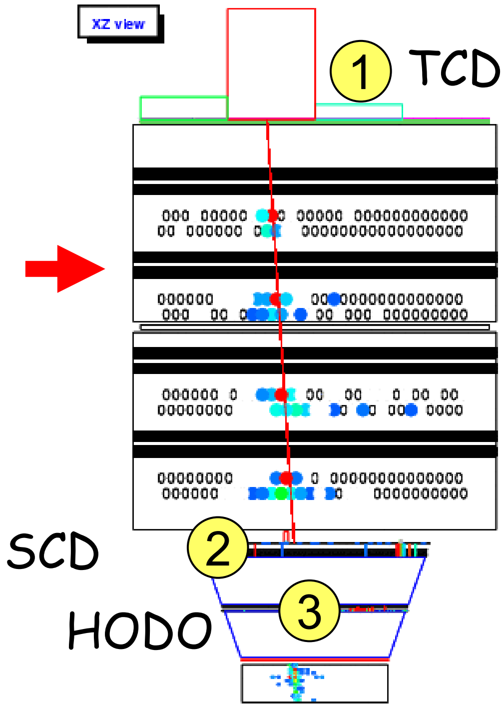
Silicon Charge Detector

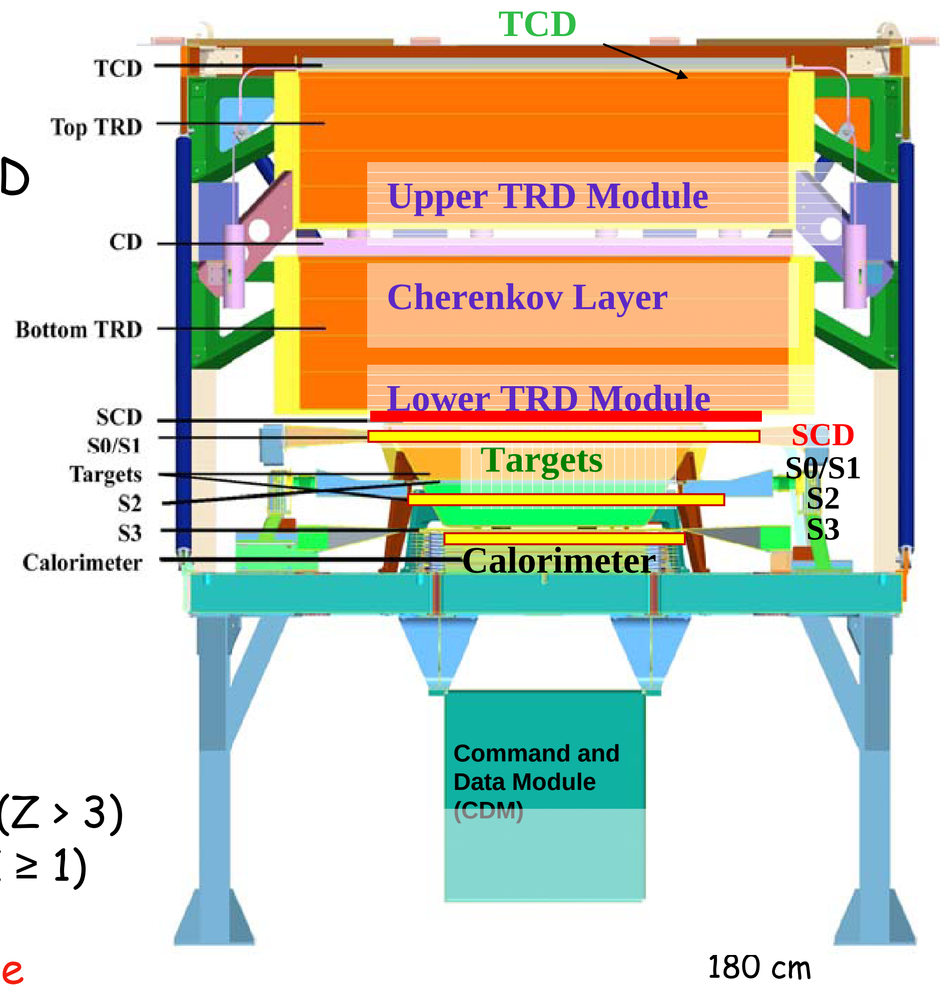
3 independent charge measurements :

- Timing-based Charge Detector (TCD)
- Pixelated Silicon Detector (SCD)
- Scintillating fiber Hodoscope (HODO)

CREAM-1 Detector configuration

Tracking above the target is provided by TRD and Hodo





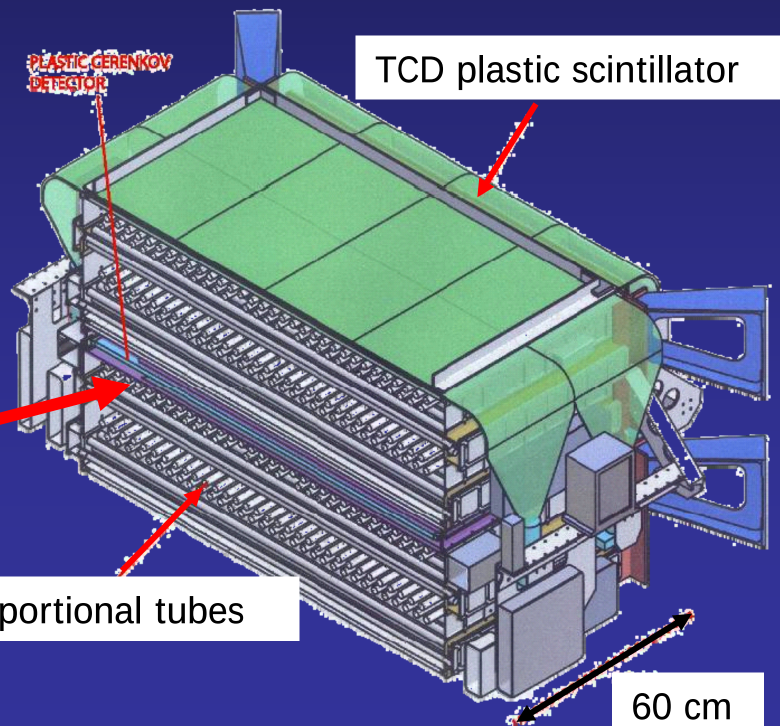
2 independent energy measurements :

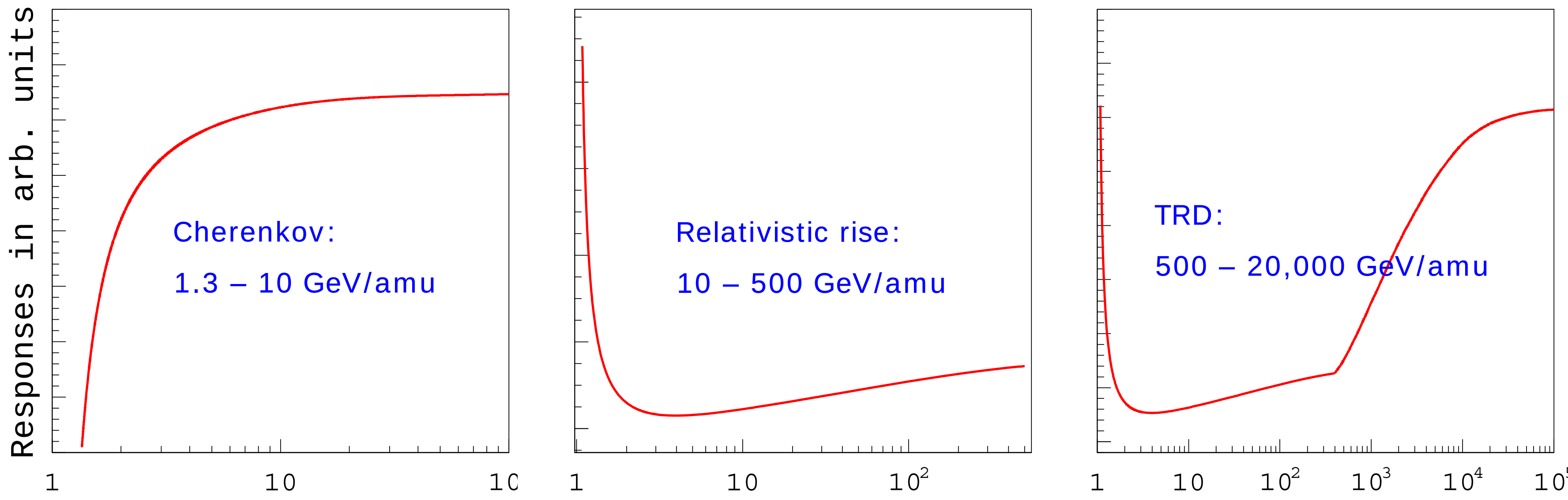
- TRD: Transition Radiation Detector (Z > 3)
- CAL: Tungsten Sci/Fi calorimeter (Z ≥ 1)

In-flight cross calibration of energy scale

Transition Radiation Detector (TRD)

- 512 Proportional Tubes
  - 2cm Aluminized Mylar (100 um)
  - 8 “X” and 8 “Y” Layers of 32 tubes
  - Embedded in Ethafoam Radiator
  - Gas: Xenon/Methane (95/5%)
  - Dual Gain Amplex Readout
  - Sensitivity to Z ≥ 3
- Cerenkov Detector
  - 1cm Acrylic Radiator
  - Wavelength-Shifting-Bar Readout

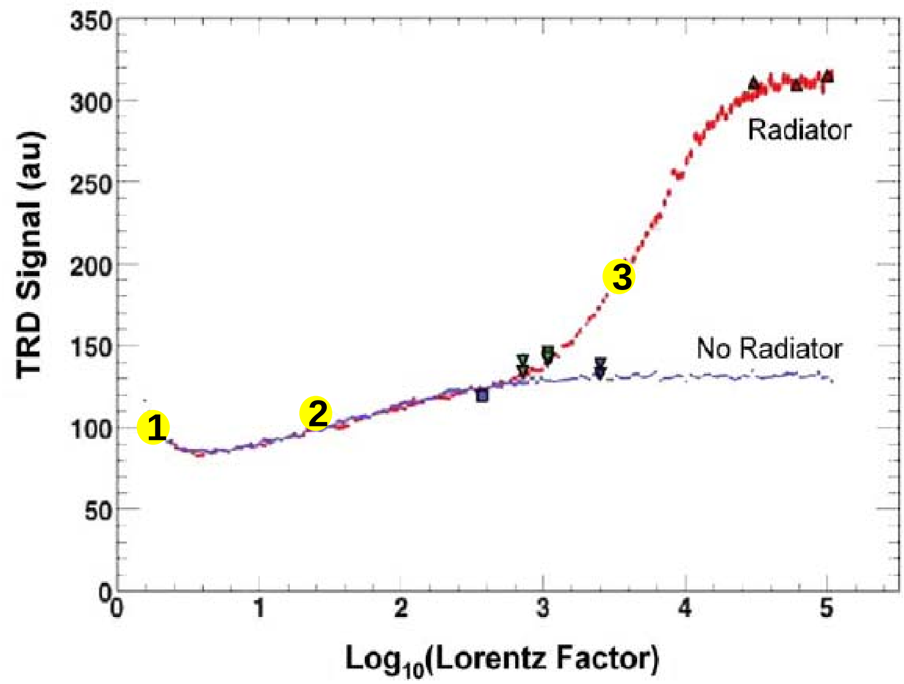




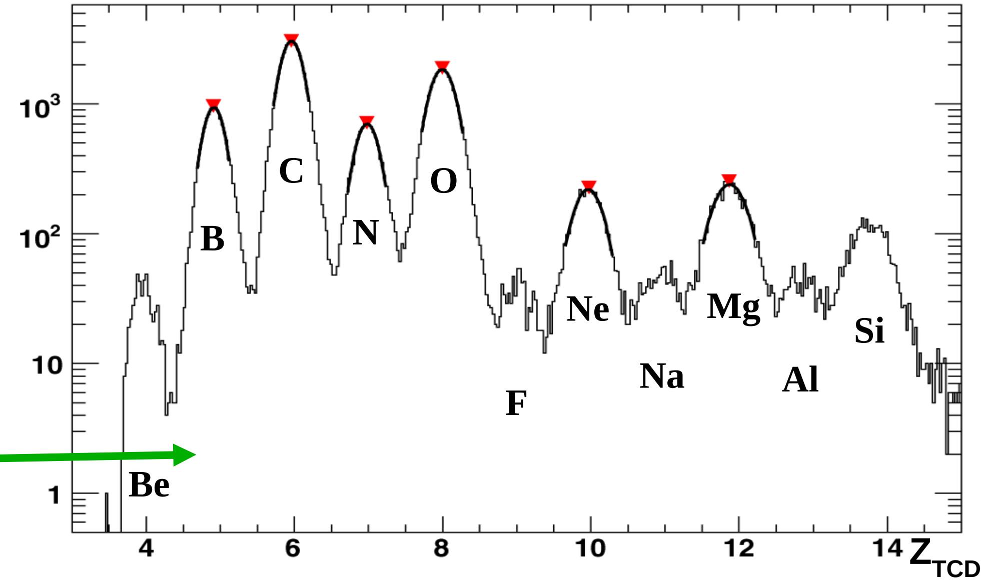
- Energy measurement in different intervals:

  1. **Cerenkov signal** $1.35 < \gamma < 10$
  2. **Multiple dE/dx sampling** $10 < \gamma < 500$
  3. **TR X-rays** $500 < \gamma < 20000$

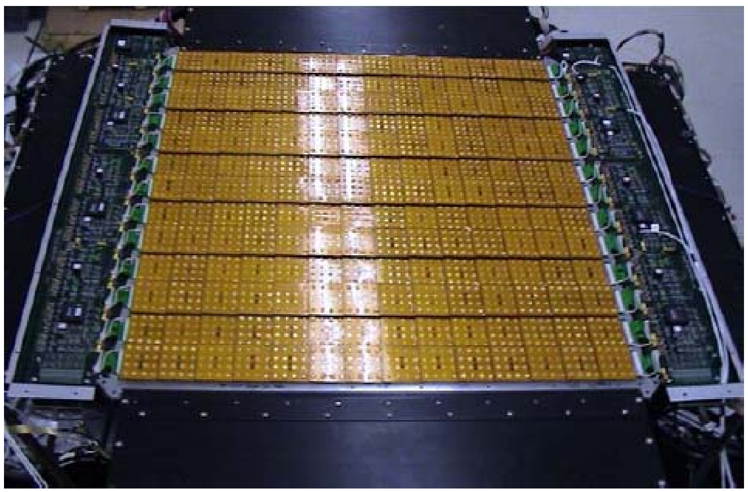
- Calibration at CERN with p, e^- and π beams.
  $\Rightarrow$ Geant4 based MC tuning

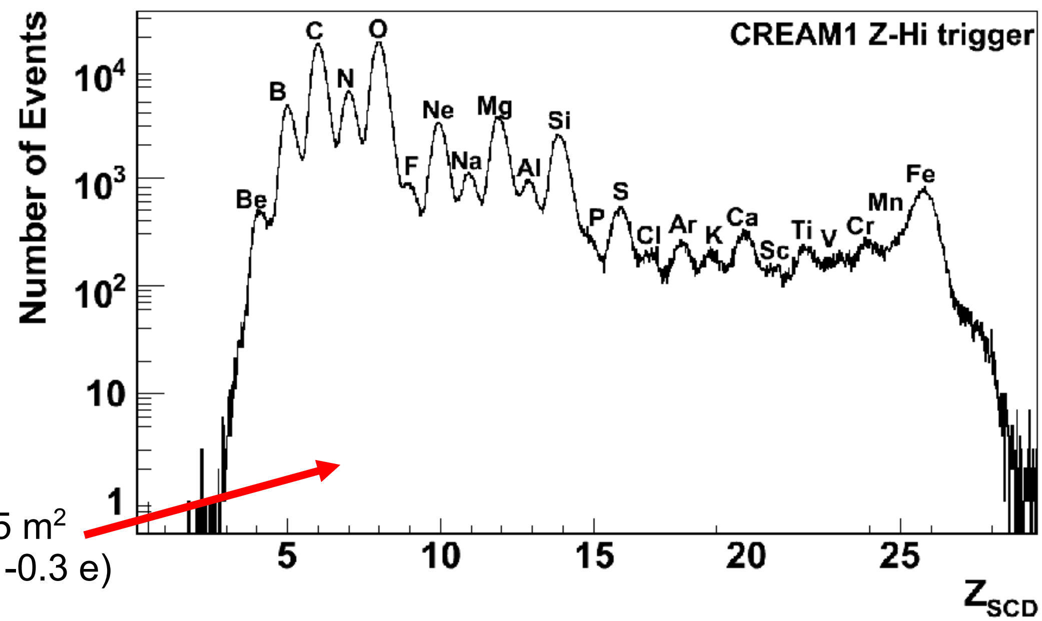


Cosmic-ray nuclei identification



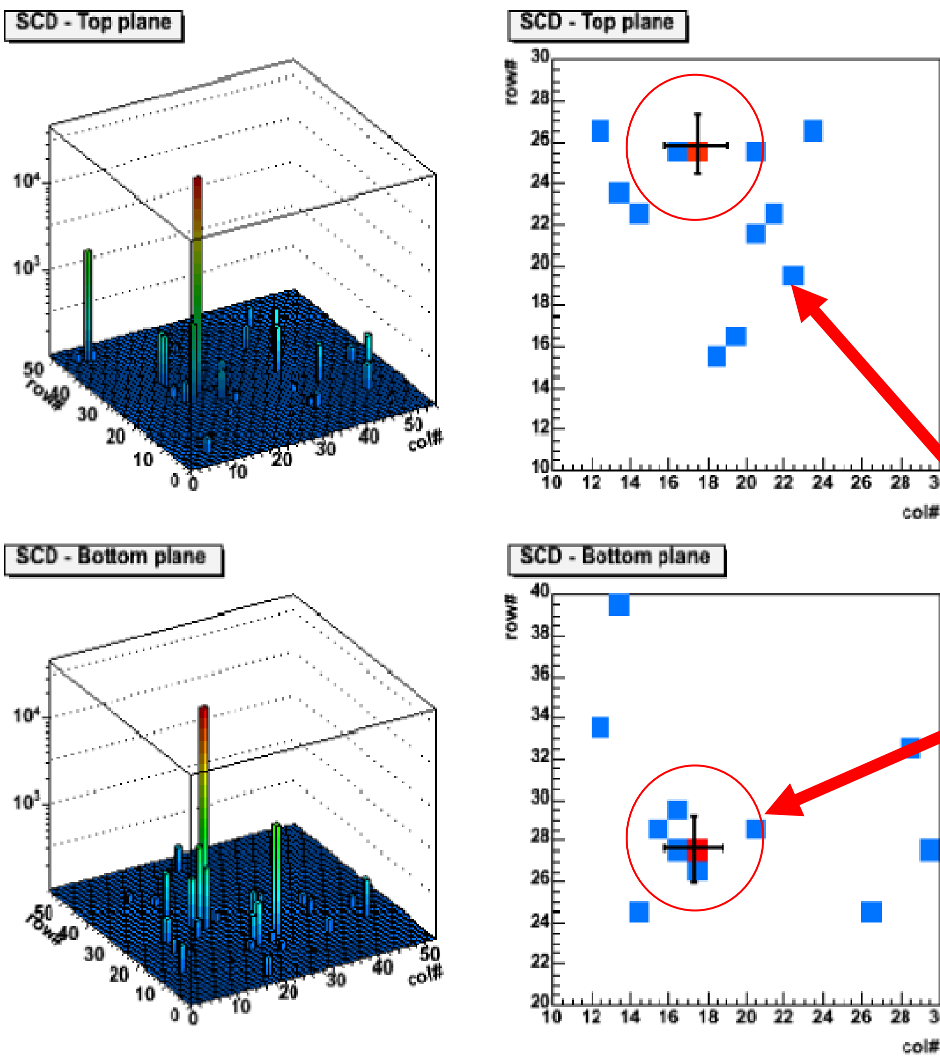
➢Timing Charge Detector (TCD)
- 5 mm thick fast (< 3 ns) plastic scintillator paddles
- charge measurement from H to Fe (σ~ 0.2-0.35 e)
- backscatter rejection by fast pulse shaping

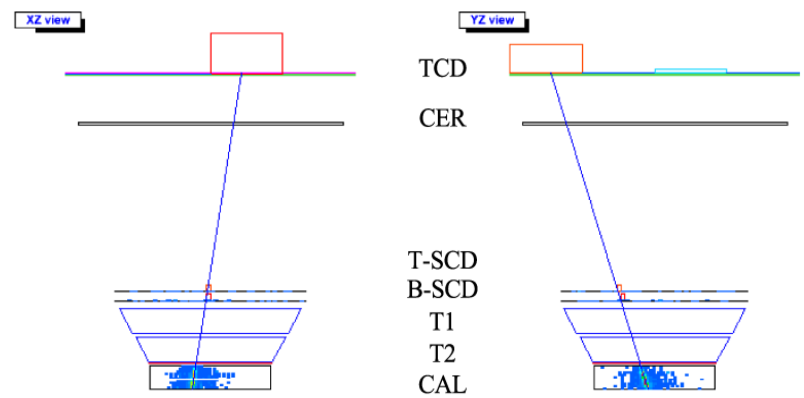




➢ Silicon Charge Detector (SCD)
- 2912 Si pixels, 380 μm thick. Active area ~ 0.65 m^2
- charge measurement from Z=1 to Z=26 (σ~ 0.1-0.3 e)

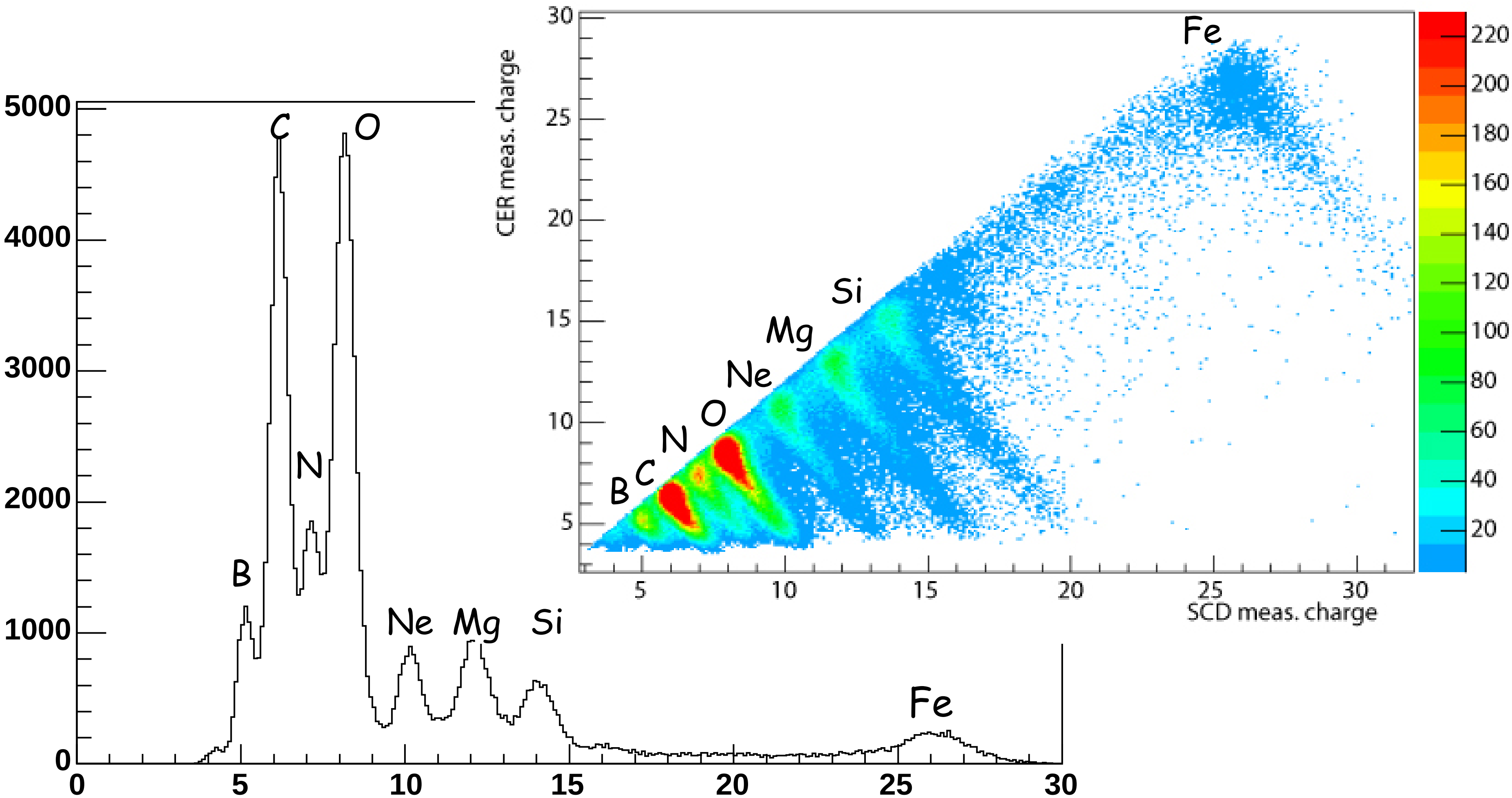
Charge-ID with the Silicon Charge Detector



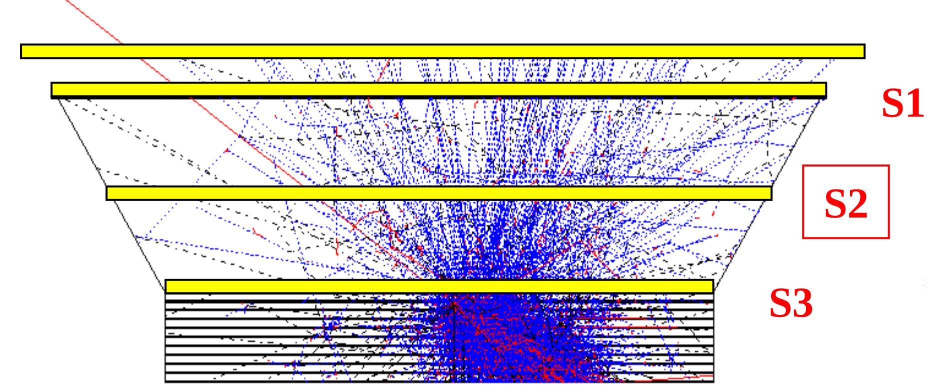


- Projection of CAL track to SCD
- The track is matched with the SCD pixel hit by the incoming particle
- ***Rejection of backscattered particles***
- ***Charge identification*** of the incoming particle (a consistent charge assignement from the 2 layers is required)

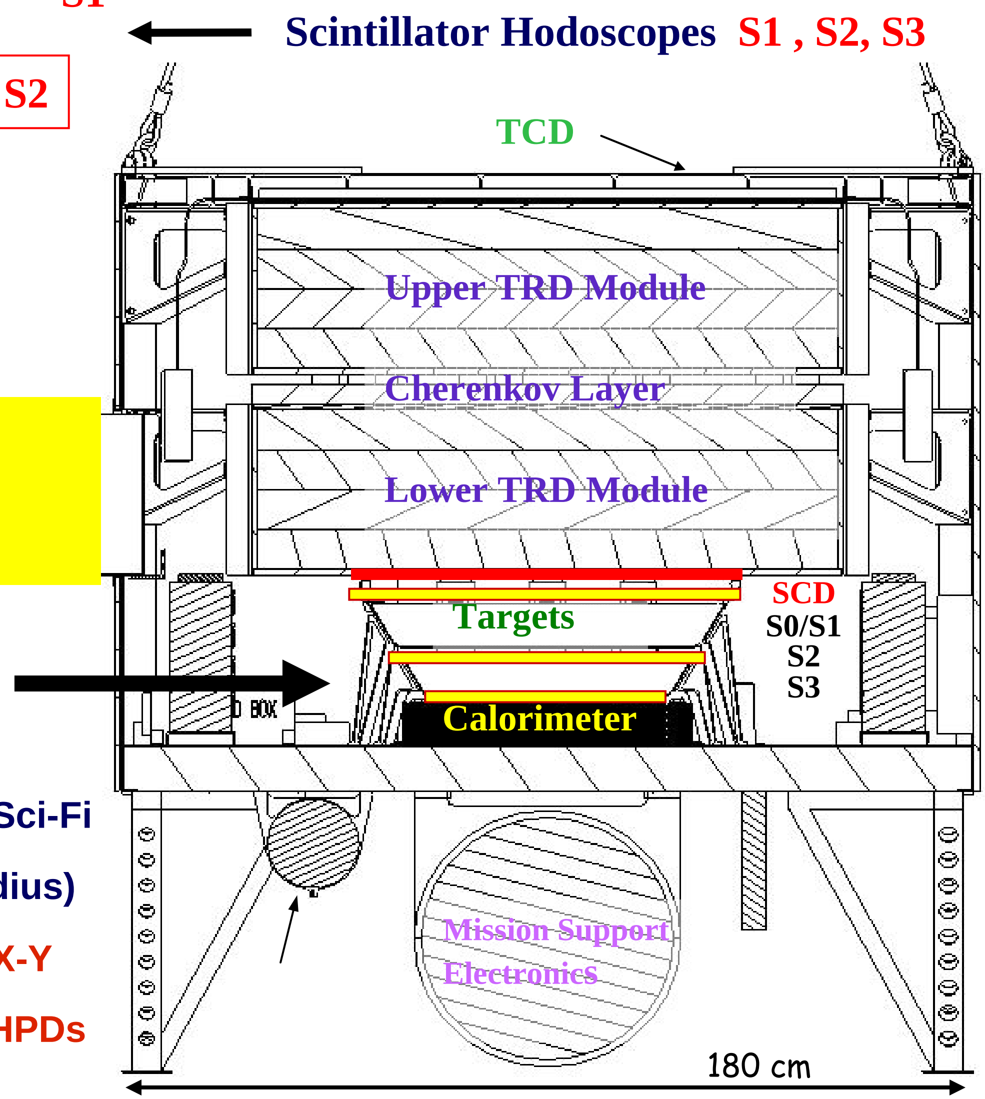
Example of charge distribution in SCD with TRD matched tracks
ZHI trigger and $\beta \sim 1$ selection from the Cherenkov



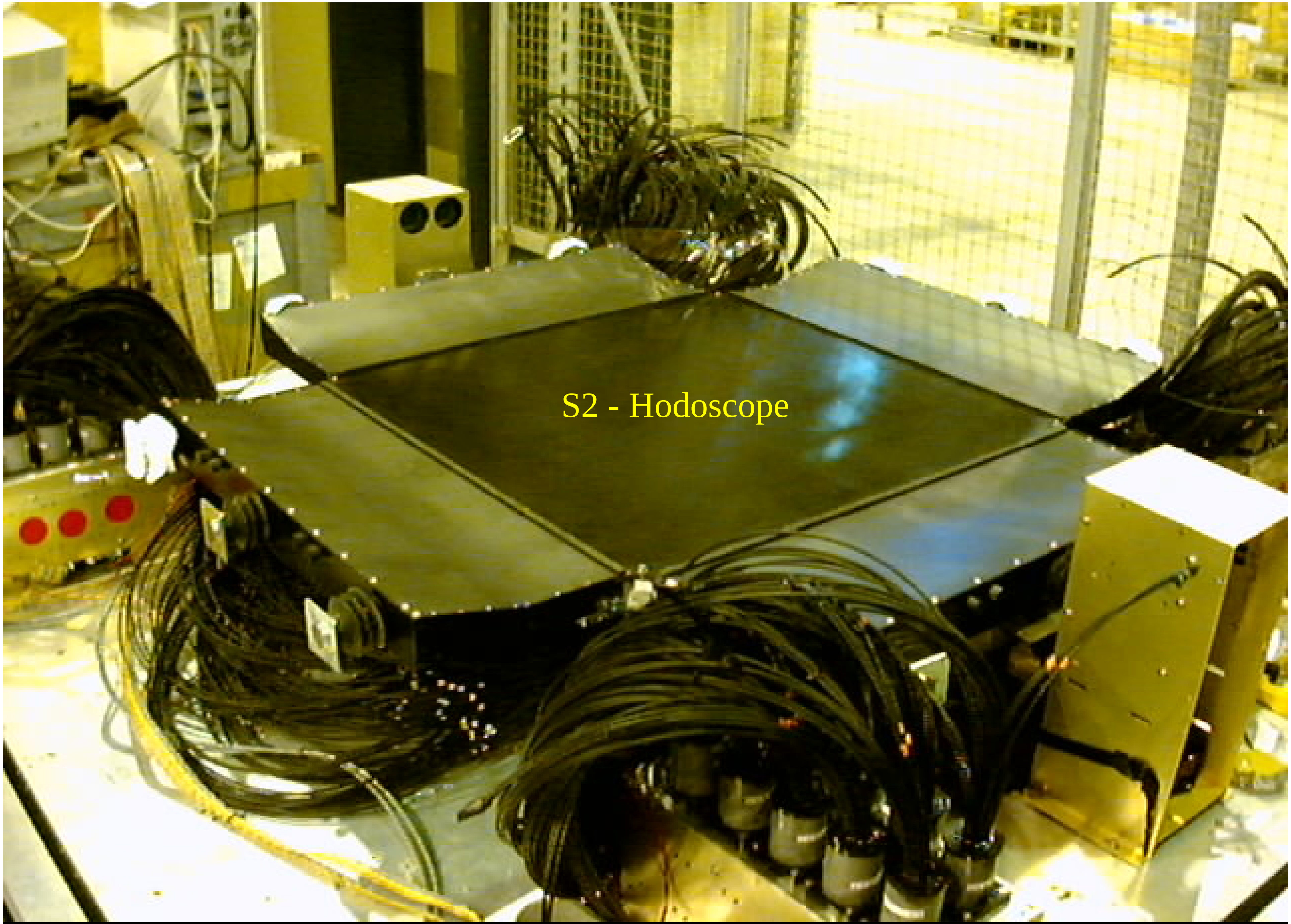
Carbon target (~ 0.5 λ_{int})



CREAM-1
Ionization Calorimeter

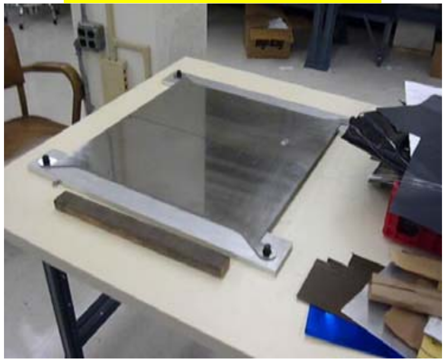


- Preceded by a graphite target
- Active area 50 × 50 cm^2
- Longitudinal sampling : 3.5 mm W + 0.5 mm Sci-Fi
- Transverse granularity : 1 cm (~ 1 Moliere radius)
- Total of 20 layers (20 X_0 , ~ 0.7 λ_{int}): alternate X-Y
- 2560 channels (3 gain ranges) readout by 40 HPDs


S2 - Hodoscope

Calorimeter readout scheme

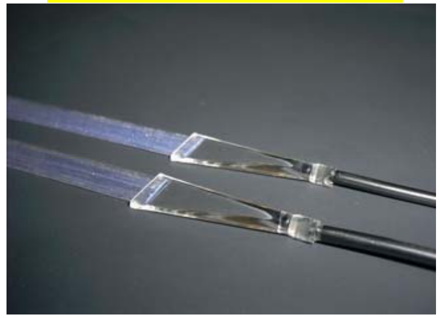
Tungsten plate



Sci-Fi ribbons

light mixer

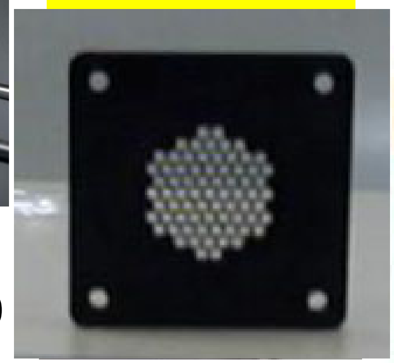
clear-fibers bundle



Fibers-to-HPD

optical interface

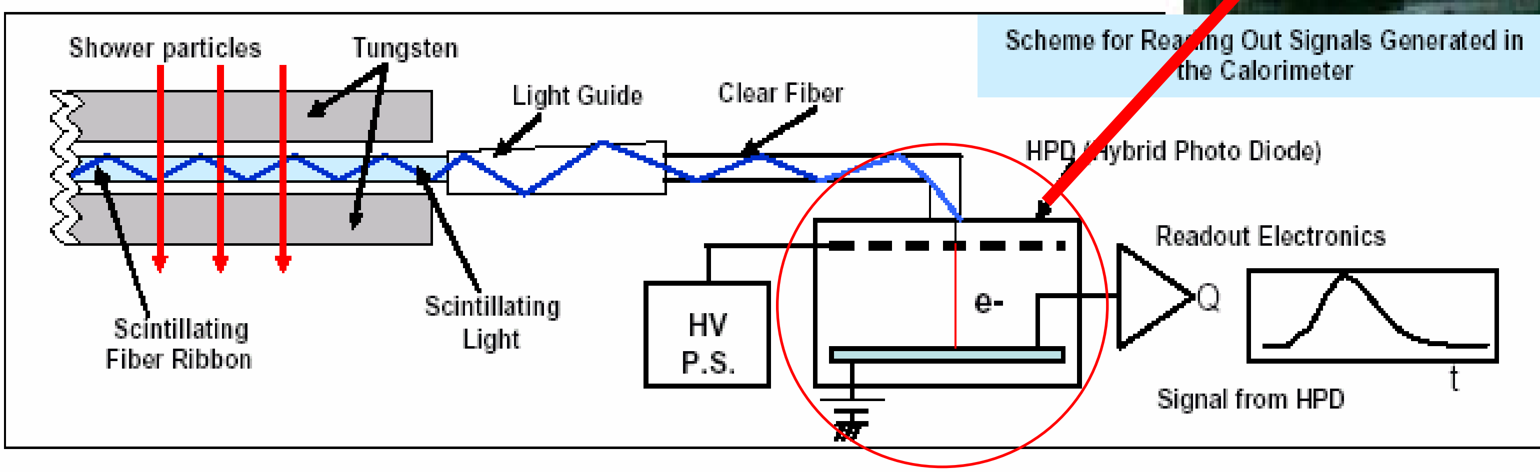
"Cookie"



Proximity focus HPD

Total number of Hybrid Photo Diodes (HPDs) : 40

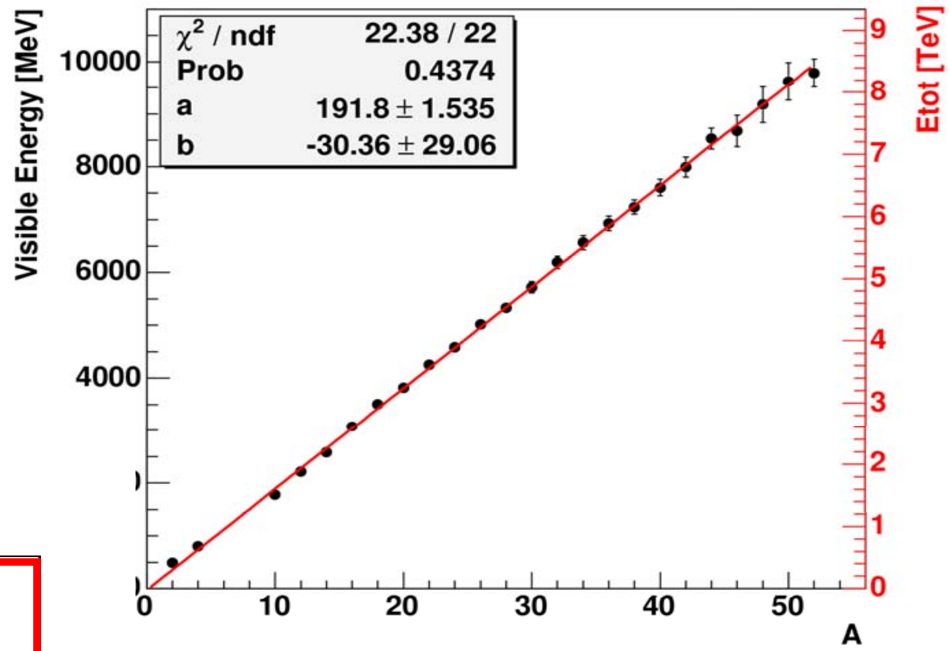
Total number of channels: 2560 (3 readout ranges)

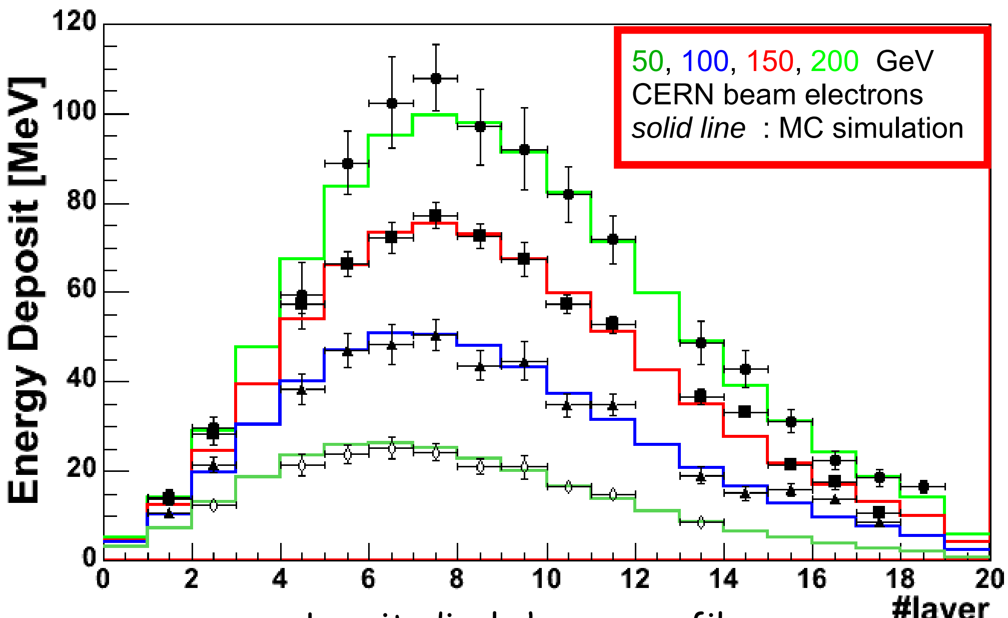



INFN calorimeter
flown with CREAM-II
POTT. 6

Calorimeter Calibration beam tests

- September 1-8, 2003 H2 beam line
  e @ 50, 100, 150, 200 GeV
  p @ 150, 250, 350 GeV
  CREAM-1 CAL was fully calibrated
- November 1-8, 2003 H2 beam line
  CREAM-1 A/Z = 2 ions @ 158 GeV/n
- September 22-29, 2004 H2 beam line
  CREAM-2 CAL was fully calibrated



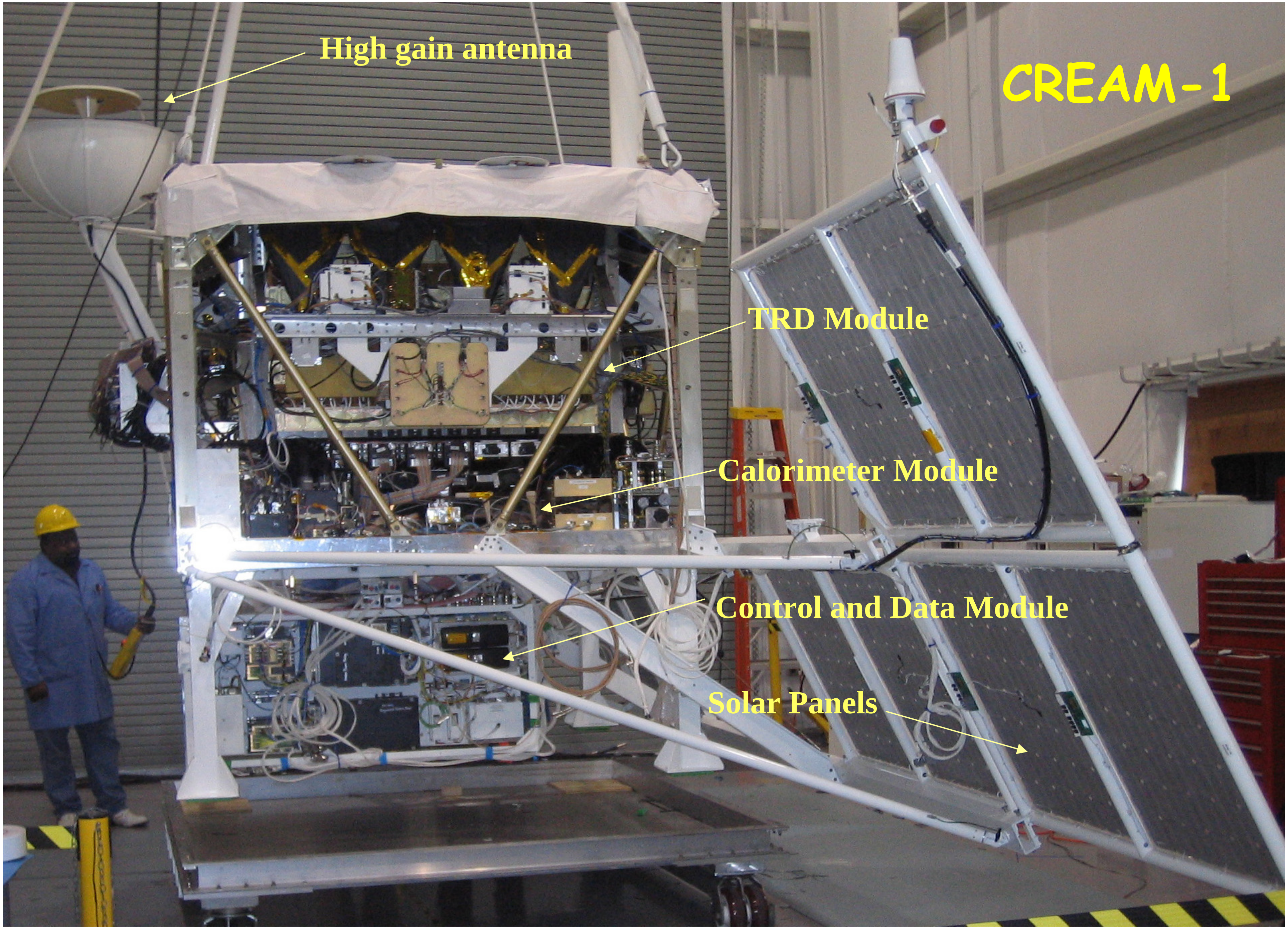


Longitudinal shower profiles

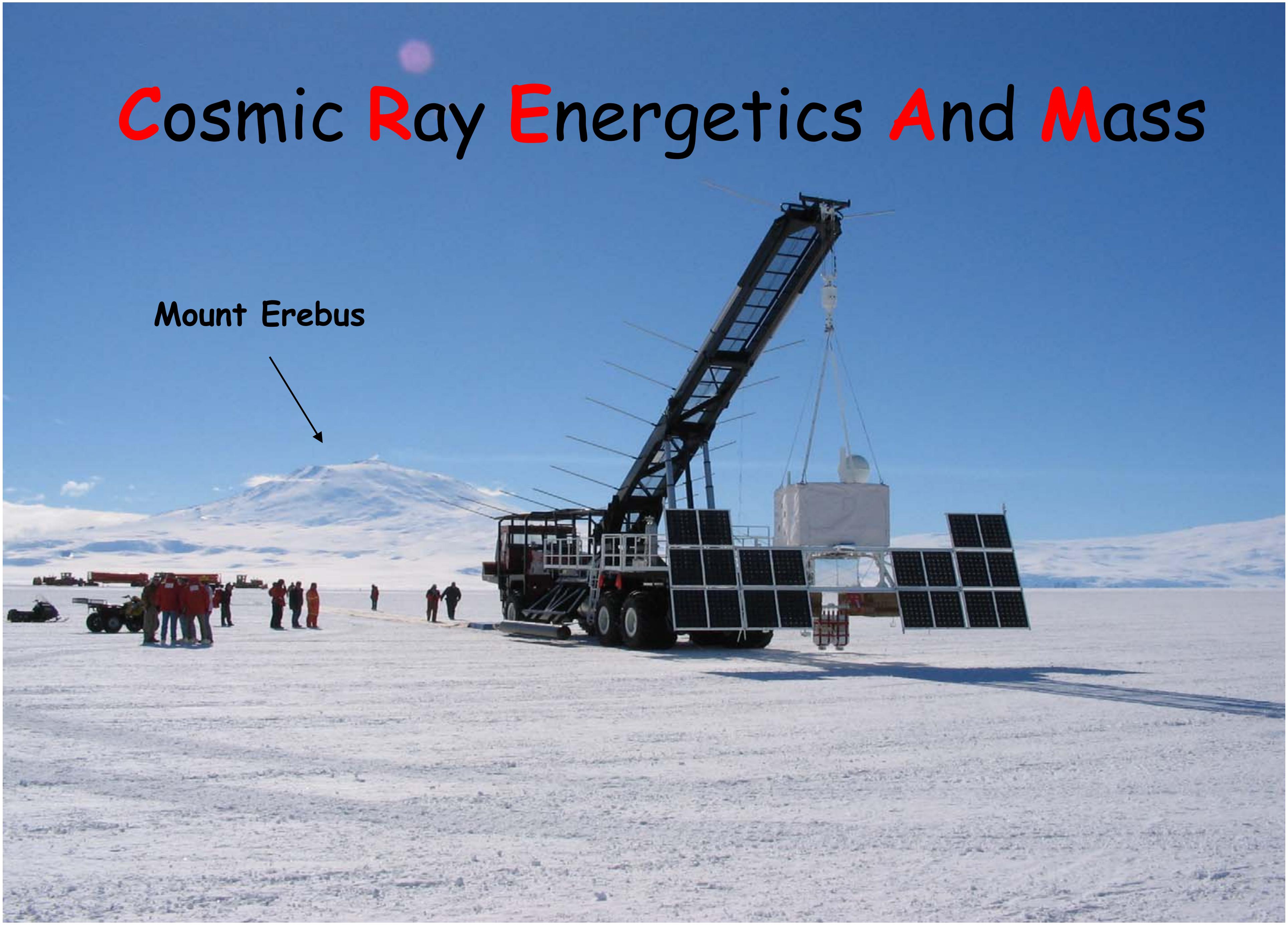
Ion beam test @ CERN

A/Z = 2 @ 158 GeV/n

Good linearity up to ~ 8.2 TeV

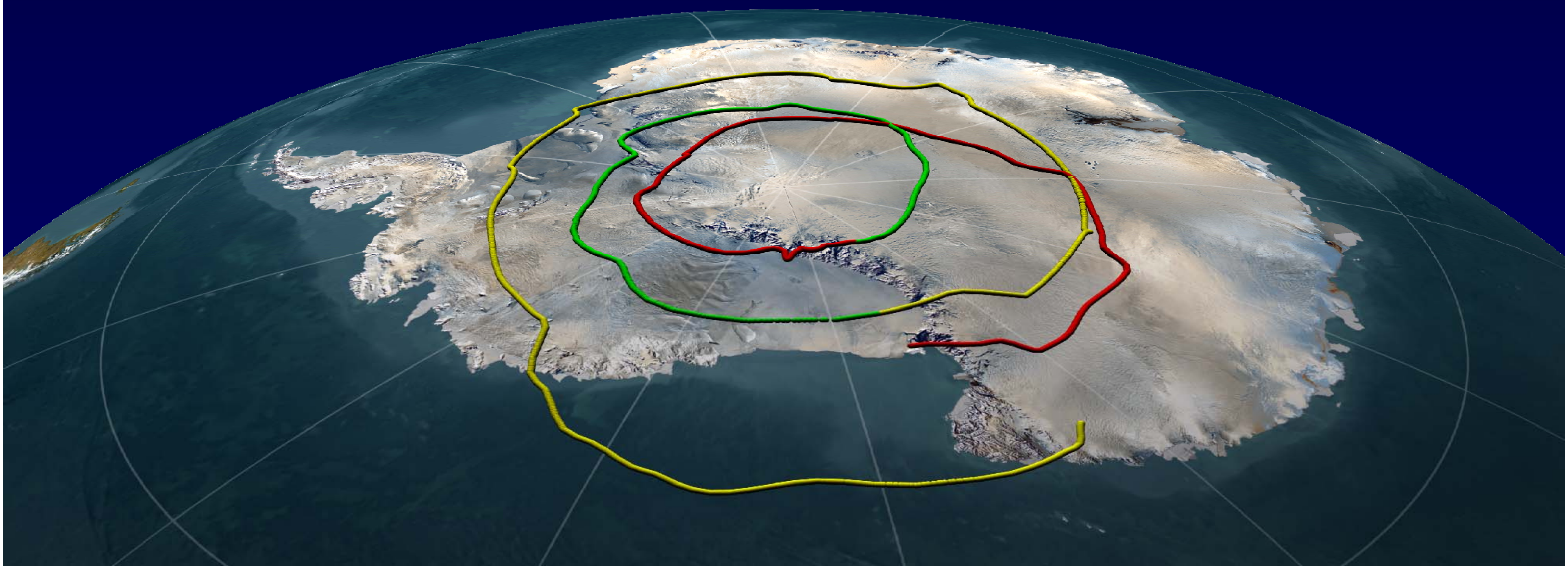

High gain antenna
CREAM-1
TRD Module
Calorimeter Module
Control and Data Module
Solar Panels

Cosmic Ray Energetics And Mass

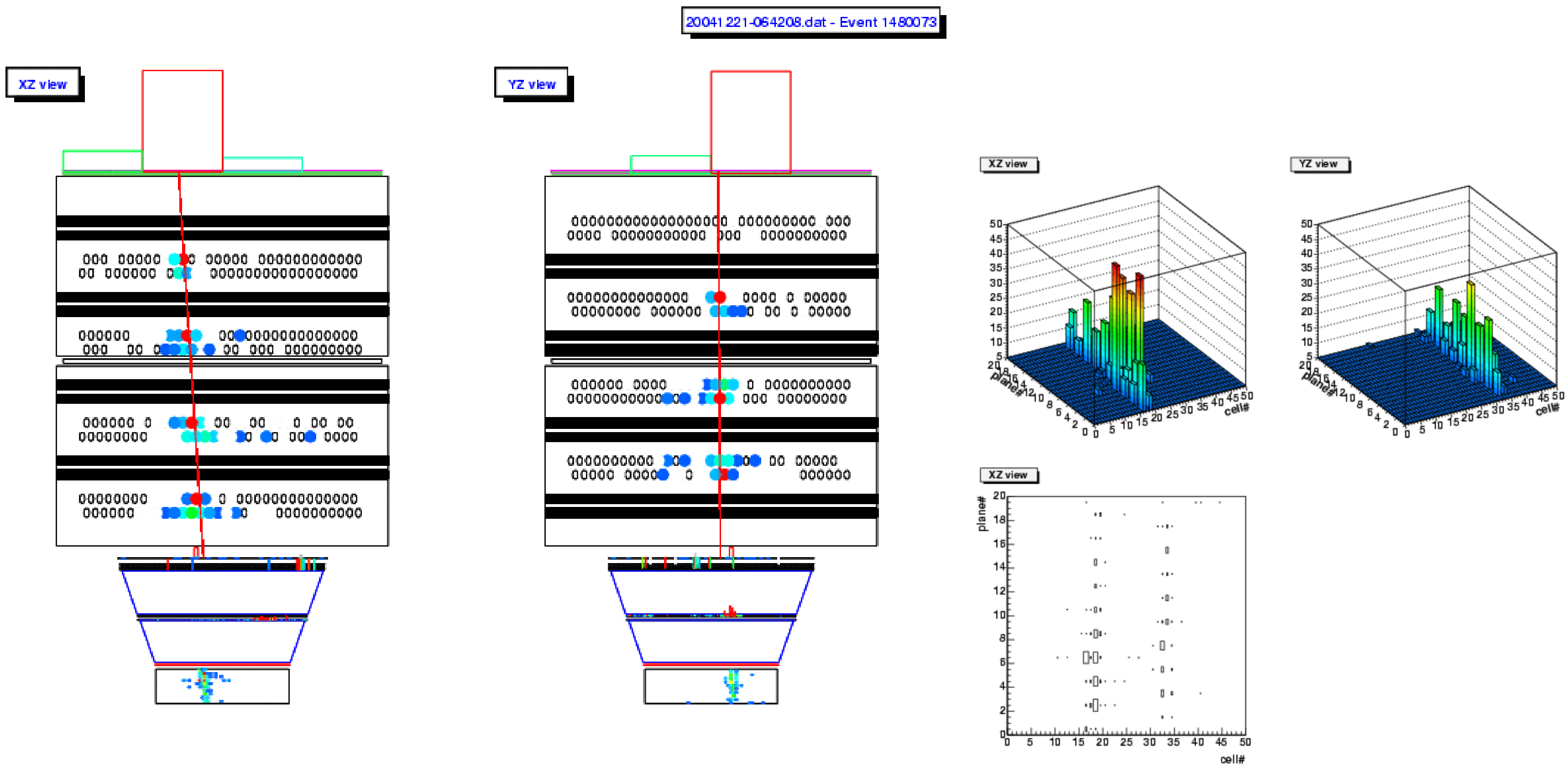


Flight I: Dec 04 – Jan 05

- 42 days – Balloon Record (now 54 days by ULDB)
- ~ 40 million Hi-Z Triggers

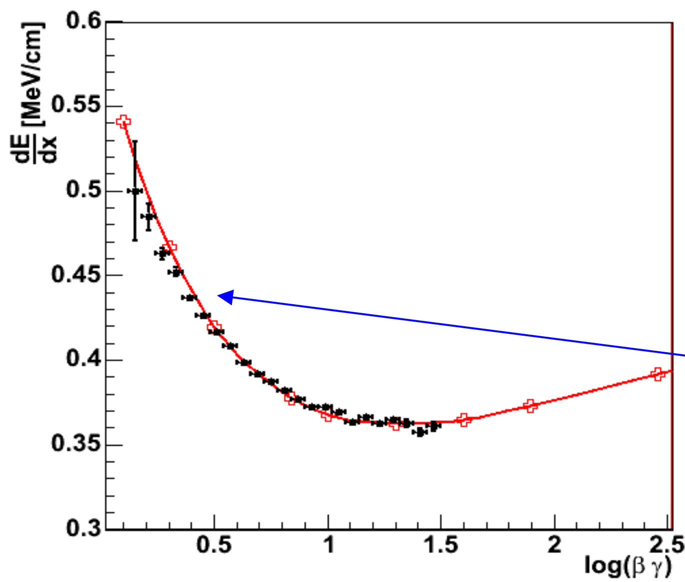


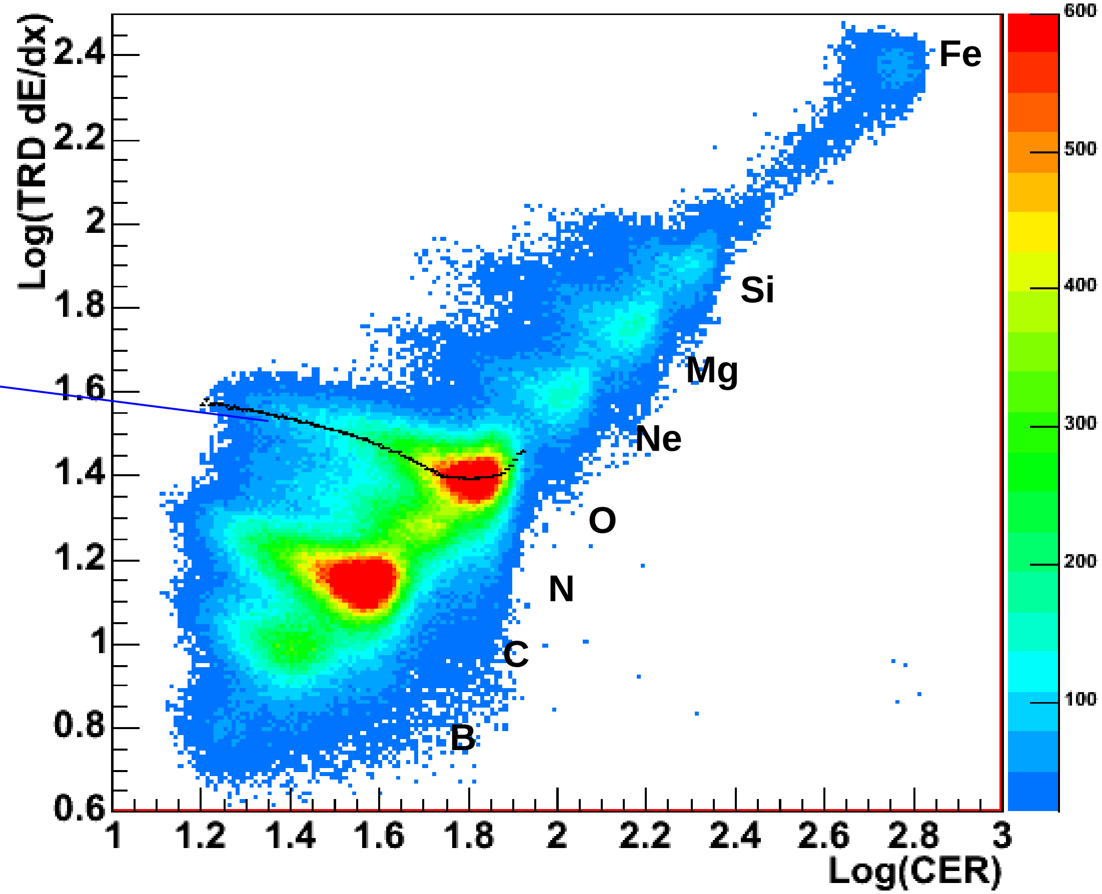
An on-line event: ~ 10 TeV Fe



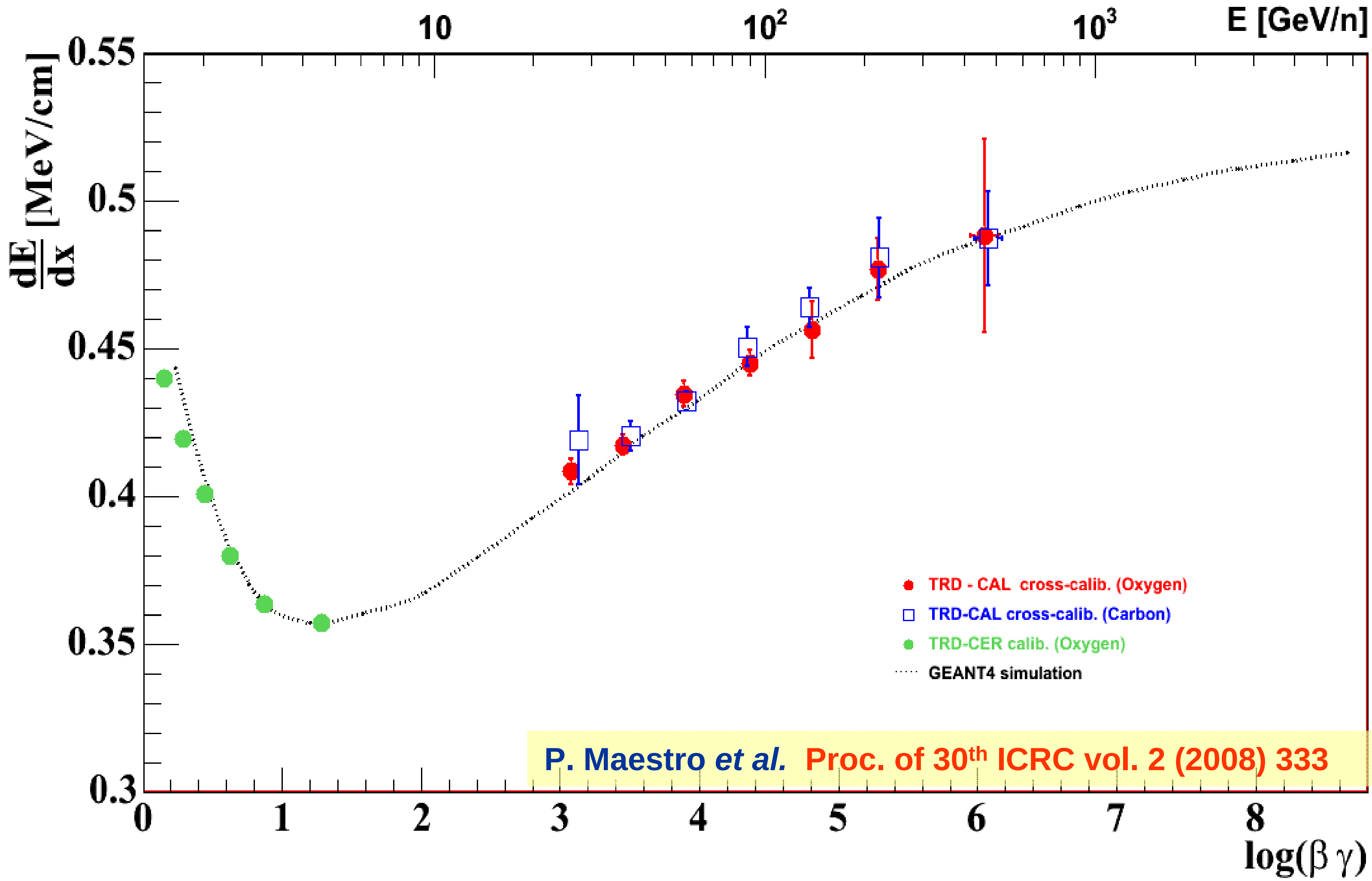
TRD-CD calibration with flight data

- TRD dE/dx vs. CD signal ⇒ calibration of the TRD response below the minimum of ionization (m.i.)
- Scale factor to convert dE/dx from arbitrary units to MeV/cm is obtained by matching the minimum ionization of O nuclei to MC simulated curve





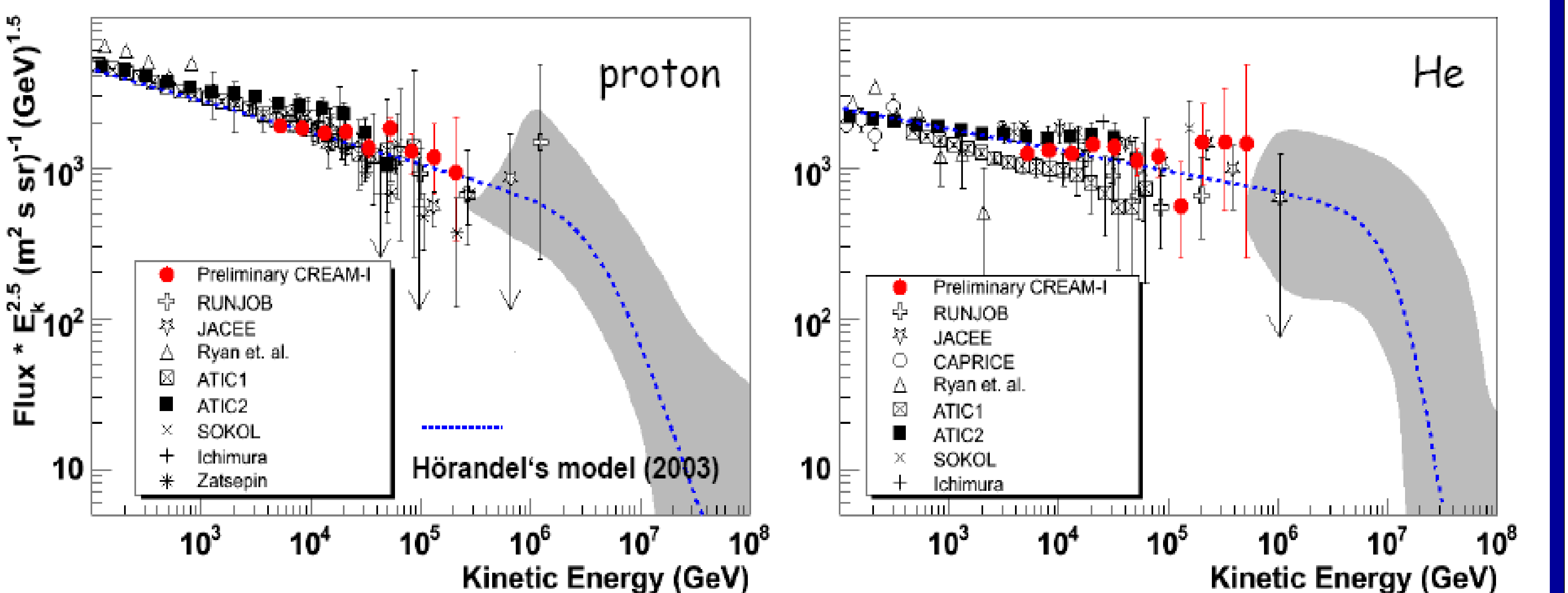
TRD-CAL cross-calibration with flight data



- About 980 Oxygen and 750 Carbon events are used to cross calibrate in the relativistic rise region ($20 \leq \gamma \leq 400$)
- TRD response is in excellent agreement with MC prediction

Preliminary proton and He spectra from 1st flight

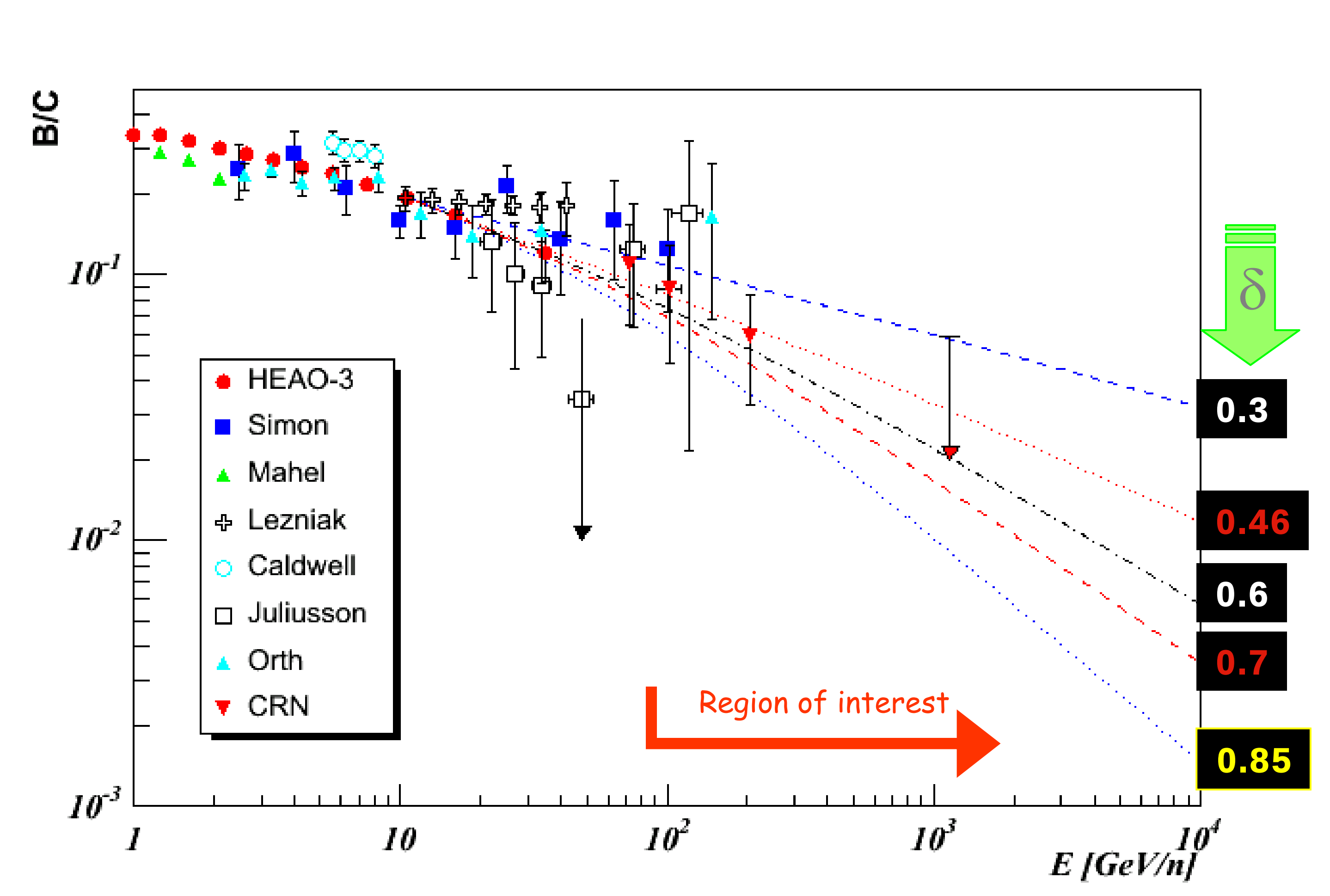
Yoon et al. OG1.1 oral; Seo et al. Proc. Int. Workshop on CRs and HE Universe, (Tokyo), in press, 2007



- Proton spectrum up to ~ 100 TeV
- He spectrum puzzle : is it softer than proton ?
  - ATIC1 vs. ATIC2 discrepancies suggest that systematic errors may play a role ?
  - more data from later CREAM flights but systematics MUST be under control

Secondary/Primary Ratios

- (e.g., B/C) are very sensitive to diffusion properties



Boron to Carbon ratio

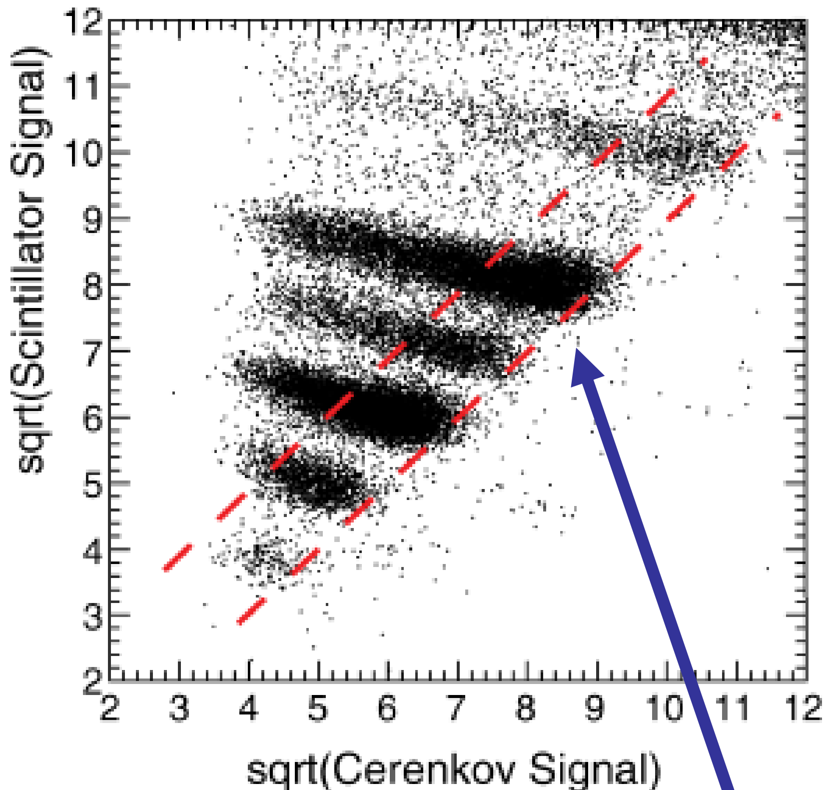
Predictions from diffusion model

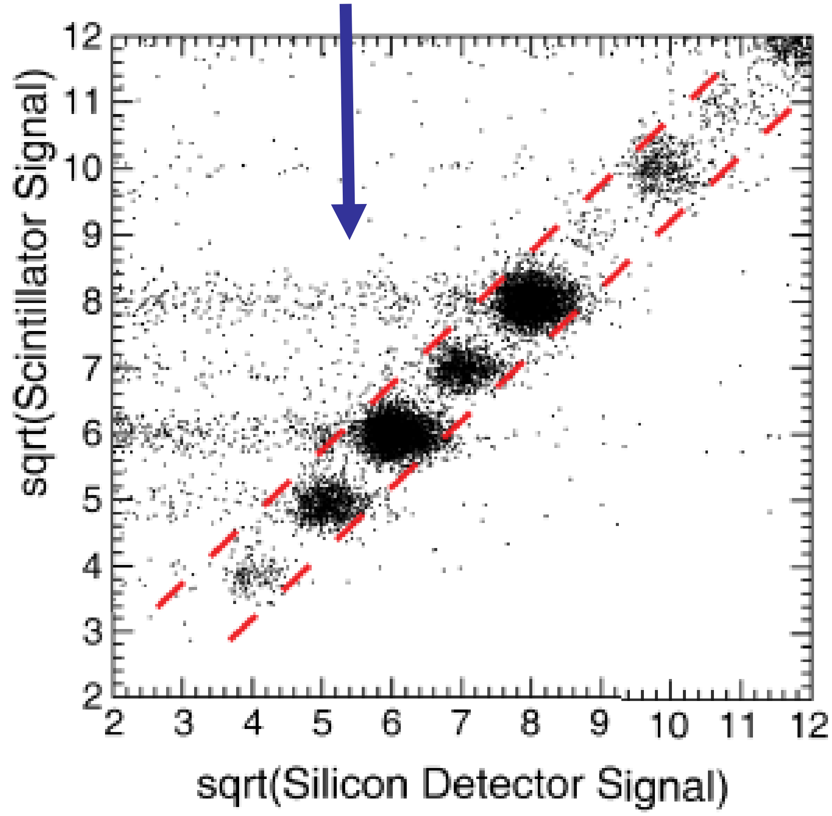
Kolmogorov $\delta = 1/3$

Kraichnan $\delta = 1/2$

Charge selection
(@ 4 σ separation)

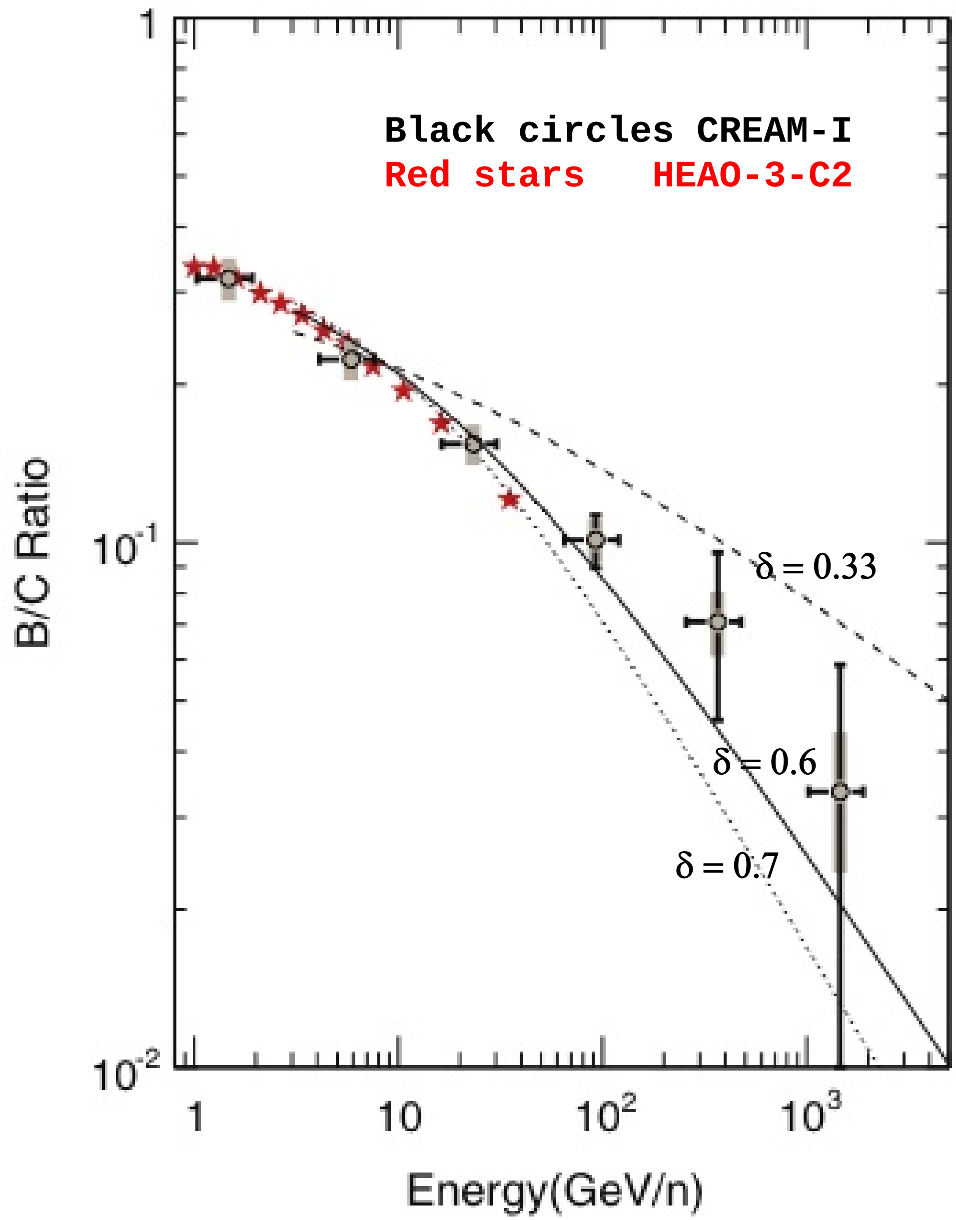
Reject events with charge-changing interactions in the apparatus





Select ultra-relativistic
Incident nuclei

Boron to Carbon abundance ratio



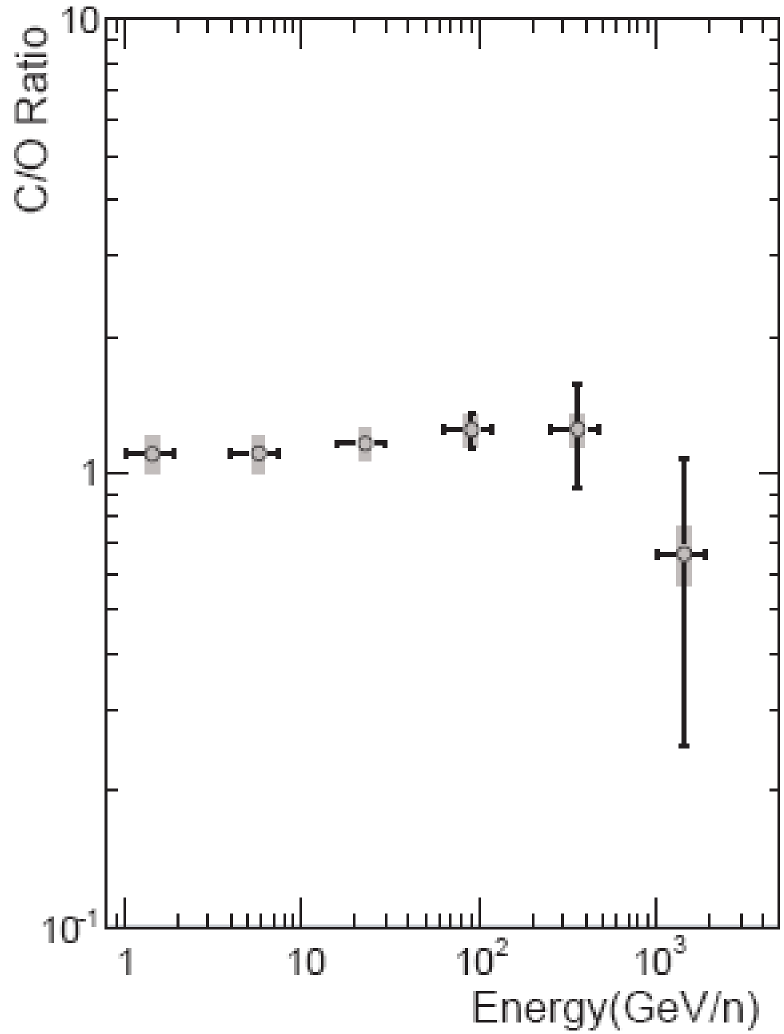
The lines in the plot represent leaky-box propagation model calculations for various values of the magnetic-rigidity dependence parameter, δ, in escape from the Galaxy.

CREAM-I measured the B/C ratio up to an energy of 1.5 TeV/n [Ahn et al., Astroparticle Physics 30 (2008) 133]

The results indicate that the interstellar propagation pathlength decreases fairly rapidly with energy, with an energy dependence **$E^{-\delta}$** in the range **$\delta \sim$ 0.5 - 0.6**

thin vertical bar = statistical error
gray vertical bar = systematic error

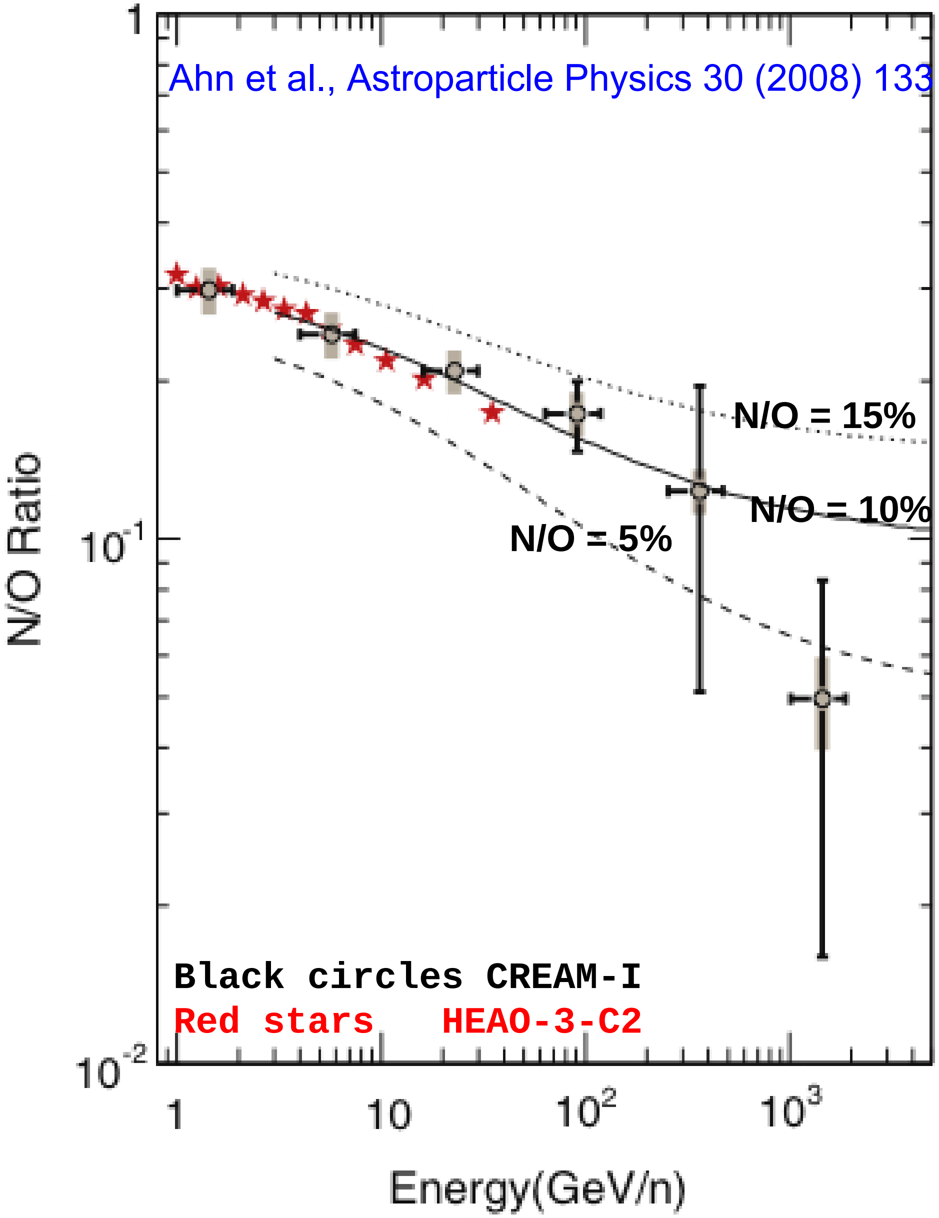
Consistency check: Carbon to Oxygen abundance ratio



CREAM-I

Consistent with unity as it should be for two primary elements

Nitrogen to Oxygen abundance ratio

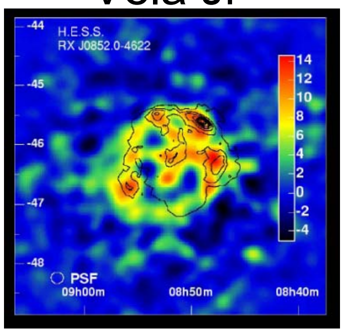


The lines in the plot represent model calculations of N/O ratio with the escape parameter $\delta = 0.6$.
The different curves correspond to different assumptions on the amount of nitrogen in the source material.

CREAM-I measurement of N/O up to 1.5 TeV/n suggests a **N/O source abundance** close to 10%, larger than some previous estimates based on lower-energy isotope measurements.

Tracking down the Source Index

Vela Jr



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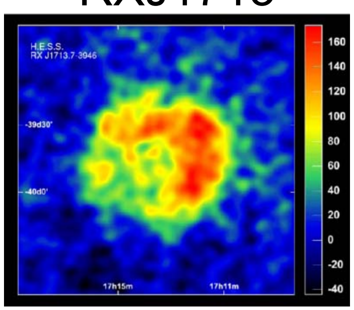
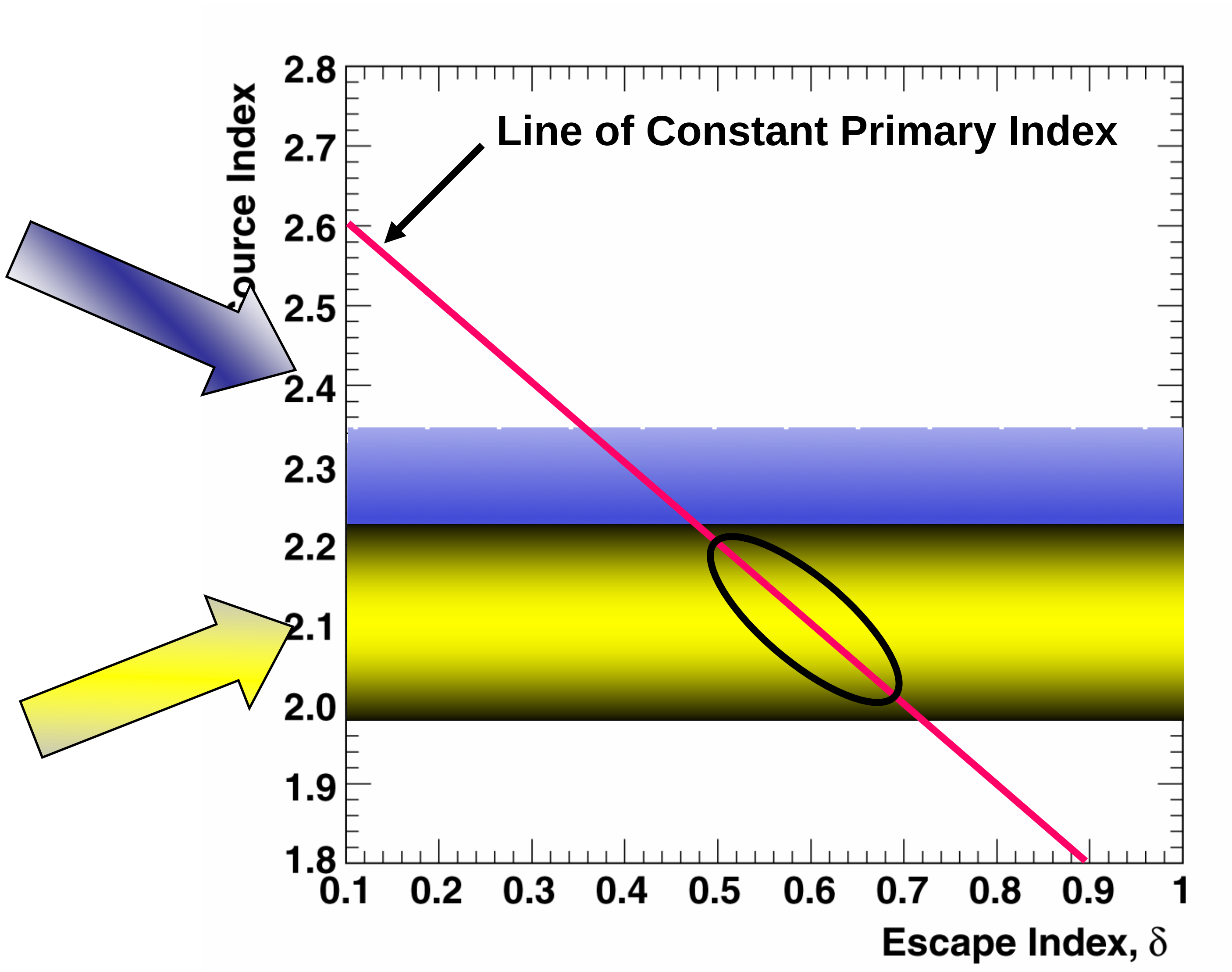


SNR



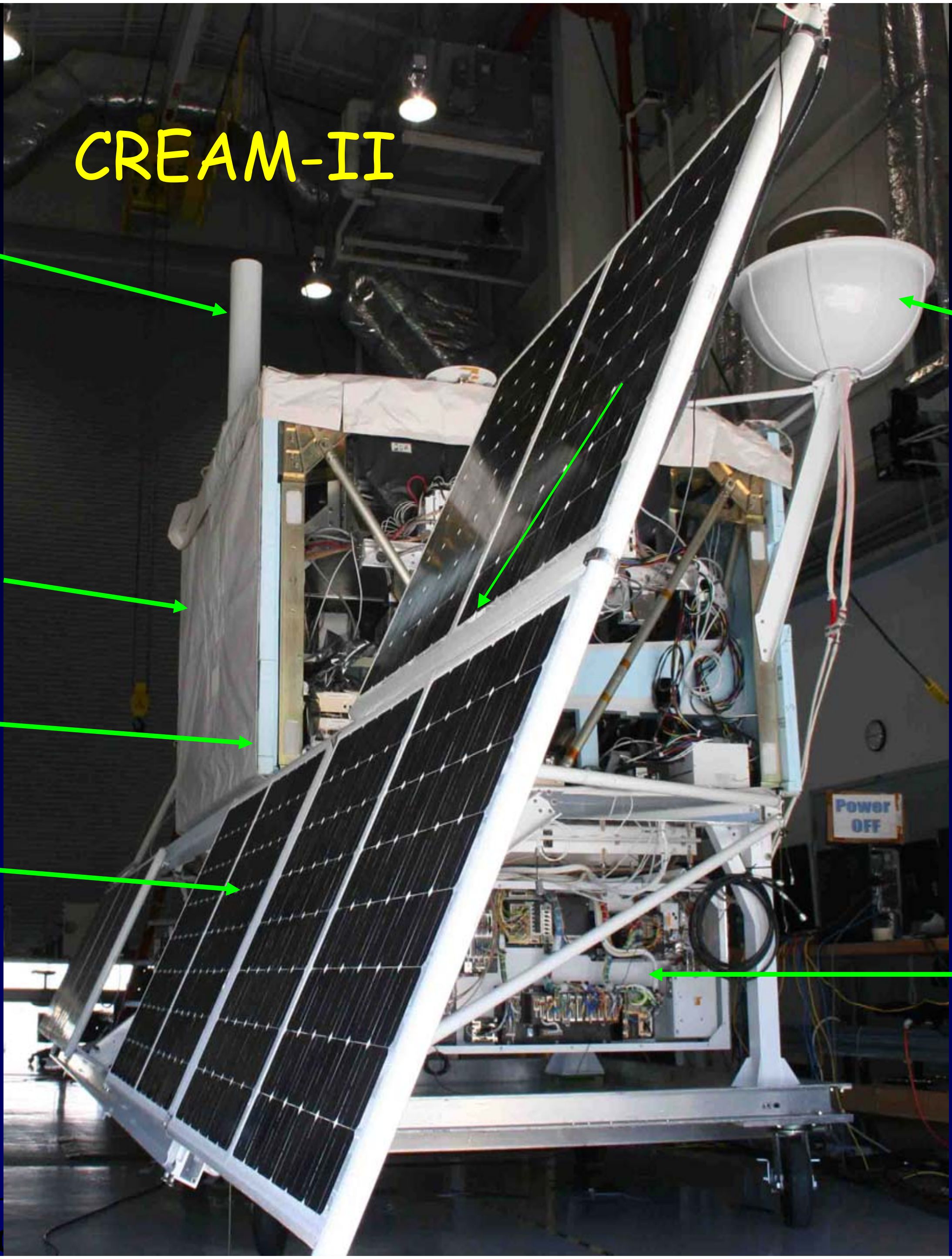
CREAM-II

TDRSS omni antenna

White thermal blanket

Styrofoam wall

Solar arrays



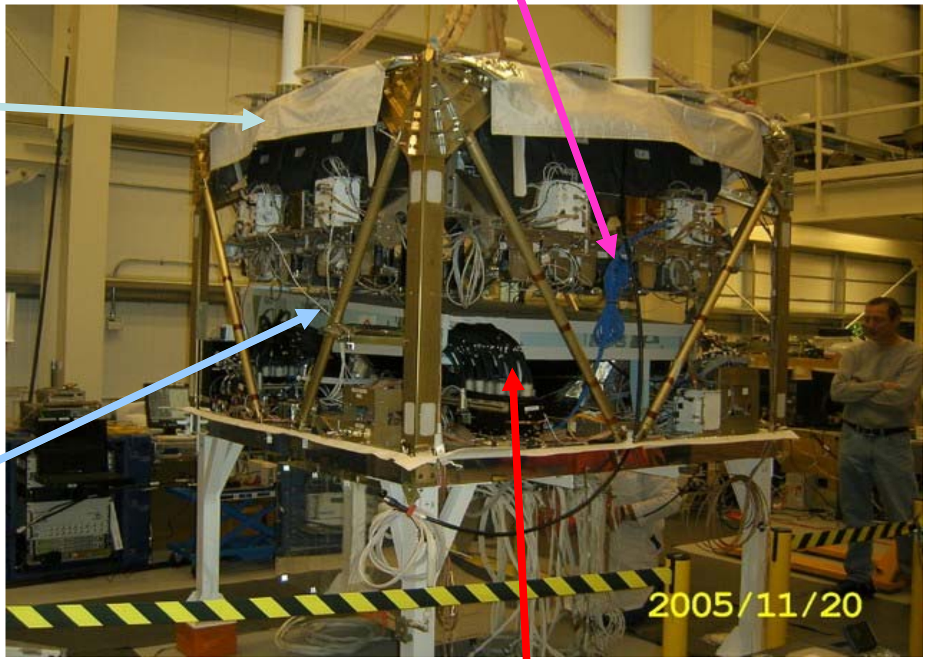
TDRSS hi-gain antenna

Control & Data Module (CDM)

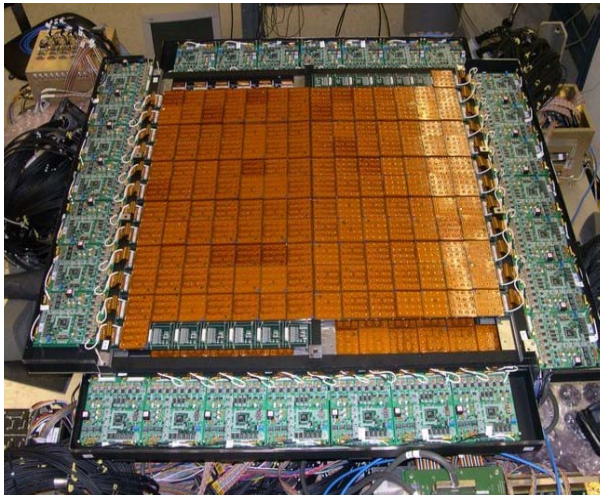
CREAM-2 Instrument

➢ **Cerenkov counter** *(University of Chicago, GSFC)*
- 1 cm thick plastic radiator with blue wavelength shifter
- low energy particles veto

➢ **Timing Charge Detector (TCD)** *(Penn State Univ.)*
- 5 mm thick fast (< 3 ns) plastic scintillator paddles
- charge measurement from H to Fe ($\sigma \sim 0.2$-0.35 e)
- backscatter rejection by fast pulse shaping

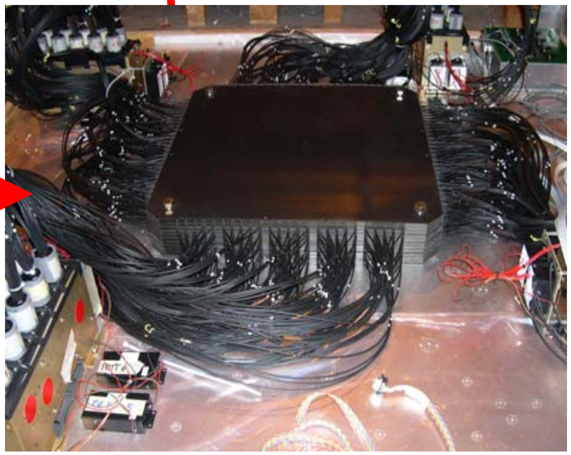


No TRD on CREAM-2



➢ **Silicon Charge Detector (SCD)**
(Ewha Womans University)
- 2 planes, 2916 Si pixels each Active area ~ 0.65 m²
- charge measurement from Z=1 to Z~33 ($\sigma \sim 0.1$-0.2 e)

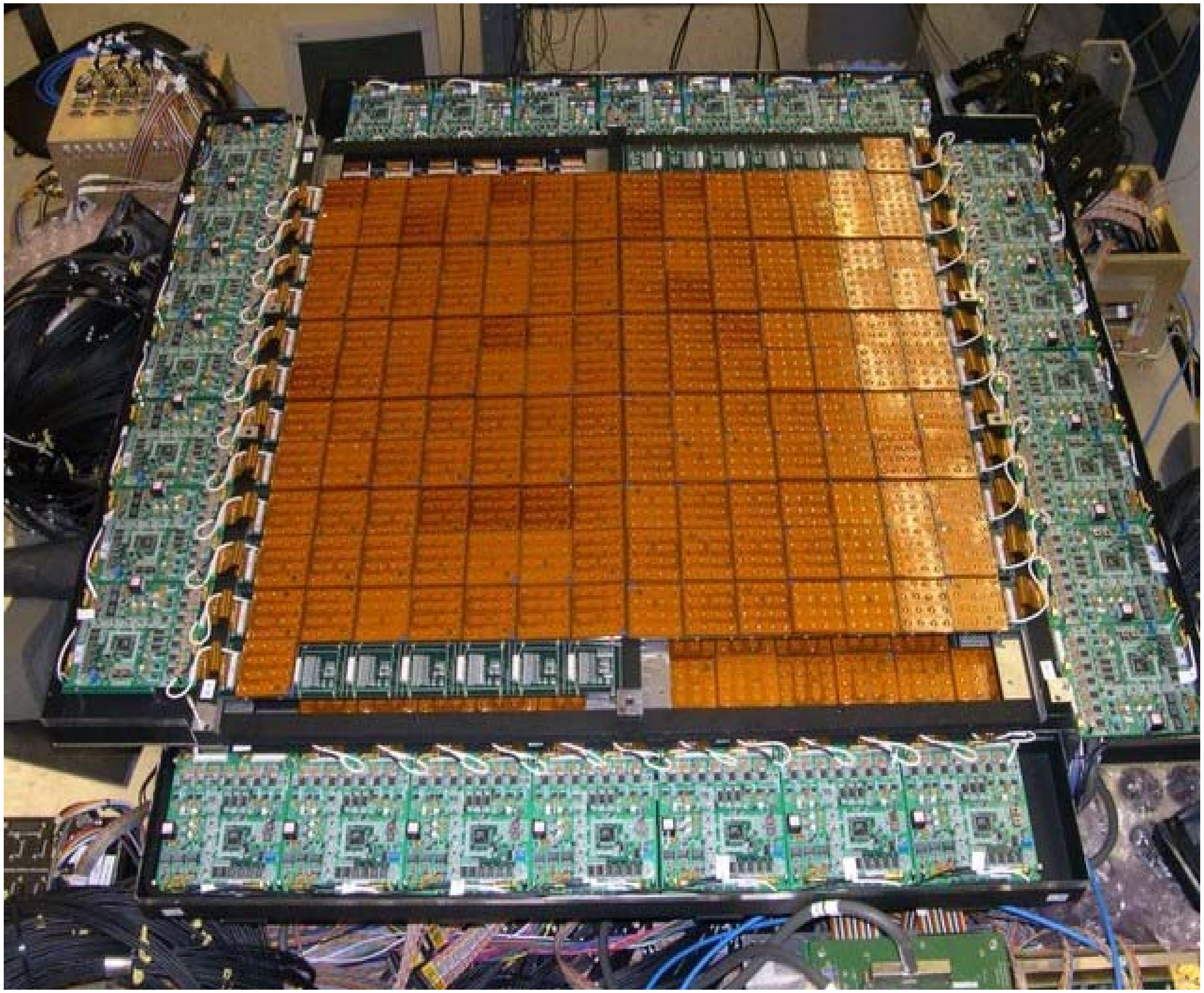
- 50 × 50 cm²
- 3.5 mm W (1 X_0)
- 0.5 mm Sci-Fibers
- 1 cm granularity
- 20 layers **20 X_0**, ~ 0.7 λ_{INT}
- 2560 channels (40 HPDs)



Tungsten-SciFi Calorimeter *(INFN)*

Silicon Charge Detector (SCD)

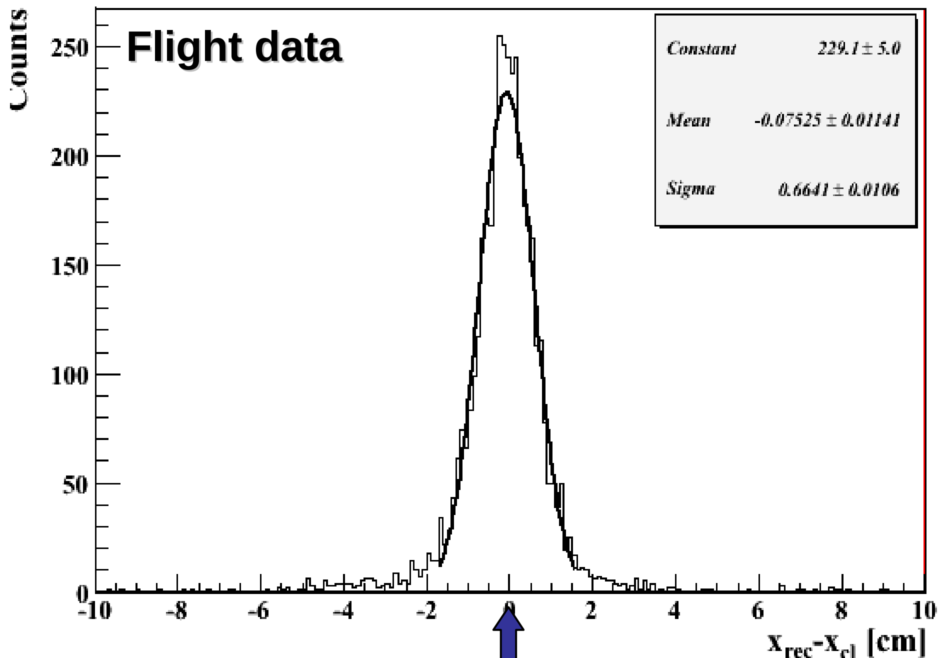
- particle-ID by charge measurement from Z = 1 to Z ~ 33 (σ ~ 0.1 - 0.2 e)



- **2 layers** of sensors
- pixel size ~ 2.1 cm^2
- **16 pixels per sensor**
- 380 mm thick Si sensor
- depletion at 70 V
- Active area per layer ~ 0.52 m^2
- 2496 chans/layer were readout

CREAM-II

Trajectory reconstruction



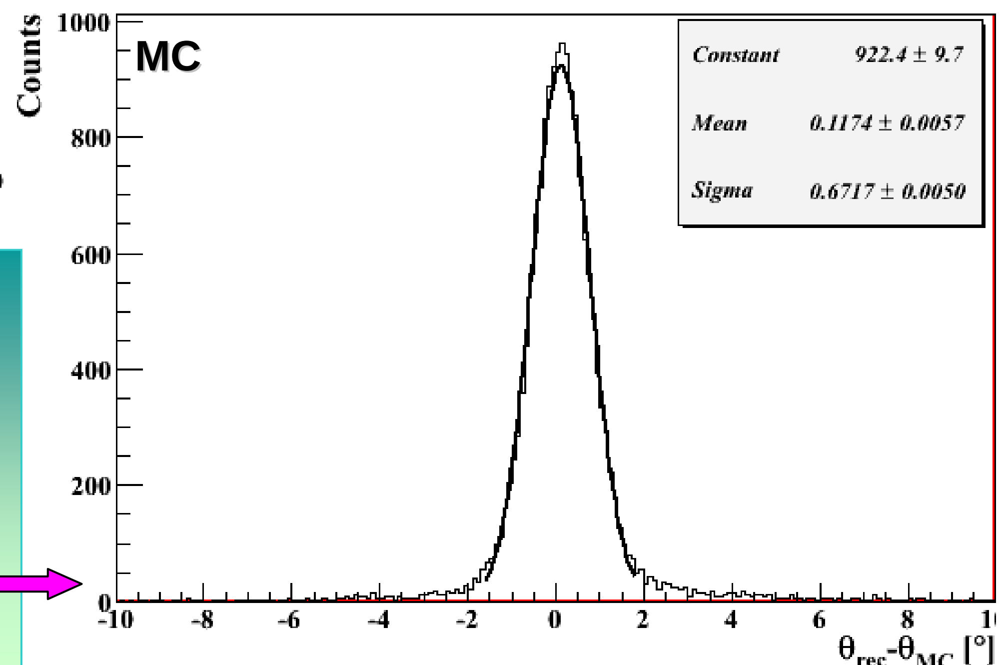
- Two steps algorithm:

  1– CAL tracking. Shower axis is projected back to SCD planes. Search for hit pixels in the circle of confusion (R ~ 3 cm)

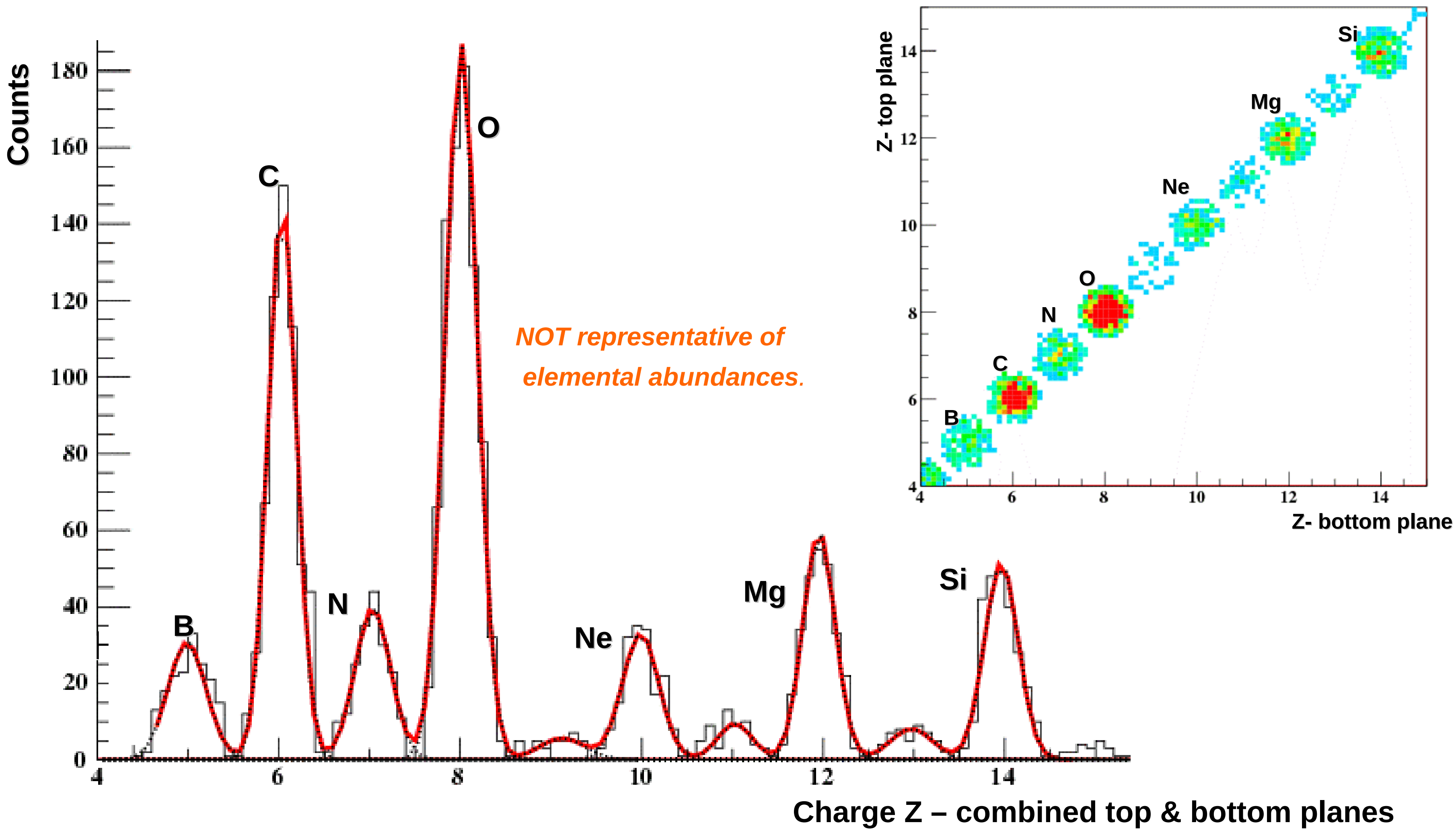
  2 – new fit including the matched SCD pixels ⇒ This improves the accuracy of the pathlength correction

- Impact point resolution on SCD is estimated comparing the reconstructed impact point with the position of the pixel with the highest count. **< 7mm**

- Accuracy on zenith angle: 0.7° (estimated from MC)

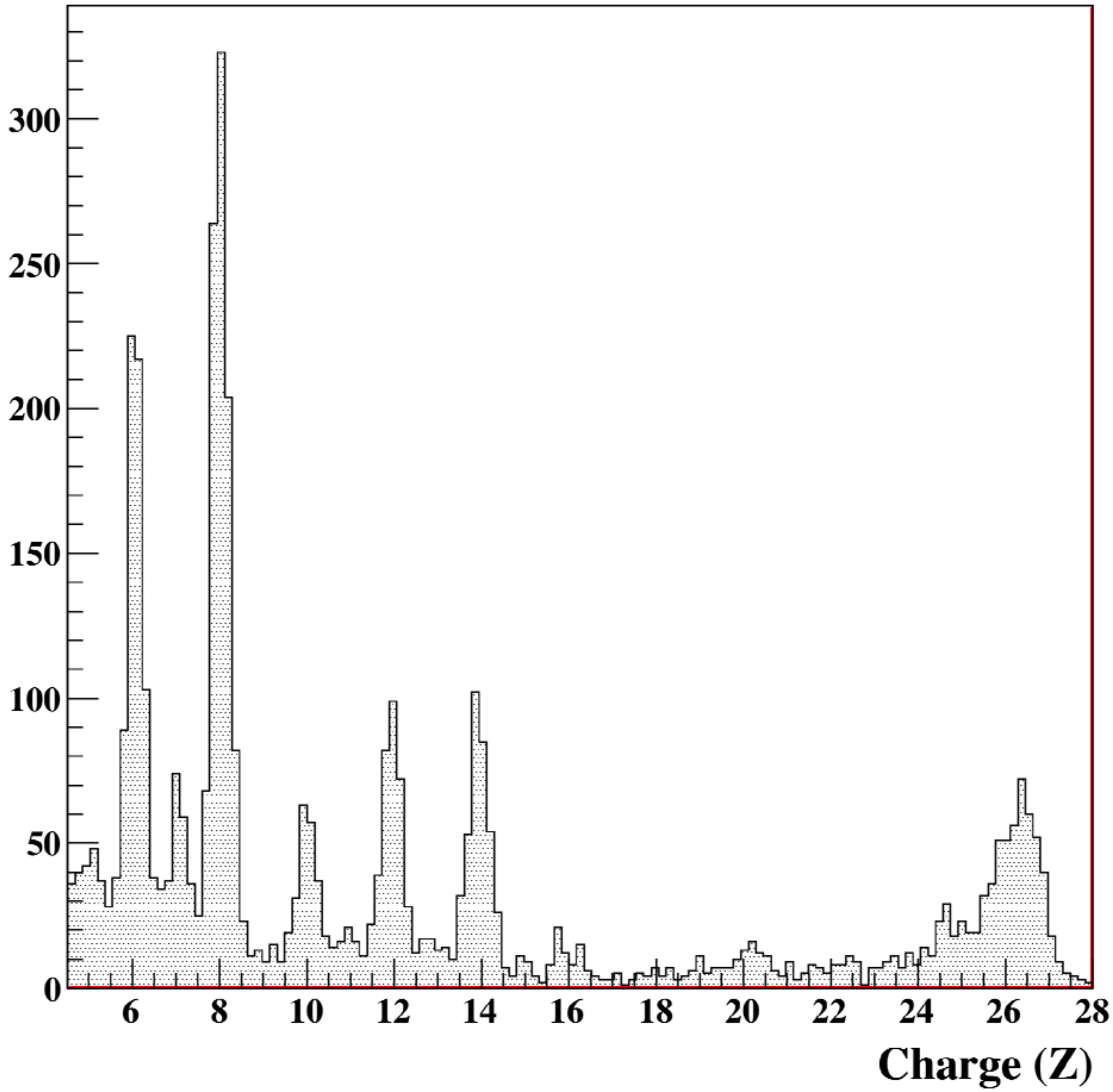


Charge measurement with SCD



Excellent charge resolution: ~ 0.2 e from C to Si

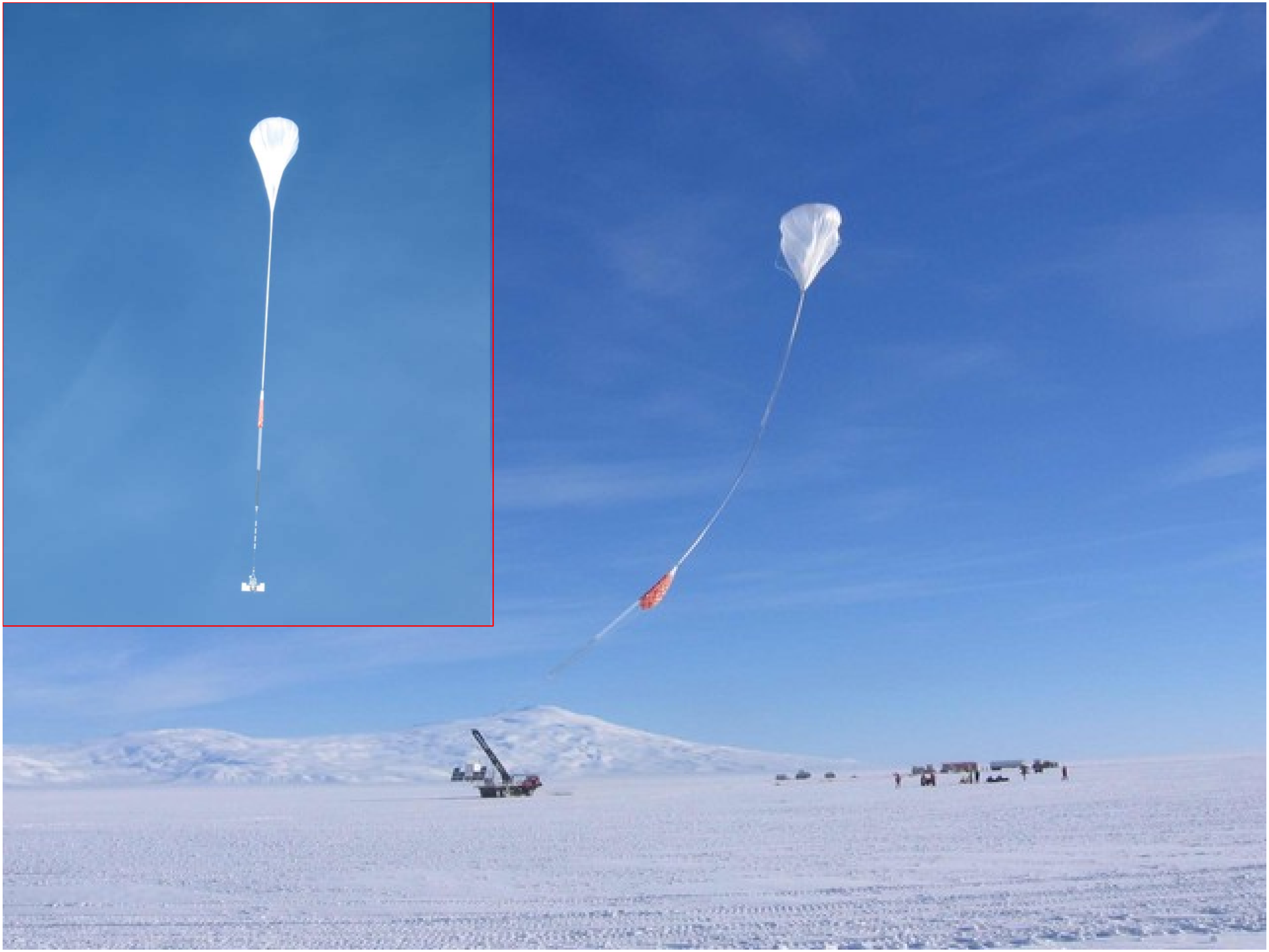
Charge measurement with SCD (up to Fe)




Willie Field –
Balloon launch facility


CREAM-2 hang test


ICE CREAM
TEAM
2005-2006



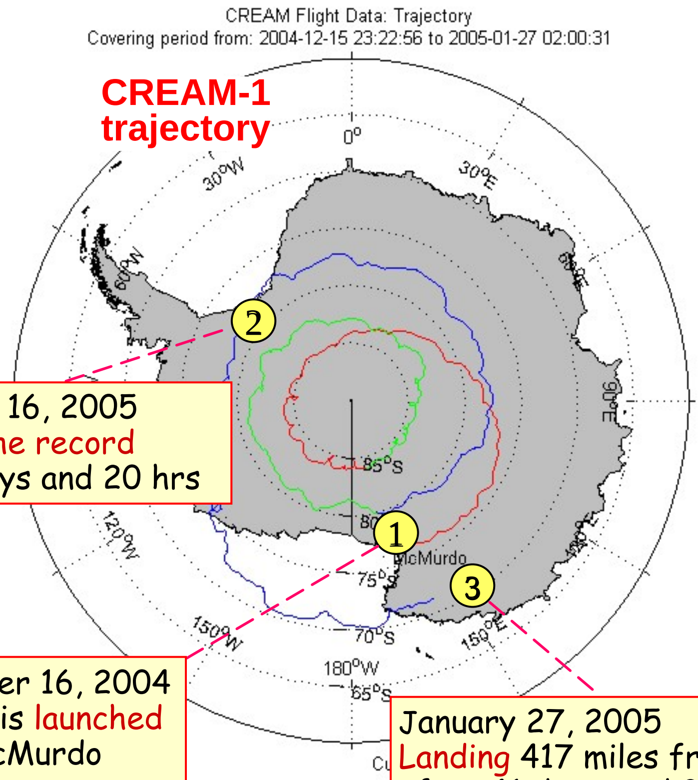
CREAM first two flights

- NASA Long Duration Balloons (LDB):
  Payload ~ 1300 kg. Science Instrument power ~ 400 W
- Altitude 38-40 km. Atmospheric overburden ~3.9 g/cm^2

CREAM-1	**42 days**	(Dec.16 2004 - Jan. 27 2005)
CREAM-2	**28 days**	(Dec.15 2005 - Jan. 12 2006)

- 85 kbps telemetry (TRDSS) of the high energy data during the flight. Lower energy data were recorded on board.

CREAM-1 trajectory

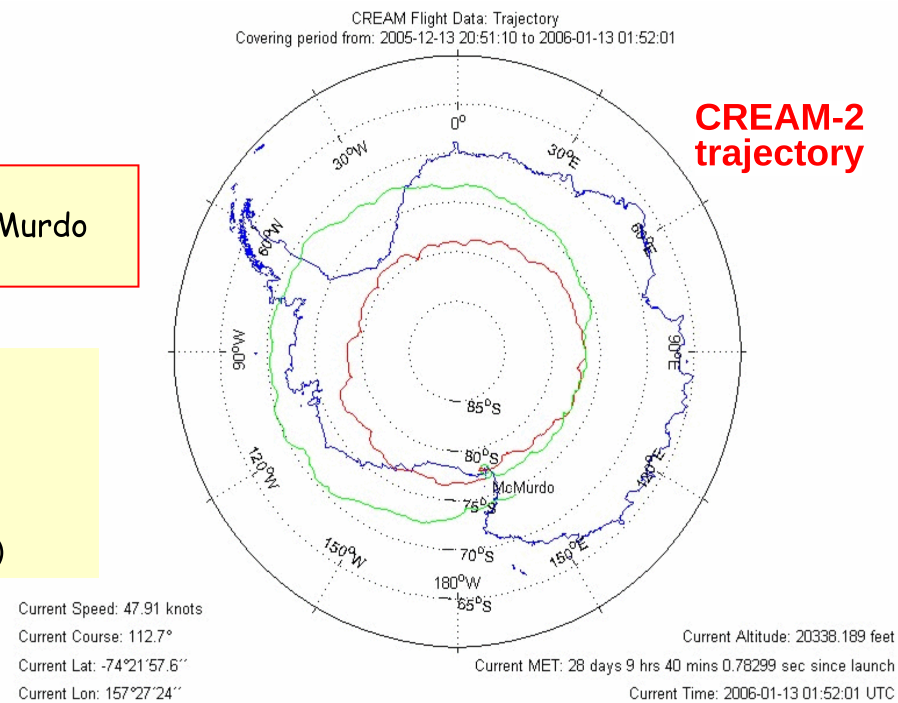


January 16, 2005
Break the record
of 31 days and 20 hrs

December 16, 2004
CREAM is launched
from McMurdo

January 27, 2005
Landing 417 miles from McMurdo
after 41 days and 21 hrs

CREAM-2 trajectory



Collected data:

CREAM-1 4×10^7 science events (60 GB data)

CREAM-2 1.5×10^7 science events (57 GB data)

Absolute differential flux measurement

$$\Phi(E_i^{med}) = \frac{\mathrm{N}_i}{\Delta \mathrm{E}_i} \times \frac{1}{\varepsilon_i \times \mathrm{TOI} \times \mathrm{TOA} \times \mathrm{S}\Omega \times \mathrm{T}}$$

- N_i are the unfolded counts in energy bin i. They are obtained by correcting the measured counts for overlap with neighbouring bins (**energy deconvolution**)
- ΔE_i = energy bin size, choosen larger than the energy resolution of the calorimeter
- E_i^{med} = median energy of bin i calculated according to definition given by Lafferty & Wyatt NIMA355 (1995) 541
- $S\Omega$ = geometrical factor
- TOI = Top of instrument correction, i.e. fraction of primary nuclei of each species reaching SCD without interacting in the above apparatus (TCD/CER/support structure)
- TOA= Top of atmosphere correction, i.e. fraction of primary nuclei of each species reaching the instrument without interacting in the air
- T = Live time
- ε_i = selection cuts efficiency in energy bin i

Monte Carlo simulation

- A detailed MC simulation of CREAM-II instrument has been done to estimate:
  - the trajectory reconstruction and charge assignment efficiencies
  - the energy deconvolution (mixing matrix)
  - the survival fraction of primary nuclei of each element reaching SCD (TOI correction)

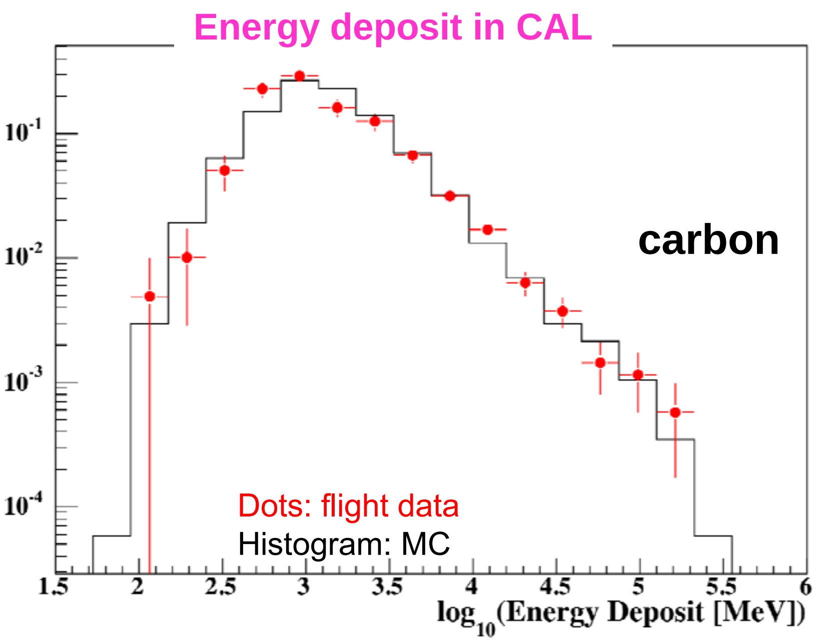
- MC based on FLUKA 2006.3b with hadronic package DPMJET-III

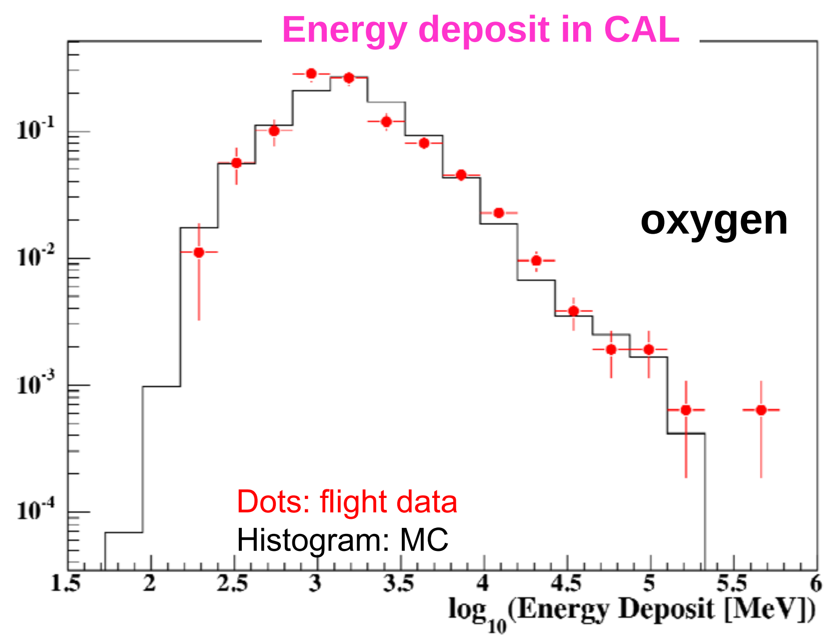
- Isotropic generation of nuclei with energy extracted from power-law energy spectra in the range 0.1 – 200 TeV.
  Spectral indexes from Hörandel compilation Astropart. Phys. 19 (2003) 193

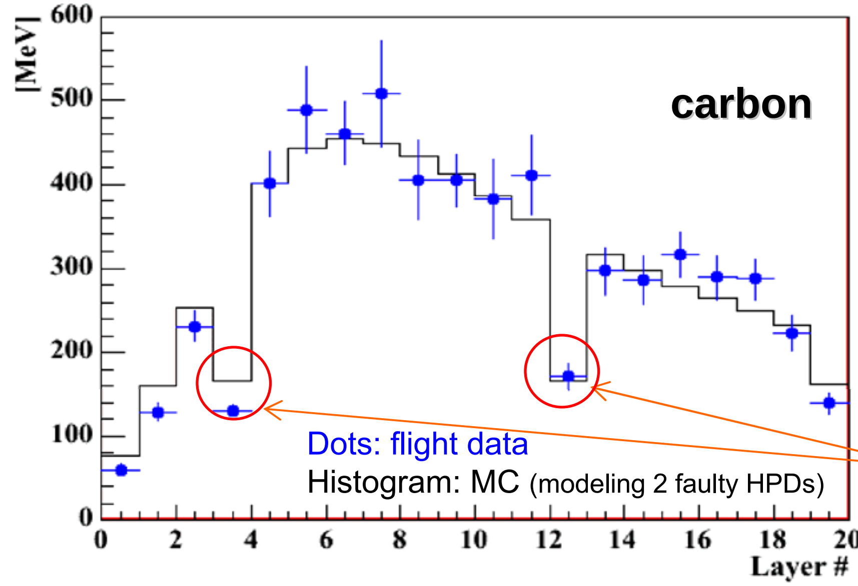
- About 10^9 events with C, N, O, Mg, Ne, Si, Fe nuclei were generated

- About 0.1% of generated events fit the detector acceptance and are reconstructed with the same analysis procedure used for flight data.

Flight data vs. MC



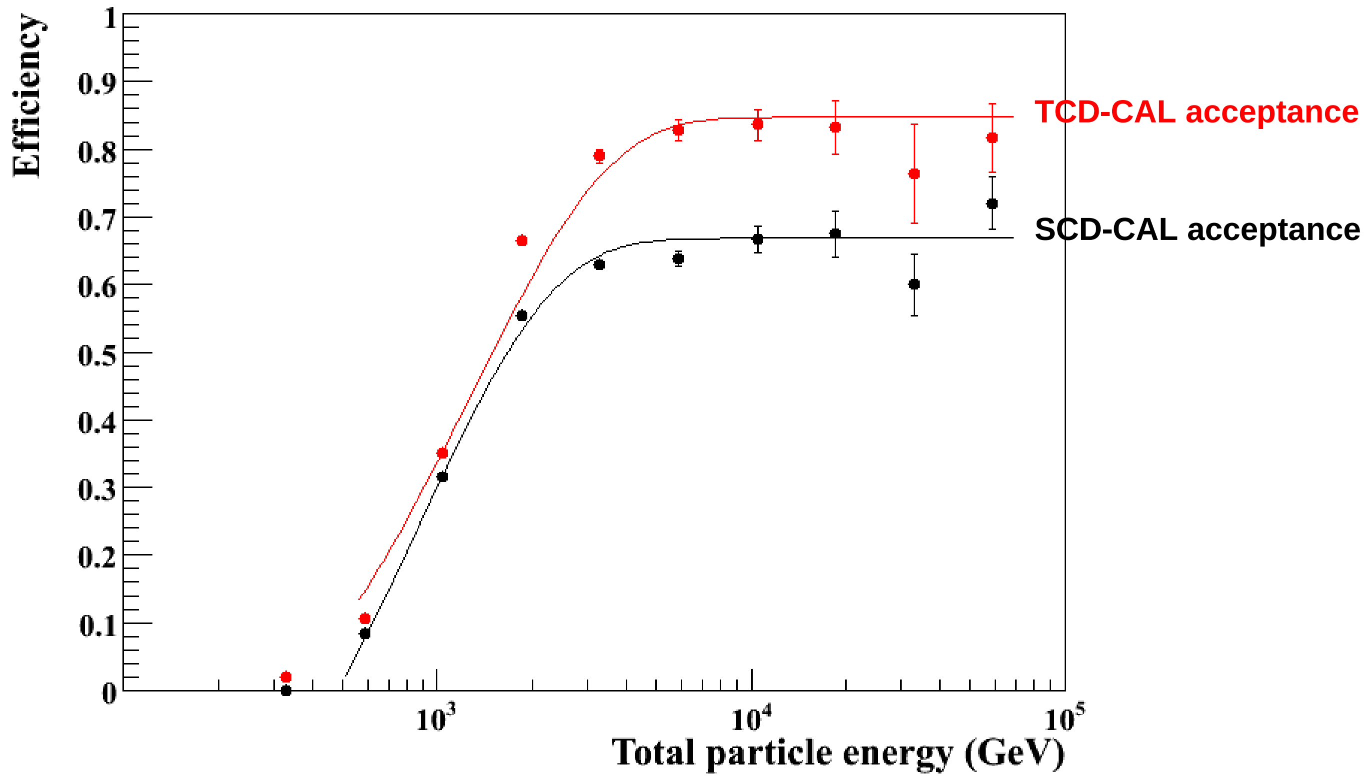




Average longitudinal profile

The two “holes” in the profile are due to 2 layers with reduced efficiency caused by 2 HPDs with problems during the flight

Selection cuts efficiency



Reconstruction efficiency includes:

- trajectory reconstruction: ~ 95% @ E> 1 TeV
- charge reconstruction (including effects of SCD dead/masked pixels)
  - steep rise below 2 TeV
  - nearly flat @ E > 3 TeV : ~ 80% (~65%) in TCD-CAL (SCD-CAL) acceptance
  - nearly Z independent

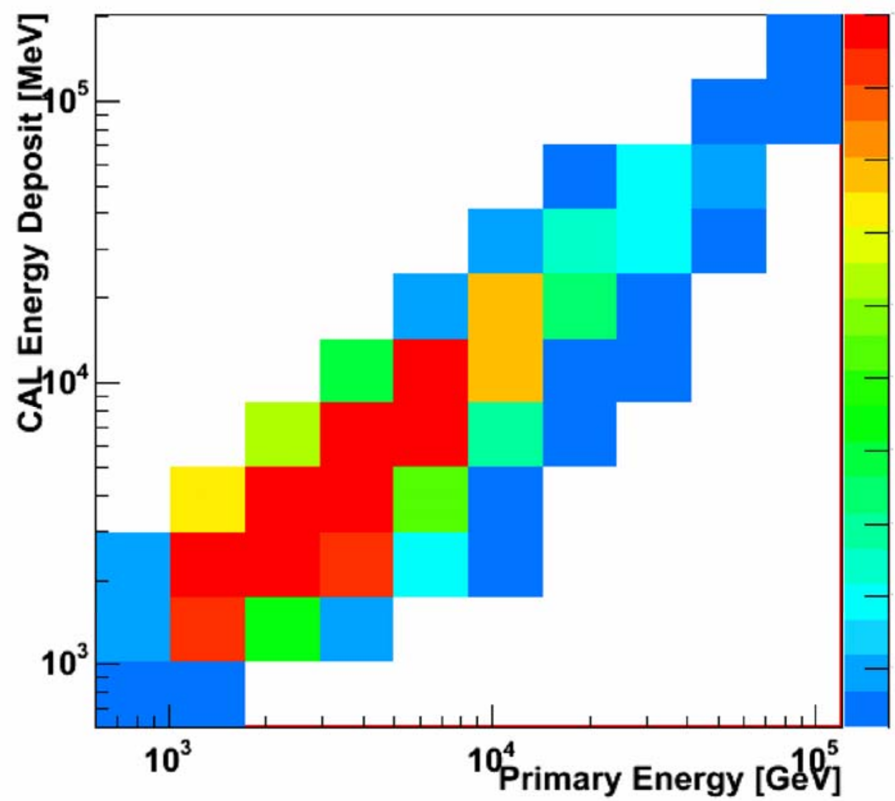
Energy deconvolution

$$M_i = \sum_j A_{ij} N_j$$

- N_j = no. events in bin j of primary particle energy scale
- M_i = no. events in bin i of CAL energy deposit scale
- A_{ij} is the mixing matrix. Its elements are determined by analyzing the MC generated statistics with the same procedure applied to flight data.

An element A_{ij} of the mixing matrix represents the probability that a CR particle, carrying an energy corresponding to a given energy bin j, produces an energy deposit in CAL falling in bin i.

Example of mixing matrix

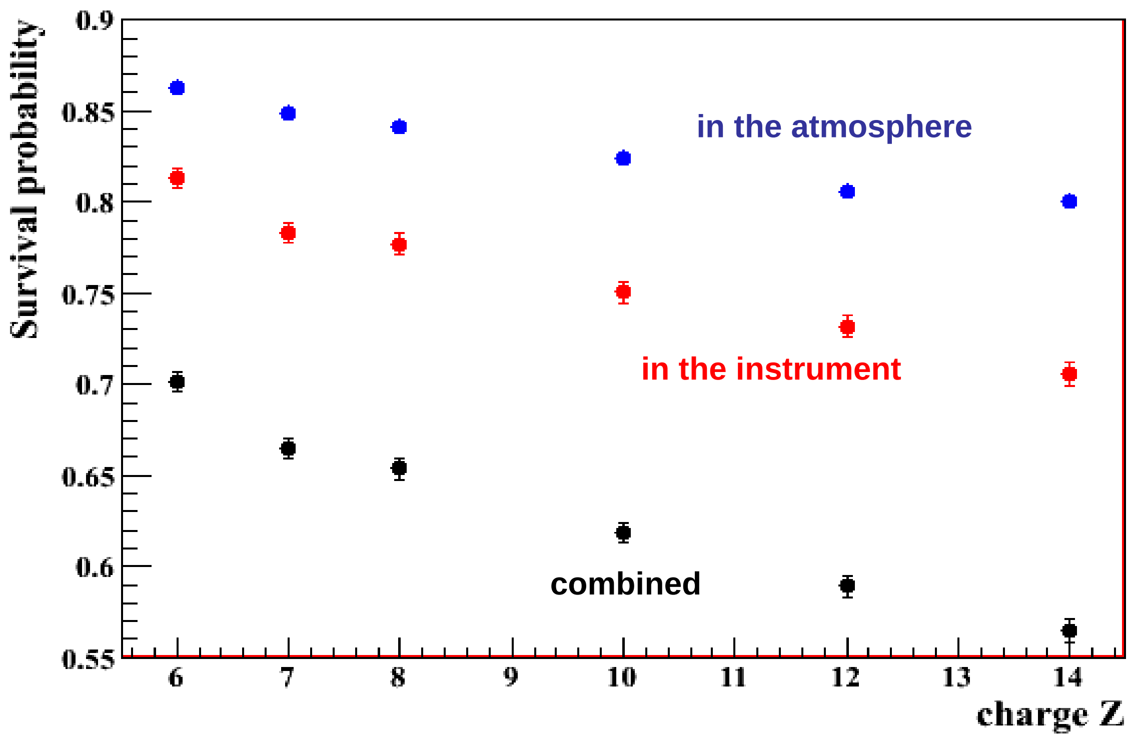


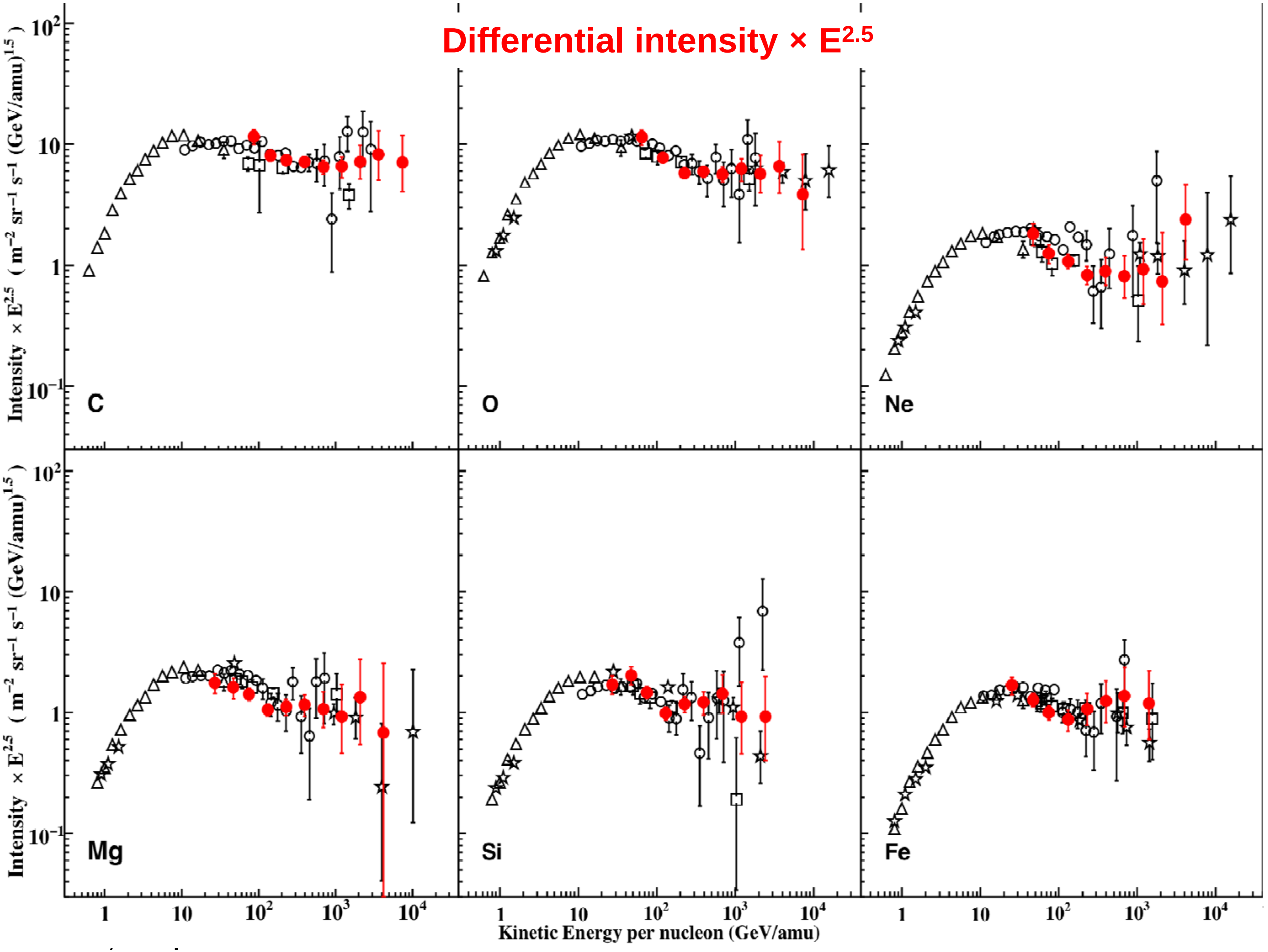
TOI and TOA corrections

- TOI (Top of Instrument) correction: ~ 5 g/cm^2 of materials above SCD

- TOA (Top Of Atmosphere) correction estimated by means of a Fluka based MC of the residual atmosphere overburden (~3.9 g/cm^2).
  Zenith angle distribution of nuclei within CREAM acceptance is taken into account

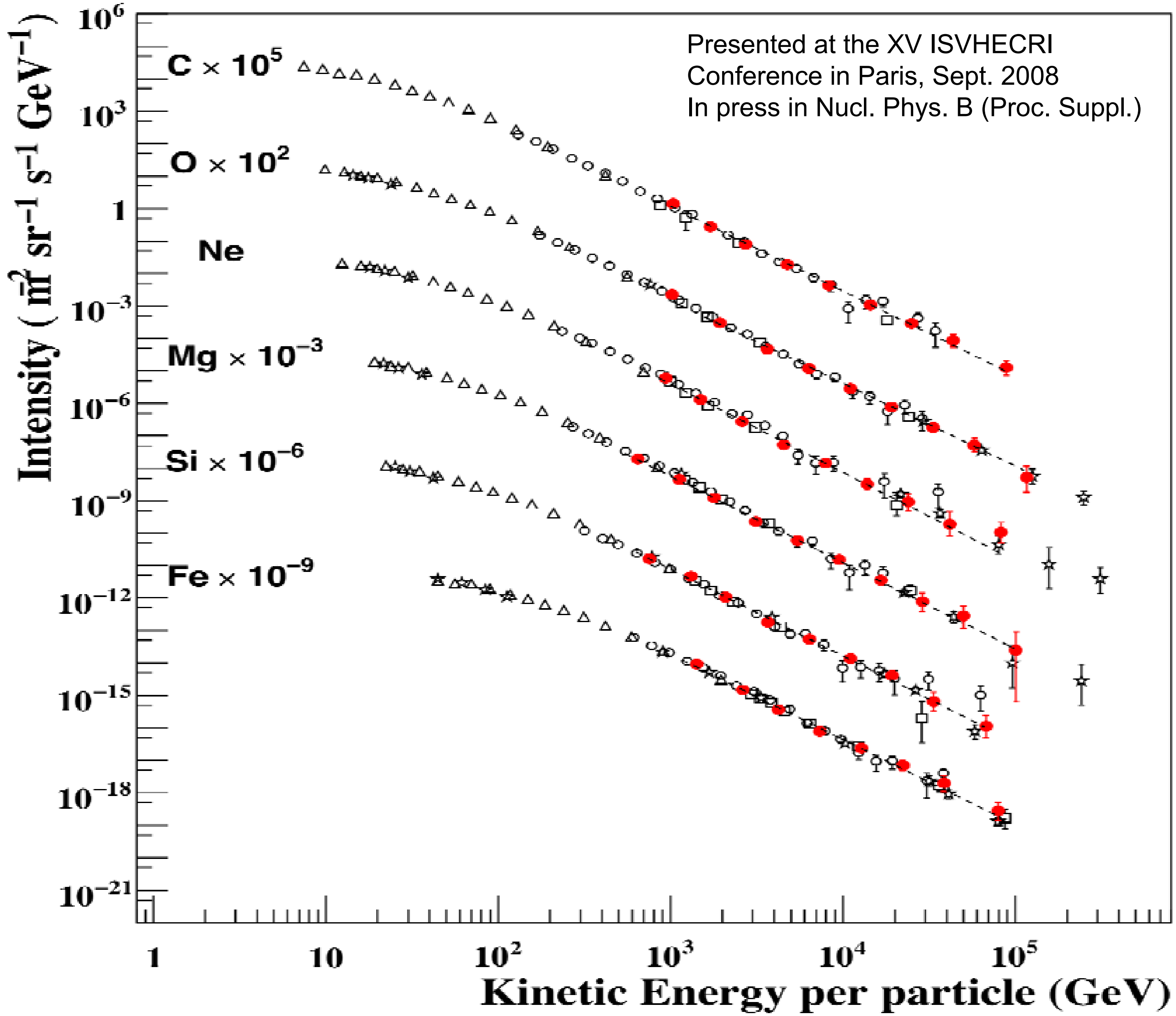
- At TeV scale the survival probabilities are nearly independent on energy





Differential intensity × E^2.5
Intensity × E^2.5 (m^-2 sr^-1 s^-1 (GeV/amu)^1.5)
C
O
Ne
Mg
Si
Fe
Kinetic Energy per nucleon (GeV/amu)

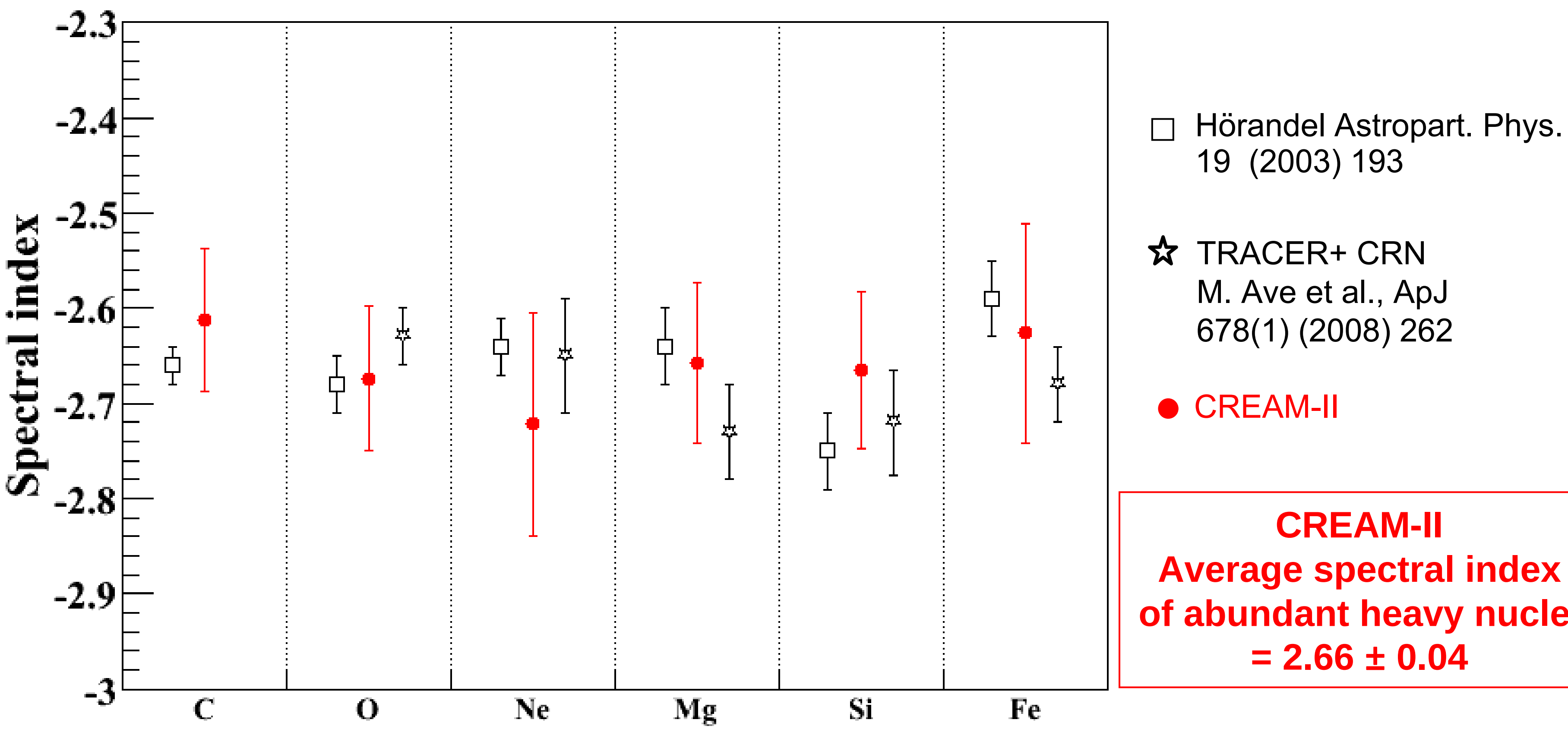
Differential intensity vs particle energy



Spectral indexes

CREAM-II measured the absolute intensities of C, O, Ne, Mg, Si, Fe in the particle energy range 800 GeV - 100 TeV.

Energy spectra are well fitted to power-laws $\phi(E) = \phi_0 \times E^{-\gamma}$ with very similar spectral indexes.



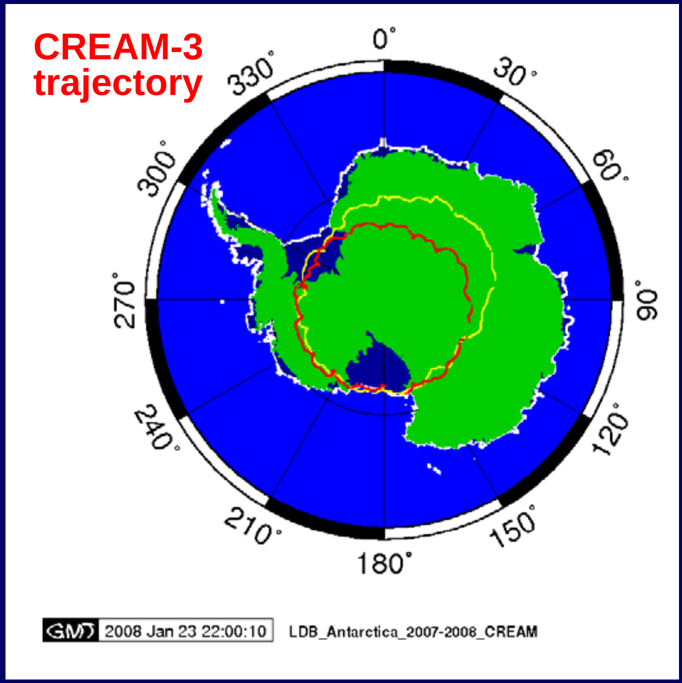
CREAM-II
Average spectral index of abundant heavy nuclei = 2.66 ± 0.04

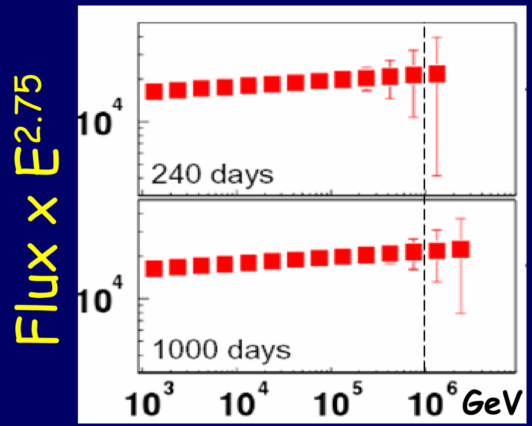
CREAM: 2 more flights in Antarctica

- NASA Long Duration Balloons (LDB)
- Payload ~ 1300 kg
- Science Instrument Power ~ 400 W
- 4 flights from McMurdo in 5 yrs (2004-2009) :

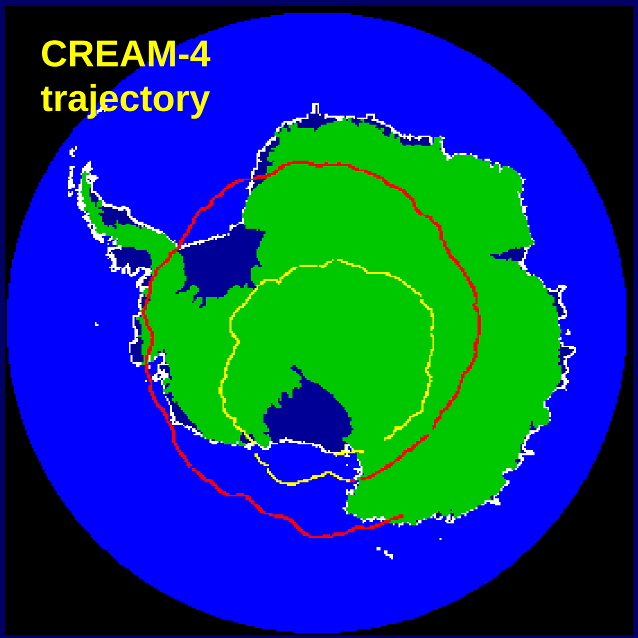
Altitude 38-40 km. Atmospheric overburden ~3.9 g/cm^2

CREAM-1	**42 days**	(Dec. 16th 2004 - Jan. 27th 2005)
CREAM-2	**28 days**	(Dec. 15th 2005 - Jan. 12th 2006)
CREAM-3	**28 days**	(Dec. 19th 2007 - Jan. 17^{h} 2008)
CREAM-4	**19 days**	(Dec. 18th 2008 - Jan. 7^{h} 2009)

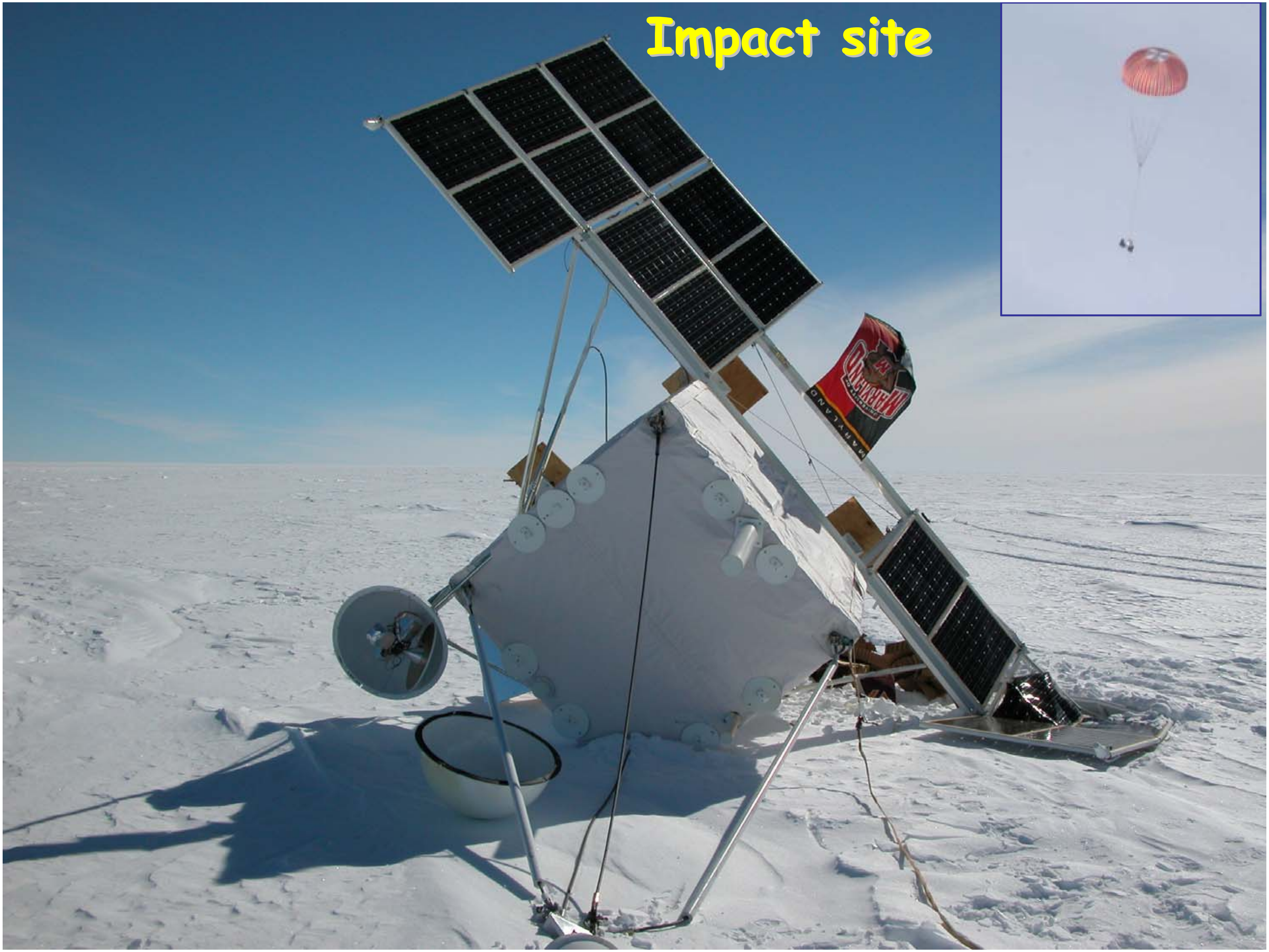




Expected energy reach for **protons**



Impact site



Recovery operations

On the Twin Otter after payload recovery