Cosmic Ray Composition

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3rd School on Cosmic Rays and Astrophysics

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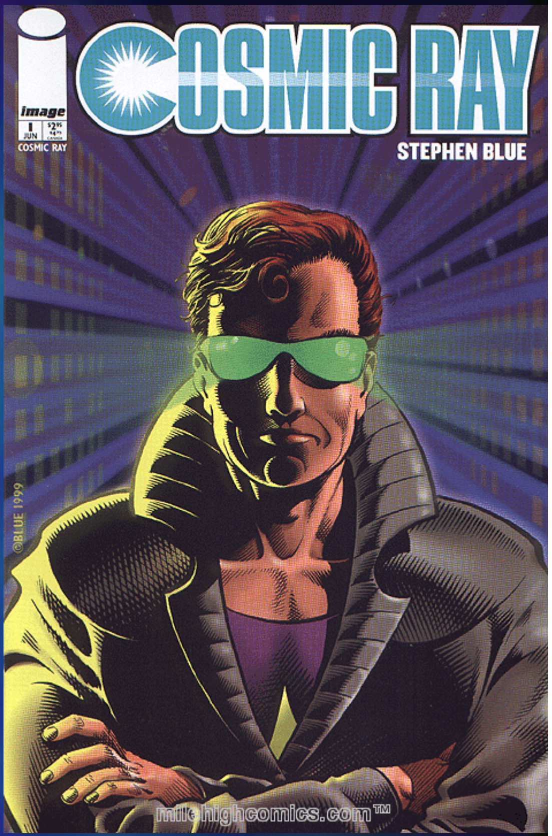
Outline

- Cosmic Rays:
  - Origin and Propagation;
  - Composition, Spectrum, Secondary Particle;
- The CREAM Experiment:
  - Instrument Design, Performance;
  - Antarctic Campaigns 2004, 2005, 2007;
  - First Results;
- Future Prospects.



The Cosmic Ray Spectrum

Cosmic rays:
- high energy nuclei from H to Fe;
- 10^9 eV to $>10^{20}$ eV.

The Knee:
Limit to SN shock acceleration?

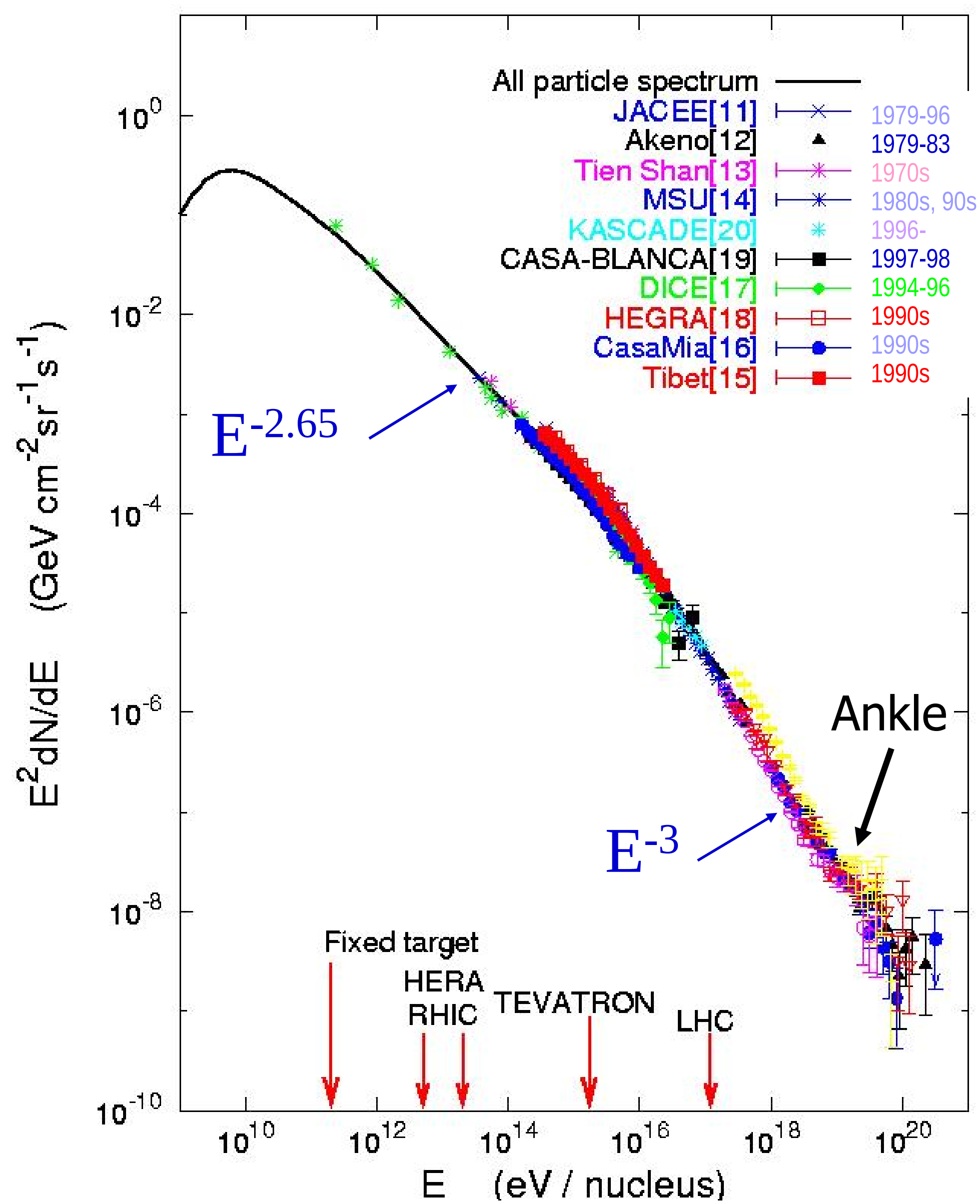
The Ankle:
Extragalactic component?

Fluxes rescaled by E^2

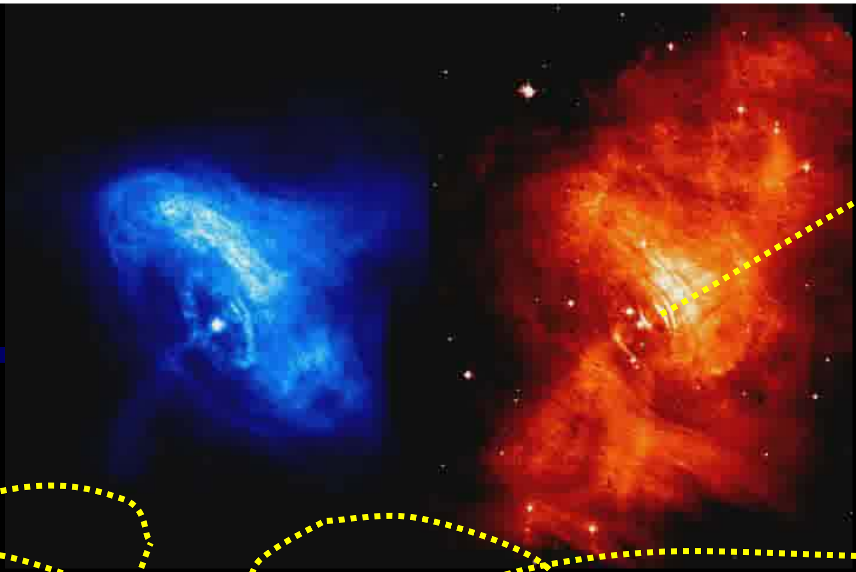
$>10^{12}$ eV: 1 per (m^2 second sr)

$>10^{16}$ eV: 1 per (m^2 year sr)

$>10^{20}$ eV: 1 per (km^2 century sr)



Cosmic Rays

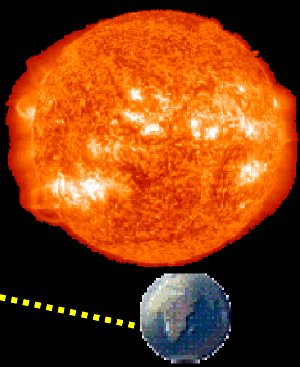


Production
Acceleration
(Crab)

Propagation

- Interaction with ISM and fields
- Escape, Reacceleration, Diffusion δ
- Production of secondaries

Solar Modulation



Geomagnetic Cutoff
Atmospheric Interactions

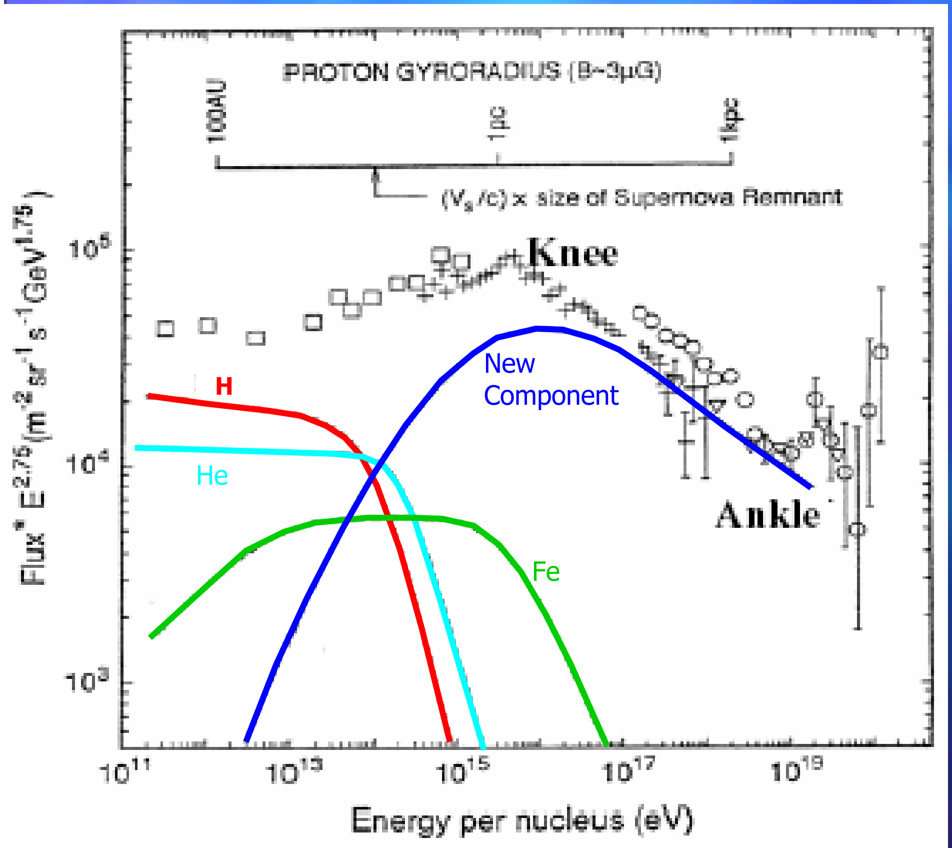
Works only up to:

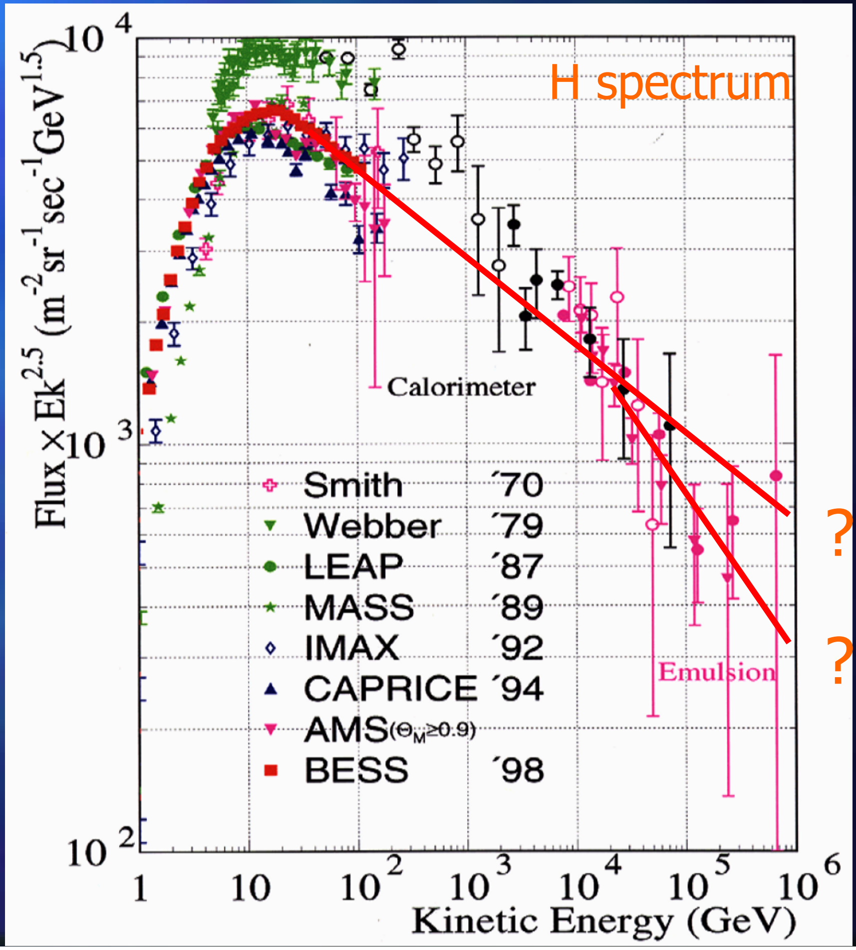
$$E_{\max} \approx \beta\, cZeBL$$

(~10^{15} eV $\Rightarrow$ knee? rigidity dependent?)

Direct Composition Near the Knee

- Under the SN shock acceleration scenario, expect charge-dependent knee, e.g., H spectrum knee at ~10^{14}eV.





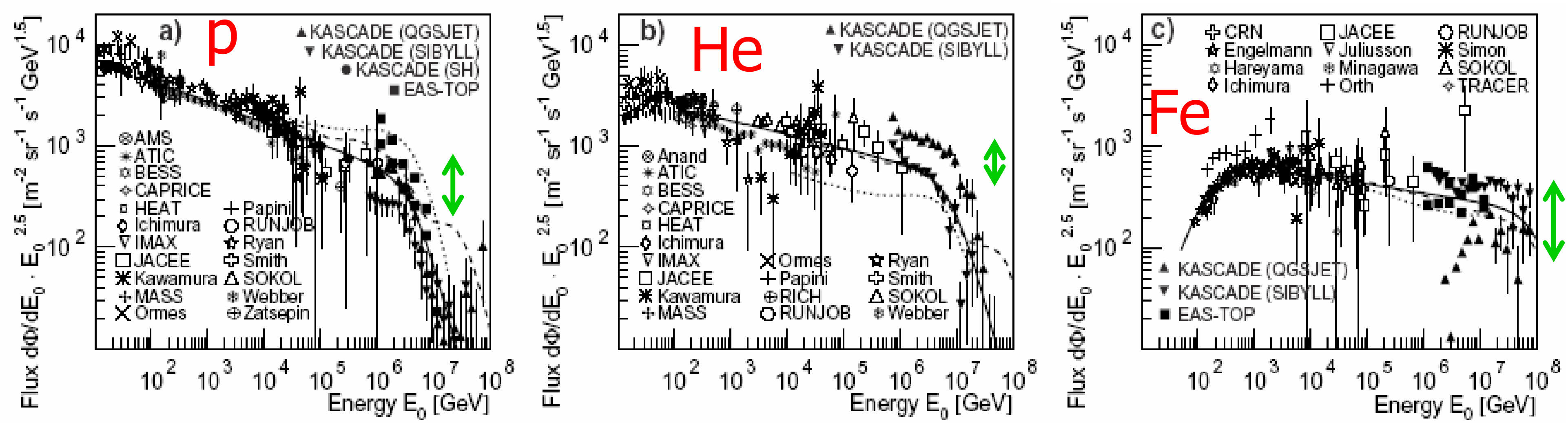
Cosmic Ray Mass Composition Status

Improved direct measurements can provide the foundation for studies at higher energies

Indirect evidence highly model dependent
Inferred fluxes can vary by factors of 2 or more

UHE cosmic rays (Auger) extend a further 3 orders of magnitude in energy

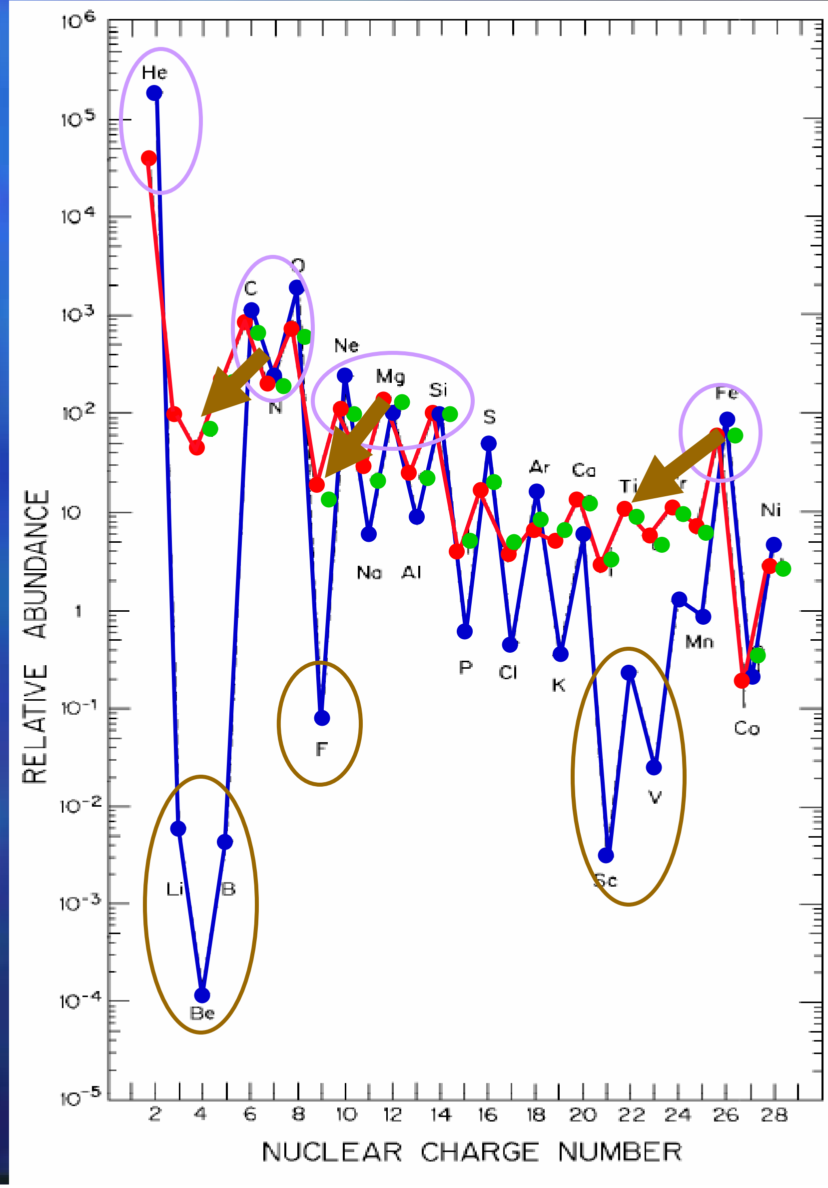
Direct measurements | Indirect inferred from air showers | Direct measurements | Indirect inferred from air showers | Direct measurements | Indirect inferred from air showers



Low Energy Cosmic Ray Abundances

- He and heavier, normalized to Si;
- ● CR 0.07 – 0.28 GeV/amu;
  ● CR 1 – 2 GeV/amu;
  ● Solar system abundances;
- Even-odd effect;
- He, CNO, NeMgSi, Fe abundant species.

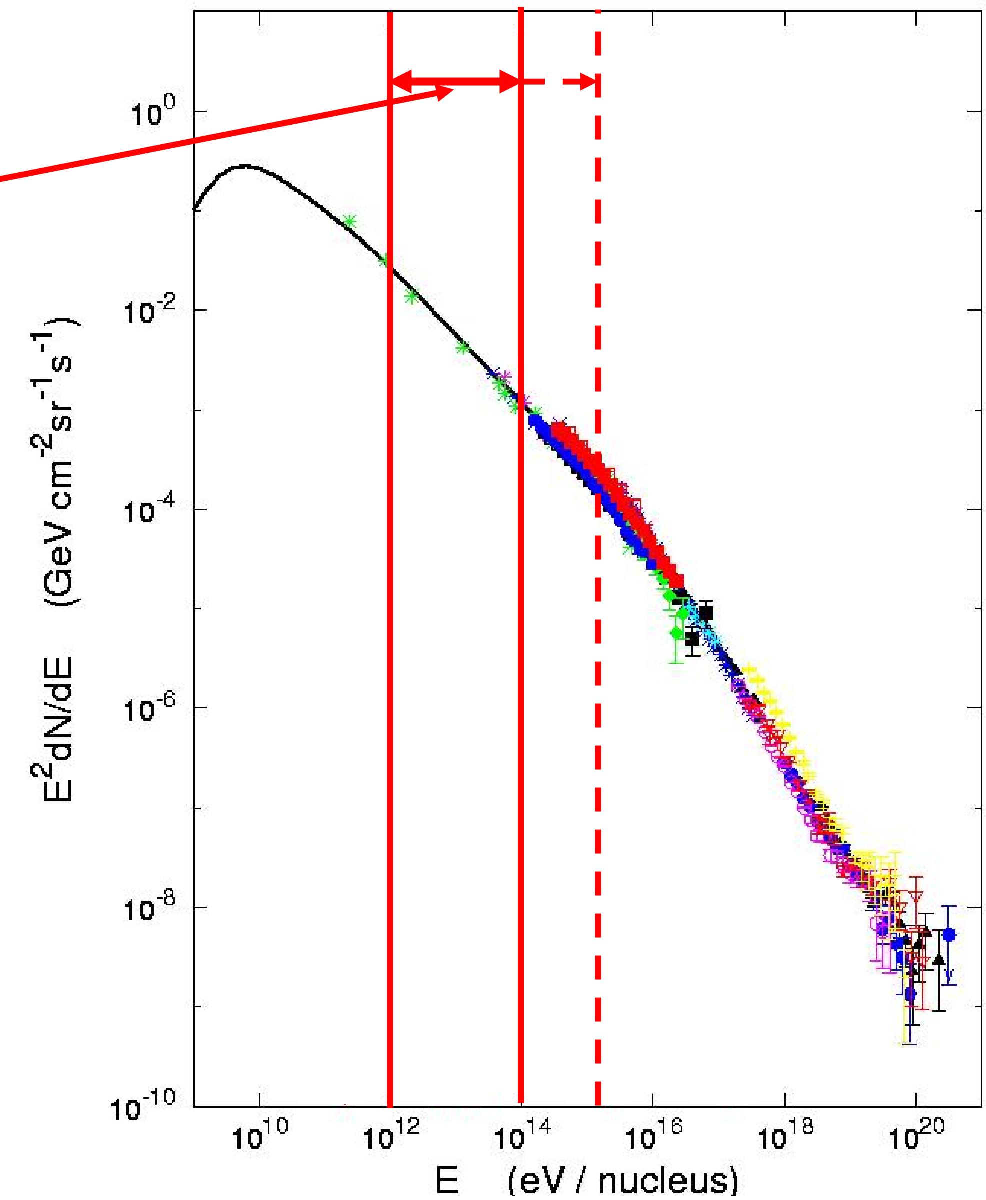
- LiBeB, F, ScTiV not present as end products of stellar nucleosynthesis.
- Higher CR abundances, produced by spallation.



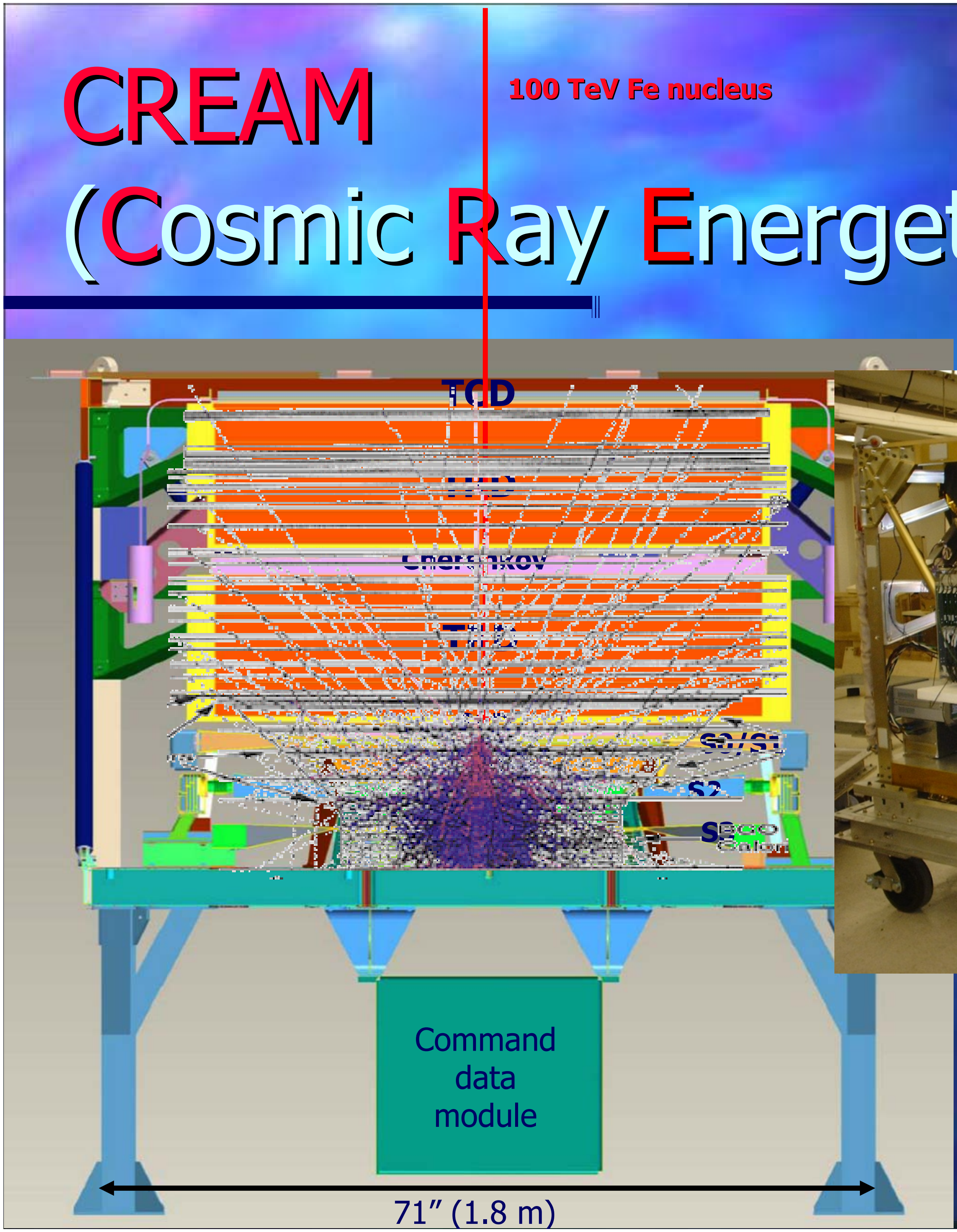
Direct Composition Measurements

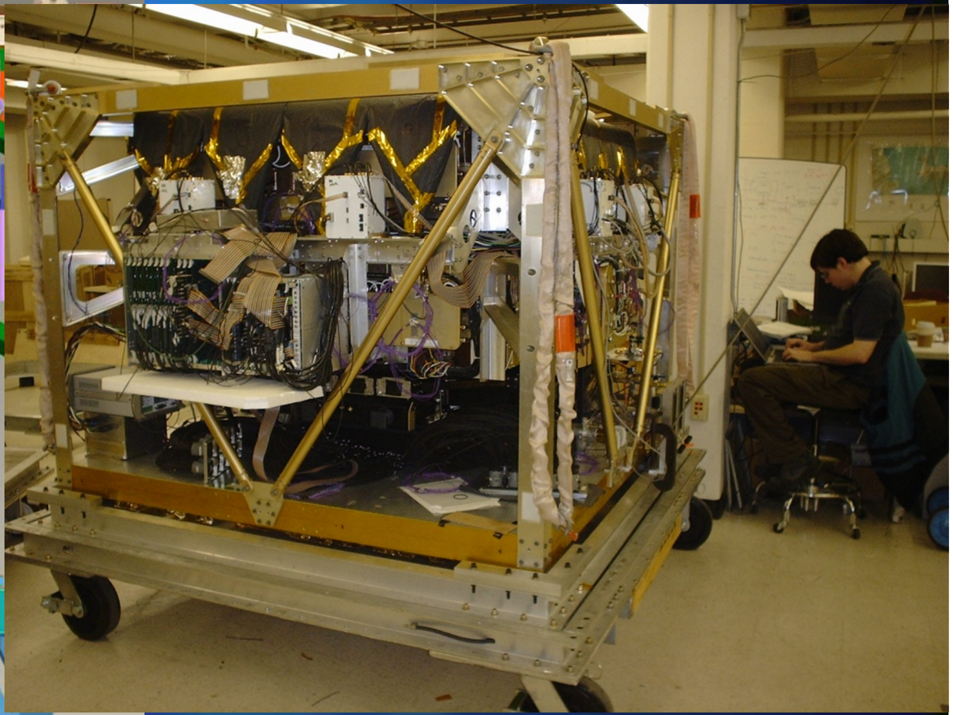
CREAM Missions (NASA)

- Direct composition measurements;
- Spectrum measurement from $10^{12} - 10^{15}$ eV;
- Elemental resolution;
- Antarctic Balloon missions;
- Redundant energy determination;
- Target: 200 days Antarctic exposure with a fully active instrument with geometric acceptance 2.2 m^2 sr.



CREAM
(Cosmic Ray Energetics And Mass)





2.2 m^2sr trigger aperture

CREAM Collaboration (Cosmic Ray Energetics And Mass)

- University of Maryland

H. S. Ahn, O. Ganel, K.C. Kim, M. H. Lee, L. Lutz, A. Malinine, E. S. Seo, R. Sina, J. Wu, Y. S. Yoon, S. Y. Zinn

- University of Chicago

P. Boyle, S. Swordy, S. Wakely

- **Penn State University**

T. Anderson, N. B. Conklin, S. Coutu, M. Geske, S. I. Mognet (B. Koger, K. Rotz, M. Stafford)

- Ohio State University

P. Allison, J. J. Beatty, T. Brandt

- University of Minnesota

J. T. Childers, **M. A. DuVernois**

- University of Sienna & INFN, Italy

M. G. Bagliesi, G. Bigongiari, P. Maestro, P. S. Marrocchesi, R. Zei

- Ehwa Womans University, S. Korea

J. H. Han, H. J. Hyun, J. A. Jeon, J. K. Lee, S. W. Nam, I. H. Park, N. H. Park, J. Yang

- Northern Kentucky University

S. Nutter

- Kent State University

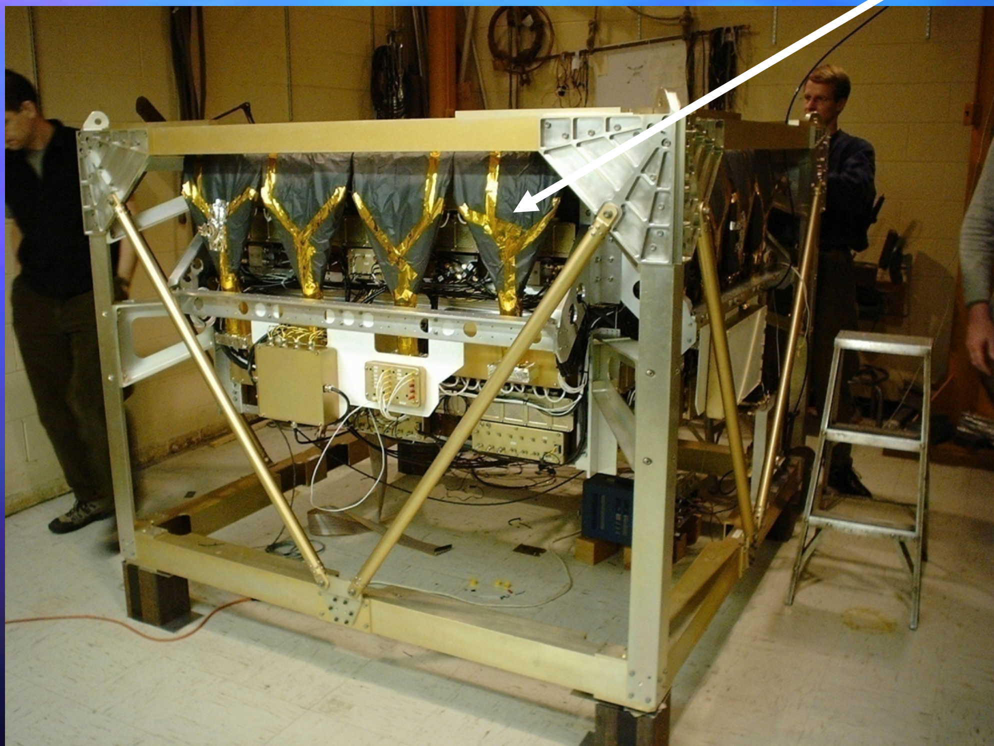
S. Minnick

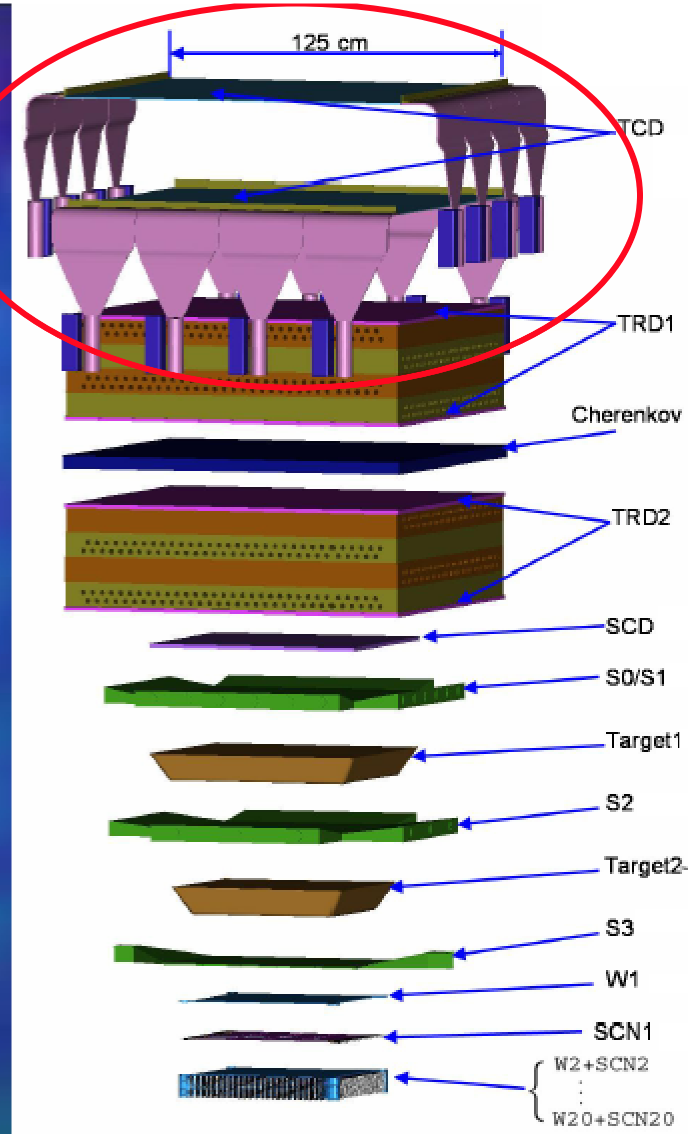
- Kyungpook National University, S. Korea

H. Park

- NASA Goddard; Grenoble, France; U. Nacional Autonoma, Mexico

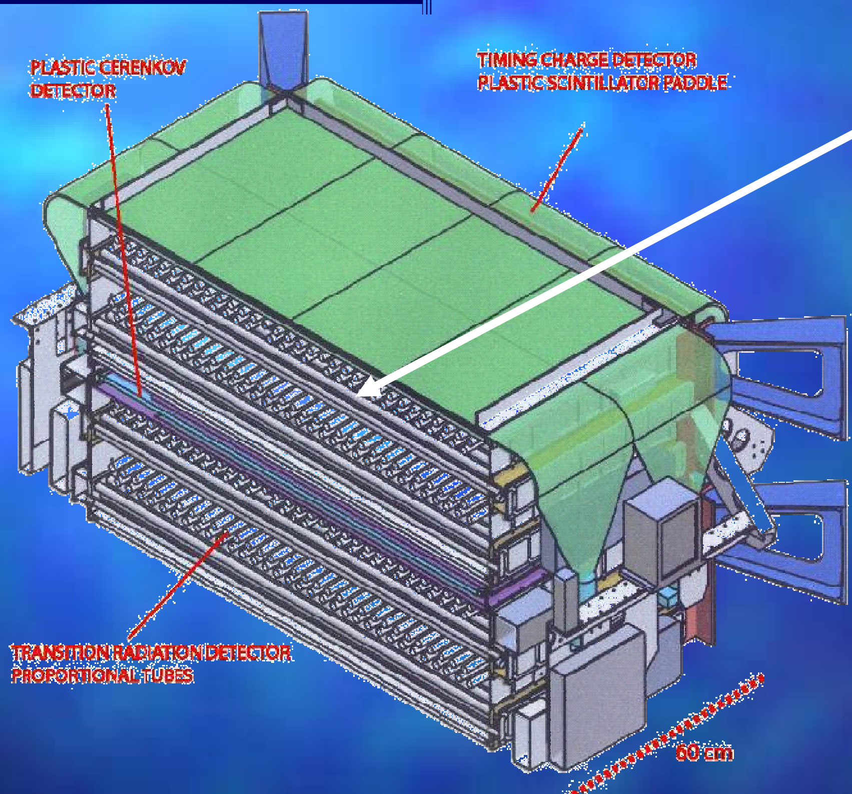
TCD System

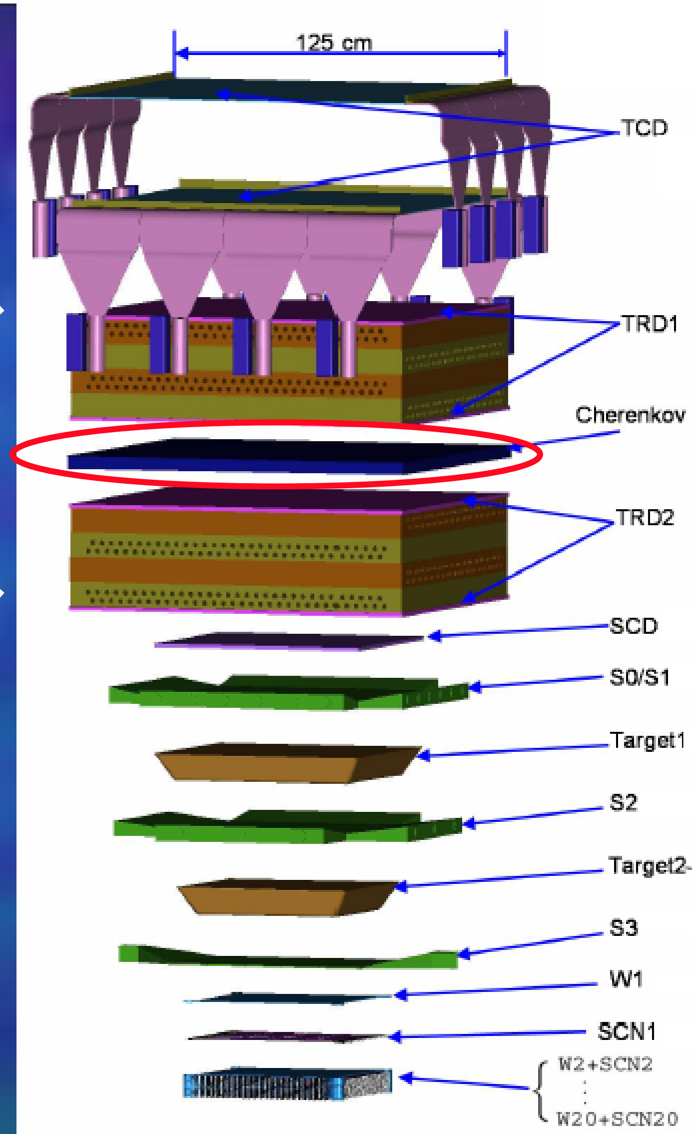




- Timing Charge Detector (TCD):
  - 8 thin (5 mm) scintillators in 2 layers, 16 fast PMTs;
  - Light pulse amplitude and time structure measured ⇒ Q measured before albedo from calorimeter, 3-8 ns after incident particle; provide Z>3 trigger;
  - Charge accuracy ~0.2e for O, ~0.35e for Fe.

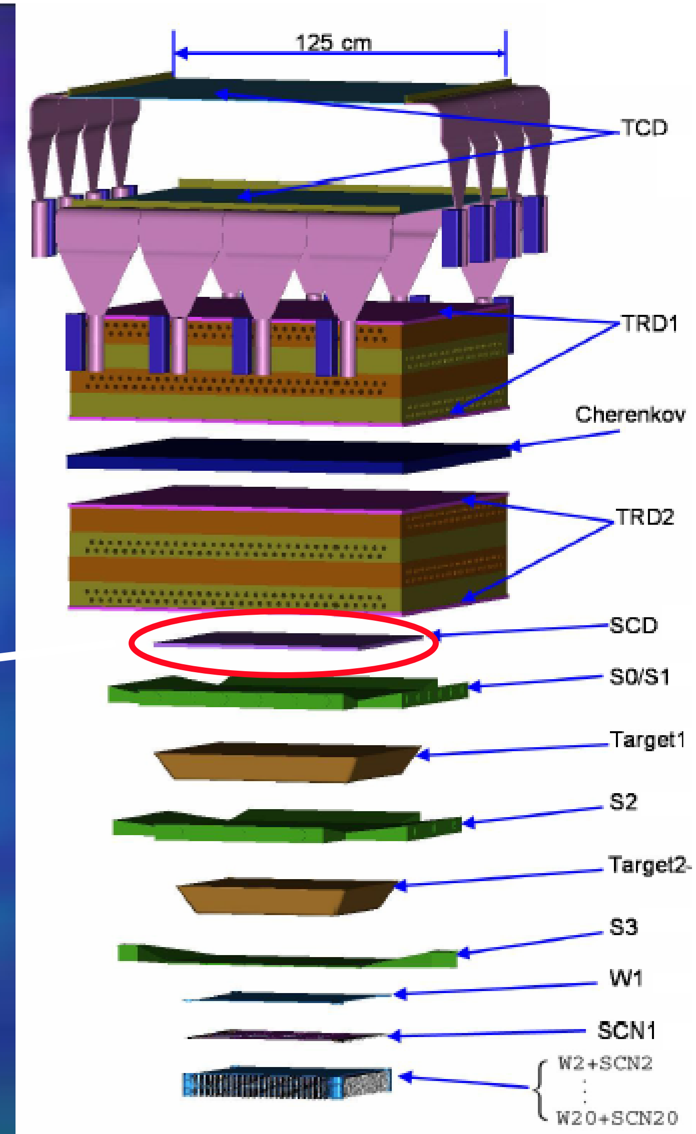
TRD System Plus Cherenkov





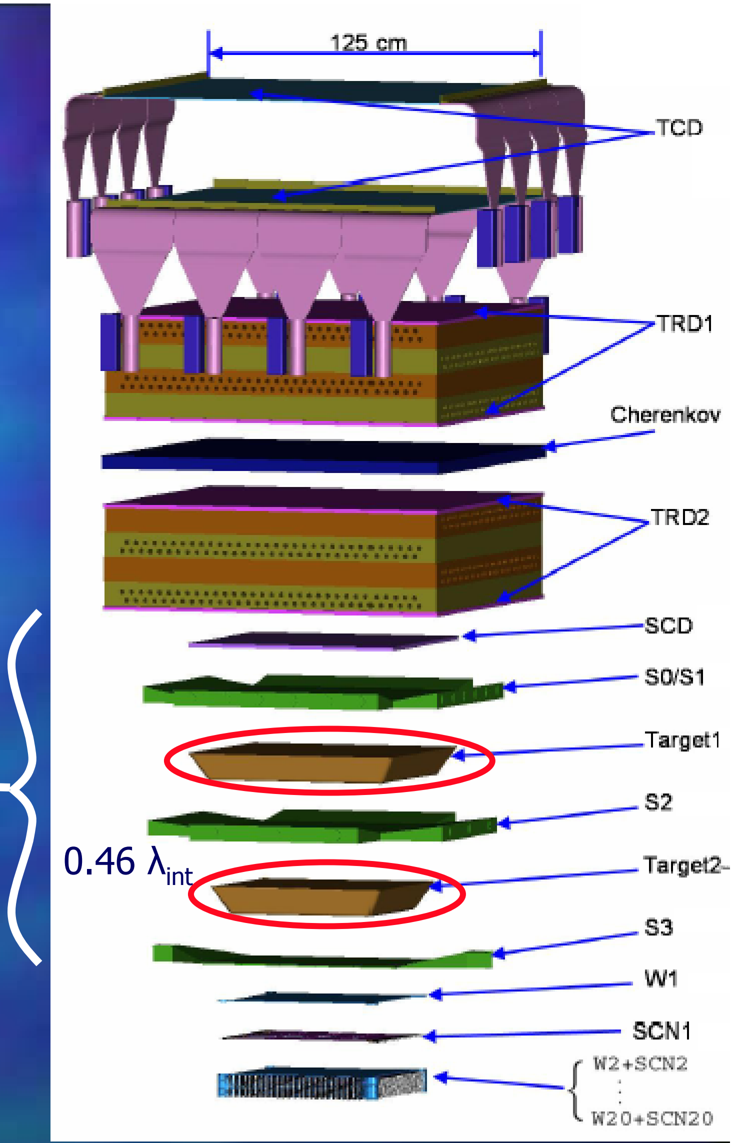
- Transition Radiation Detector (TRD):
  - 512 thin-walled (100 μm) proportional tubes (2 cm diameter) in 16 layers in foam matrix;
  - Filled with Xe(95%)-methane(5%);
  - Hit pattern ⇒ 3D track with σ_{RMS} ~ 5 mm (ultimately 2 mm);
  - dE/dx (+TR @ >1 TeV/n) yields E until saturation at γ ~ 20,000; sensitivity to Li and heavier.

SCD System



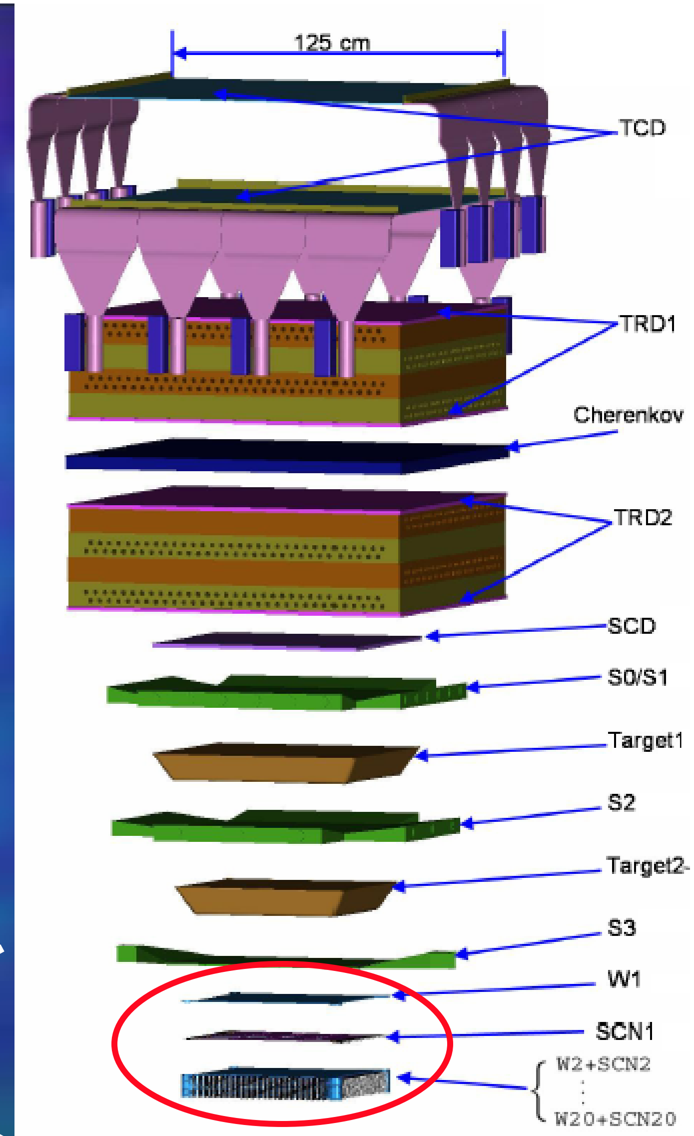
- Silicon Charge Detector
  - 26 ladders, each with 7 silicon sensor modules, each with 16 cells 2.12 cm^2;
  - Charge measurement, resolution ~0.1e;
  - Segmentation reduces back-scatter impact.

Hodoscope System Plus Graphite Targets



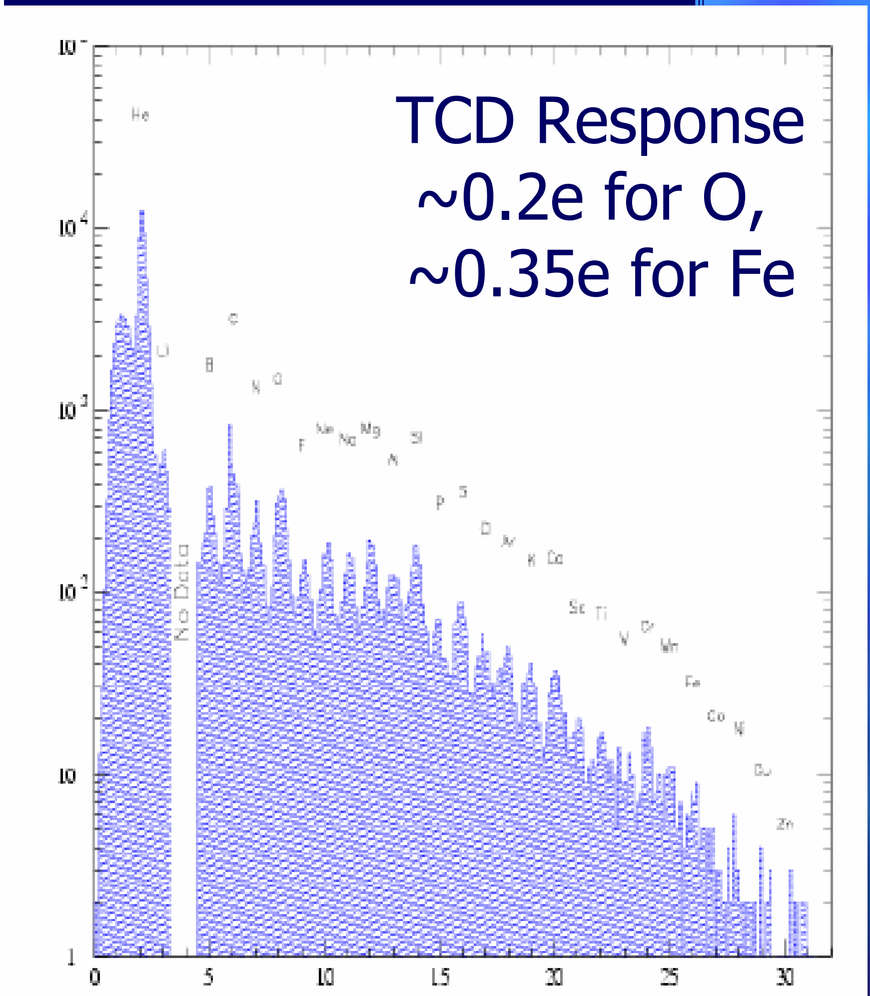
- Hodoscopes
  - 640 2×2 mm² scintillating fibers arranged in 2 orthogonal planes (exc. S3);
  - HPD readout (bundles of 64 fibers), PMT readout for S3;
  - Redundant charge measurement, plus trigger and tracking.

Calorimeter System

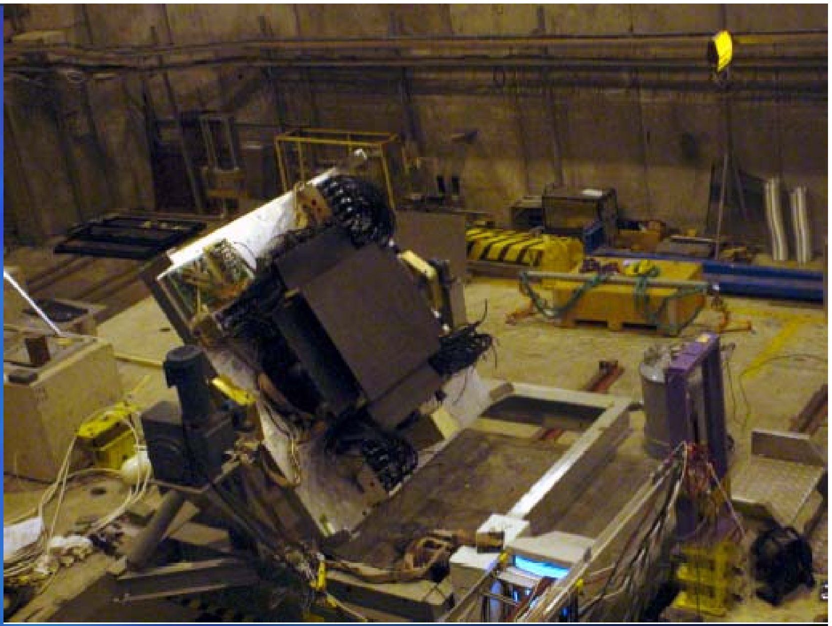


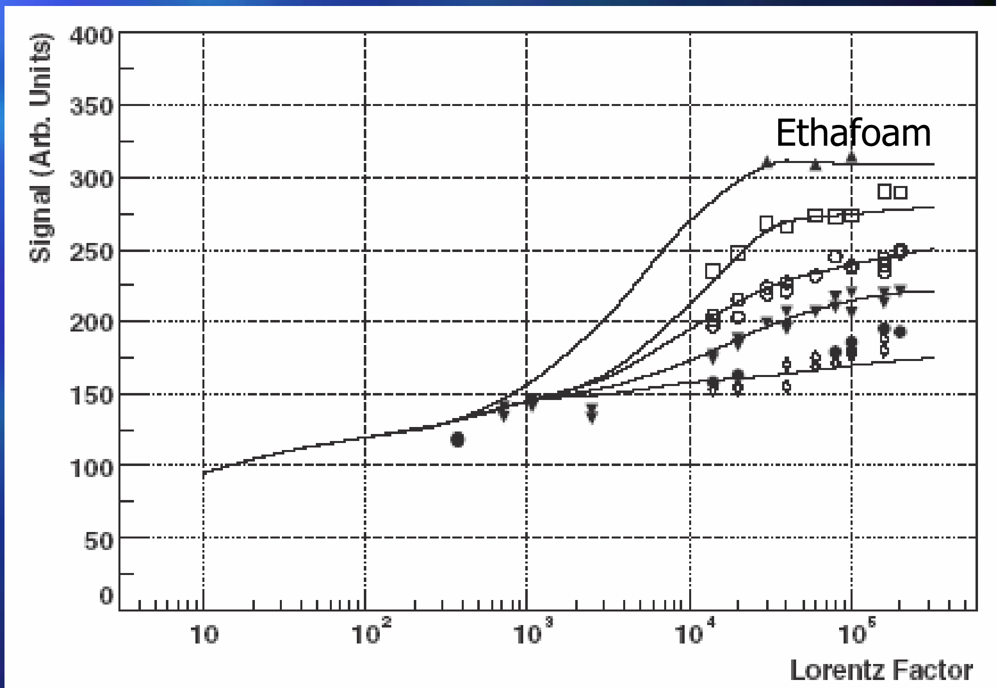
- Calorimeter stack
  - 20 W plates, 3.5 mm thick, 1 X_0 ;
  - 20 scintillating fiber layers, 1 cm wide ribbons (Moliere radius 9 mm), 0.1 mm dia. fibers;
  - HPD readout (40 HPDs, 2560 channels); fibers divided into low, mid, high energy readouts;
  - Tracking, energy measurement Z=1-26, E=~200 GeV-1000 TeV (45% resolution).

CERN Beam Tests



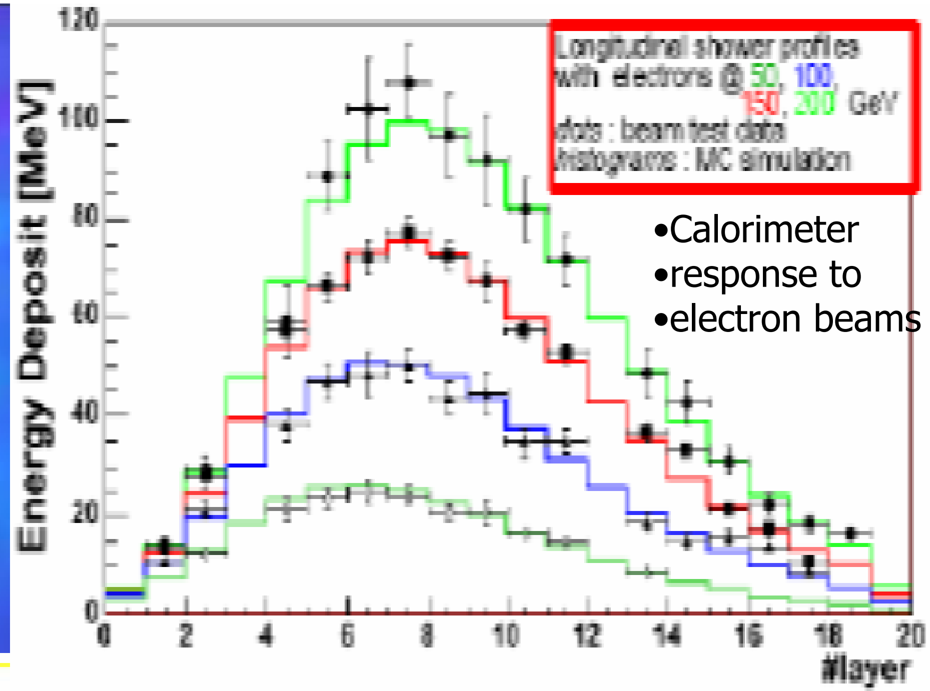
In beam fragments





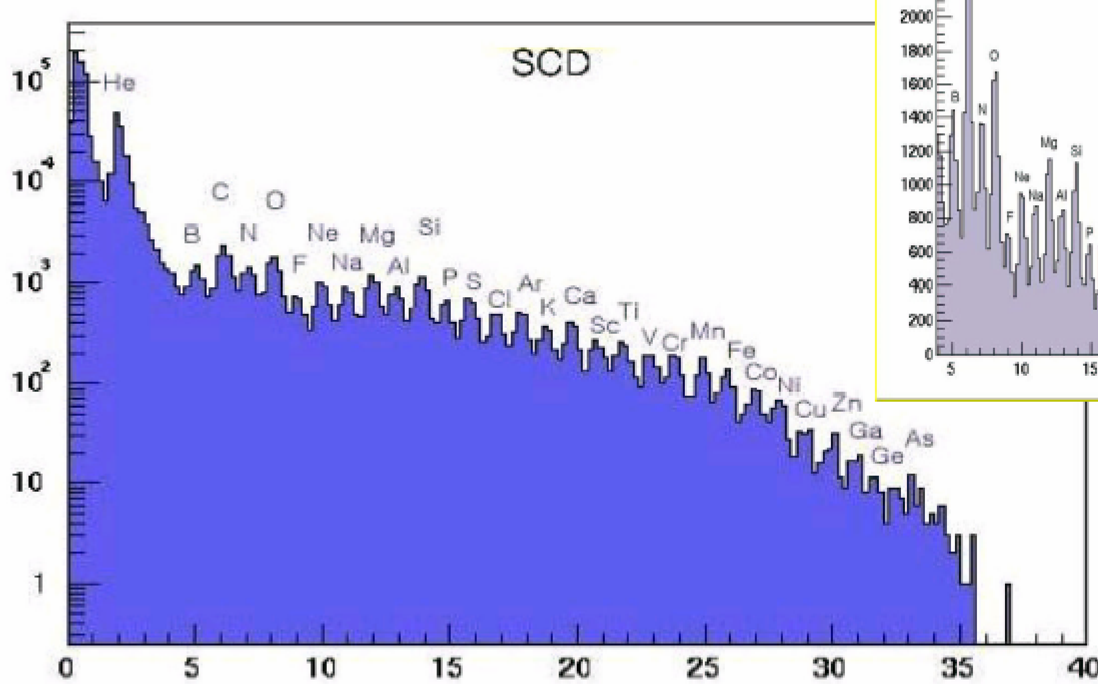
TRD Response vs Simulations

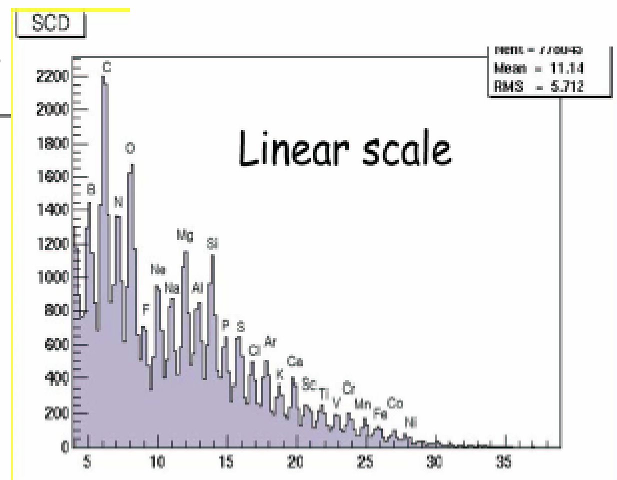
CERN Beam Tests



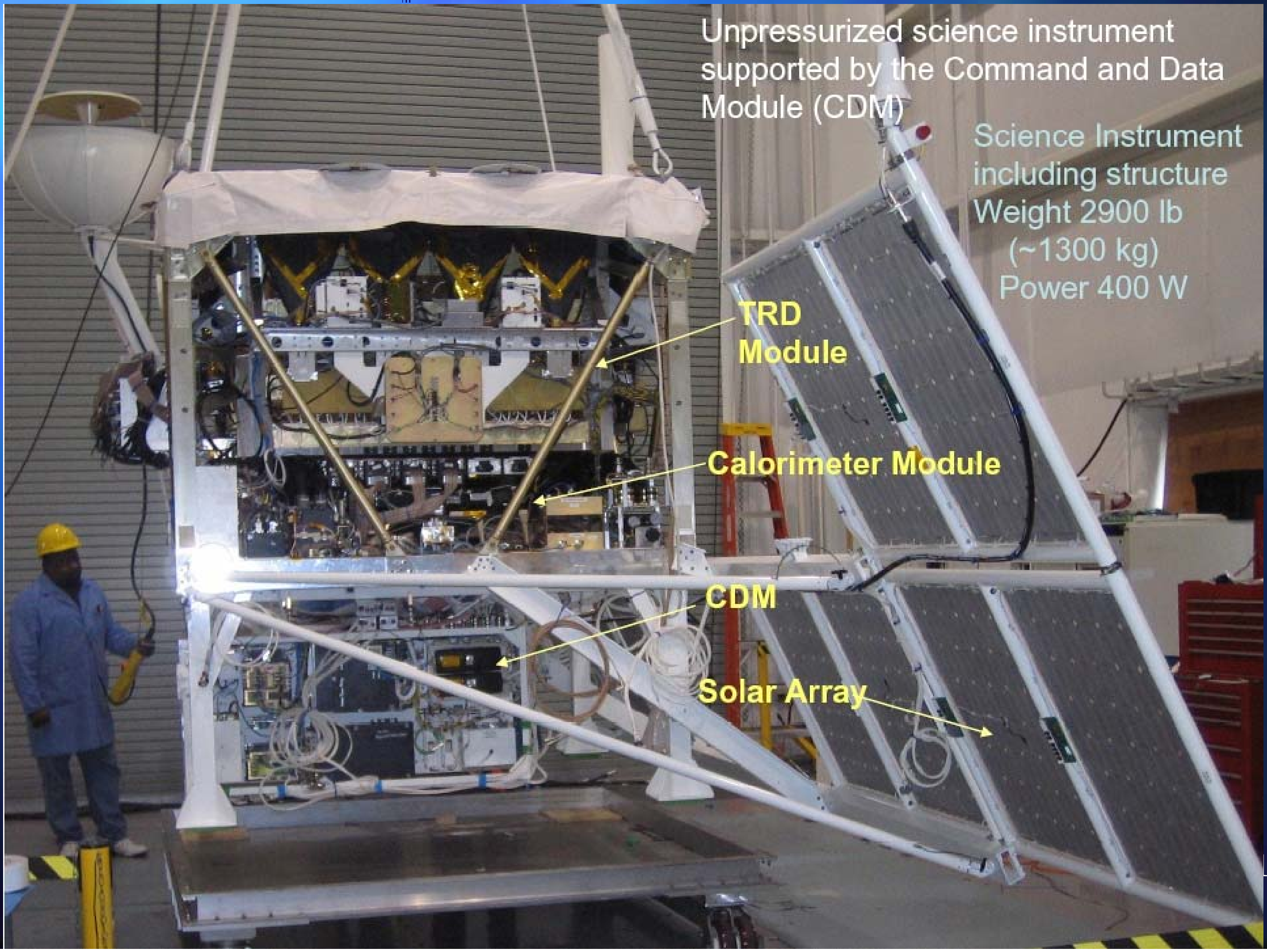
- Calorimeter
- response to
- electron beams

SCD Response to In beam fragments

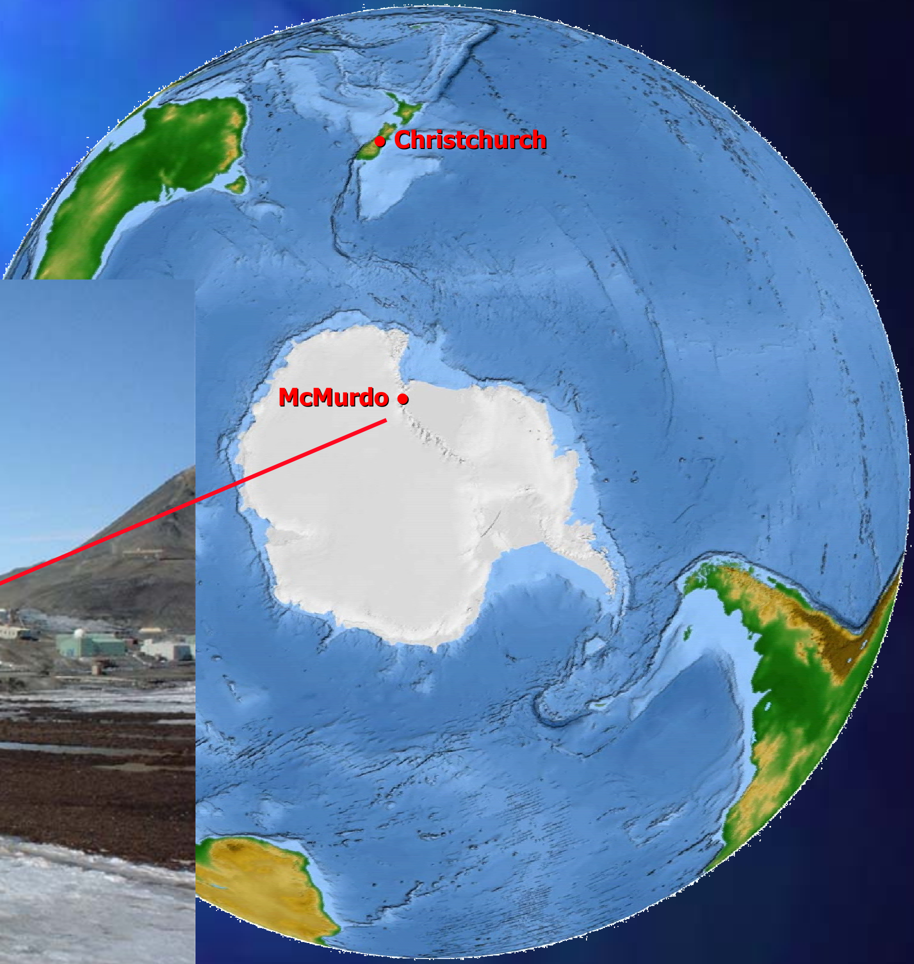




Overall Flight Configuration



Getting to Antarctica



Antarctica!


IVAN THE
TERRA BUS

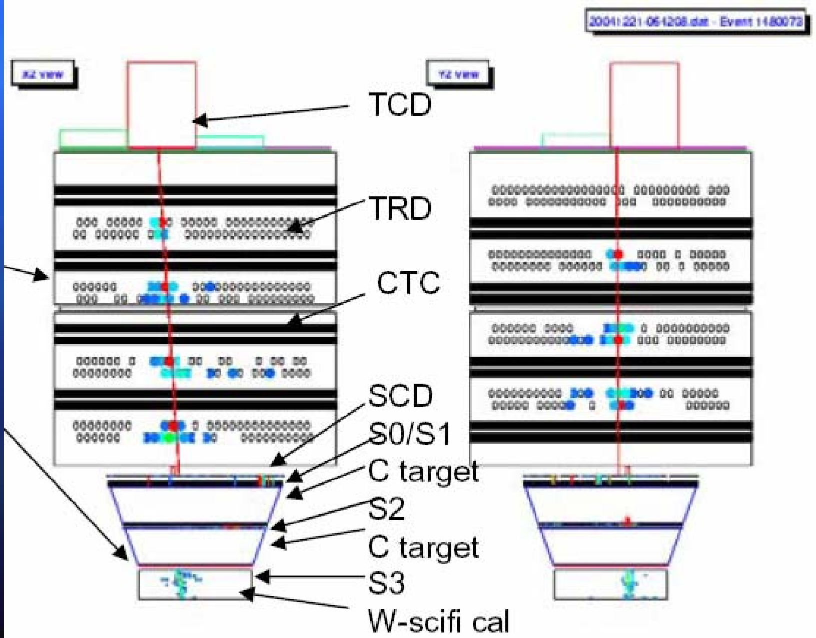

Colman's
Mustard
FRY'S
PURE CONCENTRATED
COCOA

CREAM 2004/05 Flight

CREAM Flights

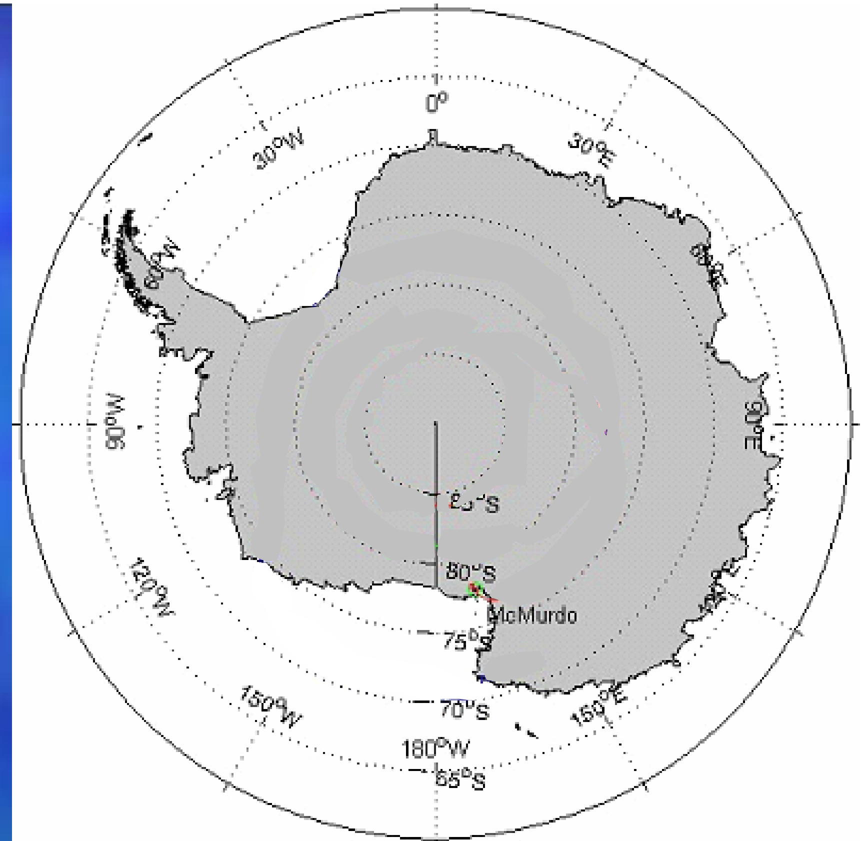
- CREAM1: Dec 15, 2004 → Jan 26, 2005
- 3 Antarctic orbits, 42 days! NASA LDB flight duration record (32 days previous)!
- CREAM2: Dec 16, 2005 → Jan 13, 2006 (28 days);
- CREAM3: Dec 19, 2007 → Jan 16, 2008 (28 days);
- CREAM4: Planned for Dec 2008 flight.

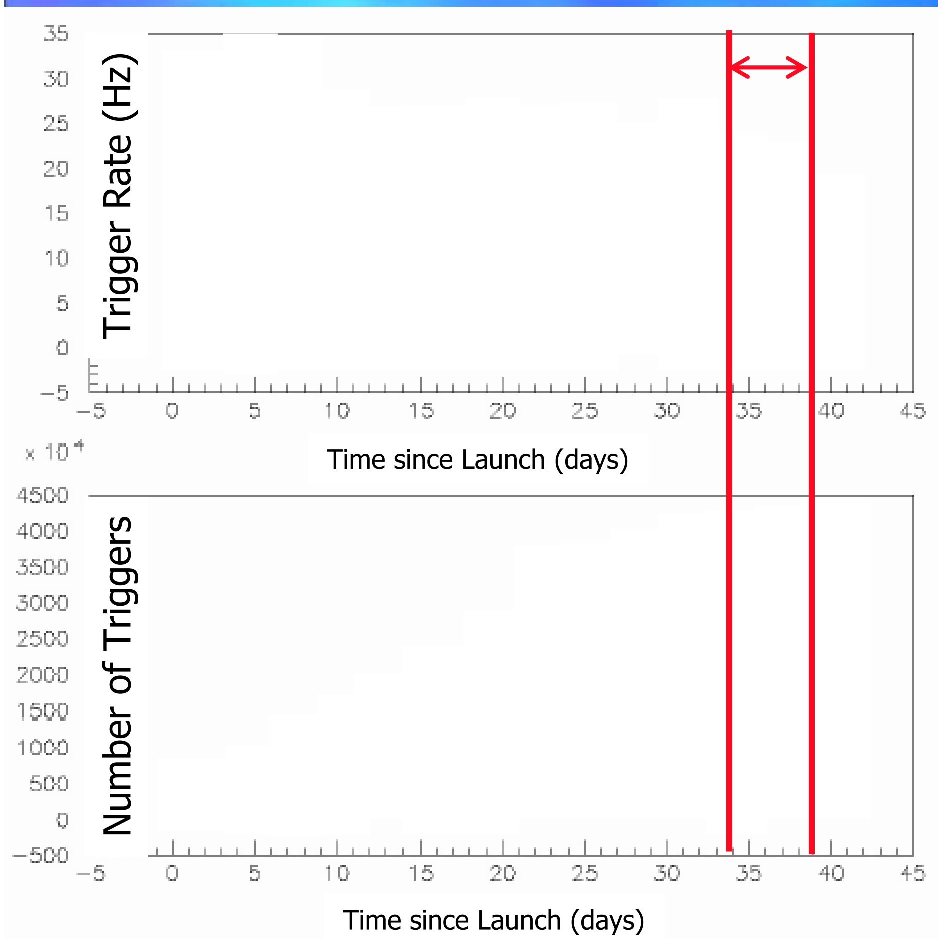
Estimated
10 TeV
Fe nucleus



Detector Performance in Flight

- 42 day flight; 40 million heavy nuclei; 0.4% atm. Depth.

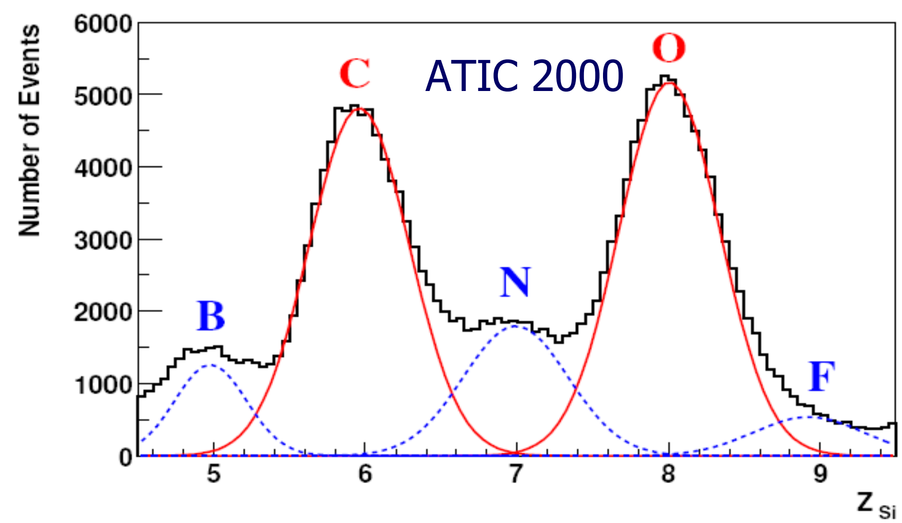


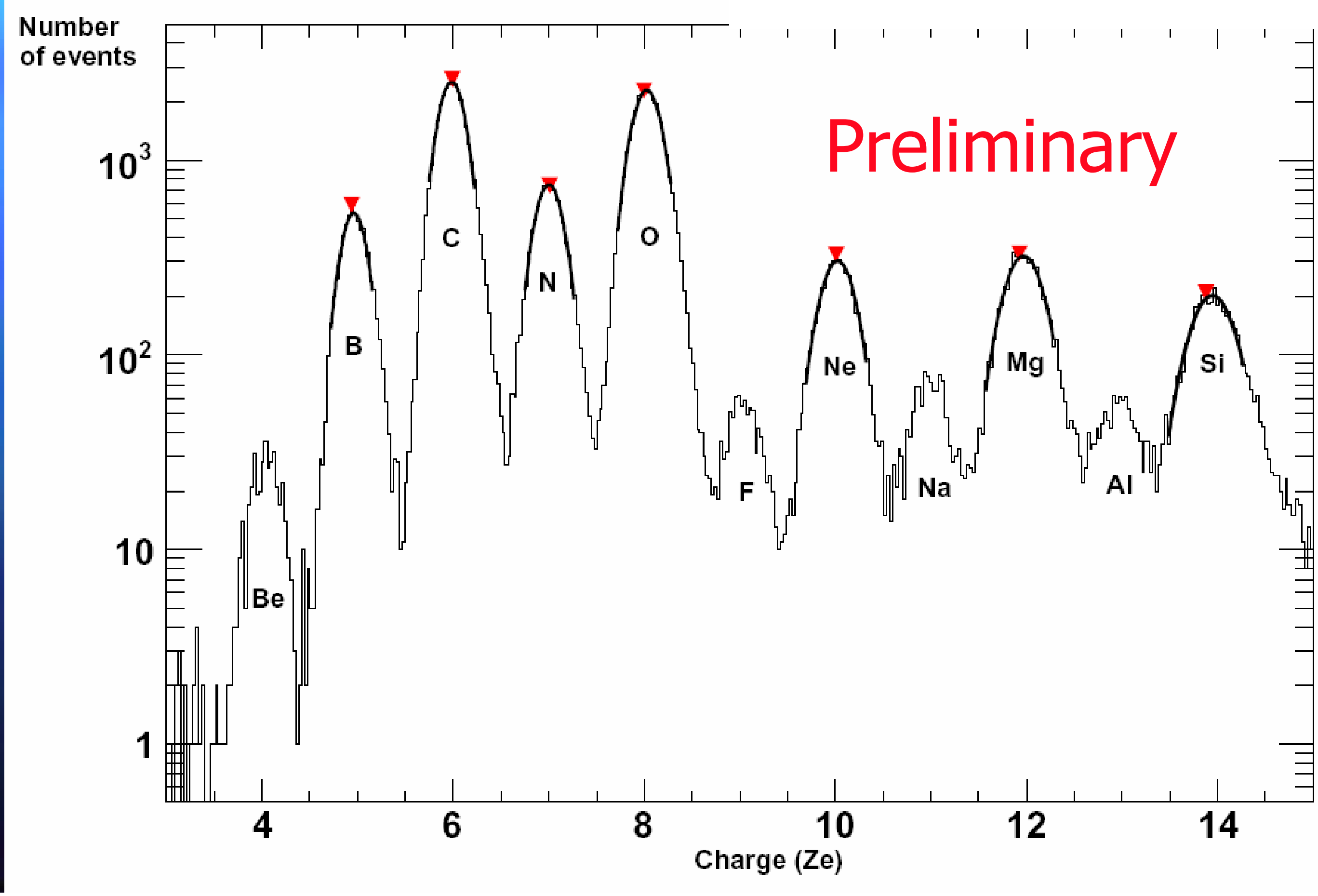


Giant solar flare (Jan 2005)! Solar flux increased by ~×7000…

Charge Distributio

- Not all corrections or event selection finali
- Only indicative of charge resolution; relati



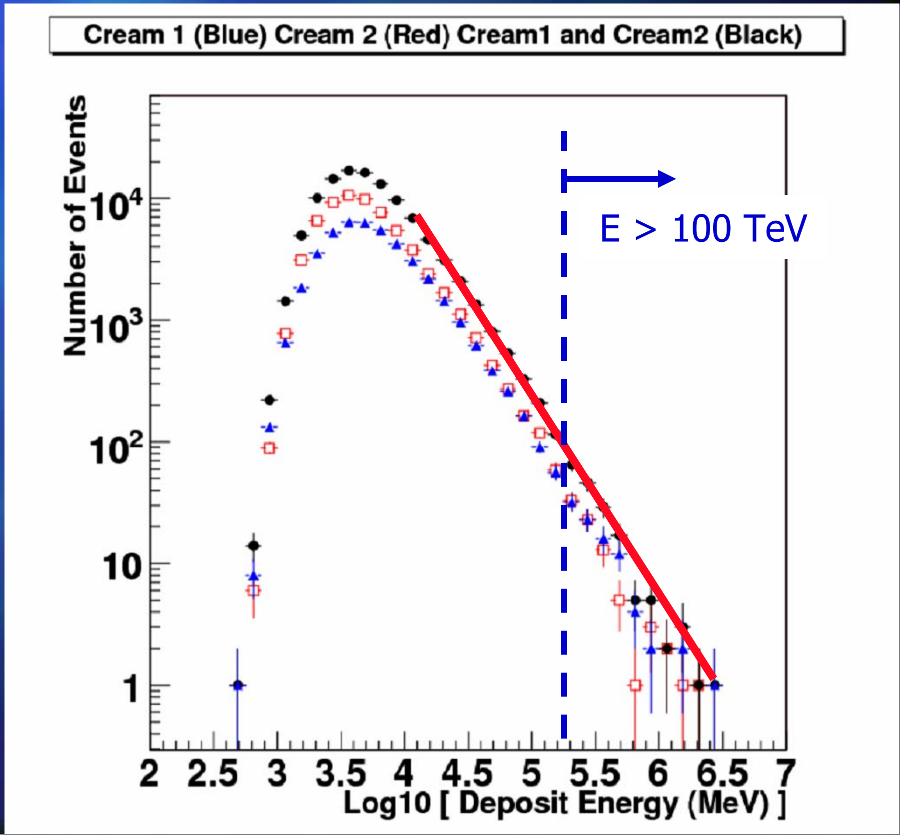


Energy Distribution

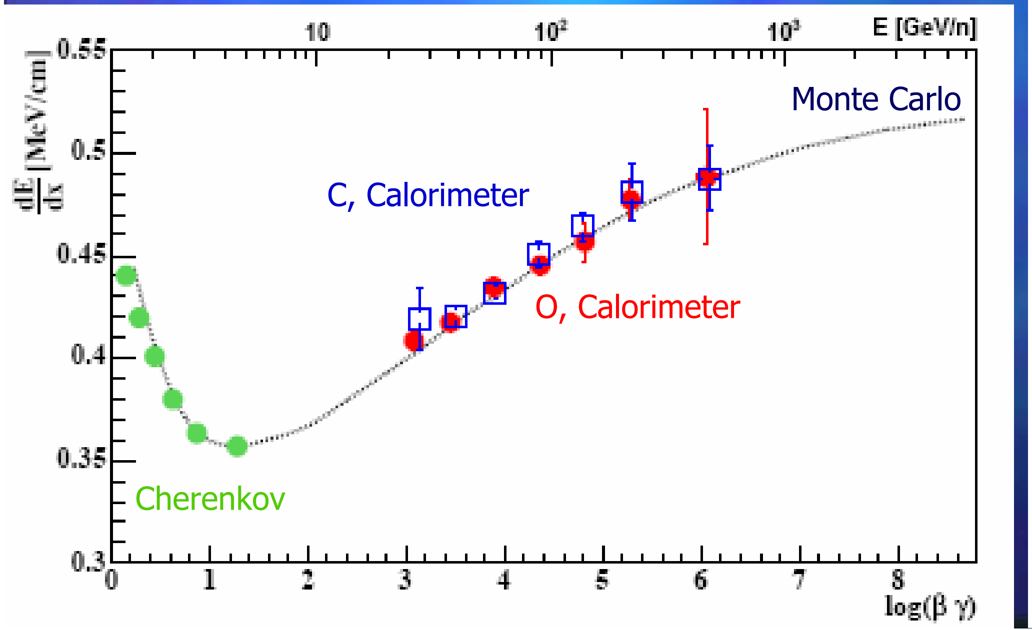
- Not all corrections or event selection finalized…
- Energy deposited, conversion to total energy under way;
- Power-law apparent;
- Events well above 100 TeV

(0.45 TeV in CoM).

Calorimeter energy deposit

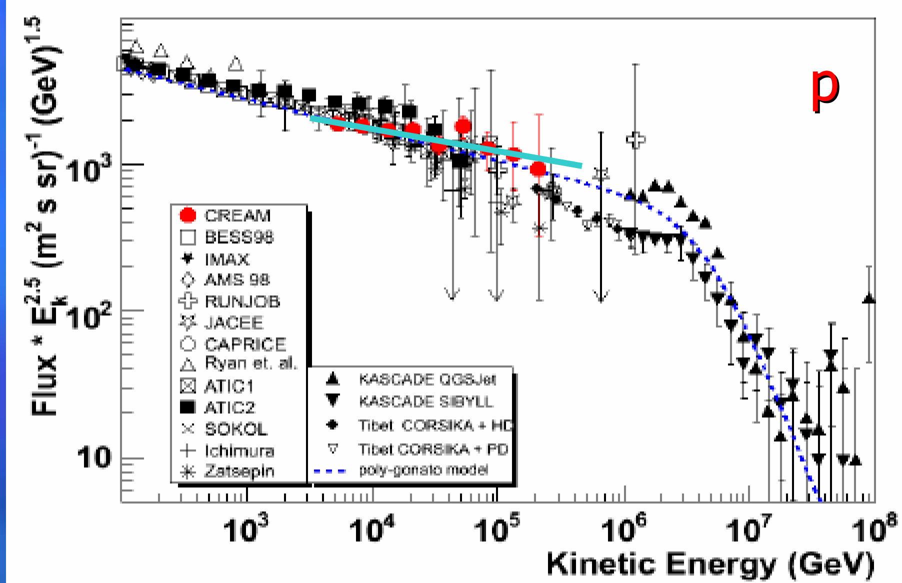


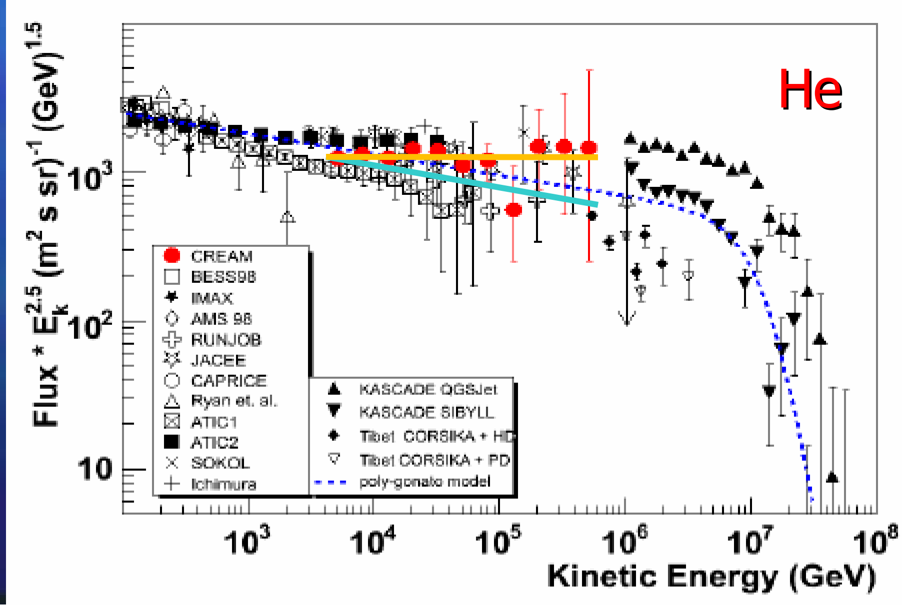
TRD energy deposit



P, He Spectra

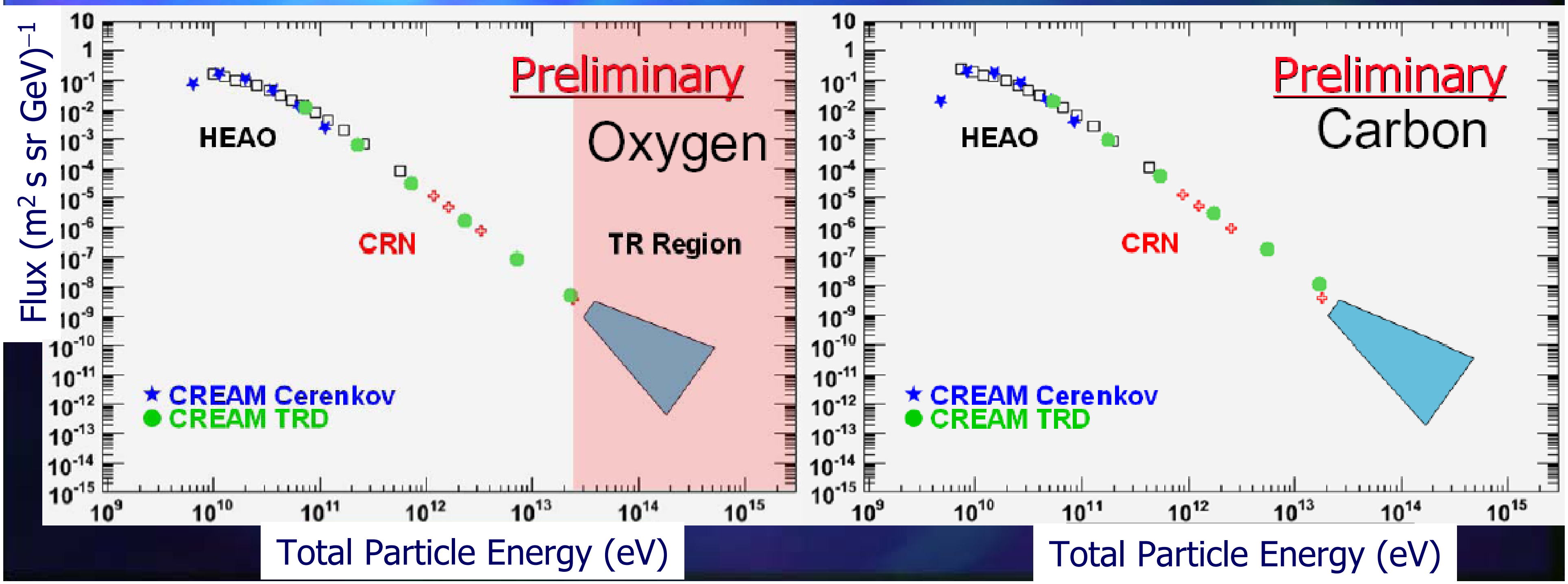
- Steeper proton source spectrum?
- High-energy protons depleted due to acceleration limit?
- Statistics will improve (CREAM1 only here);
- Better anchor point for higher-energy, indirect studies.





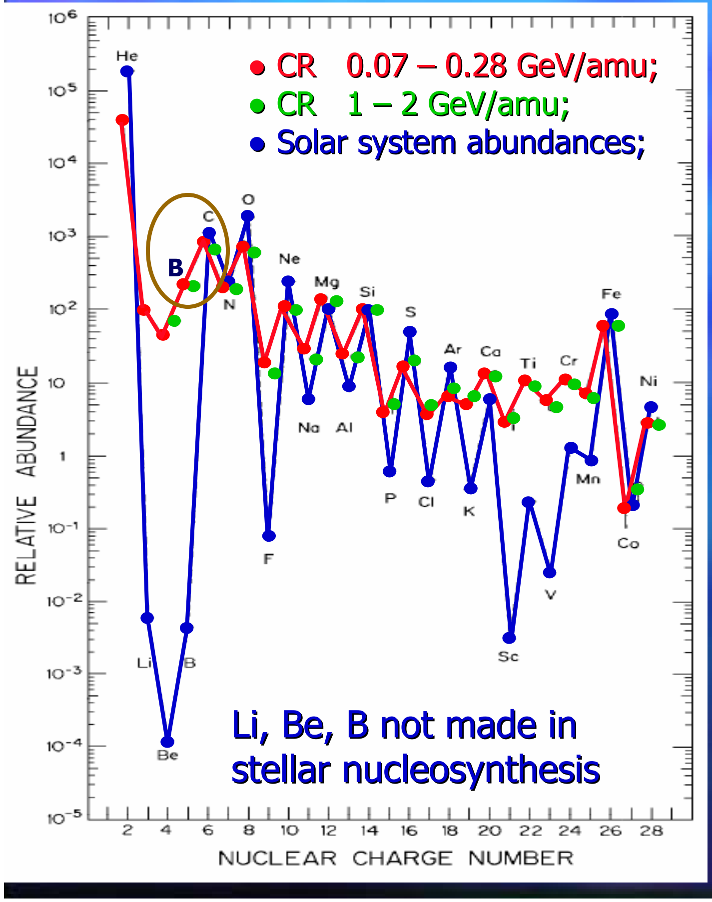
C, O Spectra

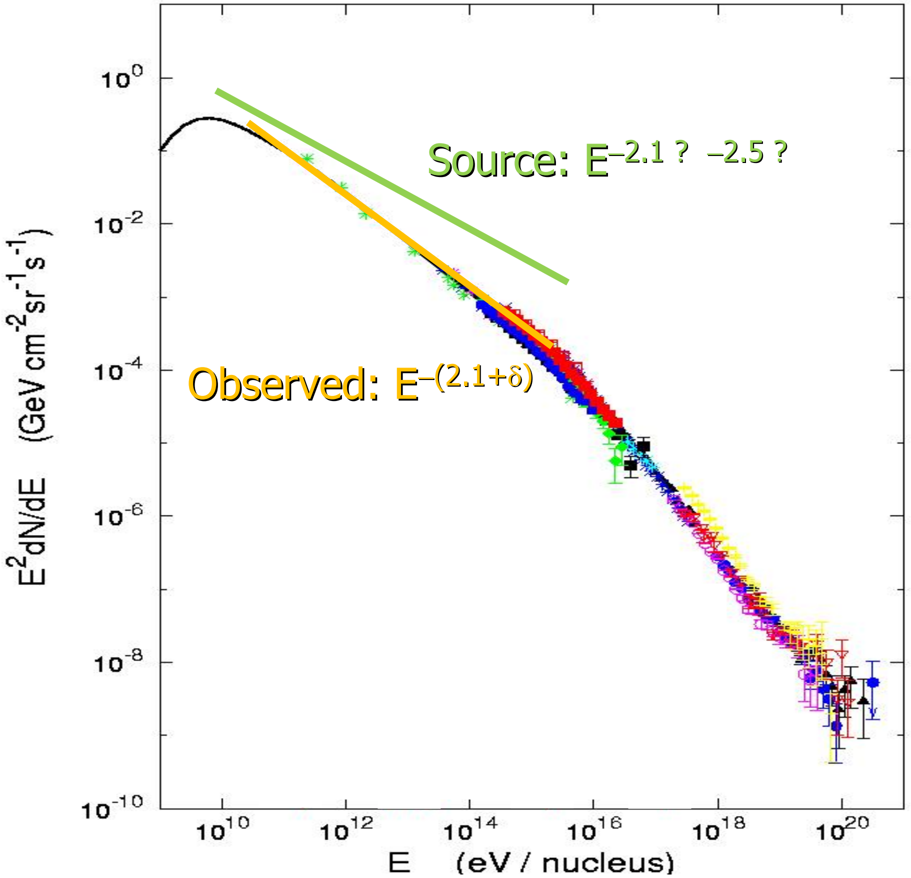
- Preliminary; arbitrary flux normalization for now;
- No atmospheric, instrumental corrections yet;
- Spectral shapes agree with HEAO and CRN data at low energy;
- CREAM data extend up to >100 TeV.



Secondary/Primary Ratio

- Secondary/primary ratio (e.g., B/C) very sensitive to diffusion properties (e.g. diffusion constant δ, possible reacceleration, etc).





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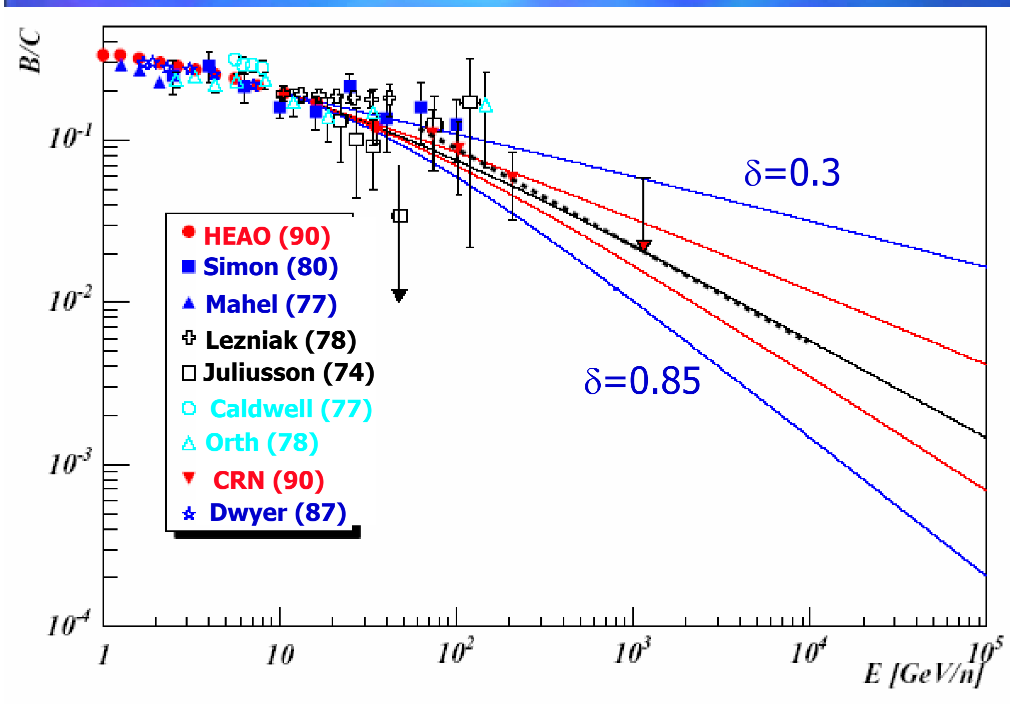

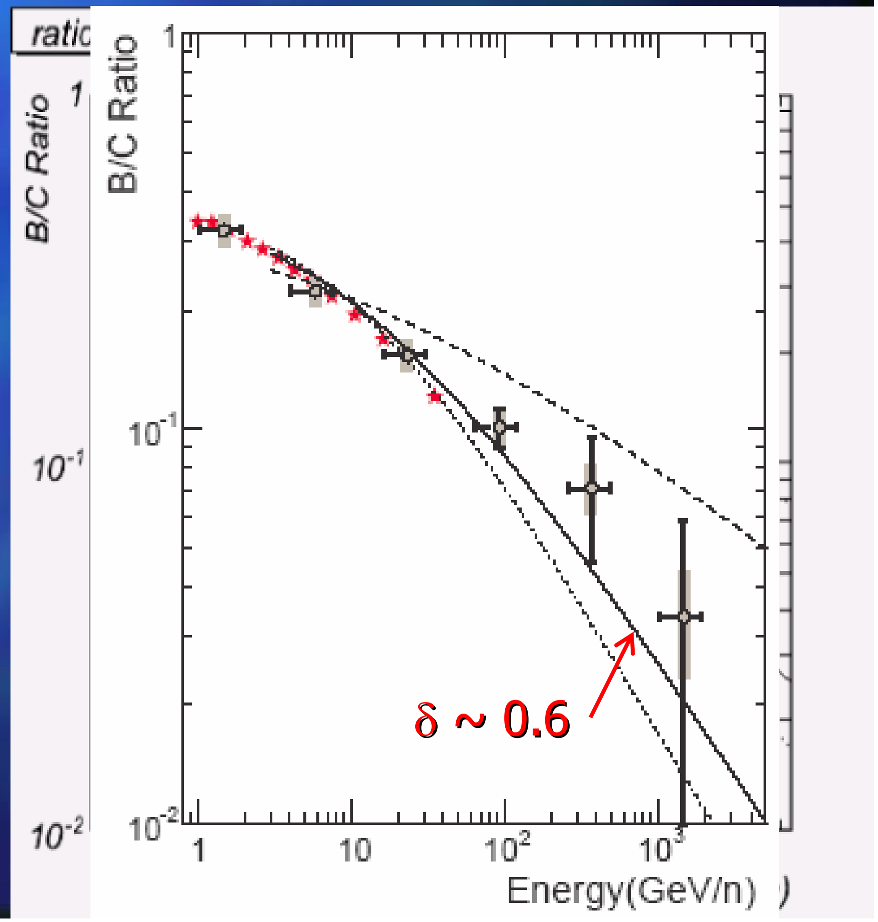

Conclusions

- World's largest set of high-energy, *direct* cosmic-ray measurements; unprecedented particle ID;
- Systems would have functioned well for >100 days (ULDB);
- Energy spectra of H, He, C, O up to ~200 TeV (eventually 900 TeV);
- He spectrum harder than H above 10 TeV? (first hint of accelerator limit on p's?);
- B/C measurements up to ~400 GeV/n favor $\delta \sim 0.6 \Rightarrow$ cosmic-ray source spectrum $\sim E^{-2.1}$; in-line with supernova shock acceleration models.