Cosmic-ray energy spectra up to 10^{14} eV from the first two CREAM flights

Paolo Maestro
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on behalf of the CREAM-I/II collaboration

Outline of the talk

- Physics goals
- Detector configurations in the 1st and 2nd flight
- Cosmic-ray charge ID and energy measurement
- Results:
    - B/C abundance ratio
    - primary nuclei energy spectra
    - energy spectra of proton and helium
    - nitrogen: differential flux and N/O ratio
    - relative abundances at the TOA and extrapolation to the CR source

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NASA

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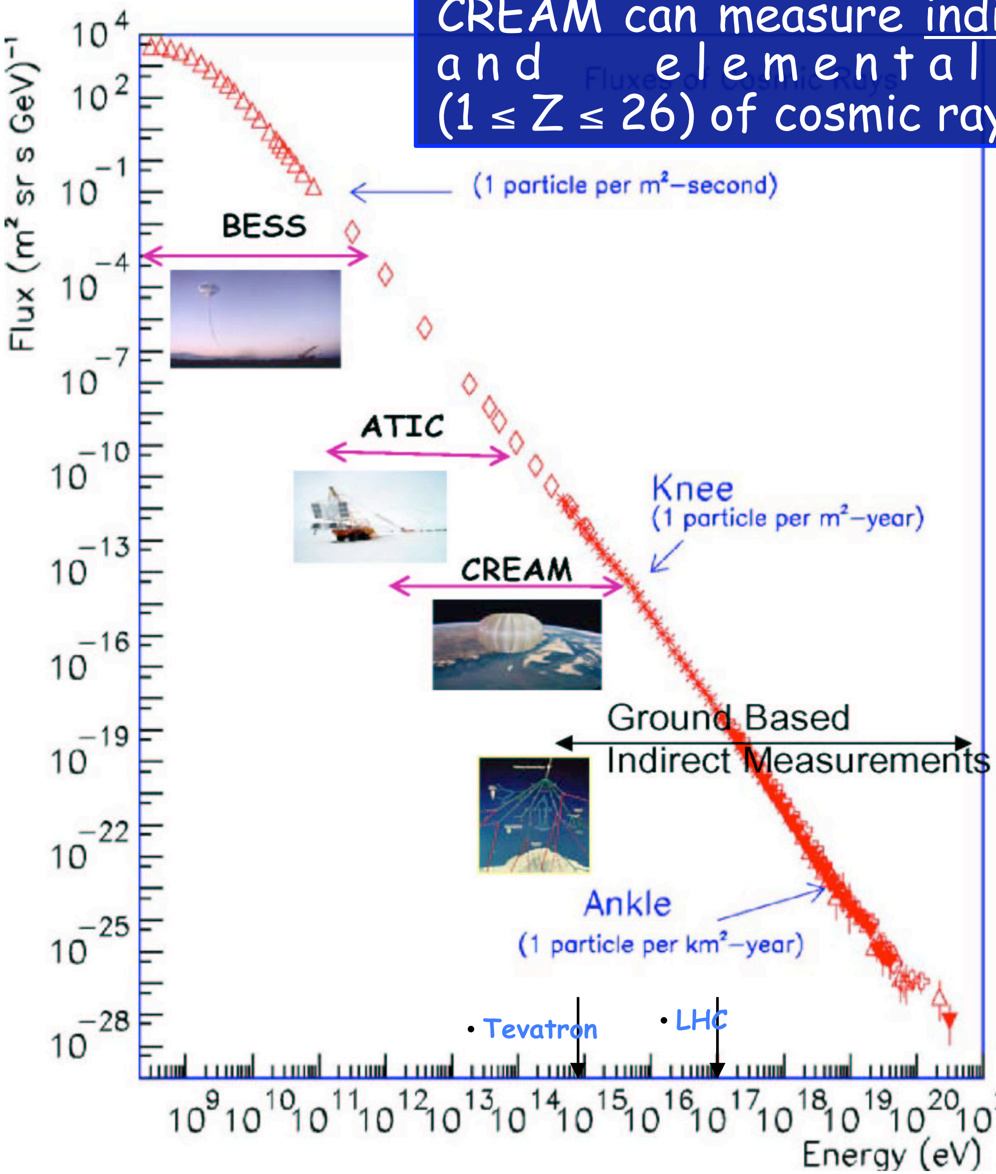
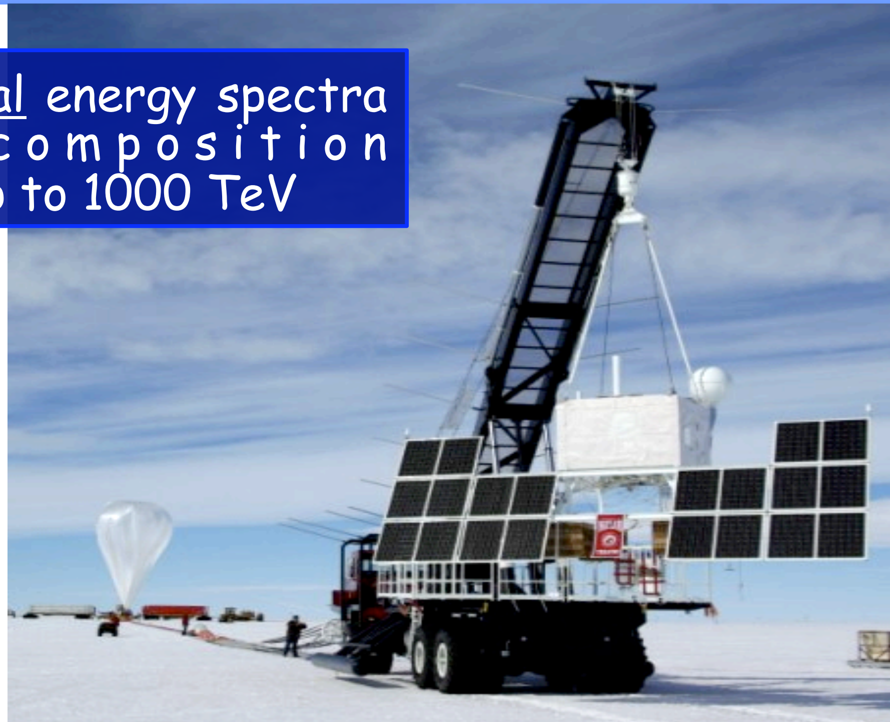
INFN Istituto Nazionale di Fisica Nucleare

PNRA s.c.r.l.

Cosmic Ray Energetics And Mass

CREAM can measure individual energy spectra and elemental composition ($1 \le Z \le 26$) of cosmic rays up to 1000 TeV





- NASA Long Duration Balloons (LDB).
- Five flights over Antarctica from McMurdo:
  - **CREAM-I 42 days** (Dec. 16th 2004 - Jan. 27th 2005)
  - **CREAM-II 28 days** (Dec. 16th 2005 - Jan. 13th 2006)
  - **CREAM-III 28 days** (Dec. 19th 2007 - Jan. 16th 2008)
  - **CREAM-IV 19 days** (Dec. 19th 2008- Jan. 7th 2009)
  - **CREAM-V 39 days** (Dec 1st 2009 – Jan 8th 2010)
- Altitude 38-40 km.
- High-energy data telemetred (via TRDSS) at 85 kbps. Low-energy data recorded on board.

Galactic cosmic rays (GCRs) – Open questions

- What is the origin of this extra solar system matter?
  - Do GCR come from a single class of source?
  - Can individual sources be detected ?
  - What does the GCR composition tell us about the nucleosynthetic history of this matter ?
  - Does the GCR elemental composition change with energy ?

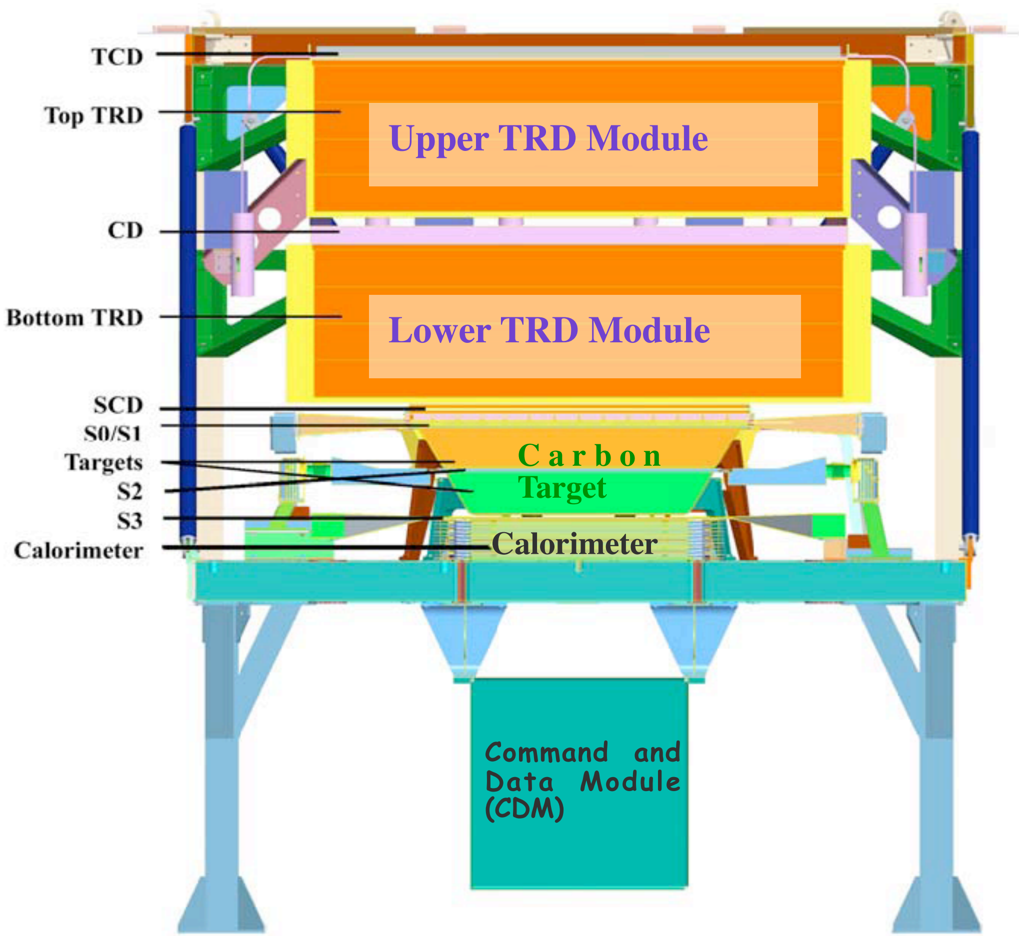
- How does this matter get accelerated to such high energies?
  - Stochastic acceleration in strong shocks in SN remnants (1977 Bell, Axford et al.)
  - Diffusive shock acceleration occurs in isolated SNR or inside superbubbles ("collective effects")? (Parizot et al. A&A 424 (2004) 747)
  - Is there an acceleration limit? Does it depend on the particle rigidity?

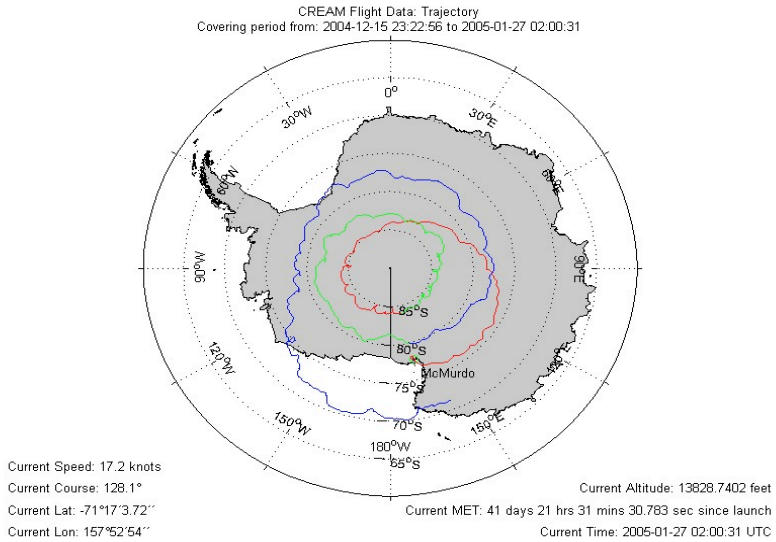
    A Z-dependent cutoff ($E_{max} \sim Z \times 10^{14}$ eV) in each element spectrum could explain the "knee" in the CR all-particle spectrum in terms of a change in the CR elemental composition, marked by a depletion of light elements, as the energy increases.
  - Are there different astrophysical sites associated with:
    different energy regimes? different element regimes?

- CRs propagation in the Galaxy
  - What is the energy dependence of the confinment time of CR in the Galaxy?
  - Is there a residual path length at high energy?

CREAM-I detector configuration

- **3 independent charge measurements**
  - Timing-based Charge Detector (TCD)
  - Pixelated Silicon Detector (SCD)
  - Scintillating fiber Hodoscopes
- **2 independent energy measurements**
  - Transition Radiation Detector (Z > 3)
  - Tungsten Sci-Fi calorimeter (Z ≥ 1)
- **Tracking provided by TRD and CAL**



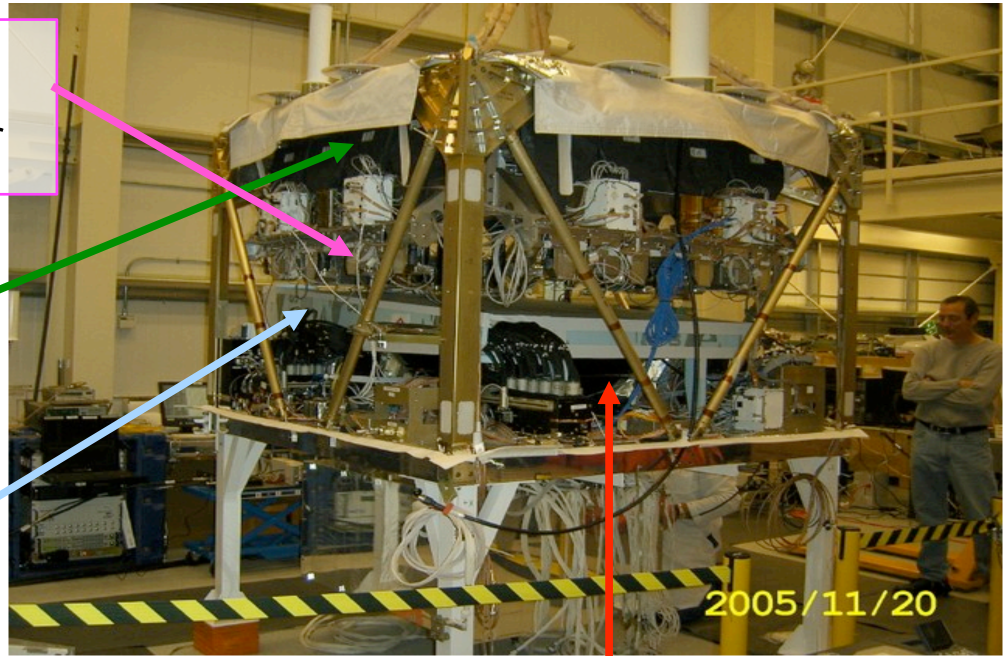


- **Collecting power** ~ 0.3 m^2 sr for Z=1, 2

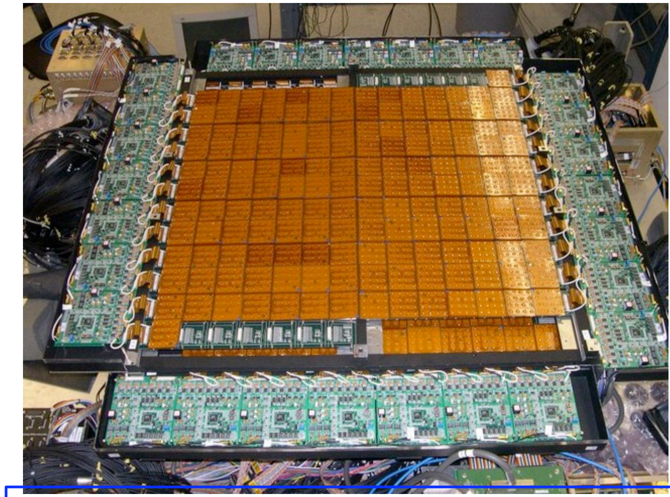
  ~ 1.3 m^2 sr for Z>3

CREAM-II detector configuration

Cerenkov counter
- 1 cm thick plastic radiator with blue wavelength shifter
- low energy particles veto

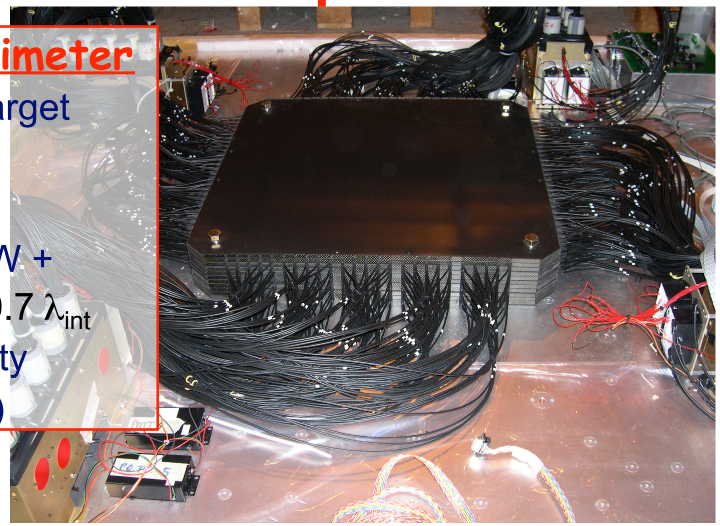


Timing Charge Detector (TCD)
- 5 mm thick fast (< 3 ns) plastic scintillator paddles
- charge measurement from H to Fe ($\sigma \sim$ 0.2-0.35 e)
- backscatter rejection by fast pulse shaping

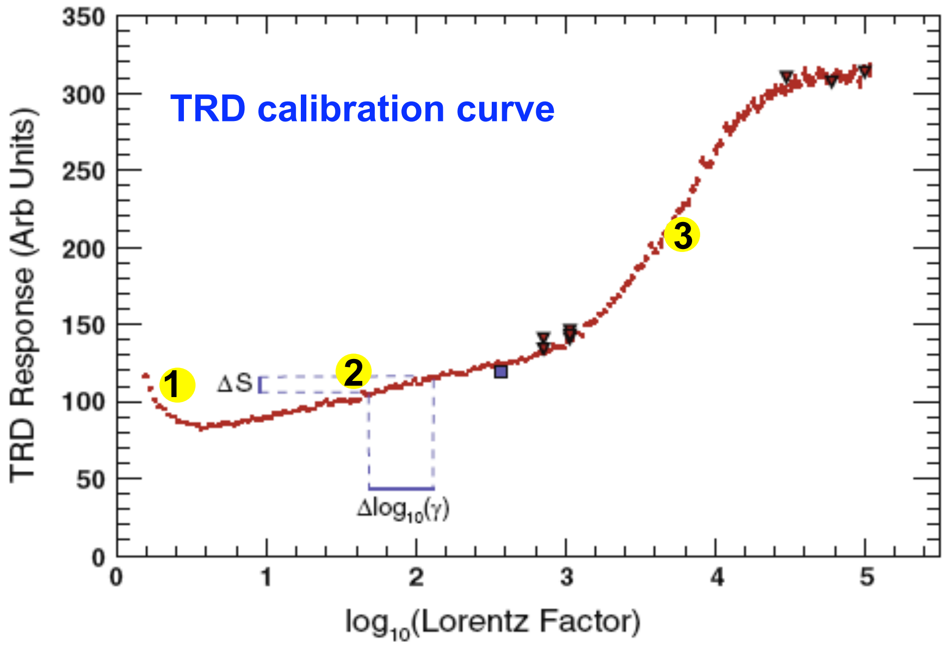


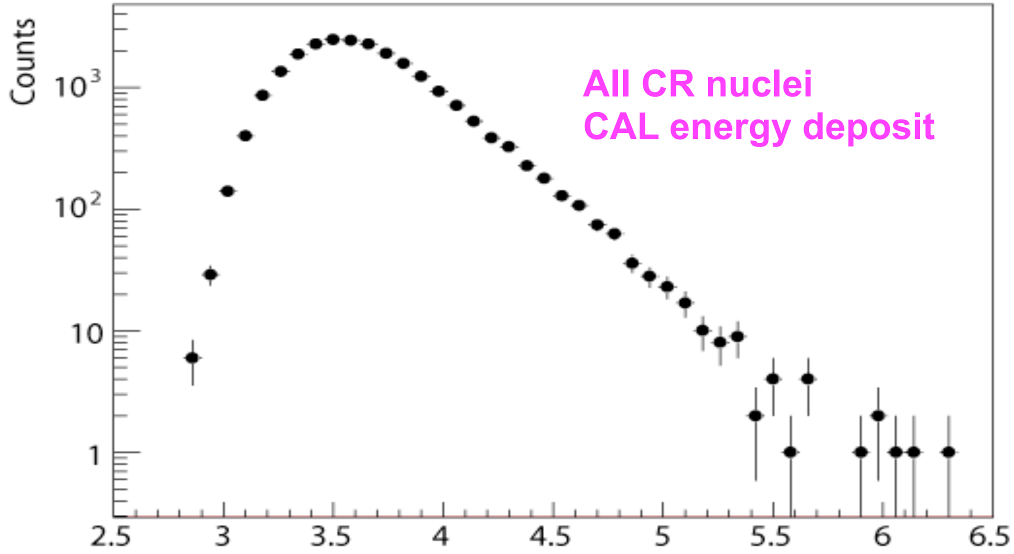
Silicon Charge Detector (SCD)
- 2 layers, 2496 Si pixels each
- Active area ~ 0.52 m^2 . No dead area
- charge measurement from Z=1 to Z~33

Tungsten-SciFi calorimeter
- Preceded by a graphite target (~ 0.5 λ_{int})
- Active area 50 × 50 cm^2
- 20 layers, each 3.5 mm W + 0.5 mm SciFi ⇒ **20 X_0**, ~ 0.7 λ_{int}
- 1 cm transverse granularity
- 2560 channels (40 HPDs)

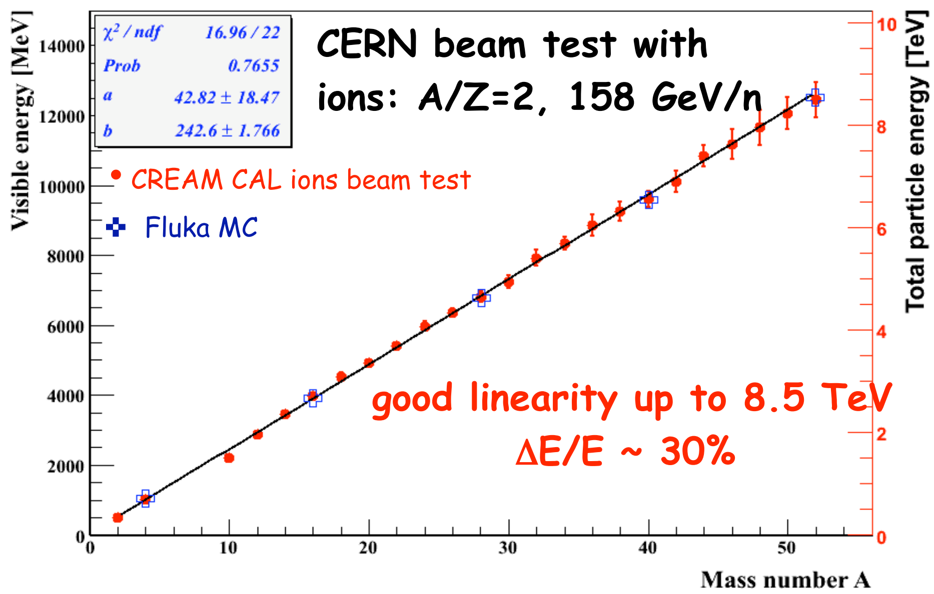


Energy measurement: TRD vs Calorimeter

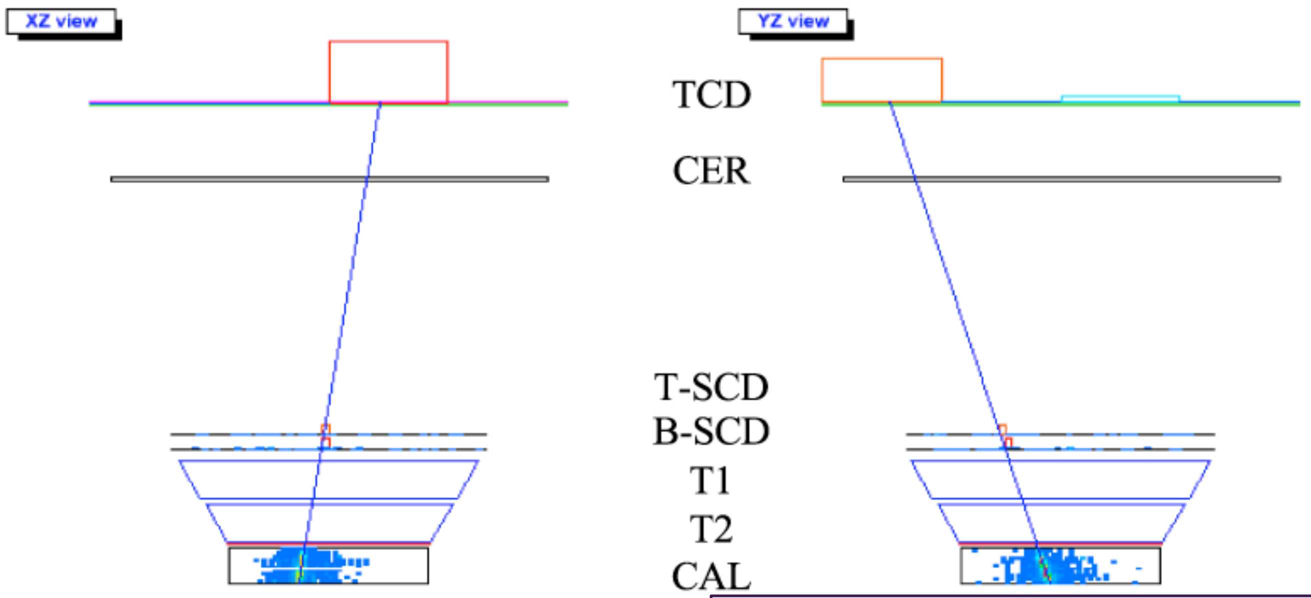




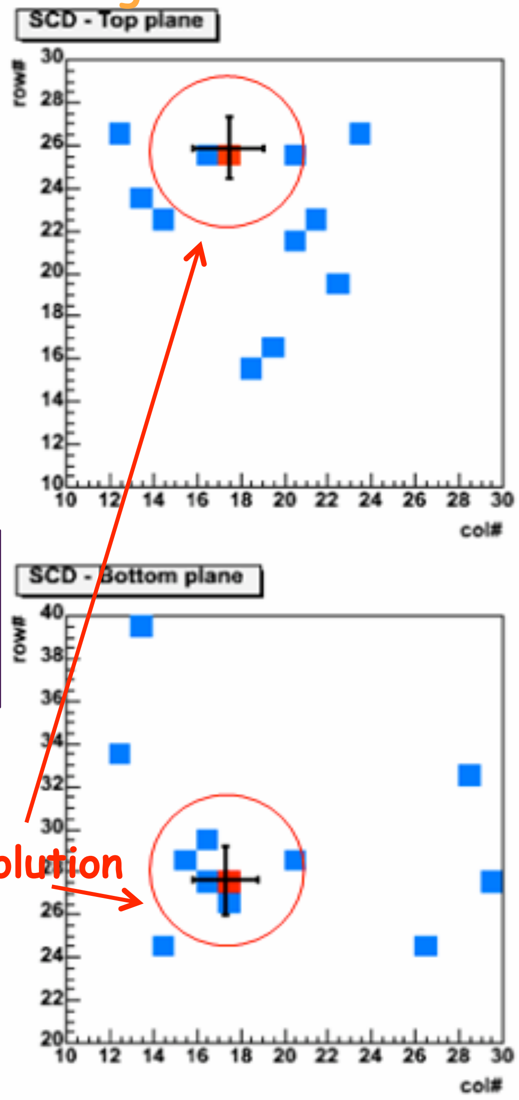
- Energy measurement in different intervals:
  1. Cerenkov signal $1.35 < \gamma < 10$
  2. Multiple dE/dx sampling $10 < \gamma < 500$
  3. TR X-rays $500 < \gamma < 20000$
- Calibration at CERN with p, e^- and π beams
- Energy Resolution $\Delta\log_{10}(\gamma) \sim 0.3$
- Tracking precision ~ 1 mm FWHM



Event reconstruction in Cream-II

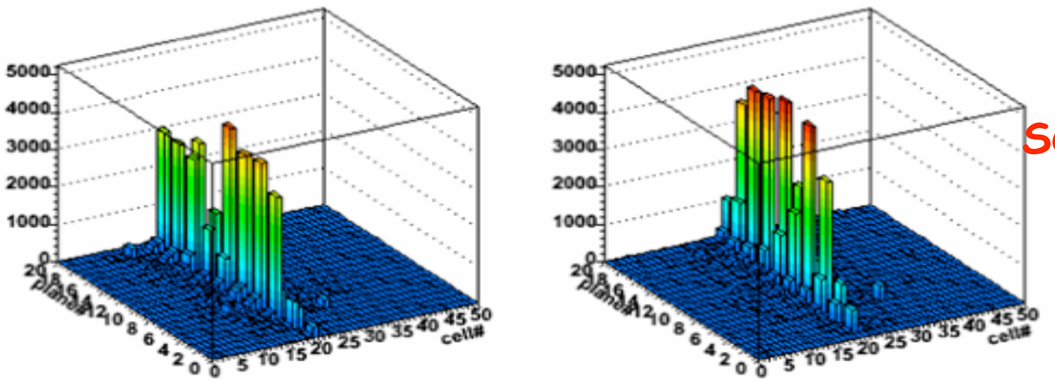


Charge-ID with SCD



Charge-ID: 26 (Fe)
Energy deposit: 105 GeV
Primary particle rec. energy: 70 TeV

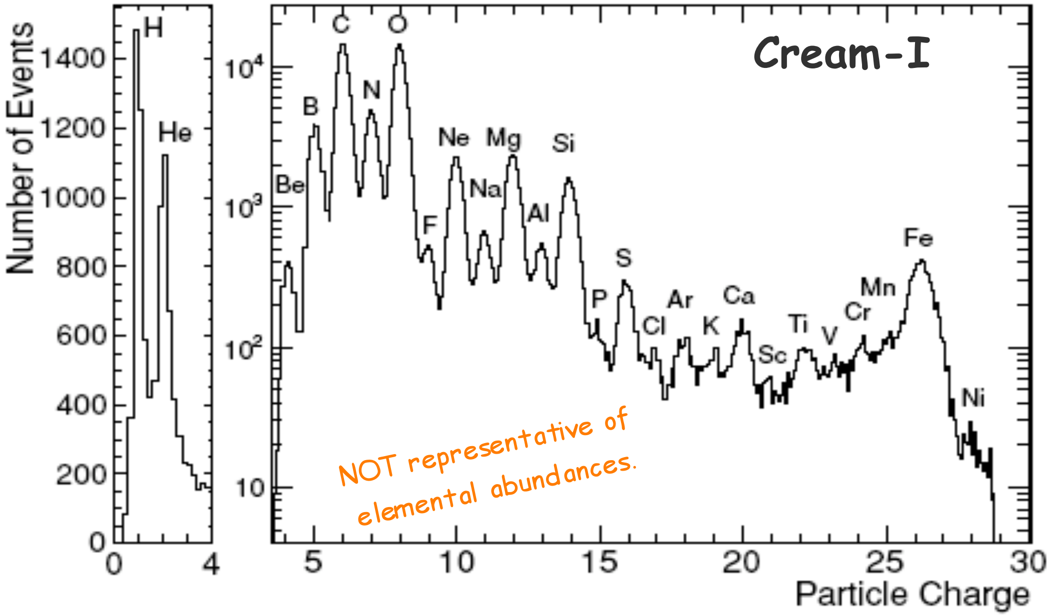
Shower imaging with CAL



CAL tracking

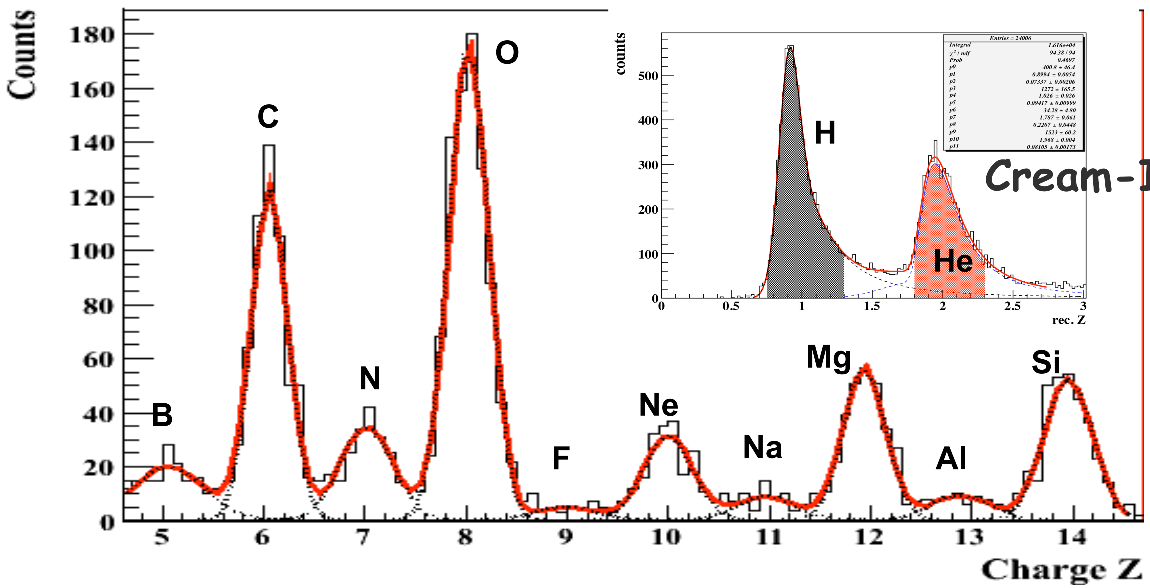
SCD impact point resolution ~7 mm

Cosmic-ray nuclei identification

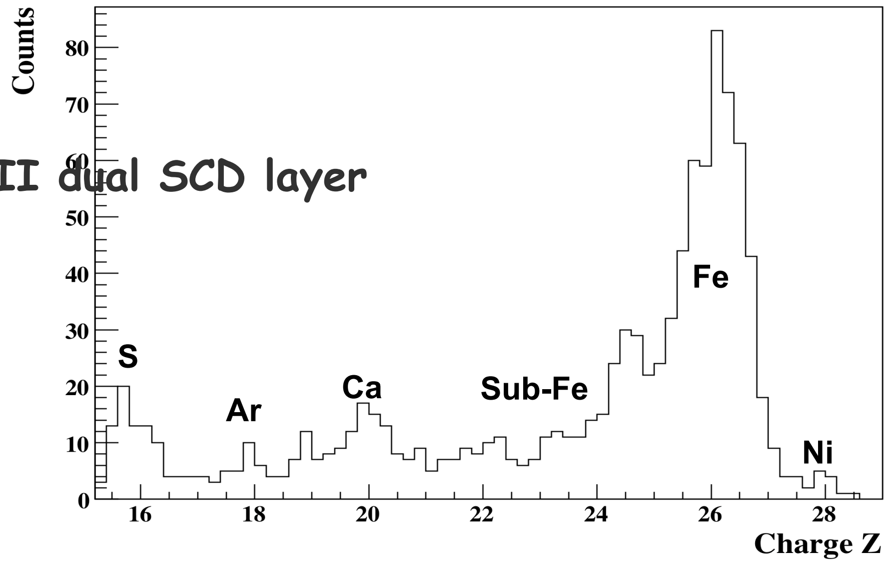


Excellent charge resolution

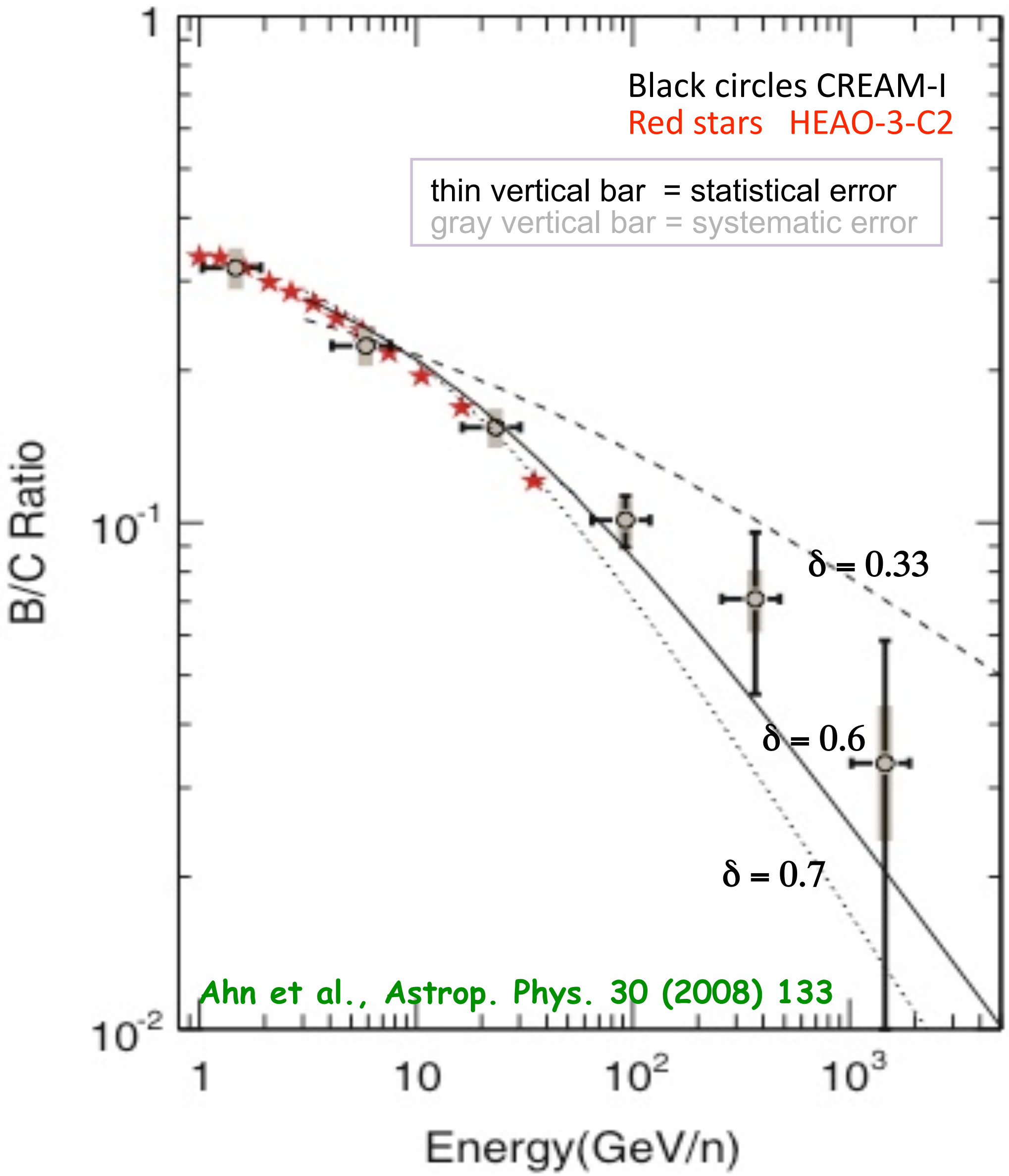
~0.2 e	H-O
0.2-0.25 e	Ne-Si
0.25-0.5 e	P-Fe



Cream-II dual SCD layer



Boron to carbon abundance ratio



Assuming a leaky-box model at high energy, the observed CR spectrum at Earth is

for primary CR $N_P(E) \propto Q_P(E)\ \tau(E) \propto E^{-(\alpha+\delta)}$

for secondary CR $N_S(E) \propto Q_P(E)\ \tau^2(E) \propto E^{-(\alpha+2\delta)}$

$$\Rightarrow \frac{N_S}{N_P} \propto E^{-\delta}$$

At E>10 GeV/n, the S/P ratio measures the energy dependence of the escape path-length λ ($=\rho_{ISM}\ v\ \tau$)

CREAM-I measured the B/C ratio up to an energy of 1.5 TeV/n

The lines represent leaky-box propagation model calculations for various δ values

The results indicate that λ decreases fairly rapidly with energy, with an energy dependence in the range

$\delta \sim$ **0.5 - 0.6**

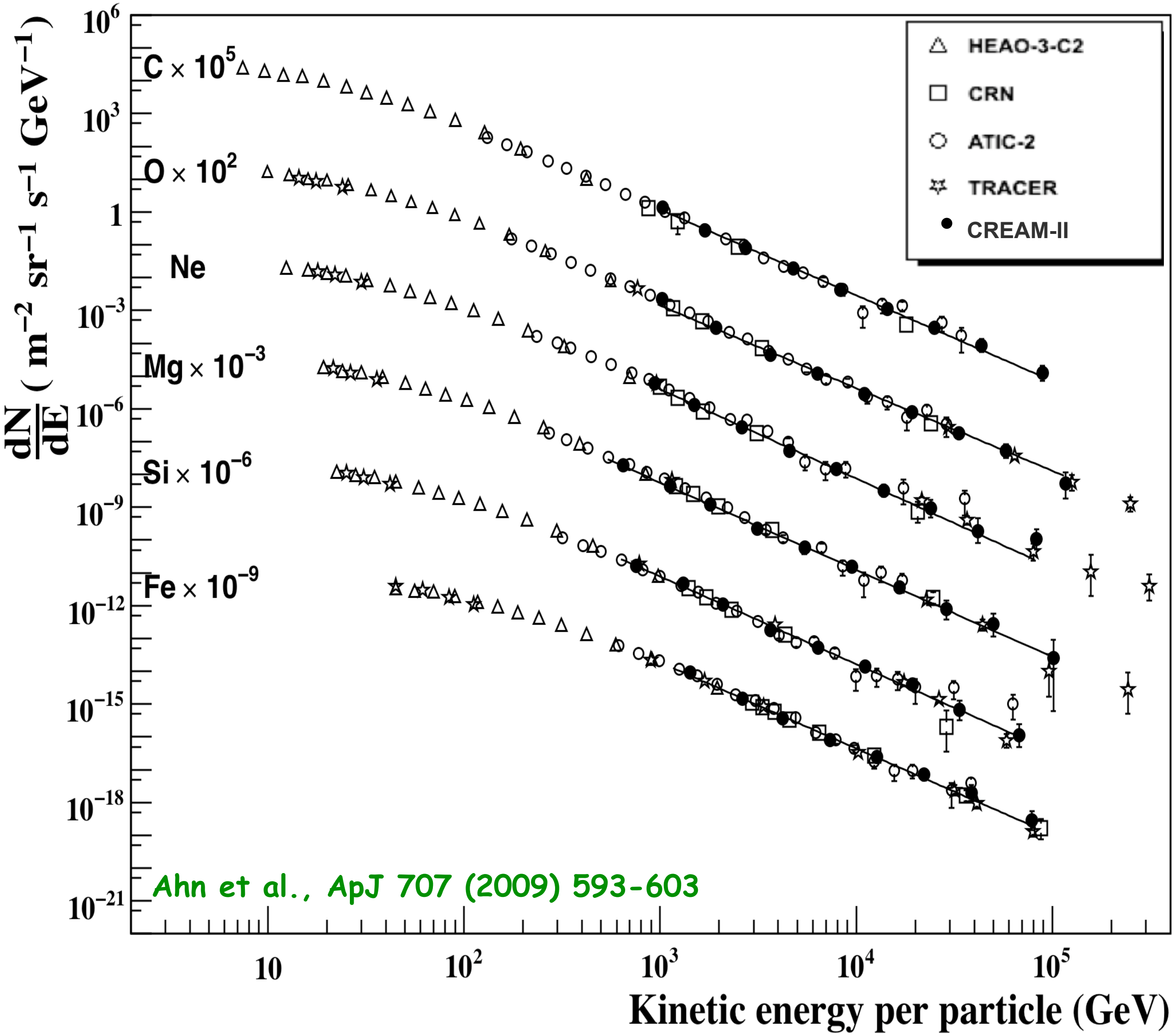
Differential intensity calculation

$$\frac{dN}{dE}\left(\hat{E}\right)=\frac{\mathrm{N}_i}{\Delta\mathrm{E}_i}\times\frac{1}{\varepsilon_i\times\mathrm{TOI}\times\mathrm{TOA}\times\mathrm{S}\Omega\times\mathrm{T}_{\mathrm{live}}}$$

- Energy deconvolution is applied. N_i are the unfolded counts in an energy bin ΔE_i.
- Median energy ($\hat{E}$) calculated according to LAFFERTY & WYATT, NIMA 355 (1995) 541
- Live Time (T_{live}) 1454802 s (~16 days 19h, ~75% of real time)
- Geometric factor ($S\Omega$) 0.46 m^2 sr (SCD-CAL acceptance)
- Selection cuts efficiency ε_i ~70% @ E>3 TeV for all nuclei
- Corrections for interactions in the instrument (TOI): ~4.8 g/cm^2 of materials above SCD ➔ Survival probability range: 81.3% for C - 61.9% for Fe
- Corrections for interactions in the atmosphere (TOA): ~3.9 g/cm^2 residual atmospheric overburden ➔ Survival probability range: 84.2% for C - 71.6% for Fe
- FLUKA MC is used to estimate TOI, TOA, ε_i and energy deconvolution matrix

Energy spectra of the major GCR heavy nuclei

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



All elements are well fitted to single power-laws in energy

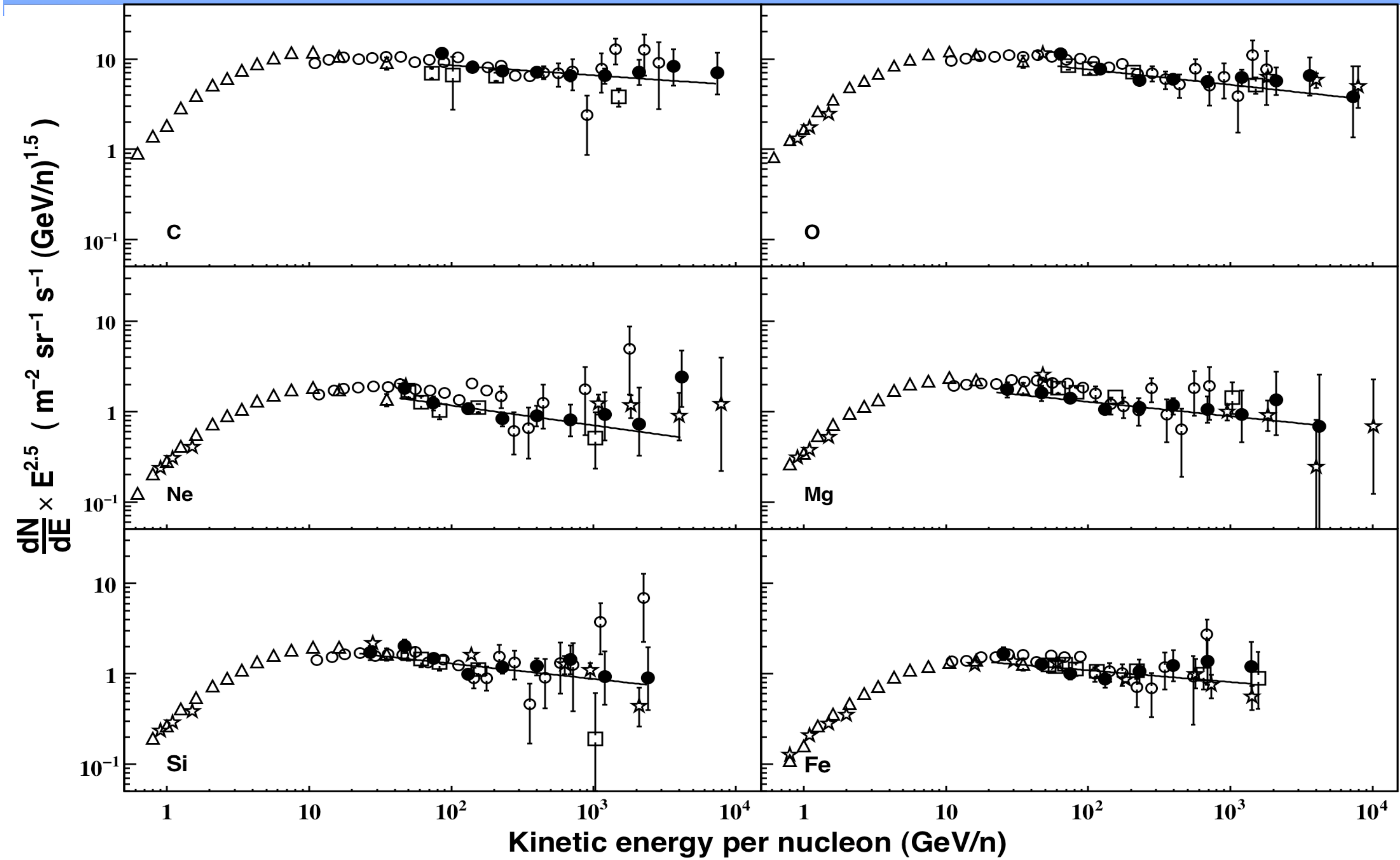
$$\frac{dN}{dE} \propto \Phi_0 \, E^{-\gamma}$$

with very similar spectral indices γ

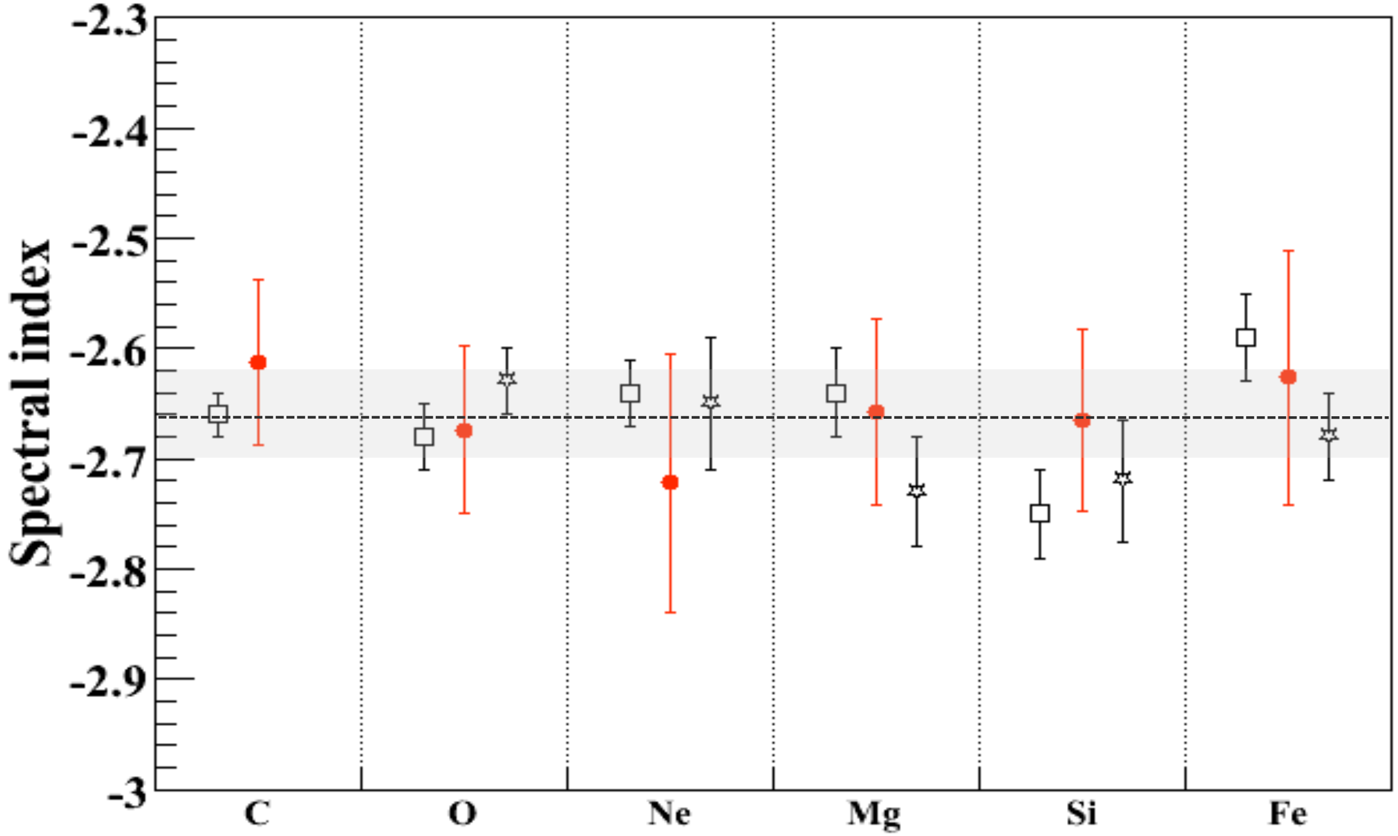
No evidence for any *Z* dependence in the spectral indices.

Points to *common origin* for all species and same mechanism of acceleration ?

Differential intensities × $E^{2.5}$



Spectral indices from a single power-law fit



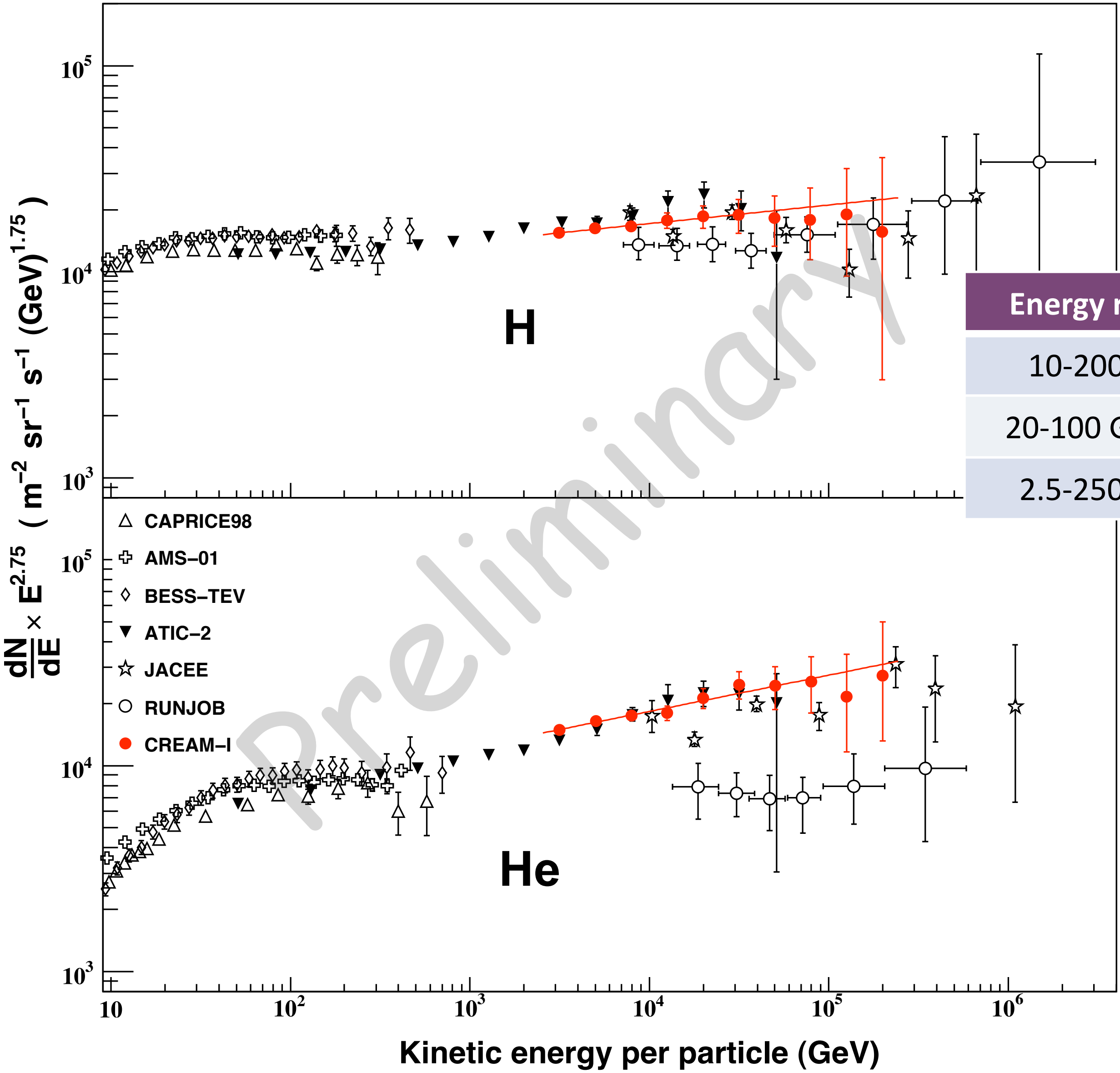
□ Hörandel Astropart. Phys. 19 (2003) 193

☆ TRACER+ CRN
M. Ave et al., ApJ 678(1) (2008) 262

● CREAM-II

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

Proton and helium spectra



➢CREAM-I measured H and He spectra in the particle energy range 2-250 TeV

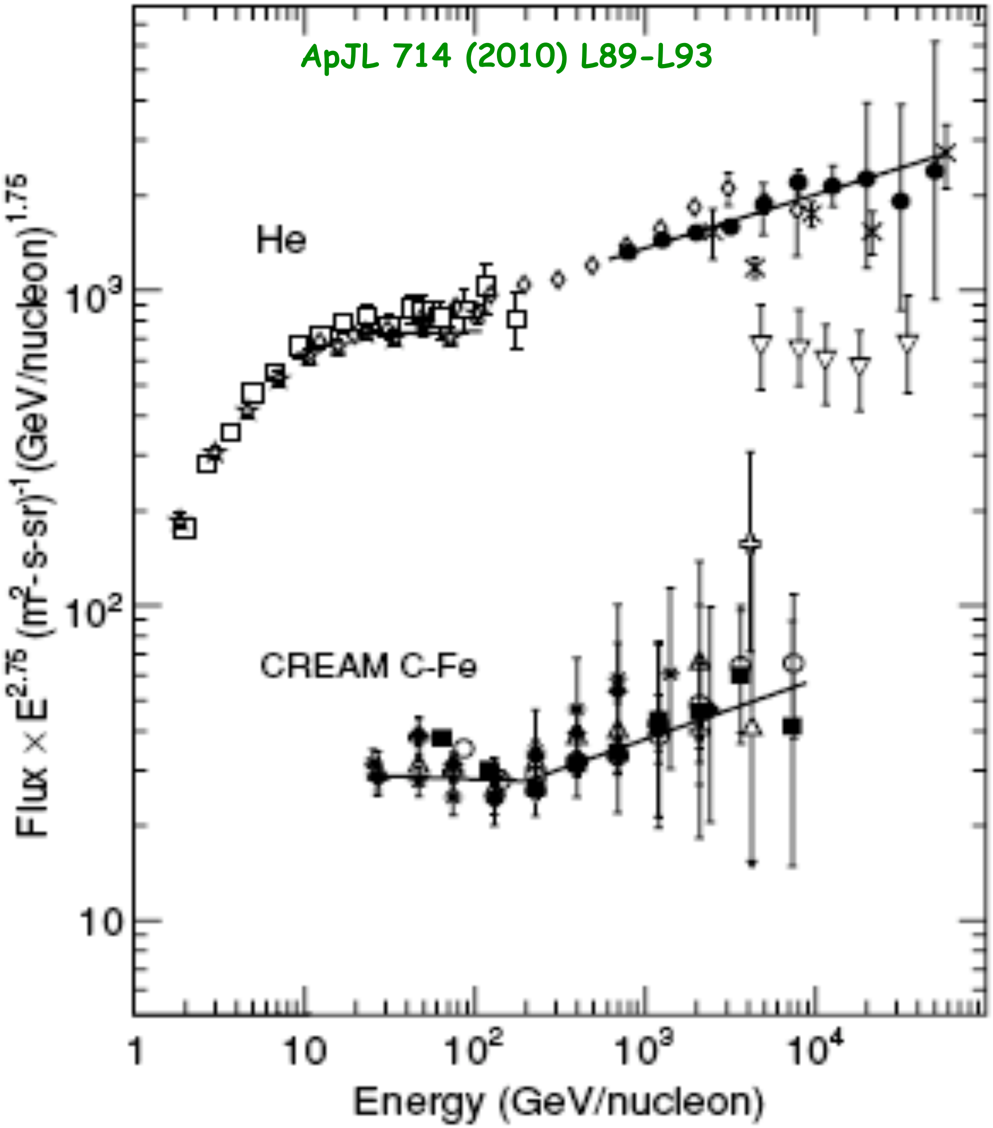
➢ **Proton and helium spectra at TeV turn out to be harder than the low-energy spectra.**

Energy range	proton	helium	Exp.
10-200 GV	2.78± 0.009	2.74± 0.01	AMS
20-100 GeV/n	2.732± 0.011	2.699± 0.040	BESS
2.5-250 TeV	2.66 ± 0.02	2.58 ± 0.02	CREAM

➢**Evidence of CRs-shock interaction (Non linear acceleration models) ?**
(Ellison et al., ApJ 540 (2009) 292)

➢ **Proton and helium spectra have different spectral shapes**
Different types of sources or acceleration mechanism? **(Biermann P. A&A 271 (1993) 649)**

Broken power-law fit ?



A broken power-law fit to combined C-Fe elements (normalized to C) gives:

γ_1 = 2.77 ± 0.03 $E_b \leq$ ~230 GeV/n
γ_2 = 2.56 ± 0.04 $E_b >$ ~230 GeV/n

γ_1 agrees with AMS He spectral index
γ_2 agrees with CREAM He spectral index

Is this coincidental ?

Could it be the hint of the **CR spectrum hardening at high energy** predicted by non-linear acceleration models?

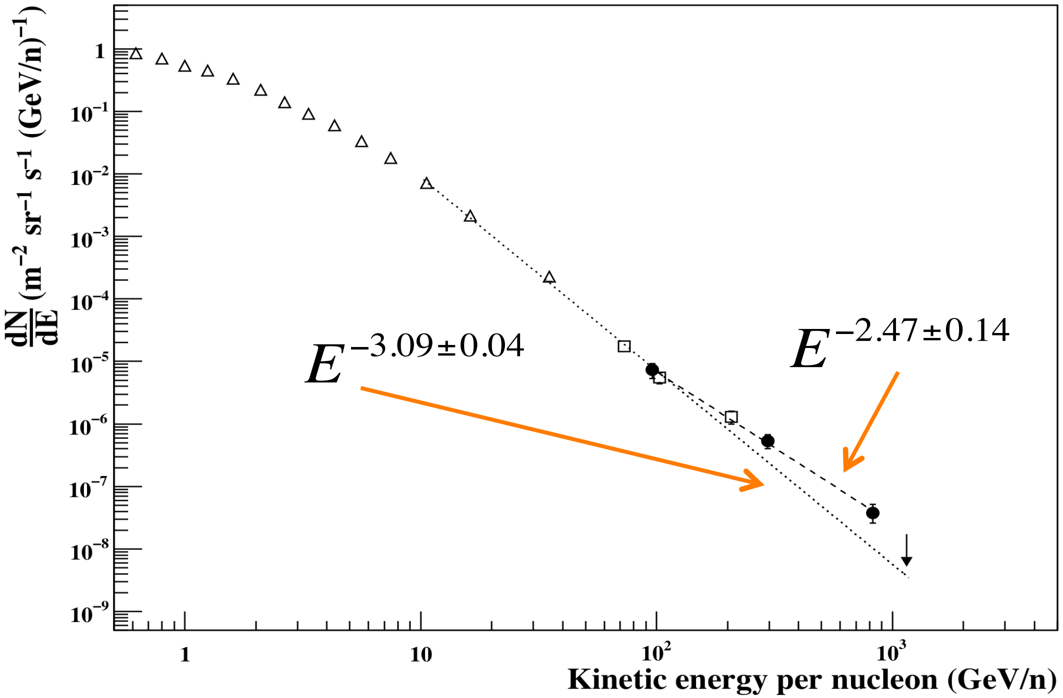
Main features of particle acceleration theories at SNR modified shock (P. Blasi Rapporteur talk @30th ICRC):

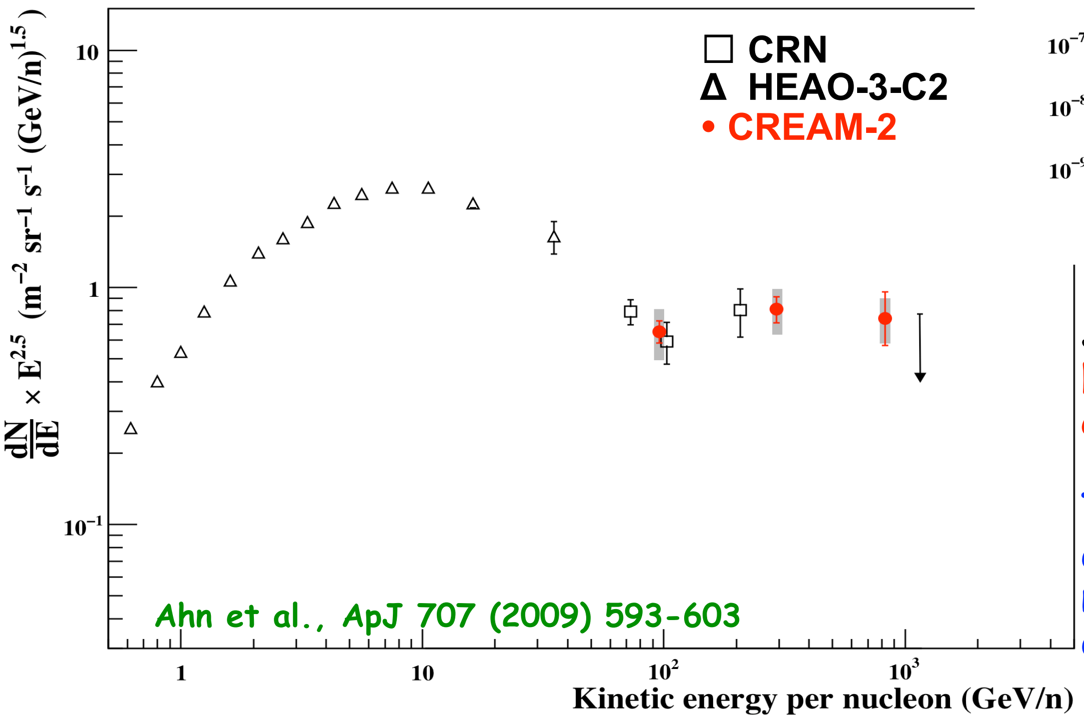
- CR spectrum is not a single power-law but shows a concavity before the knee and becomes harder at HE
- Magnetic field amplification ➔CRs can be accelerated efficiently up to E_{max} ~ Z×10^6 GeV

Nitrogen spectrum

- Challenging measurement:
  - excellent charge separation
  - good understanding of secondary N production in air and instrument.

- Large systematic error ~25% (grey band) reflects uncertainties in partial charge-changing cross-sections needed for TOI and TOA corrections.

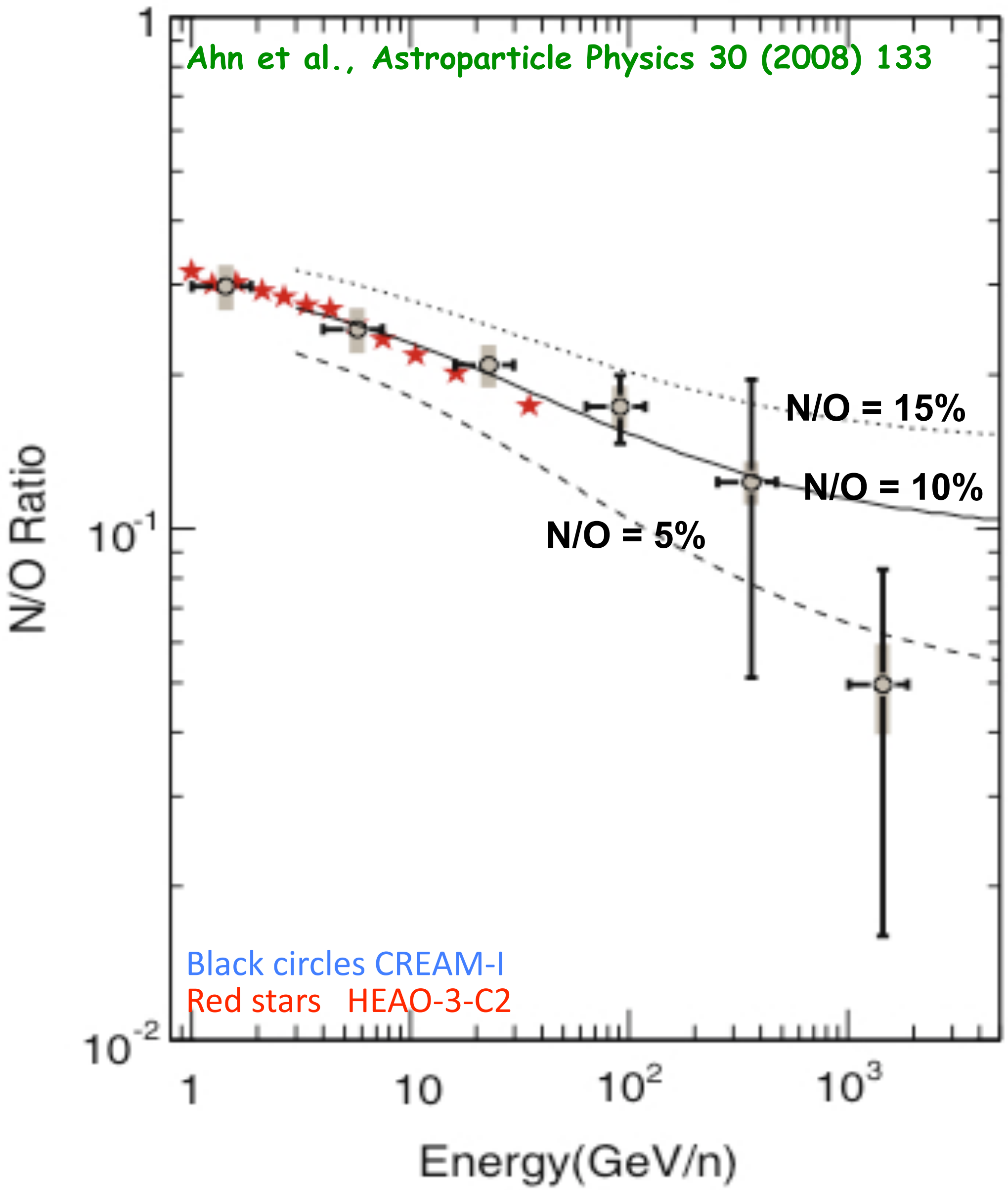




Spectrum hardening above 100 GeV/n ➔
N has secondary as well as primary components.

The primary component survives at high energy where the secondary becomes negligible, since the path length rapidly decreases with energy.

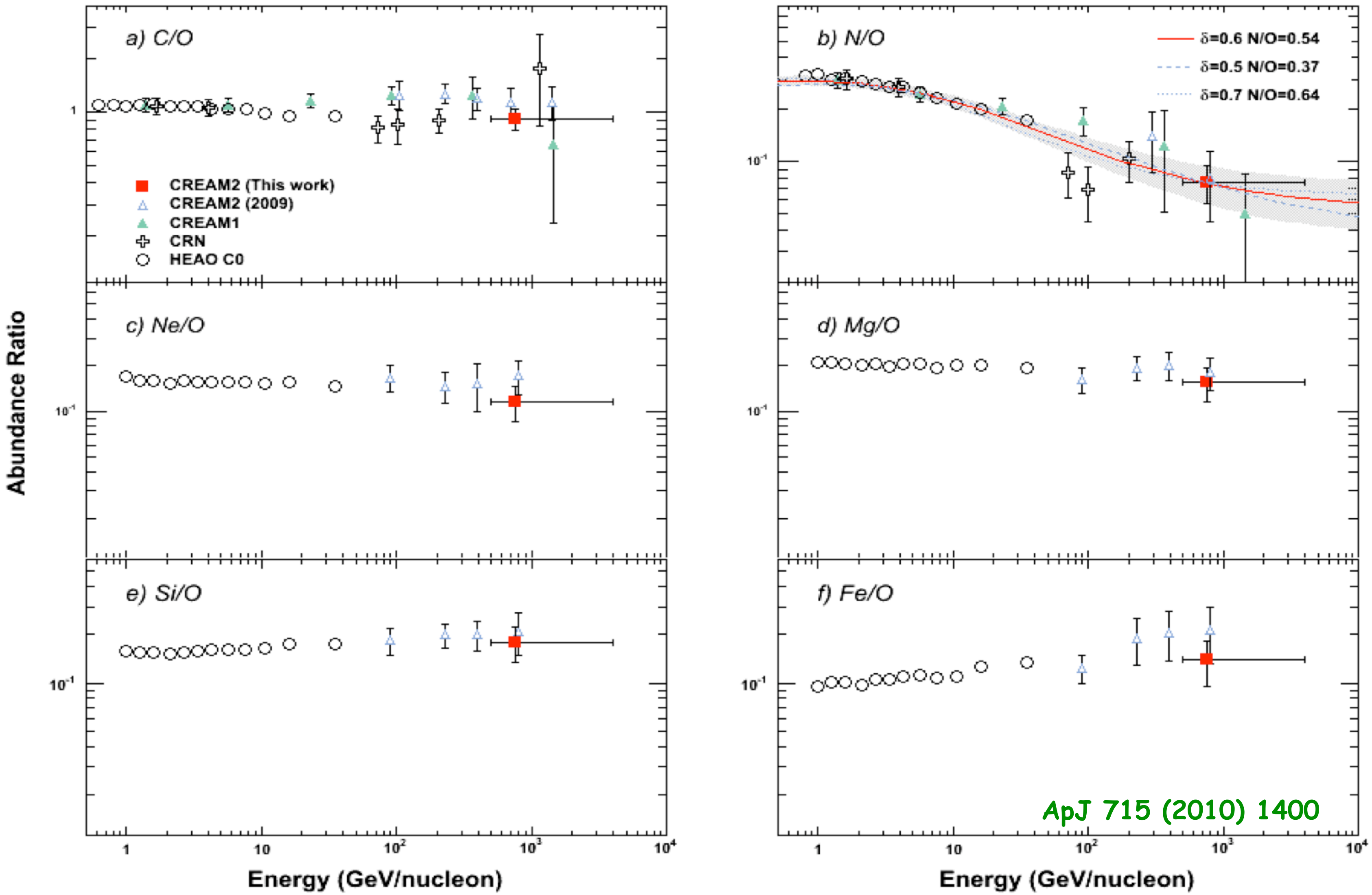
N/O abundance ratio



The curves in the plot represent model calculations of N/O ratio, for δ=0.6 and with different assumptions on the amount of nitrogen in the source material.

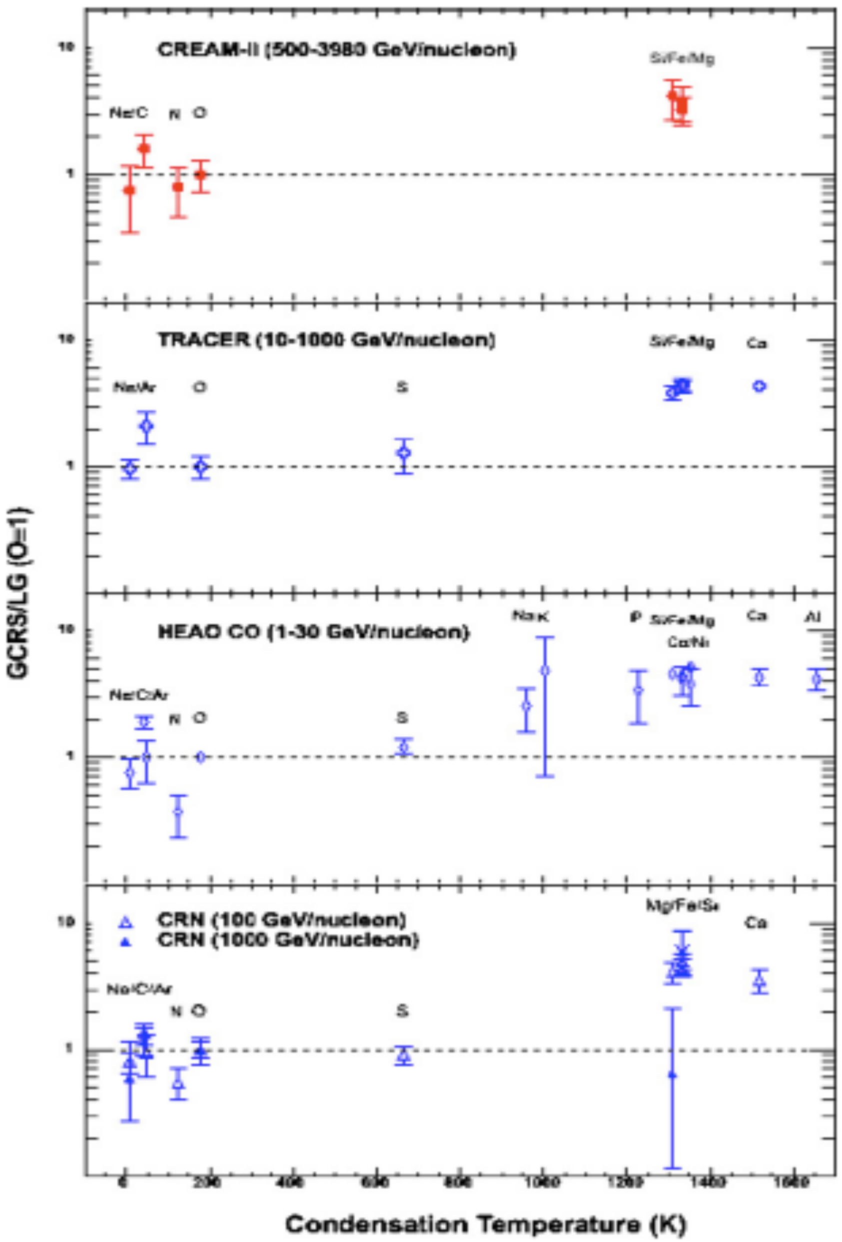
CREAM-I measurement of N/O up to 1.5 TeV/n suggests a N/O source abundance between 5-10%

Relative abundances at the TOA



Observed elemental abundances of GCRs at the TOA are corrected for the effects of fragmentation in the ISM to determine the source abundances, which provide information about: **mechanism and site of acceleration**

Refractory vs. volatile elements



Source abundance calculated with GALPROP (δ=0.6 D=2.28×10^{28} cm^2 s^{-1})

Refractory elements (T_c>1200 K) are more abundant in CR source (relative to solar system abundances) than volatile elements

(Meyer et al., ApJ 487 (1997) 182)

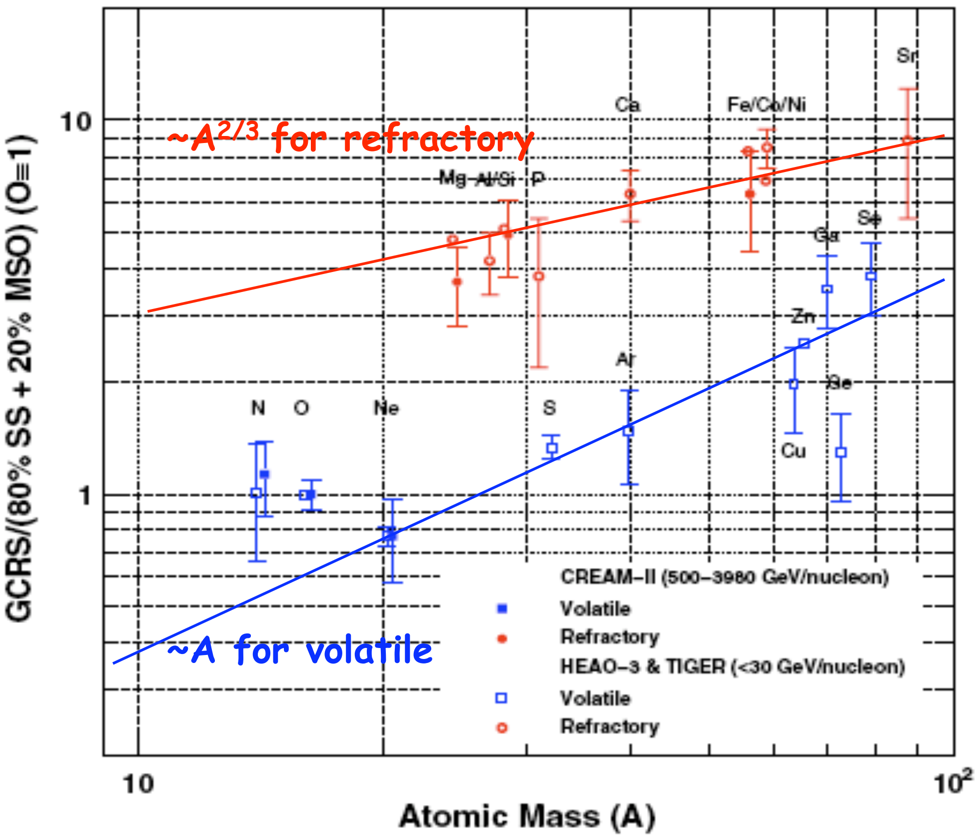
CREAM data confirm the volatility fractionation above 500 GeV/n

Implications → Acceleration models based on preferential CR injection from the sputtering of refractory dust grains in SN ejecta, previously charged by photo-ionization and accelerated to moderate energies by supernova shocks.

Atoms that are sputtered off of these grains have suprathermal energies and are accelerated more efficiently to CR energies than atoms originating in the thermal interstellar gas.

Higdon et al. ApJ 509 (1998) L33
Lingenfelter et al. ApJ 500 (1998) L153

Sites of acceleration



CREAM data confirm the same trend of separation between refractory and volatile elements and the same atomic mass A dependence of the GCR/(80% SS+ 20% MSO) ratio, as seen in the low energy range (HEAO, TIGER)

Recent observations

- $^{22}Ne/^{20}Ne$ ratio in GCRs ~5 times (ACE/CRIS, Binns et al. 634 (2005) 351) higher than the Solar System value.
- Trans-Fe/Fe abundances (TIGER, Rauch et al. APJ 697 (2009) 2083) discrepancies with the solar system values ($^{31}Ga/^{32}Ge$ ~1 in GCRs vs. 0.3 in SS)

are consistent with a CR source mixture of about 20% ejecta of massive stars mixed with 80% material of solar system composition

➔ support a model of GCR origin in OB associations

➔ Multiple SN shock acceleration in superbubbles ?

- $E_{max} \approx Zx10^{17}$ eV
- More efficient injection mechanism
- Spectrum hardening at high energy

(Parizot et al. A&A 424 (2004) 747)

CREAM Impact site

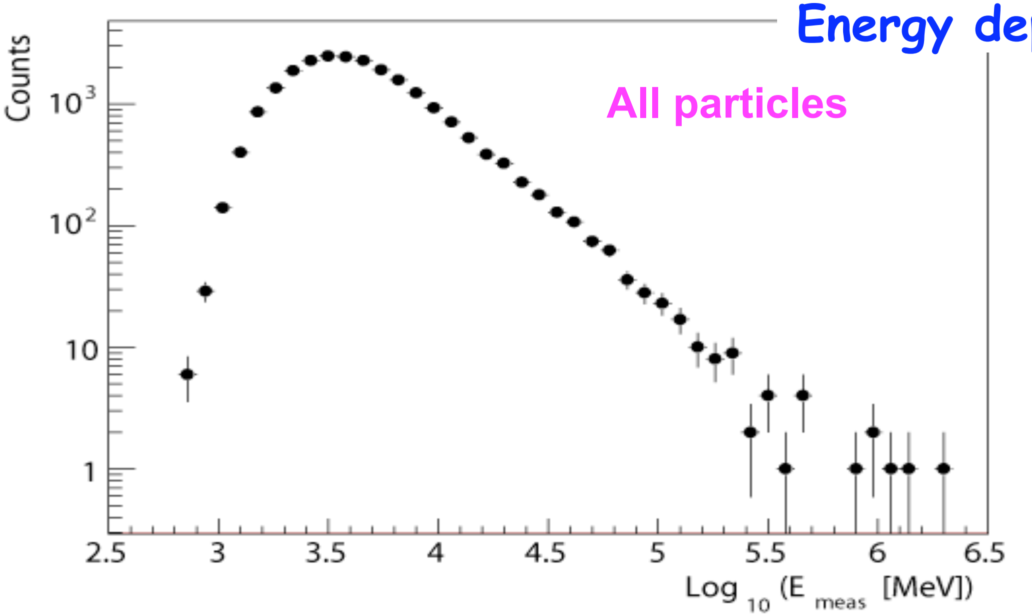
Conclusions

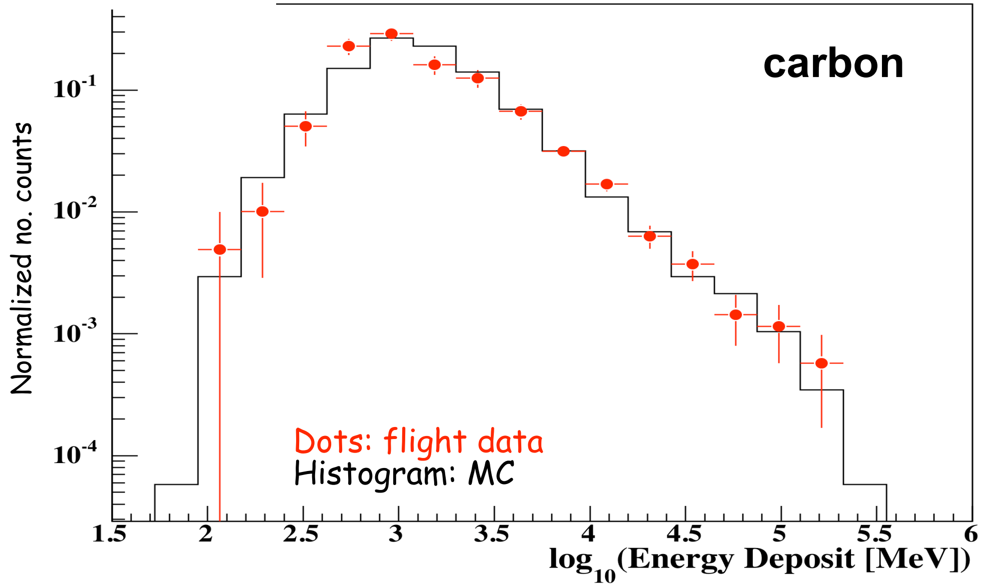
- CREAM-I/II carried out measurements of high energy CRs with an excellent charge separation and a reliable energy determination
- Our data are in good agreement with previous observations.
- The heavy ion spectra seem to be remarkably similar up to ~10^{14} eV
- Spectral hardening for all elements around 200 GeV/n?
- Harder Nitrogen spectrum above 100 GeV/n w.r.t. lower energy.
  N has secondary as well as primary component.
- B/C measurement shows that CRs have a lower residence time in the Galaxy at higher energies. Need for higher energy data (residual path-length?).
- Helium spectrum is flatter than hydrogen – A result first pointed out by JACEE and confirmed by ATIC and CREAM. Different source type? Or acceleration process?
- There is some evidence for curvature in the p and He spectra at VHE
- The Source material for acceleration as cosmic rays appears NOT to be simply solar system like material, but has an ADMIXTURE (20%) of a processed component.

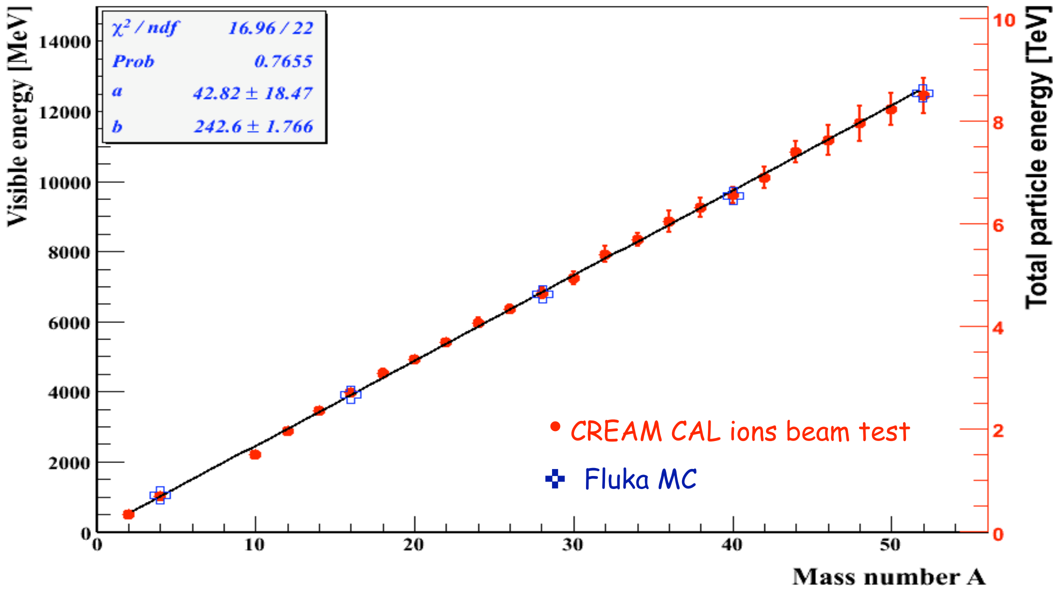
BACKUP SLIDES

Energy measurement with CAL

Energy deposit in CAL







- CAL calibration @ CERN with beam of ions A/Z=2 @ 158 GeV/n ➔

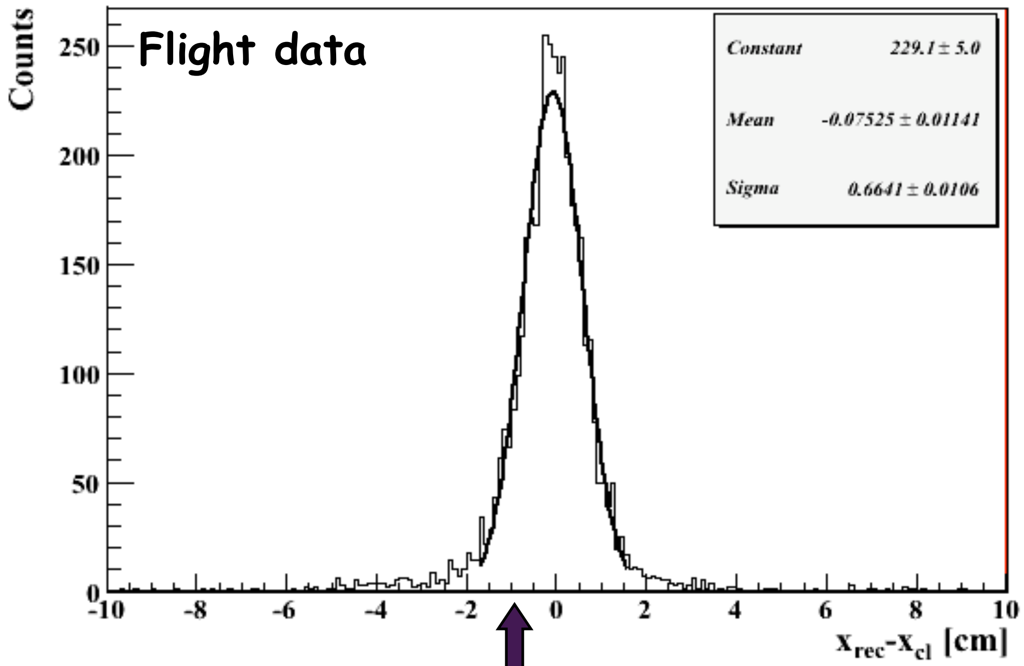
  linear up to 8.5 TeV

  $\Delta E/E \sim 30\%$

- Fluka MC was finely tuned to reproduce both flight and calibration data.

Energy response from MC is in good agreement with data.

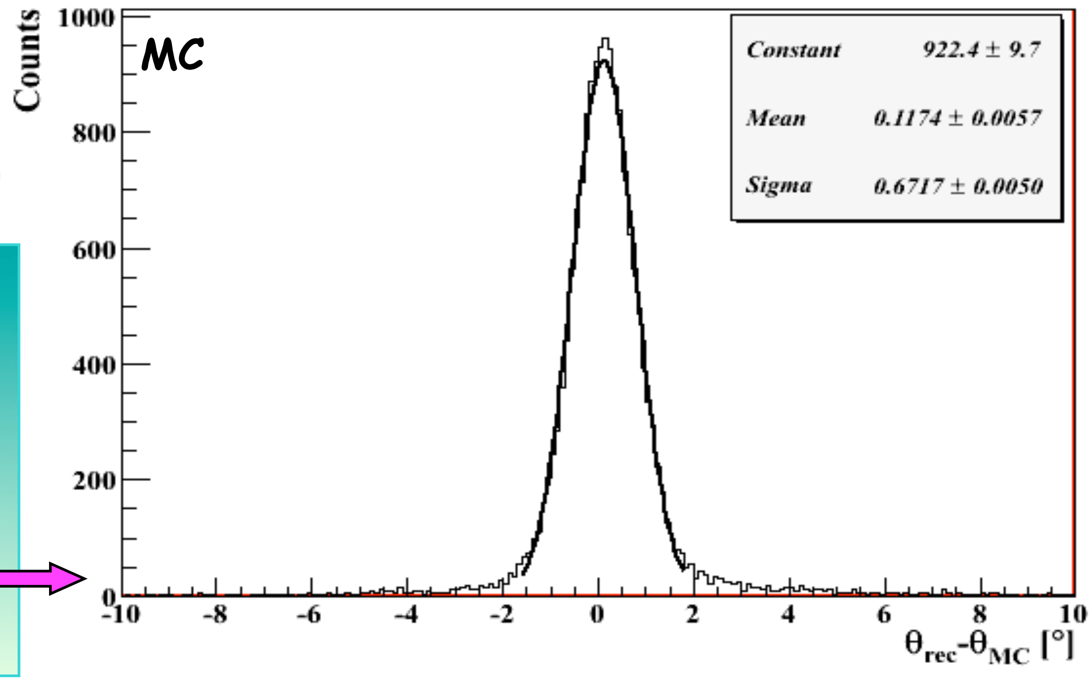
Trajectory reconstruction



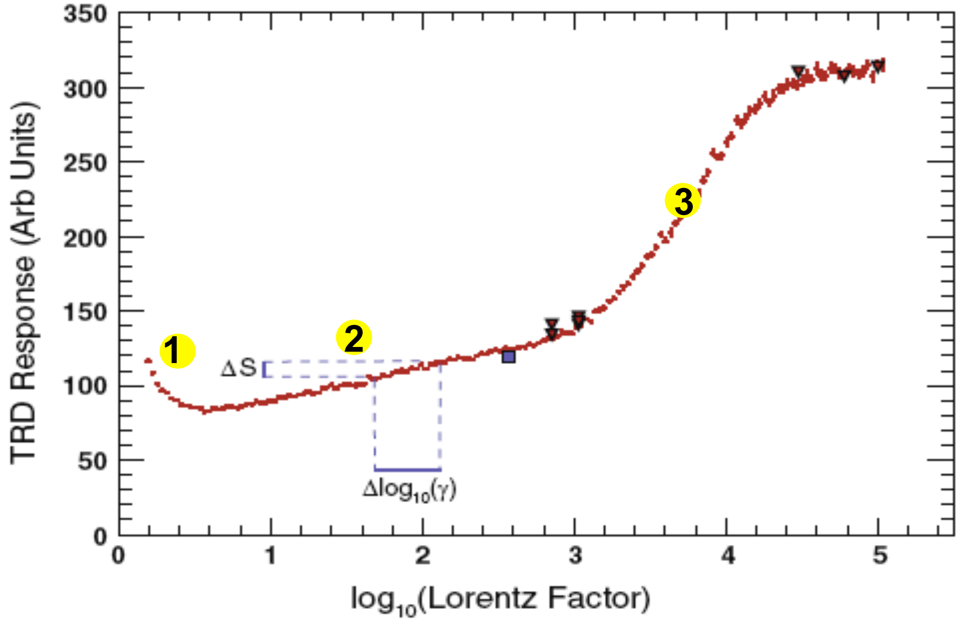
- Two steps algorithm:
  1- CAL tracking. Shower axis is projected back to SCD planes. Search for hit pixels in the circle of confusion (R ~ 3 cm)
  2 - new fit including the matched SCD pixels ⇒ This improves the accuracy of pathlength correction

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

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

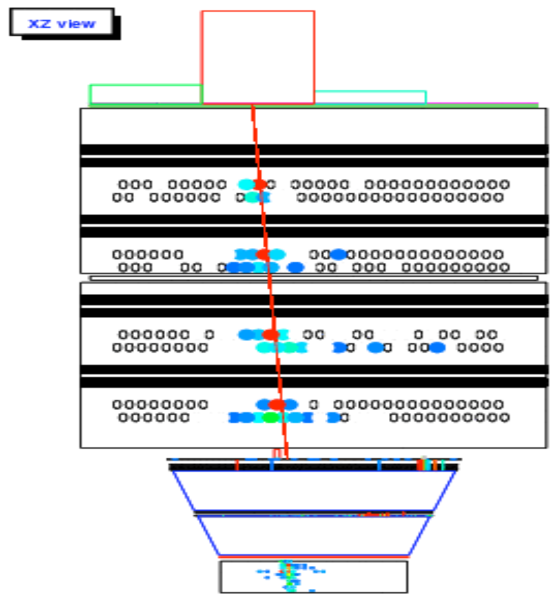


Energy measurement with TRD



- 512 single-wire mylar thin-walled proportional tubes
- 1 cm-radius tubes filled with Xe/CH_4 (95/5%) @ 1 atm
- 16 layers of 32 tubes with alternating X/Y orientations
- Tubes embedded in polystyrene foam radiator

- **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**
- **Energy Resolution $\Delta\log_{10}(\gamma) \sim 0.3$**
- **Tracking precision ~ 1 mm FWHM**



Event reconstruction in CREAM-I

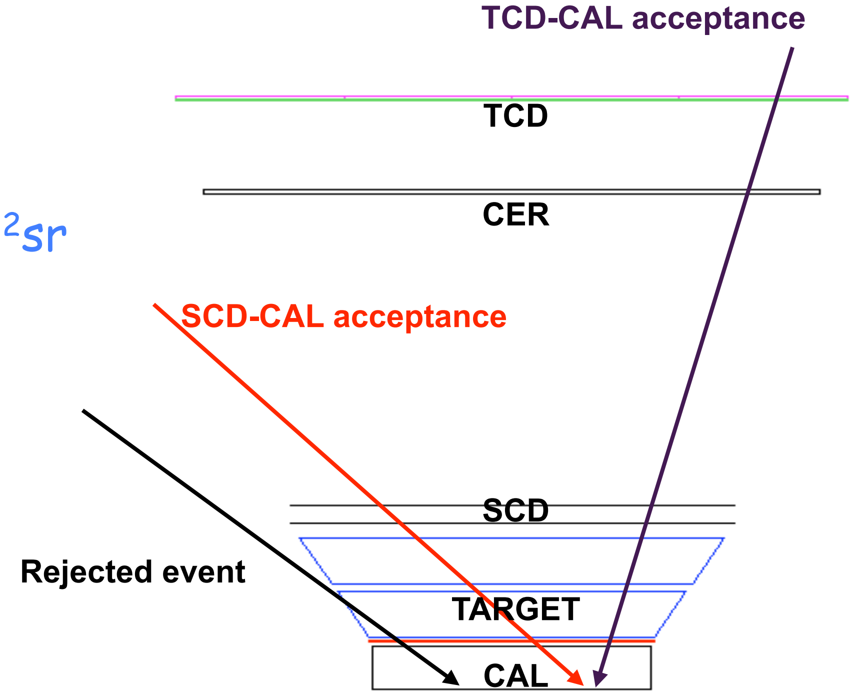
Geometrical Factor and Live Time

➢ Geometrical acceptance for events crossing:

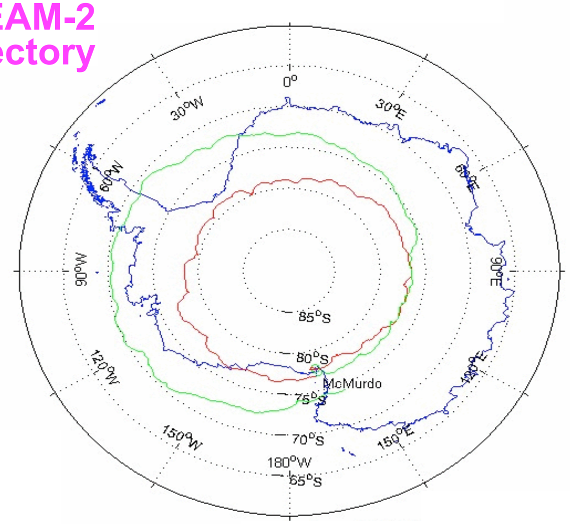
- TCD (120×120 cm^2), SCD (78×78 cm^2) and CAL top plane (50×50 cm^2) ⇒ GF_{small}= 0.194 m^{2}sr

- SCD and CAL top plane ⇒ GF_{large}= 0.462 m^{2}sr

Two independent estimates based respectively on MC simulation and analytical calculation turned out to be in good agreement.



CREAM-2 trajectory

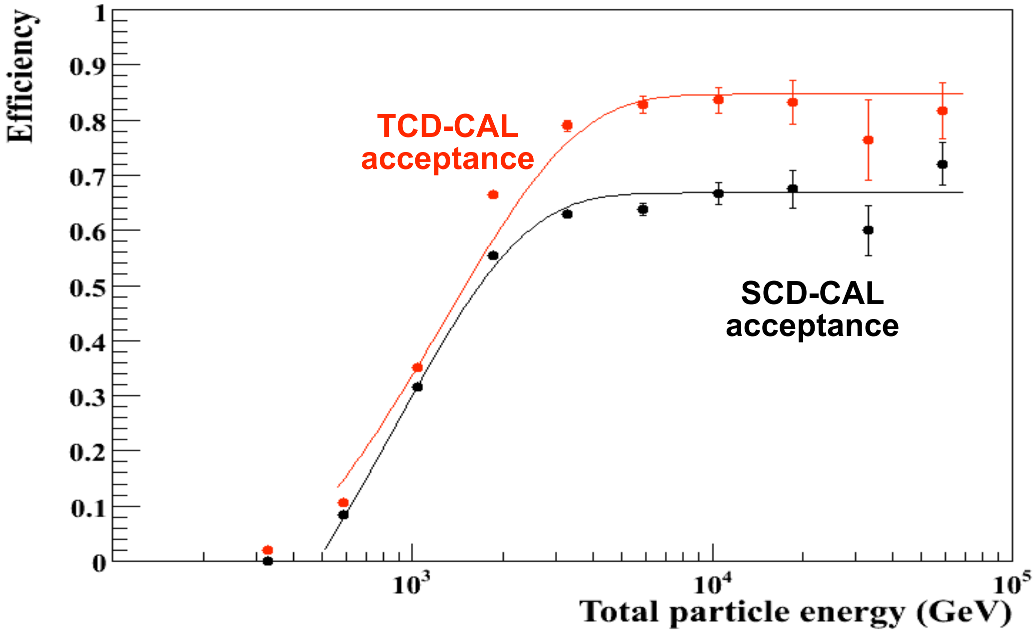


➢ Live Time is computed for the period:
Dec. 19th 5am - Jan. 12th 7:30 pm

Effective Live Time: 24246.7 min
(~16 days 19h 75% of real time)

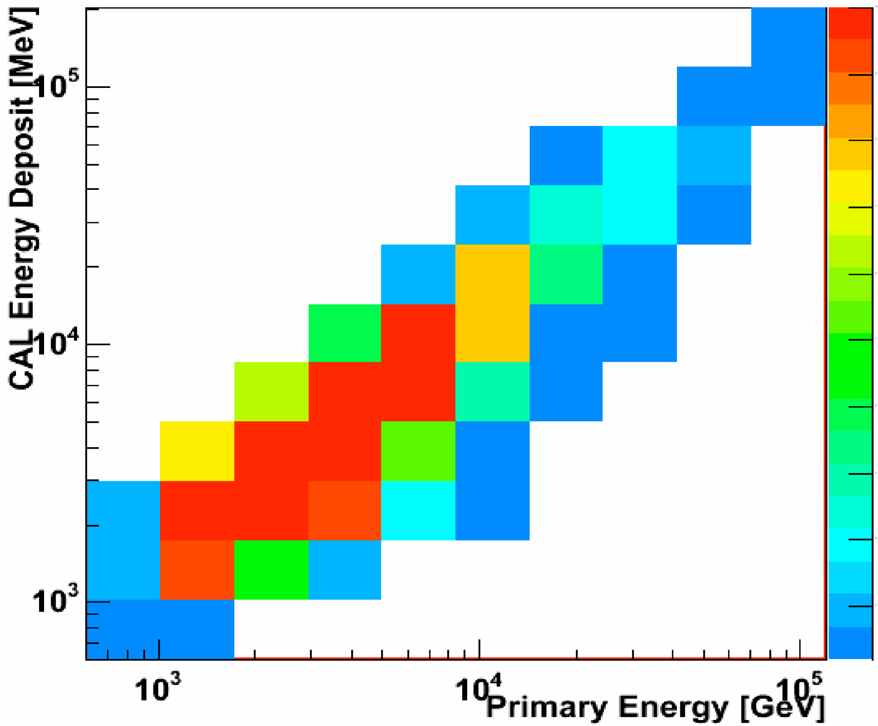
MC simulation

- A detailed MC simulation of CREAM-2 instrument has been done to estimate:
  - the trajectory reconstruction and charge assignment efficiencies
  - the energy deconvolution or overlap matrix
  - TOI correction for each nucleus
- MC based on FLUKA 2006.3b with hadronic package DPMJET-III
- Isotropic generation of nuclei extracted from power-laws energy spectra [0.1–200 TeV]



Reconstruction efficiency:
- nearly flat @ E > 3 TeV: ~ 80% (65%) in TCD (SCD) acceptance
- nearly Z independent

Each element A_{ij} of the overlap matrix represents the probability that events in the deposited energy bin i come from the primary particle energy bin j



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 atmospheric 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