TIGER: Progress in Determining the Sources of Galactic Cosmic Rays

Martin H. Israel

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B. F. Rauch, K. Lodders, M. H. Israel, W. R. Binns, L. M. Scott
Washington University in St. Louis

J. T. Link, L. M Barbier, J. W. Mitchell, E. R. Christian,
J. R. Cummings, J. W. Mitchell, G. A. de Nolfo, R. E. Streitmatter
NASA/Goddard Space Flight Center

S. Geier, R. A. Mewaldt, S. M. Schindler, E. C. Stone
California Institute of Technology

M. E. Wiedenbeck
Jet Propulsion Laboratory

C. J. Waddington
University of Minnesota

B. F. Rauch, J. T. Link, et al. *ApJ* 2009 in press.
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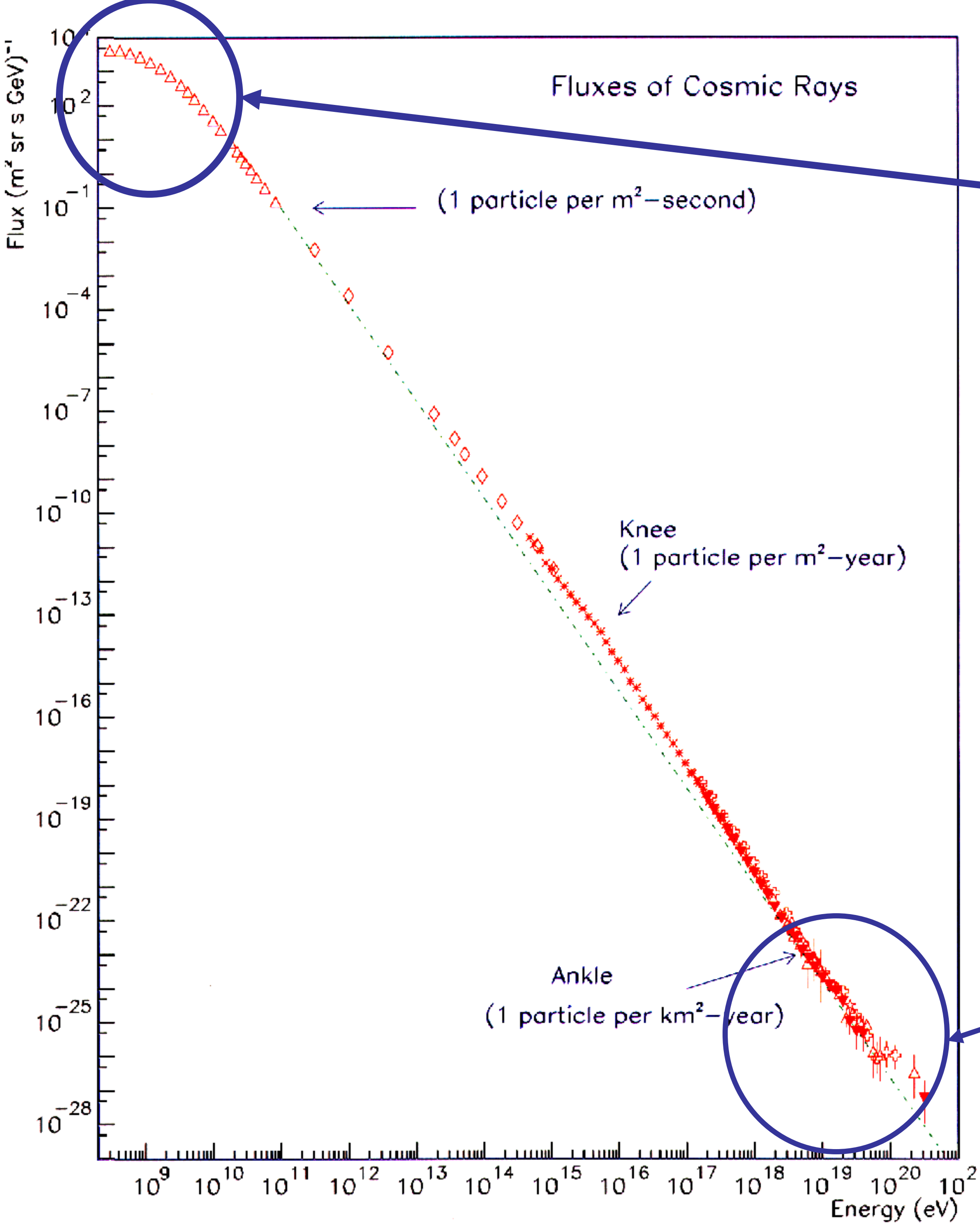


This paper
TIGER data

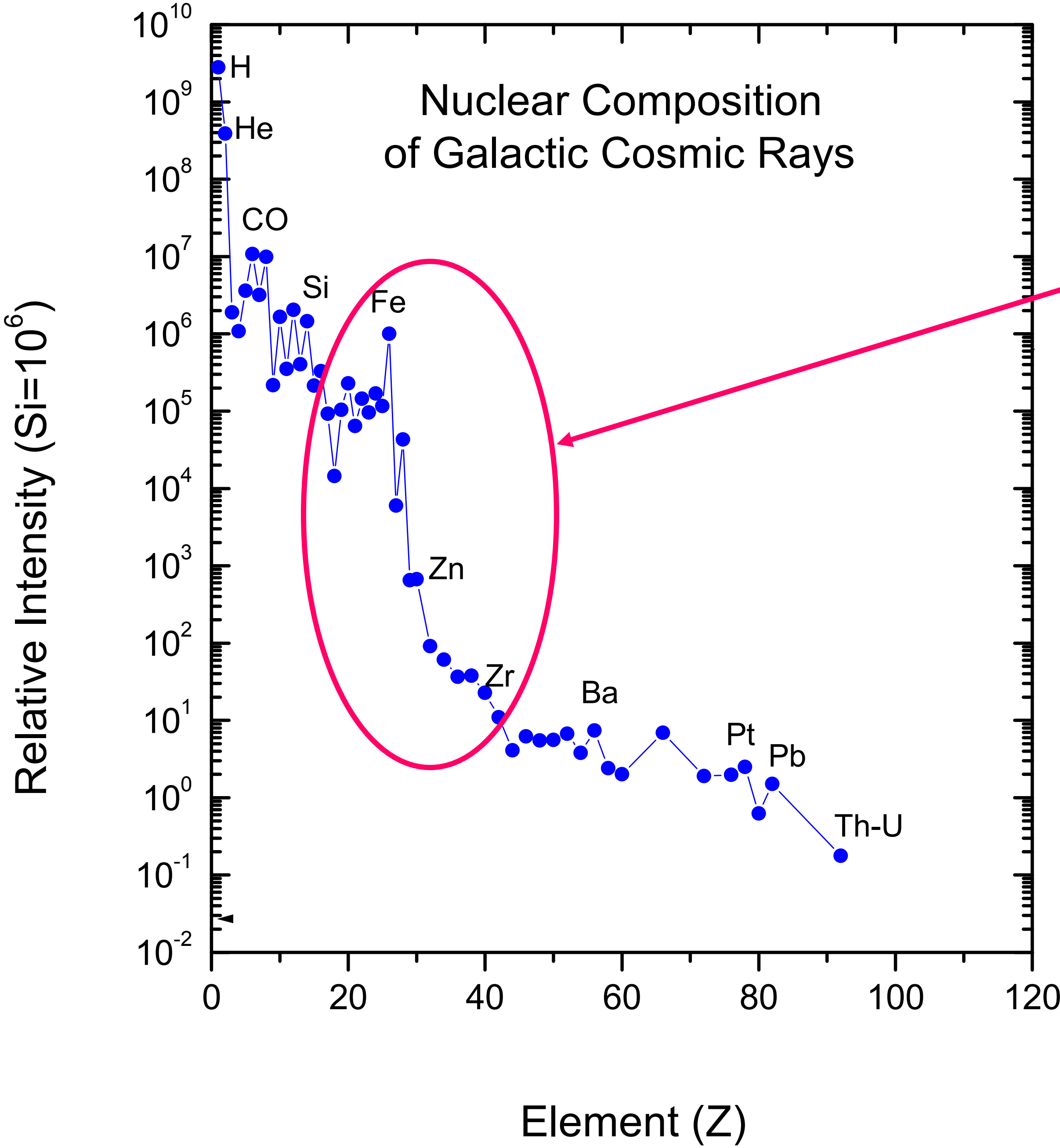
0.5 < E <~10 GeV/nucleon

Identify atomic number Z of individual nuclei.

Learn about sources from composition.

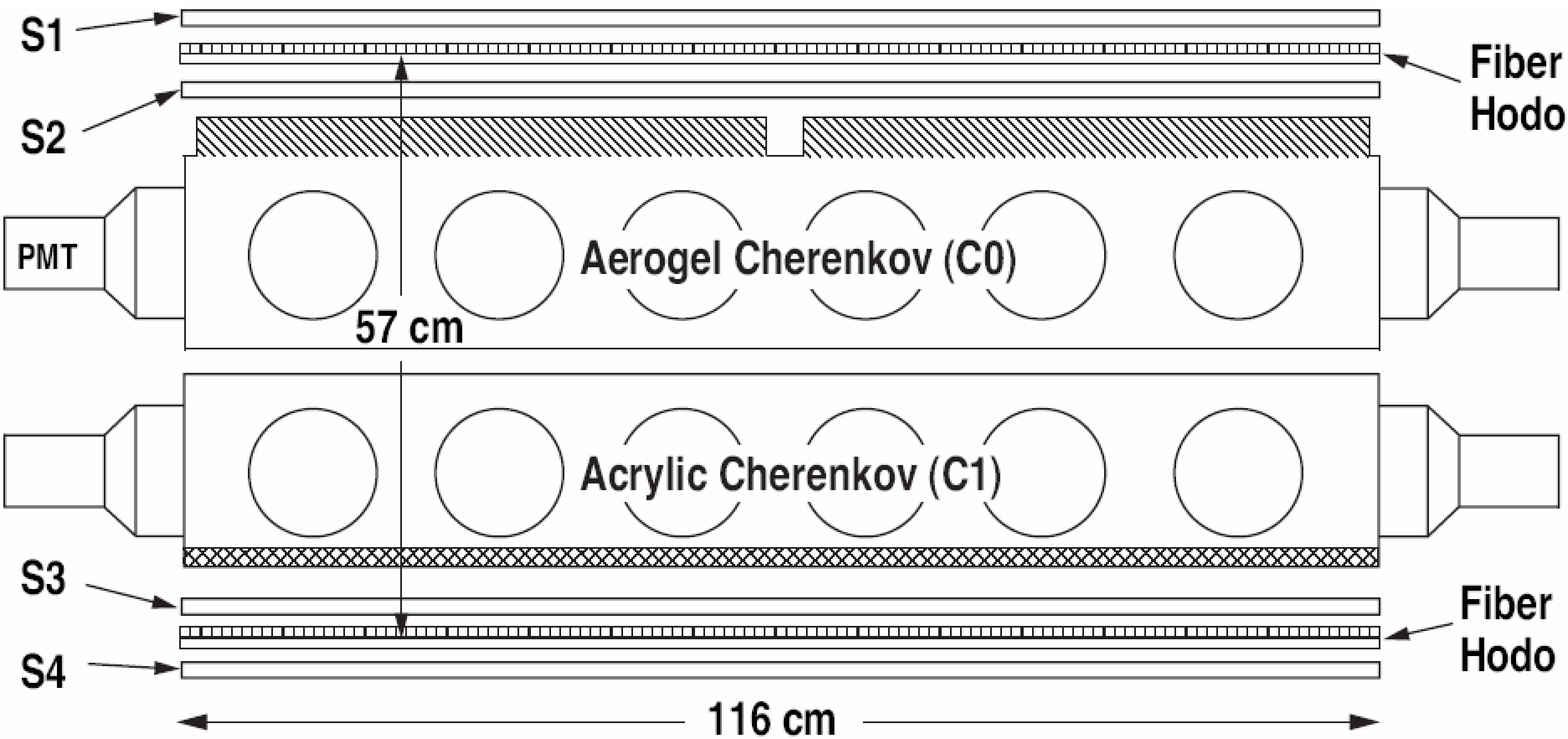
Previous paper
Auger data
E > 10^9 GeV

Learn about sources from arrival direction

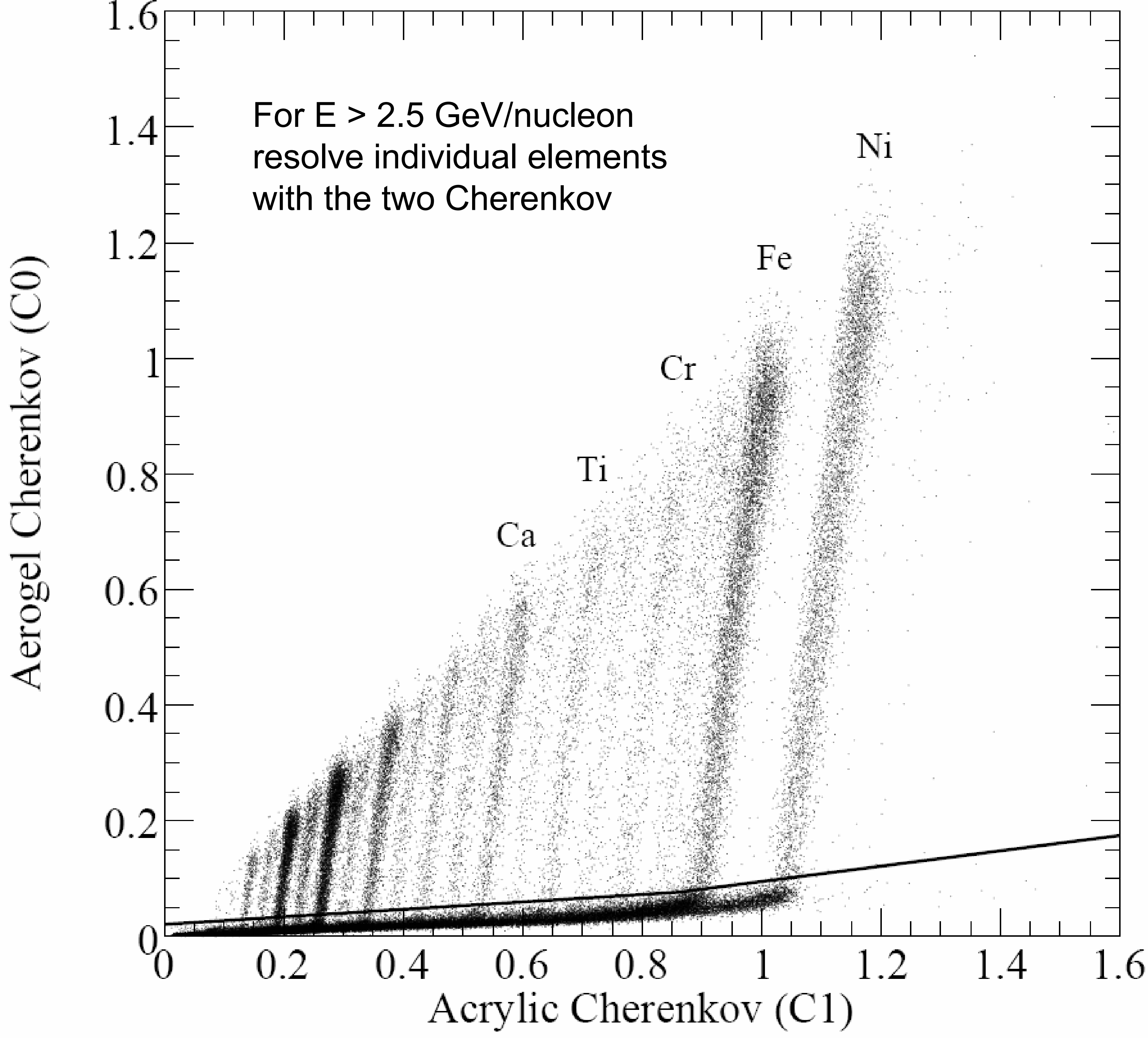


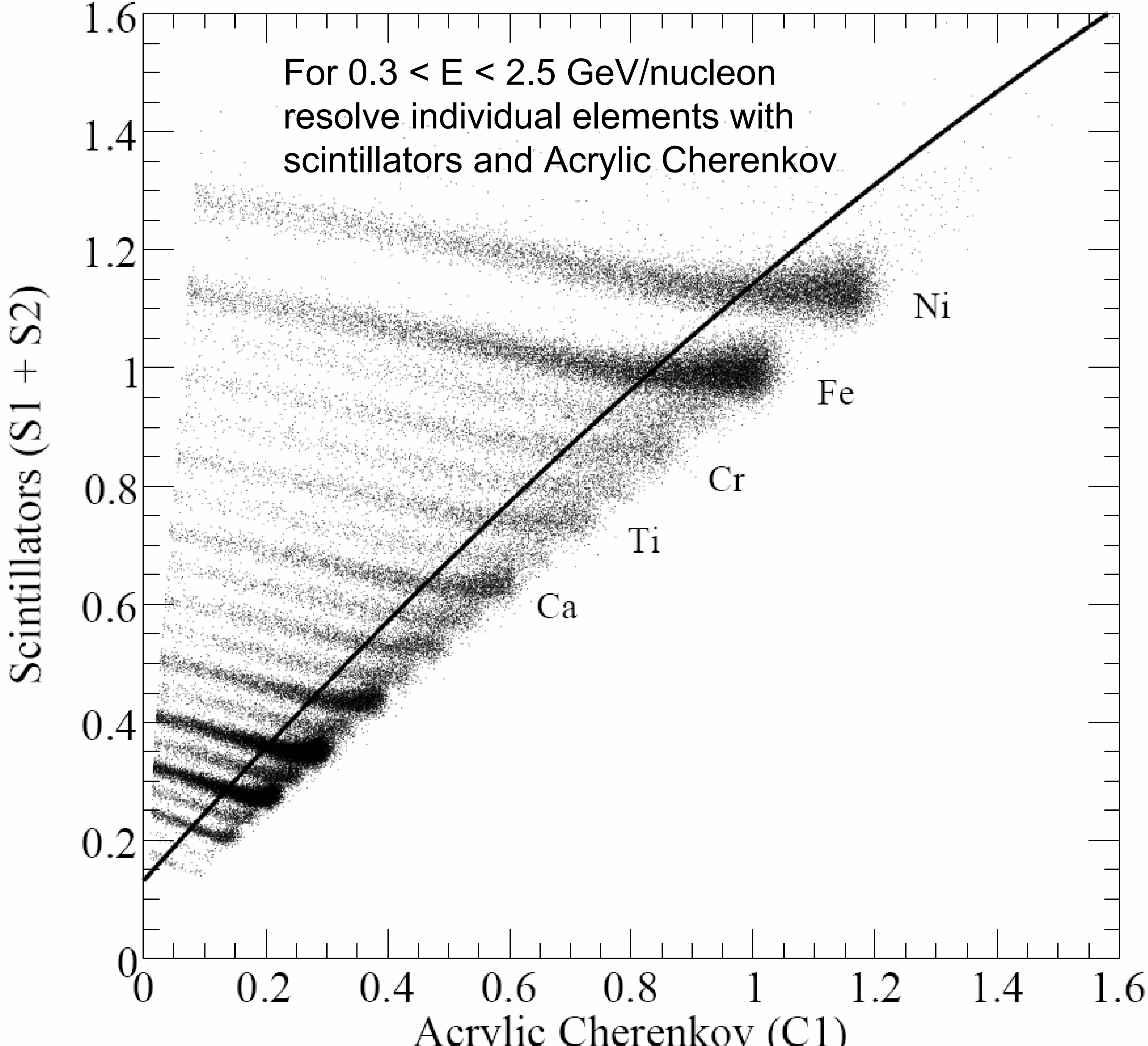
Trans-
Iron
Galactic
Element
Recorder

Resolve
individual
elements
heavier than
Iron



S are scintillation detectors.
Acrylic has n = 1.5   Energy threshold 0.3 GeV/nucleon
Aerogel has n = 1.04   Energy threshold 2.5 GeV/nucleon
Fiber hodoscope determines trajectory on incident cosmic ray.

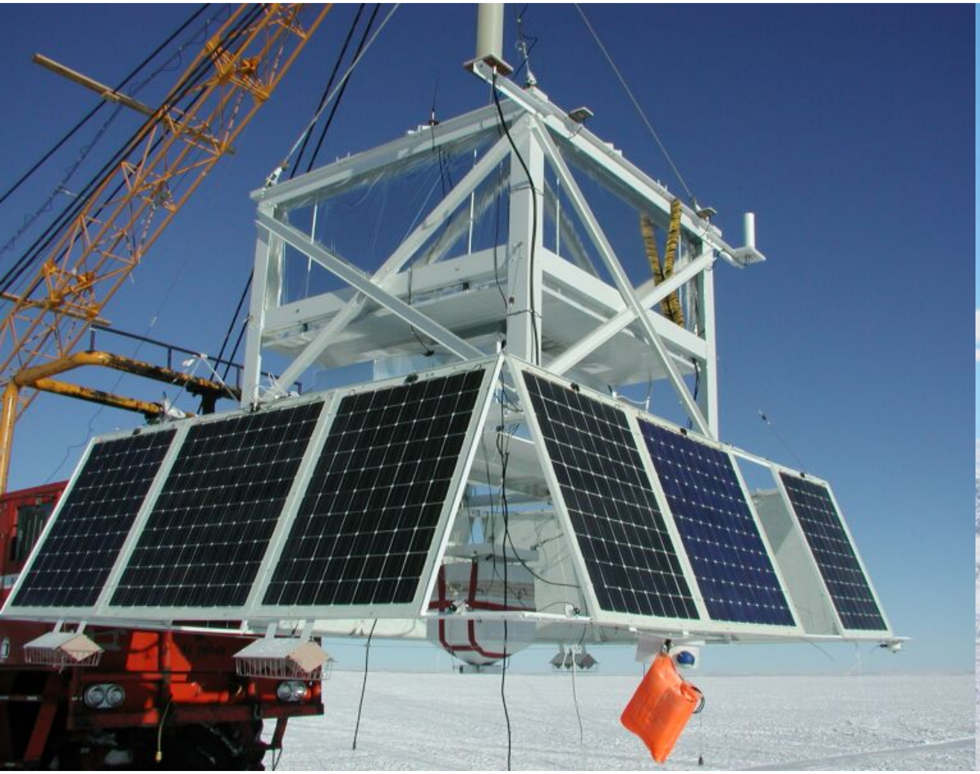

For E > 2.5 GeV/nucleon
resolve individual elements
with the two Cherenkov
Ni
Fe
Cr
Ti
Ca
Aerogel Cherenkov (C0)
Acrylic Cherenkov (C1)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

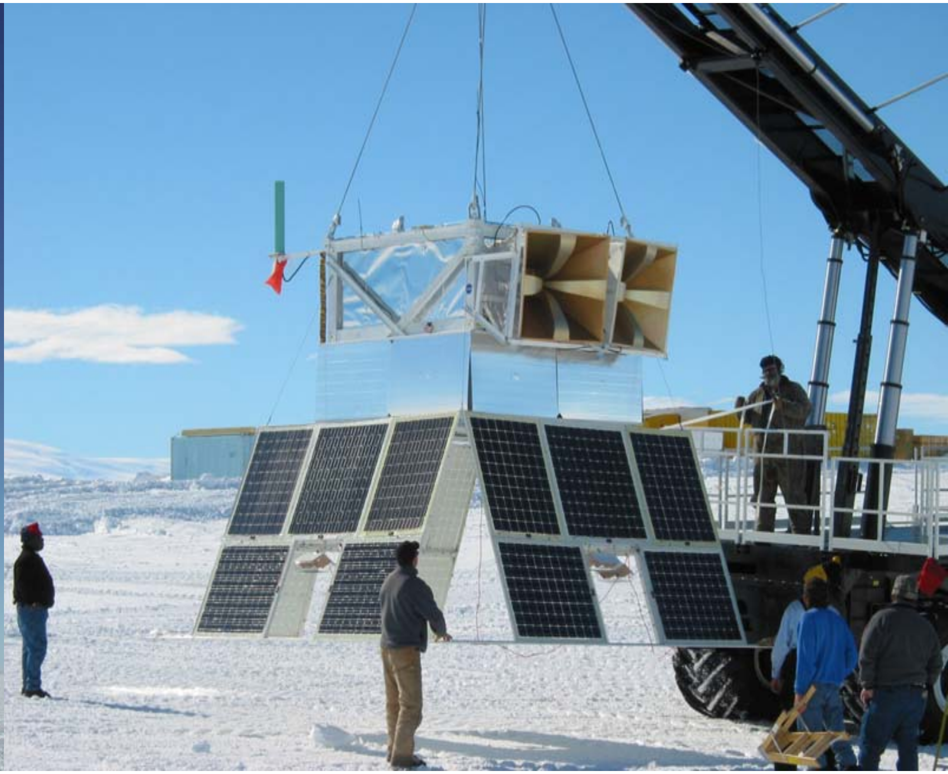


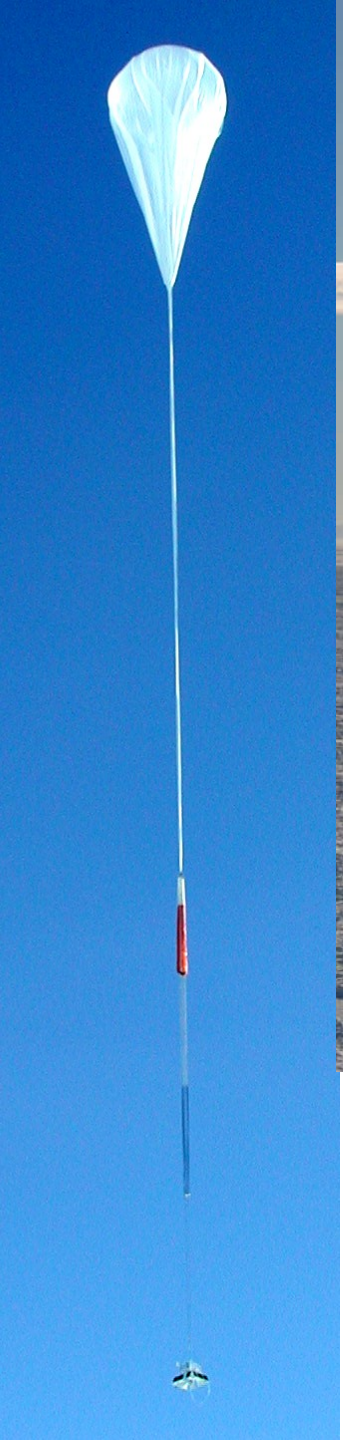
For 0.3 < E < 2.5 GeV/nucleon
resolve individual elements with
scintillators and Acrylic Cherenkov
Ni
Fe
Cr
Ti
Ca
Scintillators (S1 + S2)
Acrylic Cherenkov (C1)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

December 2001

December 2003

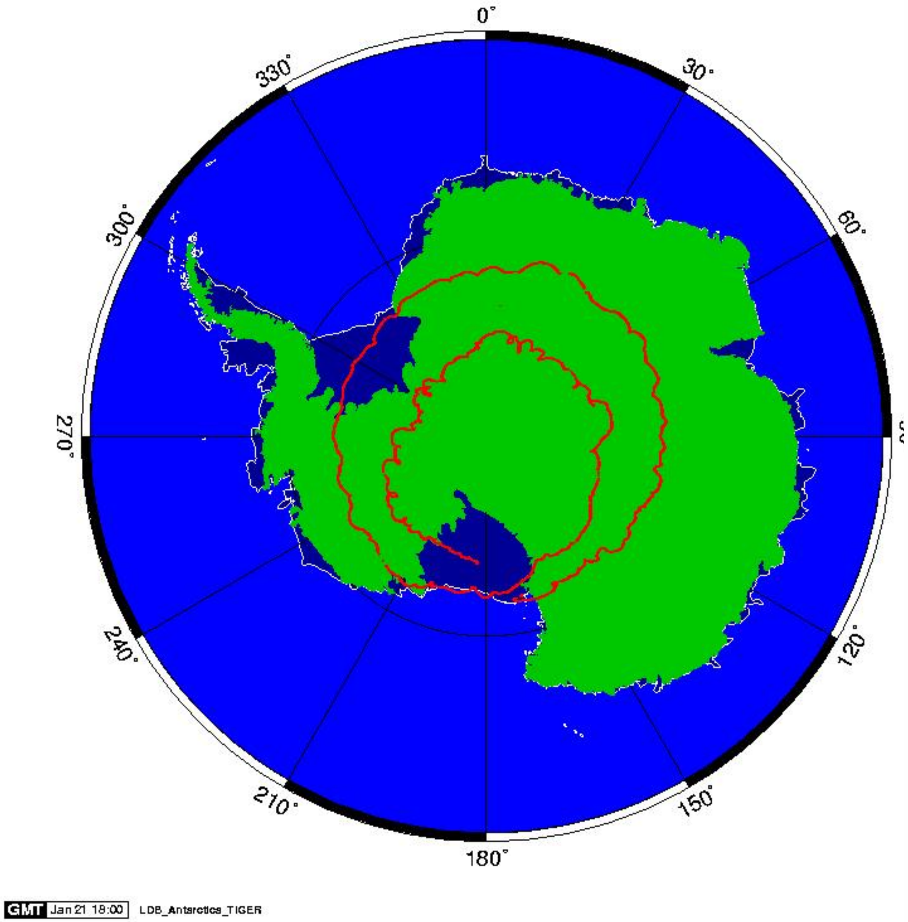




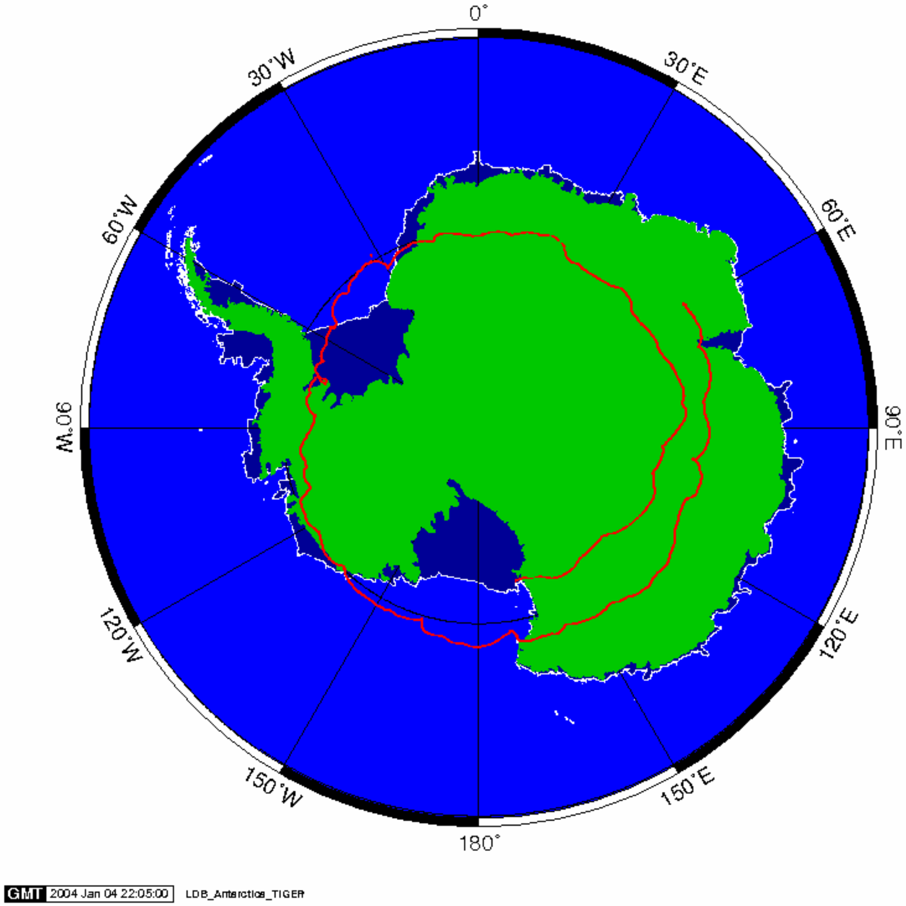


Flight Trajectories

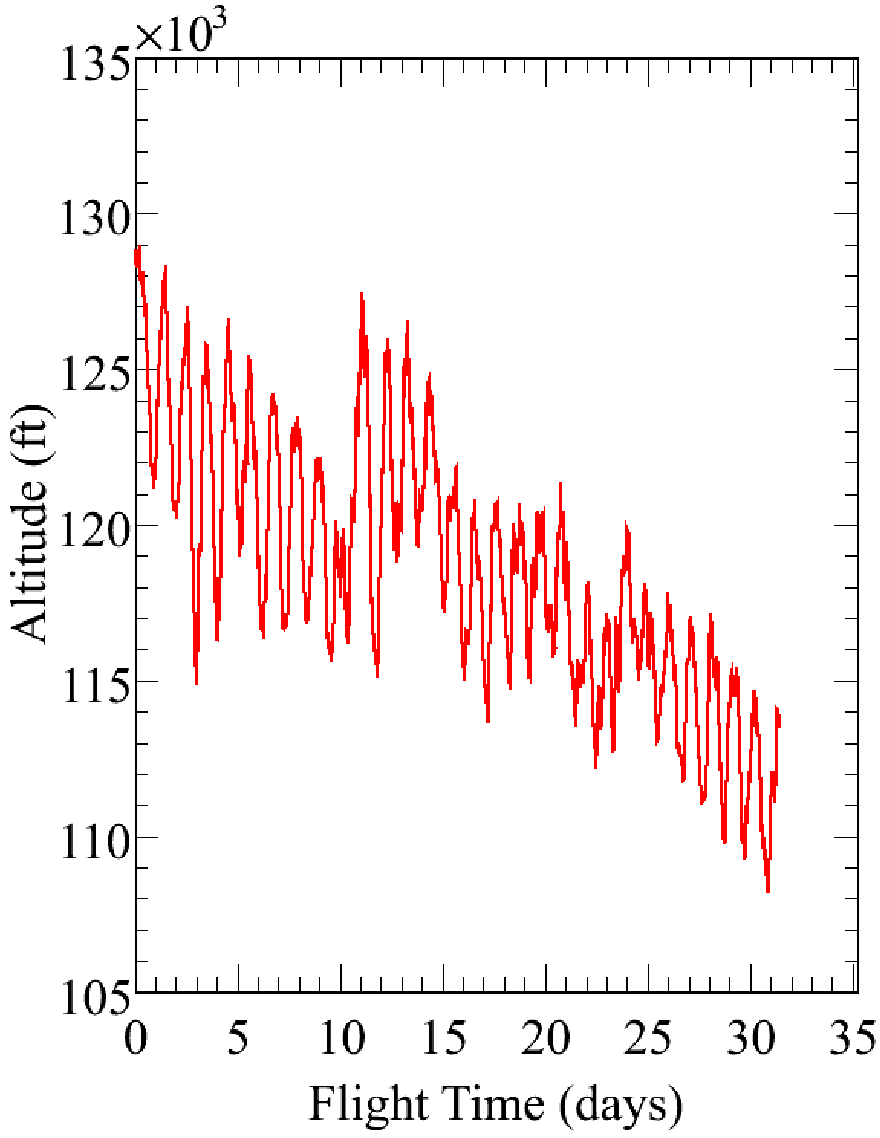
Dec 21, 2001 – Jan 21, 2002



Dec 17, 2003 – Jan 4, 2004



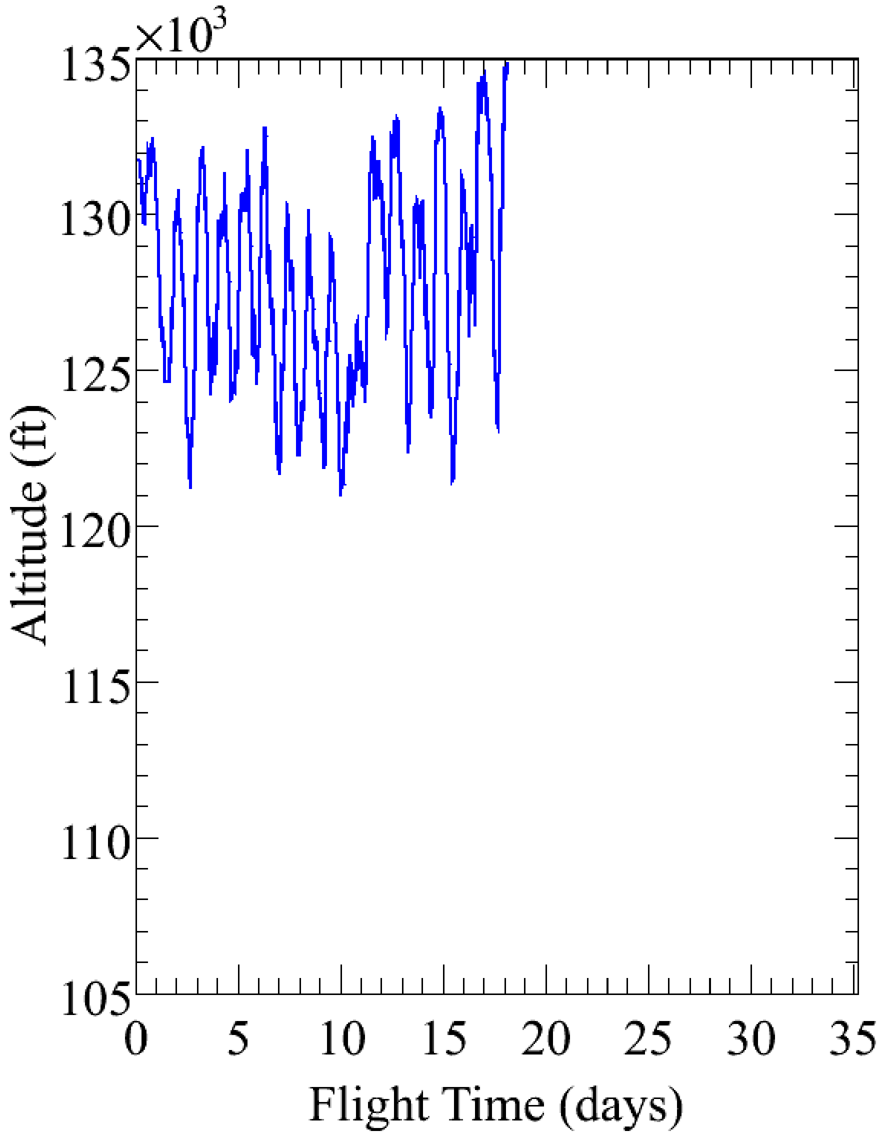
Dec 21, 2001 – Jan 21, 2002



Average: 118,800 ft, 5.5 mb

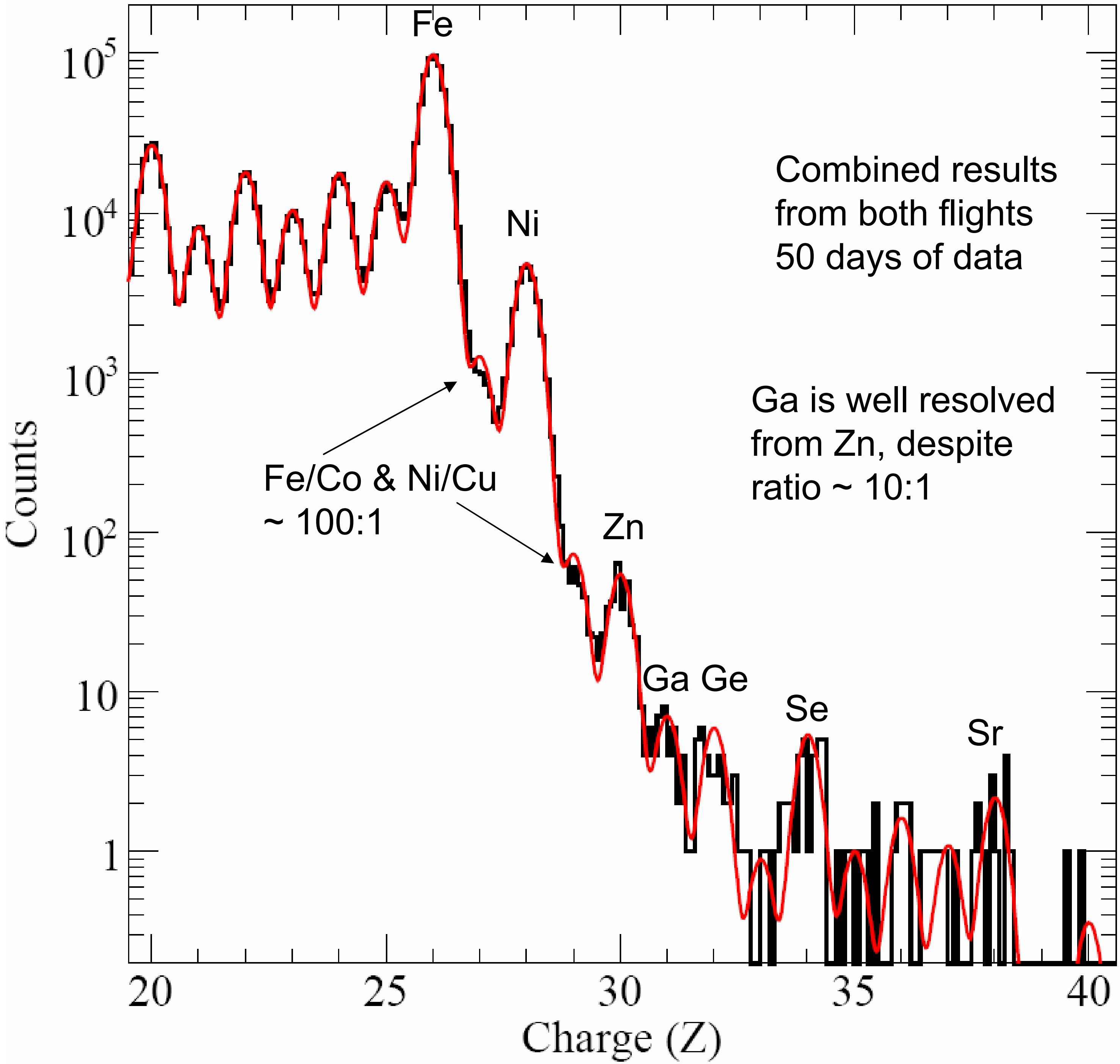
372,977 Fe events

Dec 17, 2003 – Jan 4, 2004

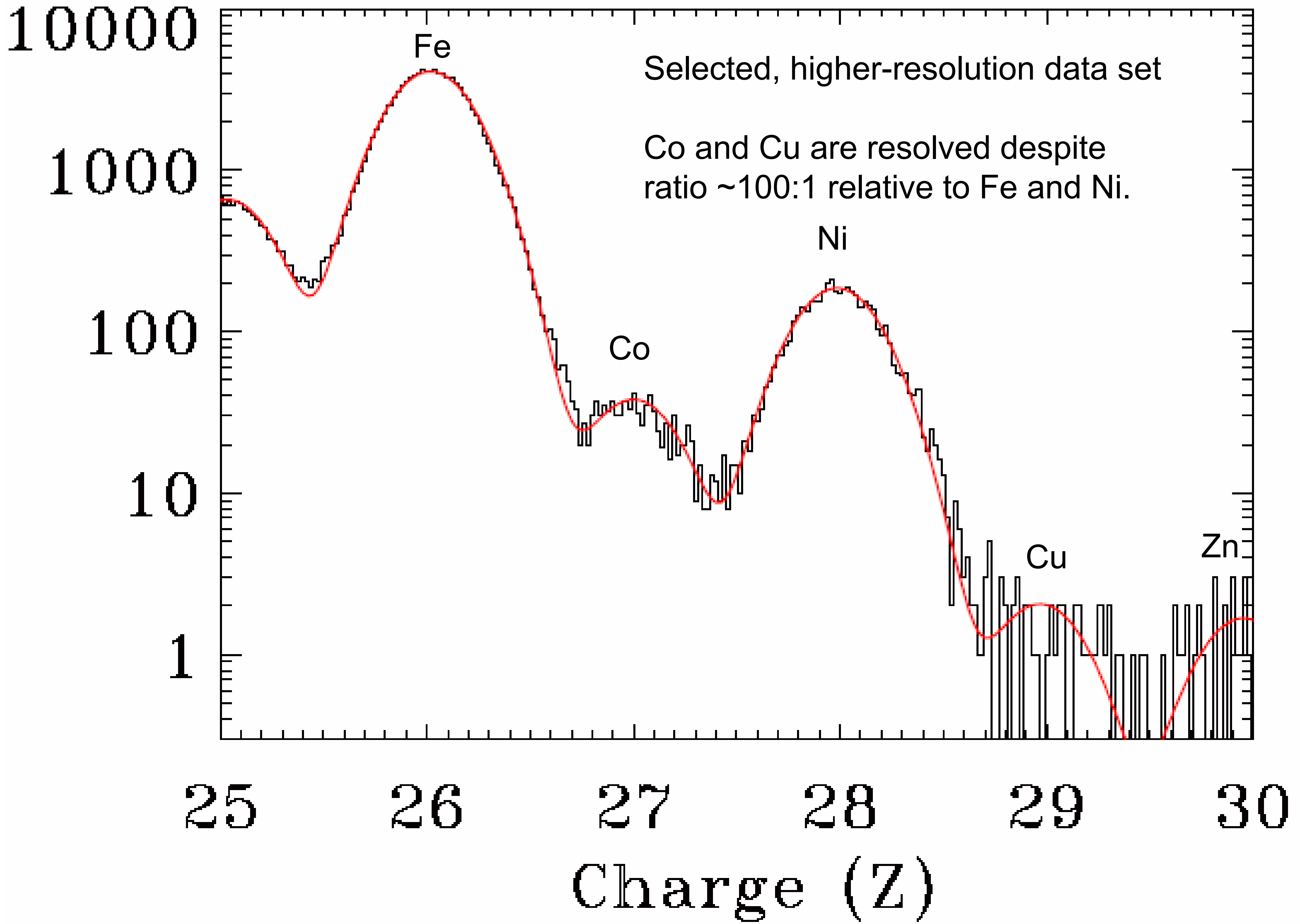


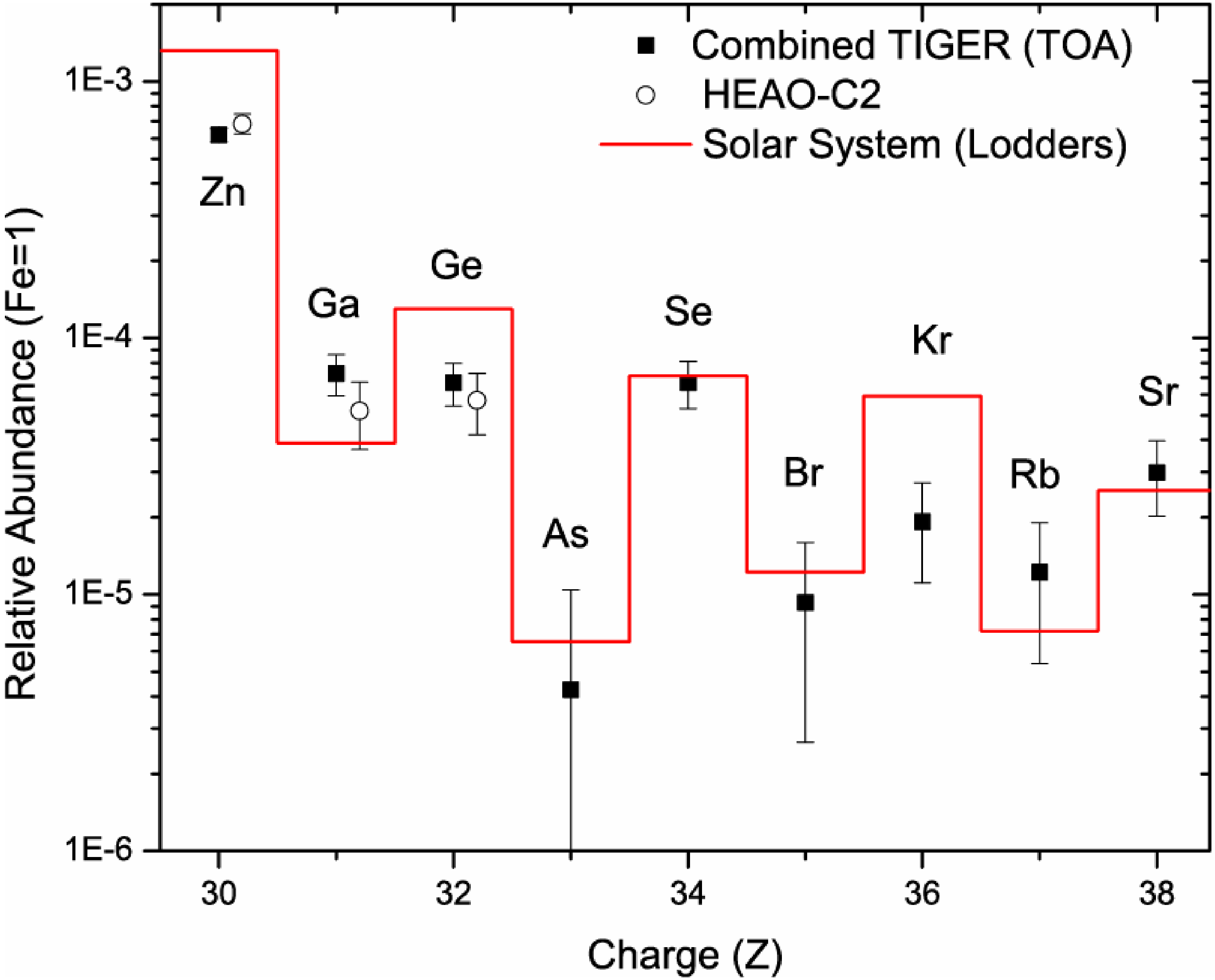
Average: 127,800 ft, 4.1 mb

245,436 Fe events



Fe
Ni
Zn
Ga Ge
Se
Sr
Combined results from both flights 50 days of data
Ga is well resolved from Zn, despite ratio ~ 10:1
Fe/Co & Ni/Cu ~ 100:1
Counts
Charge (Z)


10000
1000
100
10
1
Fe
Selected, higher-resolution data set
Co and Cu are resolved despite
ratio ~100:1 relative to Fe and Ni.
Ni
Co
Cu
Zn
25
26
27
28
29
30
Charge (Z)

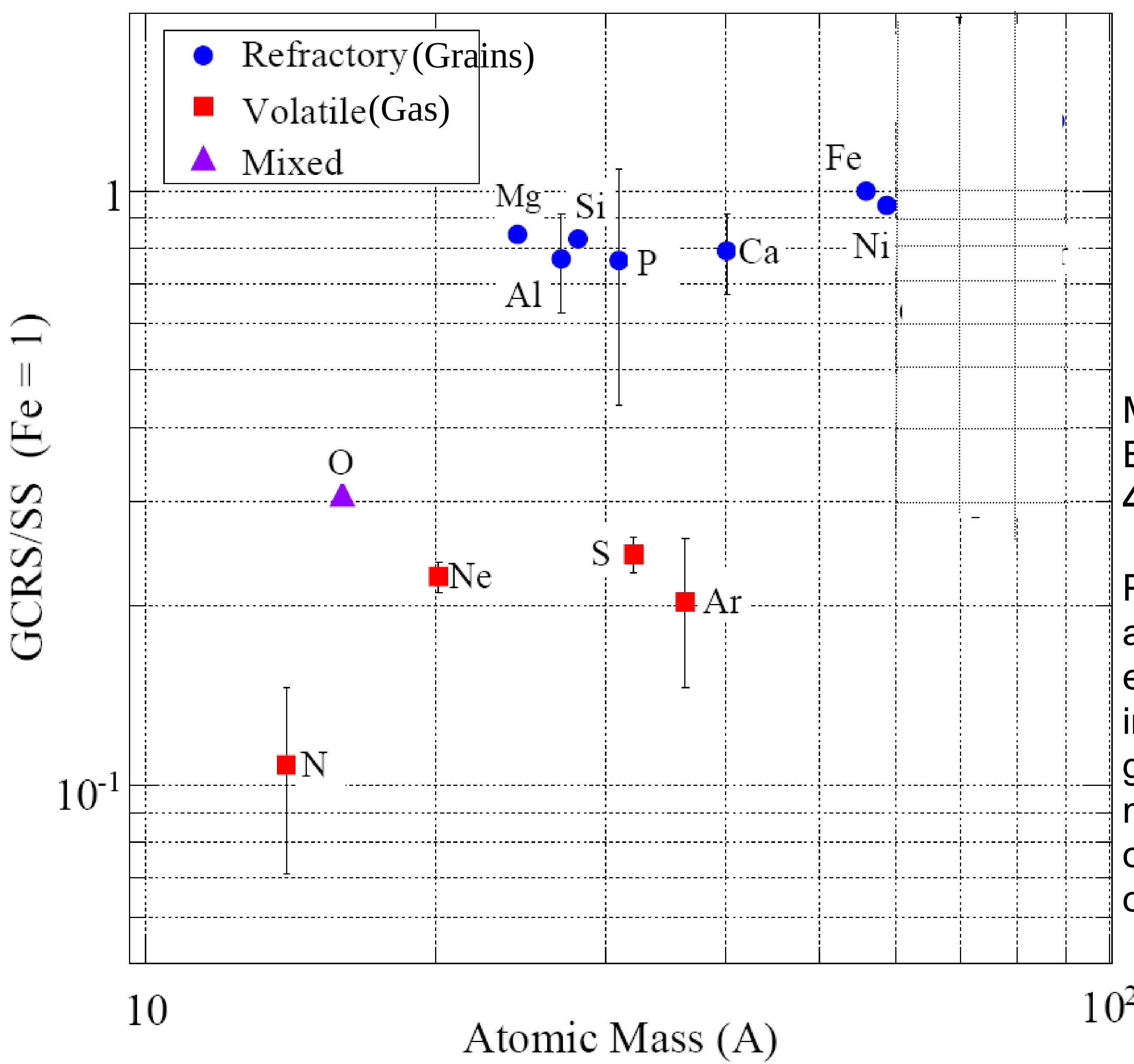


Zn and Ge low relative to Fe is not surprising. These Zn & Ge are volatile.

Ga so abundant is surprising!

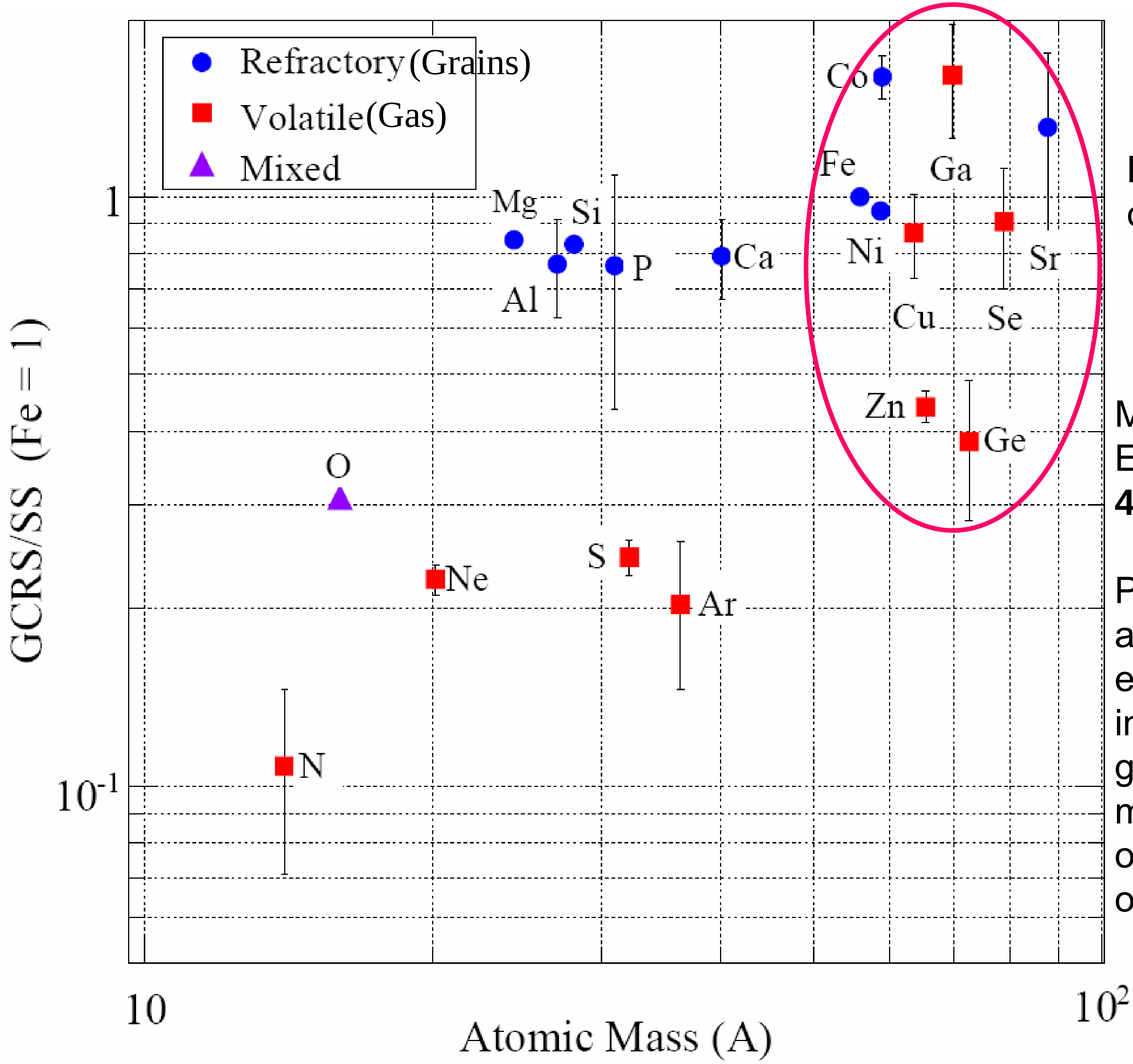
In this and following plots Solar System abundances are from Lodders *Ap.J.* **591** 1220 (2003).

See also paper by W. R. Binns et al. in session R8 Monday 1:30 pm for preliminary results on 30 ≤ Z ≤ 34 from ACE/CRIS.



Meyer, Drury, & Ellison *Ap.J.* **487** 182 (1997)

Preferential acceleration of elements found in interstellar grains, and mass-dependent of acceleration of the volatiles.

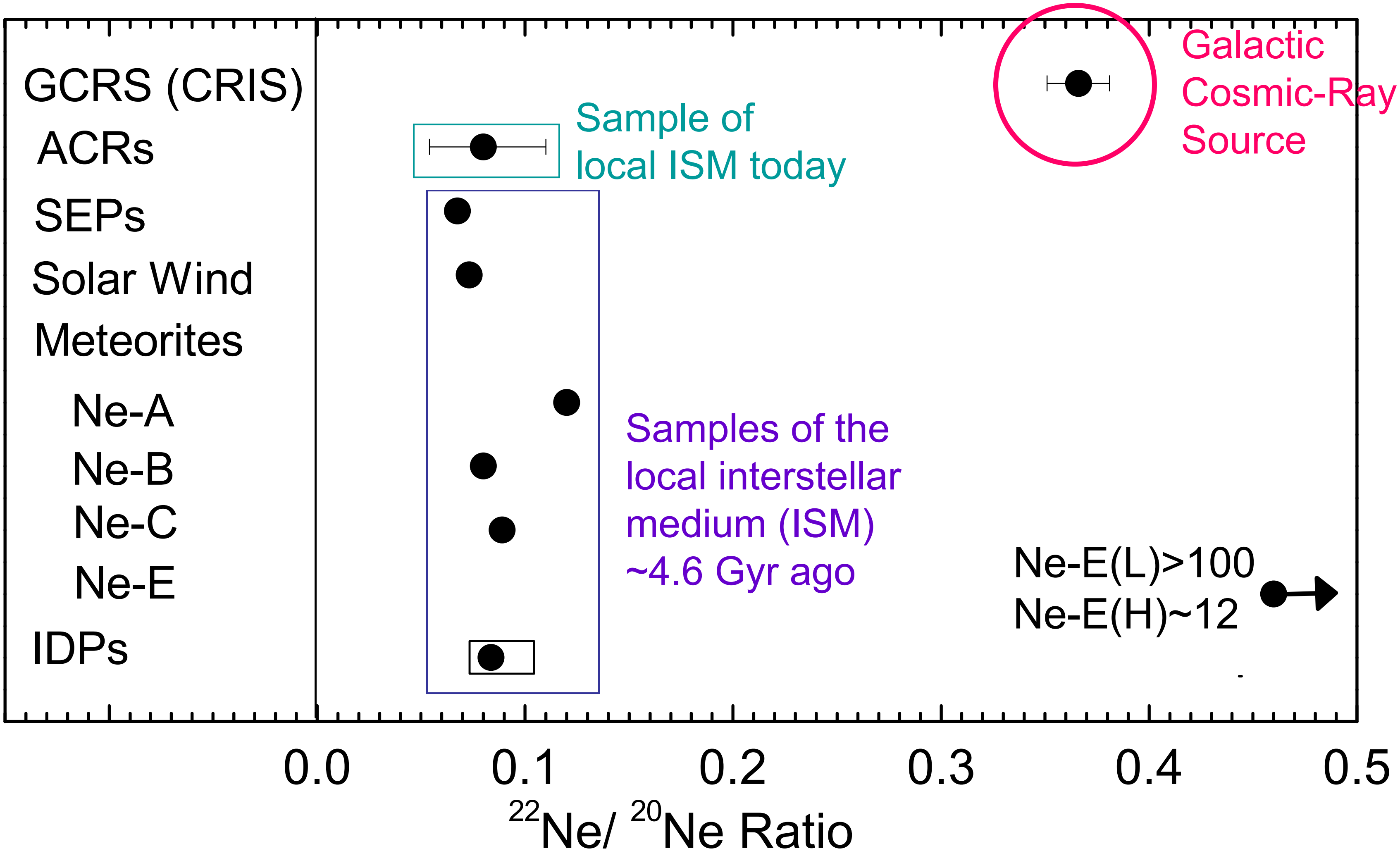


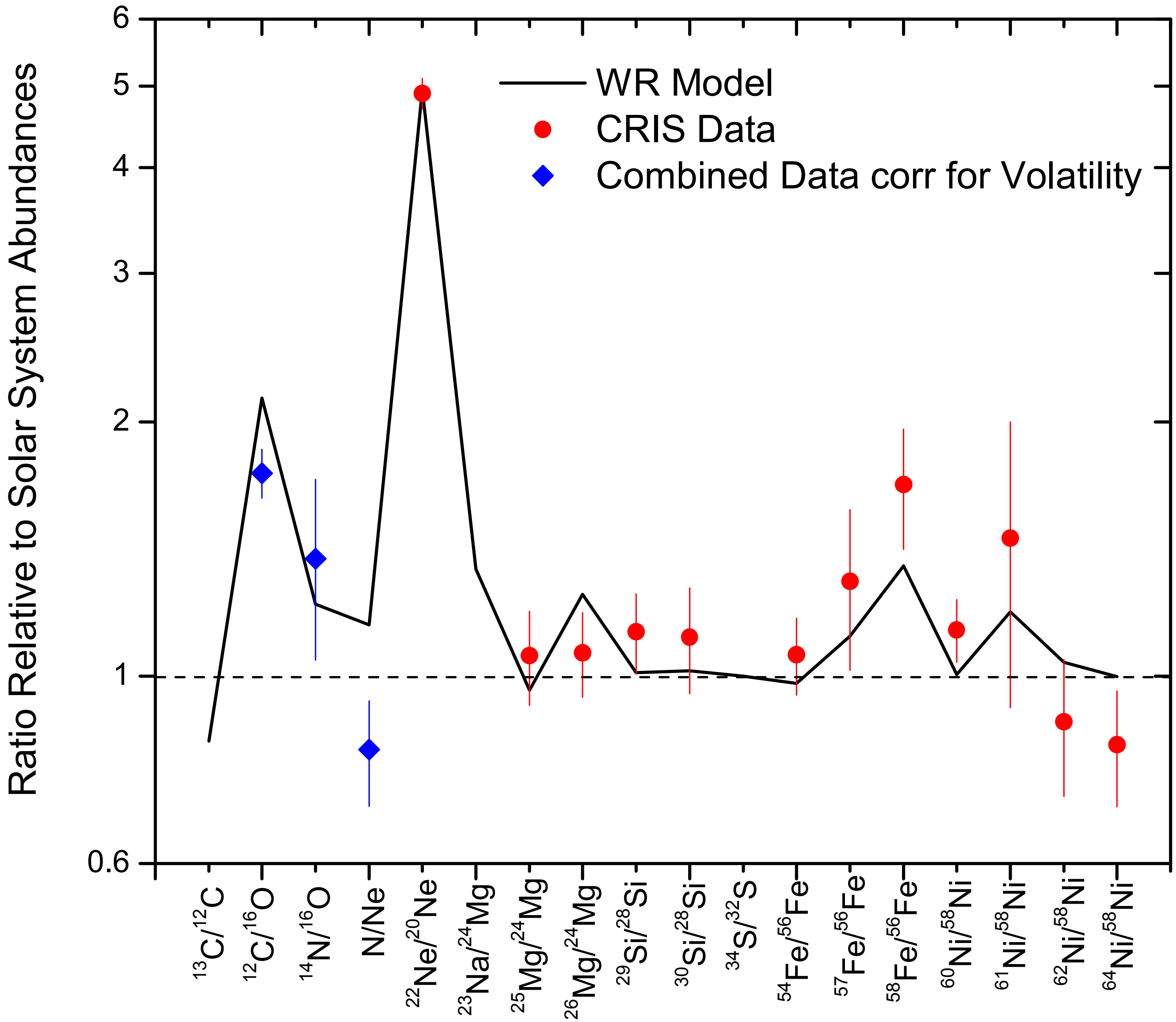
But there is a lot of scatter here.

Meyer, Drury, & Ellison *Ap.J.* **487** 182 (1997)

Preferential acceleration of elements found in interstellar grains, and mass-dependent of acceleration of the volatiles.

Isotope data, most recently from CRIS instrument on ACE, shows that the cosmic-ray source does not have the same composition as the Solar System.

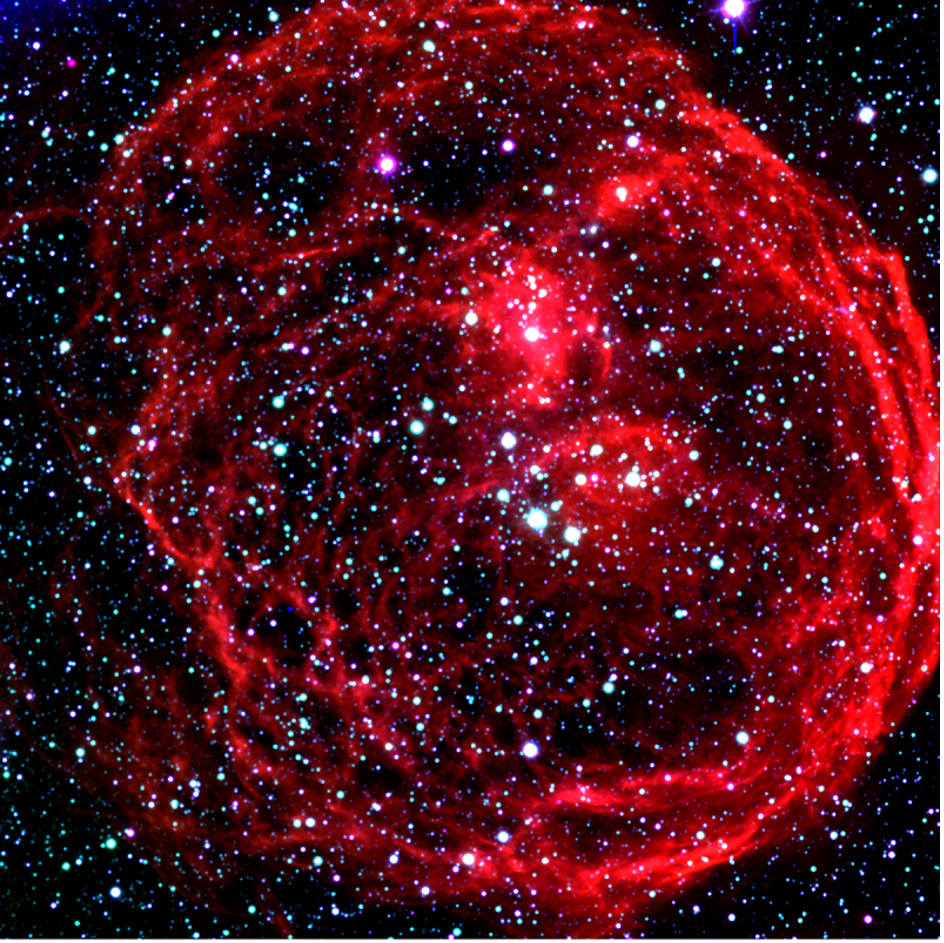




Line shows expected composition from a mixture of 80% SS abundances plus 20% outflow from Wolf-Rayet stars.

Data points give cosmic-ray source abundance ratios relative to SS.

Binns et al. *Ap.J.* **634** 351 (2005)



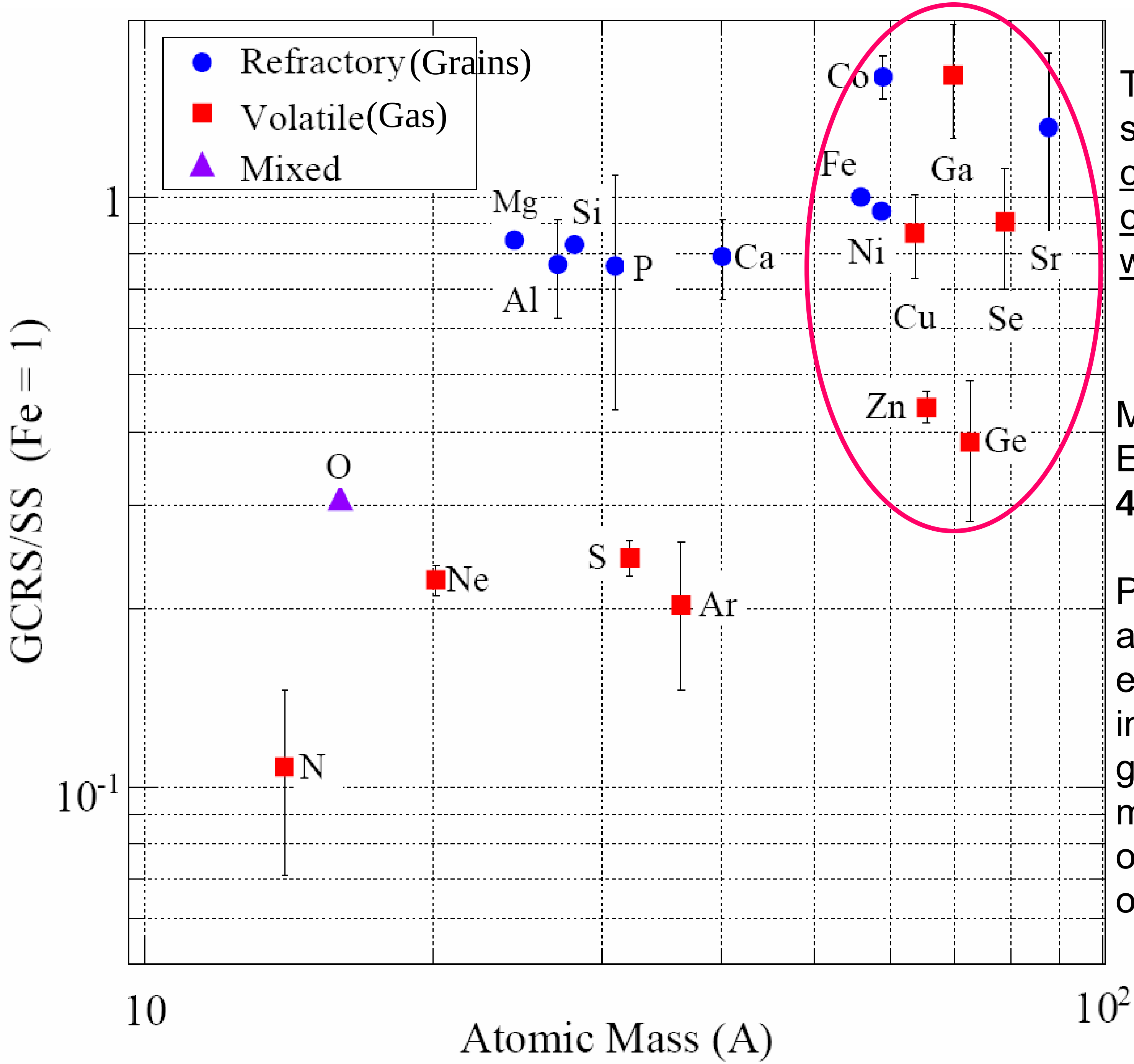
Superbubble (N 70) in the
Large Magellanic Cloud

Diameter ~ 100 pc

Wolf-Rayet star (Sharpless 308)
in Milky Way ~1600 pc distant

Diameter of bubble around star ~ 20 pc

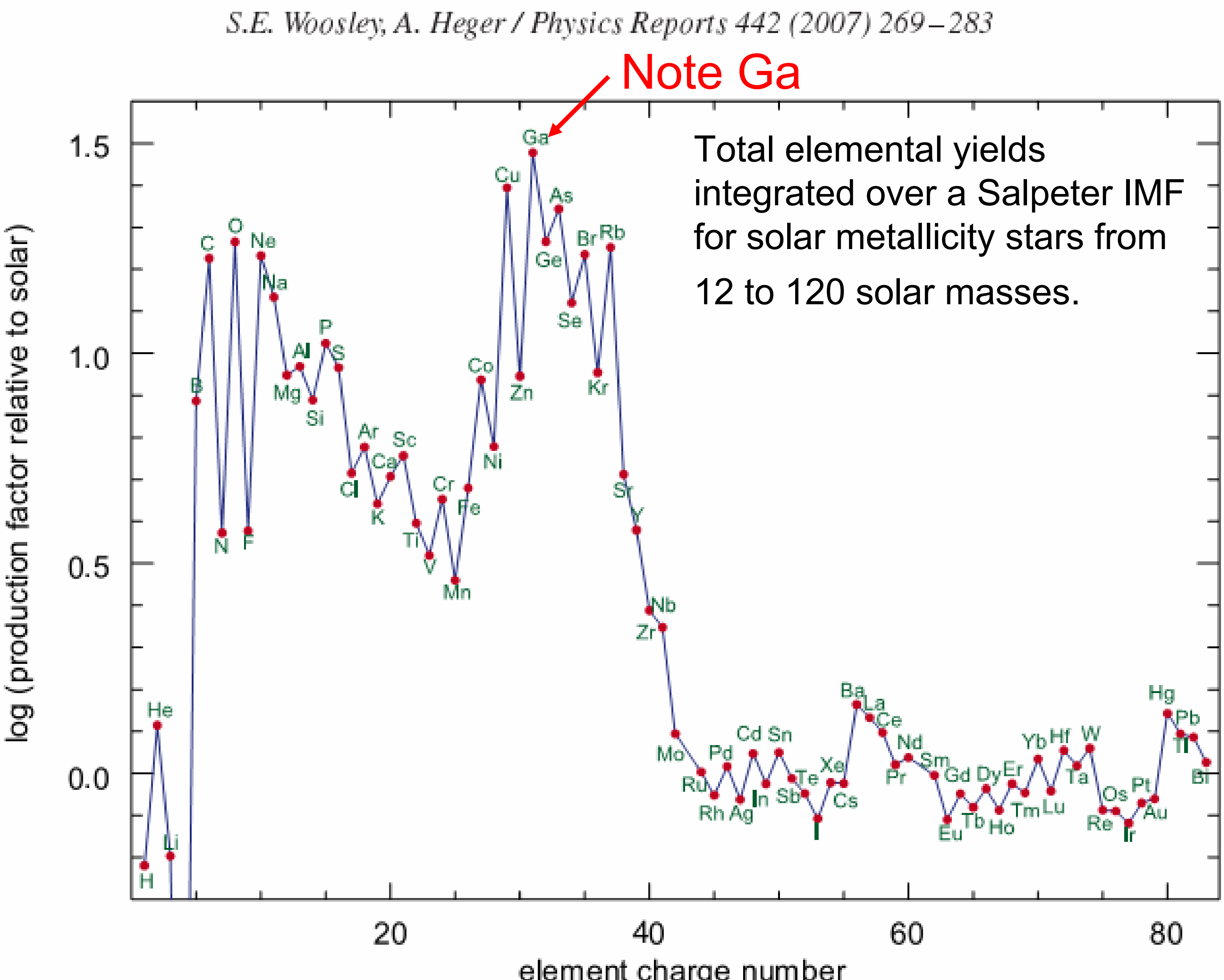
Higdon and Lingenfelter *Ap.J.* **590**, 822 (2003):
"… the ^{22}Ne abundance in the cosmic rays is not anomalous but is the natural consequence of the superbubble origin of cosmic rays …"

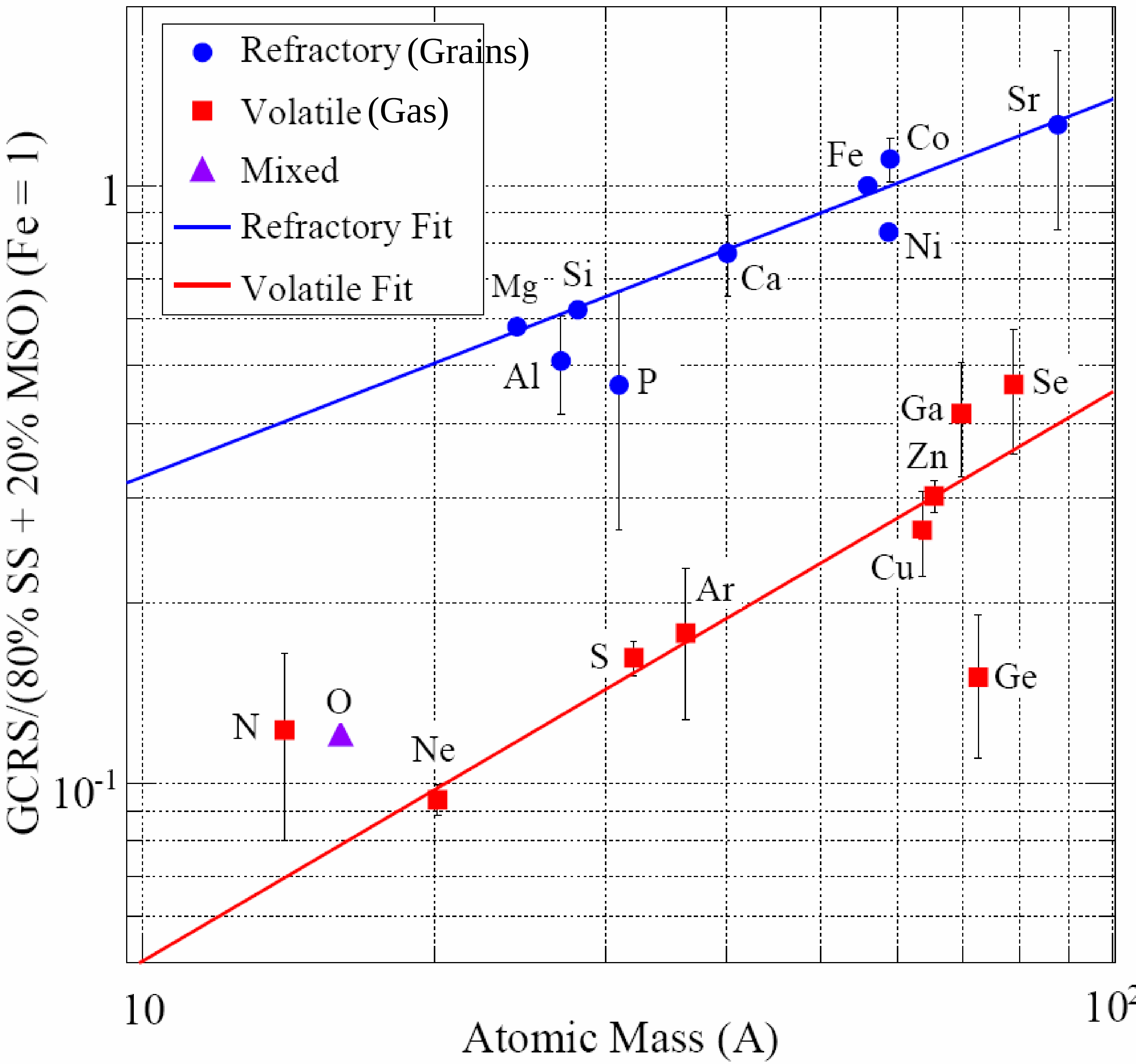


There is a lot of scatter here when <u>comparing the cosmic-ray source with solar system</u>.

Meyer, Drury, & Ellison *Ap.J.* **487** 182 (1997)

Preferential acceleration of elements found in interstellar grains, and mass-dependent of acceleration of the volatiles.


S.E. Woosley, A. Heger / Physics Reports 442 (2007) 269–283
Note Ga
Total elemental yields integrated over a Salpeter IMF for solar metallicity stars from 12 to 120 solar masses.
log (production factor relative to solar)
element charge number
1.5
1.0
0.5
0.0
20
40
60
80
H He Li B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Ru Rh Pd Ag Cd In Sn Sb Te I Xe Cs Ba La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi



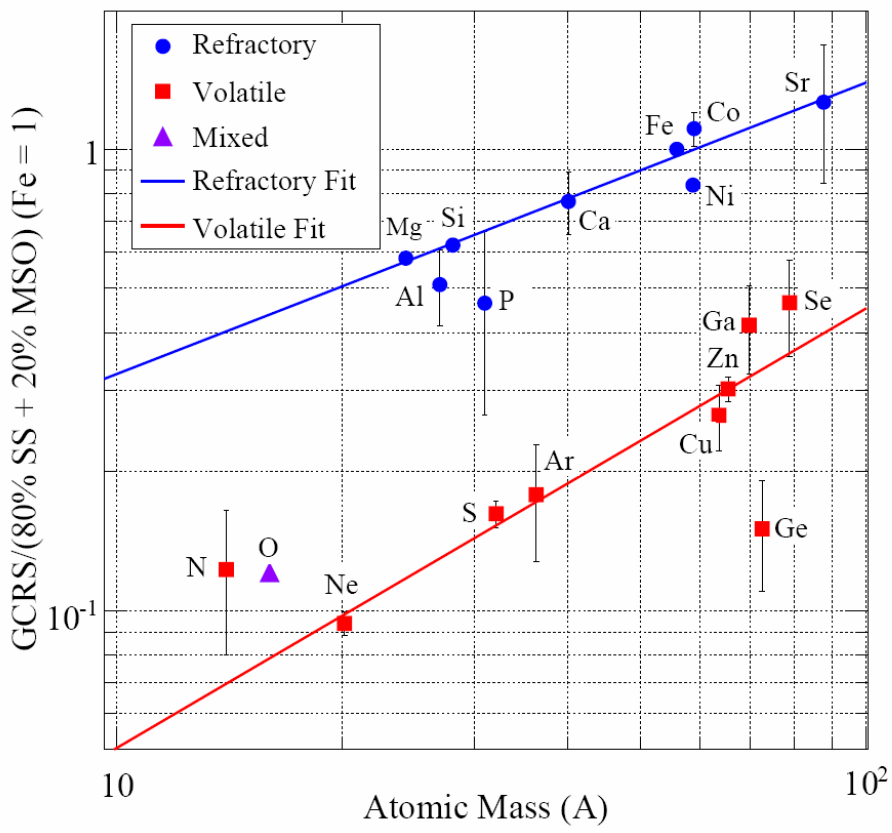
Now compare GCR source abundances with a mixture of 80% SS (Lodders) and 20% Massive Star Outflow (Woosley & Heger).

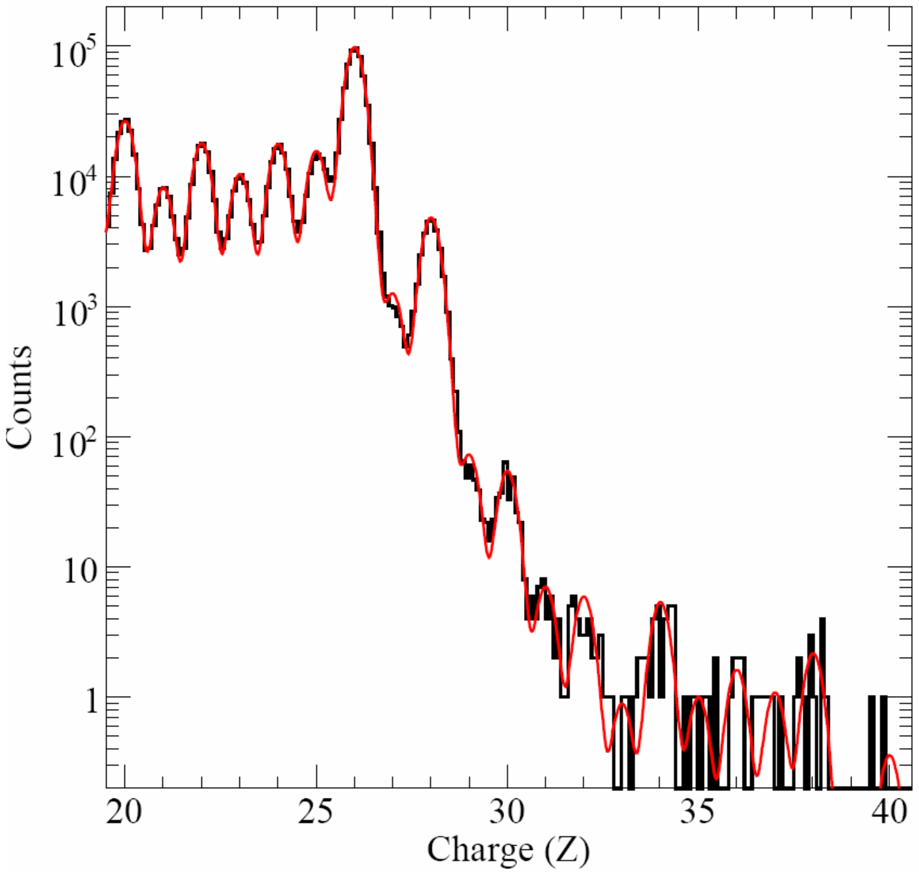
About 12% of oxygen is expected to be in grains, so the position of O between the two lines is about right.

Conclusions

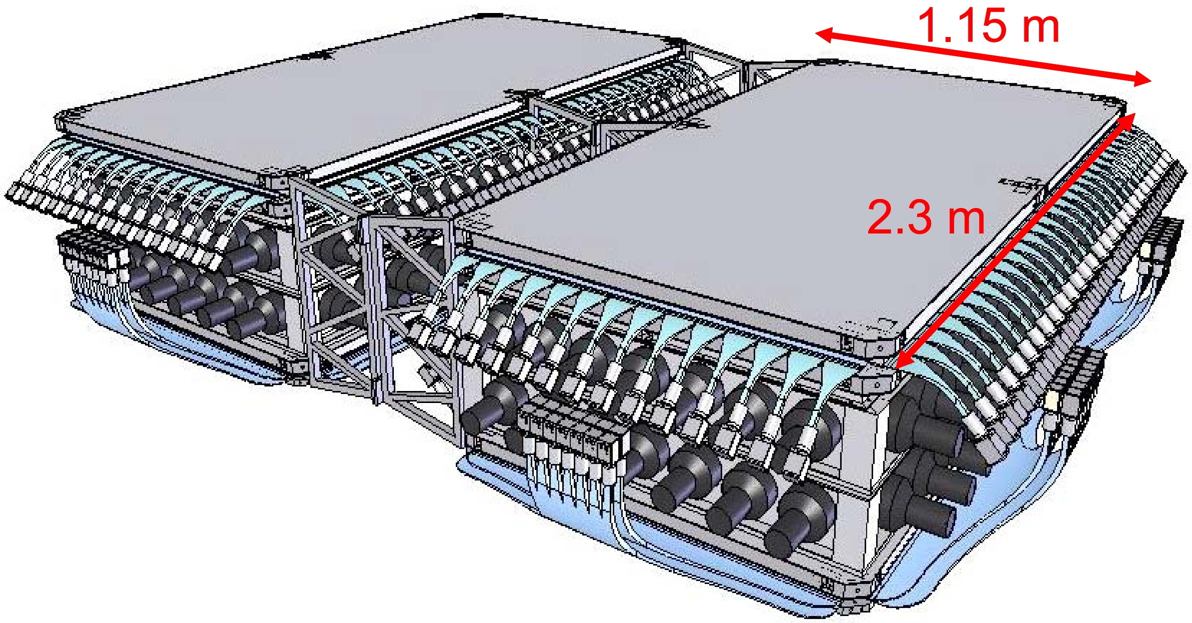
- Cosmic rays come from the core of super-bubbles, where OB associations enrich the interstellar medium with the outflow of massive stars (Wolf-Rayet phase and Supernovae).
  - Conclusion is supported by the isotopic composition for $Z < 30$ and by the elemental composition for $Z \geq 26$.
- The CR acceleration process favors elements found in interstellar dust grains.
- Both the acceleration of volatile and of refractory elements appear to have a mass-dependence $\sim A^n$.
  - $n \sim 2/3$ for refractory elements
  - $n \sim 1$ for volatile elements

Next step beyond TIGER: Improve statistics and determine more elements

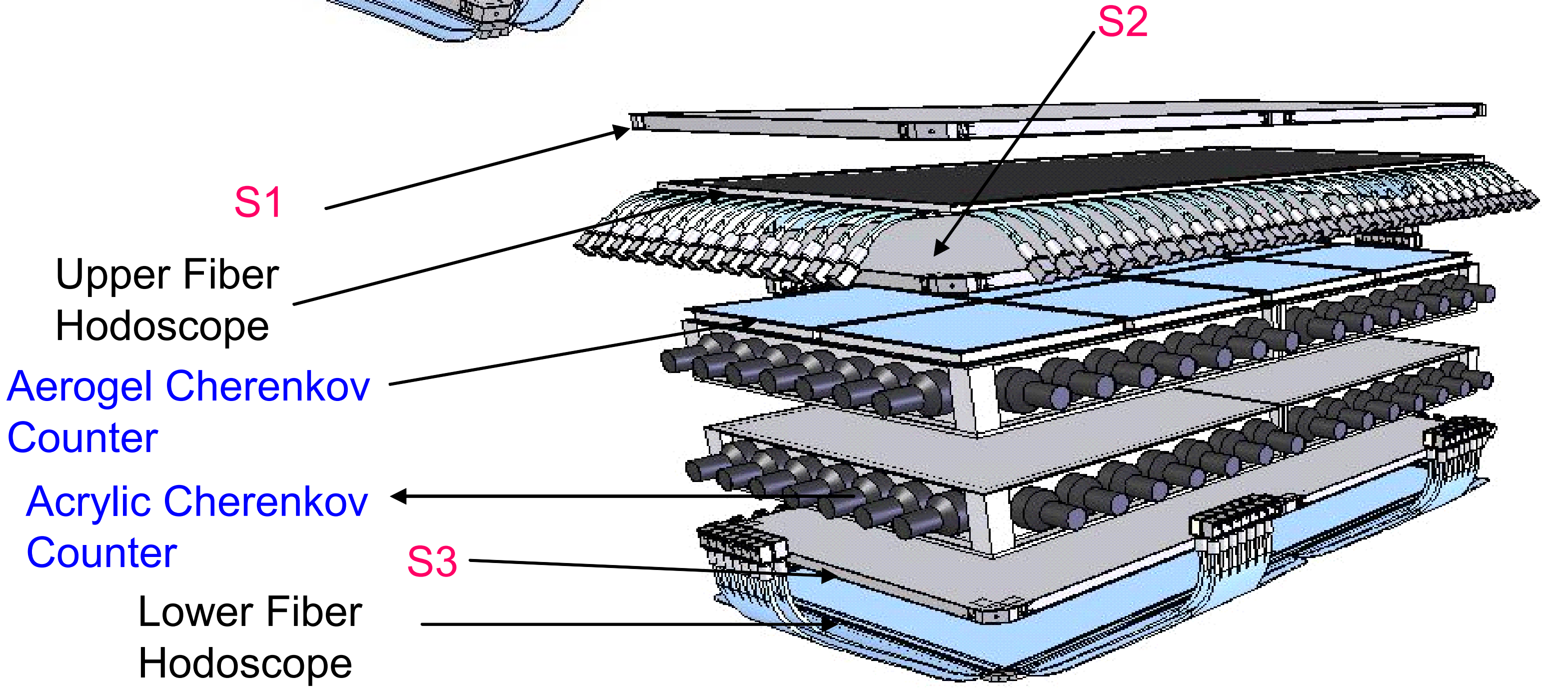




Super-TIGER Instrument



Funded for development and first balloon flight in December 2012.



In an advanced mission concept study:

ENTICE (one of two instruments on OASIS).

With three years in polar orbit would detect at least 100 cosmic-ray actinides.

Numbers of Events