Probing Galactic Cosmic Ray Origins with the SuperTIGER LDB Instrument

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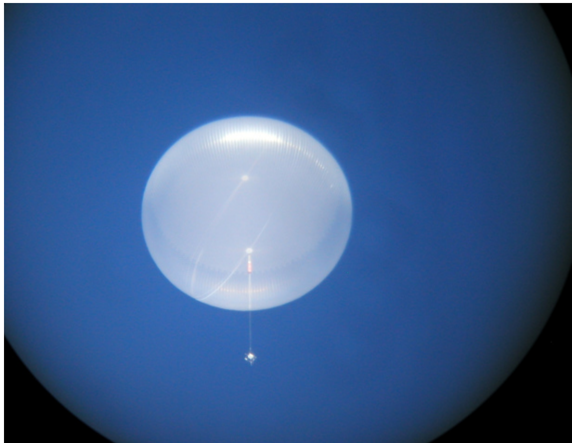


SUPER TIGER
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Goal: Understand Source of GCRs

- Cosmic ray composition measurements point to an OB association origin of GCRs (Higdon & Lingenfelter ApJ 2003, Binns et al. ApJ 2005, and Rauch et al. ApJ 2009)
  - Acceleration occurs in core-collapse SNRs and probably also in the superbubble
- γ-ray measurements (Fermi, Veritas, HESS) point to SNRs, mostly remnants of core-collapse SNe, as at least part of the acceleration source of hadrons.
  - ~85% of SNe are core-collapse type (van den Bergh & McClure APJ 1994) and most of these occur in OB associations
  - SNRs IC443 and W44—both are core-collapse SNRs and IC443 is a member of the Gem OB-1 association (Ackermann et al. Science 339 (2013) 807).
  - Distributed emission of γ-rays with energy 1-100 GeV observed in "cocoon" along line between Cygnus OB2 to NGC 6910 (Ackermann et al. Science 334 (2011) 1103).
- Cosmic and γ-ray measurements are complementary
- SuperTIGER will provide a strong test of the OB association origin of GCRs

SuperTIGER Science Objectives

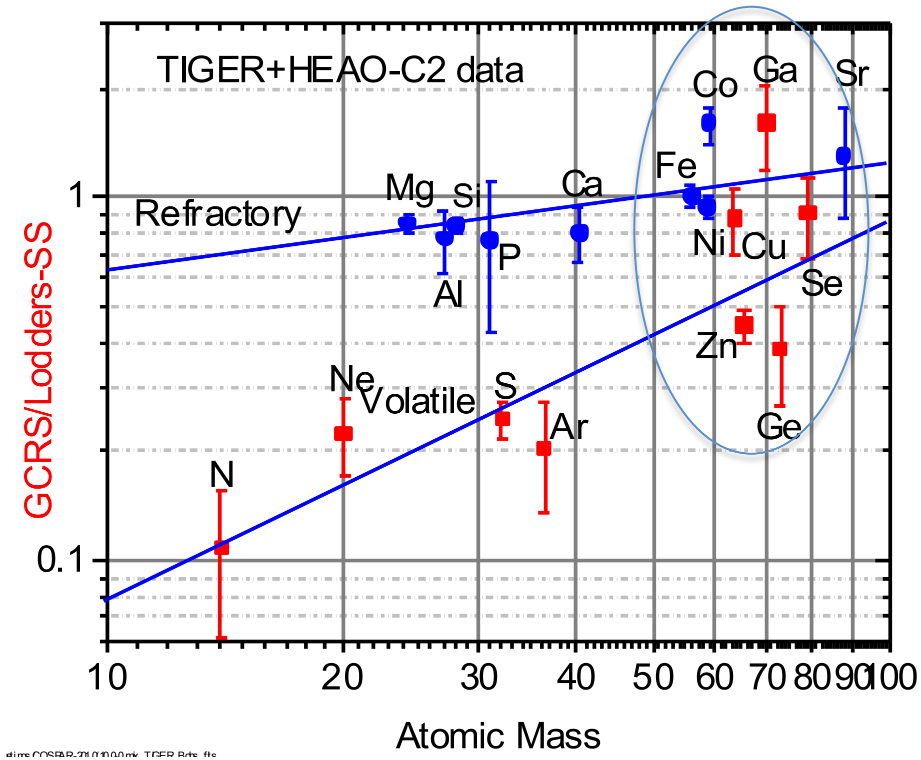
- Primary objective
  - Measure composition of cosmic rays $26 \le Z \le 42$ with good statistics and individual-element resolution and make exploratory measurements to $Z \approx 56$
  - Test of OB-association source model for galactic cosmic rays
  - Test of mass dependence of acceleration
- Secondary objective
  - Energy spectra of elements $10 \le Z \le 28$ 0.3-10 GeV/nuc
  - Search for evidence of nearby microquasars

30 Doradus in LMC

Credit: NASA, ESA,F. Paresce (INAF-IASF), R. O'Connell (U. Virginia), & the HST WFC3HST Science Oversight Committee

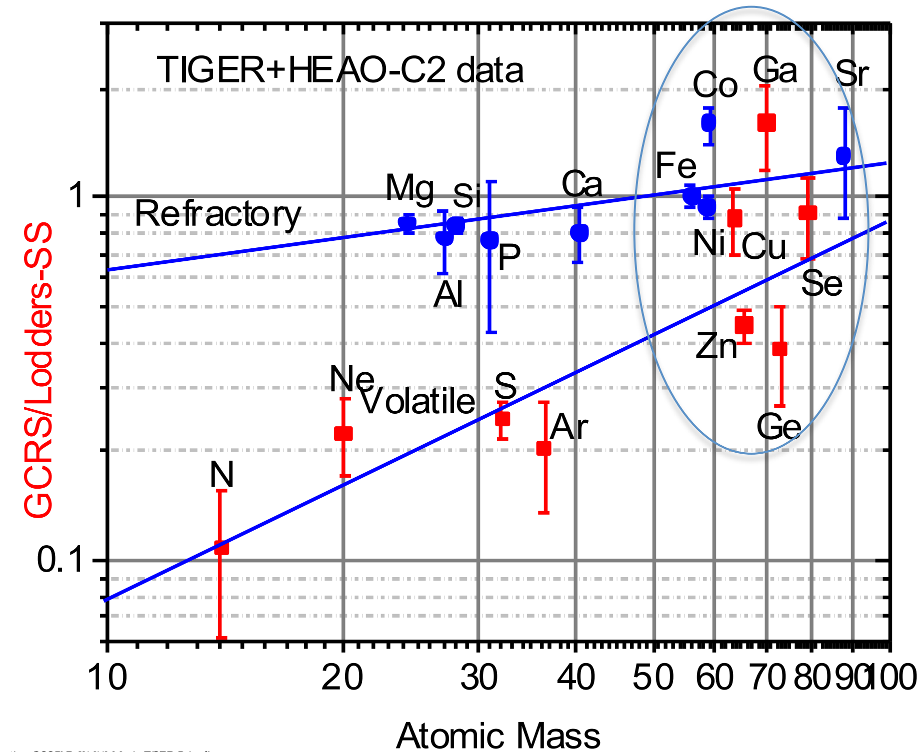
N44 Superbubble in LMC--Credit:Gemini Obs, AURA, NSF

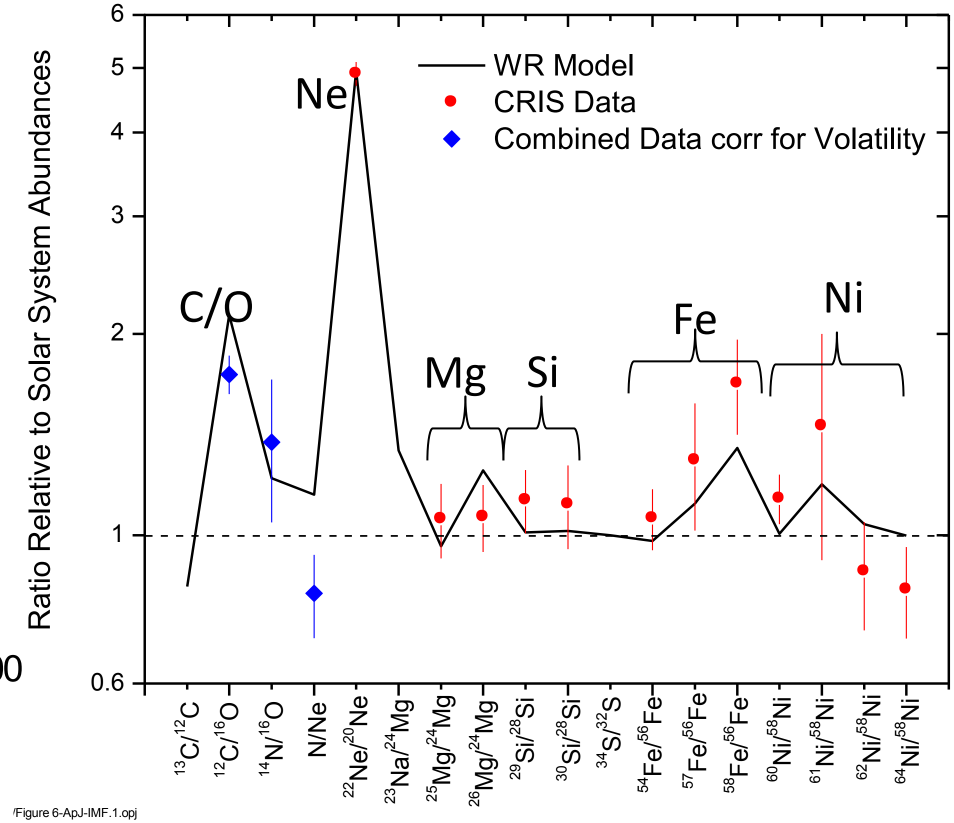
Refractory and Volatile Elements—TIGER and ACE measurements



- Meyer, Drury & Ellison ApJ. 487 182 (1997)
  - Preferential acceleration of elements found in interstellar grains, and mass-dependent of acceleration of the volatiles.
  - But considerable intermixing of abundances for high-mass elements

Refractory and Volatile Elements— TIGER and ACE measurements





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  - Preferential acceleration of elements found in interstellar grains, and mass-dependent of acceleration of the volatiles.
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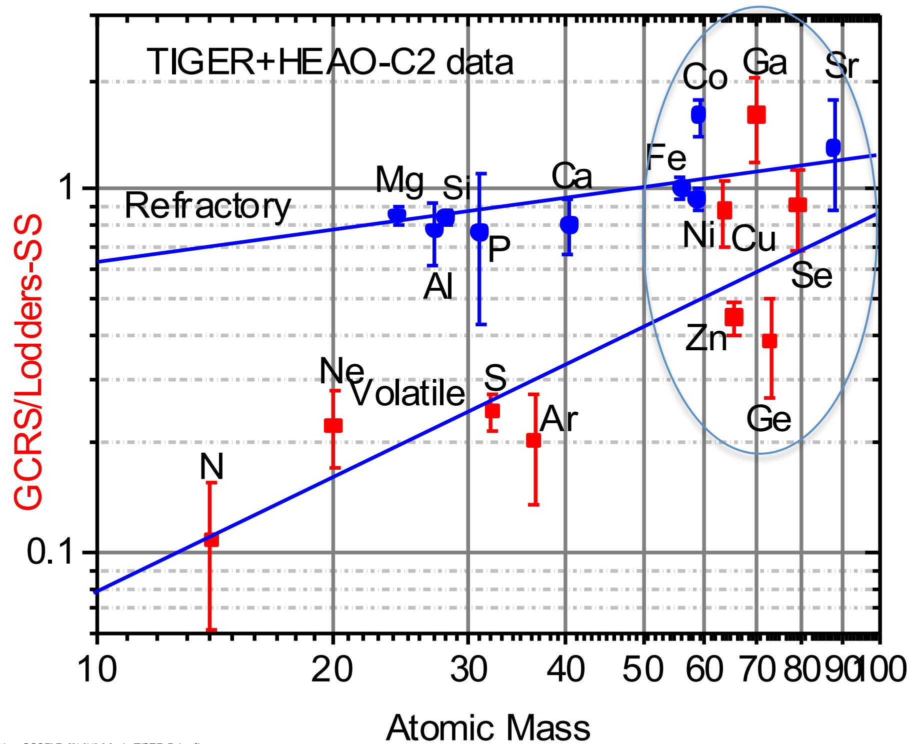
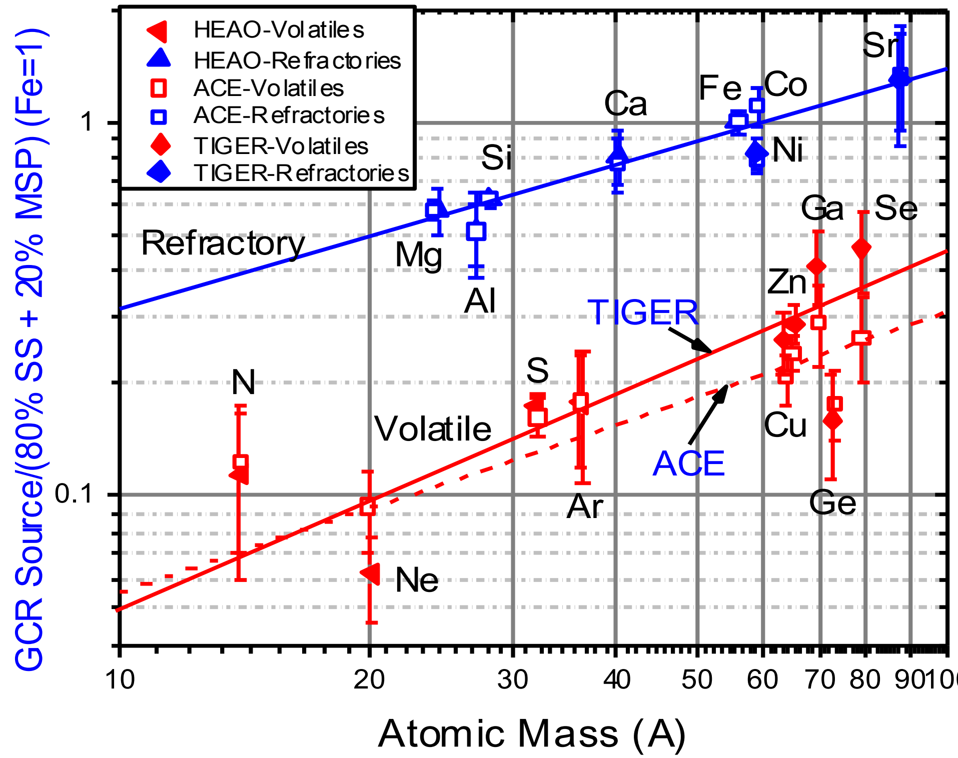
- ACE--$^{22}Ne/^{20}Ne$ ratio matched by mixing ~20% massive star outflow with ~80% normal ISM (Higdon & Lingenfelter 2003; Binns et al. 2005)
- The likely astrophysical site for such a mix is in OB associations

Refractory and Volatile Elements—TIGER and ACE measurements





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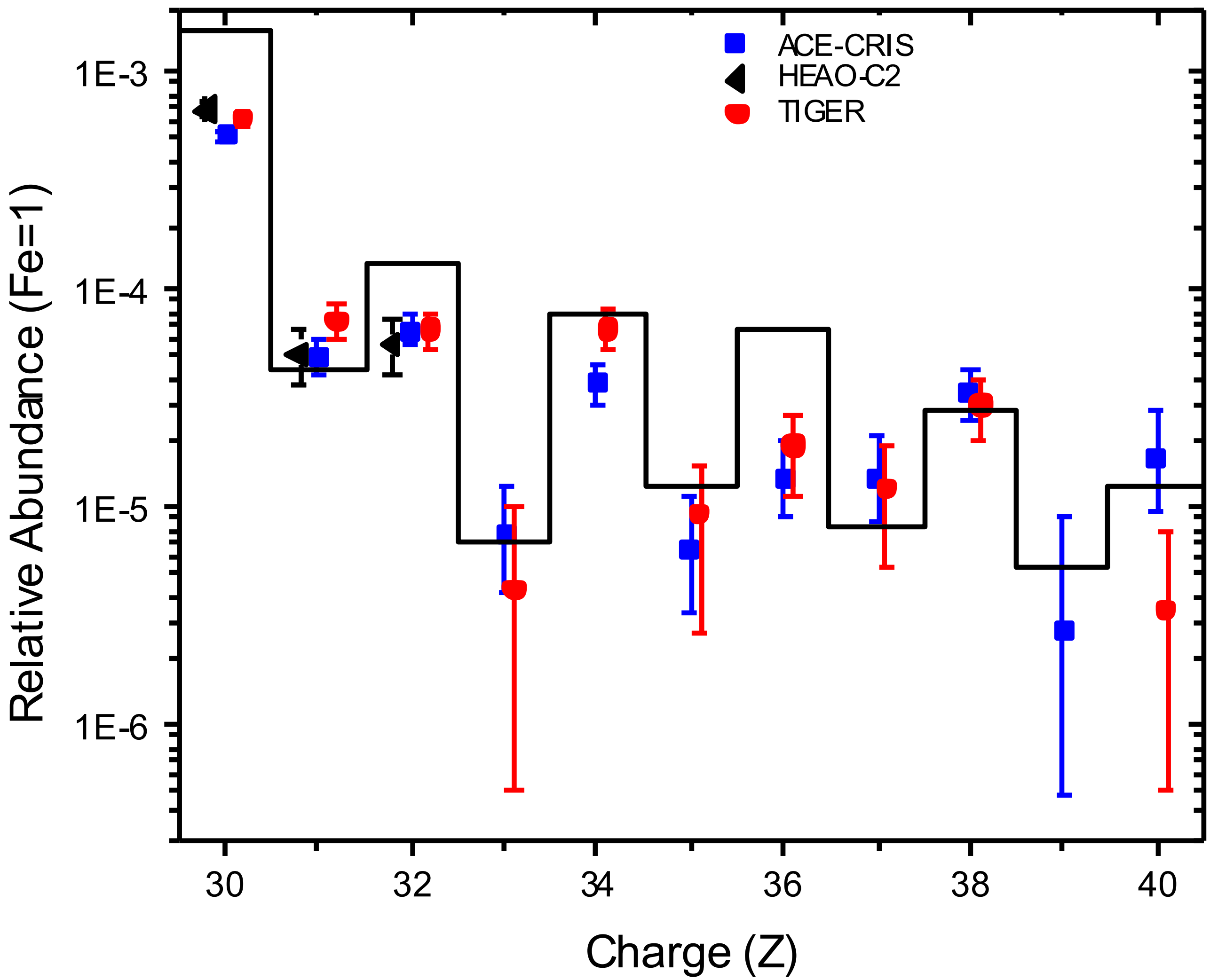
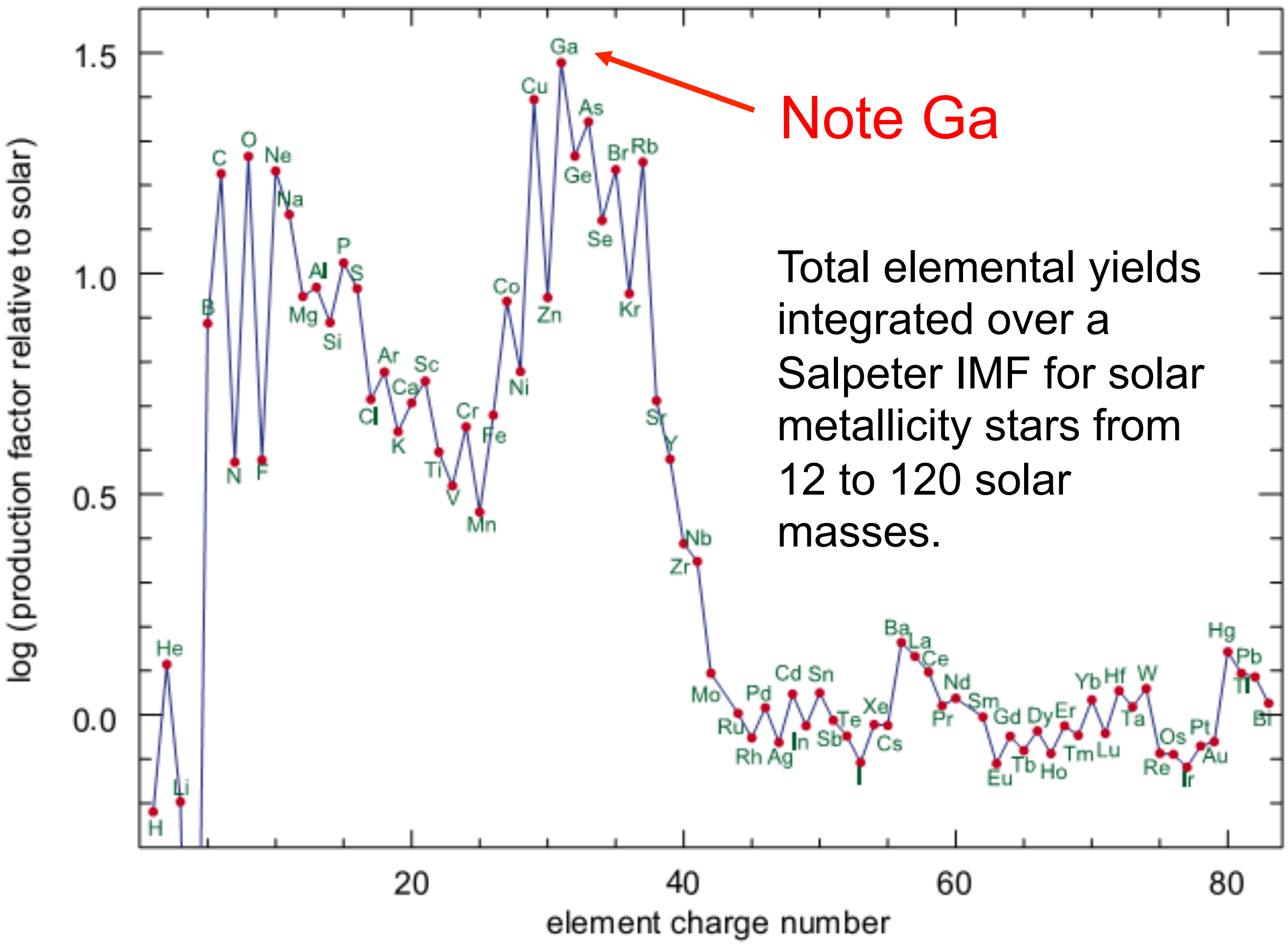
  - Preferential acceleration of elements found in interstellar grains, and mass-dependent of acceleration of the volatiles.
  - But considerable intermixing of abundances for high-mass elements
- Same data (plus ACE-CRIS data)
  - Taking abundances relative to a 20%-80% mix of massive star material (wind outflow plus SN ejecta) and normal ISM organizes data much better than when taken relative to SS abundances.
- Support for OB association origin of GCRs

Measured Element Abundances Compared to SS



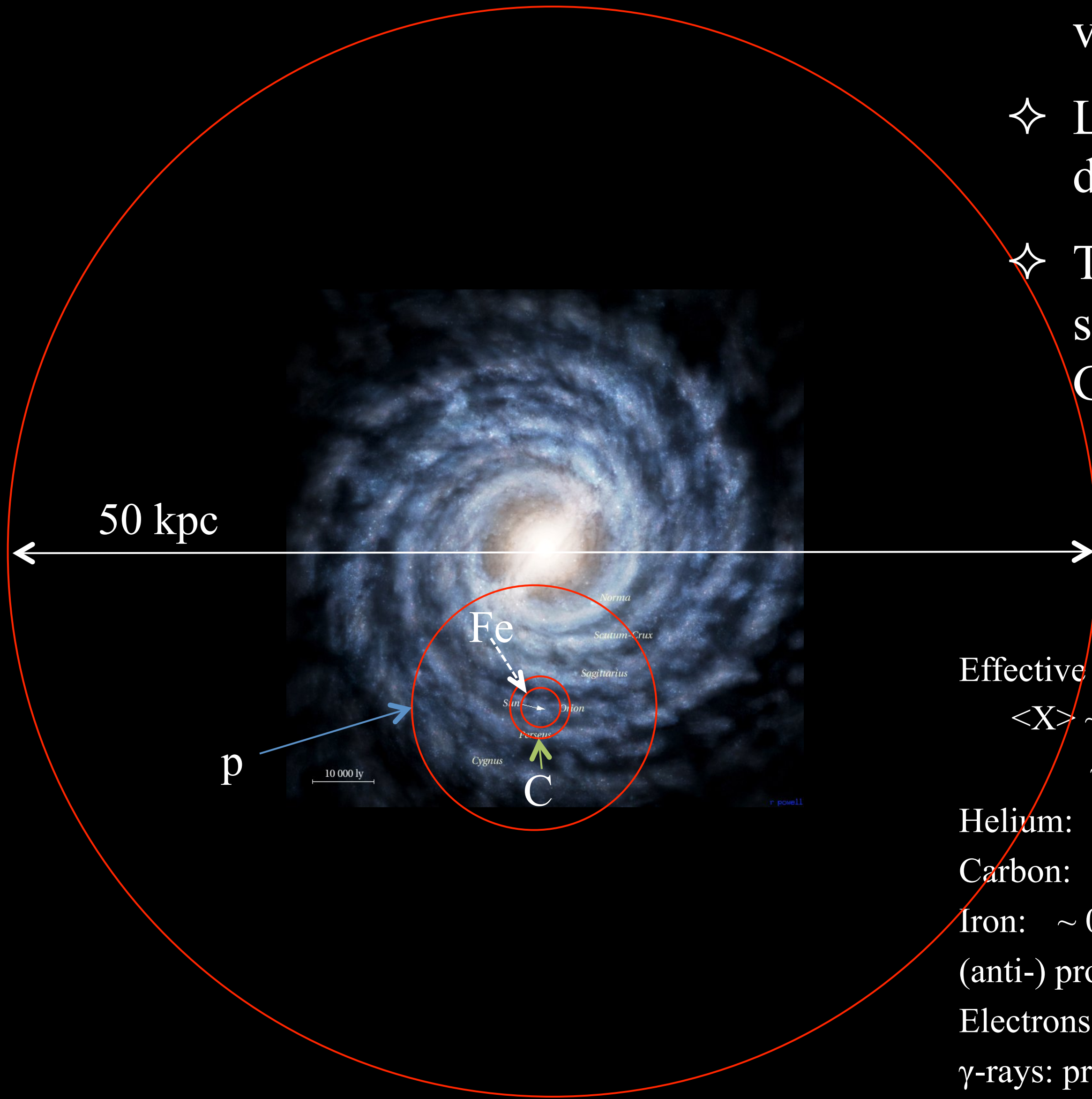
Massive Star Contributions

S.E. Woosley, A. Heger / Physics Reports 442 (2007) 269–283



Total elemental yields integrated over a Salpeter IMF for solar metallicity stars from 12 to 120 solar masses.

Cosmic Ray Sampling of Galaxy



- Direct measurements probe a very small volume of the Galaxy
- Light & heavy nuclei probe different propagation volume
- The propagation distances are shown for nuclei for rigidity ~1 GV

Effective propagation distance:

$\langle X\rangle \sim \sqrt{6D\tau} \sim 4.5\times10^{21}\ R^{1/4}\ (A/12)^{-1/3}$ cm

~ 1.5 kpc $R^{1/4}\ (A/12)^{-1/3}$

Helium: ~ 2.1 kpc $R^{1/4}$

Carbon: ~ 1.5 kpc $R^{1/4}$ - 0.36% of the surface area

Iron: ~ 0.9 kpc $R^{1/4}$ - 0.16%

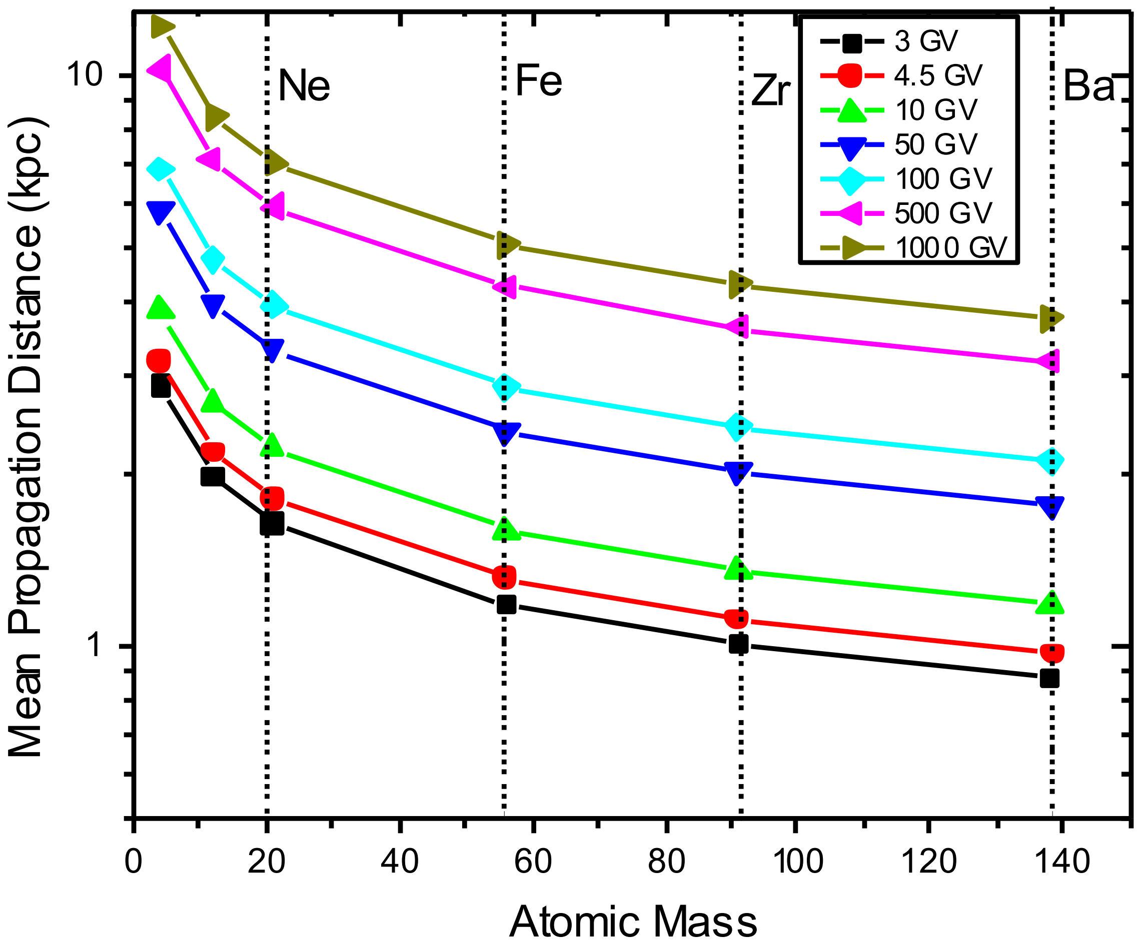
(anti-) protons: ~ 6 kpc $R^{1/4}$ - 5.76%

Electrons ~ 1 kpc $E_{12}^{-1/4}$

γ-rays: probe CR p (pbar) and e± spectra in the whole Galaxy ~50 kpc across

Chart provided by Igor Moskalenko

Propagation Distance as Function of Mass and Rigidity



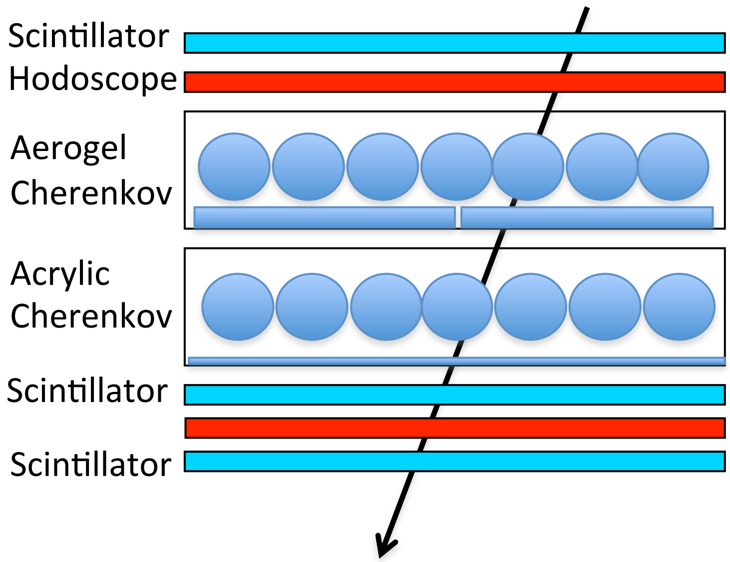
- Mean propagation distance calculated from Moskalenko and Strong model is shown at left.
- Mean propagation distance of SuperTIGER nuclei is of order 1.5 kpc

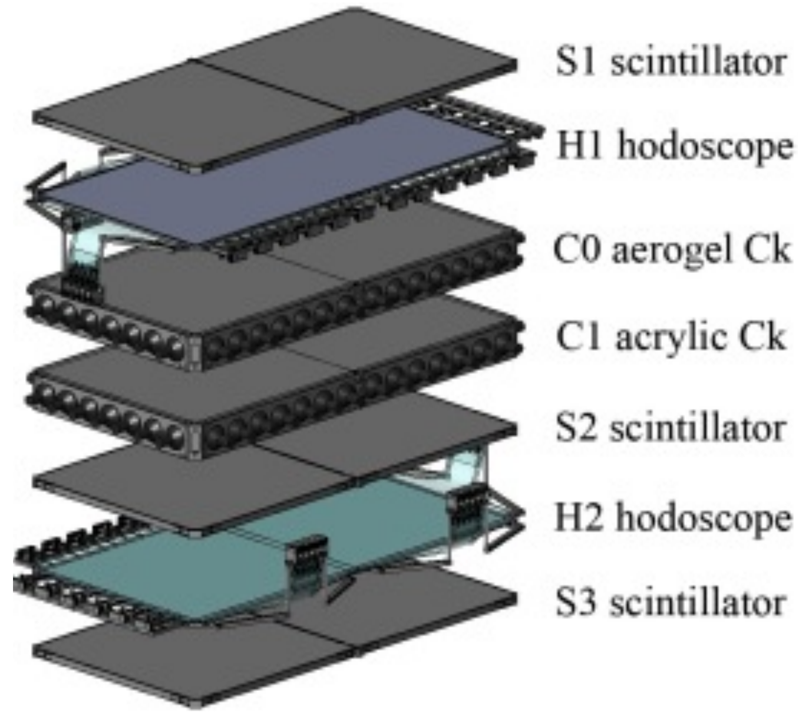
UNTITLED

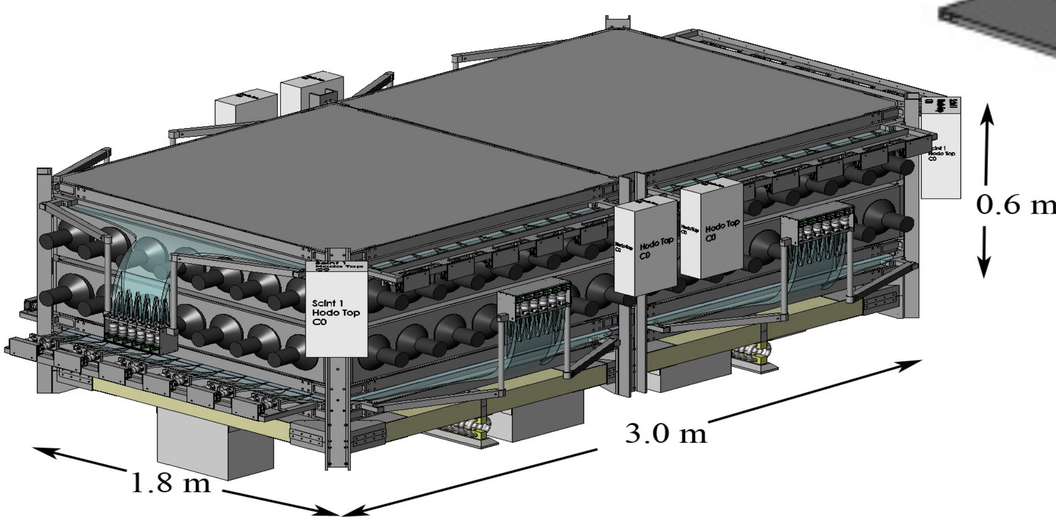
SuperTIGER Design Goals

- Single element resolution with maximum Z measured limited by only by exposure - $\sigma_Z \approx 0.2$ charge units
- Wide electronic dynamic range (design goal $10 \leq Z \leq 60$)
- Proven techniques from TIGER
- As large an instrument as practical to maximize collecting area
- Wide viewing angle to maximize AΩ (~ 60° from zenith)
- Limited nuclear interactions in atmosphere or instrument
  - Light instrument (<1800 kg) to fly on a 1.11 Mcm (40 Mcf) light balloon for maximum altitude
  - Materials chosen to minimize column density of the instrument
- High degree of reliability for long flights
- Redundancy for "graceful degradation"
- Fast assembly in the field
- Recovery using any available aircraft (Twin Otter or Basler) with minimal damage

The SuperTIGER Instrument





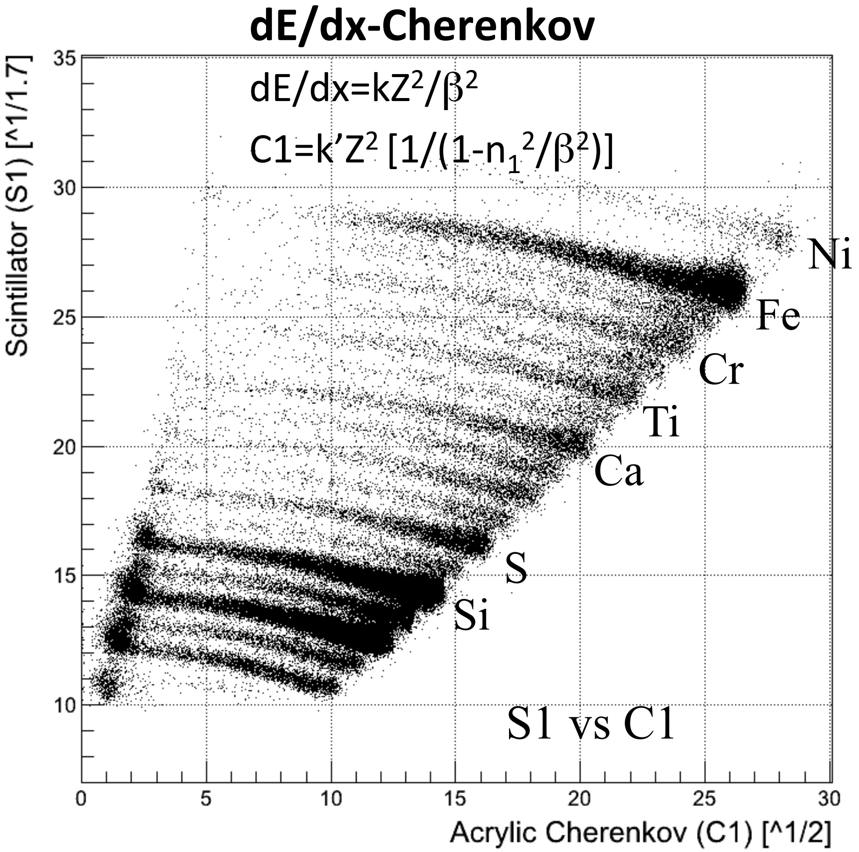


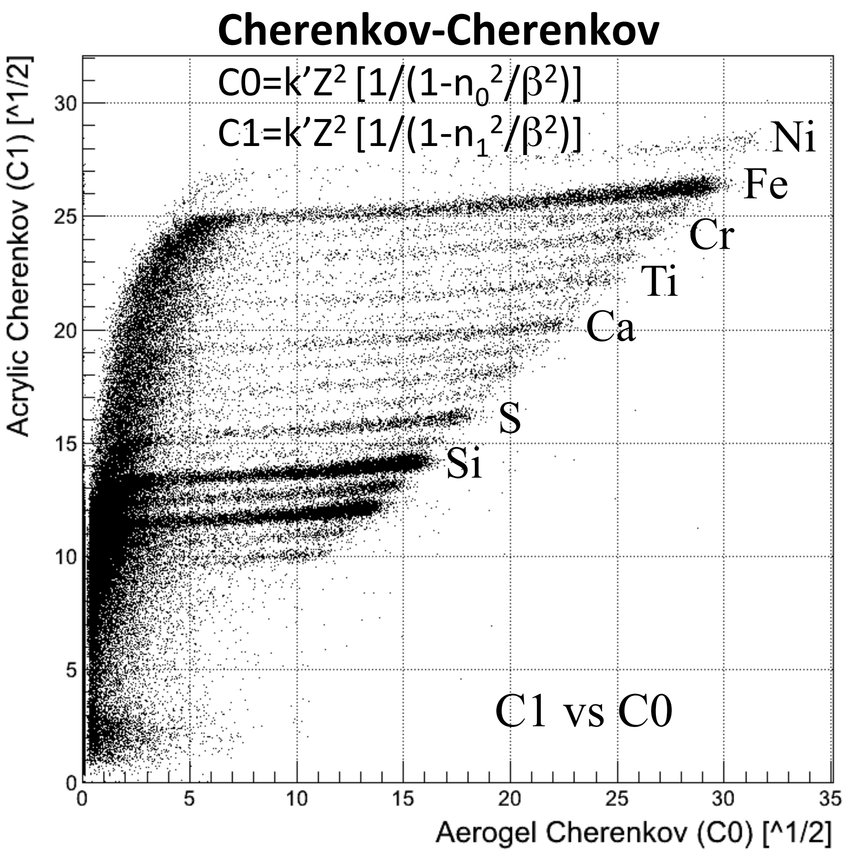
- Two nearly identical modules
- Each module is about the size of two TIGER instruments.
- Single Module Mass—660 kg (1452 lb)

Charge Identification Methods

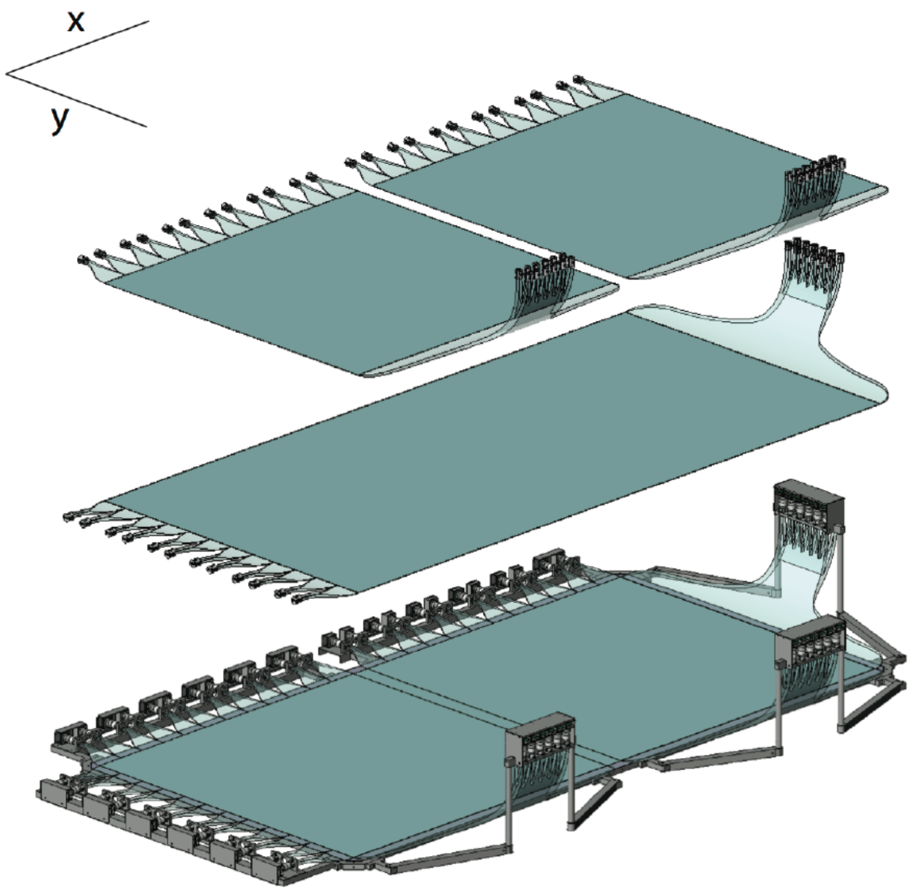
Energy ≤ 2.5 GeV/nucleon (aerogel threshold) ➔ dE/dx vs. Acrylic Cherenkov

Energy >2.5 GeV/nucleon ➔ Acrylic Cherenkov (C1) vs. Aerogel Cherenkov (C0)



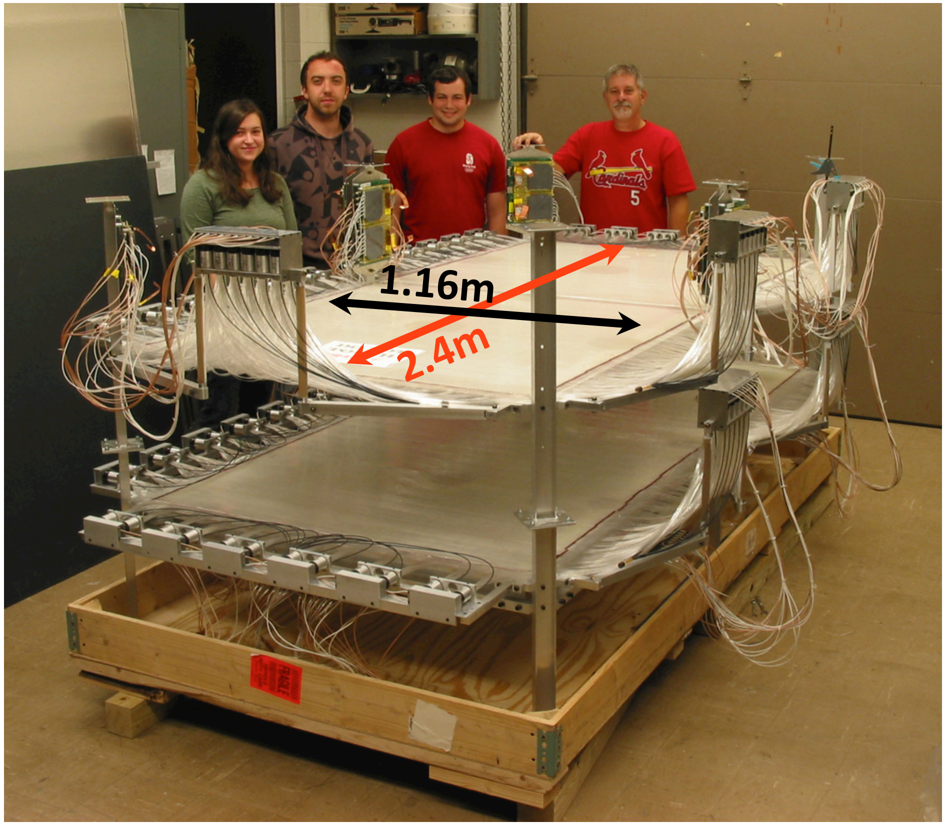


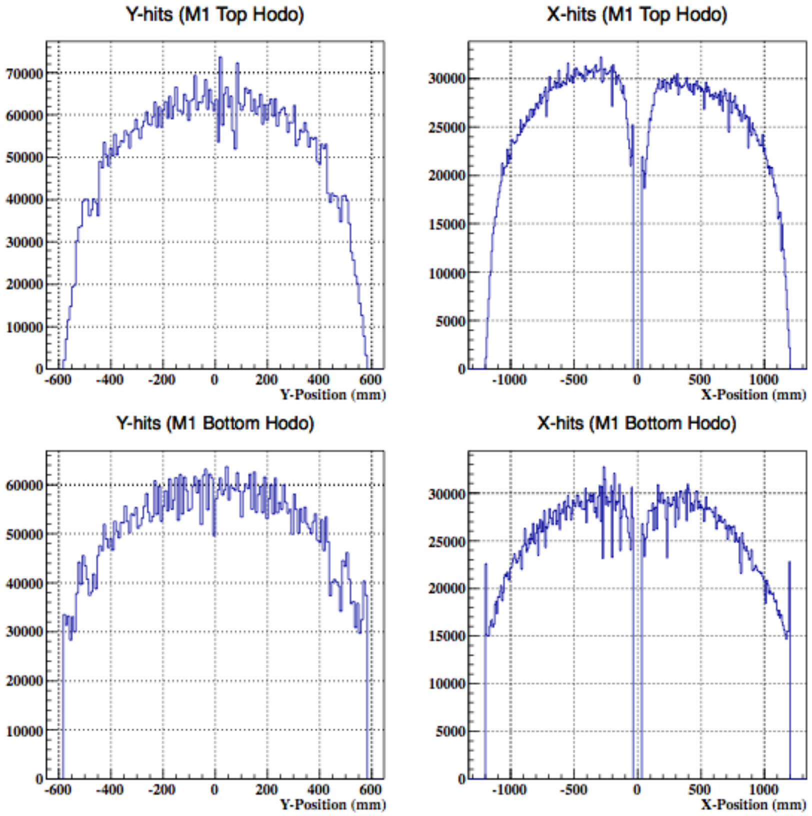
Hodoscope



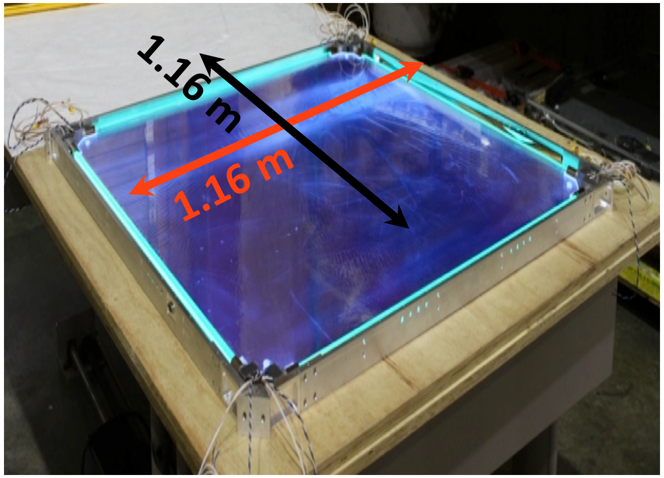
- Two hodoscope planes in each module.
- Each plane consists of one "long" hodoscope layer (length 2.4m, width 1.16m) providing a "y" direction and a "short" hodoscope layer of two subsections (length and width 1.16m) providing a "x" direction. Y layer and each X subsection consist of 144 fibers.
- Coded readout to reduce number of PMTs and readout channels needed
- 144 fibers can be read out by 24 PMTs - 12 coarse (groups of 12 adjacent fibers) and 12 fine (sequentially routed, one from each coarse group)

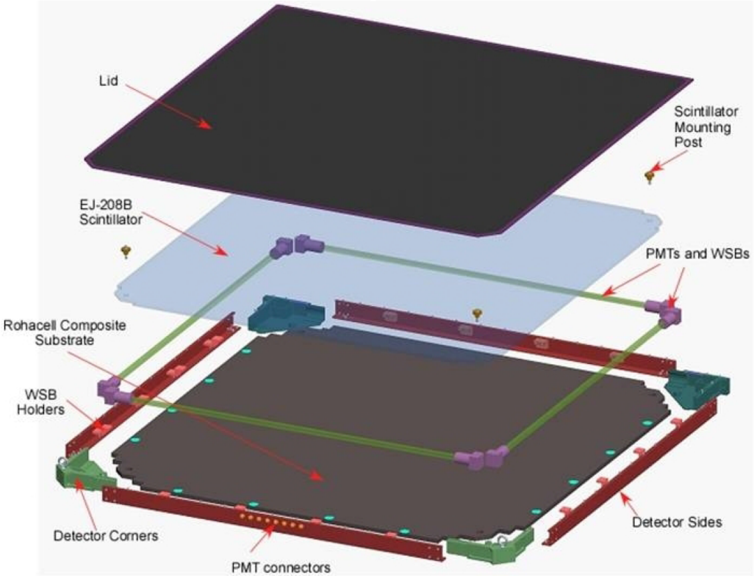
Hodoscope


1.16m
2.4m


Y-hits (M1 Top Hodo)
X-hits (M1 Top Hodo)
Y-hits (M1 Bottom Hodo)
X-hits (M1 Bottom Hodo)
Y-Position (mm)
X-Position (mm)

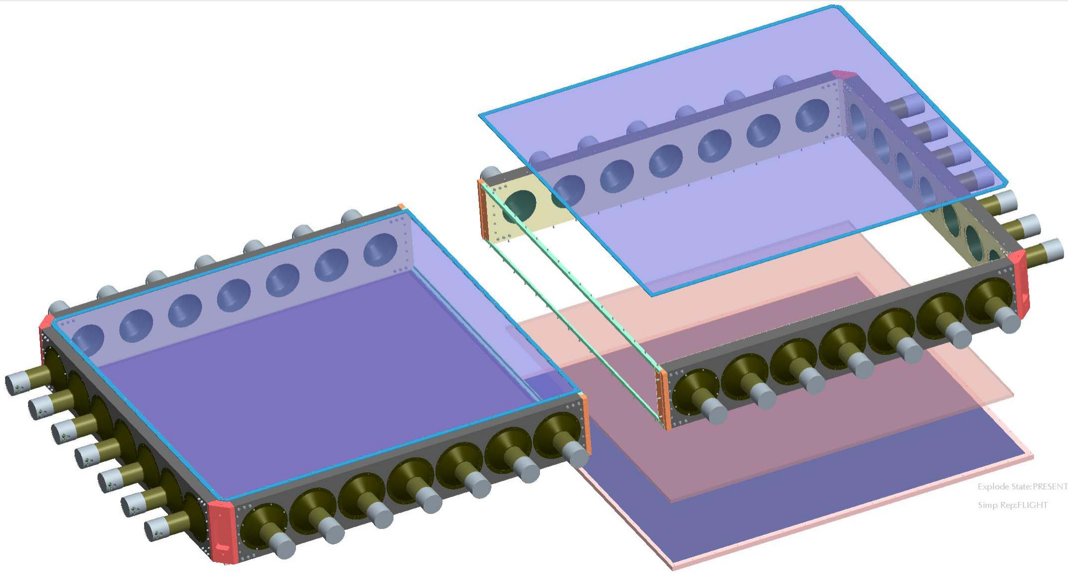
Scintillation Detectors

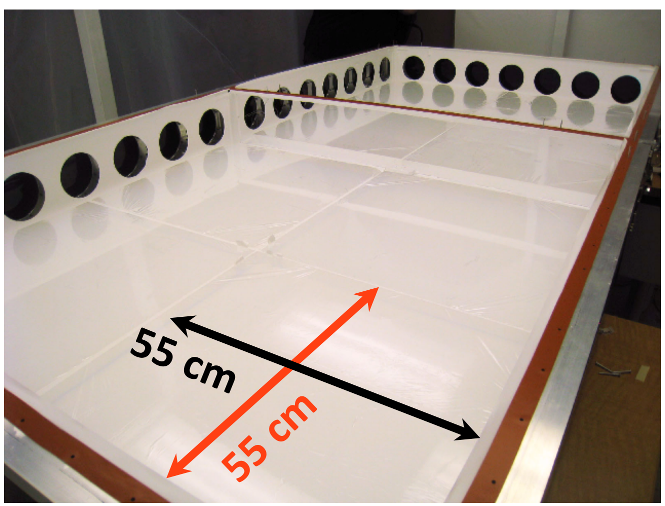




- Each module has three layers of scintillator.
- Each layer has two optically separate subsections to facilitate recovery.
- 1.16 m x 1.16 m x 1cm EJ-208B plastic scintillator – the largest pieces that could be successfully cast. Selected for thickness uniformity and thickness variation gradient.
- EJ-280 green wavelength-shifter bars air coupled to edges of scintillator
- Read out by Hamamatsu R1924A (1 inch diameter) PMT
- Enclosures use thin 0.1 mm Al top windows and floors of Al/foam composite to reduce interactions. (Also used in Cherenkov detectors and for hodoscope supports.)

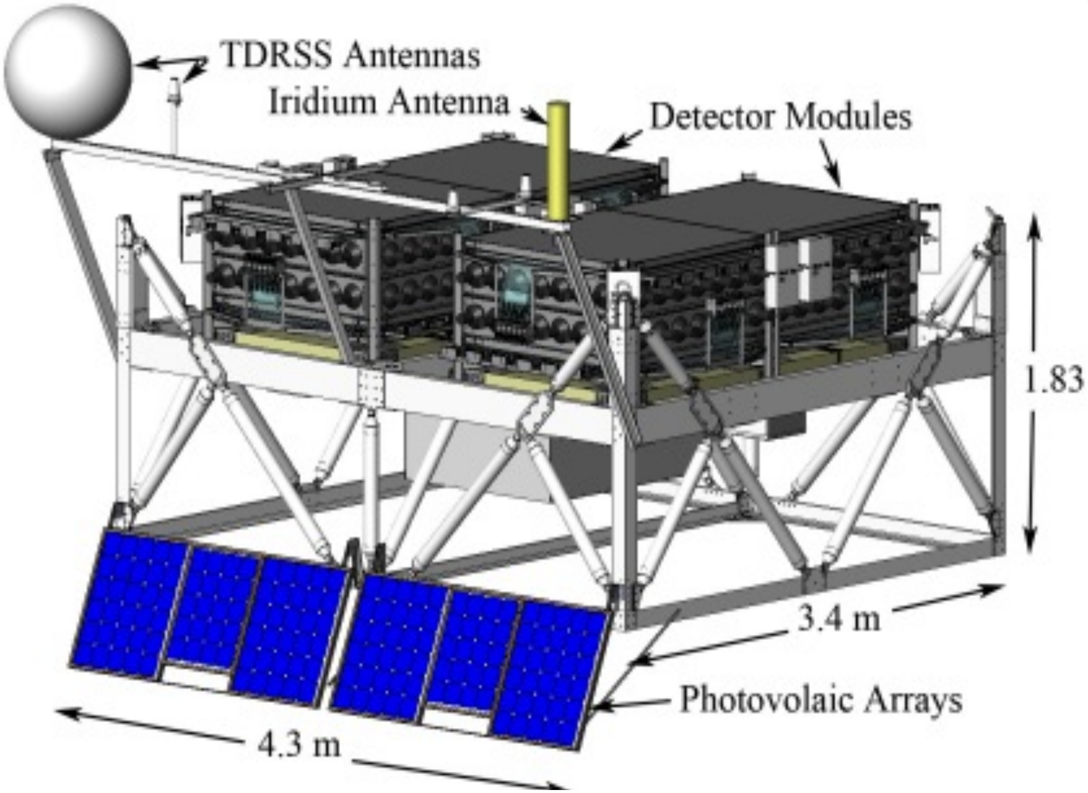
Cherenkov Detectors

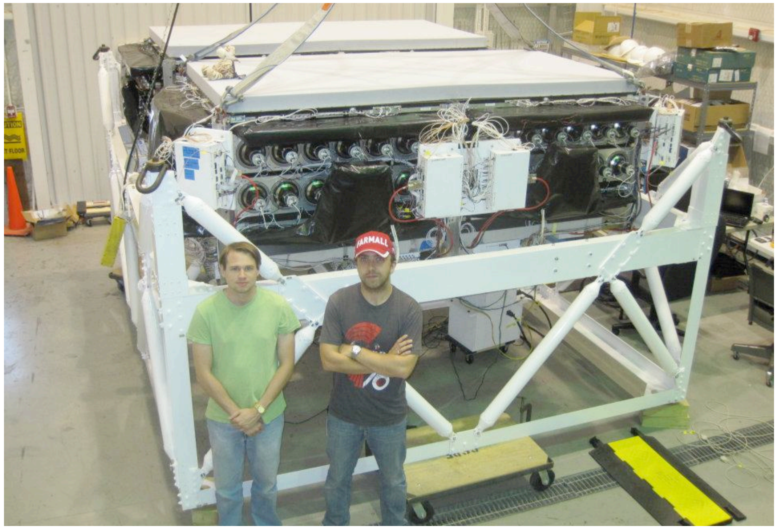




- Configuration
  - Light integration volumes lined with Gore-Tex reflector
  - Each read out by 42 Hamamatsu R877-100 PMTs (5 inch diameter)
  - Common optical volume, but separable sections for recovery
- Aerogel Cherenkov Detector (C0)
  - Each C0 module contains eight aerogel blocks, each approximately 55cm x 55cm x 3cm.
  - Three of the four half-modules contain aerogel blocks with n = 1.043 (12 blocks) and one half-module contains n = 1.025 (4 blocks).
- Acrylic Cherenkov Detector (C1)
  - Each C1 module contains two acrylic radiators 1.16 m x 1.16 m with index n = 1.49

The SuperTIGER Instrument





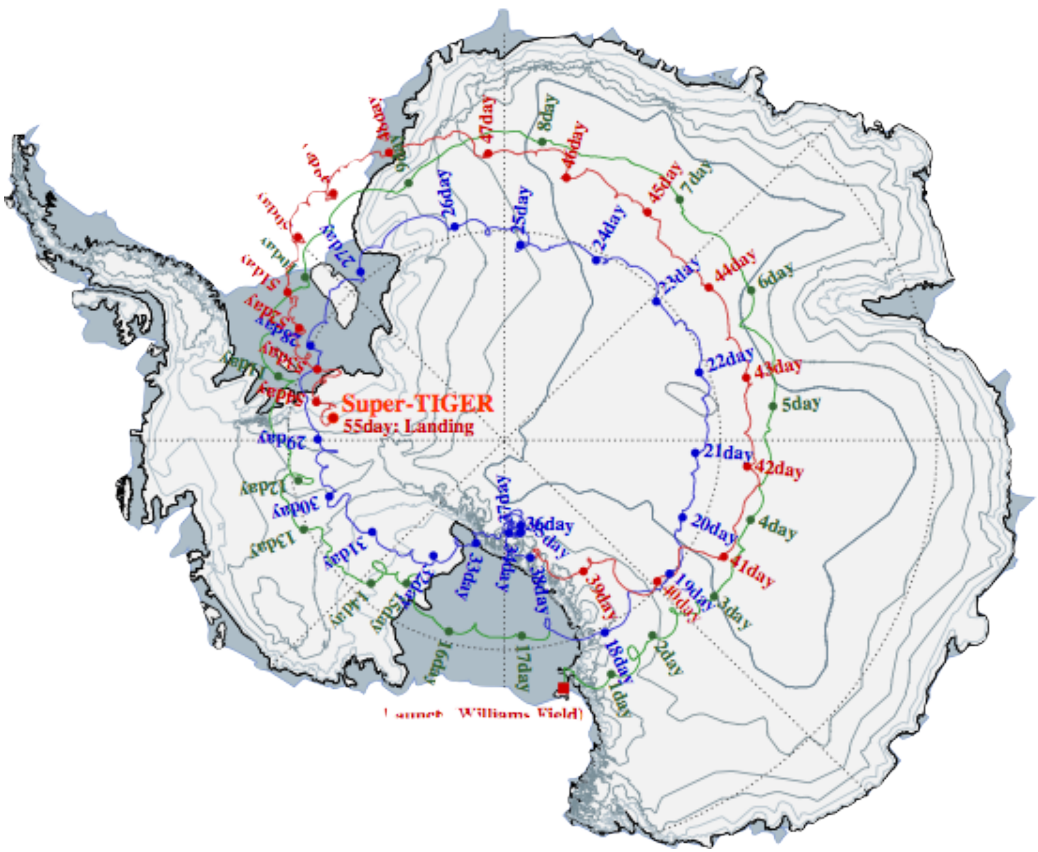
- Active area 5.4 m^2
- Effective geometry factor (including interactions) at $_{34}$Se 2.5 m^2sr (6.4 times TIGER - 0.4 m^2sr).
- Full Instrument + Gondola Mass—1770 kg
- Power—250 Watts

Launch day

SuperTIGER Launch

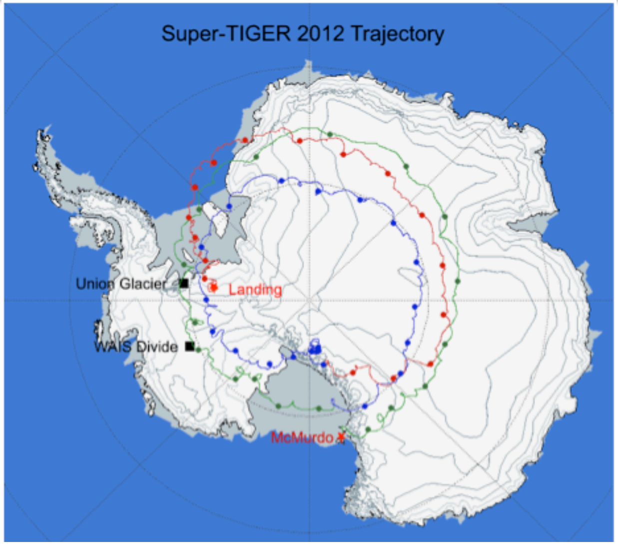
Liftoff at 09:45 am NZDT Dec 9th, 2012—A perfect launch day!!

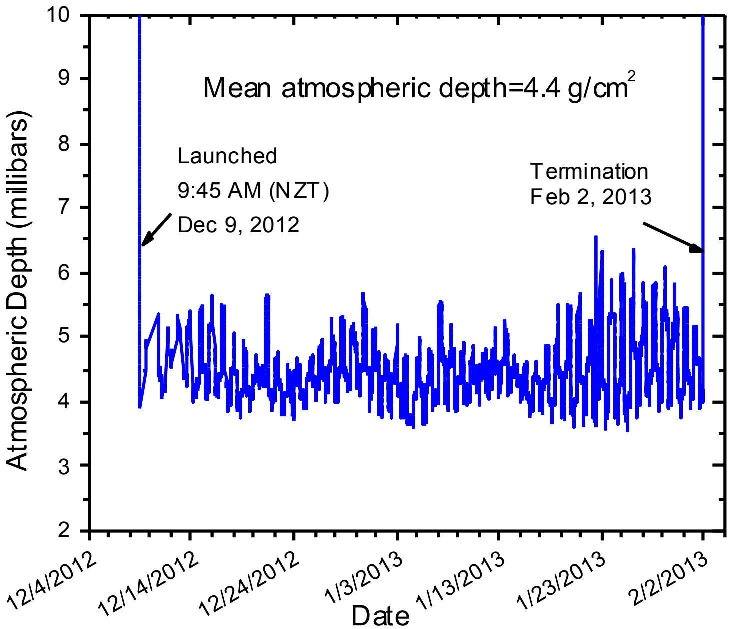
SuperTIGER Flight



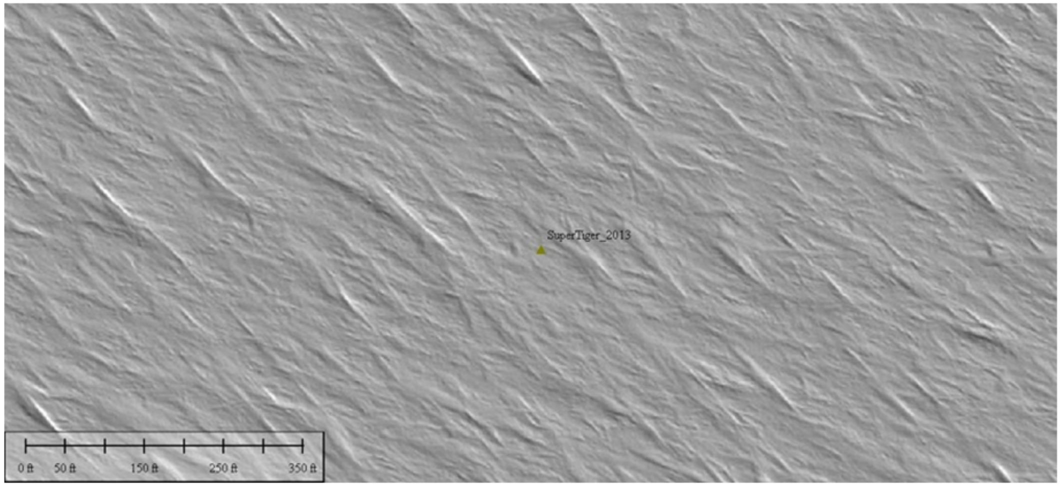
- SuperTIGER was launched on Dec 08, 2012, 20:45 GMT.
- Reached float altitude (>35km) on Dec 09, 2012, 00:12 GMT
- The instrument collected data until Feb 01, 2013 20:58 GMT
- The SuperTIGER instrument could not be recovered in 2012/2013 season. This is planned for 2013/2014

SuperTIGER Flight





- SuperTIGER flew for 55 days, 1 hour, and 34 minutes.
- Failure of on-board solid state disks resulted in 44 equivalent days of data
- Record long-duration balloon (LDB) Flight for Heavy-Lift Balloon
  - Previous Record: CREAM I ~42 days
  - NASA Super Pressure Balloon Test ~54 days
- Super-TIGER coordinates 82°14.80’ S, 81°54.72’ W.

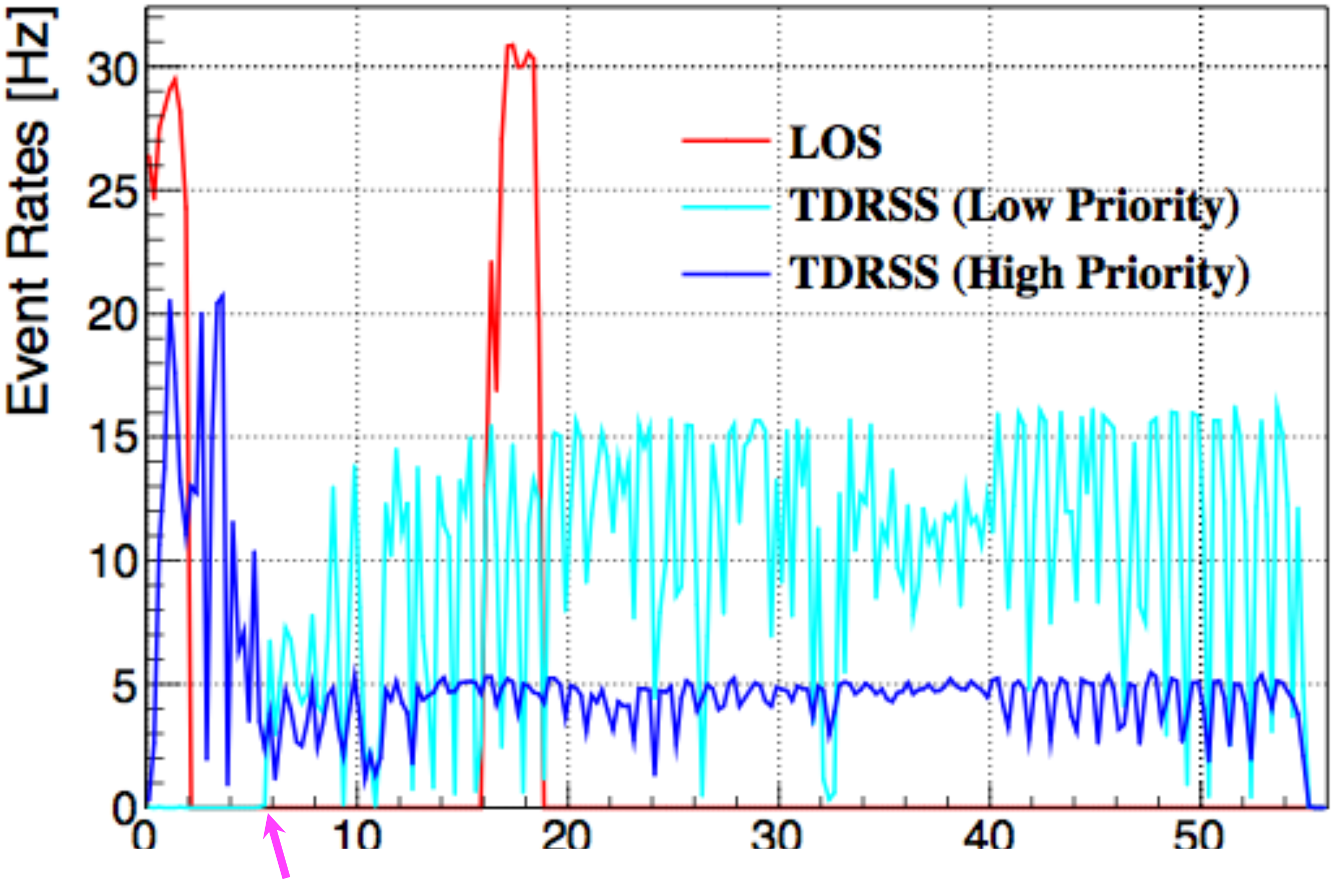


Data Transmission

- TDRSS
  - Available during the entire flight duration.
  - Transfer compressed instrument data.
  - 67,730,679 events between Dec 09, 2012 00:12 and Feb 01, 2013 20:58 GMT at the float altitude (>35km)
- Line-of-sight (LOS)
  - Available while the balloon was near the launch site.
  - Transfer full instrument data.
  - 4,528,063 events between Dec 09, 2012 00:12 and Dec 10, 2012 21:01 GMT and 6,068,108 events between Dec 24, 2012 23:50 and Dec 27, 2012 12:59 GMT at the float altitude (> 35km)
- Overall event transmission efficiency 83% for high priority events

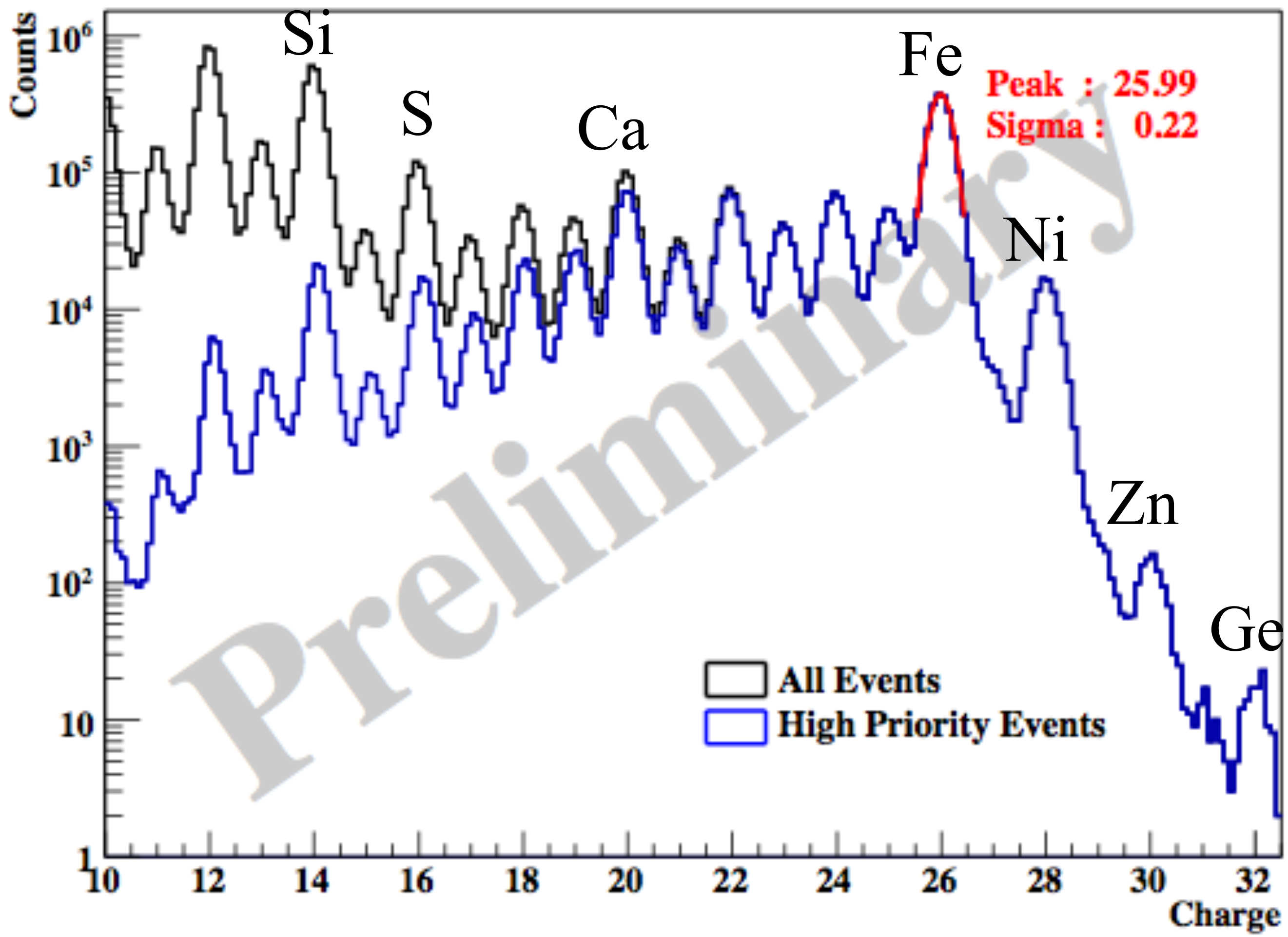
Event Rates

83% of High Priority events were recorded.



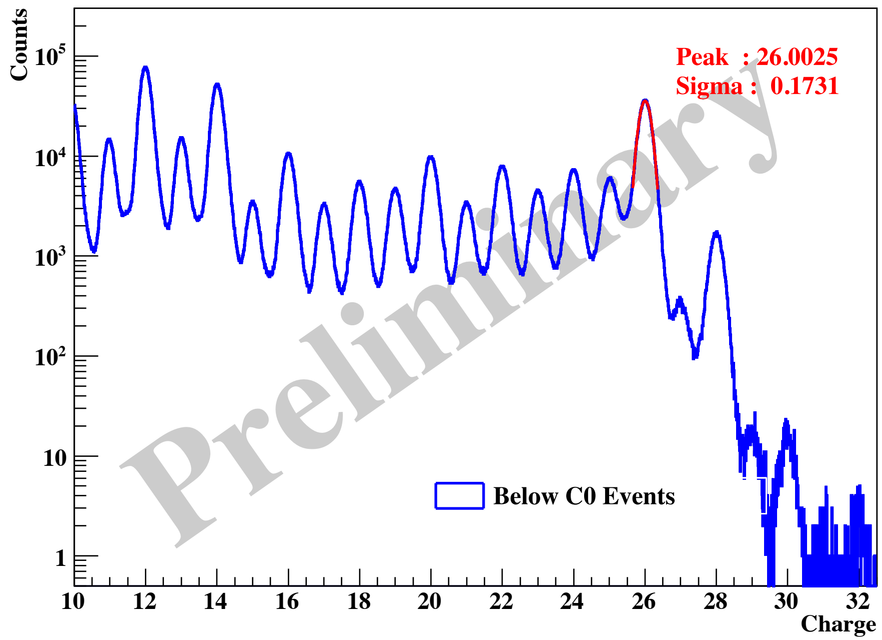
Set priority threshold (Z >=22)

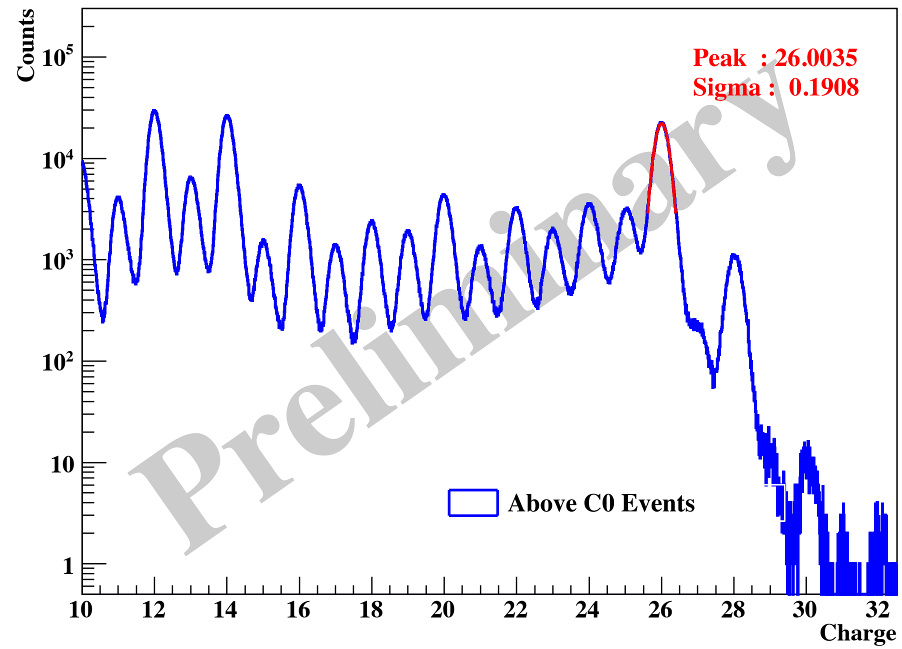
Preliminary Results



Charge histogram (not final charge resolution) showing agreement between "High Priority" and "All Event" datasets.

Preliminary Results

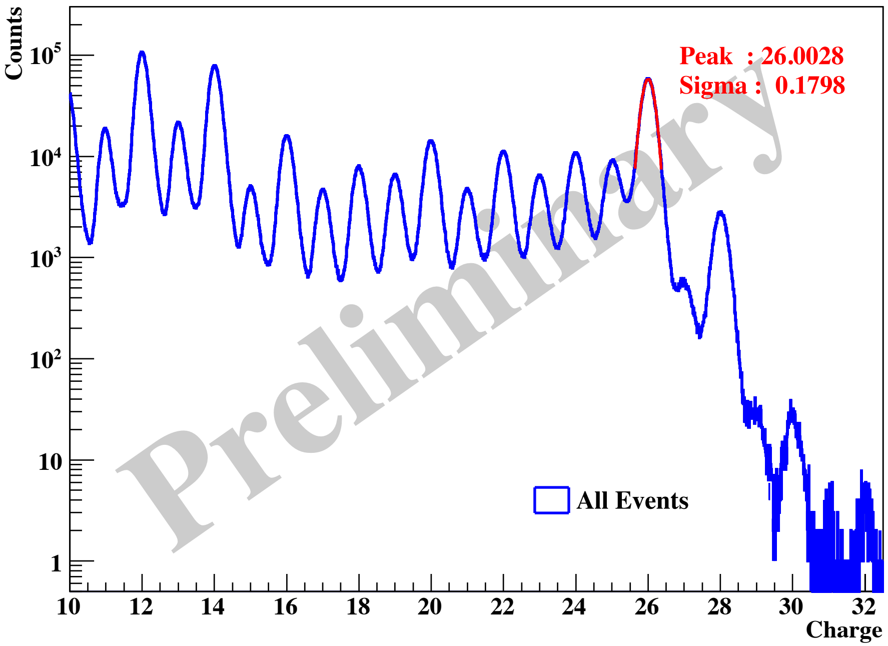


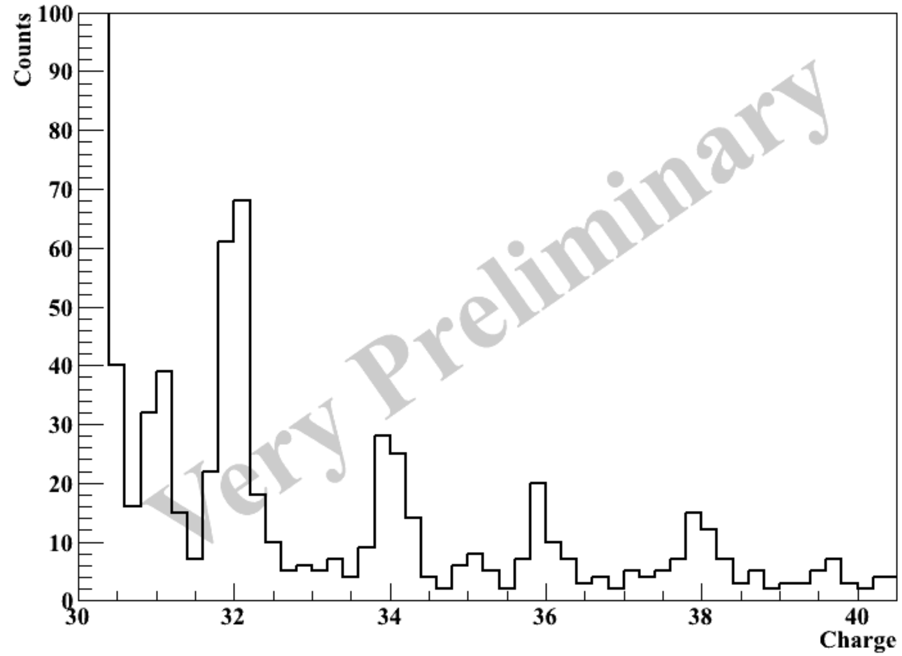


- Events below aerogel threshold
- dE/dX from scintillators S1 and S2 with velocity correction from acrylic Cherenkov C1
- Interacted events removed using scintillator S3
- σ_Z = 0.173 charge units at Fe

- Events above aerogel threshold
- Acrylic Cherenkov C1 signal with velocity correction from C0
- dE/dX from S1 and S2 with velocity correction from C1
- Interacted events removed
- σ_Z = 0.191 charge units at Fe

Preliminary Results



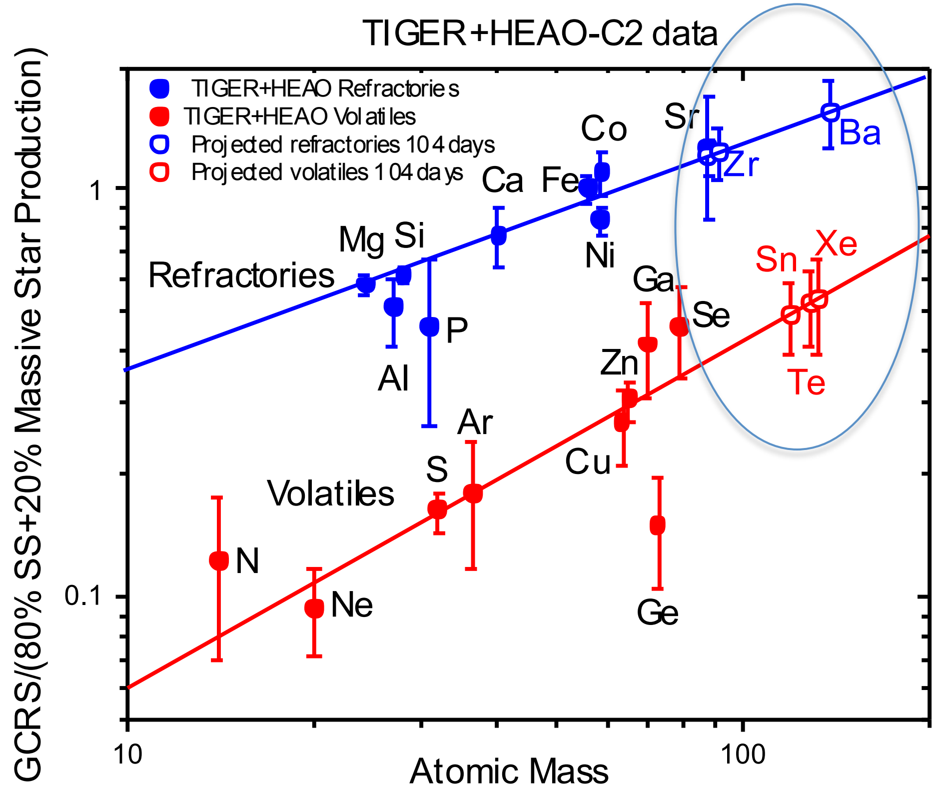


- All events
- σ_Z = 0.18 charge units at Fe (compare to 0.23 reported by TIGER)

- Events with Z > 30
- Resolution is expected to improve with better models of velocity and charge dependent scintillator saturation

Expected SuperTIGER Results

- The first Super-TIGER flight has increased statistics > factor of 4 over TIGER
  - $_{30}$Zn, $_{31}$Ga, $_{32}$Ge, $_{34}$Se, and $_{38}$Sr statistical uncertainties will be reduced by more than 2×
  - Will have sufficient statistics to add data points for $_{36}$Kr (highly-vol), $_{37}$Rb (mod-vol), and $_{40}$Zr (refr)
- On the right, we show the TIGER +HEAO data points plus estimated error bars for heavier elements <u>assuming</u> that, in addition to the 44 days of Super-TIGER flight in-hand, we get another 60 days from future flights.



Solid symbols—measured TIGER data
Open symbols—estimated error bars for heavier elements for an additional 60 days of flight

Summary

- SuperTIGER measured cosmic-ray nuclei for 55 days over Antarctica.
- More than 83% of High-Priority data (Z >= 22) were recorded through TDRSS.
- Instrument worked as expected during the flight.
- Preliminary σ_Z = 0.18 charge units at Fe.
- SuperTIGER data will be a strong test for the OB Association model of GCR origins.
- Recovery planned for 2013/2014

BESS-Polar II Recovery 2009-2010

- Staged from WAIS Divide/Byrd Surface Camp

BESS-Polar II Recovery 2009-2010

- Basler (turboprop DC-3) used due to range and instrument size

BESS-Polar II Recovery 2009-2010

- Camped on site 13 days for disassembly