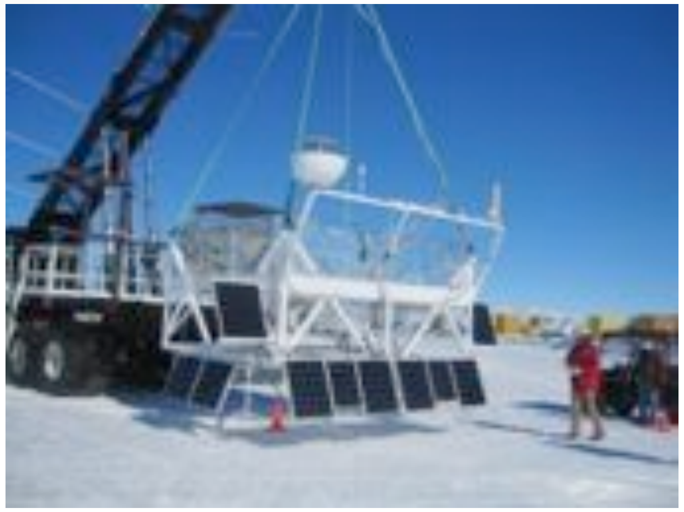
SuperTIGER and the hunt for Galactic Cosmic-Ray Origins

John E Ward

IFAE 28/05/14

Overview

- Brief introduction to Cosmic Rays
- What is the origin of Galactic Cosmic Rays (GCR)?
- The ACE/CRIS and TIGER experiments
- SuperTIGER
- Future



The SuperTIGER Collaboration

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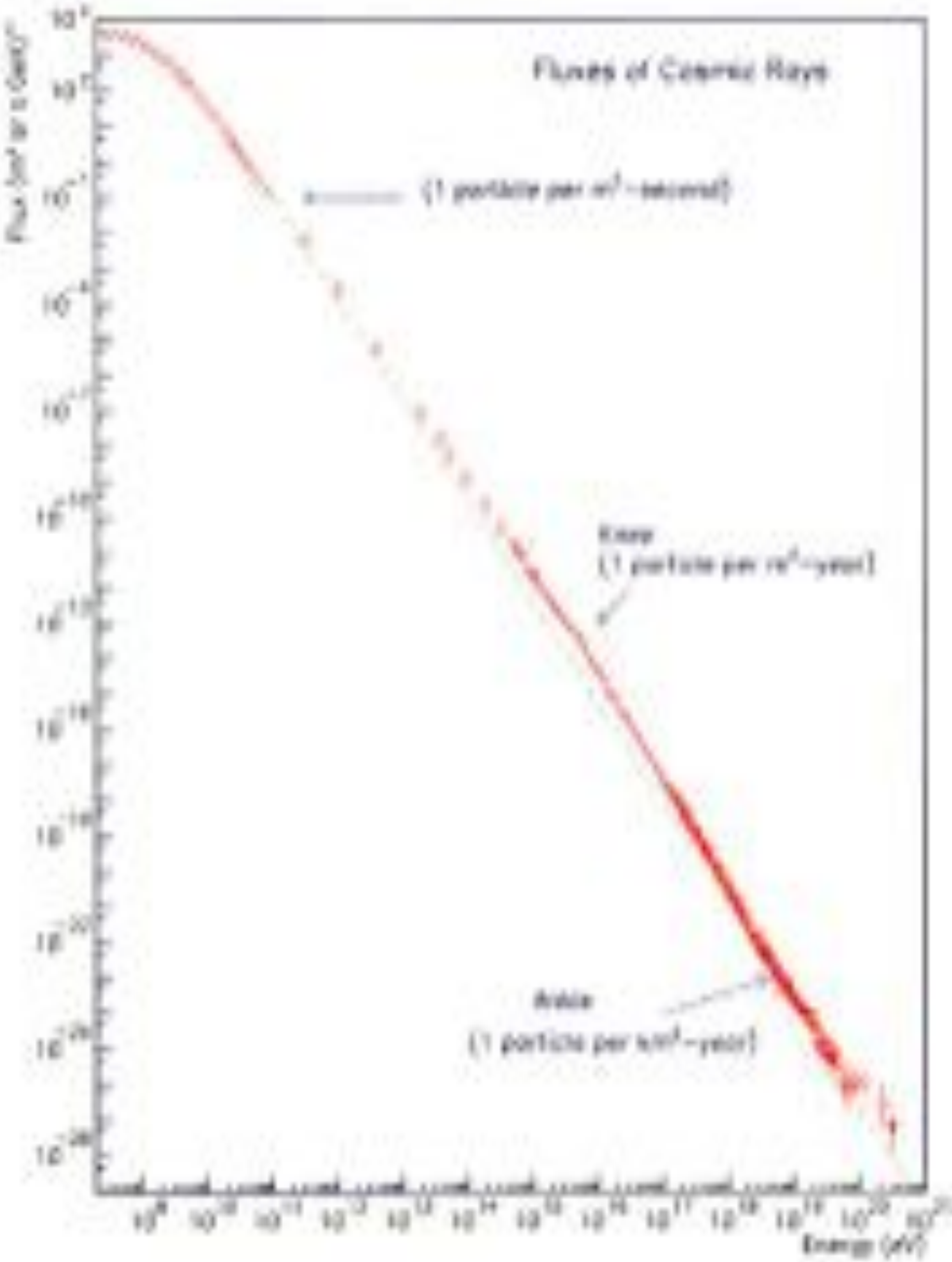
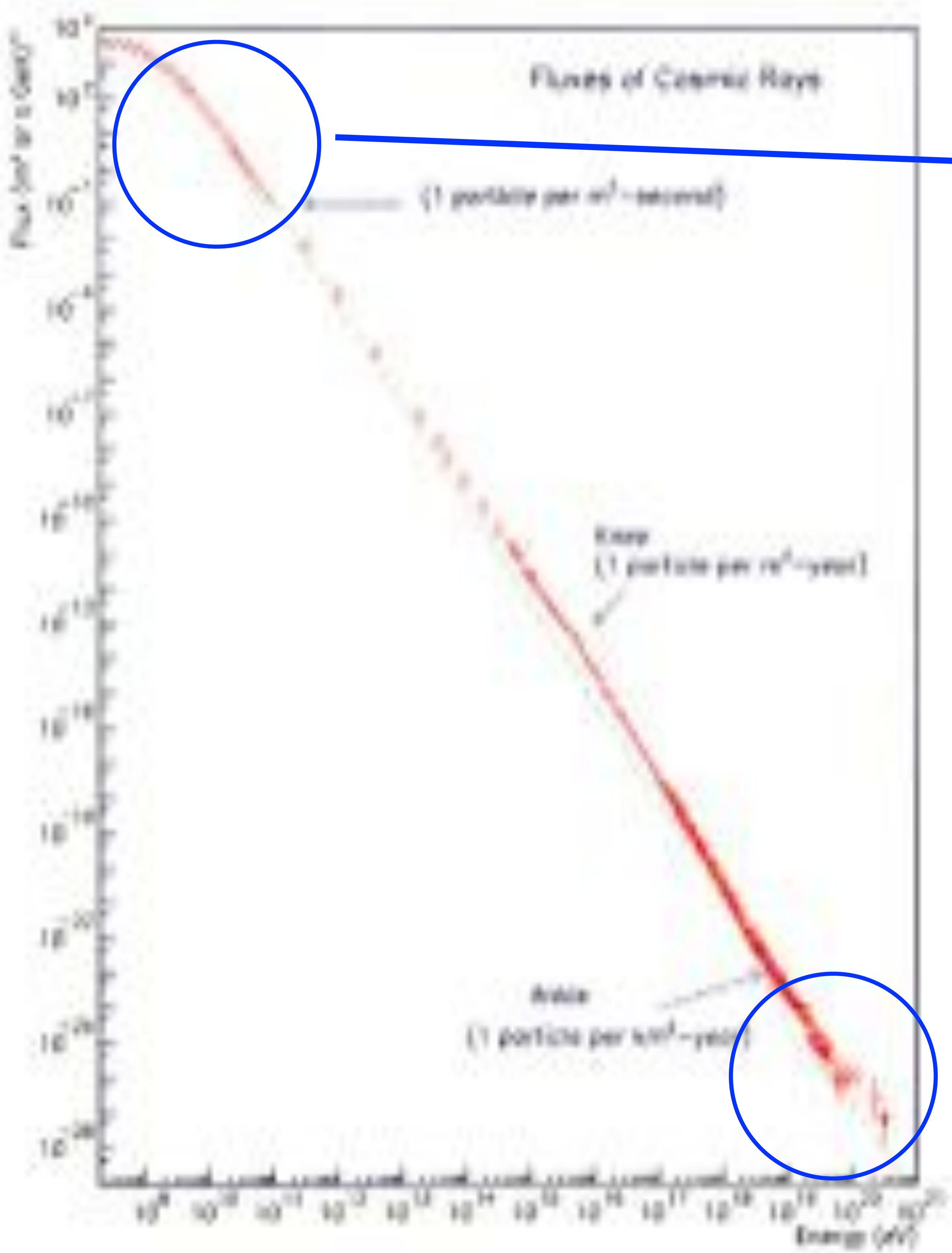
What are Cosmic Rays?



- Charged particles
  - ~99% ionized nuclei and ~1% electrons/ positrons
  - 90% protons, 9% α particles, 1% other nuclei
  - Heavier chemical elements formed via nucleosynthesis in stars
- Exhibit power-law spectrum
- Vast flux and energy range (relativistic speeds)
- Multiple origins: Sun, galactic and extra-galactic

What are Cosmic Rays?



Origin within our galaxy

30 GeV Proton in B~3μG has gyro radius ~ 10^{-5} pc

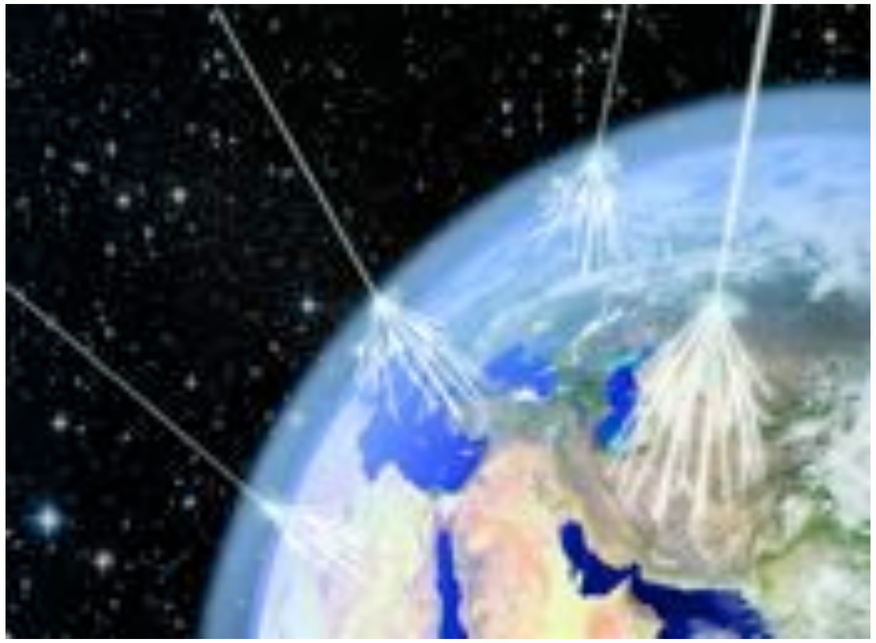
Learn about cosmic-ray sources directly from elemental and isotopic composition (i.e. information on the regions where the bulk of GCRs come from)

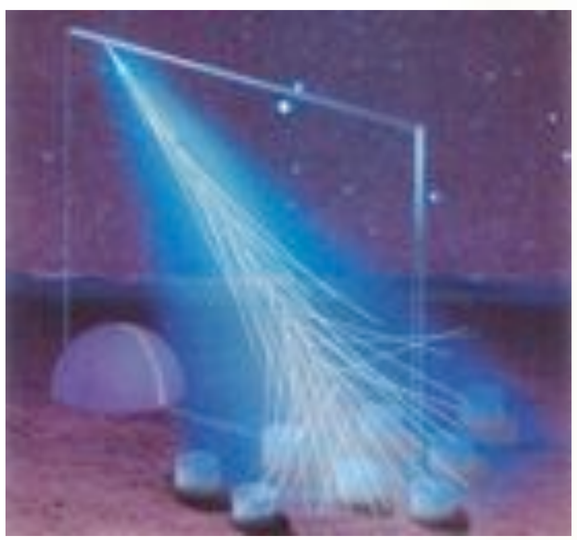
Extragalactic origin

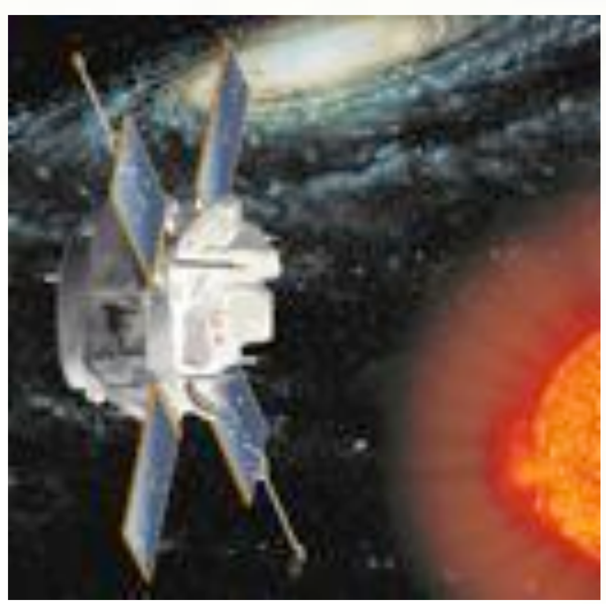
$3x10^{19}$ eV Proton in B~3μG has gyro radius ~10 kpc

Learn about cosmic-ray sources from arrival direction

Study of Cosmic Rays





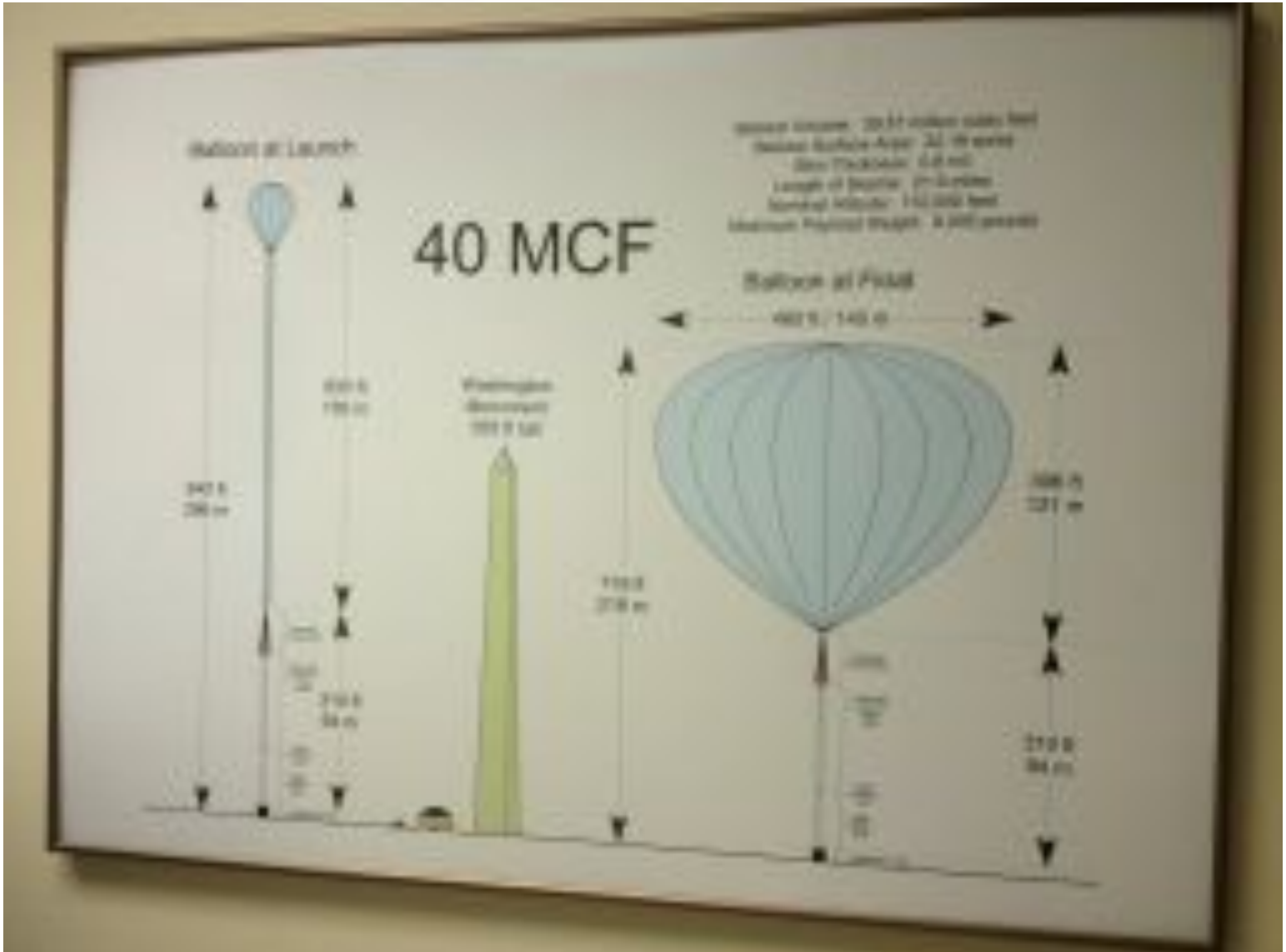


- Cosmic rays interact in Earth's atmosphere
- Isotropic distribution for lower energies
  - Arrival direction scrambled by interstellar magnetic fields
- Indirectly with "air-shower arrays" and gamma rays
- Study directly with satellites or balloon-borne detectors (composition and energy spectra)

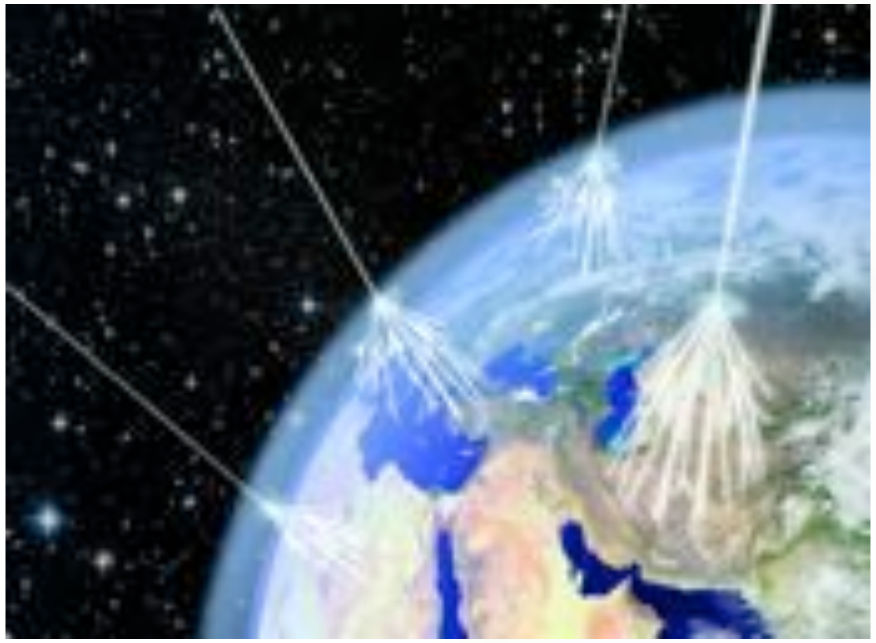
Aside I: Balloons? Antarctica? Why?

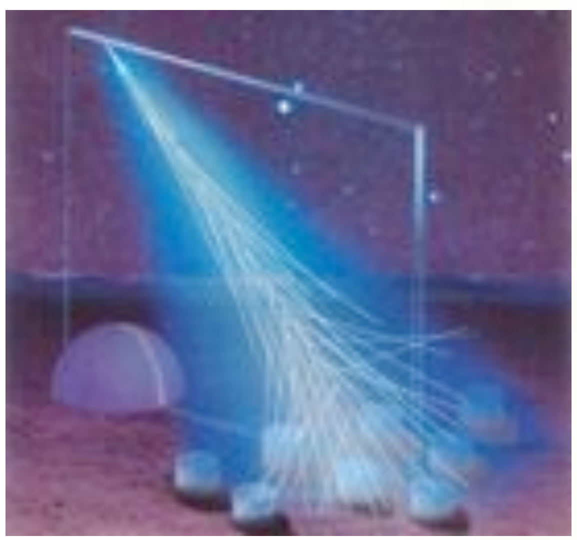
- Long Duration Balloons (LDB) are an effective and cheap way of getting above ~99% of Earth's atmosphere
- Particle-detectors can be much larger (and *much* cheaper) than satellite versions
- Shorter development time (3-4 years versus 10-15 years)
- Can recover, re-furbish and re-fly the payload (usually ...)
- Antarctica is a great site for scientific ballooning
  - Circumpolar wind
  - Politically neutral
  - Sparsely populated
  - Magnetic poles allows for higher cosmic-ray flux

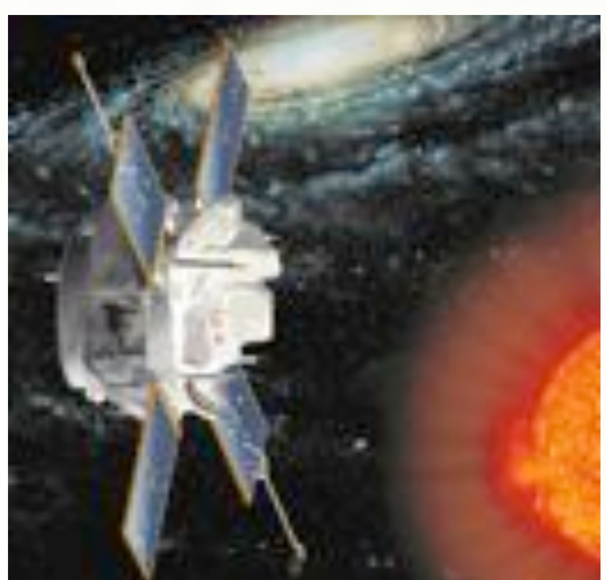
Aside 1: Balloons? Antarctica? Why?



Study of Cosmic Rays: Relative Abundance Approach



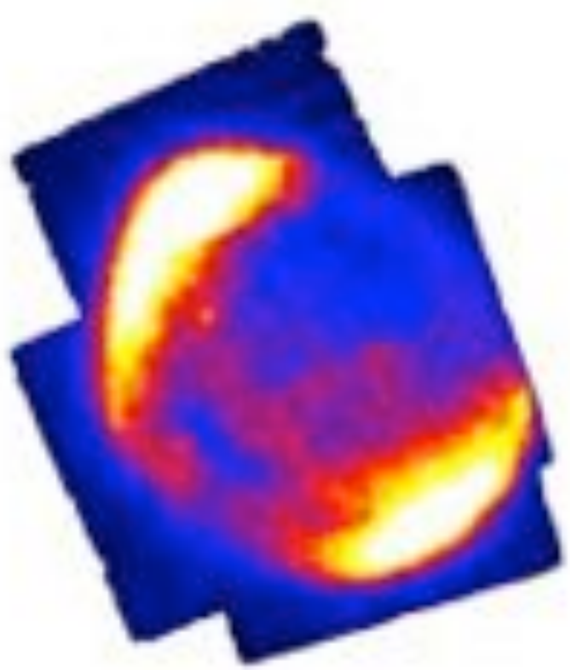


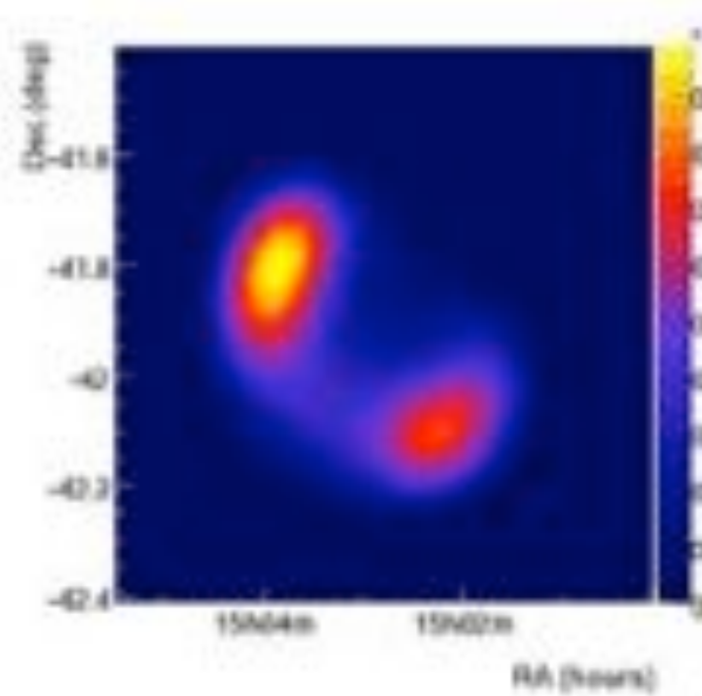


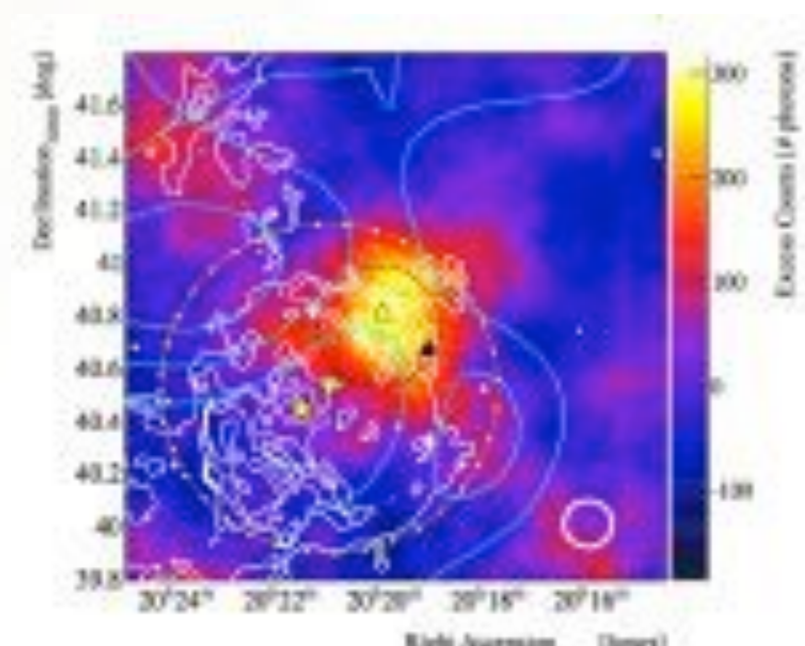
- Questions that can be answered by isotopic and elemental composition of cosmic rays
- How old (time since acceleration) are the GCR we observe?
- How long after nucleosynthesis were GCR nuclei accelerated?
- In what environment in the galaxy are they accelerated?

Galactic Cosmic Rays: What is the Mechanism of Acceleration?

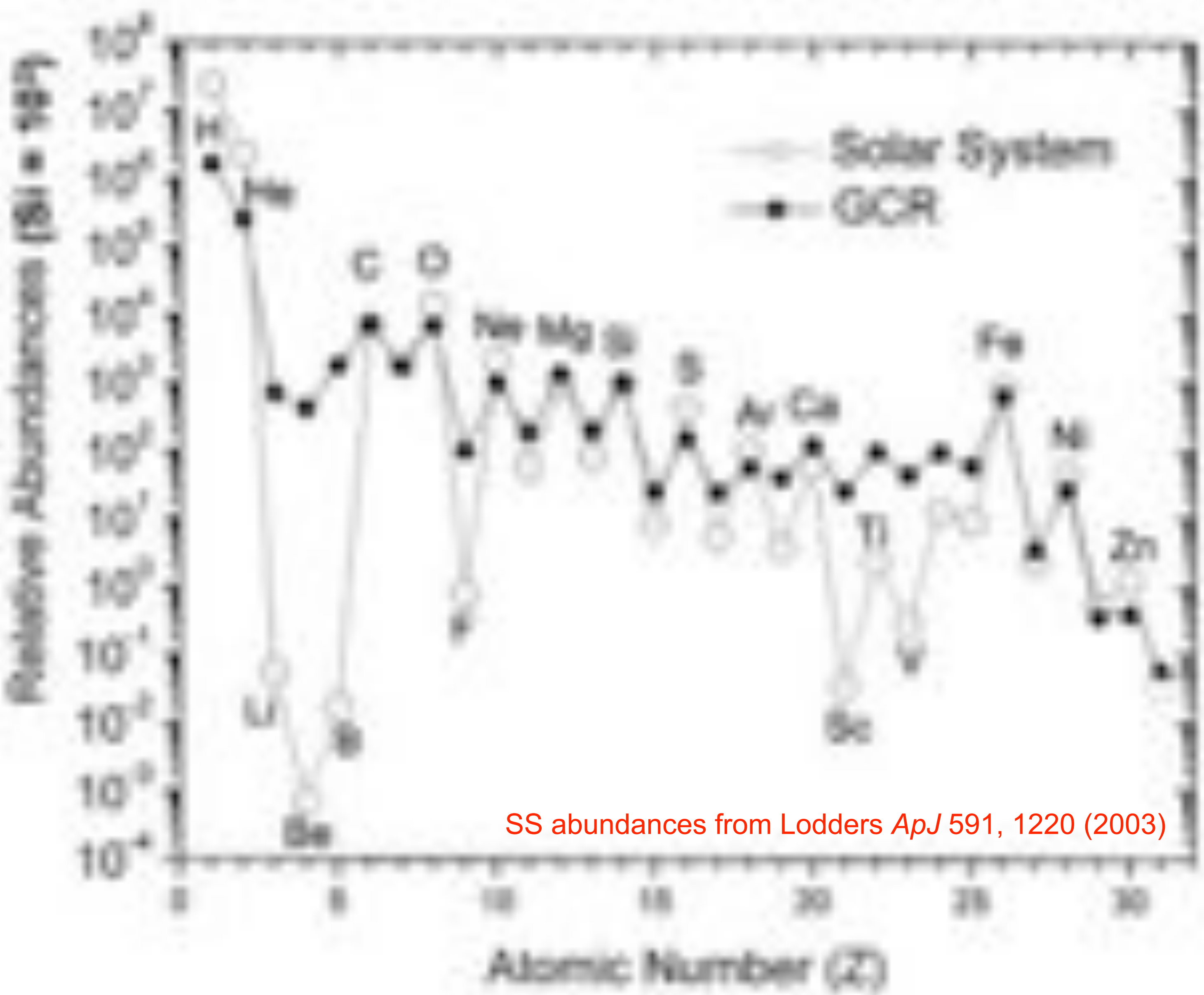
- What mechanism within our galaxy provides the energy for the acceleration of galactic cosmic rays?
- Best candidate: supernovae (SNe) and their shocks
  - 10% of supernovae energy given to cosmic-ray acceleration will account for observed GCR flux
  - Good theoretical description of shock front acceleration with First Order Fermi acceleration







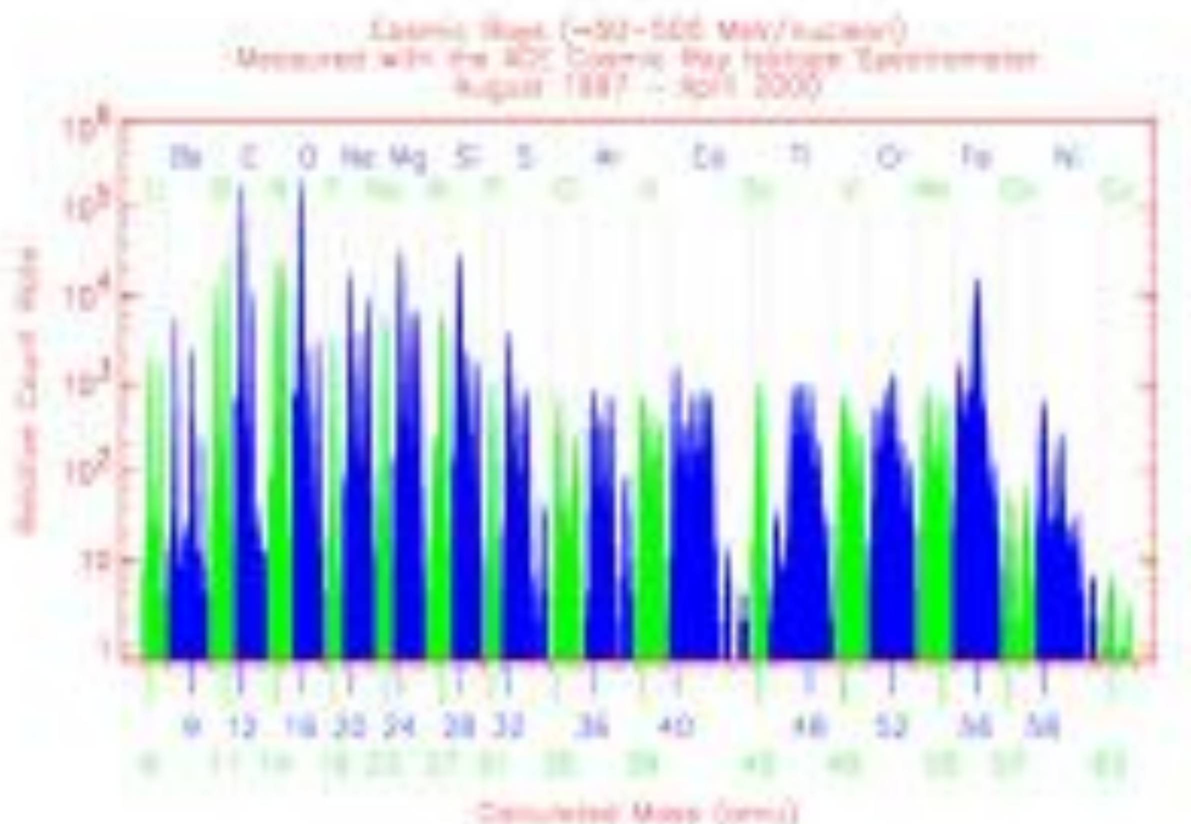
Finding GCR Origins: Composition measurements

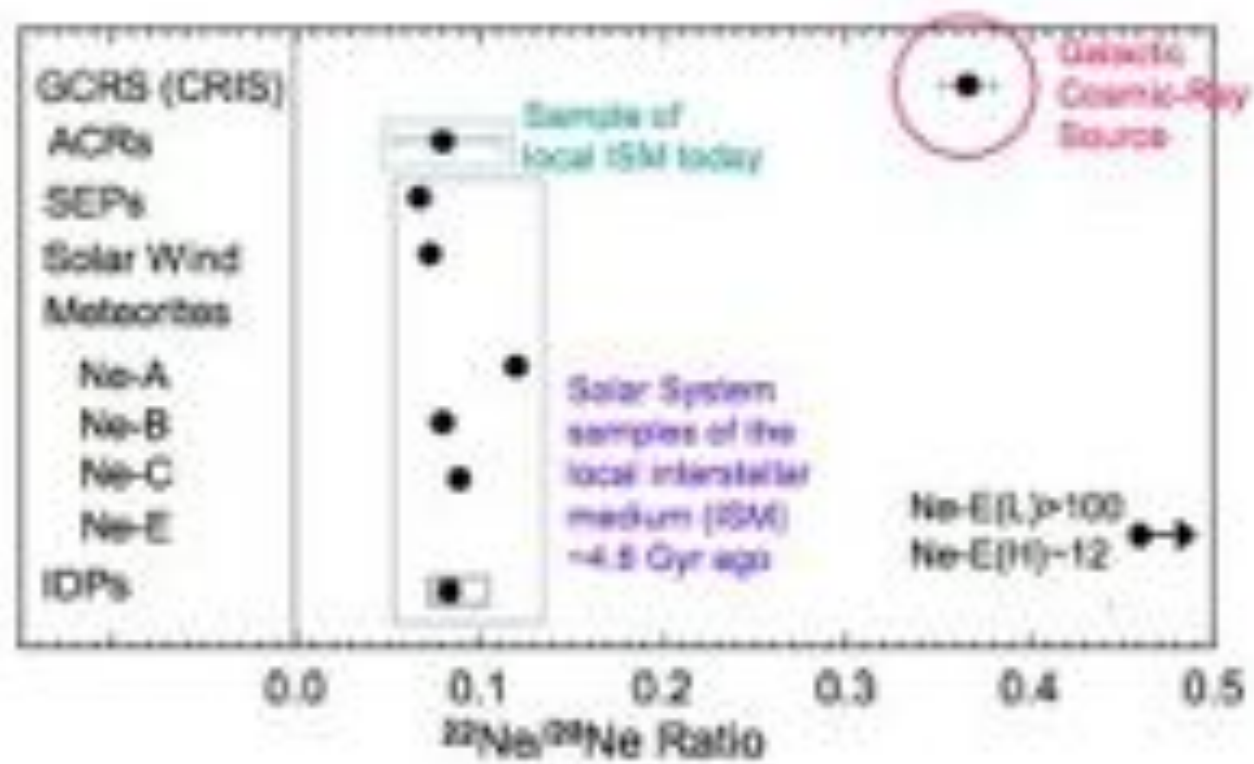


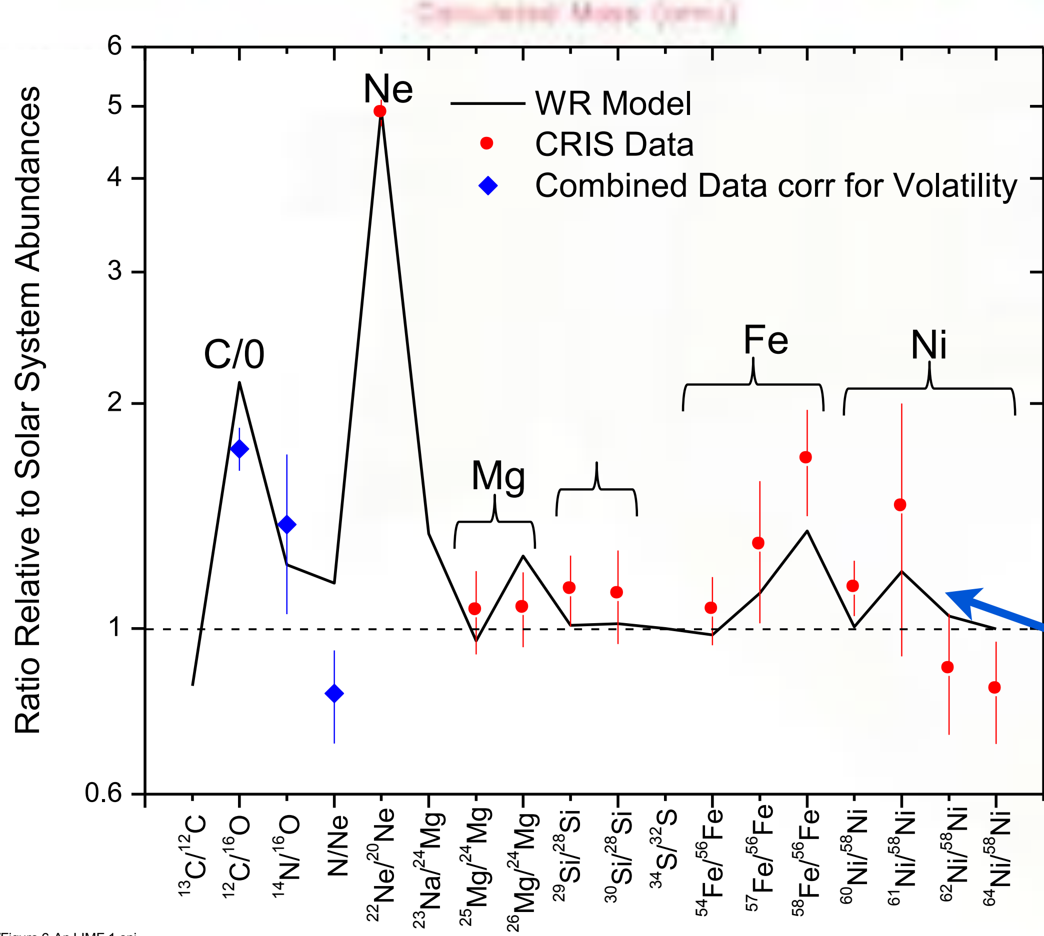
Differences in the two compositions gives us information about the cosmic-ray acceleration environment

- Since for GCR, arrival direction information is lost, one alternative is to look at GCR elemental and isotopic composition
- Measure individual elements and compare their cosmic-ray abundances with a "baseline"
- Baseline is the Solar-System (SS) elemental composition (considered representative of the general interstellar medium)

ACE/CRIS composition measurement: The Ne^{22}/Ne^{20} enhancement







- Based on this enhanced Ne^{22}/Ne^{20} ratio, Higdon and Lingenfelter (ApJ, 590, 822, 2003) showed that this ratio was consistent with a GCR source made of a mixture of ~80% SS composition and 20% ejecta from massive stars in the Wolf-Rayet (WR) phase (such as those found in the cores of super-bubbles i.e. OB associations)
- Binns, et al (ApJ 634, 351, 2005) followed up with a more detailed study that also showed cosmic-ray isotopic and elemental abundances of elements with Z ≤ 28 can be described well by a model of WR massive star outflow

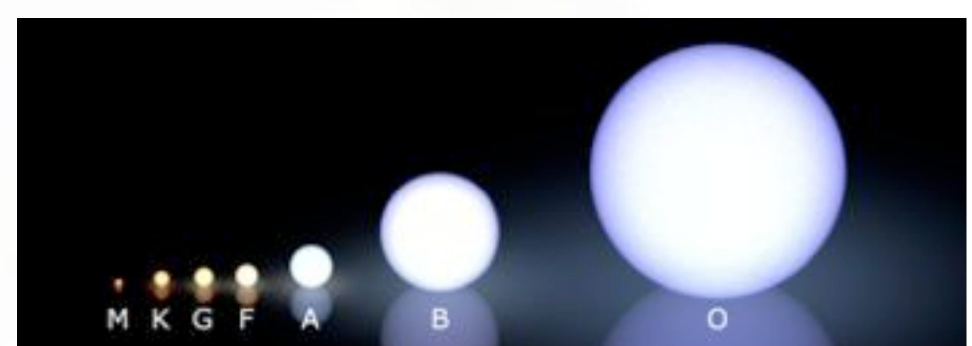
Black line shows expected composition from a mixture of 80% SS abundances plus 20% outflow from massive (WR) stars.

OB Association/Superbubble Origin for GCR?

- Group of many O and B type stars
  - Massive (15-45 $M_\odot$), hot and short-lived
- Stars in the “Wolf-Rayet” (WR) phase
  - losing mass rapidly via stellar winds (~10^{-5} $M_\odot$/year)
  - Winds rich in ^{22}Ne and ^{58}Fe
- Super-bubble: gas shell around OB association formed by stellar winds and supernovae
- Core-collapse supernovae (SN) are common in superbubbles (80-90% of core-collapse SN)

30 Doradus in LMC

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

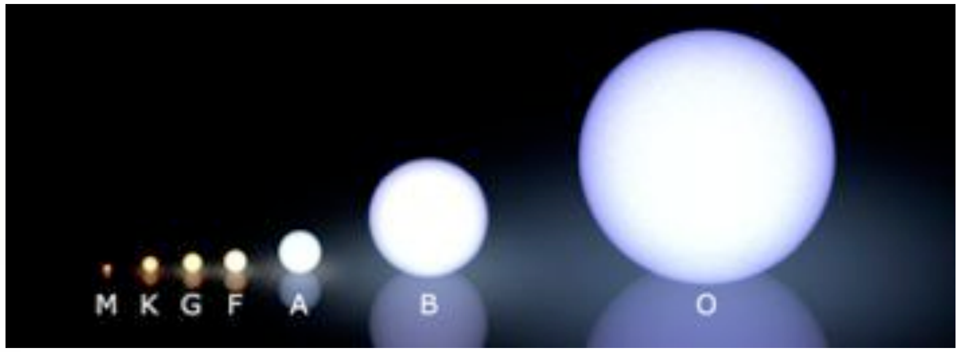


OB Association/Superbubble Origin for GCR?

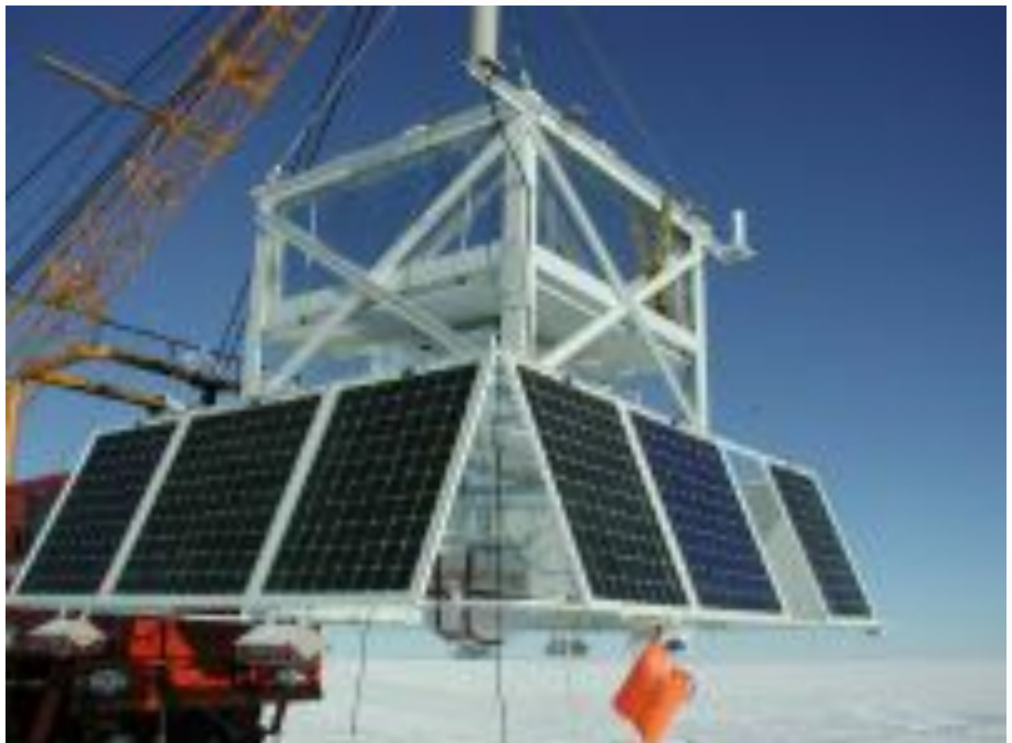
- WR star wind ejecta (enriched in ^{22}Ne and ^{58}Fe), mixes within the super-bubble with
  - Average ISM (represented by Solar-System abundances)
  - Ejecta from core-collapse SNe
- Refractory elements--mostly in grains; volatile elements mostly gas
- SN shocks accelerate this mix of material in super-bubbles to cosmic ray energies
  - Grains pref. accelerated (Ellison et al. 1997)
- Complementary approach to isotopes: Look at elemental composition, extend to heavier elements

30 Doradus in LMC

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



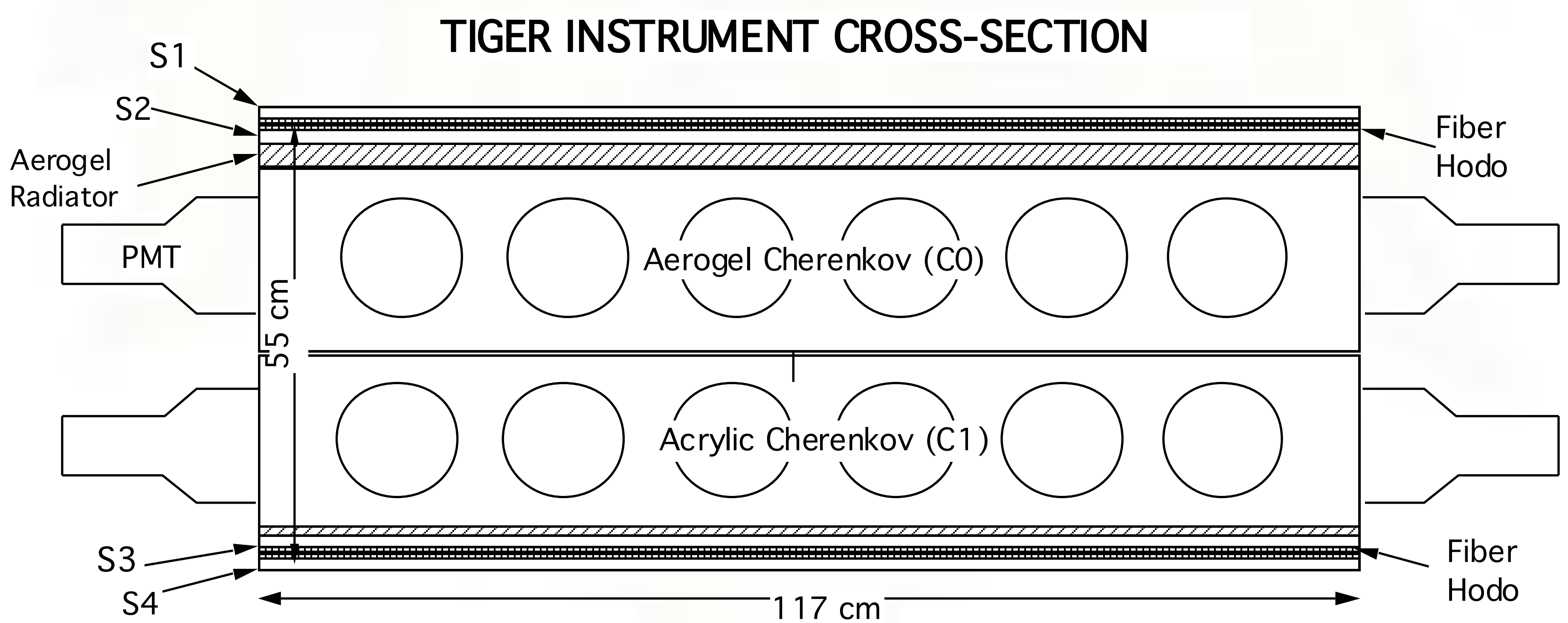
Further Probe of OB Association Origin: TIGER experiment



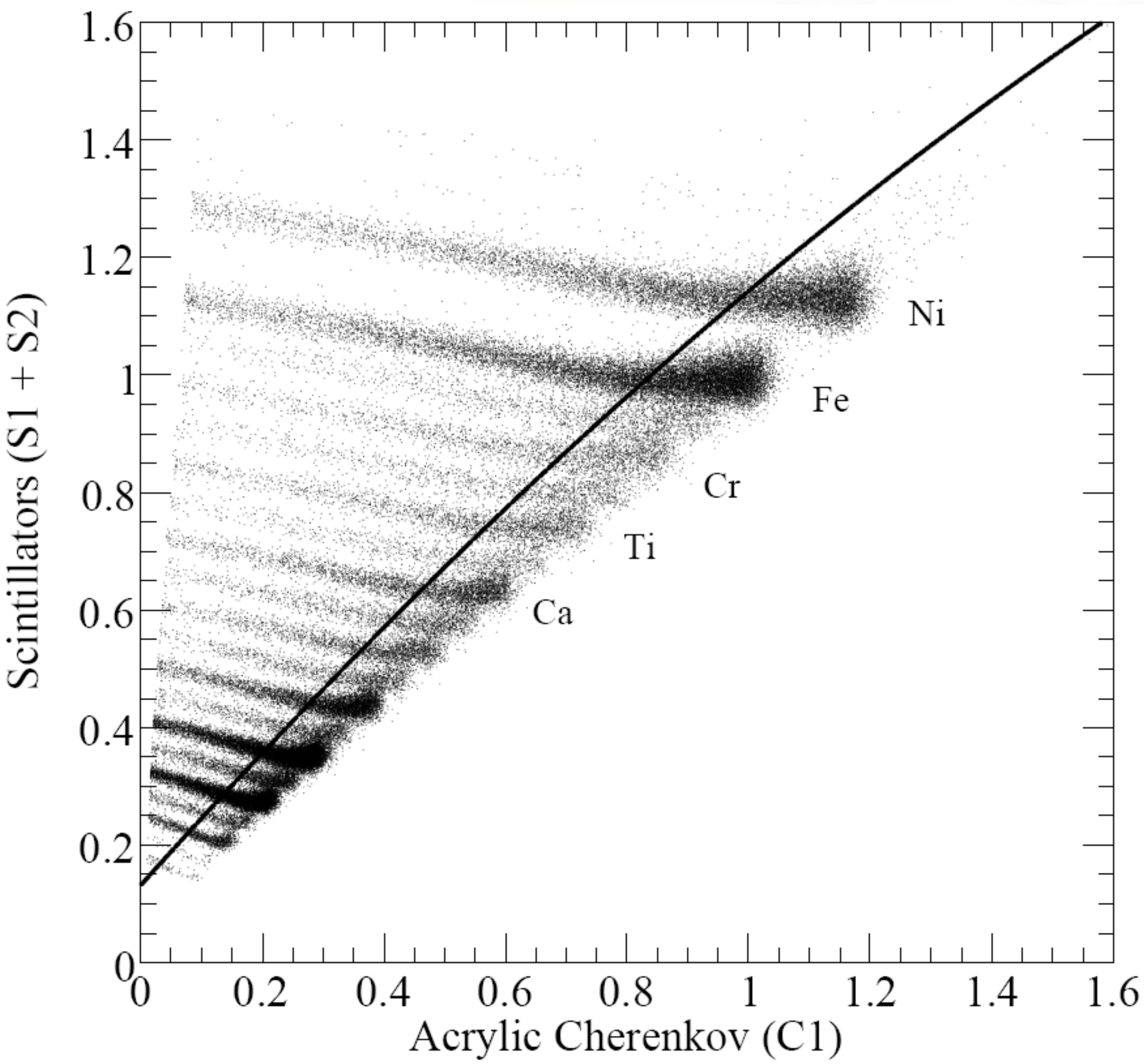
- Trans-Iron Galactic Element Recorder
- Measure abundances of Z>20 to Z=40
- 3 campaigns in North America 1995-7
- 2 Long Duration Balloon (LDB) flights from Antarctica (2001 and 2003)

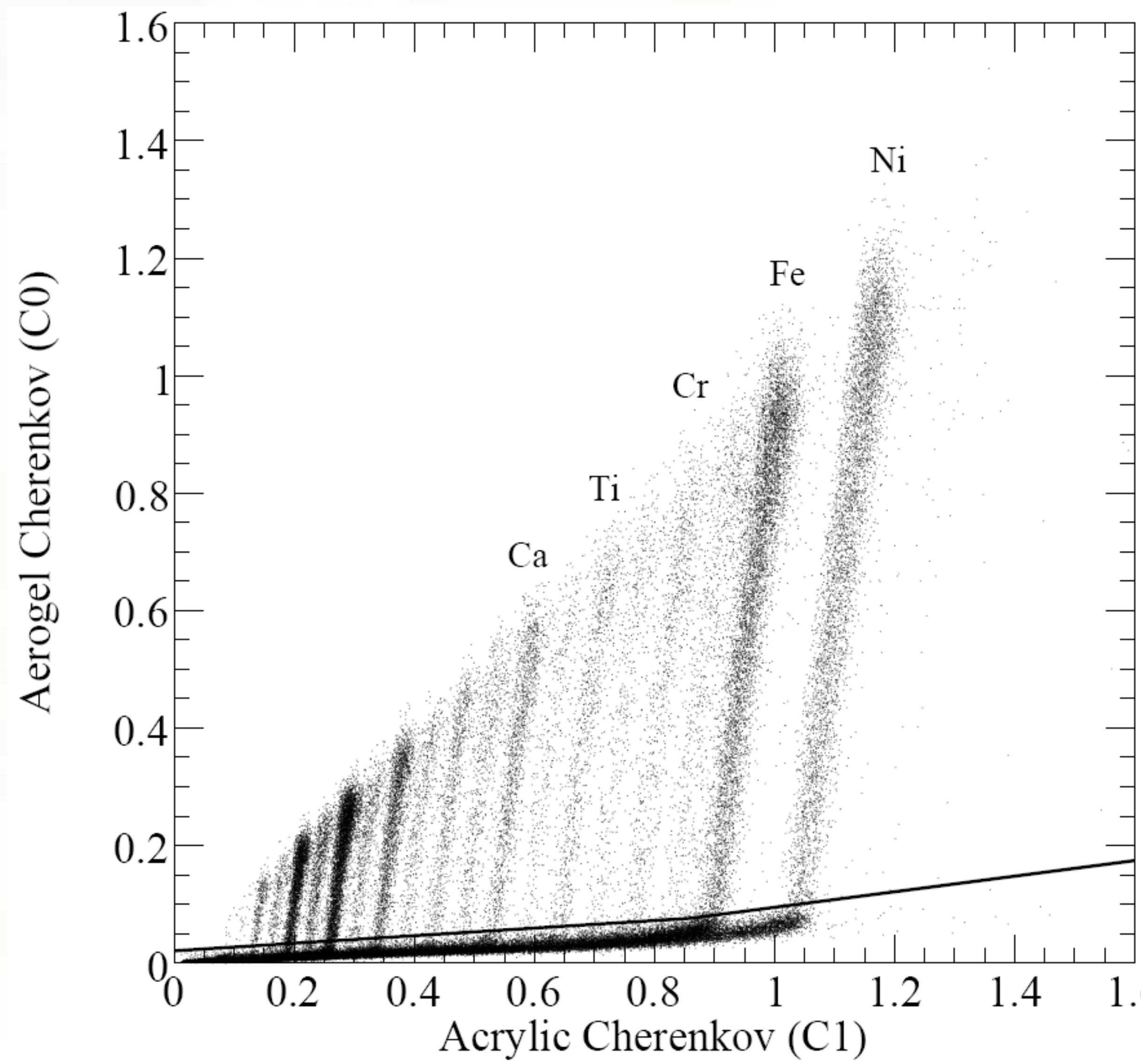
(Super)TIGER methodology

- TIGER was composed of plastic scintillators, Cherenkov detectors with two different indices of refraction, and a scintillating fiber hodoscope
- The charge, Z of each cosmic-ray nucleus that penetrated the instrument is determined from a combination of signals from the scintillators and Cherenkov detectors
- Scintillators emit light as function of ~ $Z^{1.7}$
- Cherenkov emits light as function of ~ Z^2
- Hodoscope particle tracker gives angle of incident particle through system - Allows for angle correction and detector response mapping



(Super)TIGER methodology

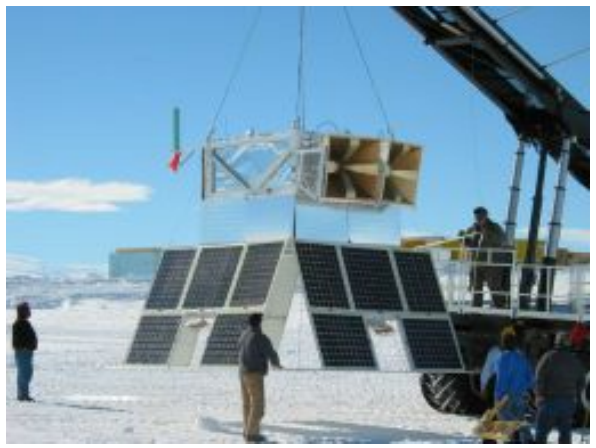




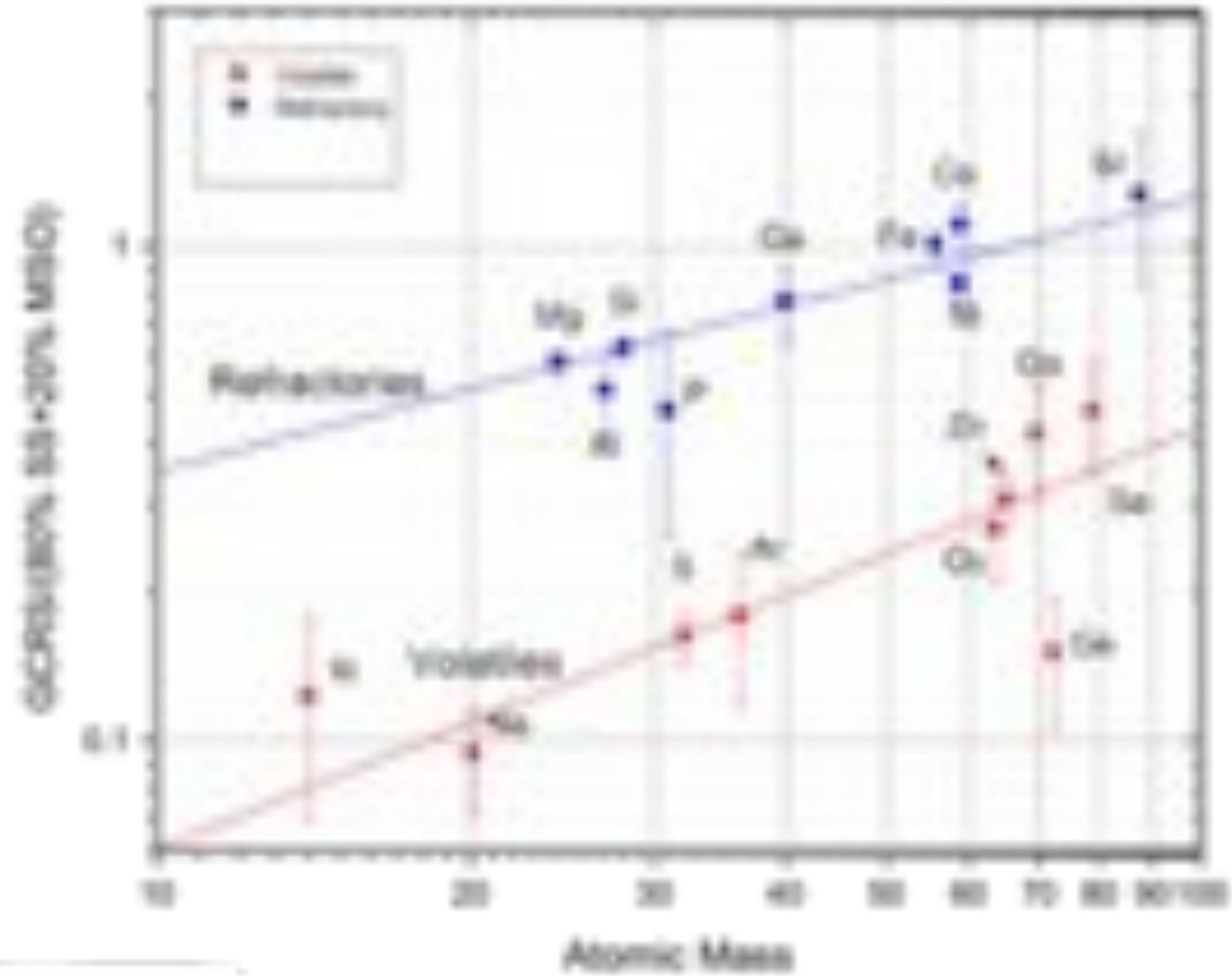
For 0.3 < E < 2.5 GeV/nucleon resolve individual elements with scintillators and acrylic Cherenkov

For E > 2.5 GeV/nucleon, resolve individual elements with the two Cherenkov detectors

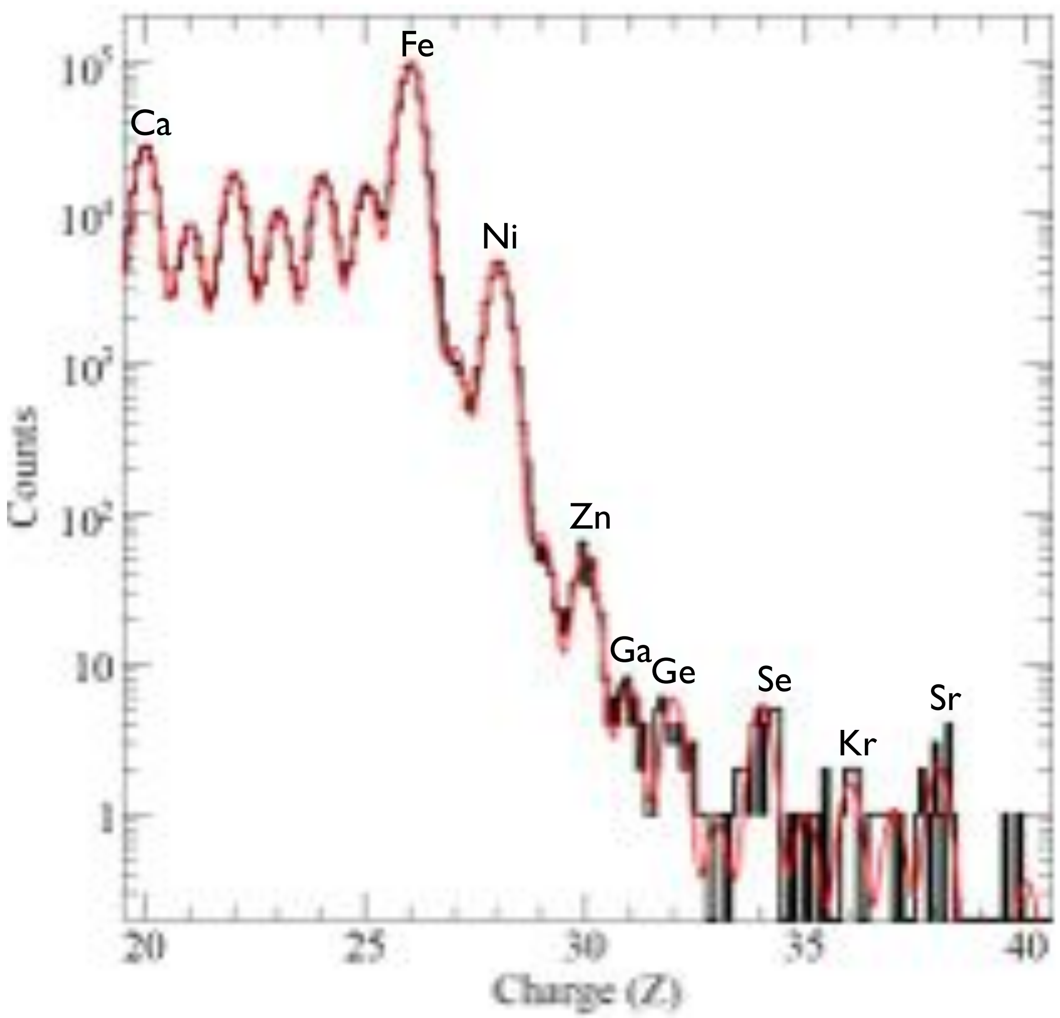
Results from TIGER



- Combined data from two Antarctic balloon flights (2001 and 2003)
- TIGER provided excellent charge resolution but limited statistics above Z=30



- GCR source mix of 80% SS and 20% ejecta from massive star provide reasonably consistent picture
- Refractory elements accelerated more efficiently than volatile elements (about 4x efficiency)



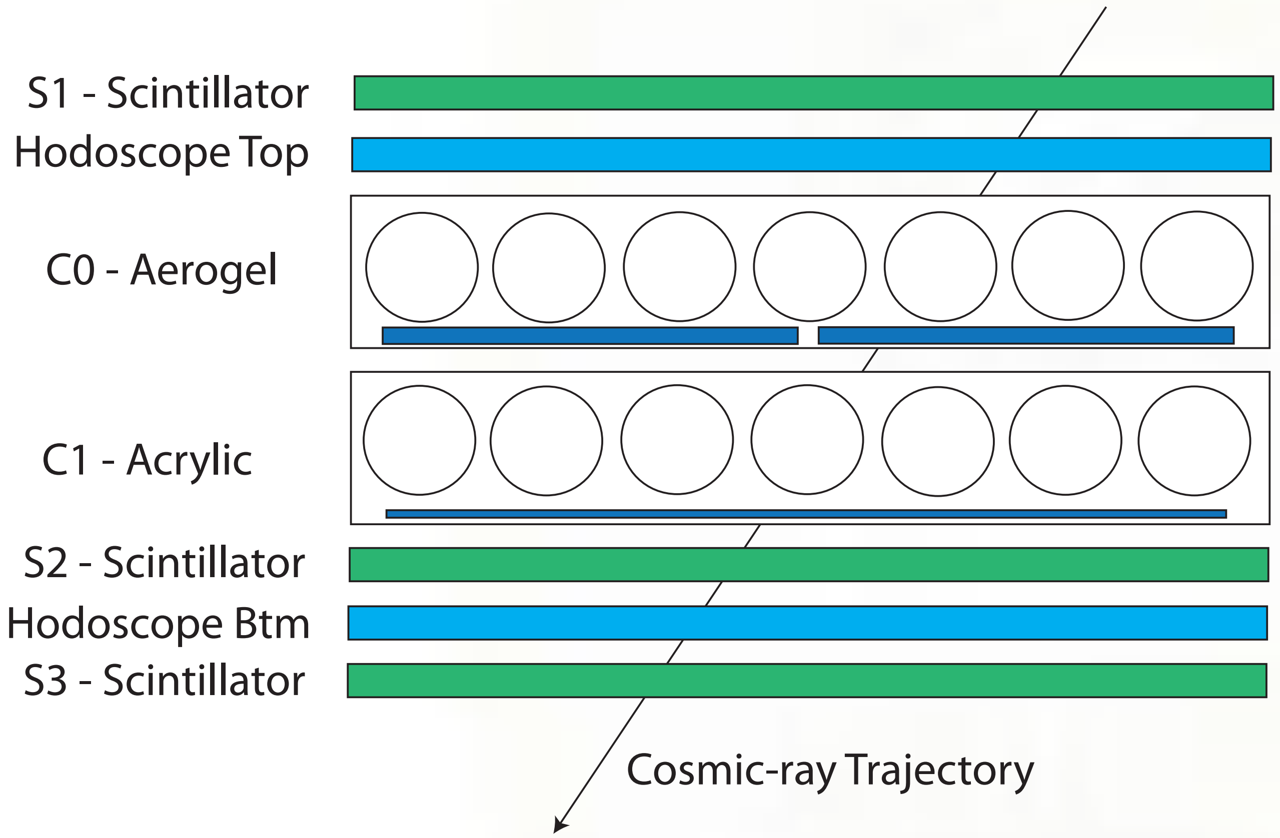
Enter the SuperTIGER

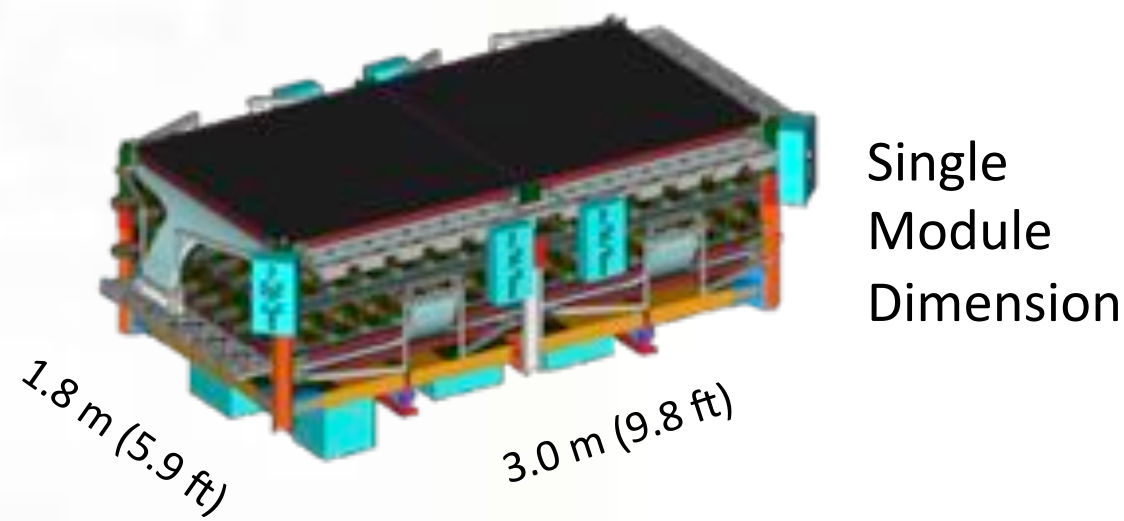
TIGER x 4

Enter the SuperTIGER

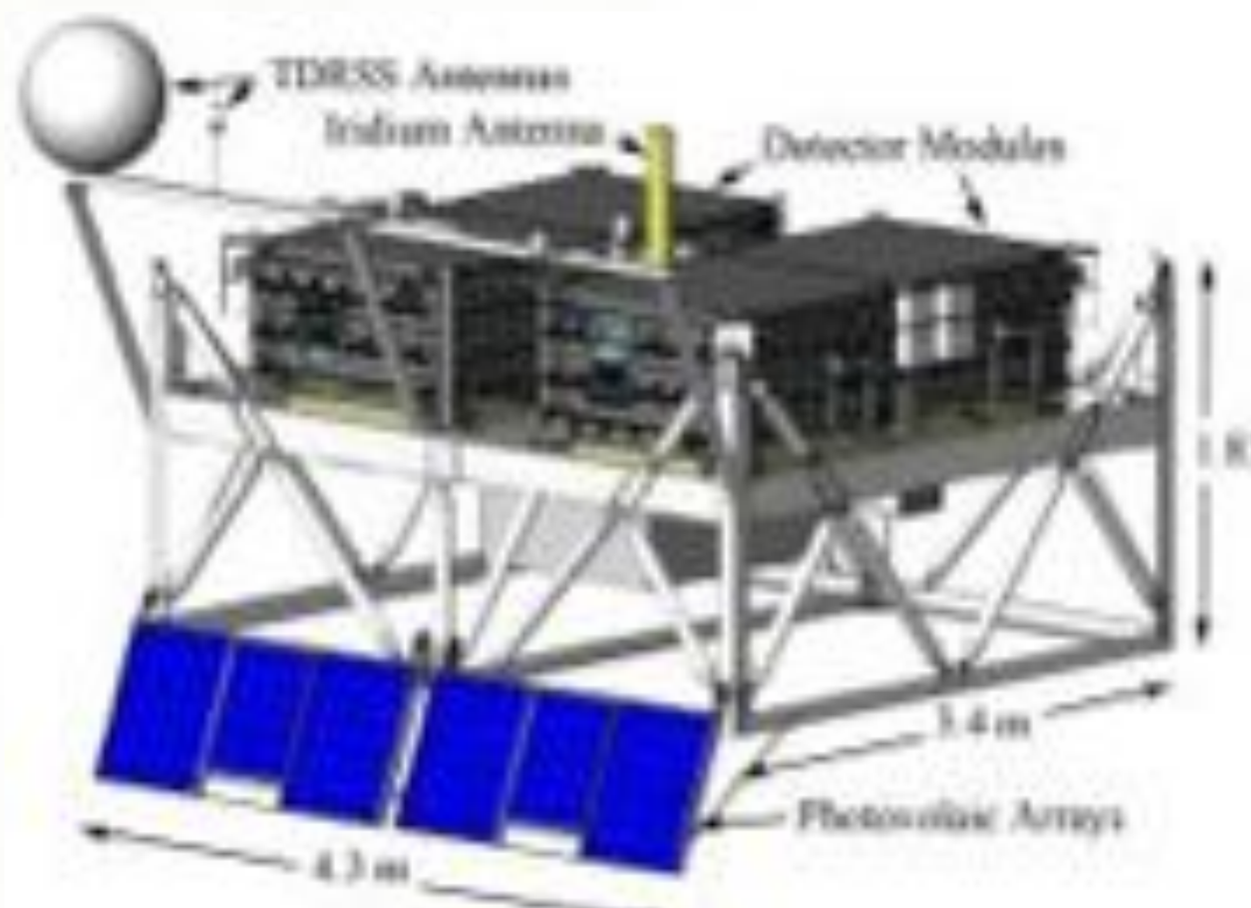
- Primary Objective: sensitive test of GCR origin
- Abundances of individual Ultra-Heavy (UH) elements $30 \le Z \le 42$
- Exploratory measurements up to $Z \le 56$
- Test of OB-association source model
- Test of A-dependence of acceleration
- Secondary objective: search for evidence of micro-quasars
- Energy spectra of elements $10 \le Z \le 28$
- UH elements are rare – need many times TIGER statistics
  - 7 to 8 times TIGER statistics
  - Large collecting area (~ 5 m^2)
  - Large exposure time required (several LDB flights)

SuperTIGER Instrument



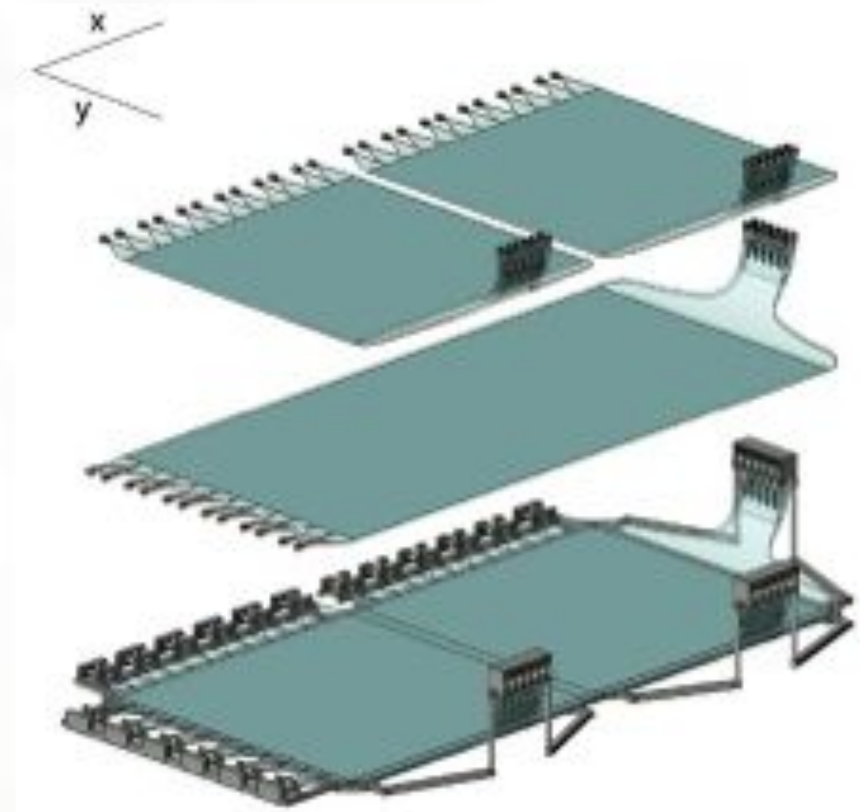


- Two nearly identical detector stacks (modules) - 2x TIGER
  - Active area 5.4 m^2
- Single Module Mass—616 kg (1358 lb)
- Full Instrument + Gondola Mass—1784 kg (3932 lb)
- Power—250 Watts
- Effective area ~6.4 x TIGER



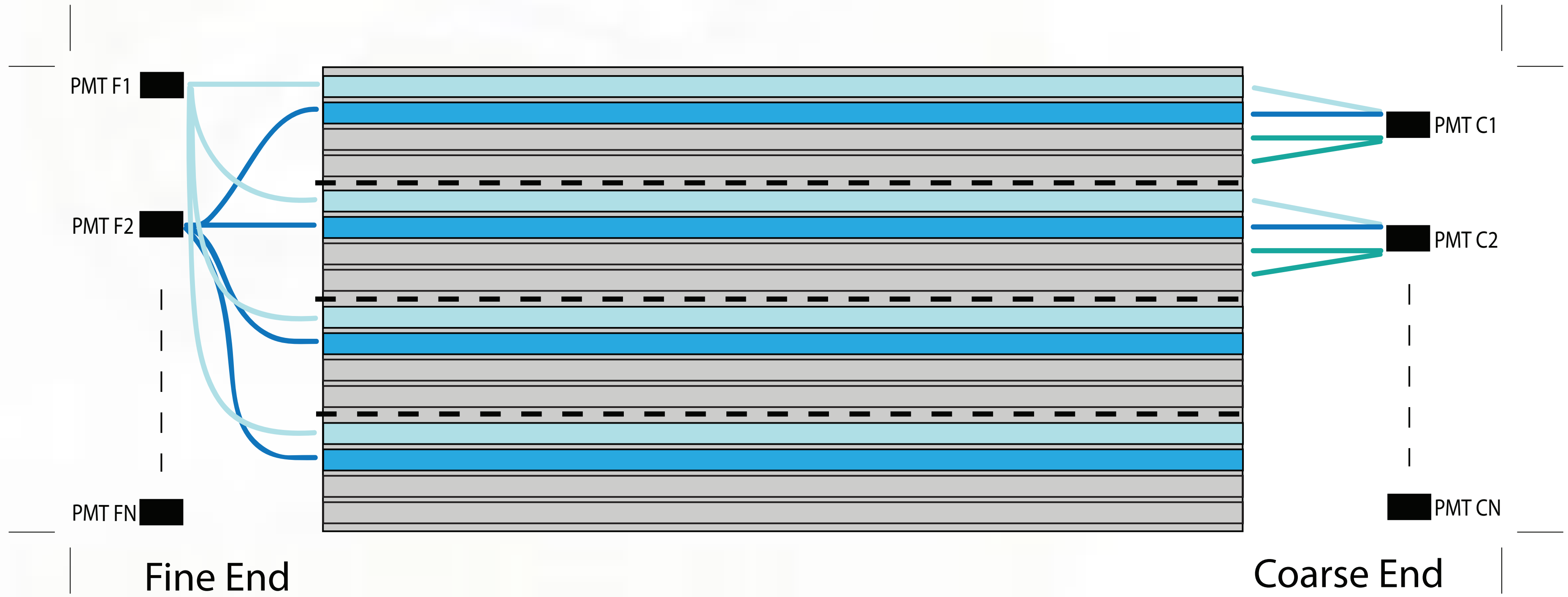
Scintillating Fiber Hodoscope

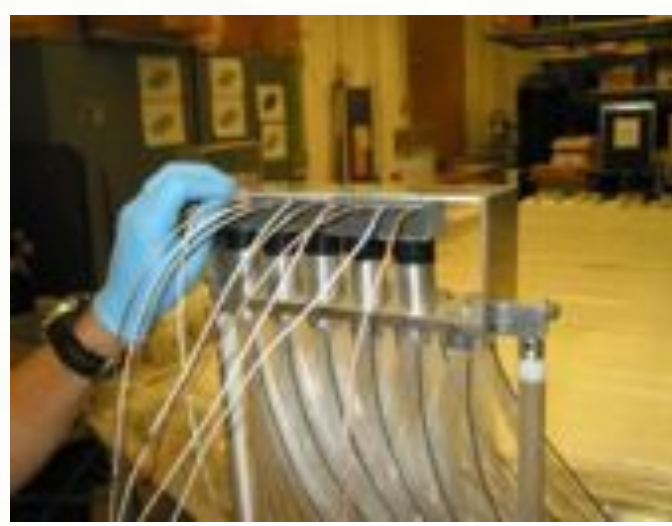
- Used to find particle's trajectory through detector stack
- X-Y plane of scintillating fibers (scintillating fiber core surrounding by non-scintillating acrylic cladding (lower *n*) → light piping)
- Two hodoscope planes in each module
- Each plane
  - "long" fiber layer (fiducial length 2.4 m, width 1.16m), core fiber size 1.4 mm → "y" coordinate
  - "short" fiber layer with two subsections (fiducial length and width 1.16m), core fiber size 1.0 mm → "x" coordinate

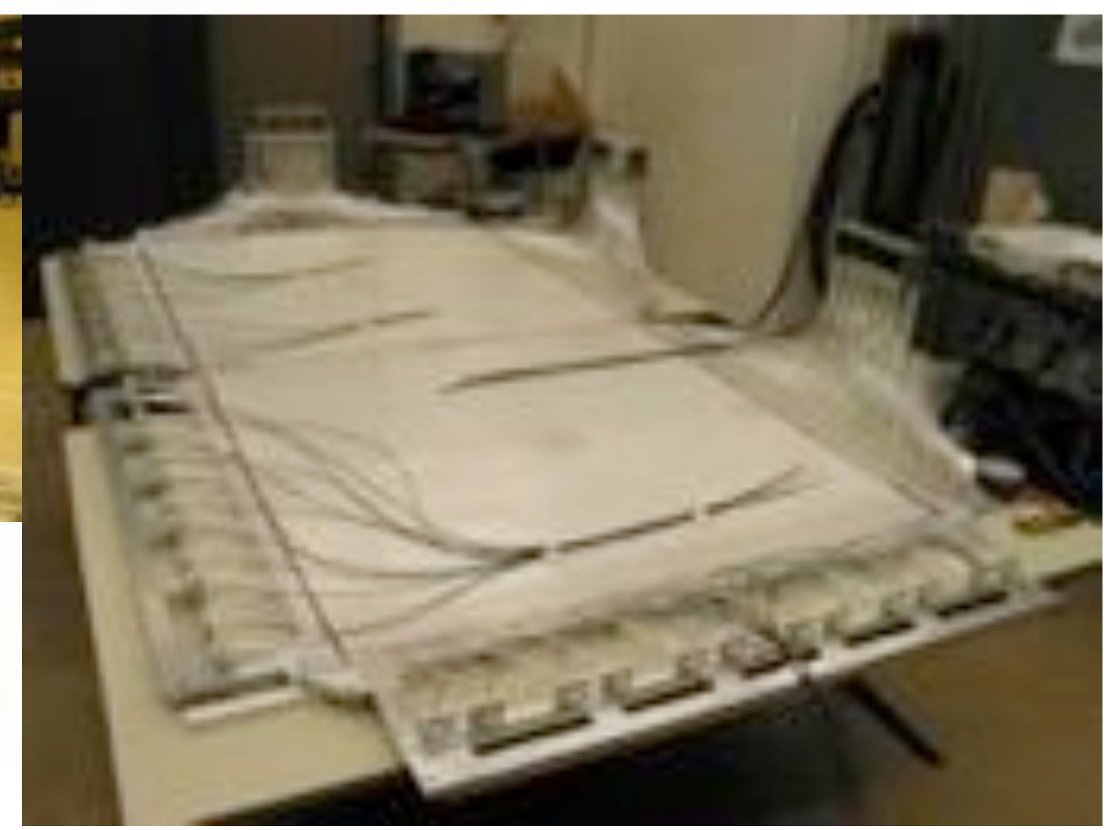


Scintillating Fiber Hodoscope

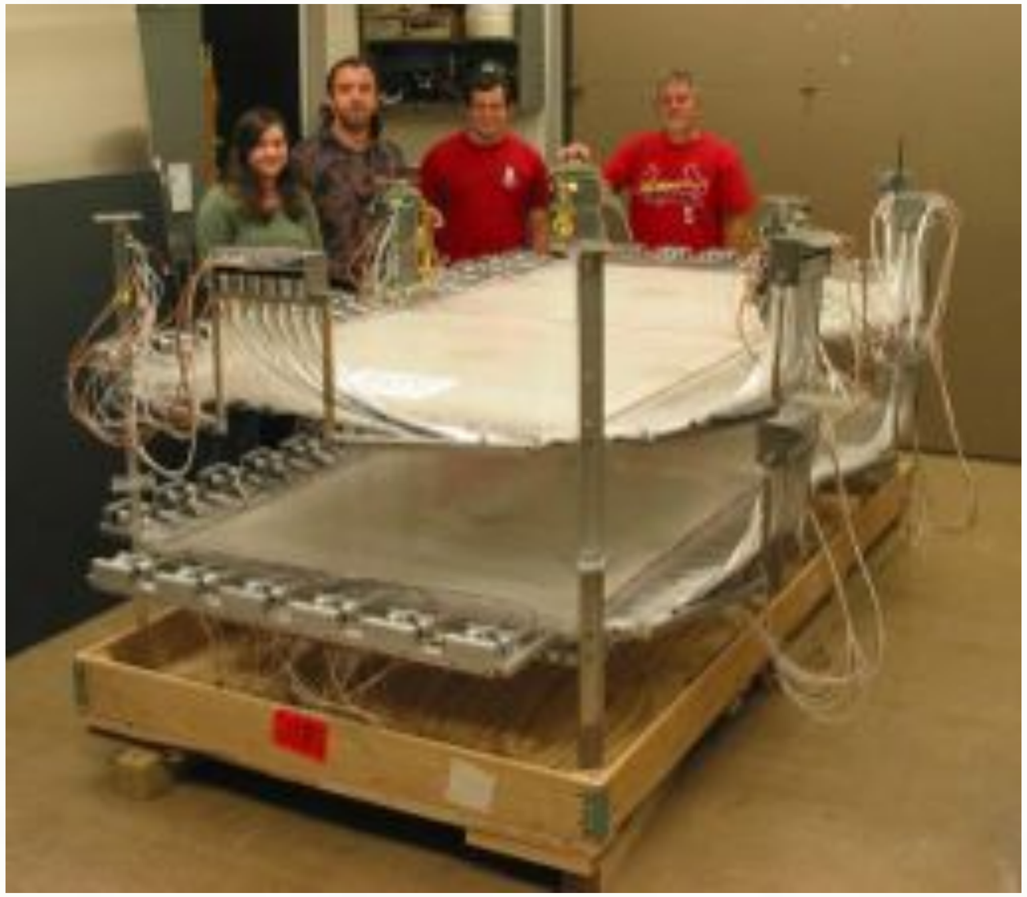
- Fibers grouped together into “tabs” of width ~ 8 mm
- Tabs grouped together into “segments” of width ~9.6 cm
- Coded readout to reduce number of PMTs and readout channels needed (coarse and fine system)
- 144 tabs can be read out by 24 PMTs - 12 coarse (one segment to one coarse PMT) and 12 fine (sequentially routed, one from each coarse segment)

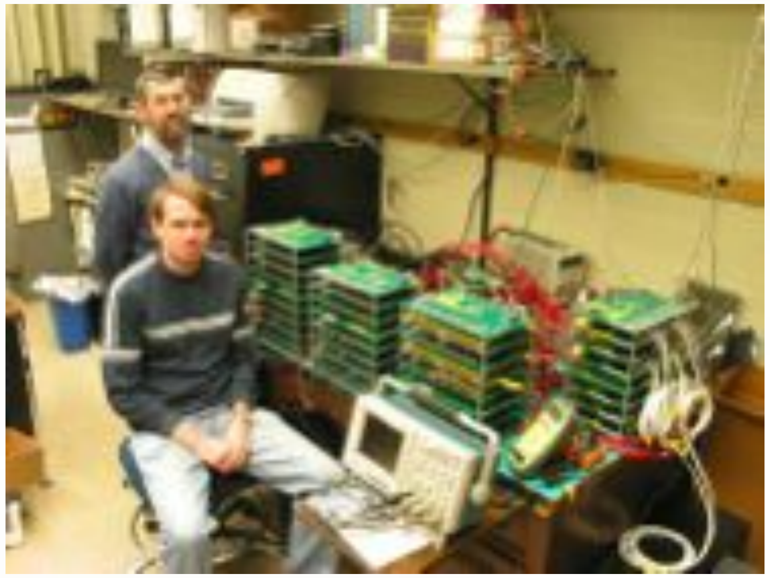






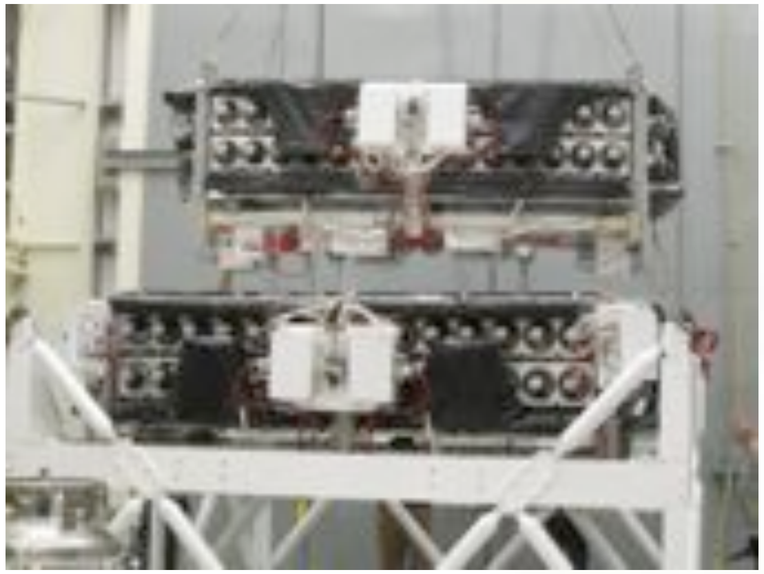
Construction and Testing





- SuperTIGER took over 3 years to design and construct
- Individual detectors and components built and tested at WUSTL and NASA's Goddard Space Flight Center (GSFC)
- Aerogel prepared at Caltech
- Instrument integration at GSFC

Construction and Testing

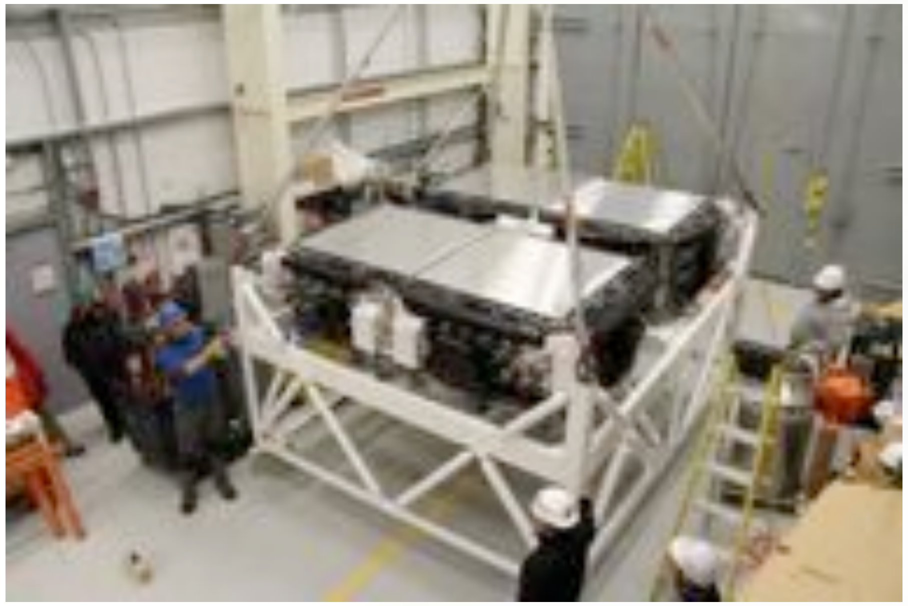


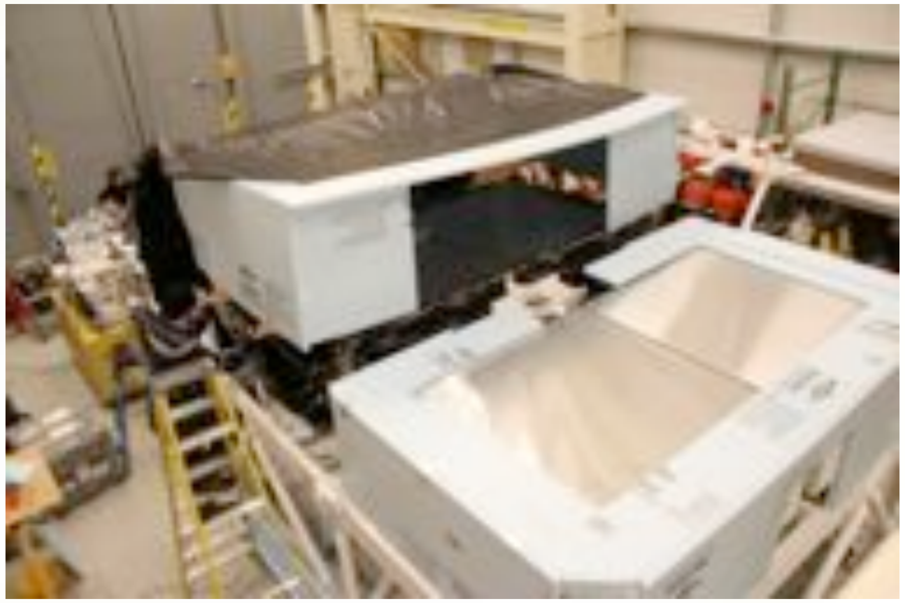
- Thermal/Vacuum testing at NASA's Plum-Brook testing facility (Ohio)
  - -30 C to + 55C
  - 4-5 mbar atmosphere (balloon altitude)
- Integration with Columbia Scientific Balloon Facility (CSBF) systems in Palestine, TX before deployment to McMurdo station, Antarctica
- Put it in a box and ship it ...

Shipping humans

- Trip to Antarctica
  - StL, LA, Sydney, Christchurch, McMurdo Station

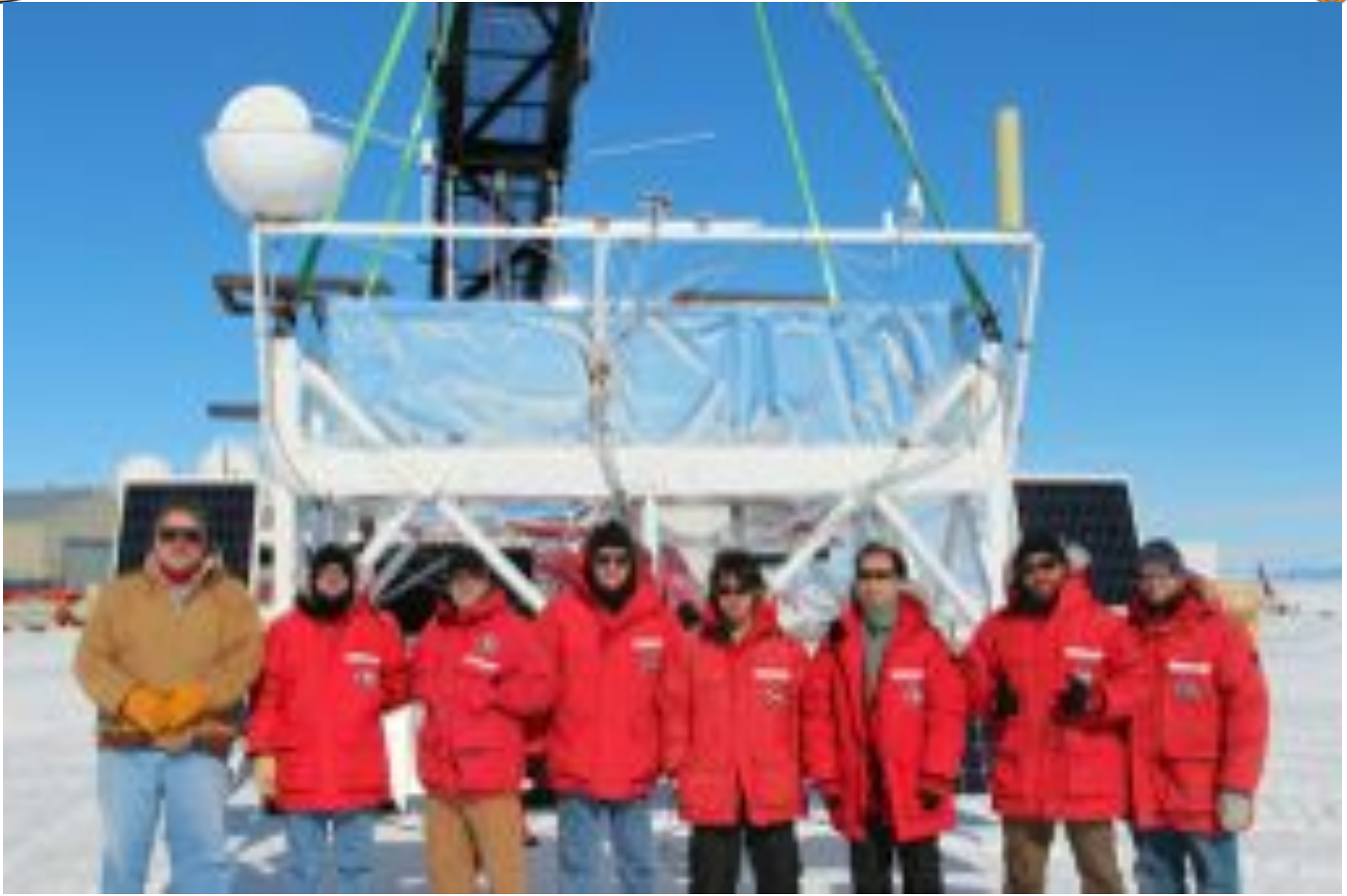
Preparation for Flight : Williams Field



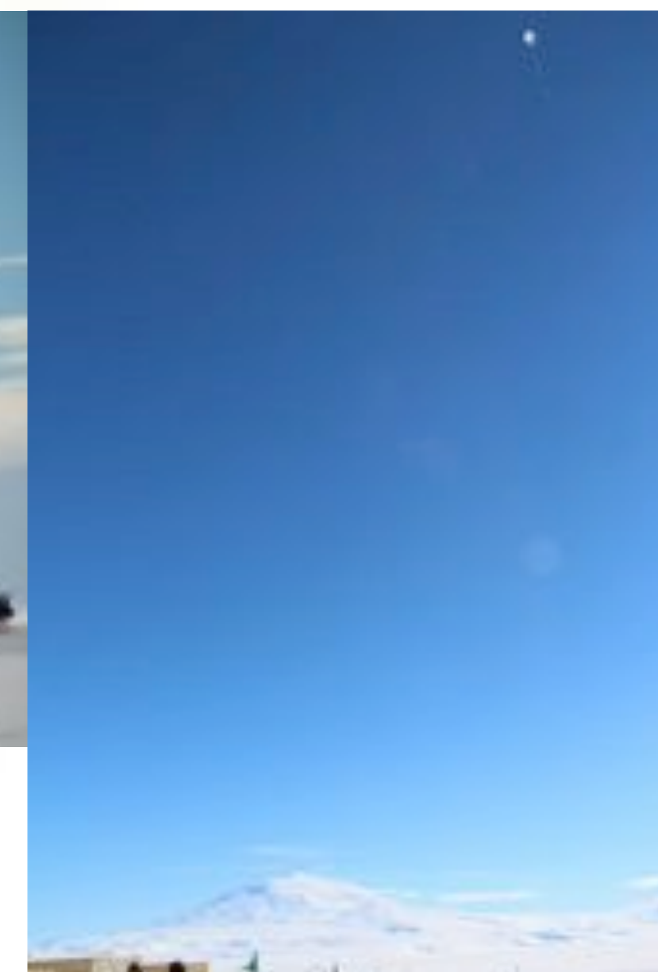


- Thermal insulation
- System checkout
- Final hang-test: Communications verification, flight train, power (battery and PV), data integrity check

Dec 1st 2012: Ready to launch!

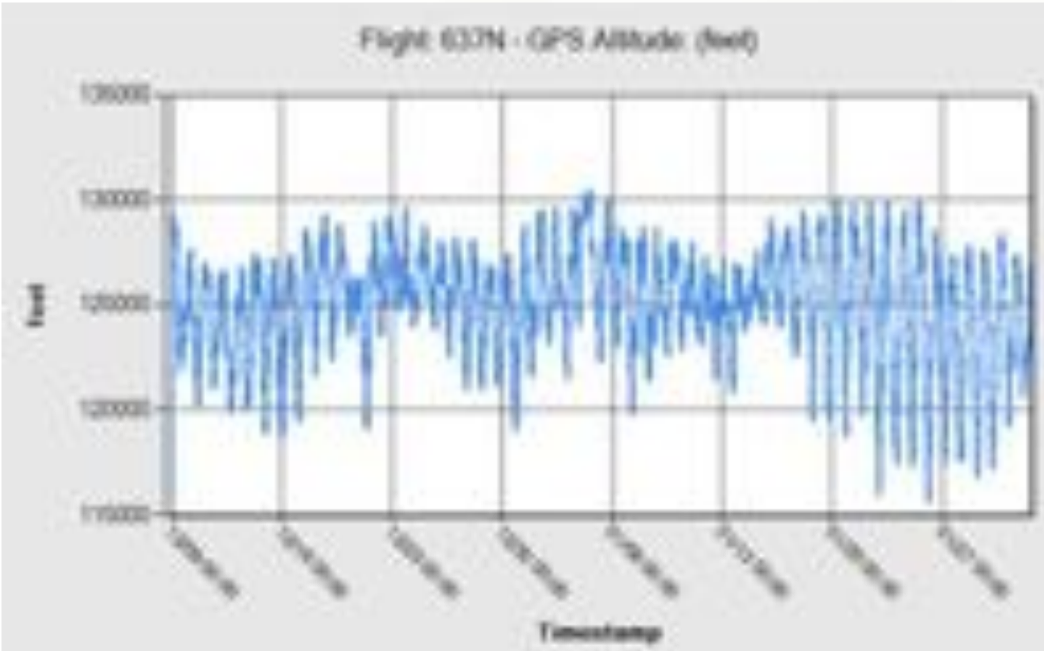


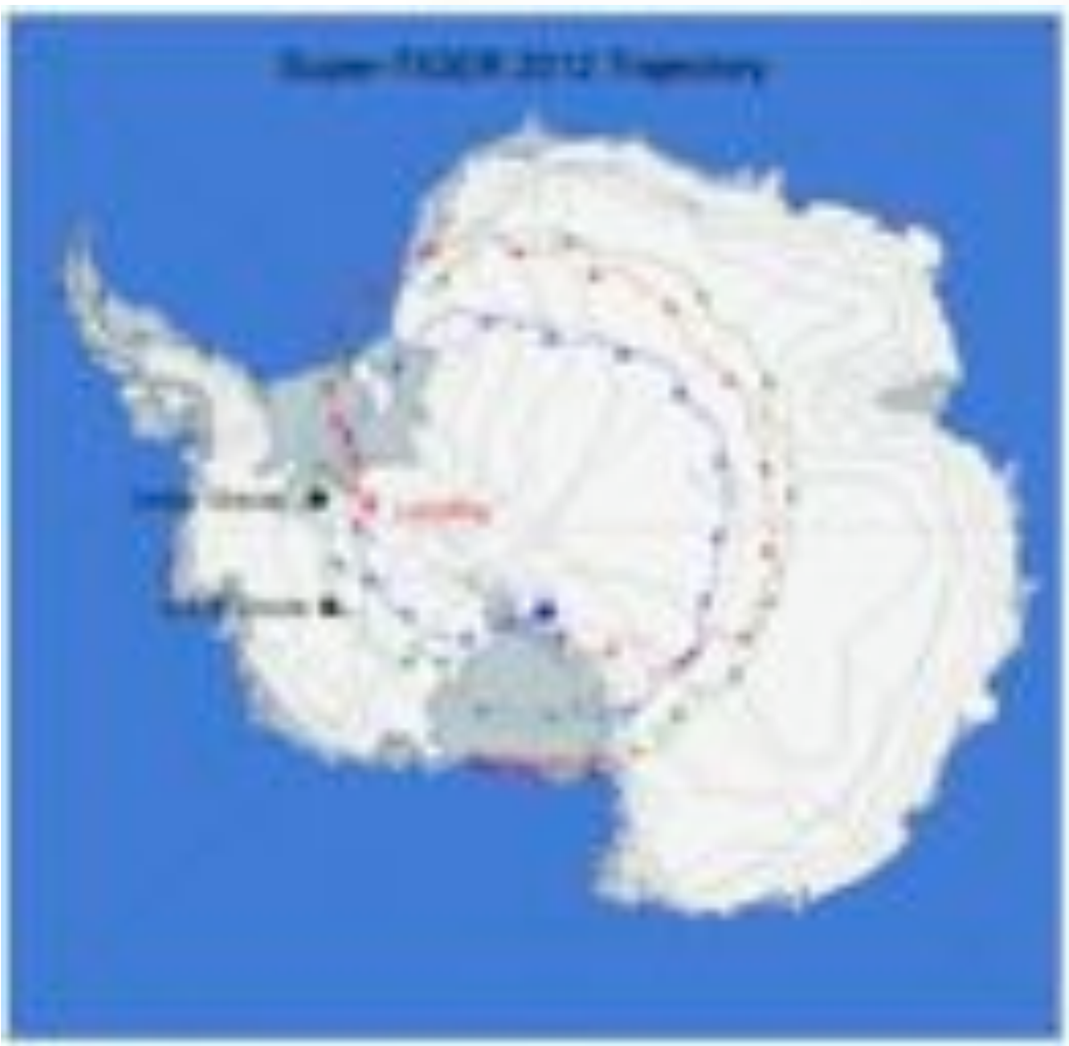
SuperTIGER Launch



Lift off at 09:45 am NZDT Dec 9th, 2012

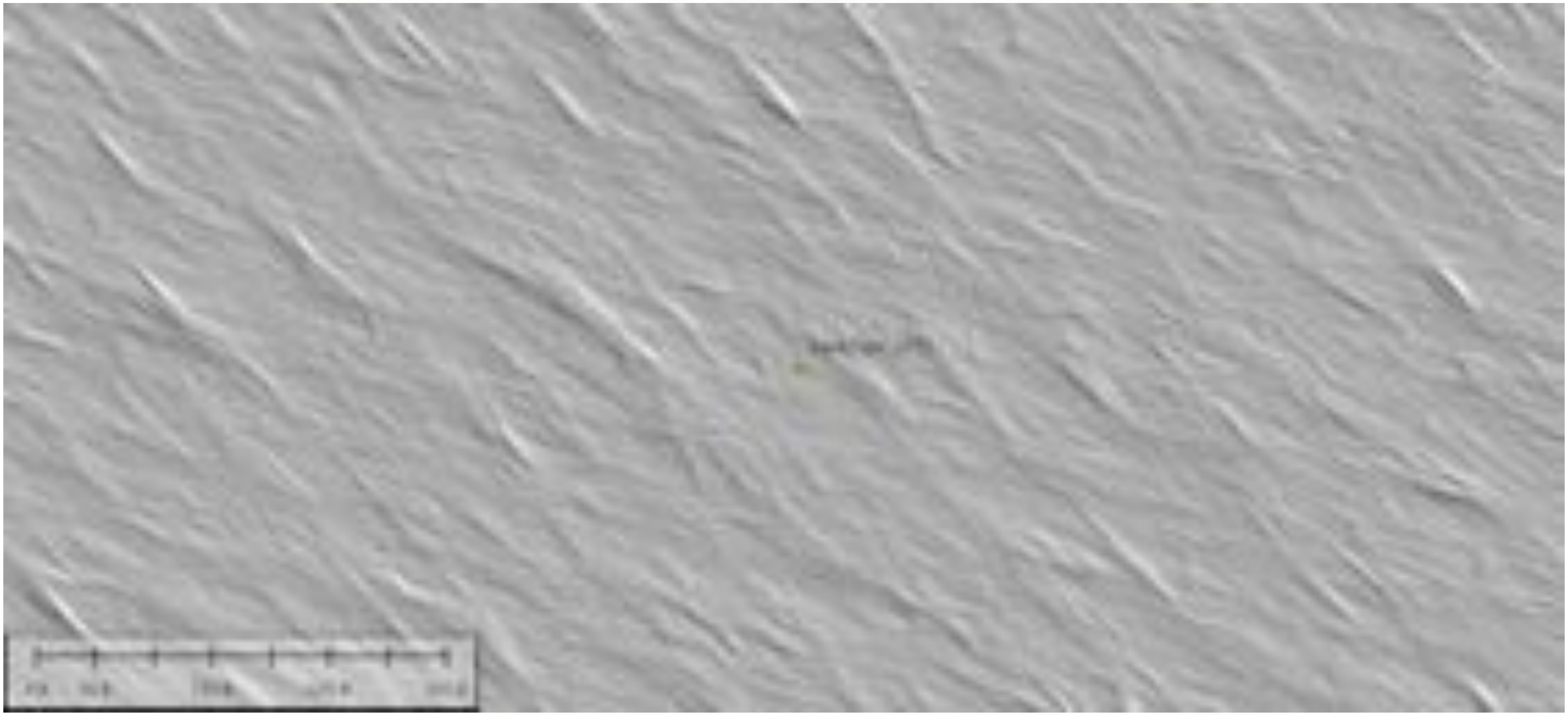
SuperTIGER Flight





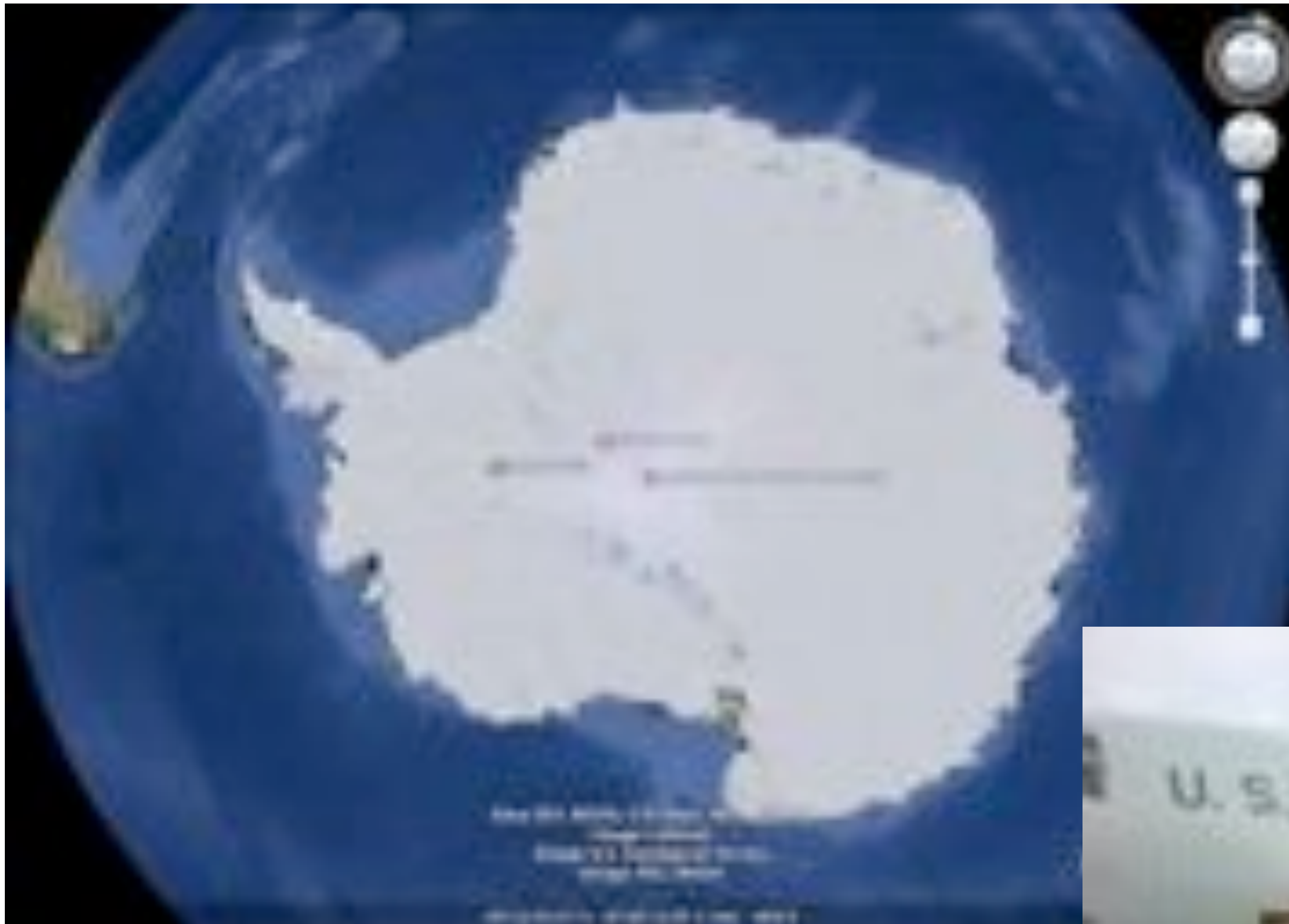
- Super-TIGER flew for 55 days, 1 hour, and 34 minutes.
  - Failure of on board solid-state disks resulted in 44 effective days of data
- NASA announced that this broke 2 records:
- Longest Antarctic Science Flight, Heavy-Lift Balloon
  - Previous Record: CREAM I at 41 days, 21 hours, 31 mins, 2004-5
- Longest Flight, Heavy-Lift Balloon
  - Previous Record: NASA SPB Test at 54 days, 1 hour, 29 minutes, 2008-9
- Came to rest on February 1, 2013 at 82°14.80’ S, 81°54.72’ W.
- Collected over 50 million cosmic-ray events via TDRSS/LOS

SuperTIGER Landing ...



- 82°14.80’ S, 81°54.72’ W

SuperTIGER (non)Recovery



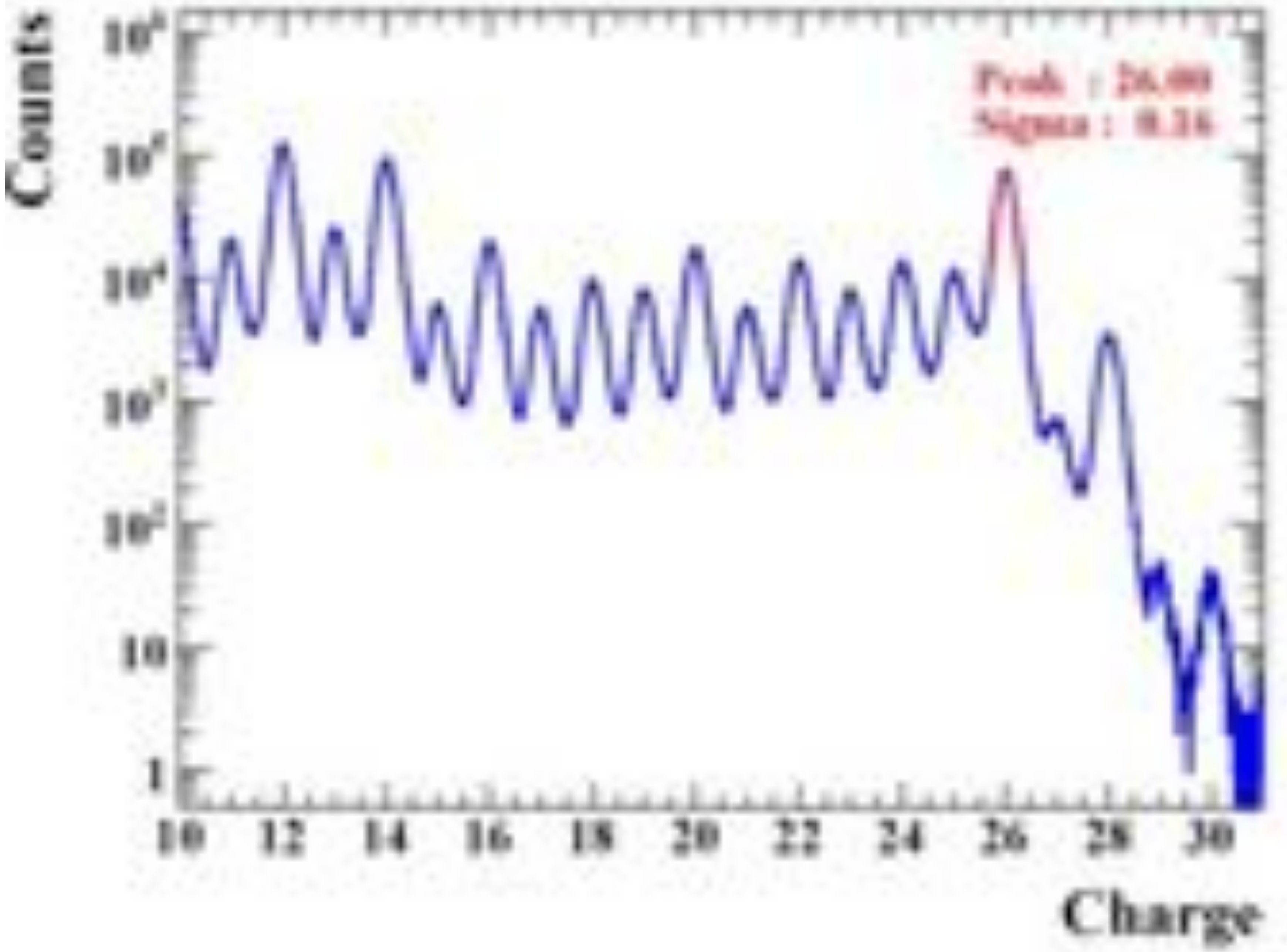
- Four person "science" recovery team (3 NASA GSFC, 1 WUSTL) + three person support team
- Deployed to McMurdo station January 3rd, 2014
- (non)Recovery of SuperTIGER payload was based out of Amundsen-Scott Station, South Pole

SuperTIGER (non)Recovery

- Recovery planned for 2014/2015 season

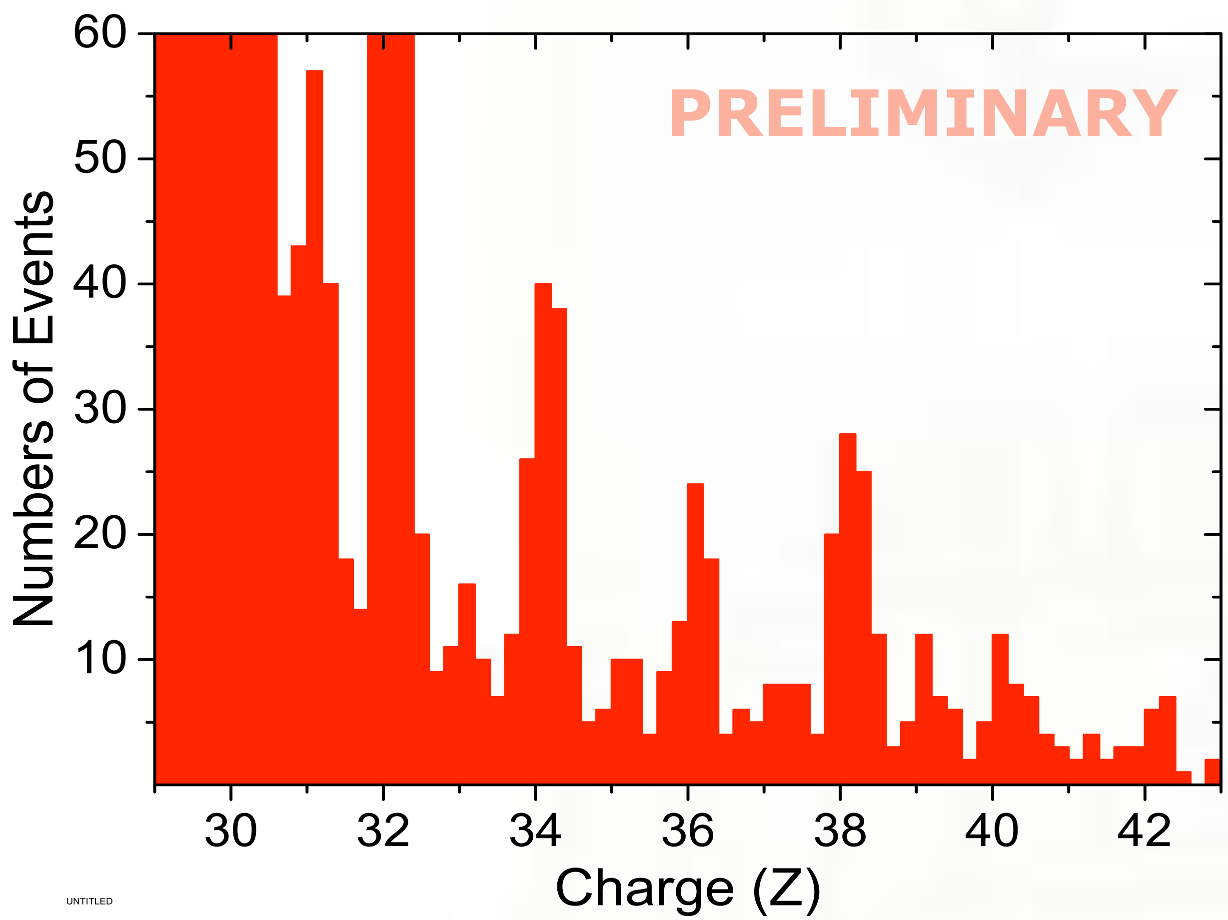
Preliminary Data

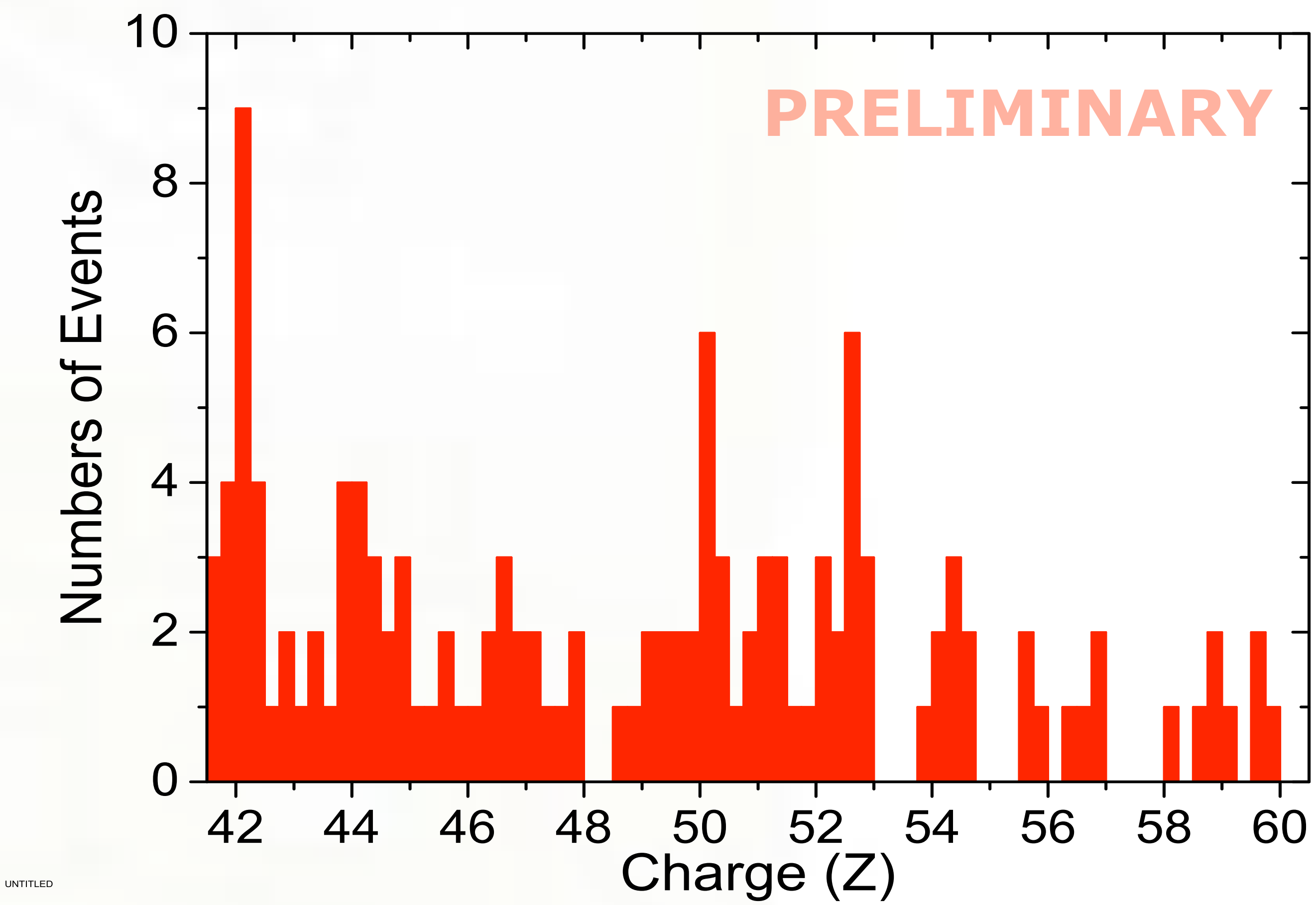
Courtesy of M. Sasaki



Histogram of combined low- and high-energy events
(bin size 0.01 cu)

Preliminary Data

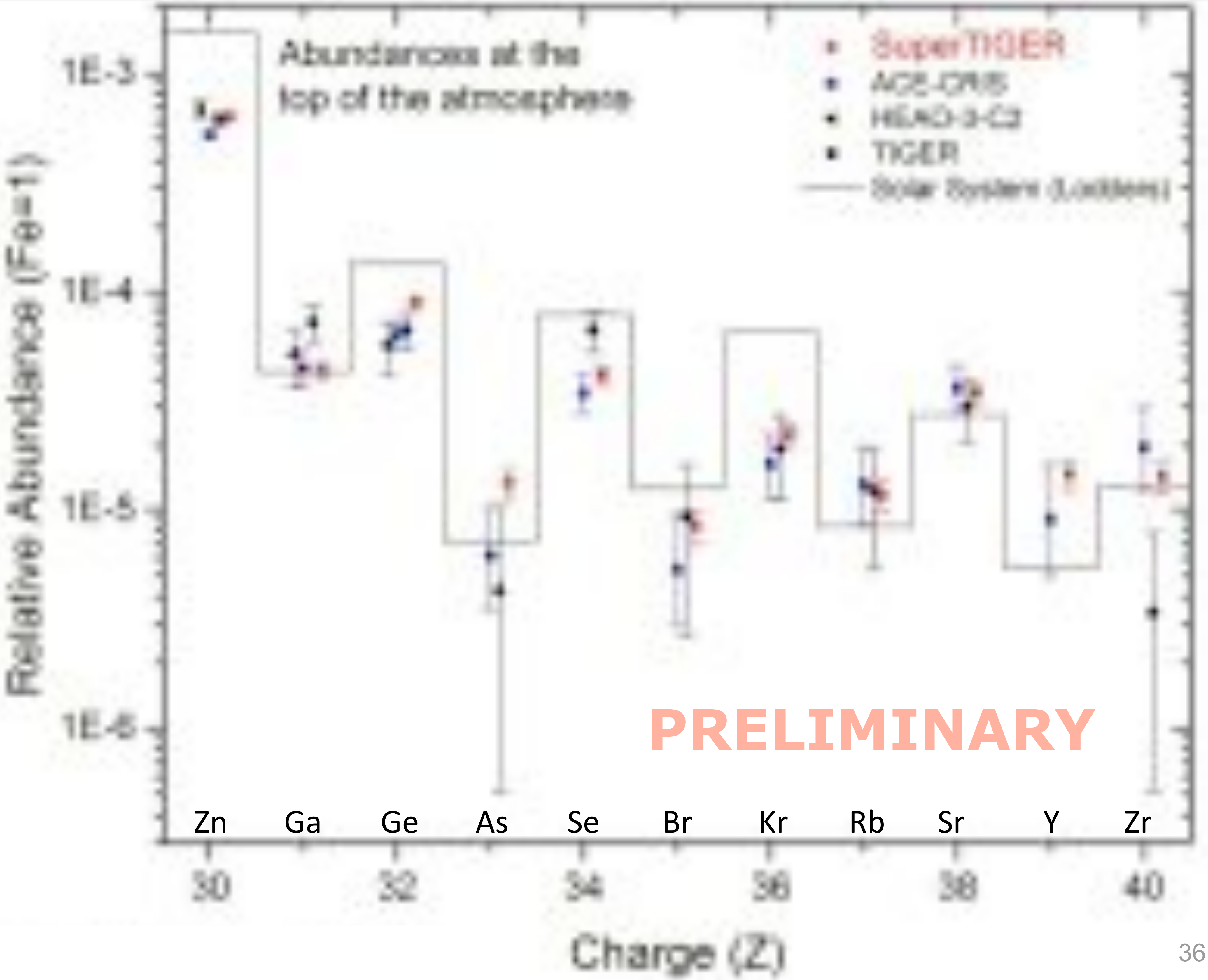




Preliminary abundances of 30 ≤ Z ≤ 42. We get well-defined charge peaks for every element from Z=30 to 40.

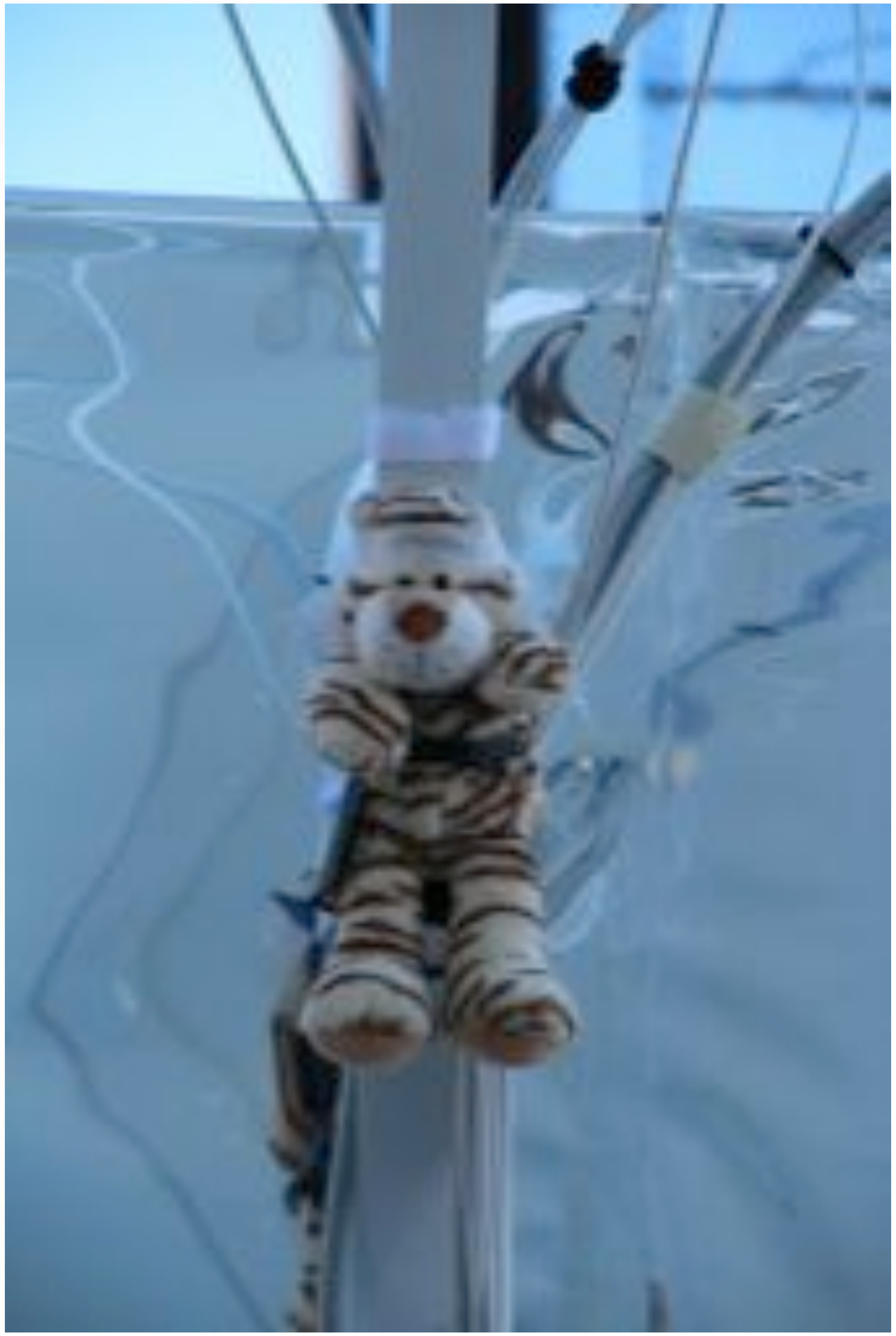
Above Z=42, we have very low statistics, but it appears that we still get charge peaks.

Preliminary Results



Conclusions and Future

- SuperTIGER measured cosmic-ray nuclei for 55 days over Antarctica
- Detectors worked as expected during flight
- Preliminary σ_z = 0.16 cu at Fe
- The first SuperTIGER flight has increased statistics > x6 over TIGER
  - $_{30}$Zn, $_{31}$Ga, $_{32}$Ge, $_{34}$Se and $_{38}$Sr (statistical uncertainties will be reduced by more than factor 2)
  - Sufficient data for $_{33}$As (mod-refr), $_{35}$Br (vol), $_{36}$Kr (highly-vol), $_{37}$Rb (mod-vol), $_{40}$Zr (refr)
- Further and strongly test the OB Association model of GCR origins
- Recover and refurbish the SuperTIGER payload (Dec 2014)
- SuperTIGER-2 proposal for even more statistics at higher charges



Thank you! Questions?

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