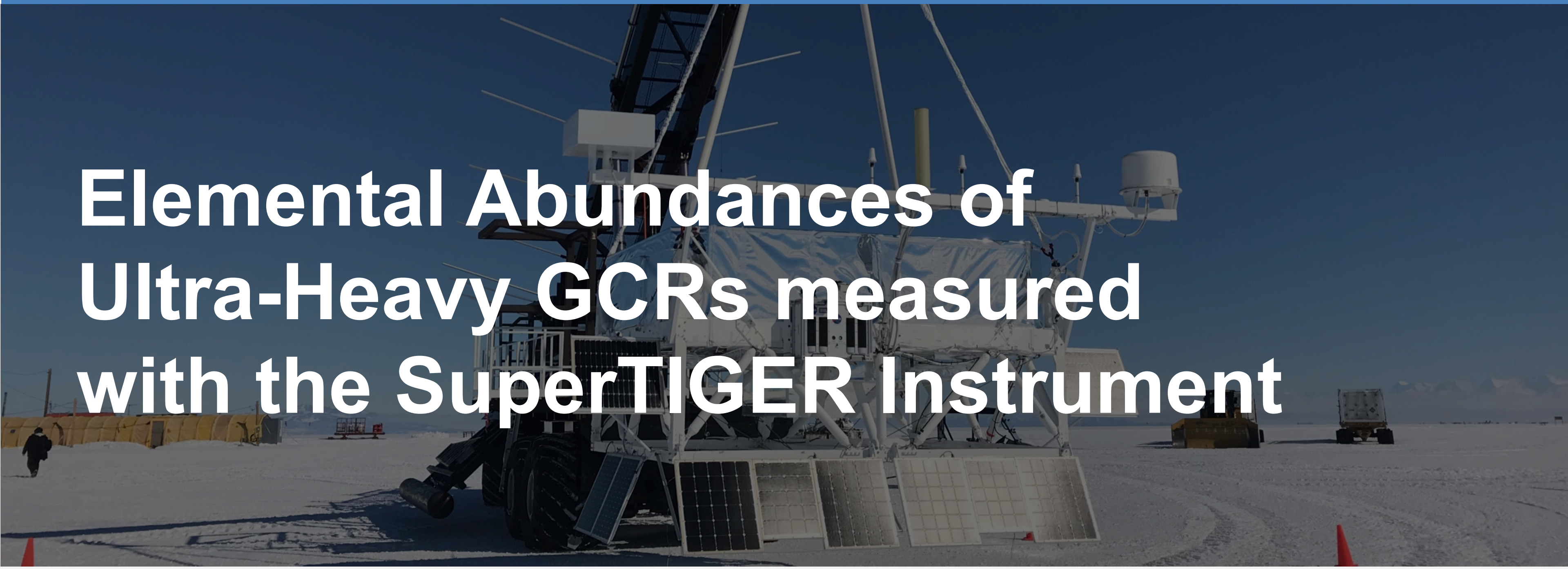
Elemental Abundances of Ultra-Heavy GCRs measured with the SuperTIGER Instrument



Kenichi Sakai
NASA/GSFC/CRESST/UMBC

For the SuperTIGER collaboration

20th International Symposium on Very High Energy Cosmic Ray Interactions
ISVHECRI2018

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Nagoya University, Nagoya, JAPAN

1 The SuperTIGER Collaboration

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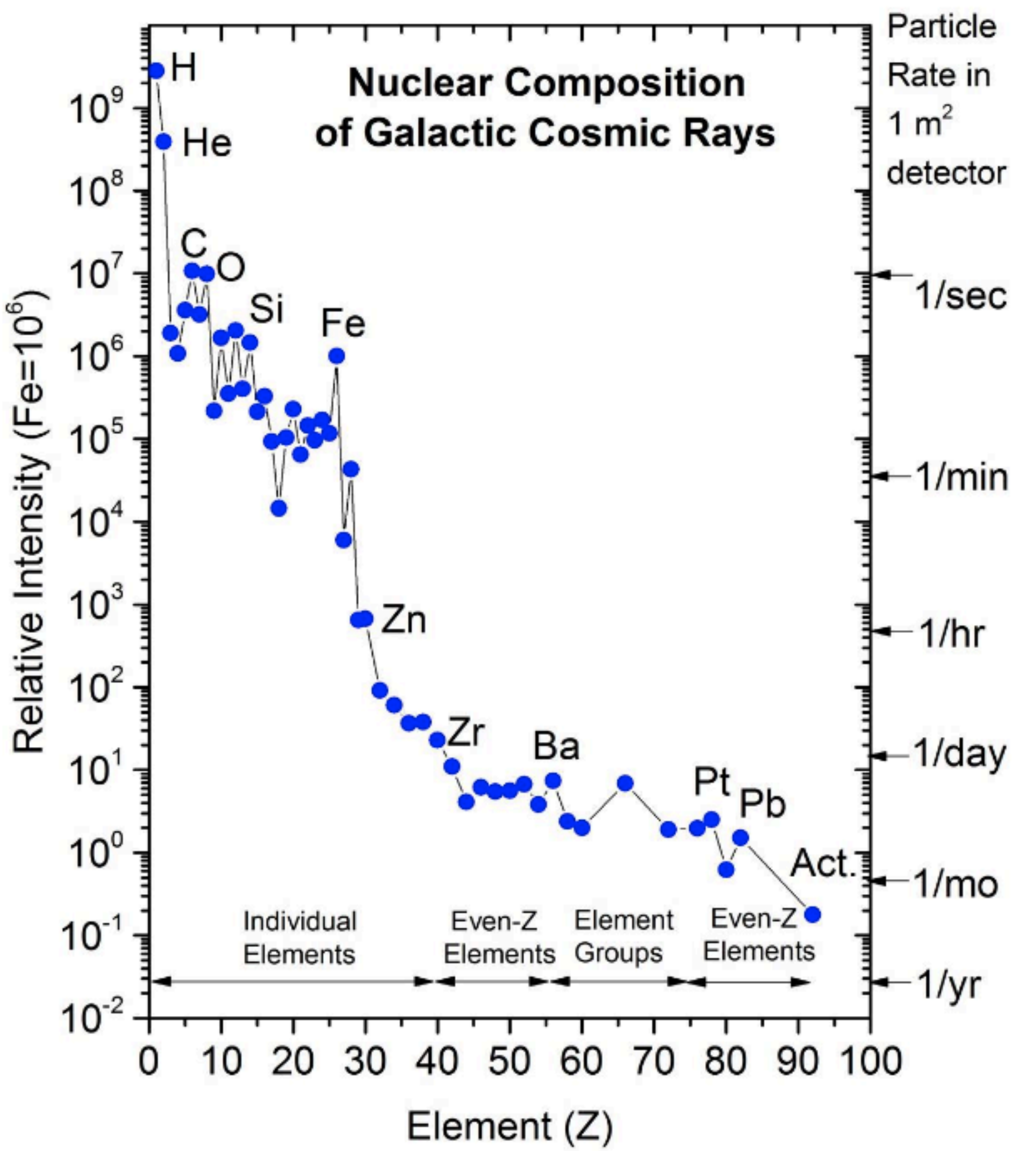
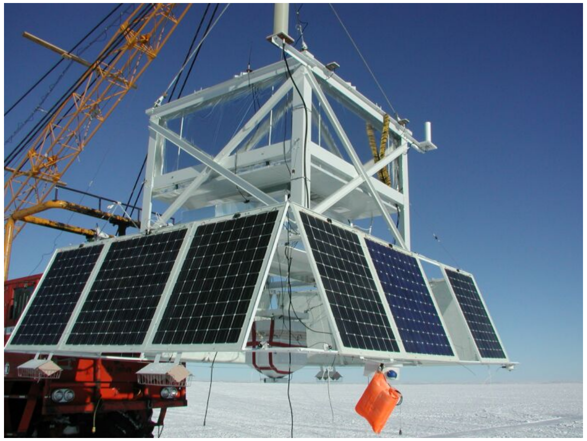
Elemental Abundances in GCRs

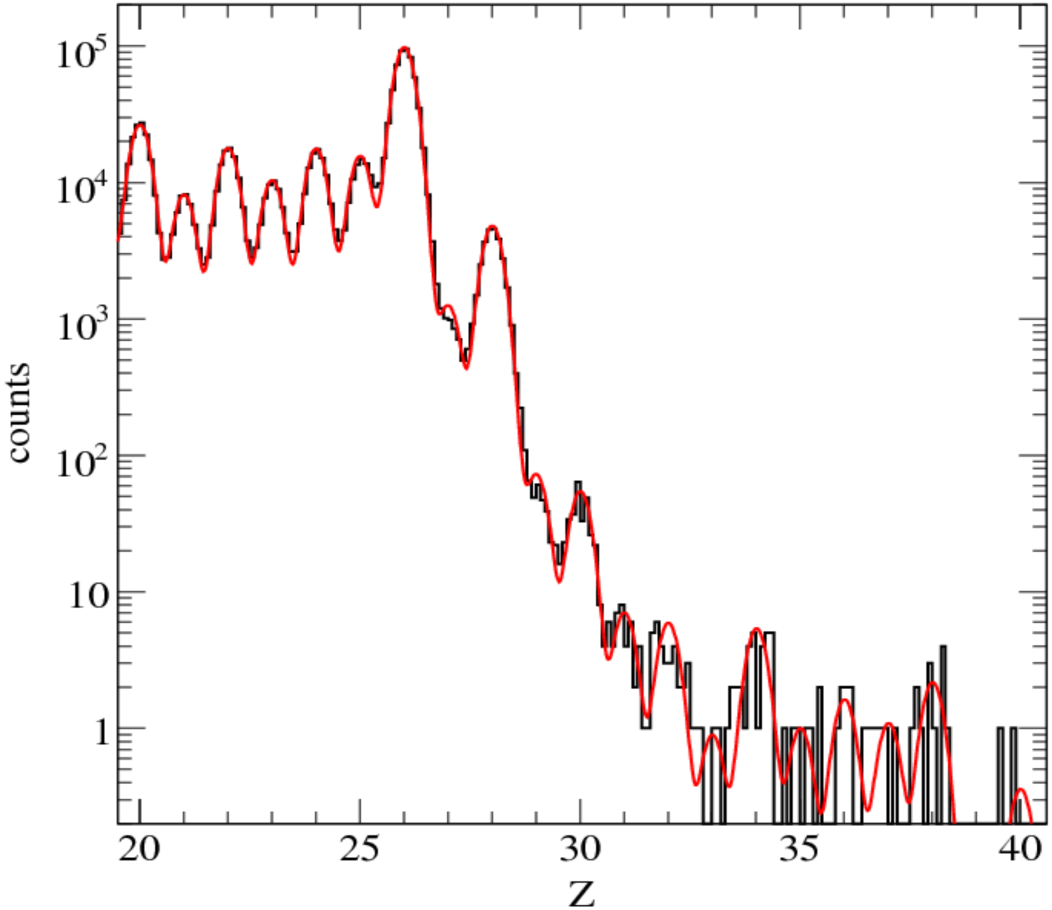
- Elements in the upper 2/3rds of the periodic table, are extremely rare compared to lighter elements.
- The heavy component contains unique information not obtainable from light cosmic rays.
- UH Measurement requires large instruments at the top of the atmosphere or in space for long exposure time.



3 Charge histograms from TIGER

Trans-Iron Galactic Element Recorder (TIGER)

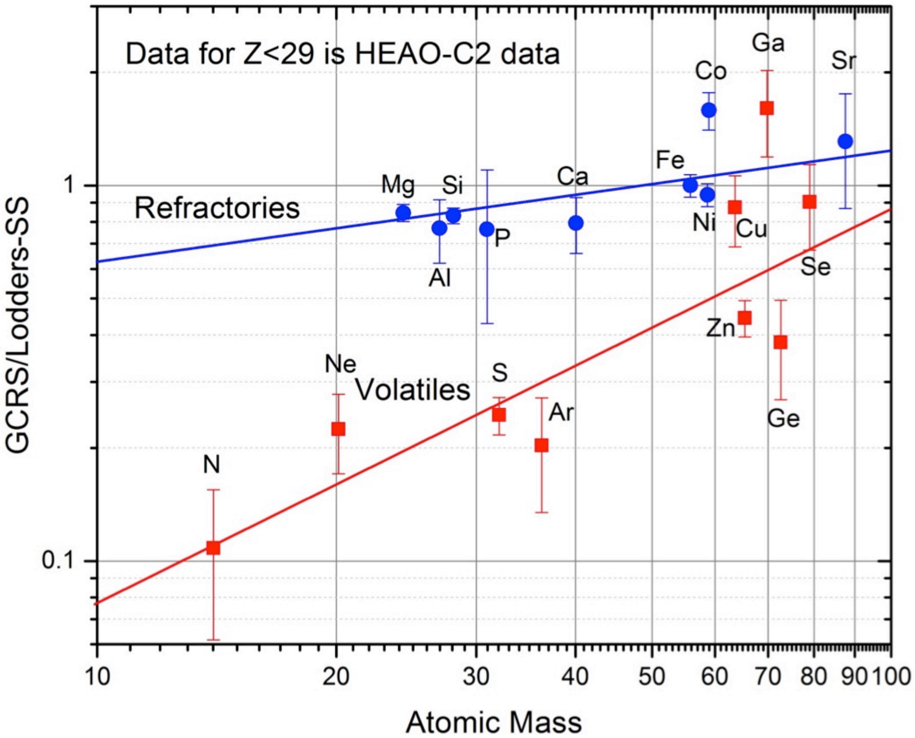




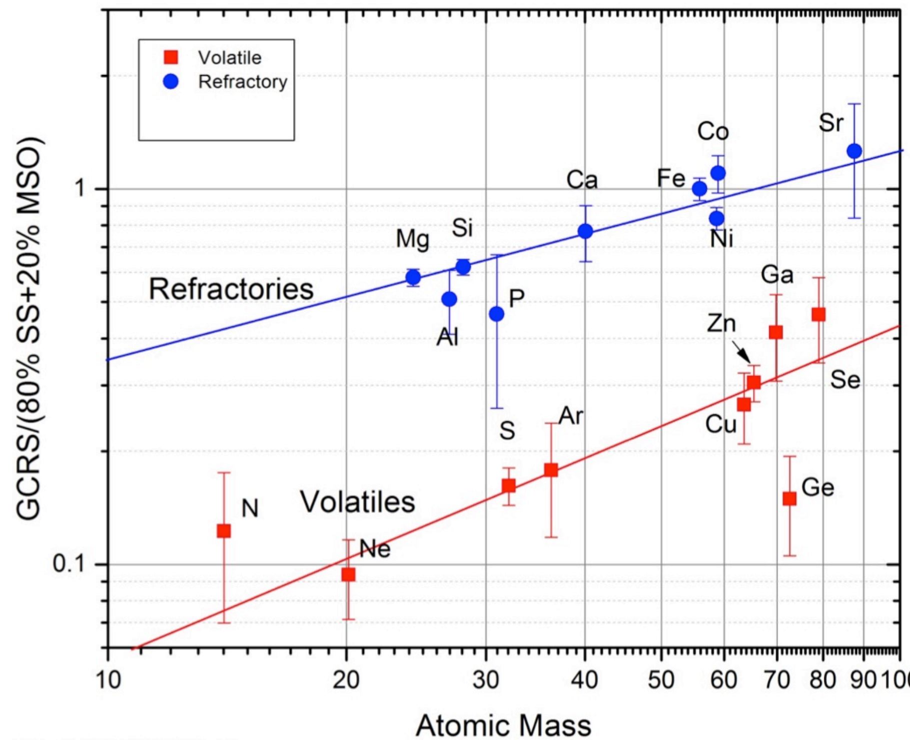
- Combined dataset from 50 days of flight over Antarctica in 2001-2002 and 2003-2004.
- Well defined peaks at $_{31}Ga$, $_{32}Ge$, $_{34}Se$
- limited statistics at higher Z

4 GCRS fractionation from TIGER & HEAO data

GCRS/SS



GCRS/(80% SS+20% MSO)



Meyer, Drury & Ellison ApJ. 487 182 (1997)

Preferential acceleration of dust (refractory) and mass-dependence of acceleration of cold ISM gas (volatiles).

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.

SuperTIGER-I

2012/2013 LDB flight

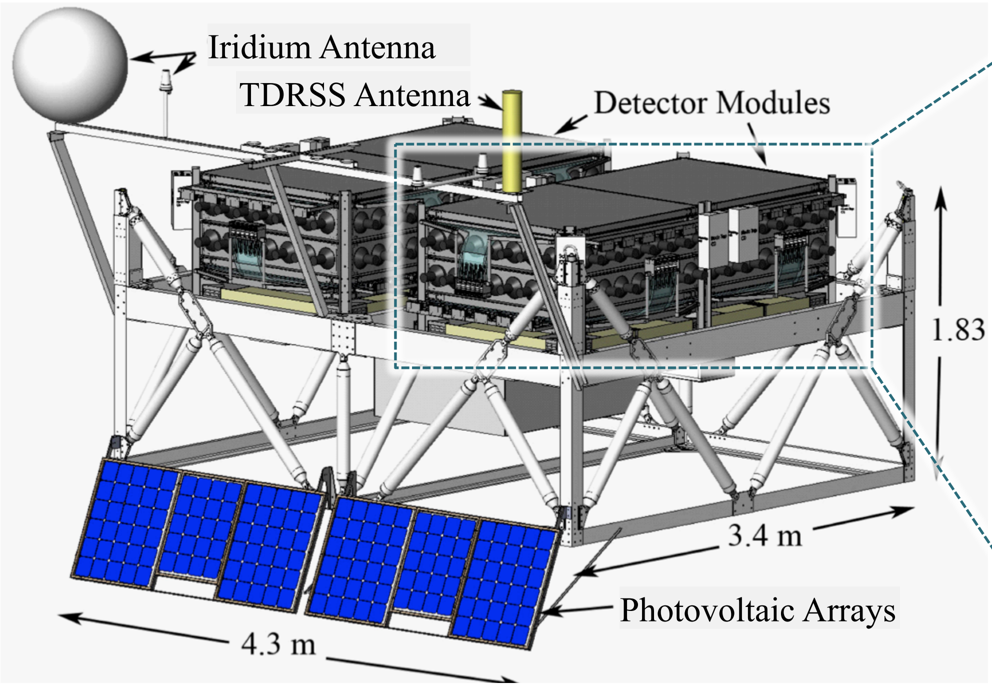
5 SuperTIGER-I Science Objectives

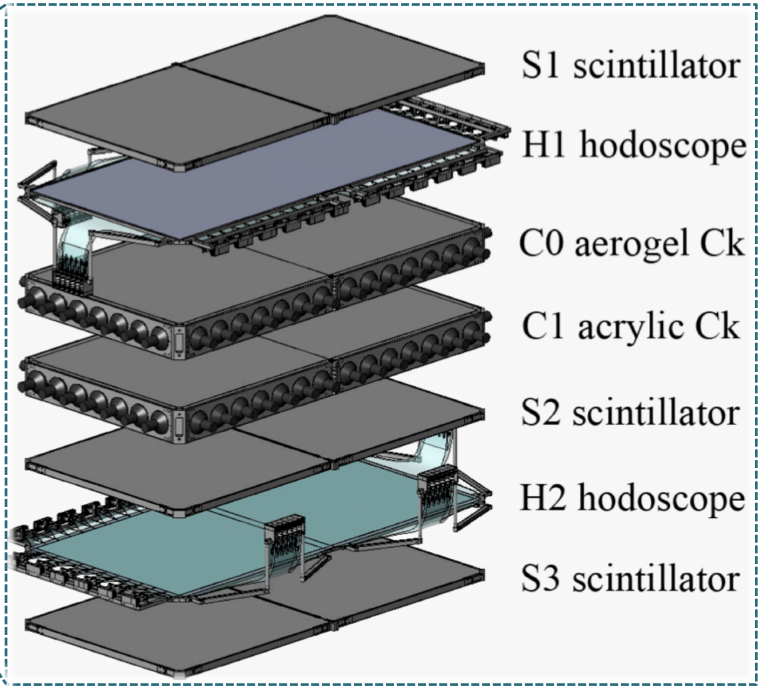
- Primary objectives
  - Measure composition of cosmic rays $26 \leq Z \leq 40$ with good statistics and individual-element resolution
  - Test of OB-association source model for galactic cosmic rays.
  - Test of mass dependence of acceleration.
- Secondary objectives
  - Energy spectra of elements $10 \leq Z \leq 28$ 0.8-10 GeV/nuc.
  - Search for evidence of nearby microquasars.

OB Association 30 Doradus in LMC
Credit: NASA, ESA, F. Paresce (INAF-IASF), R. O'Connell (U. Virginia), & the HST WFC3HST Science Oversight Committee

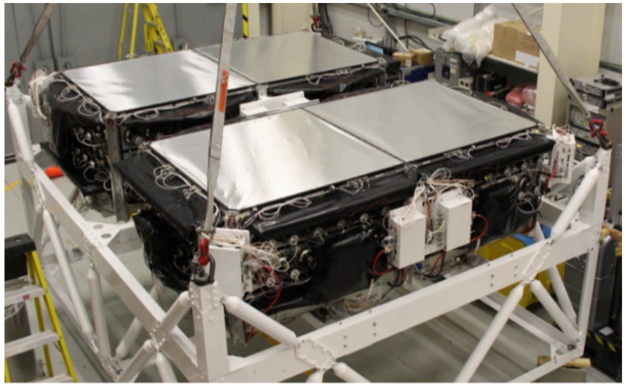
N44 Superbubble in LMC Diameter ~100pc
Credit: Gemini Obs, AURA, NSF

6 Instrument

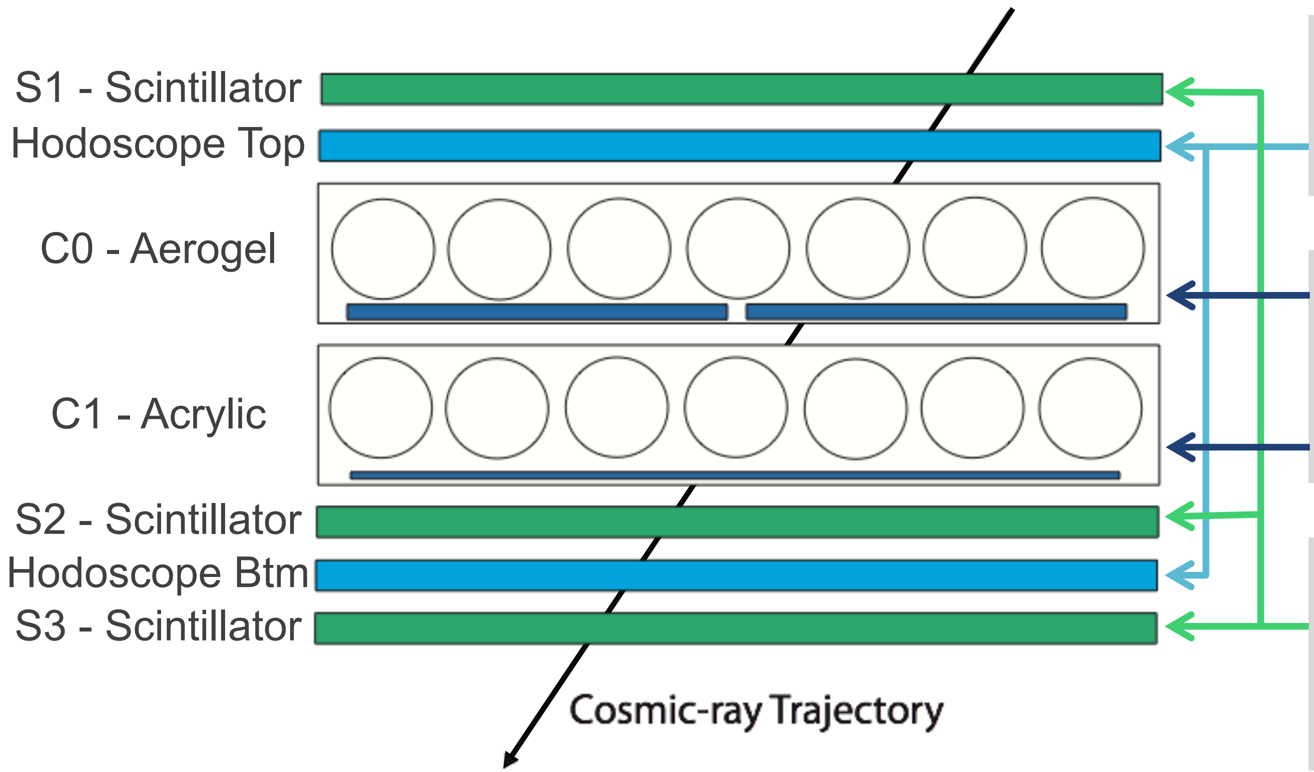




- Acceptance ~8.3 m^2sr
- 2 nearly identical modules, each module consists of
  - 2 scintillating fiber hodoscopes (H1, H2)
  - 3 Layers of scintillator detectors (S1, S2, S3)
  - Aerogel Cherenkov detector (C0, n=1.043, 1.025)
  - Acrylic Cherenkov detector (C1, n=1.49)



7 Measurement Technique



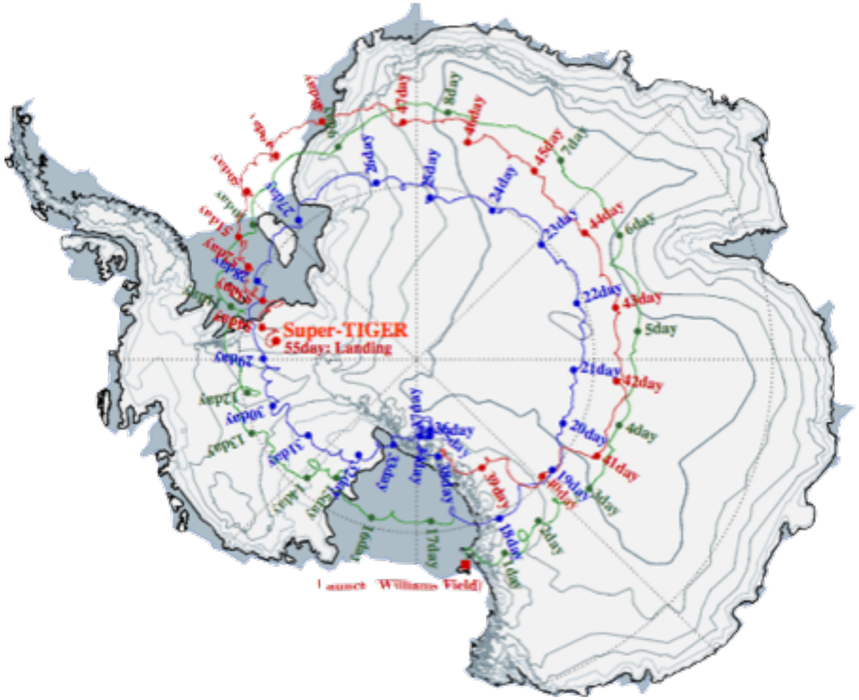
Hodoscope
Determine the trajectories of incident particles

Cherenkov Detector
Determine the charges and energy of incident particles

Scintillation Detector
Trigger and determine the charges of incident particles

Flight Status

SuperTIGER flight was carried out over Antarctica.

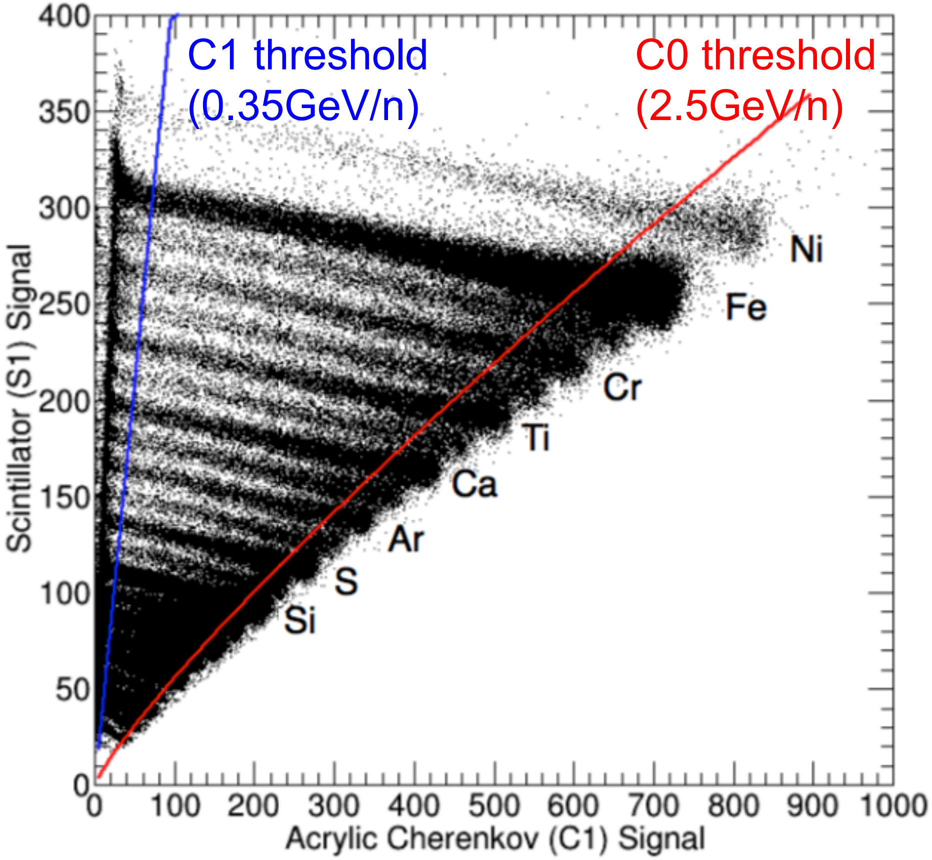


- SuperTIGER flew for 55 days, 1 hour, and 34 minutes
  December 9, 2012-February 2, 2013 (NZ)
- Collected over 50 million cosmic-ray events
  (~44 total days of data, 82% high-priority telemetry)
- SuperTIGER Recovery was carried out in the 2014/2015 Austral Summer.

Charge Determination

Low Energy (0.35~2.5GeV/n)

Scintillator VS Acrylic Cherenkov



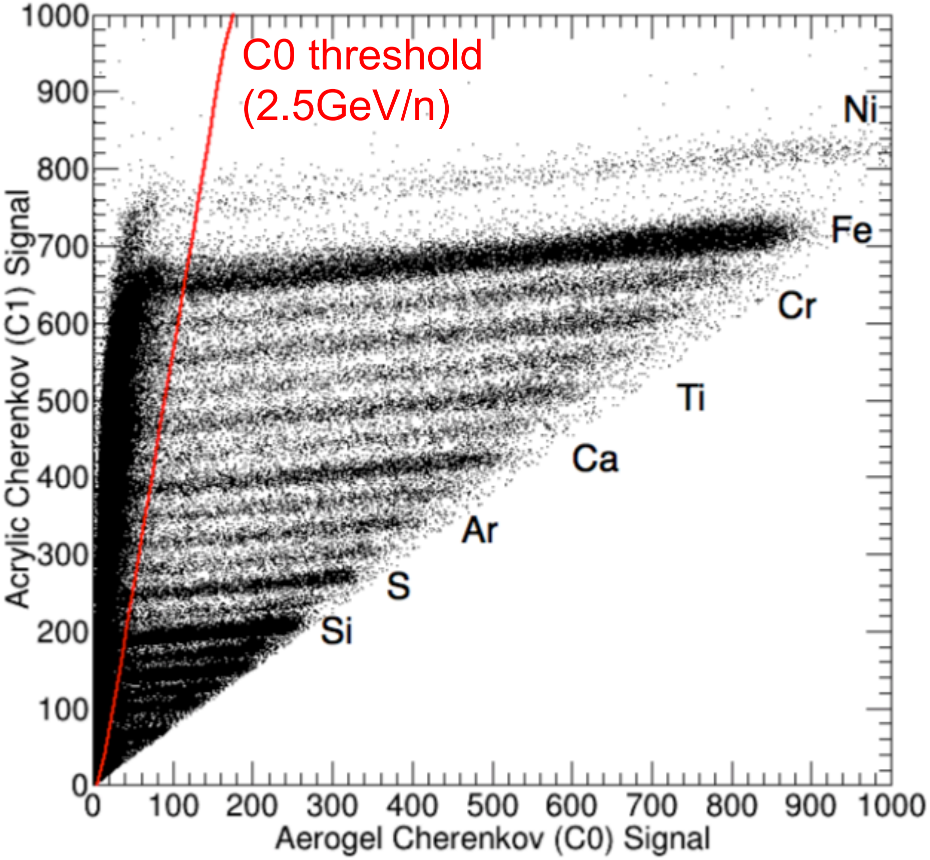
dE/dx-Cherenkov

$dE/dx = kZ^2/\beta^2$

$C1=k'Z^2[1/(1-n_1^2/\beta^2)]$

High Energy (>2.5GeV/n)

Acrylic Cherenkov VS Aerogel Cherenkov



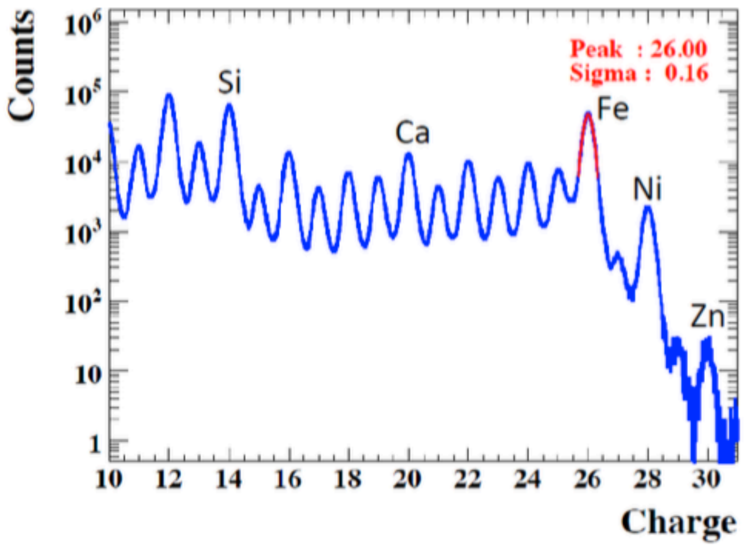
Cherenkov-Cherenkov

$C0=k''Z^2[1/(1-n_0^2/\beta^2)]$

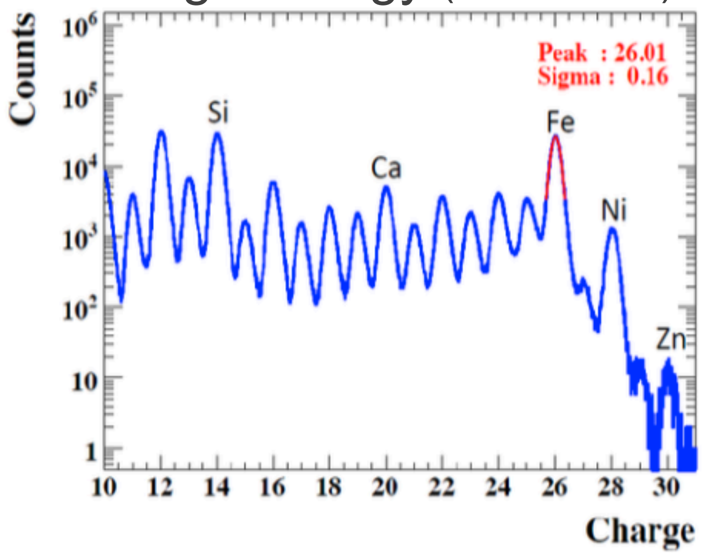
$C1=k'Z^2[1/(1-n_1^2/\beta^2)]$

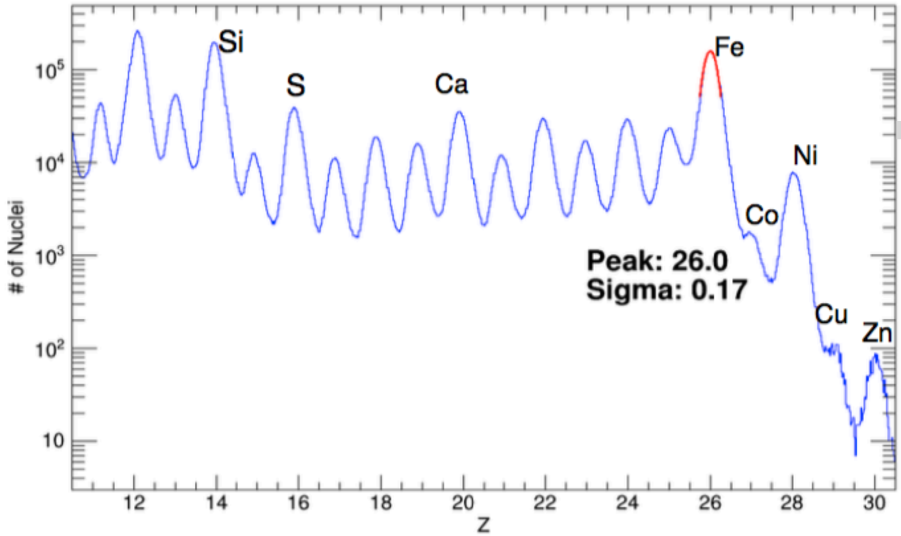
10 Resolution for Z ≤ 30

Low Energy (0.35~2.5GeV/n)



High Energy (>2.5GeV/n)

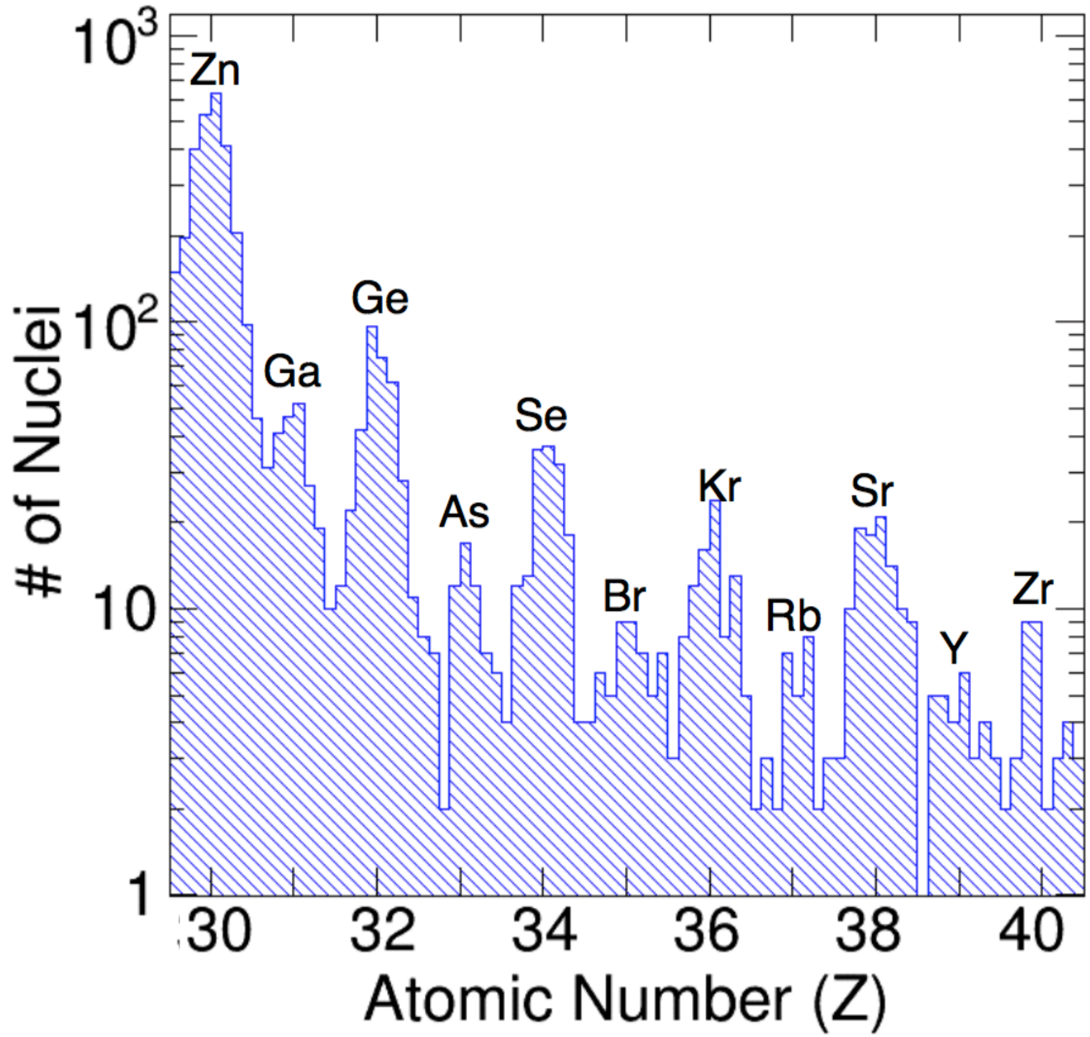




Combined

11 Charge histograms for 30 ≤ Z ≤ 40 nuclei

- First high statistics measurement of abundances of all elements with 30 ≤ Z ≤ 40
- Complementary to ACE measurement taken in space, but ACE has lower numbers of events

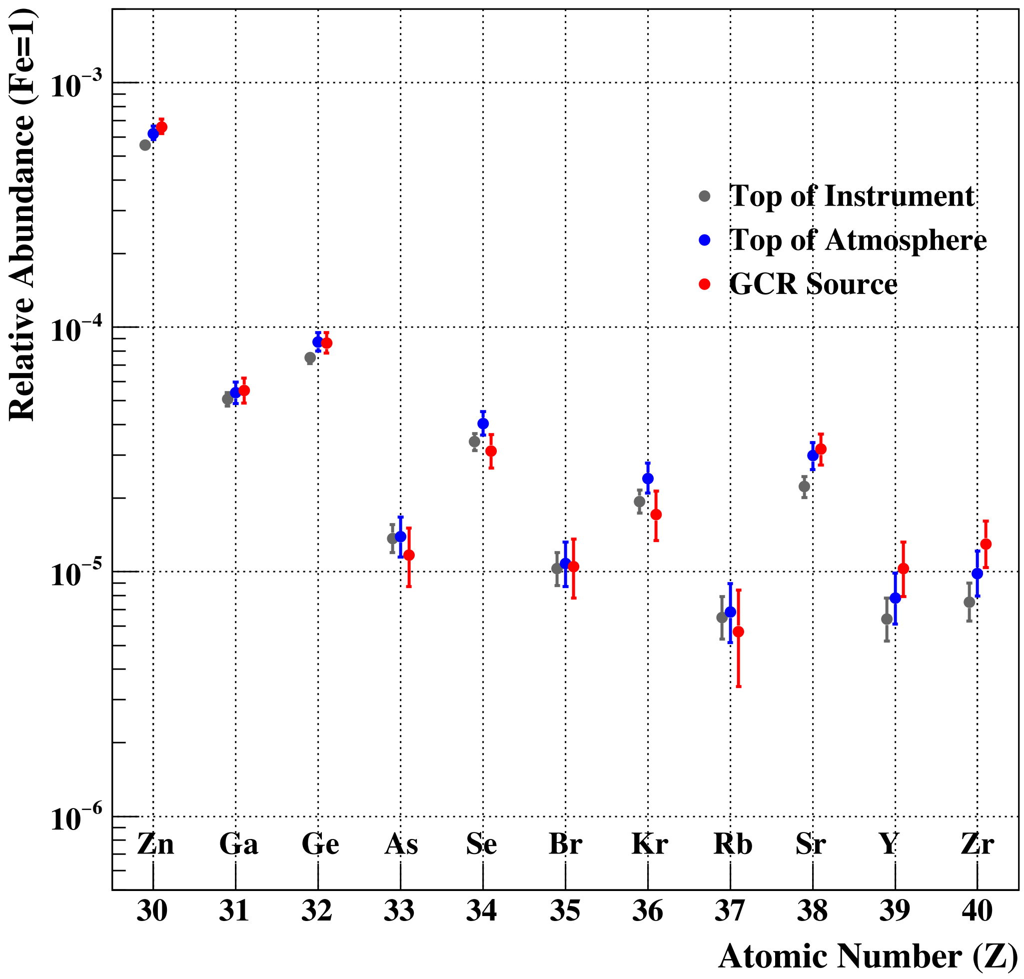


Air correction & Propagation to source

- TOI → TOA:
  Atmospheric correction of 4.4 g/cm^2 (36.6~39.6km) includes both the fraction of particles interacting (~36% for ^{34}Se) and secondary production.

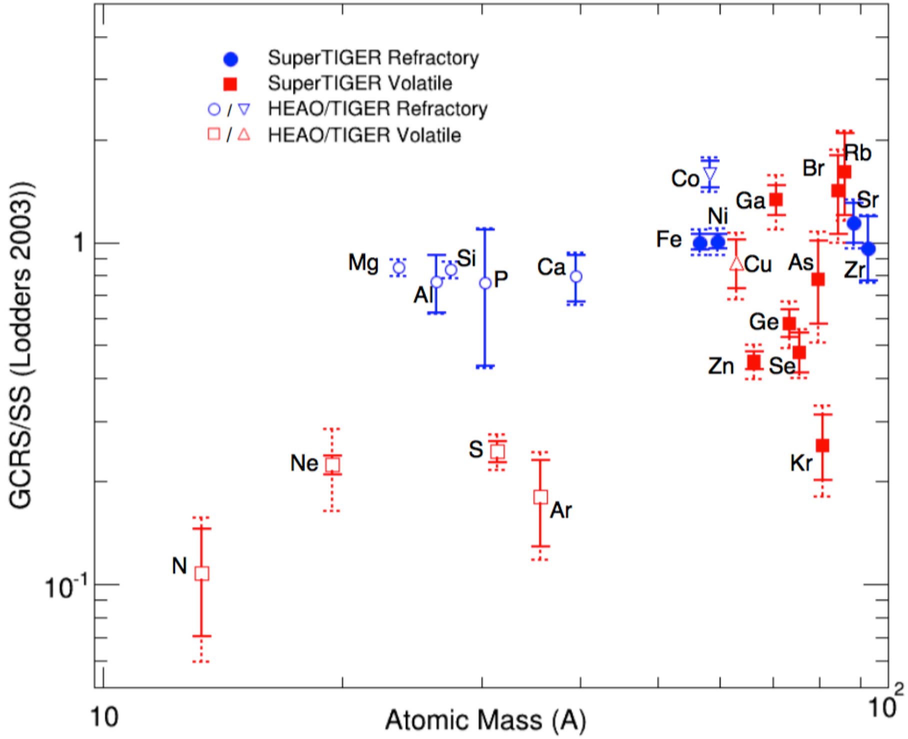
- TOA → Local interstellar:
  Solar modulation: Fisk model with a modulation parameter = 543 MV and a typical Top-of-Atmosphere energy of ~3.1 GeV/n.

- Local interstellar → Source:
  Leaky box propagation model (Wiedenbeck et al. 2007), which uses cross sections from Webber et al. (1990) and Silberberg et al. (1998).



13 GCRS fractionation from SuperTIGER-I

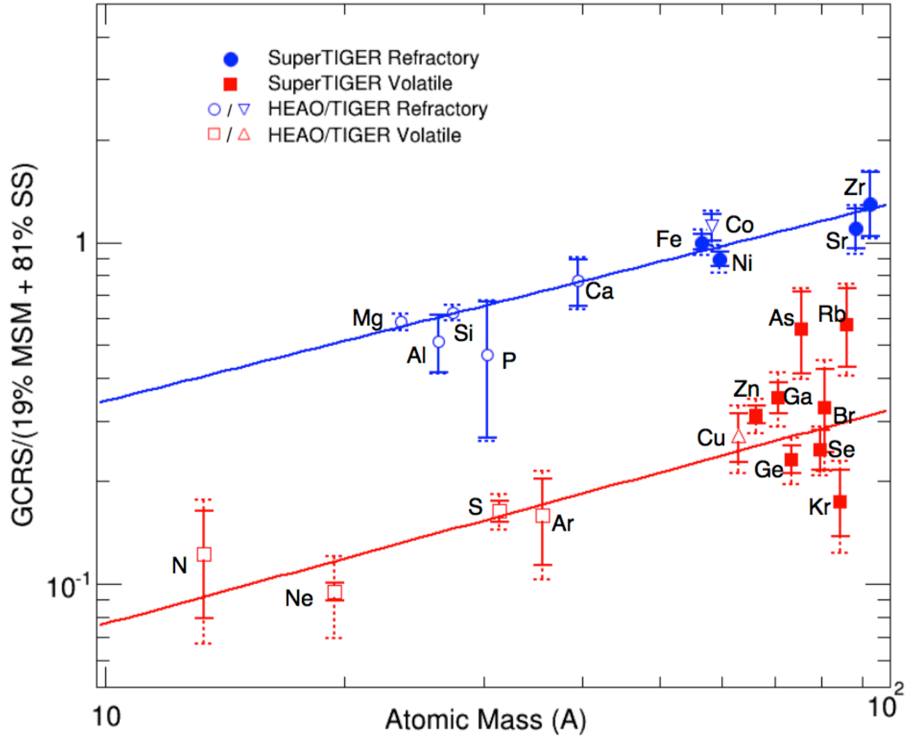
GCRS/SS



R. P. Murphy et al. ApJ. 831 148 (2016)

Ratio of GCRS abundances to SS abundances (Lodders 2003) vs. atomic mass (A).

GCRS/(81% SS+19% MSO)



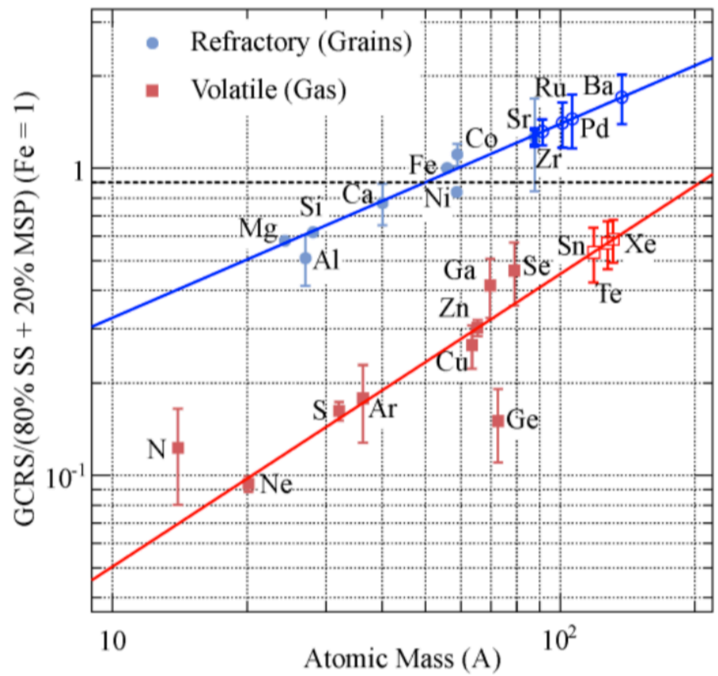
The reference abundances to which GCRS abundances are compared to a mixture of 81% SS abundances (Lodders 2003) and 19% MSO (Woosley & Heger 2007).

SuperTIGER-II

2017/2018 LDB Campaign

SuperTIGER-II Science Objectives

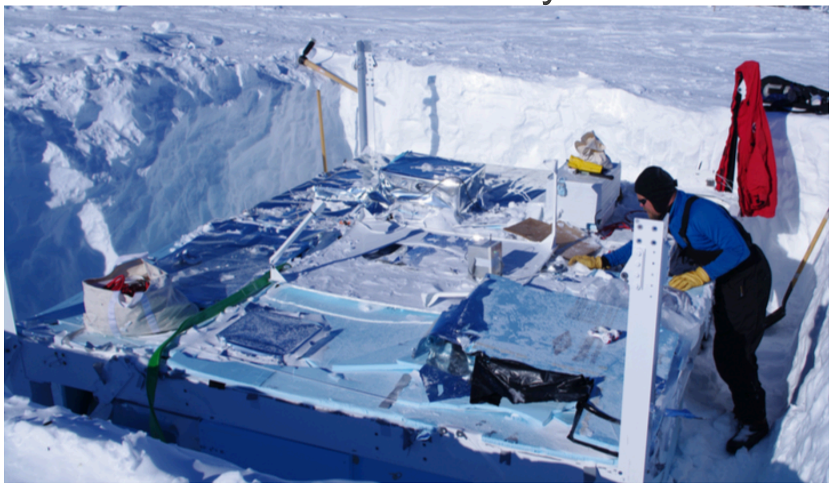
- Primary objectives
  - Measure composition of cosmic rays 26 ≤ Z ≤ 40 with good statistics and individual-element resolution (It's hard to define the peaks for Z > 40 due to limited statistics).
    SuperTIGER-I
  - Measure composition of cosmic rays 26 ≤ Z ≤ 40 with improved statistics and expand our measurements in the 40 ≤ Z ≤ 56 range
  - Test whether nuclei in the Z=50's charge range are produced and accelerated by the same sources as those in the Z ≤ 40 range



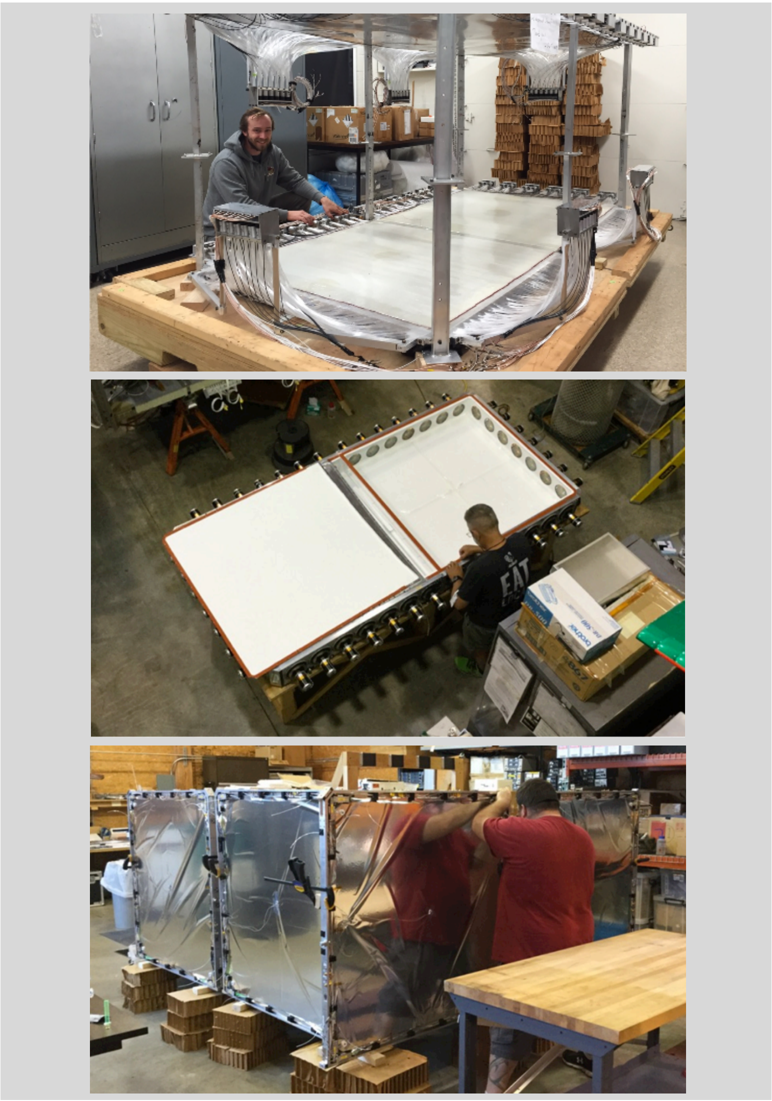
Expected data of $_{38}$Sr, $_{40}$Zr, $_{50}$Sn, $_{52}$Te, $_{54}$Xe and $_{56}$Ba detected by SuperTIGER (44 days+60 days)

15 From ST-I Recovery to ST-II Flight Ready

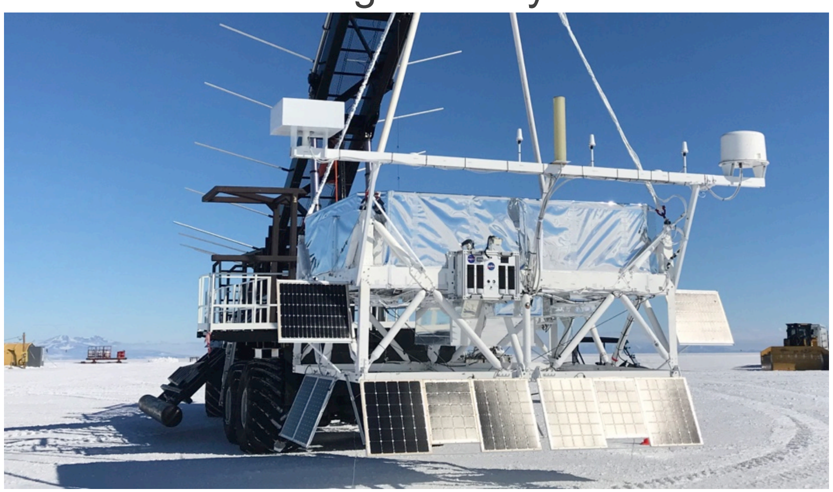
2014/2015 Recovery



2016/2017 Refurbish



2017 Flight Ready



16 16 Launch attempts of SuperTIGER-II in 2017/2018

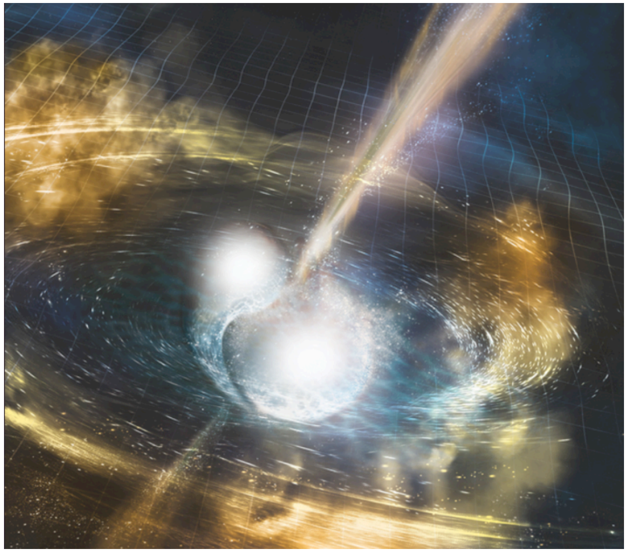
Dec09, 2017, 10:00:00	Showing 1st
Dec14, 2017, 18:00:00	Showing 2nd
Dec17, 2017, 18:00:00	Showing 3rd
Dec18, 2017, 18:00:00	Showing 4th
Dec 21, 2017, 16:00:00	Showing 5th
Dec24, 2017, 18:00:00	Showing 6th
Dec25, 2017, 23:00:00	Showing 7th
Dec29, 2017, 07:00:00	Showing 8th
Jan02, 2018, 04:00:00	Showing 9th
Jan02, 2018, 19:00:00	Showing 10th
Jan03, 2018, 16:00:00	Showing 11th
Jan07, 2018, 04:00:00	Showing 12th
Breaking McMurdo record of the most showings (GRIPS's record: 11 showings)	
Jan08, 2018, 04:00:00	Showing 13th
Jan10, 2018, 16:00:00	Showing 14th
Jan11, 2018, 10:00:00	Showing 15th
Jan14, 2018, 16:00:00	Showing 16th

…

Jan15, 2018, 12:22:00
Campaign Termination

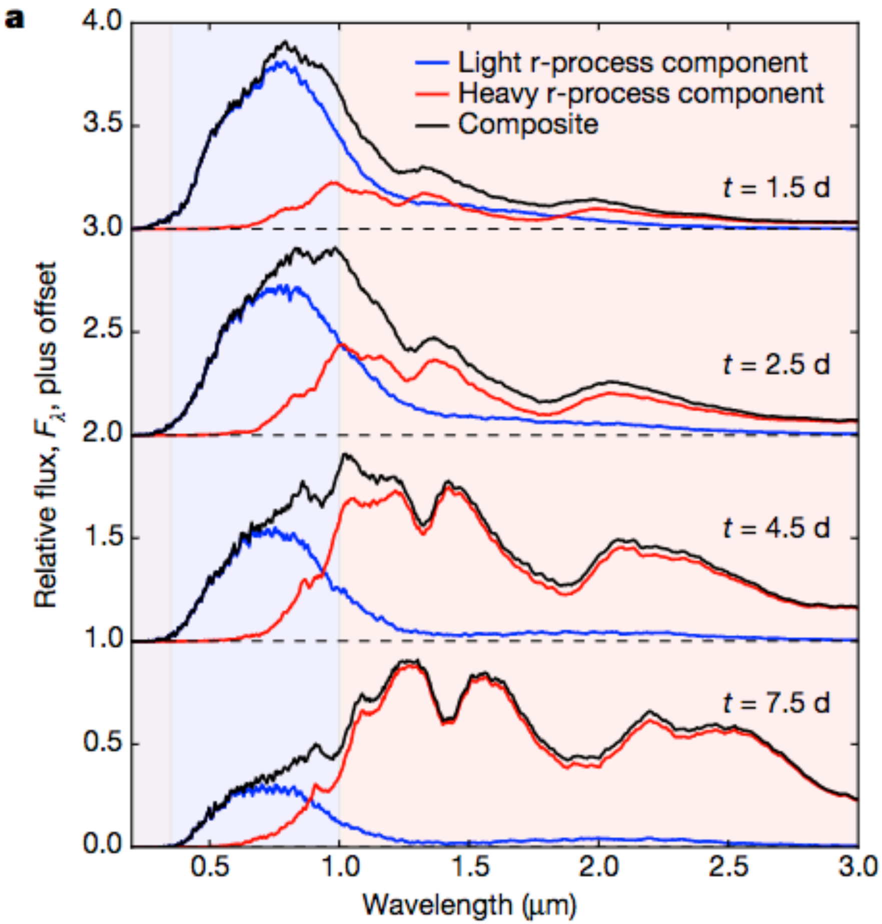
2018/2019 LDB flight

Heavy r-process elements in binary neutron star mergers



Binary neutron star mergers (BNSM)
Credit: LIGO Caltech

- Analysis of light curves from GW170817 suggests ultra-heavy elements like gold and platinum are produced in the kilonova from the binary neutron star merger.
  - Light r-process elements: 28 ≤ Z ≤ 58
  - Heavy r-process elements: 58 ≤ Z ≤ 90

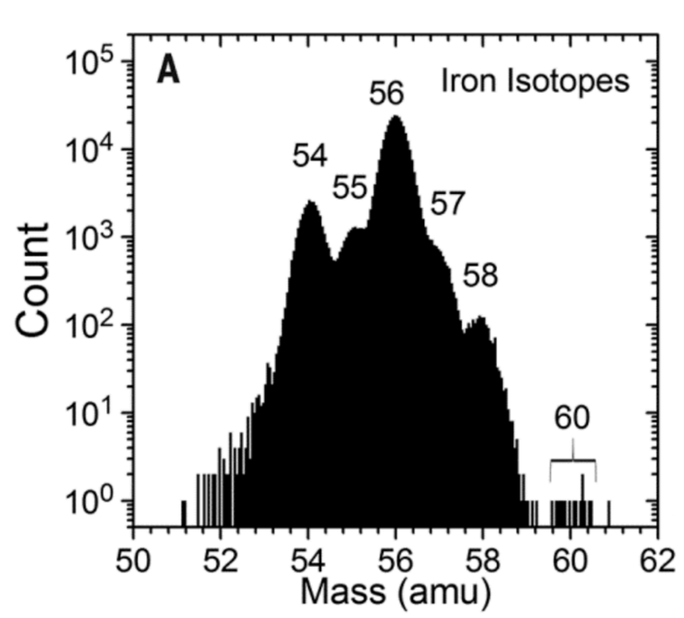


D Kasen et al. Nature 551, 80–84 (2017)

18 Source of heavy r-process nuclei: SNe VS BNSM

- Recent measurement of $_{60}$Fe (radioactive with half-life 2.6 Myr) by the ACE-CRIS experiment is the first conclusive evidence that there is a recently synthesized component in the cosmic rays
- The $_{60}$Fe almost certainly comes from SNe from nearby Sco-Cen OB associations

W. R. Binns et al., Science 10.1126 (2016)



- If SNe synthesize and accelerate all of the r-process nuclei
  - expect to see significant numbers of the short lived $_{94}$Pu and $_{96}$Cm
- If binary neutron star mergers (BNSM) are the source of the heavy r-process nuclei
  - expect to see little or no $_{94}$Pu and $_{96}$Cm since BNSM in the vicinity of the solar system are much less frequent than SNe and the short lived $_{94}$Pu and $_{96}$Cm should have mostly decayed

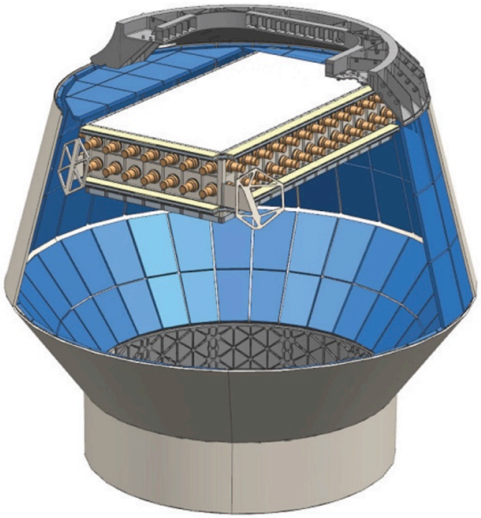
HNX Mission

Space based experiment (proposed)

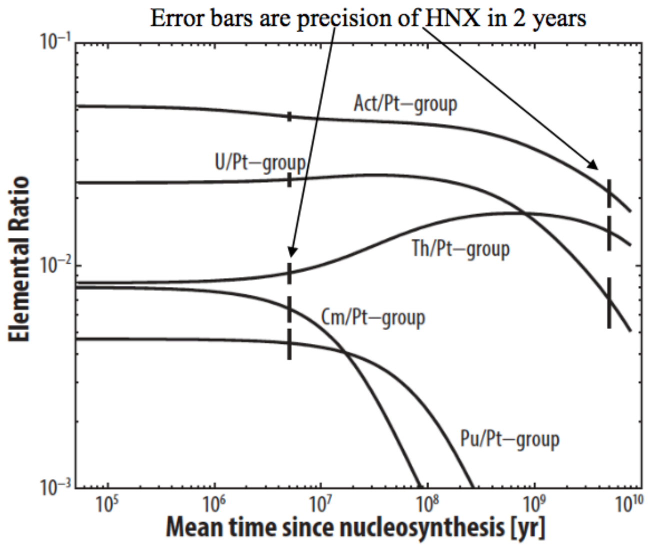
HNX Science Objectives

○ Primary objectives

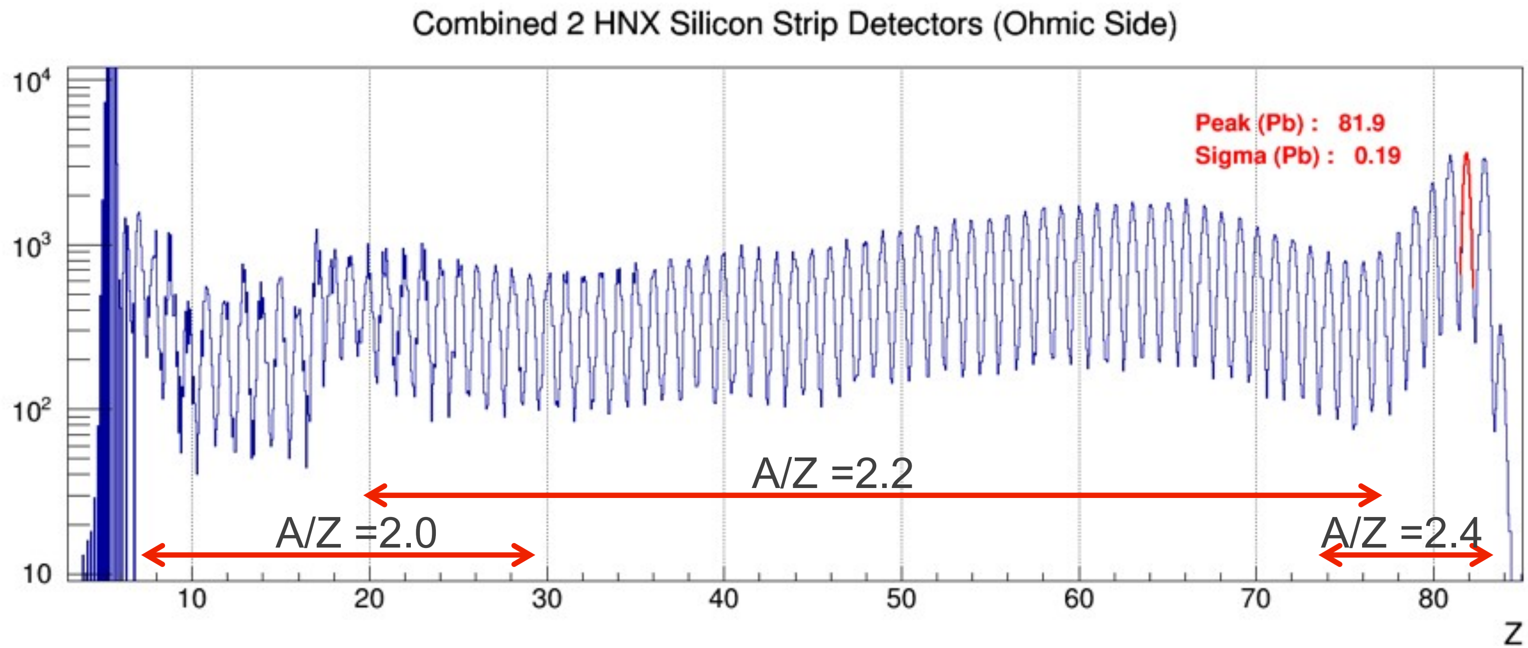
- Measure composition of cosmic rays $26 \leq Z \leq 56$ with good statistics and individual-element resolution (Charge resolution of $Z > 56$ is reduced due to scintillator saturation).
  SuperTIGER-II

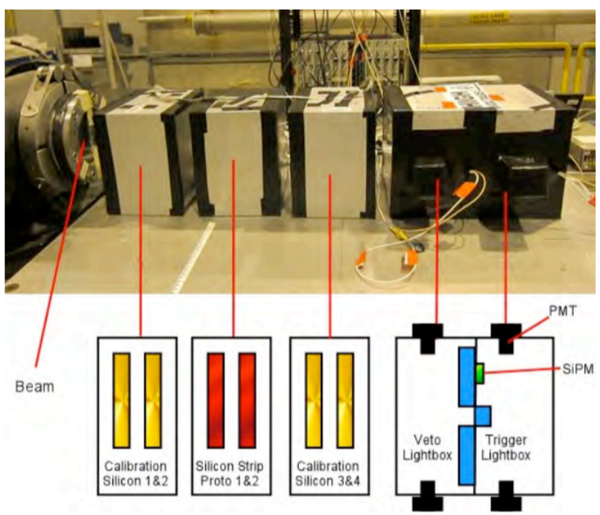


- Measure composition of cosmic rays $6 \leq Z \leq 96$ with ECCO (21 m^2 of Barium Phosphate glass) and CosmicTIGER (2 m^2 Silicon and Cherenkov Detectors) on DragonLab Capsule
- Because actinides ($89 \leq Z \leq 103$) are clocks that measure absolute age of the UHGCR, HNX will determine whether UHGCRs are accelerated from newly synthesized or old material.



20 CERN SPS Test (Pb beam, Nov 2016)





- The 500 µm thick, single-sided prototype silicon detectors have 32 DC-coupled strips with 3 mm pitch on the junction side with an approximate 10 × 10 cm^2 active area.

- The prototype SSD can measure nuclei from carbon through lead with superb charge resolution, $\sigma_Z < 0.2$ at Z = 82 in CERN Pb beam test.

Summary

○ SuperTIGER-I

- The first flight of SuperTIGER in December, 2012 was highly successful
- 55 day flight duration: Breaking the record for the longest flight by a balloon of its size
- Measured the elemental abundances of GCR from $_{26}Fe$ to $_{40}Zr$
- The results support a model of cosmic-ray origin in OB associations, with a source mixture of 19% MSM and 81% normal ISM material with solar system abundances (Based on the models of Woosley & Heger 2007 and Lodders 2003)
  R. P. Murphy et al. ApJ. 831 148 (2016)

○ SuperTIGER-II (expand measurements in the $40 \leq Z \leq 56$)

- The second flight of SuperTIGER in December, 2017 was cancelled due to bad weather
- 16 flight attempts: Breaking McMurdo record of the most showings
- Next LDB flight in 2018

○ HNX (for measurements in the $6 \leq Z \leq 96$)

- The silicon strip detector was tested with CERN SPS beam