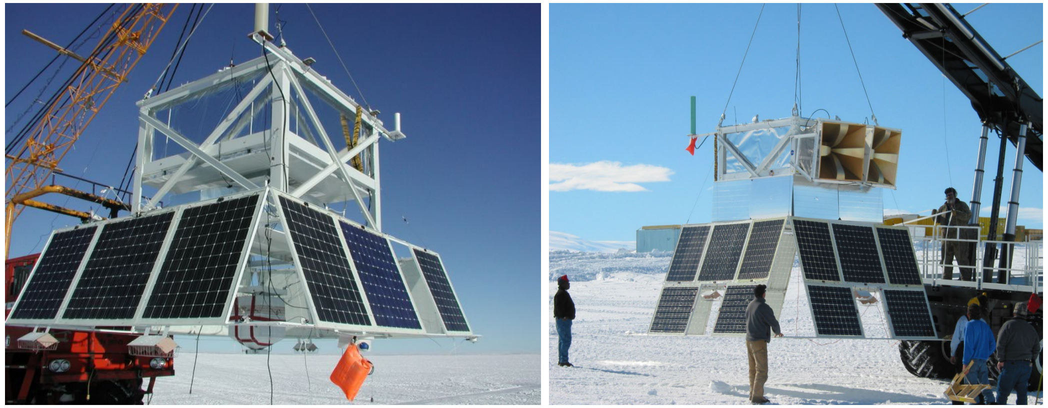
Ultra-Heavy Galactic Cosmic Ray Measurements with TIGERs

Brian Flint Rauch

November 4, 2025

TIGER: Trans-Iron Galactic Element Recorder
SuperTIGER: Super Trans-Iron Galactic Element Recorder
TIGERISS: Trans-Iron Galactic Element Recorder for the International Space Station

TIGER

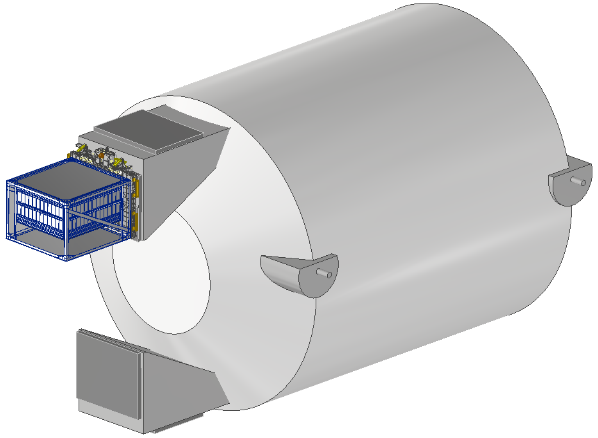


2001 for 32 days & 2003 for 18 days

SuperTIGER

2012 for 55 days & 2019 for 32 days

TIGERISS Columbus-SOX Payload



September 2027 launch

TIGER Collaboration

1995/1996: Lynn Lake, MB, Canada

Washington University in St. Louis: J.J. Beatty, W.R. Binns, D.J. Crary, D.J. Ficnec, P.L. Hink, J. Klarmann, D.J. Lawrence, **B.F. Rauch**
Goddard Space Flight Center: L.M. Barbier, E.R. Christian, K.E. Krombel, **J.W. Mitchell**, R.E. Streitmatter
University of Minnesota: C.J. Waddington

1997: Ft. Sumner, NM

TIGERISS Team Members

Washington University in St. Louis: W.R. Binns, J.R. Cummings, P.L. Hink, M.H. Israel, S.H. Sposato
California Institute of Technology: G.A. de Nolfo, R.A. Mewaldt, S.M Schindler
Goddard Space Flight Center: L.M. Barbier, E.R. Christian, **J.W. Mitchell**, R.E. Streitmatter
University of Minnesota: C.J. Waddington

TIGER-LDB Collaboration

Trans-Iron Galactic Element Recorder

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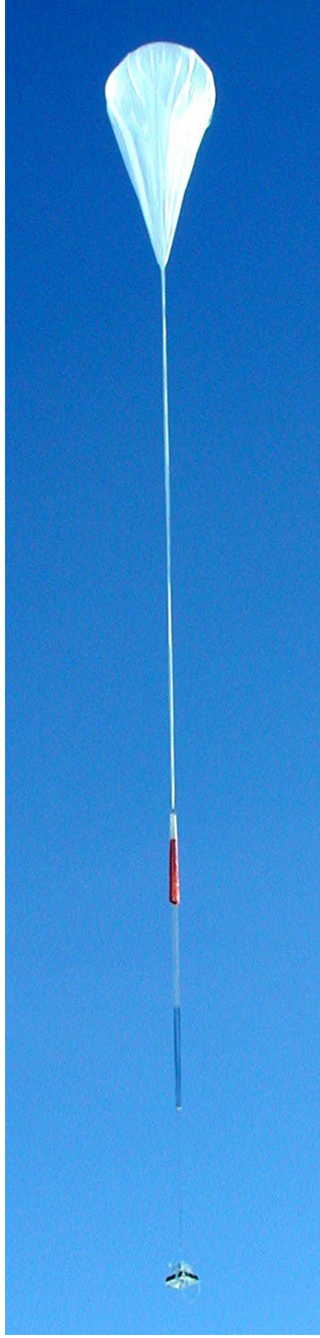
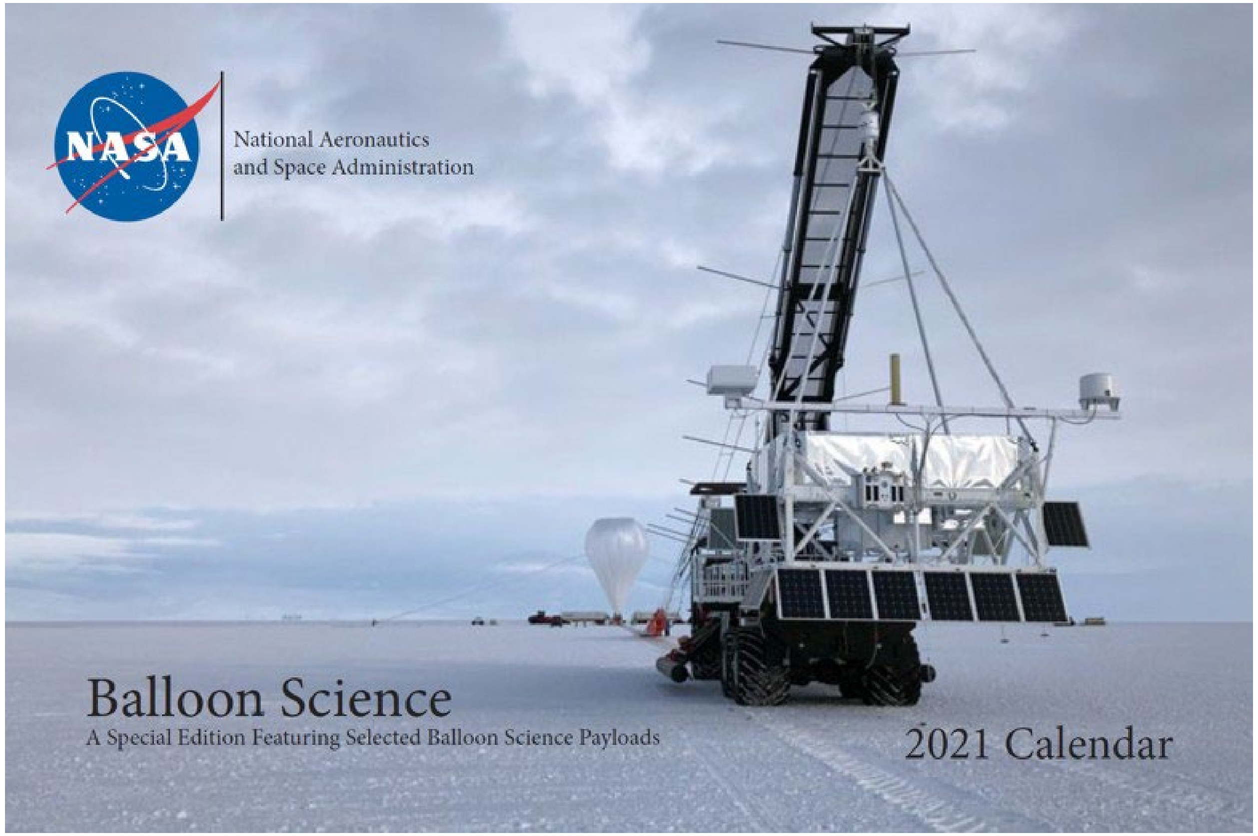
University of Minnesota
C.J. Waddington

TIGERISS team members

This work was supported by NASA under grant NNG05WC04G, and by the Graduate School of Arts and Sciences at Washington University in St. Louis with a Dean's Dissertation Fellowship.



GCR Measurements with Balloon Experiments



- Economical access to near space for large payloads up to ~6,000 lbs, possible reflight.
- Student involvement spanning entire project life and include many project roles.

SuperTIGER Collaboration

Y. Akaike[2,5], W.R. Binns[1], R.G. Bose[1], T.J. Brandt[2], D.L. Braun[1], N. Cannady[2,5], W.M. Daniels[2], P.F. Dowkontt[1], S.P. Fitzsimmons[2], D.J. Hahne[2], T. Hams[2], M.H. Israel[1], J.F. Krizmanic[2], A.W. Labrador[3], R.A. Mewaldt[3], J.W. Mitchell[2], R.P. Murphy[1], G.A. De Nolfo[2], S. Nutter[6], M.A. Olevitch[1], N.E. Osborn[1], B.F. Rauch[1], K. Sakai[2,5], F. San Sebastian[2], M. Sasaki[2,5], G.E. Simburger[1], T. Tatoli[2], N.E. Walsh[1], J.E. Ward[1], M.E. Wiedenbeck[4], W.V. Zober[1]

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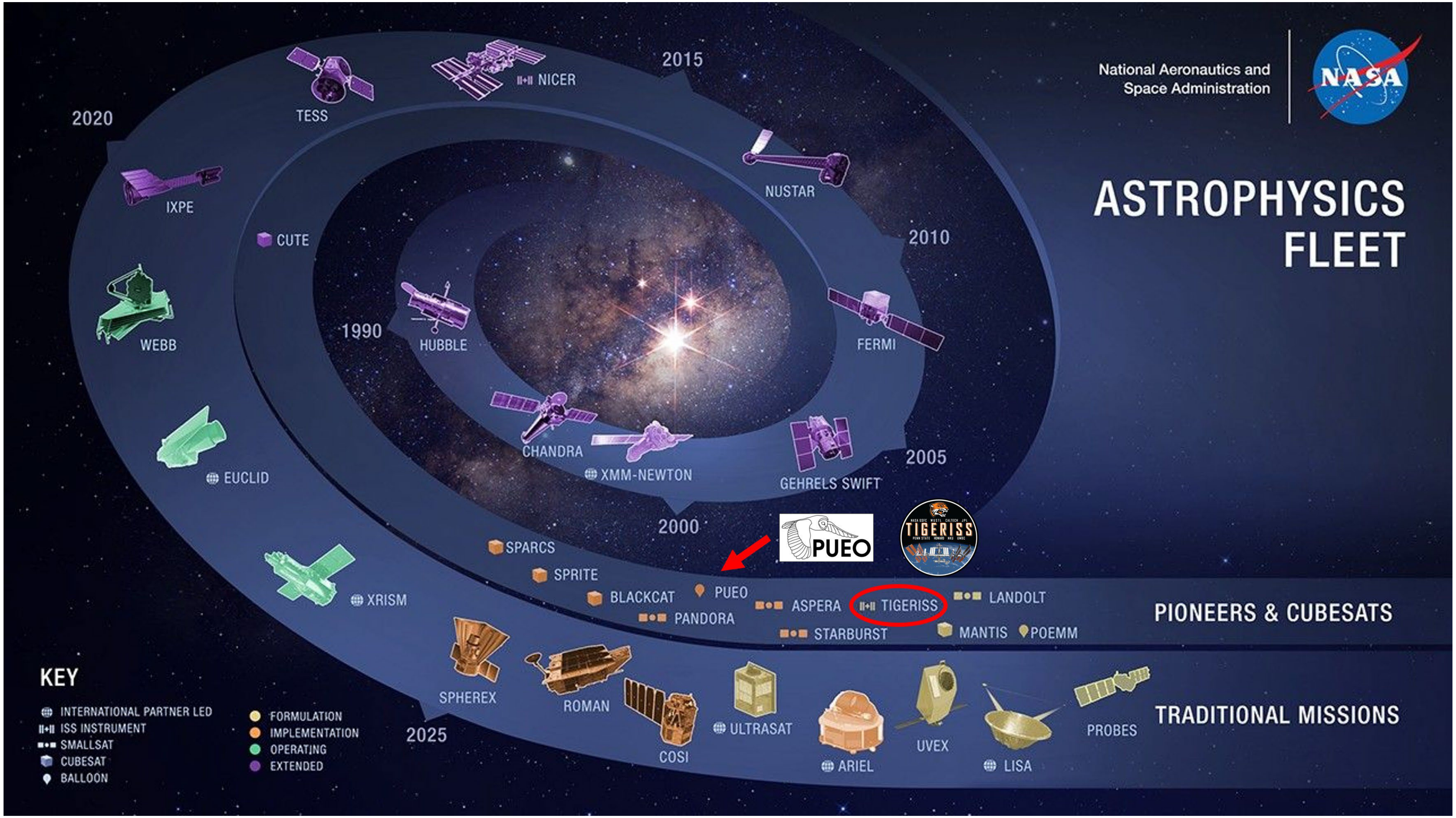
TIGERISS – ISS Pioneers Mission



TIGERISS Collaboration

Trans-Iron Galactic Element Recorder for the International Space Station

H. Allen,[1] R. F. Borda,[2] R. G. Bose,[3] D. L. Braun,[3] J. Calderon,[4] Z. Campbell,[5] N. W. Cannady,[6] R. M. Caputo,[6] M. Clark,[7] J. Coldsmith,[8] S. Coutu,[1] G. A. de Nolfo,[9] T. Forstmeier,[1] M. Fratta,[5] P. Ghosh,[2, 6, 10] S. Graham,[8] S. Jones,[4] J. F. Krizmanic,[6] W. Labrador,[3] L. Lisalda,[3] J. V. Martins,[2] M. P. McPherson,[7] J. G. Mitchell,[9] J. W. Mitchell,[6] S. I. Mognet,[1] A. Moiseev,[11, 6, 10] T. L. Ng,[5] S. Nutter,[4] N. Osborn,[3] M. Pant,[4] I. M. Pastrana,[3] D. Radomski,[3] B. F. Rauch,[3] H. Salmani,[7] M. Sasaki,[11, 6, 10] G. E. Simburger,[3] S. Smith,[7] H. A. Tolentino,[7] Y. Tufail,[5] D. Washington,[1] T. Widmyer,[5] L. Williams,[8] W. V. Zober,[3]

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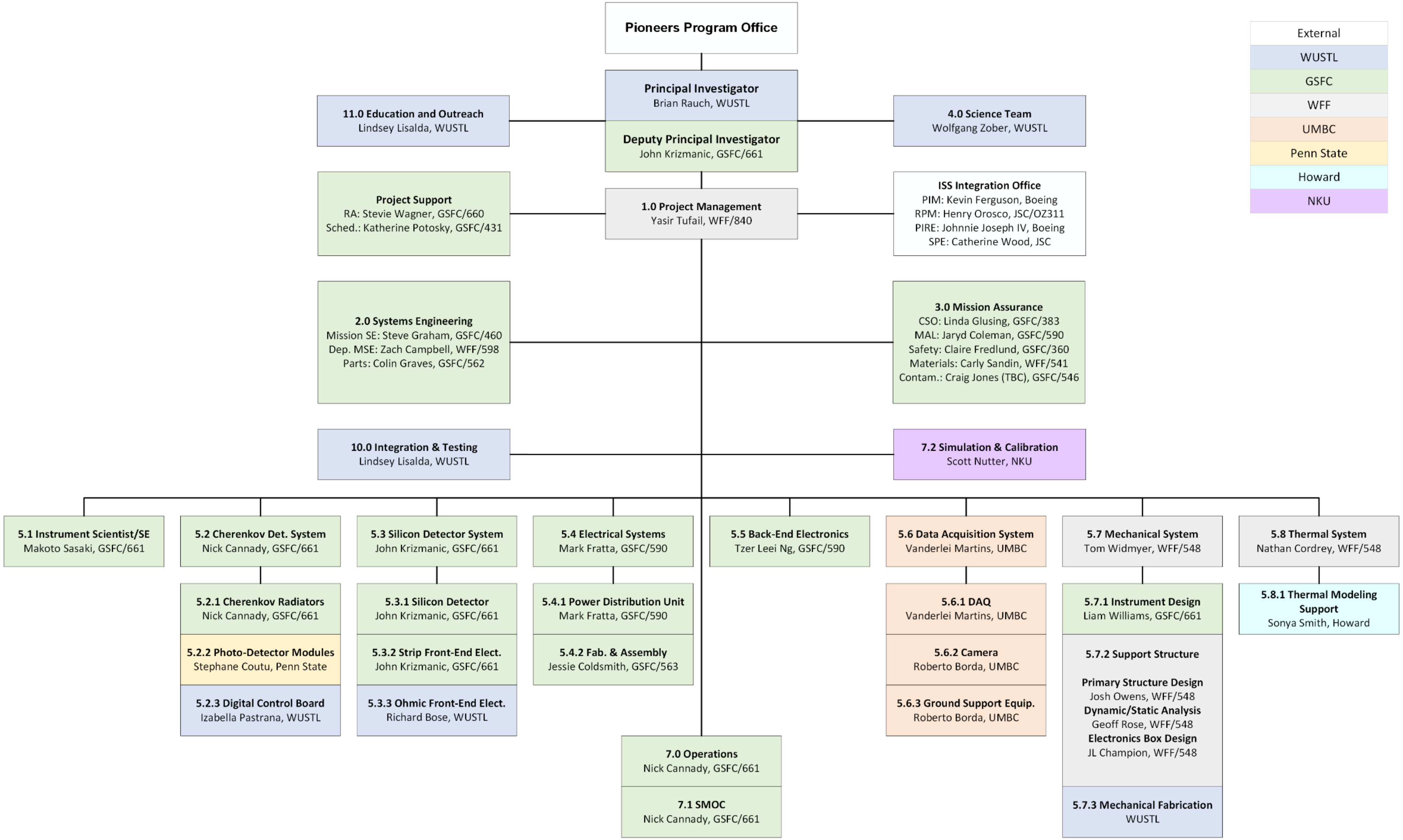
5) NASA Wallops Flight Center
6) NASA Goddard Space Flight Center, Astrophysics Science Division
7) Howard University
8) NASA Goddard Space Flight Center
9) NASA Goddard Space Flight Center, Heliophysics Science Division
10) Center for Research and Exploration in Space Sciences and Technology II
11) University of Maryland, College Park

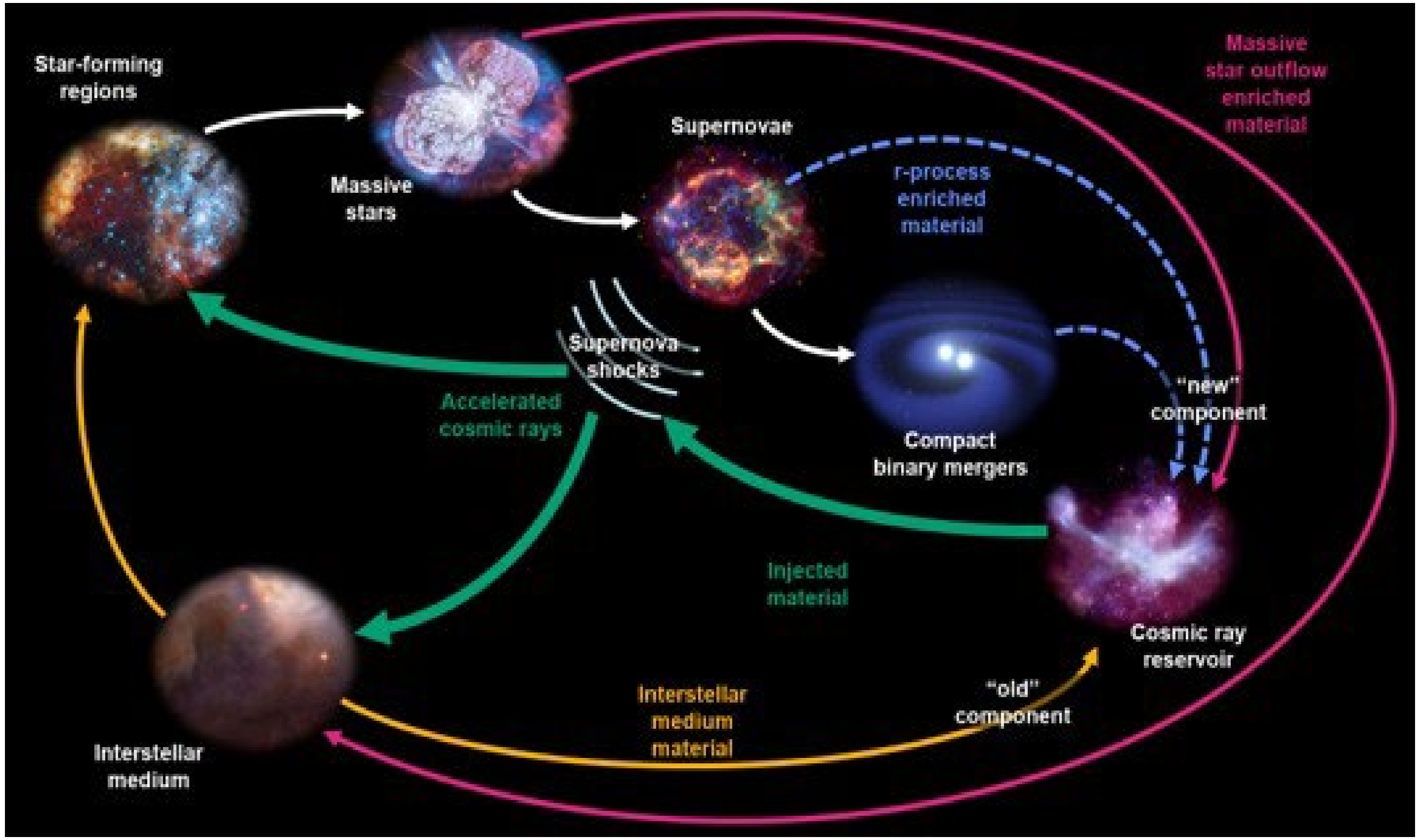
TIGERISS Collaboration Org Chart



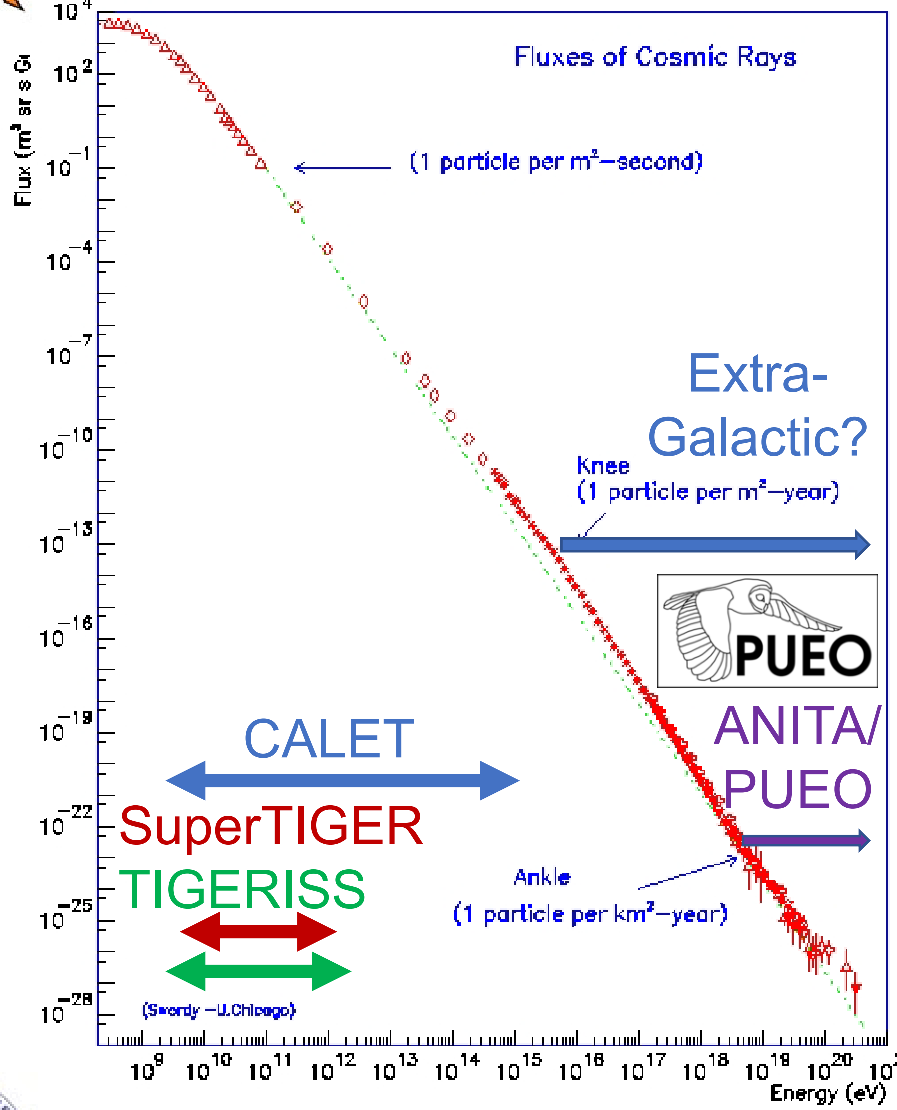
Cosmic Rays in the Grand Cycle of Matter

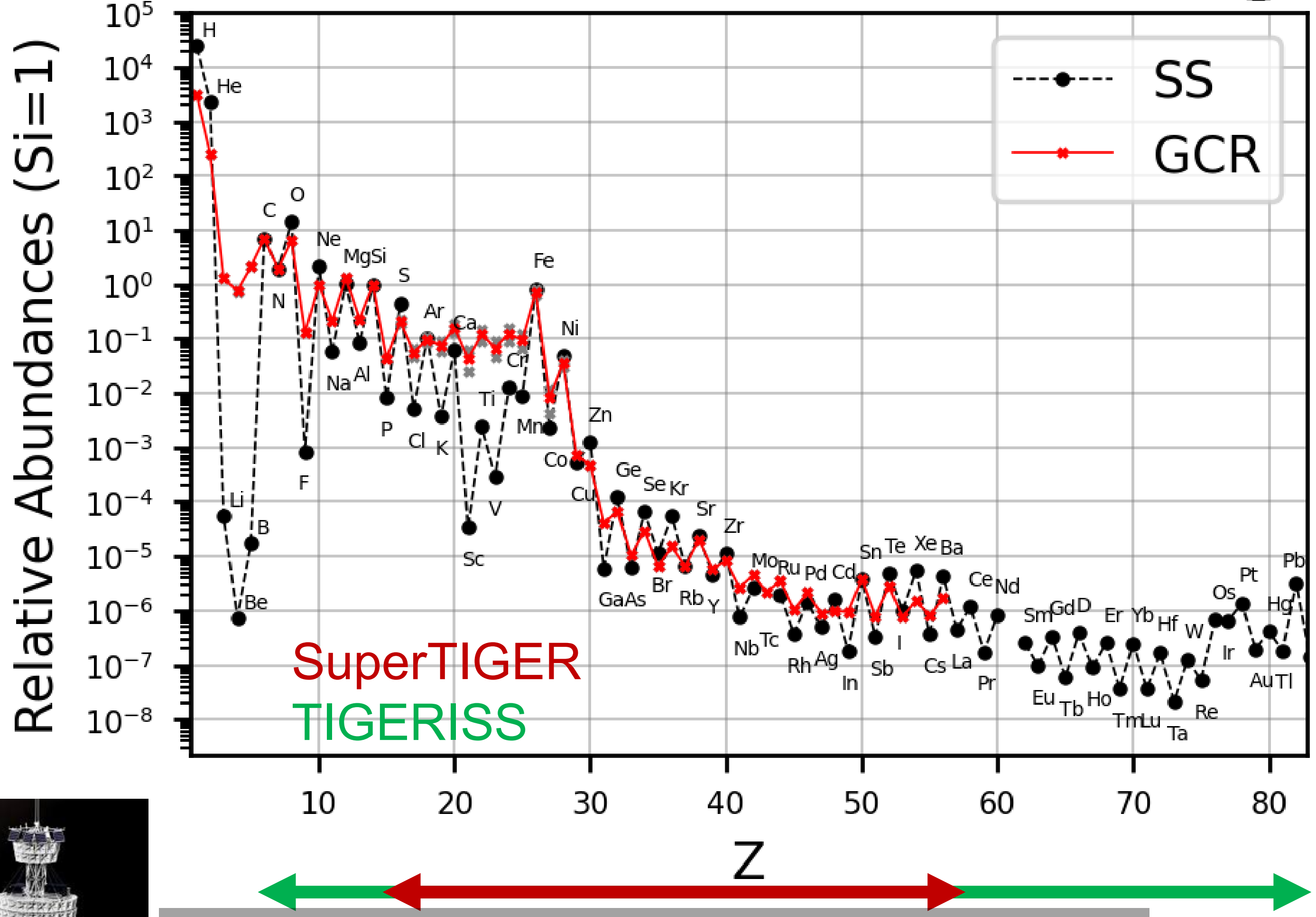
The overall TIGERISS mission goal is to increase our understanding of how the Galaxy produces and distributes the elements. These goals come from the NASA decadal survey's questions:

- Where is main site of r-process nucleosynthesis?
- How the "injection of energy, momentum, and metals from stars" circulates matter?



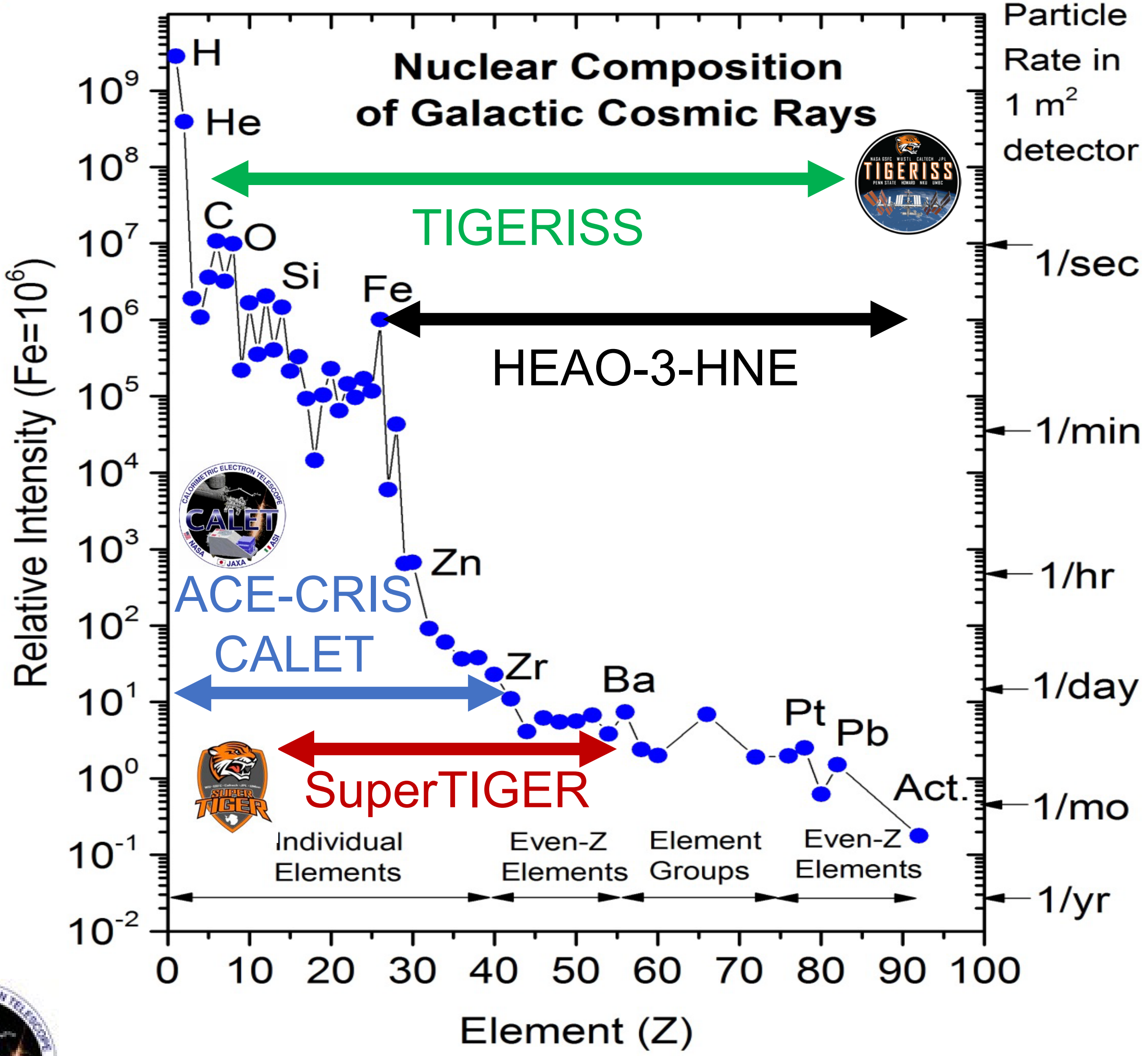
Ultra-Heavy Galactic Cosmic Rays (UHGCRs)





Christoph Welling: Prospects for UHE neutrino flavor measurements with PUEO 05/11/2025, 15:15, Room 1.1+1.2, ADEIT

Cosmic Rays and Atomic Number



Relative abundances depend on nucleosynthetic sources

1. Big Bang: ${}_{1}$H and ${}_{2}$He
2. Fusion: up to ${}_{26}$Fe
3. r- and s-process neutron capture: past ${}_{26}$Fe
4. Cosmic-ray spallation: ${}_{3}$Li, ${}_{4}$Be, and ${}_{5}$B

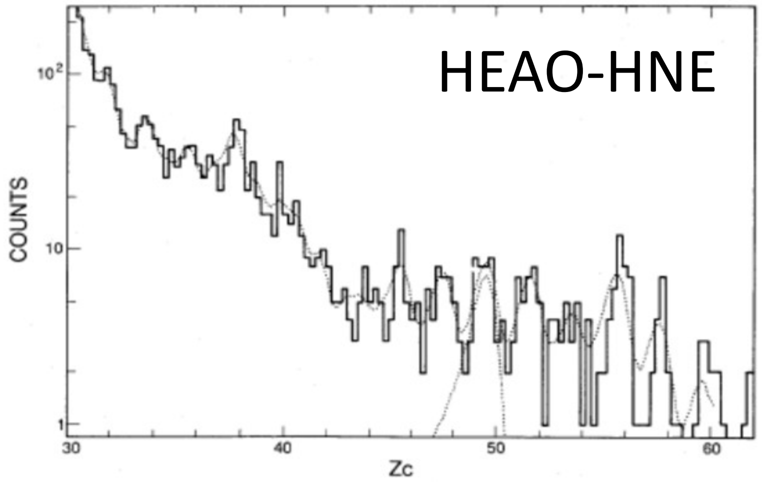
What source for s-process neutron capture versus atomic number

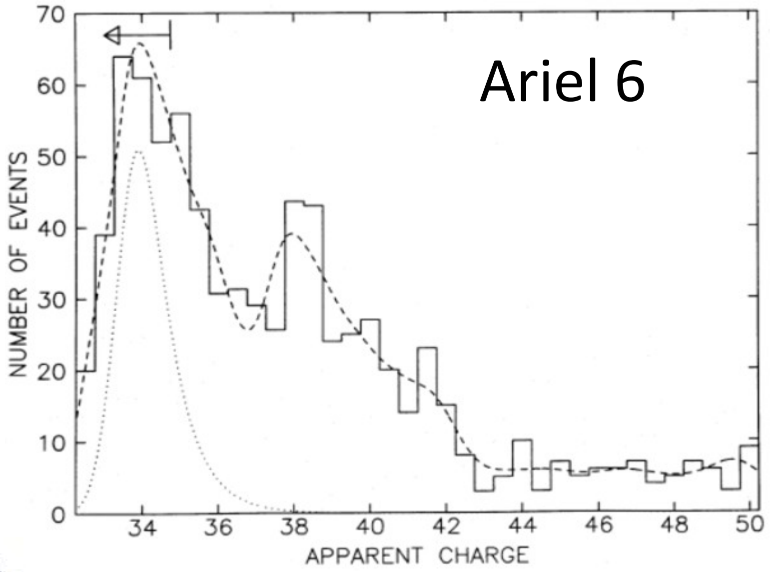
1. Massive star outflow prior to supernovae
2. ?

What source for r-process neutron capture versus atomic number

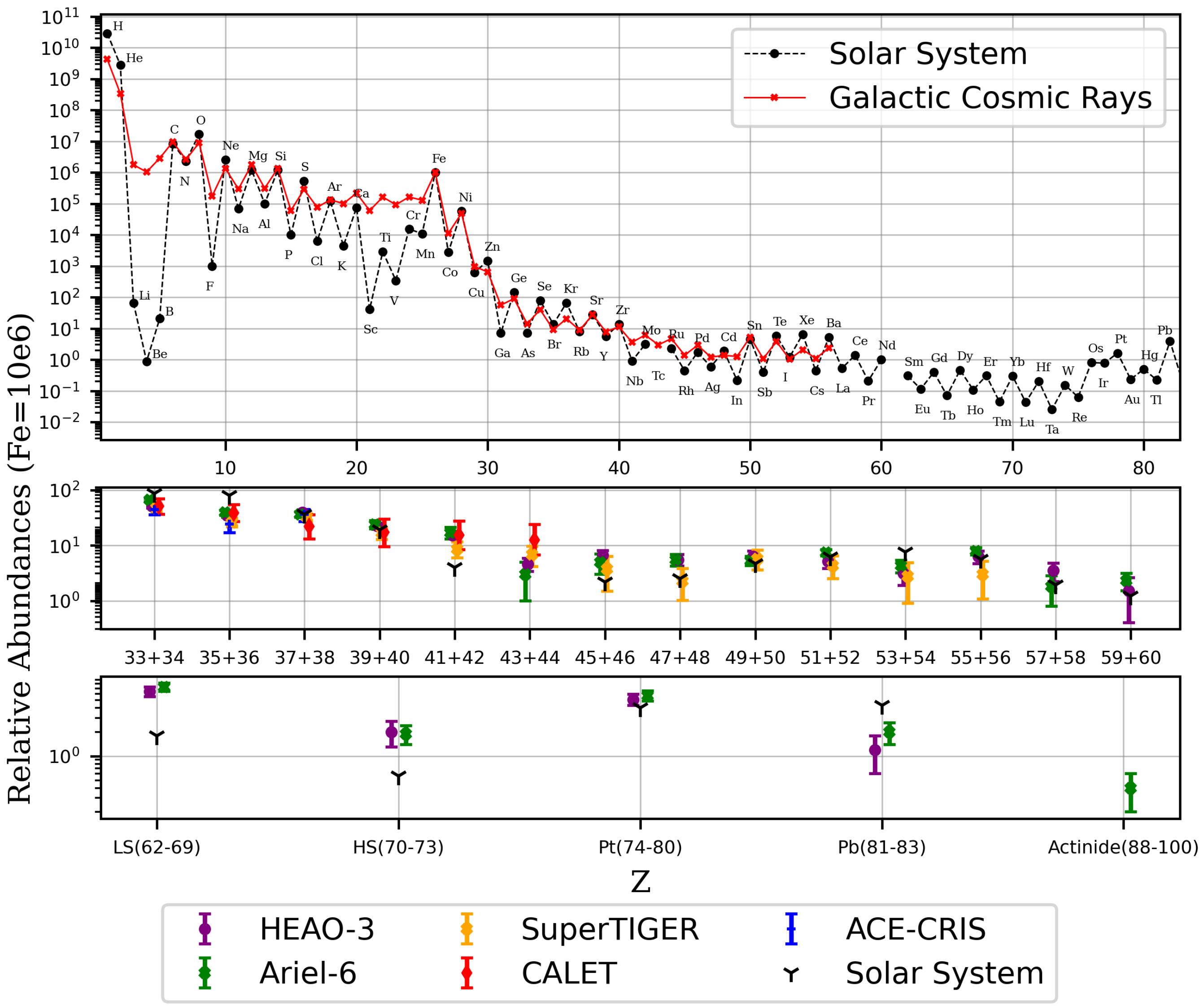
1. Supernovae (SNe)
2. Compact binary merger (CBM), e.g., binary neutron star mergers (BNSM)
3. ?

Previous Ultra-Heavy Cosmic Ray Results

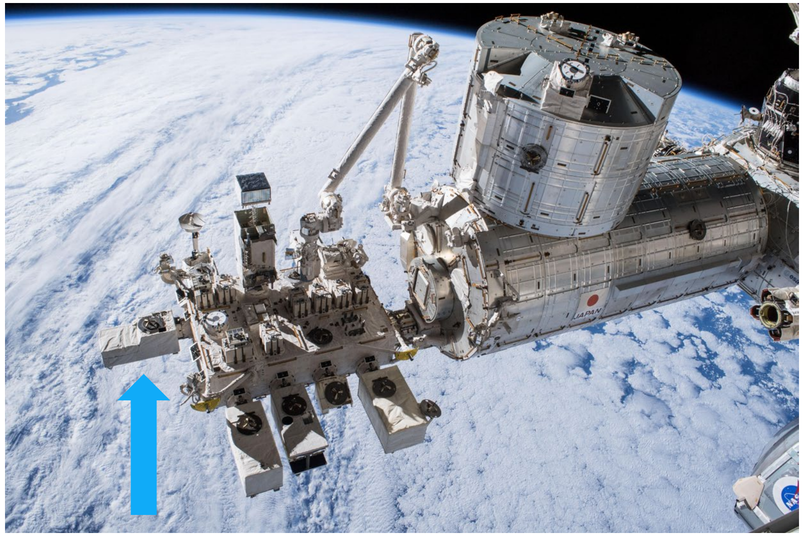




Galactic Cosmic Ray Measurements



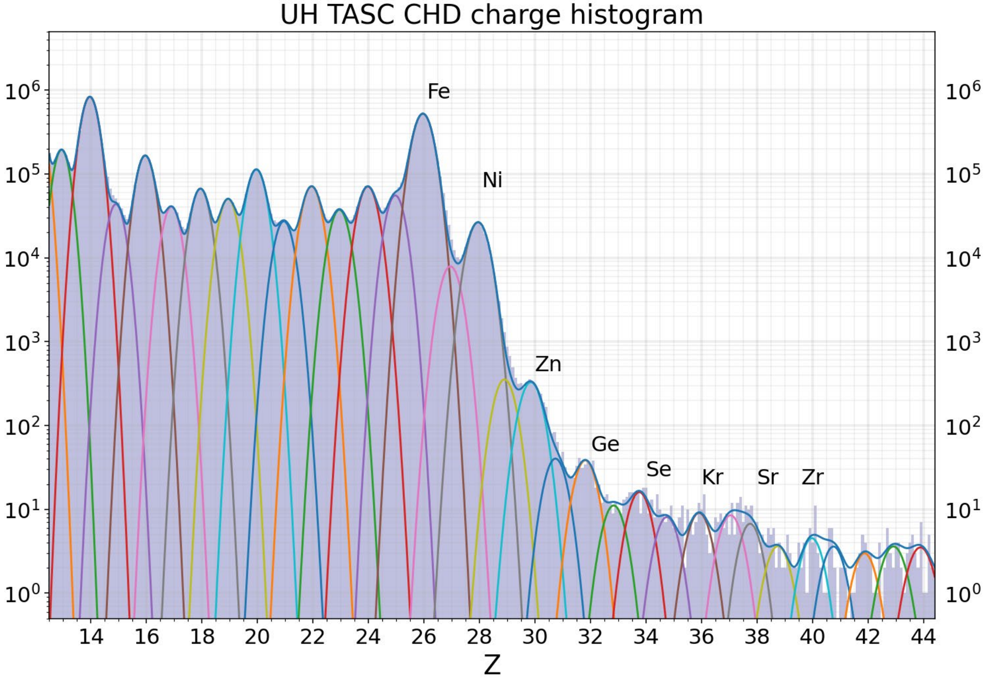
Calorimetric Electron Telescope (CALET)

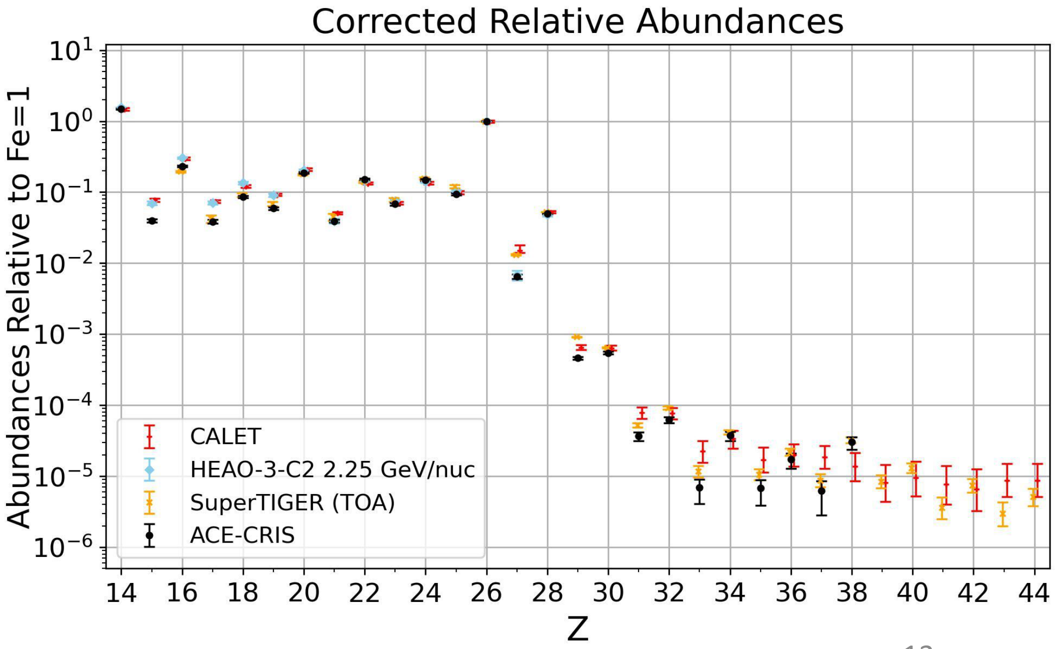


CALET

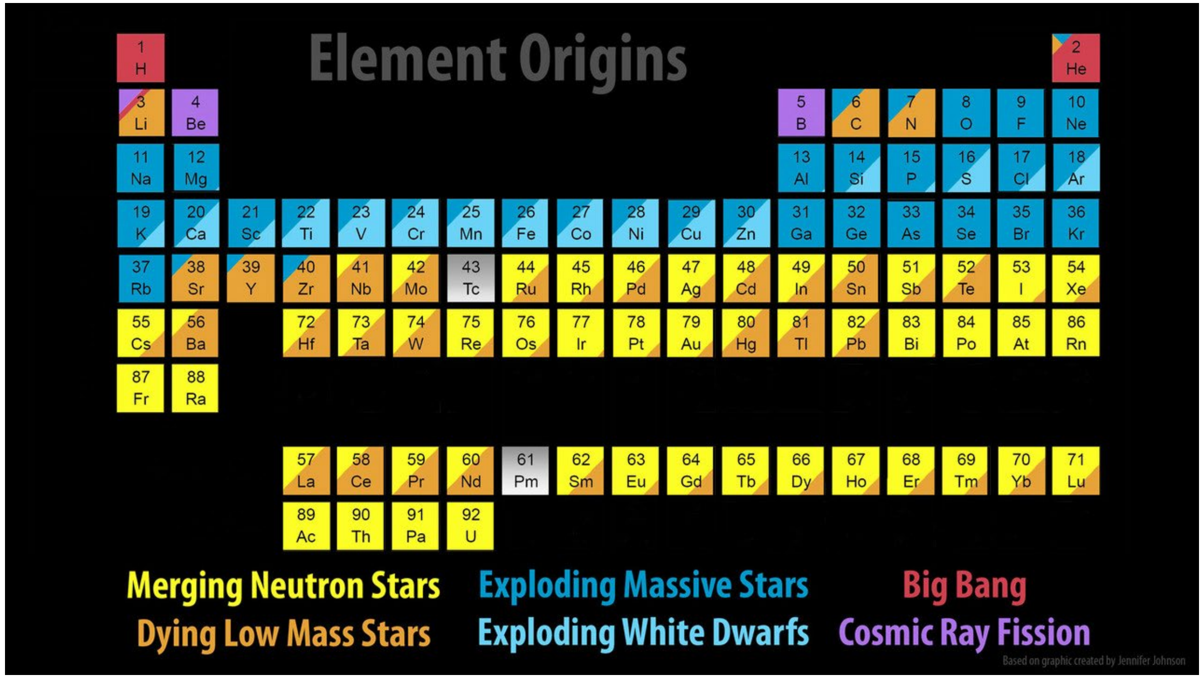
Yosui Akaike: A Decade of CALET Observations: Cosmic-Ray Results from the ISS
04/11/2025 14:45 Room 2.1+2.2, ADEIT

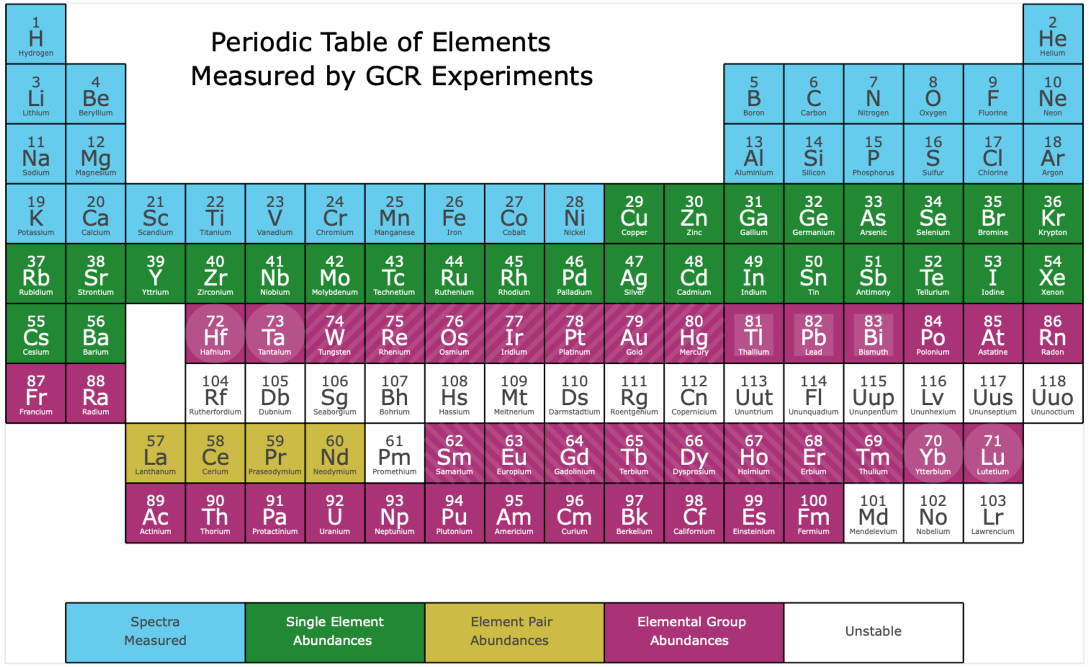
Wolfgang Zober
Detected Abundances of Nuclei Relative to $_{26}$Fe for Elements $_{14}$Si through $_{44}$Ru with CALET on the International Space Station
2025ApJ...988..148A
DOI 10.3847/1538-4357/ade3cc

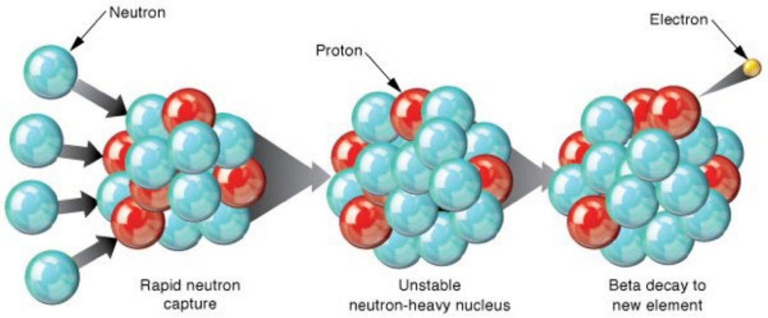




Nucleosynthesis vs. GCR Measurements







r-process neutron capture

- **Explosive nucleosynthesis r-process AND/OR Neutron star merger r-process : signature in elemental ratios.**

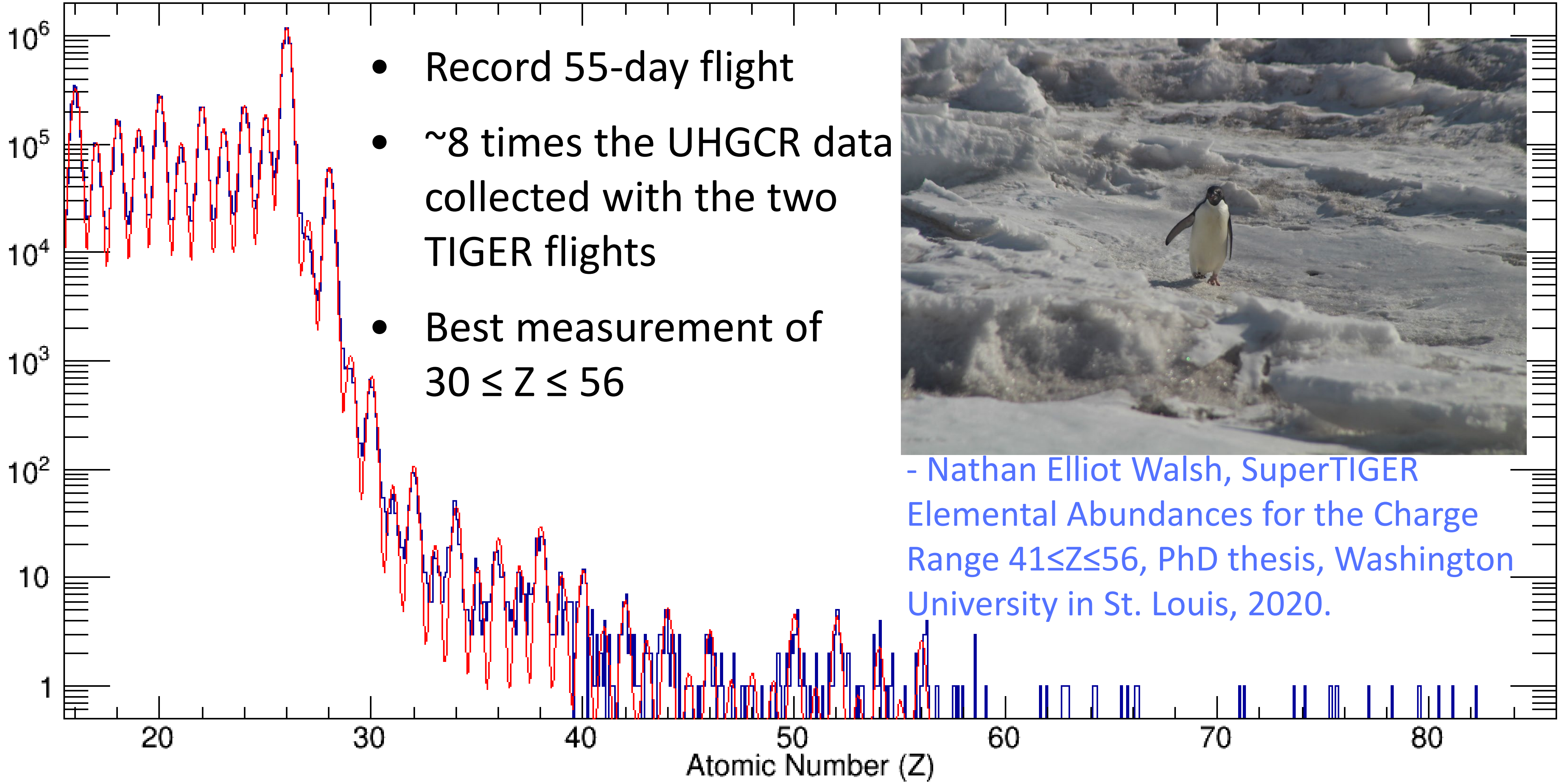
1 year of TIGERISS Data

$_{50}$Sn + $_{56}$Ba (s-process: 63; r-process 19)

$_{52}$Te + $_{54}$Xe (s-process: 12; r-process 60)

SuperTIGER Cosmic Ray Abundances

- Record 55-day flight
- ~8 times the UHGCR data collected with the two TIGER flights
- Best measurement of $30 \leq Z \leq 56$



- Nathan Elliot Walsh, SuperTIGER Elemental Abundances for the Charge Range 41≤Z≤56, PhD thesis, Washington University in St. Louis, 2020.

OB Association Source Model Good Z≤40

Current OB association Galactic cosmic ray source (GCRS) model predictions:

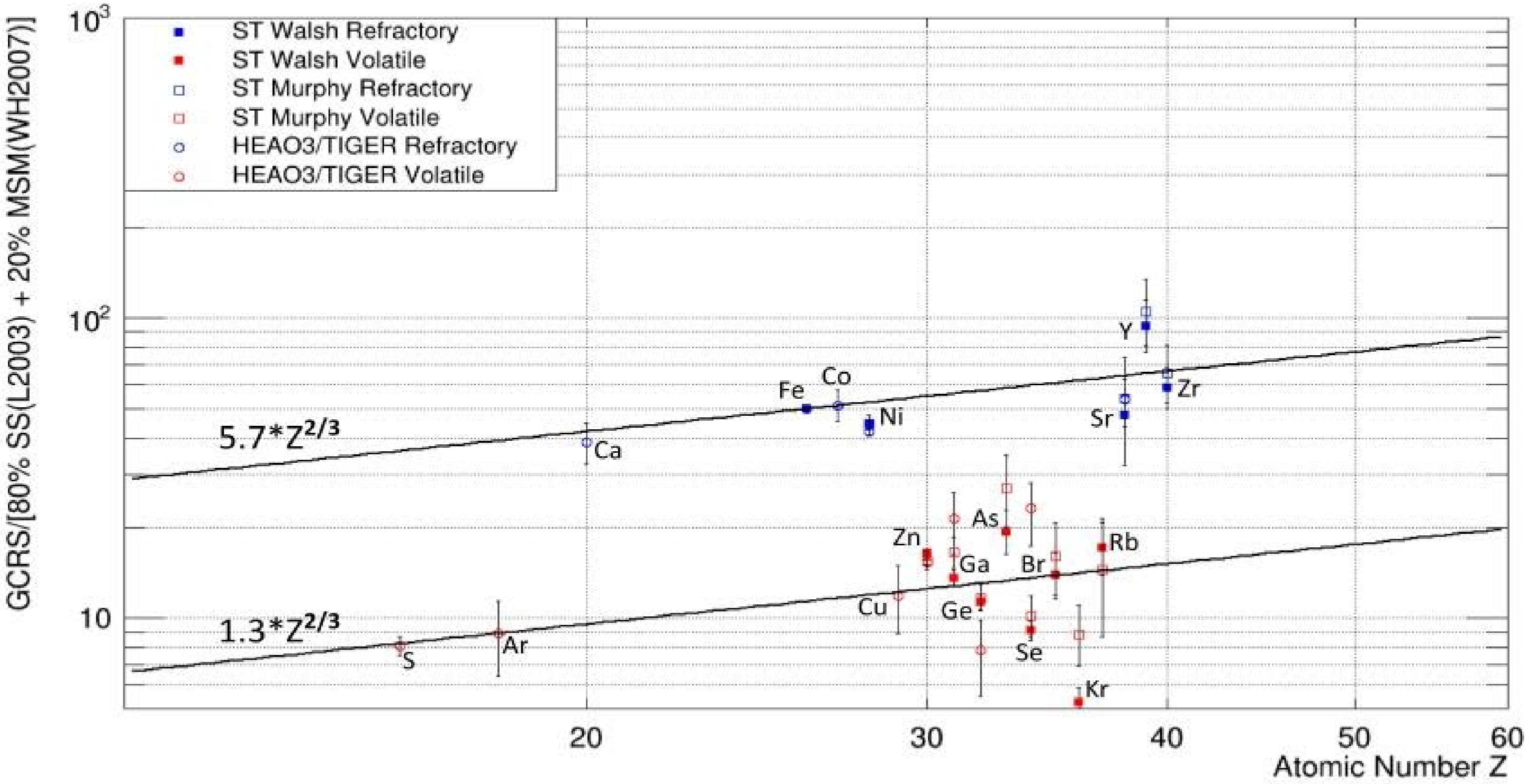
- GCRS = ~80% ISM + ~20% MSM
- interstellar medium (ISM) is similar in composition to Solar System (SS) material
- massive star material (MSM) includes stellar wind outflow and supernova (SN) ejecta

Refractory elements more likely in dust grains than volatiles preferentially injected into the accelerator

$Z^{2/3}$ injection dependence from grain sputtering cross sections seen for both refractories and volatiles

N44 Superbubble in LMC
Credit: Gemini Observatory, AURA, NSF

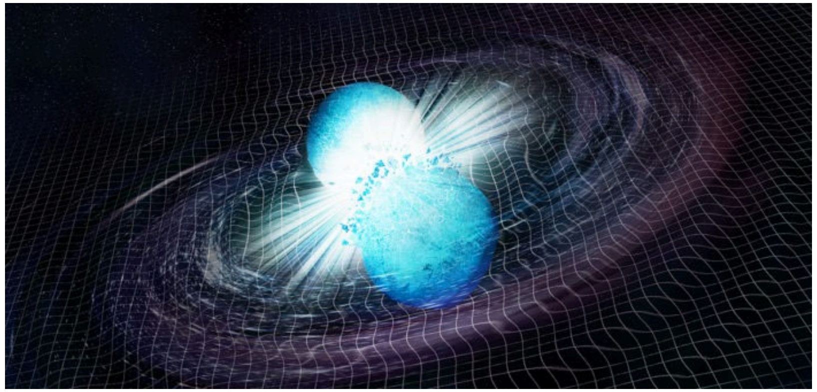
- Nathan Elliot Walsh, SuperTIGER Elemental Abundances for the Charge Range 41≤Z≤56, PhD thesis, Washington University in St. Louis, 2020.
- Rauch et al. 2009
- Murphy et al. 2016



Apparent Model Breakdown for Z>40

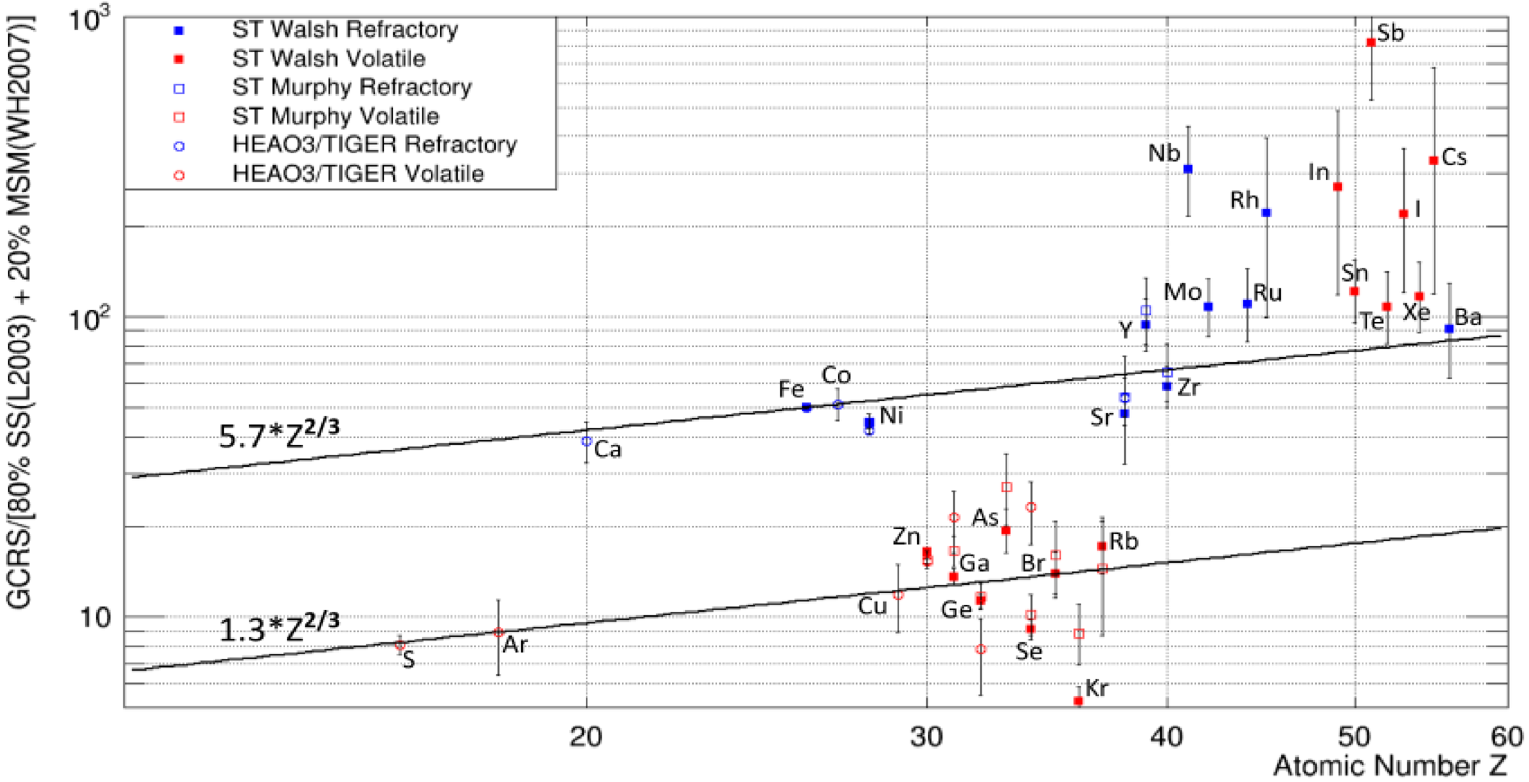
SuperTIGER Z>40 abundances elevated over refractory line: Model is missing something

- Change in acceleration mechanism?
- New source component, e.g., neutron star mergers? (Observed in ejecta from GW170817)



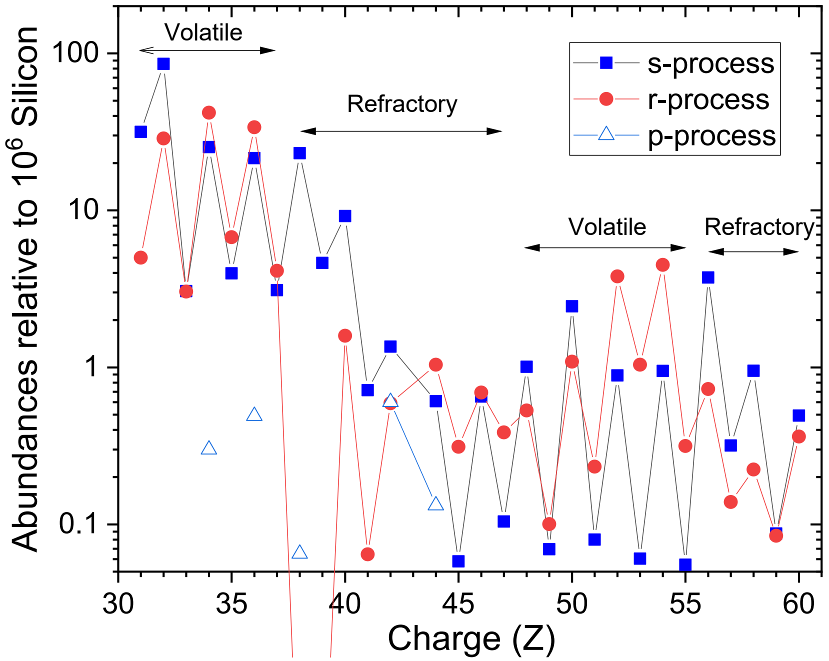
Artist's illustration of the merger of two neutron stars. [NASA/CXC/M.Weiss]

- Nathan Elliot Walsh, SuperTIGER Elemental Abundances for the Charge Range 41≤Z≤56, PhD thesis, Washington University in St. Louis, 2020.

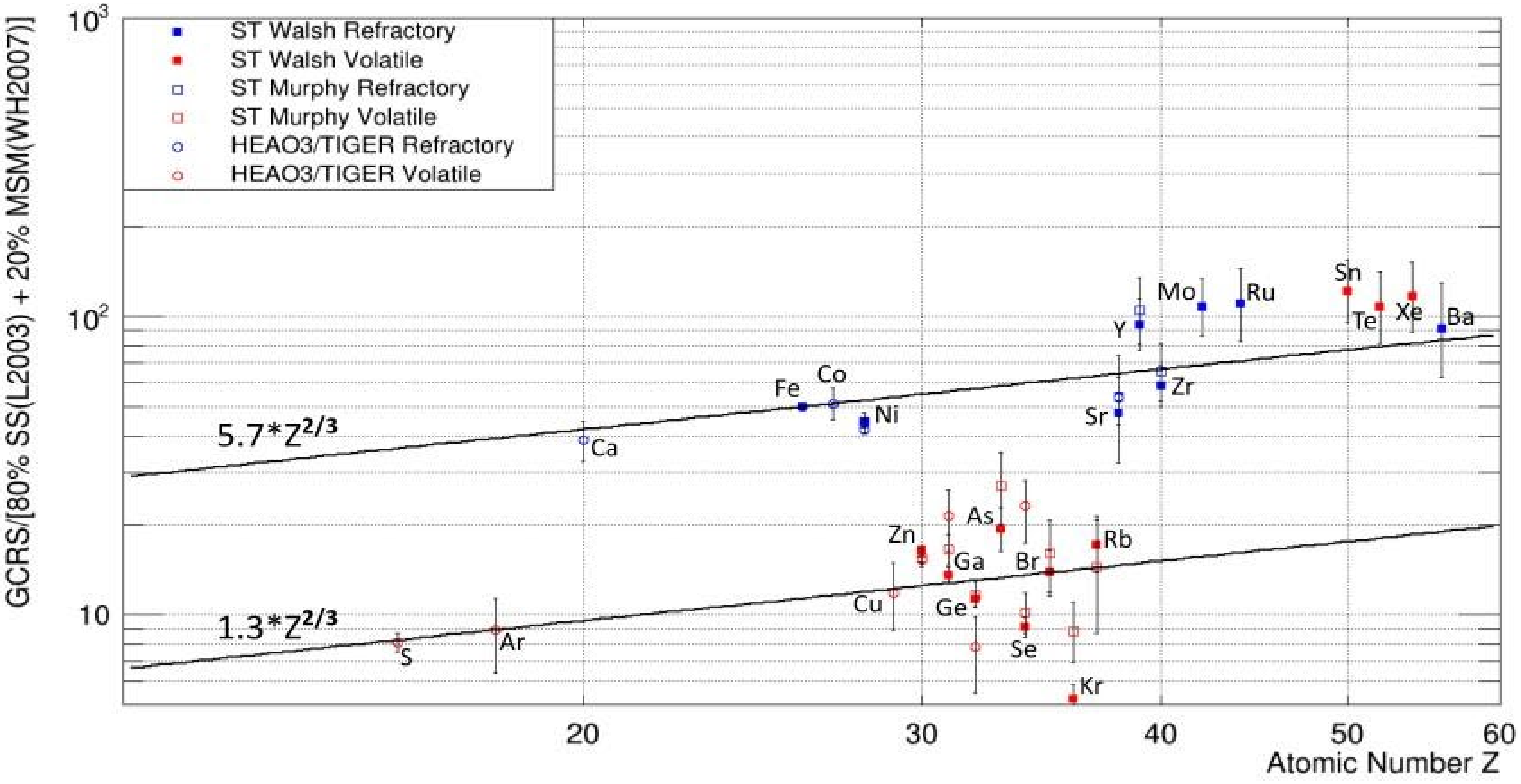


Apparent Model Breakdown for Z>40 Even Elements Only

- Odd elements likely overestimated due to contamination from even-element peak spill over
- Elevated volatile elements largely r-process



r- ,s-, and p-process decomposition of solar system abundances
West & Heger (2013) ApJ 774:75



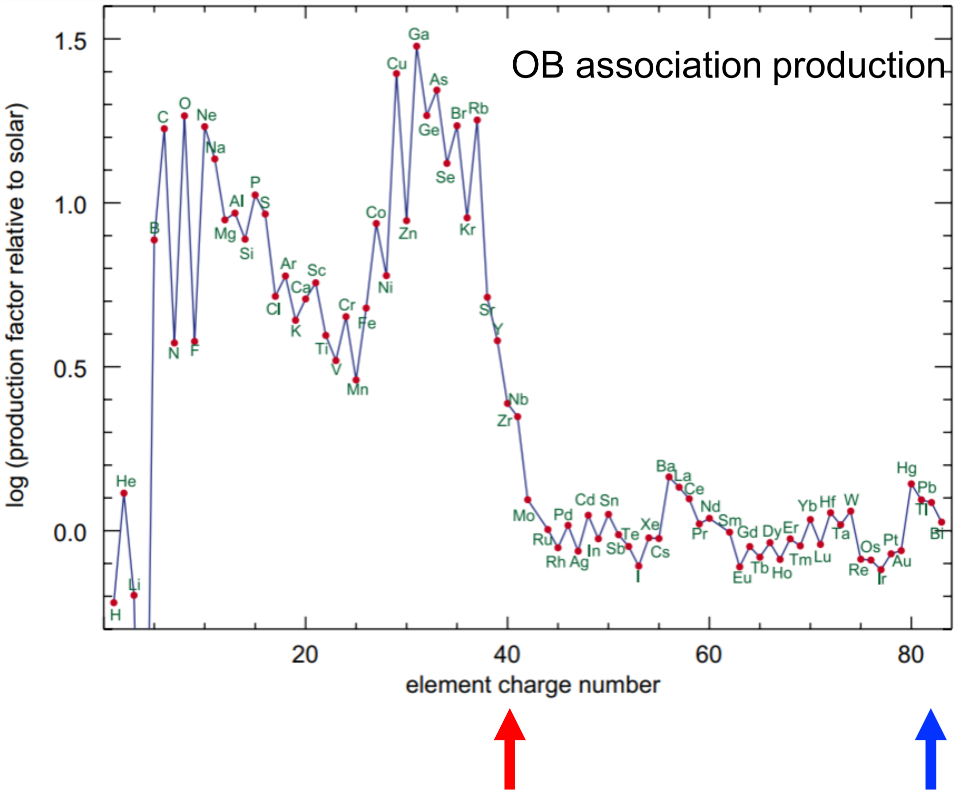
Heavy Element Production Models

How and where are the heaviest elements created?

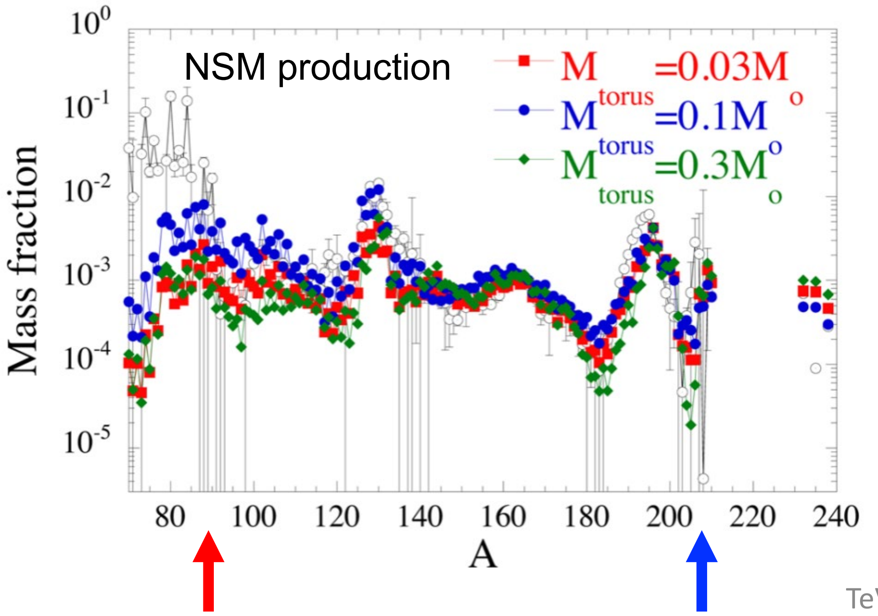
•Absolute and relative abundances of r- & s-process elements probe NSM physics and contributions to GCRs – part of a multi-messenger approach

•SuperTIGER measured part of the transition region between SN and NSM production at Z~40 (A~90)

•Nathan's dissertation results paved the way for TIGERISS, which will reach $_{78}$Pt-$_{82}$Pb region with single element resolution and further constrain NSM production models



Supernova (SN) production relative to solar composition
Woosley & Heger (2007) PhR 442:269W



Neutron star merger (NSM) production model compared to solar composition (open circles)
Just et al. (2015) MNRAS 448:541J

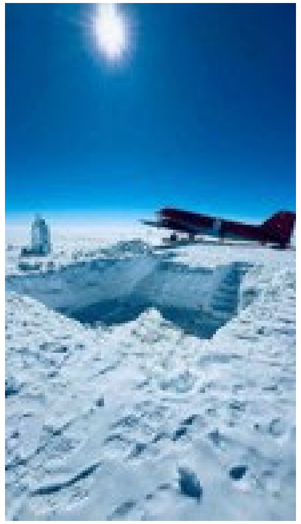
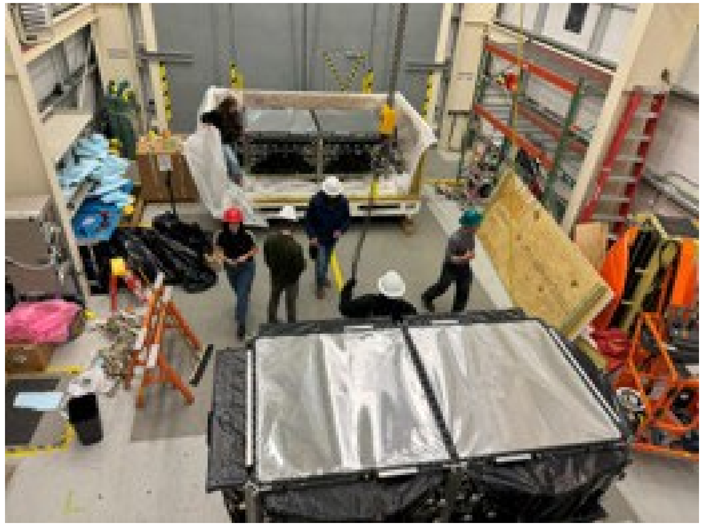
ST-2.3 Recovery



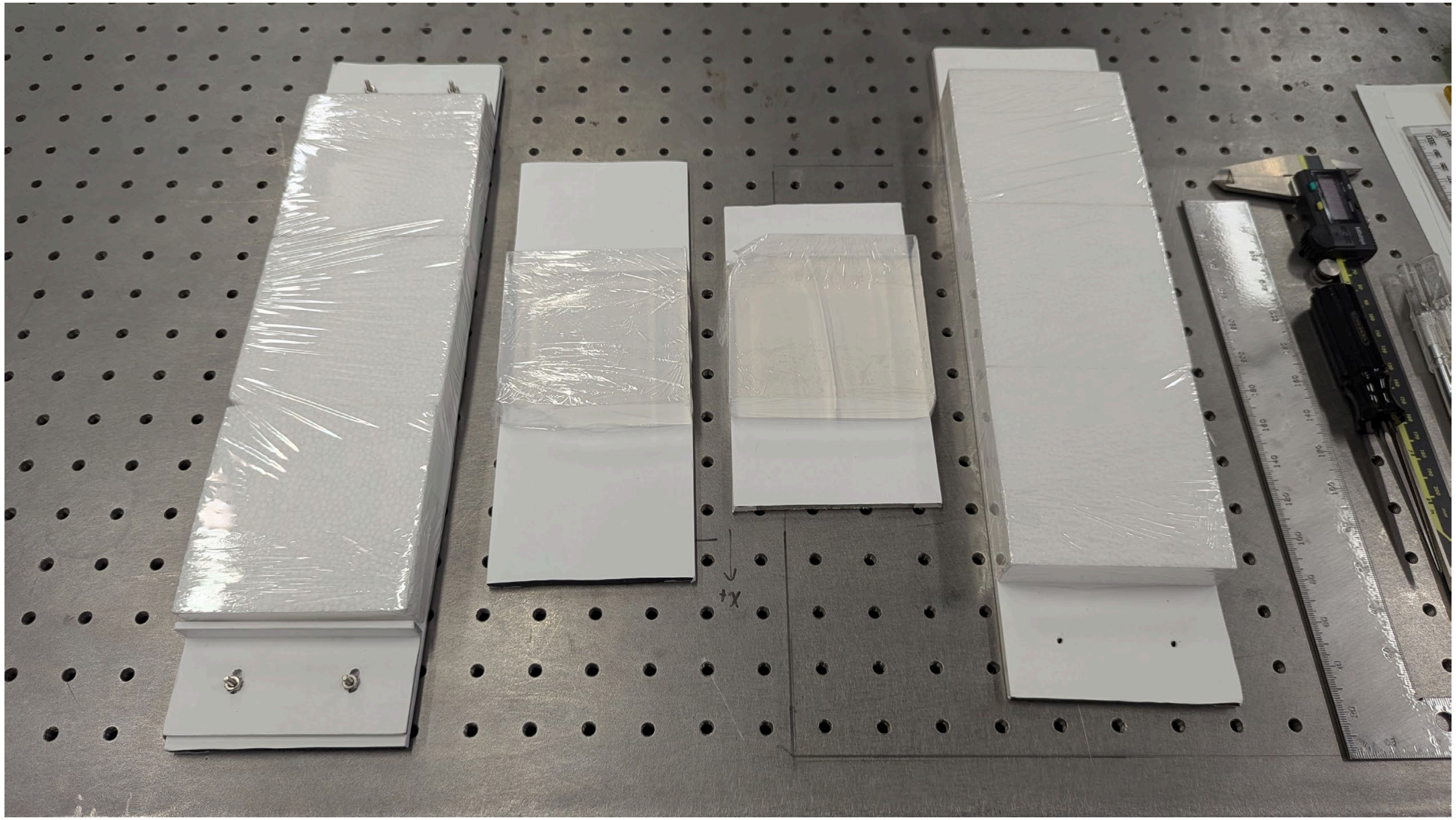




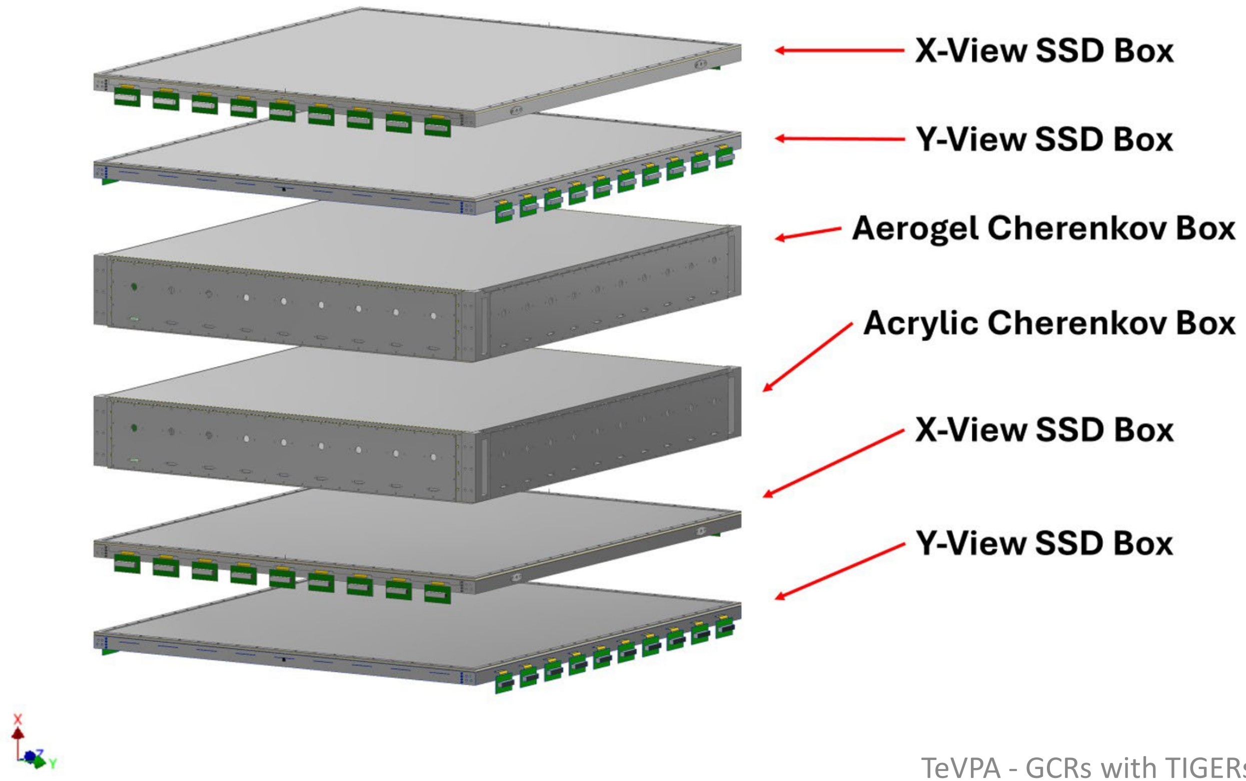


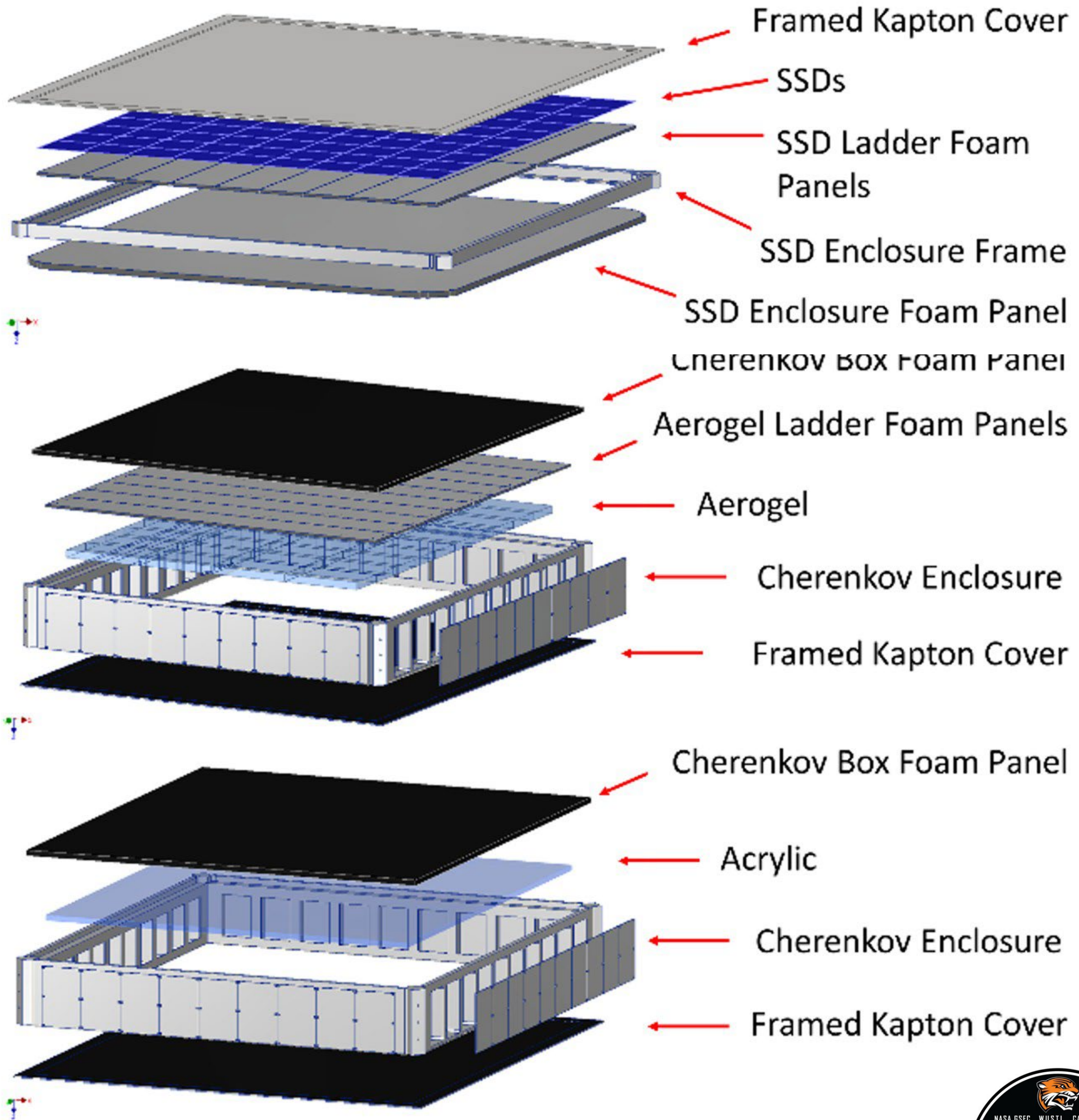



SuperTIGER vs TIGERISS Aerogel Mounting

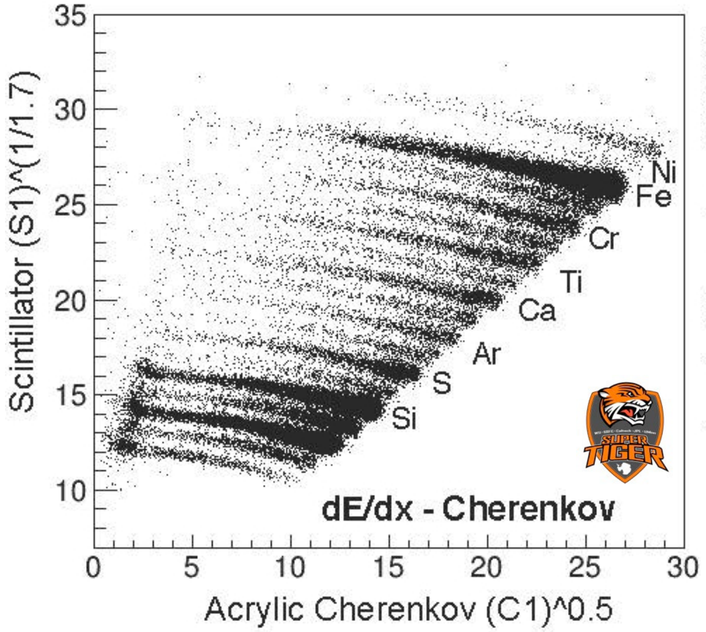


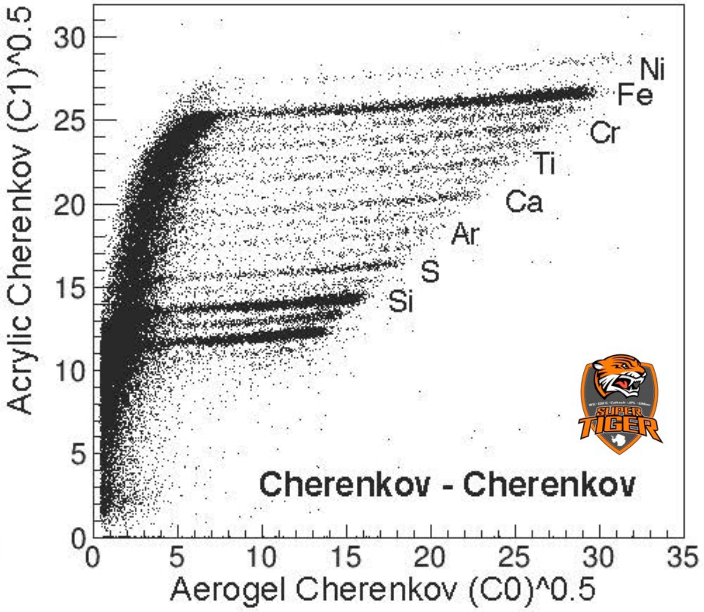
TIGERISS Columbus SOX Instrument





TIGER Measurement Methods





dE/dx vs. Acrylic Cherenkov
0.33 to 2.12 GeV/nucleon

Acrylic Cherenkov vs. Silica Aerogel Cherenkov > 2.12 GeV/nucleon

Acrylic Cherenkov Detectors

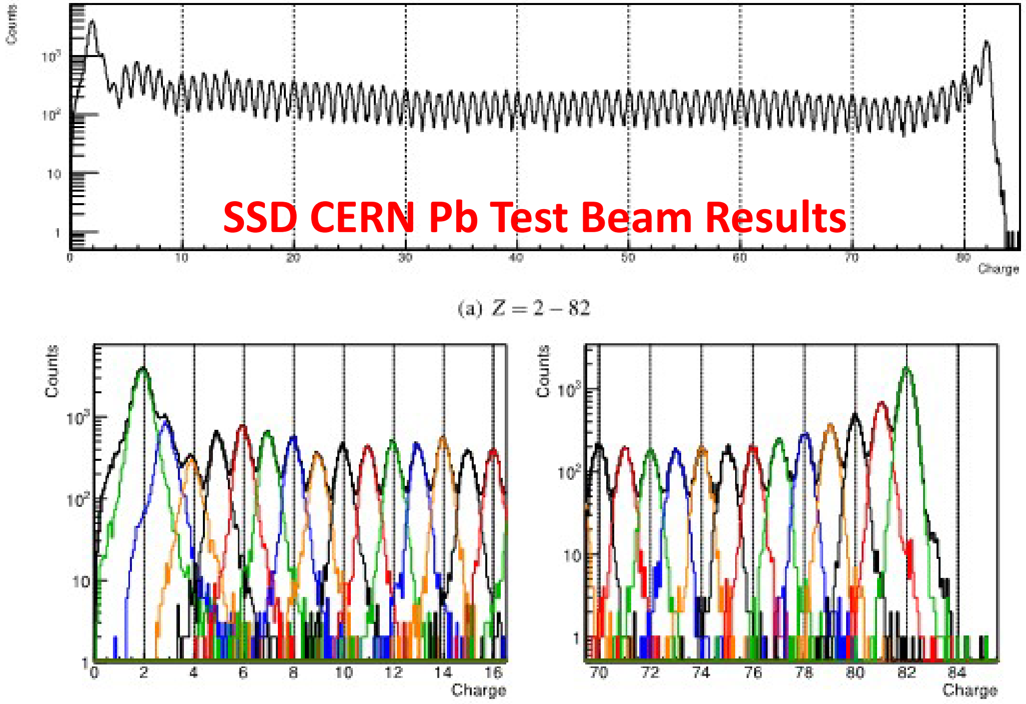
- **n = 1.5**
- **β ≥ 0.67**
- **KE ≥ 325 MeV/nucleon**

Silica Aerogel Cherenkov Detectors

- **n = 1.05**
- **β ≥ 0.0.95**
- **KE ≥ 2.12 GeV/nucleon**

SiPM readout instead of PMTs

Silicon strip detector (SSD) for precision charge measurement σ_Q < 0.24e for 5 ≲ Z ≤ 82 and SiPM Cherenkov detector readout based on CERN testing.



(a) $Z = 2 - 82$

(b) $Z = 2 - 16$

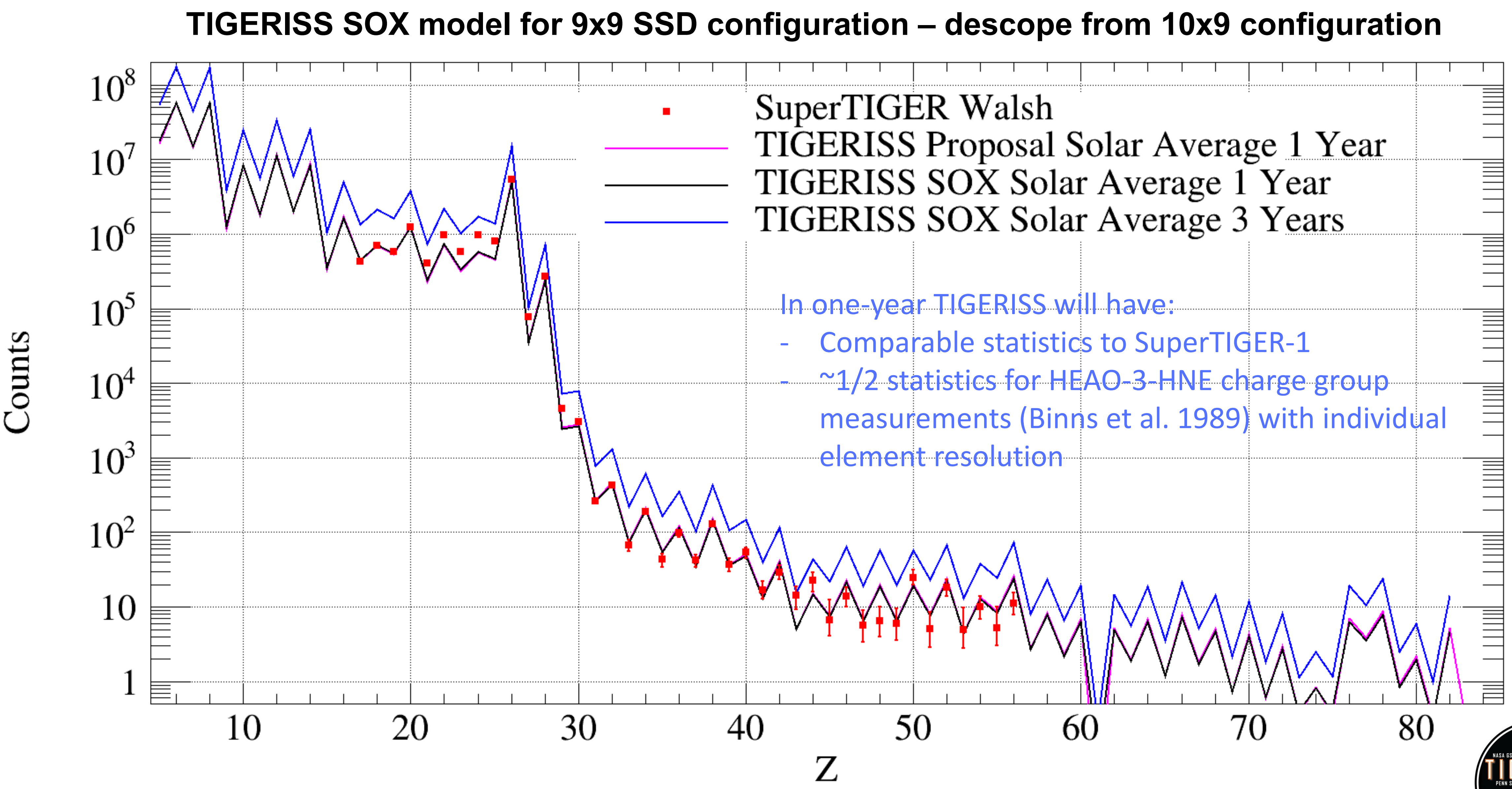
(c) $Z = 70 - 82$

SuperTIGER data for dE/dx from scintillator detectors

σ_Q < 0.19e up to $_{30}$Zn - measured
σ_Q < 0.20e up to $_{56}$Ba - measured
σ_Q < 0.21e up to $_{82}$Pb - extrapolated

TIGERISS with SSDs will do better

TIGERISS Predicted Observations



TIGERISS – Summary

- **TIGERISS will make revolutionary measurements that will transform our understanding of galactic nucleosynthesis.**
- **Key to answer are measurements of abundances of Ultra-Heavy Galactic Cosmic Rays: UHGCRs: Z > 28 (above Nickel)**
- **Astro2020 Decadal Survey Questions:**
  - “Are neutron star mergers the main site of r-process nucleosynthesis, or are there supernovae and other core collapse events that contribute significantly to the r-process budget of the universe?”
  - scientists “may be able to use heavy cosmic-ray abundance measurements in the Milky Way to constrain sites of r-process nucleosynthesis.”
- **TIGERISS will accomplish this by measuring the elemental composition from ^{5}B through ^{82}Pb.**

Acknowledgements and Disclaimer

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- The ANITA, SuperTIGER and TIGERISS efforts has been supported at Washington University in St. Louis by a grant from the Peggy and Steve Fossett Foundation and by the McDonnell Center for the Space Sciences.
- **We thank the NASA Columbia Scientific Balloon Facility, the NASA Balloon Program Office, the NSF United States Antarctic Program, and the Antarctic Support Contract for the record long-duration balloon flight for SuperTIGER-1, the successful recovery efforts, and the 32-day SuperTIGER-2.3 flight providing scientific and technical background for TIGERISS.**
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Peggy and Steve Fossett Foundation