The Astrophysics of Ultra-Heavy Galactic Cosmic Rays and techniques for their measurement.

John W. Mitchell, NASA/GSFC, 22nd ISCRA August 6,2022

TIGERISS:
A Proposed NASA Astrophysics Pioneers Mission

Selected for Concept Study

WU · GSFC · Caltech · JPL · UMinn
SUPER TIGER

NASA GSFC WUSTL PENN STATE
TIGERISS
KBR HOWARD NKU UMBC

Heavy Nuclei eXplorer
HNX
6 C
96 Cm

Many Slides from:
Nicholas Cannady
(UMBC/NASA GSFC/CRESST II)

Deepest thanks to W.R. "Bob" Binns and M.H. "Marty" Israel, retired from WUSTL. Also, to R.E. "Bob" Streitmatter and C.J. "Jake" Waddington, Deceased

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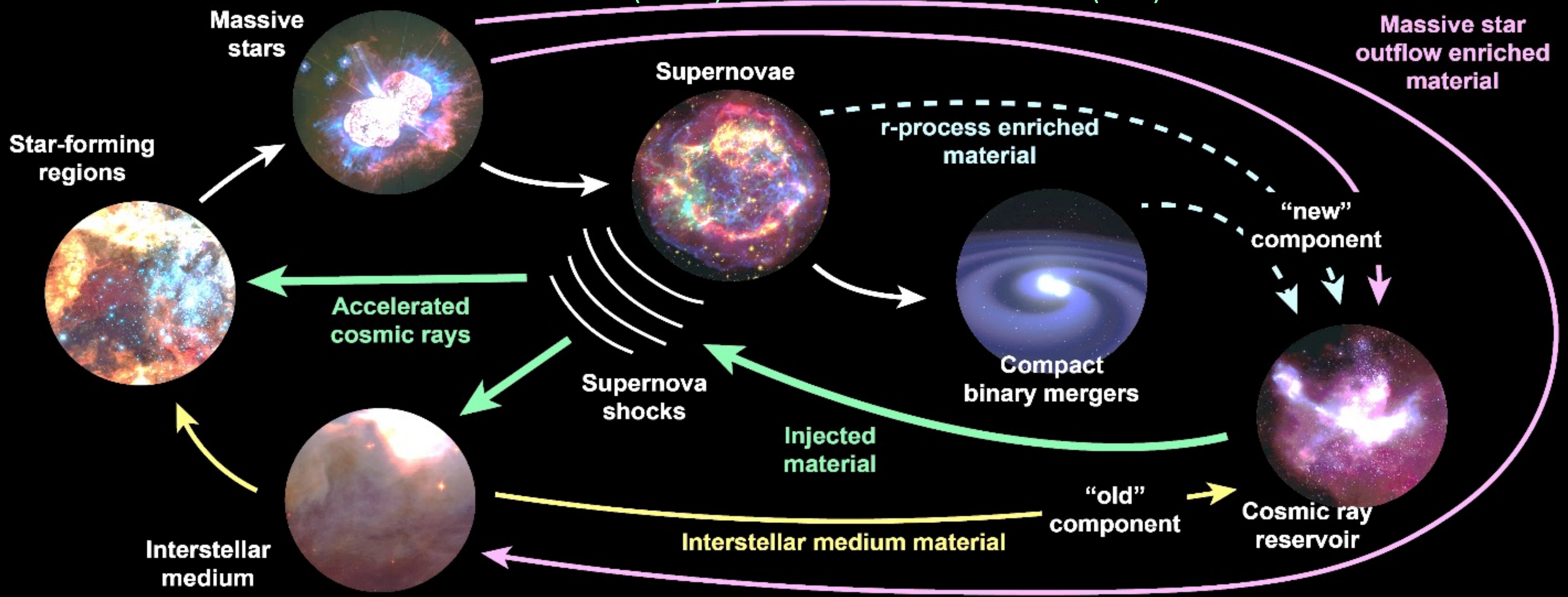
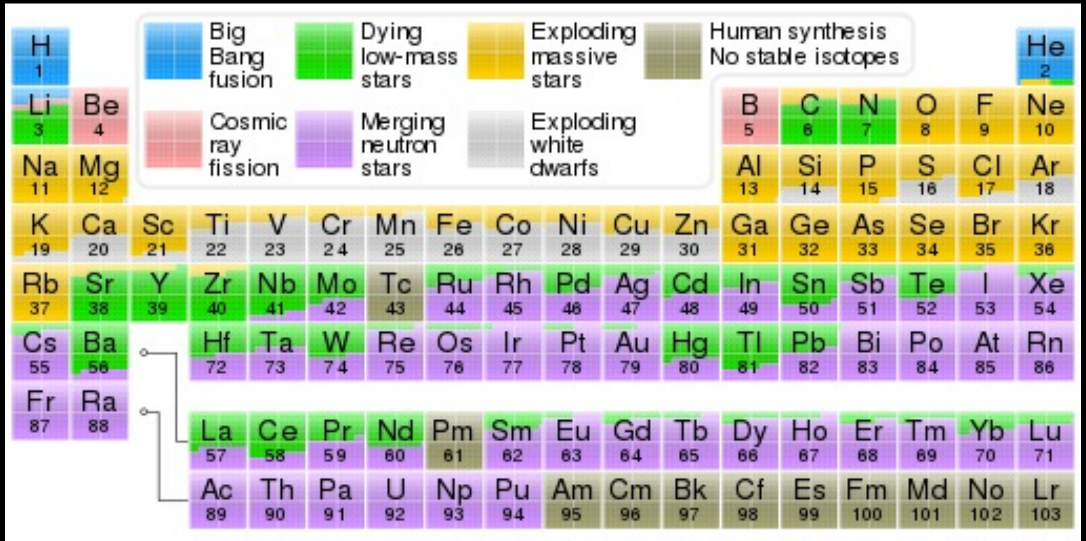
The Experimental Ultra-Heavy Galactic Cosmic Ray (UHGCR) program addresses outstanding issues in the grand cycle of matter in the Galaxy:

- The location of heavy element nucleosynthesis
- The relative contributions of binary neutron star mergers (BNSM) and core-collapse supernovae (SNe) to the Galactic r-process budget
- The enrichment of massive star material (MSM) in the interstellar medium (ISM)



UHGCR: Science Measurements

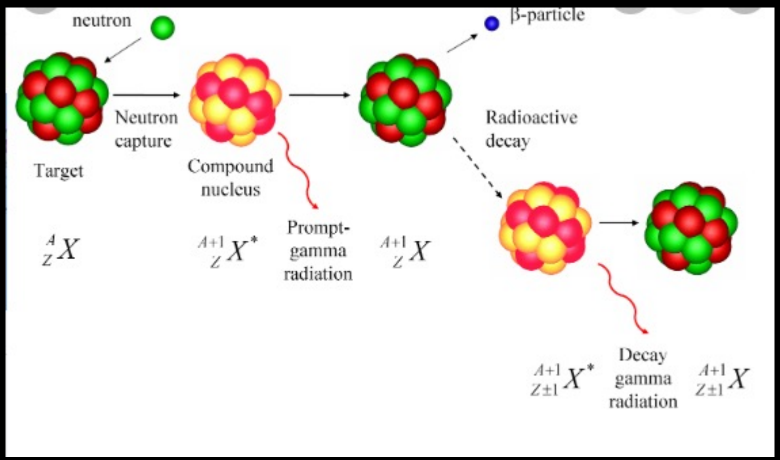


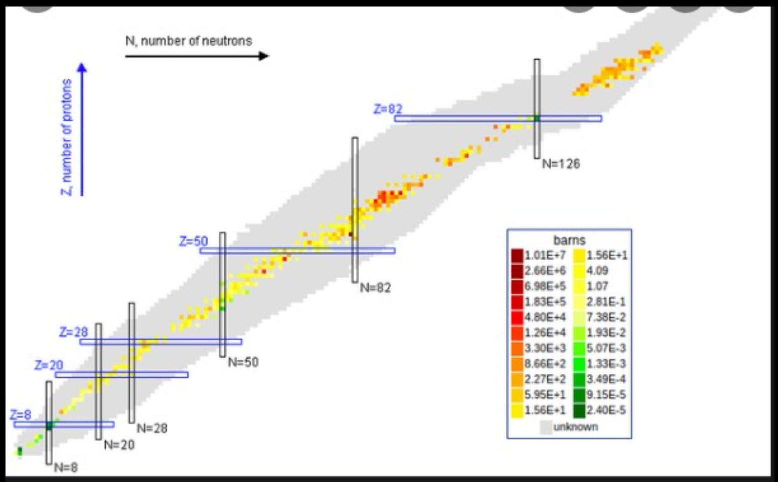
- Big Bang nucleosynthesis: H, He, some Li
- Stellar nucleosynthesis: Fusion ~C to Fe
  - Cosmic ray spallation : Li, Be, B from C,N,O
- Neutron Capture – Slow (s-process)or rapid (r-process) converts Fe to heavier elements
- **Explosive nucleosynthesis r-process AND/OR Neutron star merger r-process : signature in elemental ratios.**

1 year of TIGERISS Data

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

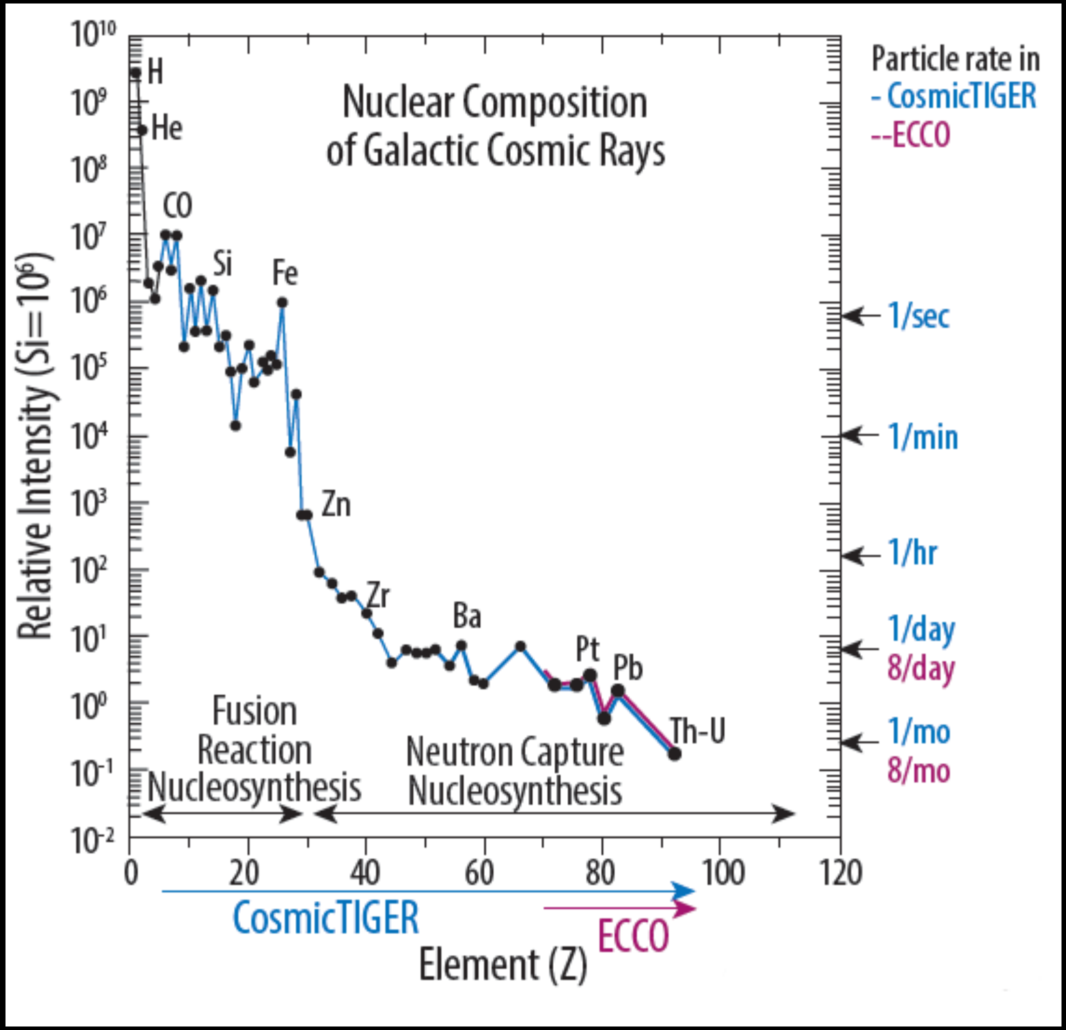
$_{52}$Te + $_{54}$Xe (s-process: 12; r-process 60)





UHGCR Measurement Challenge

- **Ideally explore to the end of the periodic table**
- Elements in the upper 2/3rds are extremely rare
- Requires a very large instrument with a long exposure in space



Experimental Technique/Particle Interactions 1

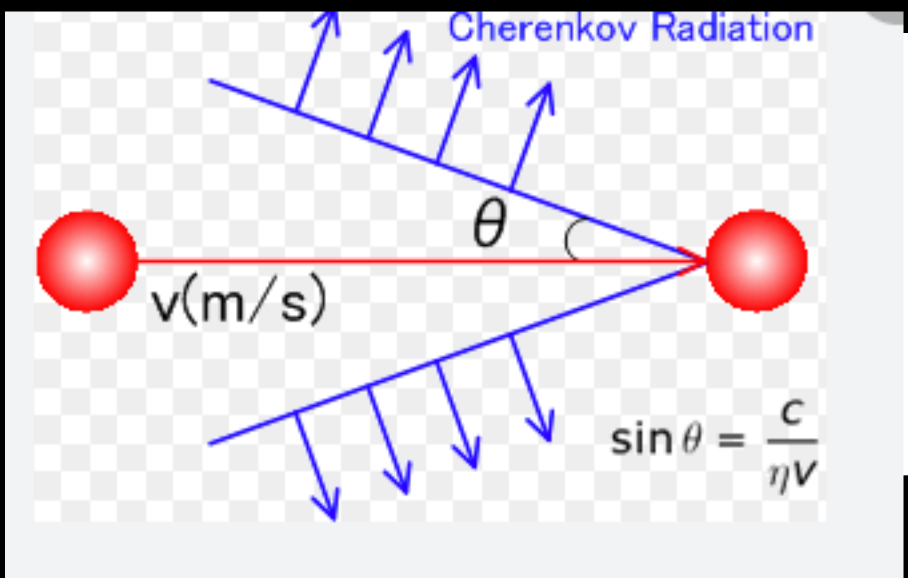
- High-energy particles predominantly interact with material by losing energy through ionizing the material through which they pass.
- The ionization energy loss follows the well-established Bethe-Bloch Formula:
- $$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$
- Thus, ionization energy loss is proportional to $z^2/\beta^2 * \ln(const\ \beta^2\gamma^2)$ and ionization can determine z if β is measured
- The great difficulty is that the relative signal difference between adjacent atomic numbers (z) decreases with increasing z. Thus, at Fe (z=26) δz^2=26^2-$25^2/25^2$=8.16x 10^{-2} while at Pb (z=82) δz^2 = 8.44x 10^{-6}. Because even elements are more abundant than odd elements a separation of $3\ to\ 4\ \sigma_z$ is required.
- Important ionization detectors include,: gas ionization detectors, inorganic scintillators, plastic scintillators, liquid scintillators, semiconductor detectors, cryogenic liquid ionization detectors.

Experimental Technique/Particle Interactions 2

- Techniques to measure β with $\mathrm{sub}-1\%$ resolution at GCR velocities include: $\mathrm{Time}-\mathrm{of}-\mathrm{Flight}$, multiple $\mathrm{dE/dx}$, and Cherenkov Radiation.
- ToF with 100ps resolution is common for z=1, $\beta = 1$ and can easily improve for heavier nuclei by a factor of approximately 1/z. 1% resolution at $\beta = 1$ with 100ps would require a 3m flight path but at 1 GeV/nucleon, $\beta = 0.866$ and a flight path of $2.6\ \mathrm{m}$ is required. For the resolution of 30-50 ps routinely achieved for heavy nuclei, a flight path of 1 m would suffice. However, this might still impact the geometric acceptance of the instrument.

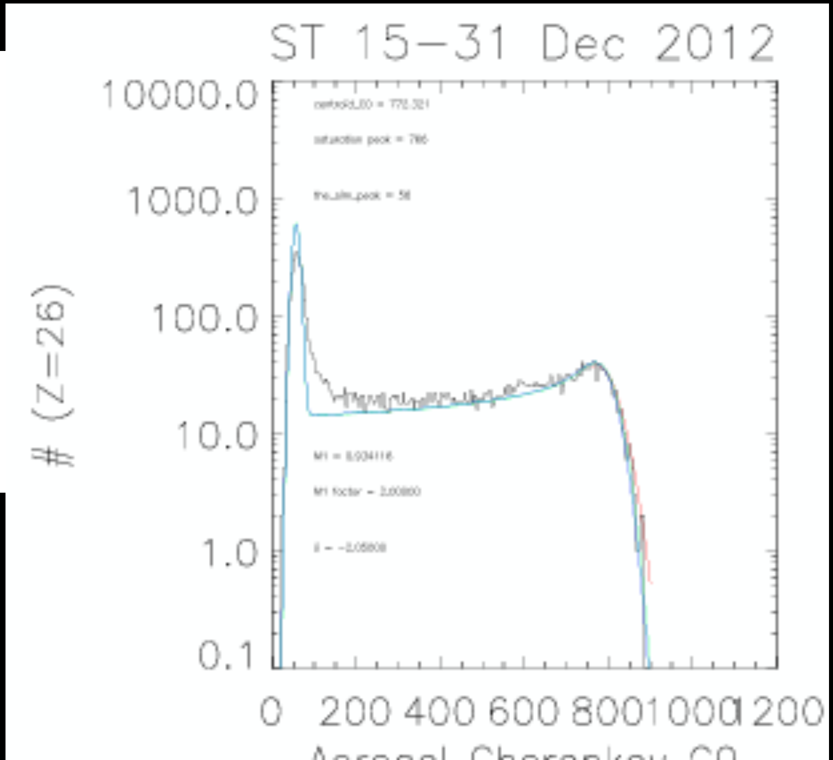
Experimental Technique/Particle Interactions 3

- A Cherenkov Detector is ideal near GCR peak. This could be light-integrating (simplest) or ring imaging (complex). Either is most effective just above its threshold for light production. Tune by using more than one optical index.
- Note that Cherenkov radiation intensity is proportional to z^2.
- Cherenkov emission has a threshold at β=1/n and rises rapidly so its resolution is best near threshold. Then “saturates” to an asymptotic value fully reached at β=1.
- A Cherenkov detector can measure z near its “saturation” β if it has, itself a β correction.

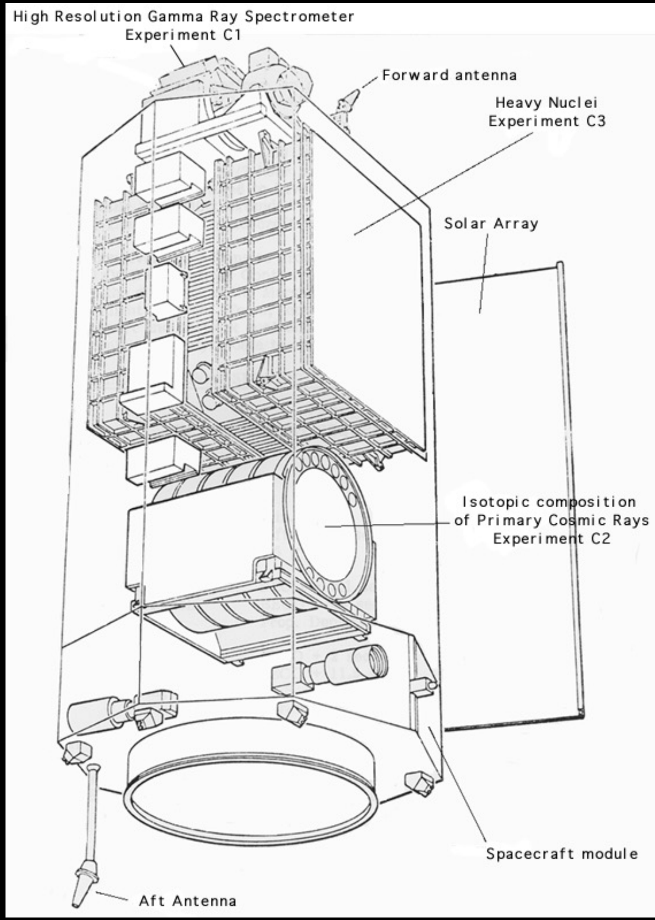


$$N_\gamma = L\frac{\alpha z^2}{r_e m_e c^2}\int \varepsilon(E)\sin^2\theta_c(E)\,\mathrm{d}E$$
$$= L\frac{\alpha z^2}{r_e m_e c^2}\int \varepsilon(E)\left(1-\frac{1}{\beta^2 n^2}\right)\mathrm{d}E$$
$$\approx L N_0\left(1-\frac{1}{\beta^2\langle n^2\rangle}\right)$$

with $\varepsilon(E)$ = Efficiency to detect photons of energy E
L = radiator length
r_e = electron radius

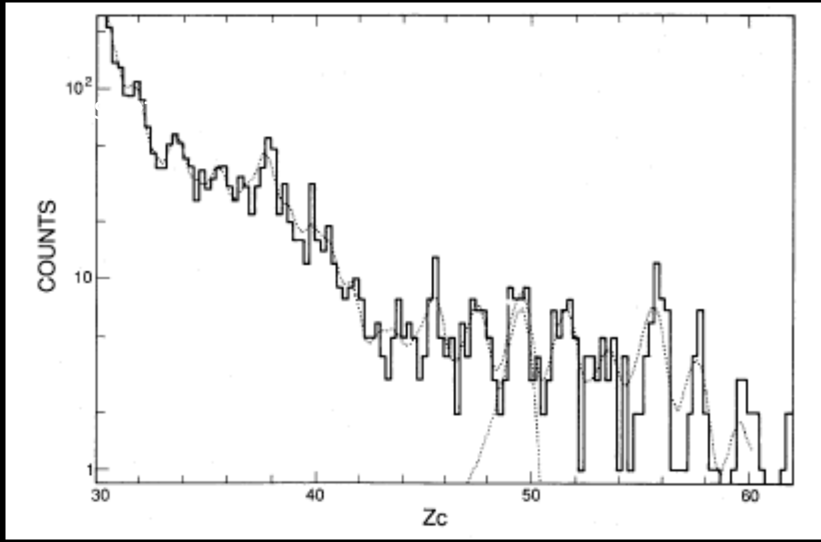


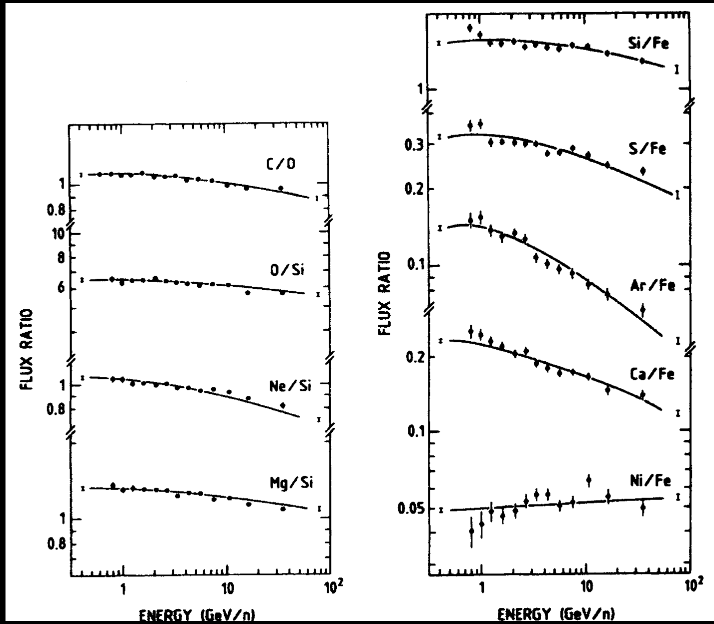
HEAO-3



The **Heavy Nuclei Experiment (C3)** measured cosmic-ray elemental composition for Z≥26 with resolution capable of distinguishing even-Z elements, but not the less-abundant adjacent odd-Z elements.

HEAO-3, launched Sept. 20, 1979, into 43° LEO returned data for 18 months.



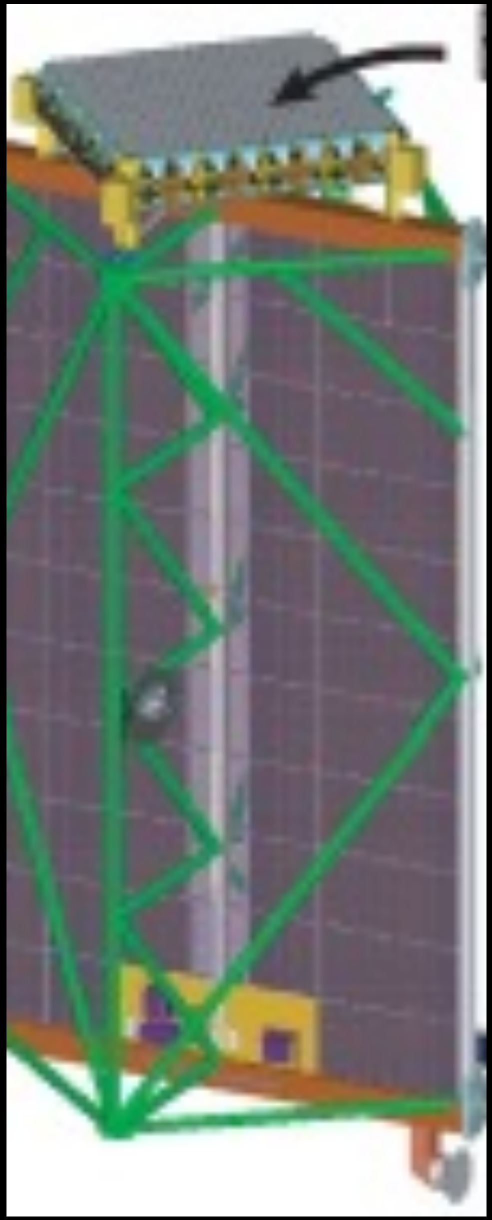


The HNE INSTRUMENT was double-ended with upper and lower hodoscopes and three dual-gap ion chambers. The two ends were separated by a Cerenkov detector

The C2 experiment measured cosmic-ray elemental composition for Z≤32 and energy spectra for Z≤28 for 0.8 < E < 30 GeV/nucleon.
Engelmann, et al., Engelmann *A&A*, **233**, 96 (1990)

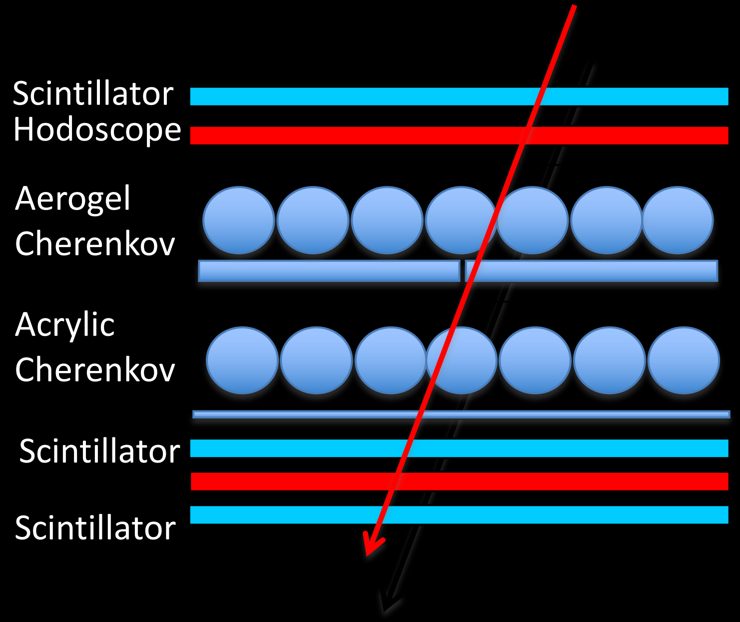
2001 HNX mission

- Designed to give individual element abundances for all elements Fe and heavier.
- Free flyer to be launched and recovered by the Space Shuttle
- Selected by NASA for 1-year Phase A study.
- Ruled “out of scope” late in the study because after Columbia crash, NASA determined that the STS would no longer support science missions not connected with the ISS.

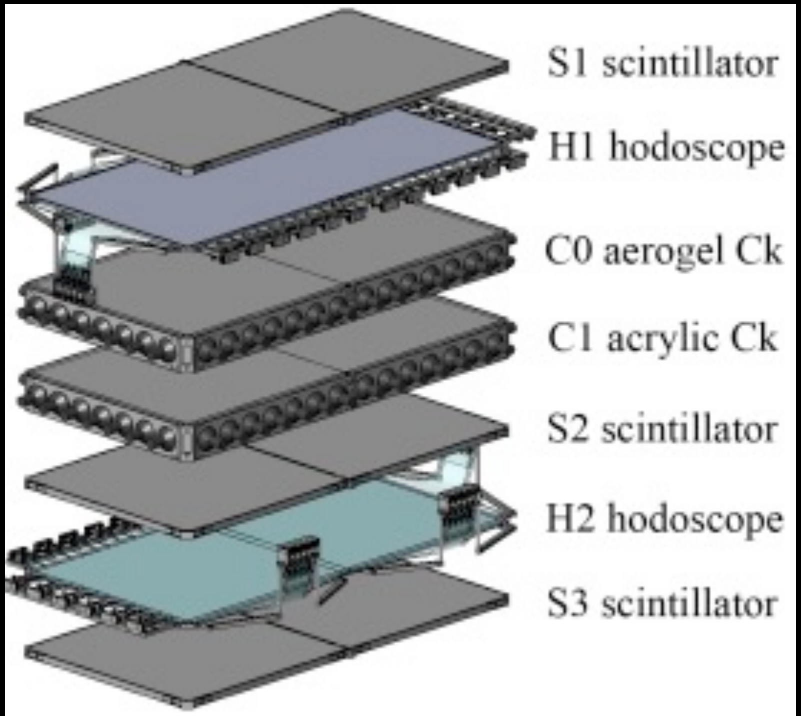


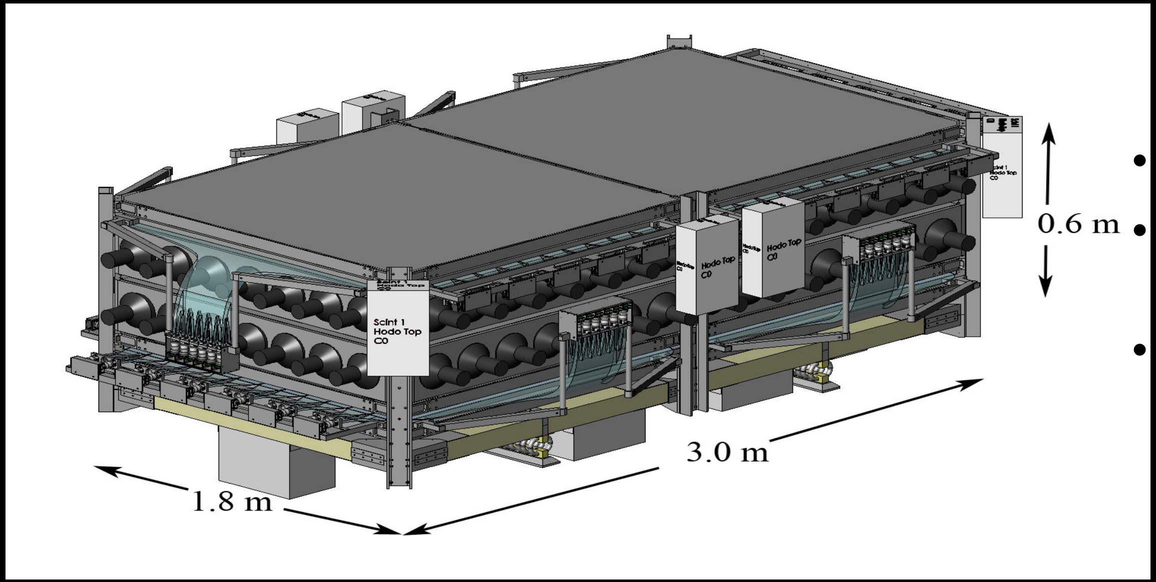
The TIGER/SuperTIGER Instruments

Trans-Iron Galactic Element Recorder



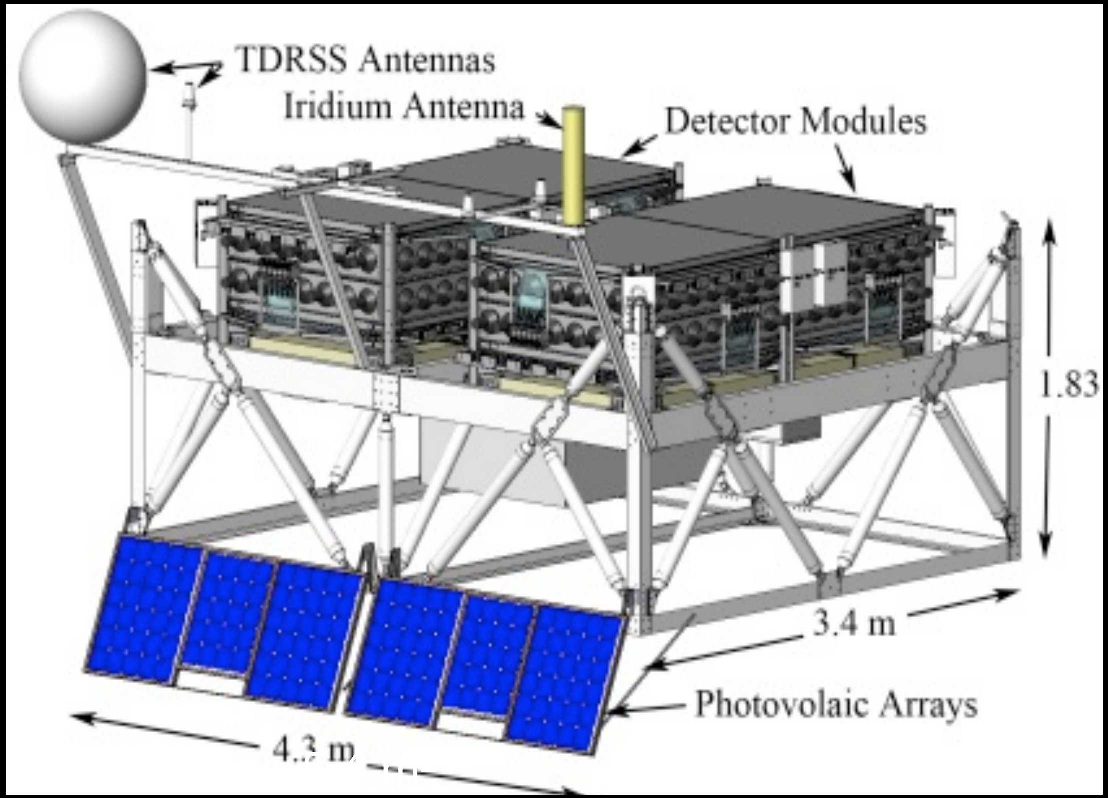
- The hodoscopes only need to give secant corrections
- Two Cherenkov indices give greater beta range and allow Ck vs Ck charge measure





- TIGER (2001,2003)single module
- SuperTIGER (2012,2019) Two nearly identical modules
- Each module is about the size of two TIGER instruments.
- Single Module Mass—660 kg (1452 lb)

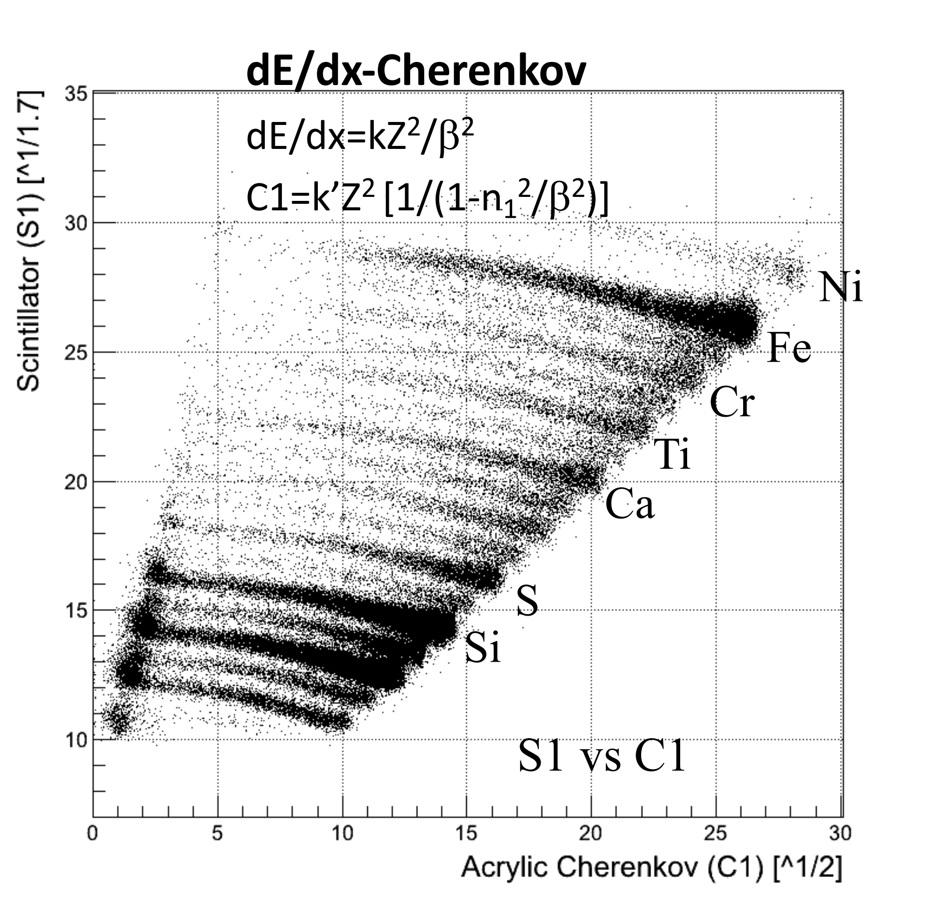
The SuperTIGER Instrument

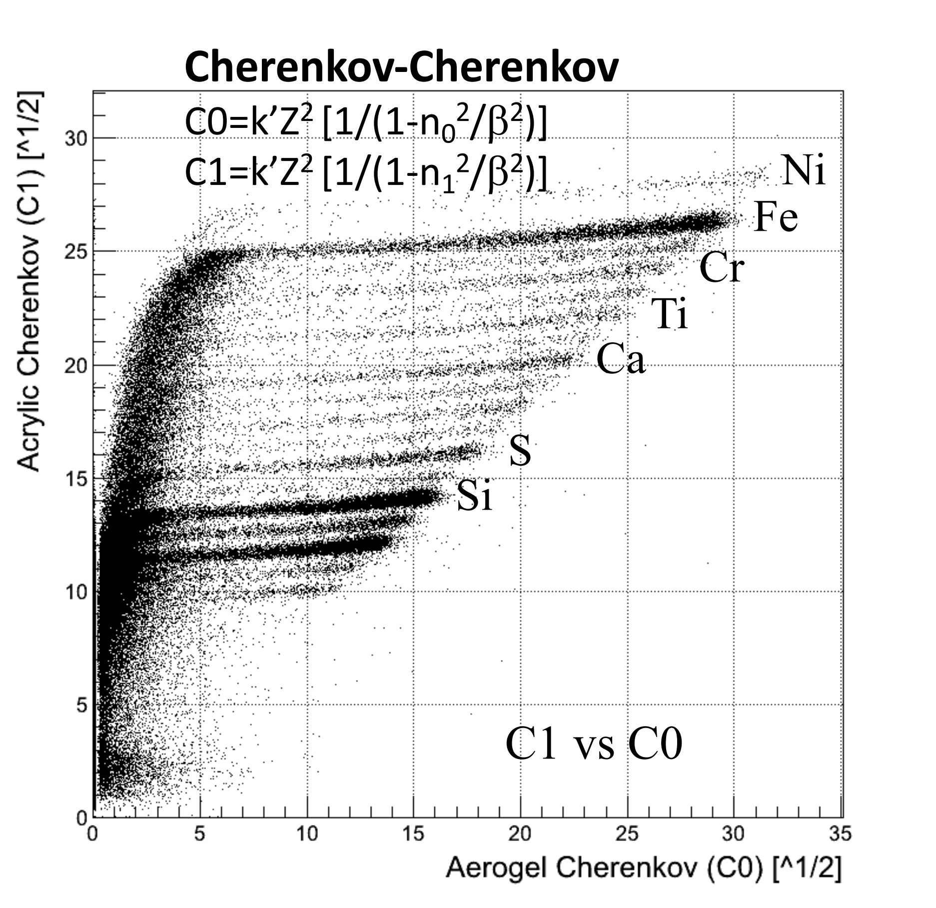


- Effective geometry factor (including interactions) at $_{34}$Se 2.5 m^2sr (6.4 times TIGER - 0.4 m^2sr).
- Full Instrument + Gondola Mass—1770 kg
- Power—250 Watts

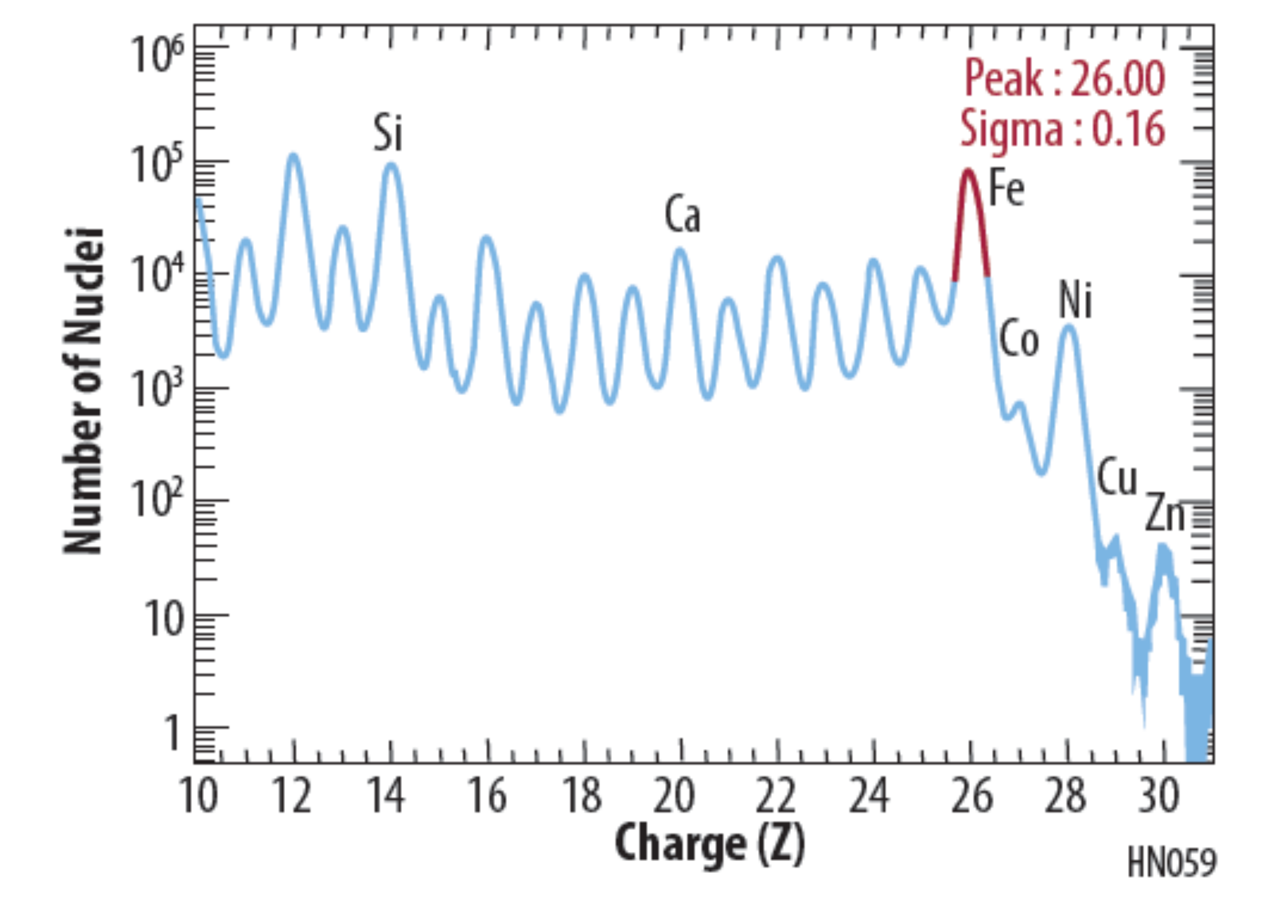
SuperTIGER flight data

- SuperTIGER -1 flight data shown 55 days.
- Energy ≥300 MeV/nucleon ≤ 2.5 GeV/nucleon (aerogel threshold) ➔ scintillator dE/dx vs. Acrylic Cherenkov
- Energy >2.5 GeV/nucleon ➔ Acrylic Cherenkov (C1) vs. Aerogel Cherenkov (C0)

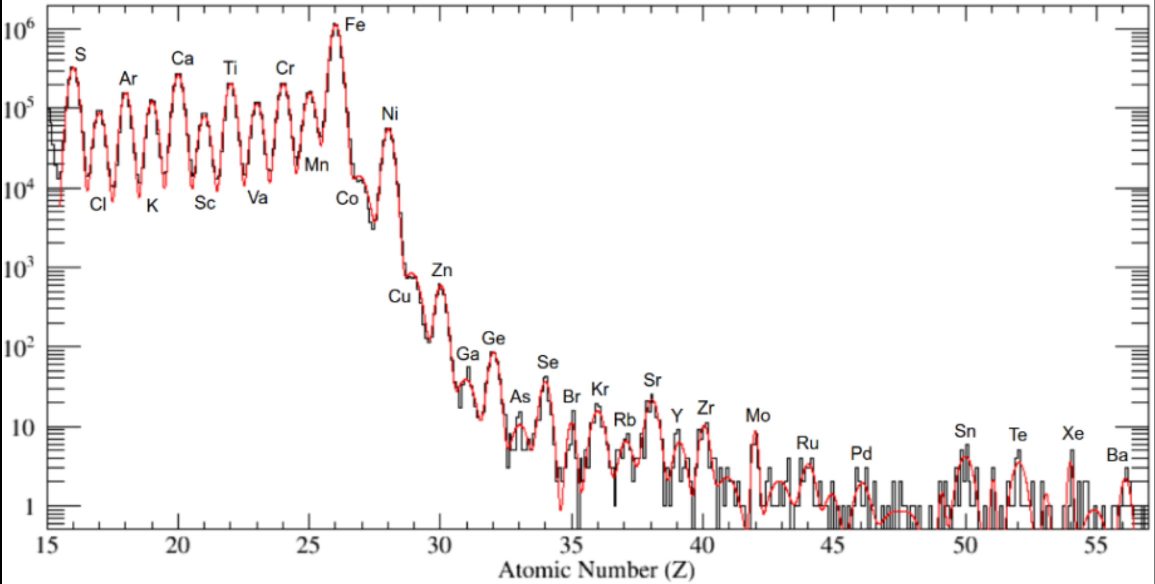




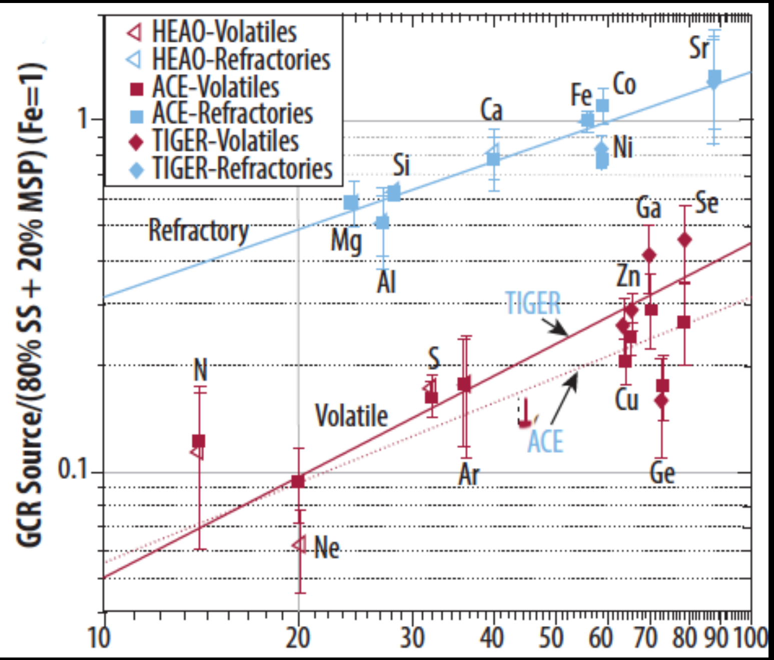
SuperTIGER Results

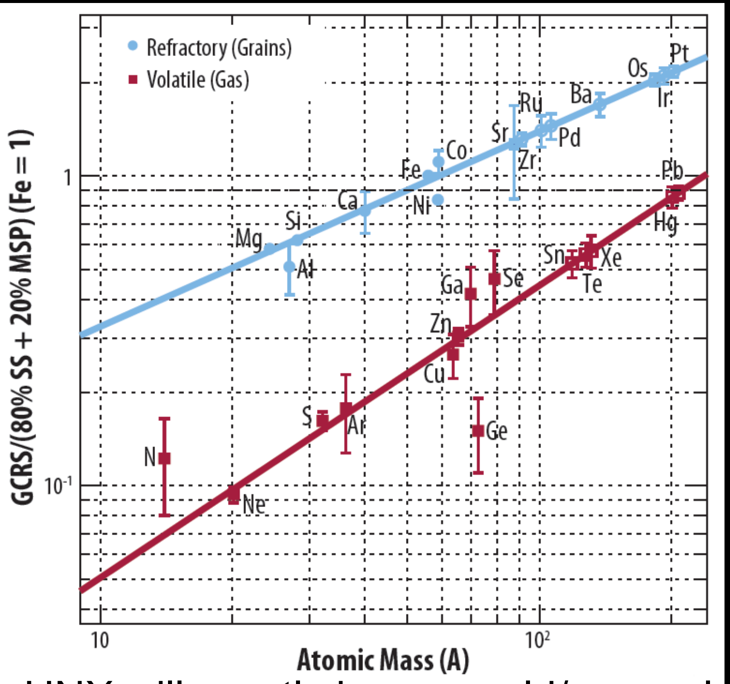


SuperTIGER resolution. Single element abundance measurements by Z, from SuperTIGER 1. Resolution at Fe, the reference species, is < 0.16 e. Resolution worsens above that due mainly to saturation due to quenching effects. TIGERISS is designed to solve this problem, yielding single-element resolution through Z = 82.



Processes Responsible for the UHGCR





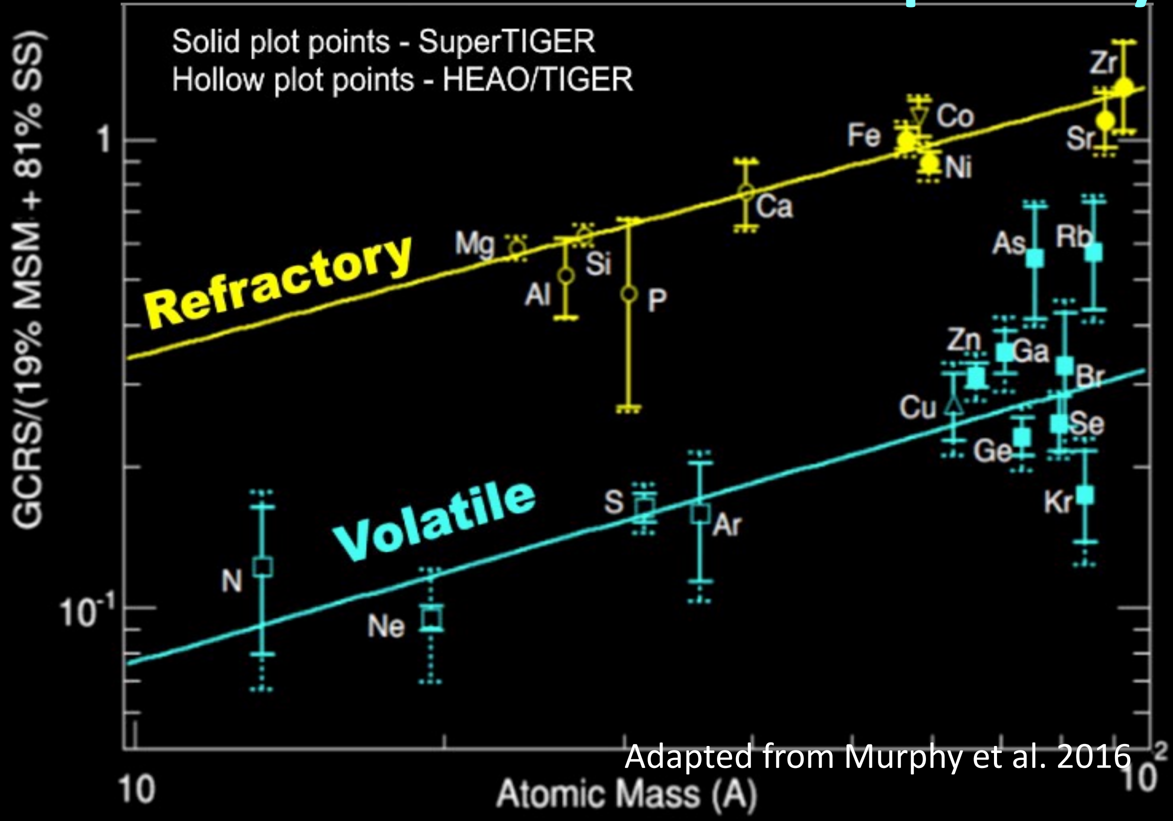
HNX will greatly improve old/new val

TIGERISS and HNX expand on science and technology from successful balloon missions. TIGERISS has been selected for a Concept Study

Cosmic ray (CR) elemental abundances can be normalized to a combination of **Solar System (SS)** and **Massive Star Material (MSM)**

HEAO, TIGER, SuperTIGER, CALET, ACE/CRIS support UHGCR source reservoir consistent with OB associations

$Z^{2/3}$ dependence consistent with grain sputtering cross section



Adapted from Murphy et al. 2016

Refractory elements have *high* condensation temperatures
→ **more likely to form grains**

Volatile elements have *lower* condensation temperatures
→ **less likely to form grains**

Refractory enhancement observed over volatile
→ **grains preferentially accelerated!**

Abundant MSM from supernovae (SNe) and stellar outflows

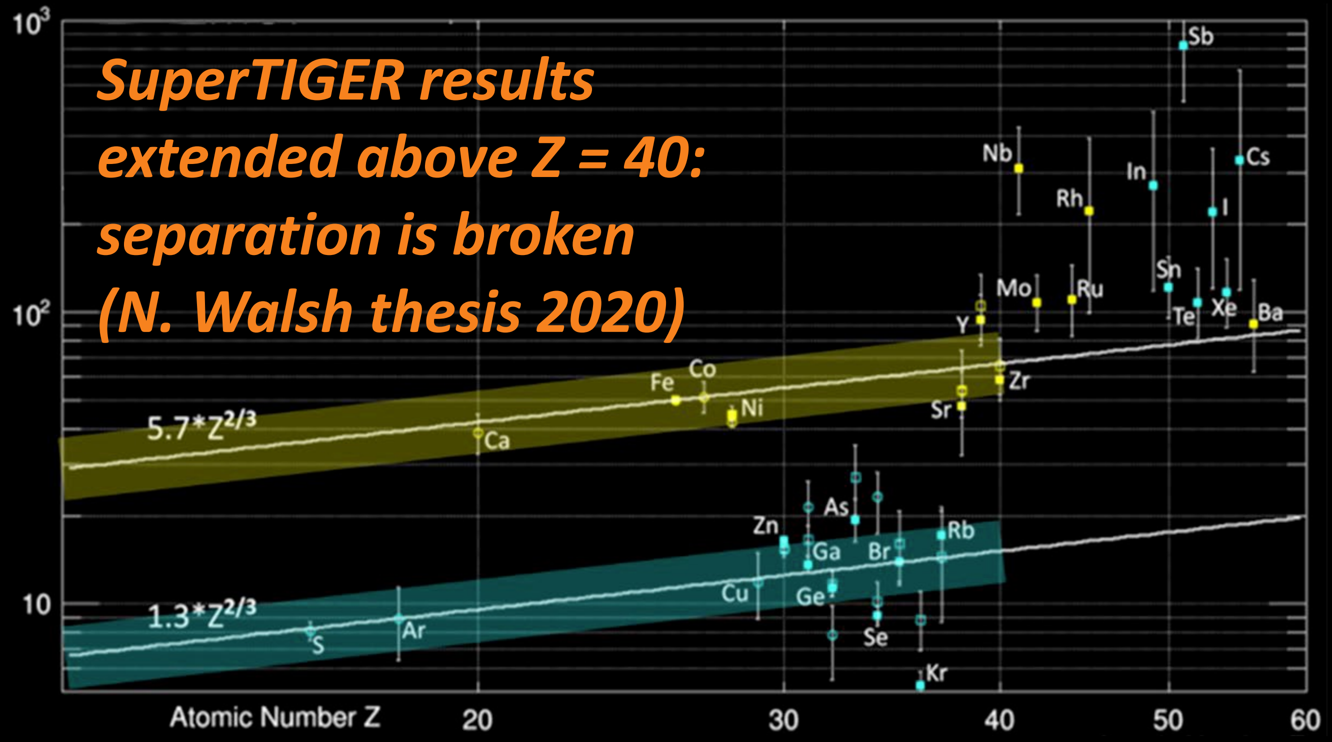
Temperature consistent with observed refractory/volatile split

Frequent supernovae to serve as accelerators

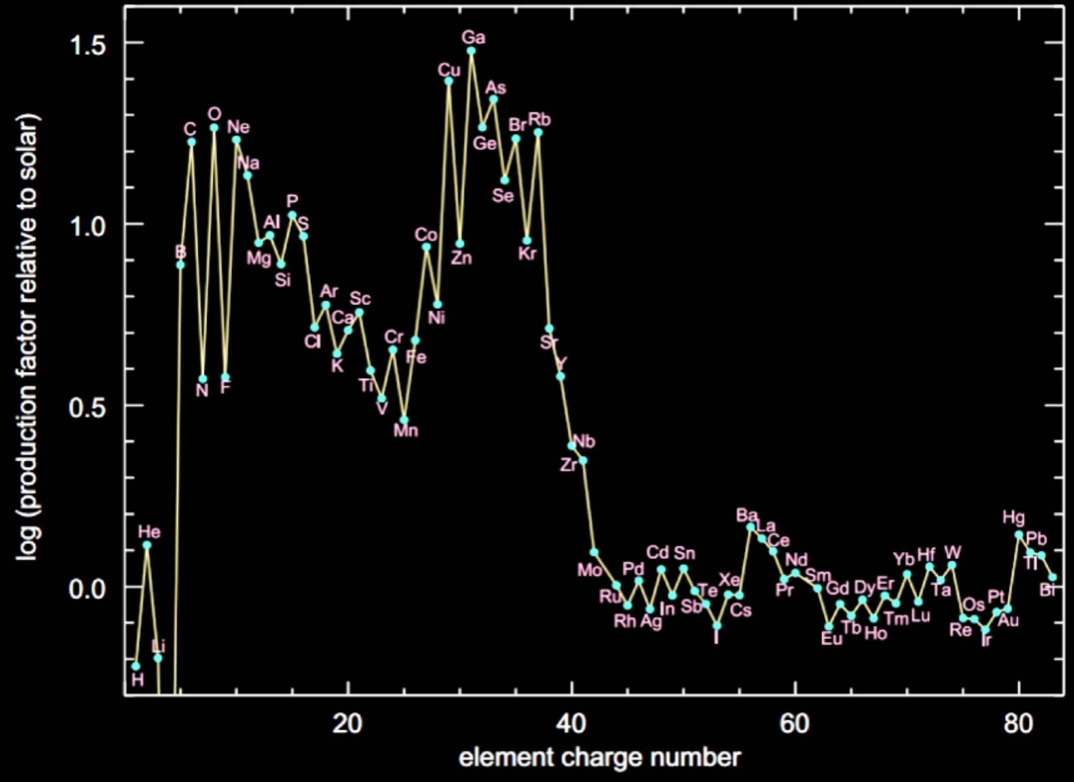
Support for OB Association origins

TIGERISS expands on science and technology from successful balloon missions

SuperTIGER results extended above Z = 40: separation is broken (N. Walsh thesis 2020)



Woosley & Heger 2007 model for OB Association contribution decreases significantly above Z = 40

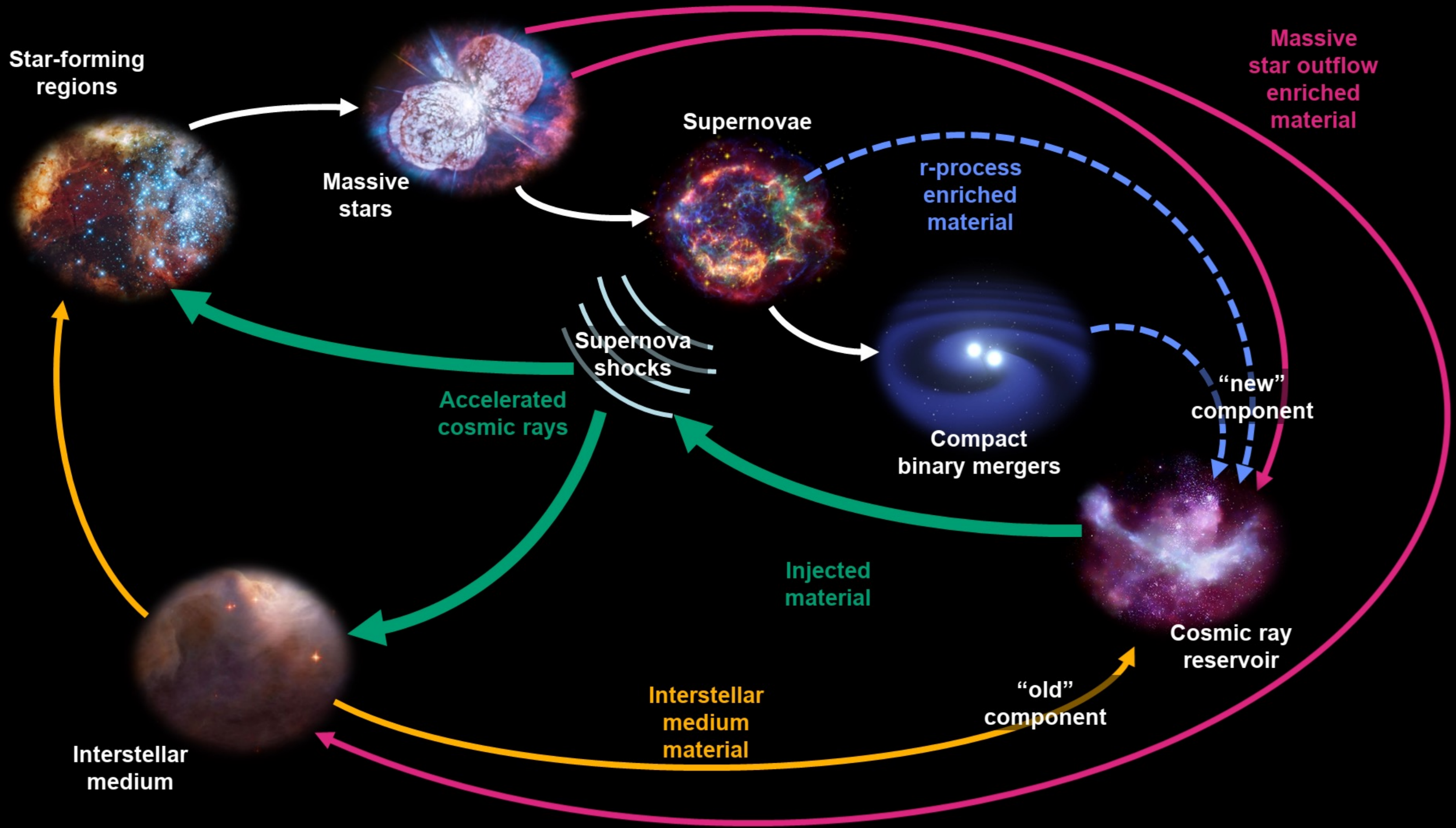


What's providing the extra material?

Is pre-acceleration of grains still the injection mechanism?

TIGERISS : Science Goals

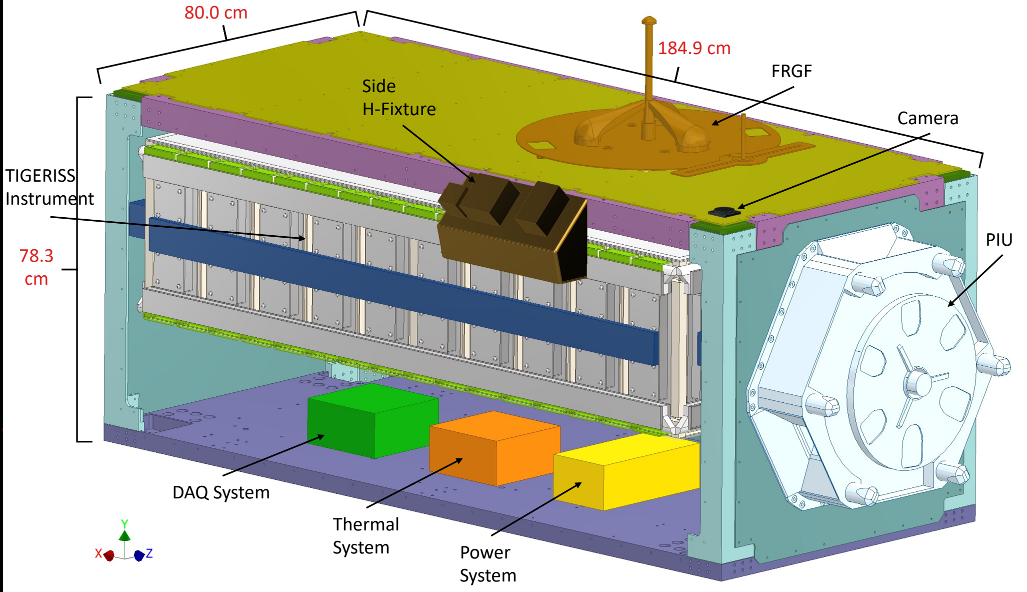
- Where matter originates, particularly nuclei produced by “r-process” rapid neutron capture
- How nuclei are injected from their source into accelerators to become GCRs

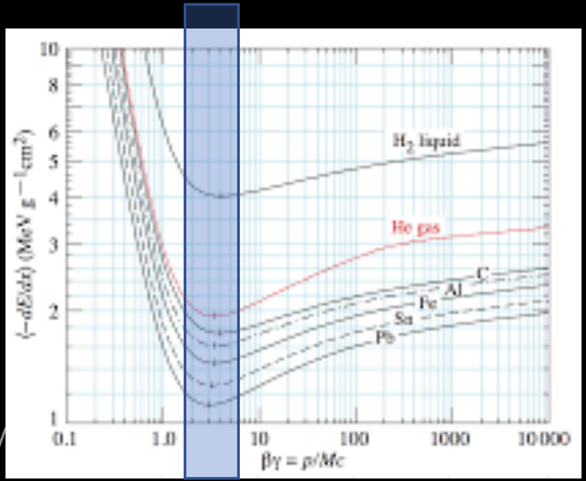


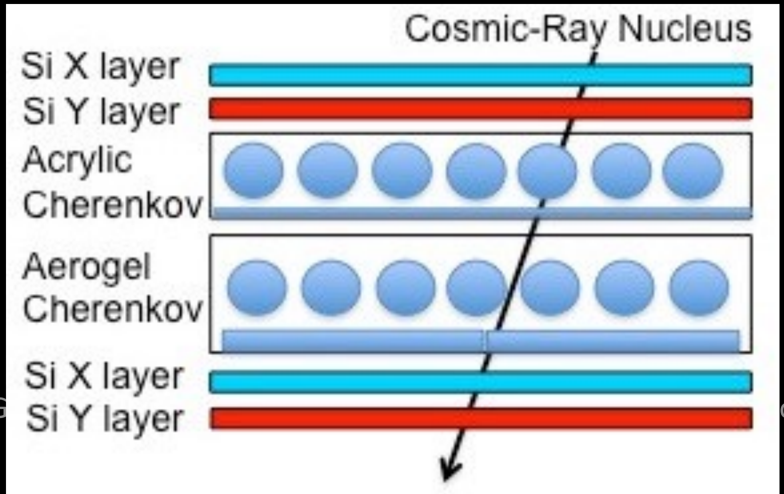
- Key to answer are measurements of abundances of Ultra-Heavy Galactic Cosmic Rays : UHGCRs: Z > 28 (above Nickel)
- Astro2020 Decadal Survey Questions:
  - “Are neutron star mergers the main site of r-process nucleosynthesis, or are there supernovae and other core collapse events that contribute significantly 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 thru ^{82}Pb.**

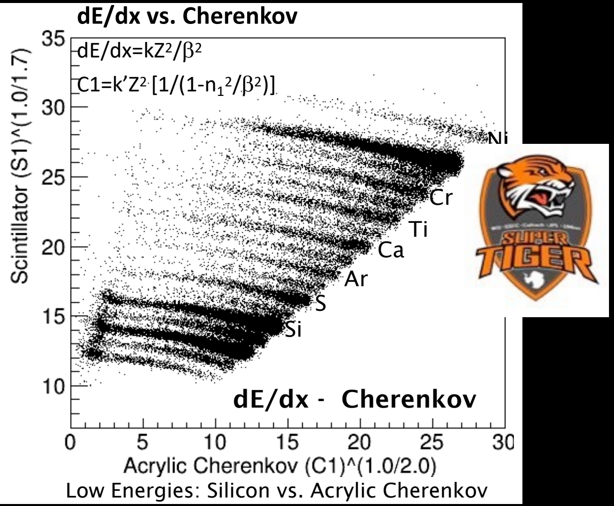
TIGERISS : UHGCR Measurement Technique

- Large electronic particle detector system – 1.1 m^2 active area, AΩ > 1.6 m^2 sr (JEM-EF version)
- Heritage from SuperTIGER, TIGER, HEAO-3, Parker Solar Probe, STEREO
- Measures nuclei $5 \le Z \le 82$ with single element resolution – proven in accelerator tests, TIGER, SuperTIGER
- Charge measurement employs three detector subsystems in dE/dx vs. Cherenkov and Cherenkov vs. Cherenkov techniques:
  - **Silicon strip detector arrays measures charge and trajectory**: Provides exceptional charge resolution over entire range $5 \le Z \le 82$
  - **Acrylic Cherenkov** measures charge and velocity **(n=1.5, $\beta > 0.67$, $E_K \ge 325$ MeV/nucleon)**
  - **Aerogel Cherenkov** measures charge and velocity **(n=1.04, $\beta > 0.96$, $E_K \ge 2.25$ GeV/nucleon)**

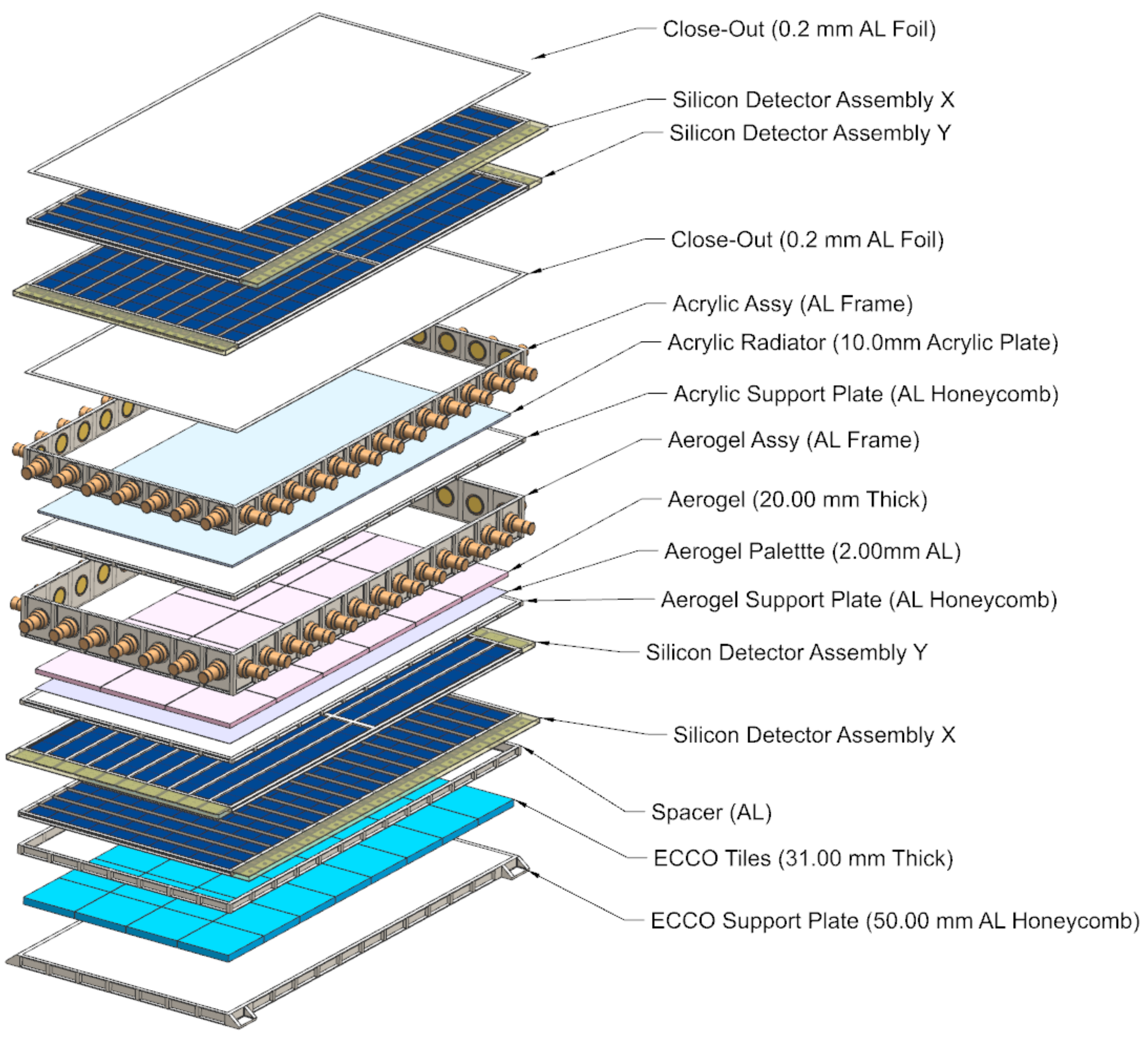






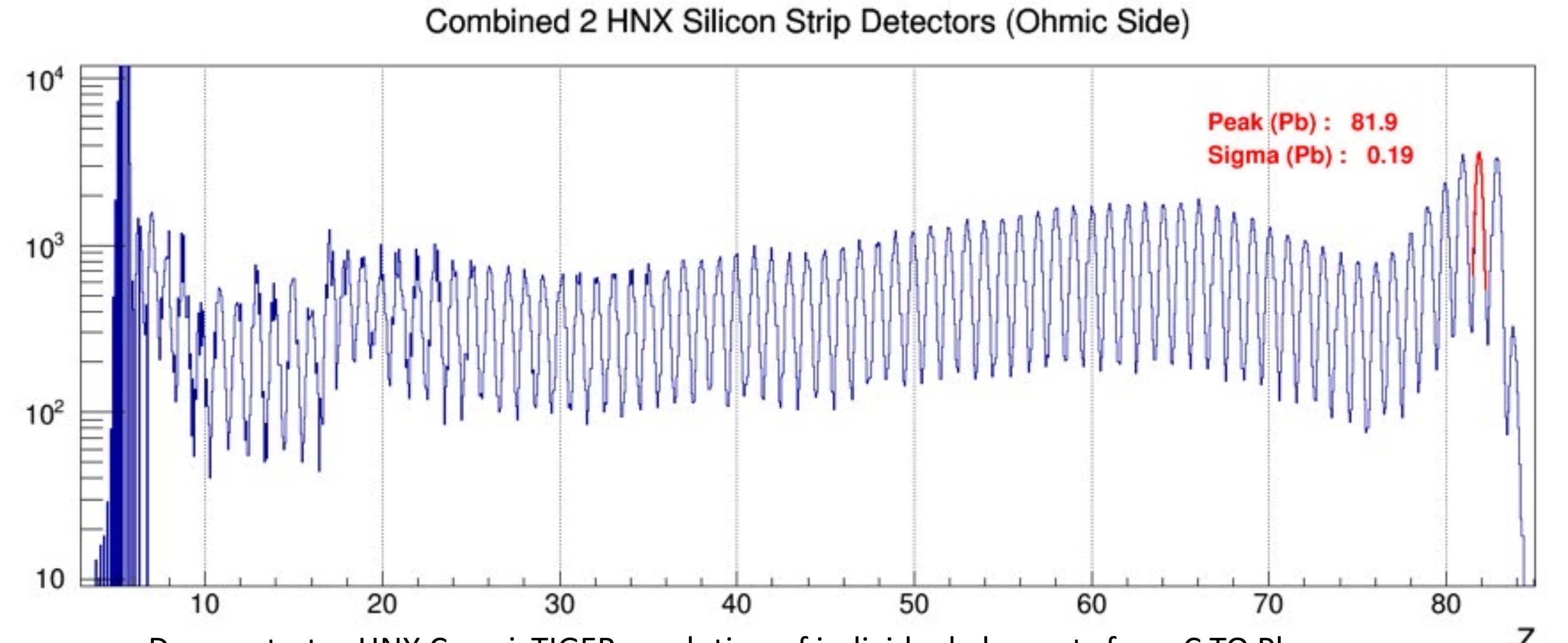


TIGERISS Expanded View



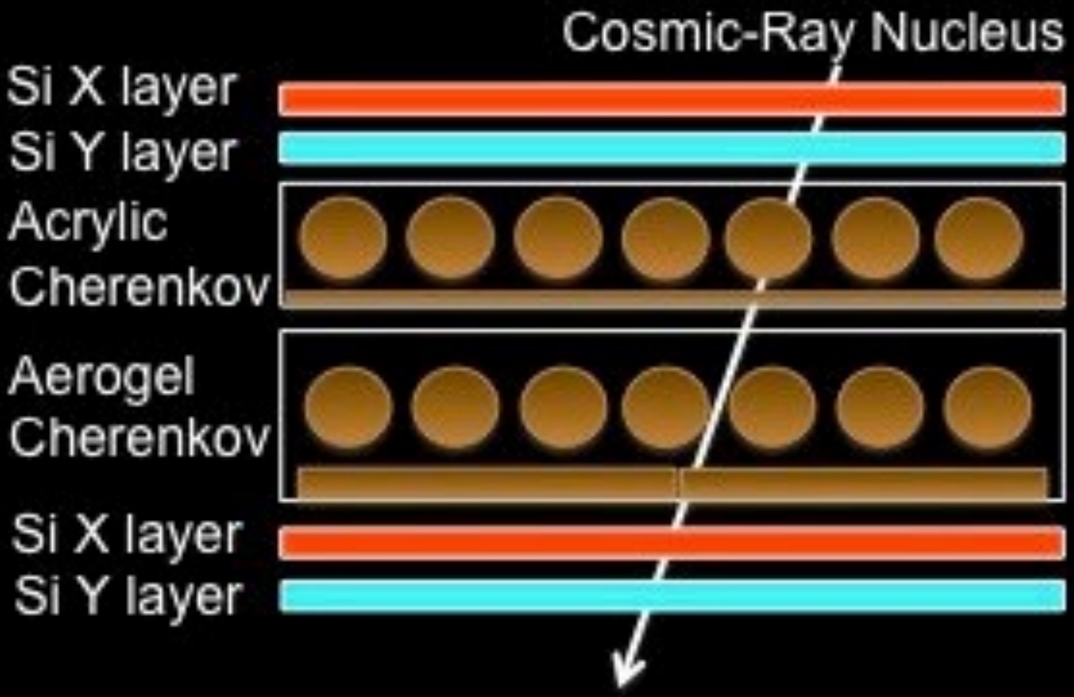
- 2 Layers of SSD (10 cm x 10 cm x 500 μm) with 3.12 mm strip pitch (50 μm gap) at top and bottom.
- Orthogonal strip direction in successive layers gives X ,Y.
- SSD connected in “ladders” with corresponding strips joined (wire bond or flex cable) between detectors and read out at end. All ladders are identical for simplicity
- Cherenkov detectors (acrylic and aerogel) use light integration boxes lined with Gore DRP reflector.
- Silicion photomultiplier (SiPM) arrays inside boxes. Figure from HNX proposal shows PMTs.
- Aspect ratio of light integration boxes is optimized for the specific radiator used

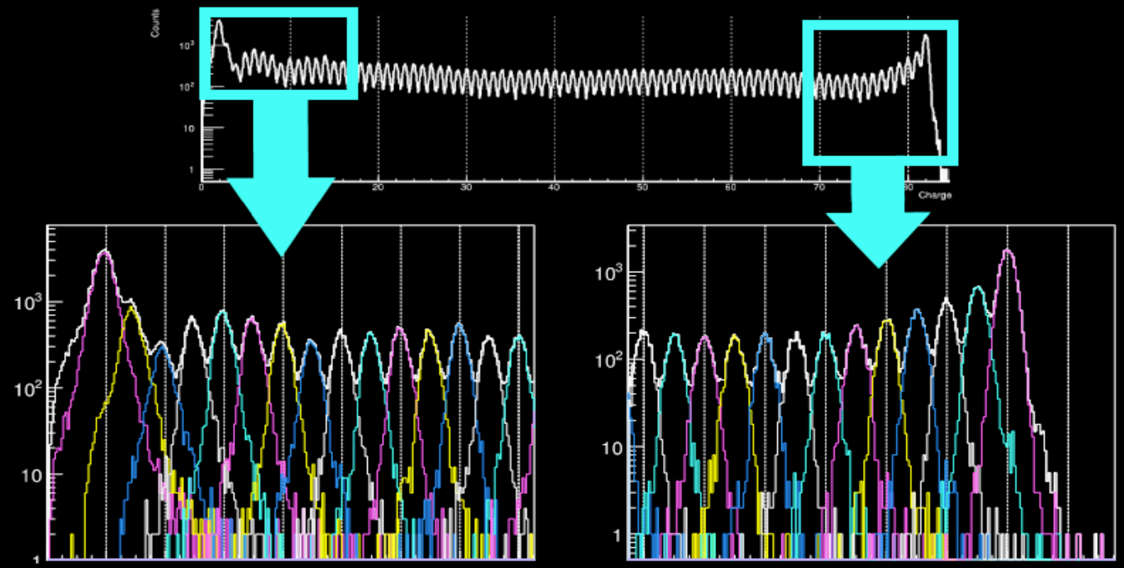
HNX/TIGERISS
Silicon Strip Detectors
(6 <= Z <= 84)



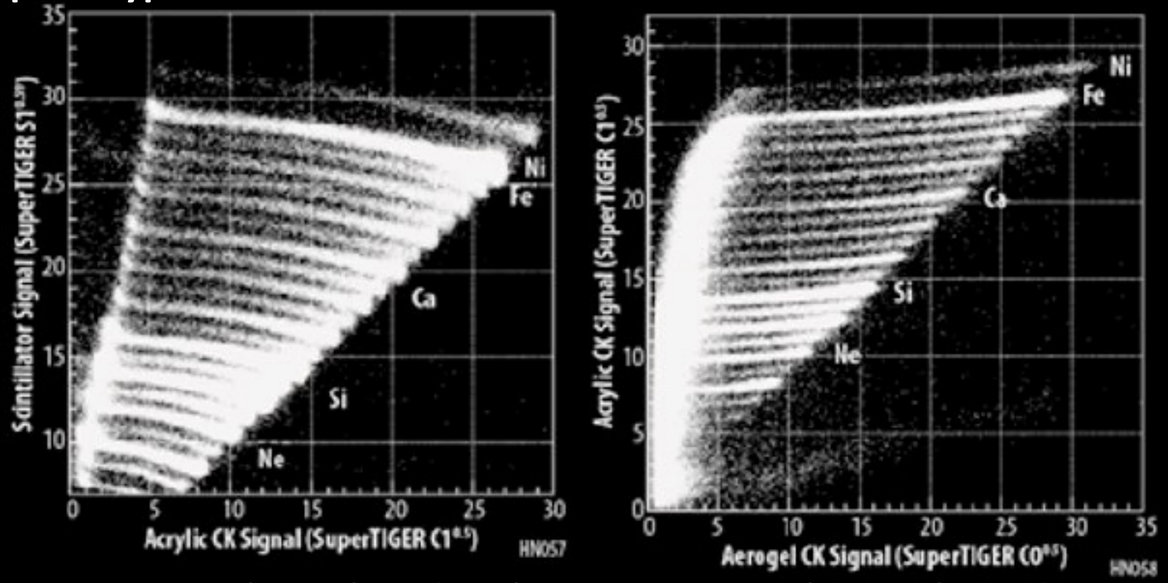
Demonstrates HNX CosmicTIGER resolution of individual elements from C TO Pb

TIGERISS detector scheme: using combined ionization and Cherenkov measurements with silicon strip detectors and SiPMs





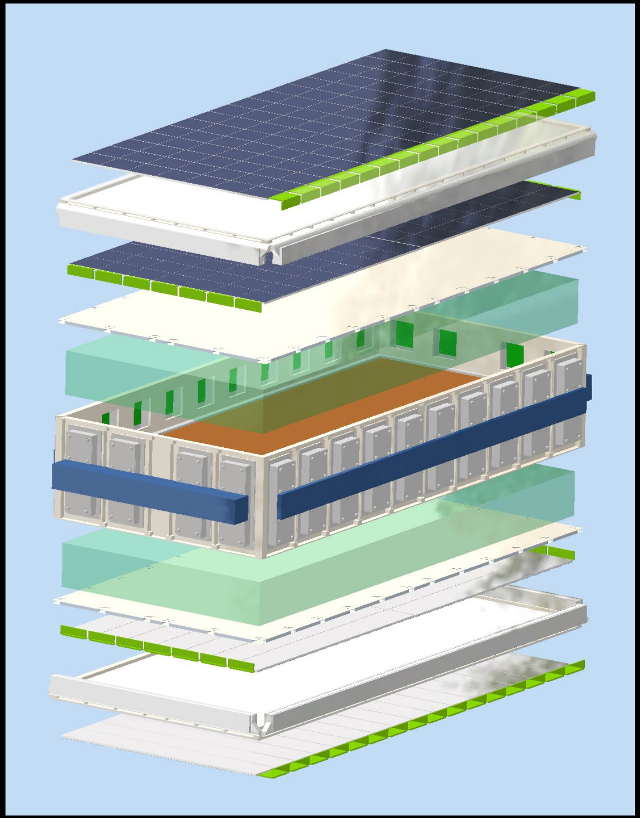
Charge spectrum from Pb fragmented beam tests at CERN in 2018 with a prototype silicon detector

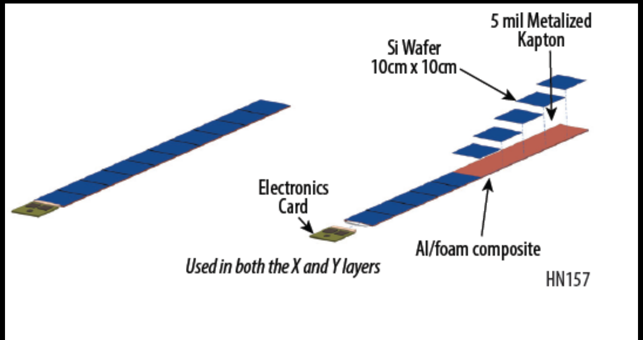


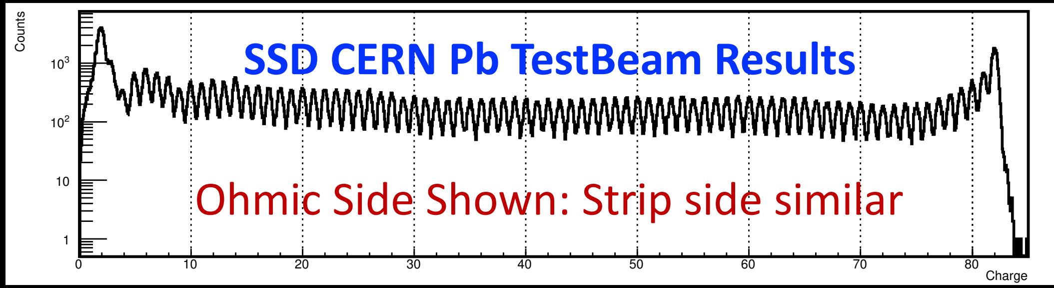
Ionization vs. Cherenkov distributions seen in the acrylic and aerogel radiators for flight data during the SuperTIGER-1 flight.

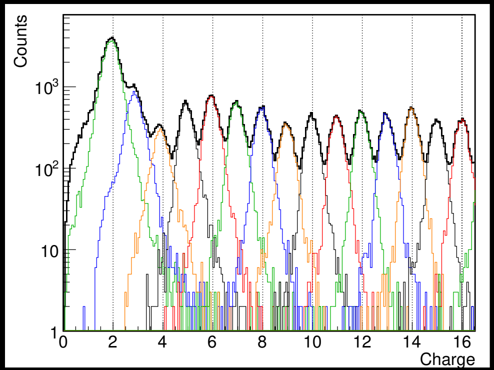
TIGERISS : Precision charge measurements using SSDs

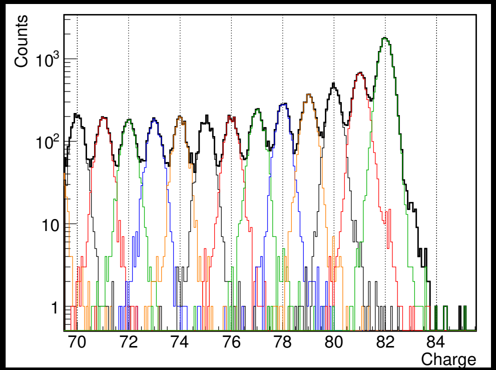
TIGERISS upgrades SuperTIGER with silicon strip detectors (SSDs) for precision tracking and charge measurement $5 \lesssim Z \leq 82$ and SiPM Cherenkov detector readout based on successful CERN test beam characterization.



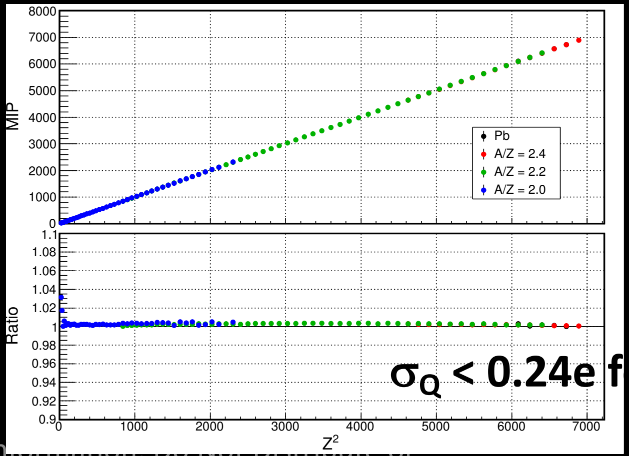


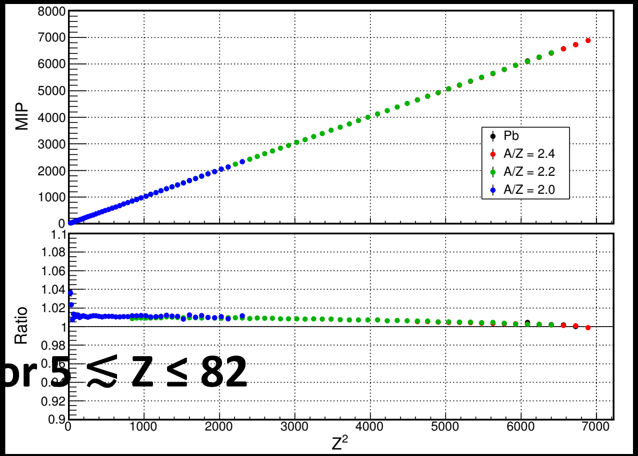




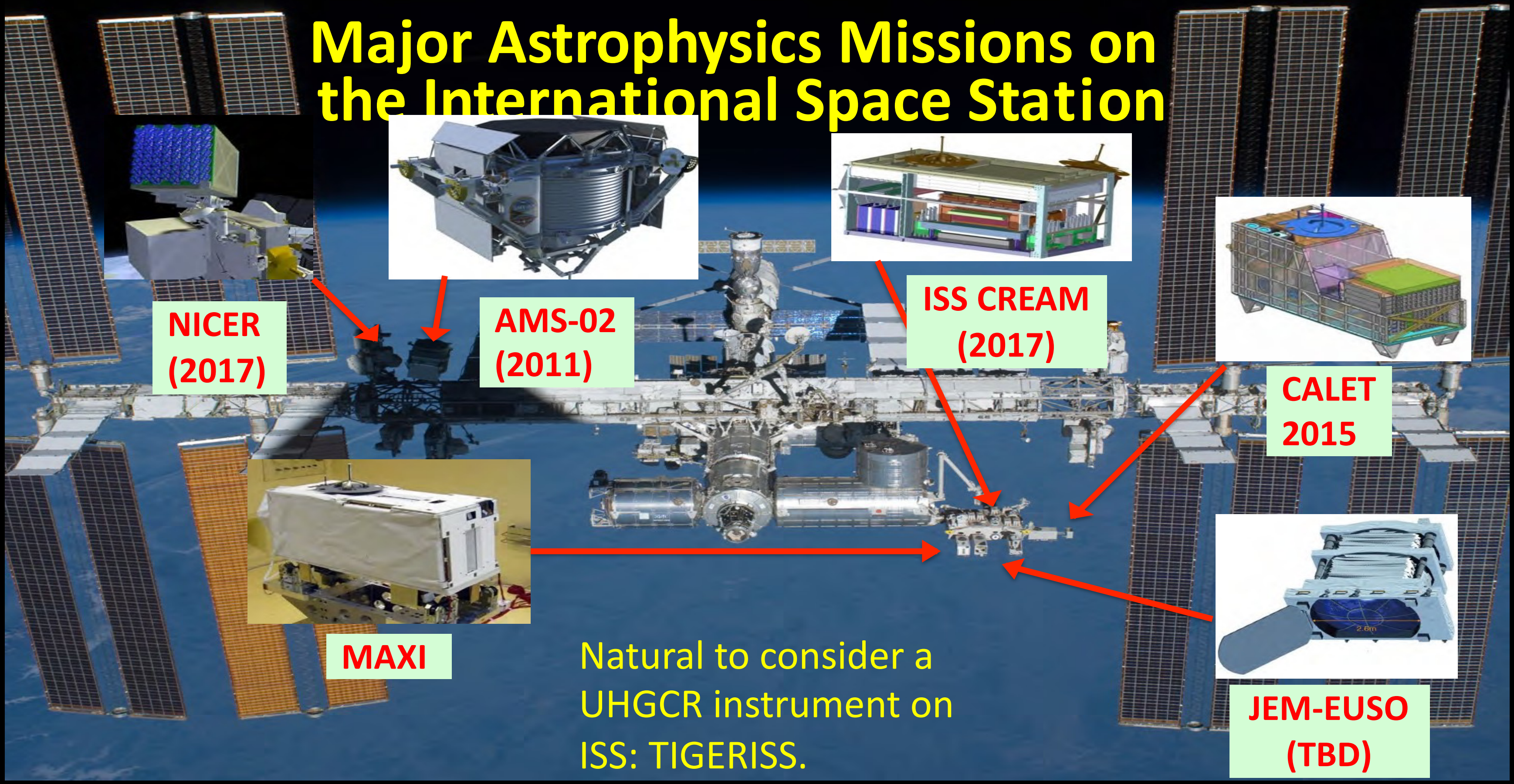


GSFC responsible for development and fabrication of SSD subsystem

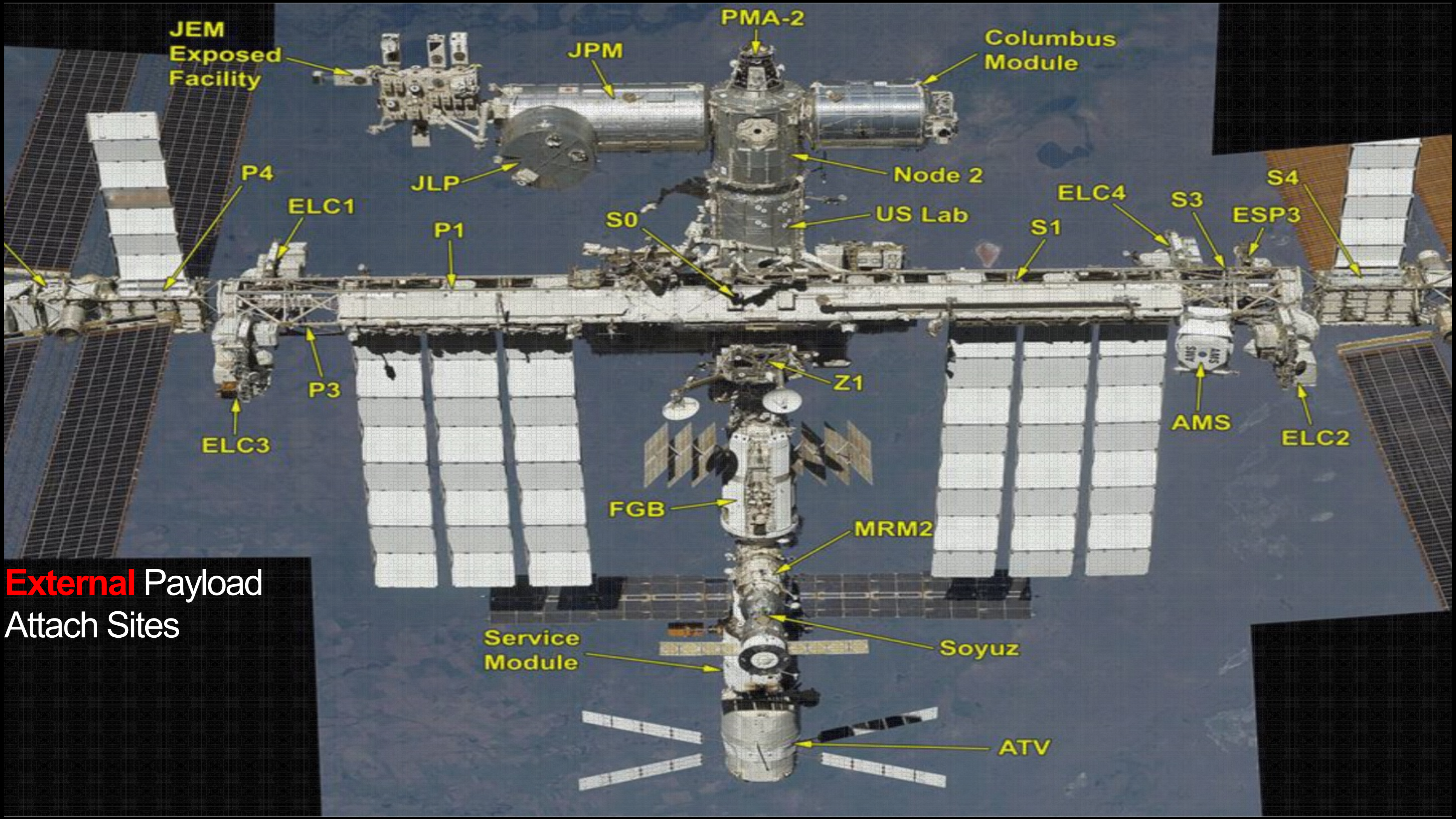




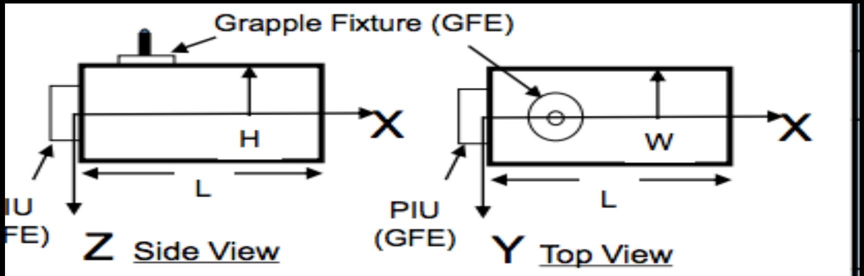
$\sigma_Q < 0.24e$ for $5 \lesssim Z \leq 82$


Major Astrophysics Missions on the International Space Station
NICER (2017)
AMS-02 (2011)
ISS CREAM (2017)
CALET 2015
MAXI
Natural to consider a UHGCR instrument on ISS: TIGERISS.
JEM-EUSO (TBD)

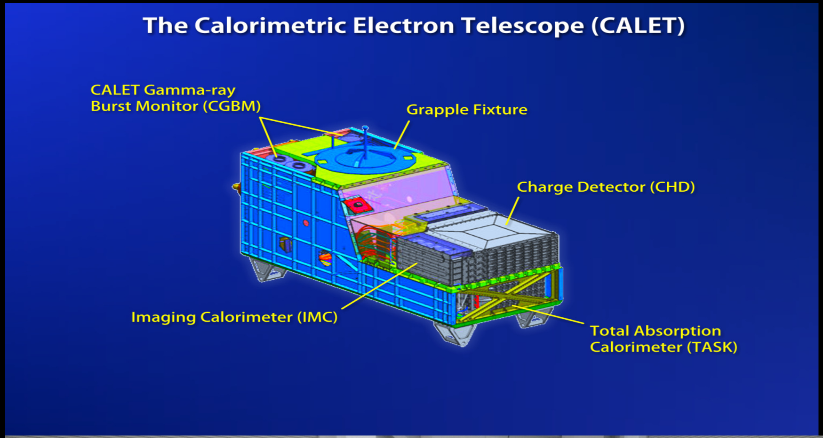
External Payload Attach Sites



TIGERISS Mission Concept 2

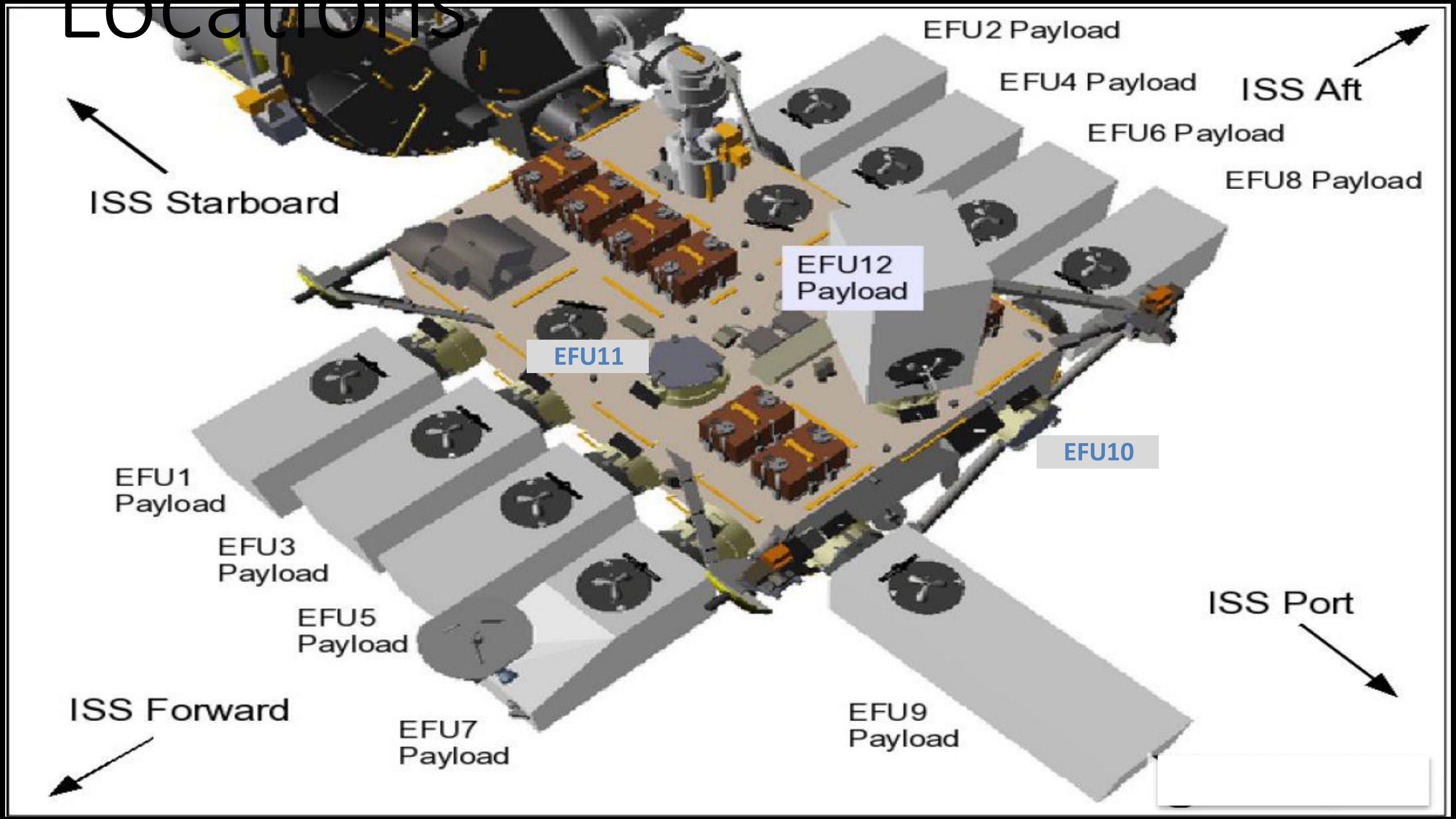


Axis	mm	ft	inch
W	800	2	7.50
H	1000	3	3.37
L	1850	6	0.83



- Dimensions of TIGERISS on Kibo-EF are constrained to about 1.67 m x 0.67 m by space on pallet and need to allow for grapple fixture.
- Total mass on standard site limited to 500 kg.
- Will make use of engineering developed at Wallops Flight Facility (WFF) for the ISS-CREAM pallet.

Locations



TIGERISS has been assigned EFU-10 as requested.

TIGERISS : Early Career Development

TIGERISS aims **to build and mentor a new diverse generation** of scientists and technicians, placing them in high-level roles to kick-start a long-term career in cosmic ray astrophysics.

TIGERISS will support

18

early career team members/year

Highlighted Early Career Leadership

Michaela Amoo, Howard U.
Howard U. PI
Power Systems PDL
Education & Diversity PDL

Wolfgang Zober, WashU
Science PI

Nicholas Cannady, UMBC
UMBC PI
Operations PDL

2

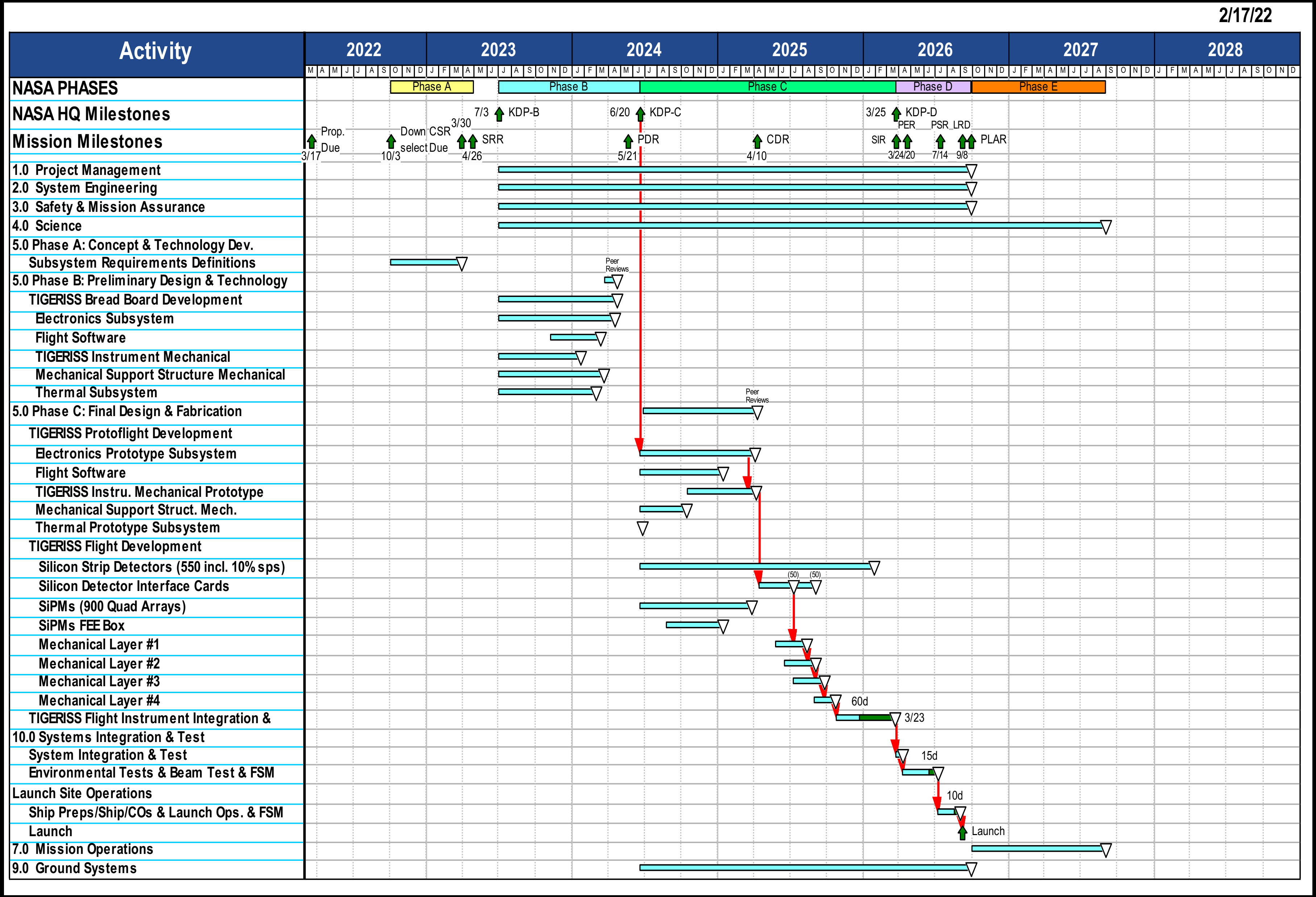
GSFC Providing Mentorship

- Senior GSFC Scientists John Krizmanic & John Mitchell & Makoto Sasaki (CRESST/UMCP) will provide mentorship to *SciencePI Wolfgang Zobler, UMBC InstPI Nick Cannady, Howard InstPI Michaela Amoo* while supporting *PI Rauch*

GSFC Receiving Mentorship

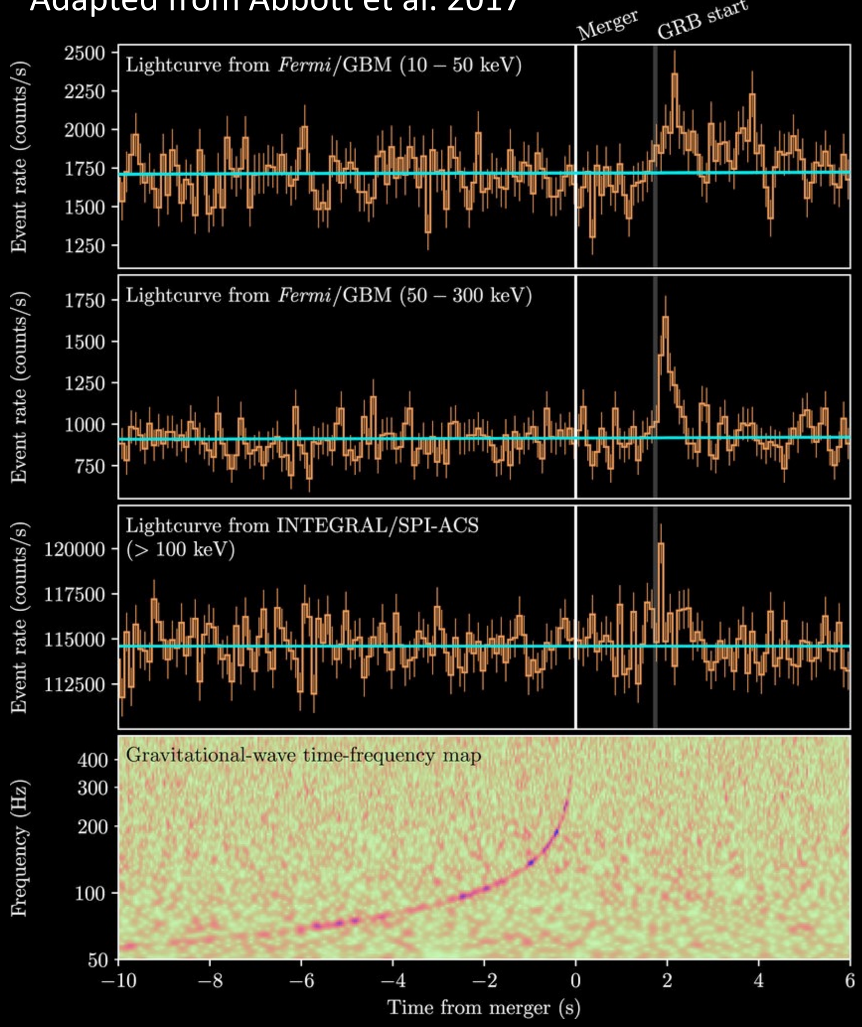
- Senior GSFC Scientists John Krizmanic & John Mitchell & Makoto Sasaki (CRESST/UMCP) will provide mentorship to *Mechanical Engineer Liam Williams (KBR) and Priya Ghosh (CRESST/CUA)*
- **To bring GSFC Early career inline w/ University partners, an Early Career new CS Code 661 Hire will be mentored in space-based instrumentation, simulation physics, and data analysis by senior GSFC scientists.**

TIGERISS : Schedule and Drivers



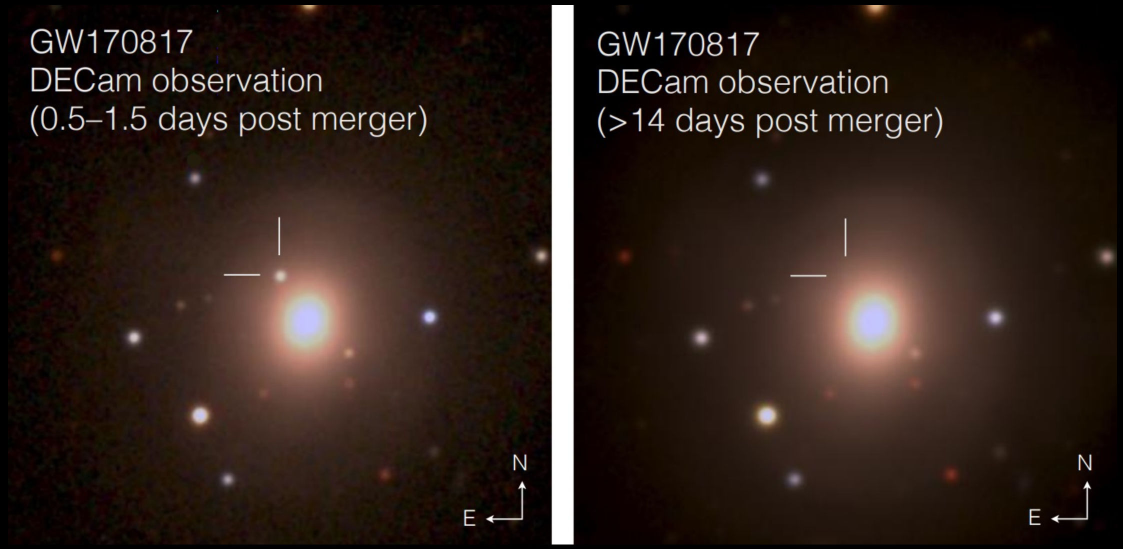
GW170817 + GRB 170817A + AT2017gfo multi-messenger observations

Adapted from Abbott et al. 2017



Short GRB coincident in gamma rays

Ejecta rich in r-process heavy nuclei!



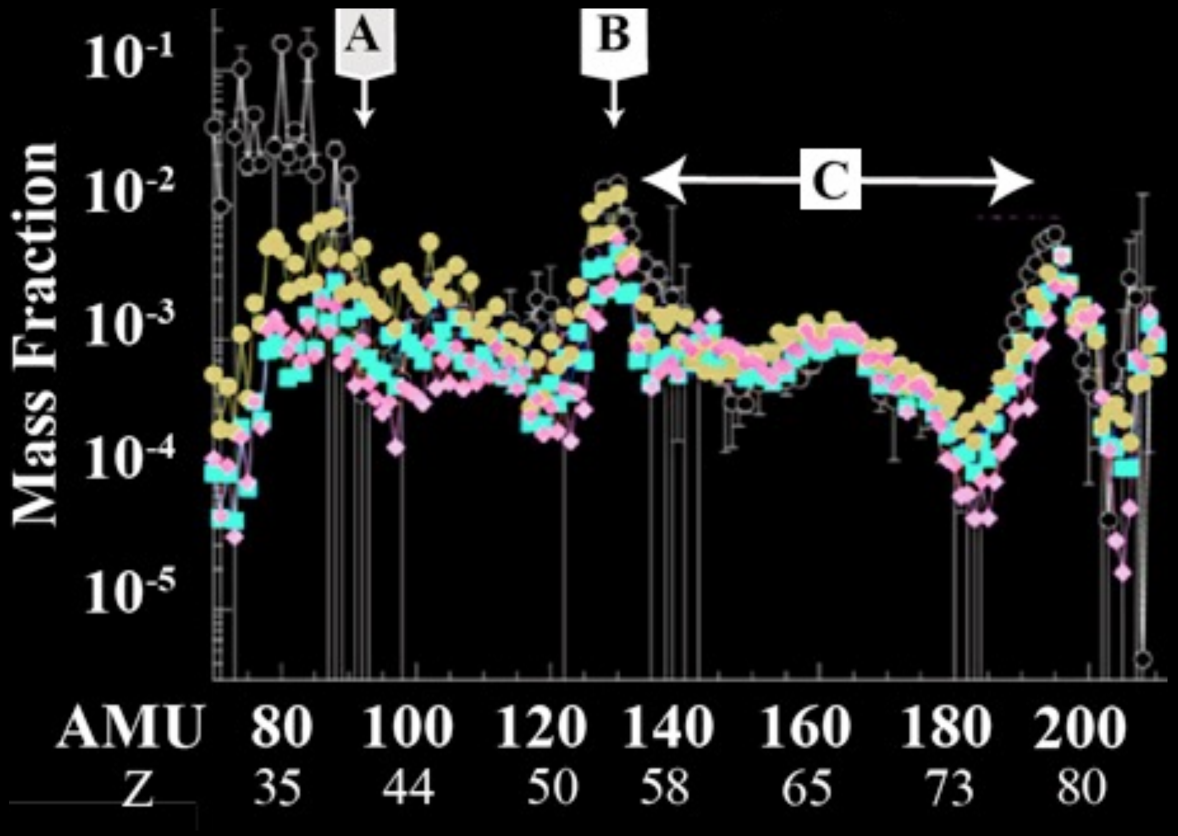
Adapted from Soares-Santos et al. 2017

Radioactive kilonova found in OIR follow-up campaign

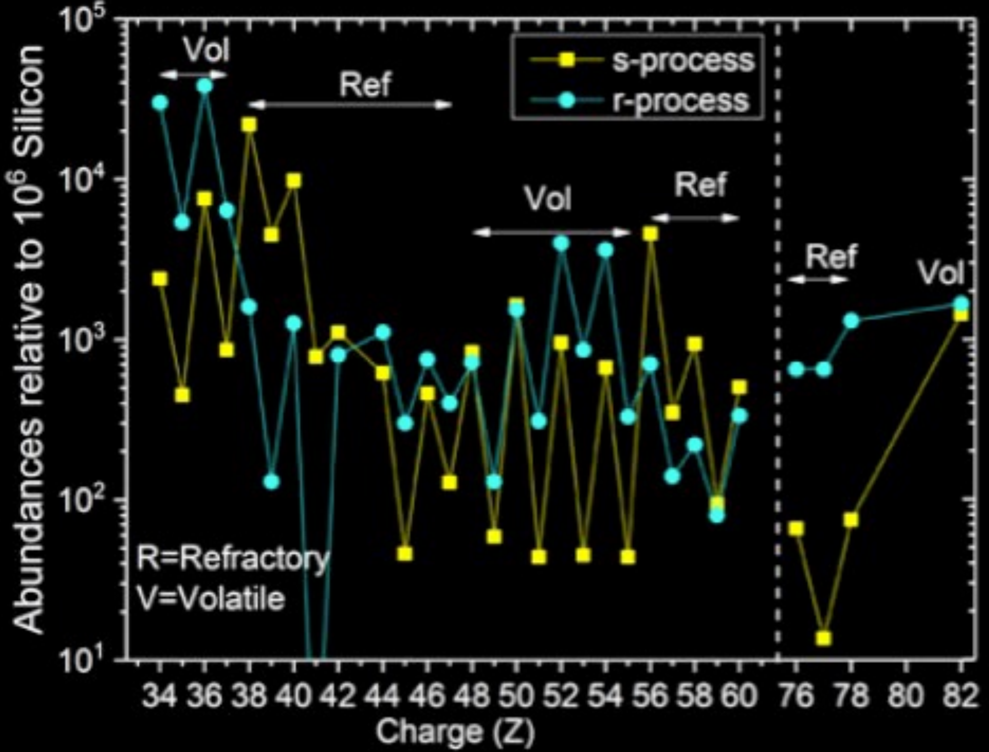
BNSM observed in gravitational waves

BNSM models and r-process/s-process and refractory/volatile breakdown

A: BNSM models could account for SS material down to Z ~ 40
B: All models show a peak at A ~ 130 amu
C: Models converge and peak at Z ~ 76

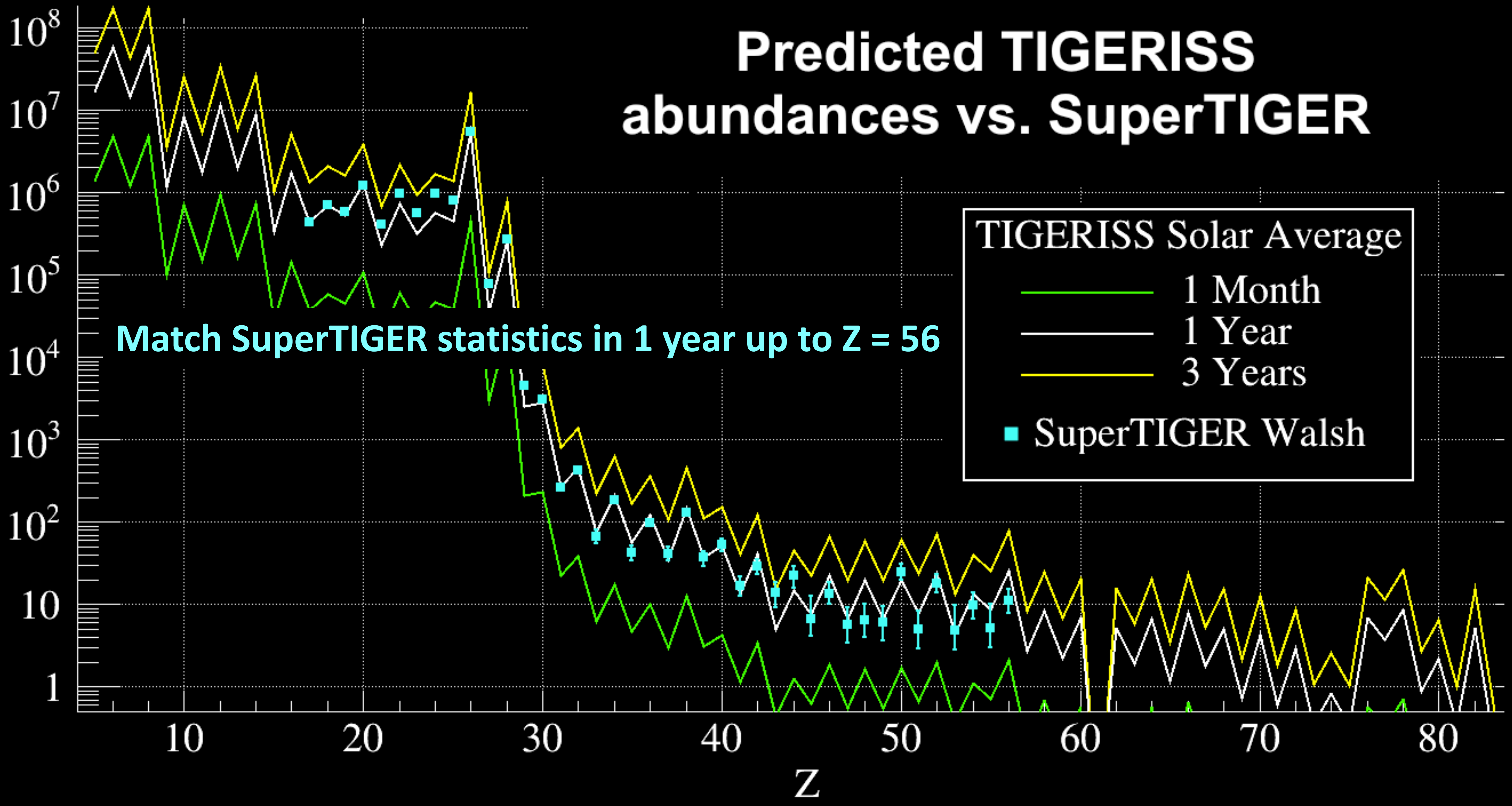


NS merger for various BH torus masses. Adapted from Just et al. 2015



Binns et al. 1985 breakdown of SS abundances into r-process and s-process components

Predicted TIGERISS abundances vs. SuperTIGER



Summary

TIGERISS will directly measure nucleosynthetic products of r-process engines

- Silicon detectors -> reliable charge measurement without scintillator saturation up to lead and heavier elements
- Exploratory measurements to probe models of r-process yields from SNe and BNSM

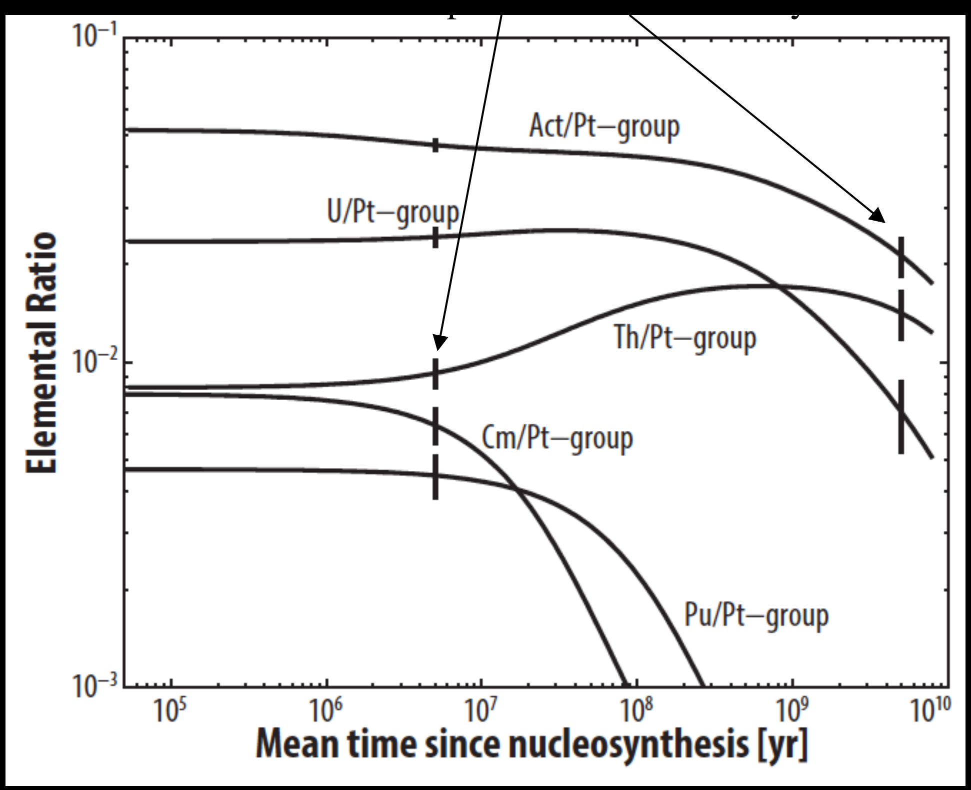
TIGERISS will test with high fidelity the grain acceleration model of cosmic-ray injection in OB associations

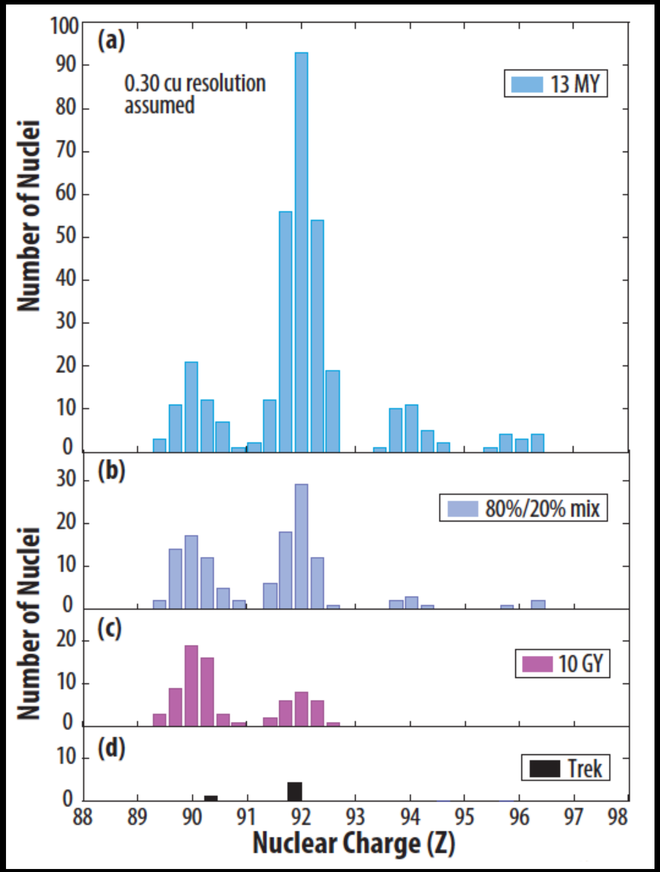
- Measure abundances across the charge ranges covered by HEAO/TIGER/SuperTIGER with a single instrument
- Test the breakdown of the current refractory/volatile paradigm with greatly decreased systematic error

Thank you!

Signature of a Young Sample

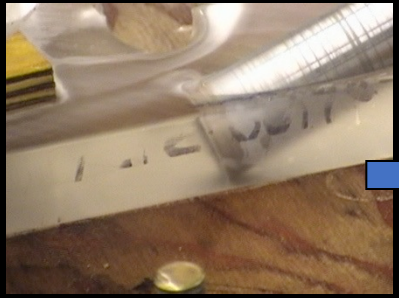
Actinides (Th, U, Pu, Cm) are clocks

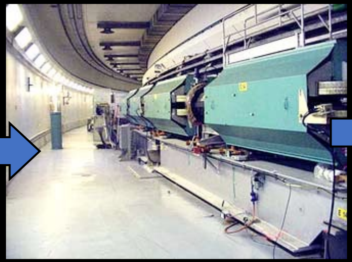


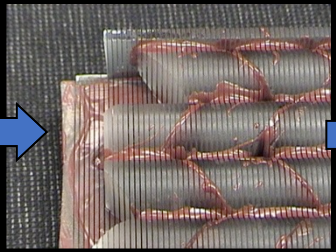


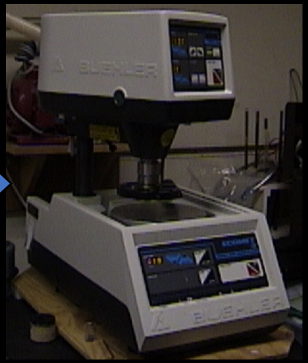
- Half-lives span the timescales for galactic chemical evolution
- Relative abundances strongly depend on the age of the GCR source material
- Ratios of daughter/parent nuclei: Th/U, (Th,U, Pu)/ Cm

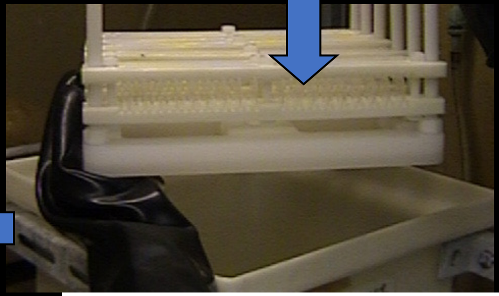
ECCO Charge Identification

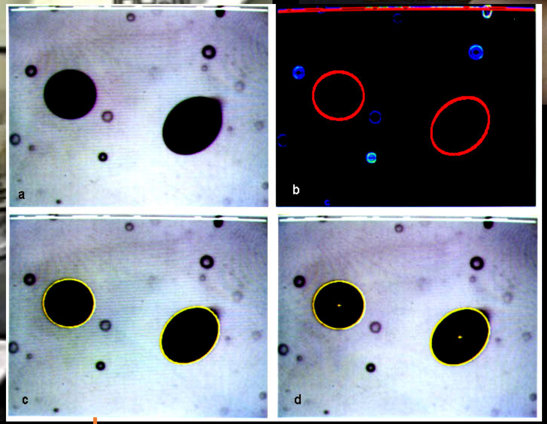






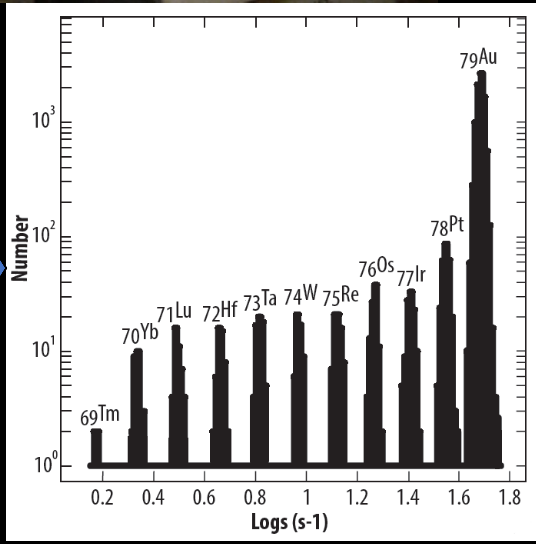




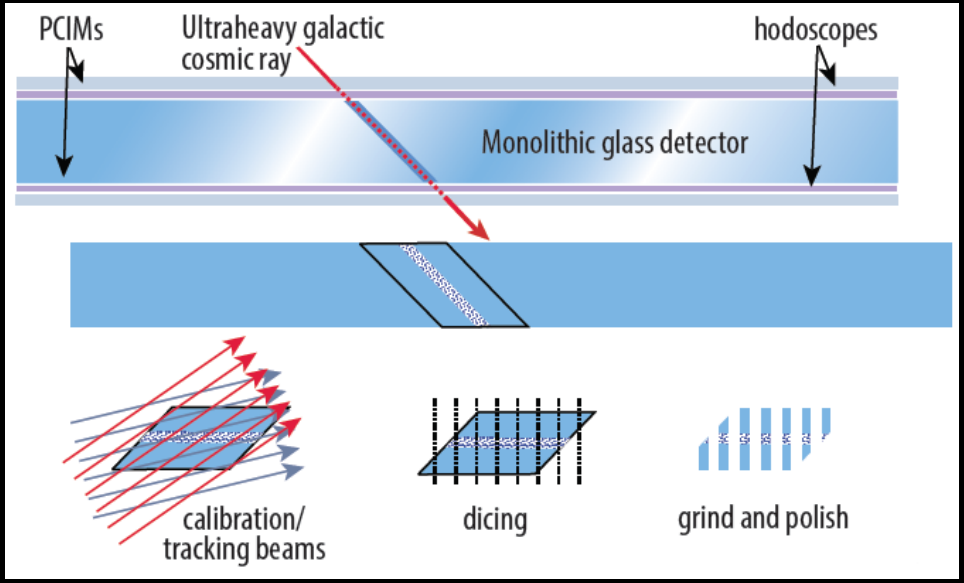


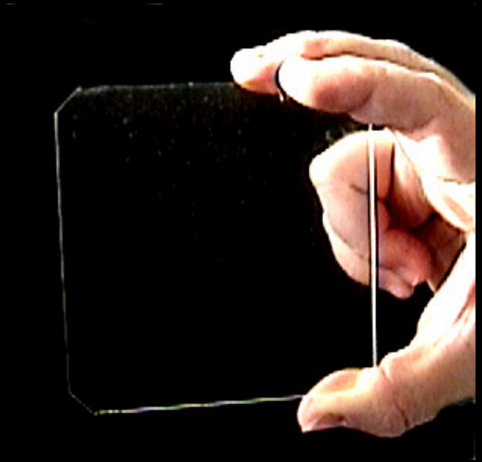
Z measurement in Au beam shown

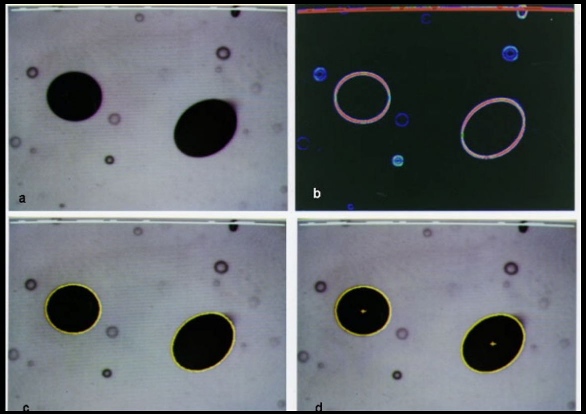
- $\sigma_z \leq 0.35e$ for $Z \geq 70$
- $\sigma_z \leq 0.25e$ for $Z \geq 70$ with reduced statistics



ECCO Overview



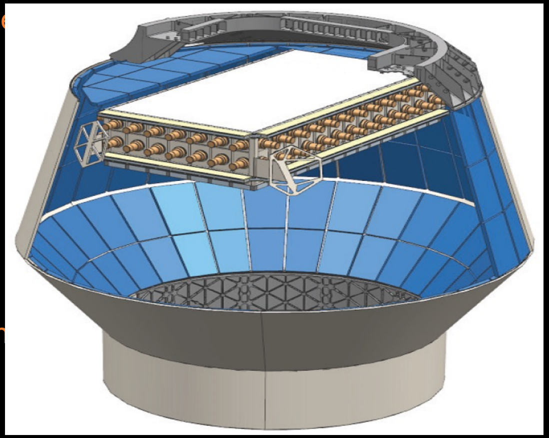




- Five layer BP-1 glass
  - — Preliminary Charge Identification Modules (PCIMs – 1 mm): identify charge group
  - — Hodoscopes (1.5 mm): initial identification and trajectory
  - — Monolithic central detector (25 mm): make accurate charge measurements and measure energy
- Glass is etched to “develop” nuclear tracks
- Tracks are measured using fully automated microscope system with resolution ≤ 50nm

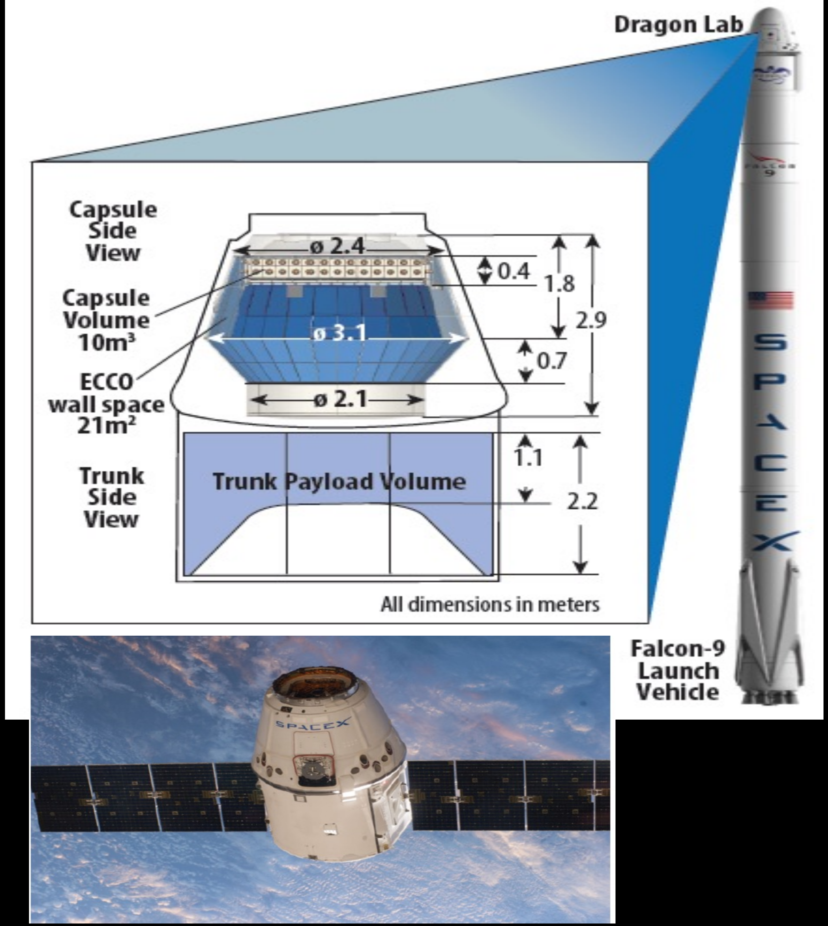
HNX 2014Mission Concept 1

- HNX uses two complementary instruments to span a huge range in atomic number (6 ≤ Z ≤ 96, Z > 96 if detected)
  - ECCO (Extremely-heavy Cosmic-ray Composition Observer)
    - Built by University of California Berkeley Space Sciences Laboratory
    - Uses ~21m^2 of Barium Phosphate (BP-1) glass tiles covering the walls and part of the top of the DragonLab Capsule
    - BP-1 proven in the Trek instrument on Mir
    - Recovery is required for post-flight processing of glass
  - CosmicTIGER (Cosmic-ray Trans-Iron Galactic Element Recorder)
    - Built by NASA Goddard Space Flight Center, Washington University in St. Louis, and JPL/Caltech
    - 2m^2 electronic instrument using well-proven instrumental techniques – silicon strip detectors an Cherenkov detectors with acrylic and silica-aerogel radiators



- HNX accommodation in DragonLab is straight forward
  - Pressurization reduces complexity of CosmicTIGER – no high-voltage potting, convective/forced air cooling
  - ECCO glass mounts directly to capsule isogrid walls
  - CosmicTIGER is attached by flexures to the sides of the capsule
  - Unfortunately, DragonLAB is too expensive for a dedicated flight and commercial rideshare as planned for HNX in 2014 is excluded from current NASA opportunities.

HNX 2014Mission Concept 2

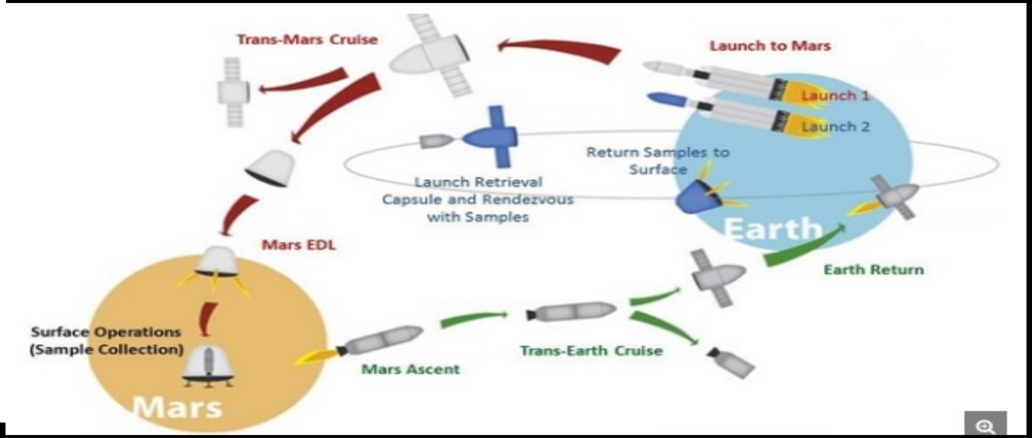


uses the SpaceX DragonLab, launched on the SpaceX Falcon 9

- DragonLab is a free-flying "laboratory" based on the Dragon ISS supply and DragonRider commercial crew spacecraft
- Pressurized and temperature controlled capsule and unpressurized "trunk"
- Capsule is recoverable, trunk is not
- Recovery is required for the ECCO instrument

- HNX is in the DragonLab capsule flying in a "rideshare" with another payload in trunk
  - DragonLab supplies all services including power, telemetry, thermal control
  - HNX is a perfect match for DragonLab and exceptionally compatible with a wide variety of co-manifested instruments
- DragonLab will be certified for 2-year flights with safe recovery (possibly

Red TIGER Mission



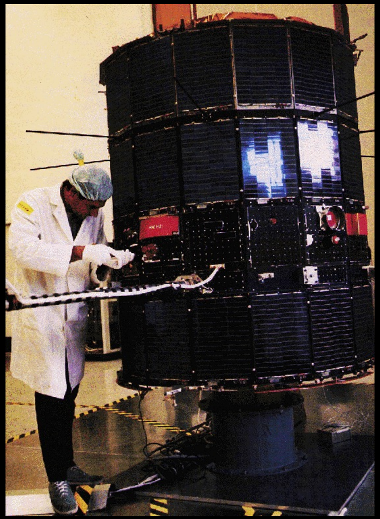
Dragon landing on Mars enabled by Dragon-2's Super Draco Thrusters.
Likely to use "Starship" instead of Dragon.
In active discussion with SpaceX to include HNX components on mission

NASA AMES is studying possible sample return mission using Red Dragon. Might enable inclusion of small amount of ECCO glass but overlying material unknown.

SpaceX Starship

- SpaceX is deciding whether to use Red Dragon or Starship for first unmanned Mars mission.
- Might carry HNX components.

Space Weather

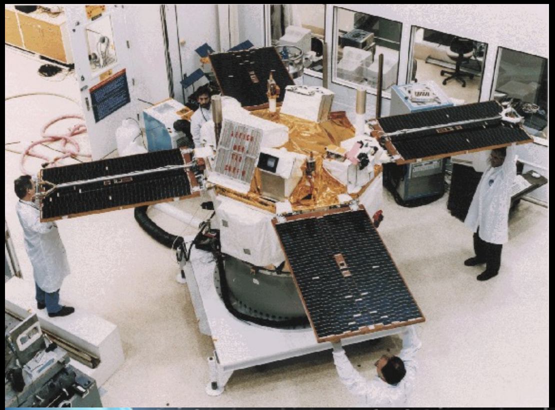


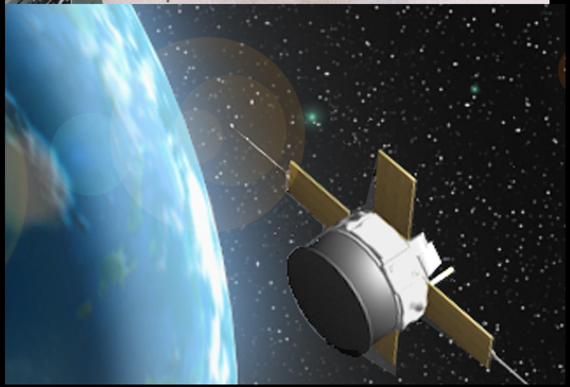
ACE: Advanced Composition Explorer (below)

Launched in 1997 & is still returning data

L1 Halo orbit

WIND, now in L2 9 since 2004, launched 1994 to L1 and still important for Space Weather, fuel for 50 more years





Goals:
Determine charge state, elemental and isotopic composition of solar corona, solar wind, interplanetary particles, Interstellar medium and galactic particles over a broad energy range

IMP-8 (J): Interplanetary Monitoring Platform (above)

Launched in 1973 & returned data for over 30 years !

Elliptical orbit 45 x 25 Earth radii

Goal: study magnetic fields, plasmas and energetic particles in near-Earth

- NASA plans to return to the moon in 2024 (including “gateway” mini-station in CIS-Lunar orbit) with habitation on moon 2028
- Instrument concepts doing astrophysics and supporting manned mission are solicited
- Lunar HNX has been initially presented as either a gateway external instrument or a surface instrument.
- Method of including ECCO is being studied.