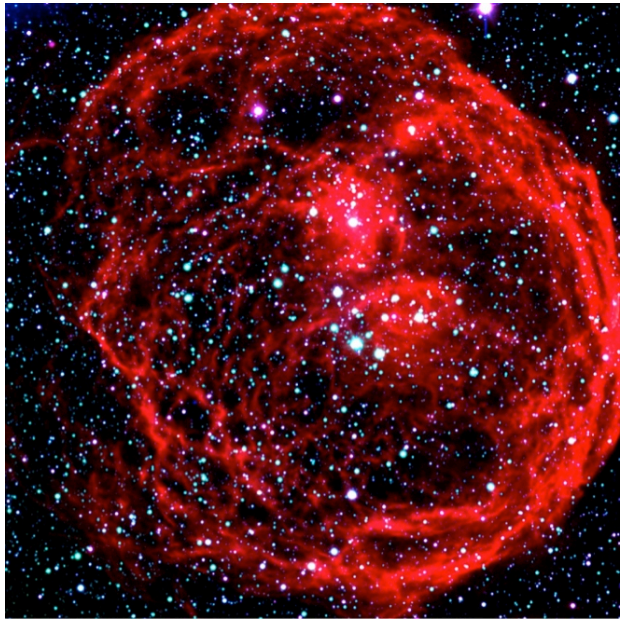
THE Heavy Nuclei Explorer (HNX)

including Lunar Heavy Nuclei Explorer/ Solar Coronal Acceleration Telescope Solar Neutron Track Chamber

36th International Cosmic Ray Conference (ICRC) 26 July 2019



John W. Mitchell NASA/GSFC

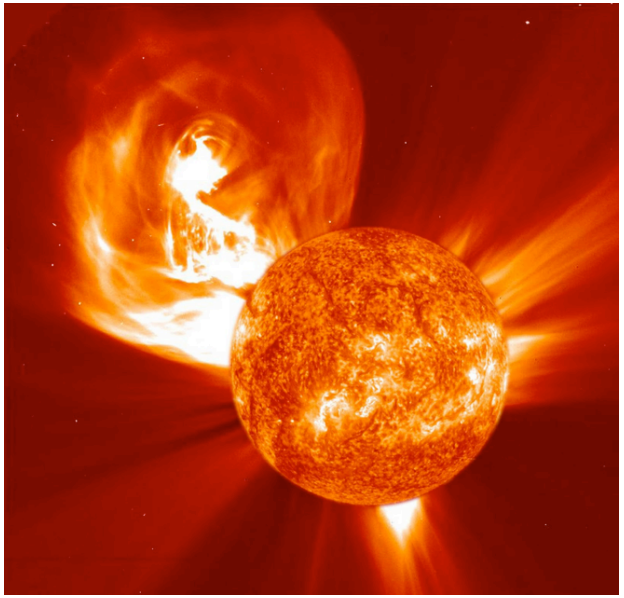
Collaborating Institutions:

UC Berkeley

NASA Goddard Space Flight Center

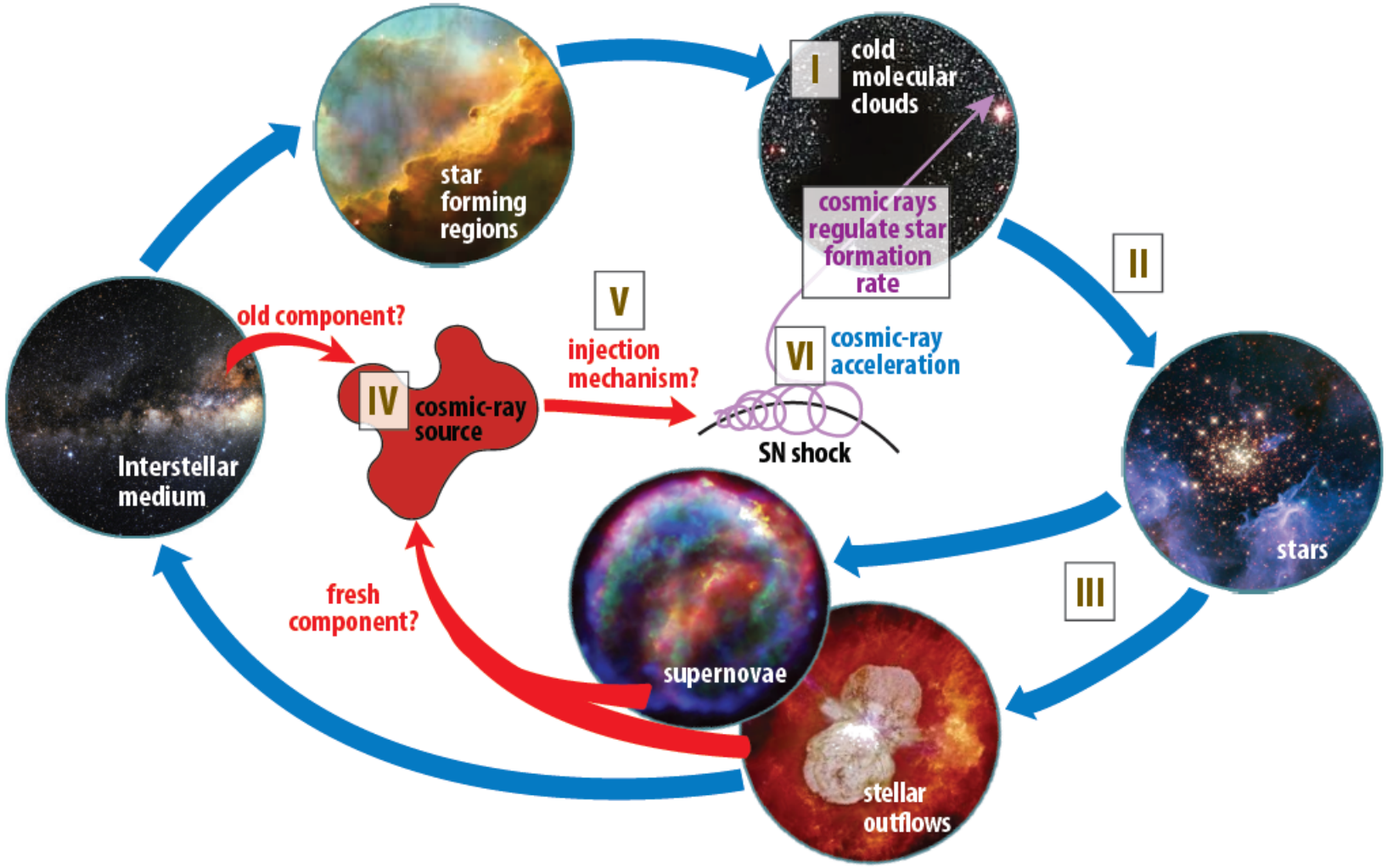
Washington University in St. Louis

JPL/Caltech



HNX UHGCR Science Goal

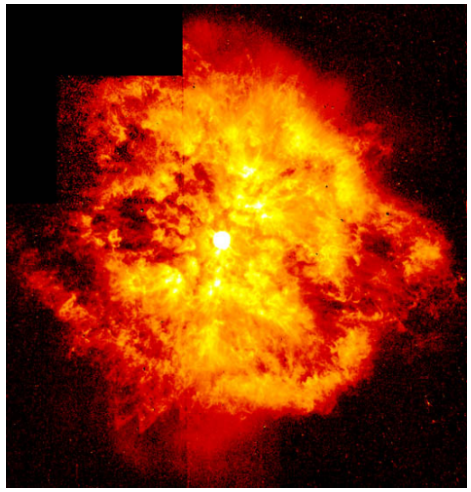
Investigate the two least understood, but critically important, aspects of the grand cycle of matter in the galaxy: the nature of the astrophysical reservoirs of nuclei at the cosmic-ray sources and the mechanisms by which nuclei are removed from the reservoirs and injected into the cosmic accelerators.



HNX UHGCR Science Questions

- **Are ultra-heavy galactic cosmic rays (UHGCRs) accelerated from newly synthesized or old material, and what is their age since nucleosynthesis?**
  - –Ratios of heavy nuclei probe age of accelerated material
  - –Actinide (Uranium group) “radioactive clocks” measure UHGCR age
  - –Relative abundances probe mixture of old and new material
- **Where and how are UHGCR accelerated and what is their subsequent history?**
  - –Element abundances carry the signature of the site of injection into the accelerator and the mechanism of selection for acceleration
  - –Secondary to primary ratios measure the integrated material pathlength of UHGCRs from acceleration to measurement
- **What mix of nucleosynthesis processes (rapid and slow) and sites are responsible for UHGCRs?**
  - – Massive stars and SN in OG Associations
  - – Binary Neutron Star Mergers
  - – Collapsar accretion disks (c.f. Collapsars as a major source of r-process elements Daniel M. Siegel, Jennifer Barnes & Brian D. Metzger *Nature* **volume 569**, pages241–244 (2019))

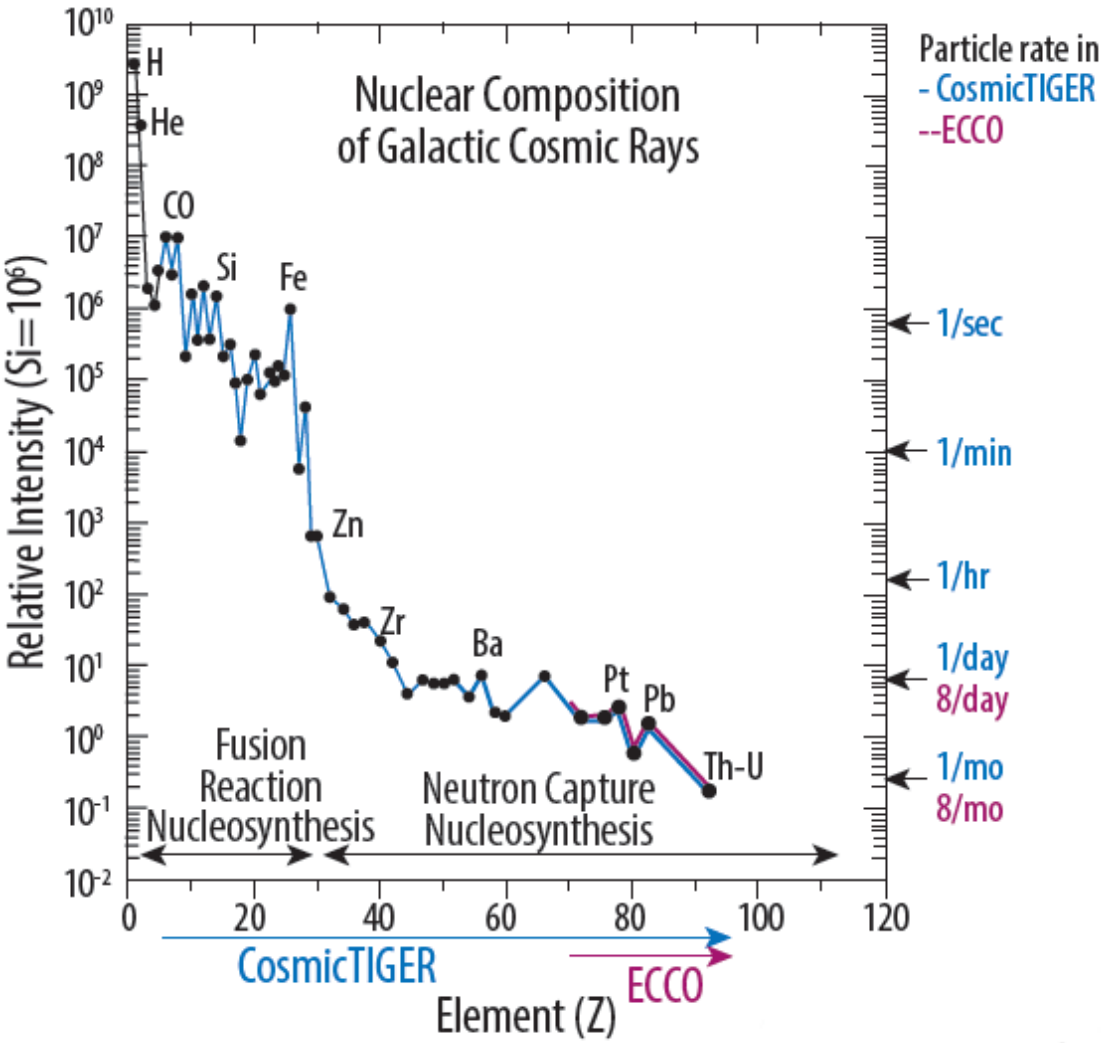
OB Superbubble 30 Doradus in LMC



Wind-nebula around WR-124 in Sagittarius

HNX UHGCR Science Design

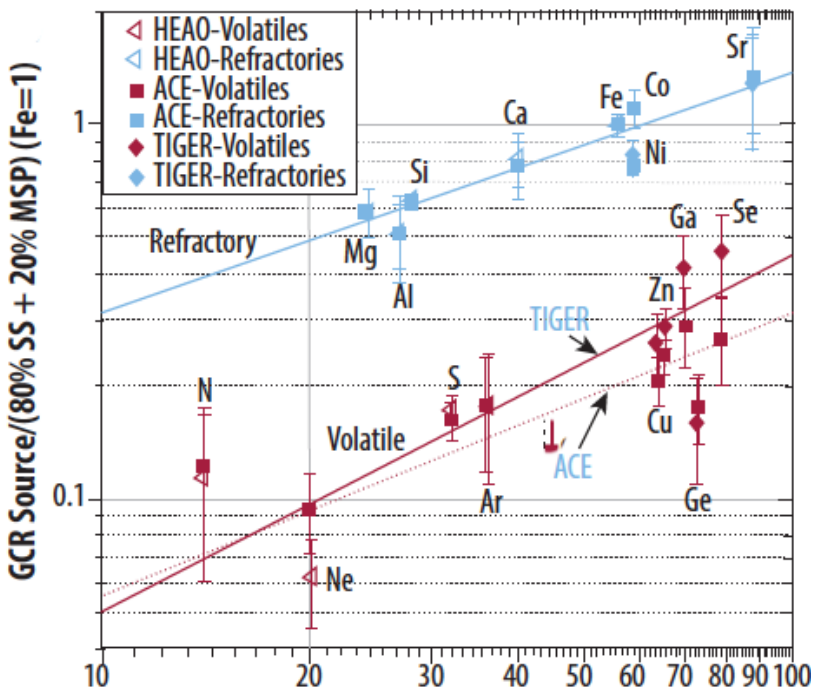
- **HNX explores to the end of the periodic table**
- Elements in the upper 2/3rds are extremely rare



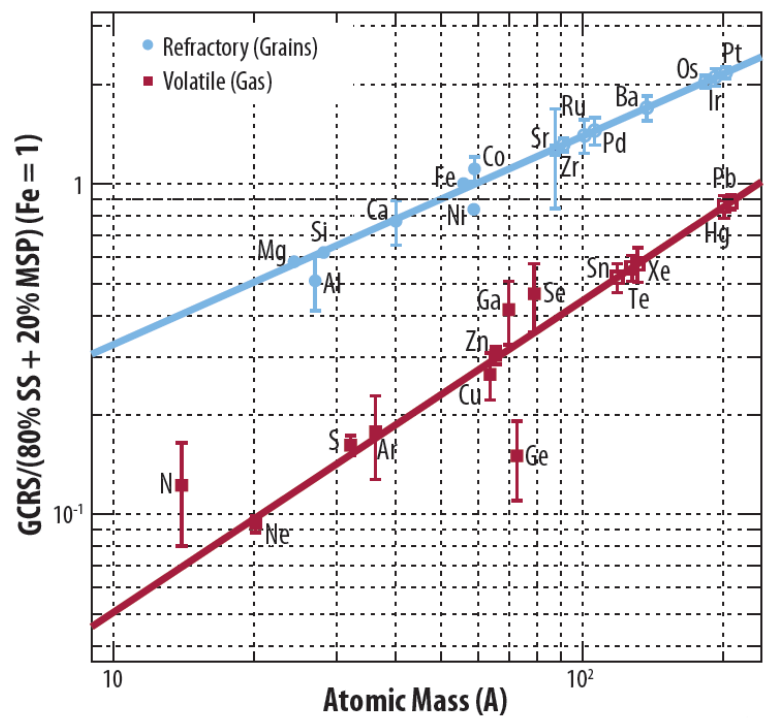
- **Requires a very large instrument with a long exposure in space!**
- *HNX uses complementary active (CosmicTIGER) and passive (ECCO) detectors to give the required ~ 50 m²sr geometric factor*
- ECCO uses BP-1 (barium phosphate) glass detectors
  - Trek experiment on Mir used BP-1 to record cosmic-ray actinides
  - Requires return to Earth for processing ➔SpaceX DragonLab
- CosmicTIGER electronic instrument is based on TIGER and SuperTIGER balloon instruments.

Processes Responsible for the UHGCR

- ACE, TIGER, and HEAO data are best represented by a source that is ~20% massive star production (wind + SN ejecta) and 80% normal ISM
- Refractory elements are significantly more abundant than volatile elements
- Refractories depend on mass as ~$A^{2/3}$ (not expected since they are initially accelerated as grains). Volatiles depend on mass as ~$A^{2/3}$ to $A^{1.}$
- **HNX Plus will measure >3600 nuclei 38 ≤ Z ≤ 83 to probe UHGCR processes**



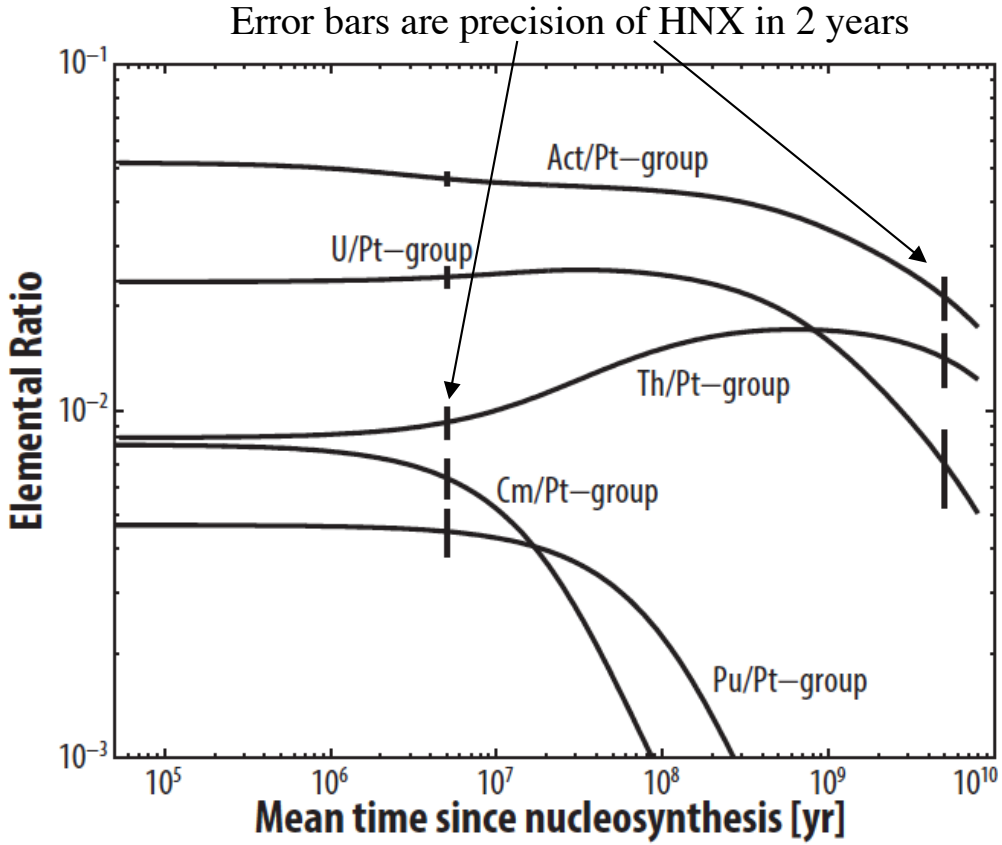
Combined TIGER, ACE, and HEAO element abundances Rauch et al., ApJ 697:2083 (2009).

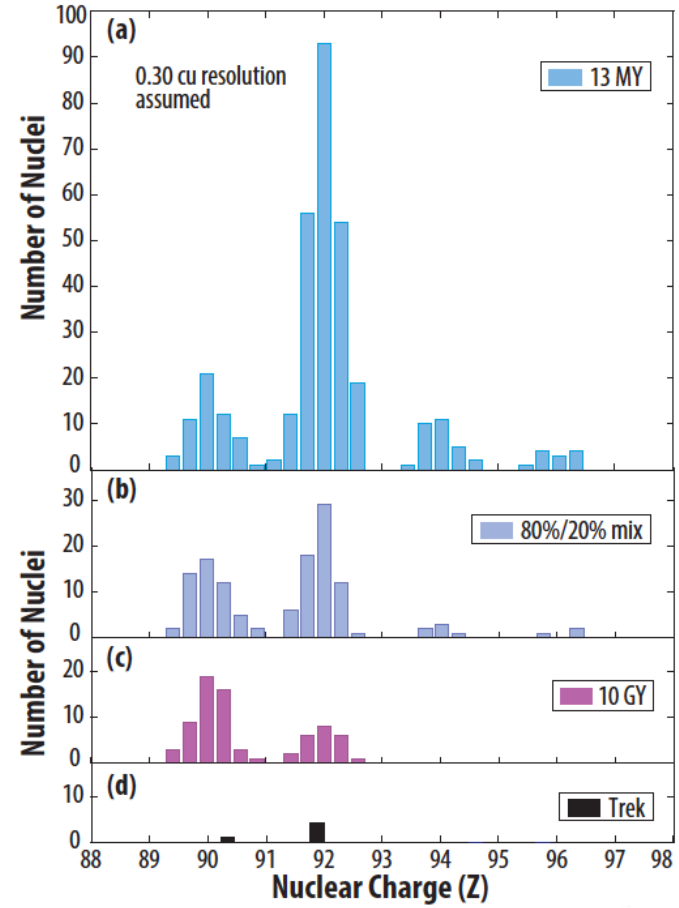


HNX will greatly improve old/new value and accurately determine mass dependence

Signature of a Young Sample

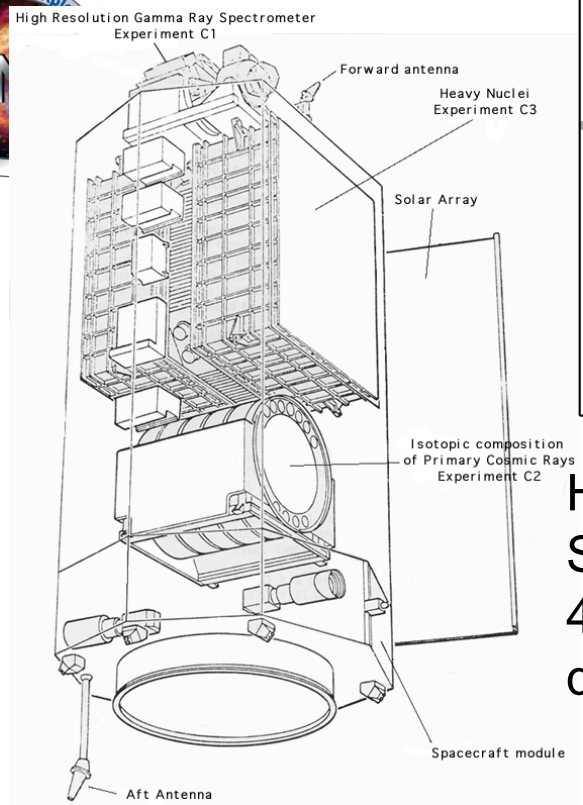
Actinides (Th, U, Pu, Cm) are clocks that measure absolute age of the UHGCR





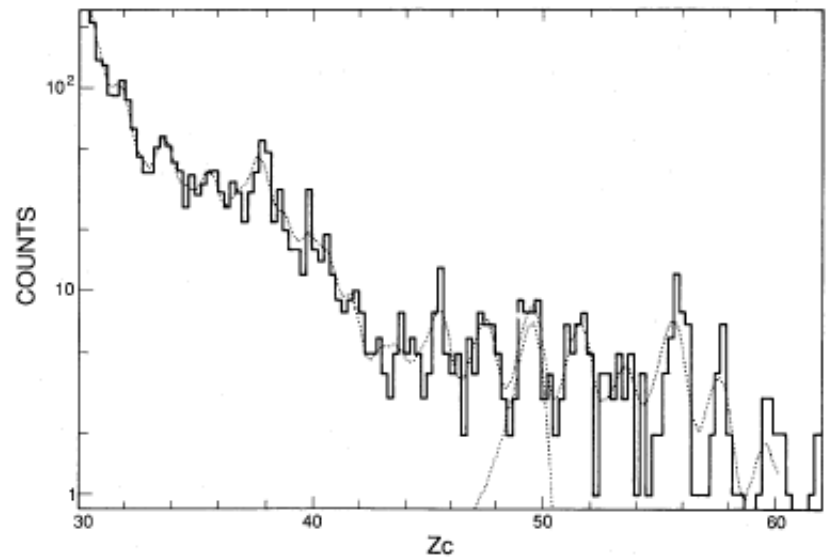
- Half-lives span the timescales for galactic chemical evolution
- Relative abundances strongly depend on the age of the GCR source material
- Ratios of daughter/parent nuclei: Th/U, (Th,U, Pu)/ Cm
- **HNX will measure ~50 actinides to probe UHGCR age**

Possible actinide abundances from 2 years of HNX data compared to Trek (Mir) 4 events. LDEF UHCR experiment reported actinides with high statistics but uncertain calibration/resolution

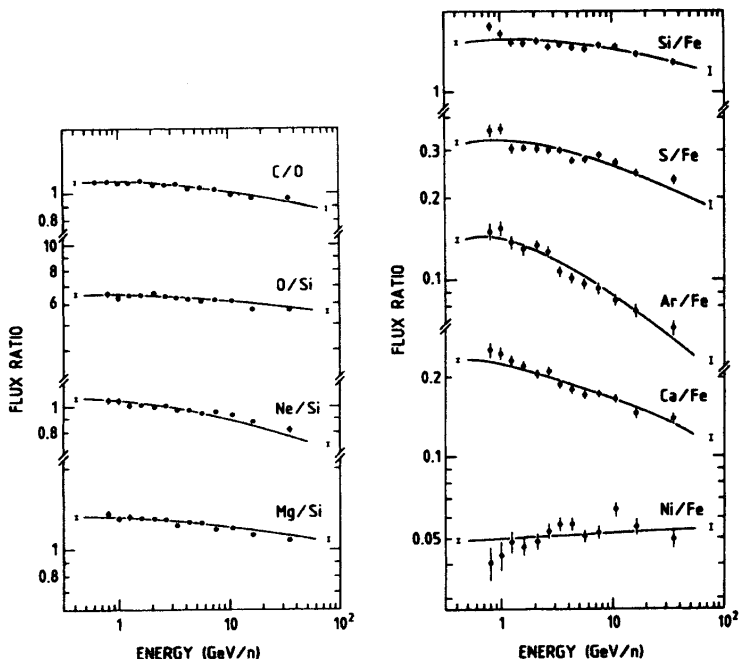


The **Heavy Nuclei Experiment (C3)** measured cosmic-ray elemental composition for Z≥26 with resolution capable of distinguishing even-Z elements, but not the less-abundant adjacent odd-Z elements.

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



Binns, et al., *Ap.J.* **346**, 997 (1989)

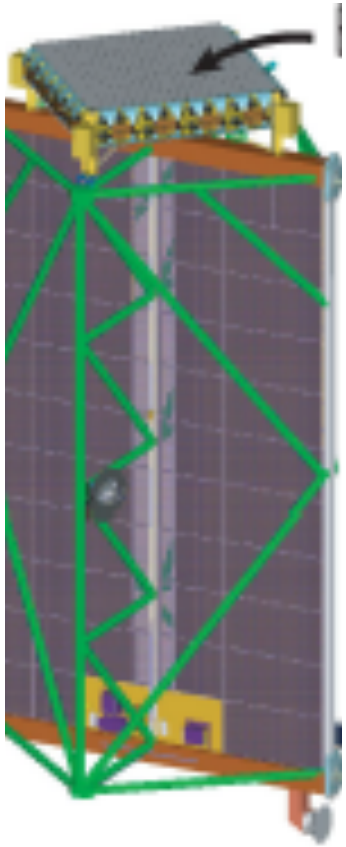


The C2 experiment measured cosmic-ray elemental composition for Z≤32 and energy spectra for Z≤28 for 0.8 < E < 30 GeV/nucleon.

Engelmann, et al., *A&A*, **233**, 96 (1990)

2001 HNX mission

- Designed to give individual element abundances for all elements Fe and heavier.
- Free flyer 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 NASA determined that the STS would no longer support science missions not connected with the ISS.



HNX2019 Overview

HNX uses three complementary instruments to span the full periodic table 6 ≤ Z ≤ 96 (Z > 96 if any present) and extended mission adds 1 ≤ Z ≤ 6 and neutrons. Extensively studied for 2014 SMEX proposal. Highly rated but not selected.

– **CosmicTIGER (Cosmic-ray Trans-Iron Galactic Element Recorder) – GSFC, Wash. U., and JPL/Caltech**
- Measures Z ≥ 6 and energy ~300 MeV/nucleon to ~10 GeV/nucleon
- 2m^2 electronic instrument using well-proven instrumental techniques – silicon strip detectors and Cherenkov detectors with acrylic and silica-aerogel radiators

– **ECCO (Extremely-heavy Cosmic-ray Composition Observer) - UCB**
- Measures Z ≥ 70
- ~21m^2 of BP-1 glass tiles
- **Recovery is required for post-flight processing of glass**

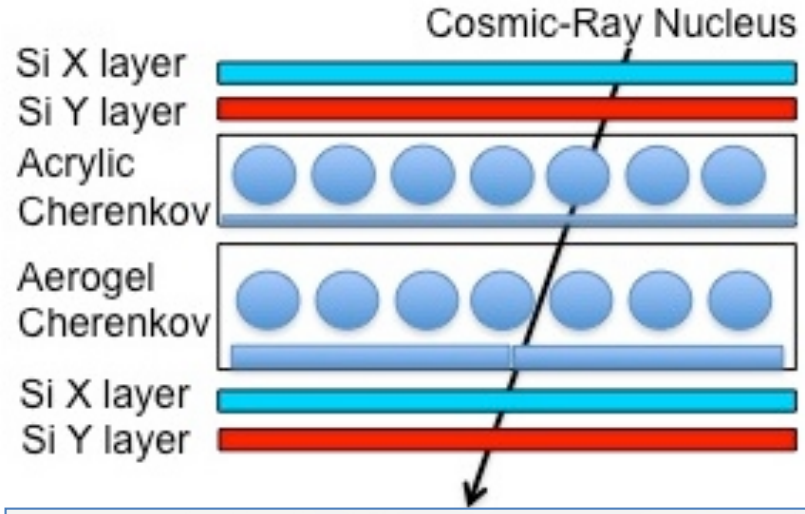
- **Extended mission instruments:**

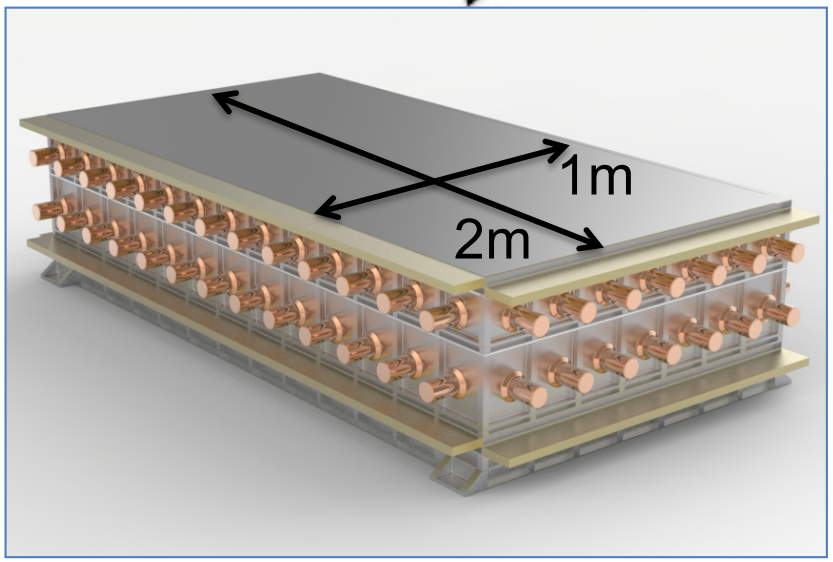
– **SolarCAT (Solar Coronal Acceleration Telescope) – GSFC, JPL/Caltech**
- Measures 1 ≤ Z ≤ 28 and 50 MeV/nucleon – ~10 GeV/nucleon effectively the full particle dose to which astronauts and equipment will be exposed.
- 0.25 - 1.0 m^2 instrument similar to CosmicTIGER plus fast time-of-flight
- Based on GSFC SPARKLE SMEX, BESS-Polar, and ISOMAX

➢ **SONTRAC (Solar Neutron Track Chamber) (GSFC CODE 672) solar neutron detector extends measurements to include neutron dose.**

CosmicTIGER Overview

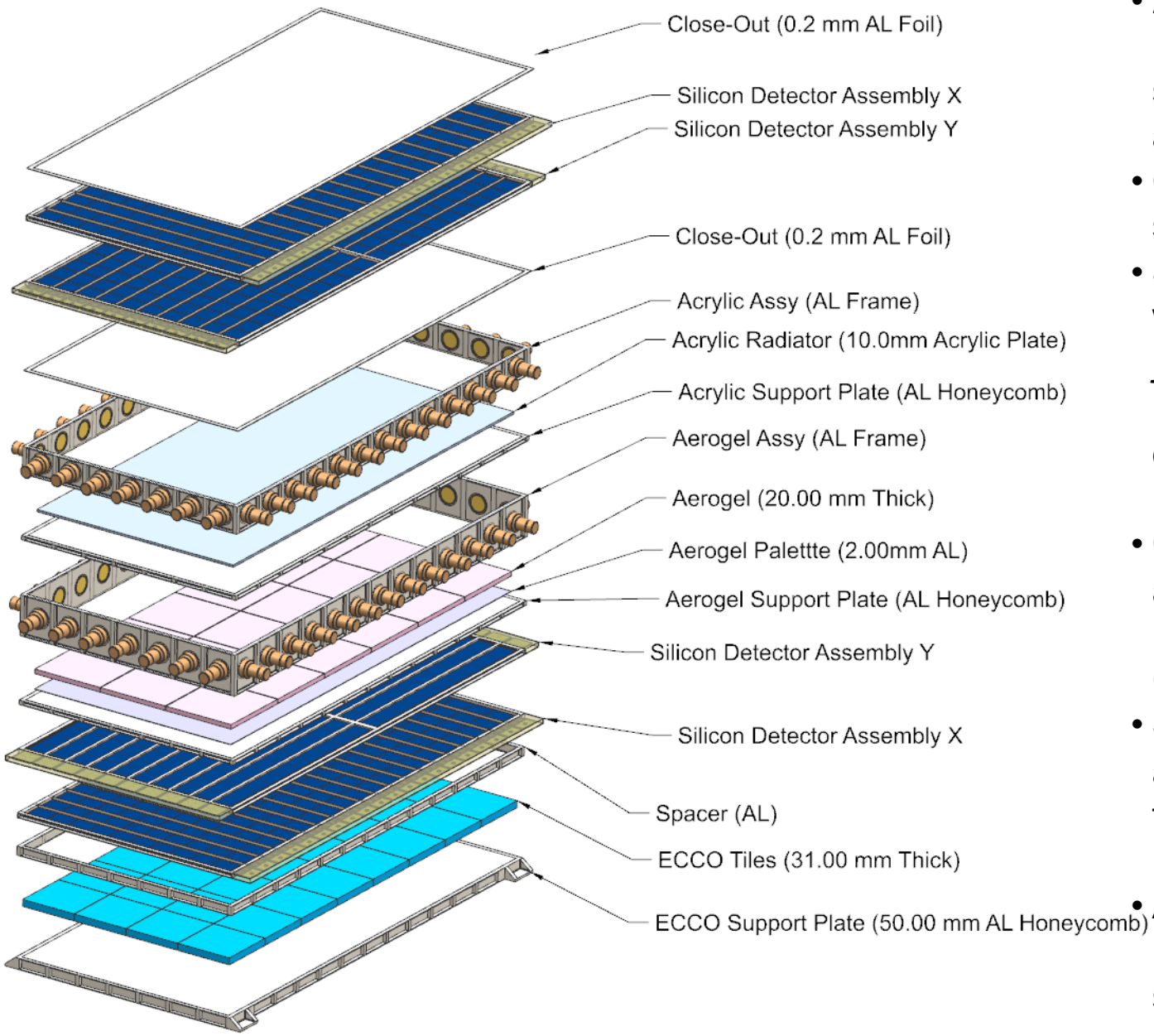
- Electronic particle detector – 2 m^2 active area, $A\Omega = 4.2\ m^2sr$
- Measures nuclei $6 \leq Z \leq 96$ with single element resolution
- Charge measurement employs three detector subsystems in dE/dx vs. Cherenkov and Cherenkov vs. Cherenkov techniques
  - Silicon strip detector (SSD) arrays at top and bottom measure dE/dx and trajectory
  - Cherenkov detector with acrylic radiator (optical index of refraction n=1.5) measures charge and velocity $E_K \geq 325$ MeV/nucleon ($\beta \geq 0.67$)
  - Cherenkov detector with silica aerogel radiator (n=1.04) measures velocity $E_K \geq 2.25$ GeV/nucleon ($\beta \geq 0.96$)
  - Deployed complete (just add wireless connection)
  - Instrument is only minimally sensitive to Lunar dust (sealed and biased positive) and concepts for measuring dust accumulation are





Artist's rendering of CosmicTIGER

CosmicTIGER Expanded View

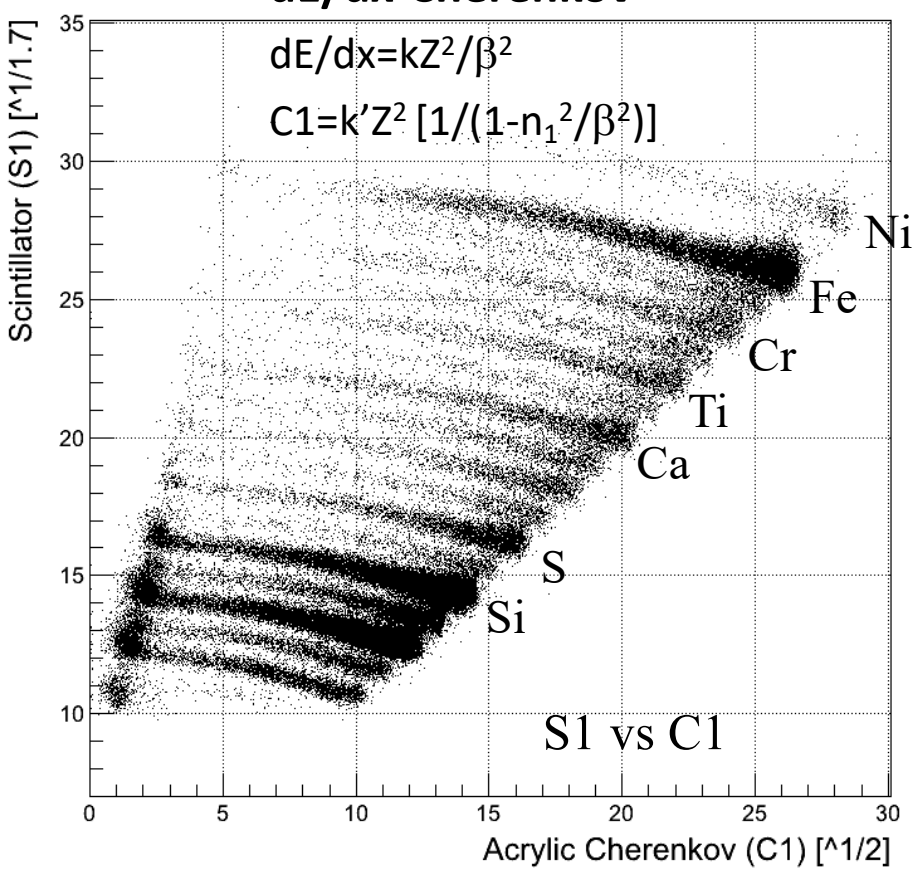


- 2 Layers of SSD (10 cm x 10 cm x 500 μm) with 3.12 mm strip pitch (50 μm gap) at top and bottom.
- Orthogonal strip direction in successive layers gives X ,Y.
- SSD connected in “ladders” with corresponding strips joined (wire bond or flex cable) between detectors and read out at end. All ladders are 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

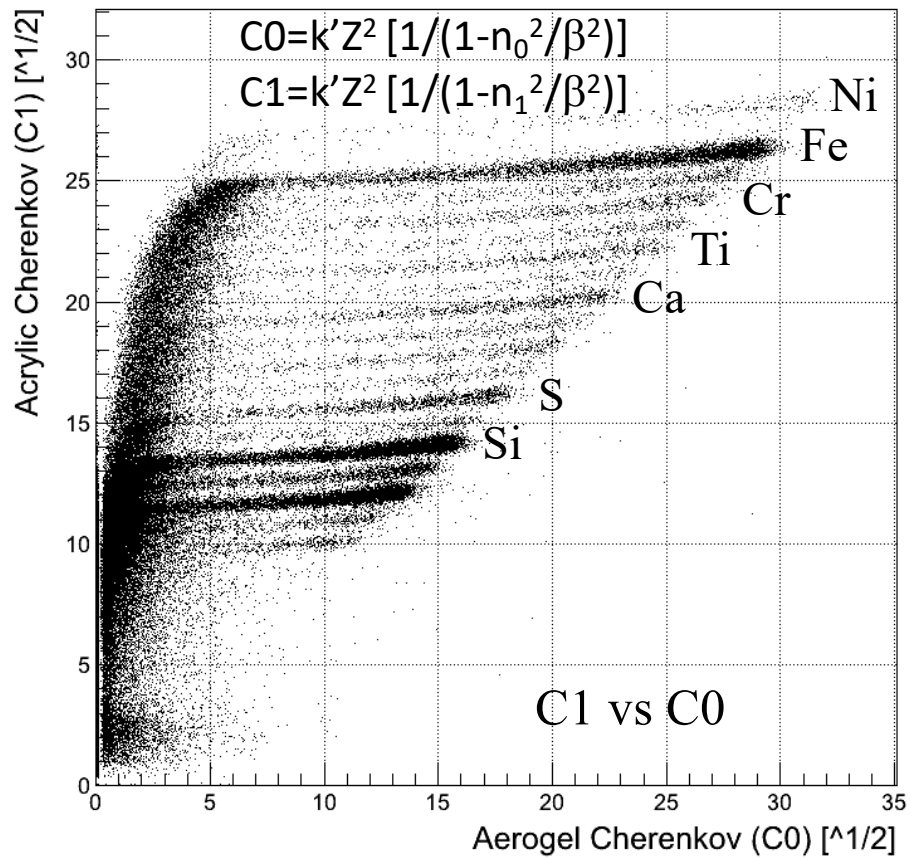
Charge Identification Methods

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

dE/dx-Cherenkov

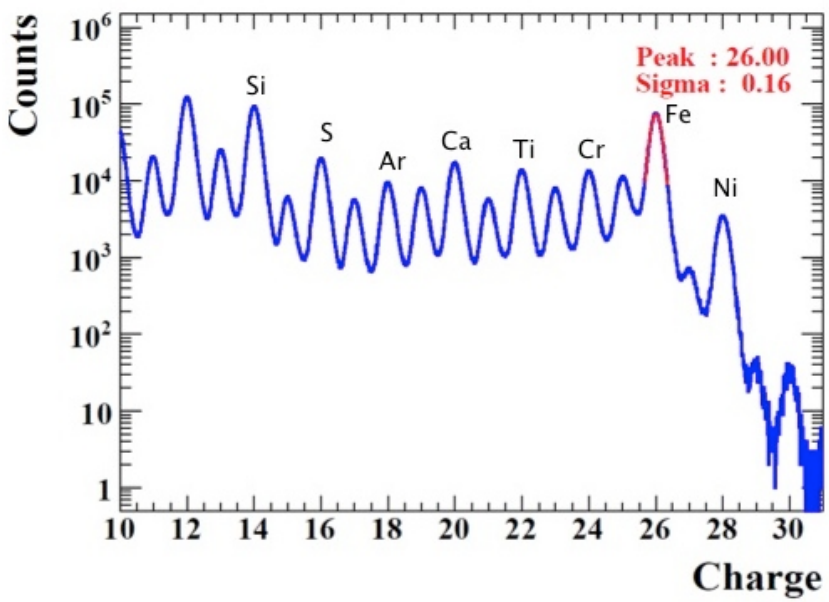


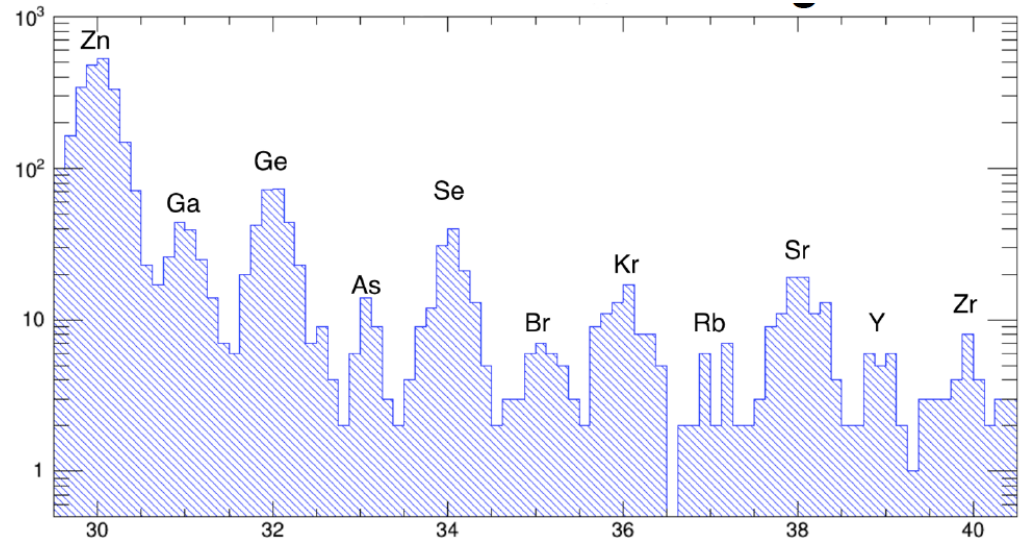
Cherenkov-Cherenkov

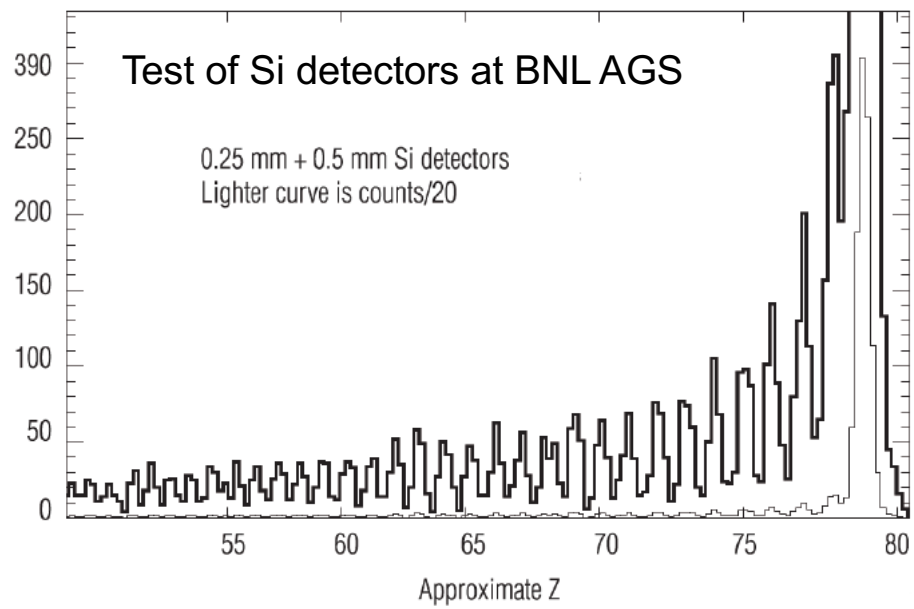


CosmicTIGER Charge Identification

SuperTIGER flight data illustrates method over full energy range - Fe σ_Z=0.16e





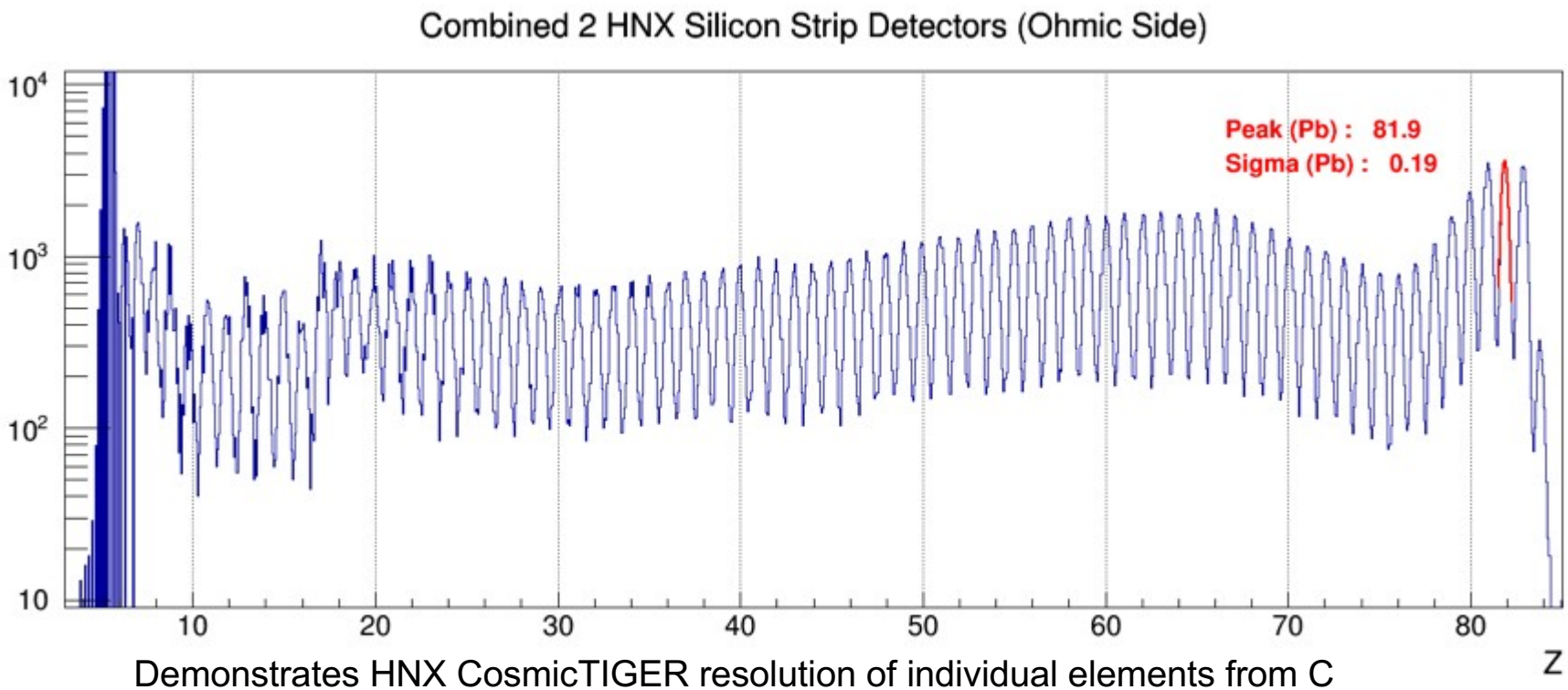


- CosmicTIGER silicon detectors extend excellent resolution to higher Z
- Expected $\sigma_z \leq 0.25e$ for $Z \geq 6$

CERN SPS Lead Beam Tests Nov-Dec 2016

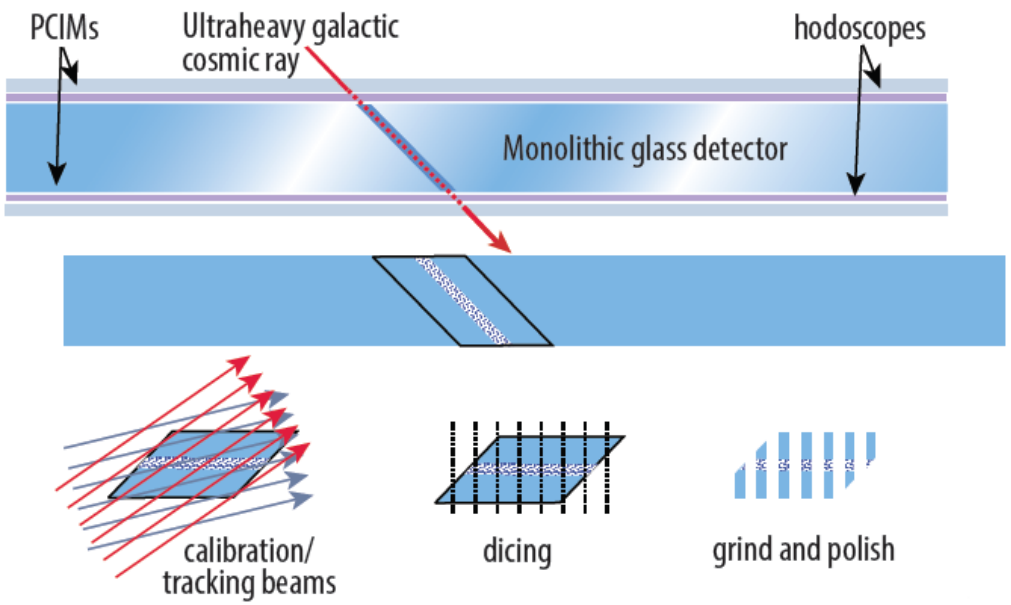
See posters PS1-15 and PS1-16 for test details.

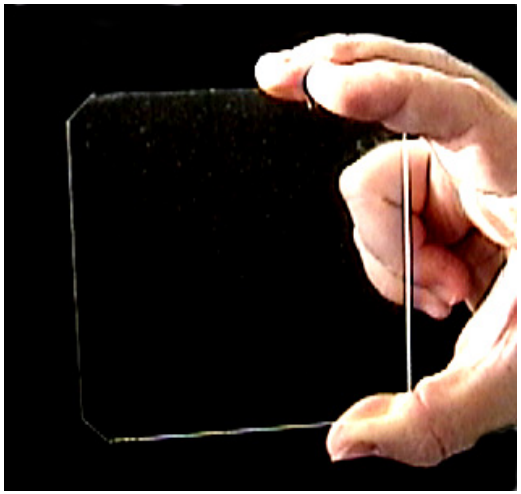
HNX
Silicon Strip Detectors
(6 <= Z <= 84)



Demonstrates HNX CosmicTIGER resolution of individual elements from C TO Pb. Can go to above Cm if particles present (not in beam).

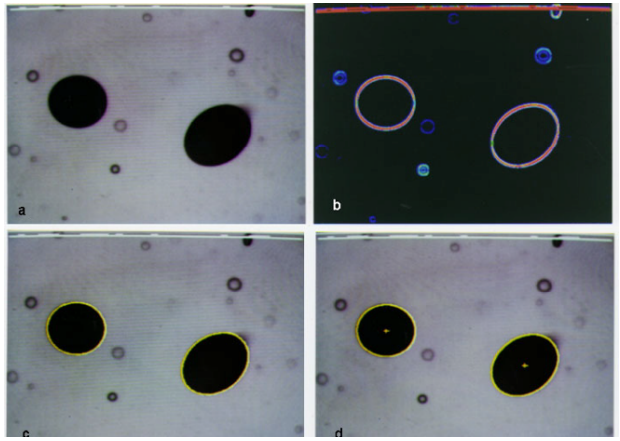
ECCO Overview





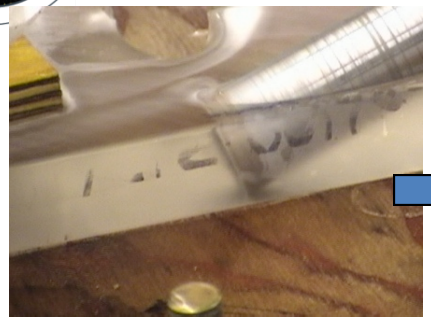
ECCO is simple on orbit…

- Active area 21 m^2, $A\Omega$ = 48 m^2sr
- Five layer BP-1 glass
  - — Preliminary Charge Identification Modules (PCIMs – 1 mm): identify charge group
  - — Hodoscopes (1.5 mm): initial identification and trajectory determination
  - — 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

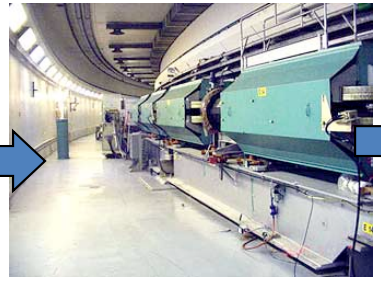


… all the sophistication is in the laboratory

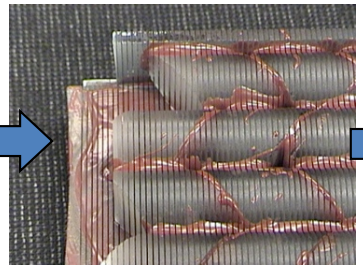
ECCO Charge Identification



coring

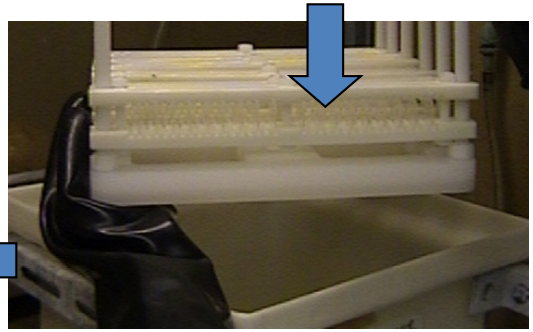


calibration

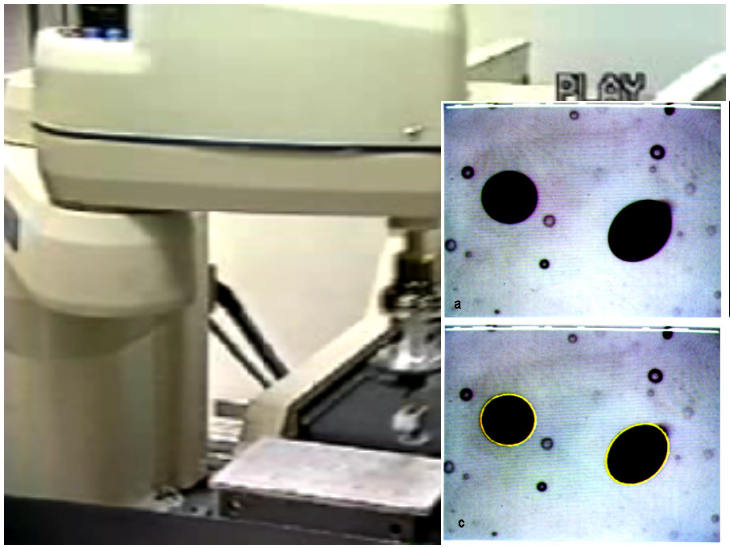


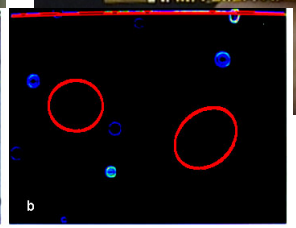
wafering

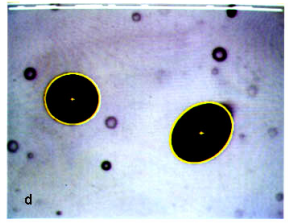
Grind and polish



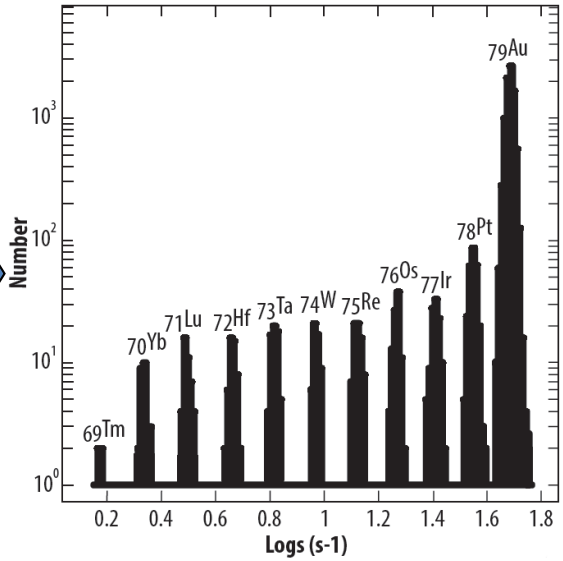
etch







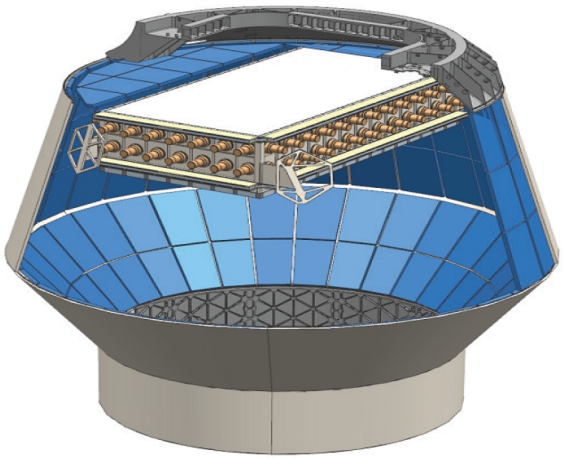
Automated scanning with robotic handling



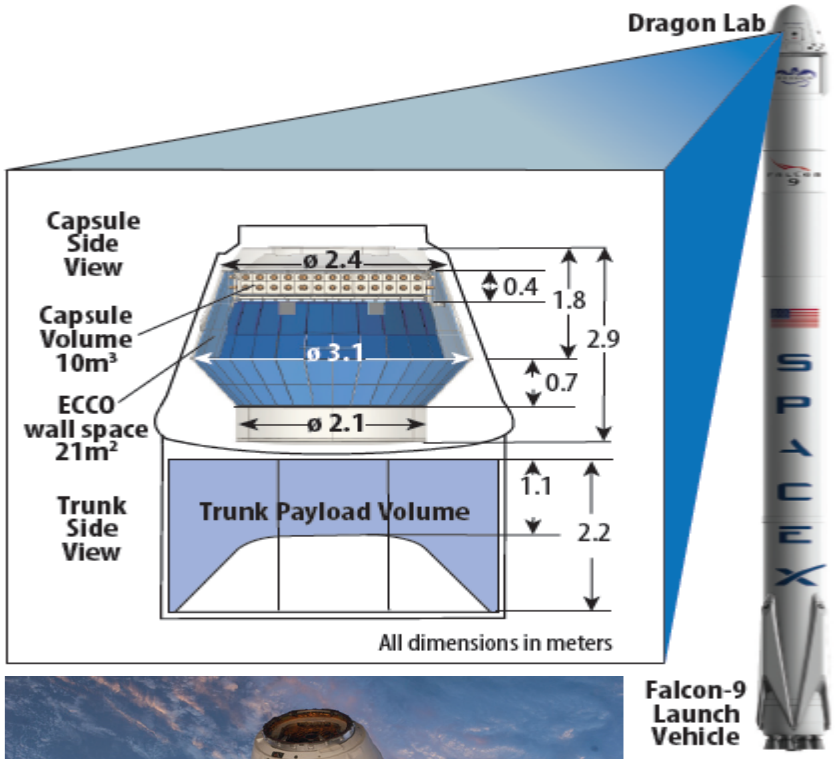
- Z measurement in Au beam shown
- $\sigma_z \leq 0.35e$ for $Z \geq 70$
- $\sigma_z \leq 0.25e$ for $Z \geq 70$ with reduced statistics

HNX Mission 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 t 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 and 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.



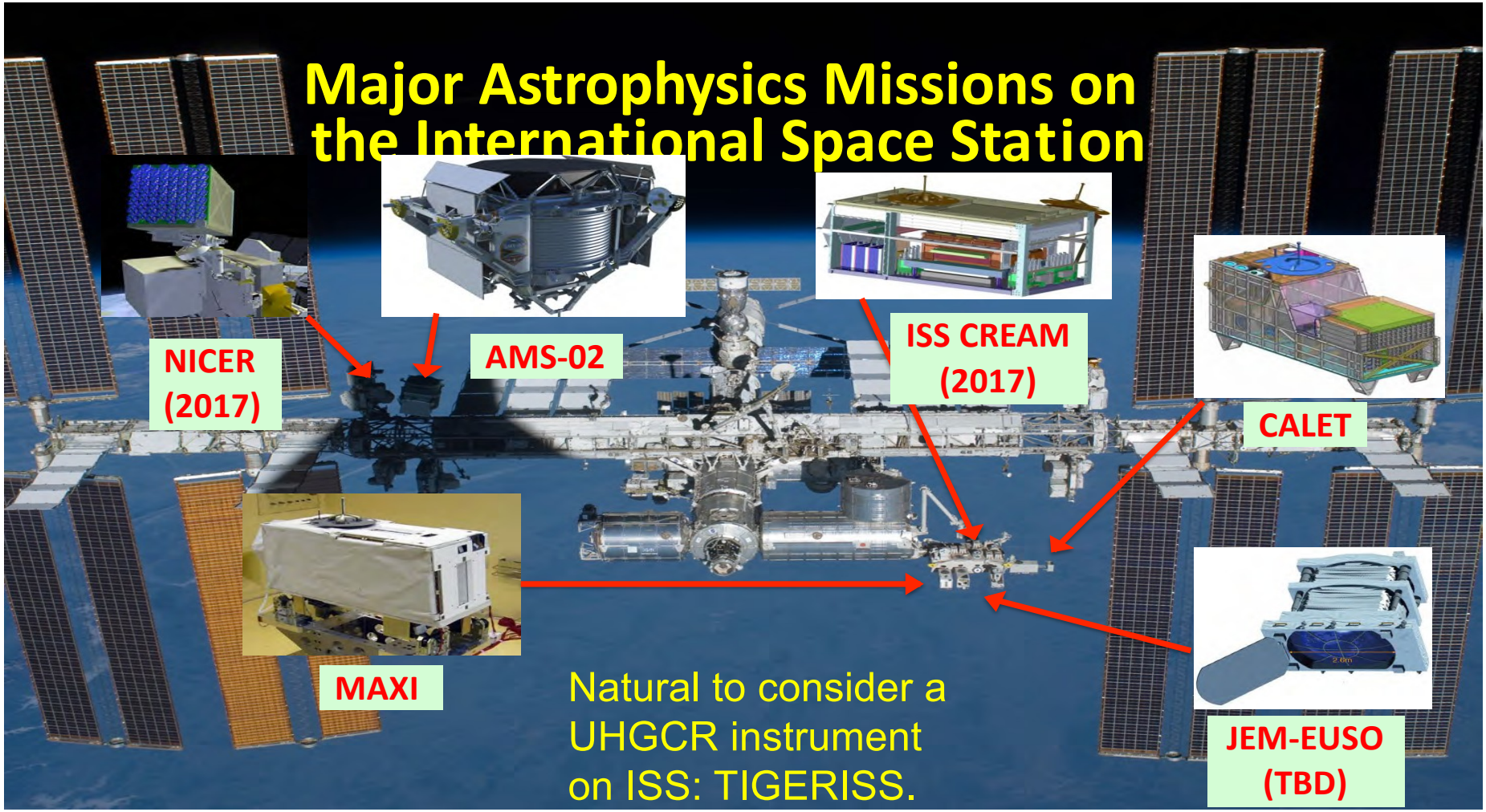
HNX Mission Concept 1

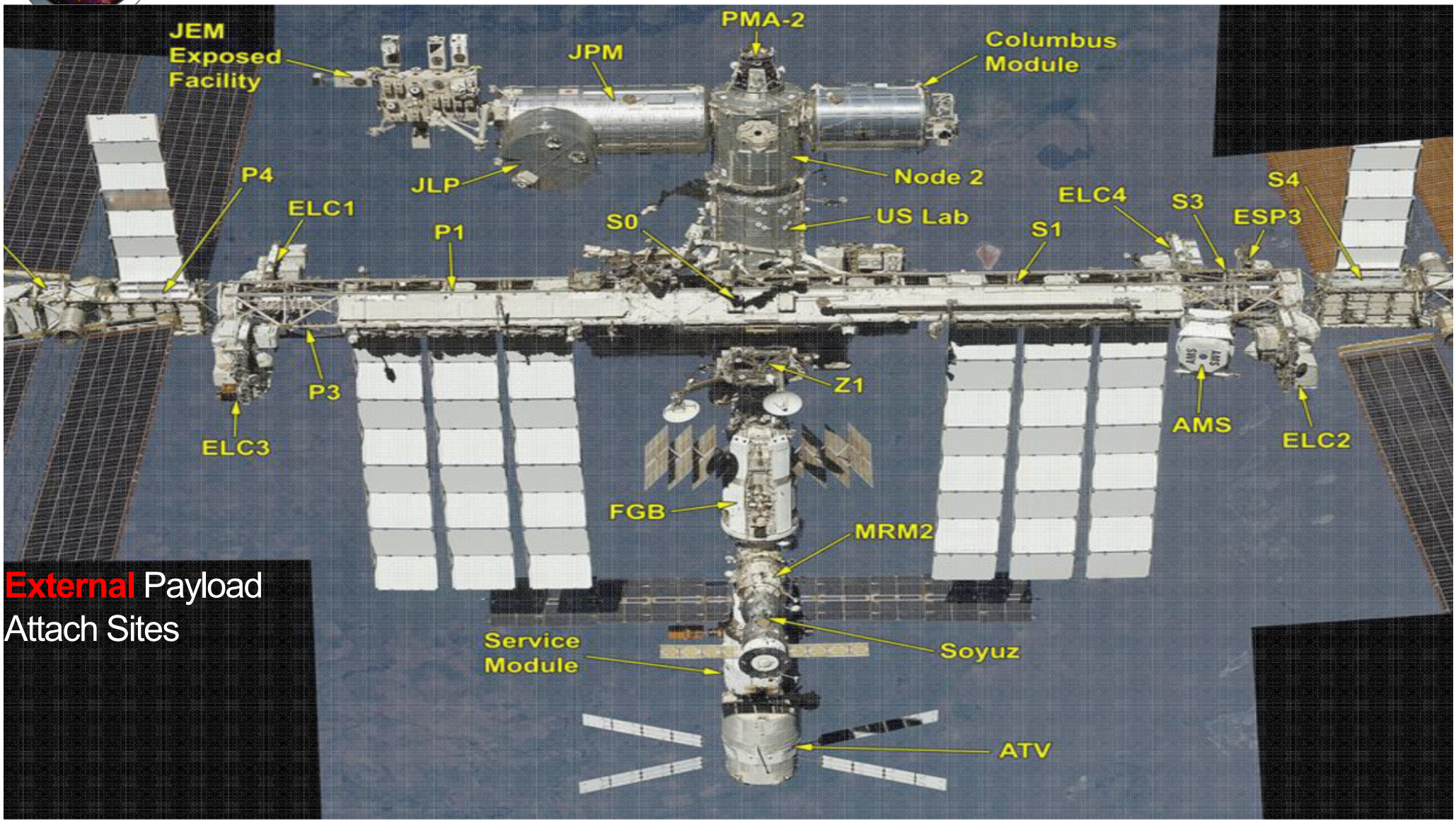


- **HNX uses the SpaceX DragonLab, launched on the SpaceX Falcon 9**
  - DragonLab is a free-flying "laboratory" based on the Dragon ISS supply and DragonRider commercial crew spacecraft
  - Pressurized and temperature controlled capsule and unpressurized "trunk"
  - Capsule is recoverable, trunk is 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 3-4 years)**

TIGERISS Concept

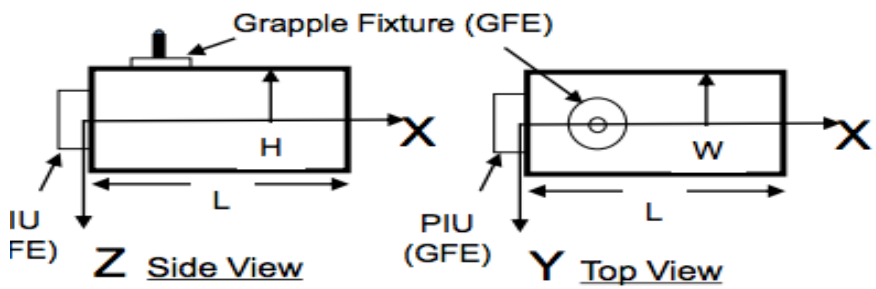
- **SuperTIGER derived instrument on ISS. Nominal name TIGERISS pronounced as tigeress.**
- **Use HNX/CosmicTIGER engineering adapted to vacuum and versions of SuperTIGER derived instrumentation developed expressly for space.**
- **Nominal attachment to Japanese Experiment Module Exposed Facility (Kibo-EF) but other attach points possible (currently looking at both ELC and Columbus)**
- **Silicon Photomultiplier (SiPM) arrays rather than PMTs on Cherenkovs to maximize geometric factor in limited area.**
- **Inclusion of ECCO is under study – needed for full science return.**
- **SolarCAT/SONTRAC could easily be included on a second (e.g. ELC) location for complementary measurements.**
- **Could be done as exceptional APRA mission (like ISS-CREAM) or MoO.**
- **Operational scenario:**
  - Launch on ISS resupply Dragon in Dragon trunk (as ISS-CREAM did)
  - STANDARD KIBO-EF pallet dimensions and mass restrict instrument to ~67 cm wide by 167 cm= 1.12 m^2 $A\Omega \approx 1.7$ m^2sr 40% of CosmicTIGER but no overlying matter (capsule).
  - Attach to Kibo- EF at TBD site (requires negotiation - underway), prefer sites 6 or 10
  - On-orbit 2 years (or longer), telemeter all TIGERISS data and housekeeping data
    TIGERISS exposure in 2 years >5x nominal SuperTIGER LDB (30 days).


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

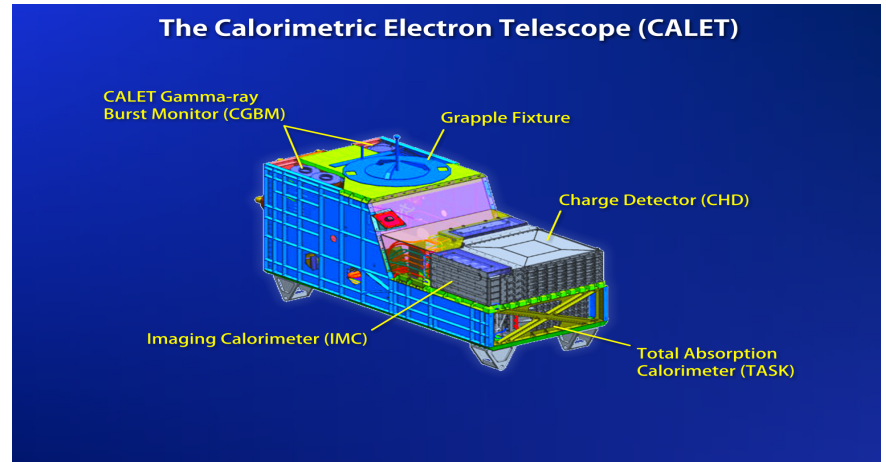


External Payload
Attach Sites

TIGERISS Mission Concept 2

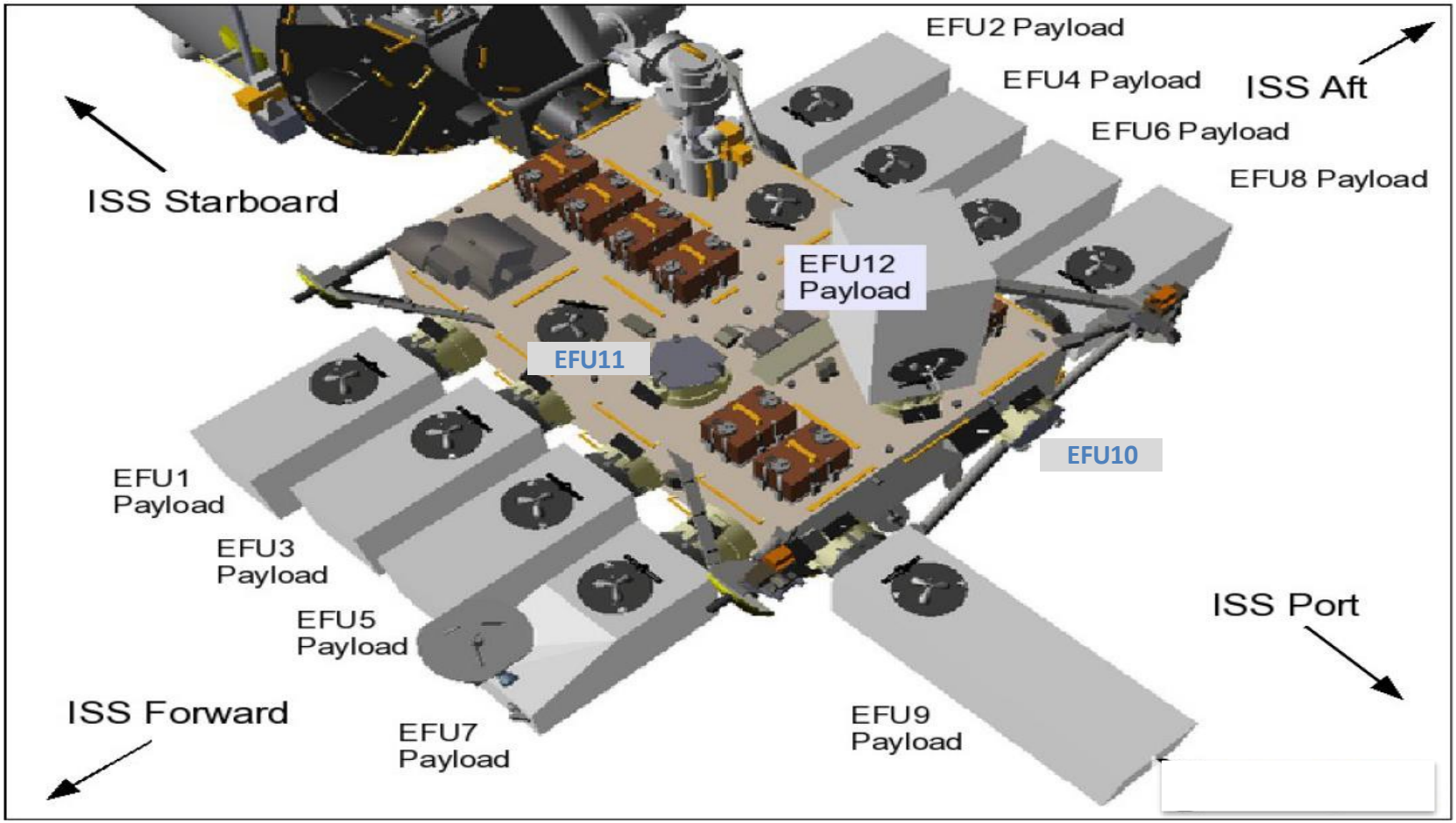


Axis	mm	ft	inch
W	800	2	7.50
H	1000	3	3.37
L	1850	6	0.83



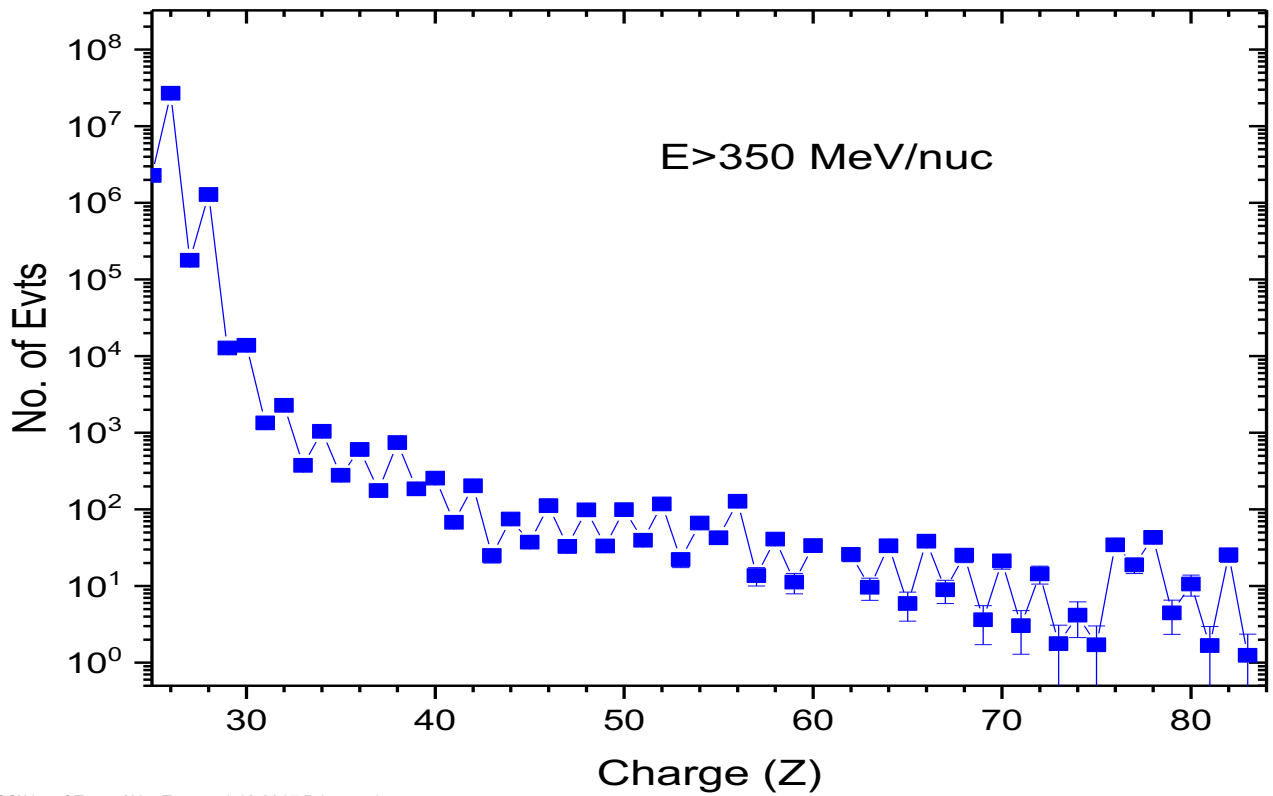
- Dimensions of TIGERISS on Kibo-EF are constrained to about 1.67 m x 0.67 m by space on pallet and need to allow for grapple fixture.
- Total mass on standard site limited to 500 kg.
- Will make use of engineering developed at Wallops Flight Facility (WFF) for the ISS-CREAM pallet.
- WFF is part of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

JEM-EF External Sites Locations



Number of events for Z=26-82

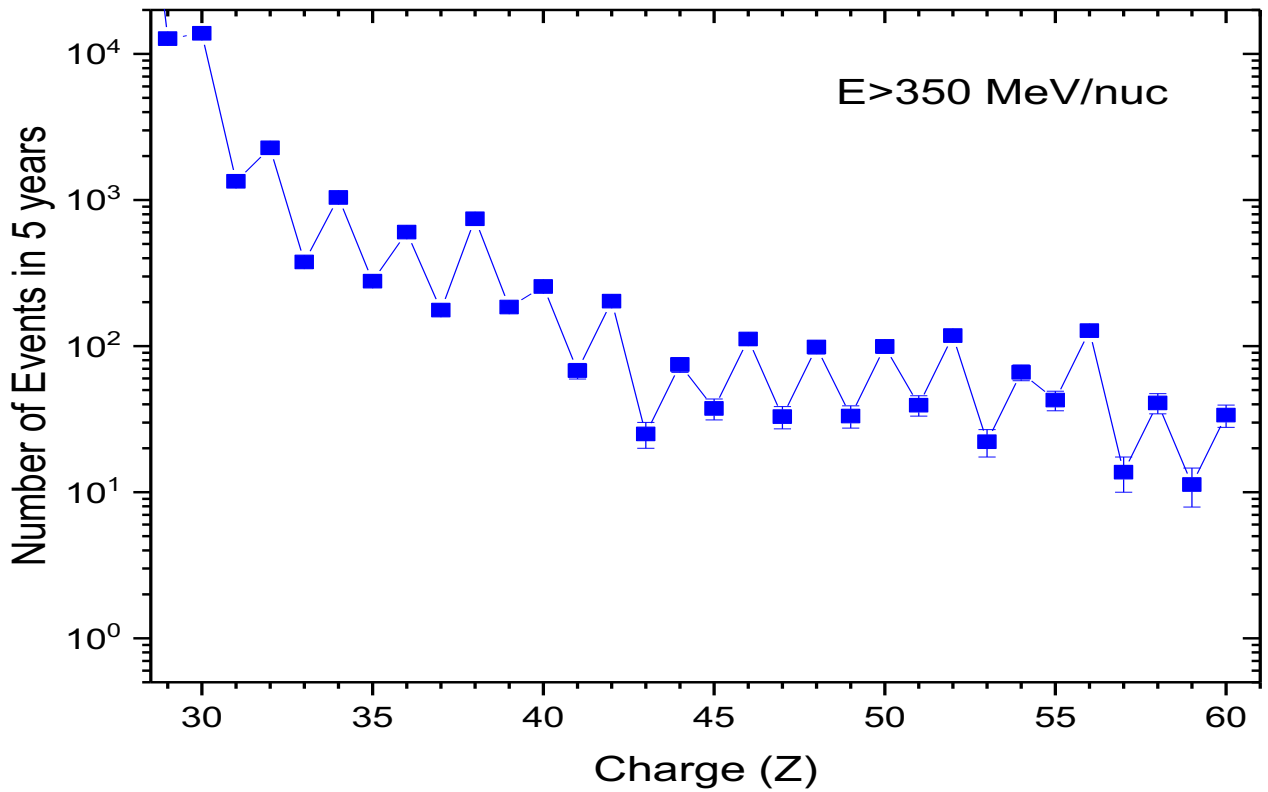
All plots assume 5 years data acquisition and energy > 350 MeV/nuc



ER-ISS\No. of Events\No. Events_1.12.2017-Brian_estimate

Number of Events for Z=30-60

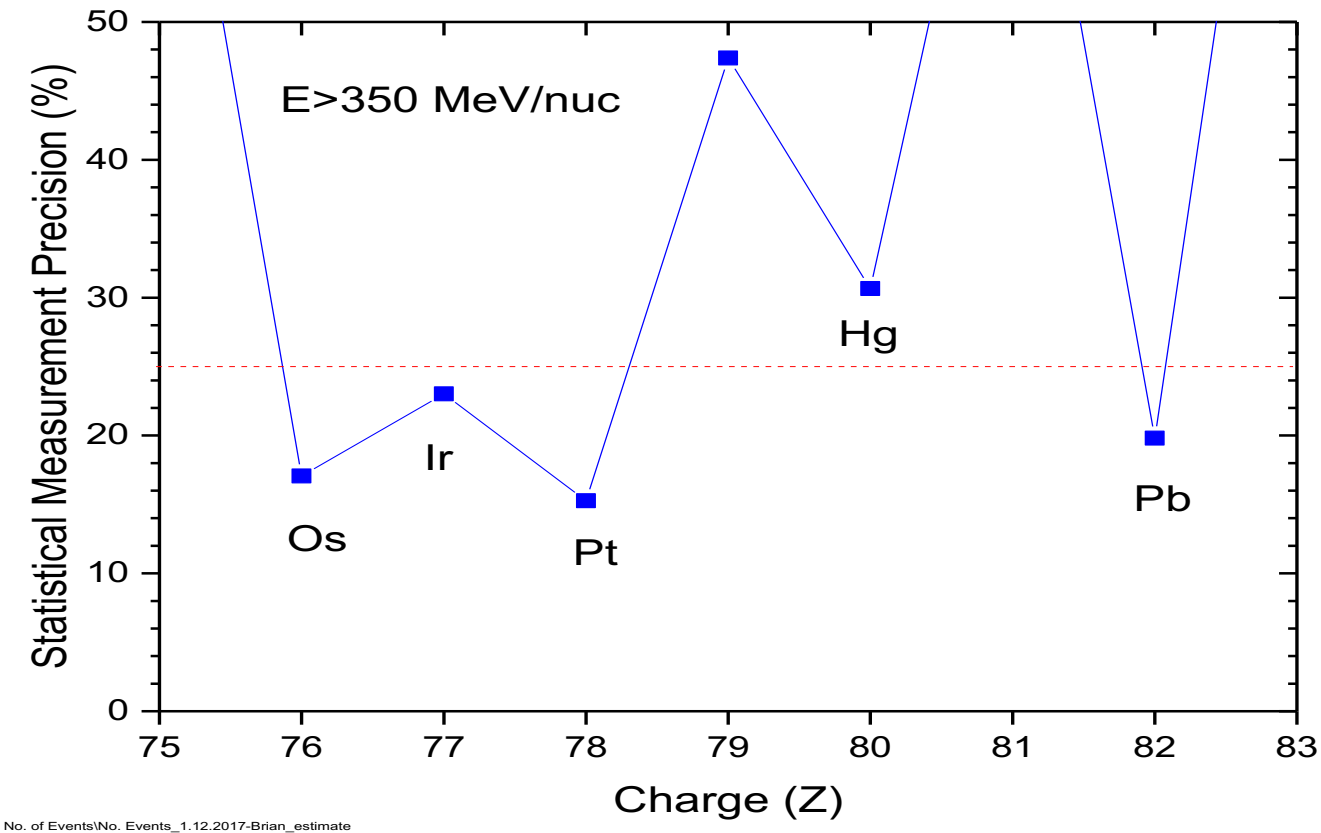
- This is the charge range that is important for binary neutron star mergers
- It is more important than the Pt-Pb range



i\No. of Events\No. Events_1.12.2017-Brian_estimate

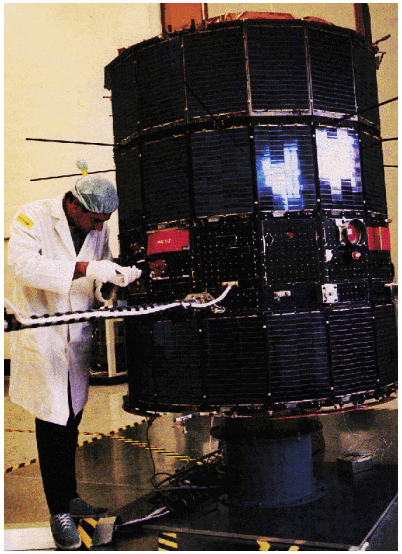
Statistical Measurement Precision for the Os-Pb Charge Region

$_{76}$Os, $_{77}$Ir, $_{78}$Pt and $_{82}$Pb all have statistical precision better than 25%



No. of Events\No. Events_1.12.2017-Brian_estimate

Space Age: Cosmic Ray Astrophysics, Space Weather

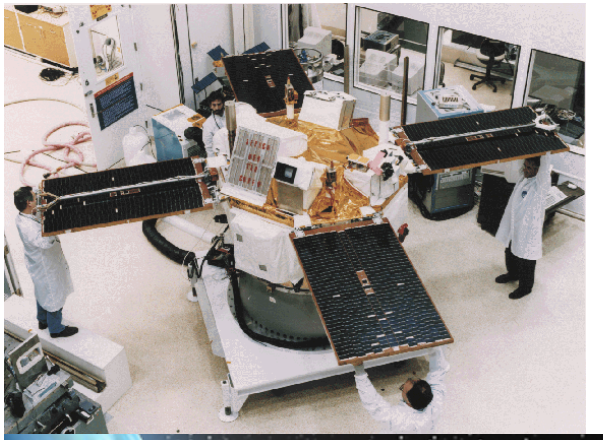


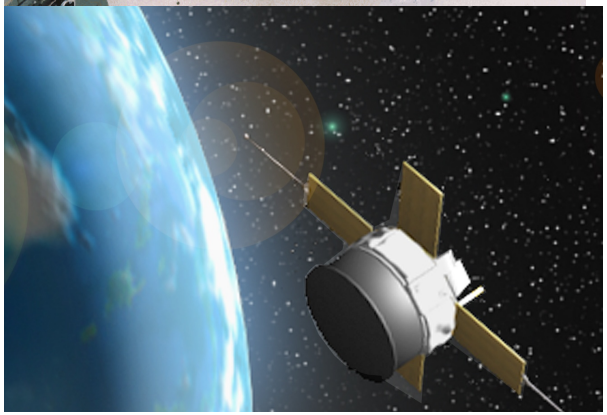
ACE: Advanced Composition Explorer (below)

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)

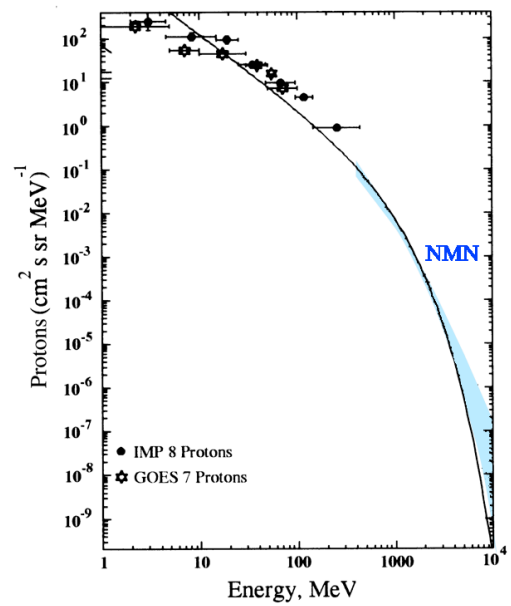
Launched in 1973 & returned data for over 30 years !

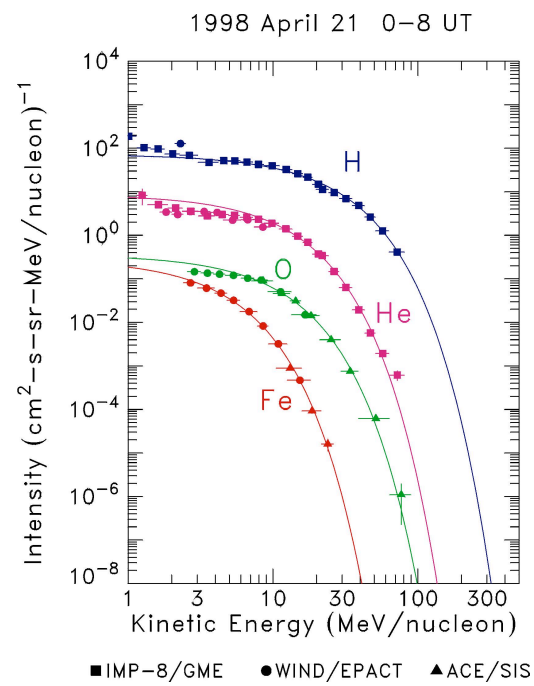
Elliptical orbit 45 x 25 Earth radii

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

Acceleration of Heavy Nuclei from the Sun

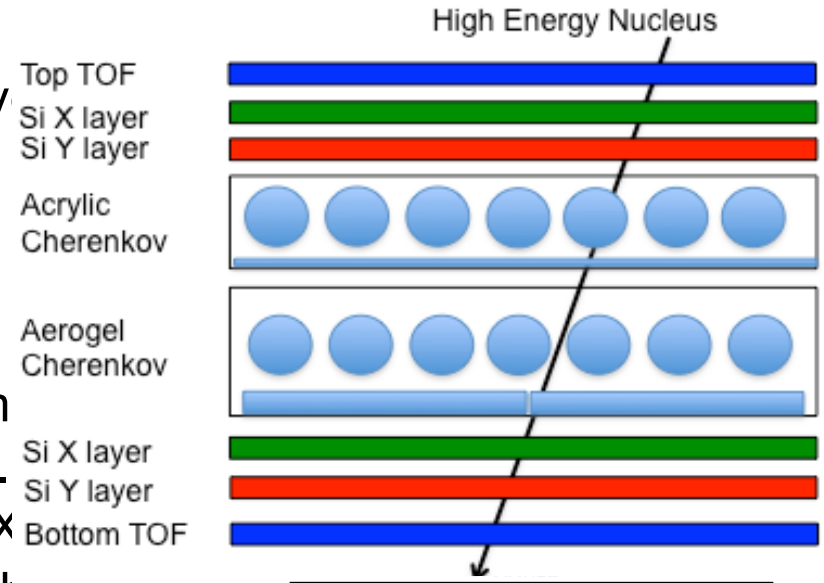
- Acceleration of nuclei from the Sun depends on the same physics as acceleration in the galaxy – the Sun is a "benchtop" laboratory to study acceleration.
- Observed processes can be extrapolated to conditions in the "young Sun" and its influence on the emergence of life – by extension has implications for exoEarths.
- A spectral knee has been observed at ~10^{15} eV in the GCR for many years but its origin is still unclear.
- Spectra with knees for H, He, O, and Fe have also been observed in Solar energetic particle (SEP) events.
- Study of acceleration to these knees and investigation of the parameters is very important for astrophysics including both cosmic-ray acceleration and understanding conditions at exoplanets.
- Can help quantify hazard to astronauts during extended missions since energetic events are most dangerous.
- No current or planned instruments can study heavy nuclei in SEP in the interesting 100 - 2000 MeV/nucleon range.
- SolarCAT on HNX moon will make these groundbreaking measurments.

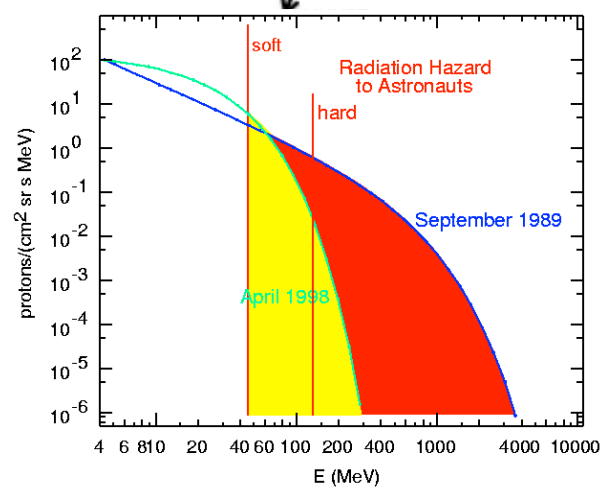




SolarCAT Overview

- Electronic particle detector system – 0.25 m^2 activ area, $A\Omega = 0.5\ m^2sr$
- Measures nuclei 1≤ Z ≤28 with single element resolution and energies from <50 MeV/nucleon to 10 GeV/nucleon.
- Similar to CosmicTIGER with time-of-flight system to extend spectral measurements to lower energy.
- Heritage from SuperTIGER, BESS-Polar, ISOMAX
- Charge measurement same as CosmicTIGER with smaller photomultipliers and thinner Cherenkov radiators
- Time of flight (TOF) system (using thin scintillating optical fibers readout by SiPMs measures lower energies and provides a redundant charge measurement. TOF flight path ~1m. (also provides tracking.
- Can help quantify hazard to astronauts during extended missions since energetic events are most dangerous.
- Added solar neutron detector based on SONTRAC (not shown) extends measurements to include neutron dose.

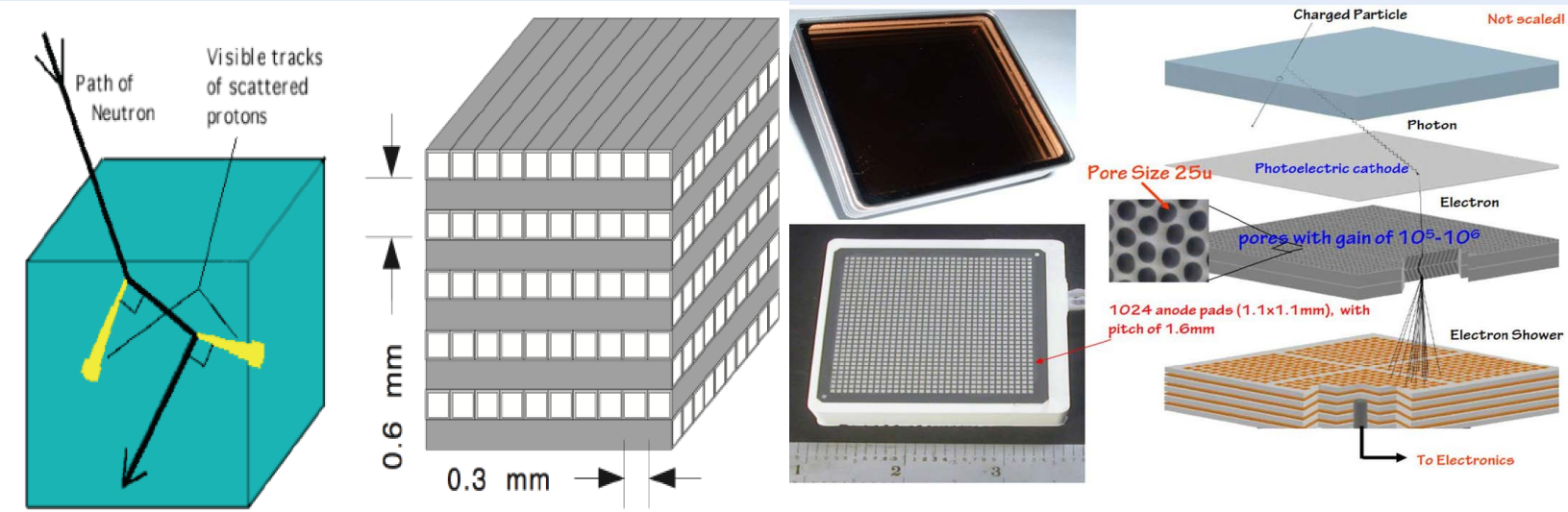


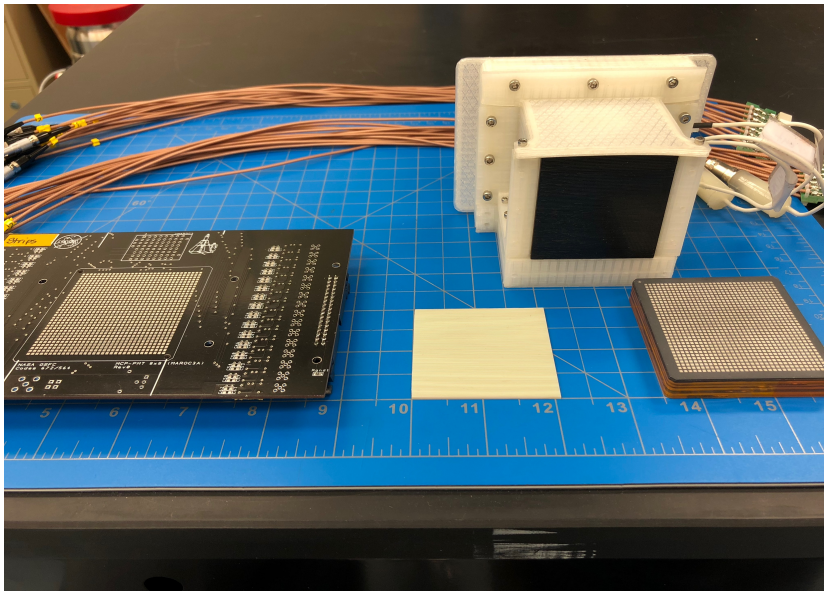


Regions of hazardous radiation compared for events with different spectral knees. Note that the two events have similar intensities at 10-20 MeV.

SONTRAC Overview

- **Novel technique: use bundles of plastic scintillating optical fibers in mutually orthogonal layers to locate scattering events and identify proton tracks, to achieve double scatter in a compact detector**
- **Results in increased effective area and sensitivity to higher energy neutrons.**



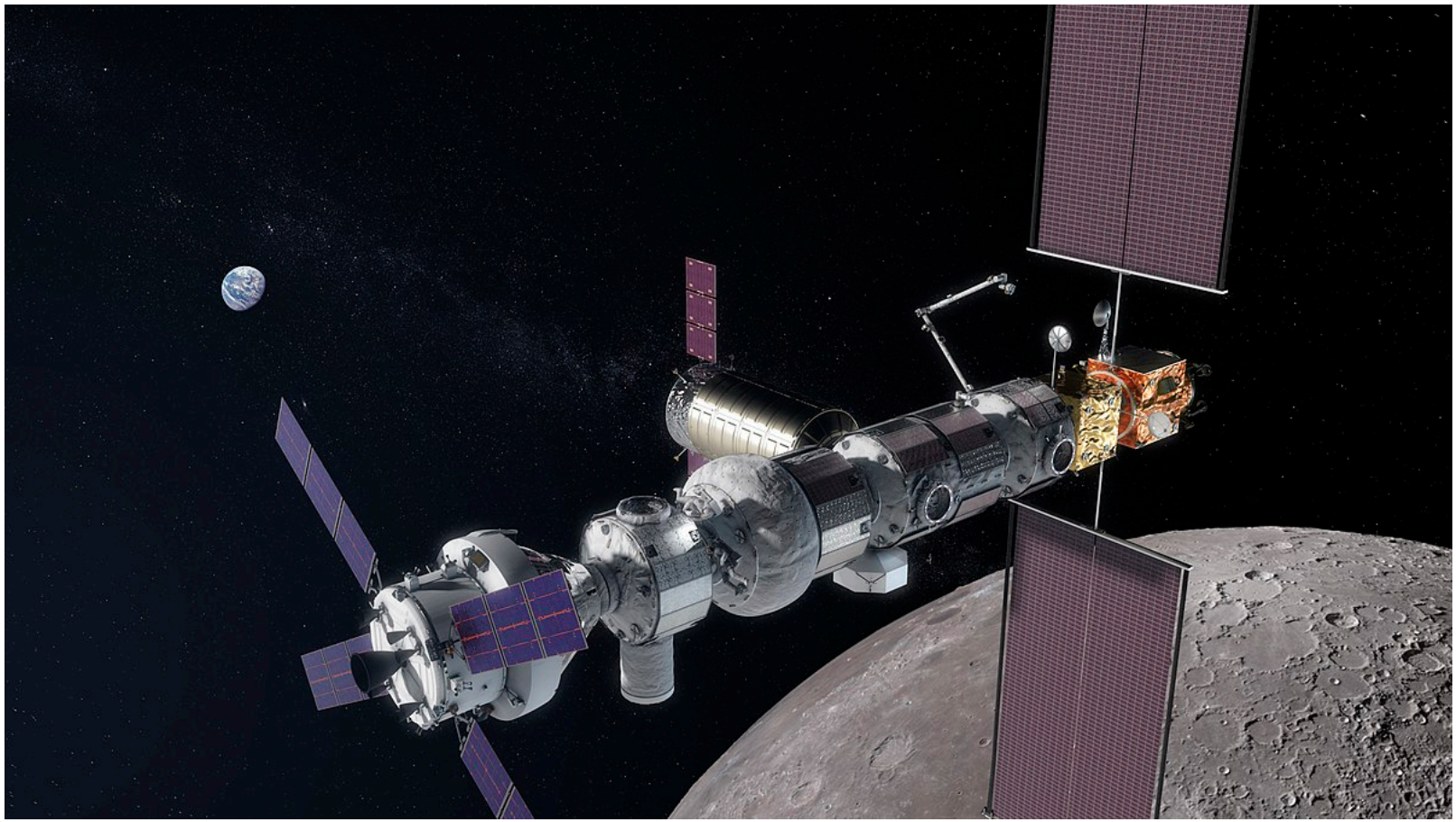


Fiber bundles are optically coupled to multiple small (~1mm) silicon photomultipliers (SiPM) using a silicone rubber optical interface

In picture of prototype at left, bundles were coupled to a multi-anode photomultiplier (detailed above)

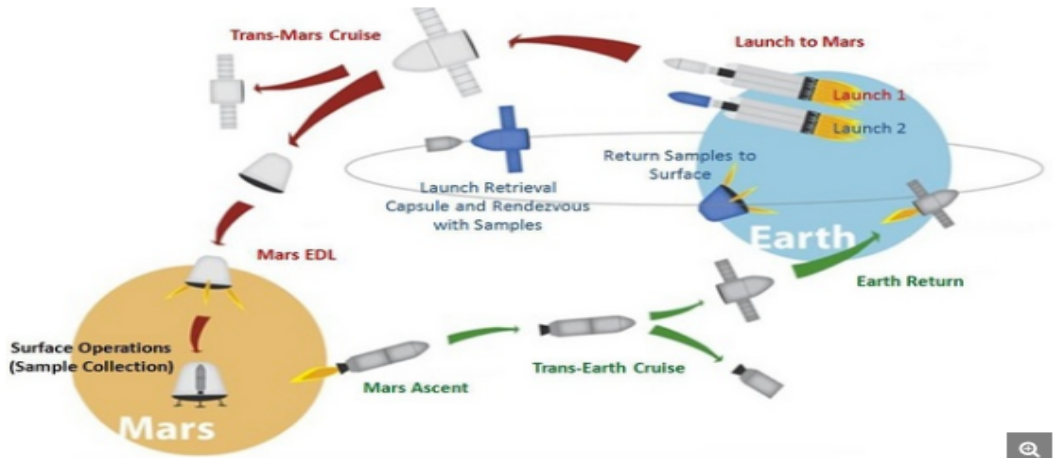
LHNX Mission Concept

- 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.
- SolarCAT/SONTRAC suggested as a surface instrument to monitor in-situ particle radiation including neutrinos. I have also pitched a magnetic spectrometer and dE/dX vs Total E telescope(s).



Red TIGER Mission

SpaceX's robotic Dragon capsule could be modified to help bring Mars samples back to Eart



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.

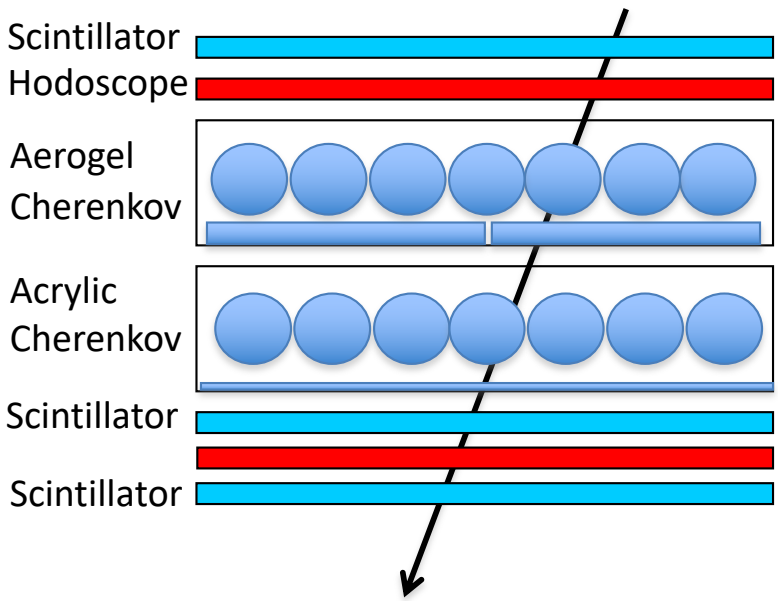
HNX Summary

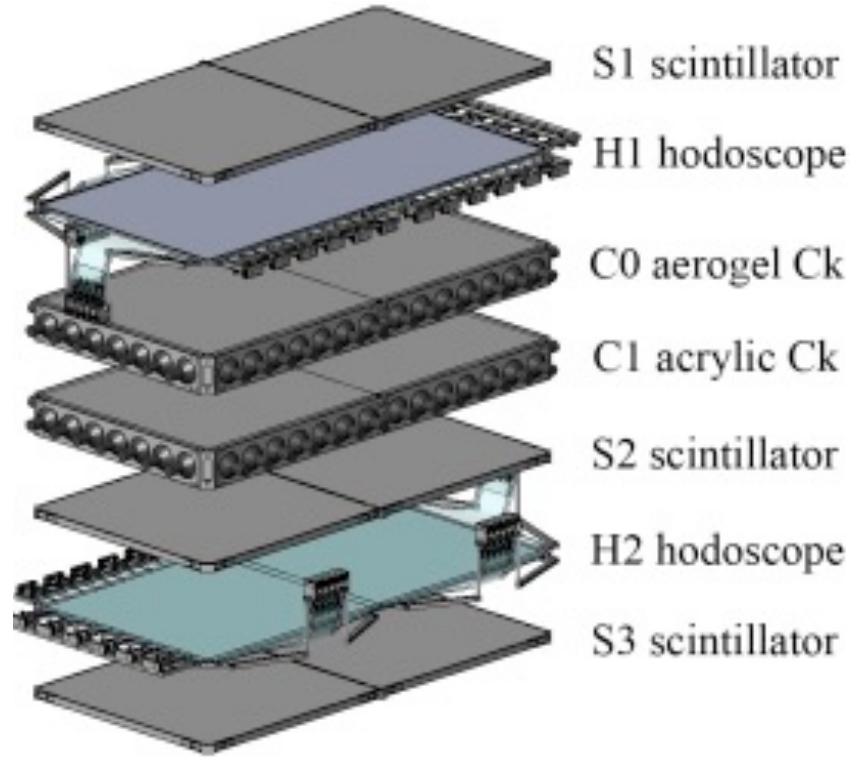
- **HNX has Compelling Science**
  - Will answer two little understood aspects of the Grand Cycle of Matter in the Galaxy complementing other investigations
  - HNX/HNX LG are the only missions capable of reaching the end of the periodic table with individual element resolution and high statistics
  - Unofficially told that HNX Science was rated Excellent in 2014 SMEX Review
  - Strong endorsements at 2015/2017 International Cosmic Ray Conferences
  - HNX Extended Mission further improves UHGCR statistics and adds important acceleration probe. May also be interesting to Manned Space Flight Directorate.
- **Very mature technologies - TRL 8**
  - ECCO and CosmicTIGER were evaluated as TRL 8 for both components and systems by the GSFC TRL Committee
  - SolarCAT not evaluated but has similar maturity to CosmicTIGER
- **Cost ~ 19 $M - 207 $M depending on requirements**
  - ➢ COST of Instruments are very well known from 2014 HNX smex proposal, If Lunar instruments can be "Do No harm" then cost drops to approximately balloon instrument for CosmicTIGER+SolarCAT+SONTRAC (~10$M) and approx. SMEX costing for ECCO (driven by ground analysis).
  - Most engineering and almost all of the proposal will carry over to HNX

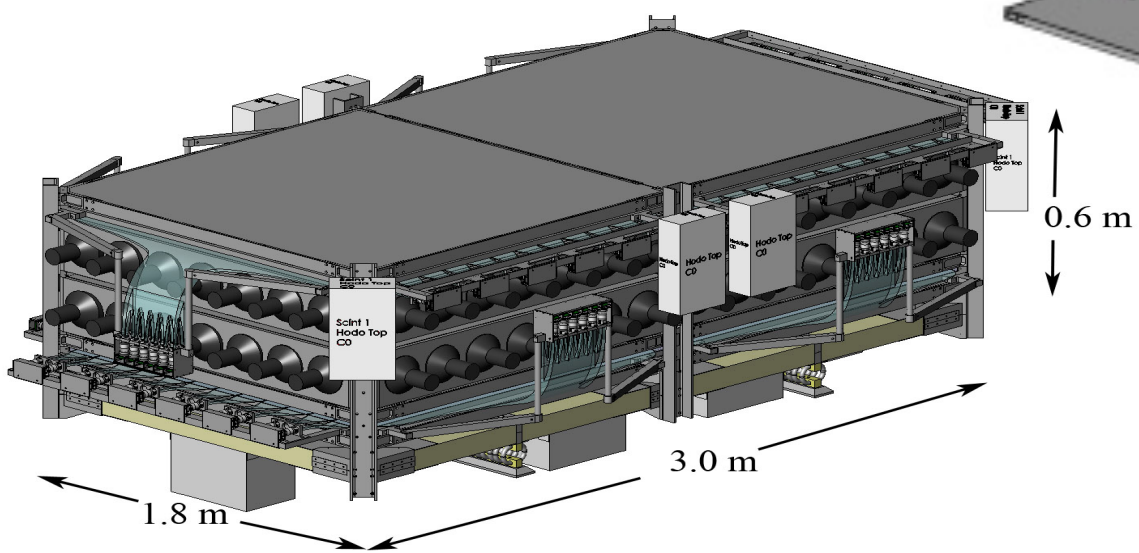
BACKUP SLIDES – SuperTIGER

- SuperTIGER flew record 55 days over Antarctica in 2012, ST2 prepared for 2017 and had to abandon after 16 launch attempts, 2018 short flight with leaking balloon,being prepared for 2019
- Proposed HNX CosmicTIGER is almost identical in size and complexity to one ST module. SolarCAT is the 0.5 size of one ST module.

The SuperTIGER Instrument

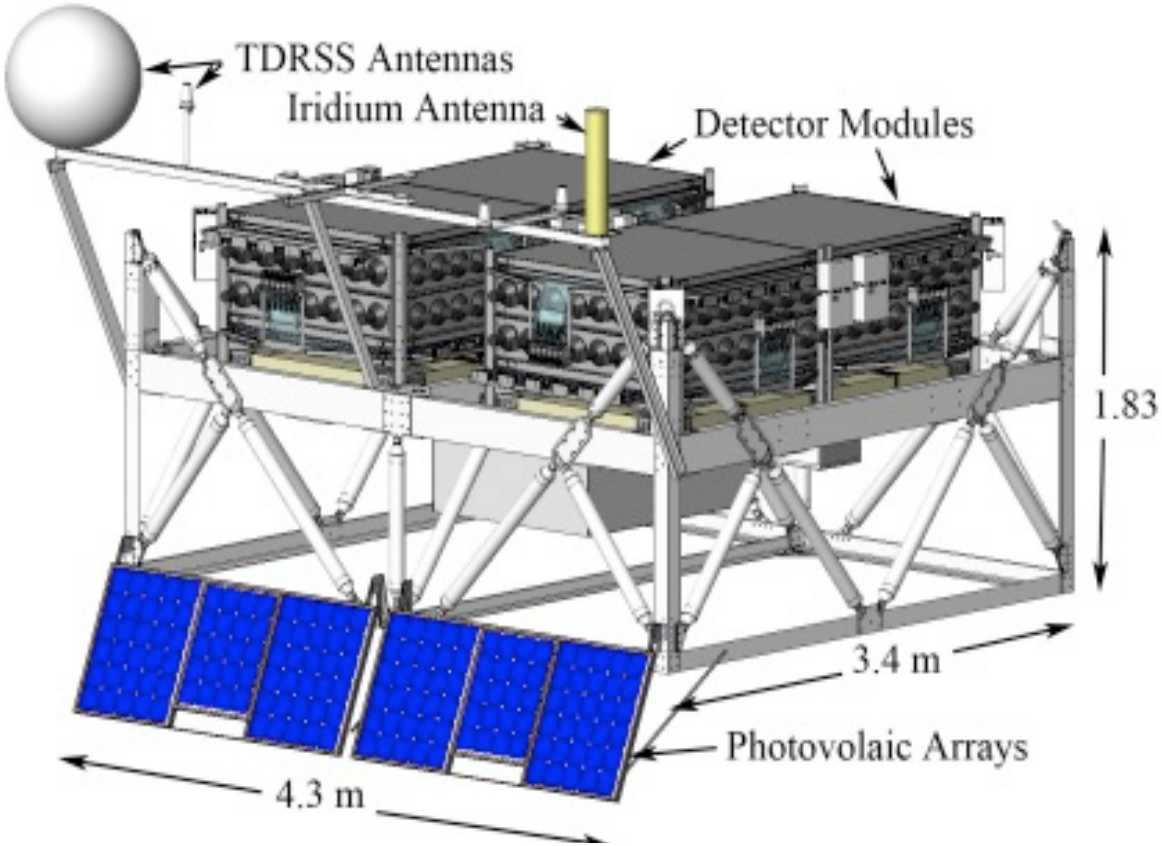


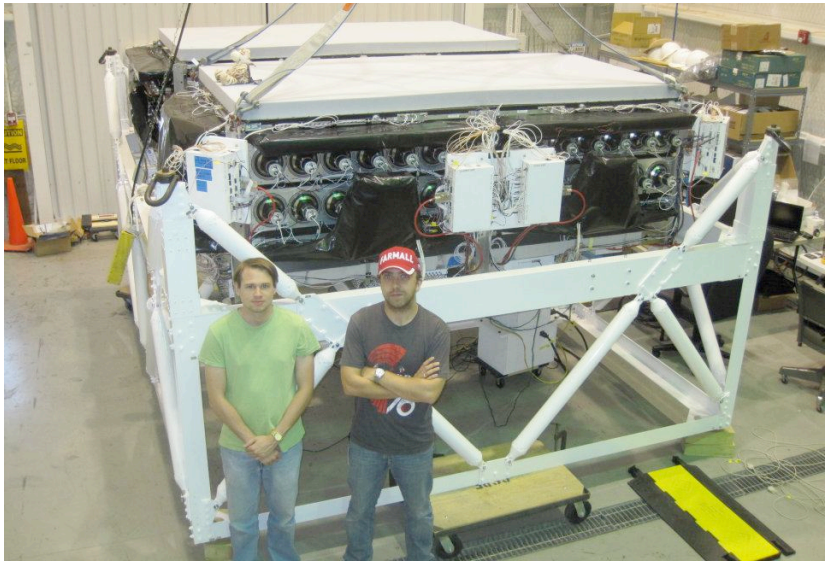




- Two nearly identical modules
- Each module is about the size of two TIGER instruments.
- Single Module Mass—660 kg (1452 lb)

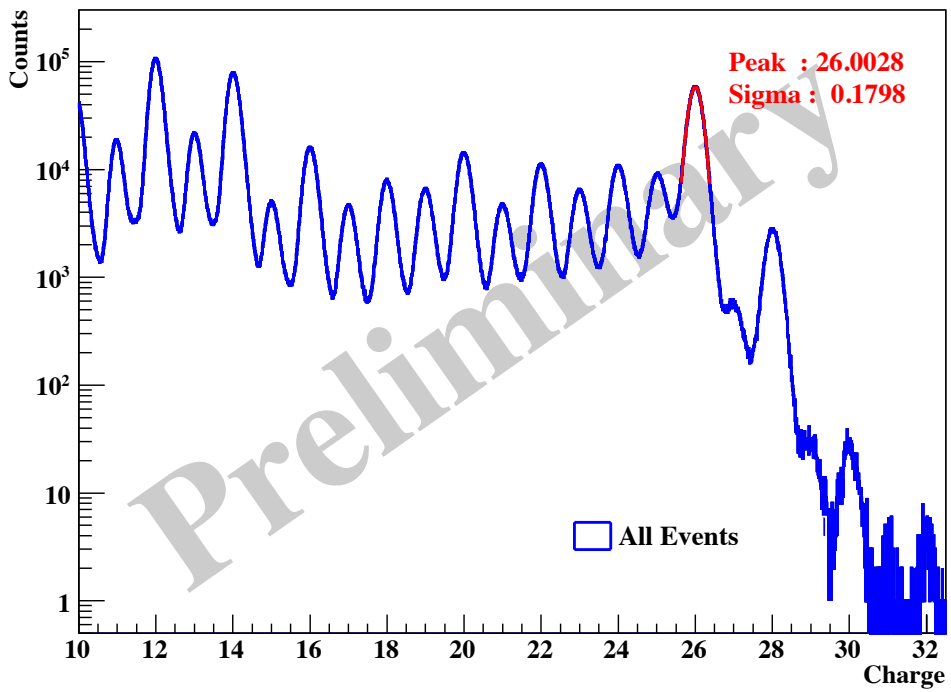
The SuperTIGER Instrument

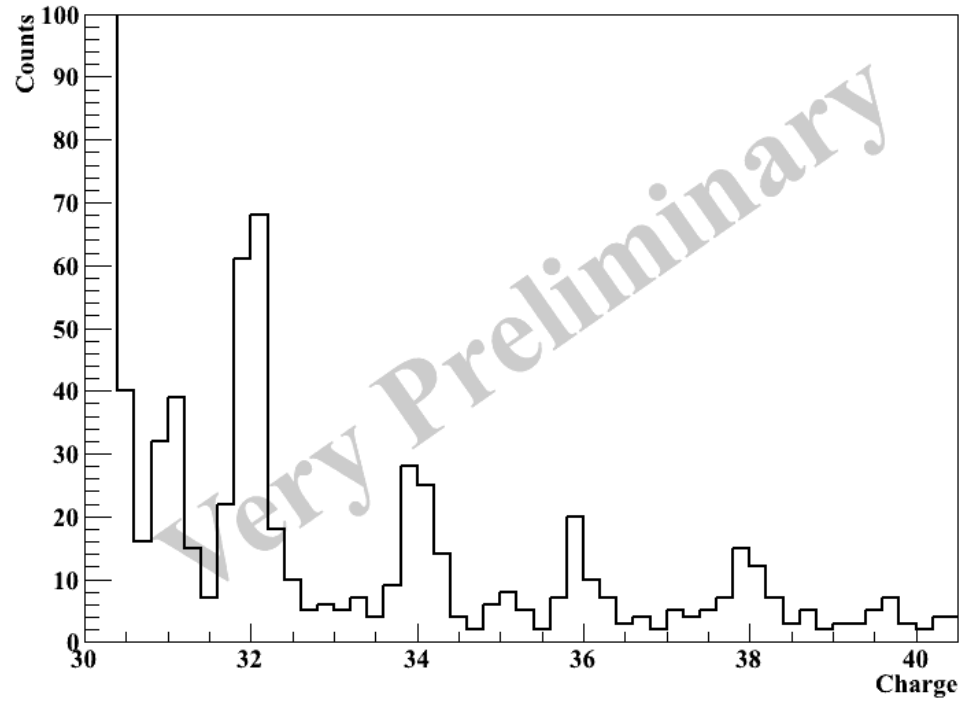




- Active area 5.4 m^2
- Effective geometry factor (including interactions) at $_{34}$Se 2.5 m^2sr (6.4 times TIGER - 0.4 m^2sr).
- Full Instrument + Gondola Mass—1770 kg
- Power—250 Watts

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