UltraHeavy GCR measurements beyond SuperTIGER: The Heavy Nuclei eXplorer

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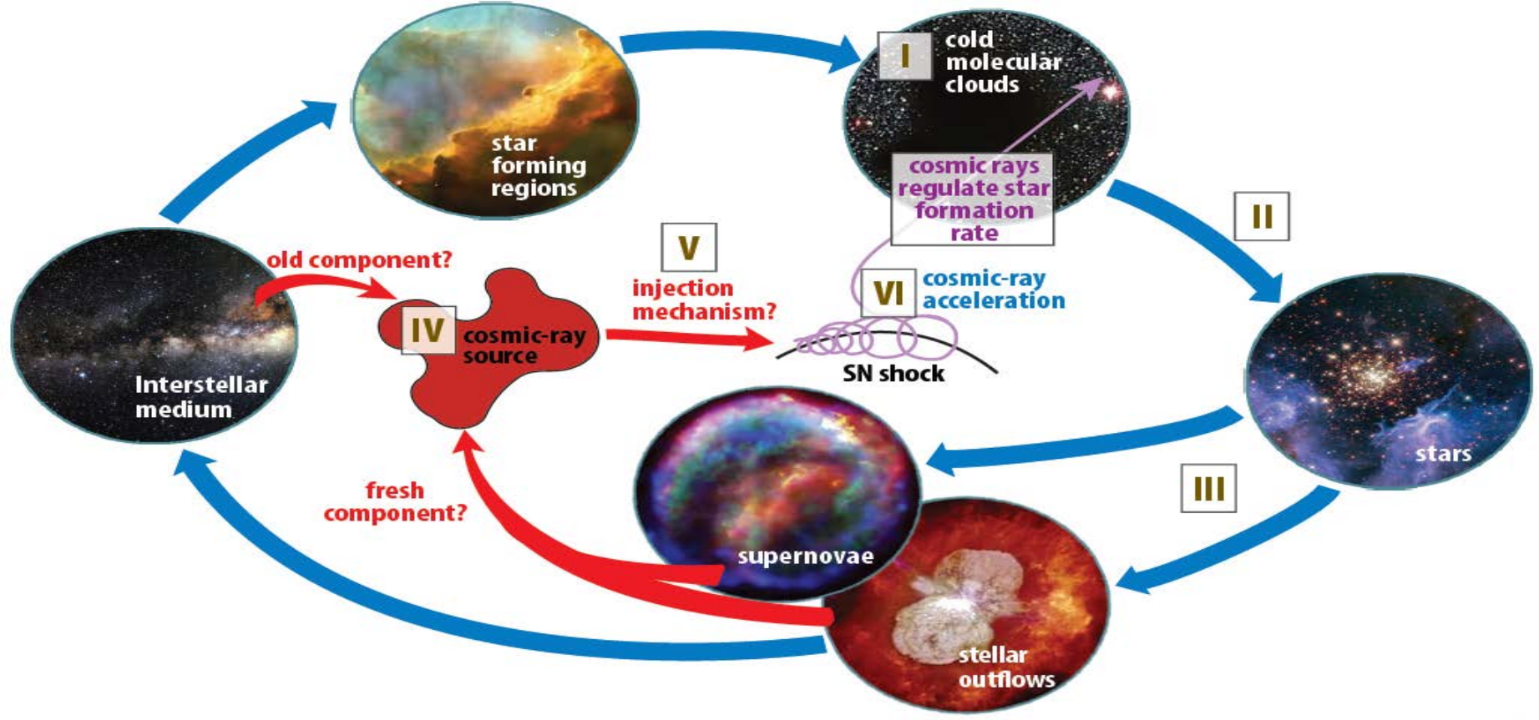
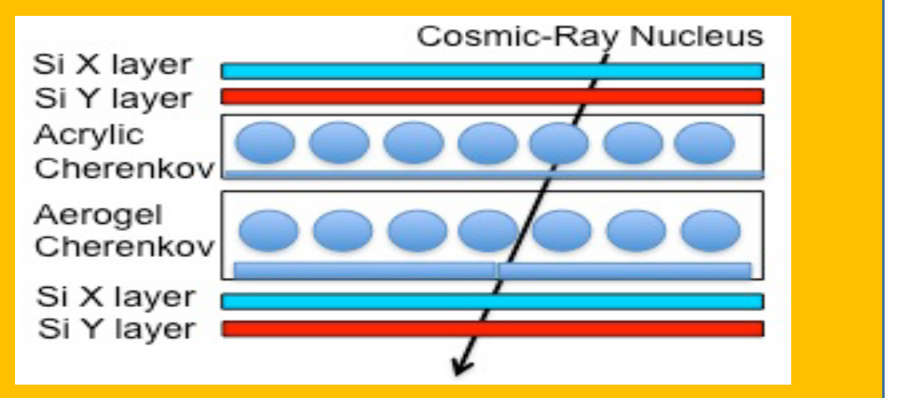
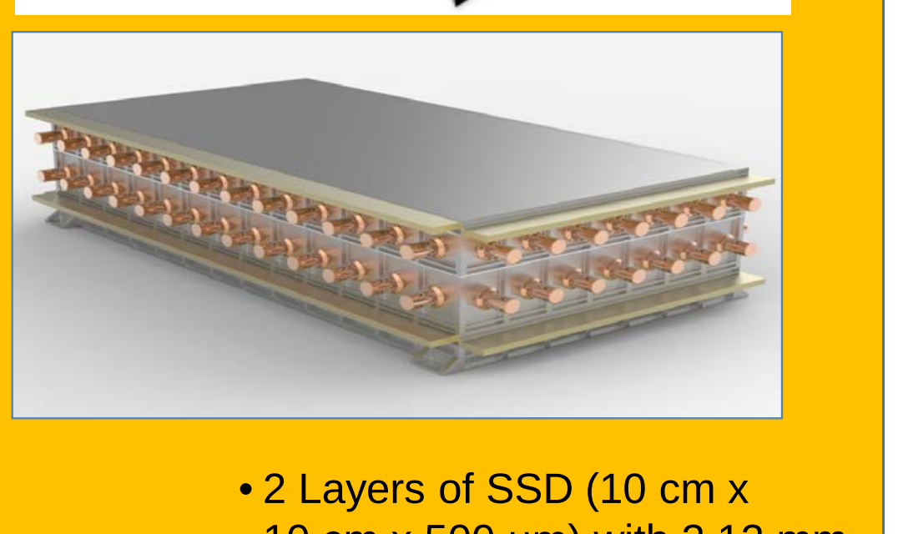
Investigate the two least understood, but critically important, aspects of the grand cycle of matter in the galaxy: the nature of the astrophysical reservoirs of nuclei at the cosmic-ray sources and the mechanisms by which nuclei are removed from the reservoirs and injected into the cosmic accelerators.

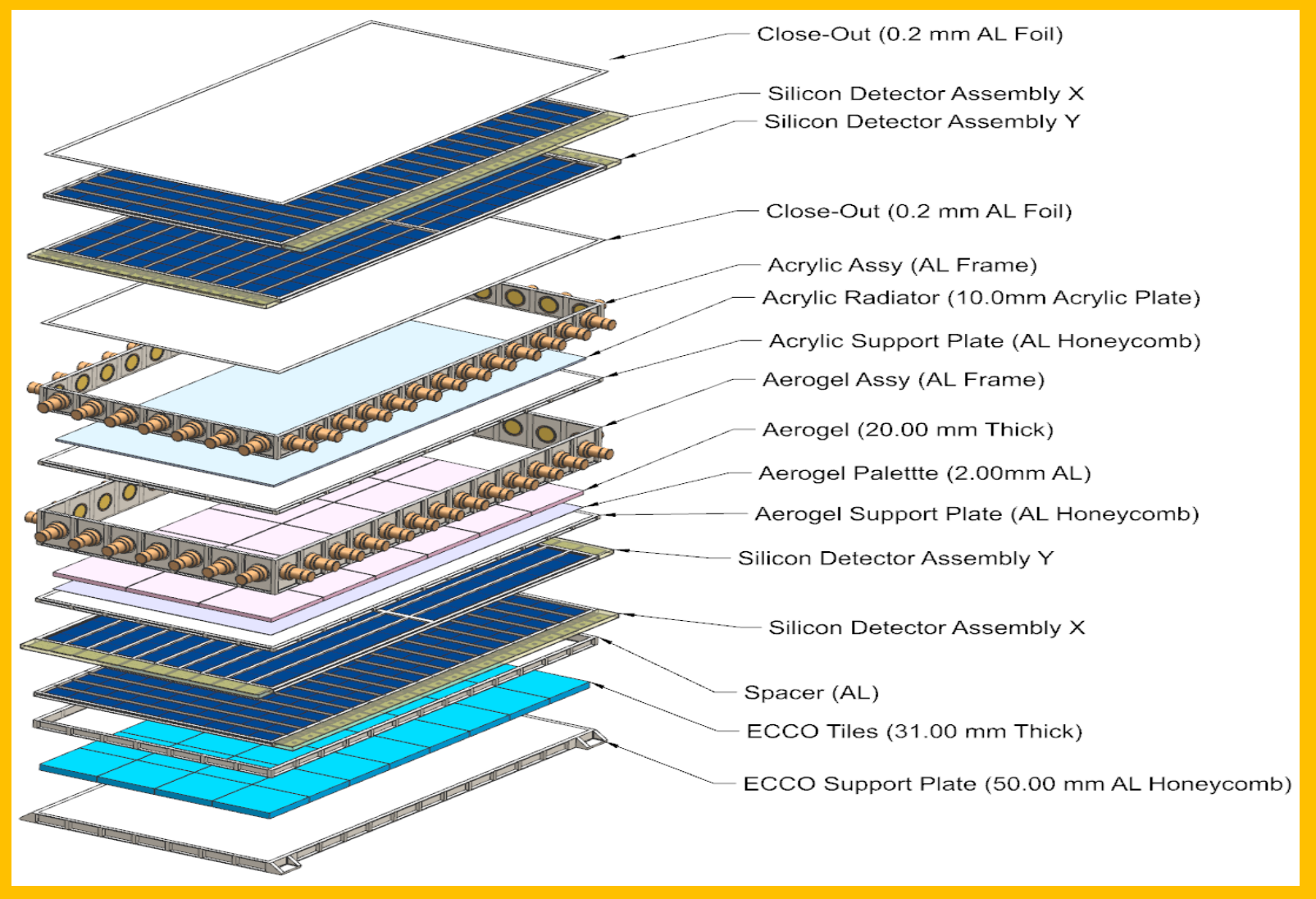


- **Determine whether ultra-heavy galactic cosmic rays (UHGCRs) are accelerated from newly synthesized or old material, and find their age since nucleosynthesis**
  - –Ratios of heavy nuclei probe age of accelerated material
  - –Actinide (Uranium group) "radioactive clocks" measure UHGCR age - relative abundances probe mixture of old and new material
- **Where/how UHGCR are accelerated and their history**
  - –Element abundances carry the signature of the site of injection into the accelerator and the mechanism of selection for acceleration
    - OB associations
    - Acceleration from dust (refractory) or cold ISM gas (volatile)
  - –Secondary to primary ratios measure the integrated material pathlength of UHGCRs from acceleration to measurement
- **The mix of UHGCR nucleosynthesis processes (r and s process, binary neutron star mergers)**
- **Search for superheavy nuclei and strange quark matter**

- Large electronic particle detector system – 2 m^2 active area, AΩ = 4.2 m^{2}sr
- Heritage from SuperTIGER, HEAO, Solar Probe Plus
- Measures nuclei $Z \geq 6$ with single element resolution – method proven in accelerator tests, TIGER, and SuperTIGER
- Measurement range extends to the end of the periodic table (adds to ECCO area for $Z \geq 70$)
- 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 ionization energy deposit (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 ($\beta \geq 0.96$)

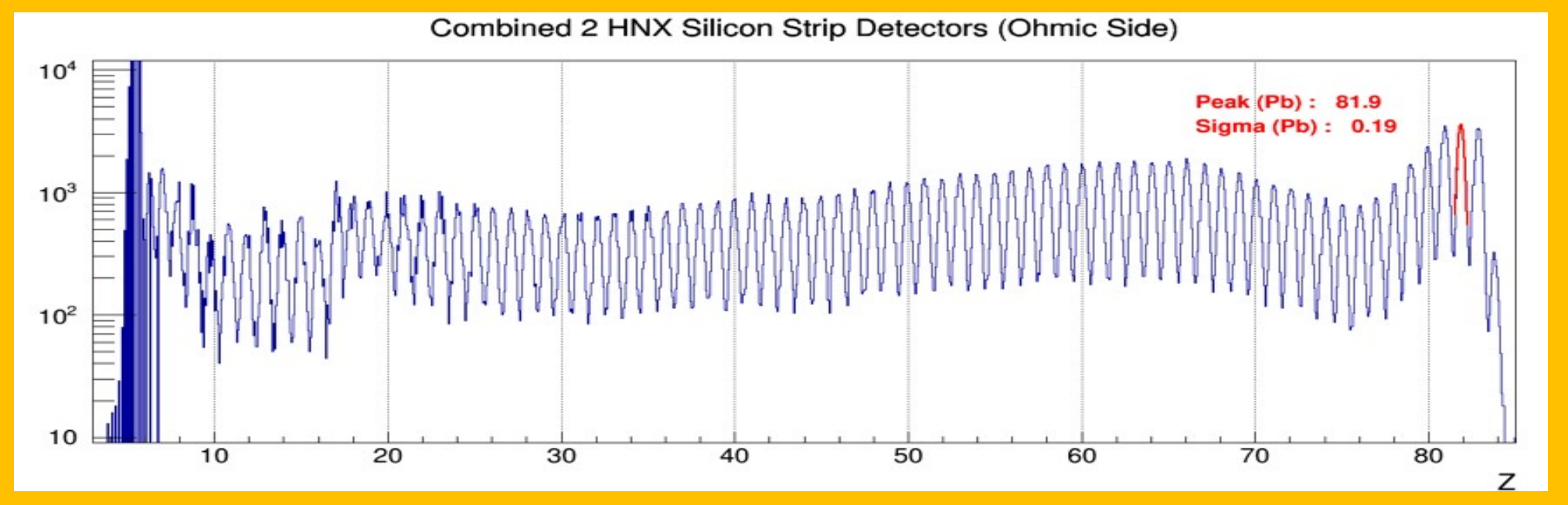






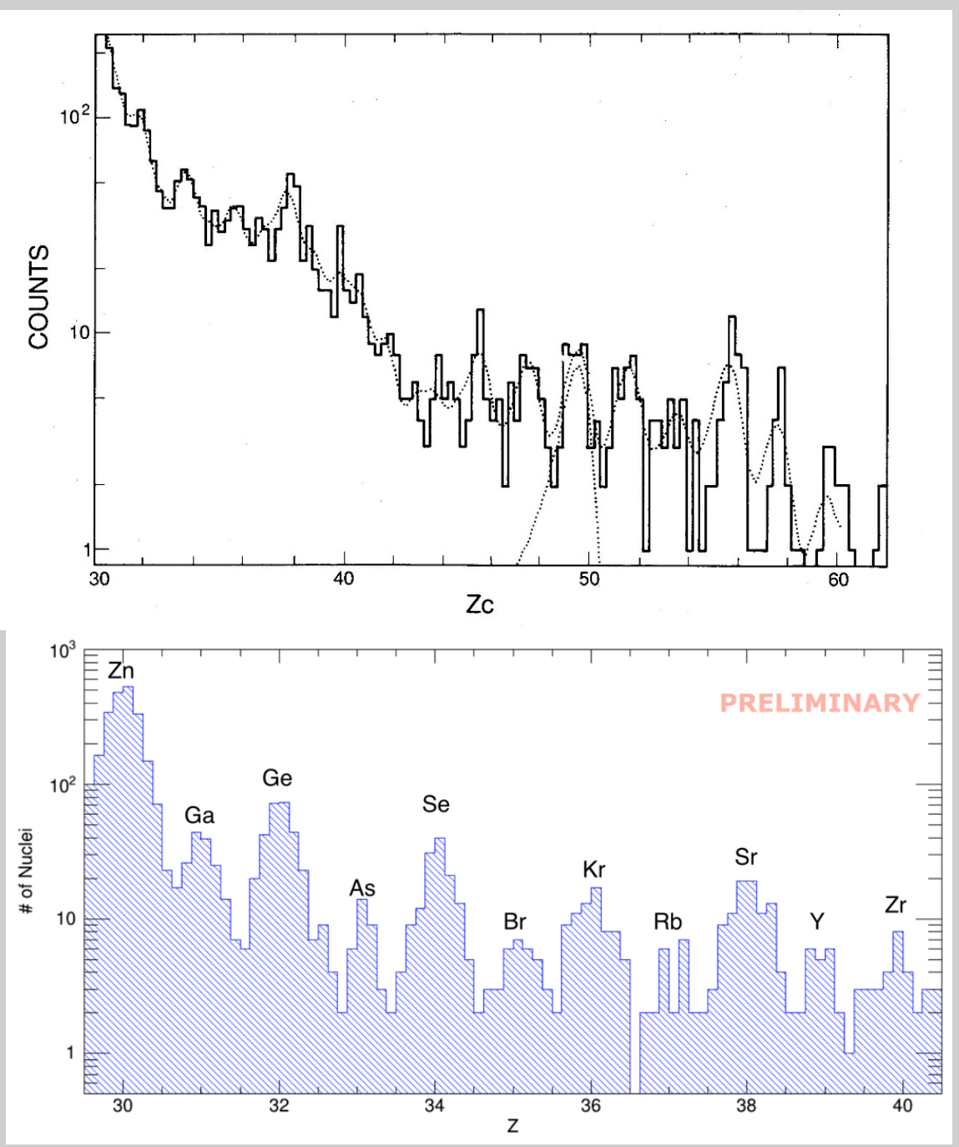
- 2 Layers of SSD (10 cm x 10 cm x 500 μm) with 3.12 mm strip pitch (50 μm gap) at top and bottom.
- Orthogonal strip direction in successive layers gives X ,Y.
- SSD connected in "ladders" with corresponding strips joined (wire bond or flex cable) between detectors and read out at end. All ladders are identical for simplicity
- Cherenkov detectors (acrylic and aerogel) use light integration boxes lined with Gore DRP reflector.
- 40 Hamamatsu R6233-100 PMTs each with 7 cm photocathodes and 30% quantum efficiency at 400 nm
- Possibly SiPM arrays rather than PMTs
- Aspect ratio of light integration boxes is optimized for the specific radiator used

CERN SPS Lead Beam Tests Nov-Dec 2016



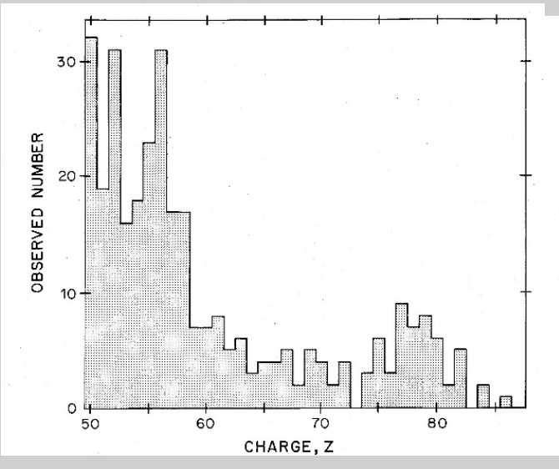
HNX Silicon Strip Detectors (6 <= Z <= 84)

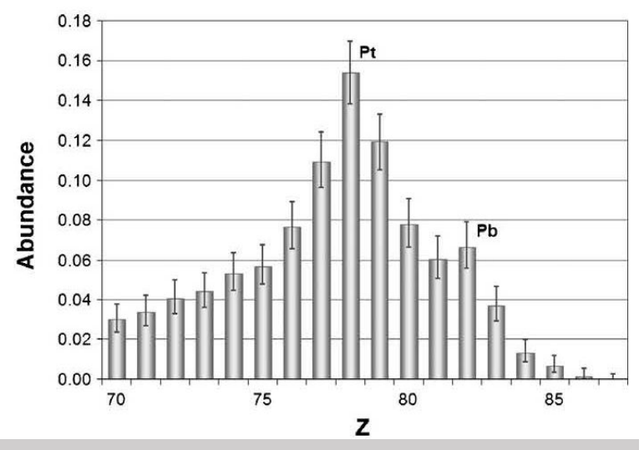
Current State of UH Measurements



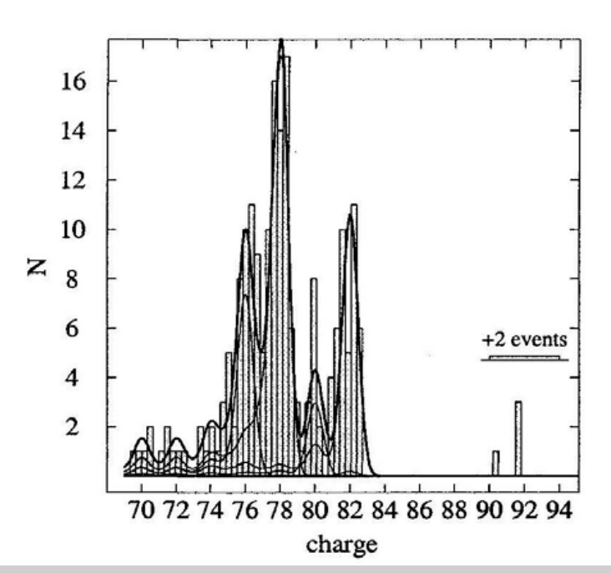
HEAO 3 Heavy Nuclei Experiment (Binns et. al. Astrophysical Journal , **346**, 1989)
SuperTIGER

UHCR Experiment	Ball/Sat	Date	Duration	Area	Ref.	Detectors used
First detection of Z>30 nuclei was in meteorite crystals; Fleischer, Price, Walker, and Maurette (1967) JGR 72, 331						
Texas Flights VHCRN	Balloon Texas	1966	0.6 days	4.5 m^2	Fowler et al. 1967	Four layers of nuclear emulsions with absorber interleaved
Barndoor I,II, & III	Balloon Texas	1967-1970	2.8 days	15 m^2	Wefel 1971	Plastic track detectors and nuclear emulsions
Heavy Nuclei Experiment	HEAO-3 Satellite	1979	1.7 years	~2 m^2	Binns et al. 1989	Ionization chambers, Cherenkov counters, wire ionization hodo.
HCRE	Areal-6 Satellite	1979	1 year equiv.	0.5 m^2	Fowler et al. 1987	Spherical gas scintillator and acrylic Cherenkov detector
UHCRE	LDEF Satellite	1984	5.75 years	20 m^2	Donnelly et al.2012	Plastic track detectors (Lexan)
Trek	Mir Satellite	1991	1/3rd 2.5 y 2/3rd 4.2 y	1.2 m^2	Westphal et al.1998	Glass track detectors-Barium Phosphate Glass (BP-1)
CRIS	ACE Satellite	1997	17 years	0.03 m^2	Stone et al. 1998	Silicon detector stack & scintillating optical fiber hodo.
TIGER	Balloon-Antarctica	2001, 2003	50 days	1.3 m^2	Rauch et al. 2009	Plastic scint, acrylic & aerogel Cherenkov, scint fiber hodo.
SuperTIGER	Balloon-Antarctica	2012	44 days equiv.	5.6 m^2	Binns et al. 2014	Plastic scint, acrylic & aerogel Cherenkov, scint fiber hodo.

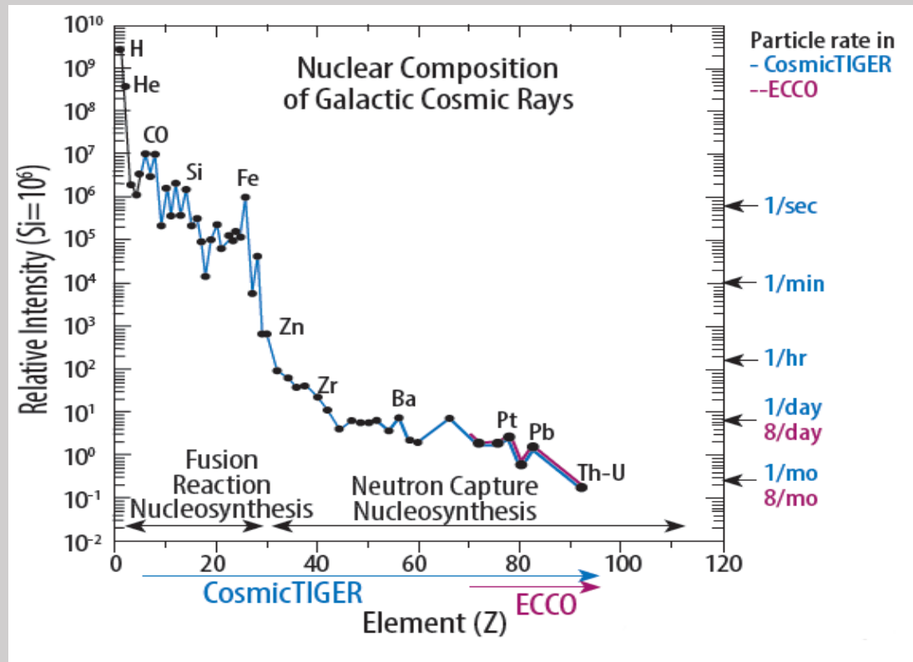

HEAO-3 C3



UHCRE



TREK



From left to right, Z > 70 results from HEAO-3 C3 (Binns et al., ApJ, 1985), UHCRE (Donnelly et al., ApJ, 2012), and TREK (Westphal et al., Nature 1998)

Ultra-Heavy Particle Production in Binary Neutron Star Mergers

Mass and Charge spectra (Shibagaki et al. ApJ 816:79 (2016)

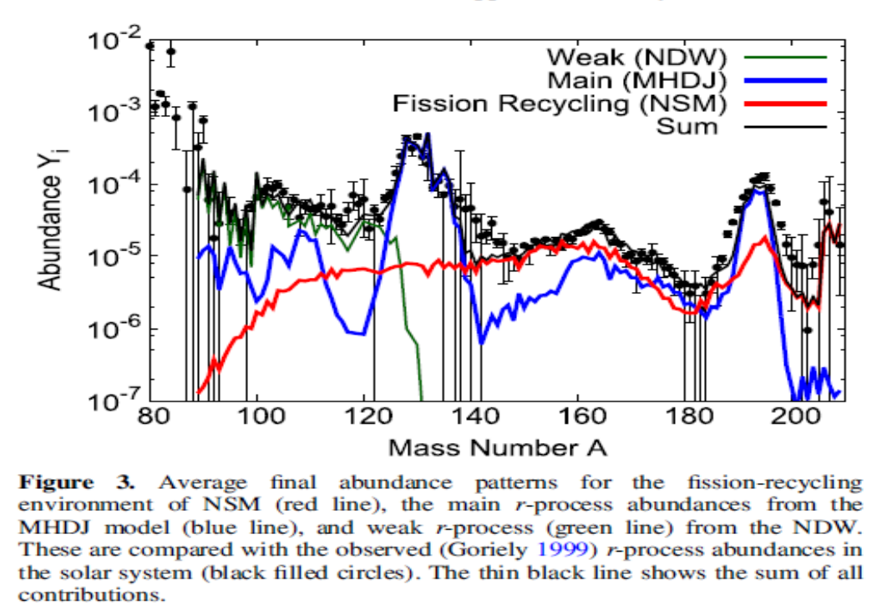


Figure 3. Average final abundance patterns for the fission-recycling environment of NSM (red line), the main *r*-process abundances from the MHDJ model (blue line), and weak *r*-process (green line) from the NDW. These are compared with the observed (Goriely 1999) *r*-process abundances in the solar system (black filled circles). The thin black line shows the sum of all contributions.

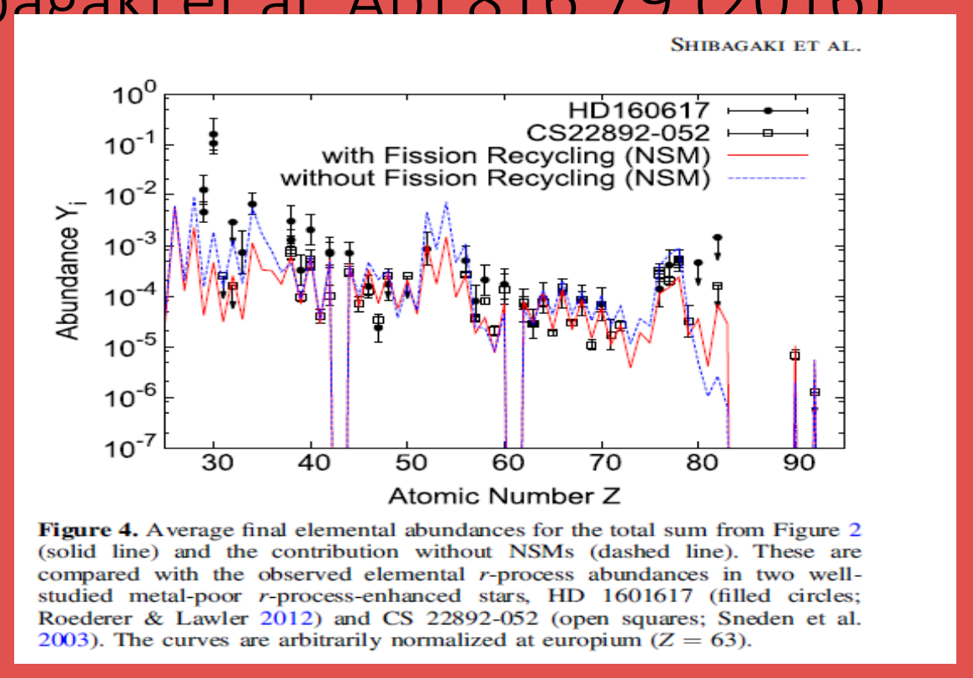
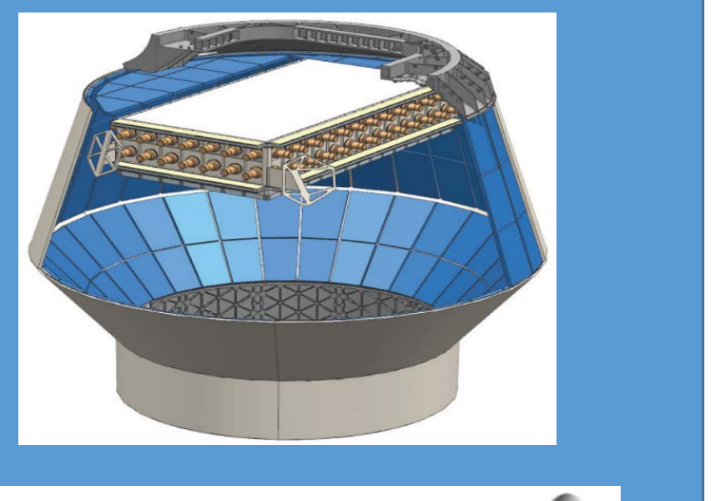


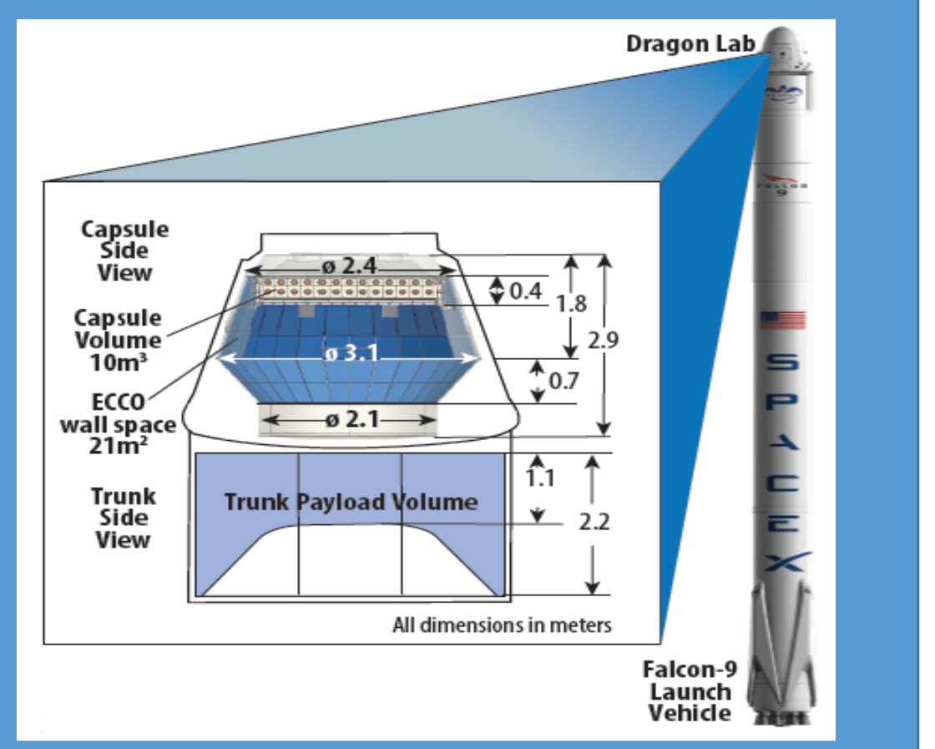
Figure 4. Average final elemental abundances for the total sum from Figure 2 (solid line) and the contribution without NSMs (dashed line). These are compared with the observed elemental *r*-process abundances in two well-studied metal-poor *r*-process-enhanced stars, HD 1601617 (filled circles; Roederer & Lawler 2012) and CS 22892-052 (open squares; Sneden et al. 2003). The curves are arbitrarily normalized at europium ($Z = 63$).

They state that supernova models often under-produce r-process nuclei just above and below closed nuclear shells.
In their treatment, the NSM material contributes mainly by fission recycling that fills up the intermediate charge range (see figure on left)
So in their model
the "weak r-process" (such as occurs in the neutrino driven wind of core-collapse SNe) produces nuclei up to A~125.
The "main r-process" (such as occurs in the MHD driven jets in core-collapse Sne) produces the abundance peaks at A=130 and 195
The "fission recycling r-process" occurs in neutron star mergers (NSM). In this model the NSM material is driven all the way up to A~300 where it fissions to fill in the valleys

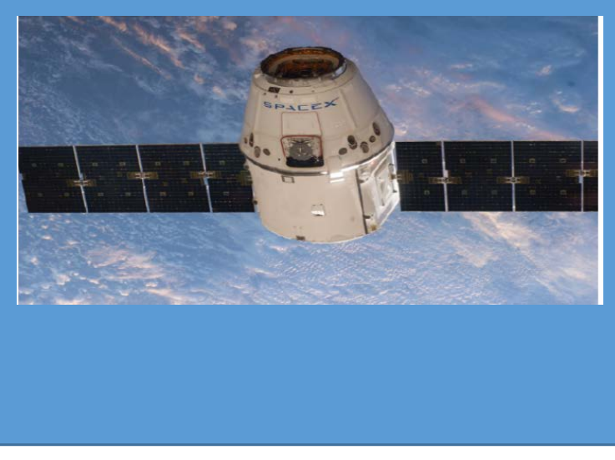
HNX Mission Concept



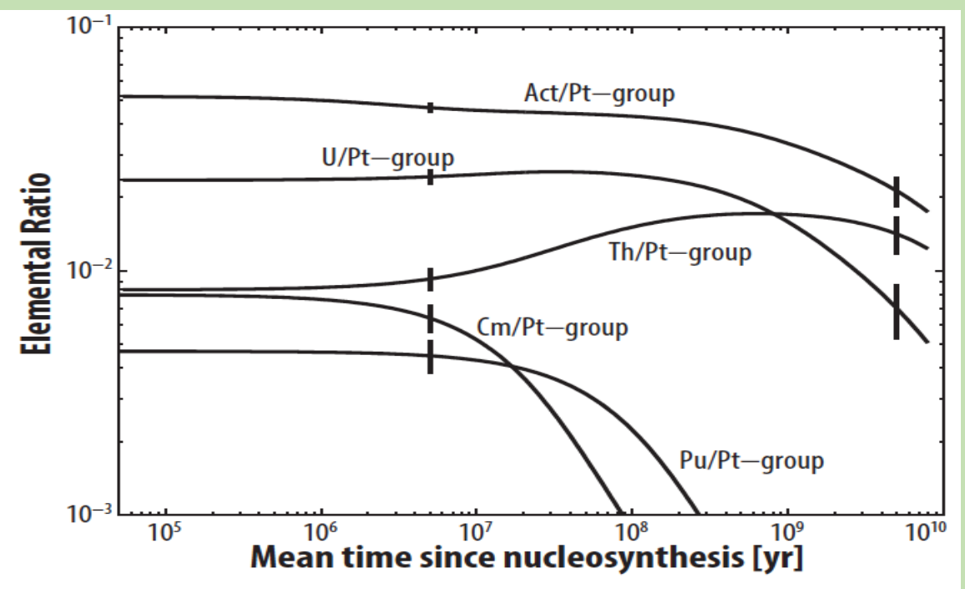
- HNX uses two complimentary instruments ECCO and CosmicTIGER to span a huge range in atomic number ($6 \leq Z \leq 96$). The detectors are sensitive to particles with $Z > 96$ but the flux of these particles is unknown.
- HNX uses the SpaceX DragonLab launched on a SpaceX Falcon 9 Launch vehicle
  - DragonLab is a free-flying "laboratory" based on the Dragin ISS supply and DragonRider commercial crew spacecraft
  - DragonLab consists of a pressurized and temperature controlled capsule and unpressurized trunk.
    - HNX would fly inside the capsule and a second instrument could be accommodated in the trunk. This rideshare arrangement helps reduce cost.
    - HNX is extremely compatible with a wide variety of co-manifested instruments. Most instruments wish to fly in the trunk to have an unobstructed view of space.
    - Capsule is recoverable, trunk is not. This is important as ECCO requires recovery for post-exposure processing.
    - DragonLab supplies all services including power, telemetry and thermal control.
- DragonLab will be certified for 2 year flights with safe recovery (this may be increased to 3-4 years with further maturation)



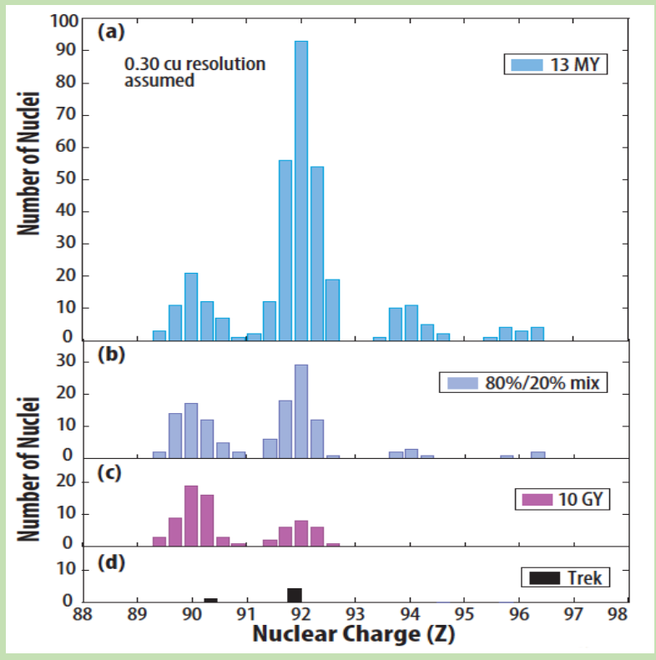
- **HNX explores to the end of the periodic table**
- Elements in the upper 2/3rds are extremely rare



Cosmic Ray Origins

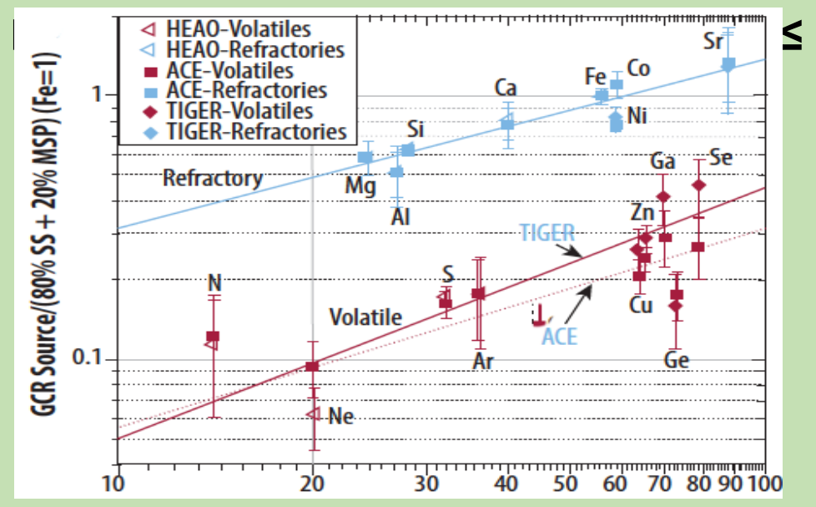


- Holy Grail" of nucleosynthesis research for over 40 years
- Half-lives span the timescales for galactic chemical evolution
- Relative abundances strongly depend on the age of the GCR source material
- Ratios of daughter/parent nuclei important: Th/U, (Th,U, Pu)/ Cm
- **HNX will measure ~50 actinides to probe the UHGCR age**

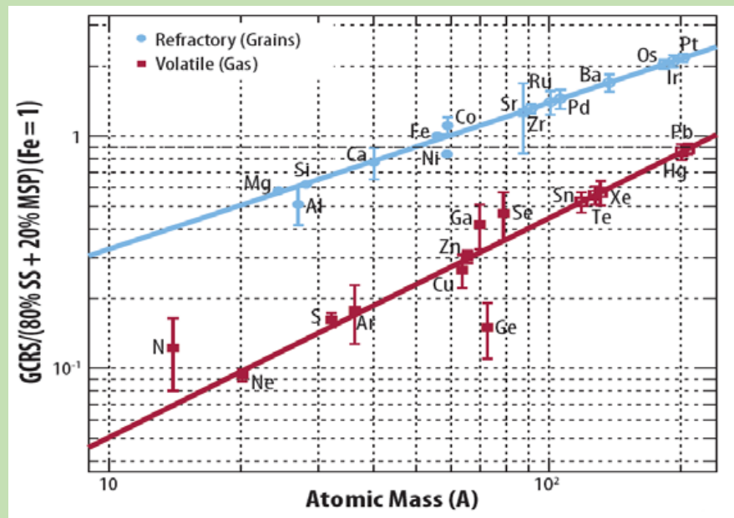


Possible actinide abundances from 2 years of HNX data compared to Trek (Mir) measurements. LDEF UHCR experiment has high statistics but limited resolution.

- ACE isotopes and TIGER, ACE, and HEAO element abundances 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 $A^{1.}$
- ≤ 83

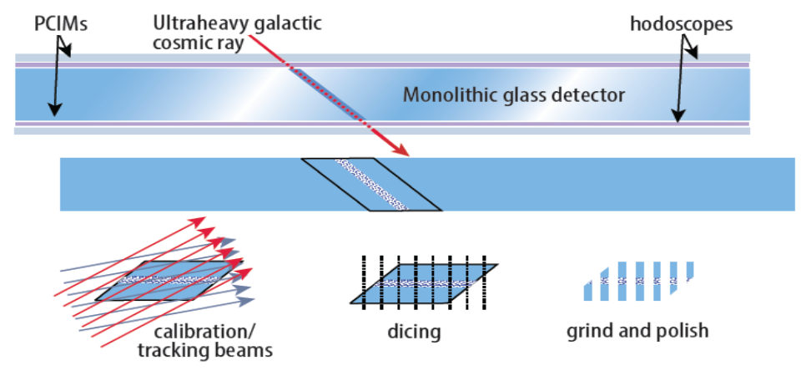


Combined TIGER, ACE, and HEAO element abundances Rauch et al., ApJ 697:2083 (2009).



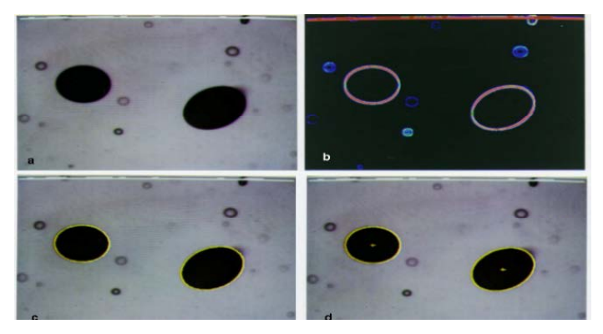
HNX will greatly improve old/new value and accurately determine mass dependence

ECCO Overview



- ECCO based on TREK experiment on MIR
- ECCO BP-1 detector modules cover capsule walls, part of top, and beneath CosmicTIGER
- Active area 21 m^2, AΩ = 48 m^{2}sr
- Five layer module made of barium-phosphate 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 slow nuclei to measure energy
- Glass is etched to "develop" nuclear tracks
- Tracks are measured using fully automated microscope system with resolution ≤ 50nm

ECCO is simple on orbit…



… all the sophistication is in the laboratory