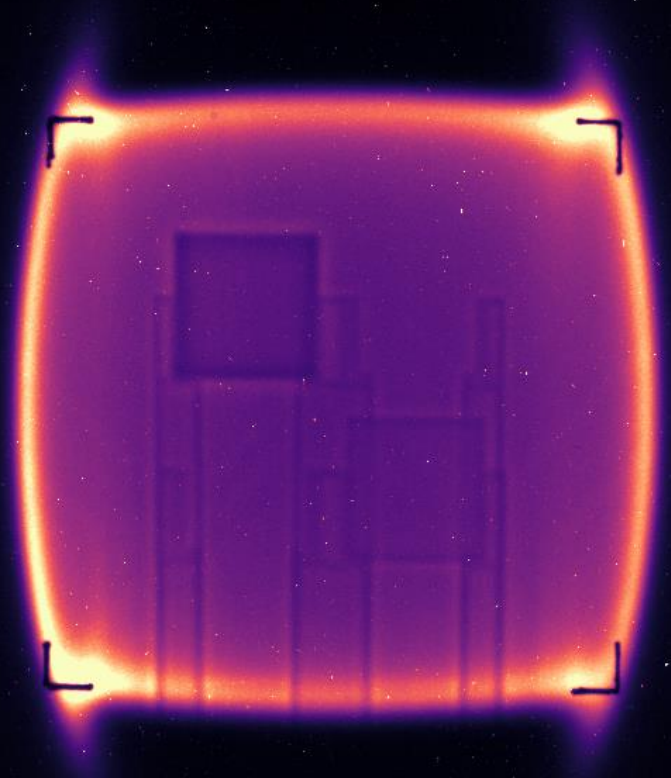
Galactic Isotopic Atlas: Trans-Iron to the Actinides



Priyarshini Ghosh, NASA GSFC

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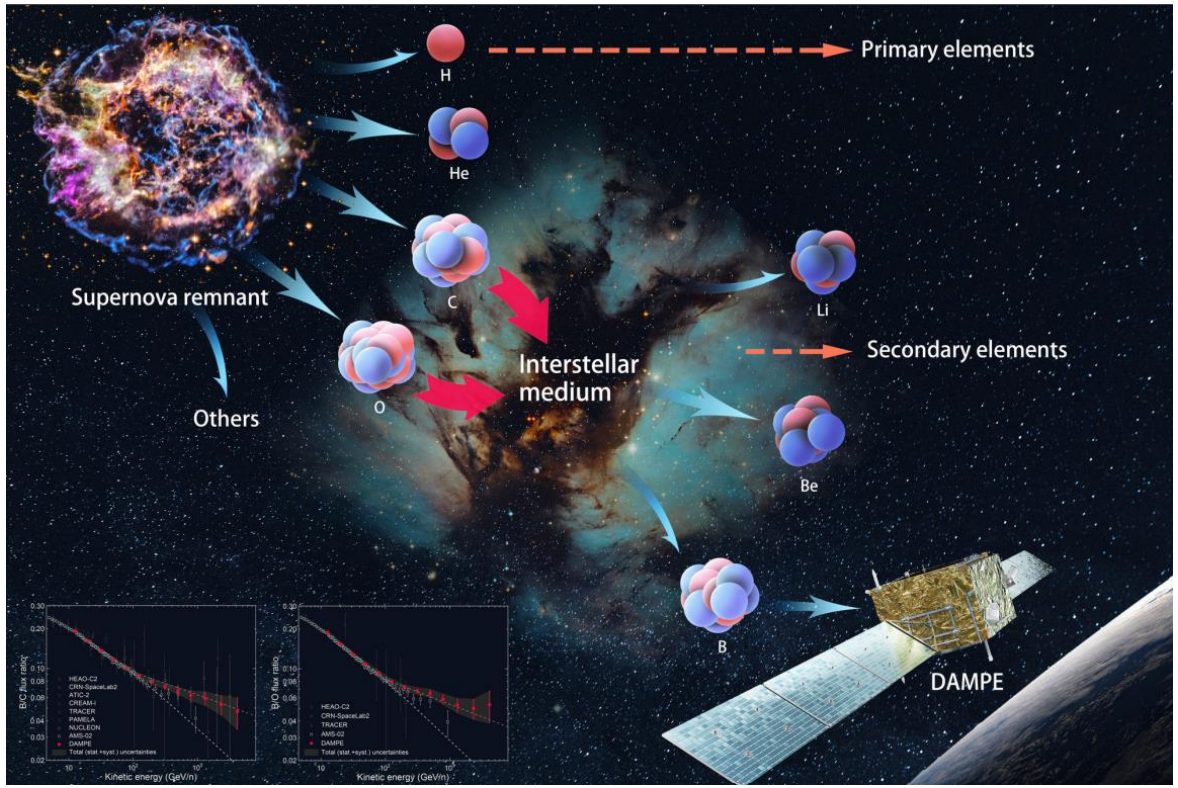
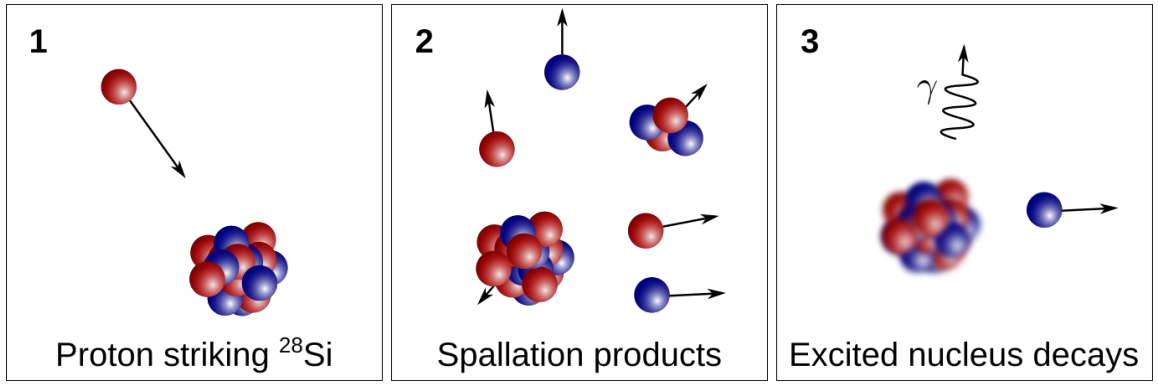
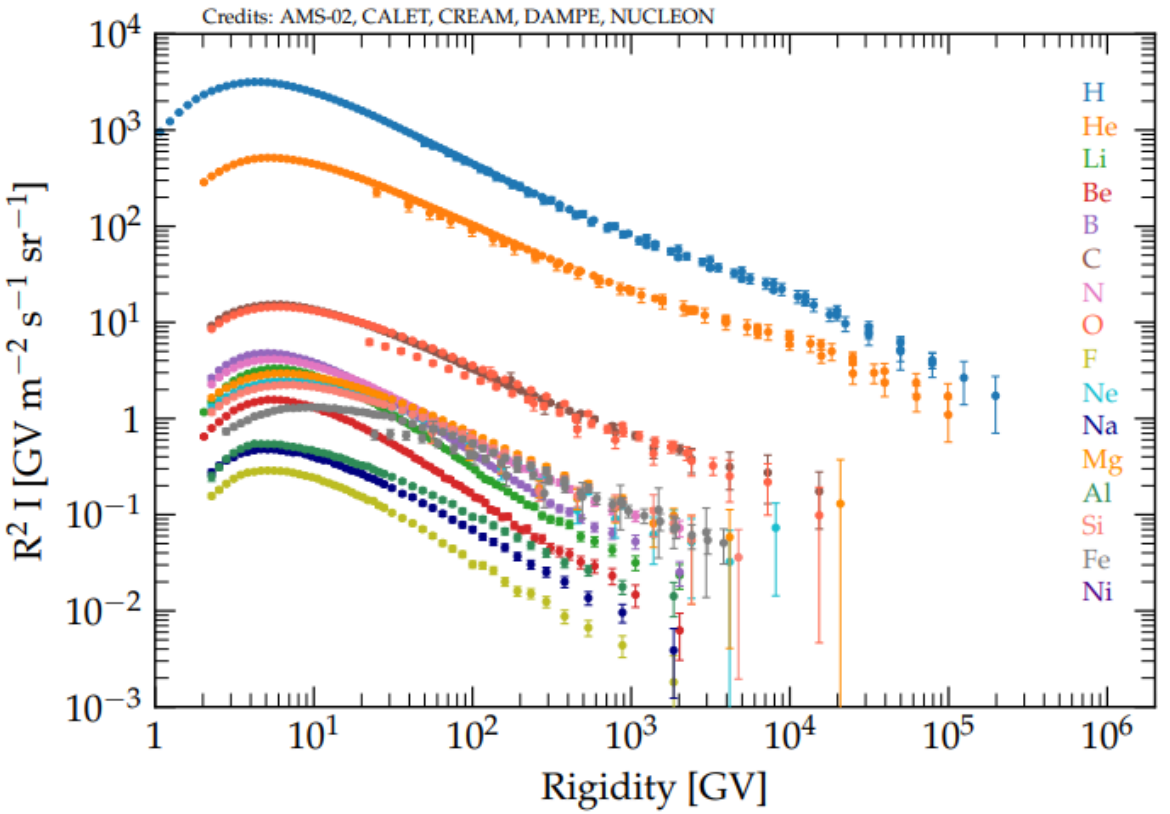
Galactic Cosmic Rays





Proton spallation of cosmic rays in the interstellar medium



The spectrum of each isotope includes contributions from various parents - both in terms of fragmentation and decays - resulting in a very complex history for each observed element

GCR component	What information it contains
Protons	Acceleration spectrum, spectral breaks, maximum energy, propagation, solar modulation
He	Tests charge/mass dependence of acceleration and propagation; comparison with protons
Electrons	Nearby/local accelerators because electrons rapidly lose energy
Positrons	Secondary production vs additional sources such as pulsars; possible exotic physics
Antiprotons	Hadronic interactions, propagation, secondary production; possible exotic contributions
Atmospheric muons	Indirectly infer primary energy/mass and test air-shower/hadronic models
Li-Be-B	Spallation and propagation; B/C gives traversed grammage/diffusion
Heavy nuclei, C–Fe	Source material, injection/acceleration chemistry, stellar-material contribution
Trans-iron nuclei	Neutron-capture nucleosynthesis, r/s-process source populations
Heavy isotopes	Nuclear fingerprints + clocks
Actinide isotopes	Recent r-process history, source chronology, possible nearby events

~99%

<1%, energy-dependent

<<1%

~1%

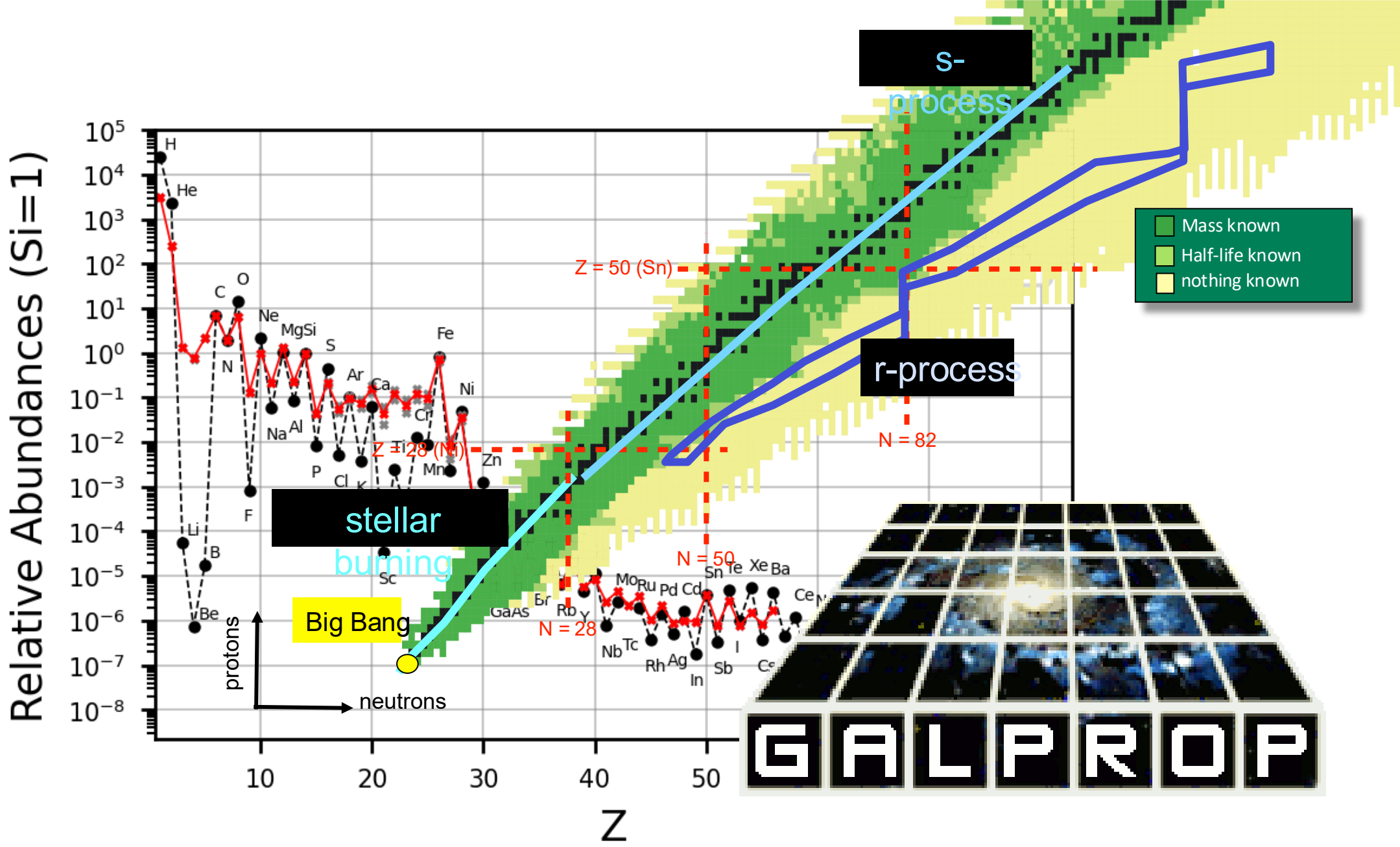
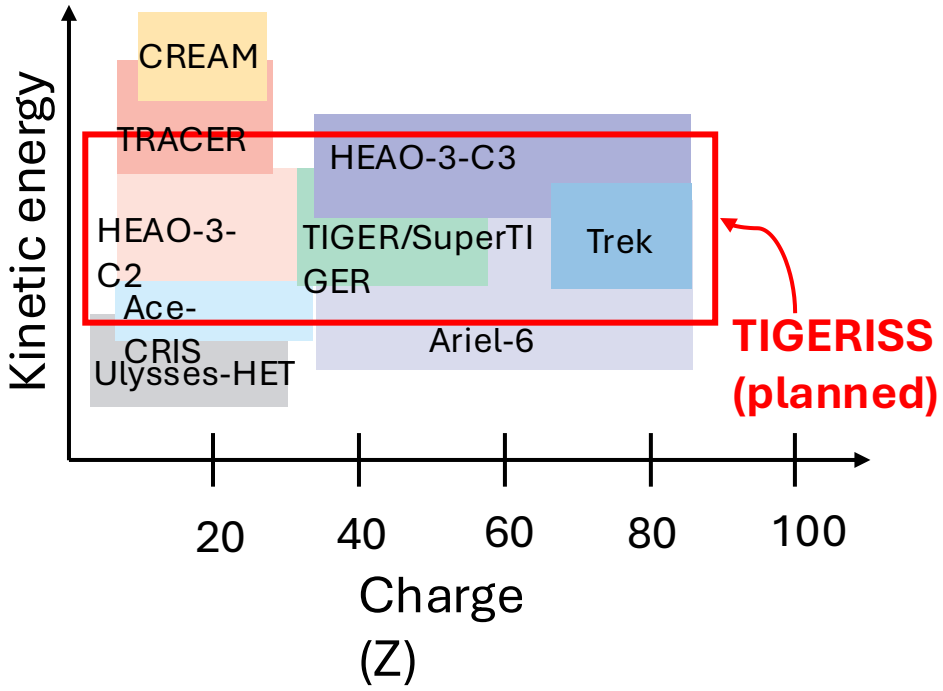


Chart of nuclides graphic credit: Fernando Montes, FRIB
Abundance graph adapted from Rauch et al., Instruments 8, 4 (2024), GCR data from BESS, AMS-01, HEAO-3-C2 and SuperTIGER; Solar-System abundances from Lodders

Ultra-Heavy GCRs: TIGERISS



How and where are the heaviest elements created?

•Absolute and relative abundances of r- & s-process elements probe NSM physics and contributions to GCRs –

•This mission 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 Question: "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?"

What science are we not extracting?

when?

How long between nucleosynthesis, acceleration, and detection?

r vs s?

What fraction came from r-process versus s-process sources?

where?

Which environments dominate: CCSNe, AGB stars, neutron-star mergers, magnetars?

recent?

Is there a cosmic-ray counterpart to recent local r-process material such as live Pu?

real?

Are abundance anomalies source physics or propagation/cross-section artifacts?

Isotopic measurements can unlock a host of new scientific discoveries

What remained hidden at Z-only — and ACE-CRIS proved recoverable

$$N(Z) = \Sigma N(Z,A)$$

Elemental abundance answers WHAT is present. Isotopic abundance preserves the nuclear fingerprint and clock.

LOST WITHOUT A:

- r-process vs s-process decomposition
- radioactive clocks and delay times
- recent local nucleosynthesis signatures
- isotope-level GCE model tests

ACE-CRIS SCIENCE DISCOVERIES:

$^{22}Ne/^{20}Ne$
≈5.3× solar-wind value → massive-star / Wolf–Rayet / superbubble fingerprint.

^{60}Fe
15 detected nuclei → recent nearby massive-star nucleosynthesis; element Fe alone would miss it.

^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn
radioactive/stable ratios → ≈15 Myr GCR confinement time in classic CRIS analyses.

EC isotopes: revealing shortcomings
^{49}V, ^{51}Cr etc. probes energy-changing processes: electron attachment, stripping, reacceleration---revealed lack of nuclear cross section data

Benchmark for isotopic measurements:
ACE-CRIS established isotope science below Fe; statistics and design limit rare ultra-heavy isotopes.

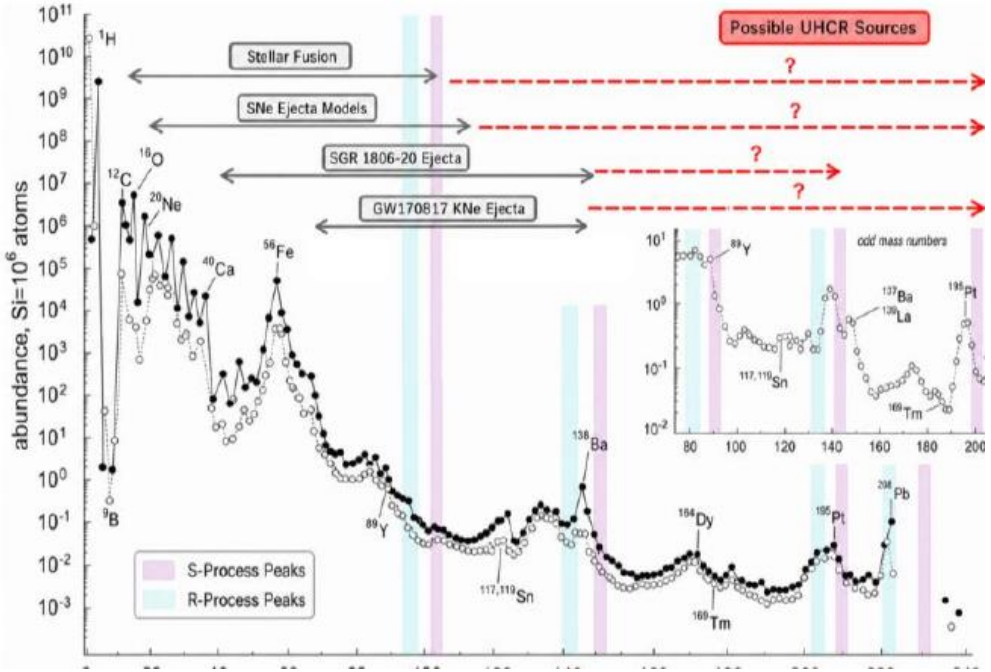
Sources: Binns et al. 2006; Binns et al. 2016 Science; Yanasak et al. 2001

A new frontier of GCR science: the “precision” era

Z = 38–50

Second r-process peak

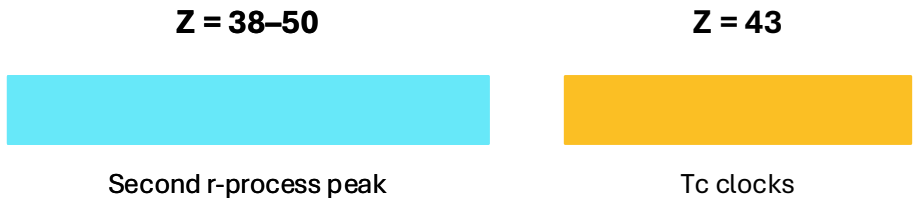
Nucleosynthetic fingerprint
Resolve r-process, main-s, and weak-s contributions isotope-by-isotope across Sr–Sn and beyond.



Which stellar factories made the trans-iron nuclei?

What causes the second-peak enhancement?

A new frontier of GCR science: the “precision” era



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Resolve r-process, main-s, and weak-s contributions isotope-by-isotope across Sr–Sn and beyond.

New radioactive clocks
Tc, I, Pd, Pu, Cm ratios constrain confinement, halo geometry, injection delay, and recent source history.

How long did these nuclei spend traveling through the Galaxy?

Observable

Radioactive-to-stable isotope ratios as a function of energy/rigidity.

Science extracted

Confinement time, diffusion/halo geometry, and delay between nucleosynthesis and acceleration.

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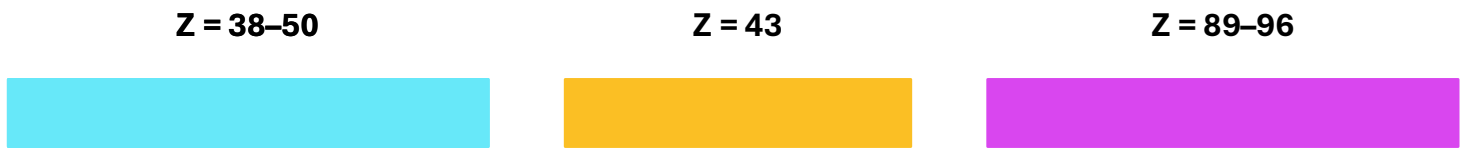

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Actinide chronology
^{232}Th/^{238}U trace long-term enrichment; live ^{244}Pu and ^{247}Cm test recent r-process events.

Was there a recent nearby r-process event?

A new frontier of GCR science: the “precision” era

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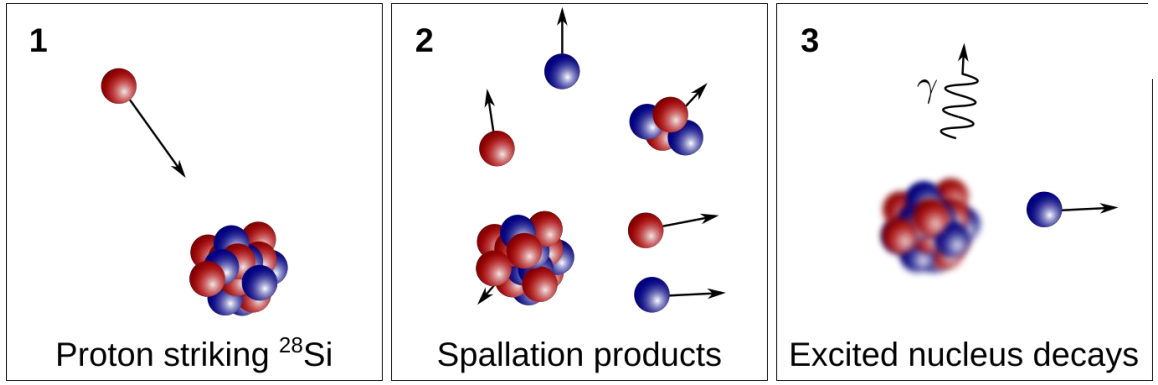
What about cross sections?

UHGCR isotope ratios are modified by spallation in interstellar H and He.
Above Z>30, cross-section data are sparse and model uncertainties can be large.



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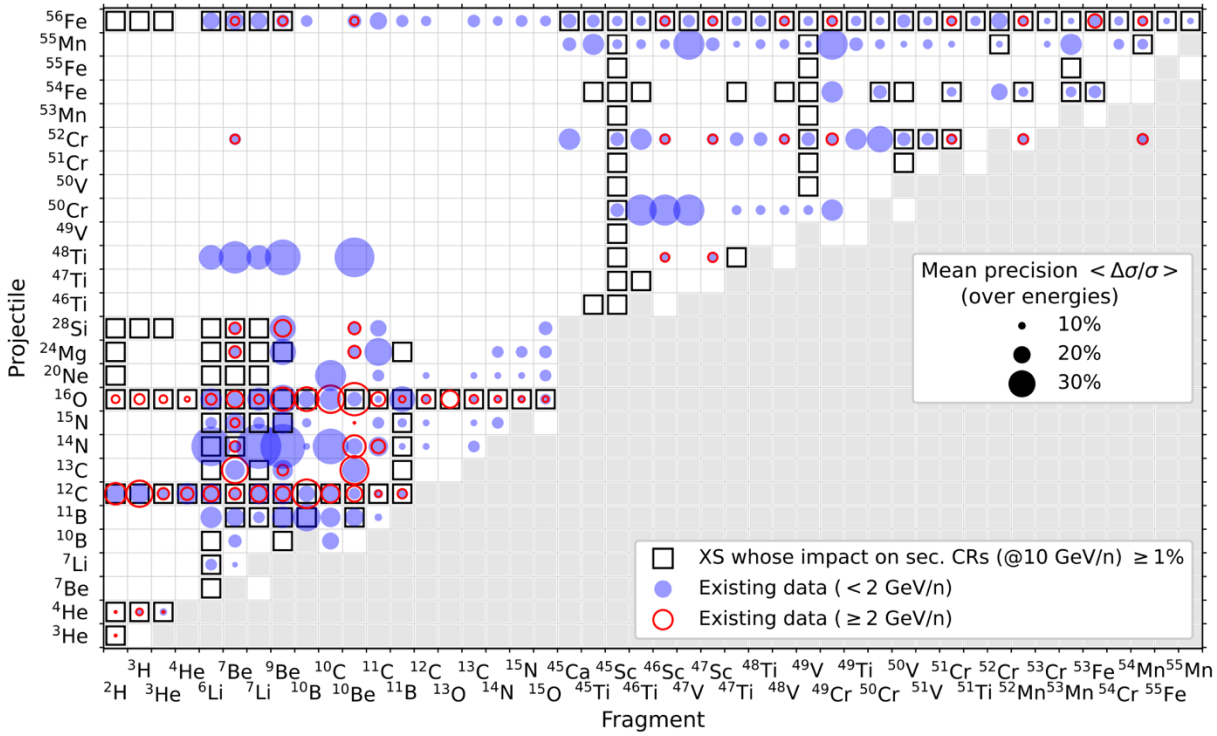

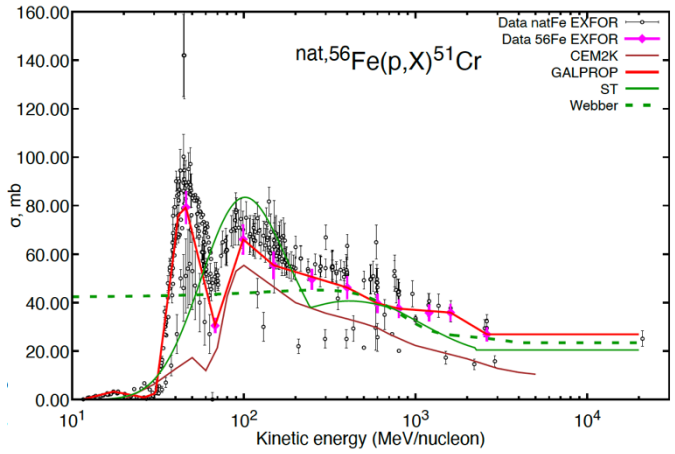

CARTIER: Cosmic-ray Actinide, R-process, and Trace Isotopic Element Recorder

See Wolfgang Zober’s poster presented by Nick Cannady!