FRIB

The Quest for the Drip Lines

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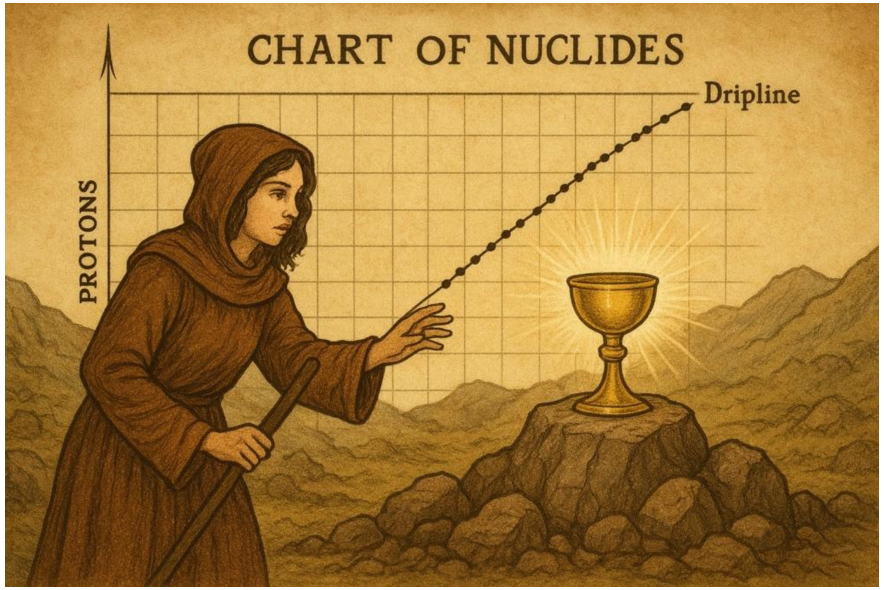
The Quest for the Drip Lines

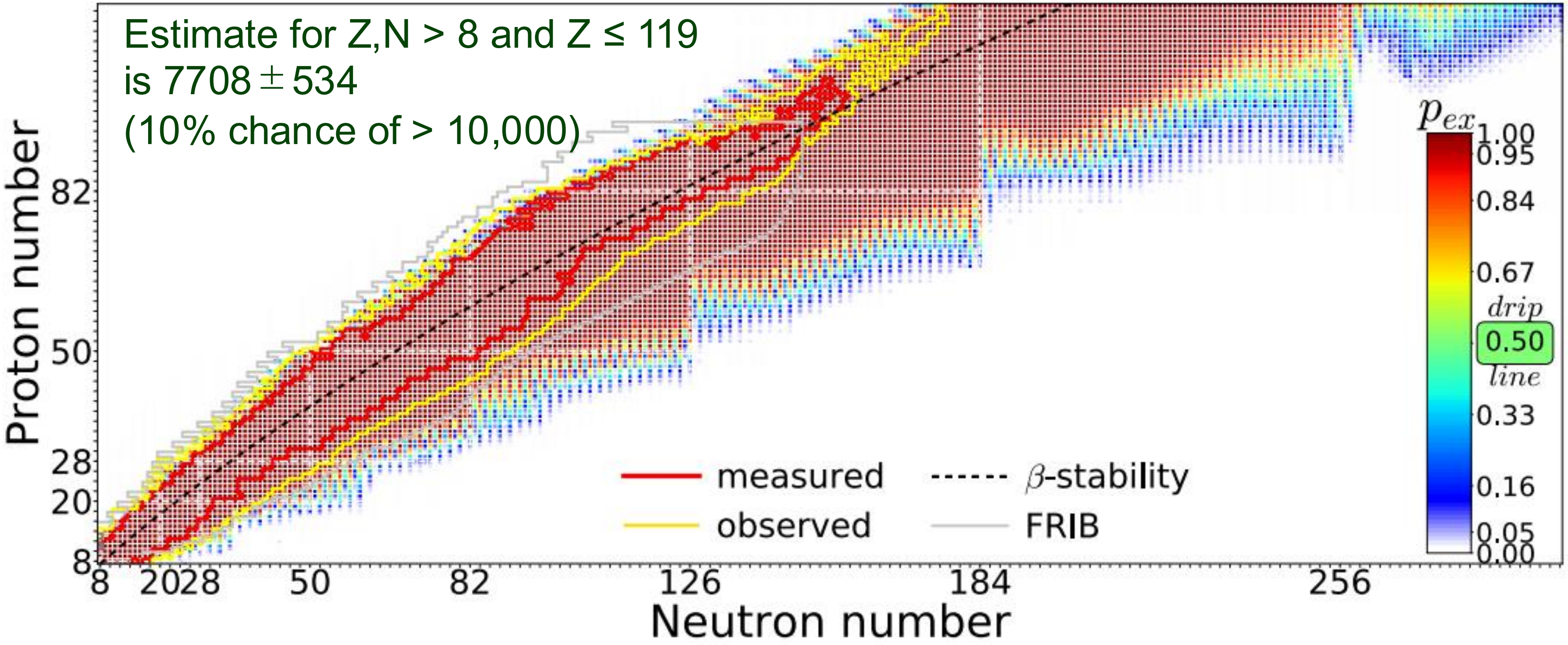
- To have an atom ("bound"), a nucleus with a lifetime greater than $1x10^{-14}$ s is necessary (IUPAC definition)
- The neutron and proton drip lines are delineated by the limits of binding for each element
- A related question
  - How many elements are possible?
- The drip lines are a benchmark for nuclear models and have consequences for astrophysics
- How do we undertake the quest explore and determine the limits in the laboratory?
  → Ultimately nuclear theory will tell us, but experimental guidance is prudent
  → Experimentally we need high-power accelerator facilities, and a good understanding of the **nuclear reactions** employed



ChatGPT Image

Estimated Extent of the Nuclear Landscape

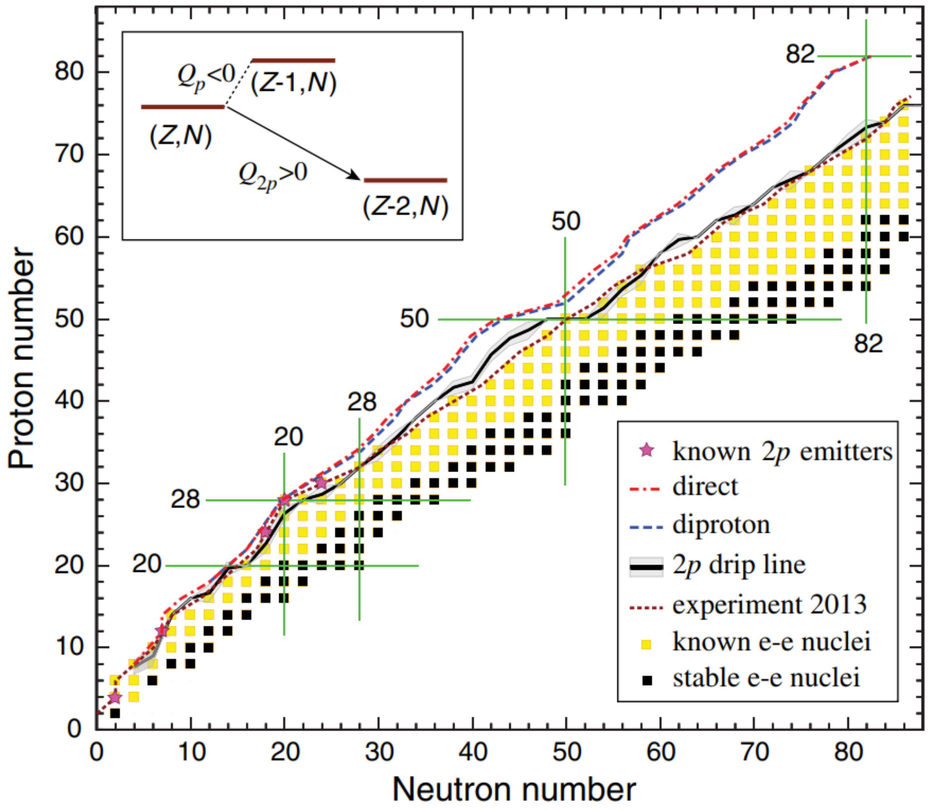
- Approximately 258 “stable” isotopes are found on Earth
- The full nuclear landscape can be estimated using existing nuclear models
- Example: Bayesian Analysis of Nuclear Models - Neufcourt et al. Phys. Rev. C101 (2020) 044307
- So far, we have observed 118 elements and about 3,300 isotopes of these elements

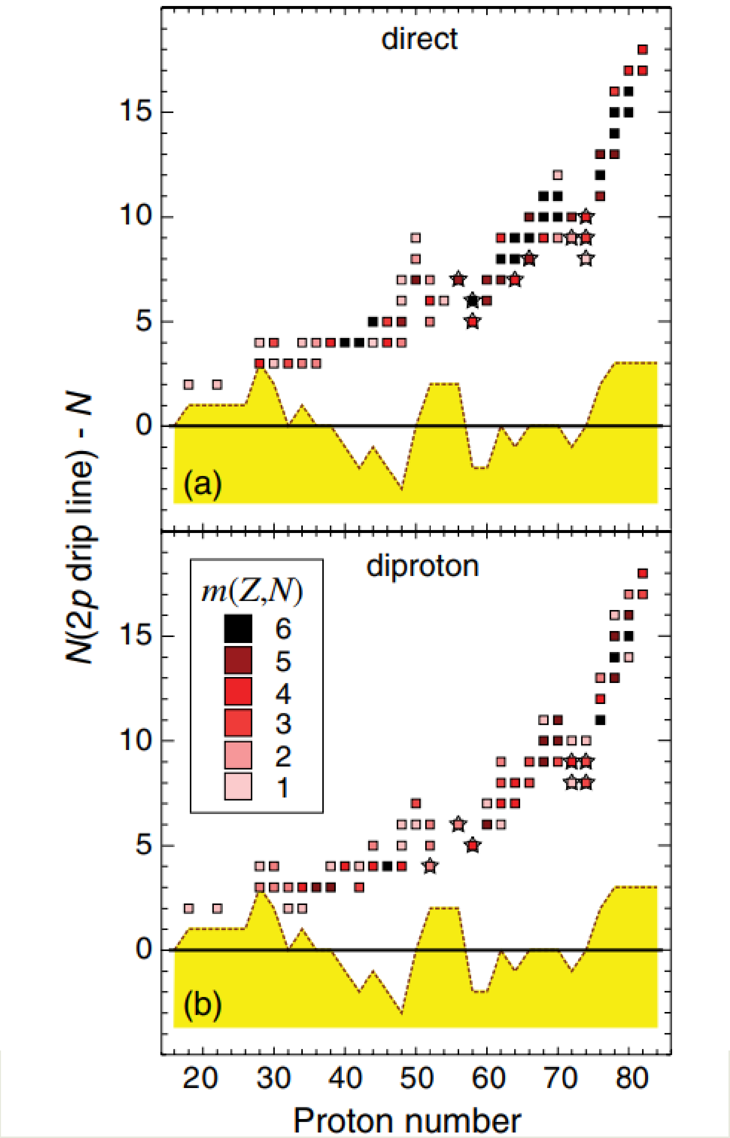


M. Thoennessen, *Discovery of Nuclides Project*, see FRIB website https://frib.msu.edu/public-engagement/learning-resources-and-programs/brief-history-of-rare-isotopes (Robert is credited with 10 isotopes discovered)

The Proton Drip Line

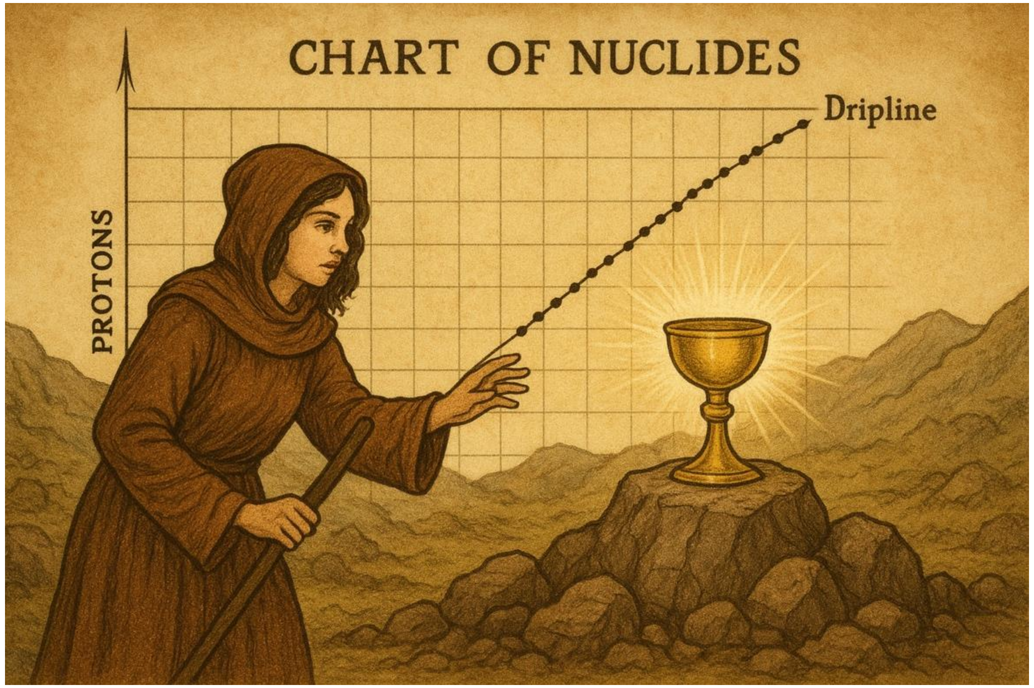
- With the definition that "bound" has a half life long enough to form an atom, the proton drip line extends well past $S_p < 0$ keV.
- See Olsen et al., PRL 110 222501 (2013)
  See also Neufcourt et al., PRC 101 014319 (2020)





The Quest For the Tools to Reach the Drip Lines

- Exploring and ultimately determining the limits depends on having the tools
- Robert could have been content with any of his quests, e.g., the quest for high spin or the quest for 4π germanium detectors
- He had the vision to embark on the quest for a next-generation rare isotope facility
- Robert's quest for FRIB will be discussed more by Thomas in the next talk



ChatGPT Image

Gang of Four – Promoting RIA/FRIB

- Rick Casten
- **Robert Janssens**
- Witek Nazarewicz
- Brad Sherrill
- Credit to the various authors

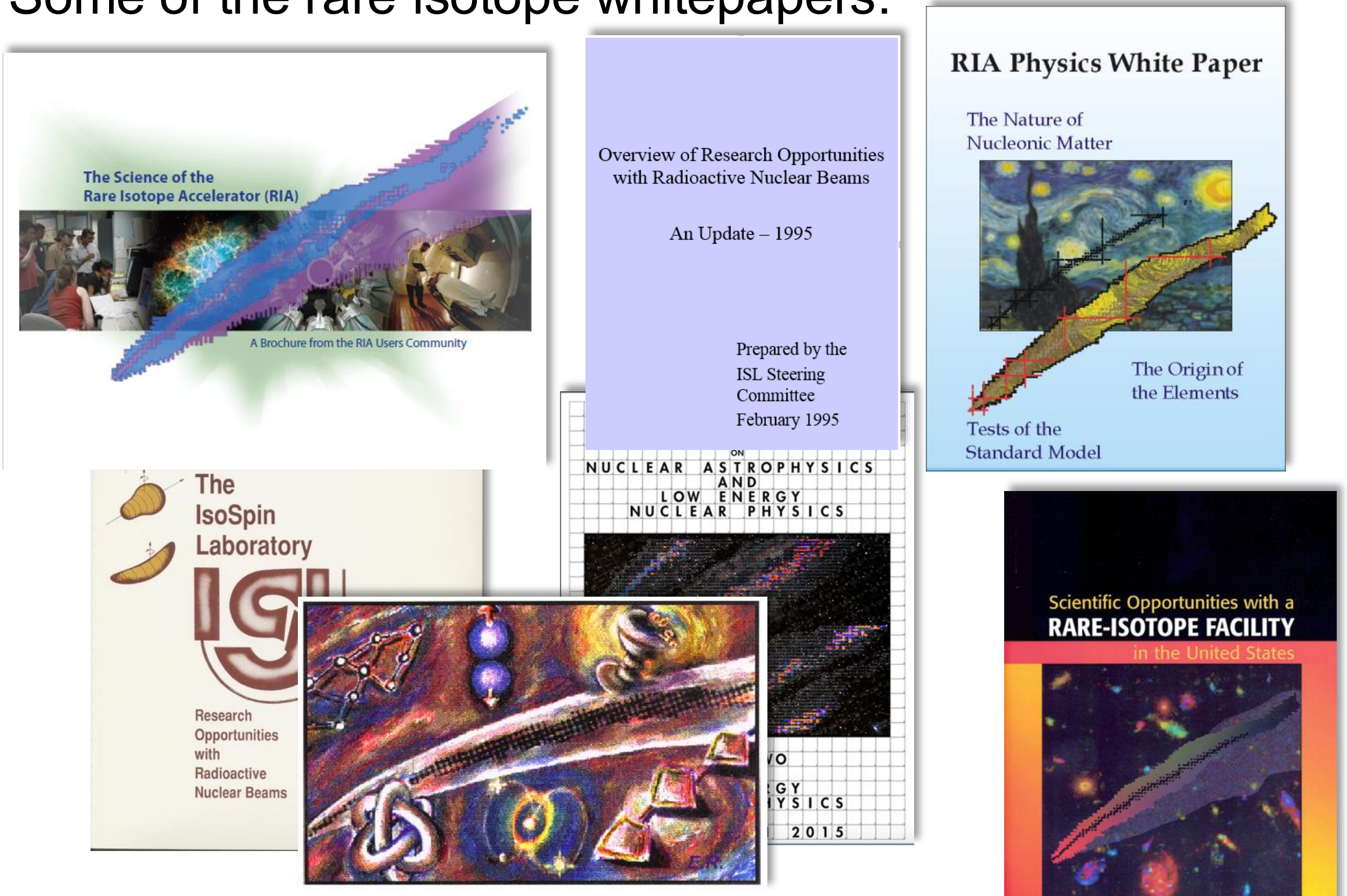
Some NSAC Subcommittee Reports:

Tribble Committee (2 – 2005,2012), Report on Scientific Facilities, Bond committee (FAIR/RIA), Symon's committee (FRIB), …

National Achadamies Reports:

Core of Matter Fule of Stars, Exploring the Heart of Matter, RISAC Report, …

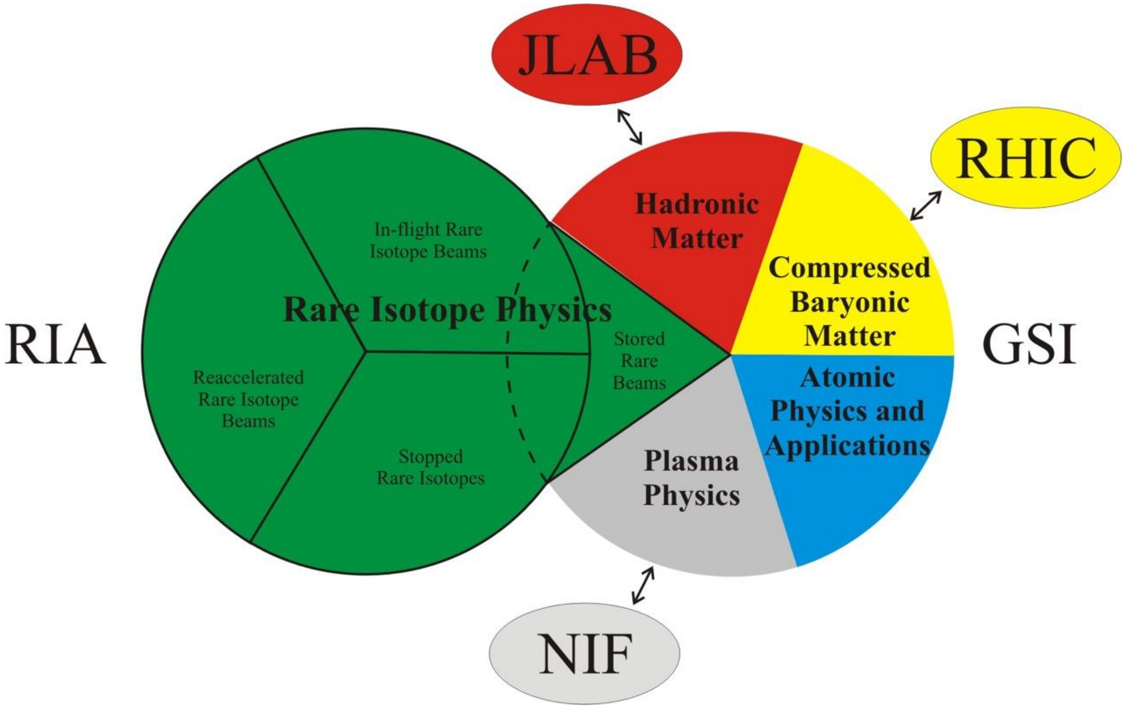
Some of the rare isotope whitepapers:

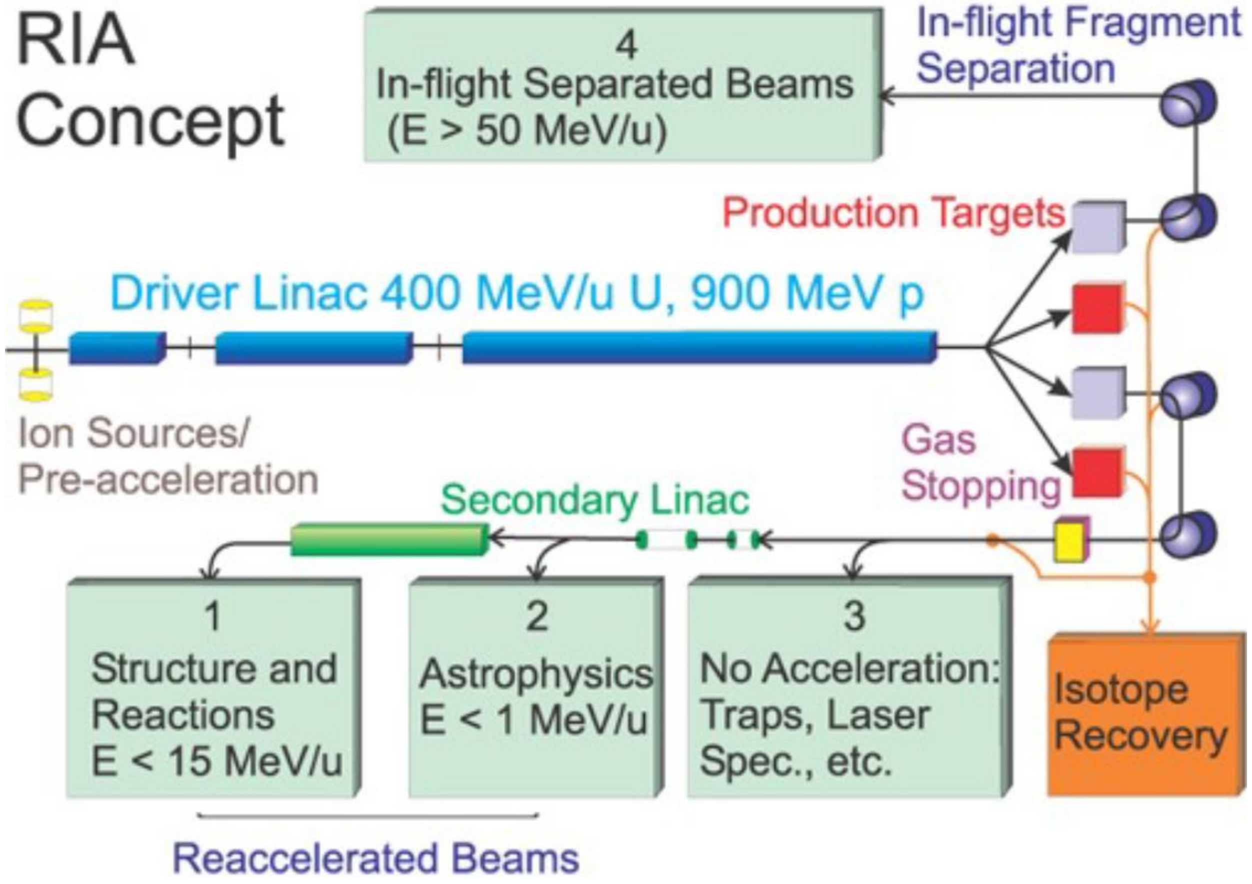


Colored Books: White, Yellow, Green, …

Robert's Quest Extended over 25+ Years

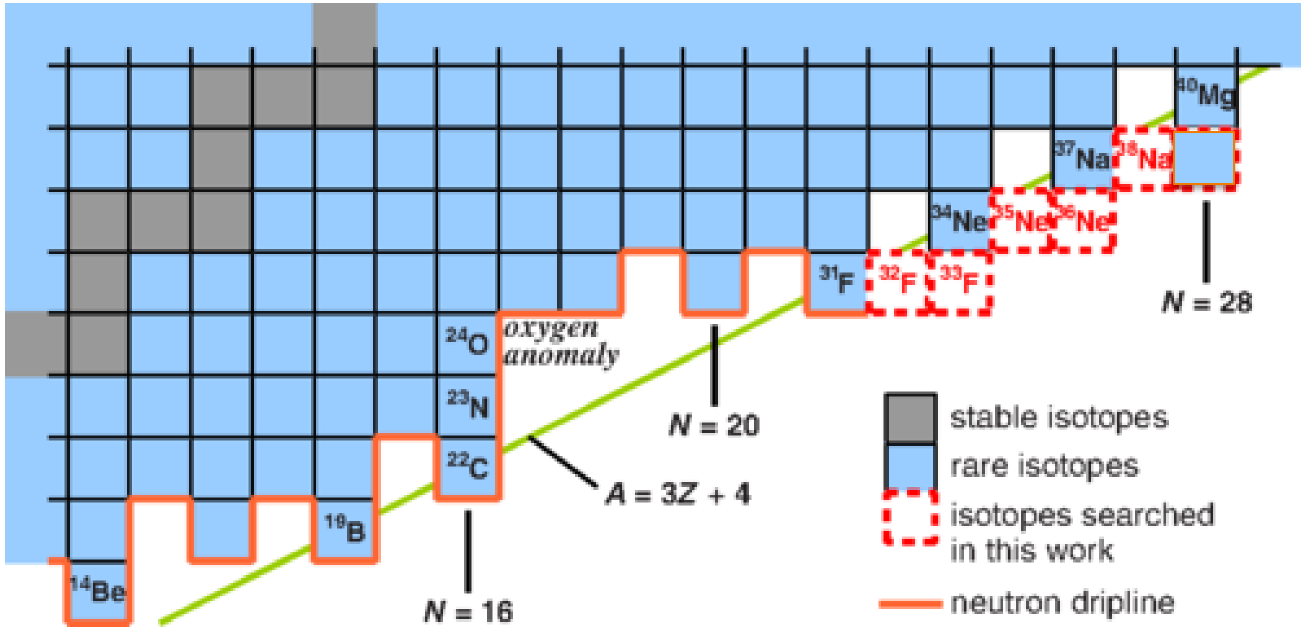
- A figure from the 2004 Bond NSAC subcommittee report on RIA vs FAIR





The Quest for the Drip Lines

- The proton drip line is known up to Kr (^{67}Kr 2p radioactivity T. Goigoux et al., PRL 117, 162501 (2016)) and touched up to ^{185}Bi (Davids et al., PRL 76 (1996) 592)
- The neutron drip line is known up to neon; ^{34}Ne, D.S. Ahn et al., PRL123, 212501 (2019)
- Sodium drip line extends farther with the observation of ^{39}Na, D.S. Ahn et al., PRL 129 212502 (2022)

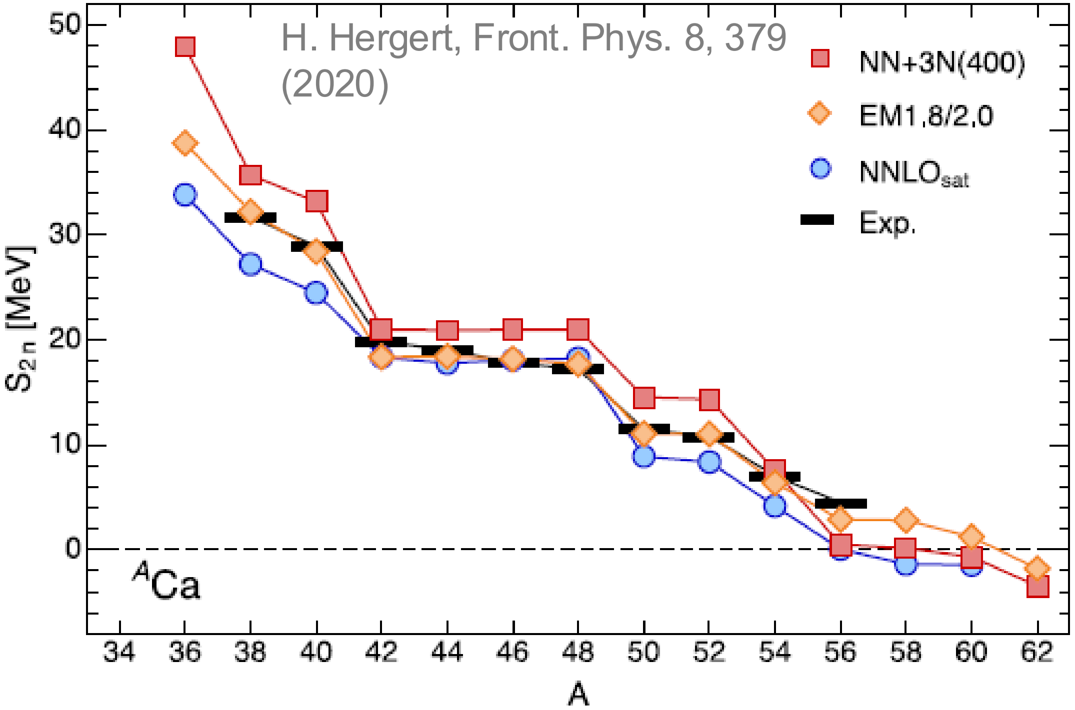


Ahn et al., Phys. Rev. Lett. 123, 212501

The Limits of Atoms Guide Our Understanding of the Validity of Models

- How many Ca isotopes exist? ^{60}Ca is the known limit (RIKEN), but are there more? Theories disagree:

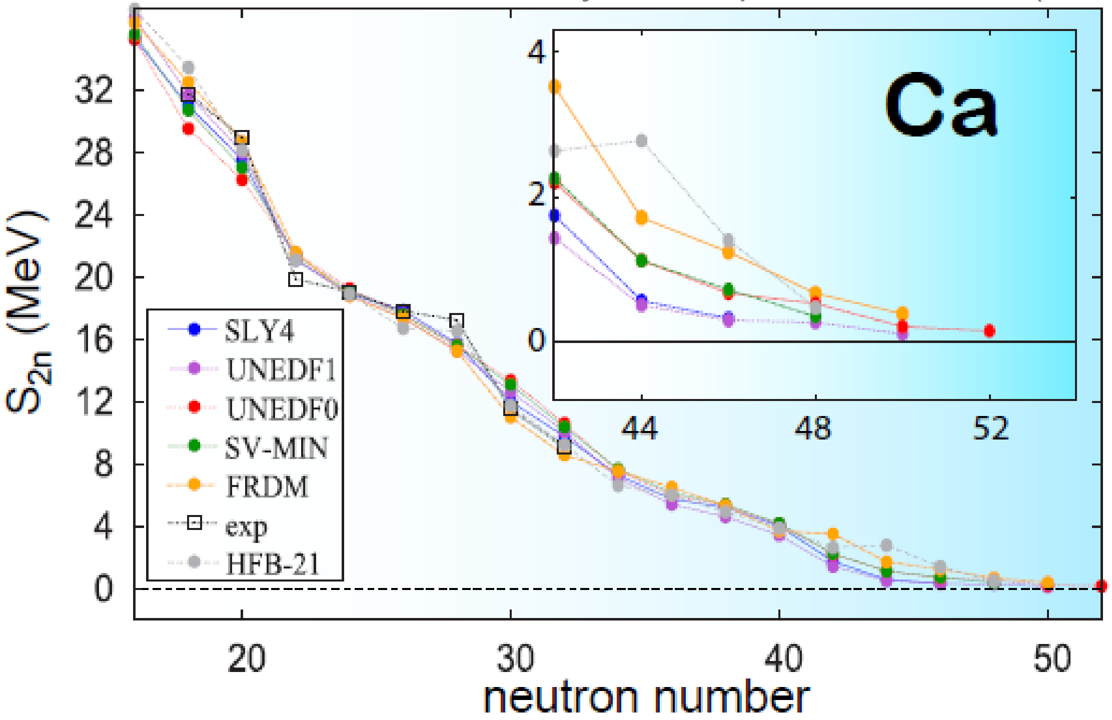
Multi-reference in-medium similarity renormalization theory



$^{56-60}$Ca are weakly bound/unbound or right at the threshold, ^{62}Ca is unbound

State-of-the-art energy density functional theory

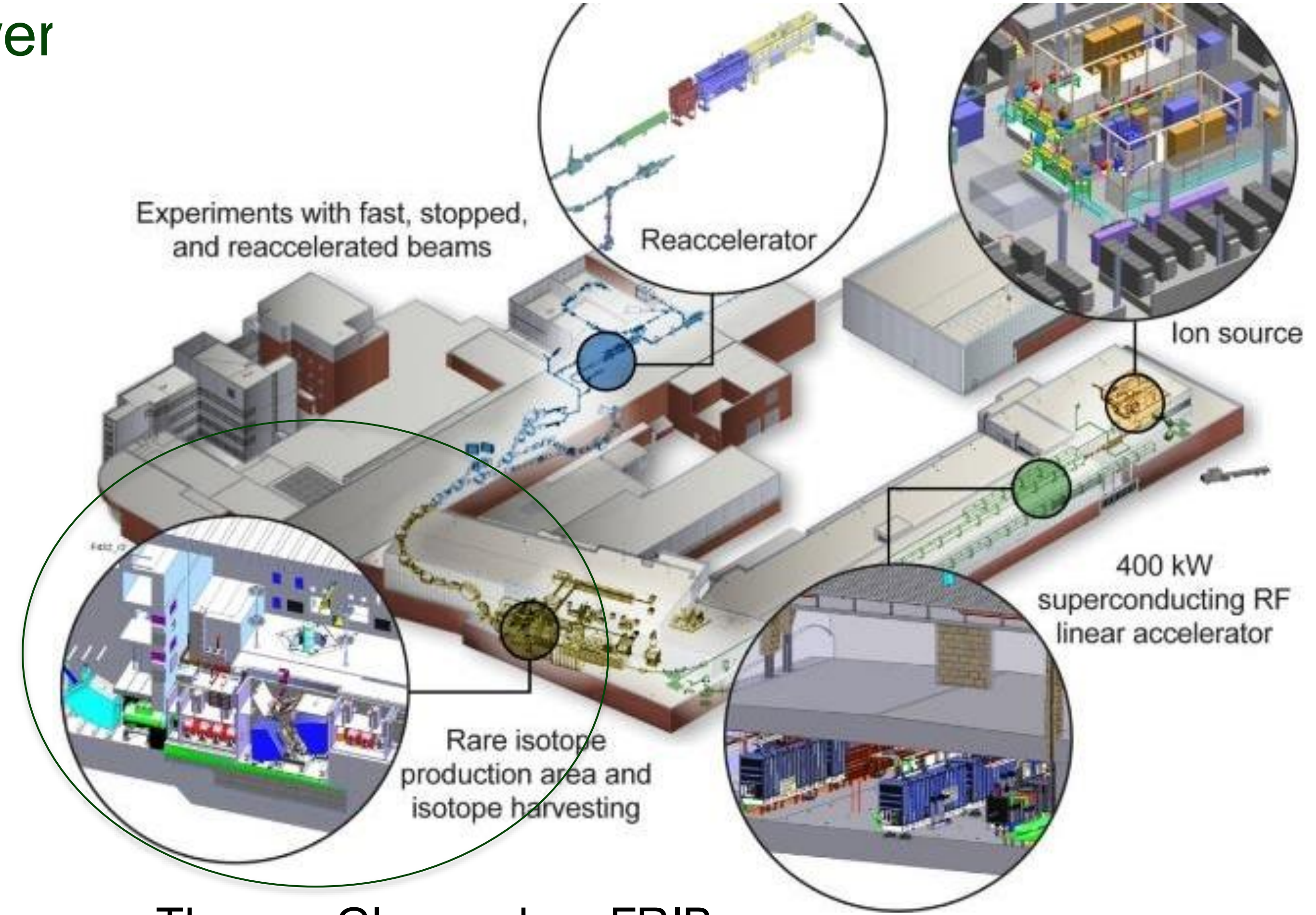
C. Forssen et al., Physica Scripta T152 014022 (2013)



Calcium isotopes are bound out to ^{70}Ca

The Facility For Rare Isotope Beams – Glasmacher Next Talk

- FRIB's key feature is 400 kW beam power
  - 8 pμA or 5 x 10^{13} ^{238}U /s
  - 42 pμA or 2.6 x 10^{14} ^{48}Ca /s
- Range of beam energies
  - Fast – 20 to 200 MeV/u
  - Stopped – 10 kV
  - Reaccelerated – 3-10 MeV/u
- Started operation in May 2022 (talk of T Glasmacher)
  - 61 experiments completed
- Isotope harvesting capability (e.g., from beam dump water)
  - 3 experiments completed

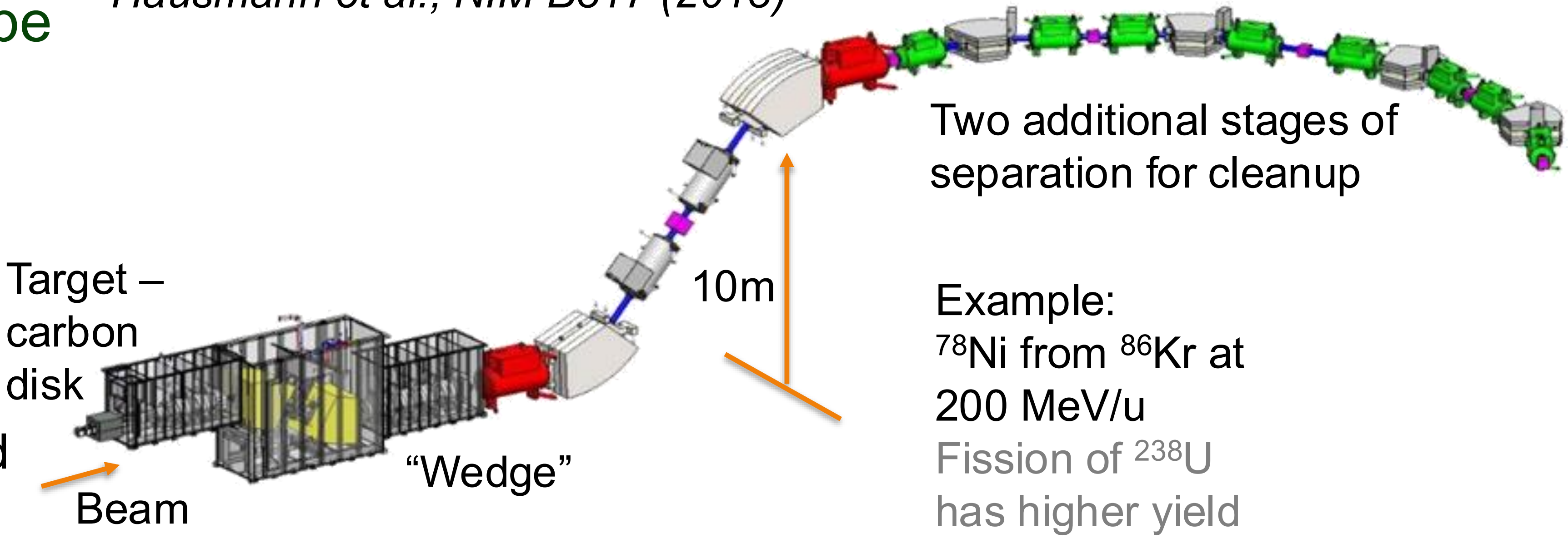


Thomas Glasmacher, FRIB Laboratory Director

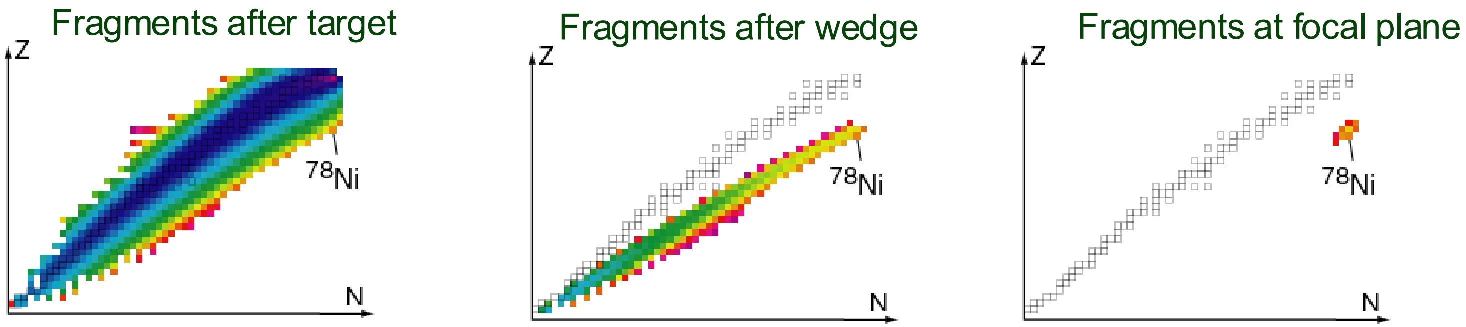
The Advance Rare Isotope Separator, ARIS

- FRIB Advanced Rare Isotope Separator, ARIS
- Three-stage separation by the use of “wedges”
- Special features
  - Momentum compression
  - A vertical preseparator followed by horizontal 2-stage separator
  - Designed for operation with 400 kW of primary beam
- Detector suite allows isotope identification and measurement of production cross sections

Hausmann et al., NIM B317 (2013)



Example:
^{78}Ni from ^{86}Kr at 200 MeV/u
Fission of ^{238}U has higher yield



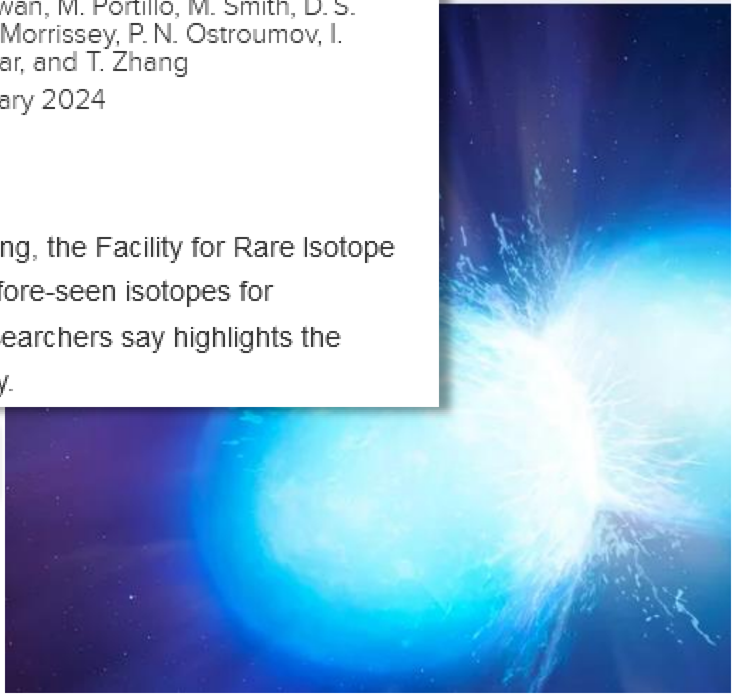
New isotopes discovered at FRIB

[Phys. Rev. Lett. 132, 072501 (2024)]

FEBRUARY 27, 2024 | 5 MIN READ

Weird Lab-Made Atoms Hint at Heavy Cosmic Origins

...avy versions of element



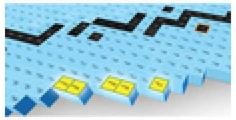
Featured in Physics | Editors' Suggestion

Observation of New Isotopes in the Fragmentation of ^{198}Pt at FRIB

O. B. Tarasov, A. Gade, K. Fukushima, M. Hausmann, E. Kwan, M. Portillo, M. Smith, D. S. Ahn, D. Bazin, R. Chyzh, S. Giraud, K. Haak, T. Kubo, D. J. Morrissey, P. N. Ostroumov, I. Richardson, B. M. Sherrill, A. Stolz, S. Watters, D. Weisshaar, and T. Zhang

Phys. Rev. Lett. **132**, 072501 (2024) – Published 15 February 2024

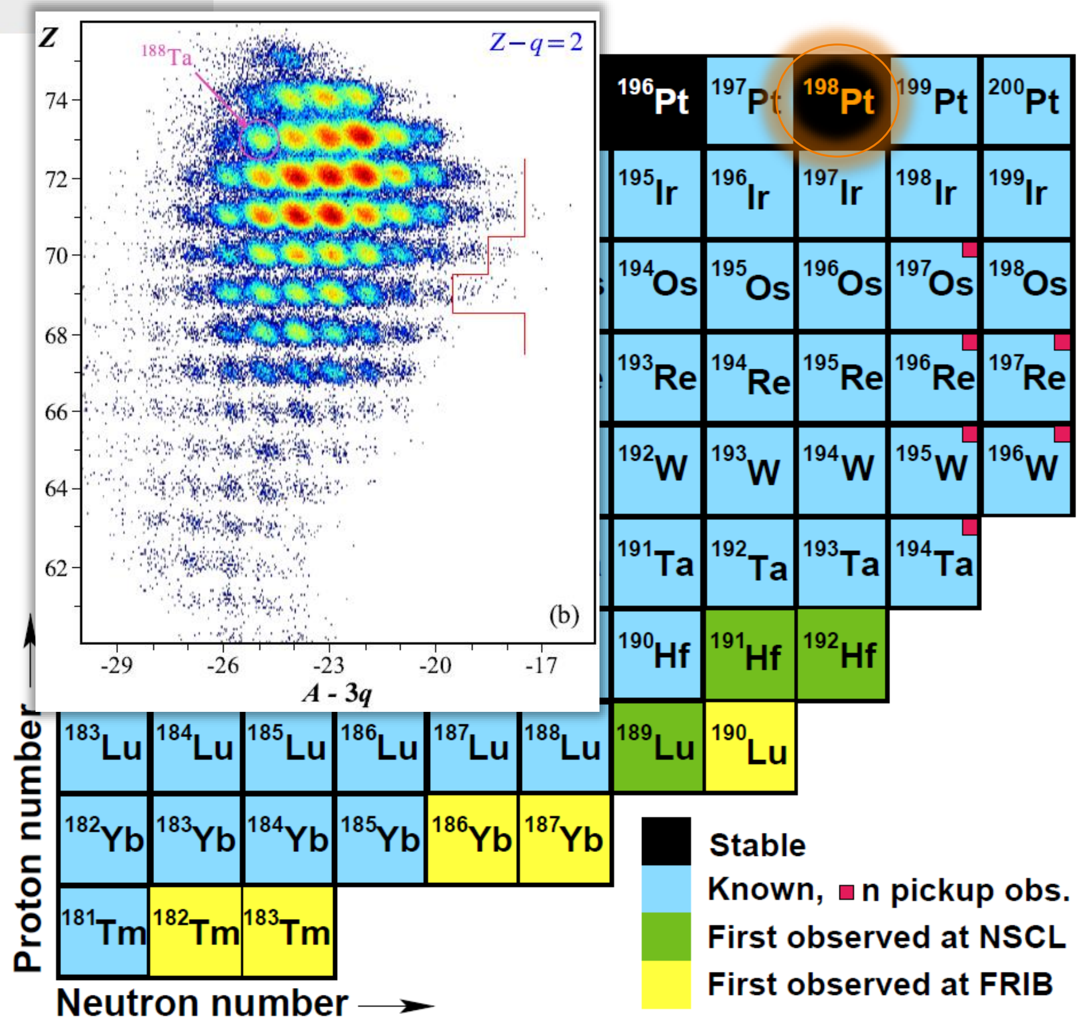
Physics: Five New Isotopes Is Just the Beginning



Less than a year after its opening, the Facility for Rare Isotope Beams produced five never-before-seen isotopes for observation, a success that researchers say highlights the discovery potential of the facility.

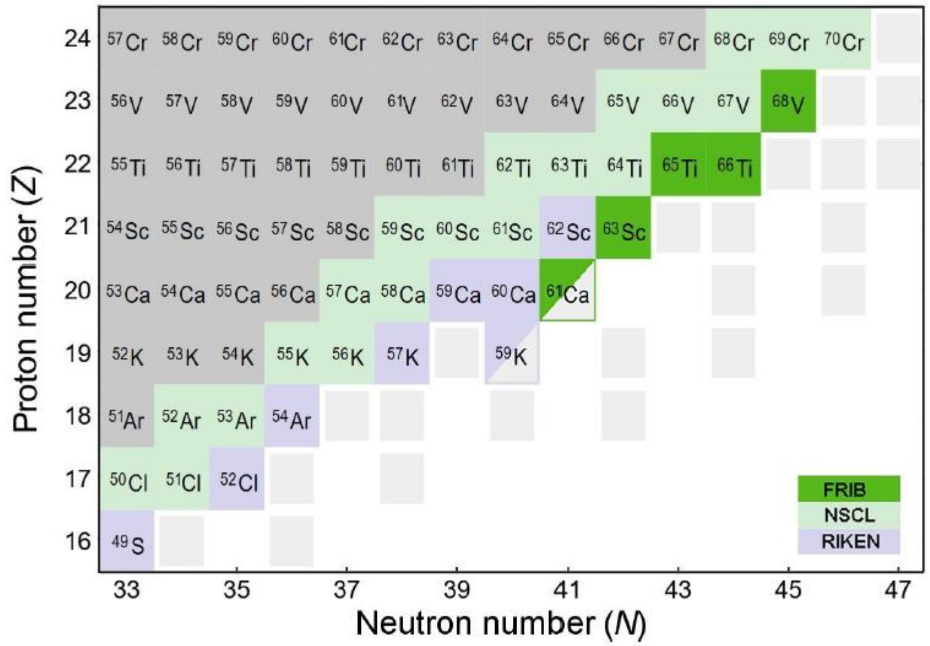
SCIENTIFIC AMERICAN

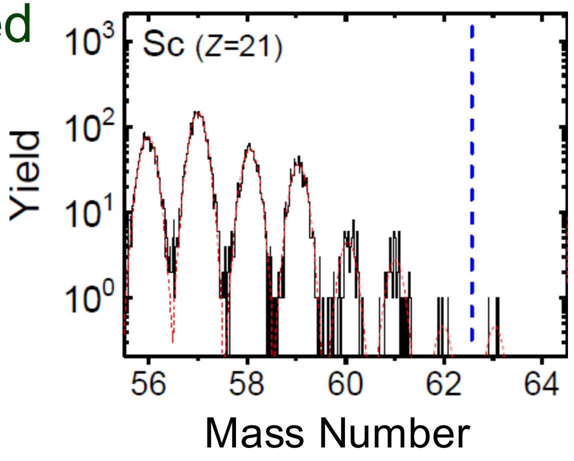
FRIB made 5 never-before-seen isotopes of the elements thulium, ytterbium, lutetium



Study of Neutron-Rich Calcium Isotopes

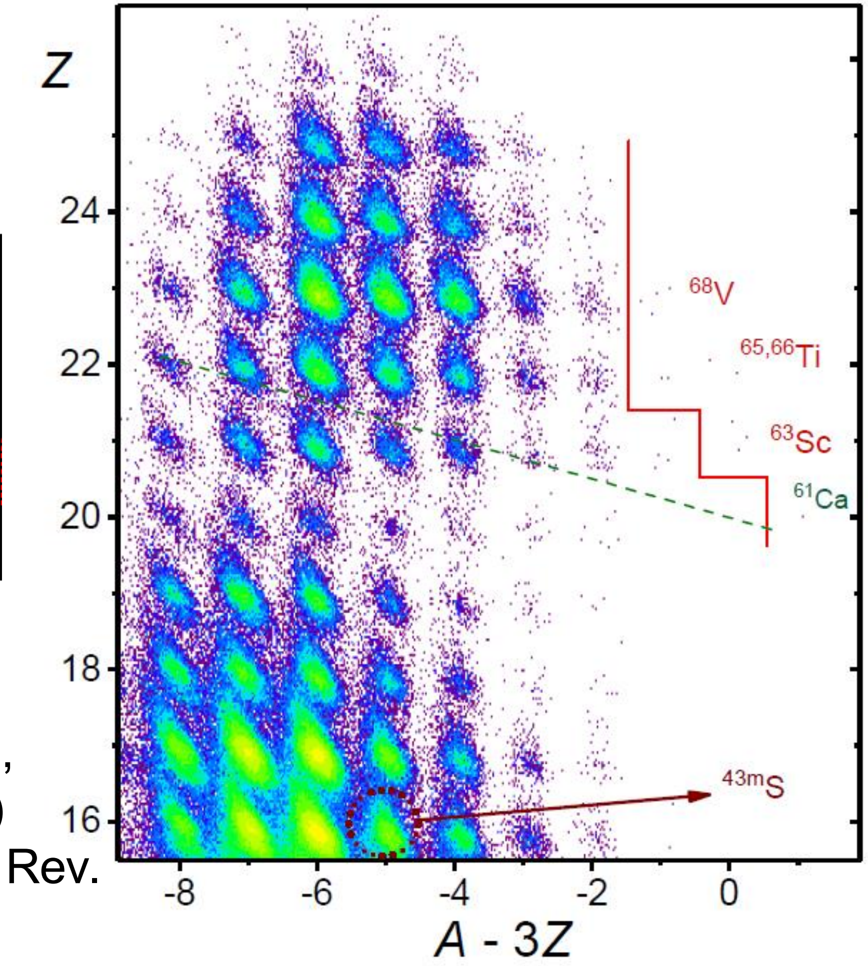
- Recently 4 (+1) new isotopes have been observed at FRIB using 225 MeV/u ^{82}Se at 20 kW (1 pμA)
- ^{63}Sc, ^{65,66}Ti, ^{68}V, ^{71}Cr (next slide)
- A candidate for ^{61}Ca was observed (needs confirmation)
- Production cross sections were measured





RIKEN: Tarasov, Ahn, et al., Phys. Rev. Lett. 121 (2018)
FRIB: Tarasov et al., Phys. Rev. C112 (2025) 034604

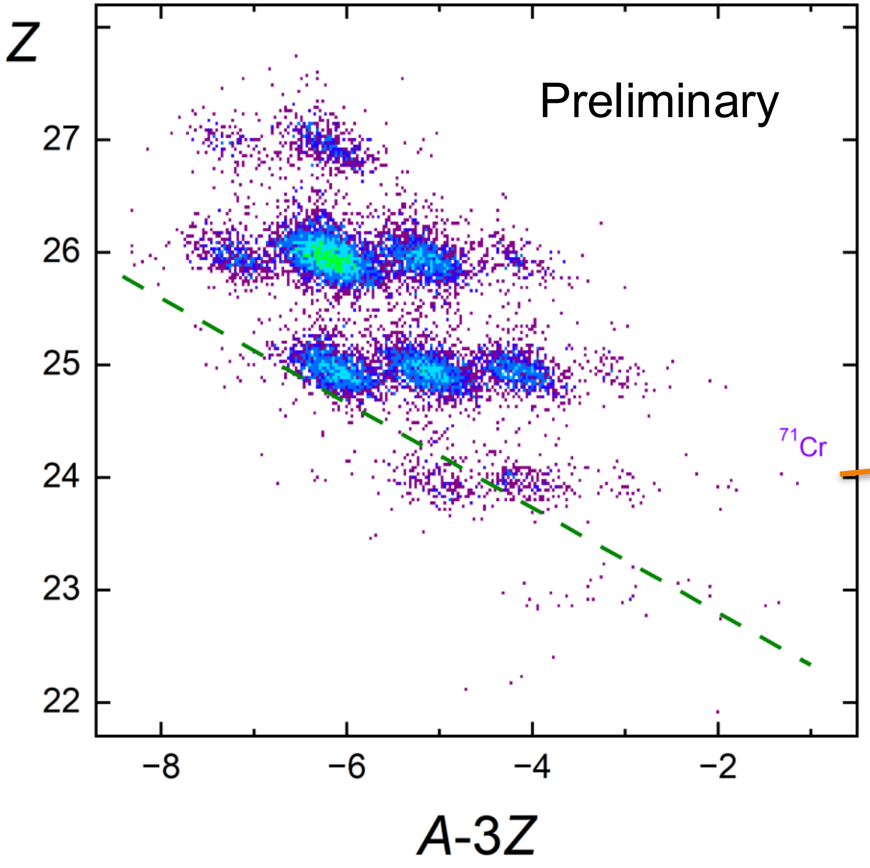
Tarasov et al., PRC 112 (2025)

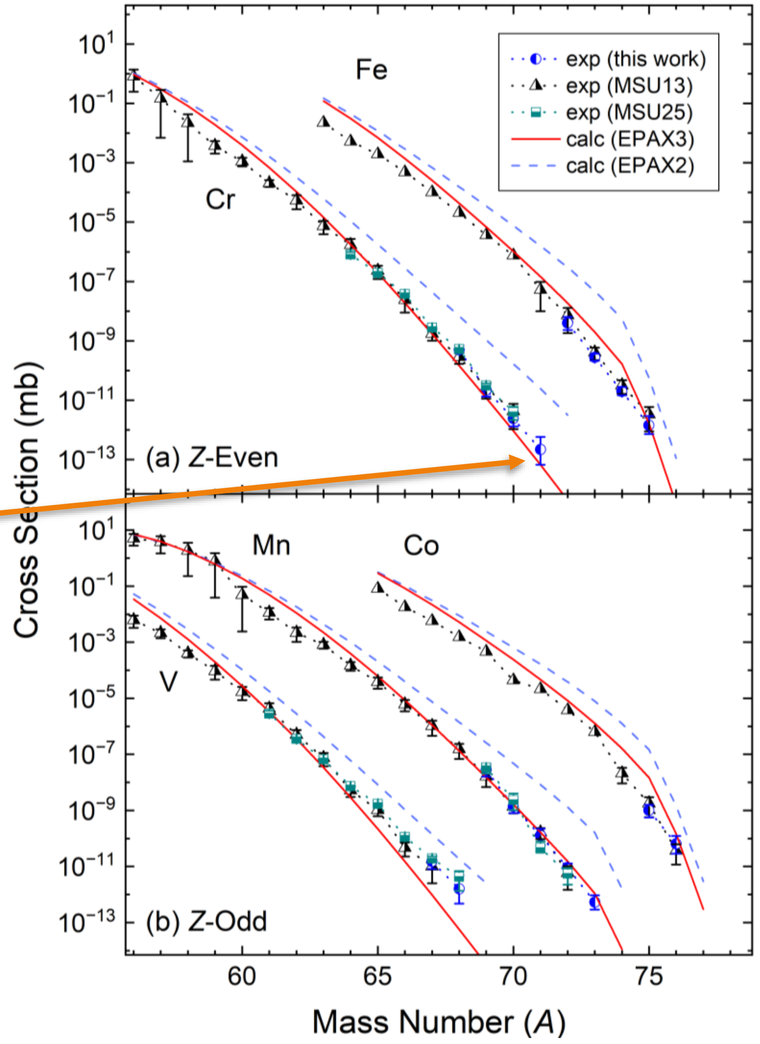


Observation of ^{71}Cr

S Watters, O Tarasov

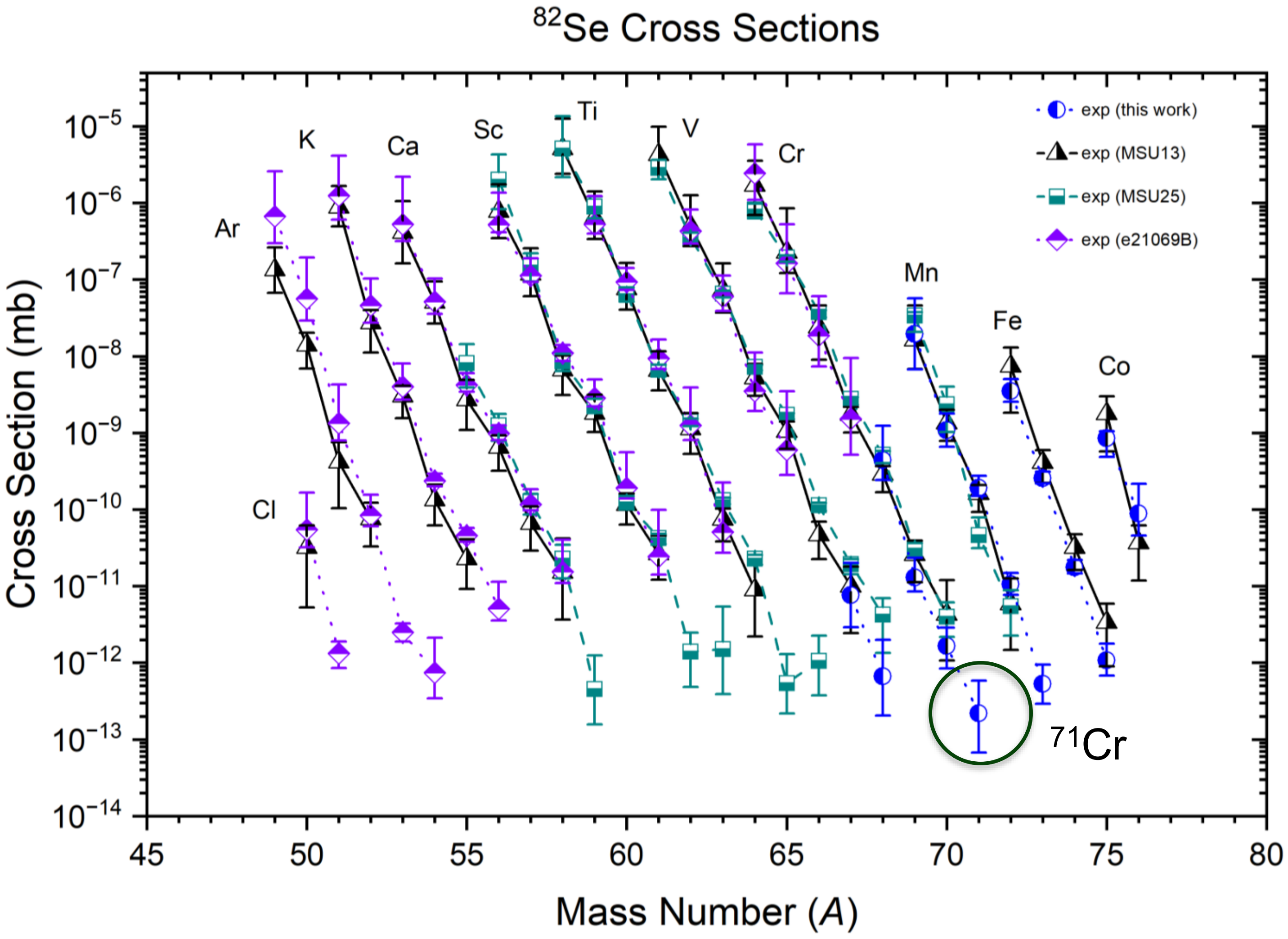
- With ^{82}Se at 225 MeV/u on an 8 mm C target 2 events of **^{71}Cr**, were observed in approximately 40 hours at 550 pnA
- 3.3 yoctomoles
- 2 events meet all PID criteria and probability of misidentification is <10^{-8}
- ^{71}Cr, is interesting because many models have it weakly bound or even unbound





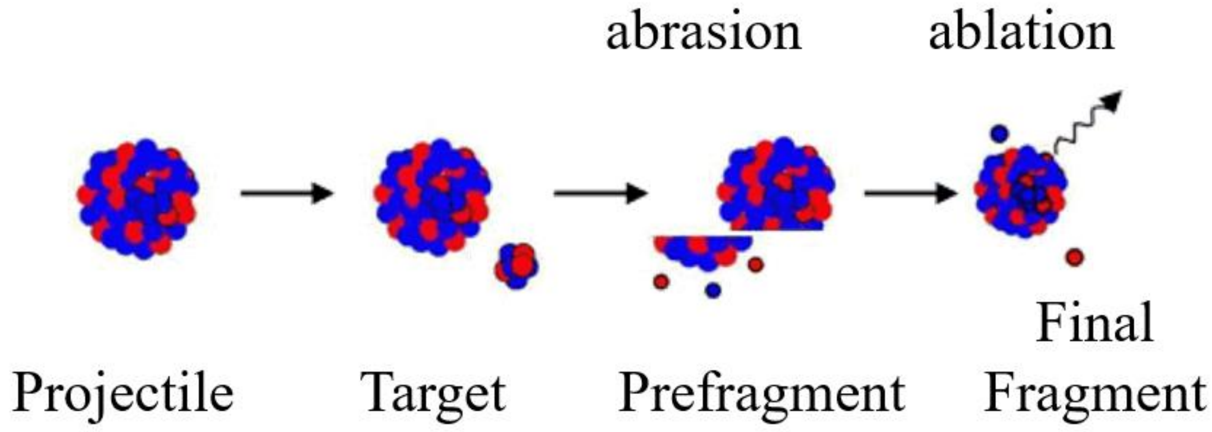
The ^{71}Cr Production Cross Section

S. Watters

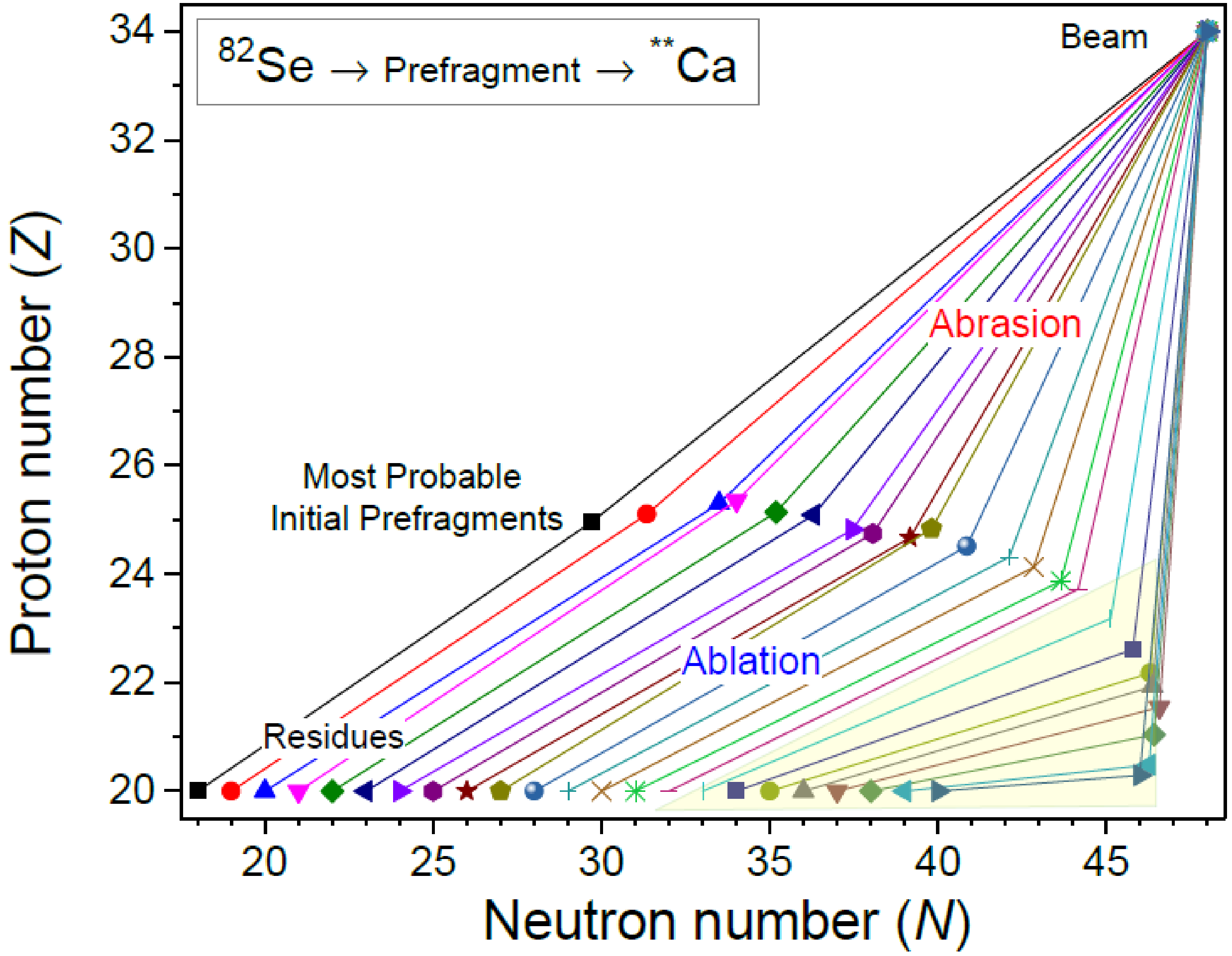


The Abrasion-Ablation Model Is a Useful Framework to Explore Rare Isotope Production

- AA Model - Wilson, Townsend, Badavi NIM B18 (1987)
- Model inputs for abrasion stage, prefagment excitation energy, ablation step



- Implemented in LISE$^{++}_{cute}$ (lise.frib.msu.edu) with wide range of models for each step
- Most probable prefragment identified



Delta Binding-Energy Systematics

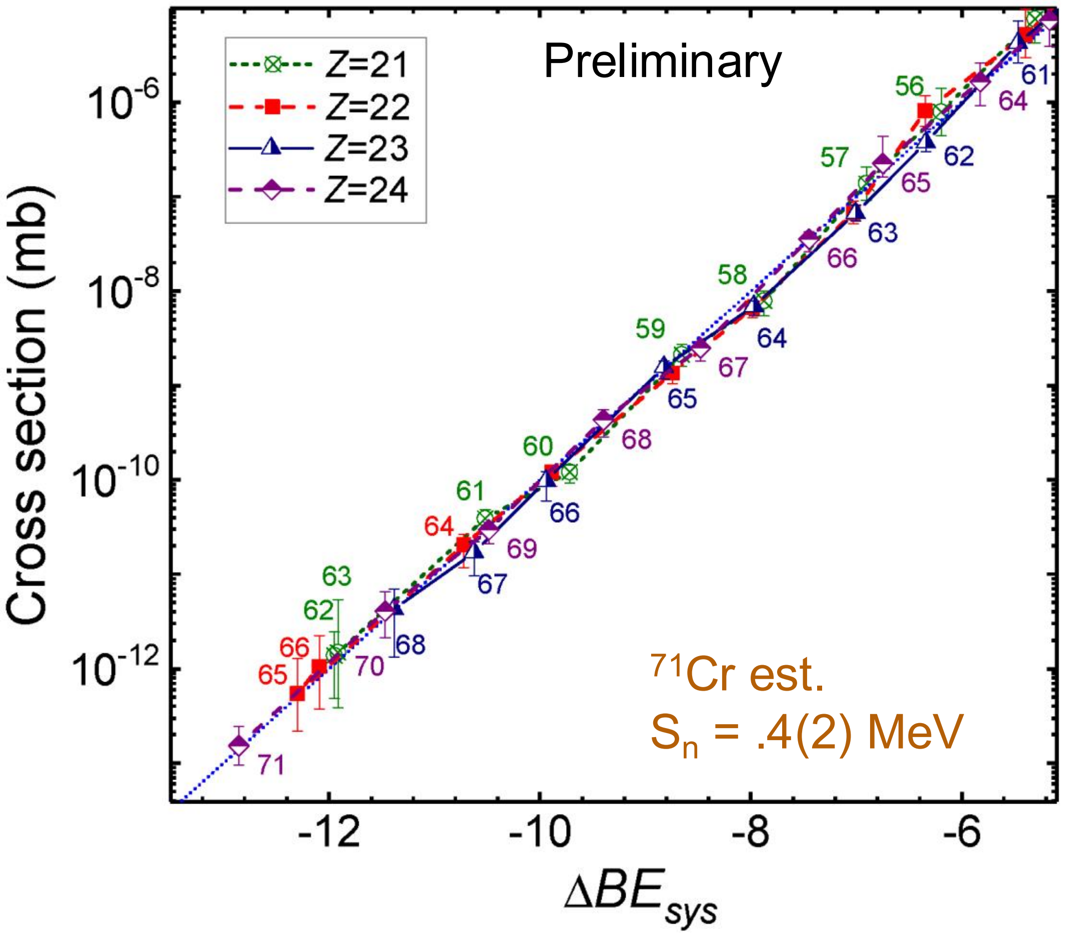
O. Tarasov et al, PRC 112 (2025)

- The production cross sections can be well parameterized by the relative binding energy of the fragment versus the pre-fragment and the neutron separation energy of the fragment
- ΔBE represents the difference in binding energy between the heaviest isotope (Z,$N_{projectile}$) of an element and the observed isotope (Z,N)

$$\log_{10}(\sigma) = k_1 \ln(\Delta BE + 1) + k_2 \ln(S_n) + b$$

Cross section~area of S_n and BE phase space

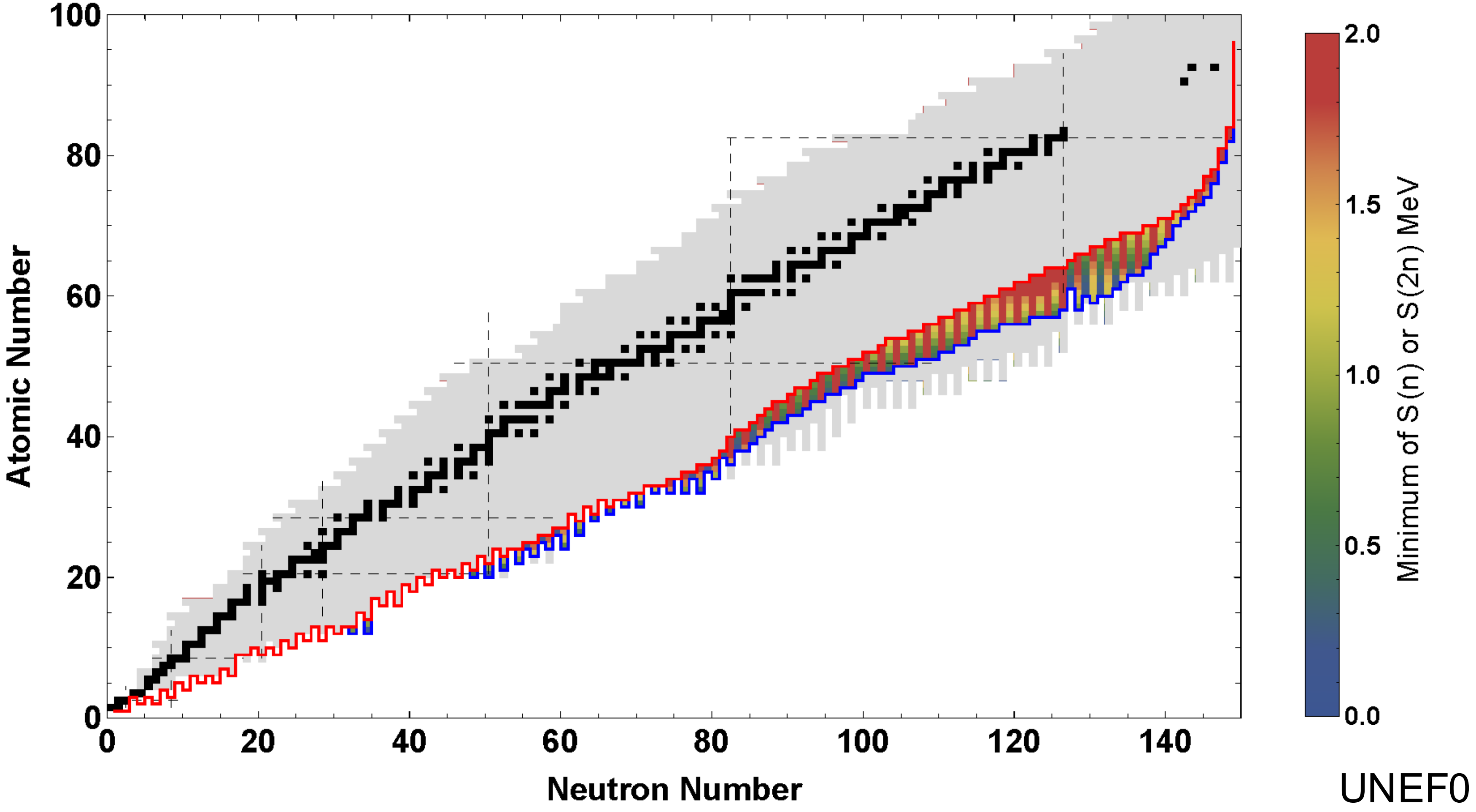
- ^{71}Cr is bound due to shell effects at N=50; reduced binding might indicates the drip line is closer than models with a strong shell effect



FRIB400 Reach Toward the Limits

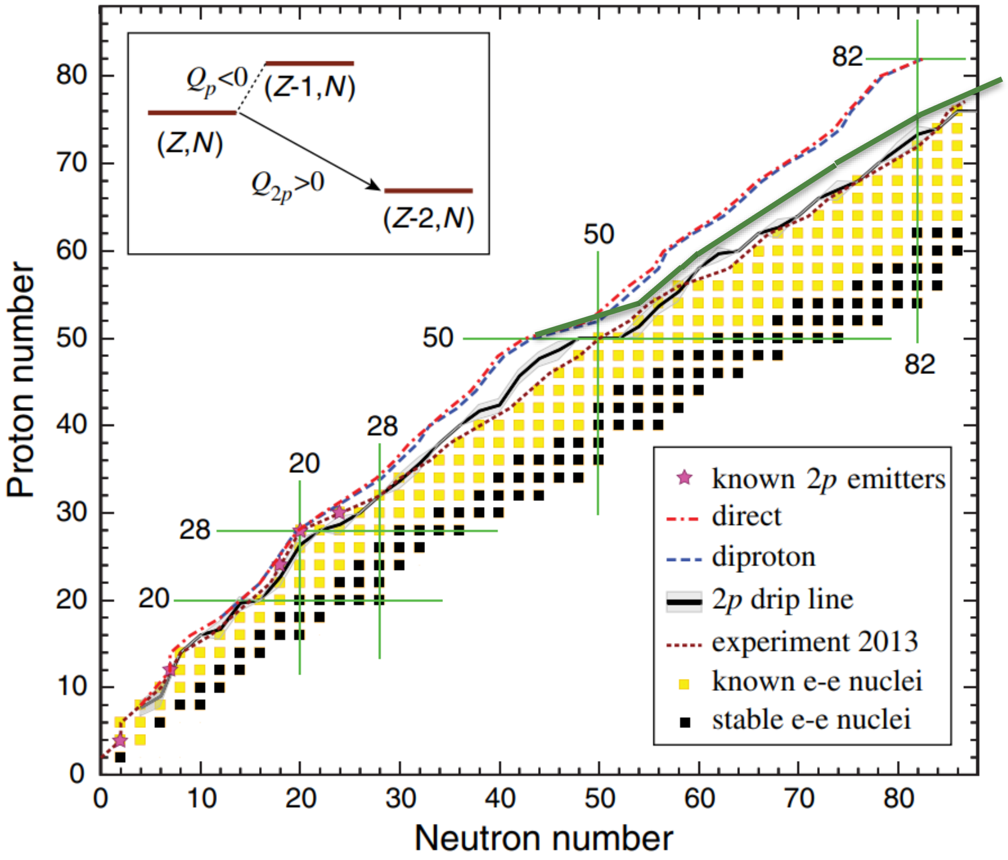
- Red – Current FRIB
- Blue – FRIB400

FRIB400 offers the possibility of reaching the drip line up to Z=60 (Z=30 for FRIB)



Prospects for the Proton Drip Line

- Olsen et al., PRL 110 222501 (2013)
- Limit of FRIB (Tarasov et al. https://frib.msu.edu/user-facilities/frib/calculator)



FRIB Limit

Acknowledgements

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- U.S. Department of Energy, Office of Science, Office of Nuclear Physics Facility for Rare Isotope Beams (FRIB); operations under Award Number DE-SC0023633.
- **ARIS Department**; NSF Grant members - **Oleg Tarasov**, PhD students Isaiah Richardson, Shane Watters, Holly Matthews, Daniel Kaloyanov
- Contributions of Robert