# Results from FRIB

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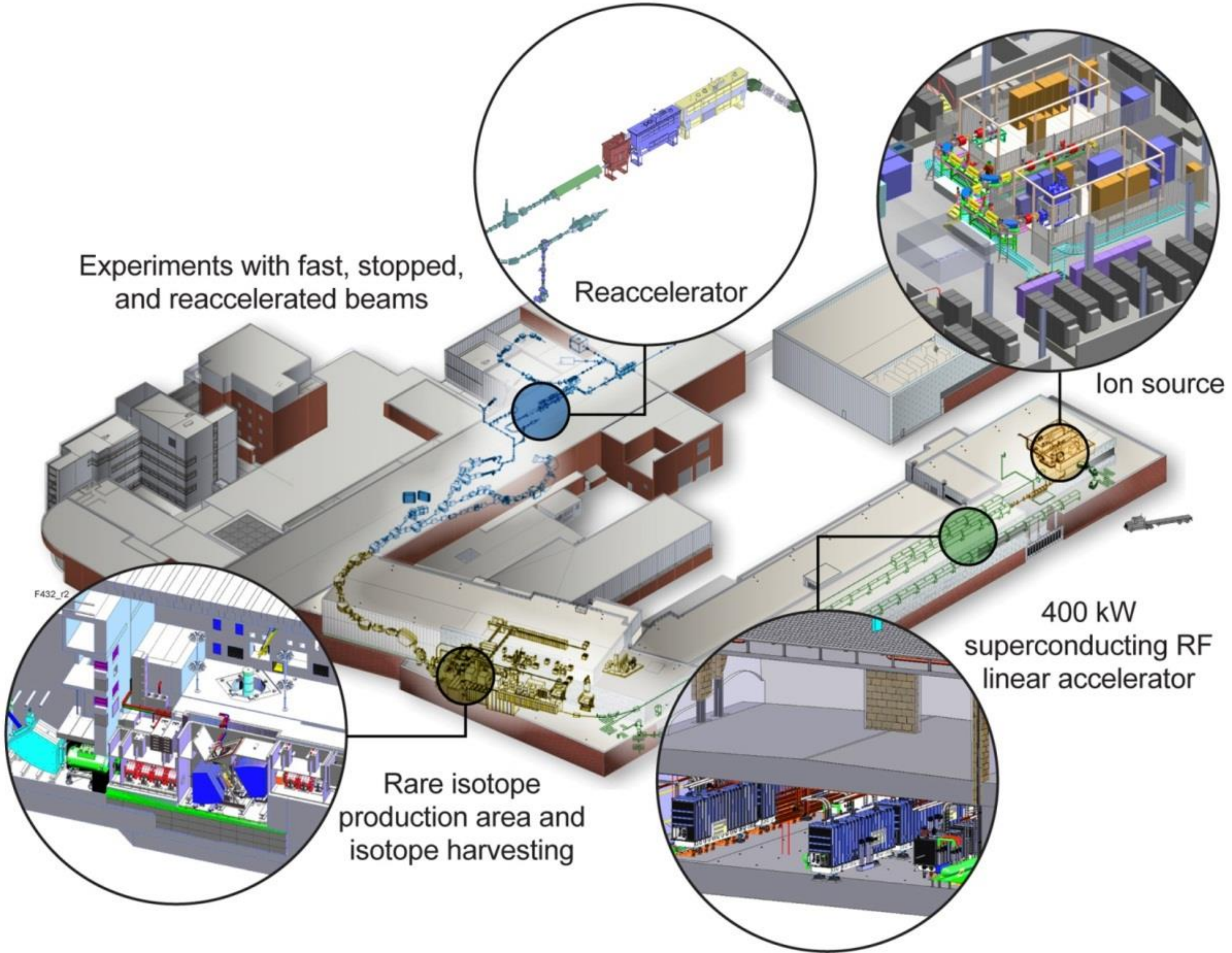
Nuclear Science Advisory Committee Meeting
12 September 2024

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

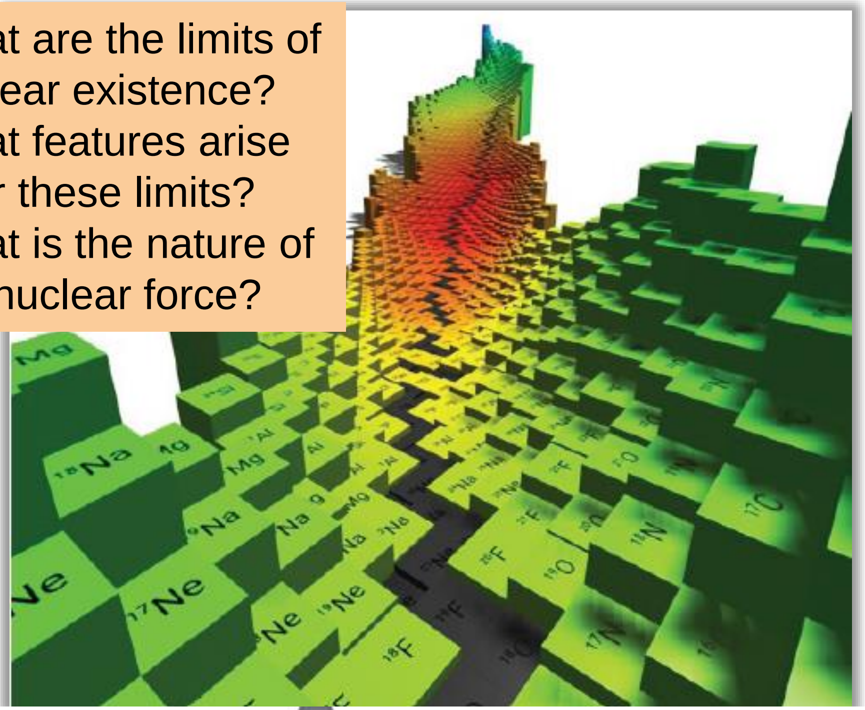
# FRIB is the newest DOE-SC user facility

- Facility for Rare Isotope Beams (FRIB) started user operations in May 2022 after being completed on time and on budget
- FRIB has been ramping up its capabilities every year
- With 22 kW of $^{82}$Se beam and 10.4 kW of $^{238}$U beam demonstrated, FRIB has surpassed RIBF/RIKEN as most powerful rare isotope beam facility in the world
- FRIB's user community has about 1800 members and beam time is oversubscribed 3:1

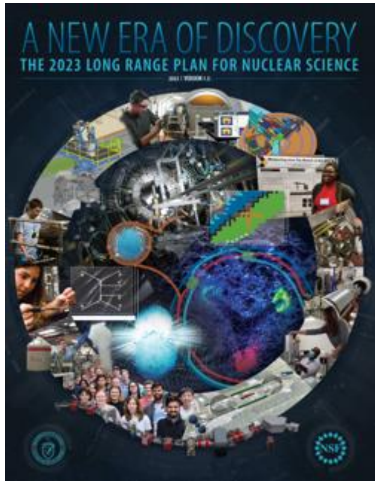


# FRIB responds to national priorities and enables answers fundamental questions posed by 2023 and earlier Long Range Plans

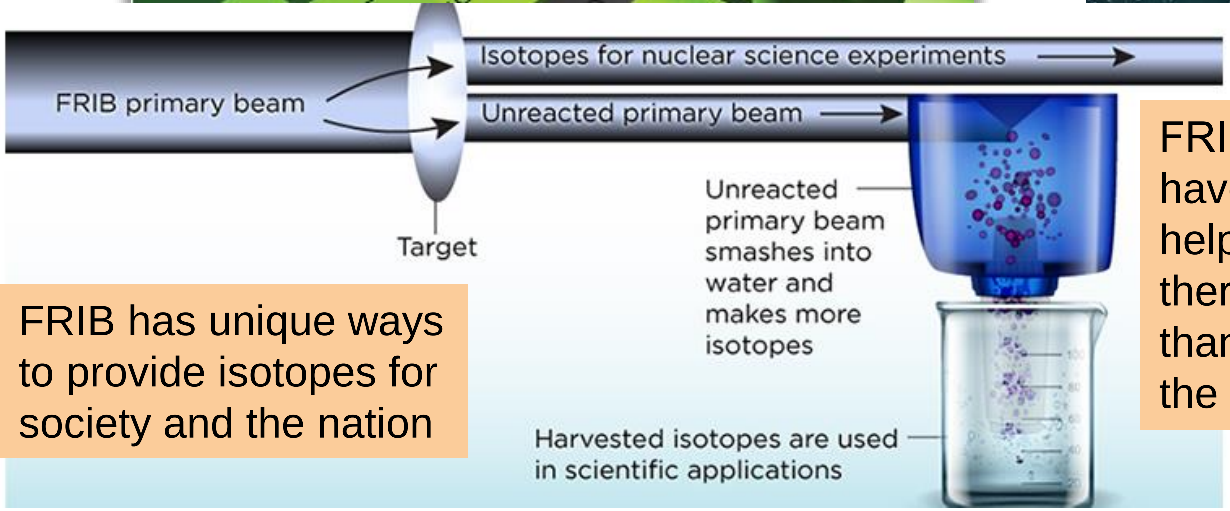
- What are the limits of nuclear existence?
- What features arise near these limits?
- What is the nature of the nuclear force?



What are nuclear processes that drive the birth, life, and death of stars?

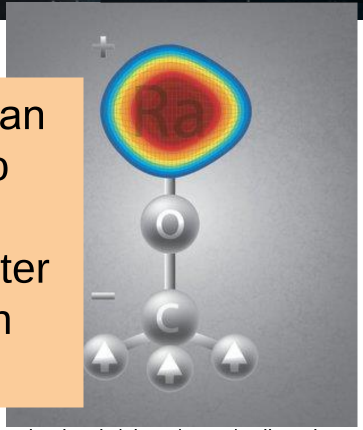




"A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science"




FRIB has unique ways to provide isotopes for society and the nation

FRIB's isotopes can have properties to help answer why there is more matter than anti-matter in the universe

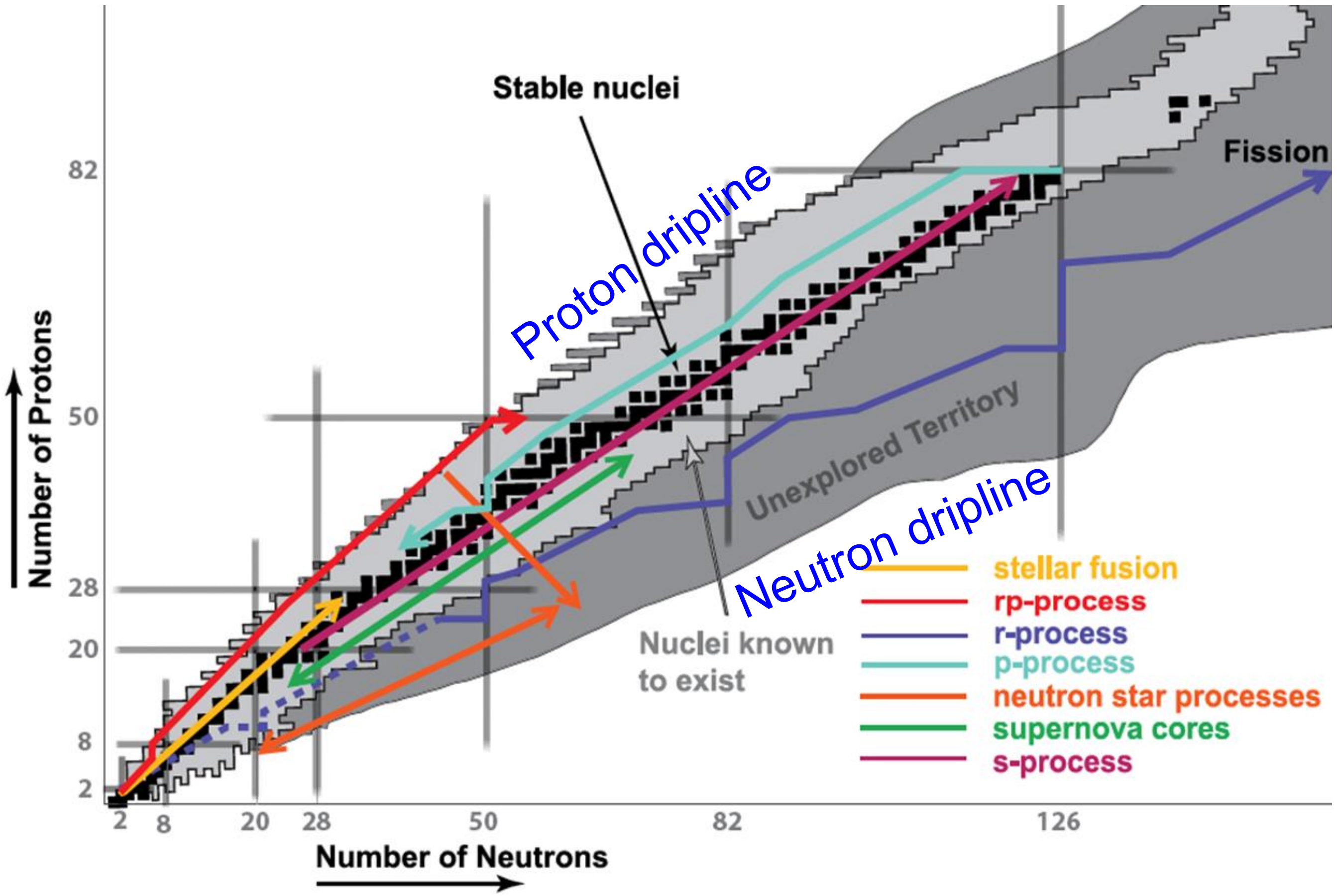



https://www.caltech.edu/about/news/radioactive-molecules-may-help-solve-mystery-of-missing-antimatter

FRIB's science is interdisciplinary and connects to astronomical observations, atomic and molecular physics, and chemistry

# Outline

- What are the limits of nuclear existence?
  - Discovery of new isotopes at FRIB
- What is the nature of the nuclear force?
  - Unraveling changes in the nuclear structure in pursuit of a predictive model of nuclei
- What are nuclear processes that drive the birth life, and death of stars?
  - The nucleosynthesis alphabet and the role of FRIB
  - Example: Getting to a key reaction rate
- Using rare isotopes to search for physics beyond the standard model
  - FRIB's fundamental symmetry program has started
- Applications



# New isotopes discovered at FRIB

Featured in Physics | Editors' Suggestion

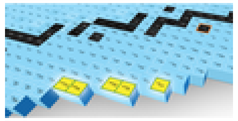
Phys. Rev. Lett. 132, 072501 (2024)

## 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.

FEBRUARY 27, 2024 | 5 MIN READ

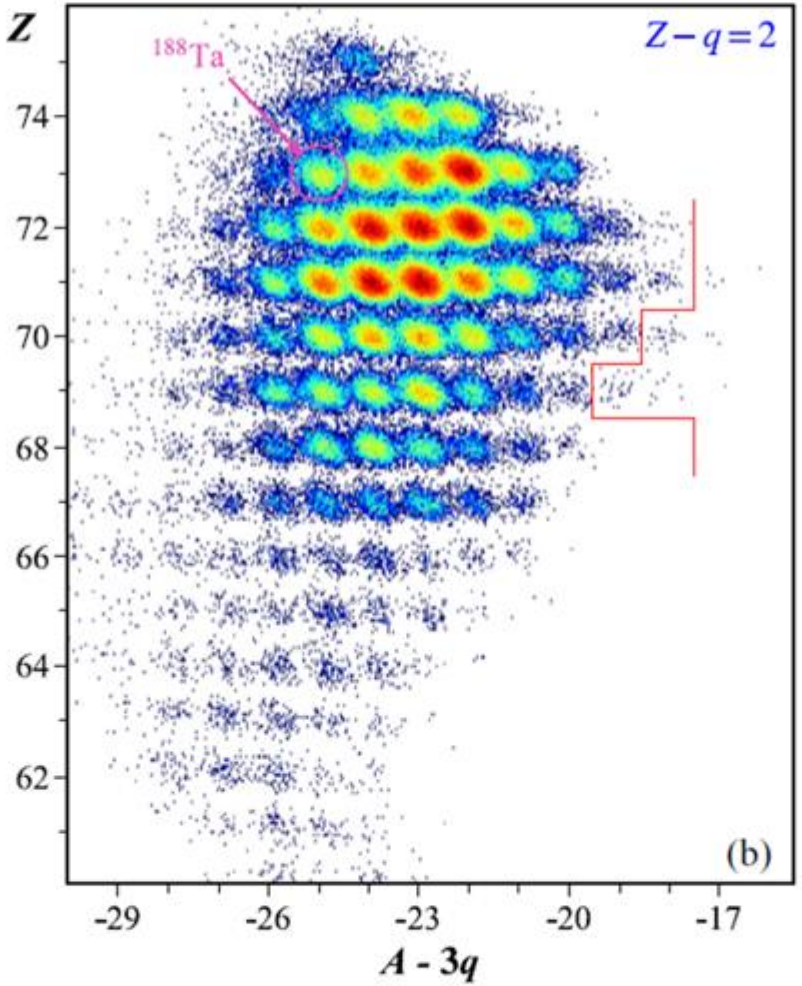
## Weird Lab-Made Atoms Hint at Heavy Metals' Cosmic Origins

Researchers have created ultraheavy versions of elements that have never existed before on Earth

SCIENTIFIC AMERICAN

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

Includes researchers from RIKEN in **Japan**, IBS in **South Korea**, and MSU in the **U.S.**

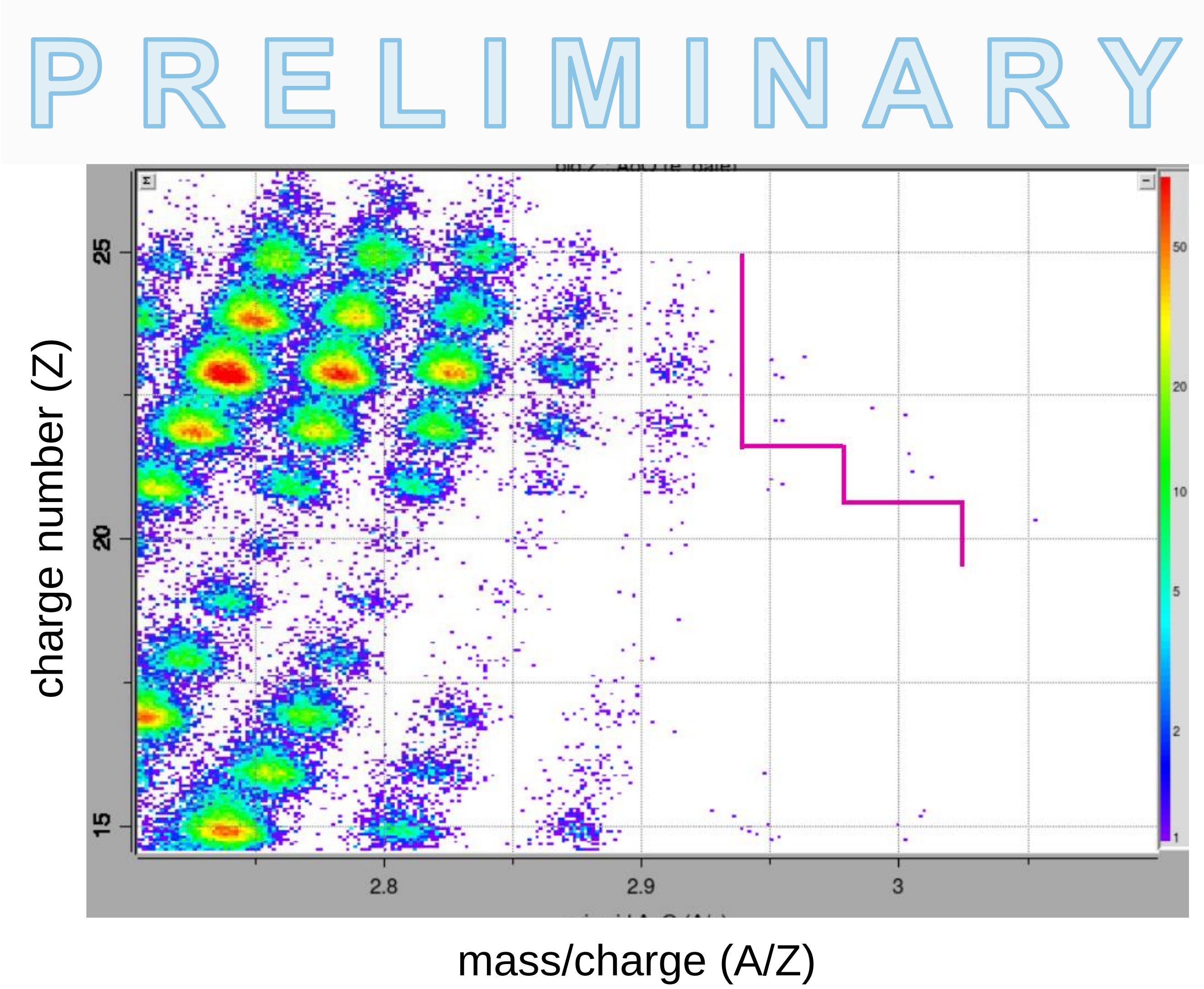



The new isotopes were formed in the fragmentation of $^{198}$Pt on C at 1.5 kW → discovery potential!

# More never-before-seen isotopes discovered in July 2024

Courtesy of O. Tarasov and B.M. Sherrill

- Four never-before-seen isotopes were produced, separated, and identified for the first time during the 20kW beam test
- $^{68}$V(4), $^{65}$Ti(2), $^{66}$Ti(2), $^{63}$Sc(2) [and $^{61}$Ca(1)]
- These are the heaviest isotopes of their respective elements
- Isotope discoveries in this region are important to understand how many Ca isotopes may exist
- FRIB400 is needed to reach $^{70}$Ca



# Context and prospects for isotope discoveries

## Why isotope discoveries matter

- Answers one of the most fundamental questions in nuclear science: What combinations of protons and neutrons can be made into a bound system
- Provides the ultimate test as to predictive power of models that describe the ground state properties across the chart
- Processes in the crusts of neutron stars proceed in so neutron-rich territory that the location of the neutron dripline is the limiting factor
- **Worldwide context and prospect:** By now, FRIB is the most powerful RIB facility in the world and charting the limits has just begun

- This is **different from the search for new elements** which requires high-intensity stable beams fusing with actinide targets

NEWS | PHYSICS

Science

**U.S. back in race to forge unknown, superheavy elements**

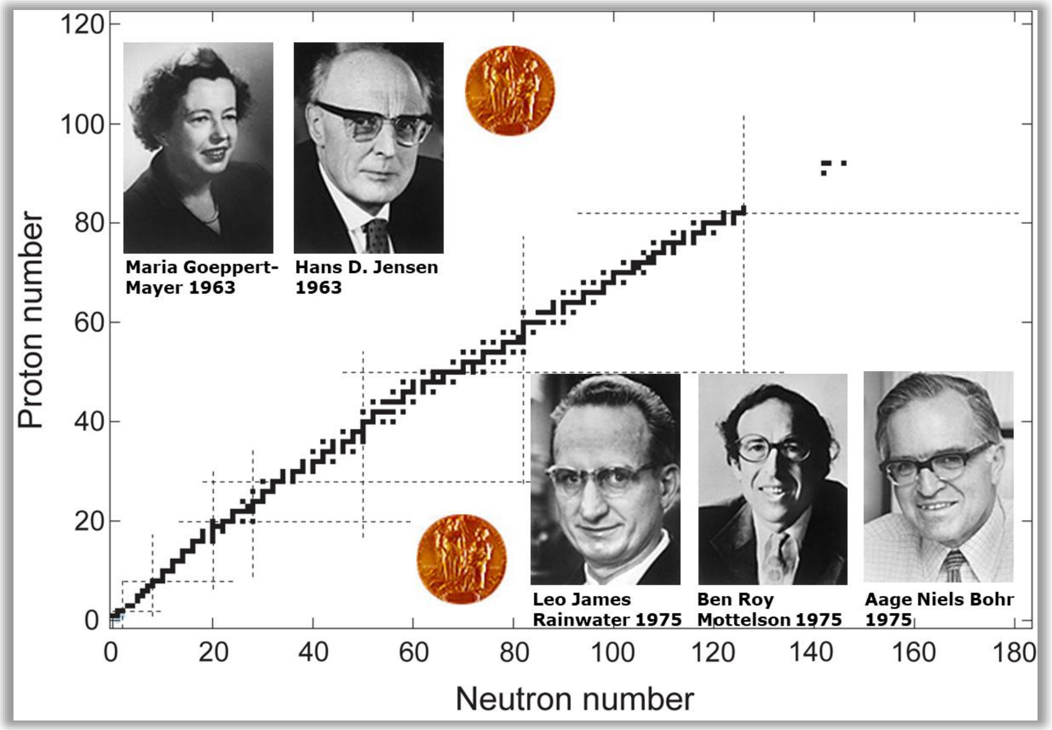
Two atoms of element 116 demonstrate path to hunt for element 120 and extend the periodic table

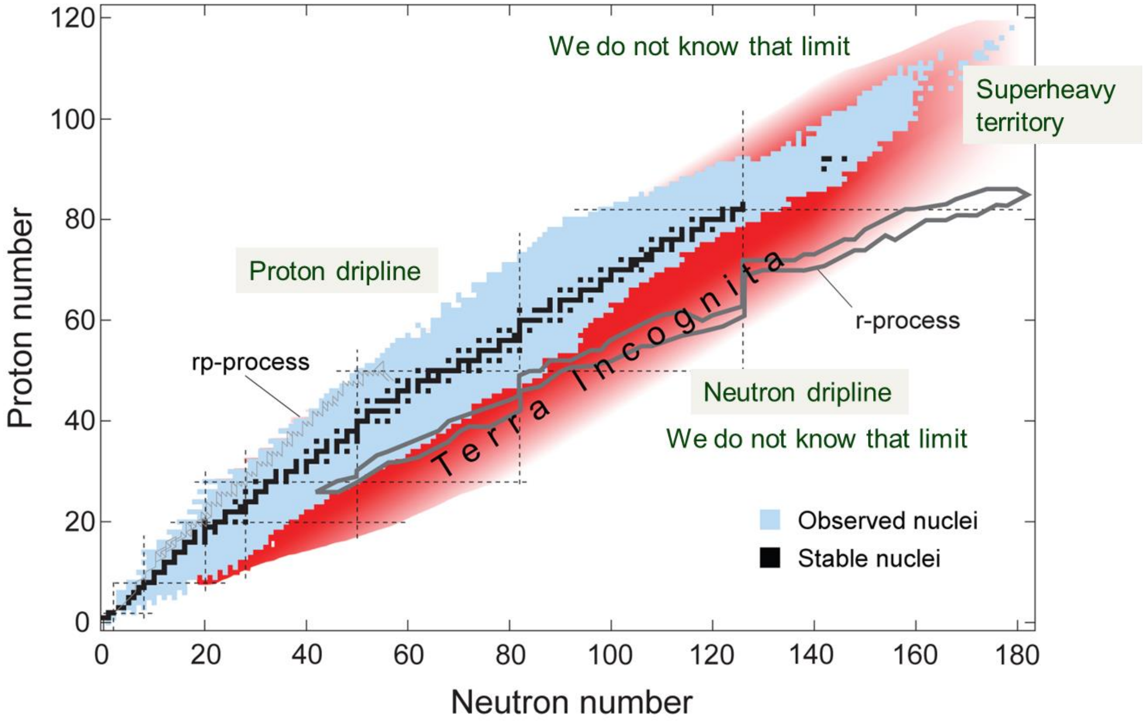
23 JUL 2024 • 5:00 PM ET • BY ROBERT F. SERVICE

- This research is performed in the US by **LBNL**, ANL and internationally at SHE factory in Dubna/Russia, RIKEN/JAPAN, and GSI/Germany where the last new elements (Z=107-118) were discovered
- Theorists at FRIB contribute by modeling fusion cross sections and the structure of superheavy elements

# Short-lived rare isotopes: Not your textbook nuclear physics

- The nucleus poses a formidable quantum many-body problem:
  - Strongly interacting constituents (and two species)
  - Open quantum system
  - Many-body computation
  - ….



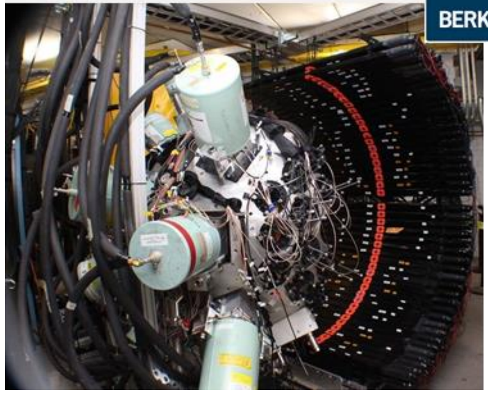




- Shell structure modified different in rare isotopes
- Exotic shapes and co-existence of different shapes occurs
- Weak binding near the driplines leads to new phenomena
- Extrapolation becomes unreliable → **Measure key nuclear properties that inform the next-generation of nuclear models on the quest for a predictive model**

# FRIB results: Not your textbook nuclear structure physics

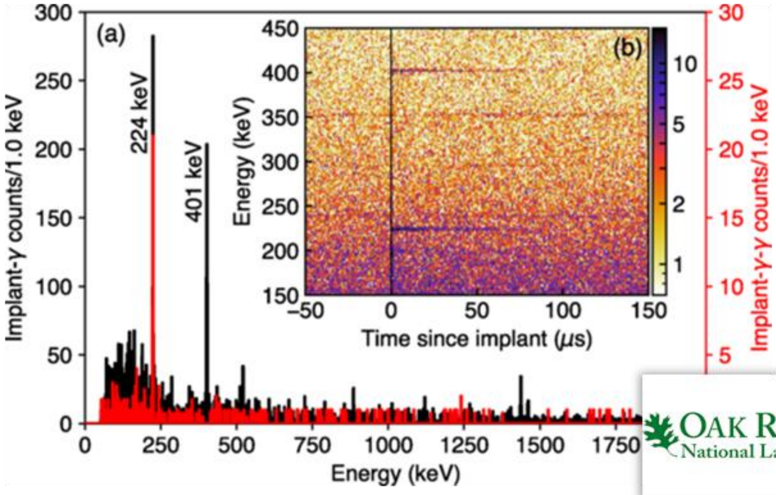
## Experimental challenge increases in complexity

First FRIB experiment: New half-lives for exotic isotopes



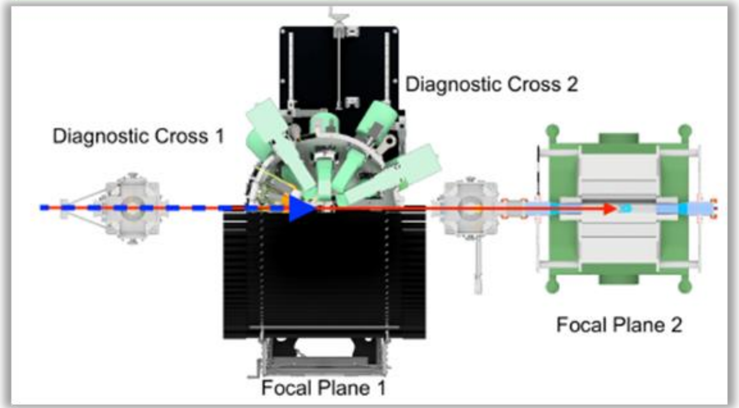
Phys. Rev. Lett. 129, 212501 (2022)

Discovery of an unusually long-lived (24 μs) isomeric state in $^{32}$Na points to hindered decay between a spherical isomer and a deformed ground state

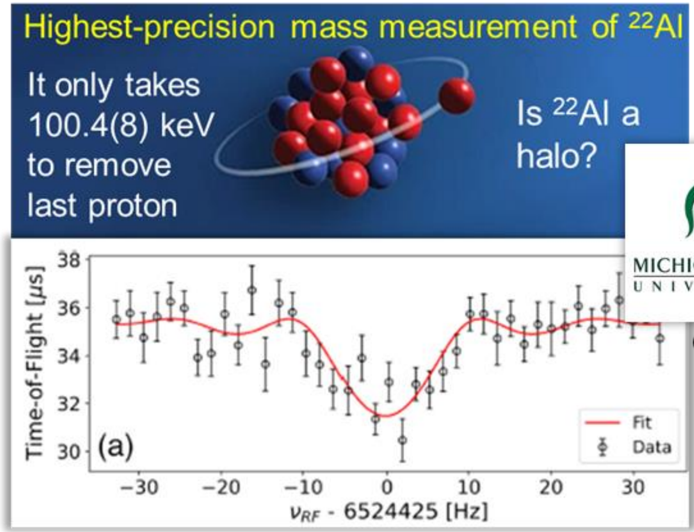



Phys. Rev. Lett. 130, 242501 (2023)

First complete spectroscopy of $^{45}$Cl β-decay strength distribution – a new approach to probe proton shell structure in neutron-rich nuclei




Phys. Rev. Lett. 132, 152503 (2024)

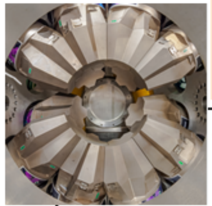


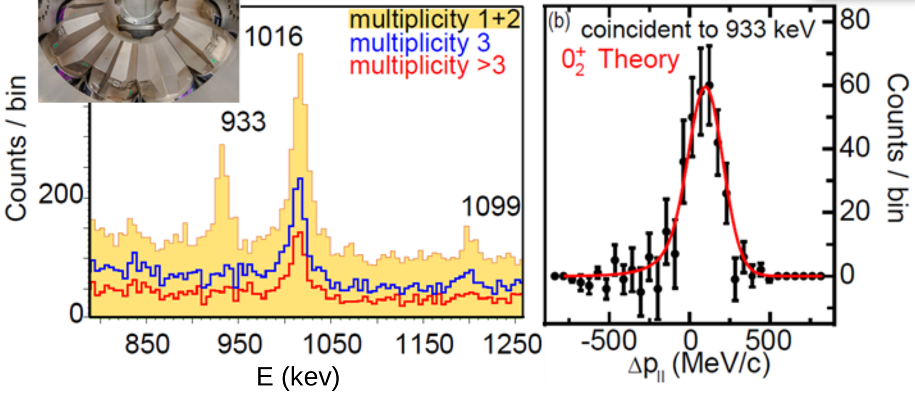

Grad student led

Phys. Rev. Lett. 132, 152501 (2024)

Stay tuned for radius measurement!

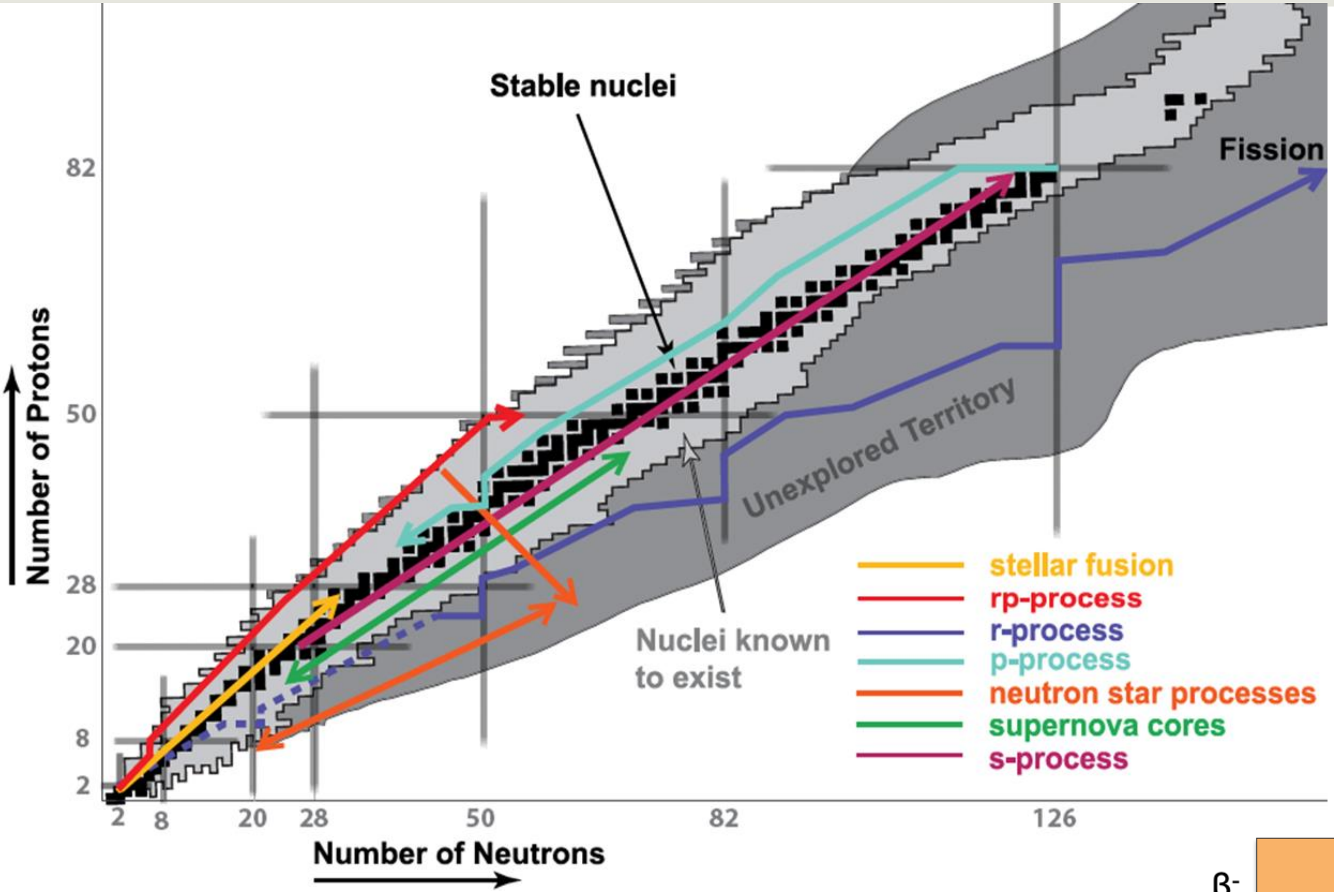
Discovery of shape-coexisting $0^+$ state in $^{62}$Cr promises interesting nuclear structure at $^{60}$Ca





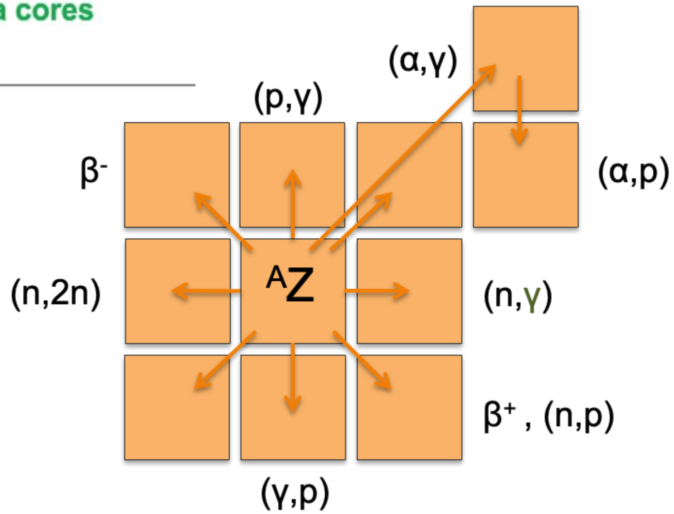

Nature Physics, accepted

# FRIB has begun to address all astrophysical processes that involve short-lived rare isotopes




- Approved and already run experiments at FRIB address all processes off stability
  - Reaction rates, masses, decay half-lives for r-process
  - Reaction rates for p process
  - Some of the most important reaction rates for X-ray bursts
  - Masses and reaction rates for neutron star crust processes
  - HI collisions to constrain the symmetry energy of the nuclear equation of state

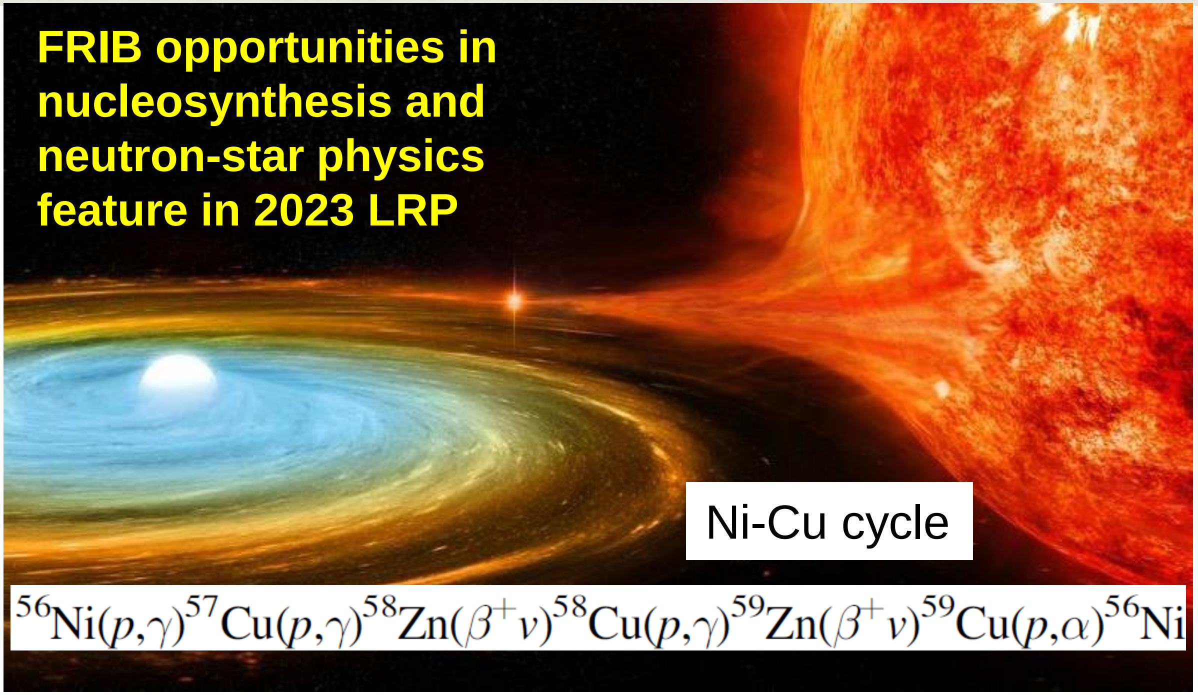
**Needed:** masses, $T_{1/2}$, β-delayed particle emission probabilities, location of capture resonances, reaction rates if possible, …

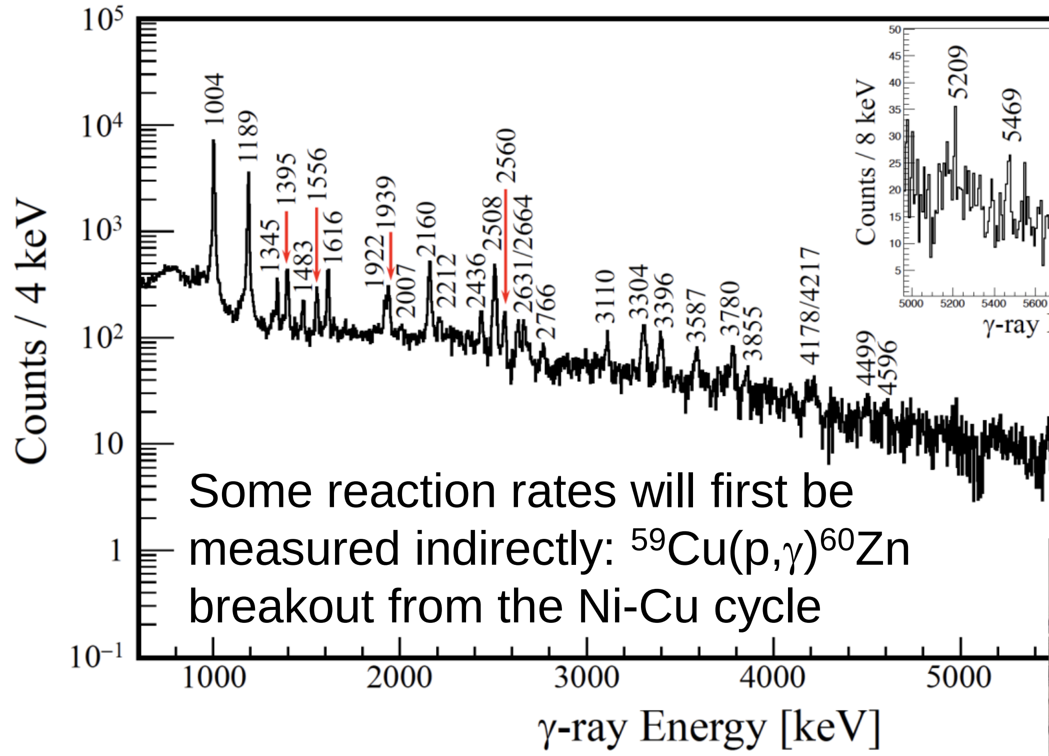



https://www.nationalgeographic.com/science

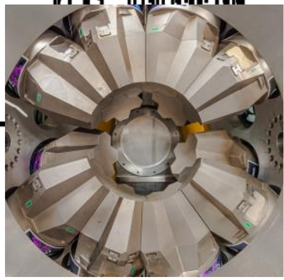
# Example: The ashes left behind in an X-ray burst – When one reaction rate makes a difference

Preliminary results courtesy of Gavin Lotay (Surrey, UK)



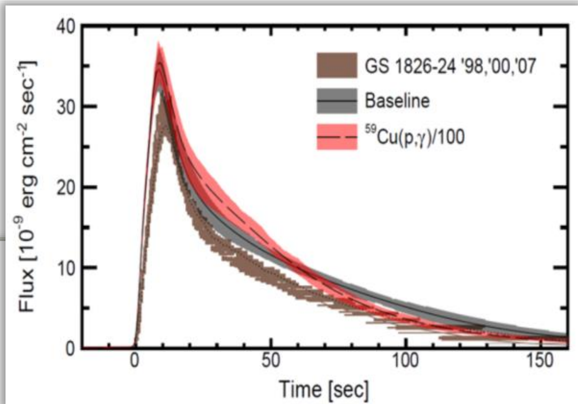




Some reaction rates will first be measured indirectly: $^{59}$Cu(p,γ)$^{60}$Zn breakout from the Ni-Cu cycle



Measured $d(^{59}\mathrm{Co},^{60}\mathrm{Zn}+\gamma)n$ transfer reaction to determine the precise energies of excited states above the proton separation energy that carry the dominant strength for the $^{59}$Cu(p,γ) breakout from the Ni-Cu cycle

First estimates indicate that the $^{59}$Cu(p,γ) breakout from the Ni-Cu cycle is weak, enabling the cycle to happen! Large impact for (i) the A=59 ashes left in the crust of neutron stars and (ii) the shape of X-ray burst light curve

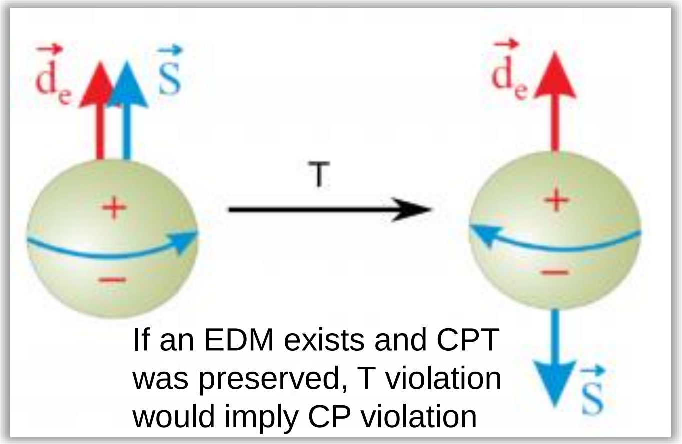



PRELIMINARY

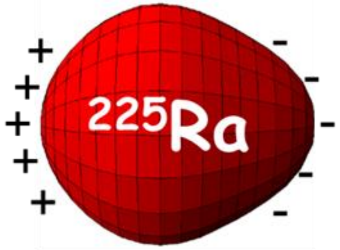
# FRIB plays a key role in multi-messenger nuclear astrophysics

# Rare isotopes as laboratory for physics beyond the standard model

- Search for permanent electric dipole moment (and symmetry violations in general) in atoms and molecules
  - Beyond the Standard Model (BSM)
  - Dominance of matter over antimatter (CP violation)
  - $^{225}$Ra, $^{229}$Pa are special (several thousand times more sensitive than $^{199}$Hg due to octupole deformation)
  - Heavy octupole-deformed atoms embedded in molecules enhance signals of symmetry violation by orders of magnitude
- Precision measurements of β decay
  - Search for new particles and interactions
  - Mass scale for possible new particles is comparable with LHC




Octupole deformation

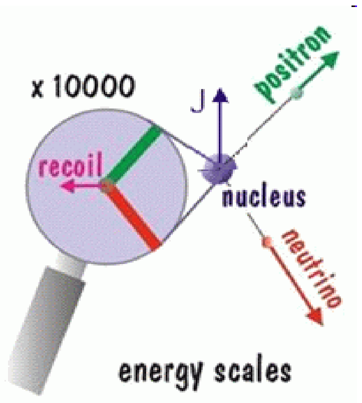


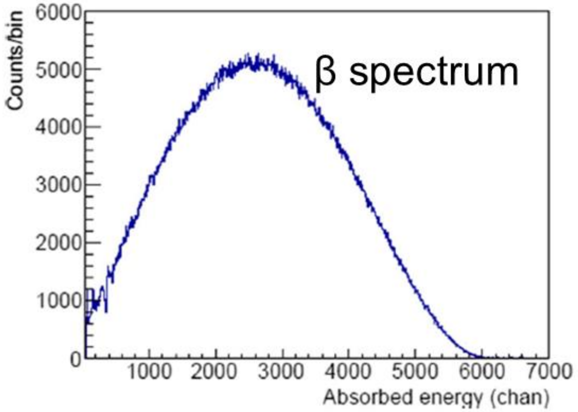

Hosted in molecule


Enhances signal of EDM or P violation

$10^5$ - $10^{10}$

https://www.garciaruizlab.com




Search for couplings beyond the standard model

# First measurements on the path to using molecules that contain heavy rare isotopes have begun

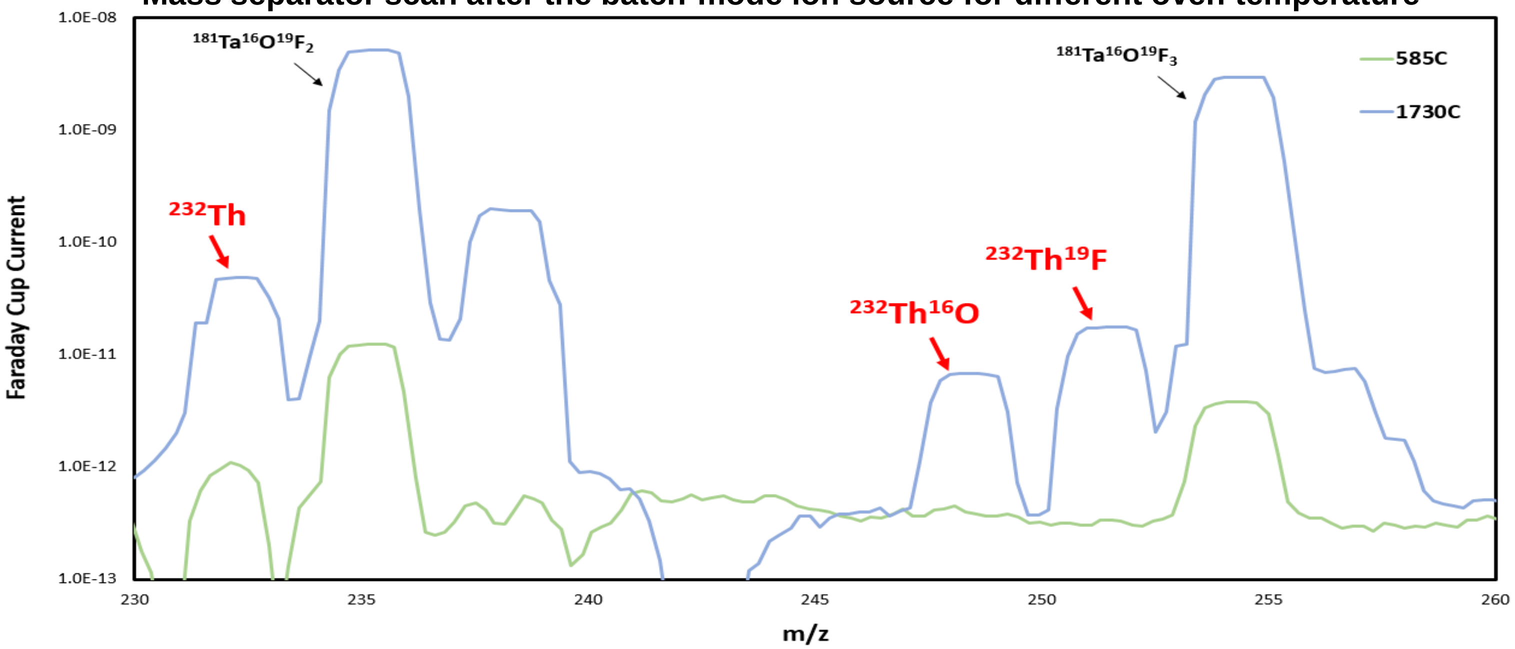
- $^{229,232}$Th, $^{229,232}$ThO, and $^{229,232}$ThF beams are isotopes of interest for beyond-standard-model studies
  - MIT-led PAC-recommended laser spectroscopy experiments with RISE/BECOLA facility started
  - Rotational and hyperfine structure of the molecules $^{229,232}$ThO and $^{229,232}$ThF for future studies of symmetry-violating nuclear properties

Garcia Ruiz Lab

- FRIB's nuclear chemistry group synthesized suitable Th compound with for use in batch mode ion source – Th, ThO, ThF delivery confirmed
- Longer term: Isotope harvesting will provide research quantities of Th and other candidate isotopes that the batch mode ion source can provided for a range of fundamental symmetry studies

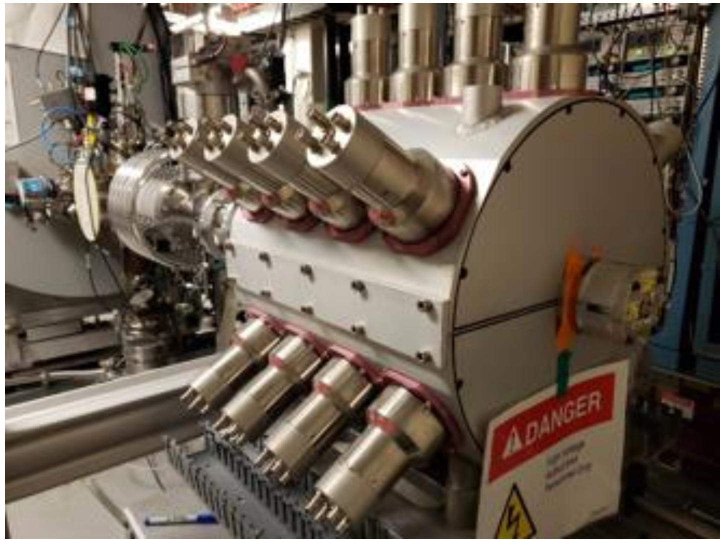
Various efforts in exploratory stages, aspiring different radioactive molecules and trapping approaches from ranging from Penning traps to capturing candidate nuclei in a solid noble-gas matrix. Engaged community is scientifically very diverse and skills needed straddle nuclear physics, AMO physics, radiochemistry, computational quantum chemistry, nuclear many-body theory …

**Mass separator scan after the batch-mode ion source for different oven temperature**



# The applied program at FRIB started

- **Indirect approach** to deduce neutron capture rates employed
- Example: Test the spin-independence of the γSF, critical for constraints on neutron capture reactions (PhD thesis experiment of MSU CEM student)
- NNSA-laboratory scientists engaged



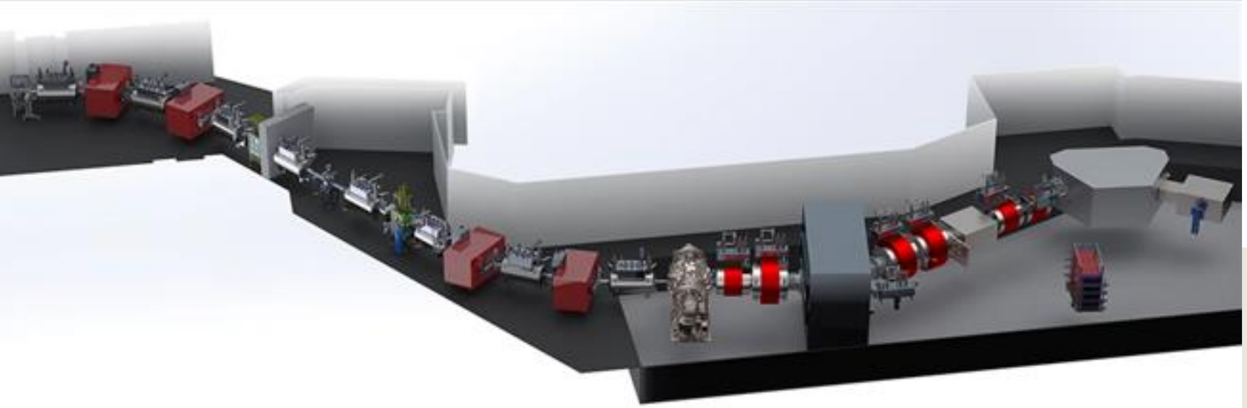

- **Isotope harvesting** at FRIB presents the unique opportunity to recover unused beam fragments for future use through commensal harvesting
- DOE-IP and MSU have invested in isotope harvesting, new faculty, and workforce development
- Experiments with dedicated harvester awaiting scheduling

- Following a request by then-DOE-SC Deputy Director, Stephen Binkley, MSU established **for-fee chip-testing facility** (FSEE) based on FRIB linac, serving government and industry
- Runs during fragment separator configuration changes or maintenance shutdowns downstream from the FRIB linac

# Future aspirations well defined: High Rigidity Spectrometer and FRIB400


## High-rigidity, large acceptance spectrometer for FRIB

- **HRS:** Extending the reach of reaction experiments to the most neutron-rich isotopes through a combined production-rate and luminosity increase of up to a factor of 100
- User community of more than 500 expected, science topics span the full FRIB portfolio, will host GRETA, features in the LRP
- HRS High-Transmission Beam Line CD2/3 OPA Review scheduled for October 2024



## FRIB400 would double the energy of the FRIB accelerator to:

- Enable significant gains in isotope yields will be realized, **nearly doubling the reach of FRIB along the neutron dripline and bringing into reach more nuclei relevant for the r process and neutron-star crust processes**
- Create dense nuclear matter of up to twice saturation density, critical for multi-messenger astrophysics
- Provide **up to two-orders-of-magnitude increase in luminosity** for spectroscopy in key regions of the nuclear chart
- Expand the scientific impact of harvested isotopes by **increasing the available yield of many isotopes by 10 times**

## FRIB400 opportunity:

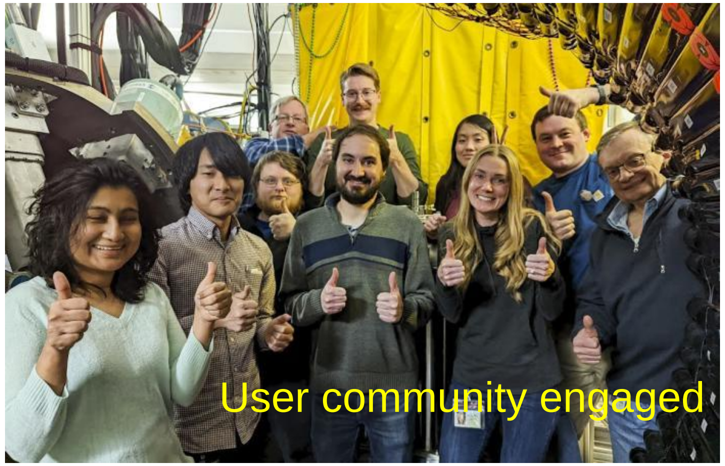
- Features in the LRP
- Technically ready
- Can be implemented in a phased approach, with gains at every stage
- Team to build it is in place

Jacketed $\beta_{OPT}$=0.65 cavity with tuners

# Summary

- FRIB has been producing science in all of its interest areas since operations commenced in May 2022 – aligned with LRP
- Results come from various experimental schemes ranging from decay studies to in-beam spectroscopy and precision measurements

Science and Technology Facilities Council





- FRIB has well-defined and community-supported upgrade path

*Thanks for your attention!*

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Crossing $N = 28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

H. L. Crawford *et al.*
Phys. Rev. Lett. **129**, 212501 – Published 14 November 2022

Physics See Viewpoint: Probing the Limits of Nuclear Existence

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Microsecond Isomer at the $N = 20$ Island of Shape Inversion Observed at FRIB

T. J. Gray *et al.*
Phys. Rev. Lett. **130**, 242501 – Published 13 June 2023

Physics See synopsis: Excited Sodium-32 with a Spherical Wave Function

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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 – Published 15 February 2024

Physics See Research News: Five New Isotopes Is Just the Beginning

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Proton Shell Gaps in $N = 28$ Nuclei from the First Complete Spectroscopy Study with FRIB Decay Station Initiator

I. Cox *et al.*
Phys. Rev. Lett. **132**, 152503 – Published 12 April 2024

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Precision Mass Measurement of the Proton Dripline Halo Candidate $^{22}Al$

S. E. Campbell, G. Bollen, B. A. Brown, A. Dockery, C. M. Ireland, K. Minamisono, D. Puentes, B. J. Rickey, R. Ringle, I. T. Yandow, K. Fossez, A. Ortiz-Cortes, S. Schwarz, C. S. Sumithrarachchi, and A. C. C. Villari
Phys. Rev. Lett. **132**, 152501 – Published 9 April 2024

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In-beam spectroscopy reveals competing nuclear shapes in the rare isotope $^{62}Cr$

Alexandra Gade[1,2*], Brenden Longfellow[3], Robert V.F. Janssens[4,5], Duc D. Dao[6], Frédéric Nowacki[6], Jeffrey A. Tostevin[7], Akaa D. Ayangeakaa[4,5], Marshall J. Basson[1,2], Christopher M. Campbell[8], Michael P. Carpenter[9], Joseph Chung-Jung[1,2], Heather L. Crawford[8], Benjamin P. Crider[10], Peter Farris[1,2], Stephen Gillespie[1], Ava M. Hill[1,2], Silvia M. Lenzi[11], Shumpei Noji[1], Jorge Pereira[1], Carlotta Porzio[8], Alfredo Poves[12], Elizabeth Rubino[1] and Dirk Weisshaar[1]

In press
nature physics