The Status and Ambitions of the US Heavy Element Program

Jacklyn M. Gates for the Heavy Element Working Group

Timeline

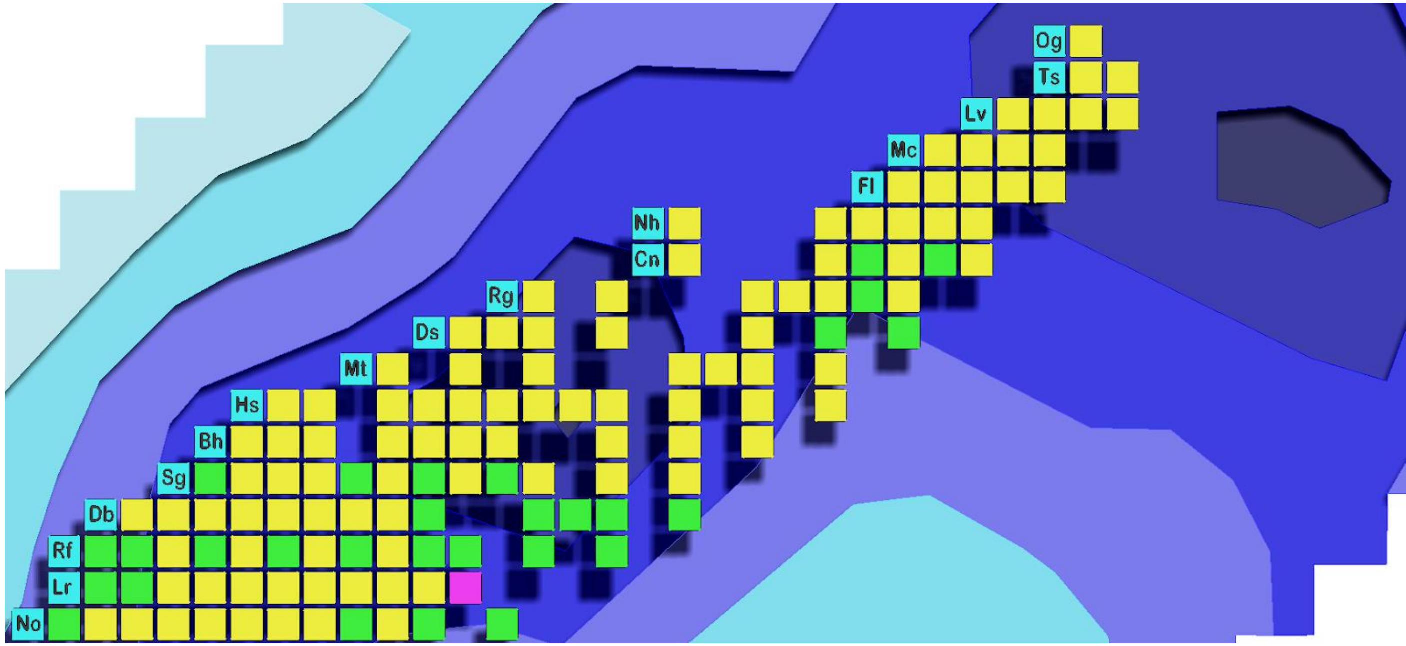
A working group meeting held during the Low Energy Community Meeting at Argonne National Laboratory (August 8-11, 2022) provided input to the 2022 Nuclear Astrophysics and Low Energy Nuclear Physics Town Meeting

Editors

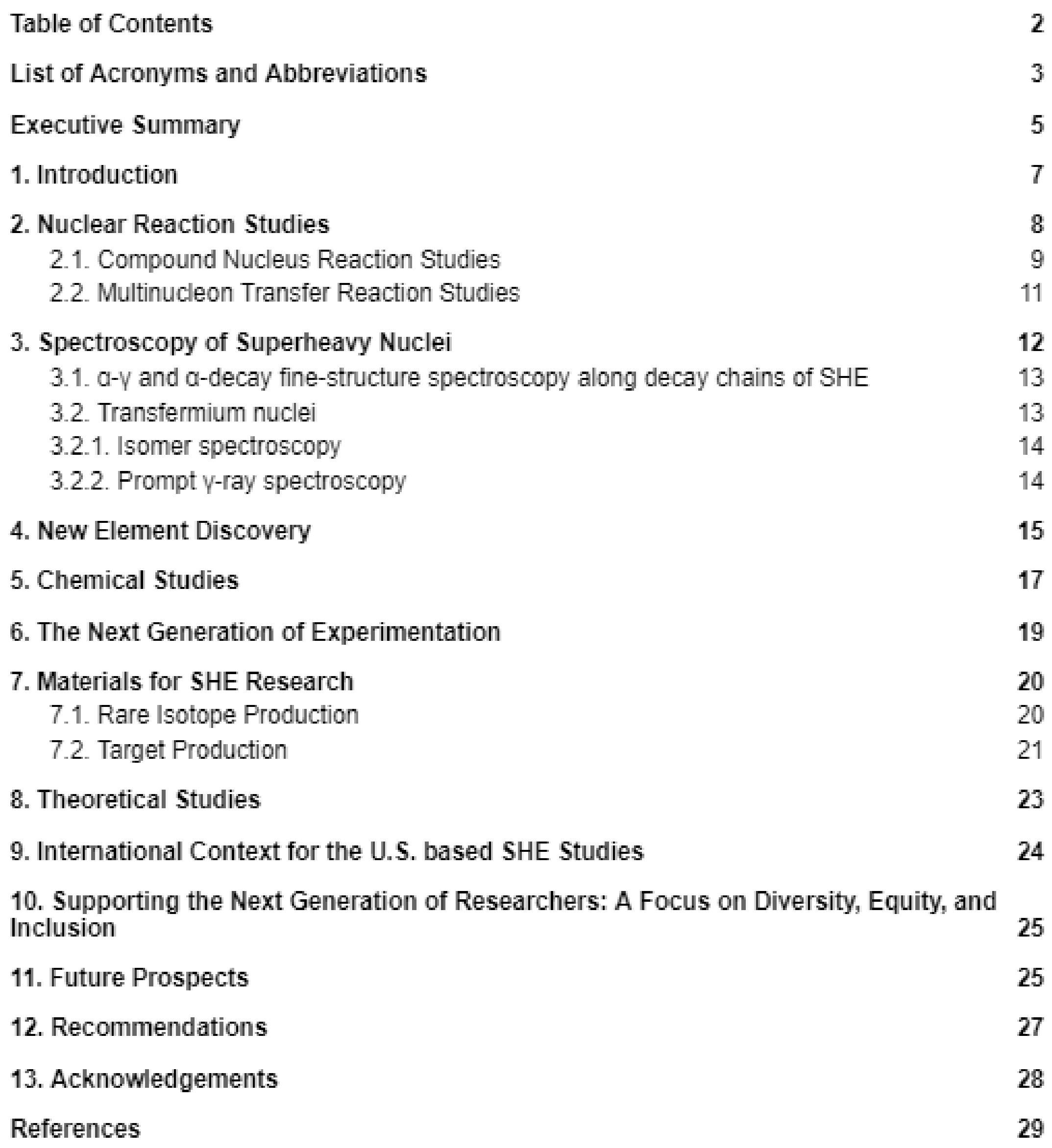
Heather Crawford
Jacklyn Gates
Jennifer Pore
Dawn Shaughnessy
Mark Stoyer

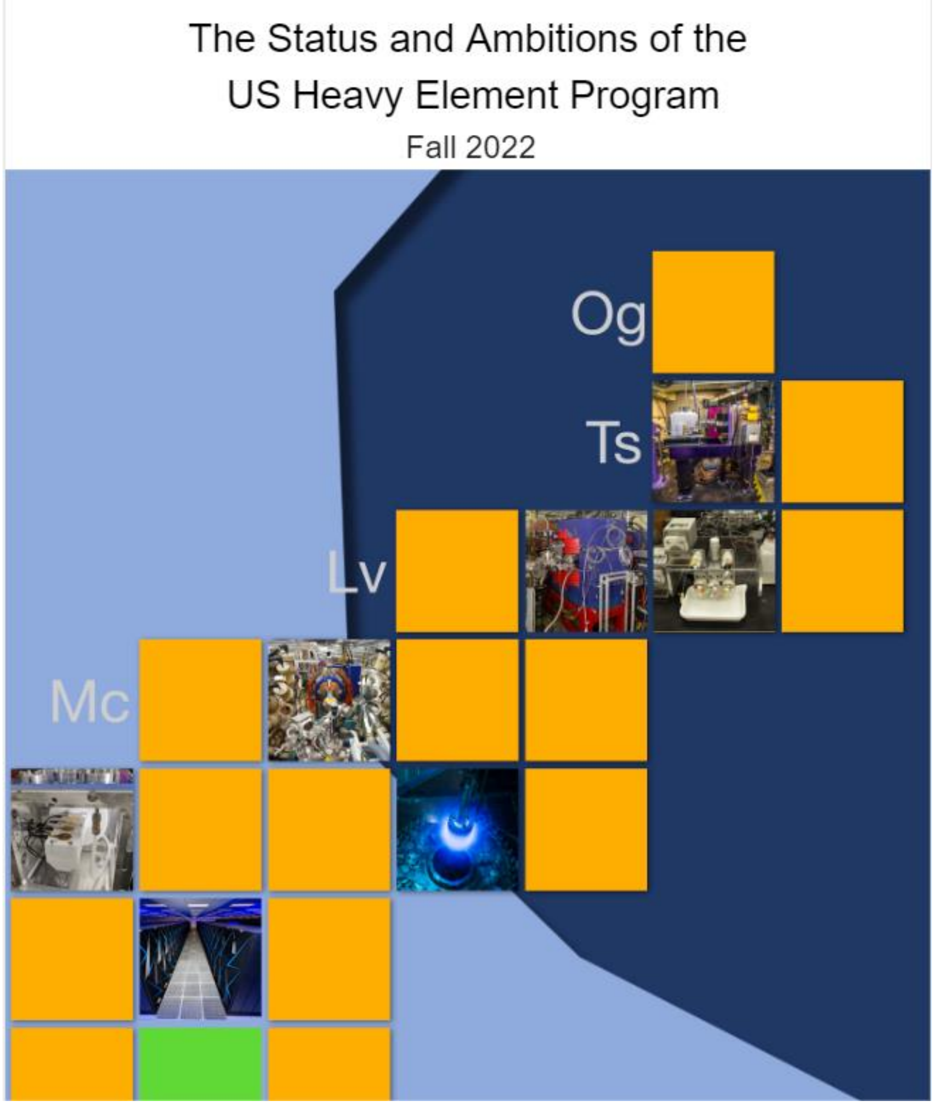
Contributors

Janilee Benitez
George Bertsch
Partha Chowdhury
Rod Clark
Heather Crawford
John Despotopulous
Nicholas Esker
Cody Folden
Jacklyn Gates
Walt Loveland
Christopher Morse
Jennifer Pore
Krzysztof Rykaczewski
Darek Seweryniak
Dawn Shaughnessy
Mark Stoyer
Evgeny Tereshatov
Damon Todd
Sait Umar
Walid Younes



White Paper





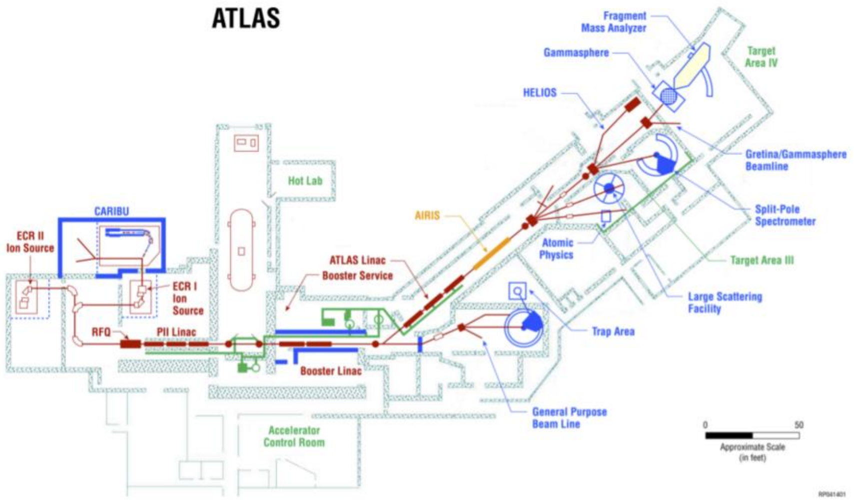
The Status and Ambitions of the
US Heavy Element Program
Fall 2022

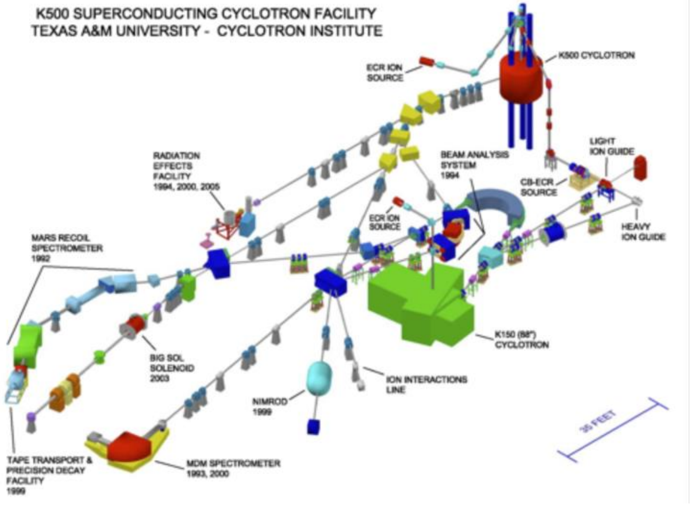
https://heavyelementgroup.lbl.gov/white-paper

Facilities

The highest priority of the US Heavy Element community is to capitalize on the current investments by supporting the operations of US facilities at optimal values.

- User facilities like ATLAS at ANL and FRIB at MSU
- DOE facilities such as 88-Inch Cyclotron at LBNL
- University laboratories such as Texas A&M University
- Material production facilities such as HFIR and SIPRC at ORNL
- Target laboratories at ORNL, ANL, LLNL, SJSU and OSU





Atlas@ANL

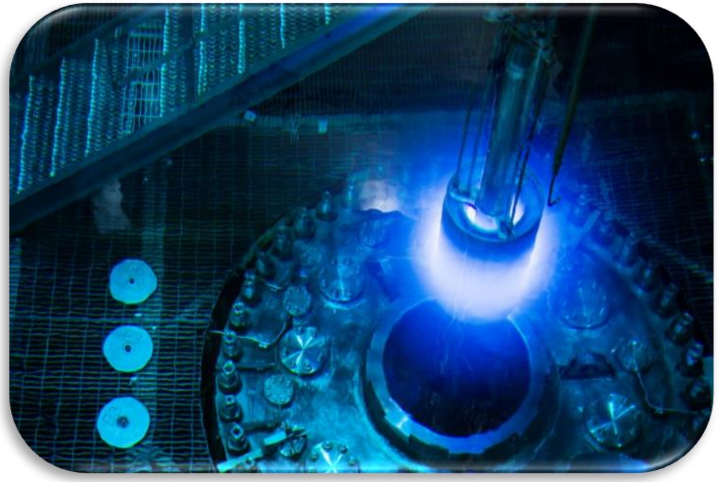
Cyclotron Institute@Texas A&M

88-Inch Cyclotron @LBNL

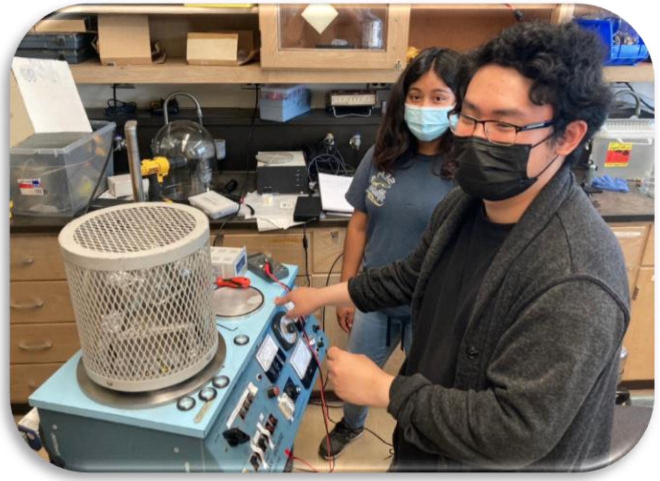
Materials and Targetry

The continued development of targets and materials and for heavy element science and retaining US-based expertise is critical for the heavy element community.

- Support production of actinide target and stable beam materials (e.g. HFIR/SIPRC)
- Support existing target laboratories (e.g. ANL, ORNL, LLNL)
- Support training the next generation (e.g. SJSU, OSU)



High Flux Isotope Reactor at ORNL



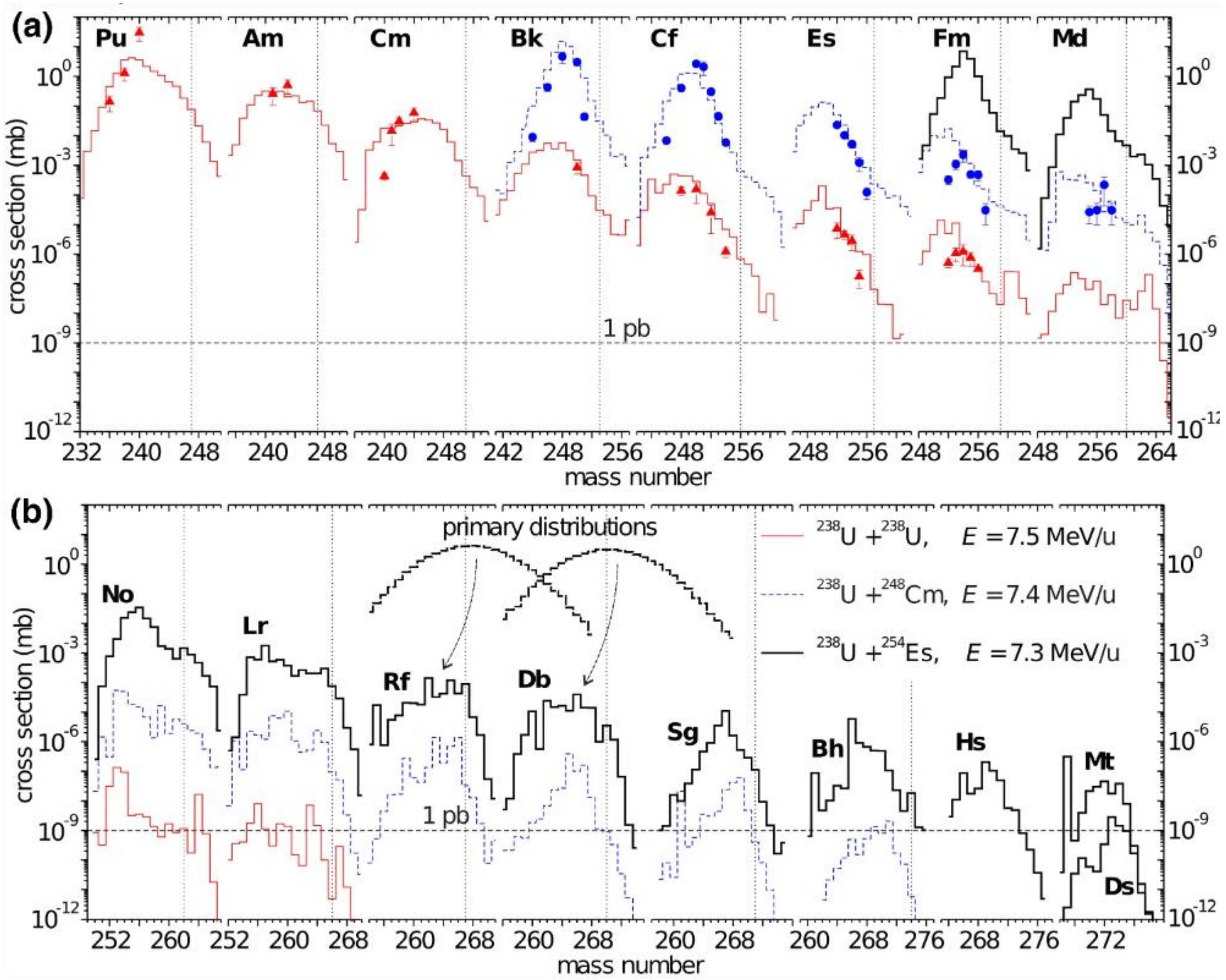
SJSU Students studying vacuum deposition targets

^{243}Am Target

Nuclear Reactions

What is the heaviest element that can be made? Can we access more neutron-rich nuclides near the island of stability?

- Understanding next generation fusion evaporation reactions is crucial for the production of elements beyond Z=118
- Multinucleon transfer reactions show promise for producing more neutron-rich isotopes
- Continued investigation of fusion evaporation, multinucleon transfer reaction and searching for the next evolution is crucial.

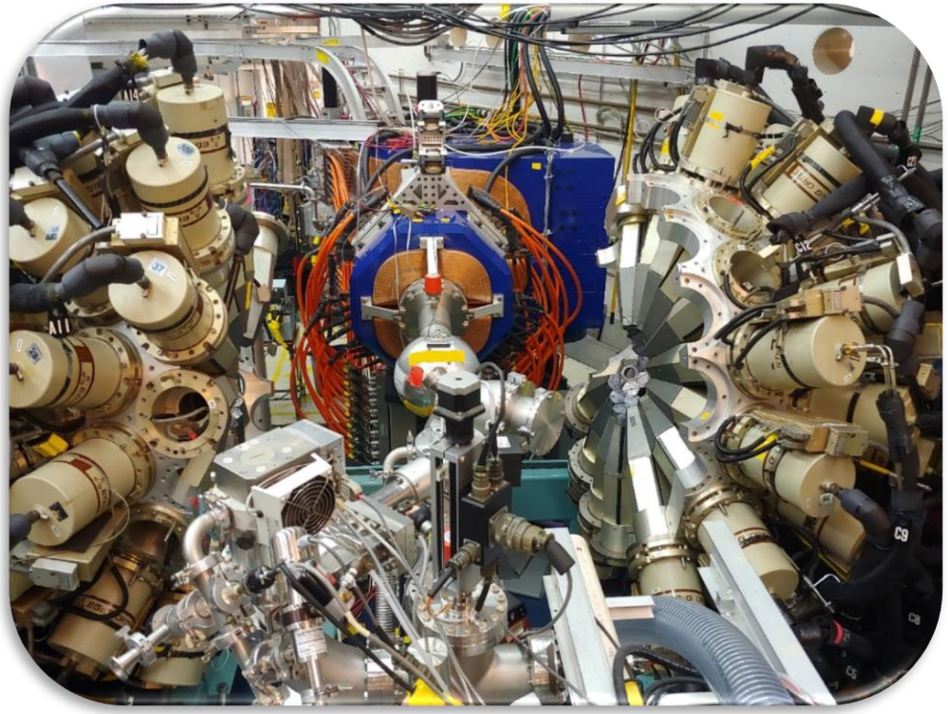


S. Heinz, Eur. Phys. J. A 58, 114 (2022)

Spectroscopy

Spectroscopy of heavy elements ($92<Z<104$) and superheavy ($Z\geq104$) is fundamental to developing a comprehensive picture of their structure and probing the island of stability.

- Direct α-γ and α-decay spectroscopy extended to the superheavy elements – directly probing levels in the heaviest elements
- Prompt and isomer spectroscopy on transfermium elements – probes the pairing, shapes, elementary excitation modes, and the robustness of fission barriers at high angular momentum for these very heavy nuclei
- Continued nuclear structure studies are key to understanding the location and properties of the island of stability



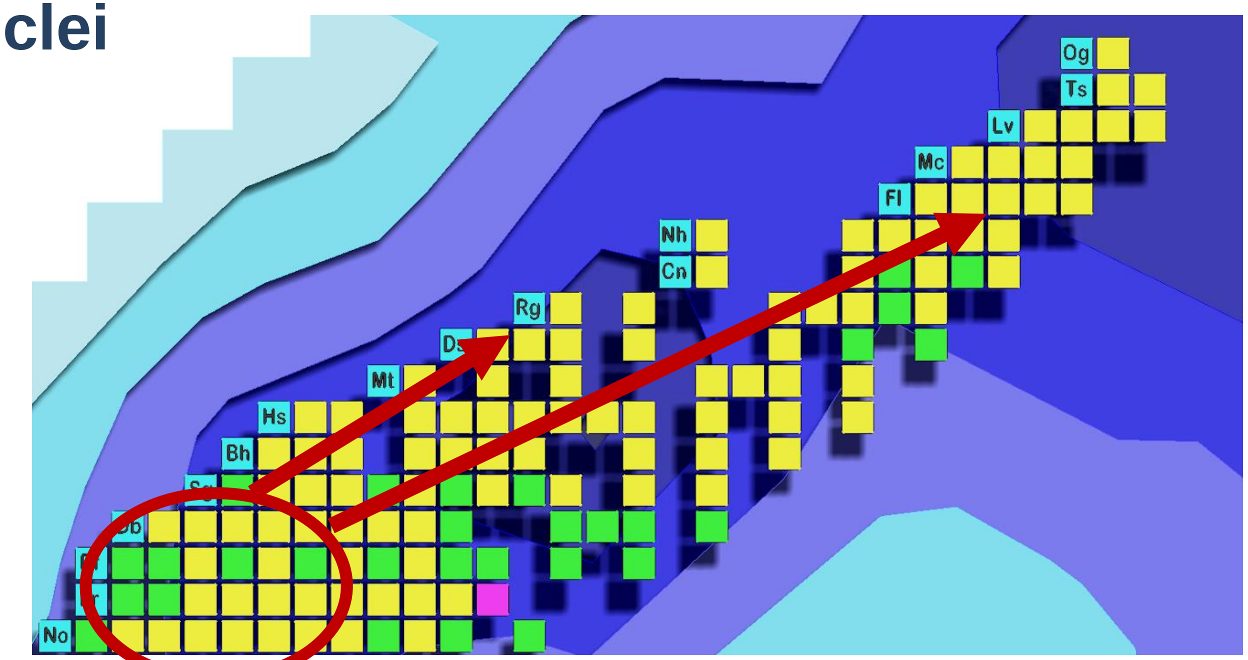
Gammasphere and AGFA @ANL

Spectroscopy

Spectroscopy of heavy elements (92<Z<104) and superheavy (Z≥104) is fundamental to developing a comprehensive picture of their structure and probing the island of stability.

Gammasphere and AGFA @ANL

- In-beam, K-isomers, α-decay fine structure near the deformed Z=100, N=152 shell gaps ➔ deformation, moments of intertia, single nucleon energies, pairing
- **Stringent testing ground for models of super-heavy nuclei**



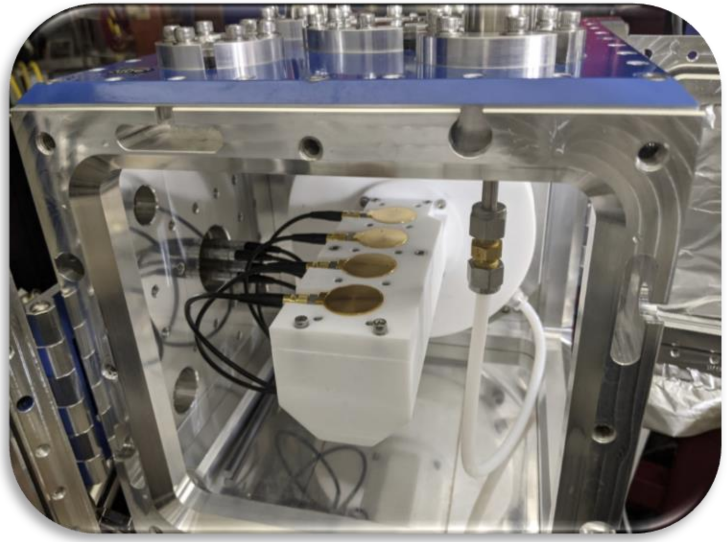
- Continued nuclear structure studies are key to understanding the location and properties of the island of stability

Chemistry

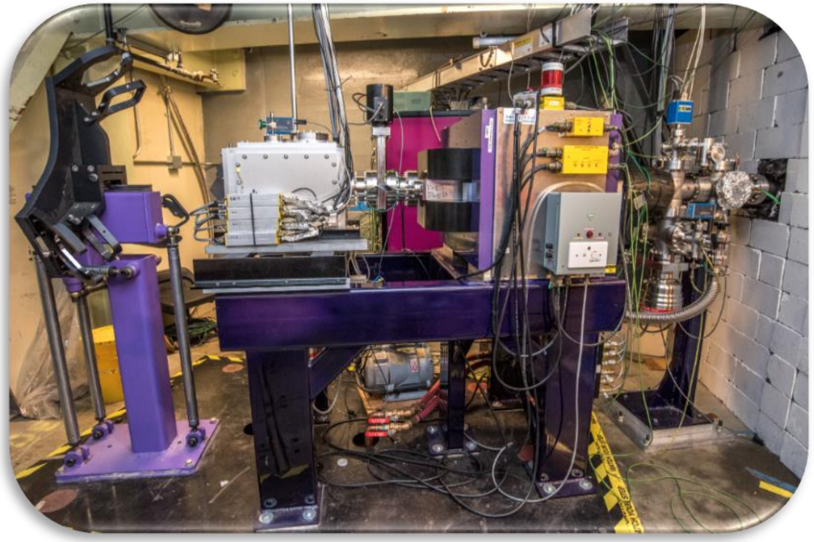
What happens to the chemical behavior of the heaviest elements due to relativistic effects in their electronic structure? Do the well studied chemical trends of their lighter counterparts break down? Do we need to rethink how to organize the Periodic Table for the heaviest nuclei?

- New advances in heavy element chemistry apparatus will begin unlocking the answers to these questions

Automated liquid-liquid extraction at LLNL



Liquid-Phase Chromatography at Texas A&M



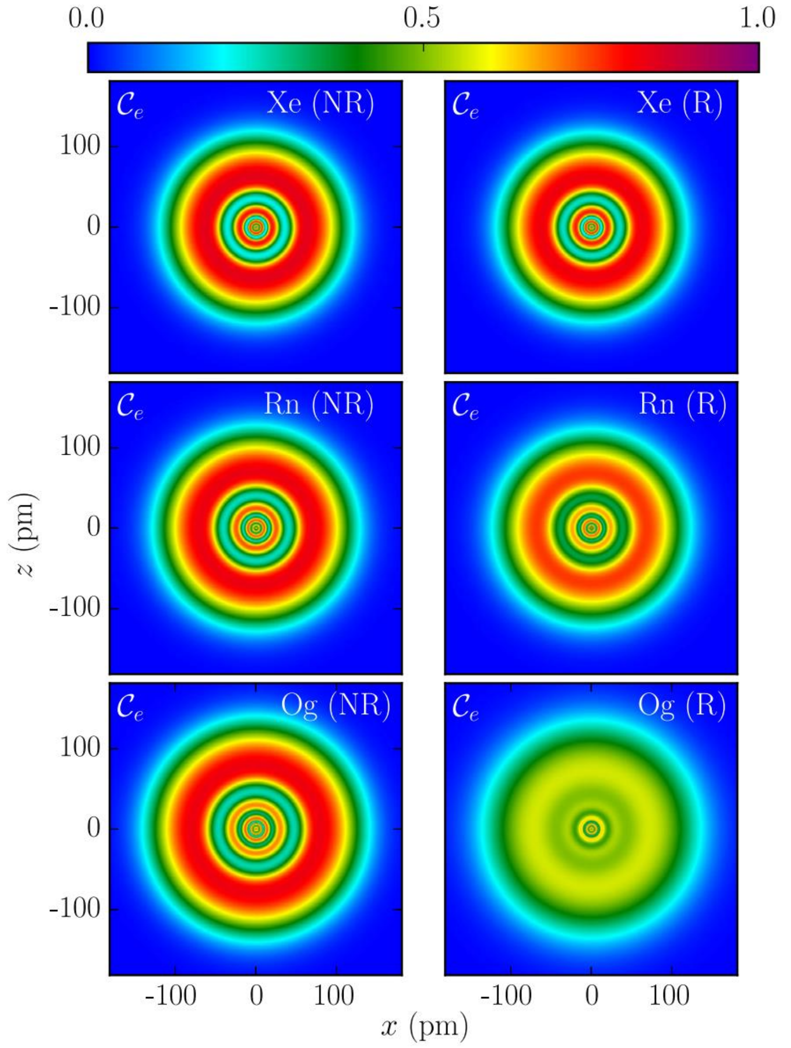
FIONA Gas Phase Chemistry at LBNL

Theory

Advances in theory are the foundation to understand how nuclei behave and to predict those behaviors in new circumstances

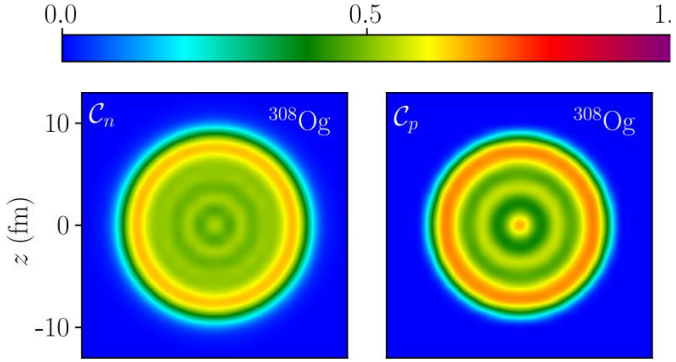
Next generation theoretical calculations are vital for understanding the shape of nuclei, limits of nuclear stability, chemistry of the heaviest elements, and reaction mechanisms for isotope discovery.

Support for theory is critical to the advancement of our understanding of superheavy elements and new Production pathways



Electron Localization Function

Non-relativistic Relativistic



Nucleon Localization Function

Non-relativistic Relativistic

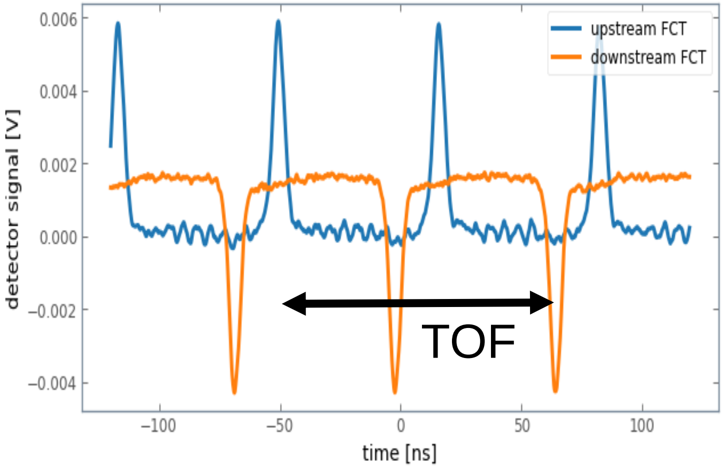
Jerabek, et al, Phys. Rev. Lett.
120, 053001 (2018)

Towards the Discovery of Element 120

Discovery of the next superheavy element can be done at US facilities

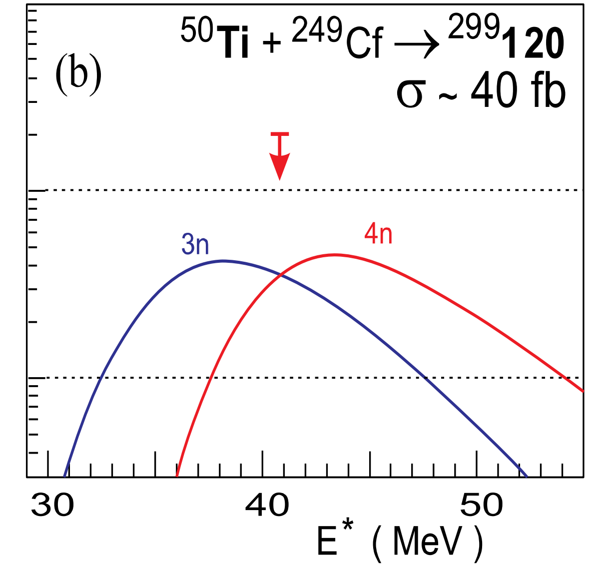
- ^{249}Cf(^{50}Ti,xn)${}^{299\text{-}x}$E120 has a predicted cross section of ~40 fb.
- Collect about ≈ 0.85 E120 events per 1000 hours
- upgrades to the BGS at LBNL underway to prepare for an FY24 E120 search
- Proof-of-Principle test: ^{50}Ti+^{244}Pu

LUND UNIVERSITY



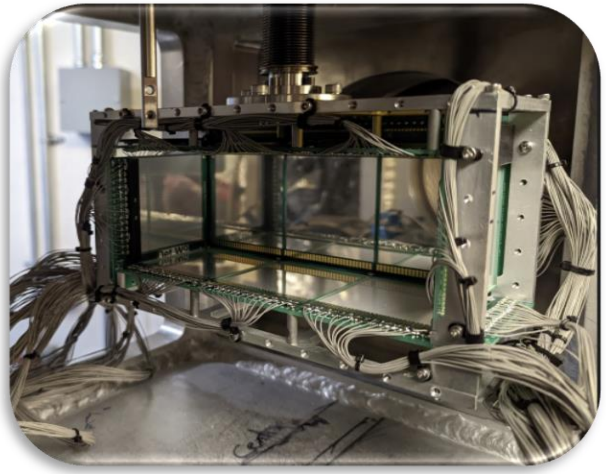
TOF Device for beam energy measurement

Digital Electronics

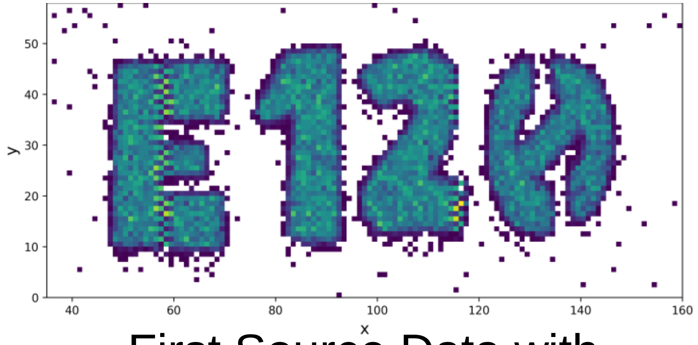


Zagrabaev, Karpov, and Greiner (2013)

Ovens for high-intensity Ti



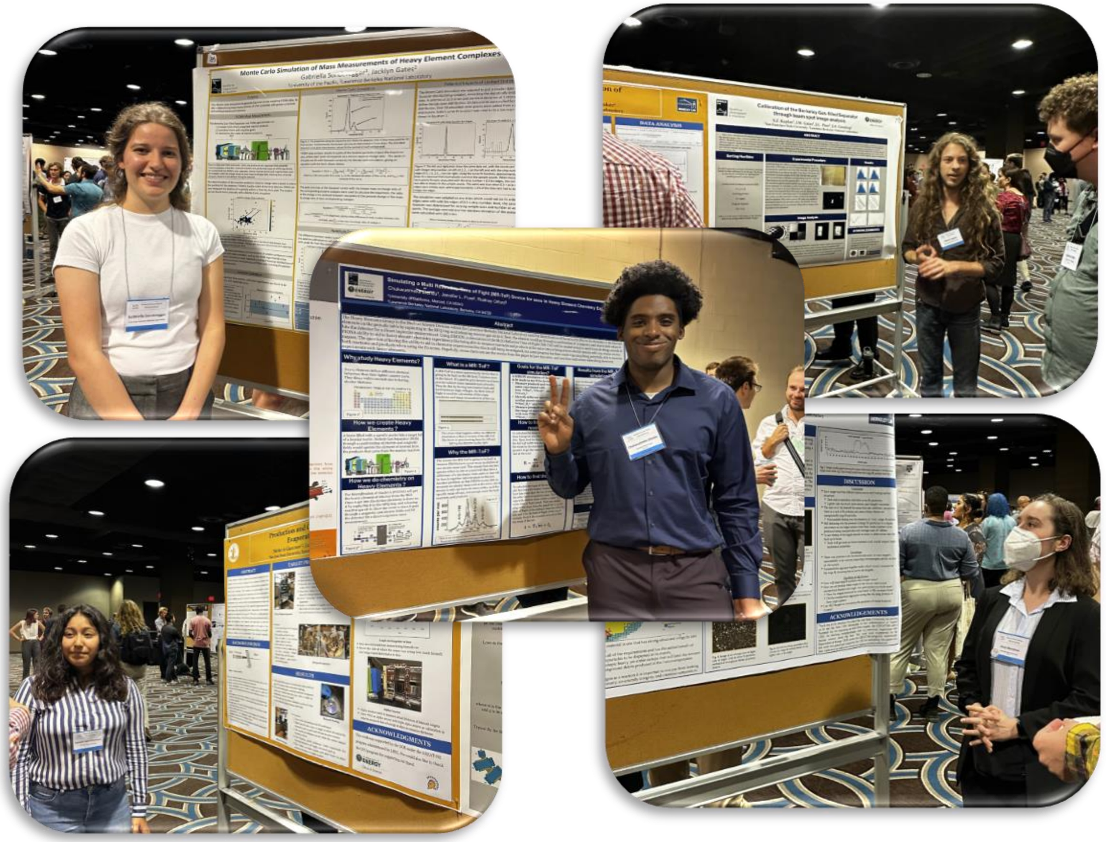
Large-area focal plane detector



First Source Data with New Detector

Training the Next Generation

The future health of the heavy element field is dependent on the continuous support of talented early career professionals at all levels. The heavy element community supports continued investment in programs with initiatives in diversity, equity, and inclusion.



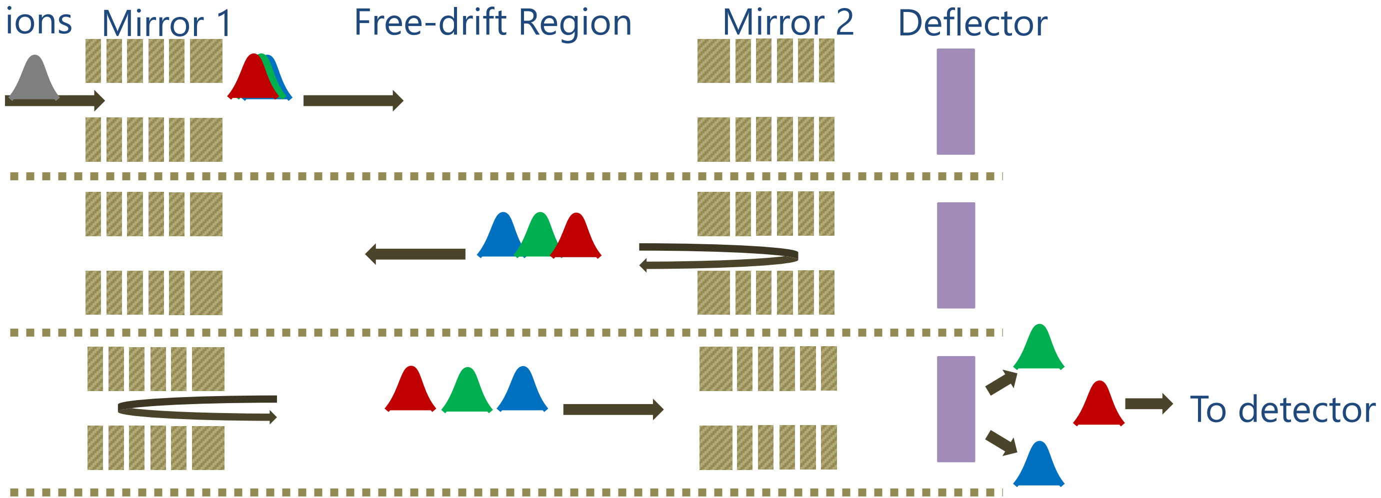
Undergraduate GREAT-NS trainees from the heavy element community at DNP

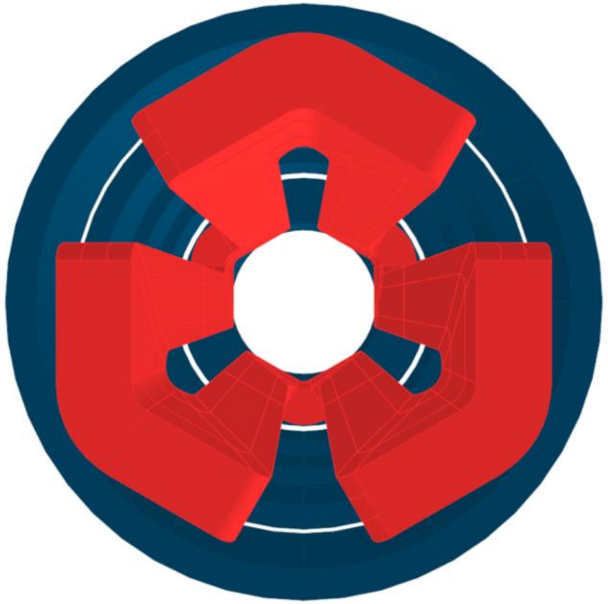
SJSU Students developing novel target techniques

A Look Towards the Future

What is the heaviest element that exists? Where does the periodic table end?

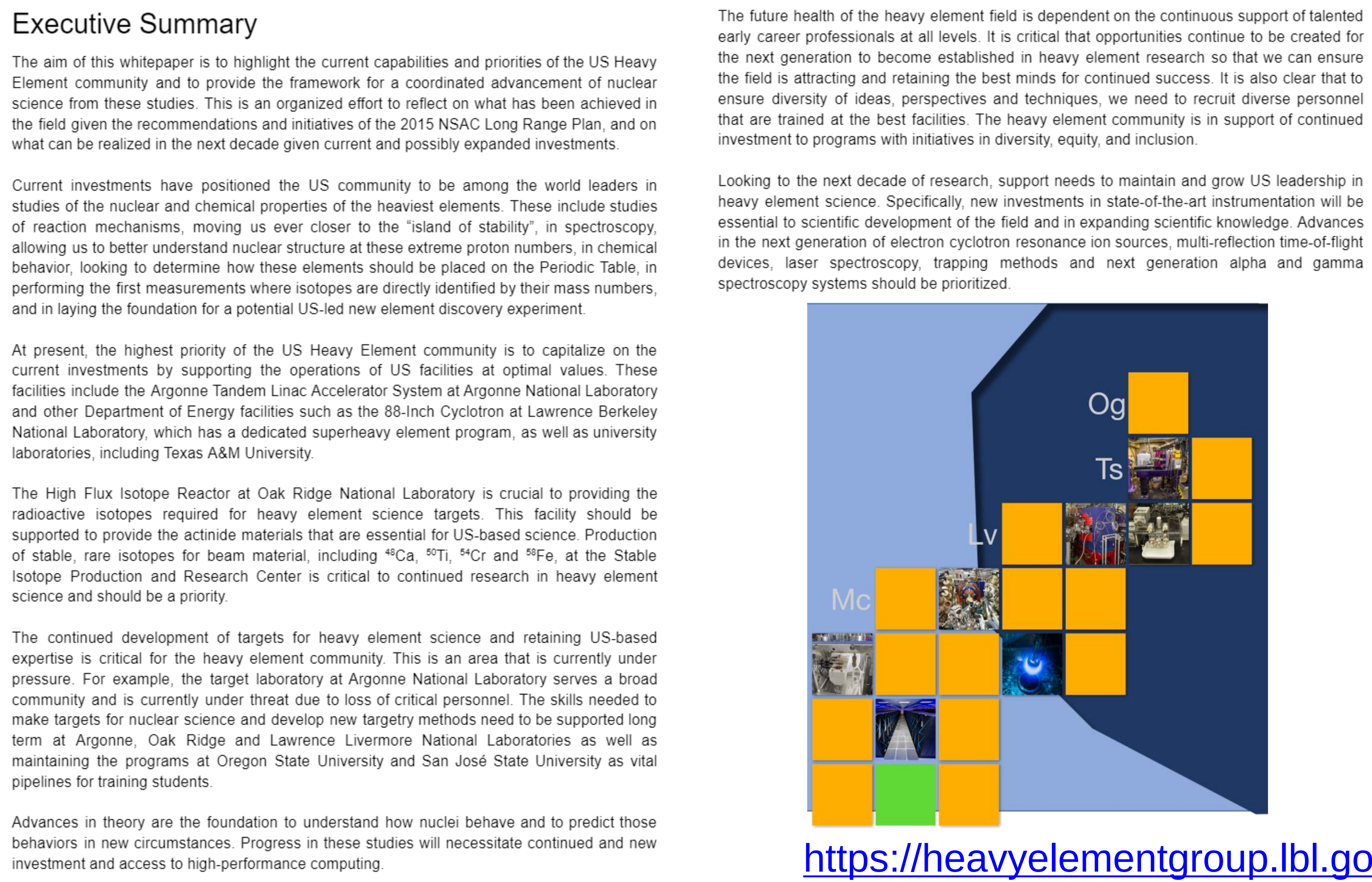
- Multi-reflection time-of-flight device for high-precision mass measurements
- Next generation of electron cyclotron resonance ion sources
- Next generation alpha and gamma spectroscopy systems
- Multi-Nucleon Transfer reactions
- Laser spectroscopy
- Trapping methods





MARS

Executive Summary



Executive Summary

The aim of this whitepaper is to highlight the current capabilities and priorities of the US Heavy Element community and to provide the framework for a coordinated advancement of nuclear science from these studies. This is an organized effort to reflect on what has been achieved in the field given the recommendations and initiatives of the 2015 NSAC Long Range Plan, and on what can be realized in the next decade given current and possibly expanded investments.

Current investments have positioned the US community to be among the world leaders in studies of the nuclear and chemical properties of the heaviest elements. These include studies of reaction mechanisms, moving us ever closer to the "island of stability", in spectroscopy, allowing us to better understand nuclear structure at these extreme proton numbers, in chemical behavior, looking to determine how these elements should be placed on the Periodic Table, in performing the first measurements where isotopes are directly identified by their mass numbers, and in laying the foundation for a potential US-led new element discovery experiment.

At present, the highest priority of the US Heavy Element community is to capitalize on the current investments by supporting the operations of US facilities at optimal values. These facilities include the Argonne Tandem Linac Accelerator System at Argonne National Laboratory and other Department of Energy facilities such as the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory, which has a dedicated superheavy element program, as well as university laboratories, including Texas A&M University.

The High Flux Isotope Reactor at Oak Ridge National Laboratory is crucial to providing the radioactive isotopes required for heavy element science targets. This facility should be supported to provide the actinide materials that are essential for US-based science. Production of stable, rare isotopes for beam material, including ^{48}Ca, ^{50}Ti, ^{54}Cr and ^{58}Fe, at the Stable Isotope Production and Research Center is critical to continued research in heavy element science and should be a priority.

The continued development of targets for heavy element science and retaining US-based expertise is critical for the heavy element community. This is an area that is currently under pressure. For example, the target laboratory at Argonne National Laboratory serves a broad community and is currently under threat due to loss of critical personnel. The skills needed to make targets for nuclear science and develop new targetry methods need to be supported long term at Argonne, Oak Ridge and Lawrence Livermore National Laboratories as well as maintaining the programs at Oregon State University and San José State University as vital pipelines for training students.

Advances in theory are the foundation to understand how nuclei behave and to predict those behaviors in new circumstances. Progress in these studies will necessitate continued and new investment and access to high-performance computing.

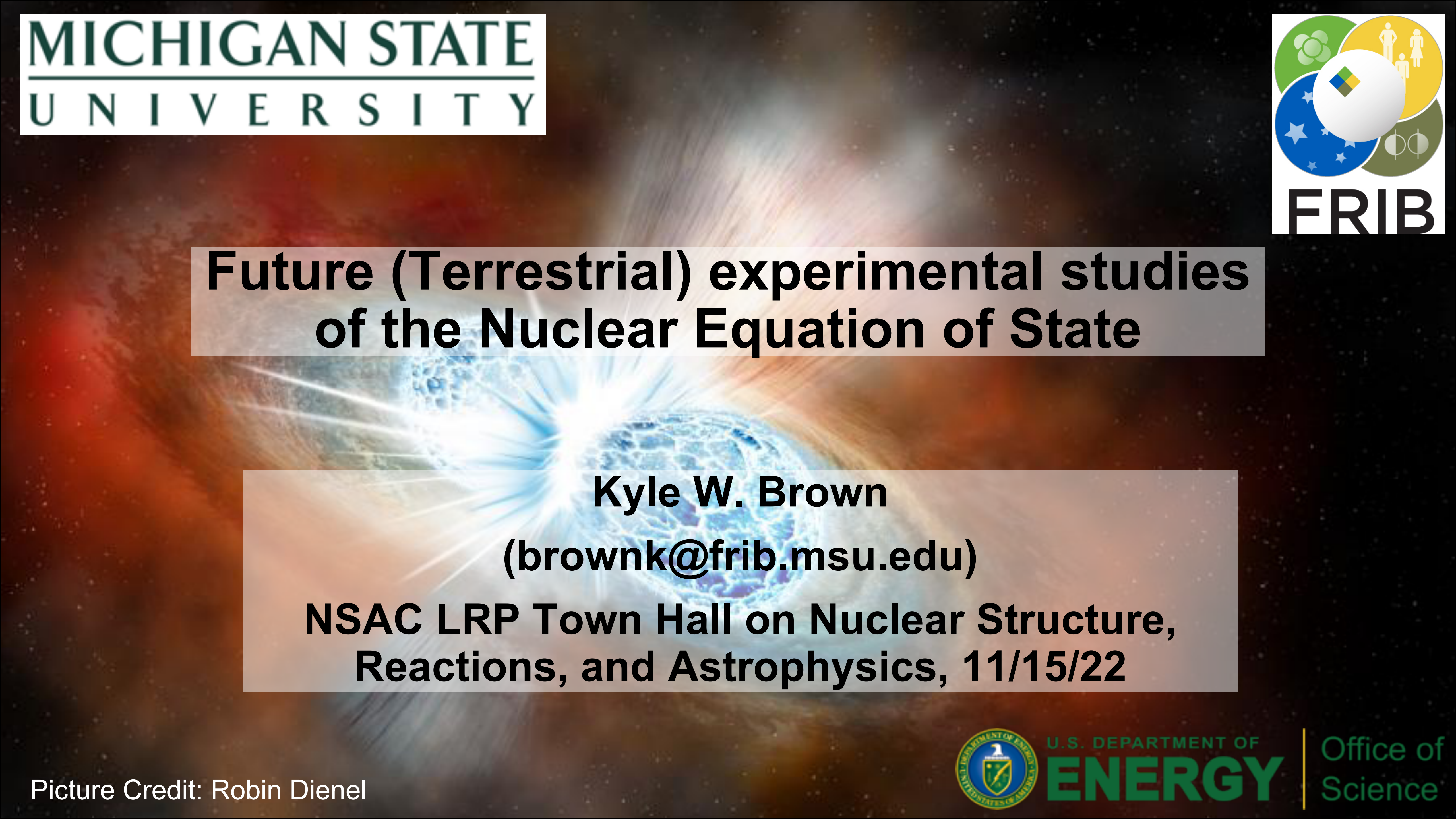
The future health of the heavy element field is dependent on the continuous support of talented early career professionals at all levels. It is critical that opportunities continue to be created for the next generation to become established in heavy element research so that we can ensure the field is attracting and retaining the best minds for continued success. It is also clear that to ensure diversity of ideas, perspectives and techniques, we need to recruit diverse personnel that are trained at the best facilities. The heavy element community is in support of continued investment to programs with initiatives in diversity, equity, and inclusion.

Looking to the next decade of research, support needs to maintain and grow US leadership in heavy element science. Specifically, new investments in state-of-the-art instrumentation will be essential to scientific development of the field and in expanding scientific knowledge. Advances in the next generation of electron cyclotron resonance ion sources, multi-reflection time-of-flight devices, laser spectroscopy, trapping methods and next generation alpha and gamma spectroscopy systems should be prioritized.

https://heavyelementgroup.lbl.gov/white-paper

MICHIGAN STATE UNIVERSITY

FRIB



Future (Terrestrial) experimental studies of the Nuclear Equation of State

Kyle W. Brown

(brownk@frib.msu.edu)

NSAC LRP Town Hall on Nuclear Structure, Reactions, and Astrophysics, 11/15/22

Picture Credit: Robin Dienel

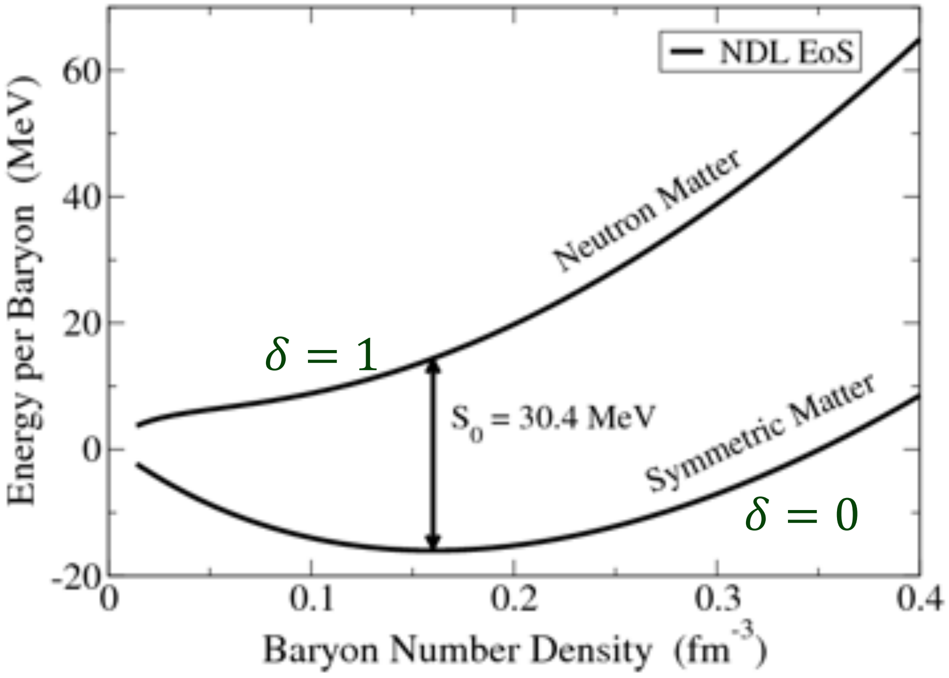
U.S. DEPARTMENT OF ENERGY | Office of Science

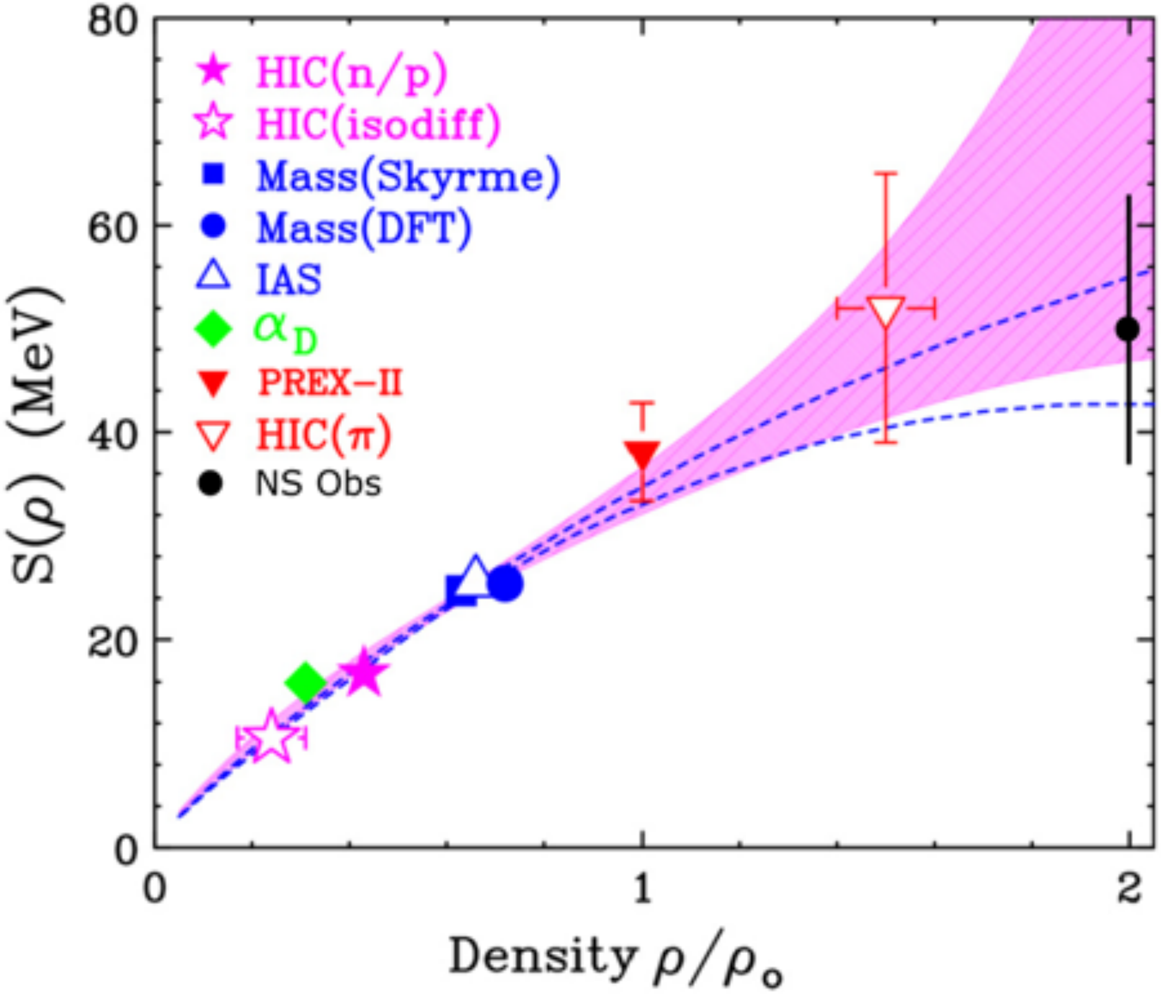
Nuclear Equation of State

Symmetric Matter

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta = 0) + S(\rho)\delta^2$$

Asymmetric Matter

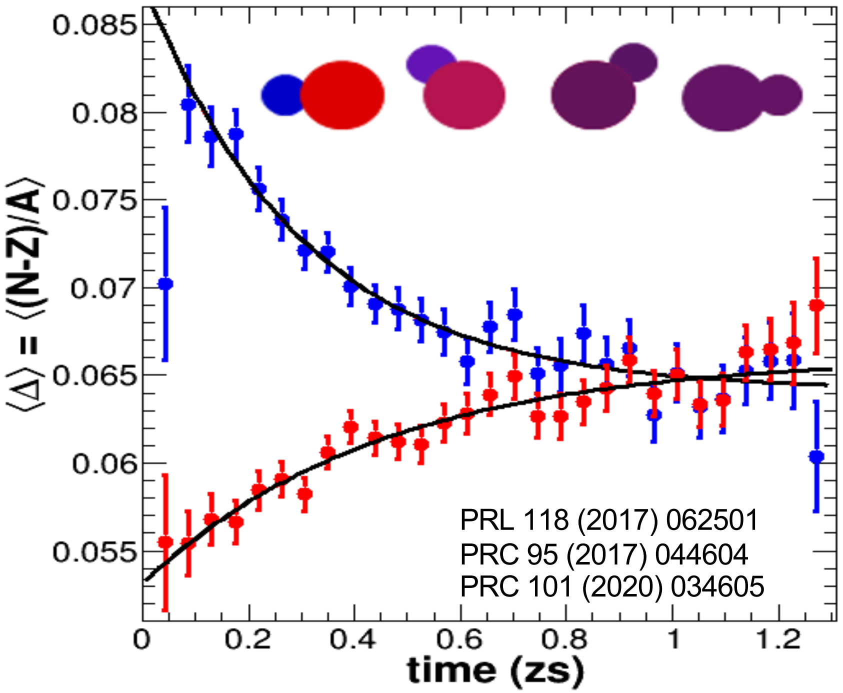




U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

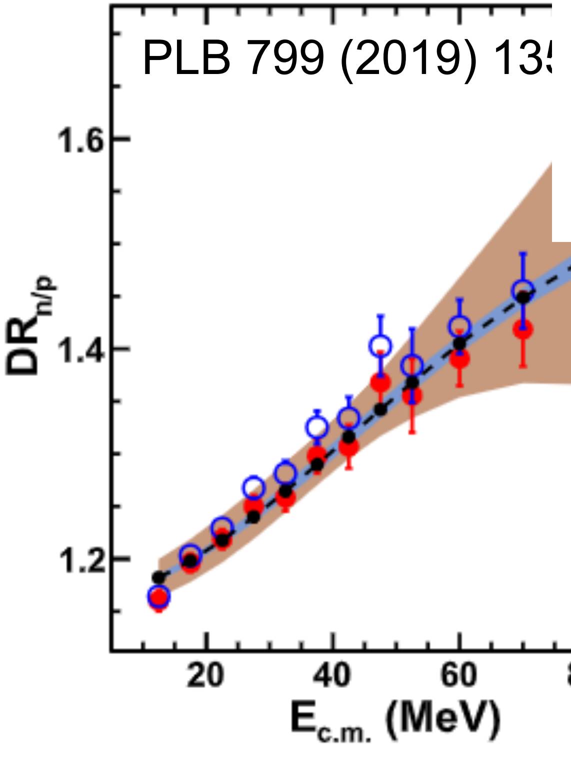
M. Meixner arXiv:1303.0064 [astro-ph.HE]
Lynch and Tsang PLB 830, 137098 (2022)

Symmetry Energy @ $\rho < \rho_0$

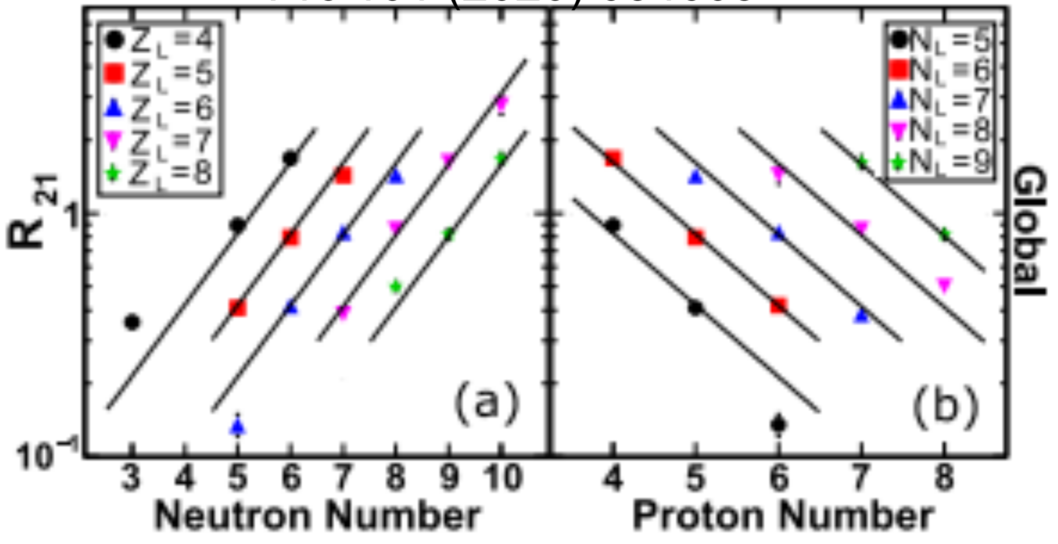


PRL 118 (2017) 062501
PRC 95 (2017) 044604
PRC 101 (2020) 034605

PLB 799 (2019) 13

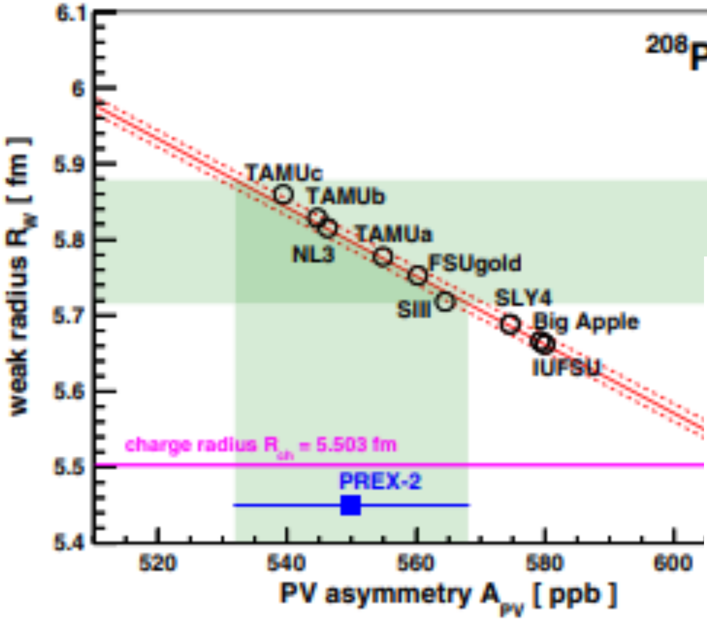


Prc 101 (2020) 034605

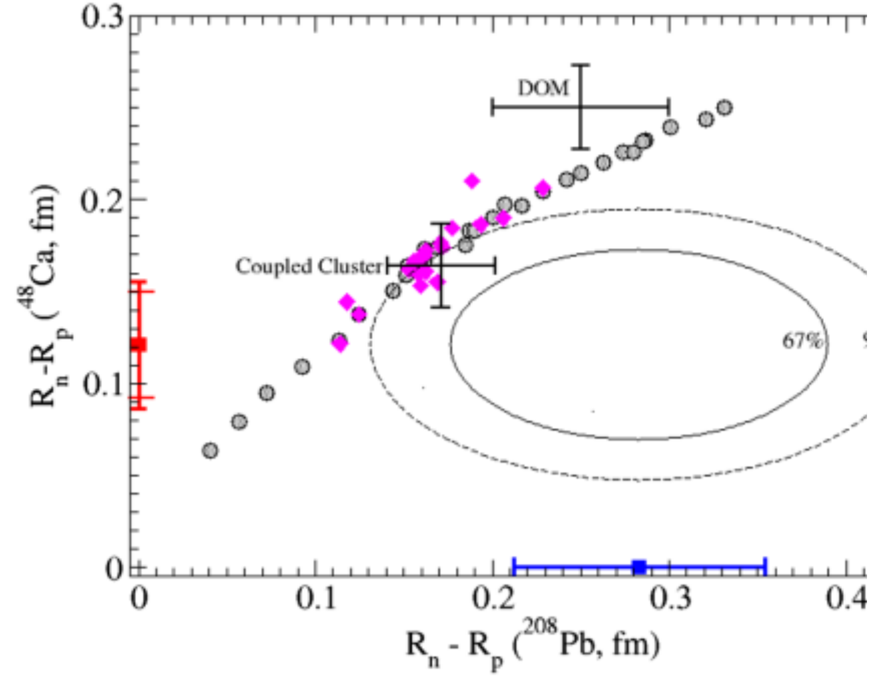


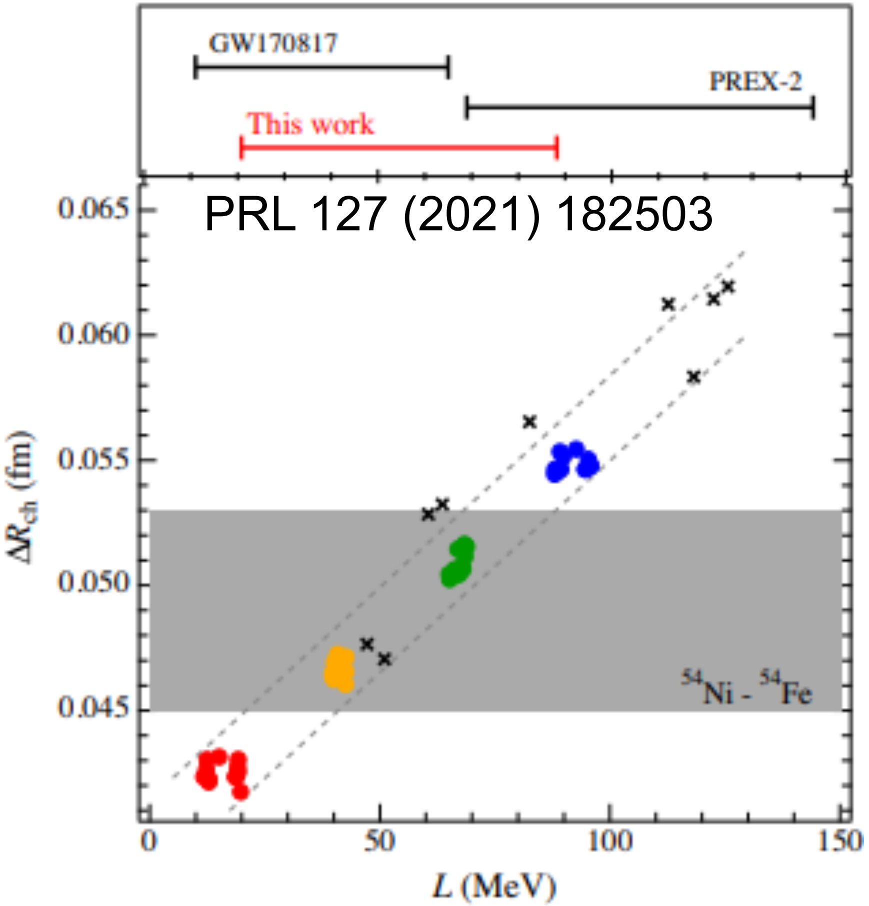
Symmetry Energy @ $\rho \approx \rho_0$

PRL 126 (2021) 172502



PRL 129 (2022) 042501

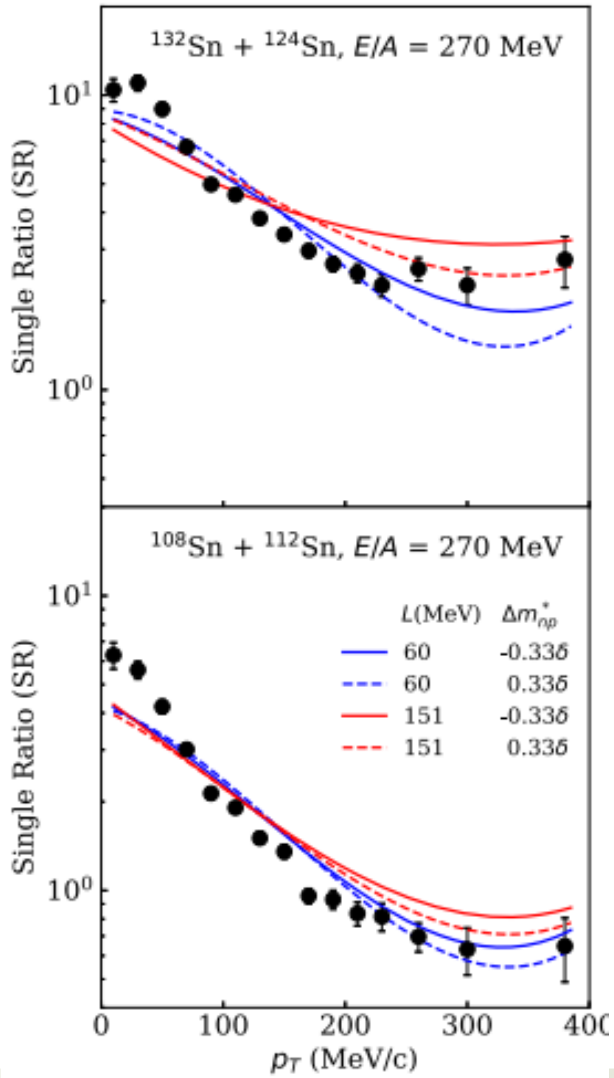




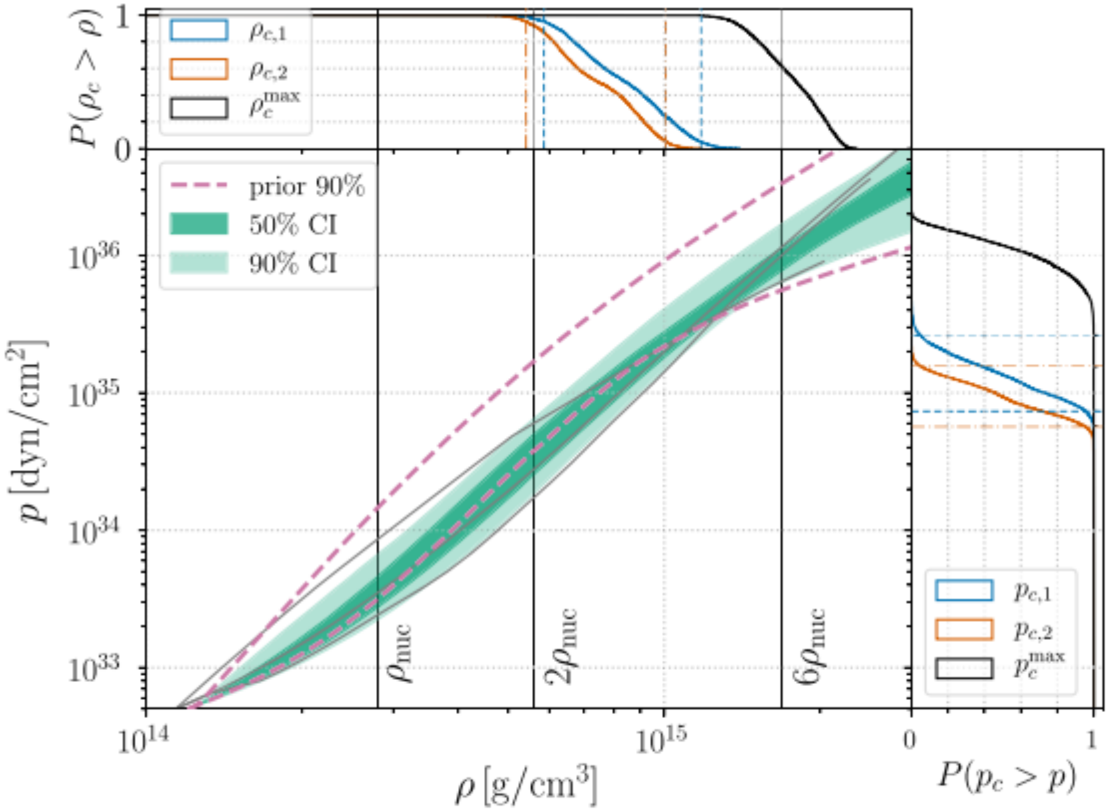
PRL 127 (2021) 182503

Symmetry Energy @ $\rho > \rho_0$

PRL 126 (2021) 162701



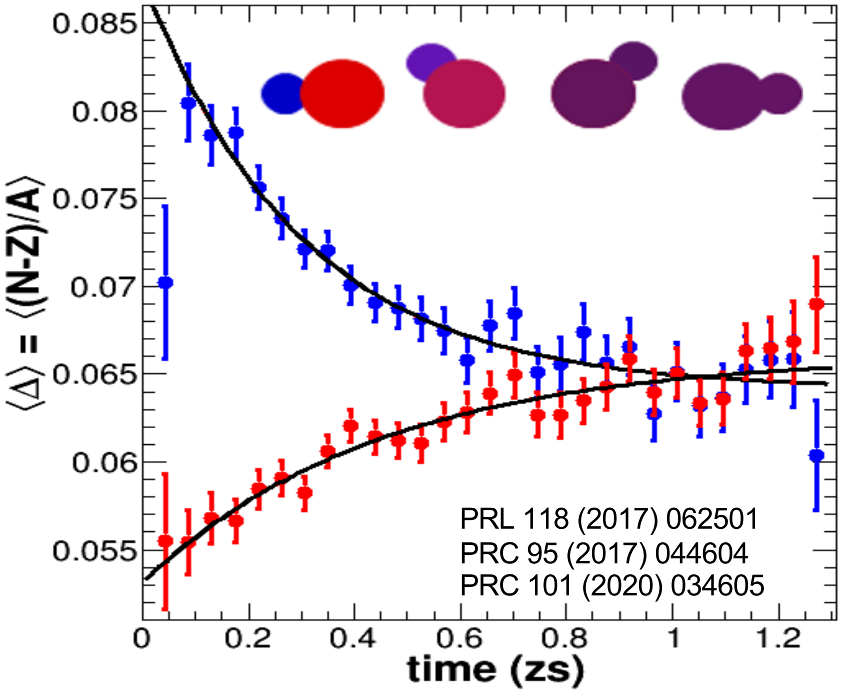
PRL 121 (2018) 161101



U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Future Perspectives and Experimental Needs

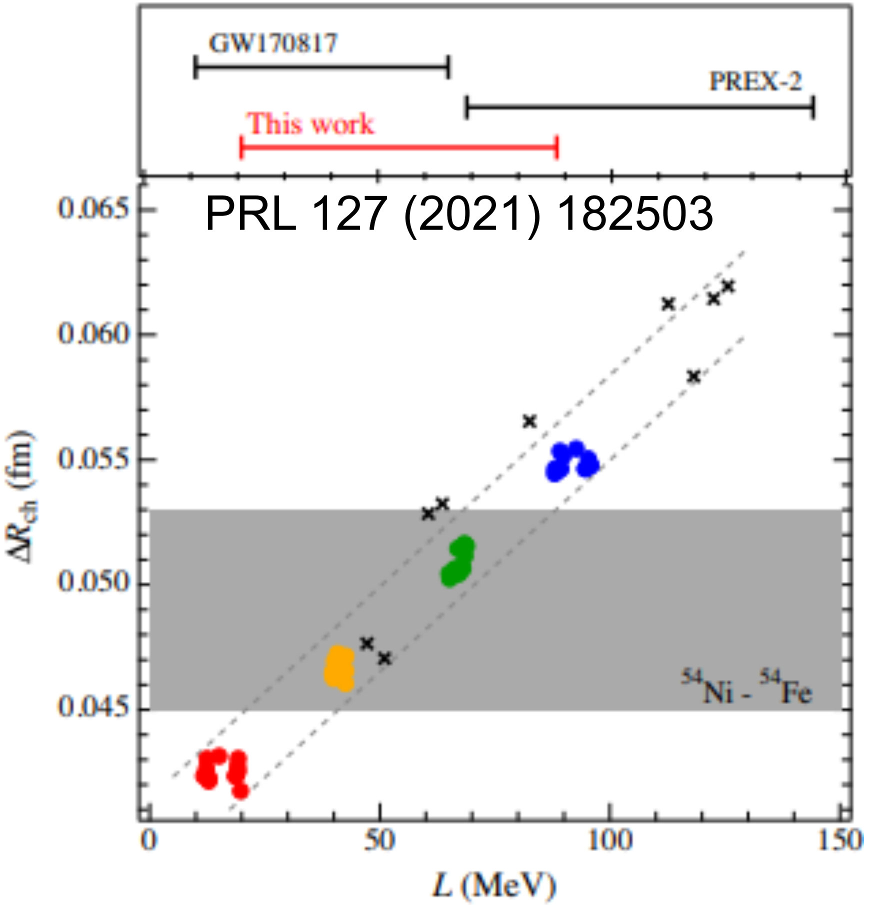
$\rho < \rho_0$



- Main physics foci:
  - Binary breakup -> N/Z equilibration
  - Isoscaling -> n and p chemical potentials
  - Particle ratios -> Momentum dependence (effective masses)

- Equipment Needs
  - High resolution and/or high solid angle charged particle arrays (NIMROD, FUAST, HiRA, Microball,etc)
  - Neutron detectors (LANA)
  - TPCs (SπRIT, AT-TPC (@ReA and S2), HRS-TPC)
  - Centrality and reaction plane (Microball, Fibers)

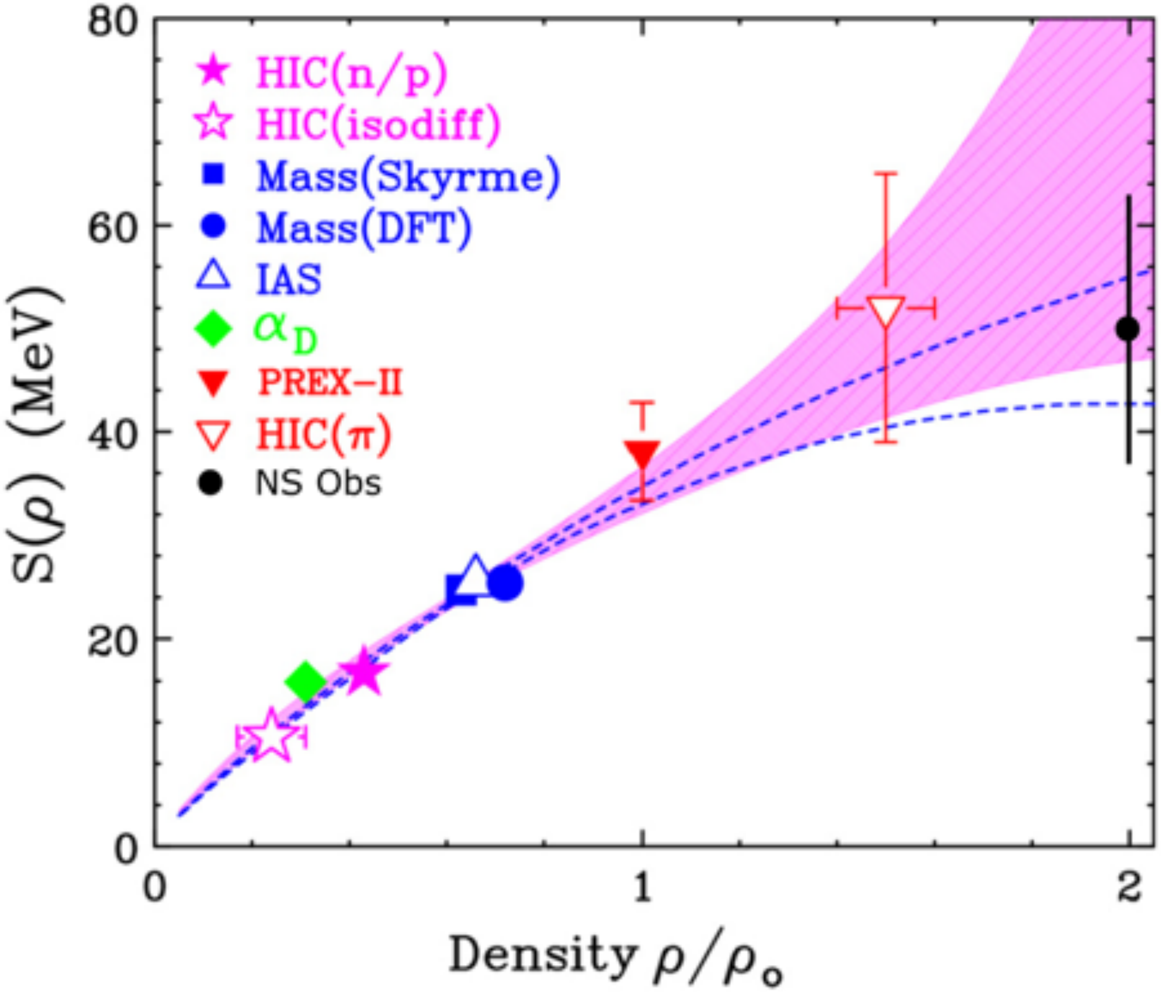
$\rho \approx \rho_0$

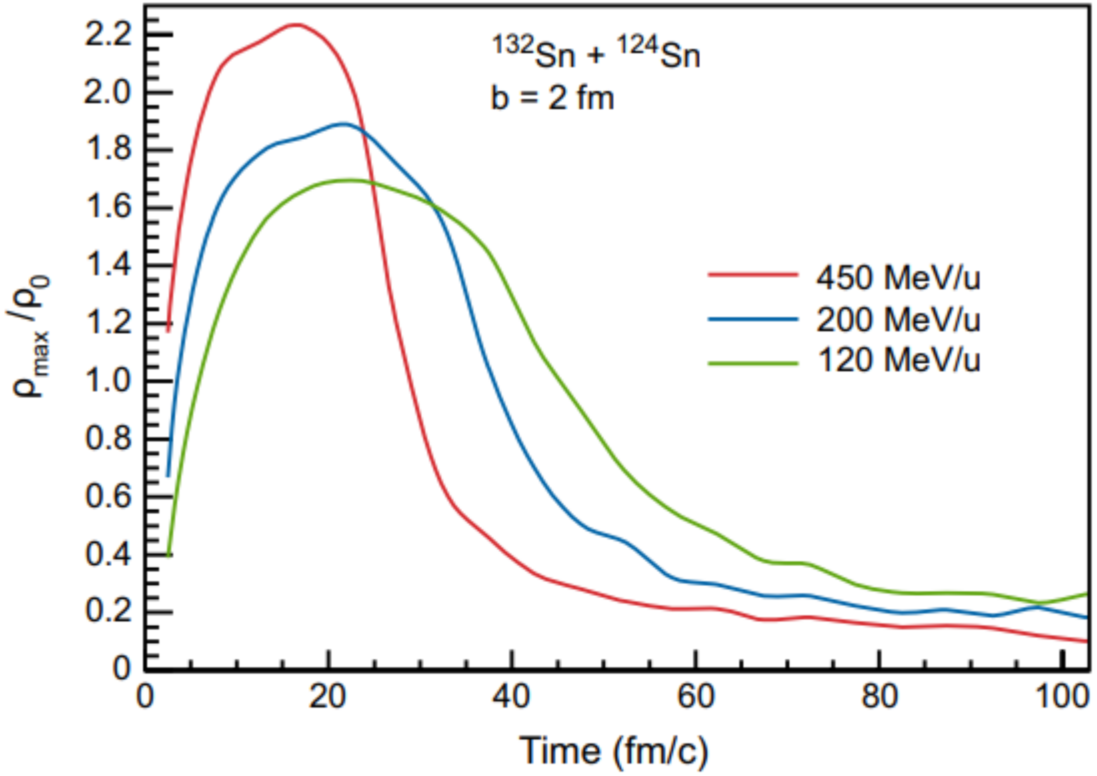


- With new n-rich and n-deficient beams at FRIB, laser measurements of charged radii will enable stringent constraints of n-skin thicknesses from mirror pairs
- Natural limit due to lifetimes
- Can we do 48Ni vs 48Ca?

$\rho > \rho_0$

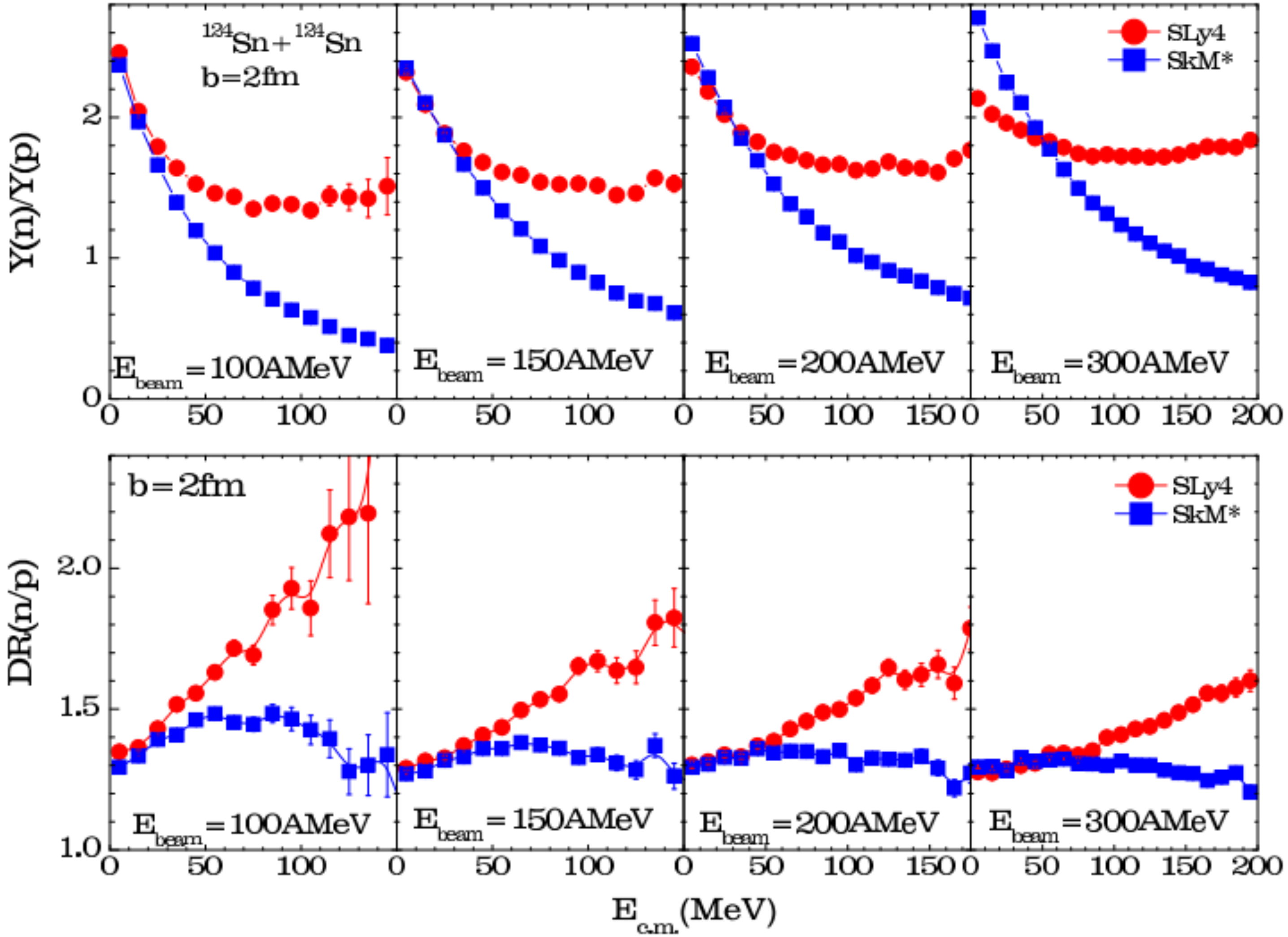
EoS Studies at FRIB





Momentum dependence

- The sensitivity of the n/p ratio on the effective mass (momentum dependence) drops off with beam energy
- If we want to measure this for higher density, we need another observable



Zhang *et al*. PLB 2014

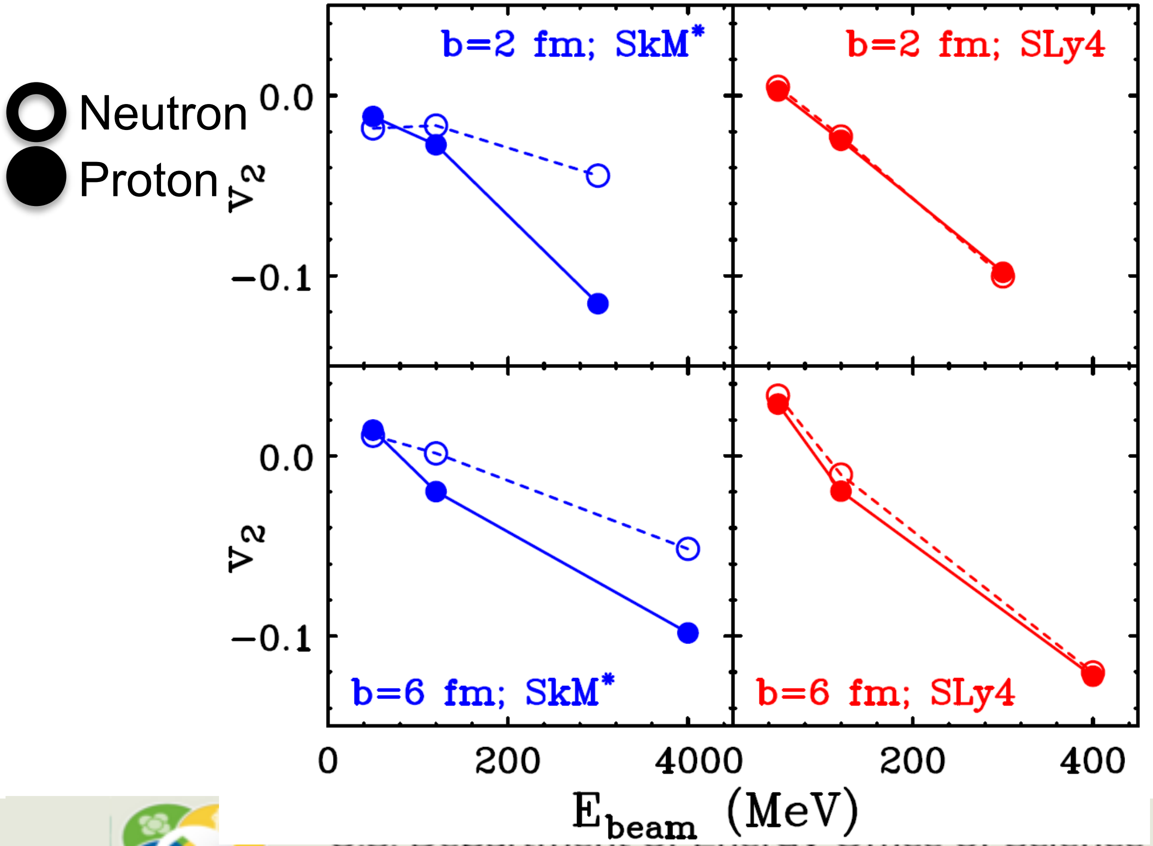
Directed and Elliptical Flow

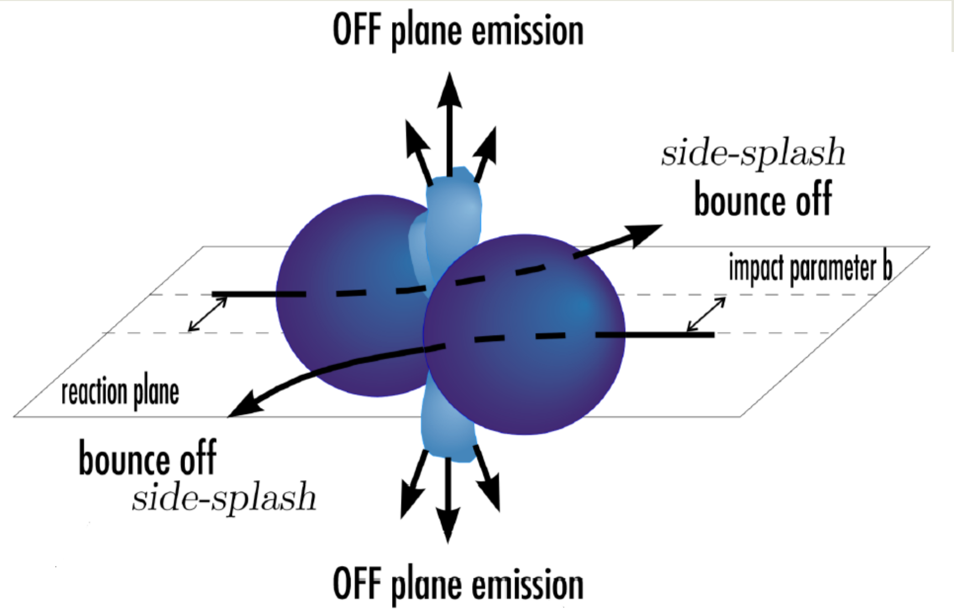
Directed flow

$$v_1 = \left\langle \frac{p_x}{p_\perp} \right\rangle$$

Elliptical flow

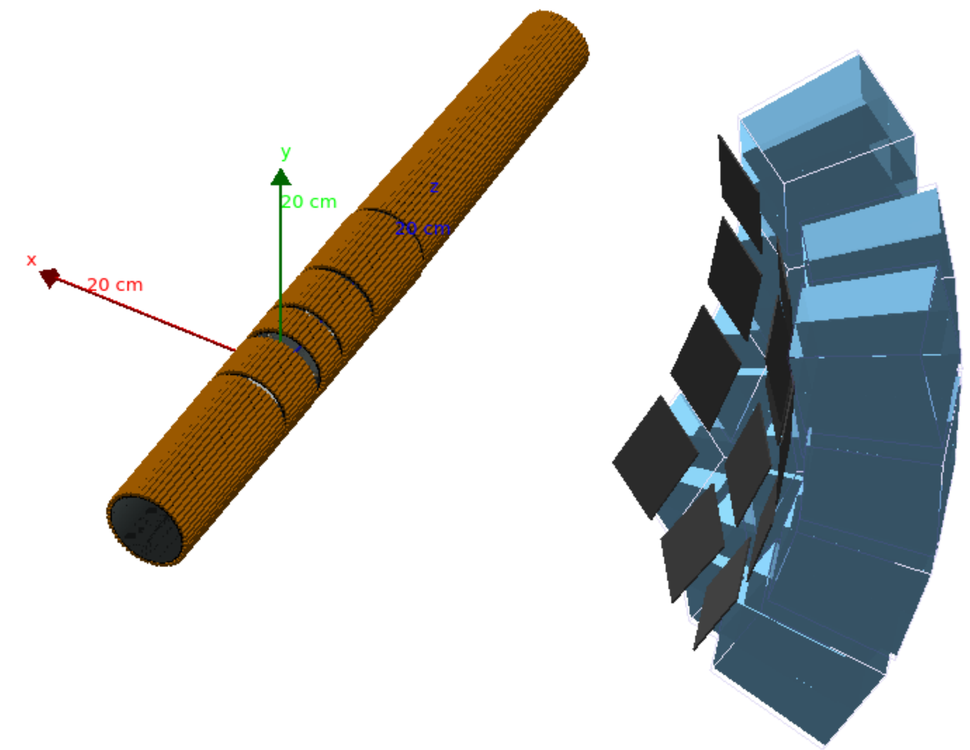
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_\perp^2} \right\rangle$$

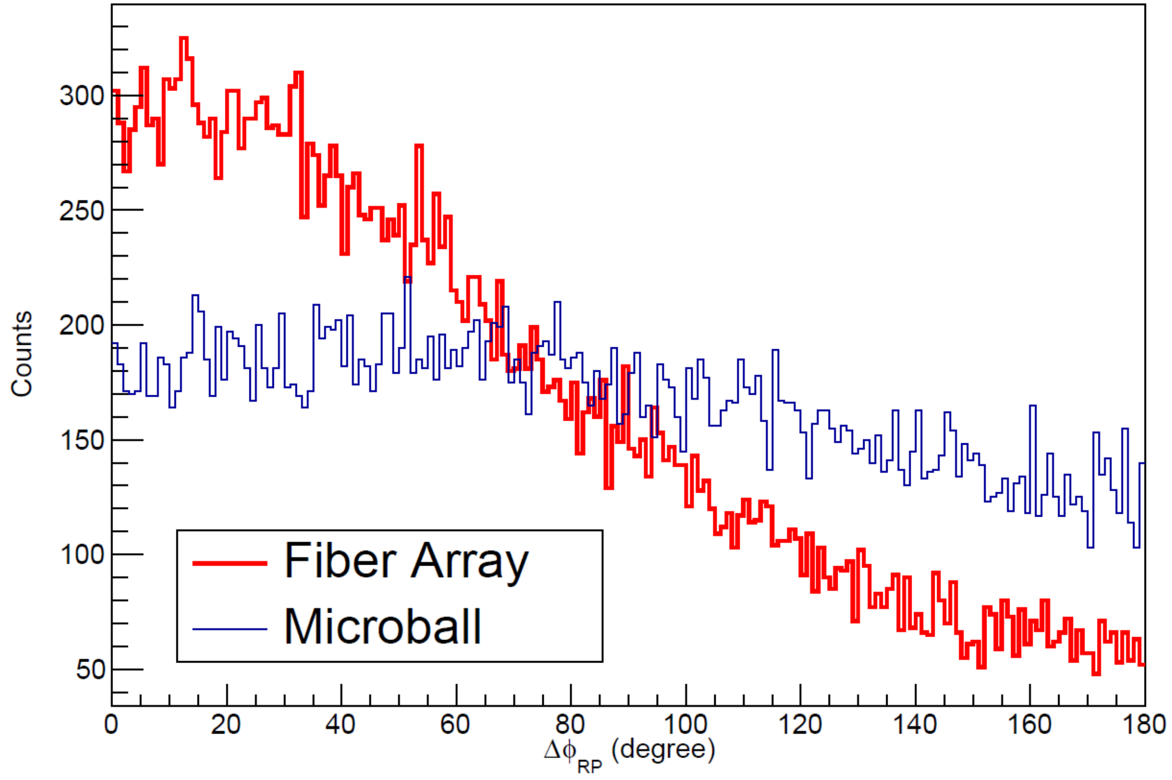




- Projectile and target “spectators” block the escape of matter rom the high P region and force it out of plane.
- Magnitude of this enhancement reflects the pressure in the central region
- v_2 more selective probe than n/p spectral ratio of the symmetry with smaller systematic errors

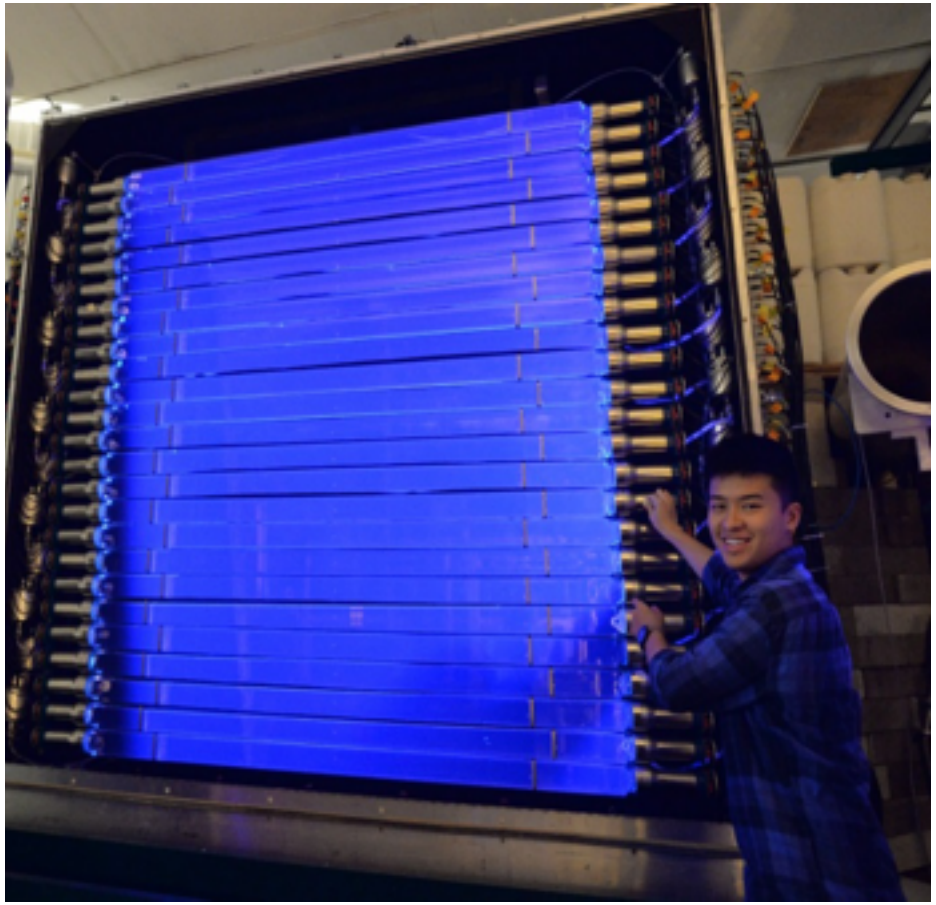
Need: Reaction plane detector





- 4 pi array made barrels of scintillating fibers
- 48 fibers per barrel
- Phi resolution is most important

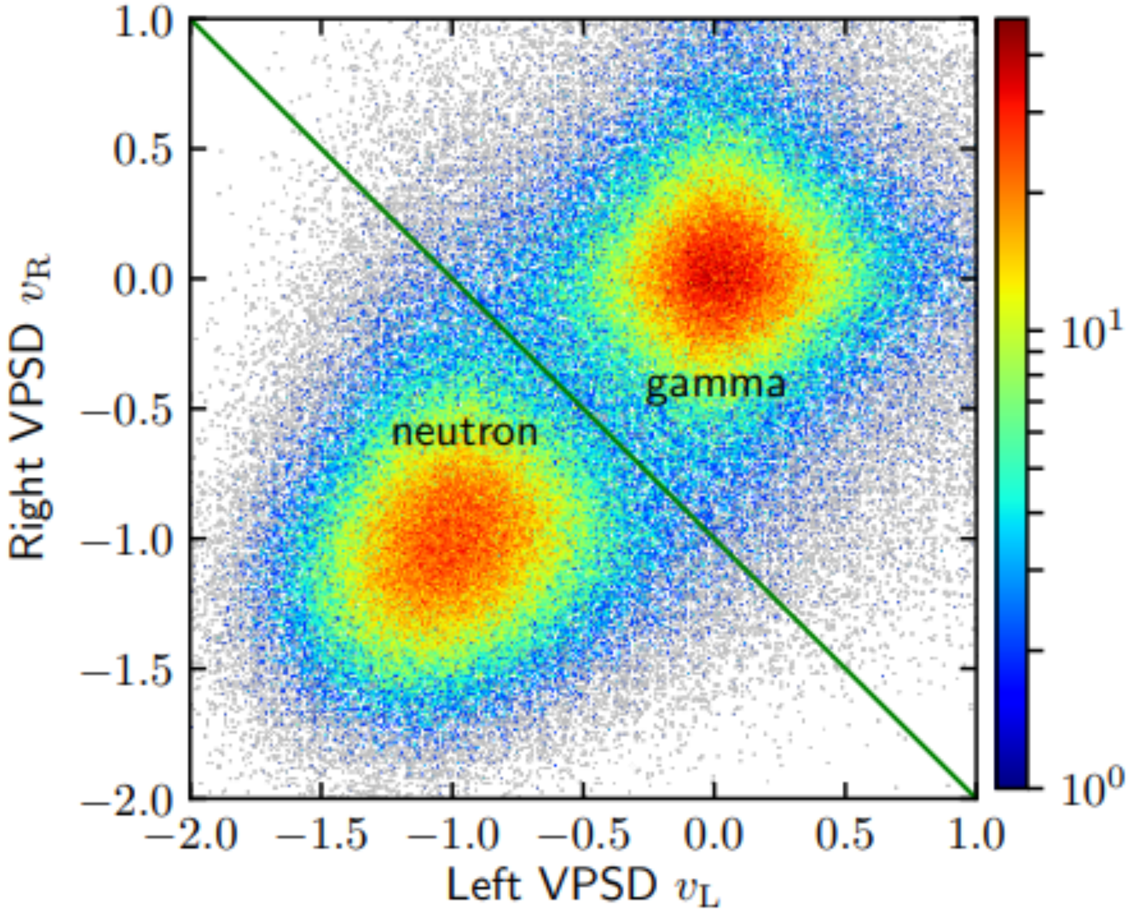
Experiment: Neutron Detection



- 50 -- 8 cm x 8 cm x 2 m long bars
- Liquid-scintillator filled for PSD

- Made at WMU
- 25 Plastic Scintillator bars
- Used to veto charged particles

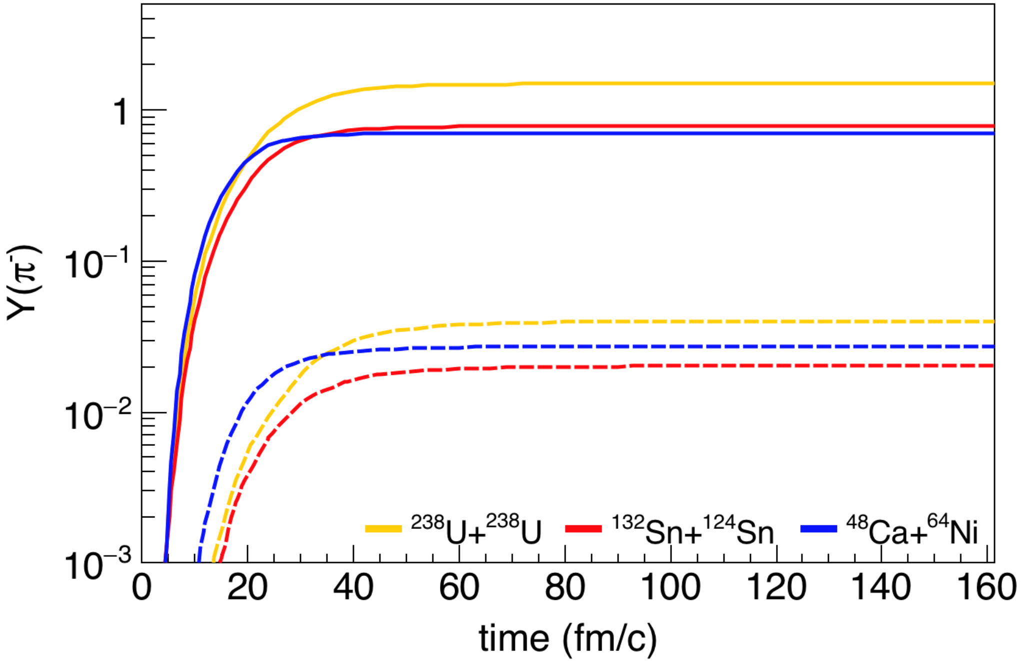
Large Area Neutron Array (LANA)

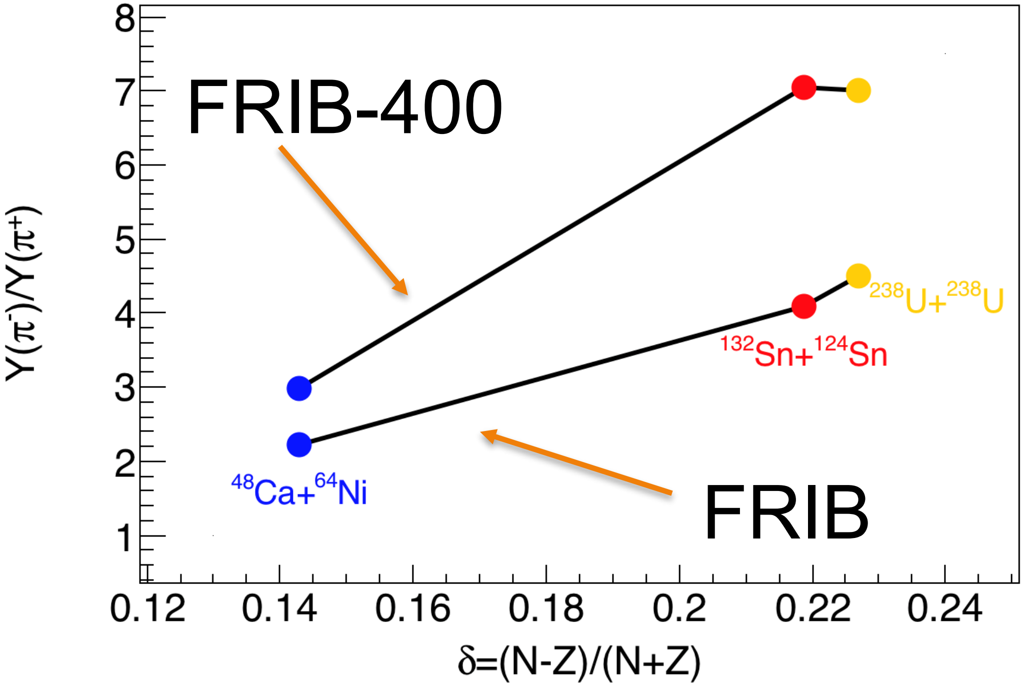


- LANA is comprised of:
  - Two Walls of 25 scintillator bars
    - 2 meters long, 7.7 cm square cross-section
    - NE-213 liquid scintillator → Being replaced with EJ-309 (No more xylene!)
- ~8 cm position resolution
- 500 ps time resolution
- ~10% detection efficiency
- Excellent Neutron/Gamma discrimination

https://arxiv.org/pdf/2001.07518.pdf

Pions @ FRIB





FRIBU boost intensities, asymmetry and pion cross-sections

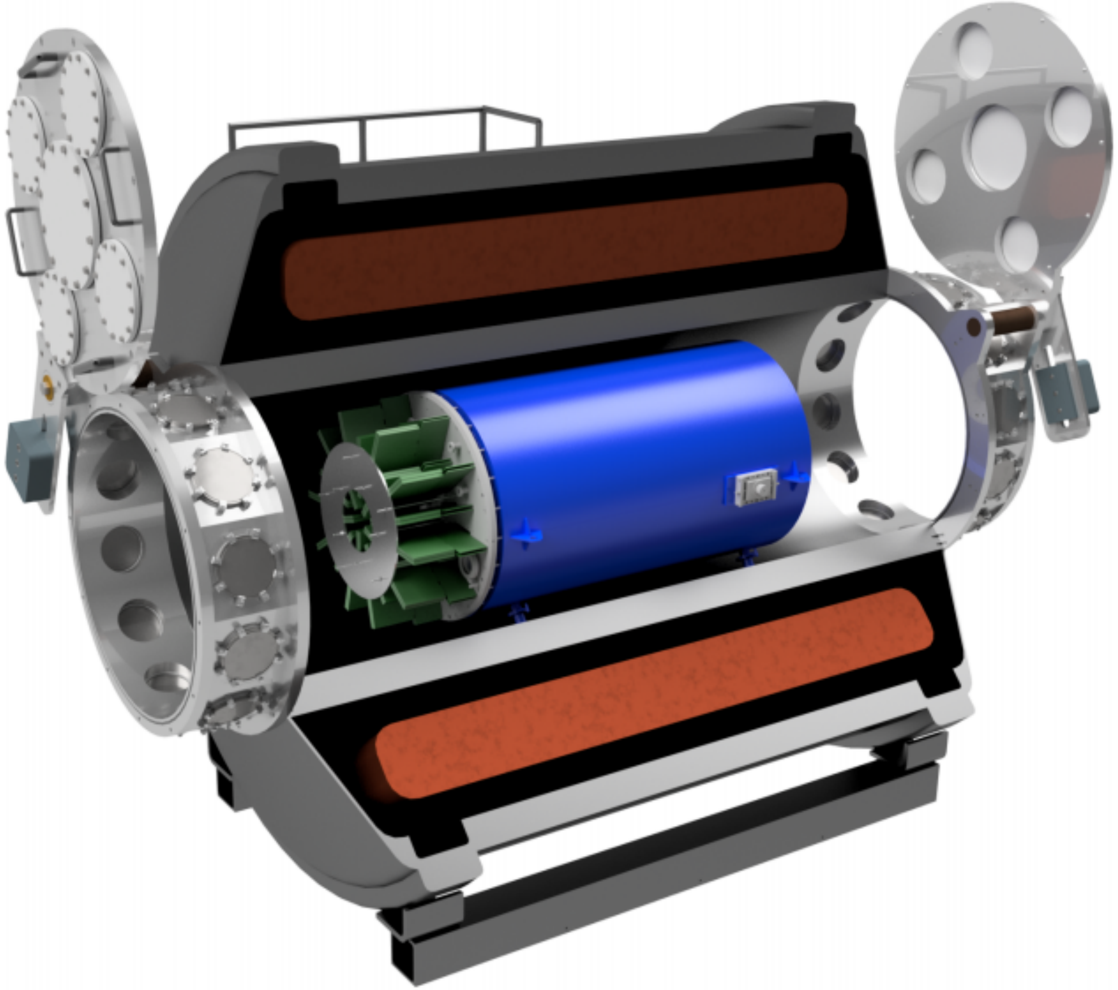
Intensity increase: Allow explorations of more asymmetric systems.

Energy increase: yields increase exponentially above pion thresholds

Regions at $\rho>1.8\rho_0$ become more extensive

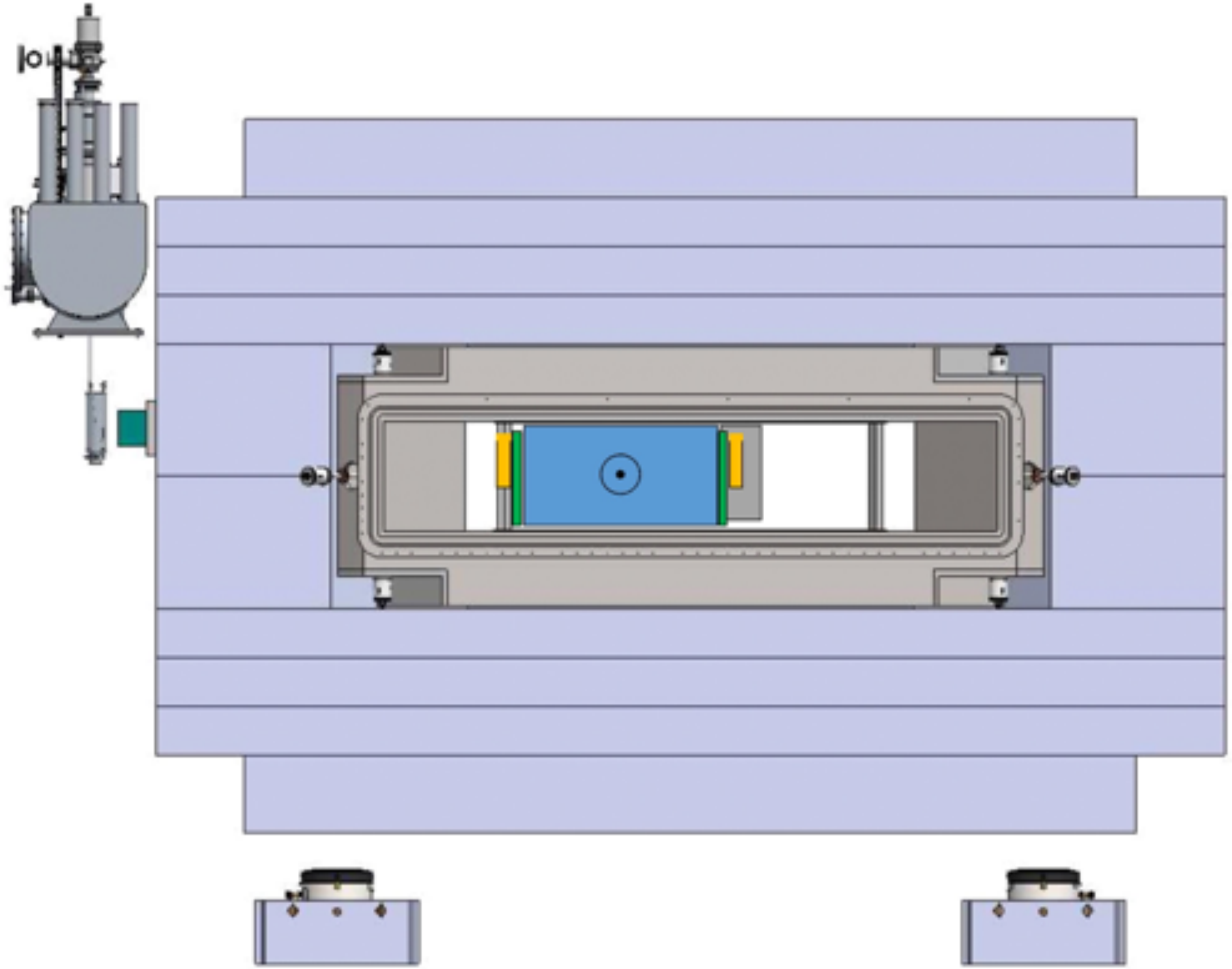
U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

SOLARIS/AT-TPC in Fast Beam Area



- 4 T solenoidal spectrometer fitted with the Active Target Time Projection Chamber
- Could be moved to the fast beam area for measuring Pion production from HIC
- Requires the fabrication of a new readout pad plane with a higher density of pads in the central region.
- Need to have inner field cage for high ionization in beam region

Future with HRS



- The SπRIT TPC could be modified to fit into the High Rigidity Spectrometer or a similar detector could be built with modern improvements
- Fits in 60 cm gap of D1
- This will enable measurements of pion production and elliptical flow
- Can be coupled with LANA or upgraded neutron walls

FRIB

Precision Measurements: Mass, Radii & Electromagnetic Moments

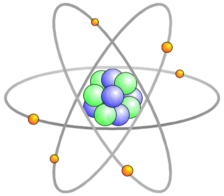
Kei Minamisono & Ryan Ringle

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Mass Measurements



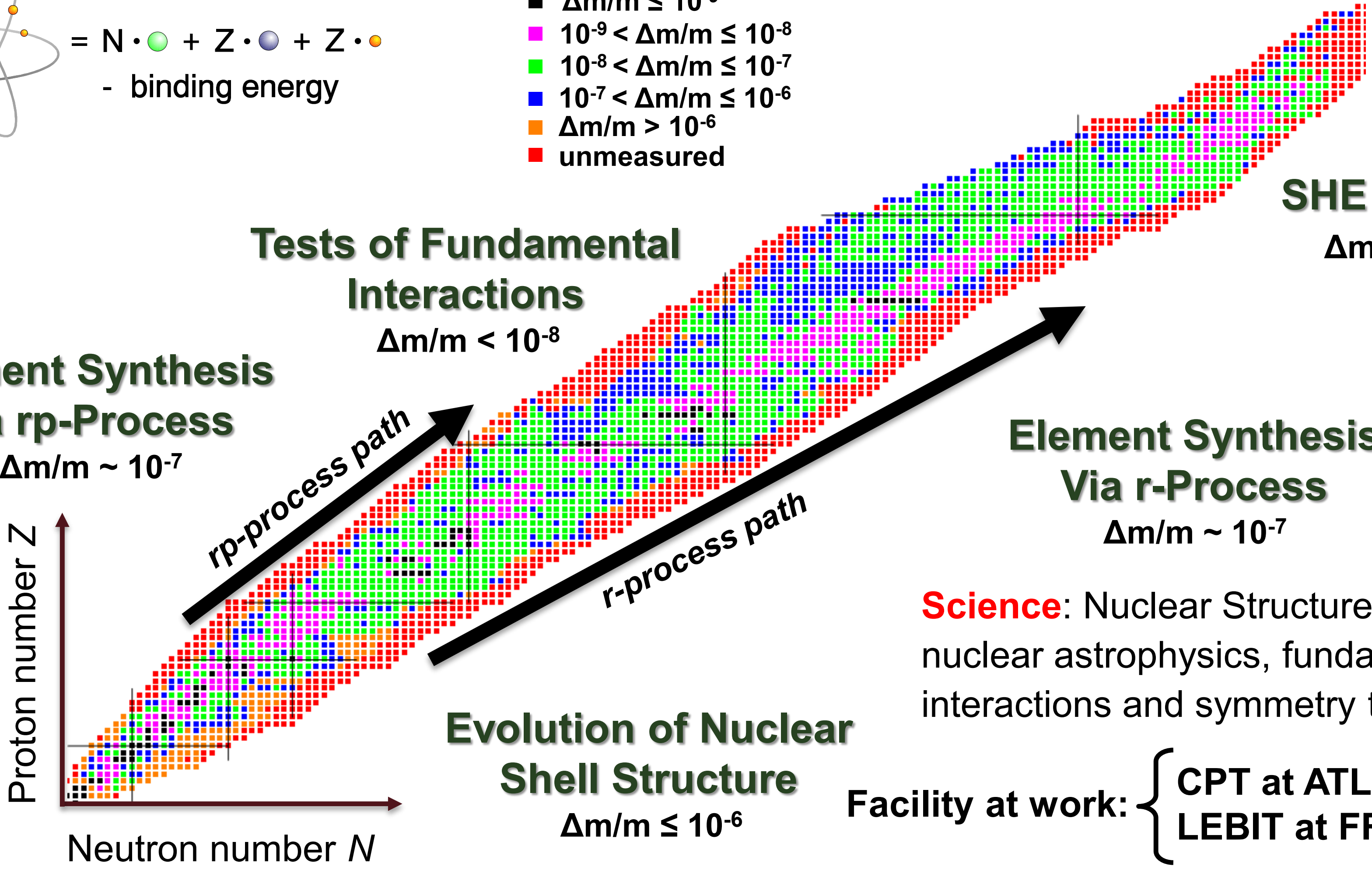
= N • 🟢 + Z • 🔵 + Z • 🟠

\- binding energy

Relative mass uncertainty

AME20: Huang et al., Chin. Phys. C 45, 030002 (2021)

- ■ **$\Delta m/m \leq 10^{-9}$**
- 🟪 **$10^{-9} < \Delta m/m \leq 10^{-8}$**
- 🟩 **$10^{-8} < \Delta m/m \leq 10^{-7}$**
- 🟦 **$10^{-7} < \Delta m/m \leq 10^{-6}$**
- 🟧 **$\Delta m/m > 10^{-6}$**
- 🟥 **unmeasured**



Element Synthesis Via rp-Process

$\Delta m/m \sim 10^{-7}$

Tests of Fundamental Interactions

$\Delta m/m < 10^{-8}$

SHE studies

$\Delta m/m < 10^{-6}$

Element Synthesis Via r-Process

$\Delta m/m \sim 10^{-7}$

Evolution of Nuclear Shell Structure

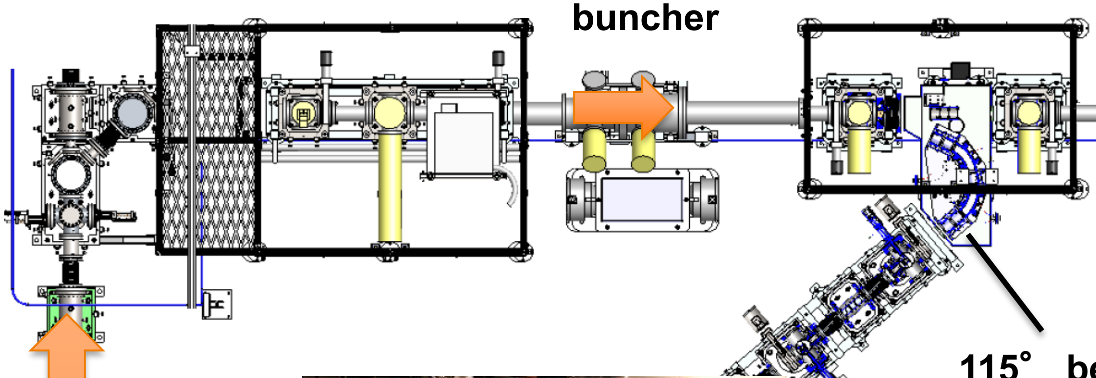
$\Delta m/m \leq 10^{-6}$

Science: Nuclear Structure and nuclear astrophysics, fundamental interactions and symmetry tests

Facility at work: { **CPT at ATLAS/ANL**
LEBIT at FRIB/MSU

LEBIT Facility at FRIB

Ringle et al., Int. J. Mass Spectrom. 349, 87 (2013)



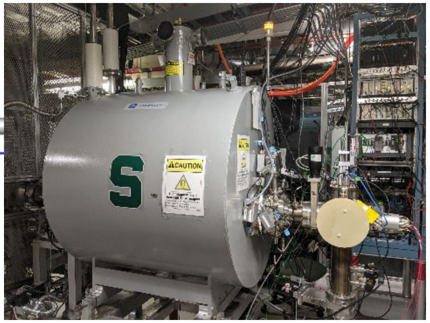
Off-line Ion sources

Schwarz et al. NIM A 816, 131 (2016)

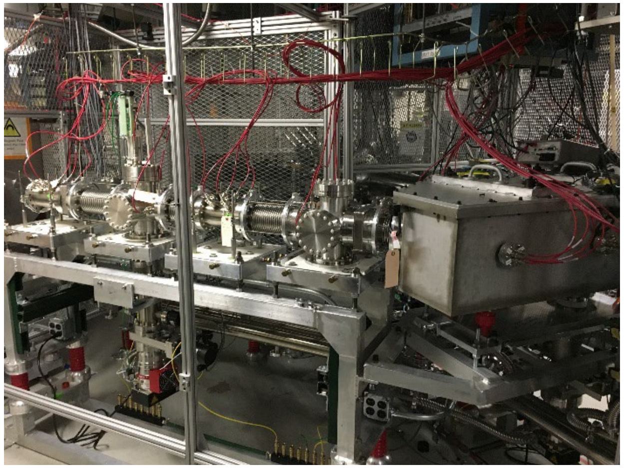
RFQ cooler buncher

Ringle et al. NIM A 604, 536 (2009)

9.4 T Penning Trap



115° bender + electrostatic quadrupoles



7 T SIPT

Hamaker et al. Hyp. Int. 240, 34 (2019)

Rare isotope beam (On-line source)

Precision Mass measurement of Lightweight Self-Conjugate Nucleus ^{80}Zr

1

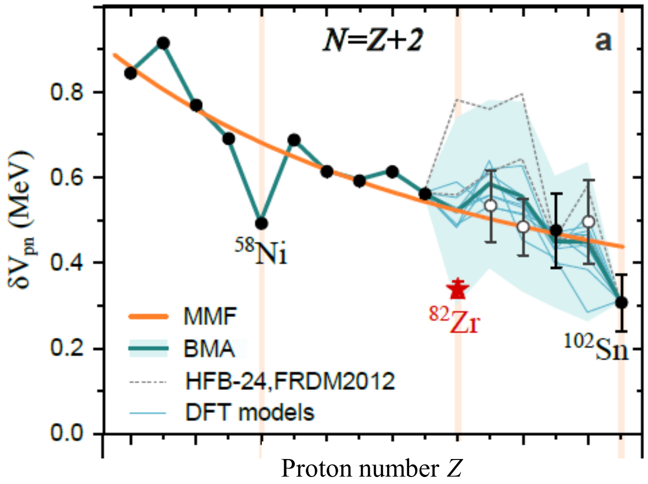
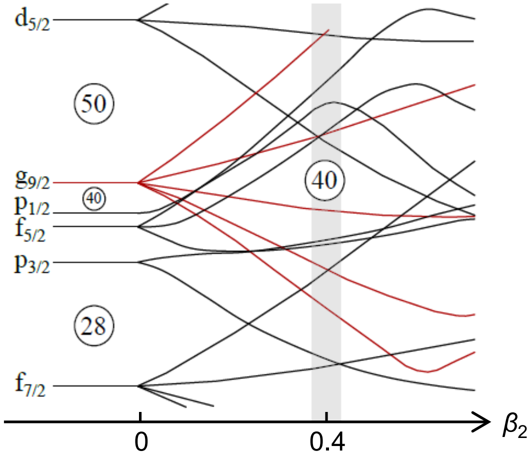


Figure 1: The effect of the anomalous mass of ^{80}Zr on the mass indicator δV_{pn}



2

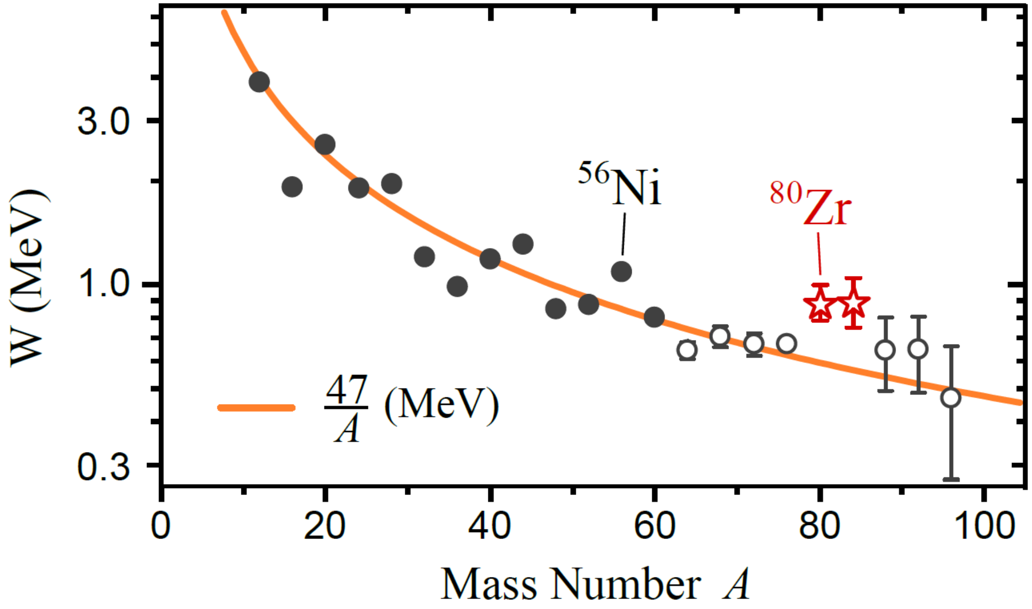


Figure 2: The Wigner-energy coefficient W(A)

^{80}Zr mass is significantly lighter than predicted in AME20.

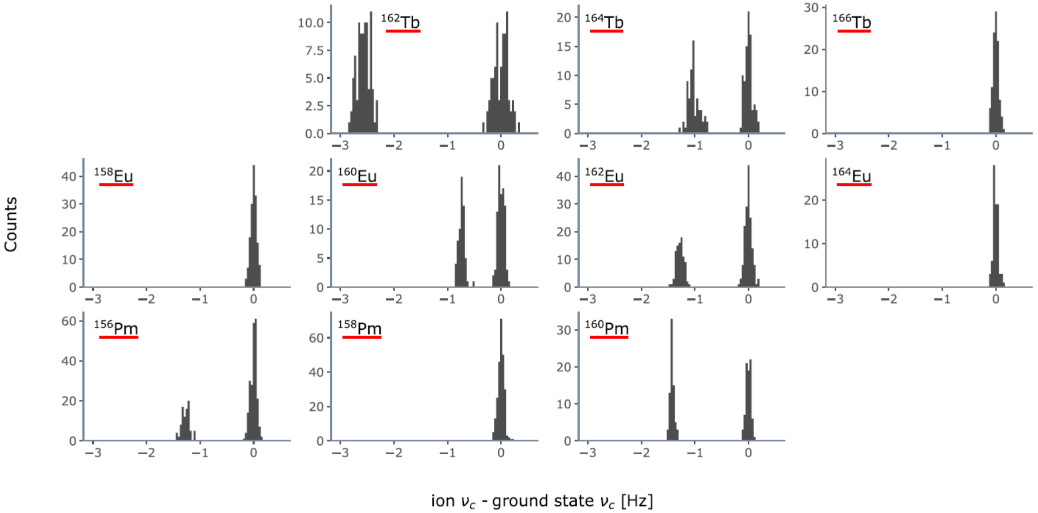
- **Evidence of a deformed (β~0.4) double shell closure in ^{80}Zr**
- **Large Wigner energy (enhanced binding for *N* = *Z* nuclei)**
- **Further mass measurements approved at FRIB**

U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

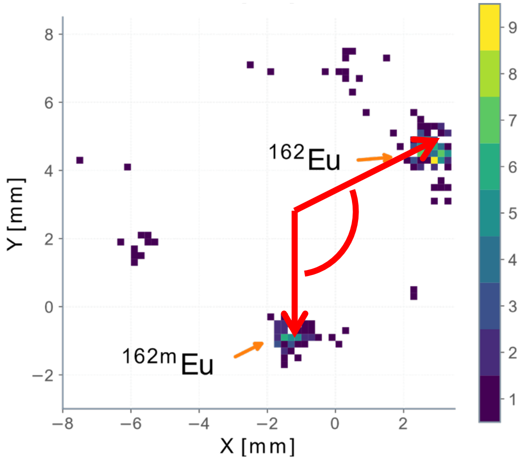
A. Hamaker et al., Nat. Phys. 17, 1408 (2021);
W. Nazarewicz et al. Nucl. Phys. A 435, 397 (1985).

PRECISION MASS MEASUREMENTS FOR NUCLEAR STRUCTURE AT THE CPT

- Identification and measurement of long-lived isomers in odd-odd deformed nuclei in the light rare earth region near N=98
- Discovery of isomers at ^{160}Pm, ^{162}Tb, ^{164}Tb
- Non-observation of isomers at ^{158}Eu, ^{158}Pm, ^{164}Eu, ^{166}Tb
- Showcases strength of phase imaging ion cyclotron resonances (PI-ICR) in identifying and measuring close-lying isomers.



Histogram of ground state ν_C (centered at 0) and isomer state ν_C for measured isotopes



^{162}Eu^{g,m}

Ex=160.2 (24) keV

Sample PI-ICR resonance showing ^{162}Eu^{g,m} and the excitation energy

Orford *et al.*, PRC **102**, 011303(R) (2020);

Hartley *et al.*, PRL **120**, 182502 (2018)

Precision Mass Measurements

Approach: to advance our understanding

- Measurements of key nuclei for structure, astrophysics, fundamental interactions and symmetry tests

How?: Ion-cyclotron frequency measurements using **Penning trap**

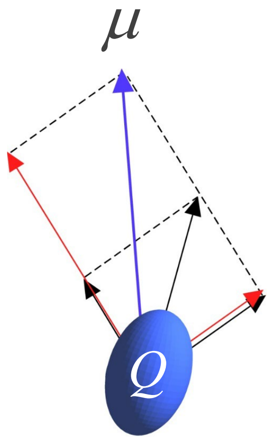
- Existing, highly sensitive
- Time of flight ion-cyclotron resonance
- Fourier transform ion-cyclotron resonance
- Phase imaging ion-cyclotron resonance

Prospective:

- Closed shells (^{100}Sn: FRIB PAC1, ^{78}Ni)
- Along $N = Z$ (^{80}Zr)
- R-process (^{132}Sn, A=130, 196, ^{65}As, ^{66}Se, ^{91}Rh, ^{82}Nb, around ^{108}Te)
- CVC $T_z = -1$ (^{46}Cr, ^{50}Fe, ^{54}Ni) and 0 (^{66}As, ^{70}Br, ^{74}Rb, ^{78}Y), and mirror superallowed (^{42}Ti, ^{42}Ca)

Magnetic Dipole μ, Electric Quadrupole Q Moments and Differential ms Charge Radius $\delta\langle r^2\rangle^{AA'}$

- μ arises from orbital-angular momentum and intrinsic spin
- Q and $\delta\langle r^2\rangle^{AA'}$ represent the nuclear-charge distribution



Science: Nuclear Structure and its Variation toward the Driplines

Why: μ, Q and $\delta\langle r^2\rangle^{AA'}$ are

- Sensitive to details of the nuclear wavefunction (μ)
- Sensitive to shape and deformation (Q: static, $\delta\langle r^2\rangle^{AA'}$: static & dynamic)
- One-body operators acting on a single nuclear state and complementary to transition moments (μ, Q)
- Originating from well-known electromagnetic interactions, and one of best probes to benchmark modern theories (e.g. SM, DFT, ab initio …)

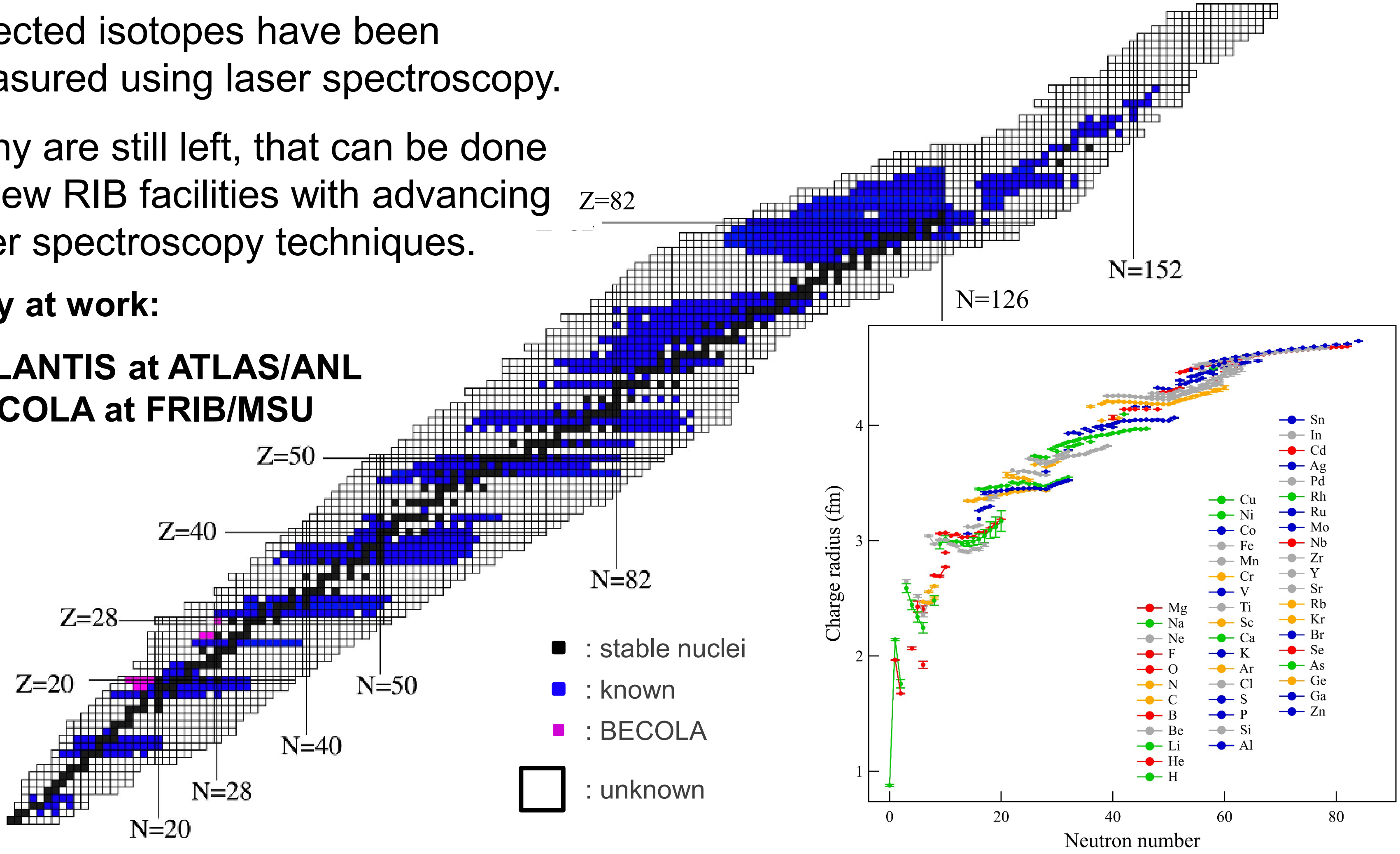
Laser Spectroscopy Measurements

Selected isotopes have been measured using laser spectroscopy.

Many are still left, that can be done at new RIB facilities with advancing laser spectroscopy techniques.

Facility at work:

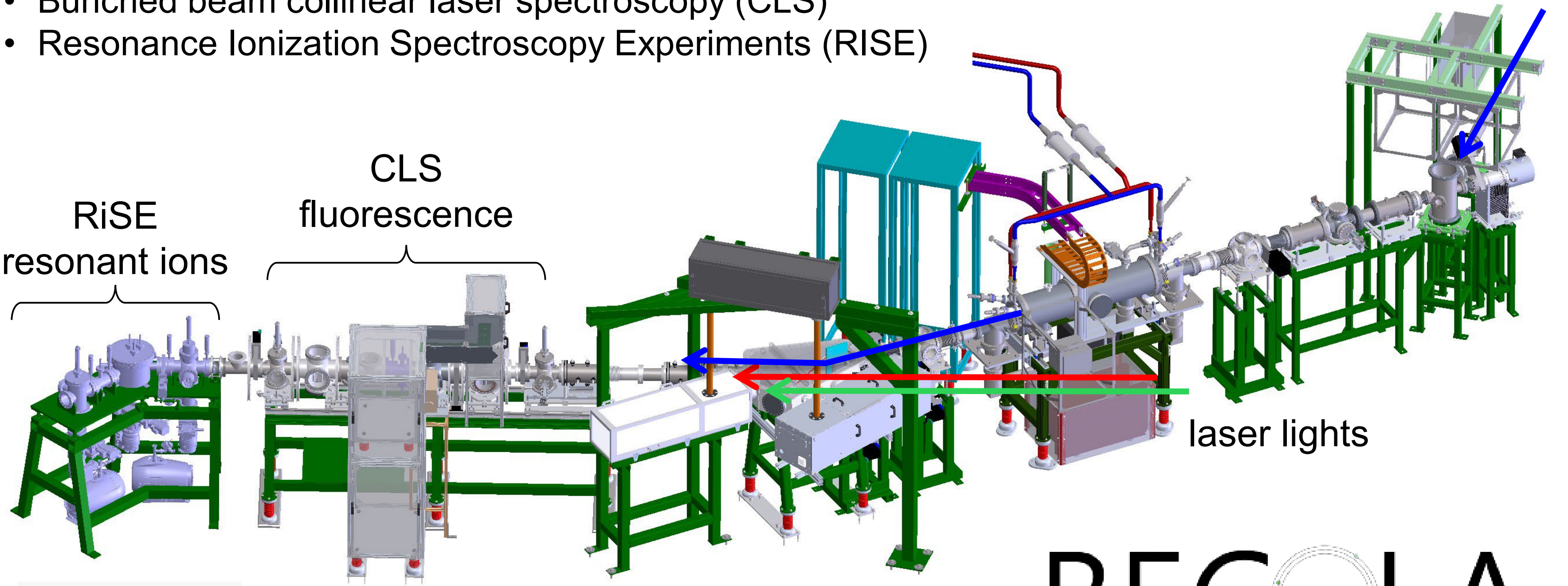
ATLANTIS at ATLAS/ANL
BECOLA at FRIB/MSU



BECOLA Facility at FRIB

BEam COoling and LAser spectroscopy (BECOLA) facility

- 30 keV beam
- Bunched beam collinear laser spectroscopy (CLS)
- Resonance Ionization Spectroscopy Experiments (RISE)



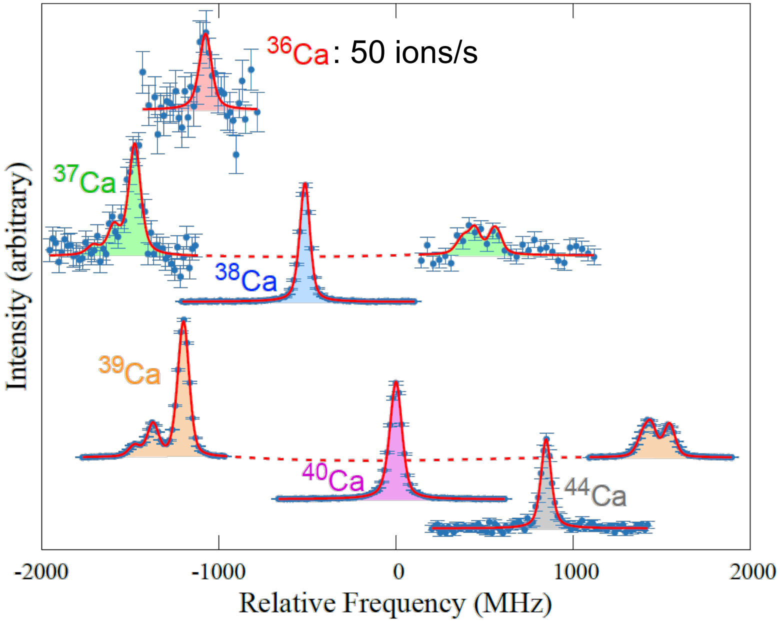
Charge Radii of Ca

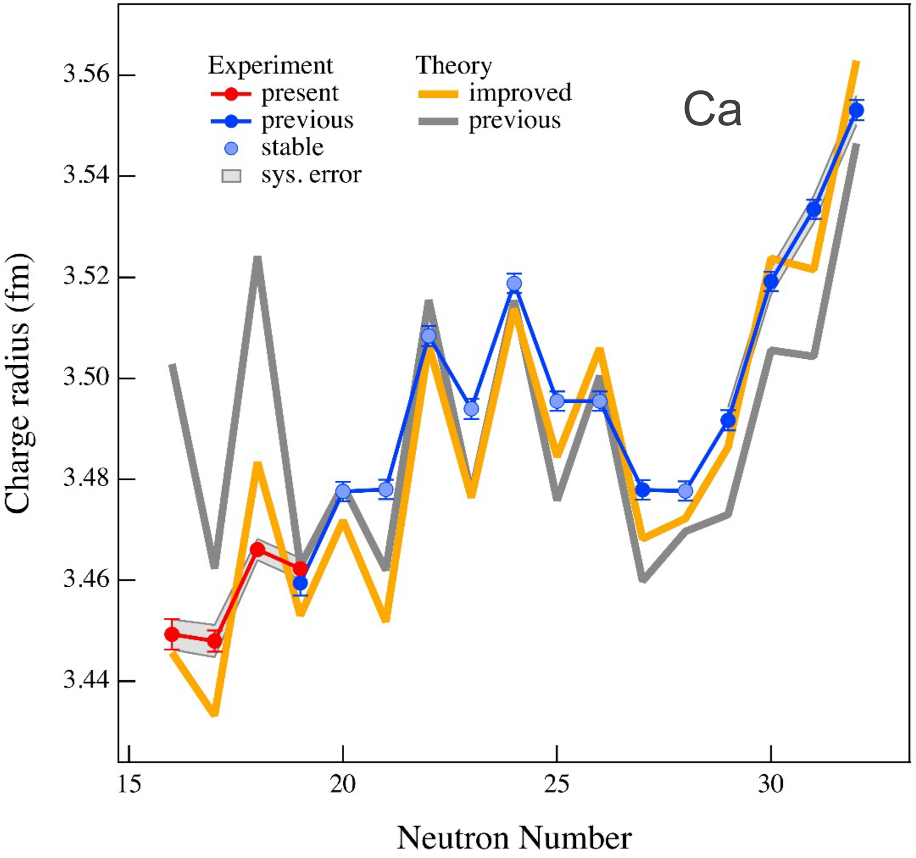
- **Intricate pattern of *R*(Ca) has been challenging nuclear theories.**
- **Measured neutron-deficient *R*(Ca) reveals:**

- very compact, much smaller than previous theory

- coupling to the particle continuum of loosely bound protons are critical

Isotope shifts of Ca isotopes





The improved understanding of the Ca charge radii will impact further developments of a global model of the atomic nuclei.

A. J. Miller et al., Nat. Phys. 15, 432 (2019).

Magnetic Dipole μ, Electric Quadrupole Q Moments and Differential ms Charge Radius $\delta\langle r^2\rangle^{AA'}$

Approach: to advance our understanding
- Measurements of key nuclei in the proximity of closed shells
- Systematic measurements, and/or extension of known, chains of isotopes

How?: Hyperfine structure and its isotope shifts by **Laser Spectroscopy**
- Existing, highly sensitive and selective
- Bunched beam collinear laser spectroscopy (fluorescence detection)
- Resonance laser ionization spectroscopy (ion detection)

Prospective: Nuclear structure evolution
- Key nuclei (^{78}Ni, ^{80}Zr, ^{100}Sn, …) and beyond in the proximity of closed shells
- Extension of known, chains of isotopes (Ca, Ni, Sn, …)
- Light mass (C, O, F) towards Driplines, and heavy mass (around U)
- Mirror charge radii for the neutron EOS (^{22}Si-O, ^{52}Ni-Cr, …)

Precision Measurements: Mass, Radii & Electromagnetic Moments

Needs?: more opportunities

- Continuing support of operating FRIB and ATLAS
- Continuing support for nuclear theories
- Multi-user capability
- Harvesting and stand-alone source (BMIS) capabilities at FRIB
- High purity beams (high resolution separator, MR ToF, …)
- Non molecular beam for laser spectroscopy

Thank you!

Resonance Phenomena at the Edges of Stability

Nathan Frank (Augustana College)
MoNA Collaboration

NSAC Long Range Plan Town Hall Meeting
Nuclear Structure, Reactions, and Astrophysics
Nuclear Experiment Working Group

NSAC Long Range Plan 2015

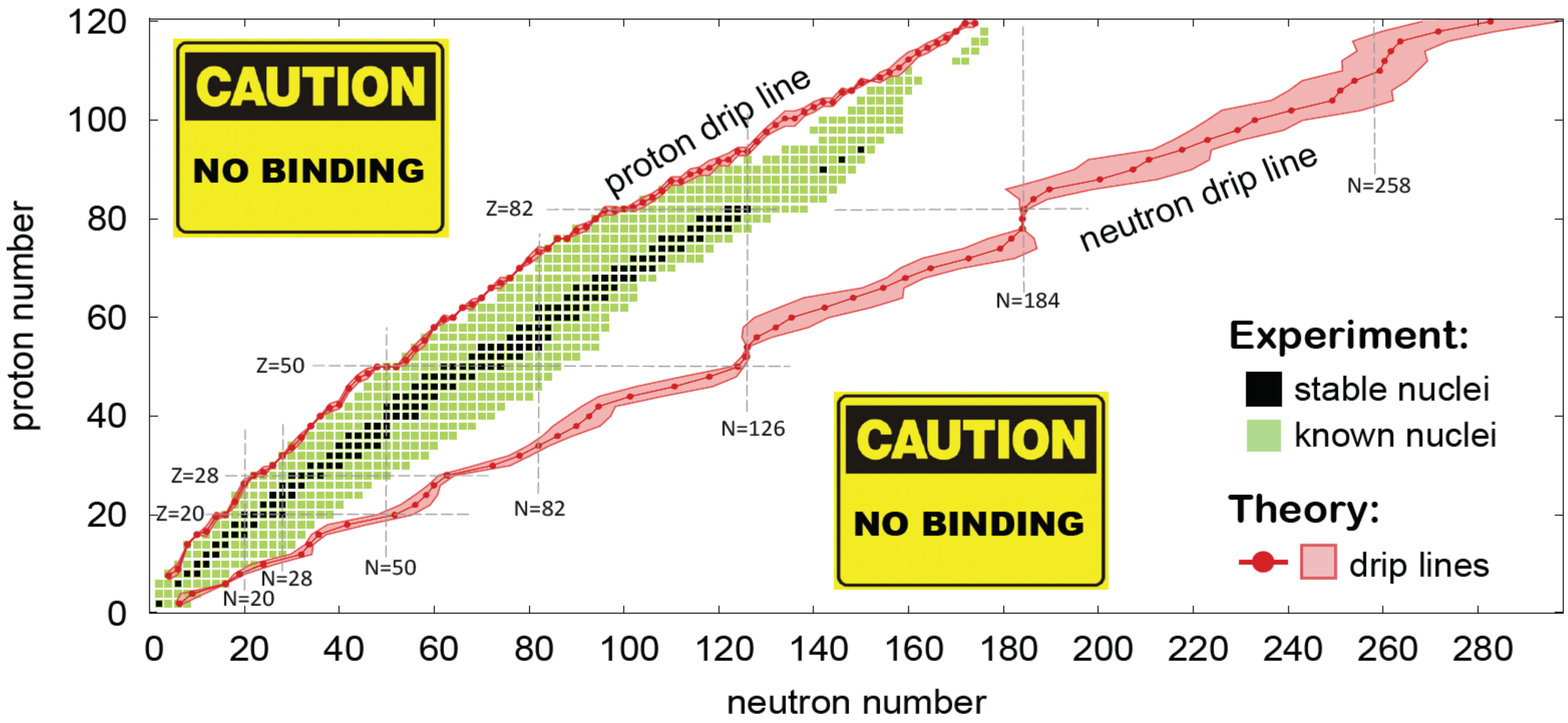
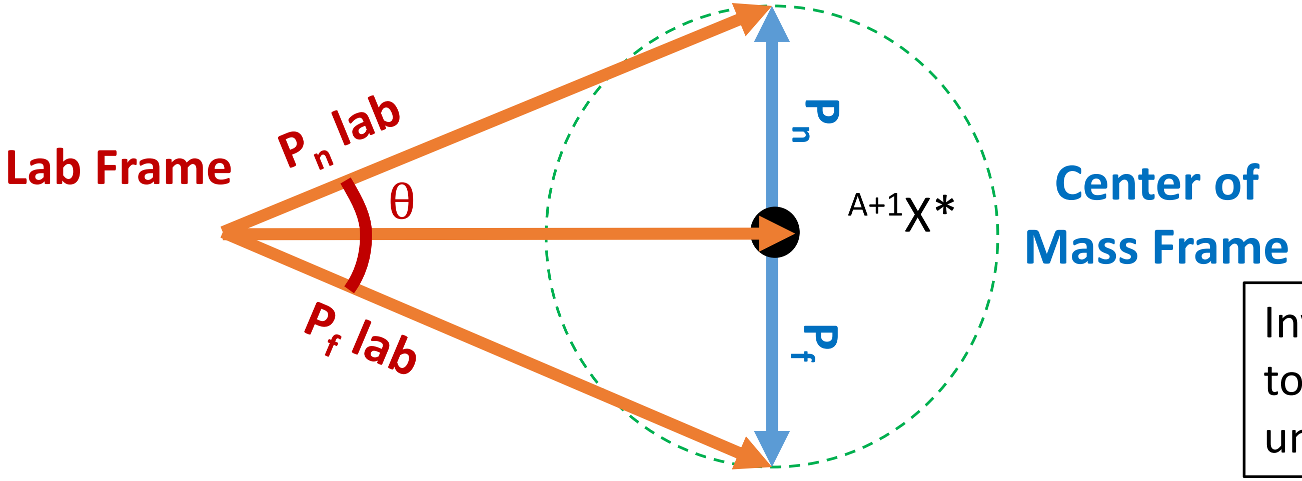


Figure 3.1: *Nuclear landscape. Map of bound nuclei as a function of Z and N. Mean drip lines, where the nuclear binding ends, and their uncertainties (red) were obtained by averaging the results of different theoretical models.*

- Figure 3.1 (pg. 44) from the 2015 Long Range Plan
- Pushing the limits:
  - 4n resonance (tetraneutron): ^{8}He – Duer *et al.*, Nature **606**, 678 (2022) → Missing mass technique due to 422 events
  - 4p emitter: ^{18}Mg - Jin *et al.*, PRL **127**, 262592 (2021)

Invariant Mass Method – Jacobi Coordinates



1n + Charged Fragment

Invariant mass technique to reconstruct the unbound system

$$E_{\text{decay}} = \sqrt{m_{\text{f}}^2 + m_{\text{n}}^2 + 2[E_{\text{f}} E_{\text{n}} - p_{\text{f}}\, p_{\text{n}} \cos(\theta)]} - m_{\text{f}} - m_{\text{n}}$$

2n + Charged Fragment

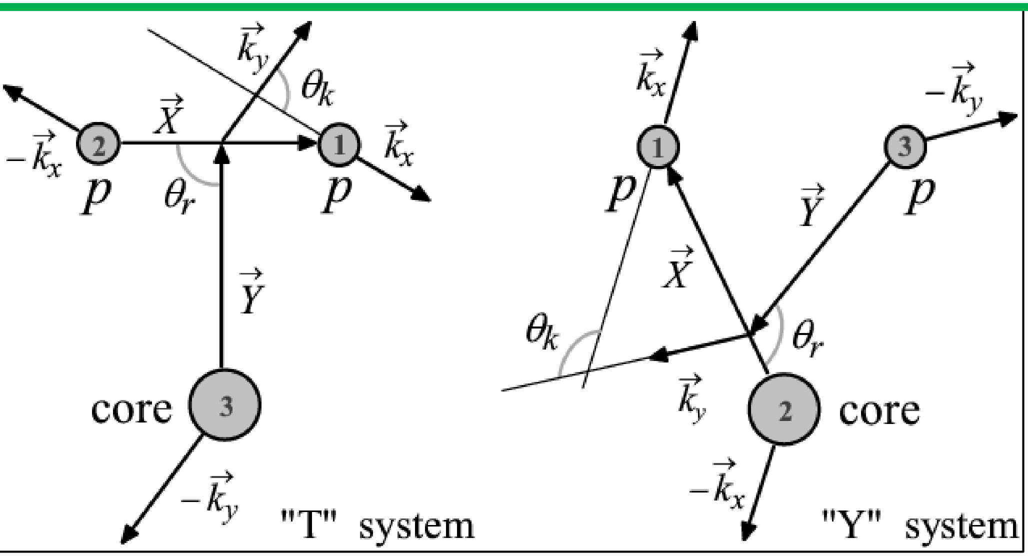
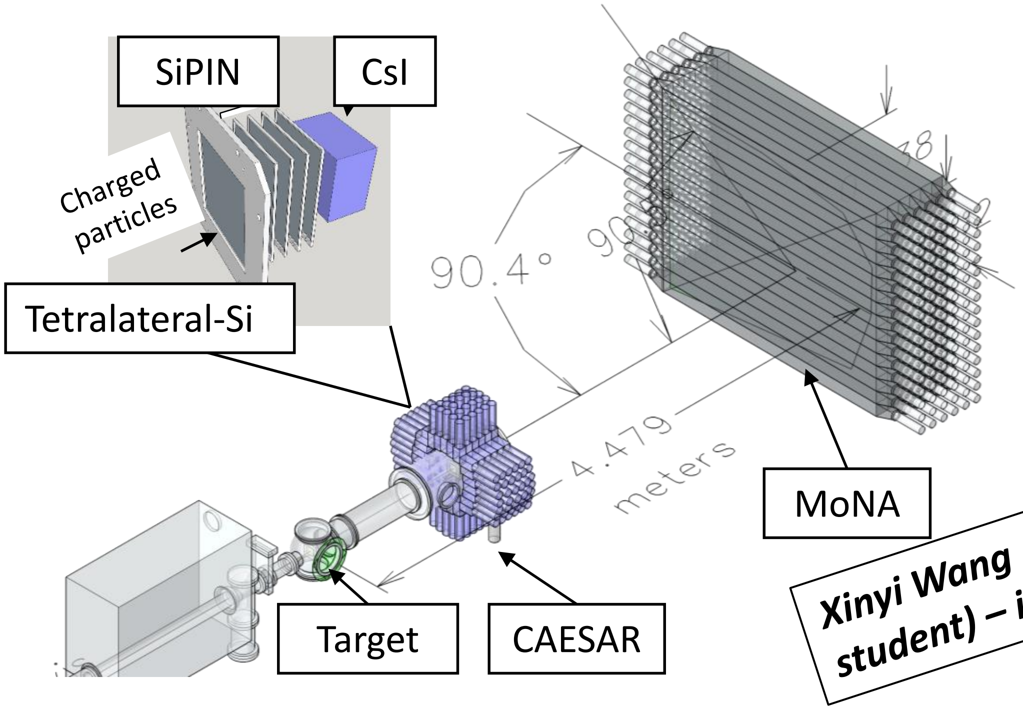


Figure adapted from L. V. Grigorenko, I. A. Egorova, M. V. Zhukov, R. J. Charity, and K. Miernik, Phys. Rev. **82**. 014615 (2010).

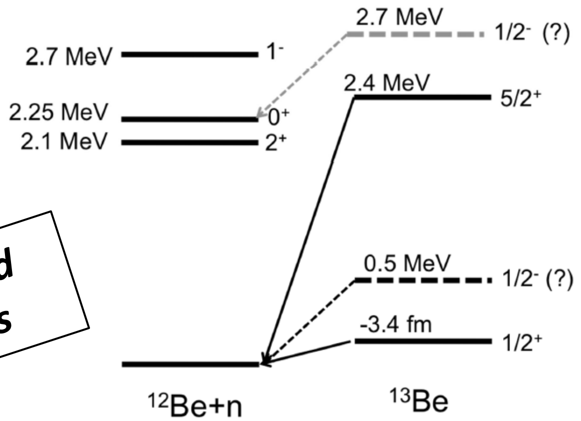
Jacobi coordinates to interpret the type of emission

Invariant Mass Method - MoNA

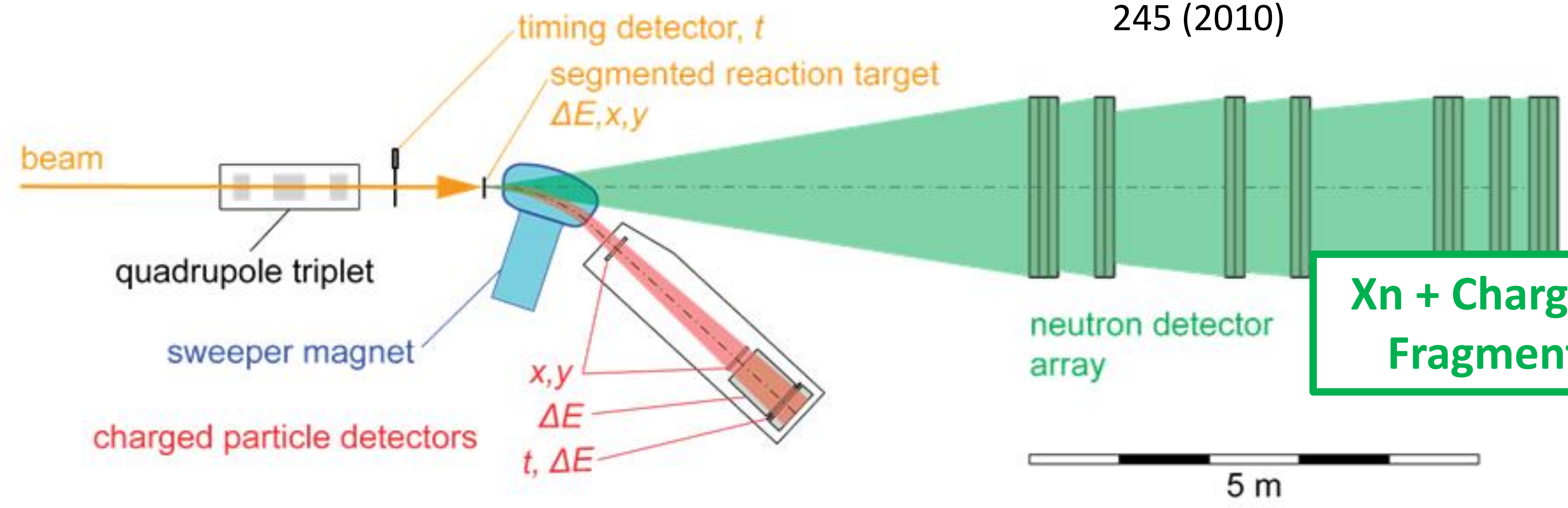
1n + γ + Charged Fragment



Xinyi Wang (MSU grad student) – in progress

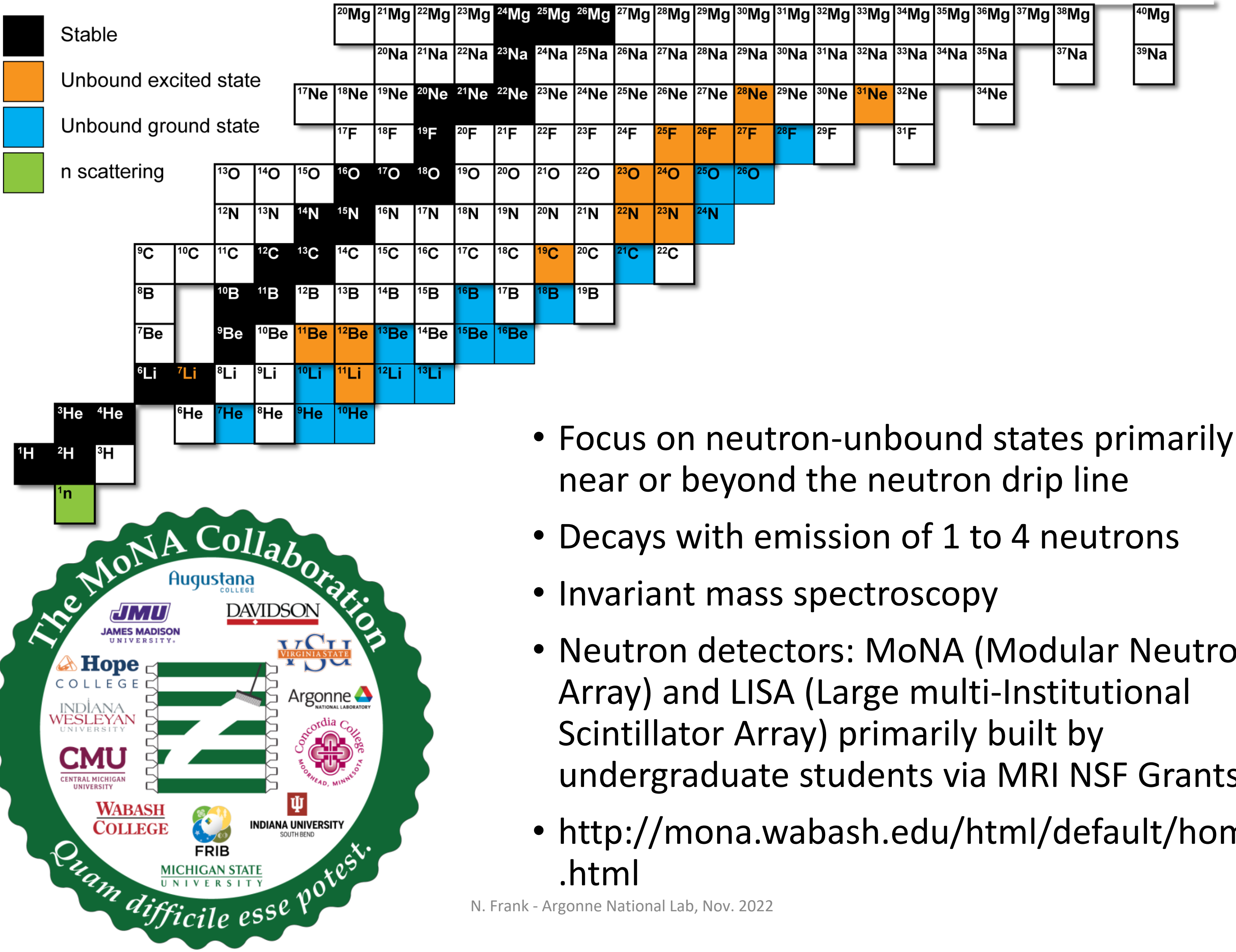


Kondo et al., Phys. Lett. B 690, 245 (2010)



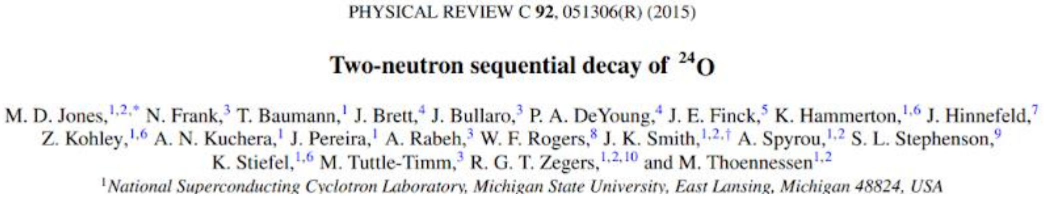
Xn + Charged Fragment

Measurements with MoNA



- Focus on neutron-unbound states primarily near or beyond the neutron drip line
- Decays with emission of 1 to 4 neutrons
- Invariant mass spectroscopy
- Neutron detectors: MoNA (Modular Neutron Array) and LISA (Large multi-Institutional Scintillator Array) primarily built by undergraduate students via MRI NSF Grants
- http://mona.wabash.edu/html/default/home.html

Unbound states near the neutron dripline – ^{24}O

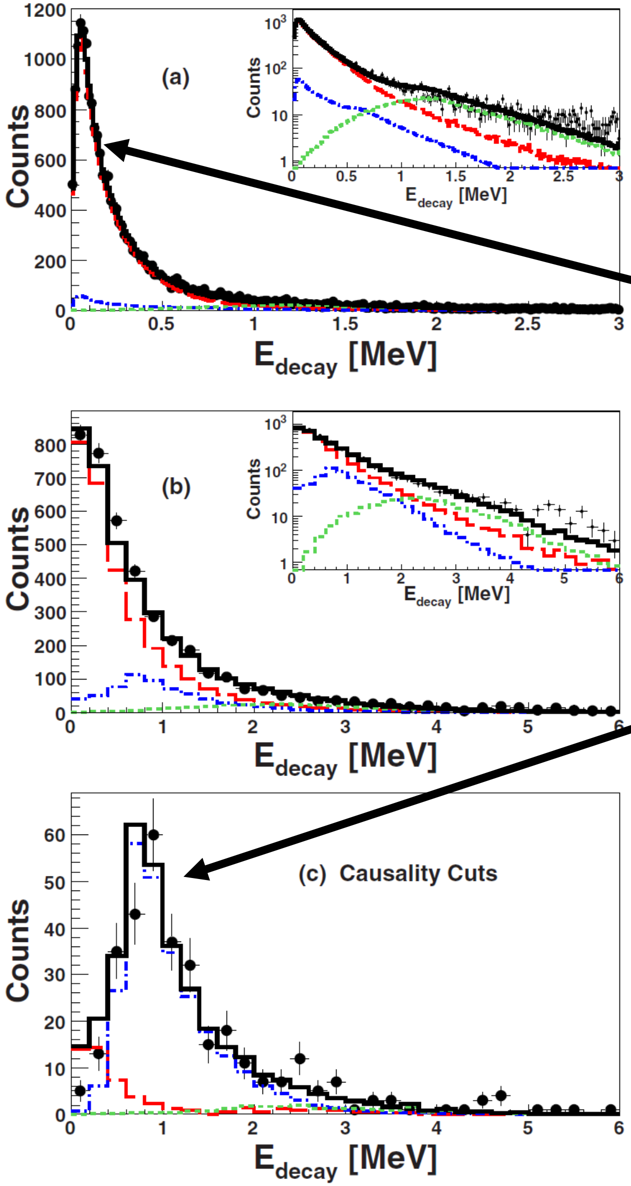


PHYSICAL REVIEW C **92**, 051306(R) (2015)

Two-neutron sequential decay of ^{24}O

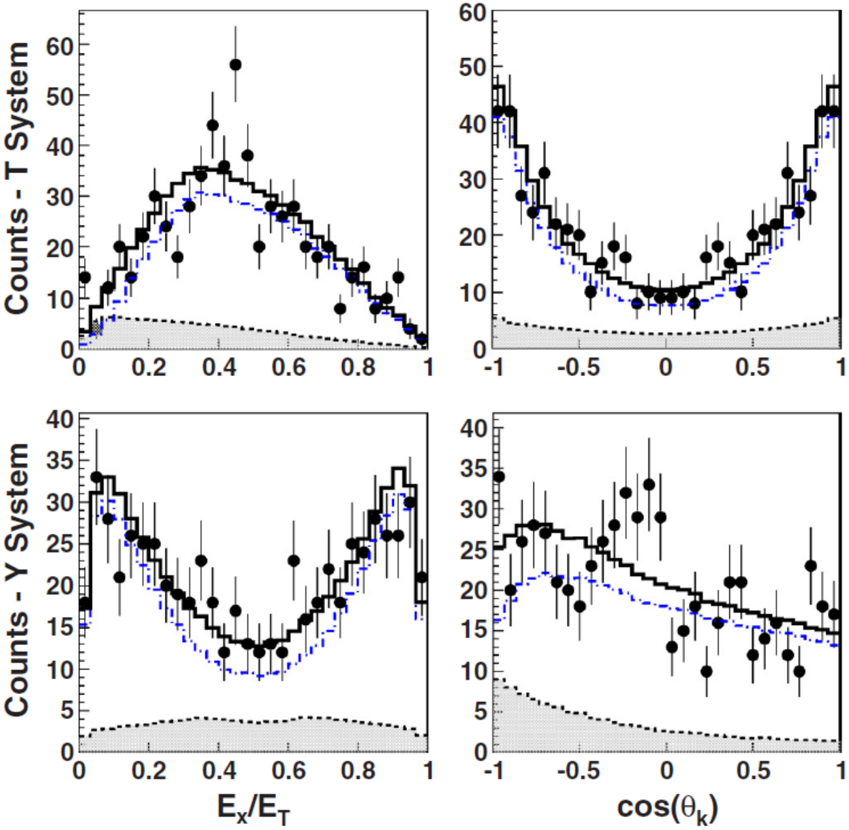
M. D. Jones,[1,2,*] N. Frank,[3] T. Baumann,[1] J. Brett,[4] J. Bullaro,[3] P. A. DeYoung,[4] J. E. Finck,[5] K. Hammerton,[1,6] J. Hinnefeld,[7] Z. Kohley,[1,6] A. N. Kuchera,[1] J. Pereira,[1] A. Rabeh,[3] W. F. Rogers,[8] J. K. Smith,[1,2,†] A. Spyrou,[1,2] S. L. Stephenson,[9] K. Stiefel,[1,6] M. Tuttle-Timm,[3] R. G. T. Zegers,[1,2,10] and M. Thoennessen[1,2]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*



~50 keV state 1n-unbound state in ^{23}O

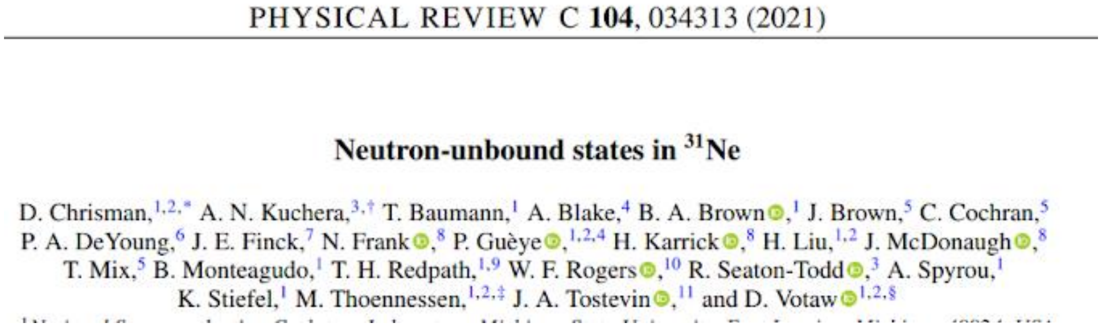
1 MeV 2n-unbound state in ^{24}O



- Produced excited ^{24}O via (d,d') reaction using the Ursinus College Liquid Hydrogen Target
- Observed sequential neutron emission from state in ^{24}O

Observation of three-neutron sequential emission for ^{25}O∗, C. Sword et al., PRC **100**, 034323 (2019)

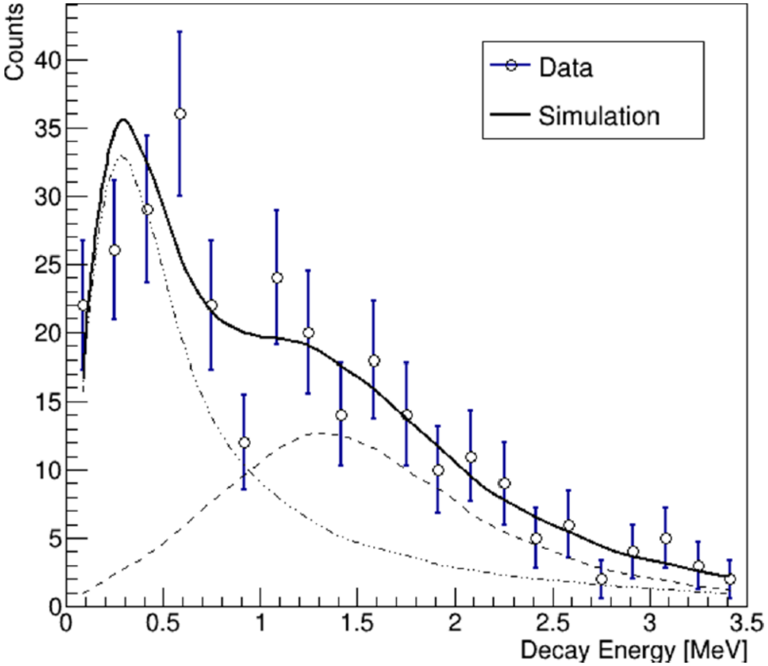
Unbound states near the neutron dripline – ^{31}Ne

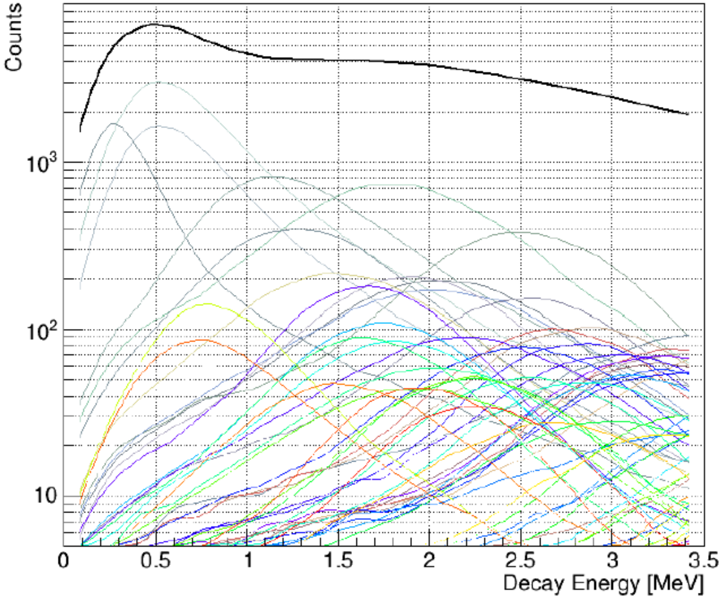


PHYSICAL REVIEW C **104**, 034313 (2021)

Neutron-unbound states in ^{31}Ne

D. Chrisman,[1,2,*] A. N. Kuchera,[3,†] T. Baumann,[1] A. Blake,[4] B. A. Brown,[1] J. Brown,[5] C. Cochran,[5]
P. A. DeYoung,[6] J. E. Finck,[7] N. Frank,[8] P. Guèye,[1,2,4] H. Karrick,[8] H. Liu,[1,2] J. McDonaugh,[8]
T. Mix,[5] B. Monteagudo,[1] T. H. Redpath,[1,9] W. F. Rogers,[10] R. Seaton-Todd,[3] A. Spyrou,[1]
K. Stiefel,[1] M. Thoennessen,[1,2,‡] J. A. Tostevin,[11] and D. Votaw[1,2,§]





- Produced via ^{33}Mg (-2p) knockout reaction using a segmented Si-Be stack
- Theory expects nearly 100 levels!
- Data consistent with theory!

Unbound states near the proton dripline – ^{18}Mg

PHYSICAL REVIEW LETTERS **127,** 262502 (2021)

Editors' Suggestion **Featured in Physics**

First Observation of the Four-Proton Unbound Nucleus ^{18}Mg

Y. Jin,[1,*] C. Y. Niu,[2,*] K. W. Brown,[2,3,†] Z. H. Li,[1,‡] H. Hua,[1,§] A. K. Anthony,[2,4] J. Barney,[2,4] R. J. Charity,[5] J. Crosby,[2,4] D. Dell'Aquila,[2] J. M. Elson,[5] J. Estee,[2,4] M. Ghazali,[2,4] G. Jhang,[2] J. G. Li,[1,6,7] W. G. Lynch,[2,4] N. Michel,[6,7] L. G. Sobotka,[5,8] S. Sweany,[2,4] F. C. E. Teh,[2,4] A. Thomas,[5] C. Y. Tsang,[2,4] M. B. Tsang,[2,4] S. M. Wang,[9,10] H. Y. Wu,[1] C. X. Yuan,[11] and K. Zhu[2,4]

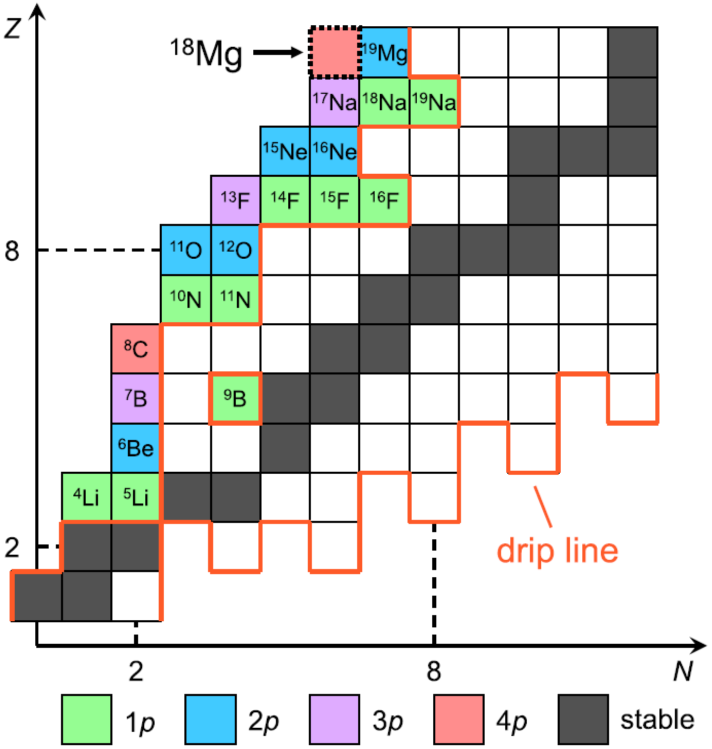
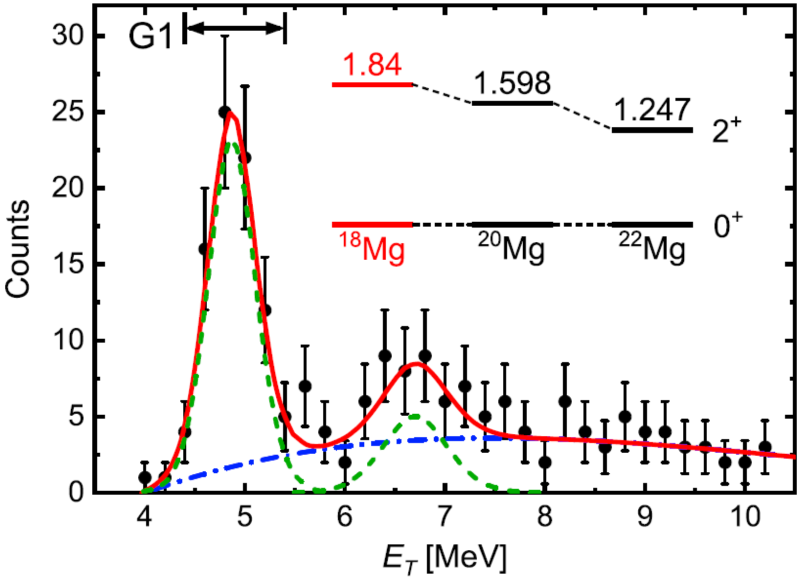
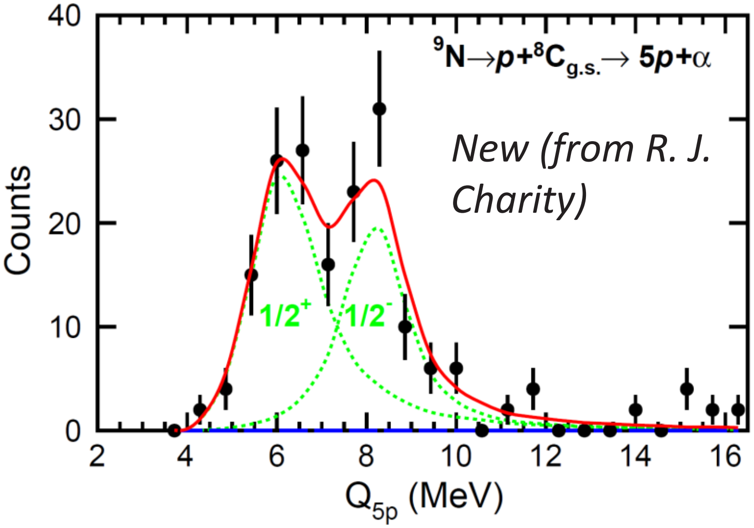


FIG. 1. Subsection of the chart of nuclei. Those nuc which have been shown experimentally to decay 1p (green), 2p (blue), 3p (purple), and 4p (pink) emissio are highlighted.



- HiRA (ΔE-E) measures protons and alphas
- Heavy residue measured by S800
- Resolution determined by the target thickness, angular resolution, and energy resolution (^{18}Mg g.s. 520 keV)

Unbound states near the proton dripline - more



New (from R. J. Charity)

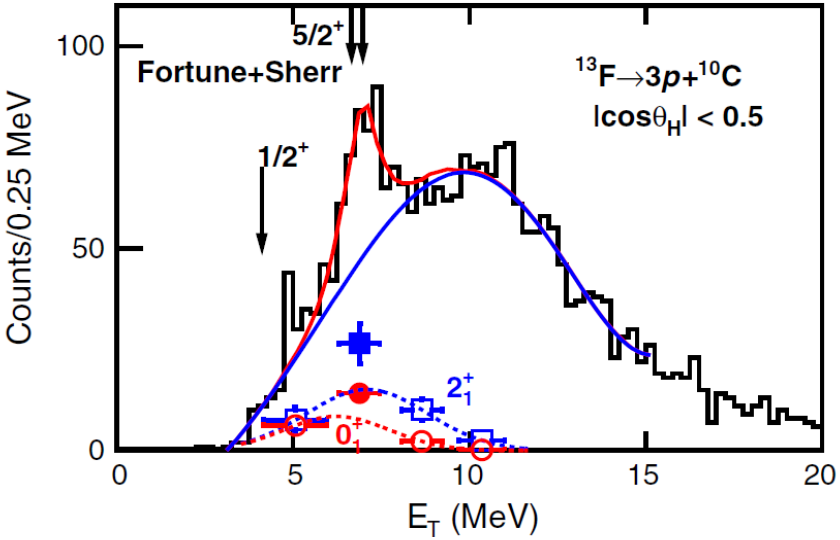


Fig. 1 from R. J. Charity et al, PRL **126**, 132501 (2021) – reduced efficiency above 10 MeV for 1st proton

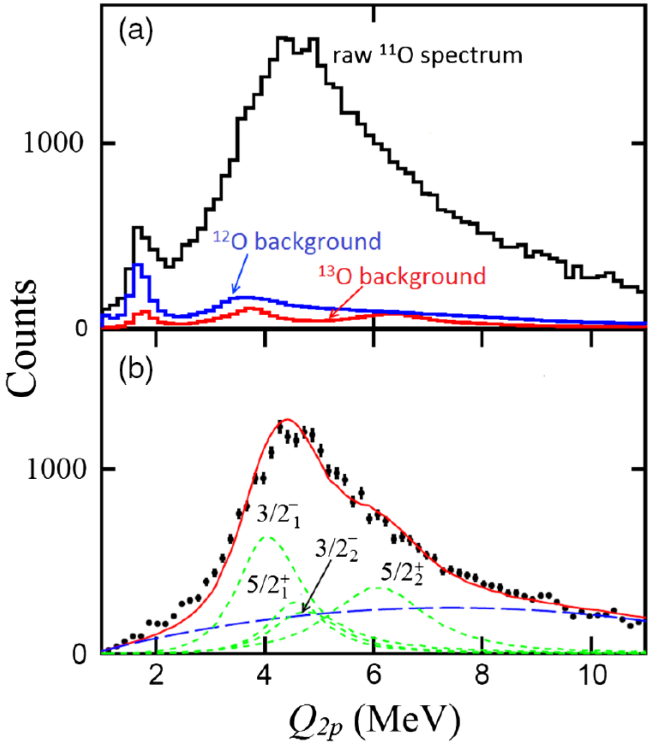


Fig. 1 from T. B. Webb et al, PRL **122**, 122501 (2019) – cannot separate states

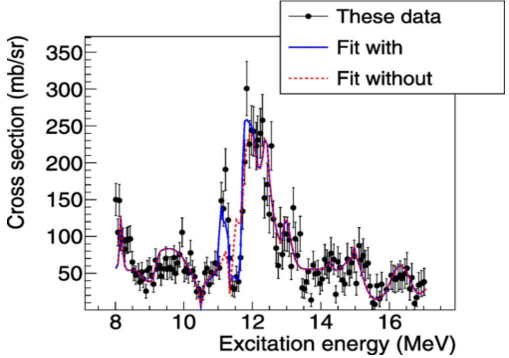
Tough challenge – lots of paths

- A-K peaks/branches (e.g. α + $^6Be_{g.s.}$) to interpret 2p decay from ^{10}C (2p+2α) or ^{11}N (3p+2α)
- R. J. Charity, L. G. Sobotka, T. B. Webb, and K. W. Brown, PRC **105**, 014314 (2022)

Unbound states using TPC

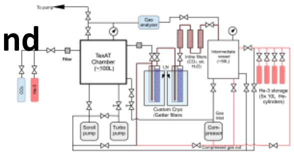
$^{14}O(\alpha,\alpha)$

^{14}O beam from MARS into TexAT filled with He:CO_2
Published last week: M. Barbui et al. PRC 106, 054310



Studying ^{18}Ne:^{18}O mirror pair – sensitivity to superradiance phenomenon? A. Volya et al. "**Superradiance in alpha clustered mirror nuclei"** preprint

^{3}He target system for TPCs coming soon! ~100L recycling and purification system

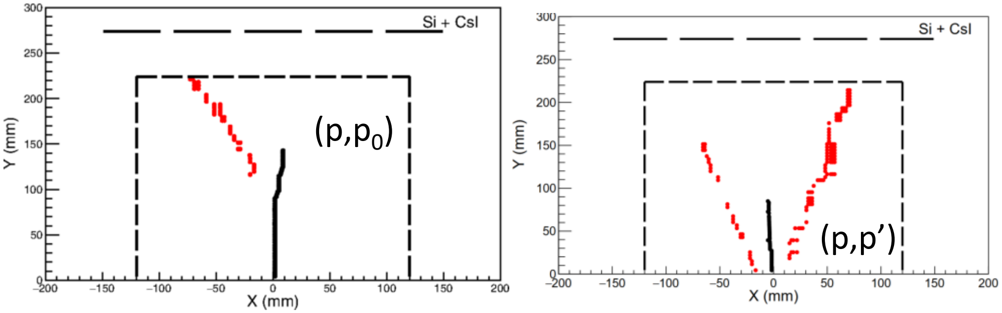


(^{3}He,n) [TexAT + TexNeut] to populate proton-dripline nuclei – use combined invariant and missing mass

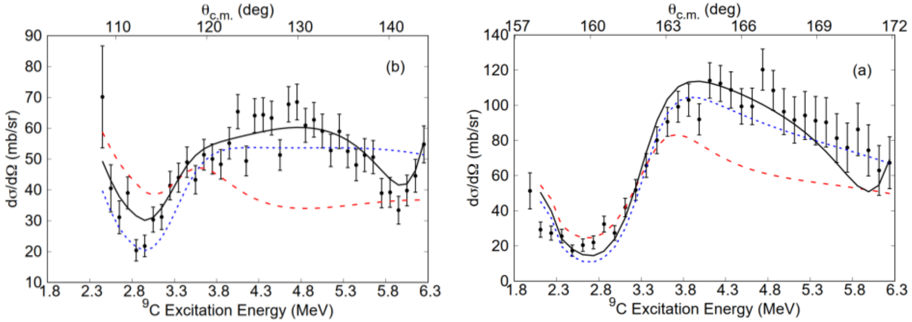
Also, (^{3}He,d) as indirect (p,g) probe with RIBs vital for astrophysics!

TexAT commissioning experiment: $^{8}B(p,p)$

^{9}C studied - new $5/2^{+}$ state at 4.3 MeV as single-particle broad s-wave resonance determined the energy of the 2s shell



^{8}B(p,p') separated, 1st excited state in ^{8}B proton-unbound → 2 light tracks



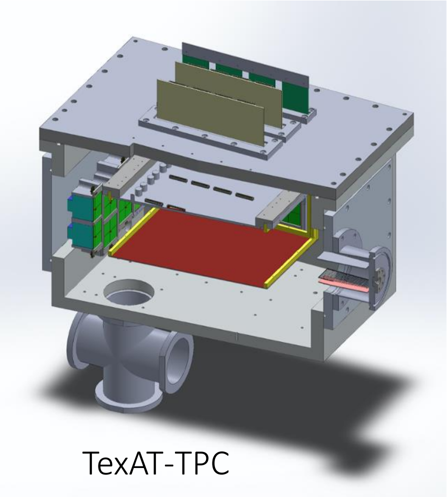
R-matrix requires $7/2^{-}$ in addition to the $1/2^{-}$, $5/2^{-}$ and $5/2^{+}$ states

J. Hooker et al. Phys. Rev. C 100, 054618 (2019)

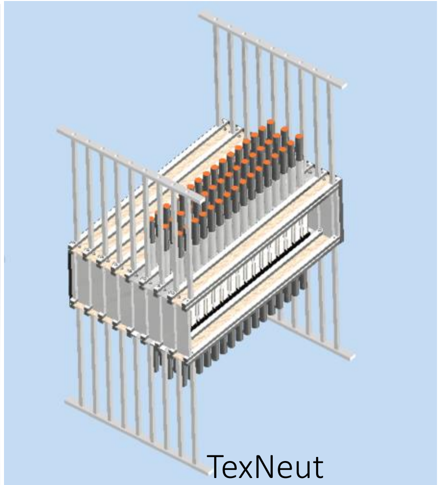
Unbound states using TPC

Structure of ^{10}Li via Isobaric Analogues in ^{10}Be by ^{9}Li(p,p) (and ^{9}Li(p,n))

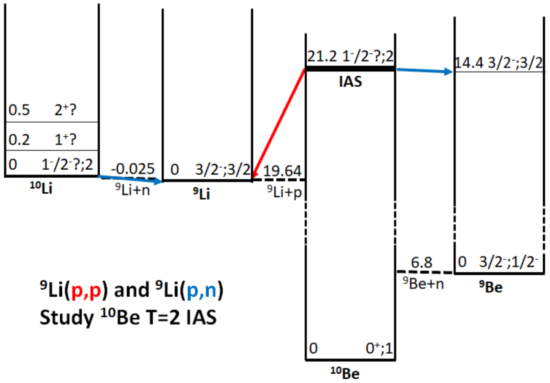
- Use TexAT and TexNeut array together to study broad resonances of ^{10}Be T=2 IAS of ^{10}Li with ^{9}Li(p,p) and ^{9}Li(p,n)
- R-matrix shows strong interference/enhancement to XS in both proton and neutron exit channels
- 48-bar prototype in conjunction with TexAT-TPC for TTIK beam and heavy recoil tracking



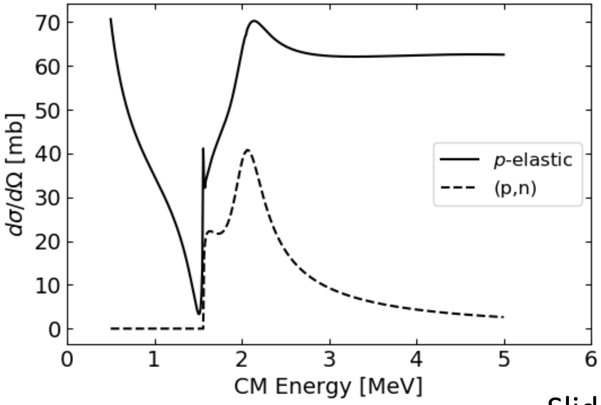
TexAT-TPC

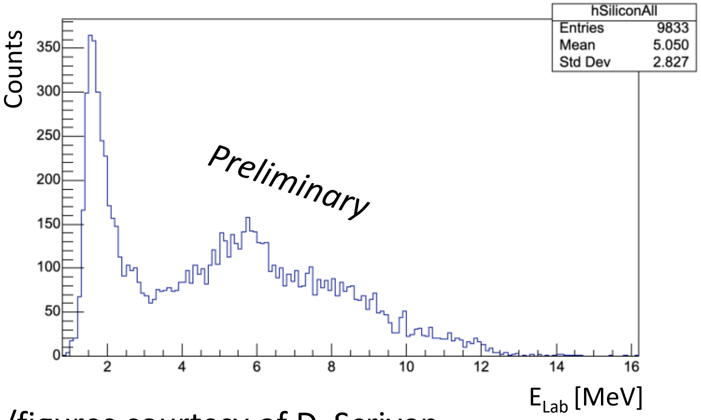


TexNeut



^{9}Li(p,p) and ^{9}Li(p,n)
Study ^{10}Be T=2 IAS



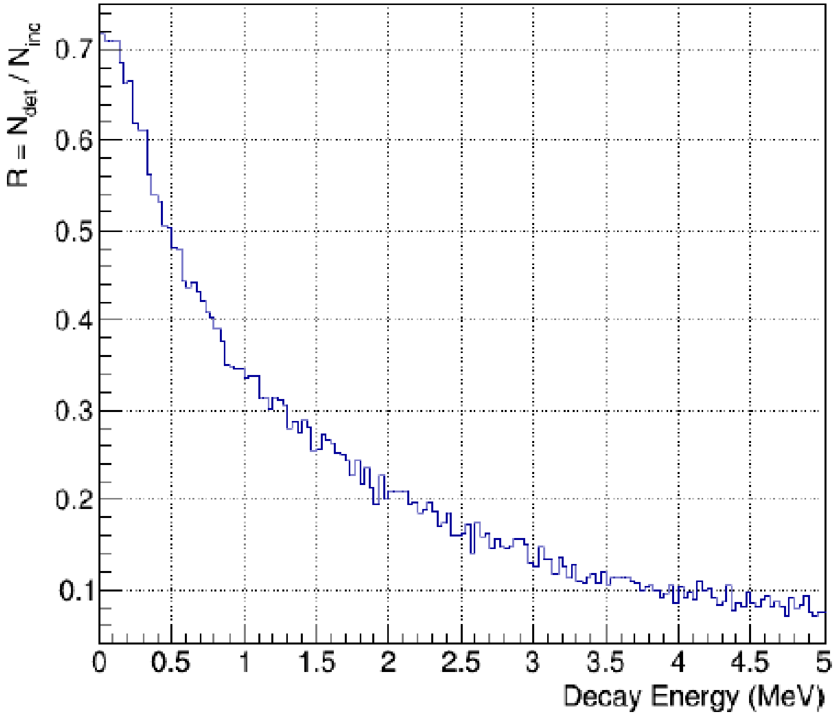


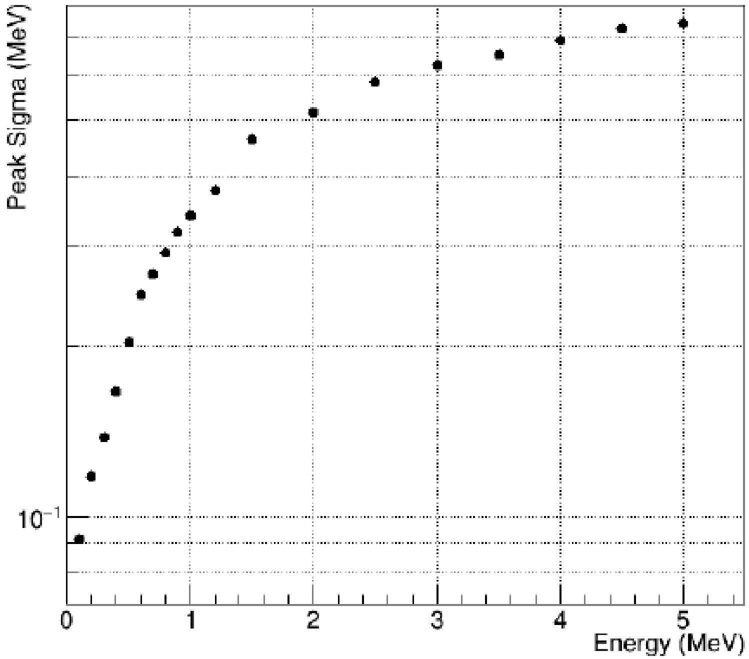
Slide/figures courtesy of D. Scriven

Summary and Outlook

- Many exciting results at the drip lines
- Many more measurements to come in the age of FRIB
  - Proton rich: ^{20}Al (charge exchange ^{20}Mg), measure 2^+ ^{22}Si – isobaric analogue of ^{22}O
  - Neutron rich: ^{53}Ca, ^{30}F
  - TexAT-TPC available – elastic scattering, transfer reactions
- Experiments far from stability
  - Energy upgrades for FRIB
  - HRS for experiments on heavier masses
  - Detailed knowledge of structure/reactions needed
  - TPC in inverse kinematics
- Upgrades to the equipment needed
  - Measurements of light-charged particles limited to 100 MeV/u protons
  - Neutron-unbound resonant state resolution is limited by multiple factors
  - Beam time limited – more research groups work together to maximize research output
- More Unbound Physics – Bob Charity and Thomas Redpath

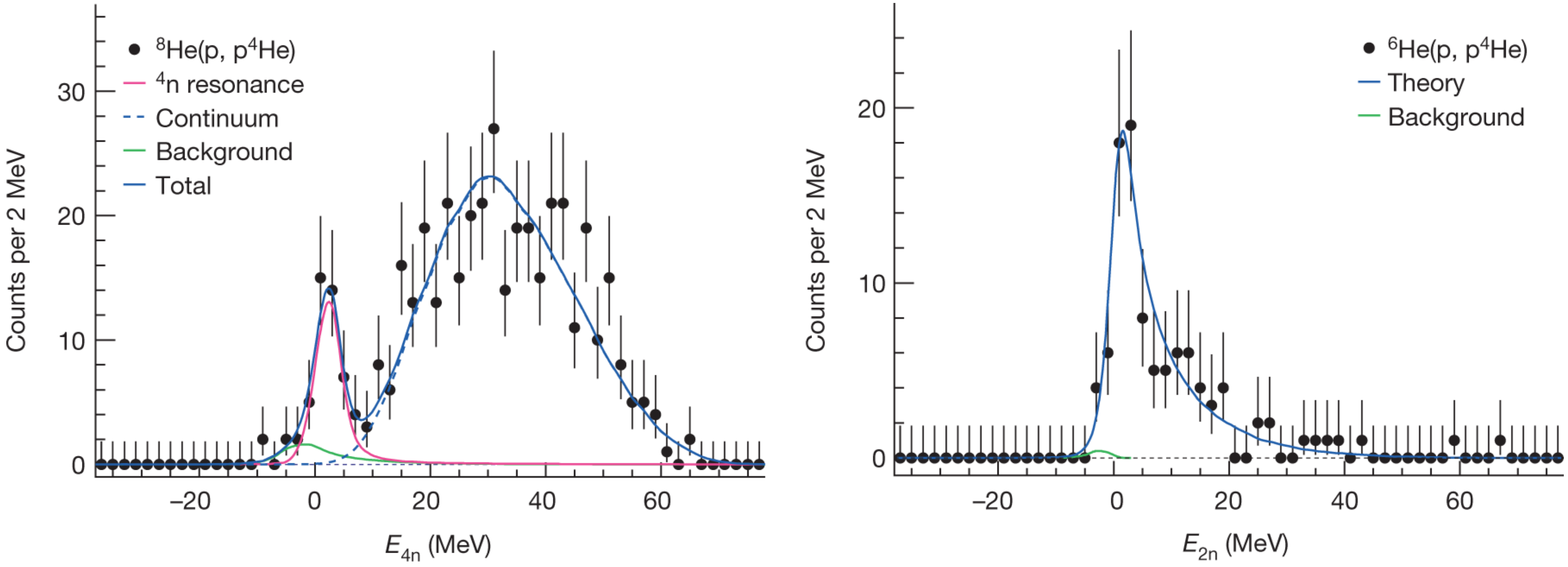
Unbound states near the neutron dripline – ^{31}Ne





- Efficiency (left) and resolution (right)

Missing Mass Reconstruction



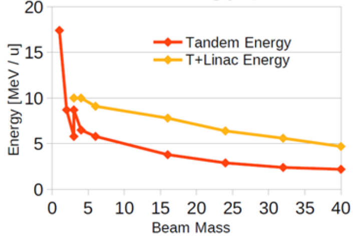
Duer *et al.*, Nature **606**, 678 (2022)

In-beam high resolution γ-ray spectroscopy at FSU

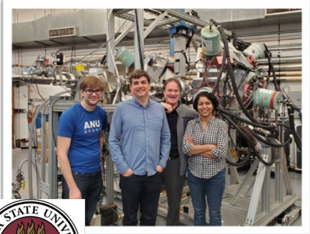
Vandana Tripathi

- ❑ Centered around the heavy ion beams from the tandem-Linac accelerator: ^{14}C, ^{18}O, ^{3}H
- ❑ Clovers, single crystal HpGe, charged particle and neutron detector for tagging
- ❑ Large graduate student community
- ❑ Diverse physics program
- ❑ Collaboration with other groups

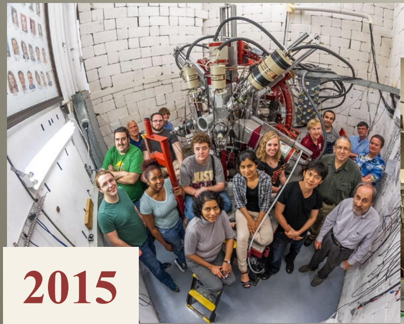
- 9 MV Tandem + 8 MV Linac
- Beam Energy profile

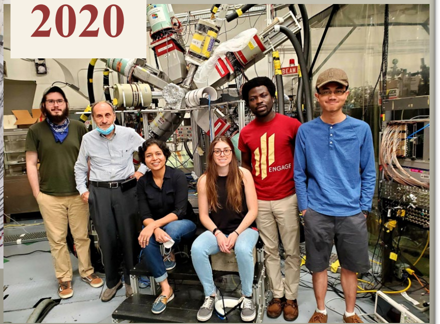



2006

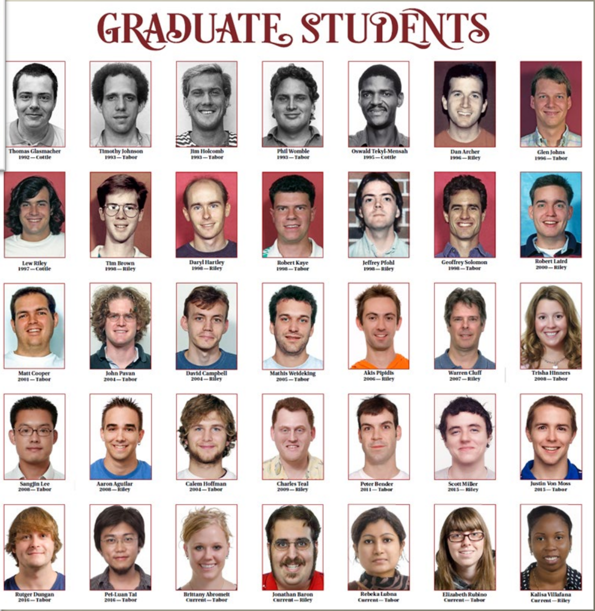


2022


2015


2020

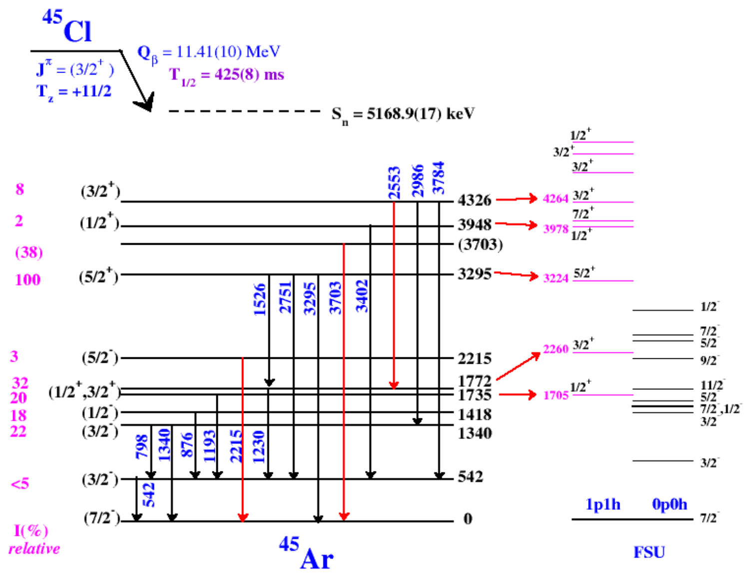

2021



Intersection with Theory

An empirical shell-model interaction, FSU, was developed within the *s-p-sd-fp* model space using the data fitting procedure.

NSCL E18016



V. Tripathi et al, to be published

physics

MDPI

Review

The Nuclear Shell Model towards the Drip Lines

B. Alex Brown

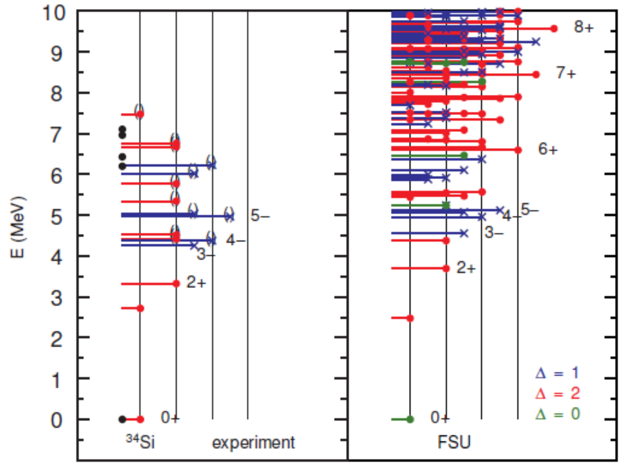


Figure 5. Spectrum of ^{34}Si obtained with the Florida State University (FSU) Hamiltonian [56] compared to experiment. The length of the horizontal lines are proportional to the the angular momentum, J. The experimental parity is indicated by blue for negative parity and red for positive parity. Experimental spin-parity, J^π, values that are tentative are shown by "()", and those with multiple of no J^π assignments are shown by the black points. The calculated results are obtained with the FSU Hamiltonian with pure Δ configurations. The parities are positive for Δ = 0 (green) and Δ = 2 (red) and negative for Δ = 1 (blue).

Phys. Rev. C 100, 034308 (2019); Phys. Rev. Research 2, 043342 (2020)

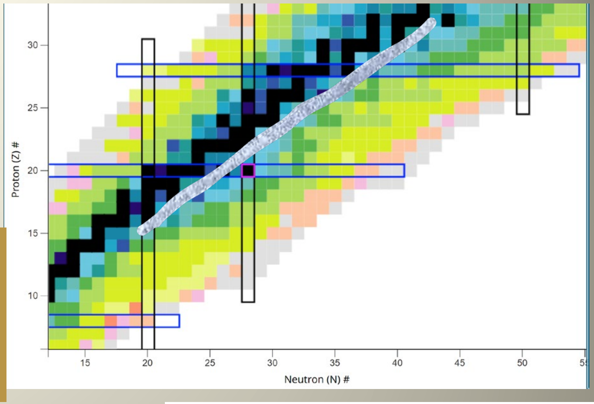
Future Plans ..

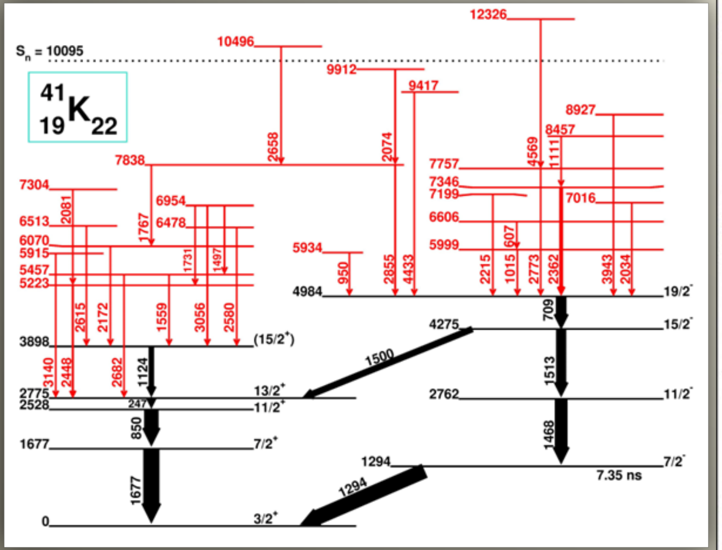
- More experiments …Expand the fit to more exotic nuclei … Include $g_{9/2}$ orbital in the valence space

Going forward

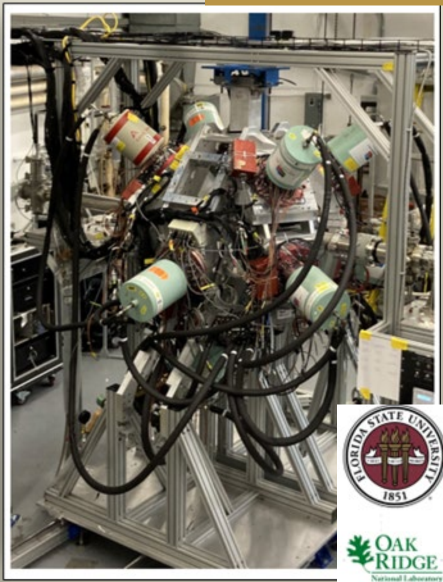
- ☐ sd and fp shell nuclei
- ☐ Detailed spectroscopy: level scheme, angular distribution, polarization, lifetime of excited states
- ☐ Targets, beams, detectors
- ☐ Overlap with FRIB physics
- ☐ Input for SM calculations
- ☐ High spin states & Cross shell excitations

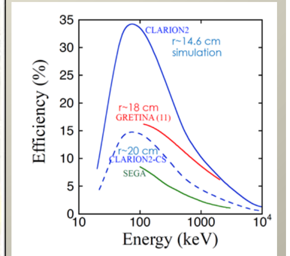
More Collaborations
ORNL, UMass L, NCSU, MSU, Westmont College,CA & NNDC

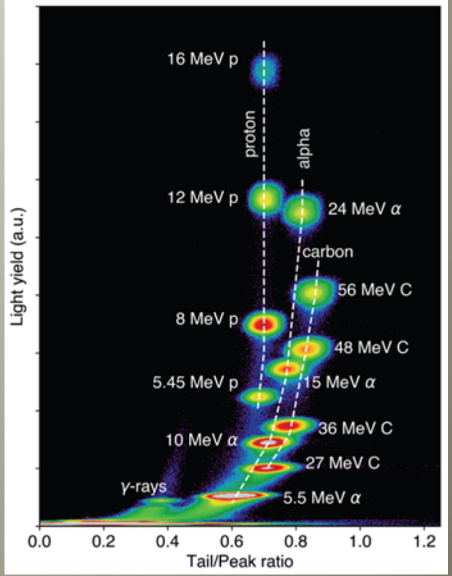




Elizabeth Rubino et al., EPJA 58, 107 (2022)







FRIB

Search for the drip lines

Oleg Tarasov

Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824 USA

Low Energy Nuclear Structure, Reactions and Astrophysics Town Meeting
Argonne National Laboratory, Nov 14 – 16, 2022

MICHIGAN STATE UNIVERSITY

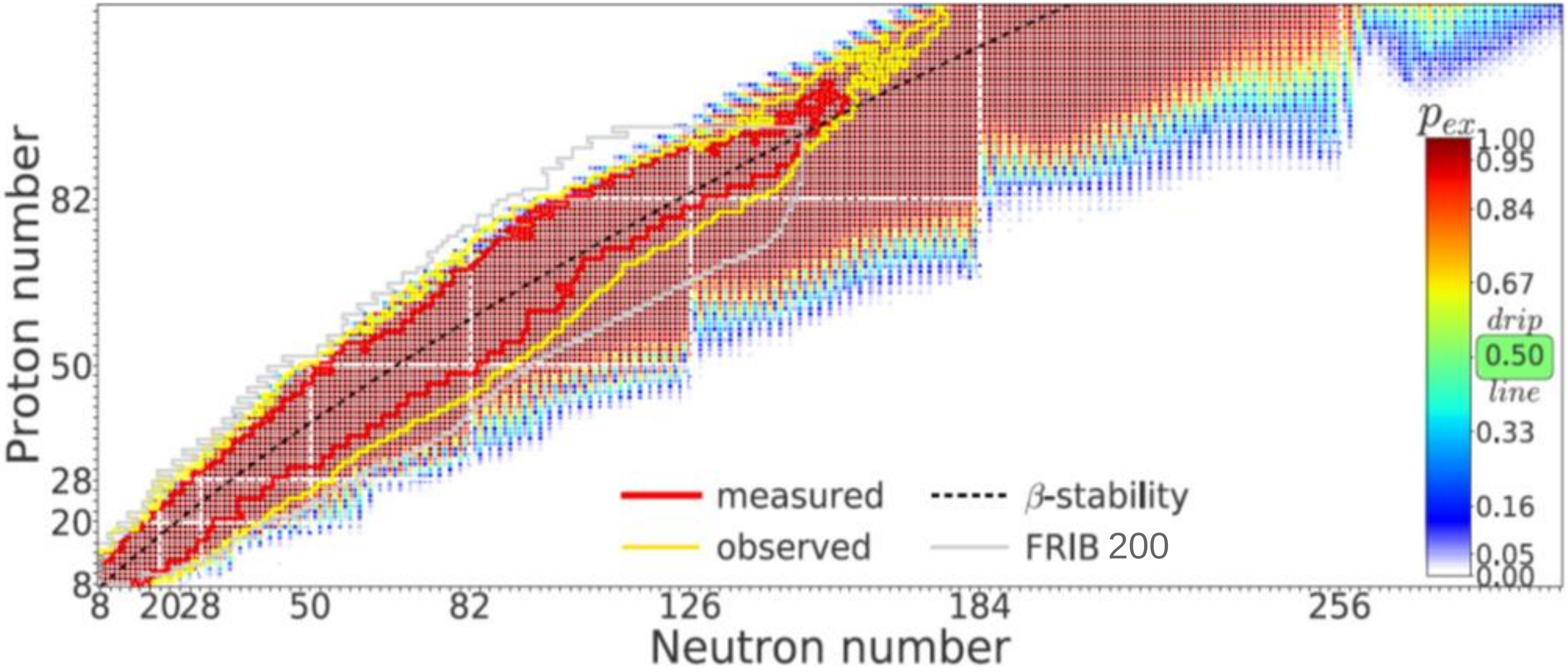
U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University operates FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Terra Incognita

LÉO NEUFCOURT *et al.* PHYSICAL REVIEW C **101**, 044307 (2020)

The quantified landscape of nuclear existence obtained in the BMA calculations



- Only around 3000 have been experimentally observed
- According to the Bayesian model averaging analysis, the number of particle-bound nuclei with Z,N ≥ 8 and Z ≤119 is 7708 ± 534 (>50% chance), and >10% chance of 10,000 isotopes

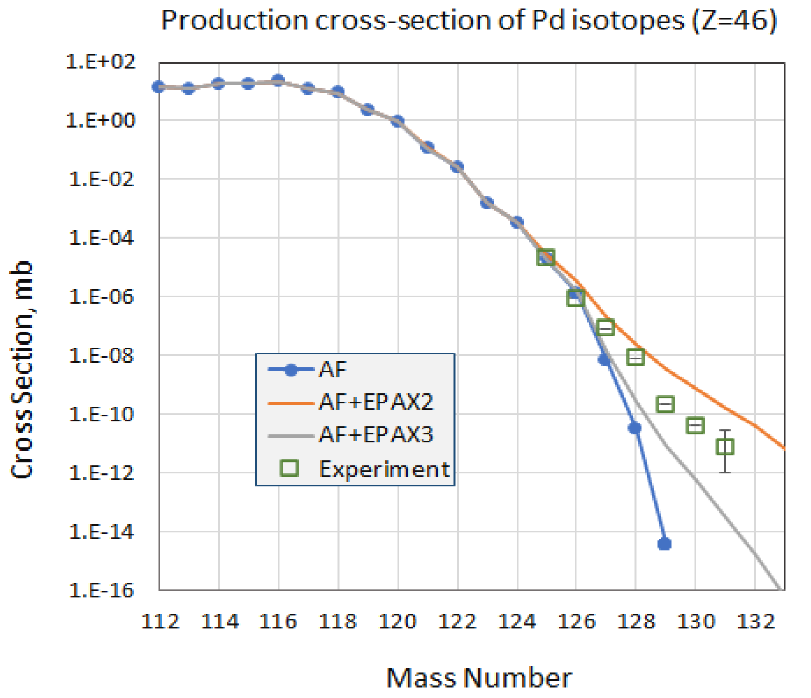
Tools to reach the drip lines

- Where ?

The Facility for Rare Isotope Beams (FRIB), a new world-leading user facility, will be capable of expanding the known Chart of the Nuclides using ARIS, large-acceptance 3-stage fragment separator.

- What steps?

Choose a reaction and optimize fragment-separator settings for maximum production rates for searching new isotopes during time-reasonable period



AF:	3EER Abrasion-Fission model, LISE v.16.8.8, masses: WS4_RBF
AF+ EPAX2,3:	With secondary reactions based on the empirical parameterizations v.2 or 3
Experiment:	Y. Shimizu et al., J. Phys. Soc. Japan 87 (2018) 014203

Key words are “choose a reaction”.

So, just the increase of beam intensity does not allow to move far in some regions using one-step reactions.

The multi-step reactions (including combination of different reaction mechanisms in some regions) become is a key factor

Experimental and theoretical directions to study

- Experiment:
  - **Measurement of cross-sections with rare isotope beams**
    with following benchmarks of models for production cross-sections, masses, excitation energies

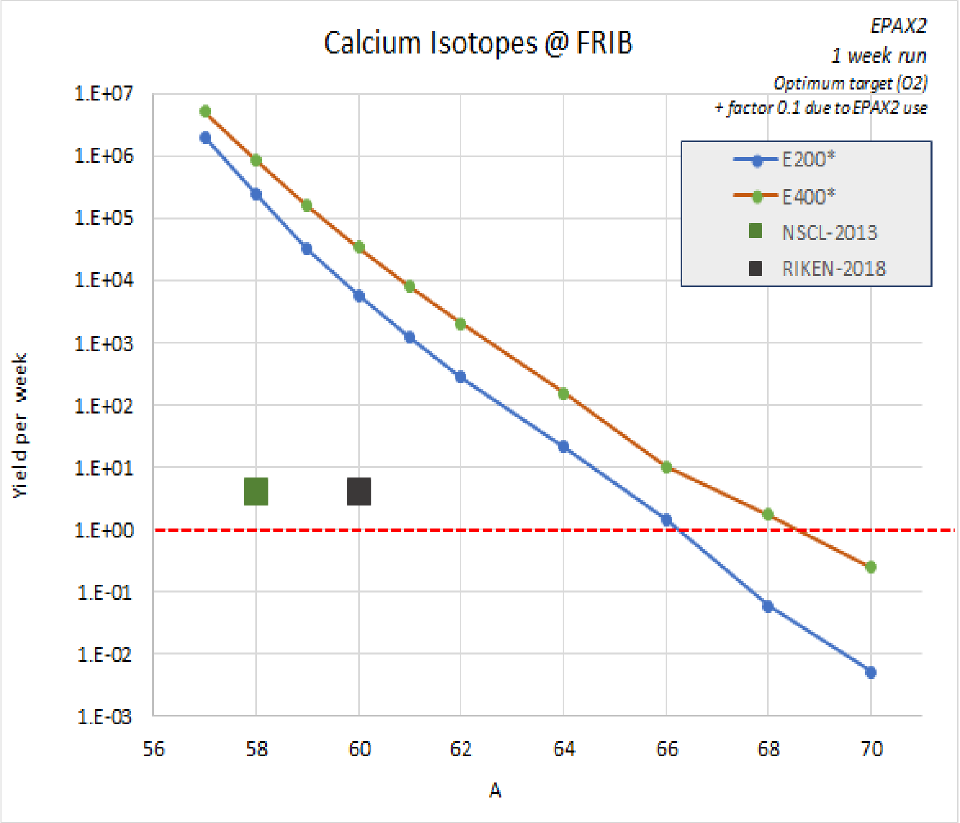
- Theory
  - Abrasion mechanism. Excitation energy distribution characteristics (shape, values)
  - Development of the fast and qualitative algorithms of multi-step reaction calculations with mass table use:
    - ✓ applying the abrasion-ablation model for secondary steps
      (no more mass-independent parameterizations based on data with stable beams)
    - ✓ codes optimization and parallelization
  - Mass models

Instrumentation impact to multi-step factor

- Upgrading FRIB to 400 MeV/u makes it possible to increase the production probability of neutron-rich isotopes in multi-step reactions by an order of magnitude
- Target production research: Use a liquid lithium target to increase the multi-step factor

<u>1 week run</u>

^{66}Ca @ E200 ~ 1 event: C-target
^{68}Ca @ E400 ~ 1 event: C-target
^{70}Ca @ E400 ~ 1 event: Li-target



Search for the drip lines with FRIB400

Brad Sherrill

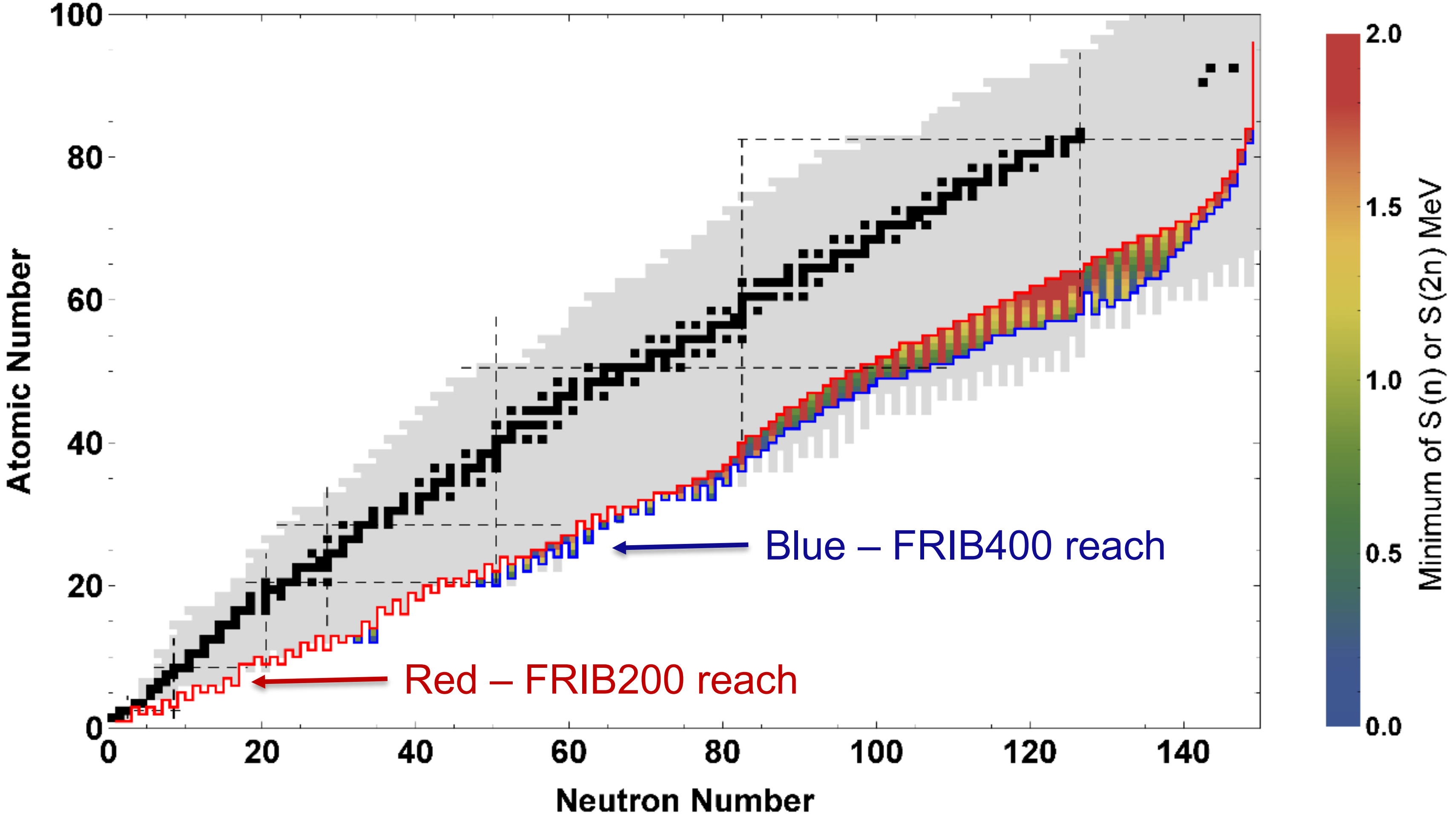
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824 USA

Low Energy Nuclear Structure, Reactions and Astrophysics Town Meeting
Argonne National Laboratory, Nov 14 – 16, 2022

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University operates FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

FRIB400 Extends Reach Along the Drip Lines

- Drip line reach extended to Z ≈ 60 by FRIB400



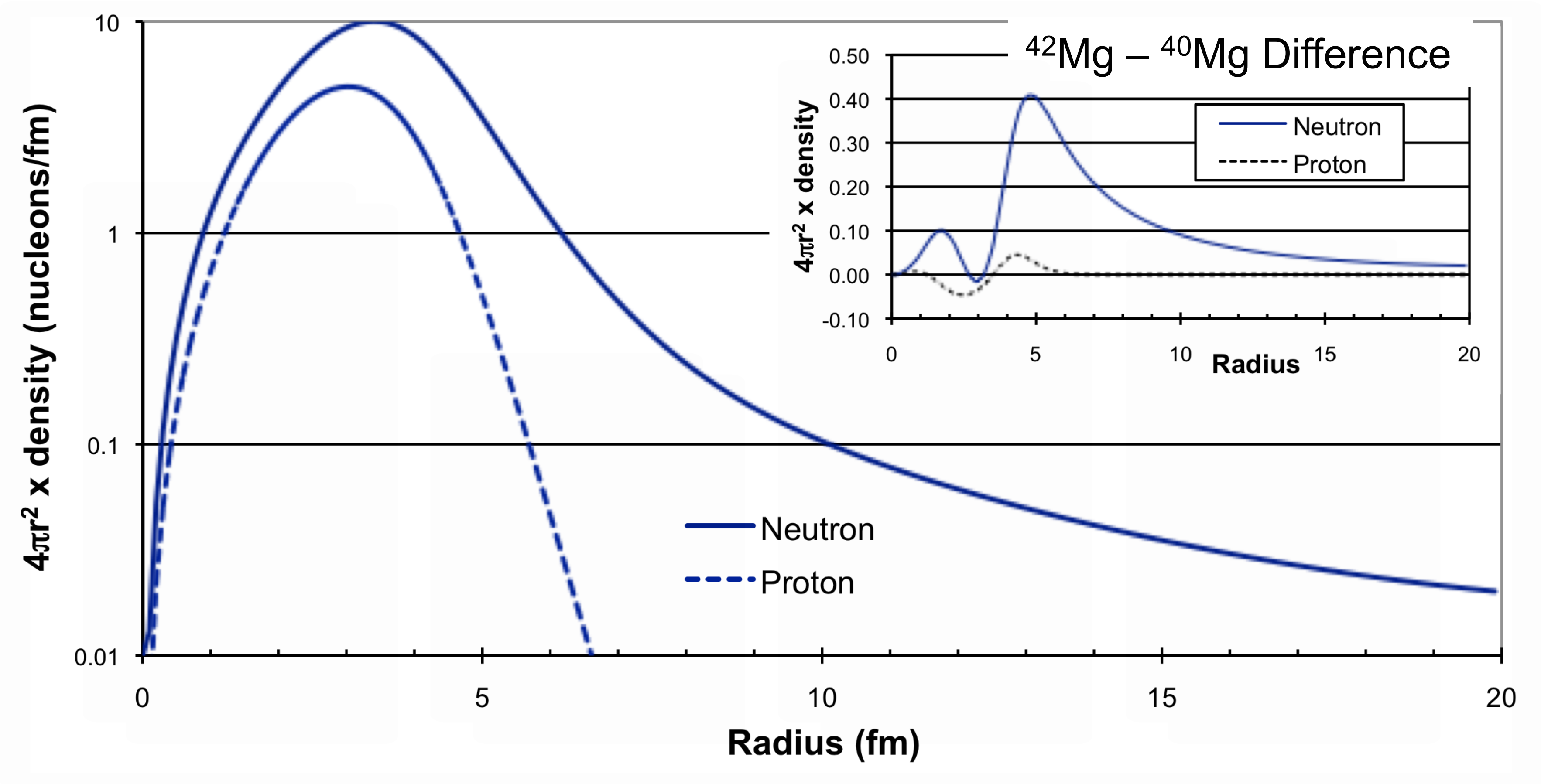
Blue – FRIB400 reach

Red – FRIB200 reach

Gray boxes are bound isotopes from UNEDF0

Example of Gains ^{42}Mg: New Insight and Physics from Extreme Halos and Skins

- Example: ^{42}Mg (predicted to be produced at 0.01/s at FRIB400 and 0.0005/s at FRIB200)
  Binding energy not known: S_n =100 keV BA Brown

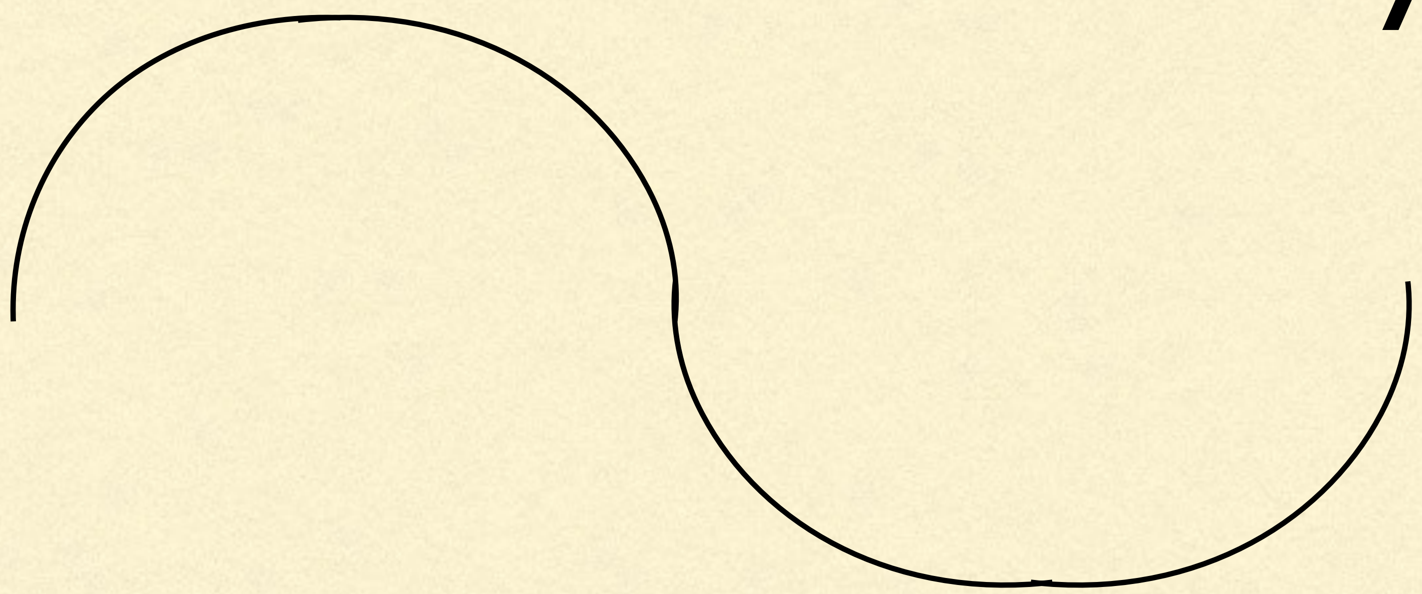


Opportunities with halo nuclei

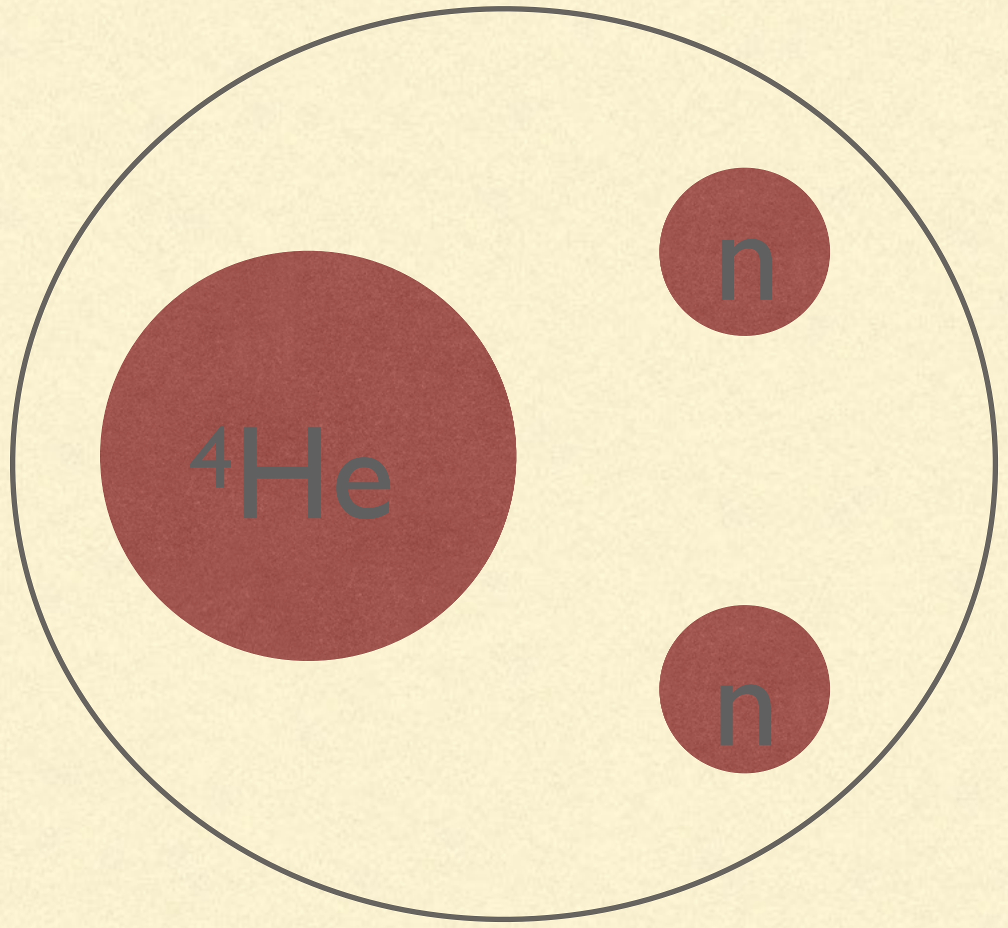
Daniel Phillips, Ohio University

RESEARCH FUNDED BY THE DOE OFFICE OF SCIENCE, NUCLEAR PHYSICS AND THE NATIONAL NUCLEAR SECURITY ADMINISTRATION

Halo EFT



$\lambda \gg R_{core}$; $\lambda \lesssim R_{halo}$



- Neutron halos are systems that exist "beyond the classical regime", this makes them insensitive to details of the core-neutron interaction
- Can be described by an EFT expansion in R_{core}/R_{halo}. Valid for $\lambda \lesssim R_{halo}$
- Complementary to *ab* initio or other microscopic approaches. Halo EFT provides a bridge from microscopic calculations to reaction theory. The EFT expansion permits identification of the key structure quantities that affect low-energy reaction observables at a given accuracy level

Example: reactions on 1n halos

- ^{11}Be: breakup on ^{12}C and ^{208}Pb target, one-nucleon knockout, (d,p)

Hammer, DP (2011); Capel, Hammer, DP (2018); Hebborn, Capel (2021); Schmidt, Hammer, Platter (2018)

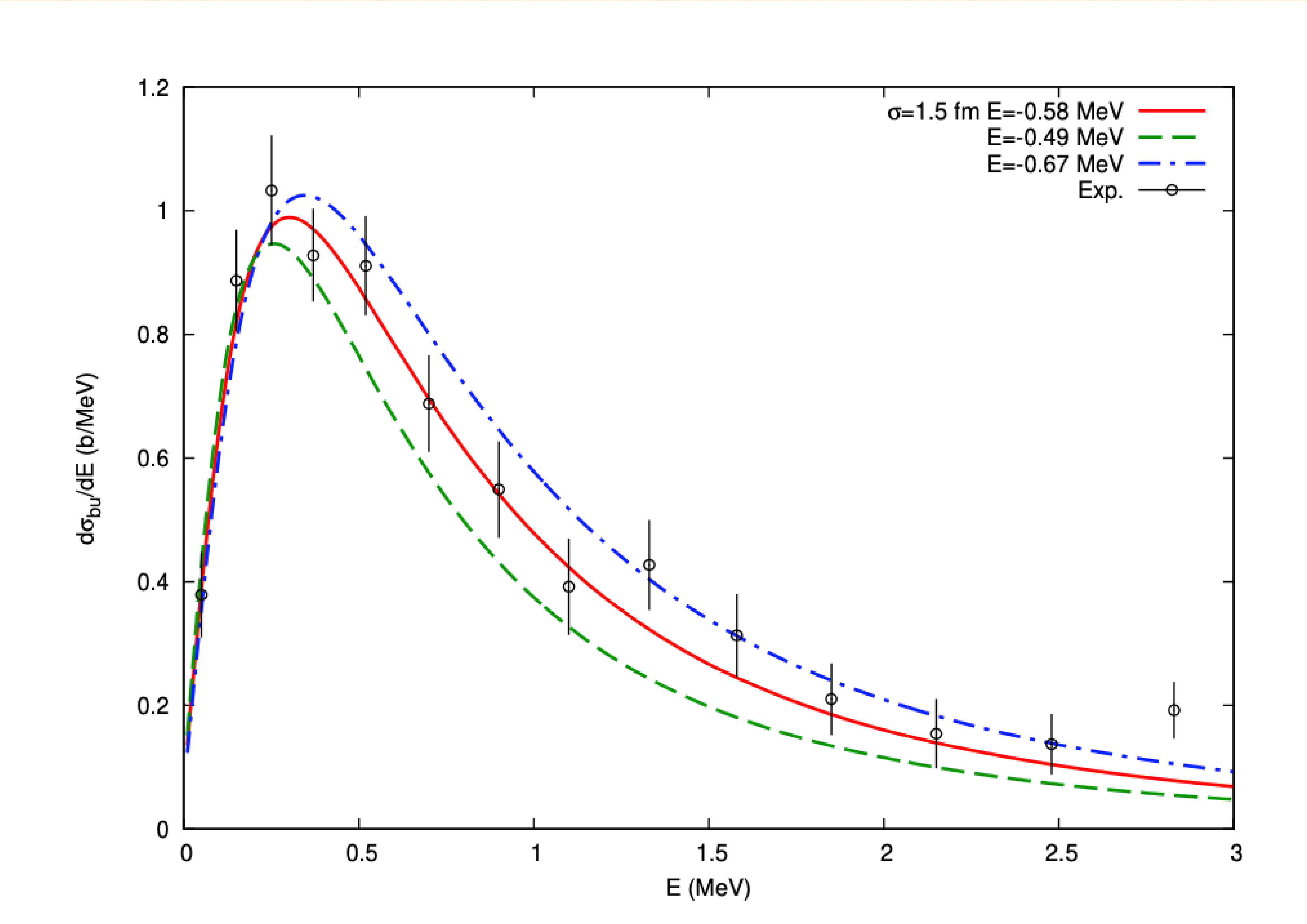
- Coulomb breakup of ^{15}C, ^{14}C(n,γ), ^{4}C(d,p), one-nucleon knockout

Moschini, Yang, Capel (2019); Hebborn, Capel (2021)

- ^{19}C: Coulomb dissociation on ^{208}Pb target

Capel, DP, + TALENT students (2023)

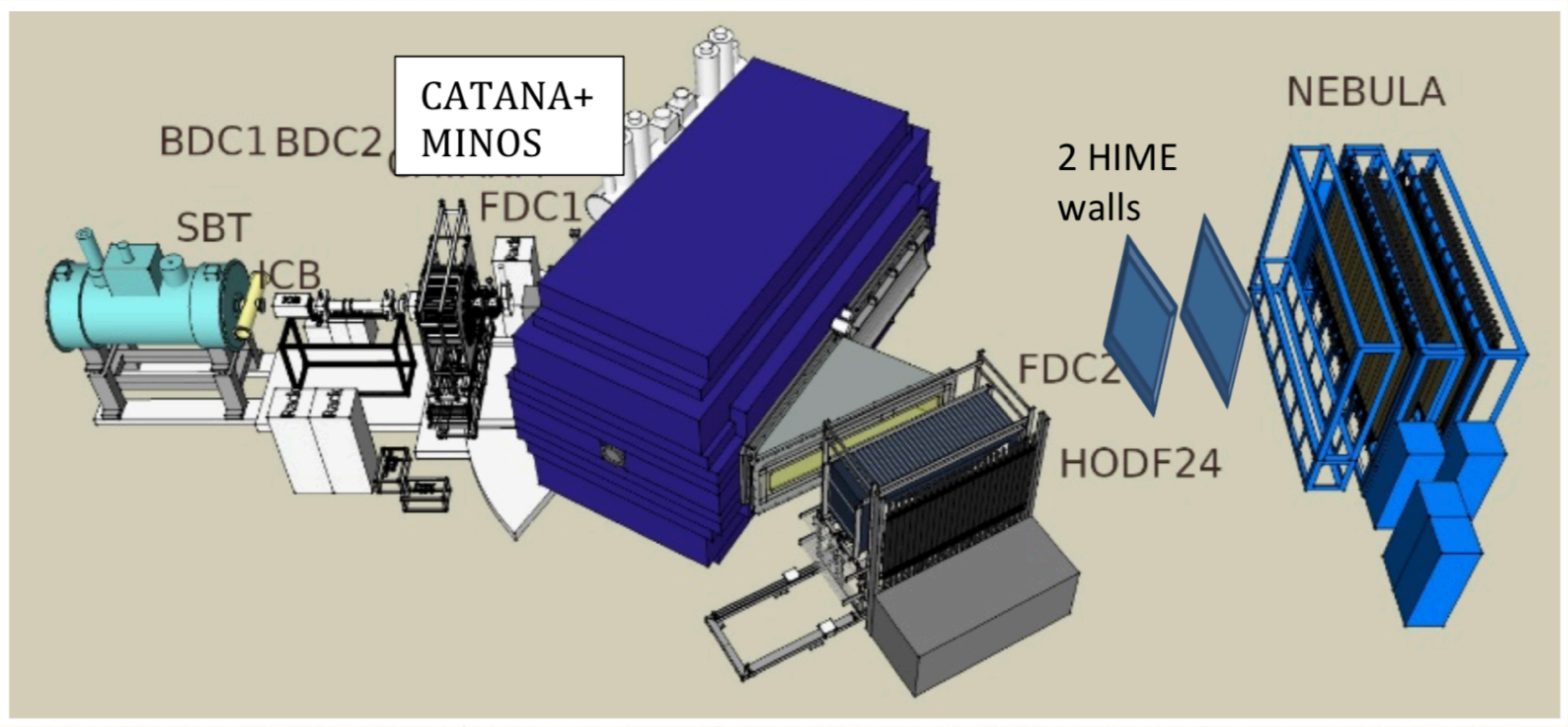
  - Further experimental opportunities: investigation of low-lying spectrum of ^{19}C through breakup on a light target; refinement of ^{208}Pb data; transfer measurements, e.g., (d,p), especially at low beam energy or forward angles, to constrain ANC. Knockout measurements with higher precision.
  - *Ab initio* theory opportunity: computation of ANCs, pattern of low-lying resonances

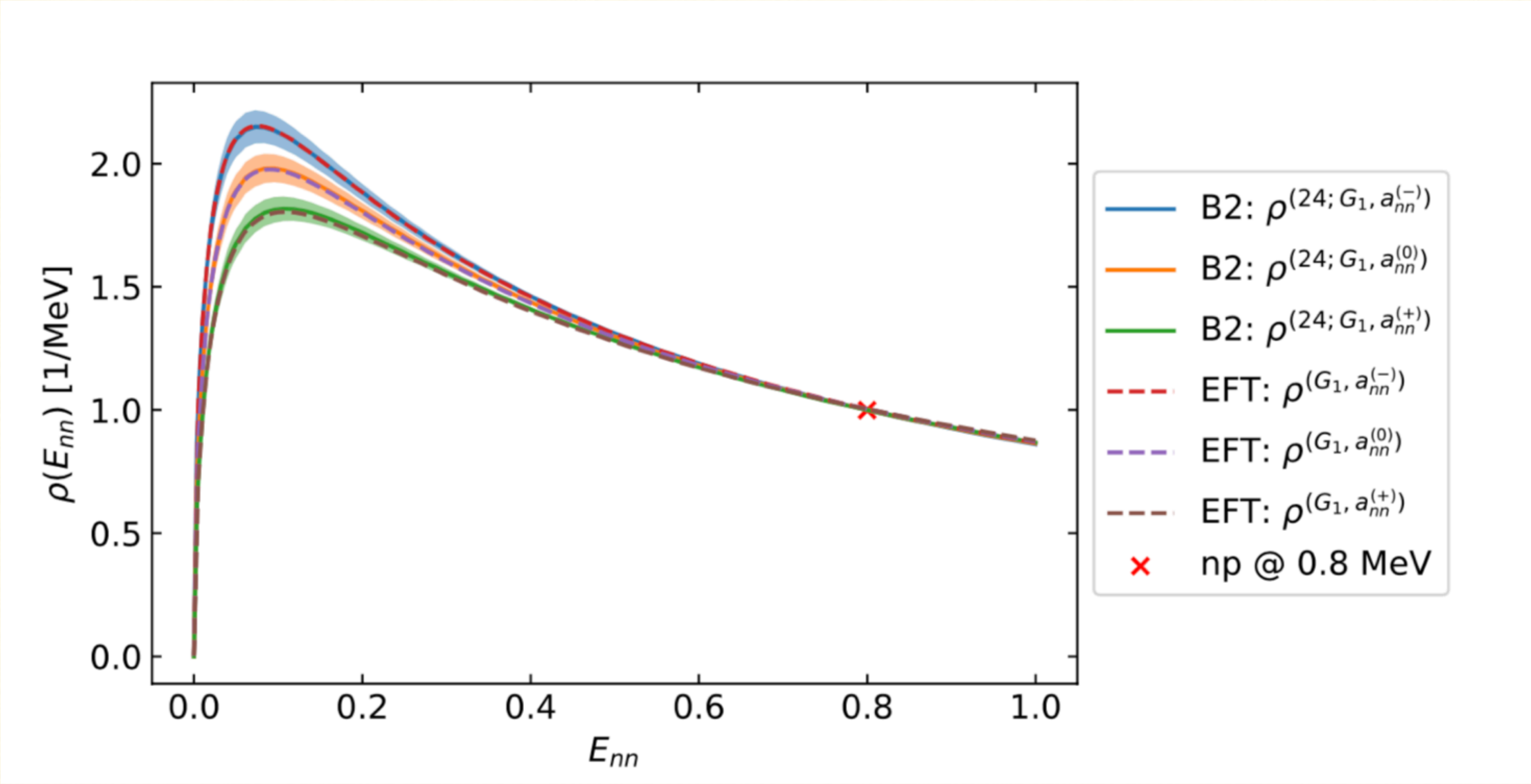


Example: 2n spectra in Borromean halos

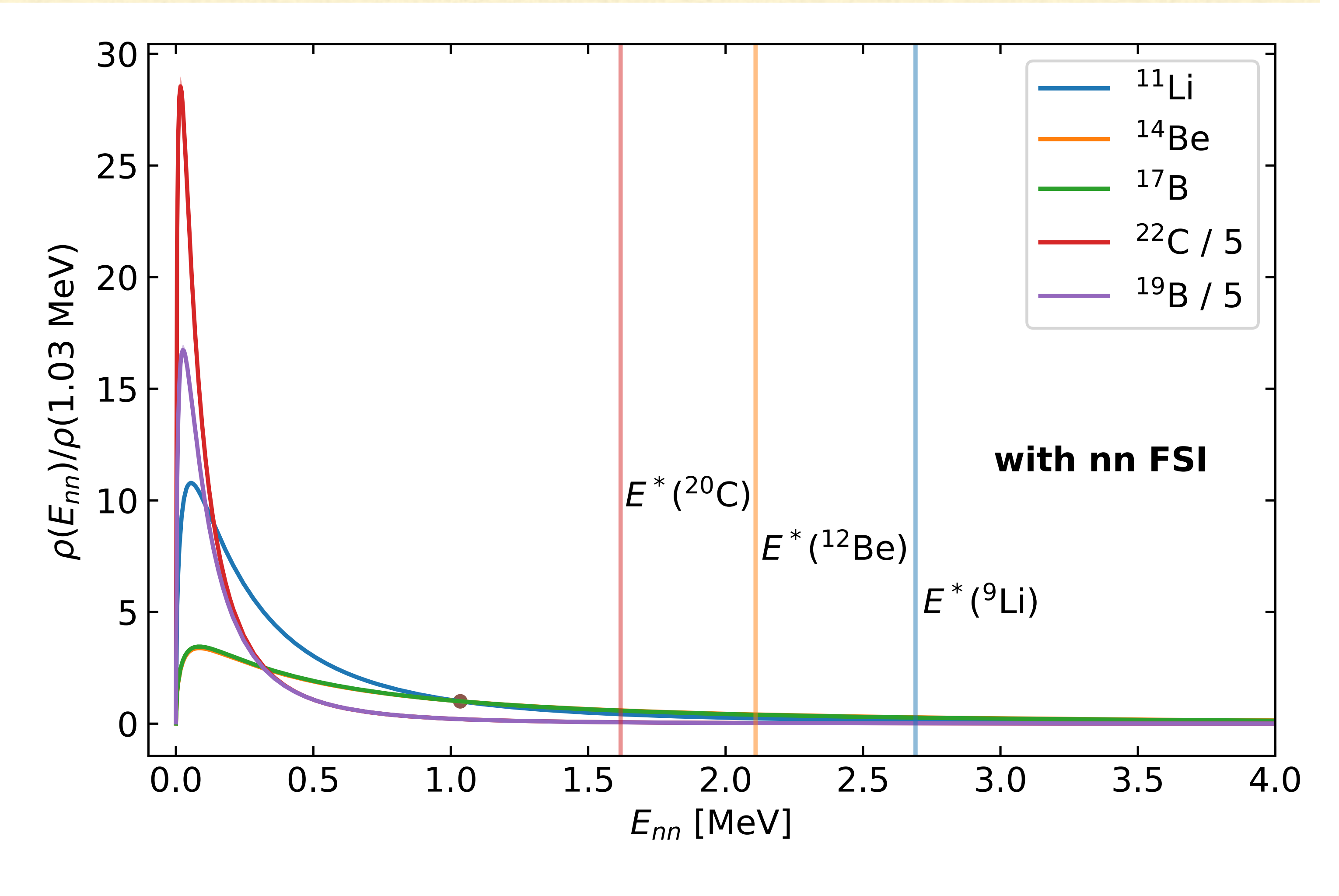
Göbel, Aumann, et al., PRC 104 (2021) 024001; Göbel et al., in preparation

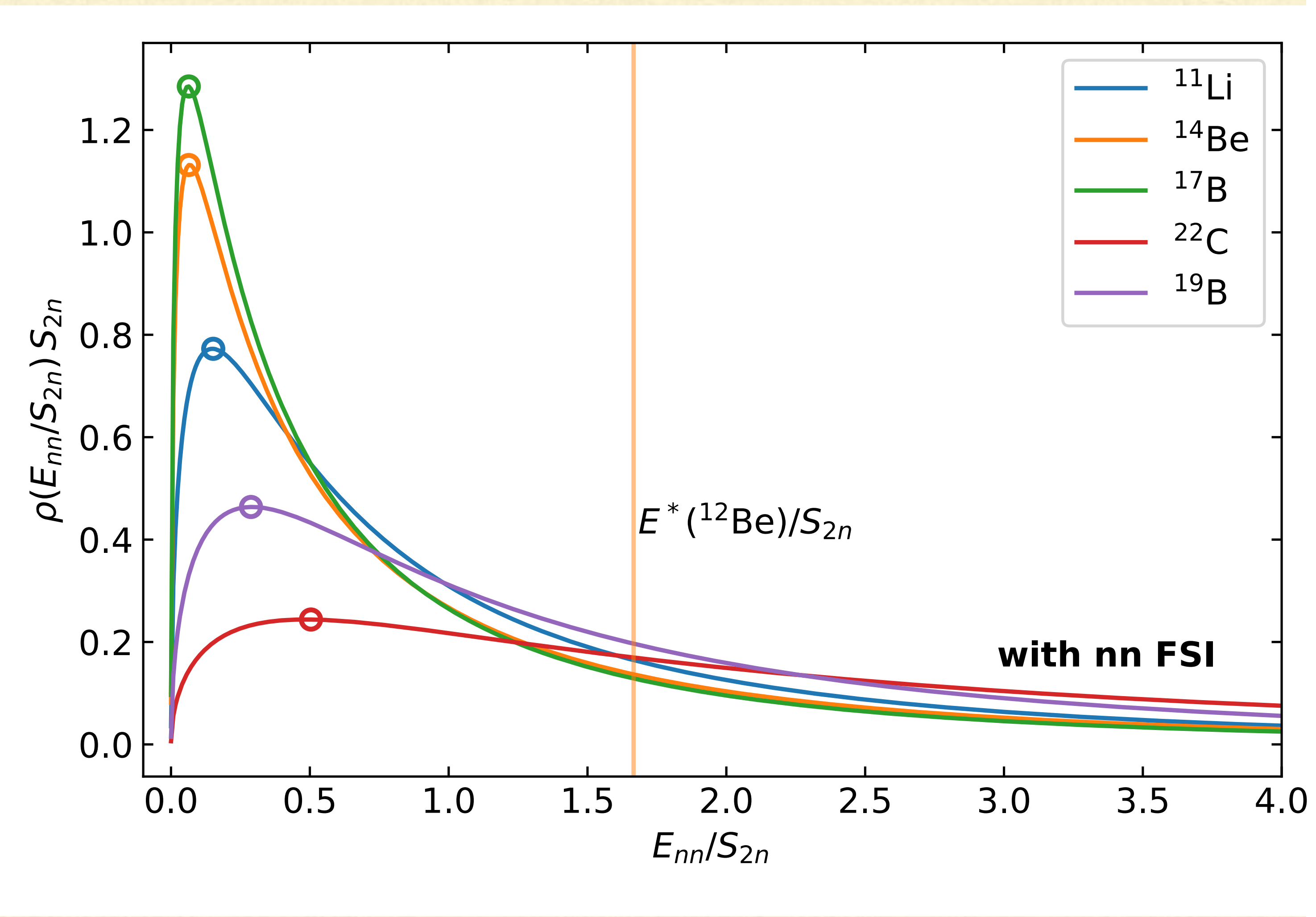
- Opportunity 1: use the halo nucleus as a “nn pair holder” and obtain an accurate value of the nn scattering length

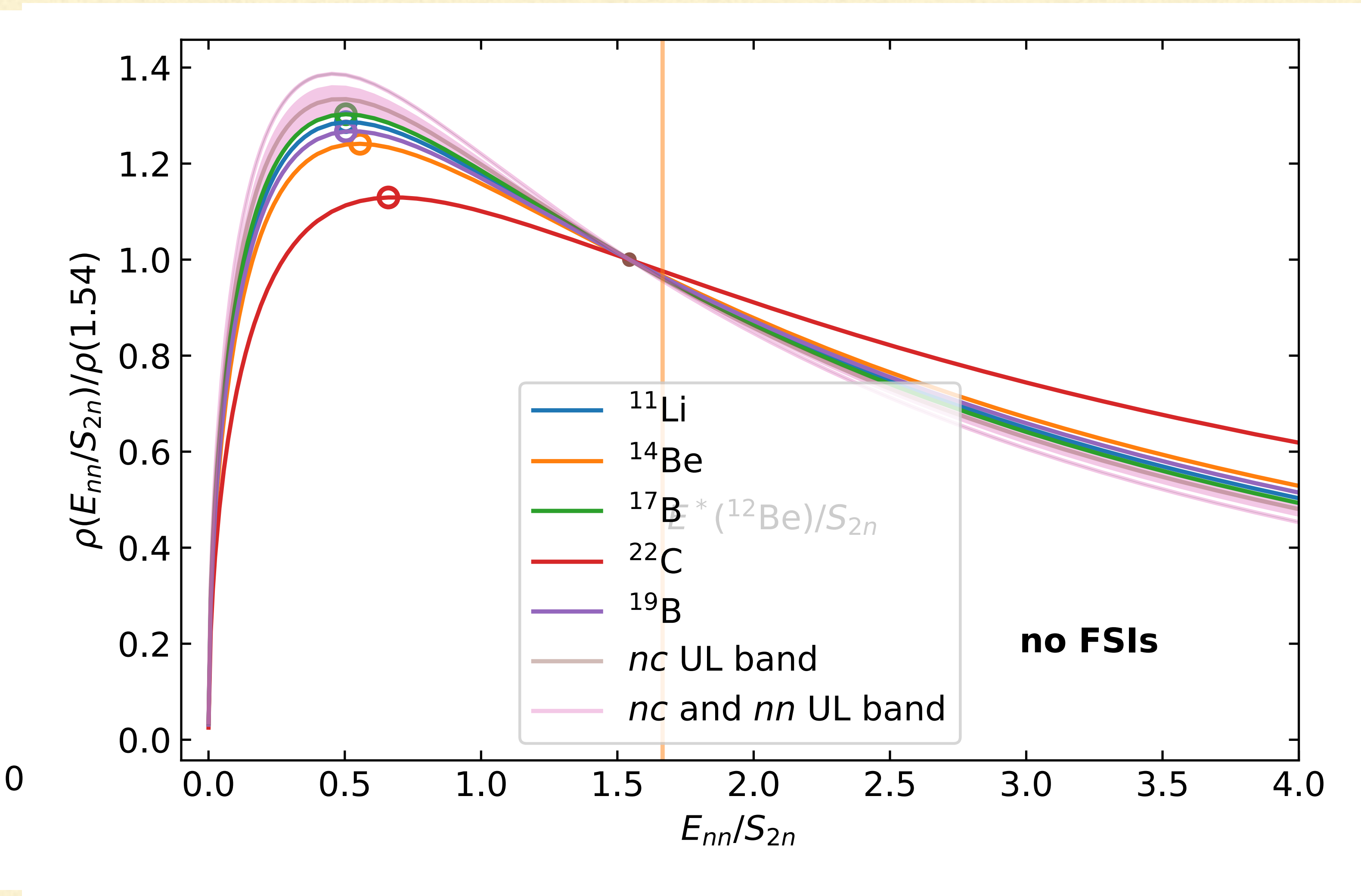




- Opportunity 2: measure the nn energy spectrum for a variety of halo nuclei and show they are related by universality

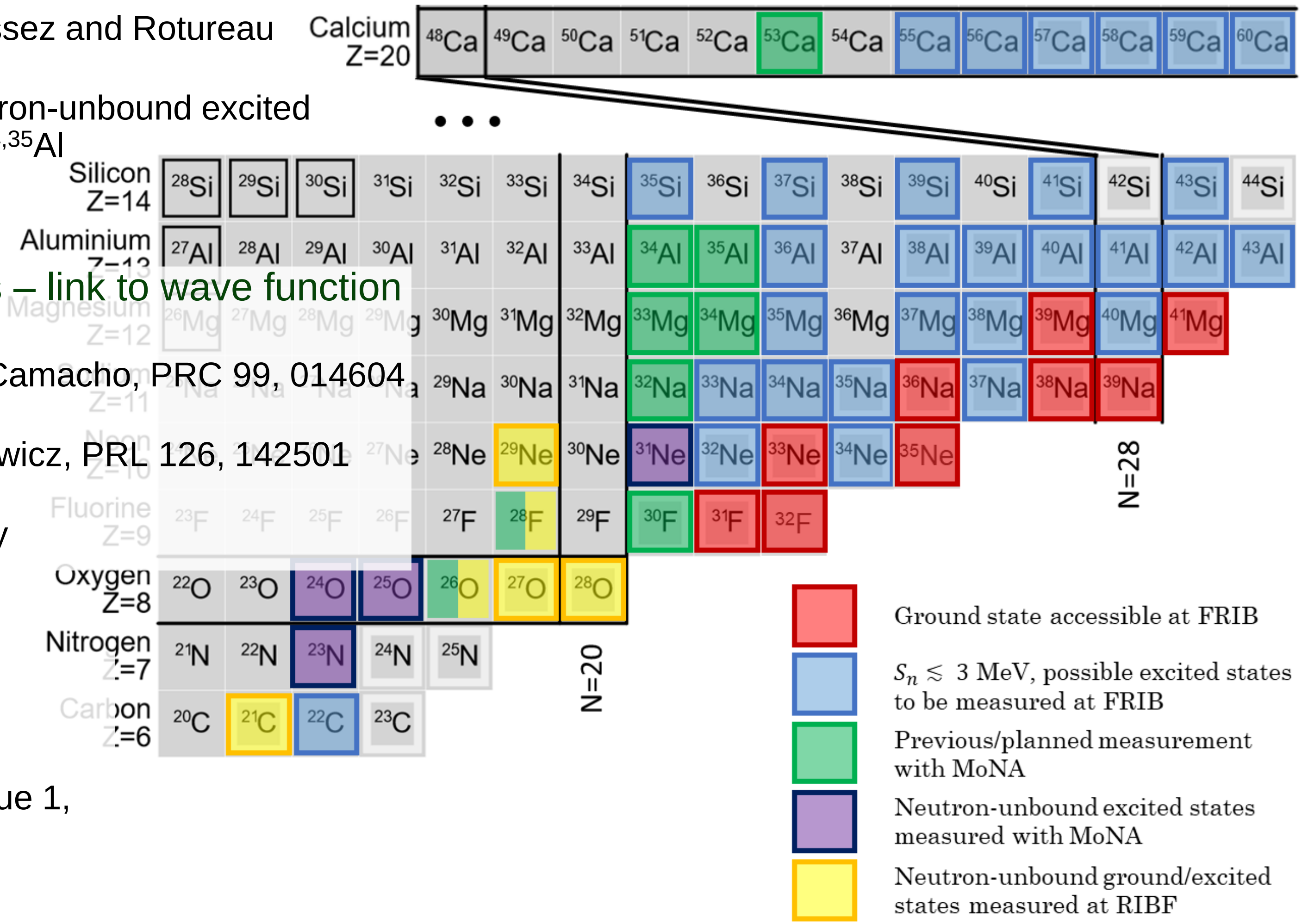






The Neutron-Unbound Landscape

- Evolution of shell structure
  - Input to models, e.g. Fossez and Rotureau PRC 106 (2022)
  - Analysis underway: neutron-unbound excited states in ^{32}Na, ^{33,34}Mg, ^{34,35}Al
- Three body correlations – link to wave function for unbound nuclei
  - J. Casal and J. Gómez-Camacho, PRC 99, 014604 (2019)
  - S. Wang and W. Nazarewicz, PRL 126, 142501 (2021)
  - Two-neutron radioactivity
- Studies of 4n emitters
  - ^{28}O (RIKEN, SAMURAI)
  - P. G. Sharov *et al*. JETP Letters, Volume 110, Issue 1, pp.5-14



🟥 Ground state accessible at FRIB

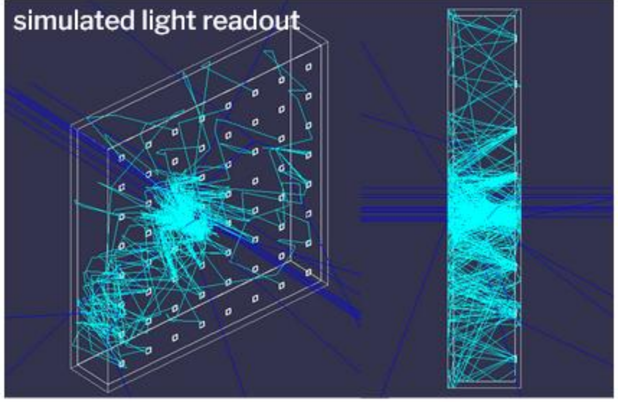
🟦 $S_n \lesssim$ 3 MeV, possible excited states to be measured at FRIB

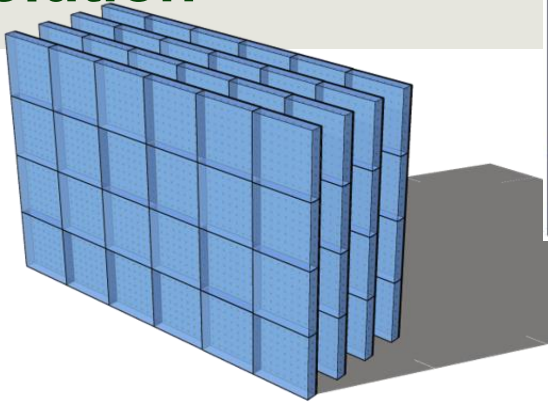
🟩 Previous/planned measurement with MoNA

🟪 Neutron-unbound excited states measured with MoNA

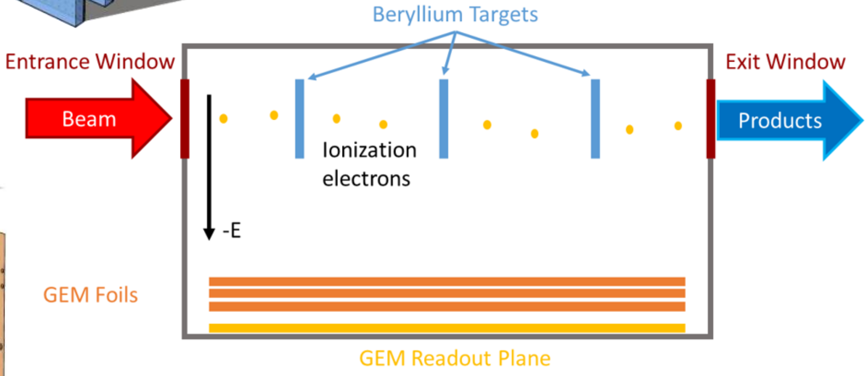
🟨 Neutron-unbound ground/excited states measured at RIBF

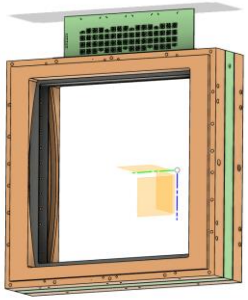
Equipment Upgrades to Improve Experimental Resolution





- Neutron detectors
  - SiPM for light readout
  - Optimized for position resolution
  - Modular detector tiles
- Targets
  - Si-Be Segmented Target
  - Multi-layer ‘Active’ Target for MoNA Experiments (MAME)
  - MINOS-style liquid hydrogen target (Berkeley Lab)
- Charged particle detectors
  - Drift chambers to be outfitted with micromegas readout
  - Timing detectors updates
- Gamma detection crucial for measuring decays to excited states in daughter fragment





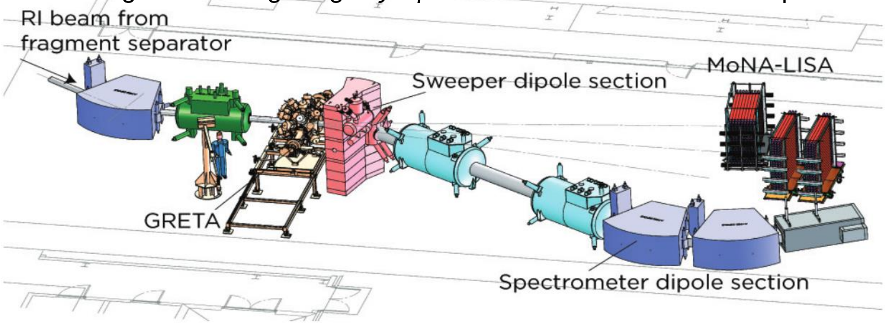
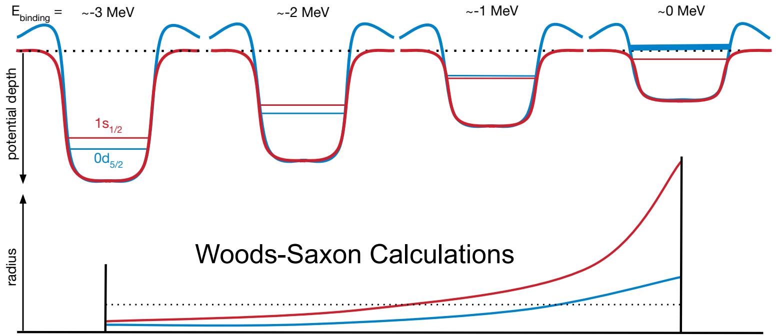
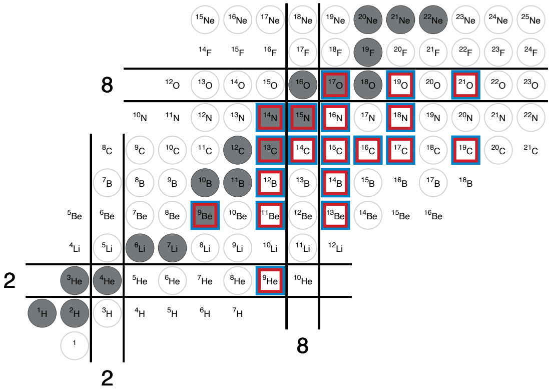


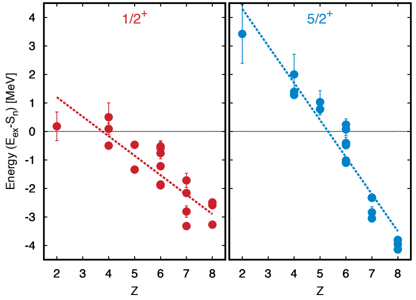
Image from *A High Rigidity Spectrometer for FRIB* White Paper.

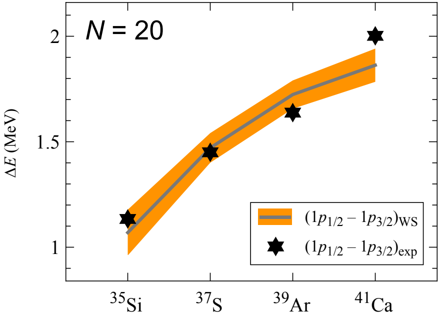
Summary

- Spectroscopy of neutron-unbound systems will continue to provide guiding constraints for nuclear theory
  - Invariant mass spectra – nuclear structure
  - N-body correlations – decay dynamics
- FRIB will make new neutron-unbound systems accessible, two PAC1-approved MoNA experiments
- Equipment upgrades are underway to improve the resolution of invariant mass spectroscopy and n-body correlation measurements
- The MoNA Collaboration invites anyone interested in proposing experiments (FRIB PAC2 and beyond) using MoNA/LISA to contact Thomas Baumann (baumann@frib.msu.edu) or me (tredpath@vsu.edu)

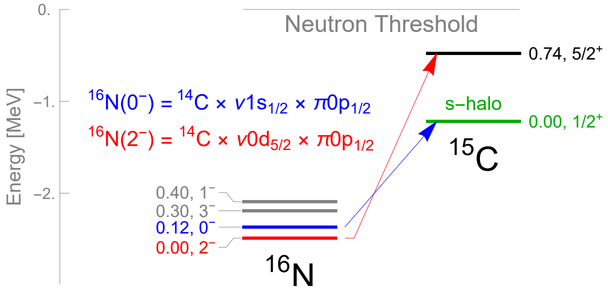




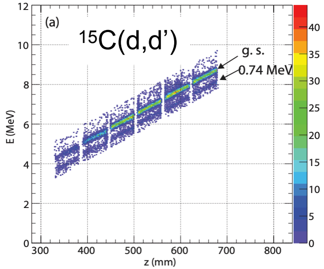




Kay PRL (2017)



Tang PRC (2022)

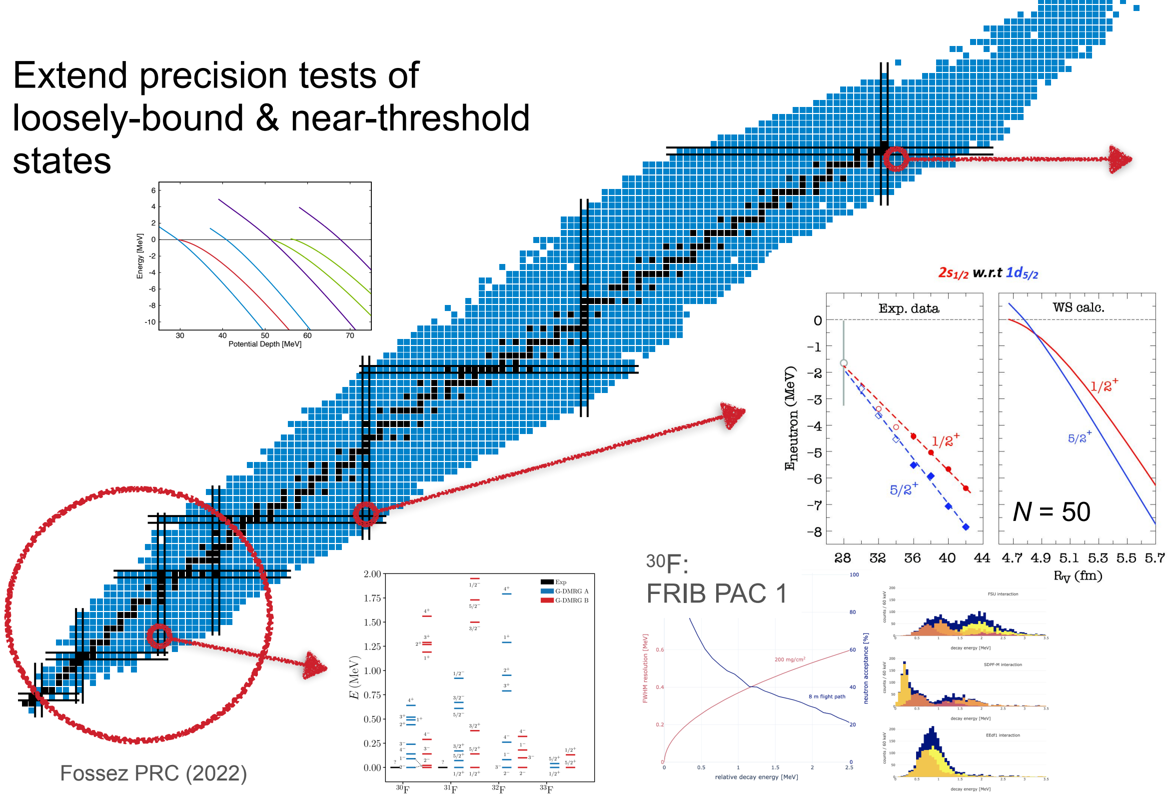


Chen PRC (to be pub.)

EXTENSION OF THE WAVE FUNCTION OUTSIDE THE NUCLEAR POTENTIAL

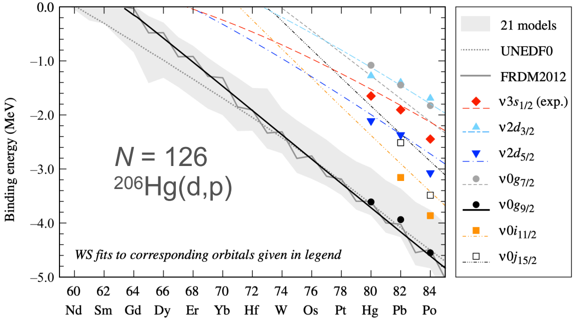
- MOST PROMINENT FOR S-STATES [S_N = BARRIER]
- NON-LINEAR EFFECT: NOT APPARENT IN CONFINING POTENTIAL
- MECHANISM RESPONSIBLE FOR / ROLE IN VARIOUS OBSERVABLE PHENOMENA
- HALO STATES, SHELL EVOLUTION, CAPTURE CROSS SECTIONS ETC…

Extend precision tests of loosely-bound & near-threshold states



Fossez PRC (2022)

^{30}F:
FRIB PAC 1



Tang PRL (2020)

WEAKLY BOUND STATES ACROSS THE CHART
- STRUCTURE DESCRIBING THE FLUORINE SPECTRA AT THE DRIP LINE
- HALO'S, SKINS & DEFORMATION IN THE SD-FP SHELLS
- $2S_{1/2}$, $3S_{1/2}$: NEUTRON STATES OUTSIDE OF N = 50 & 126
- PARALLELS FOREFRONT WORK IN THEORY OF OPEN QUANTUM SYSTEMS [UNIFYING REACTIONS + STRUCTURE]

Reactions:

transfer, knockout (quasi-free), inelastic scattering, break-up

[(d,p), (t,p), (3He,d) … -1p, (p,2p), (p,pn), … (p,p'), (d,d'), …]

Equipment:

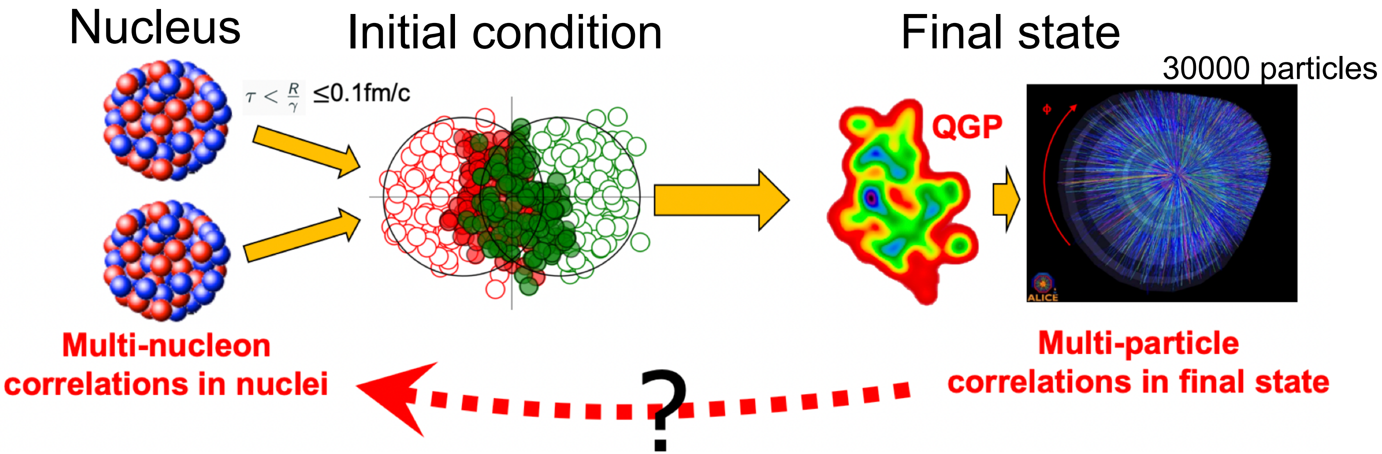
MoNA-LISA, HRS [Sweeper], SOLARIS/ HELIOS, proton / tritium / gas targets, AT-TPC, TexAT, and more

Facilities / Beams:

Stable, radioactive, isomeric beams at appropriate energies, rates, purities, and emittance …

Imaging nuclear structure with heavy-ion collisions

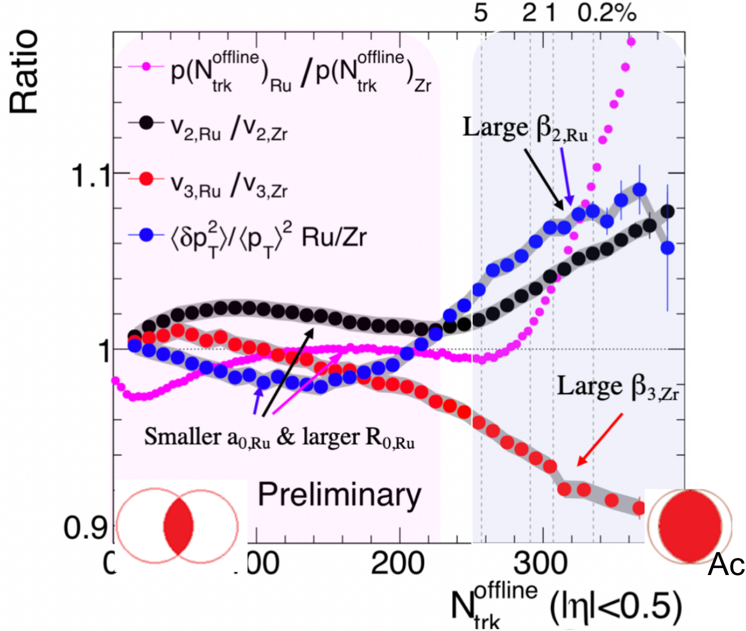
Atomic nuclei are strongly-correlated systems exhibiting rich structures in their shapes and radial distributions. These structures impact the initial condition and dynamics of quark-gluon plasma (QGP) in high energy collisions, where, due to short crossing time and abundant particle production, nuclear structure becomes easy to access: nucleon configurations are probed on an event-by-event basis via multi-particle correlations

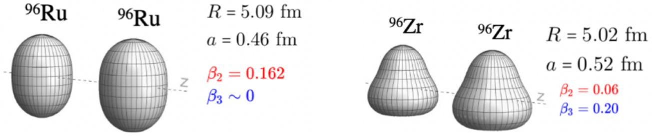


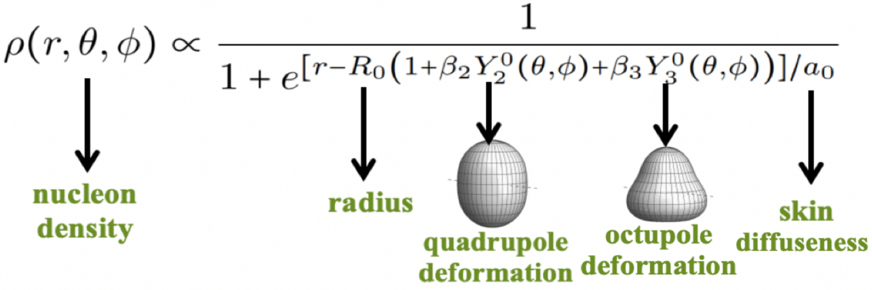
High-energy collisions is a good tool to reveal collective structures in atomic nuclei.

How impact of nuclear structure shows up?

Nuclear structure influences show up ubiquitously in comparison of data between isobar collision species (^{96}Ru and ^{96}Zr at $\sqrt{s_{NN}} = 200$ GeV).







$$\rho(r,\theta,\phi) \propto \frac{1}{1+e^{[r-R_0(1+\beta_2 Y_2^0(\theta,\phi)+\beta_3 Y_3^0(\theta,\phi))]/a_0}}$$

X and Y are isobars, O is an obervable:

$$\frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \stackrel{?}{=} 1 \longrightarrow$$

Departure from unity from nuclear structure.

Access structure differences: $$\boxed{R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{Ru}}{\mathcal{O}_{Zr}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a}$$

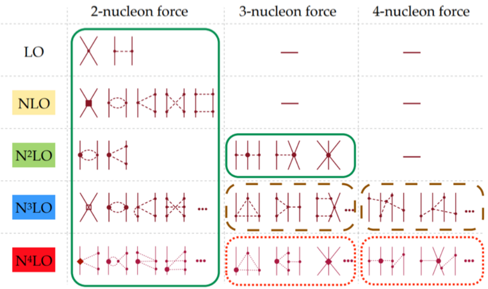
Connect to neutron skin: $\Delta r_{np} = \langle r_n\rangle^{1/2} - \langle r_p\rangle^{1/2}$

charge

$$\Delta r_{np,Ru} - \Delta r_{np,Zr} \propto (R_0\Delta R_0 - R_{0p}\Delta R_{0p}) + 7/3\pi^2(a\Delta a - a_p\Delta a_p)$$

mass

US nuclear community can explore the interdisciplinary connection between Heavy ion and structure of atomic nuclei in collisions of well-motivated species across the nuclear chart at the LHC



Impact on nuclear structure program.

Emergence of correlations from ab-initio description of the strong force, rapid progress expected in the next LRP period.

High-energy colliders are right laboratory.

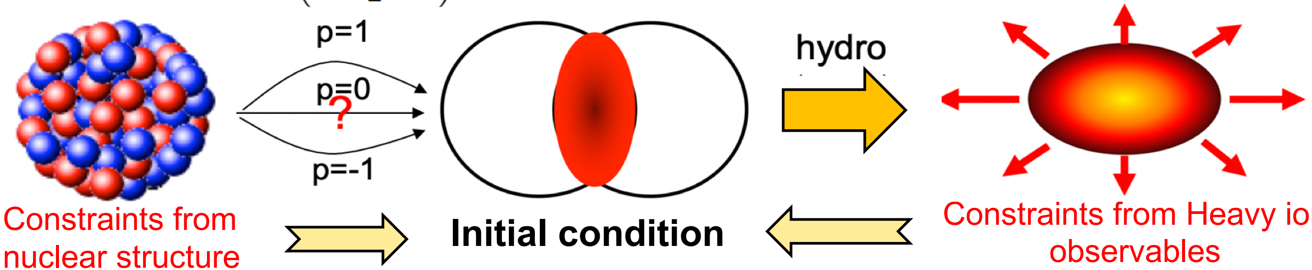
Energy deposition mechanism:

$$T \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{q/p}$$

Impact on heavy-ion collision program.

heavy-ion initial condition from lever-arm of nuclear structure

Key limitation in the extraction of QGP transport properties



Constraints from nuclear structure

Initial condition

Constraints from Heavy ion observables

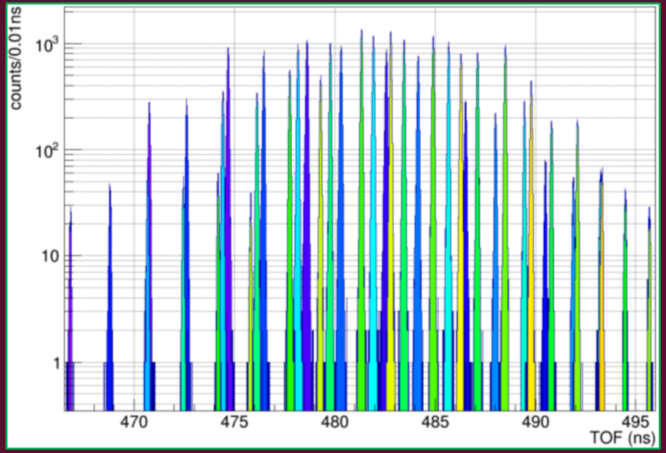
Proposals are under discussion. LHC 2025+ (to be defined) and/or before end of RHIC (opportunistically), see white paper arXiv:2209.11042 for more detail

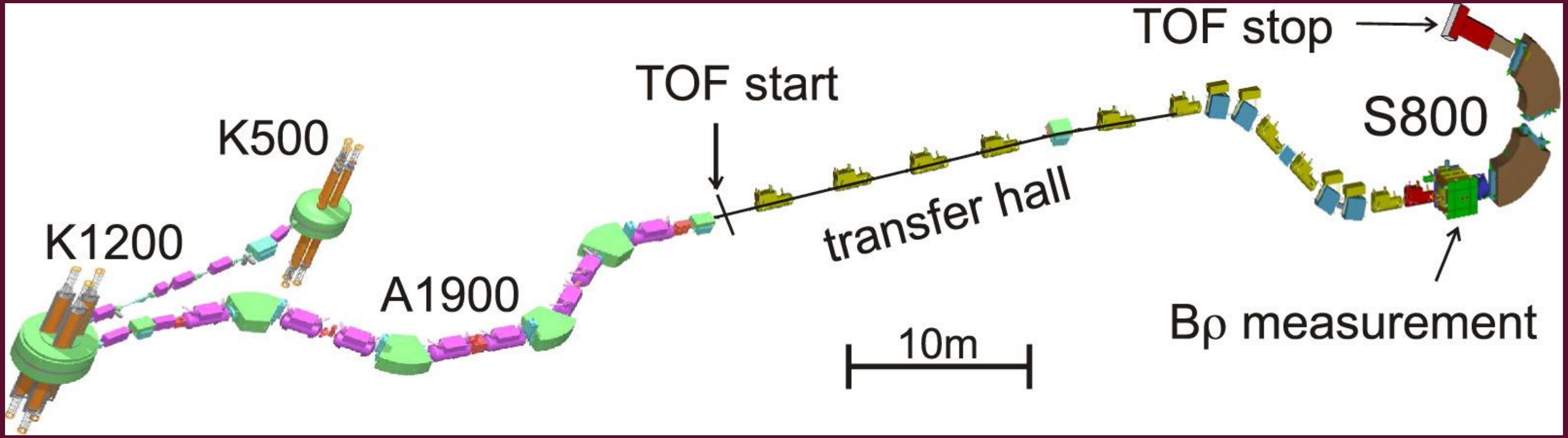
TOF-Bρ Mass Measurements

- Extend measurements a few neutrons beyond reach of precise Penning trap experiments
- Mass resolution: 10000
- half-lives: μs; production rates: 10^{-3} pps
- Mass obtained from measurement of TOF and Bρ of beam ions

$$\frac{m}{q} = \frac{B\rho(TOF)}{\gamma\, L}$$

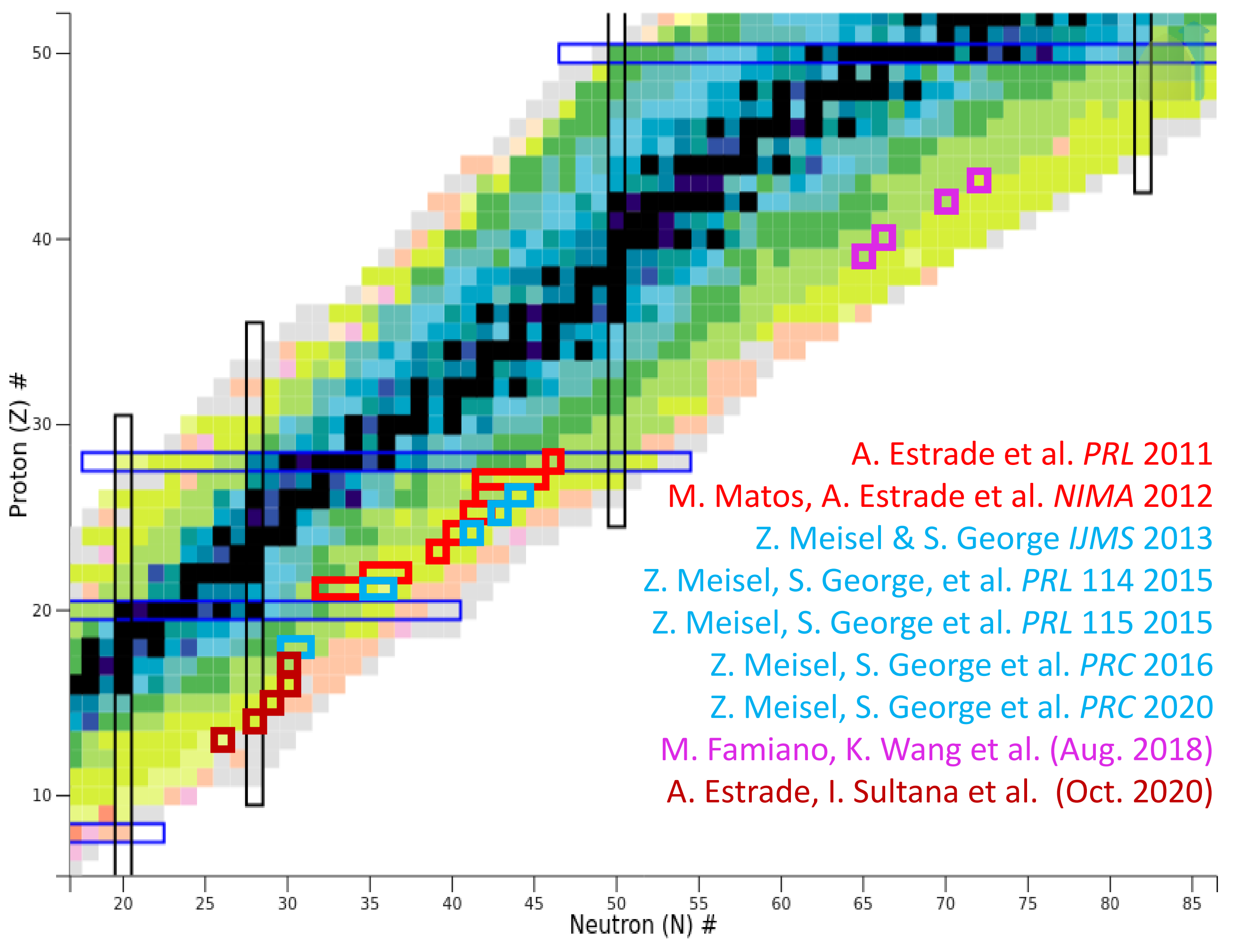
Momentum corrected TOF
(Mo region experiment)





Experimental setup at NSCL

Experiments at NSCL



A. Estrade et al. *PRL* 2011

M. Matos, A. Estrade et al. *NIMA* 2012

Z. Meisel & S. George *IJMS* 2013

Z. Meisel, S. George, et al. *PRL* 114 2015

Z. Meisel, S. George et al. *PRL* 115 2015

Z. Meisel, S. George et al. *PRC* 2016

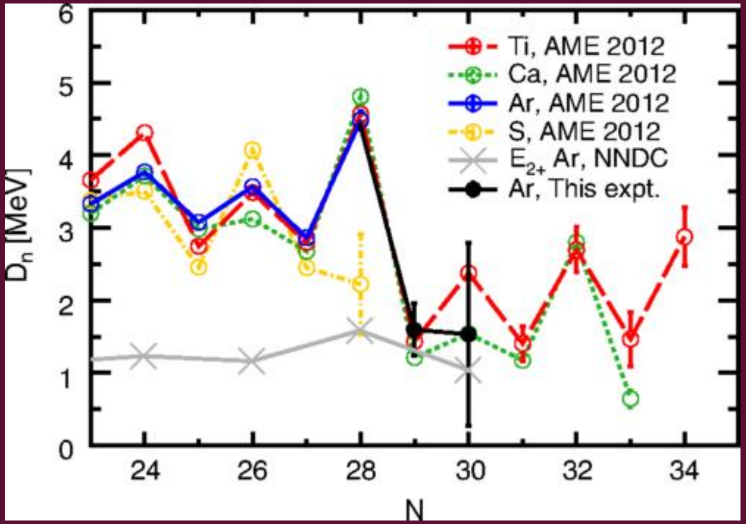
Z. Meisel, S. George et al. *PRC* 2020

M. Famiano, K. Wang et al. (Aug. 2018)

A. Estrade, I. Sultana et al. (Oct. 2020)

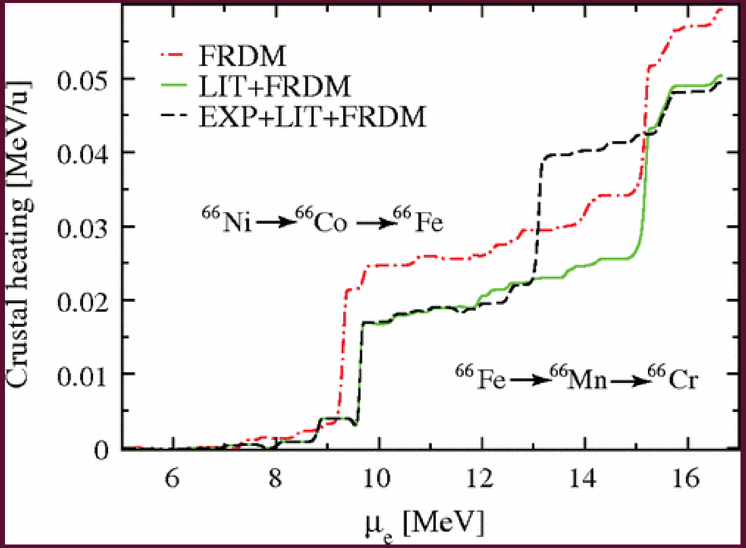
Evolution of shell structure

Meisel++ 2015



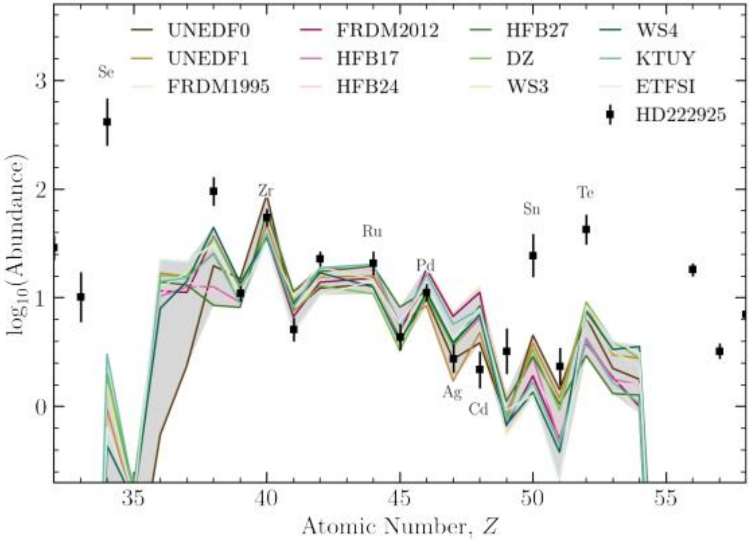
Neutron star crust models

Estrade++ 2011



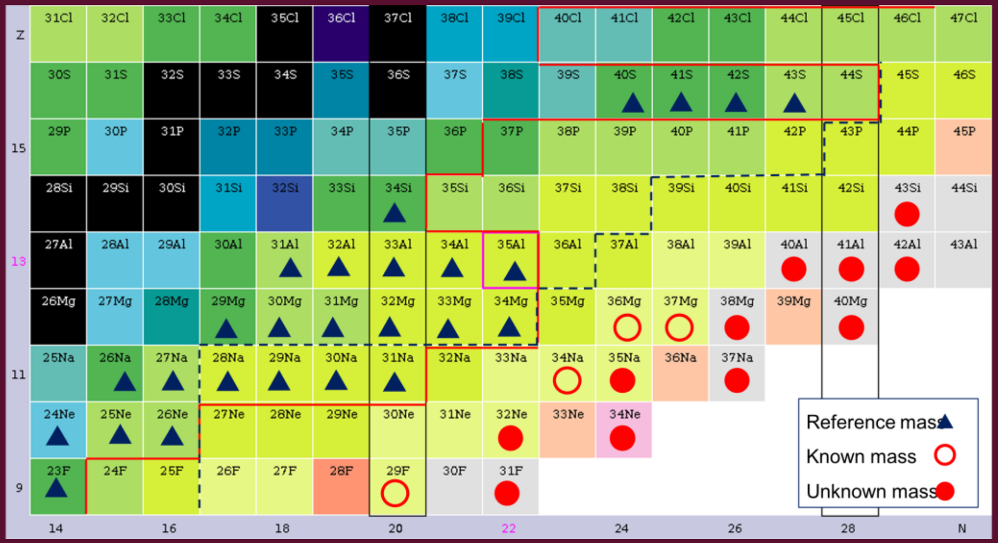
Opportunities at FRIB

Masse of heavy neutron-rich nuclei for heavy-element nucleosynthesis models

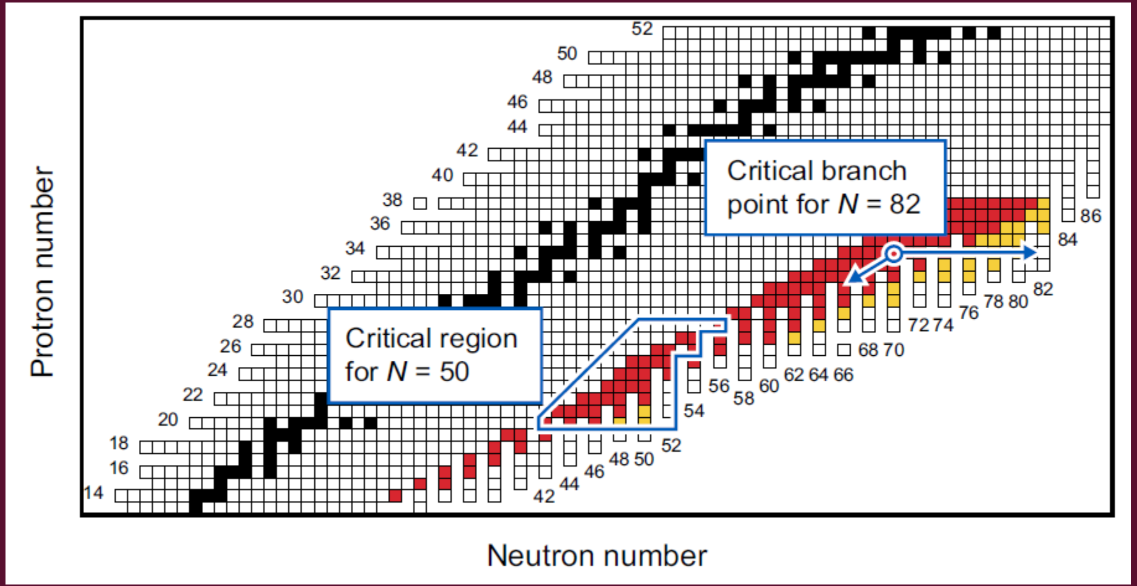


Mass uncertainty in evaluation of origin of weak r-process isotopes in HD222925 - Holmbeck++ 2022

Nuclear masses at the dripline: Day 1 at FRIB



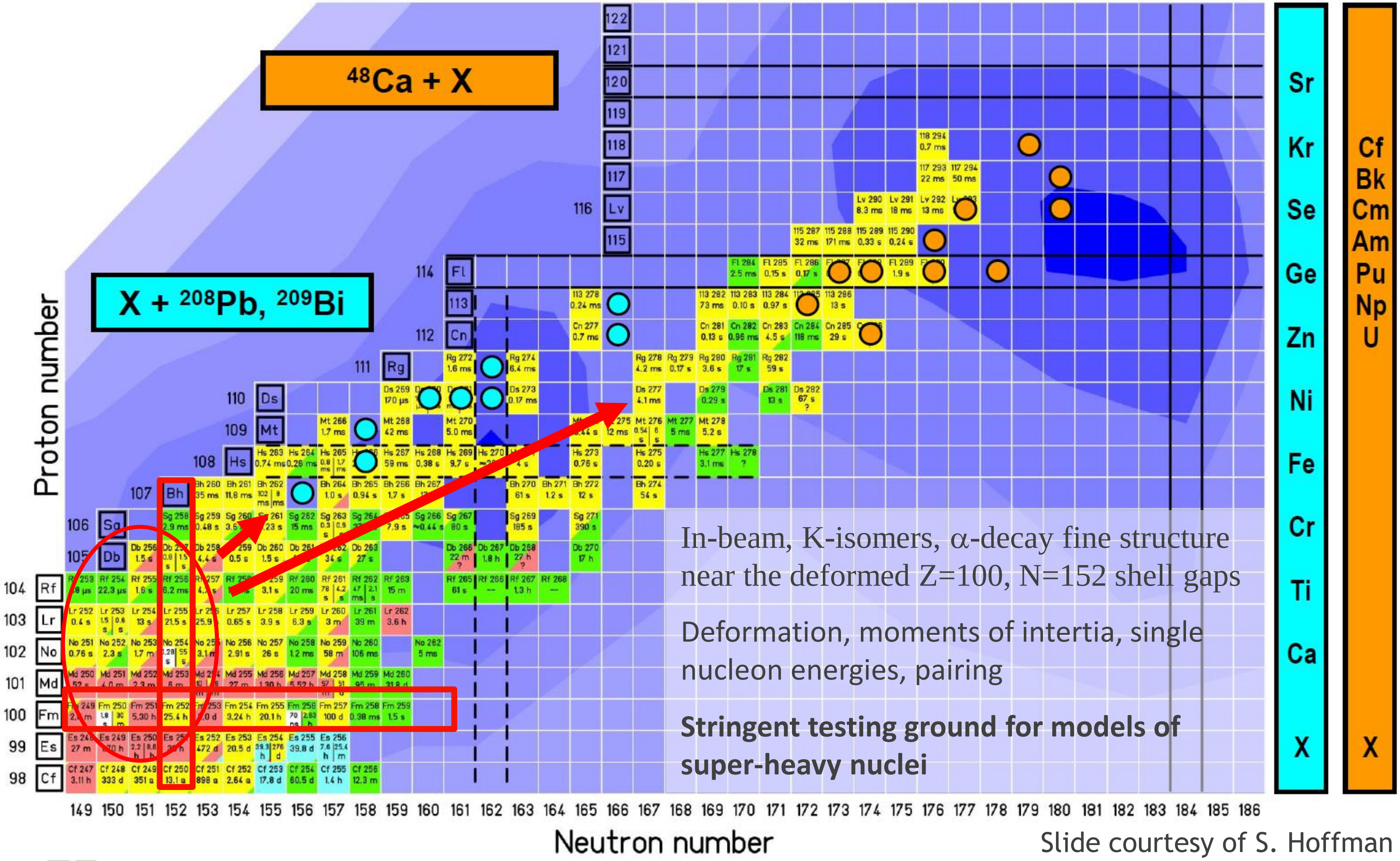
Nuclear masses at the dripline: realizing full FRIB potential requires HRS and 400 MeV/u upgrade



Critical branch point for *N* = 82

Critical region for *N* = 50

Spectroscopy of trans-fermium nuclei



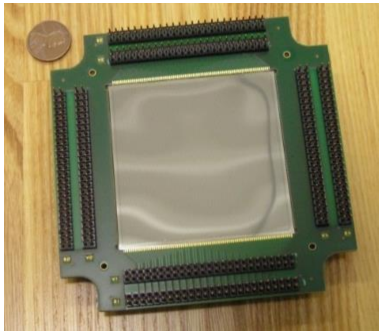
In-beam, K-isomers, α-decay fine structure near the deformed Z=100, N=152 shell gaps

Deformation, moments of intertia, single nucleon energies, pairing

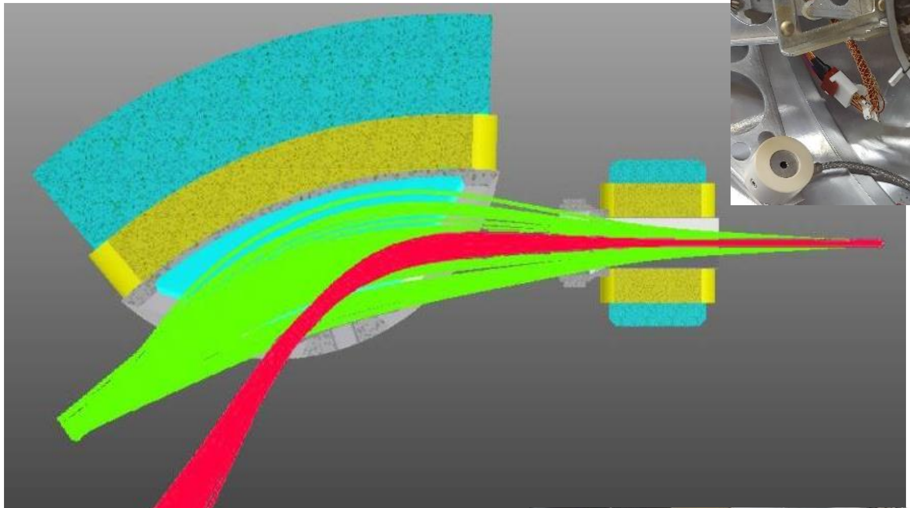
Stringent testing ground for models of super-heavy nuclei

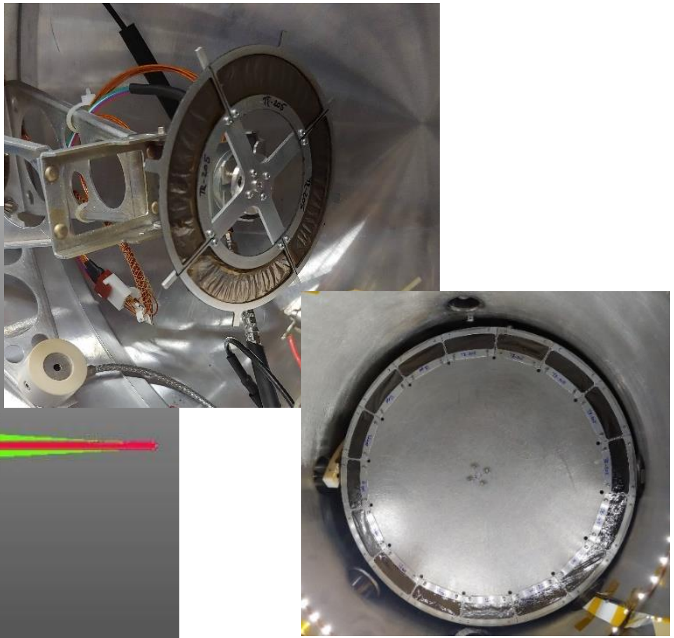
Slide courtesy of S. Hoffman

Argonne Gas-Filled Analyzer

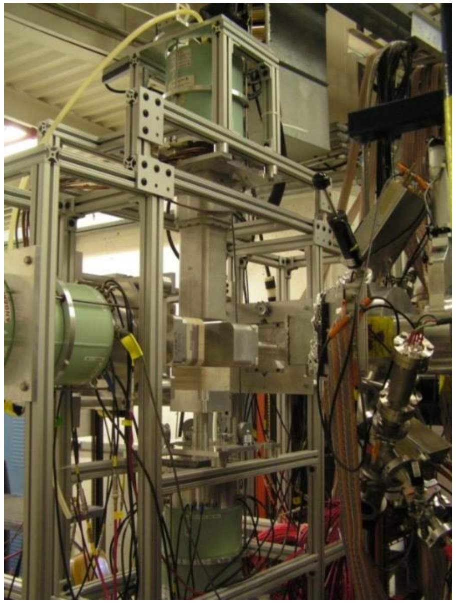


High-granularity DSSD





Target wheels

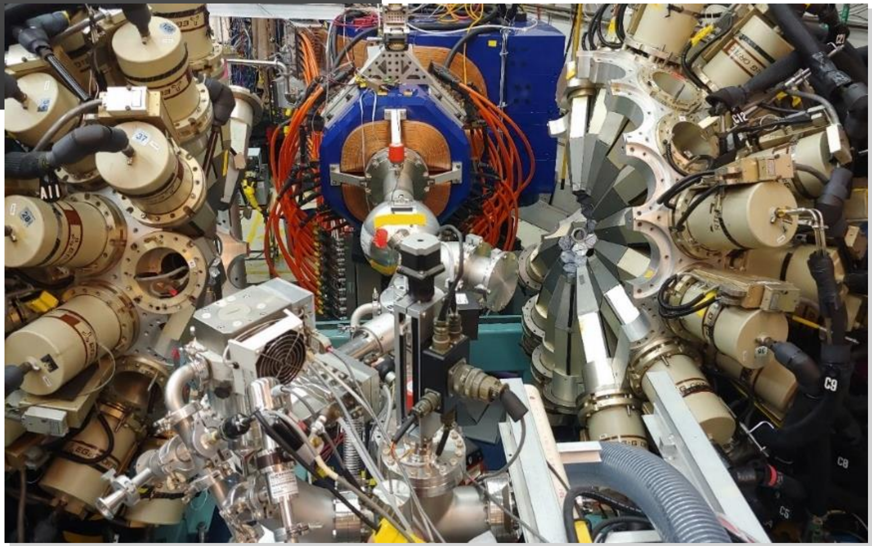


X-Array Ge clover array

UNIQUE DESIGN

Enough space to
accommodate
4π Ge array
at the target position

Compact focal plane



AGFA and Gammasphere

Experimental program with AGFA

RECENT HIGHLIGHTS

Rotational band in the very fissile ^{254}Rf

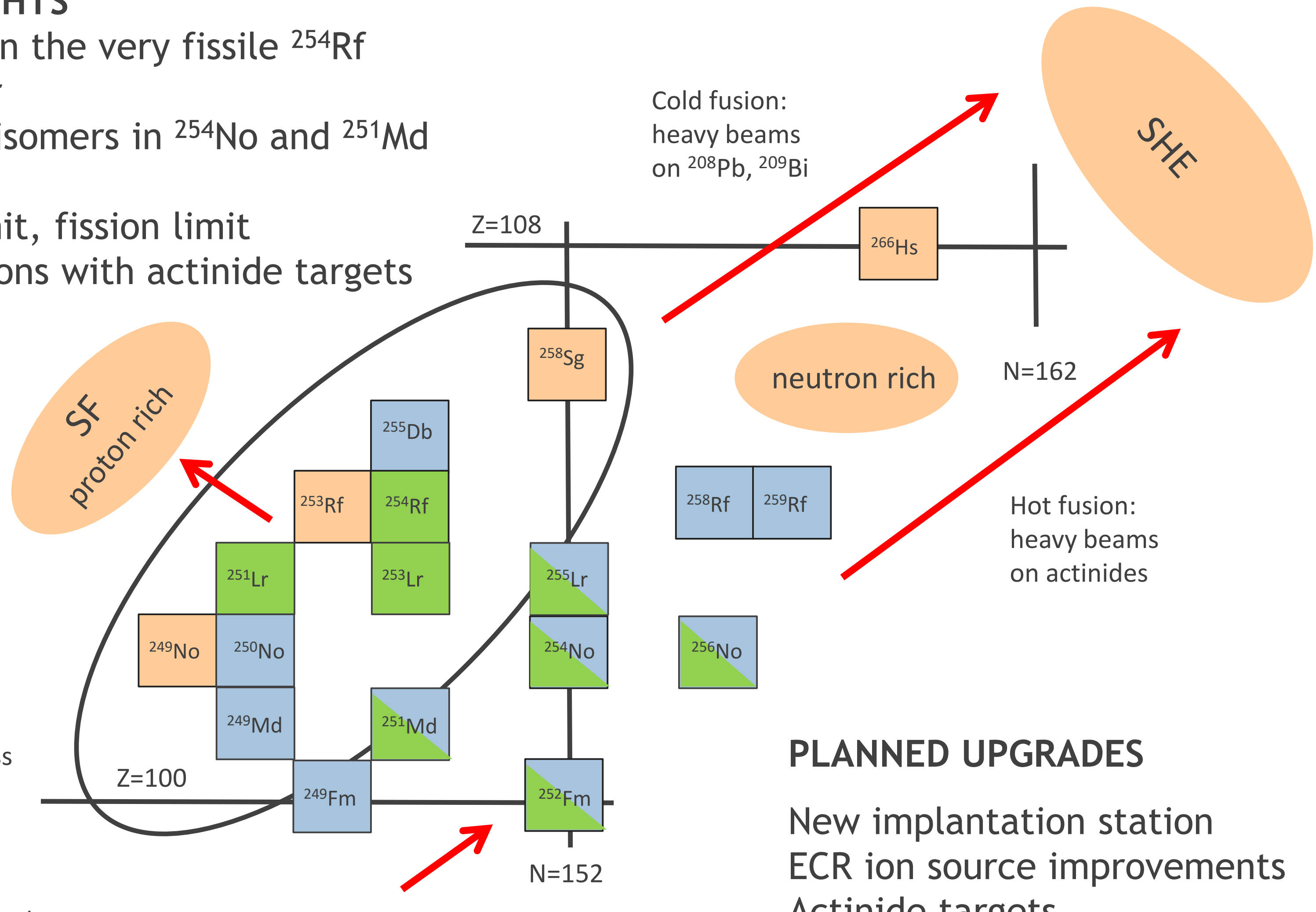
New isotope ^{251}Lr

Bands feeding K-isomers in ^{254}No and ^{251}Md

FUTURE

Towards mass limit, fission limit

Hot fusion reactions with actinide targets



Cold fusion: heavy beams on ^{208}Pb, ^{209}Bi

Hot fusion: heavy beams on actinides

Hot fusion: light beams on actinides

🟩 Done

◩ Done/In progress

🟦 Approved

🟧 Possible future goals

PLANNED UPGRADES

New implantation station

ECR ion source improvements

Actinide targets

Electrostatic beam raster

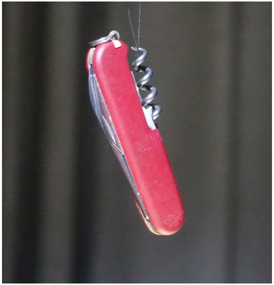
GRETINA/GRETA

Paradigm: 3-Differential Yields from HI Data

Distributions for *Fixed Direction of Reaction Plane*
from Theory and Experiment

no control over plane

some control, v_n



full control, $\frac{d^3N}{dp^3}$

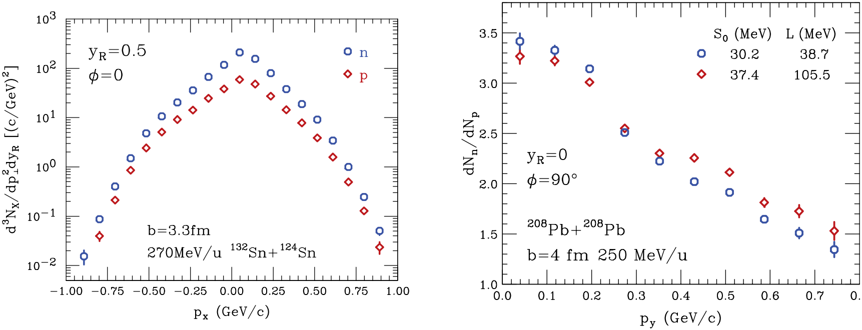
Claim: You can go from center to right panel through deblurring *for data*, given faithful simulation of measurement

Danielewicz & Kurata-Nishimura PRC105(2022)034608
Berkowitz Physics 15(2022)s26

FRIB

Transport Theory Predictions

Transport-theory motivations: Specific d^3N_X/dp^3 features



Transport Model Comparison Project: narrow inference uncertainties, w/tests against exact results & between codes

Wolter *et al.* ProgPartNuclPhys125(22)103962

Colonna *et al.* PRC104(21)024603

FRIB

LASER SPECTROSCOPY & NUCLEAR STRUCTURE AT ATLAS

PETER MUELLER

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.

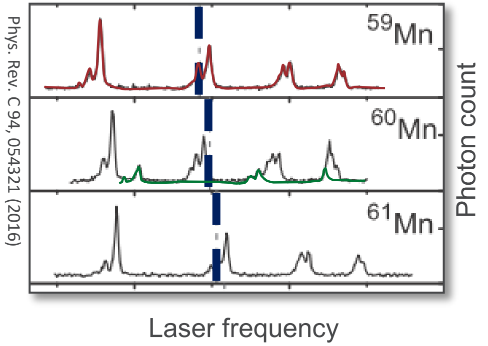
NSAC LRP Townhall 2022

LASER SPECTROSCOPY & NUCLEAR STRUCTURE

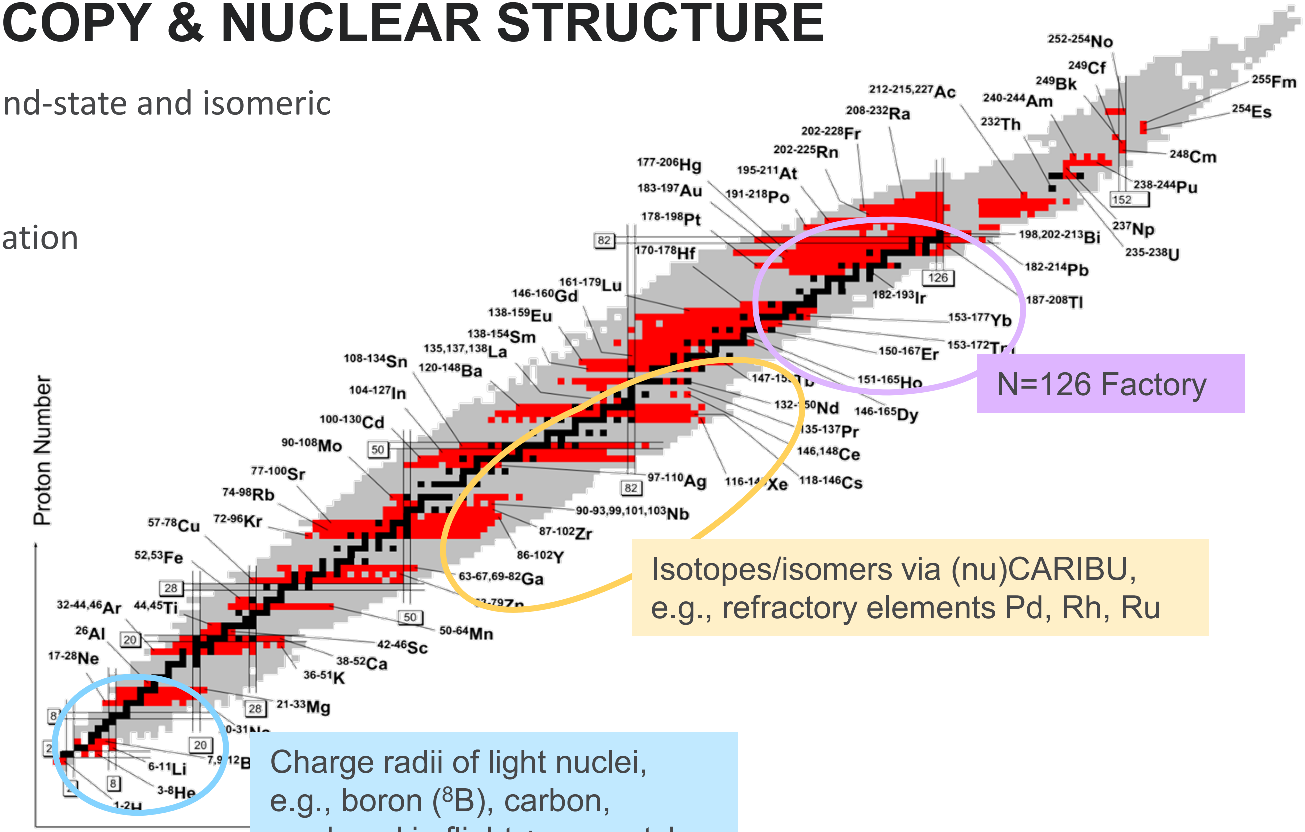
Precision measurements of ground-state and isomeric properties such as

- nuclear charge radii & deformation
- nuclear spin
- nuclear moments

via atomic isotope/isomer shifts and hyperfine-structure



Phys. Rev. C 94, 054321 (2016)



N=126 Factory

Isotopes/isomers via (nu)CARIBU, e.g., refractory elements Pd, Rh, Ru

Charge radii of light nuclei, e.g., boron (^{8}B), carbon, produced in flight + gas catcher

Opportunities at ATLAS

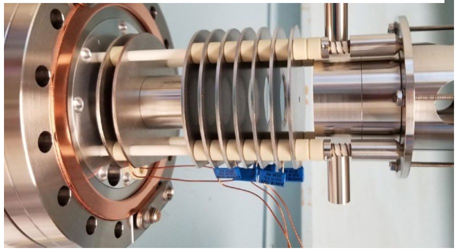
LASER SPECTROSCOPY AT ATLAS / CARIBU

ATLANTIS – Collinear laser spectroscopy with cooled & bunched beams in ATLAS Area I

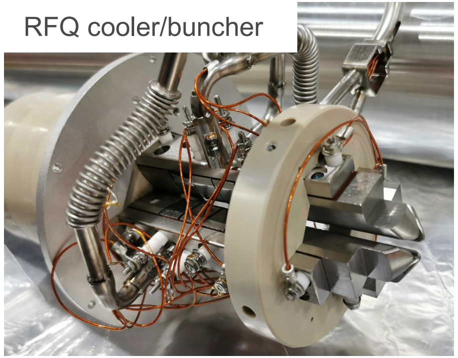
- Time-resolved, high-resolution laser induced fluorescence detection
- Commissioned in Oct. 2022 with LIF measurements of stable Zr^+ and Pd (neutral)
- First CARIBU experiment ongoing (Nov. 2022): Pd + Ru

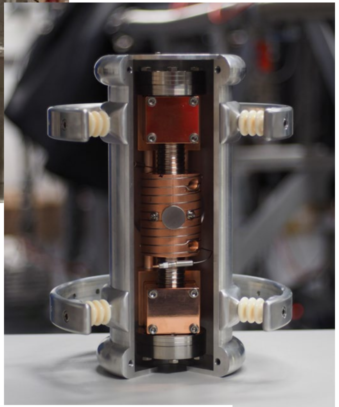
Collinear laser spectroscopy beamline

Laser ion source for stable isotopes



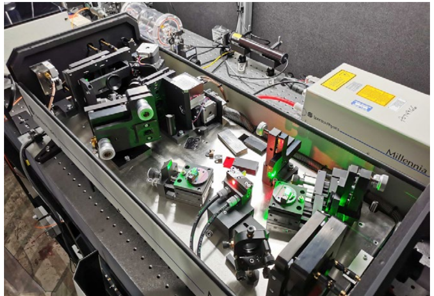
RFQ cooler/buncher





Mg vapor charge exchange cell

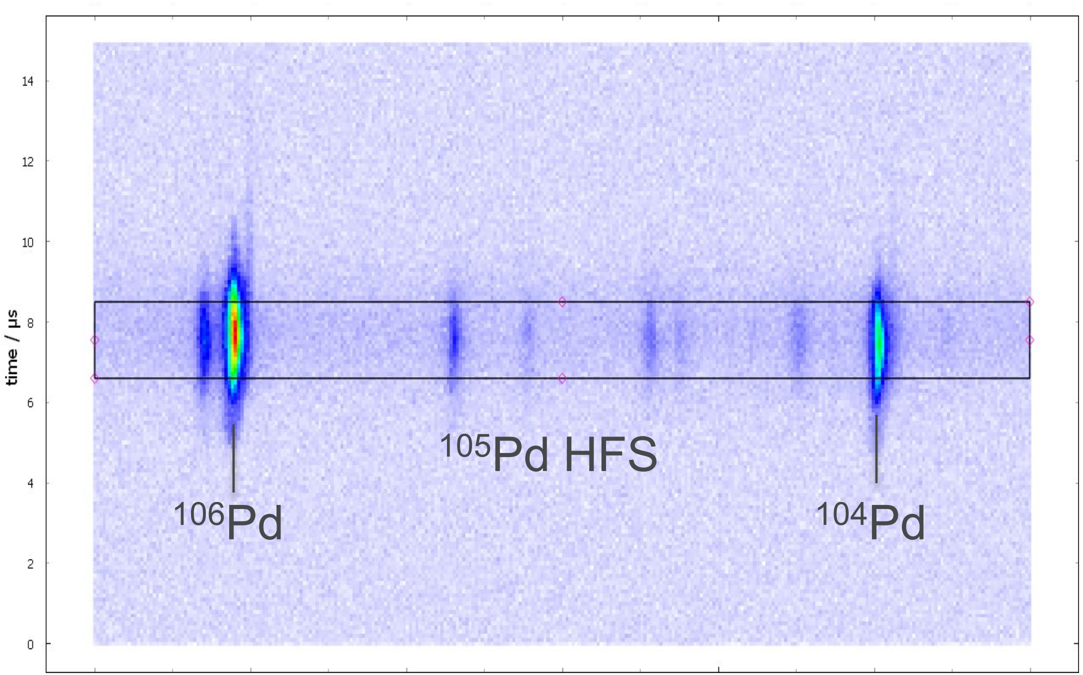
Laser system
(cw Ti:Sa + frequency doubler)



Collaboration with TU Darmstadt, MSU, Notre Dame

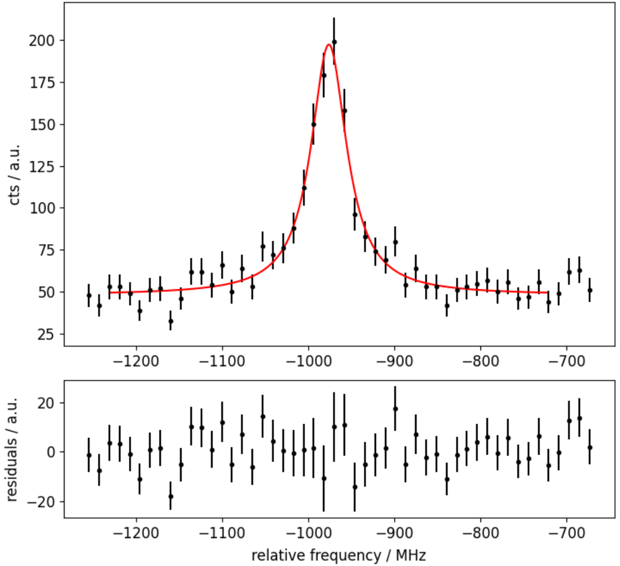
LASER SPECTROSCOPY WITH CARIBU – FIRST RESULTS

LIF signal of stable Pd @ 364 nm



Photon counts vs.
time and beam energy (Doppler tuning)

^{114}Pd from CARIBU
~1000 ions/s



Photon counts vs.
effective laser frequency

Now covered $^{112\text{–}116}$Pd

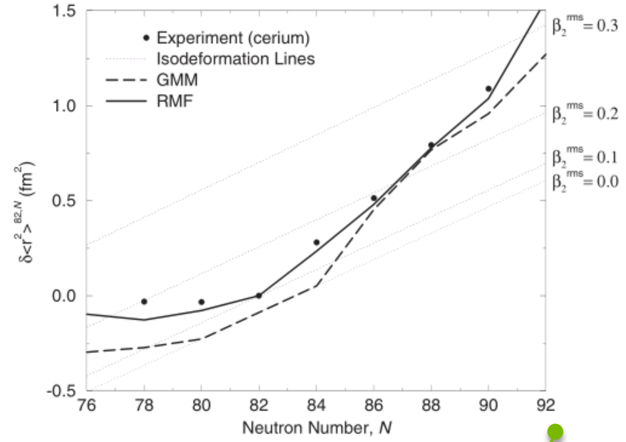
LASER SPECTROSCOPY WITH nuCARIBU

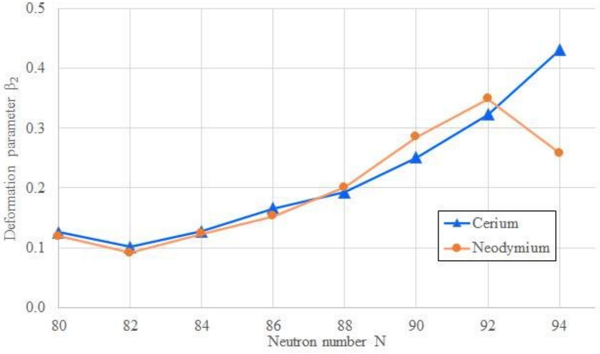
- Approved Exp #1991 (Priority I, 13 days): *Collinear Laser Spectroscopy on Ce 150 & 152, Nd 152 & 154*

- Deviation from simple droplet model is interpreted as (QP) deformation:

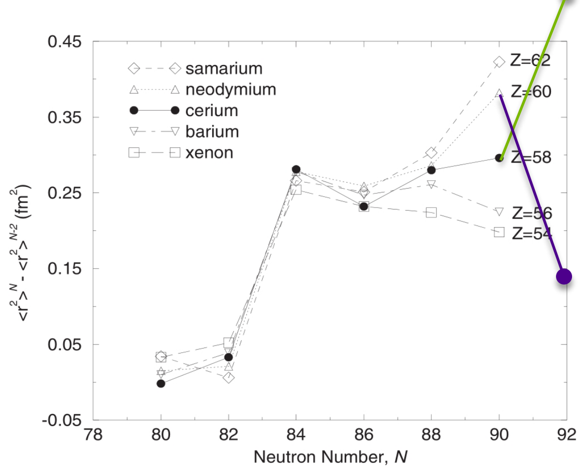
$$\delta\langle r^2\rangle = \delta\langle r^2\rangle_{\text{sph}} + \langle r^2\rangle_{\text{sph}}\frac{5}{4\pi}\sum_i \delta\langle\beta_i^2\rangle$$

- Onset of large deformation for N>90, Z>58
- Typical Assumption $\beta_i = \beta_2$ (Only QP deformation)





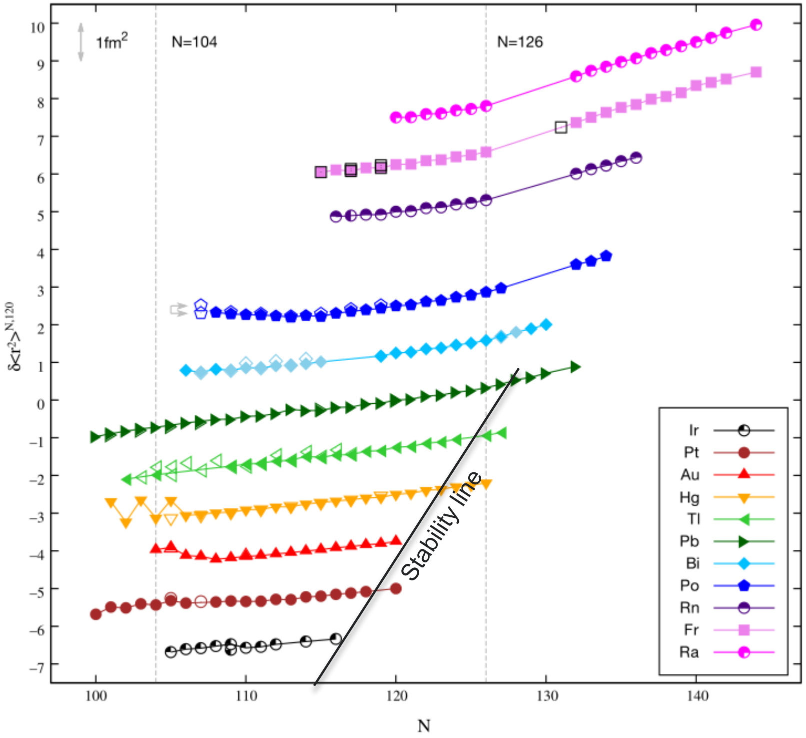
National Nuclear Data Center, Brookhaven National Laboratory, URL https://www. nndc.bnl.gov/nudat3/, 2022



Cheal, B. et al., J. Phys. G 29, 2479, 2003

LASER SPECTROSCOPY AT THE N=126 FACTORY

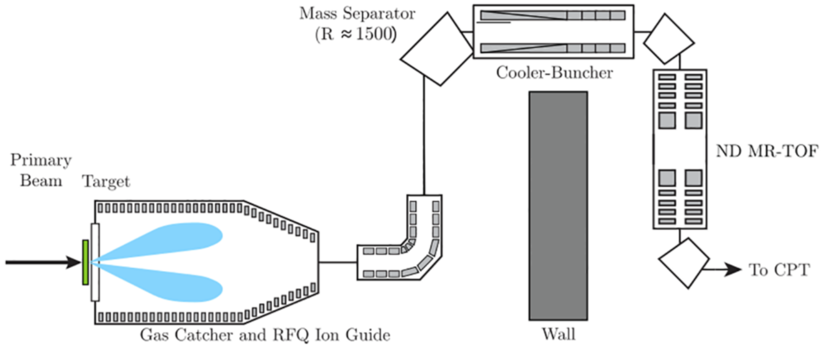
- Positive respones to Letter of Intent (LOI #1998)
- Collaboration with SFB1245 at TU Darmstadt



P. Campbell et al., Prog. Part. Nucl. Phys. 86 (2016) 127–180

Heavy elements investigated with laser spectroscopy are mostly on the p-rich side

- Shape coexistence in tellurium
- Strong OES in mercury



- Deep-inelastic reactions (e.g. Xe + Pt, MNT)
- Low-energy beams produced in gas catcher
- Cooler/Buncher + MRTOF

Laser spectroscopy approach:

- Develop dedicated, compact CLS beamline and/or
- Transport LE beams into Area I

SOME MORE THOUGHTS

Laser spectroscopy of light nuclei

- Precision charge radii, sensitive to halos, comparison with ab-initio theory
- Requires highest experimental resolution + sensitivity – CLS well adapted
- Accurate atomic theory – now up to 5-electron systems
- Generate nuclei in-flight + gas catcher – molecular formation + breakup

Synergies of laser spectroscopy efforts -> push sensitivity and resolution

  - Develop optimal atomic excitation schemes
  - Optimize and characterize RFQs
  - Explore new methods of charge exchange (high-T, large HV bias)
  - Improved photon detection (UV collectors, spatially resolved via SIPMs)
  - Explore alternative detection techniques (RIS)
  - Adapt to different isotope production approaches

Great opportunities for NS & Laser Spec for next 5 – 10 years at multiple facilities
Generally excellent networking between small number of groups worldwide

THANK YOU!

U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.

Argonne
NATIONAL LABORATORY

Recent achievements in invariant-mass studies of proton-rich nuclei

Robert Charity and Lee Sobotka , Washington University

1) Pushing to the edge of the chart of nuclides

Discovery of new isotopes ^{11}O->2p+^{9}C (mirror of ^{11}Li) *PRL 122 (2019) 122501*
^{13}F->3p+^{10}C *PRL 126 (2021) 132501*
^{18}Mg->4p+^{14}O *PRL 127 (2021) 262502*
^{9}N->5p+α ($>1/2$ nucleons unbound)

Consistency with theory including continuum

2) Correlations in prompt two-proton decay

High-statistics measurements for ^{6}Be, ^{12}O, ^{16}Ne *PRC 100 (2019) 024306*

Development of theory to predict these (Wang, Nazaewicz, Grigorenko…)

Sensitivity to nuclear structure.

Use of correlations to assignment spin/parity 0_2^+ state in ^{10}C

3) Two-proton decay of alpha-cluster configurations in ^{10}C and ^{11}N *PRC 105(202) 014314*

Future prospects

How does the effects of the continuum modify the structure of resonances?

1) Magic numbers beyond the proton drip line.

Possible double-closed shell isotopes beyond the proton drip line: ^{22}Si,^{24}S, ^{34}Ca, ^{48}Ni
while the mirrors of these are described as doubly magic (^{22}O,^{24}O,^{34}Si,^{48}Ca), do continuum effects
(e.g. single-particle Thomas-Erhman shifts) change shell gaps quenching or enhancing a magic number.

2) search for threshold states – located in energy close to the threshold for a particular exit channel.

Theory suggest the structure of such states can be strongly altered do to continuum coupling modifying their decay properties (widths, branching ratios) and production probabilities in transfer and knock-out reactions.

Such states have been found in ^{15}F, ^{10}Be, ^{9}Li for example, but many more should exit.

Determine high statistics correlations in two-proton decay of heavier nuclides

At present ^{45}Fe correlations were determined for ~70 detected events and only a handful of events for ^{48}Ni, .

Correlations give information on nuclear structure. Study the change in the correlations as different proton orbits are available. (^{34}Ca, ^{45}Fe,^{48}Ni,^{54}Zr,^{67}Kr) Some of these need TPC's

Requirements: a)Some of this can be done with present FRIB and some require upgraded FRIB
b)Our invariant-mass program is expected to move to the HRS when it is built:
improved detection efficiency for multi-particle exit channels.
c) theory.