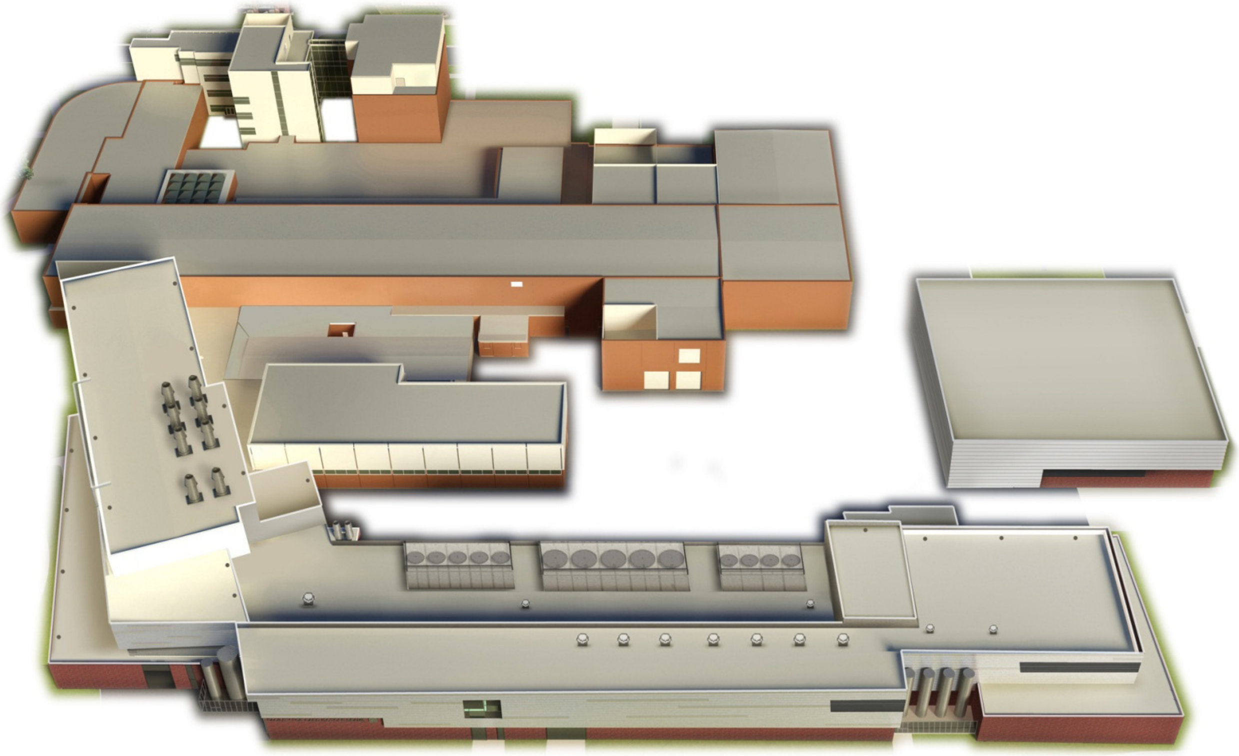


The FRIB project and prospects for γ-ray spectroscopy

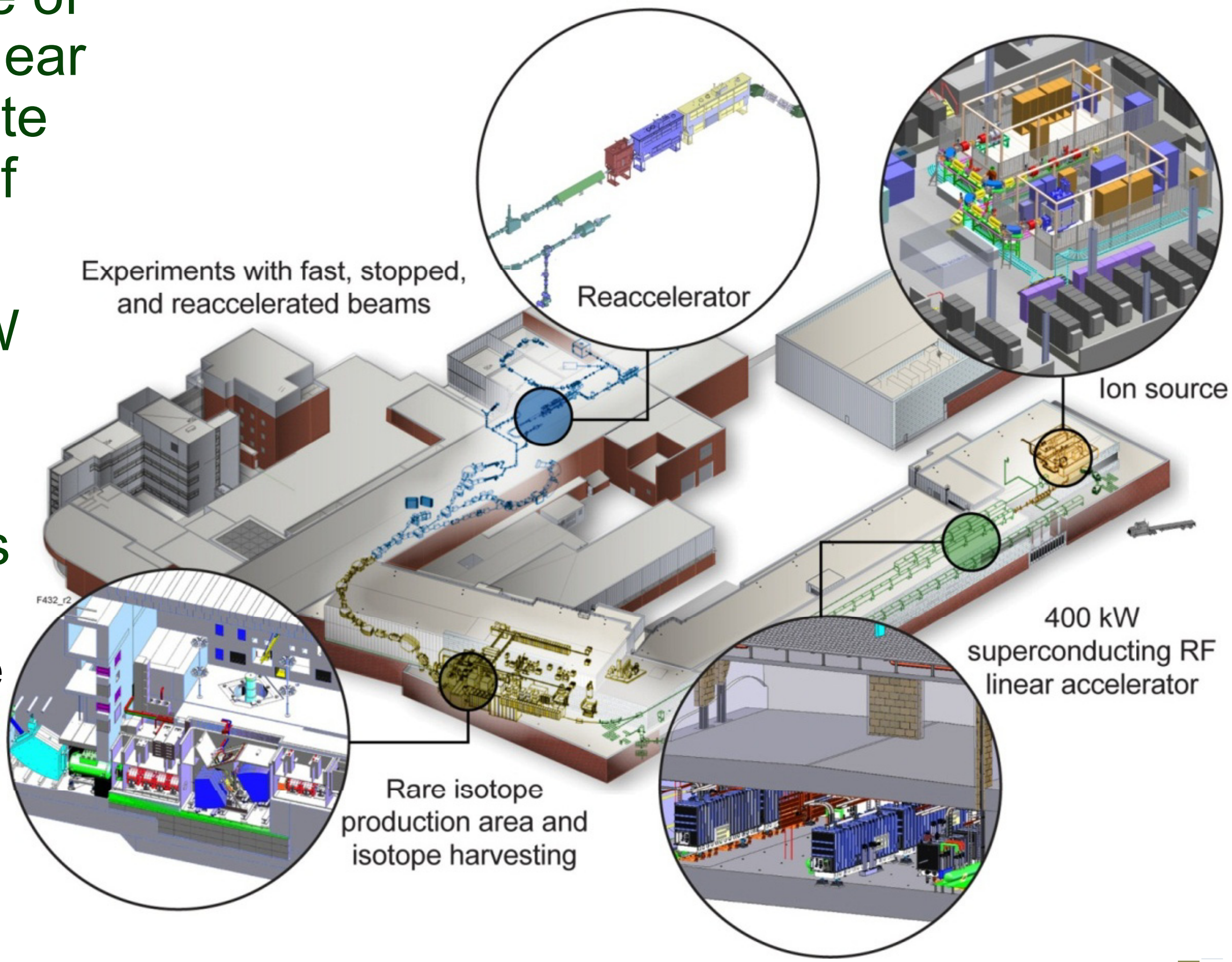
Alexandra Gade
Michigan State University

Outline

- FRIB at MSU
- Opportunities for in-beam γ-ray spectroscopy

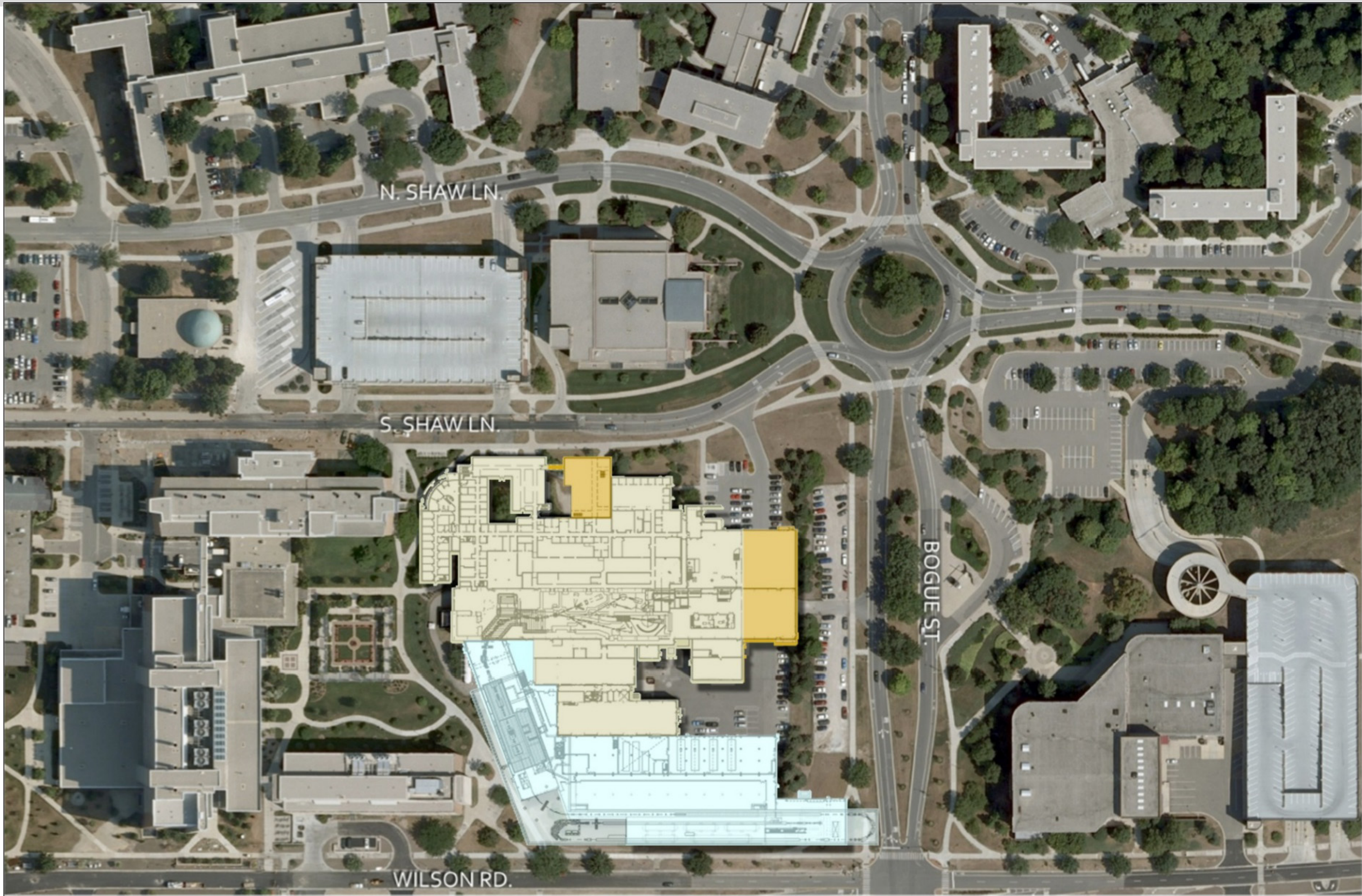
Facility for Rare Isotope Beams

- Funded by DOE Office of Science Office of Nuclear Physics, Michigan State University and State of Michigan
- Key Feature is 400 kW beam power (5 x10^{13} ^{238}U/s)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Facility for Rare Isotope Beams, FRIB

on the Michigan State University Campus



MSU was Selected in December 2008 Following Competitive Procurement

FRIB history and progress

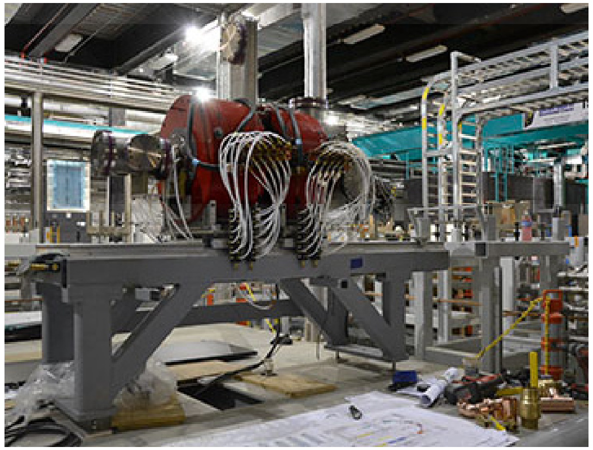
- 8 June 2009 – DOE-SC and MSU sign Cooperative Agreement
- September 2010 – CD-1 approved, DOE issues NEPA FONSI
- April 2012 – Lehman review, baseline and start of civil construction
- August 2013 – CD-2 approved (baseline), CD-3a approved (start civil construction pending FY2014 federal appropriation)
- March 2014 – Start civil construction
- 23-25 April 2014 – MSU President's Independent CD-3b readiness review
- September 2014 – CD-3b approved
- October 2014 – Start technical construction
- March 2015 – DOE OPA review
- November 2015 – DOE OPA review
- January 2016 – DOE Operations Cost review

- June 2016 – DOE OPA review
- Managing to early completion in fiscal year 2021, CD-4 is June 2022
  - Tunnel and first surface buildings (ECR and frontend) complete in 2015 (16 months ahead of baseline schedule)
  - First beam from room temperature ECR in 2016

FRIB construction progress

Mech/Electrical Linac Fit-Out 12 Months Ahead of Baseline Schedule

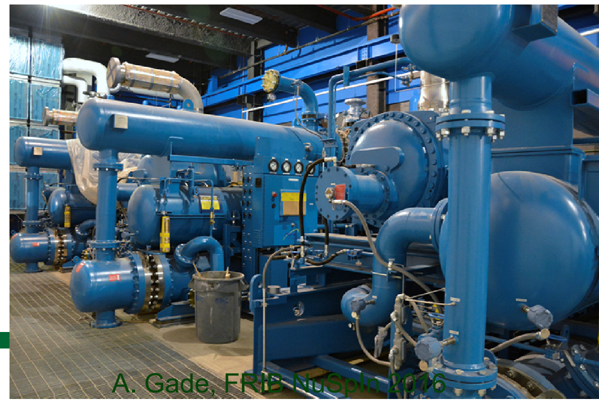
The ARTEMIS ion source is now installed on the platform in the front-end building



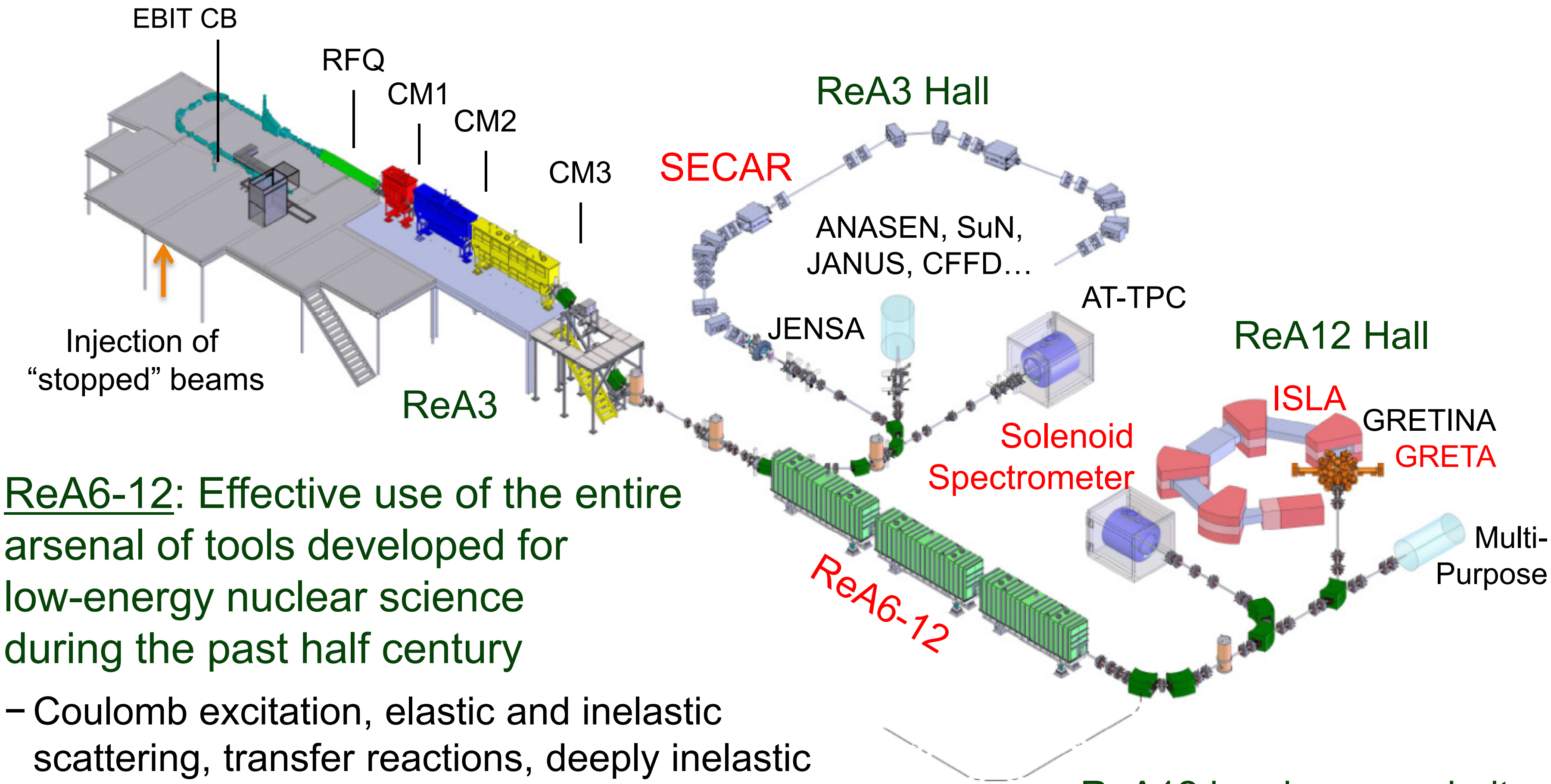
Cryogenic piping installation in the east end of the linac tunnel

Cabling in the electrical vault on upper second floor

Helium compressors in compressor room



ReA3 operational at NSCL – ReA6-12 upgrade articulated in whitepaper



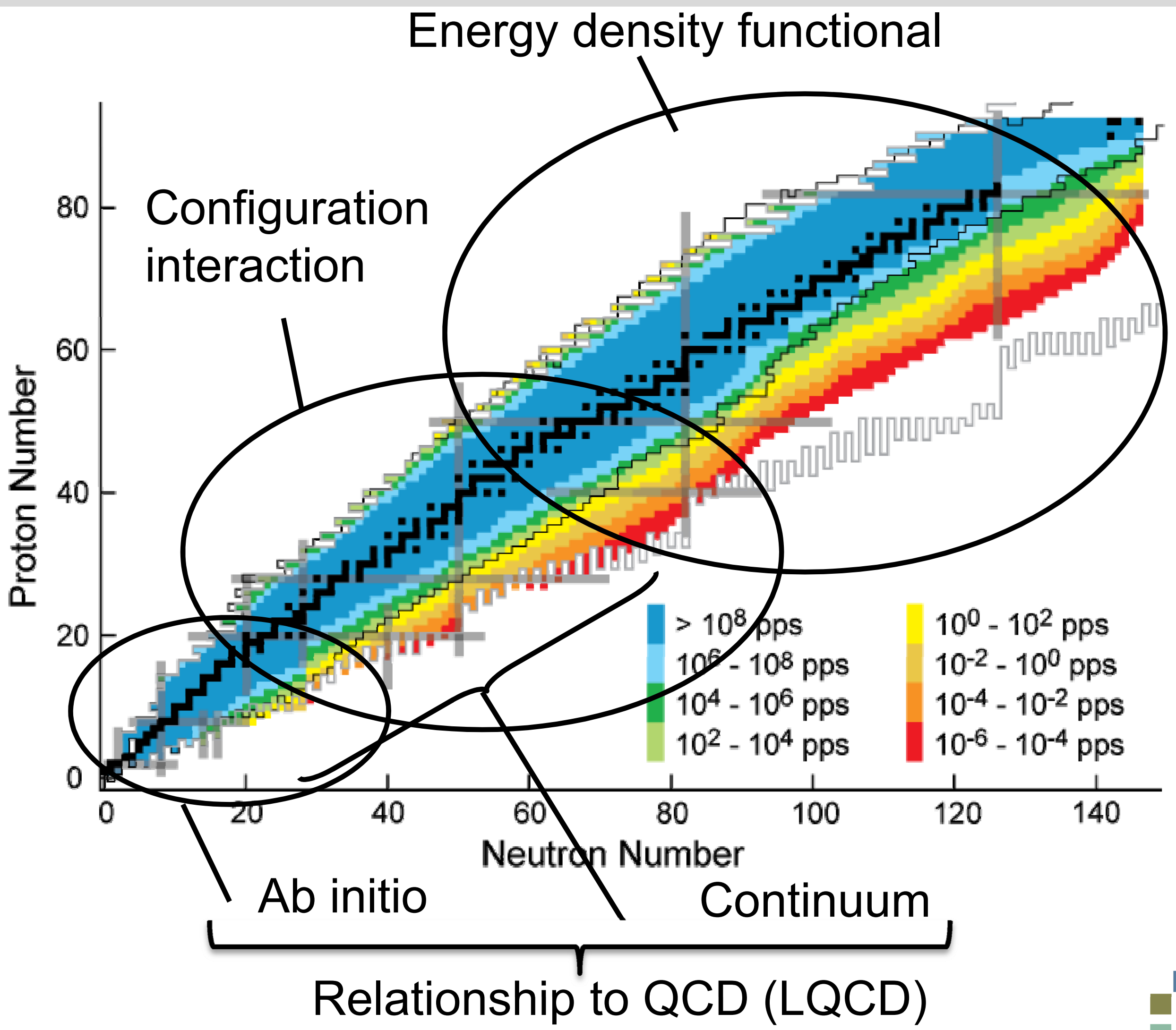
ReA6-12: Effective use of the entire arsenal of tools developed for low-energy nuclear science during the past half century

- Coulomb excitation, elastic and inelastic scattering, transfer reactions, deeply inelastic transfers, complete & incomplete fusion, fission …
- Surrogate reactions for nuclear astrophysics and stockpile stewardship

ReA12 has been a priority of the FRIB science community

Lofty goal: Comprehensive model of nuclear structure and reactions

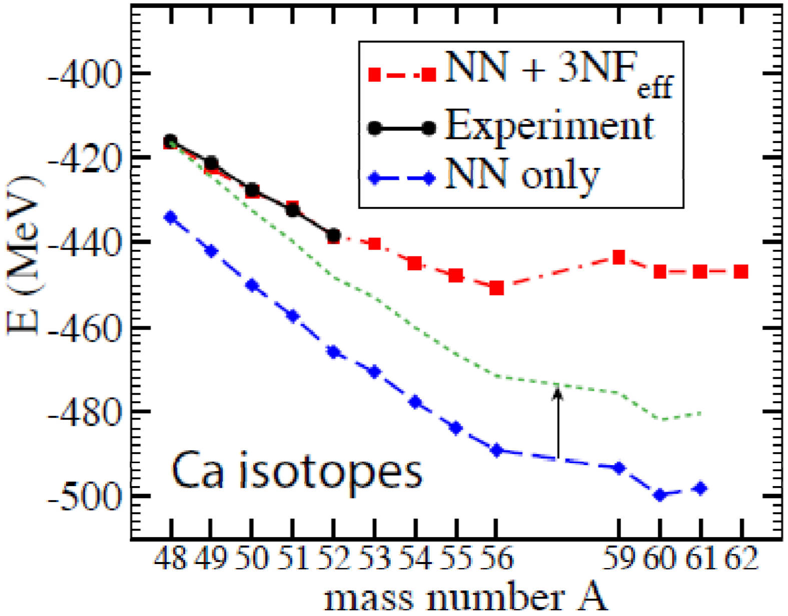
- A comprehensive and quantified model of atomic nuclei does not yet exist
- In recent years, enormous progress has been made with measurements of properties of rare isotopes and developments in nuclear theory and computation
- Access to key regions of the nuclear chart constrains models and identifies missing physics
- Theory identifies key nuclei and properties to be studied



Calcium isotopes – where ab-initio, configuration interaction models and density functionals meet

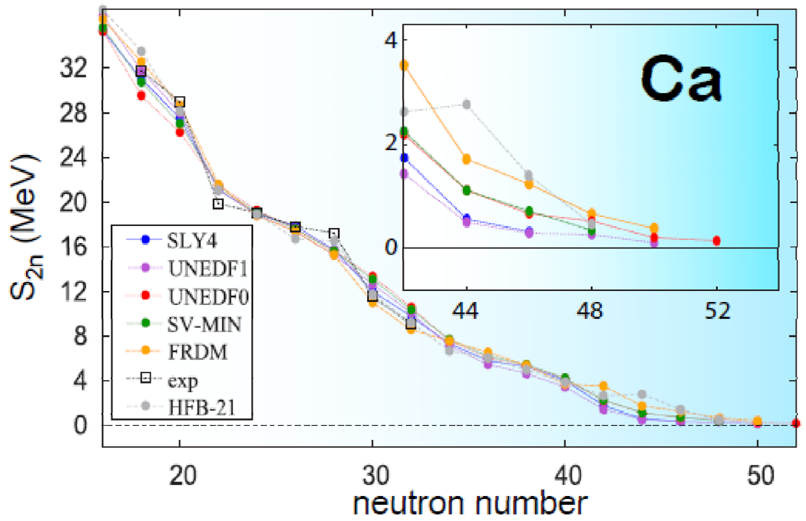
- How many Ca nuclei exist? ^{58}Ca was observed in experiments. Theory: The jury is still out …

Coupled-cluster calculations based on chiral EFT



^{60}Ca weakly bound/unbound, $^{61\text{-}62}$Ca are located right at threshold

State-of-the-art energy density functionals

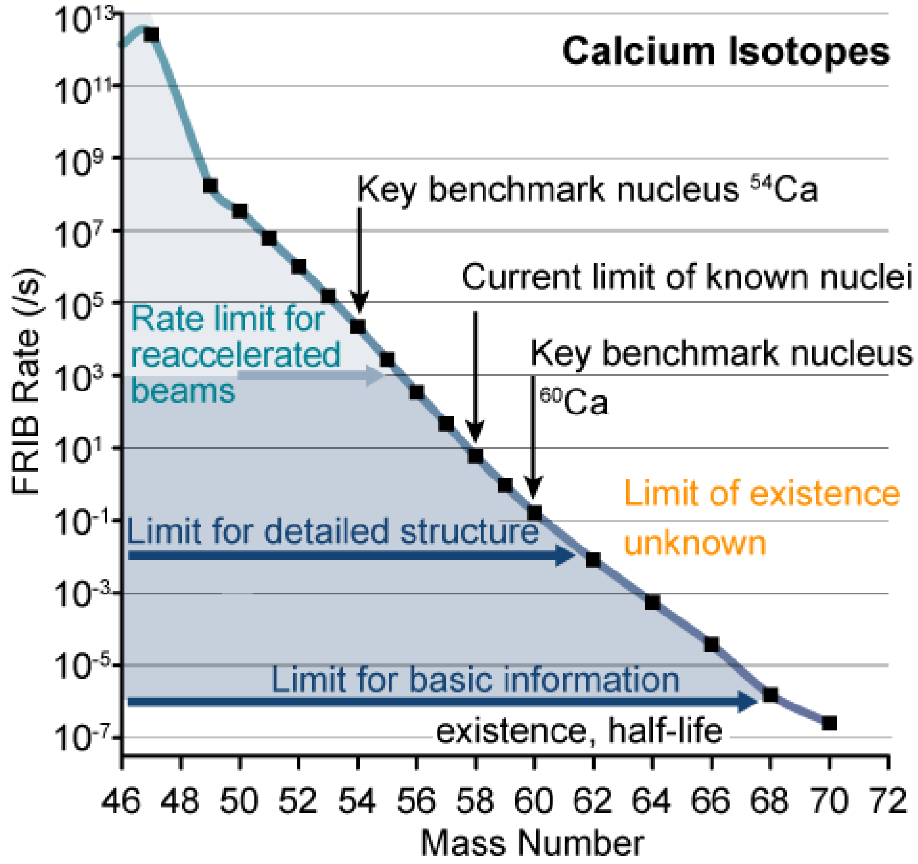


Calcium isotopes bound out to about ^{70}Ca

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

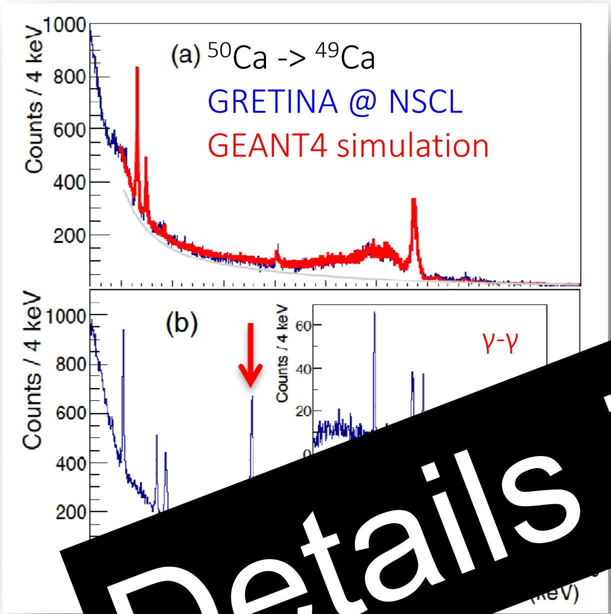
Access to Calcium isotopes at FRIB

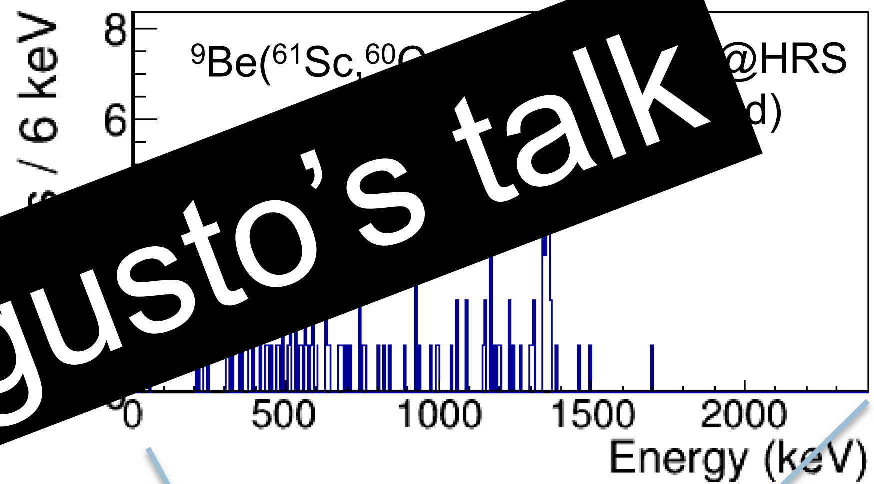
- Calcium isotopic chain (*Z=20*) is crucial
- FRIB provides access to the relevant neutron-rich Ca isotopes with intensities sufficient to measure important observables
  - Masses, half-lives, decay properties, single-particle and collective degrees of freedom
  - Structure of heavy Ca isotopes will quantify the role of the 3N forces and weak binding
- In general: Long isotopic chains are essential
  - Evolution of nuclear properties can be benchmarked as a function of isospin



Understanding the nuclear force – Calcium isotopes, where we are and where we can go

- The neutron-rich Ca isotopes beyond ^{48}Ca provide textbook examples of structural evolution
- Theory suggests a sensitivity of the detailed structure to the inclusion of a variety of many-body correlations, including 3N forces





Details in Augusto's talk

Enabled by the GRETA γ-ray tracking array coupled to the High Rigidity Spectrometer (HRS)

10^{10} 10^{5} 10^{2} 10^{-2}

Rare isotope beam intensity (pps) at optimum rigidity

^{48}Ca	^{49}Ca	^{50}Ca	^{51}Ca	^{52}Ca	^{53}Ca	^{54}Ca	^{55}Ca	^{56}Ca	^{57}Ca	^{58}Ca	^{59}Ca	^{60}Ca

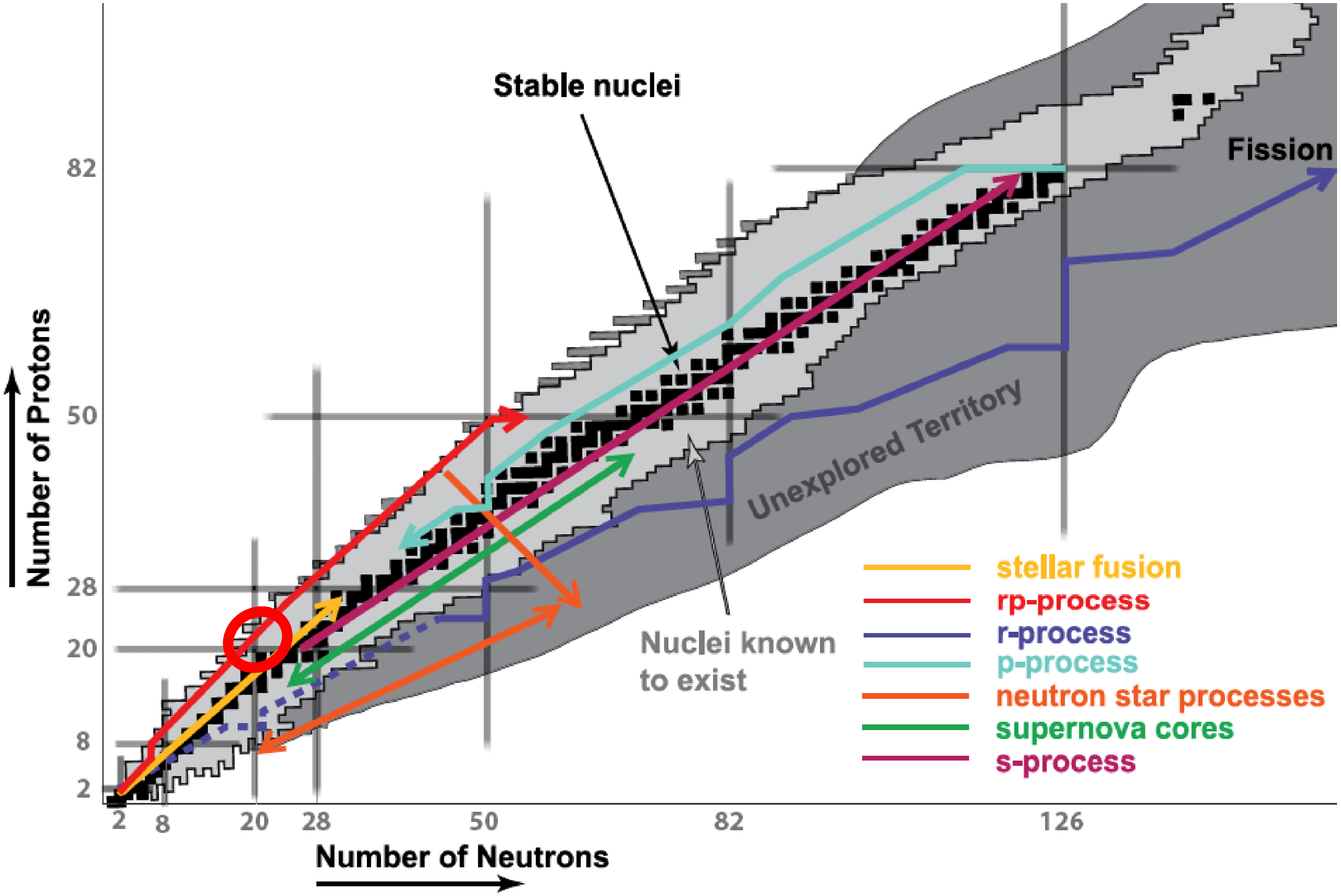
stable

detailed spectroscopy at HRS

first spectroscopy at HRS

The structure around ^{60}Ca informs the location of the drip line at Z = 20

Rare isotopes are important to understand astrophysical scenarios

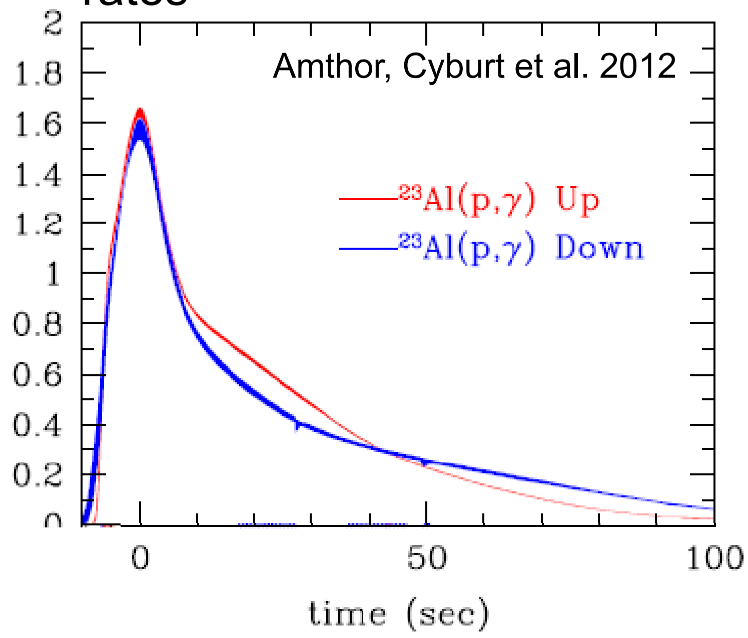


- Data on rare isotopes and their reactions are required to elucidate many astrophysical scenarios

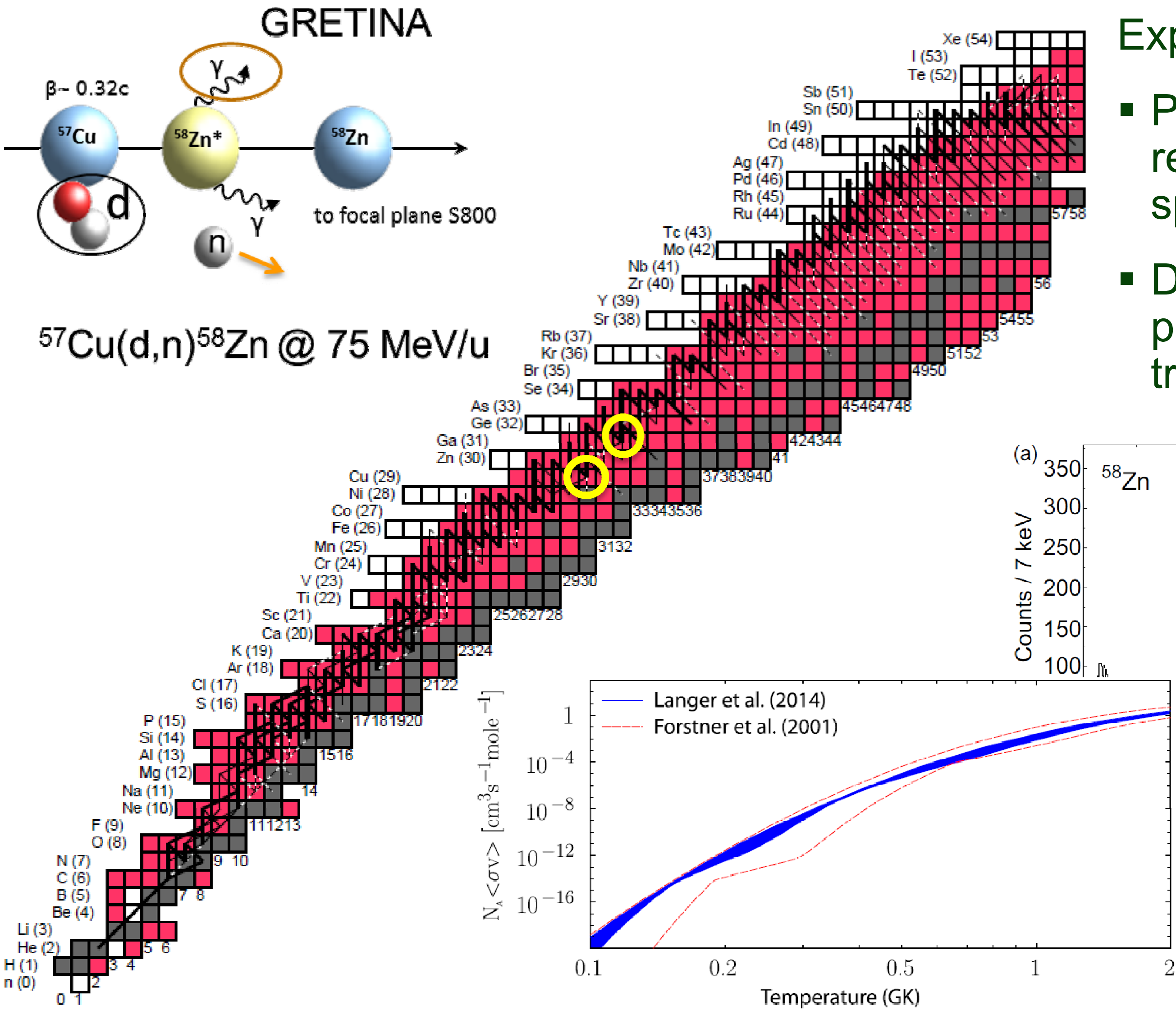
Example: Understanding X-ray busrst, the most frequent explosions in the Universe

- X-ray bursts are frequently observed thermonuclear flashes ignited on the surface of accreting neutron stars
- Type I X-ray bursts are powered by the rapid proton-capture process
- X-ray burst light curves – from satellite observations – are sensitive to the rp-process reaction network
- Once the underlying nuclear physics is understood, comparisons of burst observations with models offer a unique pathway to constrain neutron-star properties such as accretion rate, accreted composition, or radii.

Burst profiles depend on nuclear rates



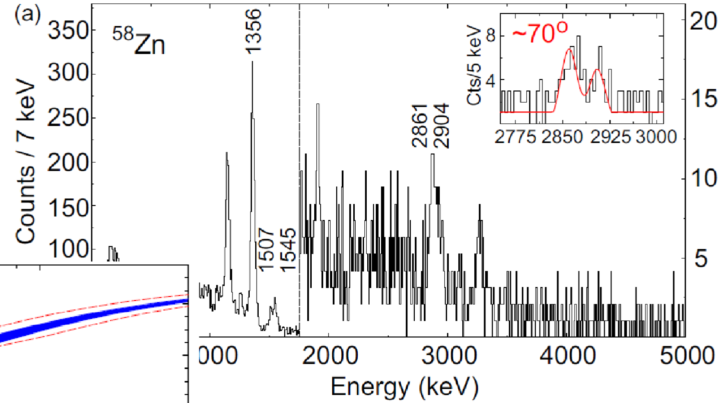
GRETA@FRIB reach for novae and X-ray burst reaction rate studies



$^{57}Cu(d,n)^{58}Zn$ @ 75 MeV/u

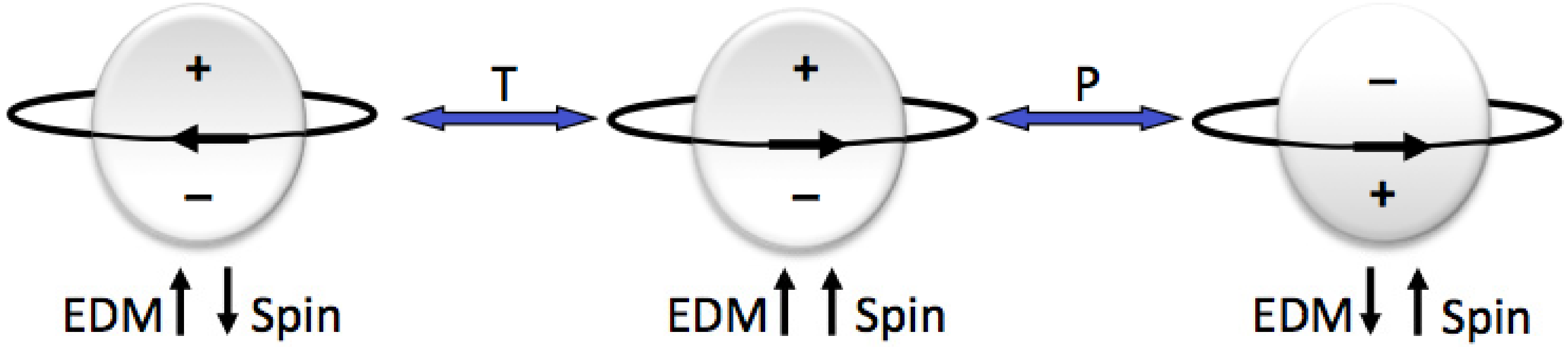
Experimental scheme:

- Populate capture resonances, typically lower-spin states above S_p
- Determine excitation energy precisely from γ-ray transitions



Scheme a la C. Langer et al., PRL 113, 032502 (2014)

Selected isotopes to test fundamental symmetries – electric dipole moment search



An Electric Dipole Moment (EDM)

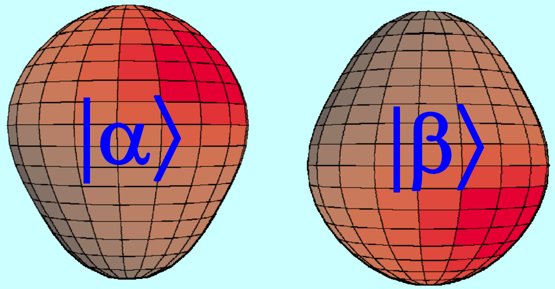
- Violates T and consequently CP symmetry
- Large value would be evidence for physics beyond the Standard Model and a possible explanation for matter dominance over antimatter

- For an atomic EDM, most sensitive limit today: $|d(^{199}Hg)| < 3.1 \times 10^{-29}$ e cm – Griffith et al. (2009)
- Properties of some nuclei enhance the signal of an EDM is enhanced, e.g. EDM(^{225}Ra) / EDM(^{199}Hg) 2-3 orders of magnitude (nuclear octupole deformation) – *Dobaczewski, Engel (2005)* and *Ban, Dobaczewski, Engel, Shukla (2010)*

EDM searches – Octupole deformation enhances the signal

- A closely spaced parity doublet near ground state enhances the appearance of parity violating terms in the underlying Hamiltonian – *Haxton & Henley (1983)*
- Large intrinsic Schiff moment due to octupole deformation – *Auerbach, Flambaum & Spevak (1996)*

Octupole deformation
(reflection asymmetric)



Parity doublet

$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$

55 keV

$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$

- Nuclear structure physics needed to interpret an EDM signal and to identify and characterize new, more sensitive, EDM candidate nuclei (e.g. EDM (^{229}Pa) / EDM (^{199}Hg) enhanced by: 3 x 10^4 - *Flambaum (2008)*)

PRL 114, 233002 (2015) PHYSICAL REVIEW LETTERS week ending 12 JUNE 2015

First Measurement of the Atomic Electric Dipole Moment of ^{225}Ra

R. H. Parker,[1,2] M. R. Dietrich,[1,3] M. R. Kalita,[1,4] N. D. Lemke,[1,*] K. G. Bailey,[1] M. Bishof,[1] J. P. Greene,[1] R. J. Holt,[1] W. Korsch,[4] Z.-T. Lu,[1,2,†] P. Mueller,[1] T. P. O'Connor,[1] and J. T. Singh[1,5]
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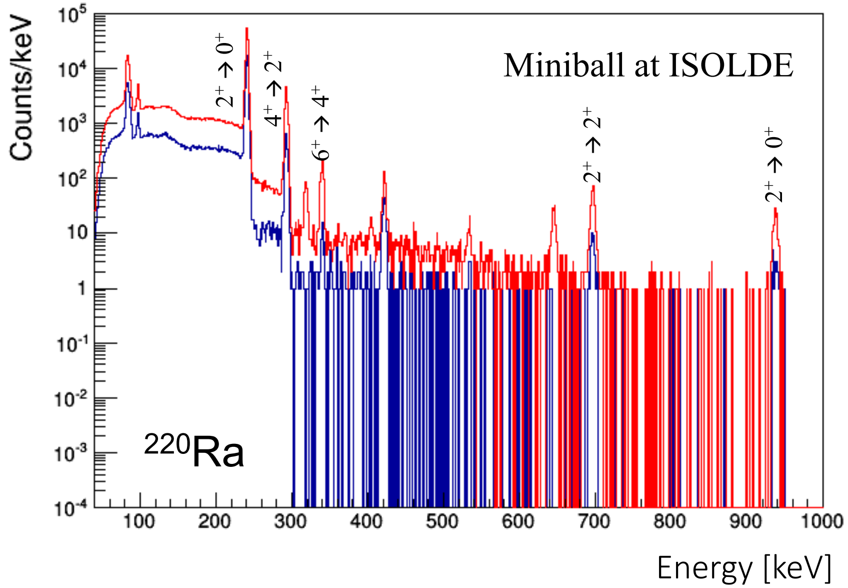
(Received 3 March 2015; published 9 June 2015)

Successful ^{225}Ra EDM efforts underway at Argonne National Lab

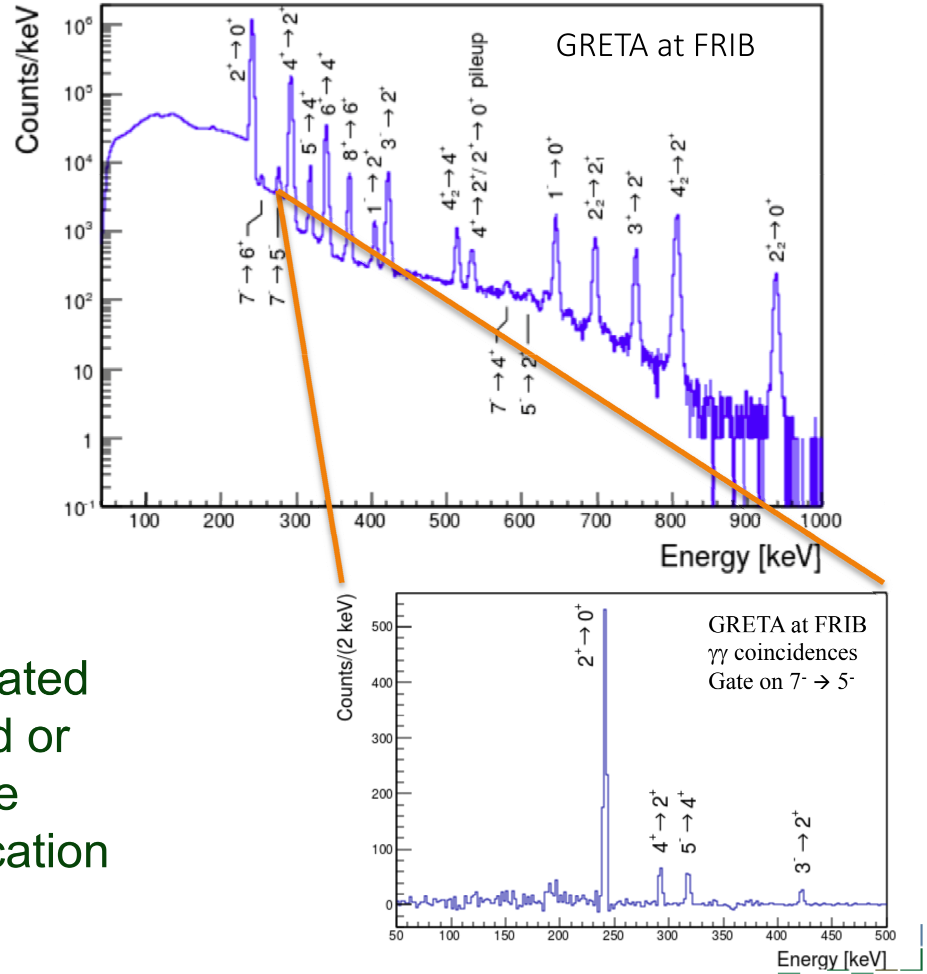
Nuclear structure input for EDM searches at FRIB – characterize octupole collectivity in Ra/Rn region

ARTICLE L. P. Gaffney et al. Nature 497 (2013)
doi:10.1038/nature12073

Studies of pear-shaped nuclei using accelerated radioactive beams



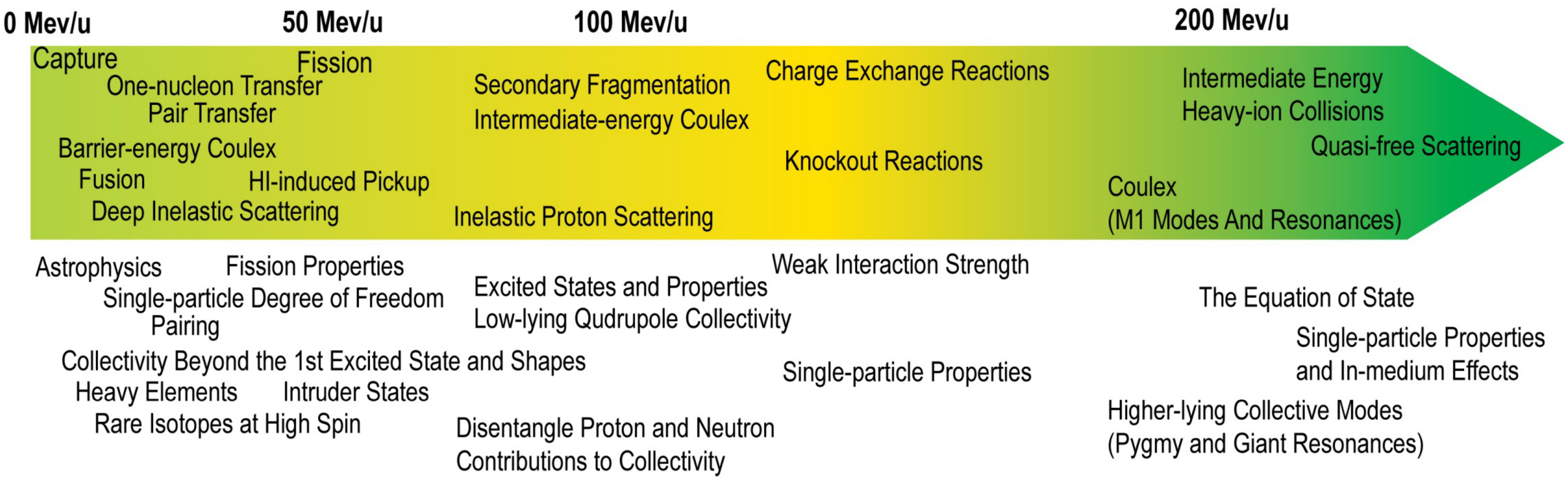
What is possible in Ra/Rn region now (left) and expected at FRIB (right)



4π GRETA combined with the FRIB reaccelerated beam intensity and energy provides a 100-fold or more increase in the intensity for studies in the region → Unprecedented potential for identification and characterization of octupole-collective candidate nuclei for EDM searches.

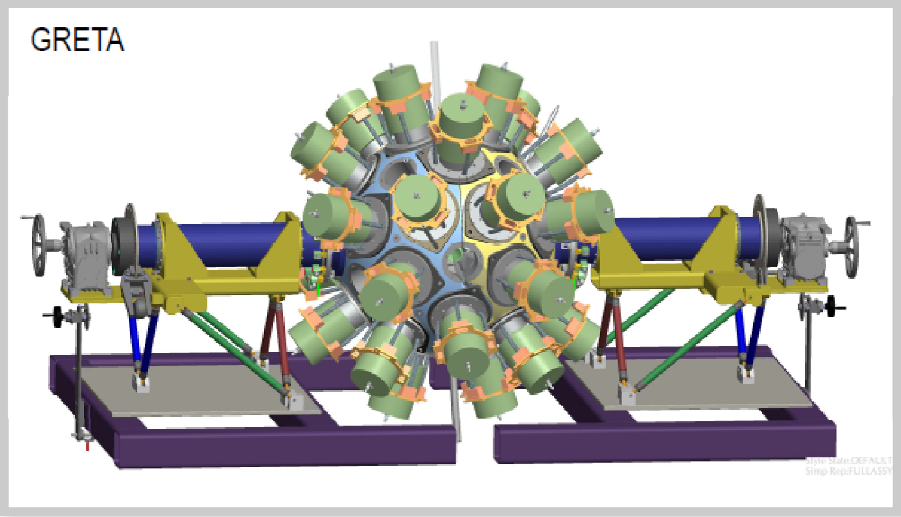
A note on nuclear reactions

- Nuclear reactions are an essential tool for the extraction of crucial information for nuclear structure physics and nuclear astrophysics
- The required beam energy range spans from keV/u (astrophysics) to above 200 MeV/u for heavy-ion reactions that will constrain the nuclear equation of state



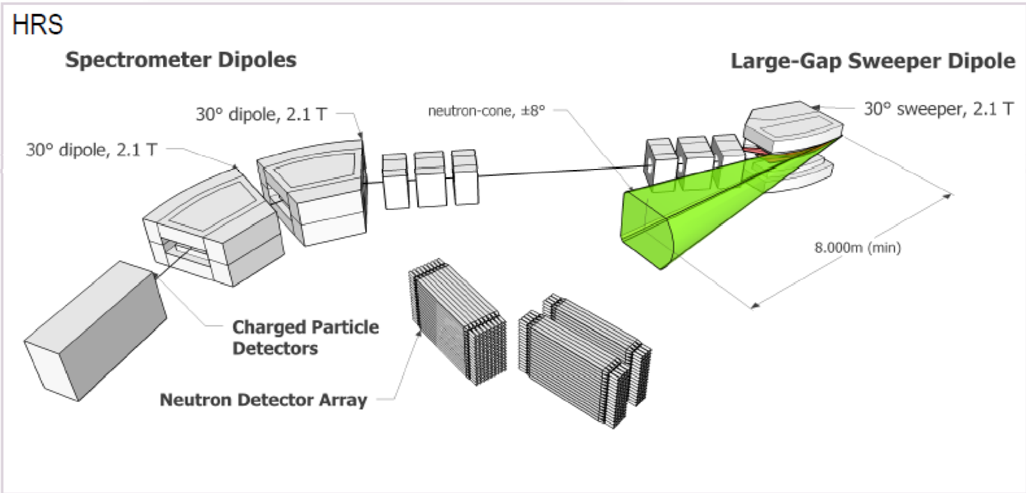
- FRIB will provide the full range of beam energies required to exploit nuclear reactions for nuclear structure and astrophysics

In-beam γ-ray spectroscopy at FRIB – New opportunities



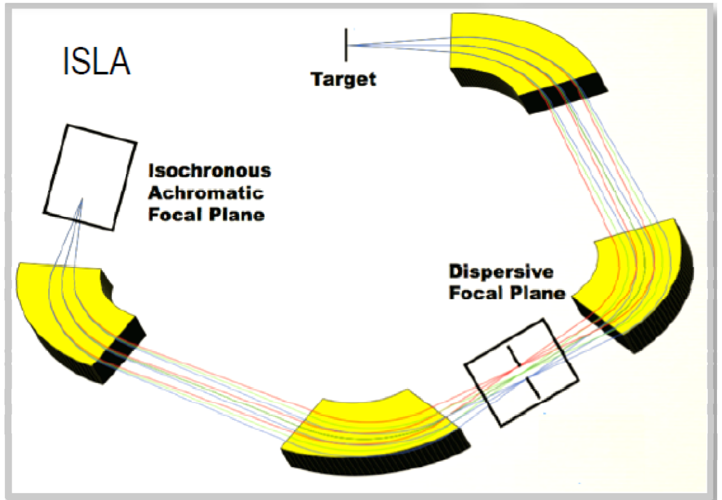
GRETA whitepaper

Fast beams



HRS whitepaper

Reaccelerated beams



ISLA whitepaper

Outlook

- Development of a predictive model for nuclei
  - To answer: What combinations of protons and neutrons can be made into abound system? What is the nature of the nuclear force?

- Foundation for astrophysical modeling
  - Access to key data needed to understand the origin of the elements in nucleosynthesis processes and extreme astrophysical environments

- Search for symmetry violations, e.g. atomic EDMs
  - Manifold opportunities at FRIB to contribute to the hunt for physics beyond the Standard Model (example: octupole collectivity)

Enormous discovery potential!

See also review article: A. Gade and B.M. Sherrill, *NSCL and FRIB at Michigan State University: Nuclear science at the limits of stability*, Physica Scripta 91, 053003 (2016)

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 under Cooperative Agreement DE-SC0000661.

Thank you