Updates on GRETA & HRS

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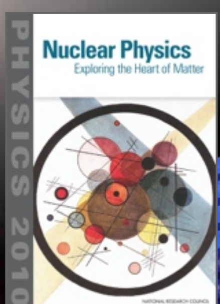
Chair, FRIB Users Organization Executive Committee
GRETA Level 2 Manager for System Assembly

The Science: The Big Questions in Nuclear Physics

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?

National Research Council Committee on the Assessment of and Outlook for Nuclear Physics Report, 2010



- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

Benchmarks for Rare Isotope Facilities

Science drivers (thrusts) from NRC RISAC 2007

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes

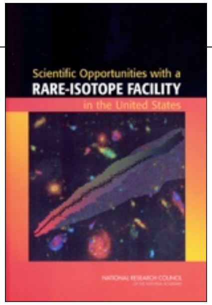
Intellectual challenges from NRC Decadal Study 2013

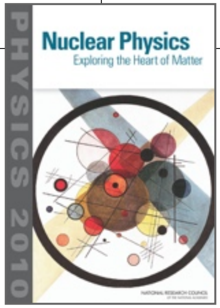
How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interac-tions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

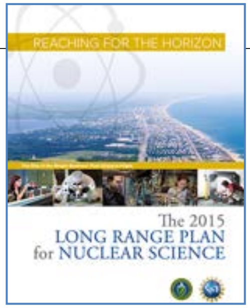
Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research 2007

1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 6. Equation of state 13. Limits of stability 14. Weakly bound nuclei 15. Mass surface	1. Shell structure 6. Equation of state 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 13. Limits of stability 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment 15. Mass surface 17. Weak interactions	10. Medical 11. Stewardship







FRIB Provides the Rare Isotope Infrastructure to Enable the Science

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Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
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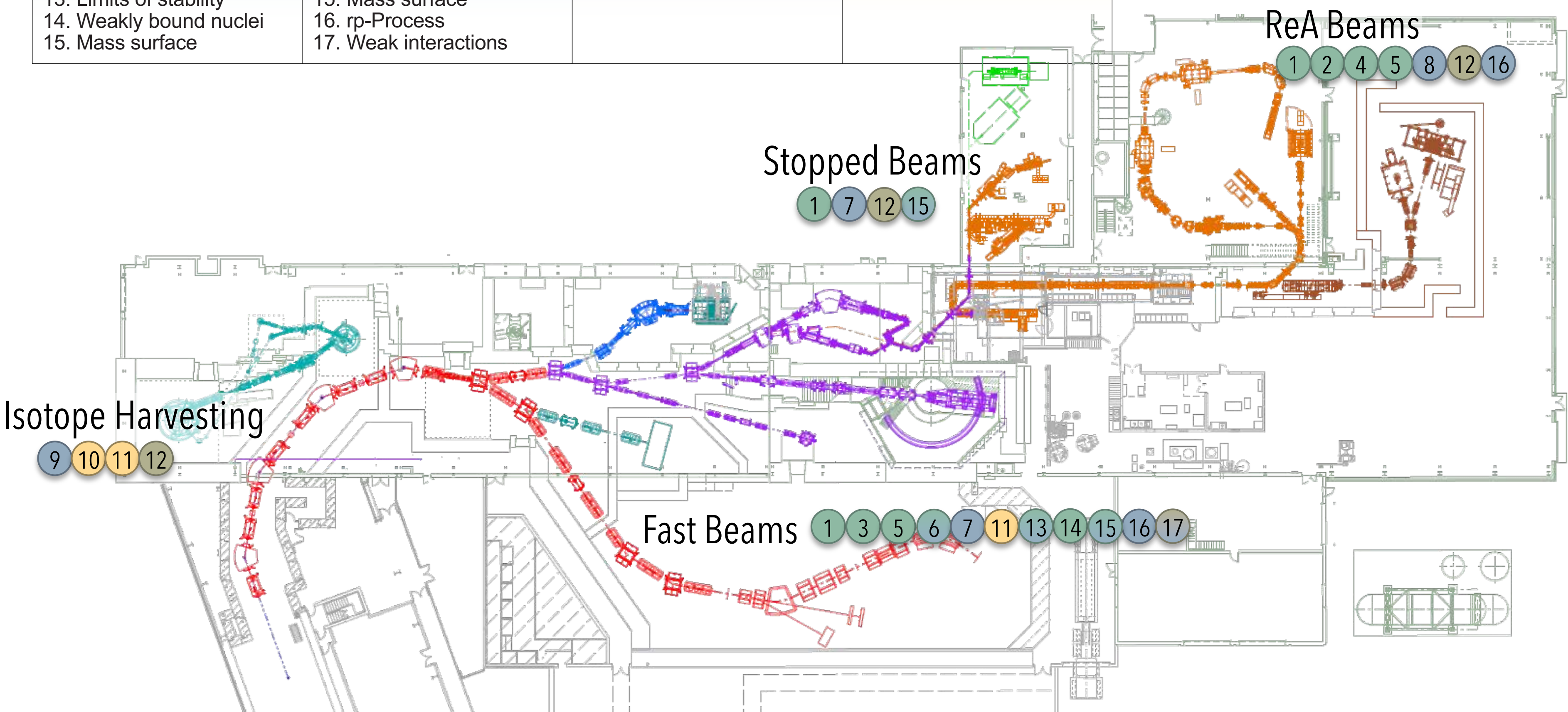

GRETA and the HRS are Key Instruments for FRIB

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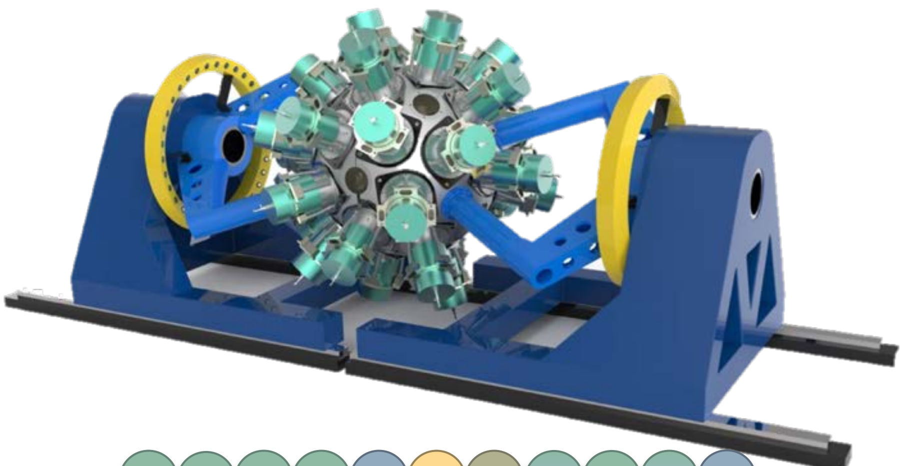
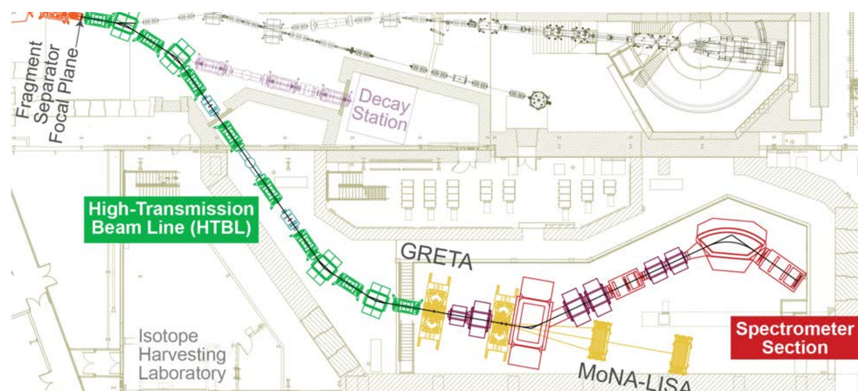


1 2 3 5 7 11 12 13 14 15 16

Gamma-**R**ay **E**nergy **T**racking **A**rray



1 3 5 6 7 11 13 14 15 16 17

High **R**igidity **S**pectrometer

GRETA Enables Experiments Addressing 11 of 17 Benchmarks

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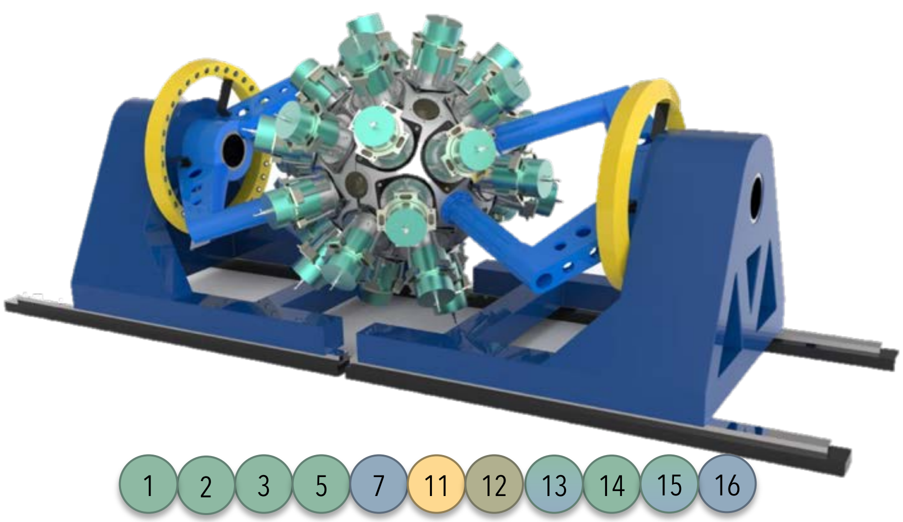

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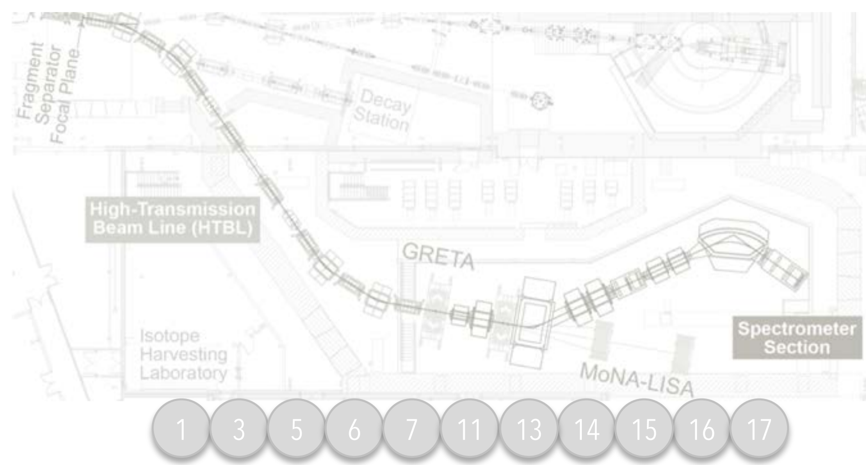
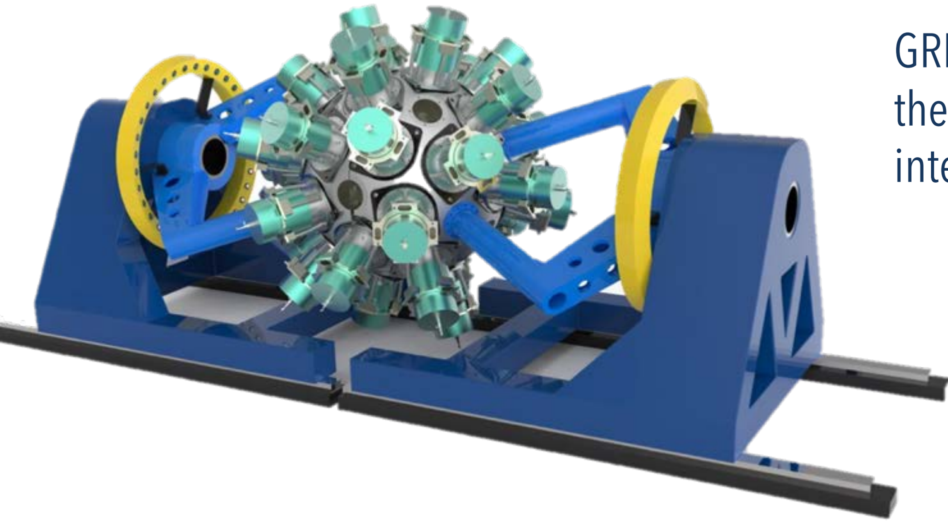


High **R**igidity **S**pectrometer

The Gamma-Ray Energy Tracking Array: GRETA



GRETA is a 4π tracking detector capable of reconstructing the energy and three-dimensional position of γ-ray interactions

Provides an unprecedented combination of
- *full solid angle coverage and high efficiency*
- *excellent energy and position resolution*
- *good background rejection (peak-to-total)*

LBNL-led project funded by DOE Office of Science, Office of Nuclear Physics and in collaboration with ANL, NSCL, and ORNL

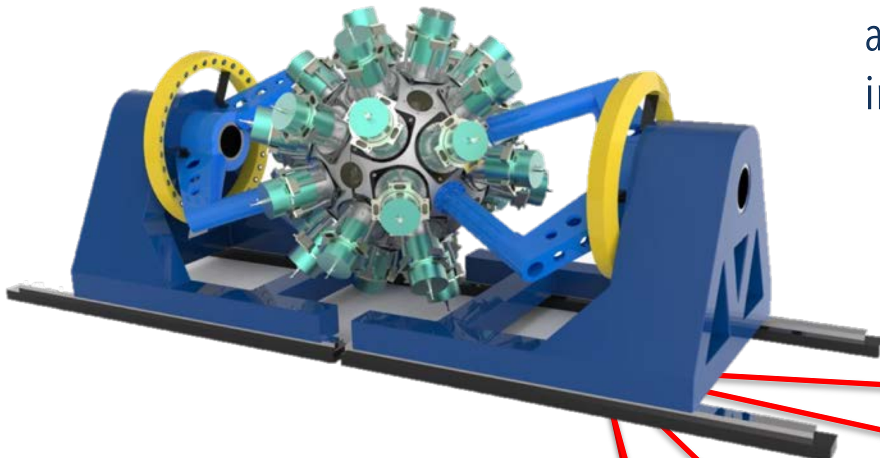
GRETA builds directly off of the success of GRETINA, which has been operating for physics since 2012, with 4 campaigns completed

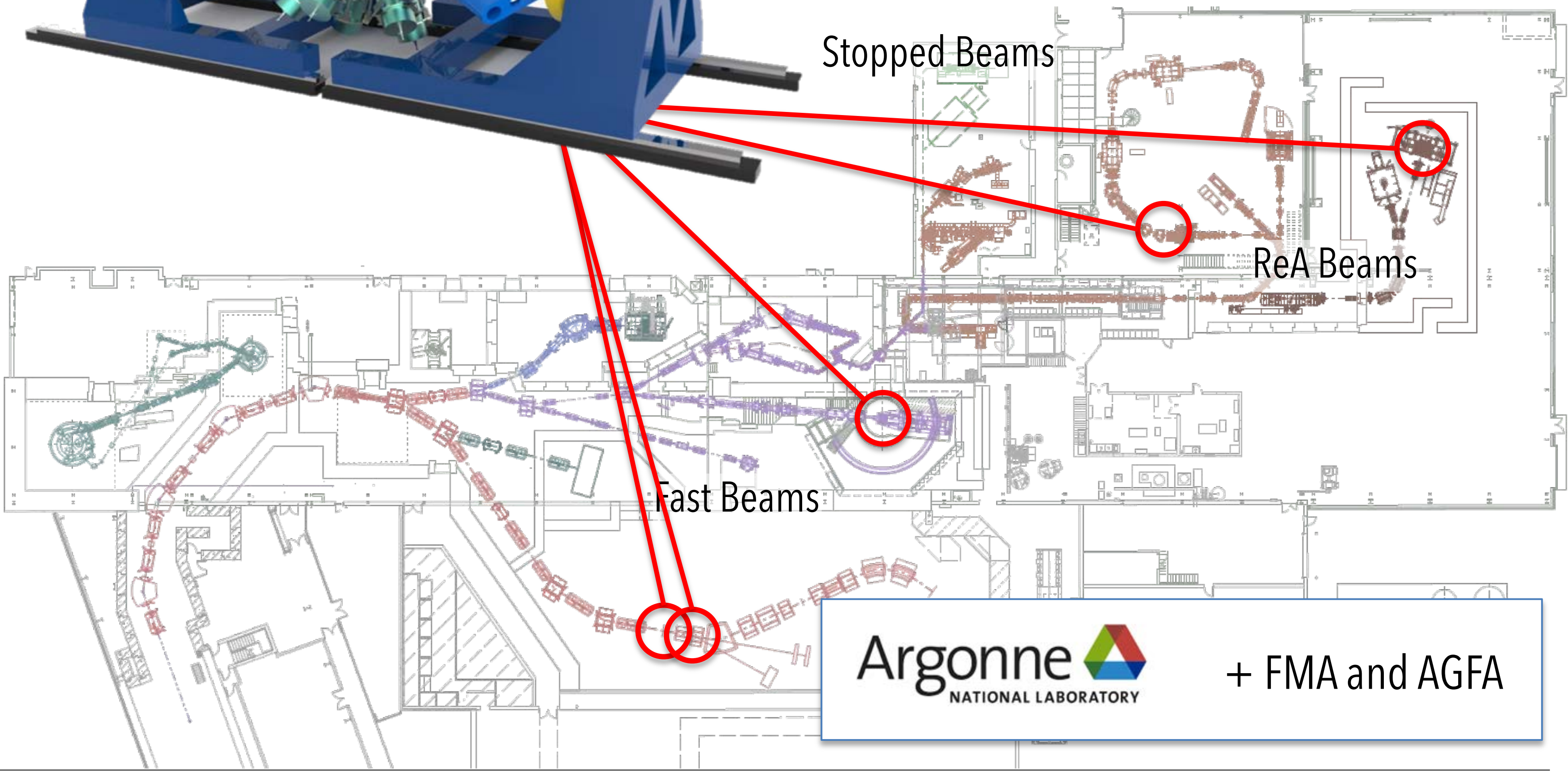
"GRETA will play a central role by adding significant new capabilities to existing facilities, such as ATLAS, NSCL, and ARUNA facilities, and as a centerpiece at FRIB for the physics opportunities with both fast-fragmentation and reaccelerated beams. … the community is eagerly anticipating a full 4π GRETA array."

Reaching for the Horizon
The 2015 Long Range Plan for Nuclear Science

GRETA Will Be Used at Multiple Beam Lines and Energies

Operation/installation sites have been identified, and design is proceeding to optimize the physics in each planned configuration





GRETINA/GRETA User Community

Established and Engaged User Community

GRETINA/GRETA Users Executive Committee (GUEC)

Peter Bender, UMass Lowell (chair)
Heather Crawford, LBNL
Alexandra Gade, NSCL/MSU
Robert Janssens, University of North Carolina
Shaofei Zhu, ANL

- Over 200 active Users
- Closely coordinated with the FRIB Users Organization
- Established Working Groups
- Past and planned workshops (next in August 2019) to keep broader user community updated and engaged

http://gretina.lbl.gov
http://greta.lbl.gov

The Gamma-Ray Energy Tracking Array: GRETA

GRETA includes:

- 18 Quad modules, to be combined with 12 GRETINA modules for a total of 30
- Full mechanical structure for 30 module close-packed array, covering 80% of solid angle
  - Removable forward and rear detector rings
  - Rotation and translation capabilities
- Electronics to instrument all 30 Quad modules
  - Detector-mounted digitizer modules with continuous streaming of waveforms to FPGA-based signal filter boards
  - New trigger, timing and controls systems

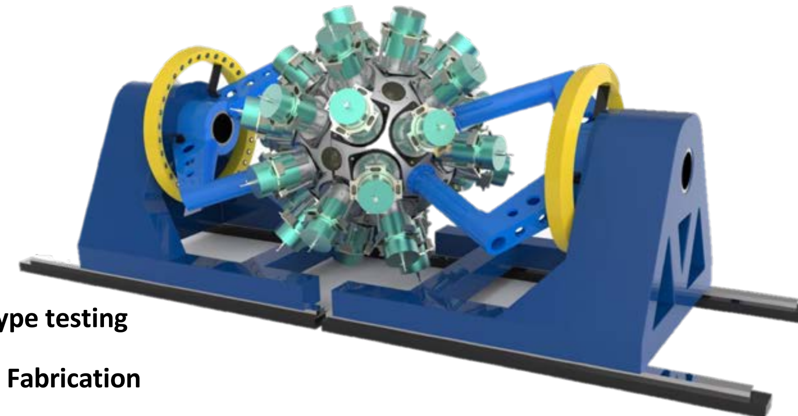
- Computing cluster to support full array
  - Real-time signal decomposition up to total through-put of 480k decompositions/s
  - High-speed local network
  - 1 PB local storage

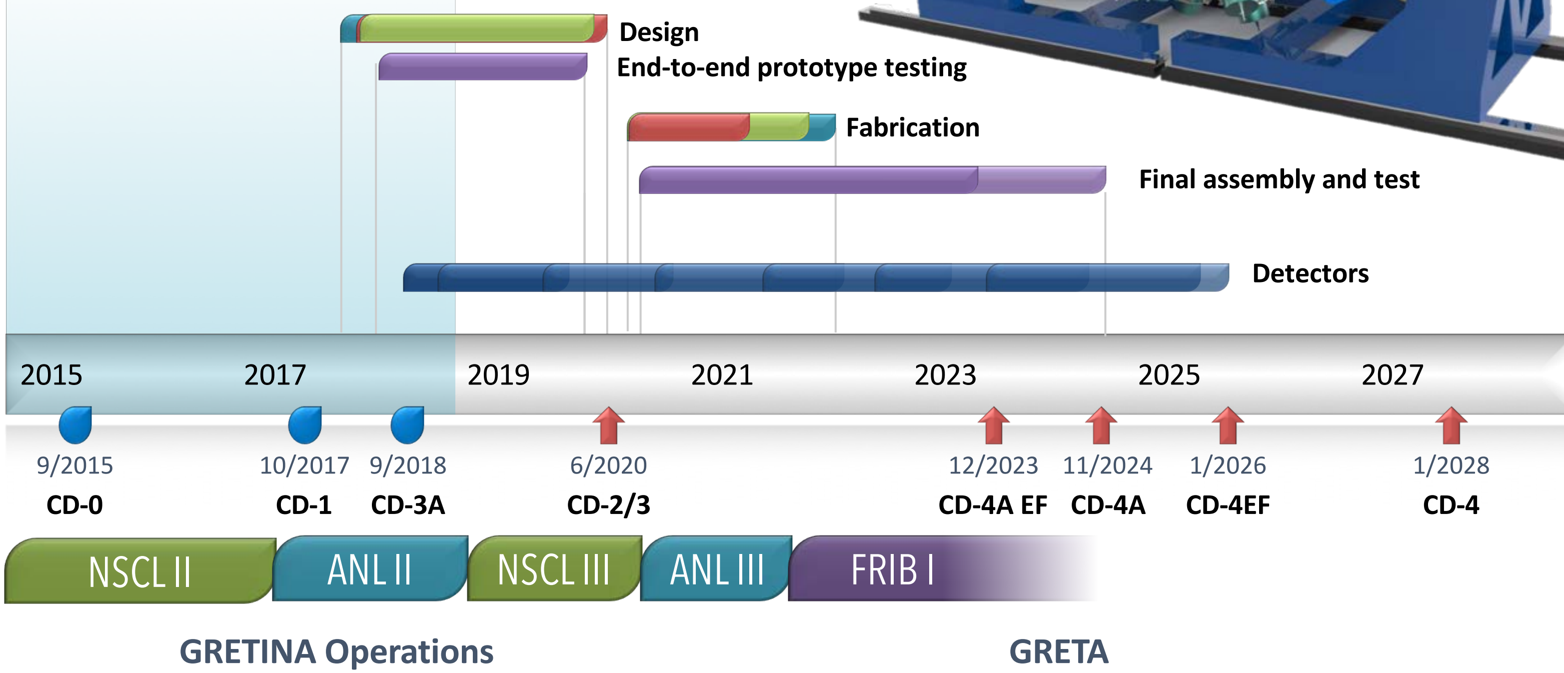
GRETA Project Status:

- Preliminary TPC: $58.3M USD
- CD-3A awarded October 2018
- CD-2/3 planned for mid 2020

Status of GRETA

- Preliminary design is nearly complete; final design activities are starting now
- Project is staged to optimize physics with early delivery to FRIB at CD4A
  - Final Mechanical, Electronics, and Computing
  - Subset of detector modules to combine with GRETINA detectors



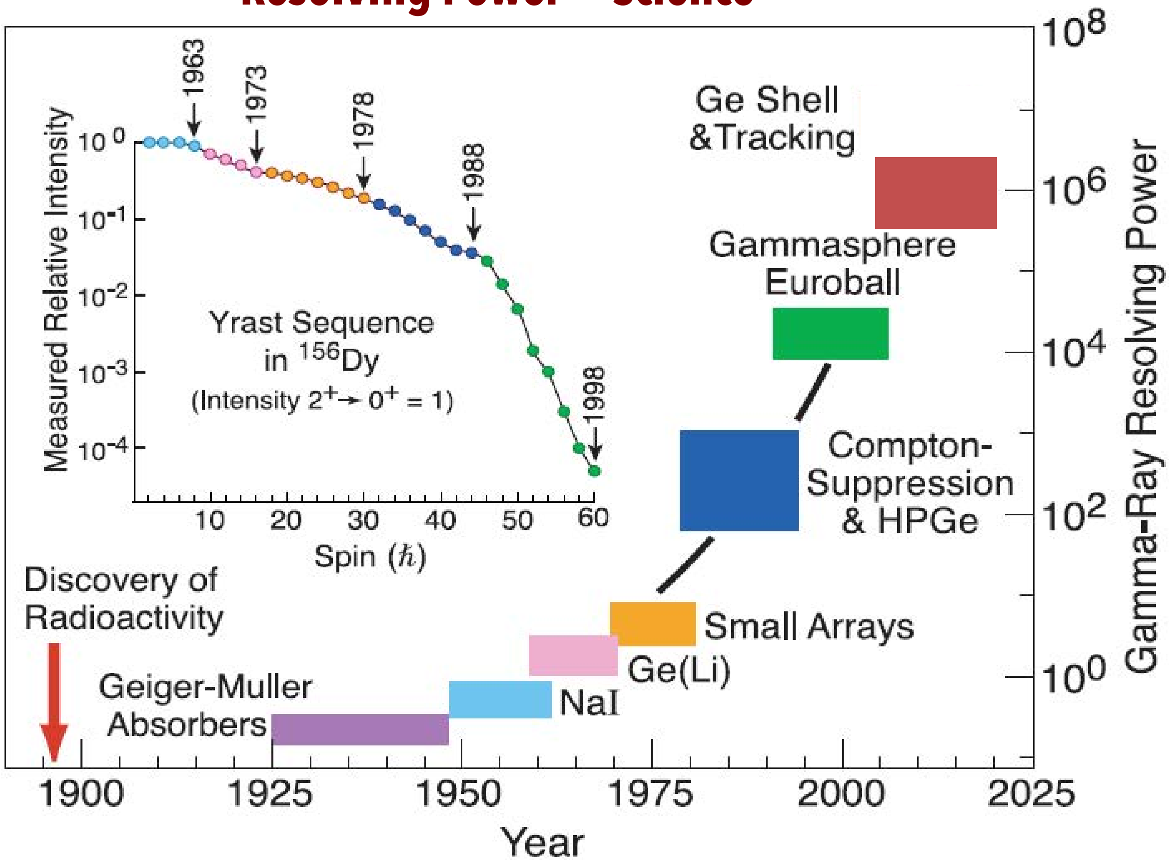


Resolving Power is a Quantitative Measure of Array Performance

The science reach of a γ-ray tracking array can be expressed in terms of the effective resolving power (RP)

Depends on Efficiency (ε); Peak-to-Total (P/T); Resolution (δE)

Resolving Power = Science



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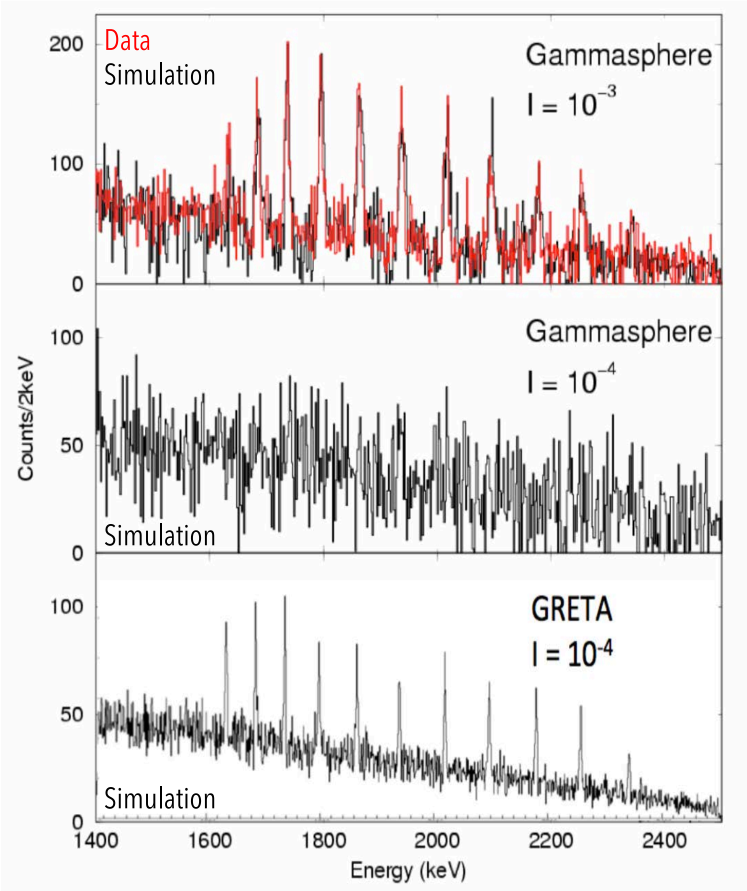

Resolving Power = Science

Efficiency alone over another HPGe array gives GRETA an order of magnitude higher sensitivity for the weakest branches – goes as ~ ε^f for high fold

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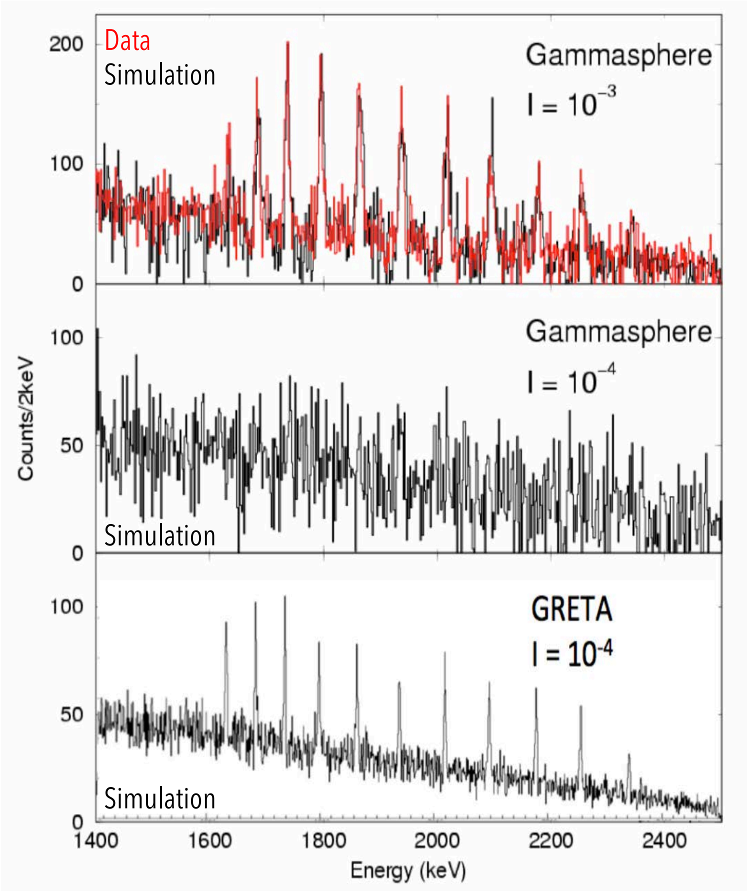
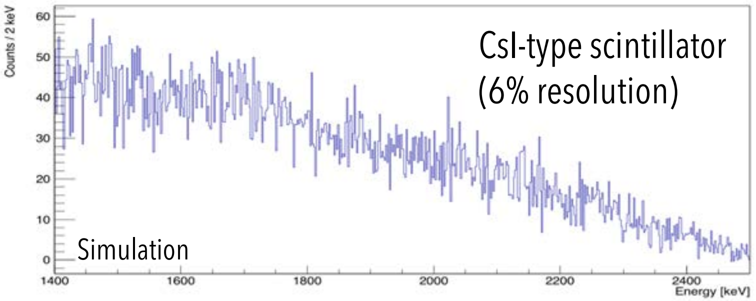


Resolving Power = Science

Efficiency alone over another HPGe array gives GRETA an order of magnitude higher sensitivity for the weakest branches – goes as ~ ε^f for high fold

Resolution gives P/T as compared to scintillators with comparable efficiency.

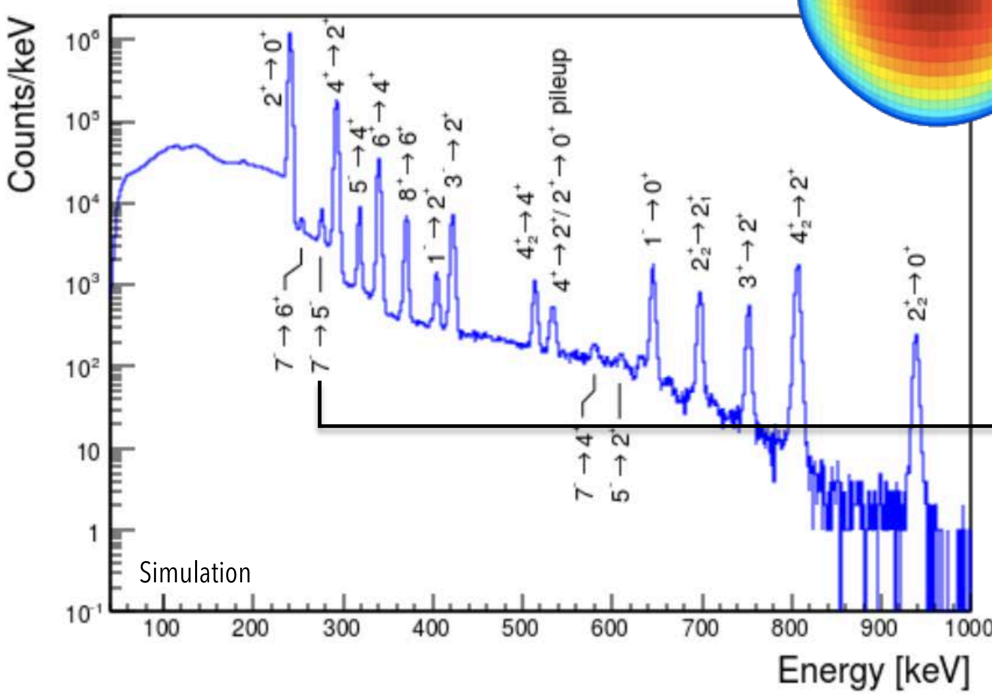


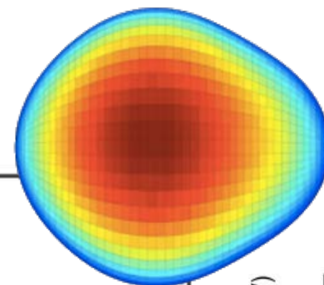
Science - Nuclear Structure Physics: Octupole Deformation and the EDM

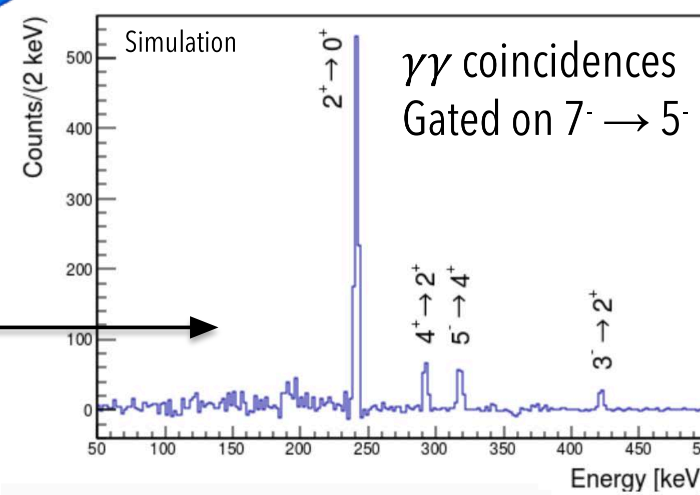
Studies of octupole collectivity, such as low-energy (multiple) Coulomb excitation of ^{220}Rn, can guide searches for physics beyond the Standard Model (atomic EDM)

- ^{220}Rn: 100-fold gain over measurement performed at REX-ISOLDE
- Access to EDM candidates ^{225}Ra and ^{223}Rn, and ^{229}Pa (predicted EDM contribution 40 times larger than ^{225}Ra)

^{220}Rn Coulex with GRETA at FRIB





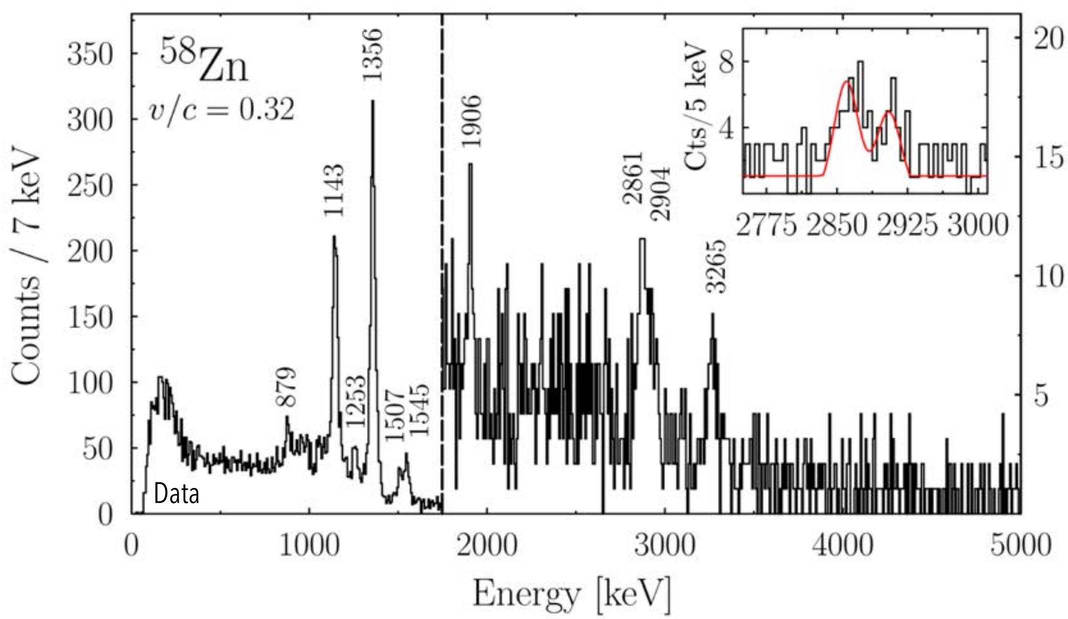


L. P. Gaffney *et al.*, Nature **497**, 199 (2013).
V. V. Flambaum, Phys Rev. A **77**, 024501 (2008).

Science – Nuclear Astrophysics: Insight with Fast and Reaccelerated Beams

Gamma-ray decay measurements are a powerful tool to constrain key astrophysically-relevant reaction rates

★ Fast-beam reactions have proven invaluable for measurement of low-lying resonances of unstable nuclei important for proton-capture rates relevant to the rp process and *x*-ray bursts – ^{57}Cu(p,γ)^{58}Zn with GRETINA



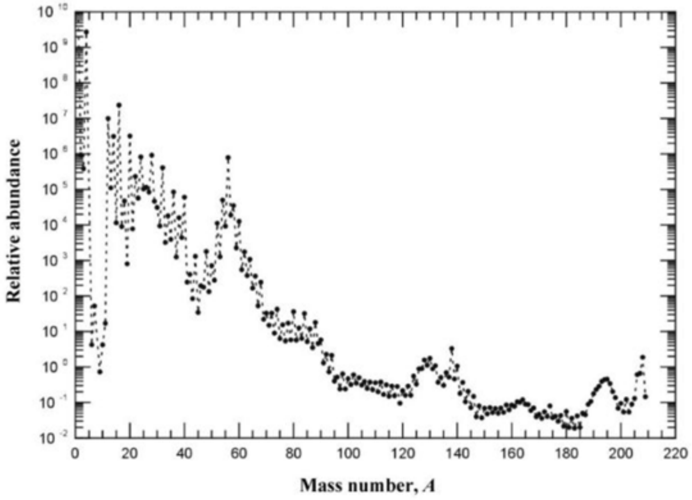
★ Charge exchange reactions with fast beams can probe information needed to constrain electron capture rates, key for understanding processes in neutron stars

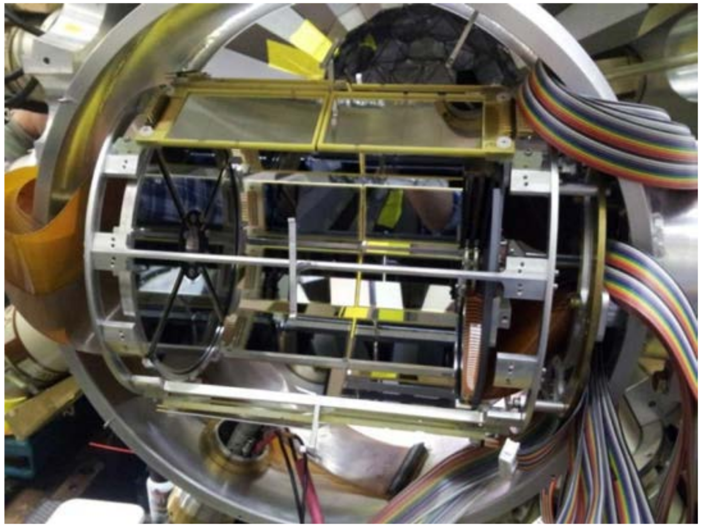
C. Langer *et al.*, Phys. Rev. Lett. **113**, 032502 (2014).

Science – Nuclear Astrophysics: Insight with Fast and Reaccelerated Beams

GRETA and reaccelerated beams expands even further possibilities for astrophysically relevant measurements

- ★ Transfer reactions such as (d,p+γ) are important surrogates for neutron-capture reactions which drive the r-process and production of elements above Iron
- ★ ^{137}Te(d, p+γ) is a representative measurement which will constrain the ^{137}Te(n, γ)^{138}Te reaction rate relevant to the A=130 peak of the r-process
  - ★ To date, no states likely relevant for neutron capture are known

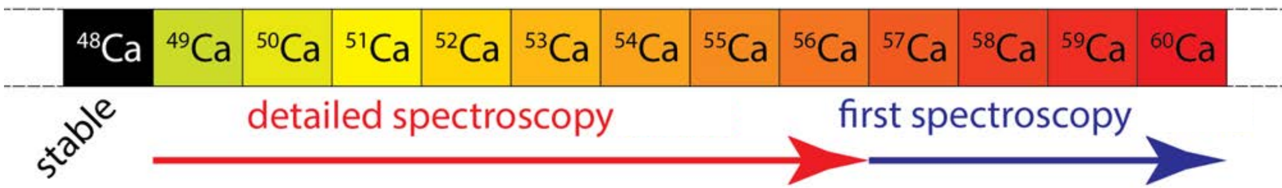


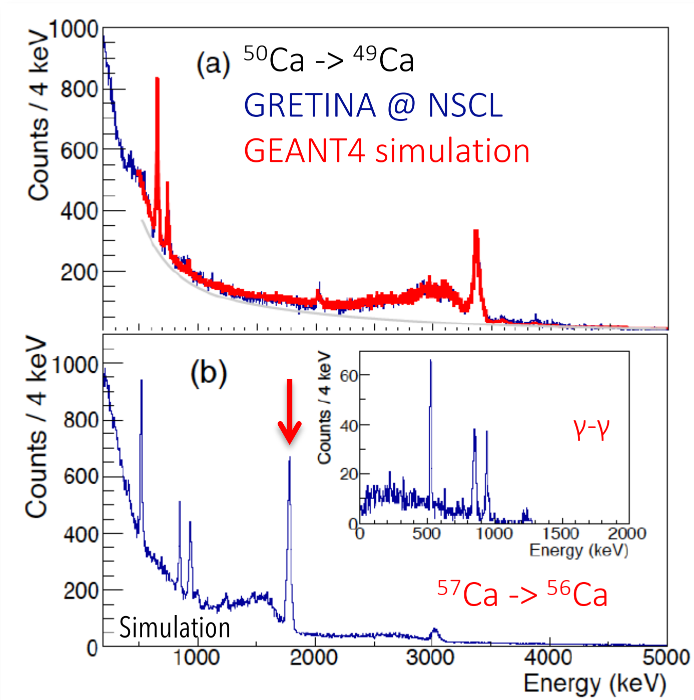


E. Anders and N. Grevesse, Geochim. Cosmochim. Acta. **53**, 197 (1989).

Science – Nuclear Structure Physics: Bound States in Calcium Isotopes

The evolution of nuclear shell structure along the Ca isotopic chain is a key benchmark for theories, including *ab initio* models, and effective interactions based on microscopically–derived NN and 3N interactions.





- Detailed spectroscopy around $N=32$, 34 will inform on strength of neutron subshell gaps, and robustness of $Z=20$ proton shell closure

- Coincidence spectroscopy with fast beams will be key to understanding level schemes

HLC *et al.*, Phys. Rev. C **95**, 064317 (2017).

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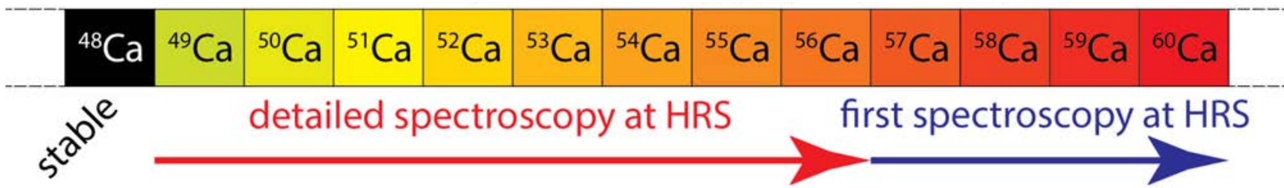
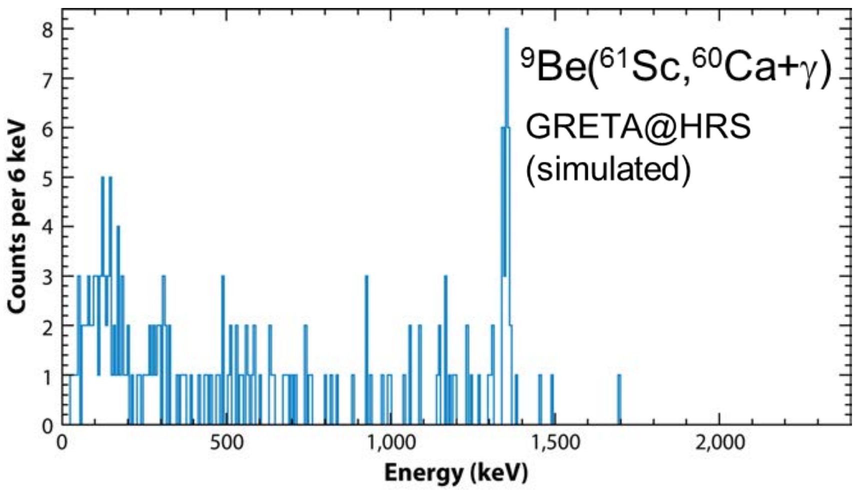


P. Fallon *et al.*, ARNPS 66, 321 (2016)



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

> *"However, the spectroscopy of ^{60}Ca will only be possible at FRIB with the Gamma-Ray Energy Tracking Array (GRETA), a high-efficiency, large-acceptance detector that can track γ-rays, and HRS, a high-rigidity recoil separator that can handle the highest energy neutron-rich beams."*
>
> Reaching for the Horizon
> The 2015 Long Range Plan for Nuclear Science

^{60}Ca region: luminosity gain over existing: *24-fold* increase in yield with HRS

The HRS Enables Programs that Address 11 of the 17 NSAC Rare Isotope Beams Task Force Benchmarks

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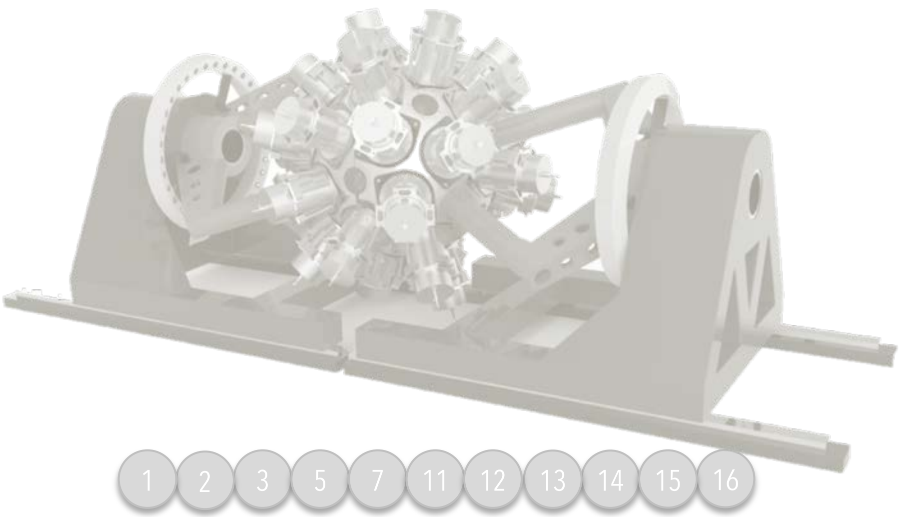
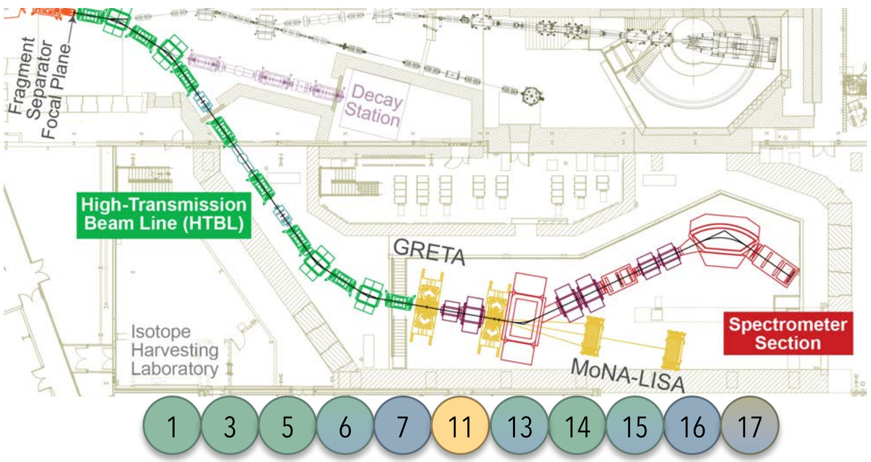


Gamma-Ray Energy Tracking Array



High Rigidity Spectrometer

A High Rigidity Spectrometer (HRS) is Needed for the FRIB Scientific Program

- HRS was recognized in the 2015 Long Range Plan as a priority
- Support from U.S. DOE-SC, Office of Nuclear Physics to complete ion-optical and magnet feasibility studies are very much appreciated
- Conceptual Design Report is complete
- HRS delivers gain factors in luminosity of up to100 for neutron-rich isotopes, with the largest gains for the most exotic species
- 500+ user community is excited about the scientific opportunities and have been engaged in the development of the conceptual design
- Estimated Total Project Cost: $88.6M

"Another key addition to FRIB is the proposed High-Rigidity Spectrometer (HRS) which would enable in-flight reaction experiments with the most neutron-rich nuclei available from FRIB. These extreme nuclei provide the most sensitive tests of nuclear models."

Reaching for the Horizon
The 2015 Long Range Plan for Nuclear Science

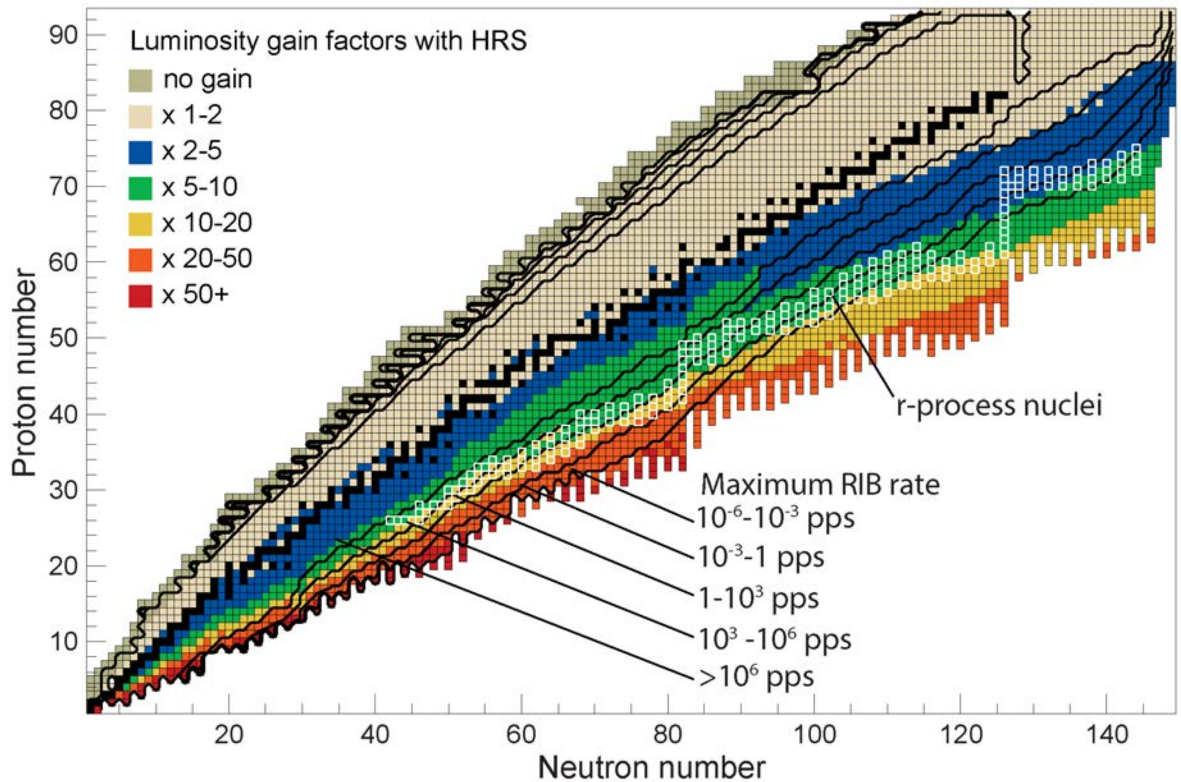
"Not all can be realized immediately, but a targeted suite to address the highest priority research programs is needed. Instruments such as GRETA, HRS, and SECAR (a recoil spectrometer for nuclear astrophysics research) will be essential to realize the scientific reach of FRIB."

Reaching for the Horizon
The 2015 Long Range Plan for Nuclear Science

FRIB Achieves Furthest Scientific Reach Through Increased Luminosity With the HRS

Increased yield afforded by the HRS:

- HRS increases the scientific reach of FRIB through increased luminosity
  - Gain: Use rare-isotope beam at the rigidity that optimizes production (up to 8 Tm)
  - Gain: Use thick reaction targets at the HRS to maximize yield



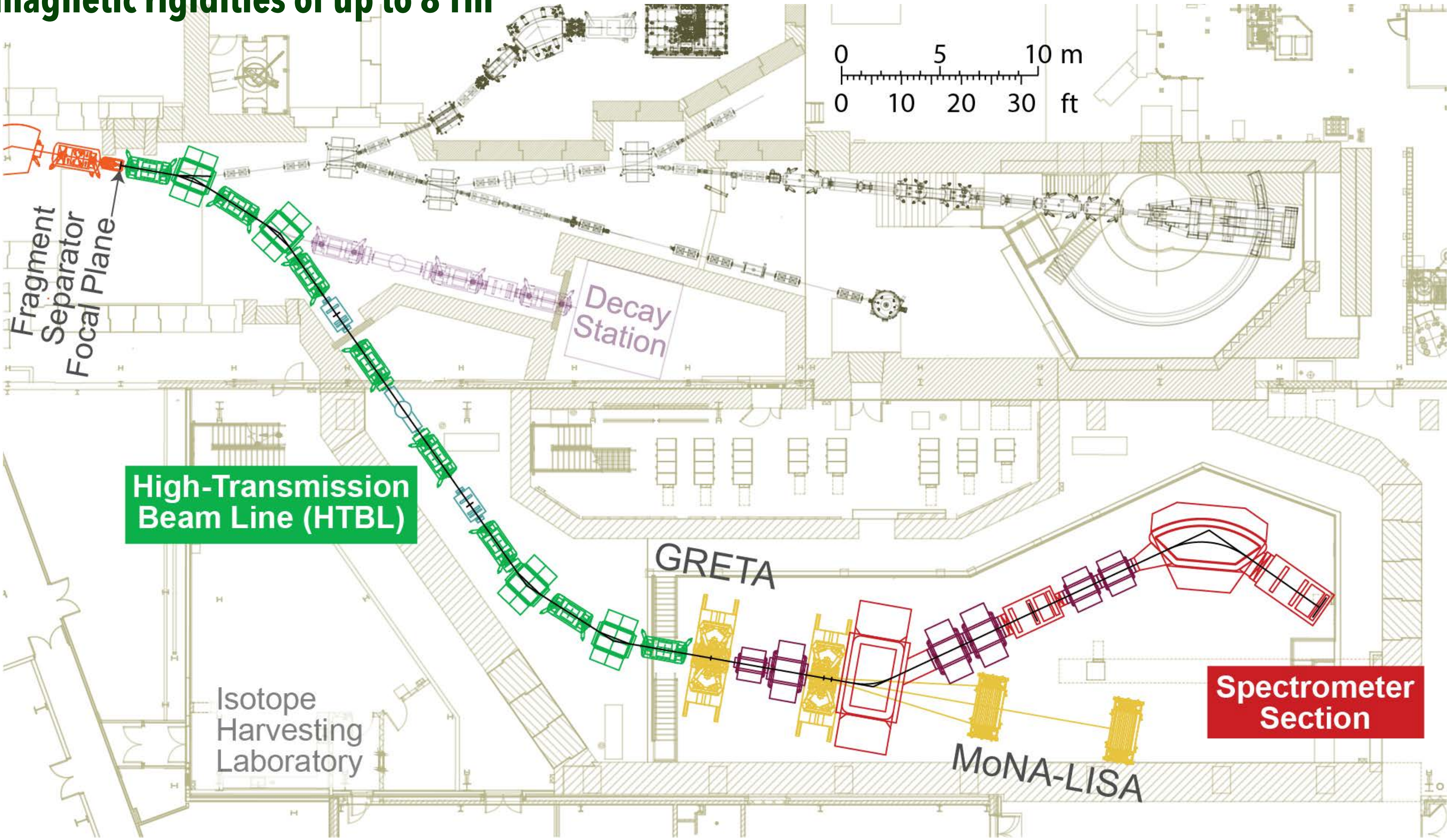
- For over 90% of neutron-rich isotopes gain factors of 2-100 are achieved; on average about 10

- For the most asymmetric neutron-rich systems, gain factors are larger than 50

- For nuclei in the path of the astrophysical r-process gain factors are 5-20

Conceptual Layout of the HRS That Enables the Scientific Program Envisioned by the User Community

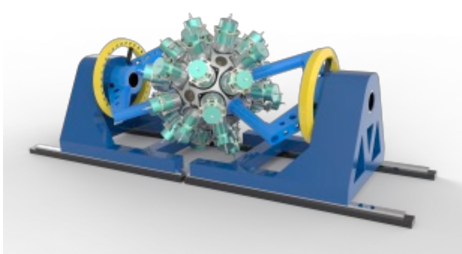
The High Transmission Beam Line (HTBL) and Spectrometer Section enable experiments at magnetic rigidities of up to 8 Tm



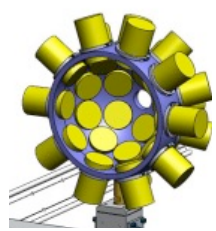
HRS Accommodates Ancillary Detectors Developed by the Community to Meet the Scientific Objectives of FRIB

500+ users will perform experiments with the HRS

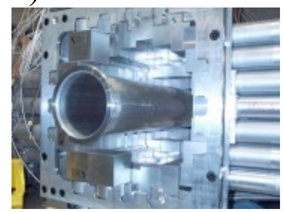
a) GRETA



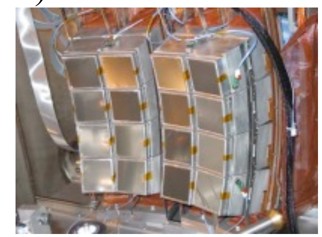
b) LANL-Apollo



c) CAESAR

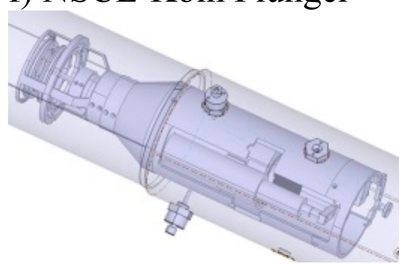


d) HiRA

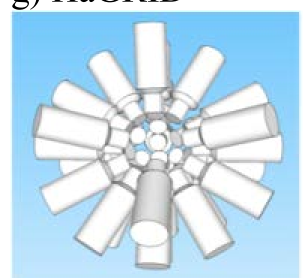


e) SeGA

f) NSCL-Köln Plunger



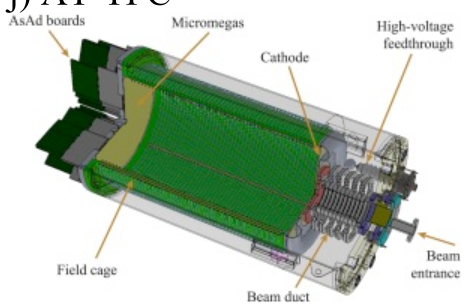
g) HaGRID



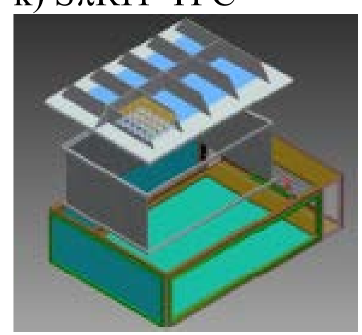
h) ORRUBA

i) LENDA & VANDLE

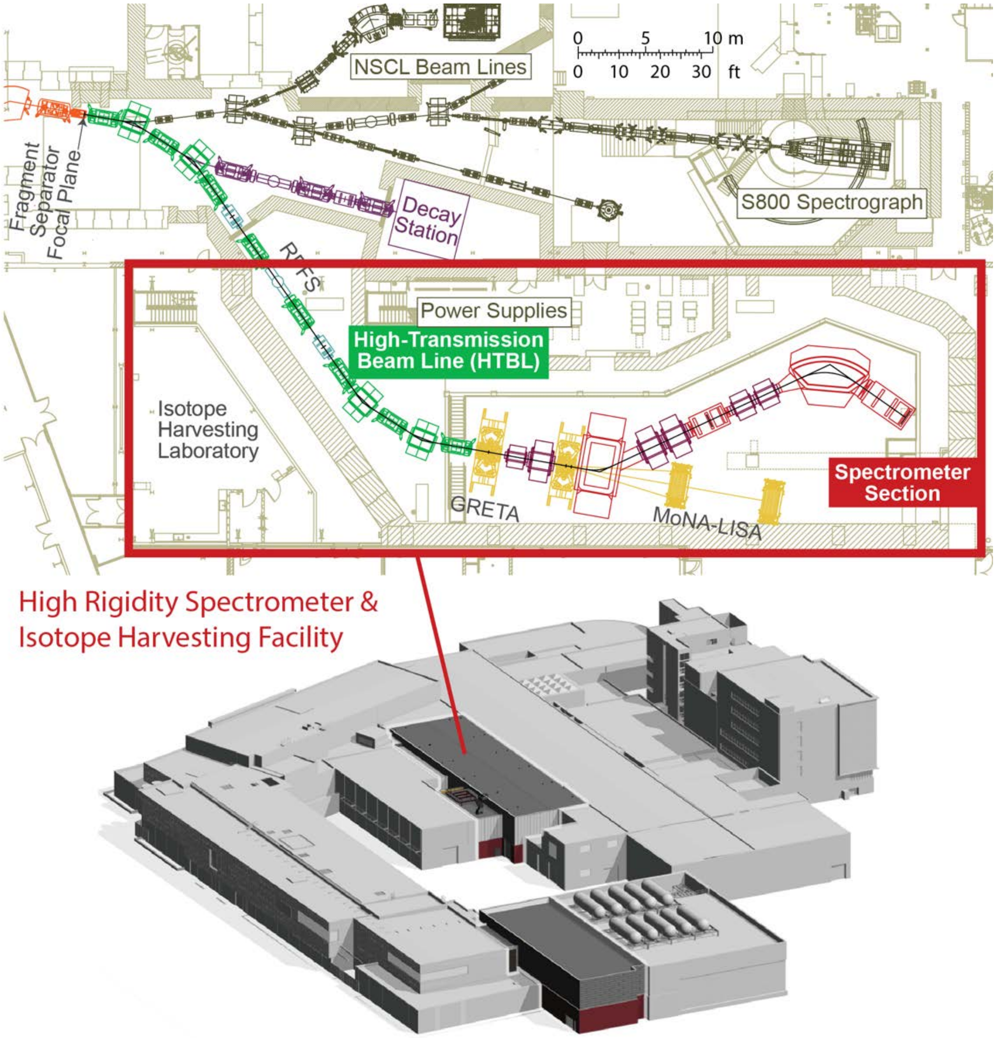
j) AT-TPC



k) SπRIT-TPC



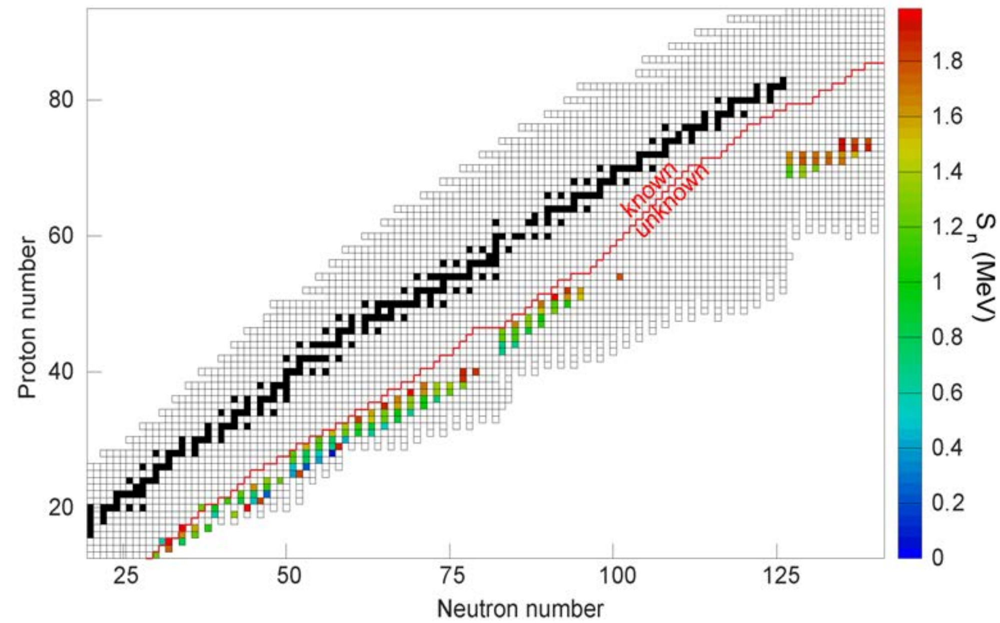
High Bay for the HRS and Isotope Harvesting Facility Under Construction



- MSU funded 31000 sq. ft. experimental area in the center of the FRIB facility
- Building occupancy: end of CY 2019

Science – Nuclear Structure Physics: In the Continuum

- Understanding unbound nuclei is a unique challenge in rare-isotope science
  - Structural change is driven by the proximity of the continuum
  - Many-body correlations are amplified in the regime of weak binding
  - New phenomena such as di-neutron decay and 2-neutron radioactivity have been discovered for neutron-unbound nuclei
- A new frontier are multi-nucleon correlations
  - ^{38}Na and ^{44}Mg are predicted to be unbound to the emission of four neutrons

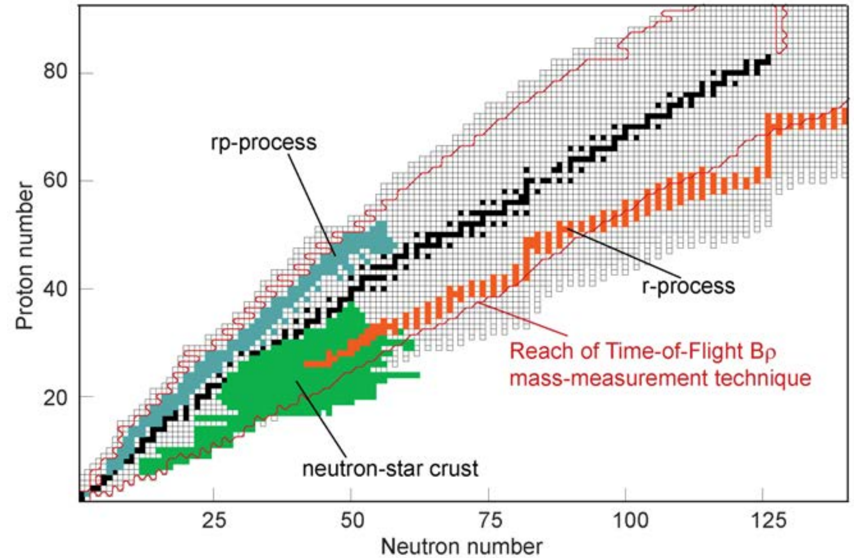


- With the HRS, many unknown systems with $S_n<2$ MeV are in reach for invariant mass spectroscopy with neutron detectors

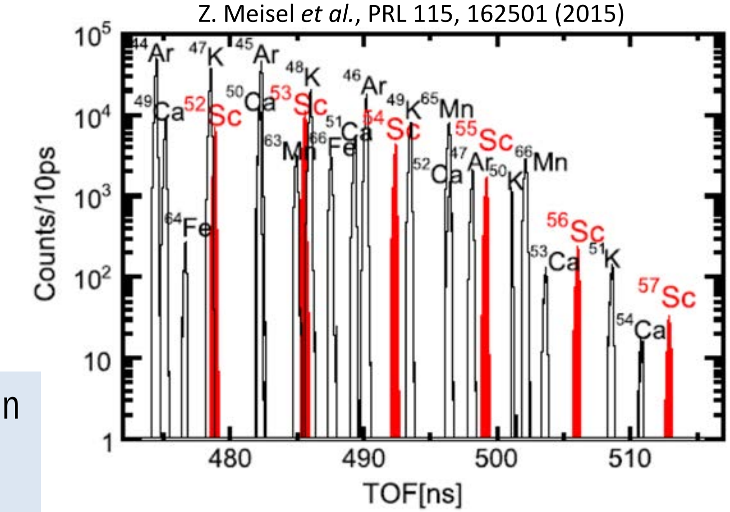
^{40}Mg region: luminosity gain over existing: 102-fold increase in yield

Science – Nuclear Astrophysics: Access Masses Closest to Dripline

- Most nucleosynthesis processes involve rare isotopes far from stability
  - Nuclear masses are needed to understand the reaction and decay paths
  - Masses can be deduced from the simultaneous measurement of an ion's time-of-flight (ToF), charge, and magnetic rigidity thorough a magnetic system of a known flight path
- ToF mass measurements (flight path: HRS transmission line and spectrometer) can reach a significant fraction of the nuclei relevant for the r-process and neutron-star (NS) crust physics
- Tens of masses can be measured in one shot, including of shortest-lived ones closest to the neutron dripline – furthest reach of mass measurements



Z. Meisel *et al.*, PRL 115, 162501 (2015)



Many masses unique to FRIB can be measured in one run, including in key regions, e.g. around ^{84}Ni (x22) (NS crust) and ^{170}Nd (x6) (r process)

Summary

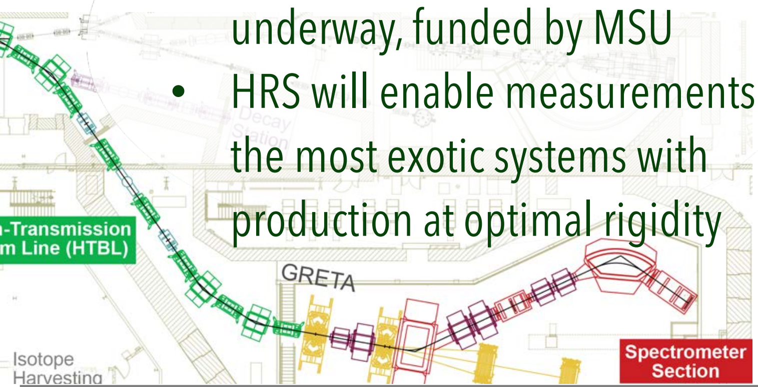
Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research 2007

1. Shell structure	1. Shell structure	12. Atomic electric dipole moment	10. Medical
2. Superheavies	6. Equation of state	15. Mass surface	11. Stewardship
3. Skins	7. r-Process	17. Weak interactions	
4. Pairing	8. $^{15}O(\alpha,\gamma)$		
5. Symmetries	9. ^{59}Fe s-process		
6. Equation of state	13. Limits of stability		
13. Limits of stability	15. Mass surface		
14. Weakly bound nuclei	16. rp-Process		
15. Mass surface	17. Weak interactions		

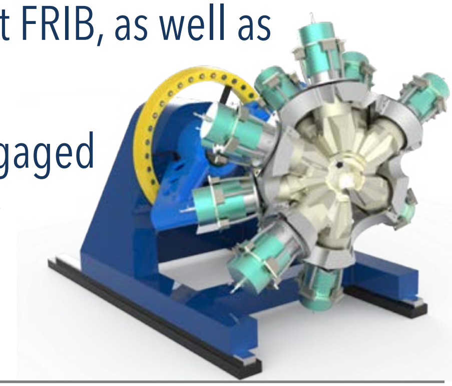
High Rigidity Spectrometer

- The Conceptual Design for the HRS is complete, with a layout that delivers on the broad scientific program envisioned by users
- High-bay civil construction is underway, funded by MSU
- HRS will enable measurements of the most exotic systems with production at optimal rigidity



Gamma-Ray Energy Tracking Array

- GRETA is underway, with detector procurements in progress and a planned CD2/3 in mid-2020
- Unparalleled resolving power of GRETA will enable spectroscopy with fast and reaccelerated beams at FRIB, as well as at ATLAS / ANL
- User community is engaged and ready for the array



Thank you!

Thank you to Paul Fallon and Remco Zegers for slides and material, and many other colleagues for comments and feedback.

GRETA: GRETA is a Major Item of Equipment supported by the U.S. Department of Energy Office of Science Office of Nuclear Physics.

HRS: This work is supported by the U.S. Department of Energy Office of Science under Grant DE-SC0014554, Ion-Optical and Associated Magnet Feasibility Study of High Rigidity Spectrometer.