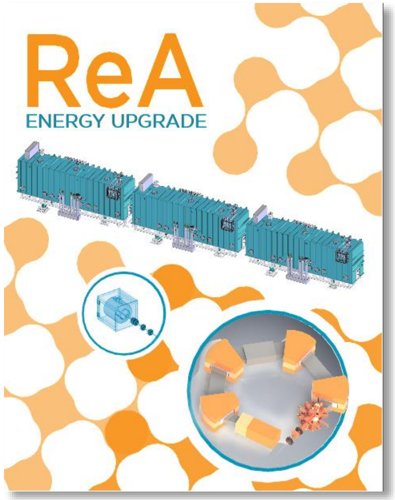
ReA energy upgrade whitepaper



Hiro Iwasaki

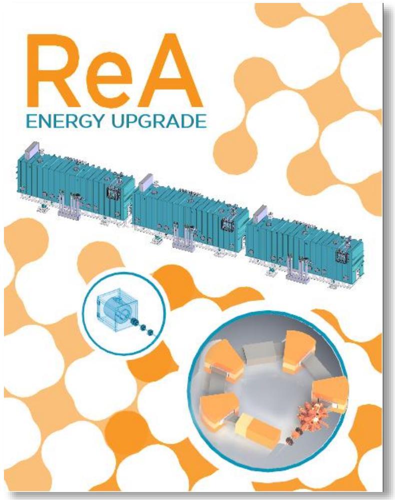
National Superconducting Cyclotron Laboratory

Michigan State University

for the user community

ReA energy upgrade whitepaper

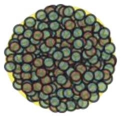
The ReA energy upgrade whitepaper was compiled based on input from the low-energy community and initiated at the **ReA3 upgrade workshop** held on August 20, 2015 (>70 registered participants).



The ReA energy upgrade whitepaper is available at
2016.lecmeeting.org/ReA_energy%20upgrade_whitepaper.pdf

The ReA energy upgrade working group conveners are: A.Wuosmaa (U. of Connecticut), G.Rogachev (Texas A&M), B.Kay (ANL), and H.Iwasaki (NSCL/MSU). The ReA WG will work closely with other WGs for detectors and spectrometers.

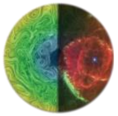
Overarching questions and science drivers for FRIB



How does subatomic matter organize itself and what phenomena emerge?

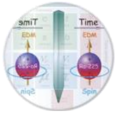
- Testing Nuclear Structure Concepts (2.4)
- Probing the modification of shell structure (2.1, 2.2, 2.3)
- Pairing and superfluidity (3.3)
- The evolution of collective motion in complex nuclei (3.1, 3.2, 3.4)
- Production and properties of the heaviest nuclei (4.1, 4.2)
- Probing neutron skins (2.4)

section # in ReA energy upgrade whitepaper



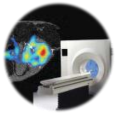
How did visible matter come into being and how does it evolve?

- The origin of the heaviest elements (5.2)
- Explosive nucleosynthesis (5.1)
- Composition of neutron stars (4.3)



Are the fundamental interactions that are basic to the structure of matter fully understood?

- Test of fundamental symmetries with rare isotopes (6.1)



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

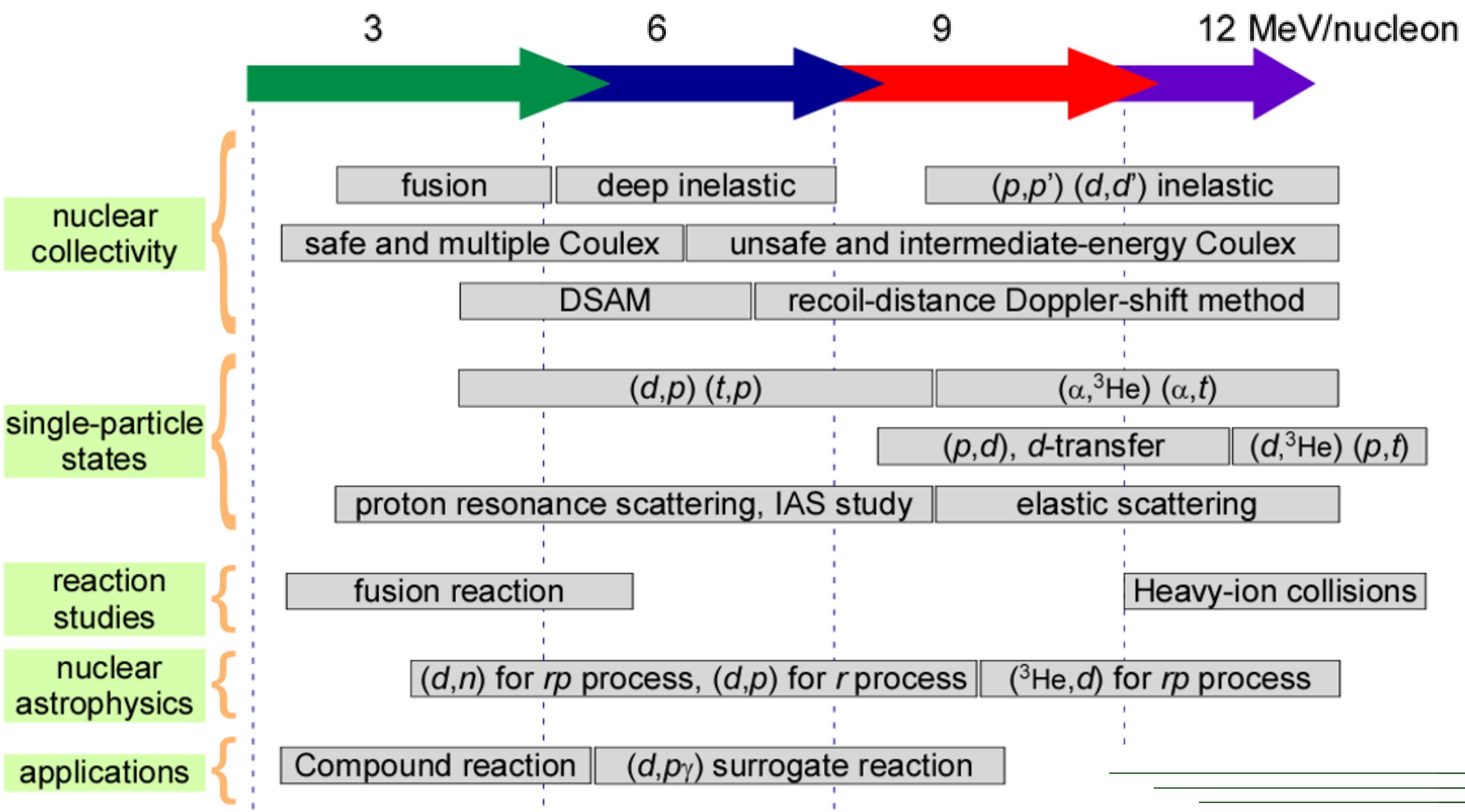
- Applications for the benefit of stockpile stewardship, materials science, medical research, and nuclear reactors (7.1, 7.2, 7.3)

Nuclear Physics: Exploring the Heart of Matter, NRC (2013)
reaffirmed by Long Range Plan (2015), RISAC report (2007)

ReA energy upgrade and key reactions

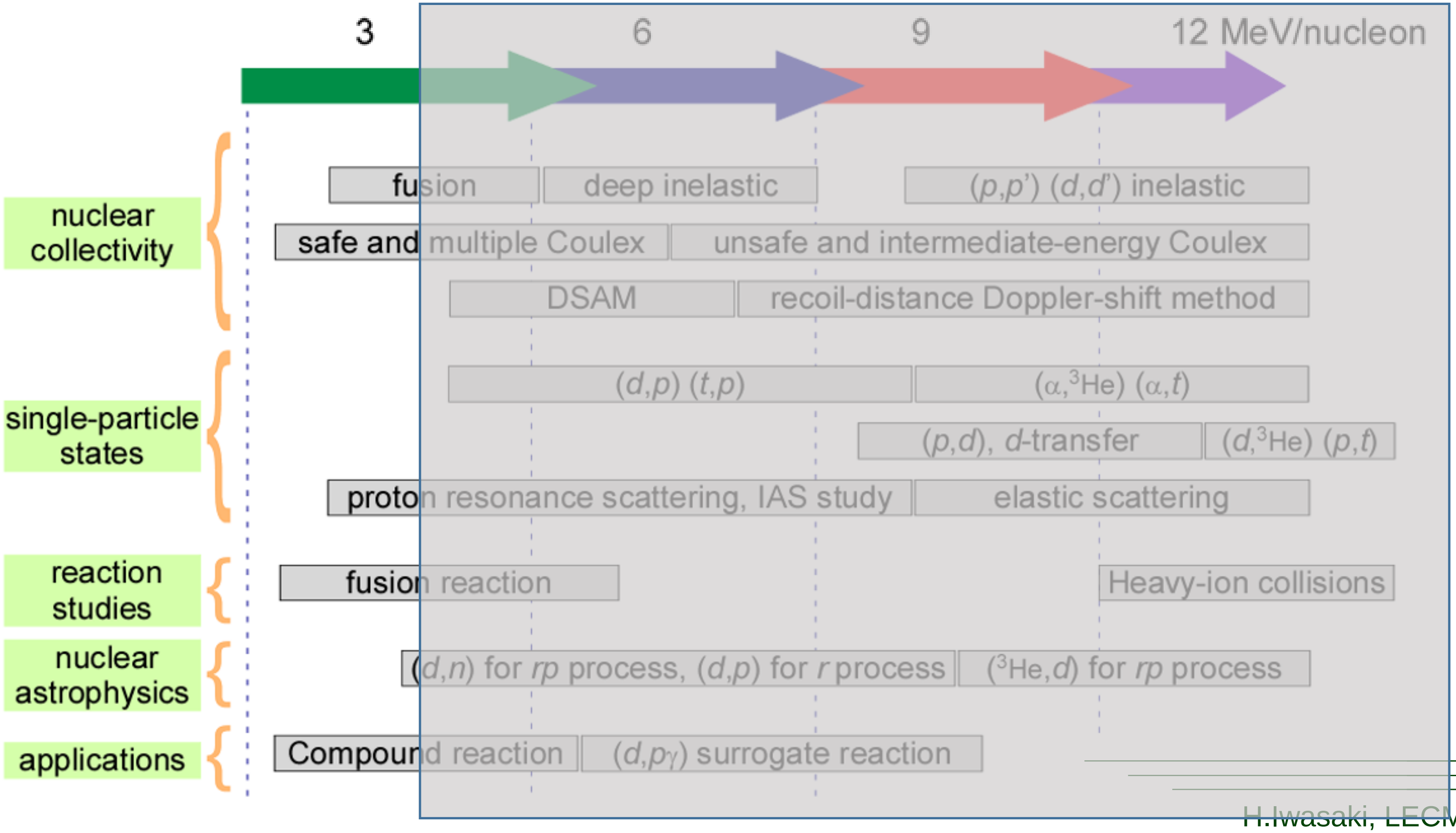
The ReA energy upgrade will provide unique beams to:

- facilitate reaction studies with well-established probes, mapping out the evolution of structural phenomena throughout the nuclear chart



From Coulomb barrier energies up to 12 MeV/nucleon

- **ReA3** – best suited for reaction studies of astrophysical interest
- **ReA6** – safe/multiple Coulomb excitation – nuclear collectivity
- **ReA9** and **beyond** – direct transfer reactions – shell evolution



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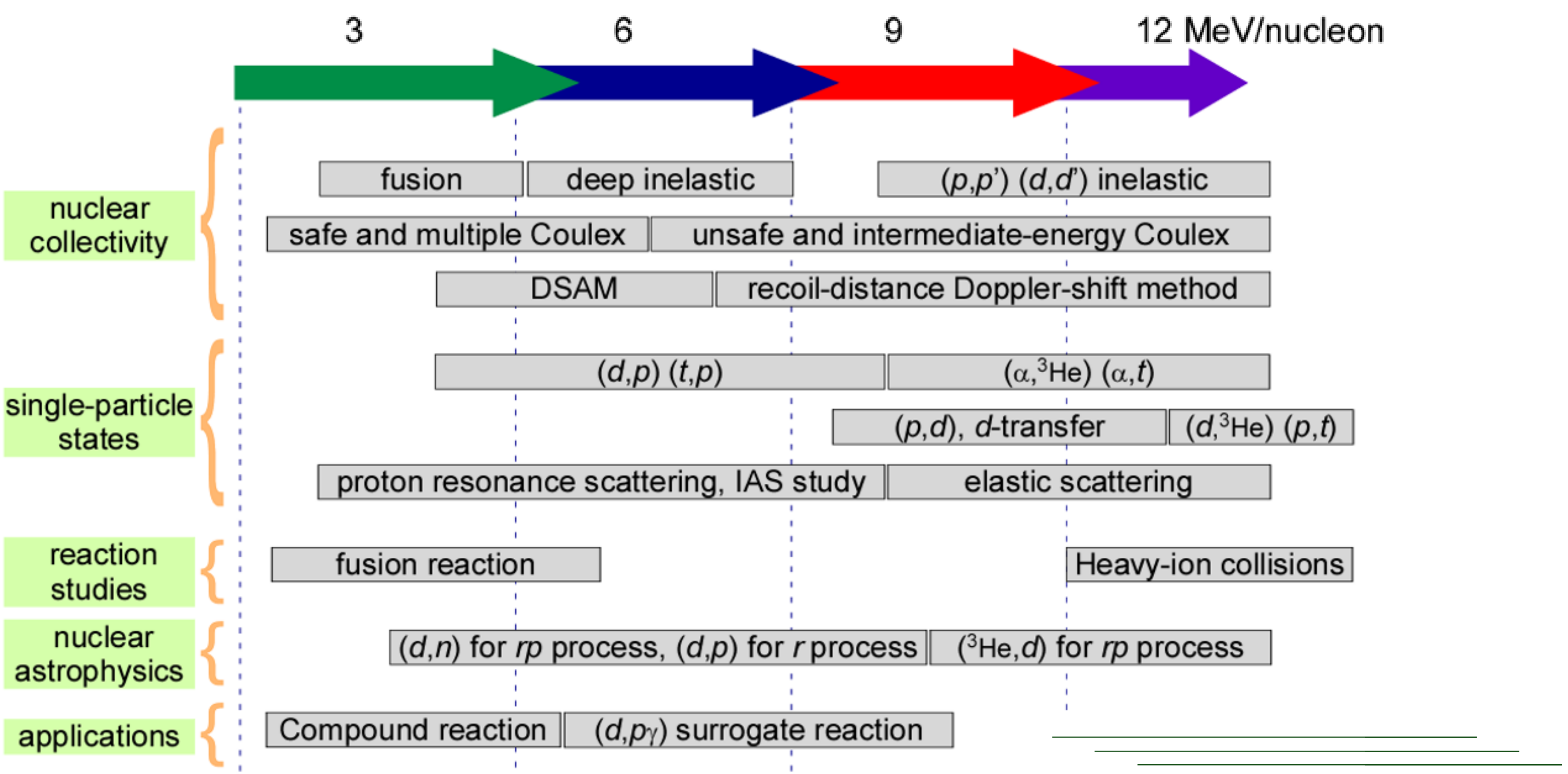
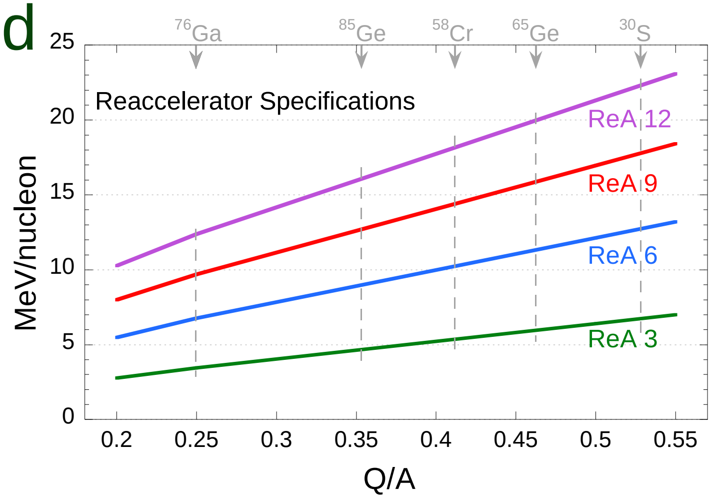
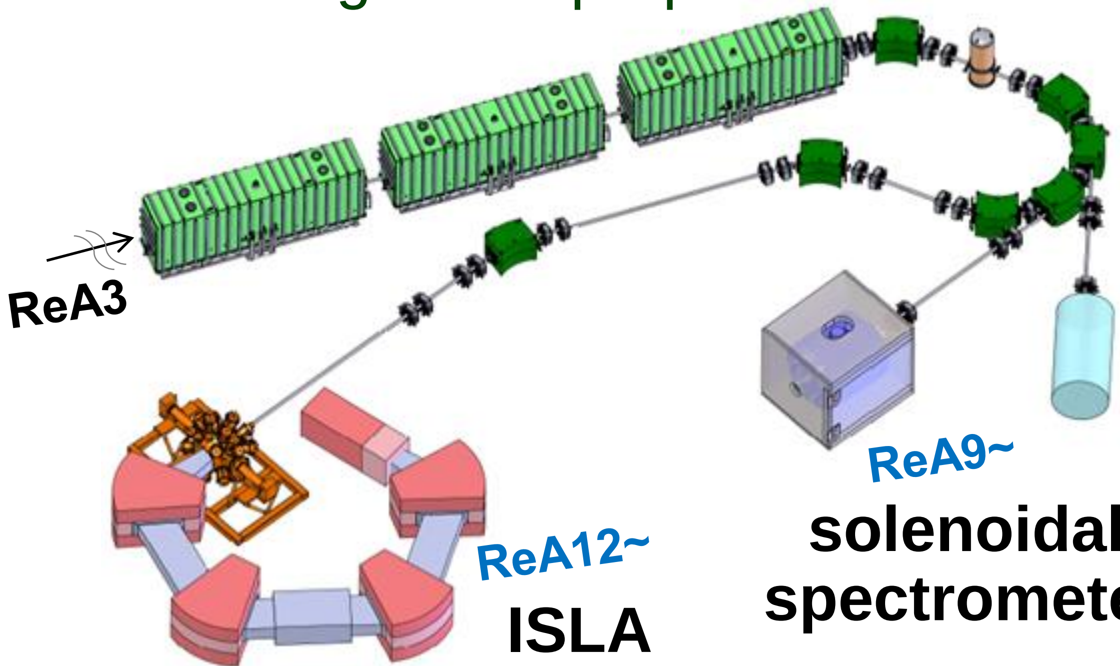
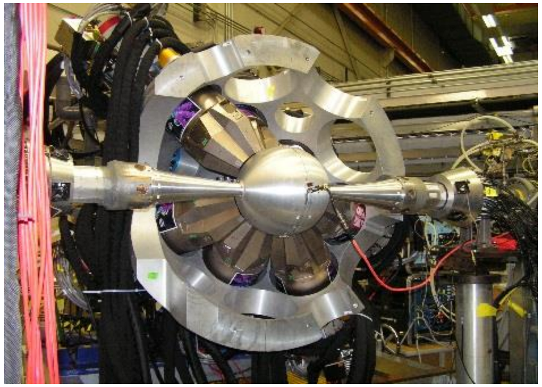


A vision of →ReA6→ReA9→ReA12

- The ReA energy upgrade will be realized by adding up to three cryomodules. ReAX provides at least X MeV/nucleon for neutron-rich beams with Q/A=0.25
- Start with three beam lines (space for many more exists): for ISLA, solenoidal spectrometer and general-purpose beam line



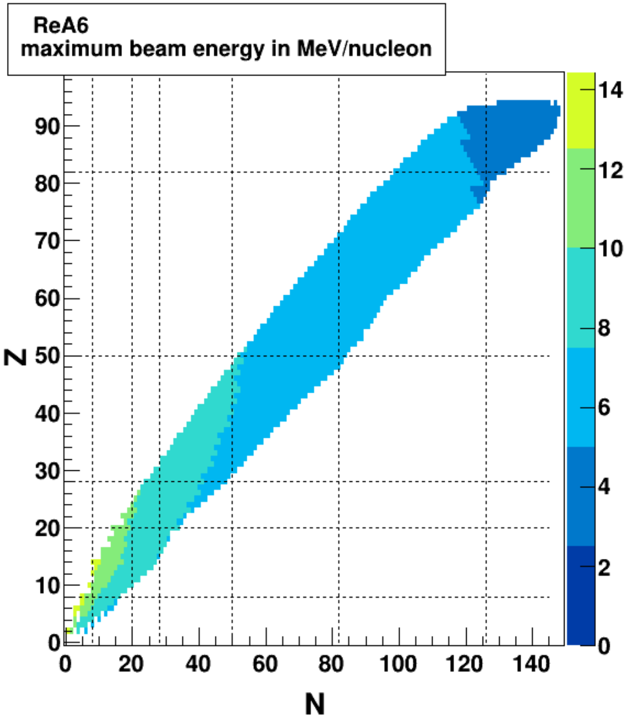




ReA6~
GRETINA/GRETA

ReA6: An important step for nuclear science

One cryomodule (ReA6) capable of accelerating ions with a charge-to-mass ratio of Q/A=0.25 up to 6 MeV/nucleon and Q/A=0.5 beyond 9 MeV/nucleon **will allow forefront science programs to be initiated at NSCL**



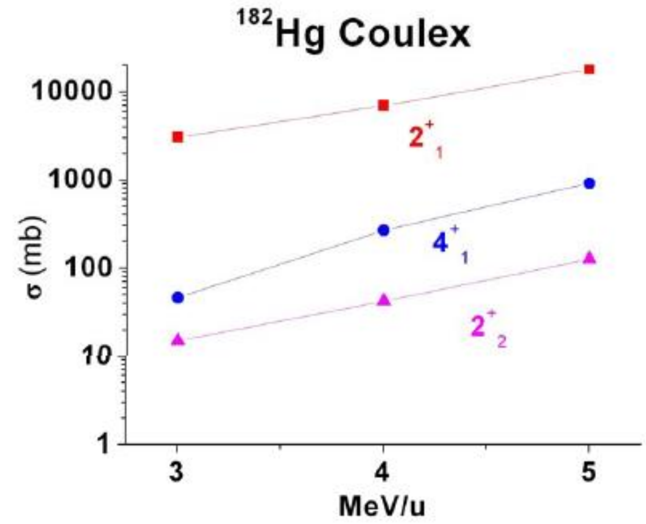
- ❑ Collectivity in medium-mass and heavy neutron-rich nuclei
- ❑ Single-particle states in proton-rich or light exotic nuclei
- ❑ Pair transfer via (*t*,*p*), (^{3}He,*p*)
- ❑ Mechanism for fusion-evaporation reactions
- ❑ Indirect studies for nuclear reaction rates relevant for astrophysics (*rp* process)

Users can perform measurements with ReA beams using powerful existing equipment and instruments
to take immediate advantage of the unique scientific capabilities

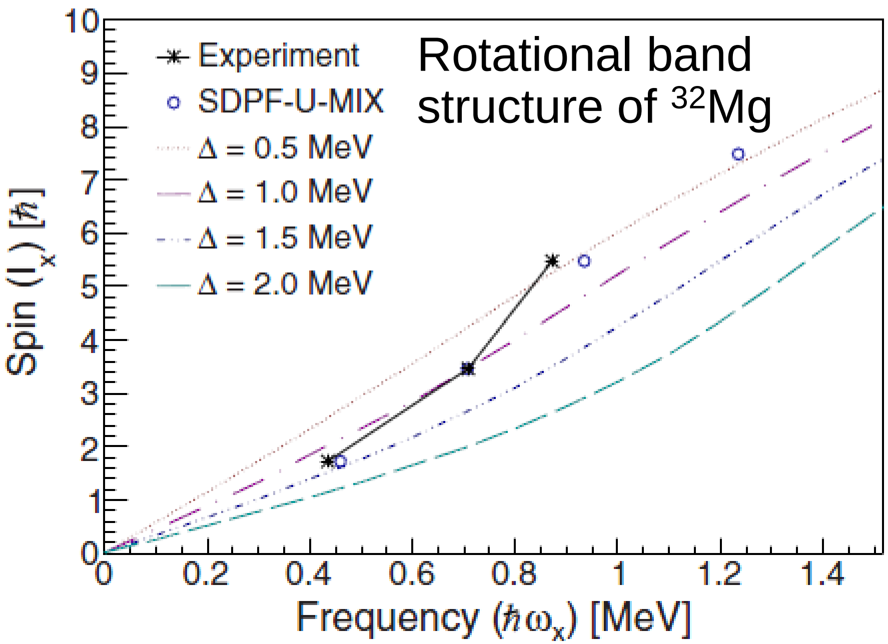
- ❑ GRETINA/GRETA
- ❑ Solenoidal spectrometer (AT-TPC/HELIOS)
- ❑ Various types of Si-arrays and TPC
- ❑ Coincident Fission Fragment detector, etc

Evolution of structural phenomena

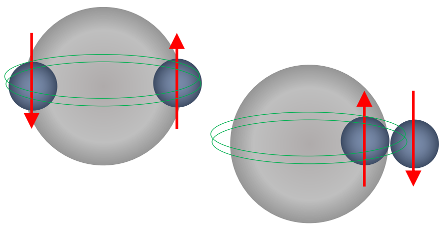
Enhanced Coulomb excitation cross sections at Coulomb barrier energies enable studies of collective excitations at moderate spin in neutron-rich nuclei, elucidating the interplay between collectivity, shell, and pairing effects



HIE-ISOLDE
CERN-2007-008



H.L.Crawford et al., PRC93, 031303(R) (2016)



Evolution of pairing in exotic nuclei

- at low densities (driplines)?··· (*t*,*p*)
- at high spins in n-rich nuclei?
  ··· *multiple Coulex, deep inelastic*
- at N=Z (p-n pairing)··· (^{3}He,*p*)

Nuclear shapes and astrophysical scenarios

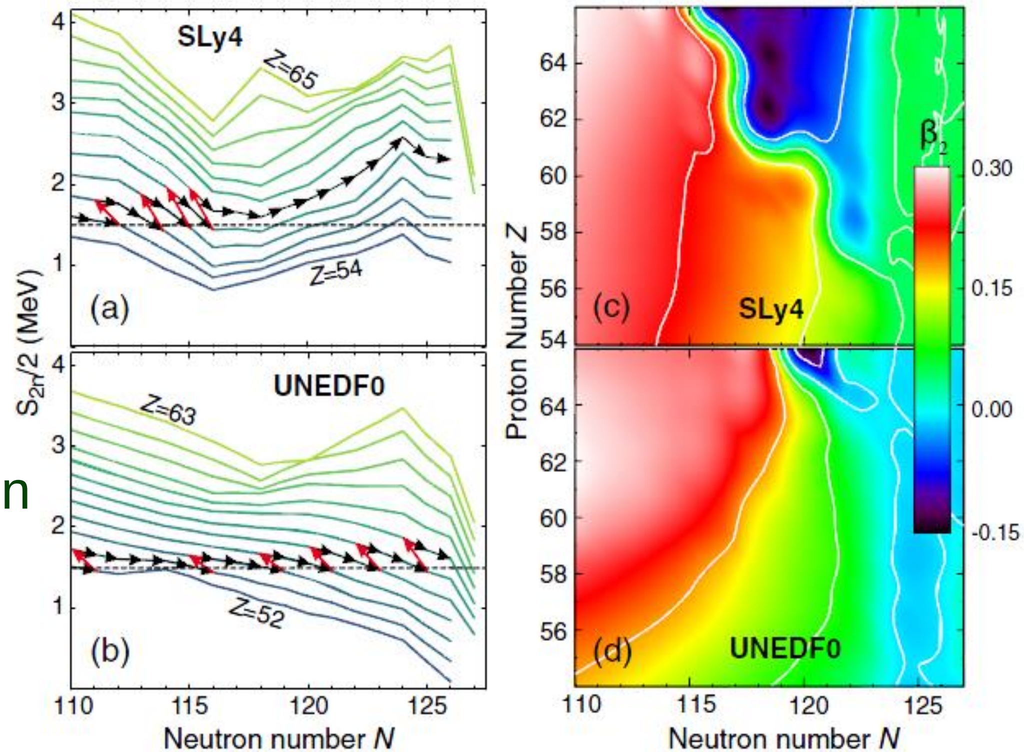
In regions around magic numbers, spherical shell closures and nuclear shape changes have a significant impact on nuclear masses, thereby affecting astrophysical scenarios such as the abundances and the origin of the heavy elements in the *r* process

Fig : SLy4 vs UNEDF0 for A~180

(left) half of S_{2n} around *r*-process path, (n, γ)-(γ,n) equilibrium

(right) quadrupole deformation

D.Martin et al., PRL116, 121101 (2016)



At ReA6, multiple Coulomb excitation and lifetime measurements can be performed to determine nuclear shapes of medium-mass nuclei and to probe the structure around N=82, a region relevant to the 2nd *r*-process peak at A~130

ReA9~

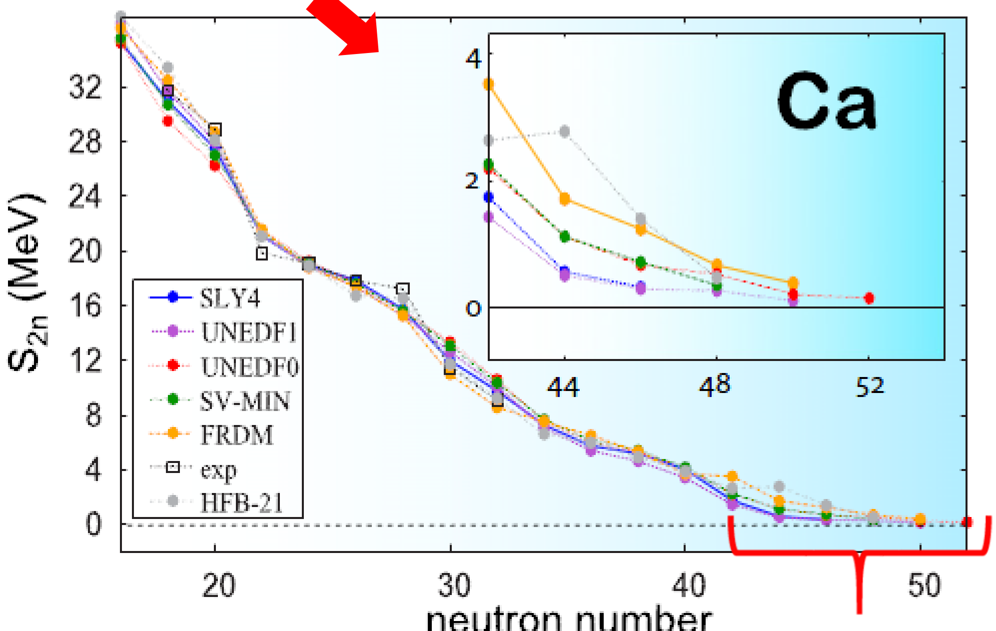
Beyond ReA6: Single-particle states

ReA experiments can characterize shell structure on the microscopic level, refining modern structure theory that incorporates realistic two- and three-body forces and continuum effects → predictions for very exotic nuclei

Evolution toward ^{60}Ca and ^{70}Ca

along Z=20 isotopes

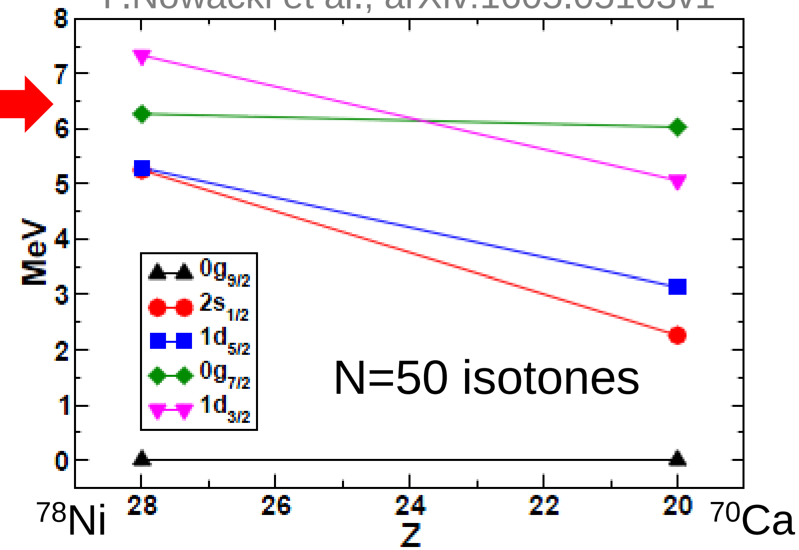
along N=50 isotones



C.Forssen et al.,
Phys. Scr. T152, 014022 (2013)

all weakly bound (halo, Efimov, …)

F.Nowacki et al., arXiv:1605.05103v1



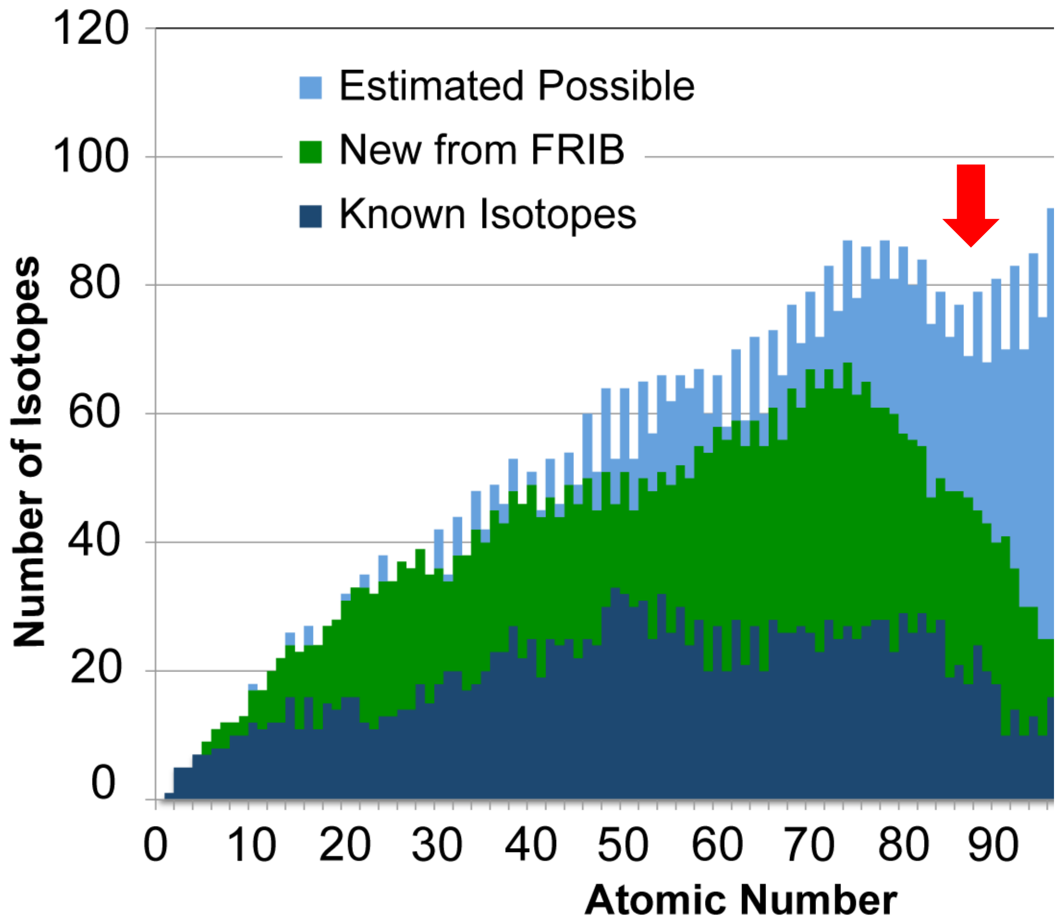
Studies with better suited probes, e.g. (α,t) (α,^{3}He), for heavier systems above A=100

Isotope discovery potential at FRIB

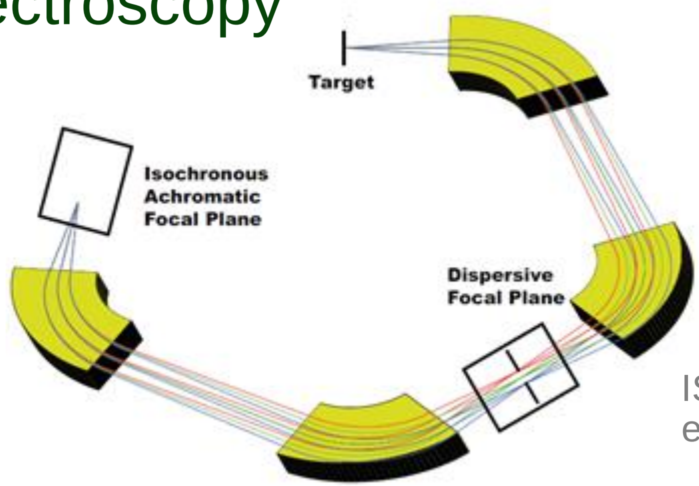
ReA12

Excellent opportunities to synthesize new neutron-rich heavy nuclei at FRIB, using neutron-rich projectiles and targets

ISLA at ReA12 will provide a direct identification of reaction products and also facilitate decay and in-beam spectroscopy



Estimated Possible : based on J.Erler et al., Nature 486, 509 (2012)

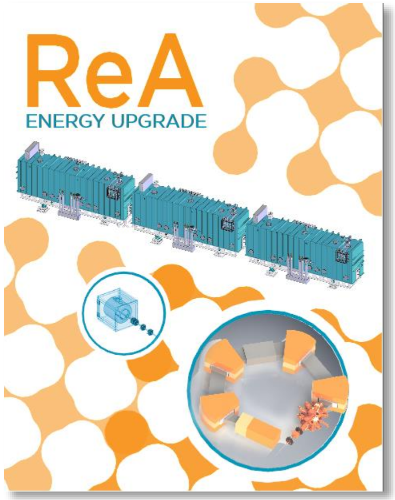


ISLA whitepaper (2015)
ed. M.Amthor and D.Bazin

Summary

The ReA energy upgrade will provide unique beams to:

- facilitate reaction studies with well-established probes, mapping out the evolution of structural phenomena
- reach medium- and high-spin states in neutron-rich nuclei, elucidating the interplay between neutron excess and angular momentum
- extend the new-isotope discovery potential at FRIB to heavier neutron-rich nuclei
- address broad topics of nuclear astrophysics and societal applications of nuclear science



- ❑ **It is important to have ReA6 before FRIB begins operation. There is a tremendous opportunity for forefront science at NSCL.**
- ❑ **In the longer term, the upgrade to ReA12 is needed to realize the full science potential of FRIB. ISLA will be a critical device at ReA12.**