NP Low Energy Facilities and the SBIR/STTR Program

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U.S. DEPARTMENT OF ENERGY | Office of Science

Acknowledgements

Many thanks for slides and input from

- Guy Savard (ANL)
- Georg Bollen, Thomas Glasmacher, Dave Morrissey, Greg Severin, Brad Sherrill (FRIB/MSU)
- Paul Fallon, Jackie Gates, Augusto Macchiavelli (LBNL)

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Thank you

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Outline

- Low-energy nuclear physics: Context and Science
- DOE Facilities: Current and Future
  - ATLAS/CARIBU
  - LBNL/TAMU/TUNL
  - FRIB
- Instrumentation for low-energy nuclear physics
- Summary

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Low Energy Community Meeting 2017

- 210+ members of the low-energy nuclear physics community -- ATLAS, NSCL, ARUNA and future FRIB users
- 5 satellite workshops, 12 working group sessions and 4 plenary sessions
  - Overviews of ATLAS/CARIBU, FRIB, NSCL, ARUNA
  - Working groups and workshops focused on instrumentation and science programs
  - FRIB Day 1 Science workshop

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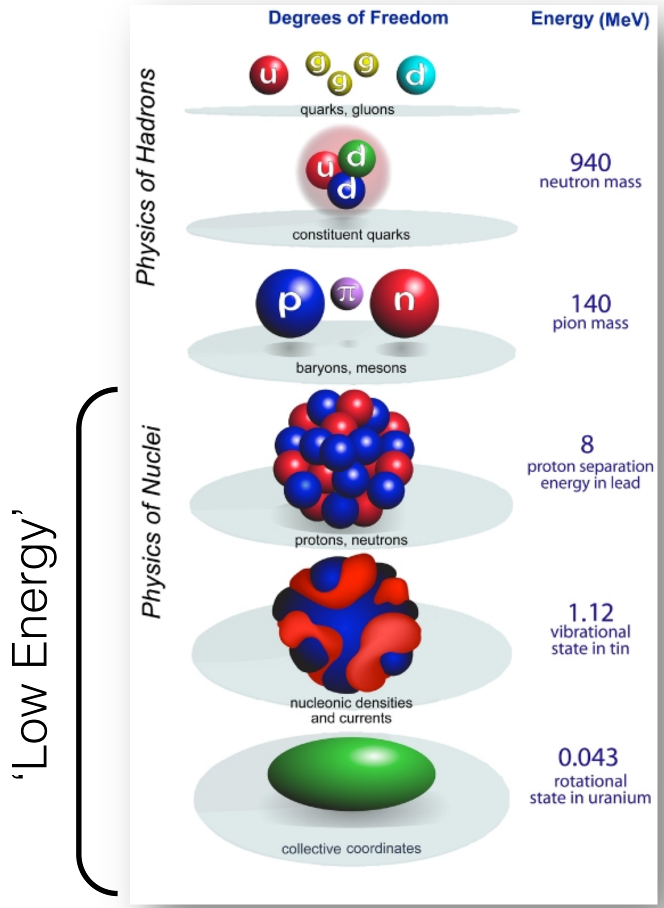
https://indico.fnal.gov/conferenceProgram.py?confId=14088

Low Energy Nuclear Physics



- The energy scale for low-energy nuclear physics is of order few MeV – *nuclear binding*
- Physics encompasses nuclear structure, decay, reactions and limits of nuclear chart
- Allows a strong connection societal applications (energy, medicine, security, …)

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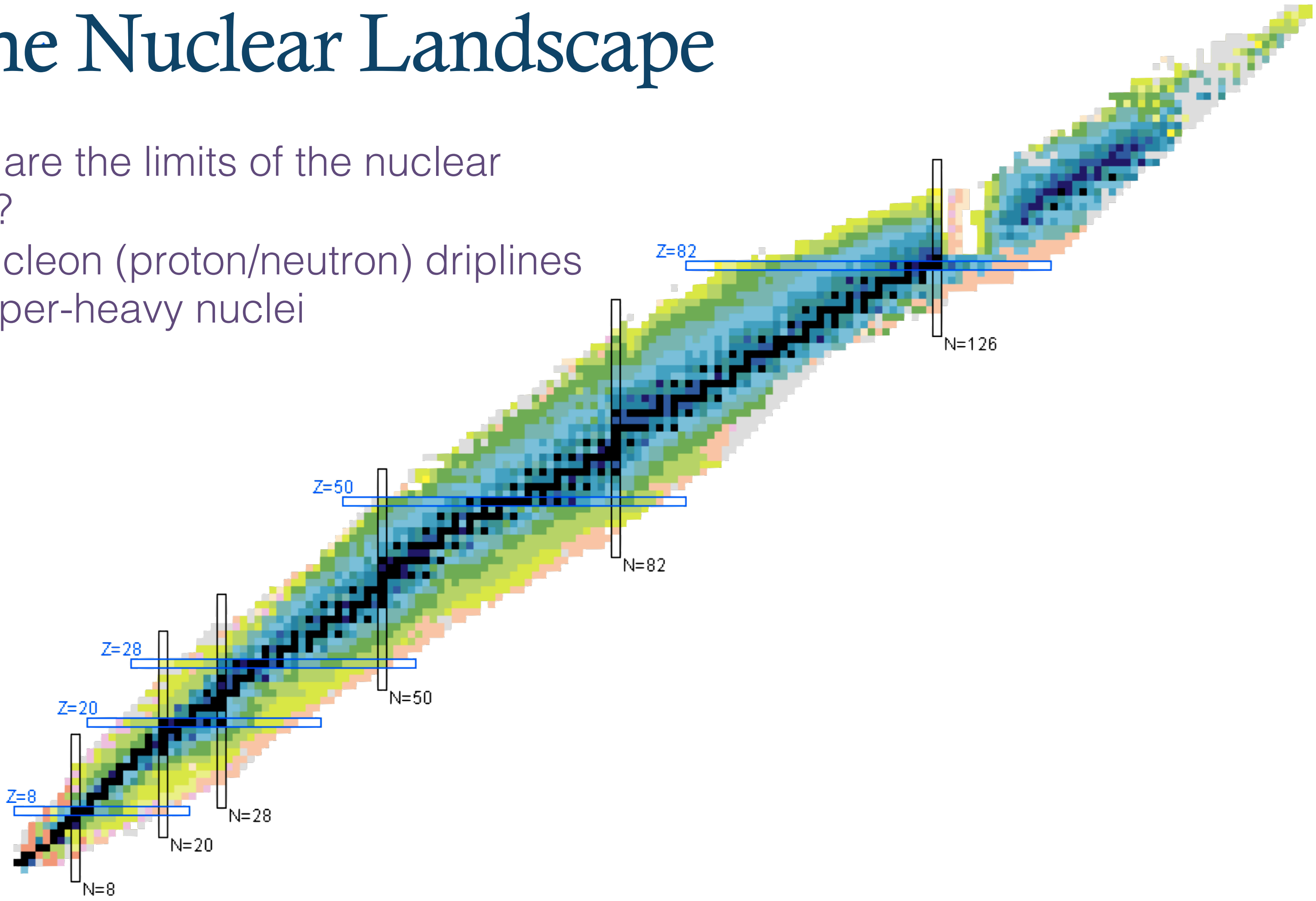
The Nuclear Landscape

What are the limits of the nuclear chart?

- Nucleon (proton/neutron) driplines
- Super-heavy nuclei



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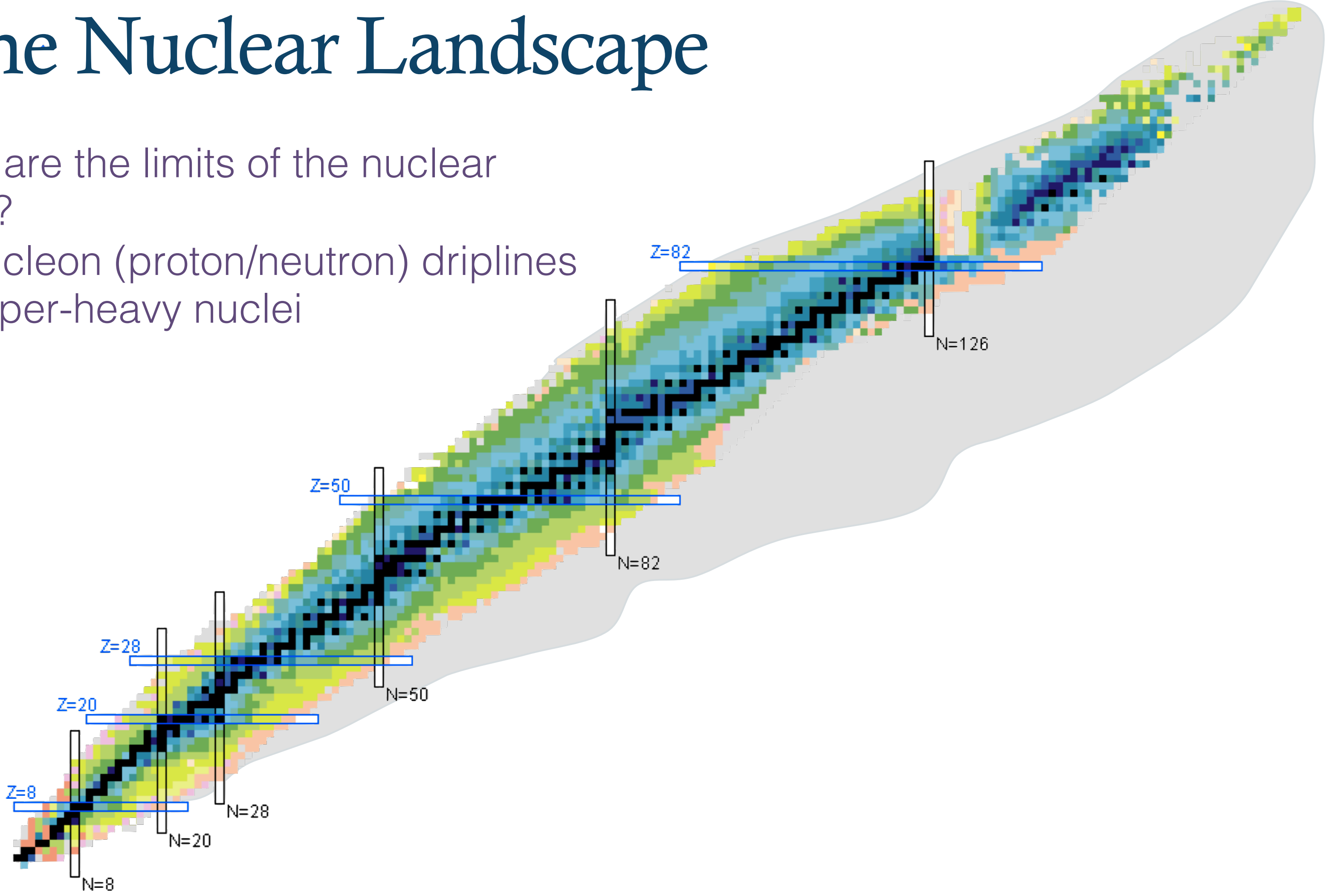

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The Nuclear Landscape

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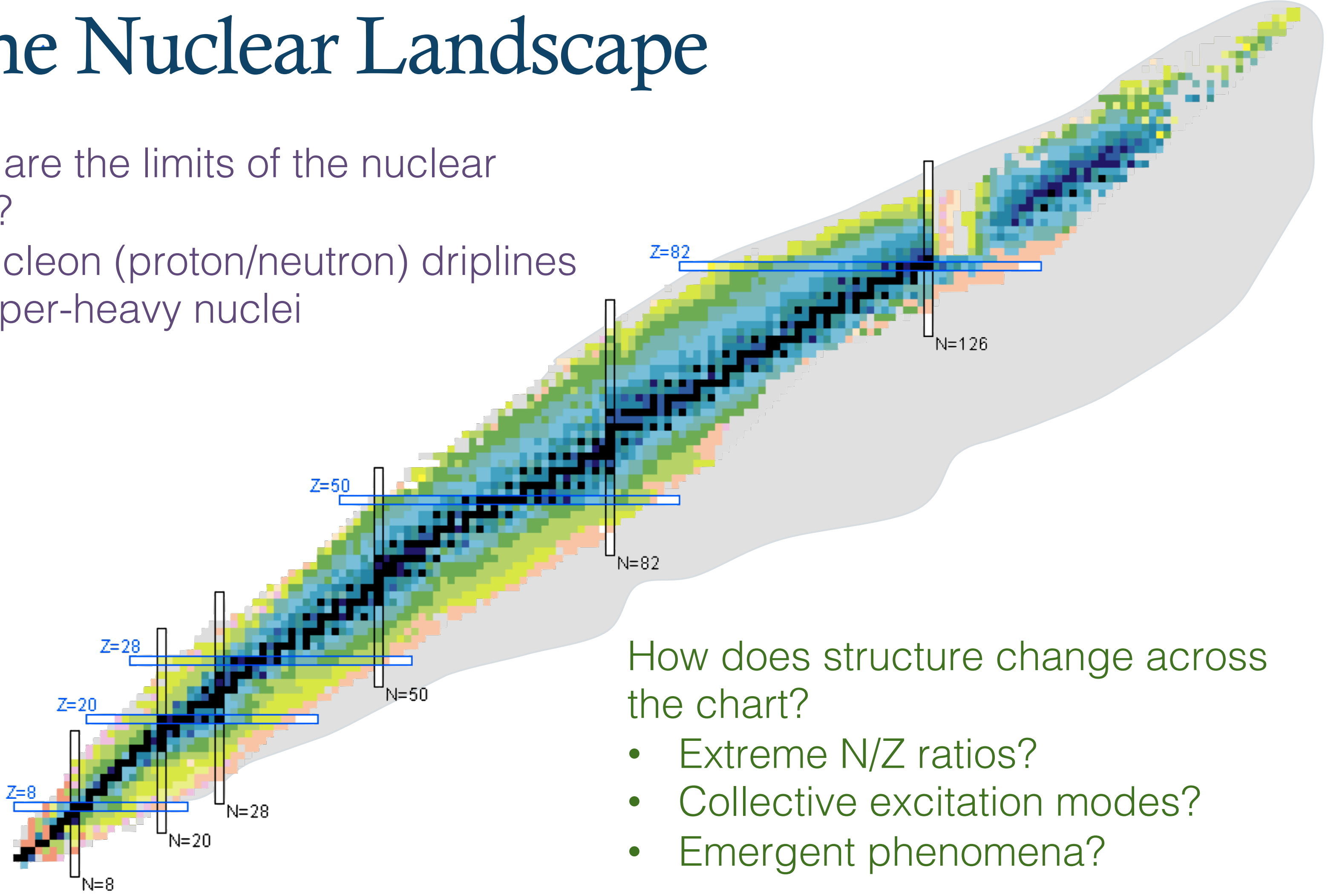

How does structure change across the chart?

- Extreme N/Z ratios?
- Collective excitation modes?
- Emergent phenomena?

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Driving Science Questions

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 interactions 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 from NSAC Long Range Plan 2015			
How are nuclei made and organized? What is the nature of dense nuclear matter?	Where do nuclei and elements come from? What combinations of neutrons and protons can form a bound atomic nucleus? How do neutrinos affect element synthesis?	Are neutrinos their own antiparticles? Why is there more matter than antimatter in the present universe?	What are practical and scientific uses of nuclei?

Overarching questions are answered by rare isotope research

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

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
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

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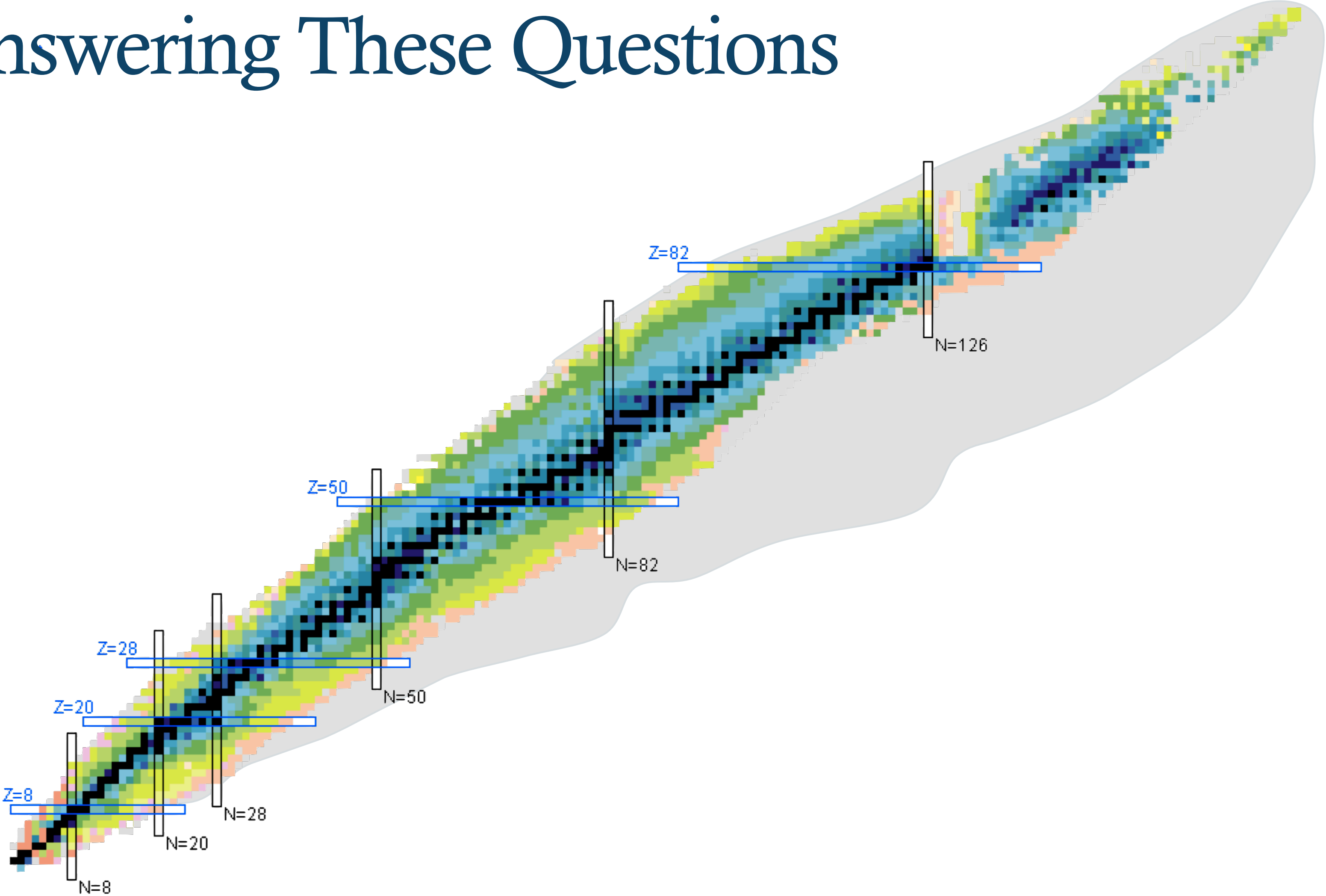
Answering These Questions



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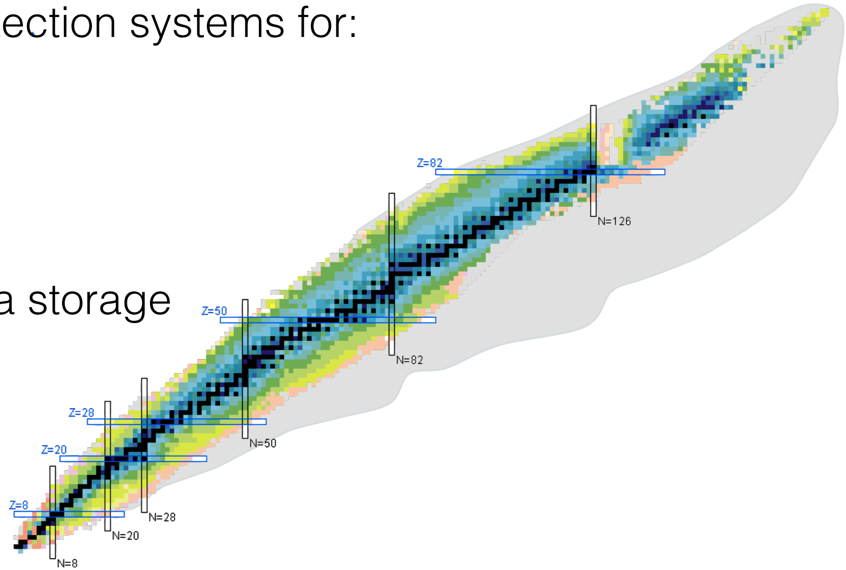
Answering These Questions

1. Accelerator facilities
   - Diverse capabilities to deliver beams of stable and radioactive ions, at energies ranging from ~ 100 keV to GeV
2. Advanced Detectors and Instrumentation
   - High efficiency, high resolution detection systems for:
     - Light charged particles
     - Heavy charged fragments
     - Gamma-rays
     - Neutrons
   - Data acquisition, software and data storage



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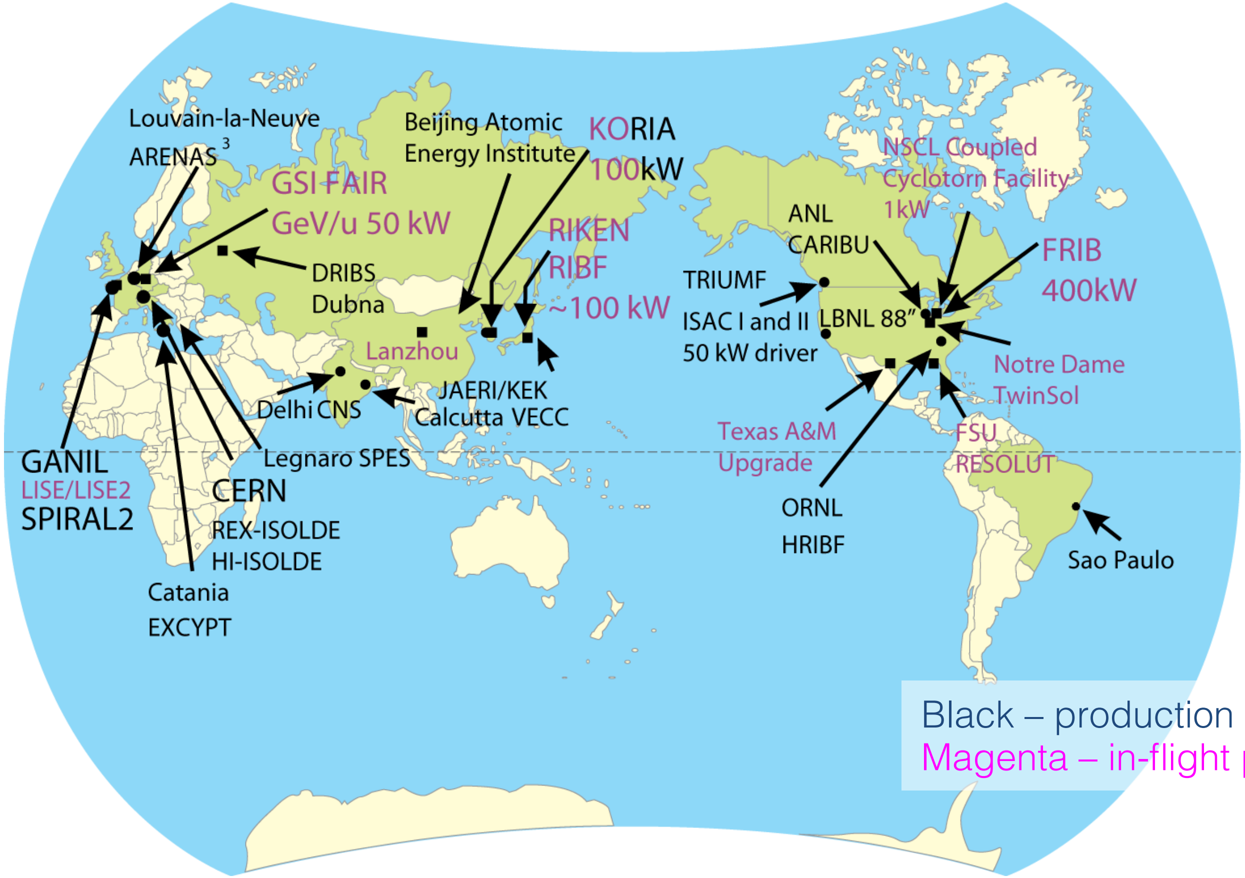
Rare Isotopes Facilities Internationally



Black – production in target
Magenta – in-flight production

From Brad Sherrill - MSU

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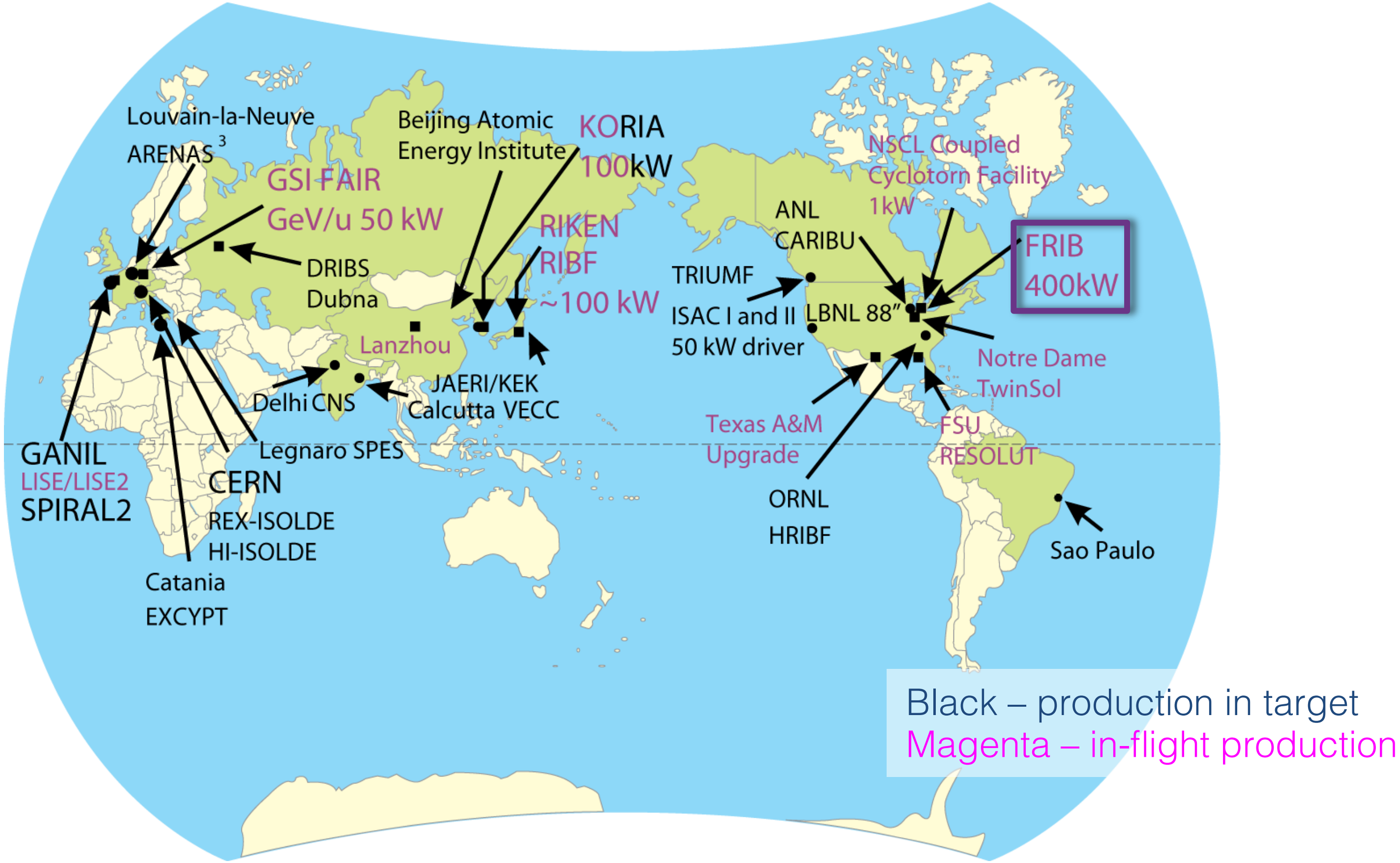
Rare Isotopes Facilities Internationally



From Brad Sherrill - MSU

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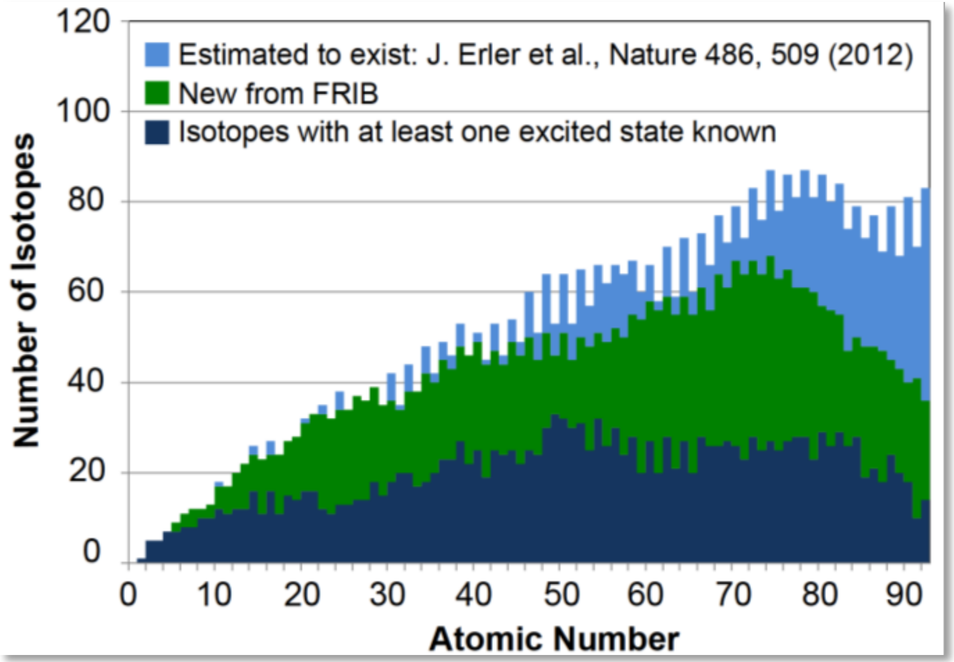
Approaching the FRIB Era

- First physics at FRIB is rapidly approaching; discovery potential is huge



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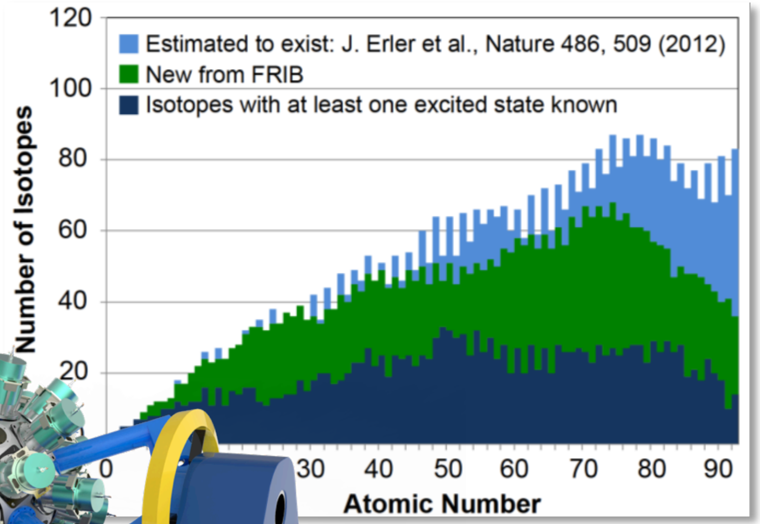
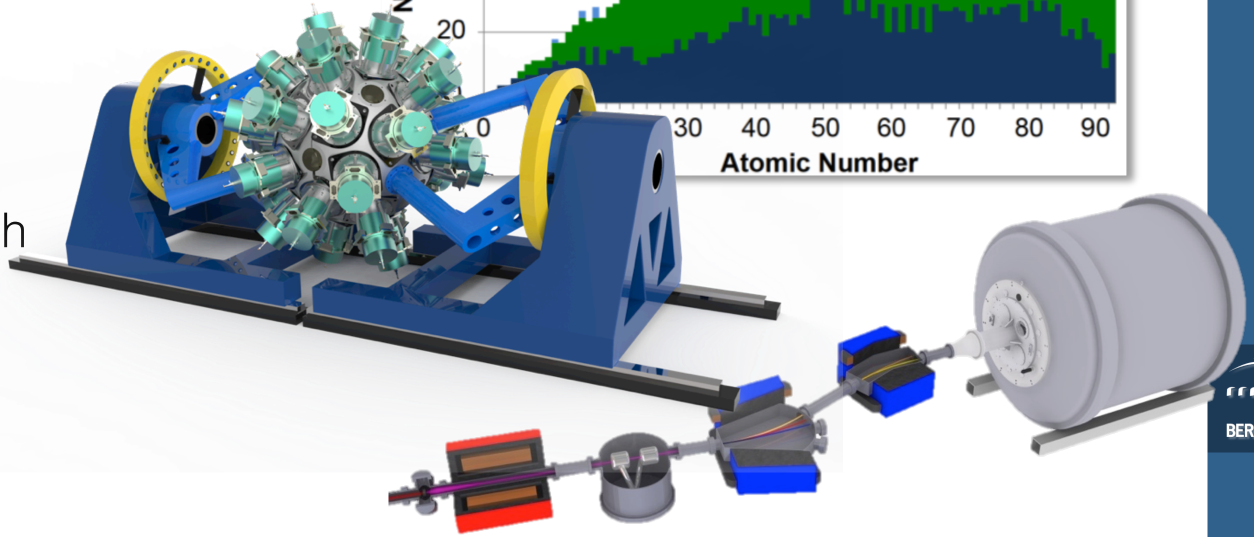
Approaching the FRIB Era

- First physics at FRIB is rapidly approaching; discovery potential is huge
- Community is preparing with investment and advances in instrumentation with impacts across all our facilities





US Low Energy Facilities

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Low Energy Nuclear Physics Facilities

DOE National User Facilities

- Argonne Tandem-Linac Accelerator System (ATLAS) – http://www.phy.anl.gov/atlas/facility
    - *High-intensity stable beams*
    - *Radioactive beam program with stopped and re-accelerated fission products and in-flight beams*
- Facility for Rare Isotope Beams (FRIB) – http://frib.msu.edu
    - *World-leading facility under construction at MSU*
    - *400 kW heavy-ion SRF line; > 200 MeV/u*
    - *Rare isotopes produced by fragmentation and in-flight fission*
    - *Fast, stopped, and reaccelerated beams*

NSF User Facilities

- National Superconducting Cyclotron Laboratory – http://nscl.msu.edu
    - *In-flight rare isotope beam production*
    - *Fast, stopped, and reaccelerated beams*

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FRIB

NSCL

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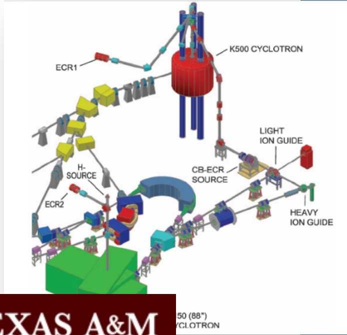
Low Energy Nuclear Physics Facilities

Other DOE Facilities (Local Use)

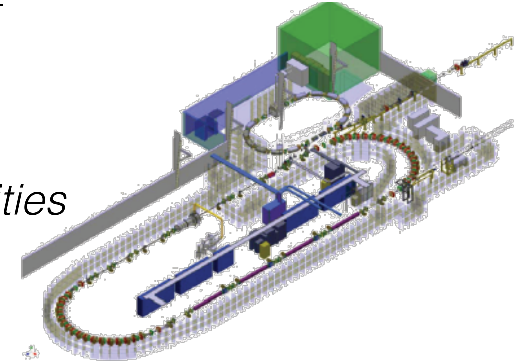
- LBNL 88 Inch Cyclotron – http://cyclotron.lbl.gov
  - *Basic and applied research with stable beams*
  - *Local program focused on heavy elements and nuclear data measurements*



TEXAS A&M UNIVERSITY

- Texas A&M Cyclotron Institute – http://cyclotron.tamu.edu
  - *Nuclear physics research with stable and radioactive re-accelerated beams*

- Triangle-Universities Nuclear Laboratory (TUNL) – http://www.tunl.duke.edu
  - *High Intensity Gamma Source (HIGS)*
  - *Laboratory for Experimental Nuclear Astrophysics*
  - *Tandem Van de Graaff accelerator – neutron capabilities*



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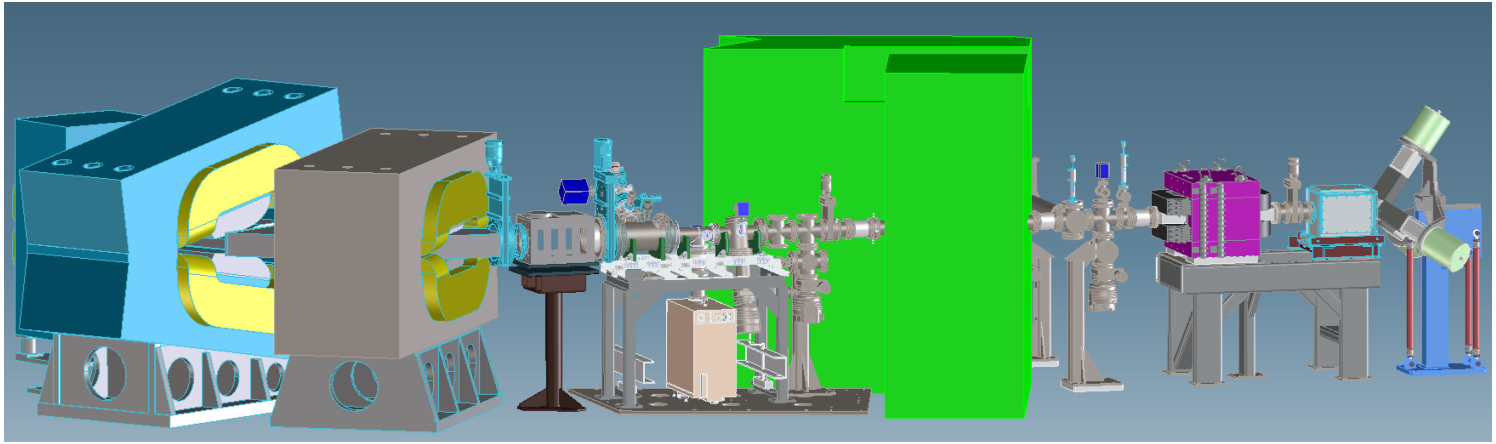
LBNL 88 Inch Cyclotron

- Local program at the 88” is centered on heavy elements, and measurements relevant to the nuclear data program
- Neutron beam capabilities in Cave0 have extended possibilities
- Heavy element mass identification underway with FIONA



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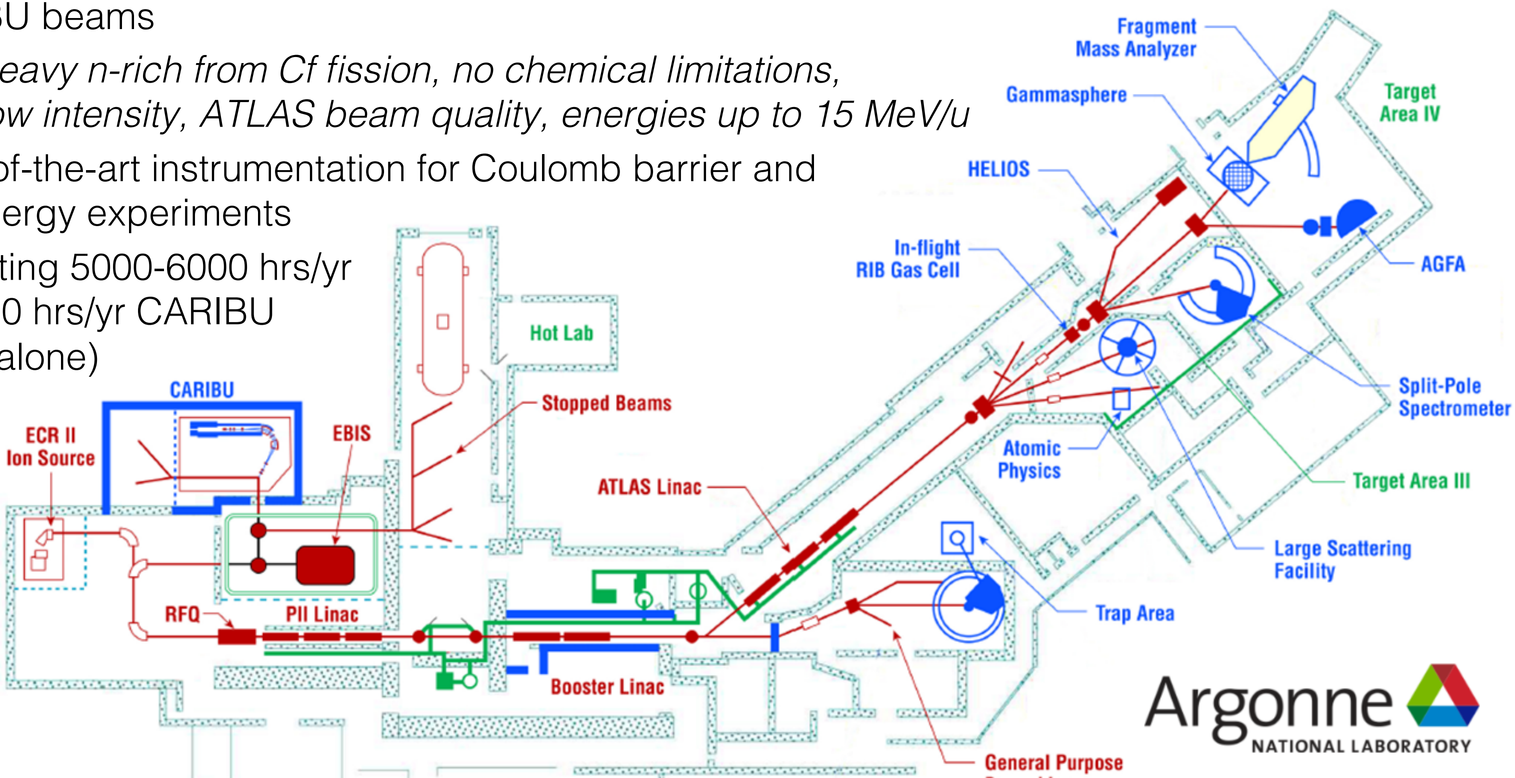
ATLAS/CARIBU Facility: Overview

- Stable beams at high intensity and energy up to 10-20 MeV/u
- Light in-flight radioactive beams
  - *light beams, no chemical limitations, close to stability, acceptable beam properties*
- CARIBU beams
  - *heavy n-rich from Cf fission, no chemical limitations,*
    low intensity, ATLAS beam quality, energies up to 15 MeV/u
- State-of-the-art instrumentation for Coulomb barrier and low-energy experiments
- Operating 5000-6000 hrs/yr (+ 2000 hrs/yr CARIBU stand alone)



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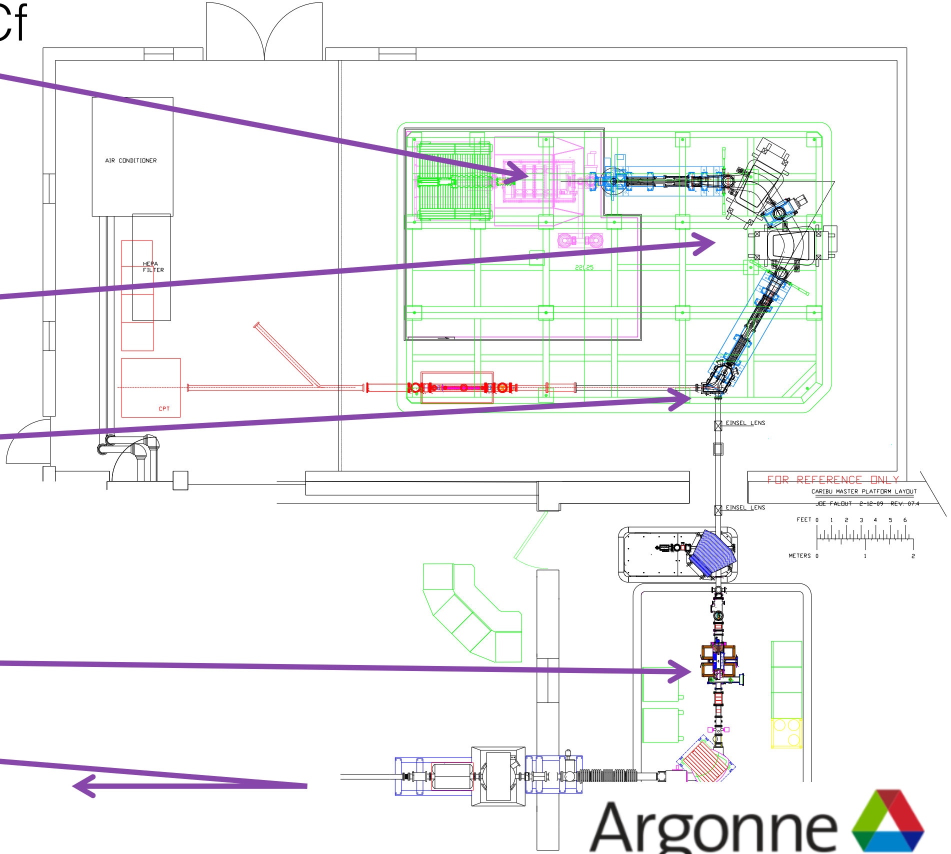
CARIBU Beams for ATLAS

- **Production:** 'Ion source' is ^{252}Cf source inside gas catcher
  - Thermalize fission fragments
  - Extract all species quickly
  - Form low emittance beam
- **Selection:** Isobar separator
- **Delivery:** Beamlines and preparation
  - Switchyard
  - Low-energy buncher and beamlines
  - Charge breeder to increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics



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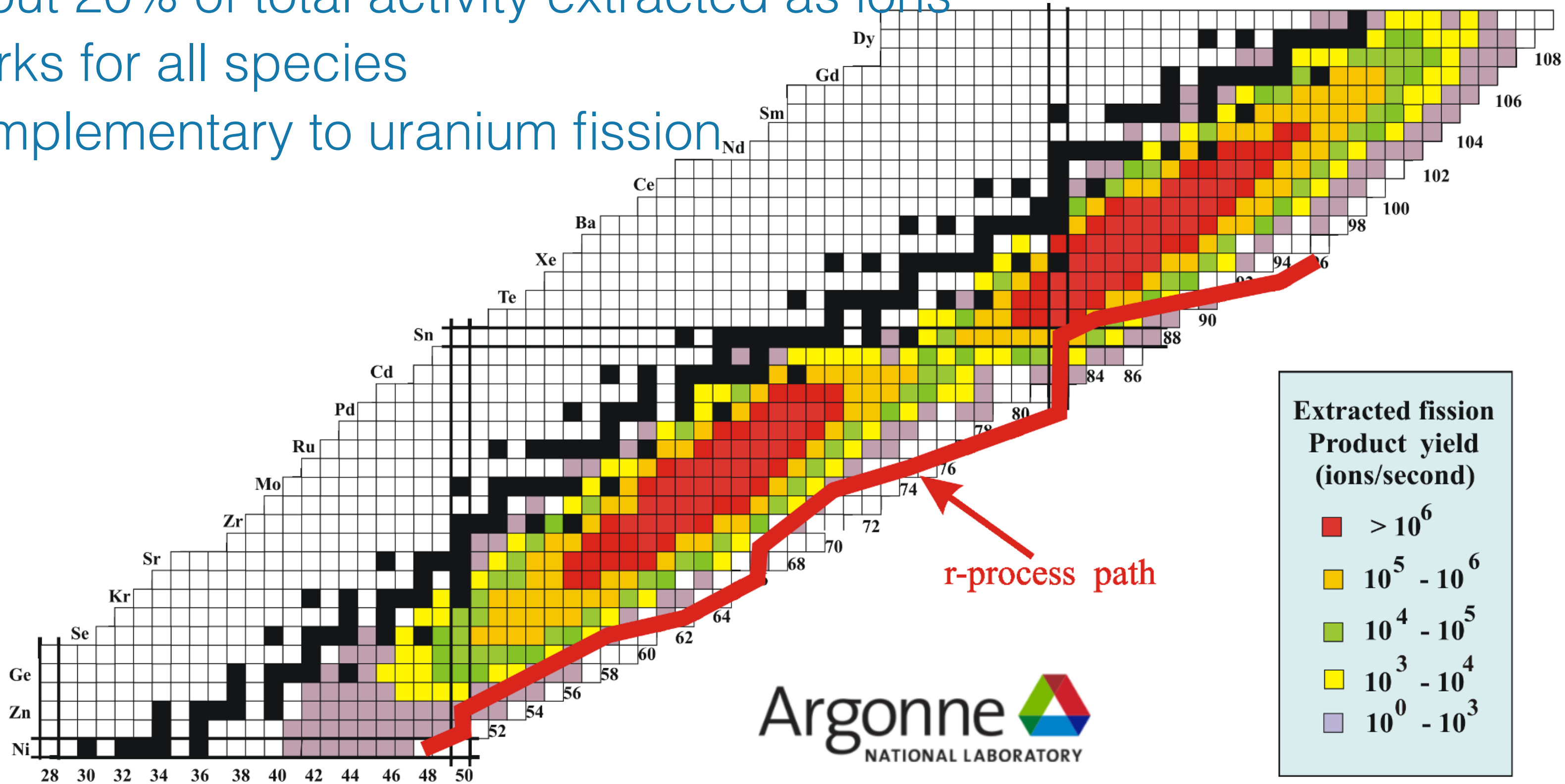
CARIBU Beams for ATLAS

- “Thin” 1 Ci ^{252}Cf source
- About 20% of total activity extracted as ions
- Works for all species
- Complementary to uranium fission



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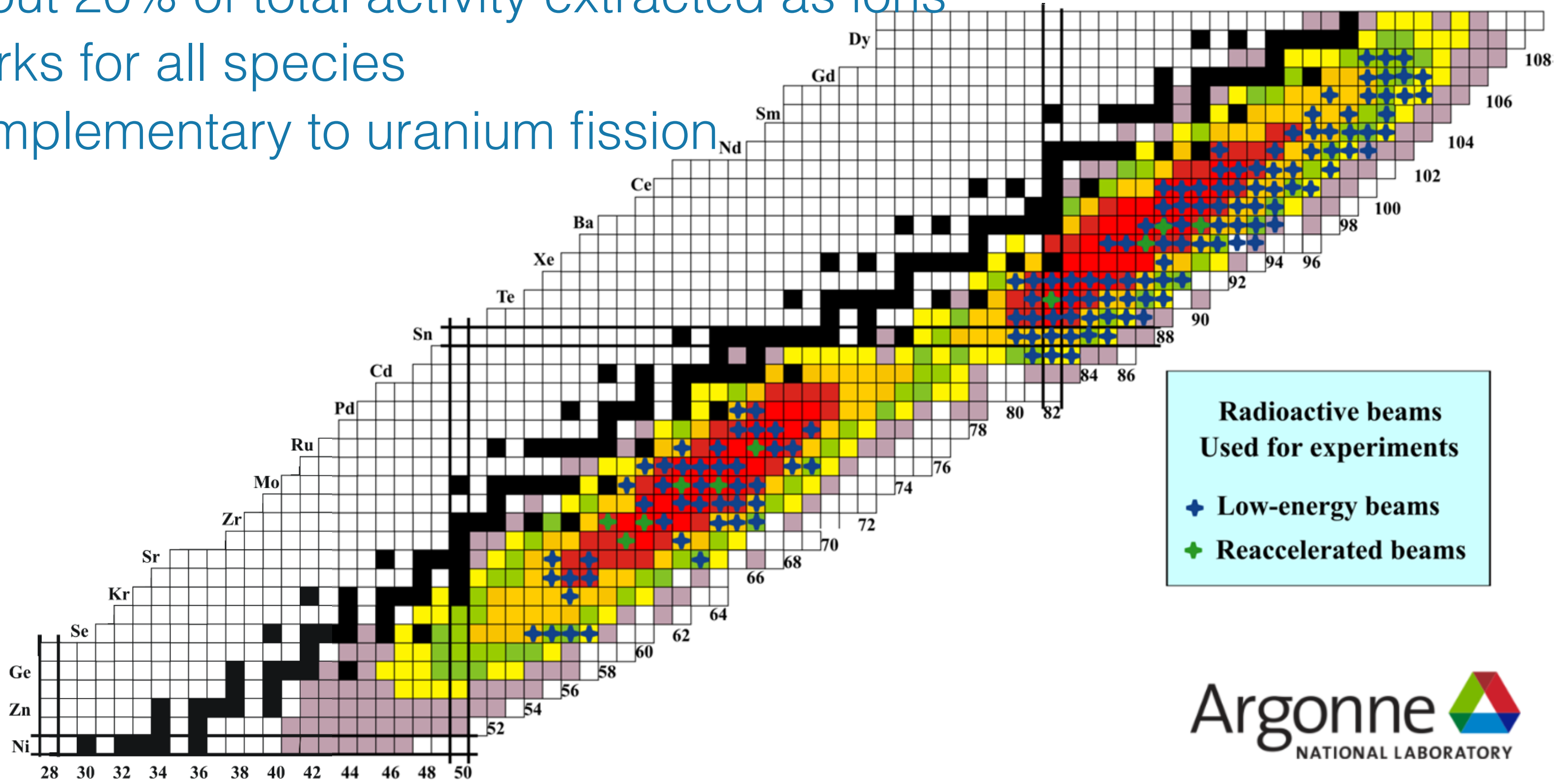
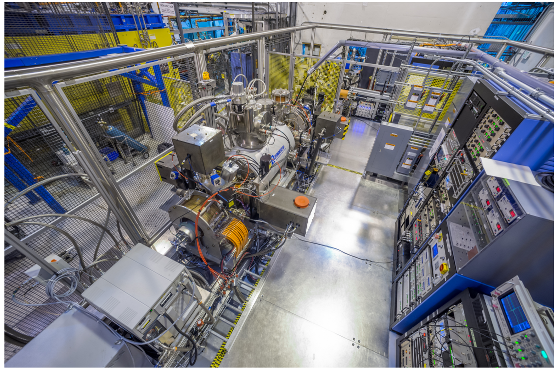


Enhancing Science at CARIBU

- EBIS Charge Breeder
  - Replaced ECR-Charge breeder for improved breeding efficiency and reduced beam contamination
  - Achieved first beam May 6, 2016



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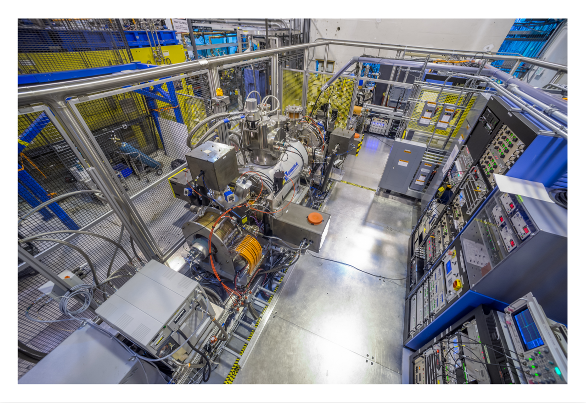
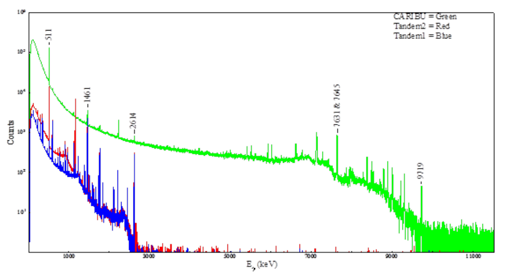


- Low-Background Low-Energy Area for CARIBU



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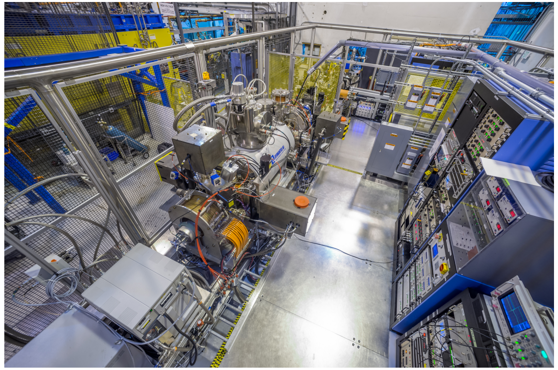

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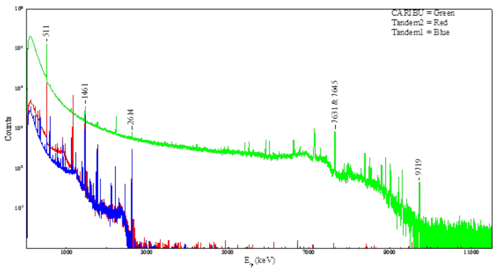
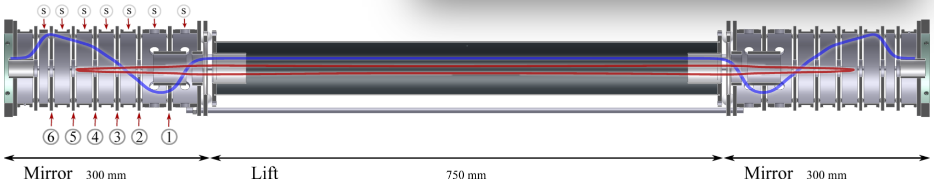


- CARIBU MR-TOF
  - Beam purification



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ATLAS Beams

- Stable beams (protons to Uranium)
  - up to 10 pmA, limited by ion source performance and radiation safety
  - Pulse separation of 82 ns or n X 82 ns with n=1, 2, 3, …
  - Pulse timing down to ~100 ps
  - Energy range from ~ 0.5 MeV/u up to 10-20 MeV/u depending on mass

Unique capabilities worldwide + coupled to unique instruments

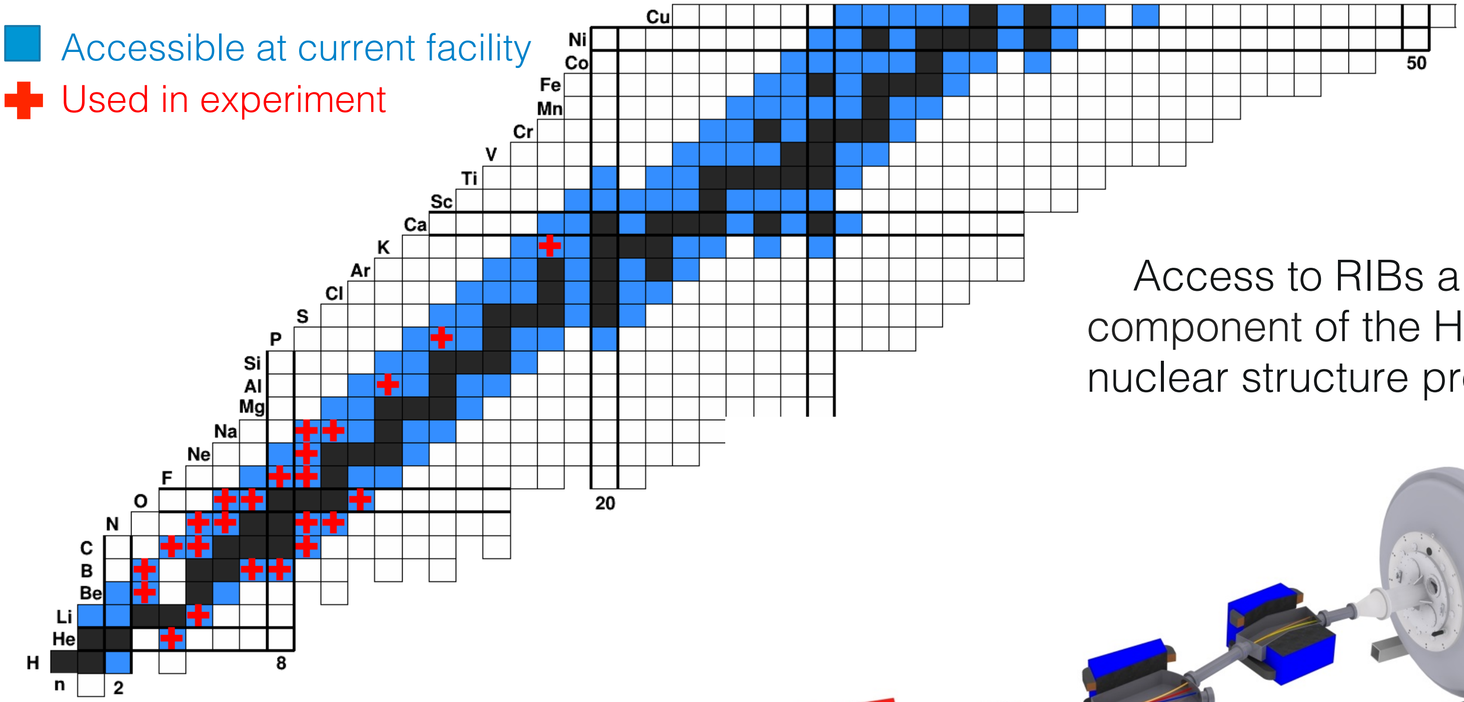
- CARIBU beams have similar properties …. but much lower intensity
  - All species, even the most refractory, are extracted efficiently

Most of the CARIBU beams (species and energy) are not available anywhere else.

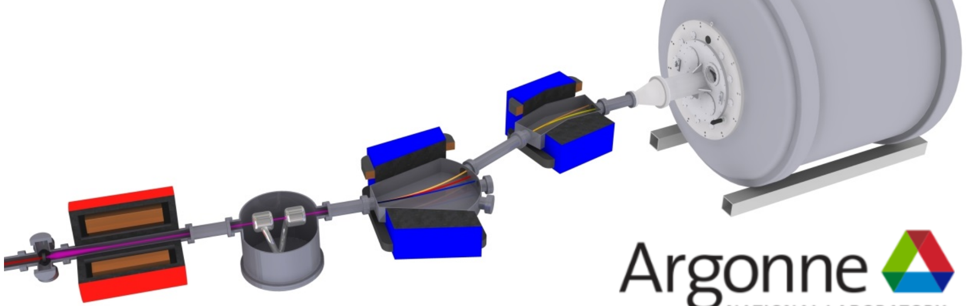
- In-flight radioactive beams: all light species, close to stability, but some compromises between beam properties, intensity and purity

A few other facilities worldwide can produce these beams but none have the ATLAS experimental equipment suite (e.g. HELIOS).

ATLAS: In-flight Radioactive Beams



Access to RIBs a key component of the HELIOS nuclear structure program



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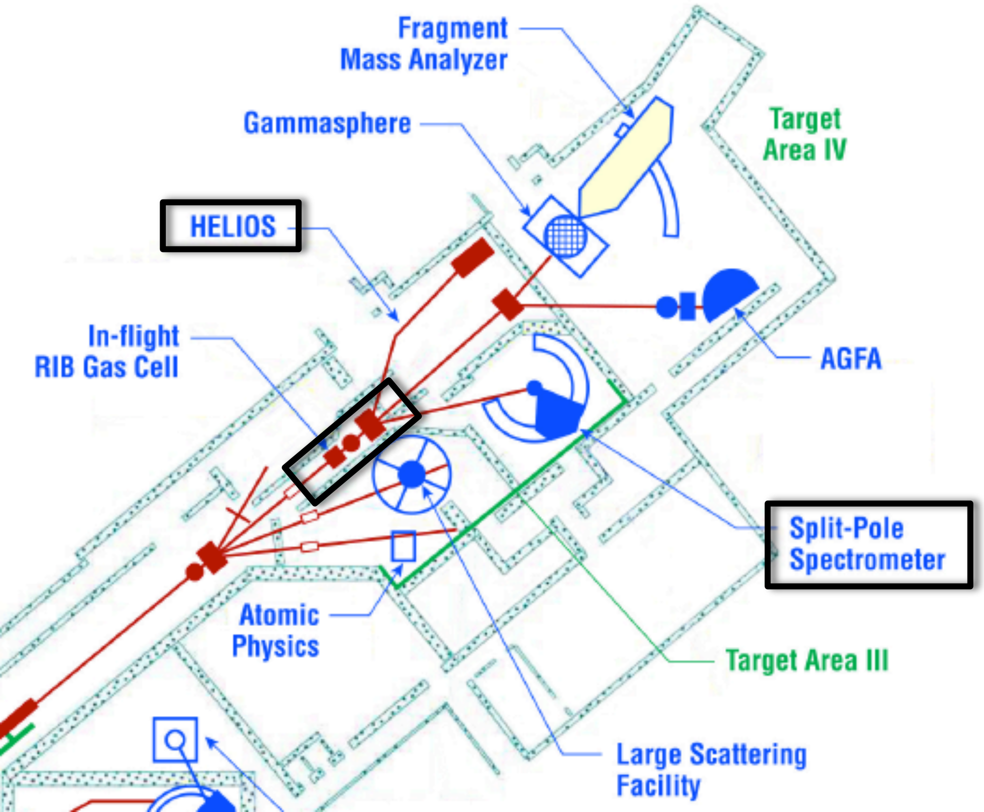
ATLAS: In-flight Radioactive Beams



- In-flight Radioactive Beams
  - Primary beam intensity limited due to availability of beam dump
  - No momentum selection to improve purity
  - Limited to only 2 experimental end-stations

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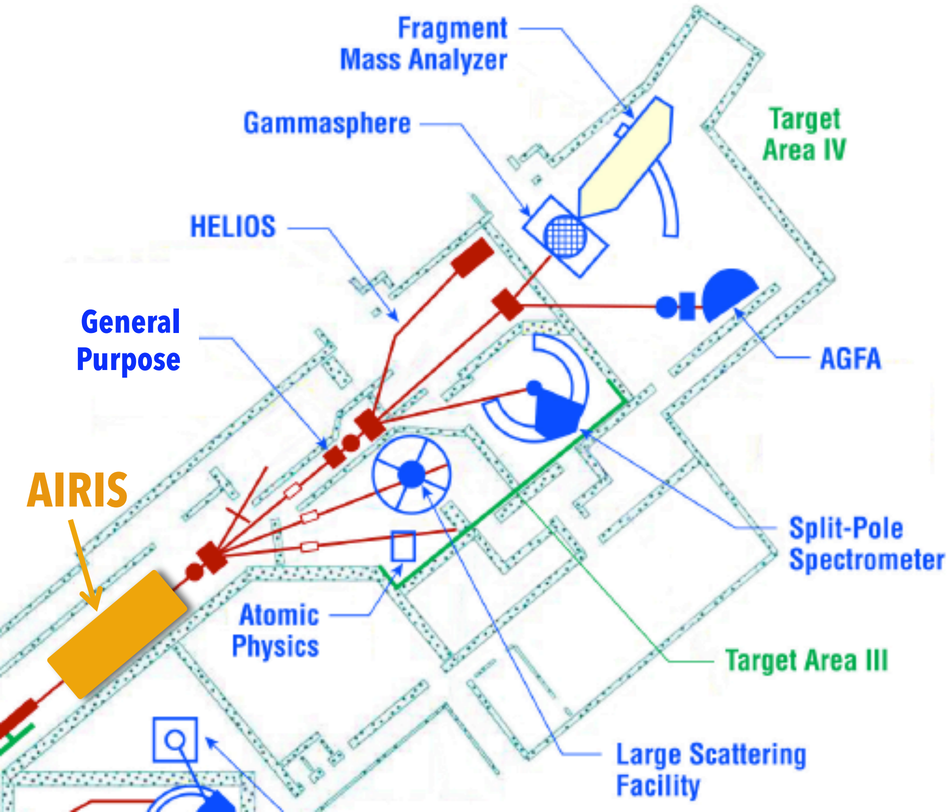
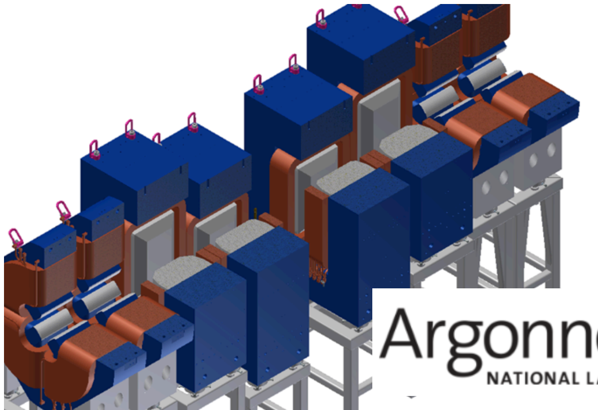
ATLAS: In-flight Radioactive Beams



- AIRIS solutions
  - Primary beam dump at AIRIS midplane
  - Magnetic chicane provides separation
  - All ATLAS targets now accessible



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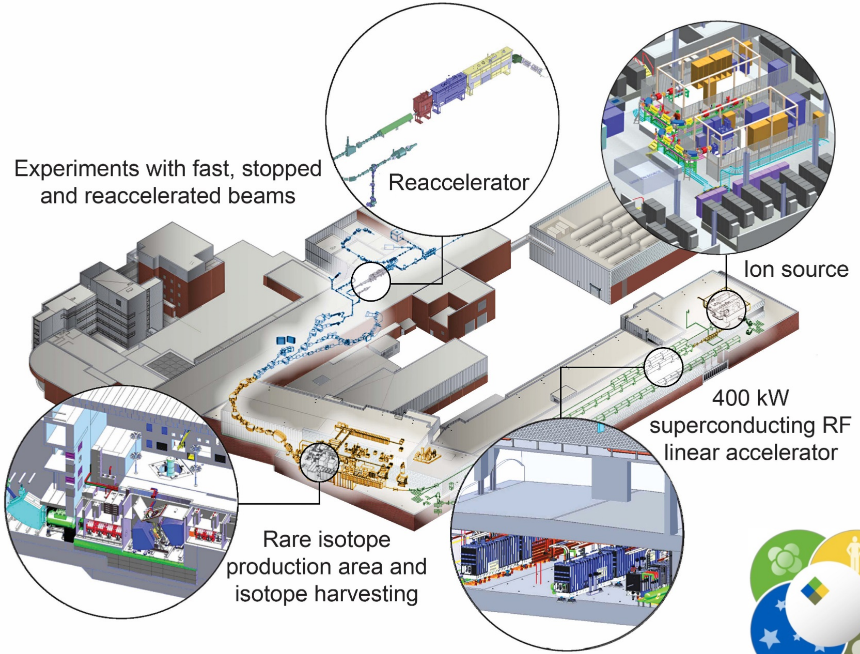
Facility for Rare Isotope Beams

- A DOE-SC Scientific User Facility, funded by DOE-SC, MSU and the State of Michigan supporting the mission of the Office of Nuclear Physics in DOE-SC
- Serving over 1400 users
- Key feature is 400 kW beam power for all ions ($5x10^{13}$ ^{238}U/s)
- Separation of isotopes in-flight
  - Fast development time any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped and reaccelerated beams on Day 1



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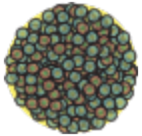
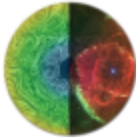
FRIB Science Themes



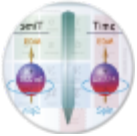
Properties of atomic nuclei

- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



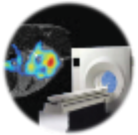
Astrophysics: What happens inside stars?

- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars



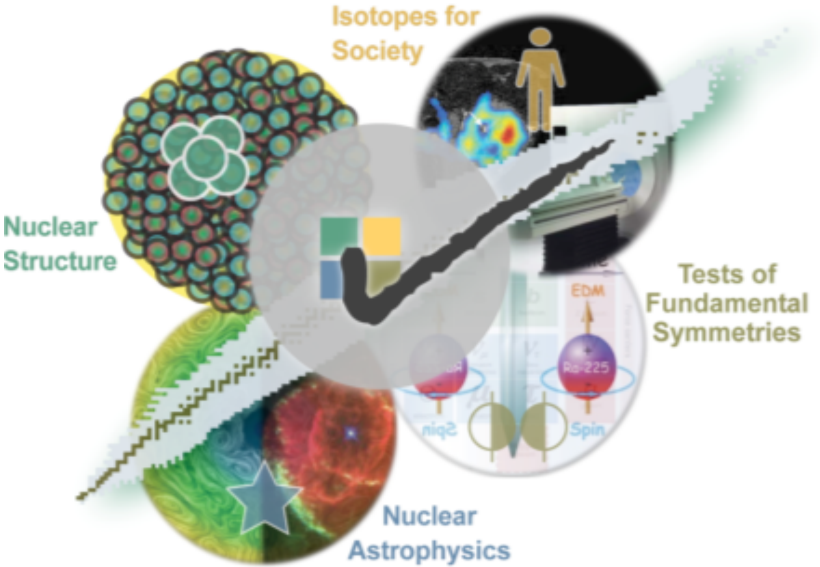
Tests of laws of nature

- Effects of symmetry violations are amplified in certain nuclei



Societal applications and benefits

- Medicine, energy, material sciences, national security



Civil Construction Substantially Complete

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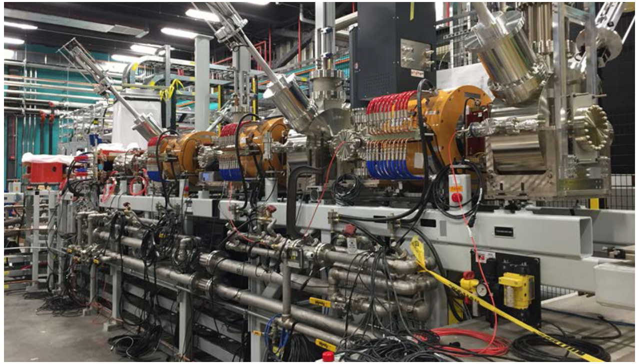
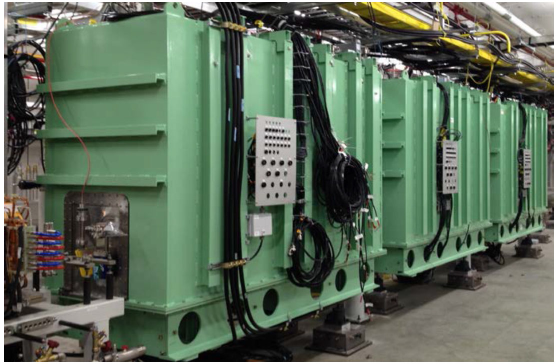
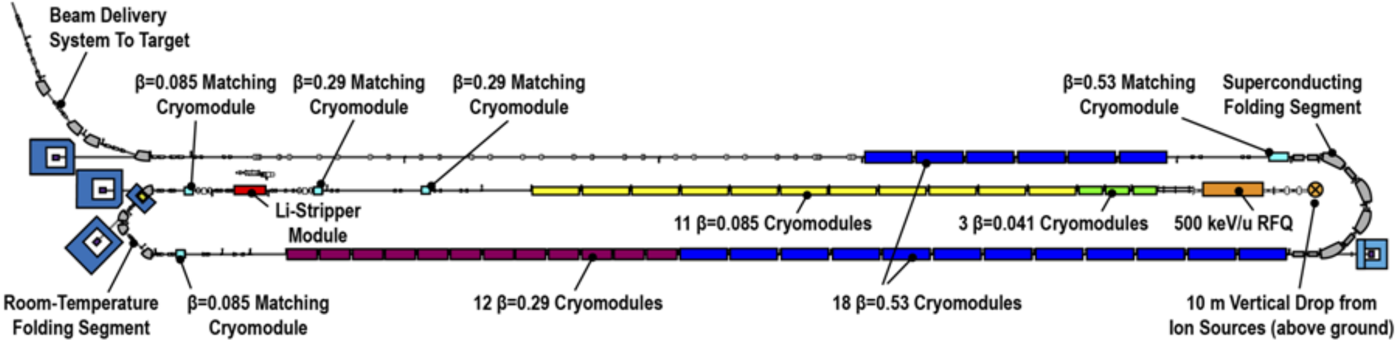
Accelerator Systems: SRF Driver Linac

- Accelerates ion species up to ^{238}U with energies of no less than 200 MeV/u, provide beam power up to 400 kW
- Technical installation is underway
- FRIB is tracking to early completion in FY2021







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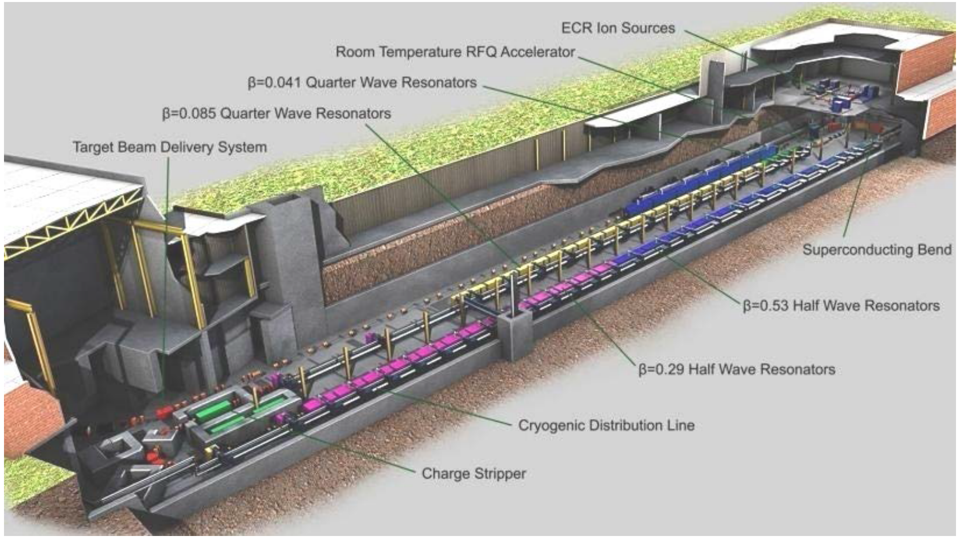
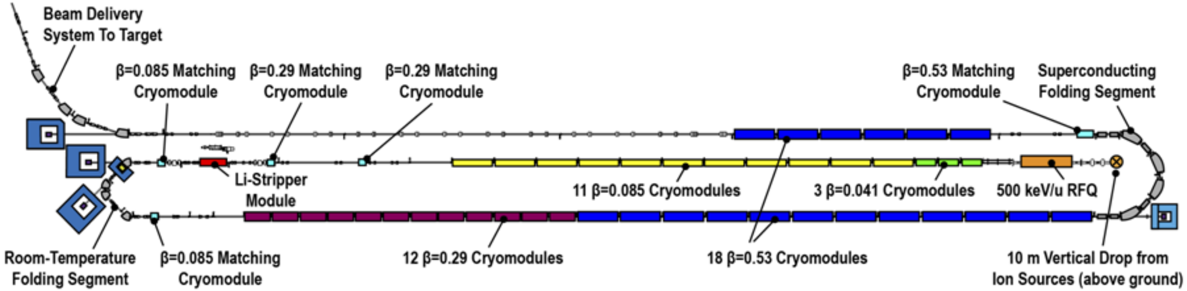
SRF Drive Linac Upgrade Options

- Ten times more yield for heavy n-rich nuclei through energy upgrade to 400 MeV/u for ^{238}U by filling vacant slots with 12 SRF modules; MSU has funded β=0.65 cavity prototype development
- Provisions for ISOL upgrade





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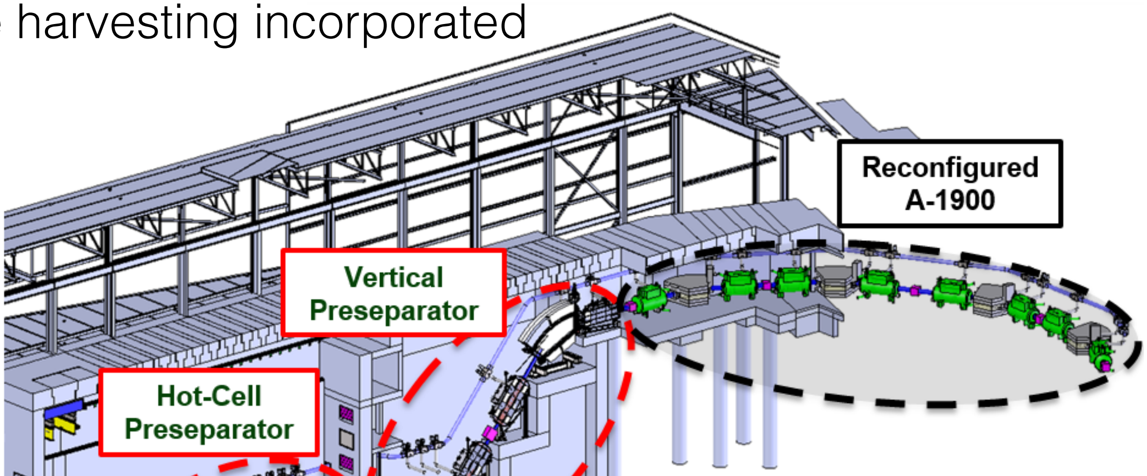
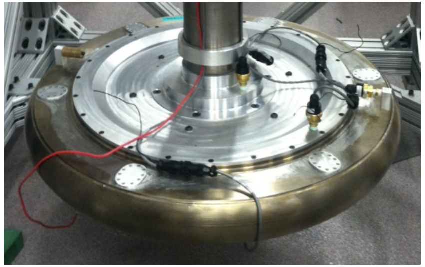
Target Facility and Fragment Separator

- Three stage magnetic fragment separator
  - High acceptance, high resolution to maximize science
  - Provisions for isotope harvesting incorporated in the design
- Challenges
  - High power densities
  - High radiation



Multi-slice rotating graphite target

Water-filled rotating beam dump



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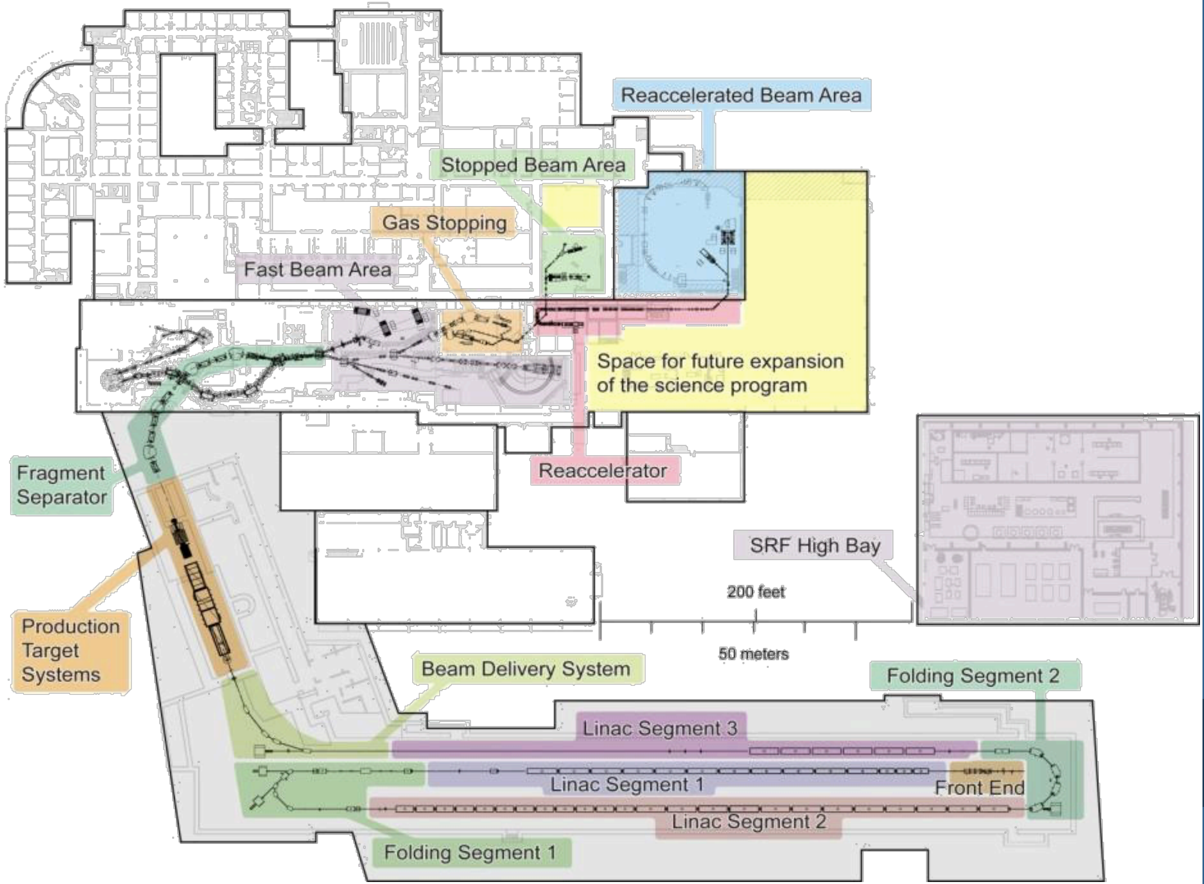
FRIB Scientific Capabilities

- Key capabilities: Fast, stopped and reacclerated beams
- NSCL enables pre-FRIB science



FRIB NSCL

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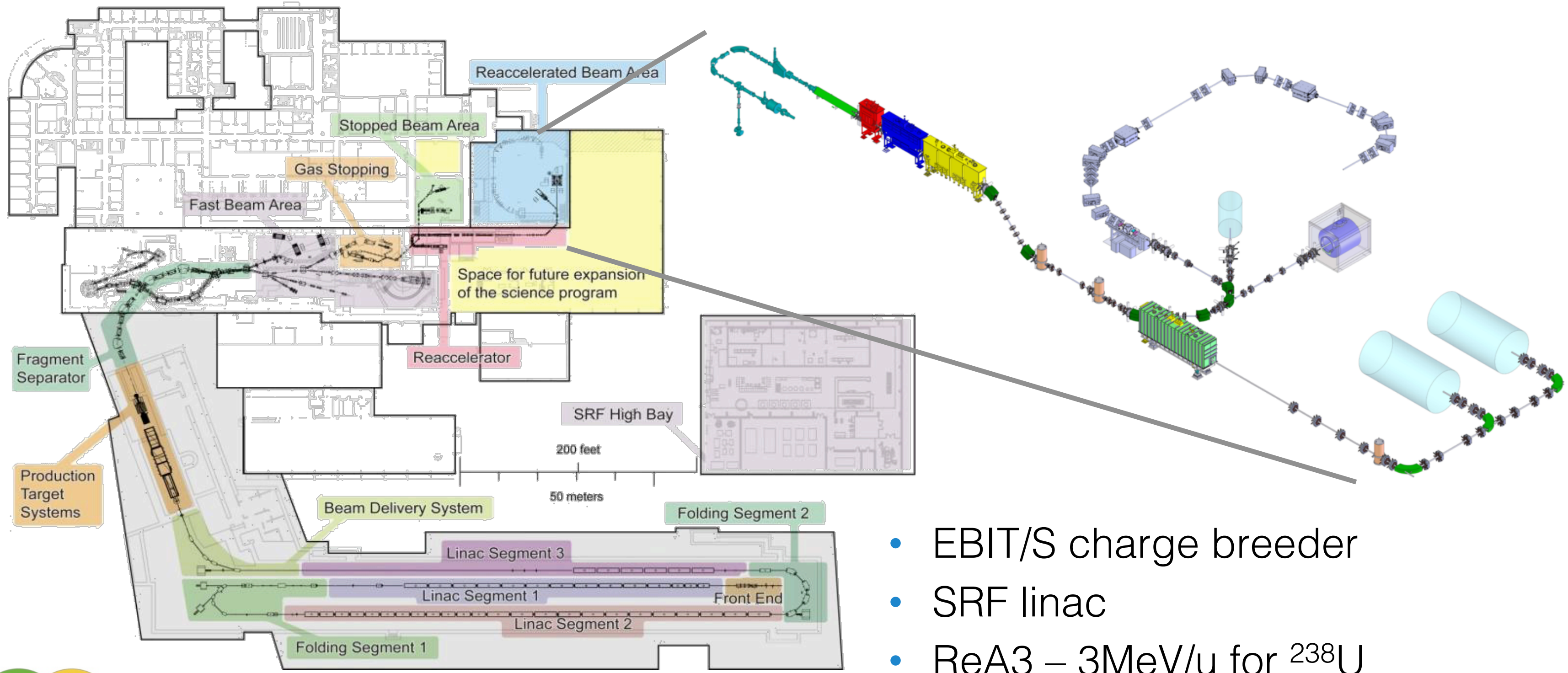
FRIB Scientific Capabilities: ReA



- EBIT/S charge breeder
- SRF linac
- ReA3 – 3MeV/u for ^{238}U
- Expandable to >12 MeV/u for ^{238}U
- ReA3 is operational at NSCL *now*

FRIB NSCL

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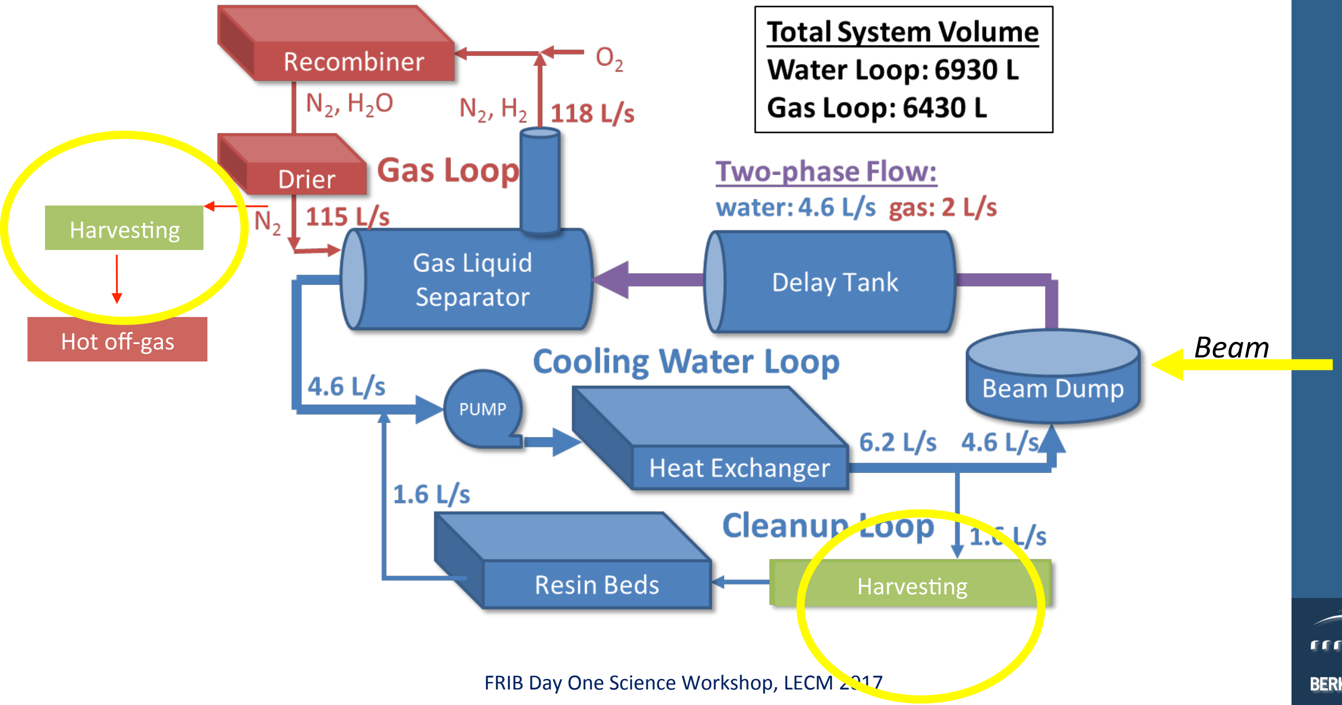
FRIB Scientific Capabilities: Isotope Harvesting

- Isotope harvesting from the FRIB beam dump will enable critical applied research for medicine, horticulture, stewardship…



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ADVANCED INSTRUMENTATION AND EQUIPMENT

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Instrumentation for Low Energy Nuclear Physics

- State of the art instrumentation is critical to maximize the scientific opportunities with rare isotope beams
  - Detectors
  - Spectrometers
  - Ion and atom traps; laser facilities
  - Control systems and DAQ
- Unique challenges in cutting-edge facilities
  - High beam rates / very low beam rates
  - Radiation damage mitigation
  - Complex measurements with multiple systems

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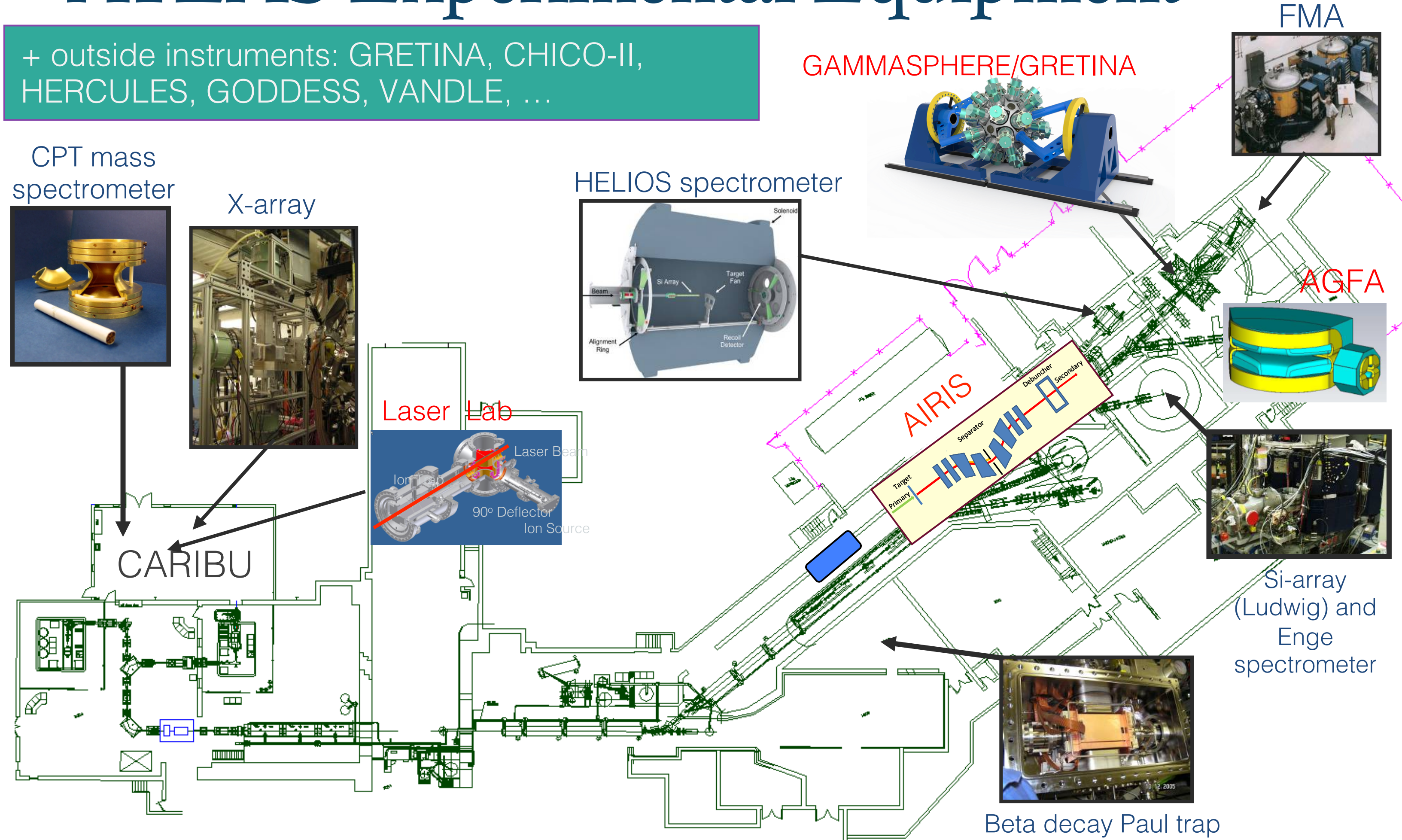
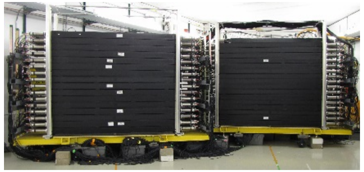
ATLAS Experimental Equipment

+ outside instruments: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, …



NSCL/FRIB Day 1 Experimental Equipment

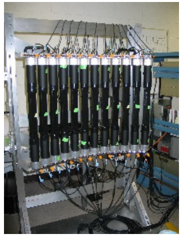


Spectrometers/Beam Line:

- S800, Sweeper Magnet, RFFS, SECAR, 92-inch chamber,

γ Detection:

- SeGA, CAESAR, SuN/MTAS, Gammasphere, GRETINA

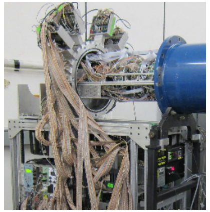


Neutron Detection:

- MoNA-LISA, Neutron Walls, NERO/3HeN, LENDA/VANDLE

Charged Particle Detection:

- BCS, HiRA/LASSA, Diamond Detectors, JANUS, superORRUBA, CHICO-X, ORISS, CFFD

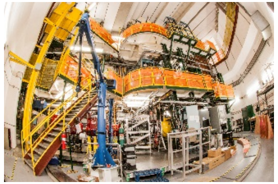


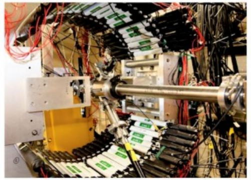
Active Targets/Advanced Targetry:

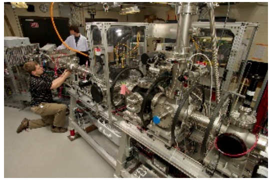
- AT-TPC, ANASEN, MUSIC, Liquid H-target, JENSA, TriPLEX

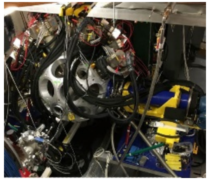
Stopped Beam Equipment:

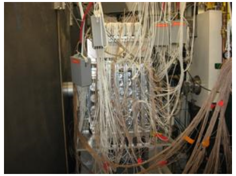
- Beta-NMR, BECOLA, LEBIT





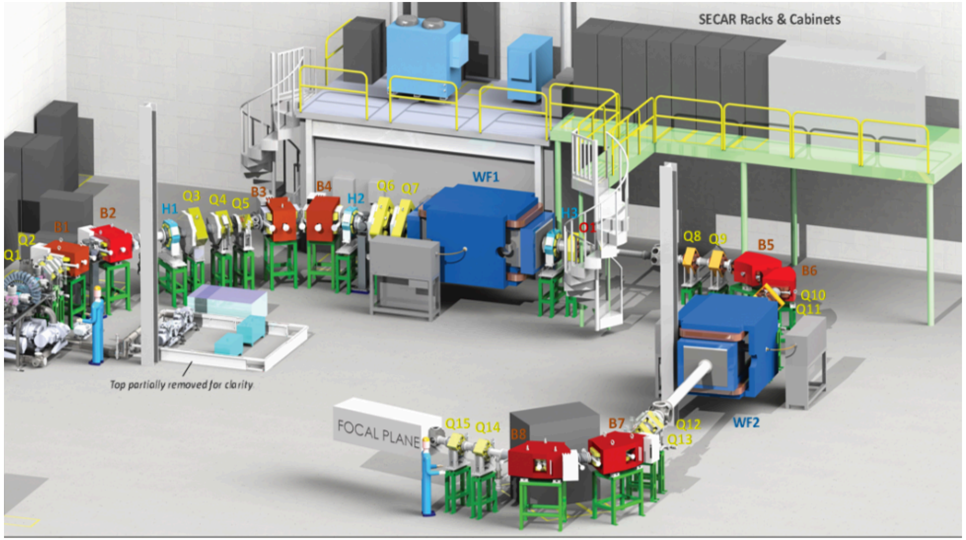






Advanced Instrumentation: SECAR

- SECAR will enable use of unique FRIB reaccelerated beams to directly measure reactions of astrophysically relevant reactions
- DOE-SC/NSF project to construct SECAR is underway – multi-institutional collaboration

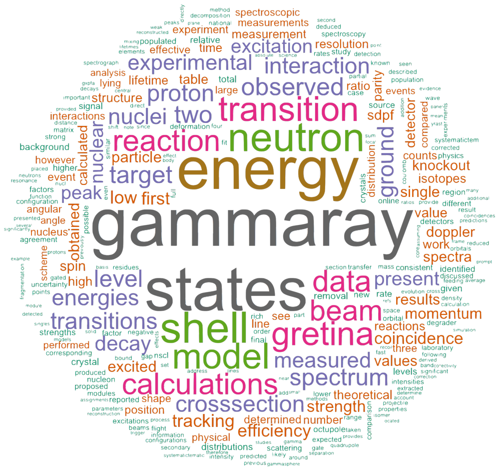


SECAR

http://fribastro.org/SECAR/SECAR.html

Advanced Instrumentation: GRETA

- GRETA will be the most advanced gamma-ray detector array for nuclear science
  - Uses highly segmented detectors to track and reconstruct γ-rays
  - GRETINA, which has been operation since 2011, has proven the technology and scientific impact with 3 completed campaigns (two at NSCL and one at ATLAS) and a fourth campaign beginning in October at the FMA
  - GRETINA will operate at the FMA with 11 modules, approximately 1/3 of the full solid angle



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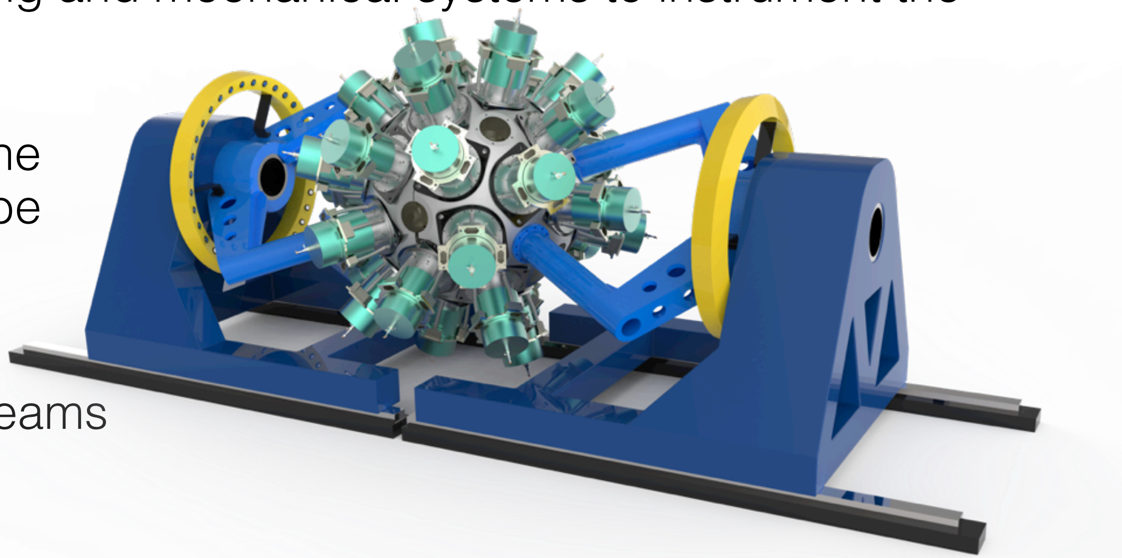
Advanced Instrumentation: GRETA

- GRETA will be the most advanced gamma-ray detector array for nuclear science
- GRETA is DOE-SC funded project; CD-0 received 2015; CD-1 is expected soon
  - The GRETA project will add 18 detector modules and new electronics, computing and mechanical systems to instrument the full array
  - The completed array will cover ~ 80% of the full solid angle, and be key in the physics programs at ATLAS and FRIB with fast and reaccelerated beams



http://greta.lbl.gov

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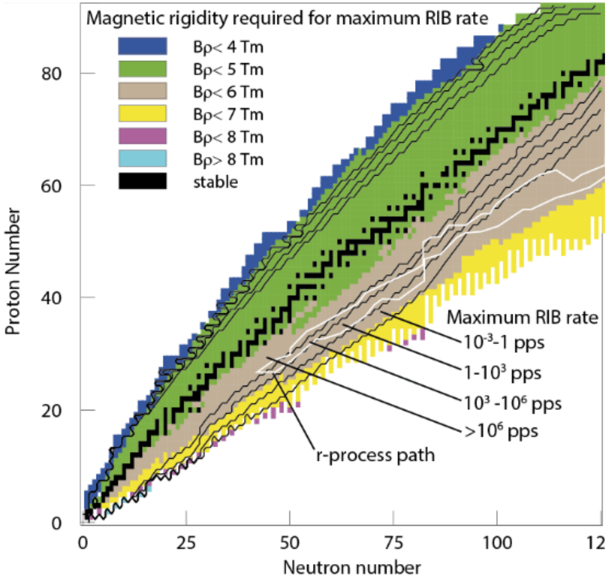
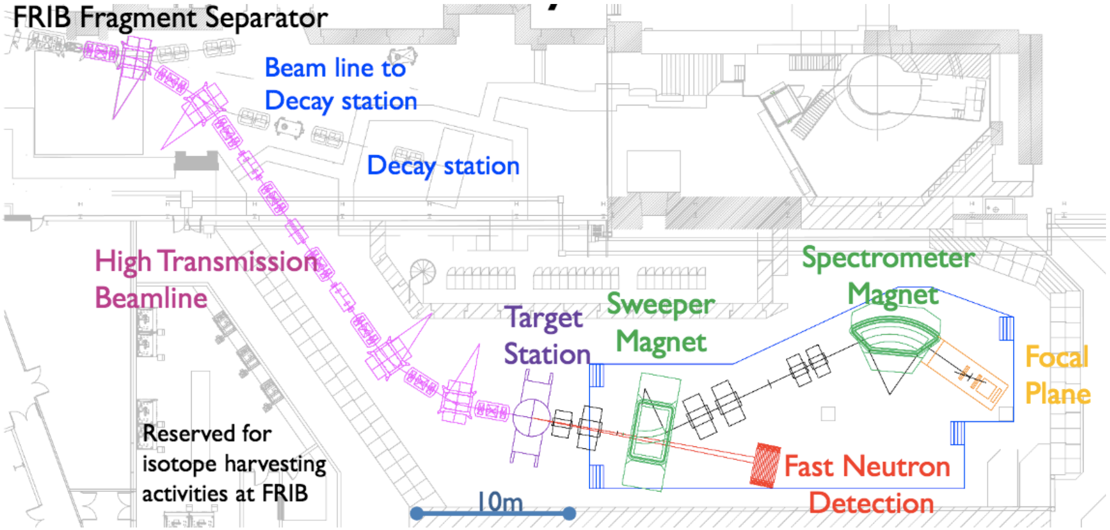
Instrumentation: HRS

- High Rigidity Spectrometer is required to make optimal use of the most exotic fast beams at FRIB
- Pre-conceptual design work is ongoing





- Focal plane and beam tracking detectors must meet demands on count rate, etc.

http://hrs.lbl.gov

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SBIR/STTR and LE Program

- Many examples of SBIR project have had (continue to have) direct relevance to the low-energy program
  - Gamma-ray detector technology (tracking detectors) – connects to imaging applications
  - FRIB developments – accelerator, detectors

- With advanced instrumentation projects moving forward, research community welcomes continued and expanded collaborations
  - Development of new techniques to address unique challenges for higher power facilities

- Possible areas for SBIR/STTR activities include
  - High-rate, position sensitive beam tracking and timing detectors
  - Fast and versatile data acquisition electronics
  - Real-time data visualization frameworks
  - Isotope harvesting techniques and diagnostics

Summary

- The area of low-energy nuclear physics in the US has exciting years ahead, in particular as FRIB moves toward completion and ATLAS pursues capability enhancements
- Today's facilities provide forefront research opportunities and a path to optimize capabilities at FRIB
- DOE NP SBIR/STTR program plays an important role in making the low energy nuclear physics program successful and will be critical moving in the FRIB era

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Summary

- The area of low-energy nuclear physics in the US has exciting years ahead, in particular as FRIB moves toward completion and ATLAS pursues capability enhancements
- Today's facilities provide forefront research opportunities and a path to optimize capabilities at FRIB
- DOE NP SBIR/STTR program plays an important role in making the low energy nuclear physics program successful and will be critical moving in the FRIB era

Thank you!

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