Nuclear Physics Low Energy Facilities and The SBIR/STTR Program

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DOE NP SBIR/STTR Exchange Meeting, August 6-7, 2015

Outline

Low Energy Nuclear Physics

Facilities

- ATLAS
- FRIB

Instrumentation

- Some examples

Summary

Outline

Low Energy Nuclear Physics

Facilities

ATLAS

FRIB

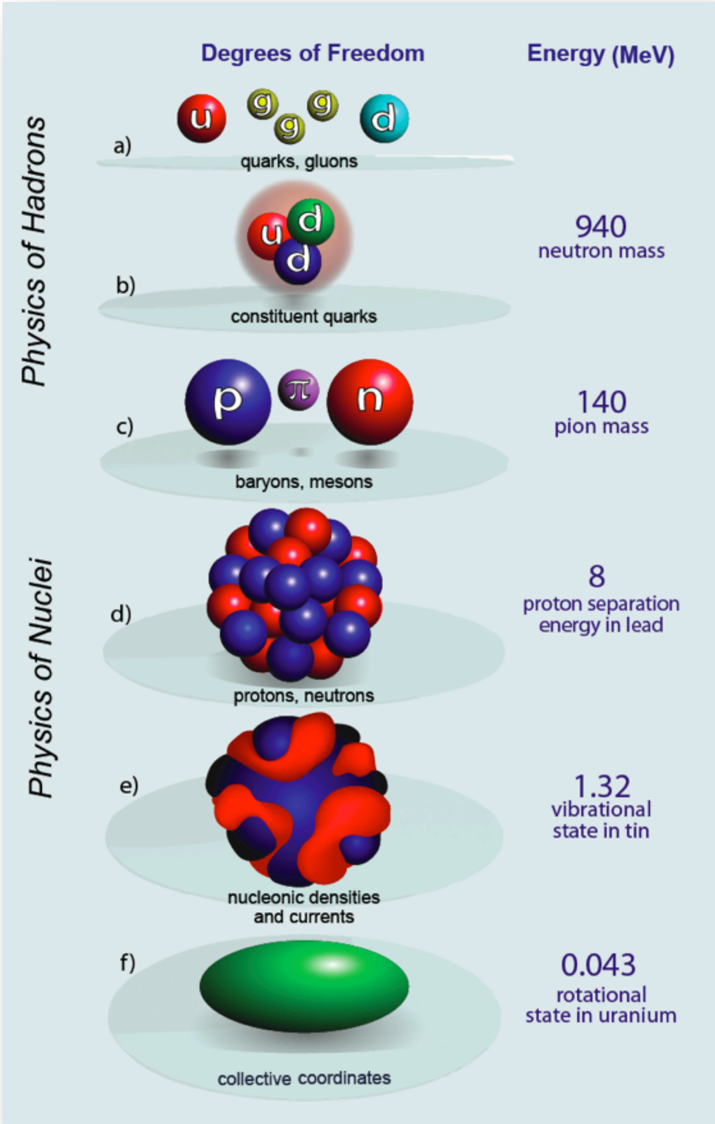
Instrumentation

Some examples

Summary

Acknowledgements:
Steve Elliot, Thomas Glasmacher, Paul Fallon, Guy Savard, and David Radford.

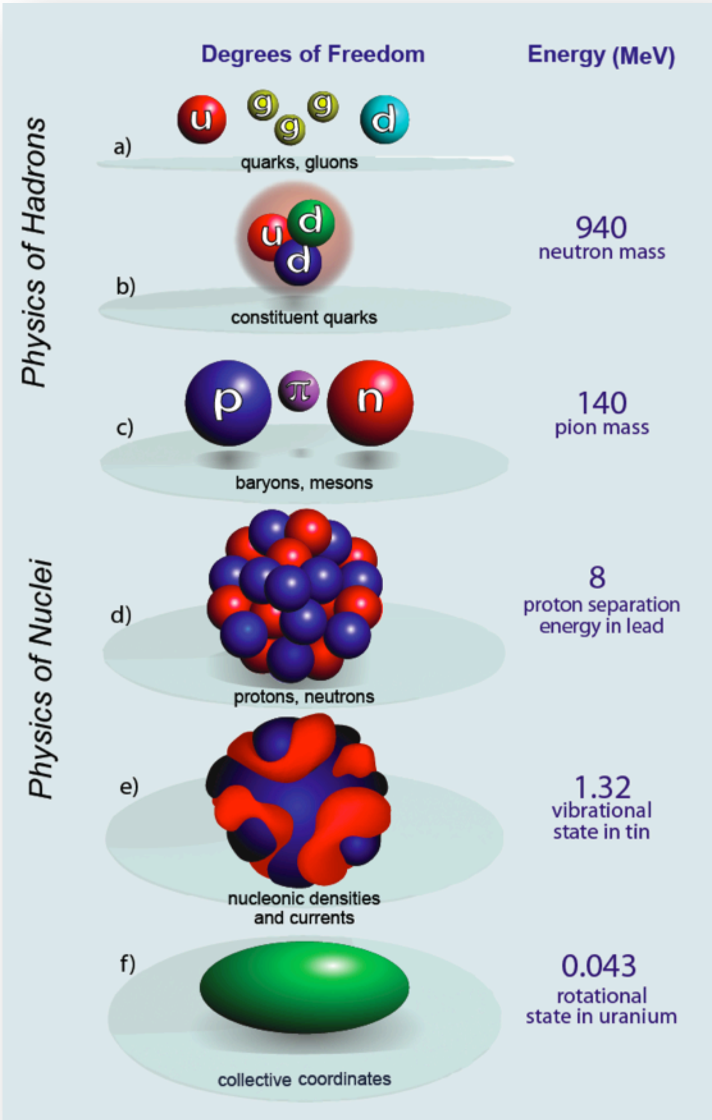
A Hierarchy of Scales



From the 2007 NSAC Long Range Plan

A Hierarchy of Scales

Theory and Accelerators



Heavy Ion

Medium Energy

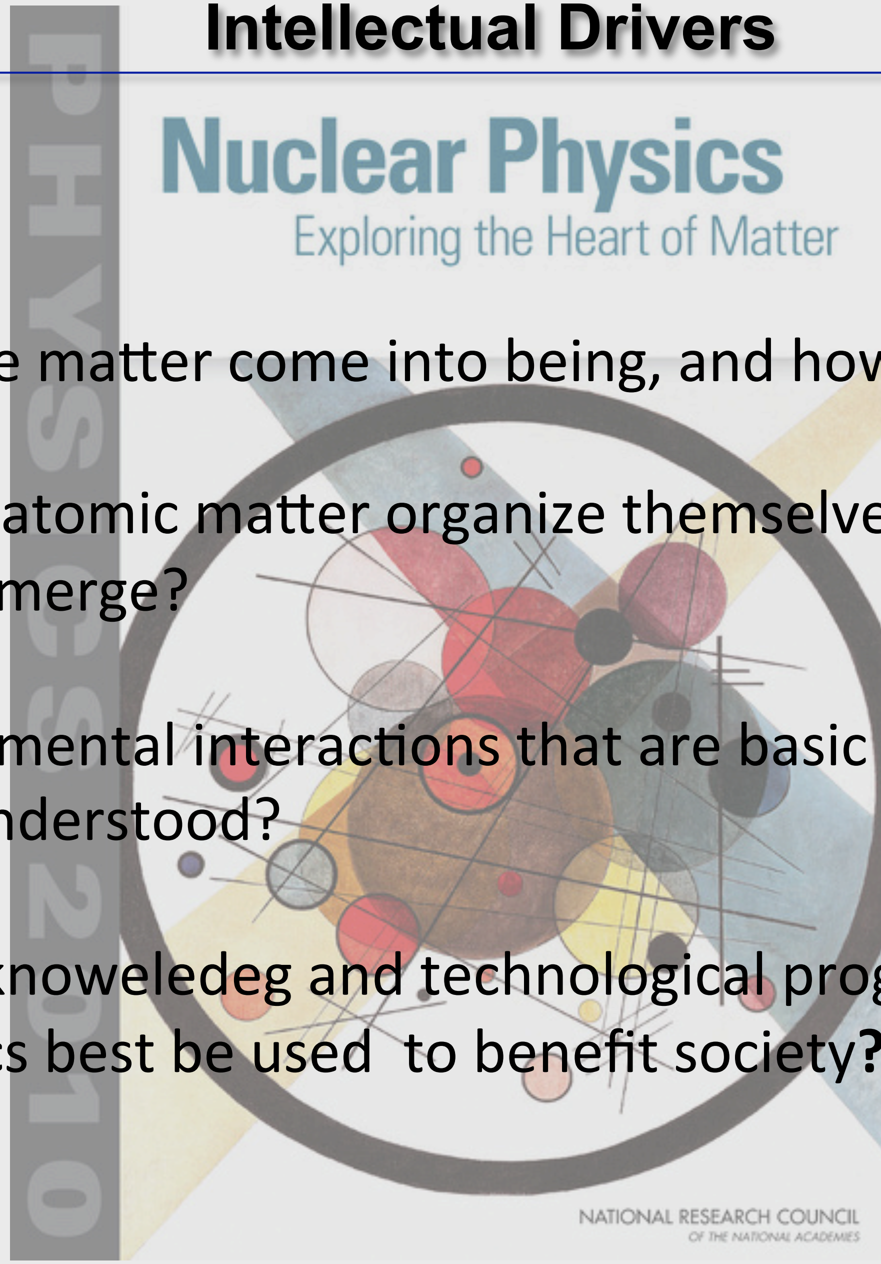
Low Energy

Nuclear Structure and Astrophysics

Fundamental symmetries

From the 2007 NSAC Long Range Plan

Intellectual Drivers



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

Atomic nuclei constitute unique many body systems of strongly interacting fermions. Their properties and structure, are of paramount importance to many aspects of physics.

Many of the phenomena encountered in nuclei share common basic physics ingredients with other mesoscopic systems, thus making nuclear structure research relevant to other areas of contemporary research, for example in condensed matter and atomic physics.

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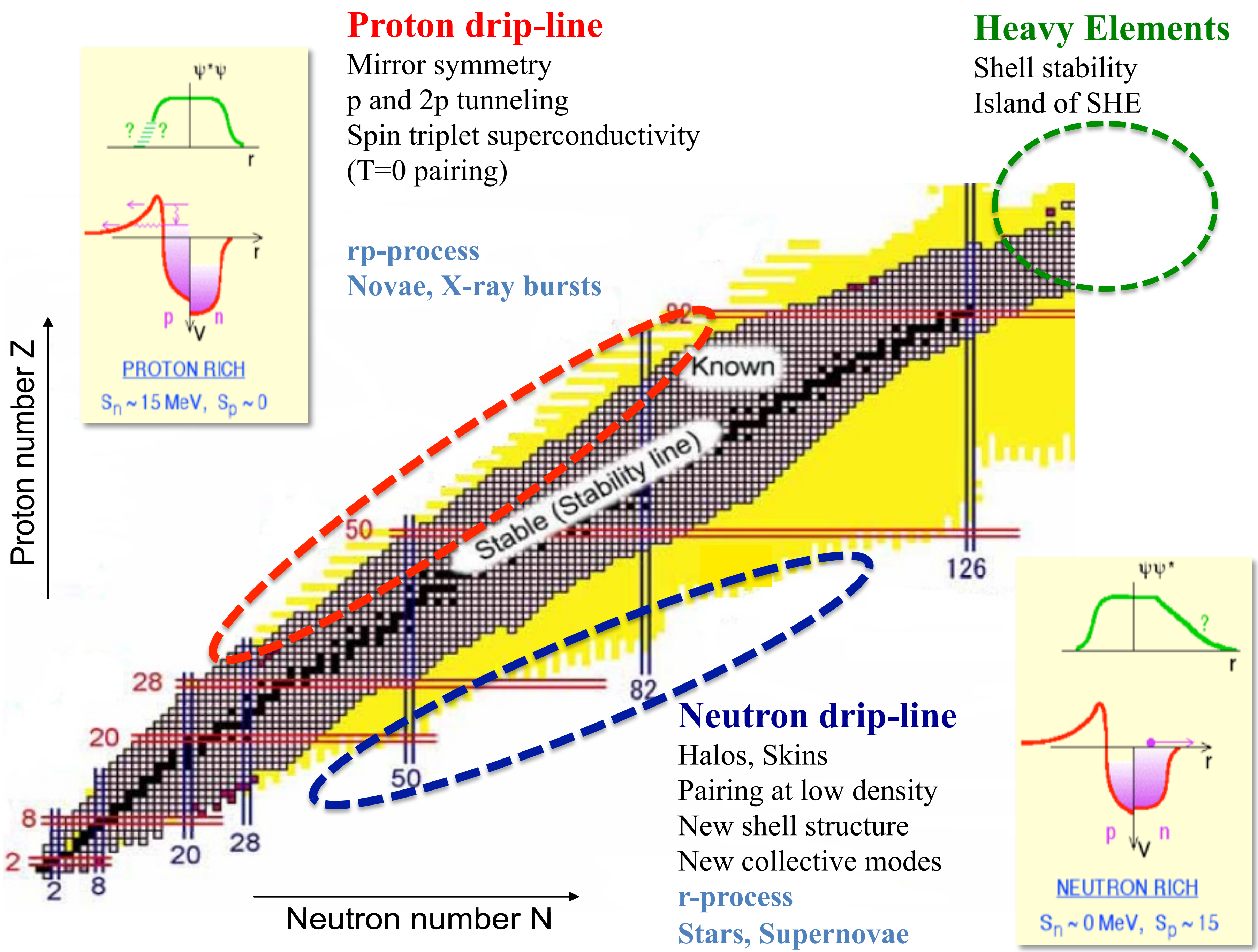
These are exciting times in the field of physics of nuclei:

Existing and planned **exotic beam facilities** worldwide and new **detector systems** with increased sensitivity and resolving power not only will allow us to answer some important questions we have today, but most likely will open up a window to new and unexpected phenomena.

New developments in **theory and computer power** are shaping a path to a predictive theory of nuclei and reactions.

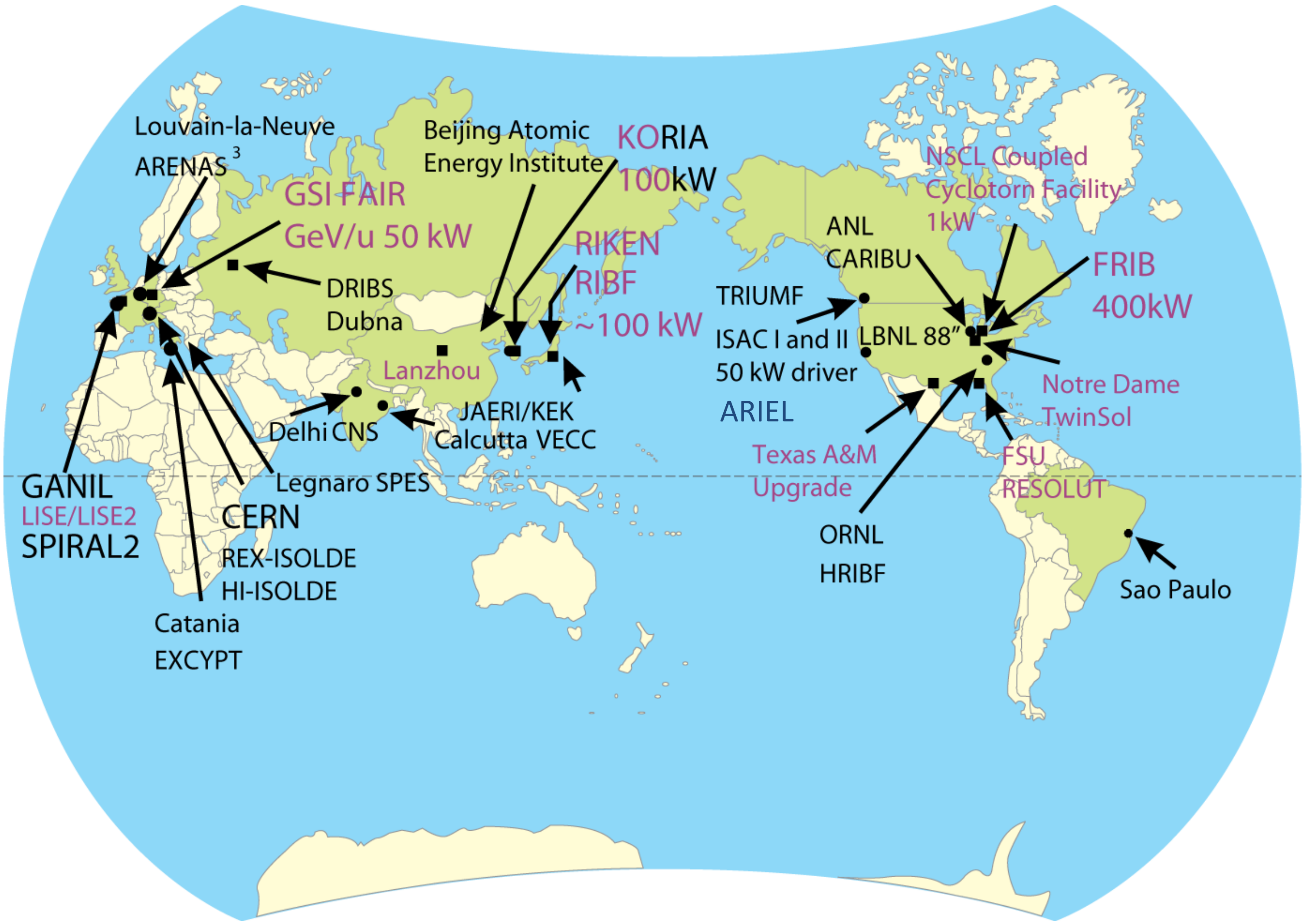


Proton drip-line
Mirror symmetry
p and 2p tunneling
Spin triplet superconductivity
(T=0 pairing)
rp-process
Novae, X-ray bursts
Heavy Elements
Shell stability
Island of SHE
PROTON RICH
$S_n \sim 15$ MeV, $S_p \sim 0$
Proton number Z
Neutron number N
Known
Stable (Stability line)
2
8
20
28
50
82
126
Neutron drip-line
Halos, Skins
Pairing at low density
New shell structure
New collective modes
r-process
Stars, Supernovae
NEUTRON RICH
$S_n \sim 0$ MeV, $S_p \sim 15$

Ingredients

- An accelerator facility to provide a beam of ions
  - Beam may be composed of unstable (radioactive) ions
  - Beam energy can be low (~100 keV) or high (~ 3 to 100 MeV per nucleon)
- A target (for higher-energy beams)
  - A small fraction of the beam ions react with target nuclei to make something of interest
- Detectors and associated electronics to study that "something"
  - Gamma-rays, light charged particle, fragments, heavy residuals, …
    - HPGe detectors
    - Double-sided strip detectors (Si or Ge)
    - Scintillators, with either PMTs or photodiodes
    - Magnetic spectrometers
    - Gas counters
    - Ion traps
    - Many more
- Digitizers, computers, data storage, and software

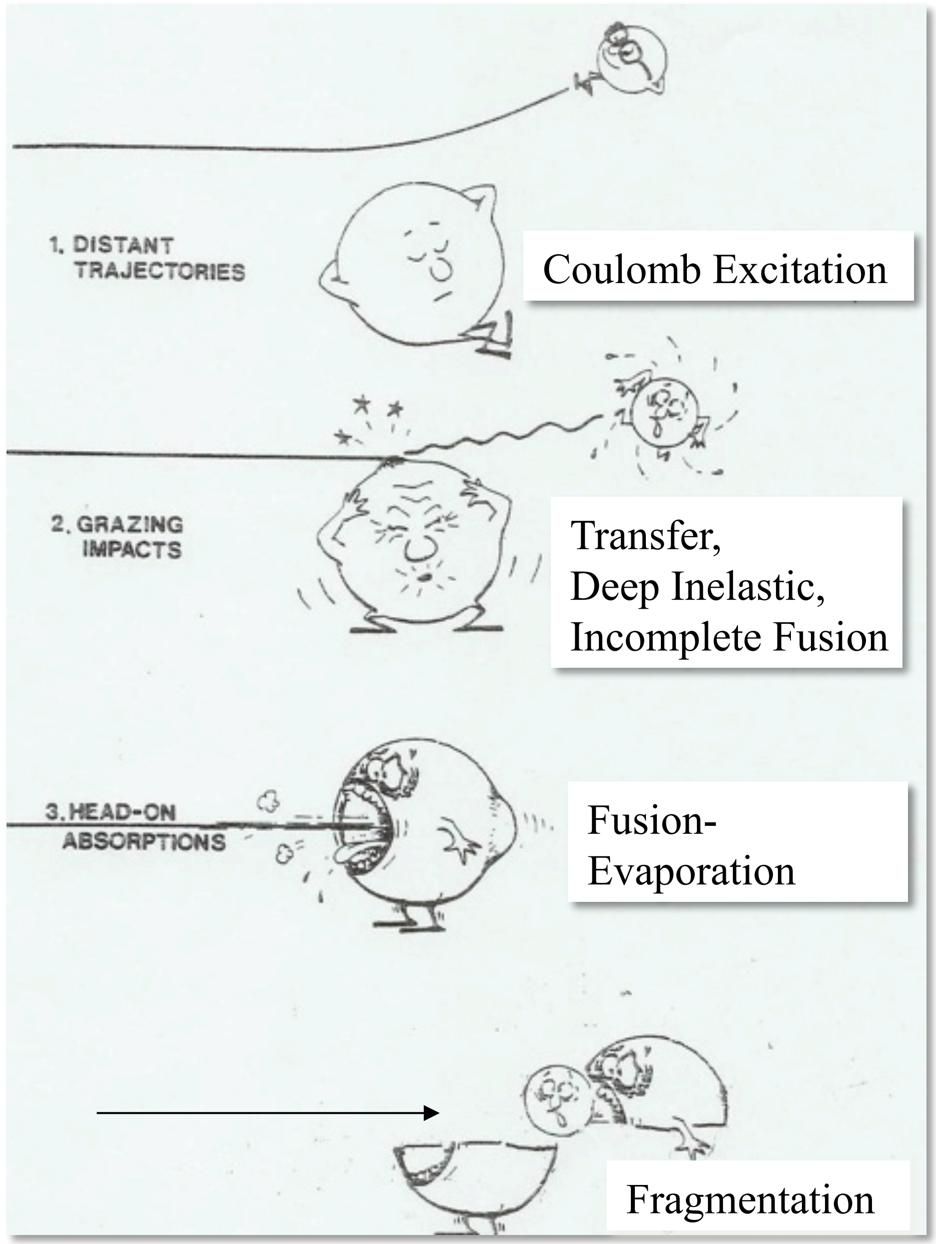
World view of rare isotope facilities



From Brad Sherrill - MSU

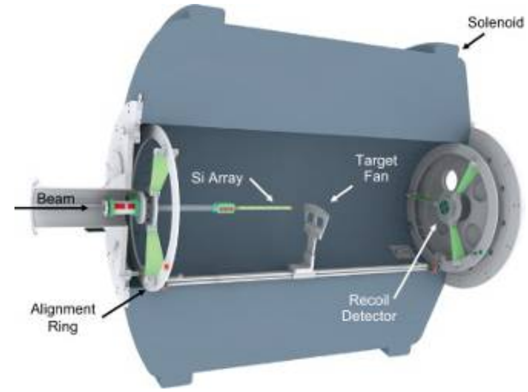
Black – production in target
Magenta – in-flight production

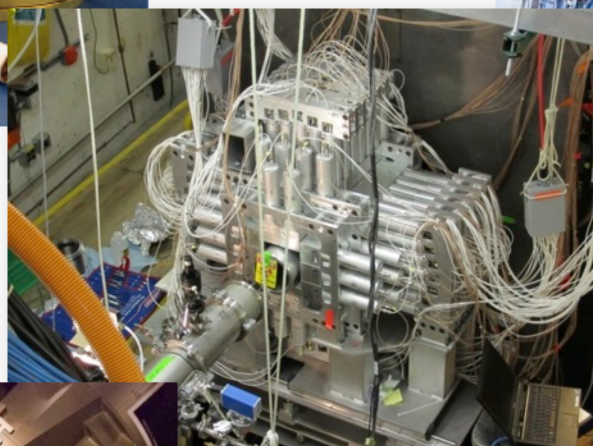
The Physics Probes (An artist's view)

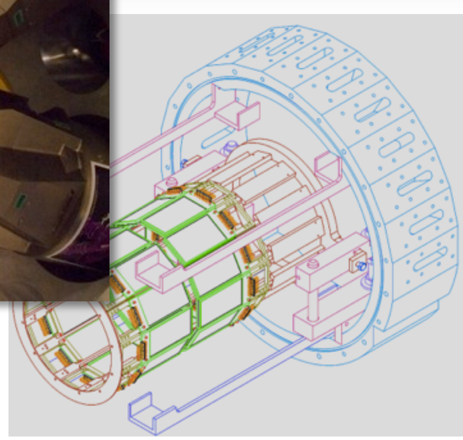


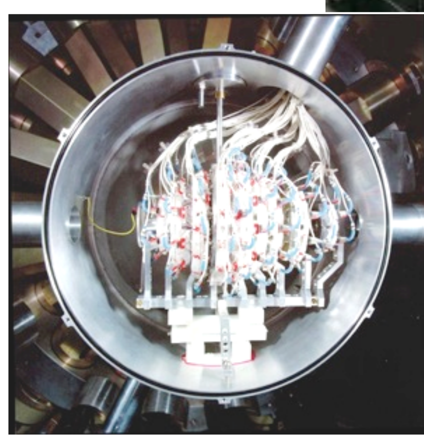
Adapted from H. A. Enge, Heavy Ions Summer Study- Oak Ridge 1972

The Detectors









FACILITIES

Nuclear Physics Low Energy Facilties

DOE National User Facilities

- Argonne Tandem-Linac Accelerator System (ATLAS) (http://www.phy.anl.gov/atlas/facility)
  - High intensity stable beams
  - Limited radioactive beam program with stopped, re-accelerated and in-flight beams

- Facility for Radioactive Ion Beams (FRIB)
  - being constructed at MSU
  - Fast radioactive beams produced by fragmentation and in-flight fission
  - Stopped beams
  - Re-accelerated beams at near Coulomb barrier energies

NSF User Facility

- National Superconducting Cyclotron at MSU (http://nscl.msu.edu)
  - Fast radioactive beams produced by fragmentation (re-accelerated beams coming online)

Nuclear Physics Low Energy Facilities

Other DOE facilities (local use)

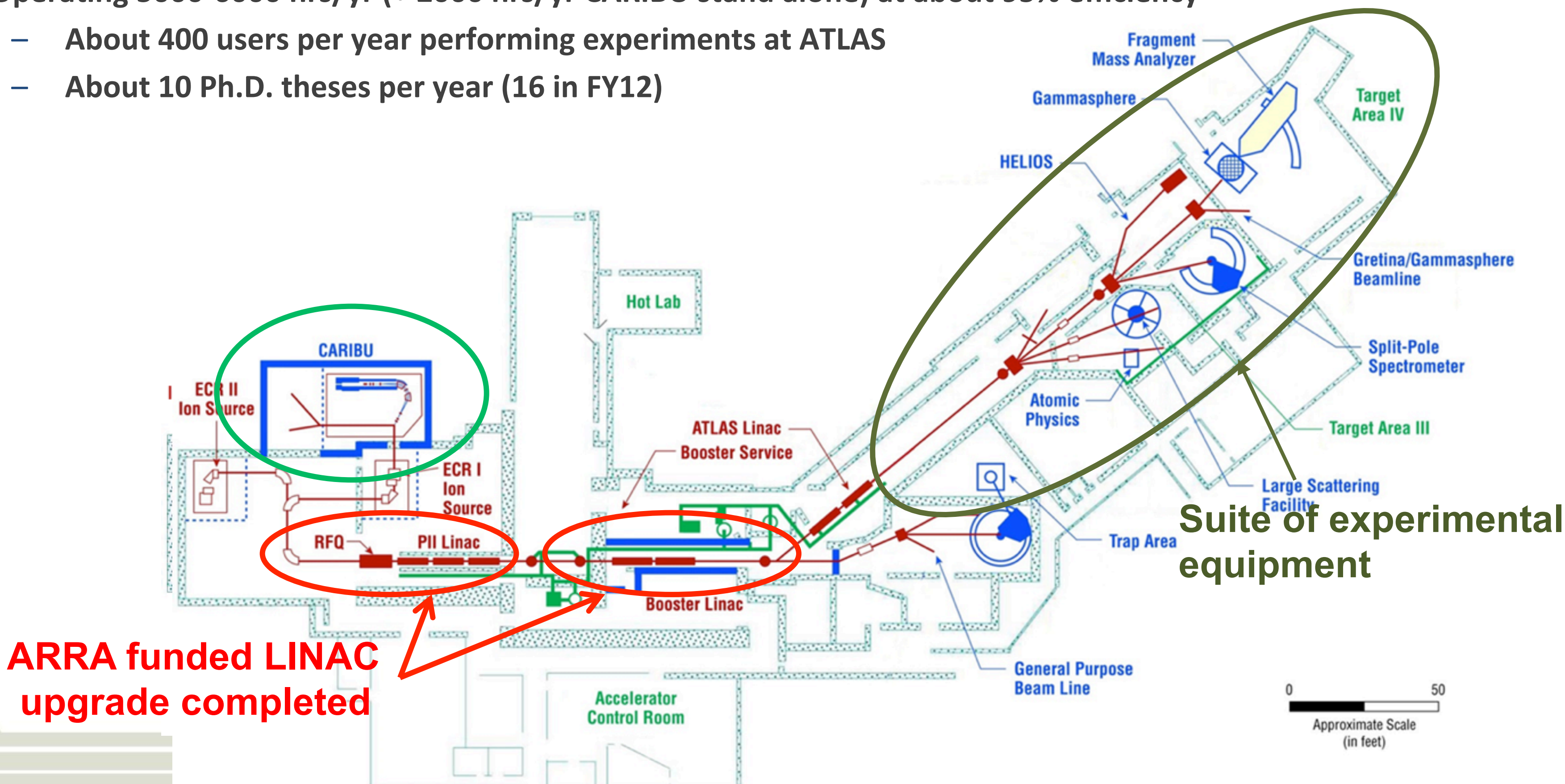
- LBNL 88-Inch Cyclotron (http://cyclotron.lbl.gov)
  - Basic and applied research w. stable beams

- 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 - neutrons

ATLAS facility

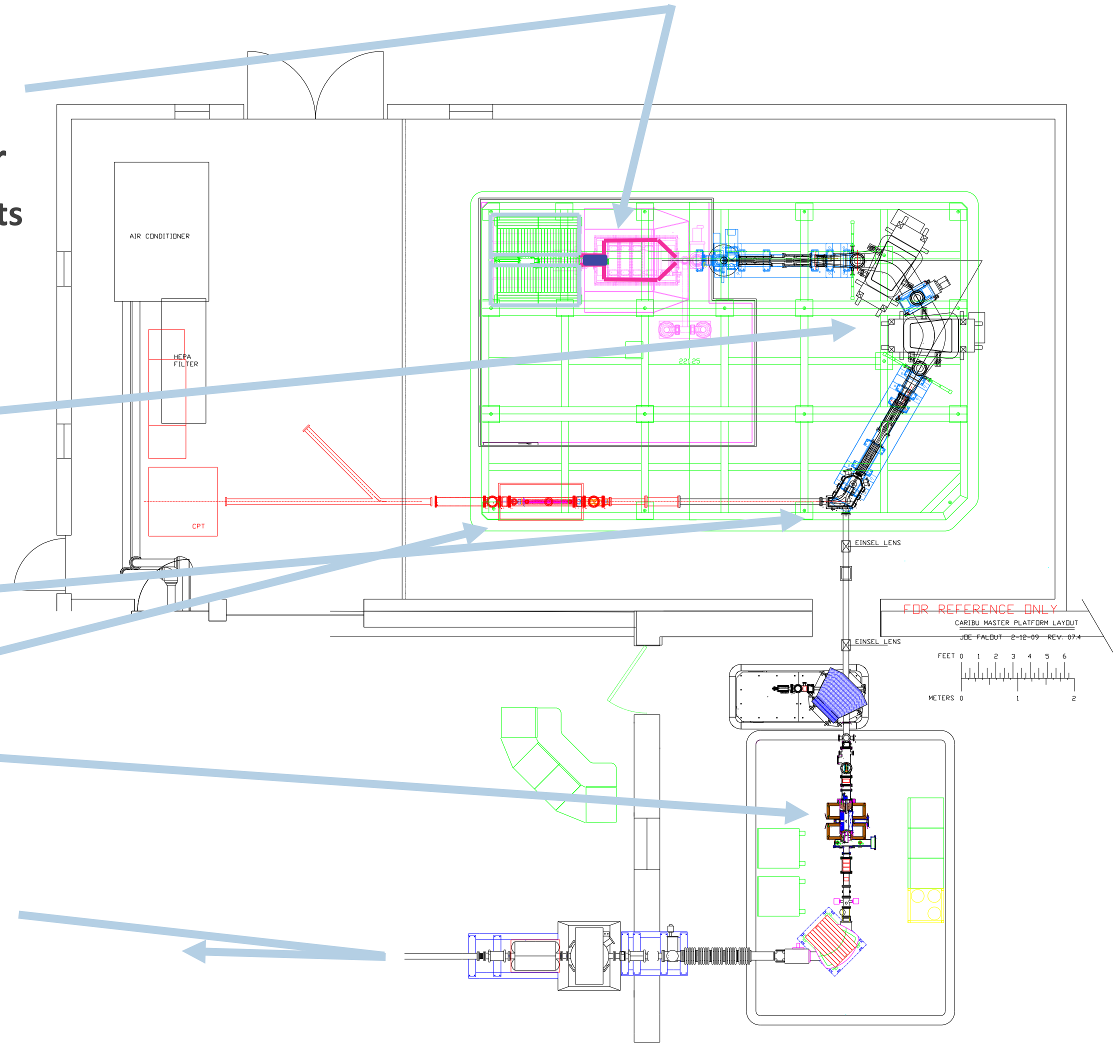
- Stable beams at high intensity and energy up to 10-20 MeV/u
- Light in-flight radioactive beams
  - *light beams, no chemical limitations, close to stability, acceptable beam properties*
- CARIBU beams
  - *heavy n-rich from Cf fission, no chemical limitations, low intensity, ATLAS beam quality, energies 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) at about 95% efficiency
  - About 400 users per year performing experiments at ATLAS
  - About 10 Ph.D. theses per year (16 in FY12)



Neutron-rich beam source for ATLAS: CARIBU "front end" layout

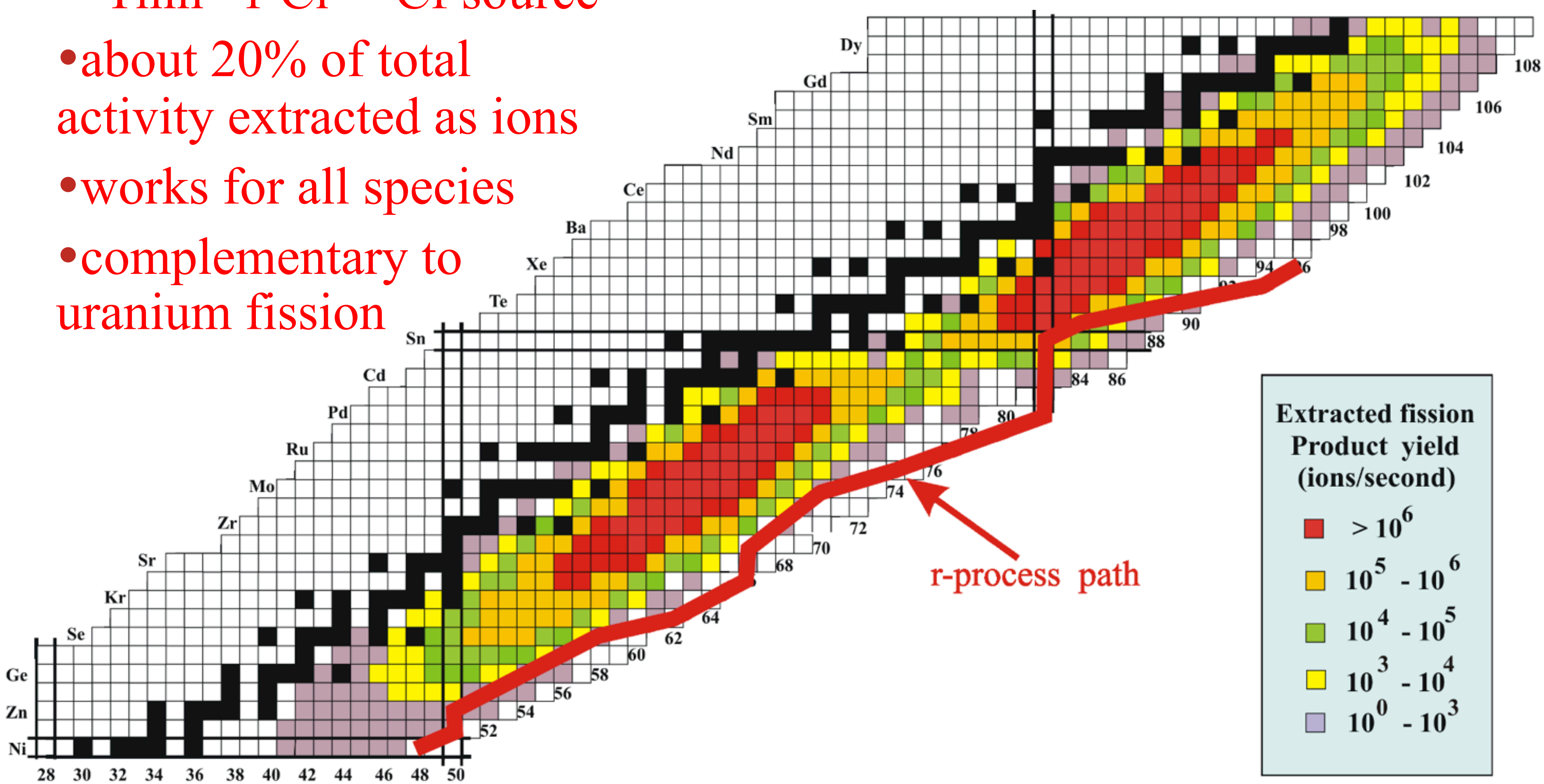
Main components of CARIBU

- **PRODUCTION**: "ion source" is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator
  - Purifies beam
- **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



Expected isotope yield distribution at low energy (50 keV)

- "Thin" 1 Ci ^{252}Cf source
- about 20% of total activity extracted as ions
- works for all species
- complementary to uranium fission

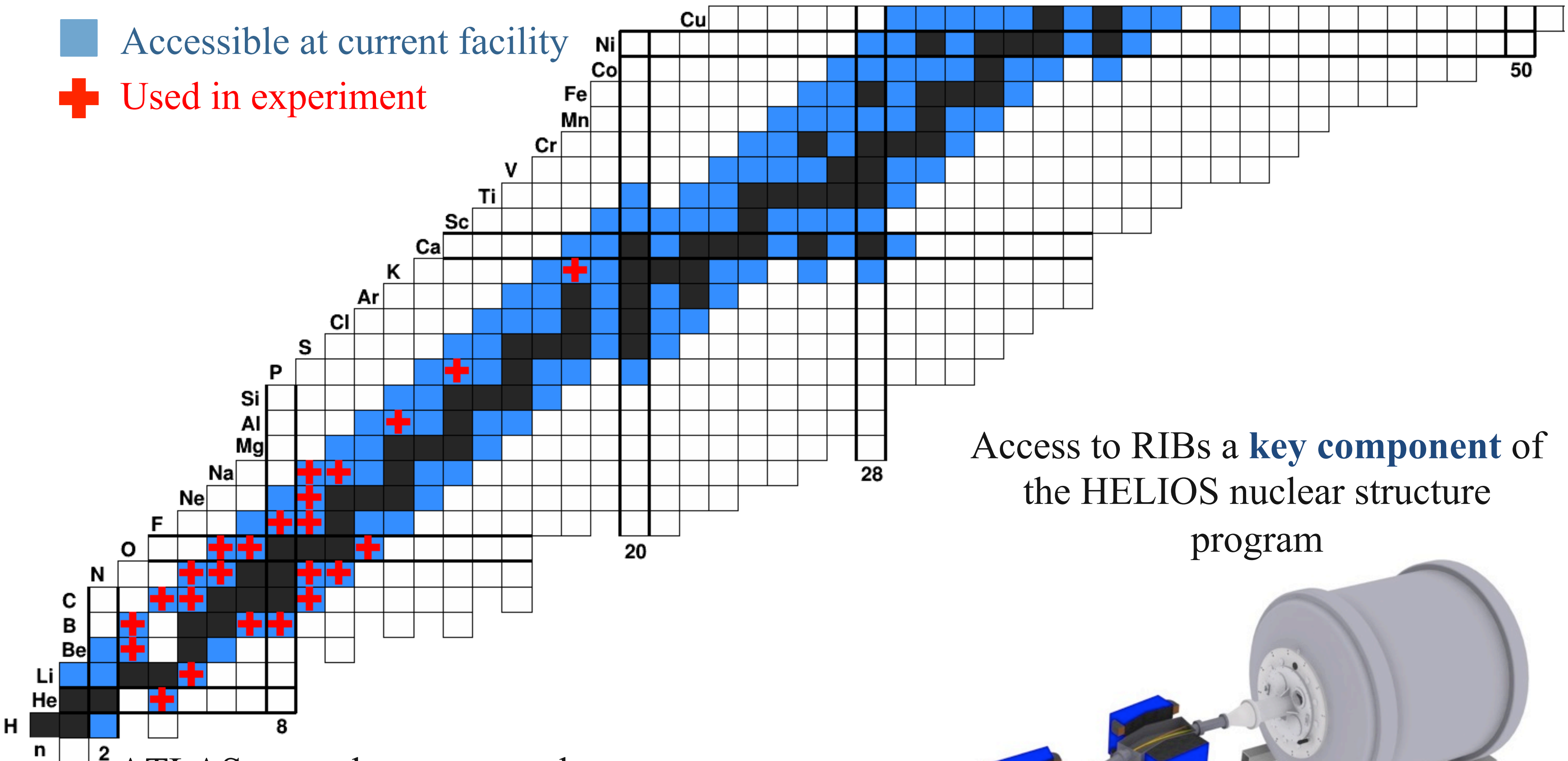


> than 500 neutron-rich species extracted at > 1/s

In-flight radioactive beams at ATLAS

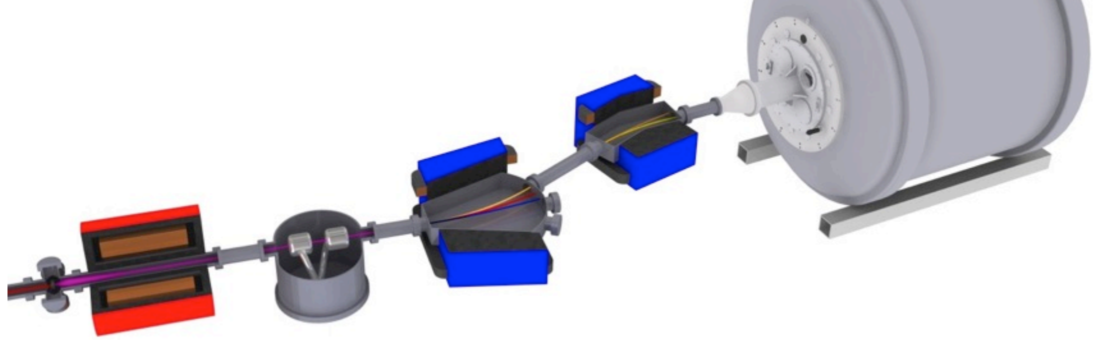
Accessible at current facility

Used in experiment



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

ATLAS upgrades, target and reaction techniques, will increase reach until arrival of the new in-flight separator **AIRIS**



ATLAS beams

- **Stable beams (protons to Uranium)**
  - up to 10 pμA, limited by ion source performance and radiation safety
  - Pulse separation of 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

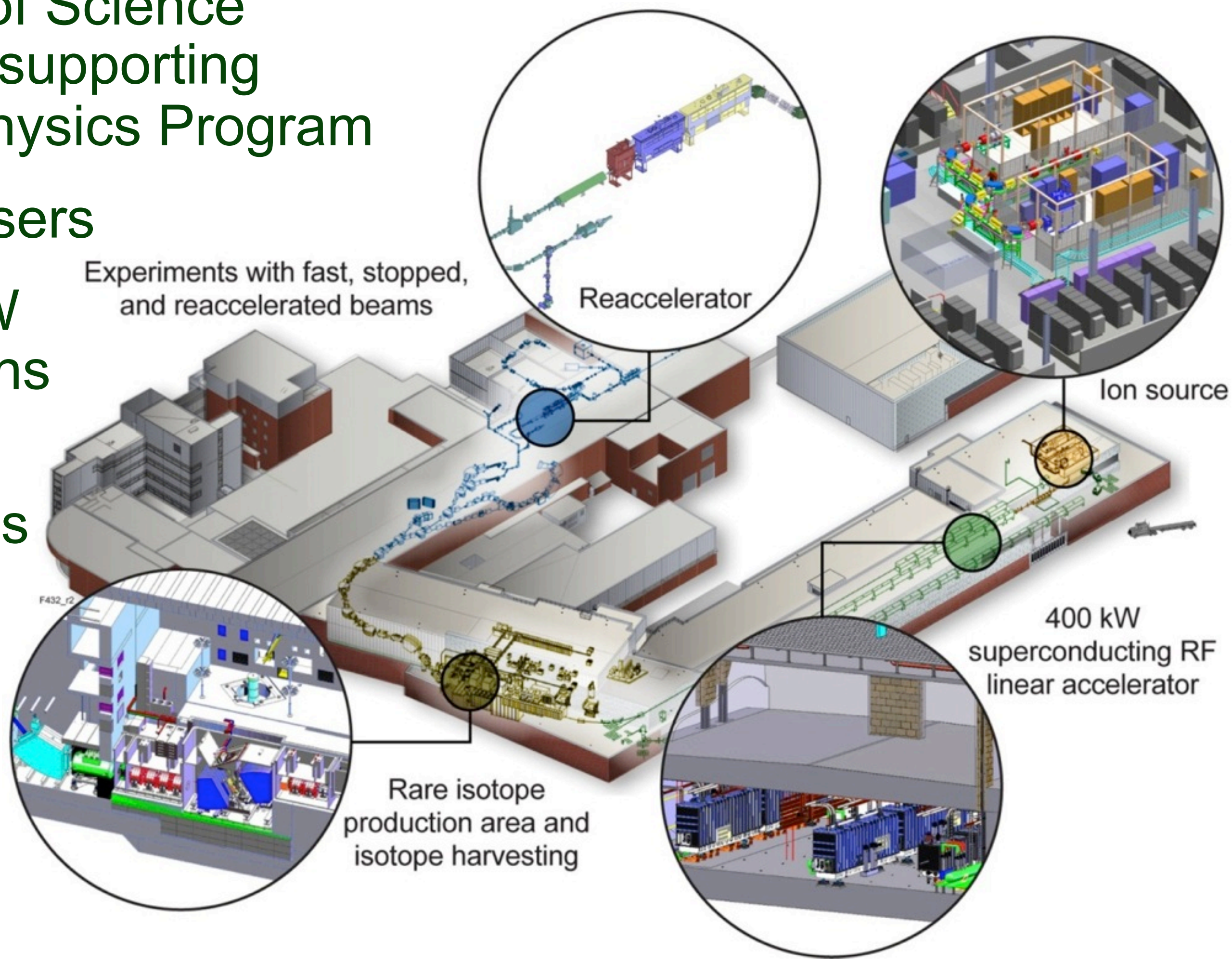
> Most of the CARIBU beams (species and energy) are not available anywhere else. This will remain so at least until FRIB turns on.

- **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).

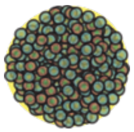
FRIB

- A future DOE Office of Science scientific user facility supporting mission of Nuclear Physics Program
- Serving over 1,400 users
- Key feature is 400 kW beam power for all ions (e.g. 5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams



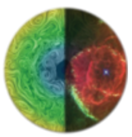
FRIB Science Is Important for the Nation

Articulated by National Research Council RISAC Report (2006), NSAC LRP (2007), NRC Decadal Survey of Nuclear Physics (2012)



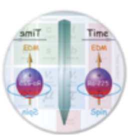
Properties of nuclei

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



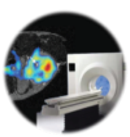
Astrophysical processes

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



Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

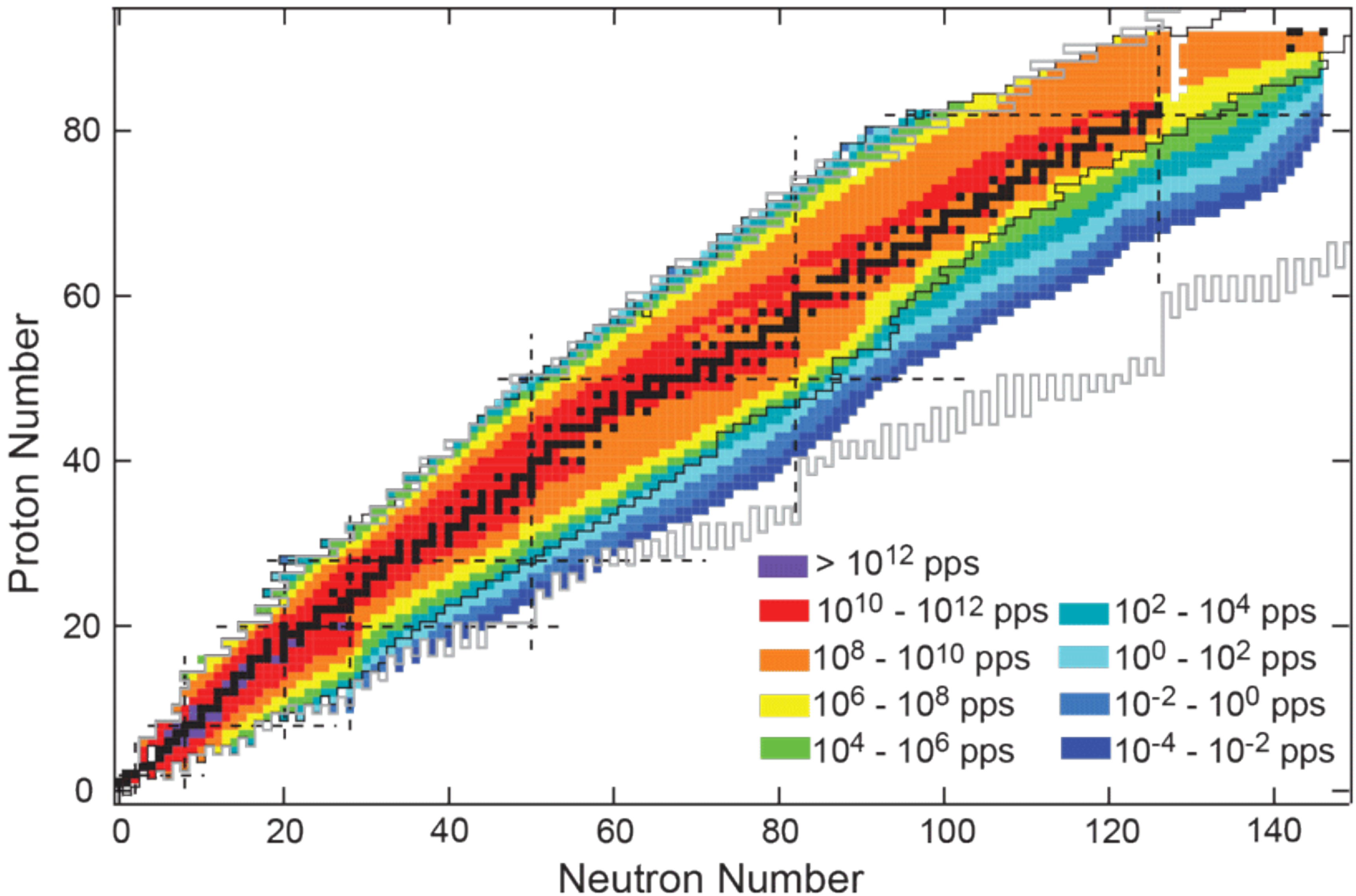


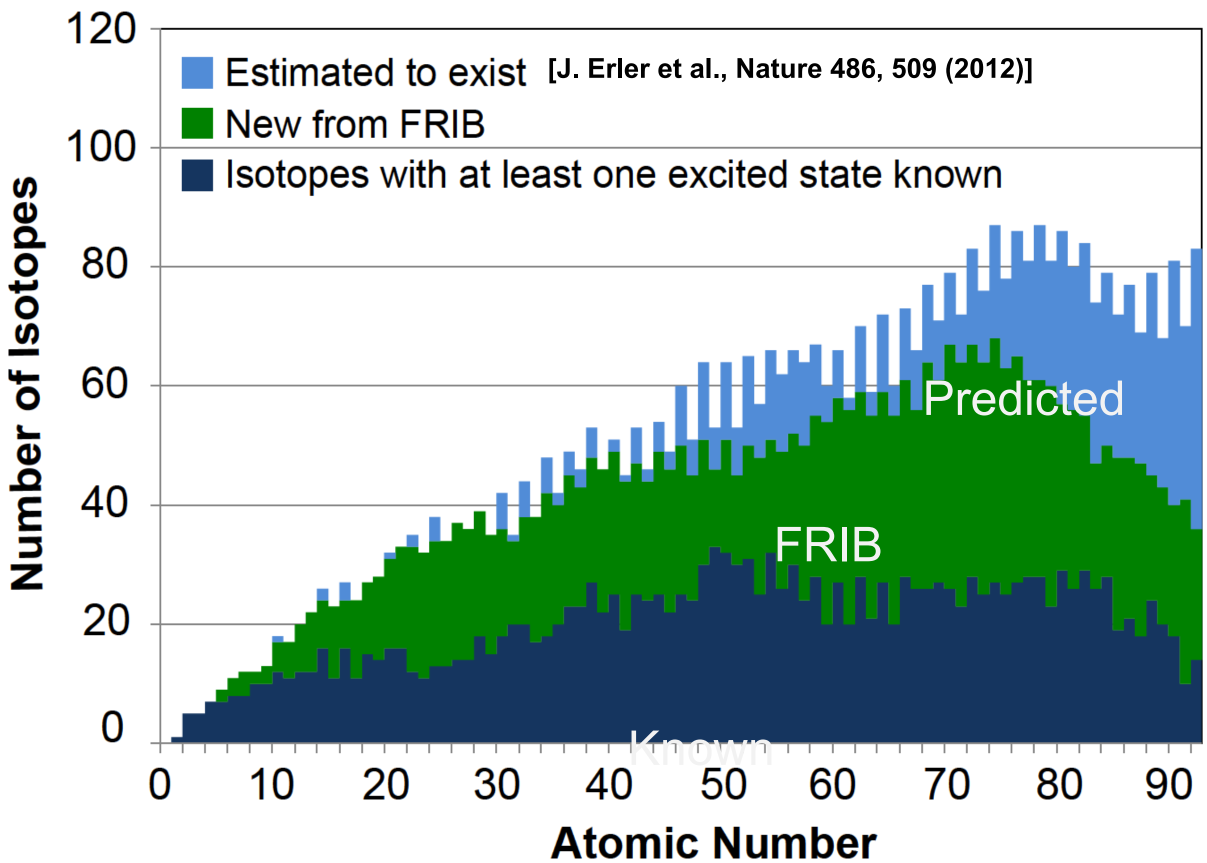
Societal applications and benefits

- Bio-medicine, energy, material sciences
- National security

> *"Data to date on exotic nuclei are already beginning to revolutionize our understanding of the structure of atomic nuclei. FRIB will enable experiments in uncharted territory at the limits of nuclear stability. FRIB will provide new isotopes for research related to societal applications, address long-standing questions about the astrophysical origin of the elements and the fundamental symmetries of nature."*
>
> 2012 NRC Decadal Study

FRIB Projected Production Rates
Drip line explored up through Zr (Z=40)

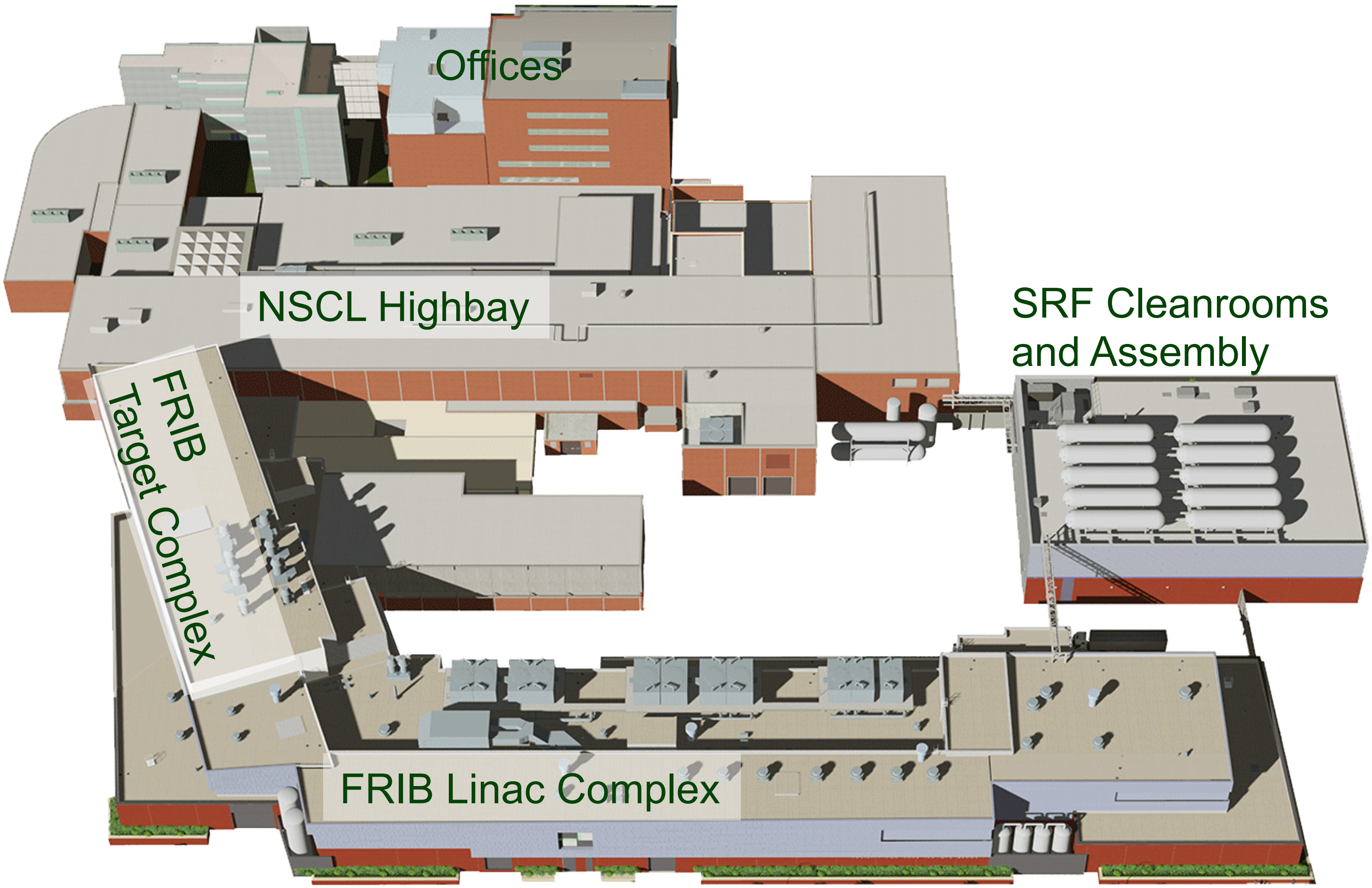




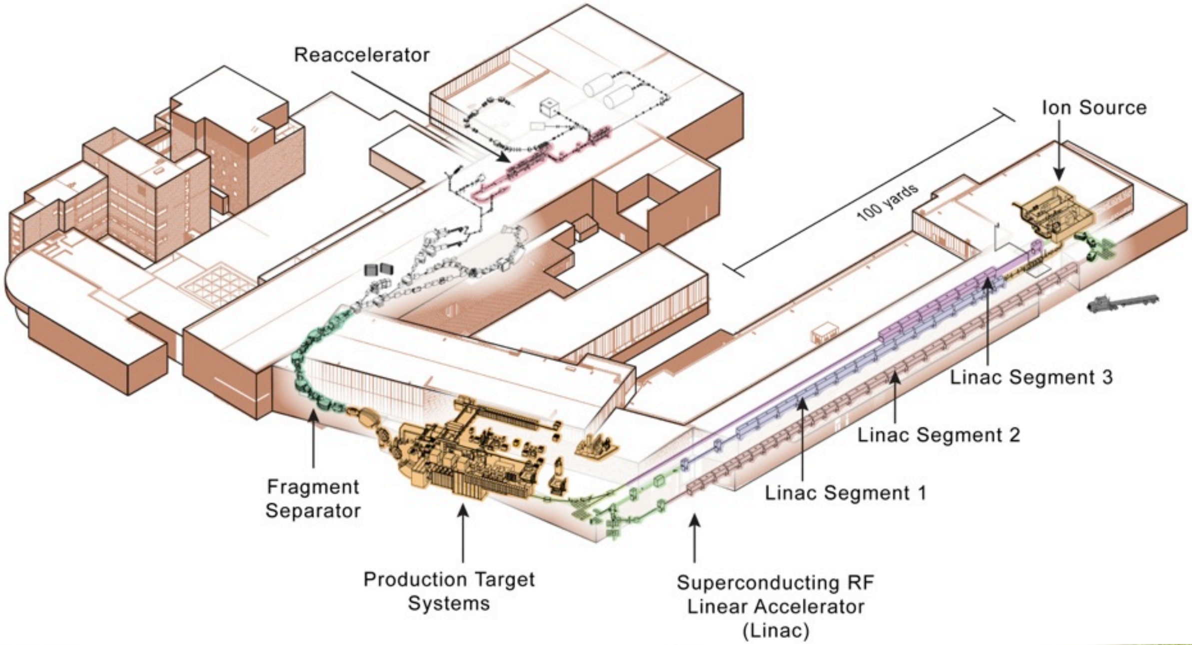
- Cross section corresponding to the production of 1 atom/week at FRIB:

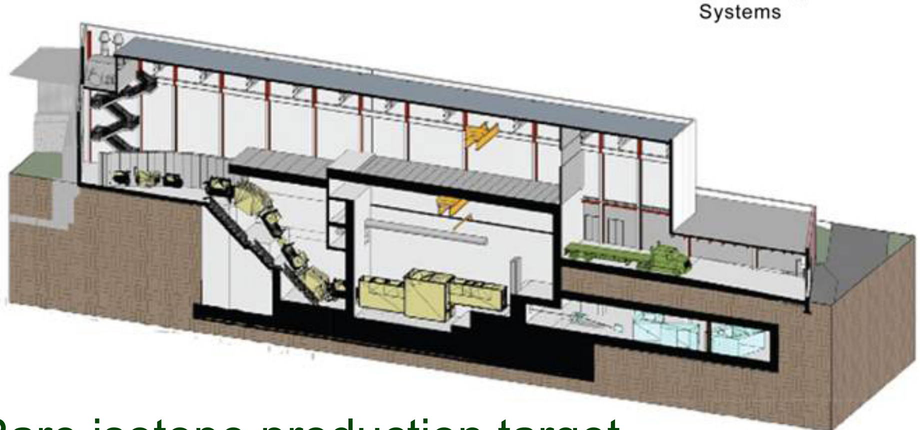
  ~ 30 $x10^{-21}$ b (zepto) , 5 orders of magnitude lower than at present facilities

Integrated Site Plan Optimized for Science

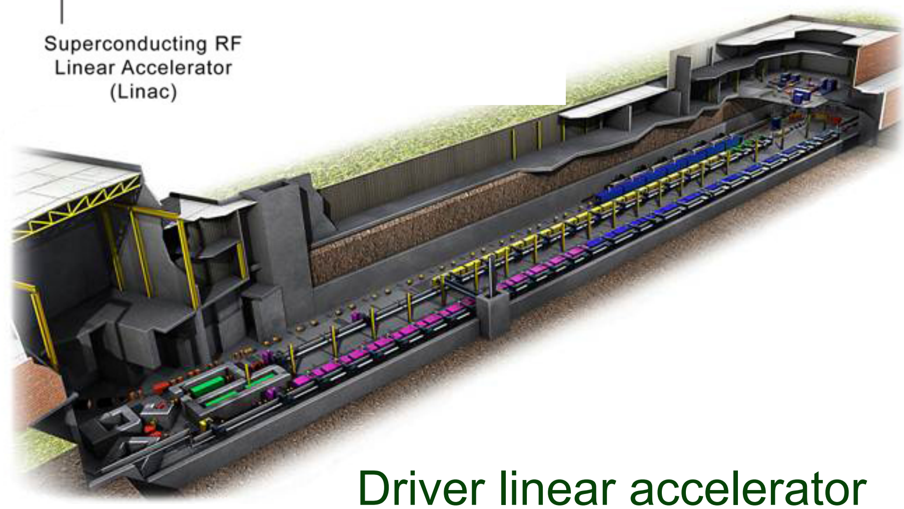


Facility Layout





Rare isotope production target



Driver linear accelerator

FRIB Technical Construction on Track

4.5 K cold box like Jlab 12 GeV

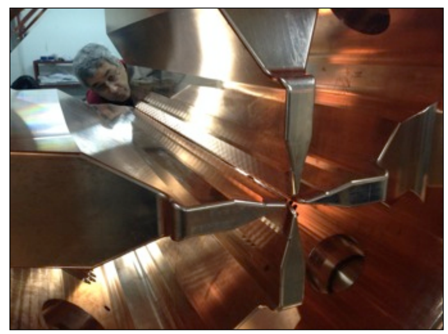
Master slave manipulators

Cryomodule

Bottom loading port

SRF half-wave cavity

Non-conventional utilities tanks



RFQ

Cold beam-position monitor

Superconducting magnet fabrication

SRF quarter-wave cavity processing

Over 1400 Users Engaged and Ready for Science

FRIB Users Organization
FACILITY FOR RARE ISOTOPE BEAMS

- Users are organized as part of the independent FRIB Users Organization (FRIBUO) www.fribusers.org
  - Chartered organization with an elected executive committee
  - 1,418 members (92 U.S. colleges and universities, 10 national laboratories, 51 countries) as of February 2015
  - 19 working groups on instruments
  - 21-23 August 2014, Low Energy Community Meeting, Texas A&M University

    "*The highest priority in low-energy nuclear physics and nuclear astrophysics is the timely completion of the Facility for Rare Isotope Beams and the initiation of its full science program.*"

    www.lecmeeting.org/preambleAndResolutionsTAMU2014.pdf

FRIB Timeline

- 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 – Civil construction started
- September 2014 – CD-3b approved (start technical construction)
- October 2014 – Technical construction started
- March 2015 – DOE Office of Project Assessment review
- Managing to early completion in December 2020, CD-4 is June 2022
- Full power 2025

INSTRUMENTATION

A variety of instrumentation is required to make use of science opportunities with rare isotope beams.

Improvements in instrumentation greatly extend the physics reach of the facilities.

Gamma detectors

- Usually *arrays* of HPGe detectors or scintillators
- *In-beam* or *out-of-beam*

Recoil and light-ion detectors

- Magnetic spectrometers and separators
- Gas counters
- Si detectors (usually DSSD or position-sensitive)
- Scintillators

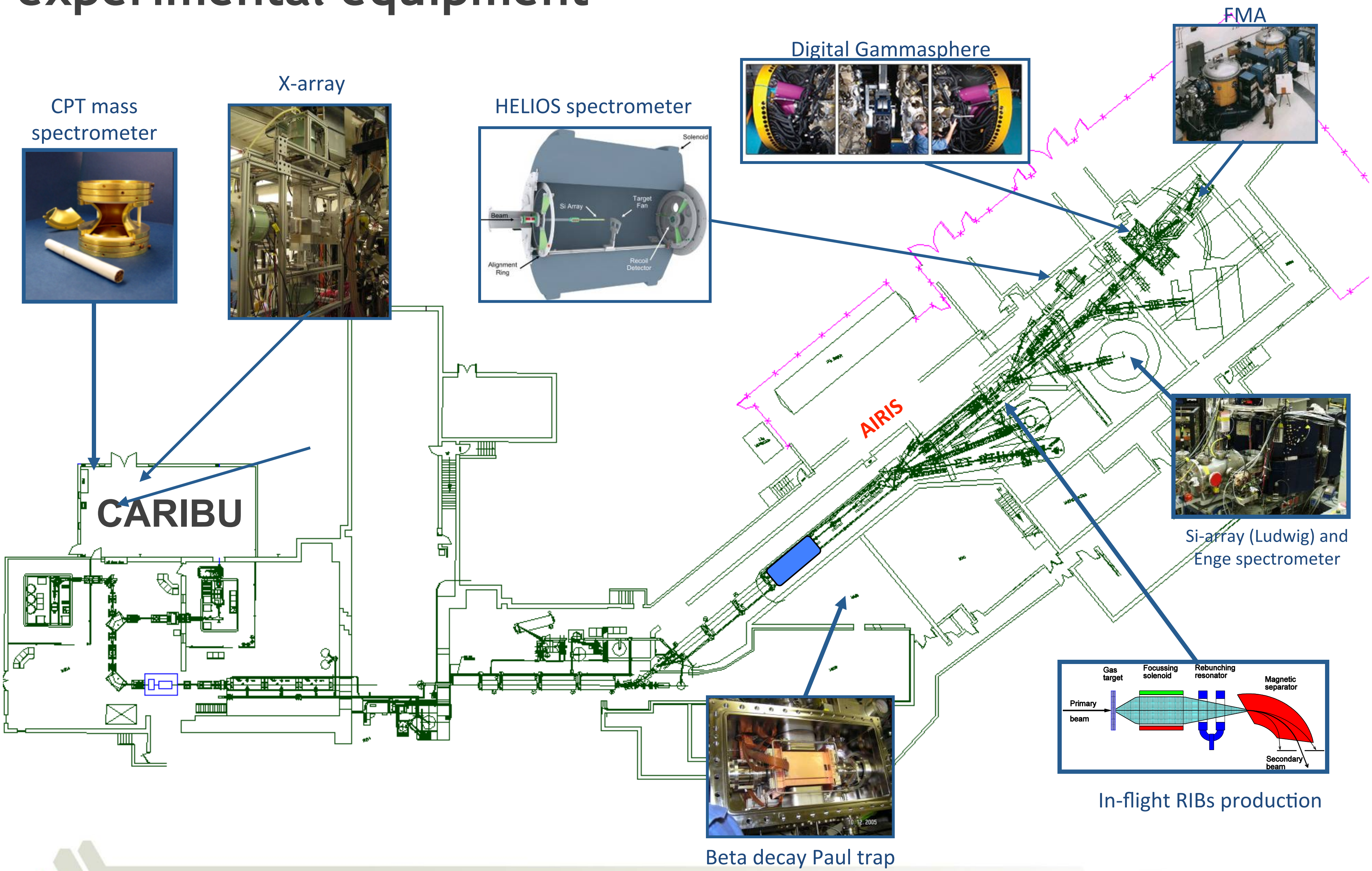
Electronics

- Waveform digitizers, ASICs, preamps
- Digital pulse processing

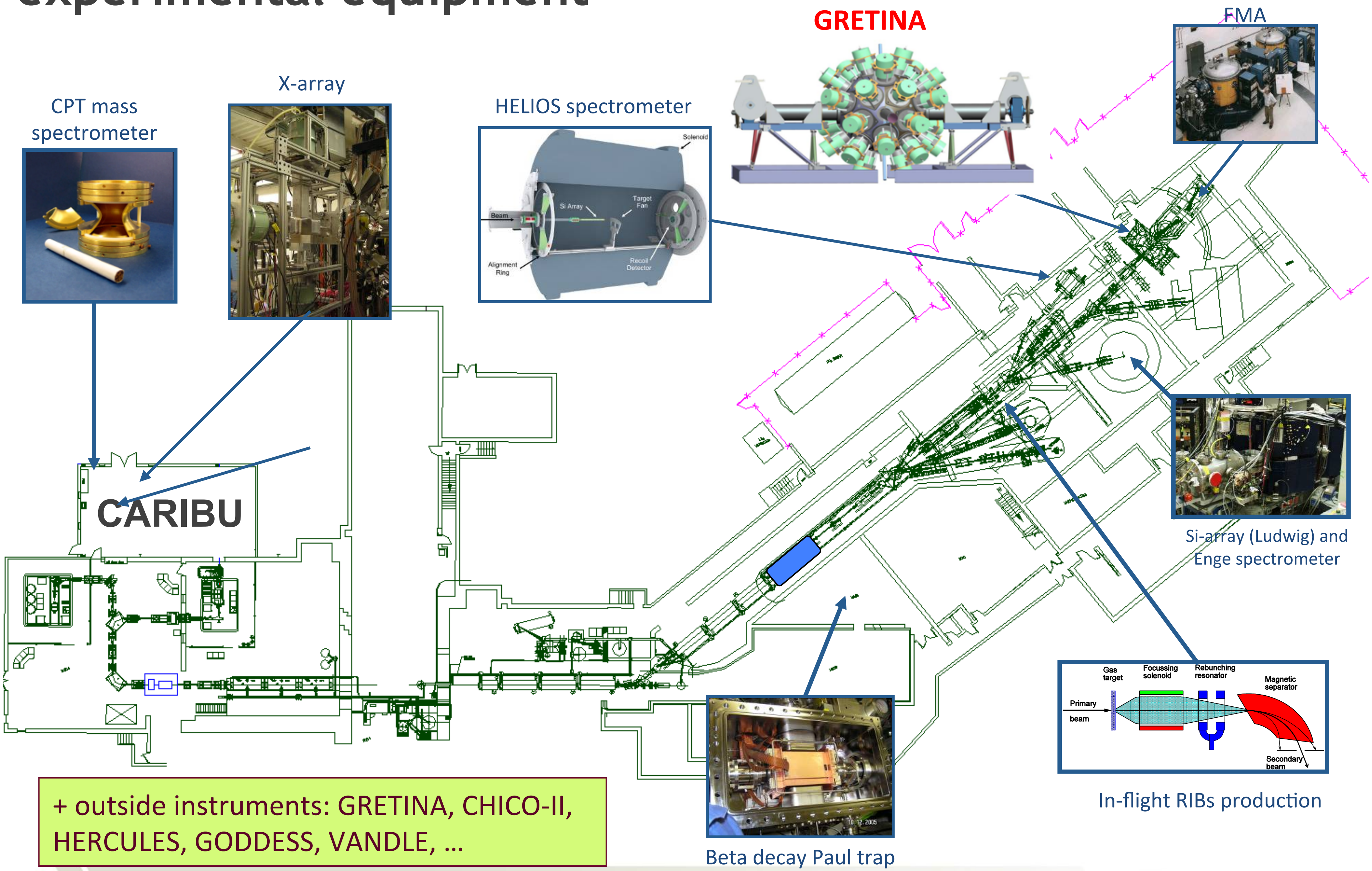
All of these have benefited greatly from the DOE-SC SBIR/STTR

Several examples presented at this meeting

Main tools enabling the physics: ATLAS suite of experimental equipment

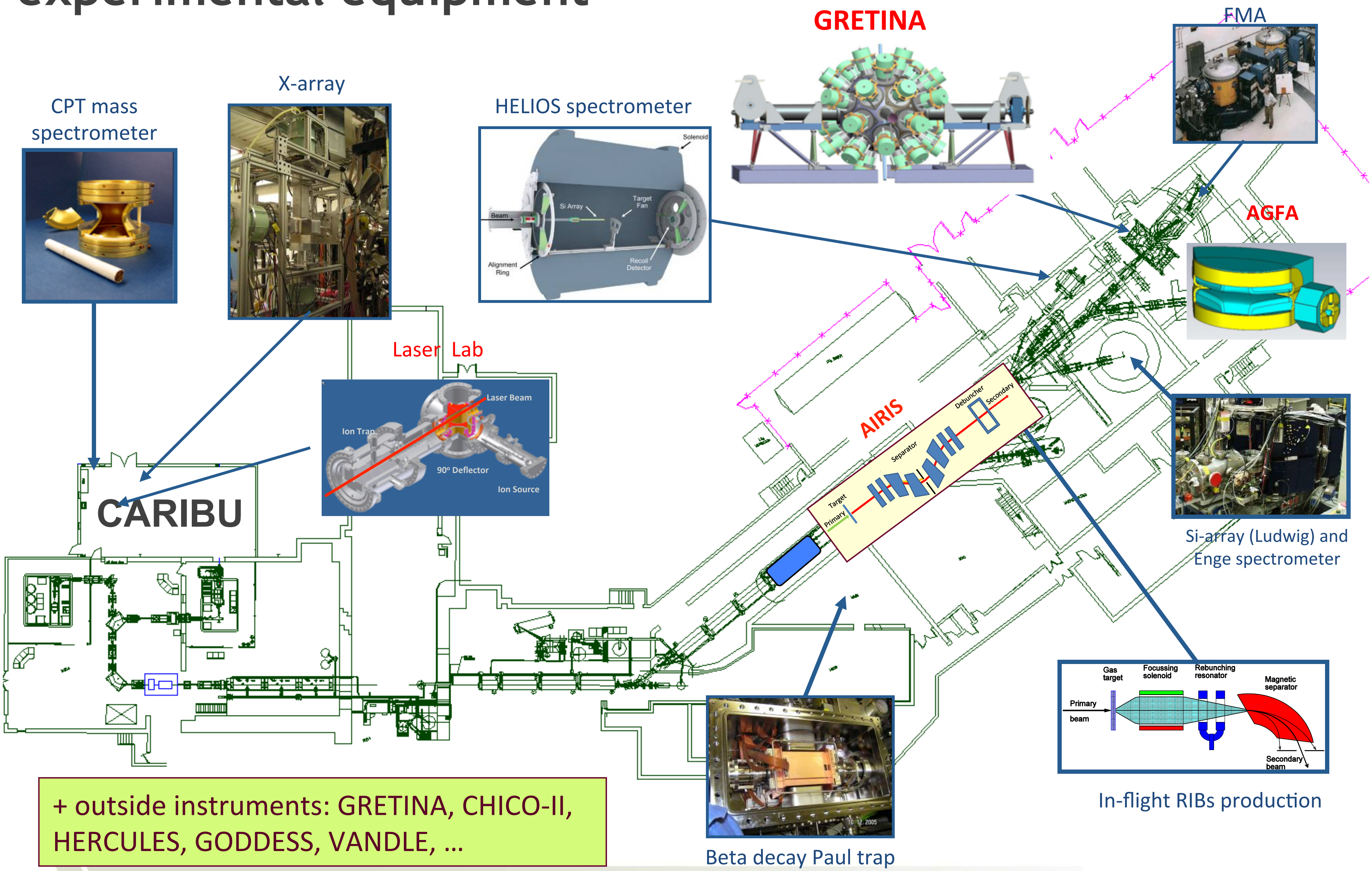


Main tools enabling the physics: ATLAS suite of experimental equipment



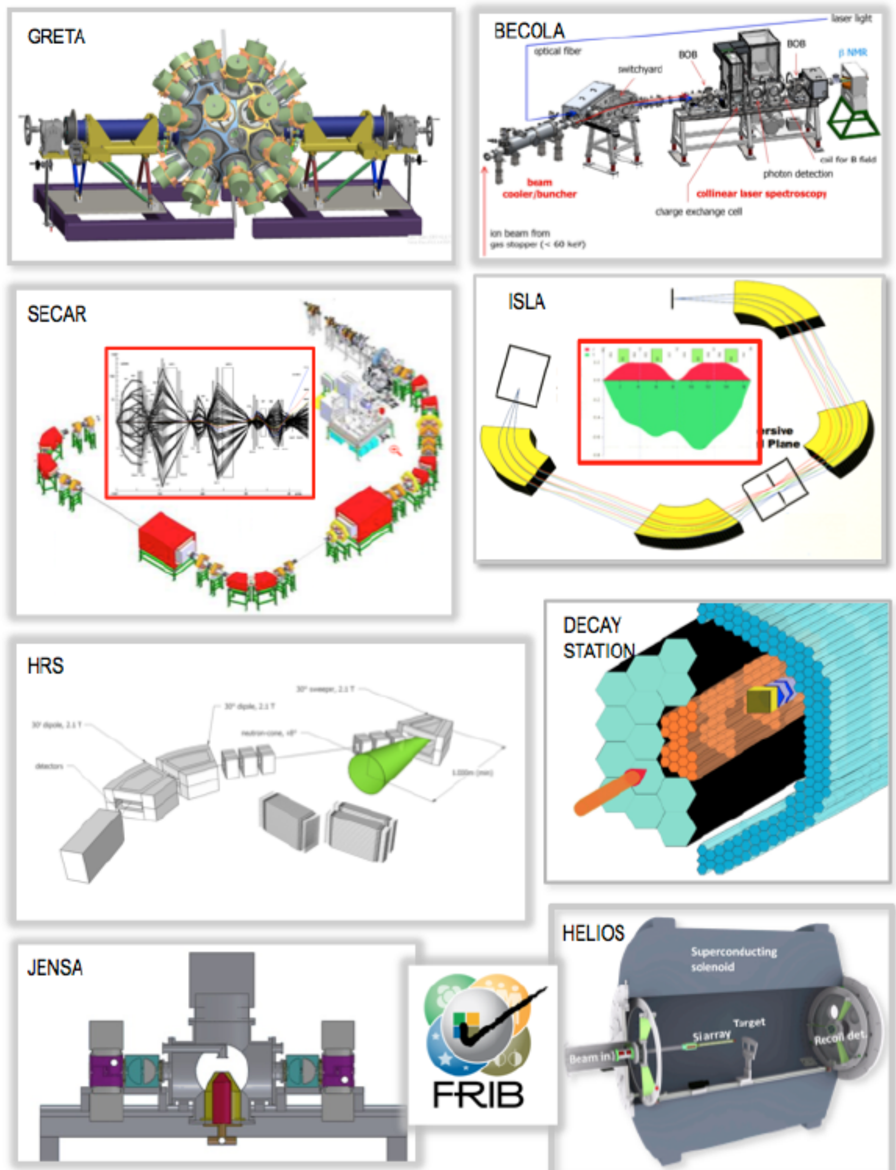
+ outside instruments: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, …

Main tools enabling the physics: ATLAS suite of experimental equipment

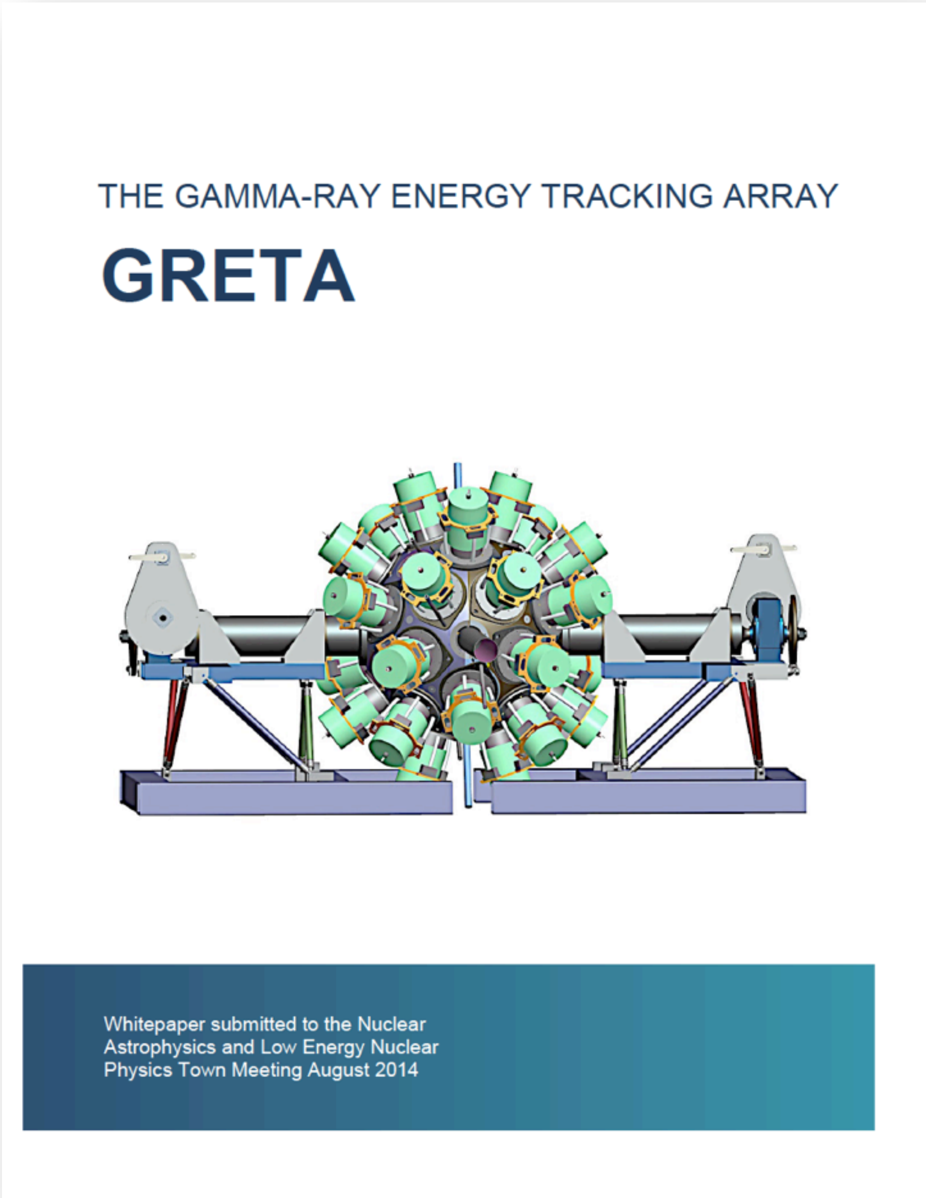


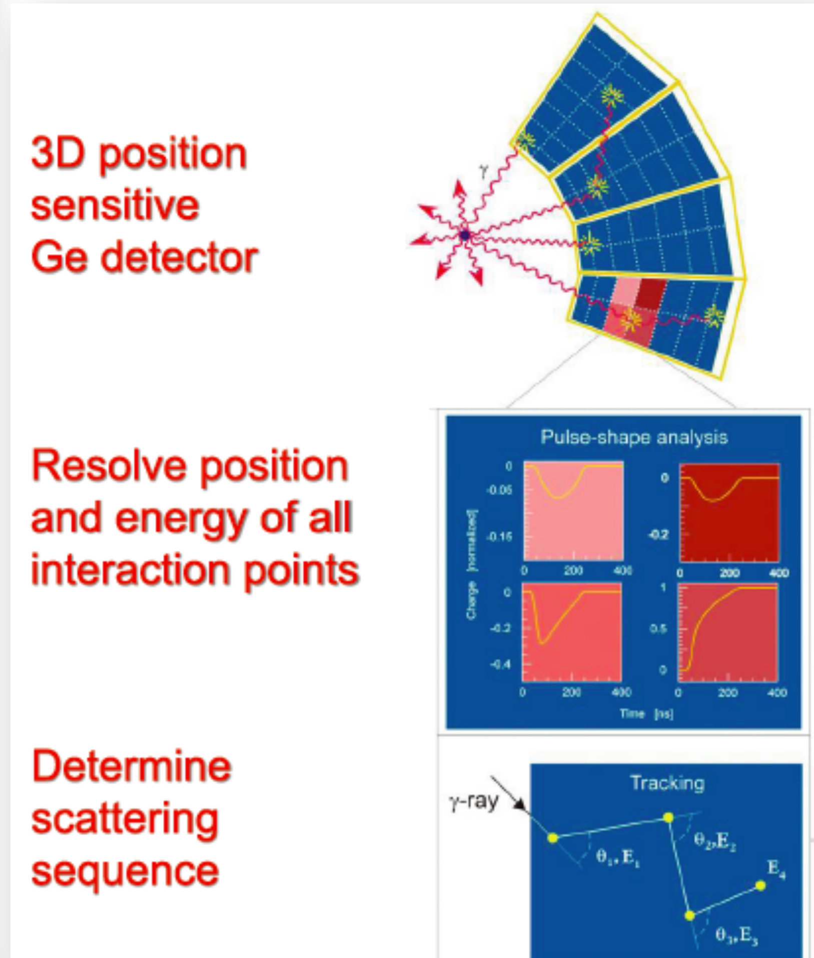
+ outside instruments: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, …

Experimental Equipment Needs for The Facility for Rare Isotope Beams (FRIB)

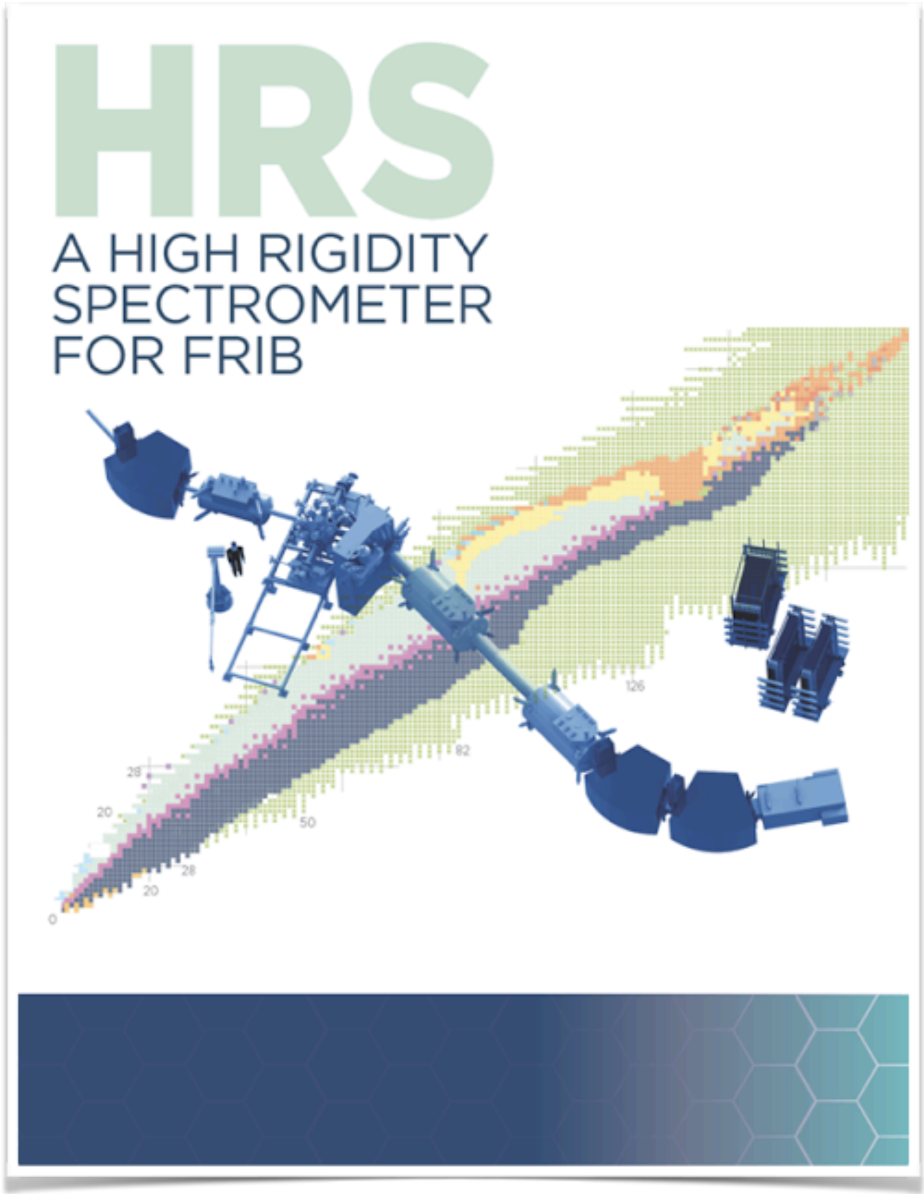


Prepared for the APS DNP Low Energy Town Meeting
August 21, 2014





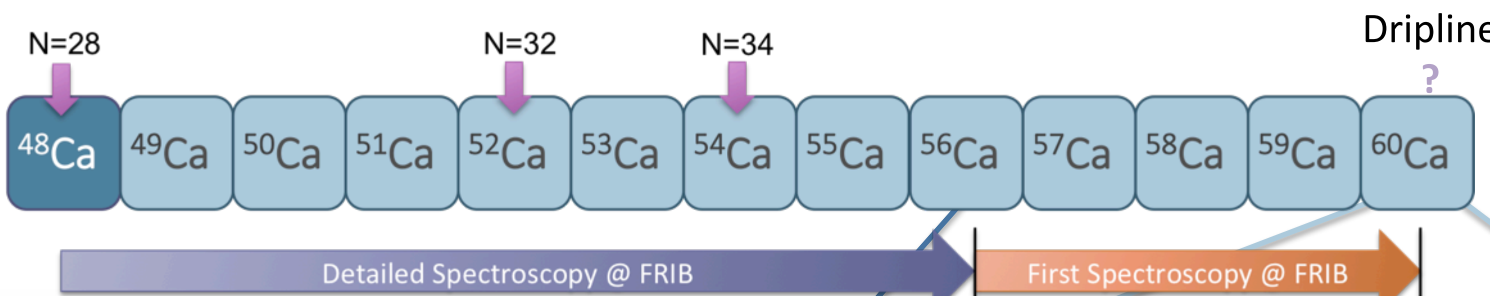
www.greta.lbl.gov

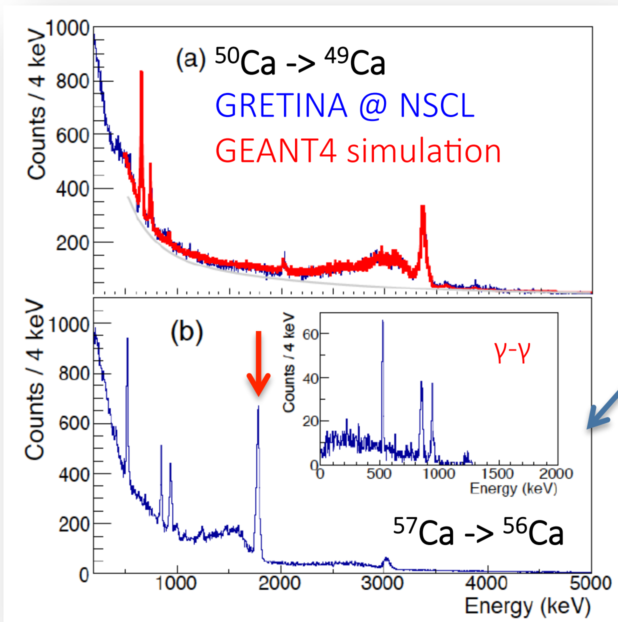


www.hrs.lbl.gov

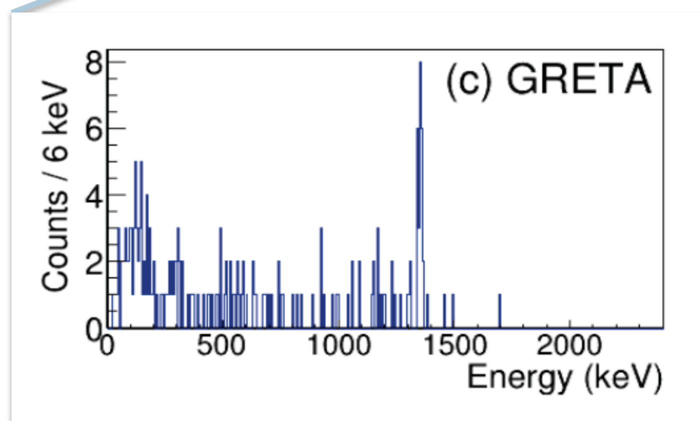
GRETA + High-Rigidity Spectrometer at FRIB

- The neutron-rich Ca isotopes beyond ^{48}Ca provide dramatic examples of shell evolution
- Microscopic calculations suggest a sensitivity of the detailed structure to the inclusion of 3N forces





- Detailed studies of single particle structure, provide a critical test of effective interactions and 3N forces
- The structure around ^{60}Ca informs the location of the dripline at Z = 20



GRETA will have superior resolving power for fast-beam experiments compared to any other γ-ray detector

Gamma Ray Energy Tracking In beam Nuclear Array

$20M Funded by US- DOE Nuclear Physics Office

- **A first realization of a Tracking Array**

  Optimized for fast beam experiments
- **Coverage ~ ¼ of 4π solid angle**
- **28 36-fold segmented Ge crystals (7 Modules)**
- **Mechanical support structure**
- **Data acquisition system**
- **Data processing software**

Gamma Ray Energy Tracking In beam Nuclear Array

Nuclear Instruments and Methods in Physics Research A 709 (2013) 44–55

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA

S. Paschalis [a,*], I.Y. Lee [a,**], A.O. Macchiavelli [a], C.M. Campbell [a], M. Cromaz [a], S. Gros [a], J. Pavan [a], J. Qian [a], R.M. Clark [a], H.L. Crawford [a], D. Doering [a], P. Fallon [a], C. Lionberger [a], T. Loew [a], M. Petri [a], T. Stezelberger [a], S. Zimmermann [a], D.C. Radford [b], K. Lagergren [b], D. Weisshaar [c], R. Winkler [c], T. Glasmacher [c], J.T. Anderson [d], C.W. Beausang [e]

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[d] *Argonne National Laboratory, Argonne, IL 60439, USA*
[e] *Department of Physics, University of Richmond, 28 Westhampton Way, Richmond, VA 23173, USA*

- **Data processing software**

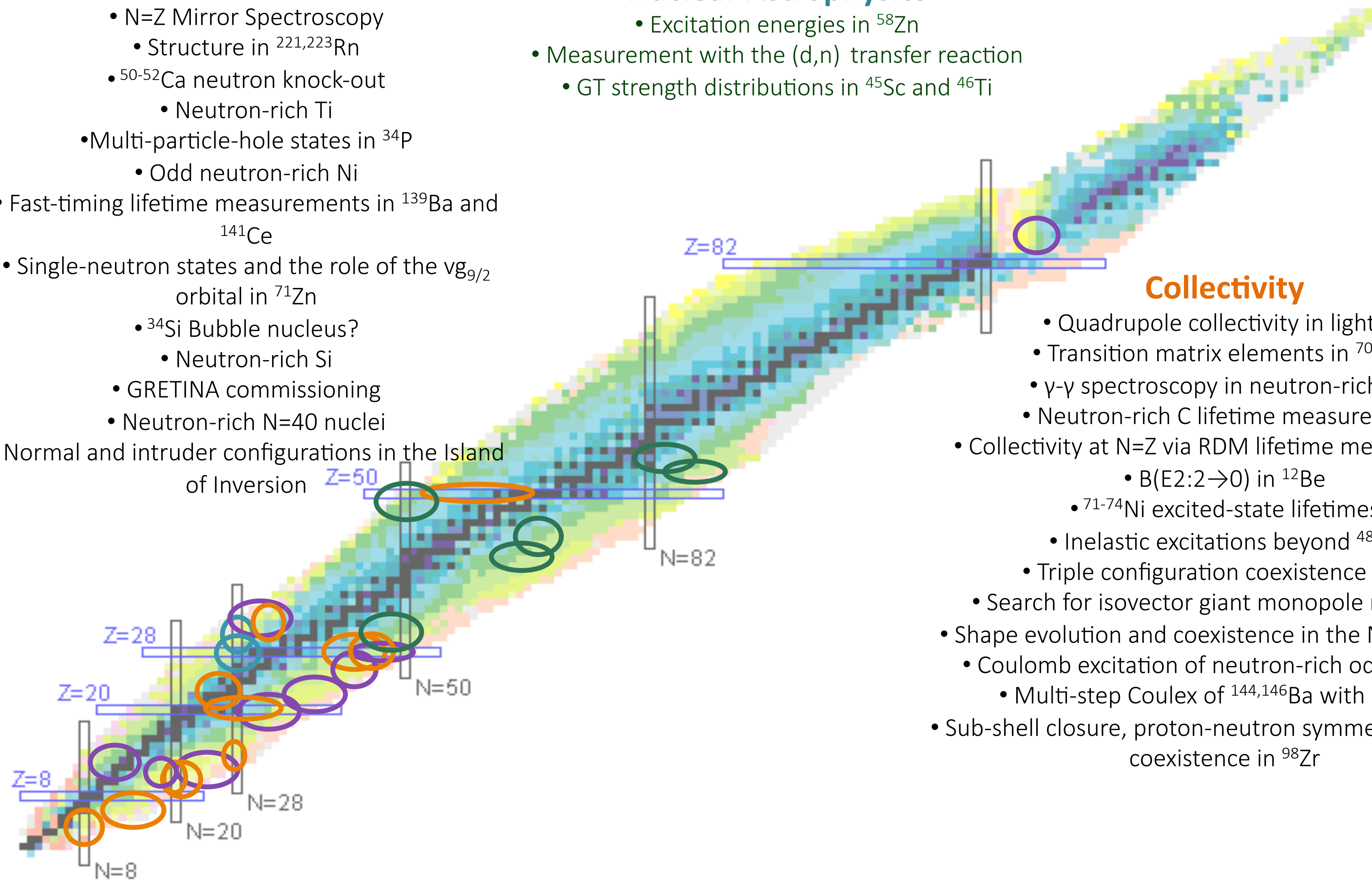
Physics campaigns: NSCL(2012/13) and ATLAS(2014/15)

Nuclear Shell Evolution

- N=Z Mirror Spectroscopy
- Structure in ^{221,223}Rn
- $^{50\text{-}52}$Ca neutron knock-out
- Neutron-rich Ti
- Multi-particle-hole states in ^{34}P
- Odd neutron-rich Ni
- Fast-timing lifetime measurements in ^{139}Ba and ^{141}Ce
- Single-neutron states and the role of the $\nu g_{9/2}$ orbital in ^{71}Zn
- ^{34}Si Bubble nucleus?
- Neutron-rich Si
- GRETINA commissioning
- Neutron-rich N=40 nuclei
- Normal and intruder configurations in the Island of Inversion

Nuclear Astrophysics

- Excitation energies in ^{58}Zn
- Measurement with the (d,n) transfer reaction
- GT strength distributions in ^{45}Sc and ^{46}Ti



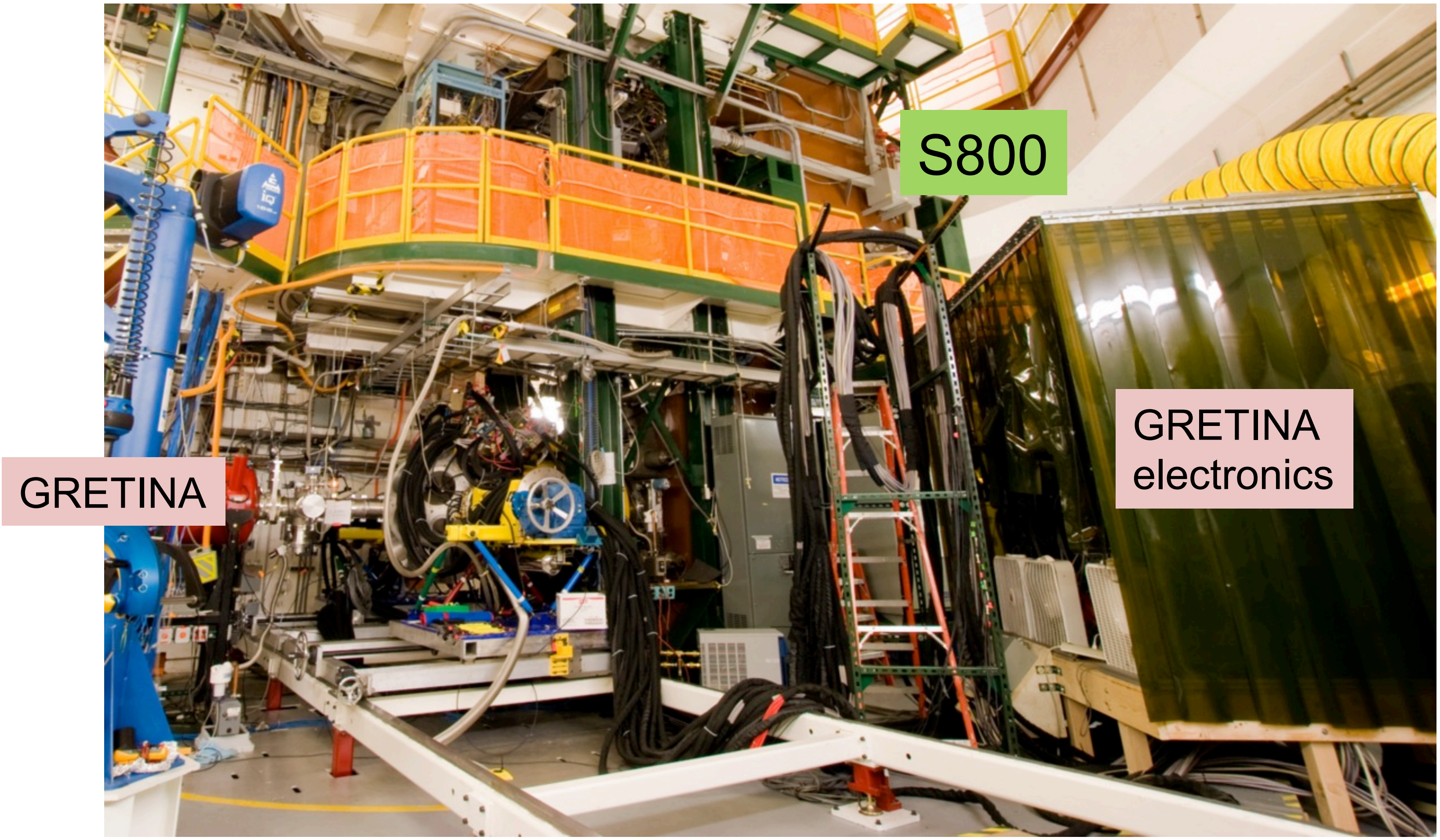
Collectivity

- Quadrupole collectivity in light Sn
- Transition matrix elements in ^{70,72}Ni
- γ-γ spectroscopy in neutron-rich Mg
- Neutron-rich C lifetime measurement
- Collectivity at N=Z via RDM lifetime measurements
- B(E2:2→0) in ^{12}Be
- $^{71\text{-}74}$Ni excited-state lifetimes
- Inelastic excitations beyond ^{48}Ca
- Triple configuration coexistence in ^{44}S
- Search for isovector giant monopole resonance
- Shape evolution and coexistence in the Mo-Ru region
- Coulomb excitation of neutron-rich odd-odd ^{98m}Y
- Multi-step Coulex of ^{144,146}Ba with CARIBU
- Sub-shell closure, proton-neutron symmetry and shape coexistence in ^{98}Zr

Thanks to Heather Crawford

Science campaign at NSCL: July 2012 – June 2013

- **23 experiments : 3360 hours**



GRETINA at target position of S800 spectrograph

Science campaign at NSCL: July 2012 – June 2013

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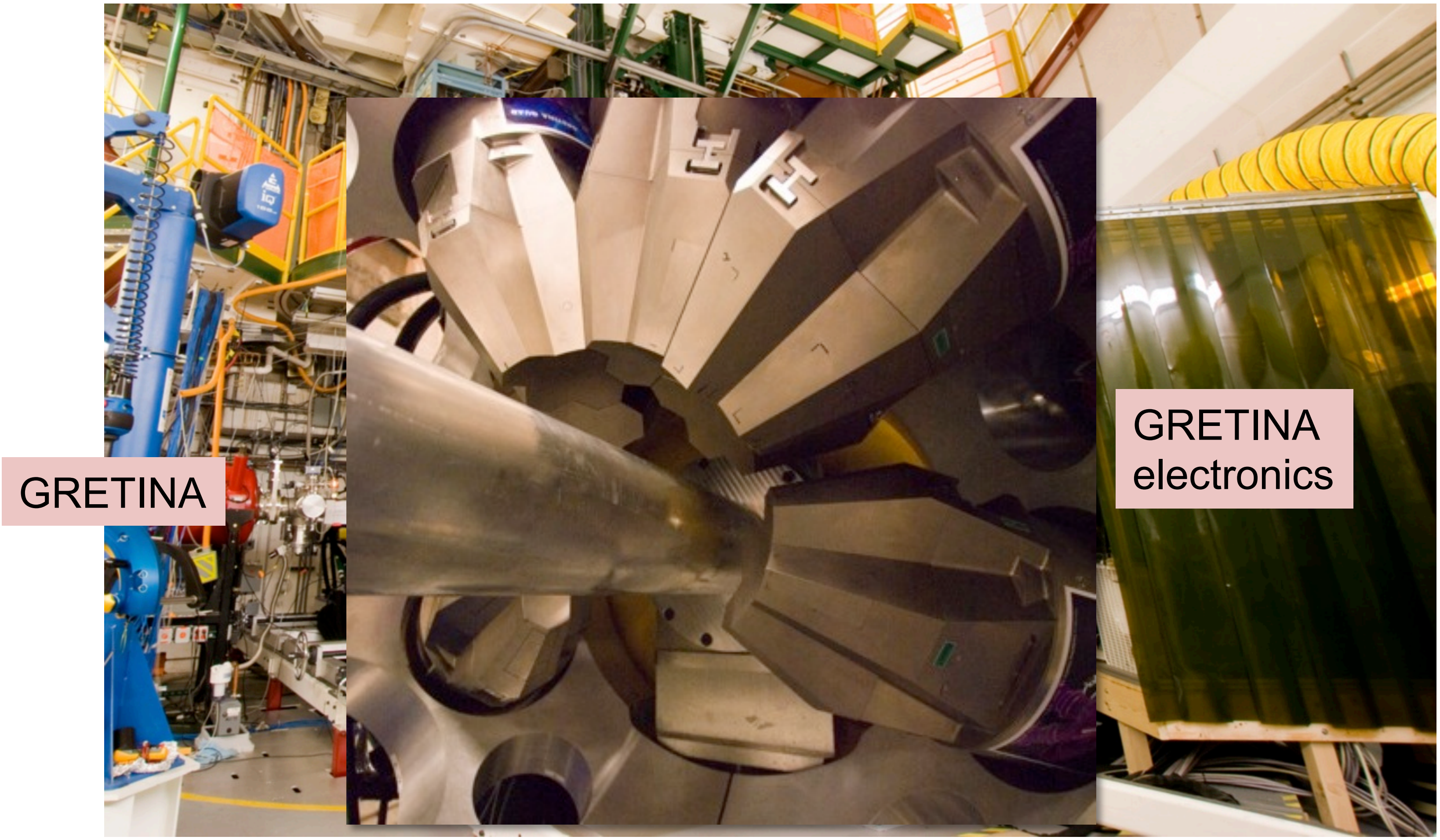
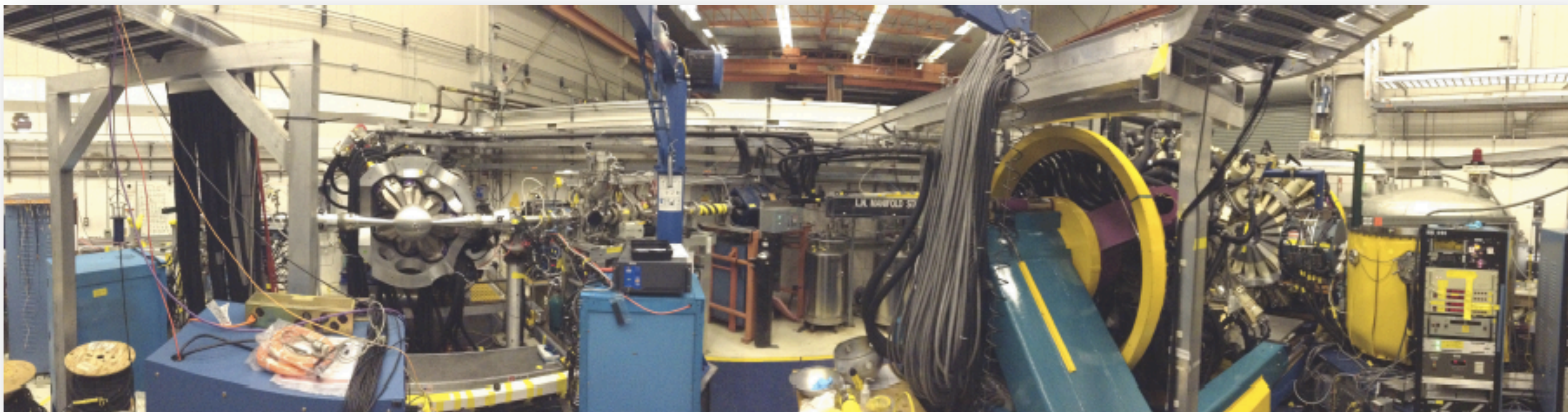


GRETINA at target position of S800 spectrograph

At ATLAS/ANL March 2014 – June 2015

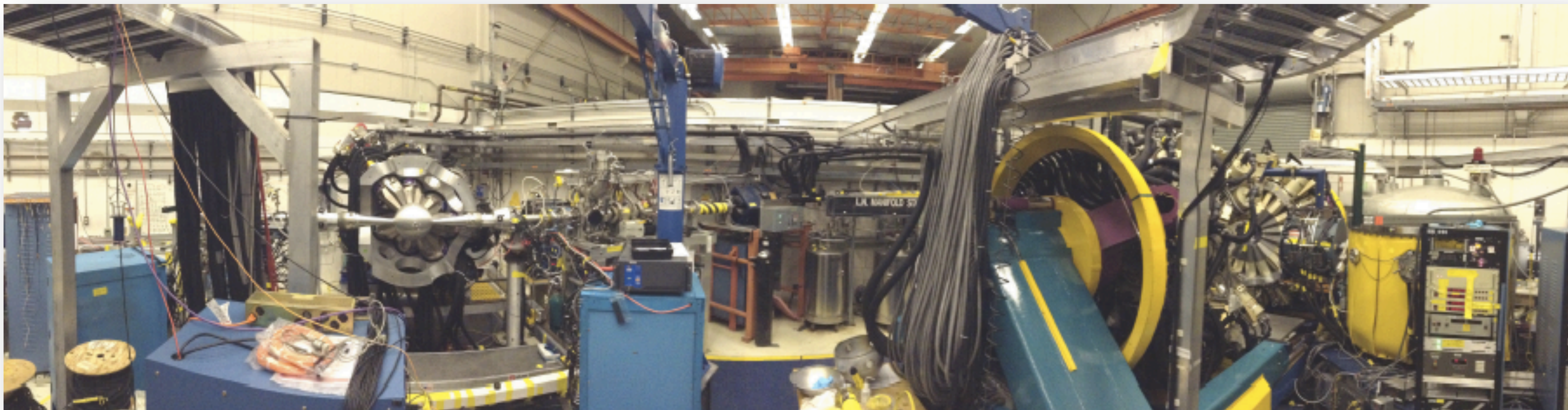
- **18 experiments : 2650 hours**



Neutron-rich nuclei – CARIBU beams

At ATLAS/ANL March 2014 – June 2015

- 18 experiments : 2650 hours

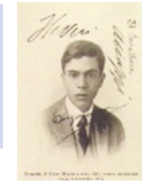


Neutron-rich nuclei – CARIBU beams

On its way back to NSCL for a 2nd campaign October 2015 – Spring 2017

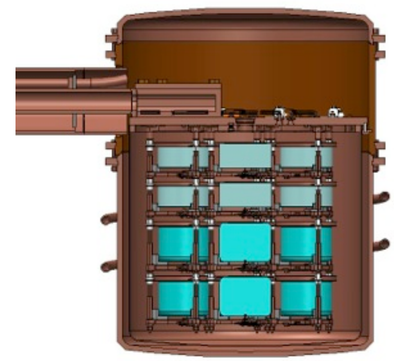
- PAC39: 11 experiments approved ~1500 hours

The MAJORANA DEMONSTRATOR

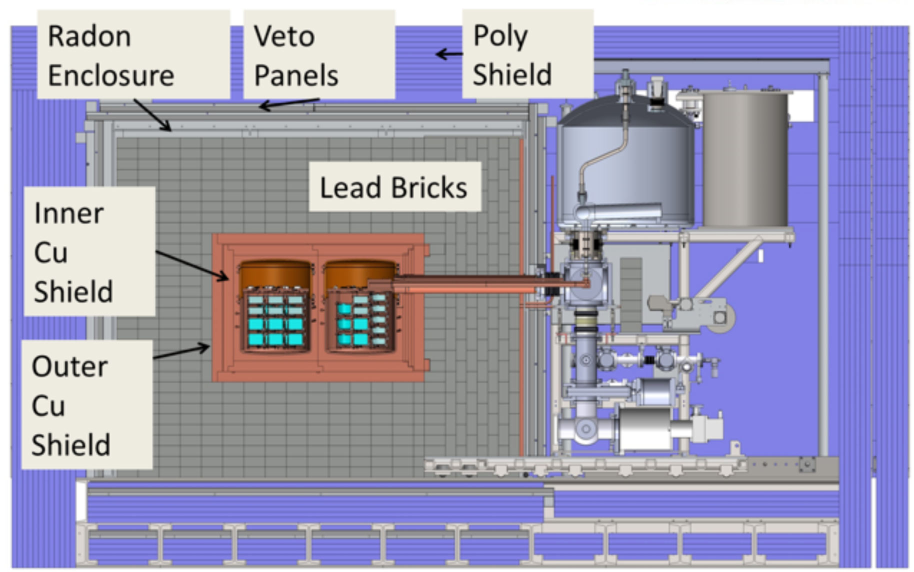


Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
with additional contributions from international collaborators.

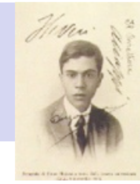
Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
  scales to 1 count/ROI/t/y for a tonne experiment
- **44-kg of Ge detectors**
  - **29 kg of 87% enriched ^{76}Ge crystals**
  - **15 kg of ^{nat}Ge**
  - **Detector Technology: P-type, point-contact.**
- **2 independent cryostats**
  - **ultra-clean, electroformed Cu**
  - **20 kg of detectors per cryostat**
  - **naturally scalable**
- **Compact Shield**
  - **low-background passive Cu and Pb shield with active muon veto**

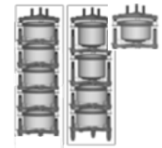


MAJORANA DEMONSTRATOR Implementation



Three Steps

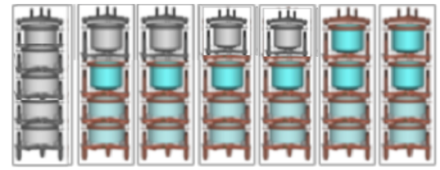
Prototype cryostat: 7.0 kg (10) ^{nat}Ge



June 2014

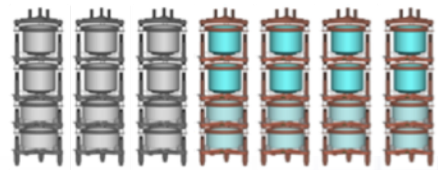
Same design as Modules 1 and 2, but fabricated using OFHC Cu Components

Module 1: 16.8 kg (20) ^{enr}Ge
5.7 kg (9) ^{nat}Ge

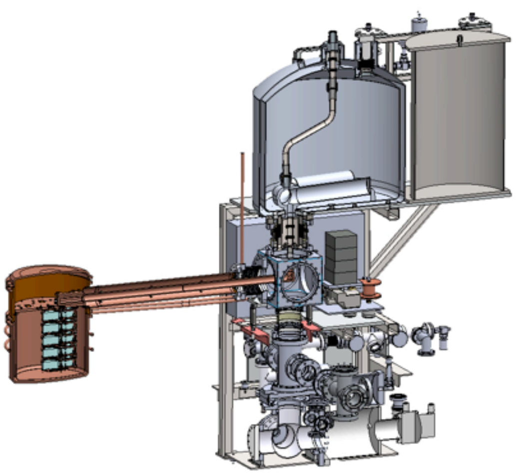


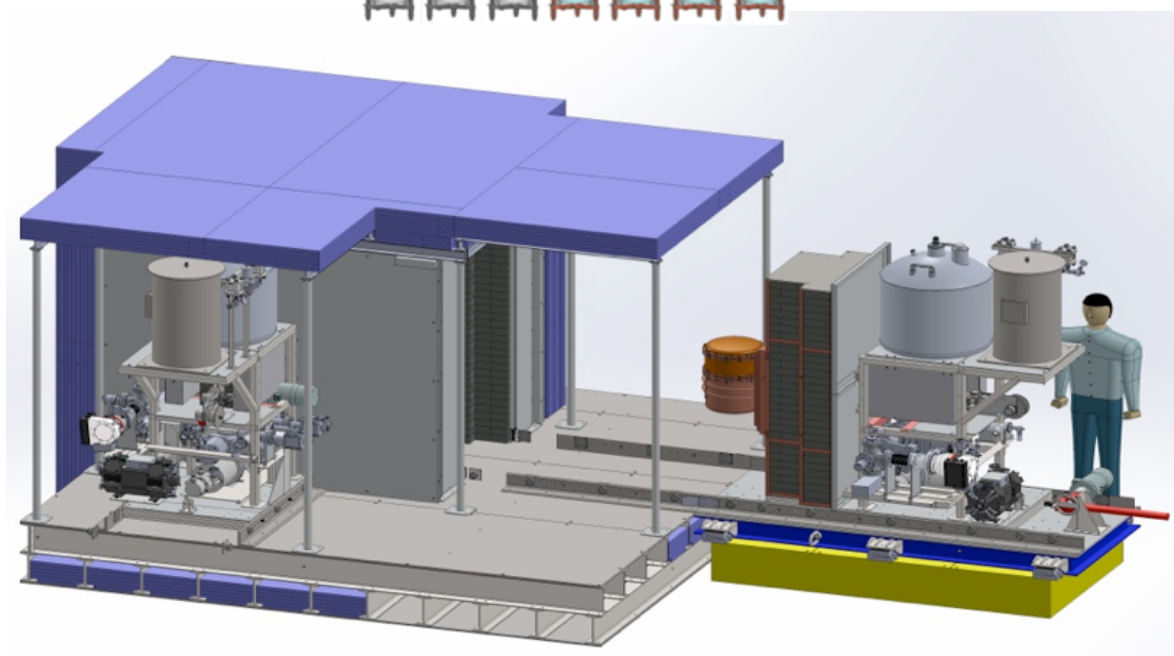
May 2015

Module 2: 12.6 kg (14) ^{enr}Ge
9.4 kg (15) ^{nat}Ge



End 2015





Summary

These are exciting times for nuclear physics research in the US

Specifically to the Low Energy Program:

- Existing facilities provide world-class research opportunities

- FRIB will be the leading rare isotope facility in the world. It will enable experiments in uncharted territory at the limits of nuclear stability.

A strong user community exists, >1400 members engaged and ready for science.

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With new facilities being built (worldwide) and existing facilities being upgraded, there is a need for new techniques, instrumentation, and supporting system to extend their physics reach.

These developments are suitable for SBIR/STTR projects in every topic .

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The DOE NP SBIR/STTR program is important to the Low Energy Nuclear Physics in the US, and contributes to its success.

Thank You!