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U.S. DEPARTMENT OF ENERGY
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Recent highlights and future prospects for GRETINA and GRETA

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INTRANS 2024 Workshop
22-25 january 2024
Auditorium P. Lehmann - bldg 200

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis
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Outline

- Introduction
  - Why we need GRETA

- The GRETINA Era
  - First Experiments at FRIB

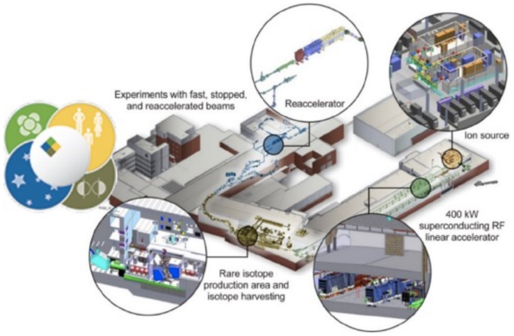
- The GRETA ERA
  - Overview and Status

GRETA: A premier γ-ray tracking detector for FRIB

The Facility for Rare Isotope Beams (FRIB) is a world leading accelerator facility to understand the properties of exotic nuclei and how the elements are synthesized.

GRETA will be a key instrument at FRIB capable of reconstructing the energy and three-dimensional position of γ-ray interactions.

Its design provides the unprecedented performance (combination of full solid angle coverage and high efficiency, excellent energy and position resolution, and good background rejection) needed to carry out a large fraction of the nuclear science programs at FRIB.



FRIB at Michigan State University

GRETA

The GRETA Physics Case Mirrors that of FRIB

… or why we need a GRETA (a high-resolution γ-ray array)

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?
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(α,γ) 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 ✓

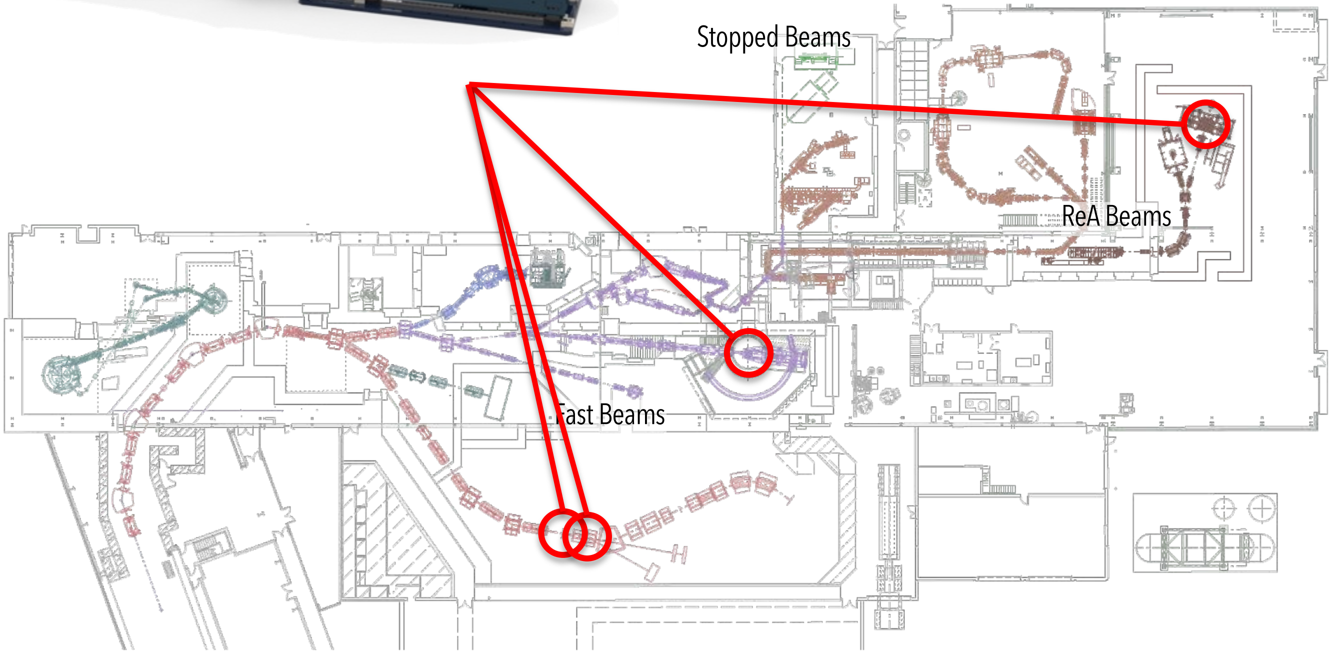
✓ indicate topics where GRETA will be used.

17 Benchmark programs introduced by the NSAC Rare-Isotope beam task force (2007).

GRETA: A Major instrument at FRIB

GRETA will be a major instrument at FRIB and provides the sensitivity to enable a broad range of physics with both fast-fragmentation and reaccelerated beams

Designed (and expected) to be used on multiple beam lines



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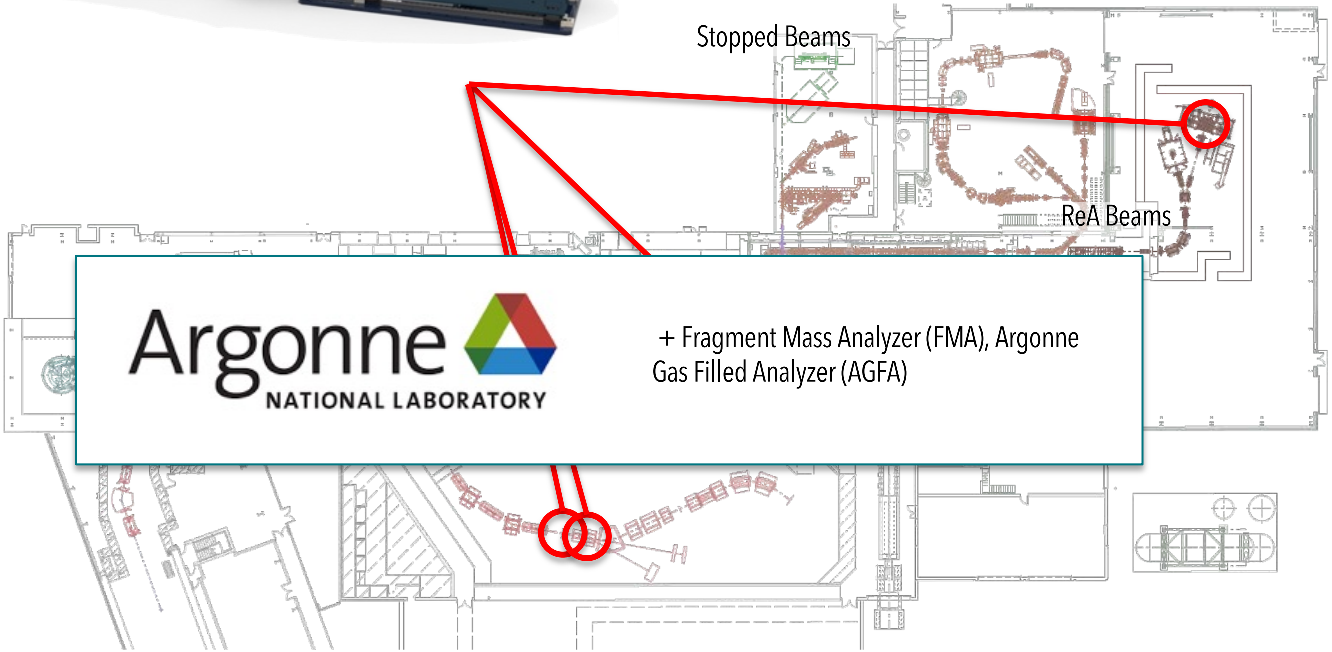


γ-ray detection plays a central role in nuclear physics

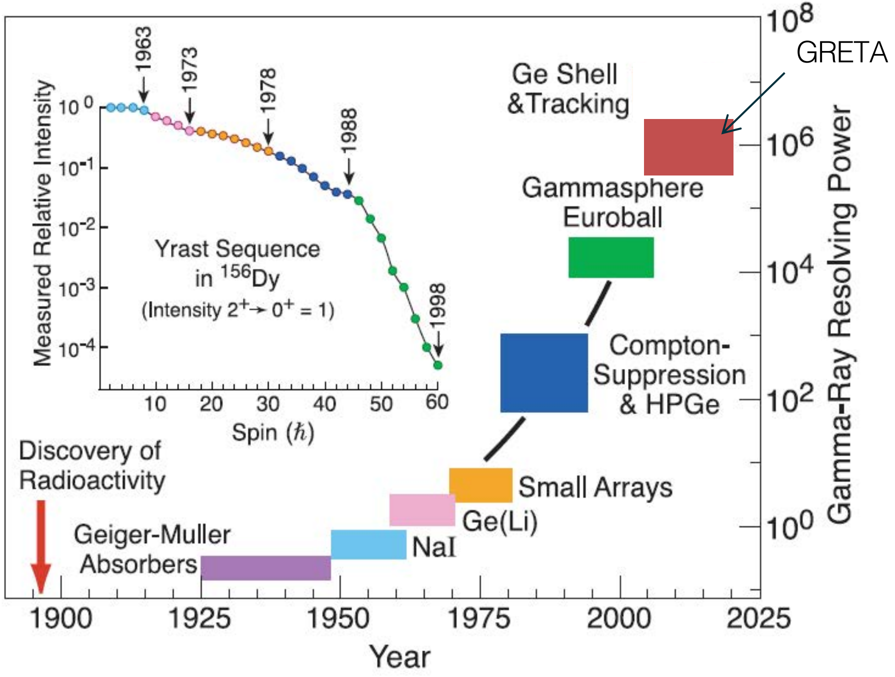
- The spectrum of excited states is key to understanding nuclear structure.

- Of the many experimental tools and techniques developed to study nuclei, high-resolution γ-ray spectroscopy has proven to be one of the most powerful

- Advances in detector technology extend science reach

- GRETA achieves large gains because it provides a detector technology to create a “Ge-shell”

- Maximizes and Optimizes
  - Efficiency, Energy Resolution, Peak-to-Total



Gamma-Ray Energy Tracking Array

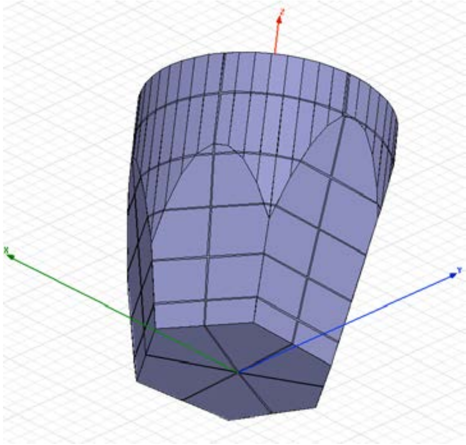
GRETINA/GRETA concept for a shell of closely packed Ge crystals

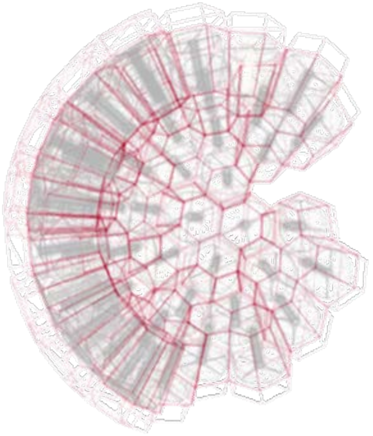
- Combines (120) highly segmented, hyper-pure germanium crystals with advanced digital signal processing techniques

- Identify the position and energy of γ-ray interaction points within a compact “shell” of detectors

- Track γ-ray path both within and between detector elements, using the angle-energy relation of the Compton scattering process

  Maximizes and Optimizes
  - Efficiency, Energy Resolution, Peak-to-Total





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I-Y.Lee

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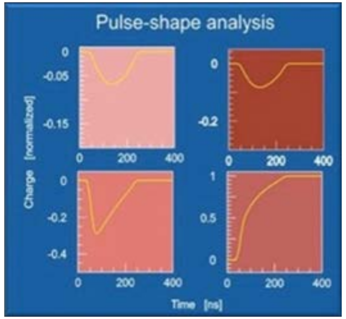

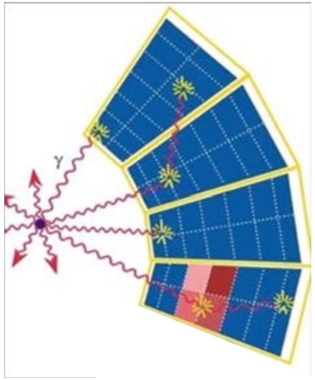

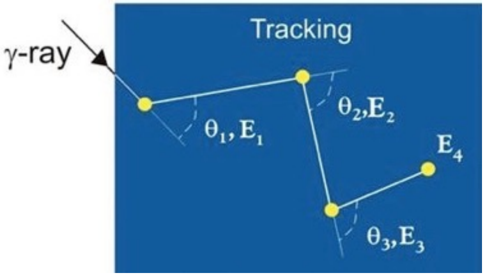

GRETINA – *first stage to get to GRETA*

Gamma-Ray Energy Tracking In-beam Nuclear Array

Between 2003 and 2011, the US low-energy nuclear physics community constructed GRETINA, a 1π tracking detector employing the same segmented detector and signal decomposition technology as GRETA.

GRETINA was a $20M project funded by US DOE-Nuclear Physics Office

- Covered ~¼ of a sphere with 7 Quad Detector Modules

GRETINA science operations at MSU and ANL have demonstrated the technology and scientific impact of a γ-ray tracking array.

Added Quad Detector Modules – total of 12 (+ 1 spare)

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GRETINA Science Campaigns

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24 experiments ~3500 hours

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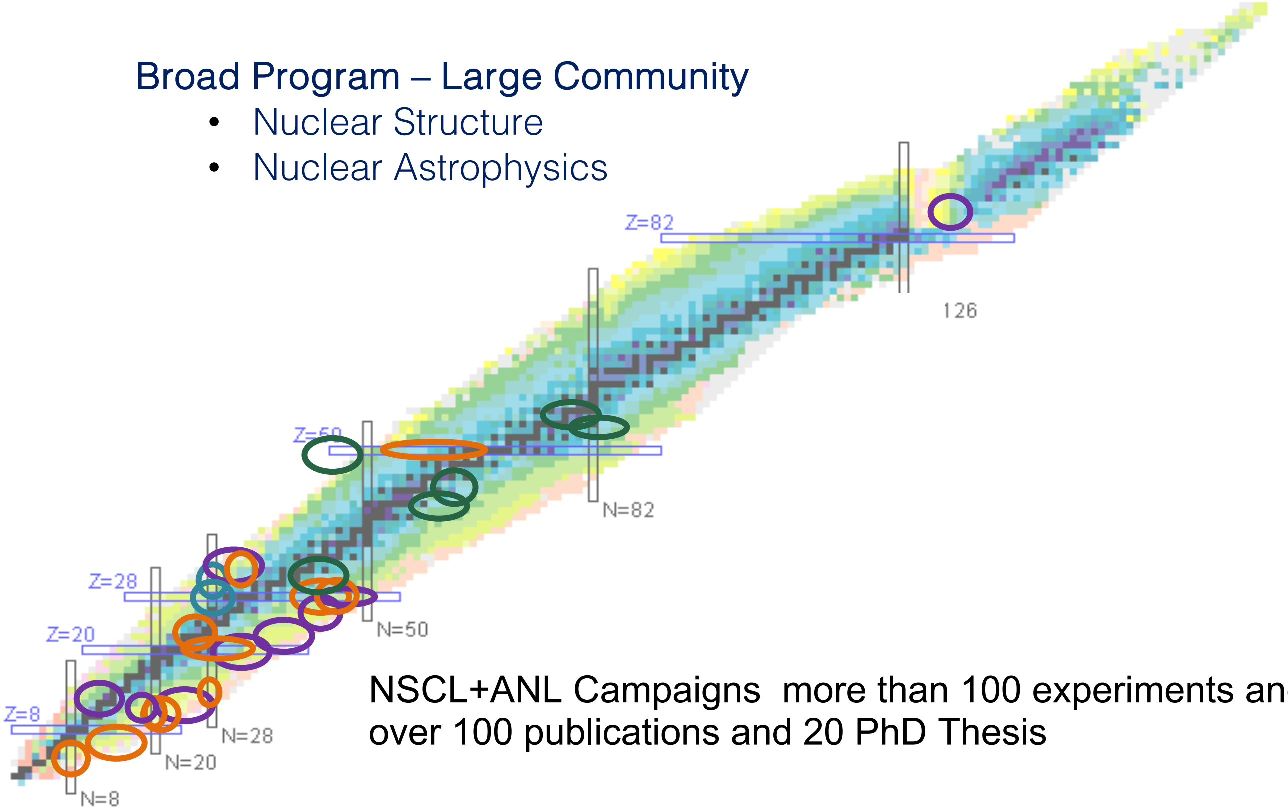
Broad Program – Large Community
- Nuclear Structure
- Nuclear Astrophysics



NSCL+ANL Campaigns more than 100 experiments and over 100 publications and 20 PhD Thesis

GRETINA uses ~50% of available running time

GRETINA has successfully demonstrated the science reach and impact of a γ-ray tracking array

GRETINA at NSCL

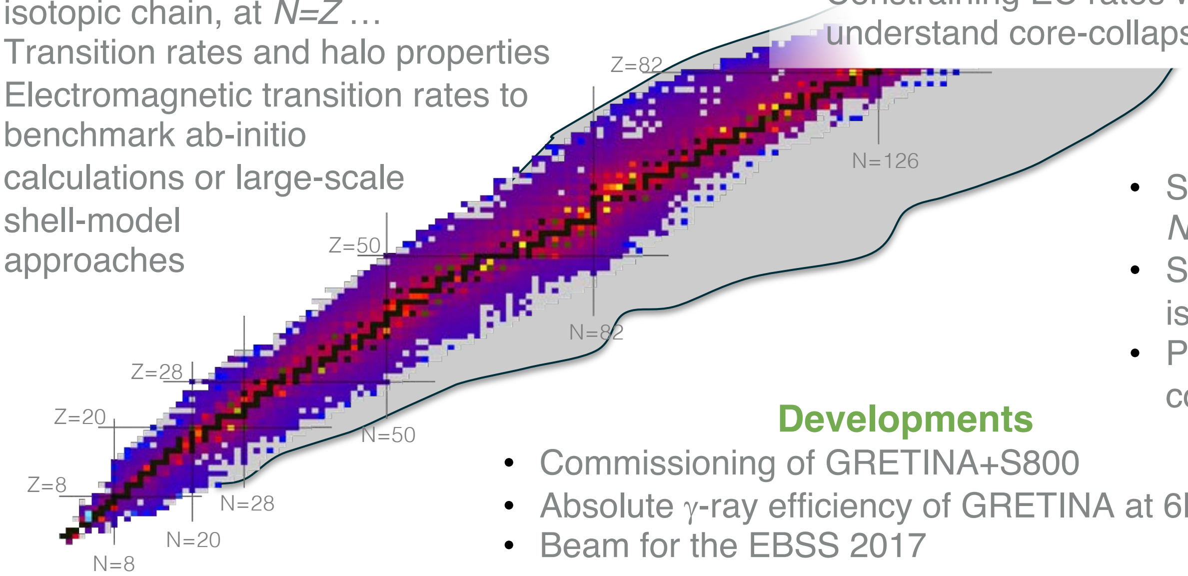
62 Experiments in 3 Campaigns

Collectivity

- Shape coexistence in *N*=20, 28, 40 Island of Inversion
- Shape changes and collectivity along the Ni isotopic chain, at *N*=*Z* …
- Transition rates and halo properties
- Electromagnetic transition rates to benchmark ab-initio calculations or large-scale shell-model approaches

Nuclear Astrophysics

- Precise energy measurements of resonances important for (p,γ) captures in the rp process
- Angle integrated measurement of (d,n) and (d,p) transfer reactions +mirror symmetry to constrain p capture rates for nucleosynthesis processes
- Constraining EC rates with (t,^{3}He+γ) CEX reactions to understand core-collapse supernovae



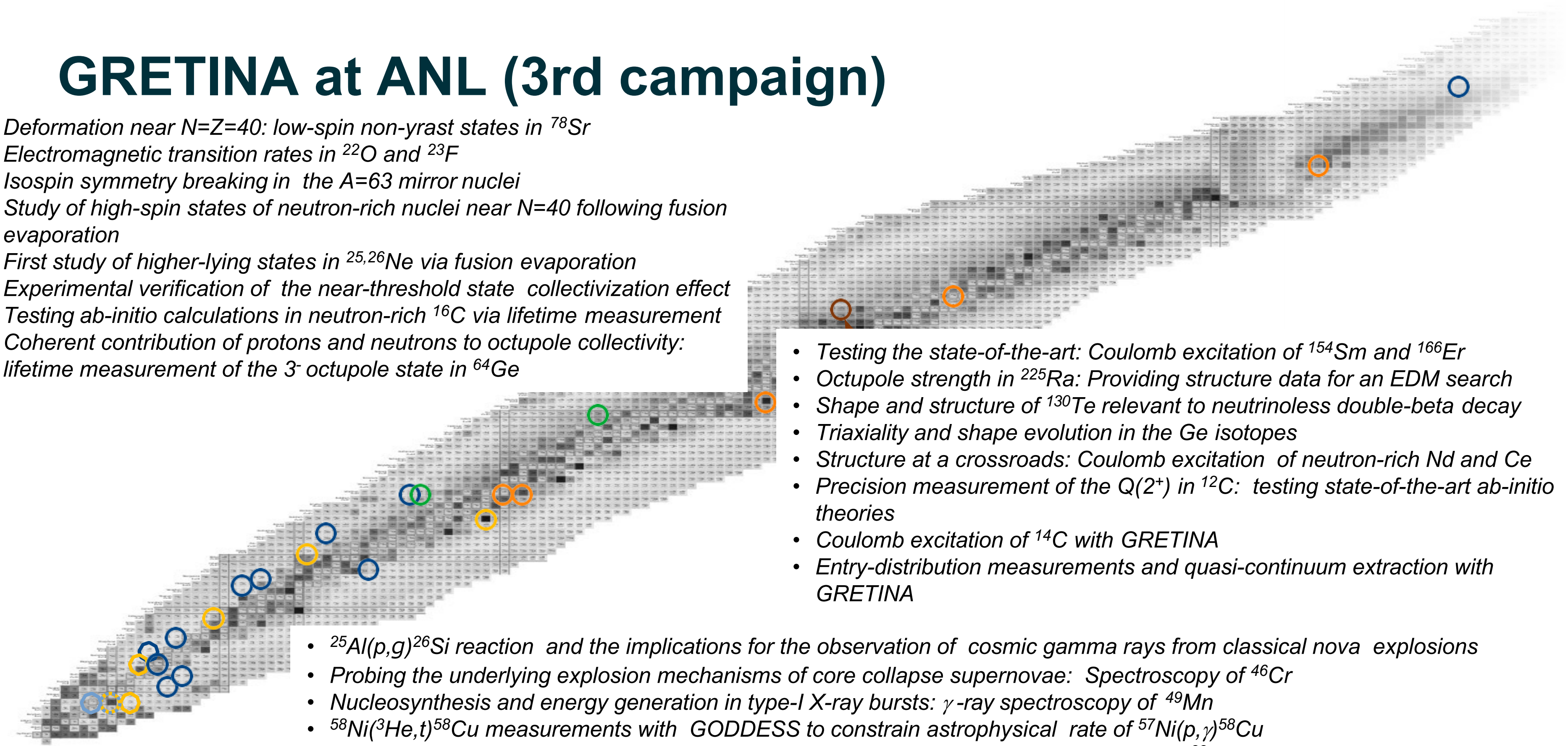
Nuclear Shell Evolution

- Single-particle structure at *N=20*, *N*=28, *N*=40 from direct reactions
- Shell evolution along the Ca, Ni, Zn, … isotopic chains from direct reactions
- Probing core excitations and shell-model cores with different methods

Developments

- Commissioning of GRETINA+S800
- Absolute γ-ray efficiency of GRETINA at 6MeV
- Beam for the EBSS 2017

GRETINA at ANL (3rd campaign)



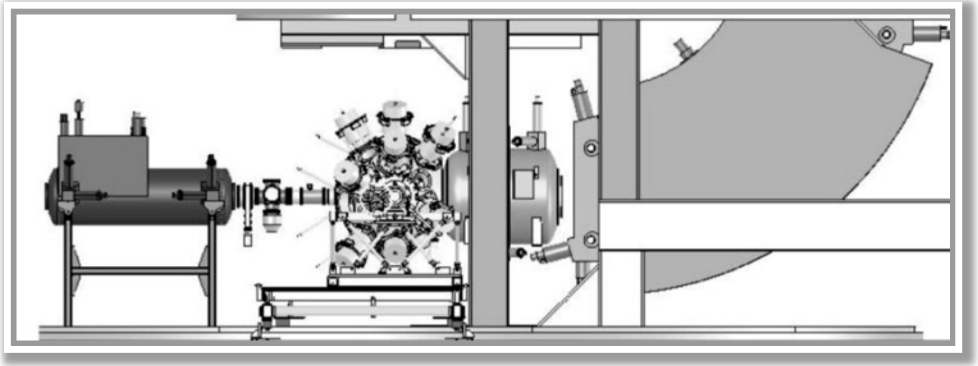
- *Deformation near N=Z=40: low-spin non-yrast states in ^{78}Sr*
- *Electromagnetic transition rates in ^{22}O and ^{23}F*
- *Isospin symmetry breaking in the A=63 mirror nuclei*
- *Study of high-spin states of neutron-rich nuclei near N=40 following fusion evaporation*
- *First study of higher-lying states in ^{25,26}Ne via fusion evaporation*
- *Experimental verification of the near-threshold state collectivization effect*
- *Testing ab-initio calculations in neutron-rich ^{16}C via lifetime measurement*
- *Coherent contribution of protons and neutrons to octupole collectivity: lifetime measurement of the 3^- octupole state in ^{64}Ge*

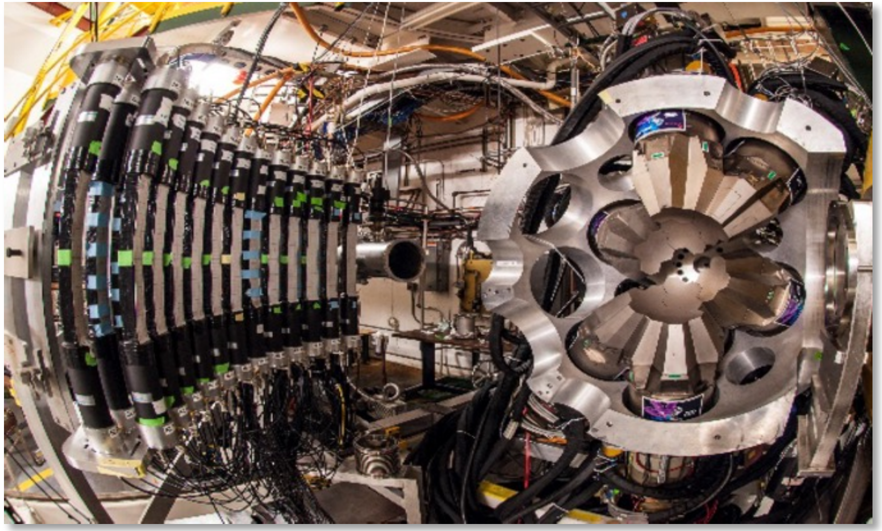
- *Testing the state-of-the-art: Coulomb excitation of ^{154}Sm and ^{166}Er*
- *Octupole strength in ^{225}Ra: Providing structure data for an EDM search*
- *Shape and structure of ^{130}Te relevant to neutrinoless double-beta decay*
- *Triaxiality and shape evolution in the Ge isotopes*
- *Structure at a crossroads: Coulomb excitation of neutron-rich Nd and Ce*
- *Precision measurement of the Q(2^+) in ^{12}C: testing state-of-the-art ab-initio theories*
- *Coulomb excitation of ^{14}C with GRETINA*
- *Entry-distribution measurements and quasi-continuum extraction with GRETINA*

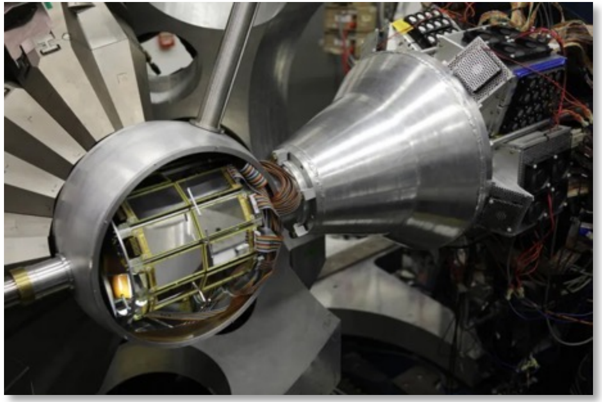
- *^{25}Al(p,g)^{26}Si reaction and the implications for the observation of cosmic gamma rays from classical nova explosions*
- *Probing the underlying explosion mechanisms of core collapse supernovae: Spectroscopy of ^{46}Cr*
- *Nucleosynthesis and energy generation in type-I X-ray bursts: γ-ray spectroscopy of ^{49}Mn*
- *^{58}Ni(^{3}He,t)^{58}Cu measurements with GODDESS to constrain astrophysical rate of ^{57}Ni(p,γ)^{58}Cu*
- *Benchmarking neutron capture on weak r-process nuclei: the (d,pγ) reaction with N=48 ^{82}Se beam*
- *^{22}Na production in novae: addressing the discrepancies in ^{22}Na(p,γ)^{23}Mg with GODDESS*
- *Measuring ^{39}K(^{3}He,a)^{38}K with GODDESS to search for energy levels in ^{38}K important for the ^{37}Ar(p,γ)^{38}K reaction rate*
- *Precision energy measurement of astrophysical states in ^{24}Mg*
- *Constraining the properties of resonant states in the ^{30}P(p,γ)^{31}S reaction*

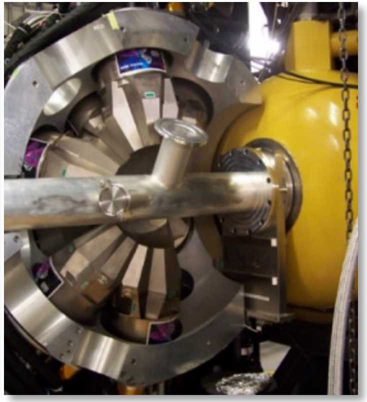
The Experimental Setup at NSCL and FRIB

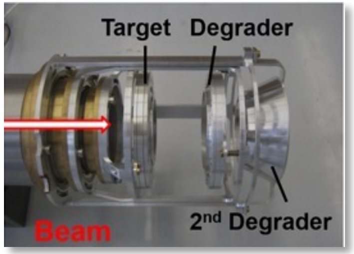
GRETINA + S800 (+ LH_2 target, + LENDA, …)

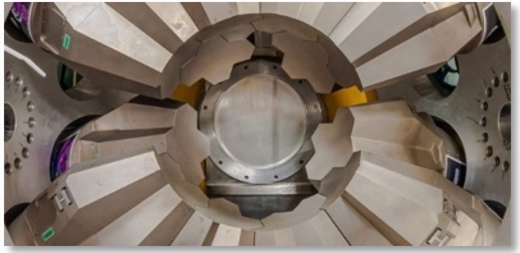




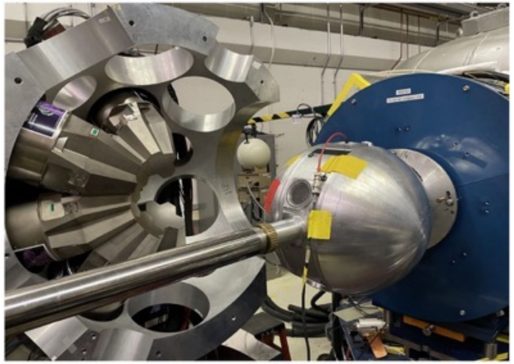


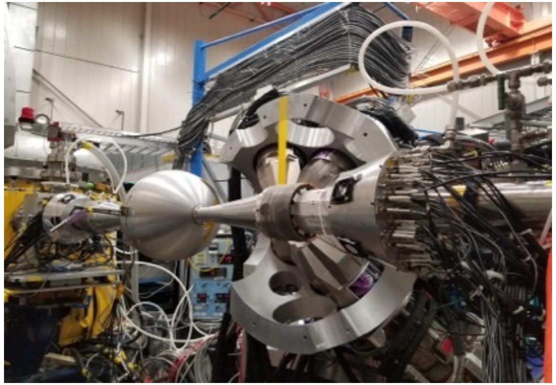


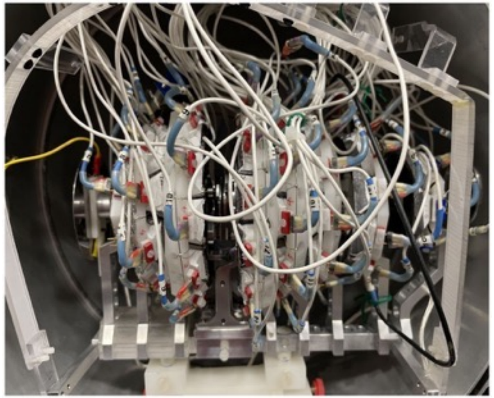


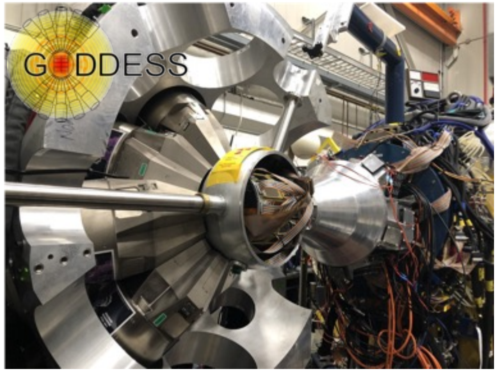


The Experimental Setup at ANL

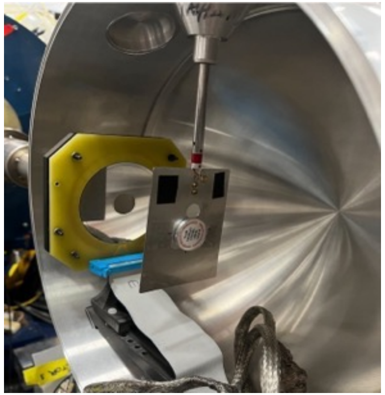

Fragment Mass Analyzer (FMA)


CHICO 2 - PPAC

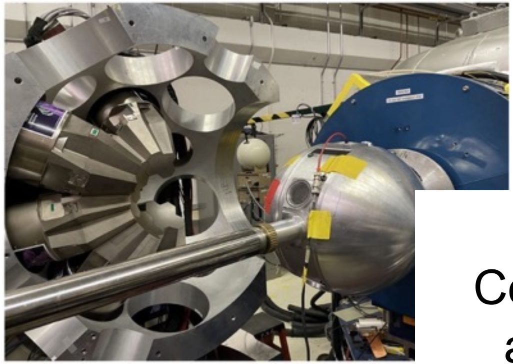

Integrated Cologne-Argonne Plunger Setup (ICAP)



ORRUBA segmented silicon

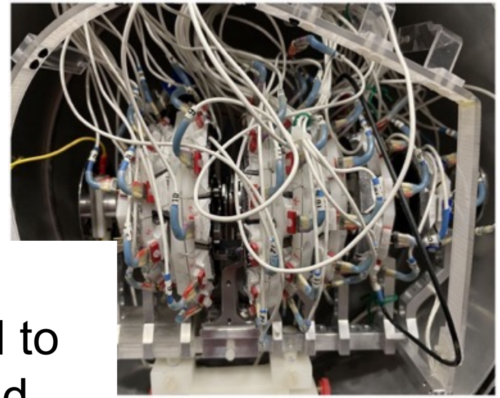

“S3” segmented silicon detector

The Experimental Setup at ANL



Fragment Mass Analyzer

Coupling to other devices is essential to address the broad science goals and achieve the required sensitivity



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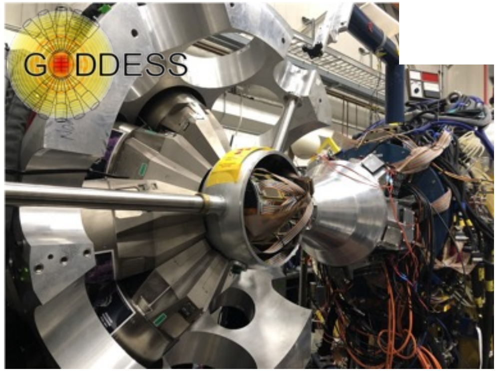

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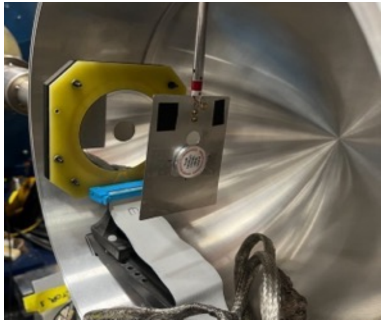

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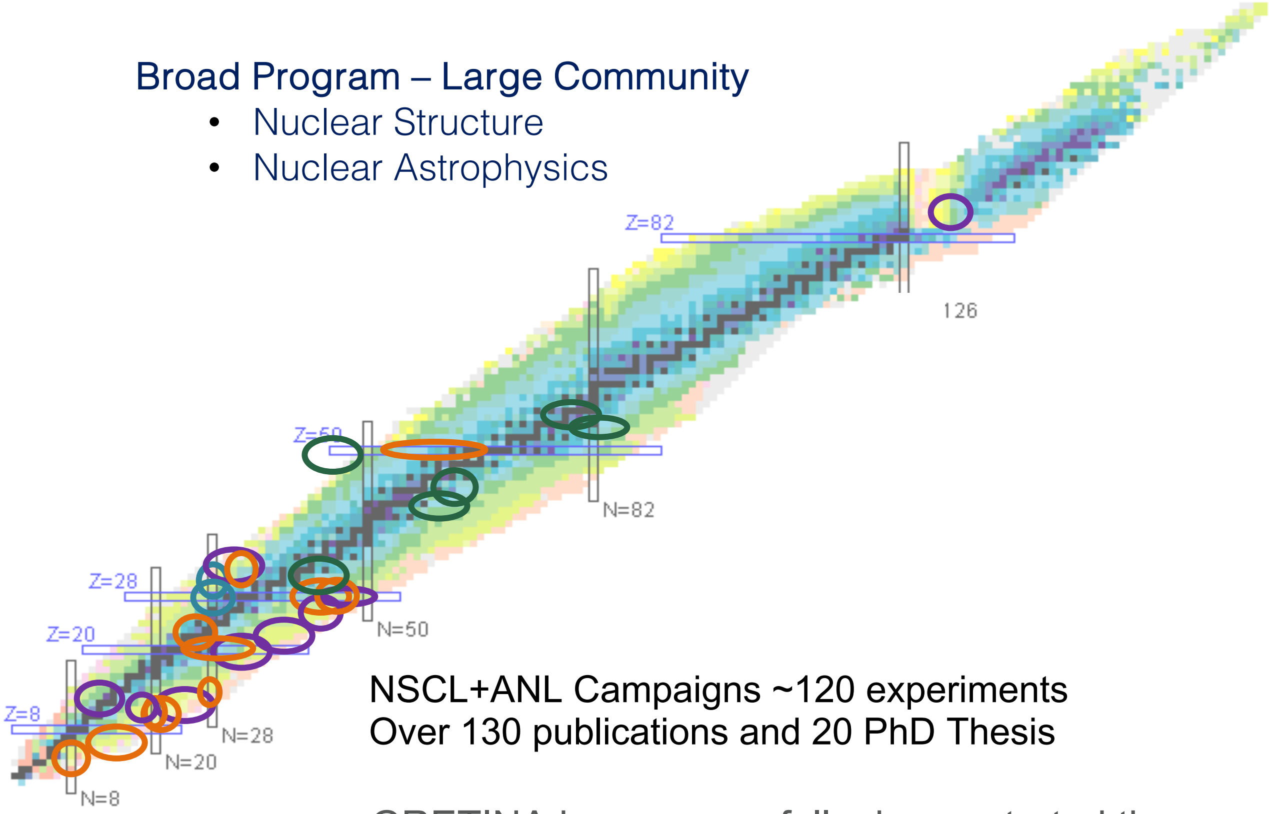

NSCL+ANL Campaigns ~120 experiments
Over 130 publications and 20 PhD Thesis

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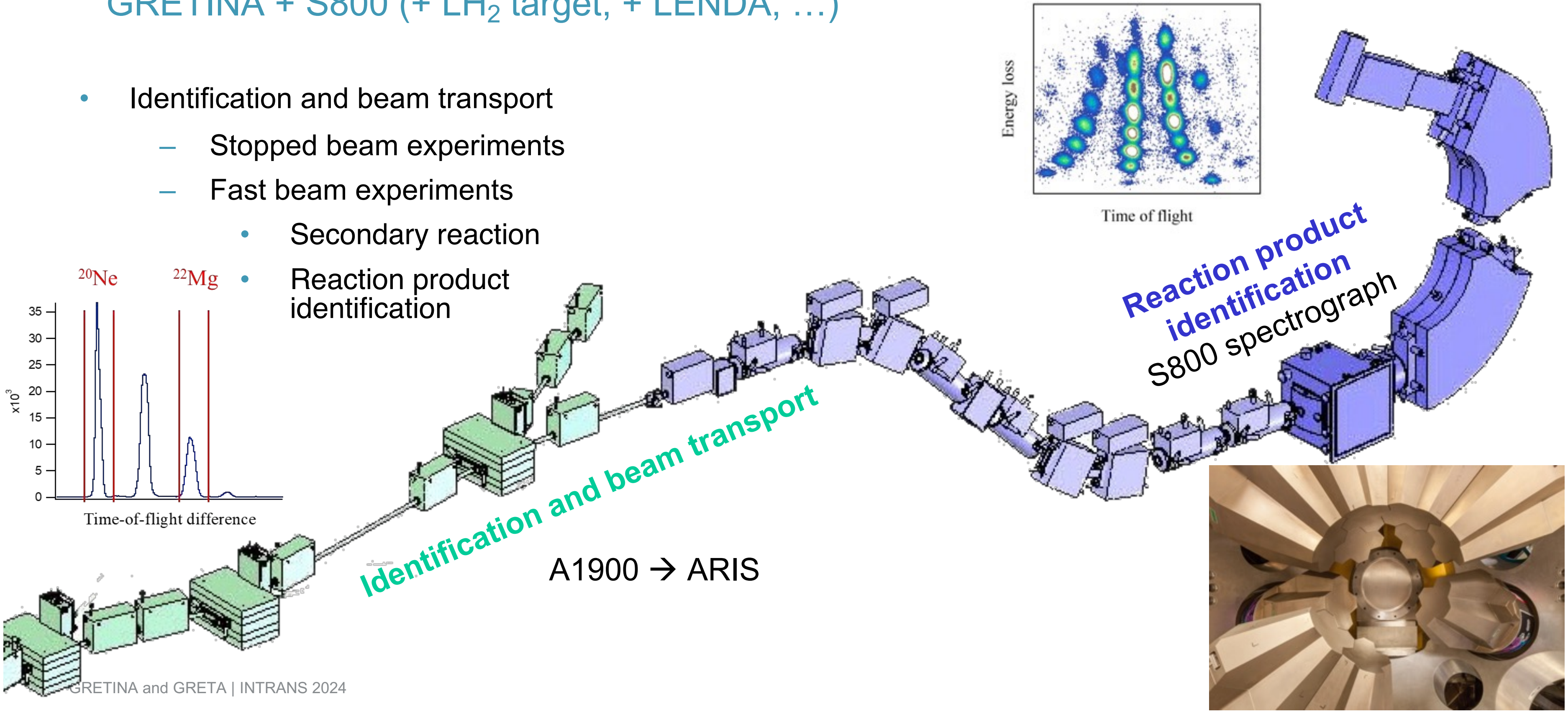
GRETINA has successfully demonstrated the science reach and impact of a γ-ray tracking array

The Experimental Setup at NSCL and FRIB (Fast Beams)

GRETINA + S800 (+ LH_2 target, + LENDA, …)

- Identification and beam transport
  - Stopped beam experiments
  - Fast beam experiments
    - Secondary reaction
    - Reaction product identification

Reactions induced by ^{20}Ne

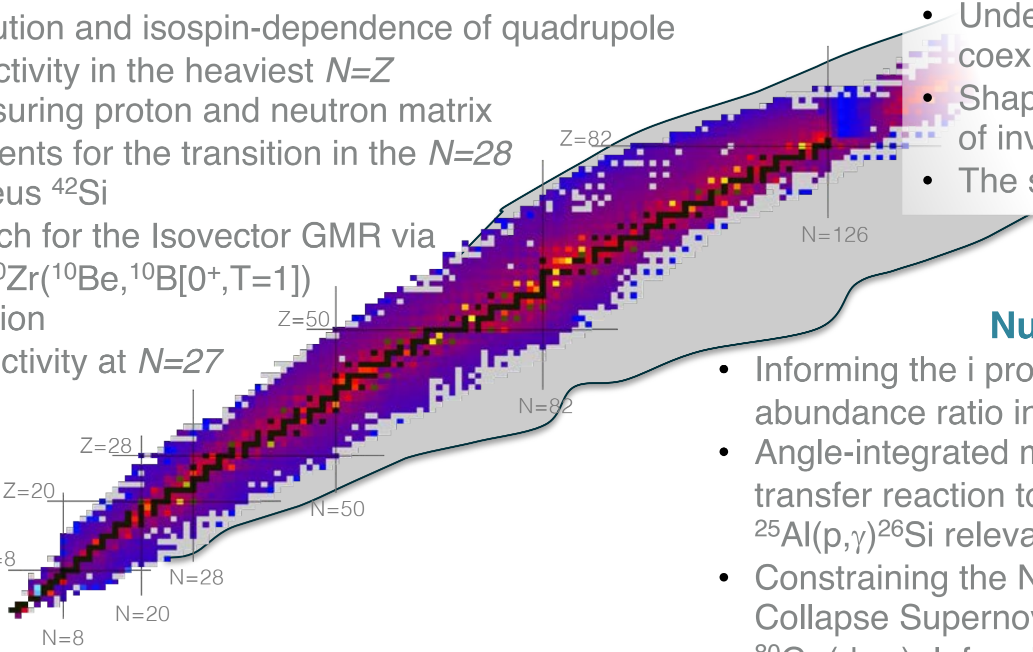


First GRETINA @ FRIB Campaign

14 Experiments Approved in 2 FRIB PACs

Collectivity

- Quadrupole Collectivity at the Boundaries of the *N*=40 Island of Inversion
- Evolution and isospin-dependence of quadrupole collectivity in the heaviest *N=Z*
- Measuring proton and neutron matrix elements for the transition in the *N=28* nucleus ^{42}Si
- Search for the Isovector GMR via the ^{90}Zr(^{10}Be,^{10}B[0^+,T=1]) reaction
- Collectivity at *N=27*



Nuclear Shell Evolution

- Single-neutron structure at the heart of the *N=28* island of inversion
- Halo formation in neutron-rich carbon isotopes
- Understanding shape and configuration coexistence at *N=28*
- Shape coexistence at the heart of the *N=40* island of inversion
- The structure of light tin isotopes

Nuclear Astrophysics

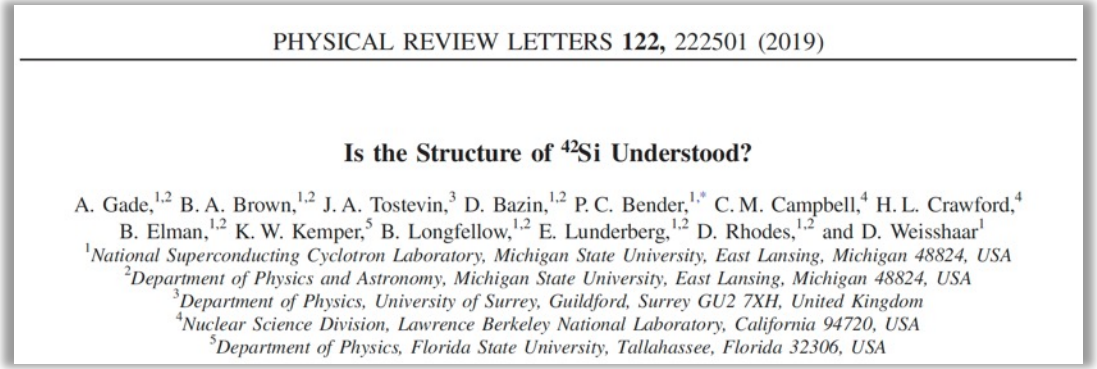
- Informing the i process: constraining the As/Ge abundance ratio in a metal poor star via ^{75}Ga(d,pγ)^{76}Ga
- Angle-integrated measurement of the d(^{25}Al,nγ)^{26}Si transfer reaction to probe resonance strengths in ^{25}Al(p,γ)^{26}Si relevant for ^{26}Al production in classical novae
- Constraining the Ni-Cu cycle in X-ray bursts and Core Collapse Supernovae: Spectroscopy of ^{60}Zn
- ^{80}Ge(d,pγ): Informing weak r-process neutron capture

Led by FRIB, U. Surrey and FSU (Gade, Tostevin, Weidenhoever et al.) with LBNL, LLNL, and Ursinus College

Shell Evolution at N=28

Testing Model Descriptions of ^{42}Si

- Motivation – theory has been unable to describe ^{42}Si and different models disagree with each other
- Approach – measure ^{44}S(-2p)^{42}Si reaction
- Initial beam time did not go to plan – had to move to Plan B, namely ^{42}S(-2p)^{40}Si reaction



PHYSICAL REVIEW LETTERS **122,** 222501 (2019)

Is the Structure of ^{42}Si Understood?

A. Gade,[1,2] B. A. Brown,[1,2] J. A. Tostevin,[3] D. Bazin,[1,2] P. C. Bender,[1,*] C. M. Campbell,[4] H. L. Crawford,[4] B. Elman,[1,2] K. W. Kemper,[5] B. Longfellow,[1,2] E. Lunderberg,[1,2] D. Rhodes,[1,2] and D. Weisshaar[1]
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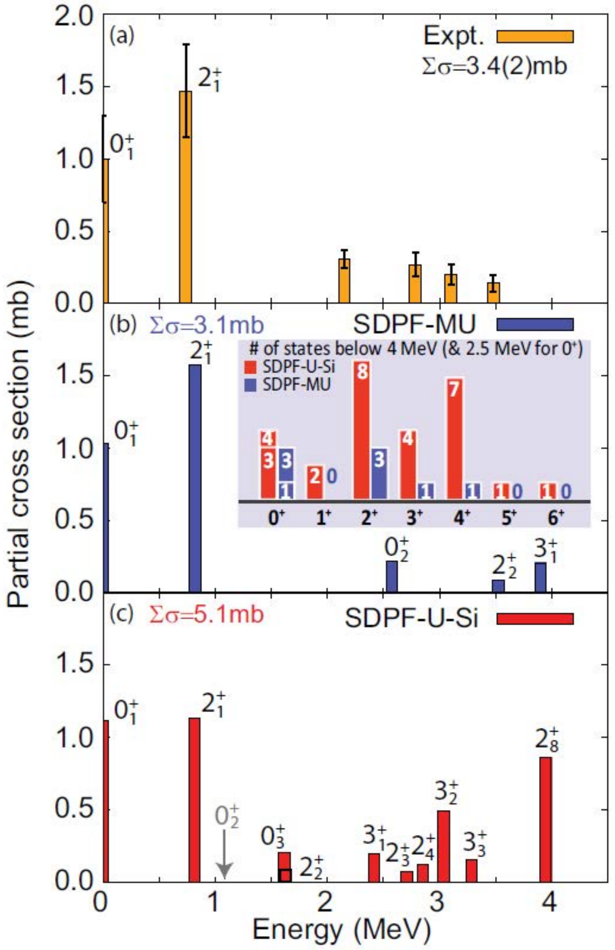
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, California 94720, USA*
[5]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*



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Shell Evolution at *N*=28

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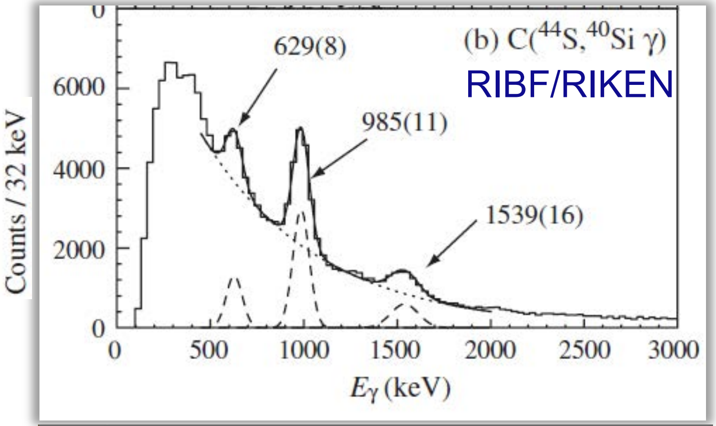
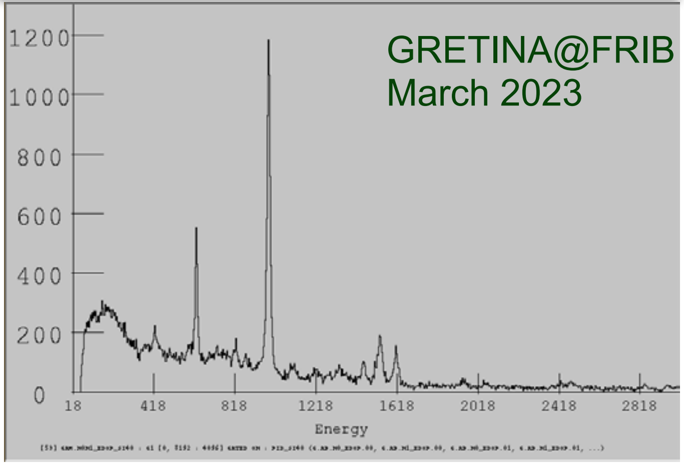
- Approach – measure ^{44}S(-2p)^{42}Si reaction
- Initial beam time did not go to plan – had to move to Plan B, namely ^{42}S(-2p)^{40}Si reaction
- Very rich data set
  - Interesting discrepancy between two different shell-model effective interactions and IM-SRG
  - Similar to the case of ^{42}Si where obviously the drivers of shell evolution are not understood



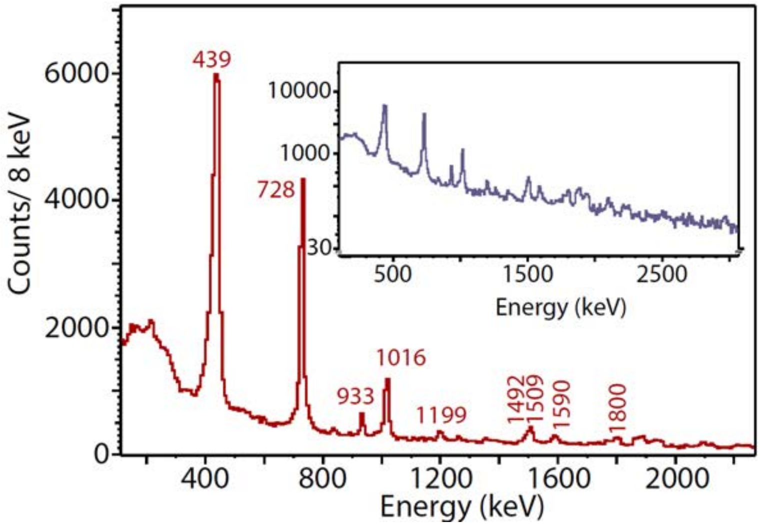


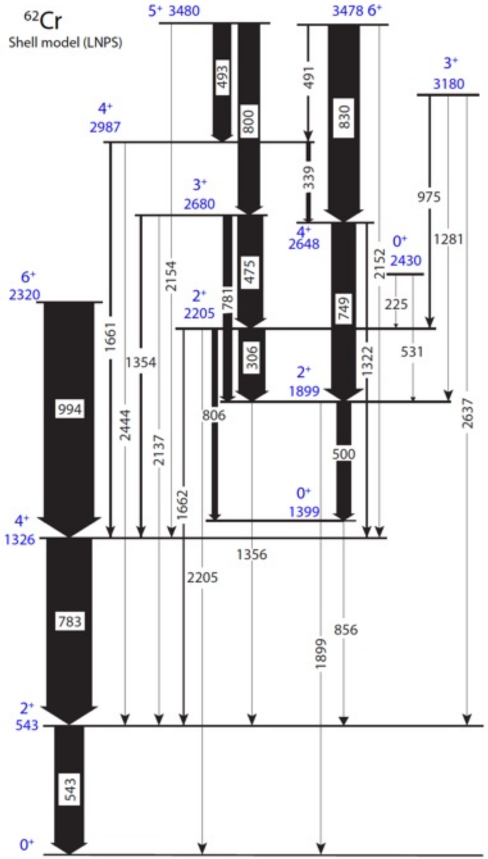
Led by FRIB and UNC (Gade, Janssens et al.) with ANL, LBNL, LLNL, and MSU

Shape Coexistence in the *N*=40 Island of Inversion

Identifying the Excited 0^+ Band-head in ^{62}Cr

- Momentum distributions of ^{62}Cr in $^{9}Be(^{64}Fe,^{62}Cr+\gamma)$ are sensitive to the final state total angular momenta
- 4^+_1 and 6^+_1 states prove approach





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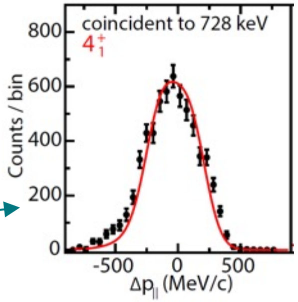
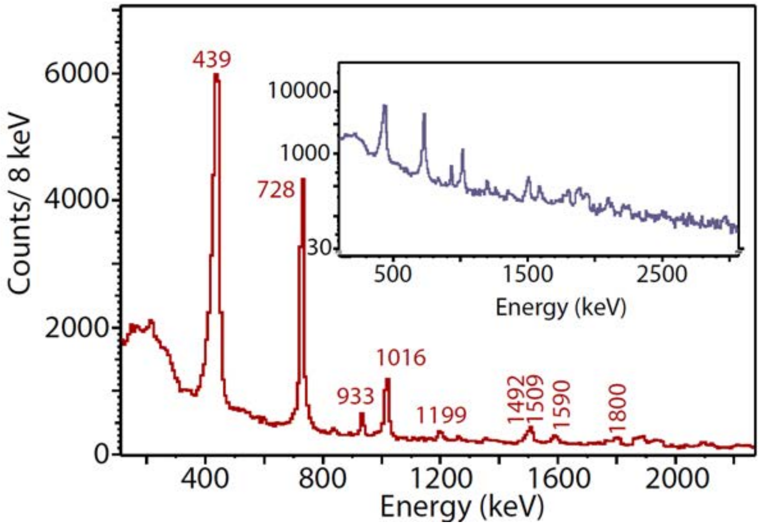
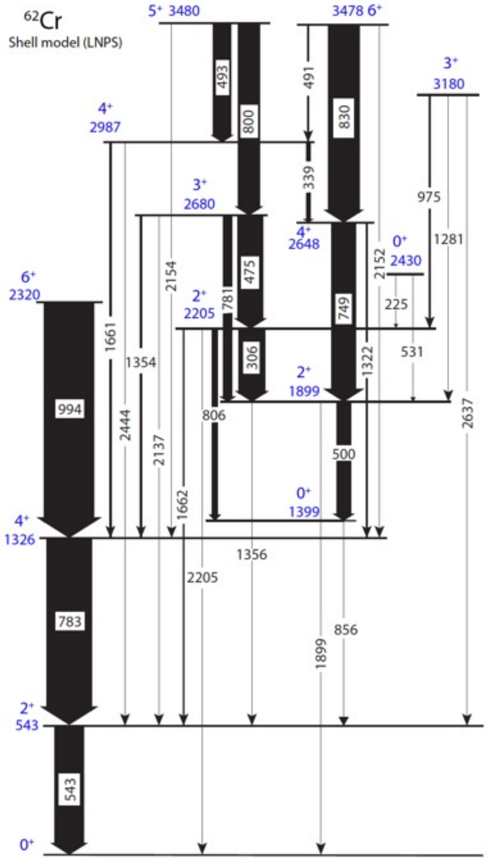




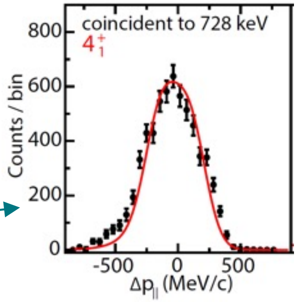


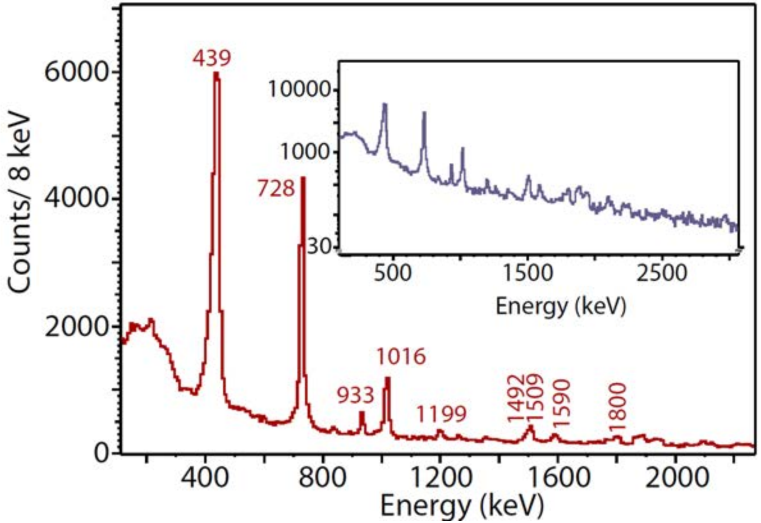
Led by FRIB and UNC (Gade, Janssens et al.) with ANL, LBNL, LLNL, and MSU

Shape Coexistence in the N=40 Island of Inversion

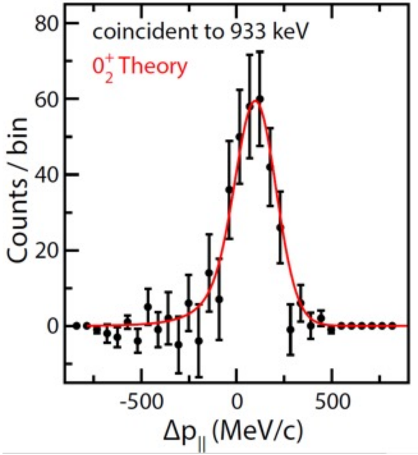
Identifying the Excited 0^+ Band-head in ^{62}Cr

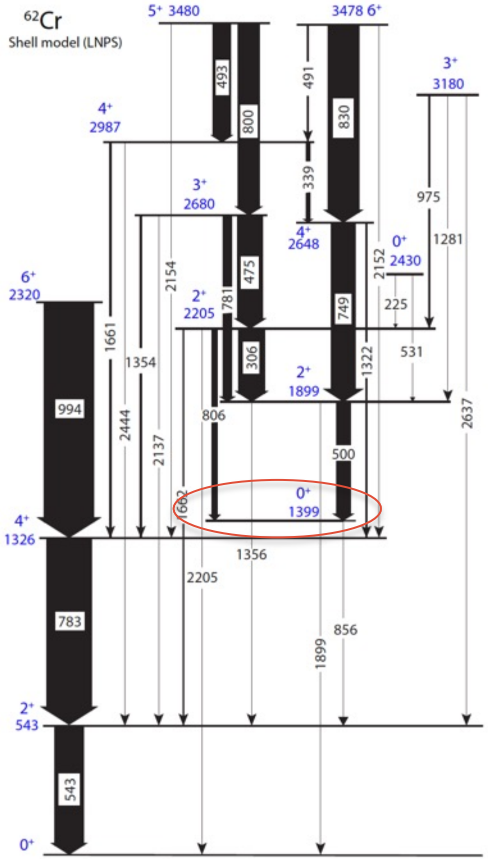
- Longitudinal momentum distributions of ^{62}Cr in $^{9}Be(^{64}Fe,^{62}Cr+\gamma)$ are sensitive to the final state total angular momenta
- 4^+_1 and 6^+_1 states prove approach





Found it!



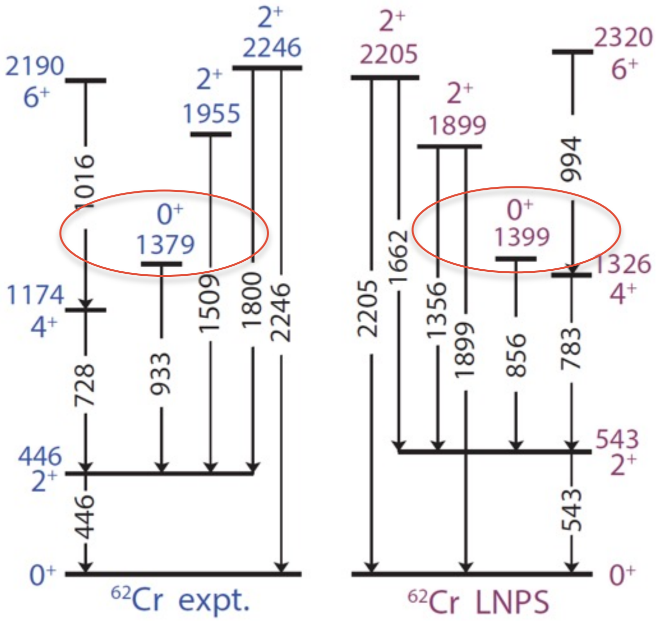


Led by FRIB and UNC (Gade, Janssens et al.) with ANL, LBNL, LLNL, and MSU

Shape Coexistence in the *N*=40 Island of Inversion

Identifying the Excited 0^+ Band-head in ^{62}Cr

- LNPS shell model effective interaction describes well the proposed level scheme
- DNO-SM study shows that triaxiality degree of freedom is important for γ band on top of the 2^+_2 and the band on top of 0^+_2



Led by U. Tenn. (Jones et al.) and FRIB with LBNL, LLNL, ORNL, and Rutgers.

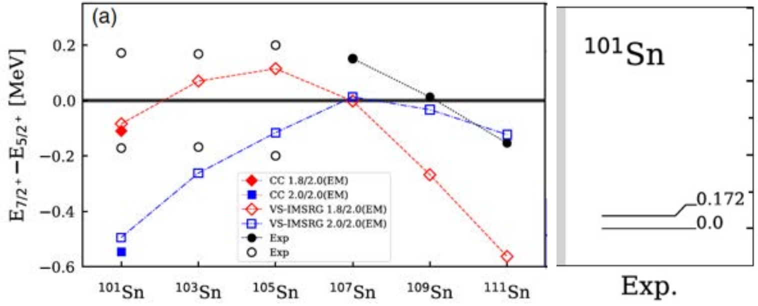
Shell Evolution Towards ^{101}Sn

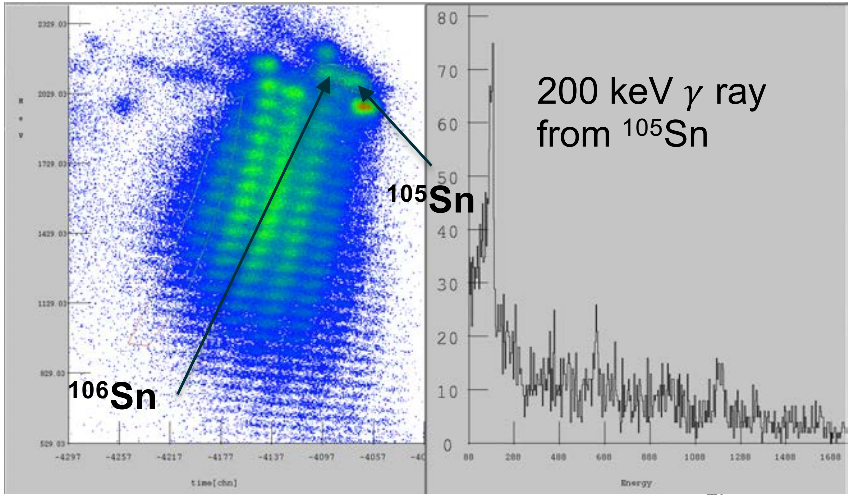
The Structure of Light Sn Isotopes

The energy splitting between the ground and first excited states in the light, odd-mass tin isotopes is small, between 151 keV (^{107}Sn) and 200 keV (^{105}Sn). It is expected that the order of these states in ^{101}Sn will be switched, with respect to $^{103, 105, 107}$Sn.

One way to make spin and parity assignments for these states is to measure the momentum distributions in coincidence with γ rays depopulating the first excited state following a knockout reaction → allows to distinguish the involved *g* and *d* neutron orbitals.

1n knockout ^{106,104,102}Sn

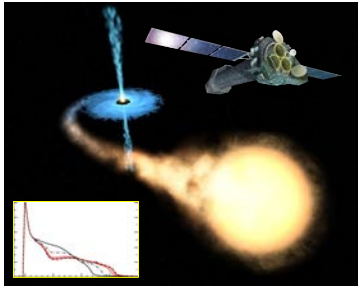




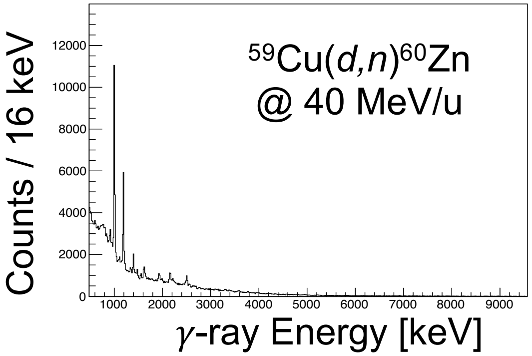
Online particle identification gated on ^{106}Sn beam and γ-ray spectrum

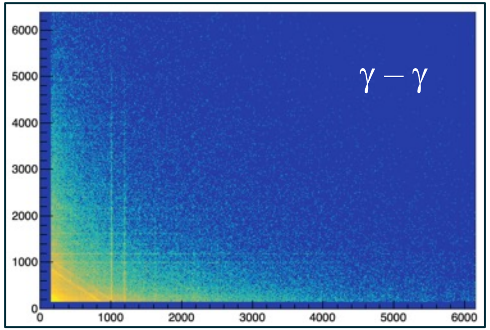
Spectroscopy of ^{60}Zn

Constraining the Ni-Cu cycle in X-ray bursts and Core Collapse Supernovae



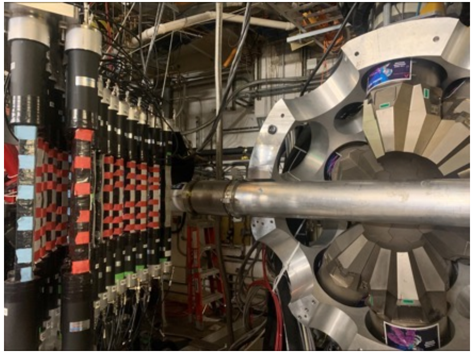
The ^{59}Cu(p,γ) reaction is expected to strongly influence the shape of Type-I X-ray burst light curves.

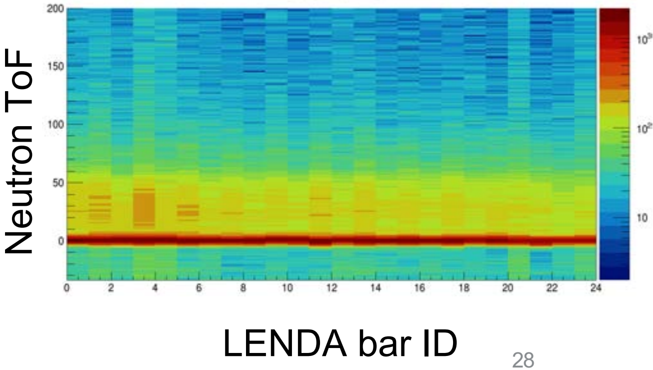




This process was studied via (d,n) transfer at FRIB using GRETINA, LENDA and the S800 spectrometer

Identify γ decays from proton-unbound states in ^{60}Zn and measuring neutron angular distributions to constrain resonance strengths in the astrophysical ^{59}Cu(p,γ) reaction.

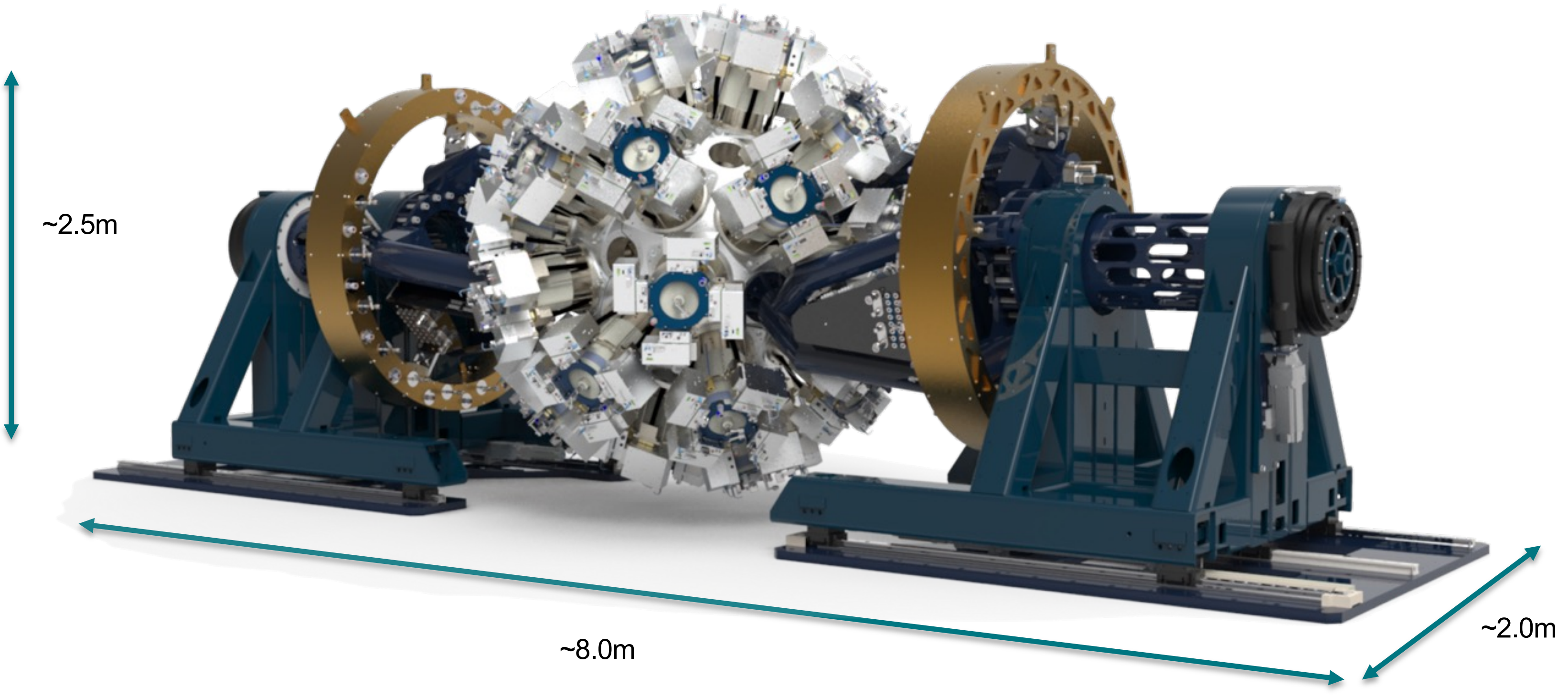




Outline

- Introduction
  - Why we need GRETA
- The GRETINA Era
  - First Experiments at FRIB
- The GRETA ERA
  - Overview and Status

GRETA: A 4π Gamma-Ray Energy Tracking Array



The GRETA Project

GRETA builds on the existing GRETINA array to subtend the full 4π coverage of γ-ray tracking detectors.

- 18 Quad modules, to be combined with 12 GRETINA modules for a total of 30
- Full mechanical structure for a 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
    - Large local RAID storage

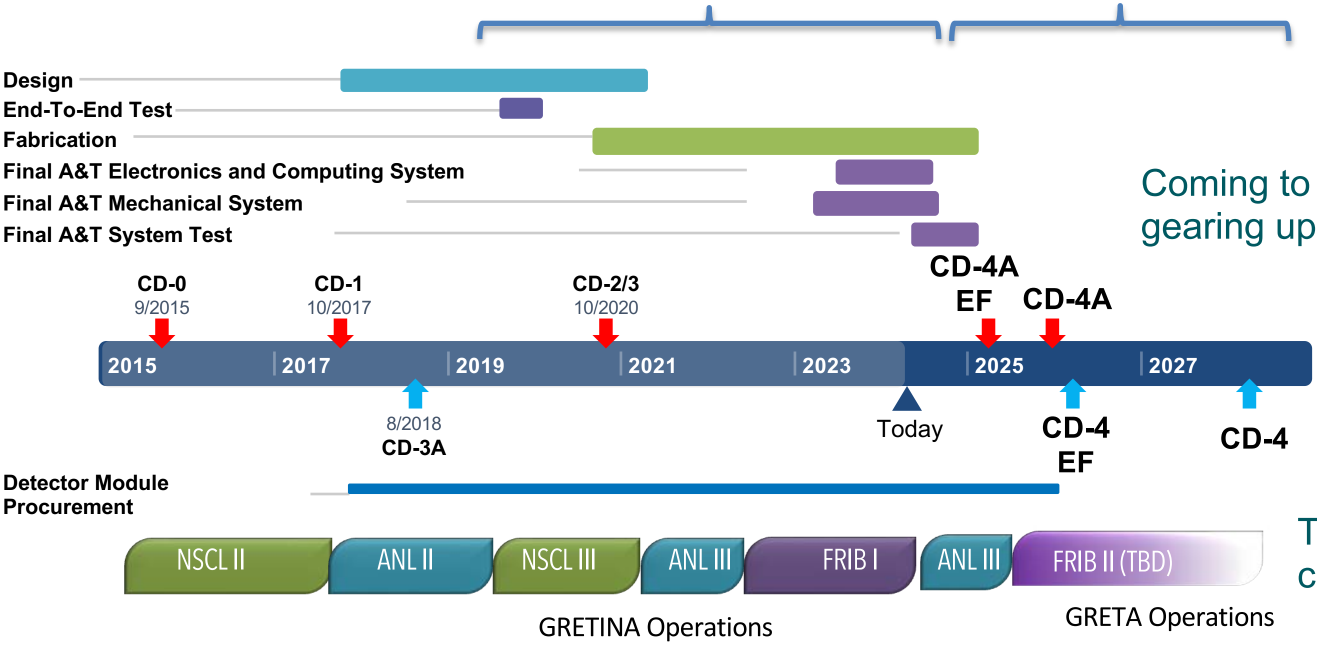
GRETA Project Phased for Early Science Operation at FRIB

CD-4A Scope

- Electronics, Computing and Mechanical systems for 30 Quad Detector Modules
- Subset of Detector Modules (6)
- Delivered to FRIB for Science Operation

CD-4 Scope

- Accept the remaining Quad Detector Modules (For a total of 18)



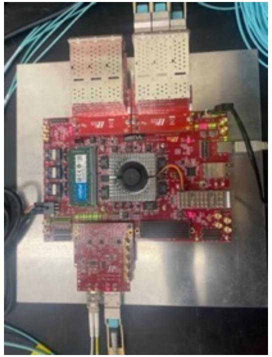
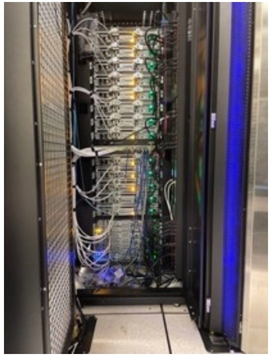
Coming to completion and gearing up to deliver.

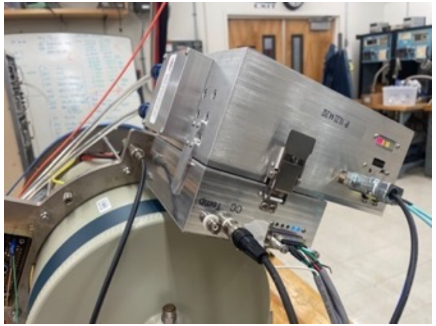
The phasing of campaigns

Technical Progress

- Working towards project completion
- Technical systems (mechanical, electronics, computing) will be done in next 2-4 months
- System Assembly and integration phase started at LBNL Bldg 88
- CD-4A (Early 2025) with delivery of GRETA phase-1 to FRIB in Spring 2025.

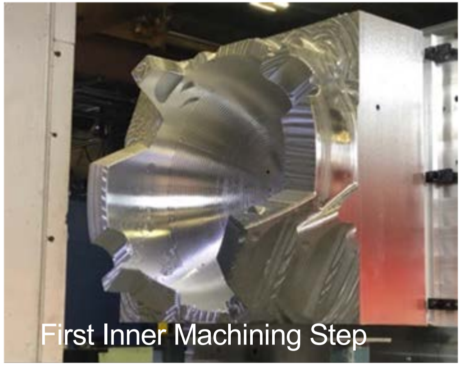


Hemispheres – Fabrication Steps

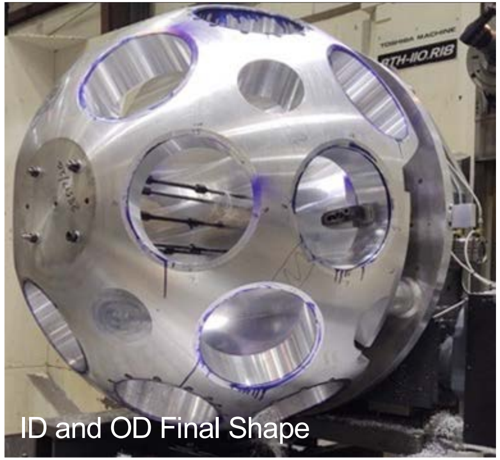

Raw Material


First Inner Machining Step


First Rough Hemisphere


Ready for Last Machining Step


Ports Added to Hemisphere


ID and OD Final Shape


Awaiting installation at Bldg. 88

Support Frame and Arm Installation

Support Frame and Arm Installation

Detectors at FRIB

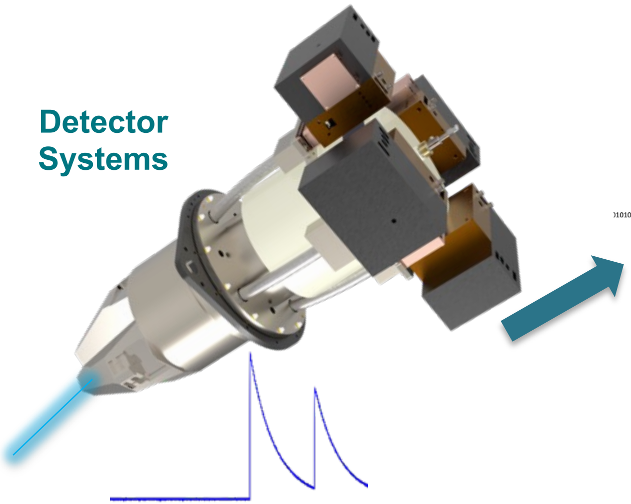
All 18 Ordered ☺

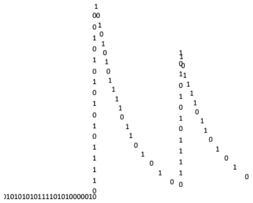
11 delivered

Expect last Quad detector to be delivered end of CY 2025

GRETA Signal Chain

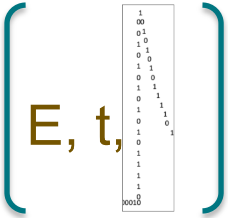
Detector Systems





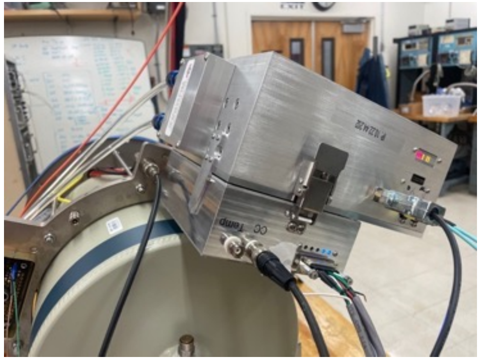
- Continuous 100MHz digitization of **40** preamplifier signals **per crystal**

Electronics Systems



x 40

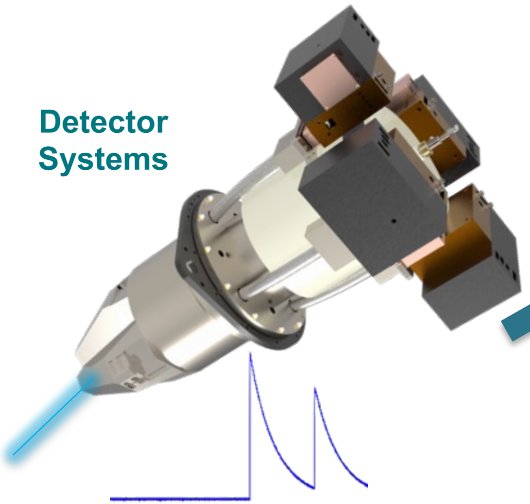
- FPGA-based energy filters, event selection in response to physics triggers

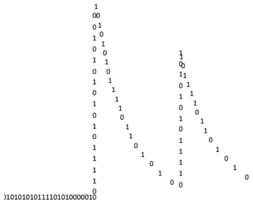


Electronics (ADC) are on the Detectors, Digitized signals sent to Signal Filter Boards

GRETA Signal Chain

Detector Systems





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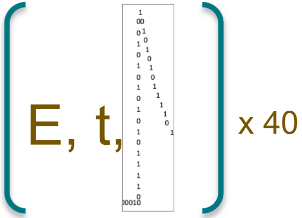
Electronics Systems



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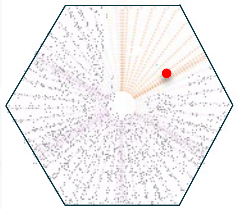
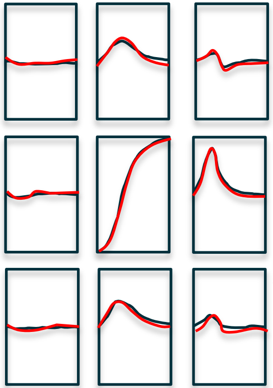
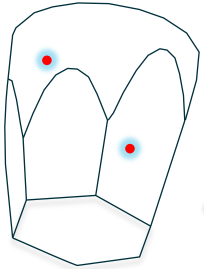


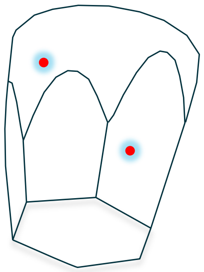


Computing Systems



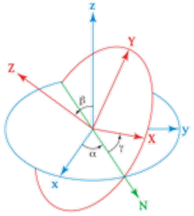
$$\left[E,\ t,\ (x,\ y,\ z)_{crystal}\right]_n$$

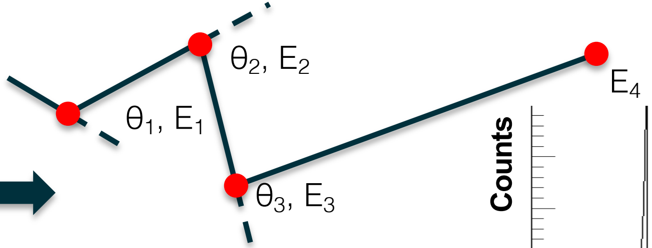
GRETA Signal Chain

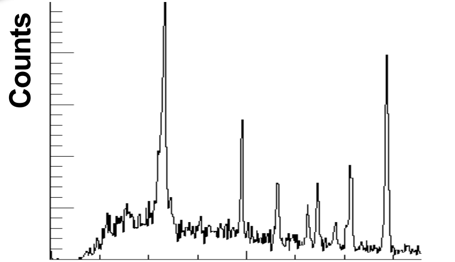


$$\left[E,\ t,\ (x,\ y,\ z)_{crystal} \right]_n$$

Mechanical Systems



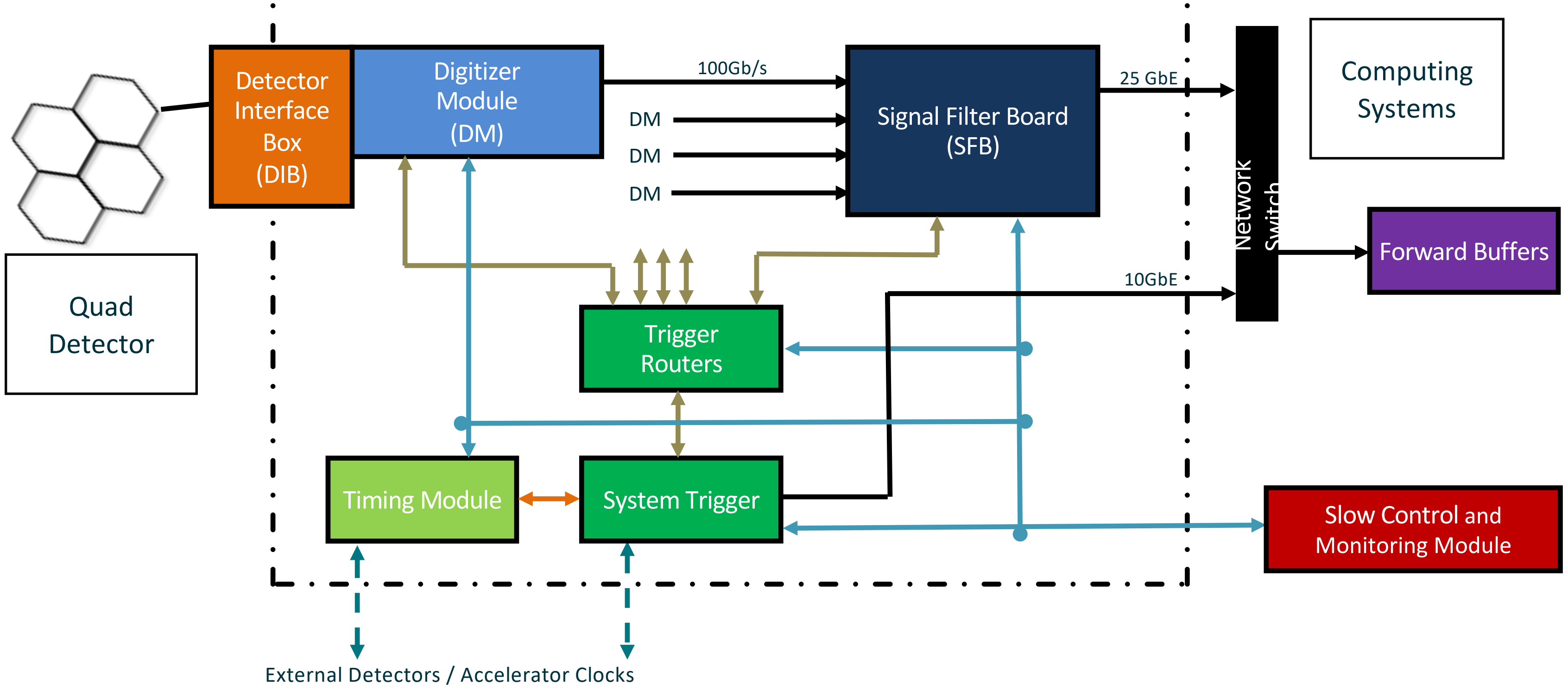




- Detectors located absolutely in space to +/- 0.4 mm

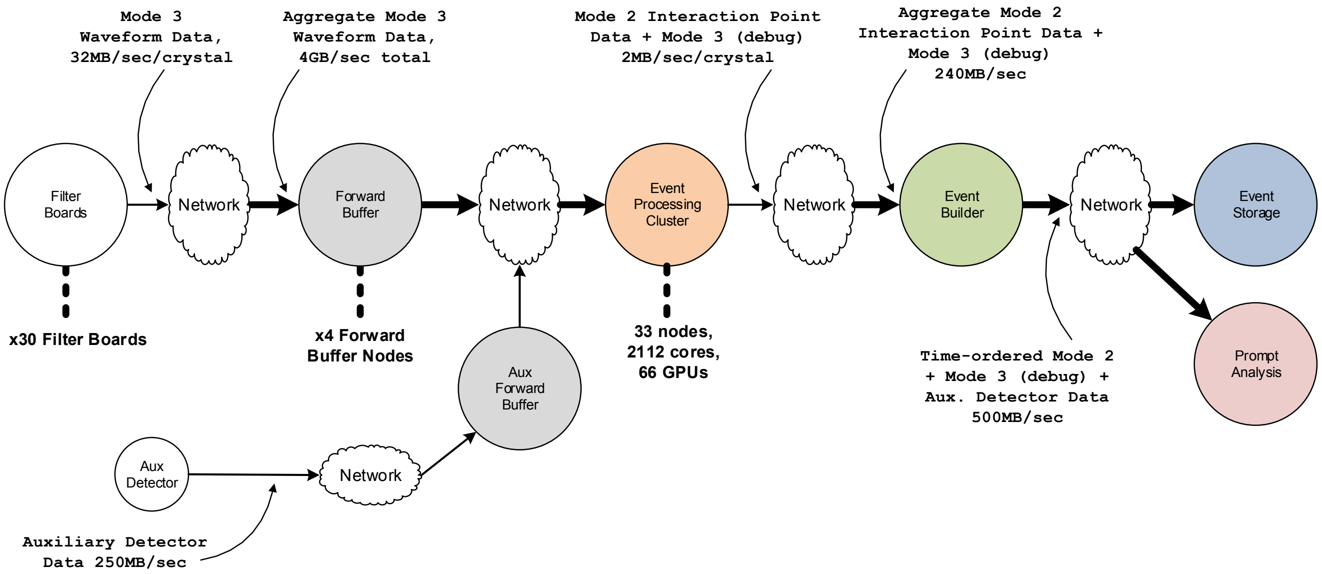
GRETA Electronics Systems

Digitize at the Detector, fiber-based network carries data and controls



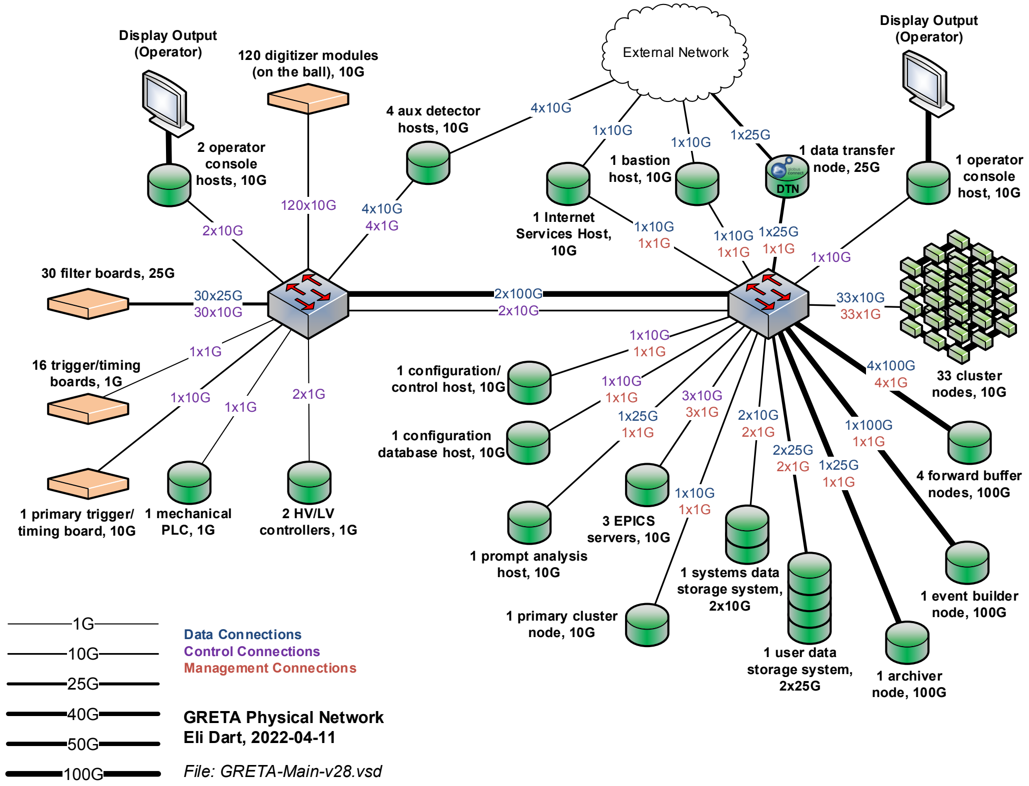
GRETA Computing Systems

Pipeline-Based Network Architecture Enables Cutting-Edge Performance



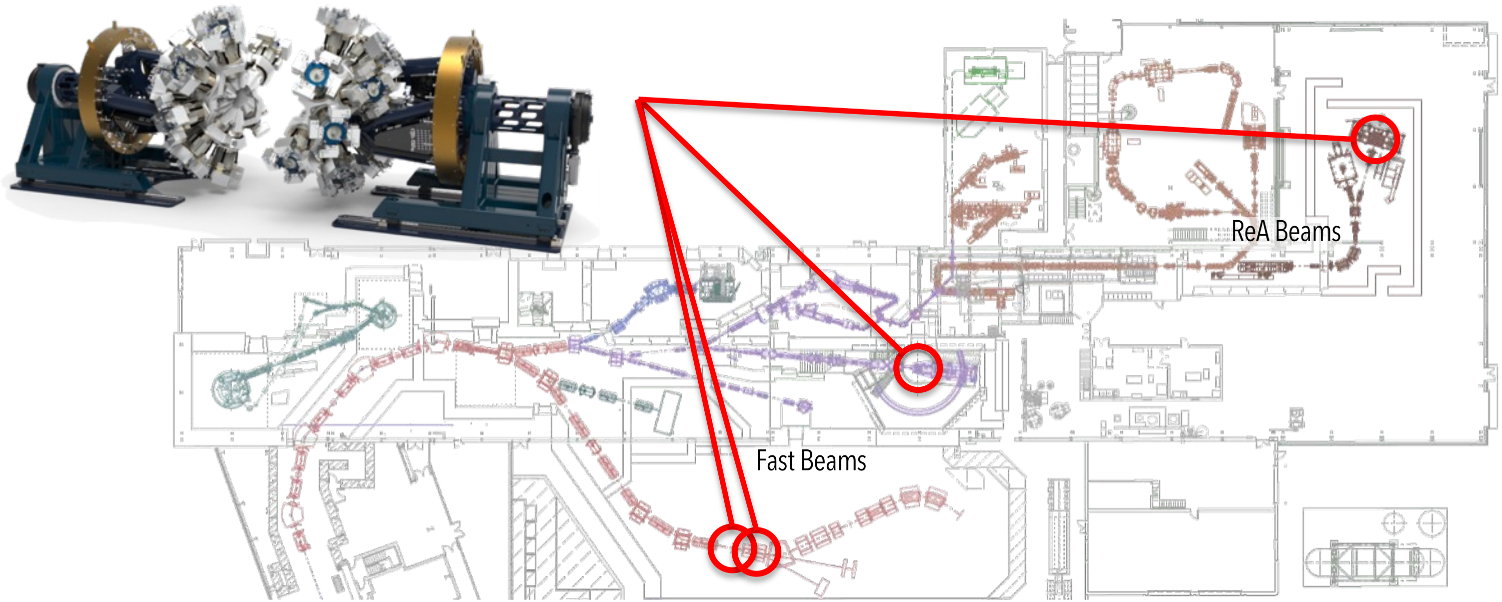
GRETA Computing Systems

Pipeline-Based Network Architecture Enables Cutting-Edge Performance



- 300TB full SSD storage array improves ability to sort online, move data quickly off the cache to the DTN
- High-performance computing cluster enables in-line compression and will support 500k signal decomposition calculations per second

GRETA Initial Operations (starting 2025)



- Reaccelerated beams
  - GRETA at ReA beam Line
- Fast Beams
  - GRETA frame is not designed for S3 vault (S800) and HRS is under construction
  - Plan to modify GRETINA frame to be able to have up to ~20 QUADS in front of the S800, with the new GRETA electronics and computing and cooling (to maximize HPGe coverage and science opportunities)

Summary

- GRETINA has completed over 100 experiments during the 6 scientific campaigns at NSCL and ATLAS; the 7^{th} campaign, and the first FRIB campaign is ongoing
- With over 100 publications since the start of operations 12 years ago, the scientific impact of GRETINA is unquestionable
- GRETA builds on the success of GRETINA with updated electronics and computing systems to enhance performance, and a full 120 HPGe crystals covering ~80% of the 4π solid angle
- GRETA is planned for delivery to FRIB in 2025 for first operations after integration with the GRETINA Quad detector modules

Thank You

And a special thanks to A. Gade, K. Jones, and G. Lotay for sharing material from their experiments!