GRETINA: Status and Recent Results

- GRETINA
  - Device Overview
  - Enhancements
  - Physics Campaigns
- Results
  - Selected highlights
- Future
  - GRETINA
  - GRETA

Christopher M. Campbell

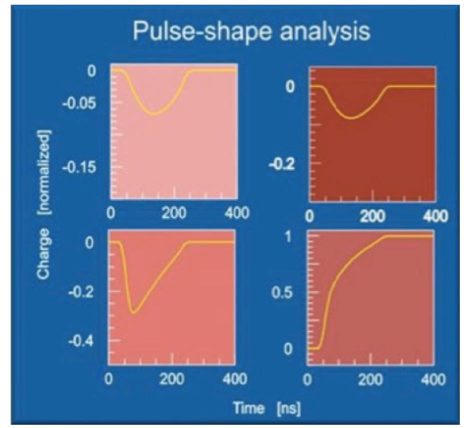
Nuclear Science Division

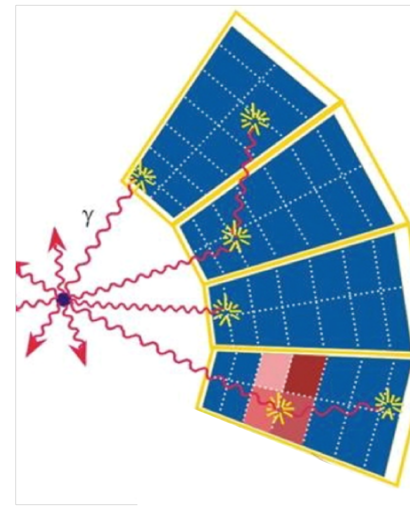
Lawrence Berkeley National Laboratory

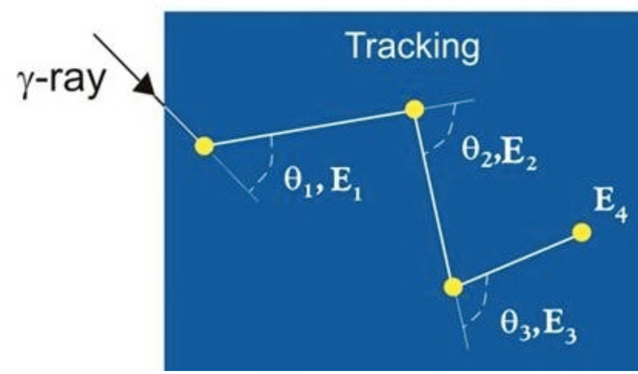
Gamma-Ray Energy Tracking Array

GRETA concept for a shell of closely packed Ge crystals

- Combines 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**
- **Also, Doppler reconstruction! (RIBs inverse kinematics)**

GRETINA

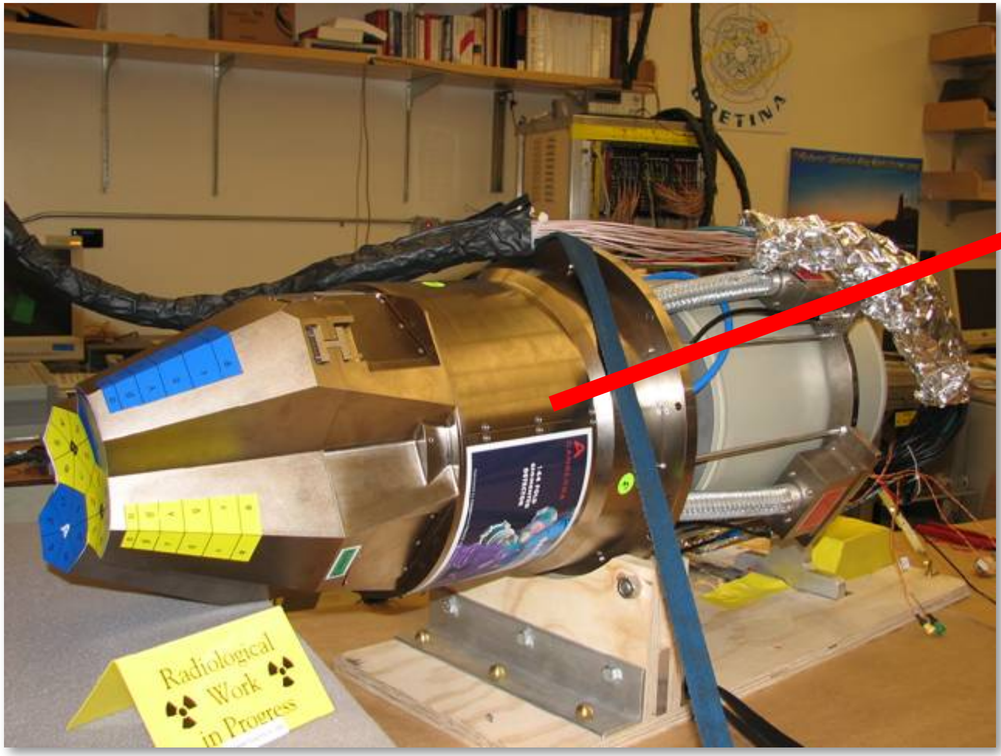
Gamma Ray Energy Tracking In beam Nuclear Array

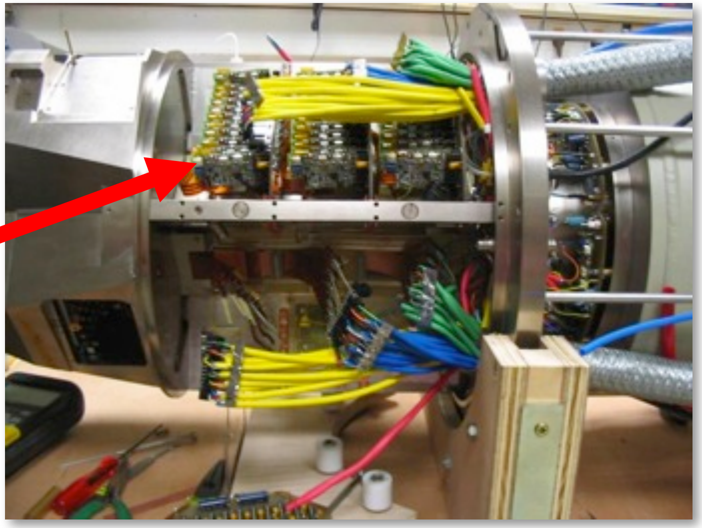
$20M Funded by US- DOE Nuclear Physics Office

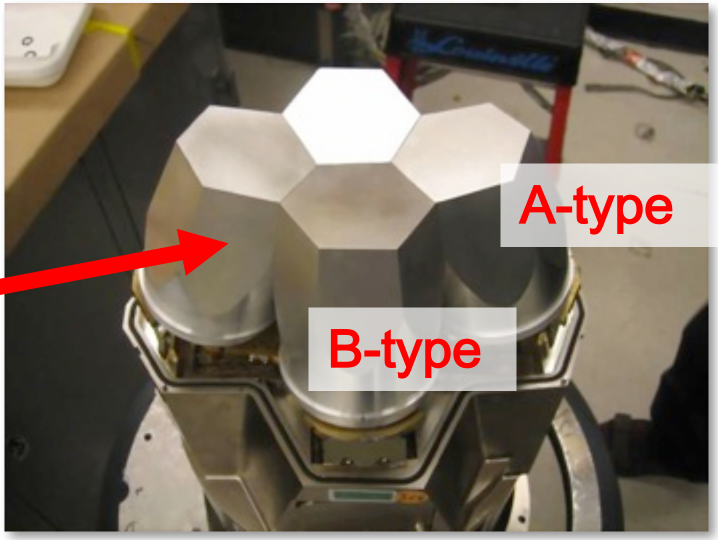
BERKELEY LAB · Argonne NATIONAL LABORATORY · OAK RIDGE National Laboratory · NSCL · Washington University in St. Louis

- 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 Quad Modules
- Mechanical support structure
- Data acquisition system
- Data processing software

Detector Quad Modules



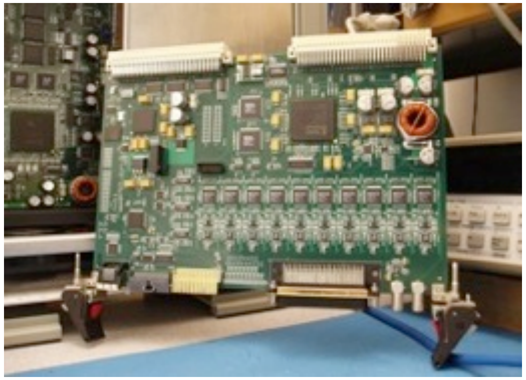




36 segments/crystal
4 crystal/ module
148 signal channels /module
Cores Cold FETs
Segments Warm FETs

Electronics and DAQ System

Digitizer (LBNL)
14bit, 100 MHz
CC Energy: 2.5, 5, 10, 30 MeV
Leading edge time
Pulse shape



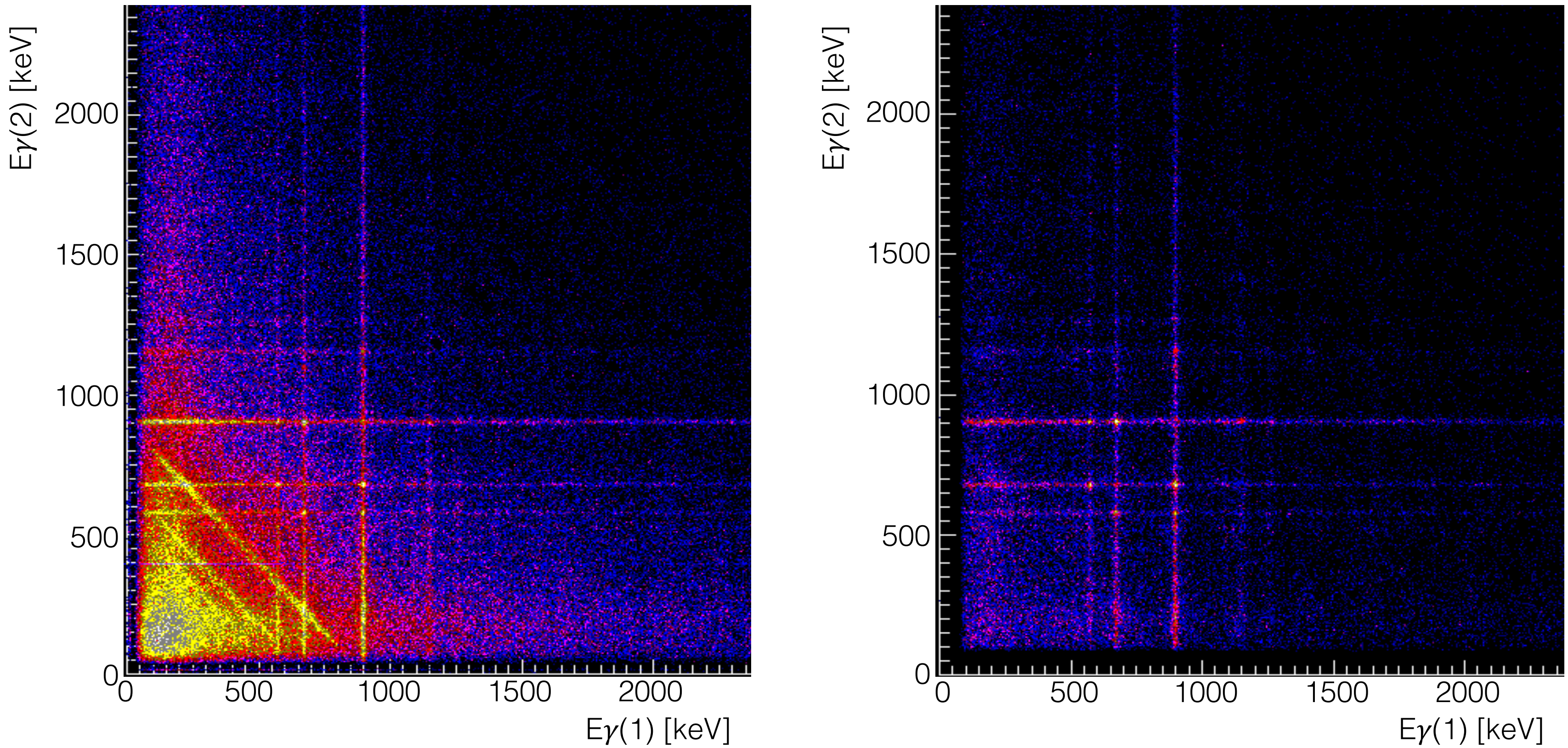
Trigger Timing & Control (ANL)

- Installed 62 nodes, 2 CPU/node, 4 core/ CPU

- 50 TB of disk space

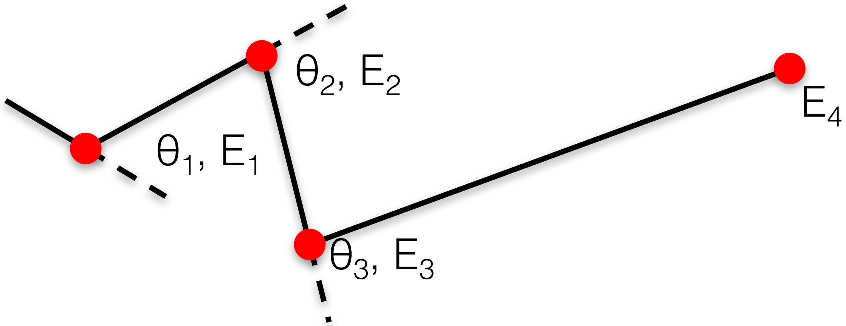
56 Nodes $\geq$ 20000 gammas/s

Tracking: Compton Rejection



^{64}Ge populated in knockout from ^{65}Ge

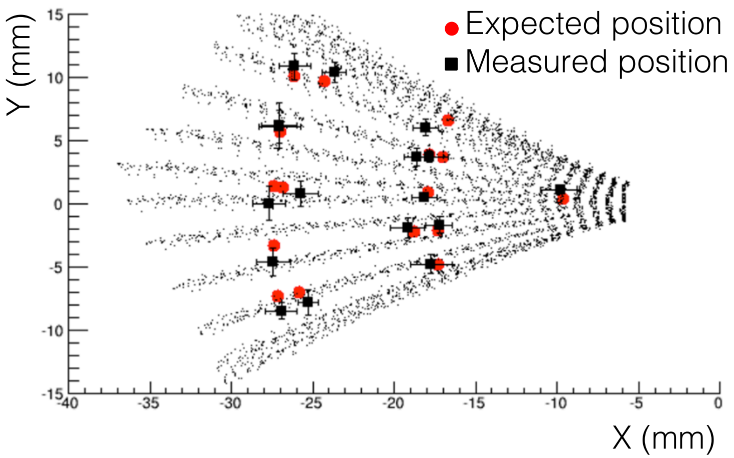
Reduction of Compton background by tracking allows spectral quality comparable to arrays with anti-Compton shields.



GRETINA "Enhancements"

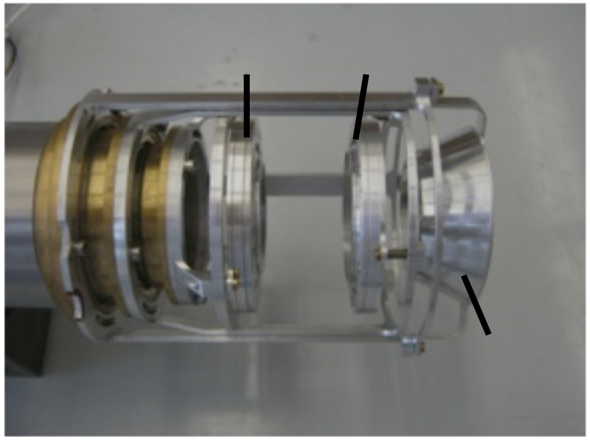
GRETINA enhancements have been supported by the U.S DOE-NP Office since completion of the project with 7 quad modules in 2011.

- Growth of the array through continued procurement of quad modules (and associated infrastructure) at a rate of ~ 1 per year
  - Purchase of Q8 - Q12
  - Electronics (digitizers, trigger modules, cables and power for each module)
  - Supplementation of the computing cluster to support the increased data rates of the larger array
- Firmware development and modifications
  - Improved DAQ stability
  - High-rate energy resolution performance improvements
  - Refined timing performance
  - Double throughput? (50MHz trace)
- Signal decomposition and tracking
  - In-depth coincidence scanning of Q4 at LBNL
  - Extended capabilities in signal decomposition algorithms
  - Enhanced simulation including the effects of signal decomposition



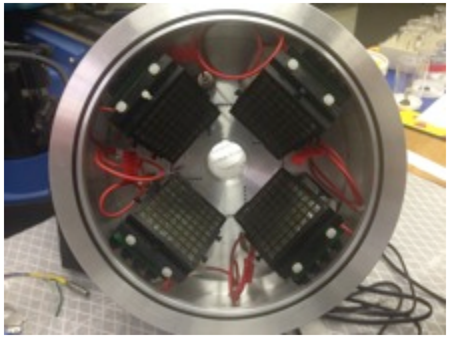
Physics campaigns: Auxiliary devices

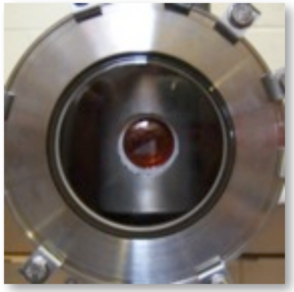
S800



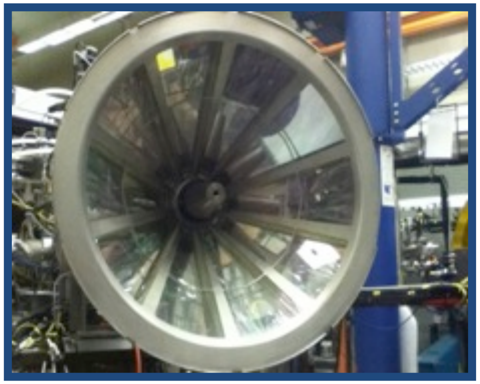
TRIPLEX

Phoswich Wall





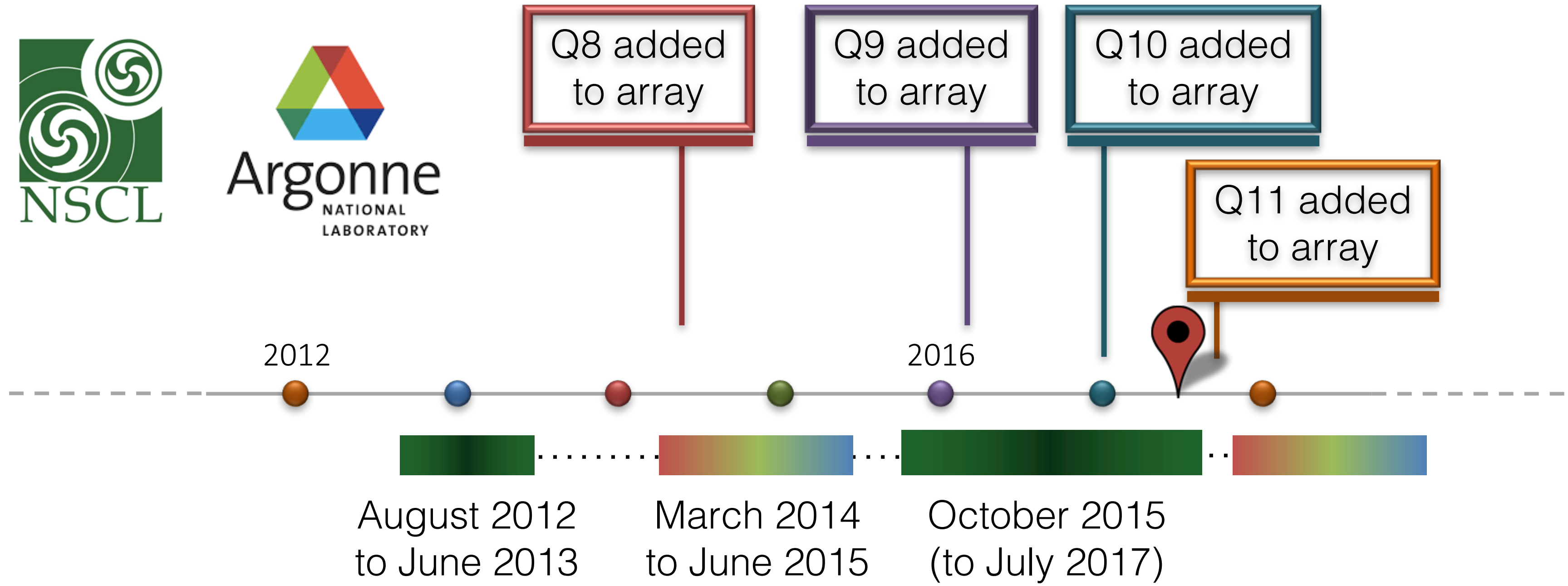
LH Target



CHICO II

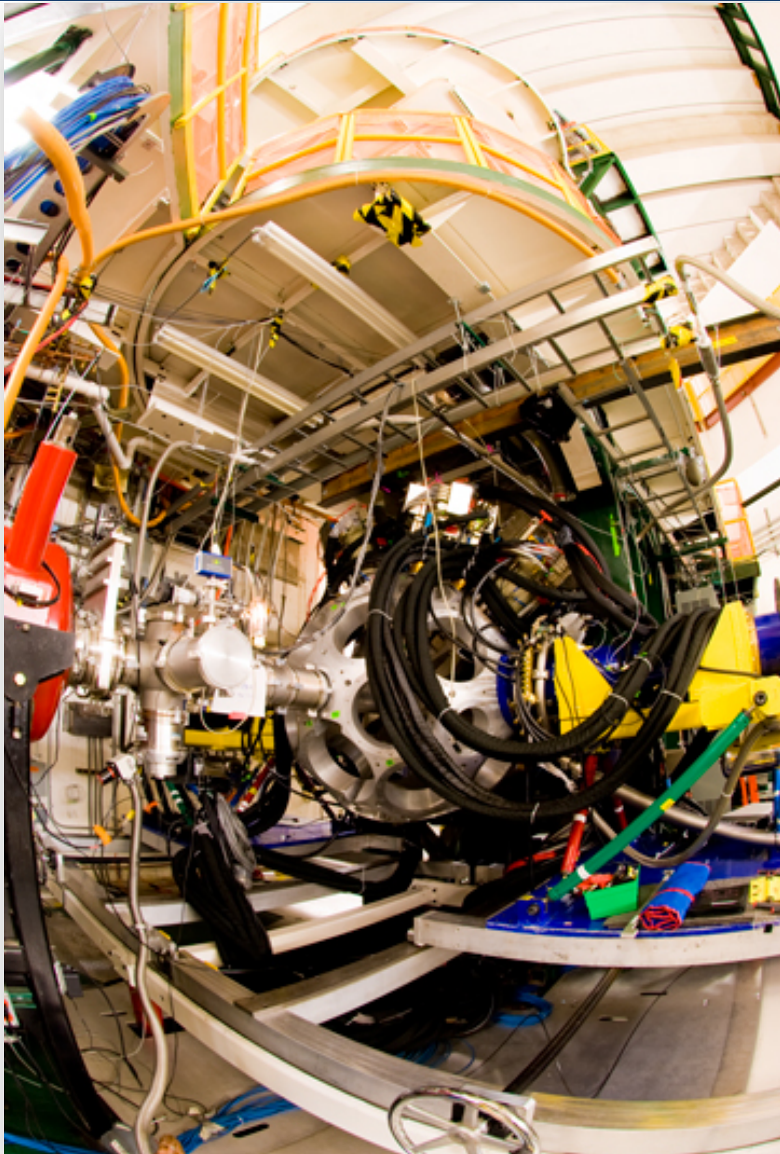
LENDA

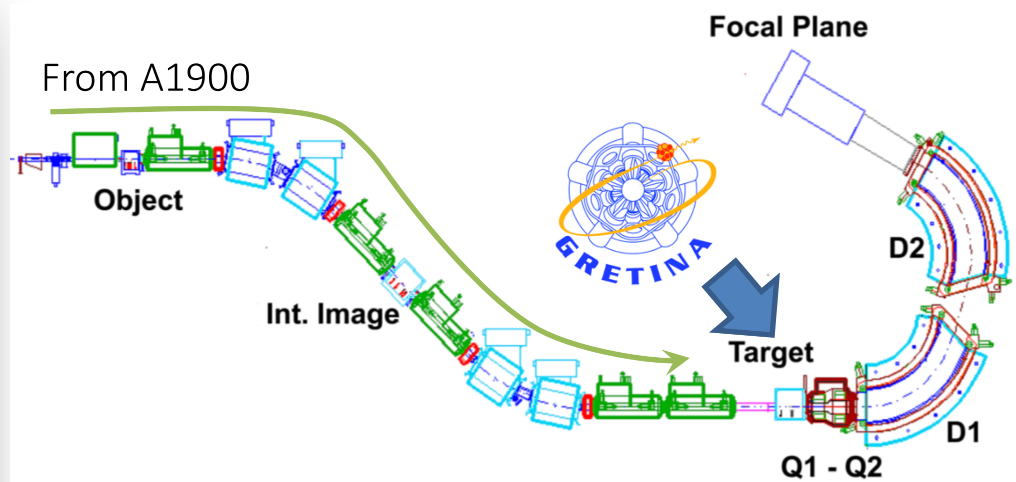
GRETINA Physics Campaigns: Overview



- First physics campaigns at NSCL and ANL (ATLAS/CARIBU) have already produced more than *25* physics papers
- Second NSCL campaign is ongoing, with 24 PAC approved experiments (~3600 hours)

First NSCL Physics Campaign (2012-2013)



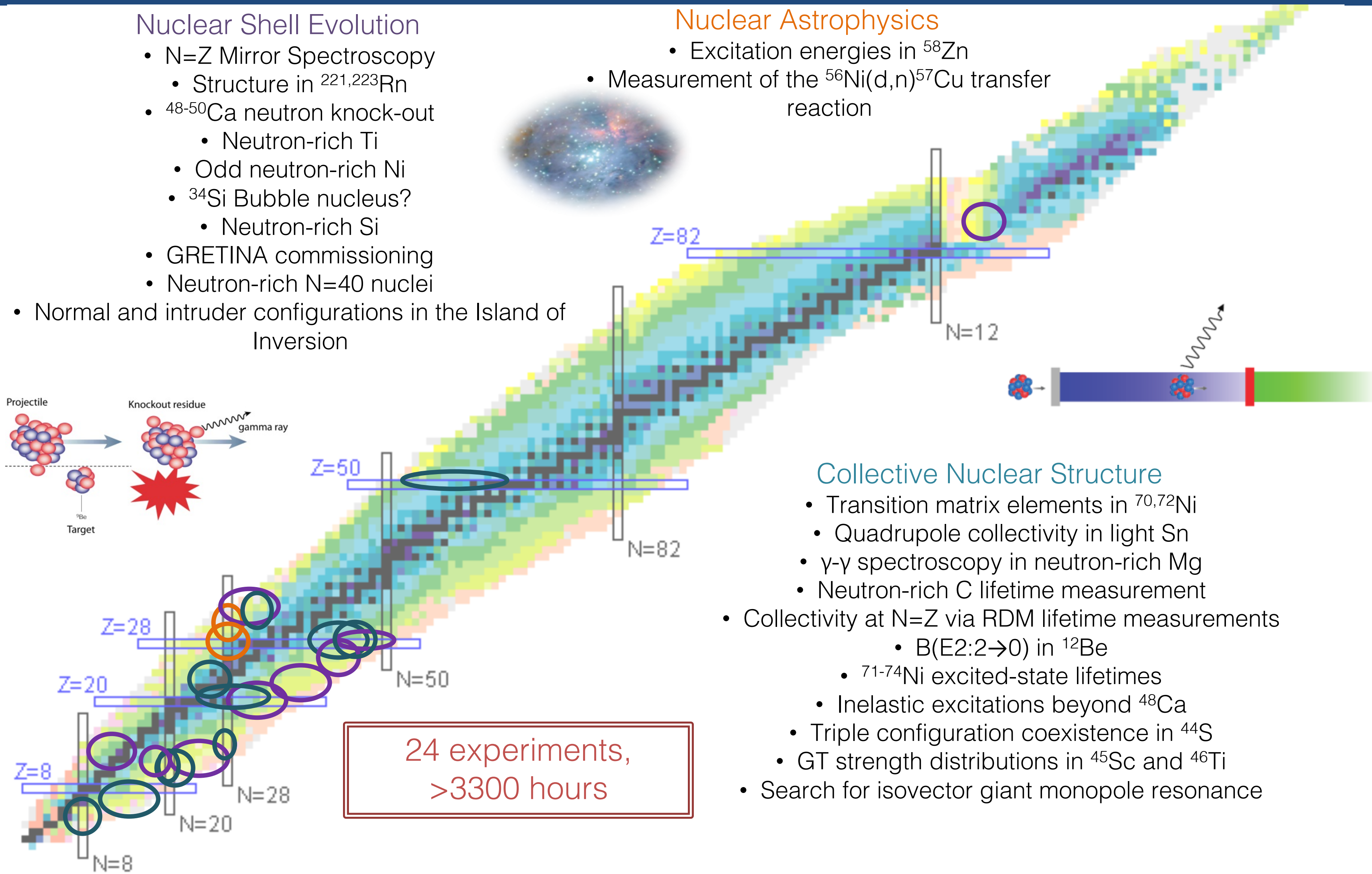


- First physics campaign coupled GRETINA with the S800 spectrograph for fast fragmentation beam (in-beam) spectroscopy
- Reaction channel selection is possible event-by-event in the S800

Challenges:

- High beam velocities ($\beta \approx 0.35$) – 2mm spatial resolution of GRETINA optimizes Doppler correction
- Low beam rates (as low as a few pps) – efficiency of GRETINA, in singles and $\gamma\gamma$ is critical

First NSCL Physics Campaign (2012-2013)



Nuclear Shell Evolution

- N=Z Mirror Spectroscopy
- Structure in ^{221,223}Rn
- $^{48\text{-}50}$Ca neutron knock-out
- Neutron-rich Ti
- Odd neutron-rich Ni
- ^{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 of the ^{56}Ni(d,n)^{57}Cu transfer reaction

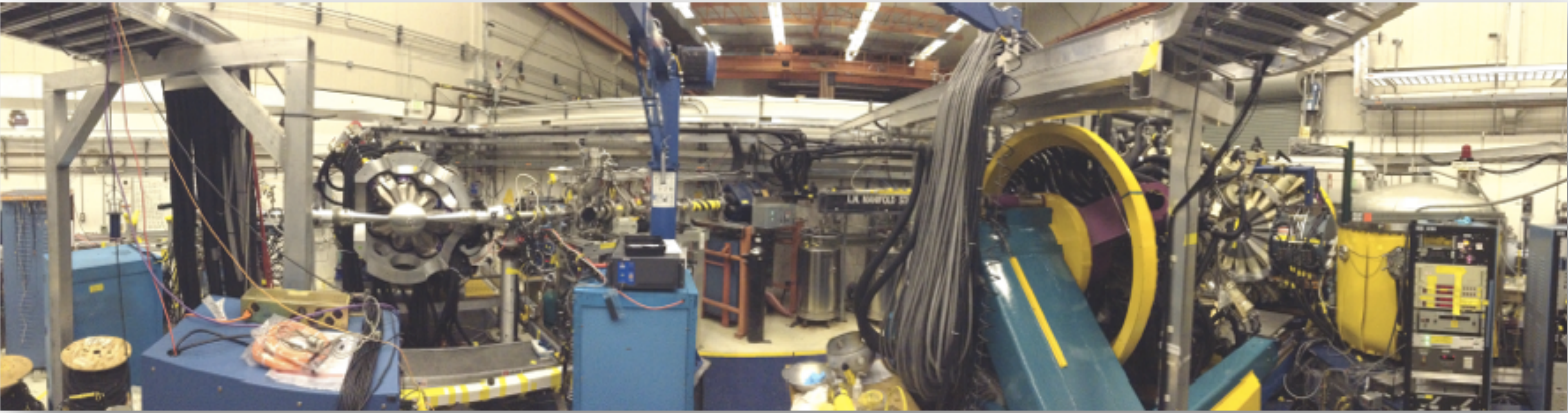
Collective Nuclear Structure

- Transition matrix elements in ^{70,72}Ni
- Quadrupole collectivity in light Sn
- 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
- GT strength distributions in ^{45}Sc and ^{46}Ti
- Search for isovector giant monopole resonance

24 experiments,
>3300 hours

First ANL Physics Campaign (2014-2015)

- **18 experiments : 3350 hours**



CARIBU and Stable beams

Position Resolution

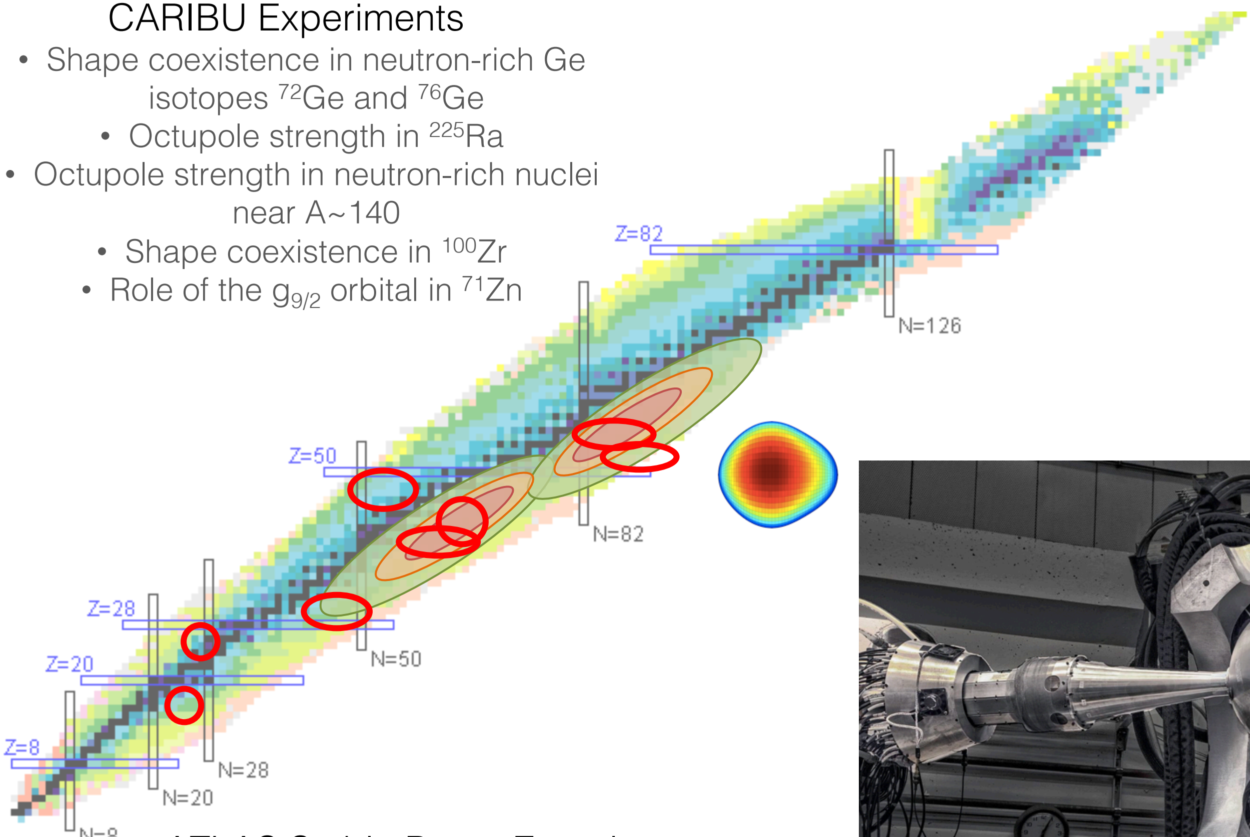
Good response for high-energy gammas

Polarization sensitivity

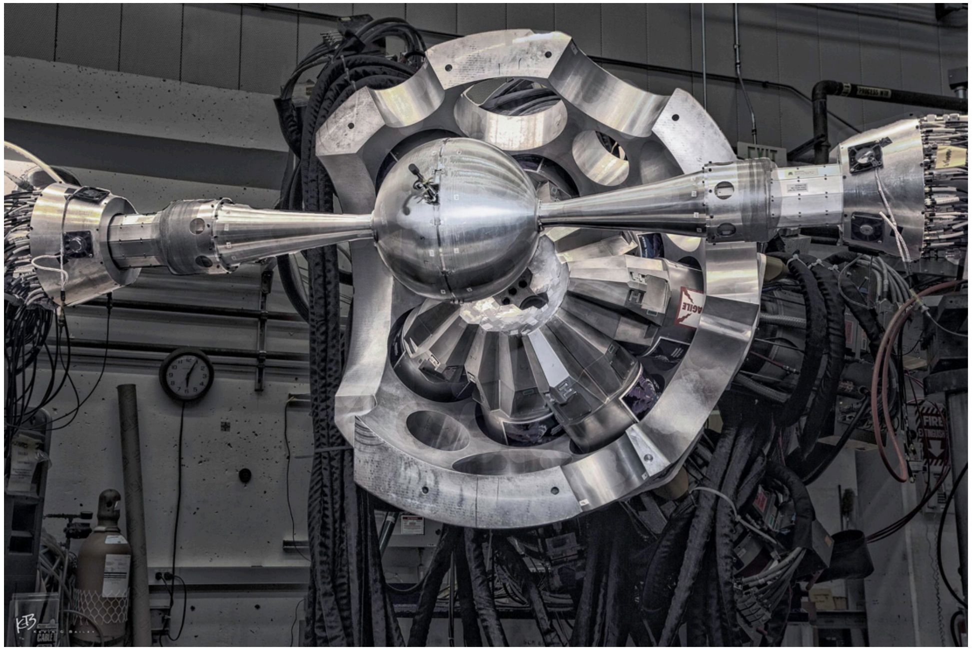
First ANL Physics Campaign (2014-2015)

CARIBU Experiments

- Shape coexistence in neutron-rich Ge isotopes ^{72}Ge and ^{76}Ge
- Octupole strength in ^{225}Ra
- Octupole strength in neutron-rich nuclei near A~140
- Shape coexistence in ^{100}Zr
- Role of the $g_{9/2}$ orbital in ^{71}Zn



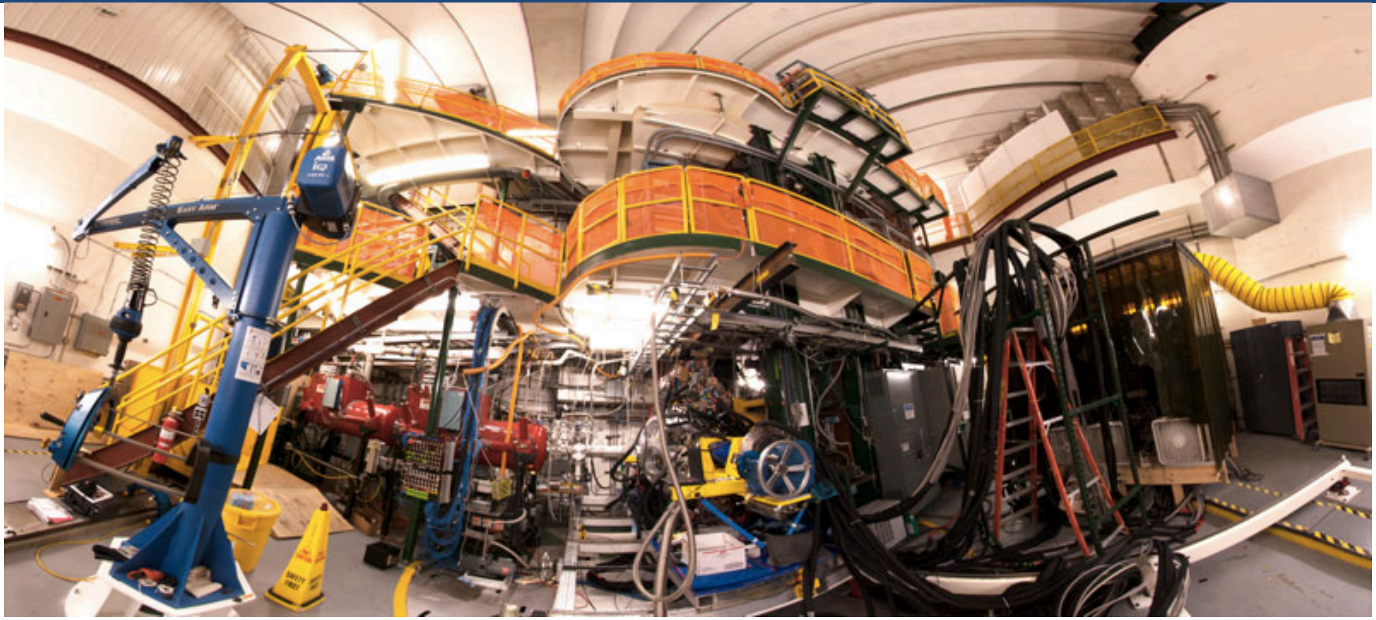
First physics campaign at ANL made use of the unique opportunities with CARIBU beams, and the combination of GRETINA with particle detectors such as CHICO-2 and the WashU Phoswich Wall.



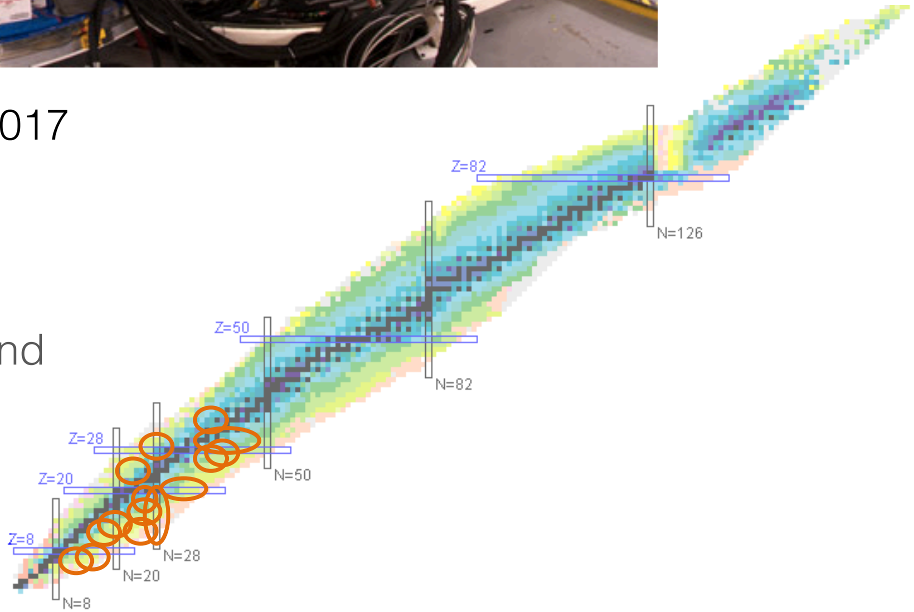
ATLAS Stable Beam Experiments

- Comparison of the performance of GRETINA and Gammasphere
- High-energy gamma-ray performance
- The polarization sensitivity of GRETINA
- Multi-particle-hole states in neutron-rich ^{34}P
- Understanding the low-energy enhancement of the photon-strength function

Current NSCL Campaign (2015-ongoing)



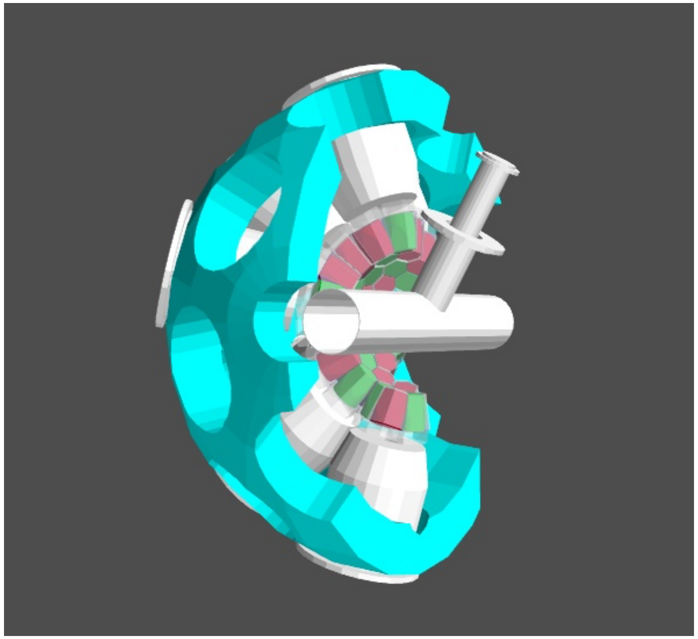
- Second NSCL campaign ongoing, ends July 2017
- 24 PAC approved experiments (~3600 hours)
- Campaign broadly covers the light to medium-mass nuclei and includes experiments with:
  - Recoil-distance lifetime measurements, and lifetimes through back-tracking
  - Gamma-ray + particle + neutron triple coincidences with LENDA + S800
  - Liquid-hydrogen target measurements

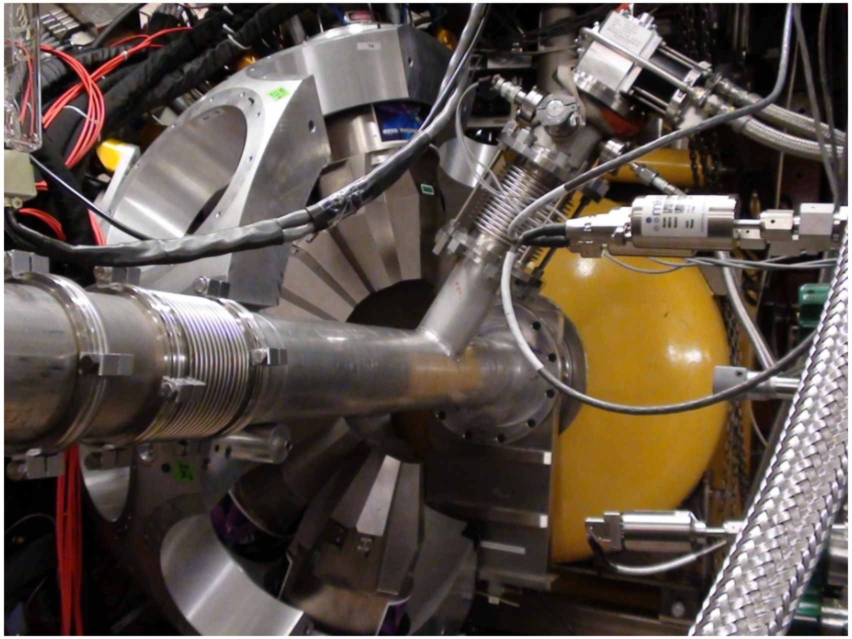


Now a biased selection of interesting experiments and results

Thick-target (p,p'), knockout, fragmentation @ NSCL

- inelastic only, γ-ray spectroscopy
- 200 mg/cm^2 target
- 1-100 pps
- simulations crucial for γ-ray efficiencies and target thickness

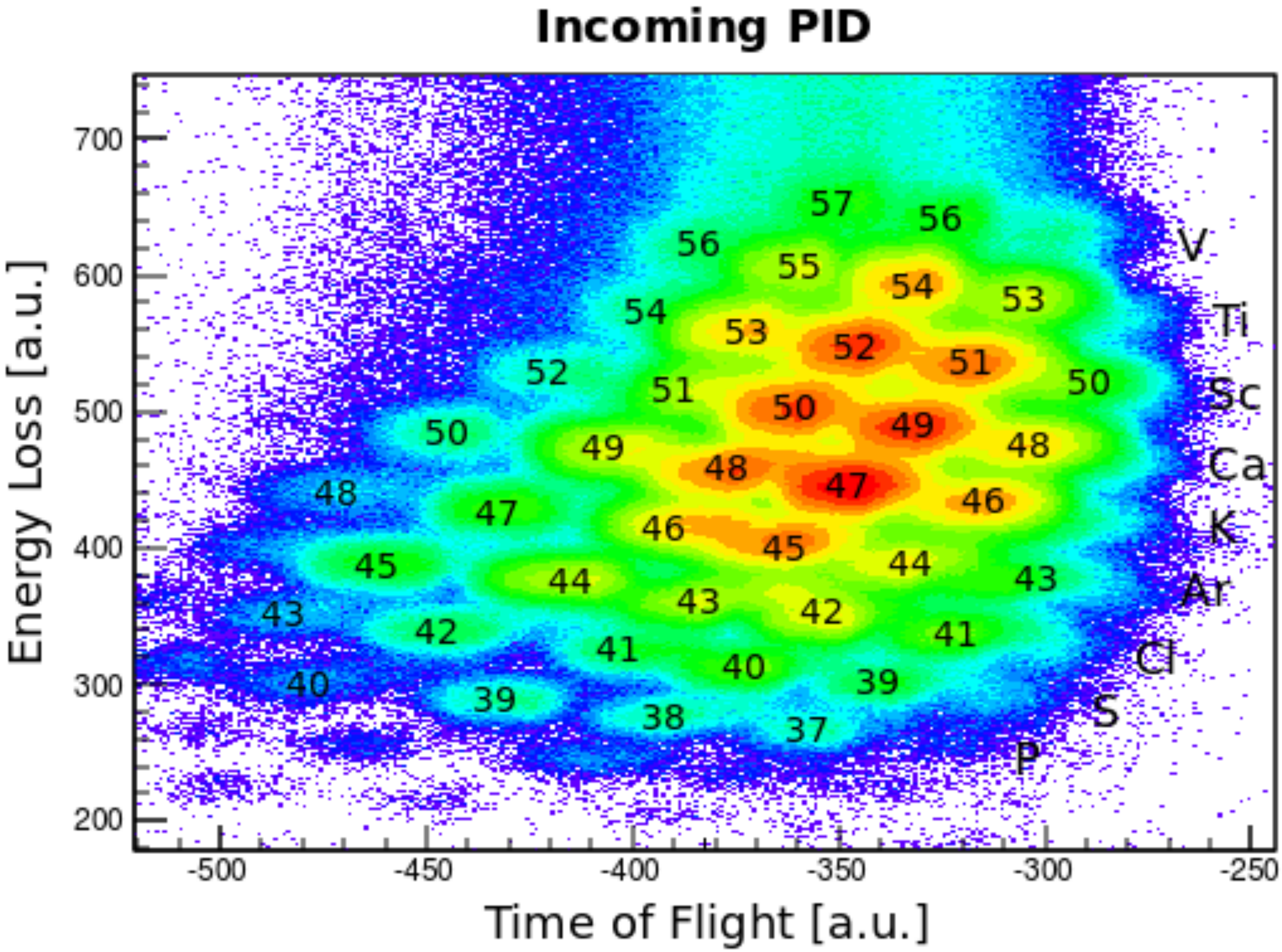




GRETINA + NSCL/Ursinus LH target + S800

NSCL Experiments 11035, 11037, 12016, 10010

NSCL Expt. 11037



Octupole Deformation in ^{144}Ba

PRL **116,** 112503 (2016) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2016

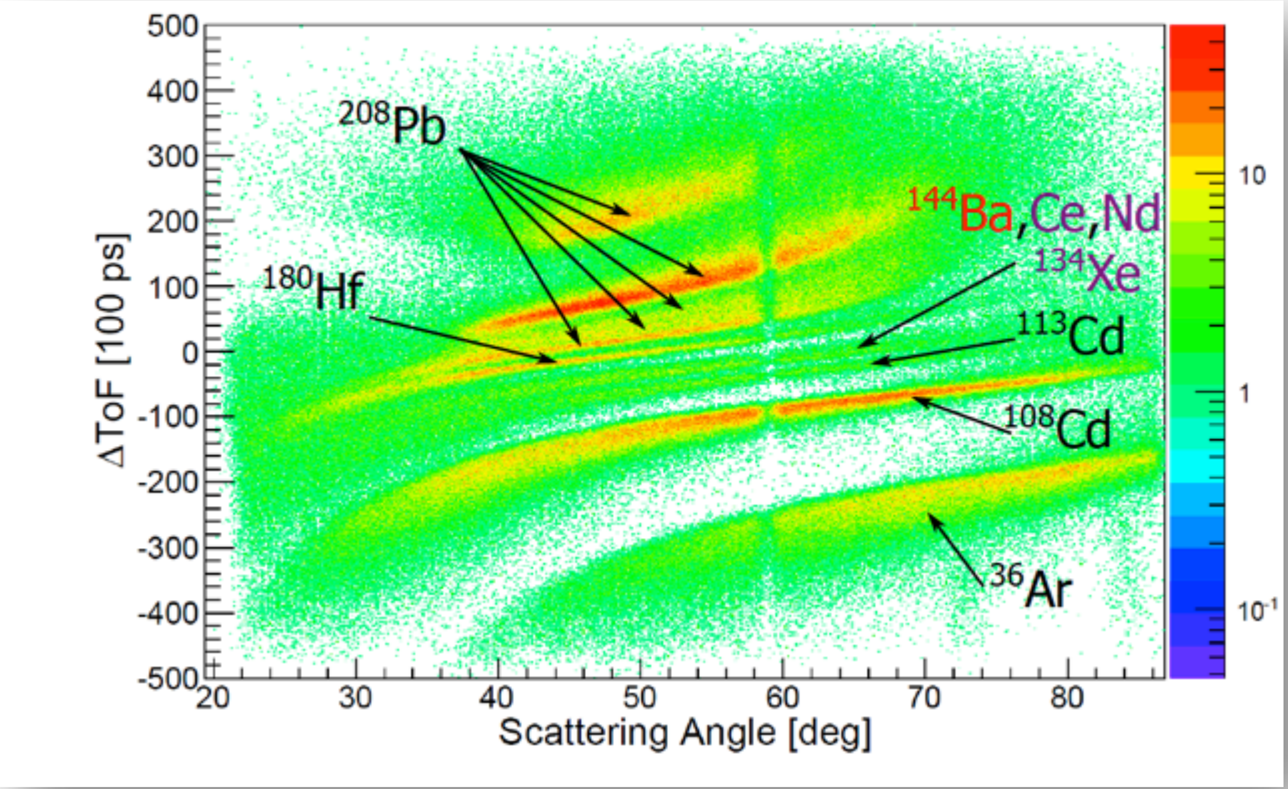
Direct Evidence of Octupole Deformation in Neutron-Rich ^{144}Ba

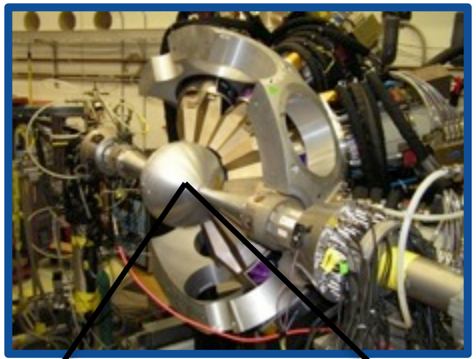
B. Bucher,[1,*] S. Zhu,[2] C. Y. Wu,[1] R. V. F. Janssens,[2] D. Cline,[3] A. B. Hayes,[3] M. Albers,[2] A. D. Ayangeakaa,[2] P. A. Butler,[4] C. M. Campbell,[5] M. P. Carpenter,[2] C. J. Chiara,[2,6,†] J. A. Clark,[2] H. L. Crawford,[7,‡] M. Cromaz,[5] H. M. David,[2,§] C. Dickerson,[2] E. T. Gregor,[8,9] J. Harker,[2,6] C. R. Hoffman,[2] B. P. Kay,[2] F. G. Kondev,[2] A. Korichi,[2,10] T. Lauritsen,[2] A. O. Macchiavelli,[5] R. C. Pardo,[2] A. Richard,[7] M. A. Riley,[11] G. Savard,[2] M. Scheck,[8,9] D. Seweryniak,[2] M. K. Smith,[12] R. Vondrasek,[2] and A. Wiens[5]

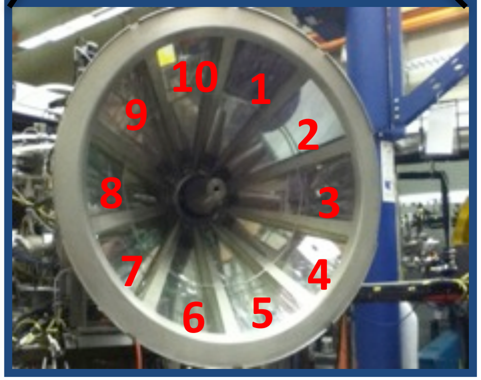
[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*University of Rochester, Rochester, New York 14627, USA*
[4]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[5]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[6]*University of Maryland, College Park, Maryland 20742, USA*
[7]*Ohio University, Athens, Ohio 45701, USA*
[8]*University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
[9]*SUPA, Scottish Universities Physics Alliance, Glasgow G12 8QQ, United Kingdom*
[10]*CSNSM, IN2P3-CNRS, bâtiment 104-108, F-91405 Orsay Campus, France*
[11]*Florida State University, Tallahassee, Florida 32306, USA*
[12]*University of Notre Dame, Notre Dame, Indiana 46556, USA*

CHICO II and GRETINA

~ 8000 pps 650 MeV ^{144}Ba Beam on a ^{208}Pb target (1 mg/cm^2) for ~ 10 days
Important stable contaminants (same m/q): $^{134}Xe^{26+}$, $^{144}Nd^{28+}$, $^{180}Hf^{35+}$, $^{108}Cd^{21+}$, $^{113}Cd^{22+}$







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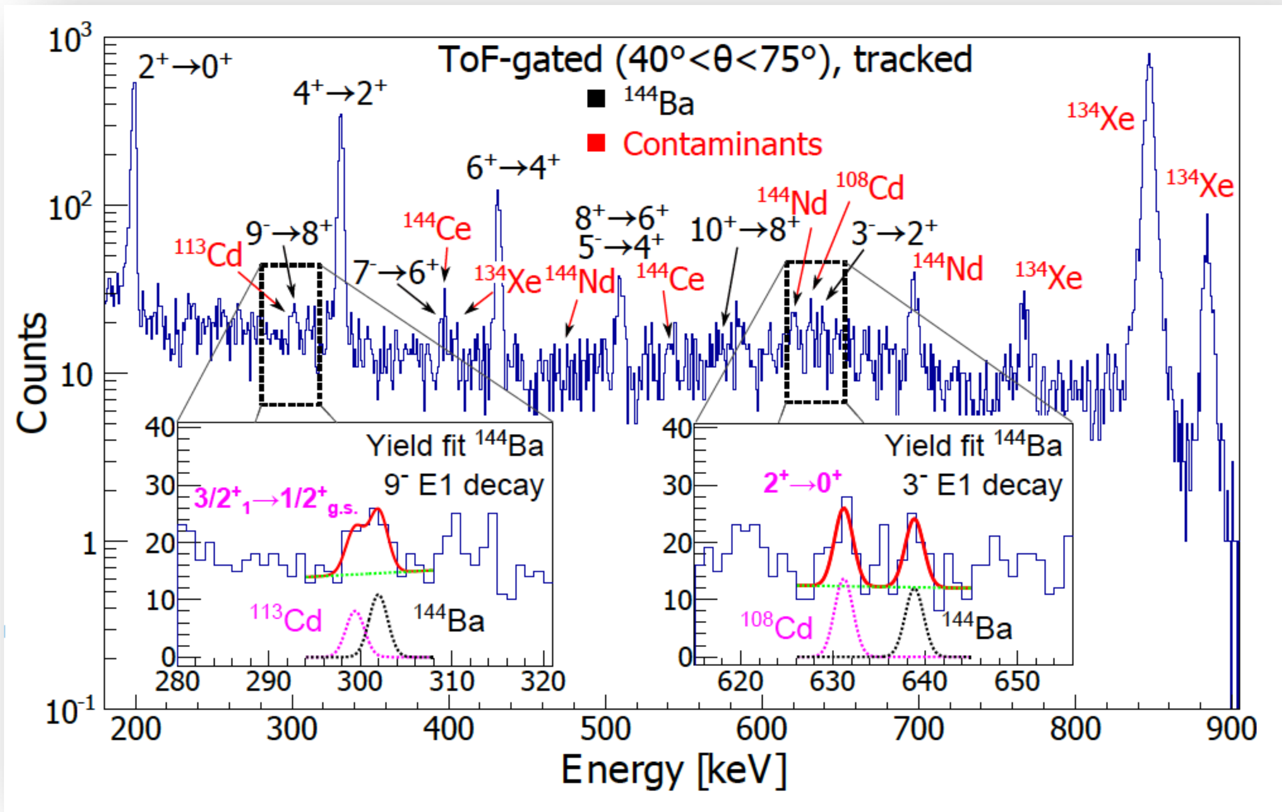
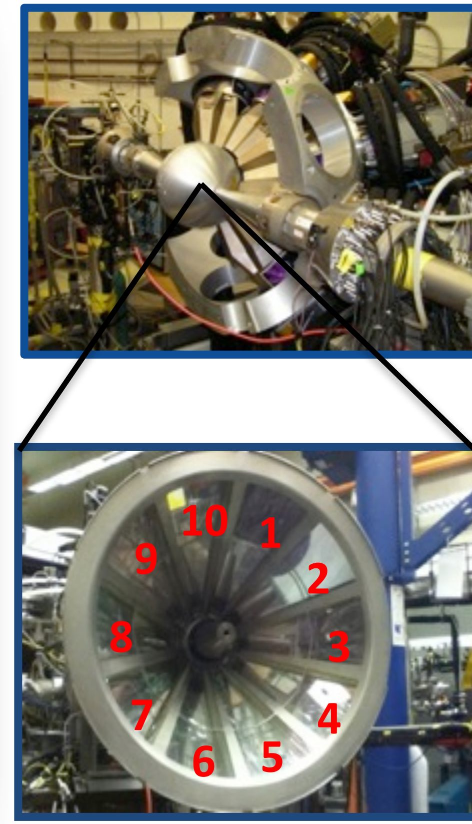
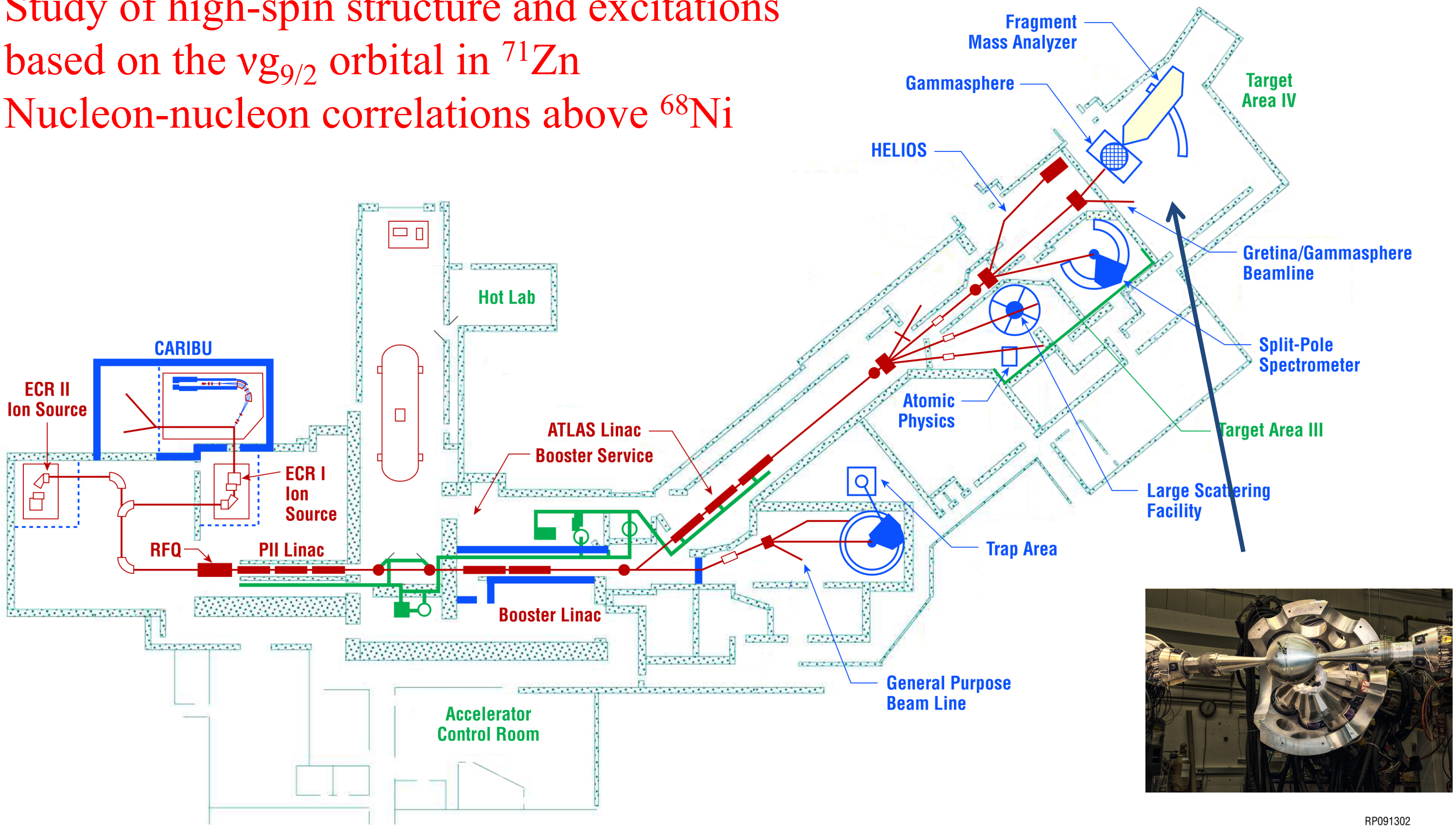




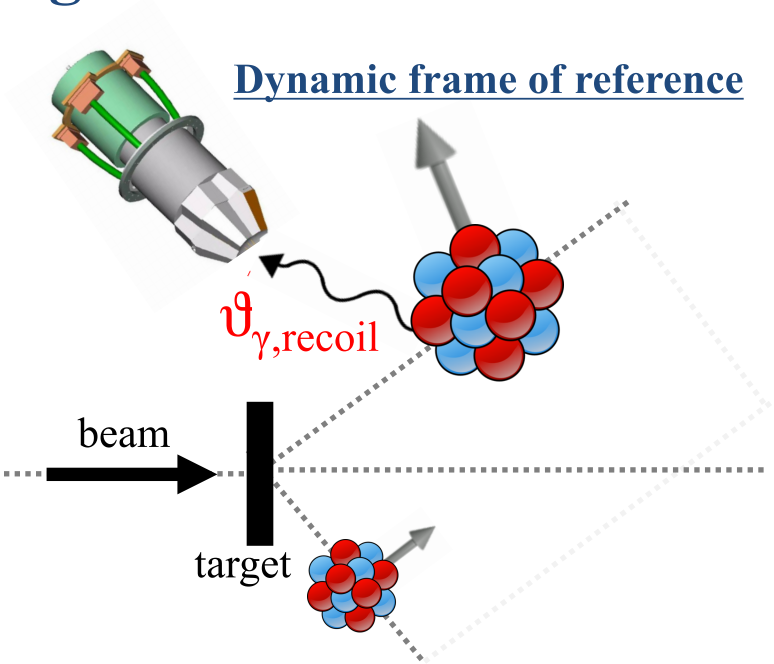
The $^{48}Ca+^{70}Zn$ experiment

- Test of heavy-ion transfer reactions with GRETINA and CHICO2
- Study of high-spin structure and excitations based on the $\nu g_{9/2}$ orbital in ^{71}Zn
- Nucleon-nucleon correlations above ^{68}Ni



$^{48}Ca+^{70}Zn \rightarrow ^{47}Ca+^{71}Zn$ @ 170 MeV (30 % above C.B.)

Angular distributions



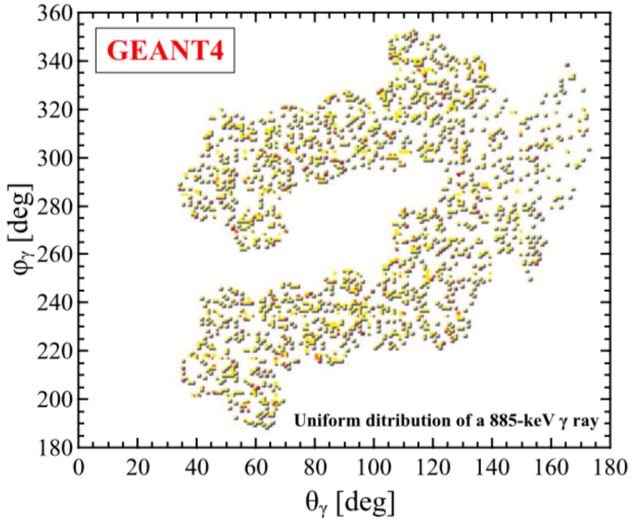
1) Simulation of an isotropic gamma ray **(GEANT4)**

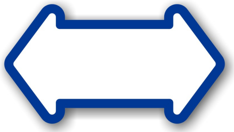
2) Process the gamma ray as real data **(tracking)**

3) Extract particle angular distribution **gated** on that gamma ray

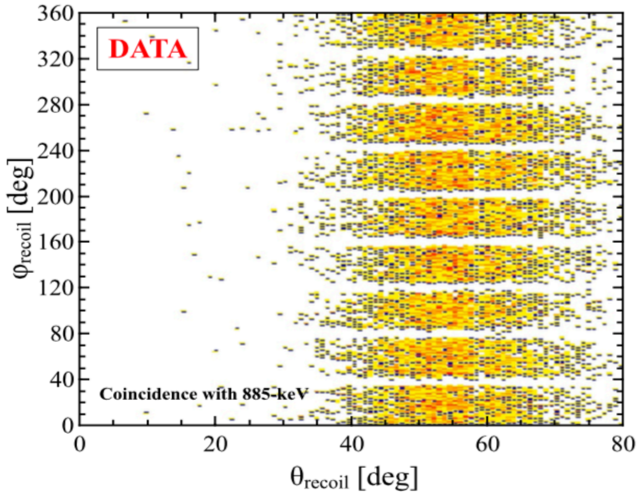
4) Fold gammas and particles **event by event**

Gamma



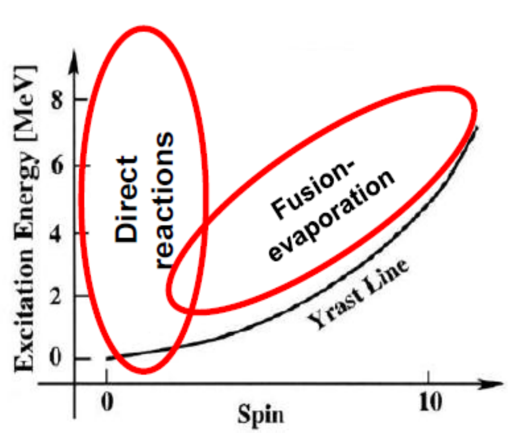


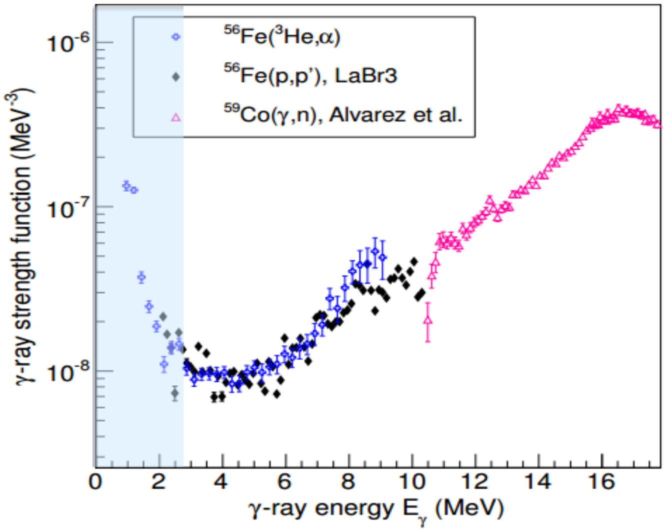
Particles



Experimental Method: Photon Strength Function

- Use a direct reaction to populate states in quasi-continuum.
- Extract PSF using a new model independent method [1].
- Identify events in the "up-bend"
  - Use GRETINA as a polarimeter to measure the M1 or E1 character.





A.C. Larsen et. al. PRL 111, 242504 (2013)

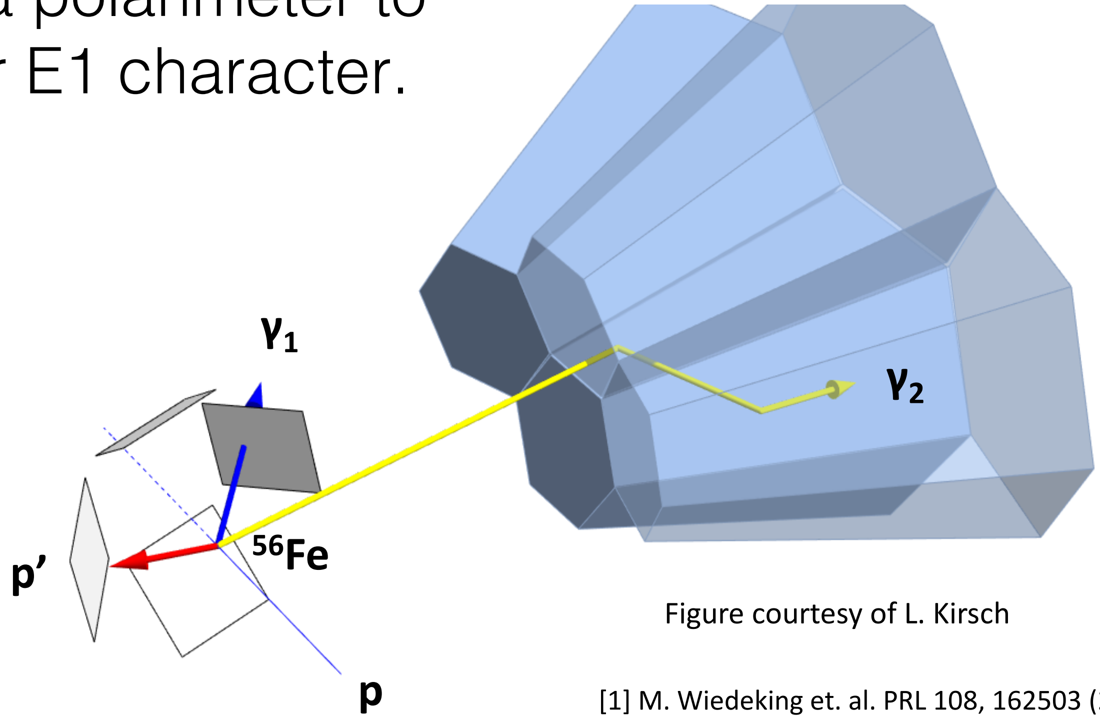
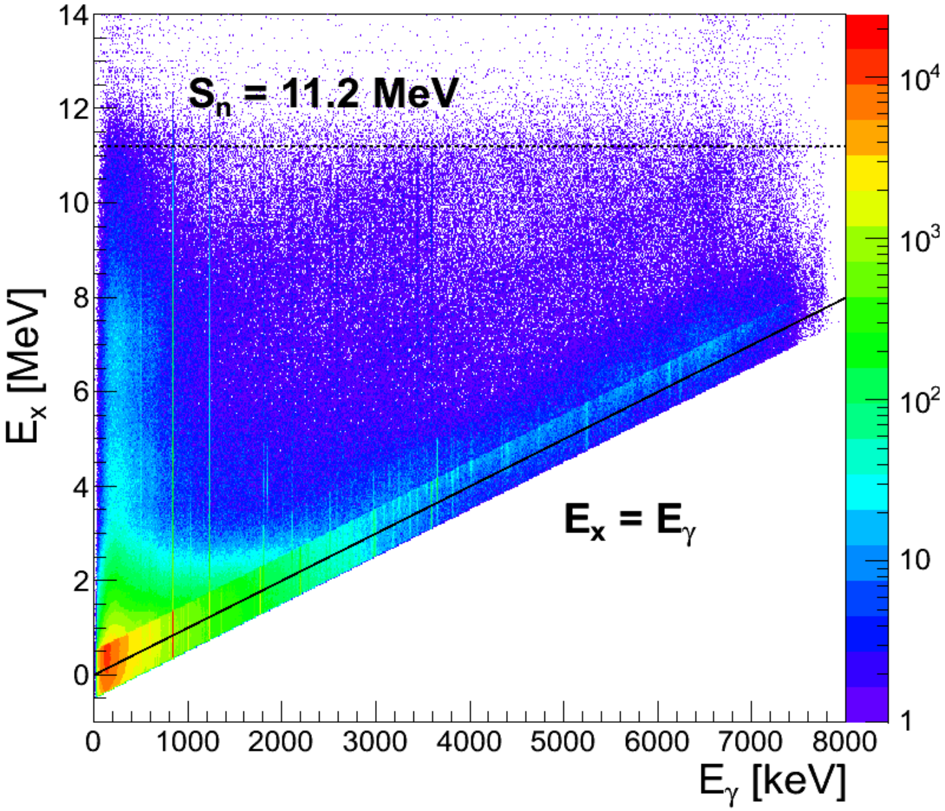


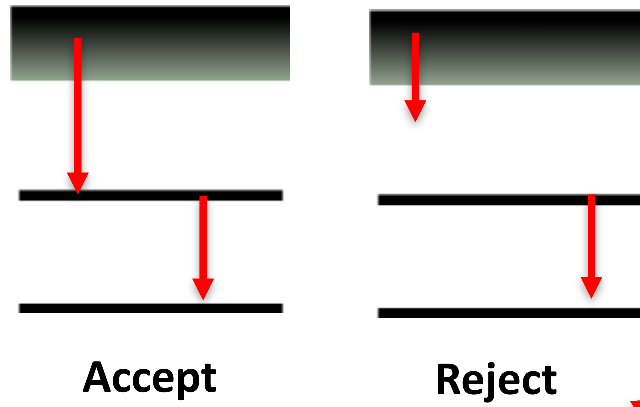
Figure courtesy of L. Kirsch

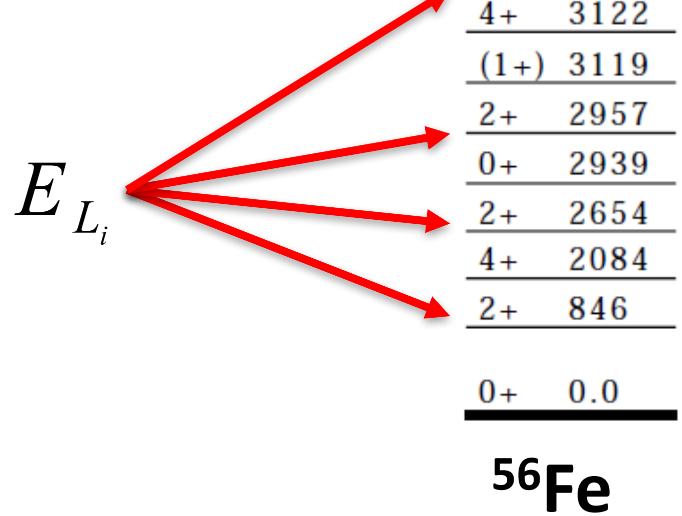
[1] M. Wiedeking et. al. PRL 108, 162503 (2012)

Calorimeter Gating

$$\Sigma E_\gamma = E_x \pm 500\, keV$$

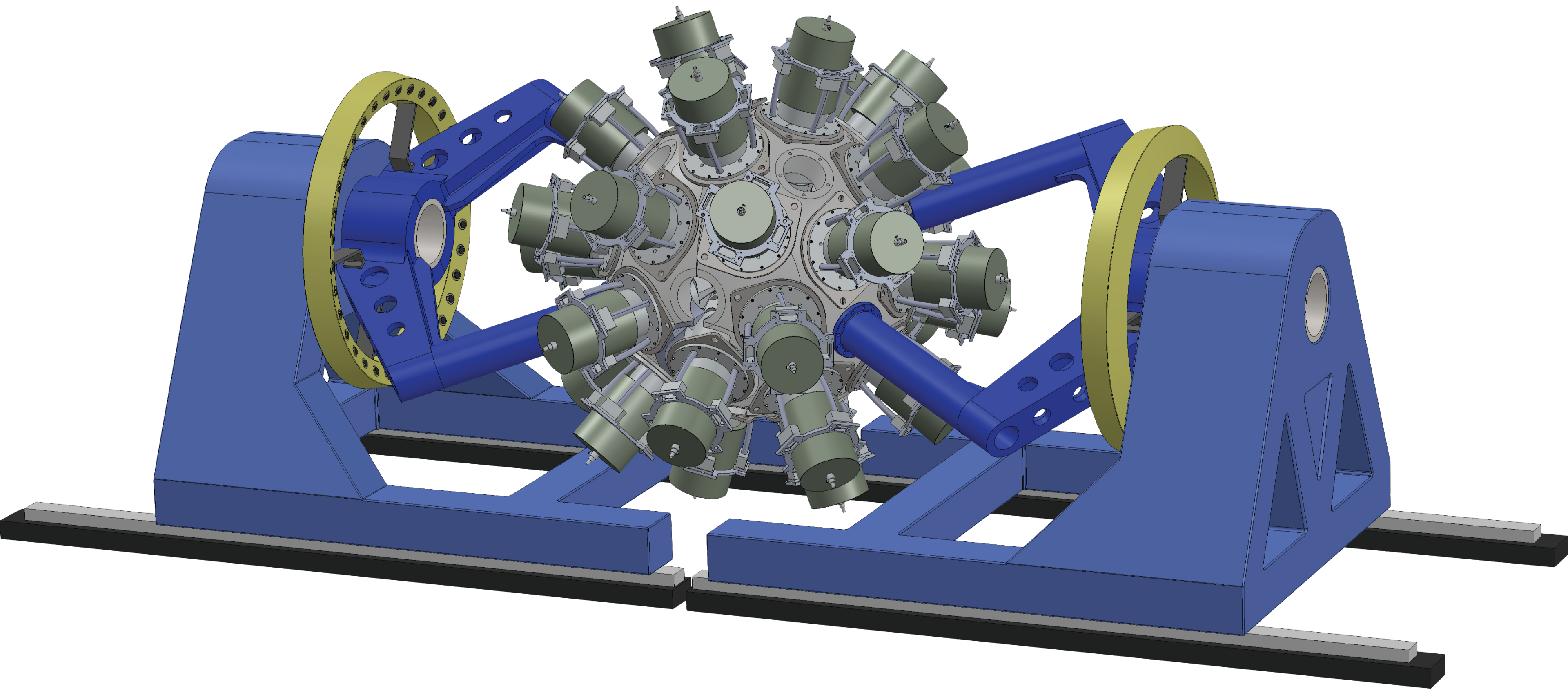






- Measure intensity of feeding to first four 2^+ states.
- Correct for efficiency, branching, and background.

Future: GRETINA to GRETA



Future of GRETINA

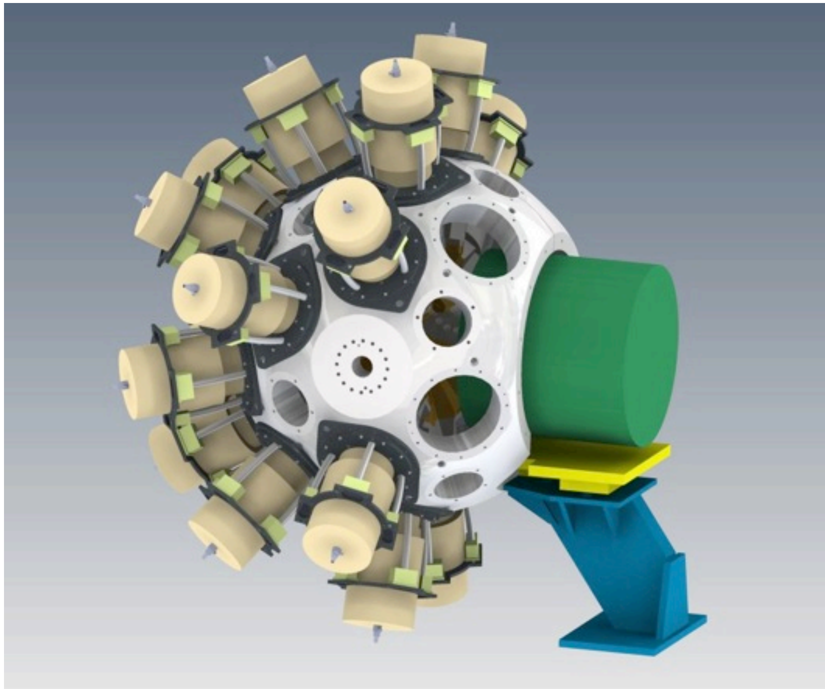
Near Term

- Move to Argonne for 2nd physics campaign, now @FMA
- Improve rate performance
- Next move(s) TBD by community + DOE

Long Term

- Serves FRIB for initial operation
- Quad modules will be incorporated into GRETA

New FMA entrance quad



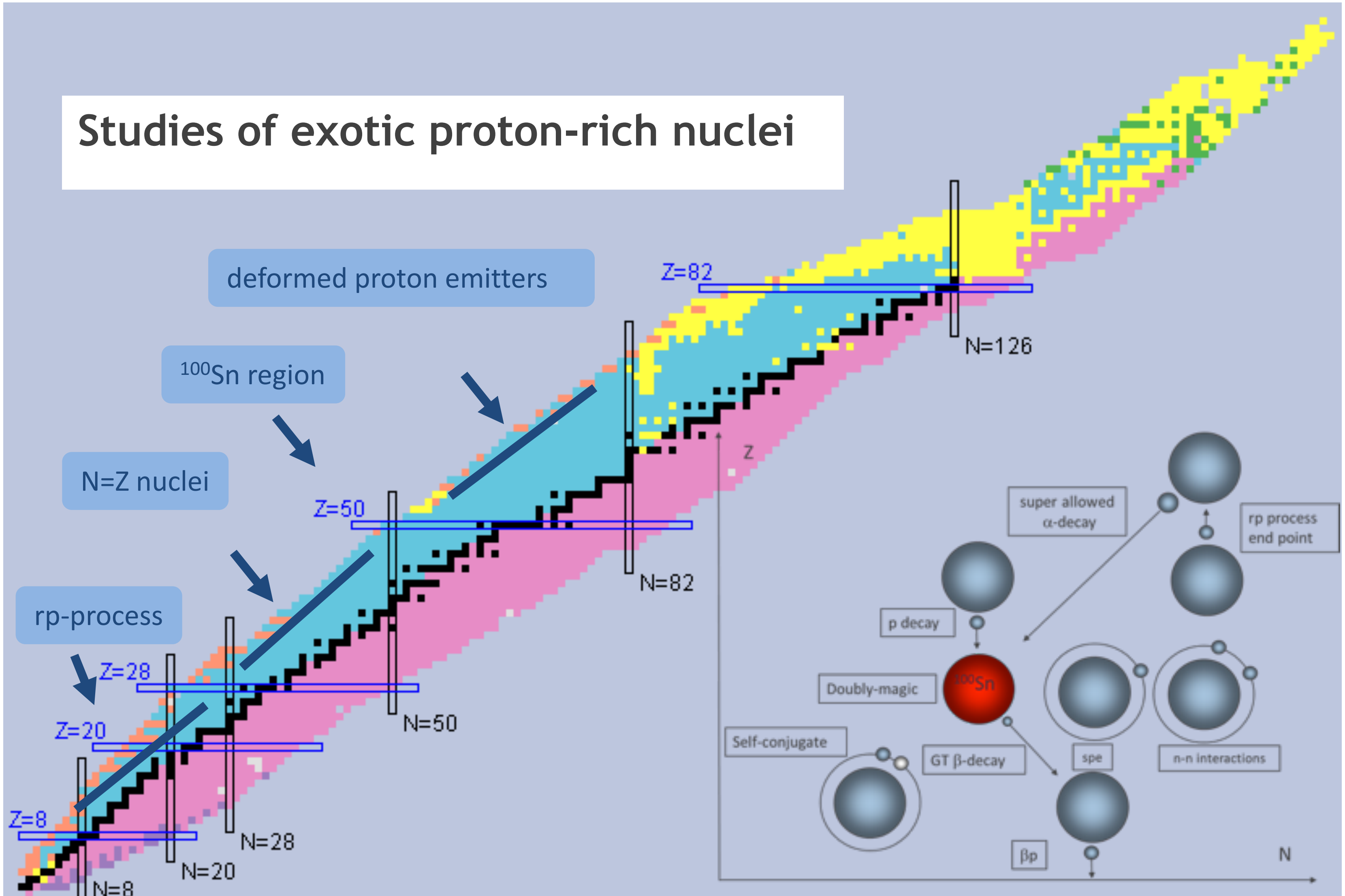
Will fit inside GRETINA frame (most forward detector ring removed)

Larger solid angle 12 msr (8 msr with FMA alone now, 2 msr with GS)

Two hemis at 90 degrees to the beam axis (>10 clusters)

high γ-ray efficiency, Doppler correction, polarization

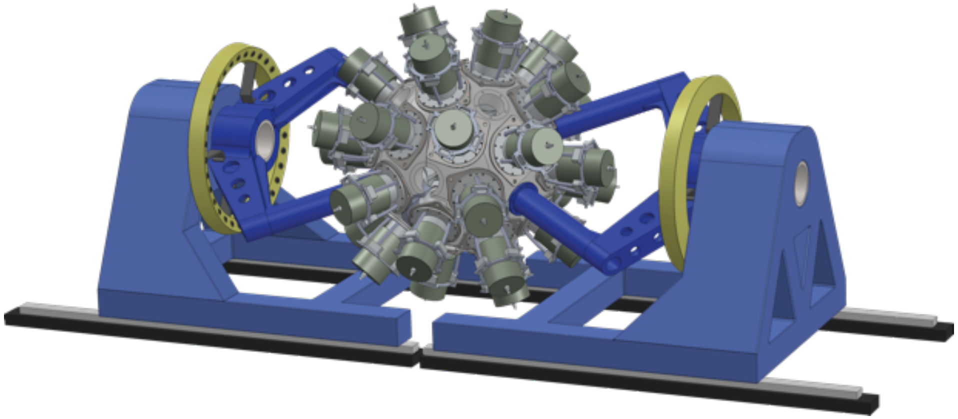
• ATLAS 2.0 GRETINA@FMA campaign ~ October 2017 ….



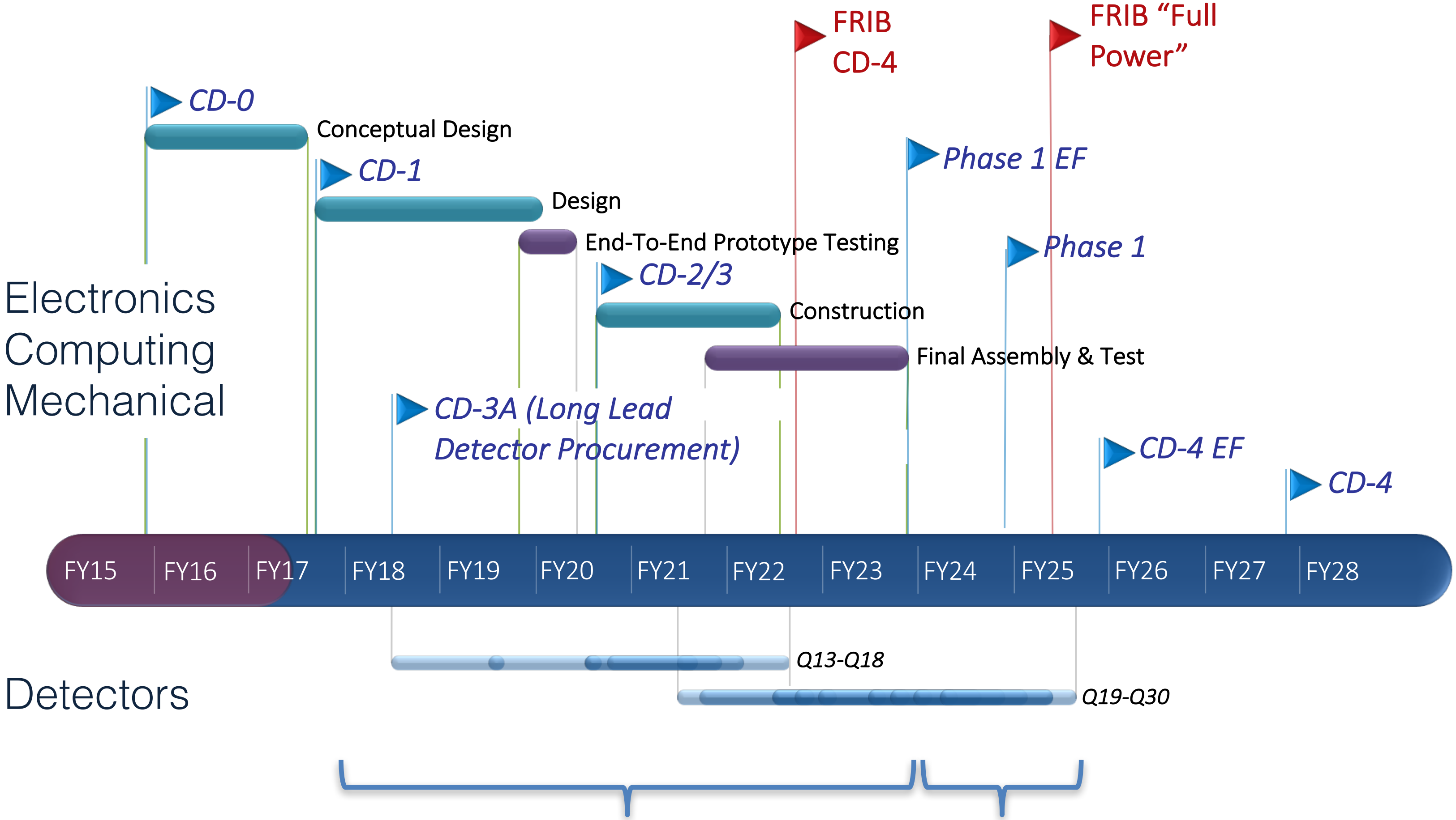
GRETA: A premier γ-ray tracking detector for FRIB

The Facility for Rare Isotope Beams (FRIB), is currently being constructed at Michigan State University. It will be a world leading accelerator facility to understand the properties of rare nuclear isotopes and how elements are synthesized.

A high resolution, high efficiency γ-ray detector array (GRETA) is an essential instrument for FRIB, required to leverage the full scientific capabilities.



Phased approach to optimize delivery of a γ-ray tracking array capability for FRIB



Phase 1	Phase 2
• Final Electronics, Computing and Mechanical systems for 30 Quad Detector Modules • Subset of Detector Modules (6 or more)	• Accept the remaining Quad Detector Modules (For a total of 18)

GRETINA/GRETA User Community

Established and Engaged User Community

GRETINA/GRETA Users Executive Committee (GUEC)

Heather Crawford (chair)
Hiro Iwasaki
Darek Seweryniak
Lew Riley
Mark Riley

Over 200 active Users

Coordinated with the FRIB Users Organization

Establishing Working Groups

First workshop planned (August 2nd 2017)

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

Summary

GRETINA, a first implementation of a tracking array, is a powerful tool for in-beam gamma-ray spectroscopy.

Physics campaigns were completed successfully at ANL and NSCL

Results show very good performance and new and exciting physics

NSCL 2.0 : October 2015 – July 2017

Next campaign at ATLAS → FMA and improved CARIBU beams

The path from GRETINA to GRETA has been proposed:

GRETINA (12 Quads) thru FRIB early operation

GRETA Phase 1 aims to take over after ~1yr : (12 + 6 =) 18 Quads + new systems

GRETA Phase 2 aims to expand GRETA+FRIB science reach by adding Quads until Full (30 Quad) GRETA is complete late 2025

The GRETA community eagerly awaits CD-1 from DOE.
CD-1 allows real design (+ prototype, test, refine, …) work to begin.

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Thank You!

Visit us at http://greta.lbl.gov/ http://gretina.lbl.gov/

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