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# Nuclear Structure at the Extremes of Isospin

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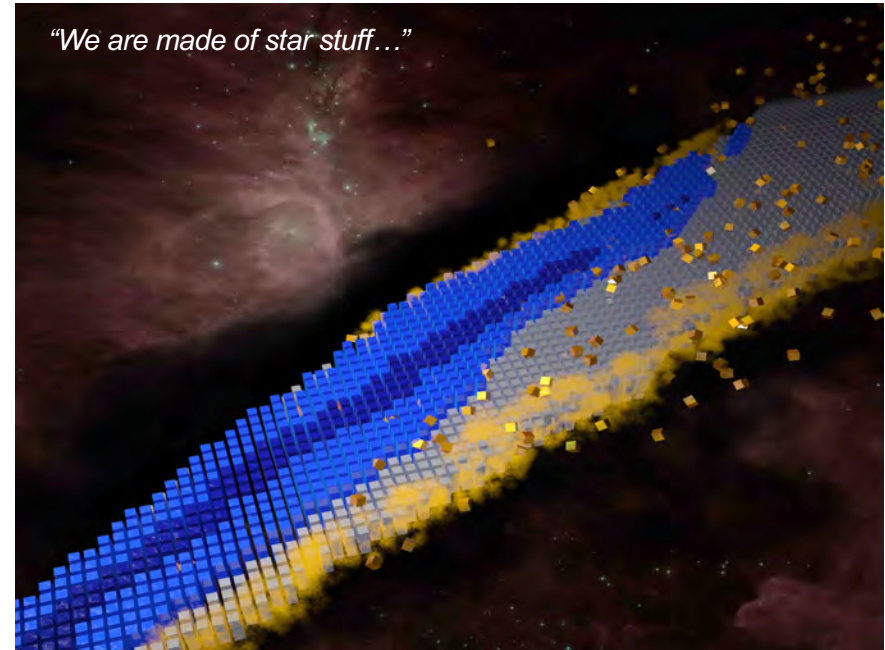
# The Science: Nuclear Landscape and Big Questions

## National Research Council Report - 2013

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the 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?

## NSAC 2015 Long Range Plan: Nuclear Structure, Reactions, and Astrophysics

- **The origin and evolution of nuclei**
  - Where do nuclei and elements come from?
  - What combinations of neutrons and protons can form a bound nucleus?
- **The origin of nuclear patterns**
  - How are nuclei organized?
    - Emergent phenomena in complex systems



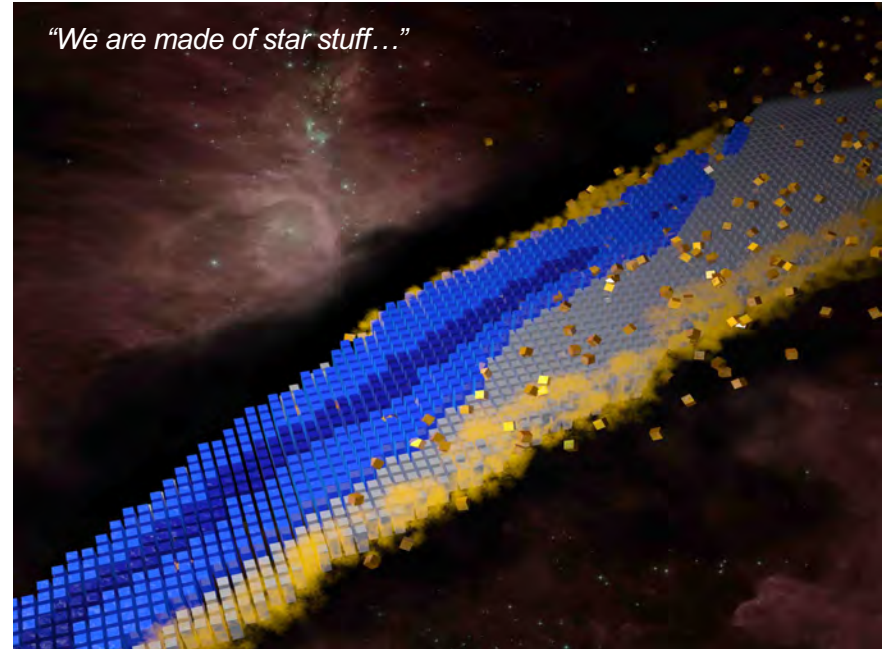
# The Science: Nuclear Landscape and Big Questions

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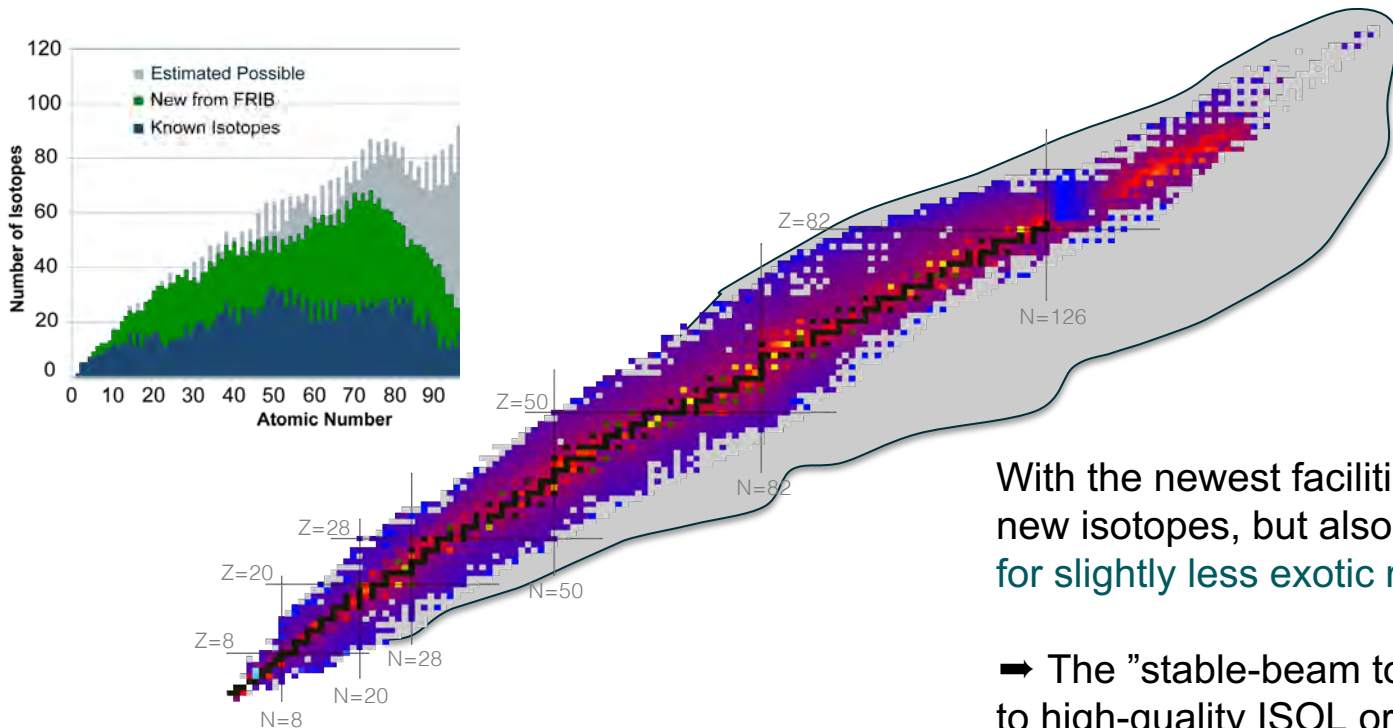
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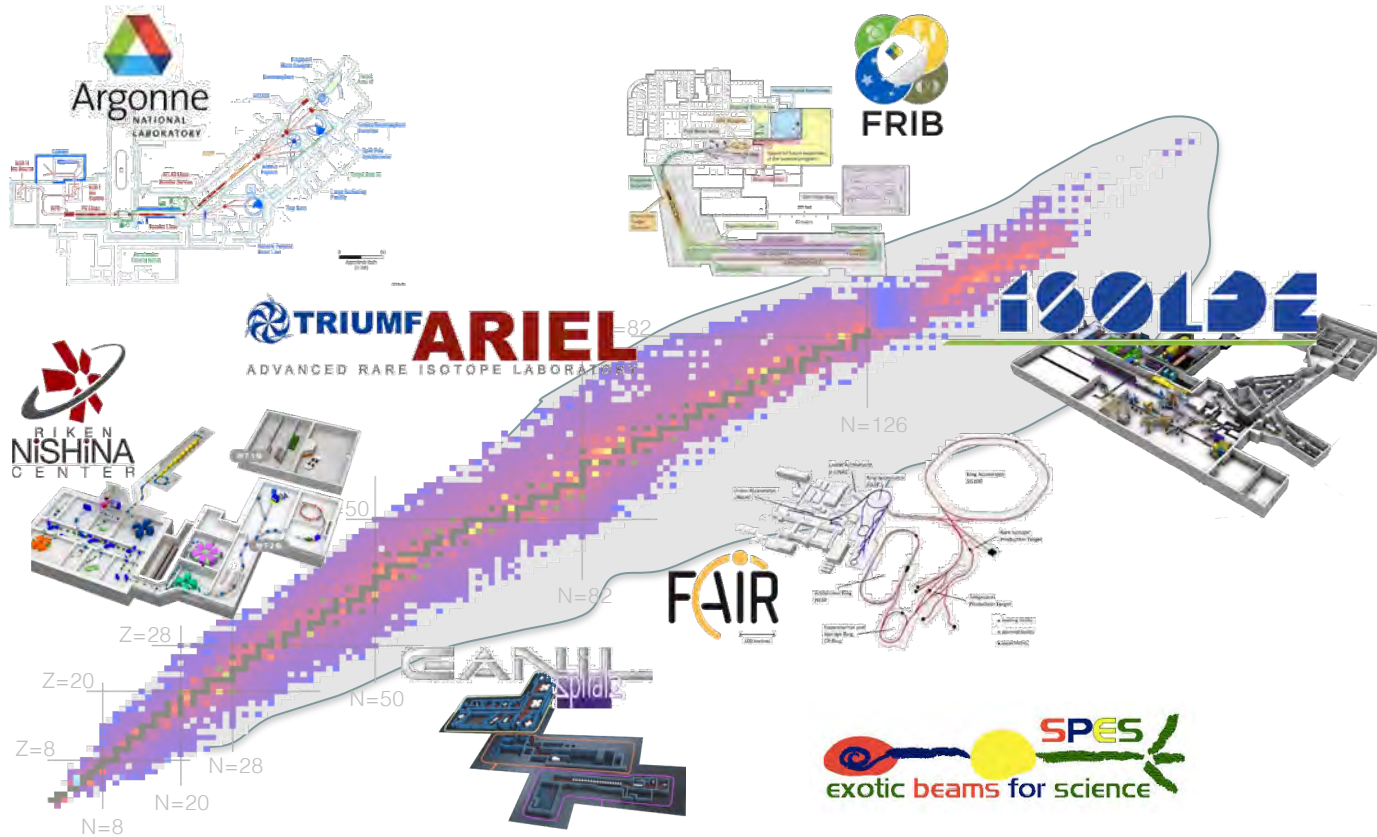
# The Nuclear Landscape



With the newest facilities the gain is not only new isotopes, but also **transformative rates for slightly less exotic radioisotopes.**

➔ The "stable-beam tool-kit" is now applied to high-quality ISOL or reaccelerated RI beams

# Current and Upcoming Facilities



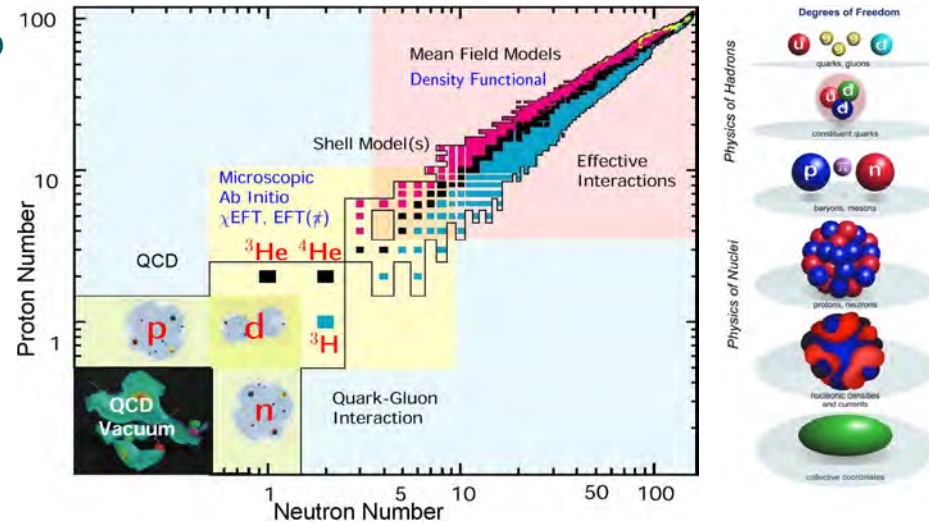
# The Key Role of Theory

There has been and continues to be active development in theory toward the goal to “develop a predictive understanding of nuclei and their interactions grounded in fundamental QCD and electroweak theory”.

“New measurements drive new theoretical and computational efforts which, in turn, uncover new puzzles that trigger new experiments.”

“A strong interplay between theoretical research, experiment, and advanced computing is essential for realizing the full potential of ... discoveries.”

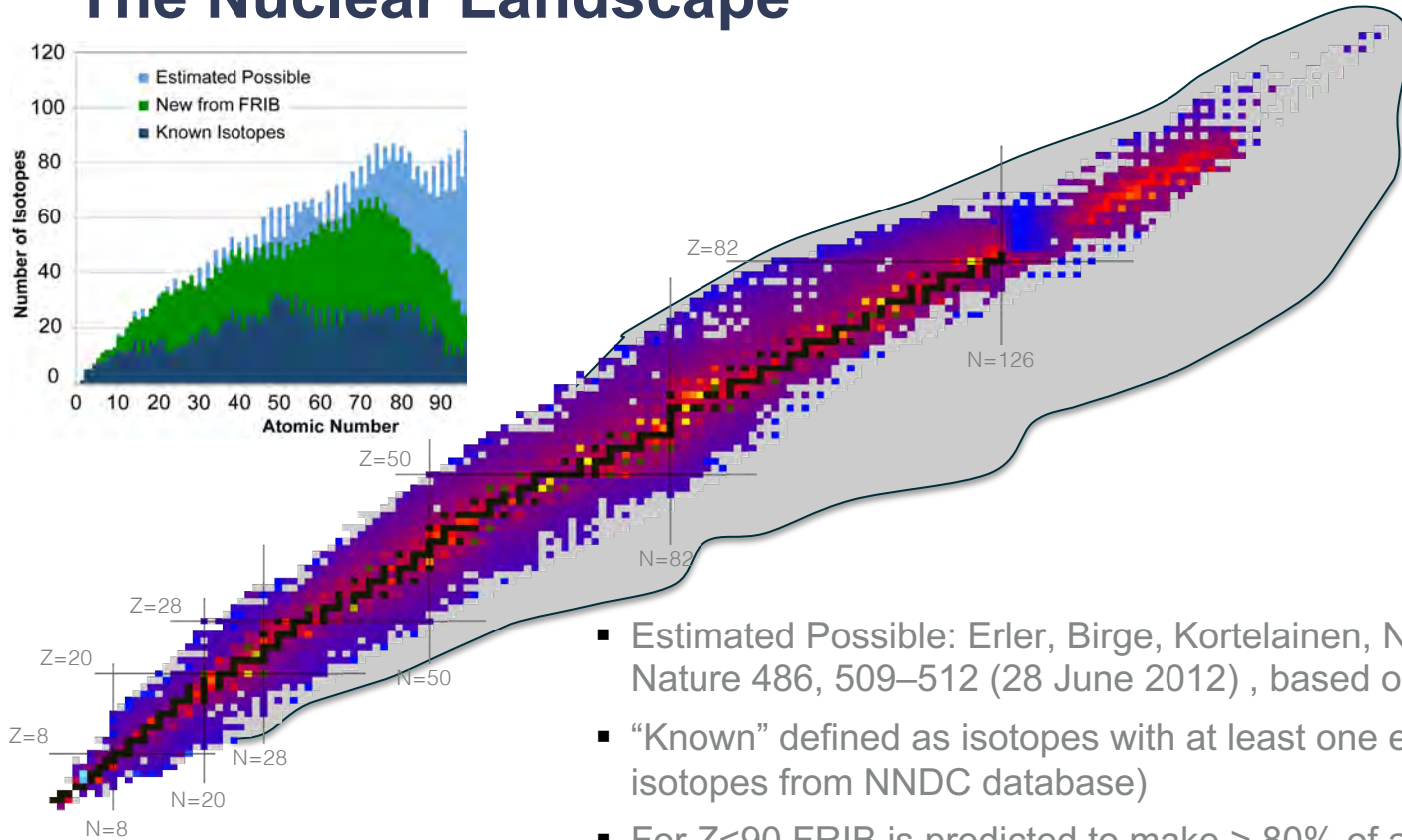
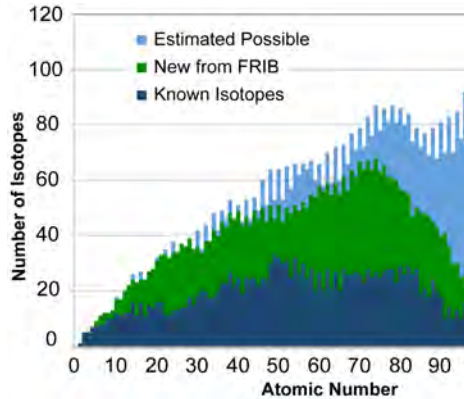
Progress relies on understanding which measurements can best inform a given theory or approach – close collaboration through analysis and publication will maximize science output and impacts in nuclear structure.



# Outline

- Introduction
- **Nuclear structure toward the driplines**
- Detailed structure studies to fine-tune our models
- Summary

# The Nuclear Landscape



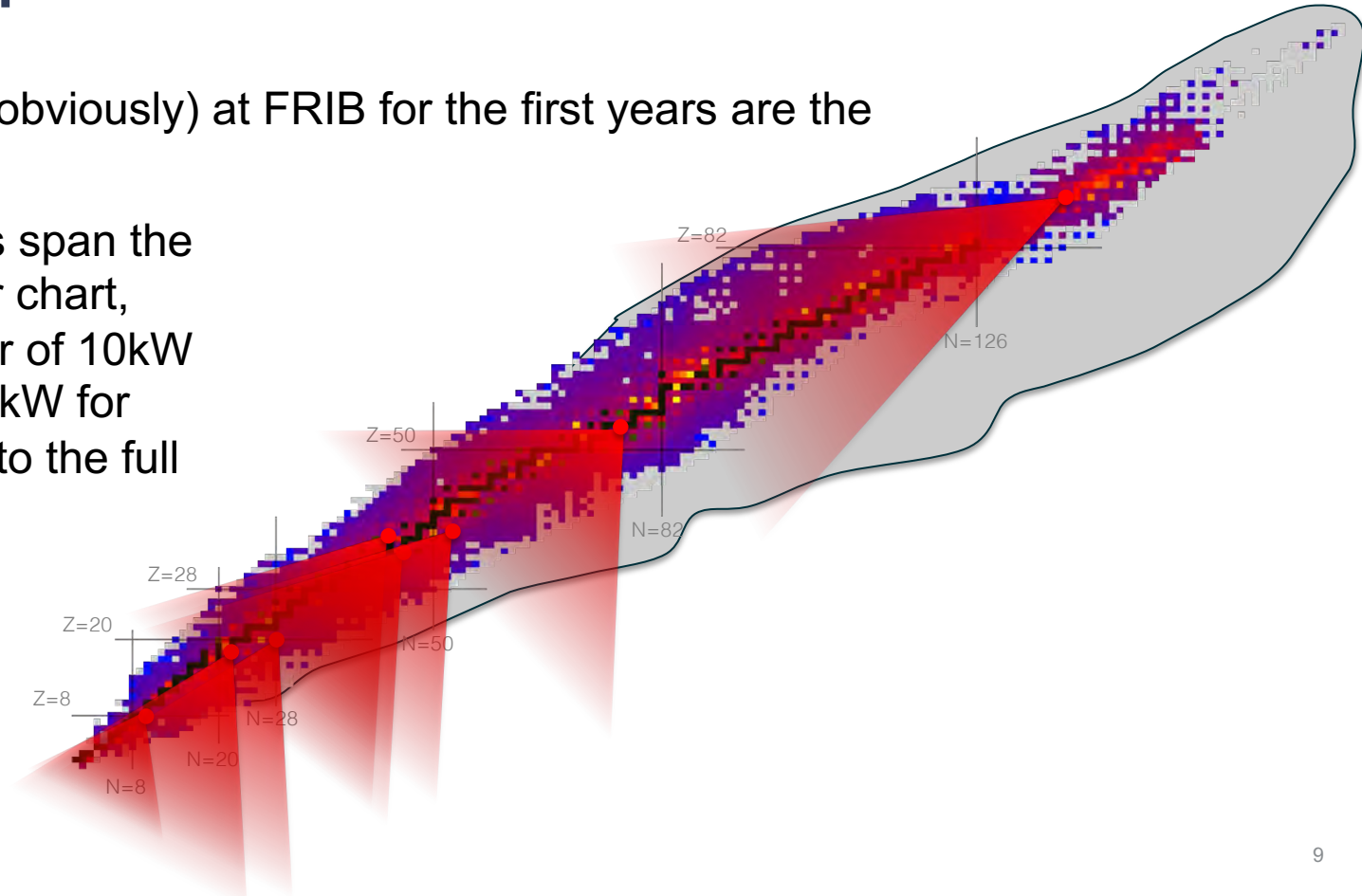
- Estimated Possible: Eler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models
- “Known” defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- For  $Z < 90$  FRIB is predicted to make  $> 80\%$  of all possible isotopes
- Even at 10kW power (Year 1) ‘new’ isotopes will be accessible to study<sub>8</sub>



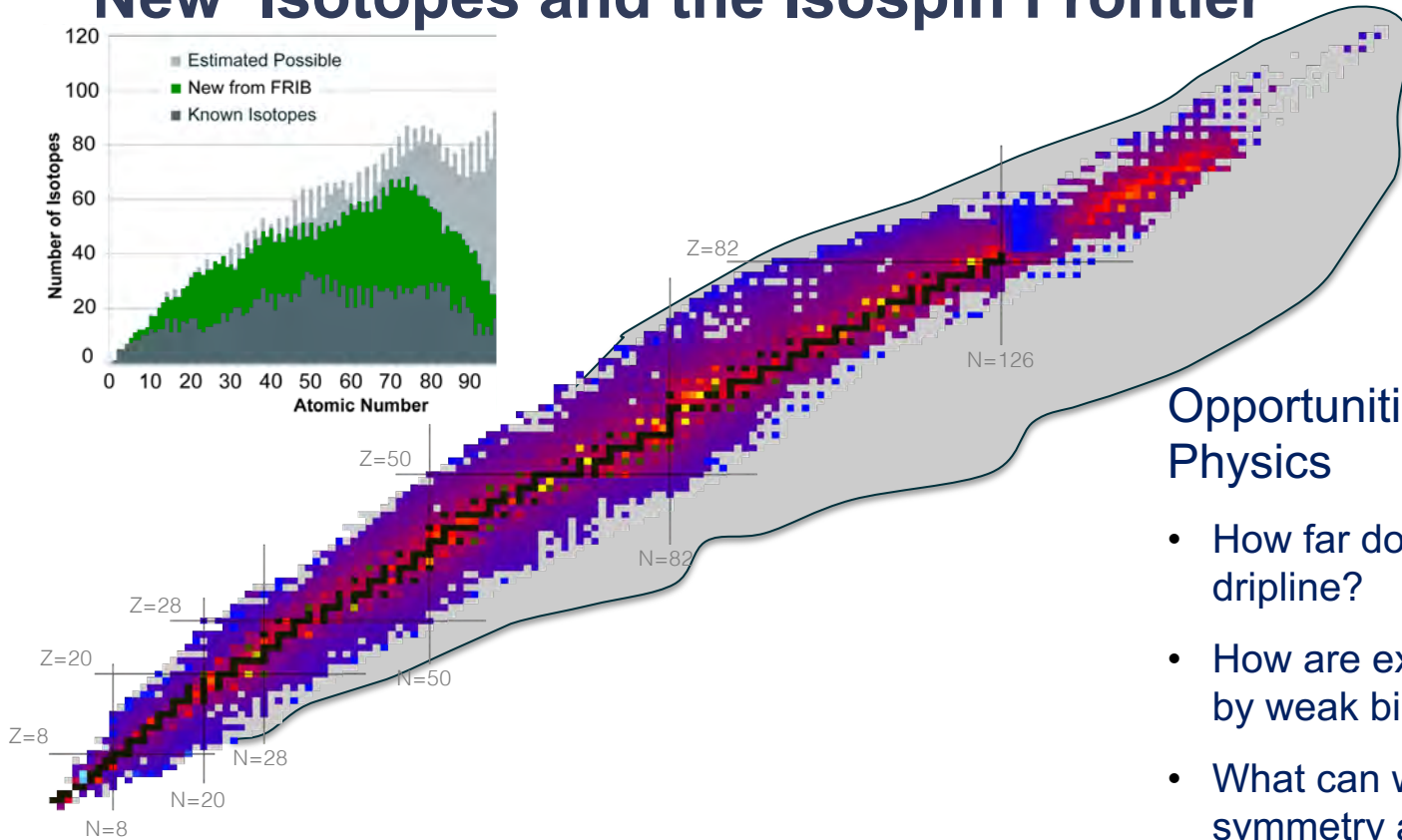
# The Beams!

Front and center (obviously) at FRIB for the first years are the primary beams.

The Year 1 beams span the bulk of the nuclear chart, with a beam power of 10kW for most beams (5kW for  $^{238}\text{U}$ ), ramping up to the full 500kW.



# 'New' Isotopes and the Isospin Frontier

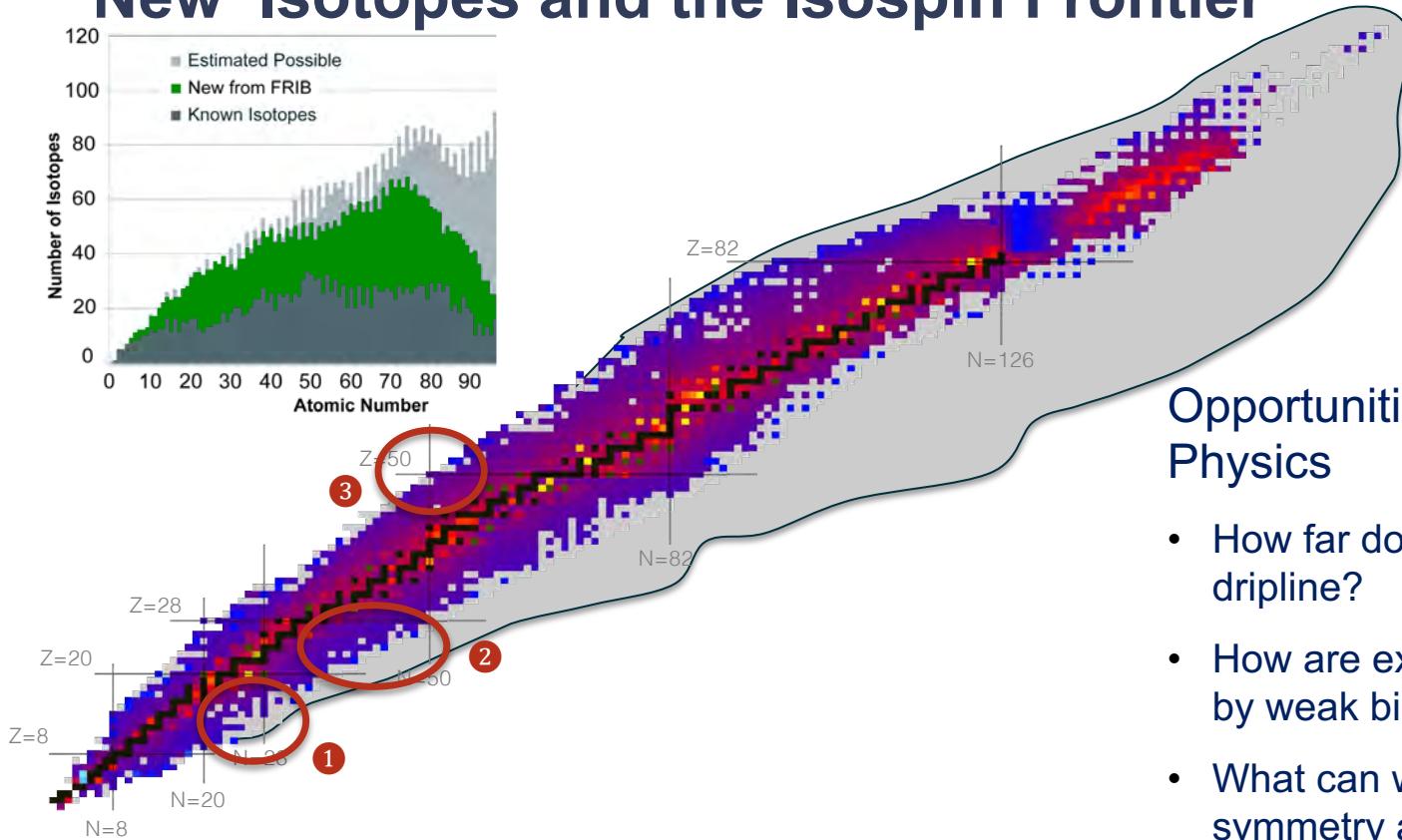


## Opportunities for “Discovery” Physics

- How far do we know the neutron dripline?
- How are excitation spectra altered by weak binding effects?
- What can we learn about mirror symmetry and np correlations at  $N=Z$ ?

We are poised for these measurements today.

# 'New' Isotopes and the Isospin Frontier



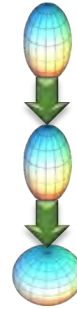
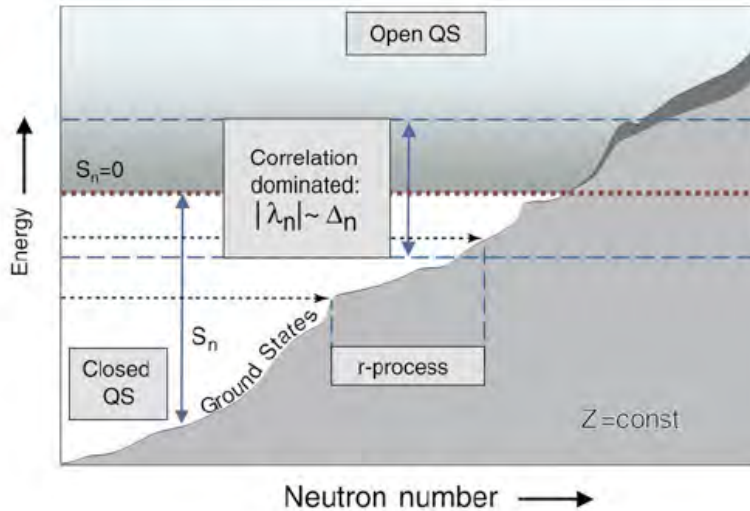
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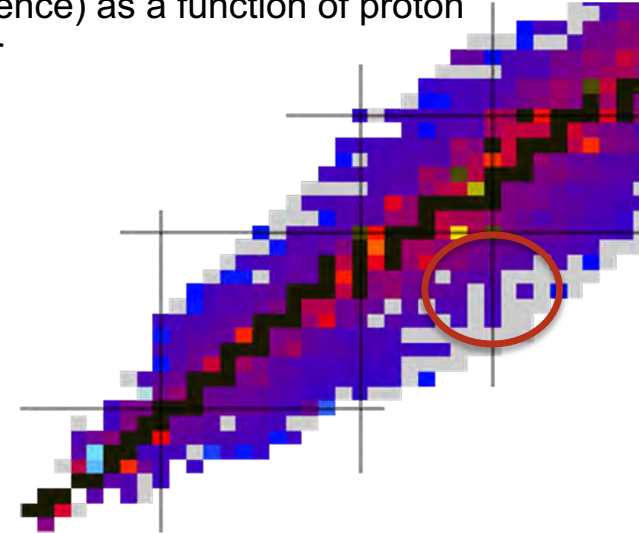
We are poised for these measurements today.

# 1 Pushing Toward the Neutron Dripline – Z=12 and beyond

Explore properties of weakly bound nuclei and ask what happens in the transition from well-bound to weakly-bound “open” systems



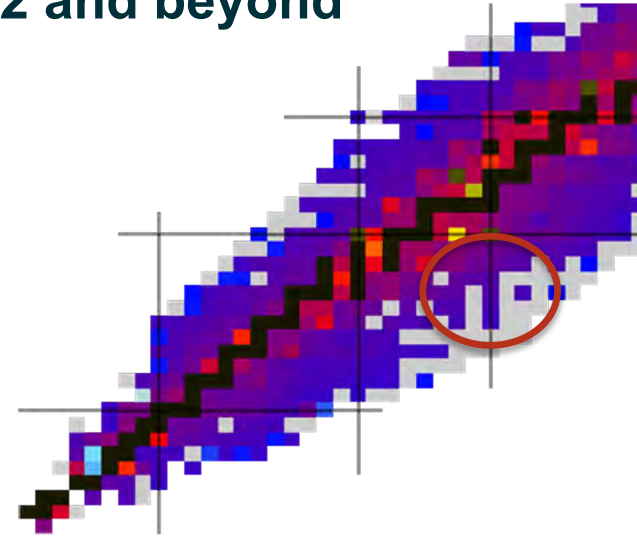
Moving south from  $^{48}\text{Ca}$ , removal of protons leads to development of collectivity, and rapid shape evolution (and coexistence) as a function of proton number



- Rates make studies all the way to  $^{40}\text{Mg}$  possible – can fully explore the N=28 isotones, and to the dripline to Z~12

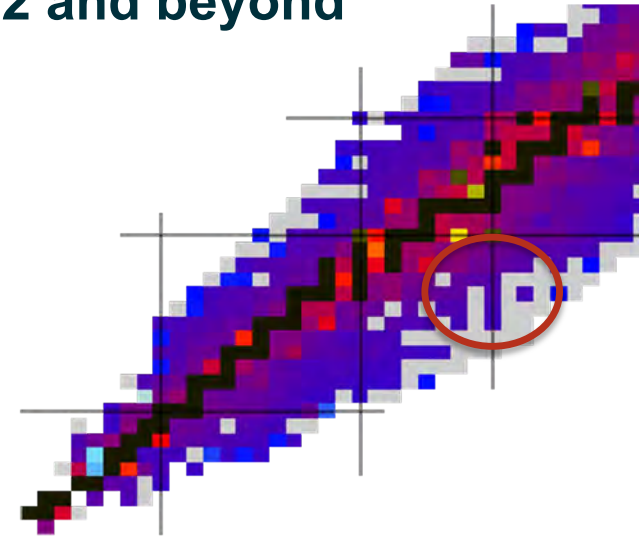
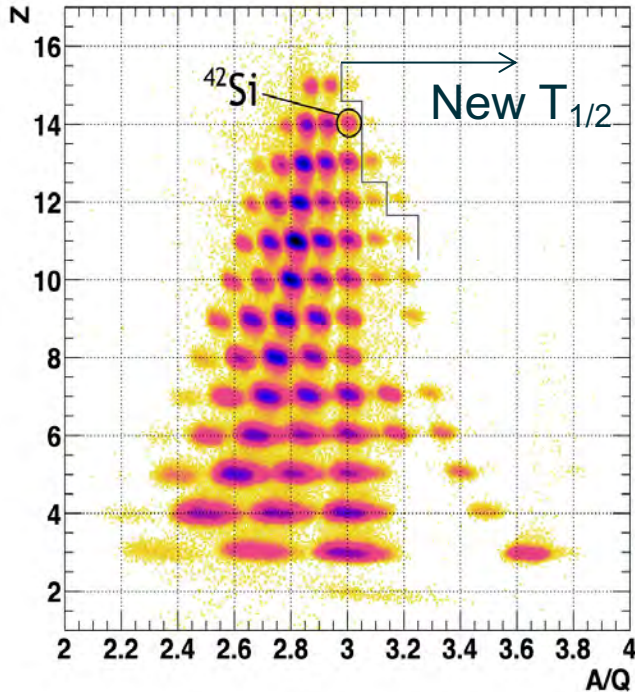
# 1 Pushing Toward the Neutron Dripline – Z=12 and beyond

- There may be a wide range of experiments in this region –
  - precision mass measurements toward N=28
  - $\beta$ -decay extending all the way to decay of  $^{40}\text{Mg}$  and beyond N=28 above Mg
  - Single-nucleon knockout studies (e.g. into  $^{38}\text{Mg}$ )
  - Coulomb excitation (intermediate energy) –  $^{42}\text{Si}$

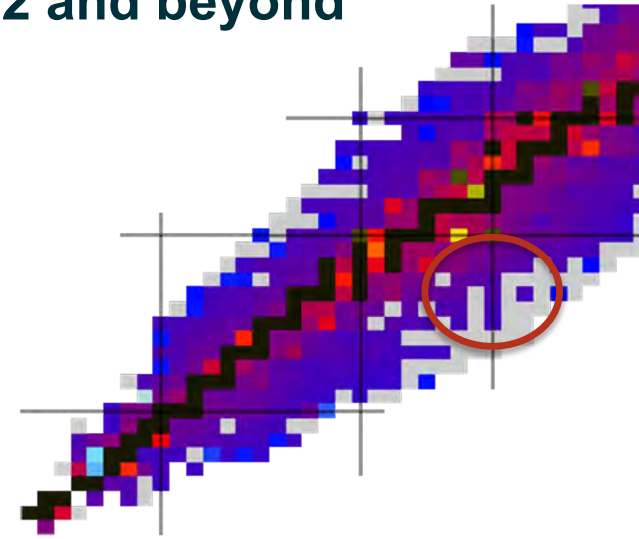
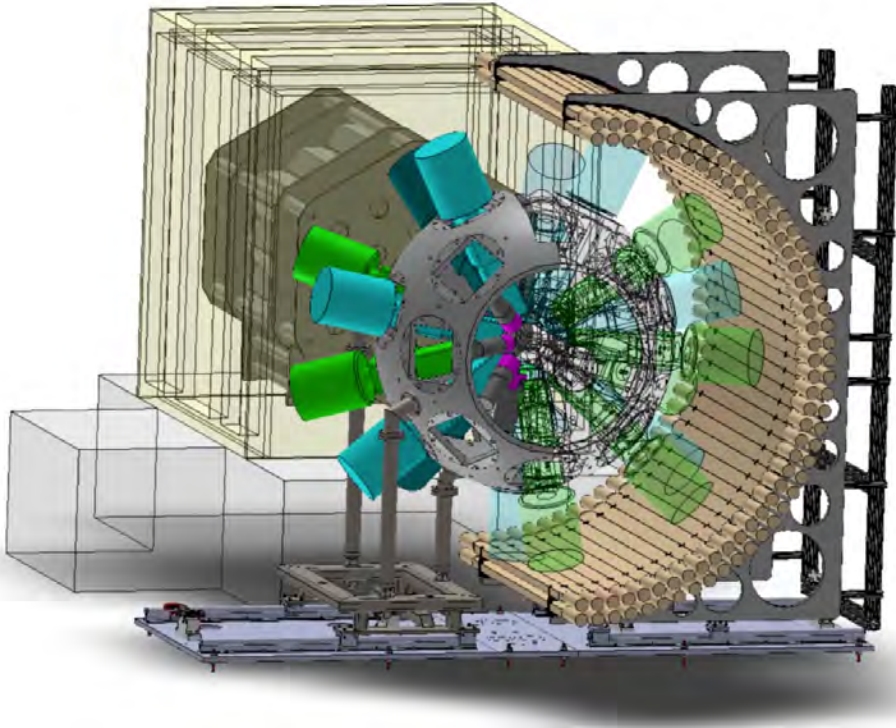


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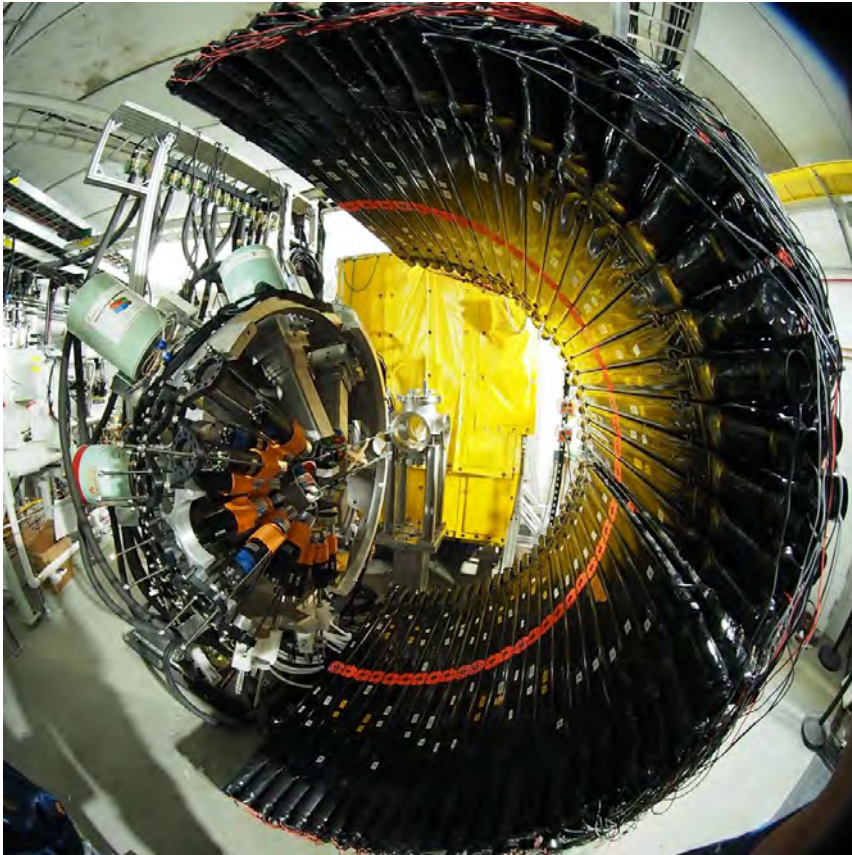
# 1 Pushing Toward the Neutron Dripline – Z=12 and beyond



## Decay studies with the FRIB Decay Station Initiator (FDSi)

- FDSi enables total decay spectroscopy, with  $\gamma$ , particle and neutron spectroscopy
- Combination with MTAS or SuN further extends the physics

# FRIB Decay Station Initiator (FDSi)

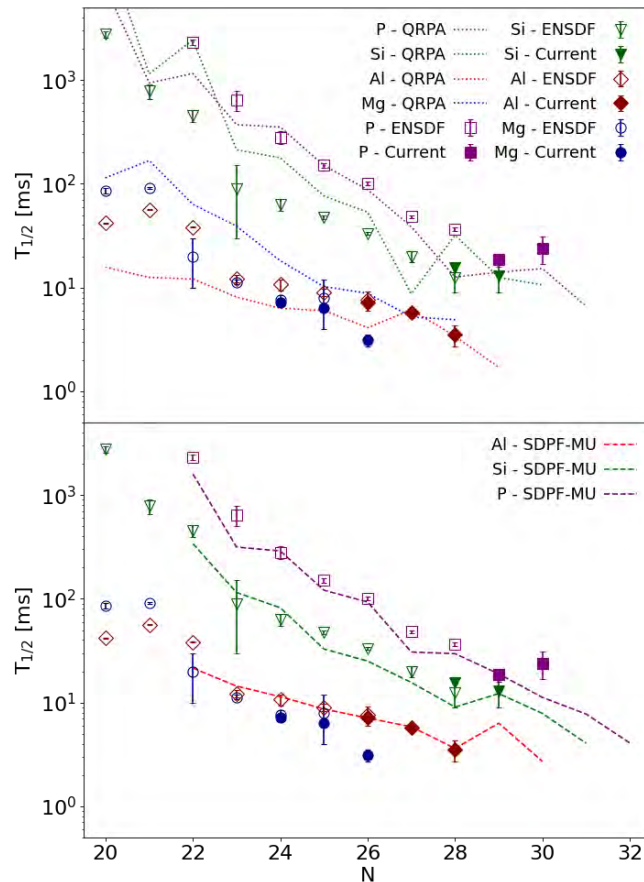
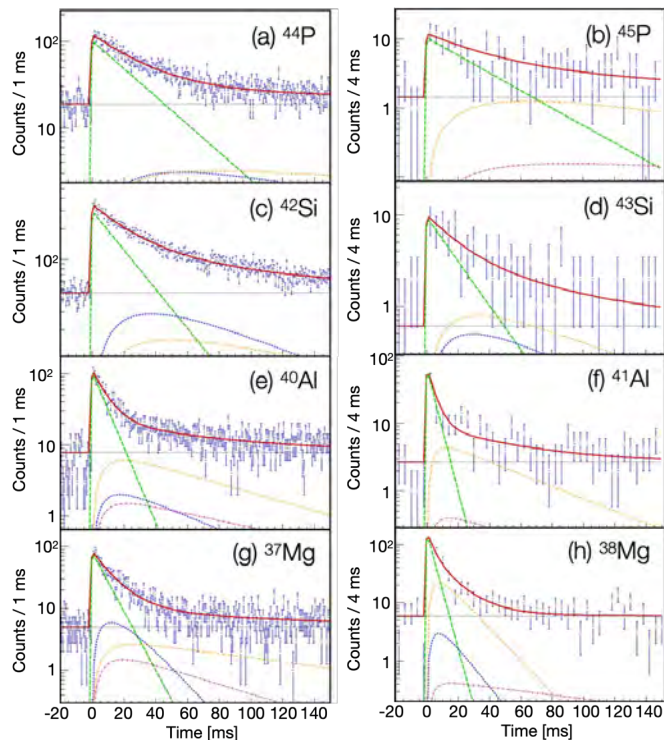




# First Results from FRIB

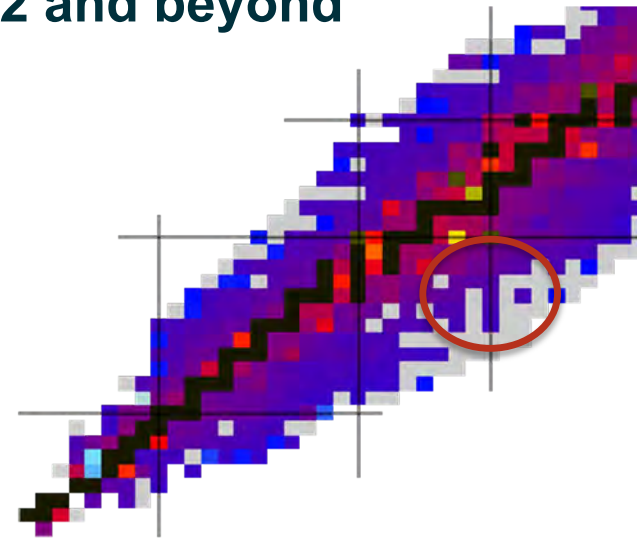
## E21062: Decay Near $N=28$

- 5 isotopes with no published half-life information were measured, with improved half-life values provided for numerous additional species

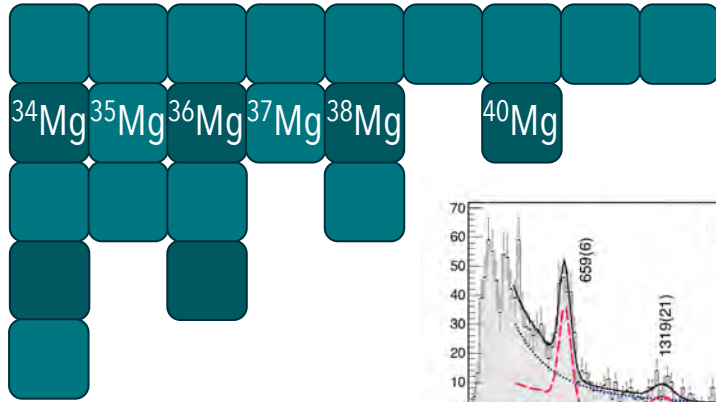


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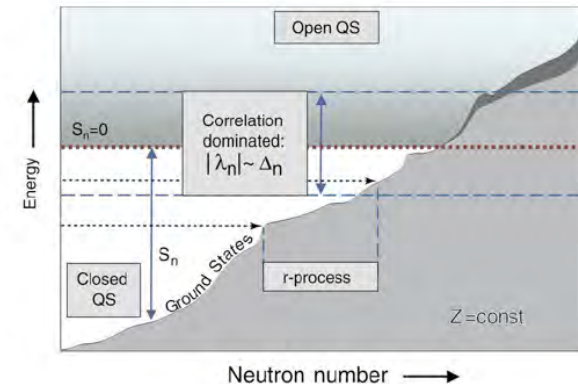
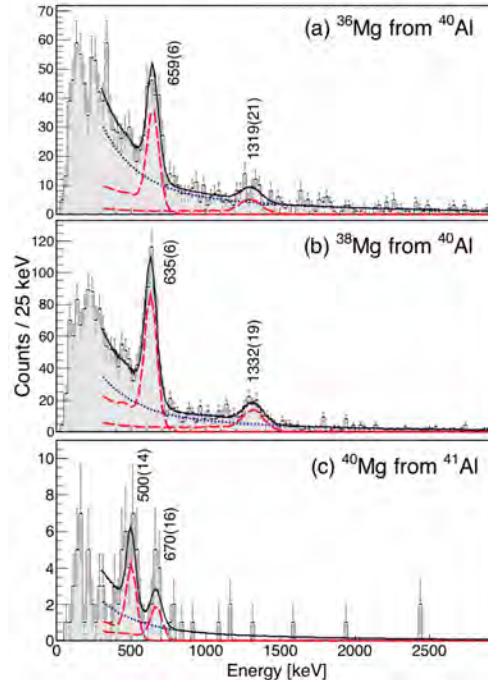
# Role of the Continuum in Nuclear Structure



Explore properties of weakly bound nuclei and ask what happens in the transition from well-bound to weakly-bound “open” systems

⇒ Due to weakly bound levels

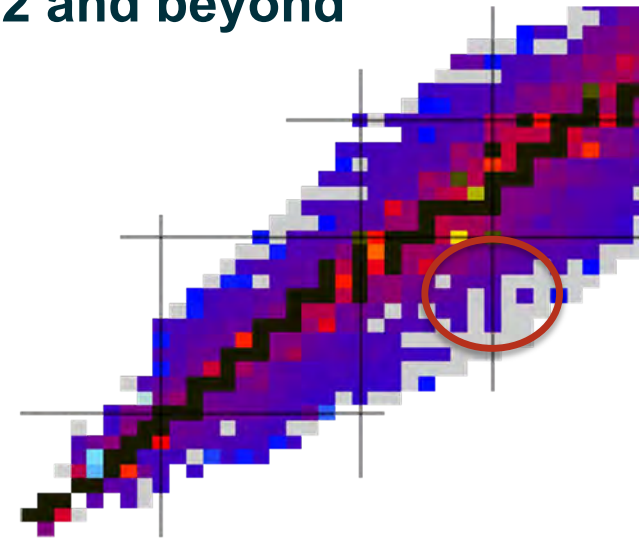
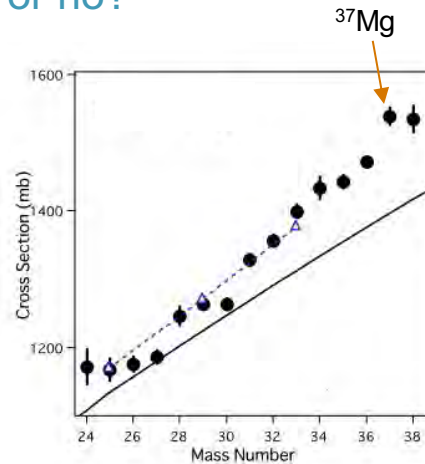
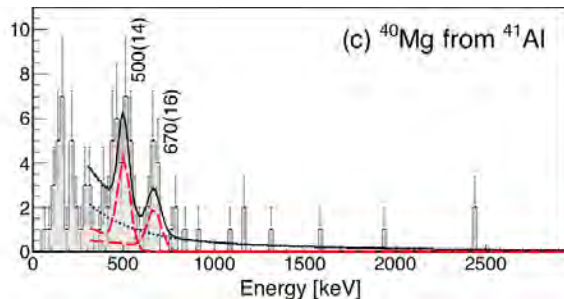
- low  $l$  levels (s, p) → extended wavefunctions (“halos”)
- changes in pairing due to surface diffuseness
- valence nucleons can become decoupled from the core
- coupling to continuum states



# 1 Pushing Toward the Neutron Dripline – Z=12 and beyond

$^{40}\text{Mg}$  reaction cross-section – halo or no?

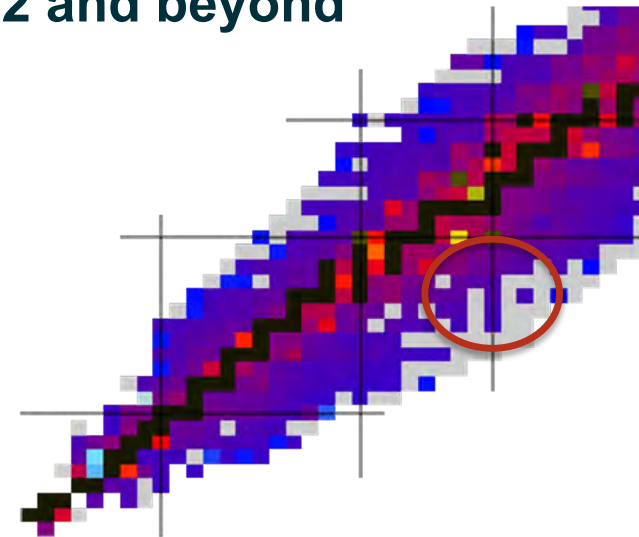
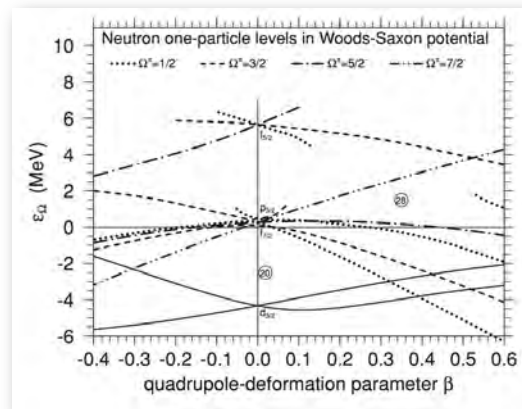
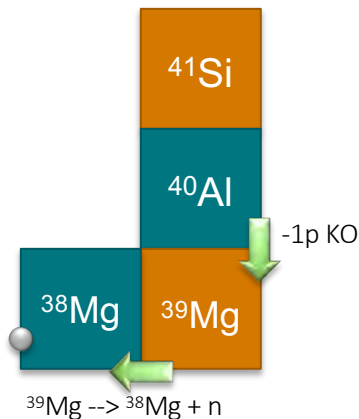
First spectroscopy in  $^{40}\text{Mg}$  shows a surprising structure – could the spectrum be evidence of weak binding / halo structure?



- With 800 pphour of  $^{40}\text{Mg}$  a total reaction cross-section measurement will answer the question of whether there is a halo or not
- Combined with a TOF mass measurement, the separation energy can be established

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  - **Invariant mass measurement in  $^{39}\text{Mg}$  with MoNA-LISA**



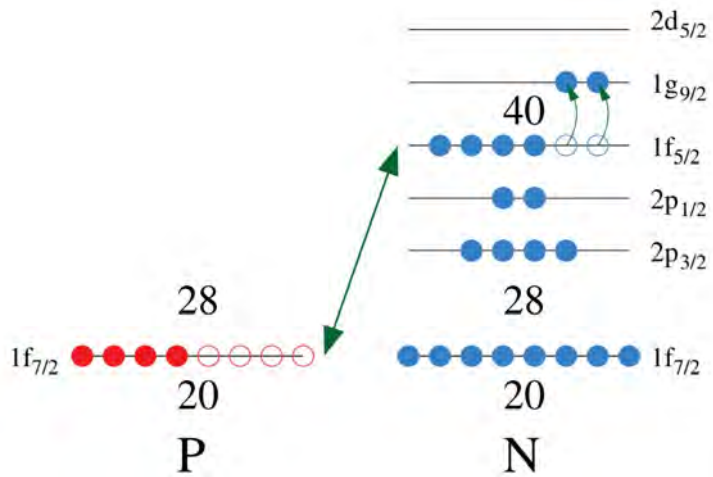
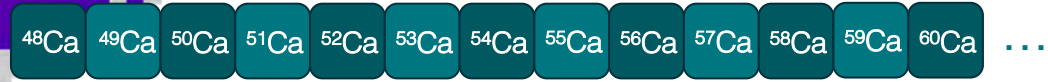
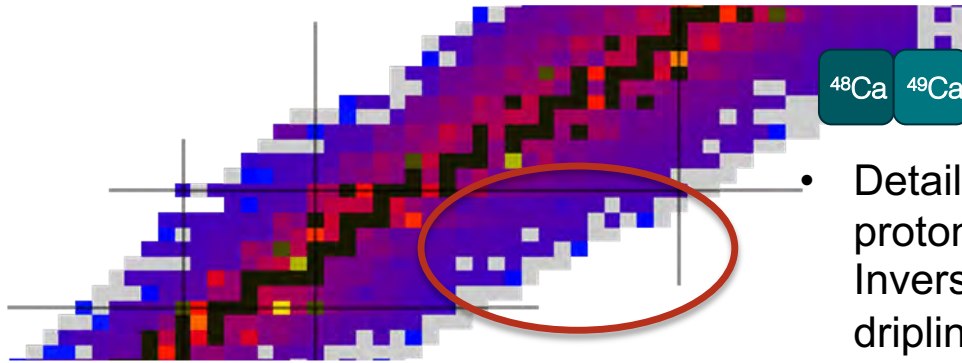
Open Questions:

- What is the neutron separation energy of  $^{39}\text{Mg}$ ?
- What is the ground-state deformation?
- Is there a ground-state halo structure arising from the  $p$ -orbital occupation?
- How large is the  $N = 28$  gap between the  $f$  and  $p$  orbitals?

Additional opportunities:

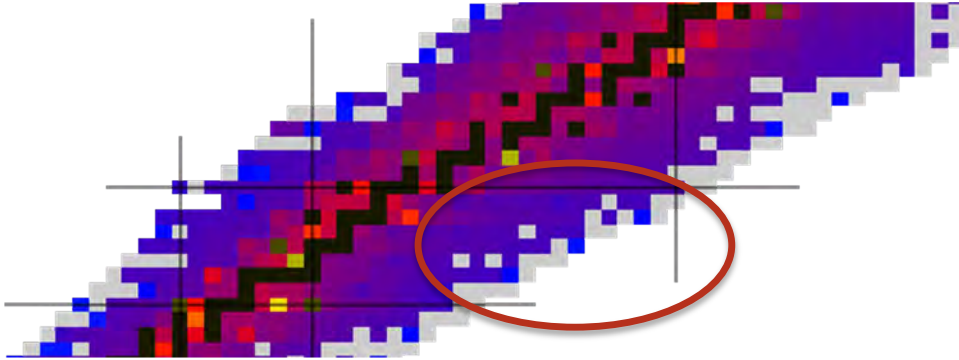
- Unbound states in  $^{40}\text{Mg}$  ( $^{41}\text{Al} - 1p$ )

## 2 Mapping Out N=40 to N=50 and Pushing Toward $^{60}\text{Ca}$



- Detailed evolution of single-particle orbitals with proton/neutron number defines the N=40 Island of Inversion, and impacts ( $\nu g_{9/2}$ ) the location of the dripline in the Ca isotopes
- Structure near the Ca isotopes may also be sensitive to impacts of 3N forces
- Rotational (collective) structures in the lol region test model predictions – both shell model and collective model descriptions
- Out to N=50 –  $^{78}\text{Ni}$  should be doubly-magic, but near N=40 Ni have shape coexistence

## ② Mapping Out N=40 to N=50 and Pushing Toward $^{60}\text{Ca}$



### Coulomb Excitation

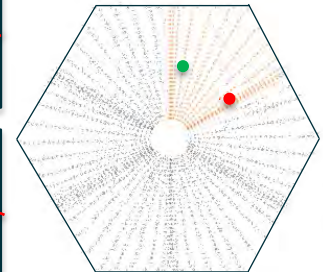
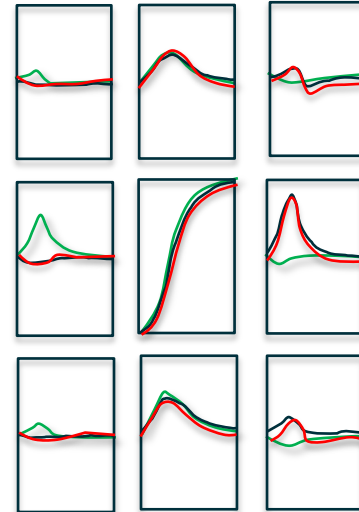
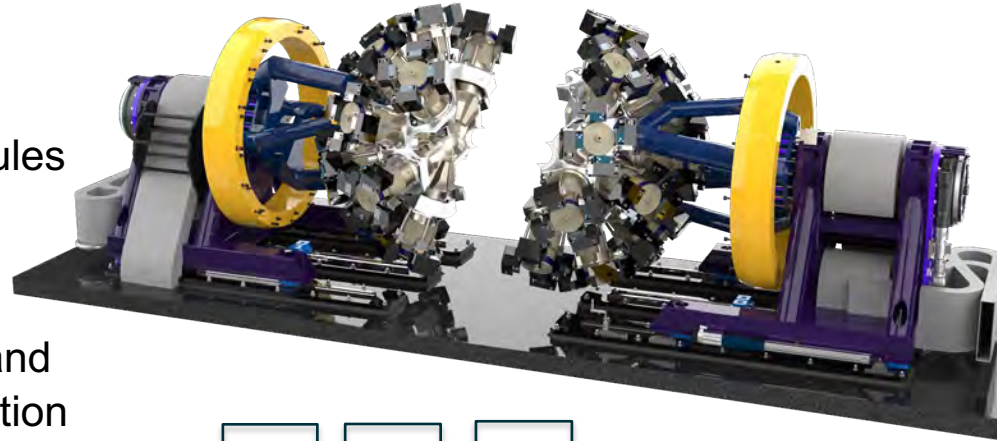
- The degree of collectivity (e.g.  $B(E2)$  in even-even nuclei) helps to define nuclei in vs. outside of the N=40 Island of Inversion
- Intermediate energy Coulomb excitation can reach out to  $^{70}\text{Fe}$ ,  $^{60}\text{Ti}$  to help delineate the limits of the region

### Nucleon Knockout

- In-beam  $\gamma$ -ray spectroscopy can map out evolution of single-particle states
- At NSCL -1p knockout has been performed up to  $^{66}\text{Fe}/^{65}\text{Mn}$  – this can be extended substantially
- Fast beam measurements with GRETINA /GRETA + S800/HRS

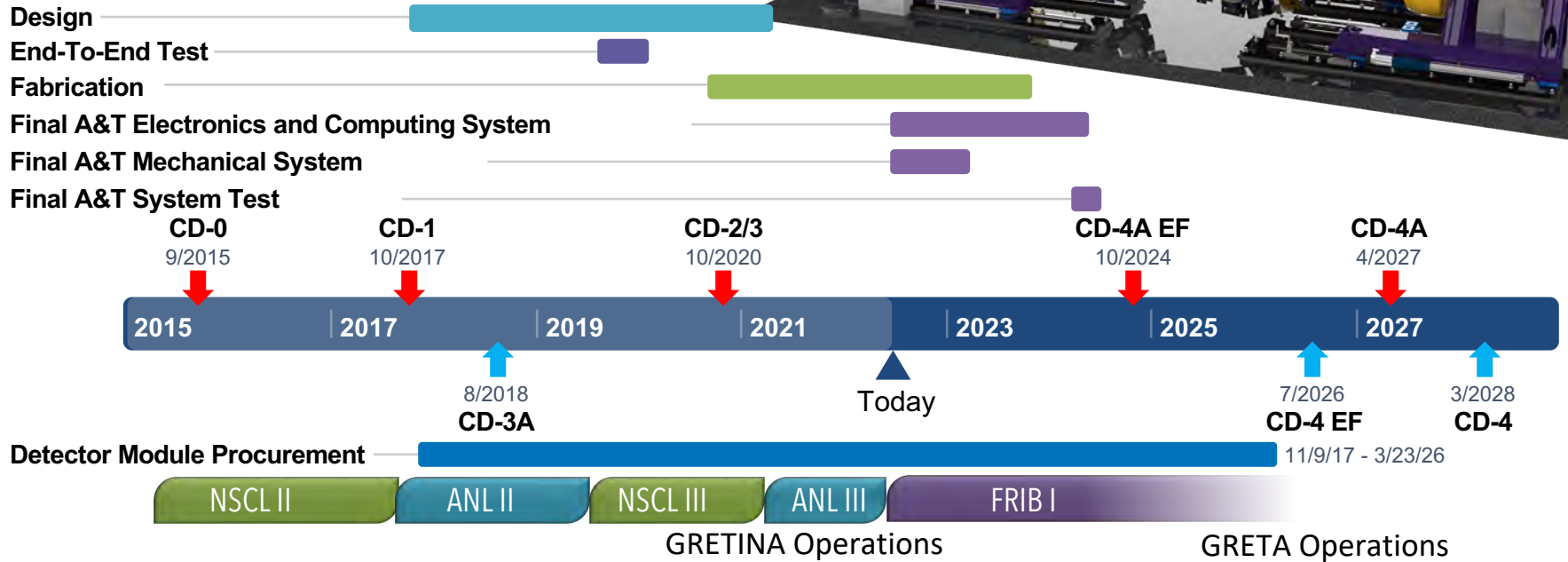
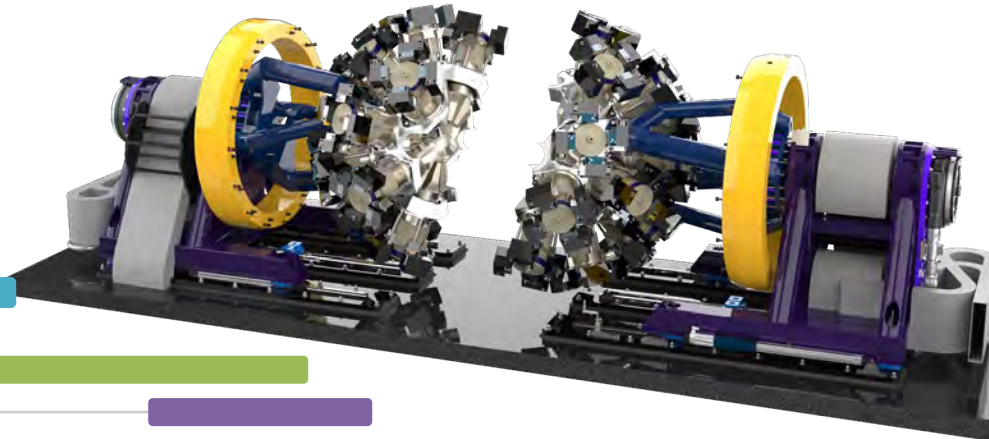
# GRETA

- GRETA will have 30 Quad Detector Modules to cover >80% of the full solid angle surrounding a target
- Its design provides the unprecedented combination of full solid angle coverage and high efficiency, excellent energy and position resolution, and good background rejection (peak-to-total) needed to carry out a large fraction of the nuclear science programs at FRIB.
- Unmatched resolving power will enable further push to the driplines and other spectroscopic frontiers

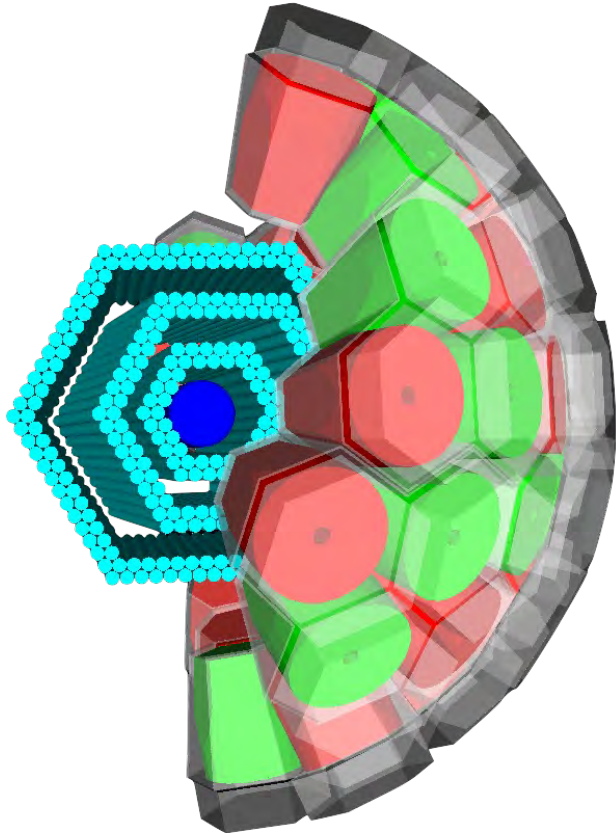




# GRETA



# Extended Proton Tracking Target to Maximize Luminosity

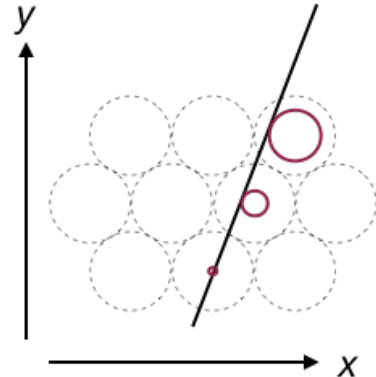


- Take the MINOS LH<sub>2</sub> target (developed by A. Obertelli *et al.*) as inspiration
- An extended (5-15 cm) LH<sub>2</sub> cell will be surrounded by a compact configuration of straw-tube (small diameter gas counters) detectors for proton detection and vertex reconstruction

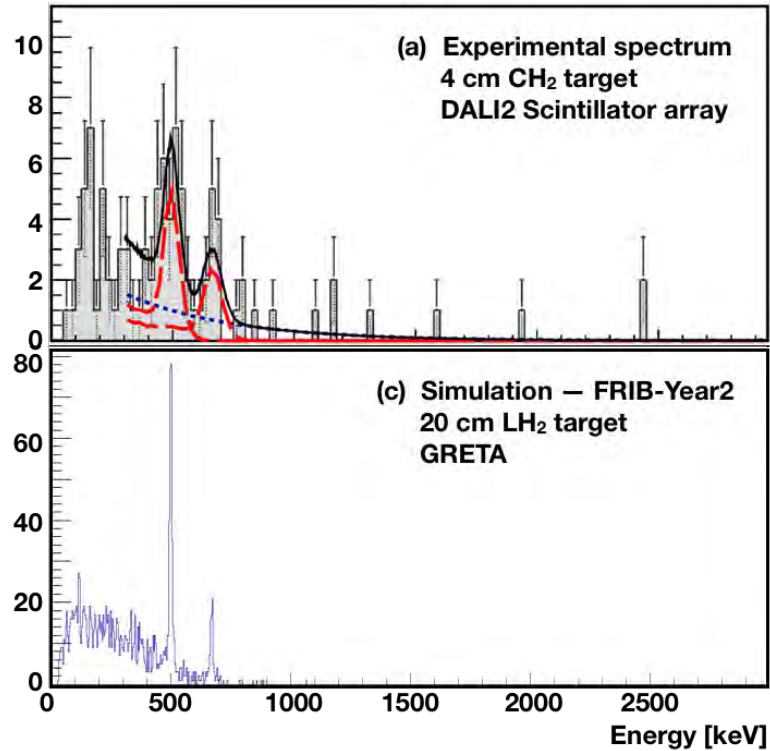
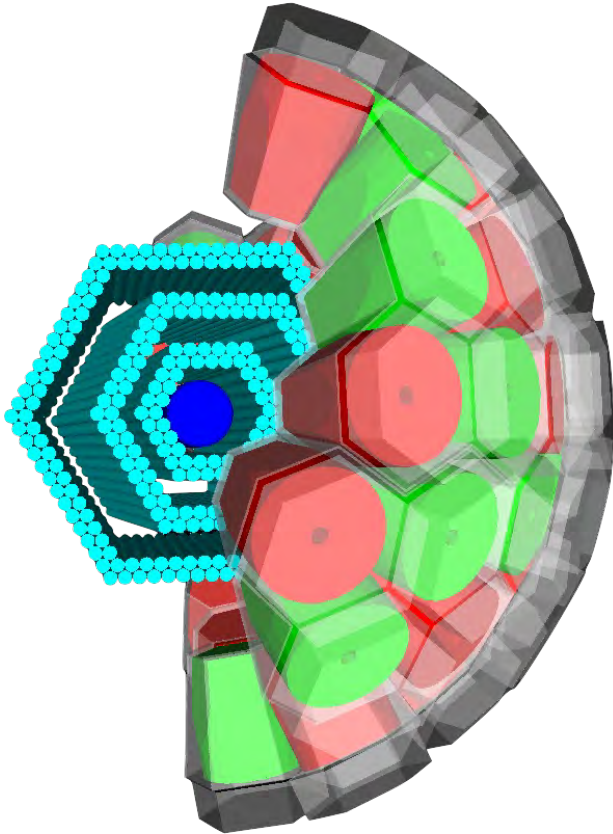


Supply (liquid)

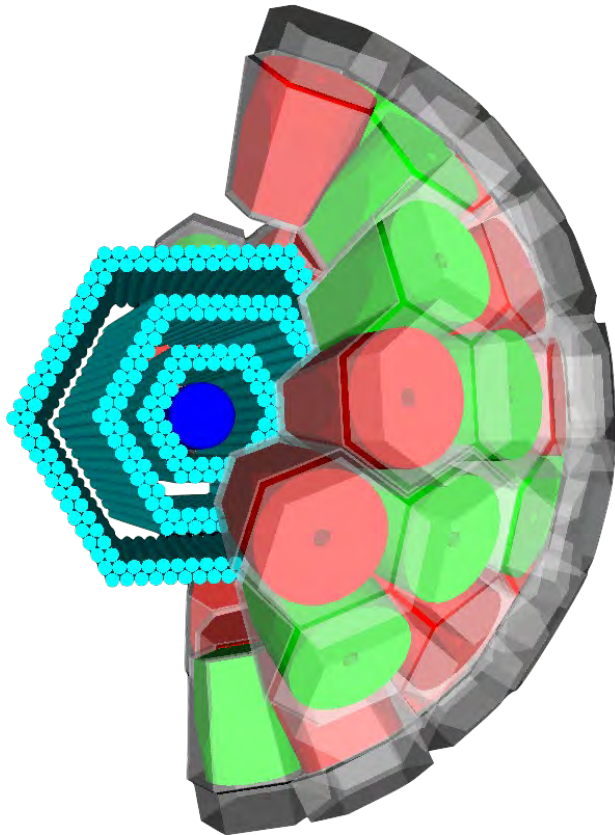
Return (gas)



# Extended Proton Tracking Target to Maximize Luminosity



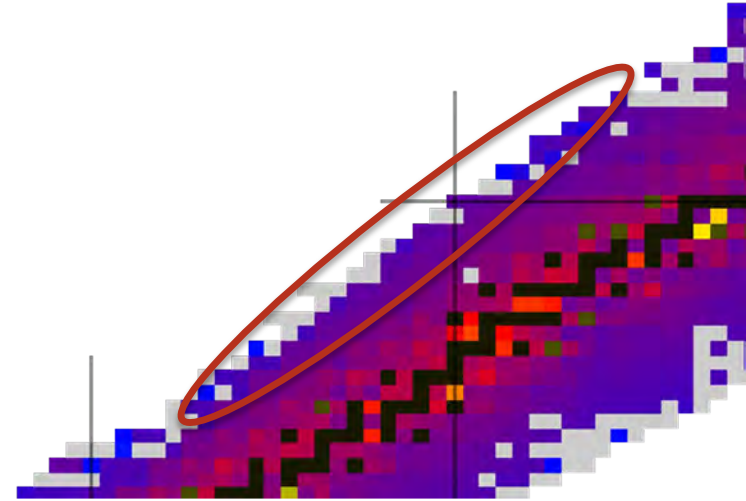
# Extended Proton Tracking Target to Maximize Luminosity



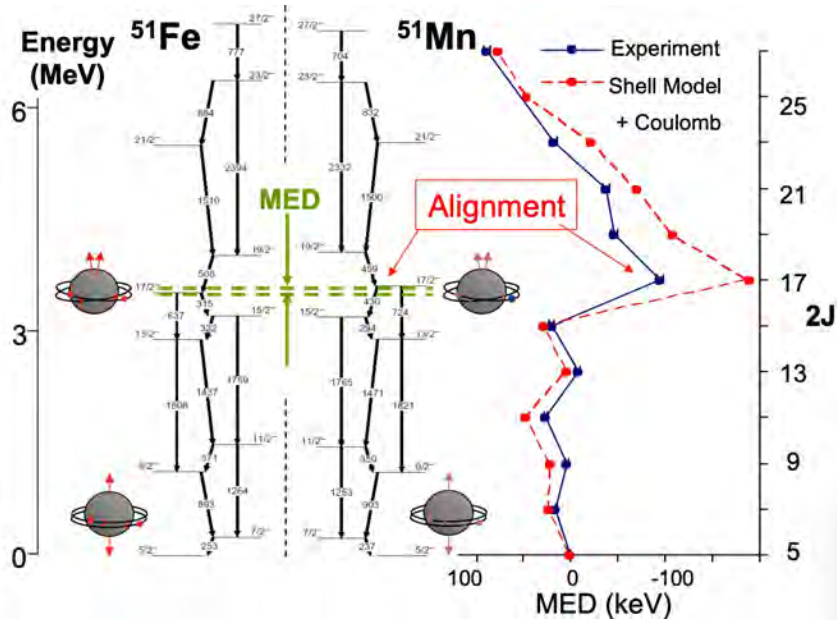
$^{66}\text{Ni}$	$^{68}\text{Ni}$	$^{70}\text{Ni}$	$^{72}\text{Ni}$	$^{74}\text{Ni}$	$^{76}\text{Ni}$	$^{78}\text{Ni}$
$^{64}\text{Fe}$	$^{66}\text{Fe}$	$^{68}\text{Fe}$	$^{70}\text{Fe}$	$^{72}\text{Fe}$	$^{74}\text{Fe}$	$^{76}\text{Fe}$
$^{62}\text{Cr}$	$^{64}\text{Cr}$	$^{66}\text{Cr}$	$^{68}\text{Cr}$	$^{70}\text{Cr}$	$^{72}\text{Cr}$	$^{74}\text{Cr}$
$^{60}\text{Ti}$	$^{62}\text{Ti}$	$^{64}\text{Ti}$	$^{66}\text{Ti}$	$^{68}\text{Ti}$	$^{70}\text{Ti}$	$^{72}\text{Ti}$
N=40			N=50			

### 3 N=Z

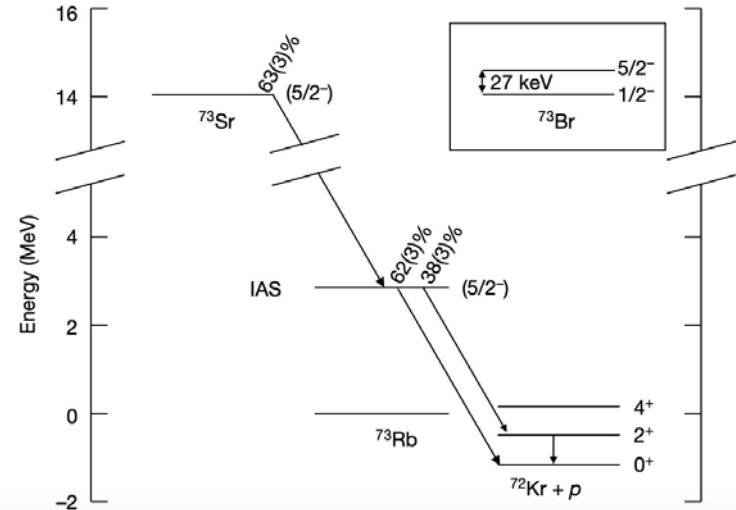
- The physics opportunities near N=Z are compelling
  - Studies of mirror symmetry can be extended within the fp shell
  - First hint of superallowed  $\alpha$  decays near  $^{100}\text{Sn}$  are unique on the nuclear chart [Aurenen *et al.*, PRL **121** 182501 (2018).]
- These nuclei are accessible, thanks to  $^{124}\text{Xe}$  and  $^{238}\text{U}$  primary beams
- This is a challenging region though, with strong momentum tails from more stable fragments contaminating the beams produced – not easy, but a promising region with future technical development



### 3 N=Z



Much effort has focused in the sd and lower fp shells to explore mirror systems looking for isospin non-conserving terms – e.g.  $J=2$  anomaly



#### Article

## Mirror-symmetry violation in bound nuclear ground states

<https://doi.org/10.1038/s41586-020-2123-1>

Received: 23 August 2019

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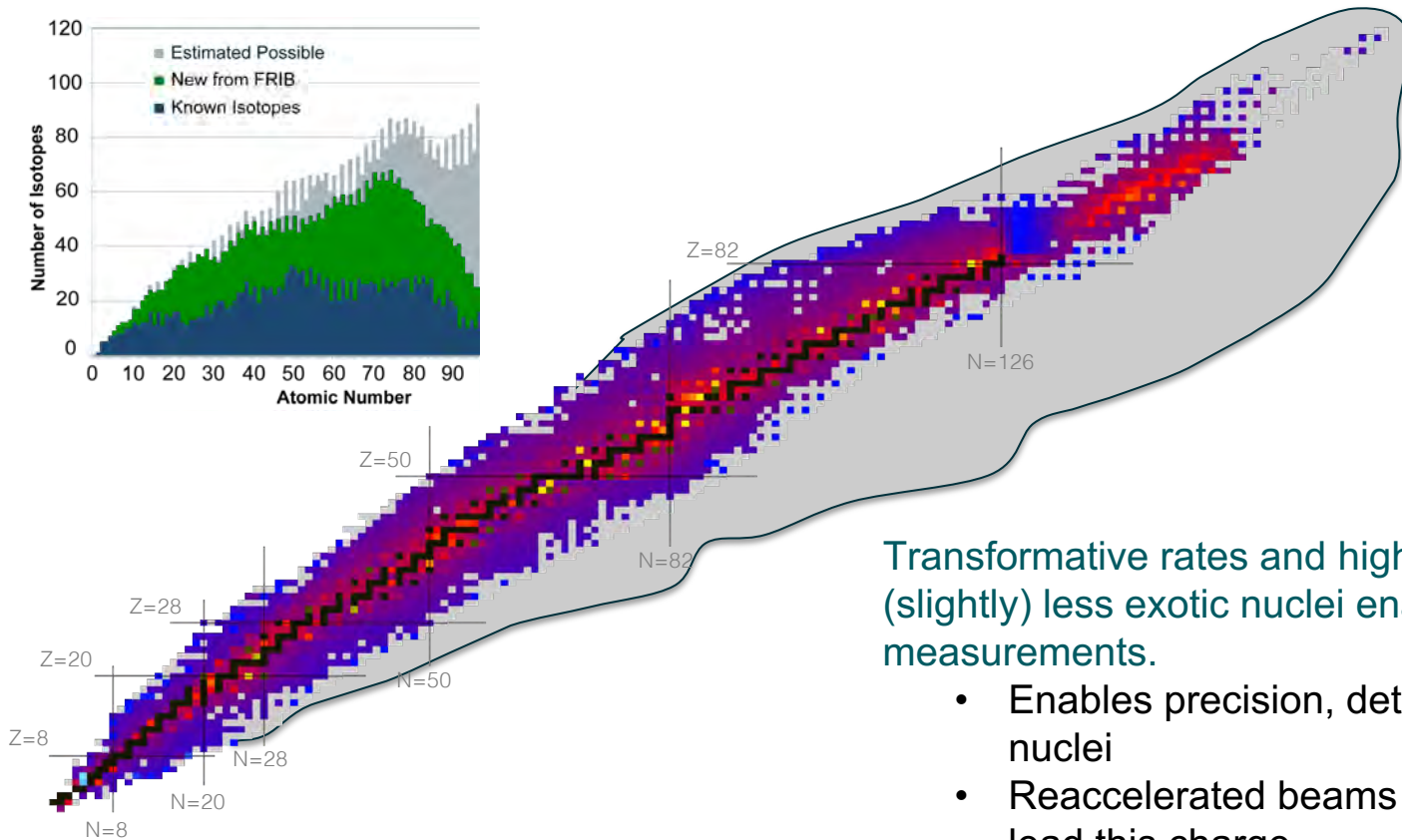
Published online: 1 April 2020

D. E. M. Hoff<sup>1,2</sup>, A. M. Rogers<sup>1,10</sup>, S. M. Wang<sup>3</sup>, P. C. Bender<sup>1</sup>, K. Brandenburg<sup>1</sup>, K. Childers<sup>2,4</sup>, J. A. Clark<sup>5</sup>, A. C. Dombos<sup>2,6,7</sup>, E. R. Doucet<sup>1</sup>, S. Jin<sup>2,7</sup>, R. Lewis<sup>2,4</sup>, S. N. Liddick<sup>2,4</sup>, C. J. Lister<sup>1</sup>, Z. Meisel<sup>1</sup>, C. Morse<sup>1,9</sup>, W. Nazarewicz<sup>8,9</sup>, H. Schatz<sup>2,8,7</sup>, K. Schmidt<sup>2,10</sup>, D. Soltész<sup>2</sup>, S. K. Subed<sup>1</sup> & S. Waniganaththi<sup>1</sup>

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# A Small Step Back From the Edge...

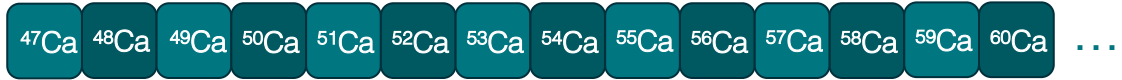


Transformative rates and high quality beams of (slightly) less exotic nuclei enable important measurements.

- Enables precision, detailed study of key nuclei
- Reaccelerated beams and ISOL facilities will lead this charge



# Consider an Example...



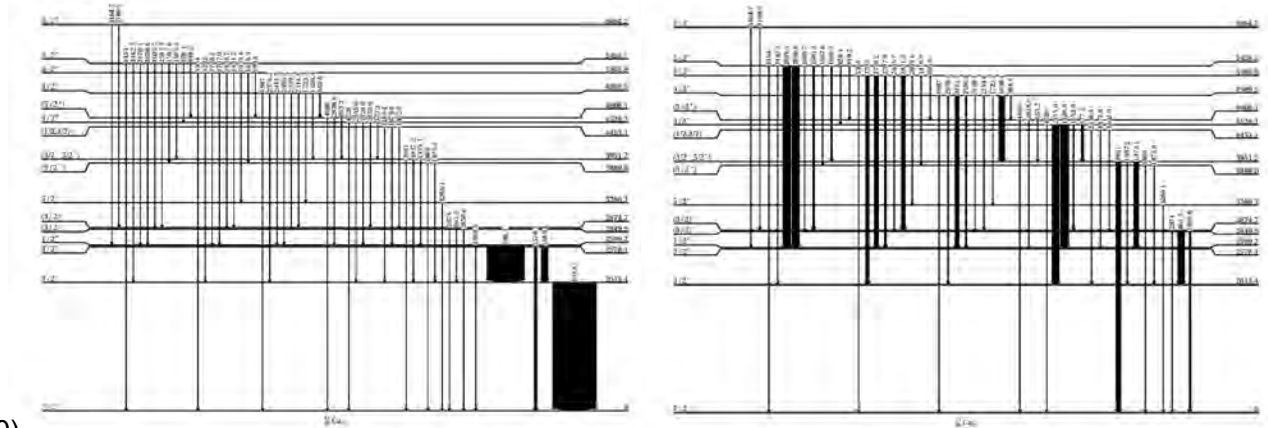
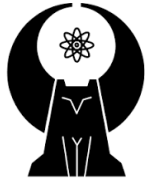
- Evolution of single-particle orbitals with proton/neutron number is a fundamental question – the Ca isotopes, with a closed proton shell are a key testing ground
- Structure near the Ca isotopes may also be sensitive to impacts of 3N forces
- Earlier, pointed out the importance of pushing toward  $^{60}\text{Ca}$  – because everything lighter is understood, right?

# Consider an Example...



- Evolution of single-particle orbitals with proton/neutron number is a fundamental question – the Ca isotopes, with a closed proton shell are a key testing ground
- Structure near the Ca isotopes may also be sensitive to impacts of 3N forces
- Earlier, pointed out the importance of pushing toward  $^{60}\text{Ca}$  – because everything lighter is understood, right?

Not quite...



# High-Intensity and High-Quality Beams

- High quality and high intensity beams possible with post-acceleration enable precision measurements of nuclei from stability to 10-12 neutrons out
- ISOL (ISAC), ARIEL, CARIBU (ANL ATLAS), ReA (FRIB) provide complementary beams to enable such measurements

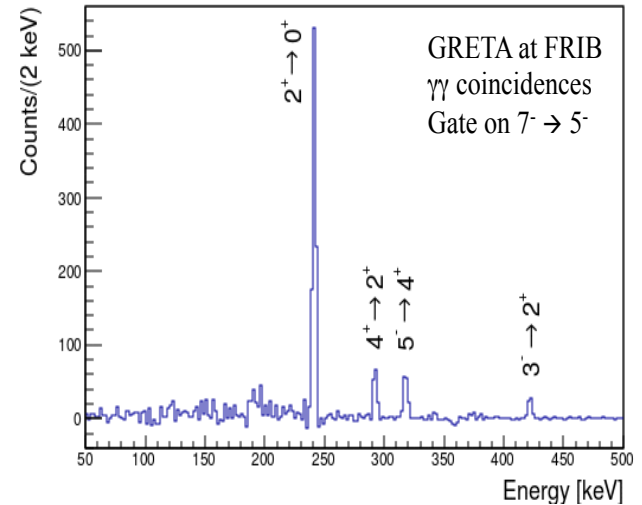
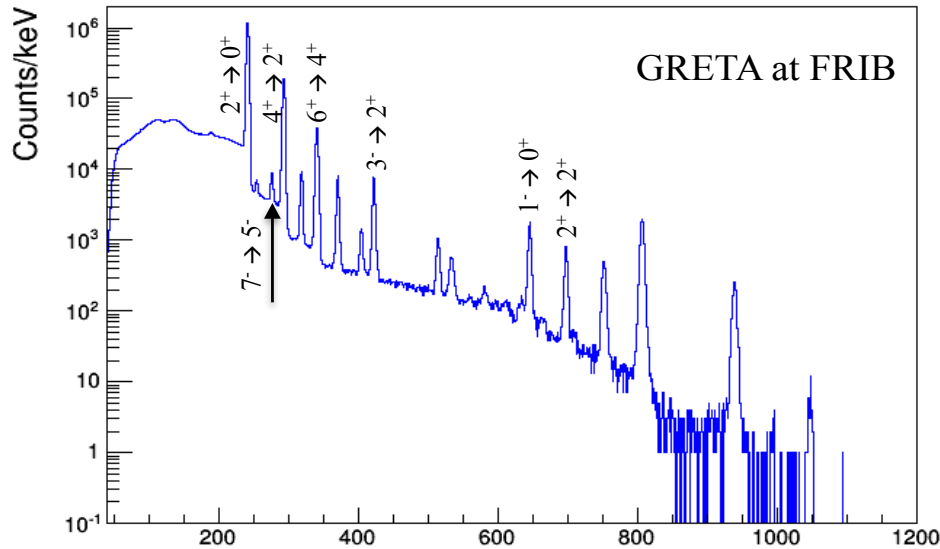
For example...

- Safe Coulomb Excitation
  - Low energy Coulex adds substantial knowledge by measuring multiple nuclear matrix elements - not possible with techniques using fast fragmentation beams
- Transfer Reactions
  - Complete transfer reaction measurements provide the possibility for fully understanding particle/hole occupations
- Laser spectroscopy and Penning trap measurements

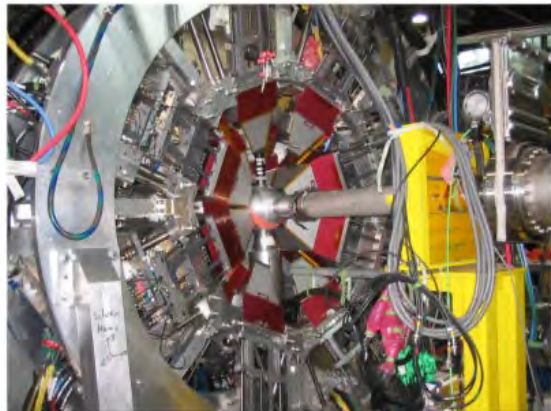
# Detailed Nuclear Structure Studies Connect to Fundamental Symmetries

Studies of octupole collectivity to guide searches for physics beyond the Standard Model

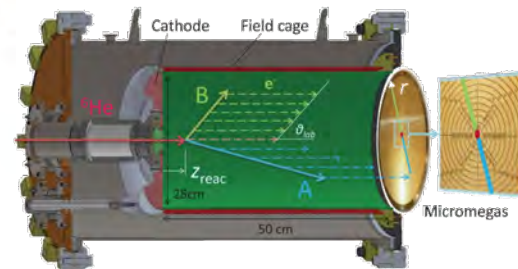
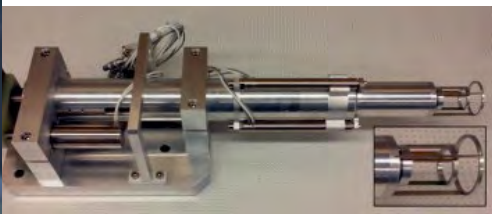
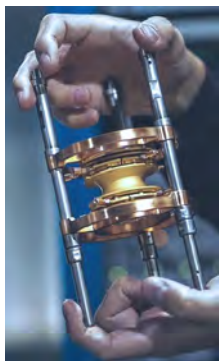
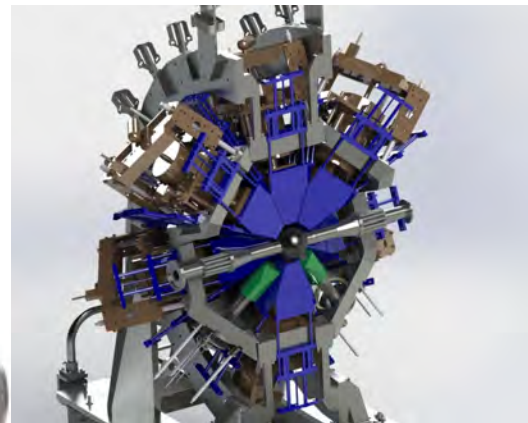
- permanent EDM (CP-violation)



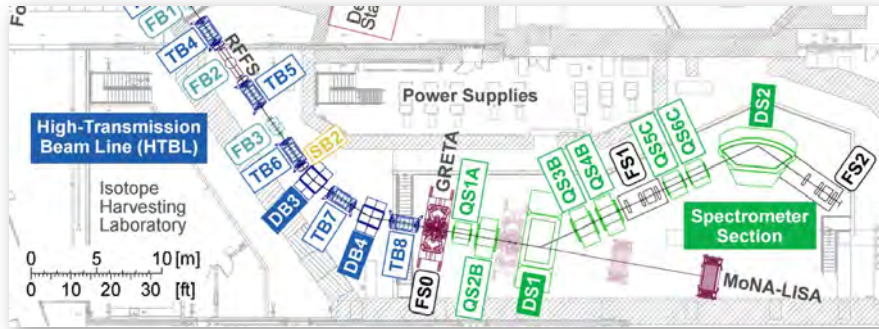
# Experimental Equipment



**JENSA**



# Experiments Will Continue to Maximize Discovery Potential and Collaboration



Combined setups of charged particle spectrometers, gamma-ray spectrometers, neutron detection, ... will enable correlated and nearly complete measurements – maximizing discovery potential.



Experiments will also be optimized to maximize reaction/decay channels for analysis and community involvement.

Collaboration and coordination across labs will also continue to be key.

# Summary

- First beam at FRIB in some ways marks a new era for nuclear structure research and the future is bright
  - New and upgraded instrumentation and rapid developments in theory are expanding capabilities constantly at facilities across the globe
  - The international community pursuing research at stable and RI beam facilities ensures discovery potential in nuclear structure is impressive
- Beyond FRIB, new capabilities expand the field
  - CARIBU and  $\nu$ -CARIBU in addition to the stable beam facilities anchor the ATLAS facility
  - ARIEL and CANREB at TRIUMF are increasing the Canadian capabilities
  - Facilities in Europe and Asia continue to evolve and develop

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    - Facilities in Europe and Asia continue to evolve and develop
- ⇒ The most exciting aspect is that the next big result is probably not related to anything in these slides.



# Acknowledgements



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**Thank you!**