TRENDS IN NUCLEAR STRUCTURE

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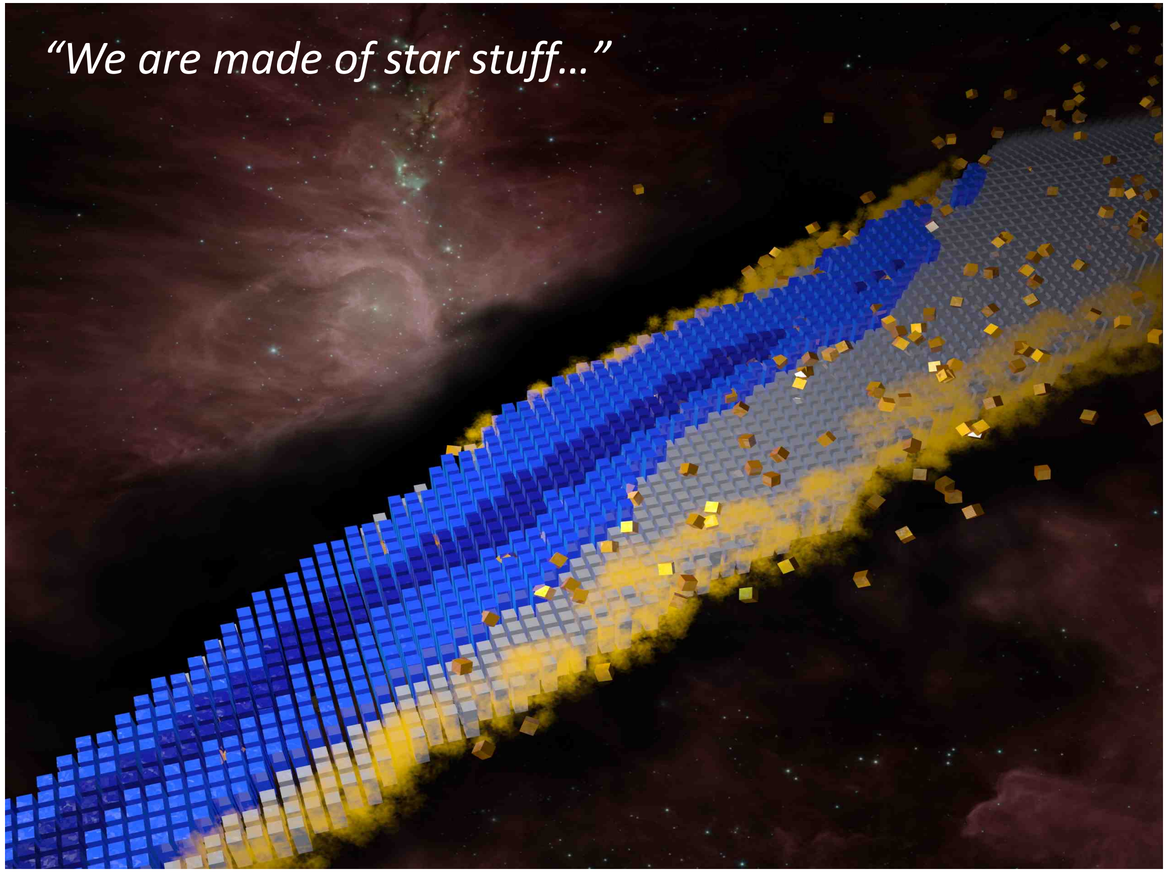
The Science: Nuclear Landscape and Big Questions

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*



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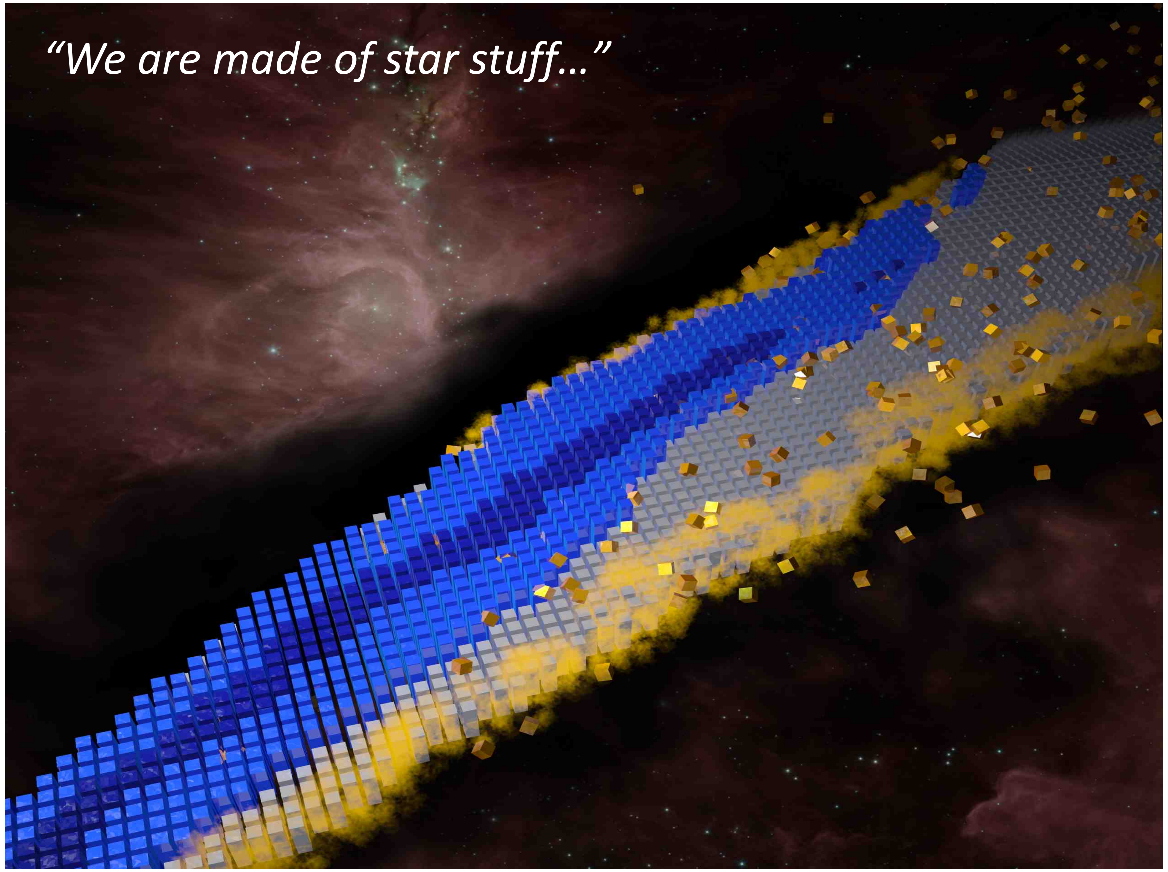
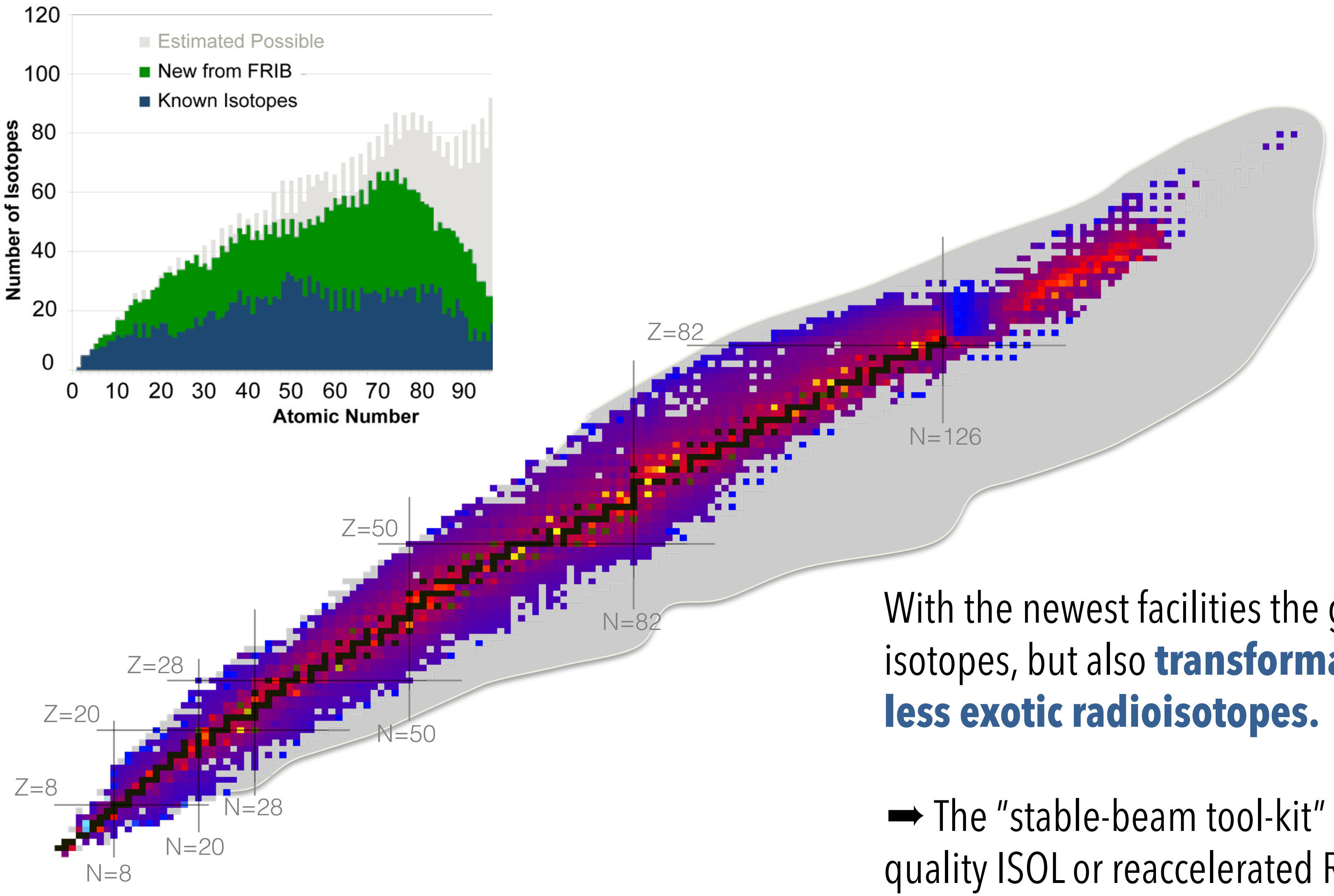


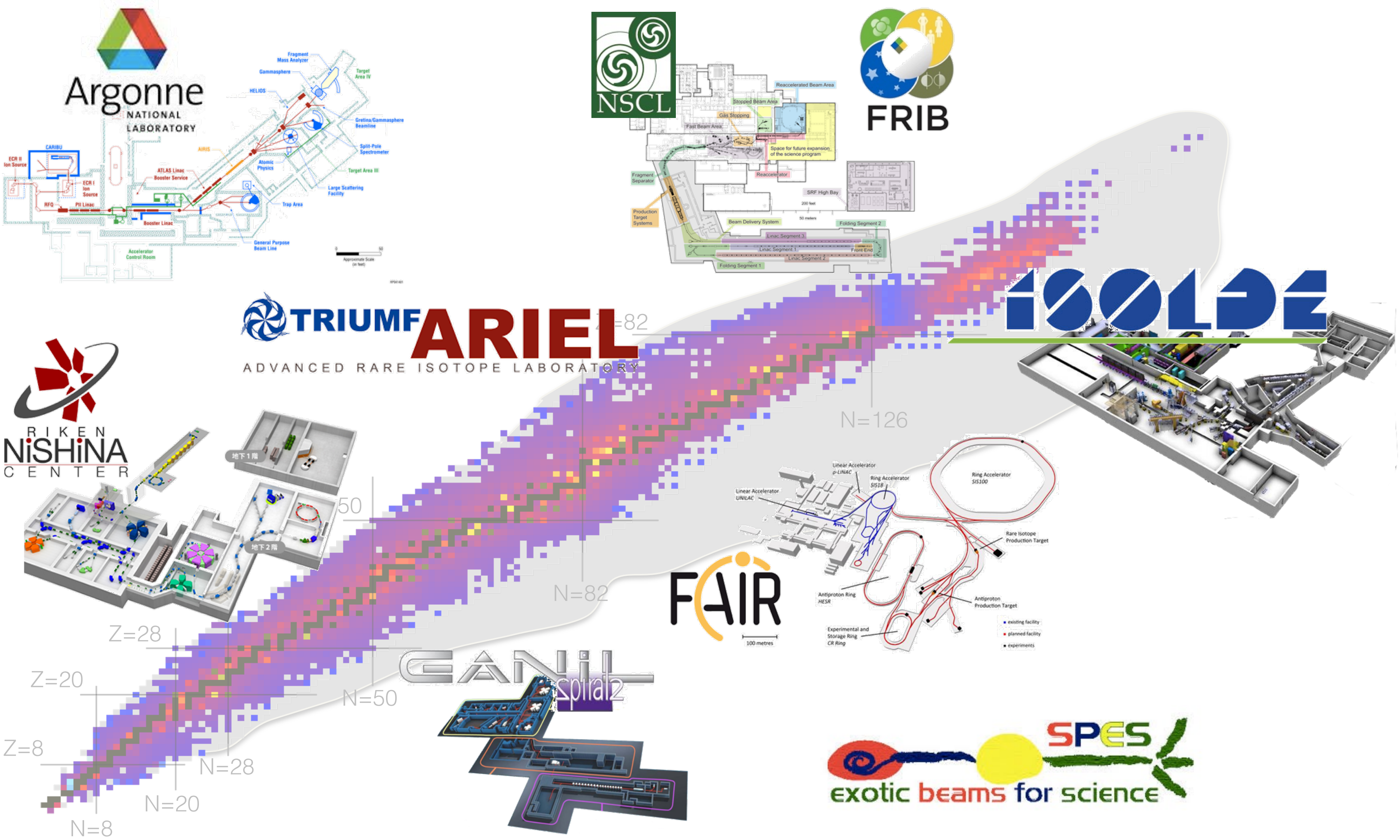
The Nuclear Landscape



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

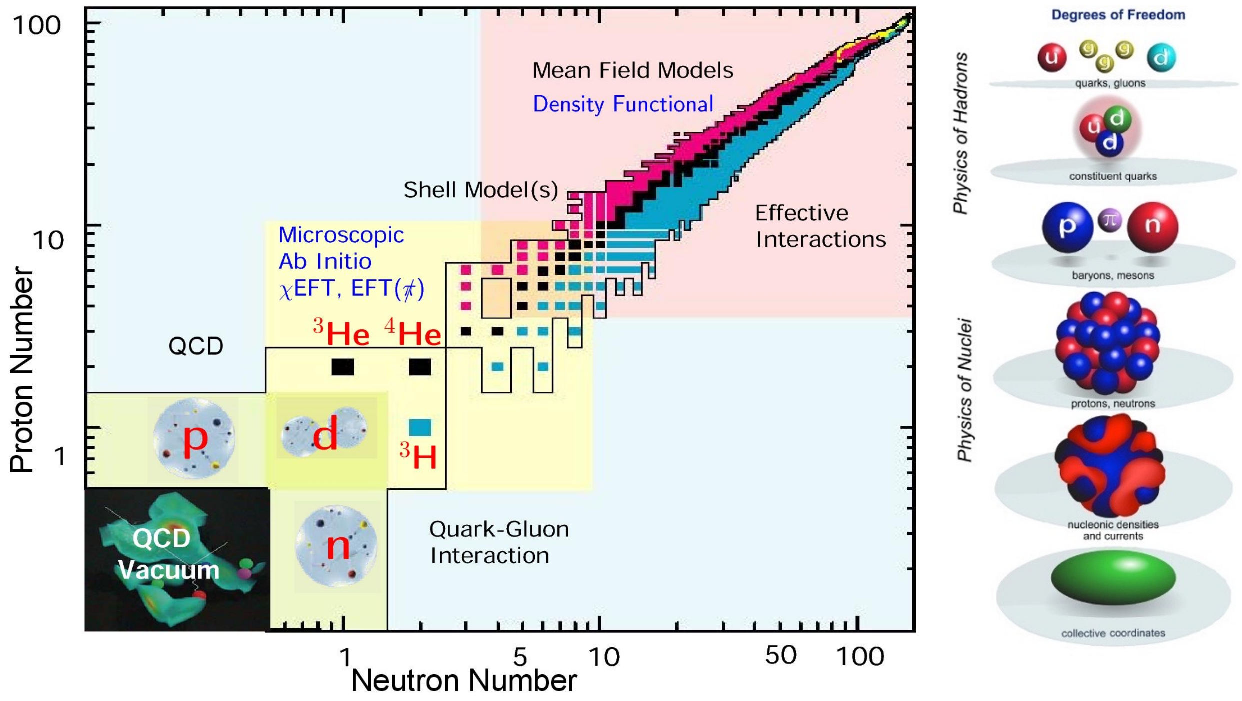


The Key Role of Theory

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."

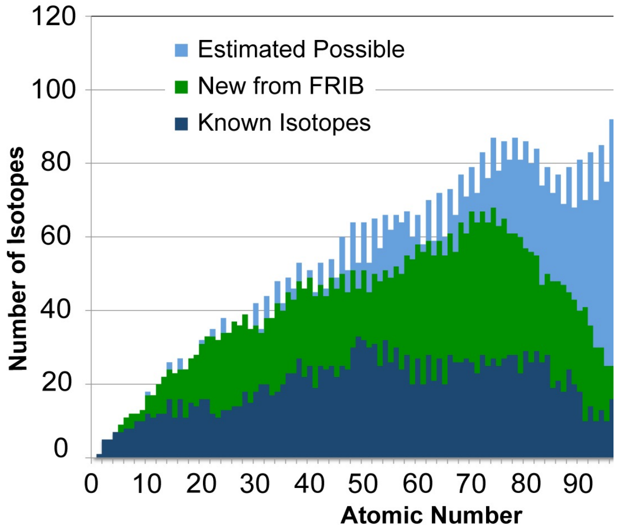


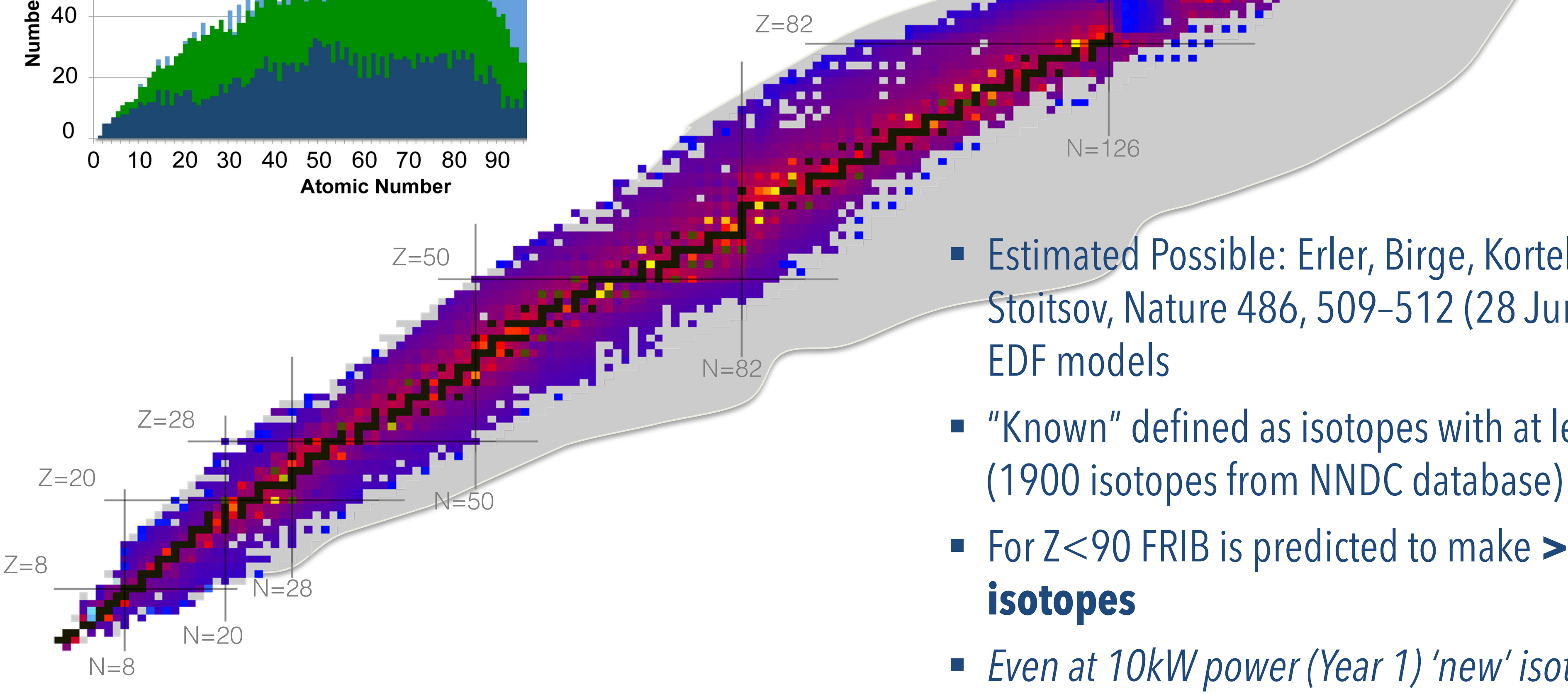
Progress relies on understanding which measurements can best inform a given theory or approach – close collaboration through analysis and publication will maximize science output and impacts in nuclear structure.

Outline

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

The Nuclear Landscape





- Estimated Possible: Erler, 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*

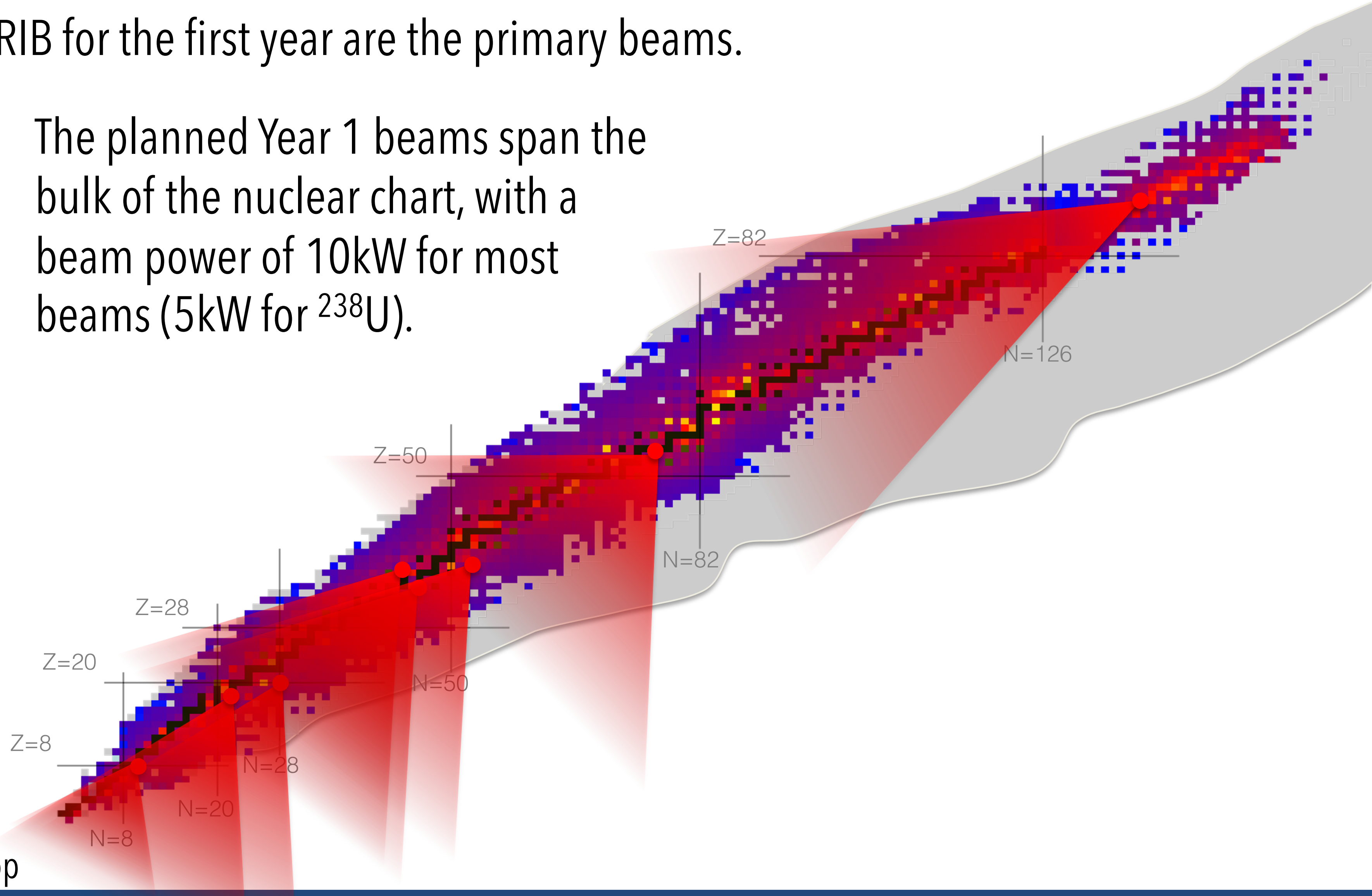
The Beams!

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

PAC	Beam power on target goal (kW)
1	10 *
2	50
3	100
4	200
5	400

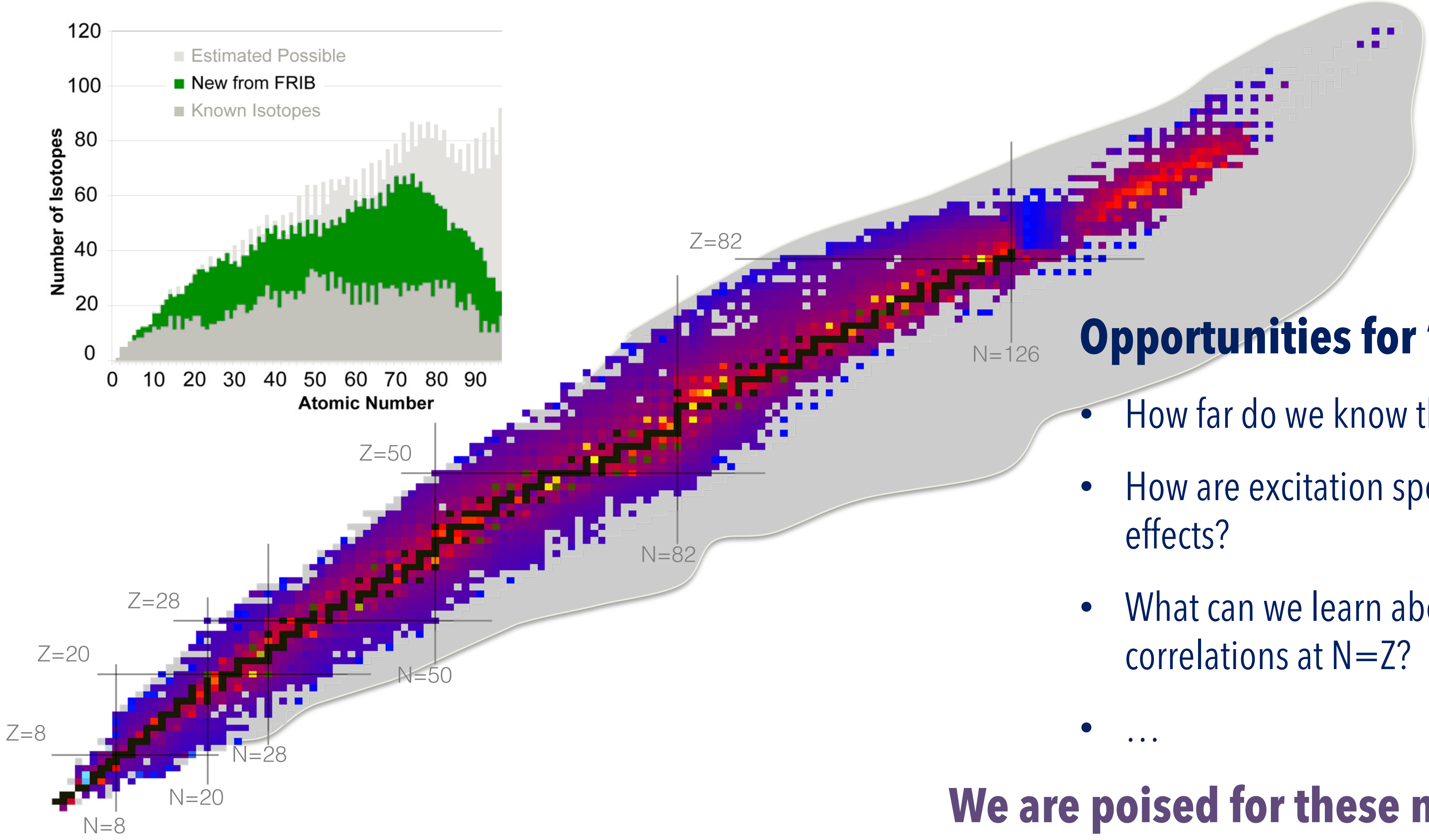
PAC 1 Beams
^{238}U
^{48}Ca
^{78}Kr
^{82}Se
^{124}Xe
^{18}O
^{86}Kr
^{16}O
^{36}Ar

The planned Year 1 beams span the bulk of the nuclear chart, with a beam power of 10kW for most beams (5kW for ^{238}U).



From B. Sherrill – May 2020 Proposal Workshop

'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*.

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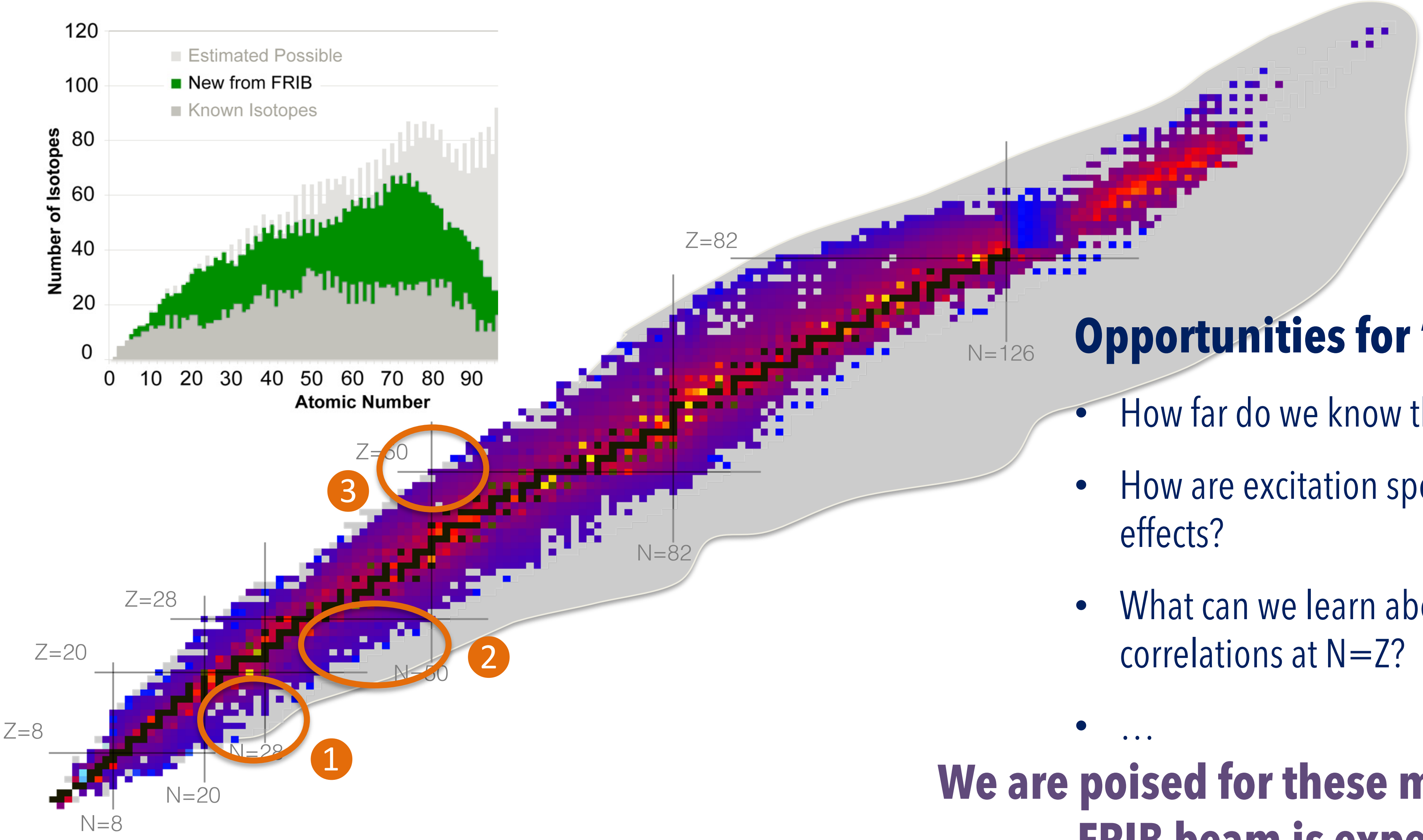

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FRIB beam is expected February 2022.

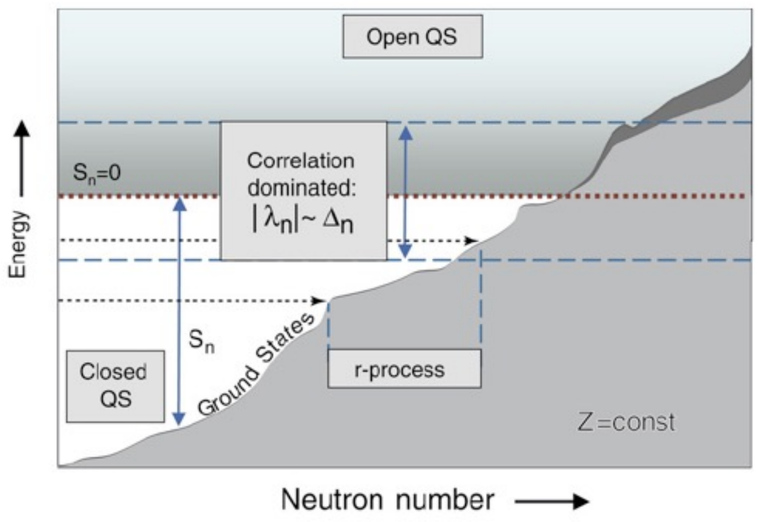
① Pushing Toward the Neutron Dripline – Z=12 and beyond

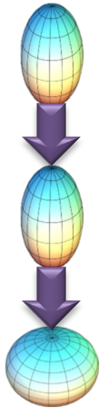
Explore properties of weakly bound nuclei and ask what happens in the transition from well-bound to weakly-bound "open" systems

⇒ Due to weakly bound levels

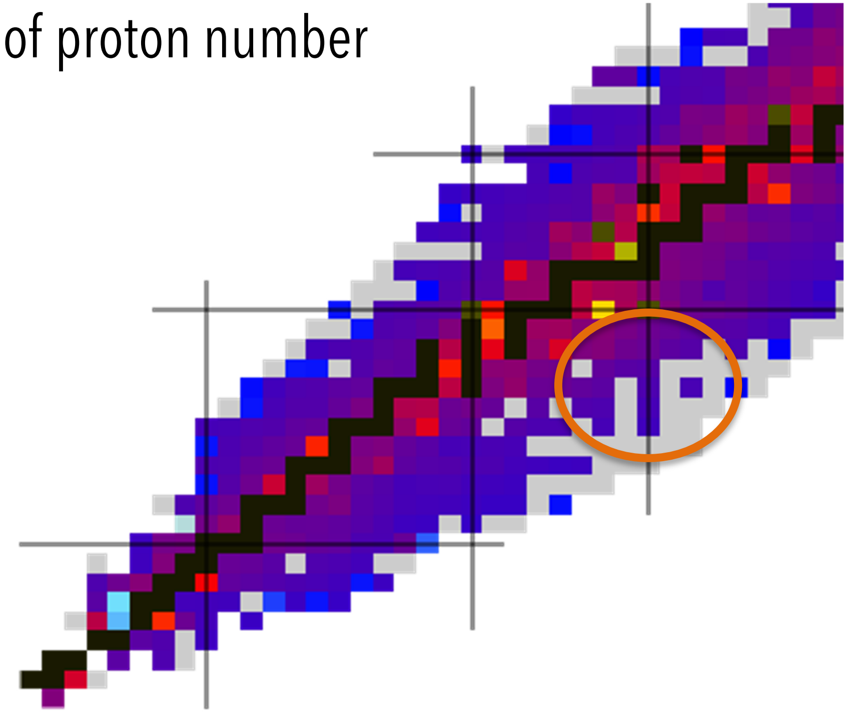
- low l levels (s, p) ⟶ extended wavefunctions ("halos")
- changes in pairing due to surface diffuseness
- valence nucleons can become decoupled from the core
- coupling to continuum states

J. Dobaczewski et al. / Progress in Particle and Nuclear Physics 59 (2007) 432–445





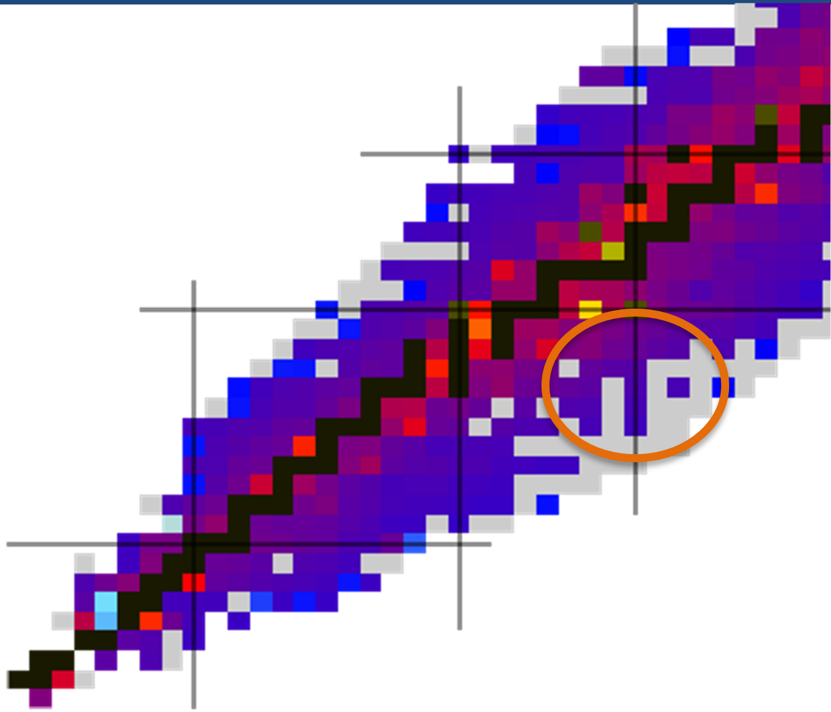
Moving south from ^{48}Ca, removal of protons leads to development of collectivity, and rapid shape evolution (and coexistence) as a function of proton number



- Rates make studies all the way to ^{40}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
  - β-decay extending all the way to decay of ^{40}Mg and beyond N=28 above Mg
  - Single-nucleon knockout studies (e.g. into ^{38}Mg)
  - Coulomb excitation (intermediate energy) – ^{42}Si



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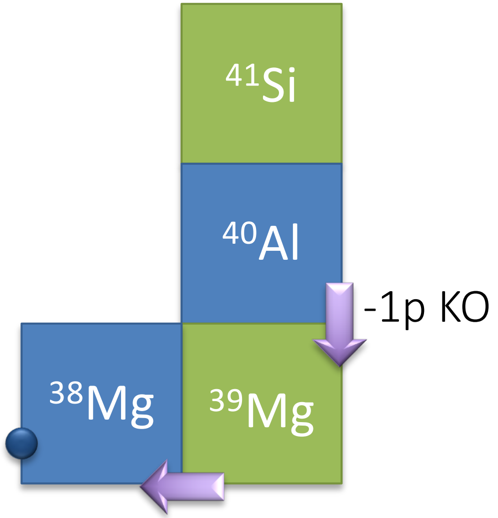
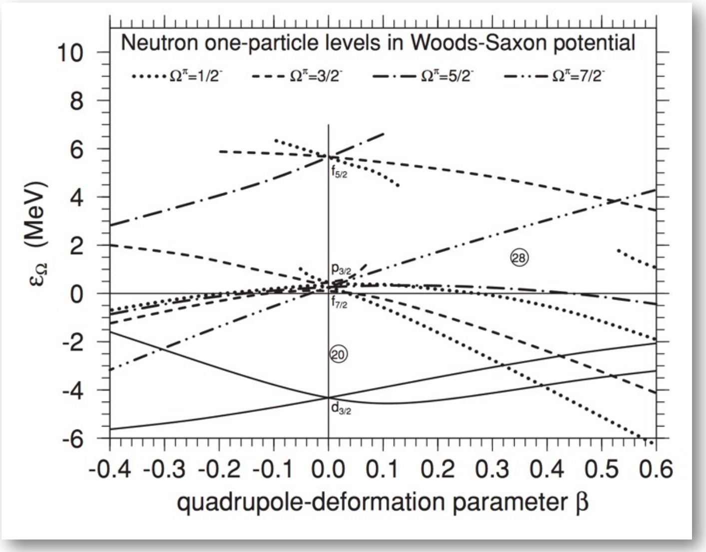
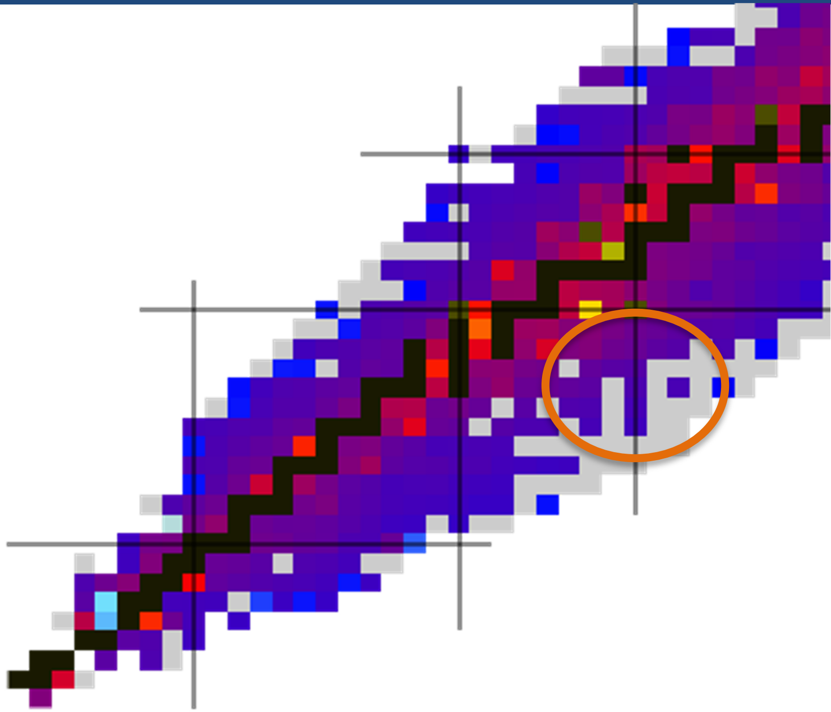
  - **Invariant mass measurement in ^{39}Mg with MoNA-LISA**



^{39}Mg --> ^{38}Mg + n





Open Questions:

- What is the neutron separation energy of ^{39}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?

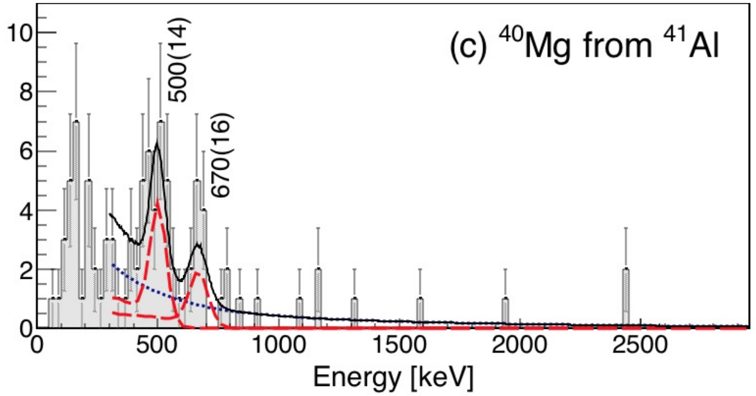
Additional opportunities:

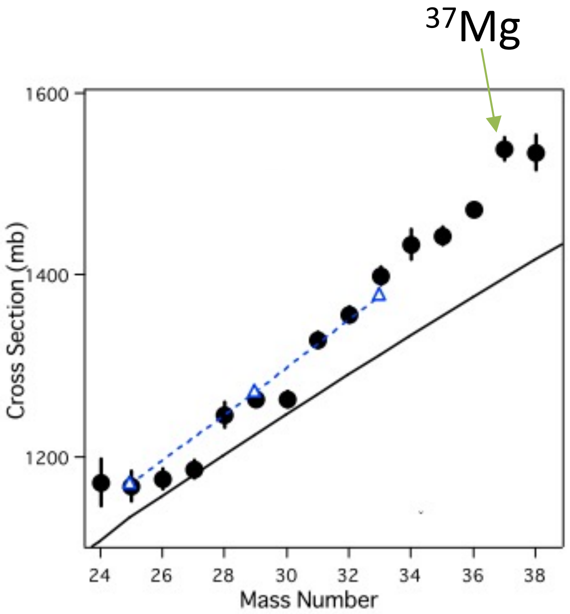
- Unbound states in ^{40}Mg (^{41}Al -1p)

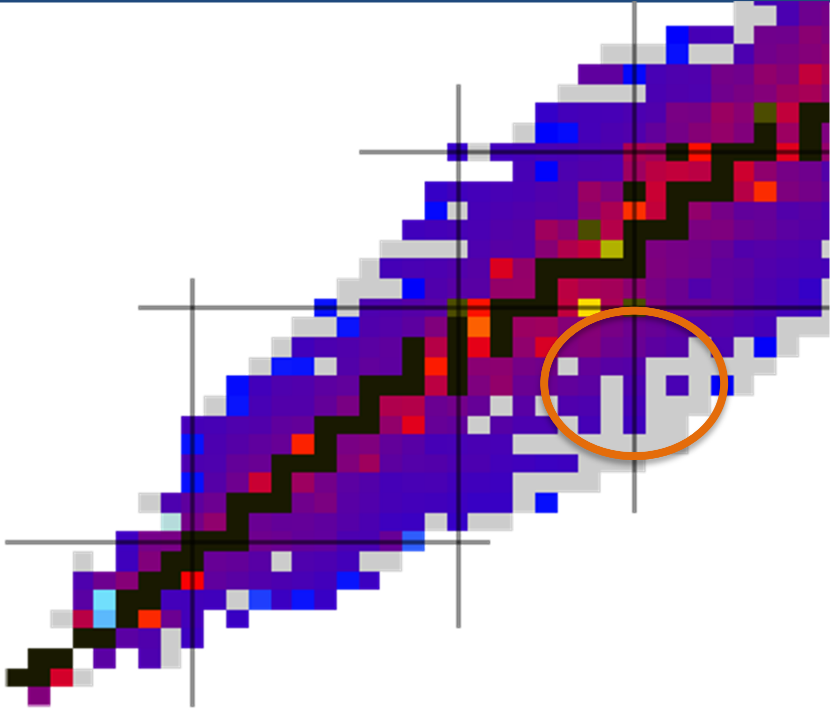
① Pushing Toward the Neutron Dripline – Z=12 and beyond

- **^{40}Mg reaction cross-section – halo or no?**

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

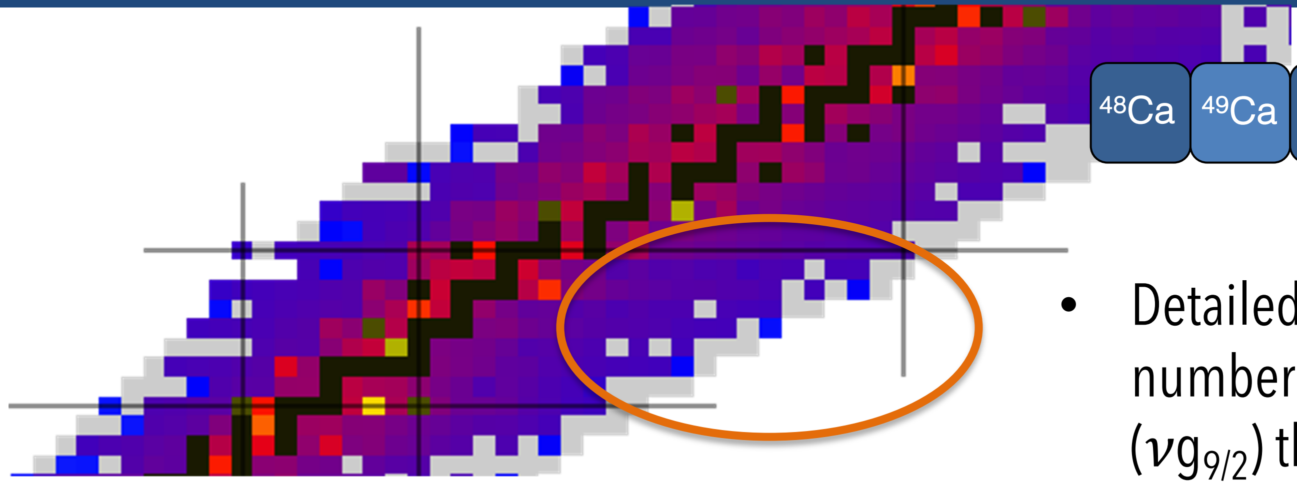






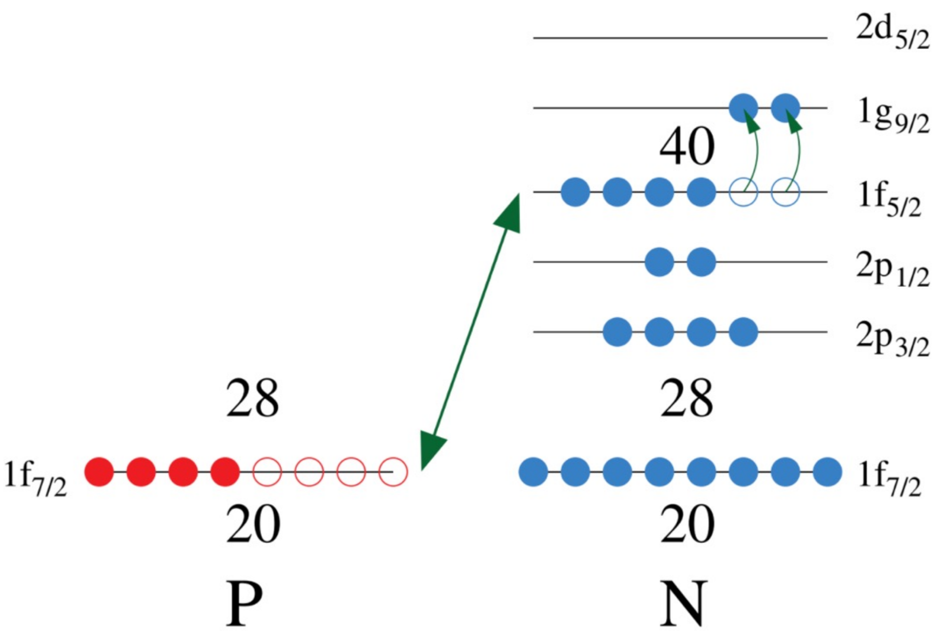
- With 800 pphour of ^{40}Mg a total reaction cross-section measurement will answer the question of whether there is a halo or not
- Combined with a TOF mass measurement, the separation energy can be established

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



^{48}Ca ^{49}Ca ^{50}Ca ^{51}Ca ^{52}Ca ^{53}Ca ^{54}Ca ^{55}Ca ^{56}Ca ^{57}Ca ^{58}Ca ^{59}Ca ^{60}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 IoI region test model predictions – both shell model and collective model descriptions
- Out to N=50 – ^{78}Ni should be doubly-magic, but near N=40 Ni have shape coexistence



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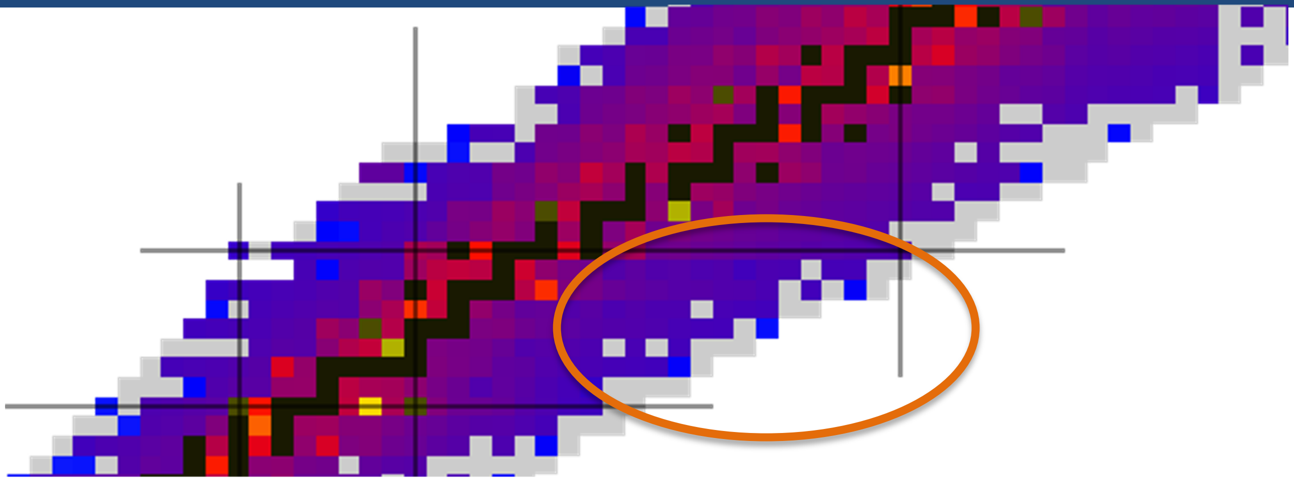


Nucleon Knockout

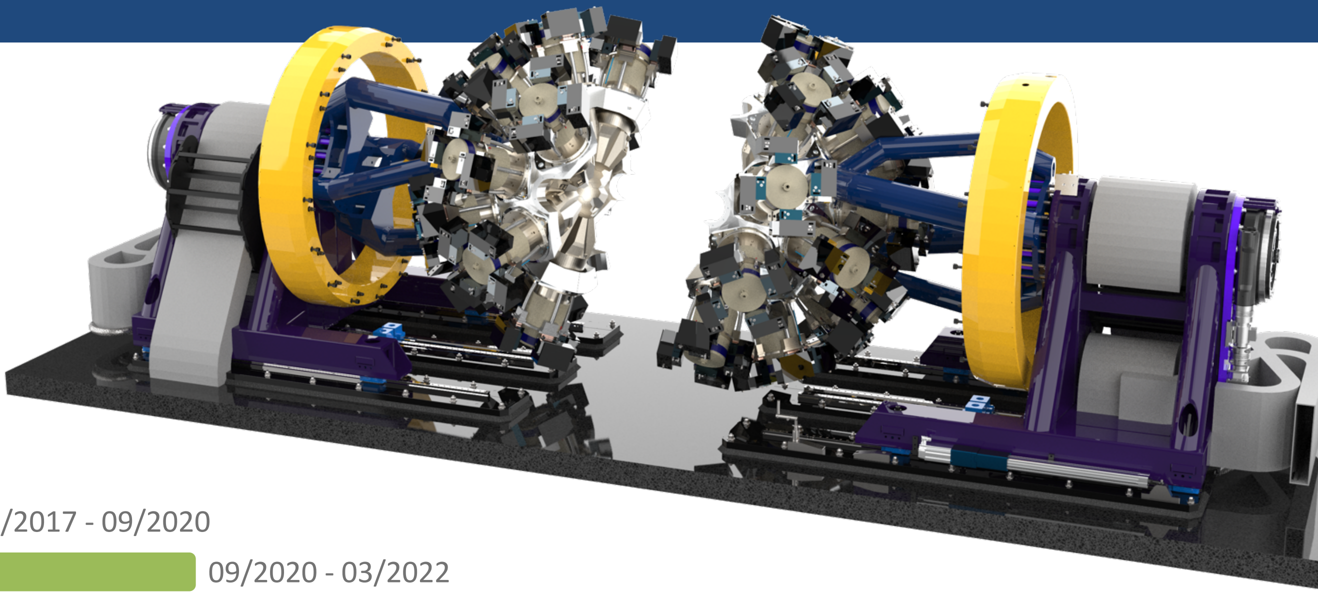
- In-beam γ-ray spectroscopy can map out the evolution of single-particle states
- At NSCL -1p knockout has been performed up to ^{66}Fe/^{65}Mn – this can be extended substantially in the first year(s) at FRIB
- Fast beam measurements with GRETINA + S800

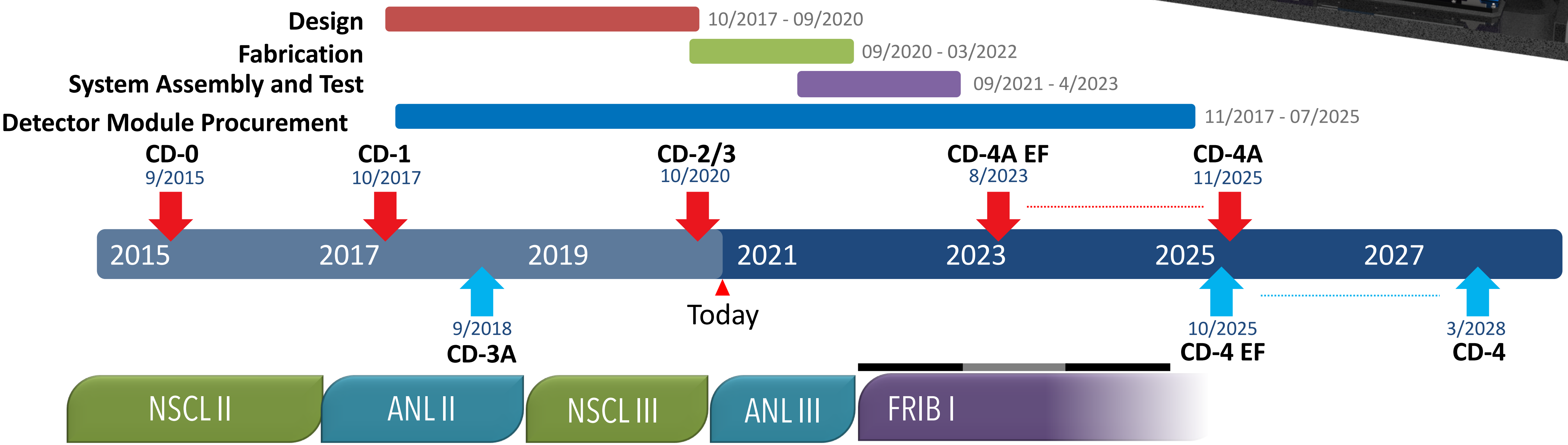
Coulomb Excitation

- 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 in Year 1 at FRIB can reach out to ^{70}Fe, ^{60}Ti to help delineate the limits of the region

GRETA

- GRETA will have 30 Quad Detector Modules to cover >80% of the full solid angle surrounding a target
- Unmatched resolving power will enable further push to the driplines and other spectroscopic frontiers





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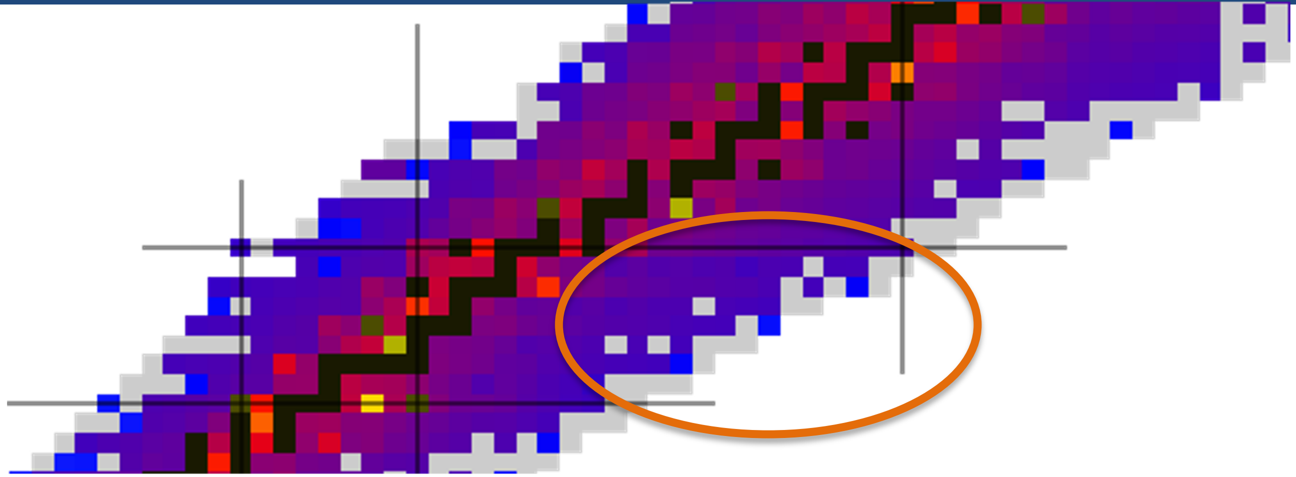
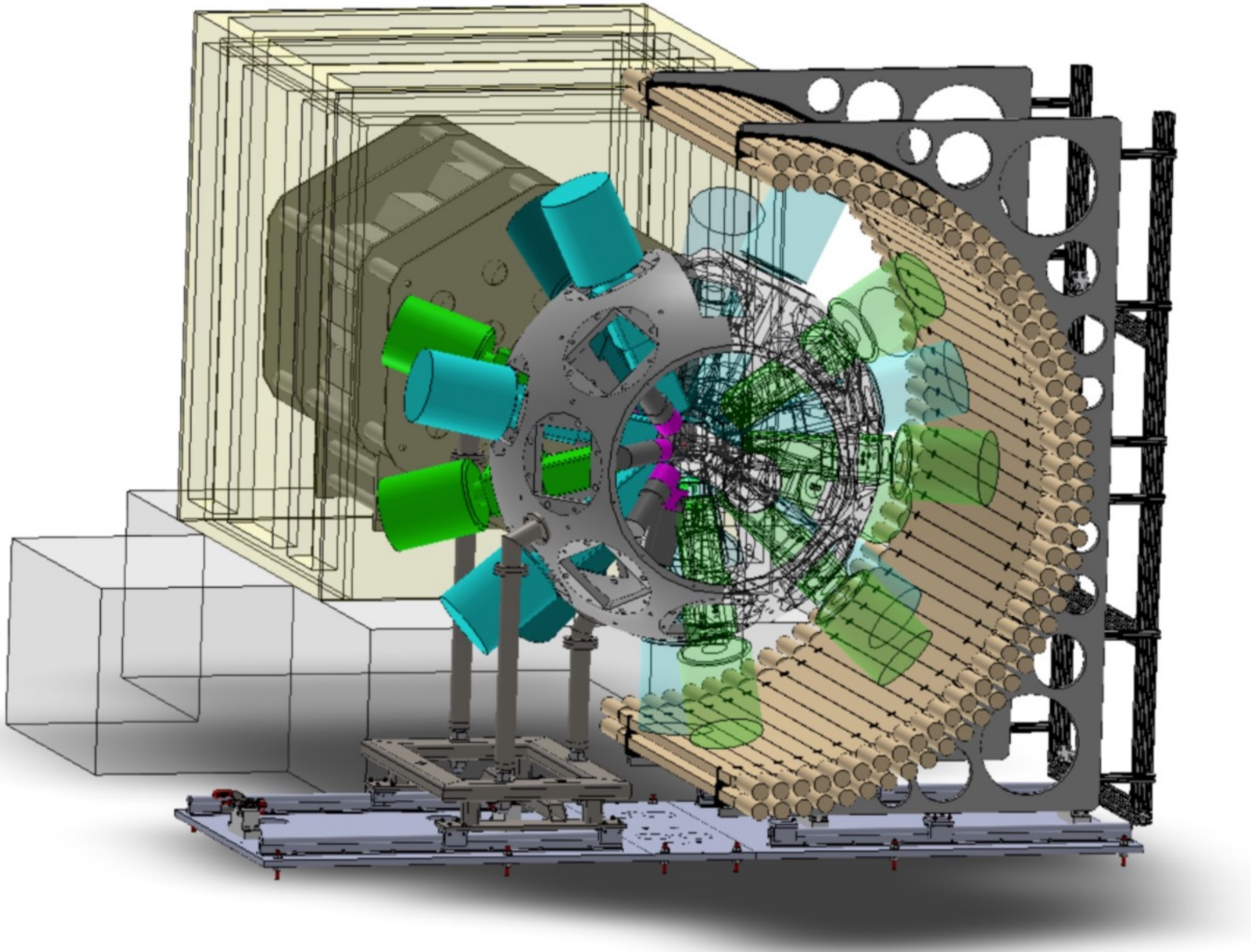


Decay studies with the FRIB Decay Station Initiator (FDSi)

- The region immediately around ^{78}Ni (N=50) is accessible to β-decay studies, with rates of hundreds of pphour
- FDSi enables total decay spectroscopy, with γ, particle and neutron spectroscopy
- Combination with MTAS or SuN further extends the physics

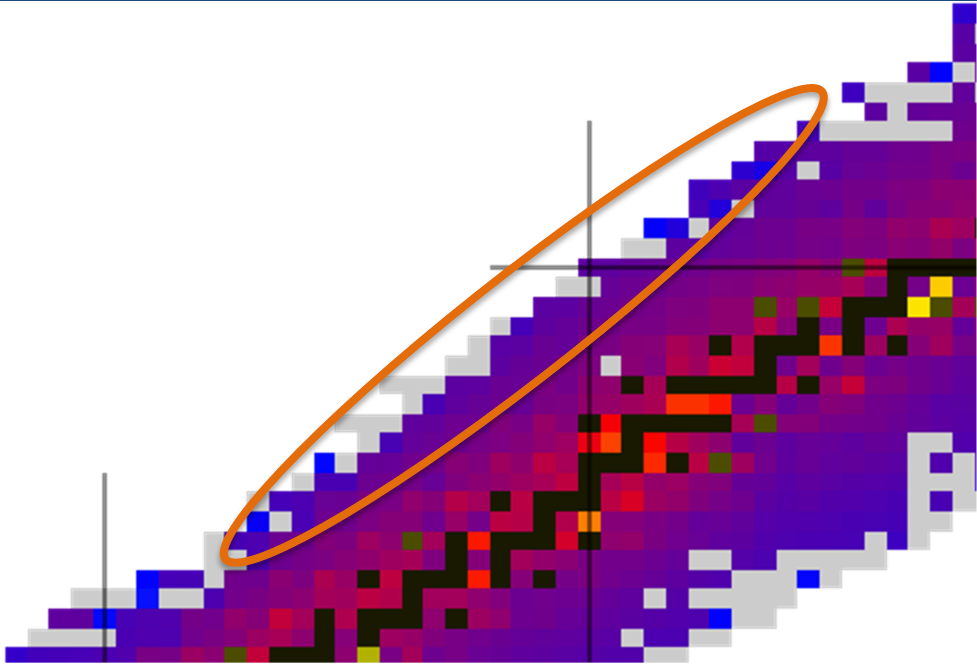


③ N=Z

- The physics opportunities near N=Z are compelling
  - Studies of mirror symmetry can be extended within the fp shell
  - First hint of superallowed α decays near ^{100}Sn are unique on the nuclear chart

- These nuclei are accessible, thanks to ^{124}Xe and ^{238}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



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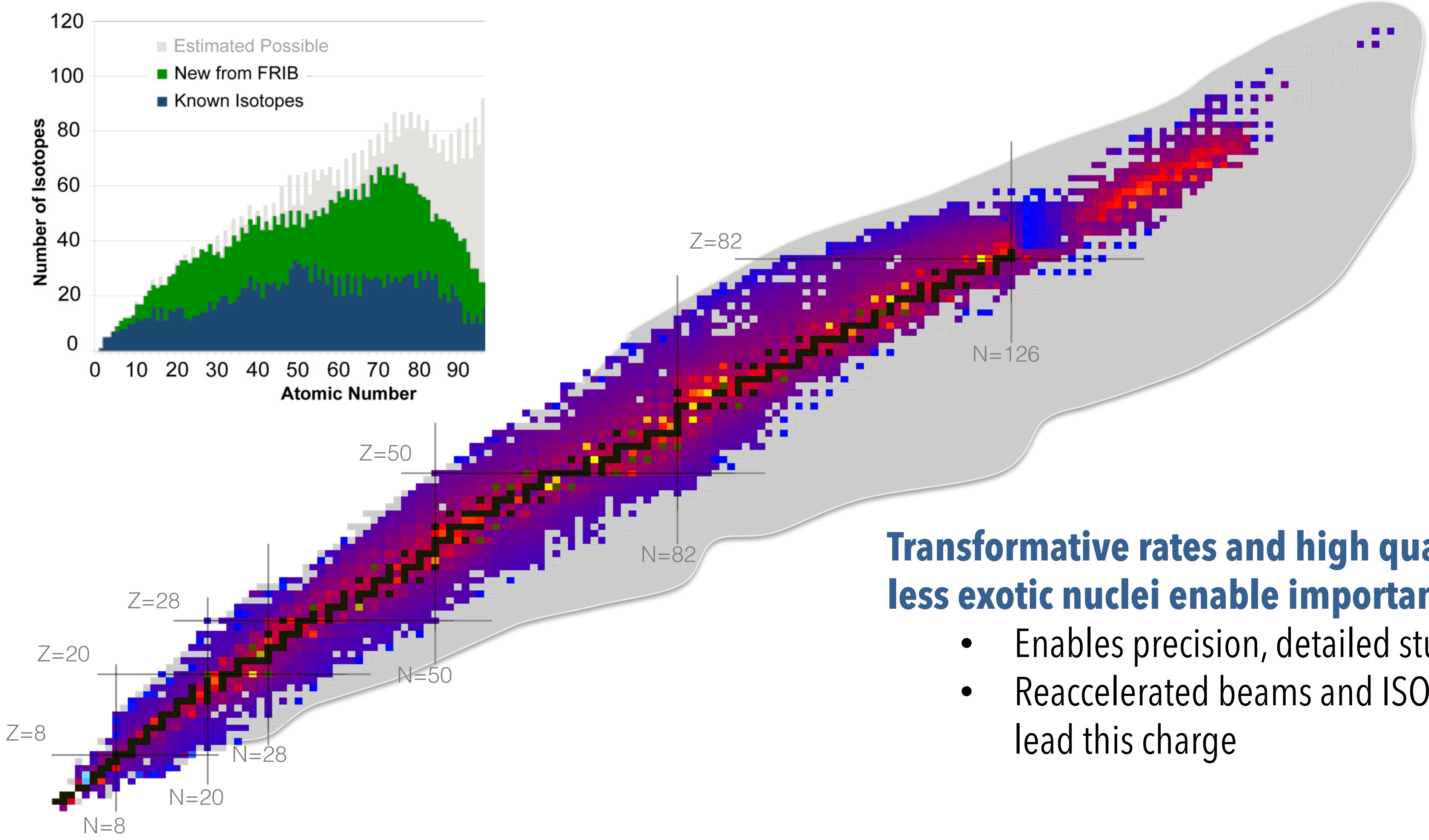
A Small Step Back From the Edge…



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, like **TRIUMF**, will lead this charge

Consider an Example…

^{47}Ca ^{48}Ca ^{49}Ca ^{50}Ca ^{51}Ca ^{52}Ca ^{53}Ca ^{54}Ca ^{55}Ca ^{56}Ca ^{57}Ca ^{58}Ca ^{59}Ca ^{60}Ca …

- 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}Ca – because everything lighter is understood, right?

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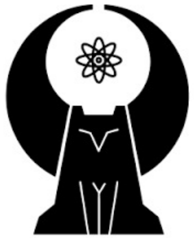
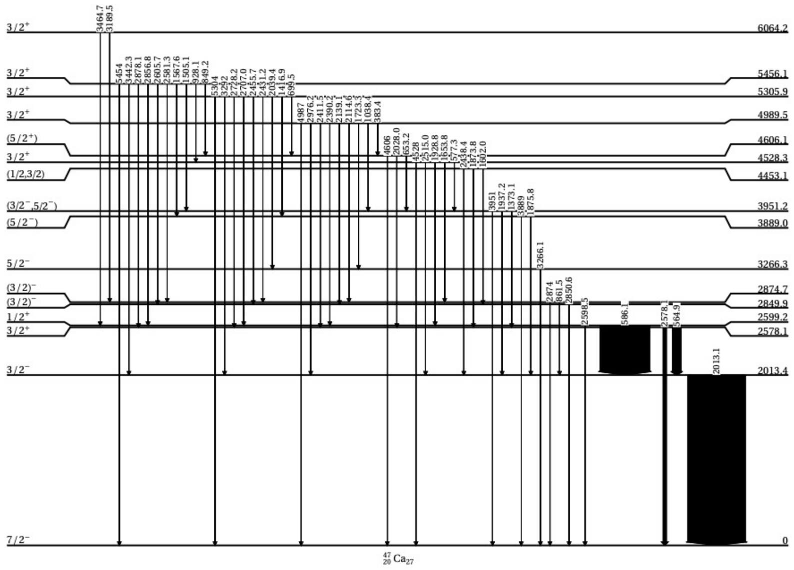
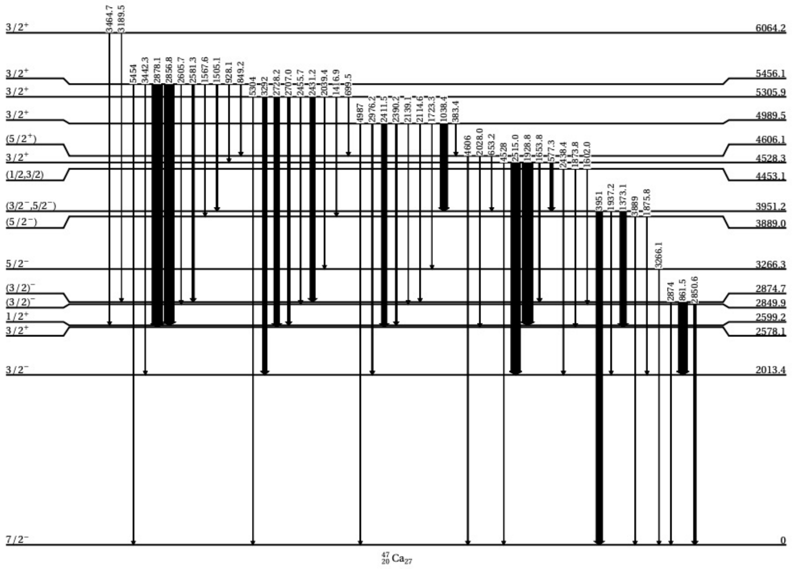
Not quite…

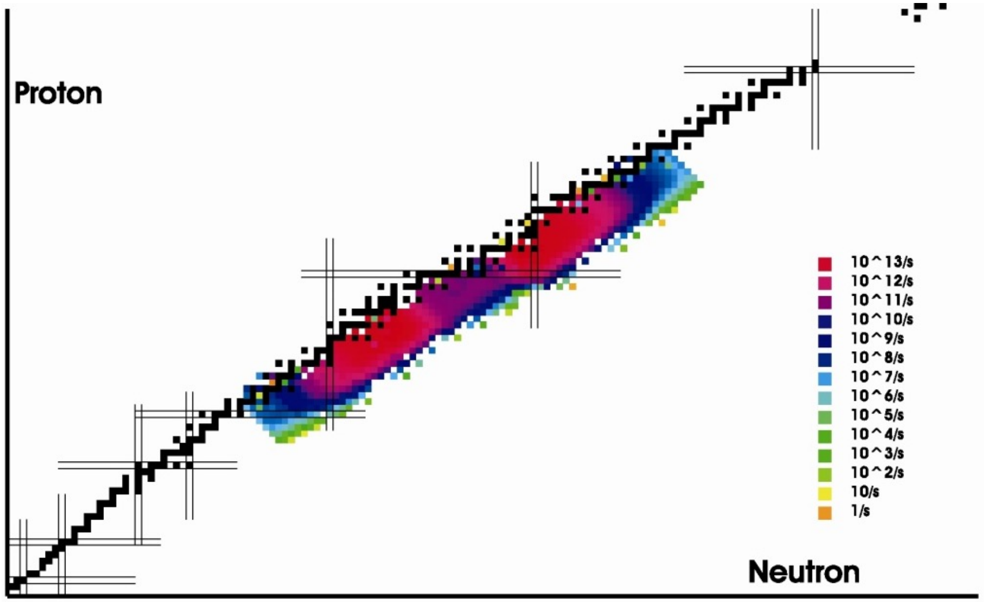






J. K. Smith *et al.*, PRC **102**, 054314 (2020).

High-Intensity and High-Quality Beams

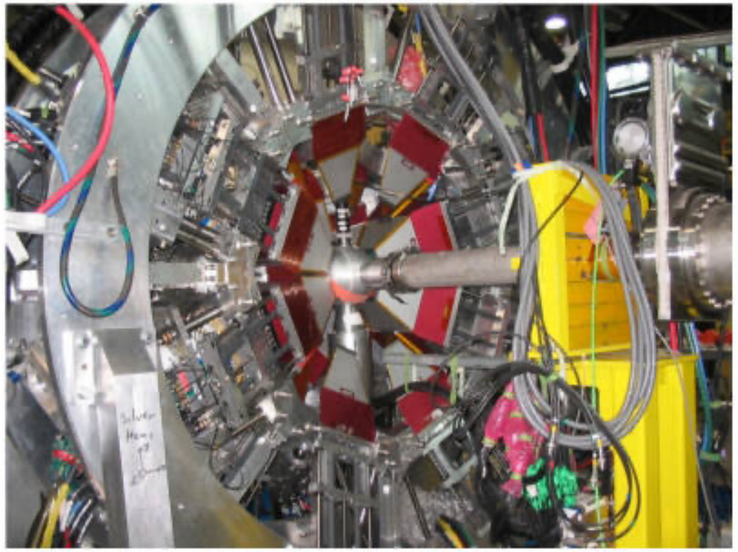


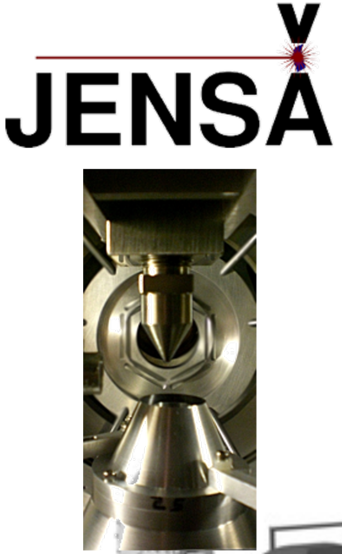
- High quality and high intensity beams possible with post-acceleration enable precision measurements of nuclei from stability to 10-12 neutrons out
- ISOL (ISAC), ARIEL, CARIBU (ANL ATLAS), ReA (FRIB) provide complementary beams to enable such measurements

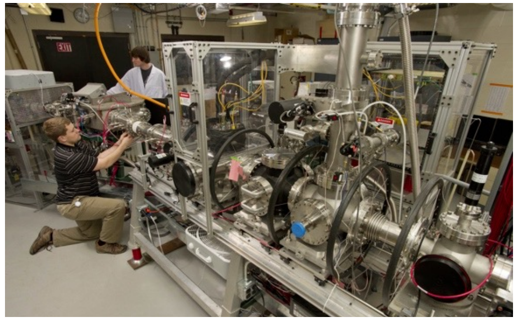
For example…

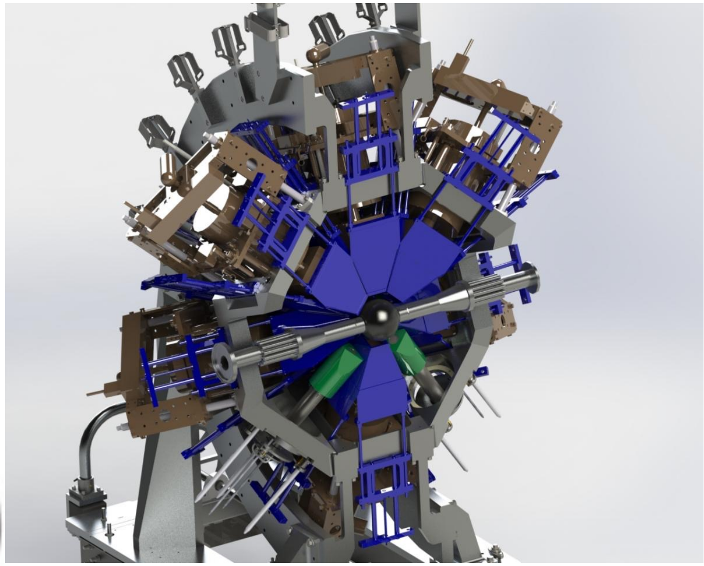
- Safe Coulomb Excitation
  - Low energy Coulex adds substantial knowledge by measuring multiple nuclear matrix elements - not possible with techniques using fast fragmentation beams
- Transfer Reactions
  - Complete transfer reaction measurements provide the possibility for fully understanding particle/hole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

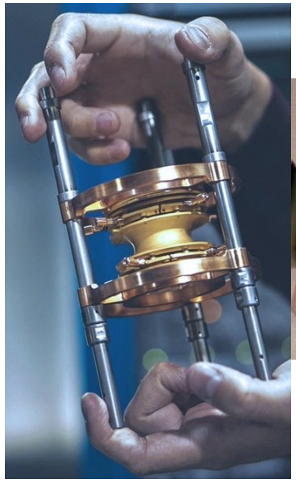
Experimental Equipment

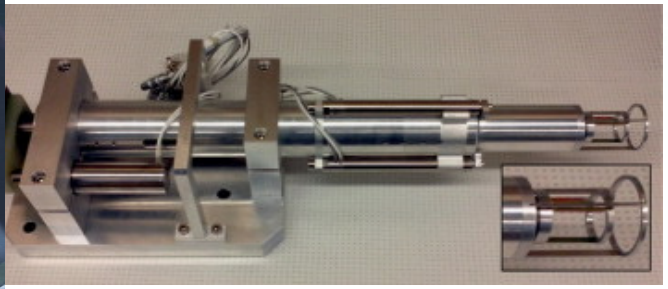


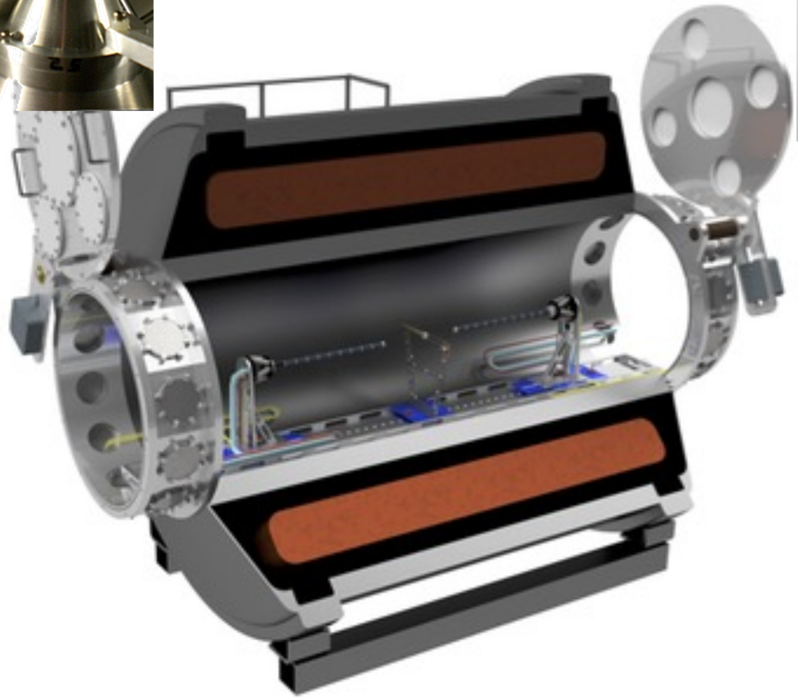


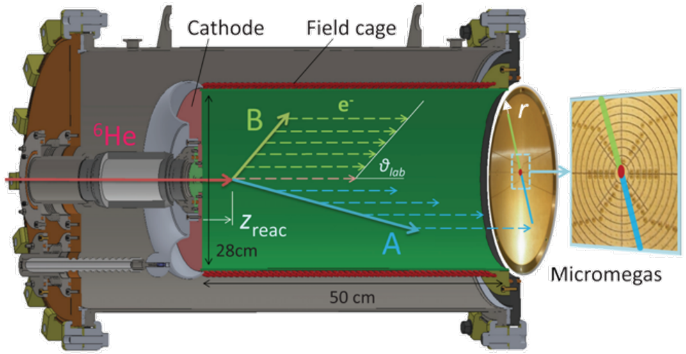












Experiments Will Continue to Maximize Discovery Potential and Collaboration

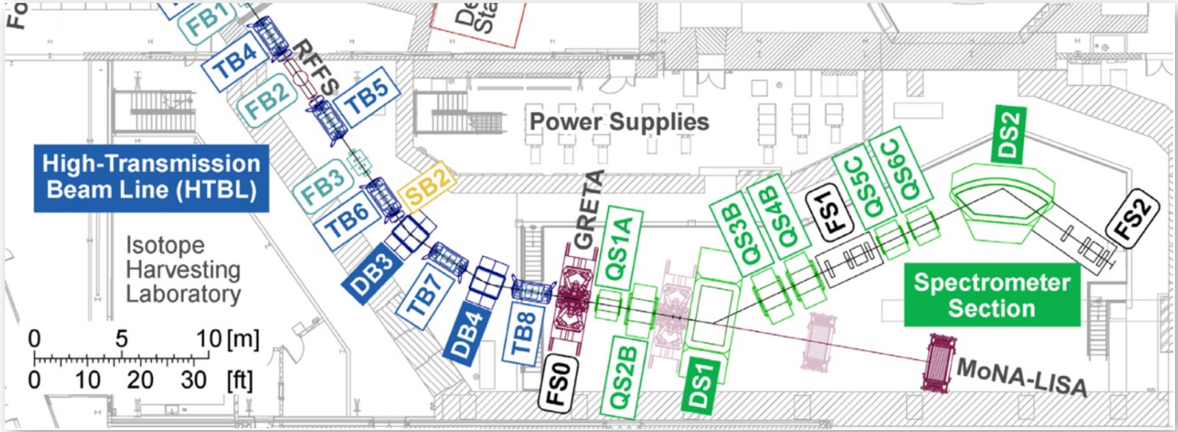


Image courtesy of Jon Lighthall

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
  - ARIEL and CANREB at TRIUMF are cementing the key role of TRIUMF in nuclear structure and nuclear astrophysics
  - CARIBU and ν-CARIBU in addition to the stable beam facilities anchor the ATLAS facility

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$\Rightarrow$ The most exciting aspect is that the next big result is probably not related to anything in these slides.

Acknowledgements

Thanks to the Nuclear Structure Group at LBNL, and colleagues at FRIB for valuable conversations and input.

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contracts No. DE-AC02-05CH11231 (LBNL).

Thank you! Merci!

Thank you!