# FRIB and the Neutron-Rich Mg Isotopes

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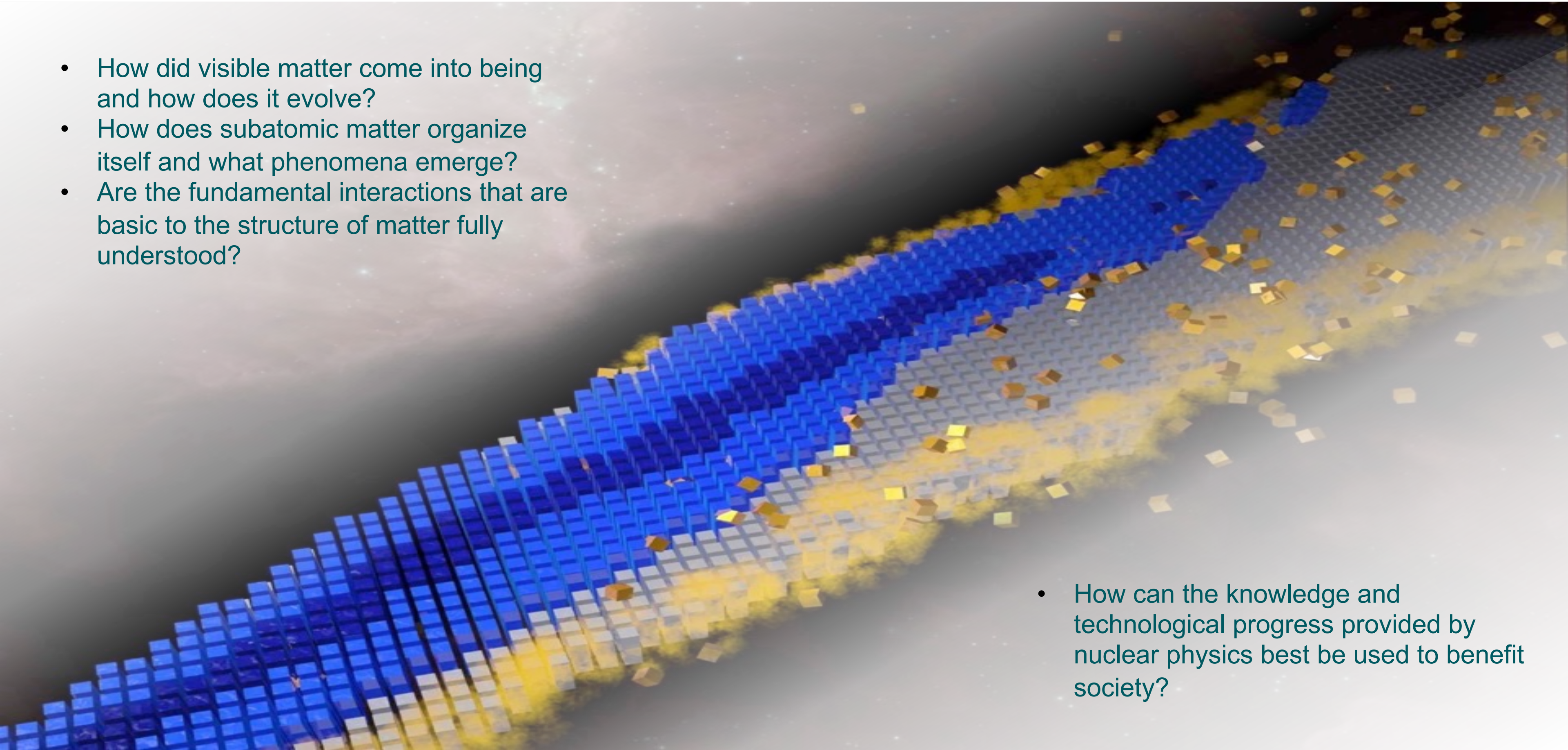
# Outline

- **Introduction**
- Toward the driplines above $Z$ = 12 – the first FRIB experiment
- Future plans in $^{40}$Mg
- The unexpected core of $^{25}$F
- Summary

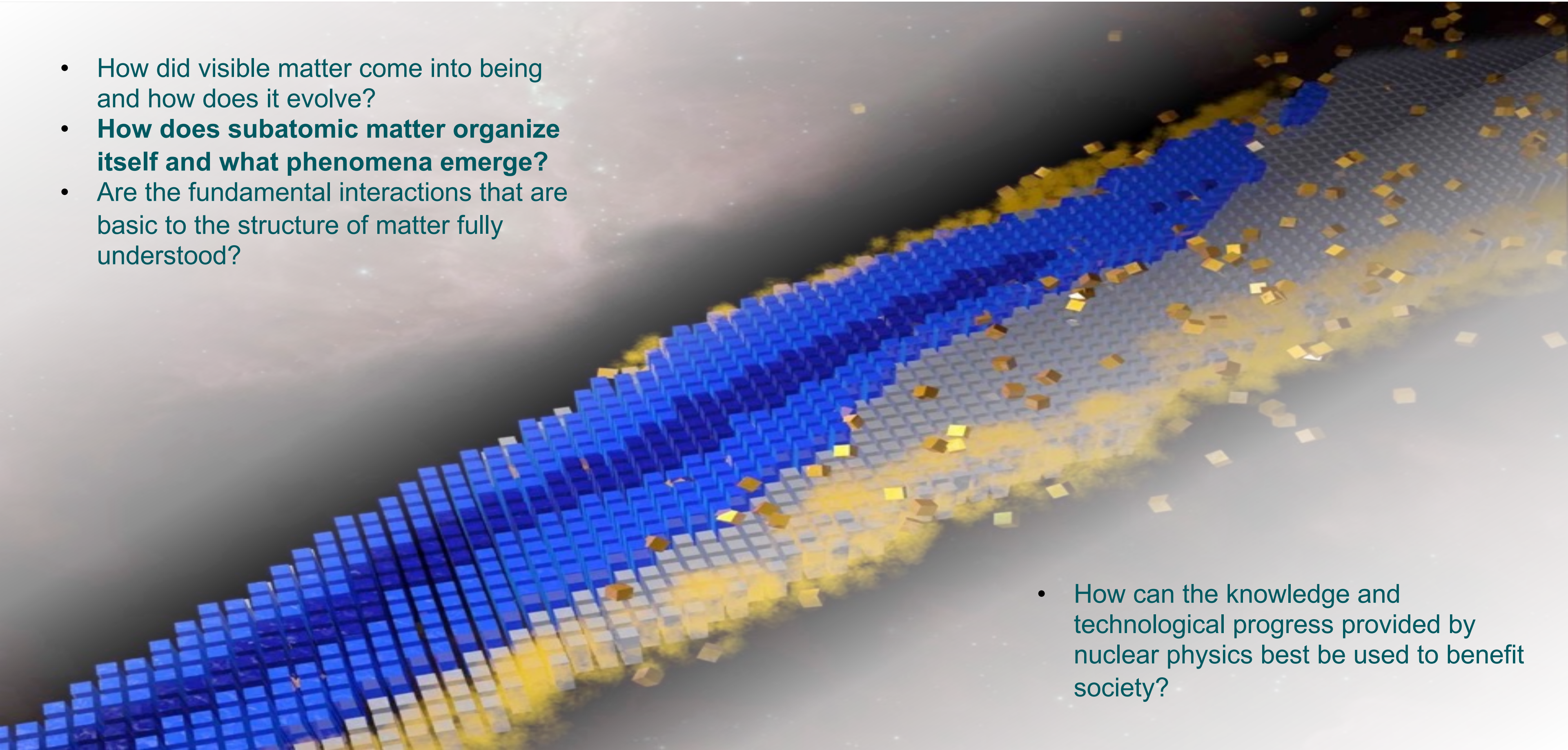
# The Science: Nuclear Landscape and Big Questions



- 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?

# The Science: Nuclear Landscape and Big Questions



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- **How does subatomic matter organize itself and what phenomena emerge?**
- Are the fundamental interactions that are basic to the structure of matter fully understood?
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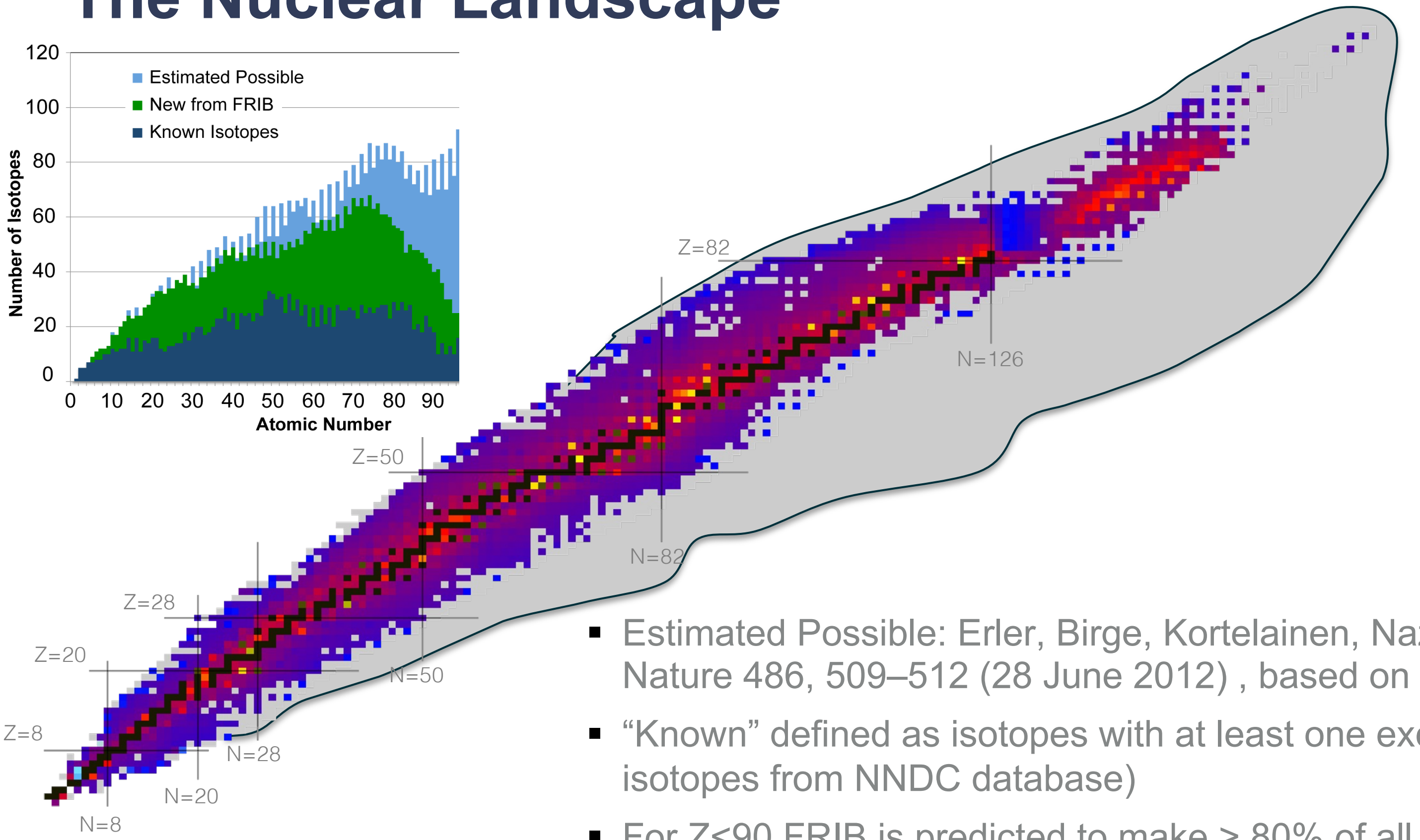
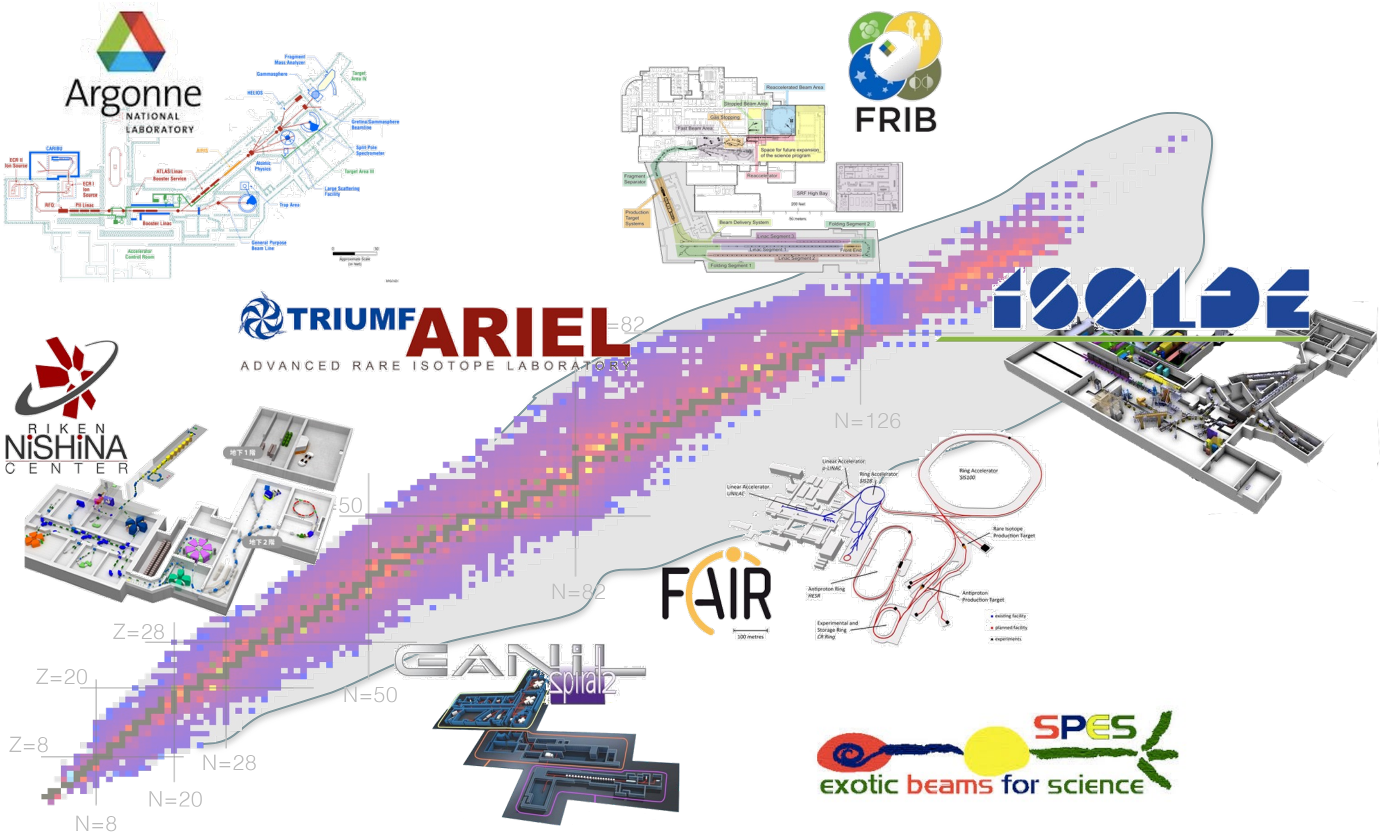
# The Nuclear Landscape



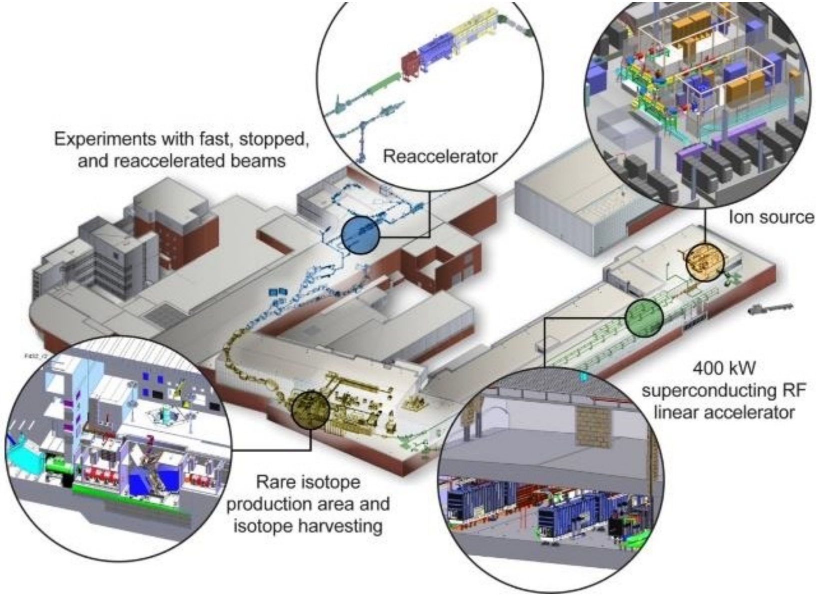

- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models
- “Known” defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- For Z<90 FRIB is predicted to make > 80% of all possible isotopes
- Even at 10kW power (Year 1/2) ‘new’ isotopes will be accessible to study

# Current and Upcoming Facilities



# FRIB will Enable Discovery

- FRIB's key feature is 400 kW beam power
  - 8 p$\mu$A or 5 x $10^{13}$ $^{238}$U /s
  - 42 p$\mu$A or 2.6 x $10^{14}$ $^{48}$Ca /s
- Experiments with fast (200 MeV/u), stopped (trapped), and reaccelerated beams (0.6 to 10 MeV/u)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
- Isotope harvesting capability from beam dump water)




Thomas Glasmacher, FRIB Laboratory Director

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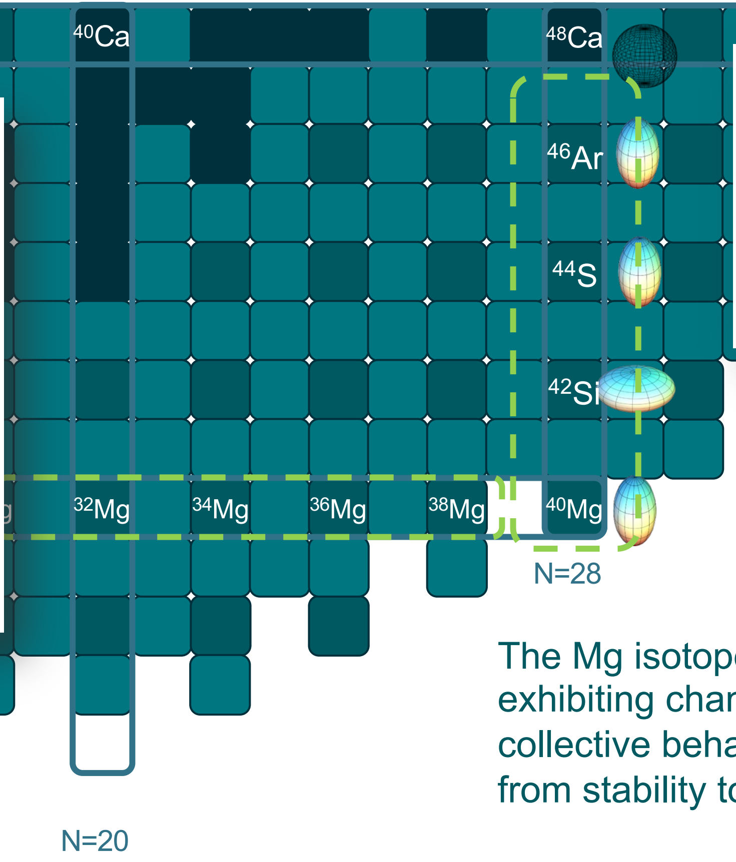
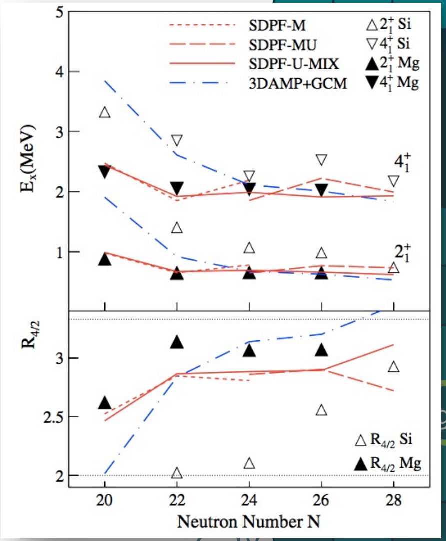
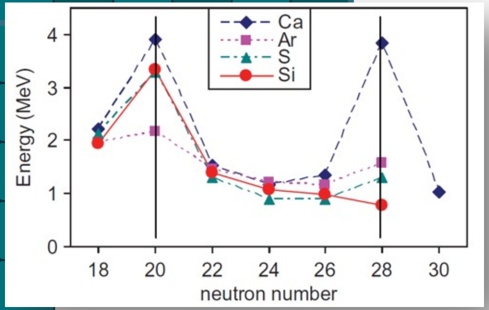
# $^{40}$Mg: The Intersection Point



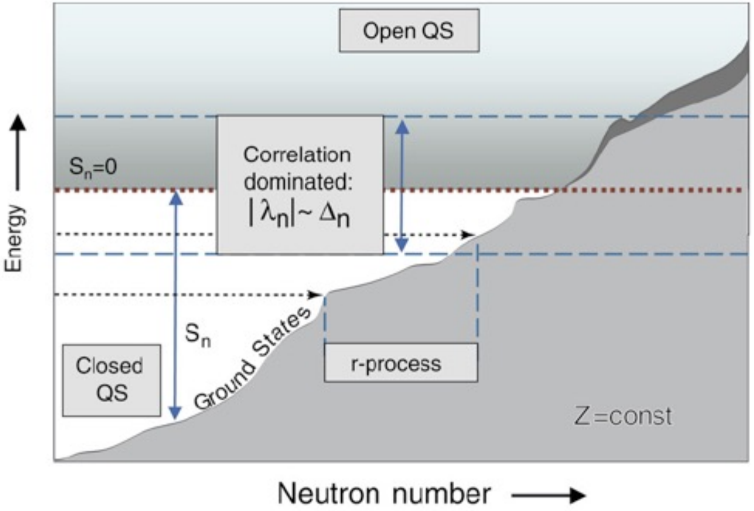



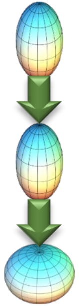

Evolution of nuclear shapes along *N*=28

The Mg isotopes present a chain of nuclei exhibiting changing single particle structure and collective behavior, experimentally accessible from stability to the **dripline**.

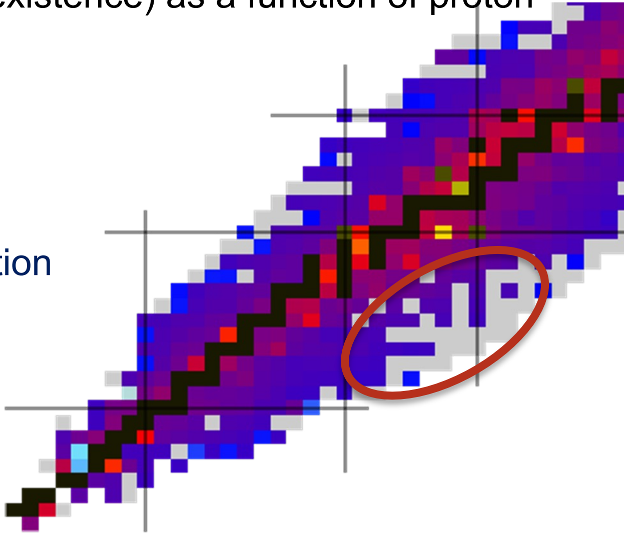
# How is the nucleus affected by weak binding and neutron excess?

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



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



## Shell Evolution

T=0 (spin-isospin) interaction

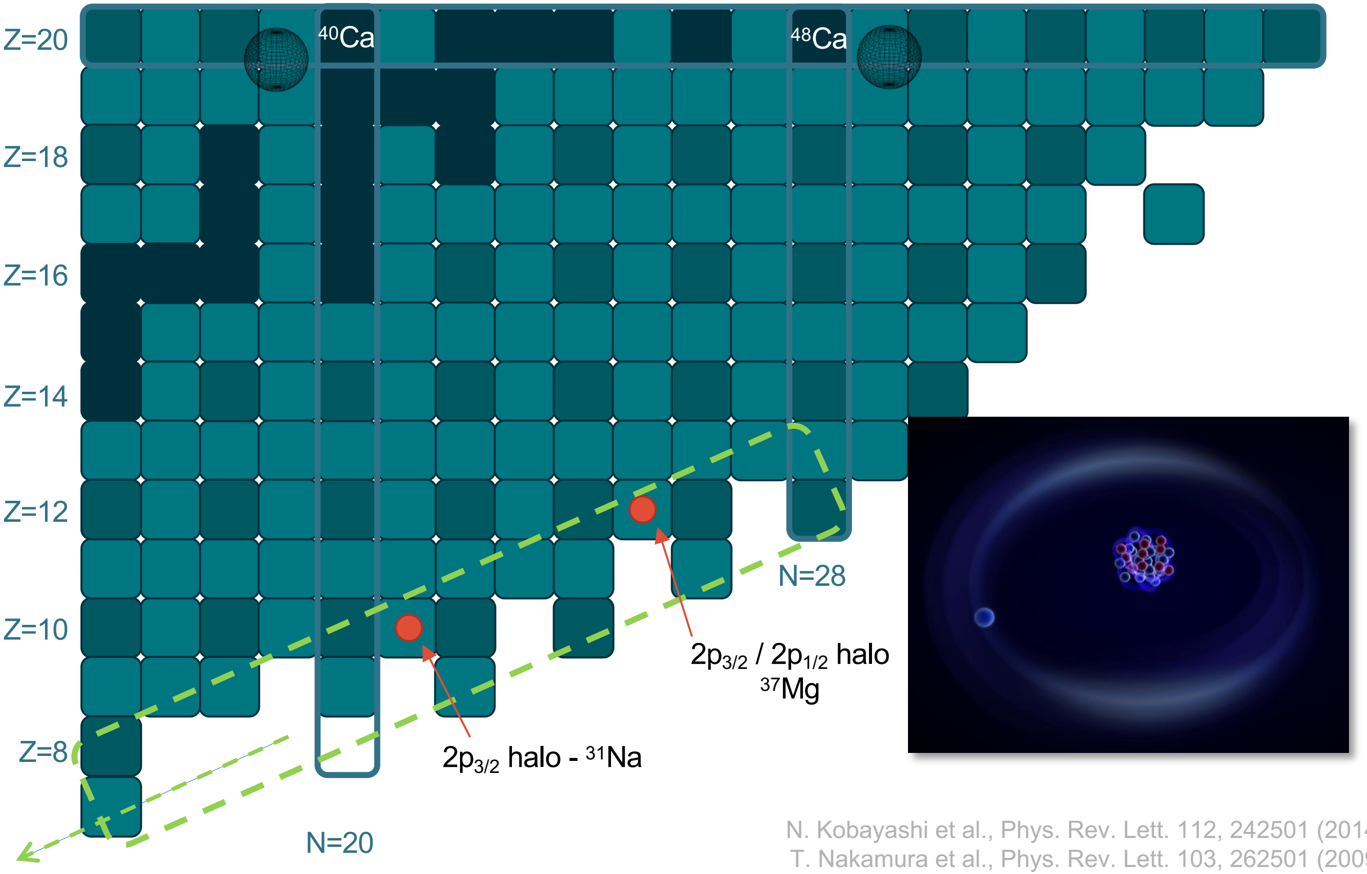
Tensor force

T=1 pairing correlations

**Weak Binding**

- 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

# Limits of Stability: Halo Nuclei



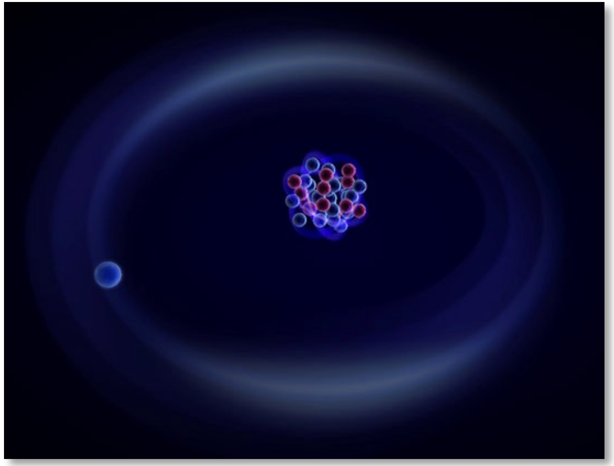

N. Kobayashi et al., Phys. Rev. Lett. 112, 242501 (2014).
T. Nakamura et al., Phys. Rev. Lett. 103, 262501 (2009).

# Weak Binding Phenomena

- Currently we know of examples of weak binding and delocalized wavefunctions giving rise to nuclear halos
- When we do have halo structures then what is the nature of the valence-core interaction?

Do the delocalized, weakly bound nucleons

- decouple from the core and/or
- couple to the continuum ?



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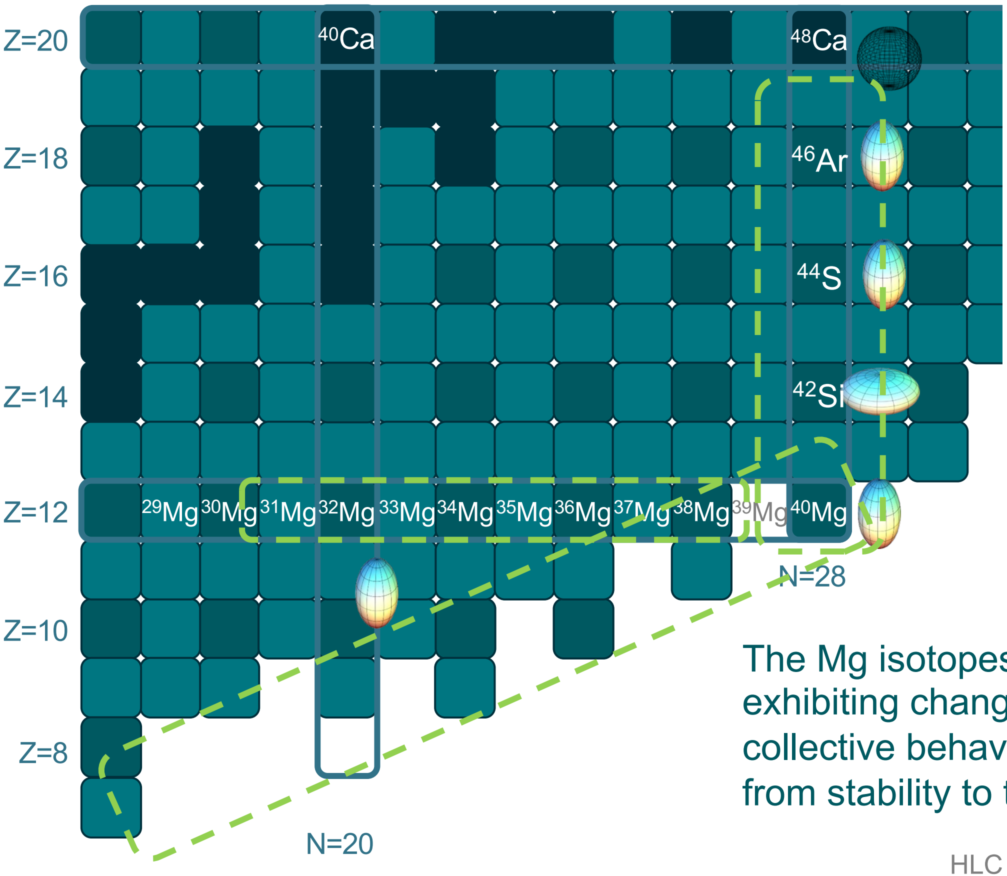
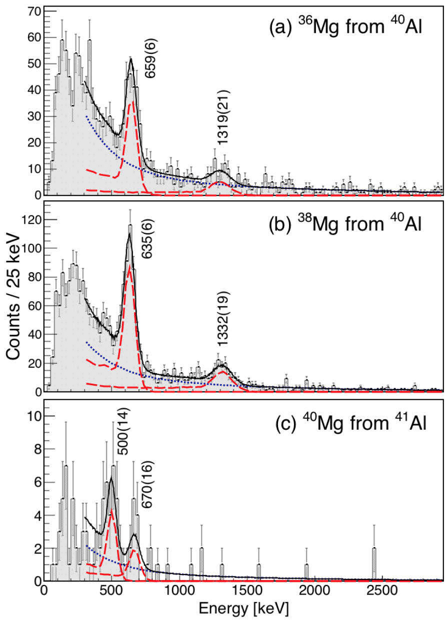


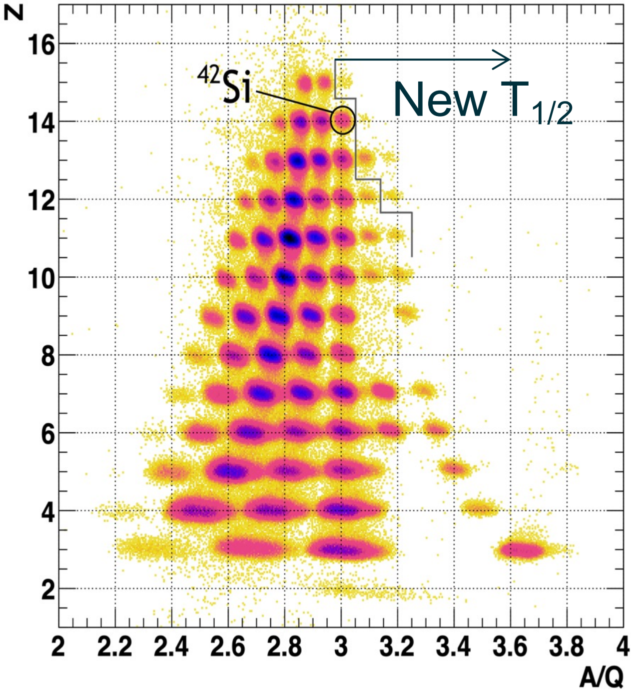

The Mg isotopes present a chain of nuclei exhibiting changing single particle structure and collective behavior, experimentally accessible from stability to the dripline.

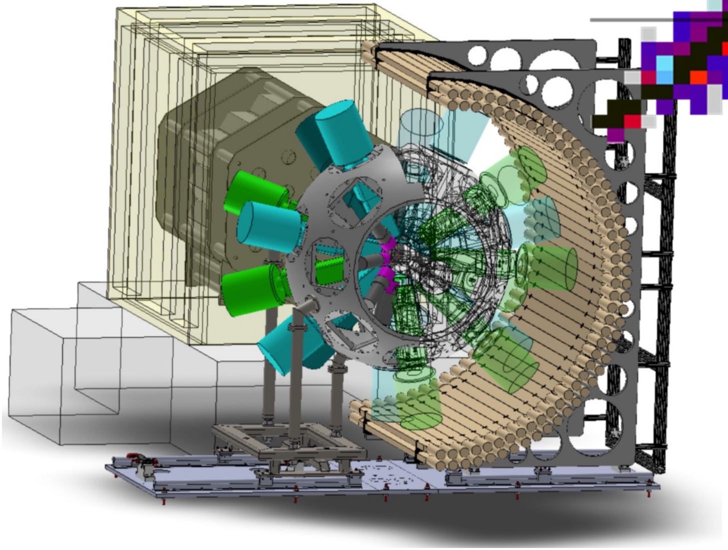
HLC *et al.*, Phys. Rev. Lett. **122**, 052501 (2019).

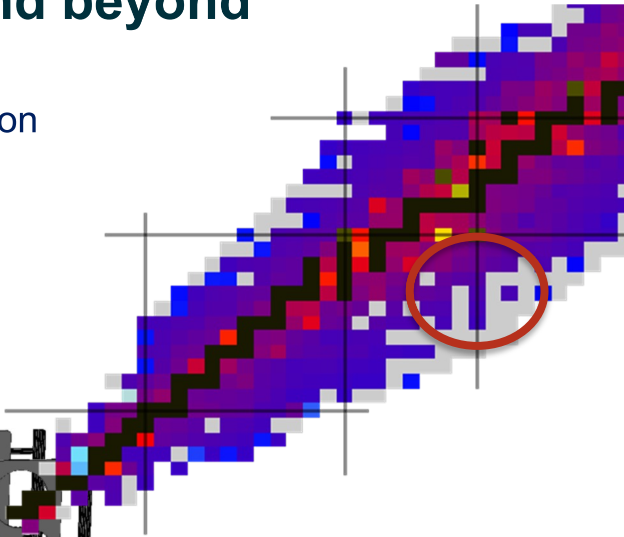
# Pushing Toward the Neutron Dripline – Z=12 and beyond

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

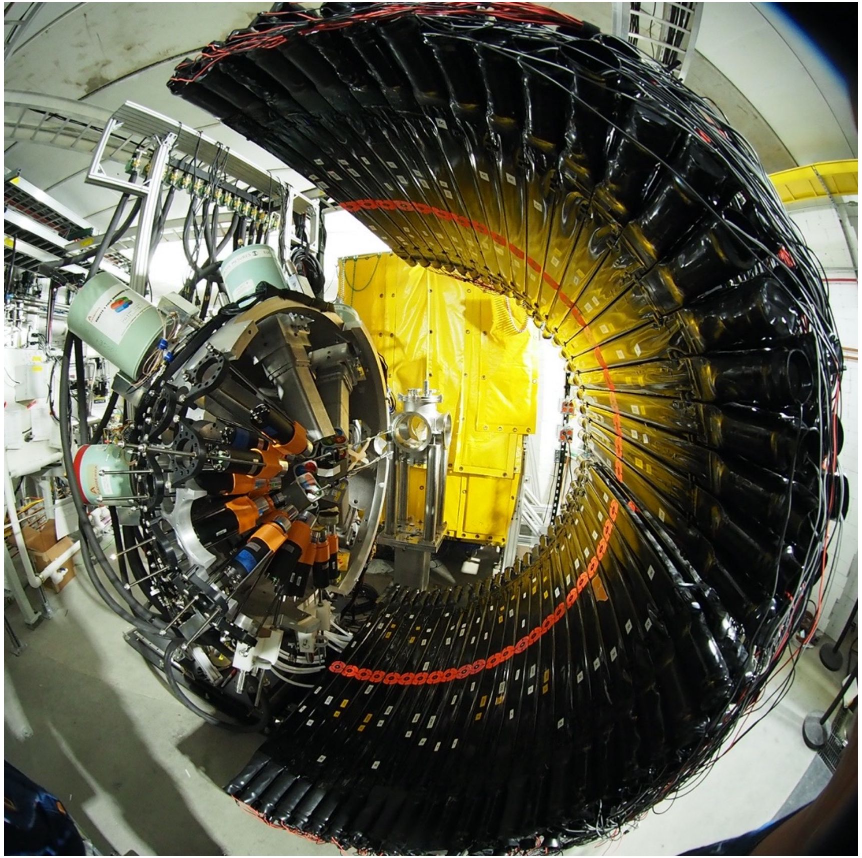
- FDSi enables total decay spectroscopy, with $\gamma$, particle and neutron spectroscopy
- Combination with MTAS or SuN further extends the physics





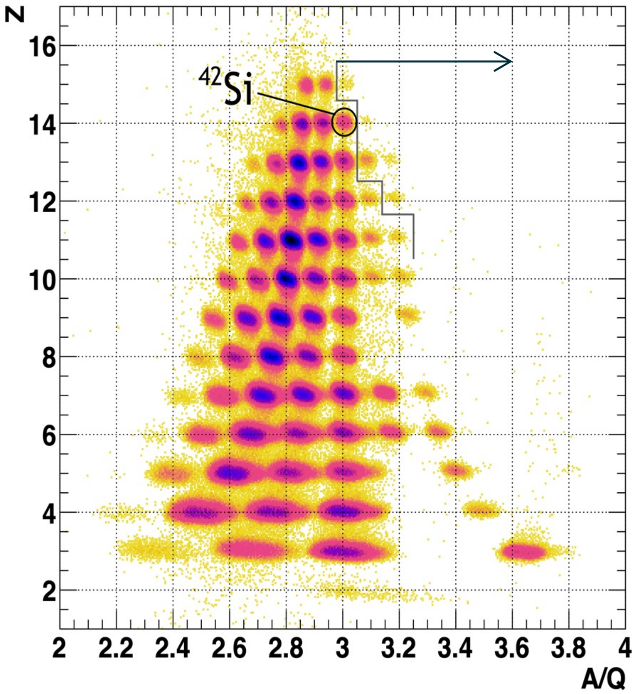
# FRIB Decay Station Initiator (FDSi)

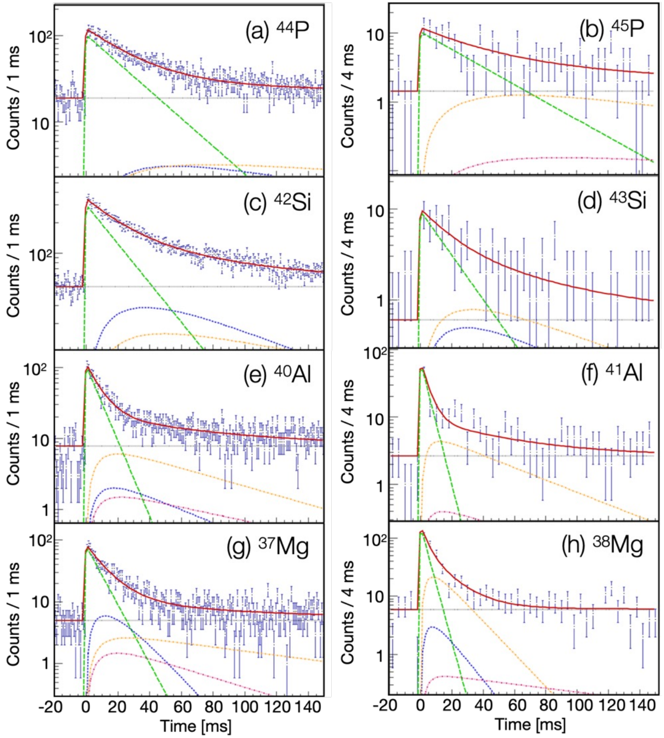


# First Results from FRIB

## E21062: Decay Near *N*=28 (Allmond, Crawford, Crider, Grzywacz, Tripathi)

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



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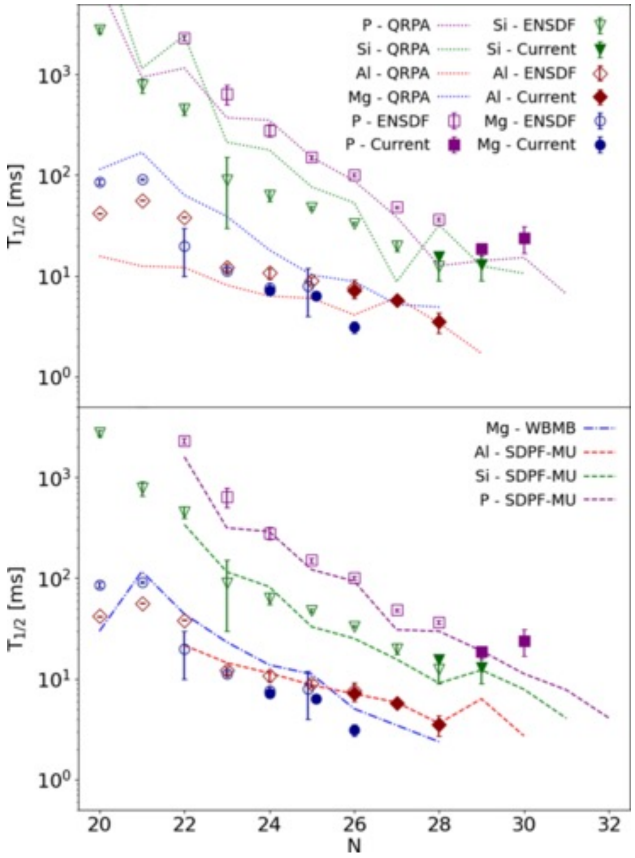



- Half-life systematics were extended the Mg, Al, Si and P chains
- Overall agreement with available shell model calculations is consistent with a well-developed region of deformation
- Clear evidence for erosion of Z=14 subshell closure
- Intriguing reduction in the half-life for $^{38}$Mg – still awaiting theoretical values


PHYSICAL REVIEW LETTERS **129**, 212501 (2022)

Editors' Suggestion    Featured in Physics

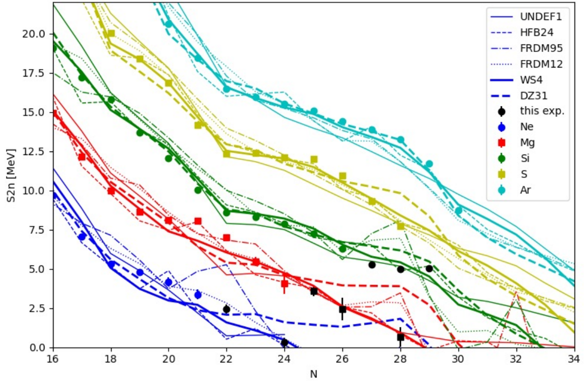

**Crossing $N = 28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB**

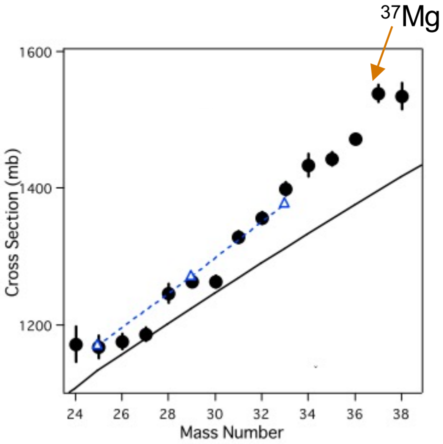

H. L. Crawford,[1,*] V. Tripathi,[2] J. M. Allmond,[3] B. P. Crider,[4] R. Grzywacz,[5] S. N. Liddick,[6,7] A. Andalib,[6,8] E. Argo,[6,8] C. Benetti,[2] S. Bhattacharya,[2] C. M. Campbell,[1] M. P. Carpenter,[9] J. Chan,[5] A. Chester,[6] J. Christie,[5] B. R. Clark,[4] I. Cox,[5] A. A. Doetsch,[6,8] J. Dopfer,[6,8] J. G. Duarte,[10] P. Fallon,[1] A. Frotscher,[1] T. Gaballah,[4] T. J. Gray,[3] J. T. Harke,[10] J. Heideman,[5] H. Heugen,[5] R. Jain,[6,8] T. T. King,[3] N. Kitamura,[5] K. Kolos,[10] F. G. Kondev,[9] A. Laminack,[3] B. Longfellow,[10] R. S. Lubna,[6] S. Luitel,[4] M. Madurga,[5] R. Mahajan,[6] M. J. Mogannam,[6,7] C. Morse,[11] S. Neupane,[5] A. Nowicki,[5] T. H. Ogunbeku,[4,6] W.-J. Ong,[10] C. Porzio,[1] C. J. Prokop,[12] B. C. Rasco,[3] E. K. Ronning,[6,7] E. Rubino,[6] T. J. Ruland,[13] K. P. Rykaczewski,[3] L. Schaedig,[6,8] D. Seweryniak,[9] K. Siegl,[5] M. Singh,[5] S. L. Tabor,[2] T. L. Tang,[2] T. Wheeler,[6,8] J. A. Winger,[4] and Z. Xu[5]

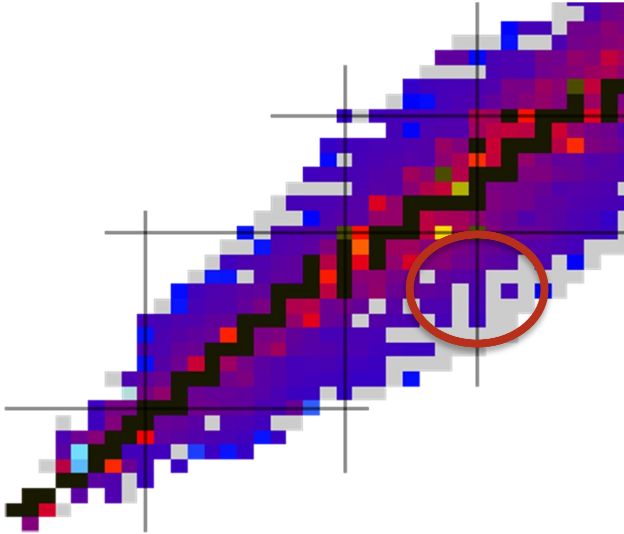
# Next Steps Along *Z*=12

## $^{40}$Mg reaction cross-section and mass measurement

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



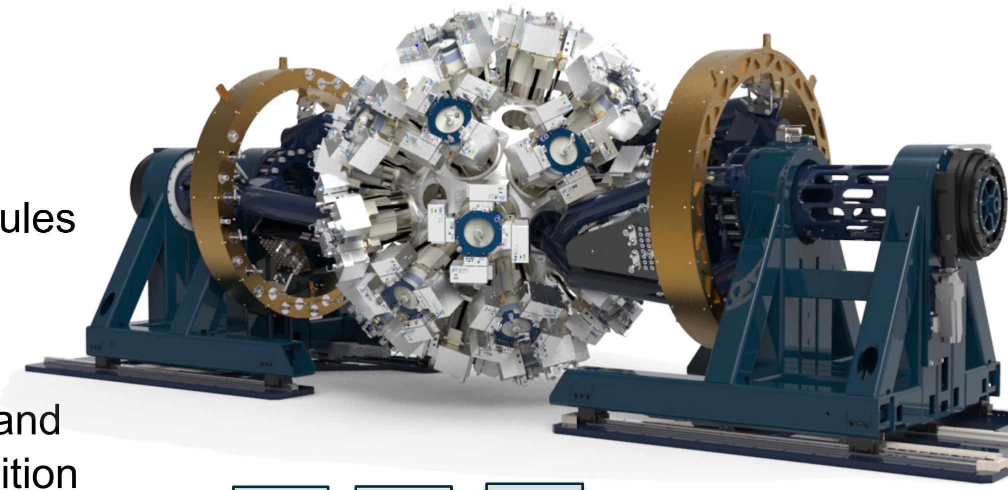



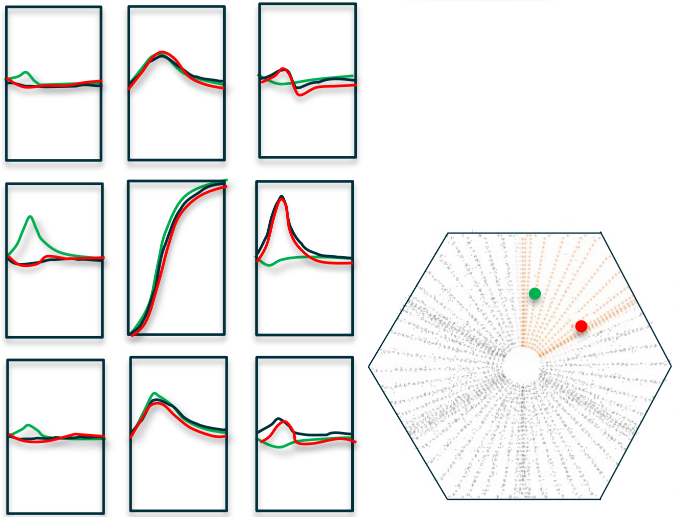
- A total reaction cross-section measurement will answer the question of whether there is a halo or not
- With a TOF mass measurement, the 2n separation energy can be established – also constrains $Q_\beta$
- Revisit the prompt spectroscopy

M. Takechi et al., Phys. Rev. C **90**, 061305(R) (2014).

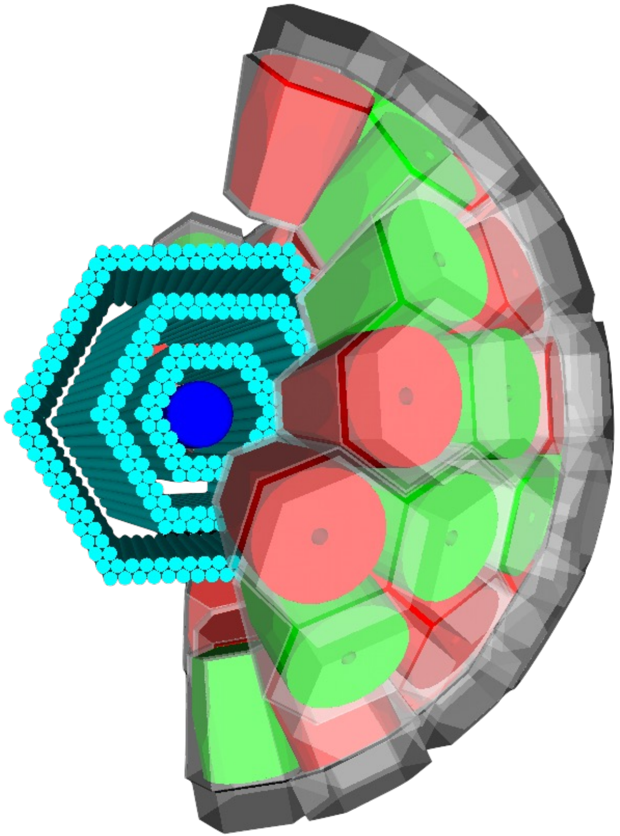
# GRETA

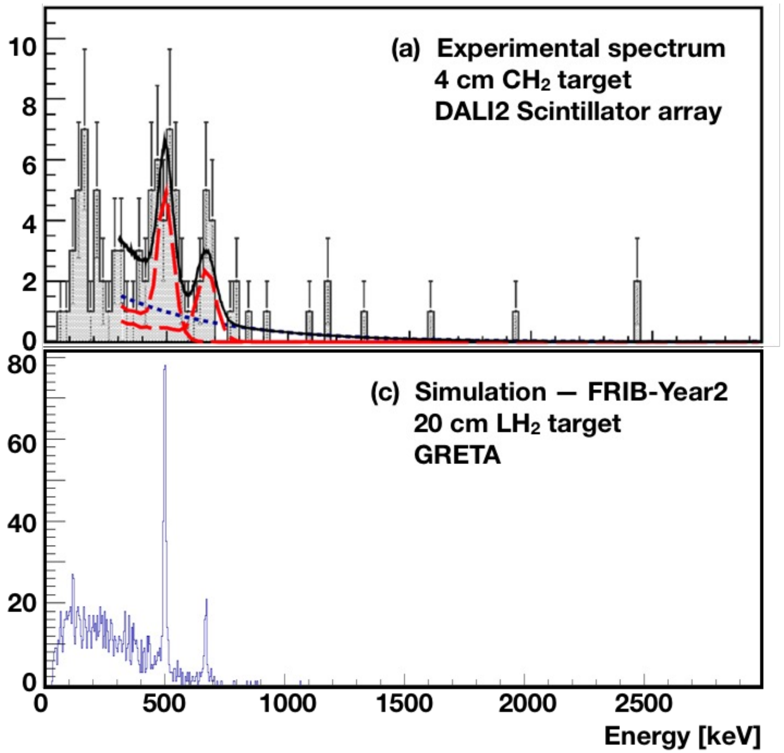
- GRETA will have 30 Quad Detector Modules to cover >80% of the full solid angle surrounding a target
- Its design provides the unprecedented combination of full solid angle coverage and high efficiency, excellent energy and position resolution, and good background rejection (peak-to-total) needed to 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
- On track for delivery to FRIB in the first half of 2025





# FRIB + GRETA + Extended Proton Tracking Target to Access $^{40}Mg$





# Summary

- First experiments at FRIB have already pushed toward the dripline in the region of $^{40}$Mg

- 5 new β-decay half-lives extend the systematics in the key region of the nuclear chart around *N*=28 and the neutron dripline

- Upcoming approved experiments will directly probe $^{40}$Mg to provide insight into any potential halo structure

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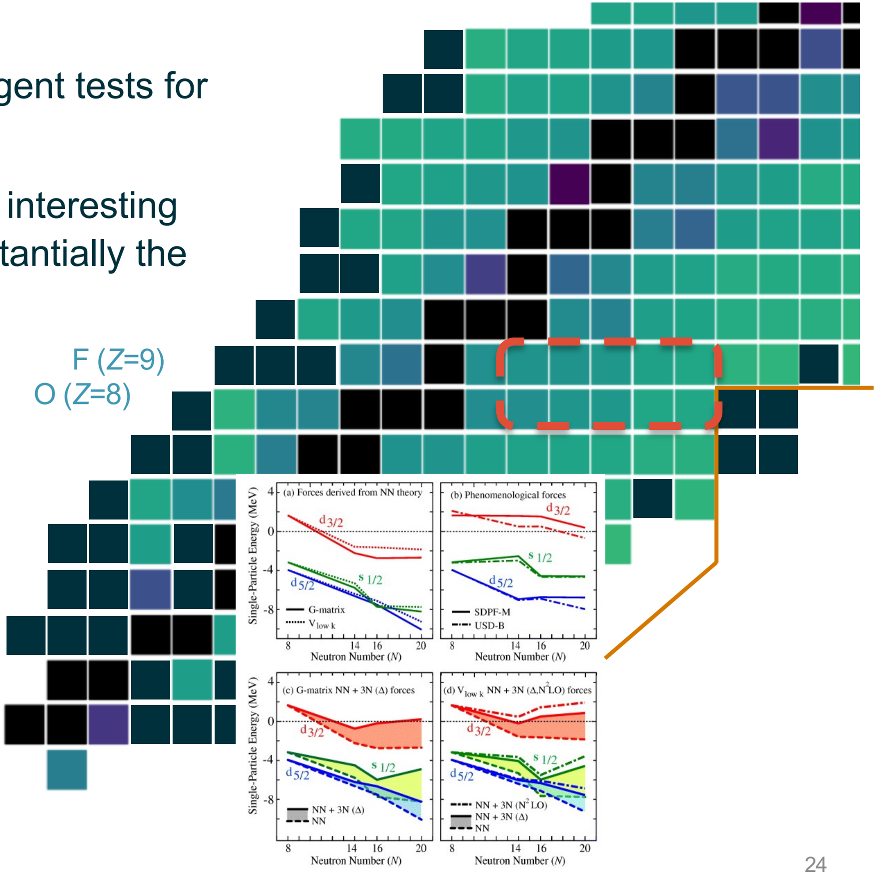
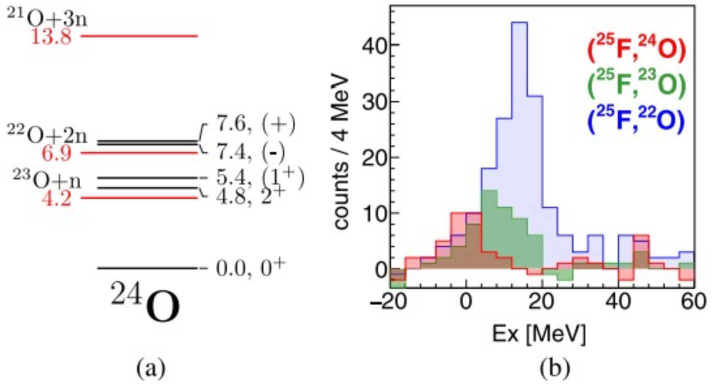
# Motivation

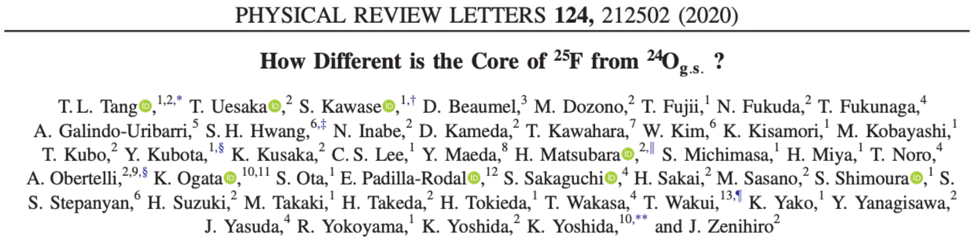
- Light nuclei remain key to providing the most stringent tests for state-of-the art theory
- The neutron-rich F and O isotopes are particularly interesting with the addition of a single proton modifying substantially the location of the dripline
- An interesting question – is the O core of the F isotope(s) the same as the corresponding “bare” O nucleus?
- Proton knockout from F into O allows a direct measure of the wavefunction overlap between the F ground state and the ground and excited states in O




Otsuka *et al.*, Phys. Rev. Lett. **105**, 032501 (2010).

# $^{25}$F(p,2p) Performed at RIBF



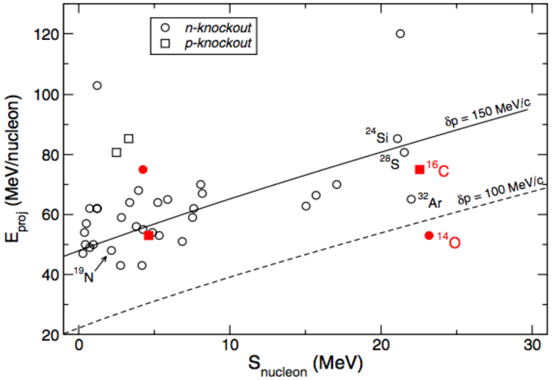
PHYSICAL REVIEW LETTERS **124**, 212502 (2020)

**How Different is the Core of $^{25}$F from $^{24}$O$_{g.s.}$ ?**

T. L. Tang,[1,2,*] T. Uesaka,[2] S. Kawase,[1,†] D. Beaumel,[3] M. Dozono,[2] T. Fujii,[1] N. Fukuda,[2] T. Fukunaga,[4] A. Galindo-Uribarri,[5] S. H. Hwang,[6,‡] N. Inabe,[2] D. Kameda,[2] T. Kawahara,[7] W. Kim,[6] K. Kisamori,[1] M. Kobayashi,[1] T. Kubo,[2] Y. Kubota,[1,§] K. Kusaka,[2] C. S. Lee,[1] Y. Maeda,[8] H. Matsubara,[2,‖] S. Michimasa,[1] H. Miya,[1] T. Noro,[4] A. Obertelli,[2,9,§] K. Ogata,[10,11] S. Ota,[1] E. Padilla-Rodal,[12] S. Sakaguchi,[4] H. Sakai,[2] M. Sasano,[2] S. Shimoura,[1] S. Stepanyan,[6] H. Suzuki,[2] M. Takaki,[1] H. Takeda,[2] H. Tokieda,[1] T. Wakasa,[4] T. Wakui,[13,¶] K. Yako,[1] Y. Yanagisawa,[2] J. Yasuda,[4] R. Yokoyama,[1] K. Yoshida,[2] K. Yoshida,[10,**] and J. Zenihiro[2]

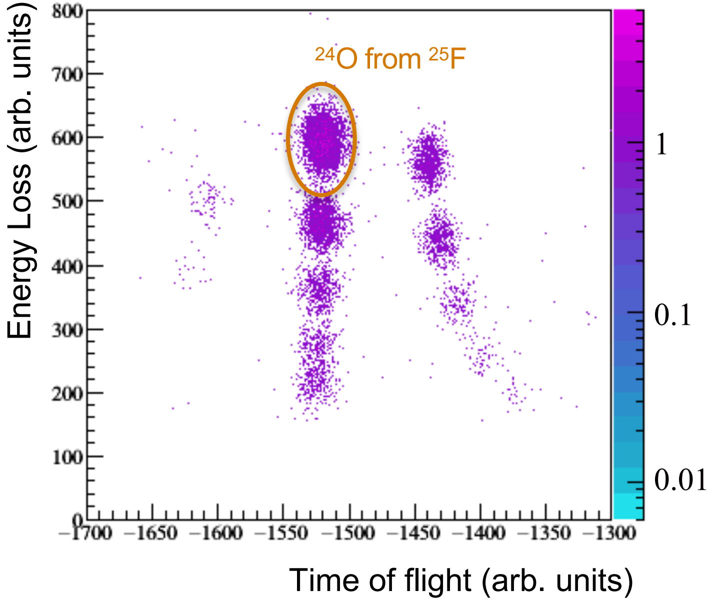
- The structure of $^{25}$F was investigated at RIBF, RIKEN Nishina Center, using the SHARAQ spectrometer, using the (p,2p) quasifree scattering reaction at 270 MeV/nucleon
- Spectroscopic factors were quoted as: 0.36(13) for ($^{25}$F, $^{24}$O), while shell model predicts a value close to 1.

# Experiment E16022

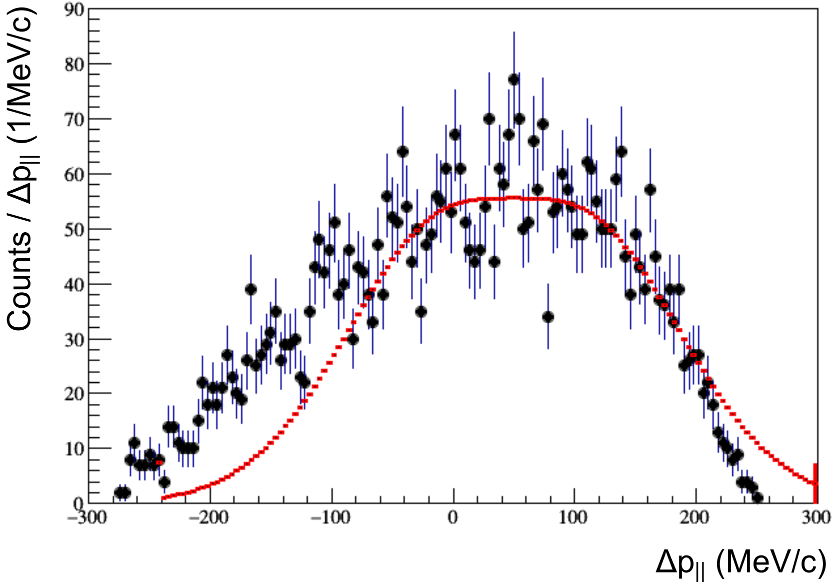



- Proton knockout from $^{21-25}$F into $^{20-24}$O respectively was performed at the NSCL Coupled Cyclotron Facility
- Primary beam of $^{48}$Ca was used to produce F secondary beams; knockout was performed on a secondary Be target at the S800 target position
- S800 spectrometer allowed detection of the O reaction residues, in coincidence with $\gamma$-detection in 10 Quad modules of GRETINA surrounding the target position
- Key for light nuclei -- knockout reactions were performed well above the threshold energy for valid application eikonal reaction theory to describe the process

# Results – The Case of $^{25}F(-1p)^{24}O$



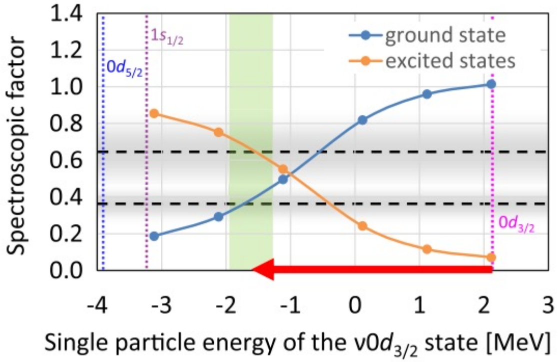

- With no bound excited states in $^{24}O$, the observed inclusive cross-section for this knockout reaction is the ground-state to ground-state transition




- Parallel momentum distribution is consistent with removal of d-wave (ℓ=2) proton; inclusive direct KO cross-section of 3.63(5)$_{stat}$ mb, giving a spectroscopic factor of **$\sigma_{exp}/\sigma_{th}$ = 0.23(1).**

# Is the $^{24}$O Core in $^{25}$F *really* $^{24}$O?

- No – all available experimental evidence suggests the $^{25}$F ground-state includes significant contributions from excited $^{24}$O wavefunction components
- In a shell-model description, one can reproduce the experimental result(s) by modifying the SPE of the $d_{3/2}$ orbital, reducing it by 3-4 MeV – a change potentially attributed to the pn interaction




- Alternatively, the Nilsson + particle-rotor model (PRM) can naturally reproduce the experimental data
  - $^{25}$F is well-described as the coupling of a proton $d_{5/2}$ Nilsson multiplet to an effective core of moderate ($\varepsilon_2 \sim 0.15$) deformation, giving rise to a decoupled band structure
  - Observed $^{25}$F(-1p)$^{24}$O cross-section results from fragmentation of strength due to deformation and reduced core overlap

Tang *et al*., Phys. Rev. Lett. **124**, 212502 (2020).
Macchiavelli *et al*., Phys. Rev. C **102**, 041301(R) (2020).

# Acknowledgements

PHYSICAL REVIEW LETTERS **129**, 212501 (2022)

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Letter

**Core of $^{25}$F studied by the $^{25}$F$(-p)$ proton-removal reaction**

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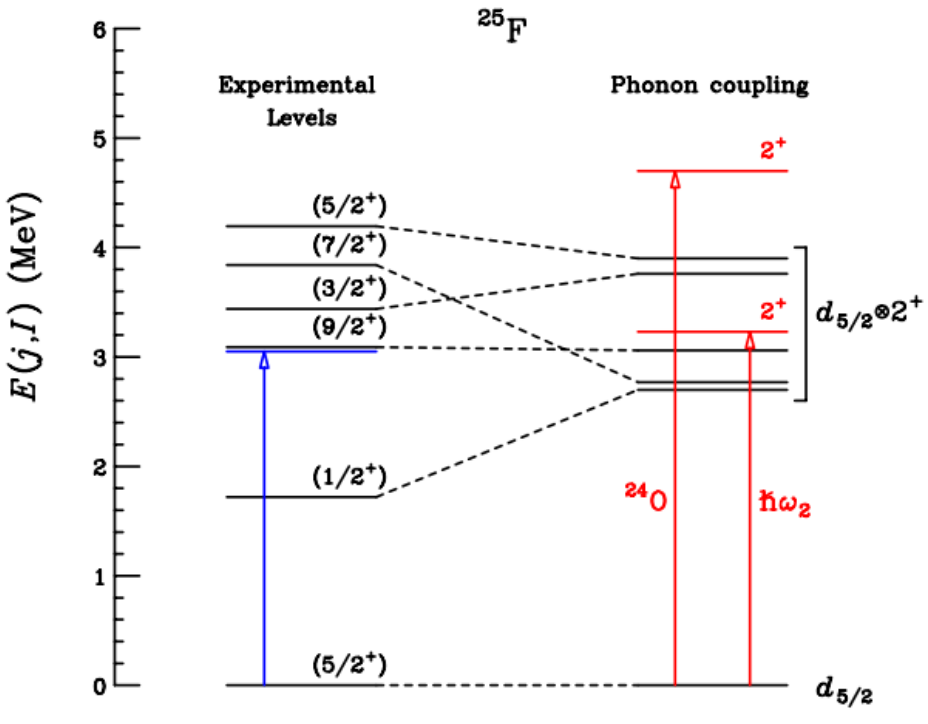
# Thank you!

# $^{25}$F in a Particle-Vibration Coupling Description




- Alternatively, given the small deformation of the effective $^{24}$O core in the PRM calculation, a description of $^{25}$F as a $d_{5/2}$ proton coupled to a quadrupole phonon of frequency $\hbar\omega_2$ (in the effective core)

| Parameter | $^{24}$O | $^{24}$O* |
|---|---|---|
| $\hbar\omega_2[MeV]$ | 4.7 | 3.2 |
| $C_2[MeV]$ | 204 | 140 |
| $B(E2)\ [e^2b^2]$ | 0.0012 | 0.0055 |

- In this description, the effective $^{24}$O core is 'softened' and made more collective in $^{25}$F
- The coupling of the phonon to the single-particle state and the renormalization accounts well for the observed cross-section values

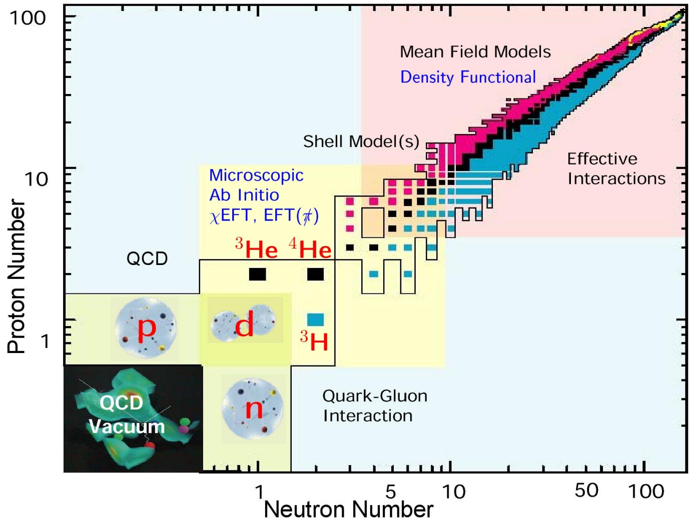
Macchiavelli *et al.*, to be published.

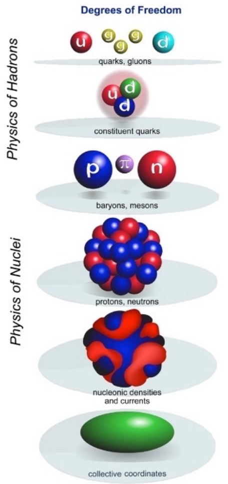
# The Key Role of Theory

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."

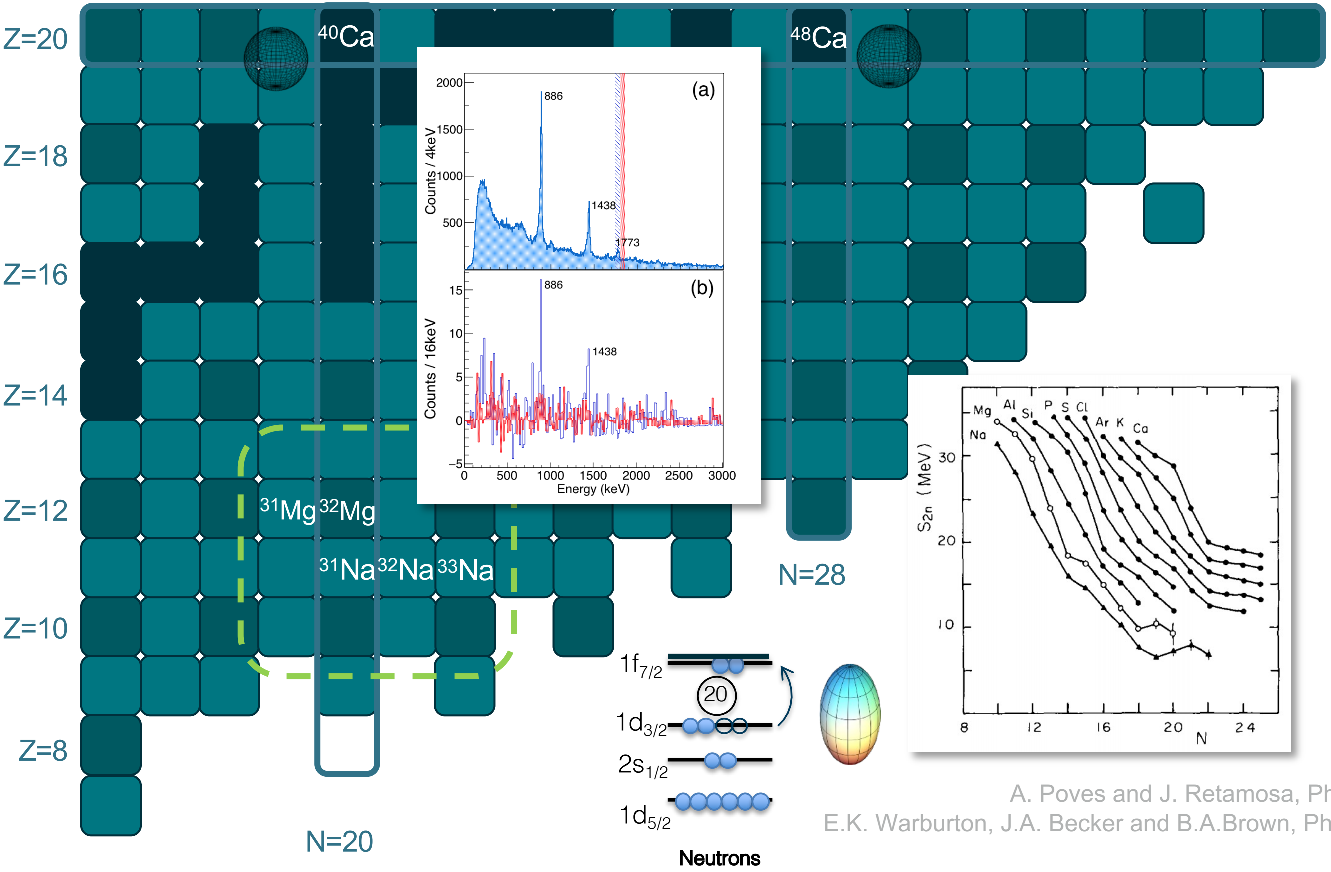
"A strong interplay between theoretical research, experiment, and advanced computing is essential for realizing the full potential of … discoveries."




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.

# N=20 Island of Inversion

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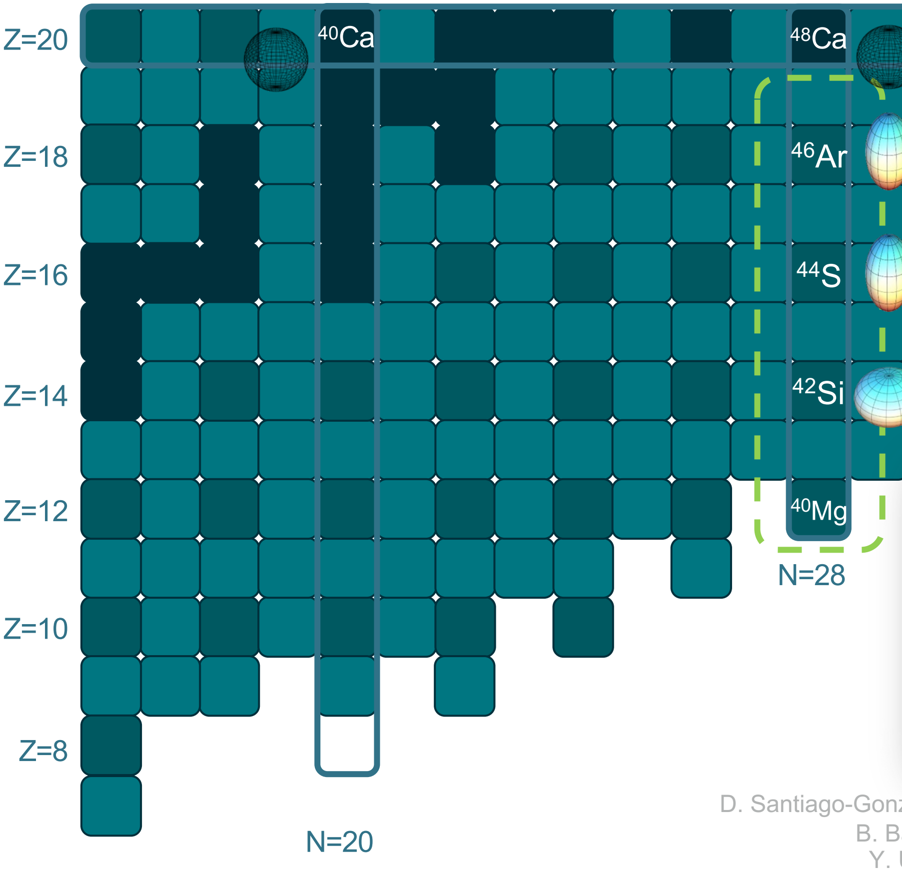
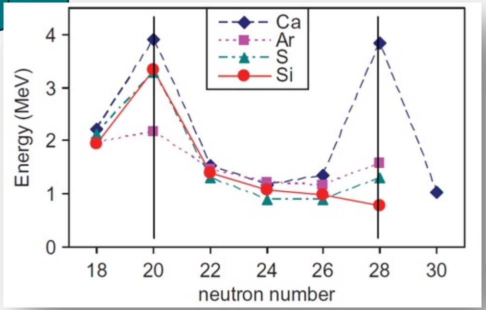
# *N*=28 Evolution of Nuclear Shapes

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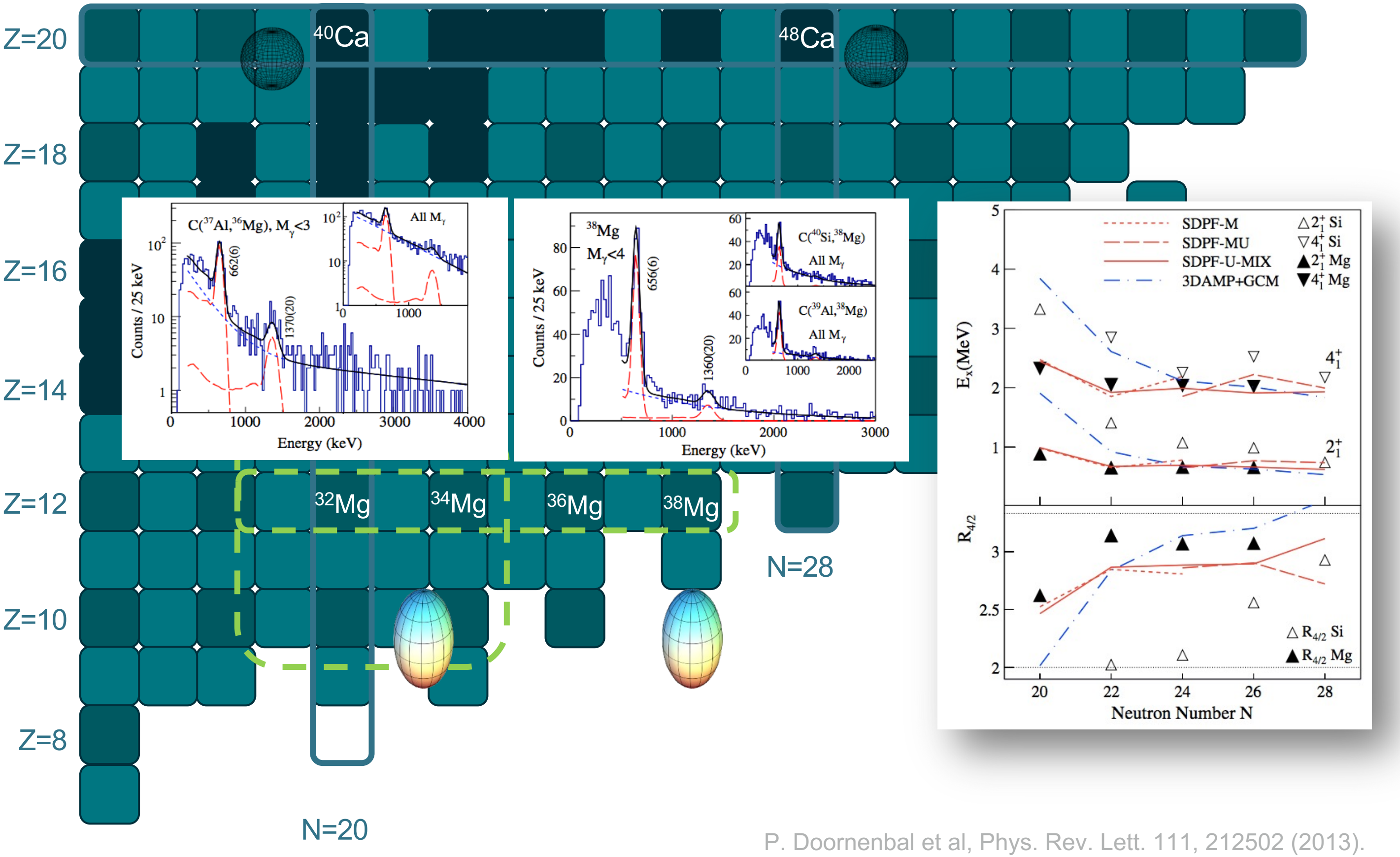
# Z=12 ‘Peninsula’ of Inversion

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