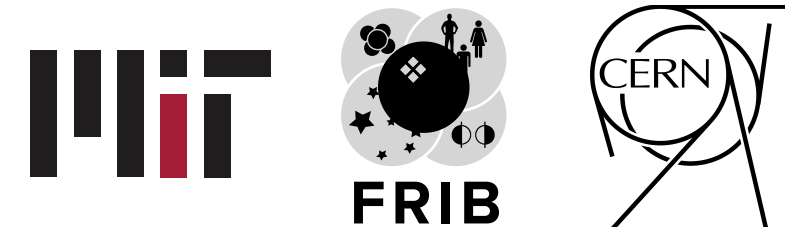


Precision Nuclear Experiments using Ion Traps and Lasers at FRIB

Dr. Jonas Karthein – Massachusetts Institute of Technology

Winter Workshop on Nuclear Dynamics - Feb. 6, 2023

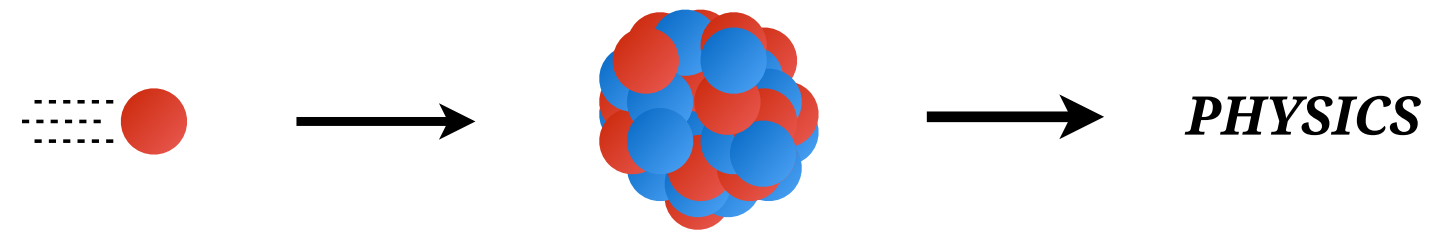


Content:

1. Locate (Low-Energy) Nuclear Physics
2. Precision Tools and Applications
3. Future Fundamental Symmetry Measurements

"Nuclear Dynamics" in Low-Energy Nuclear Physics

Most people here:



Projectile

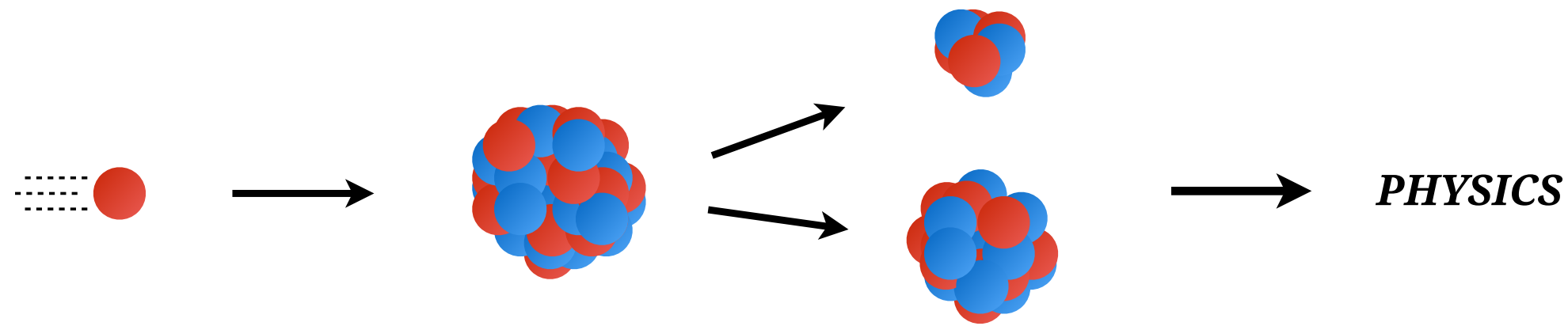
Target

$$v_P \approx c_0$$

$$v_T \approx c_0 \text{ OR } v_T = 0$$

"Nuclear Dynamics" in Low-Energy Nuclear Physics

Low-energy nuclear physics:



Projectile = p

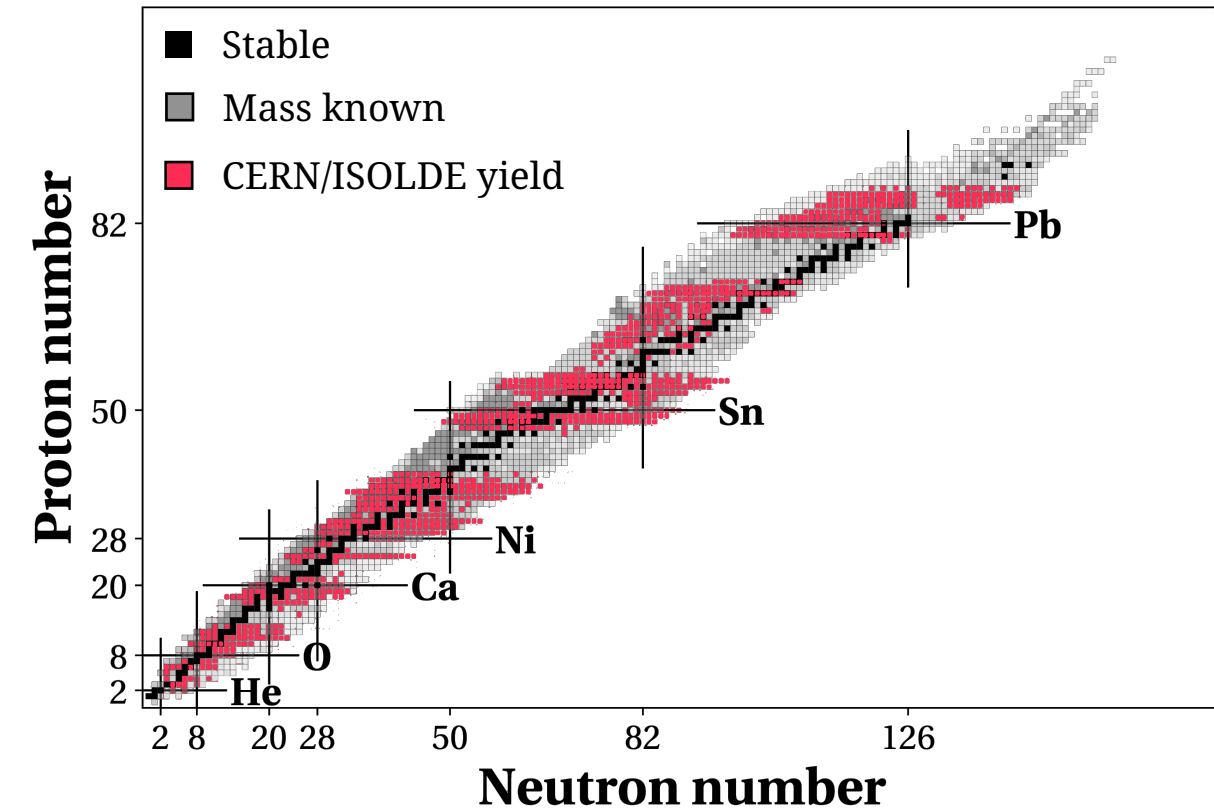
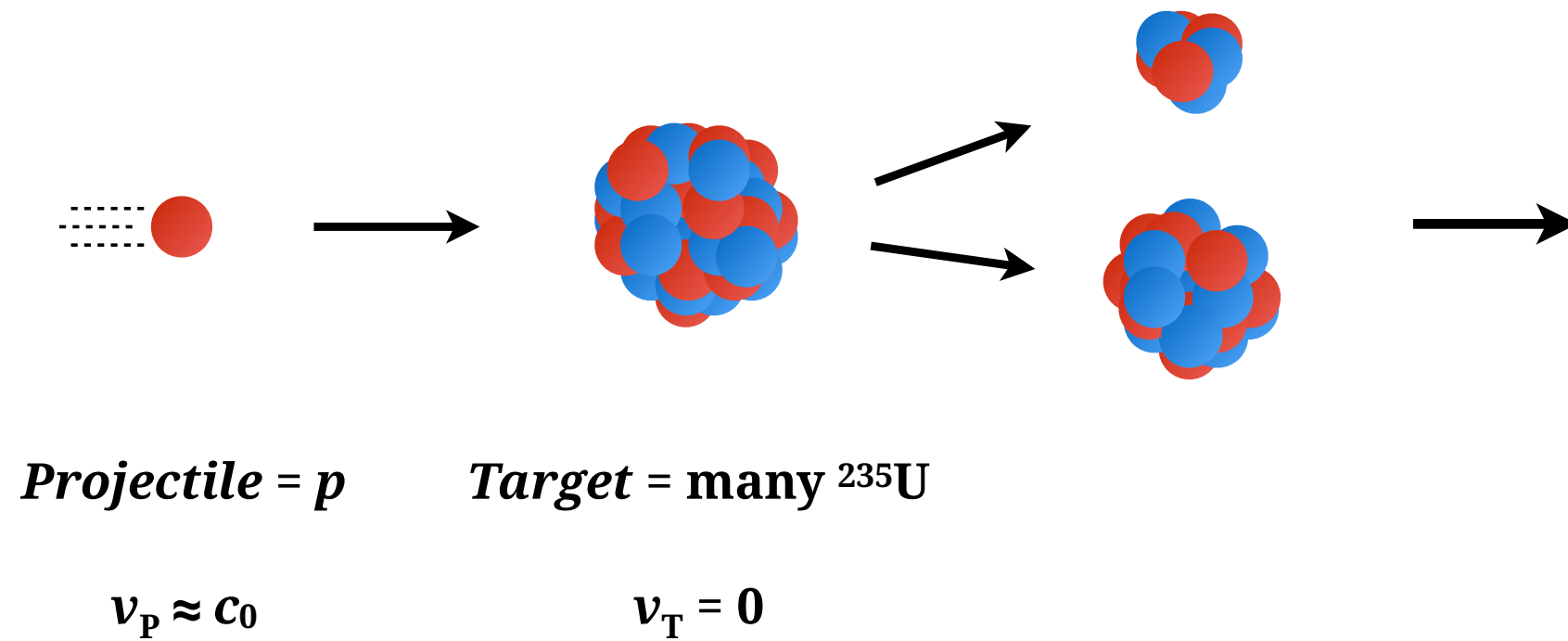
Target = many ^{235}U

$$v_p \approx c_0$$

$$v_T = 0$$

"Nuclear Dynamics" in Low-Energy Nuclear Physics

Low-energy nuclear physics:



Low-Energy Nuclear Physics: Binding Energies

Low-energy nuclear physics:



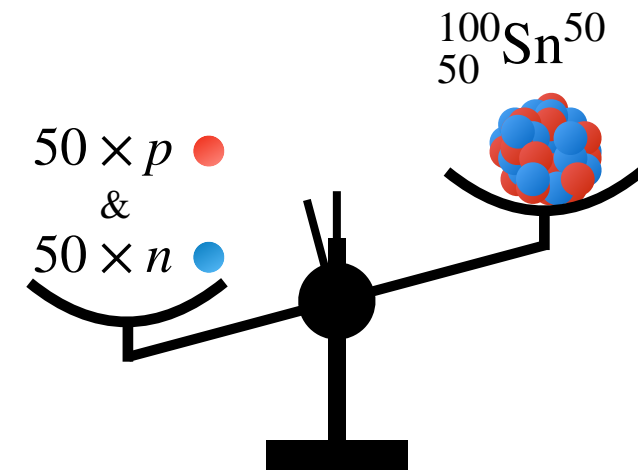
Projectile = p

Target = many ^{235}U

$v_P \approx c_0$

$v_T = 0$

Ion Trap



$$M_{\text{nucleus}} = N \cdot m_n + Z \cdot m_p - E_B/c^2$$

→ direct access to the ***nuclear binding energy***, thus to all underlying interactions!

Low-Energy Nuclear Physics: Binding Energies

Low-energy nuclear physics:



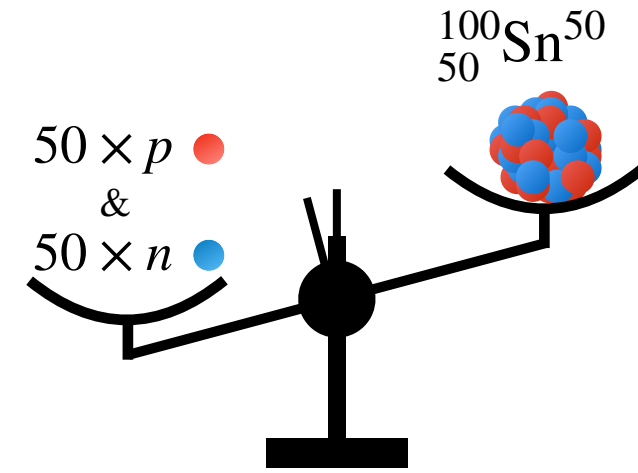
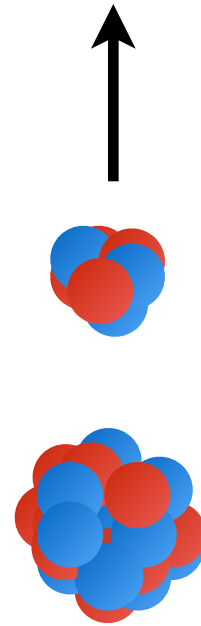
Projectile = p

Target = many ^{235}U

$v_p \approx c_0$

$v_T = 0$

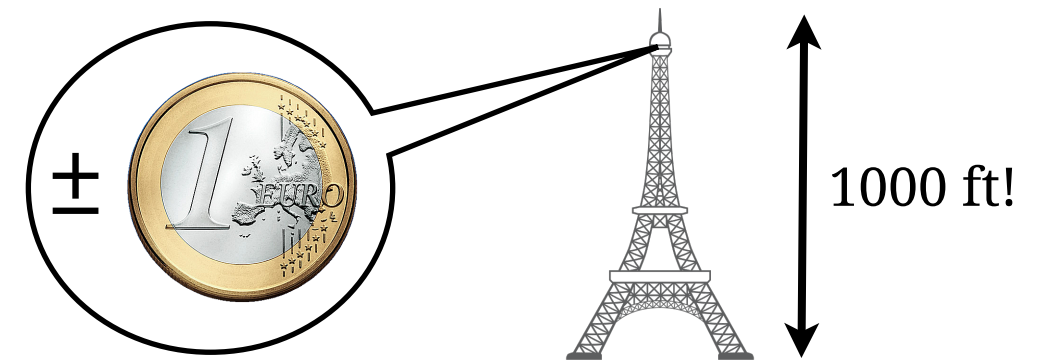
Ion Trap



$$M_{\text{nucleus}} = N \cdot m_n + Z \cdot m_p$$

$-E_B/c^2$

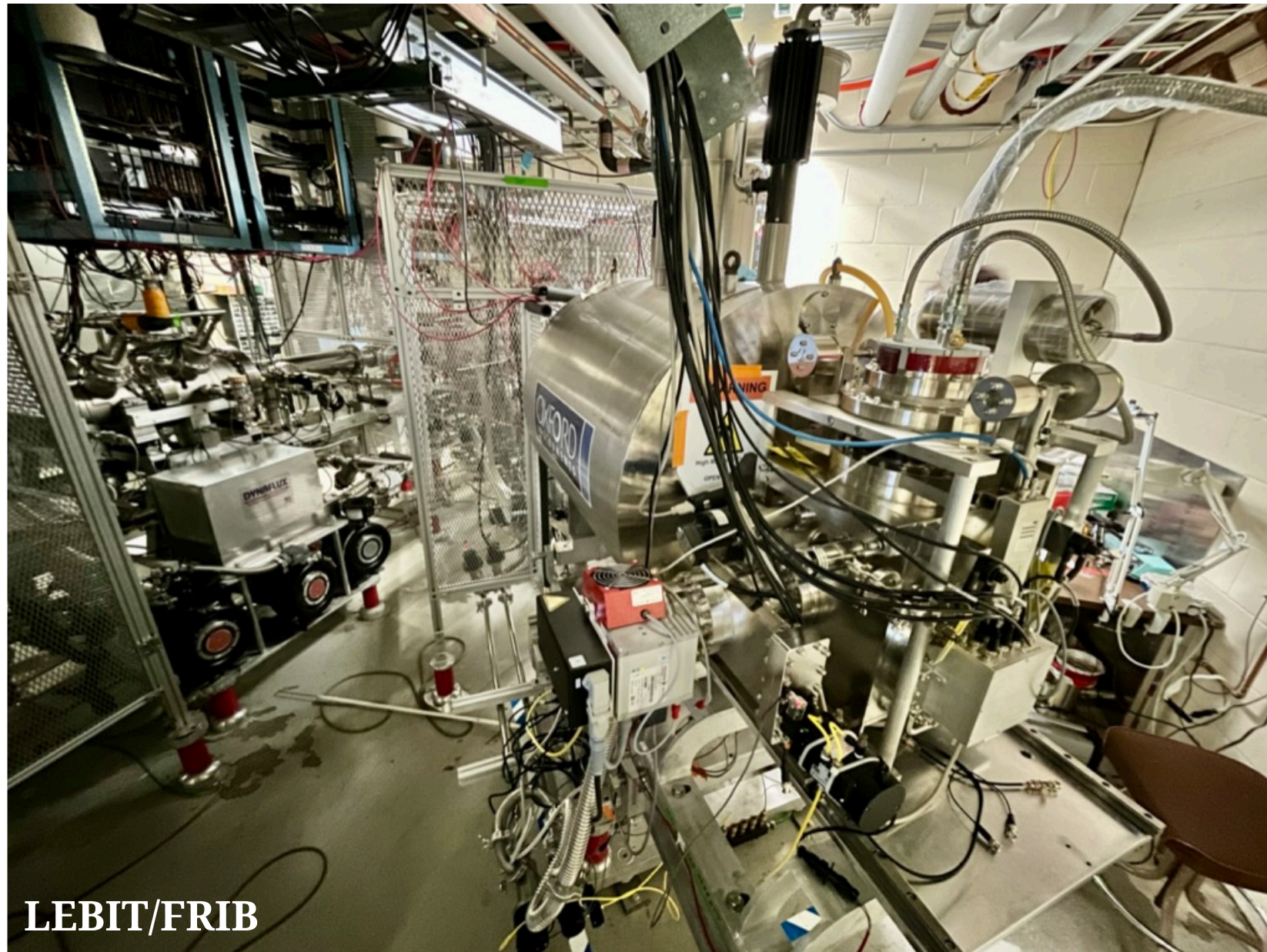
$\delta M/M \sim 10^{-6} - 10^{-9}$



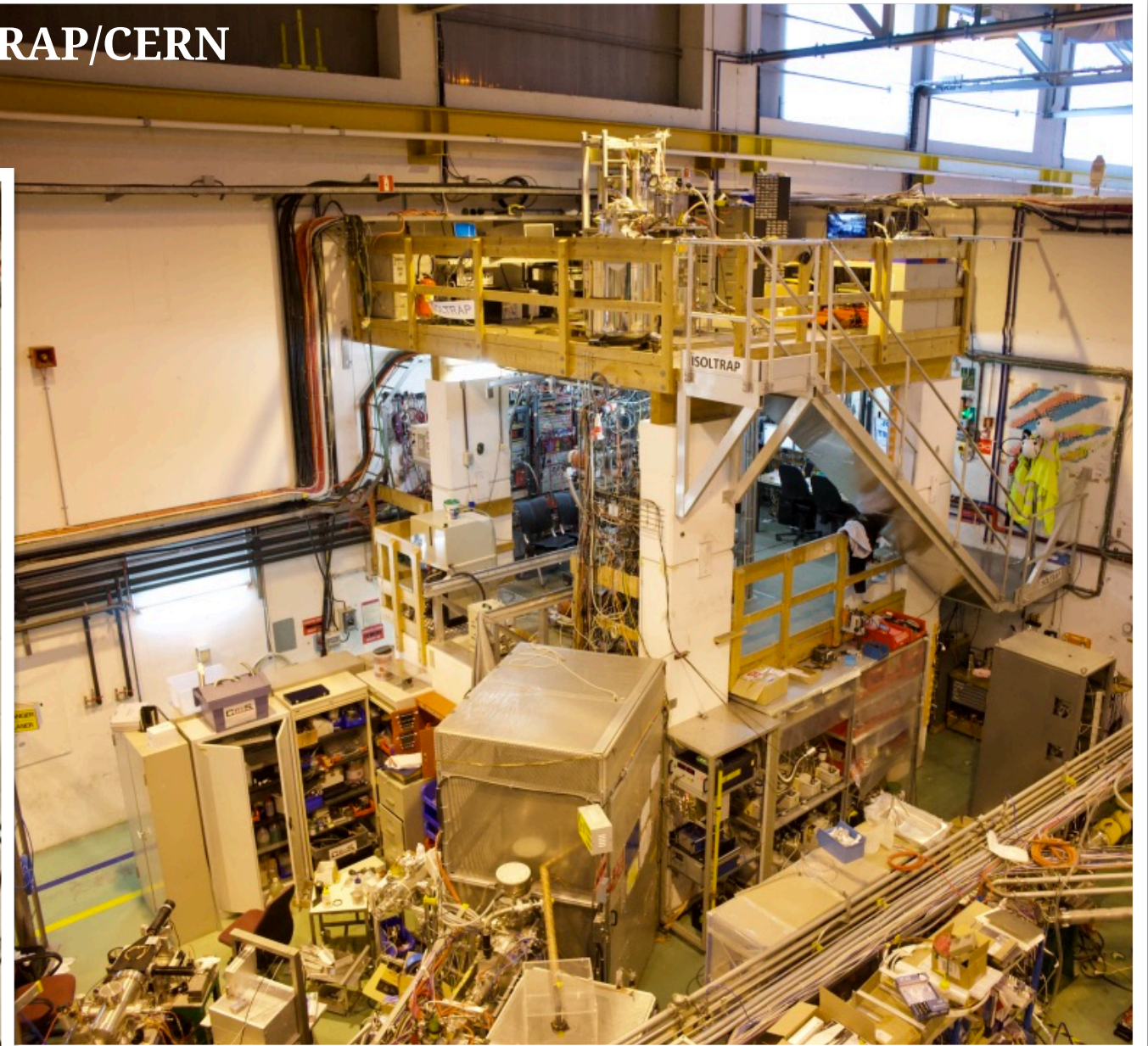
Low-Energy Nuclear Physics: Binding Energies

Ion Trap

ISOLTRAP/CERN



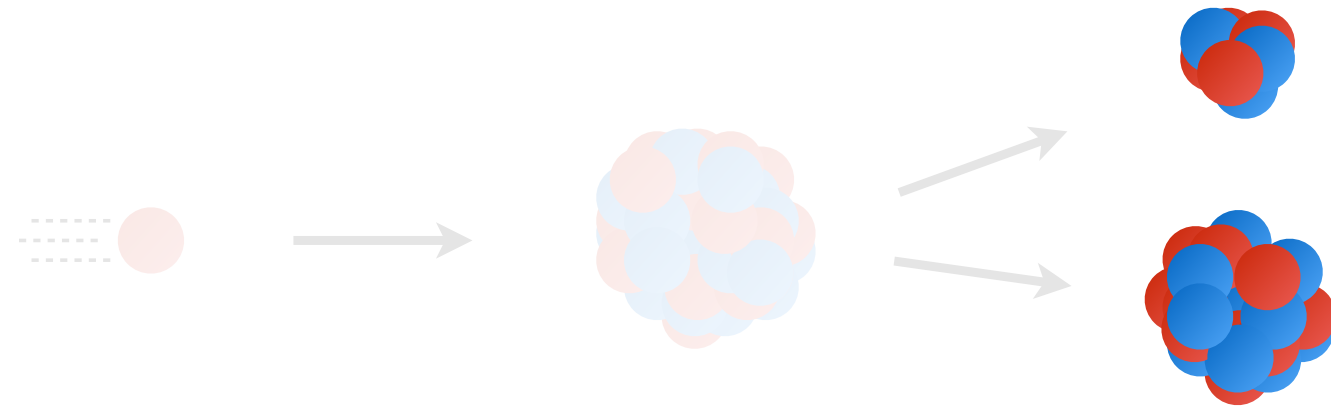
LEBIT/FRIB



Low-Energy Nuclear Physics: Laser Spectroscopy

Laser Spectroscopy

Low-energy nuclear physics:

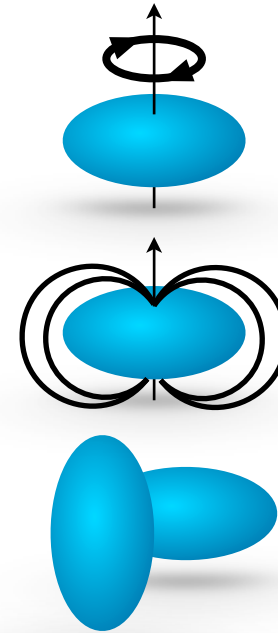
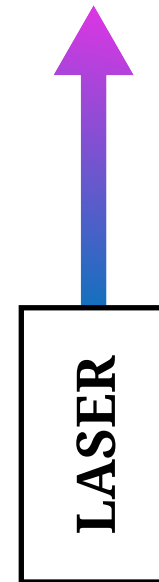


Projectile = p

Target = many ^{235}U

$$v_p \approx c_0$$

$$v_T = 0$$



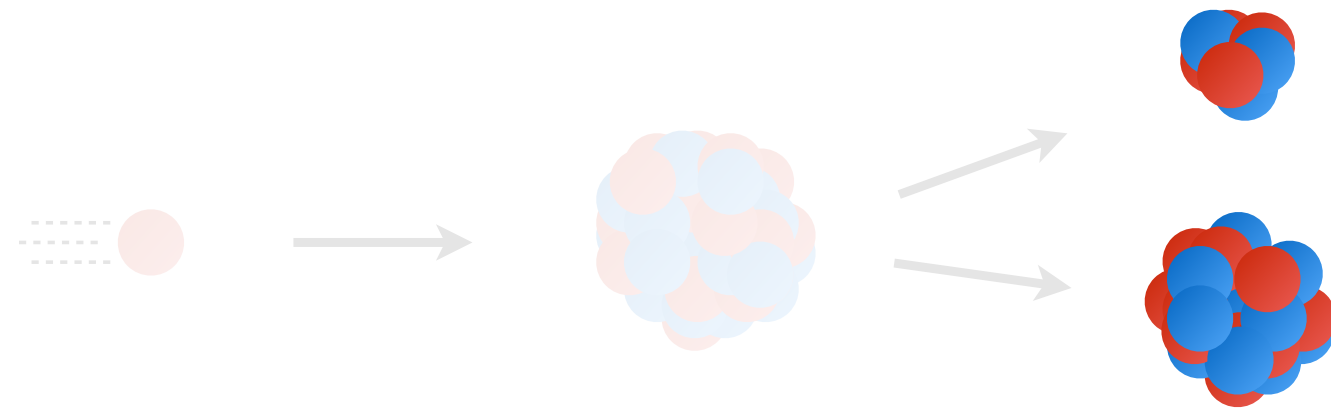
→ **Nuclear spin**

Magnetic moment
→ **Nuclear magnetic field**

Quadrupole moment
→ **Nuclear deformation**

Low-Energy Nuclear Physics: Laser Spectroscopy

Low-energy nuclear physics:

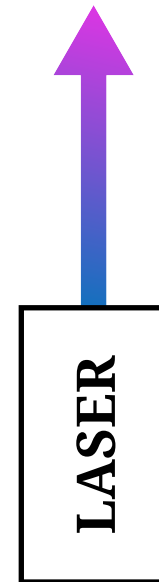


Projectile = p

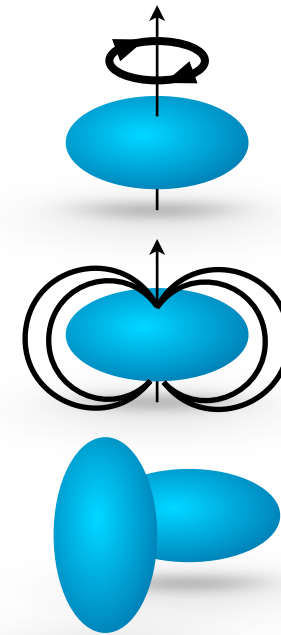
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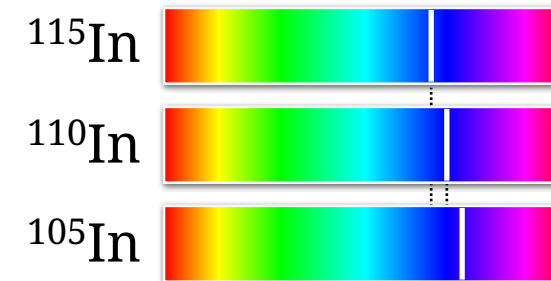
Laser Spectroscopy



→ **Nuclear spin**

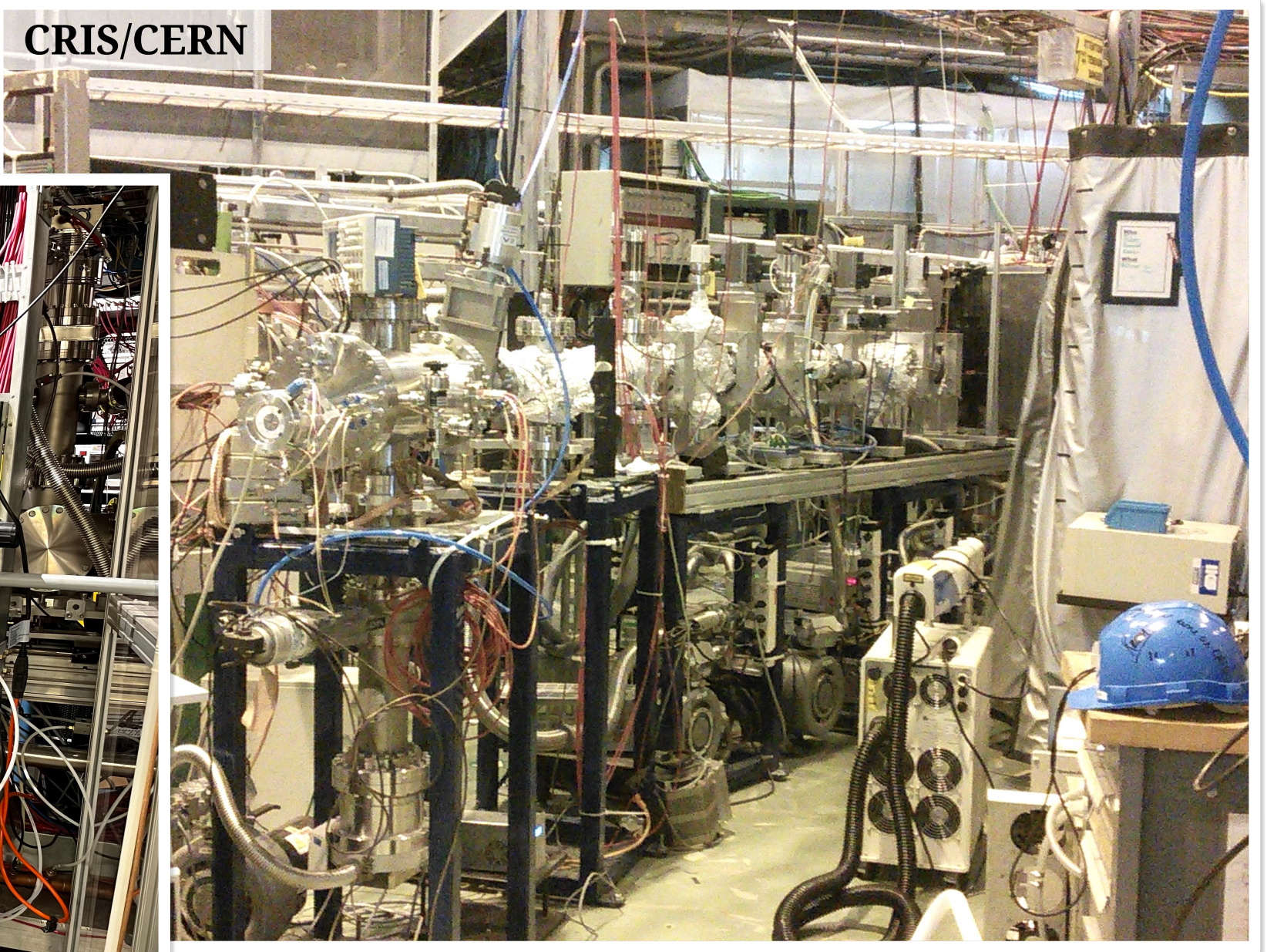
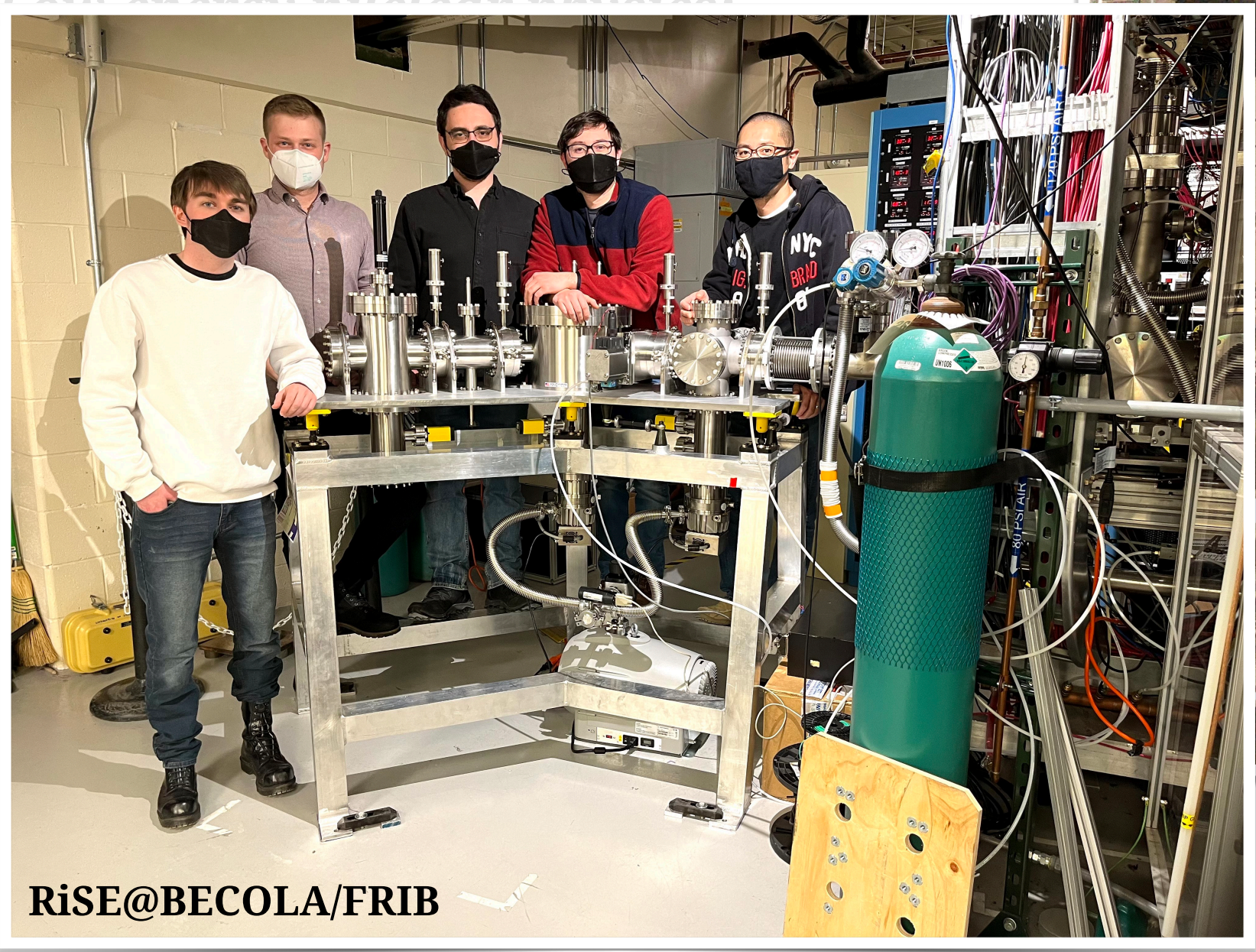
Magnetic moment
→ **Nuclear magnetic field**

Quadrupole moment
→ **Nuclear deformation**



Isotope shift
→ **Nuclear size**

Low-Energy Nuclear Physics: Laser Spectroscopy



Fundamental Properties Across the "Quantum Ladder"

Journey to explore the position of fundamental nuclear physics (mass, size, symmetries...)



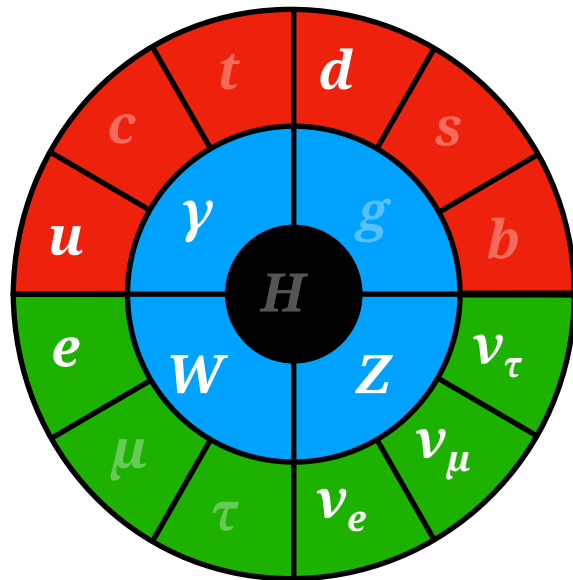
Fundamental Properties Across the "Quantum Ladder"

Journey to explore the position of fundamental nuclear physics (mass, size, symmetries...)



Fundamental Properties Across the "Quantum Ladder"

Standard Model:



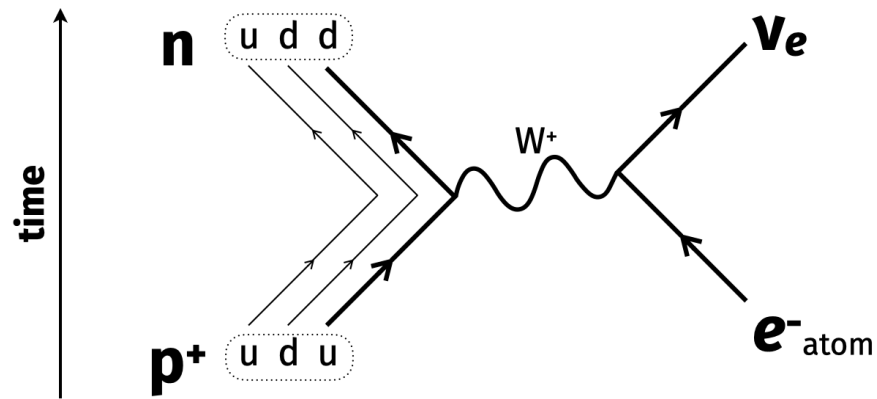
$\sim 10^{-15}$ m \rightarrow fundamental physics

*What are the properties of SM particles/interactions?
Dark matter/energy? (Anti)matter asymmetry?*

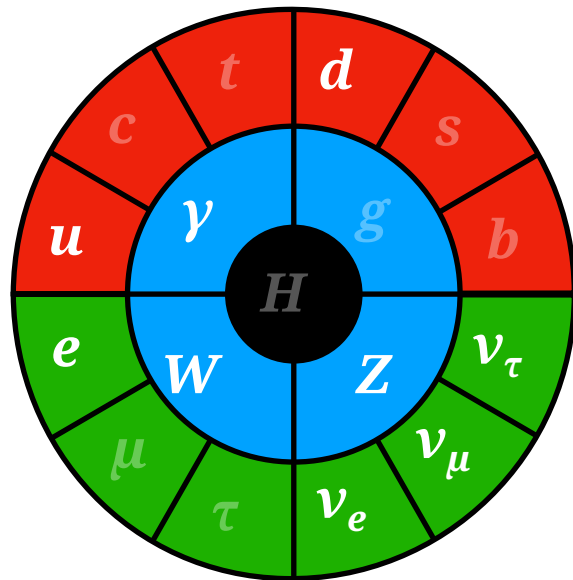


Fundamental Properties Across the "Quantum Ladder"

Neutrinos, u, d, W:



Standard Model:



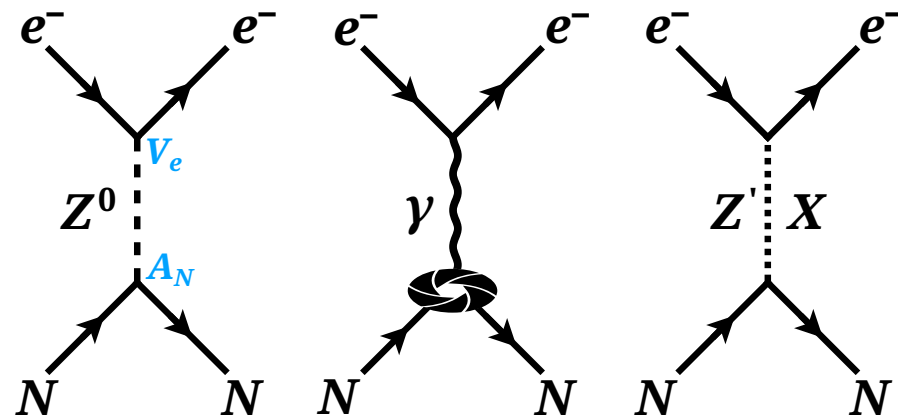
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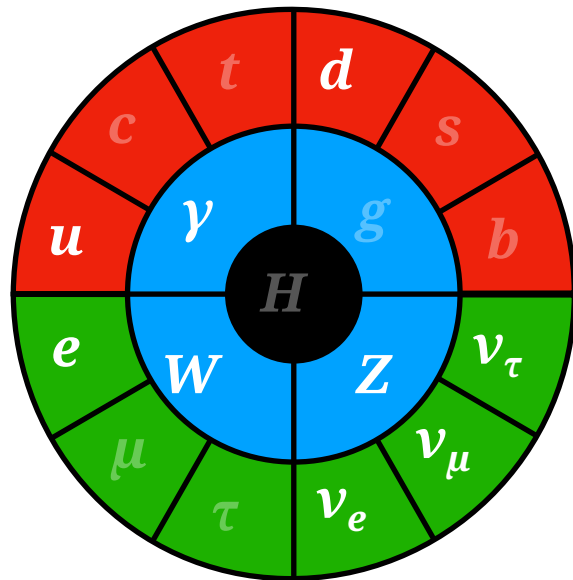


Fundamental Properties Across the "Quantum Ladder"

γ , Z, symmetry violation:



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Fundamental Properties Across the "Quantum Ladder"

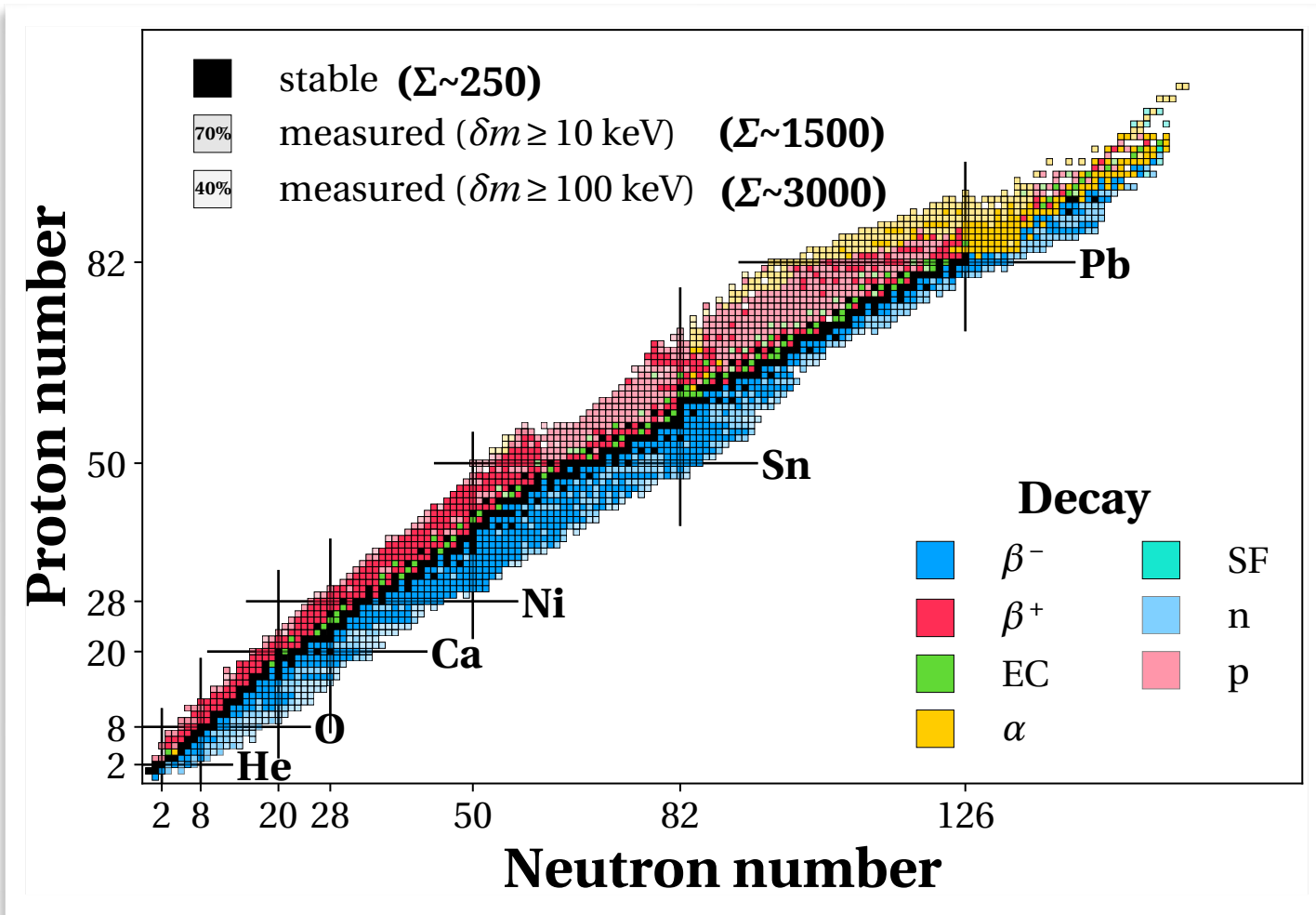
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How do nuclei form and why?

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Fundamental Properties Across the "Quantum Ladder"



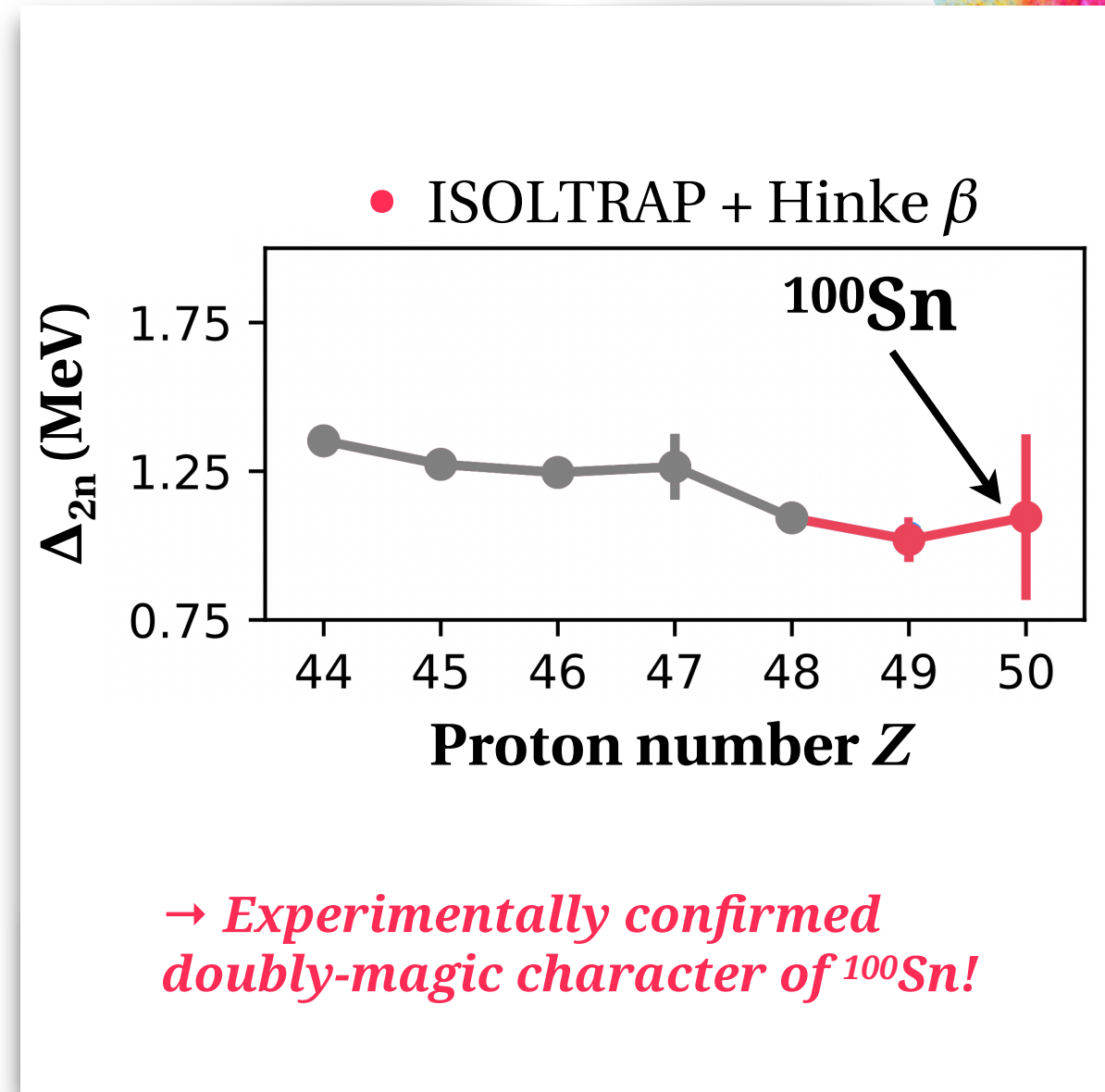
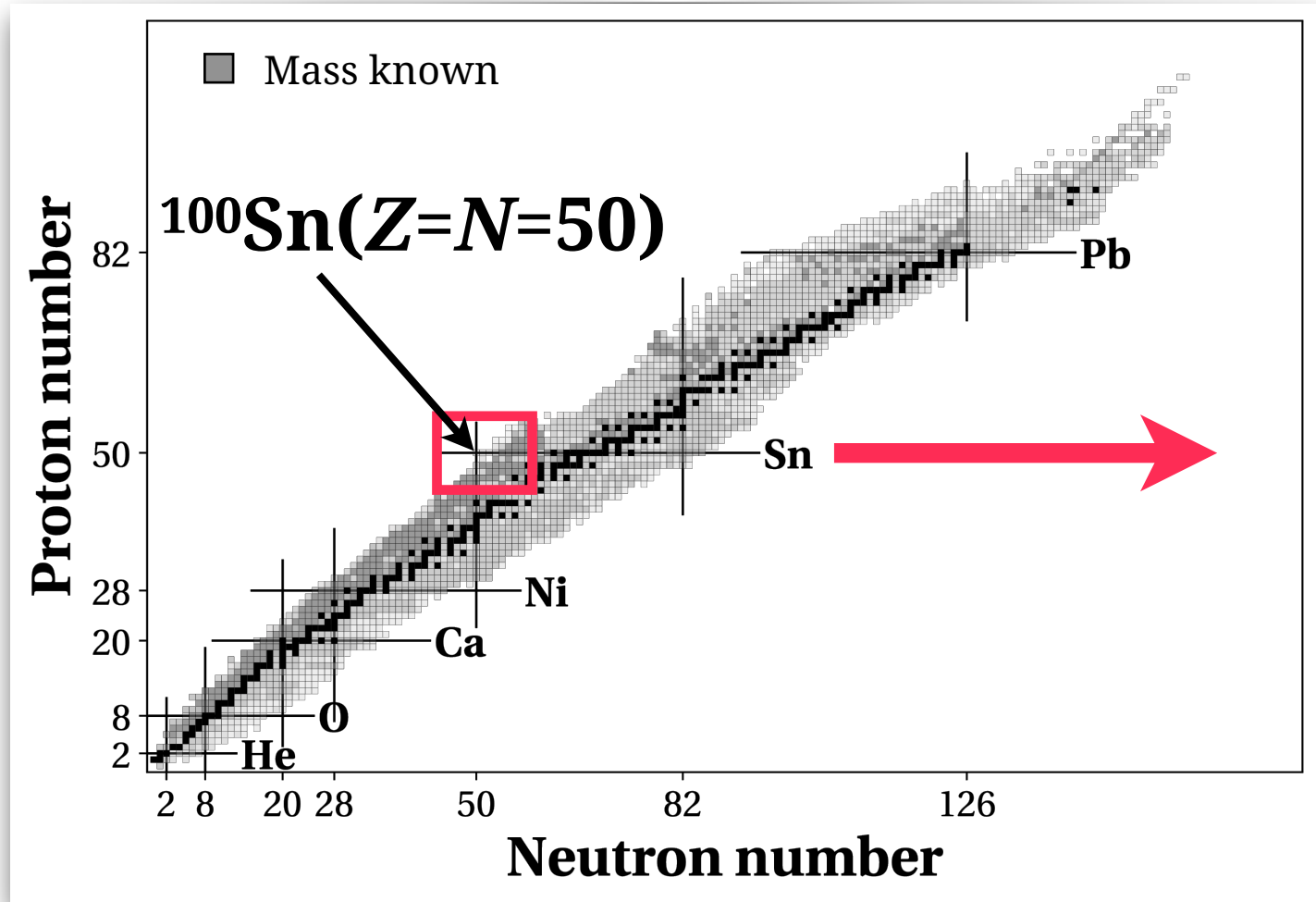
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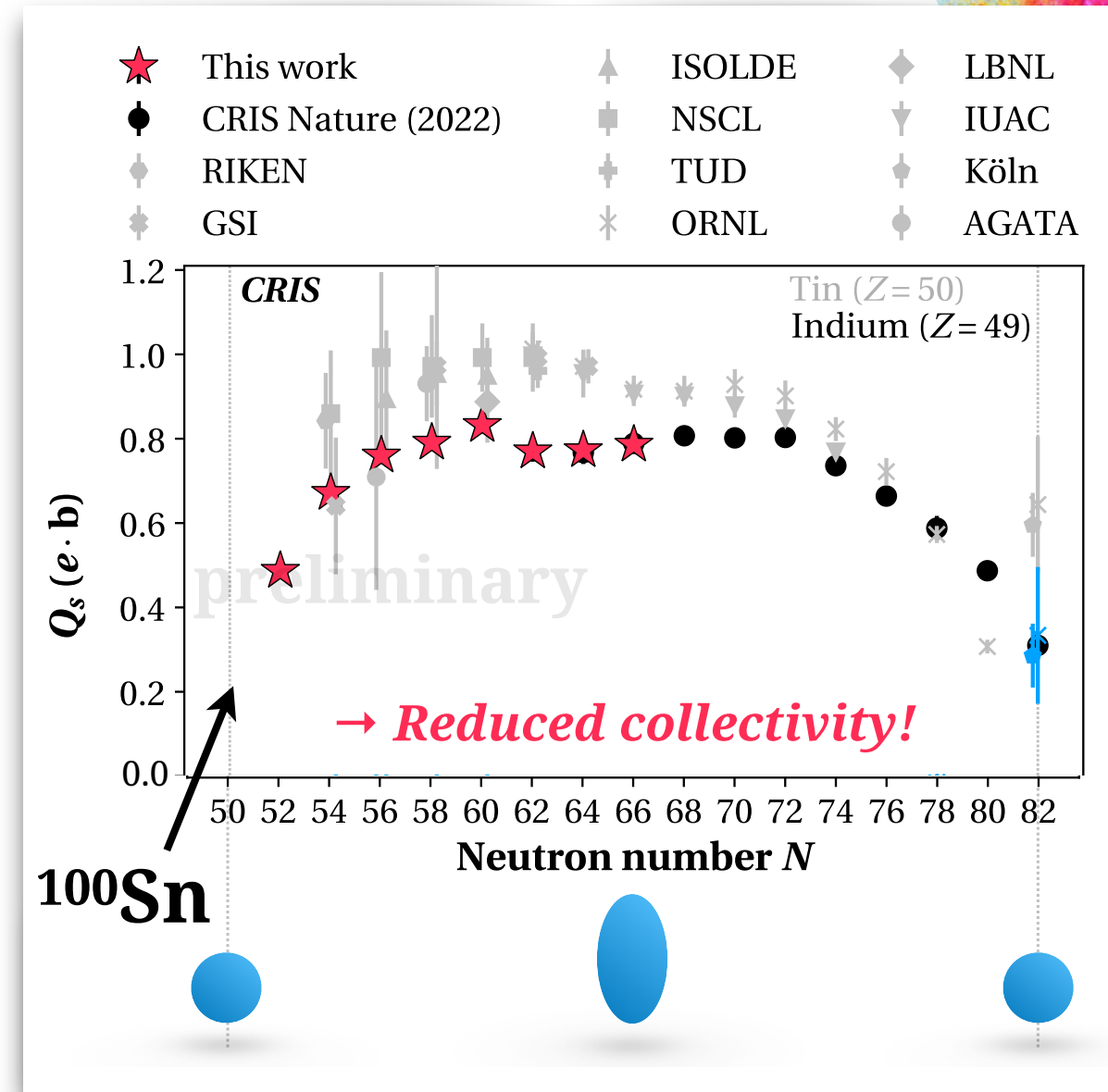
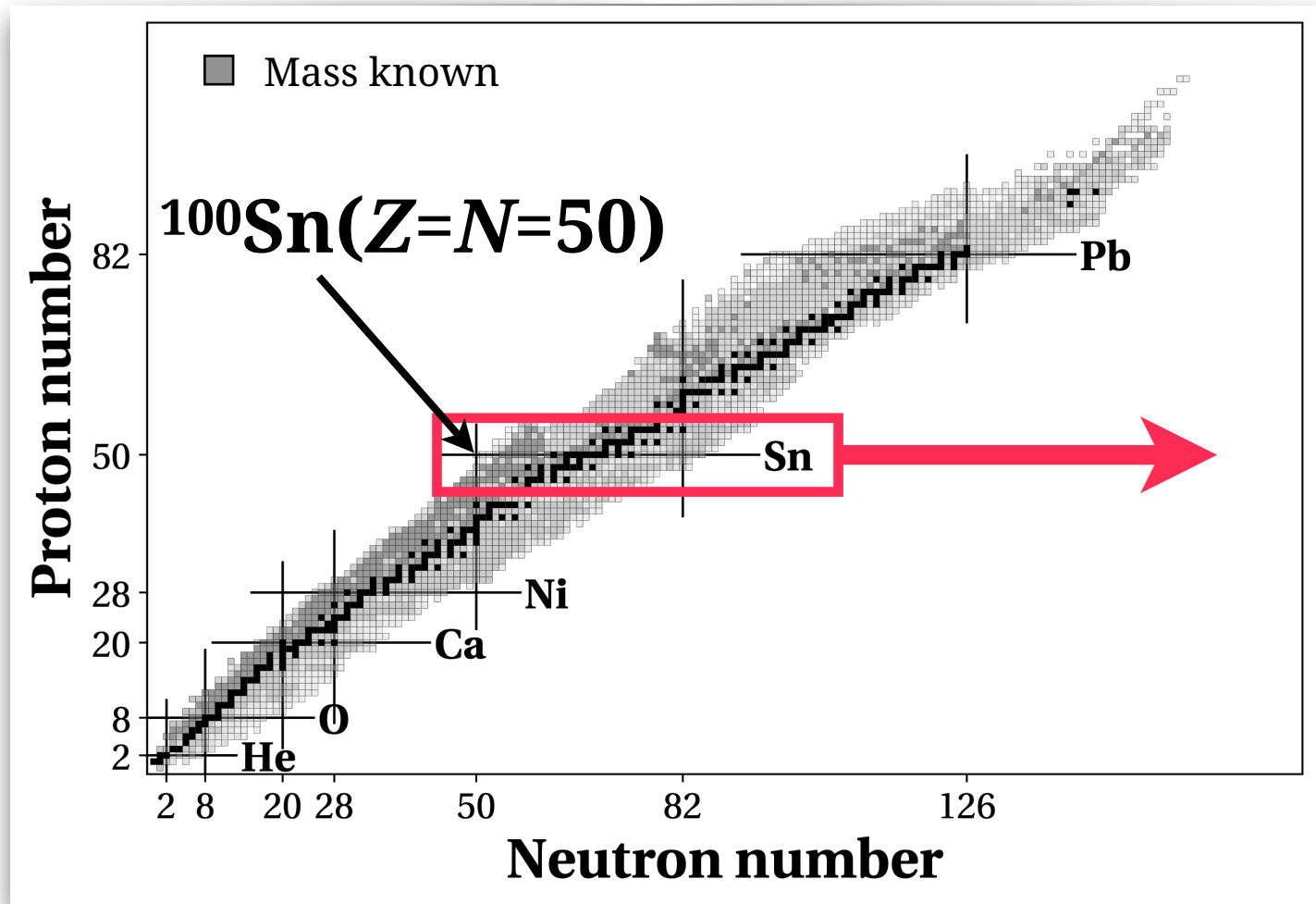


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system size, complexity →

Fundamental Properties Across the "Quantum Ladder"



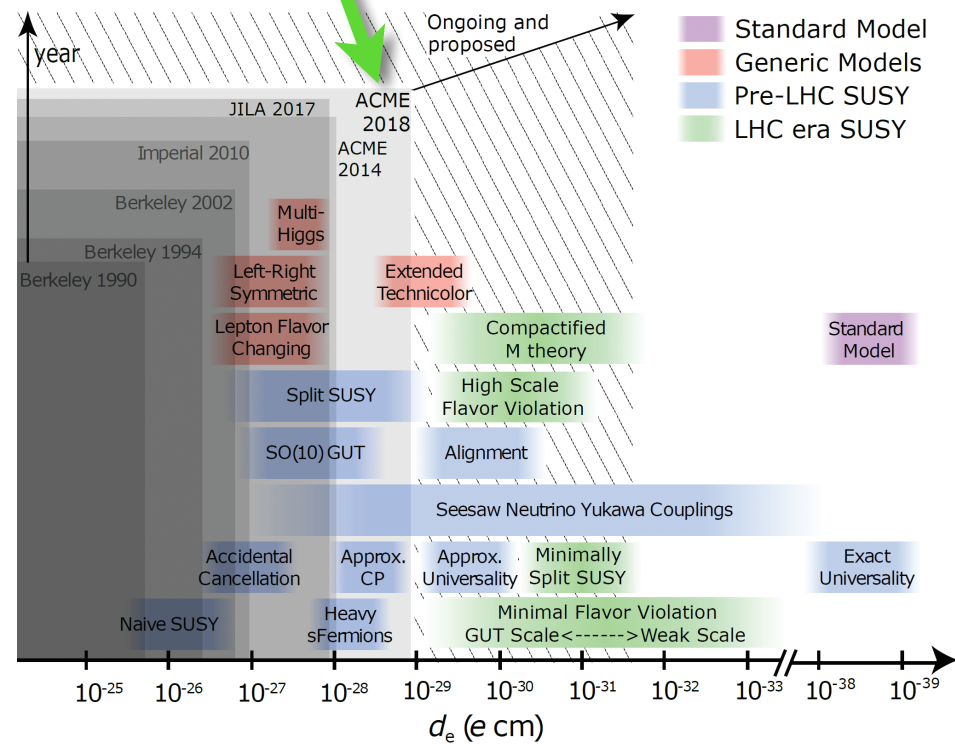
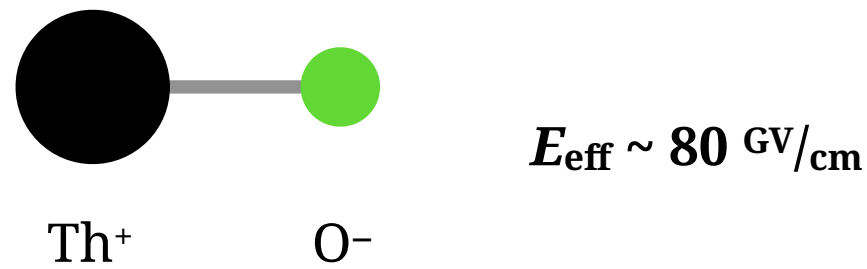
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Fundamental Properties Across the "Quantum Ladder"

e- Electric Dipole Moment:
 → ***Enhancement through high internal fields:***



$\sim 10^{-12}$ m → (radioactive) molecules
How can we leverage their amplifications?

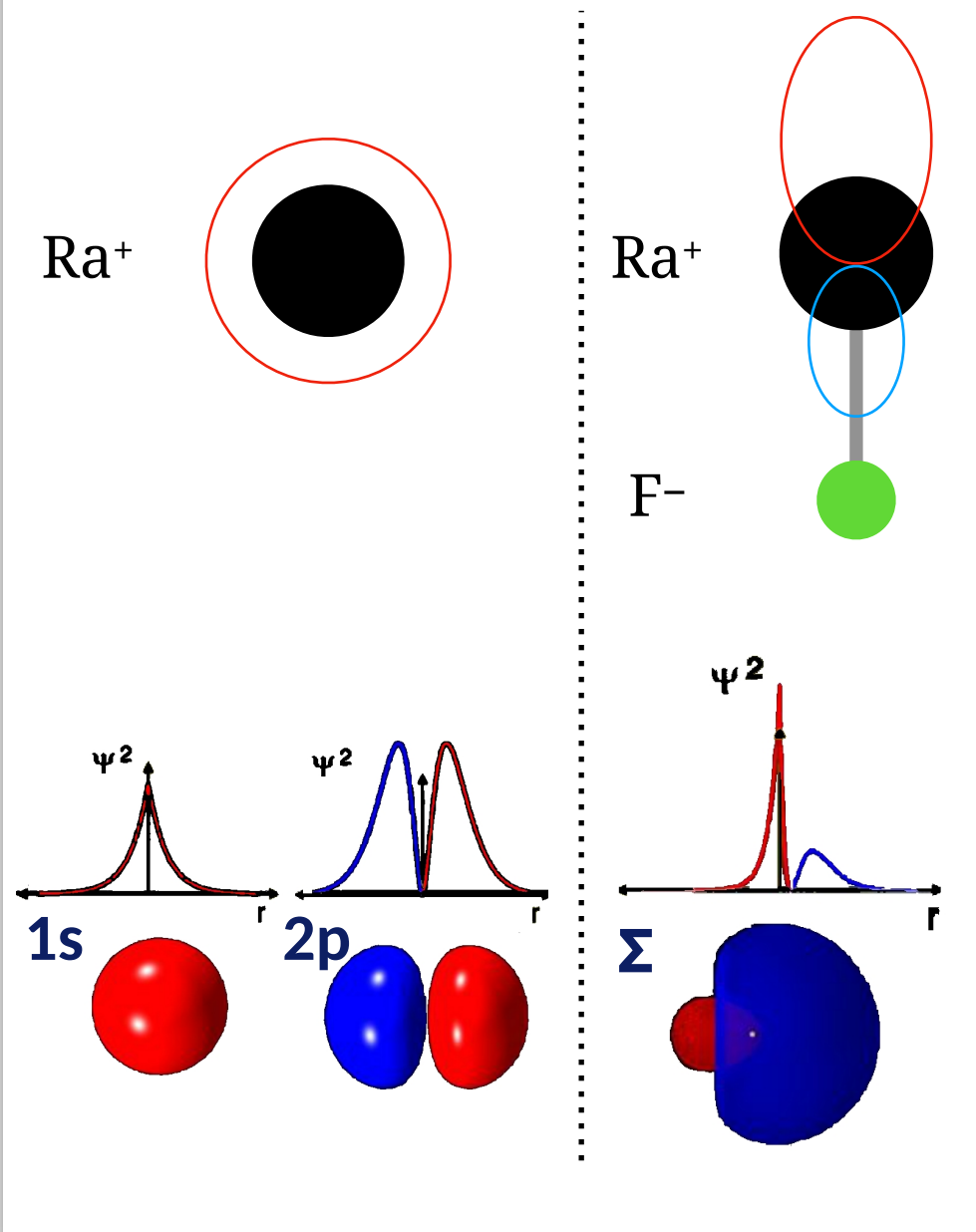
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Fundamental Properties Across the "Quantum Ladder"

Short-range nuclear interaction:
→ Enhancement through large e^- overlap



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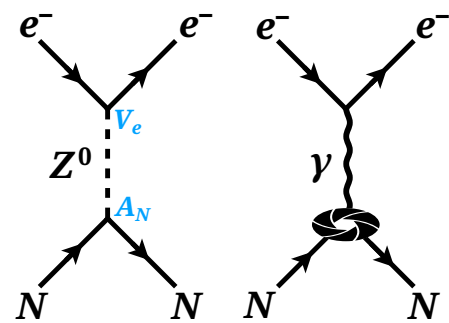
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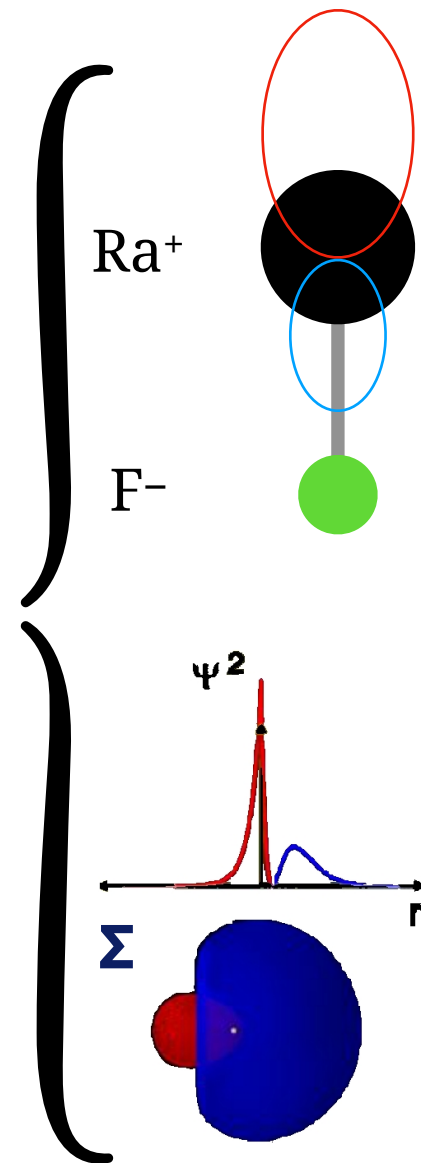
Fundamental Properties Across the "Quantum Ladder"

Short-range nuclear interaction:
 → Enhancement through large e^- overlap

Enormous Amplification to Symmetry-Violating Effects!



Not Measured in Molecules; Only 1 Atom!



New, Unexplored Window Into the Nucleus!

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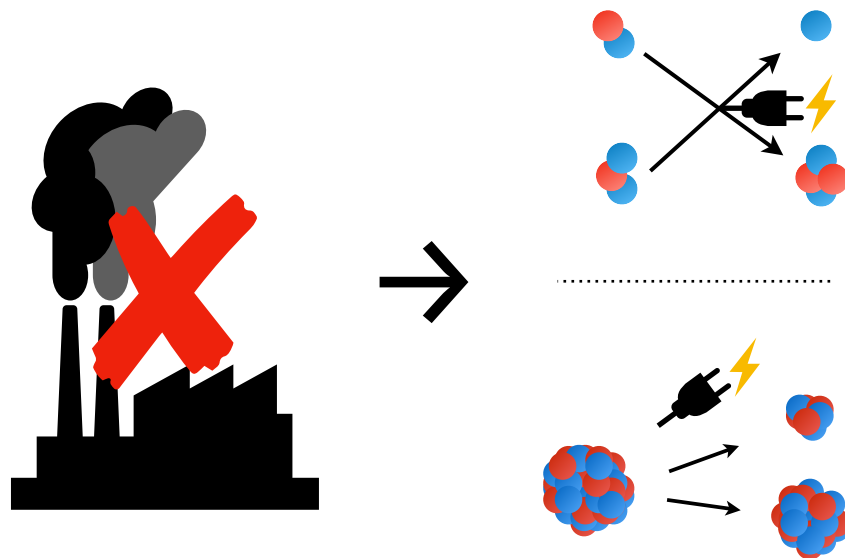
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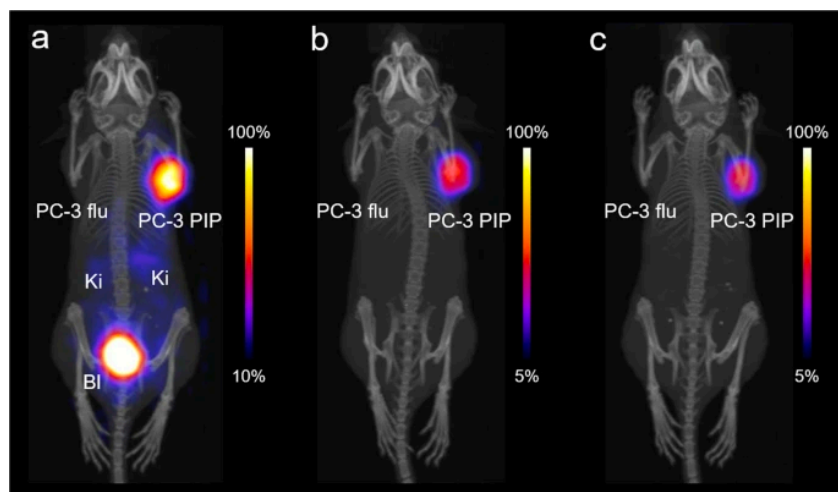
Fundamental Properties Across the "Quantum Ladder"

Nuclear Energy:



Nuclear Medicine:

^{149}Tb



$\sim 10^0$ m \rightarrow applications

*Safe uses of clean energy (fission, fusion)?
Cancer therapy based on radionuclides?*

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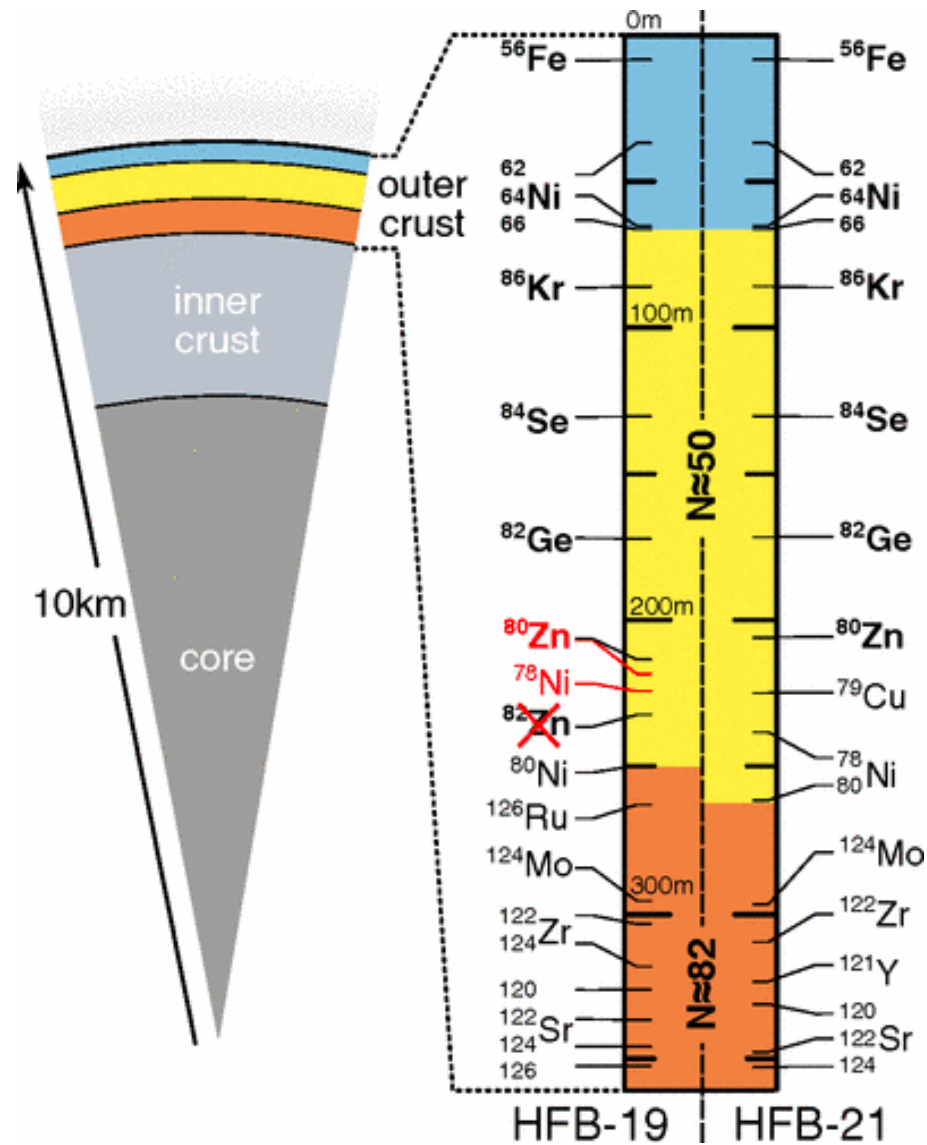
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Fundamental Properties Across the "Quantum Ladder"

Neutron star composition:



$\sim 10^4$ m \rightarrow neutron stars

How does the n-star composition look like?

$\sim 10^0$ m \rightarrow applications

*Safe uses of clean energy (fission, fusion)?
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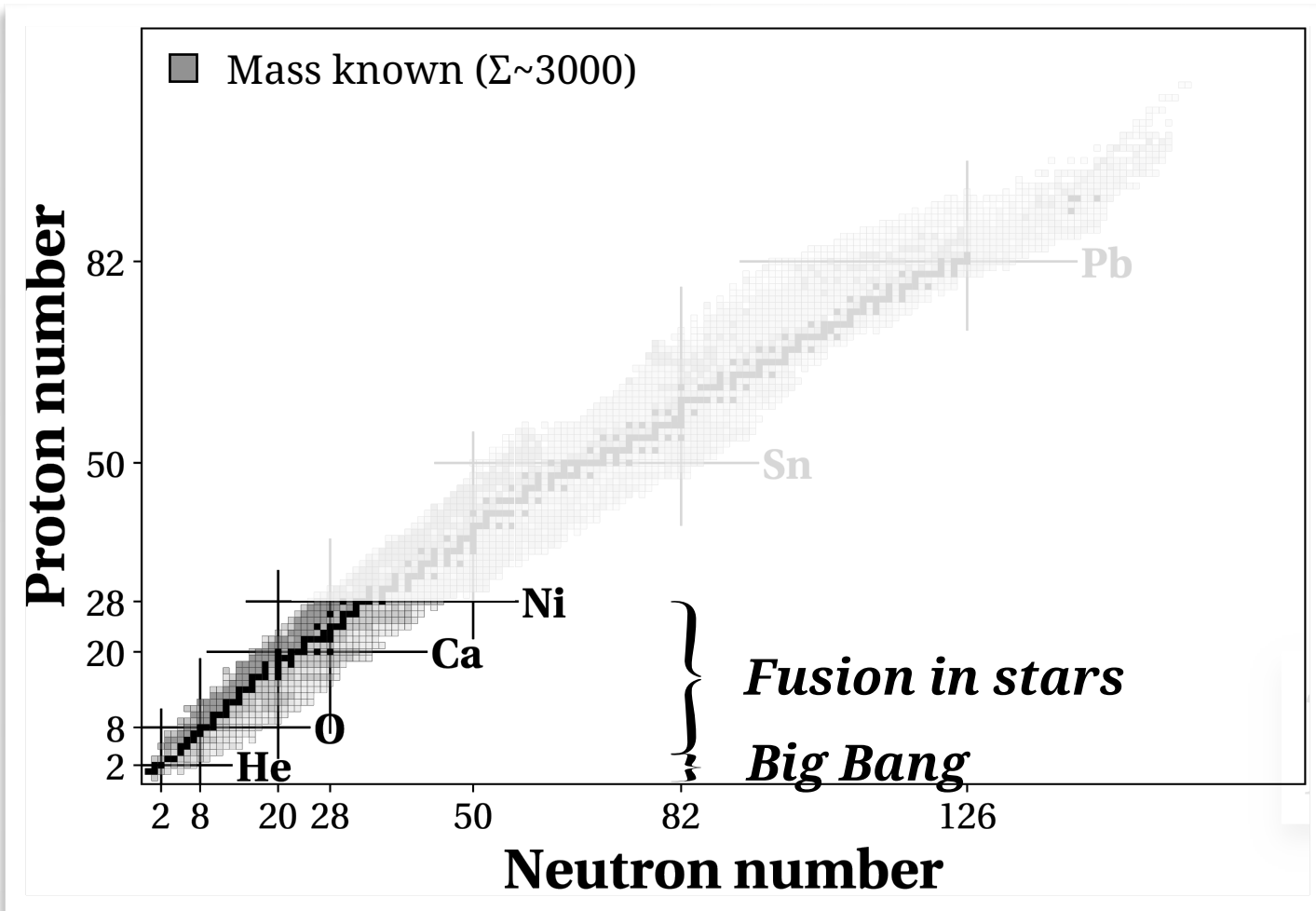
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Dark matter/energy? (Anti)matter asymm.*



Fundamental Properties Across the "Quantum Ladder"



$>10^9$ m \rightarrow stars and supernovae

How were (heavy) elements created?

$\sim 10^4$ m \rightarrow neutron stars

How does the n-star composition look like?

*Safe uses of clean energy (fission, fusion)?
Cancer therapy based on radionuclides?*

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How can we leverage their amplifications?

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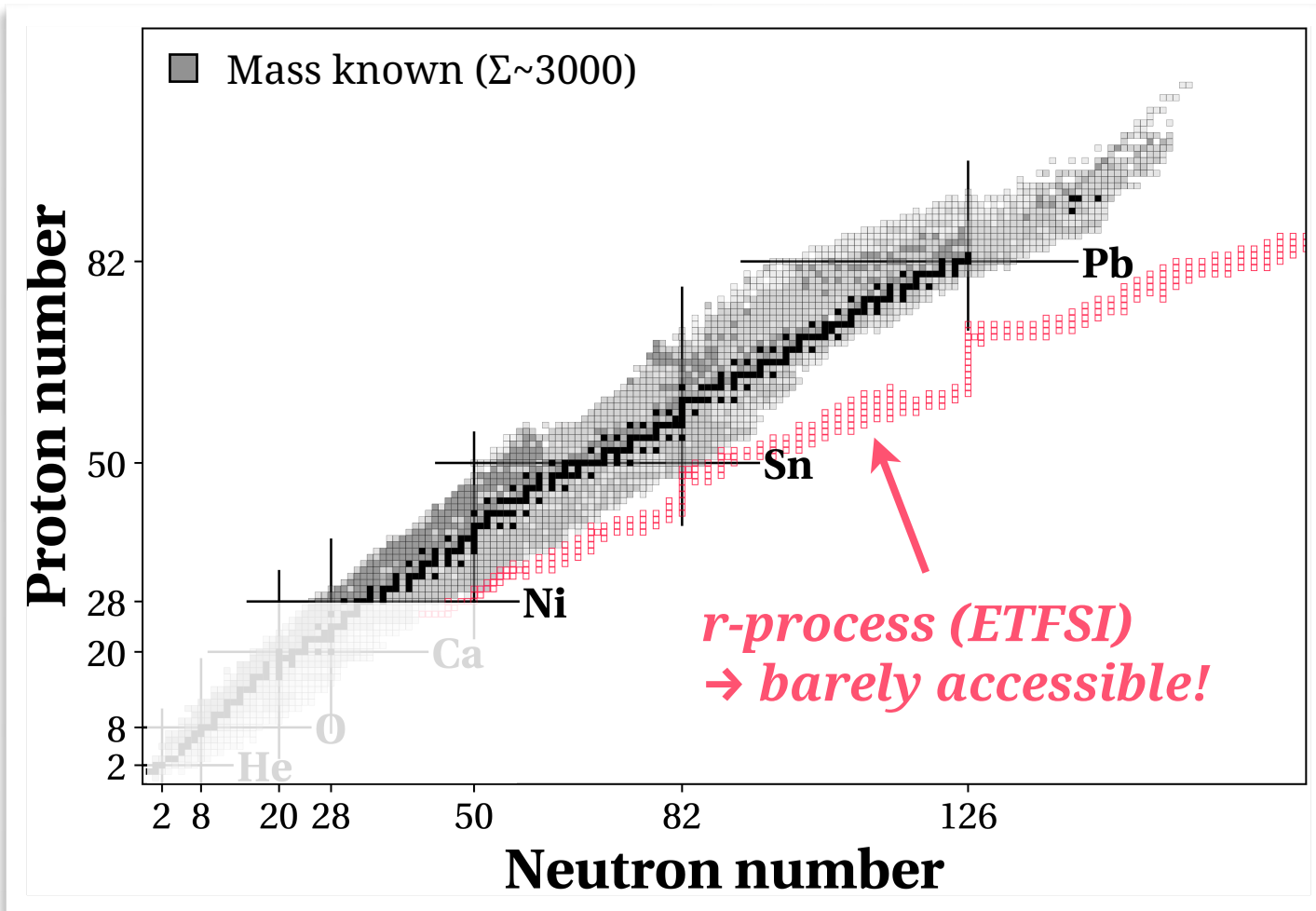
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system size, complexity \rightarrow

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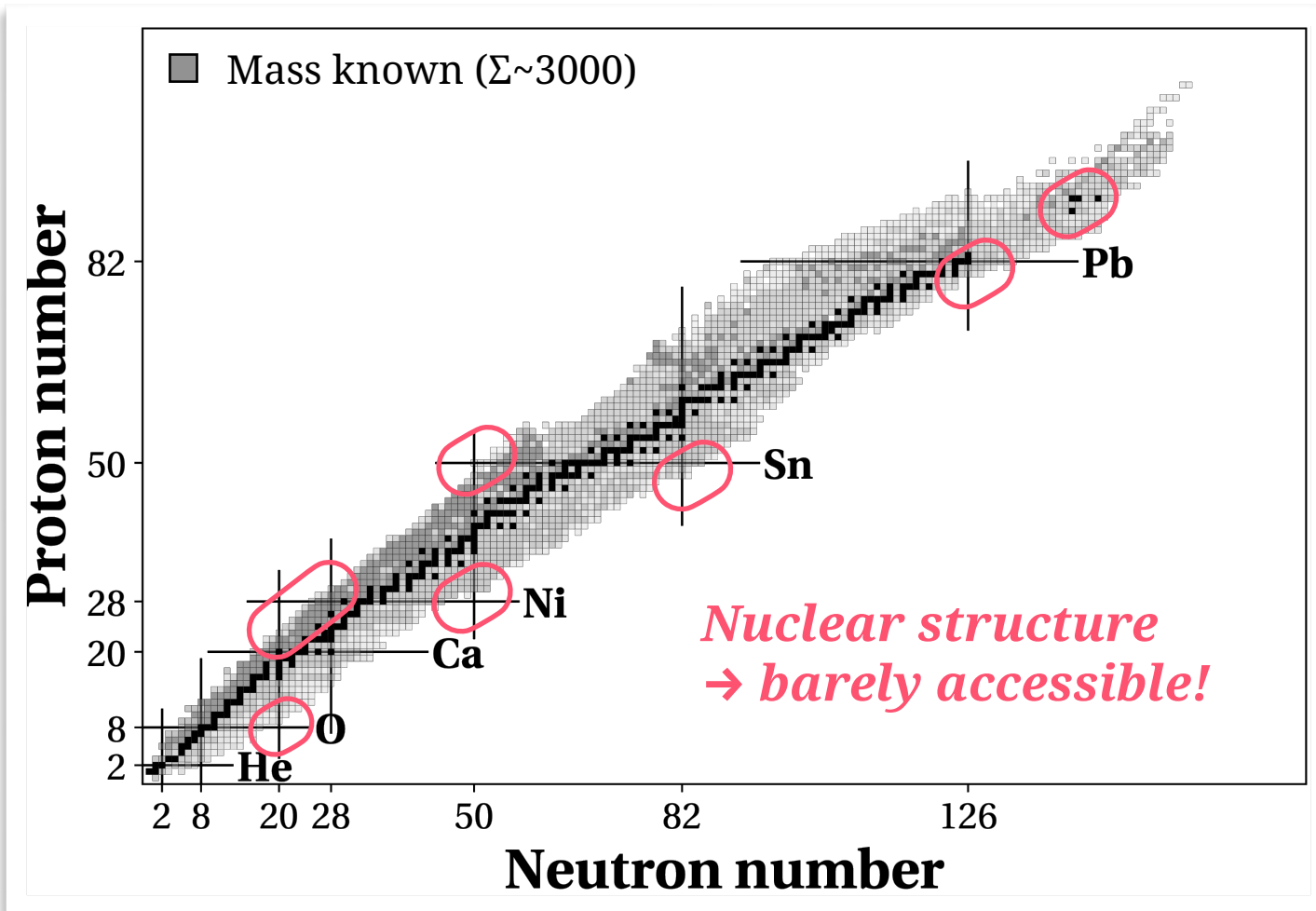
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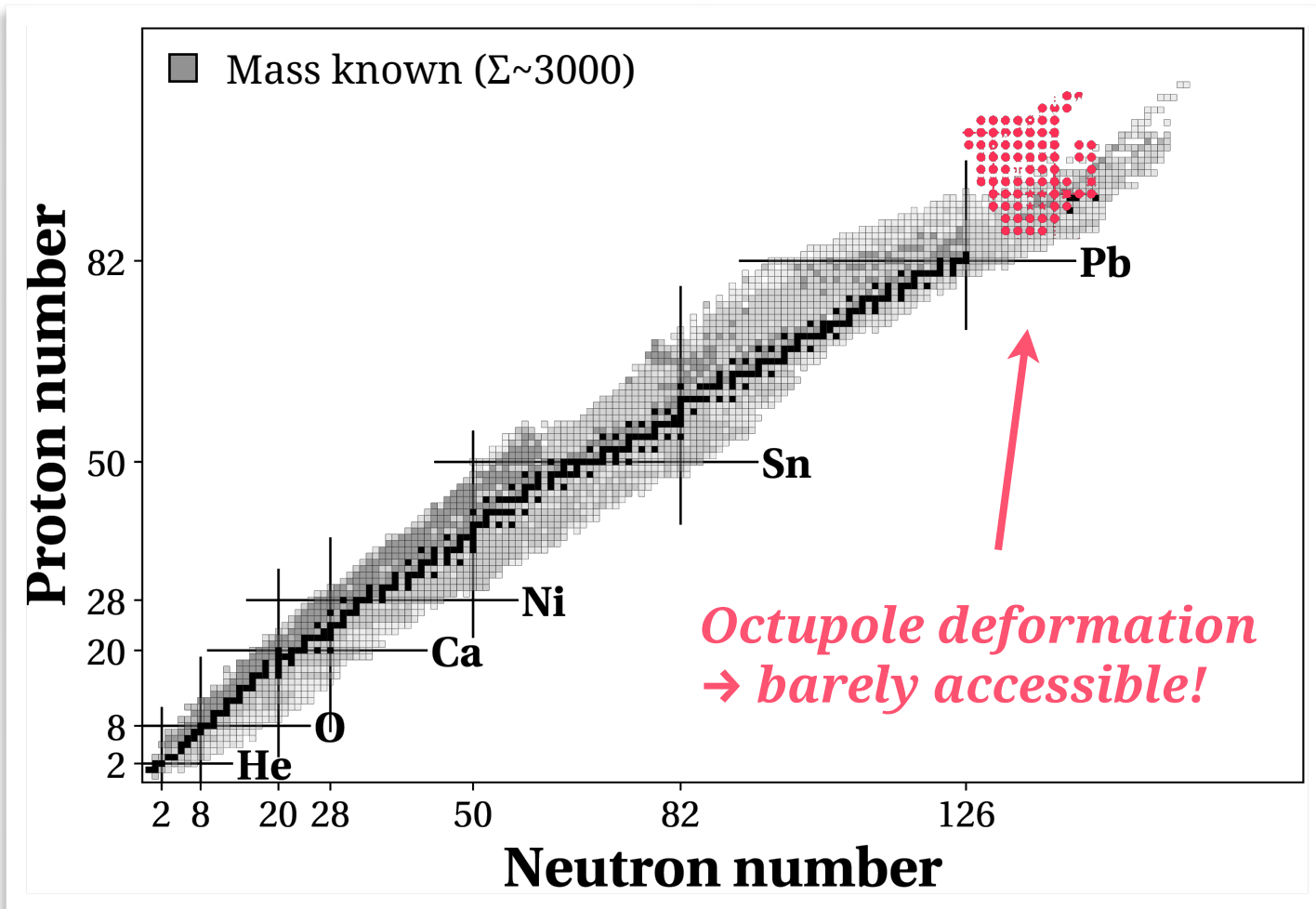
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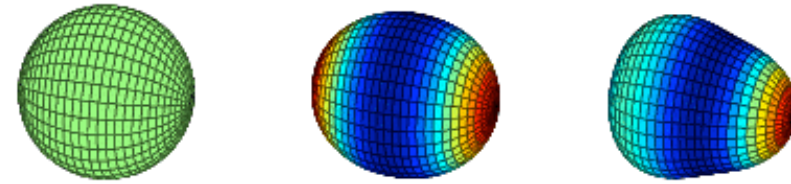


Fundamental Properties Across the "Quantum Ladder"



$>10^9$ m \rightarrow stars and supernovae
How were (heavy) elements created?

Spherical Quadrupole Octupole



Safe uses of clean energy (fission, fusion)?
Cancer therapy based on radionuclides?

10^{-12} m \rightarrow radioactive molecules
How can we leverage their amplifications?

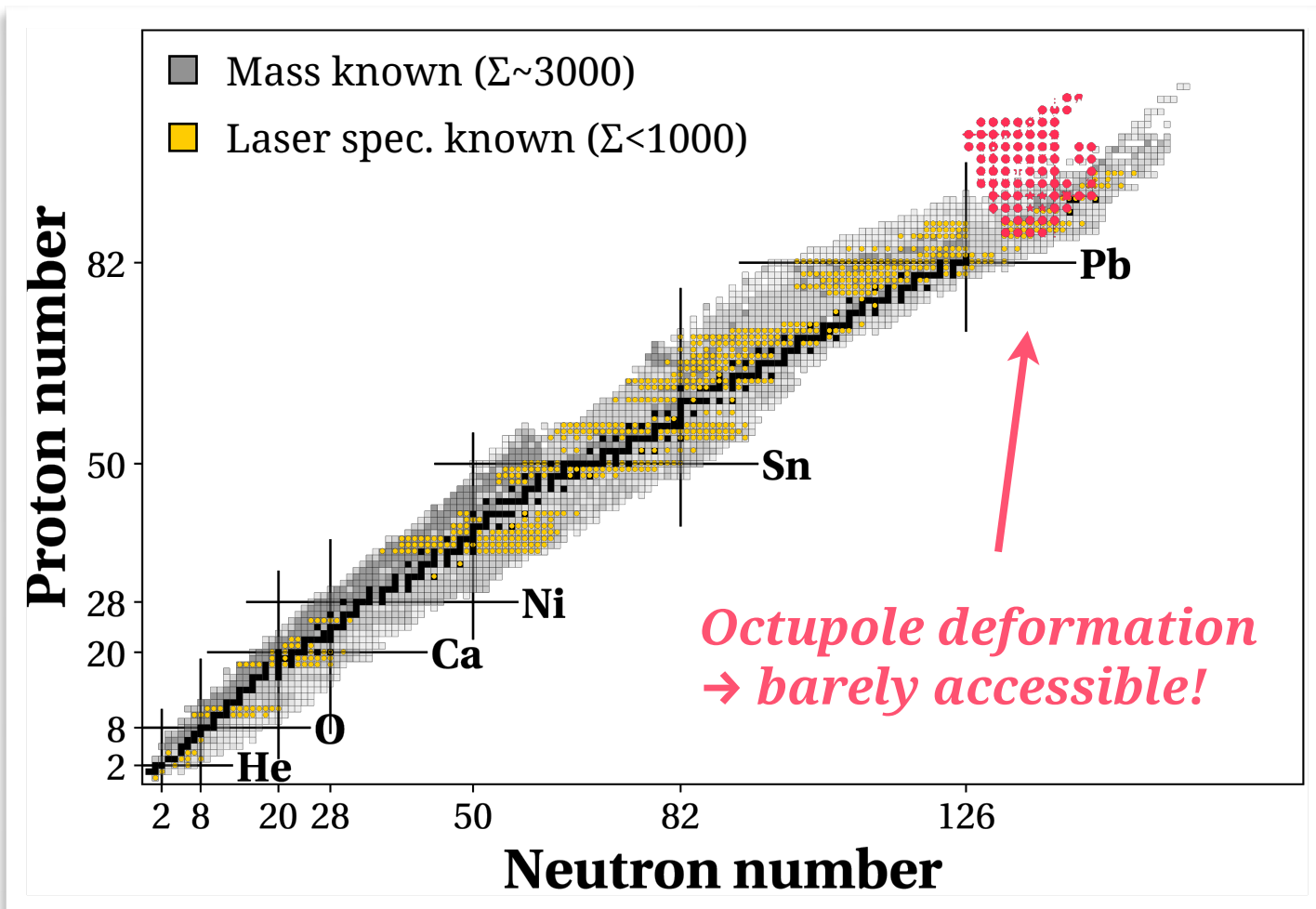
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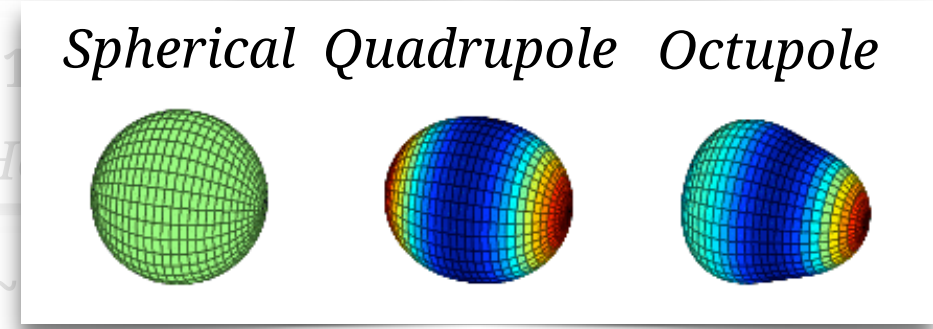
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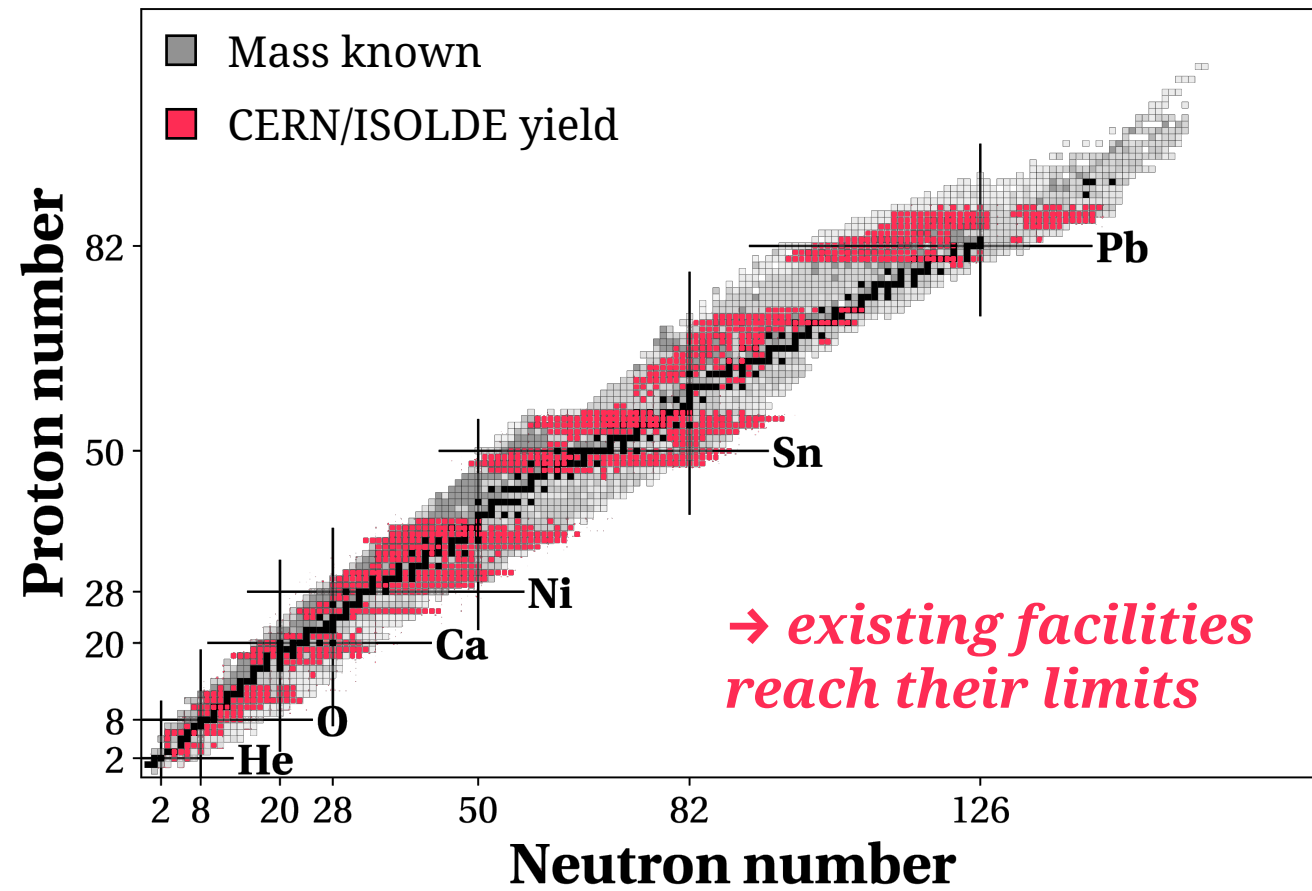
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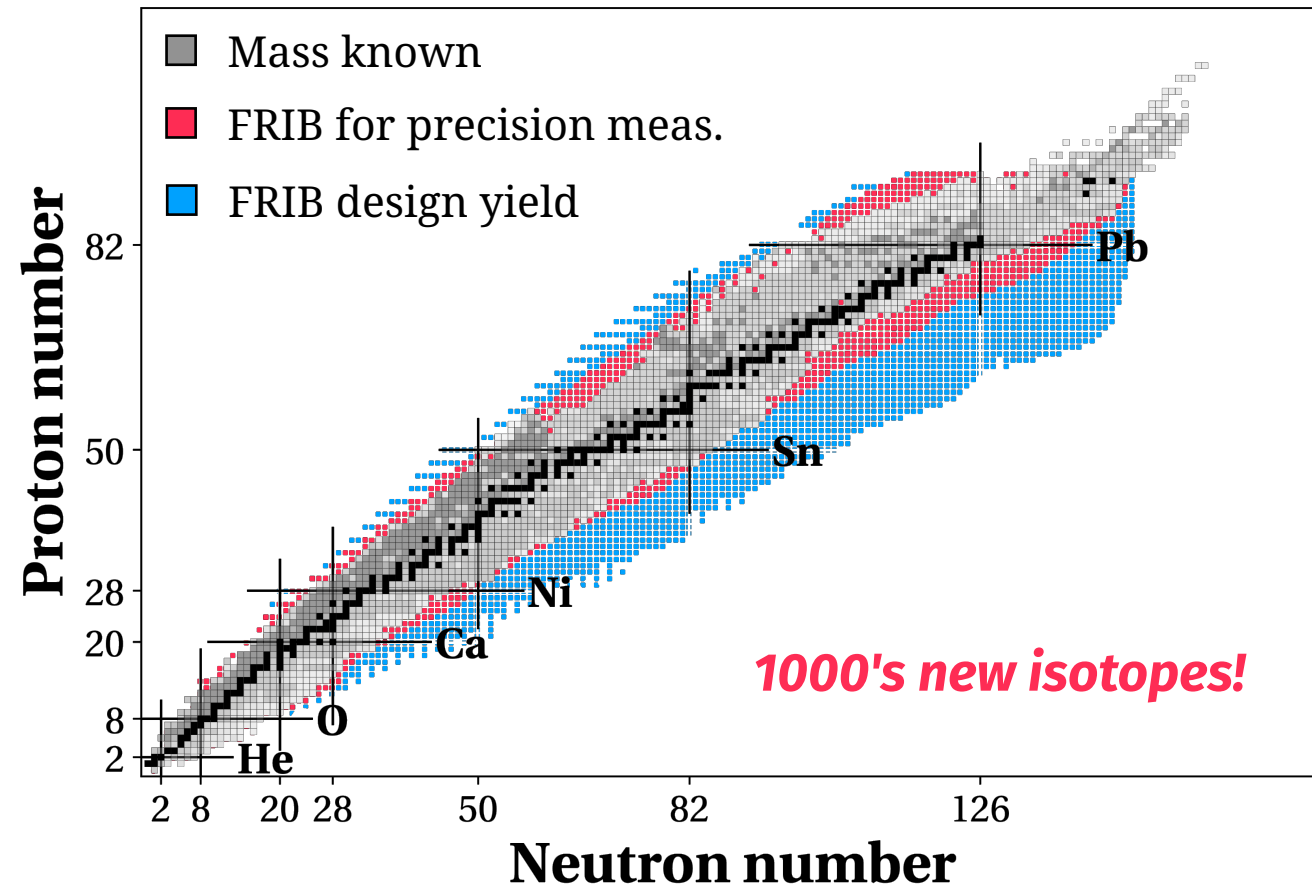
The Challenges in Nuclear Physics

1. Yield of Isotopes of Interest



The Challenges in Nuclear Physics

1. Yield of Isotopes of Interest



→ *Next-Gen RIB Facilities*

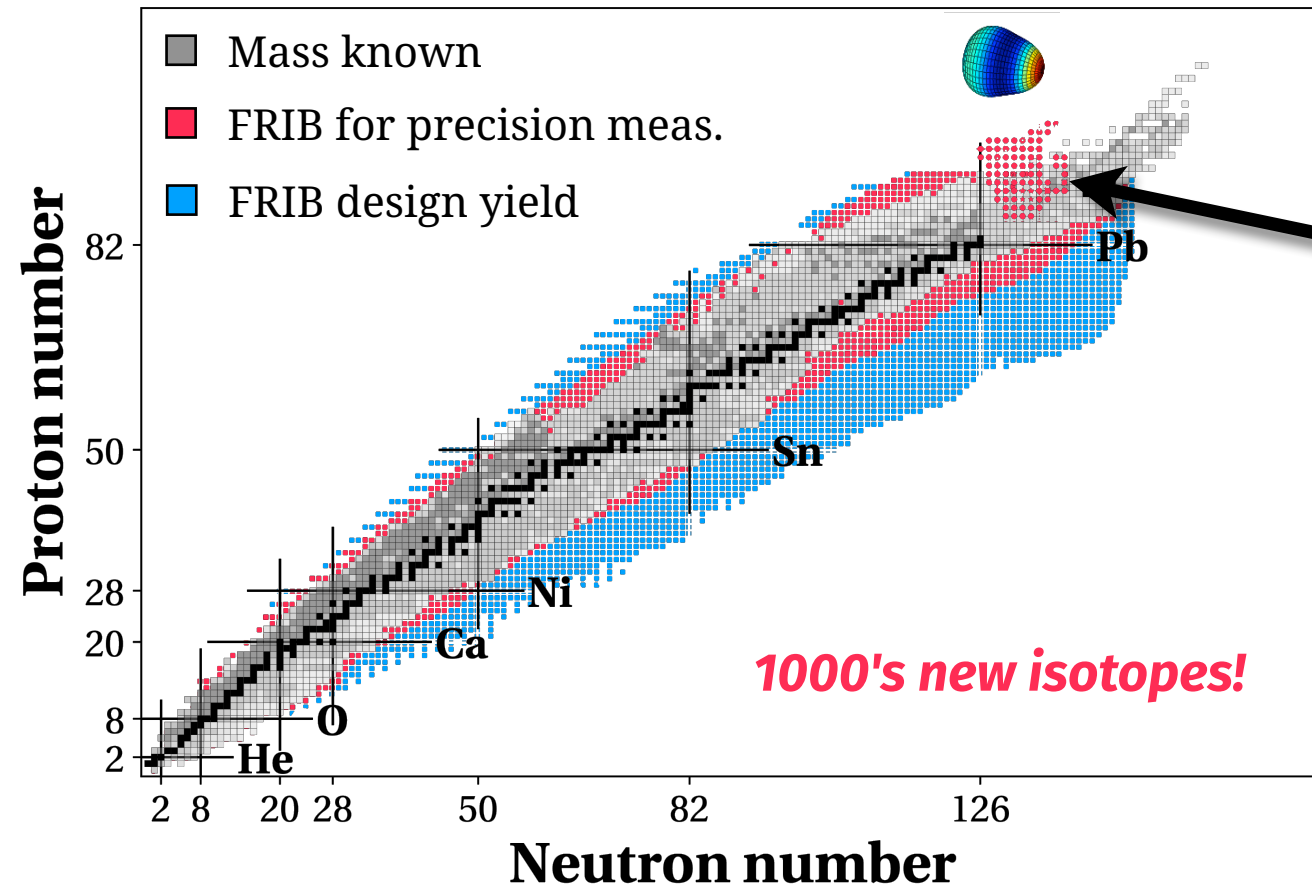
U.S. Department of Energy's new ~\$1B Facility for Rare Isotope Beams (FRIB) at Michigan State University



U.S. DEPARTMENT OF
ENERGY

The Challenges in Nuclear Physics

1. Yield of Isotopes of Interest

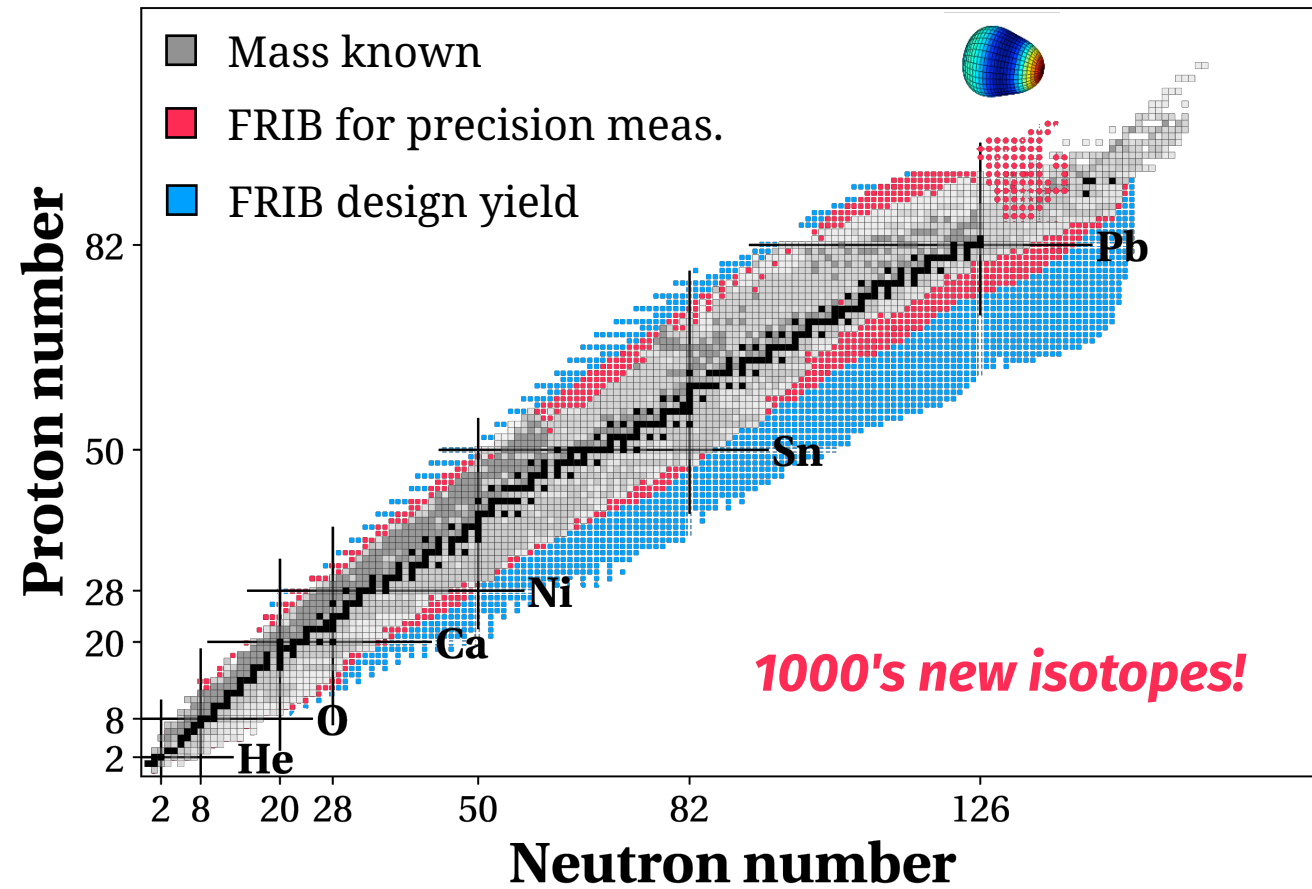


First High-Yield Access to Octupole-Deformed Nuclei (Actinides)!

→ *Next-Gen RIB Facilities*

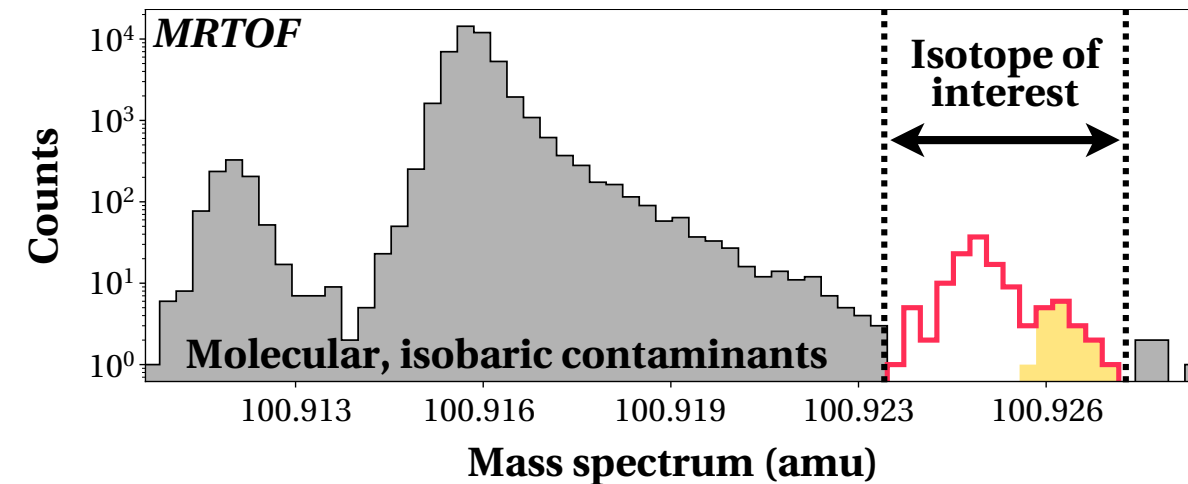
The Challenges in Nuclear Physics

1. Yield of Isotopes of Interest



→ Next-Gen RIB Facilities

2. Long-Lived Contamination



→ Next-Gen Techniques

Exciting future for low-energy nuclear physics ahead of us!



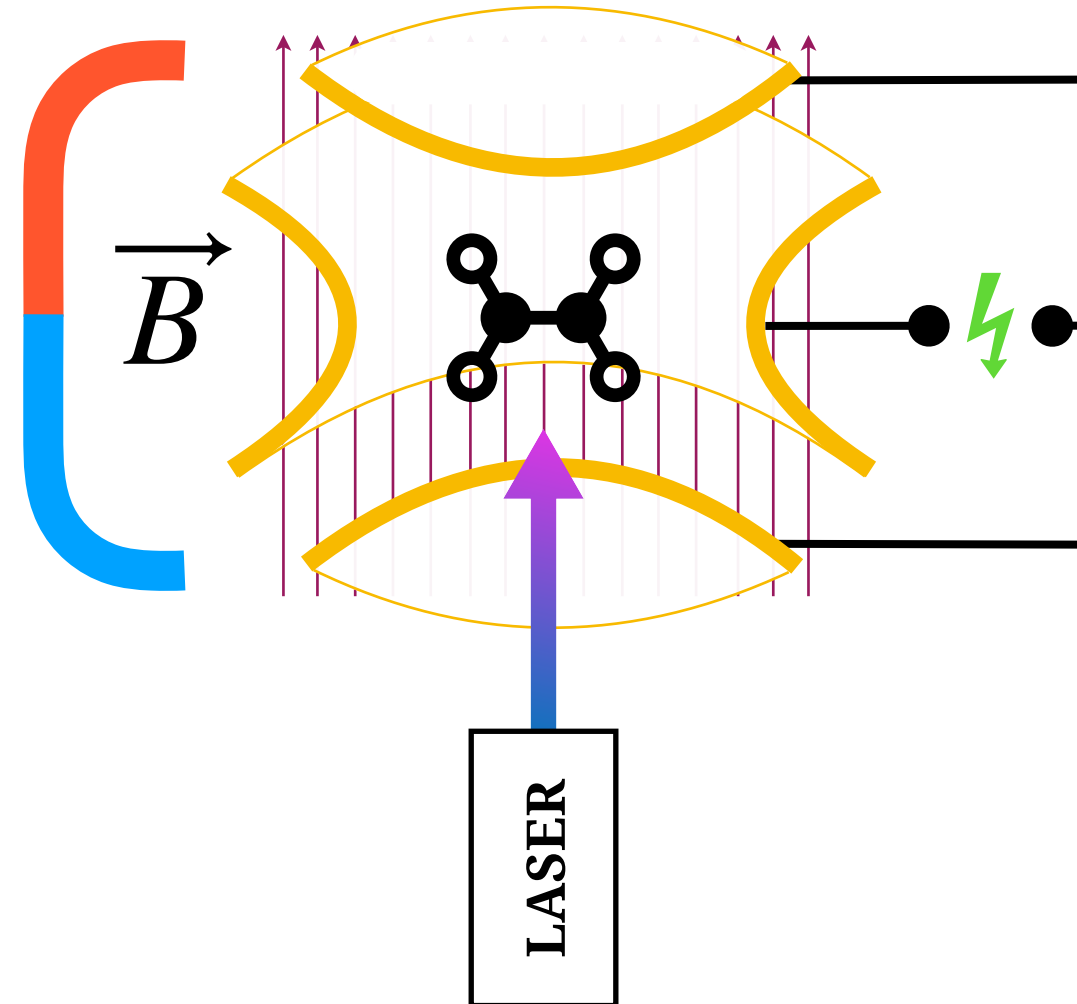
→ *Next-Gen RIB Facilities*

→ *Next-Gen Techniques*

Quantum Sensing Through Symbiosis

Penning Ions Trap

= *magnetic* + electrostatic fields

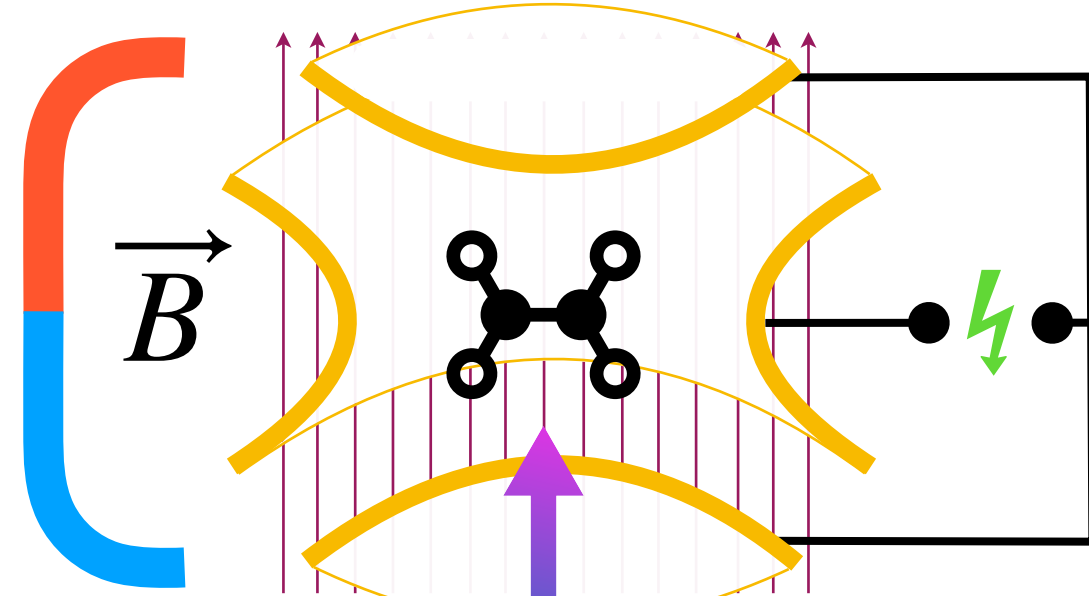


Laser Spectroscopy

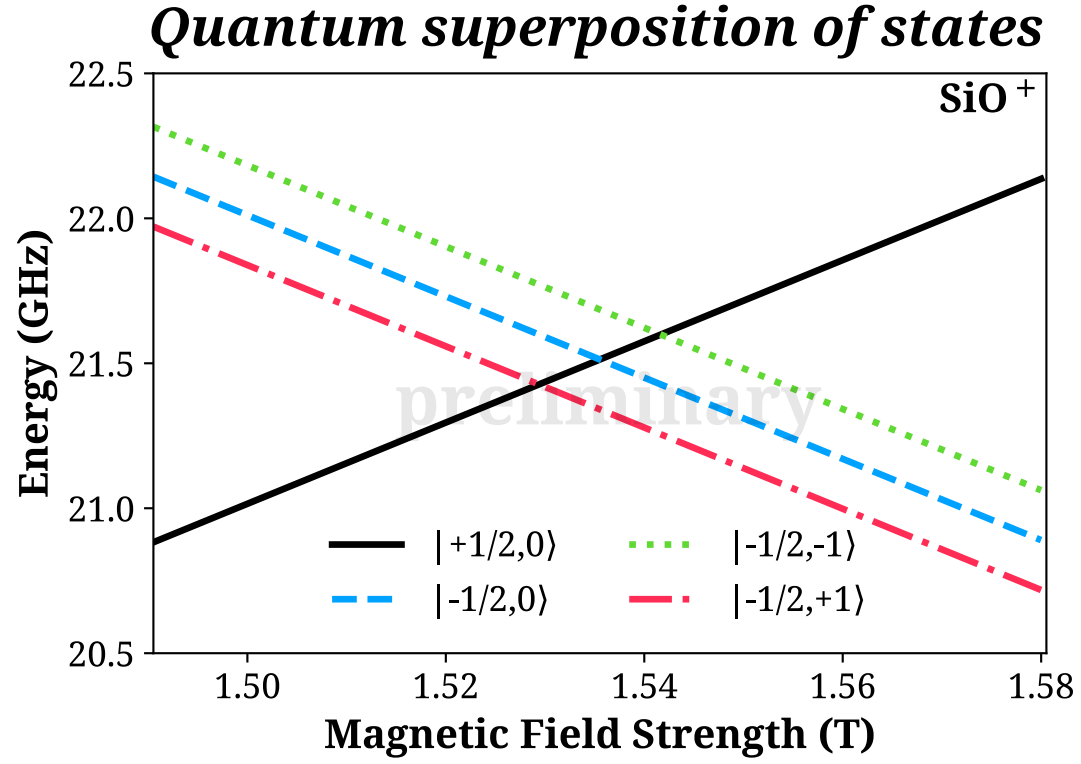
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Penning Ions Trap

= **magnetic** + electrostatic fields



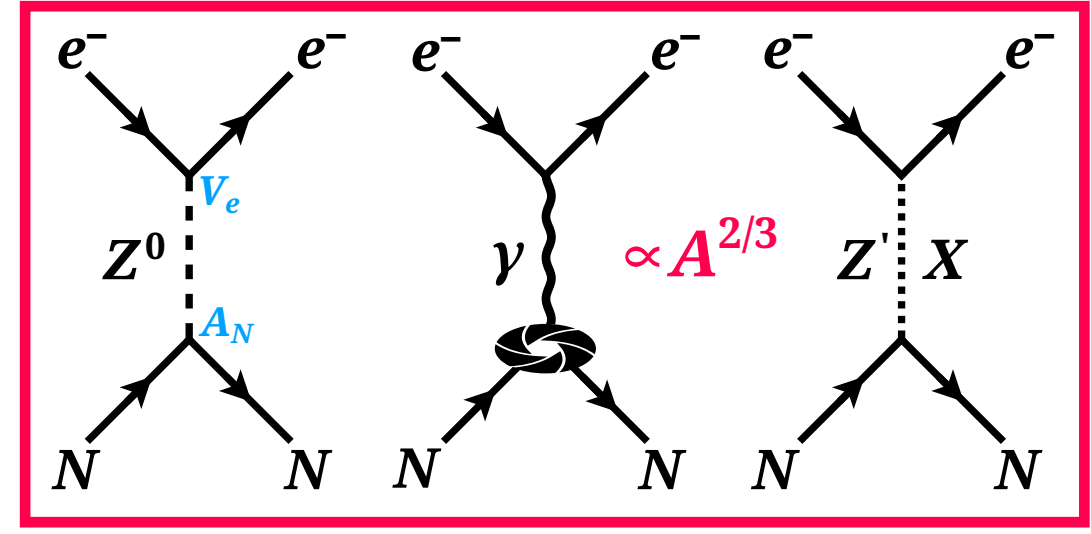
Laser Spectroscopy



LASER

$$E_{PV} \sim \frac{\langle \psi_{\uparrow}^+ | H_{\pm} | \psi_{\downarrow}^- \rangle}{E_- - E_+}$$

NSD Parity Violation

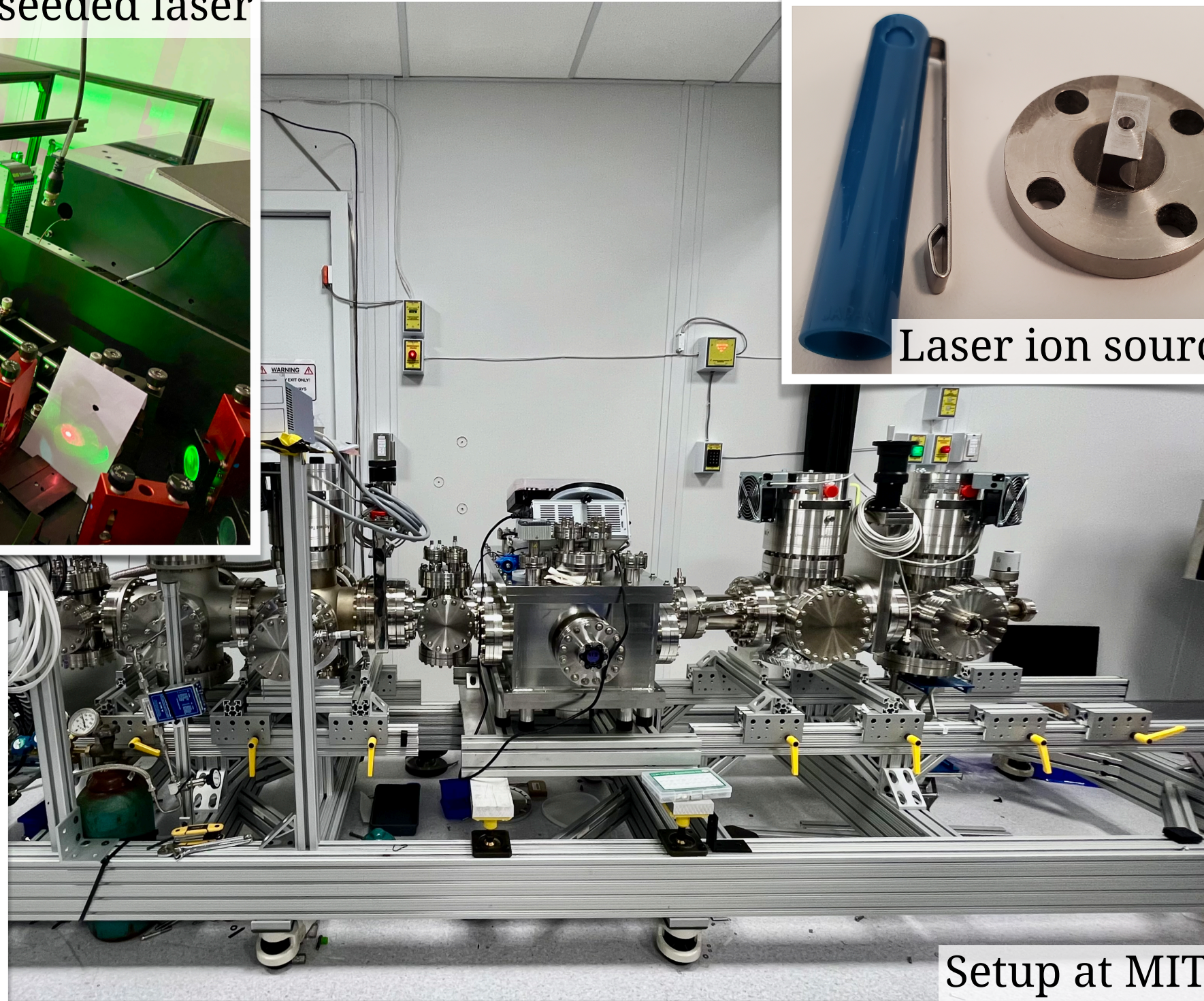
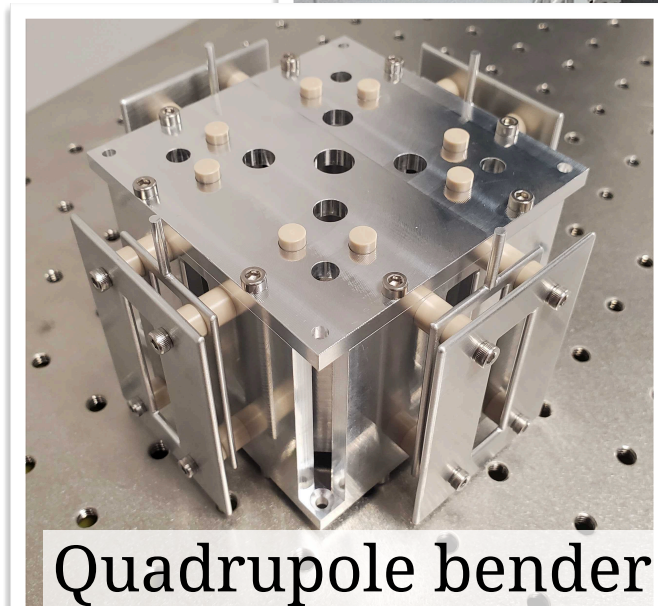
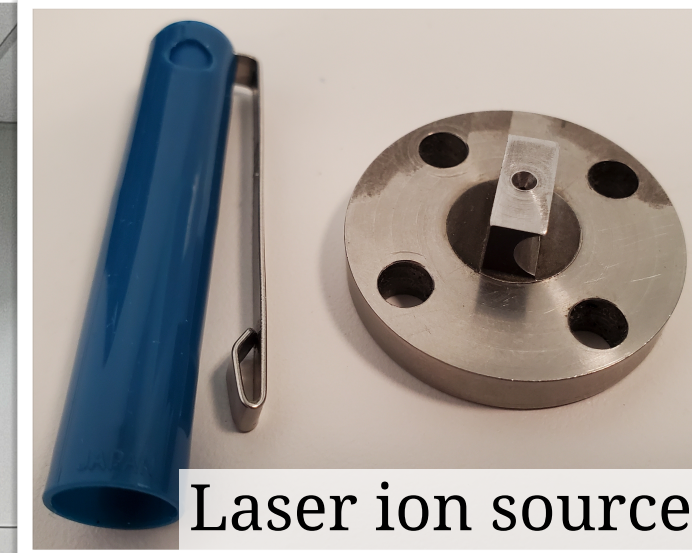


Quantum Sensing Through Symbiosis



Setup at MIT

Quantum Sensing Through Symbiosis



→ *FRIB!*

*1. Next-Gen Precision Tools Are Ready for Application
at Next-Gen Facilities (I.E., FRIB)*

1. Next-Gen Precision Tools Are Ready for Application at Next-Gen Facilities (I.E., FRIB)

2. Combining these techniques allows for unique leverage to access unstudied parity-violating nuclear properties

Acknowledgments: ISOLTRAP/CERN



D. Atanasov, K. Blaum, T. Cocolios,
S. Eliseev, F. Herfurth, A. Herlert,
J. Karthein, **I. Kulikov**, Y. A. Litvinov,
D. Lunney, V. Manea, **M. Mougeot**,
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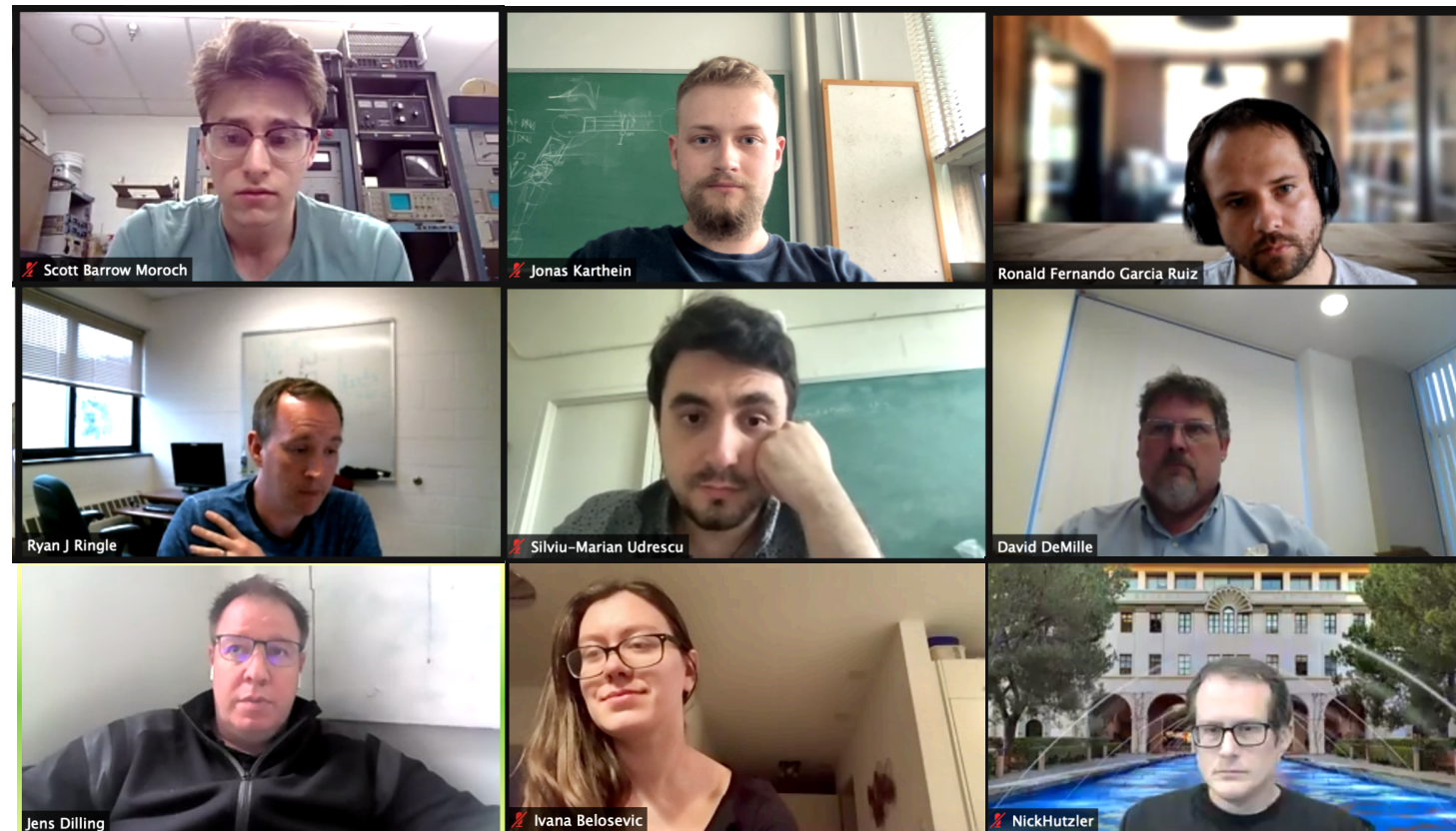
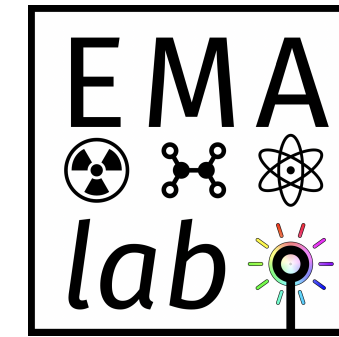
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