Fundamental Physics Research with Radioactive Atoms & Molecules

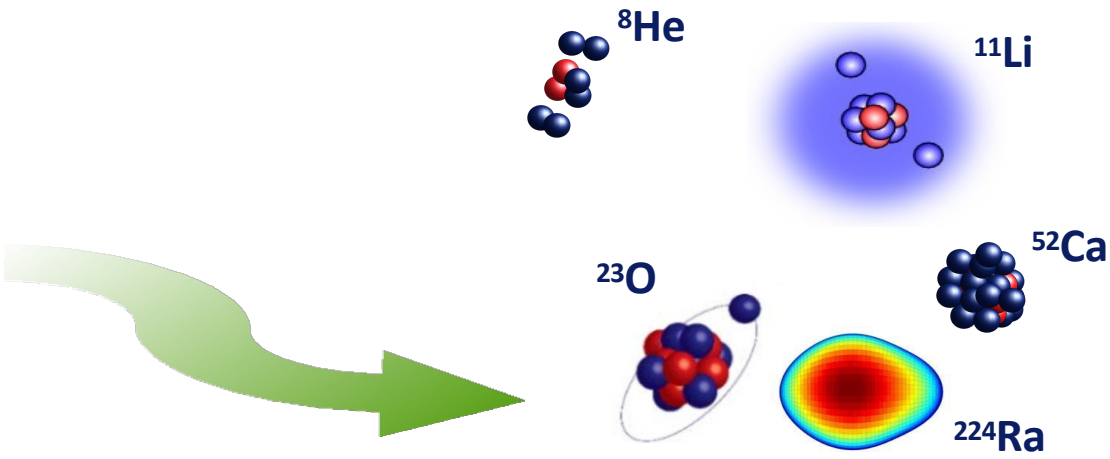


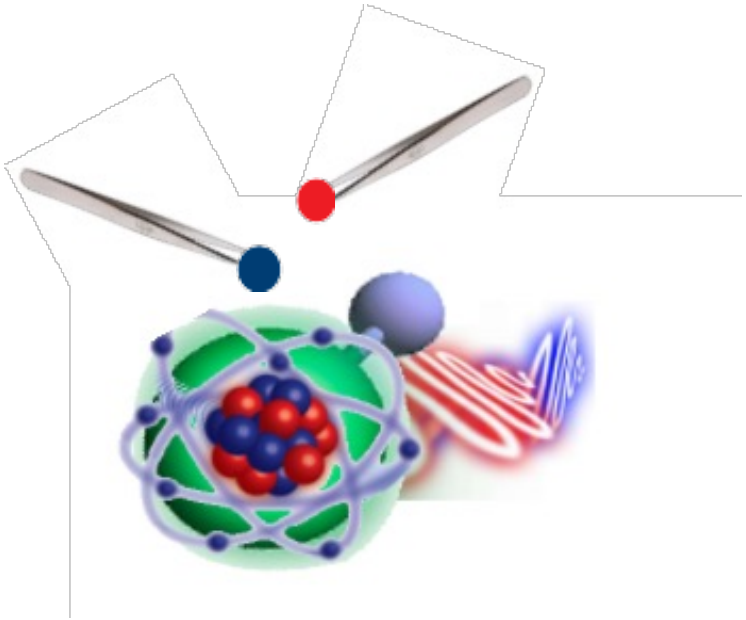
Figure modified from https://sphereofinfluence360.com/

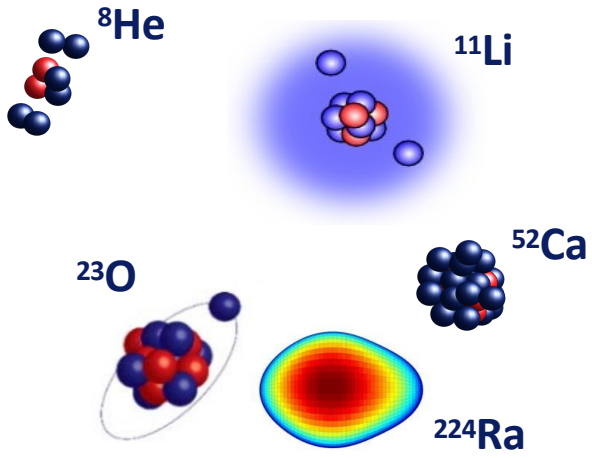
Ronald Fernando Garcia Ruiz

MIT

14th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2022)

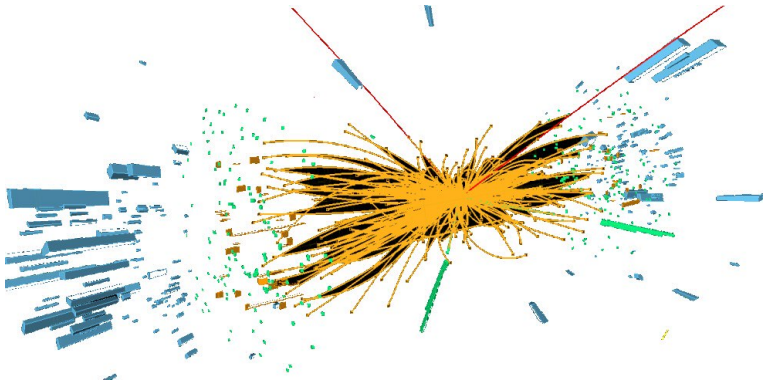
Fundamental Physics Research with Radioactive Atoms & Molecules





What are the fundamental particles and forces of nature?

Energy frontier



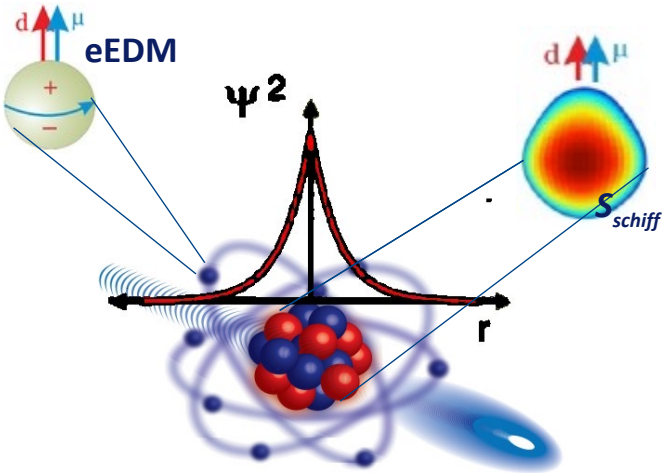
TeV <10^{-14}

GeV 10^{-9}

MeV 10^{-6}

eV 10^{0}

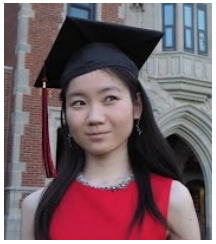
Precision frontier



How do complex nuclear phenomena emerge?

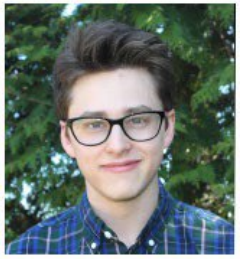
Exotic Molecules and Atoms (EMA) Lab @MIT

Graduate students


H. Kakioka


A. Brinson


S. Udrescu

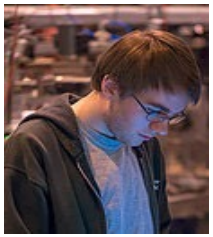

S. Moroch

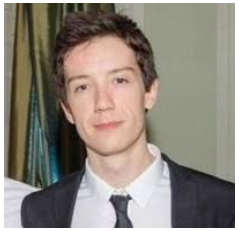

F. Pastrana

PI


R.F. Garcia Ruiz

Postdocs


A. Vernon


S. Wilkins


J. Karthein


I. Belosevic

UROPs

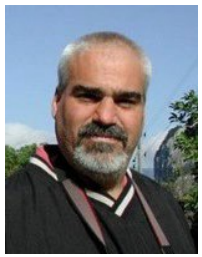
- Antonio Luera
- Angel Luera
- Athira Arayath
- Nicolas Tanaka
- Erick Padilla
- Andoni Fernandez

Support LNS/Bates


A. Convertino


E. Ihloff


D. Petterson

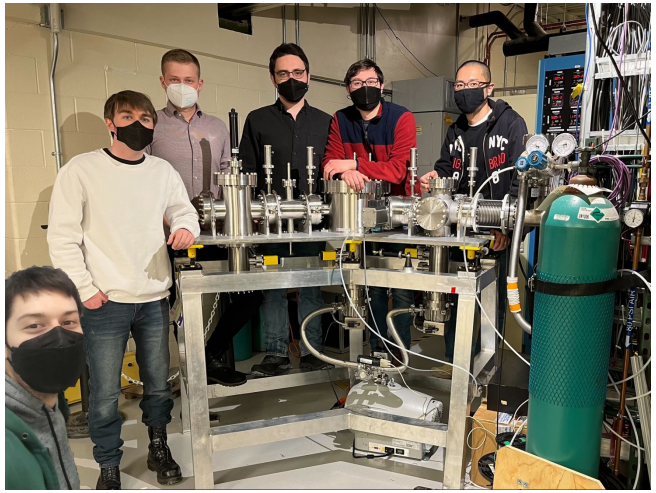

C. Vidal

Small Size – Big Science

COLLAPS

CRIS

RISE @ FRIB



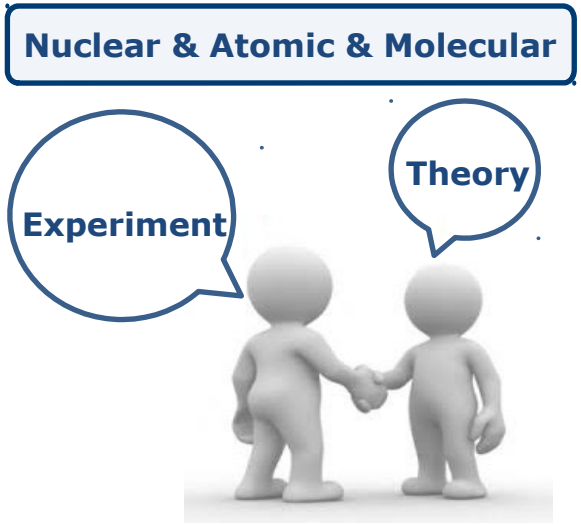
Recent highlights:

- Nature 607, 260 (2022)
- Physical Review Letters 128, 022502 (2022)
- Nature Physics 17, 439 (2021)
- Physical Review Letters 127, 033001 (2021)
- Physical Review Letters 127, 192501 (2021)
- Nature 581, 396 (2020)
- Nature Physics 16, 120 (2020)
- Nature Comm. 11, 3824 (2020)
- Physical Review Letters 124, 132502 (2020)

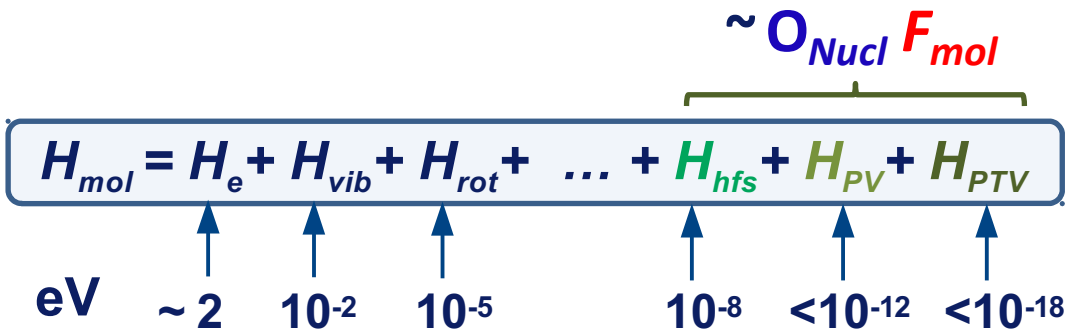
Many exciting results:
www.garciaruizlab.com/publications

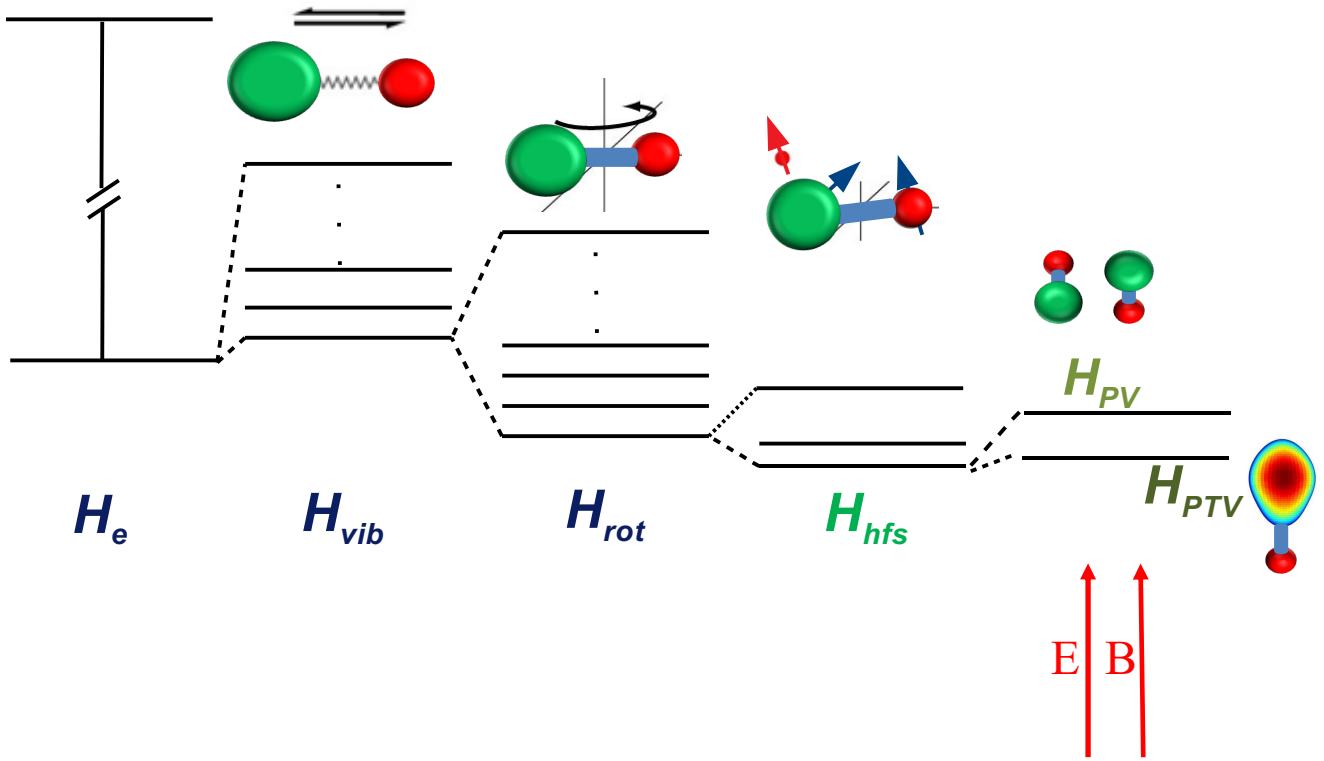
Overview

- Why atoms & molecules?
- Recent results
  - Atoms
  - Molecules
- New Opportunities
- Summary & Outlook



Why atoms & molecules?

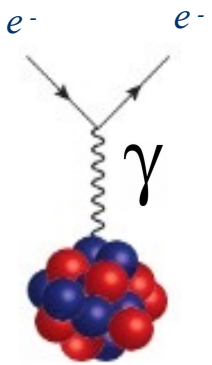




Why atoms & molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

H_{hfs}



P,T-even

- Nuclear structure
- Nuclear matter

Why atoms & molecules?

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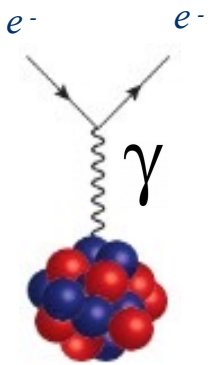

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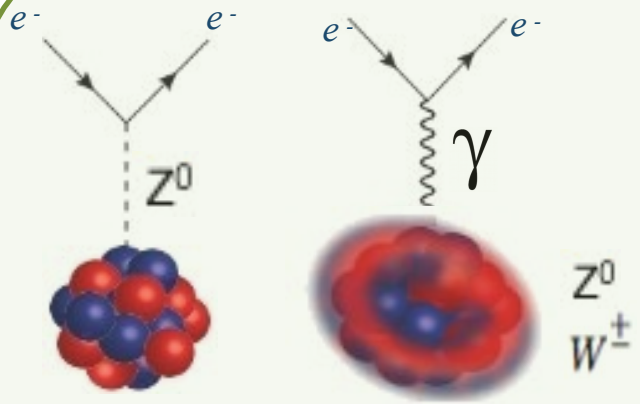
H_{PV}



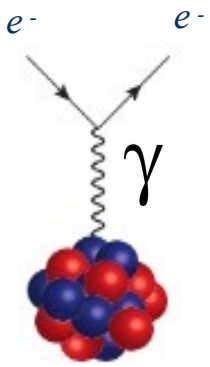
P-violation

- Electro weak structure
- Precision Standard Model tests
- Dark Mater properties?
- New forces?

Why atoms & molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

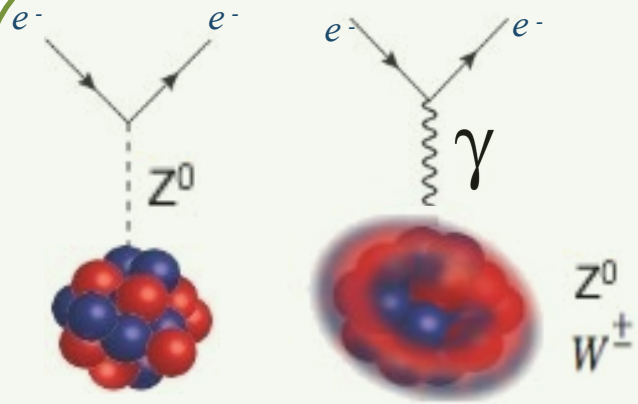
H_{hfs}



P,T-even

- Nuclear structure
- Nuclear matter

H_{PV}



P-violation

- Electro weak structure
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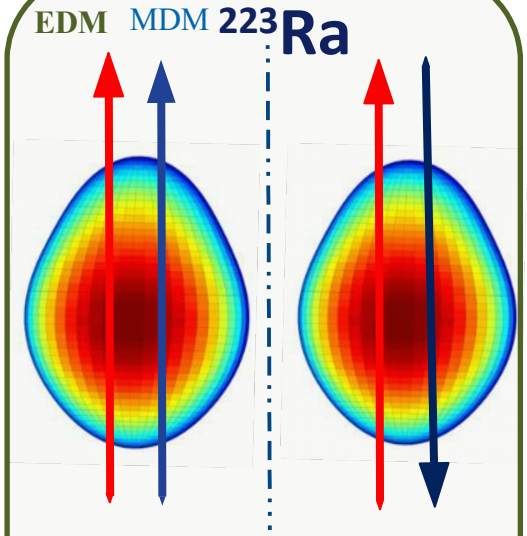
- Dark Mater properties?
- New forces?

H_{PTV}



T-violation

- Matter-antimatter asymmetry
- New particles?

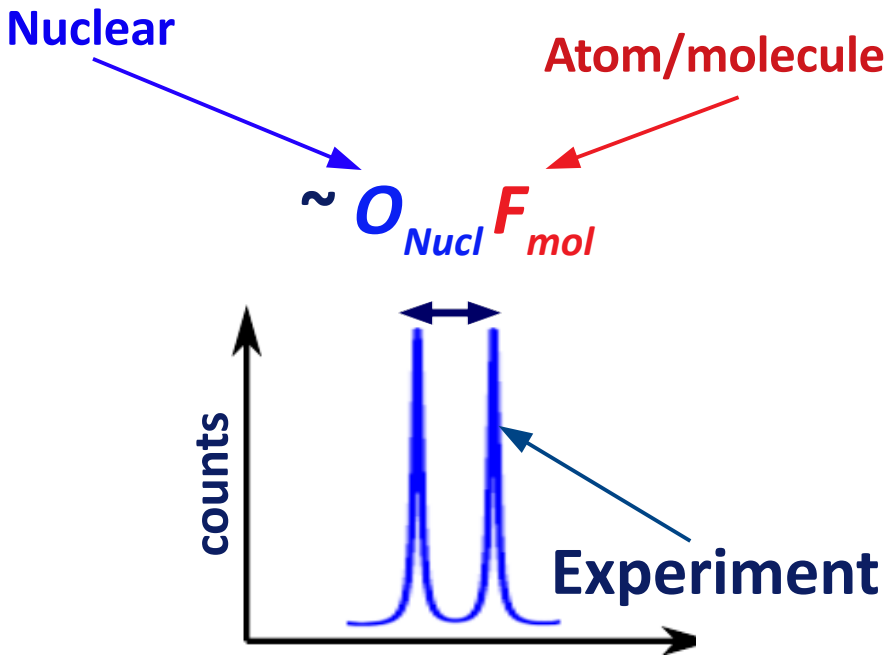
Why atoms & molecules?

$\sim O_{Nucl} F_{mol}$

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

$H_{mol} - H'_{mol} \sim O_{Nucl} F_{mol}$ -> Direct measurements!



Why atoms & molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

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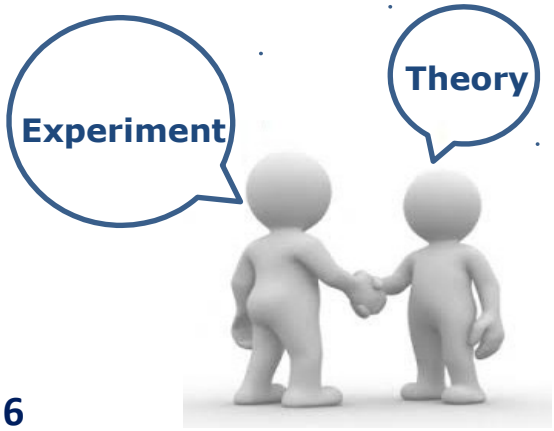
$H_{mol} - H'_{mol} \sim O_{Nucl} F_{mol}$ -> Direct measurements!

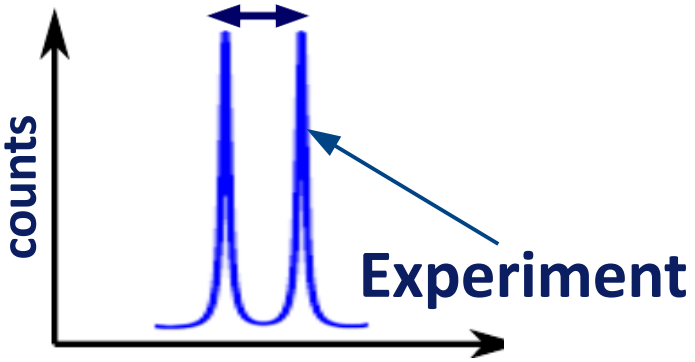
Nuclear

Atom/molecule

$\sim O_{Nucl} F_{mol}$

Nuclear & Atomic & Molecular

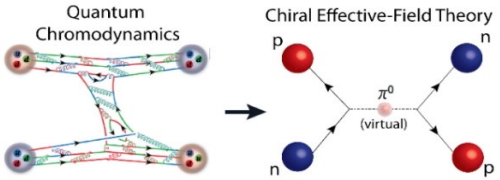




Overview

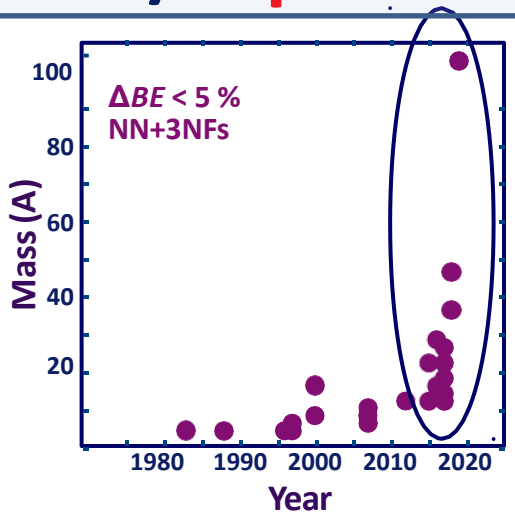
- Why exotic atoms & molecules?
- **Recent results**
  - **Atoms**
  - Molecules
- New Opportunities
- Summary & Outlook

Theoretical/Experimental Progress



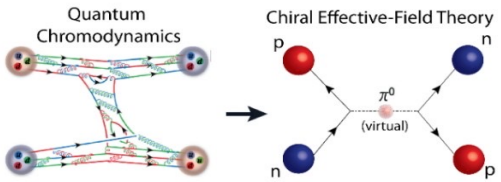
Ab-initio methods

QMC, GFMC, CC, IMSRG, GGF….



- *Can we connect the description of nuclei with QCD?*
- *How do nuclear phenomena emerge?*

Theoretical/Experimental Progress



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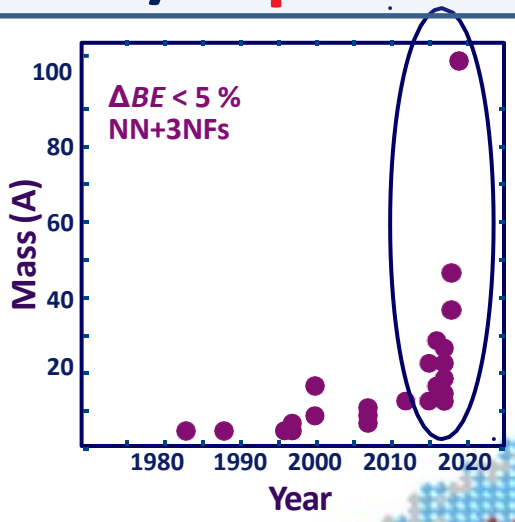
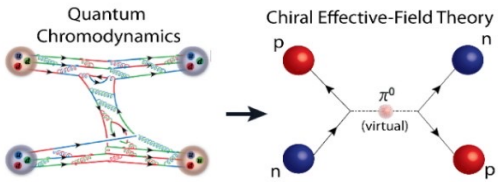


Main focus of our recent work!

Theoretical/Experimental Progress



Ab-initio methods

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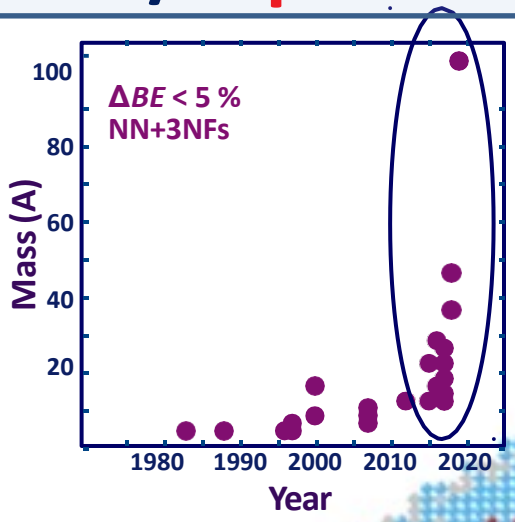


Main focus of our recent work!

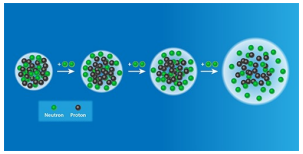
Experimental Challenges:

1. **Small quantities (a few per second)**
2. **Have short lifetimes (< 1s < days)**
3. **Extreme environments (>2000 oC) & highly contaminated (1:10^8)**
4. **High precision is critical (>1:10^6)**

Recent Highlights

Tin (Z=50) region

[Nature 607, 260 (2022)]
[Phys. Rev. Lett. 122, 192502 (2019)]
[Phys Rev X 8, 041005 (2018)]...



Physics VIEWPOINT
Editors' Suggestion | Featured in Physics

Physics VIEWPOINT
Featured in Physics

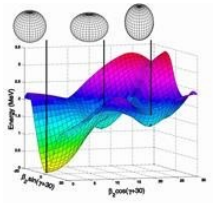
Radium (Z=88)

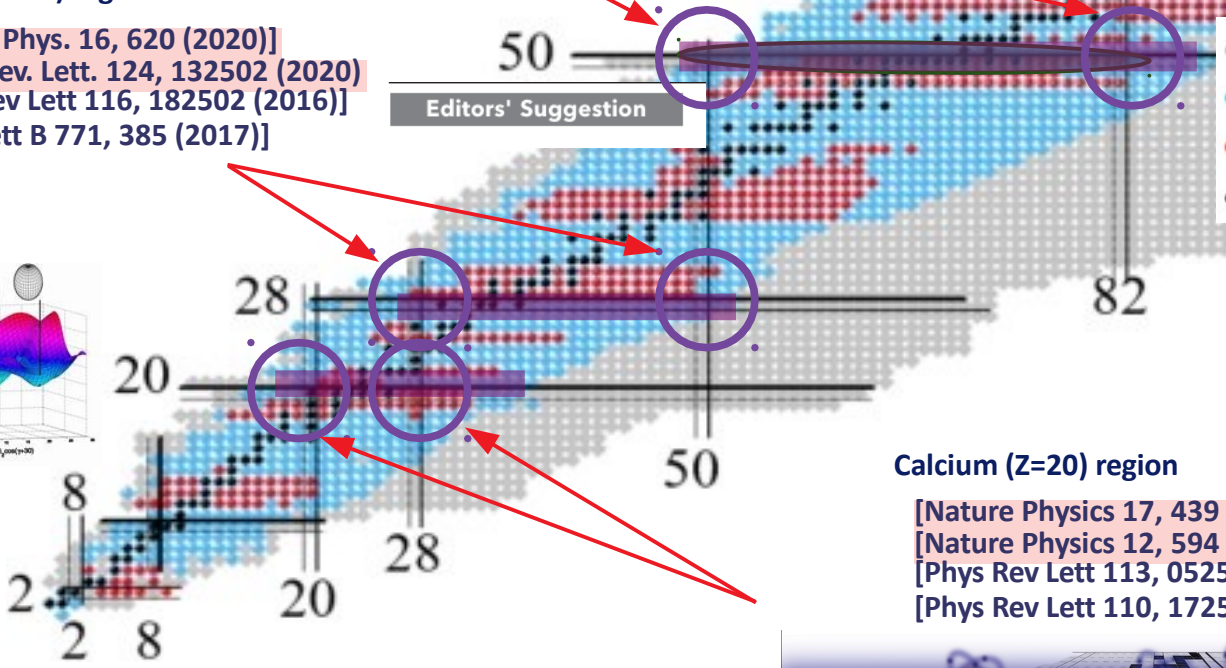
[Phys Rev Lett 127, 033001 (2021)]
[Nature 581, 396 (2020)]

Nickel (Z=28) region

[Nature Phys. 16, 620 (2020)]
[Phys. Rev. Lett. 124, 132502 (2020)]
[Phys Rev Lett 116, 182502 (2016)]
[Phys Lett B 771, 385 (2017)]
...

Editors' Suggestion

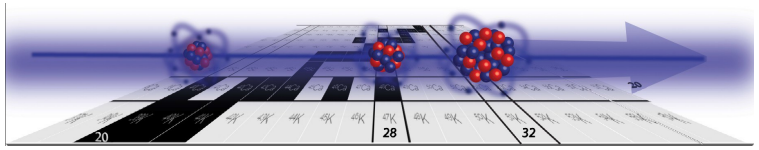




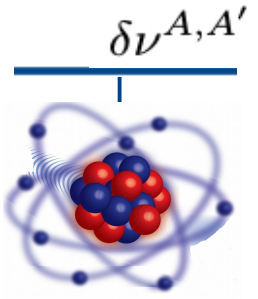
$\langle r^2 \rangle$ I Q μ

Calcium (Z=20) region

[Nature Physics 17, 439 (2021)]
[Nature Physics 12, 594 (2016)]
[Phys Rev Lett 113, 052502 (2014)]
[Phys Rev Lett 110, 172503 (2013)]. . .

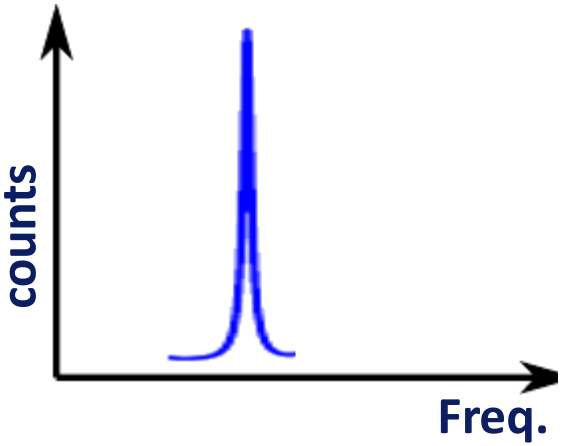


Evolution of the nuclear size away from stability



M_A

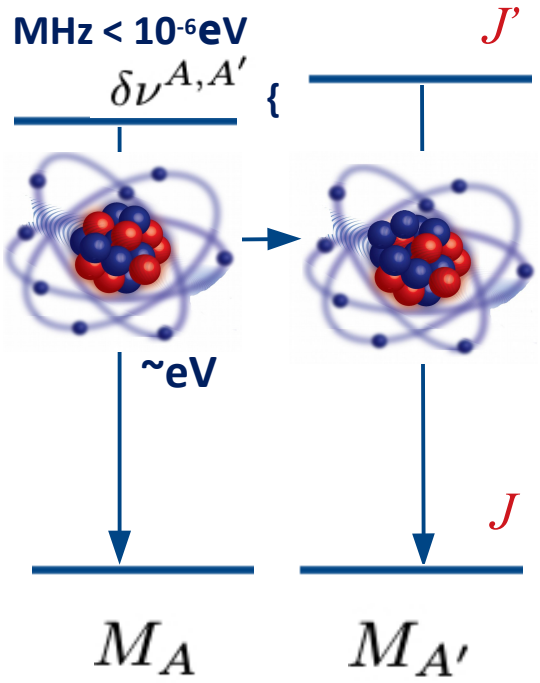
$I = 0$



Evolution of the nuclear size away from stability

Isotope shift

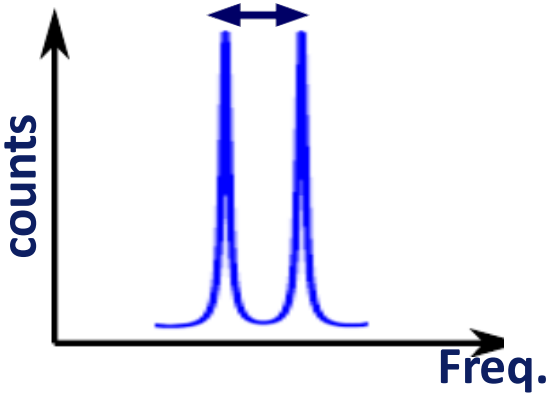
MHz < 10^{-6}eV



$I = 0$

$\sim F\delta\langle r^2\rangle^{A,A'}$

Atom/molecule
Nuclear



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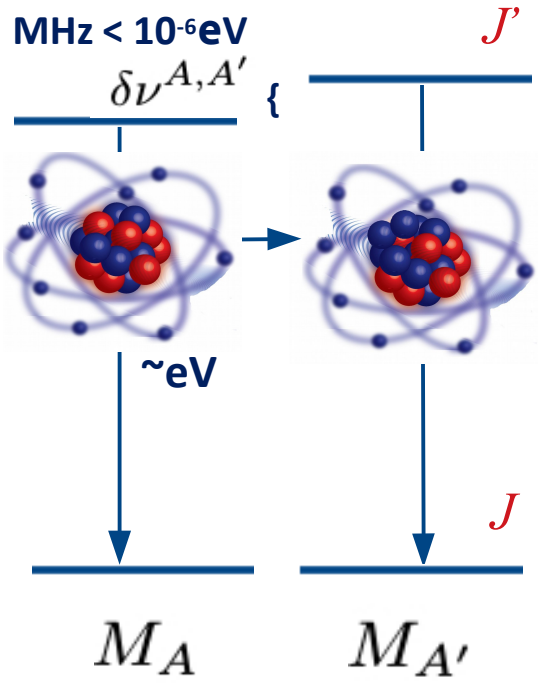

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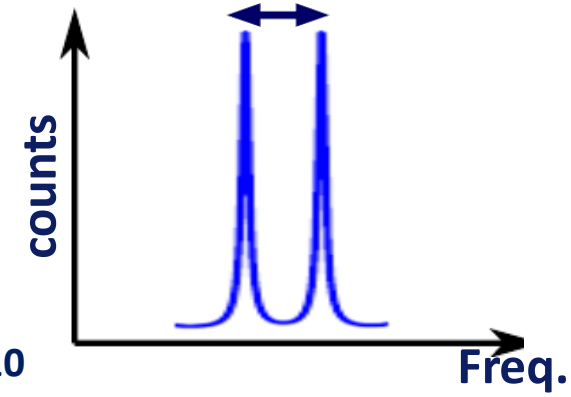
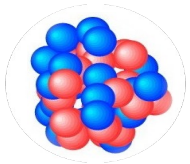


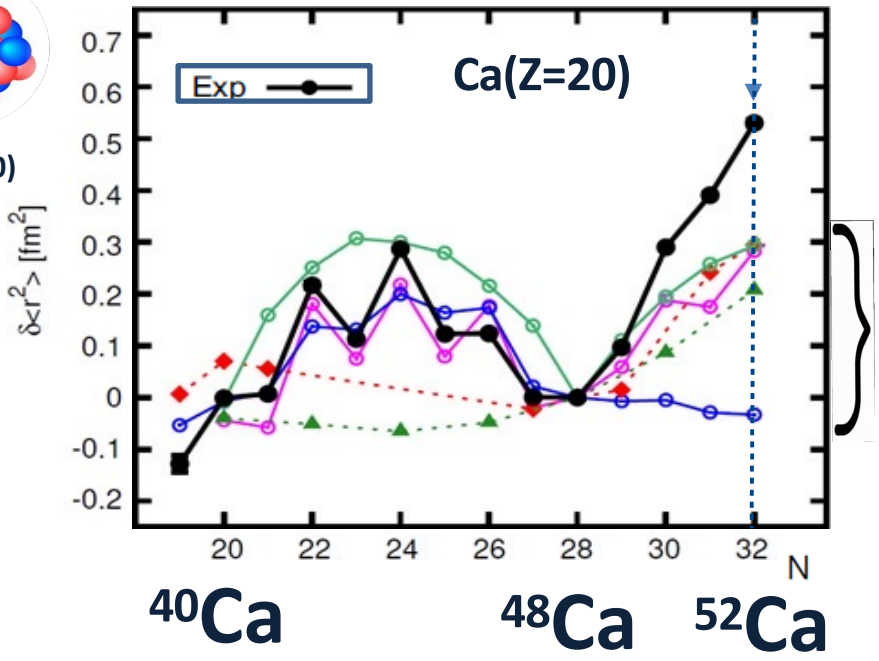
Atom/molecule

Nuclear

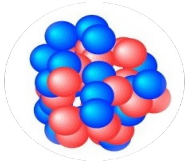


Ca(Z=20)

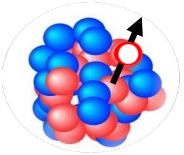
[Garcia Ruiz et al., Nature Phys.12, 594 (2016)]



Evolution of the nuclear size away from stability

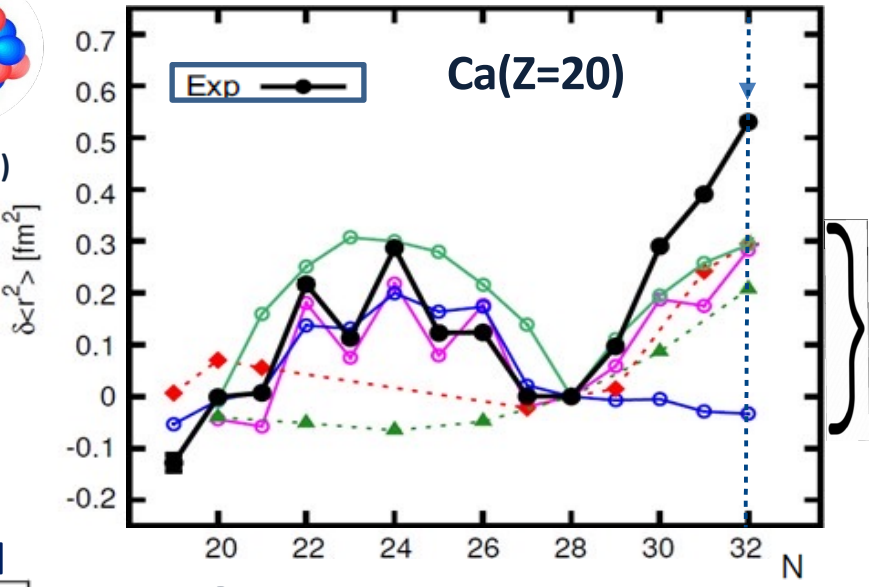


Ca(Z=20)



K(Z=19)

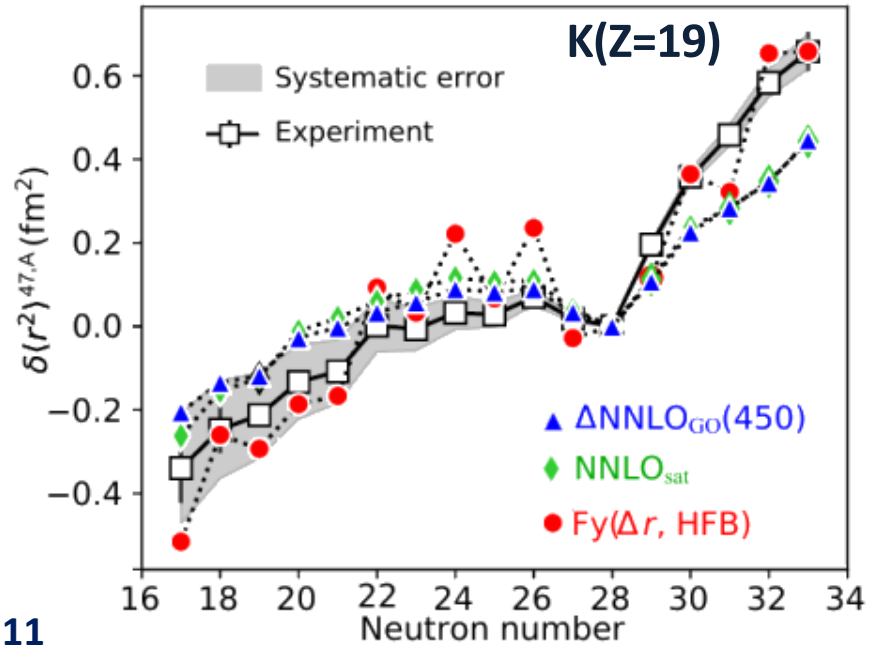
[Garcia Ruiz et al., Nature Phys.12, 594 (2016)]



Theory
(ab-initio, shell-model, DFT, global fits)

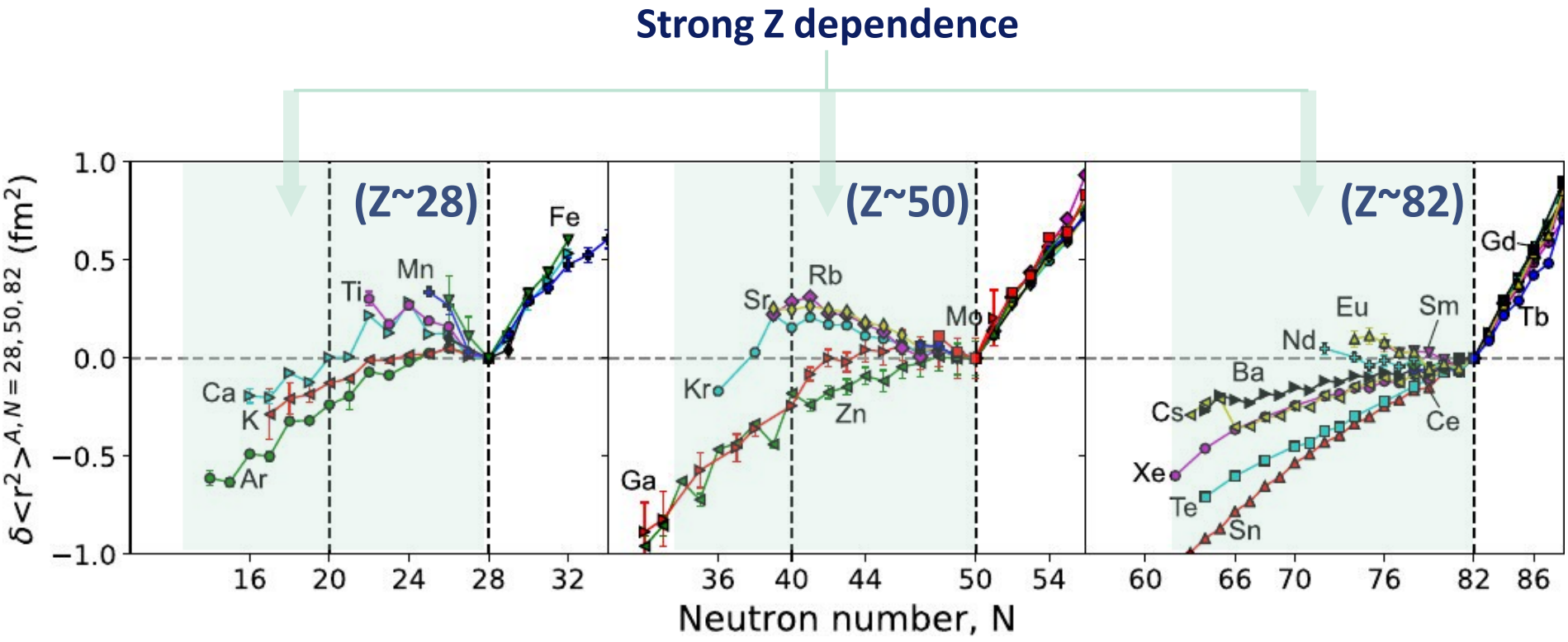
^{40}Ca ^{48}Ca ^{52}Ca

[Koszorus et al. Nature Phys. 17, 439 (2021)]



A. Koszorus

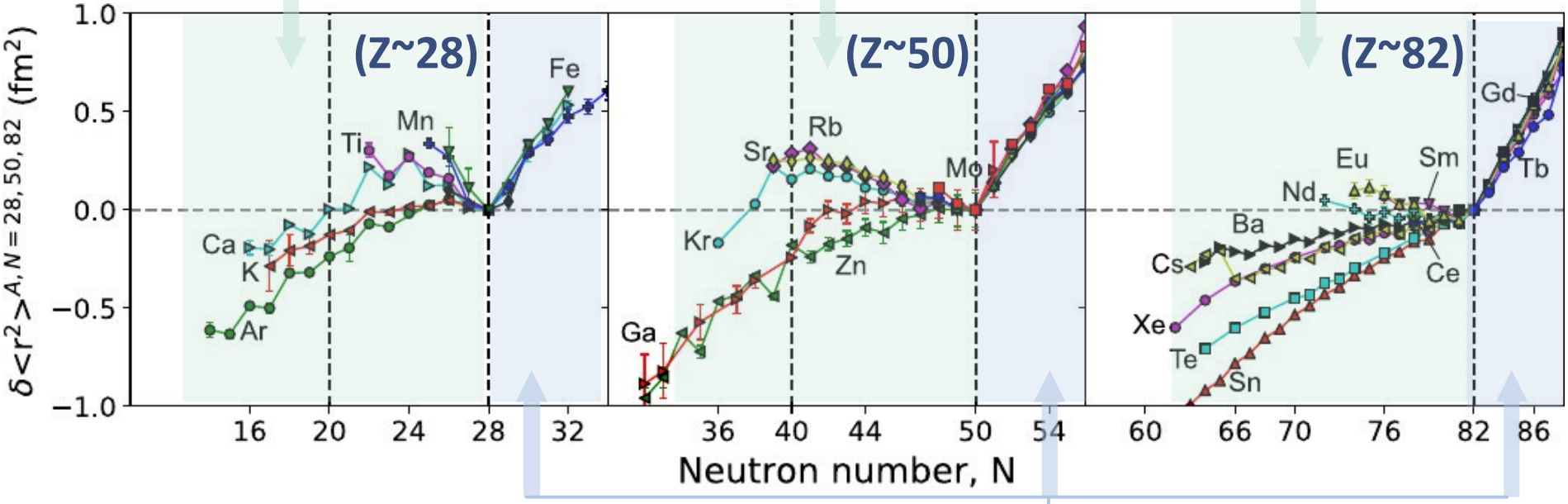
Evolution of the nuclear size away from stability



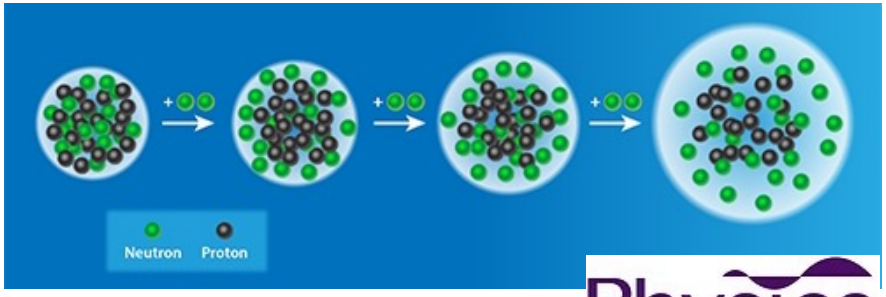
[Koszorus et al. Nature Phys. 17, 439 (2021)]
[Barzakh et a. Phys. Rev. Lett. 127, 192501 (2021)]
[Reponen et al. Nature Comm. 12, 4596 (2021).
[Degroote et al. Nature Phys. 16, 620 (2020)]
[Kaufmann Phys. Rev. Lett. 124, 132502 (2020)]
[Garcia Ruiz & Vernon EPJ A 56, 136 (2020)]
[Gorges et al. Phys. Rev. Lett. 122, 192502 (2019)]
[Garcia Ruiz et al. Nature Phys. 12, 594 (2016)]

Evolution of the nuclear size away from stability

Strong Z dependence



Similar trends for neutron-rich



[Koszorus et al. Nature Phys. 17, 439 (2021)]
[Barzakh et a. Phys. Rev. Lett. 127, 192501 (2021)]
[Reponen et al. Nature Comm. 12, 4596 (2021).
[Degroote et al. Nature Phys. 16, 620 (2020)]
[Kaufmann Phys. Rev. Lett. 124, 132502 (2020)]
[Garcia Ruiz & Vernon EPJ A 56, 136 (2020)]
[Gorges et al. Phys. Rev. Lett. 122, 192502 (2019)]
[Garcia Ruiz et al. Nature Phys. 12, 594 (2016)]

Radii of mirror nuclei & equation of state

Can we use the properties of nuclei to constraint the properties of neutron stars?

Talks: Juliette Mammei
Christian Drischler

E.g. PREX: neutron skin thickness of ^{208}Pb
[Adhikari et al. Phys. Rev. Lett. 126, 172502 (2021)]

Equation of state of nuclear matter

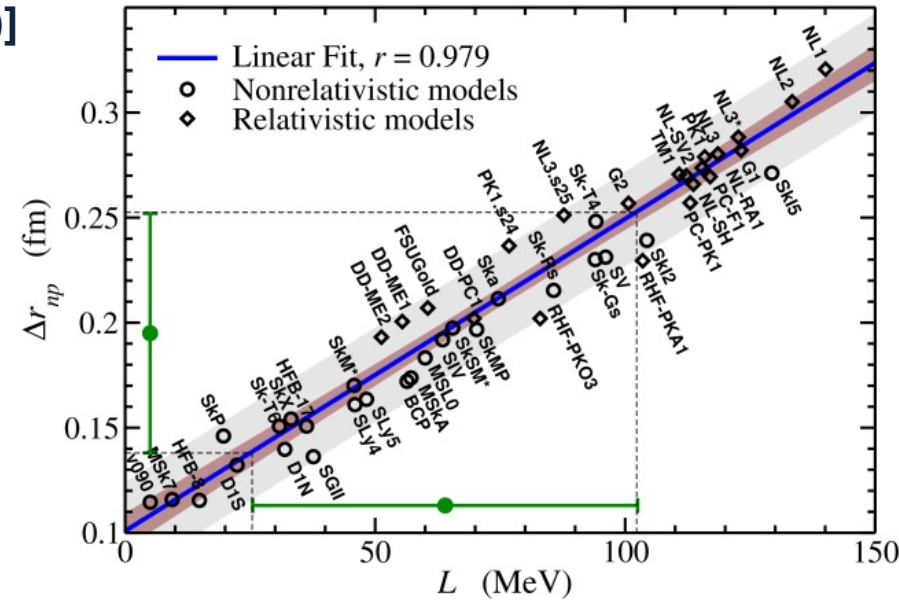
$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

$$E_{sym}(\rho) = S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \cdots$$

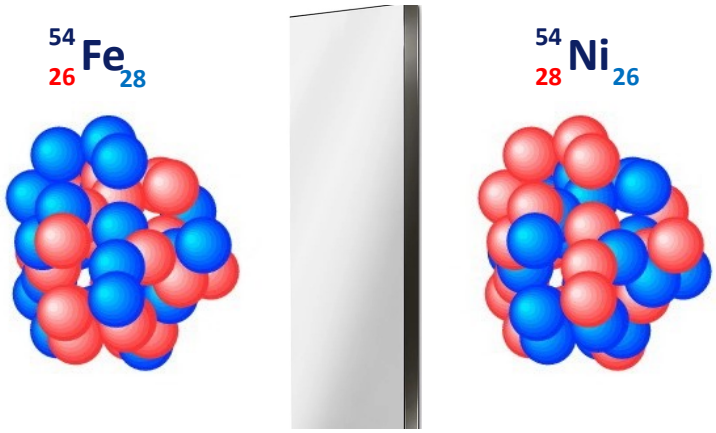
Symmetry energy

Slope ?

[Roca-Maza et al. PRL 106, 252501 (2011)]



Radii of mirror nuclei & equation of state



[S. Pineda Phys. Rev. Lett. 127, 182503 (2021)]

[Brown. Phys. Rev. Lett. 119, 122502 (2017)]
[Yang & Piekarewicz, PRC 97, 014314 (2018)]

$$\Delta R_{\rm ch} = R(^{54}{\rm Ni}) - R(^{54}{\rm Fe})$$

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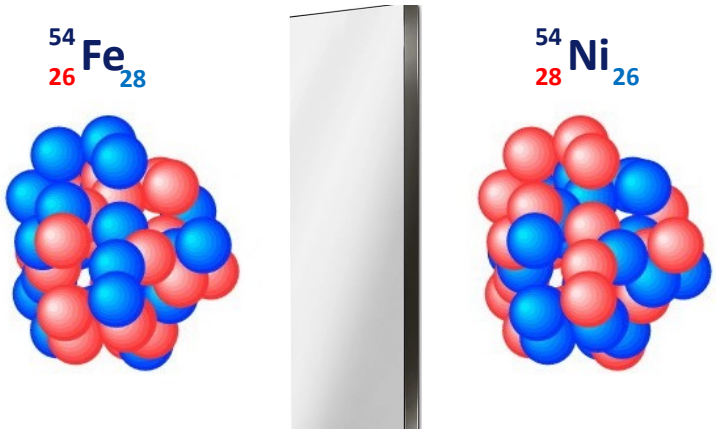

[Brown. Phys. Rev. Lett. 119, 122502 (2017)]
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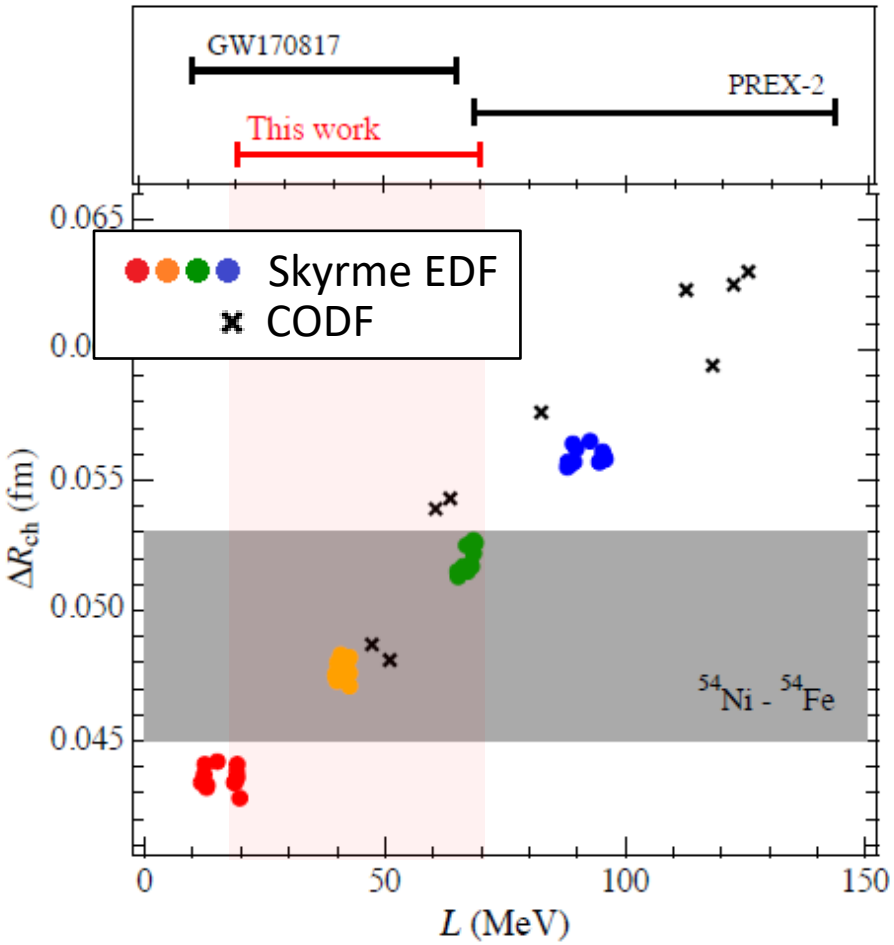
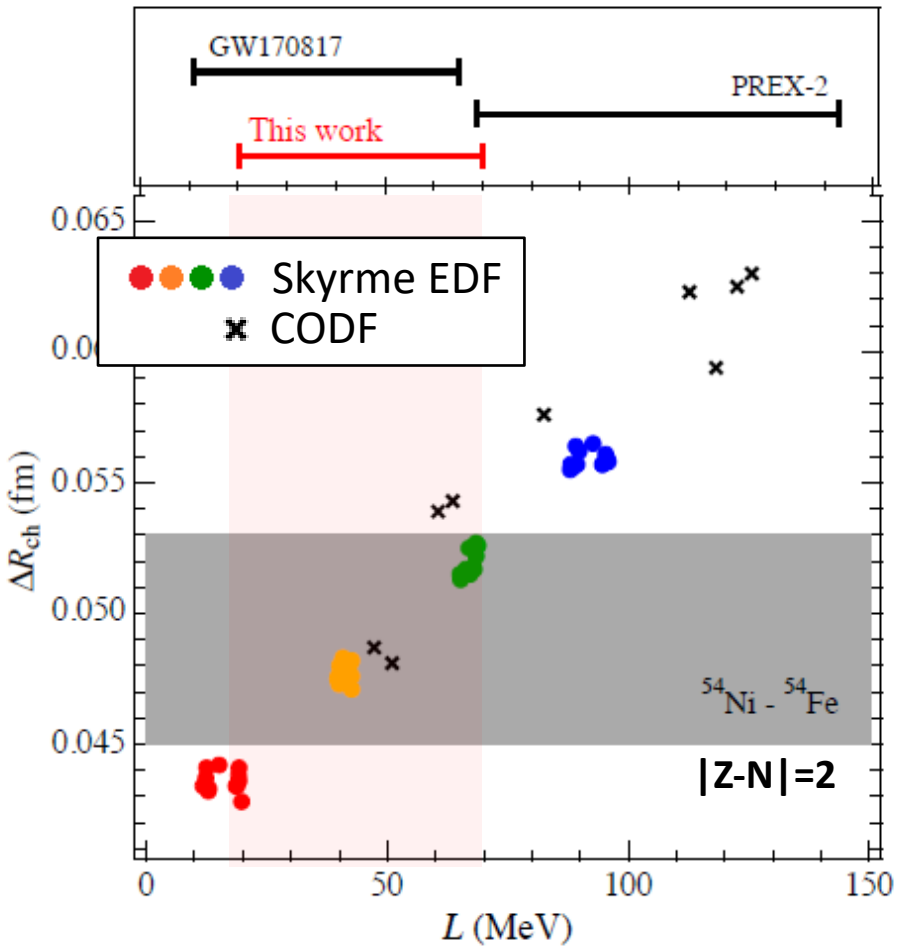


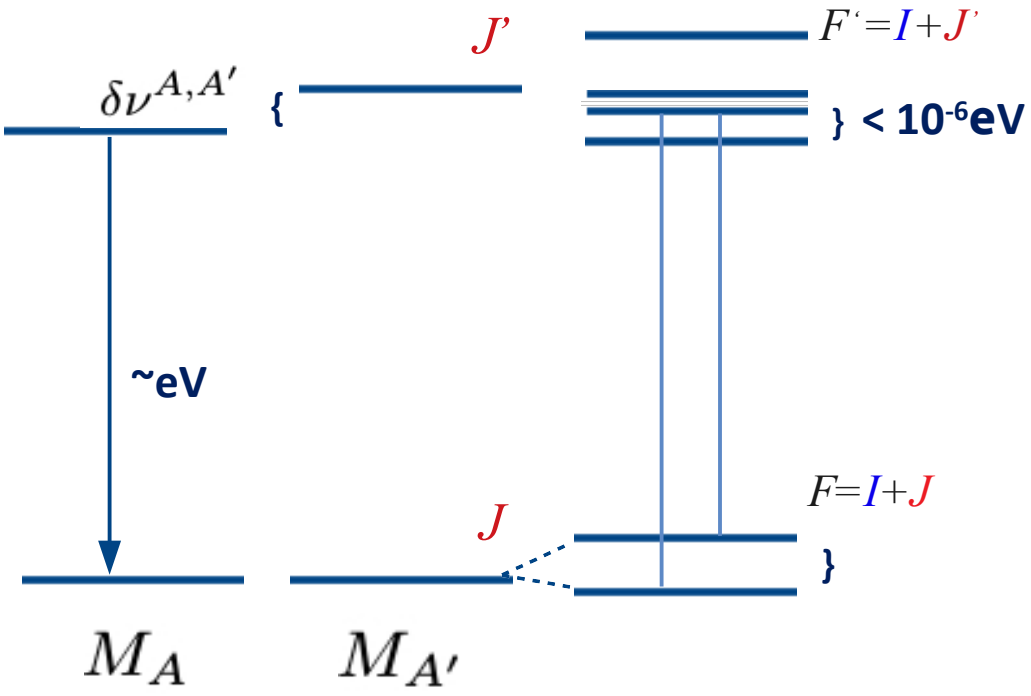
Radii of mirror nuclei & equation of state

[S. Pineda Phys. Rev. Lett. 127, 182503 (2021)]



FRIB

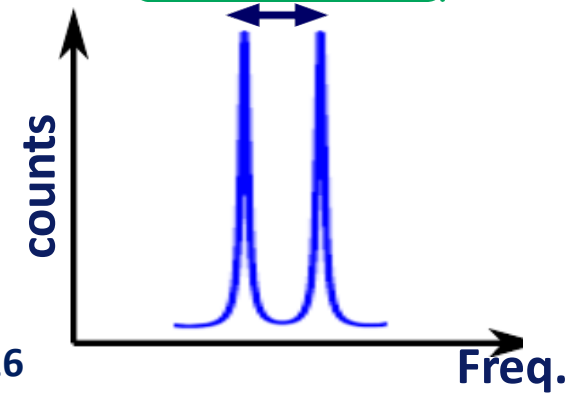
Hyperfine Structure



$I = 0$ $I > 0$

~ $\mu B + Q \nabla E$

Atom/molecule
Nuclear

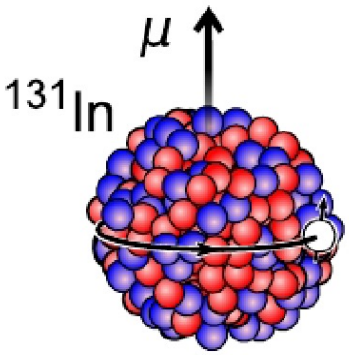


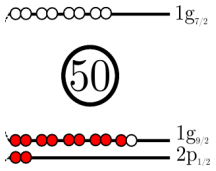
Electromagnetic structure
Rms charge radii: $\langle r^2 \rangle$
Nuclear spin: I
Magnetic moment: μ
Quadrupole moment : Q

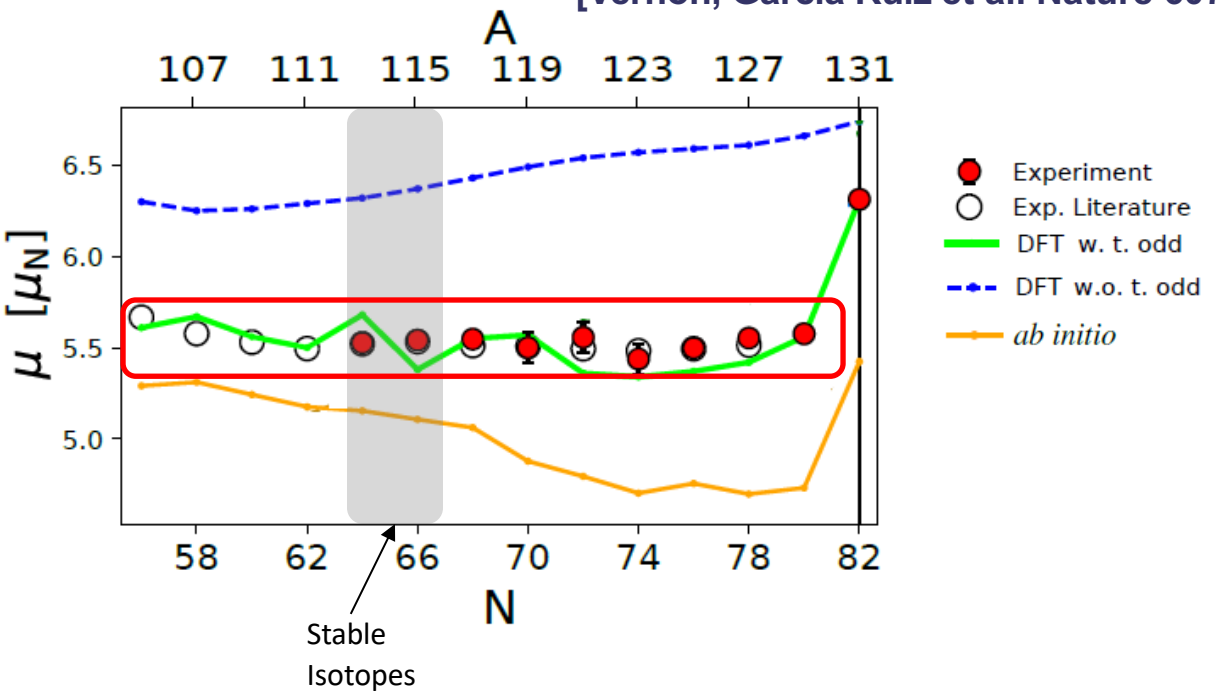
Simple Structure of Complex Nuclei

"Indium isotopes (Z=49): A text book example" Heyde. "*The Nuclear Shell Model*". Springer (1995)

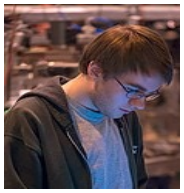
[Vernon, Garcia Ruiz et al. Nature 607, 260 (2022)]







Challenging our textbook nuclear physics!

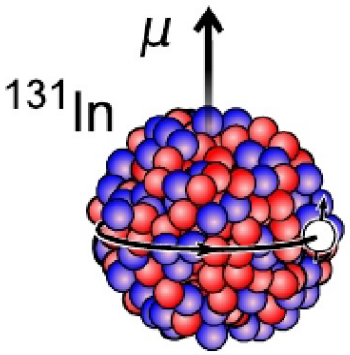


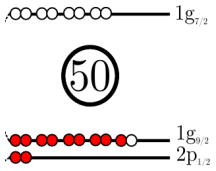
A. Vernon

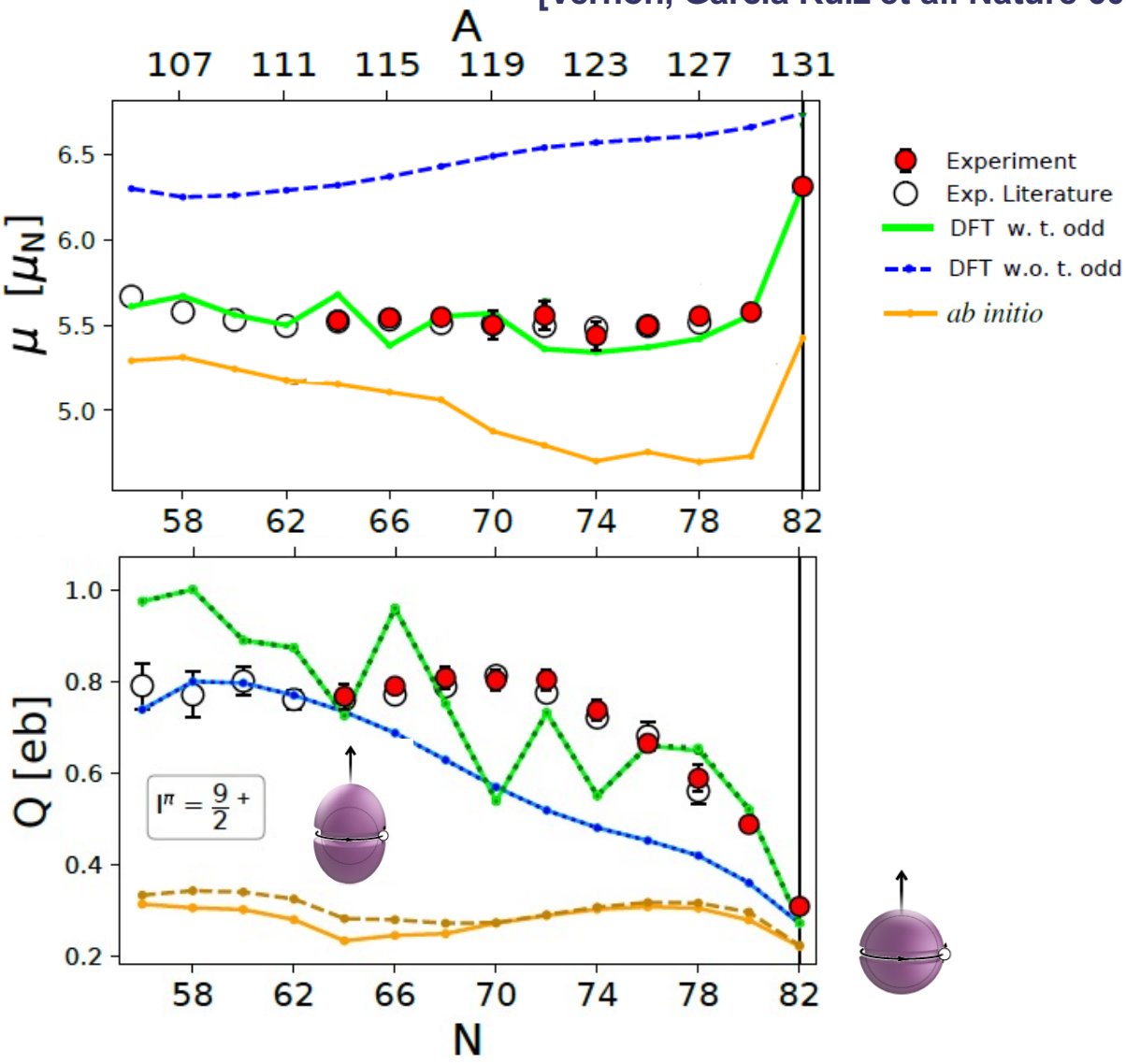
Simple Structure of Complex Nuclei

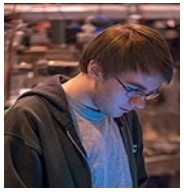
"Indium isotopes (Z=49): A text book example" Heyde. "*The Nuclear Shell Model*". Springer (1995)

[Vernon, Garcia Ruiz et al. Nature 607, 260 (2022)]







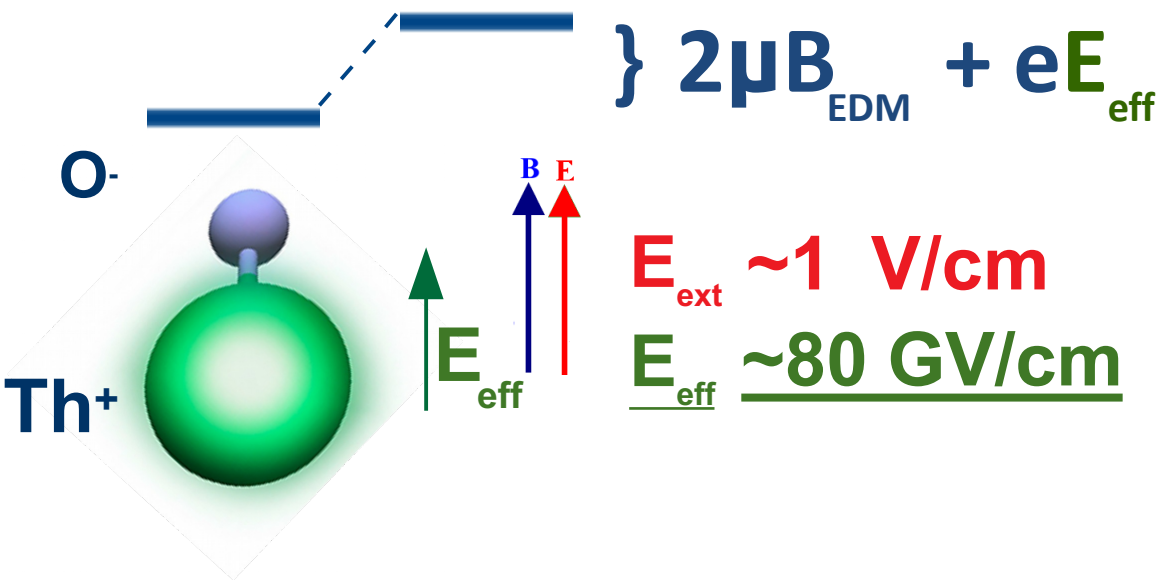


A. Vernon

Overview

- Why exotic atoms & molecules?
- **Recent results**
  - Atoms
  - **Molecules**
- New Opportunities (MIT & FRIB)
- Summary & Outlook

Molecules for EDMs measurements

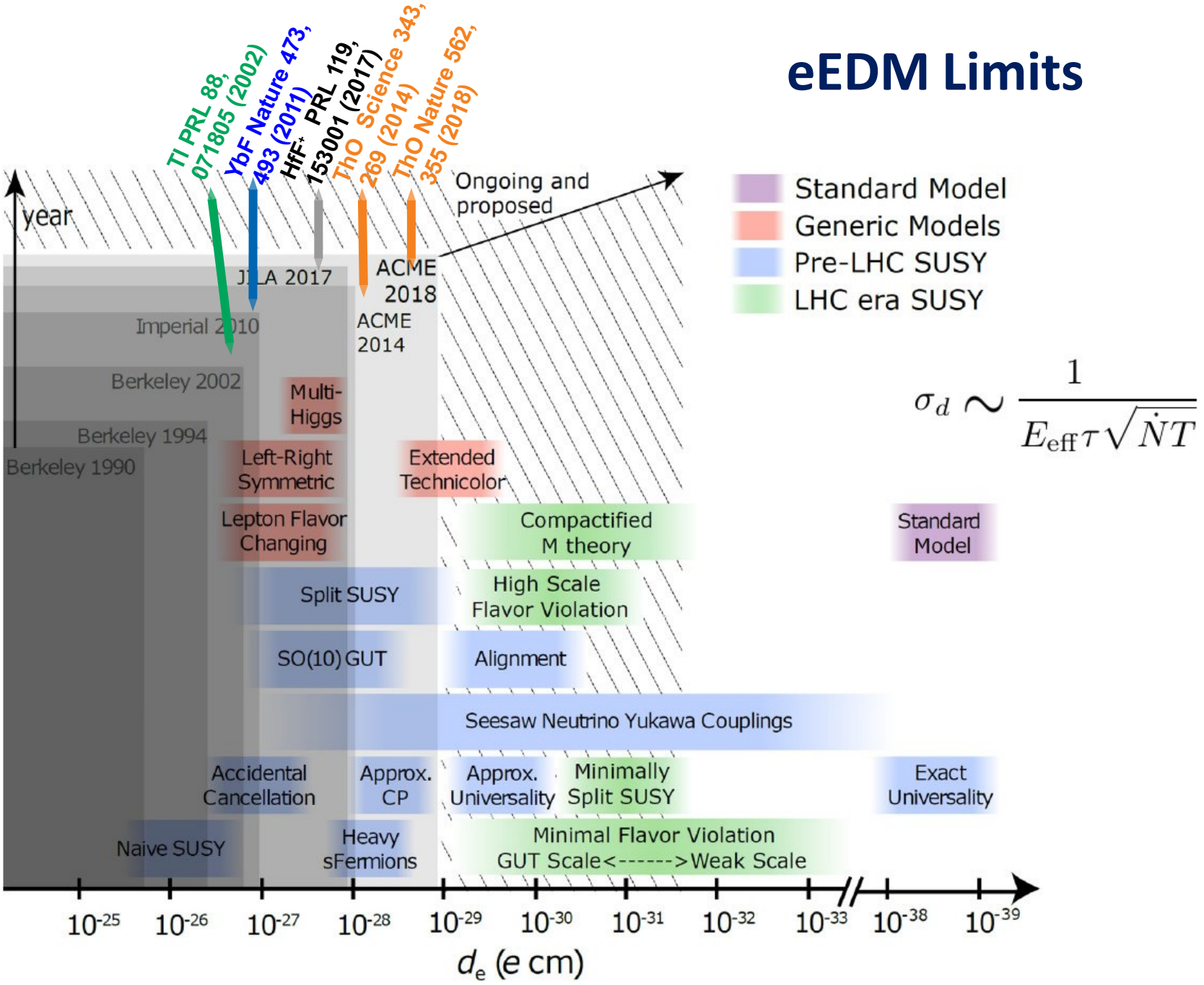


$|d_e| \leq 1.1 \times 10^{-29}\ e \cdot cm$

Molecular enhancement > 10^3

[ACME, Nature 562, 355 (2018)]
[Baron et al. Science 343, 269 (2014)]
[Sandars Phys. Rev. Lett. 18, 1396 (1967)]

eEDM Limits



$$\sigma_d \sim \frac{1}{E_{\text{eff}}\tau\sqrt{\dot{N}T}}$$

[Source: D. DeMille. Manipulating Quantum Systems: An Assessment of Atomic,Molecular, and Optical Physics in the United States (2019)]

Recent Results (RaF)

$\sim O_{Nucl} F_{mol}$

$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$

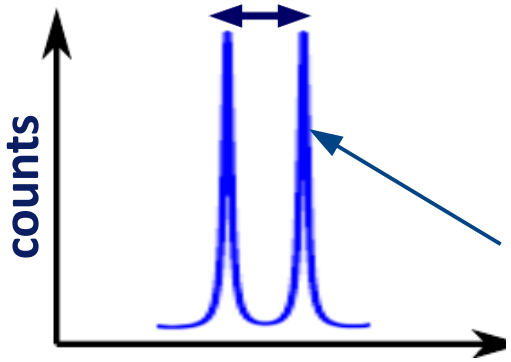
eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

Atom/molecule

$\sim Z^c/(E_+^N - E_-^N)$

$E_+^N - E_-^N \sim 10^{-5}$ eV

$\sim O_{Nucl} F_{mol}$



Nuclear *x* **Molecule**

Molecule	$> 10^3$

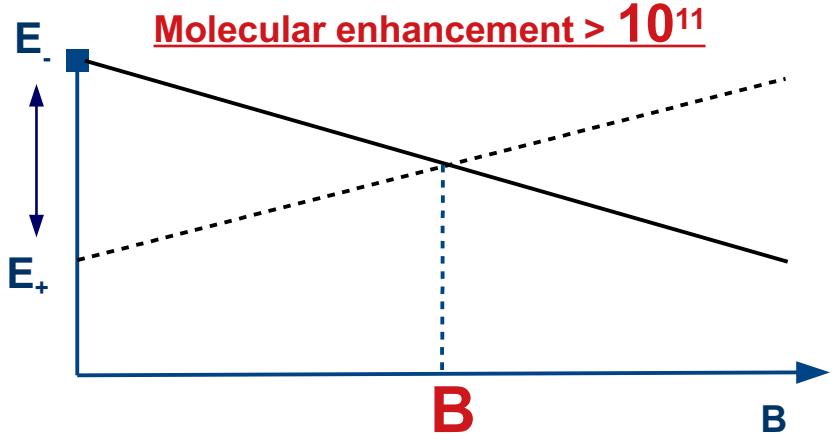
Molecules: Extreme sensitivity to Hadronic PV

Demille's Talk: *ZOMBIES: an experiment to measure nuclear anapole moments*

Molecule:

$$H_{PV} \sim F(Z^c) / (E_+^e - E_-^e)$$

Molecular enhancement > 10^{11}

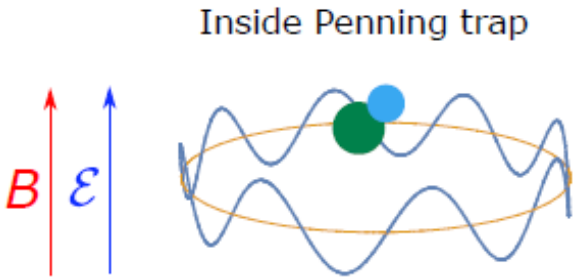


- Parity and Time reversal violation > 10^3
- Parity violation > 10^{11}
-

[Altunas et al. Phys. Rev. Lett. 120, 142501 (2018)]

Molecules: Extreme sensitivity to Hadronic PV

In collaboration with: D. Demille's group (U Chicago & ANL), J. Dilling (TRIUMF), N. Hutzler (Caltech), K. Blaum (MPIK), R. Ringle (FRIB)




J. Karthein

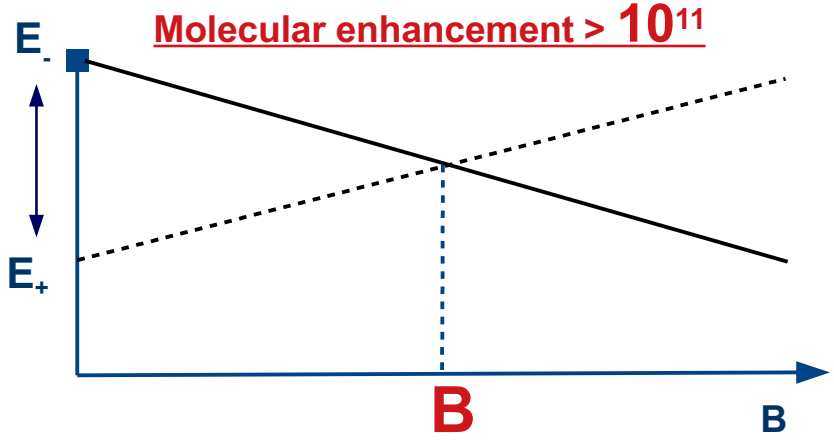

S. Udrescu


S. Moroch

Molecule:

$H_{PV} \sim F(Z^c) / (E_+^e - E_-^e)$

Molecular enhancement > 10^{11}



- Parity and Time reversal violation > 10^3
- Parity violation > 10^{11}
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[Altunas et al. Phys. Rev. Lett. 120, 142501 (2018)]

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eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

Nuclear

$\sim Z^a A^b \beta_2 \beta_3 / (E_+^N - E_-^N)$

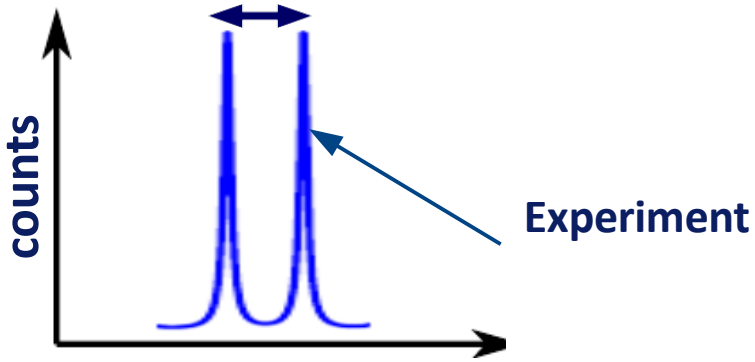
Atom/molecule

$\sim Z^c / (E_+^N - E_-^N)$

$E_+^N - E_-^N < 10^{-5}$ eV

$\sim O_{Nucl} F_{mol}$

Talk: Jaideep Singh



Radioactive molecules=> Best of all worlds!

Recent Results (RaF)

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

$\sim O_{Nucl} F_{mol}$

	H_{hfs}	H_{PV}	H_{PTV}
eV	10^{-8}	$<10^{-12}$	$<10^{-18}$

- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ $\beta_2\ \beta_3 > 0$

Nuclear

$\sim Z^a A^b \beta_2\beta_3 / (E_+^N - E_-^N)$

Atom/molecule

$\sim Z^c / (E_+^N - E_-^N)$

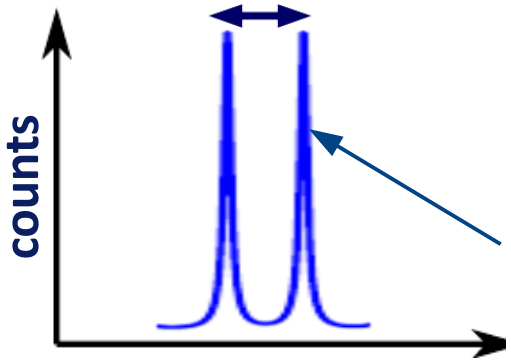
$E_+^N - E_-^N < 10^{-5}$ eV

$\sim O_{Nucl} F_{mol}$

^{225}Ra

Talk: Jaideep Singh

[Gaffney et al. Nature 497, 199 (2013)]



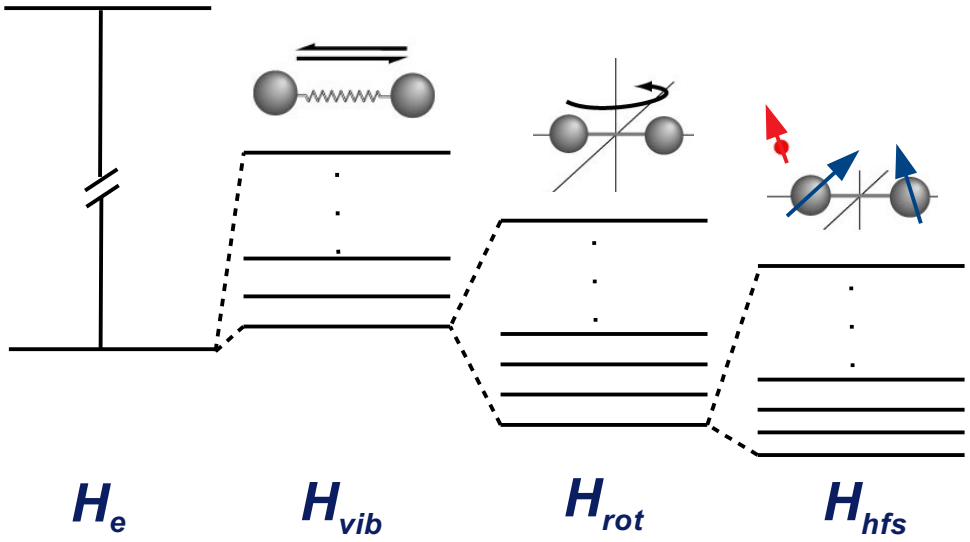
Nuclear x Molecule

Molecule	$> 10^3$
Nuclear amplification	$> 10^3$

Radioactive molecules=> Best of all worlds!

Recent Results (RaF)

[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]



$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

	H_e	H_{vib}	H_{rot}	H_{hfs}	H_{PV}	H_{PTV}
eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-15}$

S. Udrescu

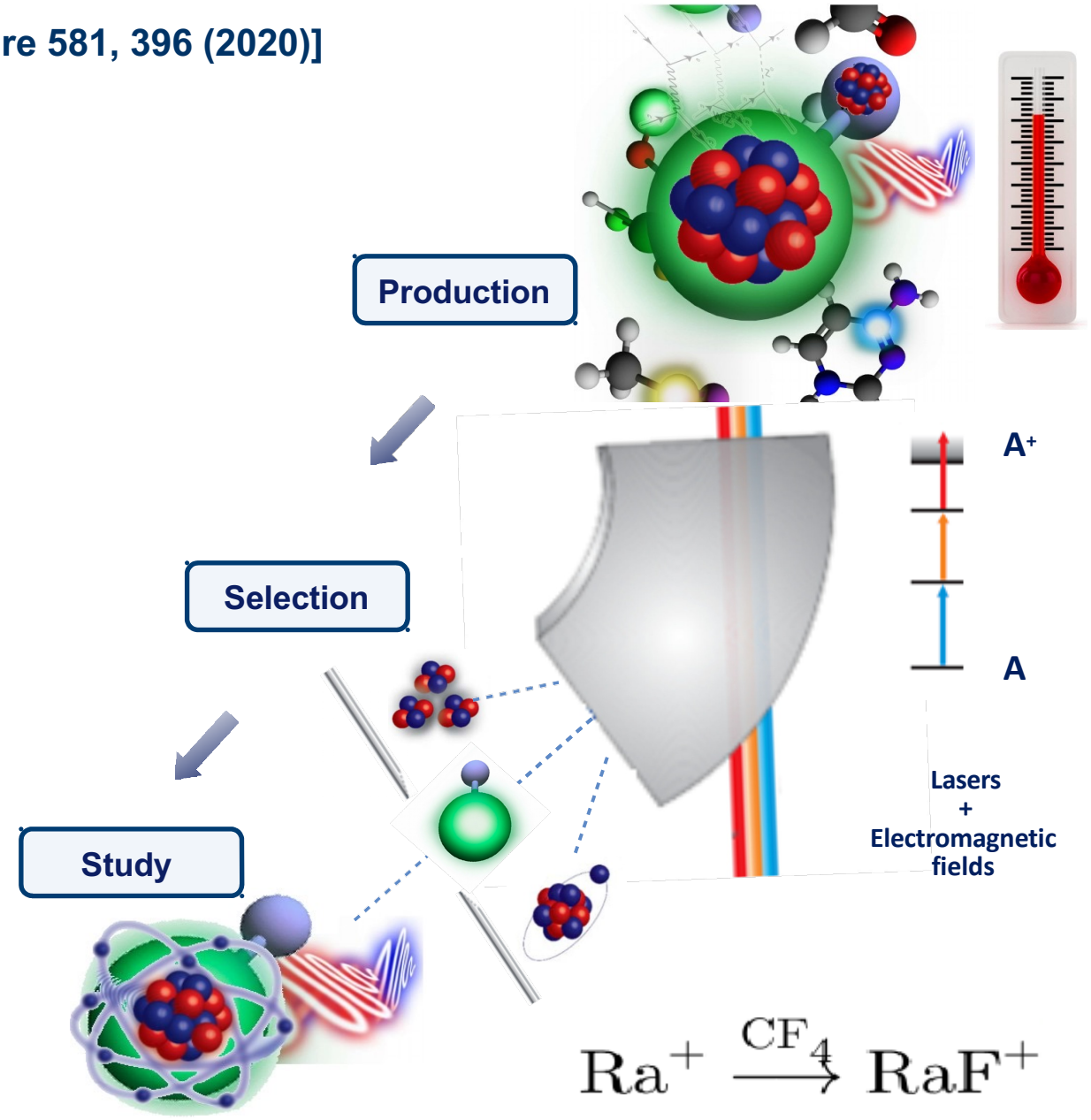
A. Brinson

S. Wilkins

Recent Results (RaF)

[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]

Traps
+
lasers



Experimental details

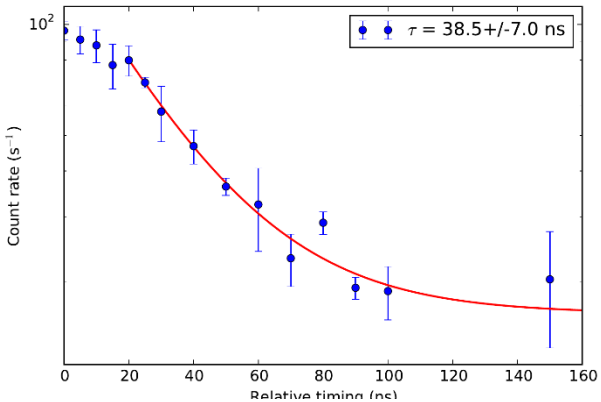
Warning:

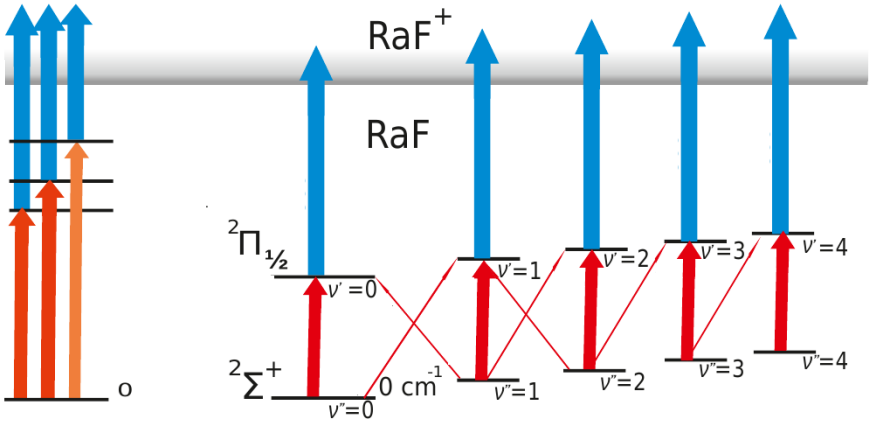
The following video contains bright, flashing lights that may cause discomfort or seizures for those with photosensitive epilepsy.

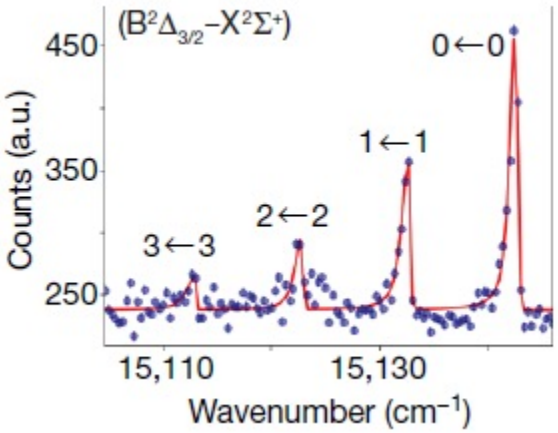
We overlap the isotopes with lasers

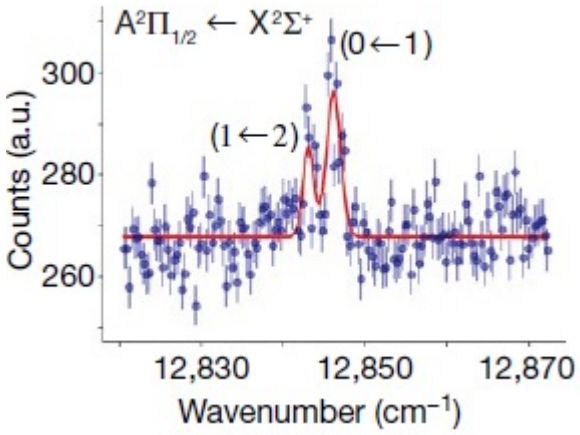
Recent Results (RaF)

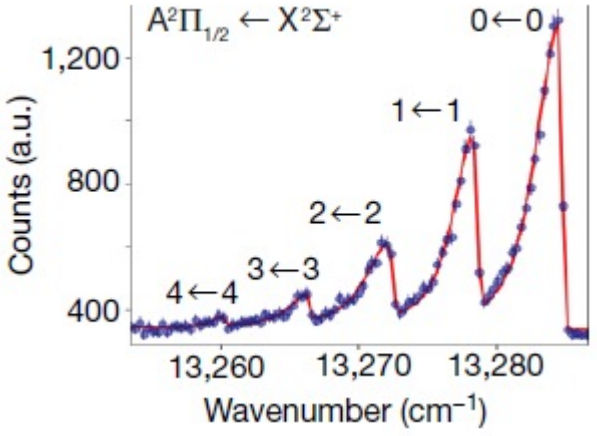
I. Low-lying structure
II. Feasibility of laser cooling?
- 1. Dominant f_{00}? → $f_{00}/f_{ij} > 0.97$
  2. Short-lived excited state ($T_{1/2}$)?→$T_{1/2} < 50$ ns
  3. Electronic states of lower energy (E)?→ 2000 cm^{-1} above











[Garcia Ruiz et al. Nature 581, 396 (2020)]

Recent Results (RaF)

"Hot" molecules can be super cool!

nature

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Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz ✉, R. Berger ✉, […]

Nature **581**, 396–400 (2020) | Cite this article

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DOI:10.1063/PT.6.1.20200611a

11 Jun 2020 in Research & Technology

Spectroscopy of molecules with unstable nuclei

Pinning down the energy transitions of radium monofluoride, and eventually other short-lived molecules, could reveal the ways they are influenced by the properties of heavy radioactive nuclei.

Andrew Grant

physicsworld

ATOMIC AND MOLECULAR | RESEARCH UPDATE

Exotic radioactive molecules could reveal physics beyond the Standard Model

05 Jun 2020

CHEMISTRY WORLD

Molecular experiments hope to reveal new physics

BY ANDY EXTANCE | 5 JUNE 2020

Detecting extremely short-lived radium fluoride can explore standard model's limits

✓ ✓

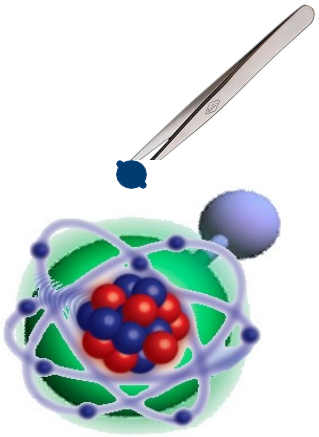
$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-15}$

S. Udrescu

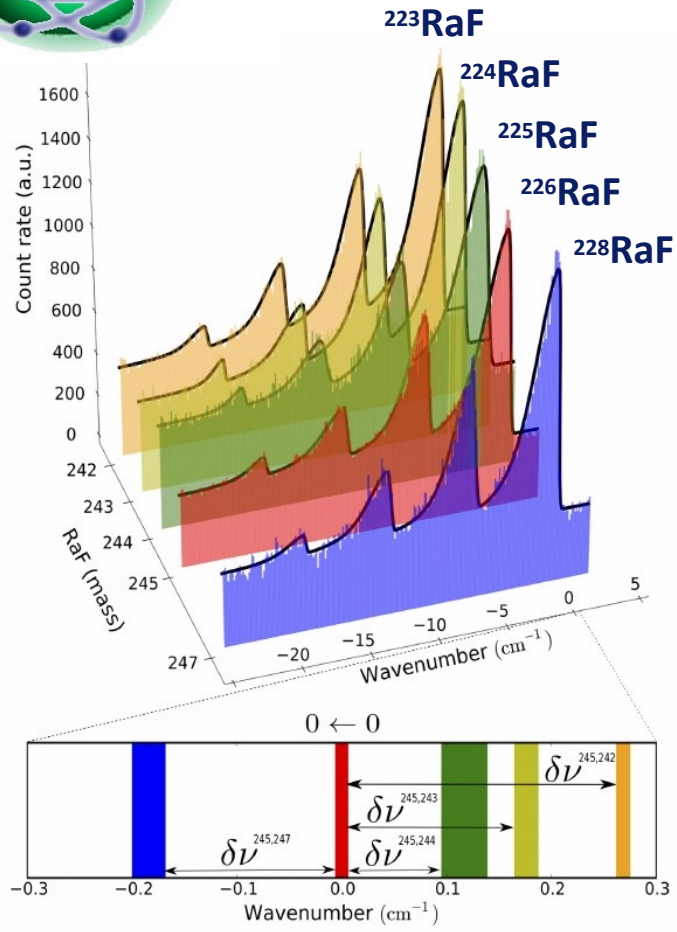
S. Wilkins

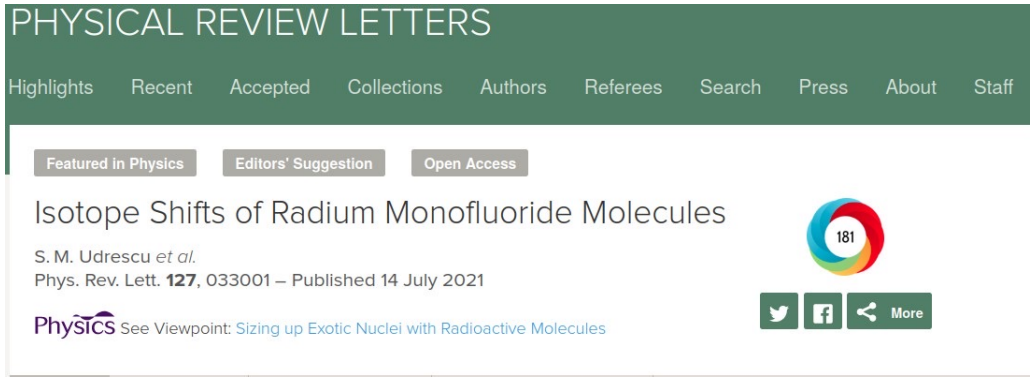
Recent Results (RaF)



New opportunities for nuclear structure studies of the heaviest elements (e.g. ThO, PaO,...)

[Udrescu et al. Phys. Rev. Lett. 127, 033001 (2021)]



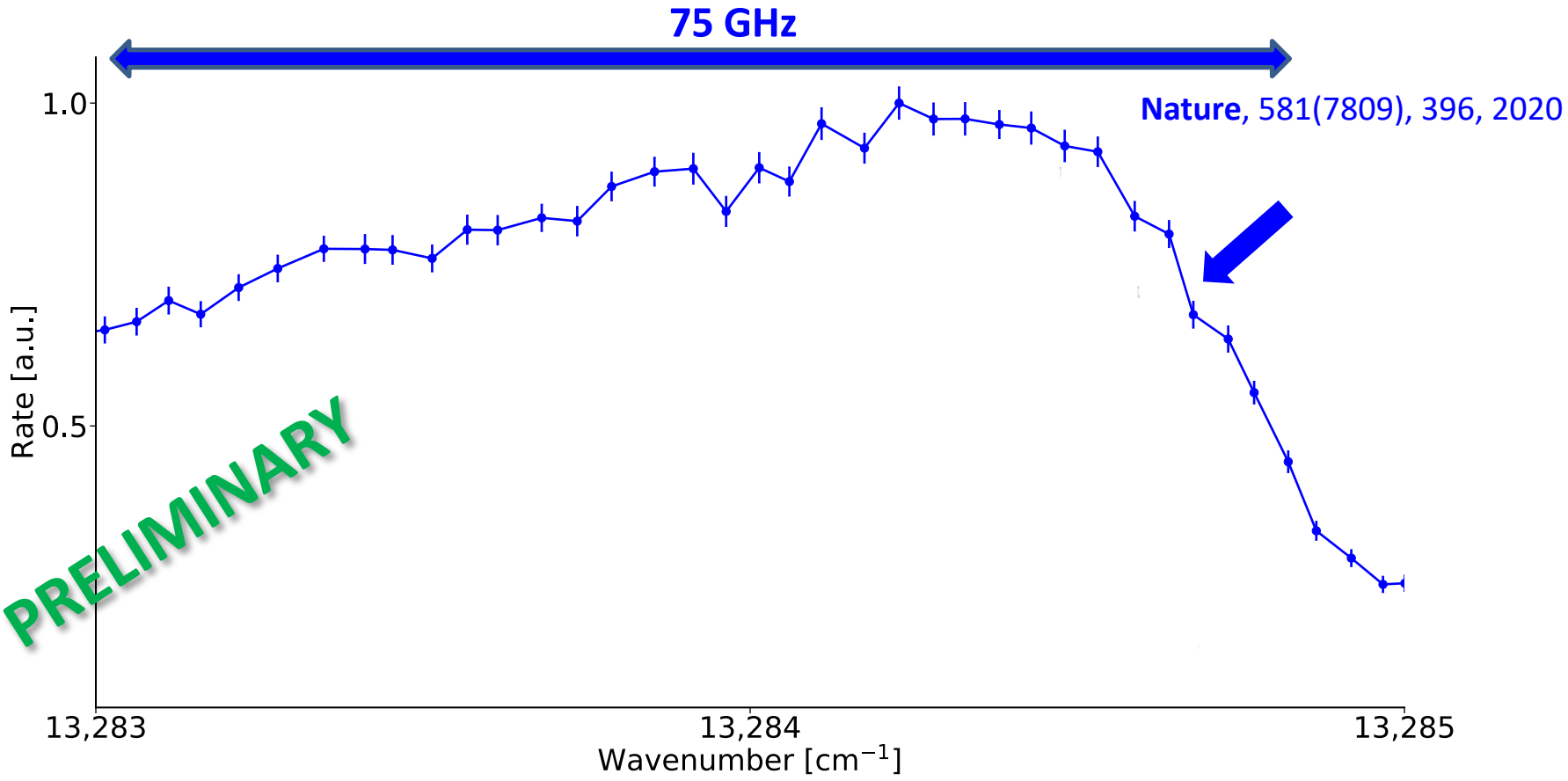


S. Udrescu

S. Wilkins

Recent Results (RaF)

^{226}RaF vibronic spectrum

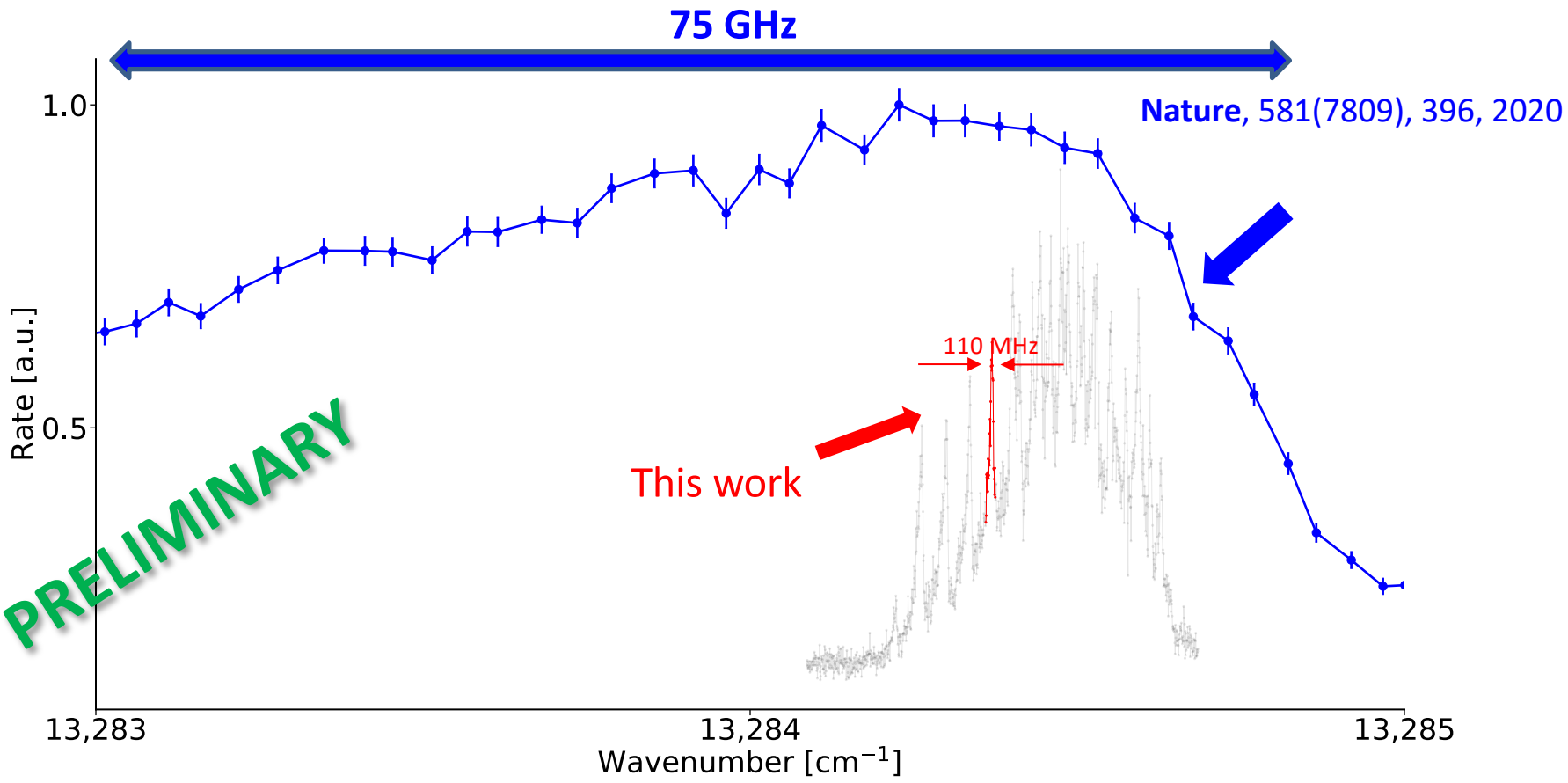


✓ ✓

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

Recent Results (RaF)

^{226}RaF rotational spectrum



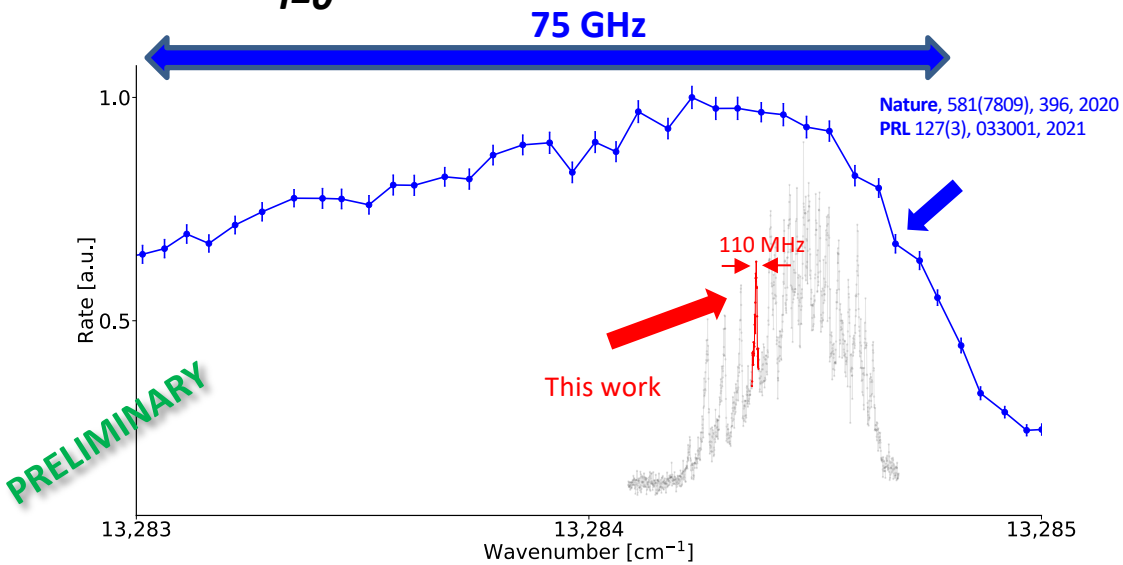
✓ ✓ ✓

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

Recent Results (RaF)

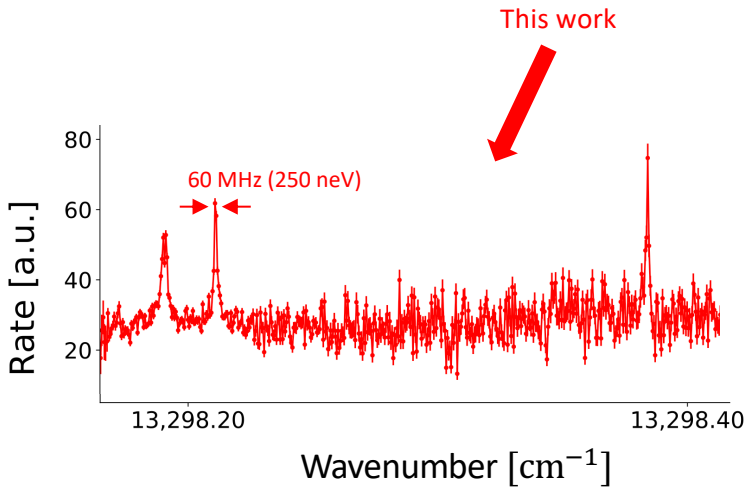
^{226}RaF rotational spectrum

I=0



^{225}RaF hyperfine spectrum

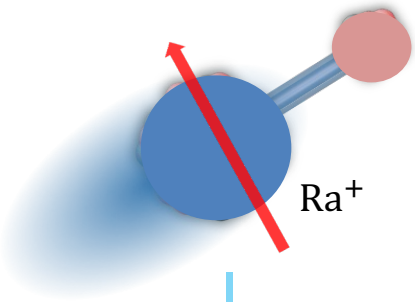
I=1/2



✓ ✓ ✓ ✓

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

Distribution of nuclear magnetization in ^{225}Ra

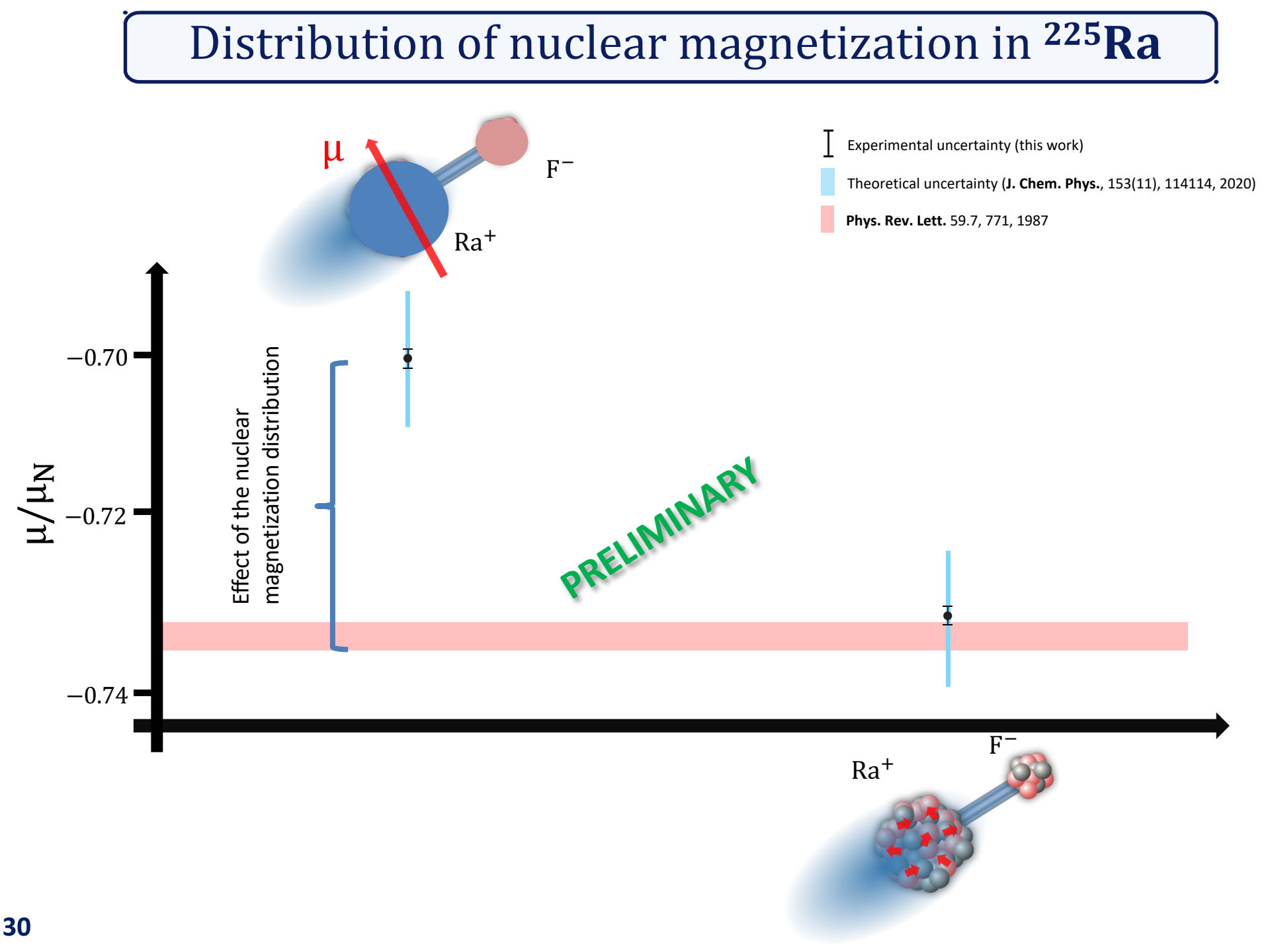


Experimental uncertainty (this work)

Theoretical uncertainty (**J. Chem. Phys.**, 153(11), 114114, 2020)

Phys. Rev. Lett. 59.7, 771, 1987

Distribution of nuclear magnetization in ^{225}Ra

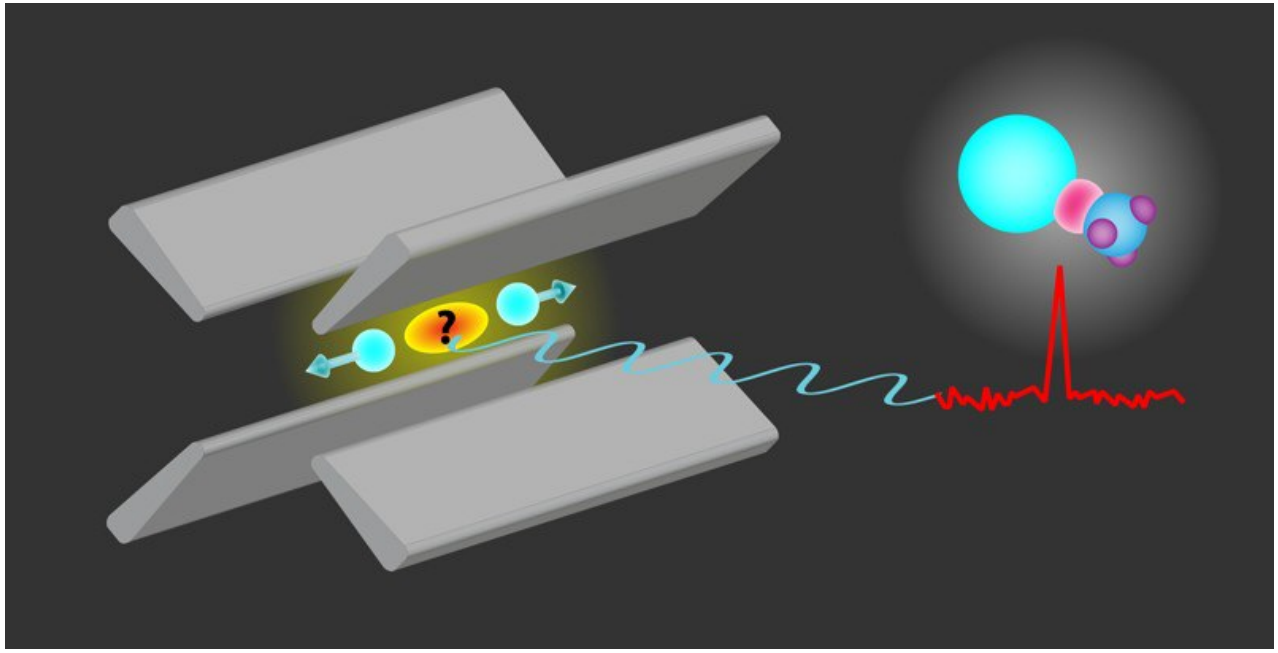


Overview

- Why exotic atoms & molecules?
- Recent results (ISOLDE-CERN)
  - Atoms
  - Molecules
- **New Opportunities**
- Summary & Outlook

Designer Molecules for Fundamental-Symmetry Tests

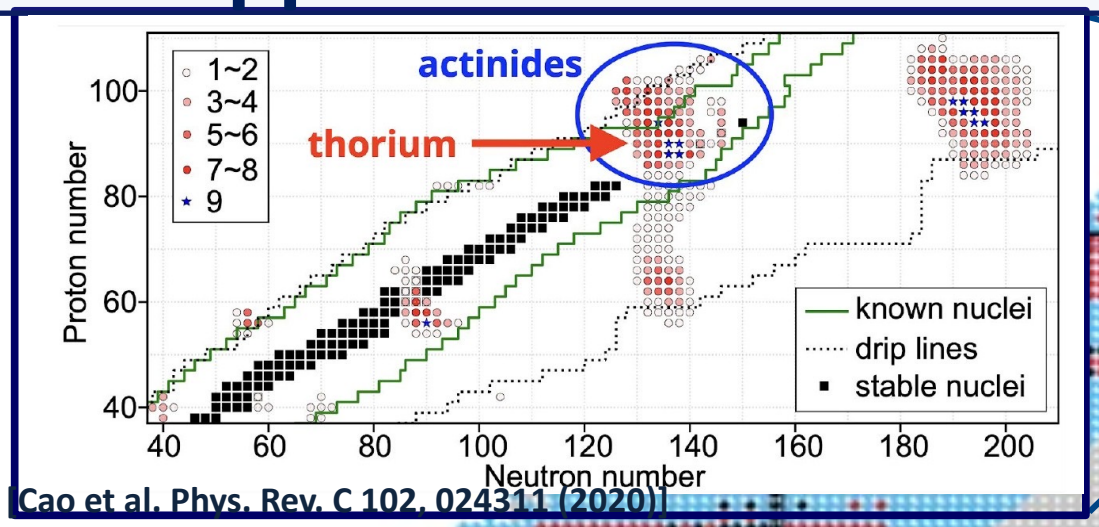
→ $RaOH^+$ and $RaOCH_3^+$ [Fan et al. Phys. Rev. Lett. 126, 023002 (2021)]
[Yu & Hutzler Phys. Rev. Lett. 126, 023003 (2021)]



→ Assembling molecules from cold atoms [Fleig & Demille]
[New J. Phys. 23, 113039 (2021)]

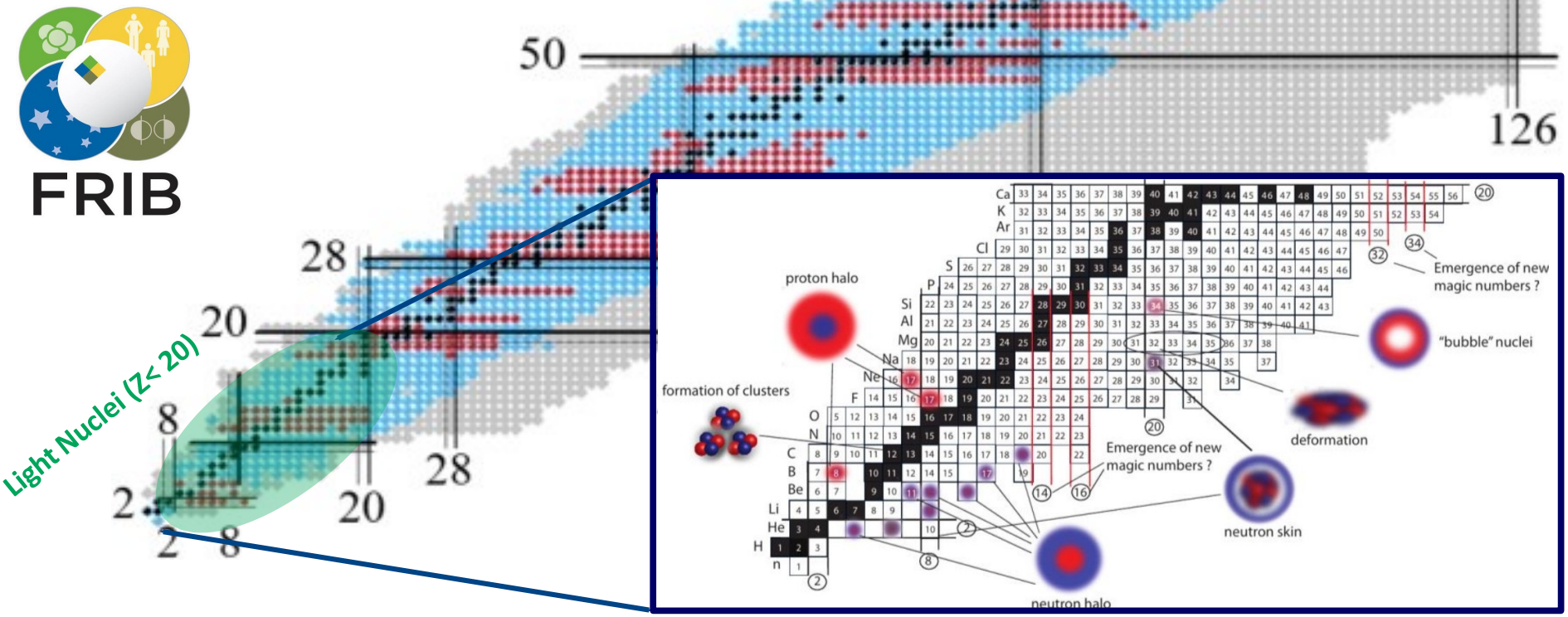
- RaAg
- FrAg

New opportunities at FRIB



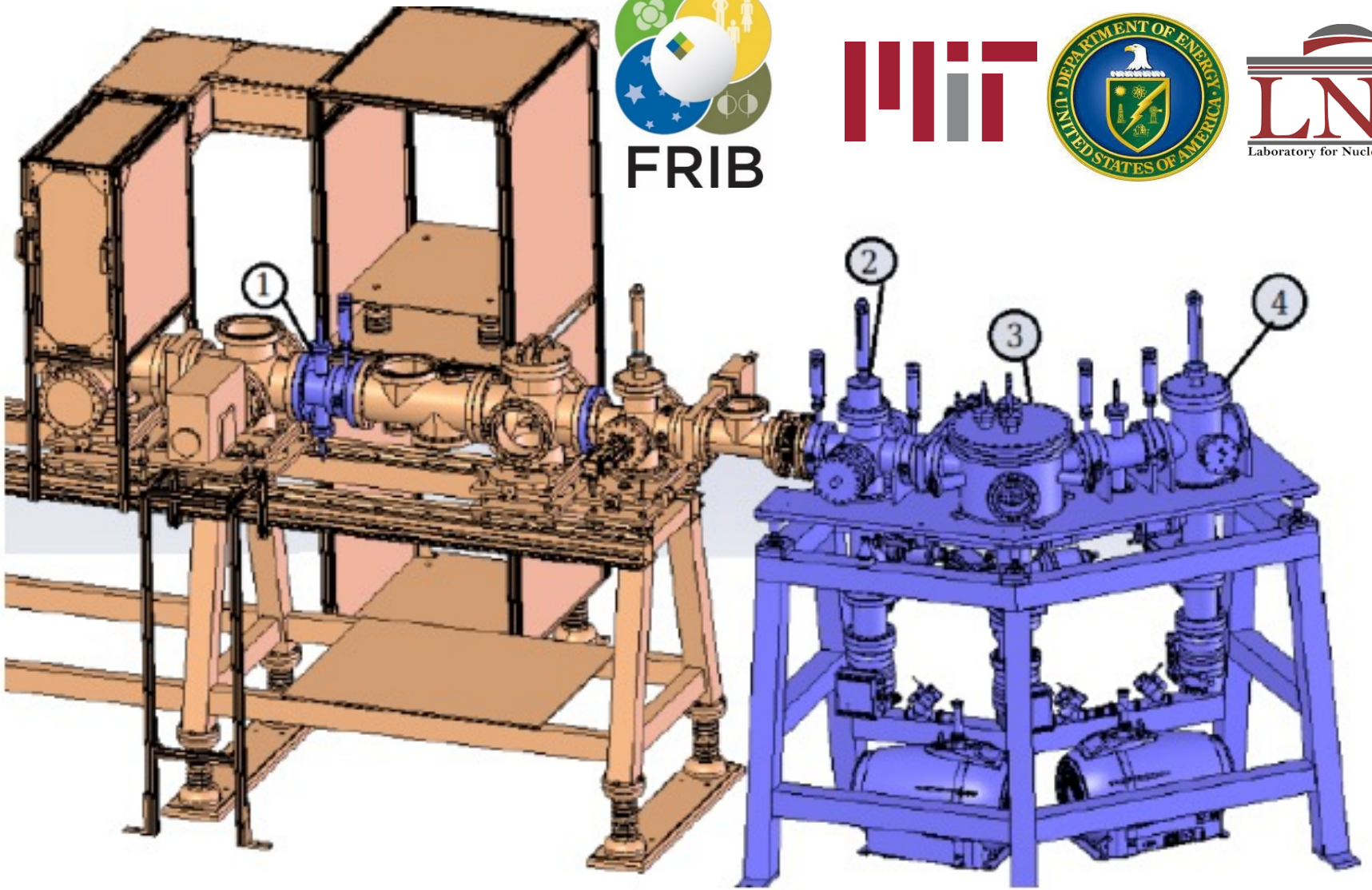
Actinides (Z>88)

Light Nuclei (Z< 20)



FRIB

RISE (Resonance Ionization Spectroscopy Experiment) @ FRIB



Resonance Ionization Spectroscopy Experiment (RiSE) at FRIB

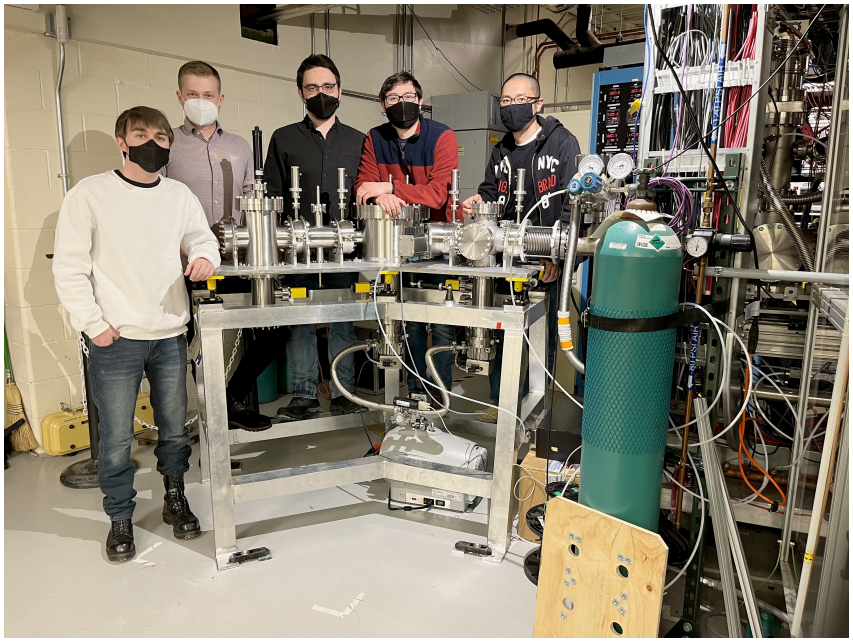
Major milestones achieved!

- ✓ December 2020: RiSE project started Dec 2020
- ✓ April 2021: Beamline Design completed
- ✓ May 2021: Experimental parts are being ordered
- ✓ September 2021: Laser setup for FRIB completed at MIT
- ✓ Commissioning at Bates, MIT in February 2022
- ✓ Installed at FRIB **in March 2022**
- ✓ **Successful experiments with ^{27}Al performed.**

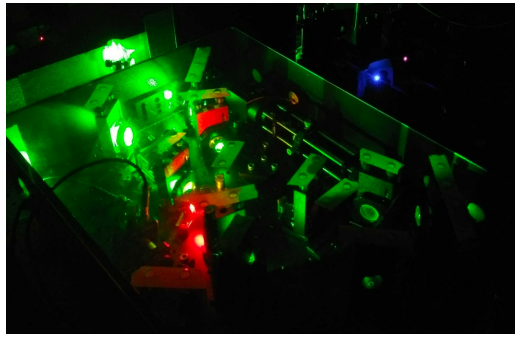
In collaboration with:

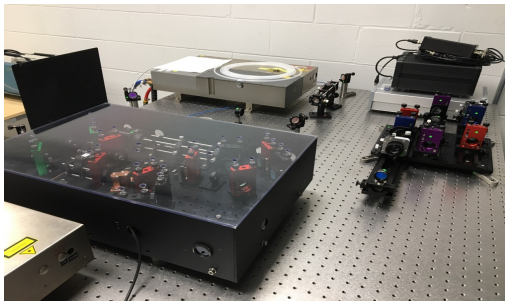
K. Minamisono

RISE beamline @ FRIB

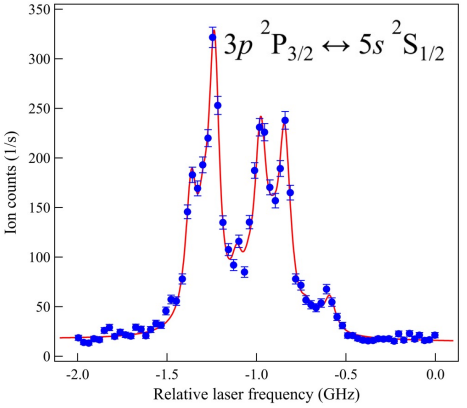


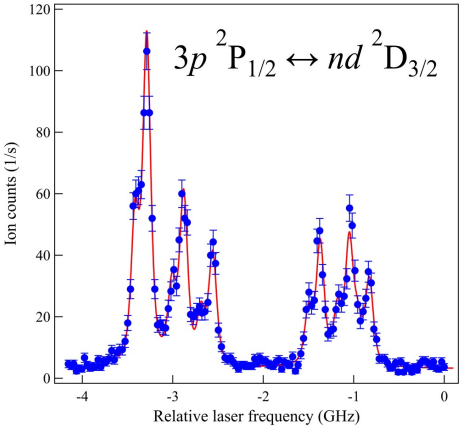
RISE lasers @ FRIB





First results with ^{27}Al @ FRIB





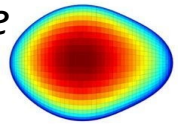
We are ready to study short-lived atoms & molecules at FRIB!

Two accepted proposals at FRIB:

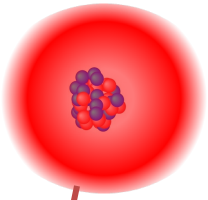
- Proton halo/skin of Aluminum isotopes
- Atoms and molecules containing short-lived thorium isotopes

Resonance Ionization Spectroscopy Experiment (RiSE) at FRIB

Atoms and molecules containing octupole deformed Thorium isotopes



"Proton skin" of Aluminum isotopes



FRIB

Two accepted proposals at FRIB:

- Proton halo/skin of Aluminum isotopes
- Atoms and molecules containing octupole deformed Thorium isotopes

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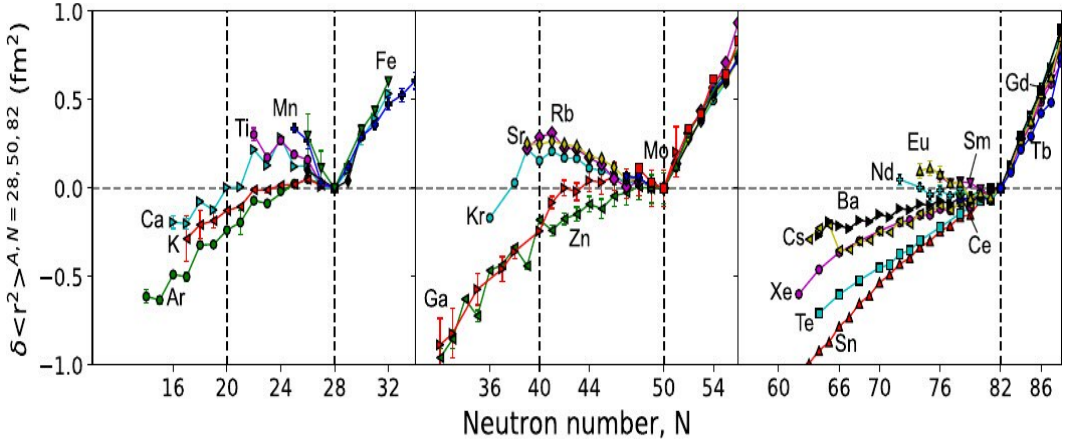
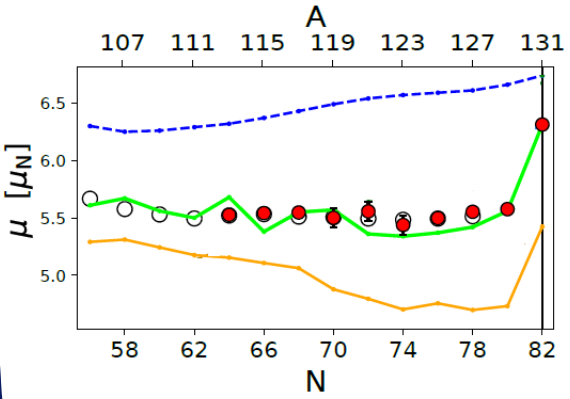
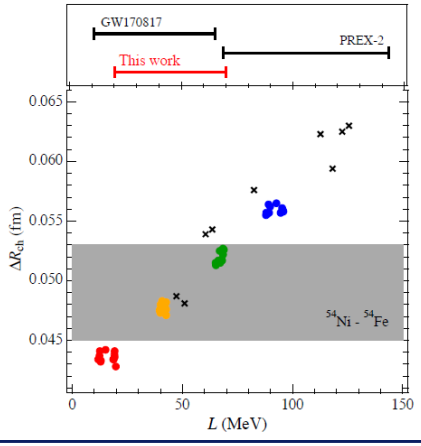
- Why exotic atoms & molecules?
- Recent results (ISOLDE-CERN)
  - Atoms
  - Molecules
- New Opportunities (MIT & FRIB)
- **Summary & Outlook**

Summary and Outlook

- **Atoms: Nuclear electromagnetic structure**
  Properties of nuclear matter

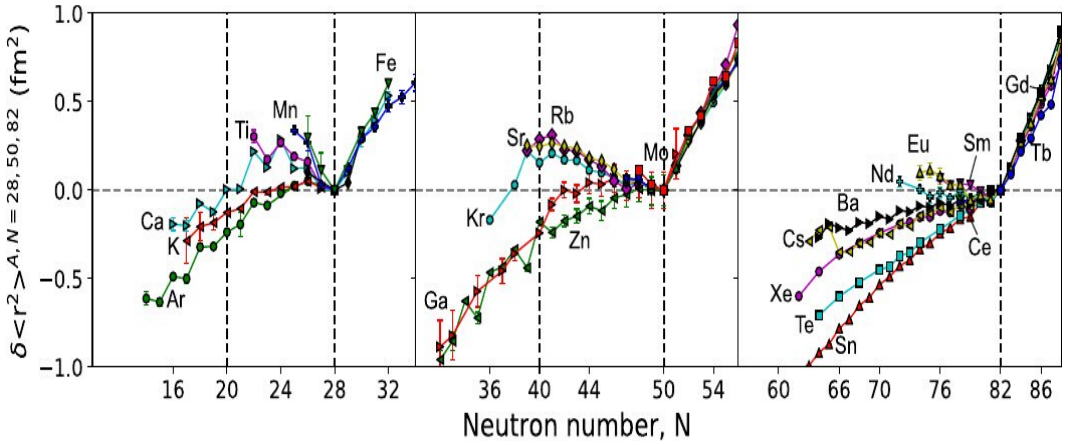


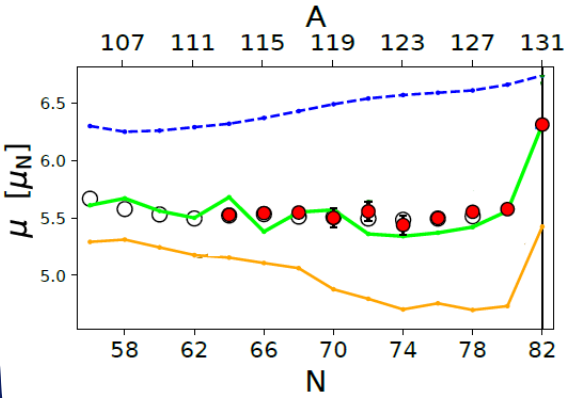


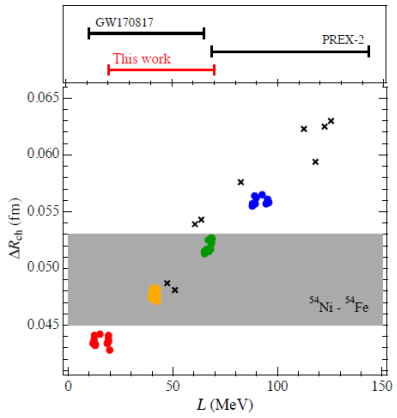


Summary and Outlook

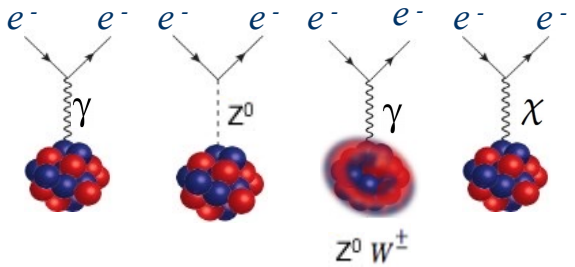
- **Atoms: Nuclear electromagnetic structure**
  Properties of nuclear matter



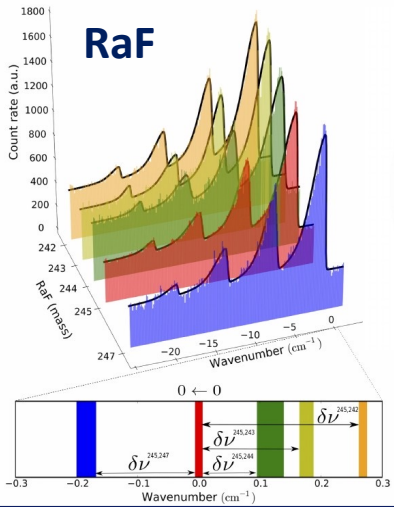




- **Molecules: Symmetry violating nuclear properties**



- Parity and Time reversal violation $> 10^3$
- Nuclear amplification $> 10^3$
- Parity violation $> 10^{11}$



$$H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

Summary and Outlook

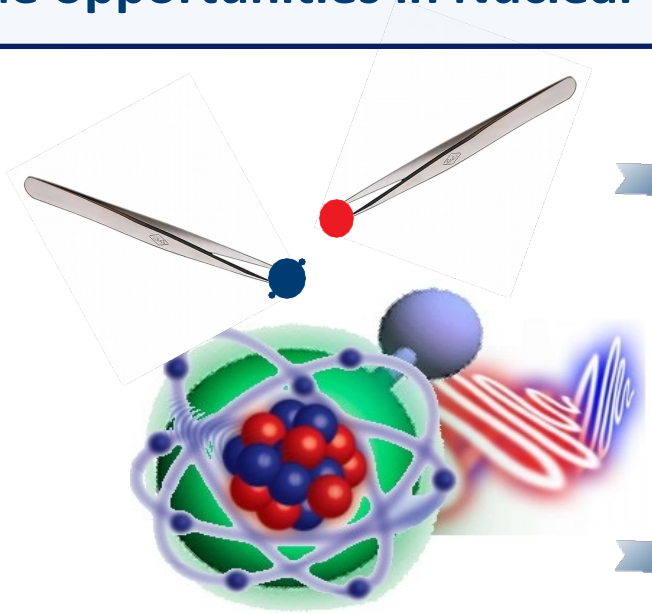
Precision measurements of radioactive atoms and molecules offer unique opportunities in Nuclear Science

Summary and Outlook

Precision measurements of radioactive atoms and molecules offer unique opportunities in Nuclear Science

Nuclear EM structure

Astrophysics



Nuclear EW structure

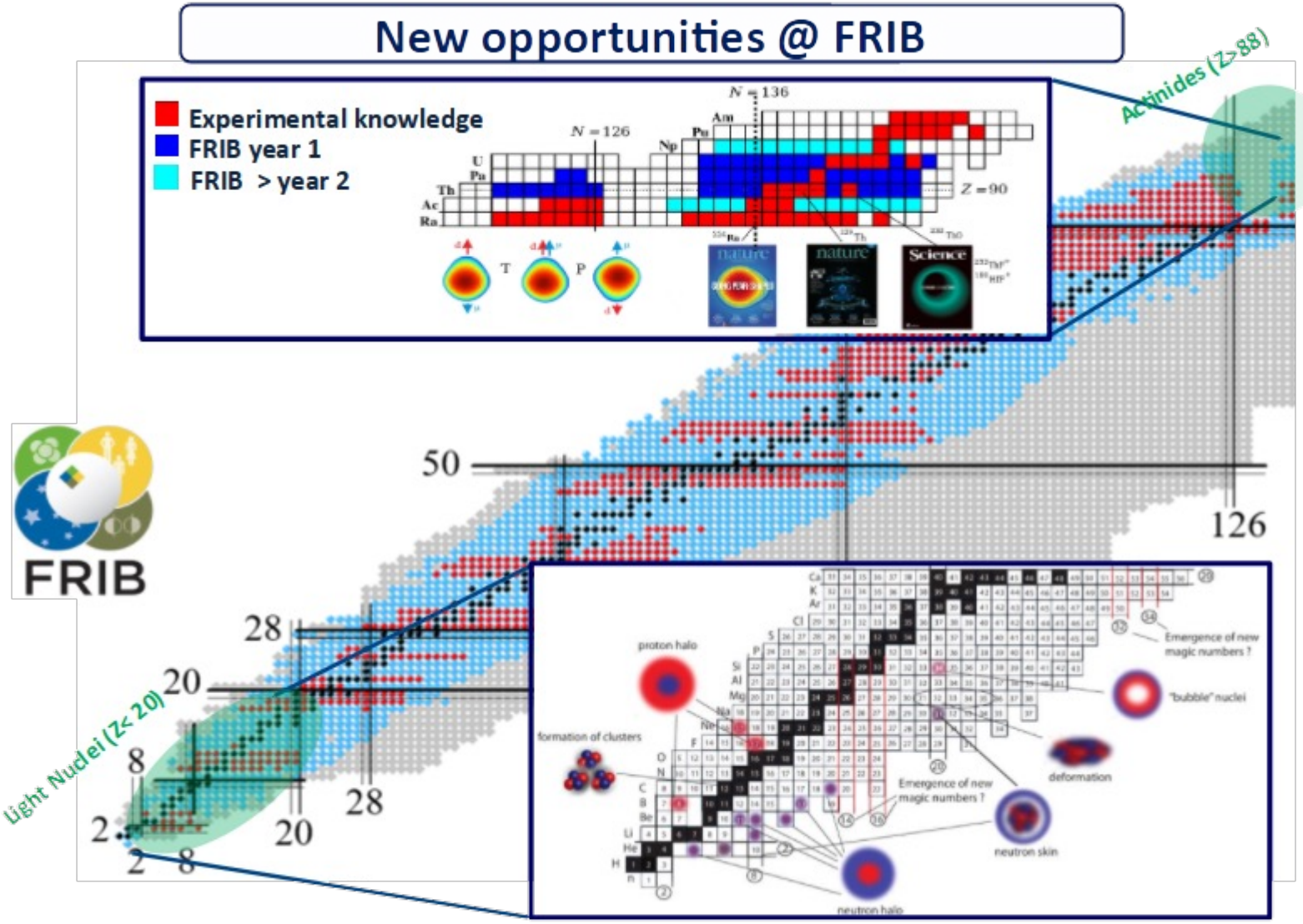
Nuclear chemistry

Fundamental symmetries

Quantum chemistry

… this is just the beginning!

A Bright Future Ahead!



Once-in-a-lifetime opportunity!

- New Facilities (FRIB)
- Precision (atomic, molecular, nuclear) Physics