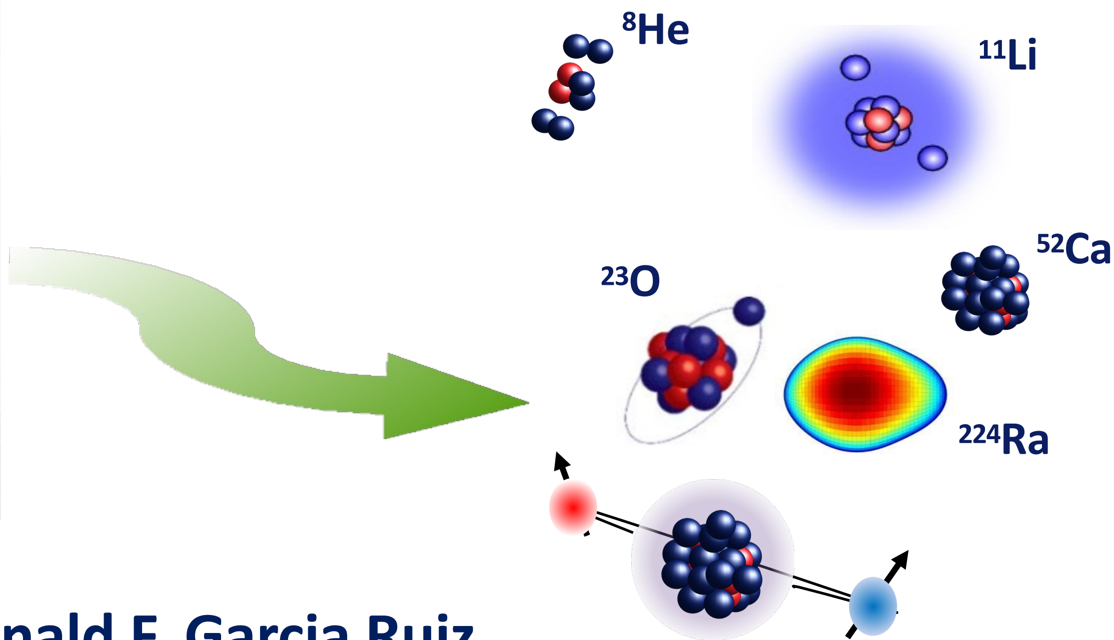
Charge radii measurements of exotic nuclei from laser spectroscopy

Figure modified from https://sphereofinfluence360.com/



Ronald F. Garcia Ruiz

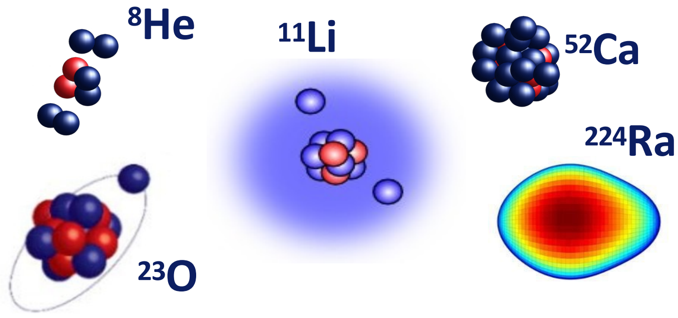
MIT

Workshop on NREC 2024

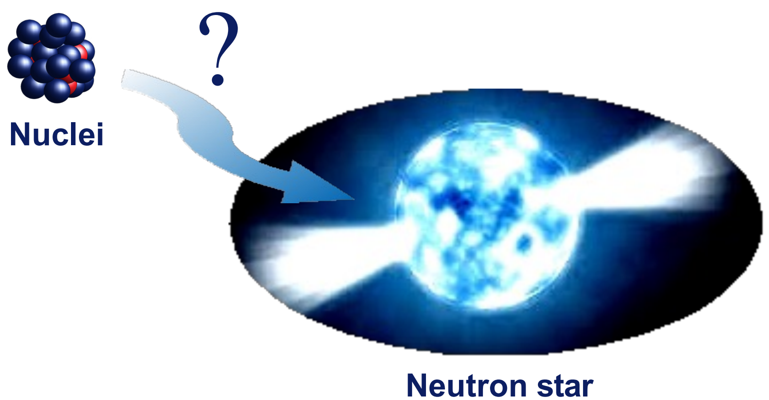
Stony Brook University, May 2024

Open questions in Nuclear and Particle Physics

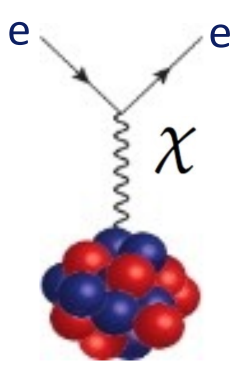
How do nuclear phenomena emerge from QCD?

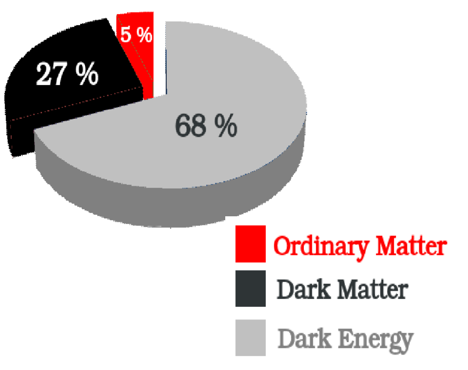


What are the properties of nuclear matter (e.g. neutron stars)?



Are there new particles?
What are the properties of Dark Matter?





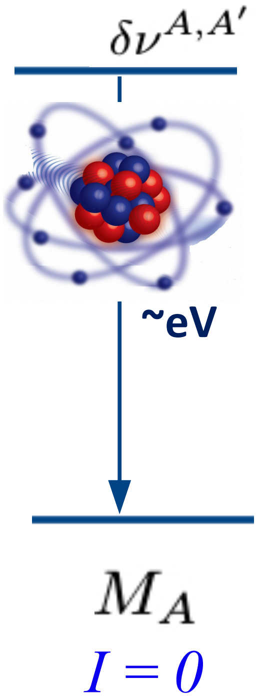
Isotope shift measurements of exotic nuclei can provide answers to these questions

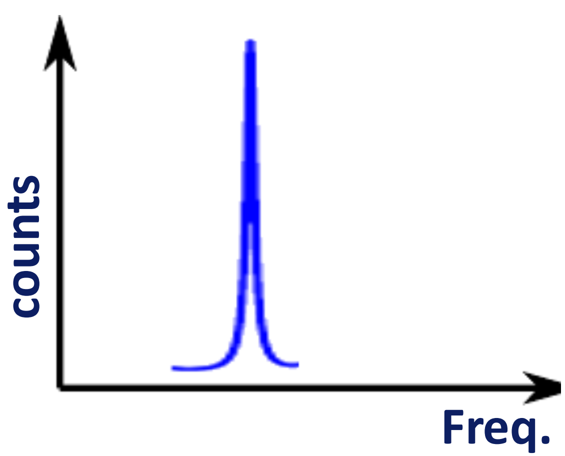
Overview

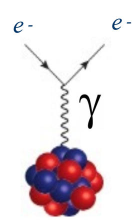
- Laser spectroscopy
- Charge radii & Nuclear Structure
- Charge radii & Nuclear Matter
- Isotope shifts & BSM Physics
- Summary & Outlook

[Yang, Wang, Wilkins, Garcia Ruiz. Prog. Part. Nucl. Phys. 129, 104005 (2023)]
[Koszorús, Groote, Cheal, Campbell, Moore. Eur. Phs. J. C 60, 20 (2024)]
[Nörtershäuser, Moore. Handbook Nucl. Phys 1, (2022)]

Laser spectroscopy -> Isotope Shifts



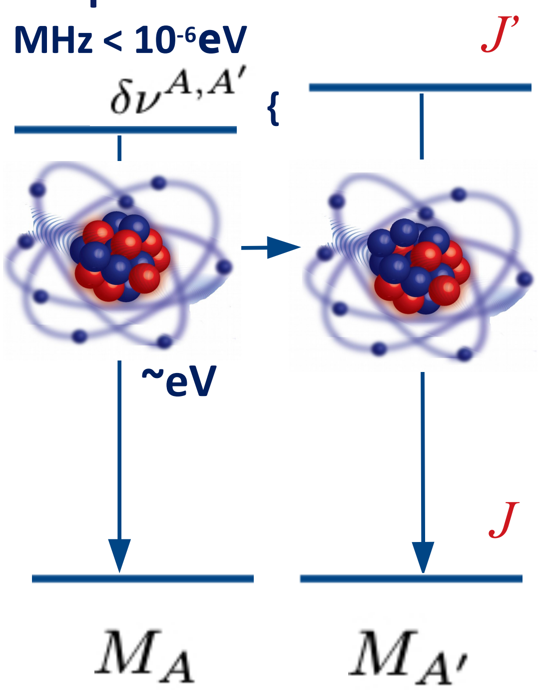




Laser spectroscopy -> Isotope Shifts

Isotope shift

MHz < 10^{-6}eV

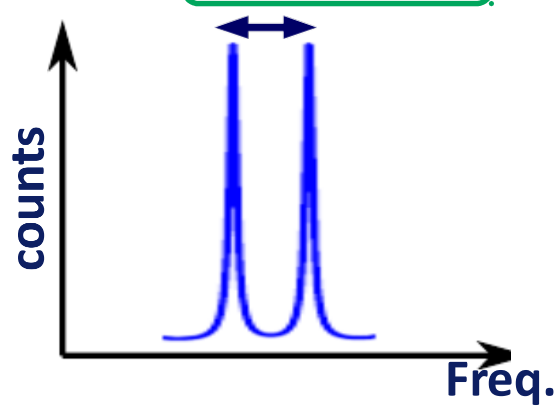


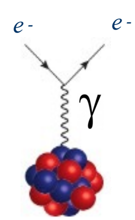
$I = 0$

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

Atom

Nuclear





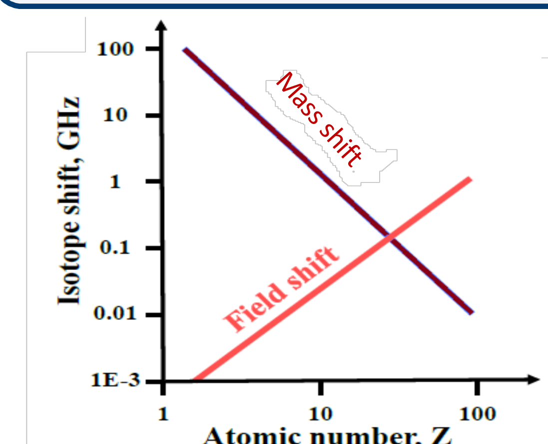
$\sim \sum_{i\neq j} \vec{p}_i \cdot \vec{p}_j$

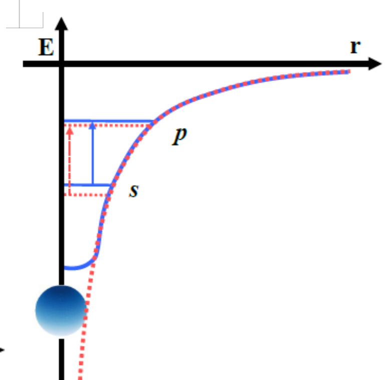
$\sim |\psi(0)|^2$

$\langle r^2\rangle = -6 \left.\frac{dF(q)}{dq^2}\right|_{q=0}$

Mass shift **Field shift** **rms charge radius**

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

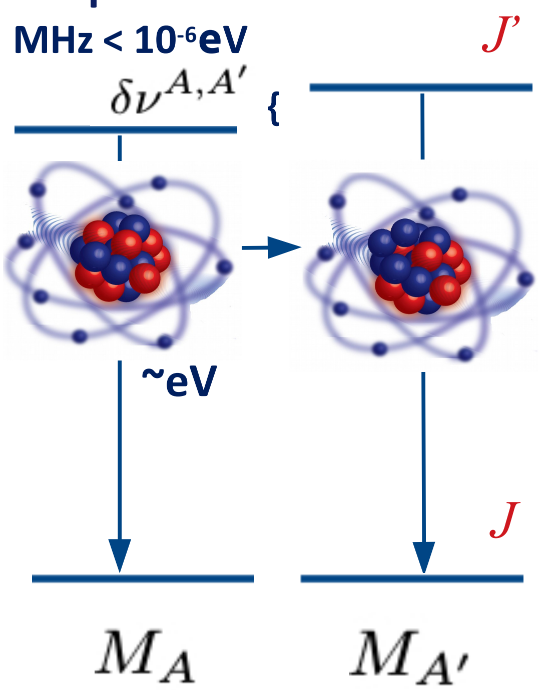


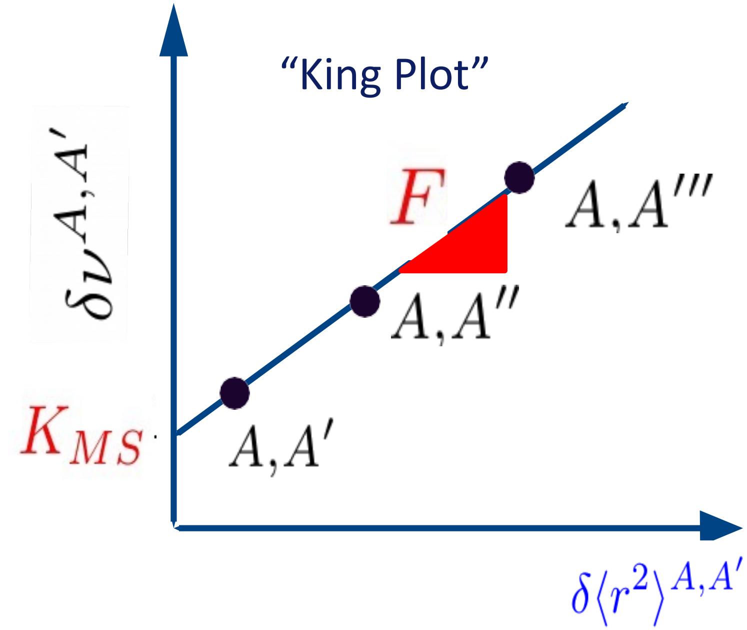


Laser spectroscopy -> Isotope Shifts

Isotope shift

MHz < 10^{-6}eV





$I = 0$

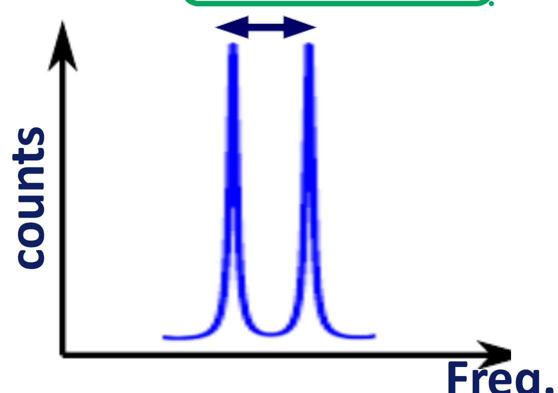
$\sim F\delta\langle r^2\rangle^{A,A'}$

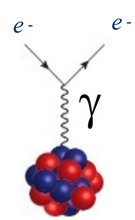
Atom

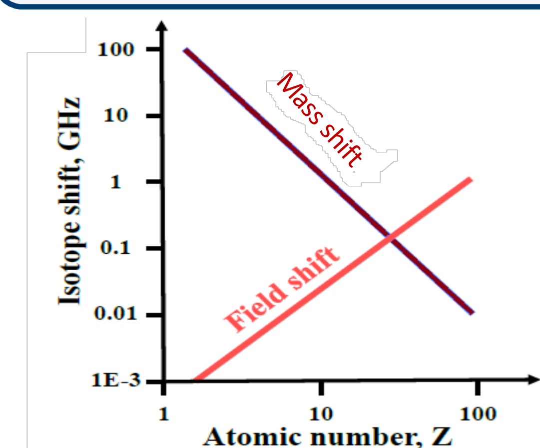
Nuclear

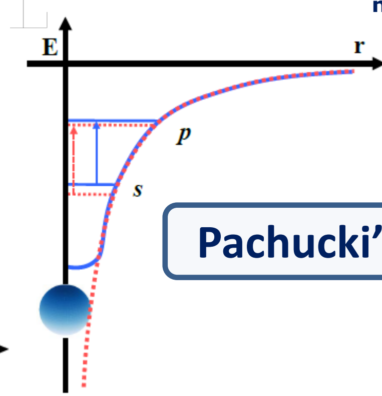
$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

+ **Higher order Corrections $\langle r^4 \rangle$, nuclear pol., ...**



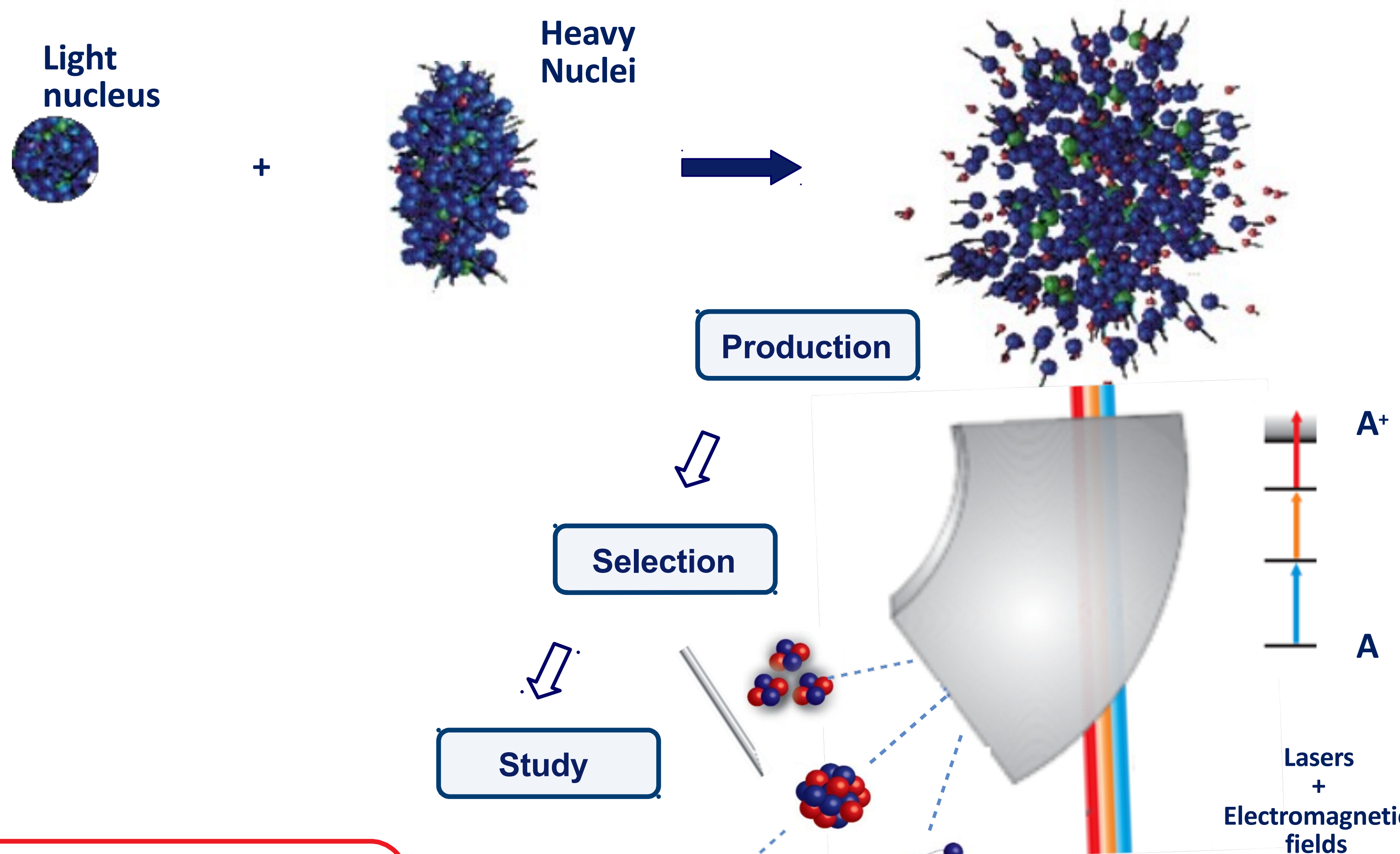


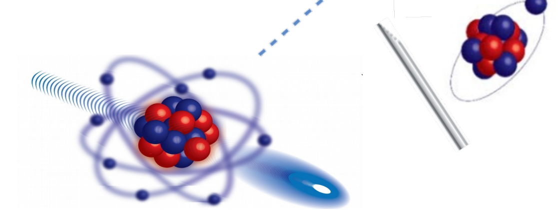




Pachucki's talk

Laser spectroscopy of Exotic Nuclei





Experimental challenges:

- High selectivity (>1/10^6)
- Short time scales (< 1 s)
- High efficiency (<100 ions/s)
- High precision/resolution (~MHz)

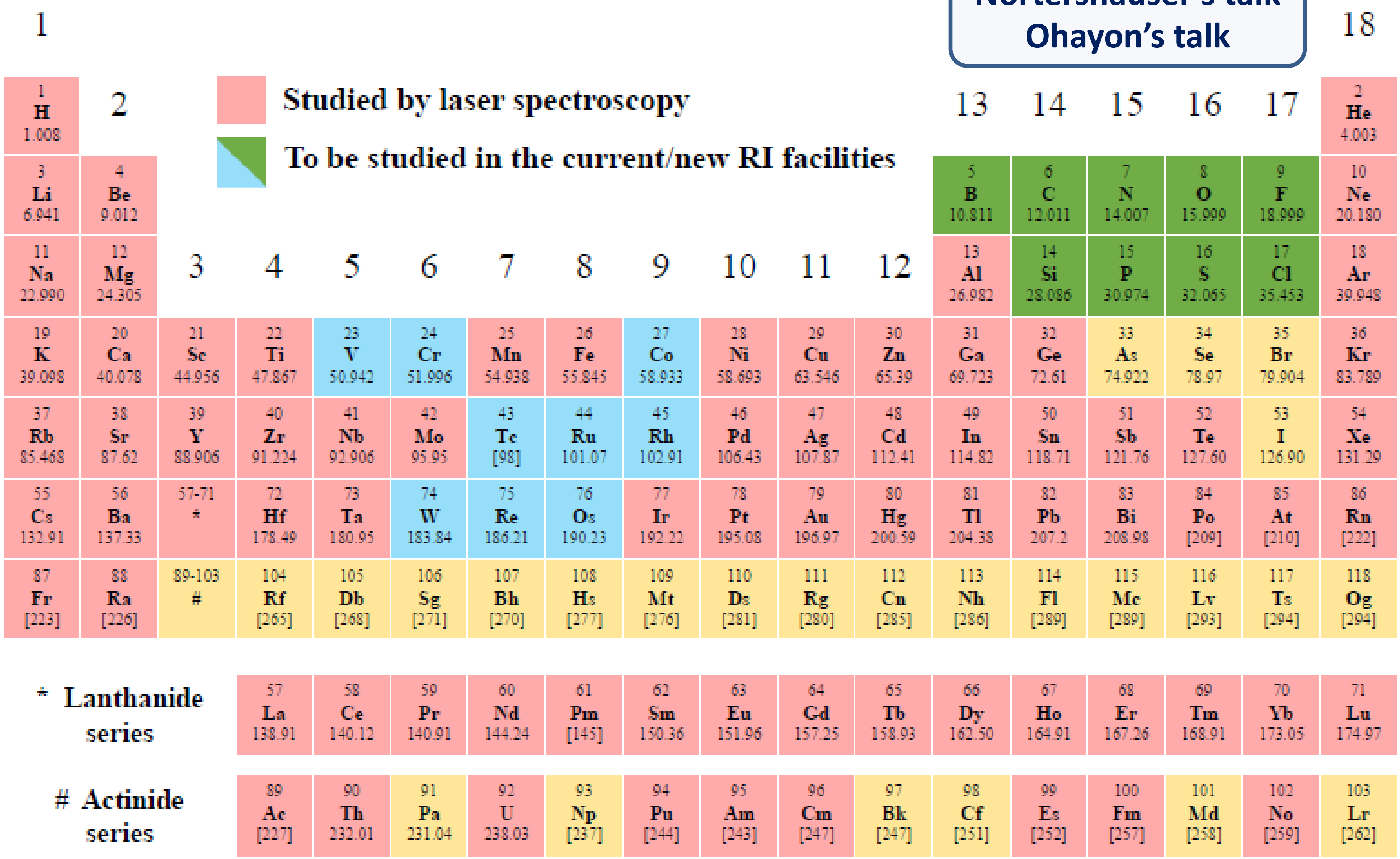
Laser spectroscopy of Exotic Nuclei

Operational | Commissioning | Planning

Nuclear properties | Laser ion source | Application

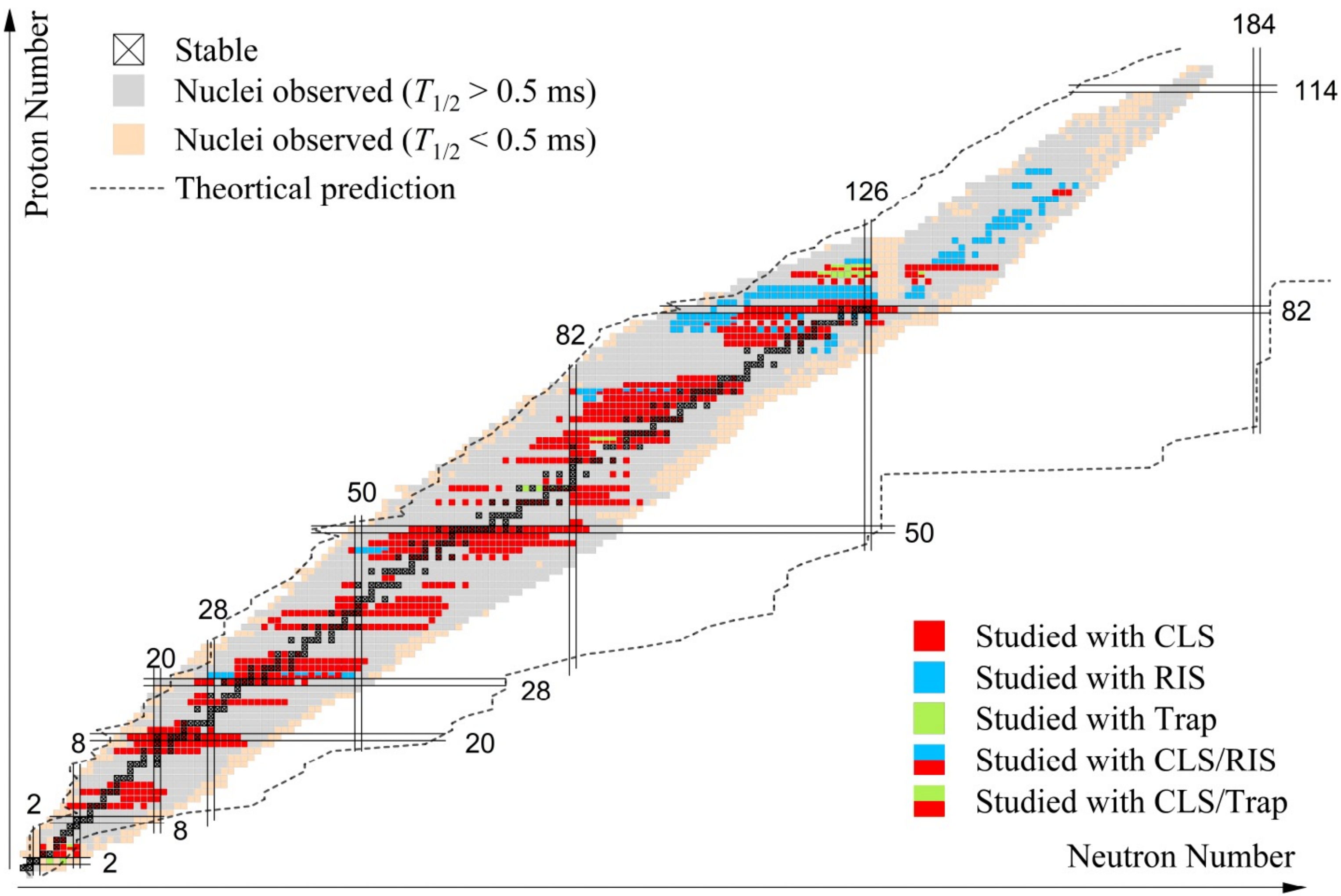
Laser spectroscopy of Exotic Nuclei

Nörtershäuser's talk
Ohayon's talk



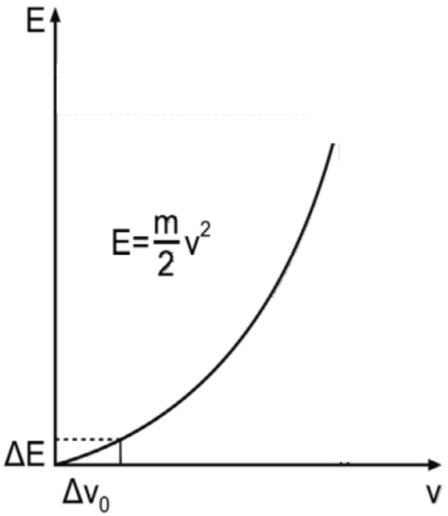
[Yang, Wang, Wilkins, Garcia Ruiz. Prog. Part. Nucl. Phys. 129, 104005 (2023)]

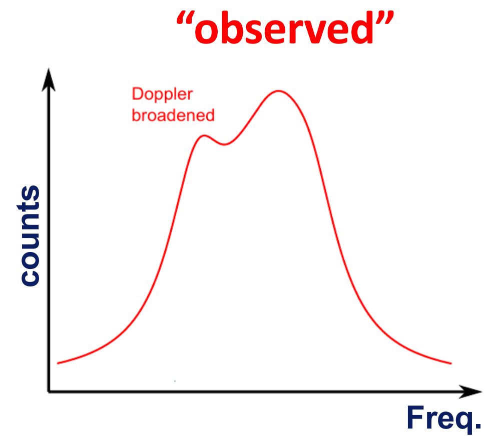
Laser spectroscopy of Exotic Nuclei



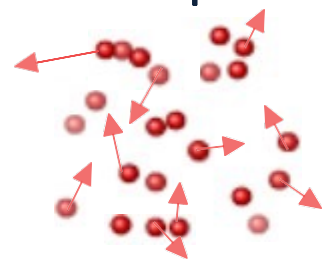
[Yang, Wang, Wilkins, Garcia Ruiz. Prog. Part. Nucl. Phys. 129, 104005 (2023)]

Collinear Laser spectroscopy of Exotic Nuclei



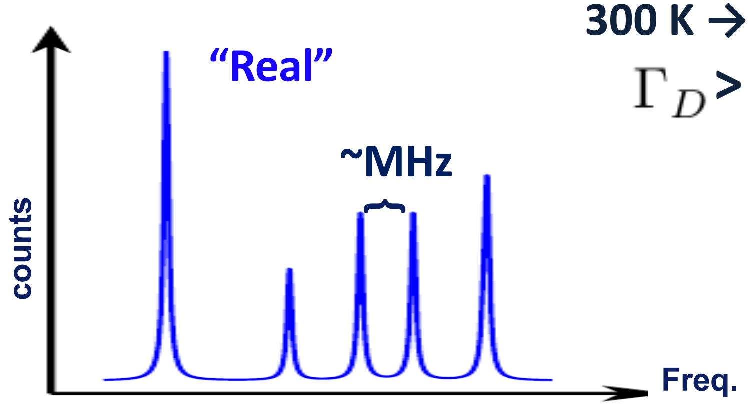


Room temperature

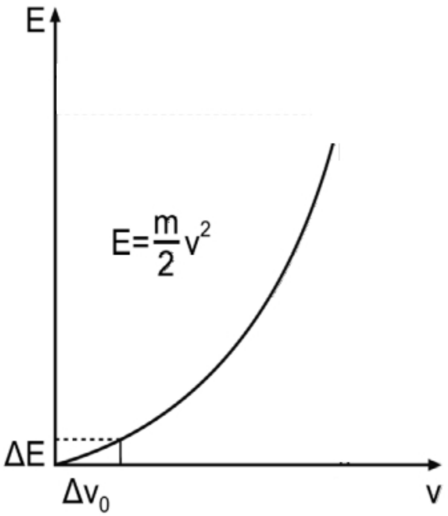


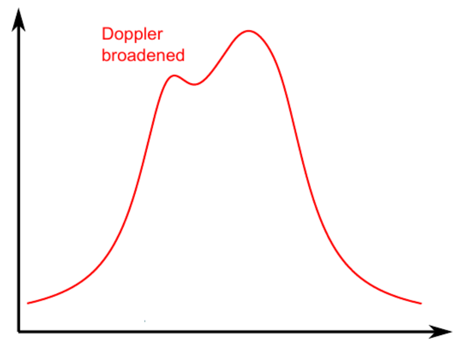
300 K → 25 meV

Γ_D **> GHz**

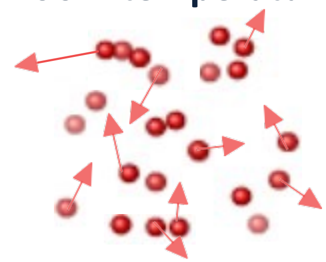


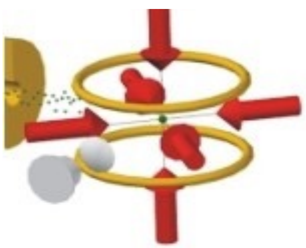
Collinear Laser spectroscopy of Exotic Nuclei





Room temperature





T < µK

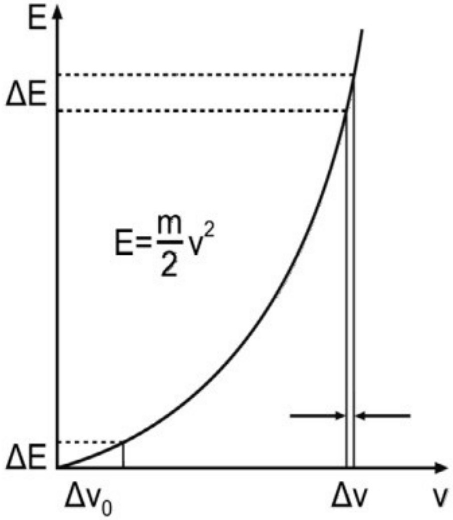
Γ_D < MHz

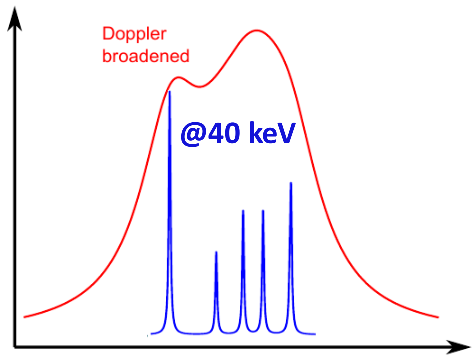
300 K → 25 meV

Γ_D > GHz

- ✔ High resolution (< MHz)
- High efficiency (<100 ions/s) ?
- High selectivity (>1/10^6) ?
- Short time scales (< 1 s)?

Collinear Laser spectroscopy of Exotic Nuclei





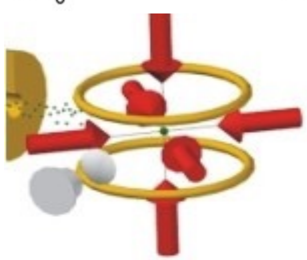
Energy spread

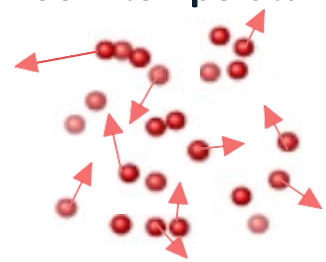
$$\Gamma_D = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}}$$

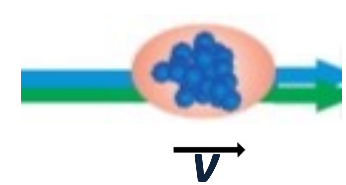
Ion beam energy

Room temperature

Fast beam







T < μK

Γ_D < MHz

300 K → 25 meV

Γ_D > GHz

@ 40 keV

Γ_D ~ MHz

- ✔ High resolution (< MHz)
- ➢ High efficiency (<100 ions/s) ?
- ➢ High selectivity (>1/10^6) ?
- ➢ Short time scales (< 1 s)?

- ✔ High resolution (~MHz)
- ✔ High efficiency (<100 ions/s)
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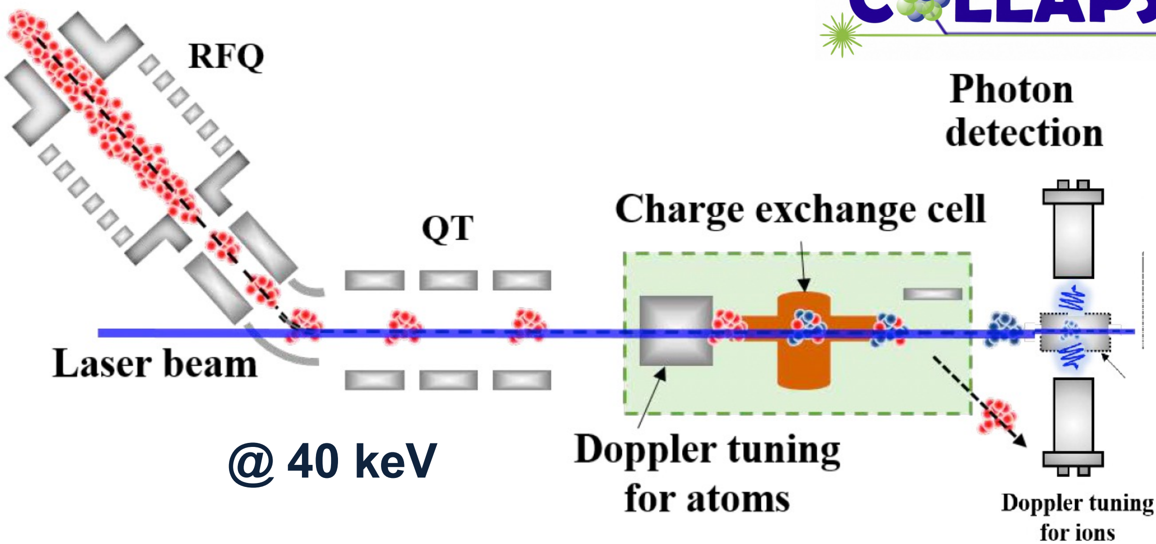
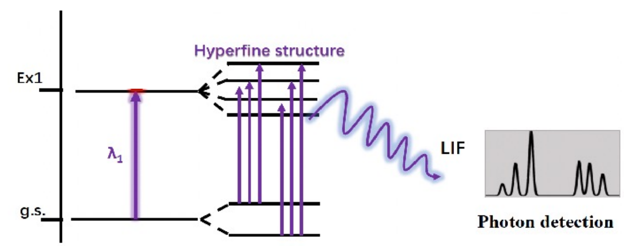
Collinear Laser spectroscopy of Exotic Nuclei



@ 40 keV



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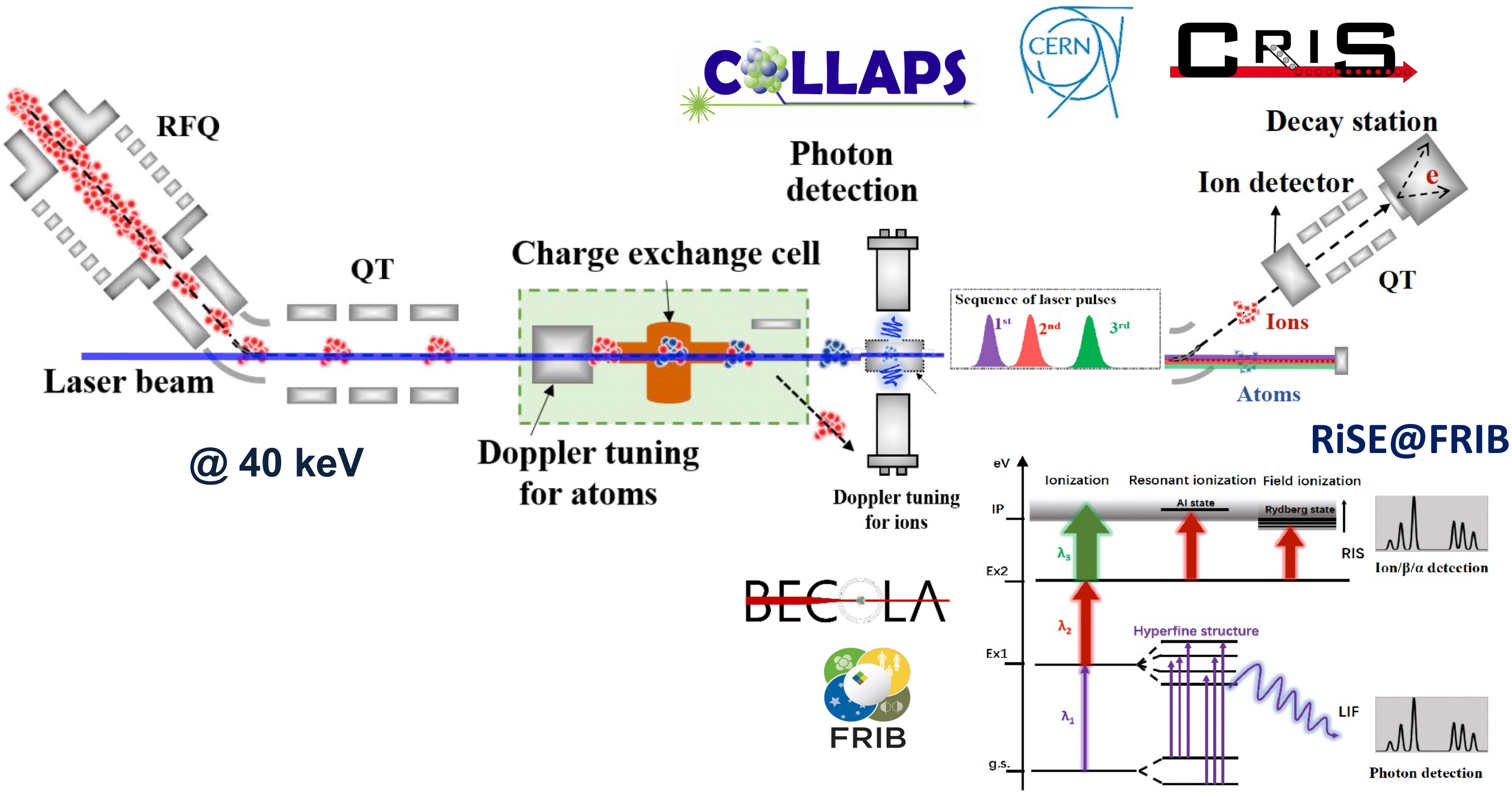
Collinear Laser spectroscopy of Exotic Nuclei



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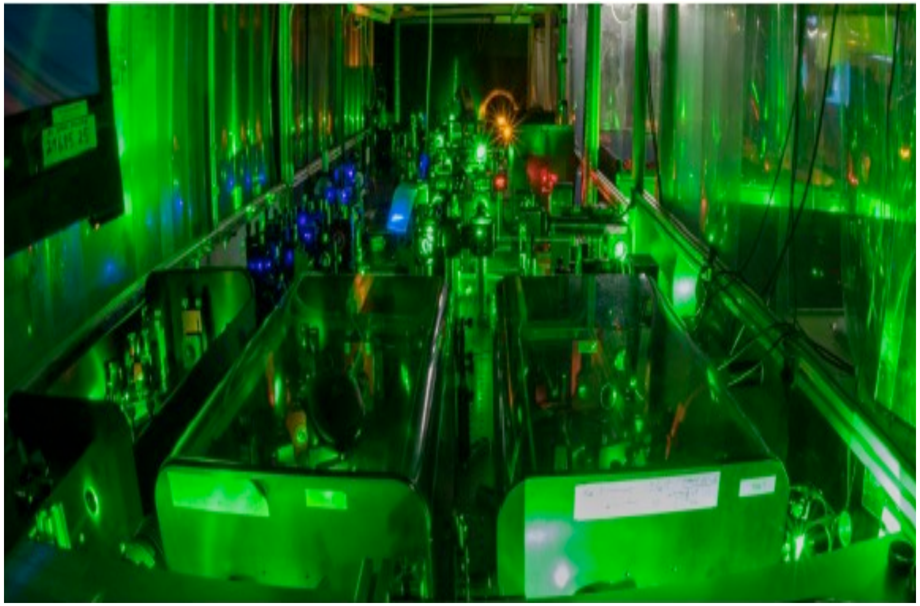
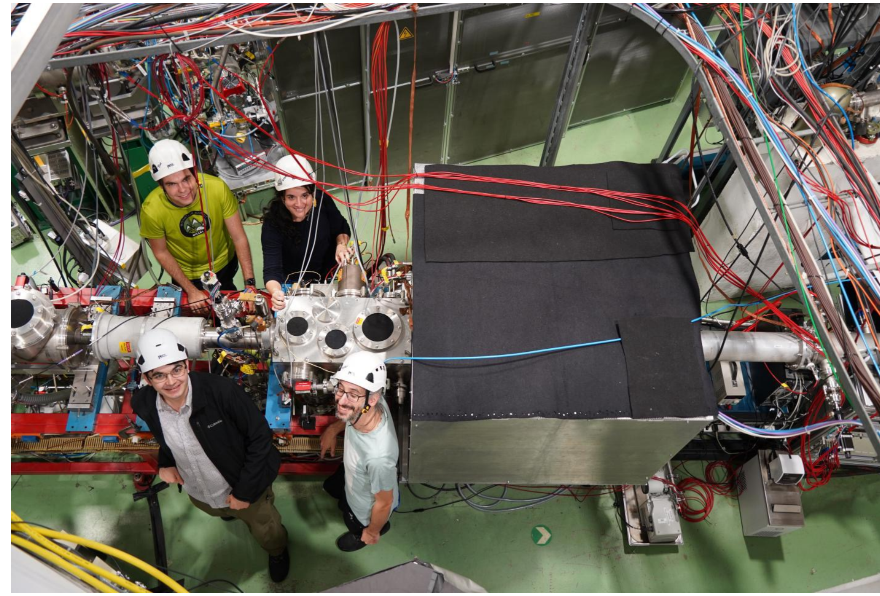
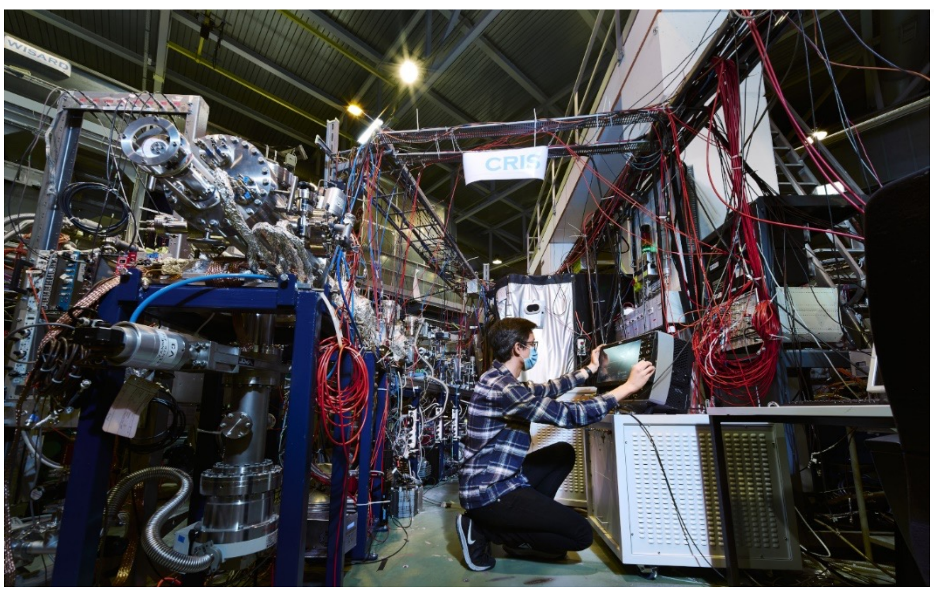
RILIS/ISOLDE @ CERN



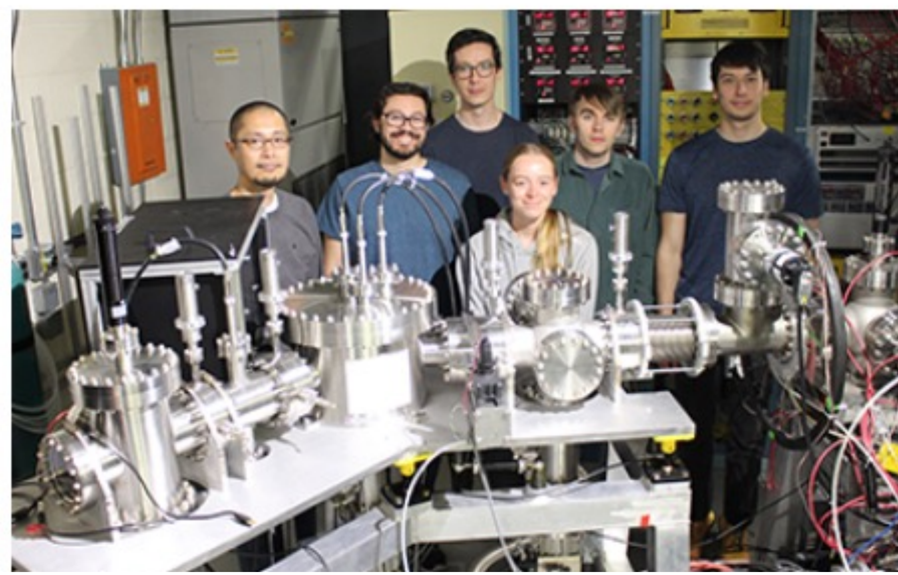
COLLAPS/ISOLDE @ CERN



CRIS/ISOLDE @ CERN



RISE/BECOLA @ FRIB



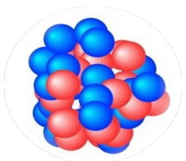
Overview

- Laser spectroscopy
- **Charge radii & Nuclear Structure**
- Charge radii & Nuclear Matter
- Isotope shifts & BSM Physics
- New Opportunities
- Summary & Outlook

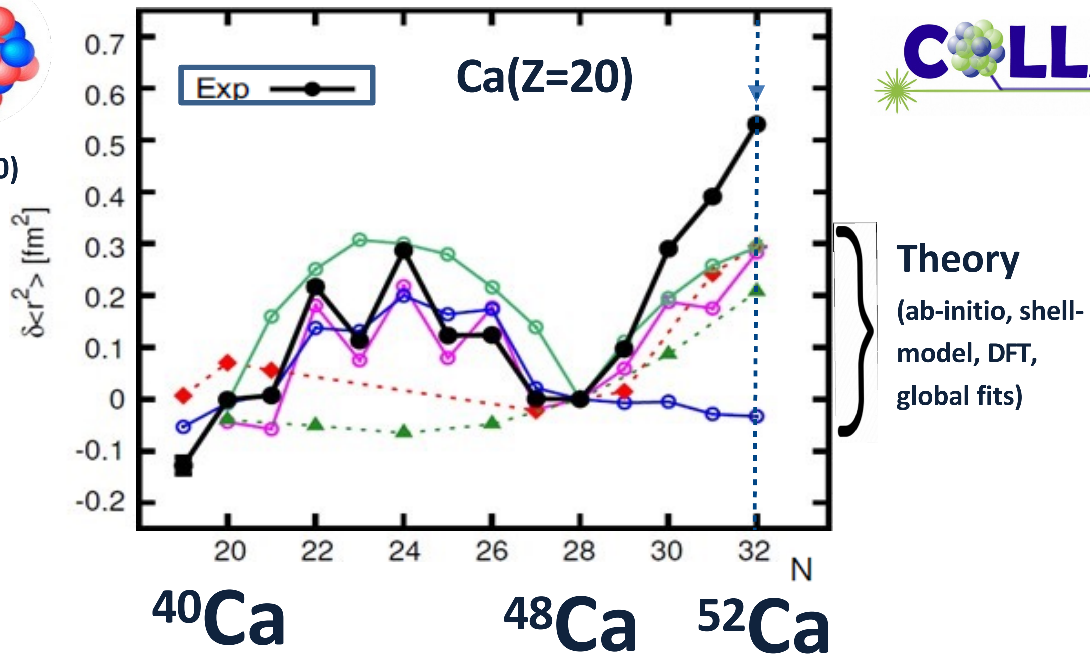
Warning: A few selected results. A non-exhaustive, biased selection.

Evolution of the nuclear size away from stability

How do nuclear phenomena emerge from QCD?



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



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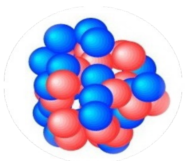
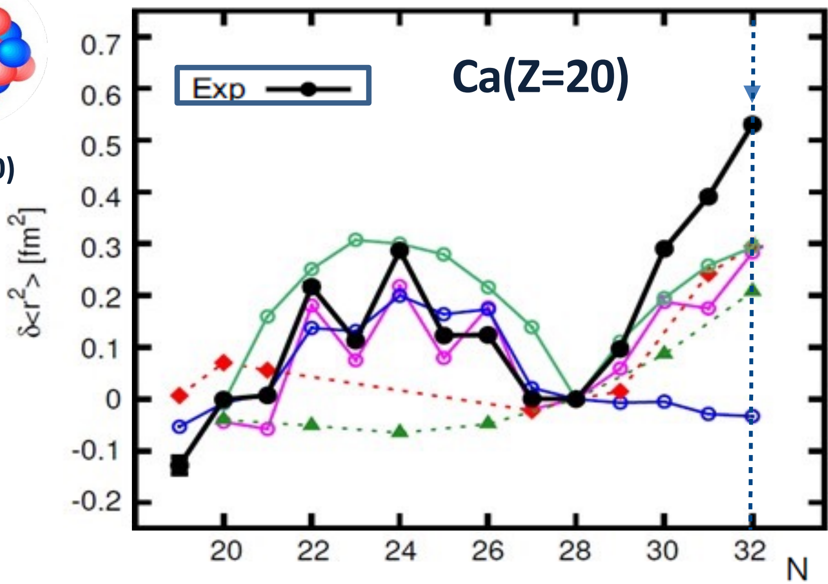
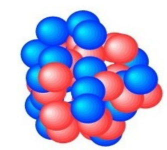
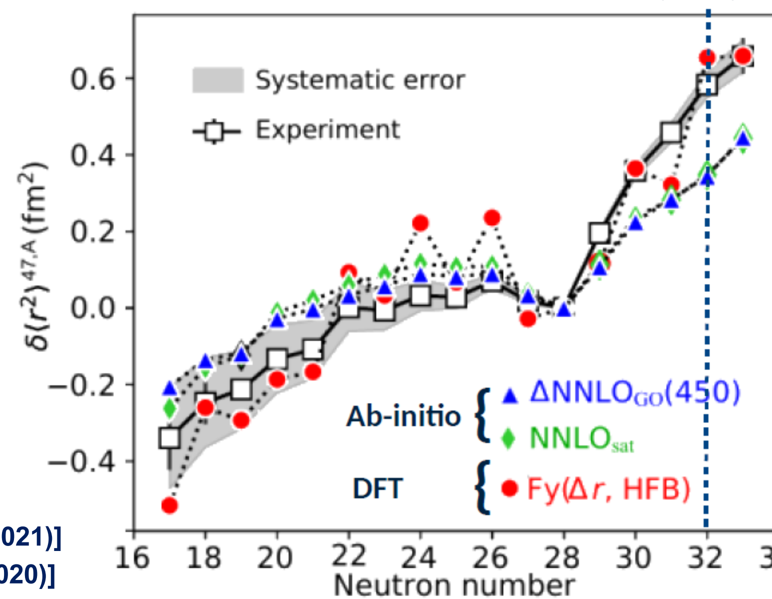




^{40}Ca ^{48}Ca ^{52}Ca

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

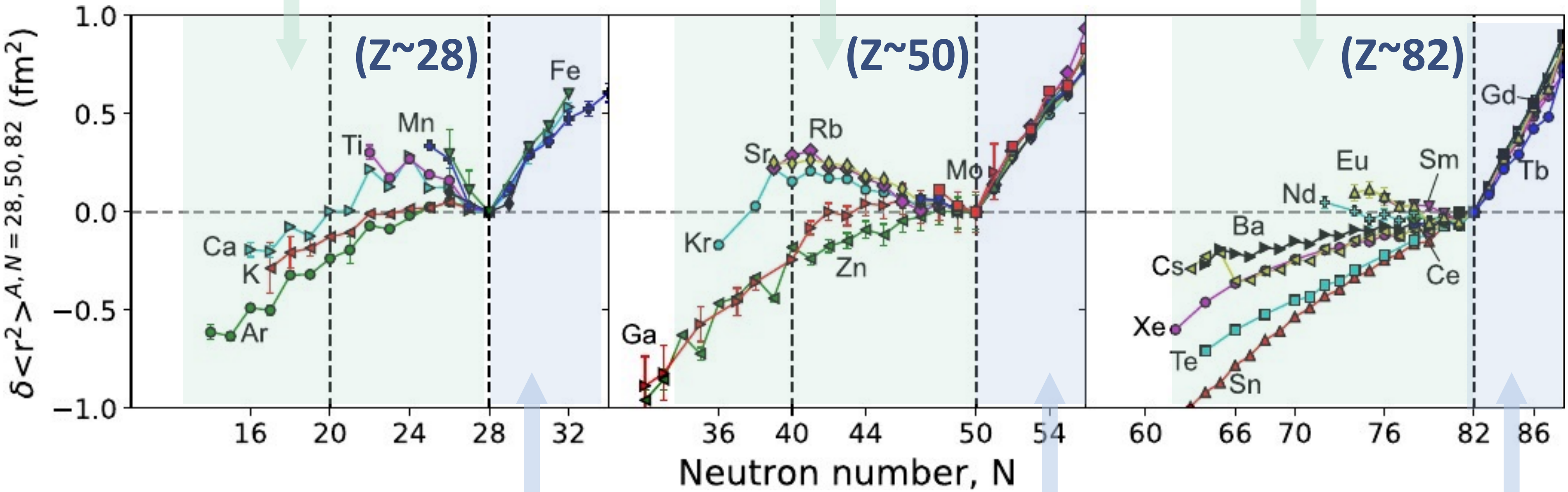




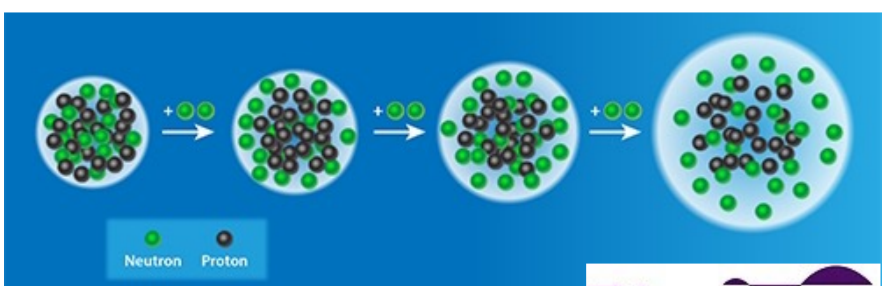
[Koszorus et al. Nature Phys. 17, 428 (2021)]
[Degroote et al. Nature Phys. 16, 620 (2020)]

Nuclear charge radii across closed-shells

Strong Z dependence



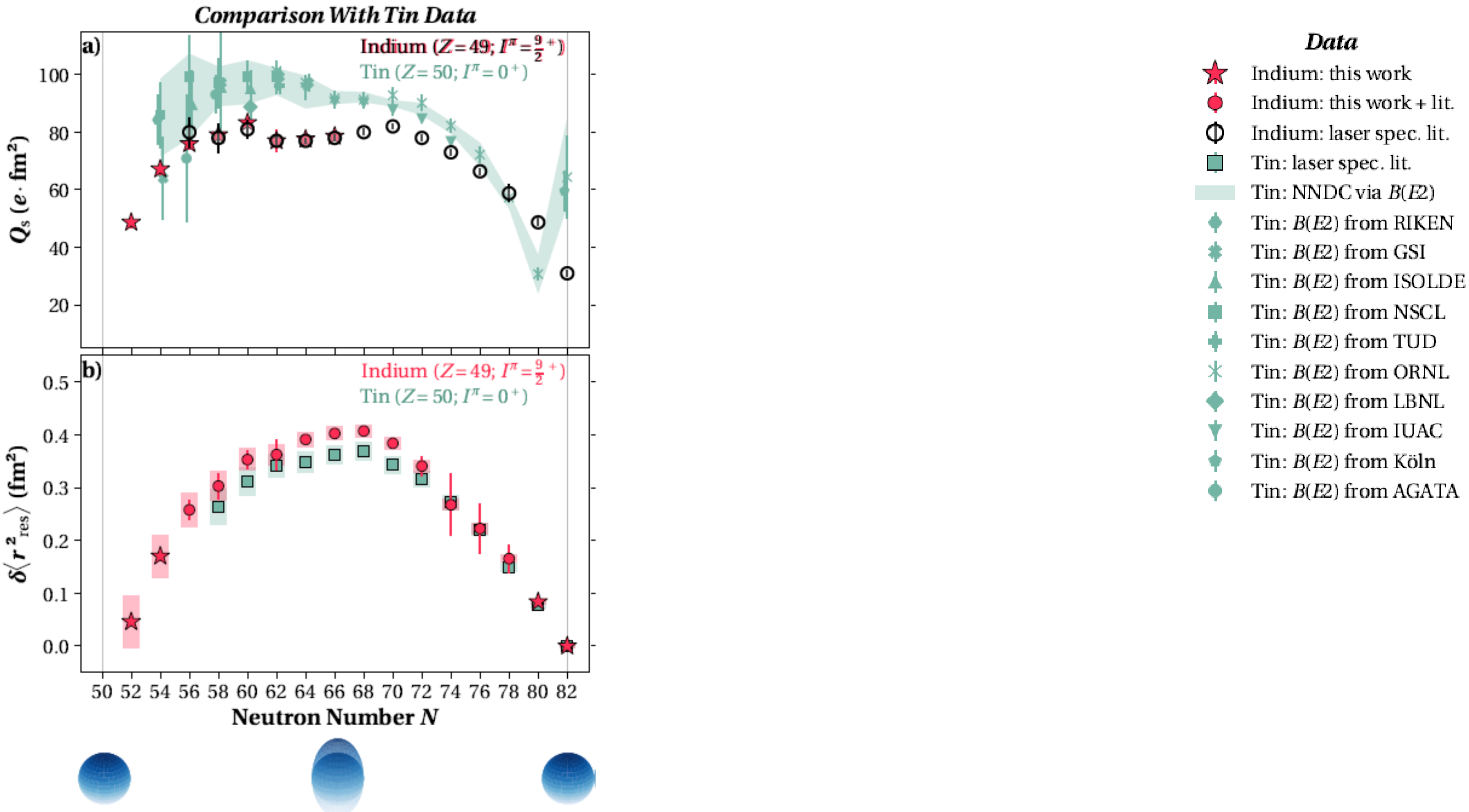
Similar trends for neutron-rich



Physics

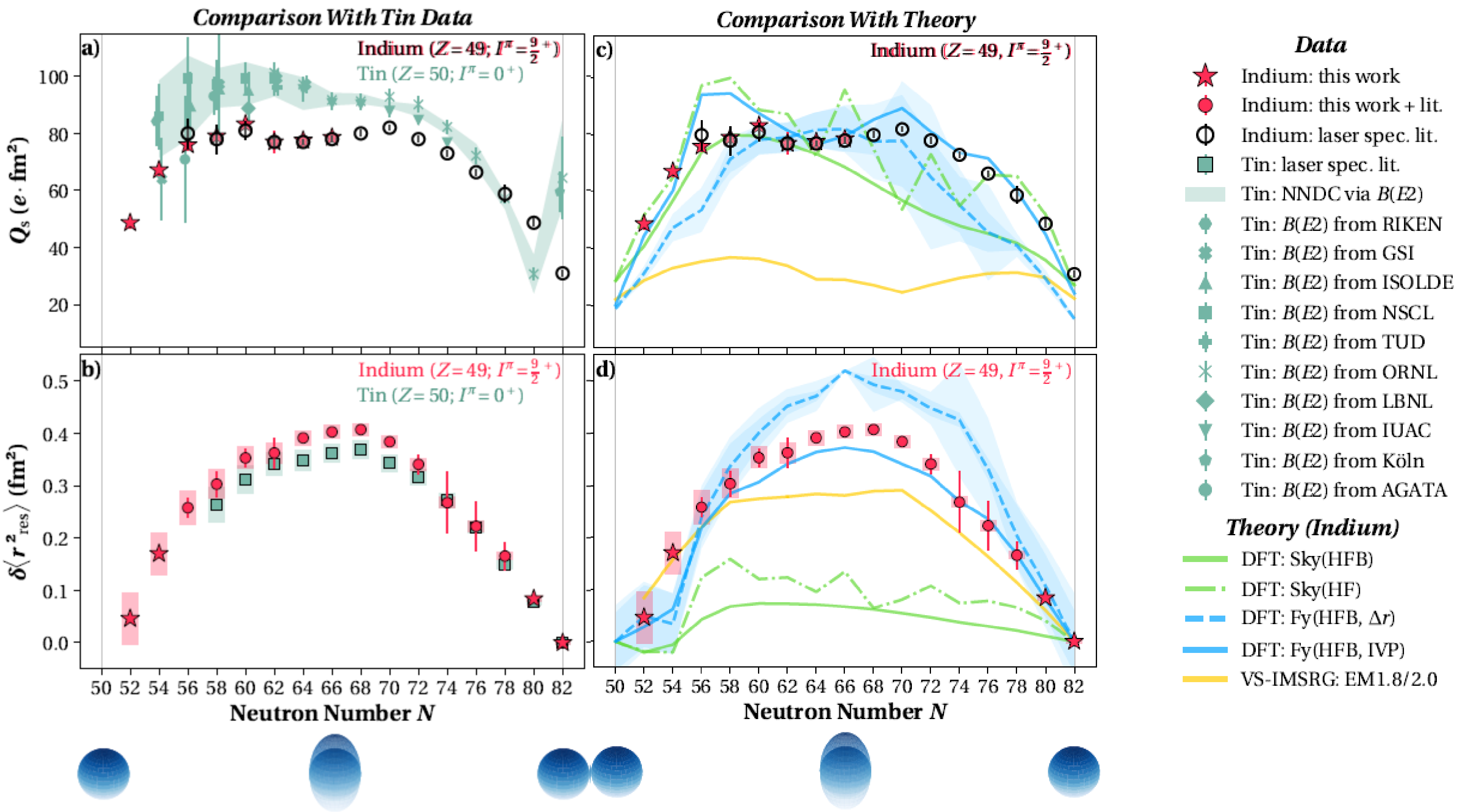
[Koszorus et al. Nature Phys. (2021)]
[Degroote et al. Nature Phys. 16, 620 (2020)]
[Kaufmann Phys. Rev. Lett. 124, 132502 (2020)]
[Garcia Ruiz & Vernon EPJ A 56, 136 (2020)]
[Gorges et al. Phys. Rev. Lett. 122, 192502 (2019)]
[Garcia Ruiz et al. Nature Phys. 12, 594 (2016)]

Evolution of nuclear collectivity between closed-shells



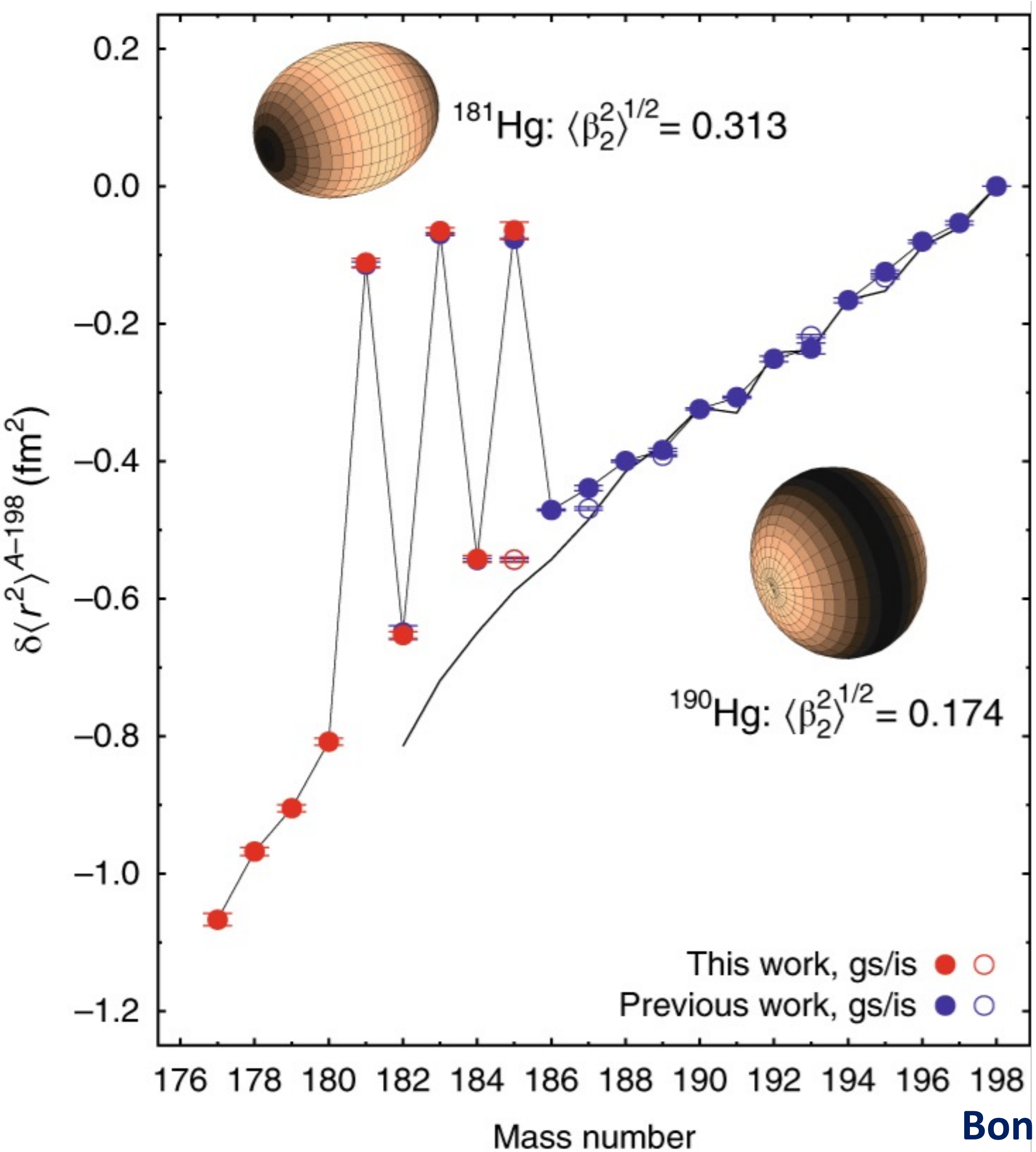
[Vernon et al. Nature 607, 260(2022)]
[Karthein et al. Accepted Nature Phys. (2024)]

Evolution of nuclear collectivity between closed-shells



[Vernon et al. Nature 607, 260(2022)]
[Karthein et al. Accepted Nature Phys. (2024)]

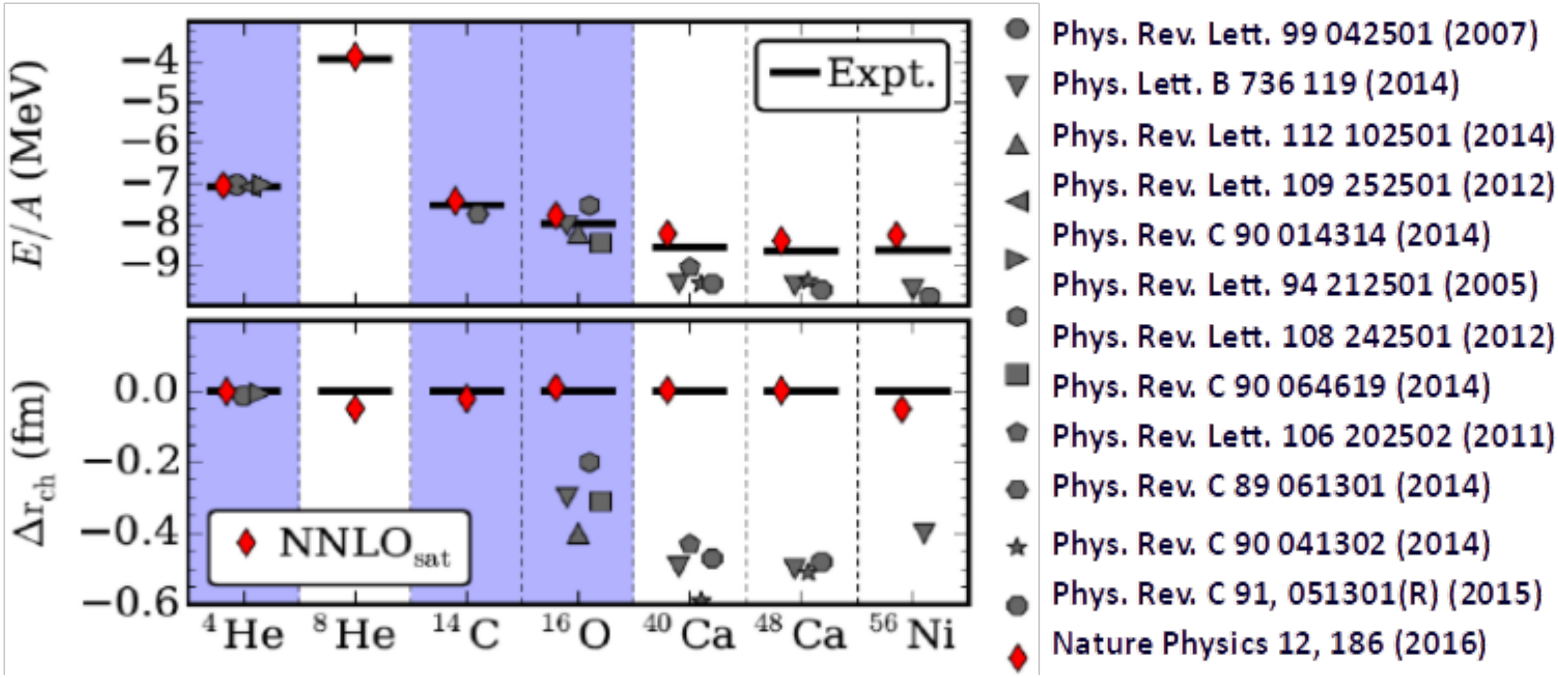
Shape staggering away closed-shells



RILIS

Bonn et al. Phys. Lett. B 38, 308 (1972)
Marsh et al. Nature Phys. 14, 1163(2018)

Open Challenge: Simultaneous reproduction of charge radii and binding energies has been a long-standing challenge for nuclear theory.



Overview

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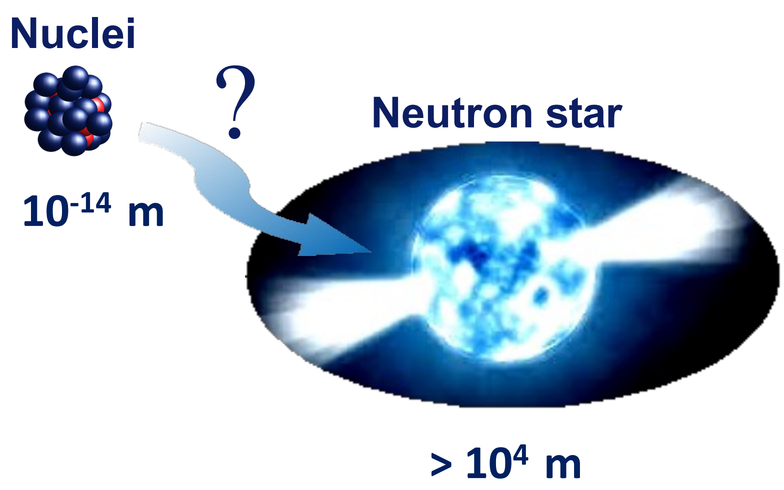
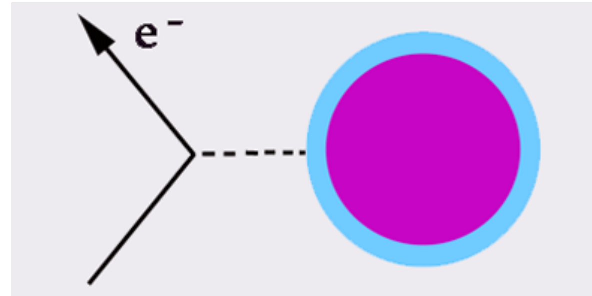
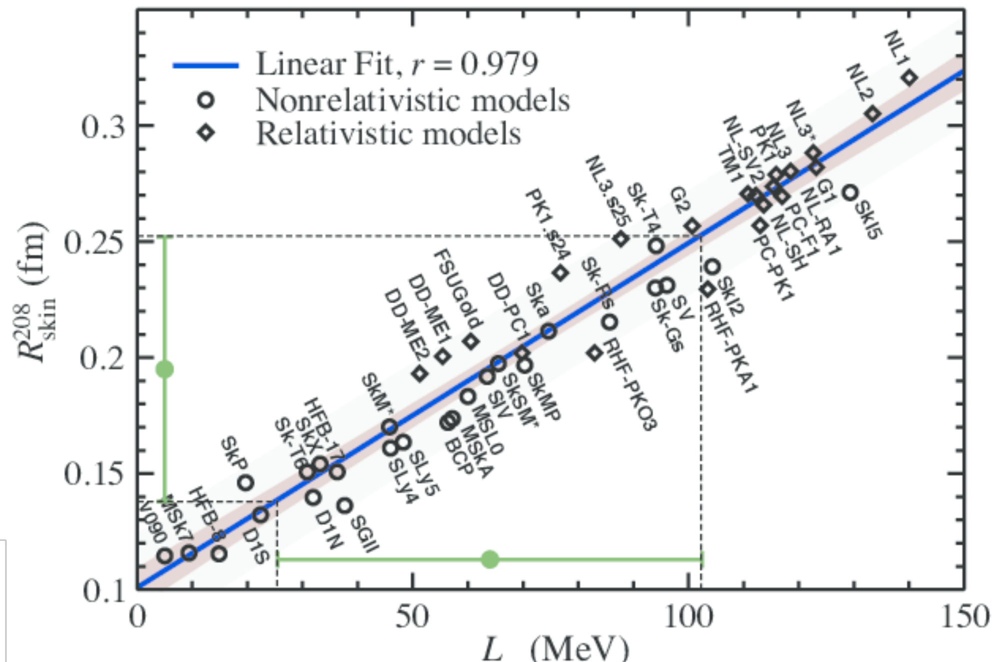
Can we use the properties of nuclei to constraint the properties of nuclear matter?



Radii of mirror nuclei & equation of state



Credit: APS



Equation of state of nuclear matter

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

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

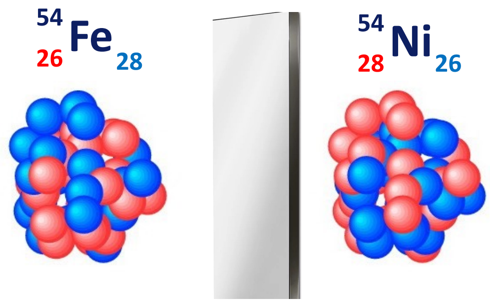
Symmetry energy (S_v)

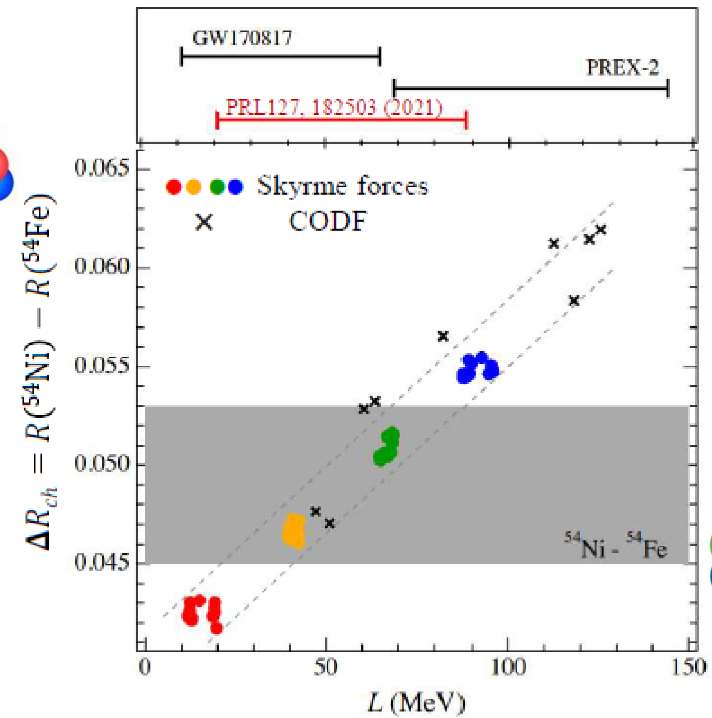
Slope ? (L)

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

PREX coll. PRL 126, 172502 (2021)

Radii of mirror nuclei & equation of state





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

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

FRIB

BECOLA

Equation of state of nuclear matter

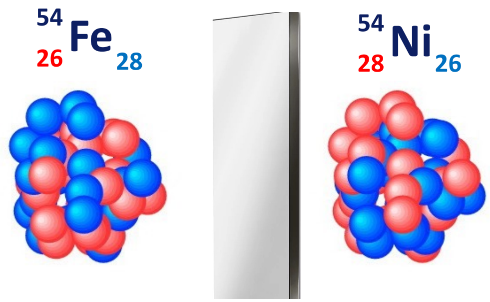
$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

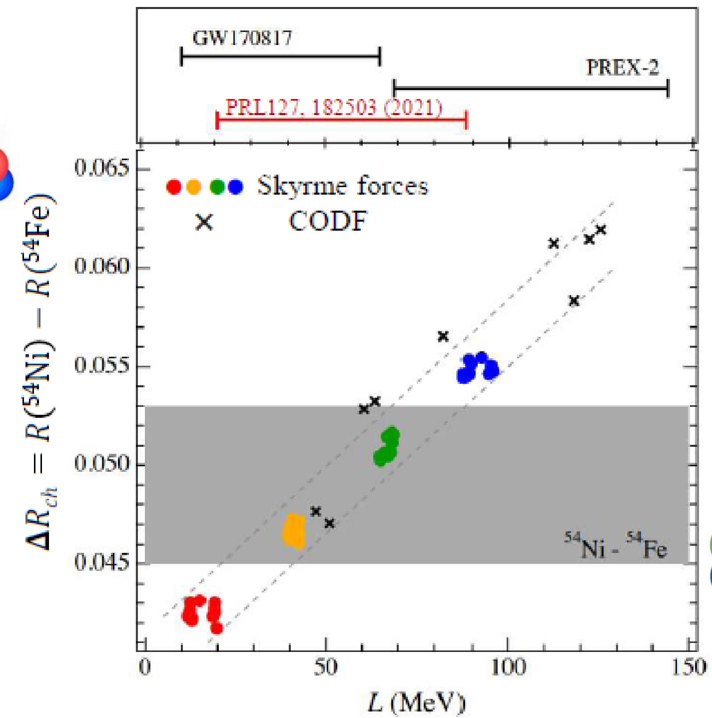
$$E_{sym}(\rho) = S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \cdots$$

Symmetry energy

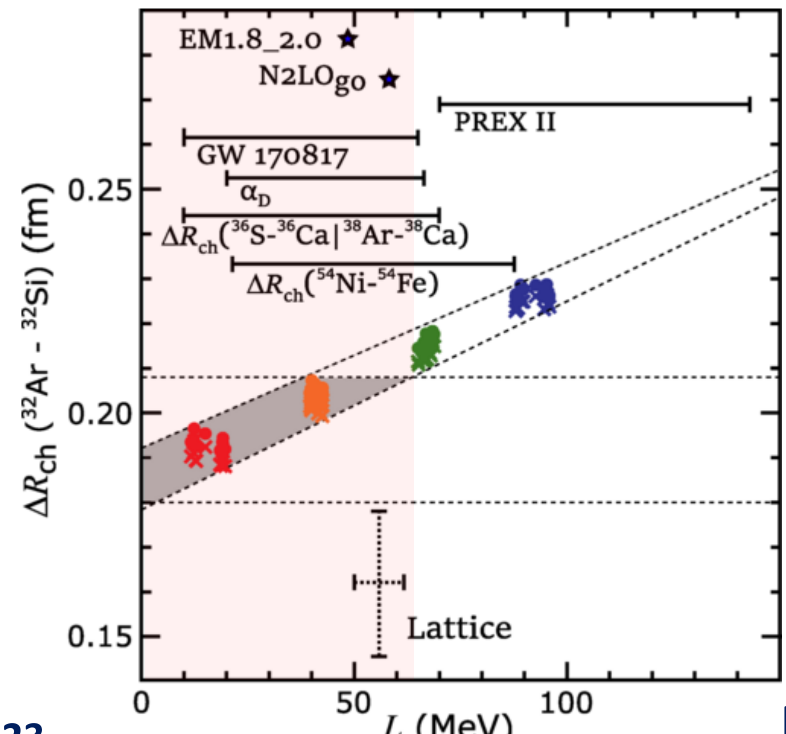
Slope ?

Radii of mirror nuclei & equation of state

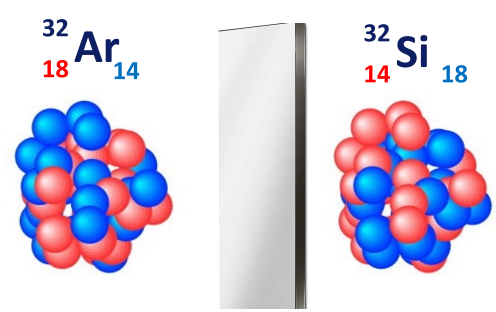




Open Challenge: Atomic theory uncertainties



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



[Koning et al. PRL 132, 162502 (2024)]

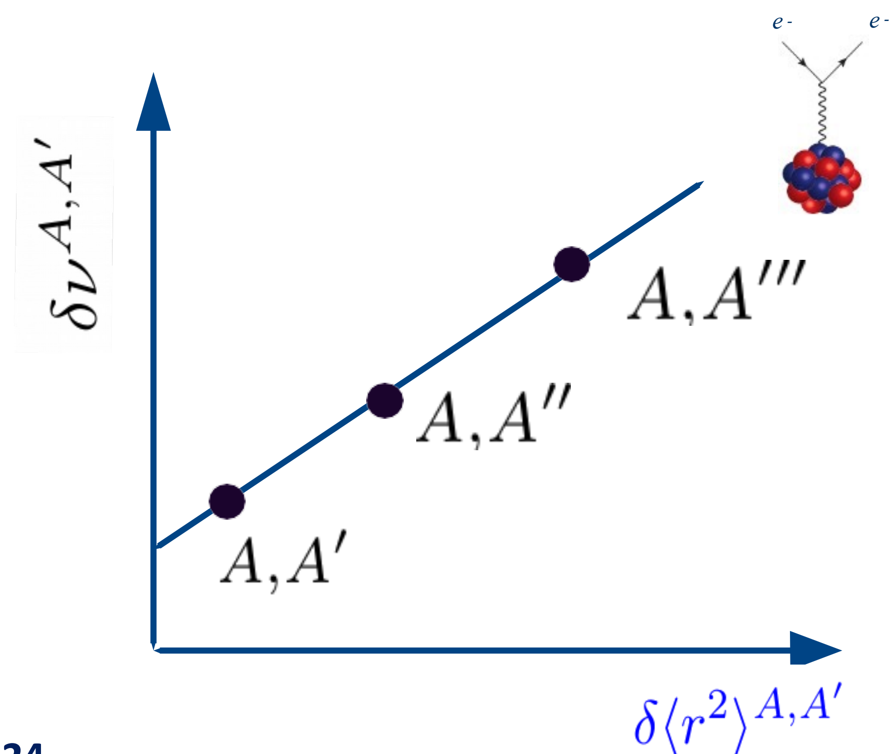
Overview

- Laser spectroscopy
- Charge radii & Nuclear Structure
- Charge radii & Nuclear Matter
- **Isotope shifts & BSM Physics**
- New Opportunities
- Summary & Outlook

Isotope shifts & BSM Physics

Atom
Nuclear

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

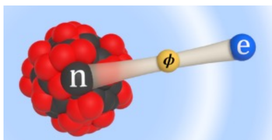


[Counts et al. Phys. Rev. Lett. 125, 123002 (2020)]

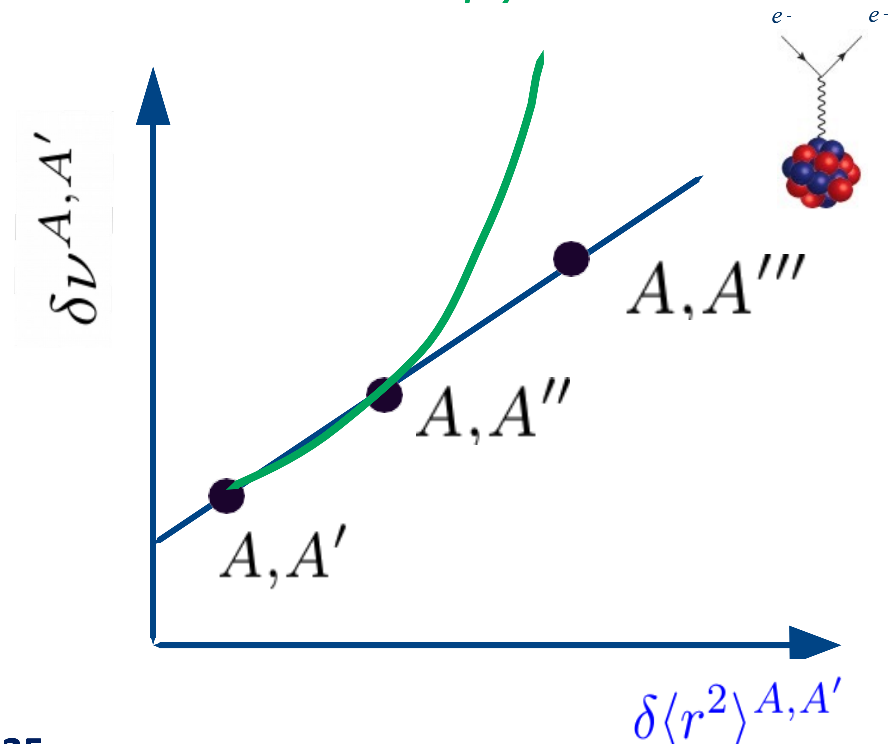
Isotope shifts & BSM Physics

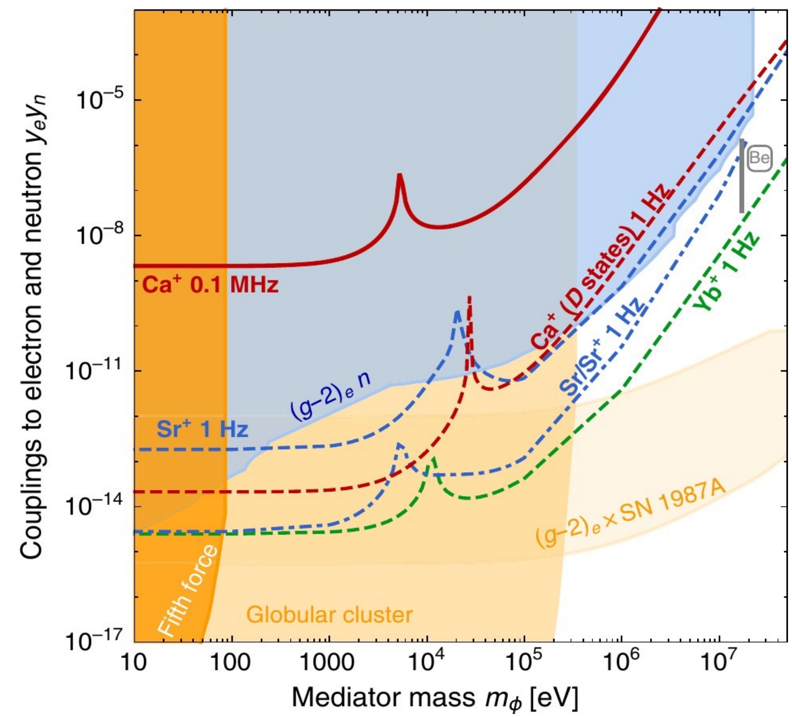
Atom
Nuclear

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} + \alpha_{\rm NP}X_i\gamma_{AA'}$$



New physics





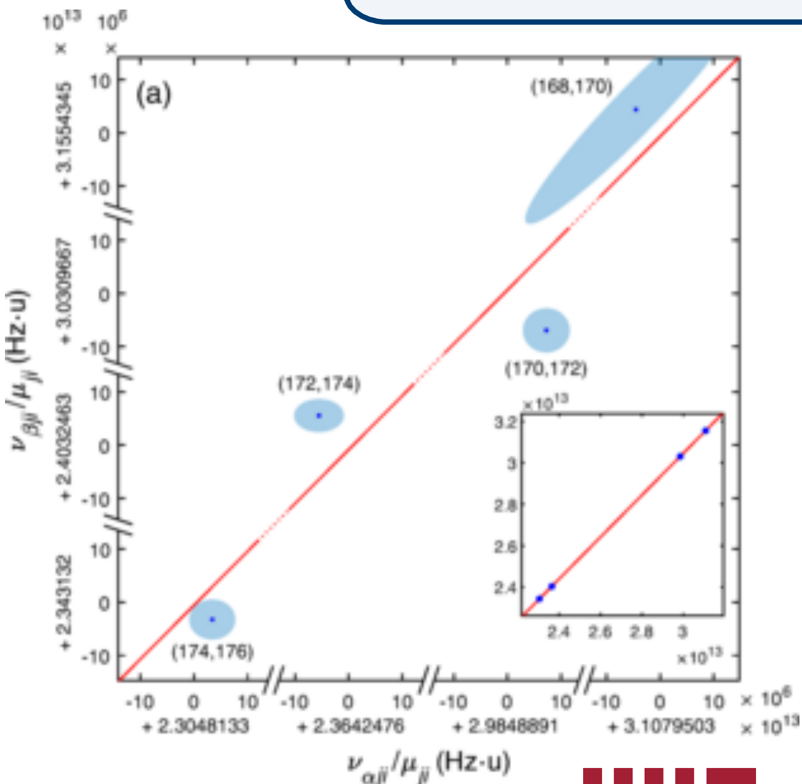
[Berengutet al. Phys. Rev. Lett 120, 091801 (2018)]
[Counts et al. Phys. Rev. Lett. 125, 123002 (2020)]
[Hur et al. Phys. Rev. Lett. 128, 163201 (2022)]

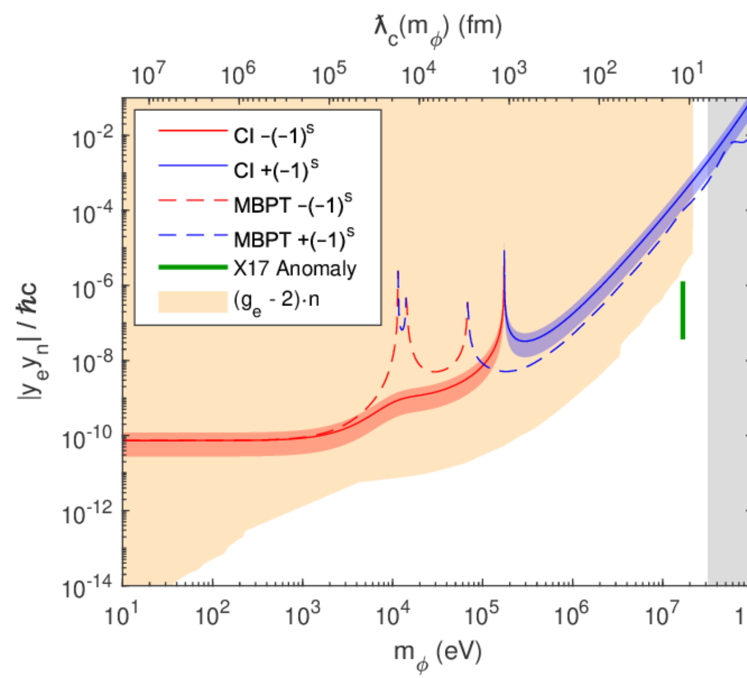
Isotope shifts & BSM Physics

Atomic factors
(two transitions)

$$\frac{\nu_2^{AA'}}{\mu^{AA'}} = \frac{F_2}{F_1}\frac{\nu_1^{AA'}}{\mu^{AA'}} + \left(K_2 - \frac{F_2}{F_1}K_1\right) + \alpha_{\rm NP}\left(\frac{X_2}{X_1} - \frac{F_2}{F_1}\frac{A-A'}{\mu^{AA'}}\right)$$

$$\mu^{AA'} = \frac{1}{M_A} - \frac{1}{M_{A'}}$$





Yb⁺ → Vuletic's group at MIT

Accuracy < 100 Hz (stable) Vs ~ 1 MHz (exotic)

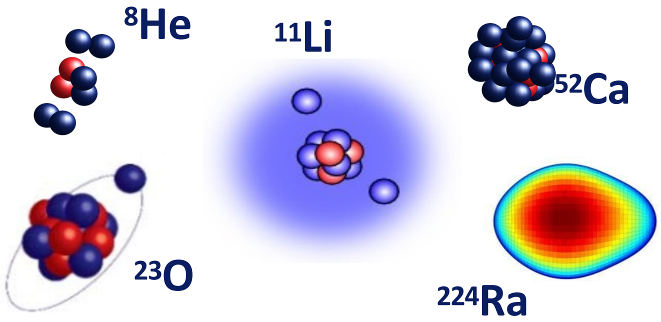
[Counts et al. Phys. Rev. Lett. 125, 123002 (2020)]
[Hur et al. Phys. Rev. Lett. 128, 163201 (2022)]

Open challenges: - Nuclear theory
- Experiments with more isotopes (exotic nuclei)

Summary & Outlook

Isotope shift measurements in Exotic Atoms allows for the exploration of rich physics phenomena

How do nuclear phenomena emerge from QCD?



Open Challenges:

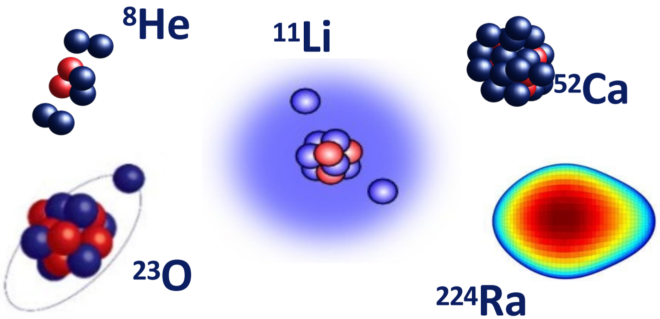
- **Description of nuclear charge radii has been a long-standing challenge for ab-initio nuclear theory**
- **Light nuclear systems require precise experiments and atomic theory calculations.**

Summary & Outlook

Isotope shift measurements in Exotic Atoms allows for the exploration of rich physics phenomena

How do nuclear phenomena emerge from QCD?

What are the properties of dense nuclear matter?



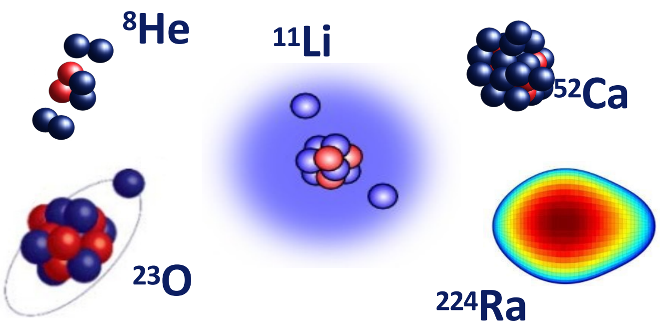
Open Challenges:

- **Description of nuclear charge radii has been a long-standing challenge for ab-initio nuclear theory**
- **Light nuclear systems require precise experiments and atomic theory calculations.**
- **Precise atomic theory needed to constrain the EOS from mirror radii.**

Summary & Outlook

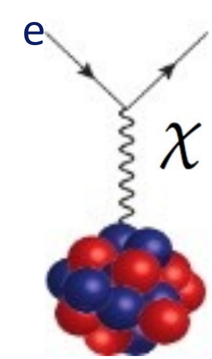
Isotope shift measurements in Exotic Atoms allows for the exploration of rich physics phenomena

How do nuclear phenomena emerge from QCD?



What are the properties of dense nuclear matter?

Are there new forces?



Open Challenges:

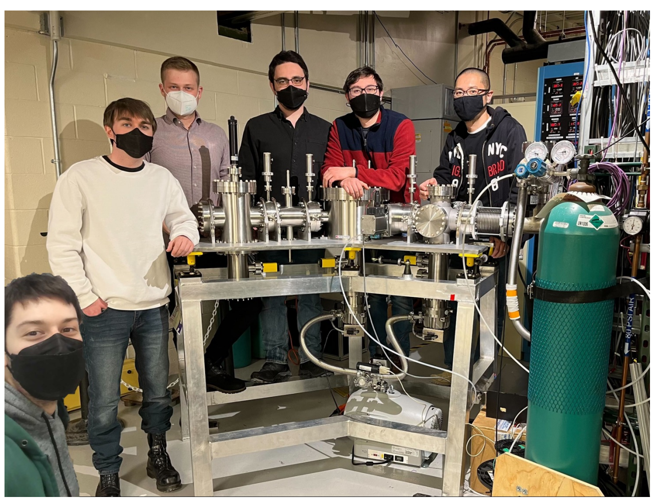
- **Description of nuclear charge radii has been a long-standing challenge for ab-initio nuclear theory**
- **Light nuclear systems require precise experiments and atomic theory calculations.**
- **Precise atomic theory needed to constrain the EOS from mirror radii.**
- **Precise nuclear theory needed to constrain BSM physics from isotope shift measurements.**

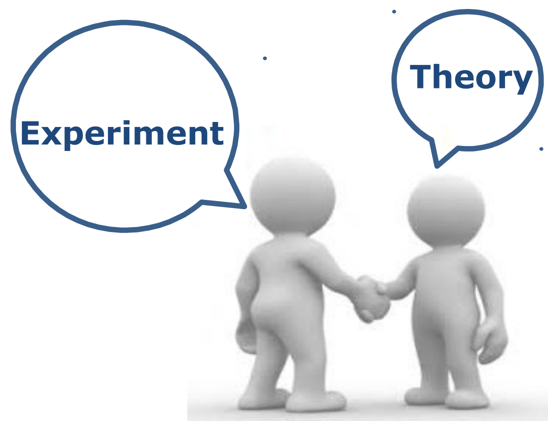
Small Size – Big Science

COLLAPS
https://collaps.web.cern.ch/subpages/people.html

CRIS
https://isolde-cris.web.cern.ch/collaboration.html

RISE/BECOLA @ FRIB
https://groups.nscl.msu.edu/becola/people.html





Nuclear & Atomic & Molecular

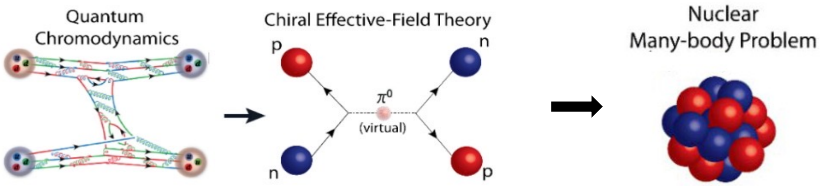
J. Dobaczewski (York)
J. Holt (TRIUMF)
R. Stroberg (U ND)
W. Nazarewicz (FRIB/MSU)

A. Borchevsky (Groningen)
B. Sahoo (PRL)
R. Berger (Malbroune)
…

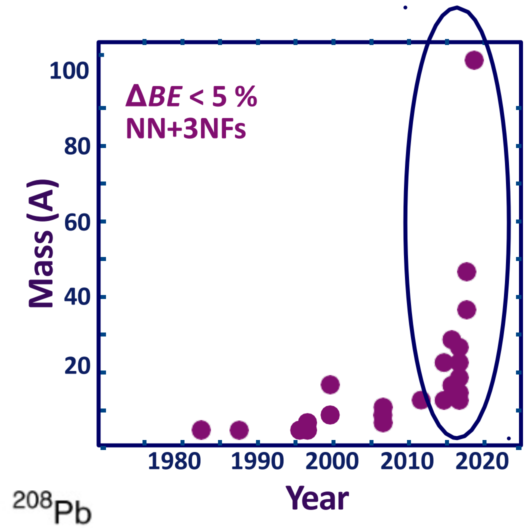
Complex Nuclei with Simple Structure

Ab-initio methods

QMC, GFMC, CC, IMSRG, GGF….



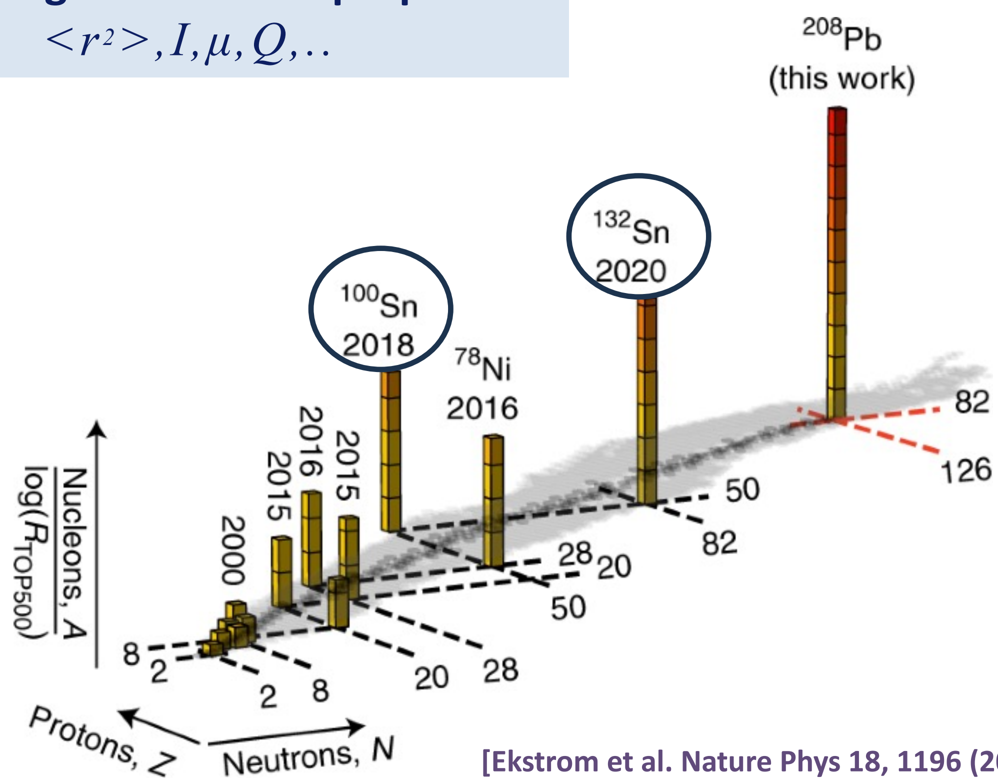
1. $\hat{H}$
2. $\hat{H}|\psi\rangle = E|\psi\rangle$
3. $\langle\psi|\hat{O}|\psi\rangle$



↓ **Theory**

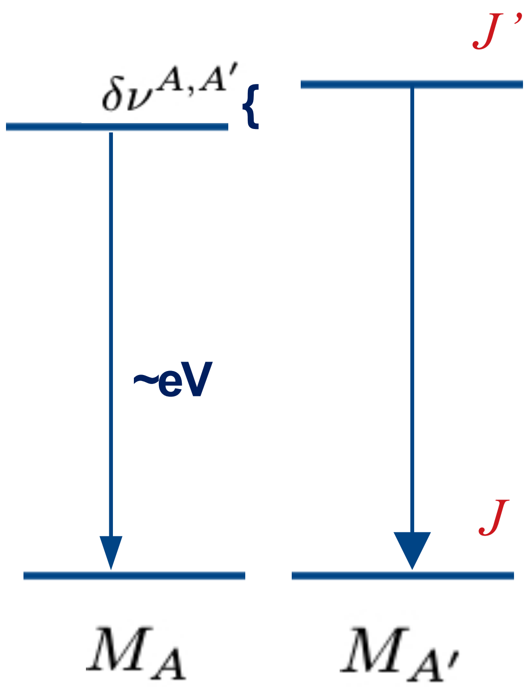
Experiment → **Electromagnetic nuclear properties**

$<r^2>, I, \mu, Q, ..$



[Ekstrom et al. Nature Phys 18, 1196 (2022)]

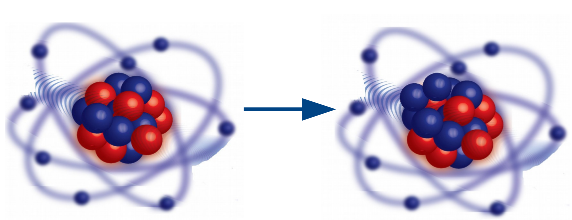
Nuclear Electromagnetic Properties from Laser Spectroscopy

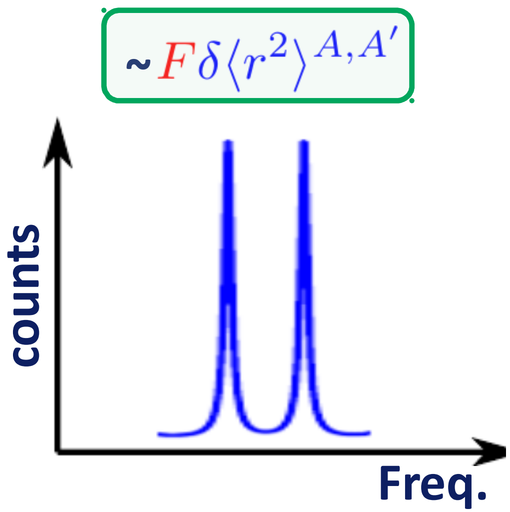


$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'} M_A} + F\delta\langle r^2\rangle^{A,A'}$$

Atomic

Nuclear

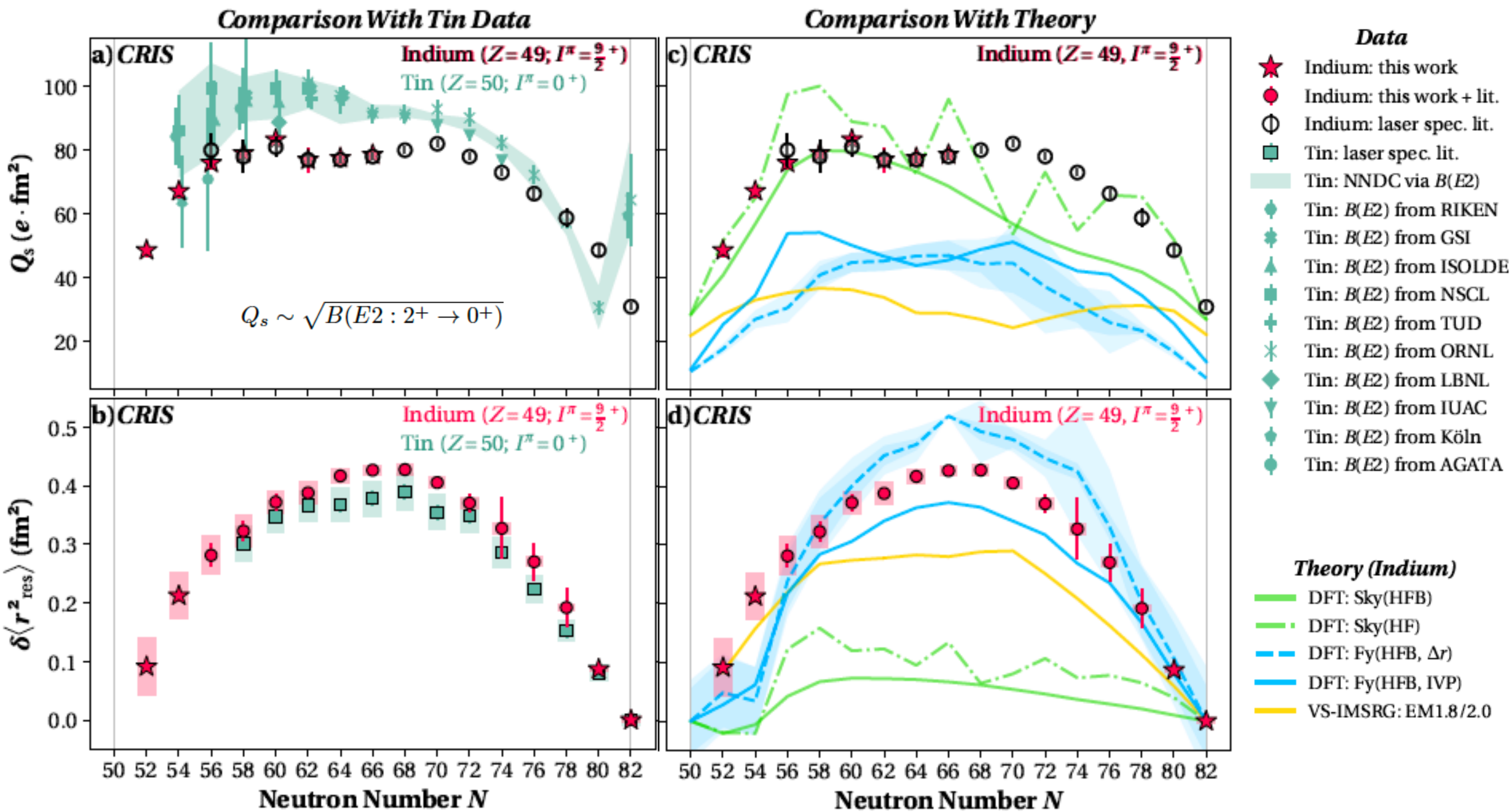




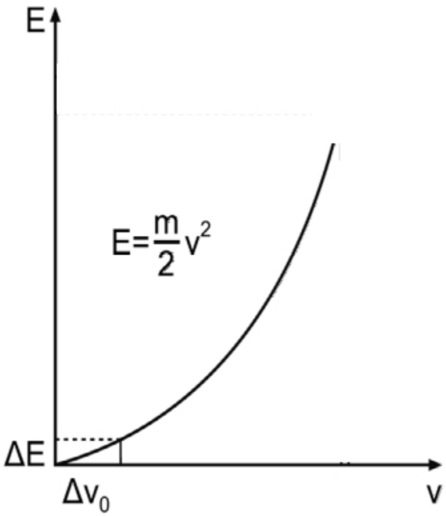
Electromagnetic nuclear properties

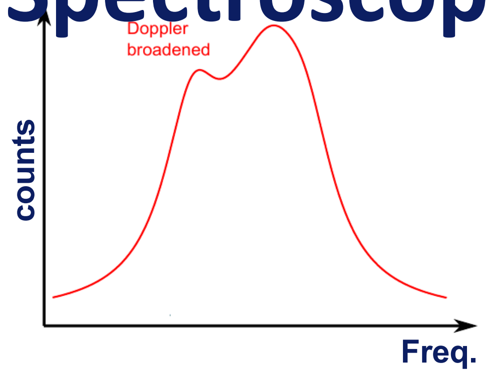
- Rms charge radii: $< r^2 >$

Complex Nuclei with Simple Structure

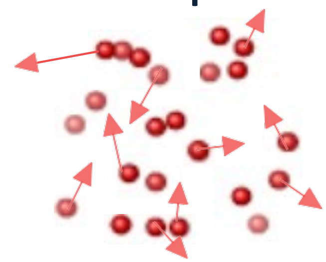


Precision Laser Spectroscopy



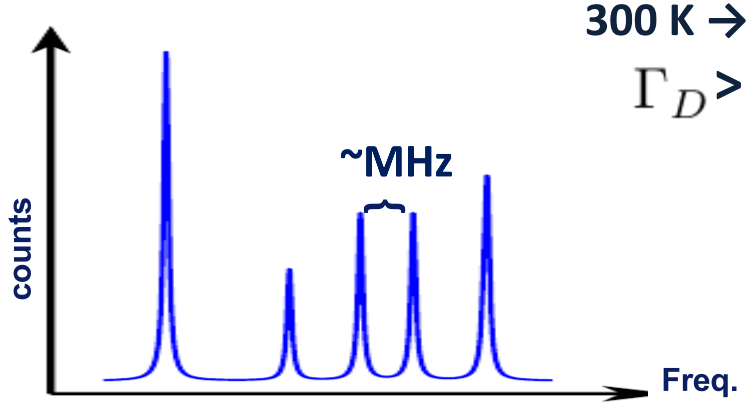


Room temperature

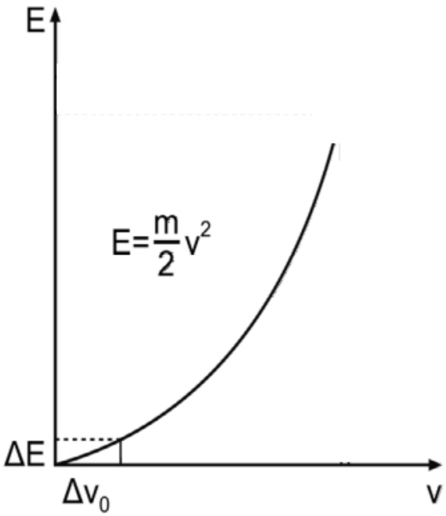


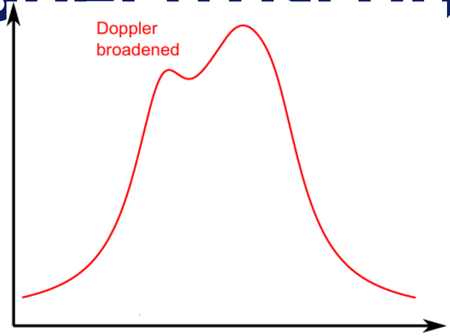
300 K → 25 meV

Γ_D > GHz

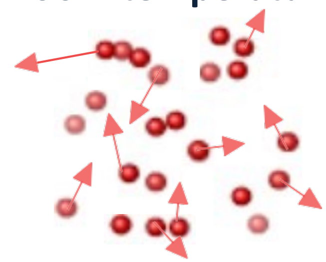


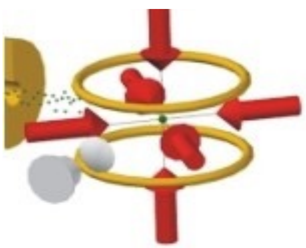
Precision Laser Spectroscopy





Room temperature





T < μK

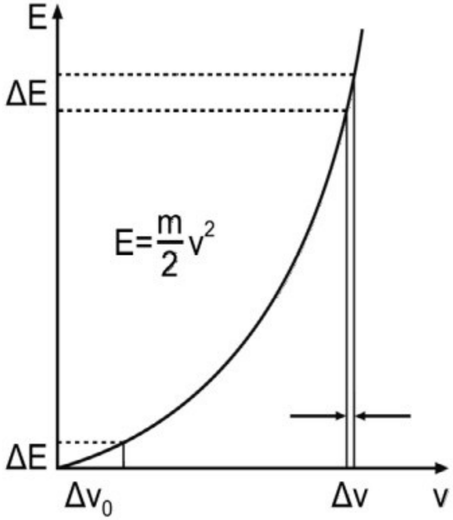
Γ_D **< MHz**

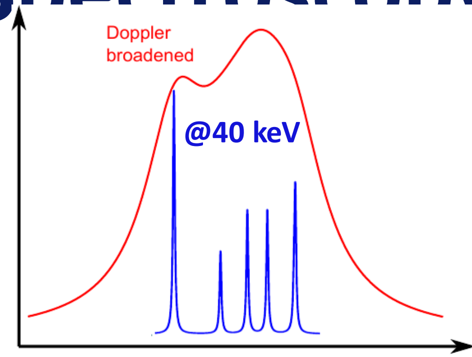
300 K → 25 meV

Γ_D **> GHz**

- ✔ High resolution (< MHz)
- High efficiency (<100 ions/s) ?
- High selectivity (>1/10^6) ?
- Short time scales (< 1 s)?

Precision Laser Spectroscopy





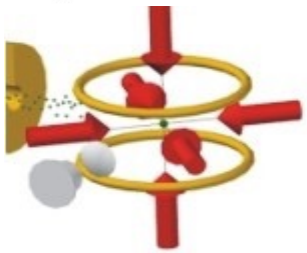
Energy spread

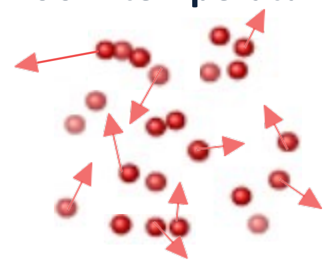
$$\Gamma_D = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}}$$

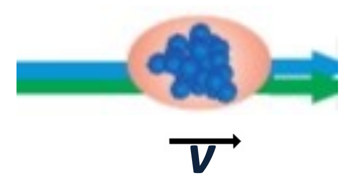
Ion beam energy

Room temperature

Fast beam







T < μK

Γ_D **< MHz**

300 K → 25 meV

Γ_D **> GHz**

@ 40 keV

Γ_D **~ MHz**

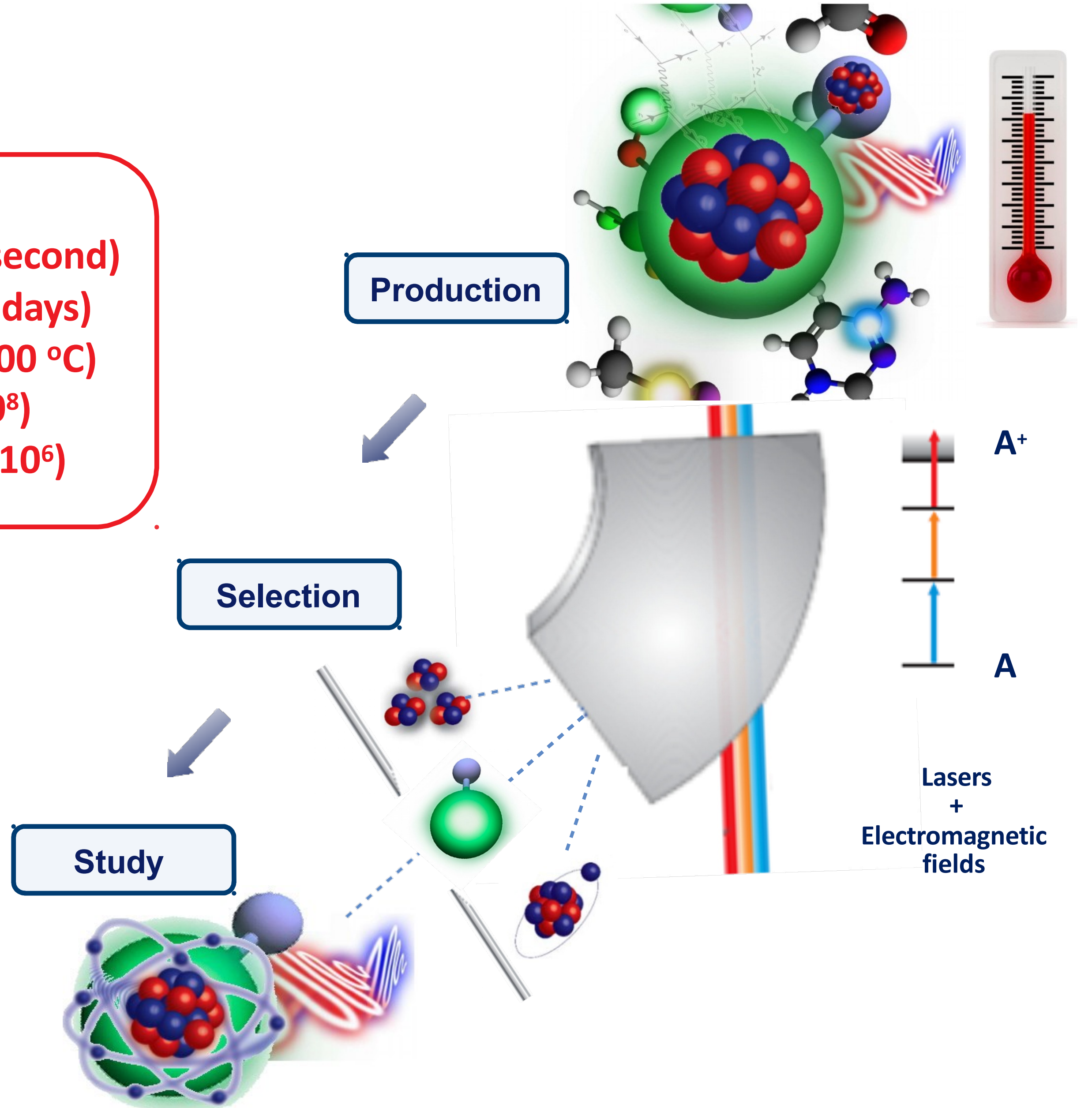
- ✔ High resolution (< MHz)
- High efficiency (<100 ions/s) ?
- High selectivity (>1/10^6) ?
- Short time scales (< 1 s)?

- ✔ High resolution (~MHz)
- ✔ High efficiency (<100 ions/s)
- ✔ High selectivity (>1/10^6)
- ✔ Short time scales (< 1 s)

Main Challenges

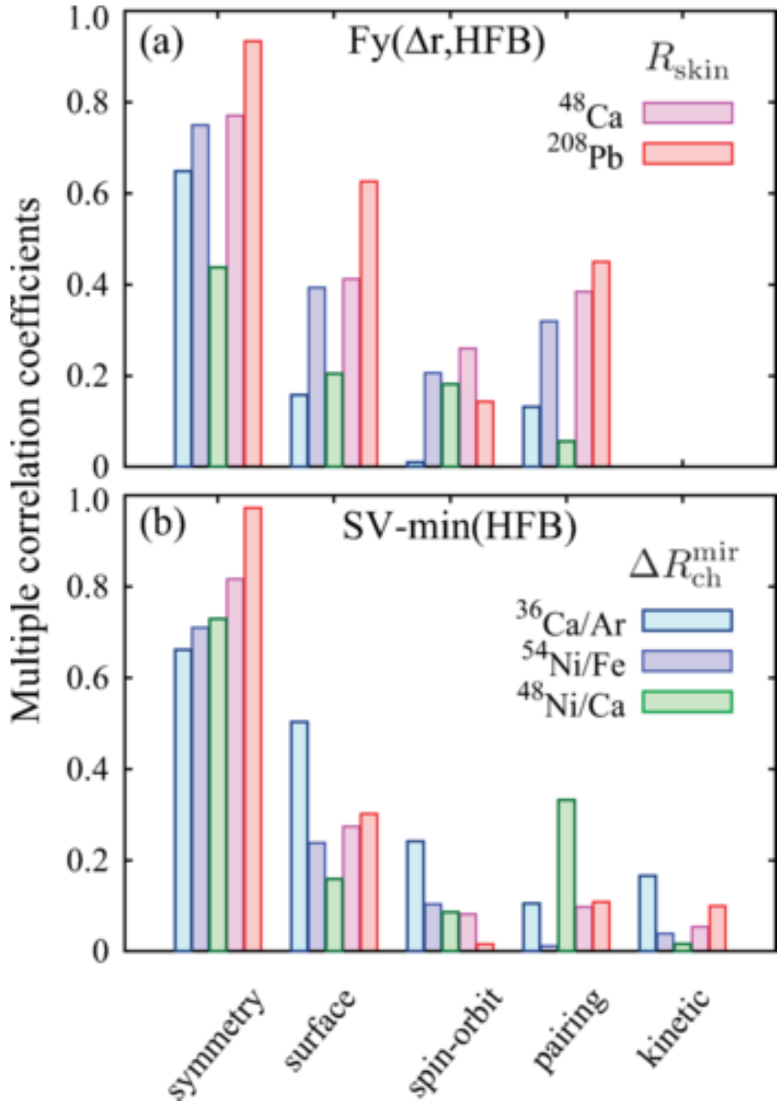
Experimental Challenges:

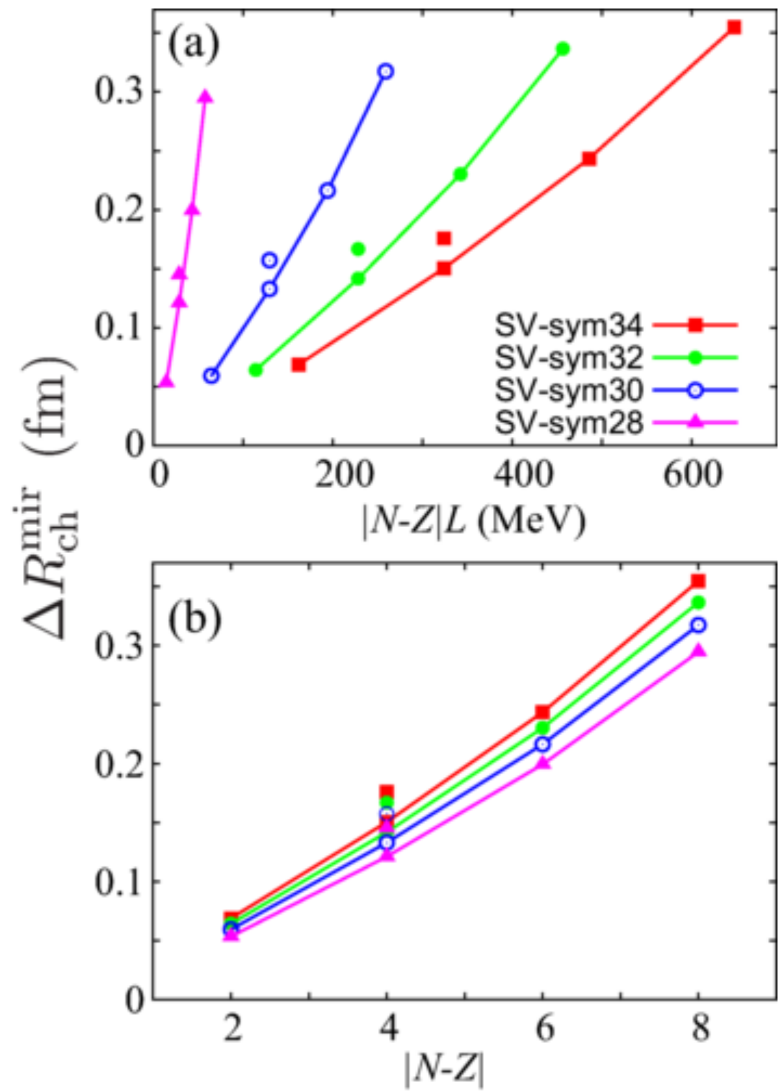
1. Small quantities (a few per second)
2. Have short lifetimes (< 1s < days)
3. Extreme environments (>2000 °C) & highly contaminated (1:10^8)
4. High precision is critical (>1:10^6)



Traps + lasers

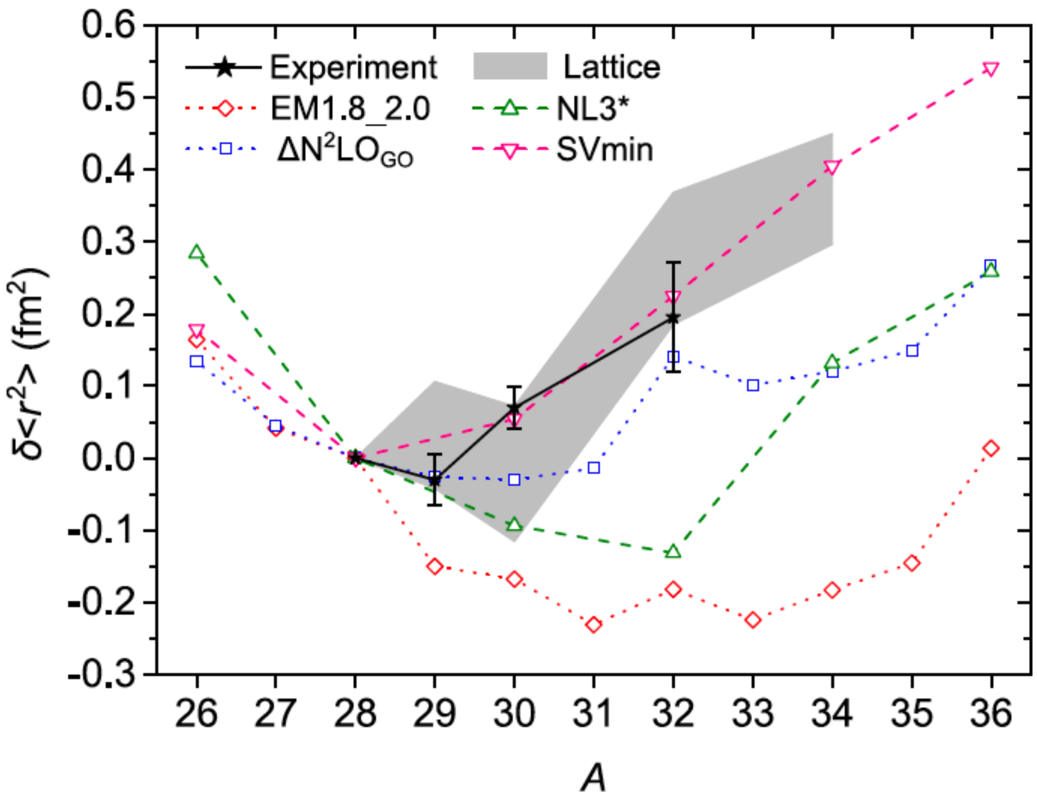
Reinhard & Nazarewicz Phys. Rev. C 105, L021301 (2022)



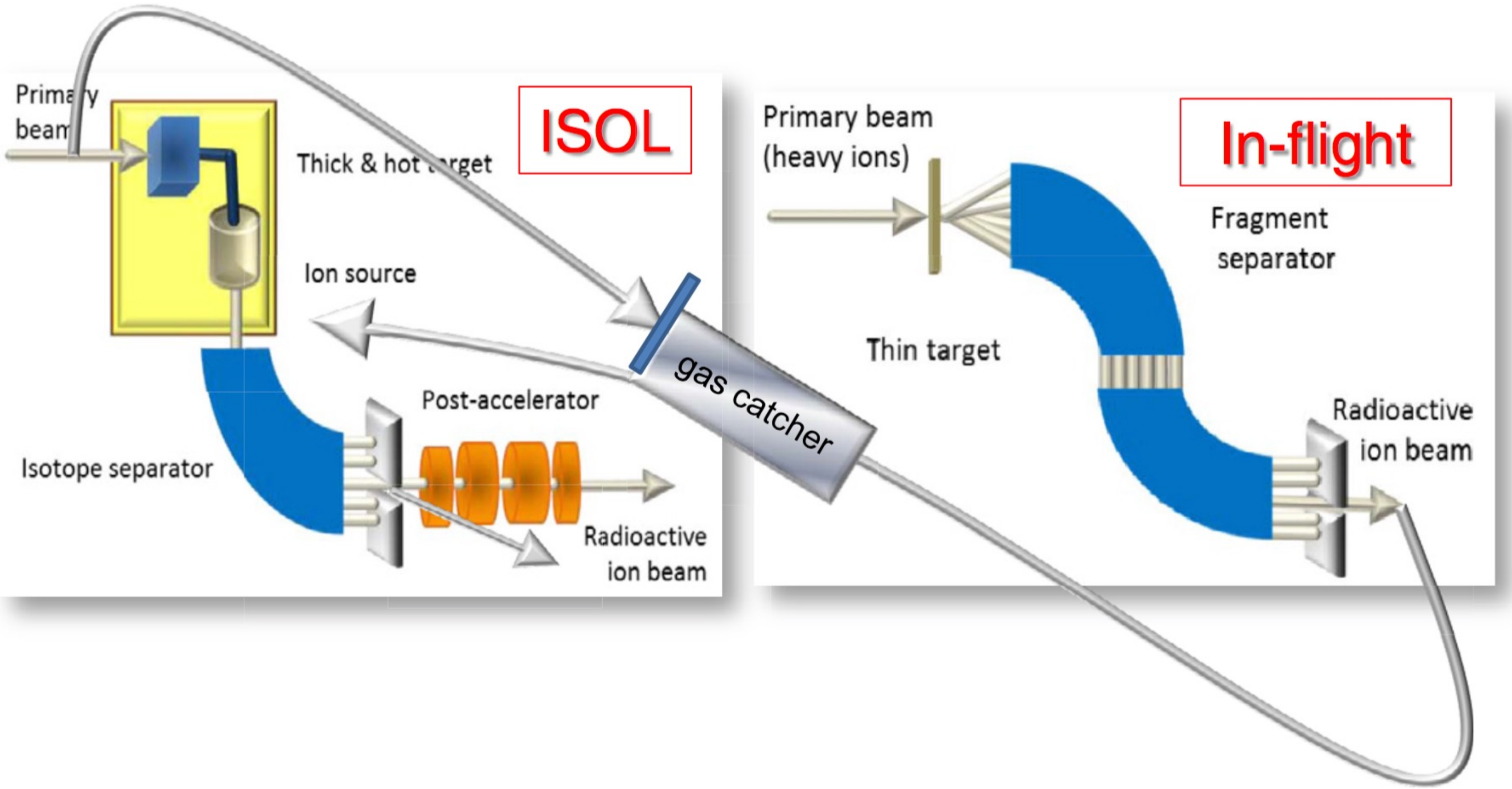


Evolution of the nuclear size away from stability

Towards a “Standard Model” of the Nucleus



[Koning et al. PRL 132, 162502 (2024)]

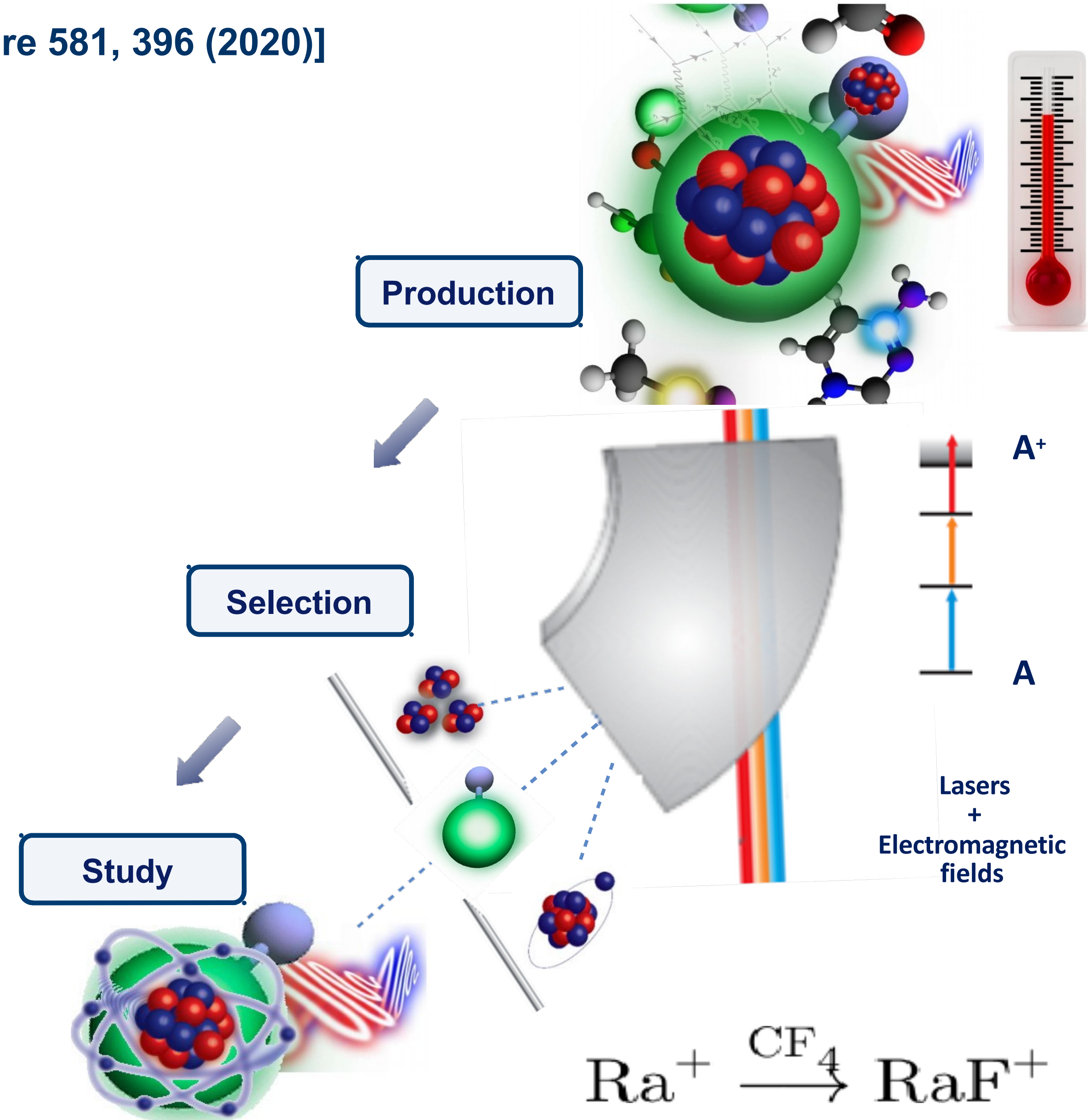


Primary beam
Thick & hot target
ISOL
Ion source
Post-accelerator
Isotope separator
Radioactive ion beam
gas catcher
Primary beam (heavy ions)
In-flight
Fragment separator
Thin target
Radioactive ion beam

Recent Results (RaF)

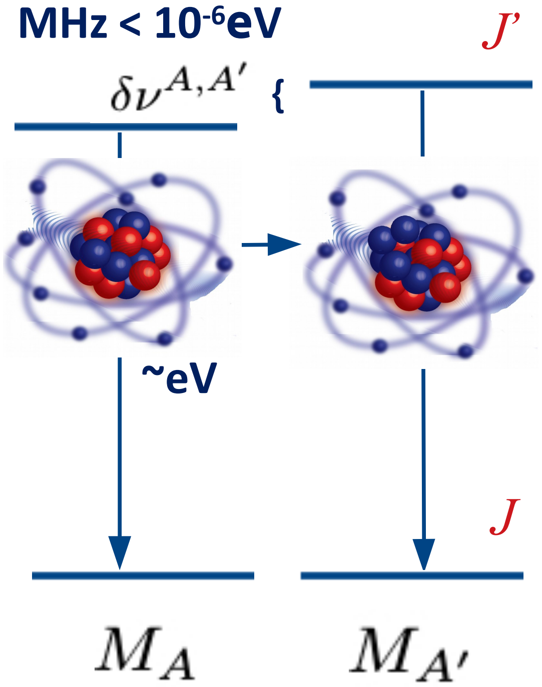
[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]

Traps
+
lasers



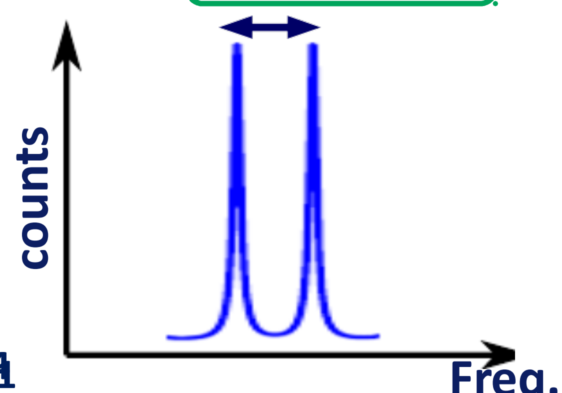
How do we do it?

Isotope shift
MHz < 10^{-6}eV



$I = 0$

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



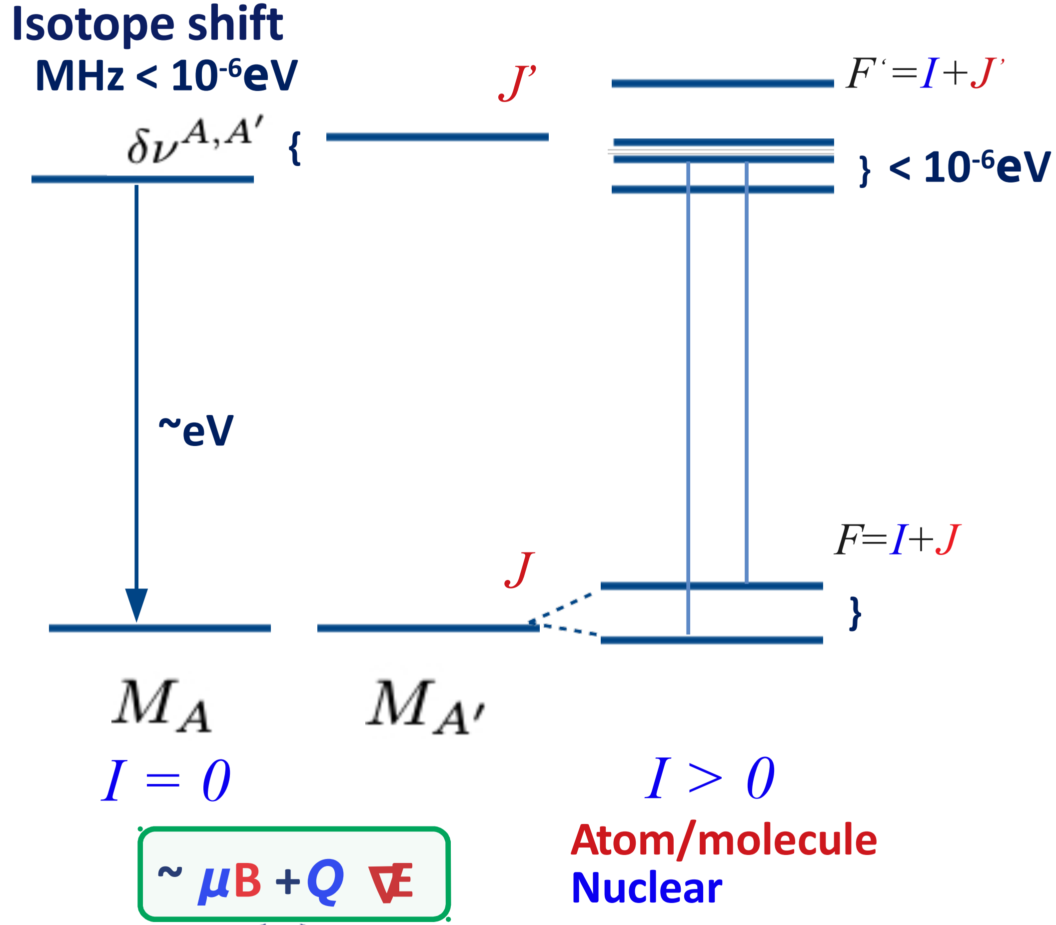
$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

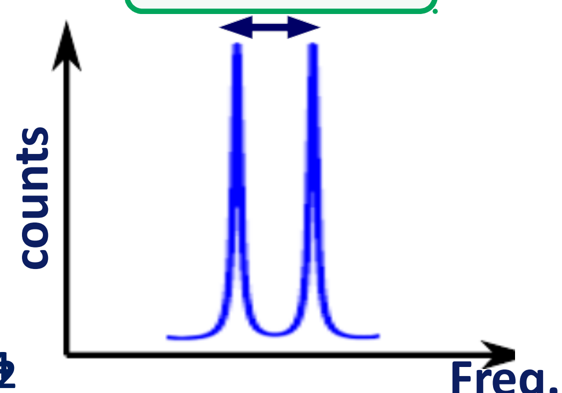
Atom/molecule
Nuclear

Electromagnetic structure

Rms charge radii: $<r^2>$

How do we do it?





Electromagnetic structure

Rms charge radii: $<r^2>$

Nuclear spin: I

Magnetic moment: μ

Quadrupole moment : Q