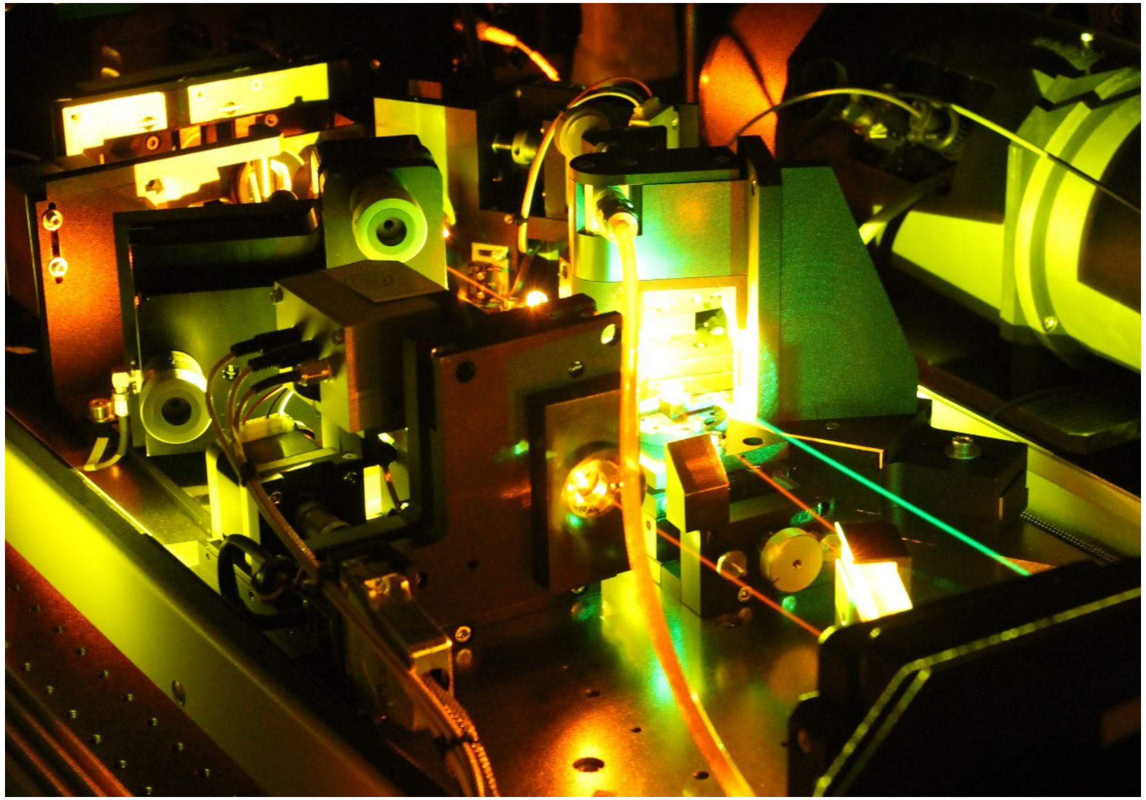
Laser spectroscopy of rare isotopes at FRIB

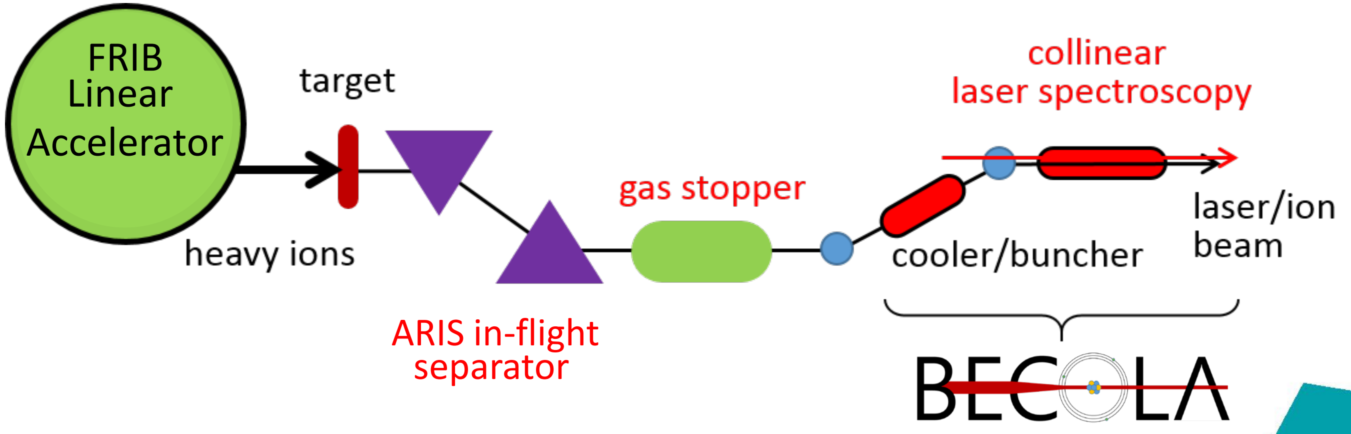


Kei Minamisono

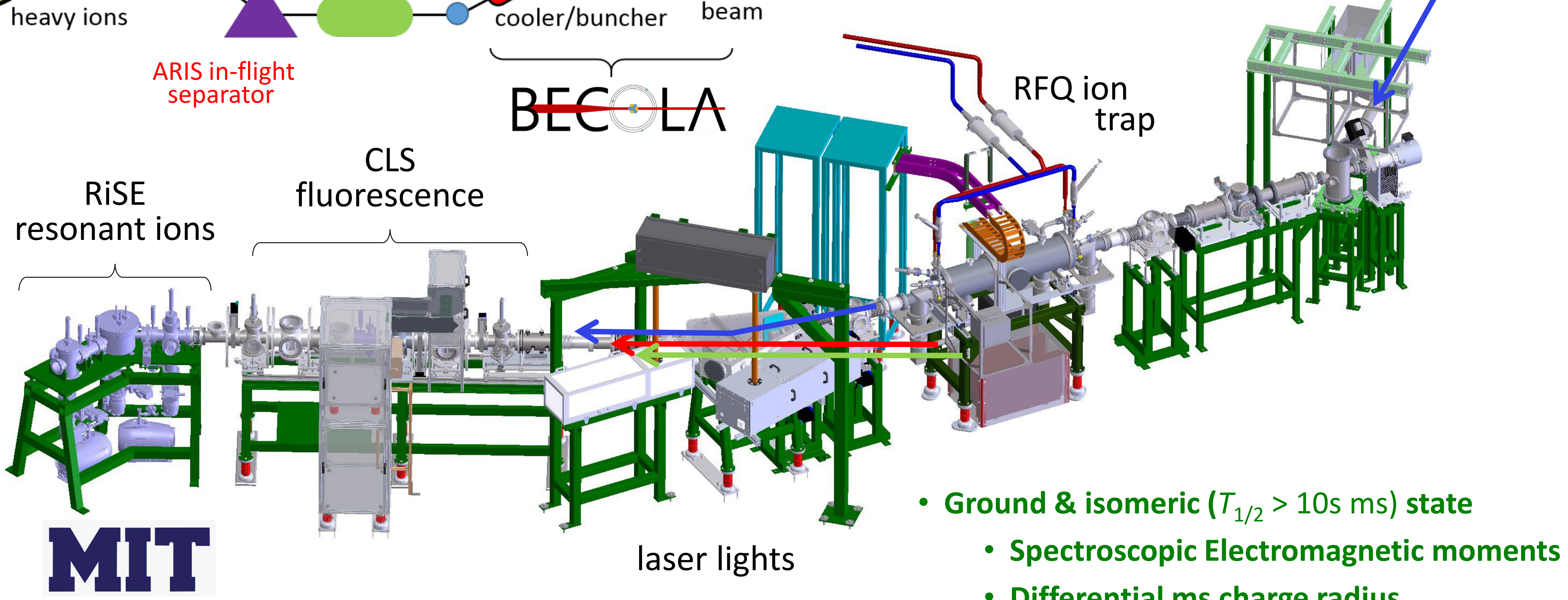
for BECOLA collaboration

FRIB TA TP: theoretical justifications and motivations for early high-profile FRIB experiments, FRIB, East Lansing, MI, May 24, 2023

BECOLA facility @ NSCL/FRIB/MSU
- Bunched beam collinear laser spectroscopy -



- **Stopped beam, 10% of fast beam**



- **Ground & isomeric (**$T_{1/2}$ > 10s ms**) state**
  - **Spectroscopic Electromagnetic moments**
  - **Differential ms charge radius**

K. Minamisono et al, NIMA 709, 85 (2013); D. M. Rossi et al., RSI 85, 093503 (2014).

Electromagnetic moments

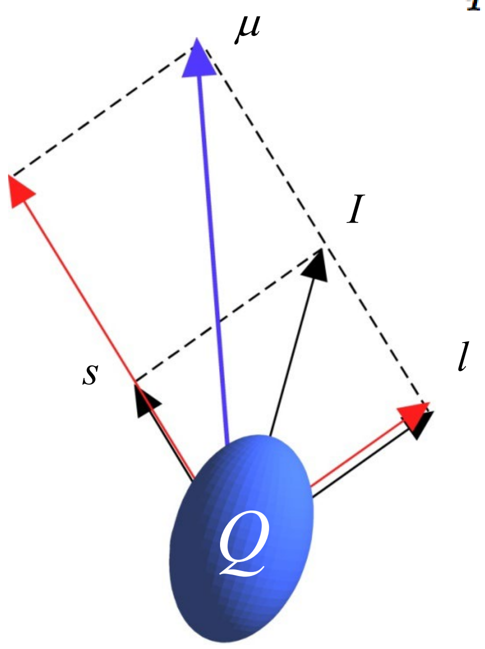
$$H_{\rm EM} = \int \rho(\boldsymbol{r})\phi(\boldsymbol{r})d\boldsymbol{r} - \int \boldsymbol{j}(\boldsymbol{r})\cdot\boldsymbol{A}(\boldsymbol{r})d\boldsymbol{r}$$

$$= q\phi(0) - \boldsymbol{P}\cdot\boldsymbol{E}(0) - \boldsymbol{\mu}\cdot\boldsymbol{H}(0) - \frac{1}{6}\sum_{ij} Q_{ij}\left(\frac{\partial E_j}{\partial x_i}\right)_0 + \cdots$$

e-monopole e-dipole m-dipole e-quadrupole

$$q = \int \rho(\boldsymbol{r})d\boldsymbol{r}$$: total charge

$$\boldsymbol{P} = \int \rho(\boldsymbol{r})\boldsymbol{r}d\boldsymbol{r}$$: electric dipole moment → 0 (time reversal)



magnetic dipole moment : $\boldsymbol{\mu} = \int \boldsymbol{r}\times\boldsymbol{j}(\boldsymbol{r}) = \mu_{\rm N}\left(\langle\boldsymbol{l}\rangle + g_{\rm p}\langle\boldsymbol{s}\rangle + g_{\rm n}\langle\boldsymbol{s}\rangle\right)$

electric quadrupole moment : $Q_{ij} = \int \rho(\boldsymbol{r})\left(3x_ix_j - \delta_{ij}r^2\right)d\boldsymbol{r}$

μ : spin, angular momentum, configuration of nucleons ↔ B(M1)

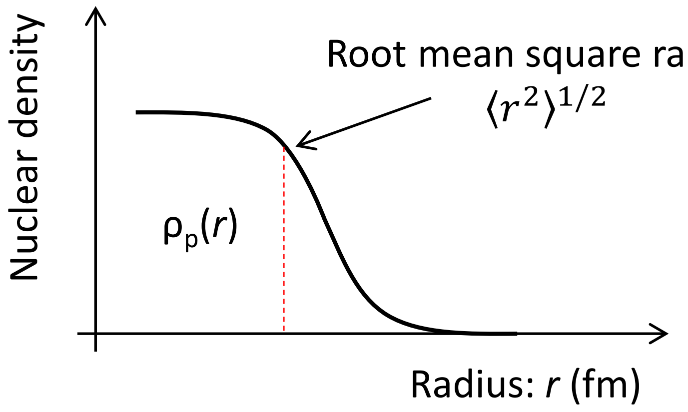
Q : deviation of proton distribution from spherical symmetry, static deformation ↔ B(E2)

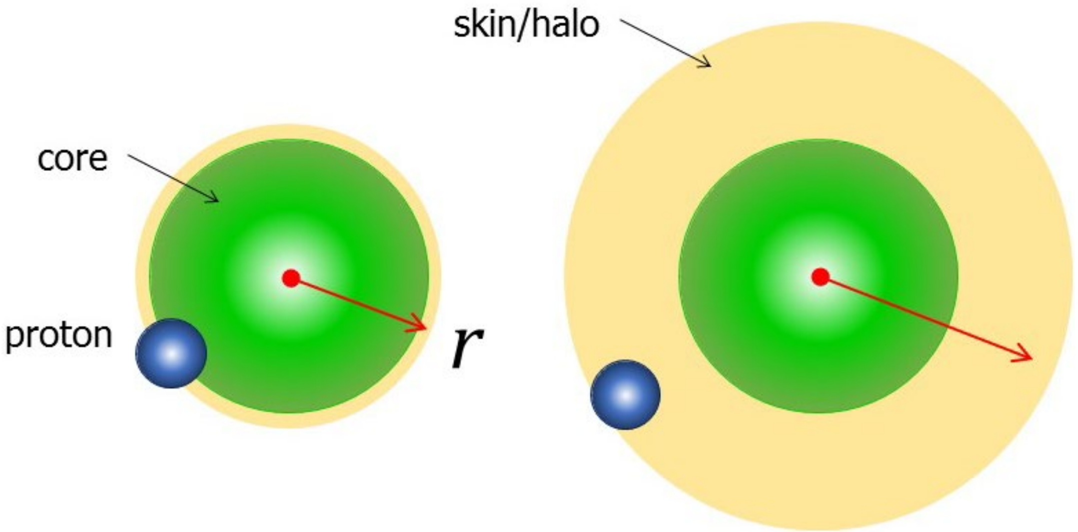
Mean-square charge radius

$$\langle r^2 \rangle \sim \langle r^2 \rangle_{\mathrm{sph}} \left(1 + \frac{5}{4\pi} \langle \beta_2^2 \rangle \right)$$

$\langle r^2 \rangle_{\mathrm{sph}}$: charge radius of spherical core

$\langle \beta_2^2 \rangle$: quadrupole deformation

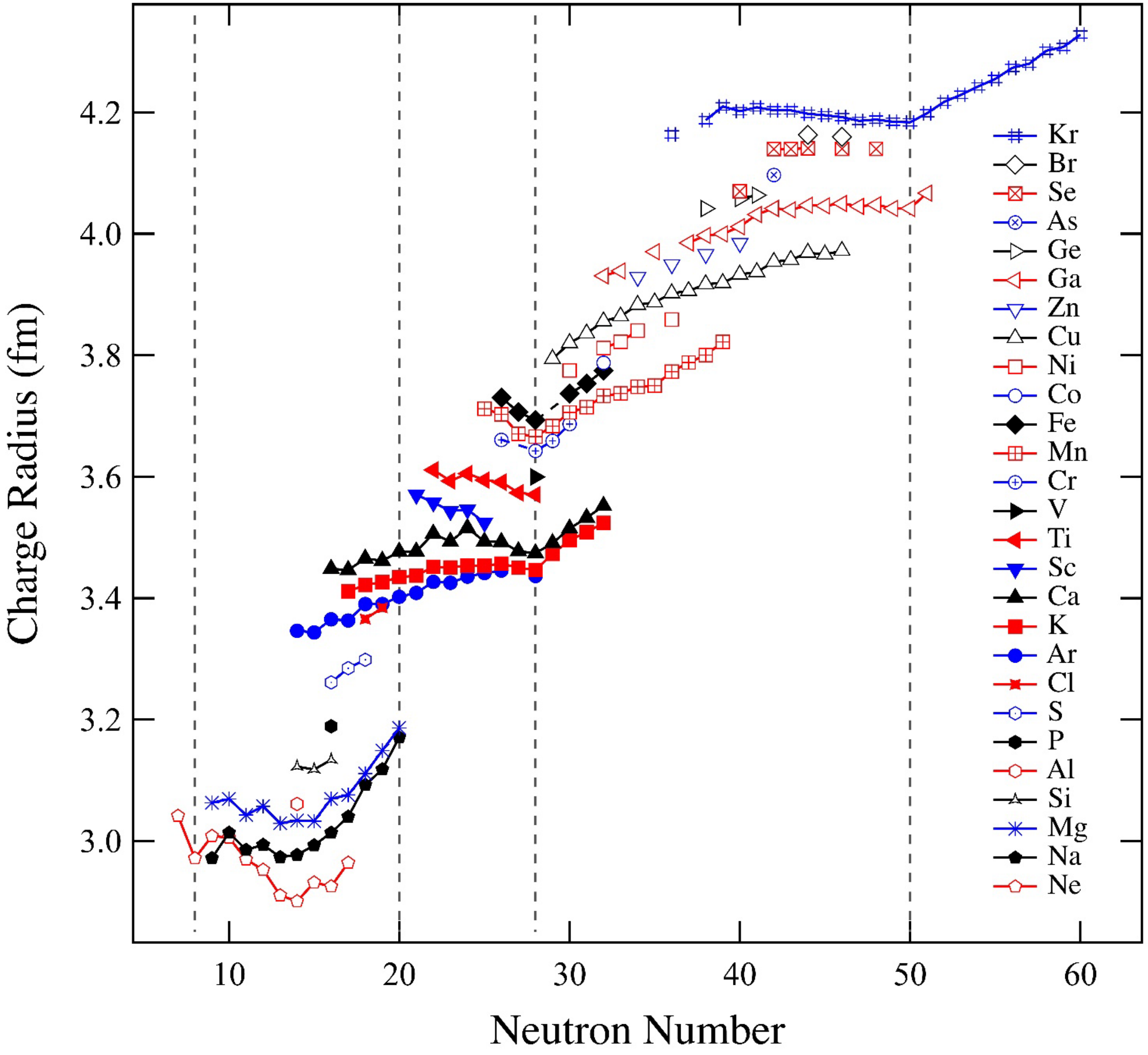




$\langle r^2 \rangle$ is sensitive to size/shape of nucleus, static and dynamic deformation (vibration)

Example: charge radii between Ne though Kr

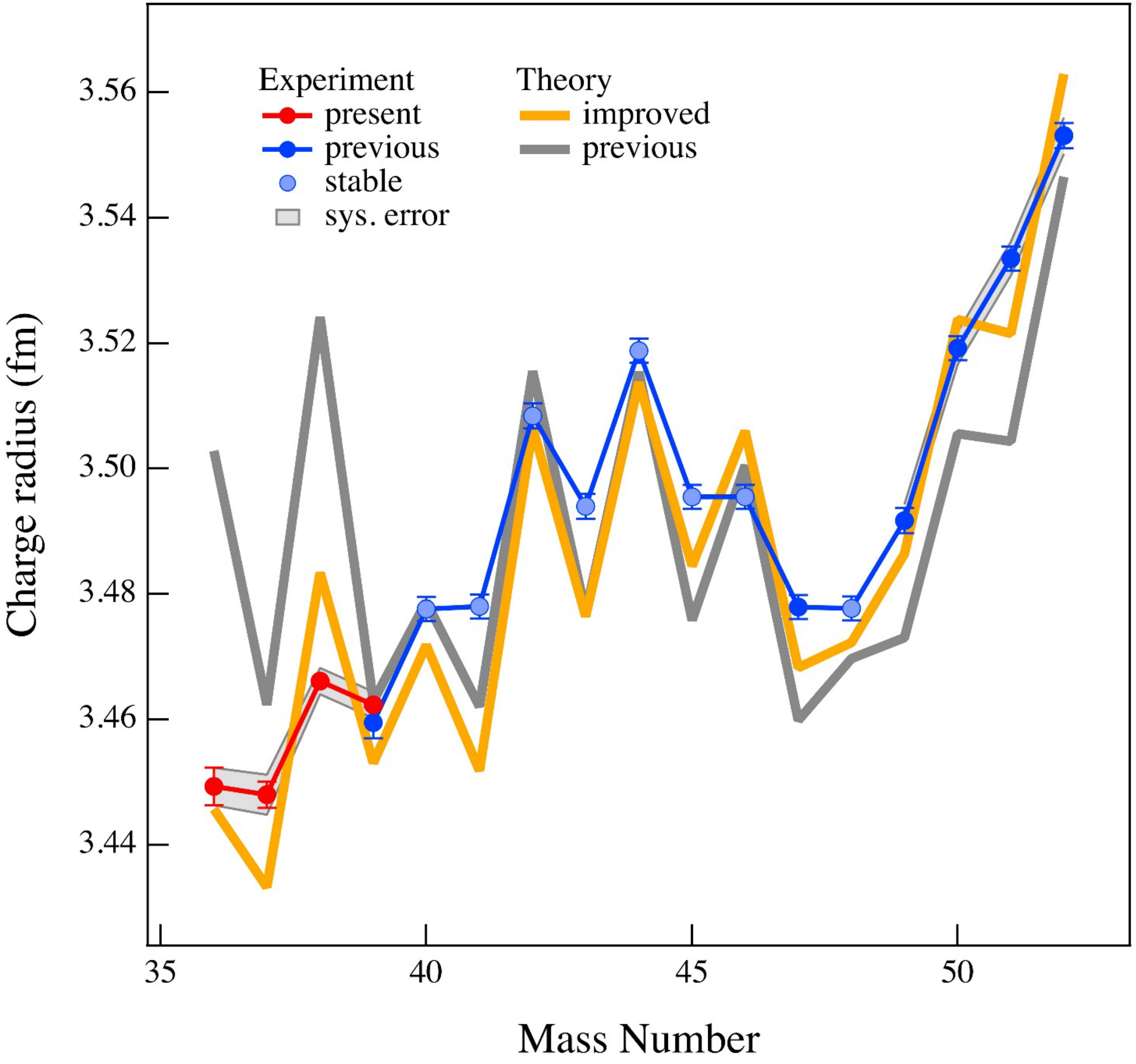
- Radius gets larger as N and Z get bigger.
- Always satisfies: R(Z) < R(Z+1)
- However not for R(N), which shows microstructures
    - smooth increase/decrease
    - zig-zag pattern
    - parabolic change
    - sharp kinks
- All these local variations are the manifestation of underlying nuclear structures, that is what we are looking for.



Data compilation: I. Angeli and K. P. Marinova, ADNDT 99, 69 (2013).

Science example: neutron-deficient Ca

- Light mass Ca isotopes are very compact.
- Maintains the zig-zag pattern (odd-even stagger)
- Our new measurements (red) deviates from the previous theory.
- The improved theory that include “superconductivity” of nuclei reproduces our data better.
- Fayans EDF reproduces Ca chain remarkably well.



A. J. Miller et al., Nature Physics 15, 432 (2019).

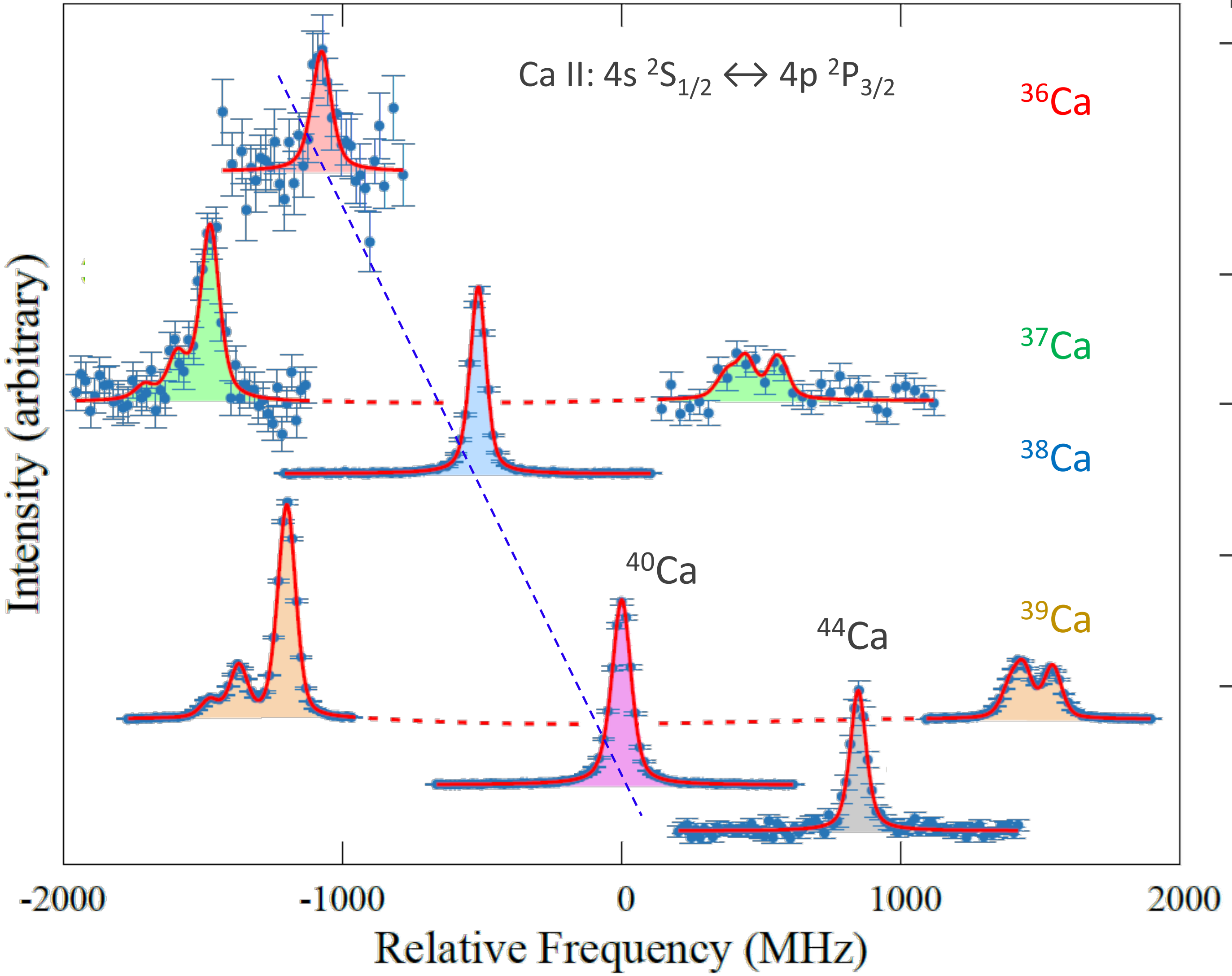
Science example: neutron-deficient Ca

- Hyperfine spectra that shows isotope shifts. Note that
  - Even-even isotope: single peak
  - Even-odd isotope: multi peaks
- From the relative shifts drm radii can be extracted.

Atomic factors well determined:

$$\begin{cases} k = 409.35(42)\ \text{GHz amu} \\ F = -284.7(82)\ \text{MHz fm}^{-2} \end{cases}$$

Isotope shifts of hyperfine spectra of Ca



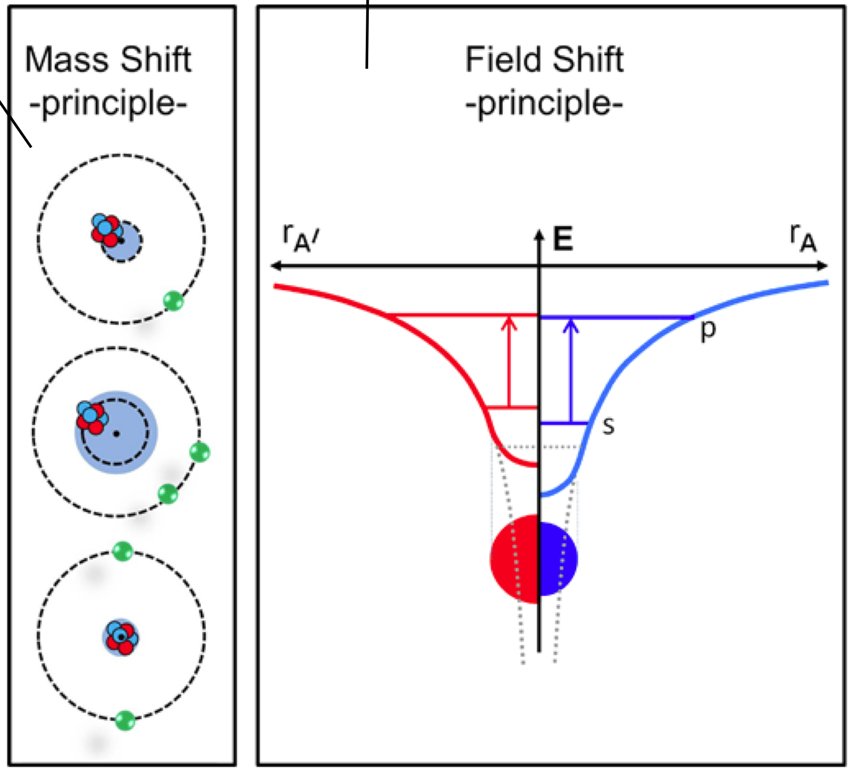
	rate (1/s)	$T_{1/2}$ (ms)
^{36}Ca	50	102
^{37}Ca	960	181
^{38}Ca	13.5k	440
^{39}Ca	60k	859.6

A. J. Miller et al., Nature Physics 15, 432 (2019).

Charge radius: isotope shift of fine structure energies

$$\delta\nu^{A,A'} = \nu^{A'} - \nu^{A} = k\frac{M' - M}{M'M} + F \times \delta\langle r^2\rangle^{A,A'}$$

- **Model independent, *R* can be determined with ~ 0.005 fm**
- **Sensitive to $\delta\langle r^2\rangle$ and requires reference to deduce absolute charge radius**: $R^2 = \boldsymbol{R_{\mathrm{ref}}^2} + \delta\langle r^2\rangle$
  - R_{ref} can be evaluated from e-scattering and μ-capture experiments.
  - but R_{ref} is not always available with high enough precision we want.
- **Using King plot, *k* and *F* can be experimentally evaluated,**
  - IF there are ≥ 3 (stable) isotopes of the element, whose *R* are know.
  - otherwise need to rely on atomic theories
    - Typically with a few ~ 10% uncertainty
    - ab-initio is feasible for 5 electron systems so far.
- In general, $\delta\langle \mathrm{r}^2\rangle$ is replaced by $\delta\langle \mathrm{r}^2\rangle + \tilde{c}_2\delta\langle \mathrm{r}^4\rangle + \tilde{c}_3\delta\langle \mathrm{r}^6\rangle + \cdots$
  - Contribution is very small and difficult to determine

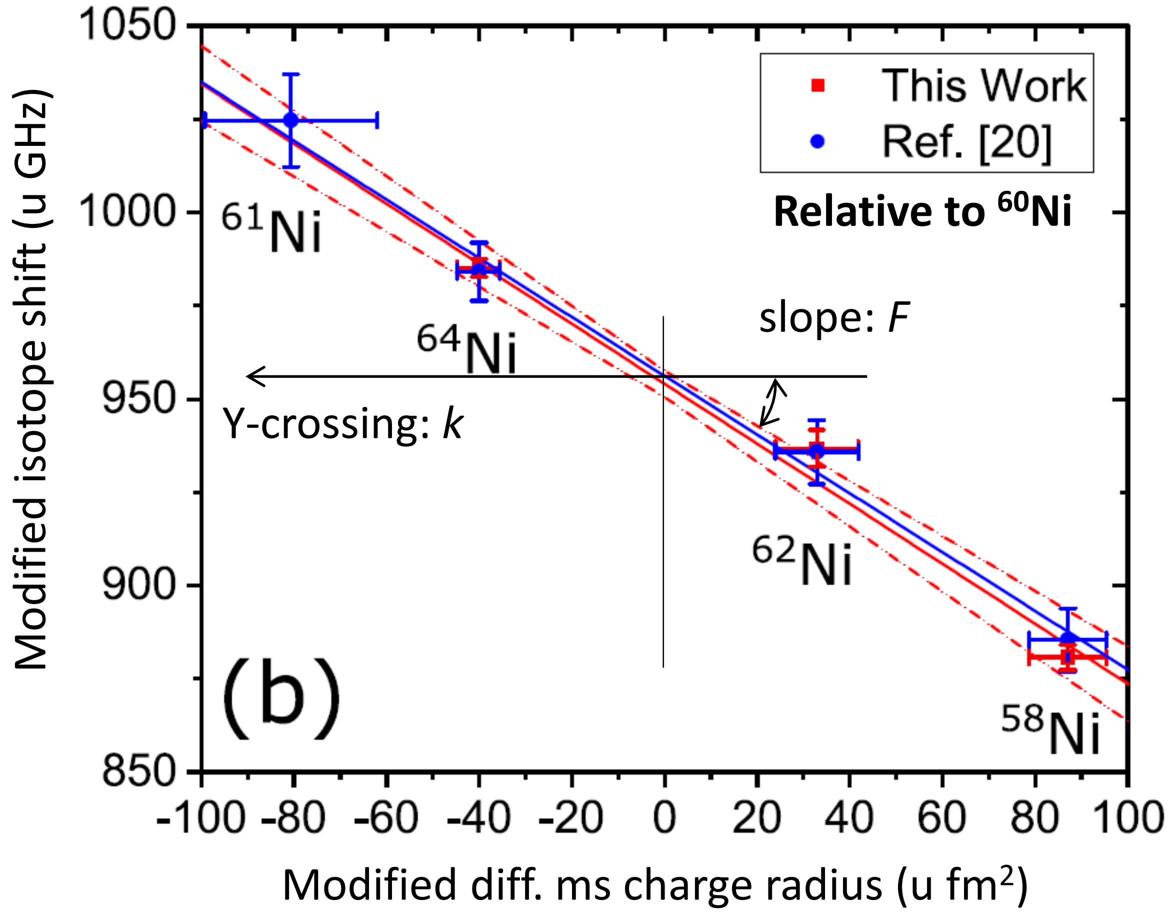


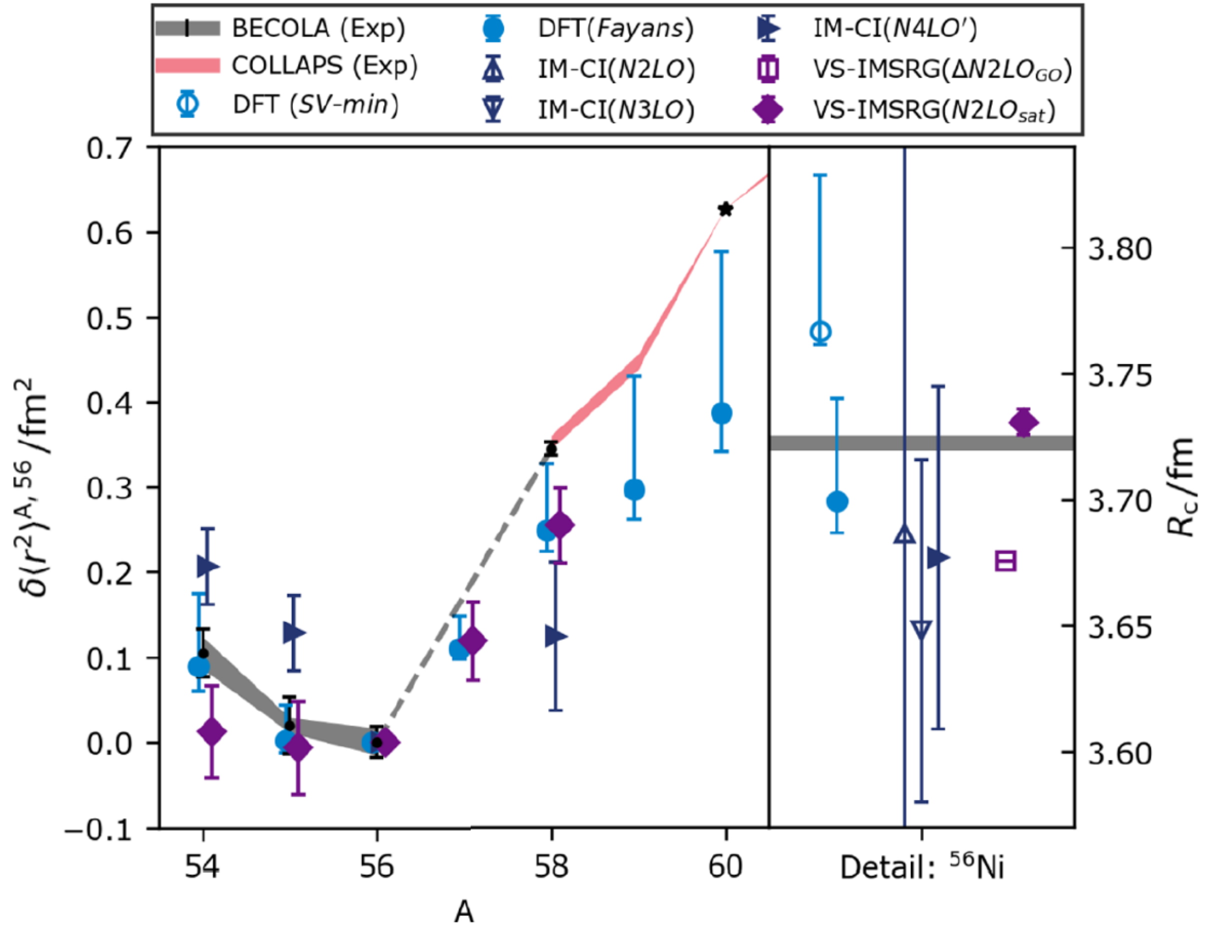
Change of the center of the motion energy

Change of the size (radius) of the nucleus

Figure taken from W. Nörtershäuser, Lecture Notes in Physics 879 (2014).

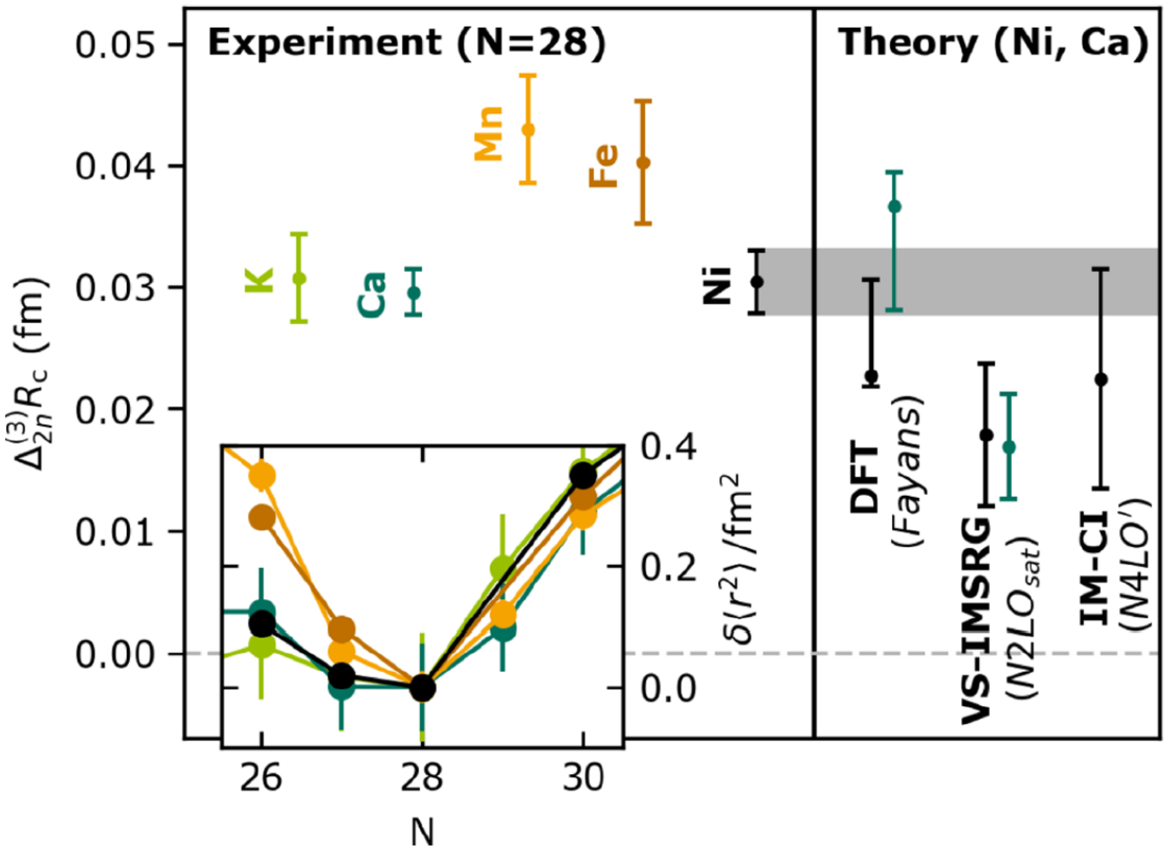
Science example: neutron-deficient Ni





K. König et al., PRC 103, 054305 (2021);
F. Sommer et al., PRL 129, 132501 (2022).

Science example: neutron-deficient Ni



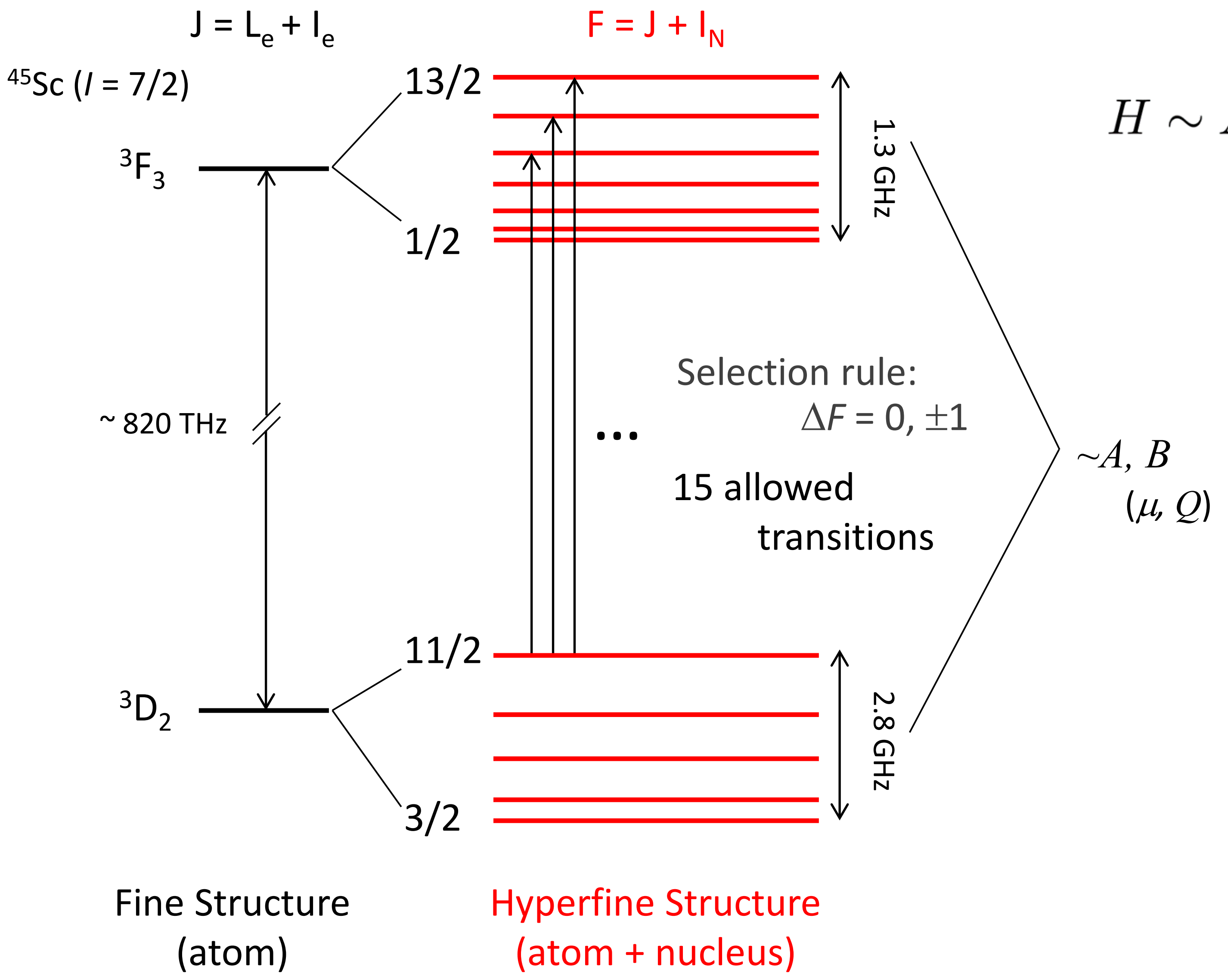
- DFT and ab-initio calculations reproduce Ni radii well.
- Ni and Ca show very similar kink structure at $N = 28$
- **Kink does not directly reflect the strength of a shell closure.**

Three-point indicator for kink structure:

$$\Delta^{(3)}_{2n}R_c(N) = \frac{1}{2}[R_c(N+2) - 2R_c(N) + R_c(N-2)]$$

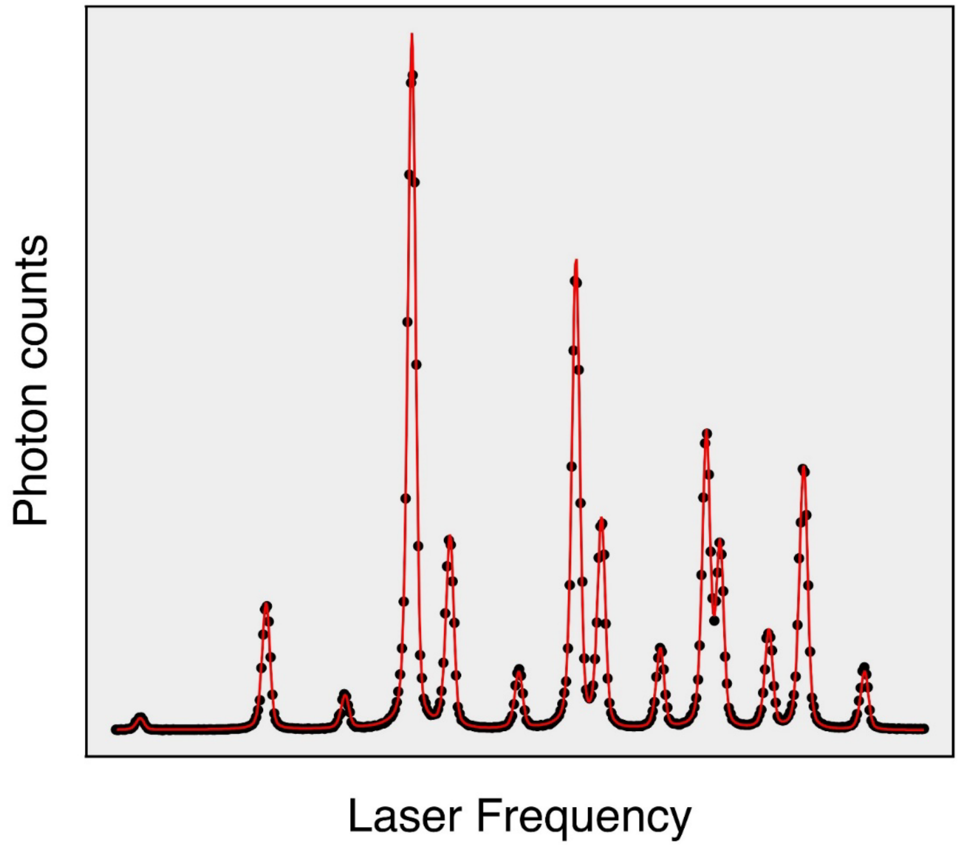
F. Sommer et al., PRL 129, 132501 (2022).

Electromagnetic moments: HF structure



$$H \sim A \cos\left(\widehat{\boldsymbol{IJ}}\right) + B\,\frac{3\cos^2\left(\widehat{\boldsymbol{IJ}}\right) - 1}{2}$$

^{45}Sc 3d4s $^3D_2$ ↔ 3d4p $^3F_3$ @ 363 nm



Electromagnetic moments: HF structure

Magnetic dipole

$$\begin{cases} A = \dfrac{\mu B_M(0)}{IJ} \\ \mu = \mu_{\mathrm{R}} \dfrac{A}{A_{\mathrm{R}}} \dfrac{I}{I_{\mathrm{R}}} \end{cases}$$

- **Dominates the pattern of hyperfine spectrum**
  - *A* and μ can be determined with high precision (<< 1%)
    - Need reference to deduce unknown μ
    - Precise μ_{R} is available from NMR or β-NMR measurements
- Can "measure" nuclear spin *I*

Electric quadrupole

$$\begin{cases} B = eQ \left\langle \dfrac{\partial^2 V_e}{\partial z^2} \right\rangle_0 \\ Q = Q_{\mathrm{R}} \dfrac{B}{B_{\mathrm{R}}} \end{cases}$$

- **Smaller contribution to the hyperfine spectrum**
  - *B* and *Q* can only be determined with poorer precision (several ~ 10%)
    - Need reference to deduce unknown *Q*
- Eventually need to rely on calculations of the field gradient d^2V/dz^2

Higher order moments

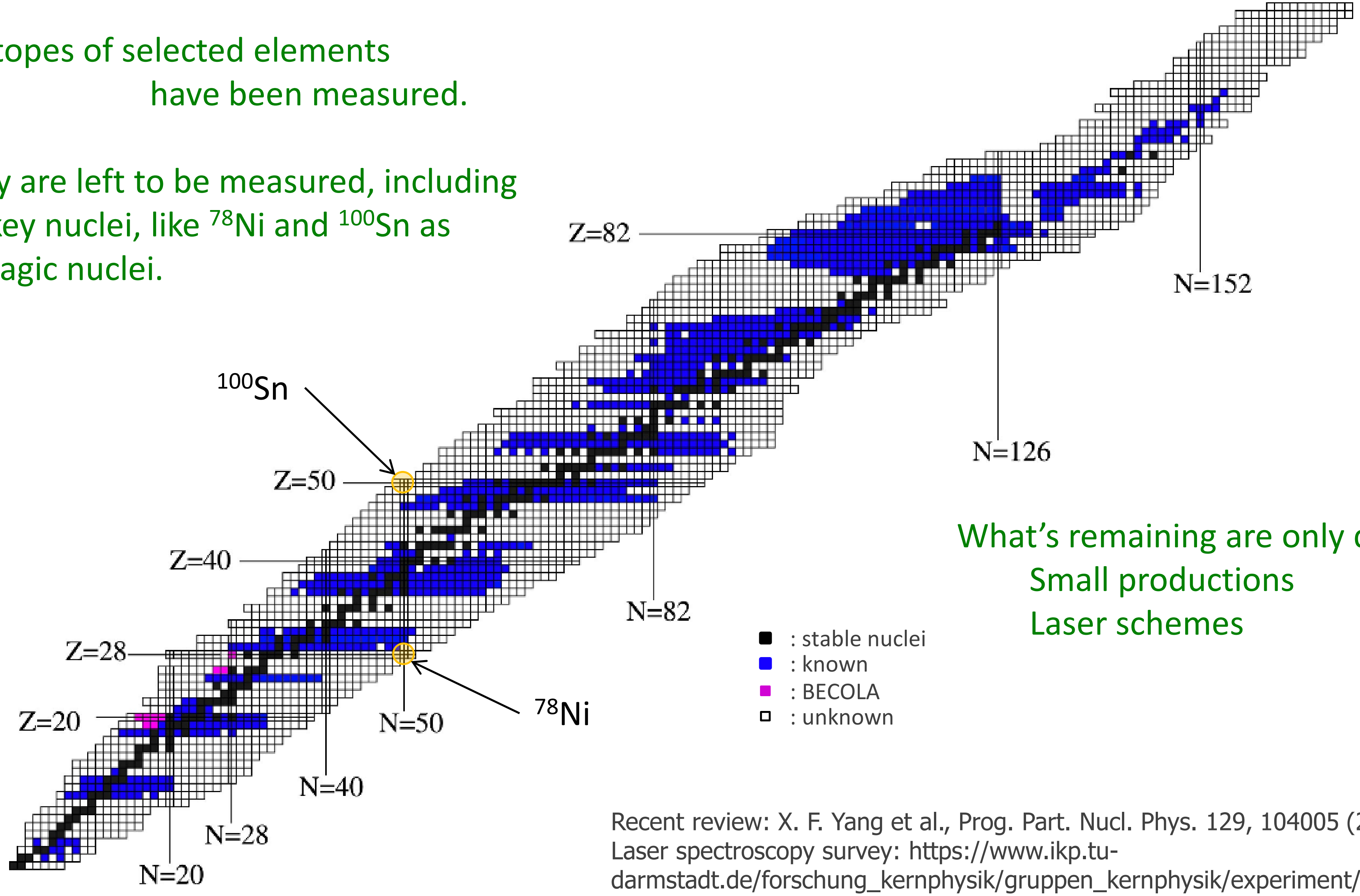
- **Much smaller and in general difficult to deduce from hyperfine spectra**
- Specific system
- RF and/or microwave spectroscopy

Laser spectroscopy measurements

- $I, \mu, Q, \delta\langle r^2\rangle$ -

Many isotopes of selected elements have been measured.

Still, many are left to be measured, including some of key nuclei, like ^{78}Ni and ^{100}Sn as doubly Magic nuclei.



What's remaining are only difficult cases.

Small productions

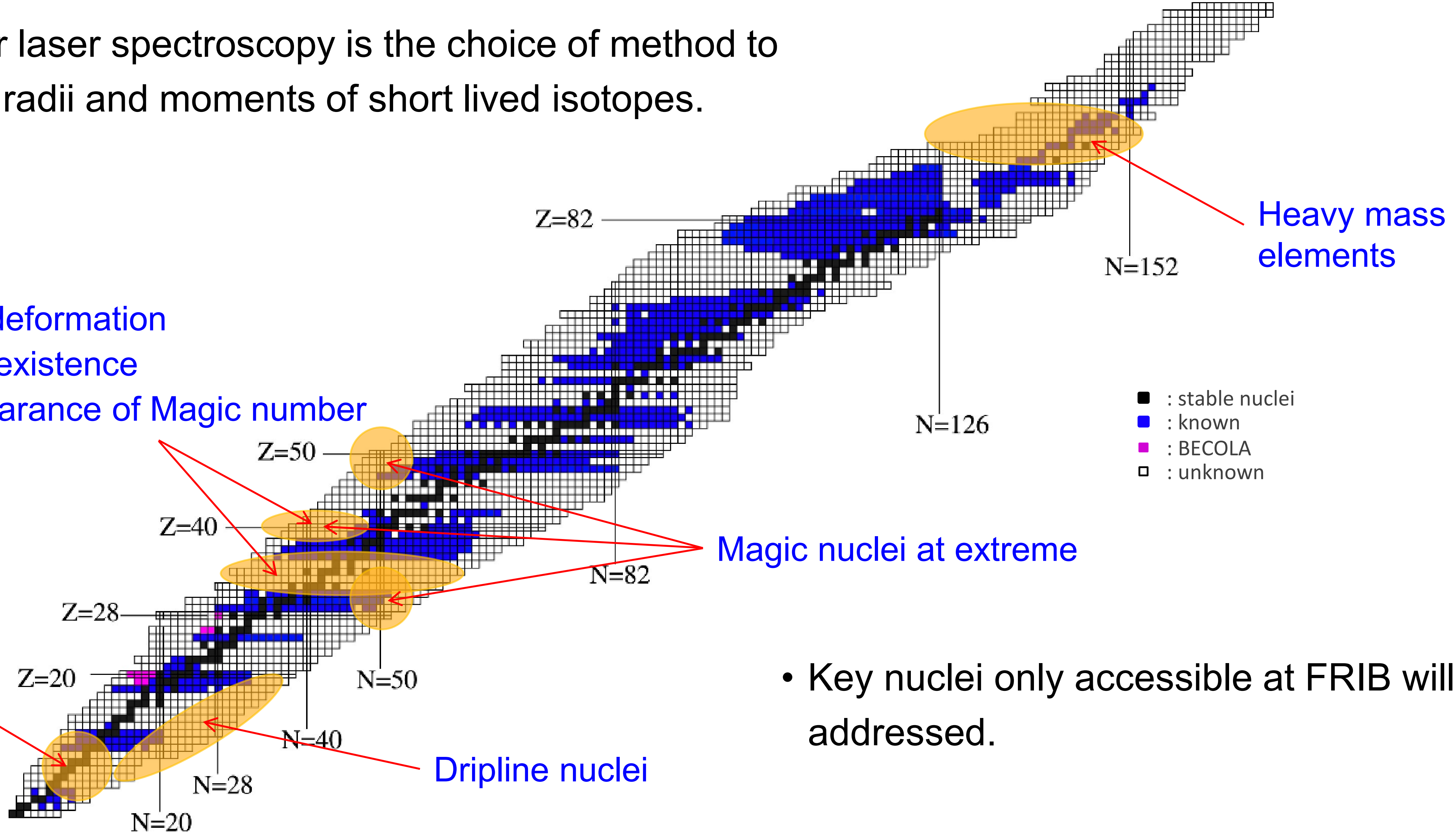
Laser schemes

Recent review: X. F. Yang et al., Prog. Part. Nucl. Phys. 129, 104005 (2023);
Laser spectroscopy survey: https://www.ikp.tu-darmstadt.de/forschung_kernphysik/gruppen_kernphysik/experiment/ag_w_noertershaeuser/

Laser spectroscopy coming 5-10 years

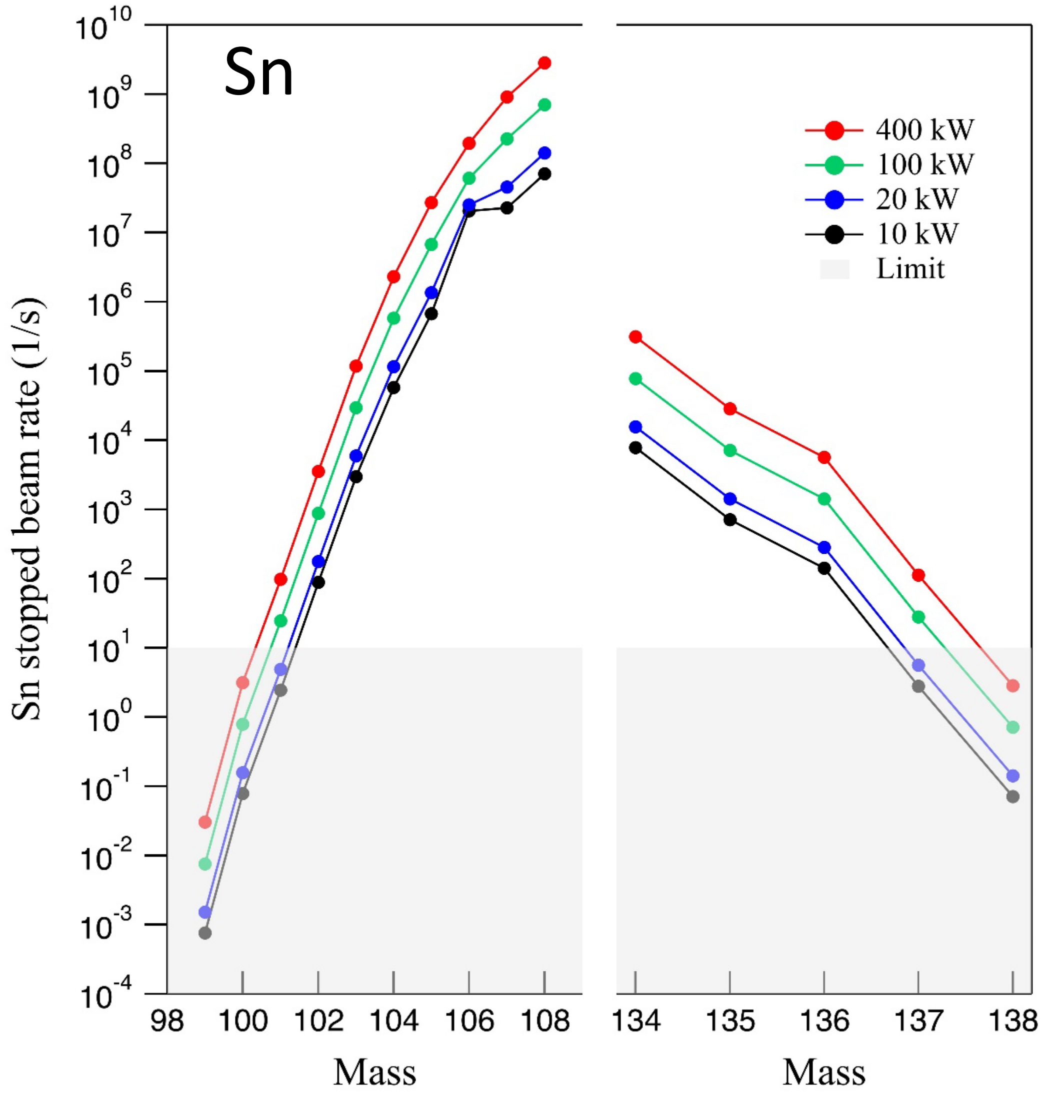
- Collinear laser spectroscopy is the choice of method to address radii and moments of short lived isotopes.

- onset of deformation
- shape coexistence
- (dis)appearance of Magic number



- Key nuclei only accessible at FRIB will be addressed.

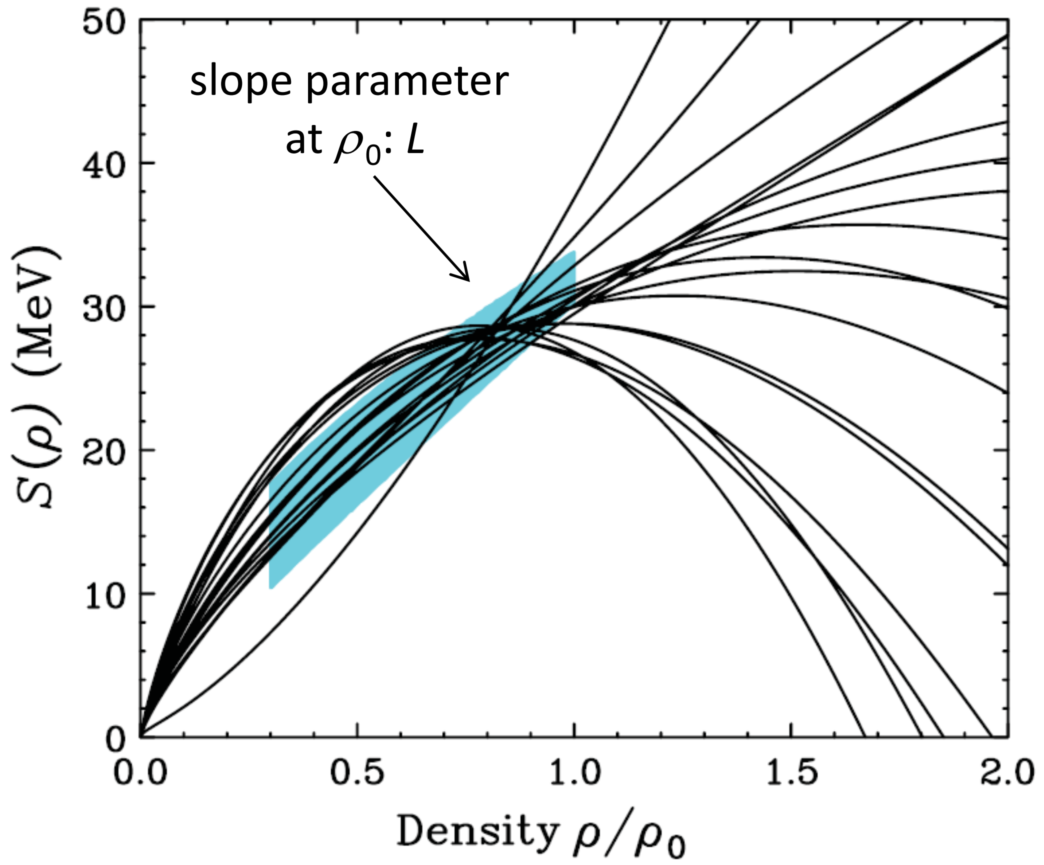
Laser spectroscopy and rate of Sn



- Significant number of isotopes are within the reach at FRIB ≤ 20 kW for laser spectroscopy.
- However, key nuclei like ^{78}Ni, ^{100}Sn and beyond seem difficult.
- New techniques required
  - Greater sensitivity
  - Smaller background
  - More efficient use of beams

Neutron Equation of State and Slope Parameter *L*

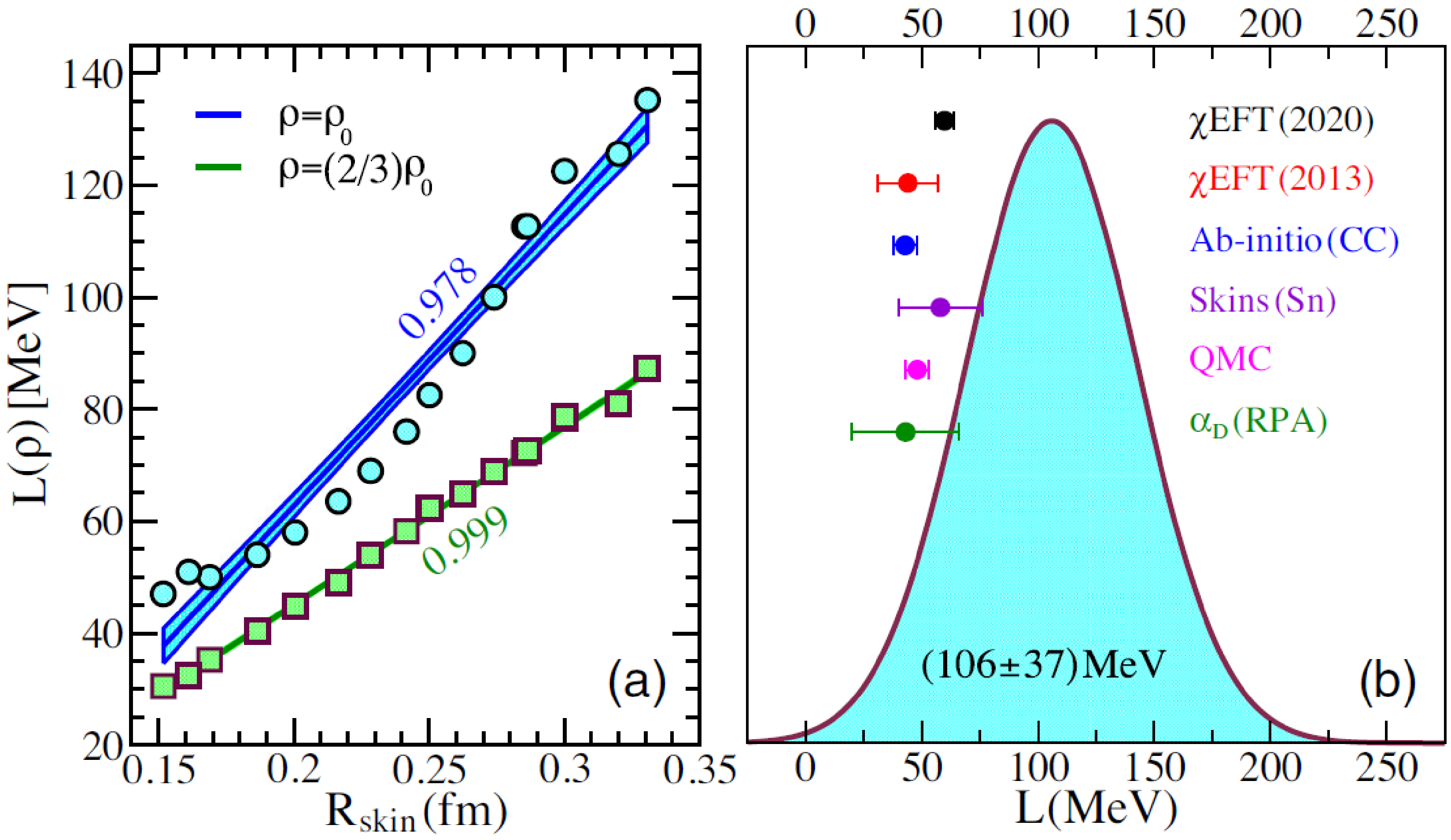
Symmetry energy



Neutrons skin/radius ↔ *L*: slope of the symmetry energy

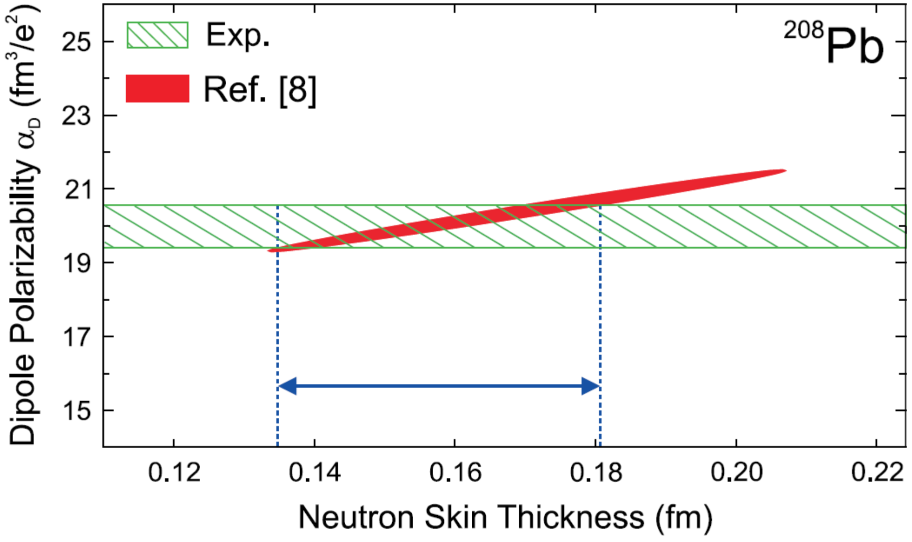
B. A. Brown, PRL 85, 5296 (2000);
M. B. Tsang et al., PRC 86, 01583 (2012).

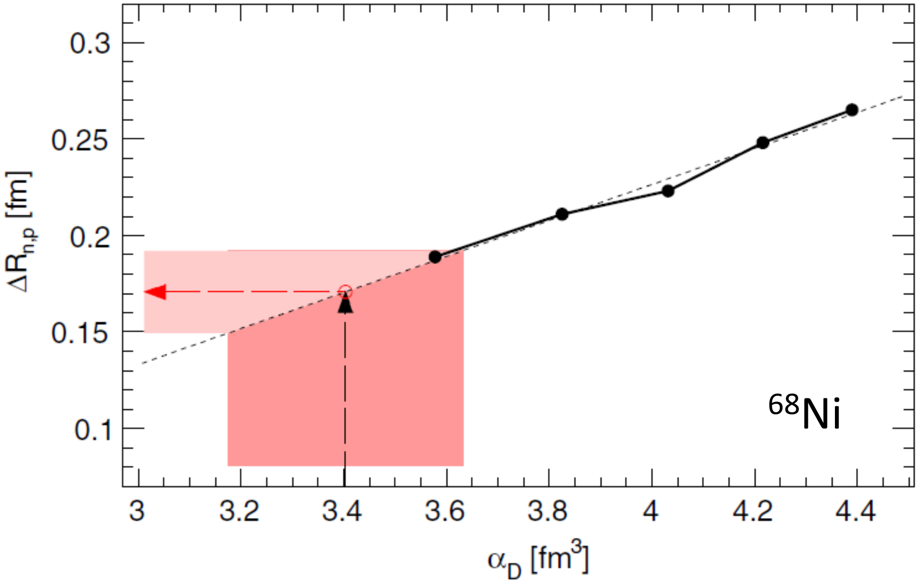
Ex. PREX Correlation between ΔR_{np} vs *L*

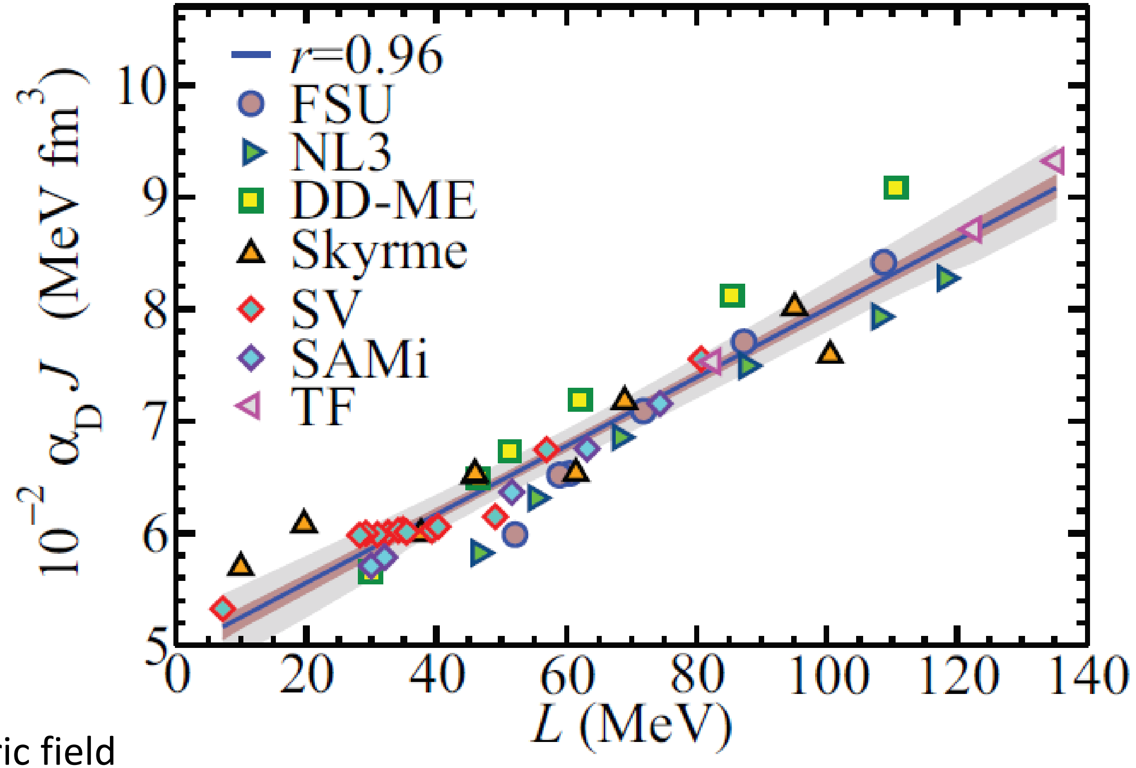


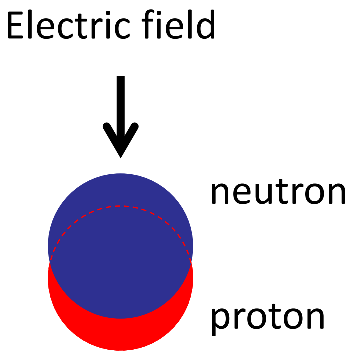
Taken from B. T. Reed et al., PRL126, 172503 (2021).

ex. Electric Dipole Polarizability to Determine *L*









X. Roca-Maza et al., PRC 88, 024316 (2013);
P. -G. Reinhard and W. Nazarewicz, PRC 81, 051303R (2010);
A. Tamii et al., PRL. 107, 062502 (2011);
D. M. Rossi et al., PRL 111, 242503 (2013).

Difference of Mirror Charge Radii

ASSUMING the charge symmetry is a perfect symmetry:

Neutrons radius of a nucleus is equal to protons radius of its mirror nucleus.

$$\Delta R_{\mathrm{np}} \equiv R_{\mathrm{n}}({}^{A}_{Z}X_{N}) - R_{\mathrm{ch}}({}^{A}_{Z}X_{N})$$

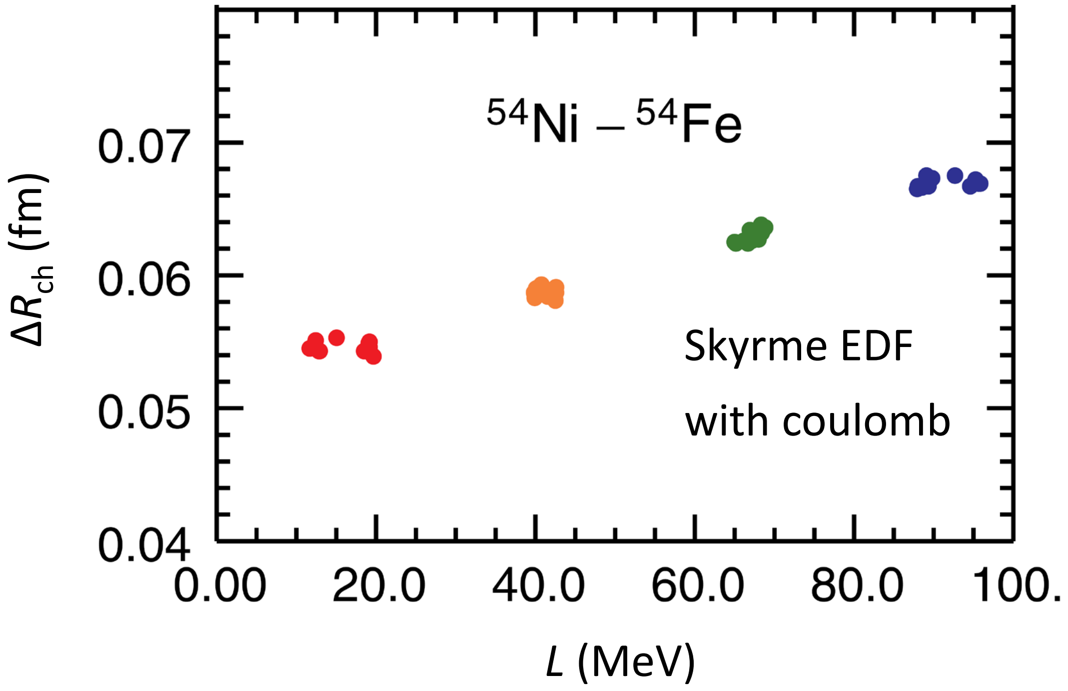
$$\longrightarrow R_{\mathrm{ch}}({}^{A}_{N}Y_{Z}) - R_{\mathrm{ch}}({}^{A}_{Z}X_{N}) \equiv \Delta R_{\mathrm{ch}}$$

- pure electromagnetic probe
- model independent determination of ΔR_{ch}

Even with Coulomb, correlation remains, also

$$\Delta R_{\mathrm{ch}} \sim |N - Z| \times L$$

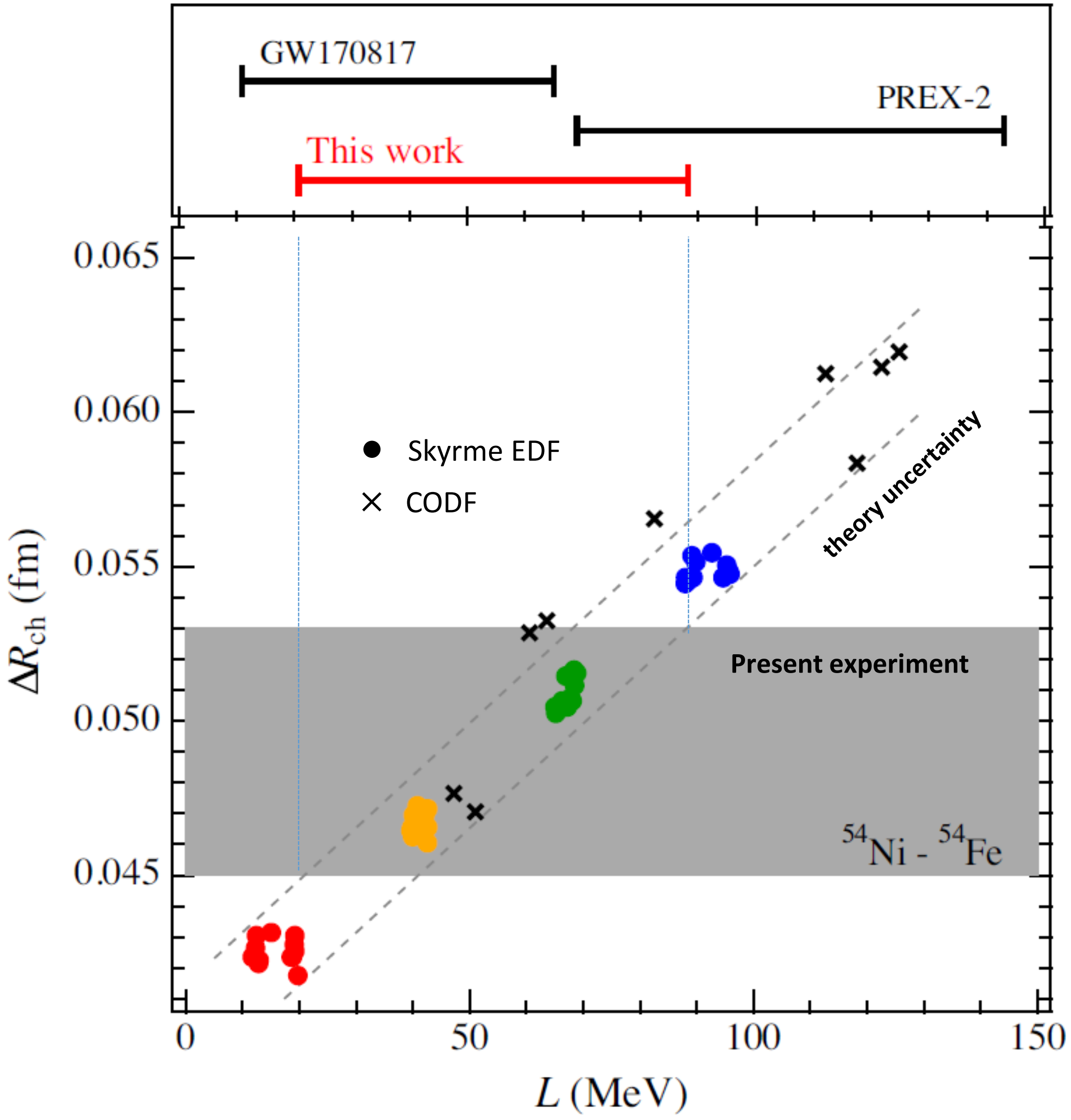
$|N - Z|$ = 6 is the largest (^{22}Si-^{22}O) ($|N - Z|$ = 8 for ^{48}Ni-^{48}Ca).



$\Delta R_{\mathrm{np}}(^{208}\mathrm{Pb})$ =
- 0.12 fm: red
- 0.16 fm: orange
- 0.20 fm: green
- 0.24 fm: blue

B. A. Brown, Phys. Rev. Lett. 119, 122502 (2017).
J. Yang and J. Piekarewicz, Phys. Rev. C 97, 014314 (2018).

Constraint on Symmetry Energy in EOS using Difference of Mirror Charge Radii ^{54}Ni and ^{54}Fe



Present result: L = 20 ~ 90 MeV

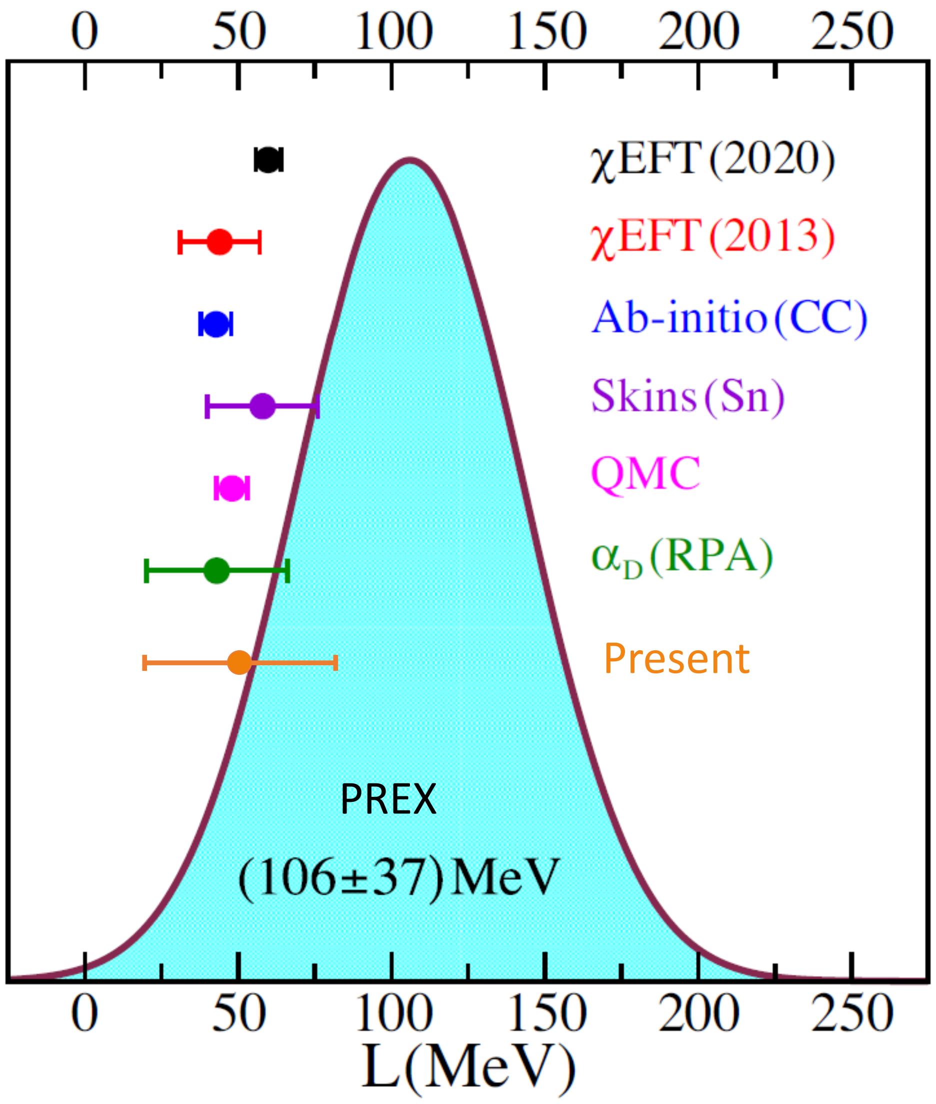
Our result:

- indicates soft EOS, and rather small radius of a neutron star
- is consistent with the binary neutron star merger GW170817 and PREX
- PREX, however, points to stiffer EOS and a larger neutron star radius.

$\Delta R_{np}(^{208}\text{Pb})$ =
- 0.12 fm: red
- 0.16 fm: orange
- 0.20 fm: green
- 0.24 fm: blue

S. Pineda et al., Phys. Rev. Lett. 127, 182503 (2021).

Constraint on Symmetry Energy in EOS using Difference of Mirror Charge Radii ^{54}Ni and ^{54}Fe



Taken from B. T. Reed et al., PRL126, 172503 (2021).

- PREX suggests a rather stiff EOS and a larger neutron star radius.

- **All *L* "measurements" are model dependent.**
- **It is critical to have variety of experimental observables. Mirror charge radii is one of them.**
- **More experimental and theoretical investigations are encouraged.**
- **Assessment of model dependence is critical.**

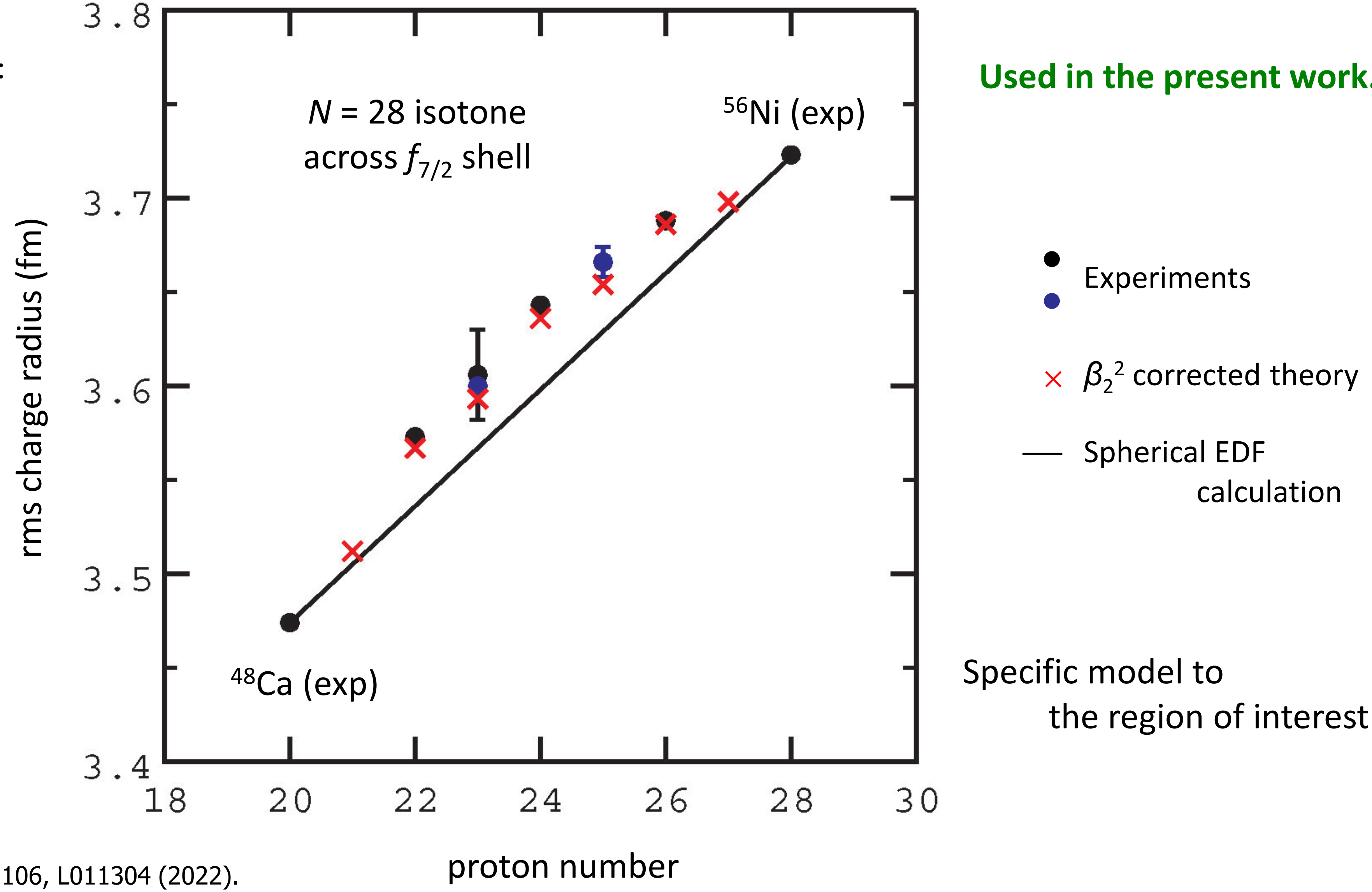
Assessing Model Dependence: β^2 Model

According to Bohr collective model:

$$\langle r^2 \rangle = \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \sum_{\lambda \geq 2} \beta_\lambda^2 \right)$$

$$\sum_{\lambda \geq 2} \beta_\lambda^2 \sim \beta_2^2$$

$$\beta_2^2 = \frac{B(E2,\uparrow)}{\left(\frac{3}{4\pi} Z R_0^2\right)^2}$$

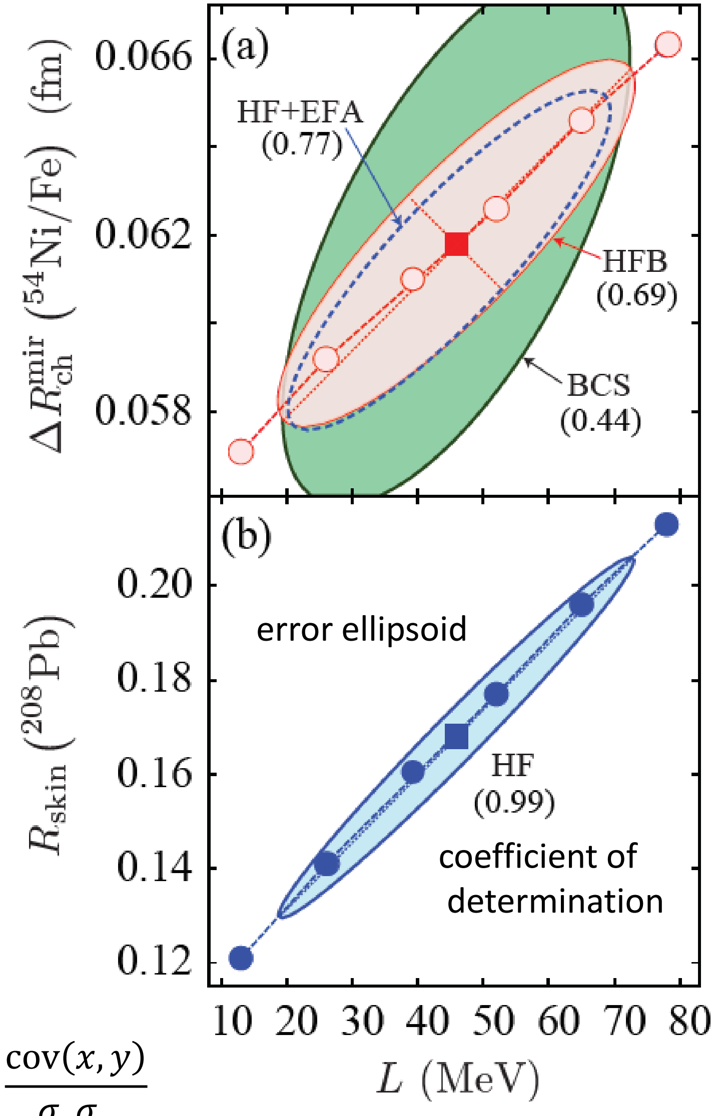


Used in the present work.

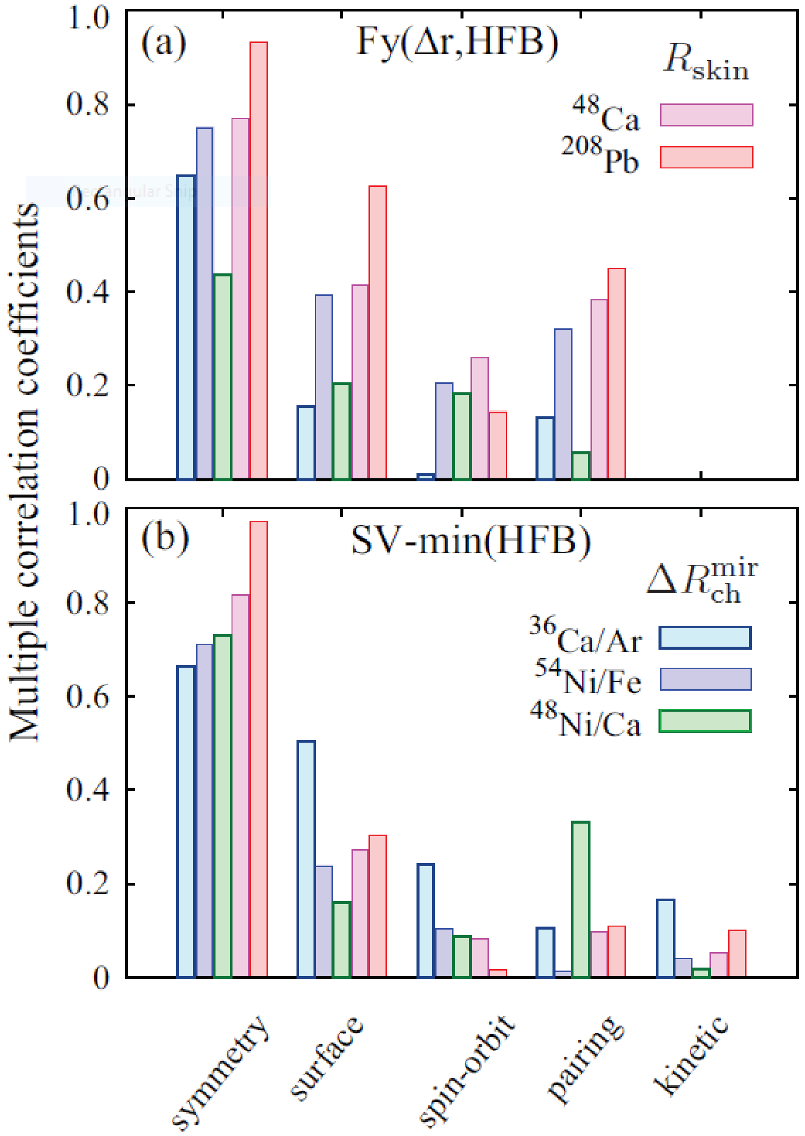
Specific model to the region of interest.

B. A. Brown and K. Minamisono Phys. Rev. C 106, L011304 (2022).

Assessing Model Dependence: Pairing Interaction



$$\mathrm{CoD} = \frac{\mathrm{cov}(x, y)}{\sigma_x \sigma_y}$$



"…precise data on mirror charge radii with an error of about 0.005 fm, while extremely valuable for studying isospin effects in nuclei and model developments, cannot provide a stringent constraint on *L*" in this model.

Global fit with
rich pairing interactions

P. -G. Reihard and W. Nazarewicz,
Phys. Rev. C 105, L021303 (2022).

Summary

- **Laser spectroscopy will provide critical inputs to benchmark theories.**
  - Spectroscopic electromagnetic moments
  - Charge radius
- **Continuing collaboration with theorists for more exotic, heavier and more deformed nuclei is critical.**
- **Tell me how we can help to develop your theories!**
  - Specific region, element, isotopes… will greatly help experimental design.
- **Mirror charge radii correlation to *L***
  - ^{52}Ni-^{52}Cr experiment approved
  - Further theoretical inputs (ab-initio calculations…)

Acknowledgement

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NSF

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Thank you!