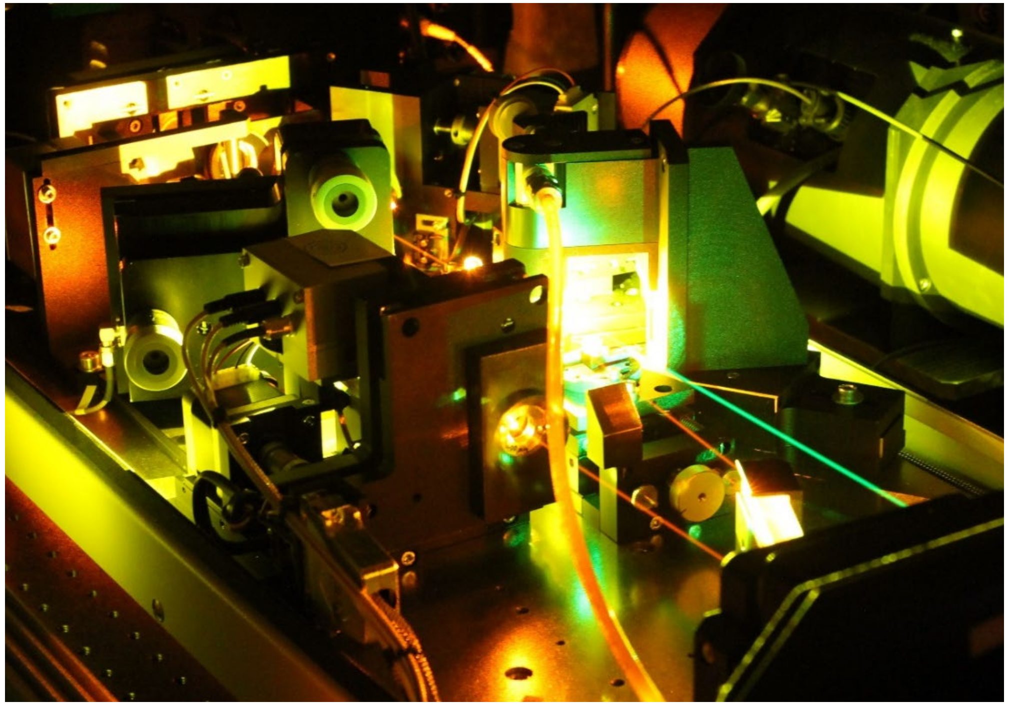
Laser Spectroscopy experiments at FRIB for nuclear structure studies



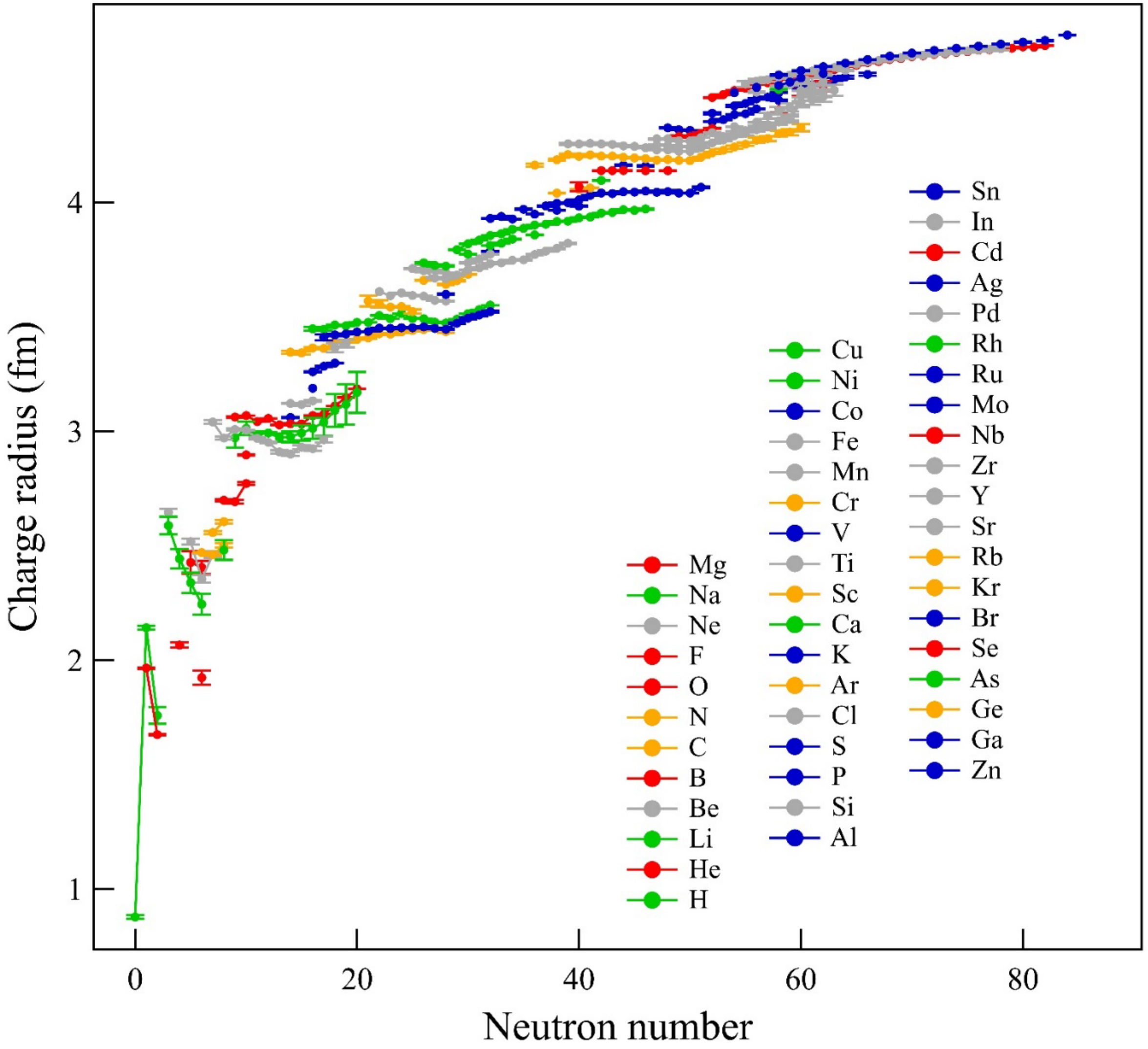
Kei Minamisono

for BECOLA collaboration

Kickoff meeting of the CNRS-MSU IRL-NPA, FRIB East Lansing, December 11-13, 2023

Plan for my talk

- **BECOLA at FRIB**
- **HFS for $\langle r^2 \rangle$, I, μ and Q**
- **"*L*" in the nuclear EOS**



Facility for Rare Isotope Beams: FRIB

U.S. DEPARTMENT OF ENERGY | Office of Science

FRIB

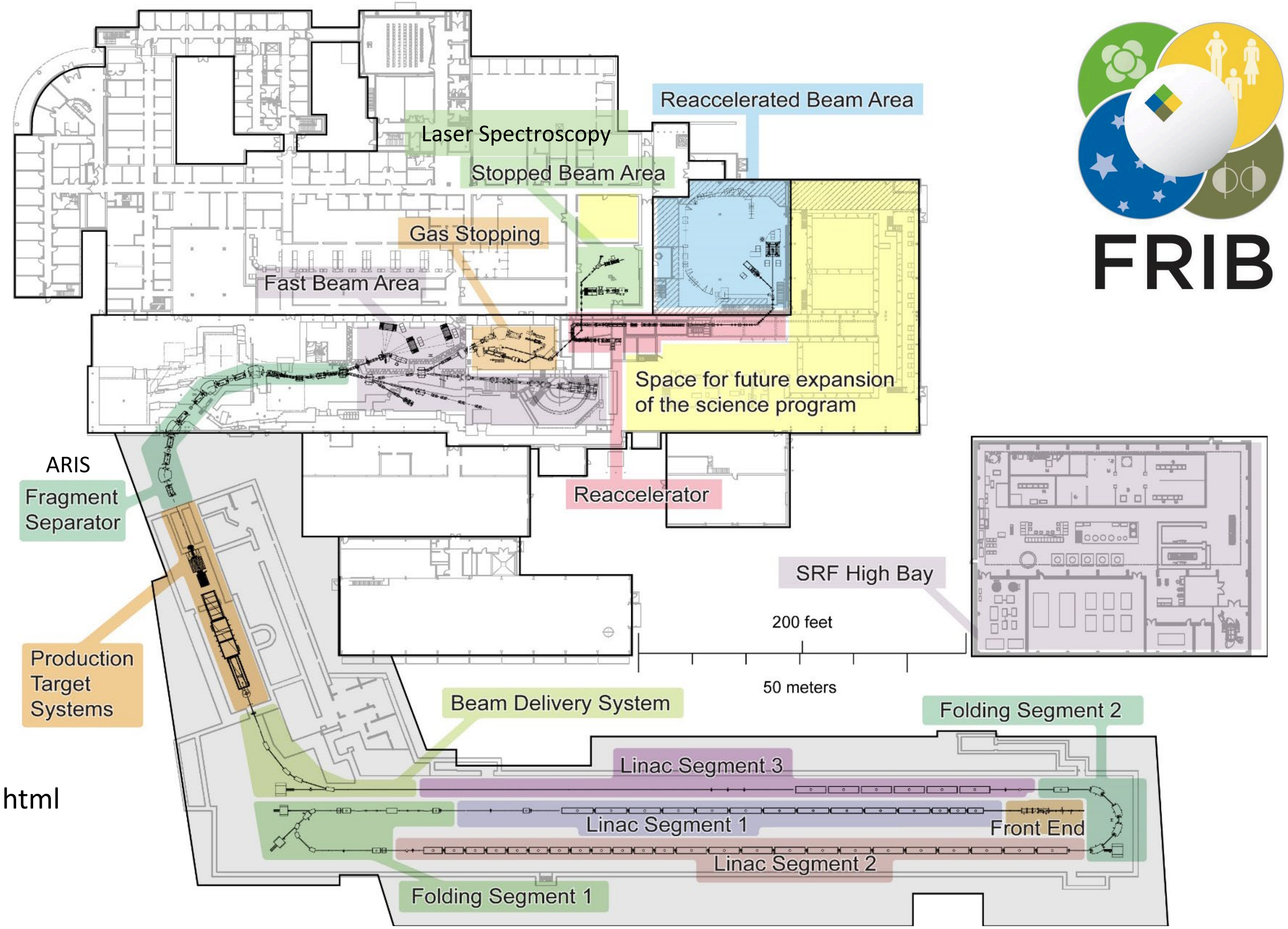
- Produces radioactive isotopes far away from stability

- Started operation in May 2022
- up to 200 (400) kW primary beam
- wider reach of radio isotopes
  - FRIB yields estimate

↓

https://groups.nscl.msu.edu/frib/rates/fribrates.html

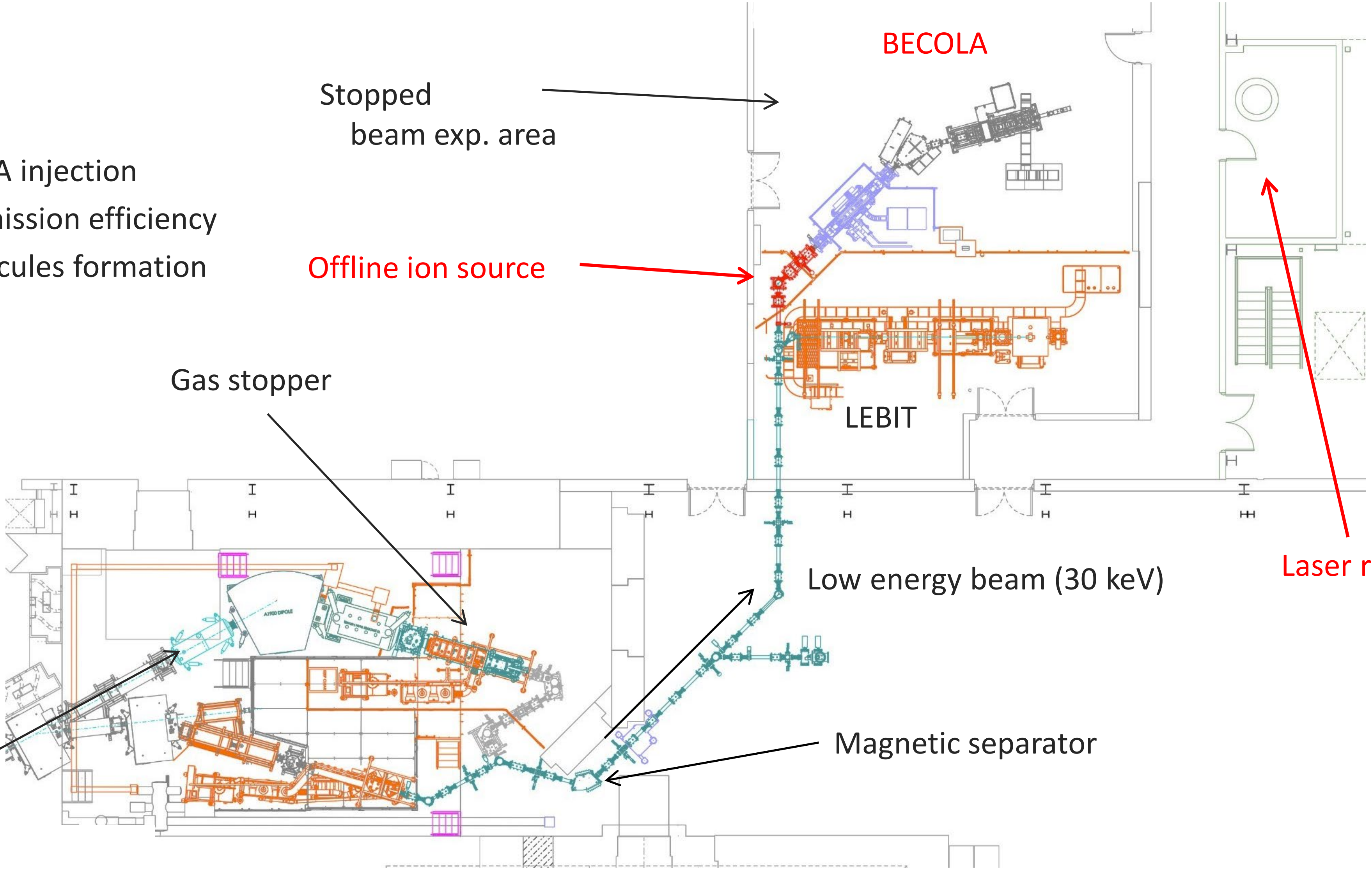
Check your favorite isotopes!



Gas Stopping & Transportation

Gas stopping

- ~100 MeV/A injection
- 10% transmission efficiency
- Some molecules formation



BECOLA

Stopped beam exp. area

Offline ion source

LEBIT

Laser room

Gas stopper

Low energy beam (30 keV)

Magnetic separator

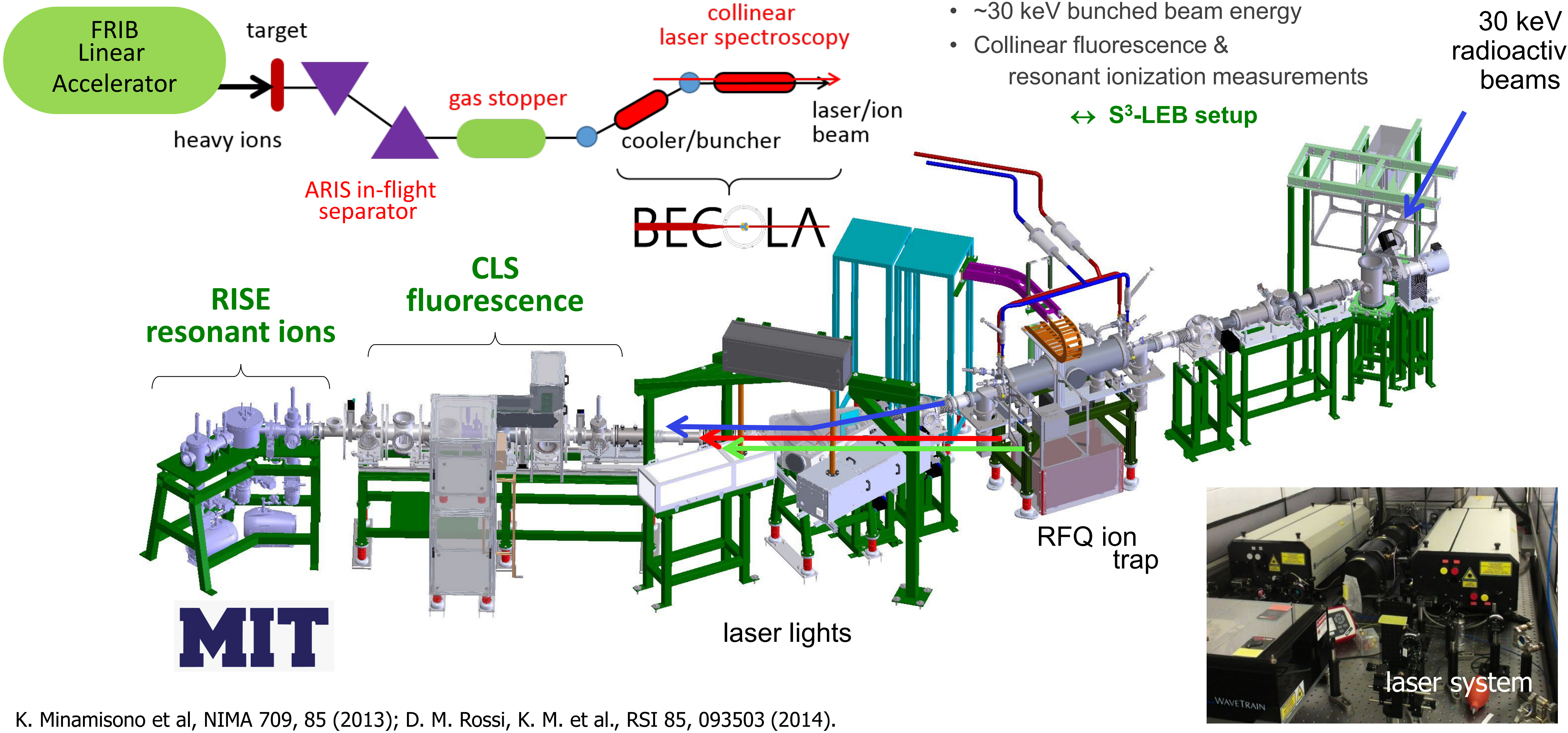
Fast beam

gas stopper: C. Sumithrarachchi et al., NIMB 463, 305 (2020), NIMB 541, 301 (2023); K. Lund et al., NIMB 463, 378 (2022).

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

- ~30 keV bunched beam energy
- Collinear fluorescence &
  resonant ionization measurements

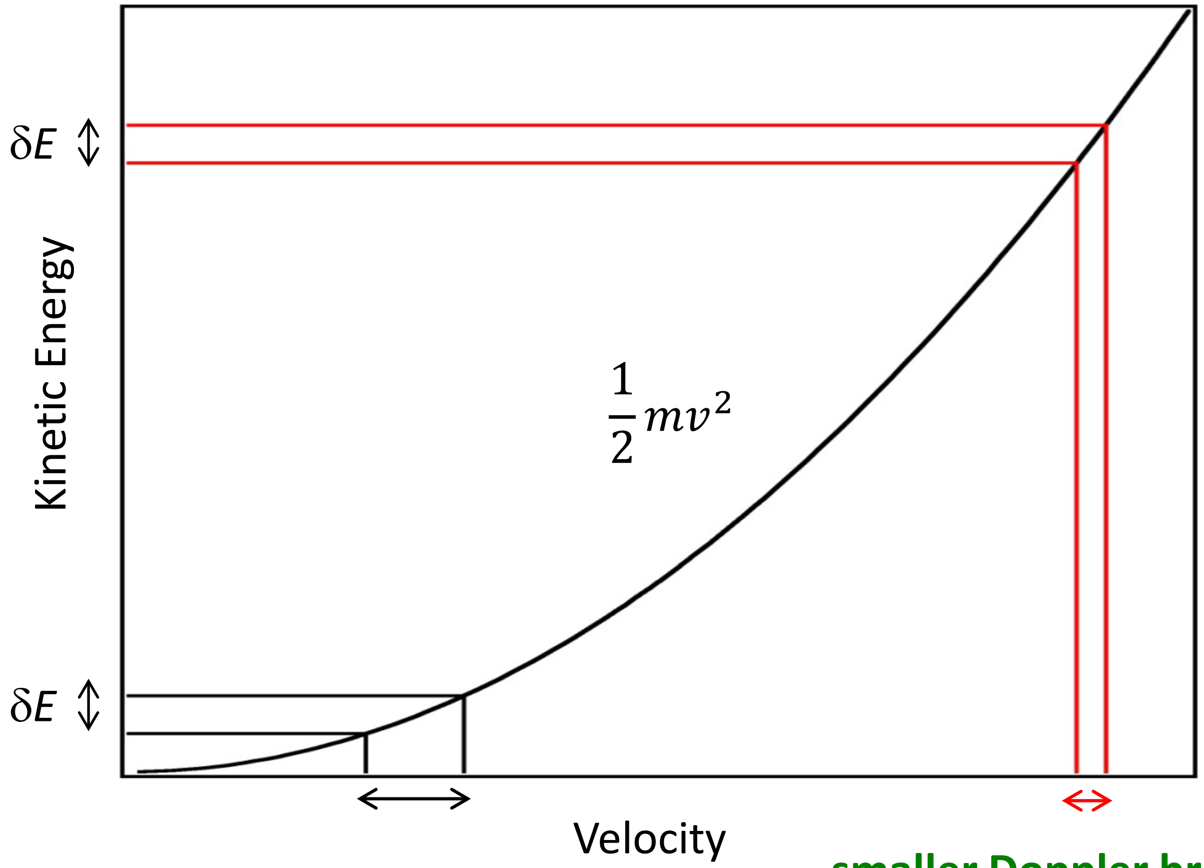
↔ S^3-LEB setup



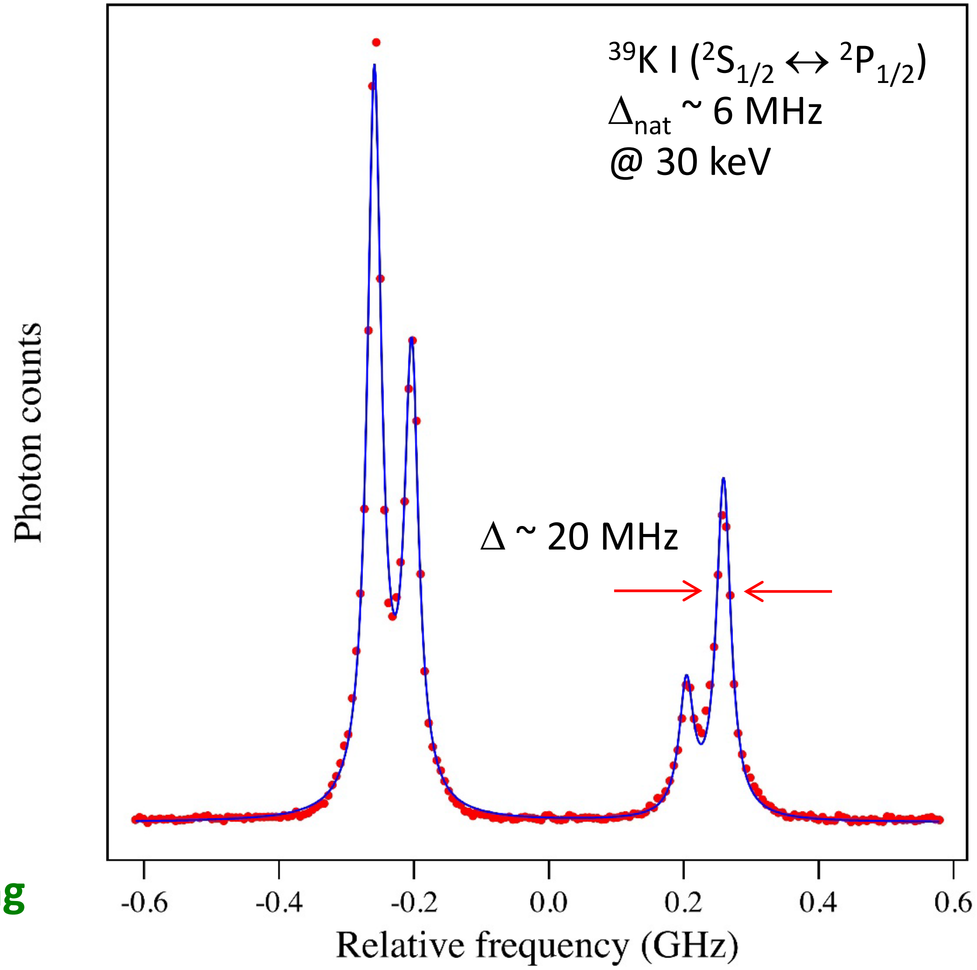
K. Minamisono et al, NIMA 709, 85 (2013); D. M. Rossi, K. M. et al., RSI 85, 093503 (2014).

High resolution: kinematical compression (velocity bunching)

Reacceleration from RFQ ion trap makes resonance linewidth narrow (near natural linewidth).

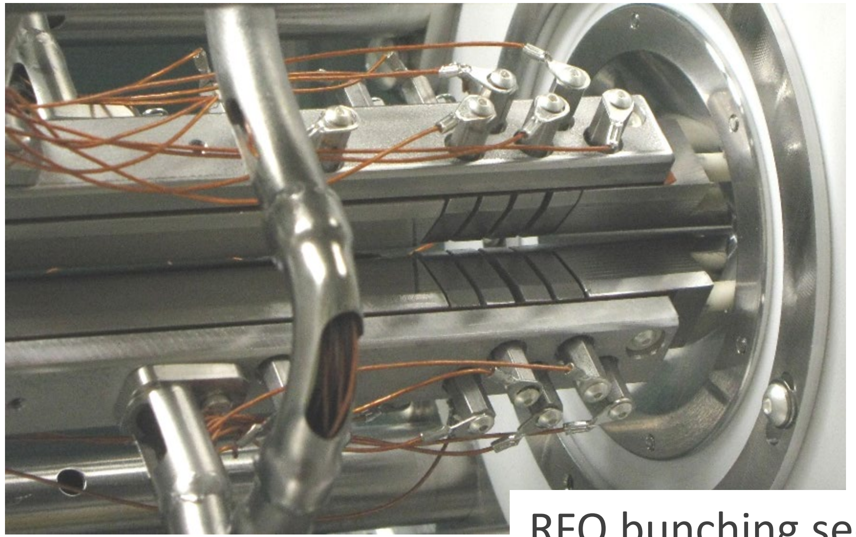


smaller Doppler broadening

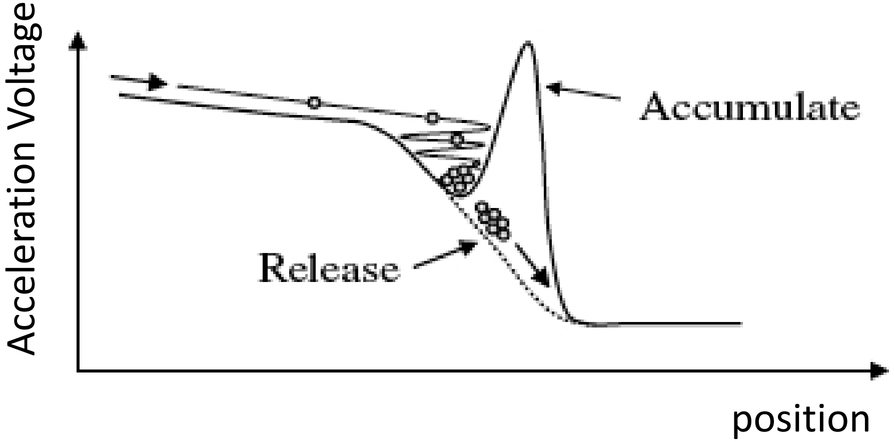


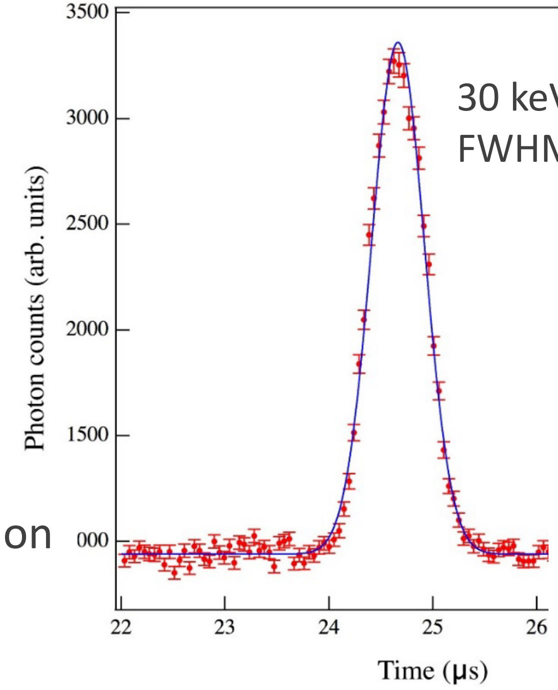
S. L. Kaufman, Optic. Comm. 17, 309 (1976).

High sensitivity: bunched beam fluorescence CLS



RFQ bunching section



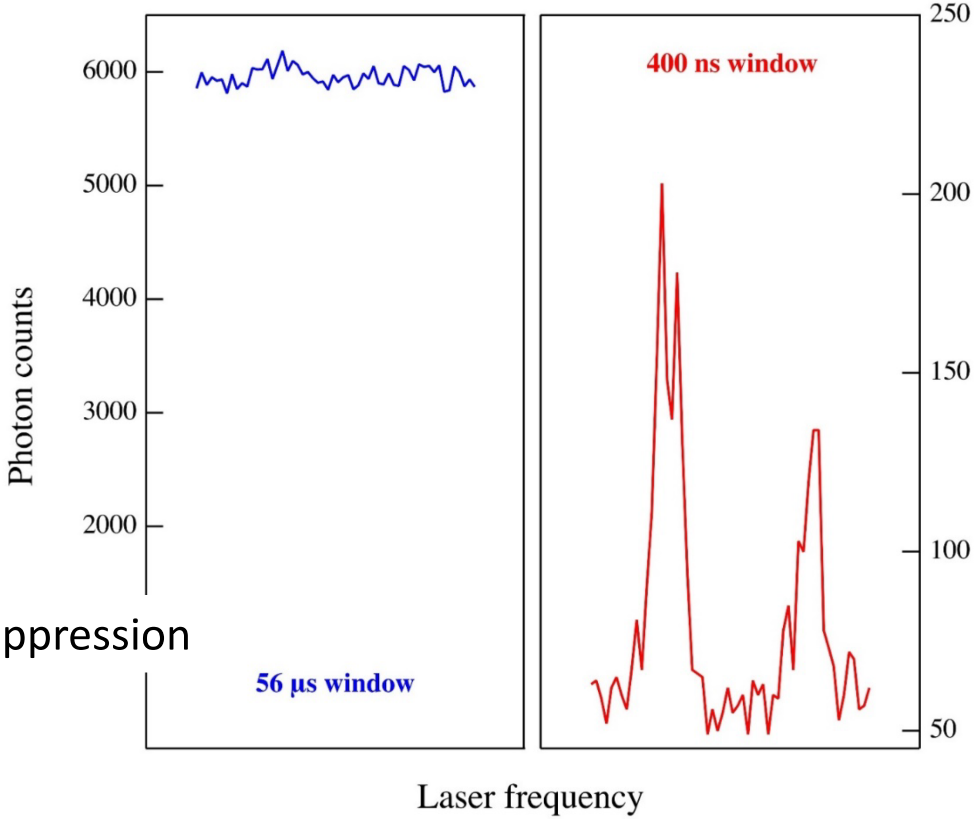


30 keV ^{53}Fe
FWHM = 850 ns

Gating on narrow time spectrum

photon counting

^{39}K I: 4p $^2P_{1/2} \rightarrow$ 4s $^2S_{1/2}$

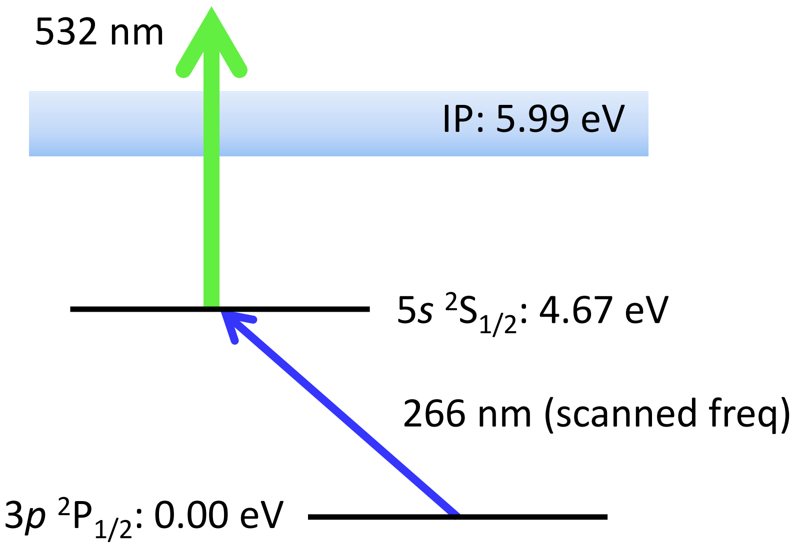


High background suppression

B. R. Barquest et al., NIMA 866, 18 (2017); P. Campbell et al., PRL 89, 082501 (2002);
A. Nieminen et al., PRL 88, 094801 (2002).

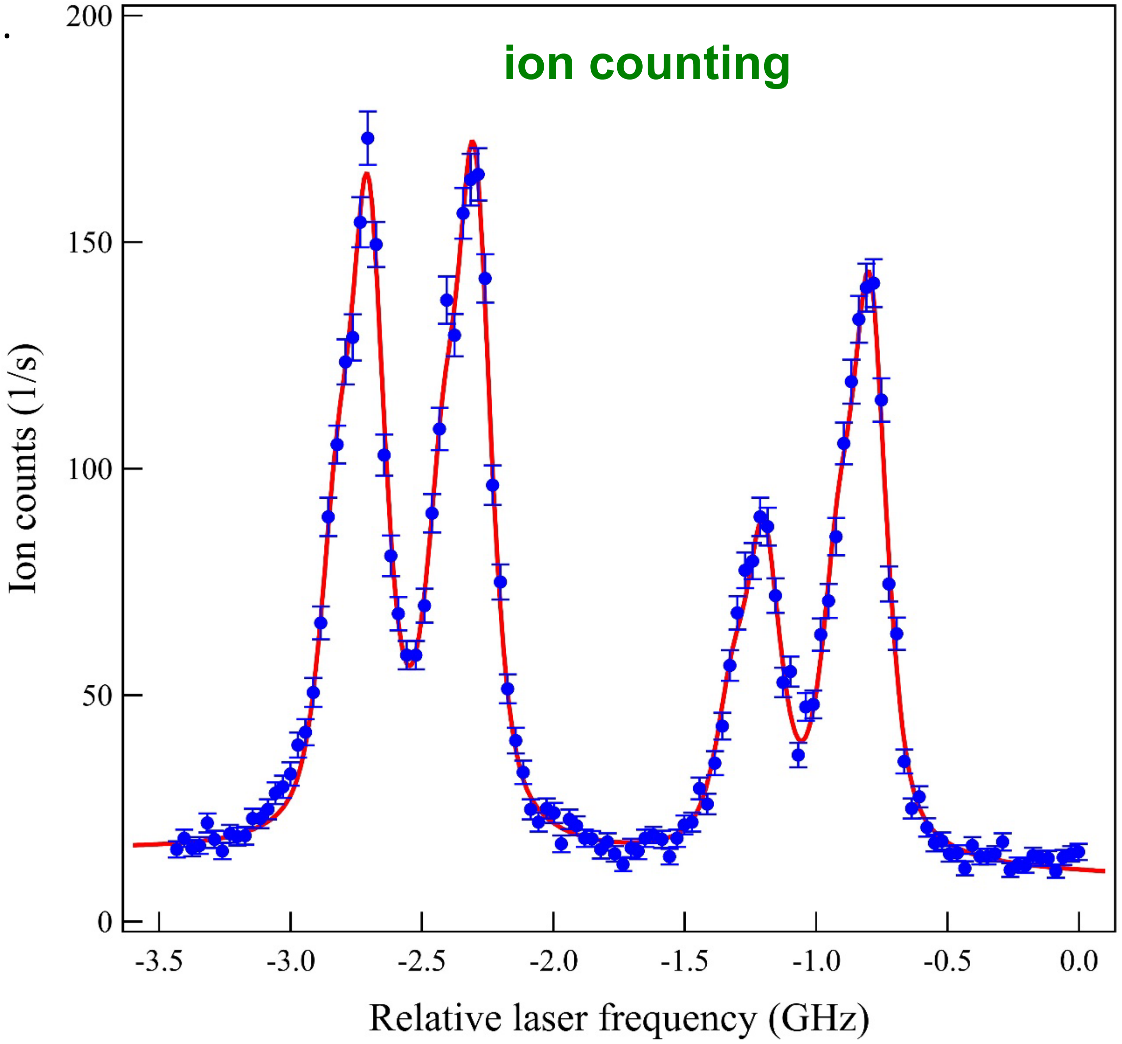
High sensitivity: Resonance Ionization Spectroscopy Experiment (RISE) @ BECOLA

- Ex. two step ionization on ^{27}Al
  - Ionize atoms using multi laser lights, and detect resulting ions.
  - Highly selective and sensitive, good for rare isotopes.
  - In collaboration with MIT, commissioned in 2022
  - Will be used firs for neutron-deficient Al isotopes.



^{27}Al partial electronic energy level

^{27}Al I: 3p $^2P_{1/2}$ ↔ 5s $^2S_{1/2}$ @ 266 nm

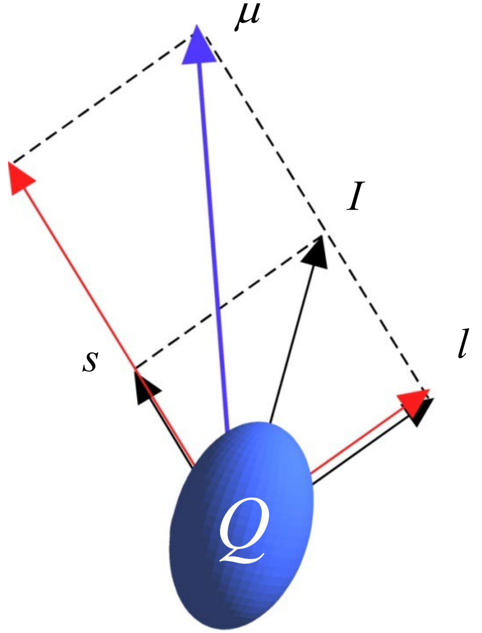


Developed in collaboration with R. F. Garcia Ruiz, S. Wilkins, A. Vernon, J. Kathein, A. Brinson at MIT.

Electromagnetic moments

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

$$= \underbrace{q\phi(0)}_{\text{e-monopole}} - \underbrace{\boldsymbol{P}\cdot\boldsymbol{E}(0)}_{\text{e-dipole}} - \underbrace{\boldsymbol{\mu}\cdot\boldsymbol{H}(0)}_{\text{m-dipole}} - \underbrace{\frac{1}{6}\sum_{ij} Q_{ij}\left(\frac{\partial E_j}{\partial x_i}\right)_0}_{\text{e-quadrupole}} + \cdots$$



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

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

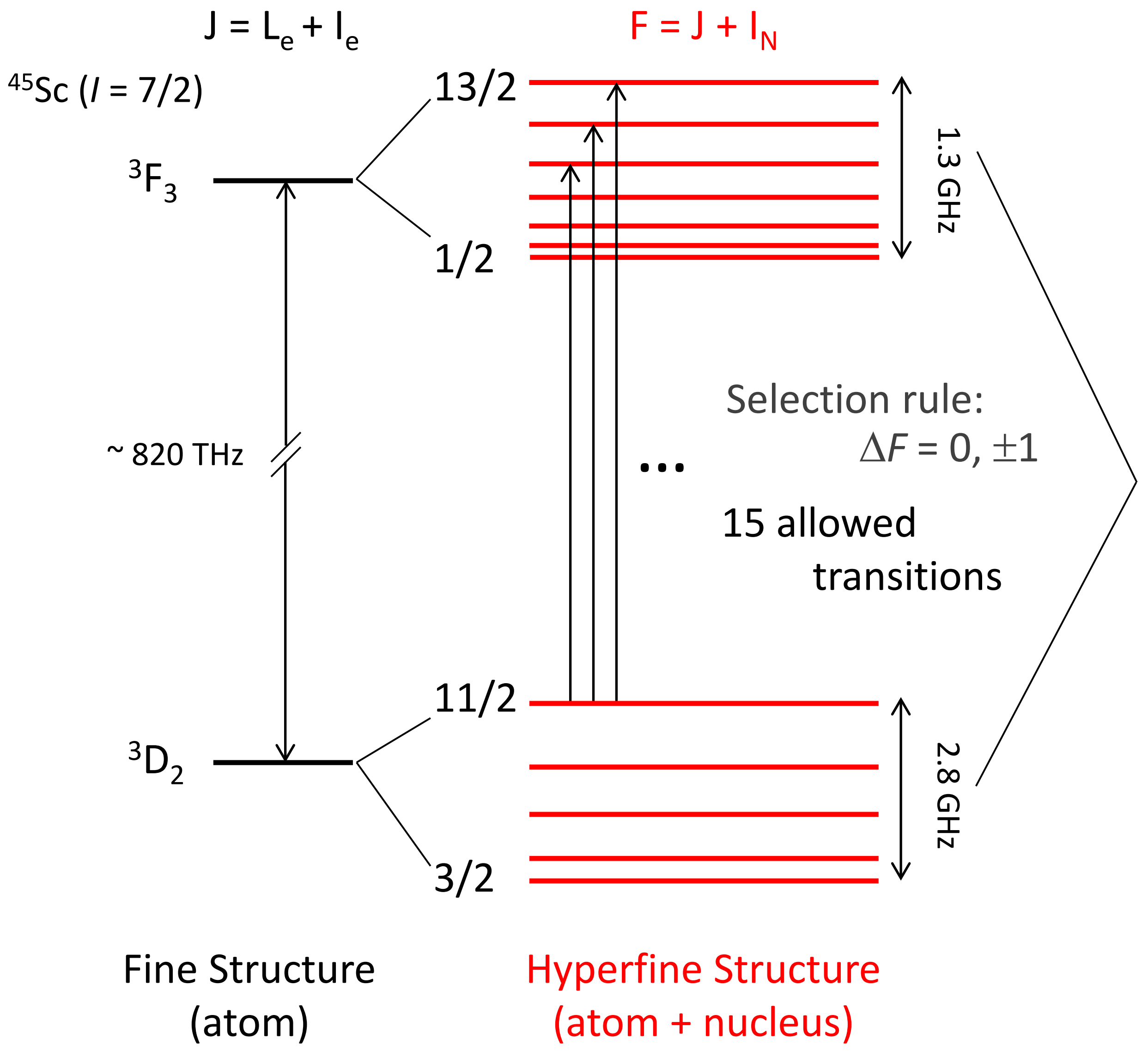
magnetic dipole moment : $\boldsymbol{\mu} = \int \boldsymbol{r}\times\boldsymbol{j}(\boldsymbol{r}) = \mu_{\mathrm{N}}\left(\langle\boldsymbol{l}\rangle + g_{\mathrm{p}}\langle\boldsymbol{s}\rangle + g_{\mathrm{n}}\langle\boldsymbol{s}\rangle\right)$

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)

Electromagnetic moments: HF structure



Selection rule:
$\Delta F = 0, \pm 1$

15 allowed transitions

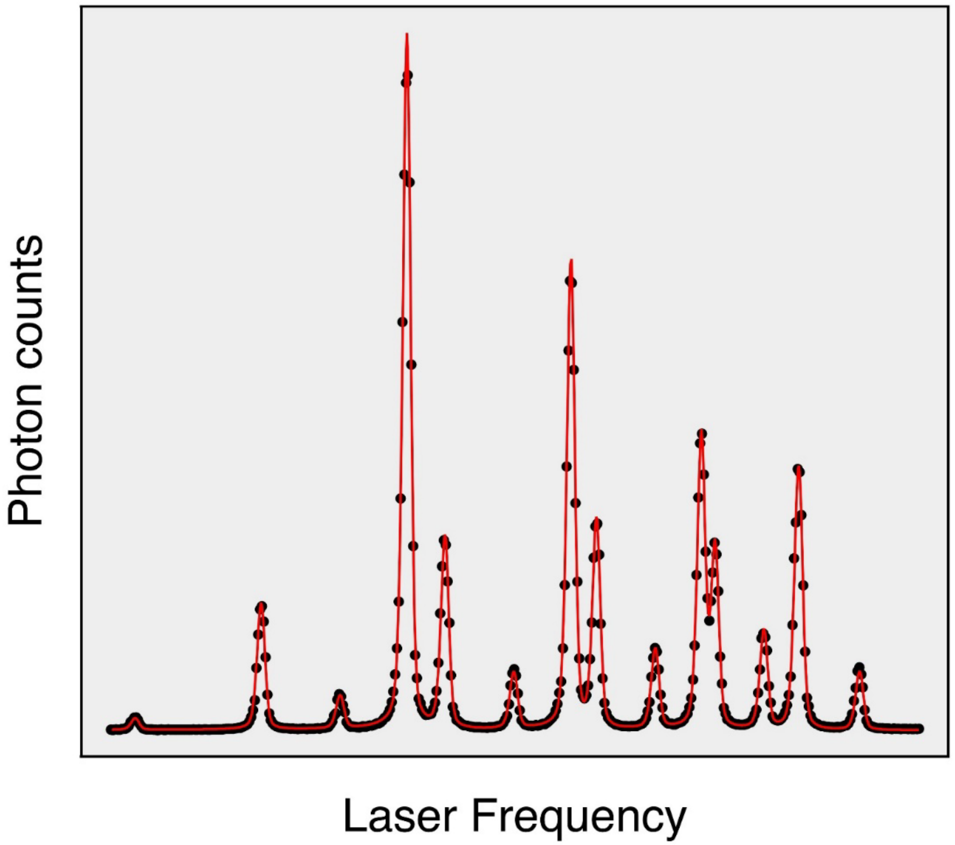
~A, B
(I, μ, Q)

Fine Structure
(atom)

Hyperfine Structure
(atom + nucleus)

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

^{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

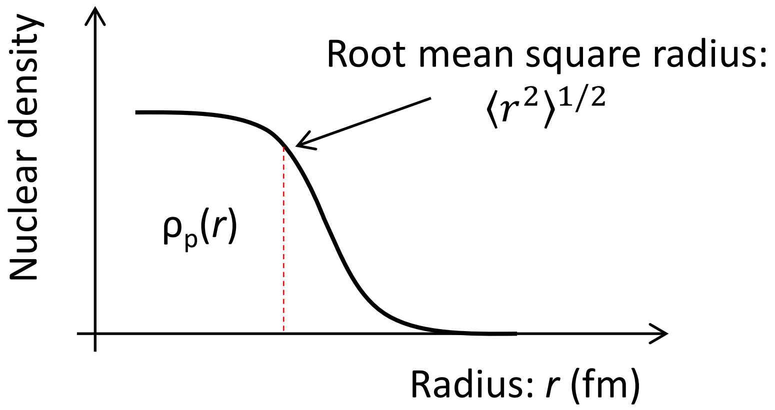
- **Much smaller and in general difficult to deduce from hyperfine spectra**
- Specific system
- RF and/or microwave spectroscopy

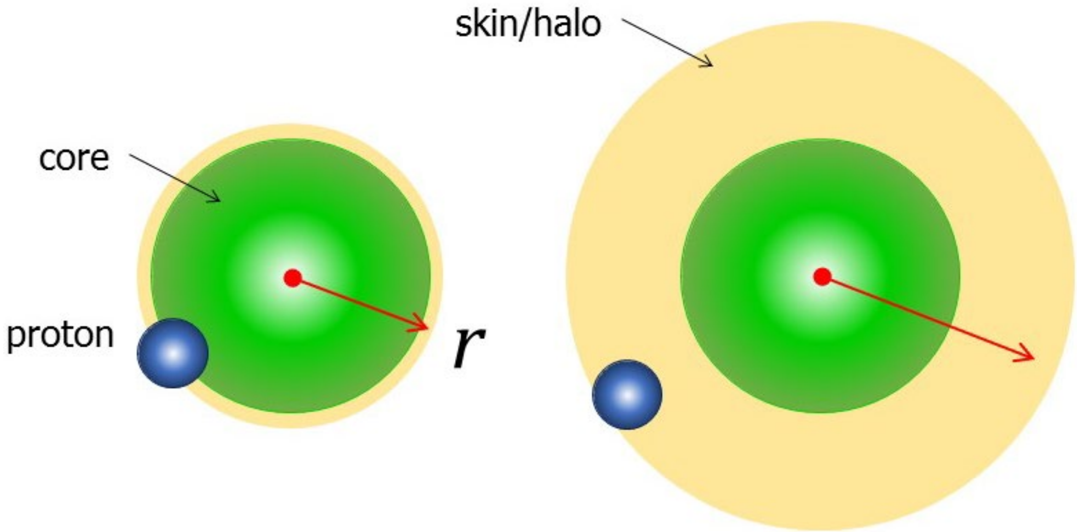
Mean-square charge radius

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

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

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

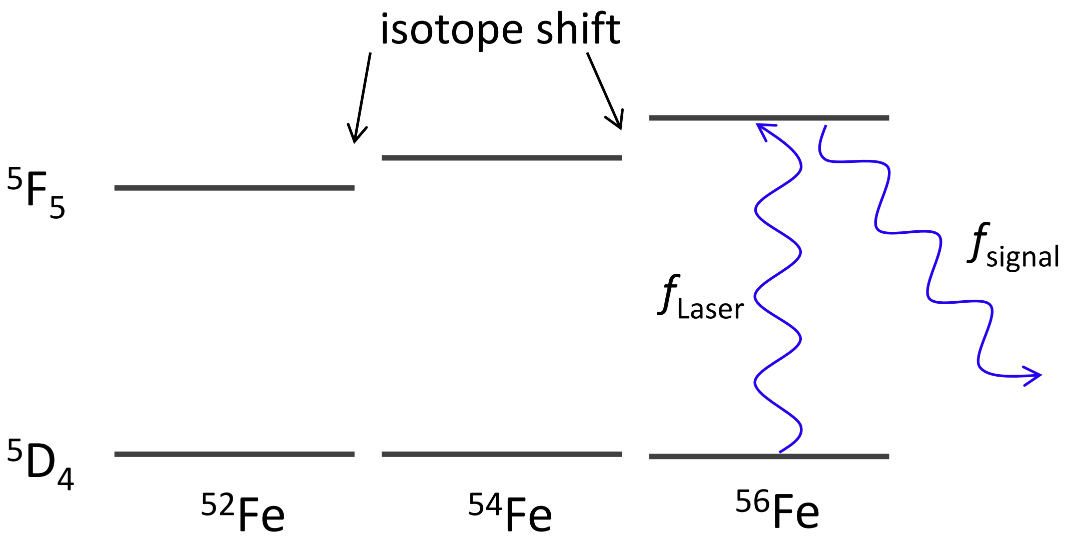




$\langle r^2\rangle$ is sensitive to size/shape of nucleus, static and dynamic deformation (vibration) ↔ B(E2) & Q

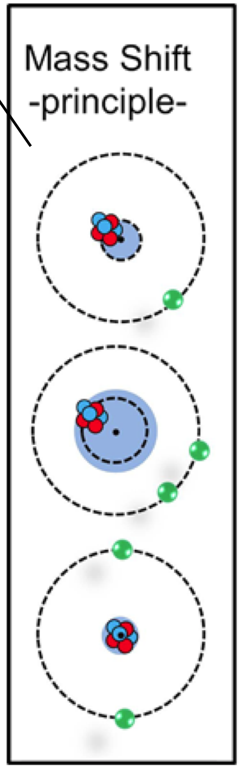
Charge radius: isotope shift of fine structure energies

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

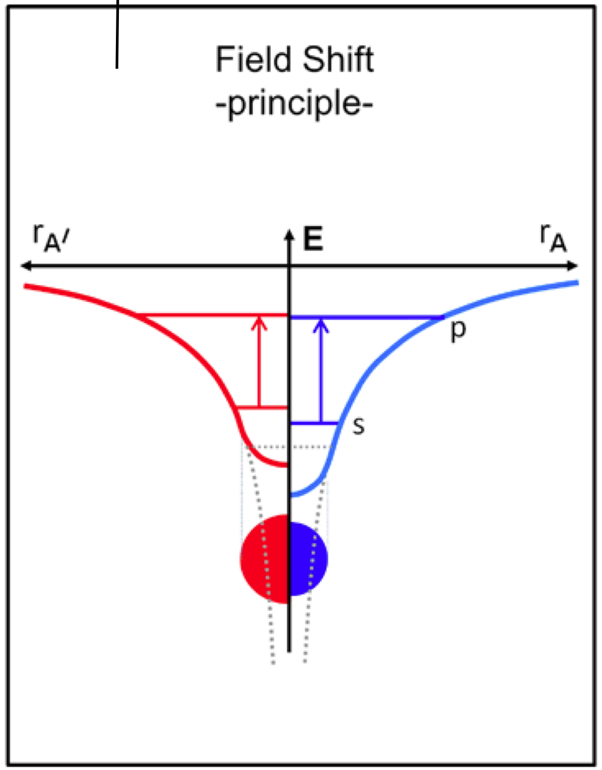


Fine structure of Fe isotopes

- *k*, *F*: atomic factors need to be known to extract $\delta\langle r^2\rangle$
- Typically obtained by experiment, otherwise theory calculation



Change of the center of the motion energy



Change of the size (radius) of the nucleus

Taken from W. Nörtershäuser and Ch. Geppert, Lecture Notes in Physics 879 (2014).

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 uncertainty
- Atomic (*k*, *F*) and nuclear ($\delta\langle r^2\rangle$) contributions are isolated each other.
- **Sensitive to $\boldsymbol{\delta\langle r^2\rangle}$ 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 (for stable isotopes).
  - but R_{ref} is not always available with high enough precision we want.
- The *k* term is negligible for heavy mass elements, but dominates for light elements.
- **Using King plot, *k* and *F* can be experimentally evaluated,**
  - IF there are 3 or more (stable) isotopes of the element, whose *R* are know with precision.
  - **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, $\delta\langle r^2\rangle$ is replaced by $\delta\langle r^2\rangle + \tilde{c}_2\delta\langle r^4\rangle + \tilde{c}_3\delta\langle r^6\rangle + \cdots$
  - Contribution is very small and difficult to determine

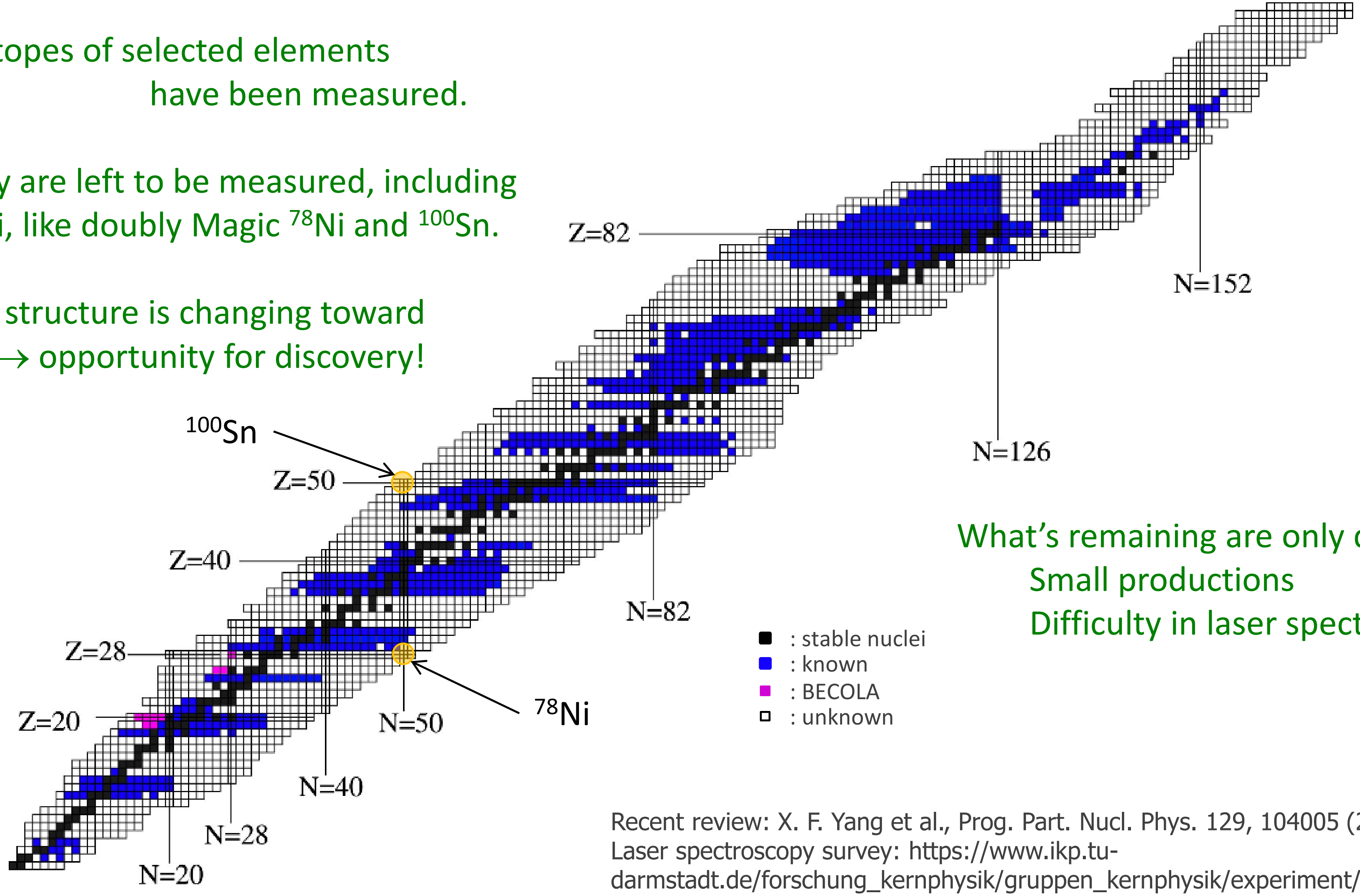
Laser spectroscopy measurements

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

Many isotopes of selected elements
have been measured.

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

We know structure is changing toward driplines → opportunity for discovery!



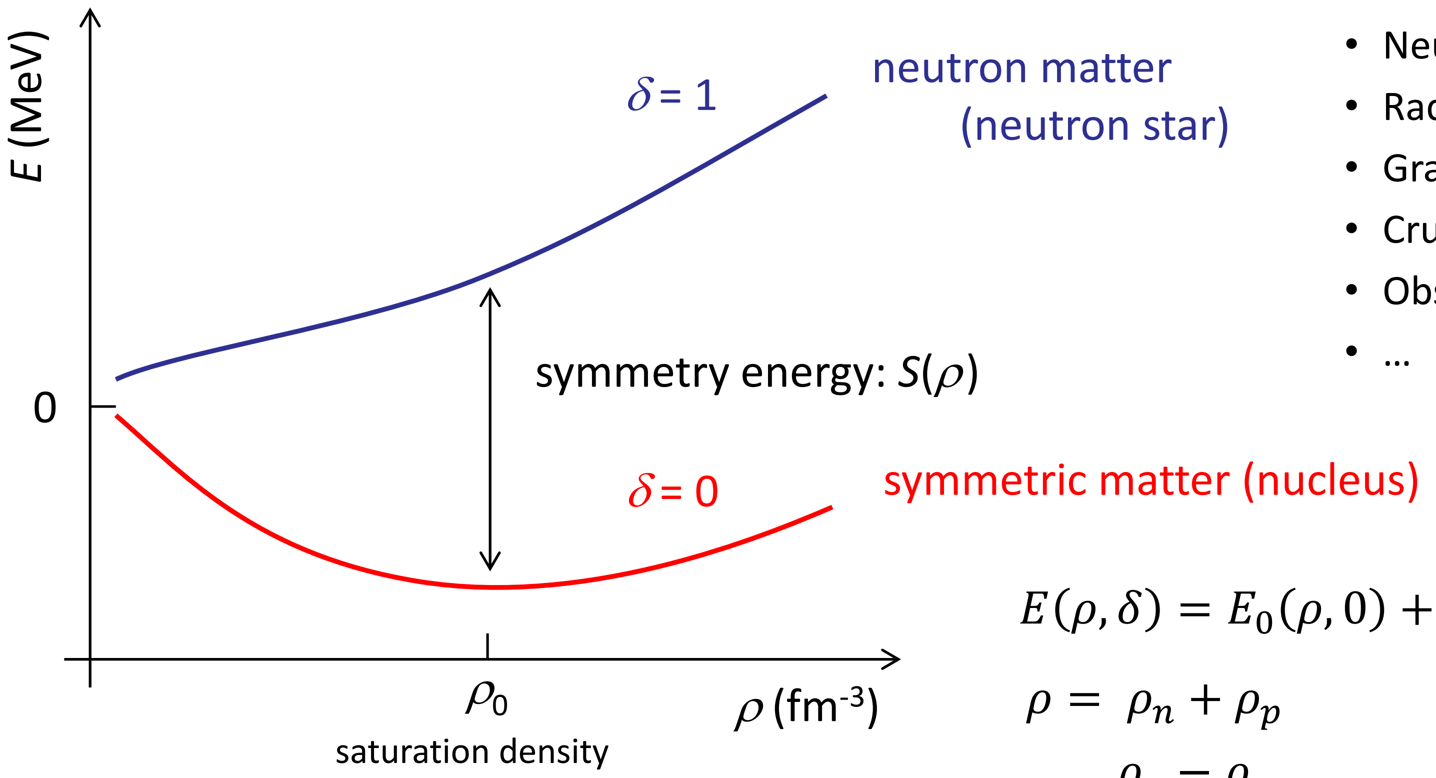
■ : stable nuclei
🟦 : known
🟪 : BECOLA
□ : unknown

What's remaining are only difficult cases.
Small productions
Difficulty in laser spectroscopy

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/

Nuclear Equation of State and Its Implications on Astrophysics

CONCEPTUAL MODEL



- Structure of halo/skin structure, heavy/super heavy elements

- Neutrino processes in supernova explosions
- Radii of neutron stars
- Gravitational signal of merging binary neutron stars
- Crust's thickness and thermal relaxation time
- Observable in cooling and accreting neutron stars
- …

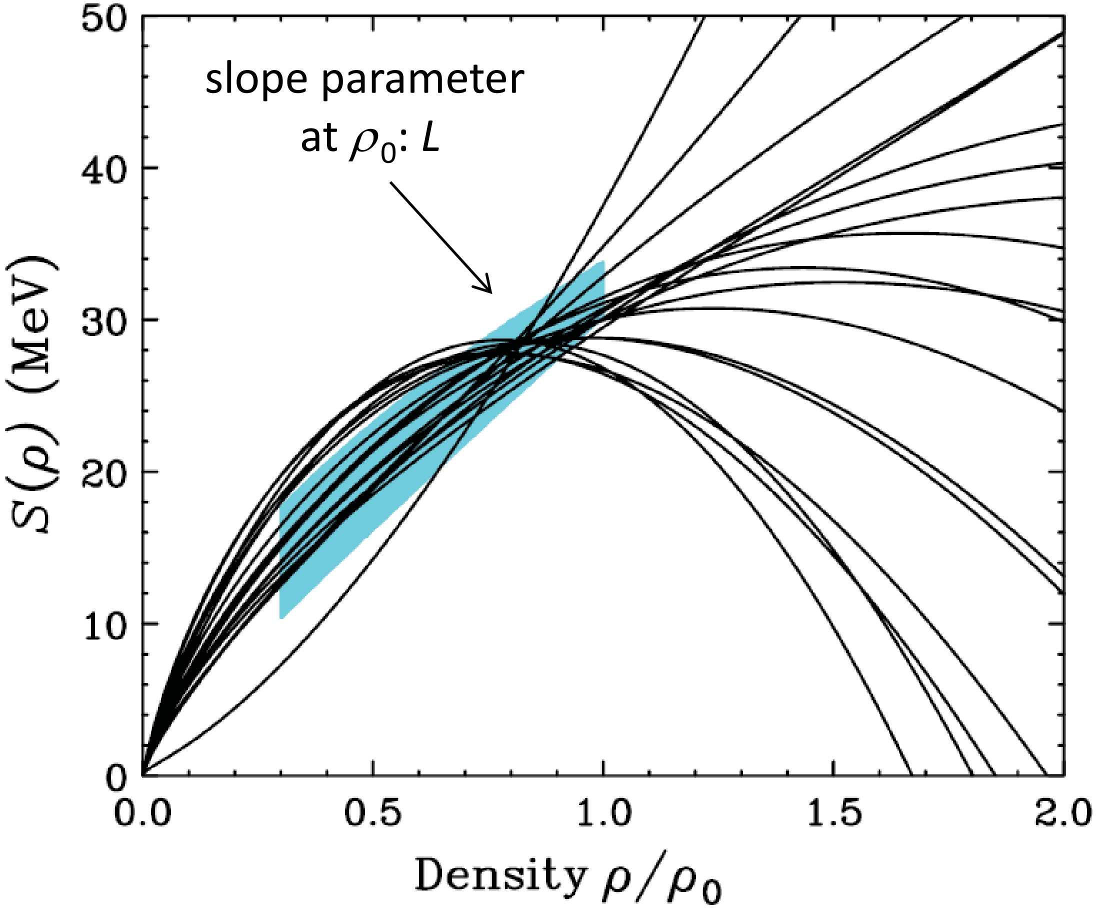
$$E(\rho,\delta) = E_0(\rho,0) + S(\rho)\delta^2 + \ldots$$

$$\rho = \rho_n + \rho_p$$

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Neutron Equation of State and Slope Parameter *L*

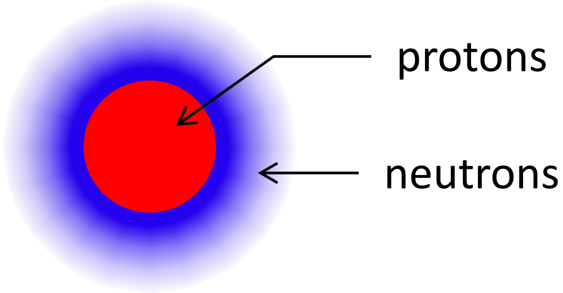
Symmetry energy



How to determine *L*?

- **No direct measurement (model dependent)**
- Heavy ion collisions
- Nuclear biding energy
- IAS
- …
- LIGO/VIRGO/KAGRA, NICER
  ; multi-messenger astronomy
- …
- Dipole polarizability
- **Neutrons skin/radius**

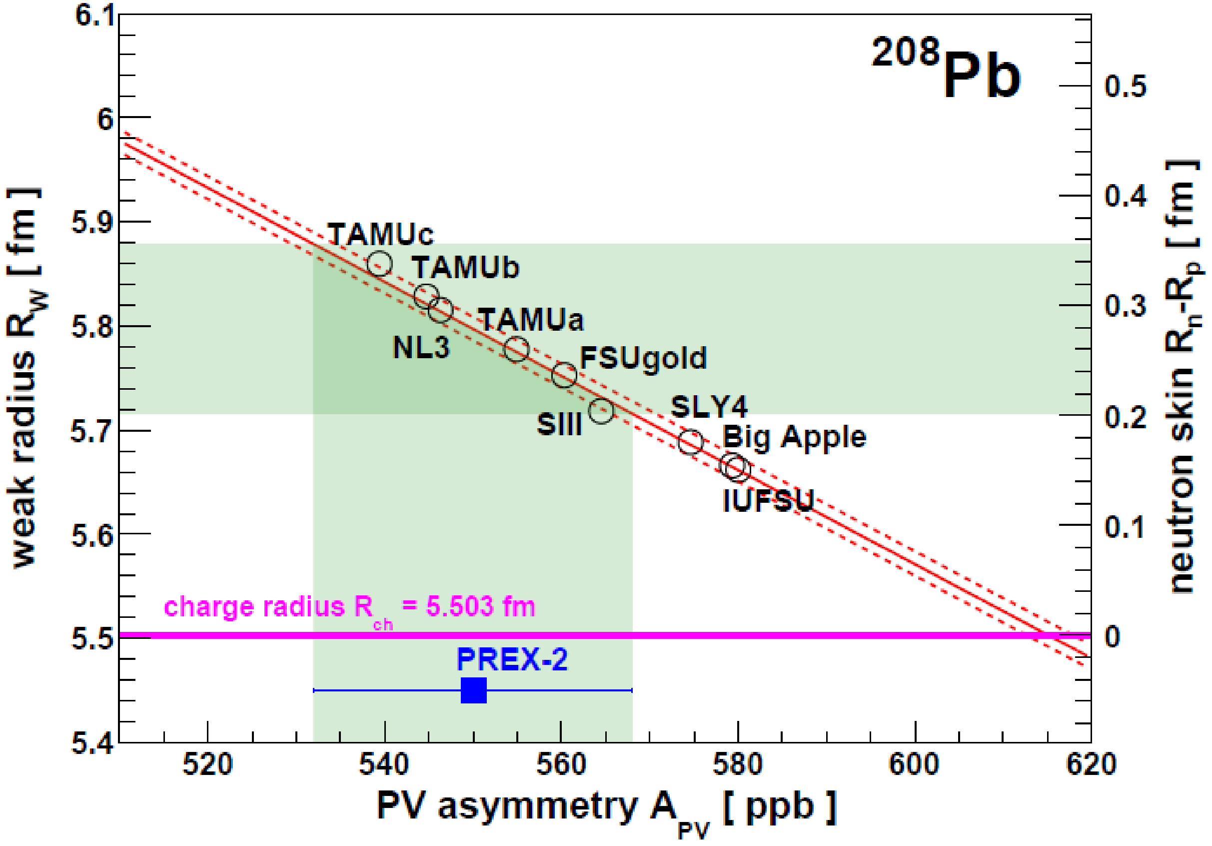
↔ *L*: slope of the symmetry energy

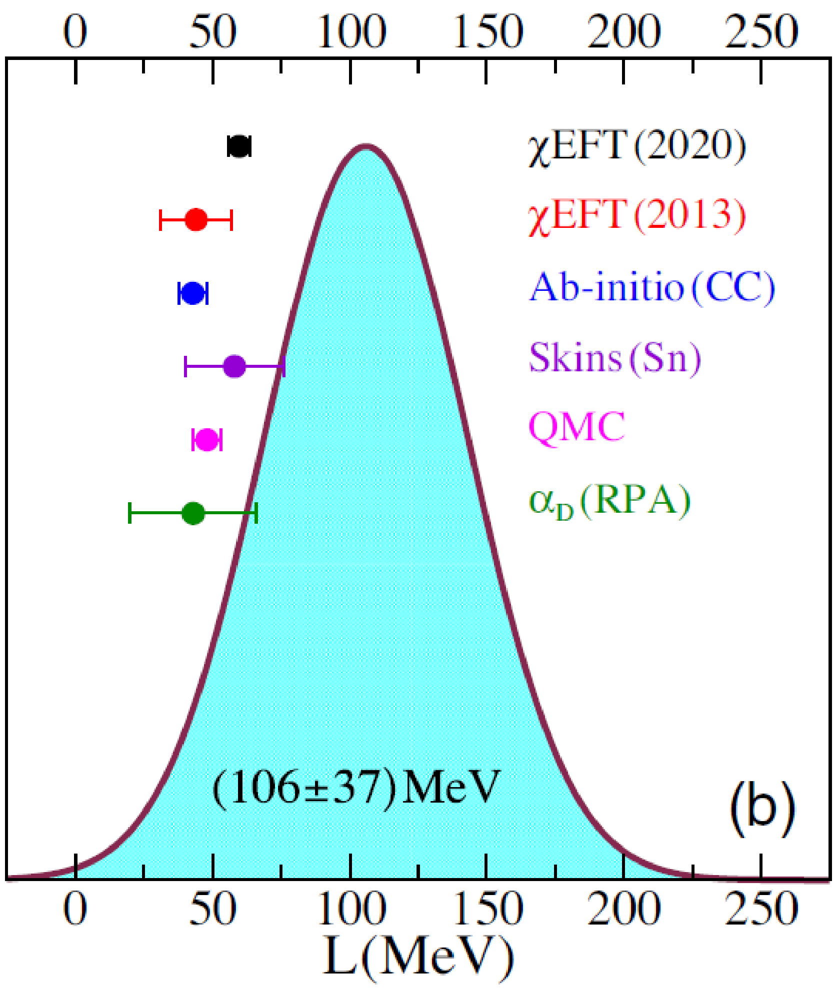


B. A. Brown, PRL 85, 5296 (2000); M. B. Tsang et al., PRC 86, 01583 (2012);
C. Y. Tsang et al., arXiv:2310.11588v1 [nucl-th], (2023).

PREX Correlation between ΔR_{np} vs L

- Parity violating e^- scattering on ^{208}Pb
  - Neutron rich double-magic nucleus
  - Weak charge is mostly carried by neutron.
  - Model independent determination of A_{PV}

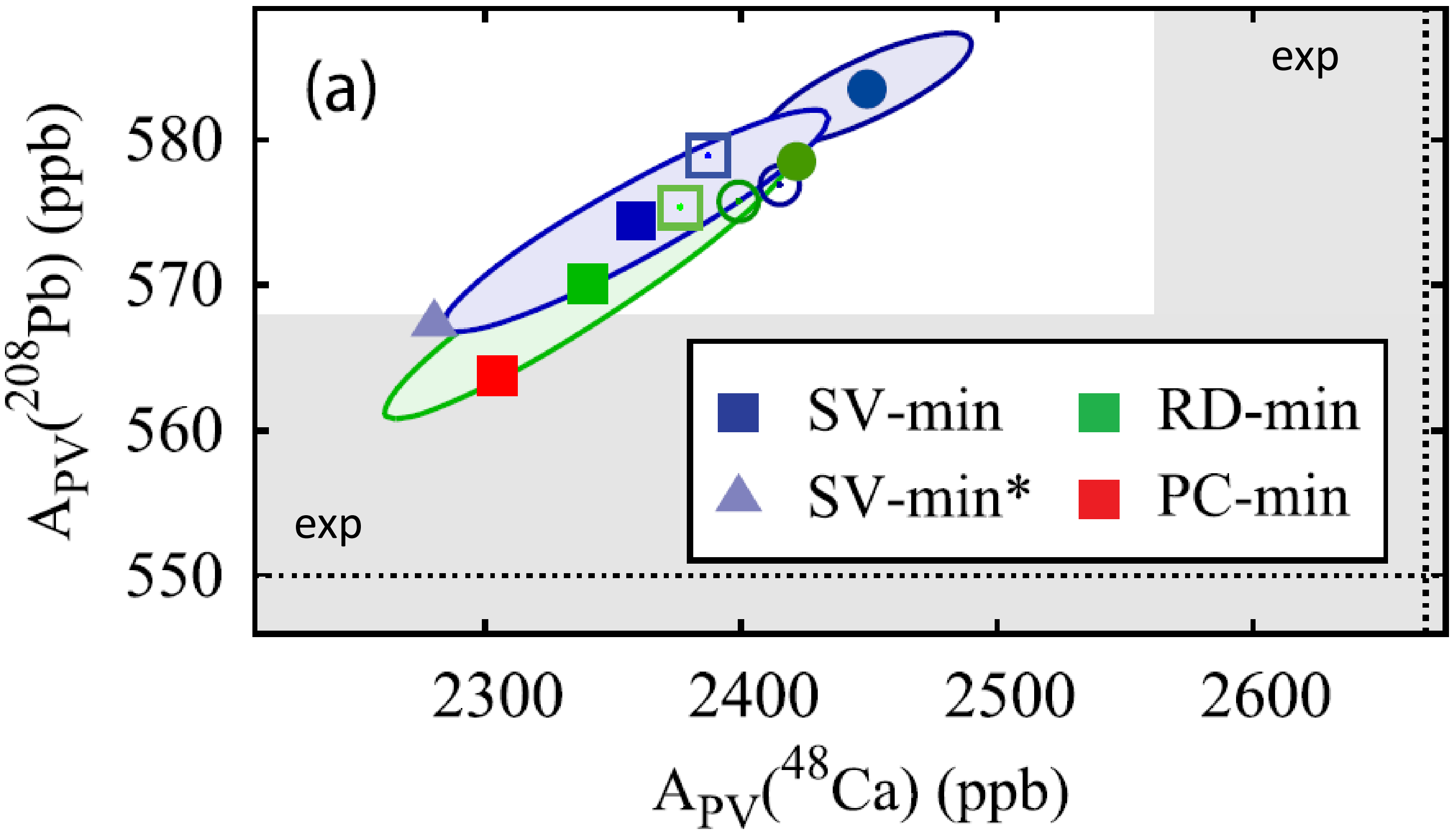




D. Adhikari et al., PRL 126, 172502 (2021); B. T. Reed et al., PRL126, 172503 (2021).

Tension between PREX and CREX

- Parity violating *e*$^-$ scattering on ^{48}Ca
  - Another neutron rich doubly magic nucleus
- PREX and CREX results are not compatible
  - Within the DFT model
  - Exp. and theory different trend
  - Cannot produce consistent explanation



D. Adhikari et al., PRL 129, 042501 (2022); P-G Reinhard et al., PRL129, 232501 (2022).

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.

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

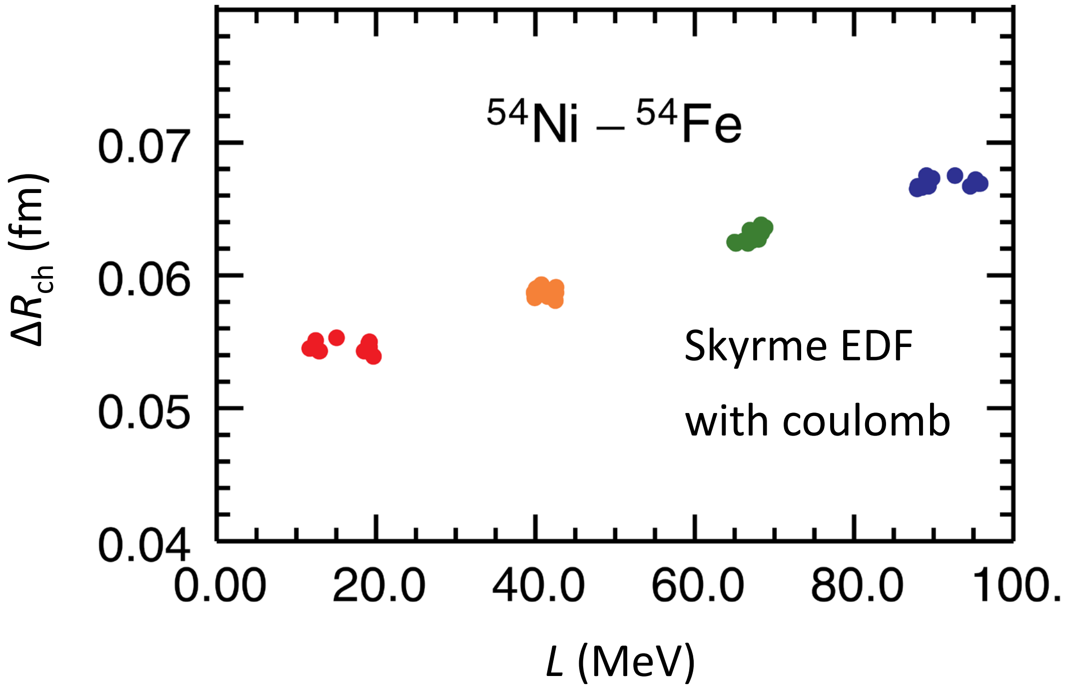
$$\longrightarrow R_{\mathrm{ch}}\left({}^{A}_{N}Y_{Z}\right) - R_{\mathrm{ch}}\left({}^{A}_{Z}X_{N}\right) \equiv \Delta R_{\mathrm{ch}}$$

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

Even with Coulomb, correlation remains, also

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

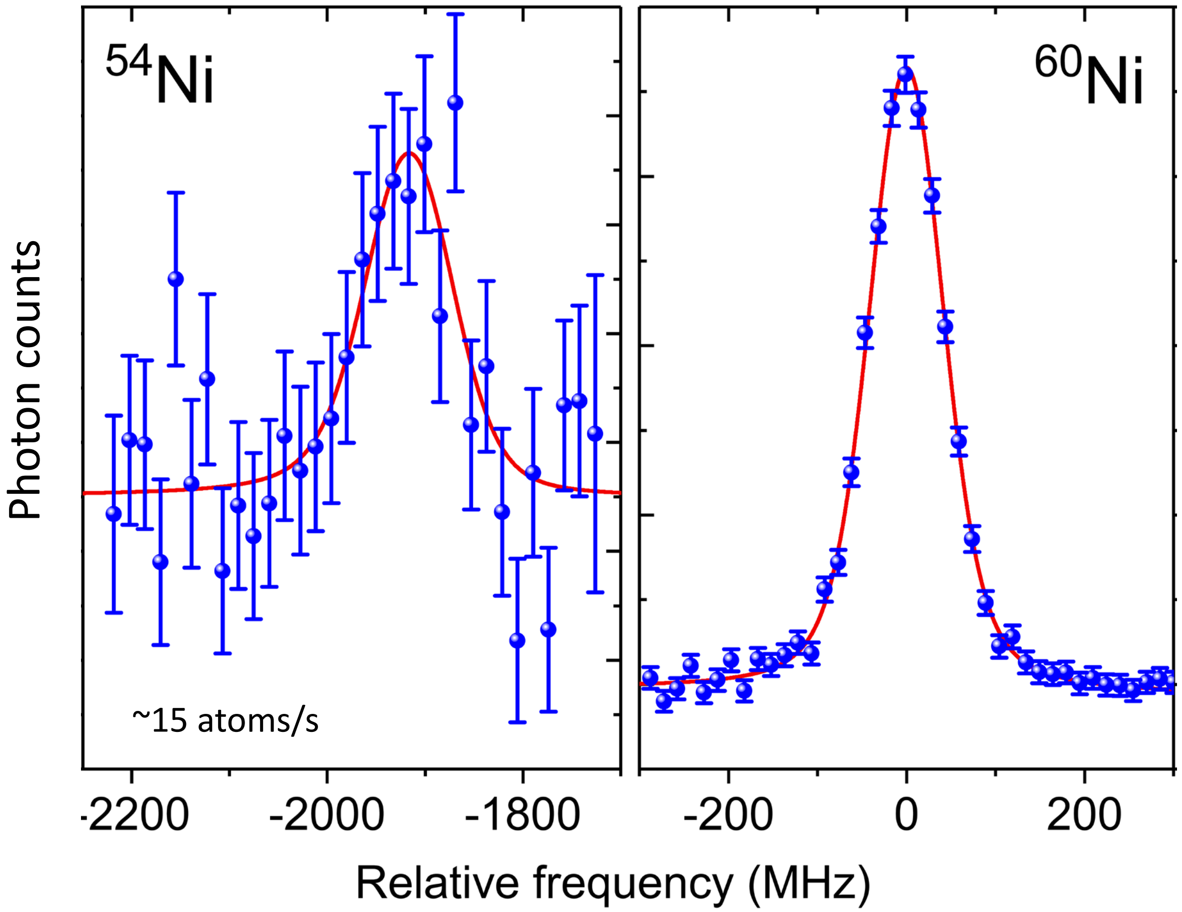
- Present: ^{54}Ni (114 ms)-^{54}Fe (stable) pair
- $|N - Z|$ = 2: not so large (the largest is 6), and
- Good experimental precision is required.



$\Delta R_{\mathrm{np}}(^{208}\mathrm{Pb})$ =
- 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).

^{54}Ni Hyperfine Spectrum



$4s\ ^3D_3 - 4p\ ^3P_2$ @ 352 nm

S. V. Pineda et al., PRL 127, 182503 (2021).

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

Atomic factors well determined using King plot analysis

$$\begin{cases} k = 1266(26) \text{ GHz amu} \\ F = -804(66) \text{ MHz fm}^{-2} \end{cases}$$

K. König et al., PRC 103, 054305 (2021).

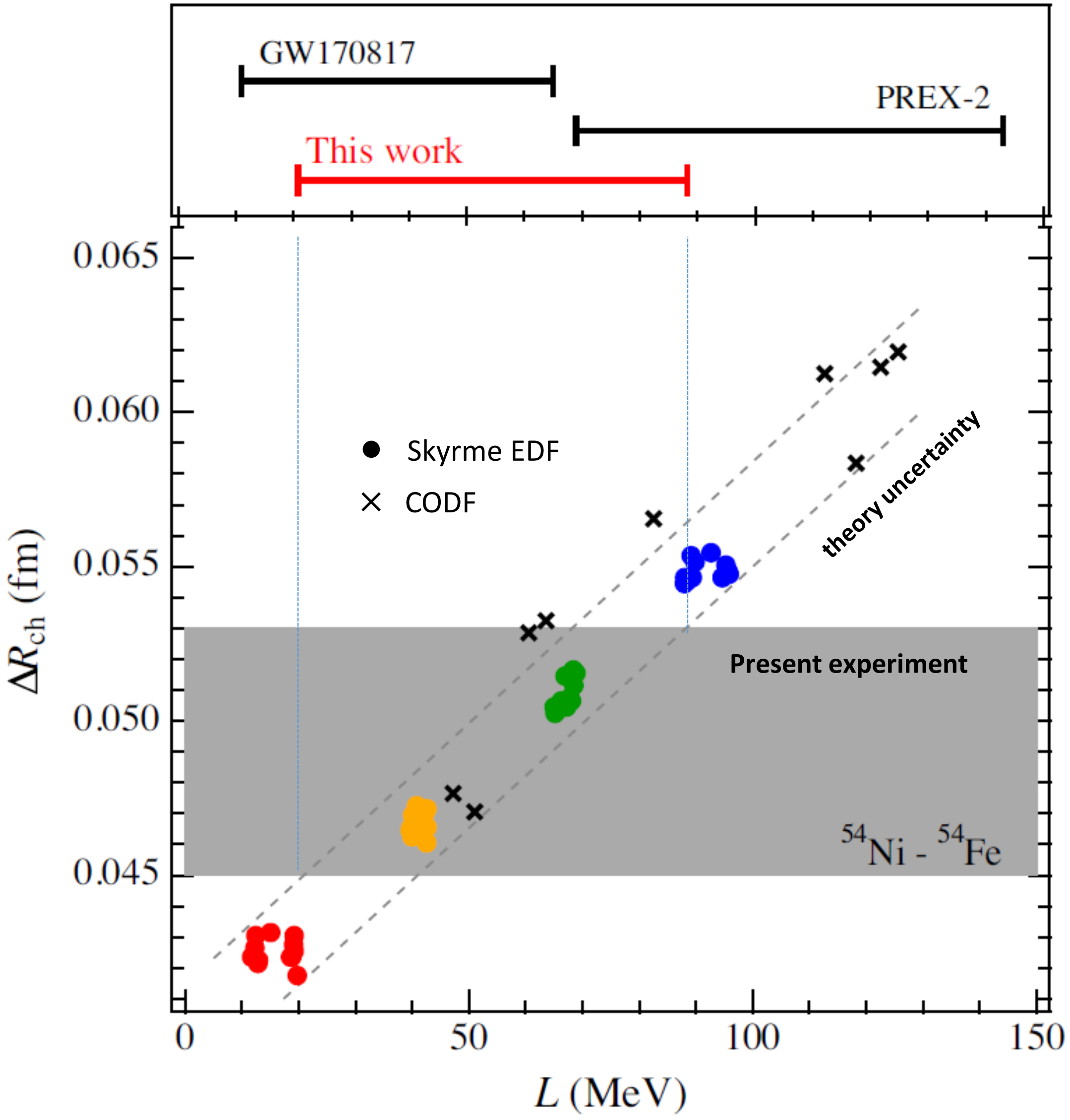
Absolute radii well determined form the *e*-scattering and μ-X ray measurements.

$$\begin{cases} R(^{60}\text{Ni}) = 3.8059(17) \text{ fm} \\ R(^{54}\text{Fe}) = 3.6880(17) \text{ fm} \end{cases}$$

G. Fricke and K. Heilig,
Nuclear Charge Radii, Springer, (2004).

$\Delta R_{ch} = 0.049(4)$ fm

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:

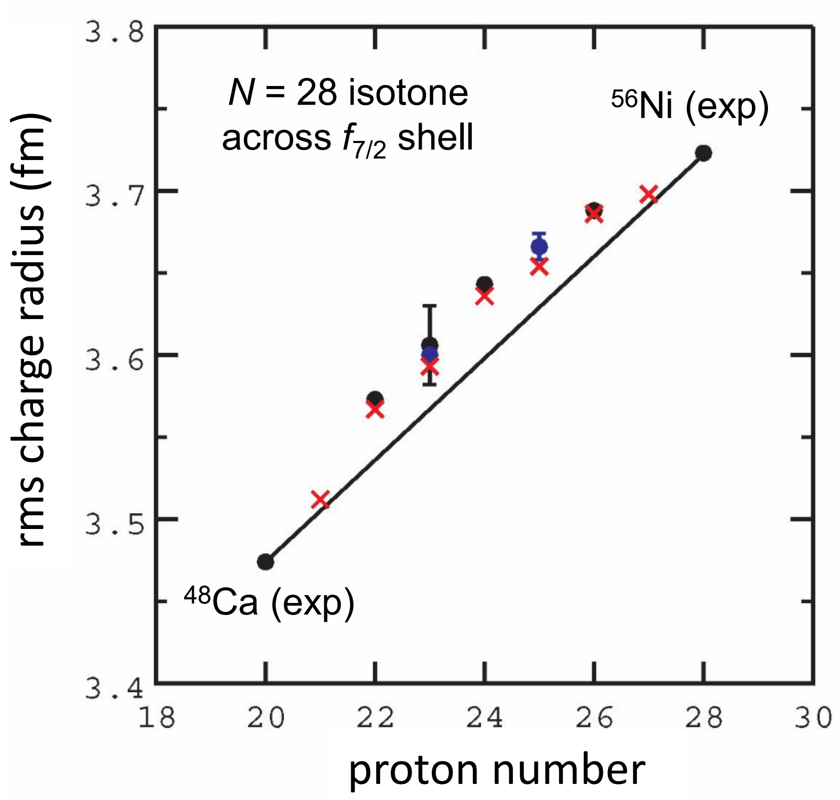
- indicates soft EOS, and smaller radius of a neutron star
- is consistent with GW170817 and PREX
- PREX, however, points to stiffer EOS and a larger neutron star radius.

- **All *L* "measurements" are model dependent.**
- **Assessment of model dependence is critical.**
- **Critical to have variety of exp. observables.**

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

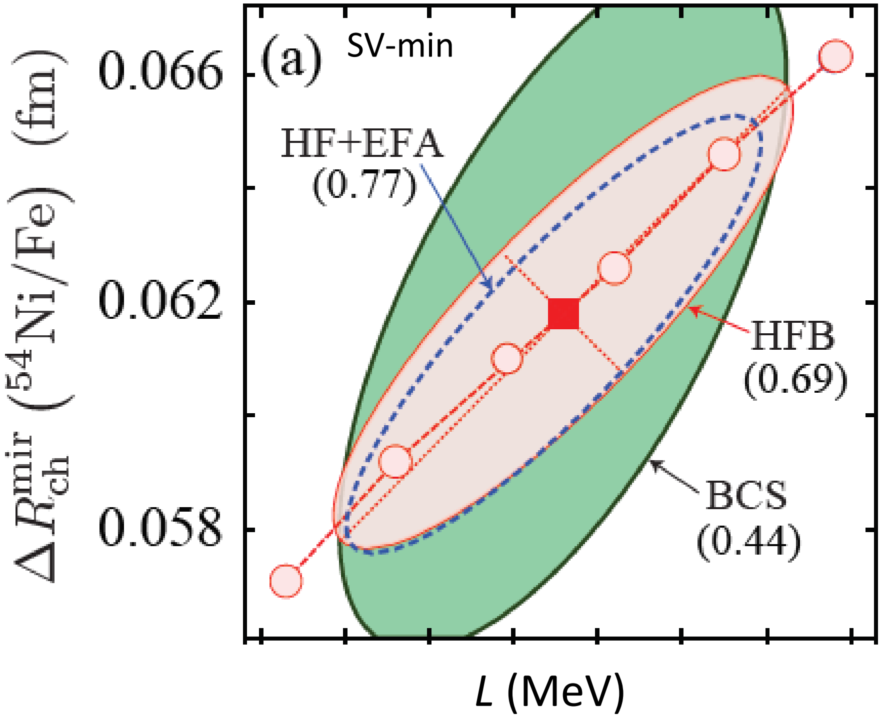
S. Pineda et al., Phys. Rev. Lett. 127, 182503 (2021).

Assessing Model Dependence



- β_2 correction model
- Used in the present study

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



$$\mathrm{CoD}^{0.5} = \frac{\mathrm{cov}(x,y)}{\sigma_x \sigma_y}$$

- Pairing interaction weakens the ΔR_{ch} and L correlation

P. -G. Reinhard and W. Nazarewicz Phys. Rev. C 105, L021301 (2022).

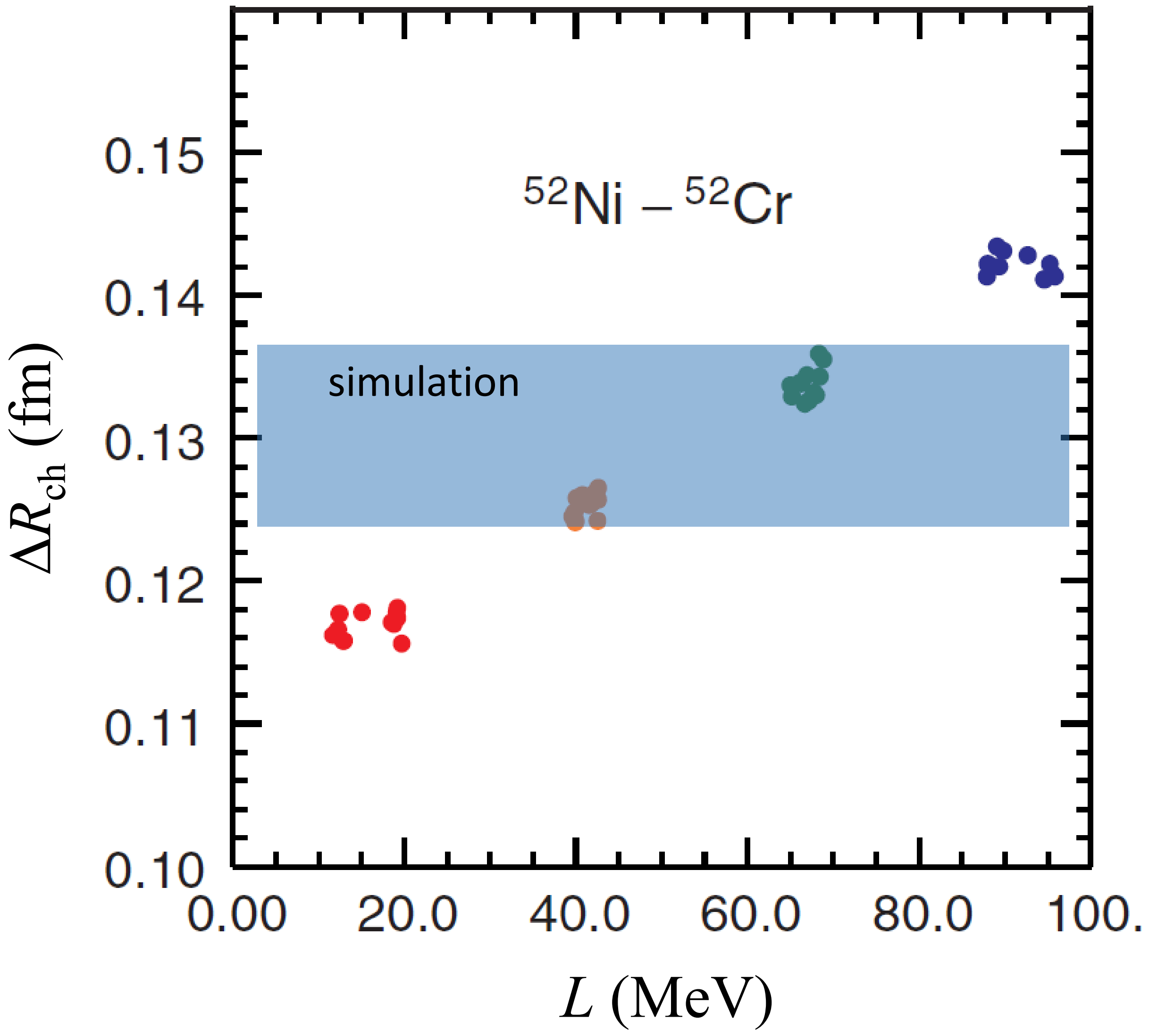
More is coming

- Y. N. Huang et al., PRC 107, 034319 (2023).
- R. An et al., arXiv:2303.14667 [nucl-th].
- P. Bano et al., PRC 108, 015802 (2023).
- K. König et al., submitted; lattice calculations for ΔR_{ch} and L

Next: Mirror Charge Radii ^{52}Ni and ^{52}Cr

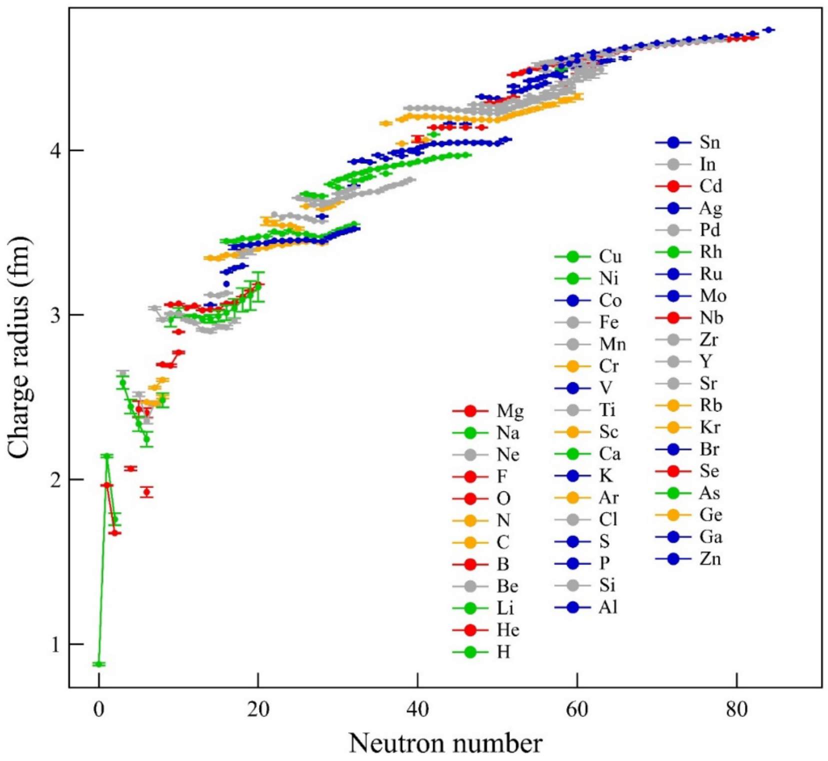
- $|N - Z| = 4$, twice bigger than the $A = 54$ system
- 2x more sensitive to L, and
- Less susceptive to systematics
- FRIB approved experiment on $R(^{52}\mathrm{Ni})$

Stay tuned!



Summary

- **BECOLA is the collinear laser spectroscopy facility at FRIB ↔ S^3-LEB**
  - Accepts low energy (~30 keV) beam, $T_{1/2}$ > ~100 ms
  - Performs laser resonant fluorescence and laser resonant ionization measurements
  - BEOLA collaboration: TUD, MIT, ANL, ORNL, MSU
- **Determines**
  - I, μ and Q: hyperfine spectrum
  - $\delta\langle r^2\rangle$: Isotope shift of hyperfine spectrum
- **Future**
  - BECOLA collaboration has six FRIB approved experiments
  - Looking to extend the collaboration with you
- **Your ideas?**



Acknowledgement

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Theory: U. Erlangen, TUD, TRIUMF, ORNL, EMMI GSI, MSU

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Thank you!