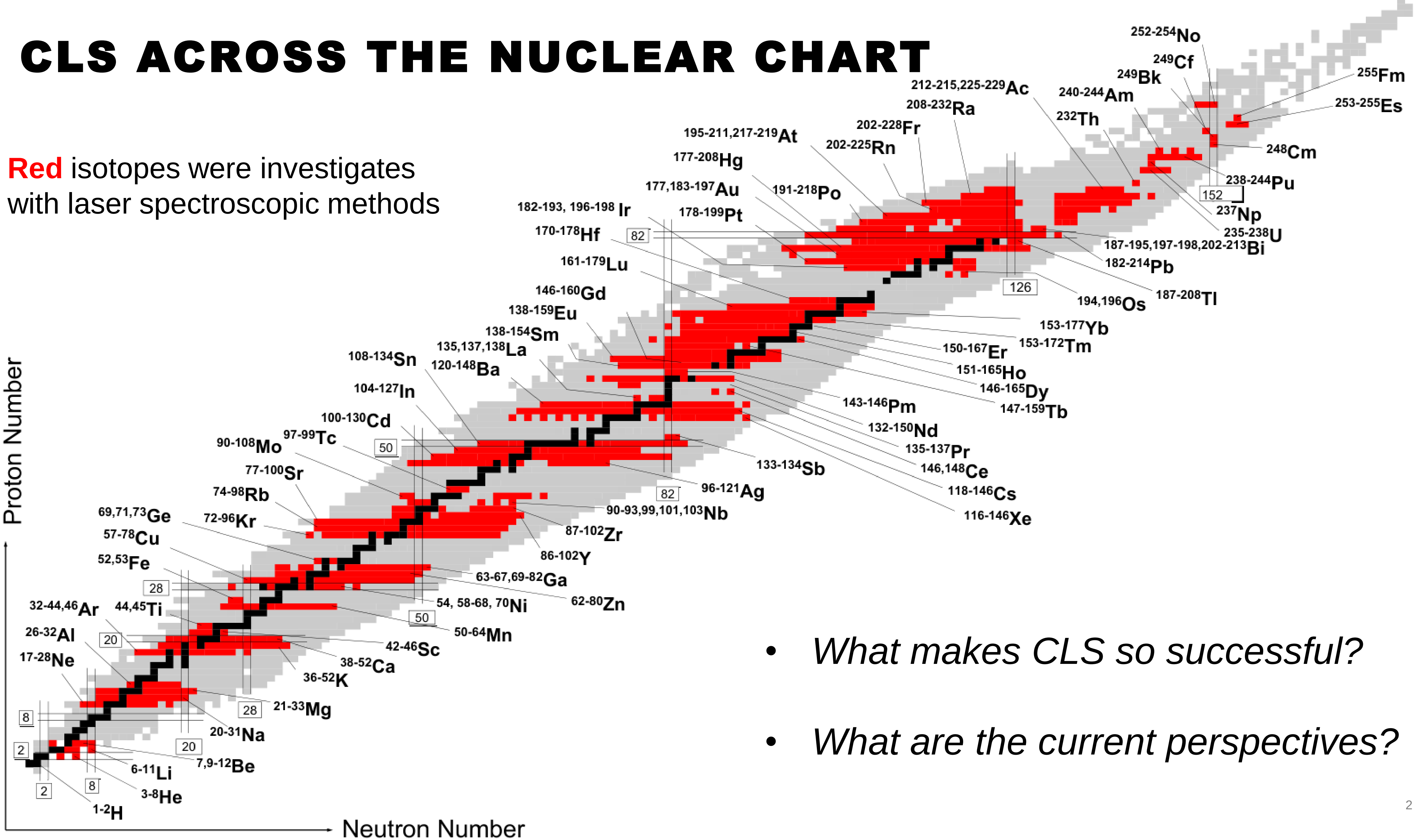
PERSPECTIVES OF COLLINEAR LASER SPECTROSCOPY

https://www.triumf.ca/laser-spectroscopy

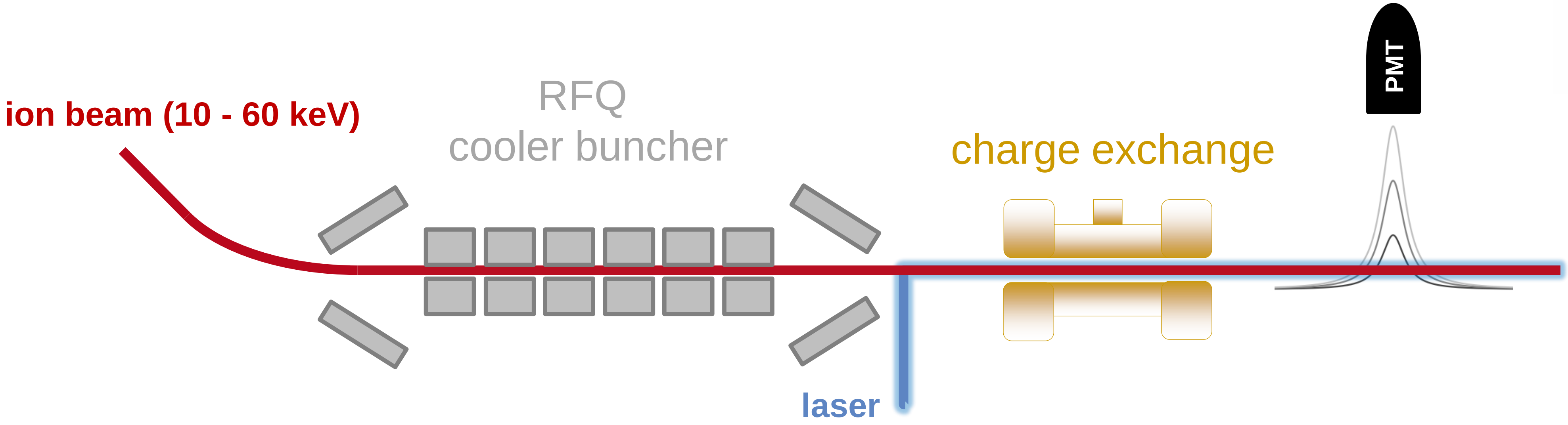
CLS ACROSS THE NUCLEAR CHART

Red isotopes were investigates with laser spectroscopic methods



- *What makes CLS so successful?*
- *What are the current perspectives?*

COLLINEAR LASER SPECTROSCOPY



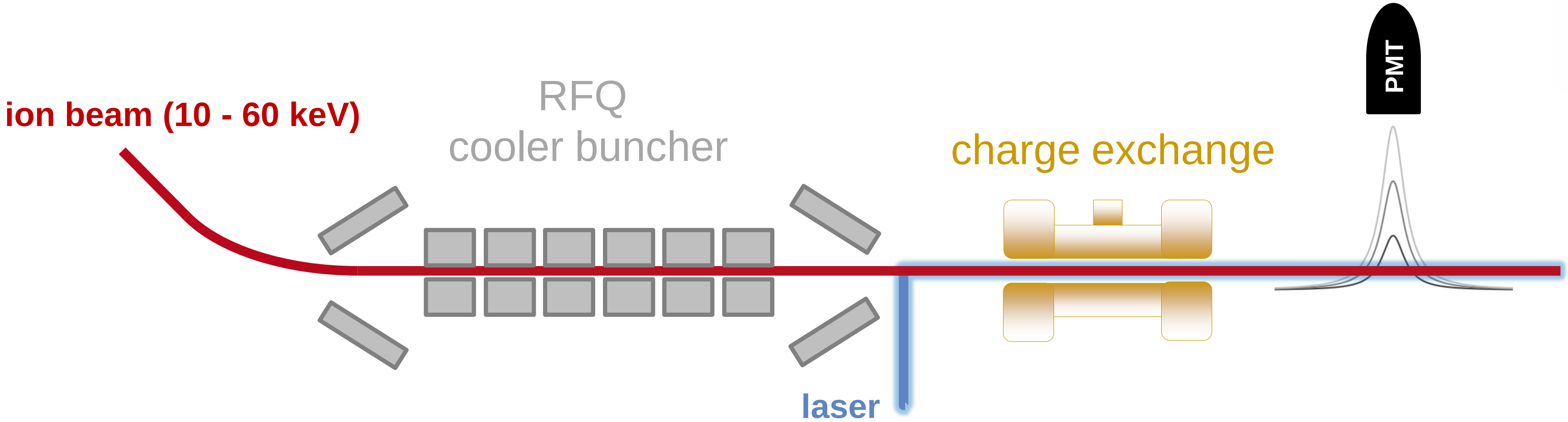
ion beam (10 - 60 keV)

RFQ
cooler buncher

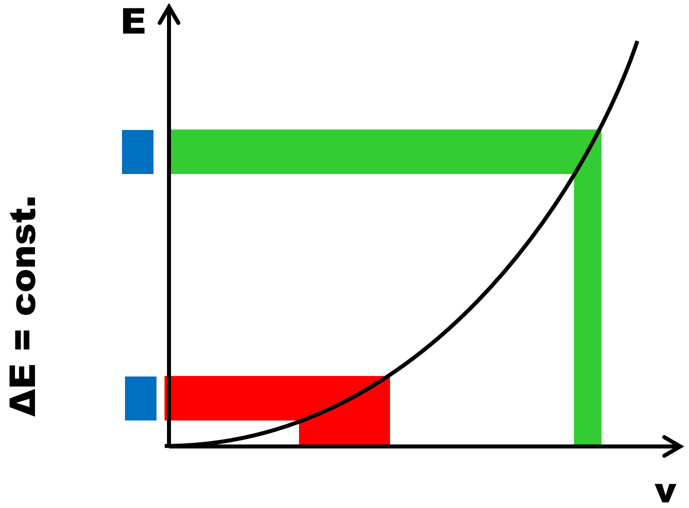
charge exchange

laser

COLLINEAR LASER SPECTROSCOPY



Doppler compression



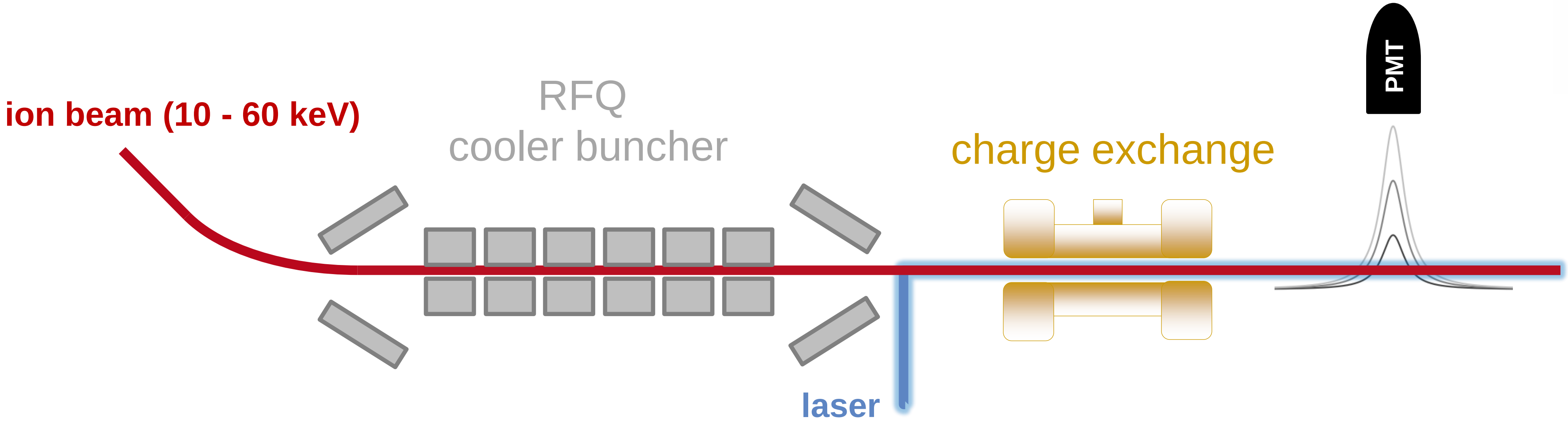
$$\frac{\delta v_U}{\delta v_0} = \frac{1}{2}\sqrt{\frac{k_B T}{eU}}$$

$$\nu_{\mathrm{c/a}} = \nu_0 \gamma (1 \pm \beta)$$

- Fast – Lifetimes of > 10 ms
- Doppler broadening free

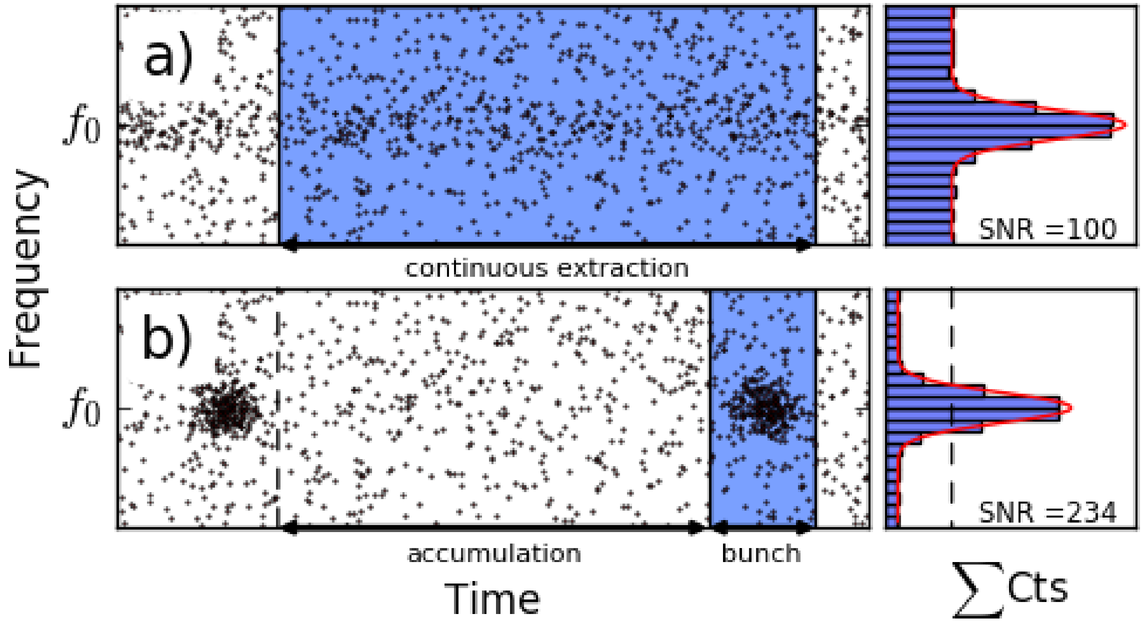
- Only dipole-allowed transitions
- Doppler-shifted resonance

COLLINEAR LASER SPECTROSCOPY

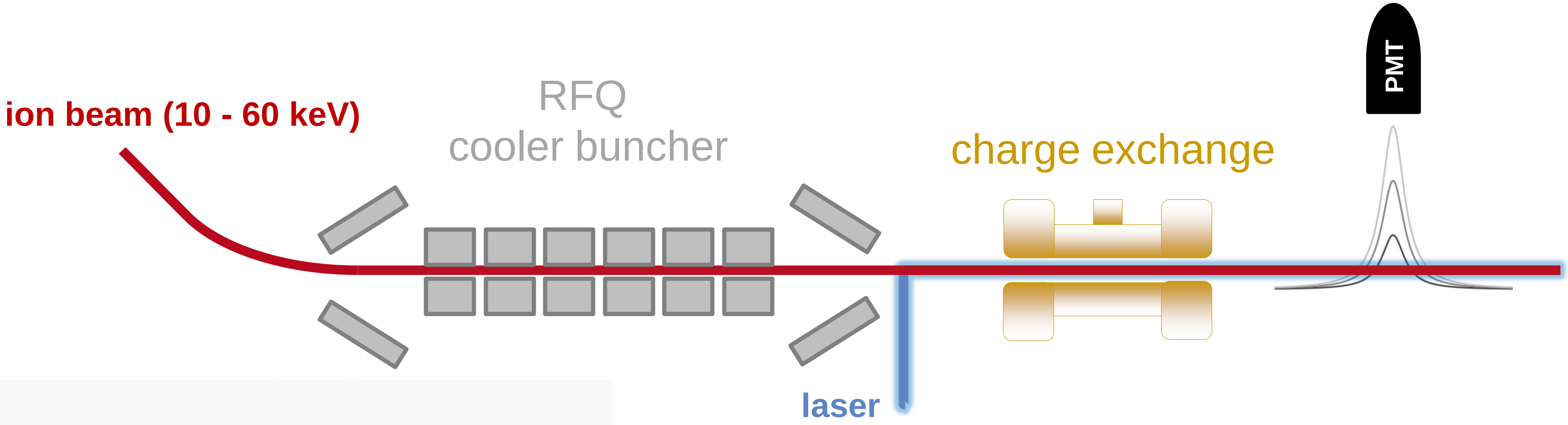


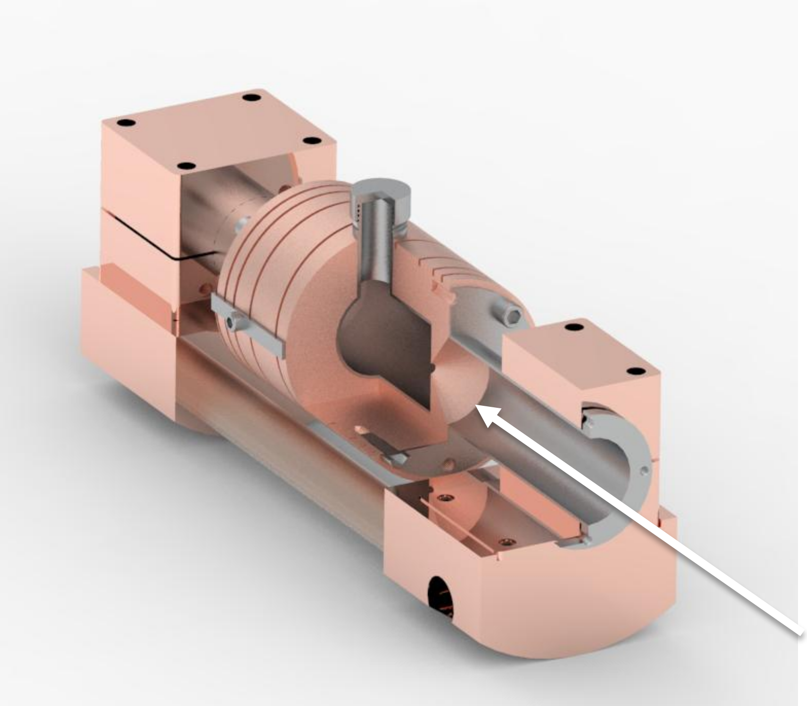
- Cooling of the ion beam
- 10^6 reduction of laser background

- Usage of pulsed spectroscopy lasers
- Optical population transfer



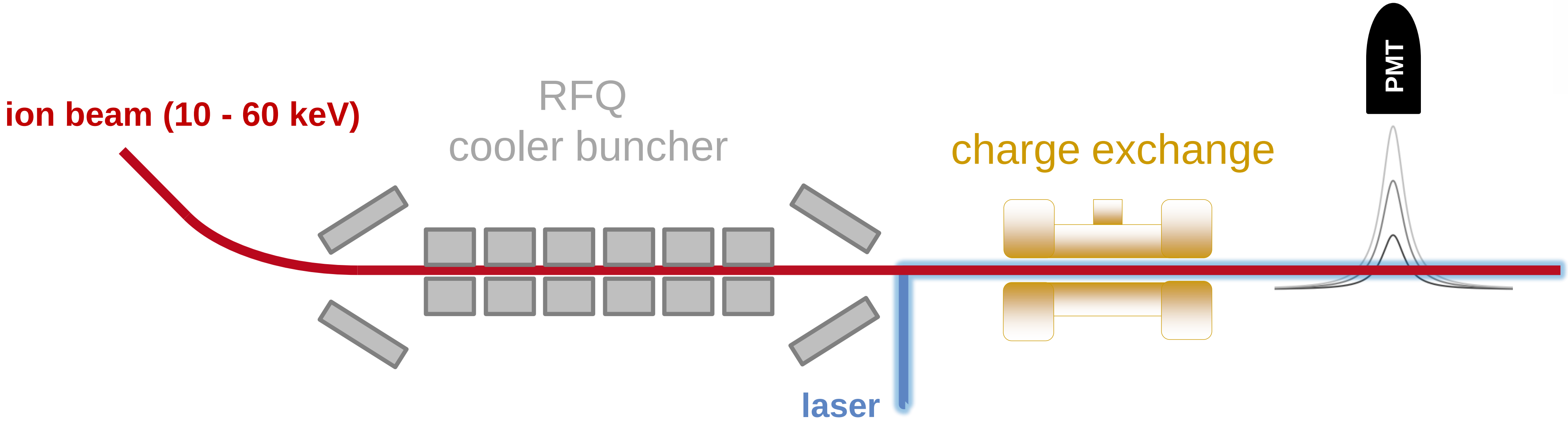
COLLINEAR LASER SPECTROSCOPY





- Limited to laser transitions > 200 nm
- ~ 50 % efficiency
- Several atomic states are populated
- Background free spectroscopy from metastable states
- New detection methods

COLLINEAR LASER SPECTROSCOPY



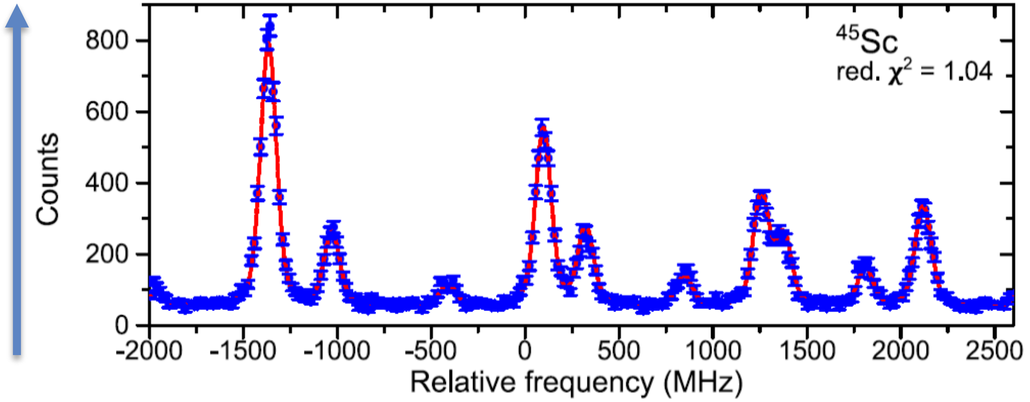
@ Collaps,
Becola,
Coala, …

$$\Delta E_{\mathrm{HFS}} = A \cdot \frac{C}{2} + B \cdot \frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(I-1)J(2J-1)}$$

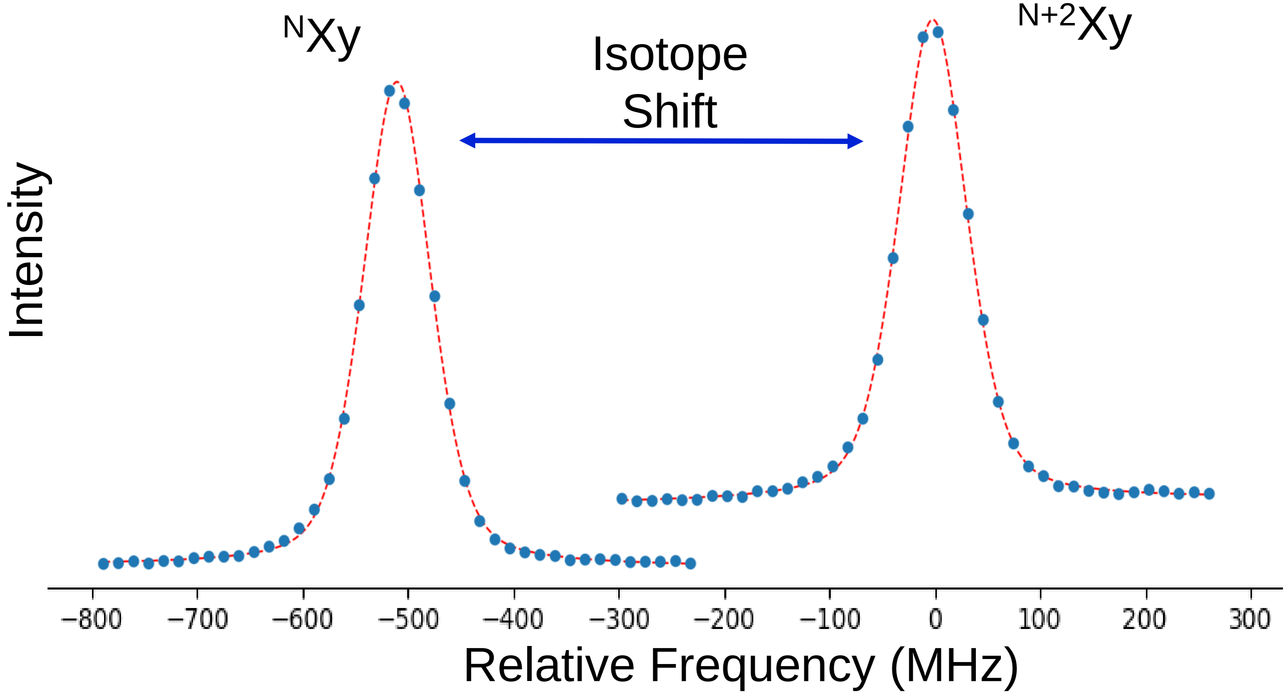
$$C = F(F+1) - I(I+1) - J(J+1)$$

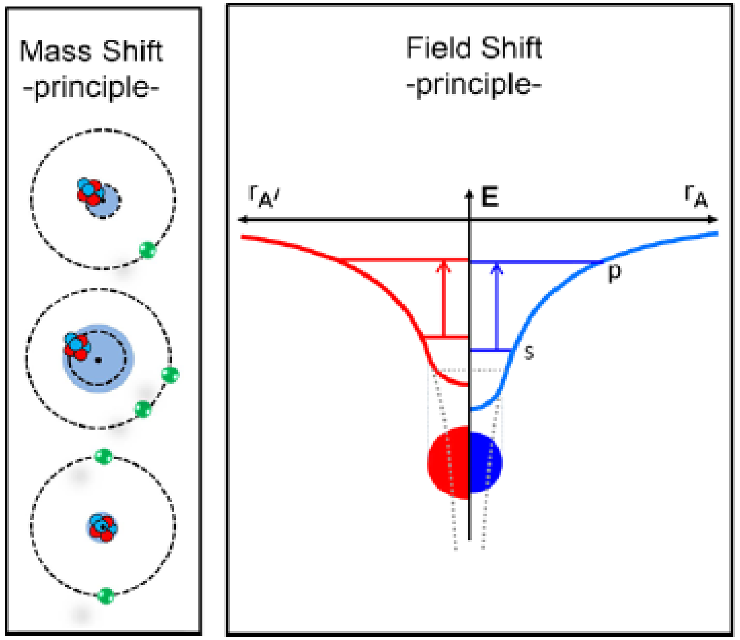
scanned frequency

photon counts



NUCLEAR CHARGE RADII



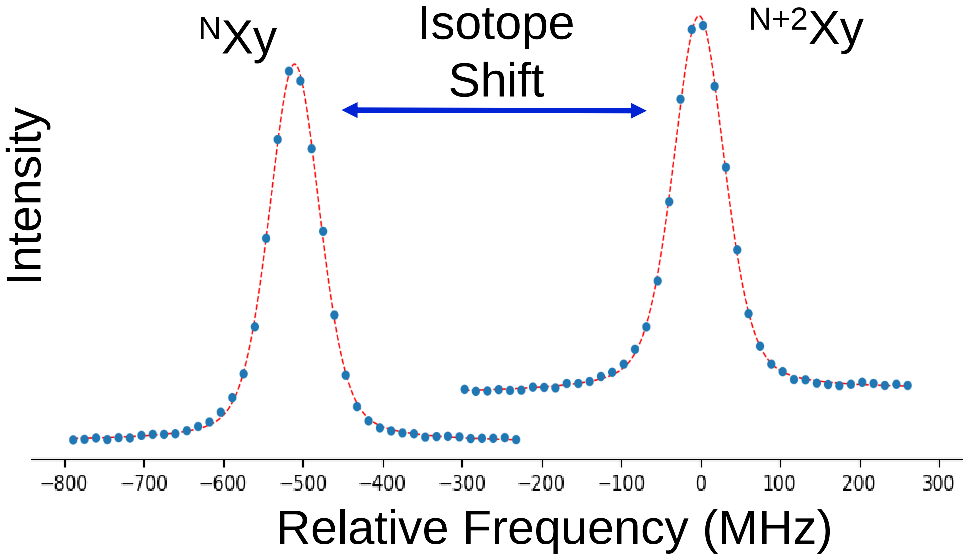


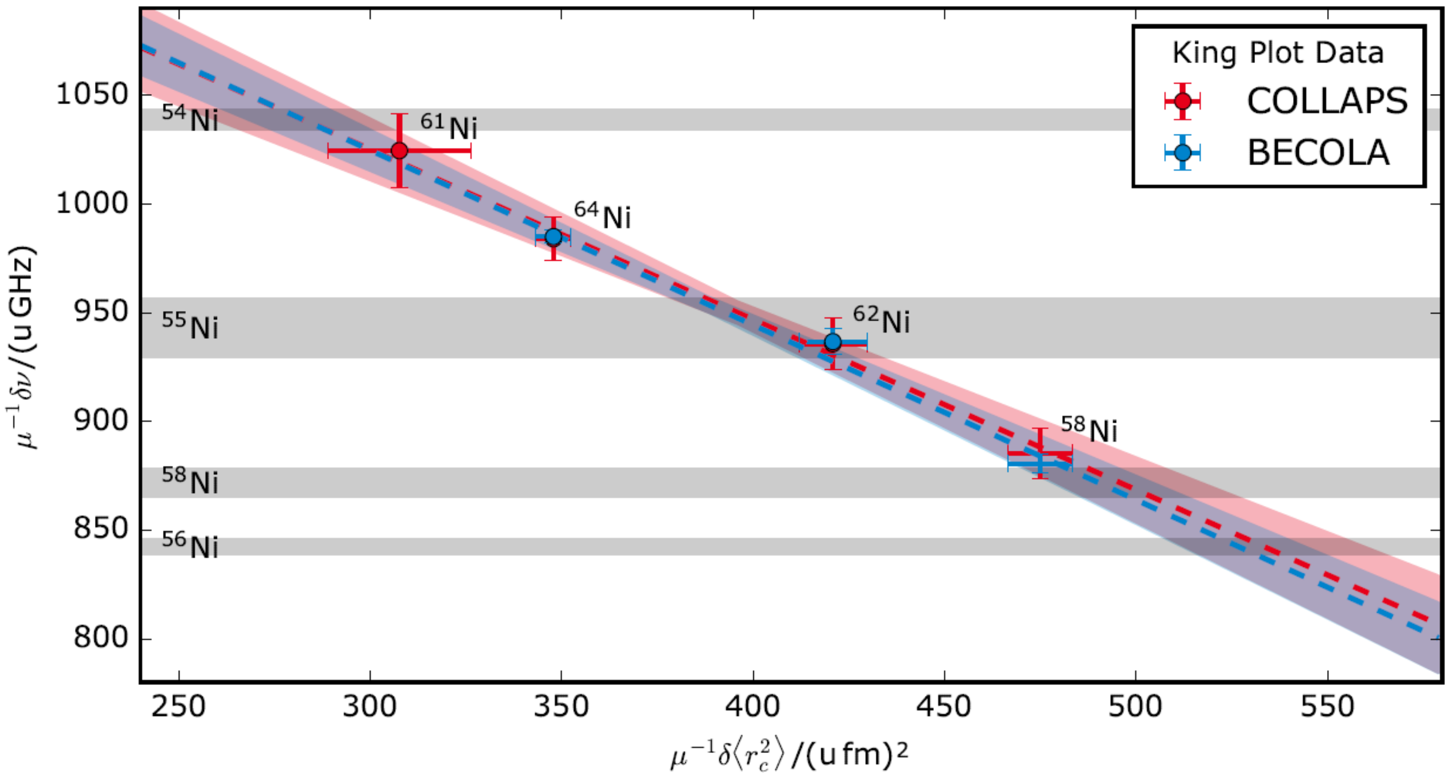
Nörtershäuser and Ch. Geppert, Lecture Notes in Physics 879 (2014)

$$\delta\nu_i{}^{A,A'} = \nu_i{}^{A'} - \nu_i{}^{A} = F_i\,\delta\langle r^2\rangle^{A,A'} + M_i\,\frac{m'_A - m_A}{m'_A m_A}$$

M_i and F_i from theory or from experiment if ≥ 3 stable isotopes (King plot)

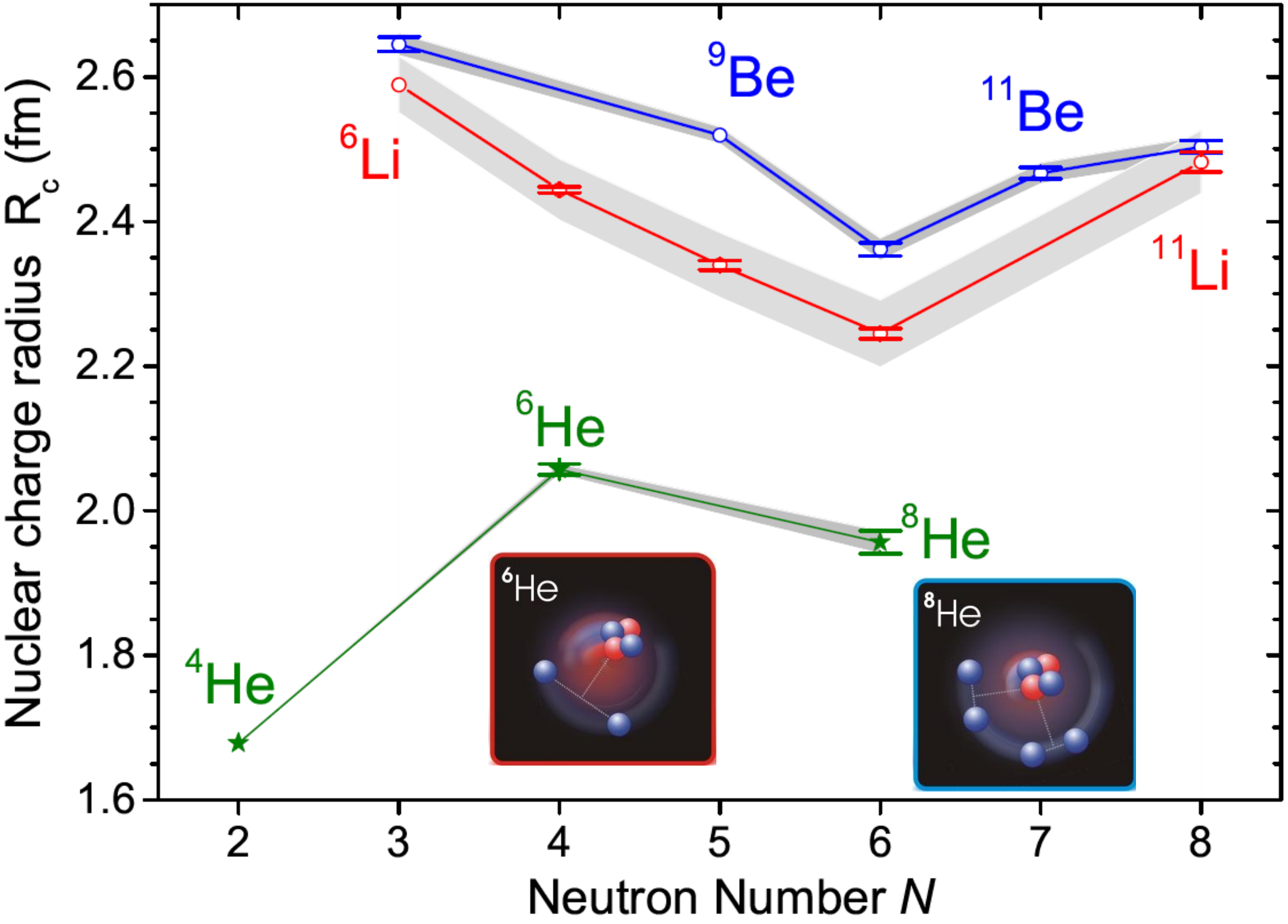
NUCLEAR CHARGE RADII





$$\delta\nu_i{}^{A,A'} = \nu_i{}^{A'} - \nu_i{}^{A} = F_i\,\delta\langle r^2\rangle^{A,A'} + M_i\,\frac{m'_A - m_A}{m'_A m_A}$$

NUCLEAR CHARGE RADII
LIGHT NUCLEI



$R_c(^9\mathrm{Be}) = 2.519\,(12)\ \mathrm{fm}$

Jansen *et al.*, Nucl. Phys. A 188, 337 (1972)

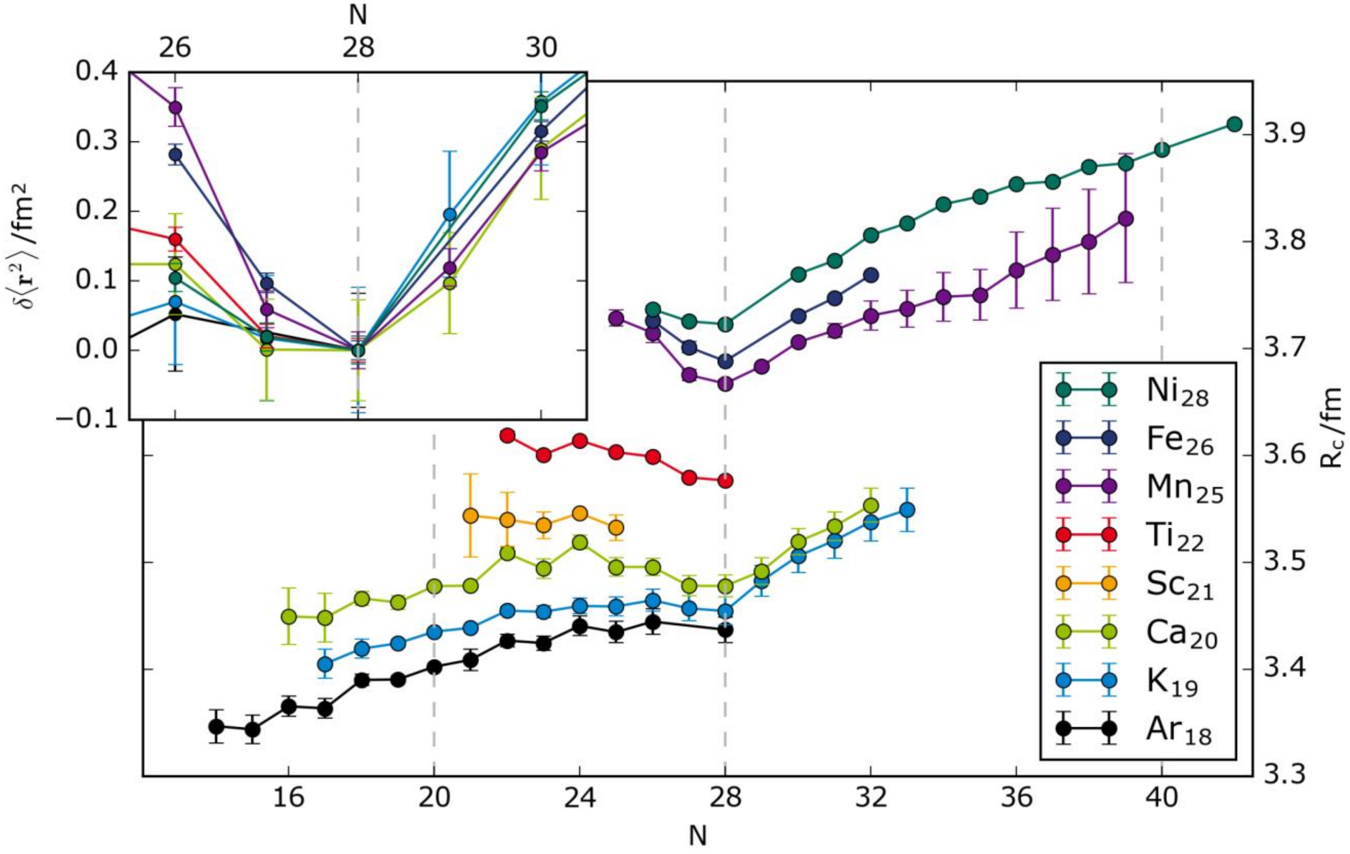
$R_c(^6\mathrm{Li}) = 2.589\,(39)\ \mathrm{fm}$

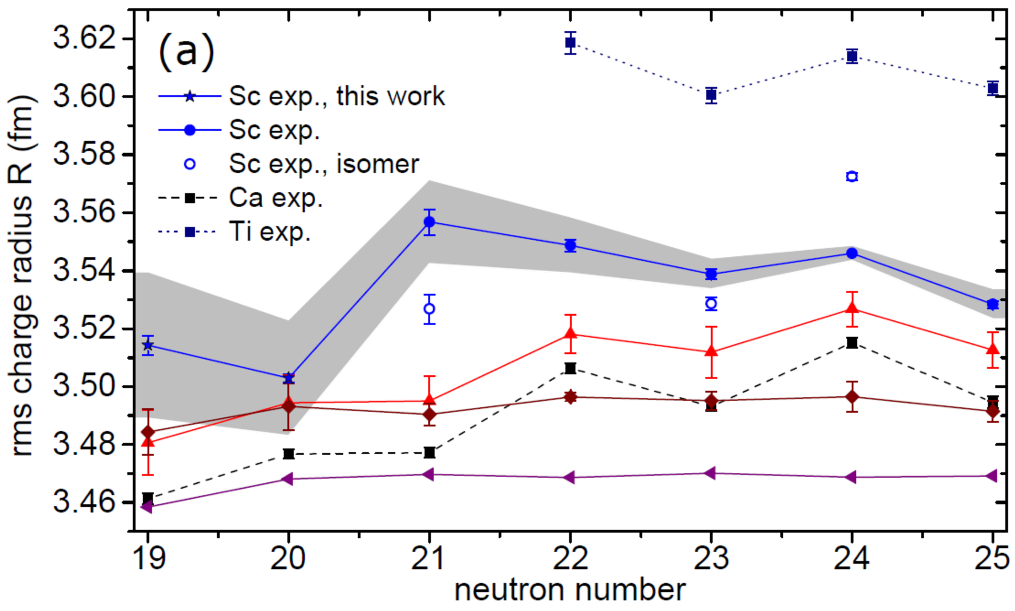
Nörtershäuser *et al.*, Phys. Rev. C 84, 024307 (2011)

$\mathbf{r}_\alpha = \mathbf{1.678\,24(83)}\ \mathrm{fm}$

Krauth *et al.*, Nature 589, 527(2021)
from $\mu\mathrm{He}^+$ (one-electron system)
“all- optical charge radius”

NUCLEAR CHARGE RADII
THE CALCIUM – NICKEL REGION





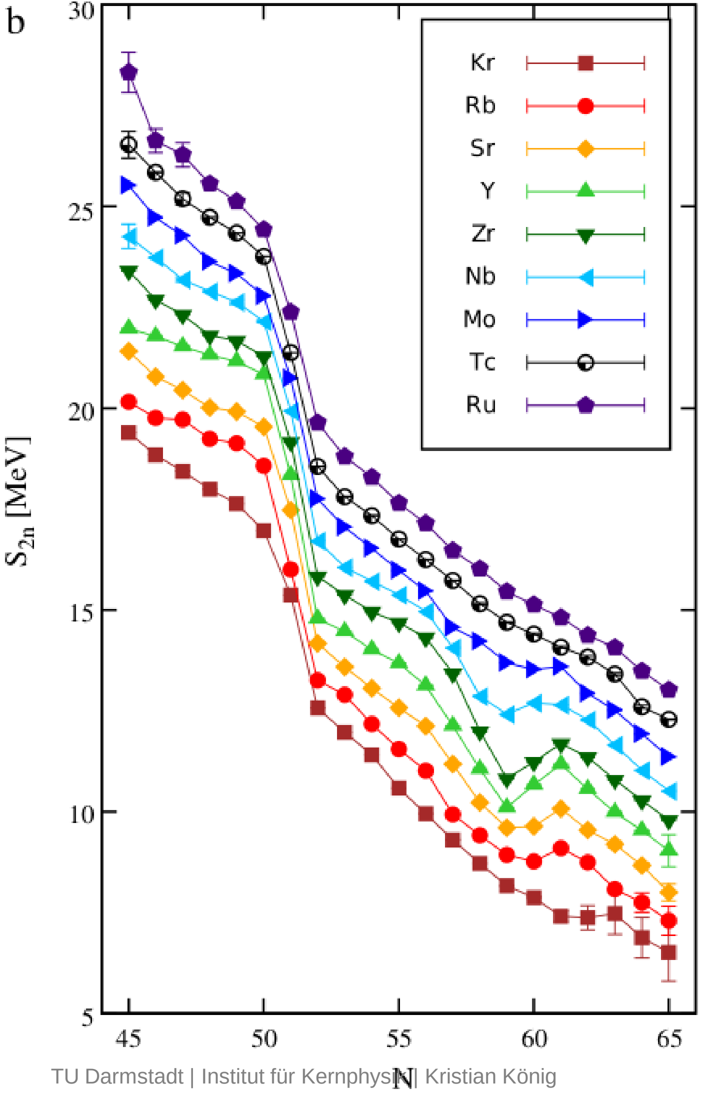
König et al., PRL in print

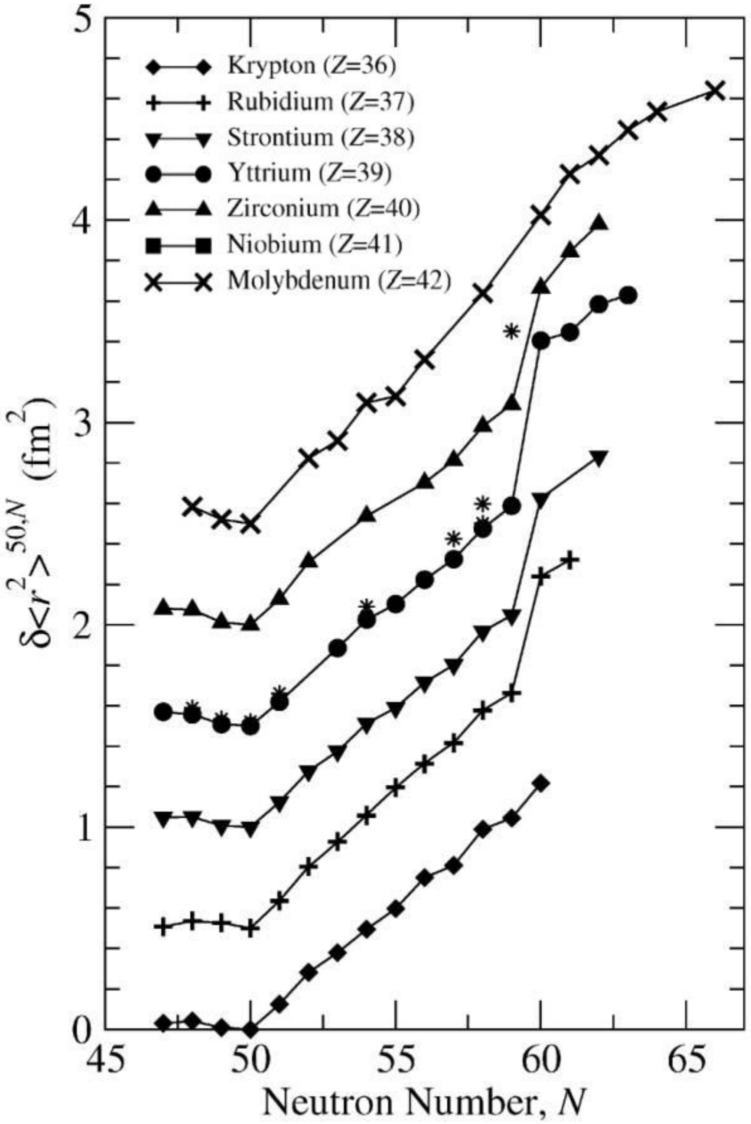
NUCLEAR CHARGE RADII
THE STRONTIUM REGION

- Evolution of nuclear charge radii along a chain of isotopes
- Correlation with S_{2n}- two-neutron separation energy

- Shows structural effects
- Onset of deformation at N=60
- Is this effect still visible for Mo, Tc, Ru, Rh?
- Observed „change in slope“ for N>60

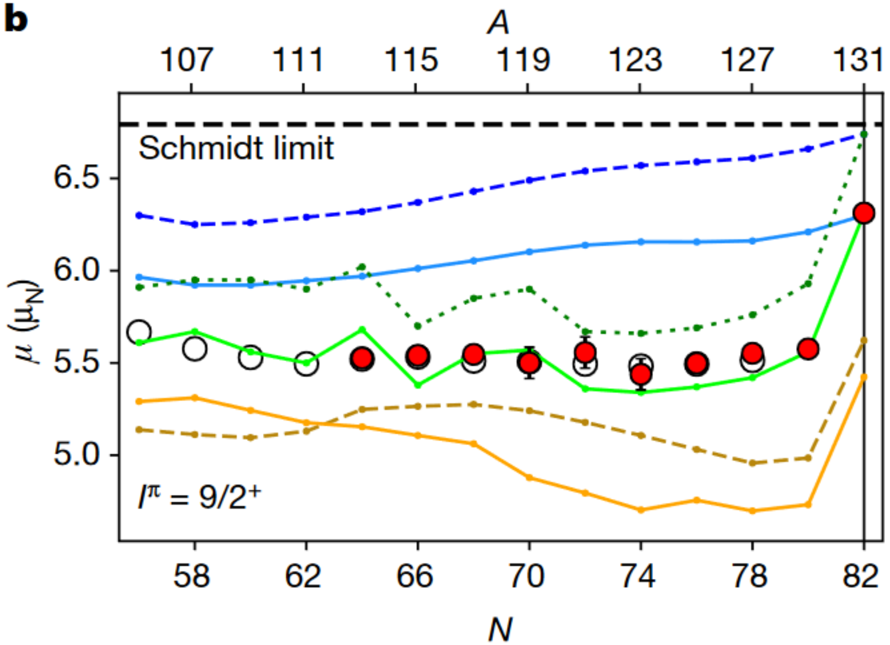
P. Campbell et al., Prog. Part. Nucl. Phys. 86 (2016) 127–180

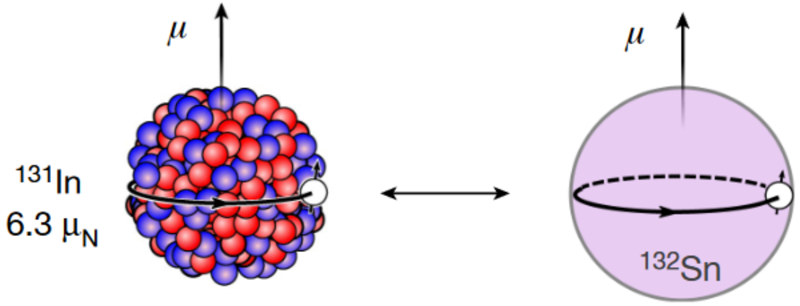




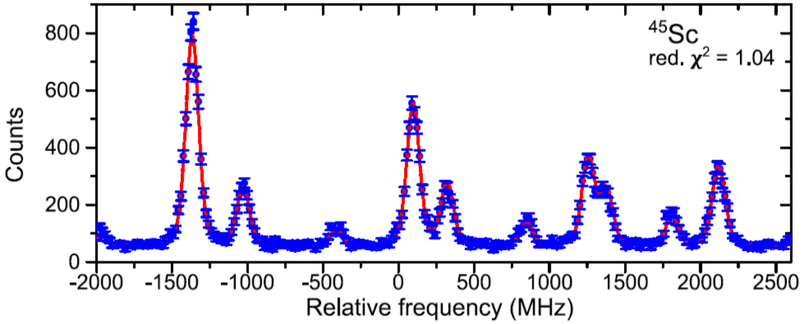
Charlwood, F. et al., Phys. Lett. B 674 (1), 23–27, 2009

NUCLEAR MOMENTS IN INDIUM ISOTOPES





A. Vernon et al., Nature 607, 260 (2022)



$$\Delta E_{\mathrm{HFS}} = A \cdot \frac{C}{2} + B \cdot \frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(I-1)J(2J-1)}$$

$$C = F(F+1) - I(I+1) - J(J+1)$$

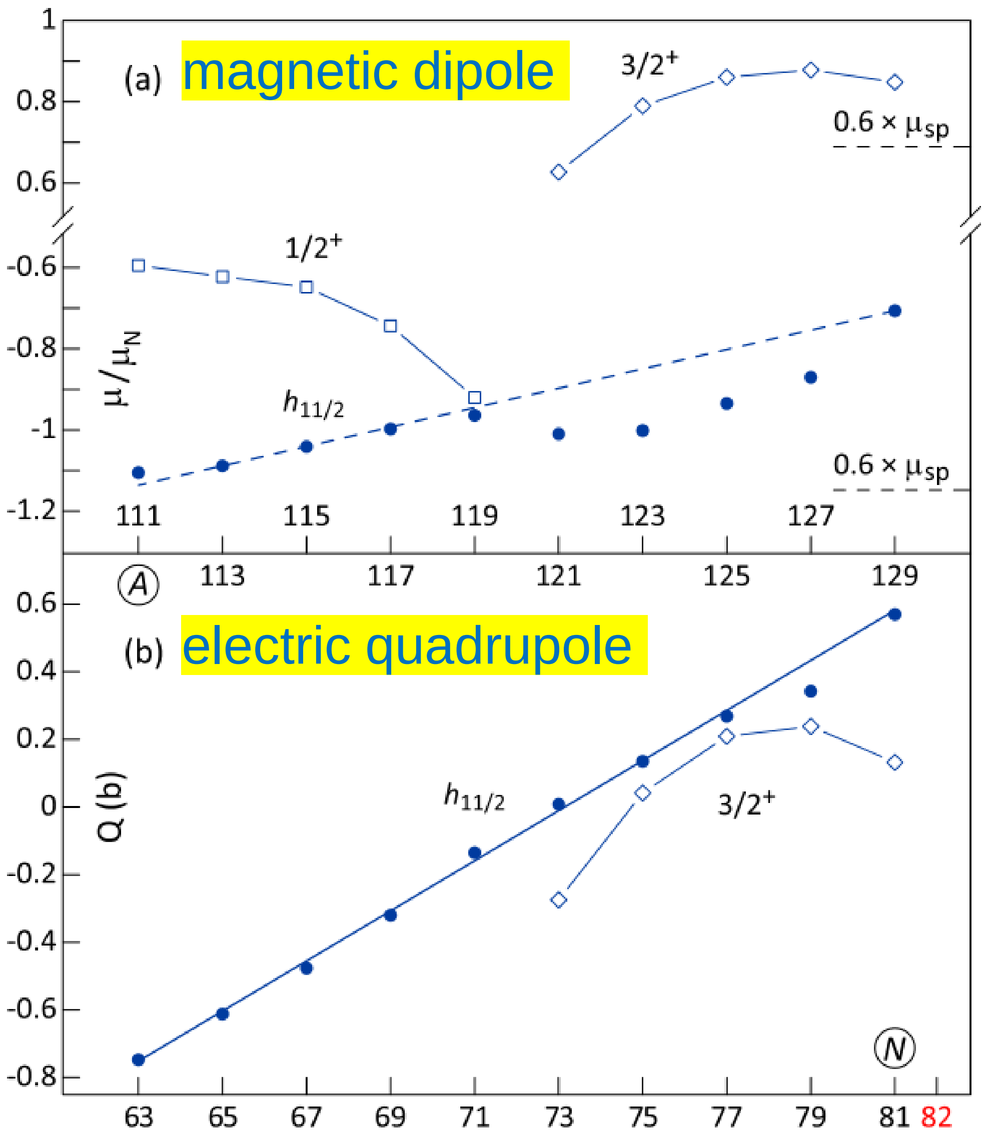
- Spin *I*, magnetic dipole moment *μ* and electric quadrupole moment *Q* can be deduced from hyperfine splitting

$$\mu_{\mathrm{meas}} = \mu_{\mathrm{ref}} \frac{A^{hf}_{\mathrm{meas}}}{A^{hf}_{\mathrm{ref}}} \frac{I_{\mathrm{meas}}}{I_{\mathrm{ref}}}$$

- *μ* probes the single-particle nature of the valence nucleon

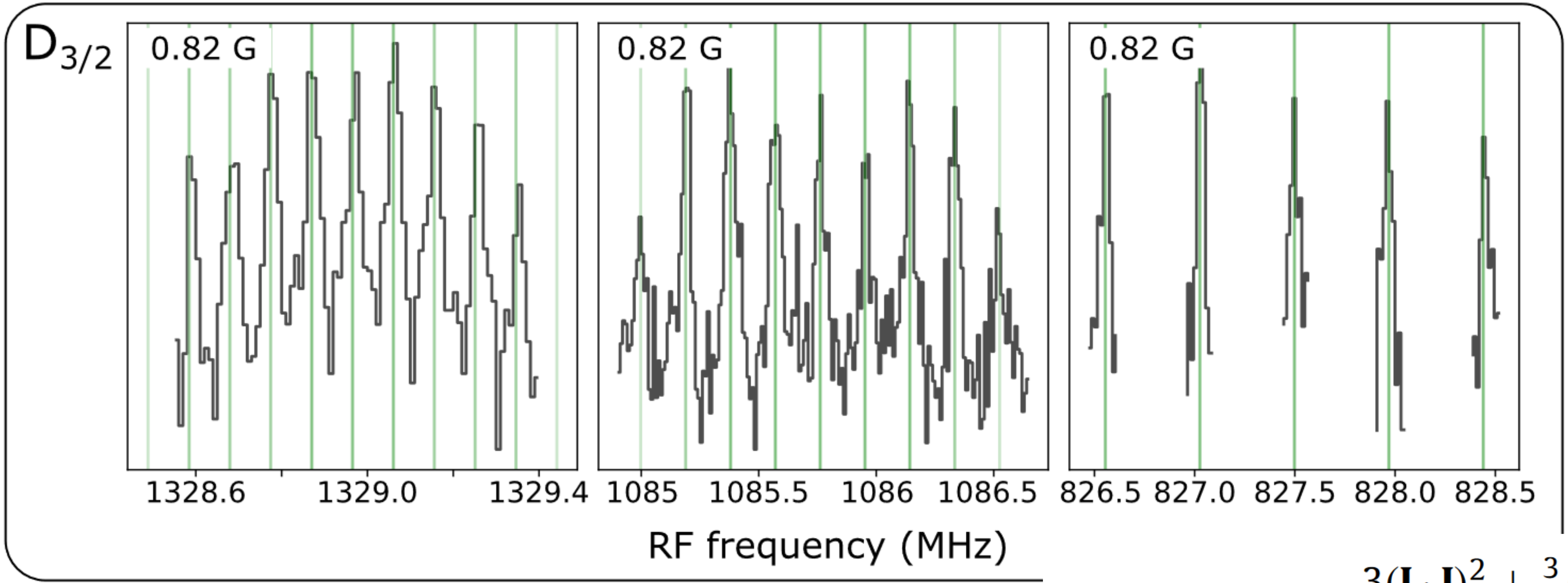
NUCLEAR MOMENTS IN CADMIUM ISOTOPES

- Linear trend in magnetic dipole and electrical quadrupole moments for cadmium I=11/2 states
- Large effective charge of the one neutron (Core polarizability for the Z-2 magic nucleus
- Trend continues across 10 isotopes, more than the volume of the occupied h11/2 shell
- Paired neutrons occupy neighbouring states, valence neutron is always in h11/2
- Follows remarkably simple trend in a complex nuclei
- For Sn (magic) the QP moment is not linear – the core is not as polarizable



Yordanov *et al.*, Phys. Rev. Lett 110, 192501 (2013)

OCTUPOLE MOMENTS



R. de Groote, Physics Letters B 827 (2022) 136930

$$\mathcal{H}_{\text{hyp}} = A\mathbf{I}\cdot\mathbf{J} + B\frac{3(\mathbf{I}\cdot\mathbf{J})^2 + \frac{3}{2}(\mathbf{I}\cdot\mathbf{J}) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$
$$+C\left[\frac{10(\mathbf{I}\cdot\mathbf{J})^3 + 20(\mathbf{I}\cdot\mathbf{J})^2}{I(I-1)(2I-1)J(J-1)(2J-1)}\right.$$
$$\left. + \frac{2\mathbf{I}\cdot\mathbf{J}\{I(I+1)+J(J+1)-3N+3\} - 5N}{I(I-1)(2I-1)J(J-1)(2J-1)}\right],$$

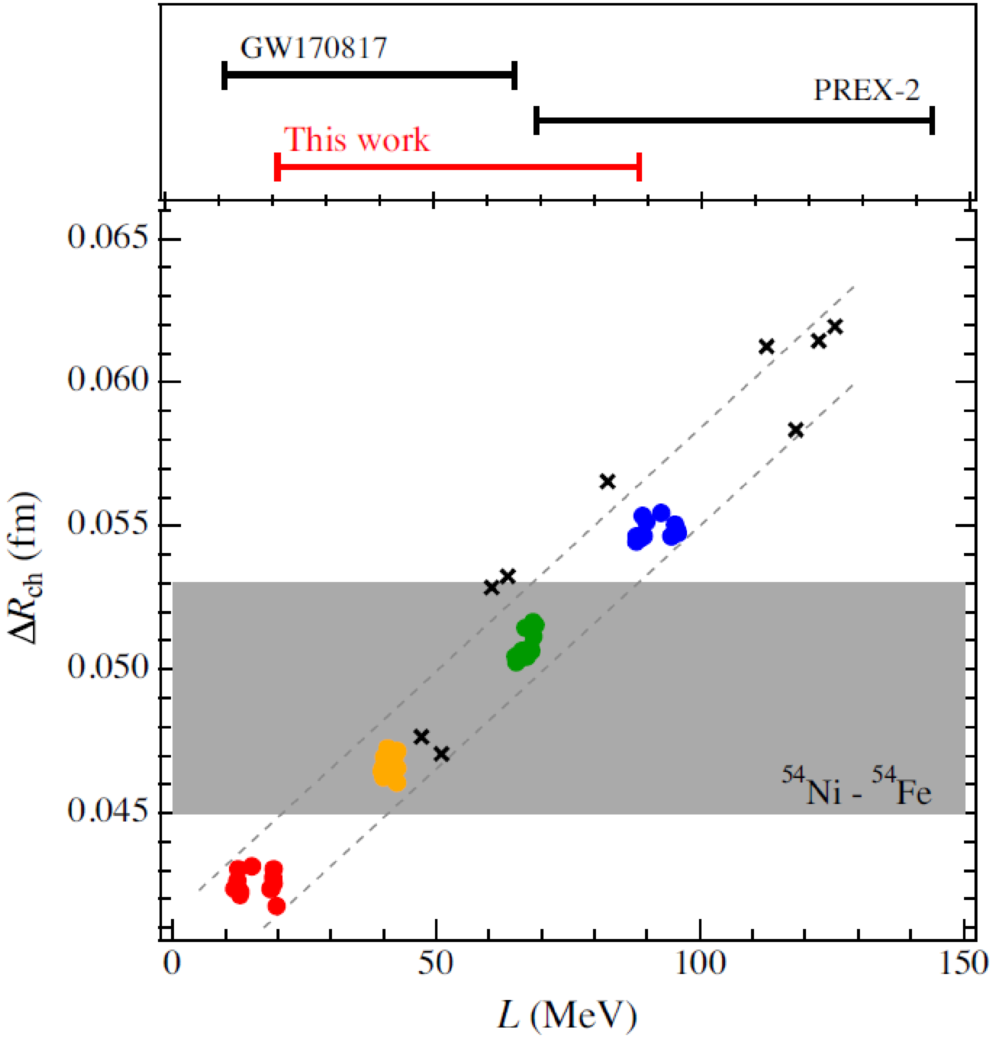
IMPLICATIONS FOR NUCLEAR EOS

Constrain the slope of the symmetry energy at nuclear saturation density (*L*)
Important to predict the properties of both super-heavy nuclei and neutron stars

$$L = 3\rho_0 \left[\frac{\partial E_{sym}(\rho)}{\partial \rho}\right]_{\rho=\rho_0}$$

$$R_{skin}(N,Z) = R_p(N,Z) - R_p(Z,N) \equiv \Delta R_{mirr}(Z,N)$$

$\Rightarrow$ Favoring a soft neutron matter EOS
$\Rightarrow$ Good agreement with new CREX and most theoretical results



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

INPUT FOR CKM MATRIX

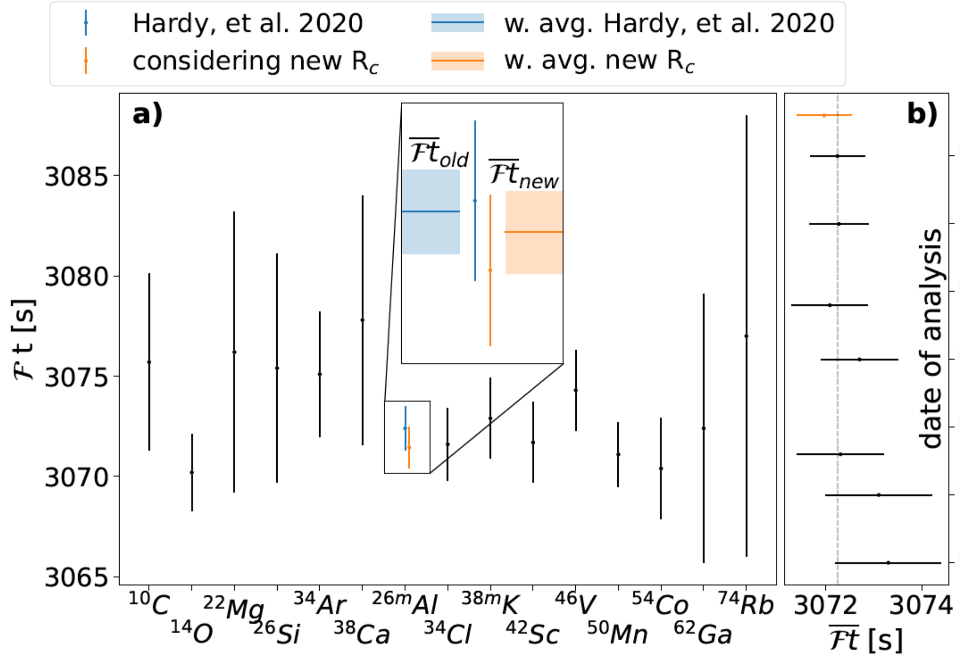
CKM matrix differs ≈ 2 σ from unitarity

$$V_{ud} = G_V / G_F$$

At present, superallowed 0+ → 0+ nuclear β decays remain the most precise way to access V_{ud}

$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{NS}-\underbrace{\delta_C}) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

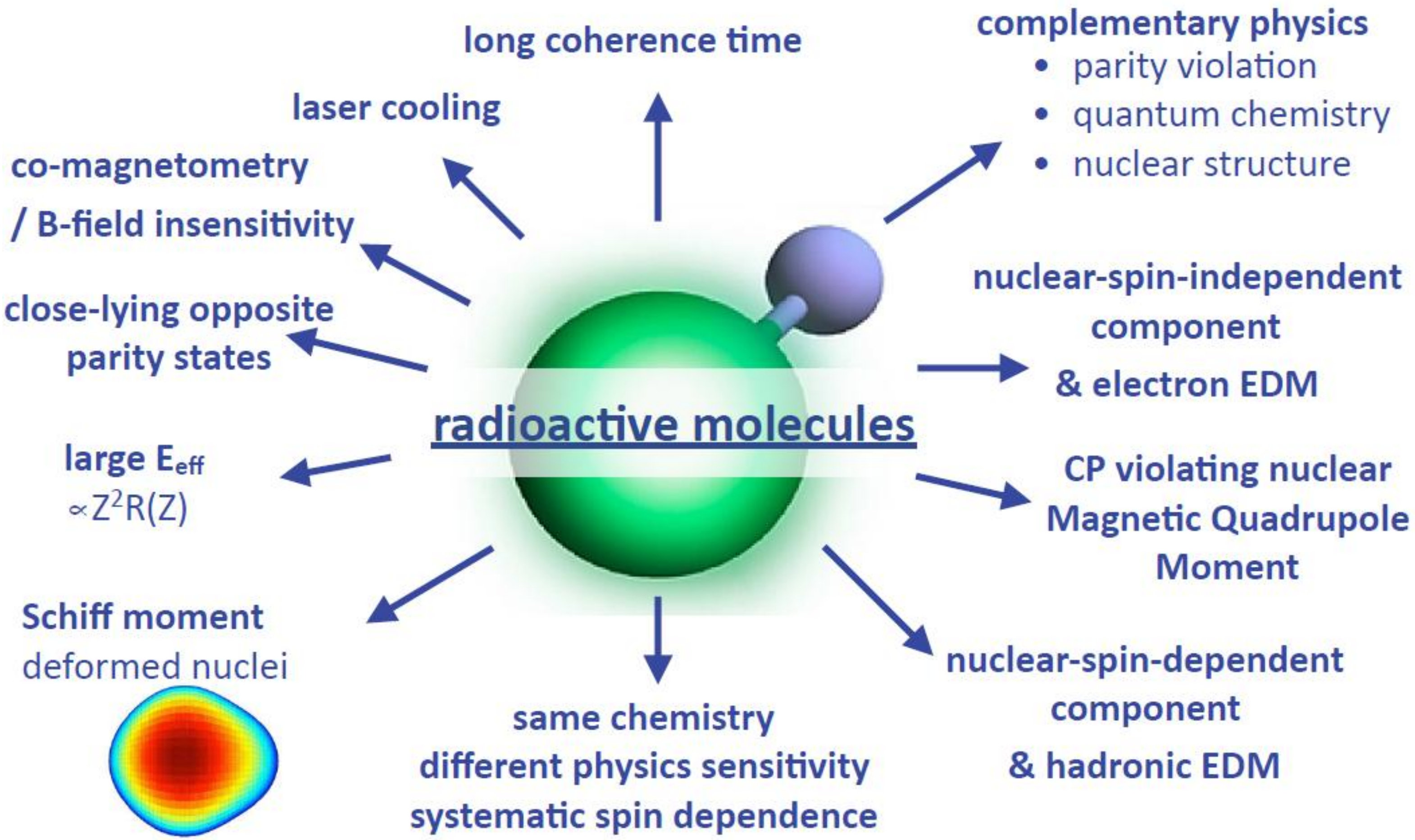
Charge radius essential input parameter for isospin-symmetry breaking (ISB) corrections



≈ 1/10 σ closer towards unitarity

^{74}Rb: Mane et al., PRL 107, 212502 (2011)
^{26m}Al: Plattner et al., submitted to PRL (2023)

SPECTROSCOPY OF MOLECULES



radioactive molecules

long coherence time

complementary physics
- parity violation
- quantum chemistry
- nuclear structure

laser cooling

co-magnetometry / B-field insensitivity

close-lying opposite parity states

nuclear-spin-independent component & electron EDM

large E_{eff} $\propto Z^2R(Z)$

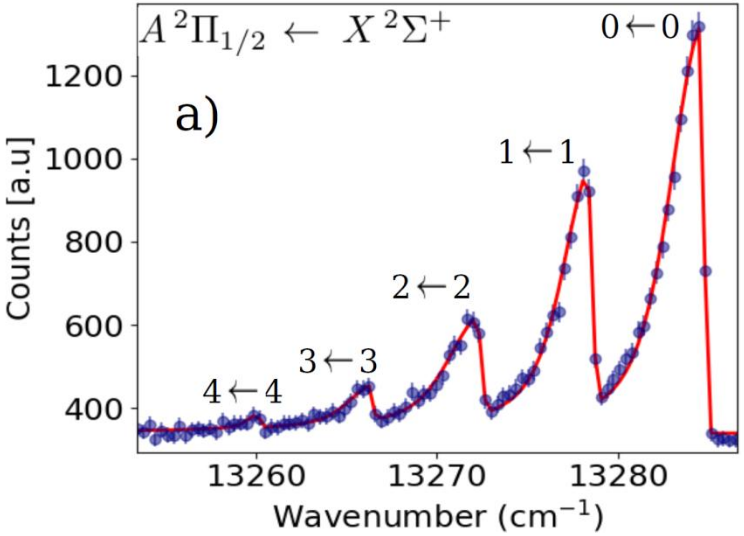
CP violating nuclear Magnetic Quadrupole Moment

Schiff moment deformed nuclei

same chemistry different physics sensitivity systematic spin dependence

nuclear-spin-dependent component & hadronic EDM

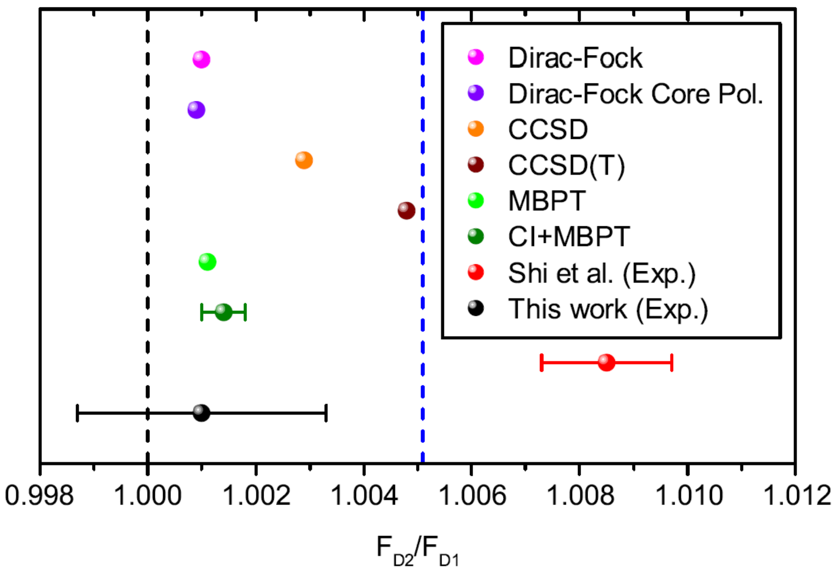
RaF @ CRIS

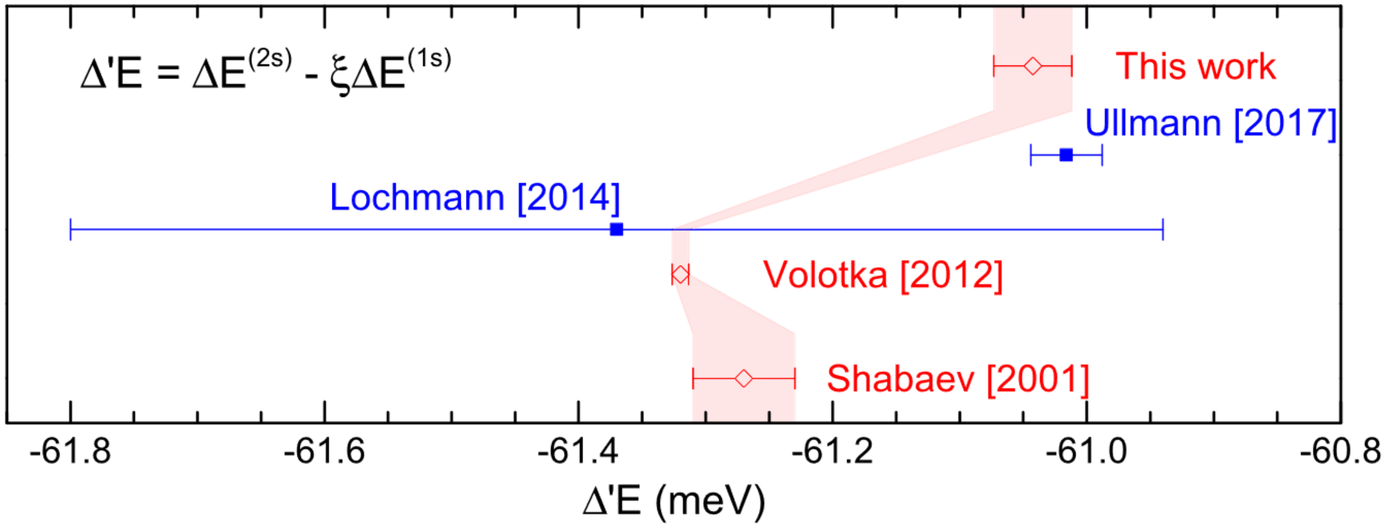


R. F. Garcia Ruiz et al., Nature 581, 396 (2020)

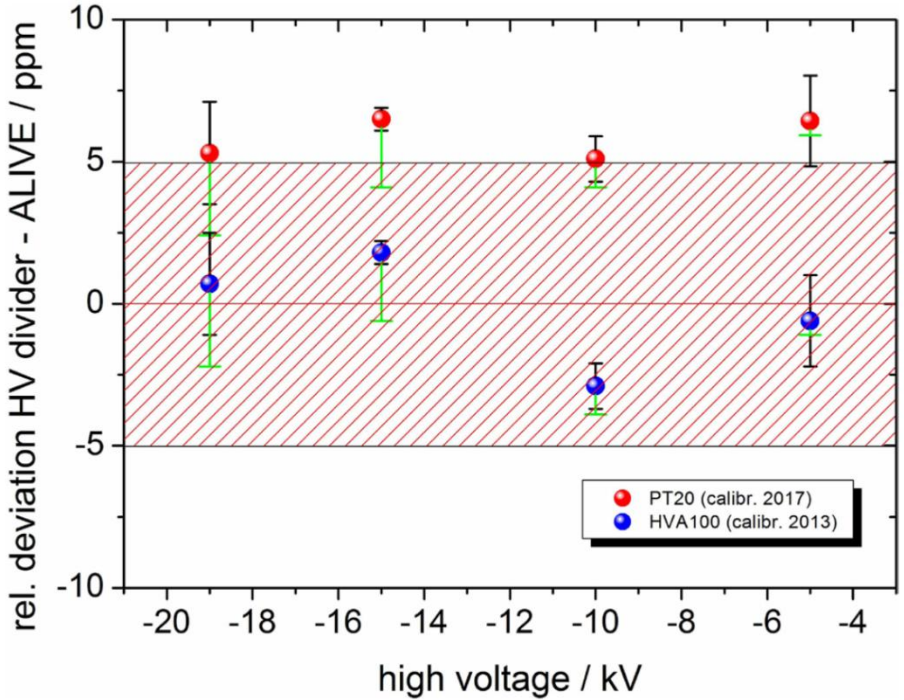
ATOMIC PHYSICS & HV METROLOGY

TECHNISCHE
UNIVERSITÄT
DT

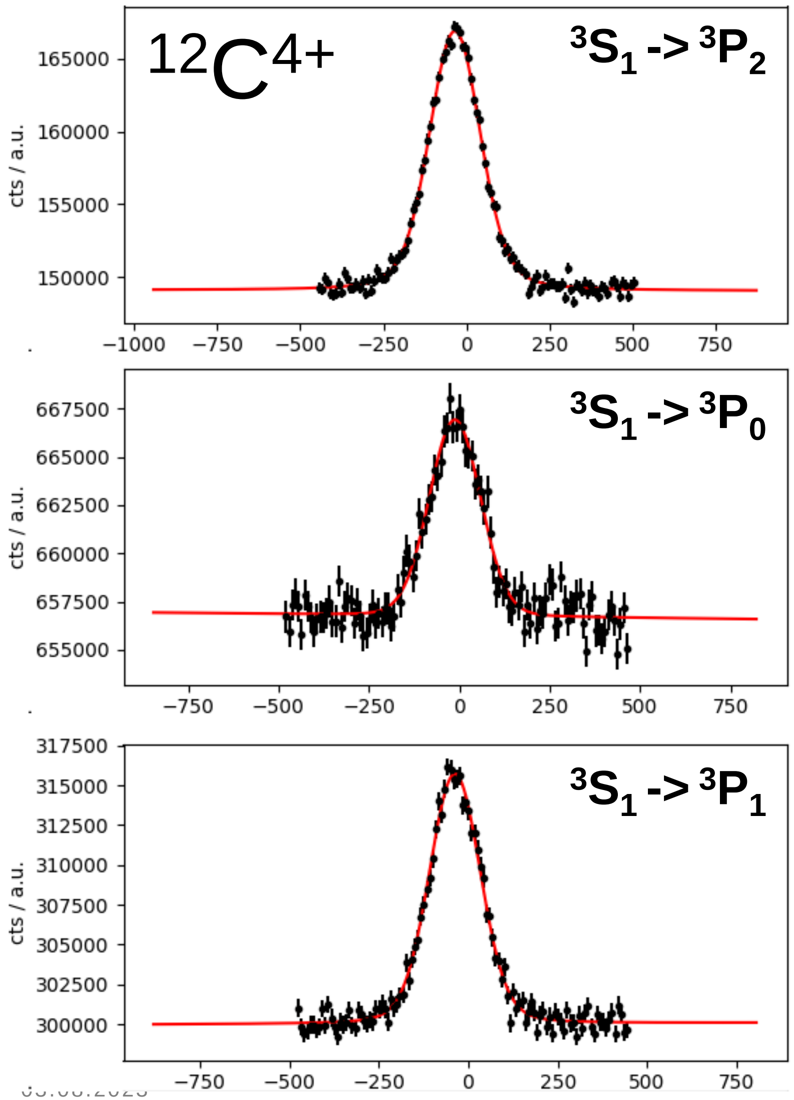


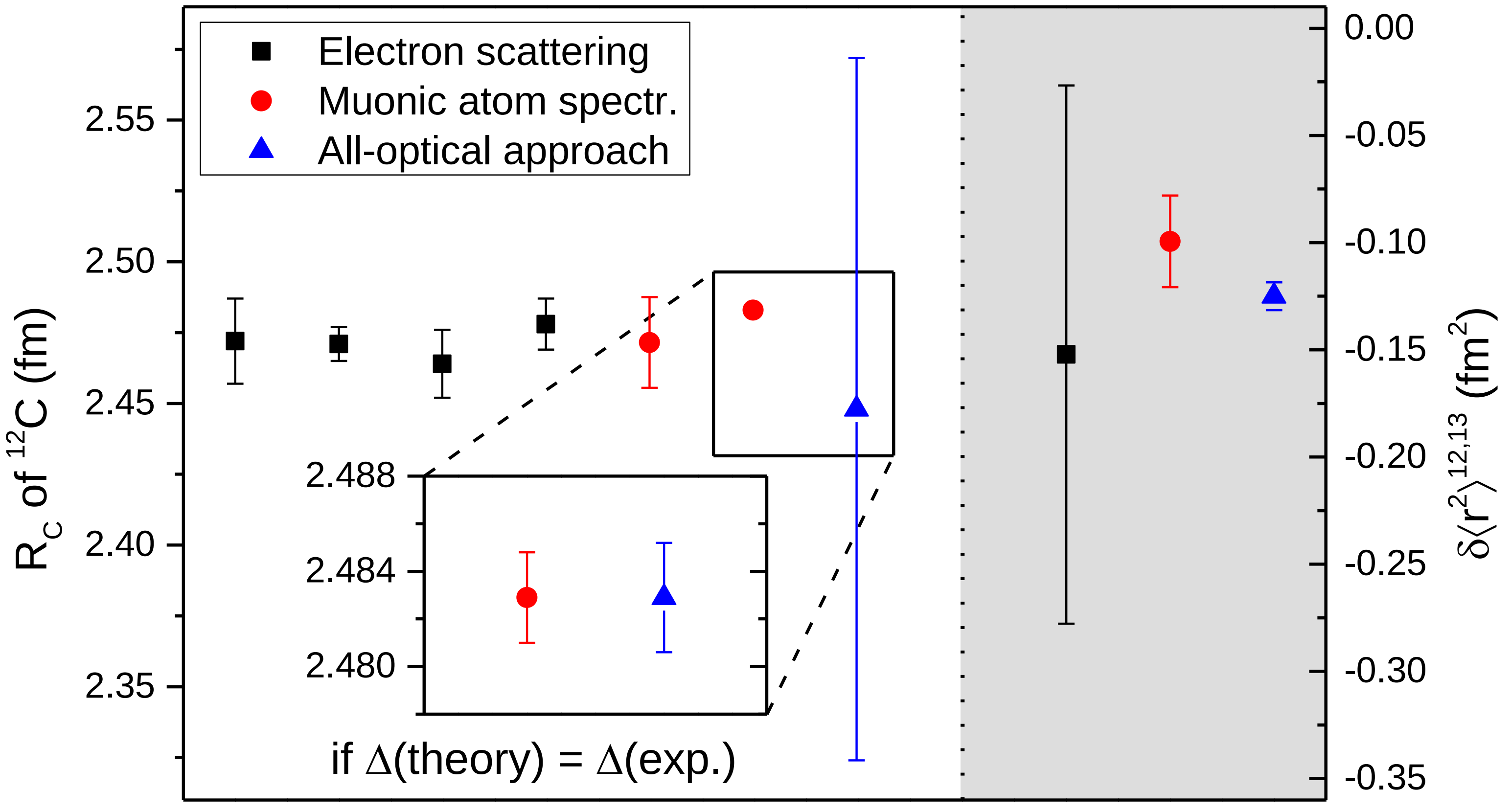


P. Müller et al., Phys. Rev. Research 2, 043351 (2020)
L. Skripnikov et al., Phys. Rev. Lett. 120, 093001 (2018)
J. Krämer et al 2018 Metrologia 55 268



HIGHLY CHARGED IONS FROM EBIS





P. Imgram et al., submitted to PRL
P. Müller et al., in preparation

THANK YOU FOR YOUR ATTENTION

https://www.triumf.ca/laser-spectroscopy