TRIUMF UNIVERSITY OF TORONTO

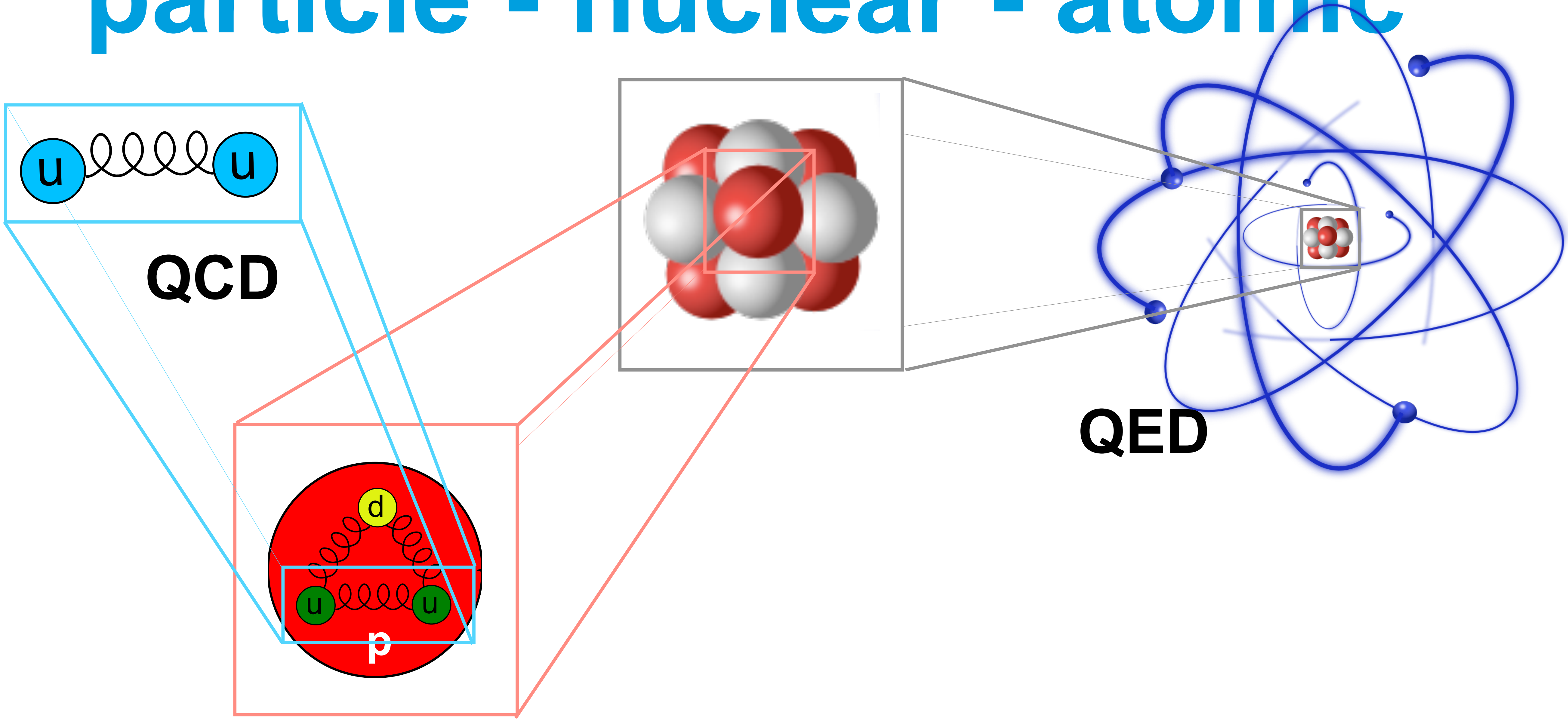
Collinear Laser Spectroscopy for the Investigation of Short-lived Radionuclides

Stephan Malbrunot-Ettenauer
TRIUMF, University of Toronto

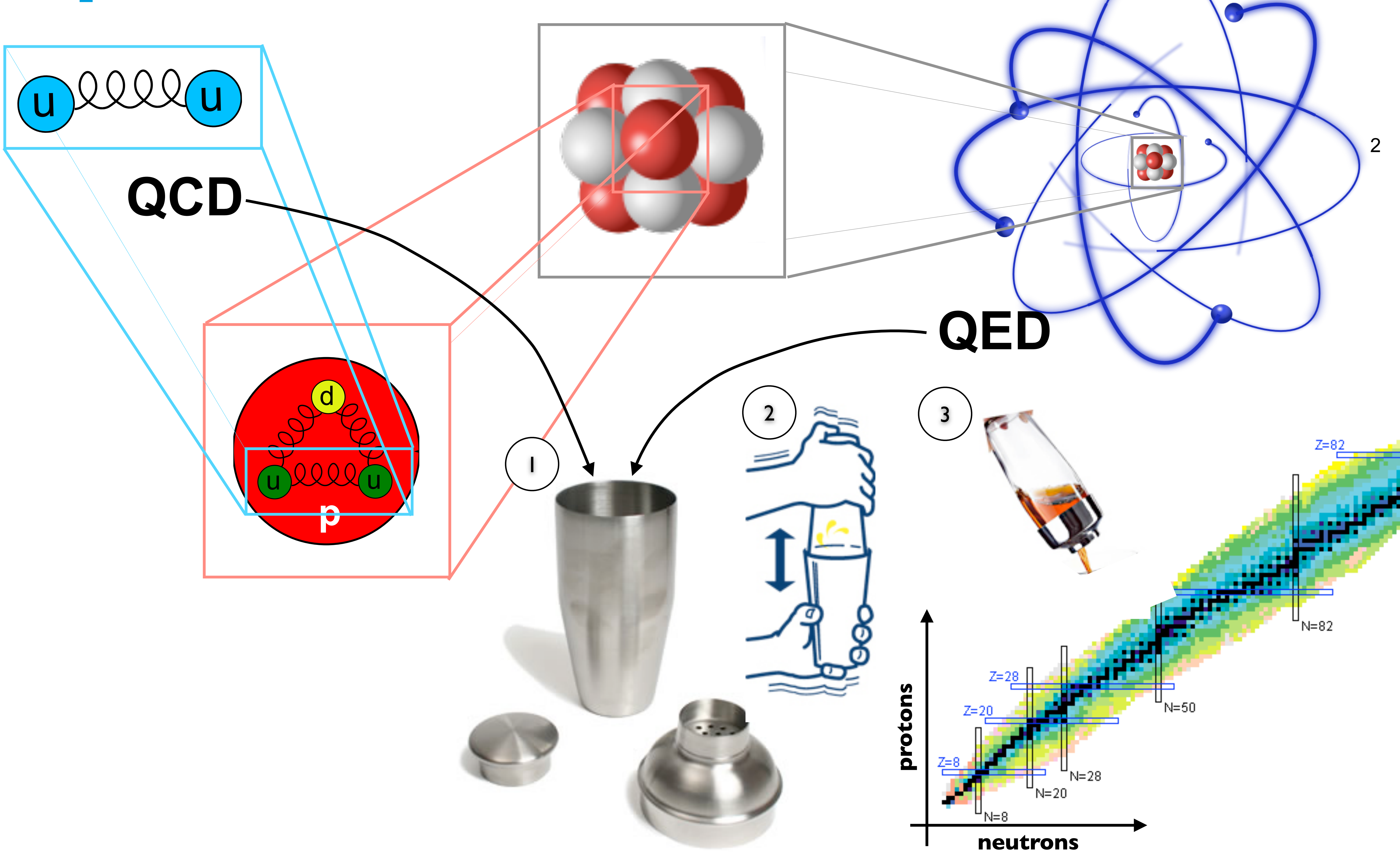
African Nuclear Physics Conference 2025

Discovery, accelerated

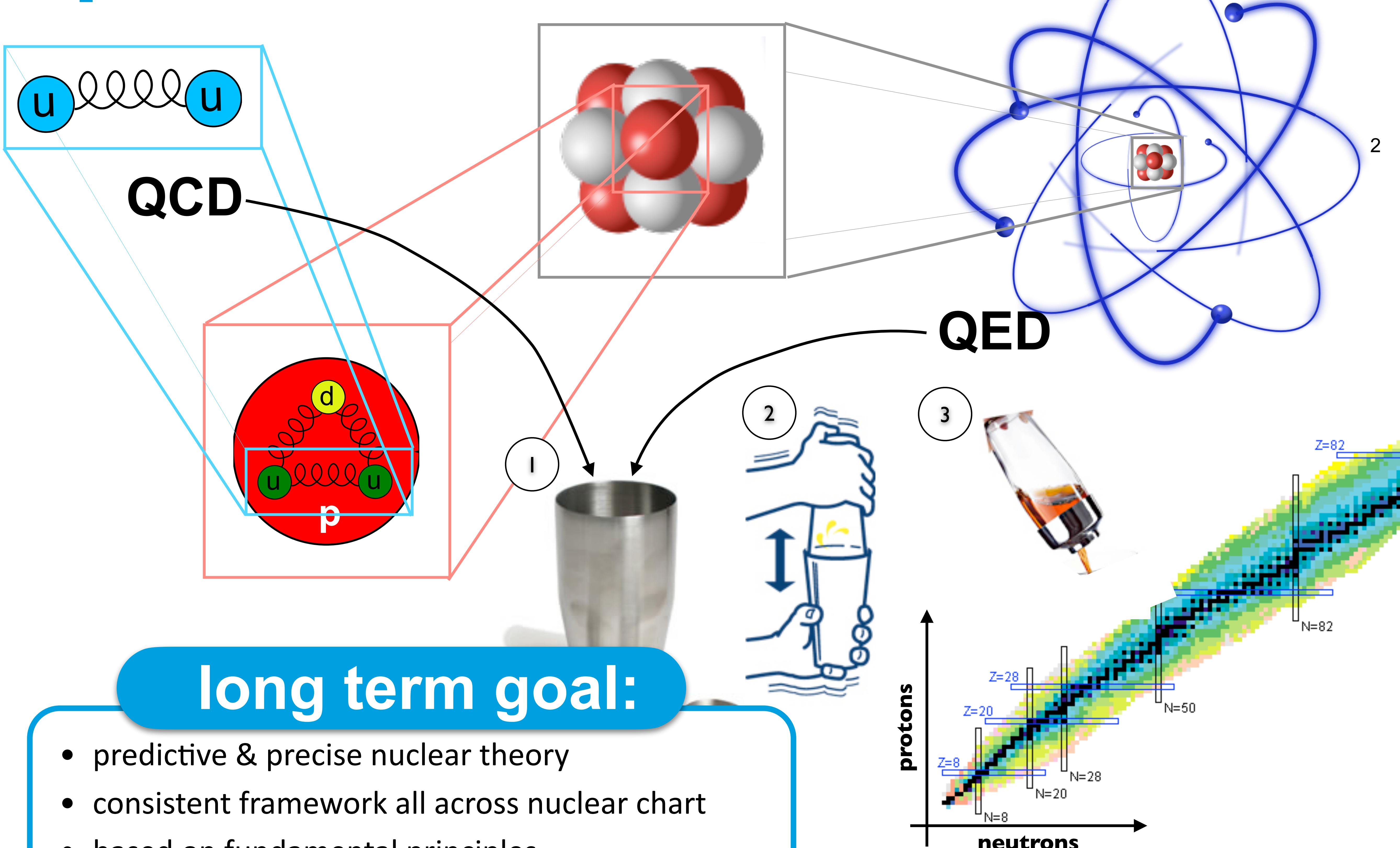
particle - nuclear - atomic



particle - nuclear - atomic



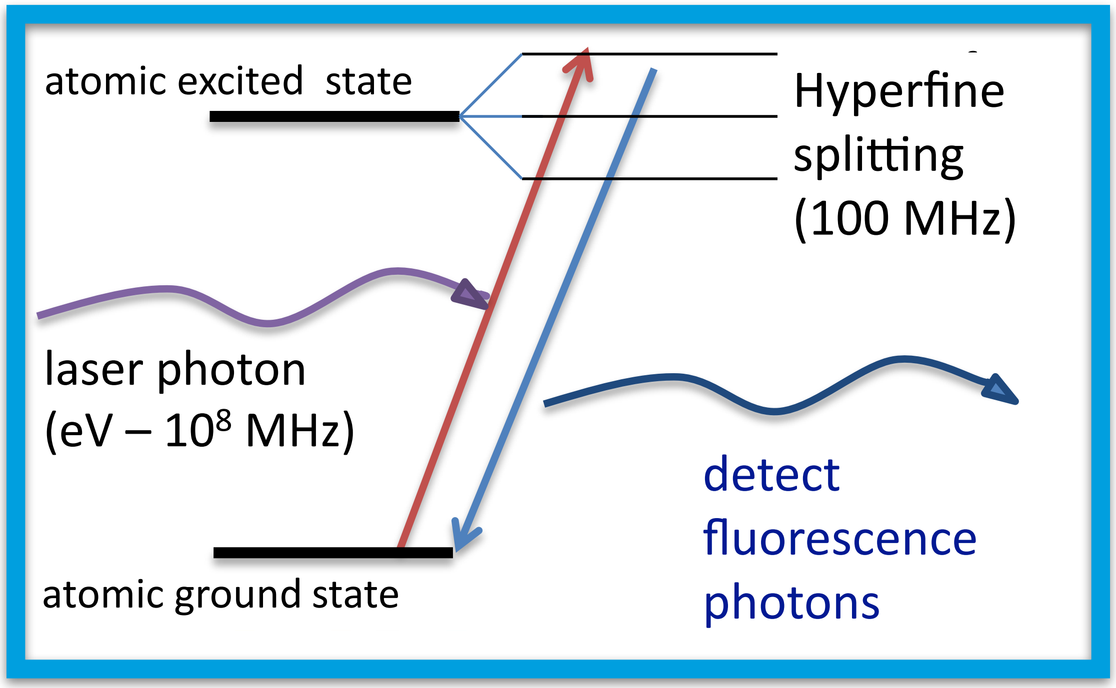
particle - nuclear - atomic



long term goal:

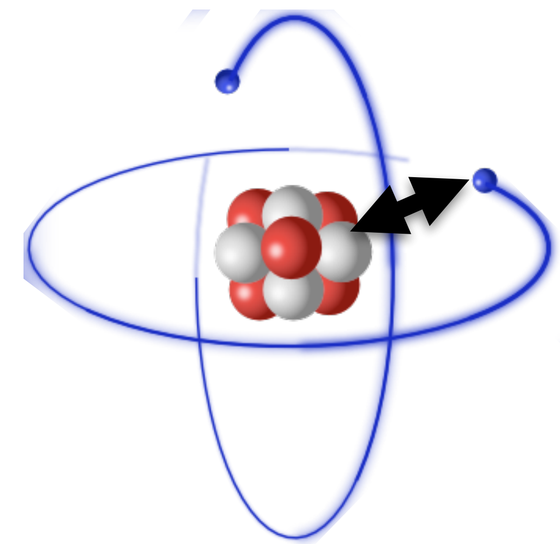
- predictive & precise nuclear theory
- consistent framework all across nuclear chart
- based on fundamental principles

laser spectroscopy of radionuclides

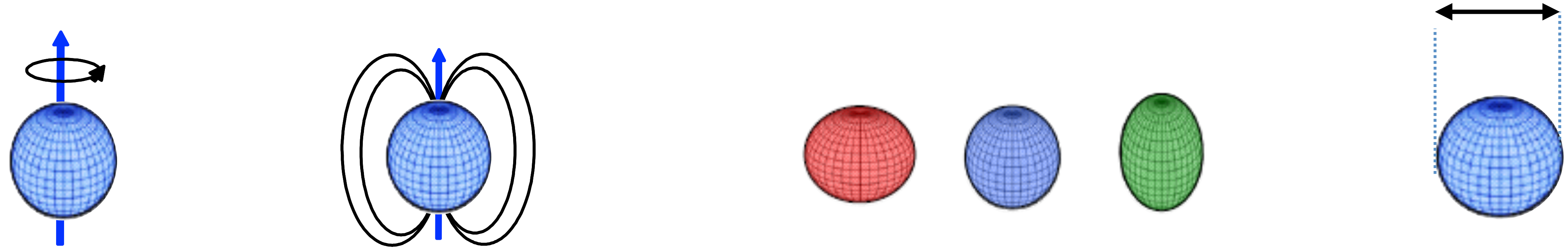


nucleus - electrons interaction

⇒ atomic hyperfine structure



spin I **magnetic moment μ** **quadrupole moment Q_s** **rms charge radius**



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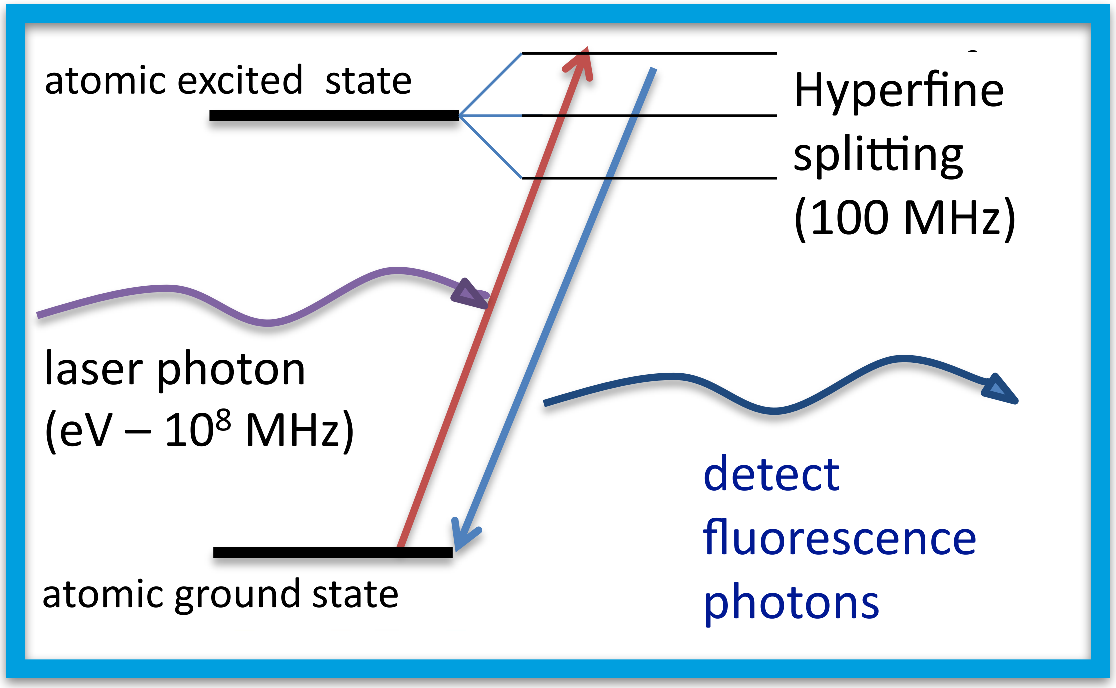

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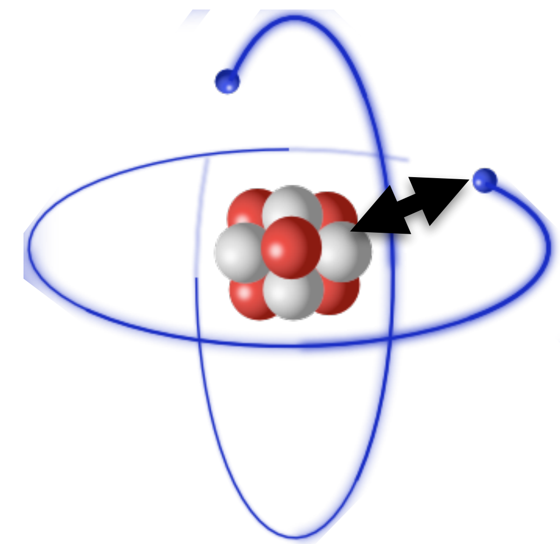
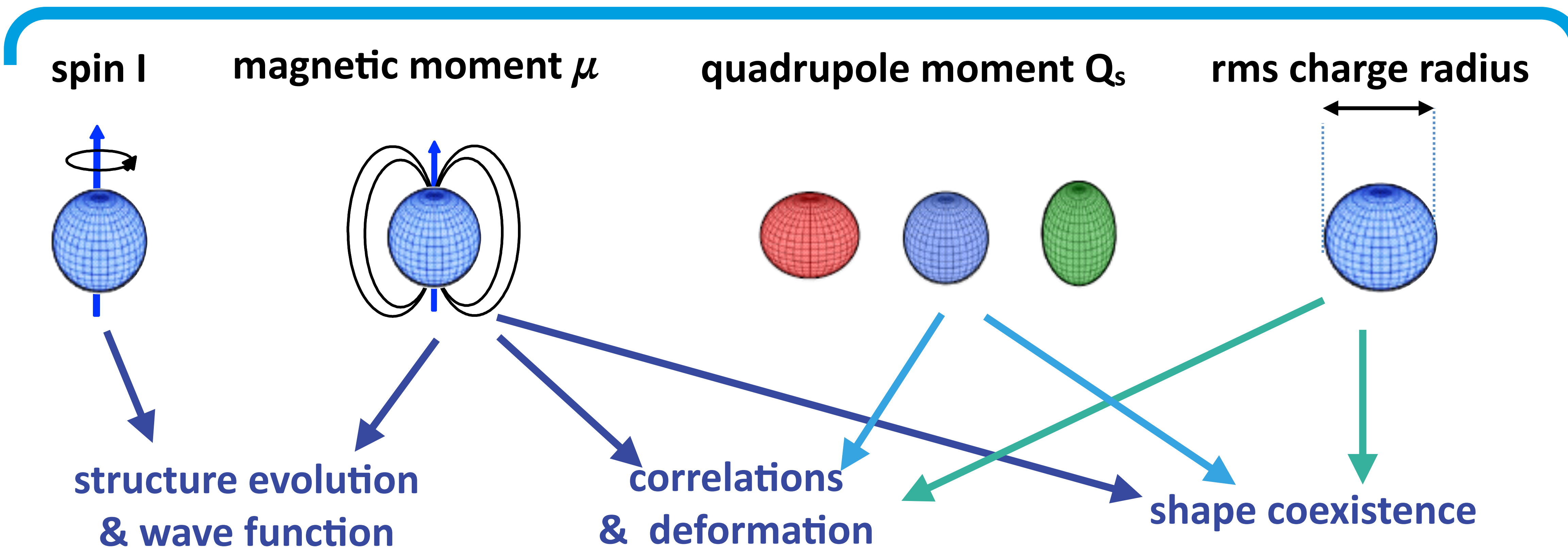
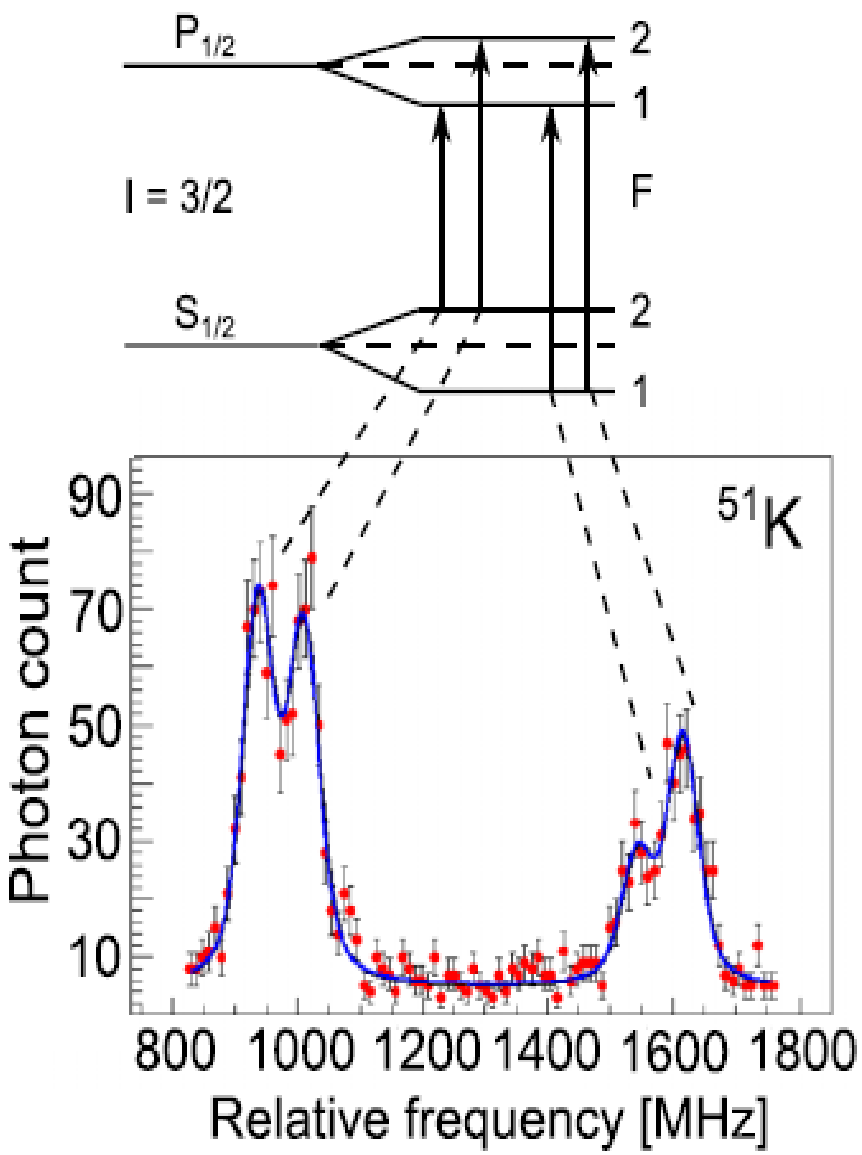


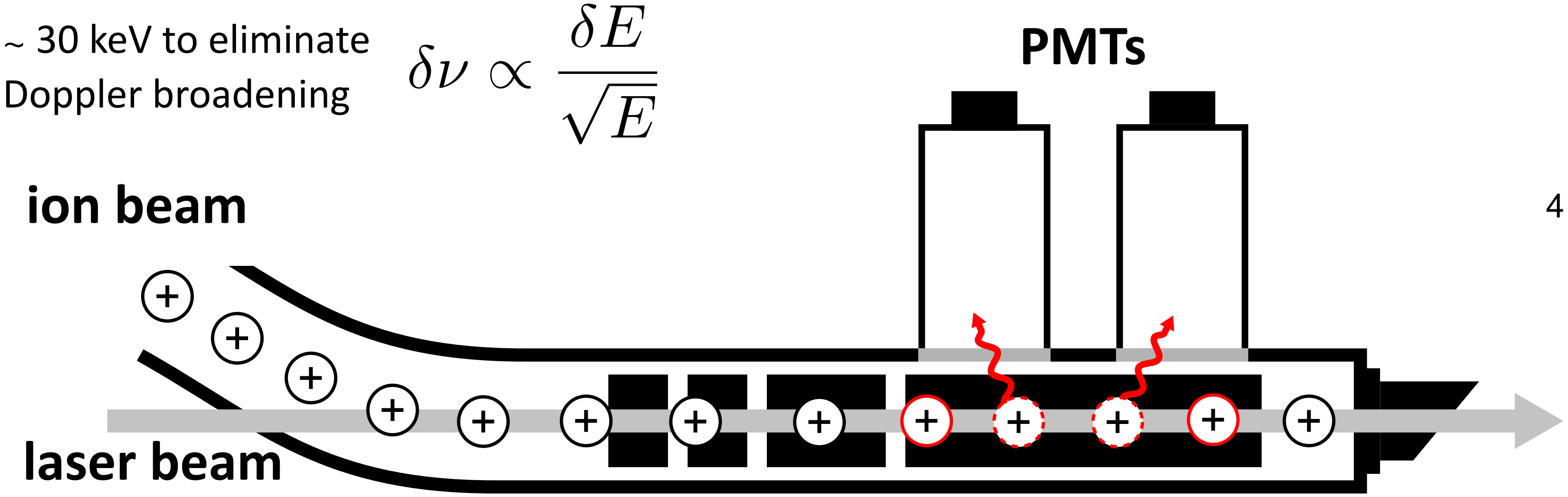


benchmark for modern nuclear structure theory

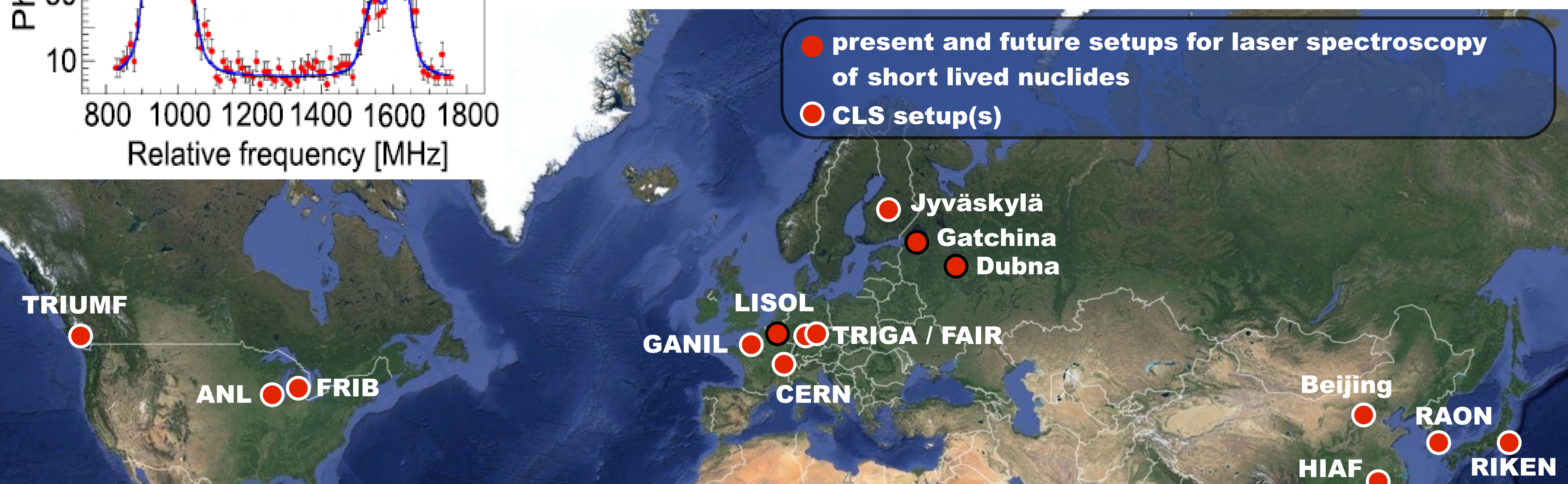
Collinear Laser Spectroscopy (CLS)



~ 30 keV to eliminate Doppler broadening $\delta\nu \propto \frac{\delta E}{\sqrt{E}}$

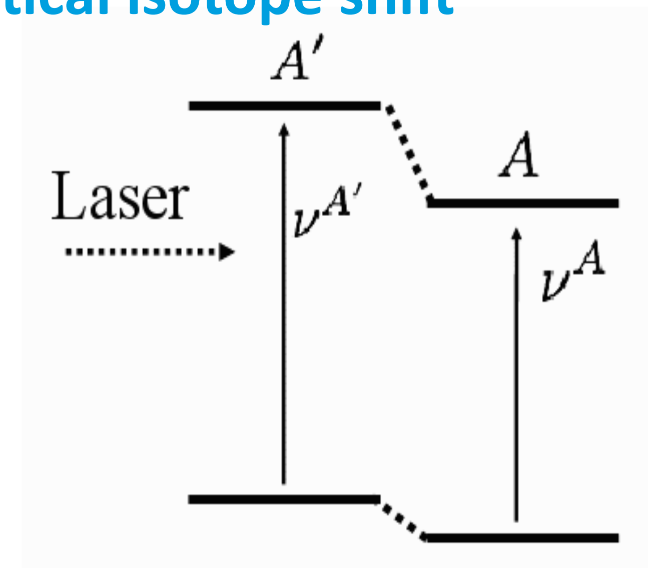


K. Blaum, et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
R. Neugart et al., J. Phys. G: Nucl. Part. Phys. 44, 064002 (2017)
X.F. Yang et al.., Prog. in Part. and Nucl. Phys. 129, 104005 (2023)



CLS & nuclear charge radii

optical isotope shift



difference in ms charge radii

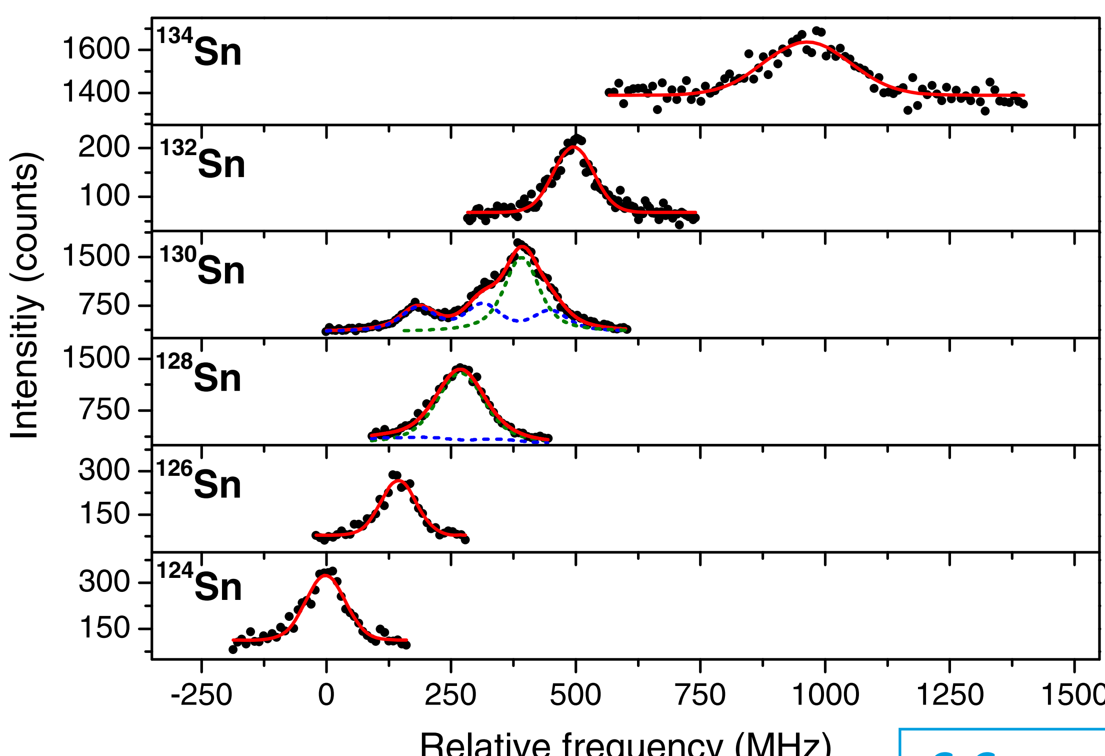
5

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

mass and field shift factors

- King-plot analysis of stable isotopes
- atomic theory

isotope shift $\delta\nu^{A,A'}$



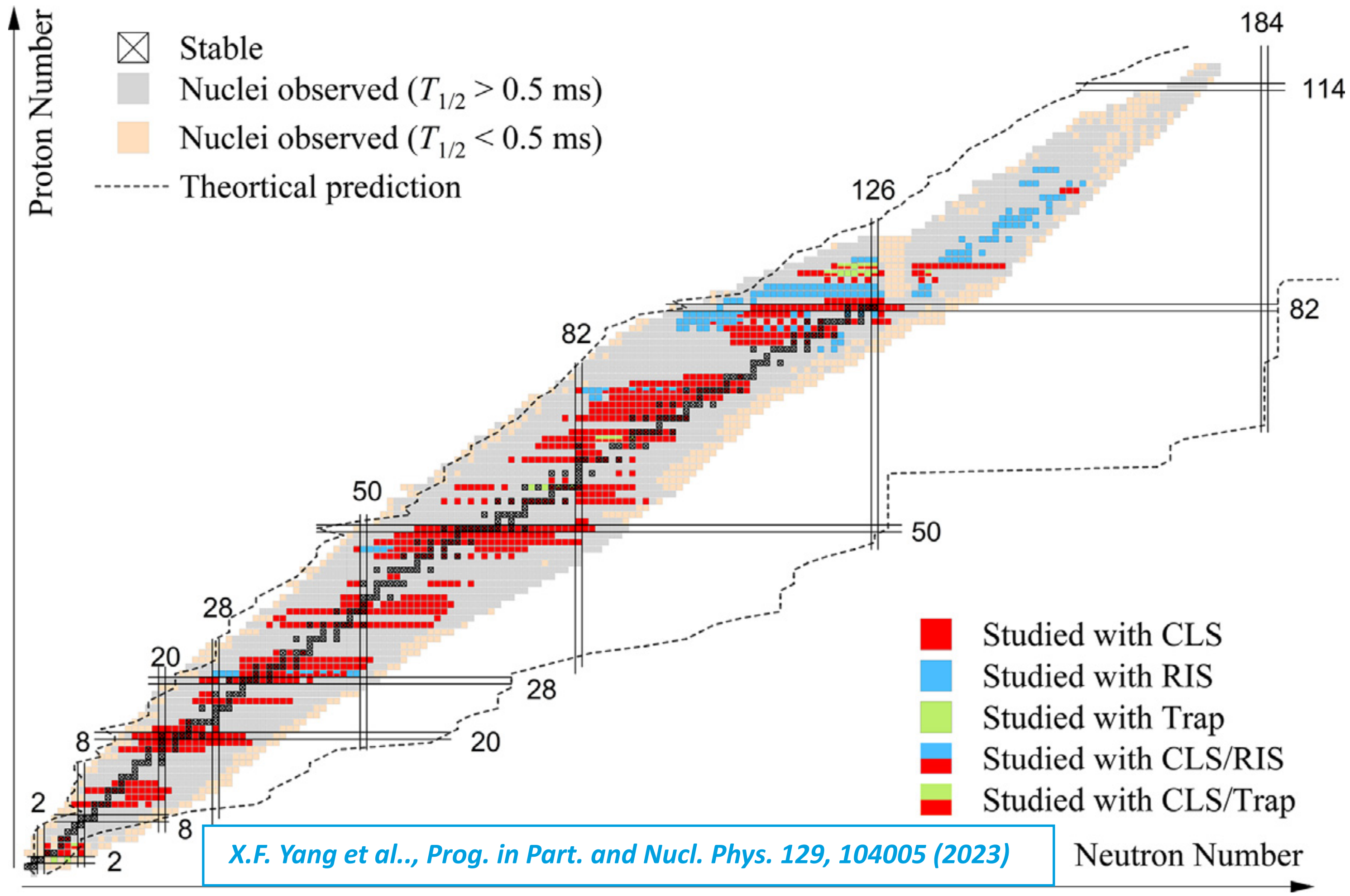
Absolute charge radii

$$R^{A'} = \sqrt{\langle r^2\rangle^{A'}} = \sqrt{\delta\langle r^2\rangle^{A,A'} + \langle r^2\rangle^{A}},$$

reference radius of stable isotope

G. Gorges et al., PRL 122, 192502 (2019)

(Some) Challenges & Opportunities



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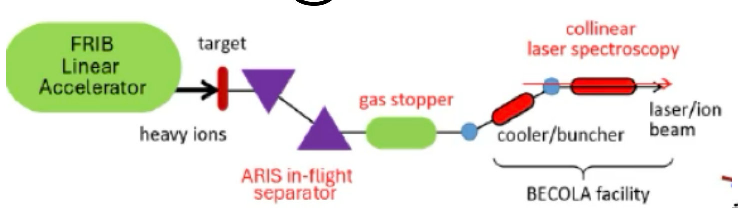
(apologies for any developments omitted due to time limitations)

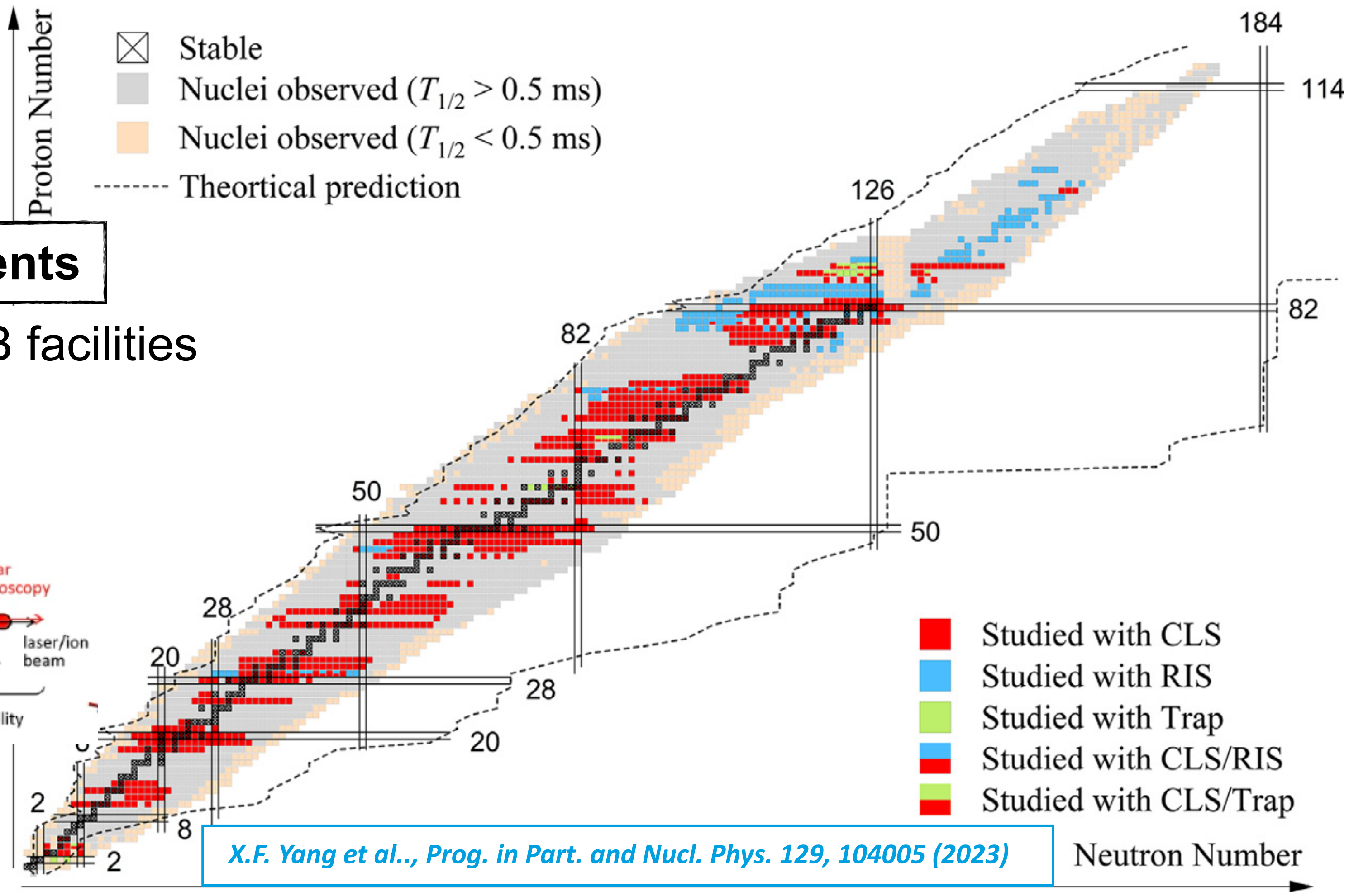
(Some) Challenges & Opportunities

Access to certain elements

variety in production & RIB facilities
- CLS @ IGISOL
- ATLANTIS @ CARIBU
- ~~BECOLA~~ @ FRIB



+ new CLS beamlines in construction



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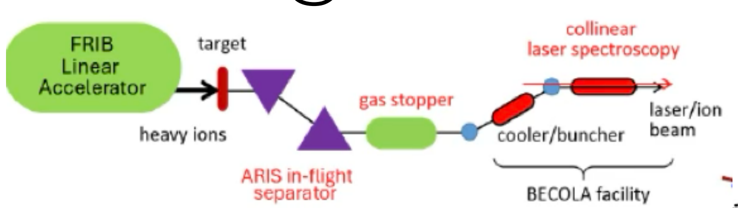

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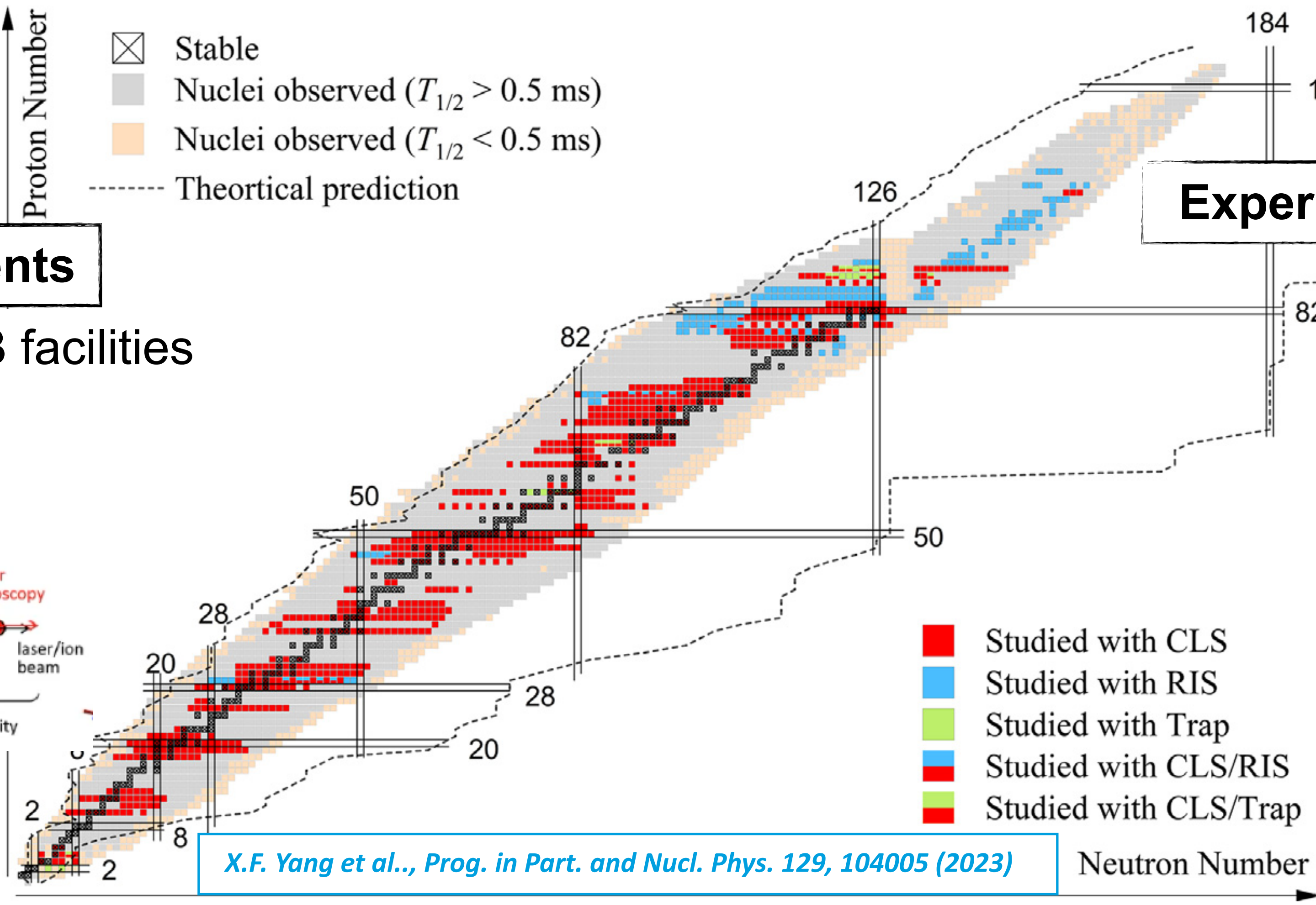
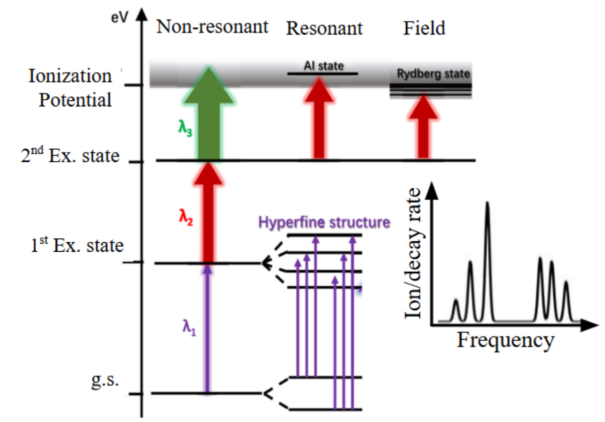


X.F. Yang et al.., Prog. in Part. and Nucl. Phys. 129, 104005 (2023)

Experimental sensitivity

new methods
- CRIS @ ISOLDE



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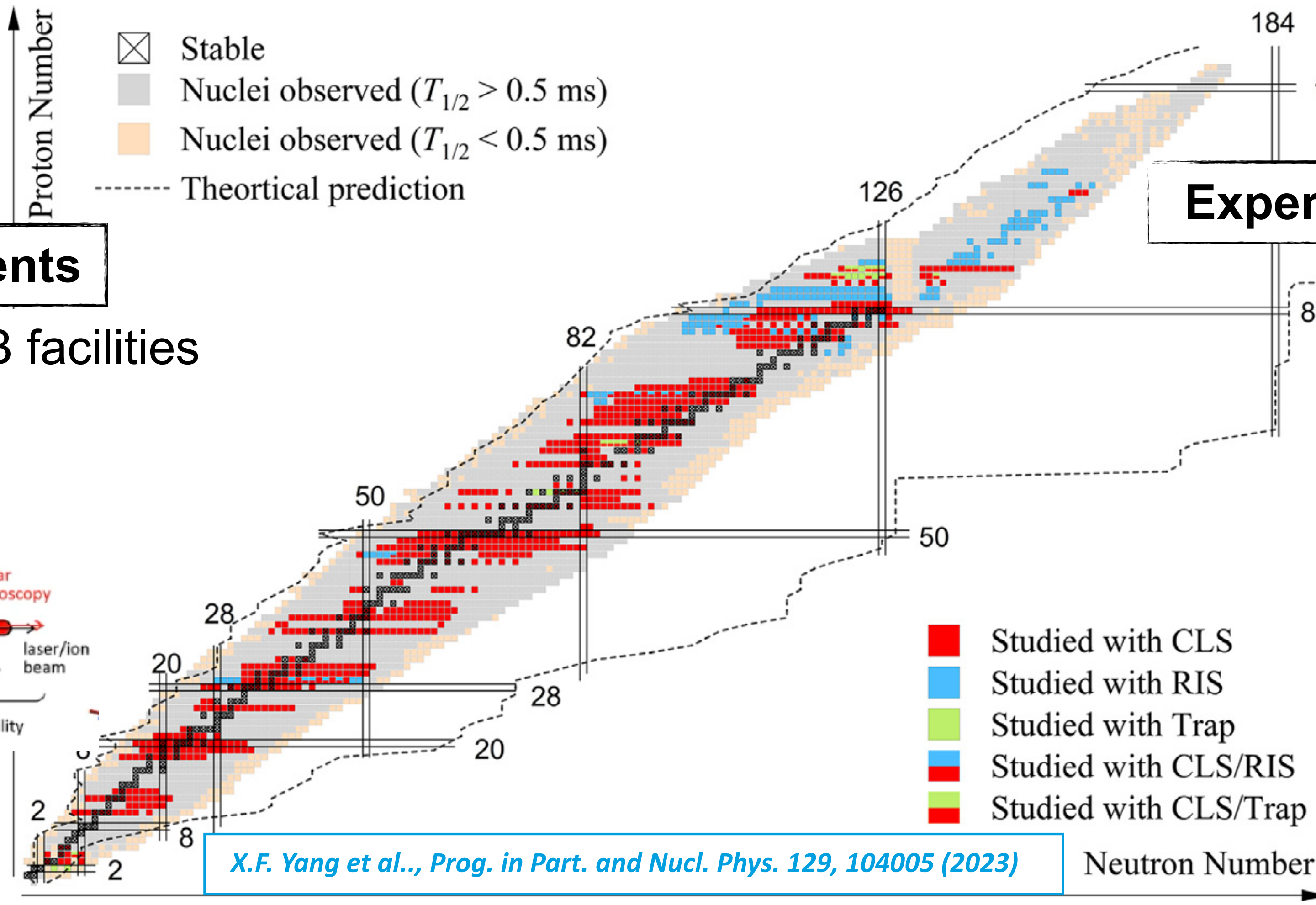

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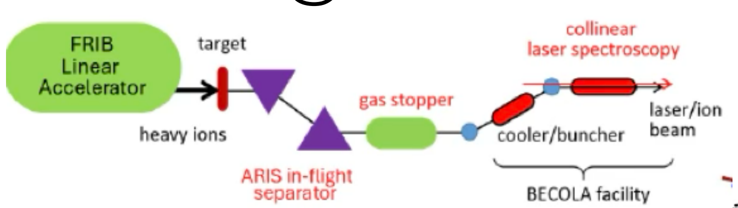

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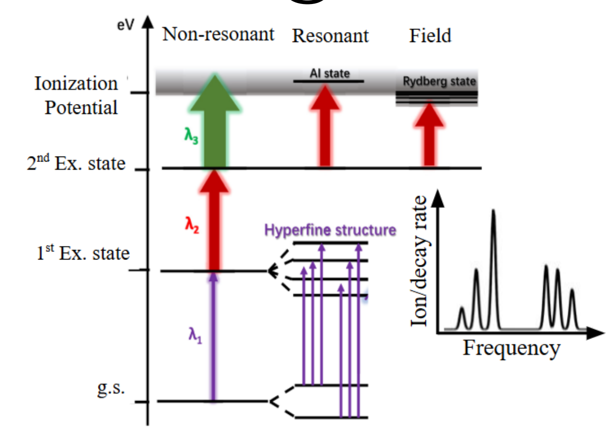

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Precision

needed for certain applications
access to new observables

- 2-photon spectroscopy @ PLASEN (Precision Laser Spectroscopy for Exotic Nuclei)
- Laser cooling - MIRACLS @ ISOLDE
  - **<u>STRIPE</u>** @ Leuven

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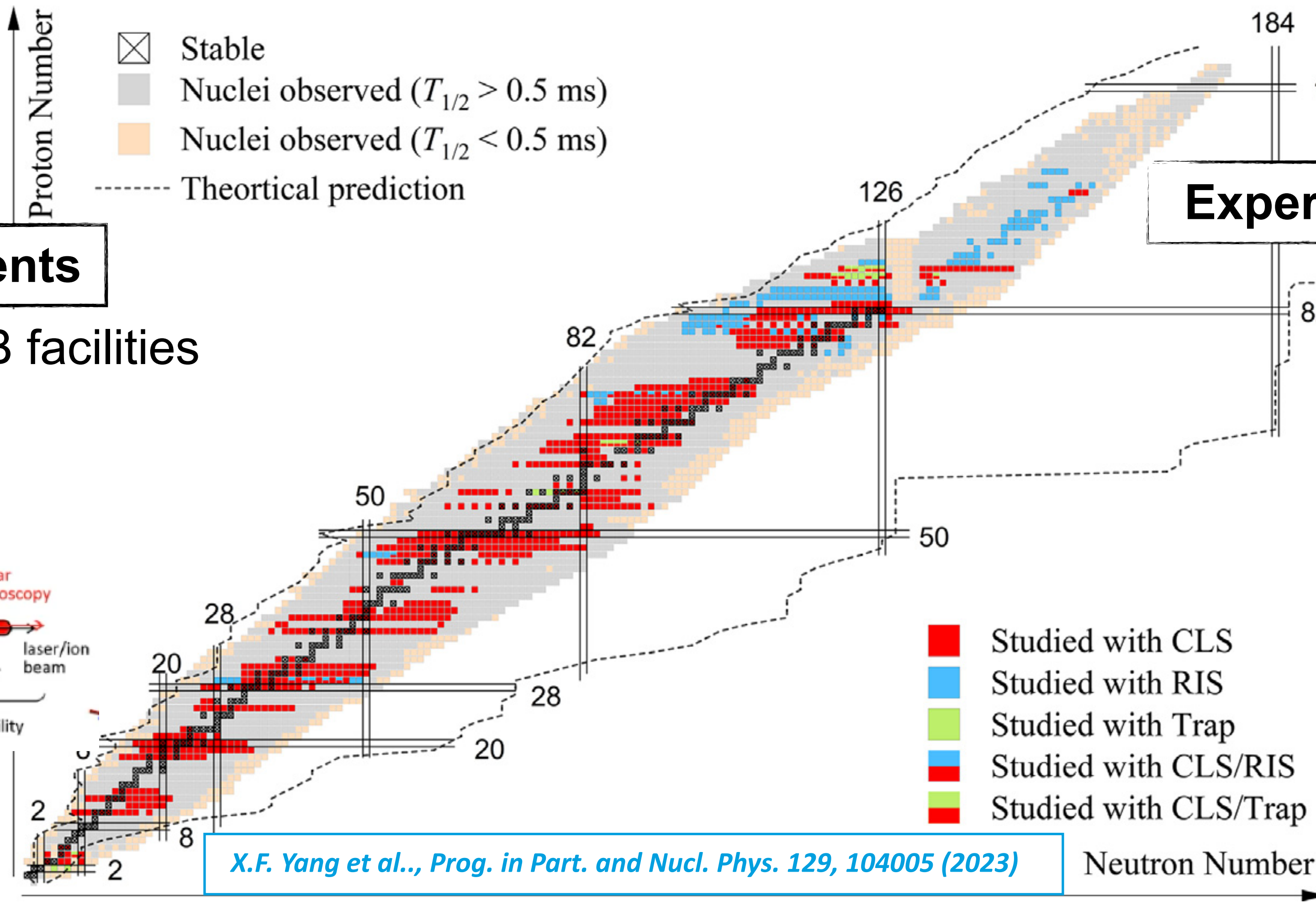

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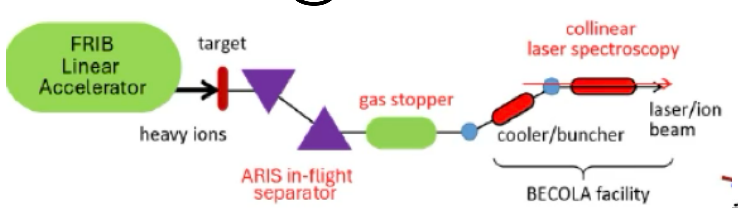

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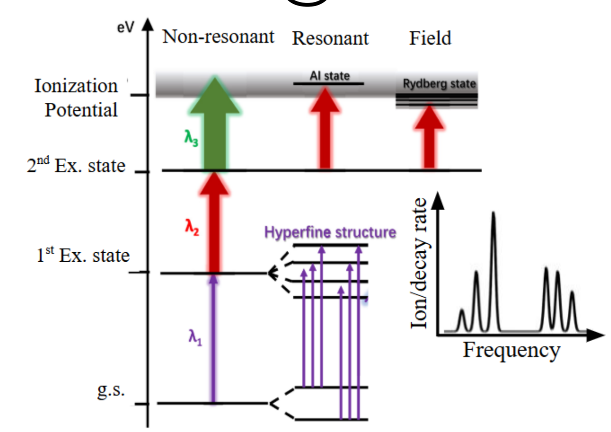

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Mass and field shift factors

↓

Reference radii

- revival of muonic X-ray spectroscopy
  muX@PSI
  e.g. ^{40}K from NRF National Research Foundation, iThemba LABS Laboratory for Accelerator Based Sciences

39K	40K	41K
STABLE	1.25e+9 y	STABLE
93.2581%	0.0117%	6.7302%
	β⁻=89.28%	
	ε+β+=10.72%	

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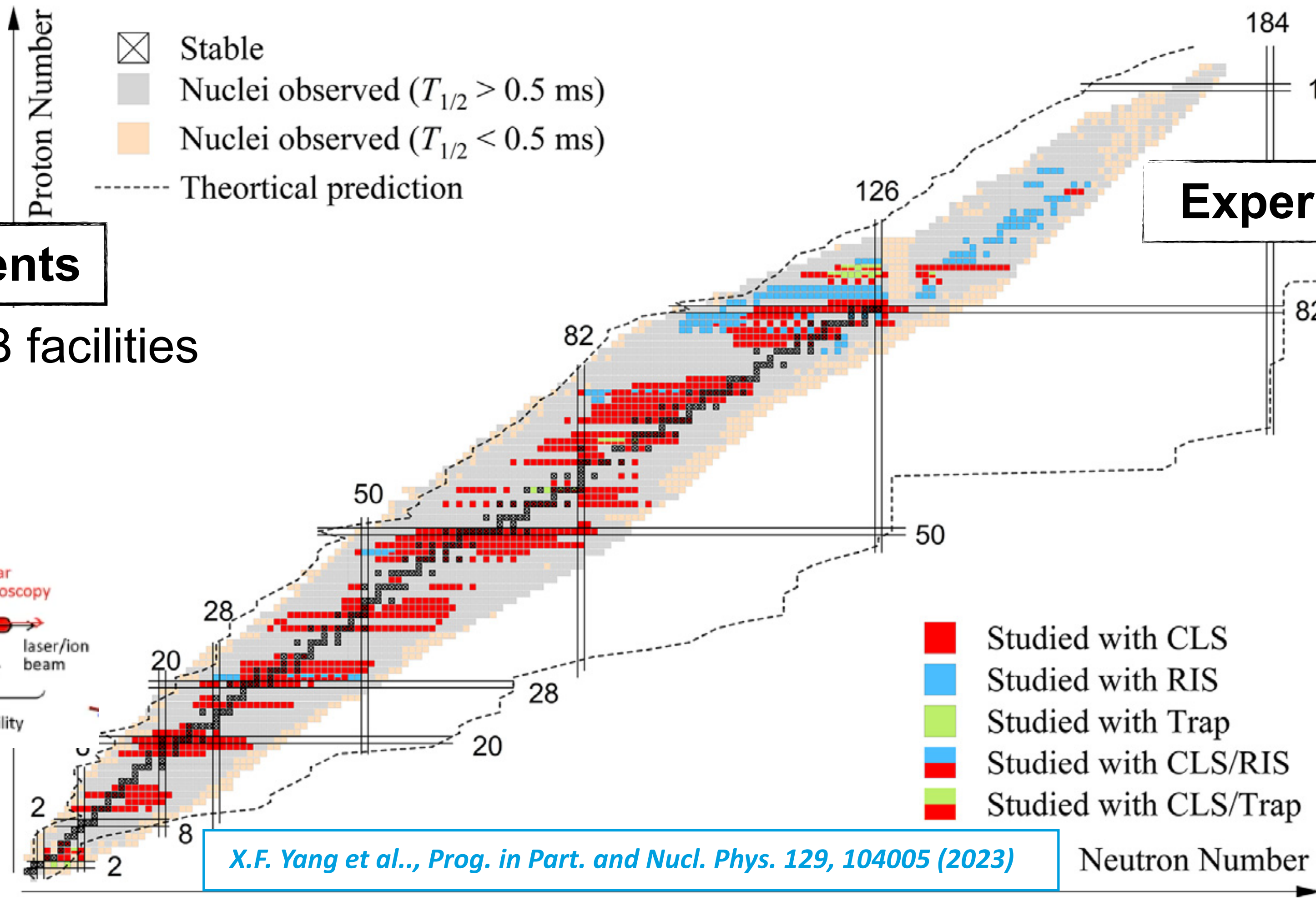

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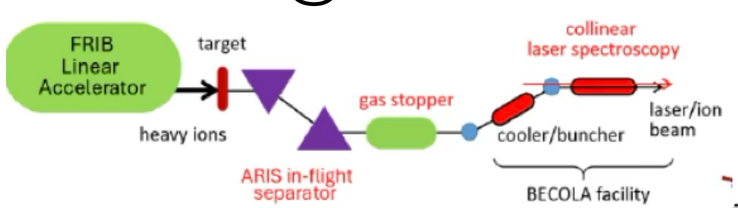

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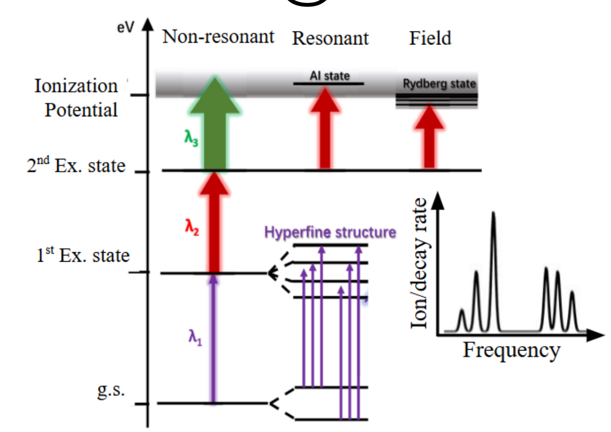

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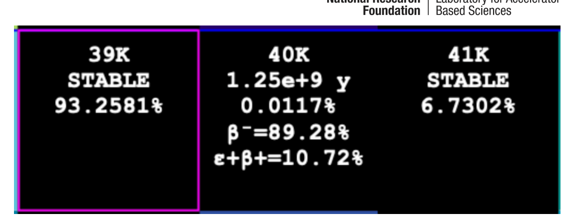
e.g. ^{40}K from NRF iThemba LABS



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Contamination

- minimization at source
- MR-TOF after CRIS: REBEL@Leuven

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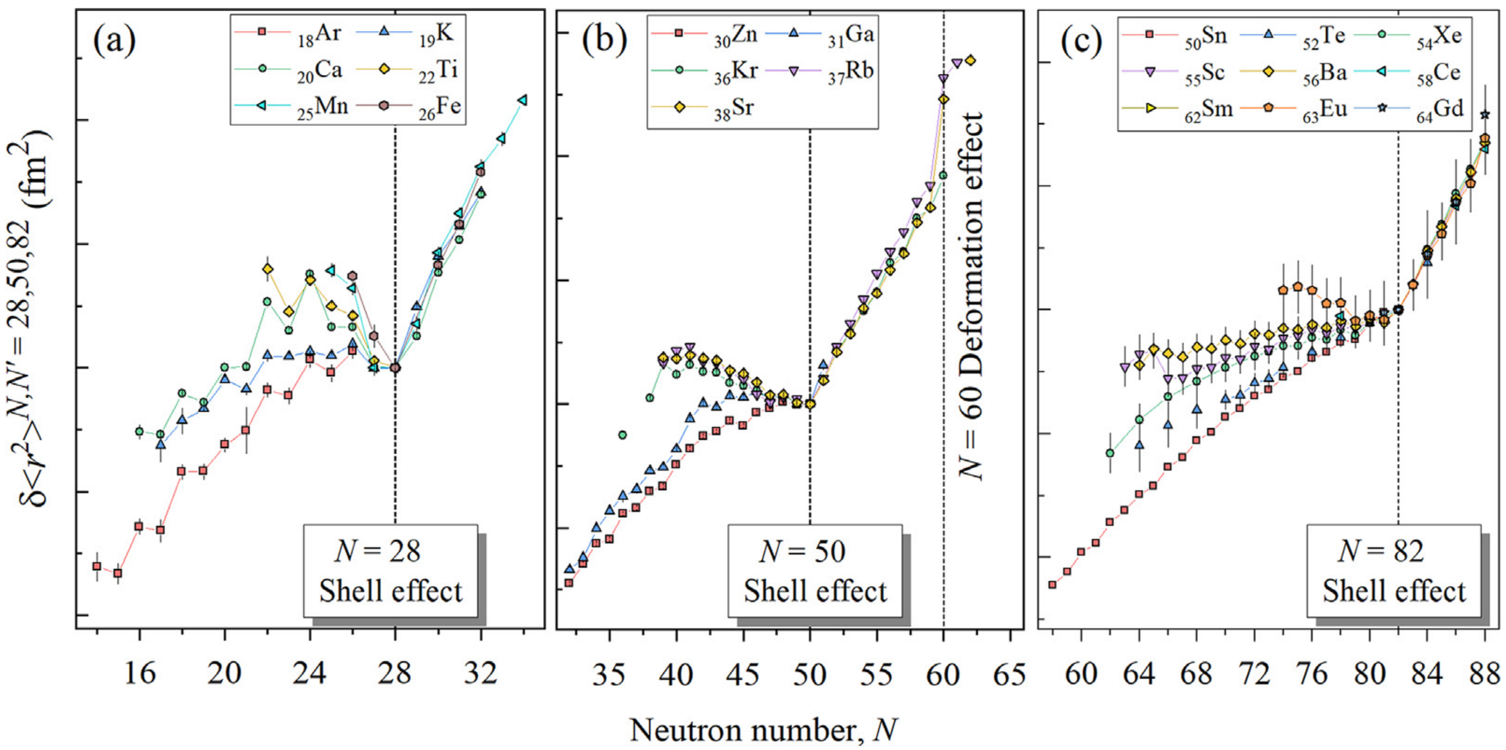
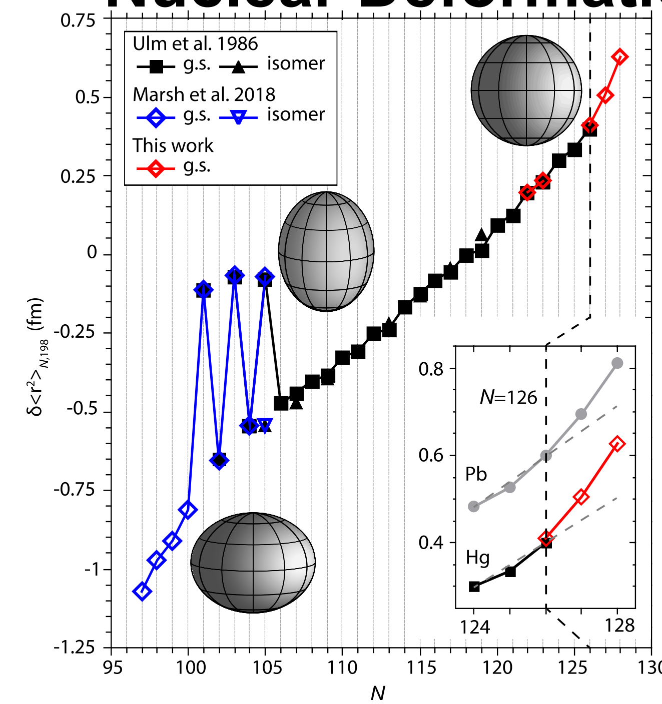
Physics of Nuclear Charge Radii

Nuclear Shell Structure



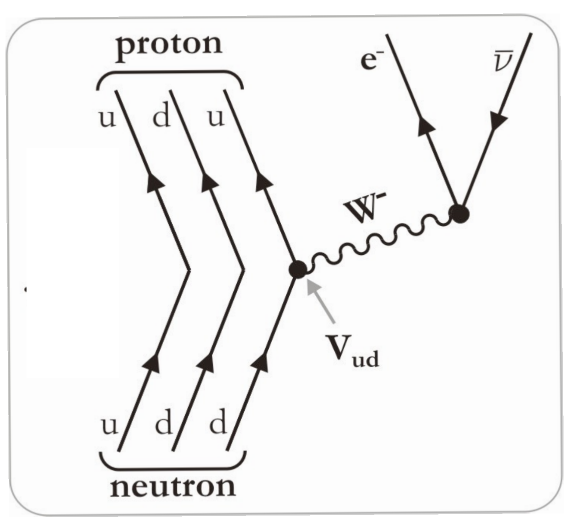
X.F.Yang et al.., Prog. in Part. and Nucl. Phys. 129, 104005 (2023)

Nuclear Deformation



B. A. Marsh et al., Nature Physics, 14, 1163 (2018)
T. Day Goodacre et al., PRL 126, 032502 (2021)

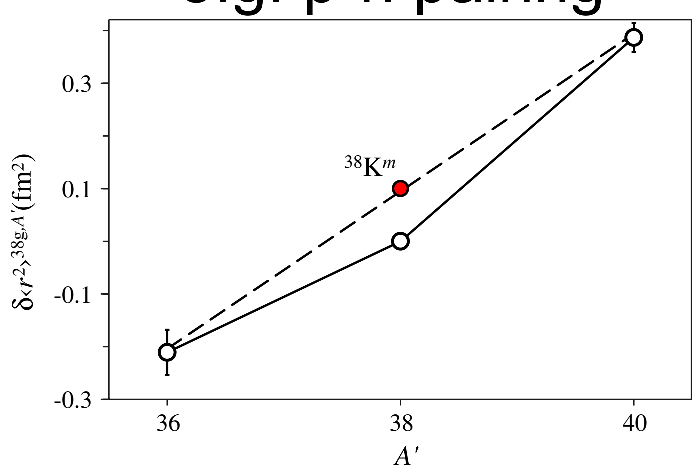
Fundamental symmetries



Mané et al., Phys. Rev. Lett. 107, 212502 (2011)
Plattner et al., Phys. Rev. Lett. 131, 222502 (2023)

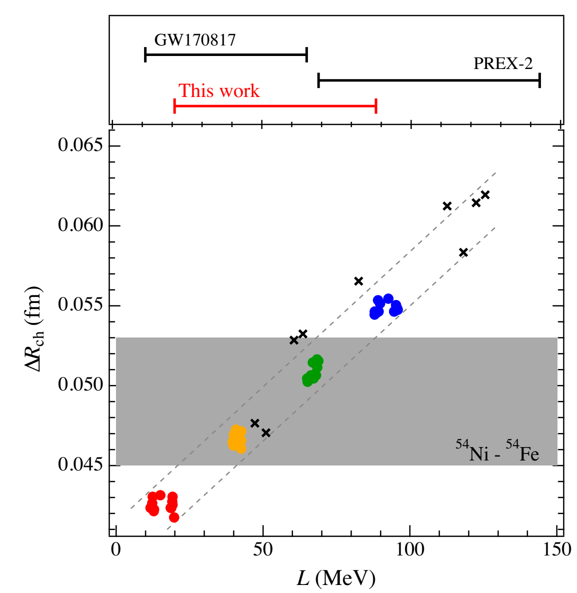
Nuclear Pairing

e.g. p-n pairing



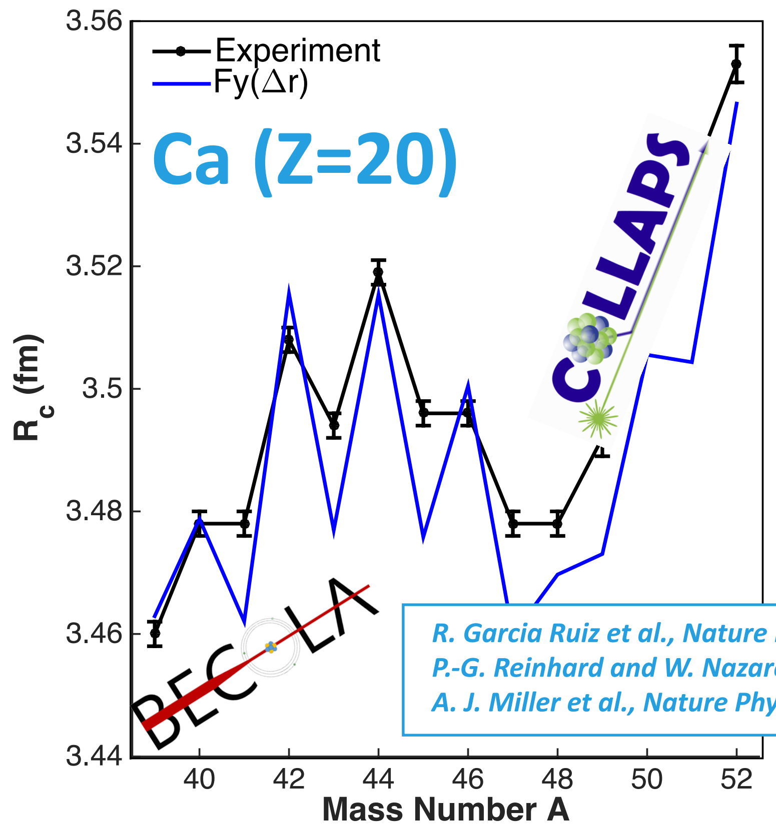
M. L. Bissell et al., Phys. Rev. Lett. 113, 052502 (2014)
Koszorús et al., Physics Letters B 819 (2021) 136439

Nuclear Matter



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

Towards a 'universal' description of charge radii



R. Garcia Ruiz et al., Nature Physics 12, 594 (2016)
P.-G. Reinhard and W. Nazarewicz, PRC 95, 064328 (2017)
A. J. Miller et al., Nature Physics 15, 432 (2019)

- remarkable progress in theory & experiment
- theoretical models:
  - ➡ applicable over wider mass range
  - ➡ including DFT and ab-initio methods
  - ➡ Fy(Δr) excellent agreement to experiment
    - 'kink' at shell closures
    - odd-even staggering

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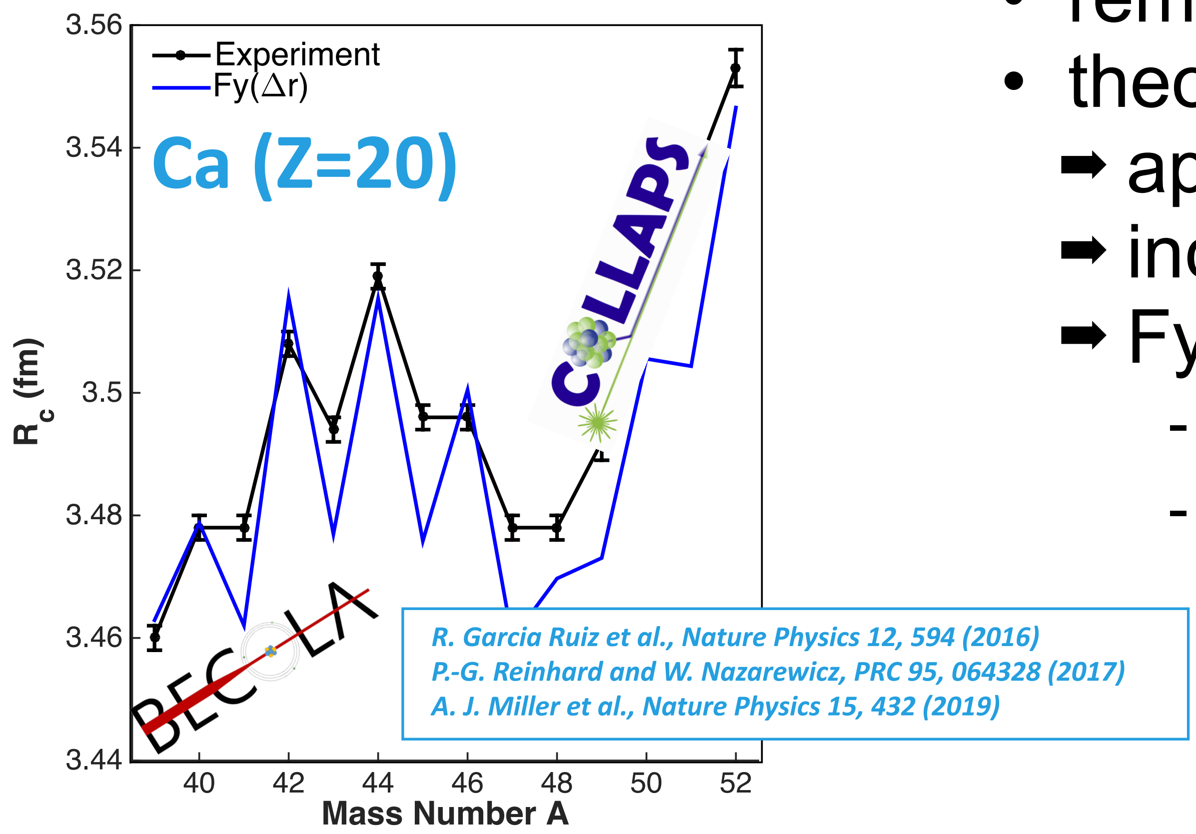

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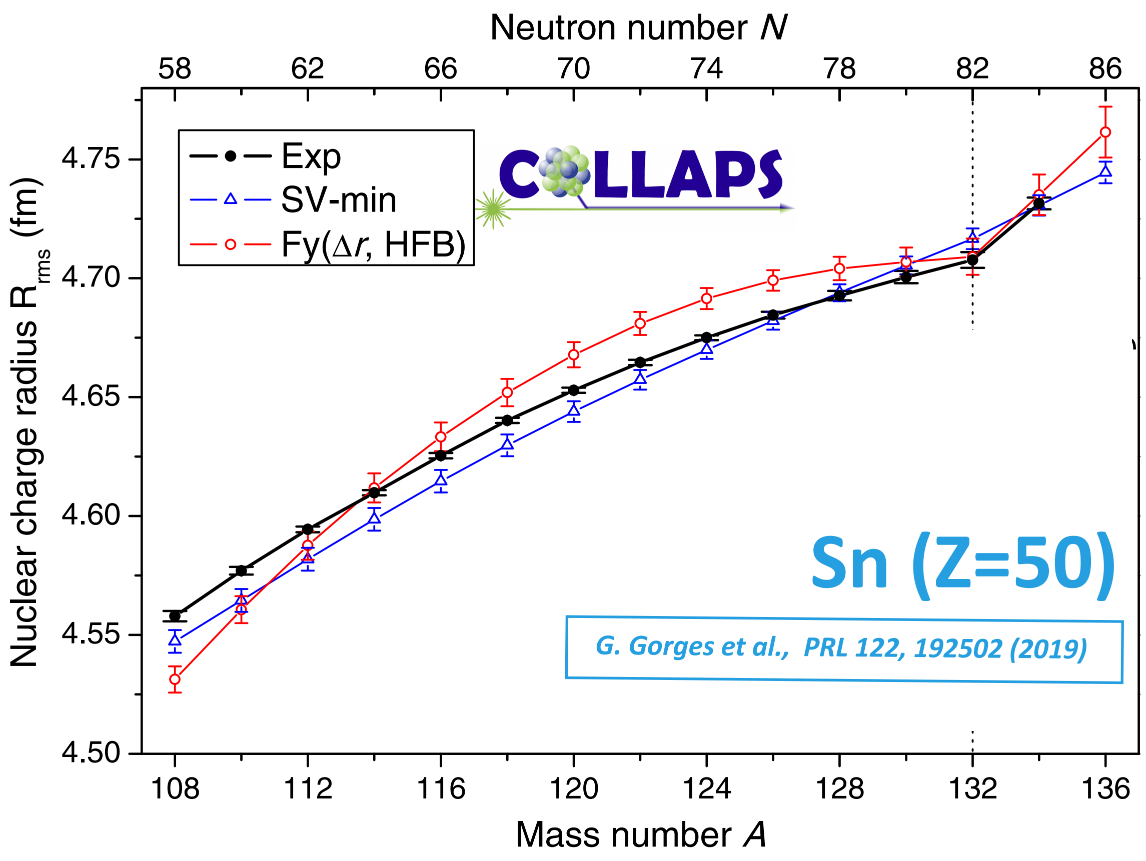

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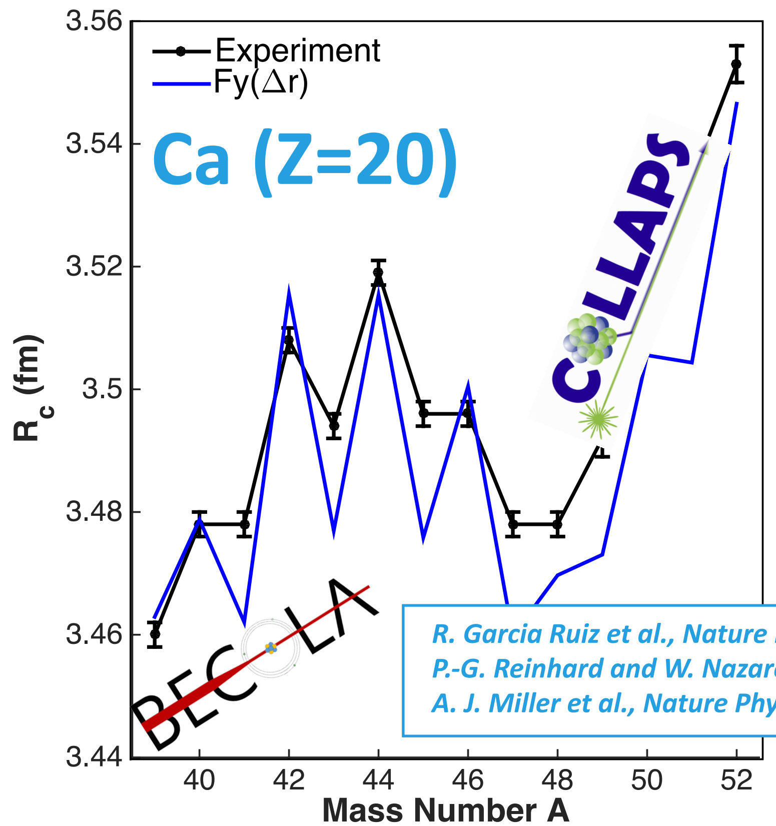

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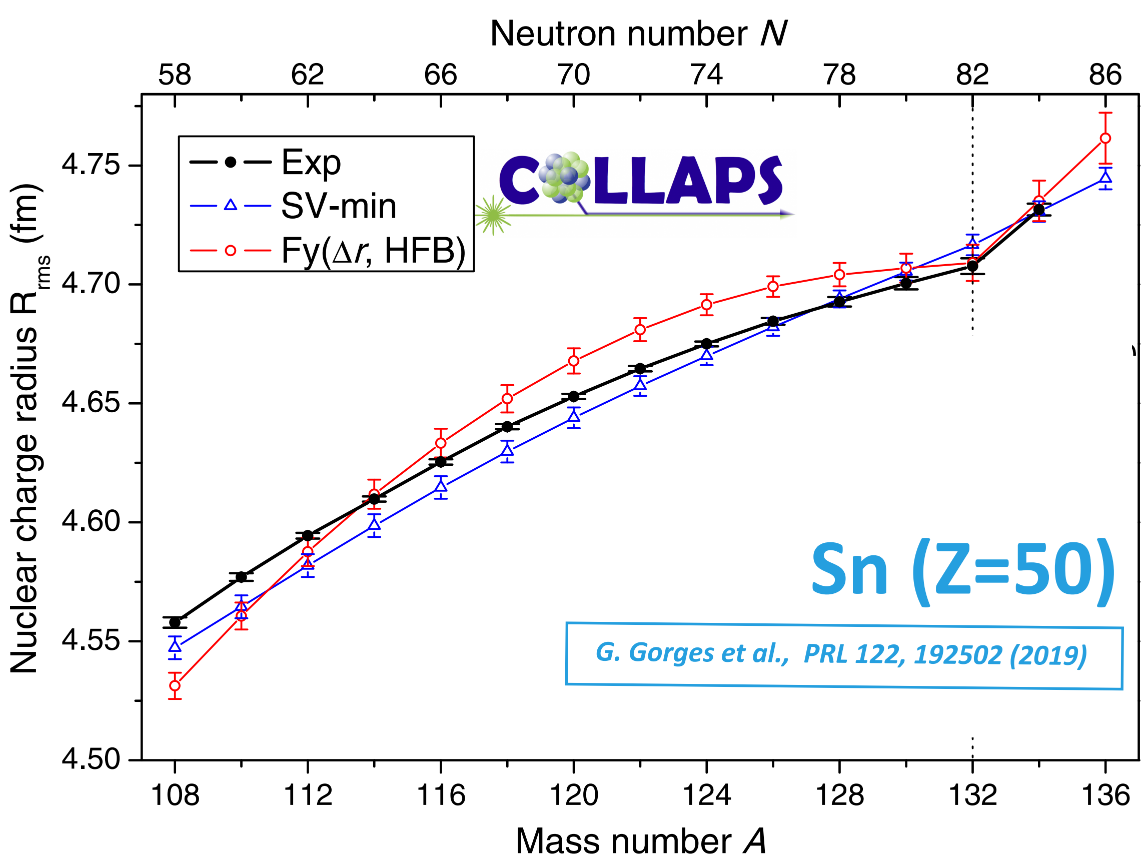


G. Gorges et al., PRL 122, 192502 (2019)

Exp. validations of Fayans DFT

Element	Z	Reference
K	19	Nature Physics 17, 439 (2021)
Ca	20	Nature Physics 12, 594 (2016) Nature Physics 15, 432 (2019)
Fe	26	Phys. Rev. Lett., 117, 252501 (2016)
Ni	28	Phys. Rev. Lett., 128, 022502 (2022)
Cu	29	Nature Physics 16, 620 (2020)
Ge	32	Physics Letters B, 856, 138867 (2024)
Cd	48	Phys. Rev. Lett., 121, 102501, (2018)
In	49	Nature Physics, 20, 1719 (2024)
Sn	50	Phys. Rev. Lett., 122, 192502 (2019)
Fm	100	Nature, 634, 1075 (2024)

A = 36 - 134 (plus 245-257)

Towards a ‘universal’ description of charge radii

- remarkable progress in theory and experiment
- theoretical models:

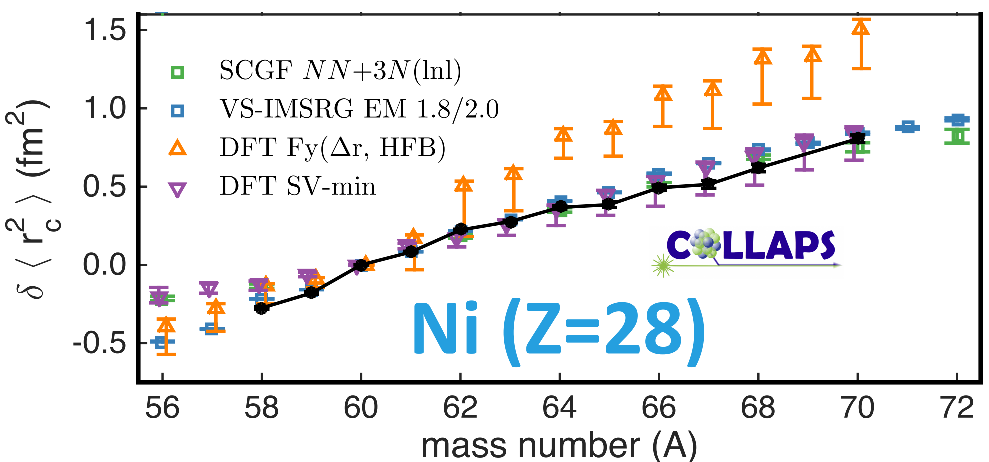
But also shortcoming in Fayans functional Fy(Δr)

e.g. parabolic trend for Ni/Cu/Cd/Sn

→ newly-introduced isovector term

9

Nature Physics, 20, 1719 (2024)
Physics Letters B, 856, 138867 (2024)



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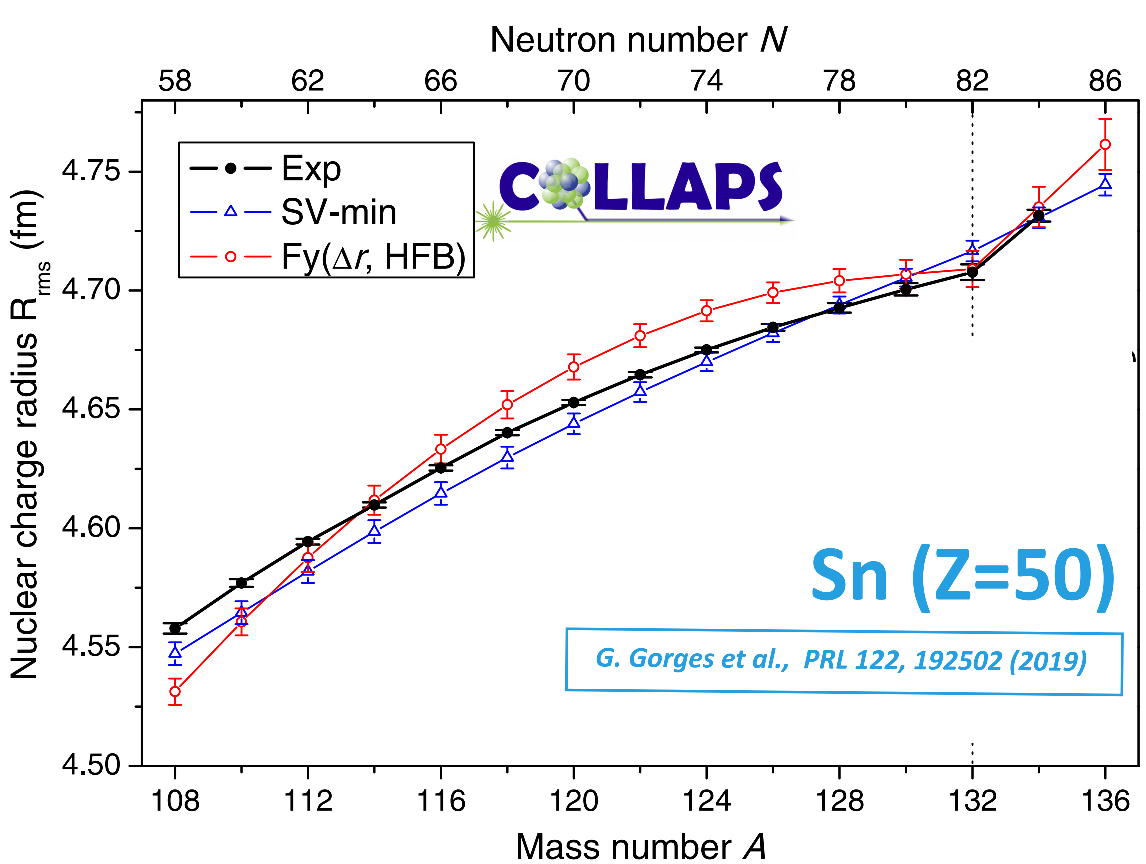

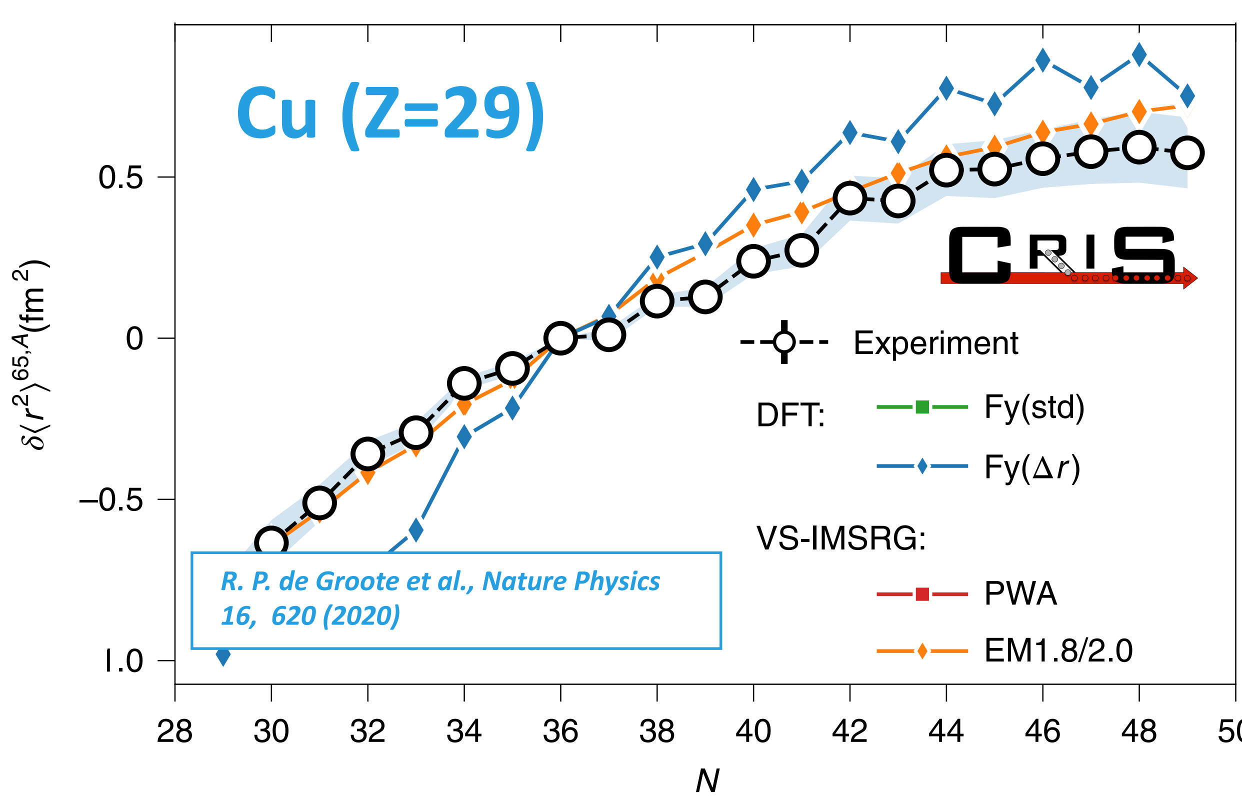

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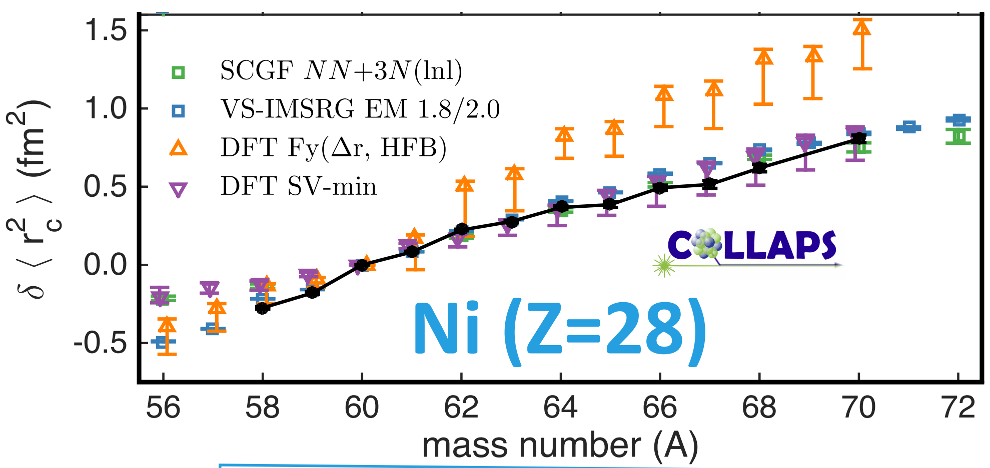

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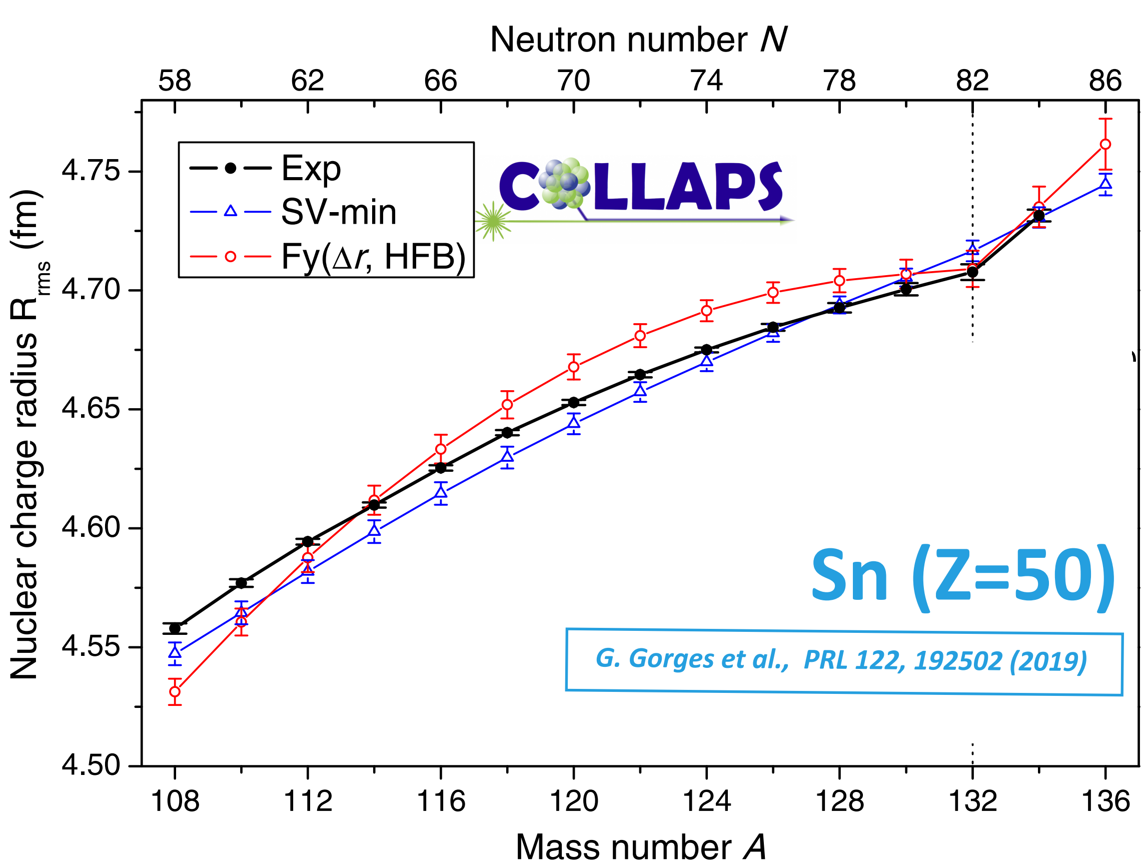
Physics Letters B, 856, 138867 (2024)

⇒ new exp. benchmarks needed!



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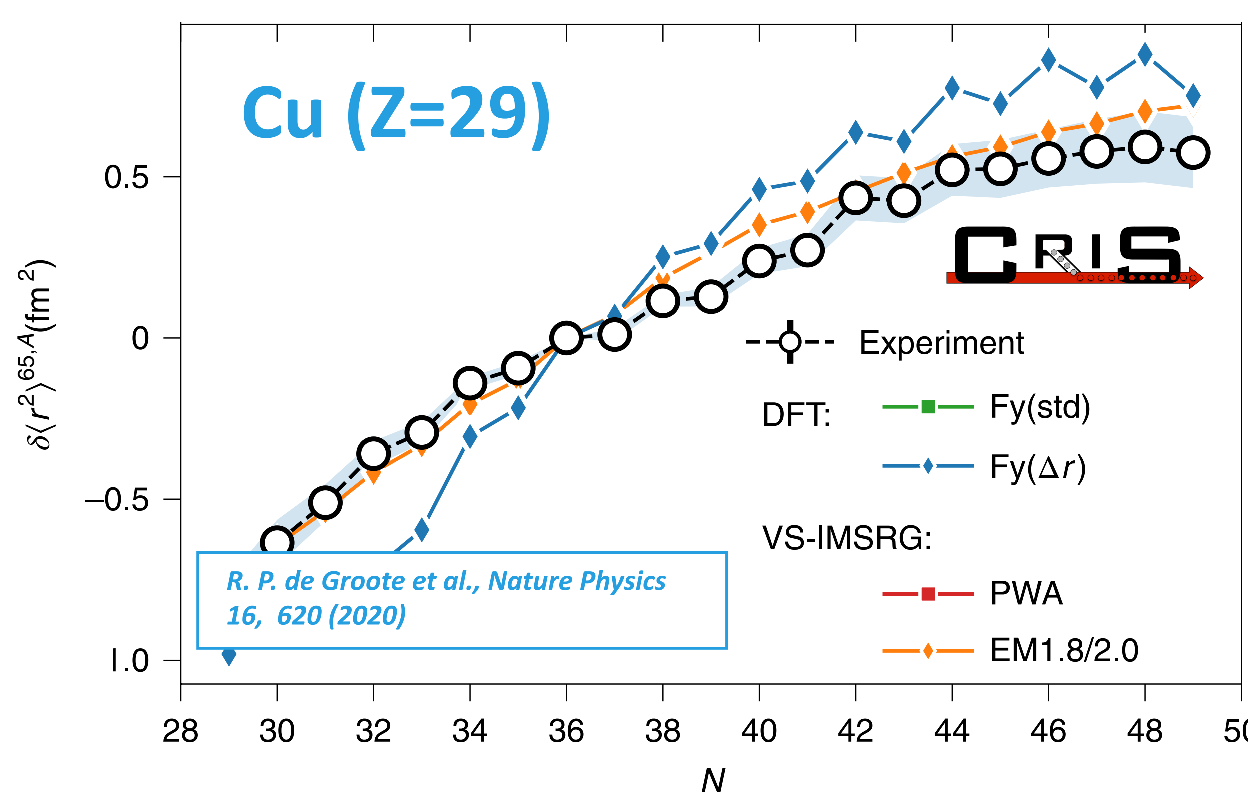

R. P. de Groote et al., Nature Physics 16, 620 (2020)

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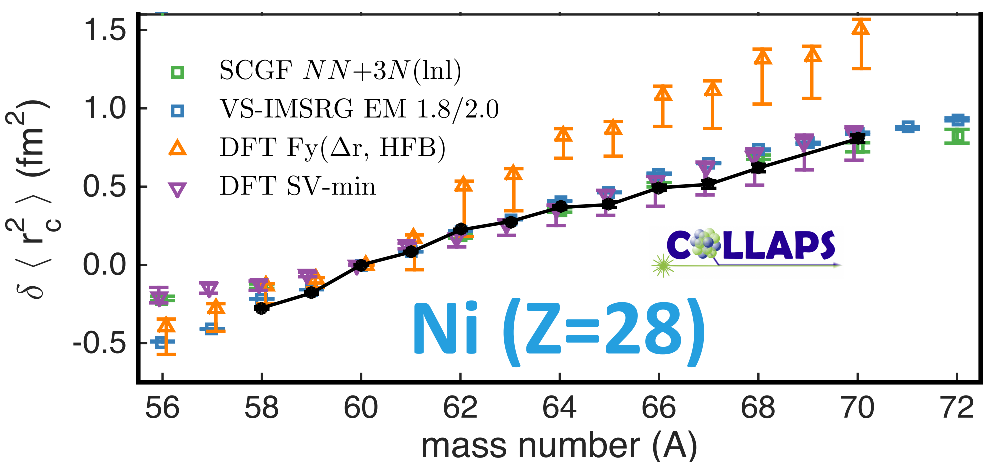

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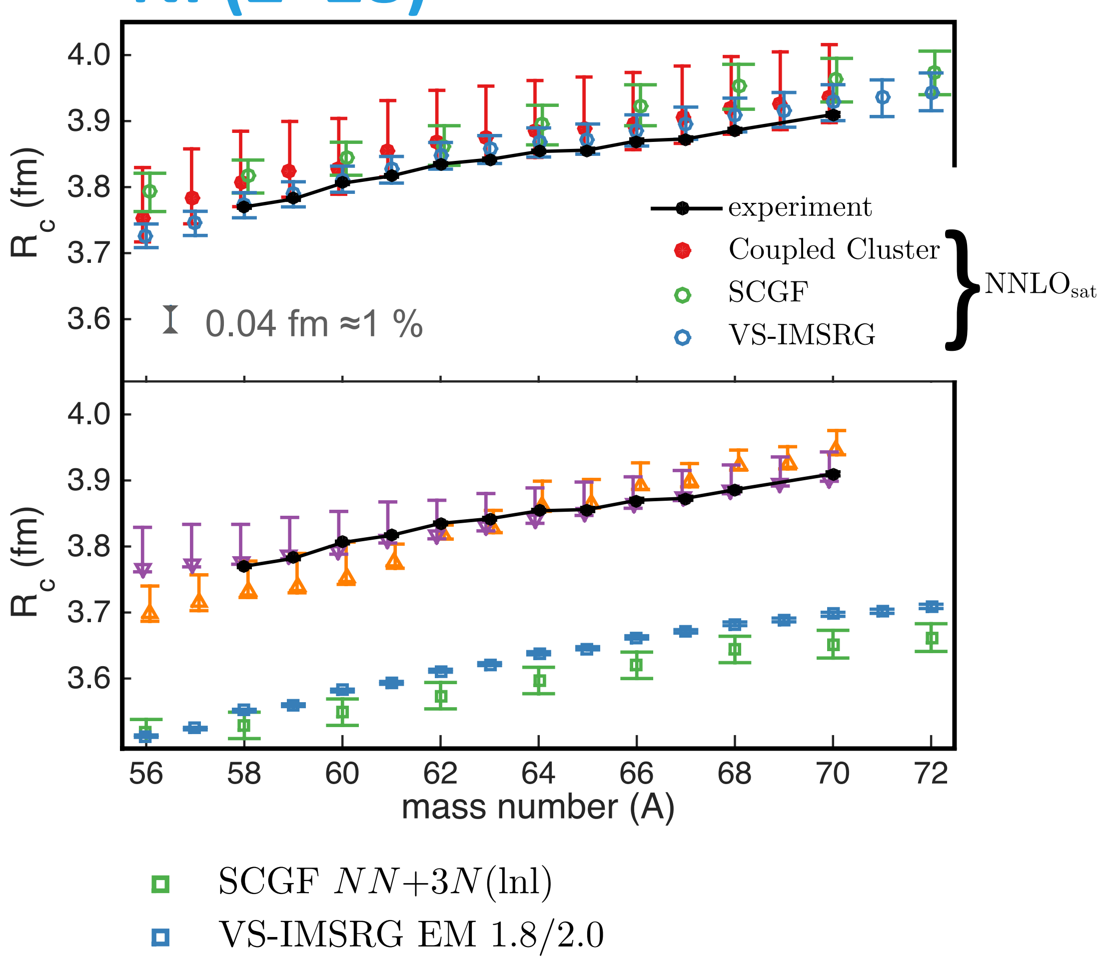
Ni (Z=28)



Benchmark: ab initio calculations next to shell closure

- reproduces experiment at the ≈1% level
- agreement within *ab initio* methods ⇒ accuracy check
- importance of used nuclear potential: needs to capture relevant physics

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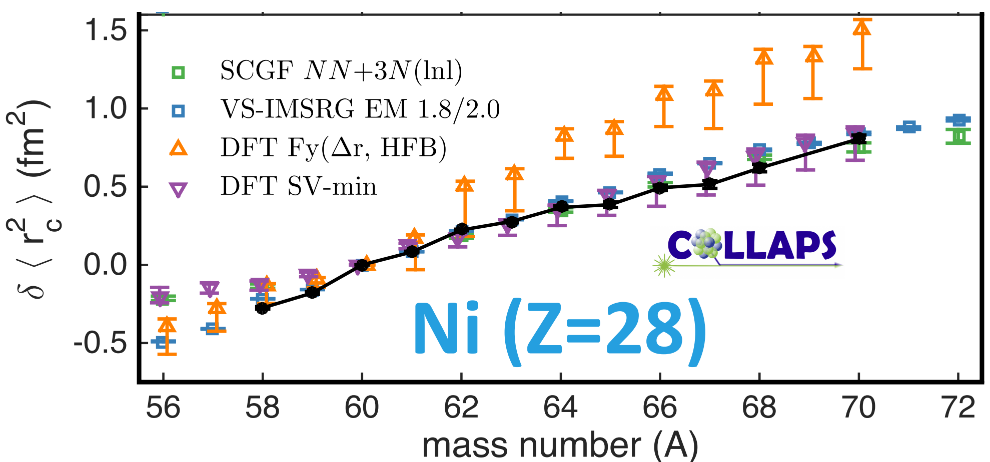
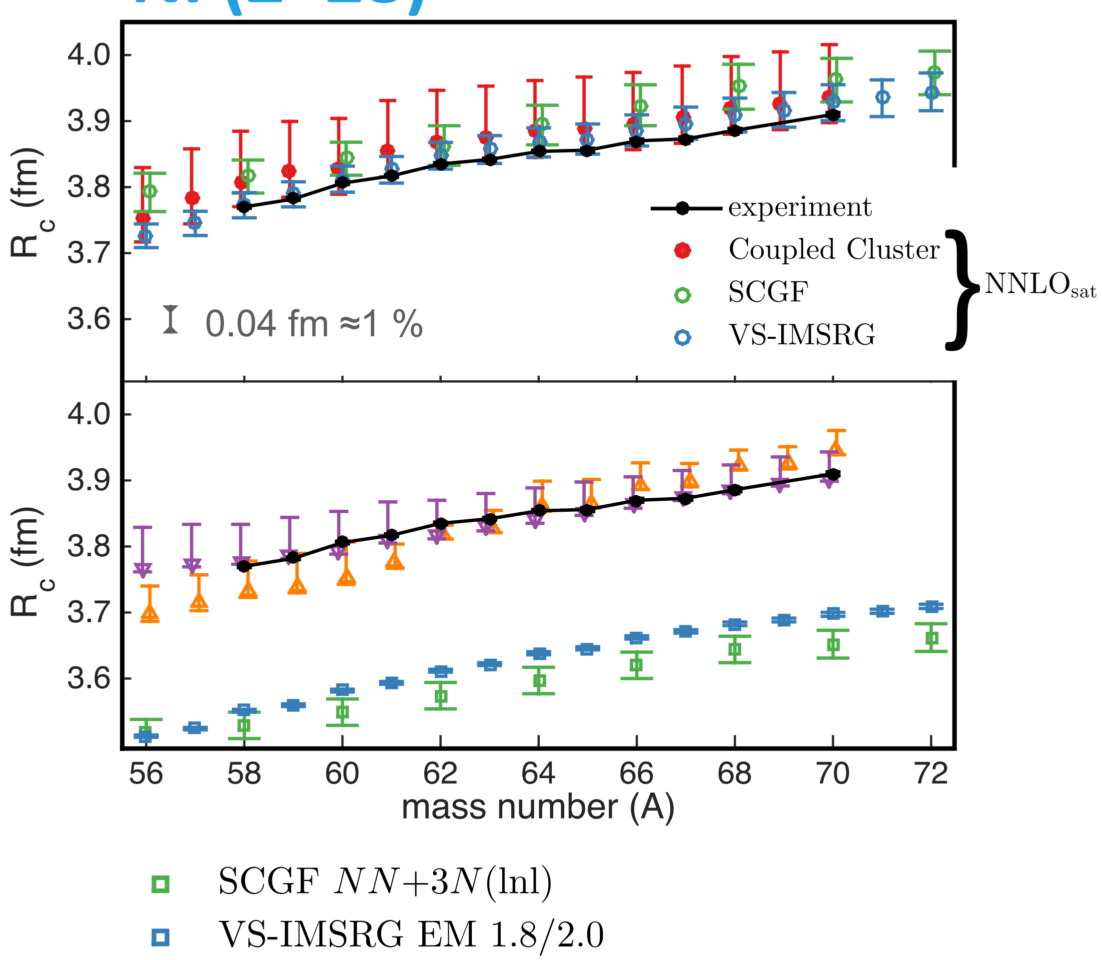
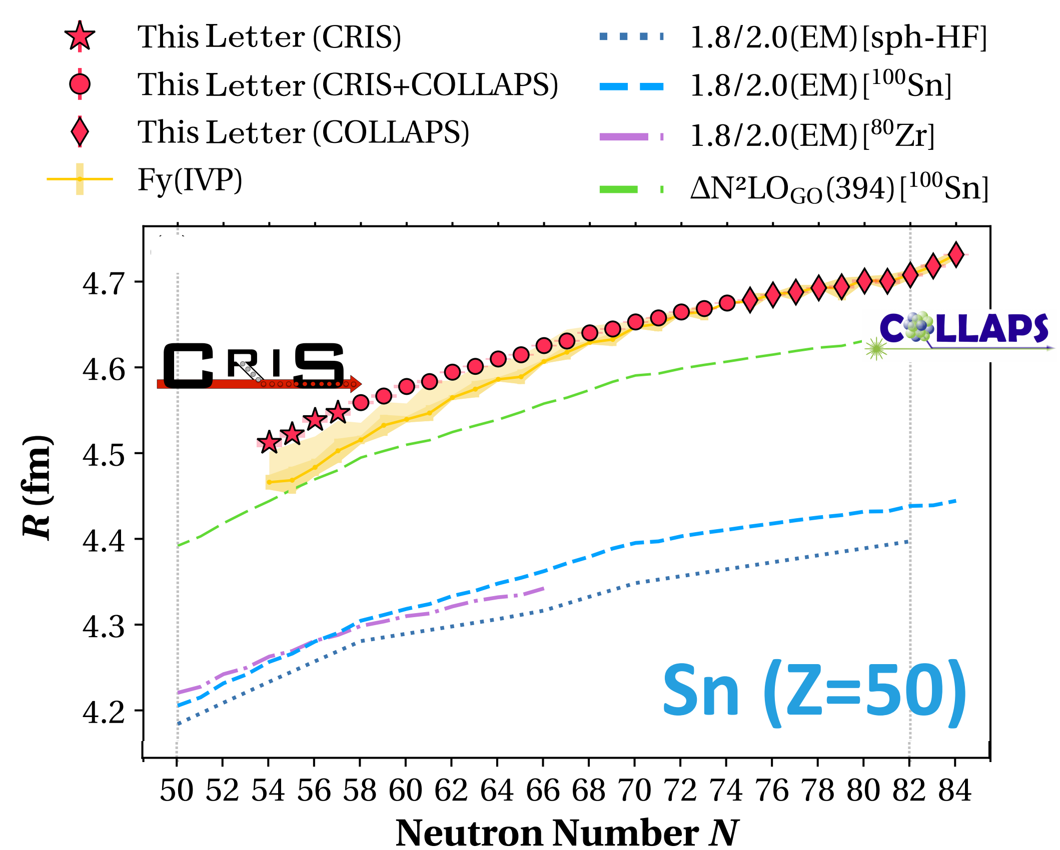


S. M.-E. et al., PRL 128, 022502 (2022)

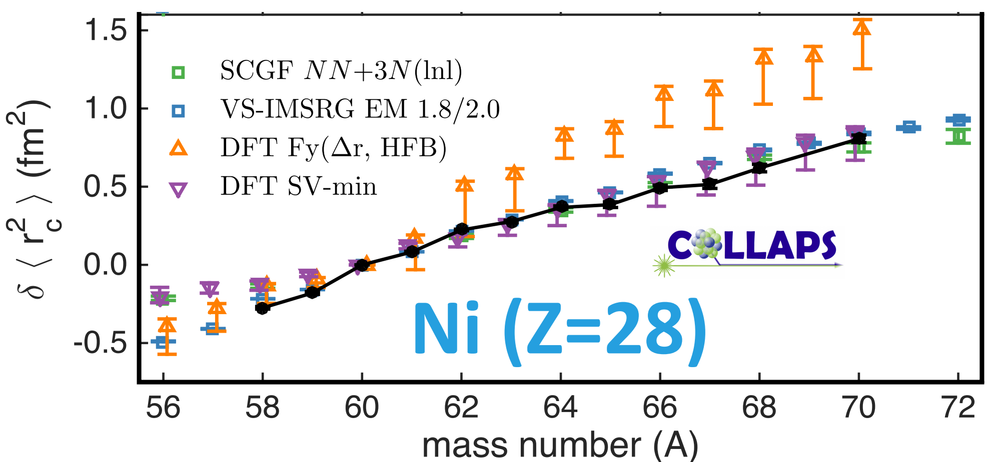
Ni (Z=28)





F. P. Gustafsson et al. arXiv:2504.17060, accepted in Phys. Rev. Lett.

Towards a 'universal' description of charge radii

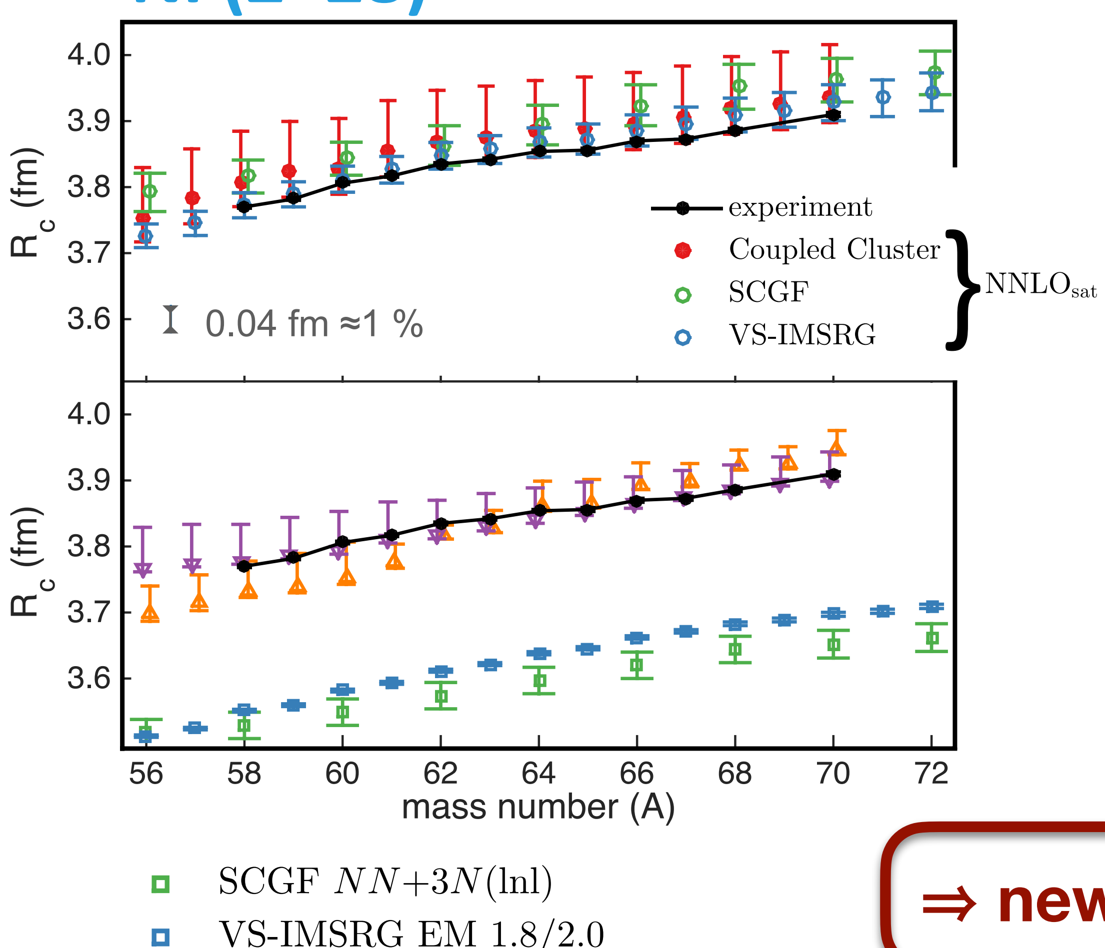


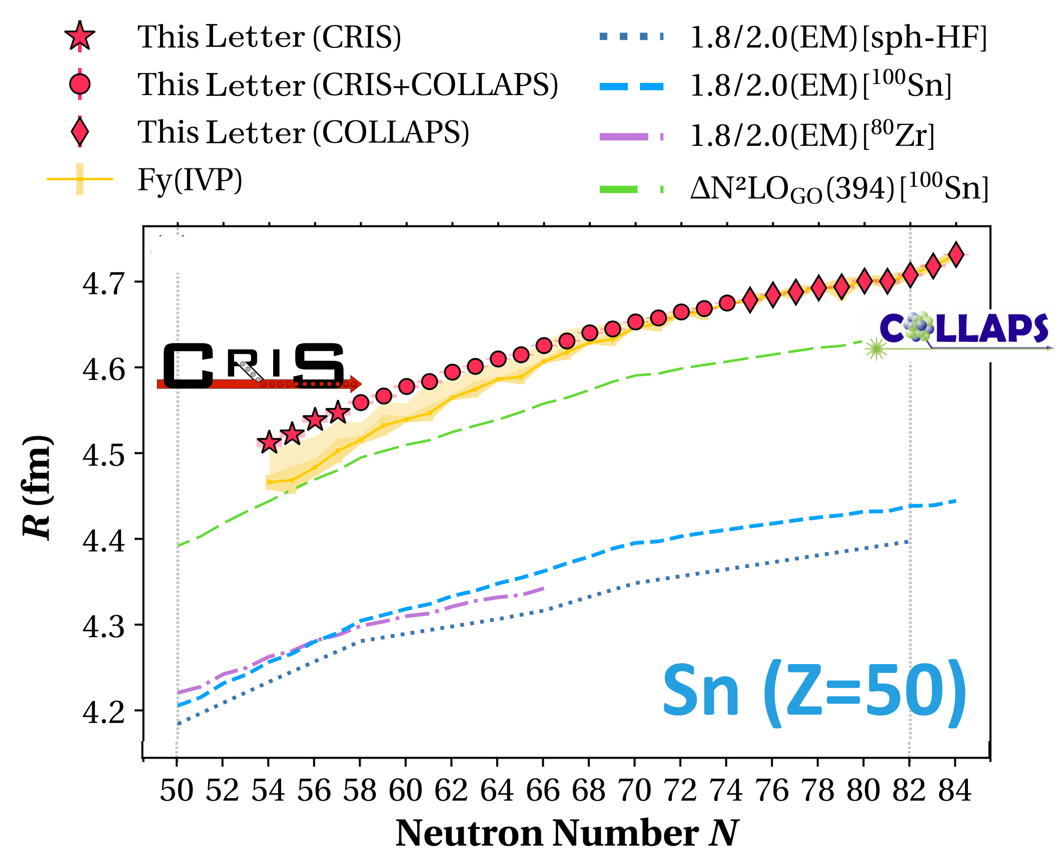
S. M.-E. et al., PRL 128, 022502 (2022)

Benchmark: ab initio calculations next to shell closure

- reproduces experiment at the ≈1% level
- agreement within *ab initio* methods ⇒ accuracy check
- importance of used nuclear potential: needs to capture relevant physics

Ni (Z=28)





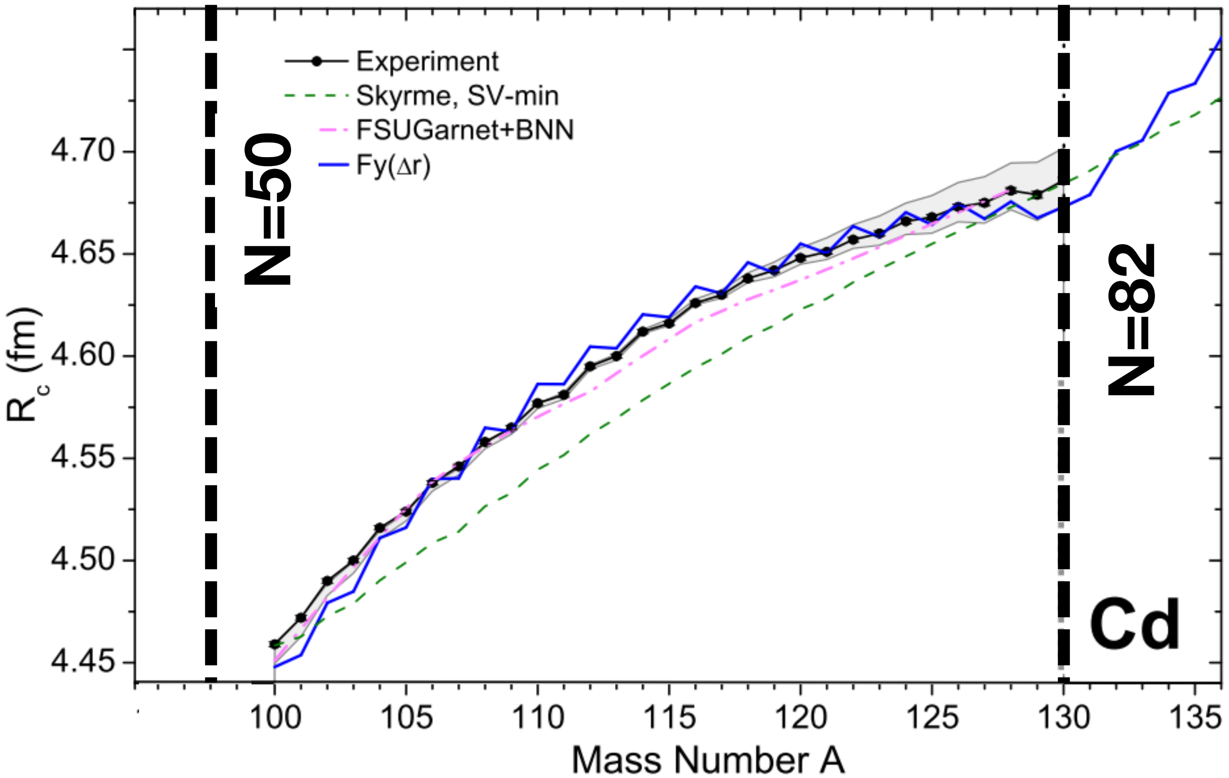
F. P. Gustafsson et al. arXiv:2504.17060, accepted in Phys. Rev. Lett.

⇒ new benchmarks in mid-shell / deformed regions

R_C: new benchmarks…

….for Fayans DFT

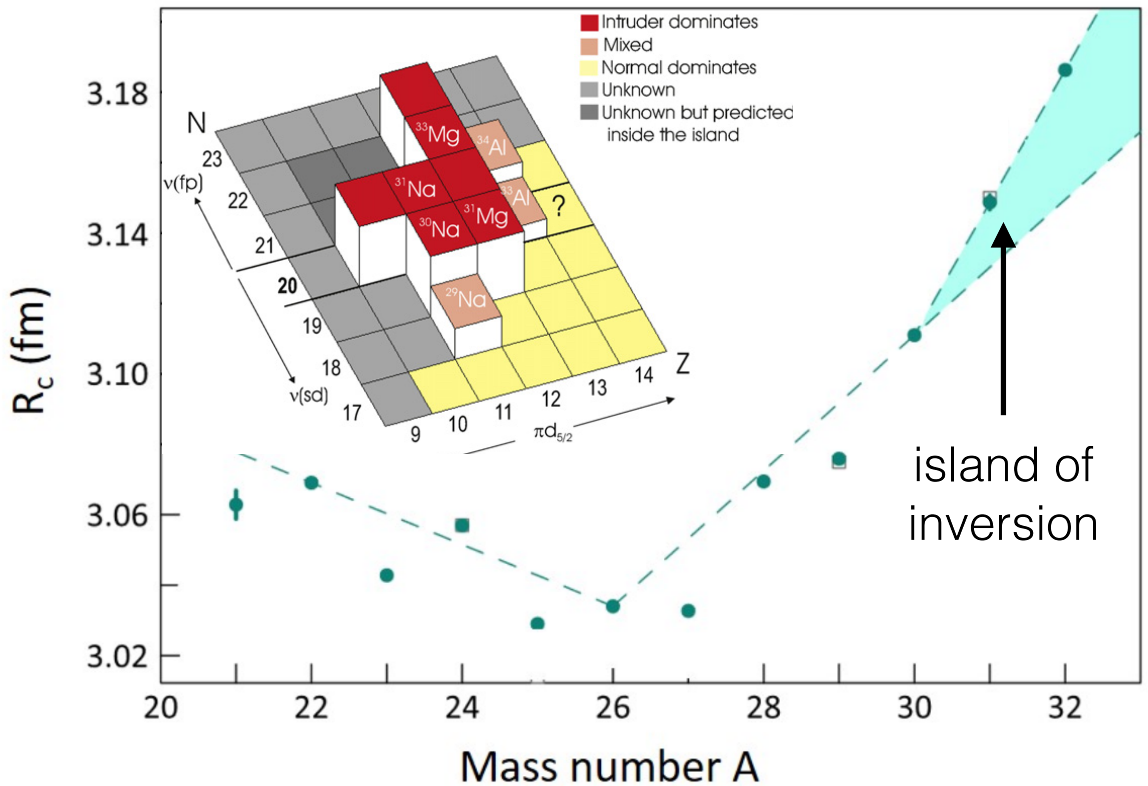
- kink at N=82?
- curvature ⇔ isovector term in DFT



G. Gorges et al., PRL 122, 192502 (2019)

… for *ab inito* in deformed region

- island of inversion around ^{32}Mg
- shell evaluation



D. T. Yordanov et al., Phys. Rev. Lett. 108, 042504 (2012)

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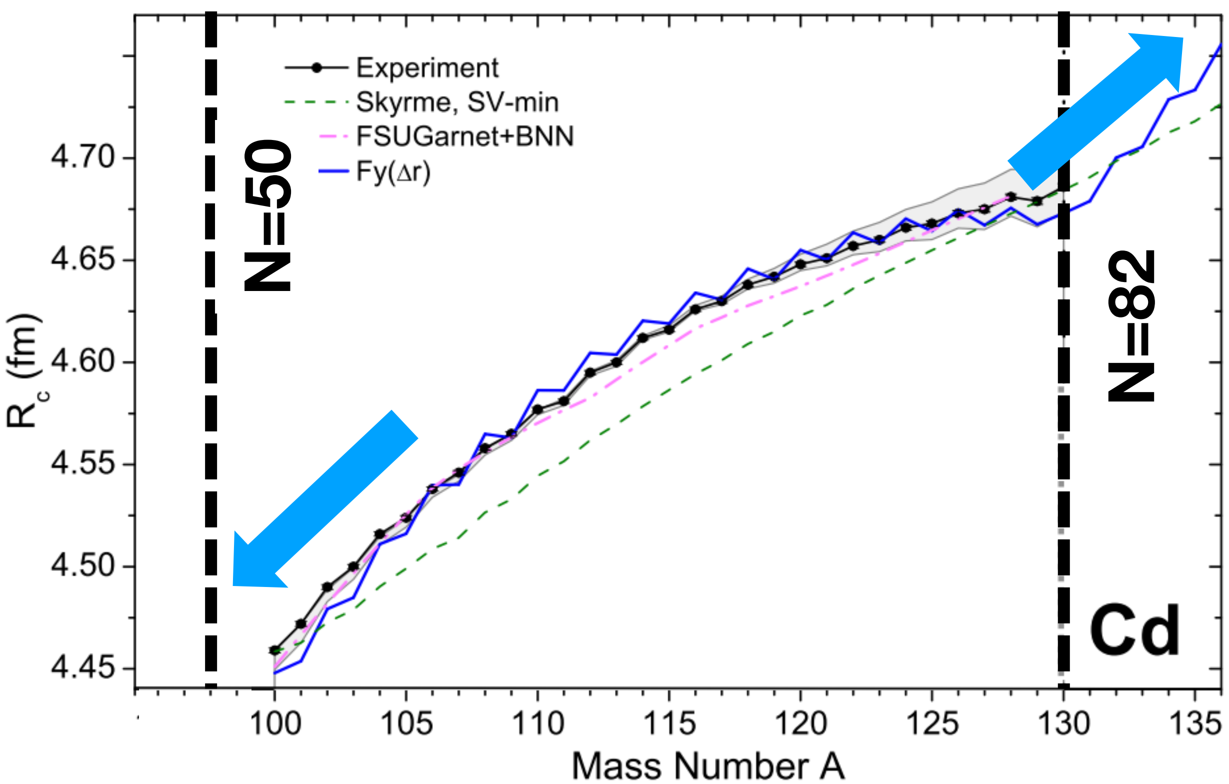

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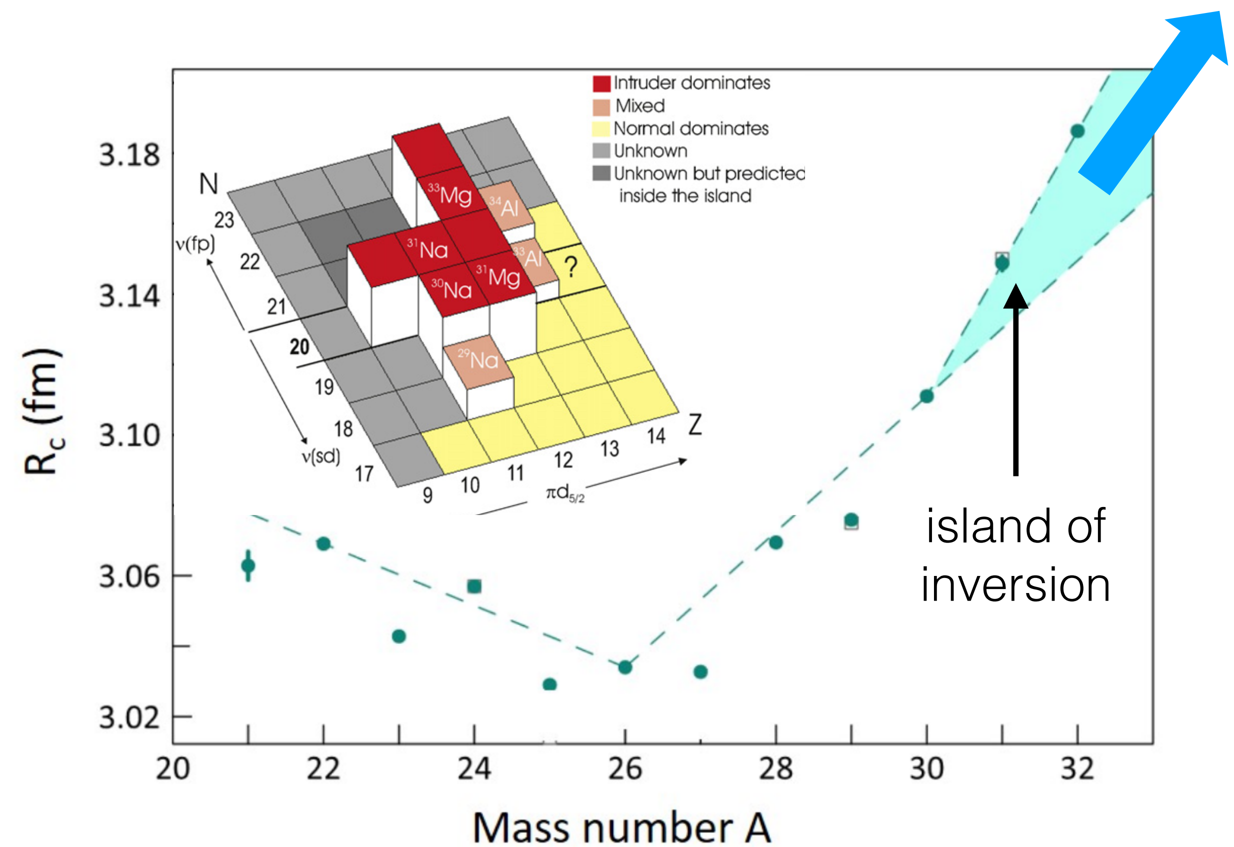
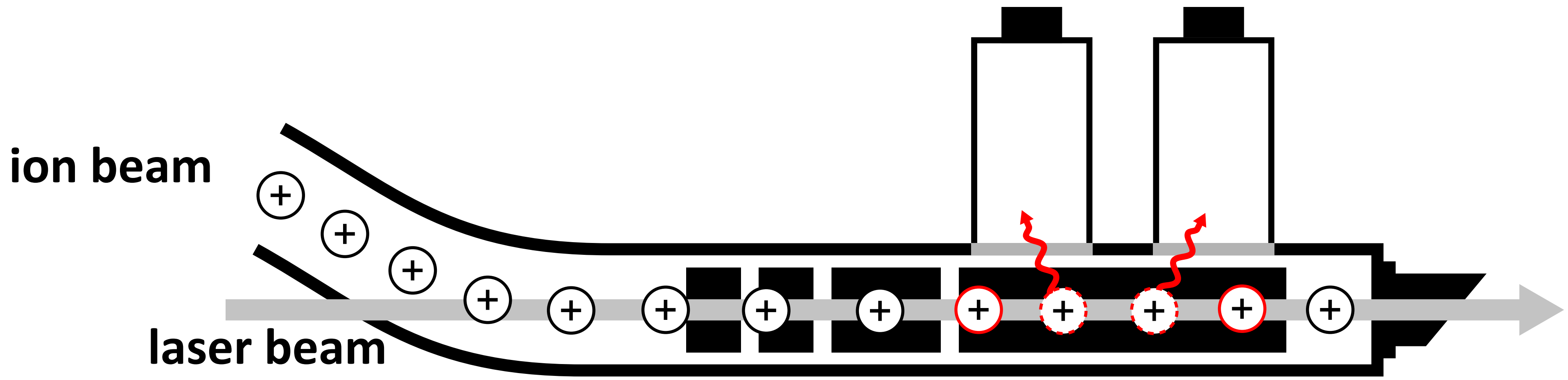


D. T. Yordanov et al., Phys. Rev. Lett. 108, 042504 (2012)

<u>Challenge:</u> very low production yields <100 ions / sec

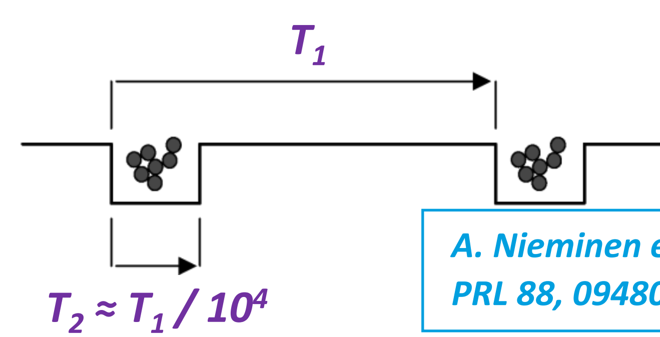
Strengths & Limitations of CLS



beams of ≥30 keV
minimizes Doppler-broadening
⇒ high resolution

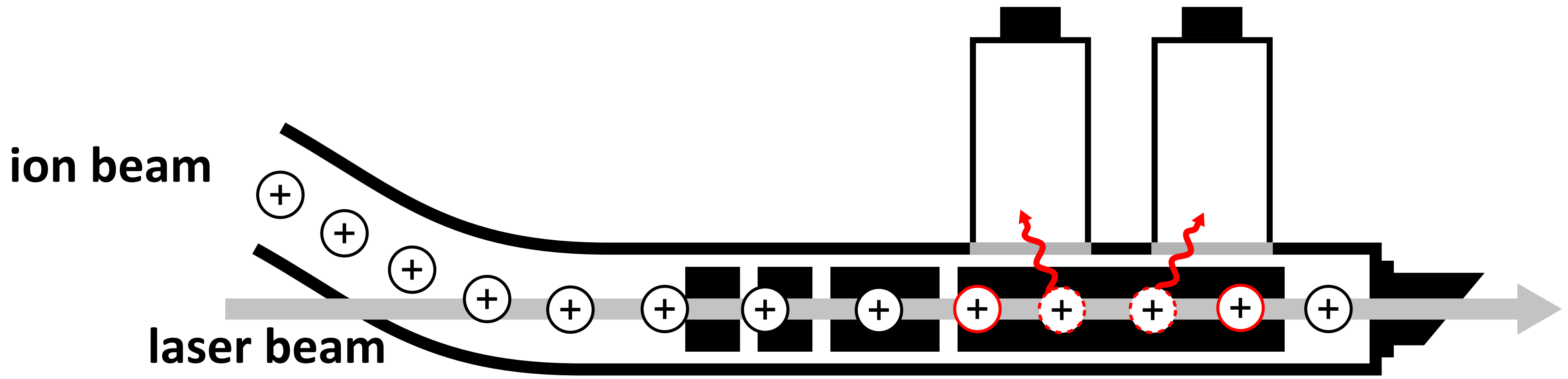
$$\delta\nu \propto \frac{\delta E}{\sqrt{E}}$$

Bunched beams:
reduce background
by gating on bunch



A. Nieminen et al., PRL 88, 094801 (2002)

Strengths & Limitations of CLS



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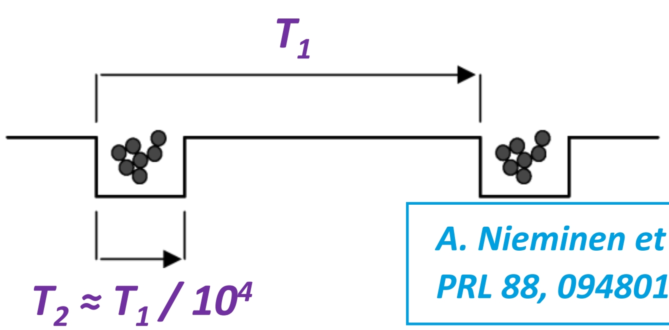


A. Nieminen et al., PRL 88, 094801 (2002)

$T_{1/2}$ of accessible radionuclides:
5 ms to seconds

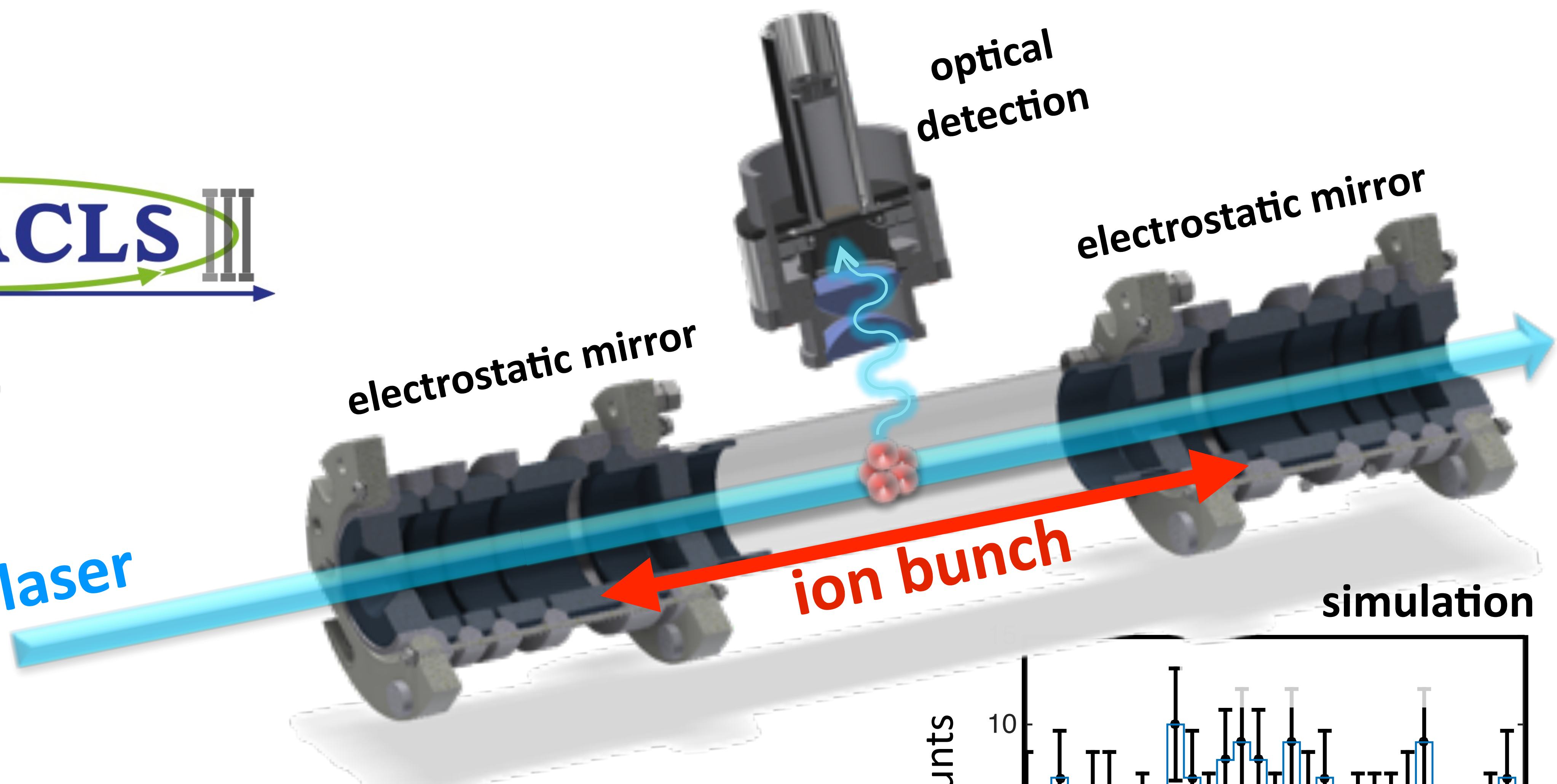
↔

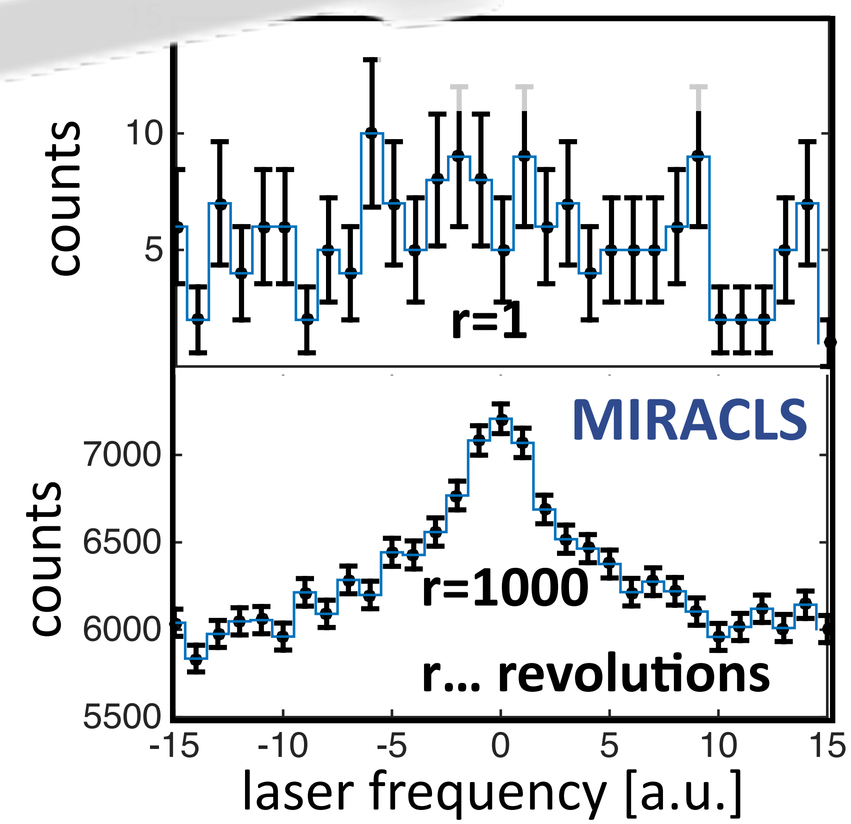
effective use for CLS
100s of ns to a few µs

¿ can one use exotic nuclides even <u>more efficiently</u> ?

the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy

trap ⇒ long observation time ⇒ higher sensitivity ⇒ more exotic nuclides accessible

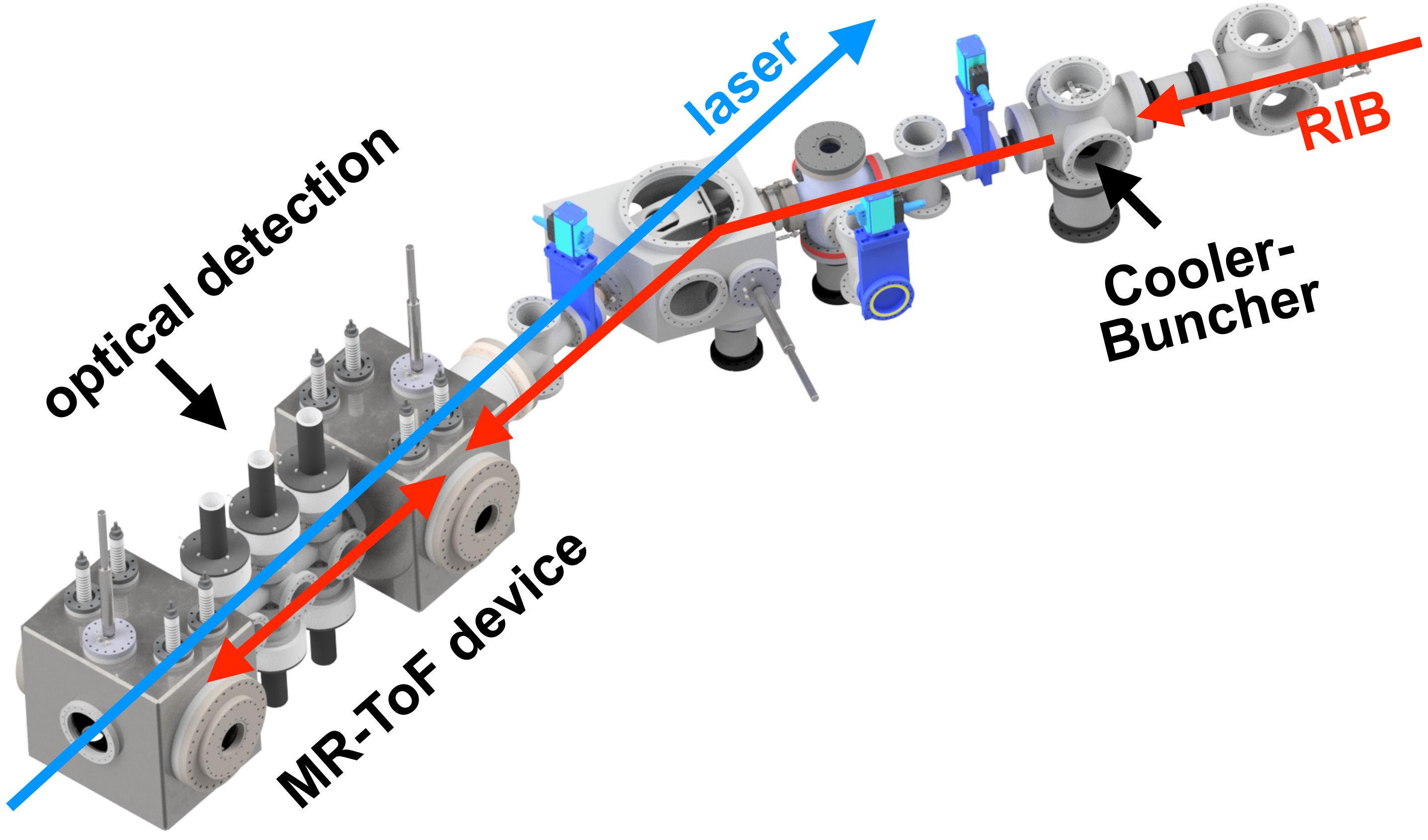




novel approach for collinear laser spectroscopy:

- ion trap ⇒ long observation time
- >10 keV beam ⇒ high resolution

MIRACLS setup at ISOLDE



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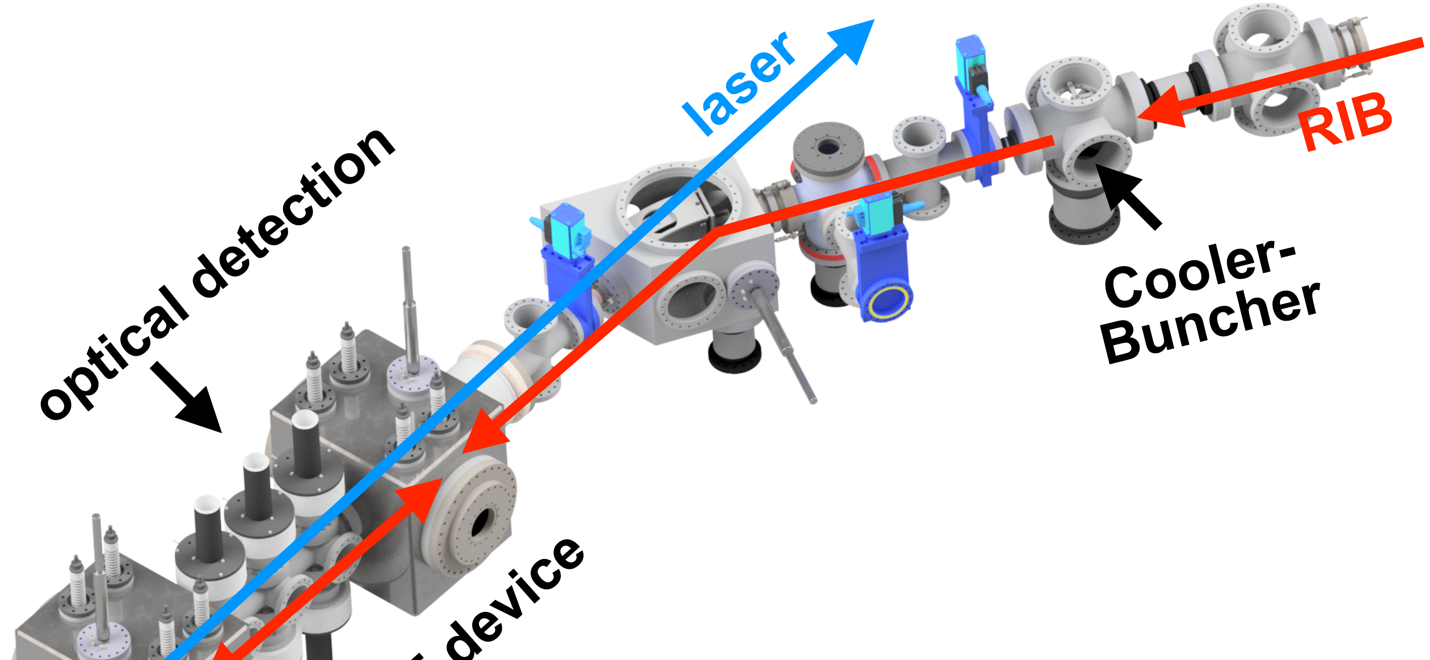
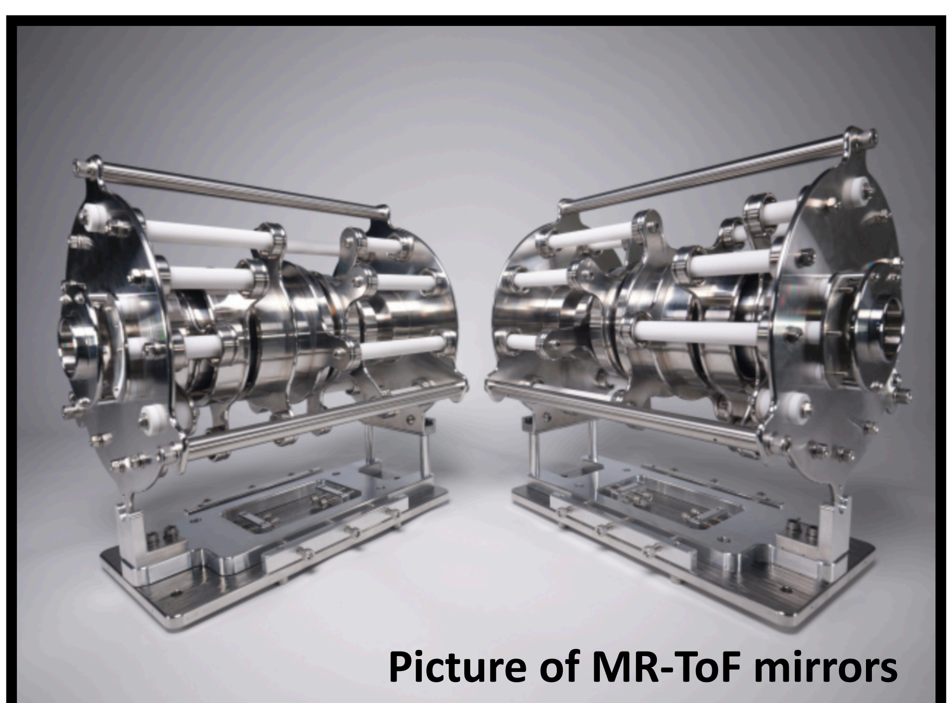
MIRACLS setup at ISOLDE



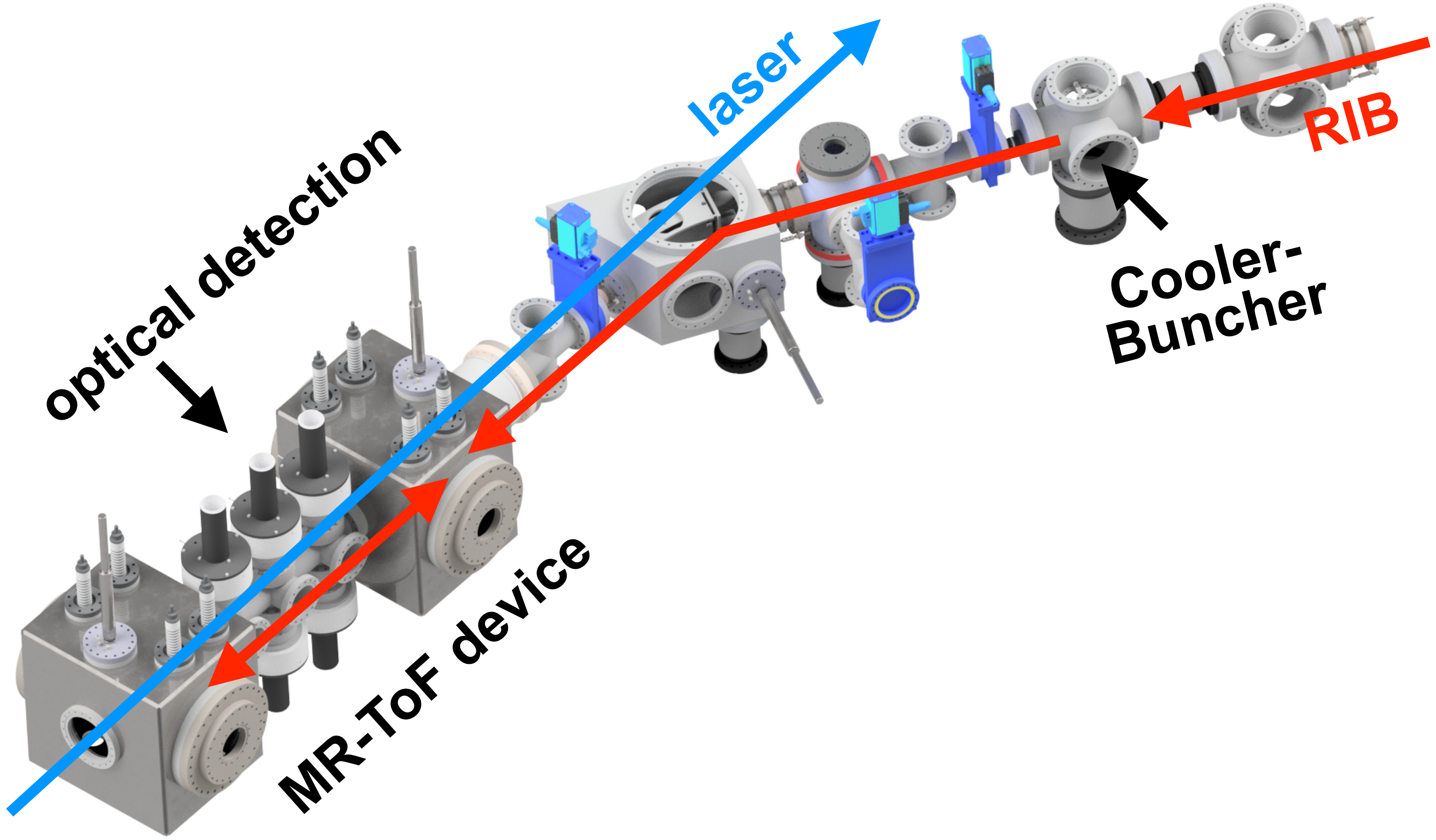

Picture of MR-ToF mirrors

MR-ToF operation: 10-15 keV
opportunity for RIB purification

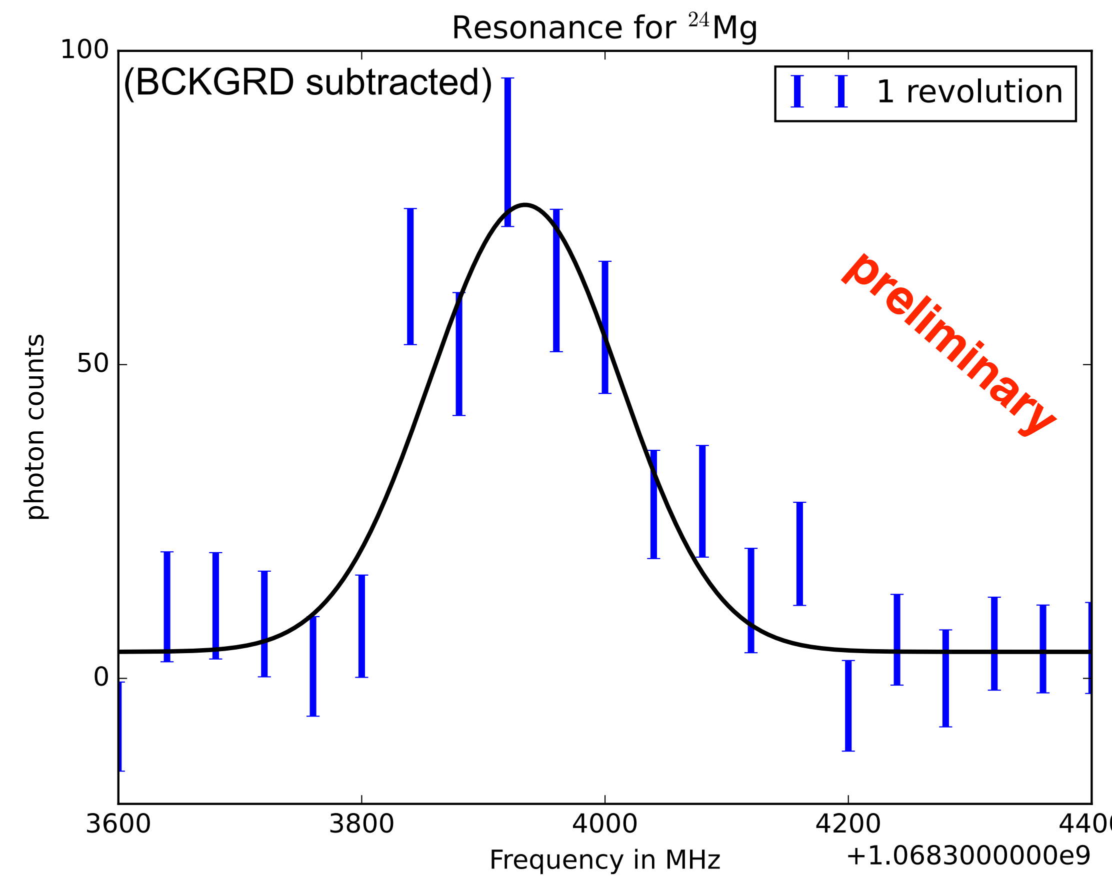
F. Maier et al., Nuclear Instrum. Meth. A, 1056, 168545 (2023)
F. Maier et al., Nuclear Instrum. Meth. A 1075, 170365 (2025)

European Research Council

MIRACLS setup at ISOLDE



Single-passage = conventional CLS



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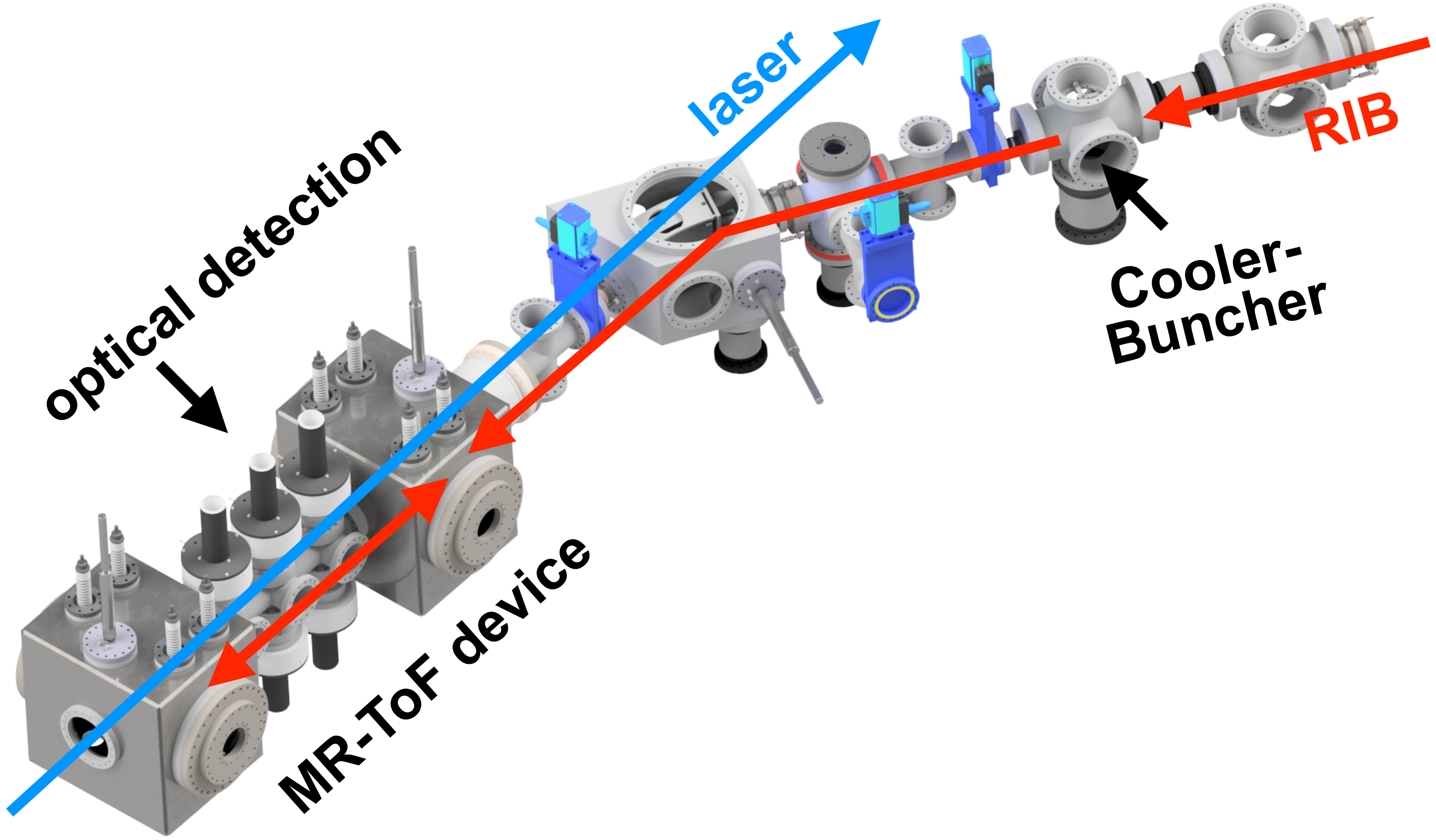
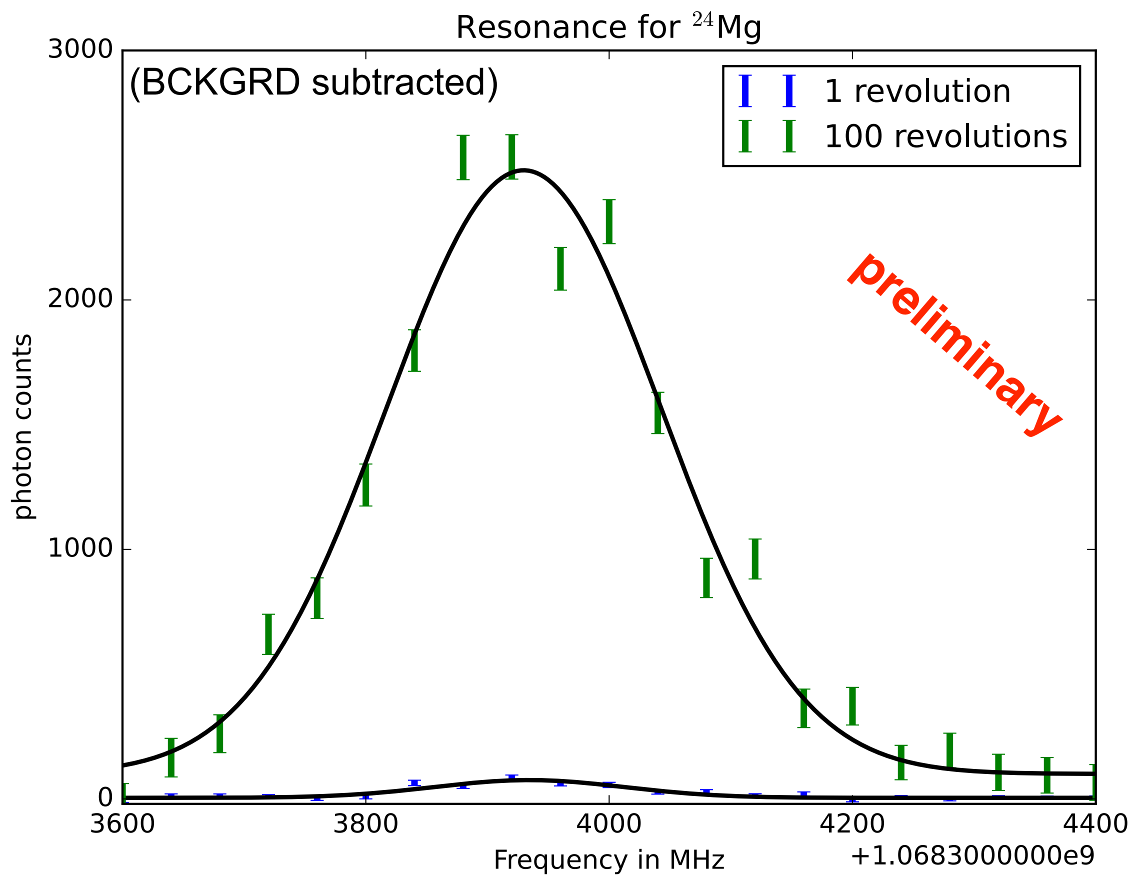
demonstration





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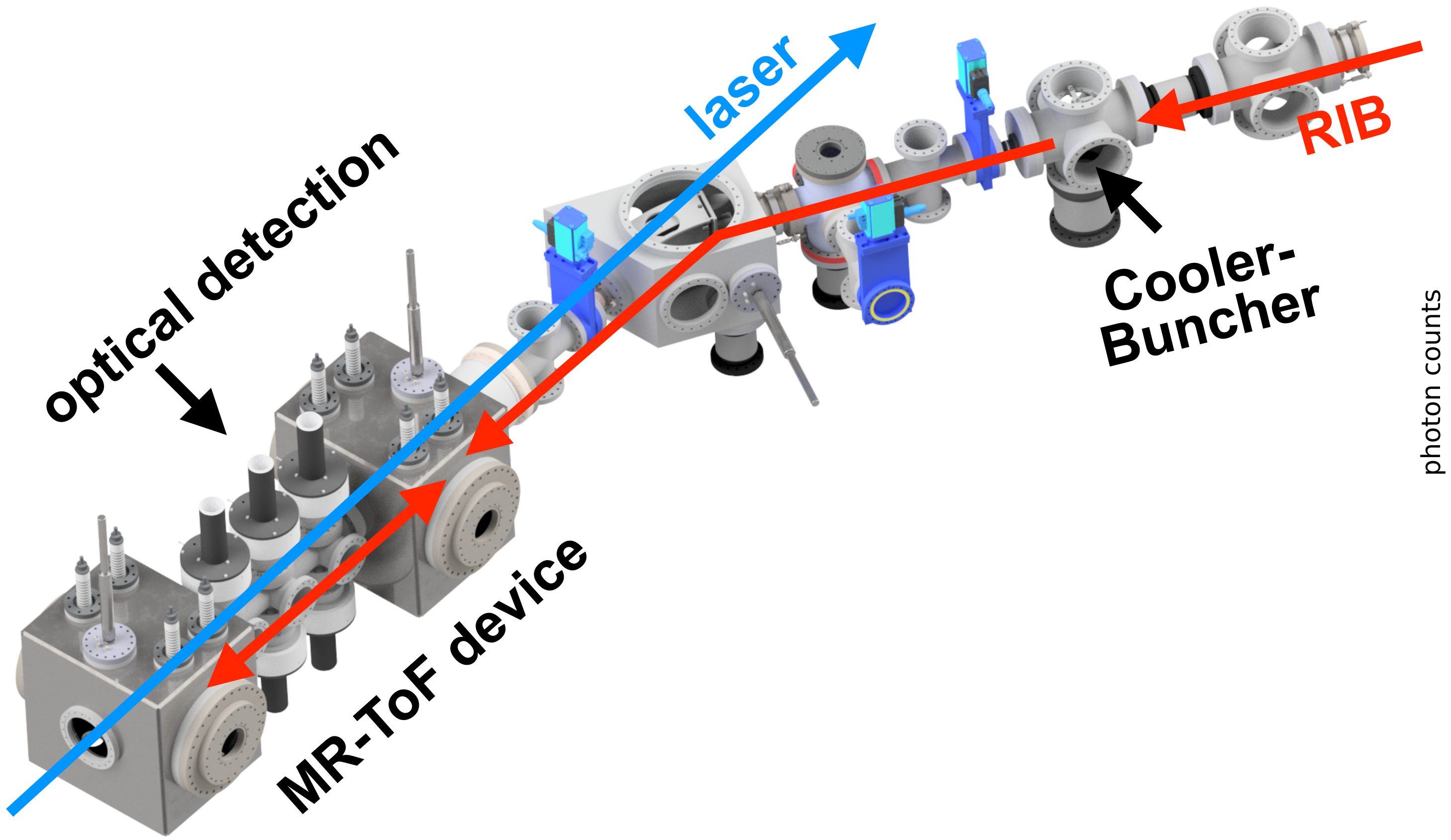
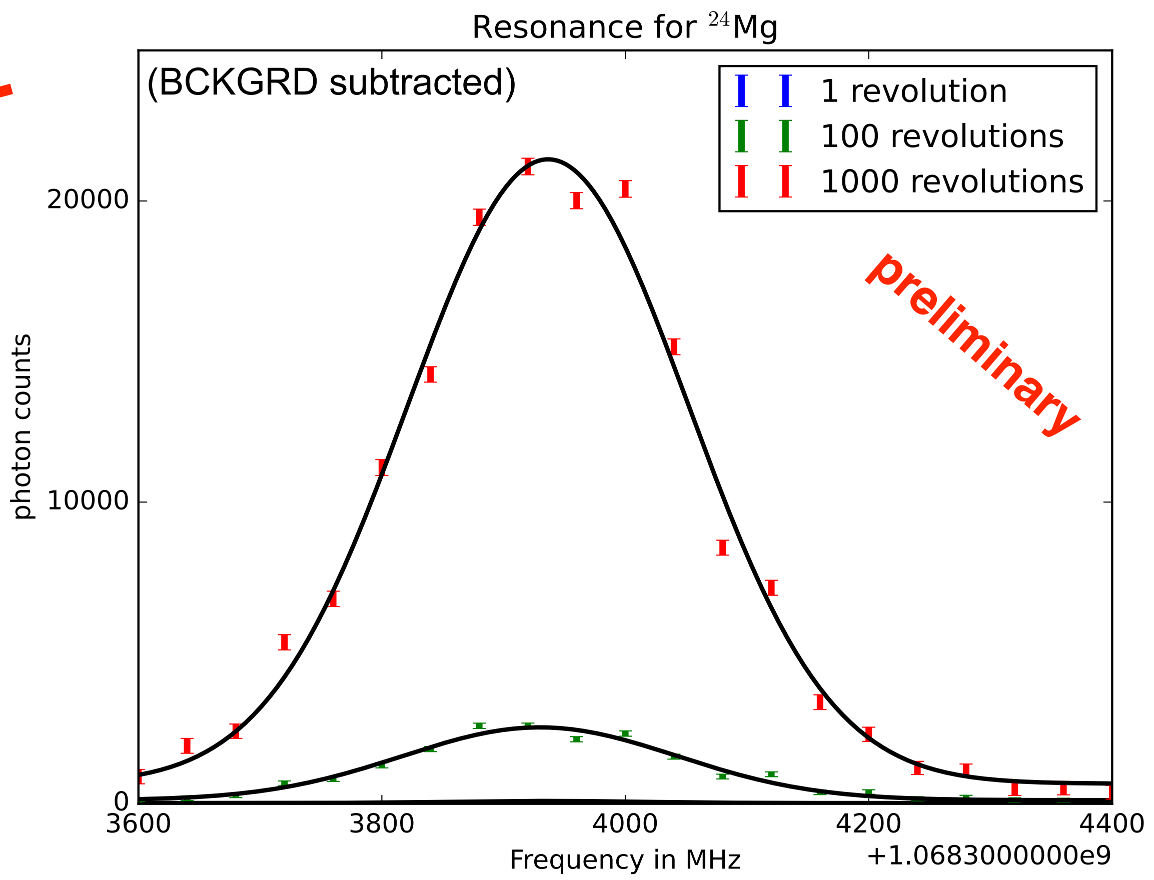
MIRACLS demonstration





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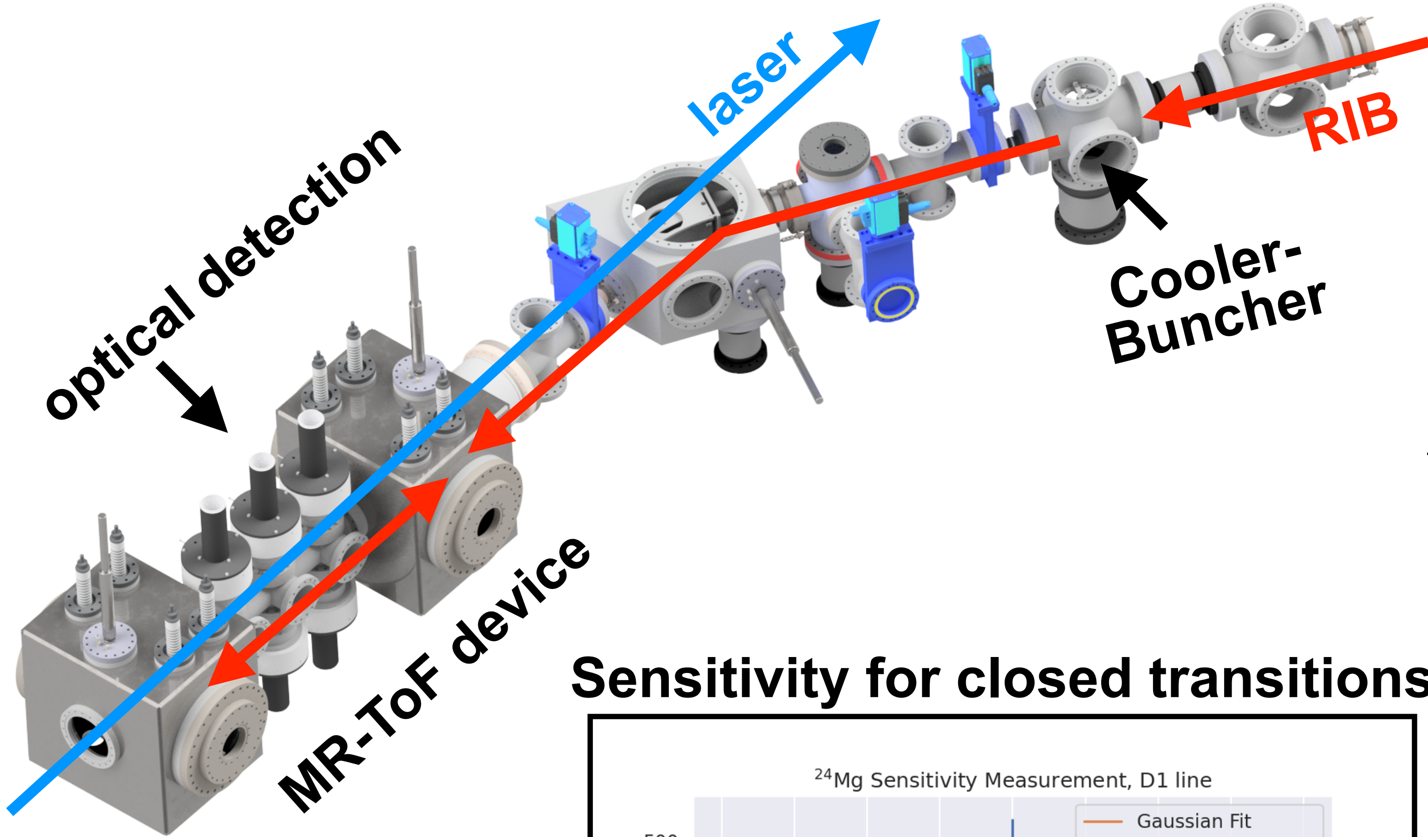
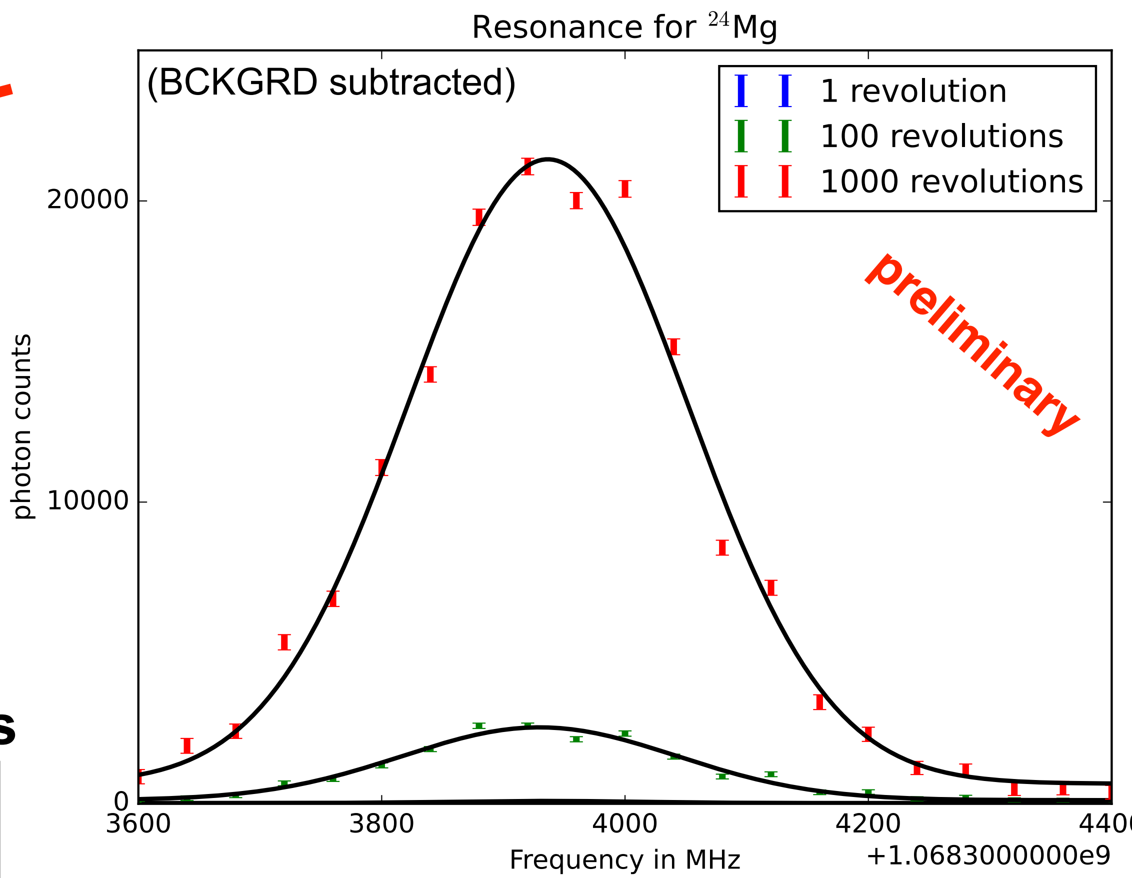
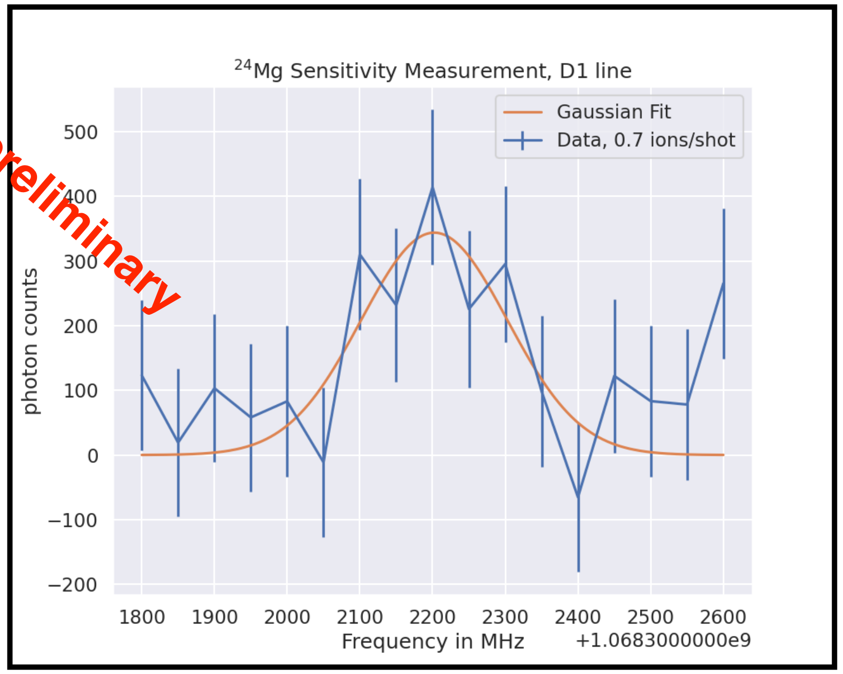
MIRACLS demonstration





Sensitivity for closed transitions



- 0.7 ions/cycle injected into MR-ToF
- buncher efficiency 15-25 %

⇒ minimal ISOLDE yield: **3-5 ions / sec**

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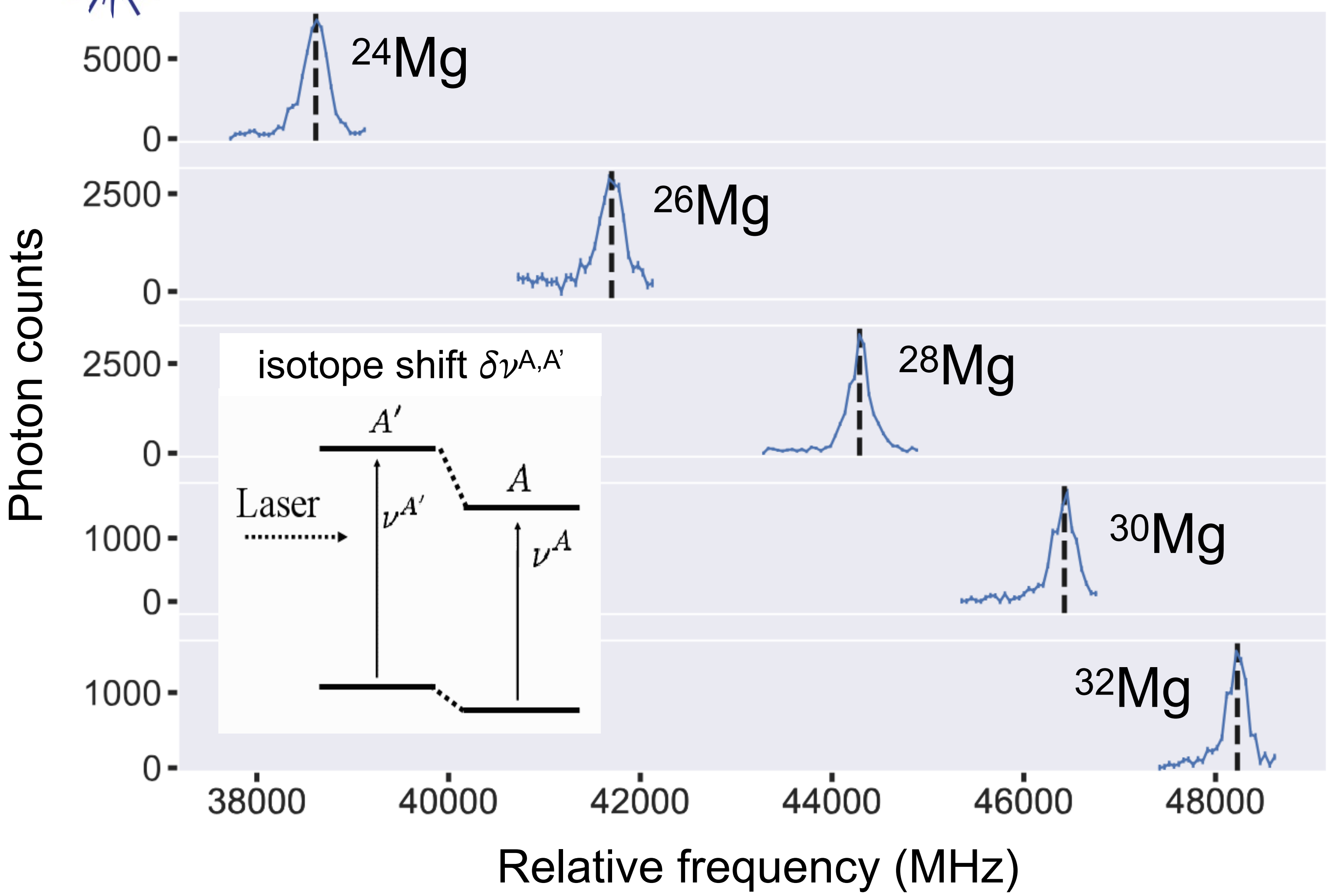
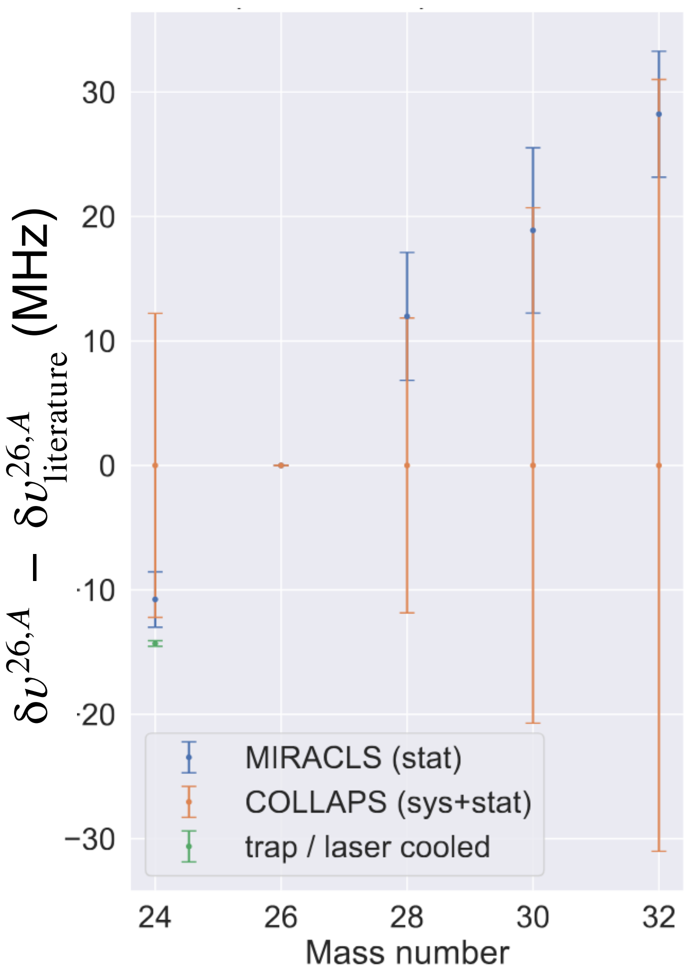
online results

all preliminary





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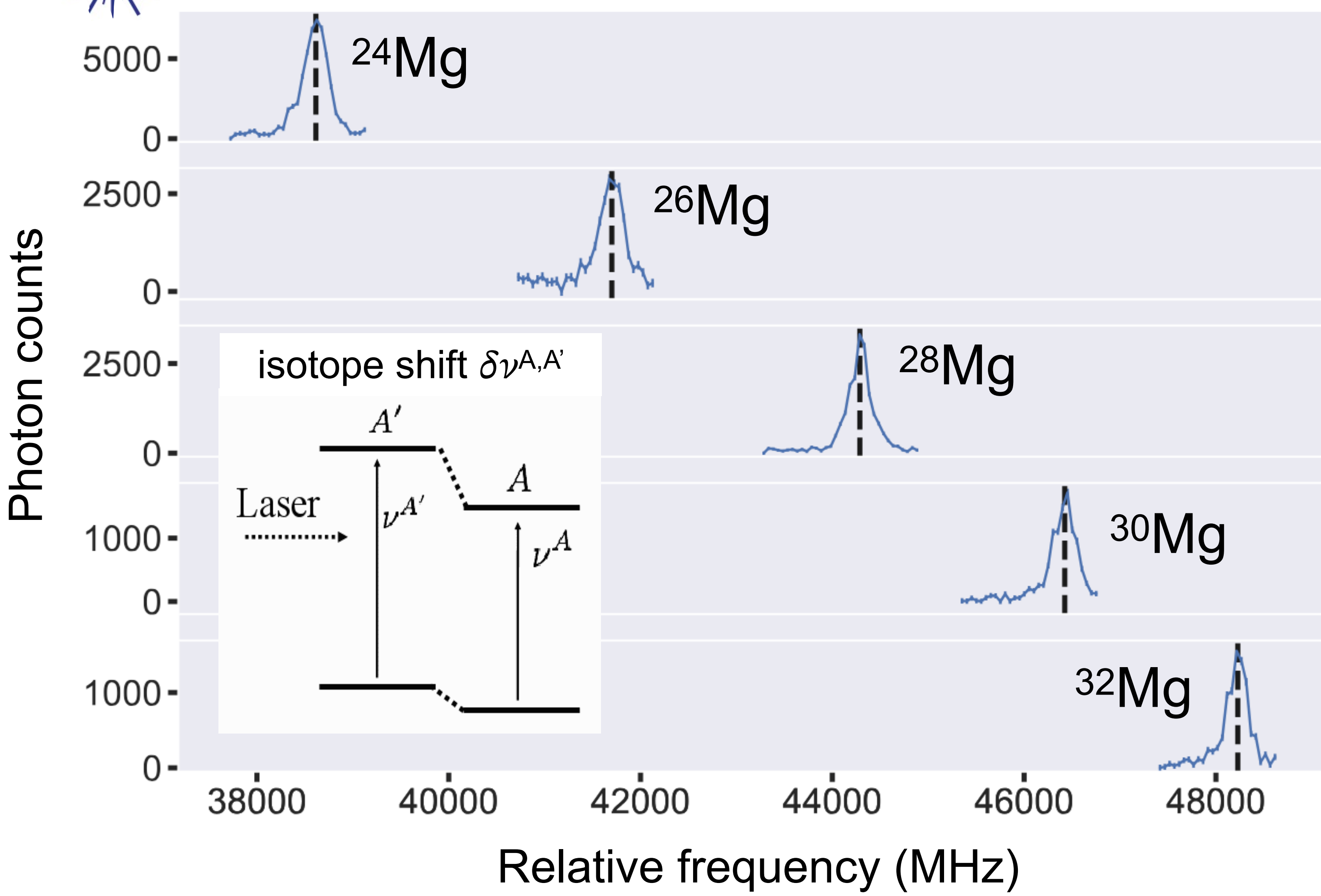

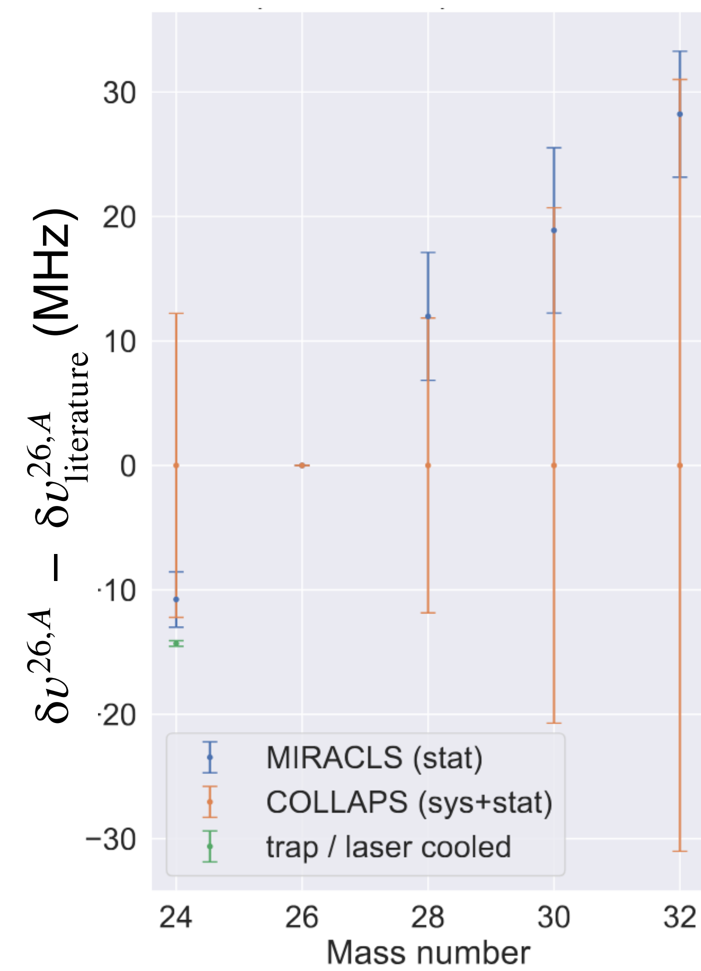

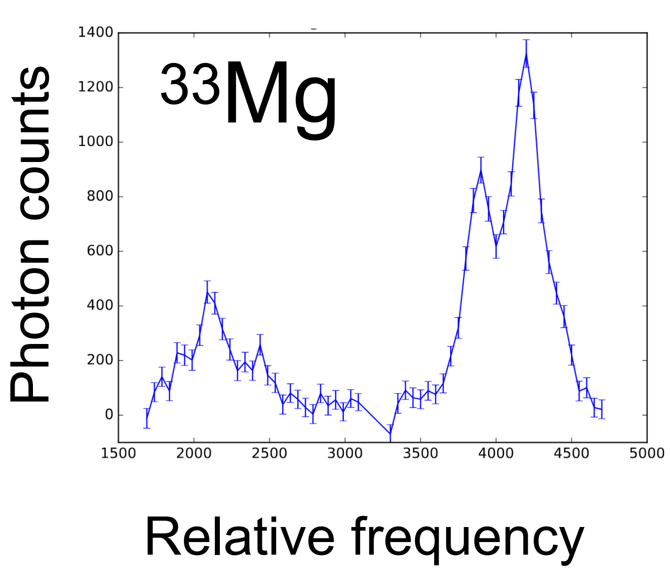

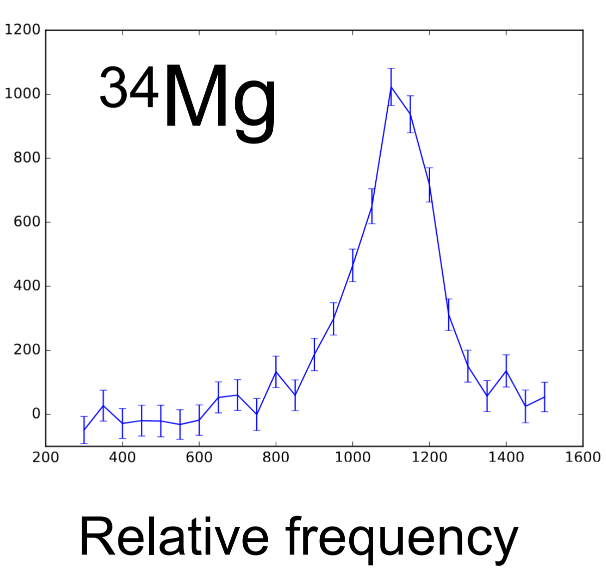

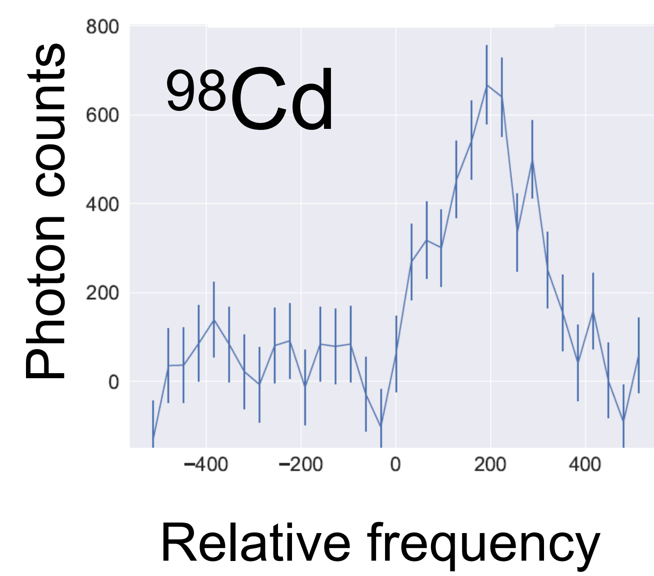

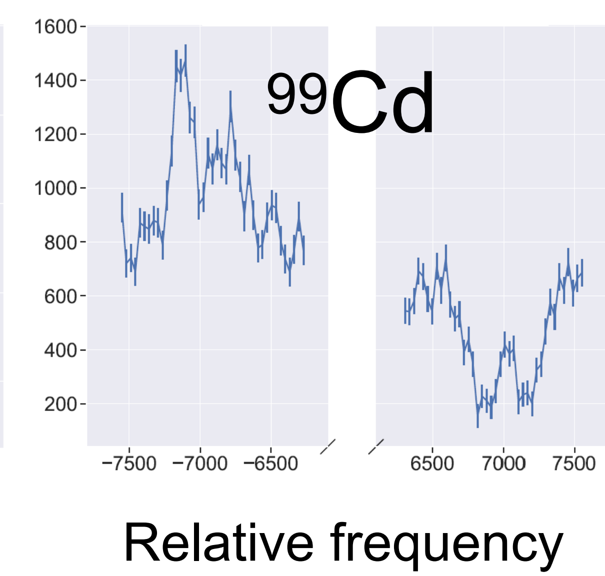

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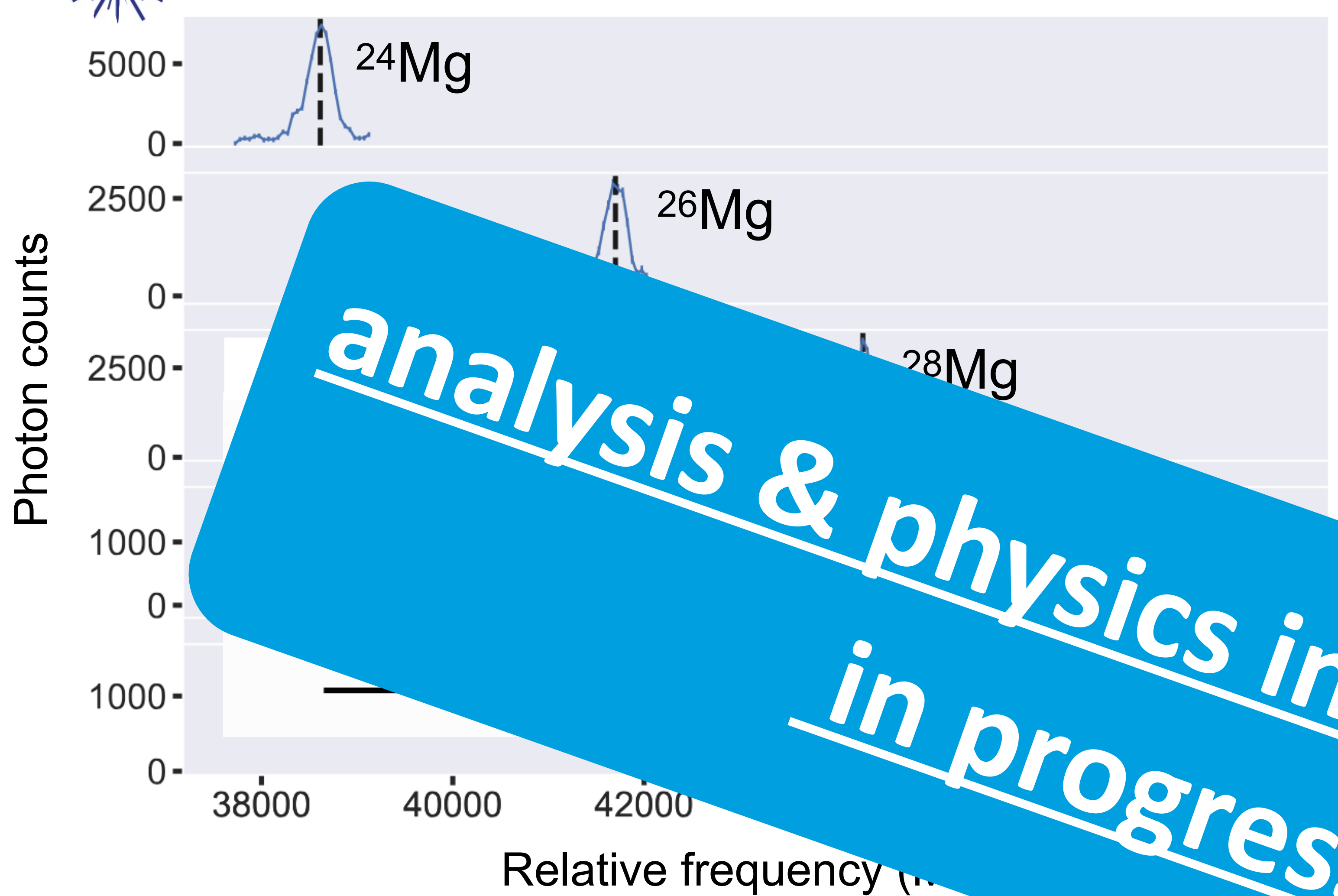
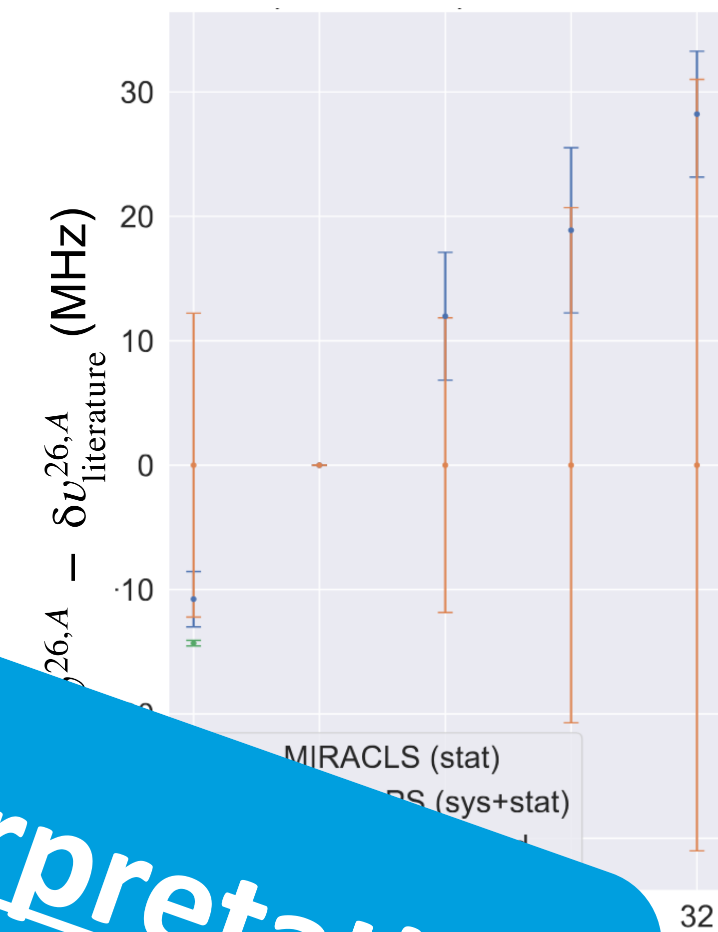
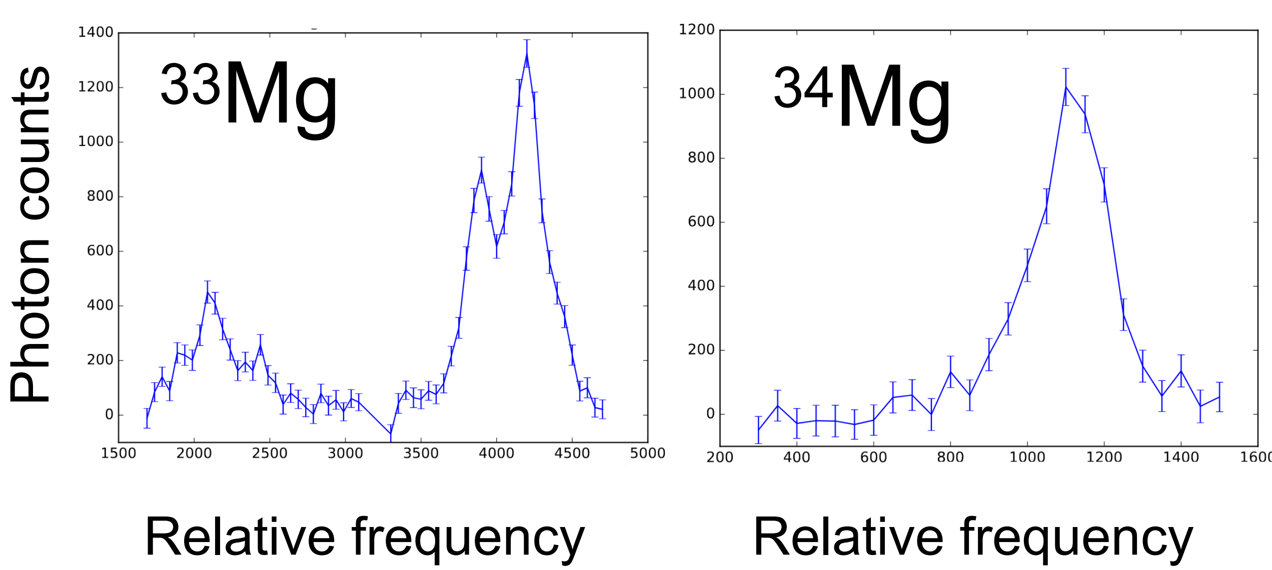
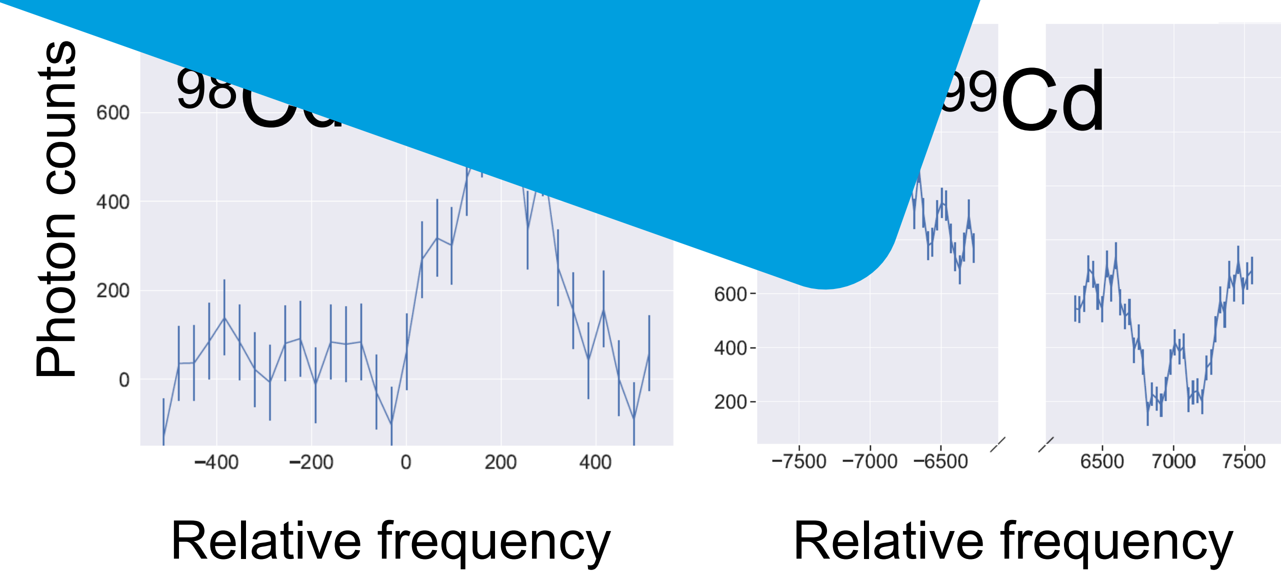




analysis & physics interpretation in progress



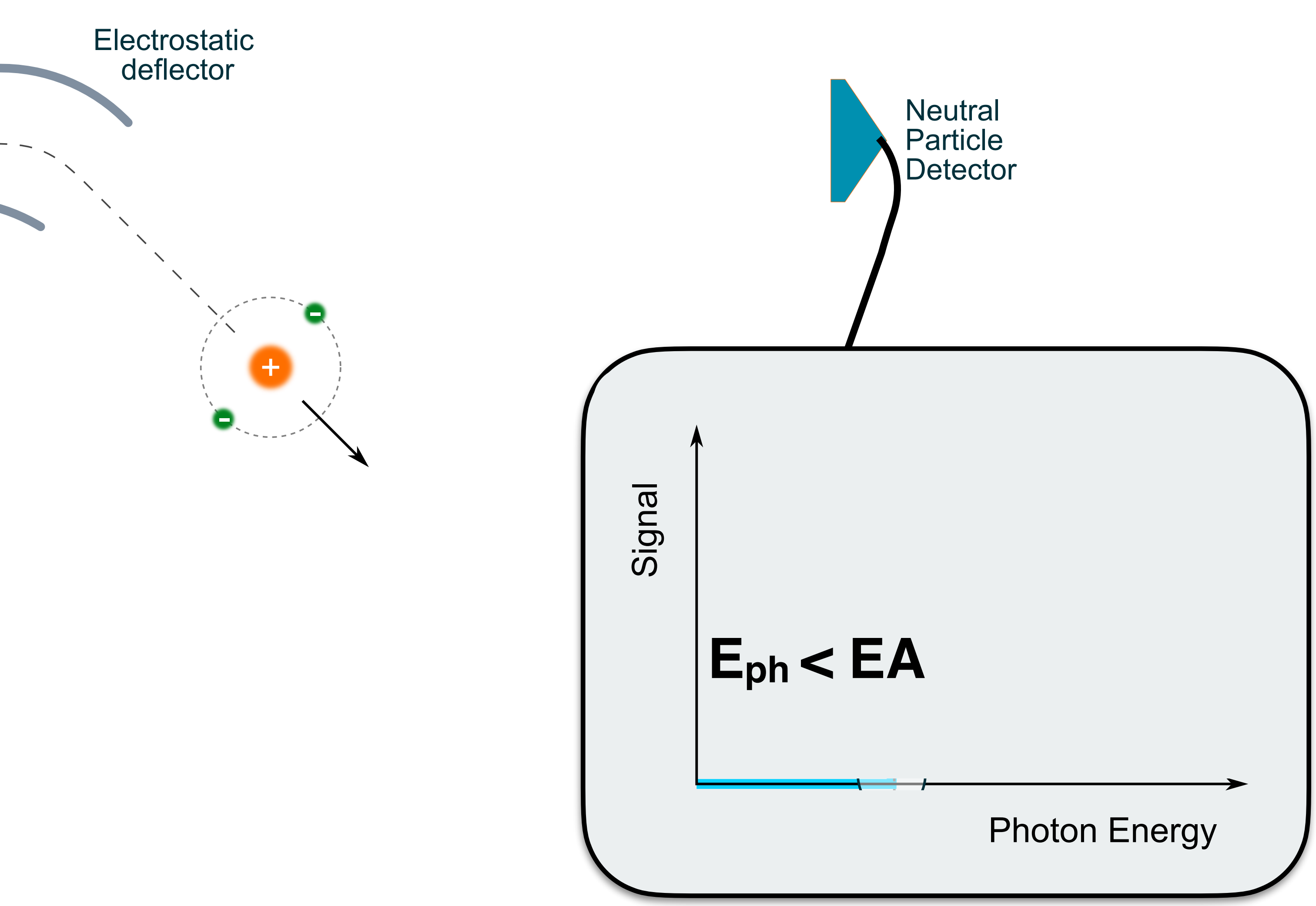


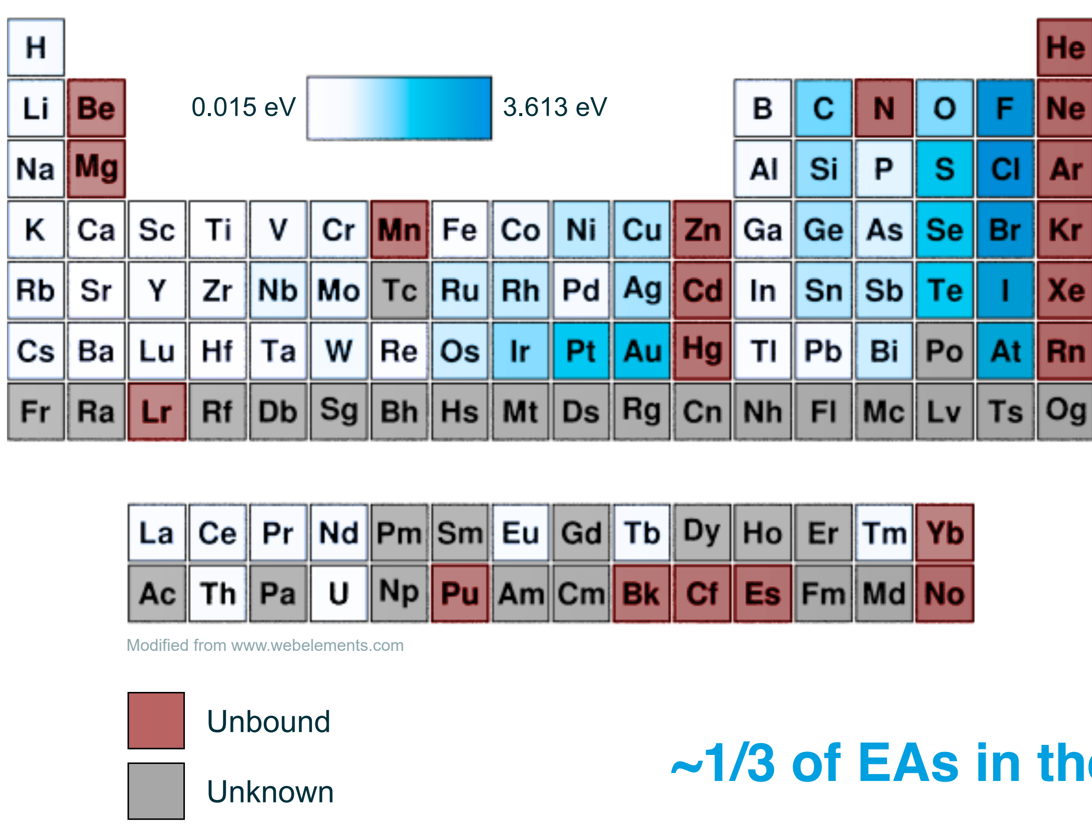
CLS for Electron Affinity

EA: energy needed to remove an electron from a negative ion

"how much an element is prone to form chemical bonds by sharing electrons"

Laser: probes the energy needed to dismantle the negative ion





~1/3 of EAs in the Periodic Table are unknown

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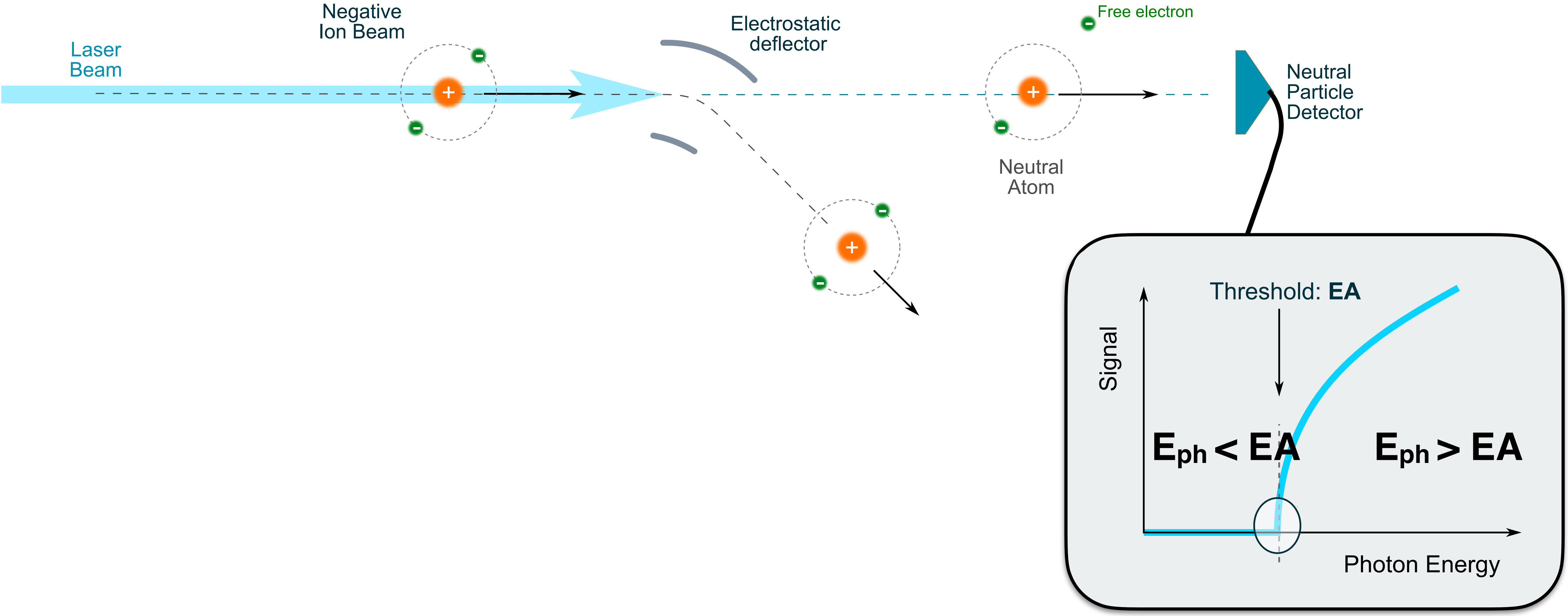

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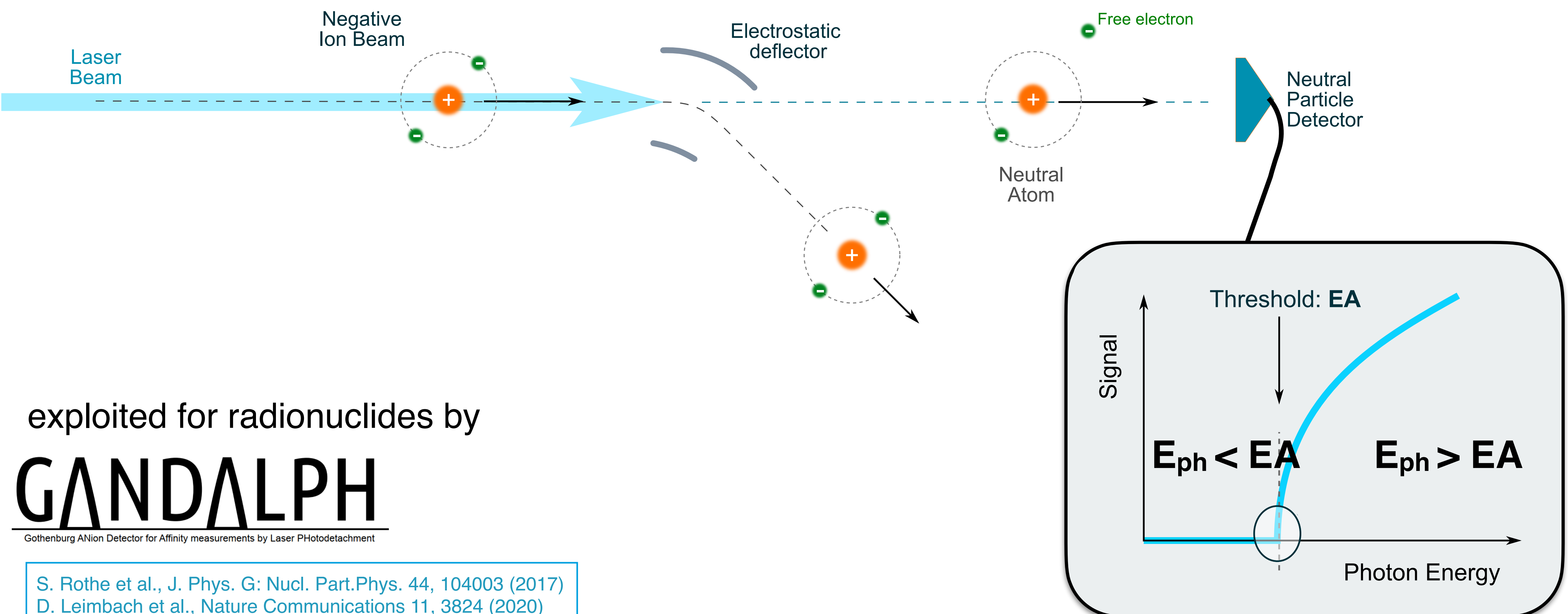


exploited for radionuclides by

GANDALPH

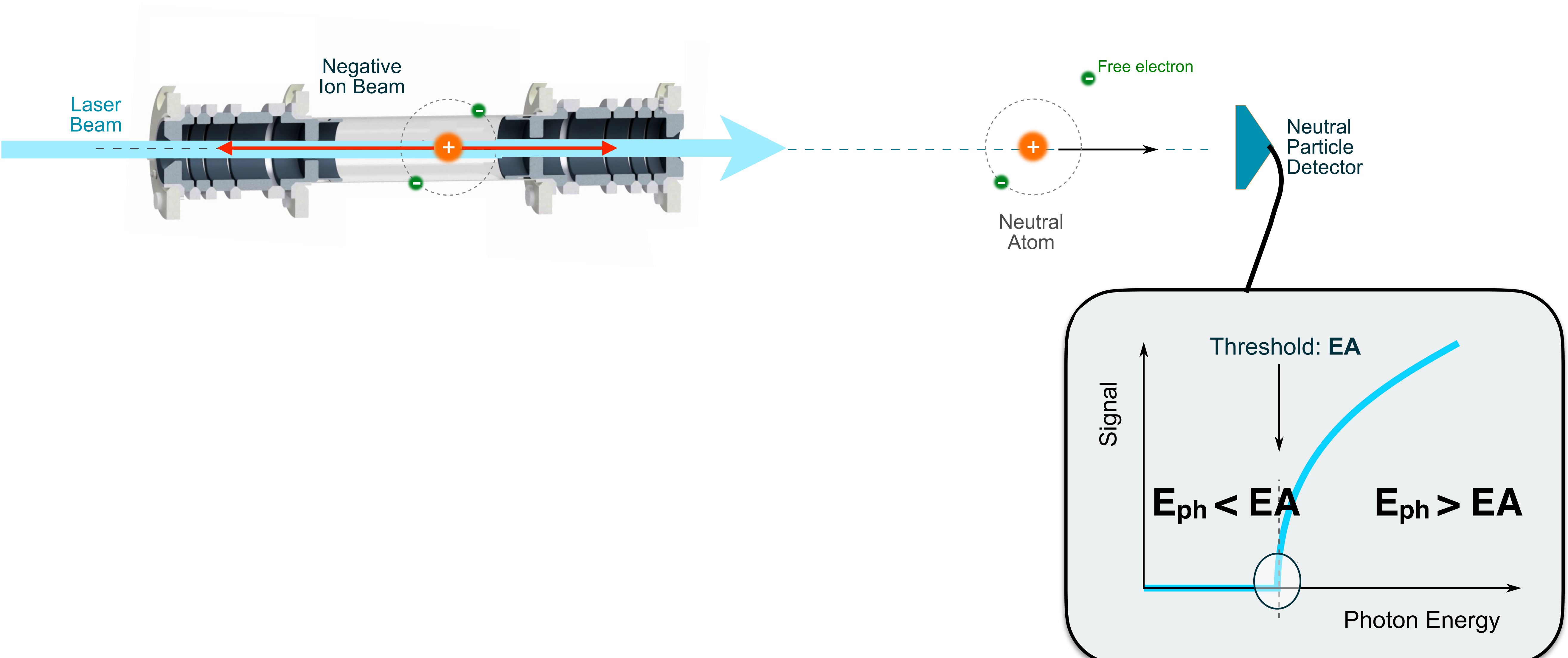
Gothenburg ANion Detector for Affinity measurements by Laser PHotodetachment

S. Rothe et al., J. Phys. G: Nucl. Part.Phys. 44, 104003 (2017)
D. Leimbach et al., Nature Communications 11, 3824 (2020)

EA studies with MIRACLS

Increase exposure to laser beam by ion-beam confinement in MR-ToF

long exposure time ⇒ less particles for same signal ⇒ gain in sensitivity



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F. Maier et al., Nature Communications, 16, 9576 (2025)

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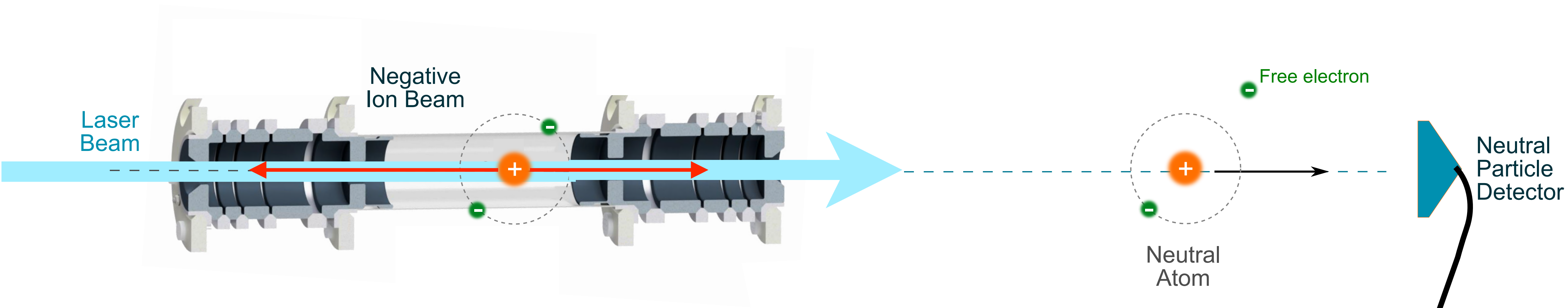
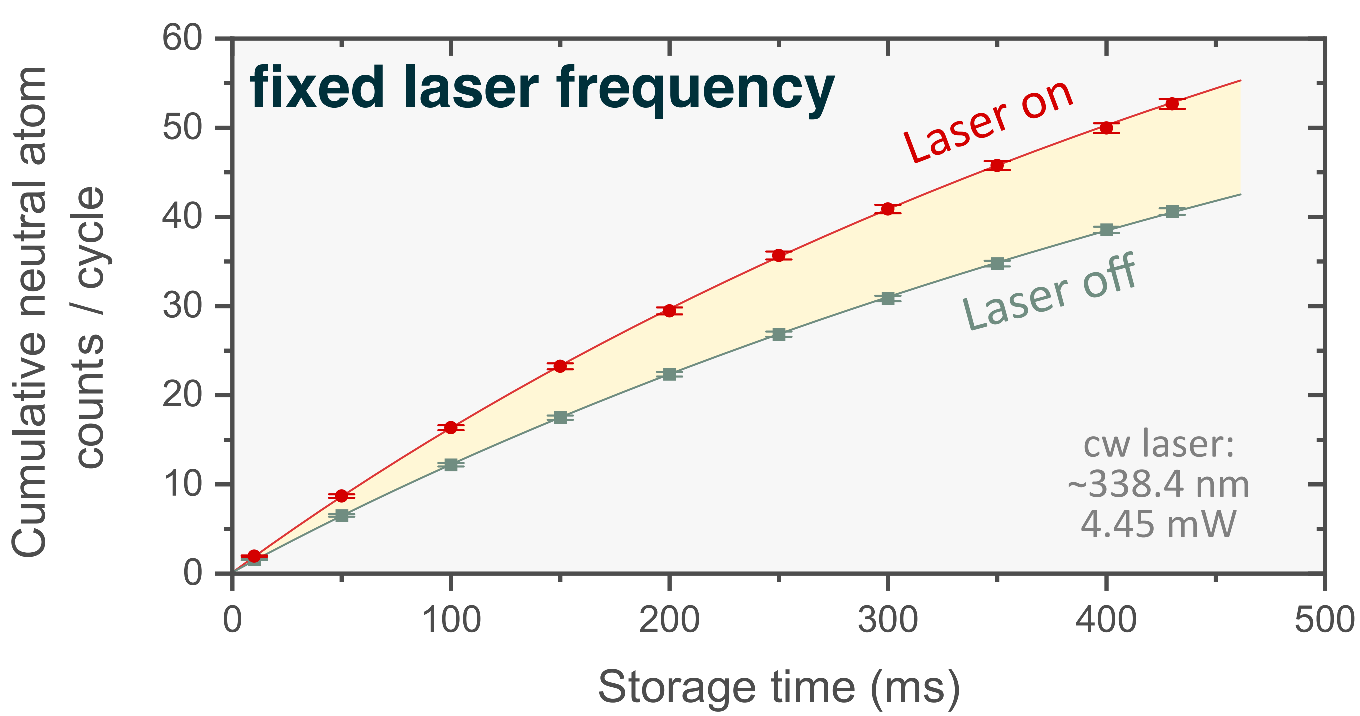
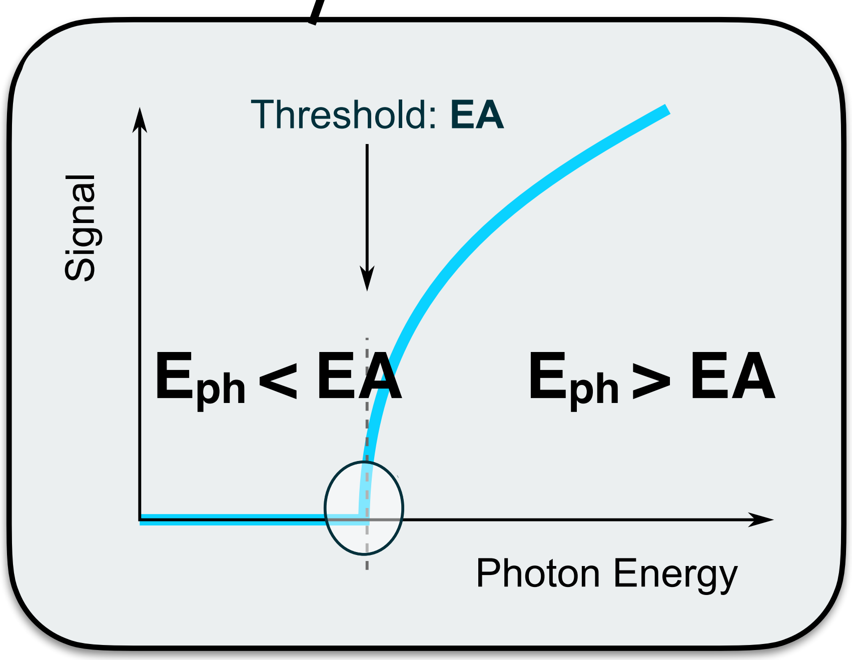
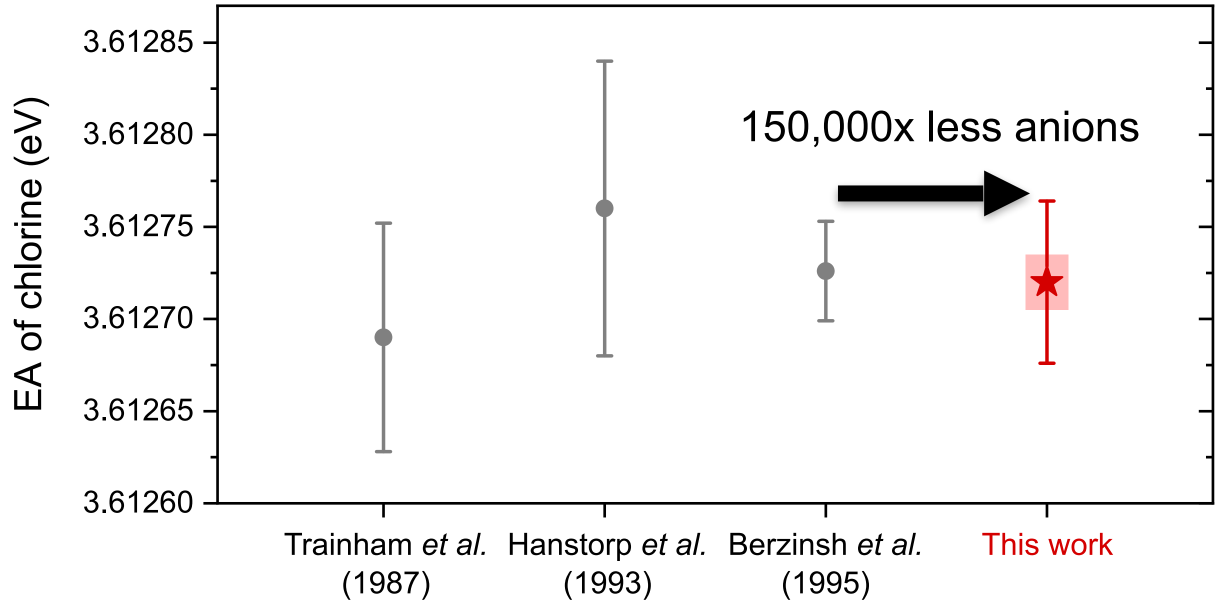






F. Maier et al., Nature Communications, 16, 9576 (2025)

EA sensitivity gain with MIRACLS



Results:

- (improved EA of Cl)
- same precision with ≈10^5 fewer anions

Opportunities:

- further improvements to be implemented
  ⇒ atom-at-a-time sensitivity
- EA isotope shifts
- EA measurements of (super)heavy elements

F. Maier et al., Nature Communications, 16, 9576 (2025)

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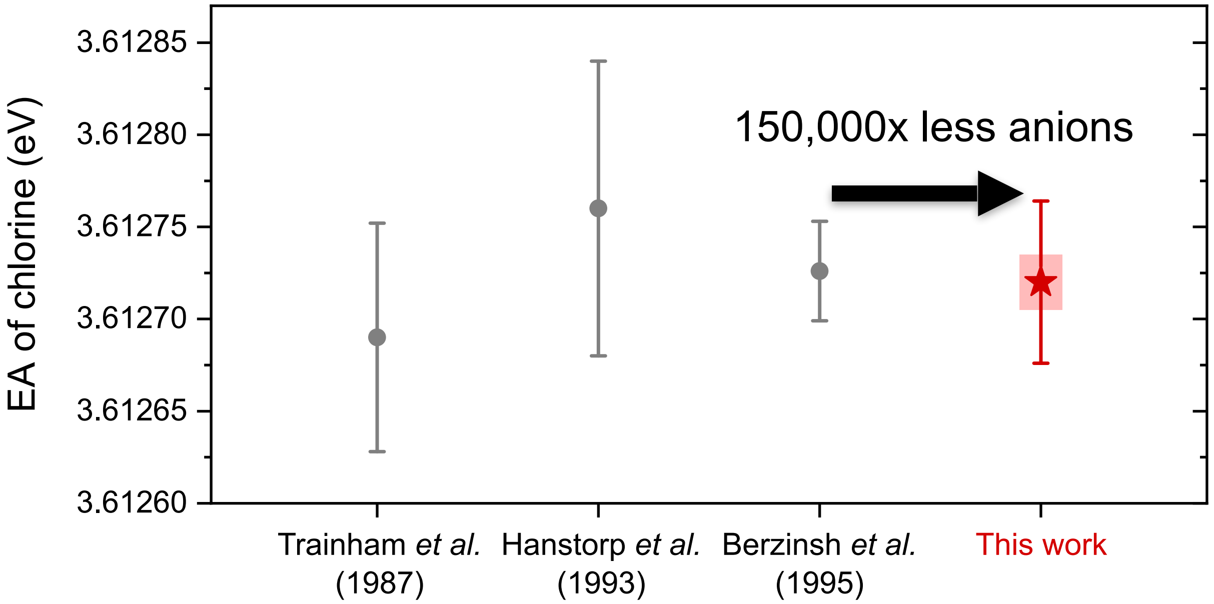

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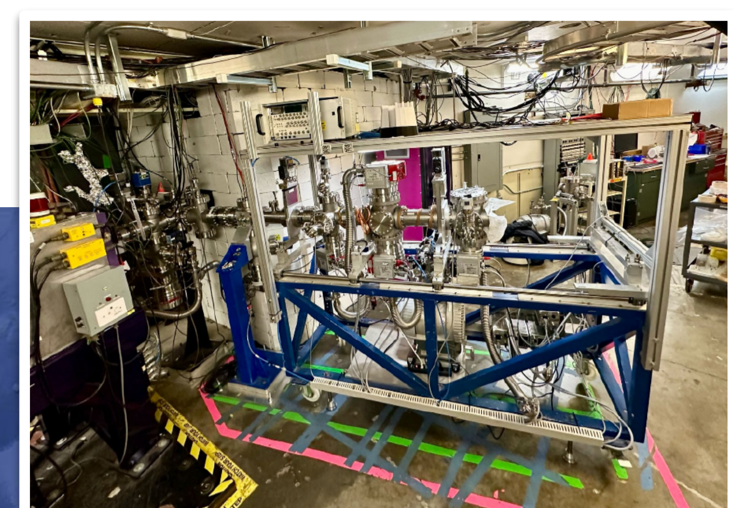
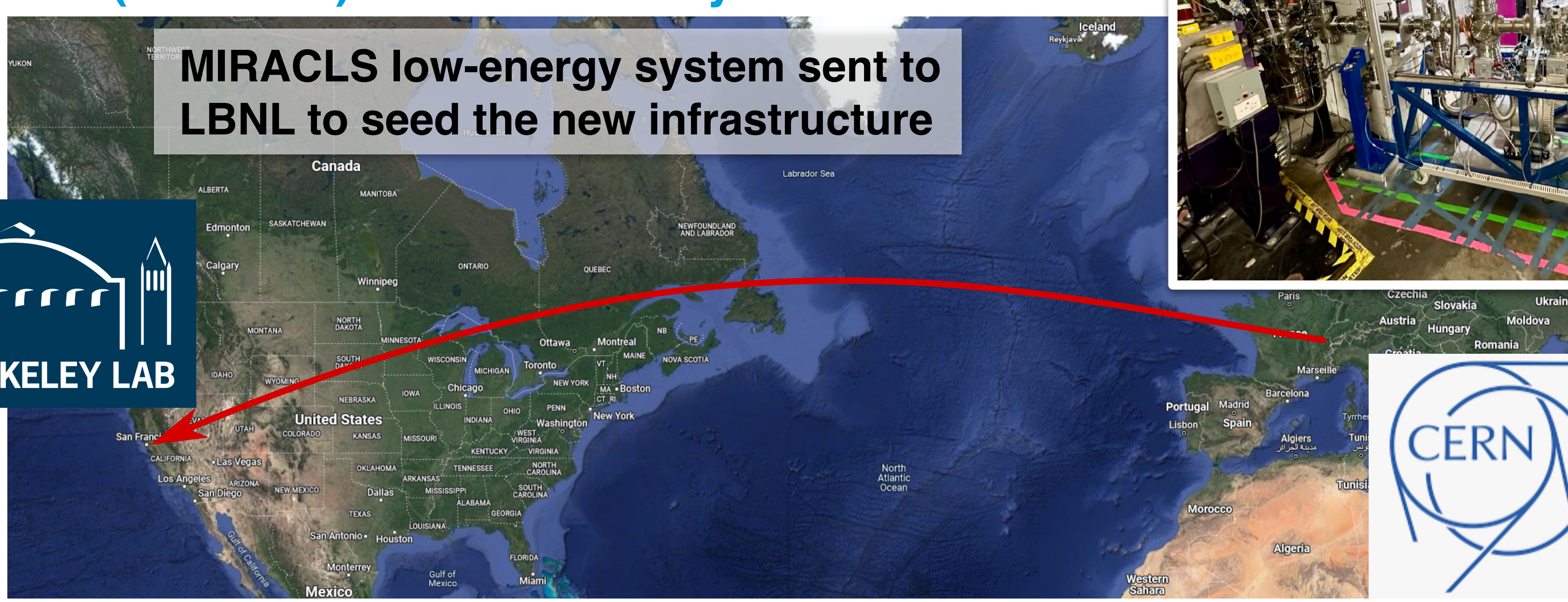
F. Maier et al., Nature Communications, 16, 9576 (2025)

Advanced Electrostatic Trap for Heavy Element Research (AETHER) @ BGS / 88" cyclotron





Summary & Conclusions

- **collinear laser spectroscopy (CLS) powerful tool to access nuclear ground-state properties**

COLLAPS CRIS BECOLA CLS@IGISOL CFBS@TRIUMF

new CLS beamlines: ATLANTIS, PLASEN (Precision Laser Spectroscopy for Exotic Nuclei), LASAGN, REBEL, CLaSsy …

- **charge radii: excellent benchmarks for nuclear theory**

  ➡ towards a 'universal' description of charge radii
  ➡ DFT Fayans: odd-even staggering + kinks at shell closures
  ➡ ab initio: 1 % accuracy in Ni
  ➡ **importance of new experimental data**

- **sensitivity challenge:**

CRIS

MIRACLS
➡ novel ion-trap system for highly sensitive CLS
➡ successful online measurements of Mg and Cd
➡ highly-sensitive EA measurements: towards (super-)heavies
➡ new opportunities, e.g., for RIB purification

collaboration:

CERN, Universität Greifswald, Technische Universität Darmstadt, McGill, TRIUMF

23

MIRACLS team and participants

L. Croquette, H. Heylen, E. Leistenschneider, S. Lechner, F. Maier, L. Nies, P. Plattner, M. Rosenbusch, F. Wienholtz, M. Vilen, R. Wolf, F. Buchinger, W. Nörtershäuser, L. Schweikhard, O. Ahmad, T. Fabritz, P. Giesel, R. Hernandez, H. Heylen, J. Hughes, F. Koehler, K. König, D. Lange, L. Lalanne, T. Lellinger, E. Matthews, A. Mcglone, K.Mohr, J. Palmes, V. Repo, L. Rodriguez, C. Shweiger, J. Spahn, J. Warbinek, J. Wilson, Z. Yue, C. Zambrano, S. Malbrunot-Ettenauer

MIRACLS EA team

F. M. Maier, E. Leistenschneider, M. Au, U. Berzins, Y. N. Vila Gracia, D. Hanstorp, C. Kanitz, V. Lagaki, S. Lechner, D. Leimbach, P. Plattner, M. Reponen, L. V. Rodriguez, S. Rothe, L. Schweikhard, M. Vilen, J. Warbinek, S. Malbrunot-Ettenauer

funding:

erc European Research Council, ATTRACT, CERN Medical Applications Funds, NSERC CRSNG

https://miracls.web.cern.ch