Collinear laser spectroscopy techniques

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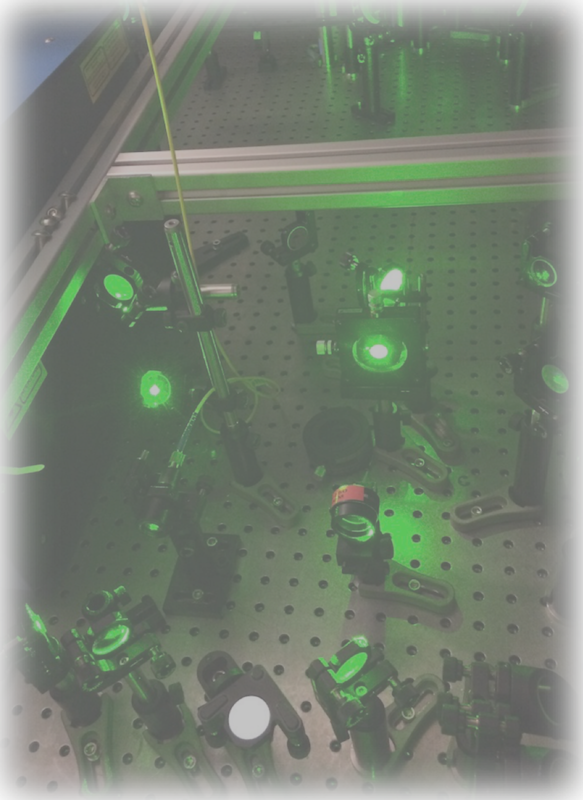


FNPMLS

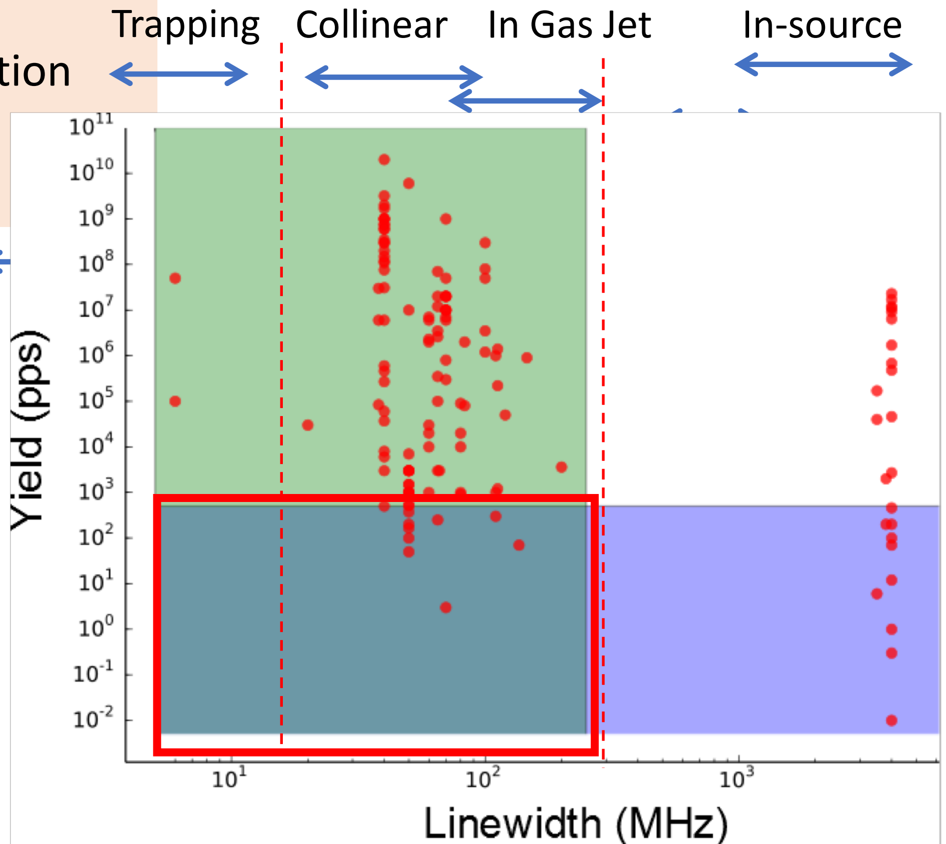
Overview

- Assume some background in laser spectroscopy
- Experimental considerations at on-line facilities
- Brief recap of collinear method and focus on collinear resonance ionization spectroscopy.
- Isotope shifts and charge radii as a test for inter-nucleon interactions and many-body methods
- Recent results from the CRIS experiment
- Concluding remarks

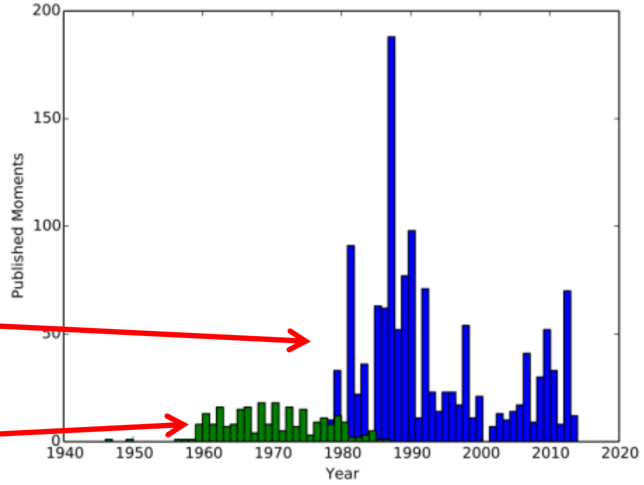
Laser Spectroscopy Requirements

Exotic nuclei at the limits of stability	Near Stability Nuclei
Expected yields <<1 atom/second Lifetimes <1s Relatively large isobar contamination	Expected yields >10^8 atom/second Lifetimes >>1s High purity (large fraction of the beam)
Very little known low resolution ok	Resolution/precision frontier
Technique : Fast due to short half-lives Highly selective due to isobars Low yield requires a high sensitivity Lower resolution is acceptable	Technique : New physics requires high resolution Sensitivity is not critical The method can be slow

Selection of published radioactive measurements (where yields are known)



Tempting to define experiments in a future laboratory with todays techniques.



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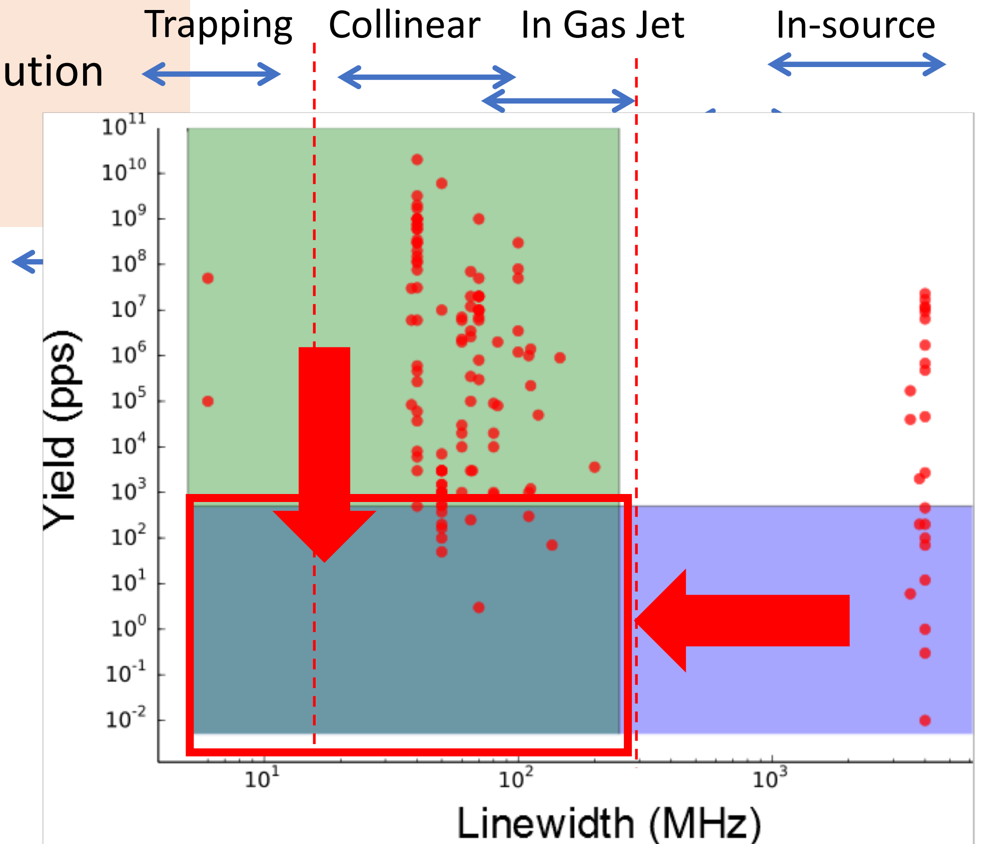

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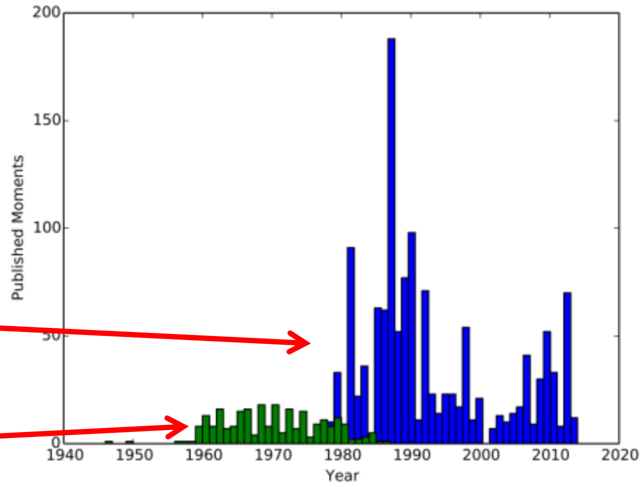
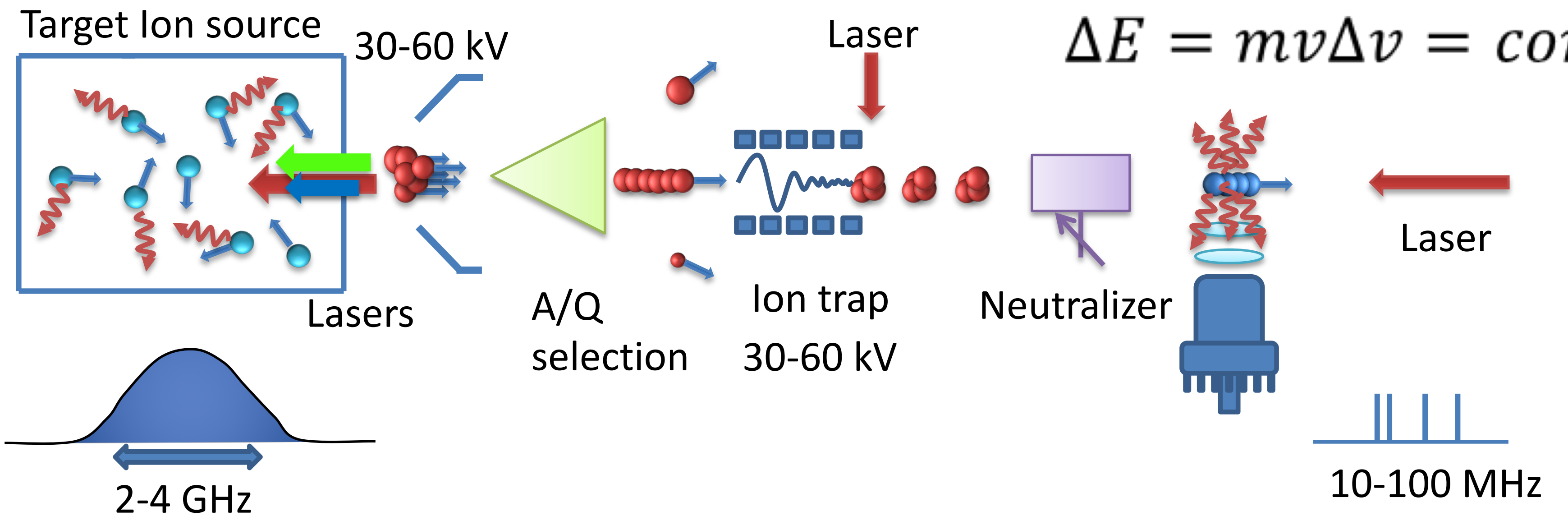
Laser Spectroscopy

Atomic Beam Magnetic Resonance



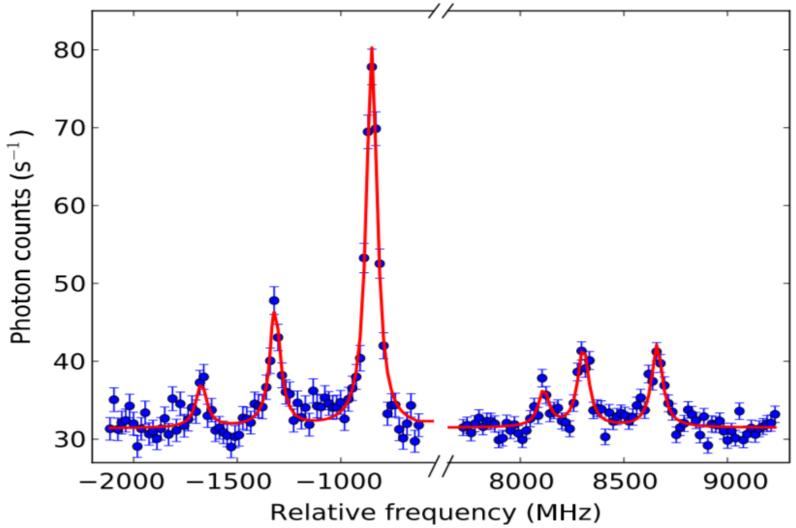
Collinear technique

$$\Delta E = mv\Delta v = constant$$



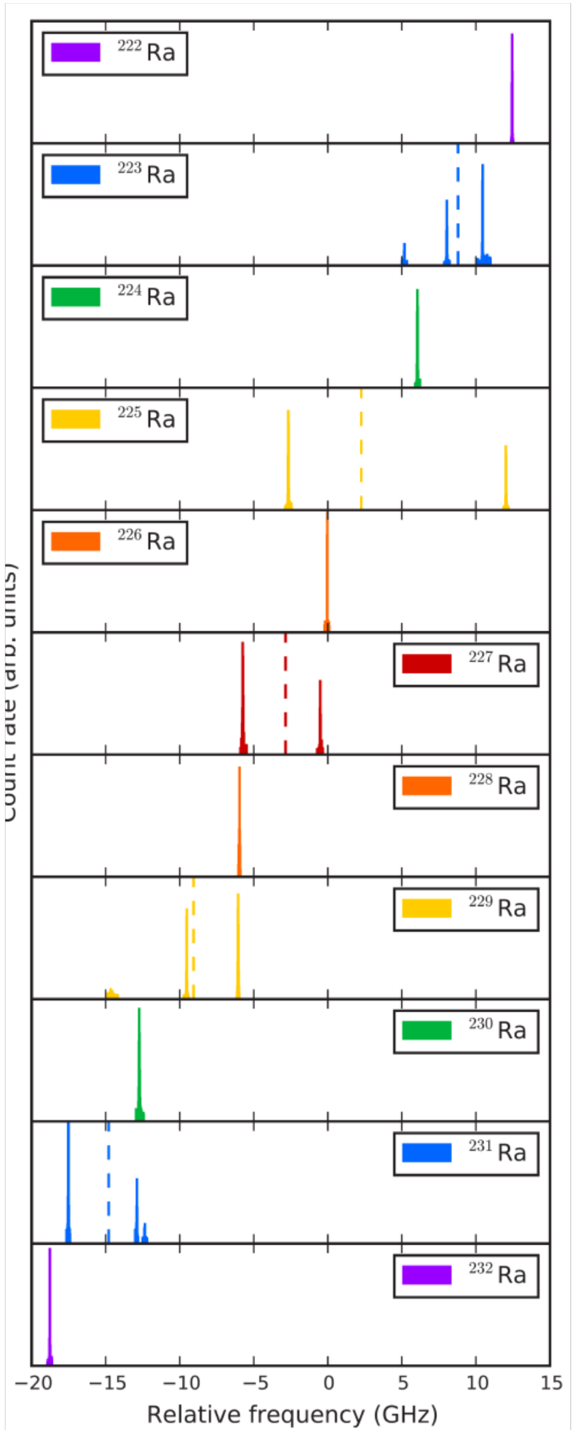
High efficiency ~10%

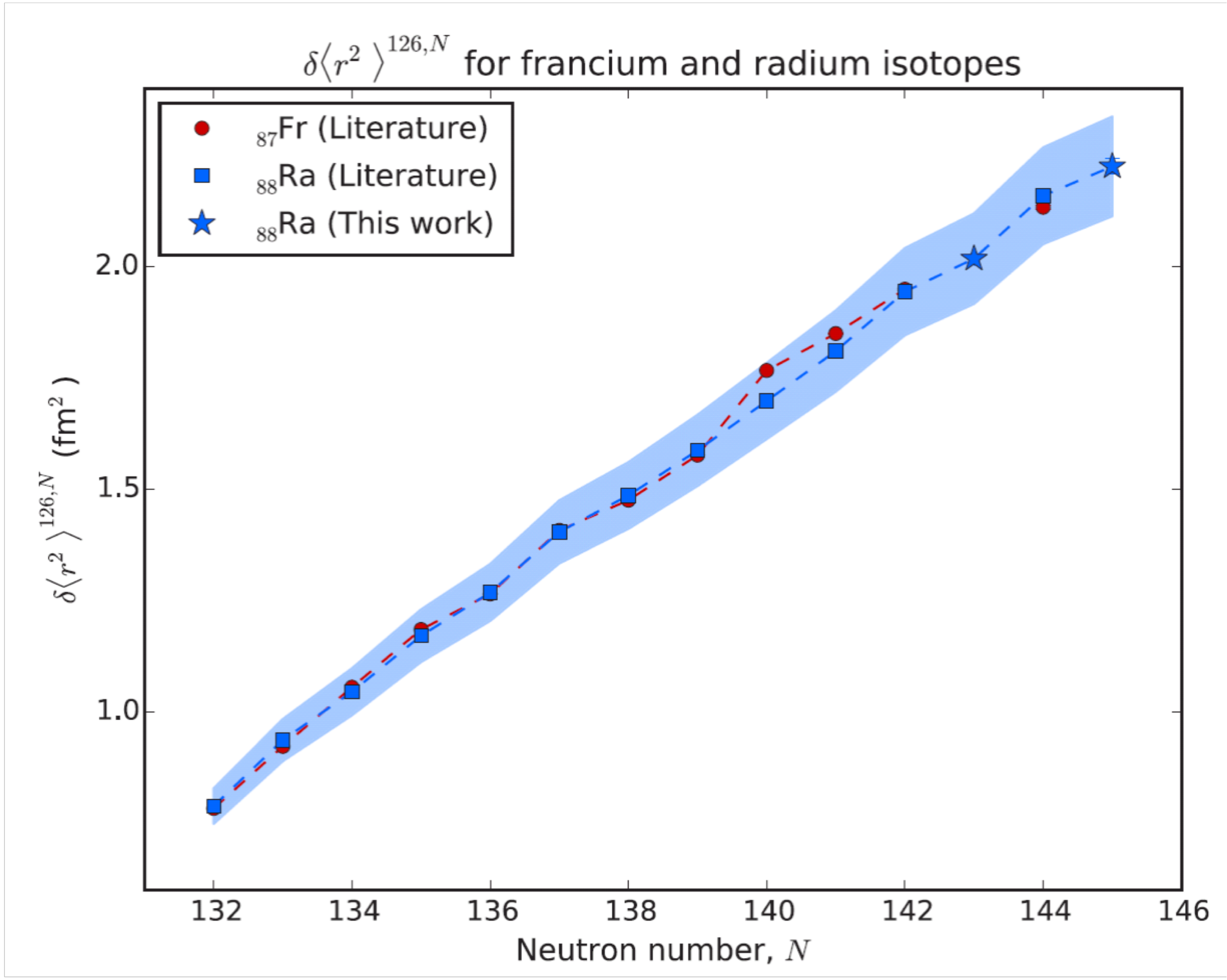
On average lower efficiency ~0.01%



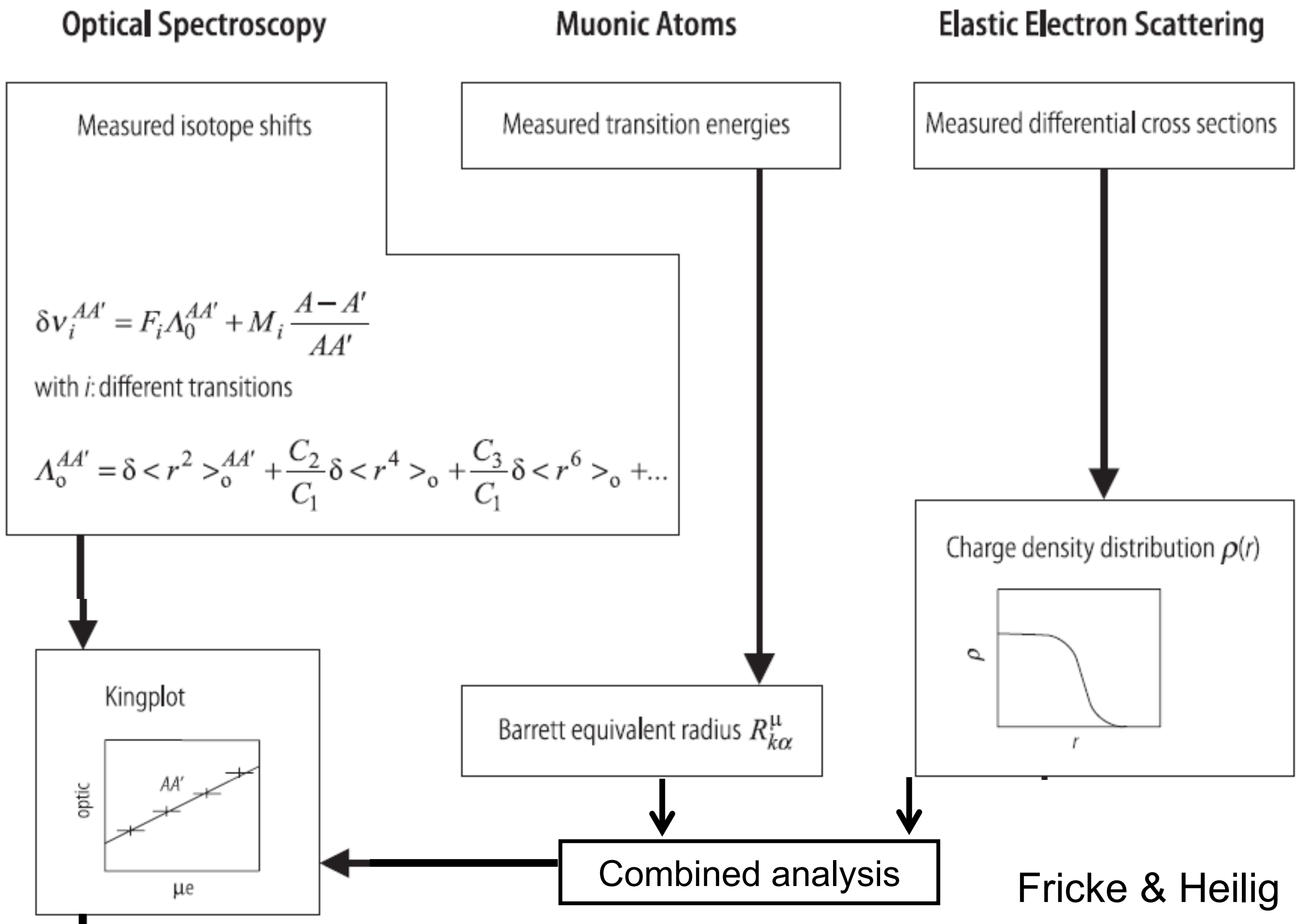
Composition, shape and size of the nuclear wave function, without introducing assumptions from nuclear models.

Charge radii from isotope shift measurements





General Approach



Requires long chains where measurements exist across many isotopes.
Typically challenging for for odd-Z cases and everything beyond Pb.

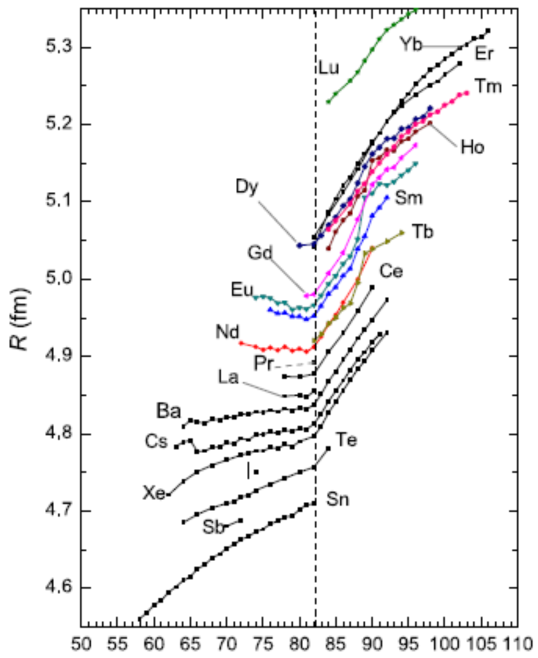
Fricke & Heilig *Nuclear Charge Radii* (Springer 2004)

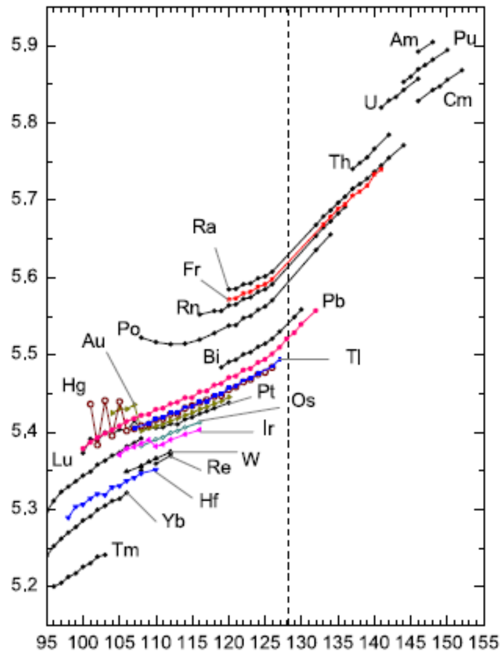
Analysis of stable isotopes

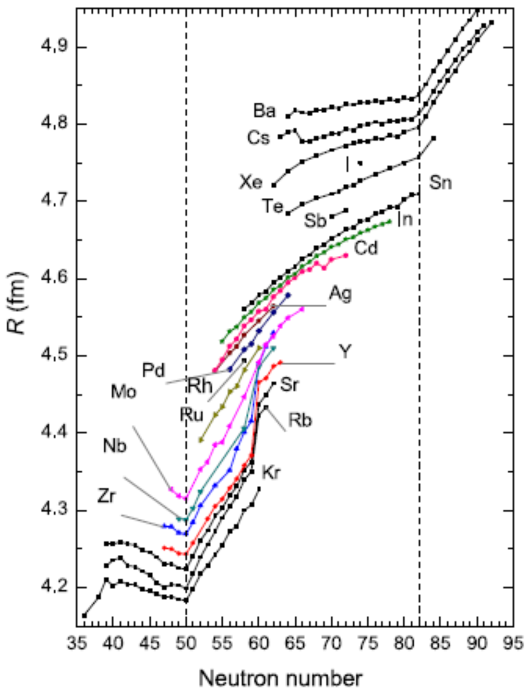
Result: F_i and M_i providing $\delta<r^2>$ for all isotopes (including radioactive)

rms nuclear charge radii,
***including radioisotopes*,**
for medium mass and
heavy elements

Angeli & Marinova
Atomic Data and Nuclear Data Tables 99 (2013) 69







Features:

- Kinks at closed neutron shells
- Regular odd-even staggering (sometimes reversed due to nuclear structure effects)
- Obvious shape effects (Light Hg, N=60…)
- Radii of isotopes increase at ~half rate of $1.2A^{1/3}$ fermi (neutron rich nuclei develop neutron skin)

Collinear resonance ionization spectroscopy

- 1982: Outline of method proposed by Yu. A. Kudriavtsev and V. S. Letokhov, *Appl. Phys.* **B29** 219 (1982)

Proposed

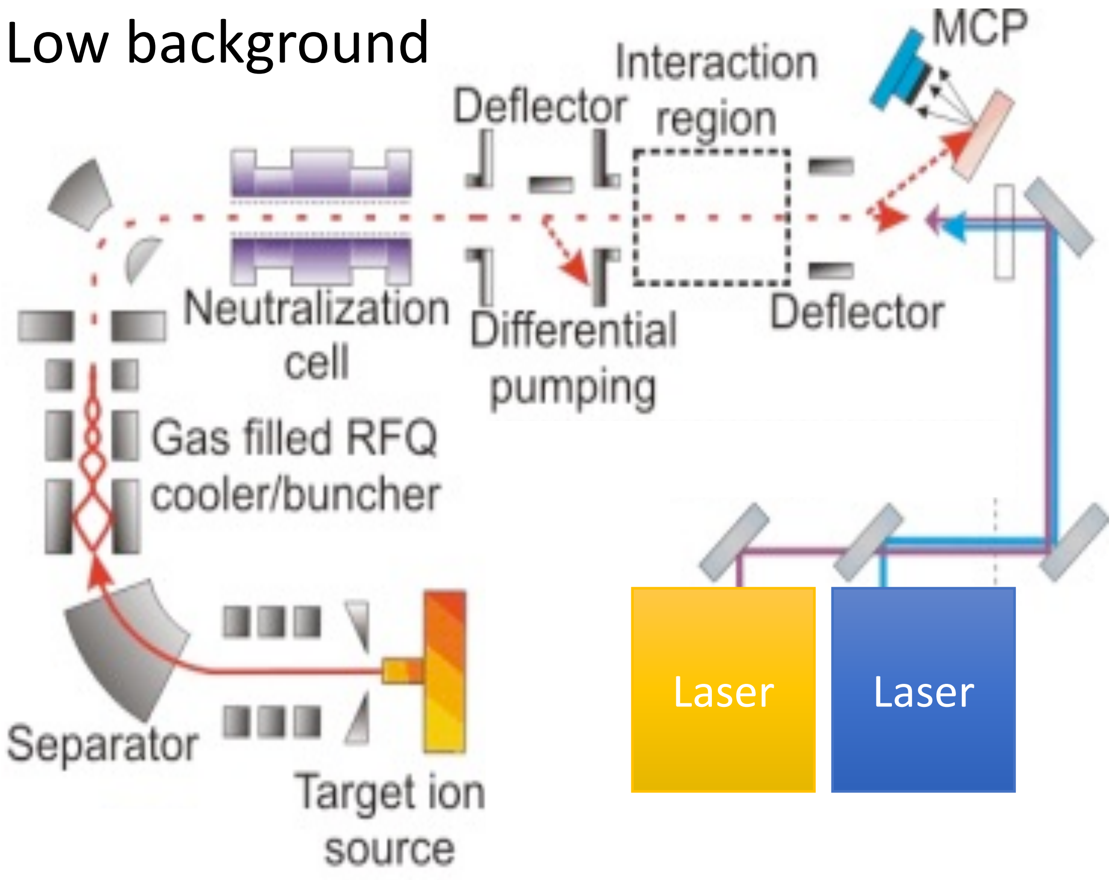
(V.S. Letokhov et al, Zinal D7, 1984)

- High resolution,
- High efficiency
- Low background

CRIS@ISOLDE

(R. de Groote et al. PRL 115 (13), 132501 (2015))

- Linewidth: 15-50 MHz
- Relatively high efficiency: 1%
- Low background: 0.001 cps

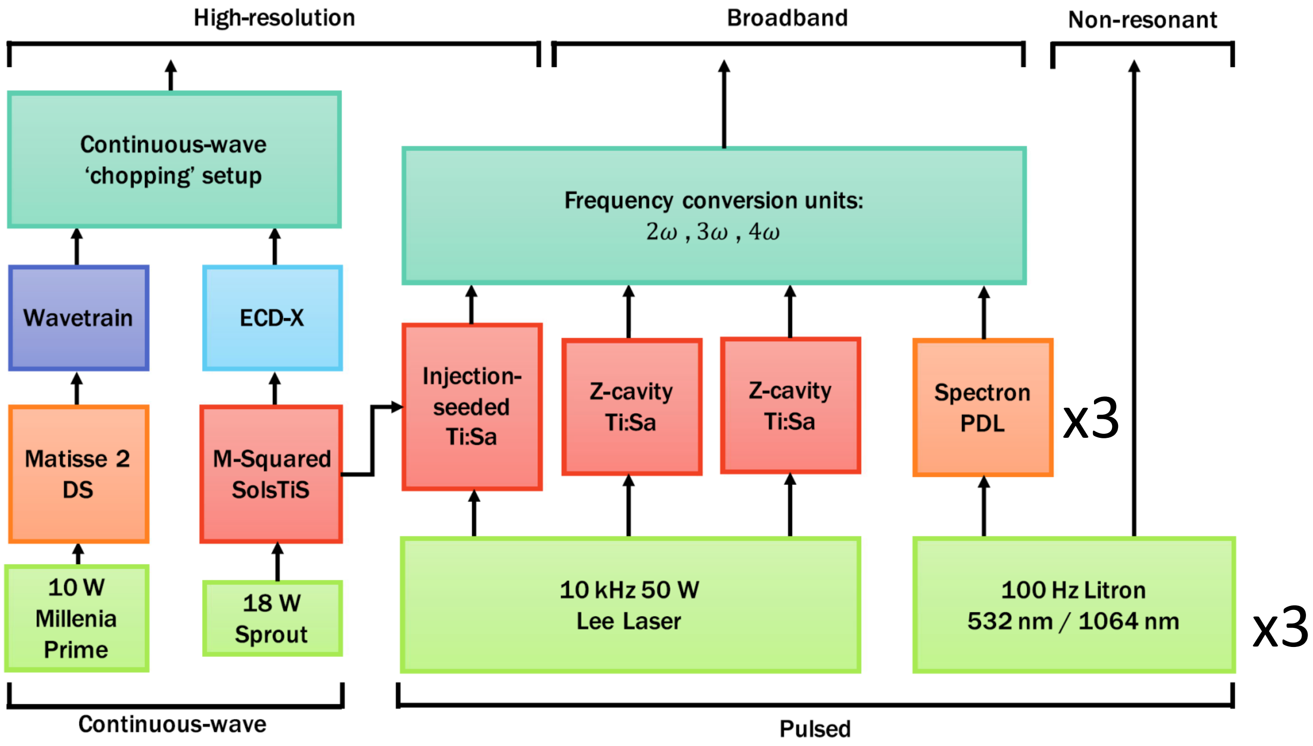


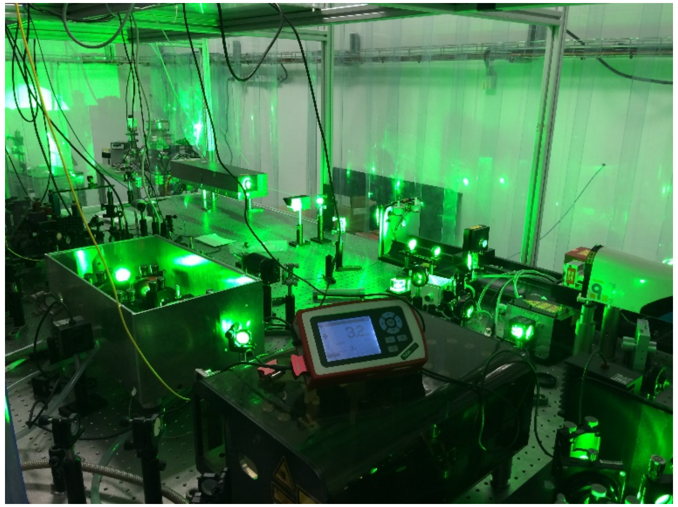
Extend measurements to new regions of the nuclear chart.

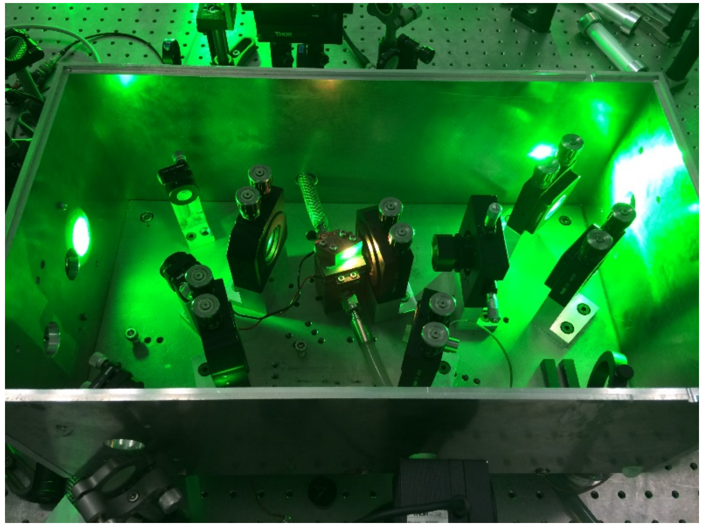
Measure states that were previously obscured.

CRIS Laser system (defence in depth)

- Variety of laser schemes, wavelengths requires a versatile system.
- Total 16 lasers (plus one on order)
- Typical experiments use 50% of the system





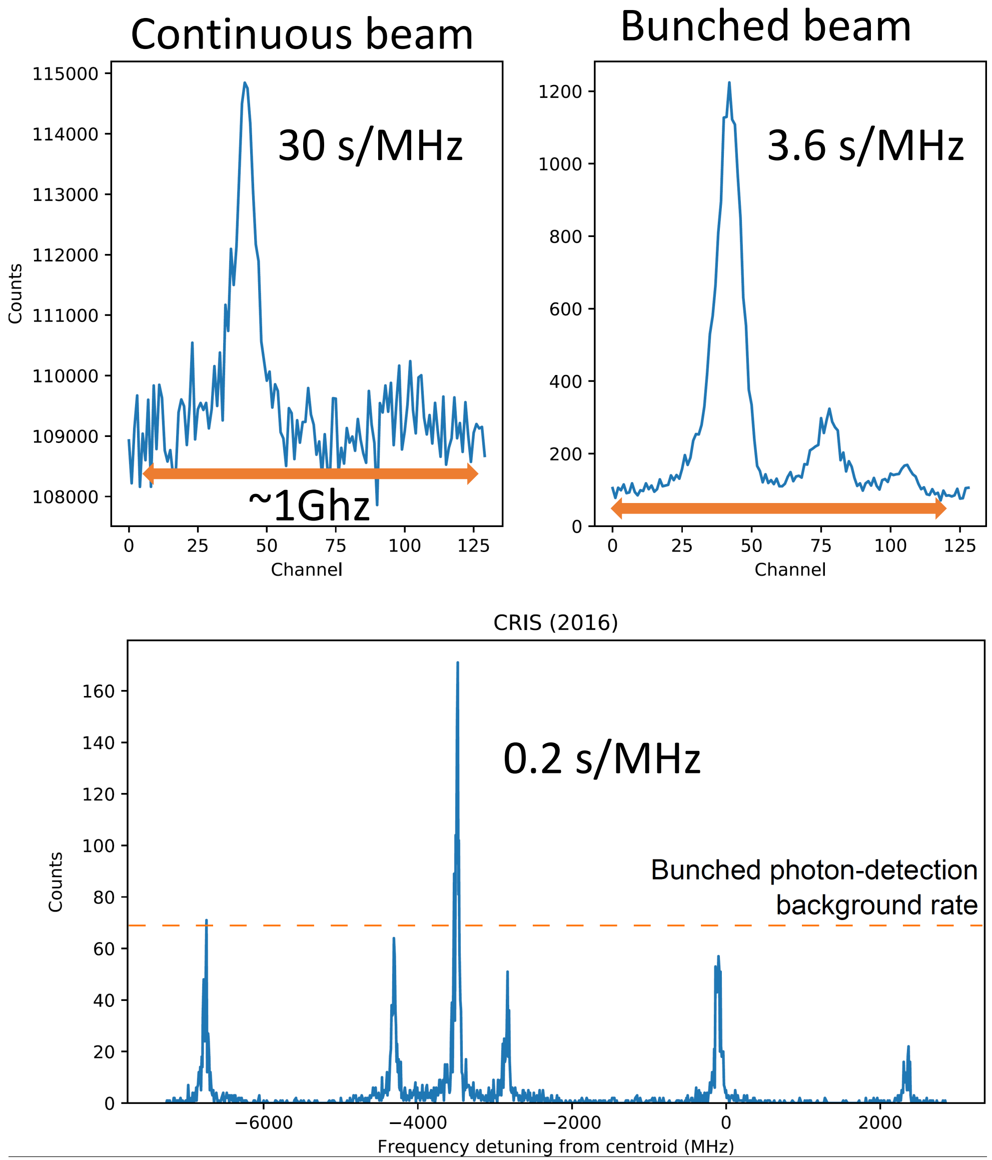


Comparison of CRIS and fluorescence detection

2007: A continuous beam it is just possible to measure ^{72}Cu in 24hrs
Background 3500 cps

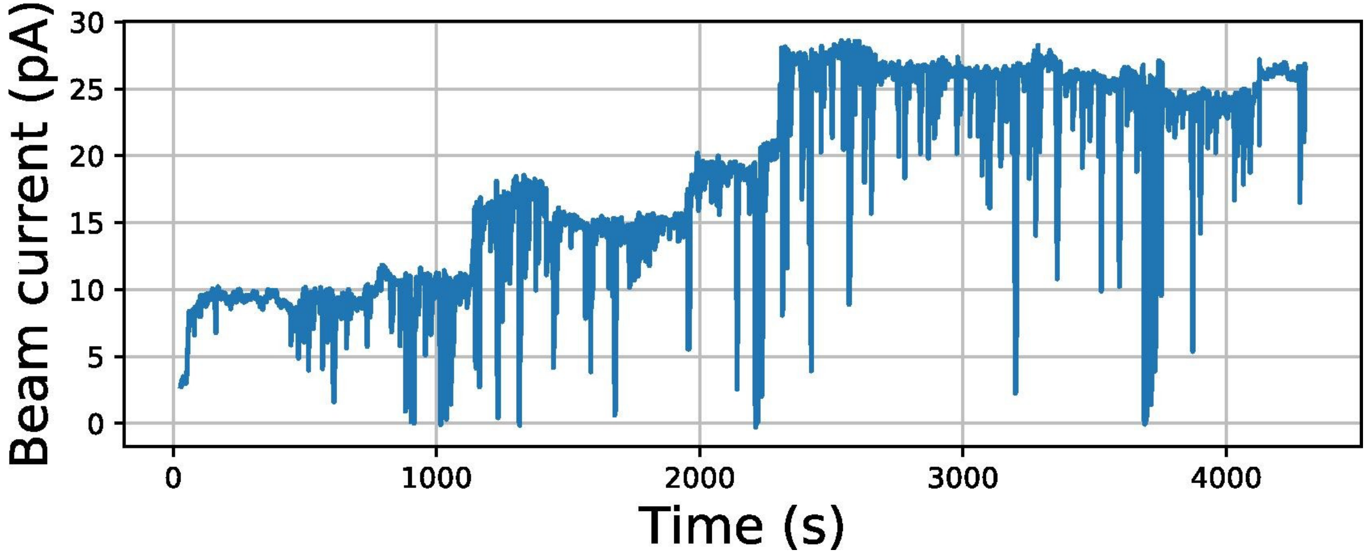
2008: Cooler buncher allows same measurement to be performed in 2 hours **Background 30 cps**

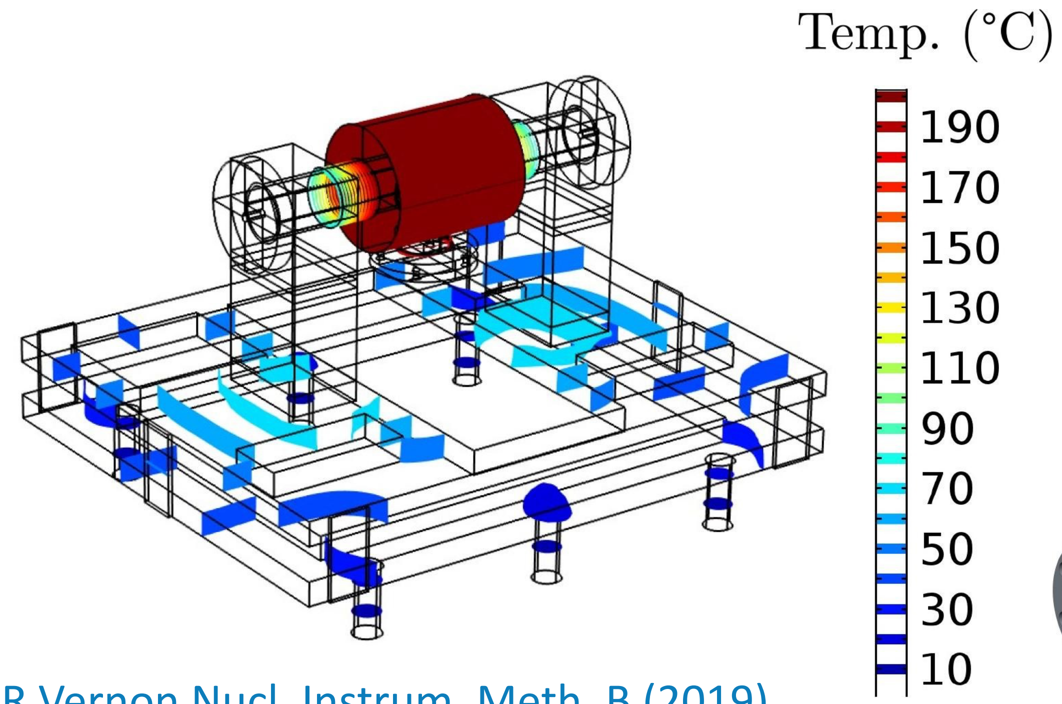
2016: CRIS (different transition) 42 mins
Background 10^{-2}-10^{-3} cps

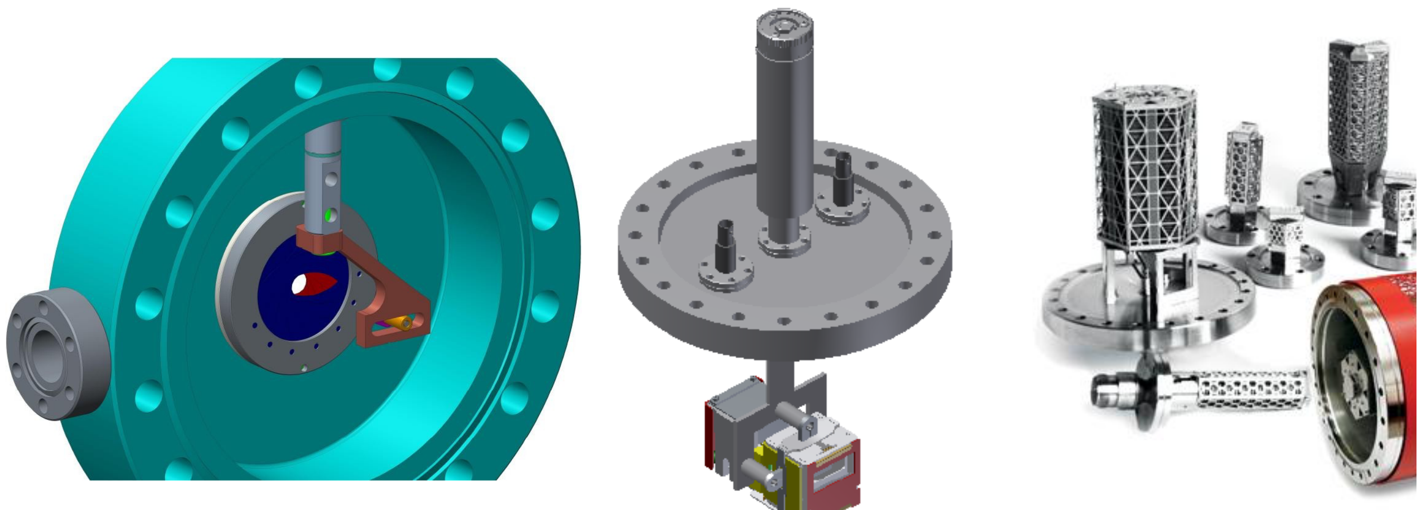


Modifications at CRIS 2017/2018

- Auto tuning
- New Charge exchange cell
- Beam alignment

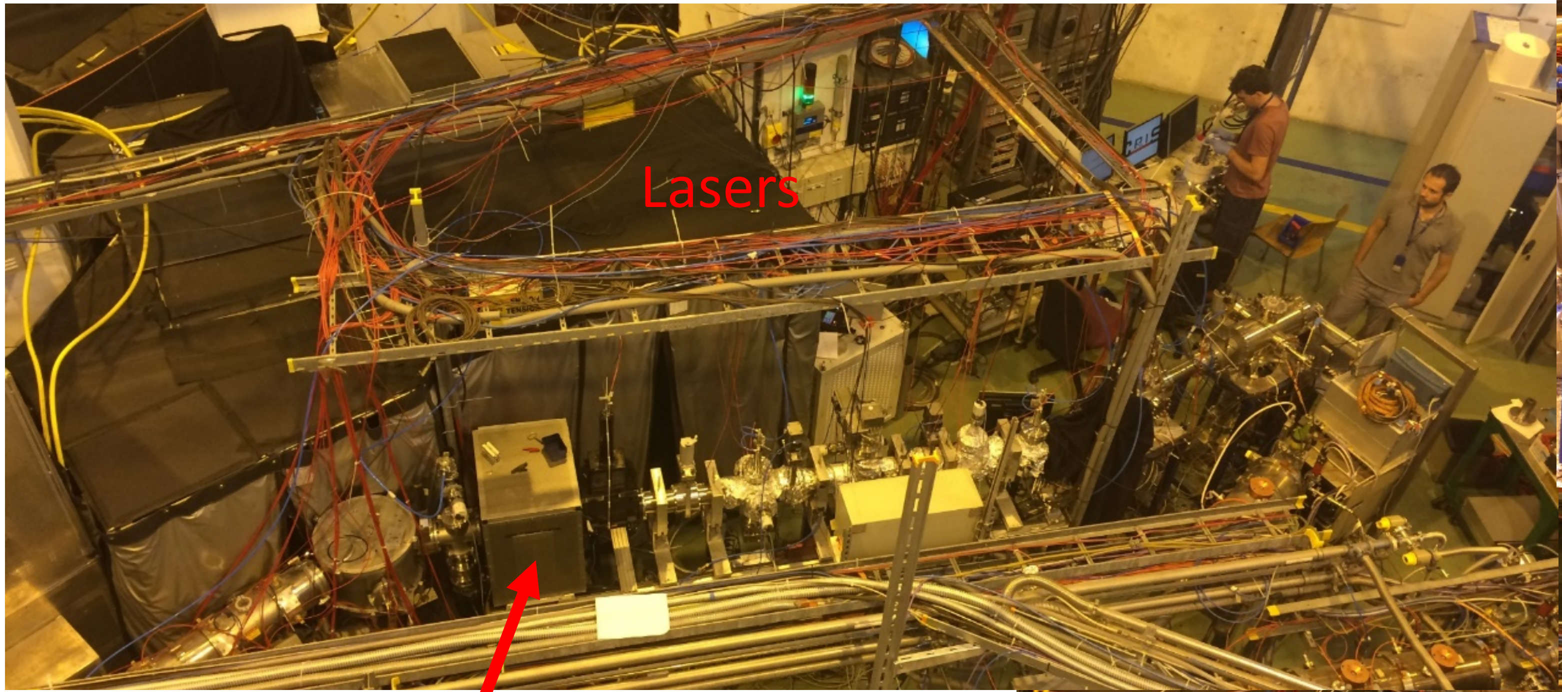


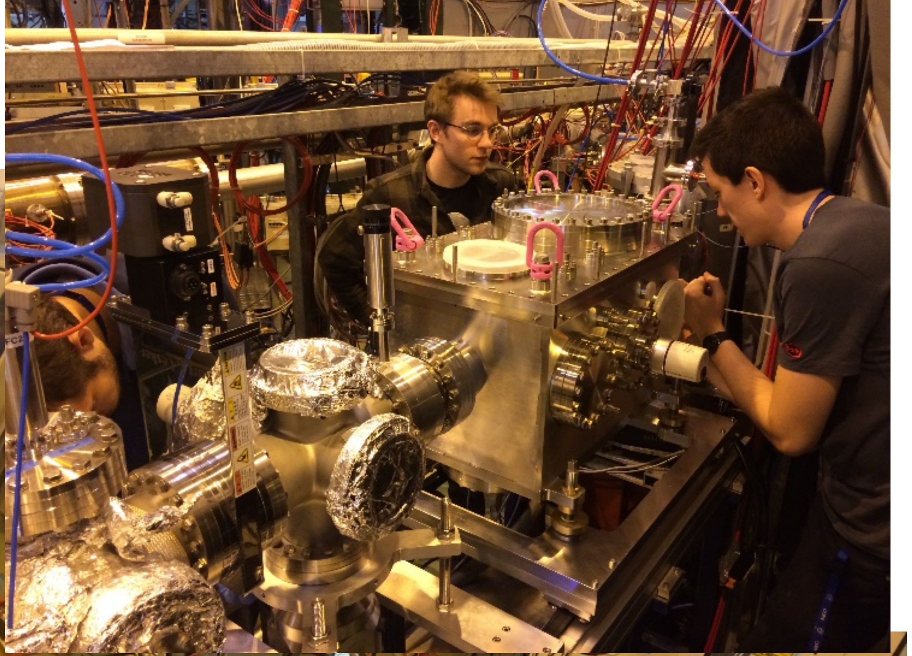


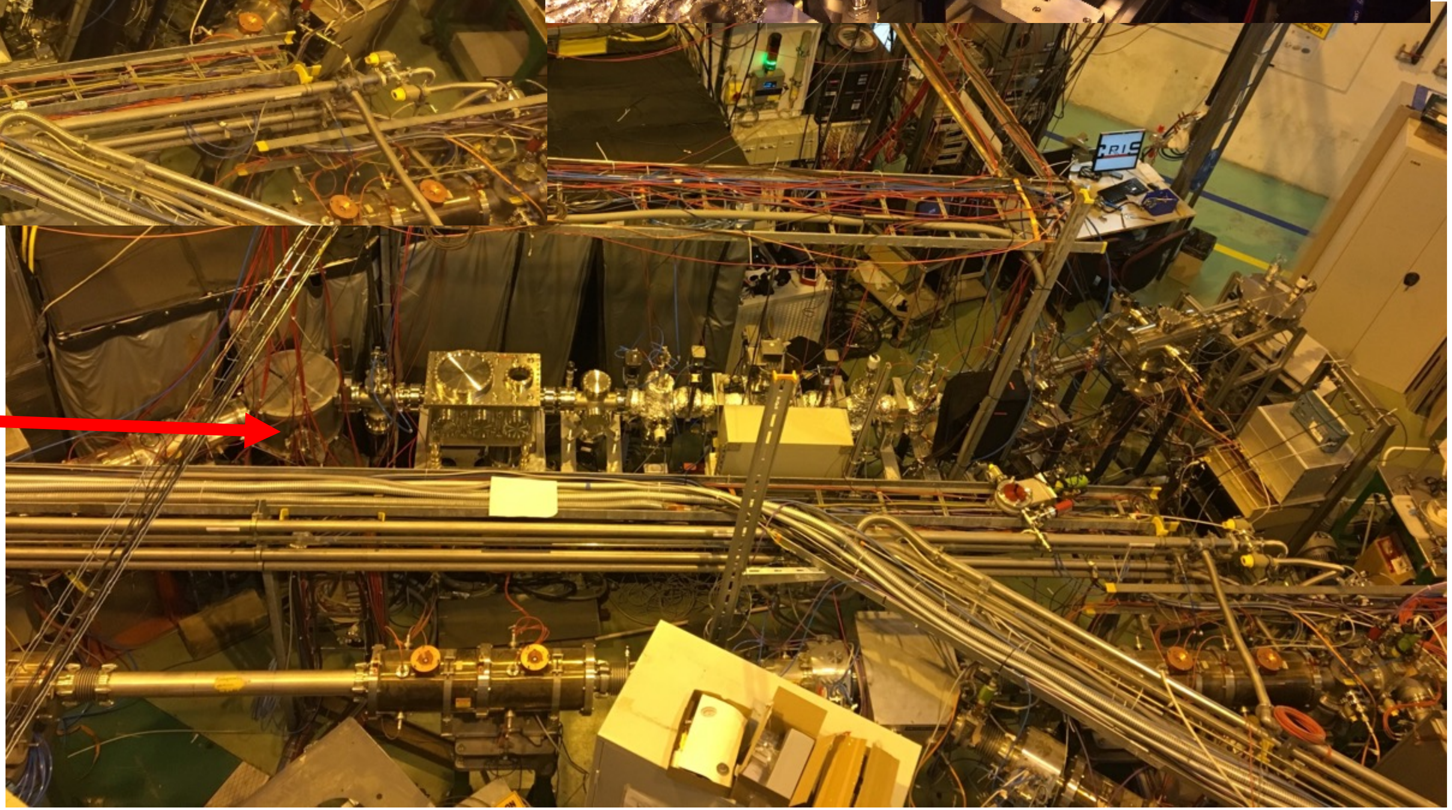


AR Vernon Nucl. Instrum. Meth. B (2019)
https://doi.org/10.1016/j.nimb.2019.04.049

Recent changes



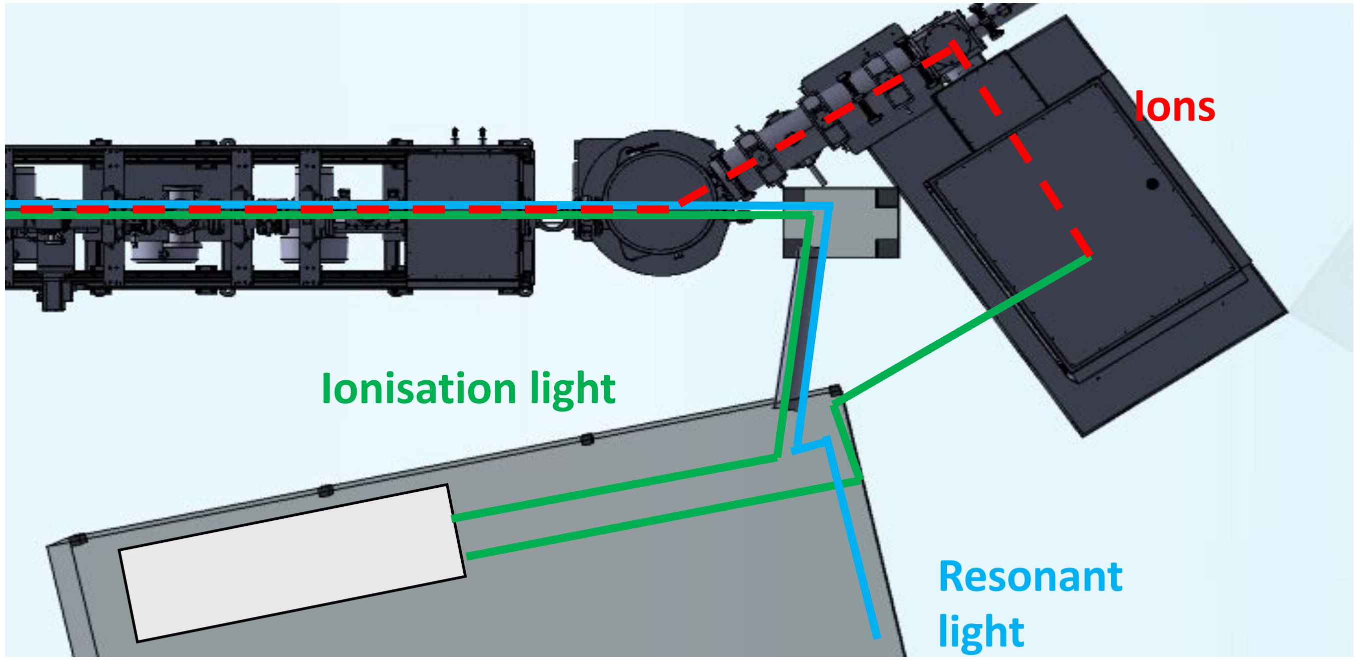


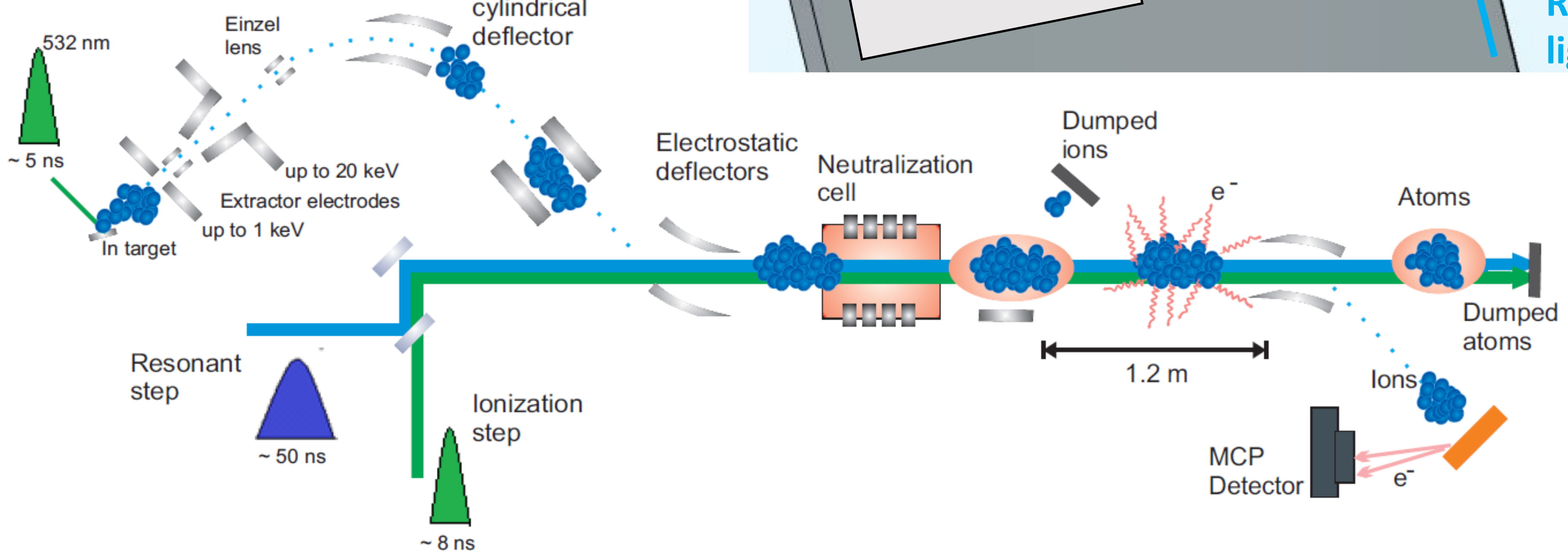


Charge exchange and two stage differential pumping.
NEG pump, better particle detectors-> x20 improvement in pressure to 1.3e-10 mbar.

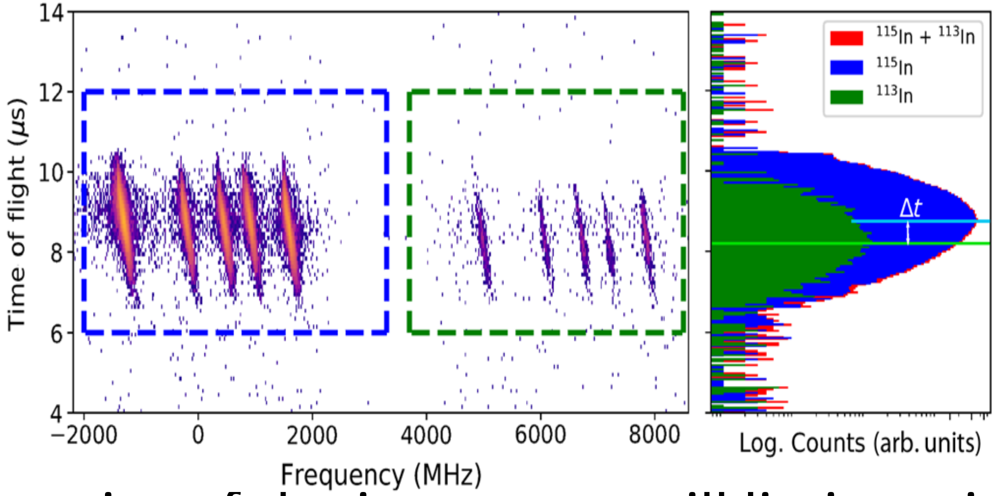
Ablation ion source

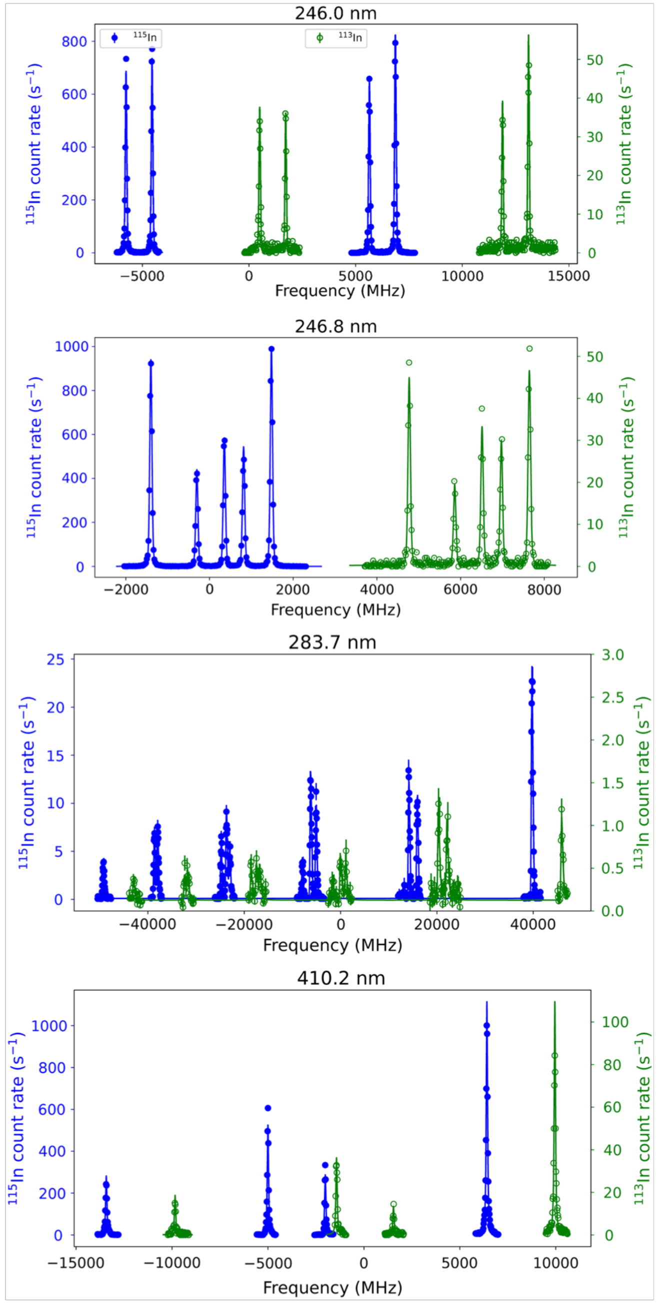
- Use 532-nm laser light to create a pulsed ion source
- Perform CRIS on these pulses



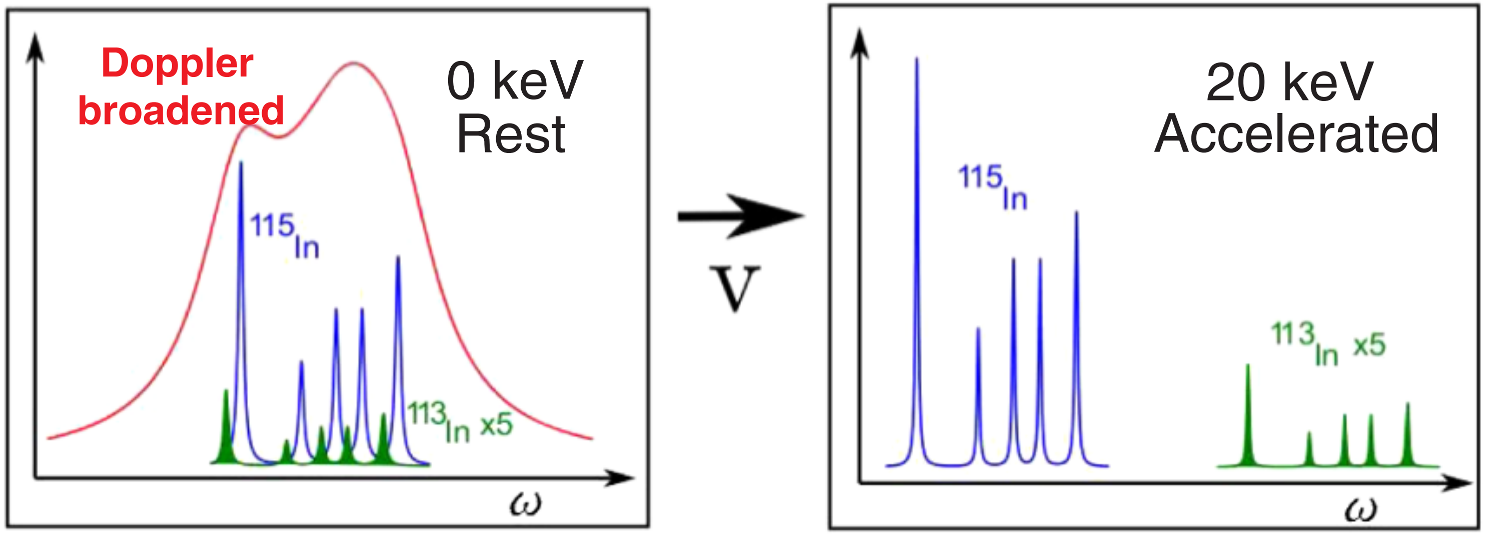


RIS scheme development





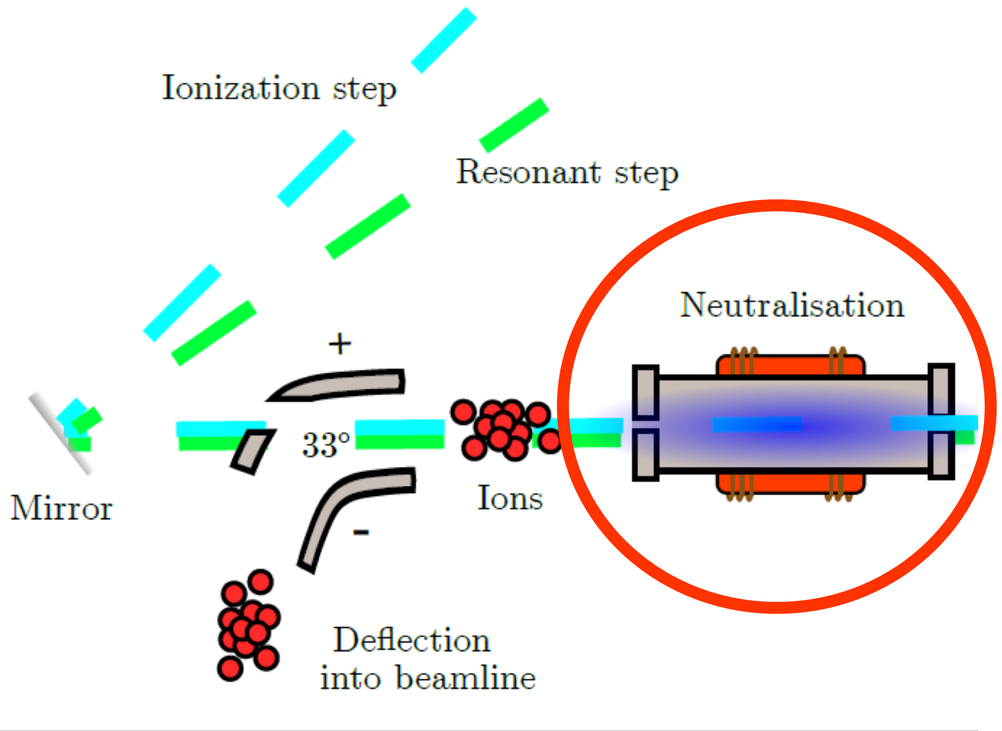
- Properties of the ion source will limit purity of the beam
- CRIS method enhances selectivity through kinematic shift

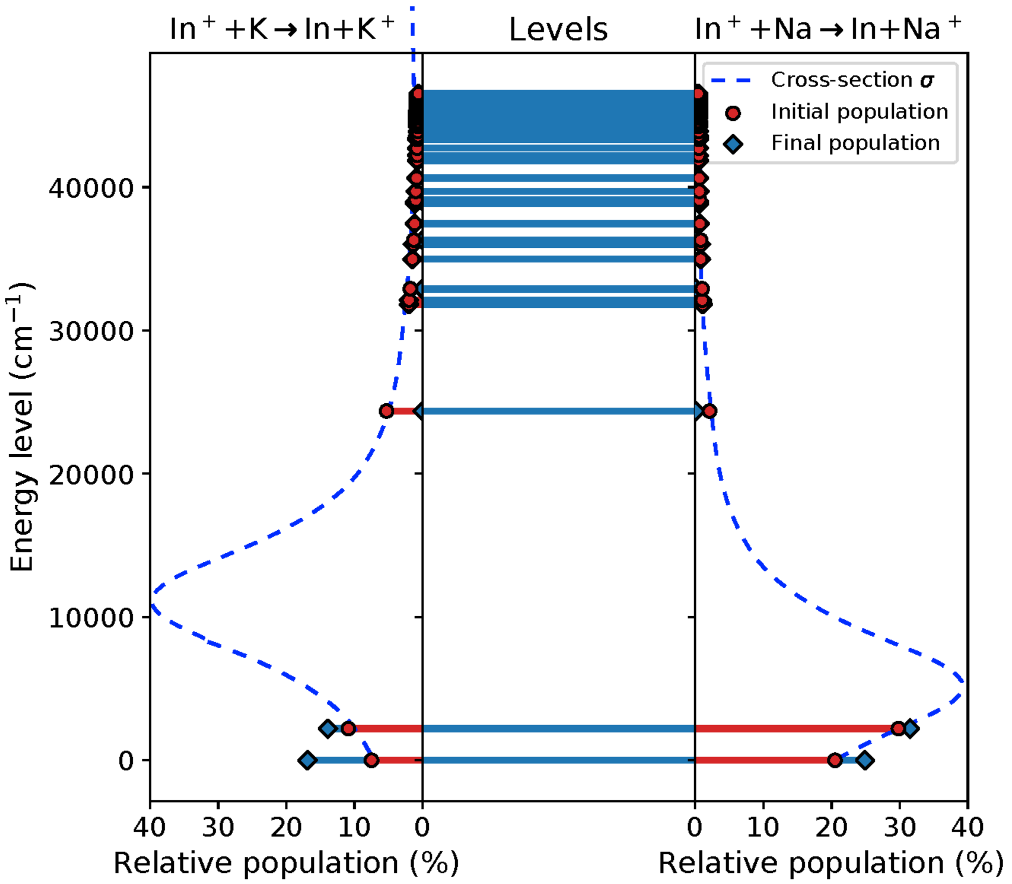


R.F. Garcia Ruiz Phys. Rev. X **8**, 041005 (2018)

Charge exchange

- Reliable predictions of the neutralization process are critical
- Ni atomic system studied at NSCL
- We extended this using NIST data tables



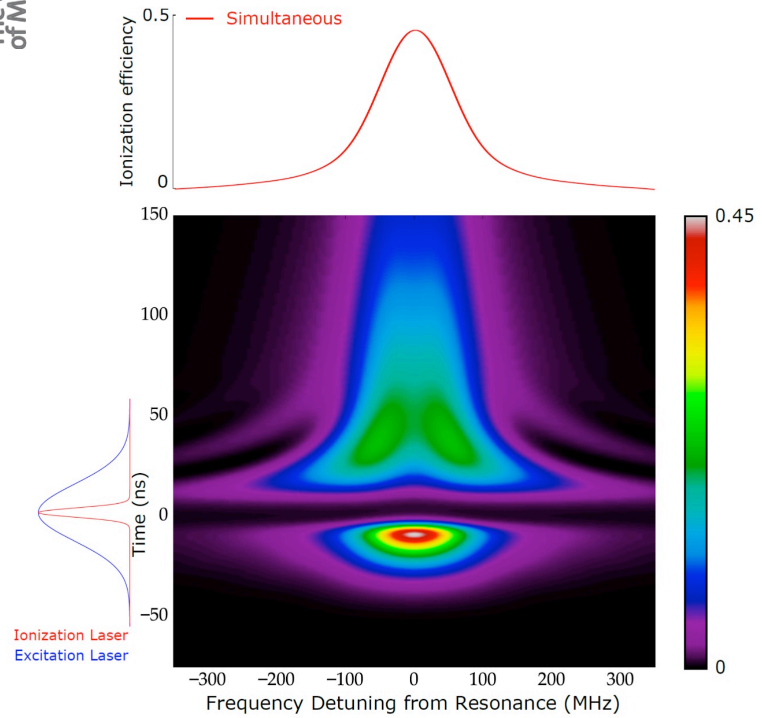


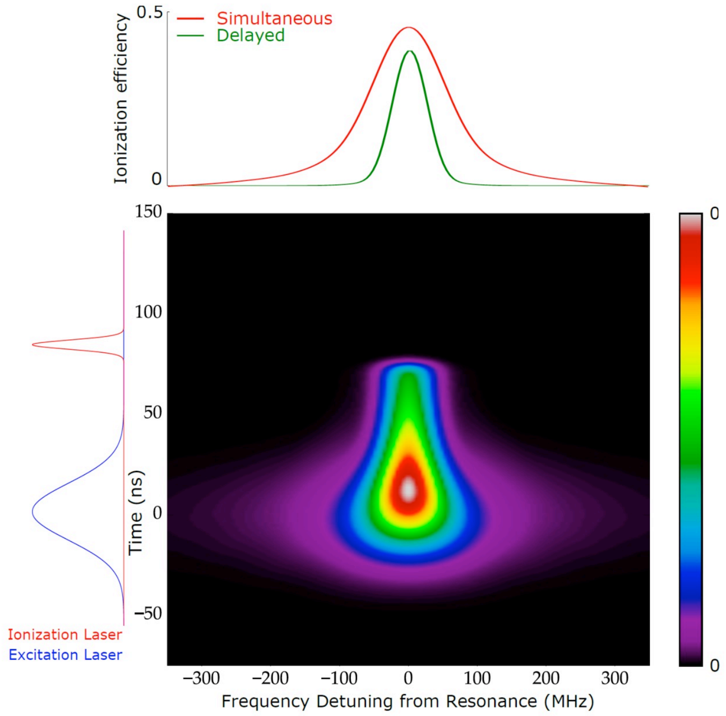
D. Rapp W.E Francis Chem. Phys., 37 (11) (1962), p. 2631

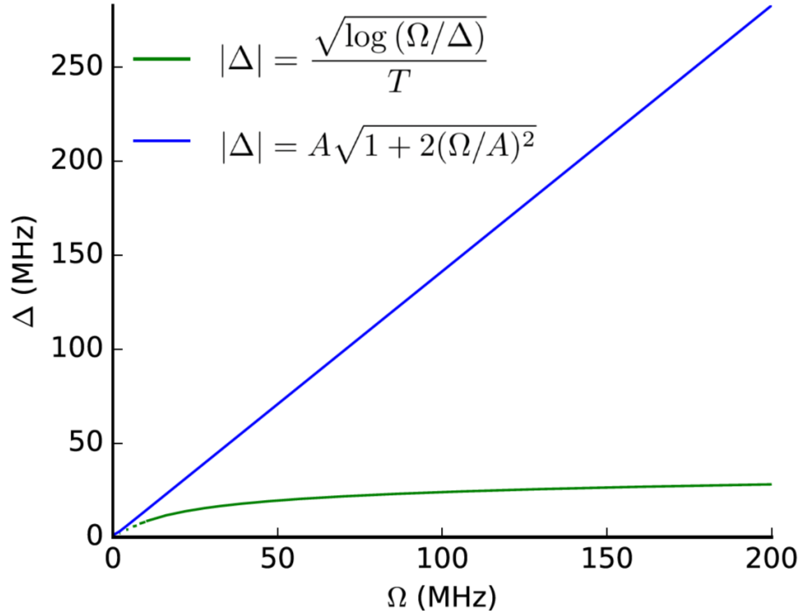
C. Ryder et al. Spectrochim. Acta Part B At. Spectrosc., 113 (2015), pp. 16-21,

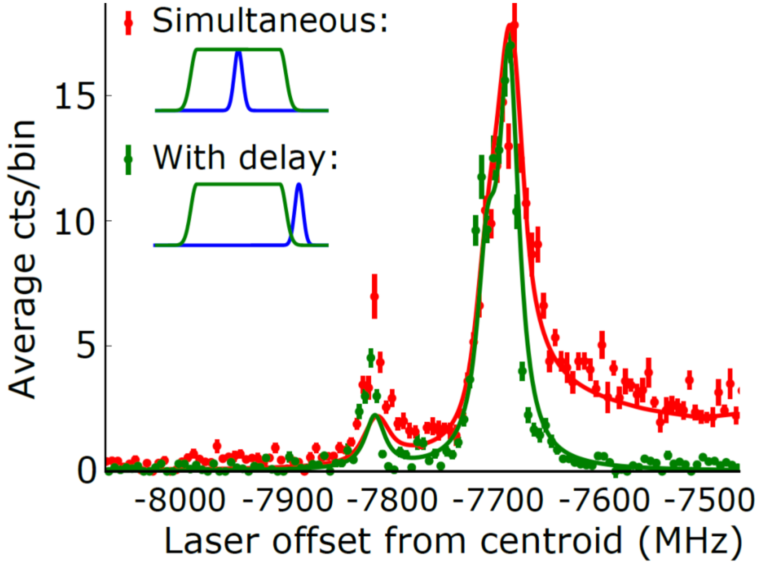
AR Vernon et al. Spectrochimica Acta Part B: Atomic Spectroscopy 153, 61-83 (2019)

Higher resolution and precision







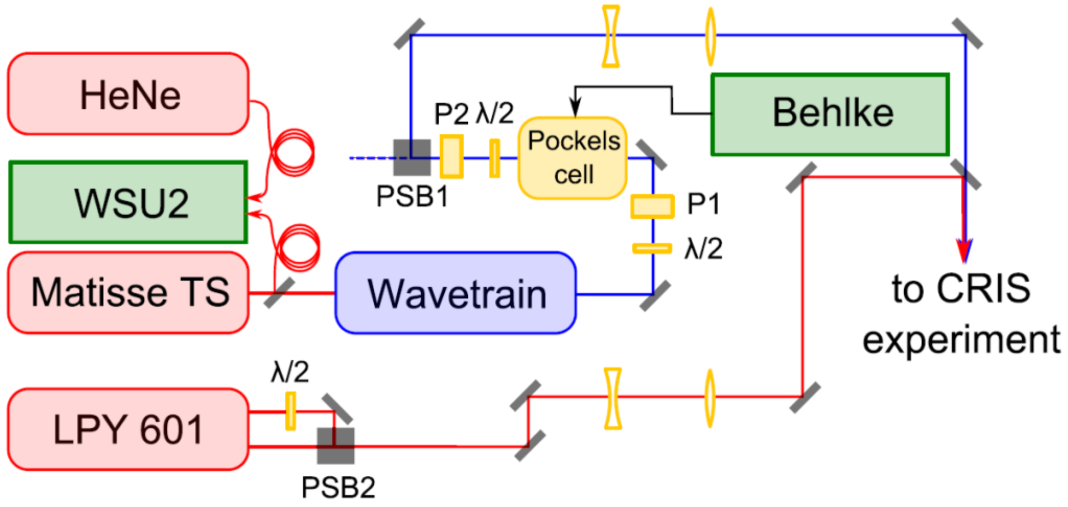


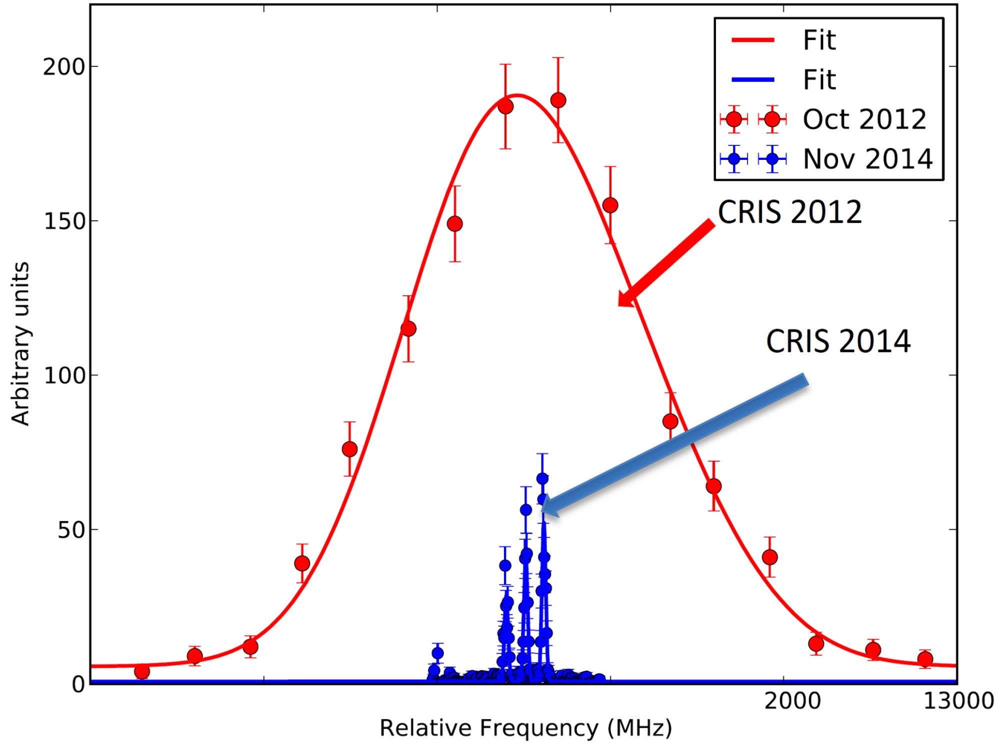
Separating pulses in time reduces line broadening and possibly interference effects associated with coherent excitation of two or more quantum states.

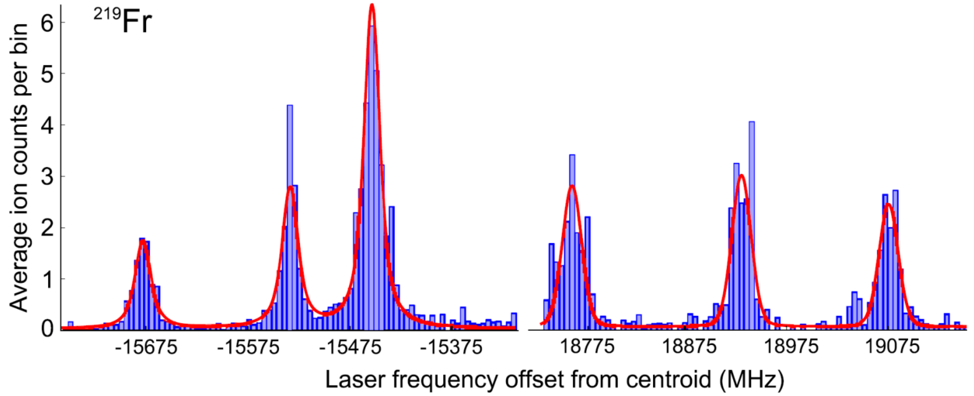
RP de Groote et al. Phys. Rev. A 95, 032502 (2018)

High resolution

- First experiments used a 1.5 GHz laser system.
- New method of chopped CW laser spectroscopy: 20(1) MHz linewidth.
- Same rate on ^{219}Fr in narrow linewidth mode.



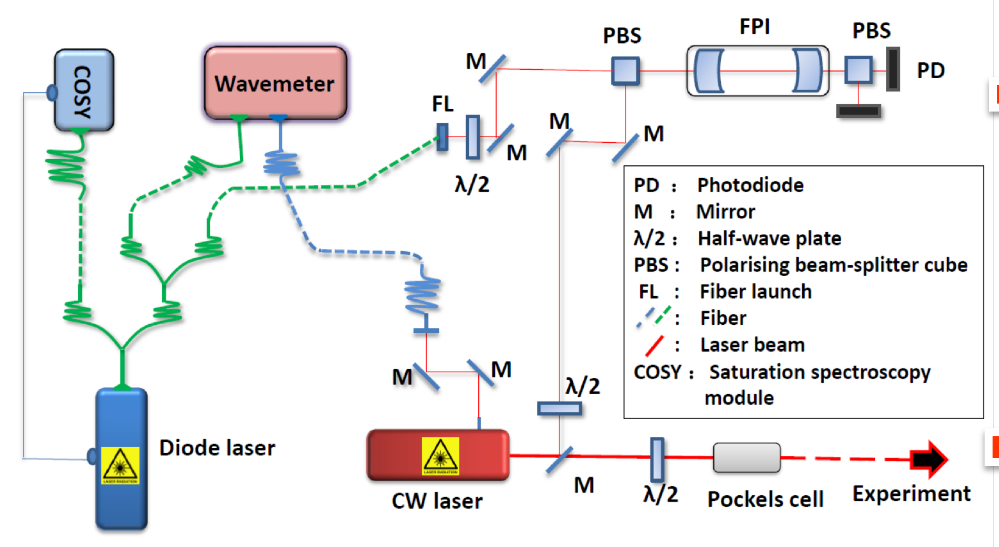


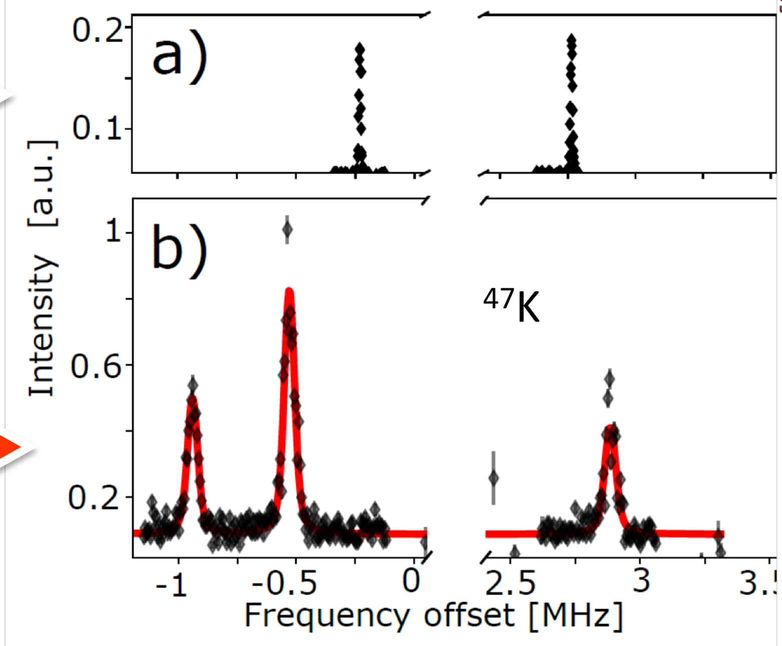


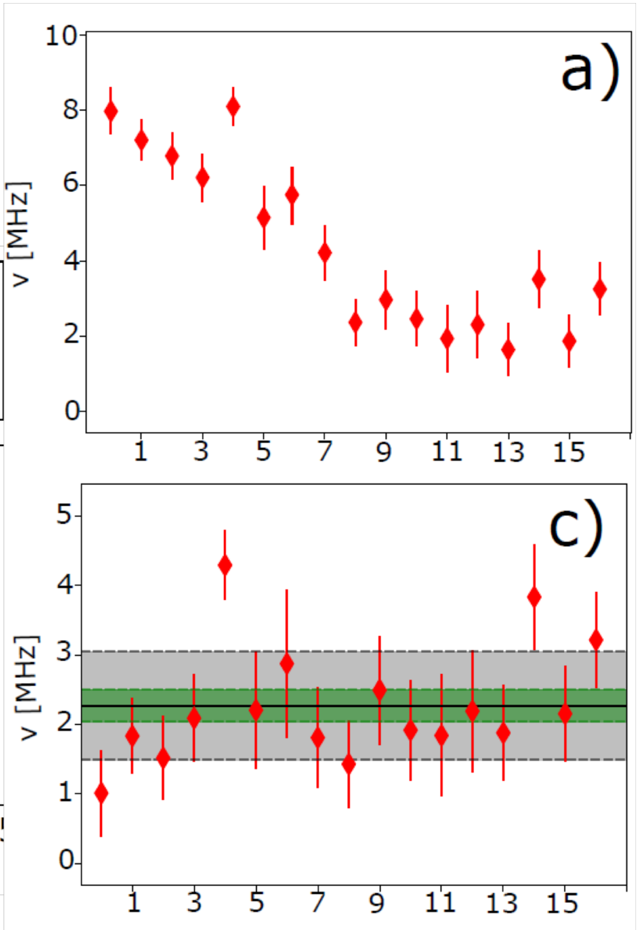
RP de Groote, et al. Phys. Rev. Lett 115 (13), 132501 (2015)

The University of Manchester

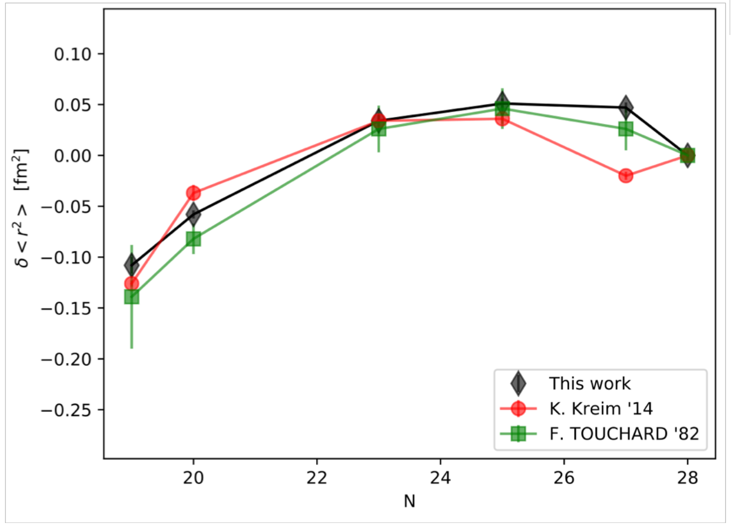
Precision and accuracy

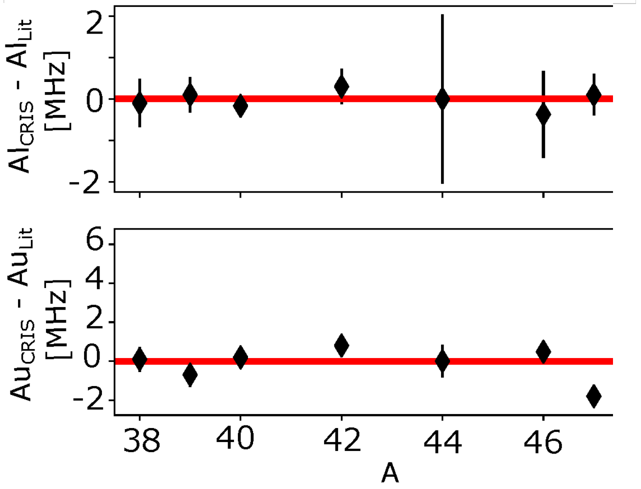






- Precision of the frequency measurement
  - σ = 0.77 MHz
- Consistency of hyperfine parameters
  - In good agreement with literature



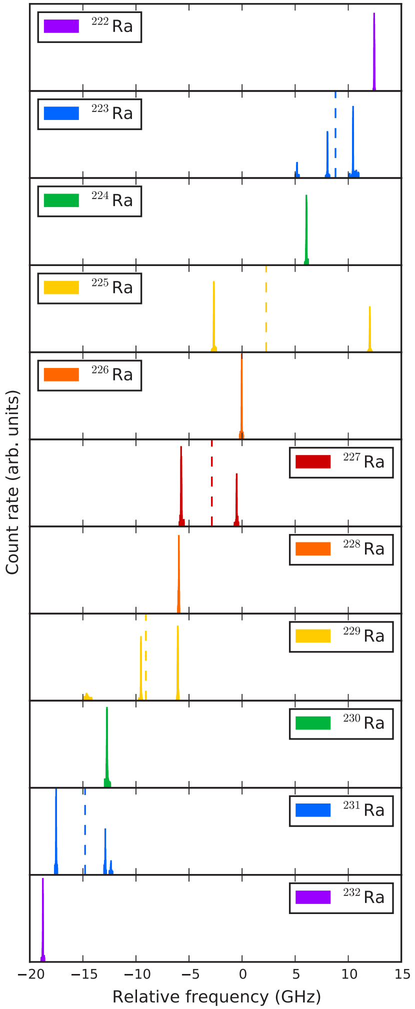


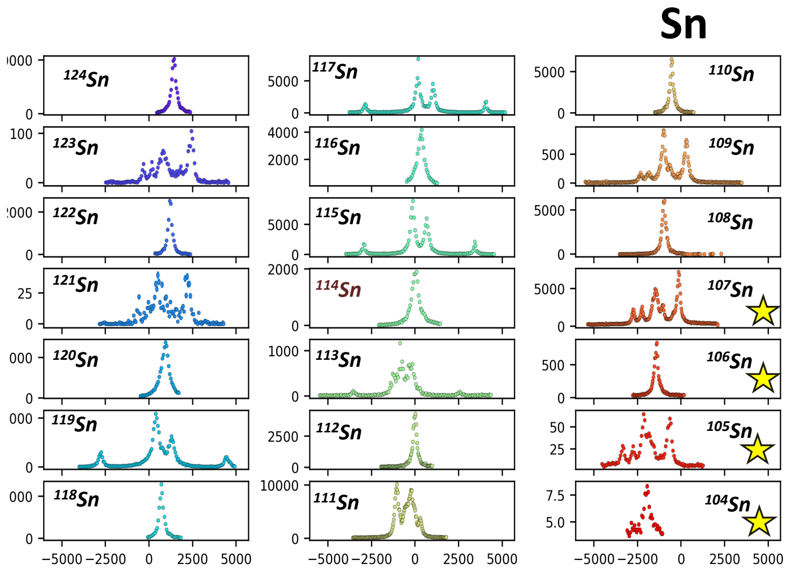
Physical Review C 100 (3), 034304 (2019)

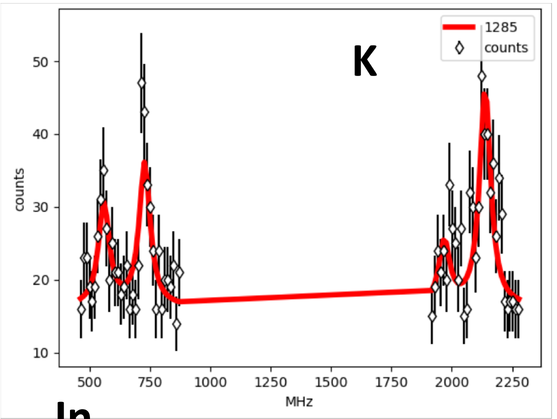
2014-2018

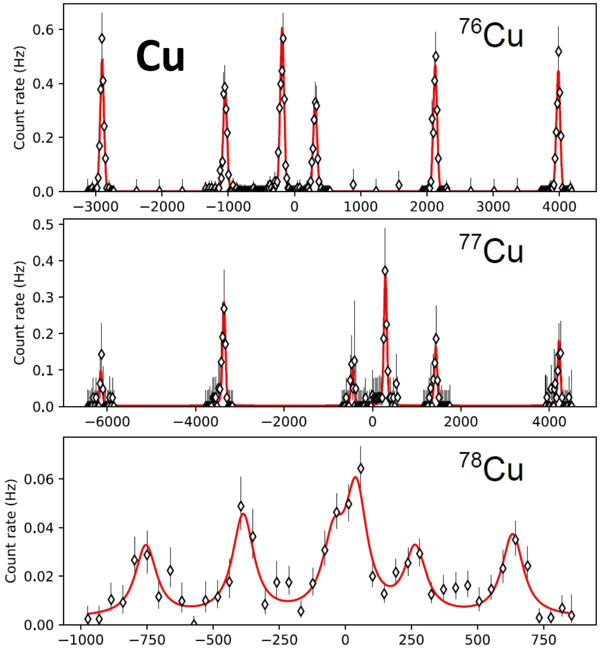
- Recent: last 4 years
- Measurements made on production rates down to ~20 atoms/second

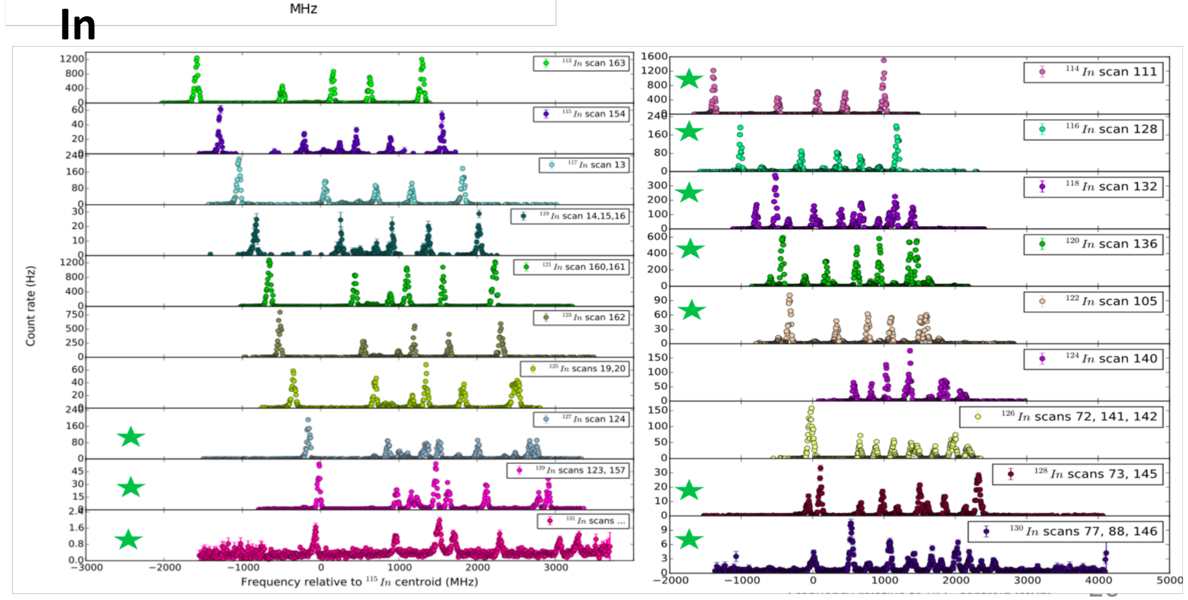
Ra







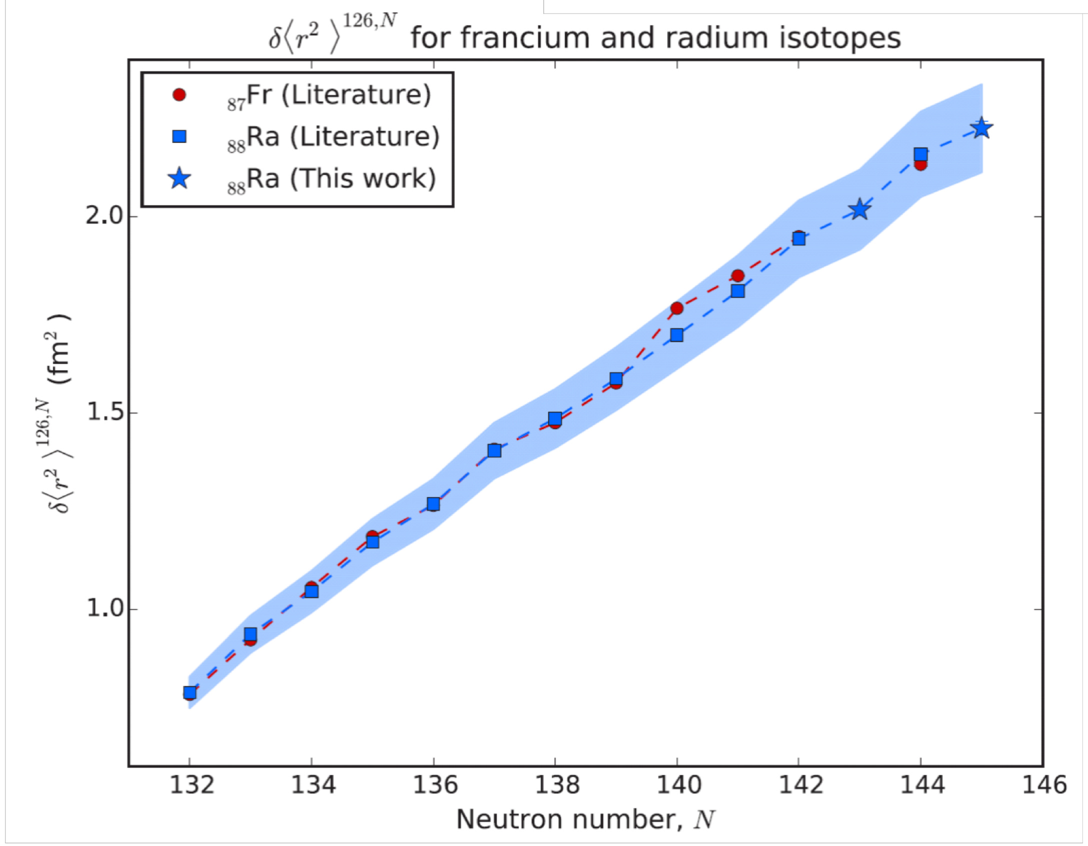


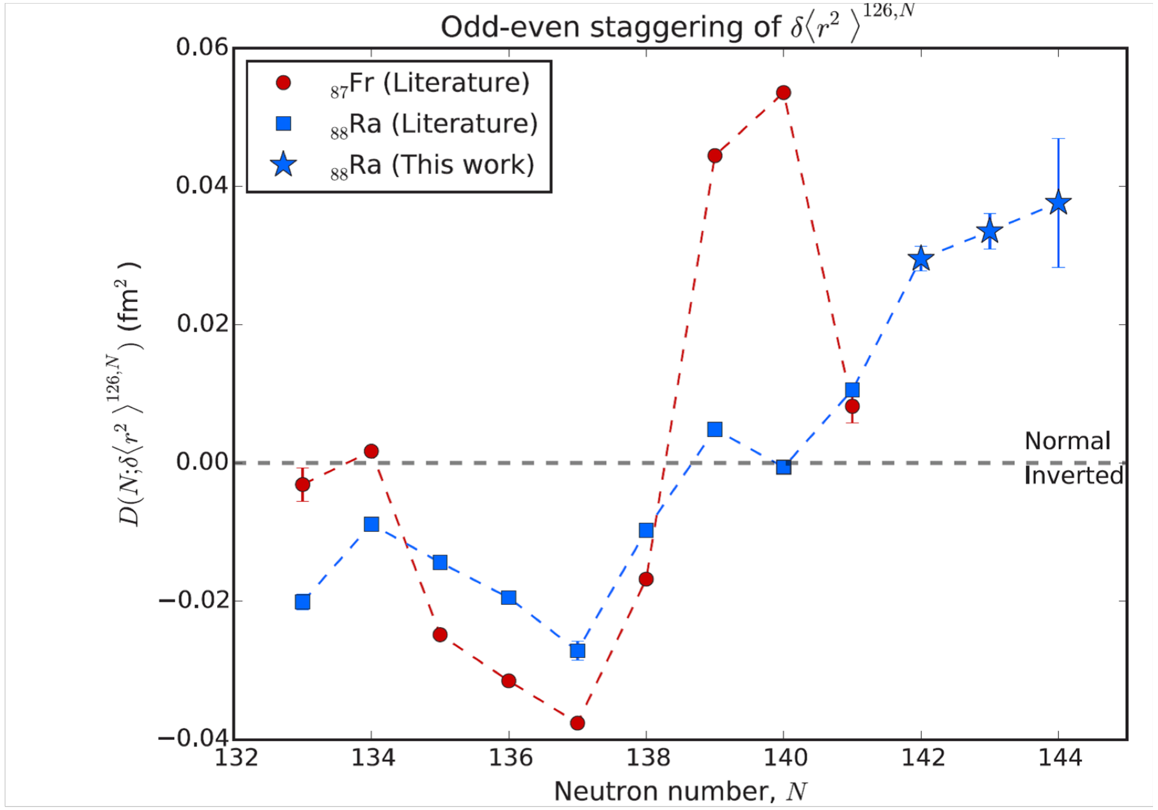


Over 90 radioactive isotopes studied (K, Sc, Cu, Ga, In, Sn, Fr, Ra)

Odd even staggering within region of reflection asymmetry

$$D(N;\delta\langle r^2\rangle^{126,N}) = (-1)^N(\delta\langle r^2\rangle^{126,N} - \tfrac{1}{2}(\delta\langle r^2\rangle^{126,N-1} + \delta\langle r^2\rangle^{126,N+1}))$$

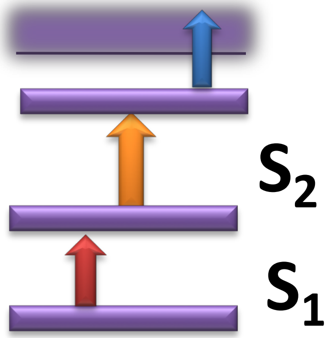




KM Lynch et al. Physical Review C 97 (2), 024309 (2018)

Previously missed isomeric state in ^{114}In

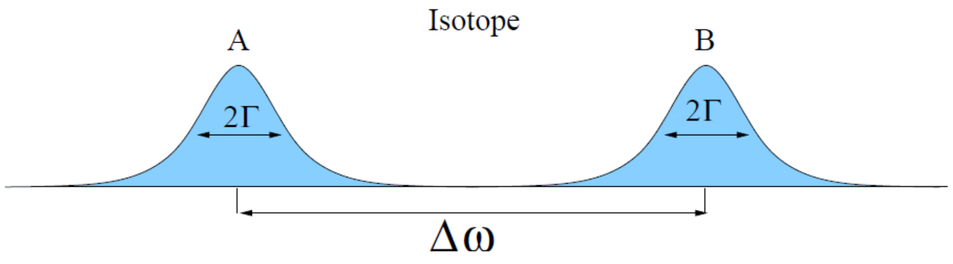
- One of the most difficult sources of “contamination” is the nuclear ground state which can be produced at rates 100s of times greater than isomeric states.
- Multistep RIS offers far higher selectivity than is possible from a mass spectrometry

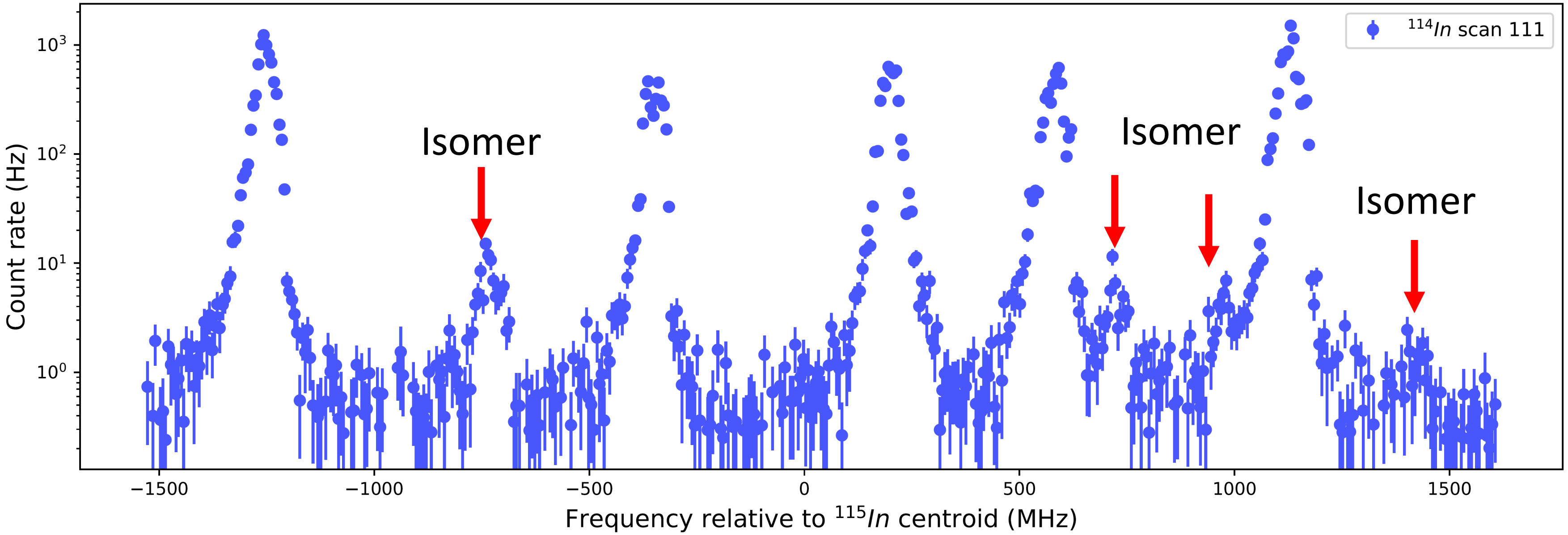


$$S = (\Delta\omega_{AB}/\Gamma)^2$$

$$S = \Pi S_i = S_1 * S_2$$

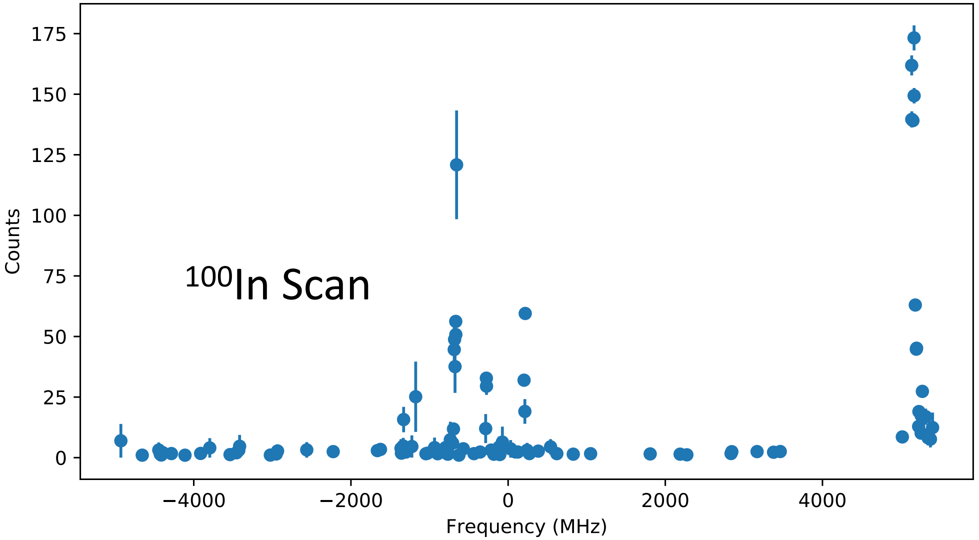
S_i of $>10^4$ is possible

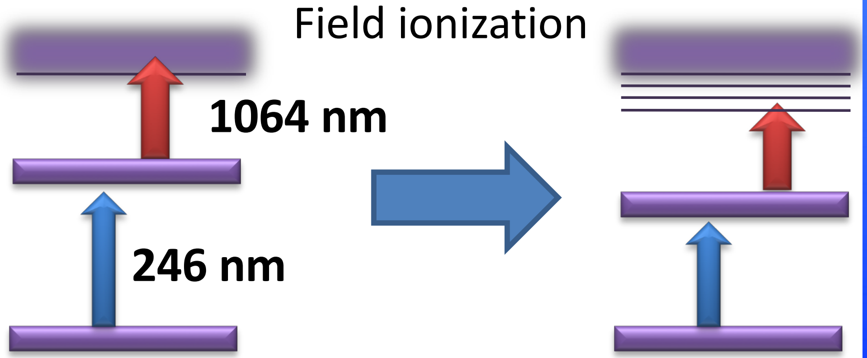


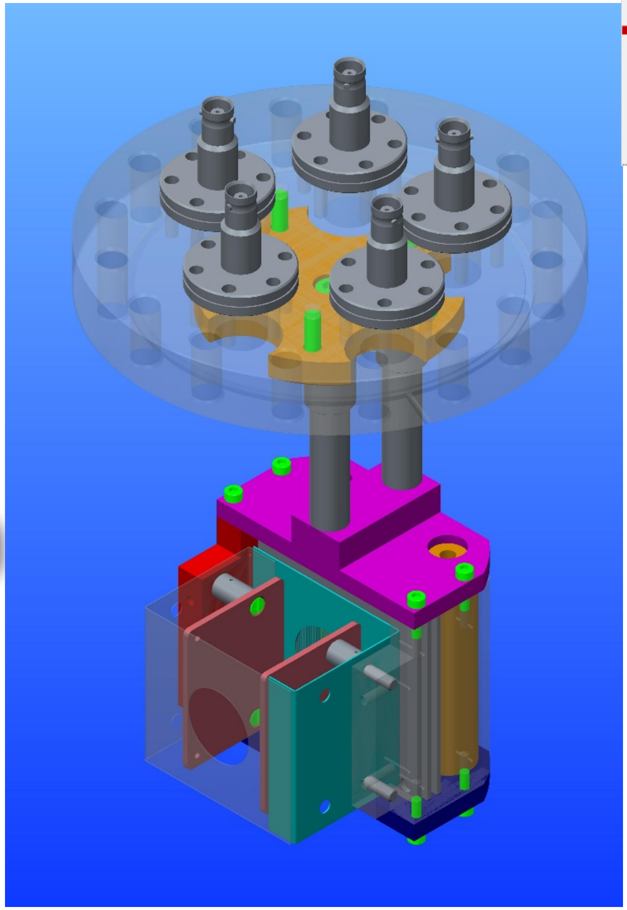


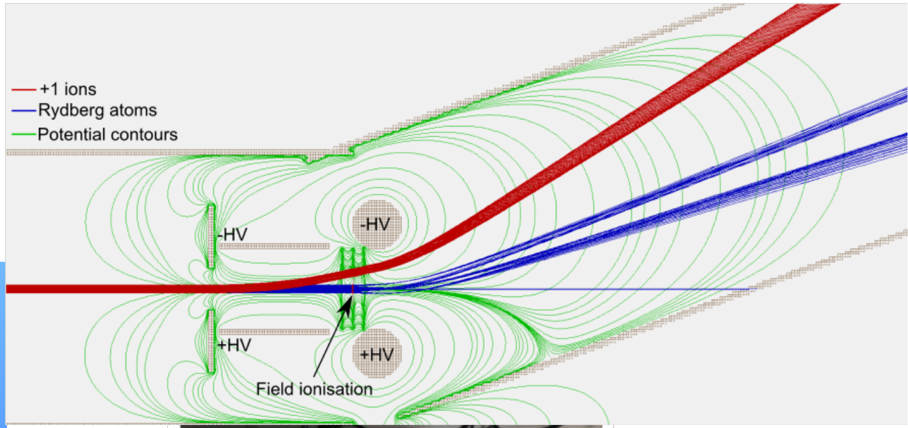
Limits of the photoionization

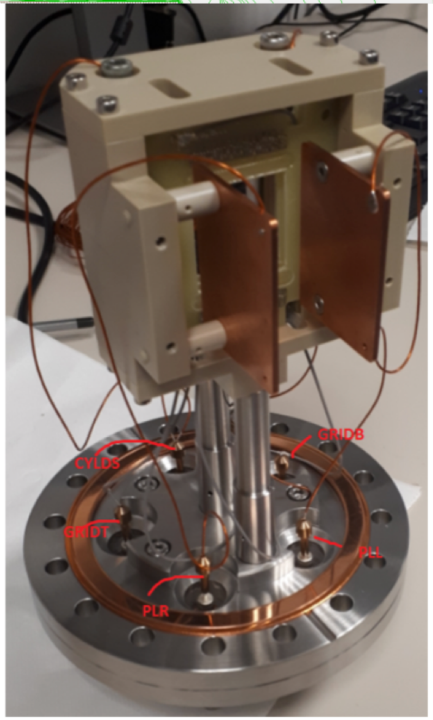
‘peaks’ are 1064nm only, large ^{100}Mn contamination







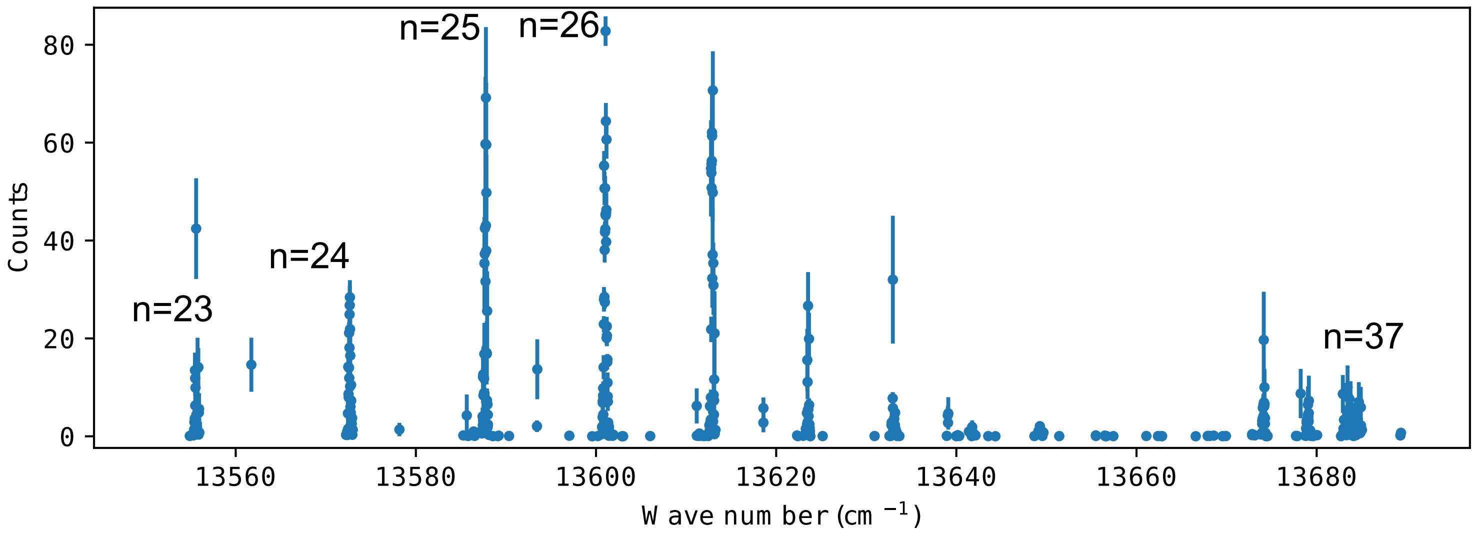


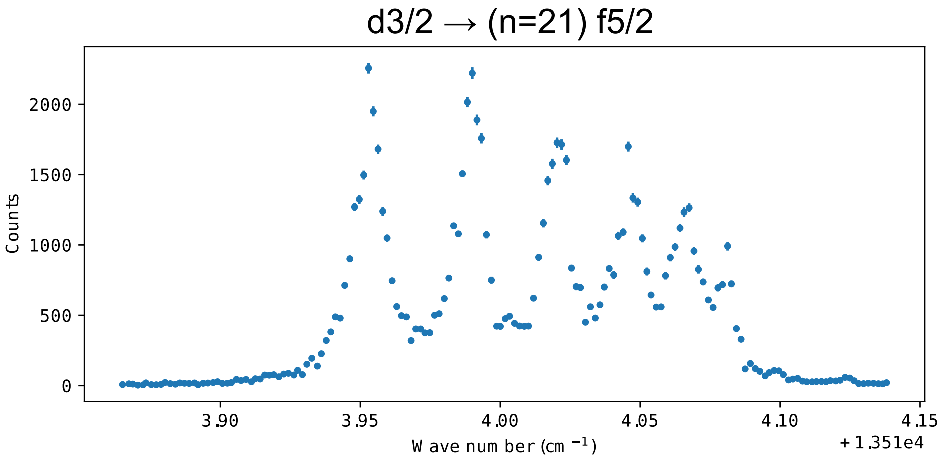


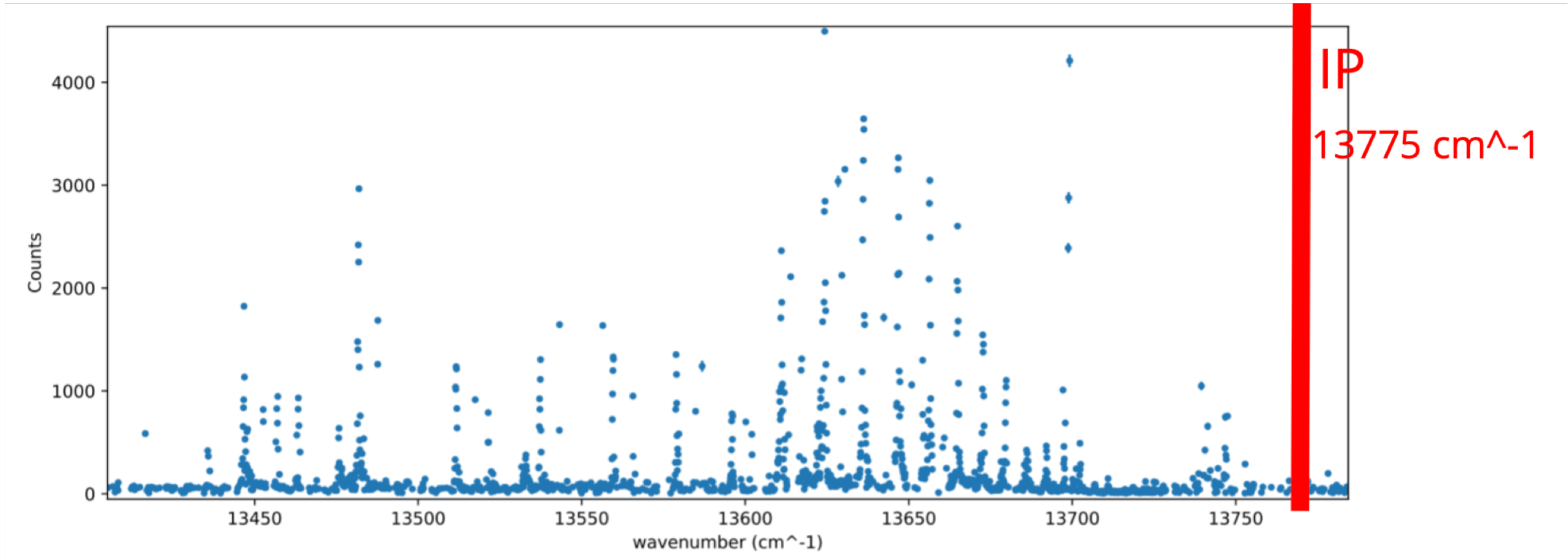
Offline work in 2019: Field ionization of indium

Next Steps:

- Optimization of design
- Modification of the end of CRIS
- Demonstration of gain in background at $1x10^{-10}$ mbar
- Expect x100-200 reduction in collisional background (and removal of photoionization background)







Remarks

- CRIS is one variety of the general collinear laser spectroscopy method.
- Laser spectroscopy is currently a very active field with many groups around the world working towards the limits of nuclear existence.
- We are continuing to upgrade and optimize the CRIS method and certainly have more yet to gain.
- Charge radii provides a test to inter-nucleon interactions and many-body methods.

The CRIS Collaboration

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Thank you

Energy spread correction