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Perspectives for laser spectroscopy of the heaviest elements

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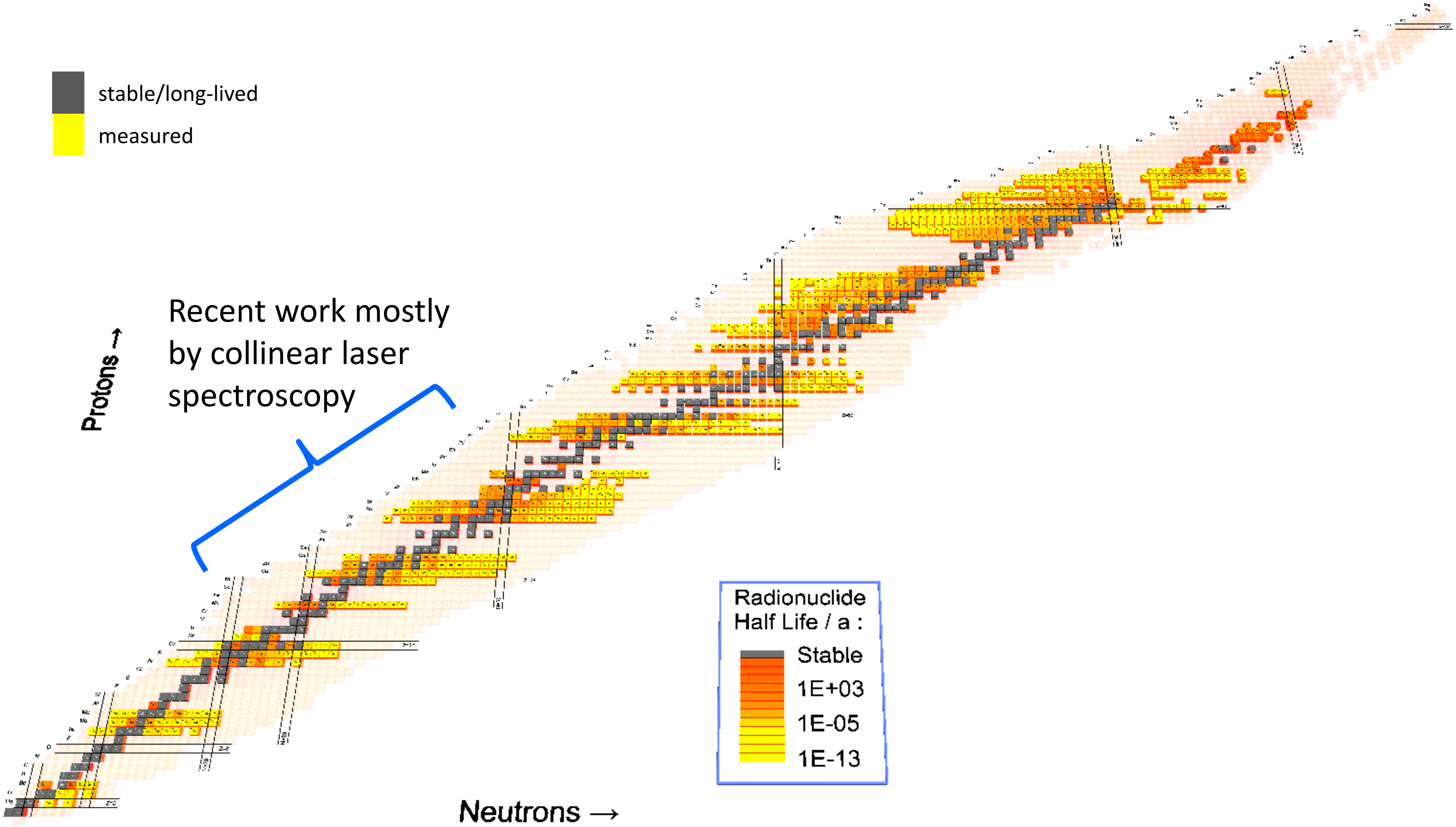
KU LEUVEN

Outline

- Motivation
- Broadband laser spectroscopy
    - The RADRIS technique
    - Level search in ^{254}No
    - Recent achievements
- Future prospects
    - Next RADRIS experiments
    - In-gas jet laser spectroscopy

Optical spectroscopy map

- ■ stable/long-lived
- 🟨 measured



Recent work mostly by collinear laser spectroscopy

Optical spectroscopy map

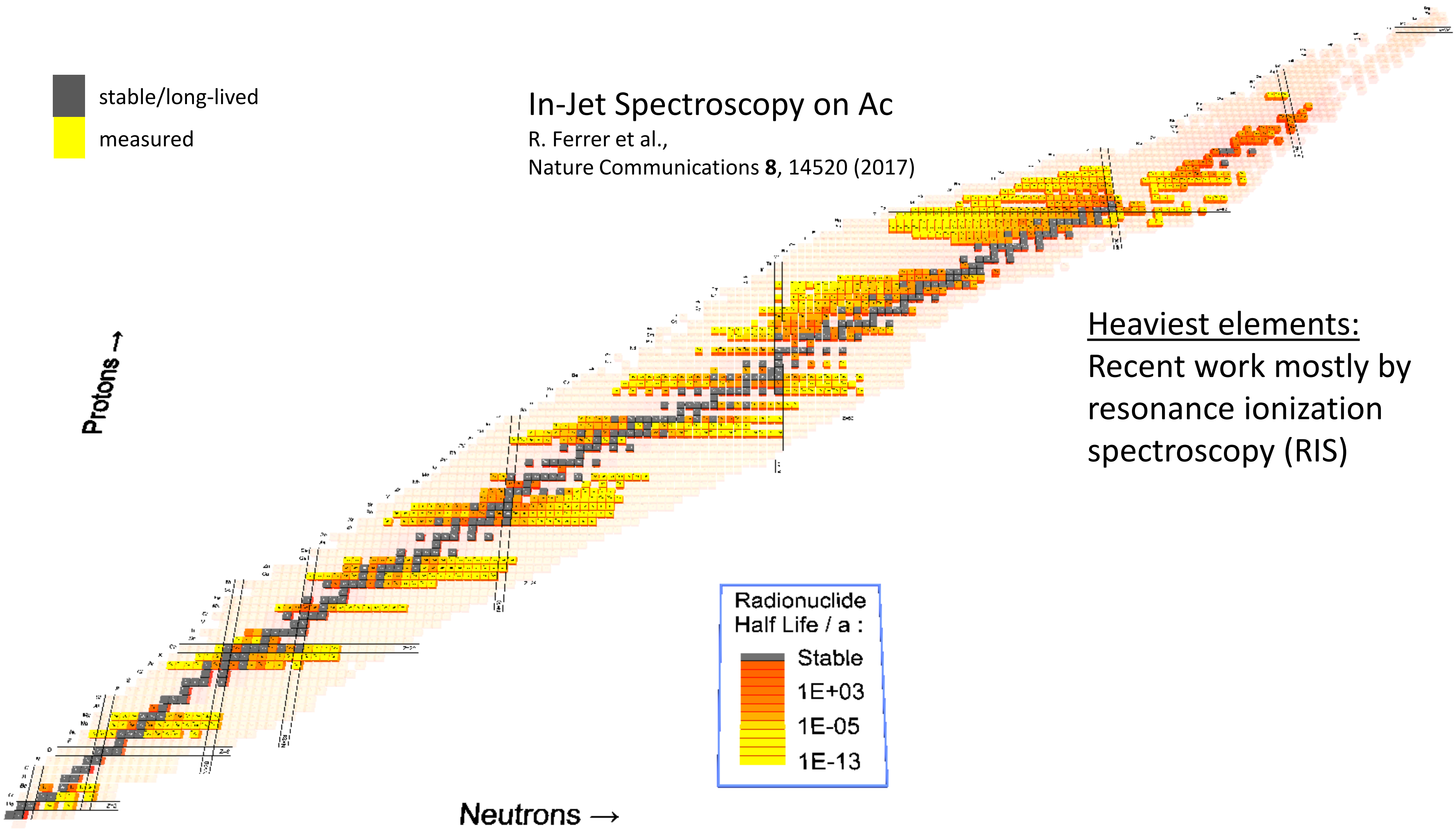
⬛ stable/long-lived

🟨 measured

In-Jet Spectroscopy on Ac

R. Ferrer et al.,

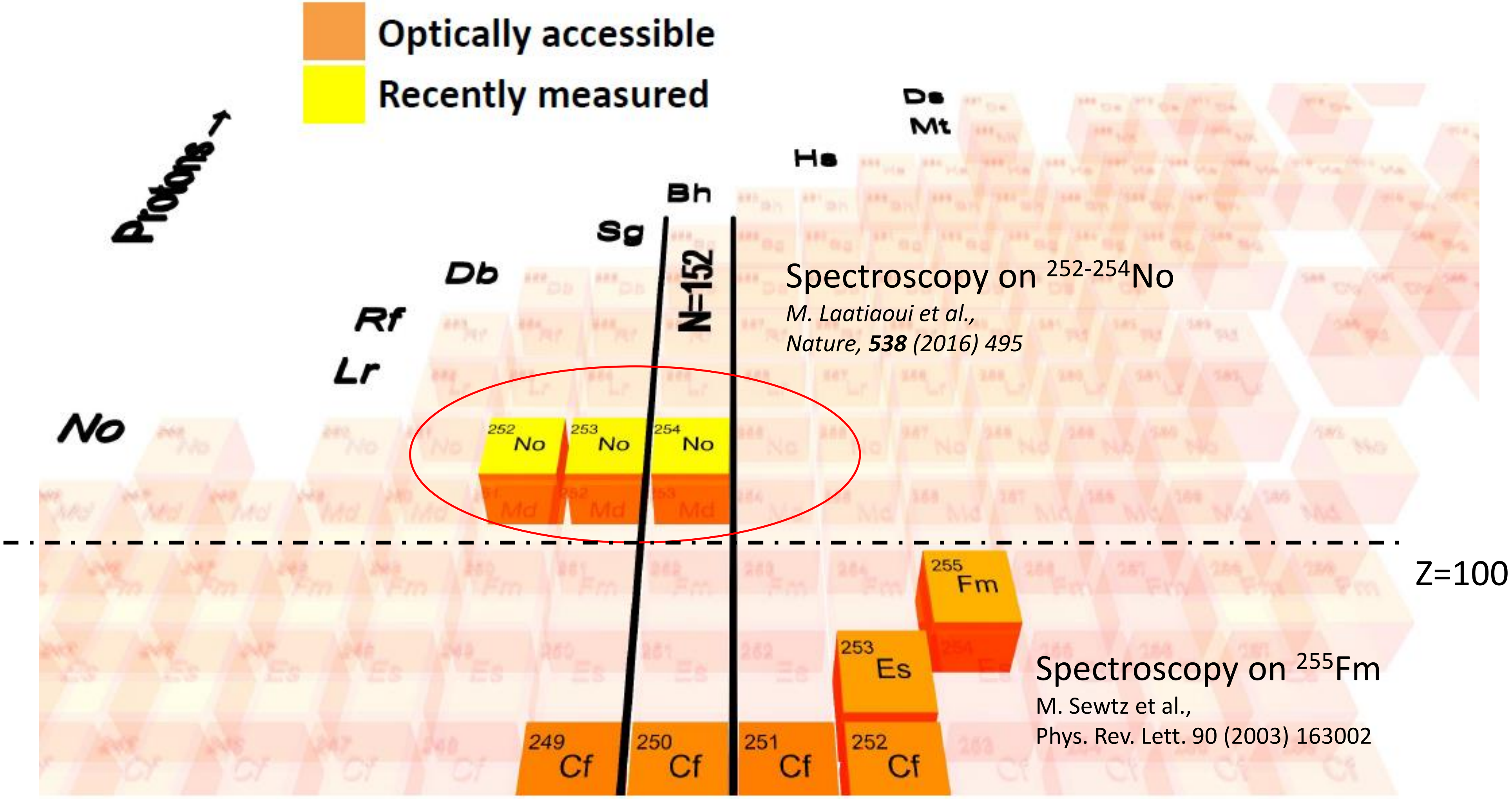
Nature Communications **8**, 14520 (2017)



Heaviest elements:

Recent work mostly by resonance ionization spectroscopy (RIS)

Optical spectroscopy map



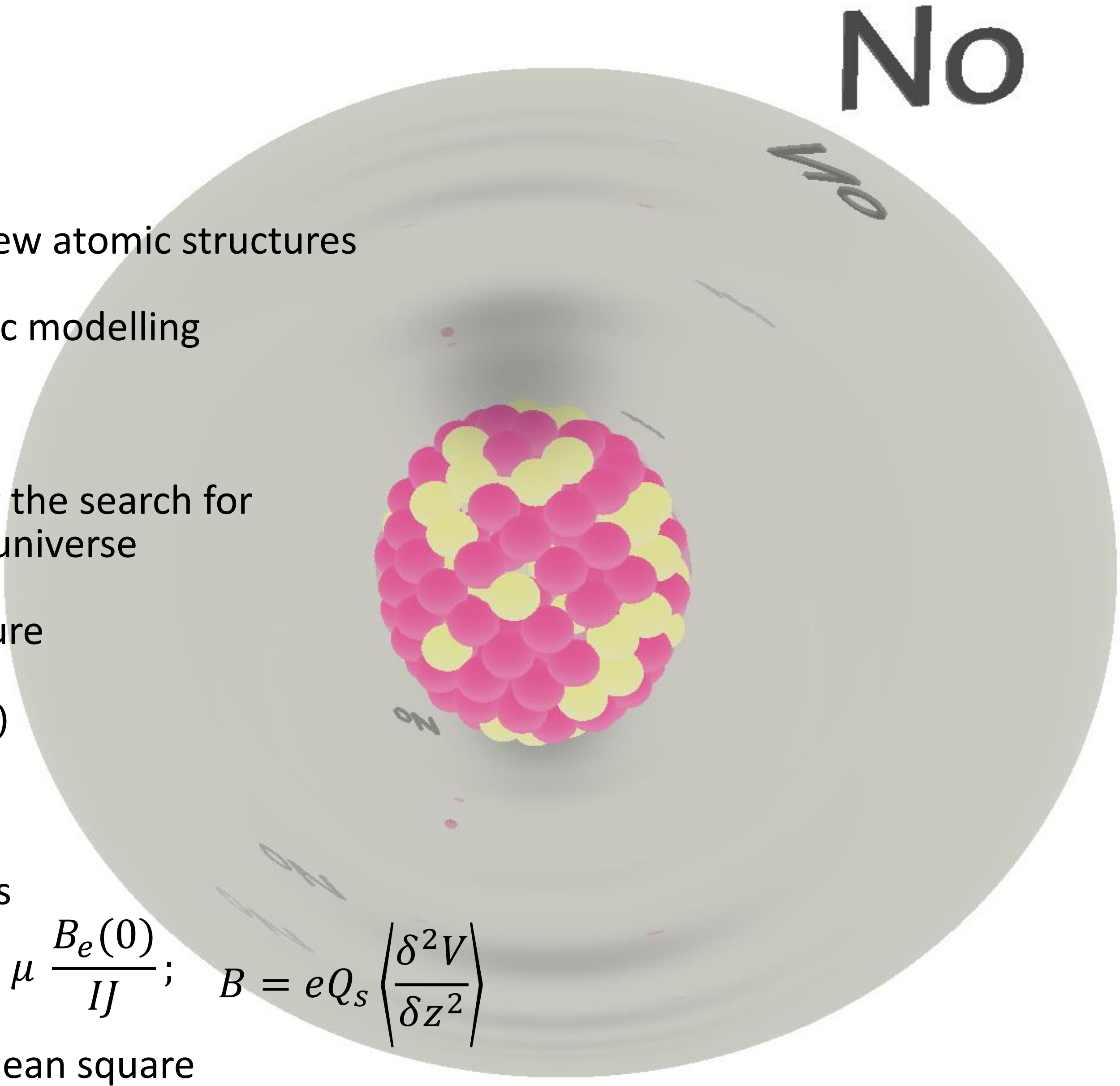
Spectroscopy on $^{252\text{-}254}$No

M. Laatiaoui et al.,
Nature, ***538*** *(2016) 495*

Spectroscopy on ^{255}Fm

M. Sewtz et al.,
Phys. Rev. Lett. 90 (2003) 163002

Motivation



- Atomic physics and chemistry:
  - ➔ Experimental exploration of new atomic structures
  - ➔ Study relativistic effects
  - ➔ Provide benchmarks for atomic modelling
- Astrophysics:
  - ➔ Provide spectroscopic data for the search for Super Heavy Elements in the universe
- Nuclear physics (via hyperfine structure studies):

$$\Delta E(hfs) = f(A, B, I, J)$$

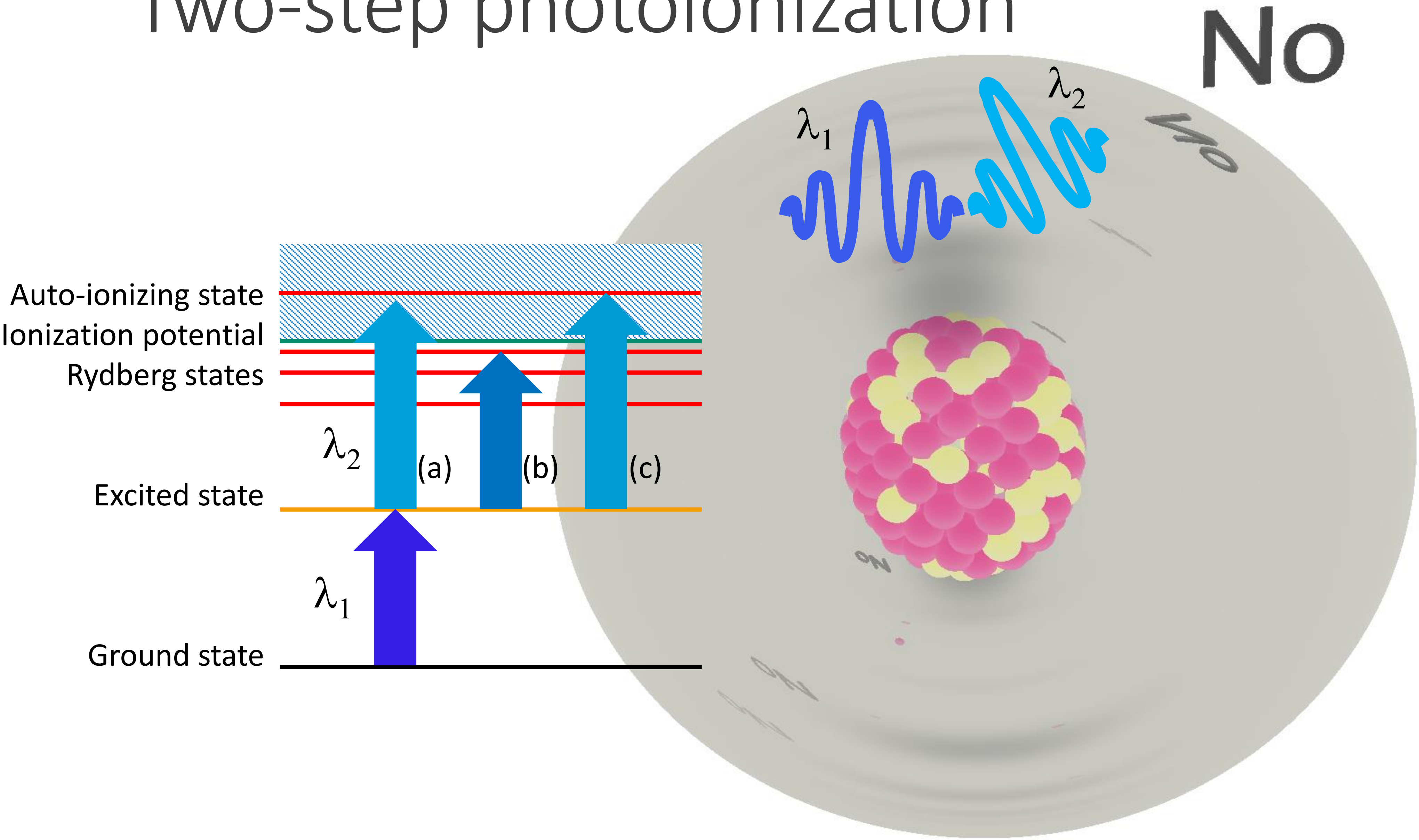
  - ➔ Study nuclear spin coupling
  - ➔ Extraction of nuclear moments

$$A = \mu \frac{B_e(0)}{IJ}; \quad B = eQ_s \left\langle \frac{\delta^2 V}{\delta z^2} \right\rangle$$

  - ➔ Extraction of changes in the mean square charge radii (via isotope shift measurements)

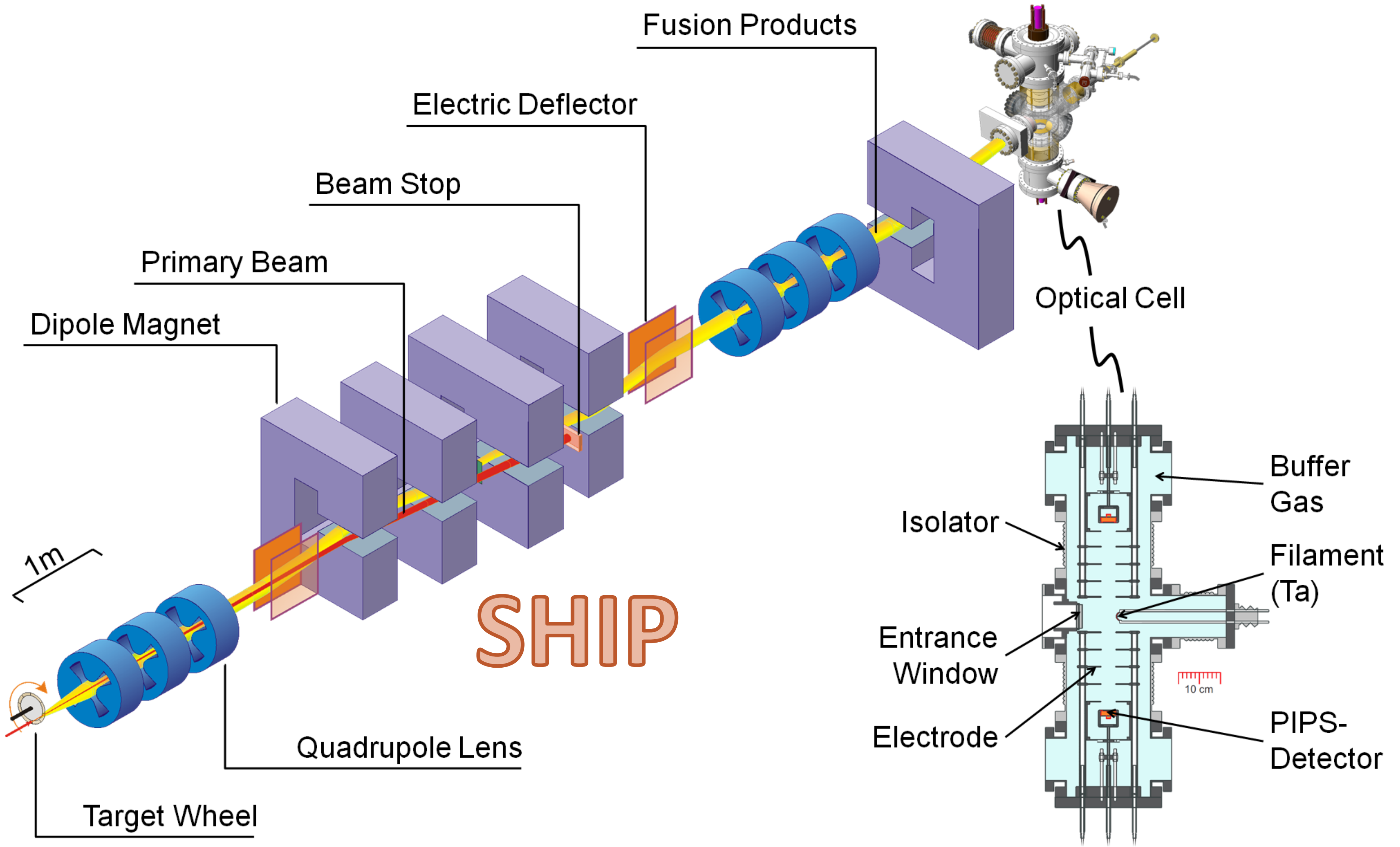
$$\delta \langle r^2 \rangle^{AA'} = \left(\Delta\nu^{AA'} - \frac{A - A'}{AA'} M \right) \frac{1}{F}$$

Two-step photoionization

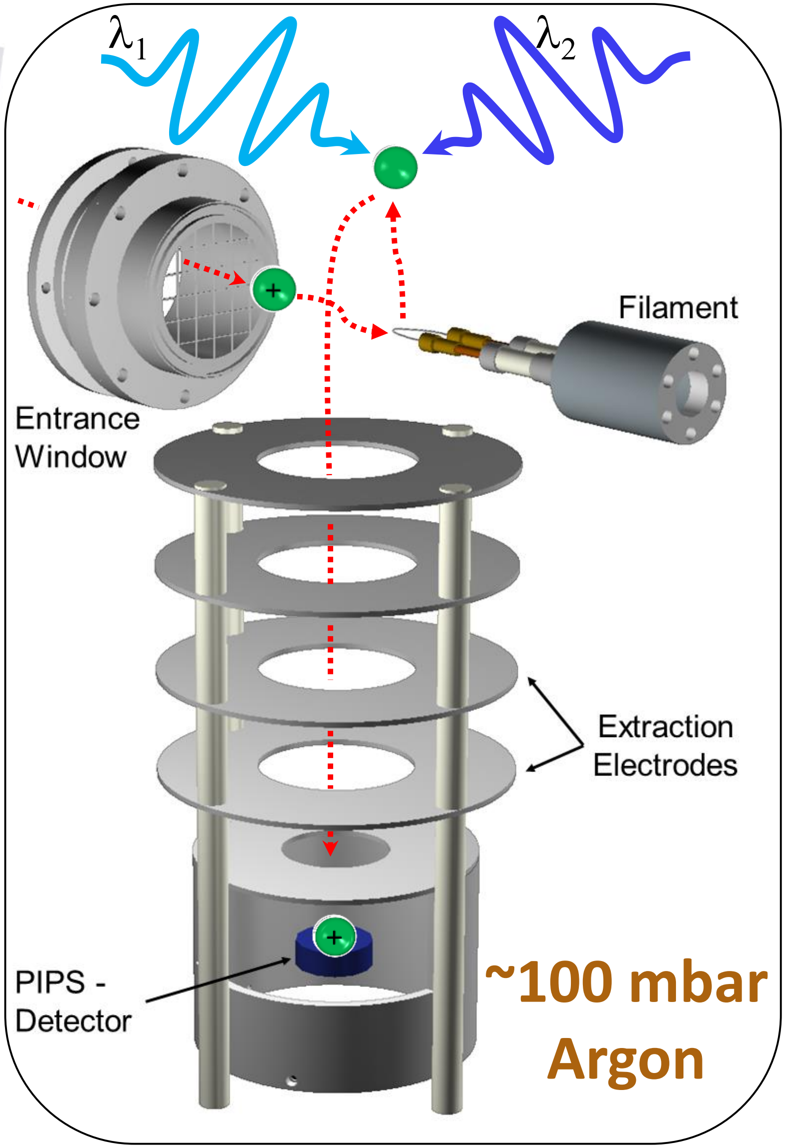


→ Scenario (a) less efficient compared with (b) and (c)

Setup @SHIP/GSI



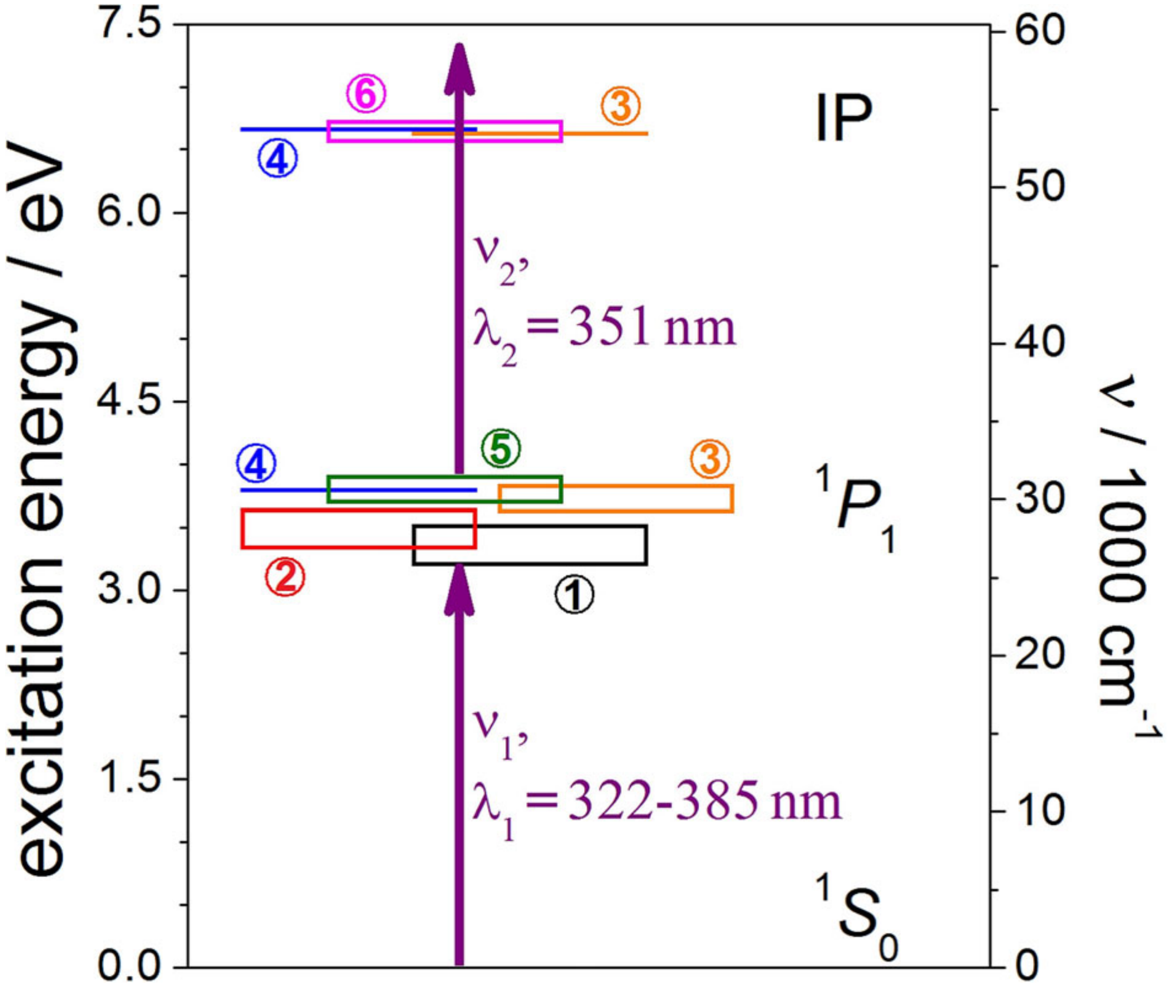
RAdiation-Detected Resonance Ionization Spectroscopy (RADRIS)



Nobelium & lawrencium isotopes

Isotope	**I^P**	**$T_{1/2}$ (s)**	**Reaction**	**Max. production rate on target (1/s)**	**α energy (MeV)**
^{251}No	0	0.8	^{206}Pb(^{48}Ca,3n)^{251}No	0.2	8.61
^{252}No	0	2.4	^{206}Pb(^{48}Ca,2n)^{252}No	4	8.42
^{253}No	(9/2$^-$)	102	^{207}Pb(^{48}Ca,2n)^{253}No	11	8.01
^{254}No	**0**	**51**	**^{208}Pb(^{48}Ca,2n)^{254}No**	**17**	**8.10**
^{255}No	(1/2$^+$)	186	^{208}Pb(^{48}Ca,1n)^{255}No	2	8.12
^{255}No	(1/2$^+$)	186	^{209}Bi(^{48}Ca,2n)^{255}Lr → EC	1	8.12
^{255}Lr	**(1/2$^-$)**	**31.1**	**^{209}Bi(^{48}Ca,2n)^{255}Lr**	**3.4**	**8.37**

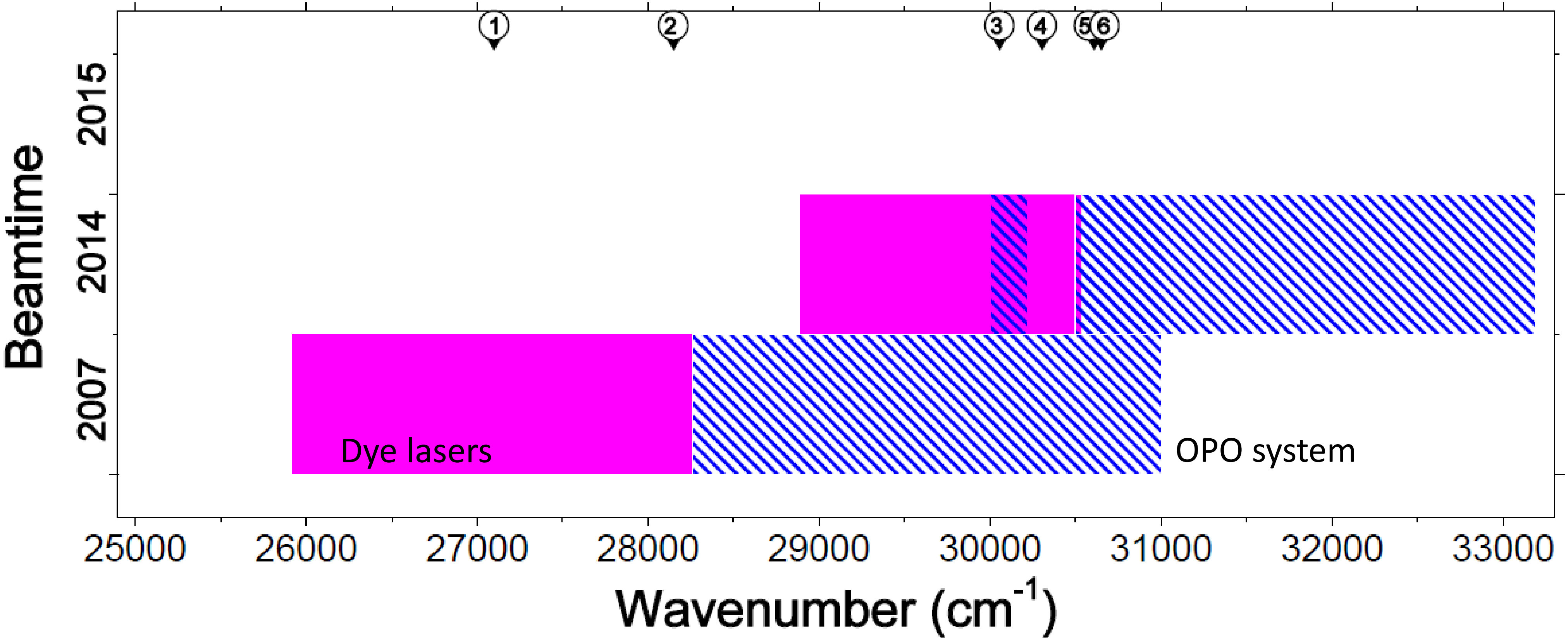
Level search in ^{254}No



1: MCDF (2005), **2**: MCDF (2005), **3**: IHFSCC (2007), **4**: RCC (2014), **5**: MCDF (2007), **6**: MCDF (2007)

Level search in ^{254}No

Year	2007	2014
Scan range (cm^{-1})	25920 – 31001	28887 – 33191
Net scan time (h)	39	67



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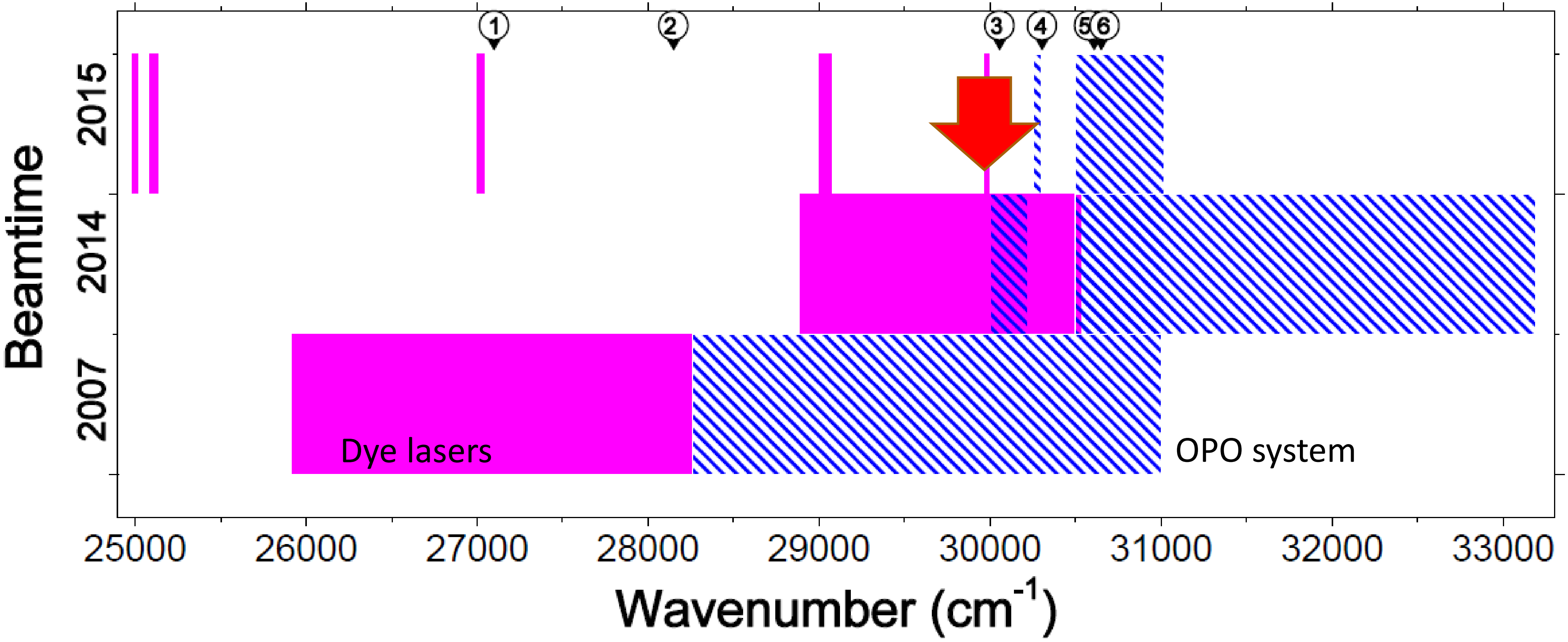

1: MCDF (2005), **2**: MCDF (2005), **3**: IHFSCC (2007), **4**: RCC (2014), **5**: MCDF (2007), **6**: MCDF (2007)

Results (part I)

- ✓ First ever successful laser spectroscopy beyond fermium
- ✓ Production cross section σ=500 nb demonstrated (^{252}No)
- ✓ 10% overall efficiency reached (^{253}No)
- ✓ Besides low-lying $^1P_1$, also $^3D_3$ atomic level and many Rydberg states identified (^{254}No)
- ✓ Ionization potential precisely measured (^{254}No)
- ✓ Nuclear spin and moments determined (^{253}No)
- ✓ Differential mean square charge radii extracted ($^{252\text{-}254}$No)

Future prospects

Next steps with RADRIS

Isotope	**I^P**	**$T_{1/2}$ (s)**	**Reaction**	**Max. production rate on target (1/s)**	**α energy (MeV)**
^{251}No	0	0.8	^{206}Pb(^{48}Ca,3n)^{251}No	0.2	8.61
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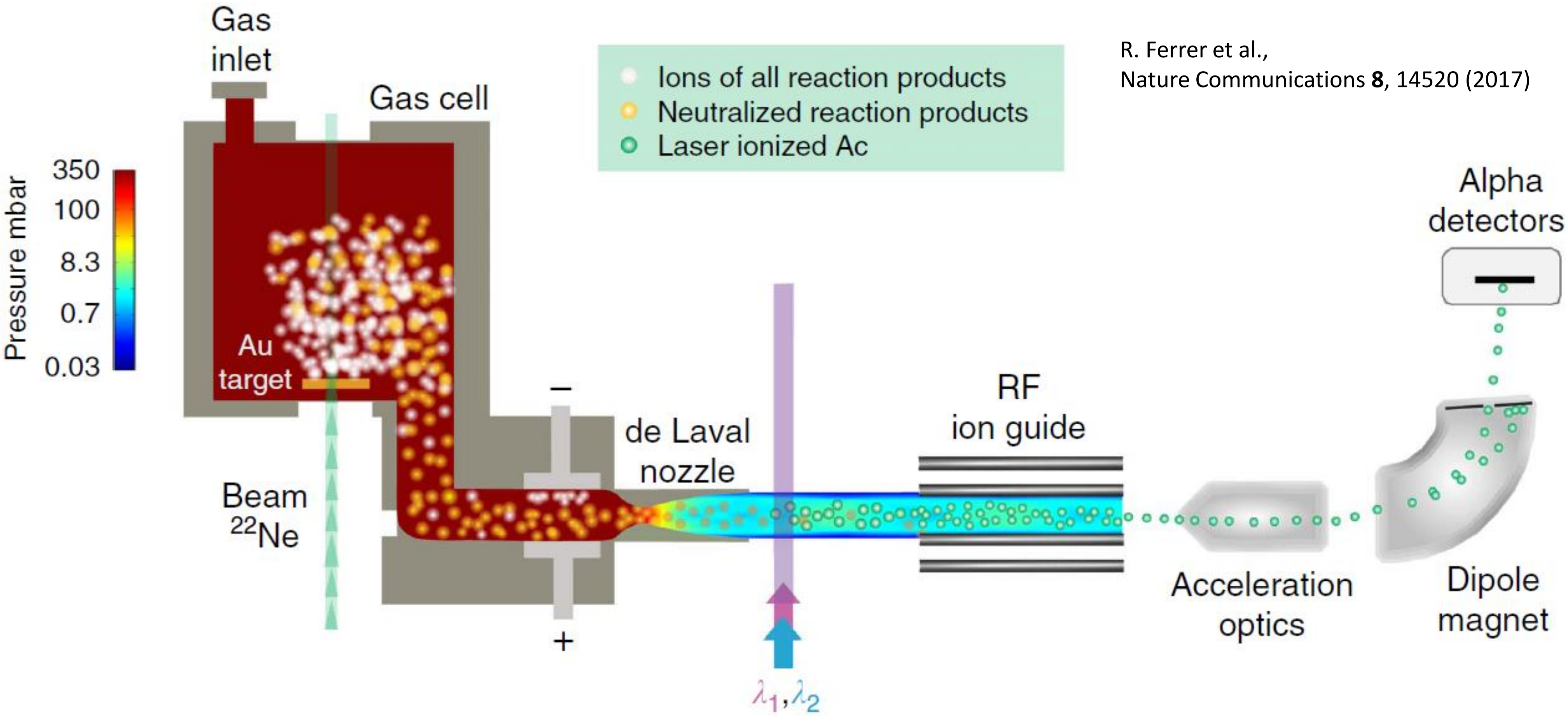
^{255}Lr	**(1/2$^-$)**	**31.1**	**^{209}Bi(^{48}Ca,2n)^{255}Lr**	**3.4**	**8.37**

- Extend RADRIS to ^{251}No and ^{255}No
- Resume level search in lawrencium

→ 84 shifts granted for these studies behind SHIP @GSI (2018 / 2019)

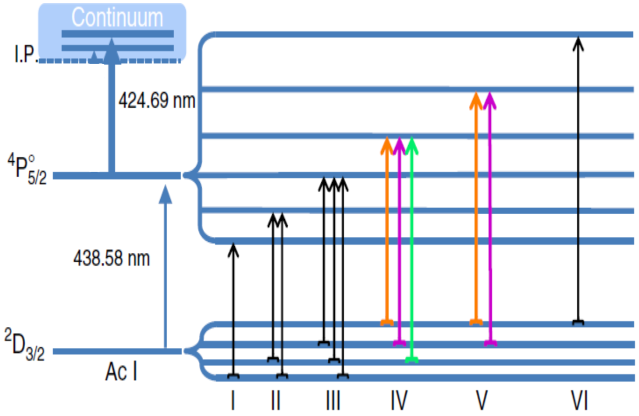
In-gas-jet laser spectroscopy



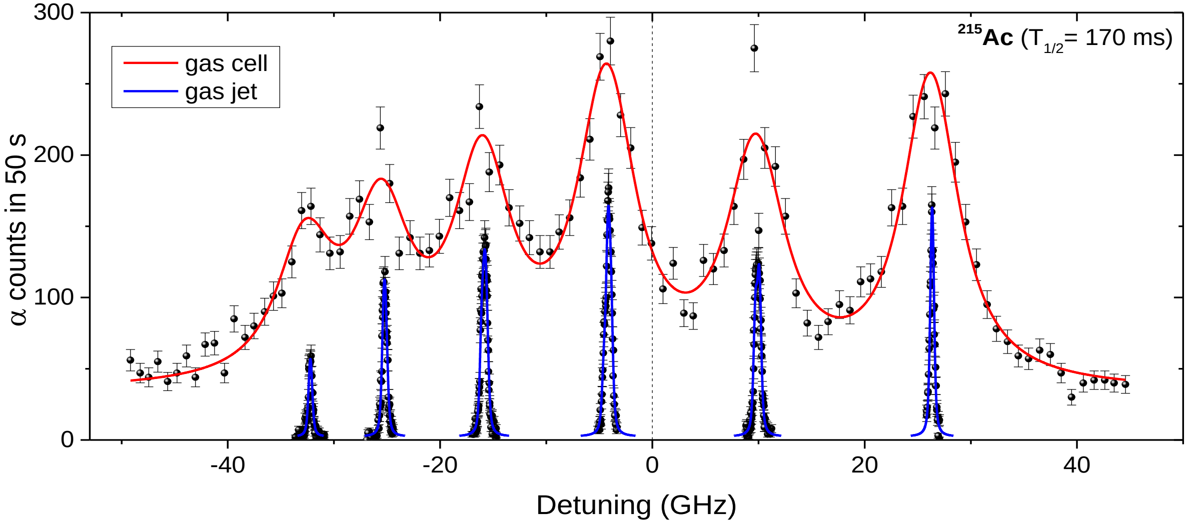
R. Ferrer et al.,
Nature Communications **8**, 14520 (2017)

In-gas-jet laser spectroscopy

^{215}Ac



R. Ferrer et al.,
Nature Communications **8**, 14520 (2017)



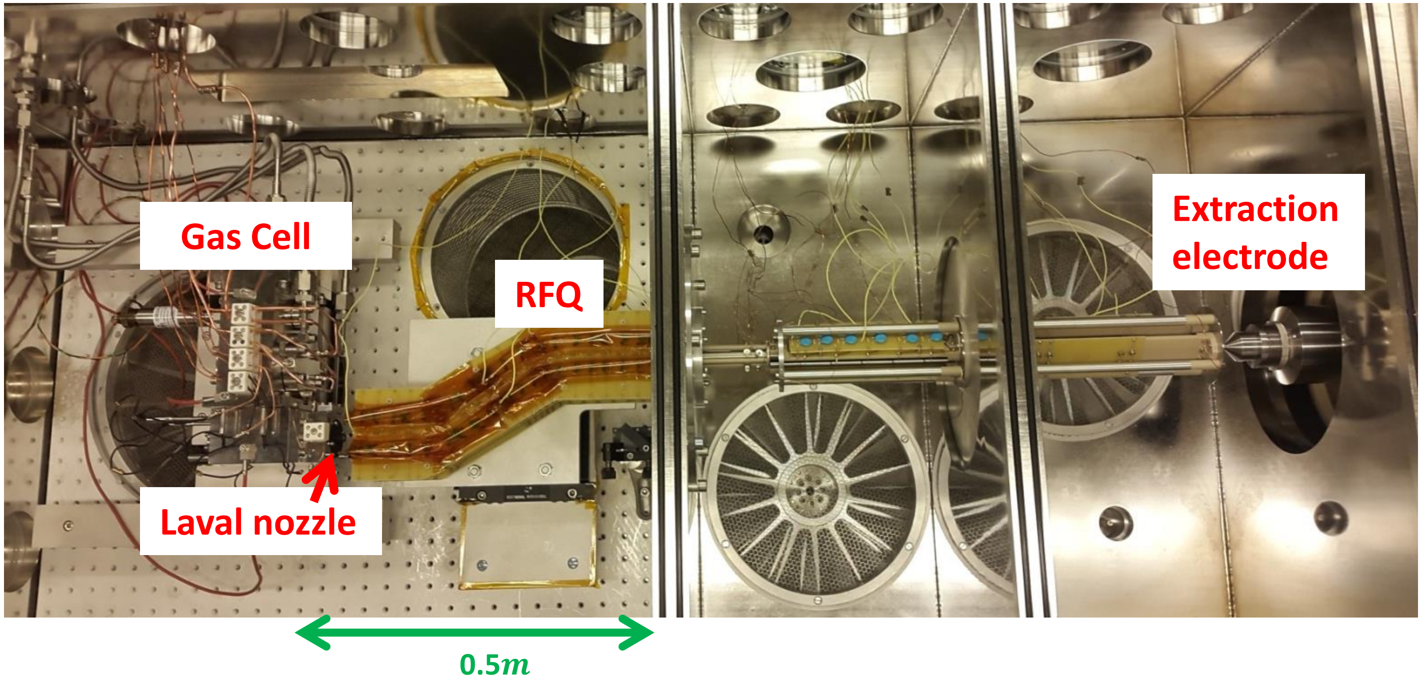
Figures of merit

- ✓ Universal method
- ✓ Fast evacuation → access to short-lived radionuclides
- ✓ Low density and temperature in the jet → high spectral resolution
- ✓ Efficiency ~ 0.5% (Ac) → improvements possible

To be implemented @ S^3

Tailoring the gas jet

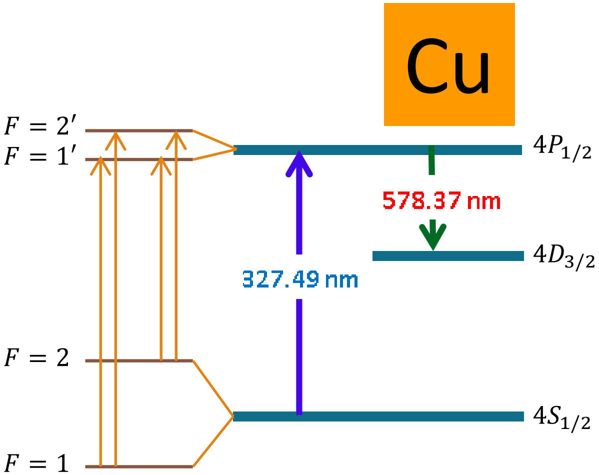
Setup @KU Leuven



Planar Laser Induced Fluorescence (PLIF) – technique

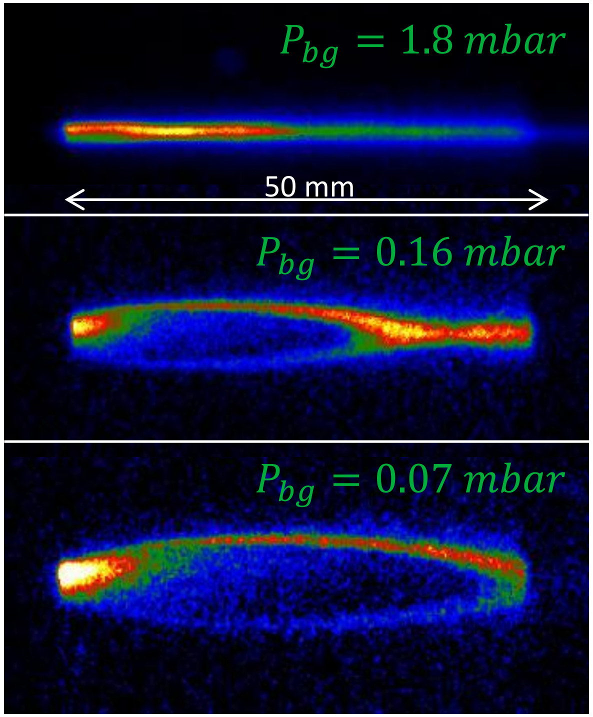
→ Mapping *temperature, velocity and density in the jet*

Courtesy S. Zadvornaya

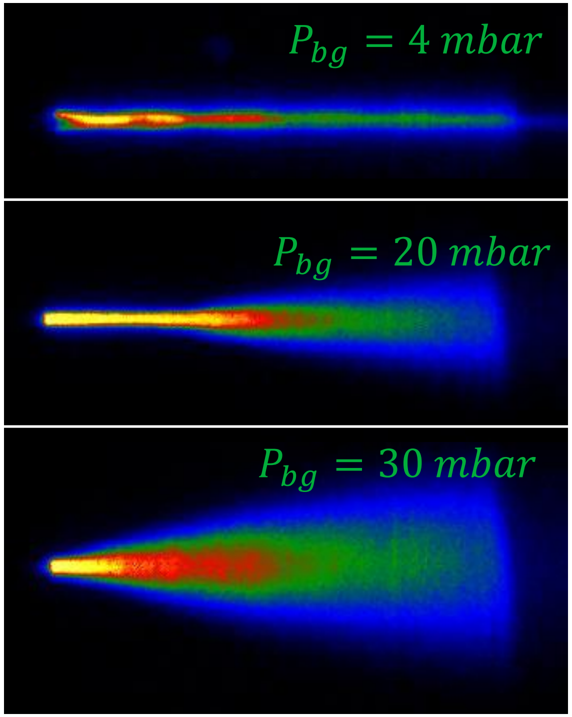


Tailoring the gas jet

Mach-5 Laval nozzle



Under-expanded jet



Over-expanded jet

- Spatial overlap of laser beams with jet is required for efficient in-jet ionization

- Formation of long jets is hindered at extreme pressure mismatch

→ Optimizing background pressure is essential

Courtesy S. Zadvornaya

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