Colloque GANIL 2023

25.–29. Sept. 2023

The LRC approach to unveiling the electronic structure of heavy and superheavy cations

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Johannes Gutenberg University

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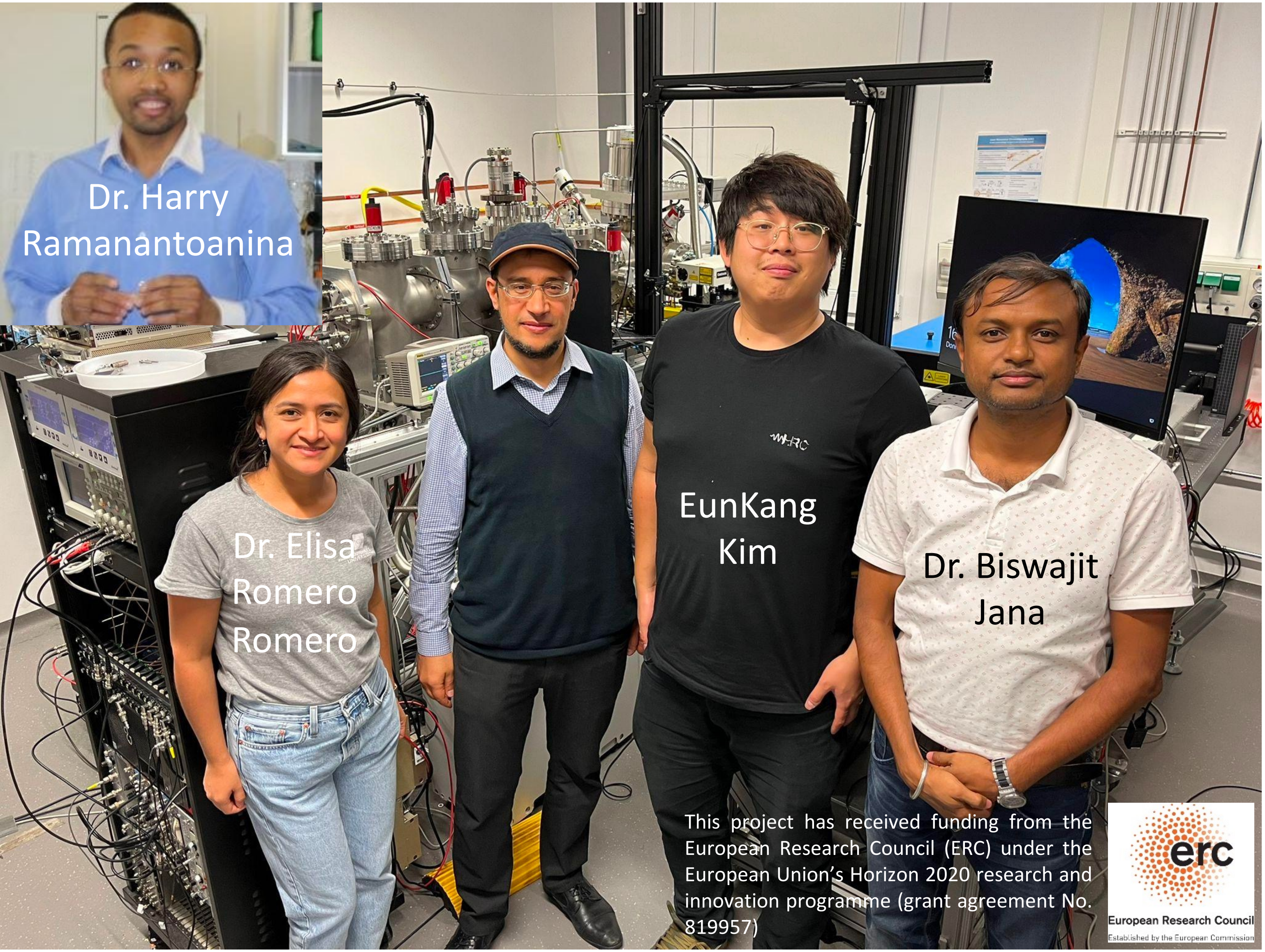
The LRC team



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European Research Council
Established by the European Commission

Research areas

- HEs/SHEs
- Transport properties
- Atomic structure
- Nuclear properties

Collaborators

- A. Borschevsky (Groningen)
- L. A. Viehland (Chatham)
- M. Block (Mainz)
- S. Raeder
- E. Rickert
- A. Aayush

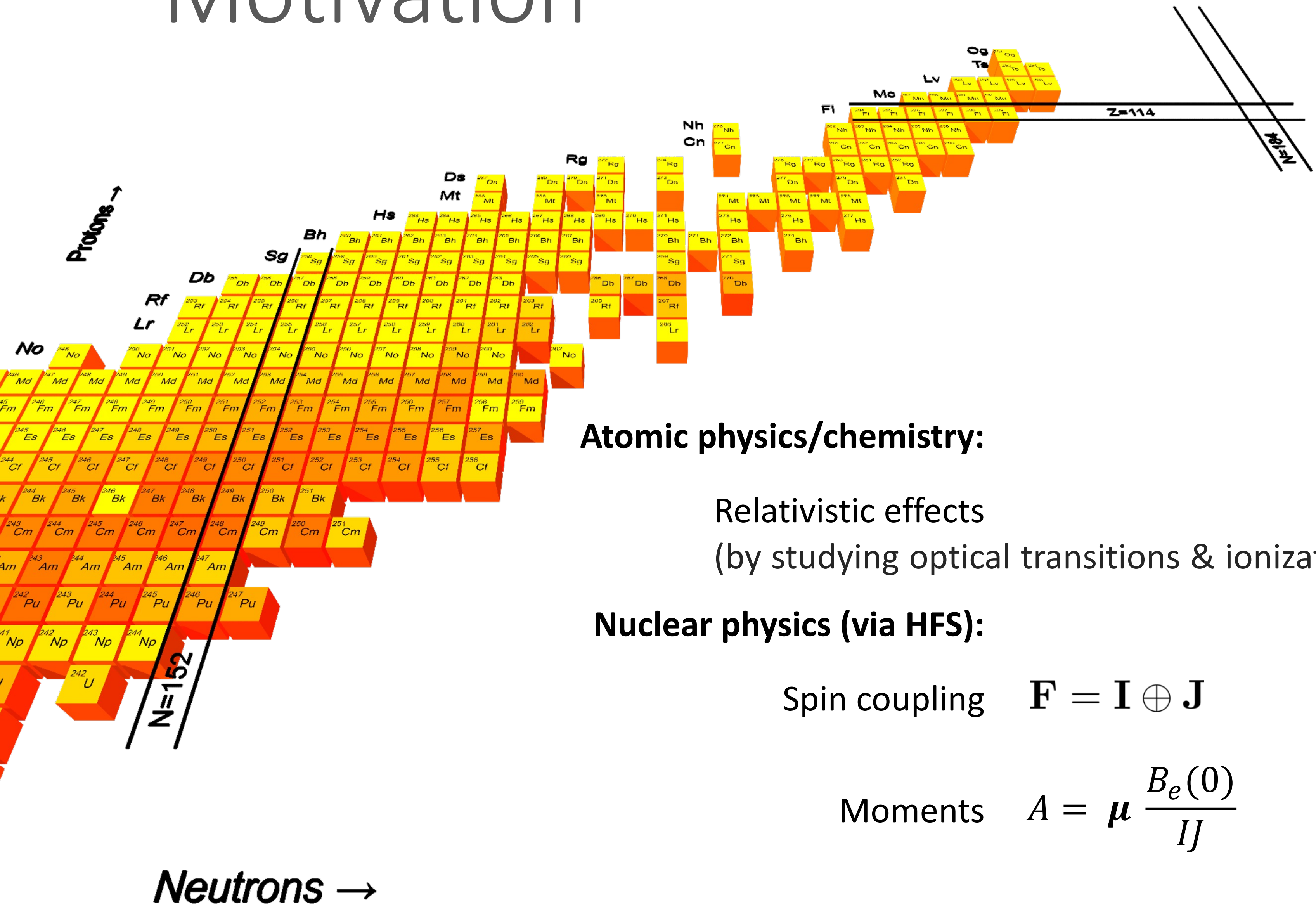
www.lrc-project.eu

LRC_Mainz

Outline

- Why is understanding the electronic structure of SHEs important?
- Experimental challenges
- Laser Resonance Chromatography (LRC)
  - The method & the setup
  - Results from inauguration experiments (Lu^+)
  - Prospects for LRC on Lr^+
- Summary & Outlook

Motivation



Atomic physics/chemistry:

Relativistic effects
(by studying optical transitions & ionization potentials)

Nuclear physics (via HFS):

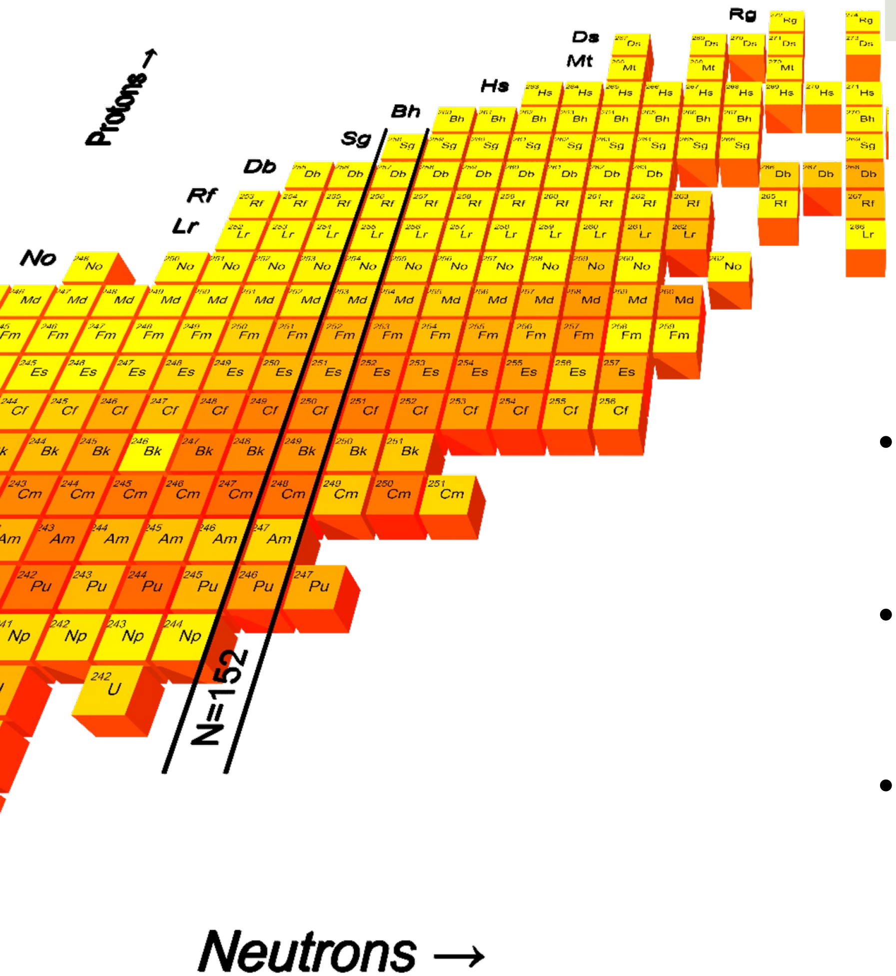
Spin coupling $\mathbf{F} = \mathbf{I} \oplus \mathbf{J}$

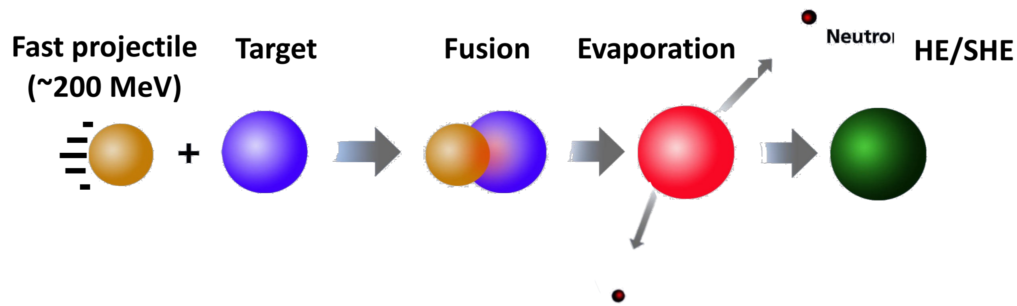
Moments $A = \boldsymbol{\mu} \frac{B_e(0)}{IJ}$ $B = e\boldsymbol{Q}_s \left\langle \frac{\delta^2 V}{\delta z^2} \right\rangle$

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

Experimental challenges

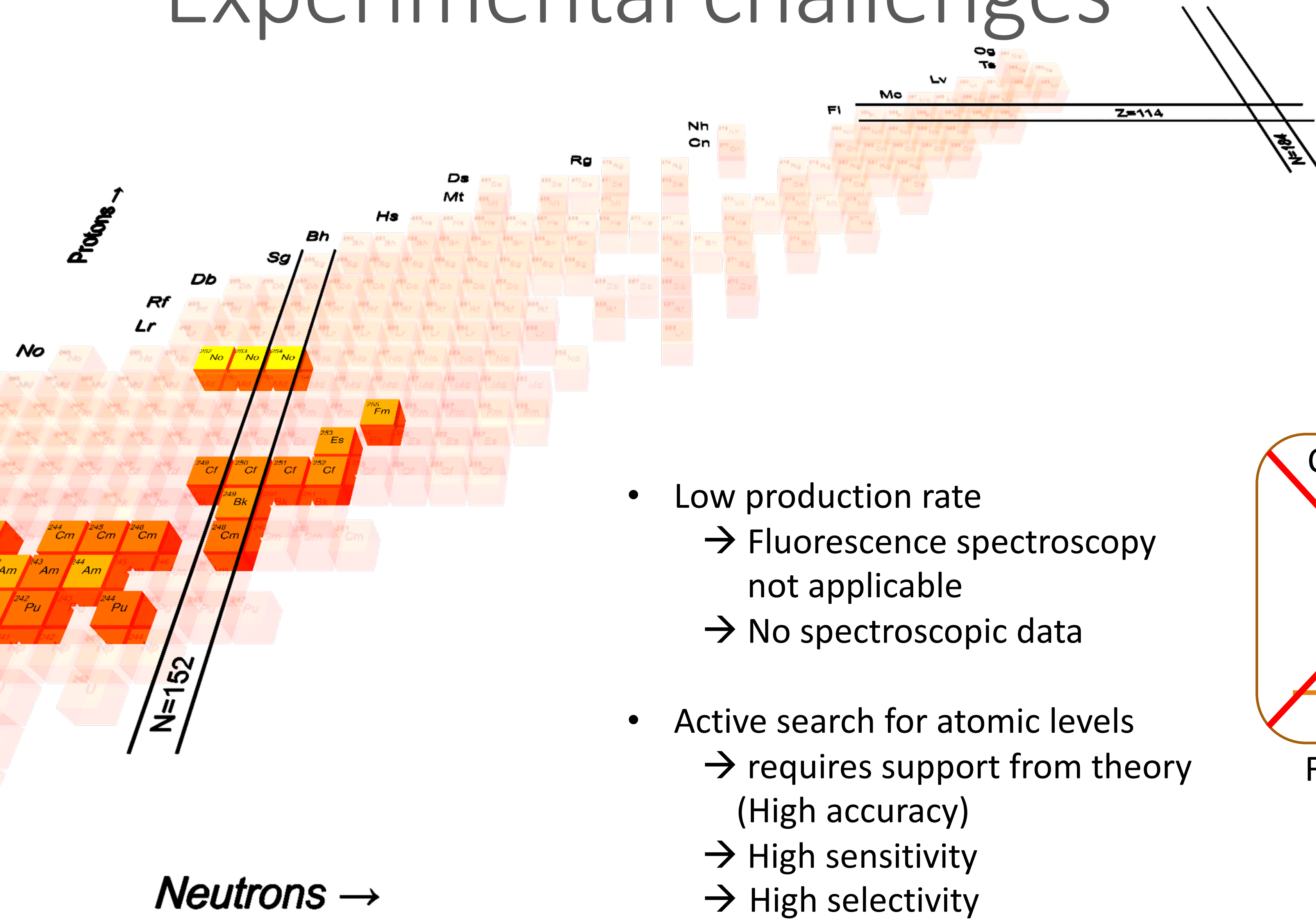
Isotope	Spin	$T_{1/2}$ (s)	Nuclear reaction	Production rate (1/s)
^{255}Lr	(1/2$^-$)	31.1	^{209}Bi(^{48}Ca,2n)^{255}Lr	3.4



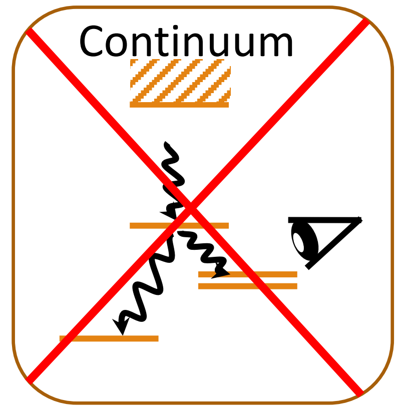


- On-line production in nuclear fusion reactions
  → requires high intensity projectile beams
- Huge background
  → requires recoil separators
- Energetic recoils + short half-lives
  → require gas catchers
  → requires fast experimental techniques
- High emittance
  → requires spatial confinement of atoms

Experimental challenges



- Low production rate
  - → Fluorescence spectroscopy not applicable
  - → No spectroscopic data
- Active search for atomic levels
  - → requires support from theory (High accuracy)
  - → High sensitivity
  - → High selectivity
  - → High efficiency

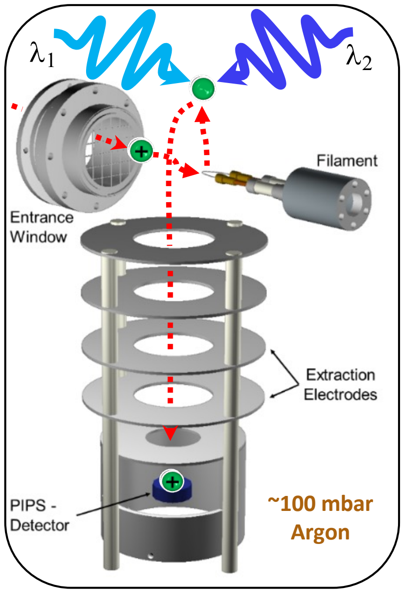


Fluorescence

RIS-based methods in the actinides

In-gas-cell based methods

Radiation Detected Resonance Ionization Spectroscopy (RADRIS)



H. Backe et al., **NPA 944** (2015) 492

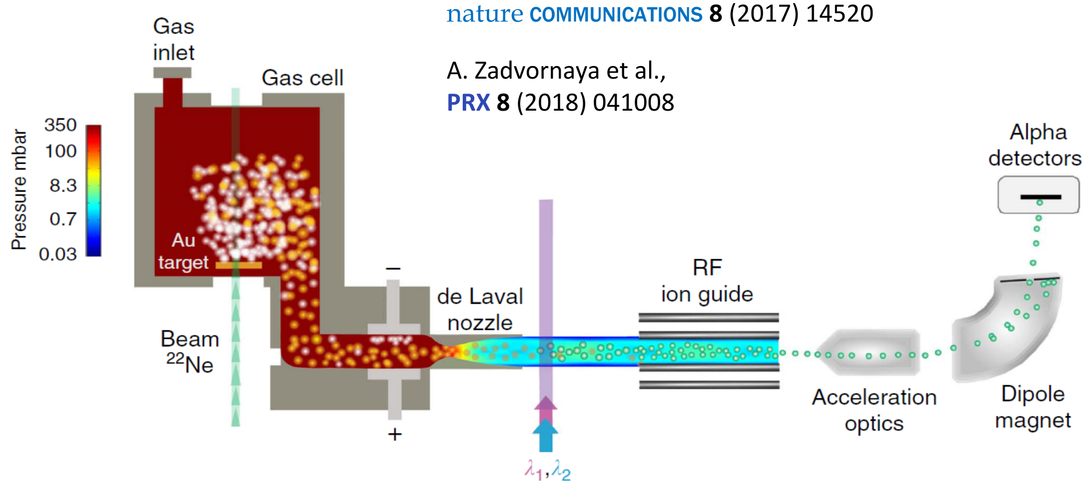
F. Lautenschläger et al., **NIMB 383** (2016) 115

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

In-gas-jet based methods

R. Ferrer et al., nature COMMUNICATIONS **8** (2017) 14520

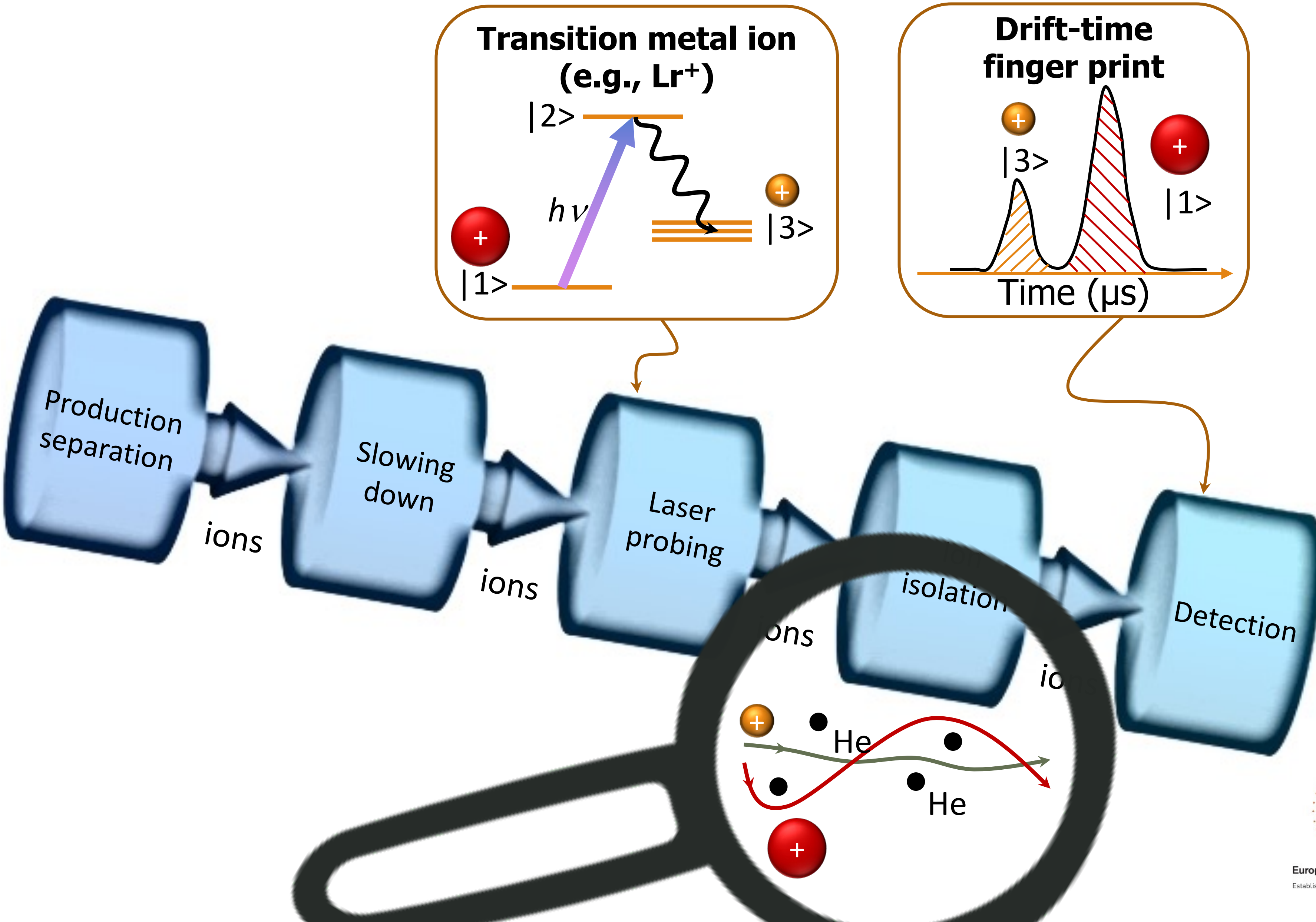
A. Zadvornaya et al., **PRX 8** (2018) 041008



Challenges with regard to SHEs:

- **Desorption** of **neutral** atoms
- **Fast neutralization** of stopped ions

Laser Resonance Chromatography (LRC)



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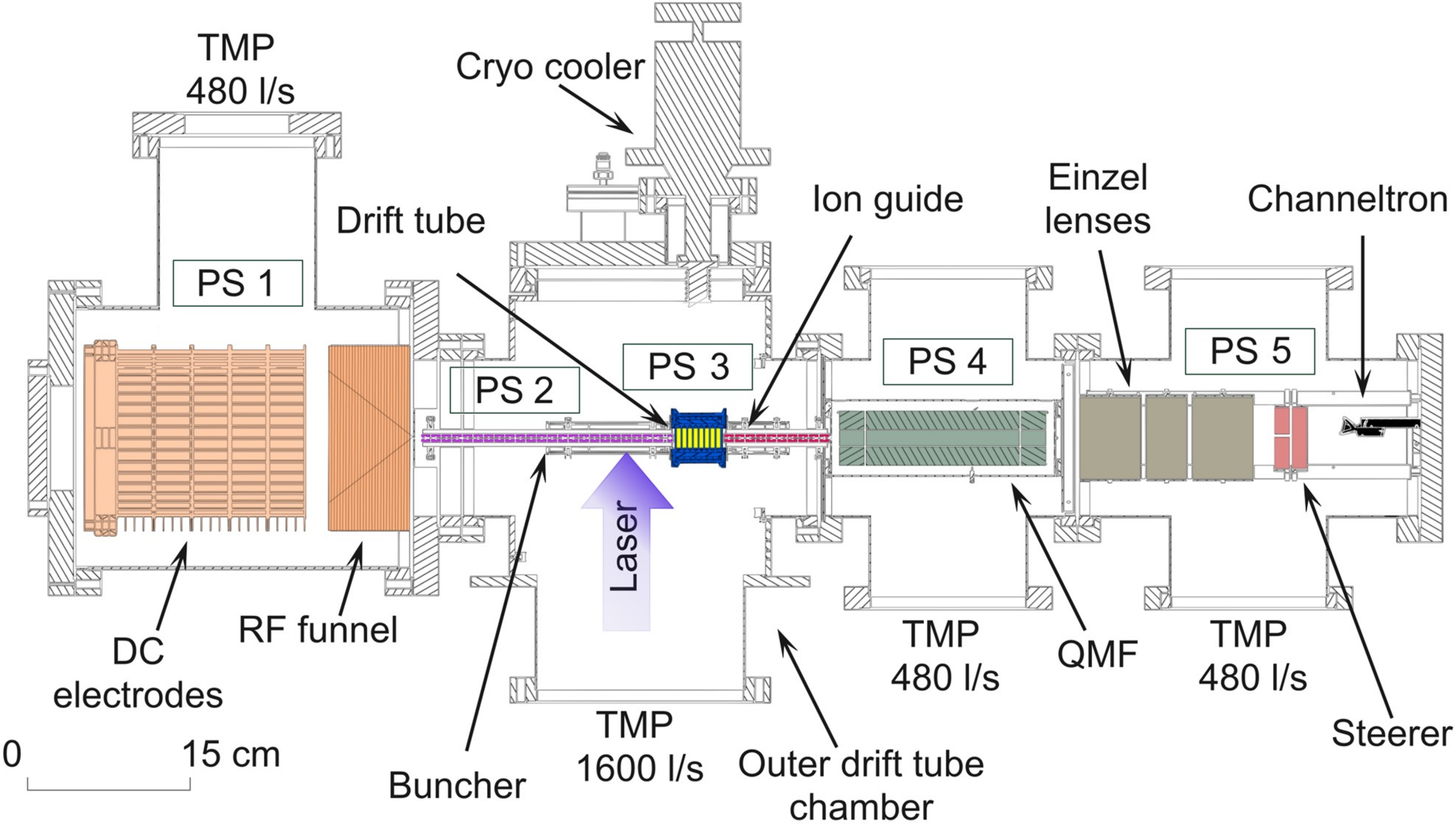
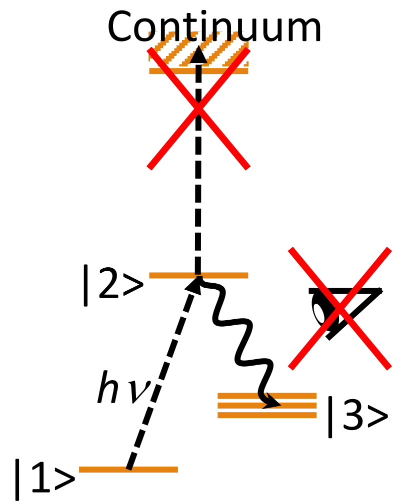
The LRC setup



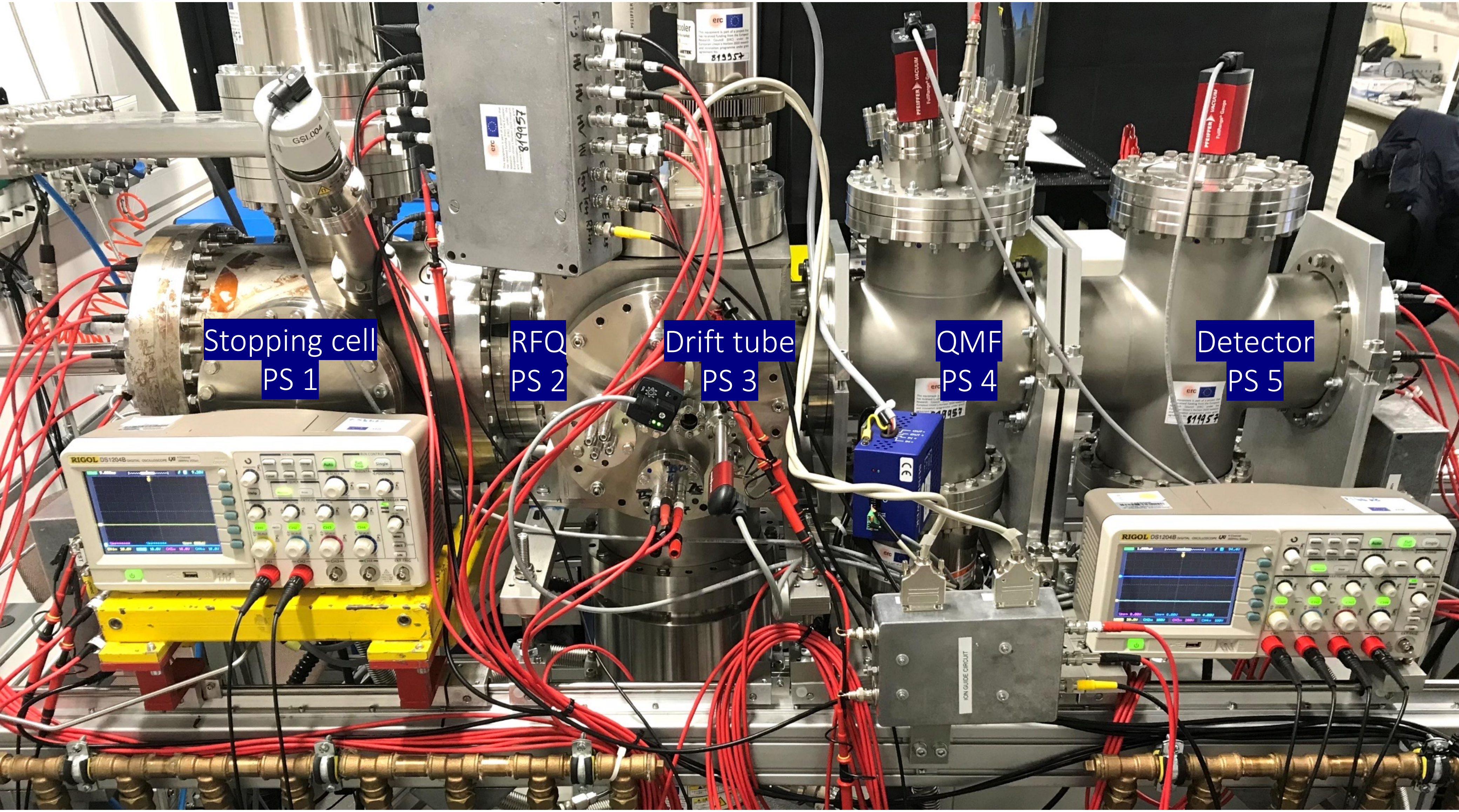
60 mbar	10^{-2} mbar	3 mbar		10^{-5} mbar	10^{-7} mbar

General features

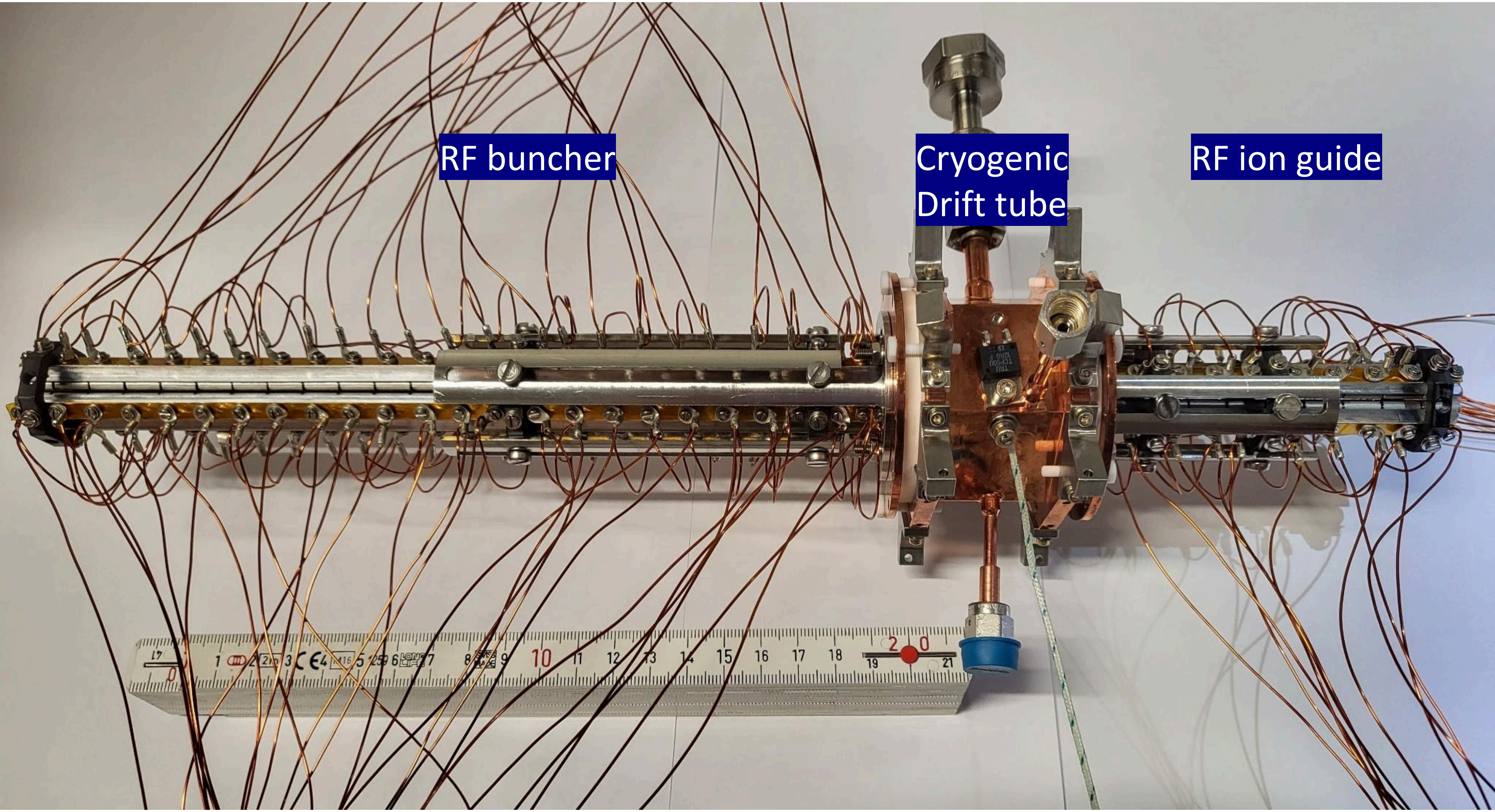
- Fast (milliseconds)
  → No need for neutralization/evaporation of sample atoms
- Sensitive
  → No need for fluorescence detection
  → No need for photoionization
- Suitable for d-block elements
  → Insensitive to physicochemical properties
- Efficient
  → No cycle losses
  → Permanent monitoring of production/extraction
- Versatile
  → Broadband initial level search
  → Precision HFS
  → Can be applied to molecules
- Disadvantages
  → No neutrals
  → No HCI
  → No access to IP



The LRC setup



The drift tube system

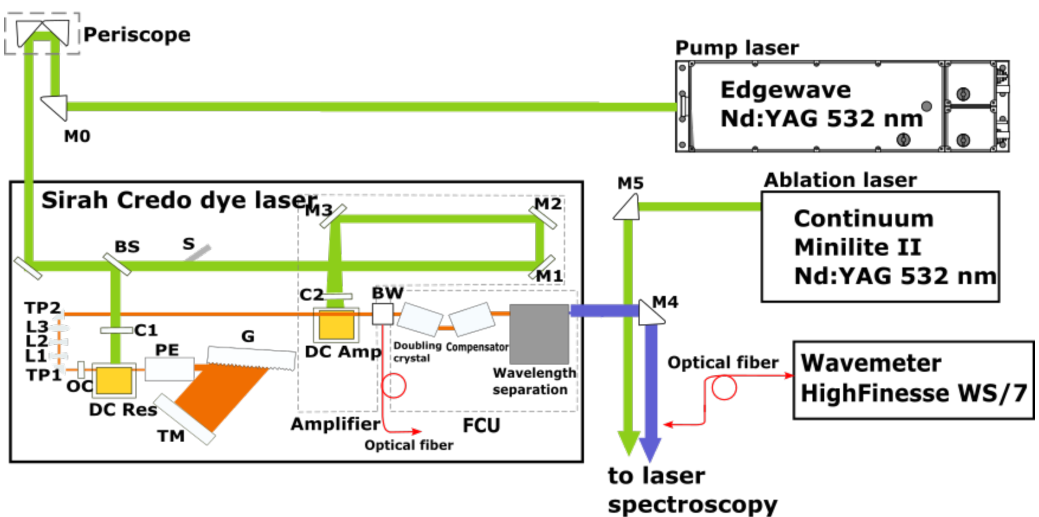


The laser system & ion source

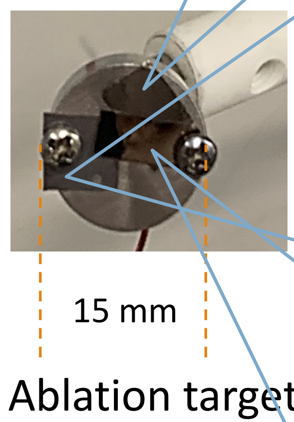
Laser 1: Minilite II for ablation (~10 W @ 532 nm)
both in cell or in vacuum

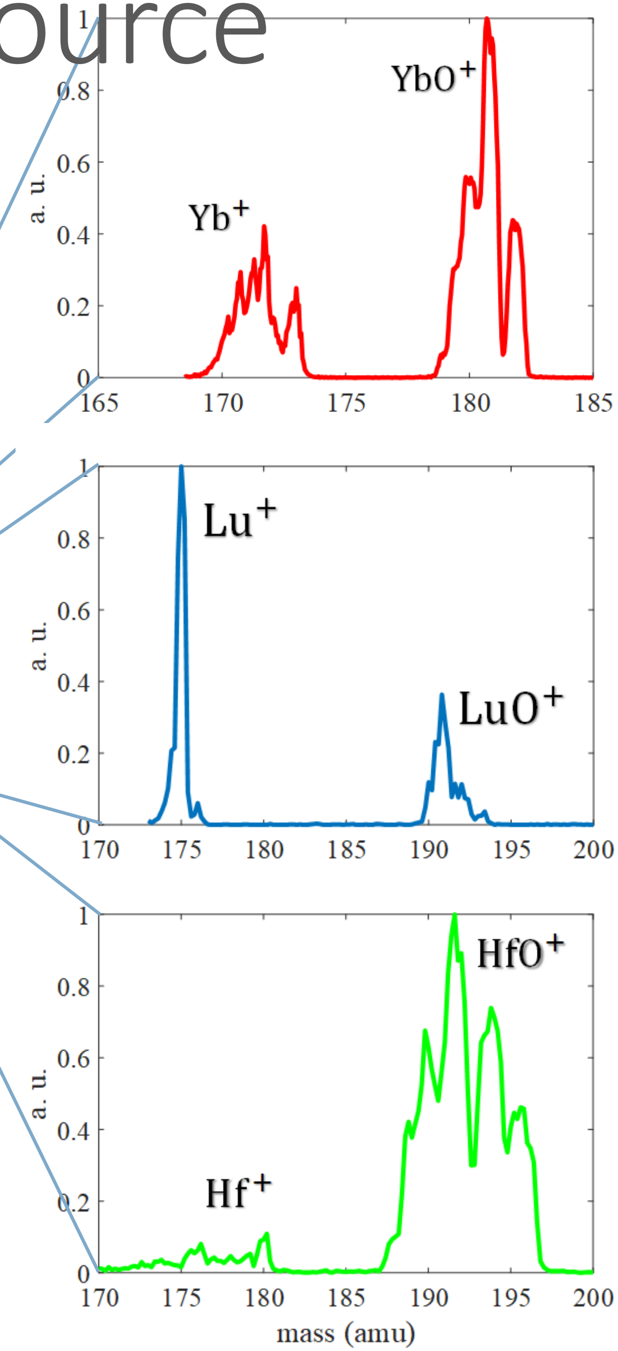
Laser 2: Edgewave Pump + Credo Dye Laser for spectroscopy

- 430 – 760 nm (250 – 380 nm with SHG)
- Bandwidth: ~1,6 GHz @ 570 nm
  (can be increased to 5 GHz)



E. Romero Romero et al.,
Atoms 10(3) (2022) 87



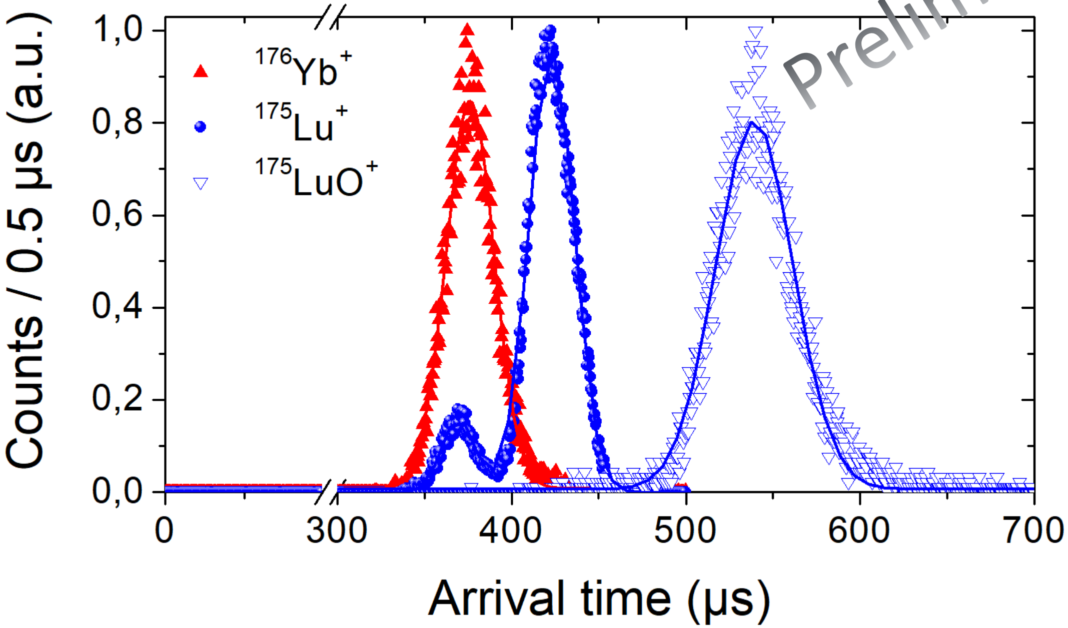


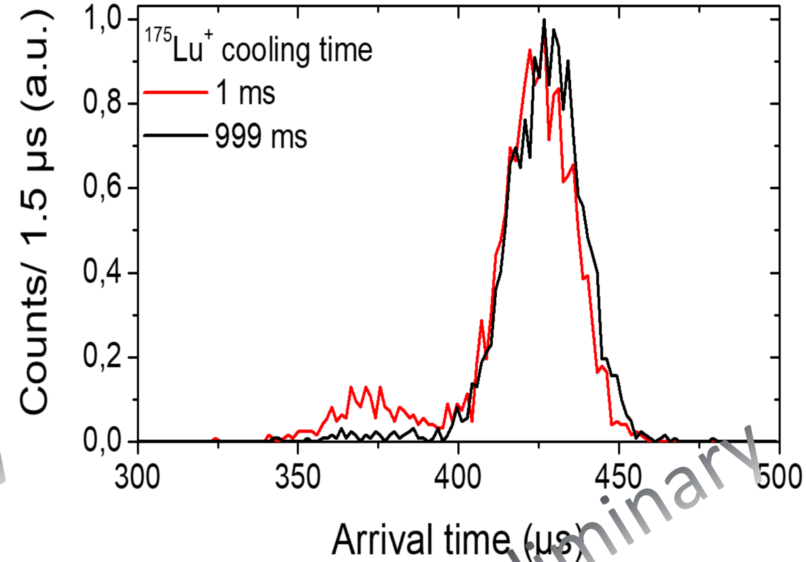
Resolving Lu^{+*}

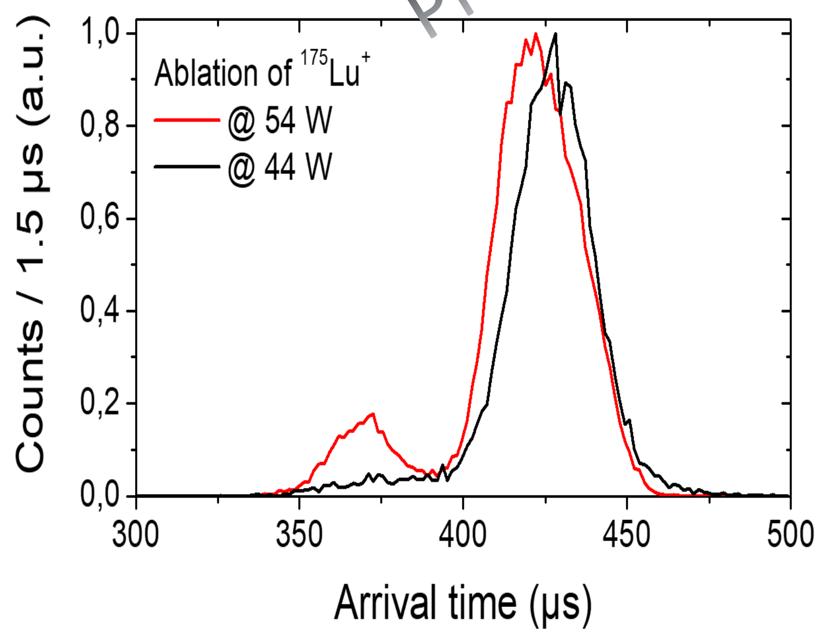
- Time resolution optimized using Lu^+ (*$4f^{14}$ $6s^2$*) and Yb^+ (*$4f^{14}$ $6s$*) ions of different GS configurations
- Metastable Lu^{+*} observed!
- Cross checked by variation of cooling time and ablation power

15%-effect as predicted

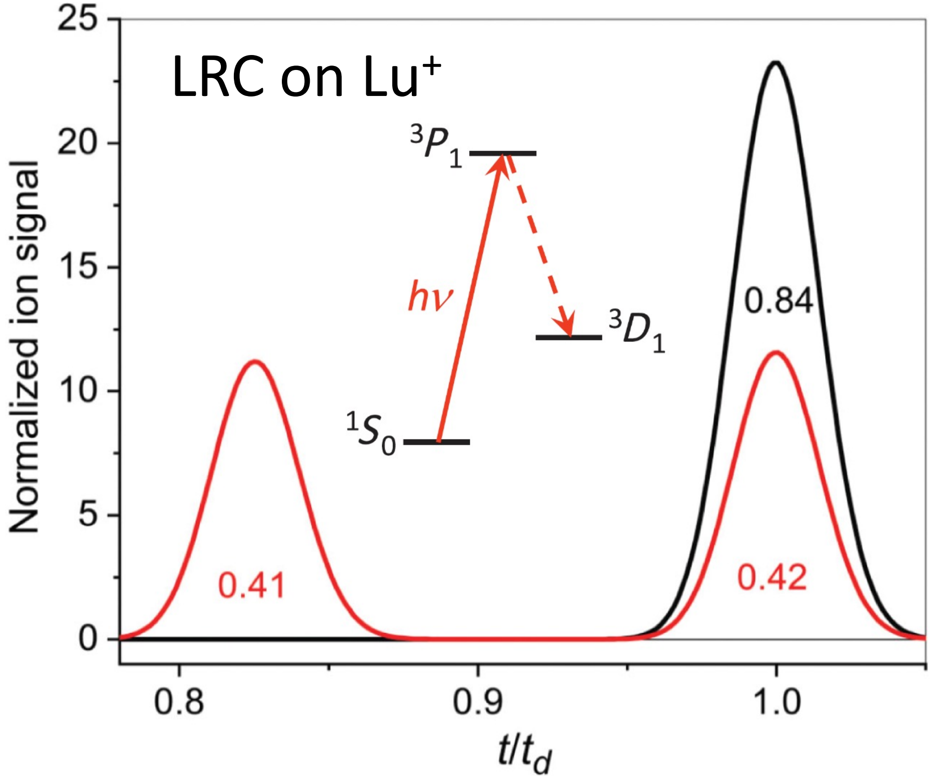
Preliminary

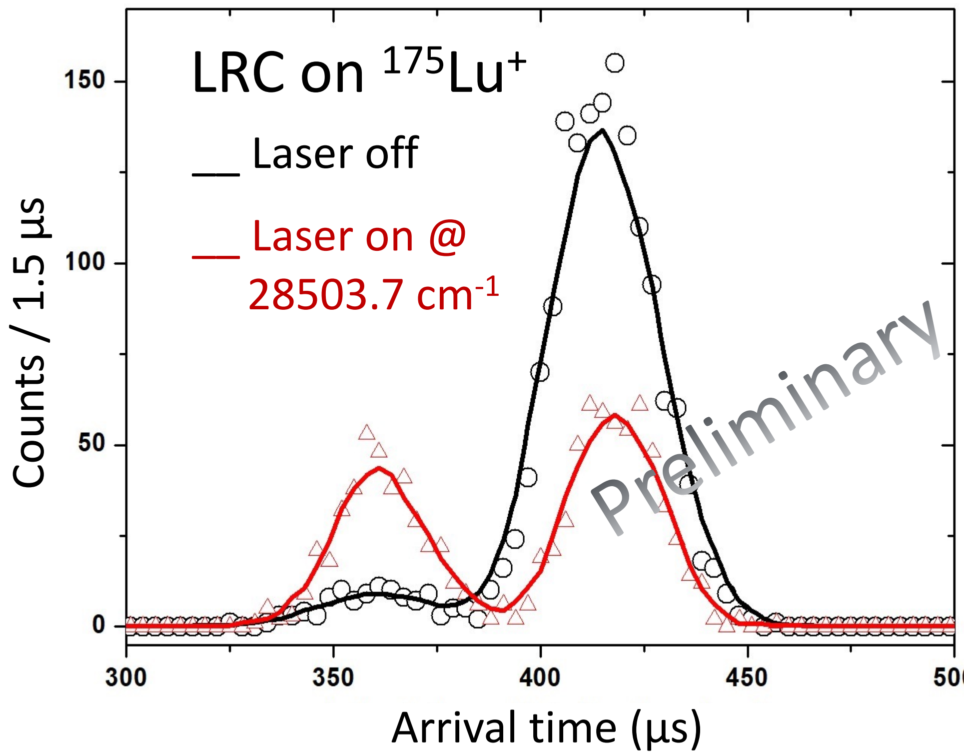






The first LRC shot



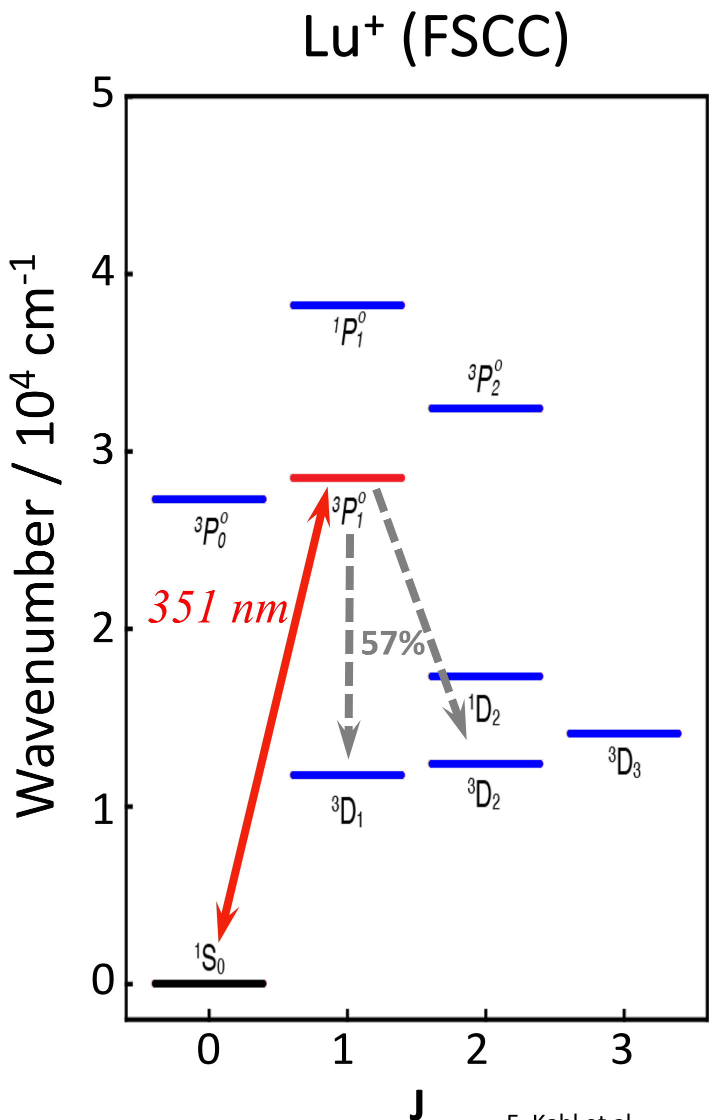


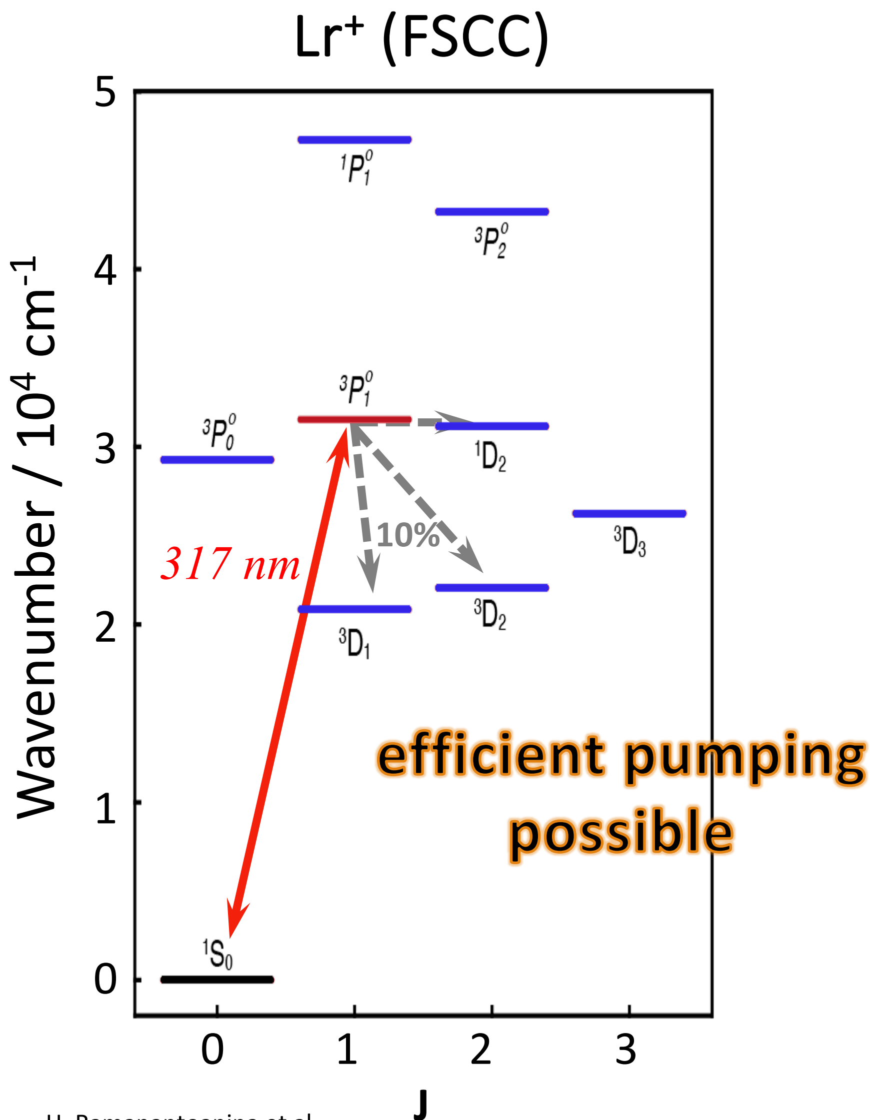
Theo. 2020

Exp. (05/2023)

M. Laatiaoui et al., **Phys. Rev. Lett.** **125** (2020) 023002

Excitation schemes for Lr^+



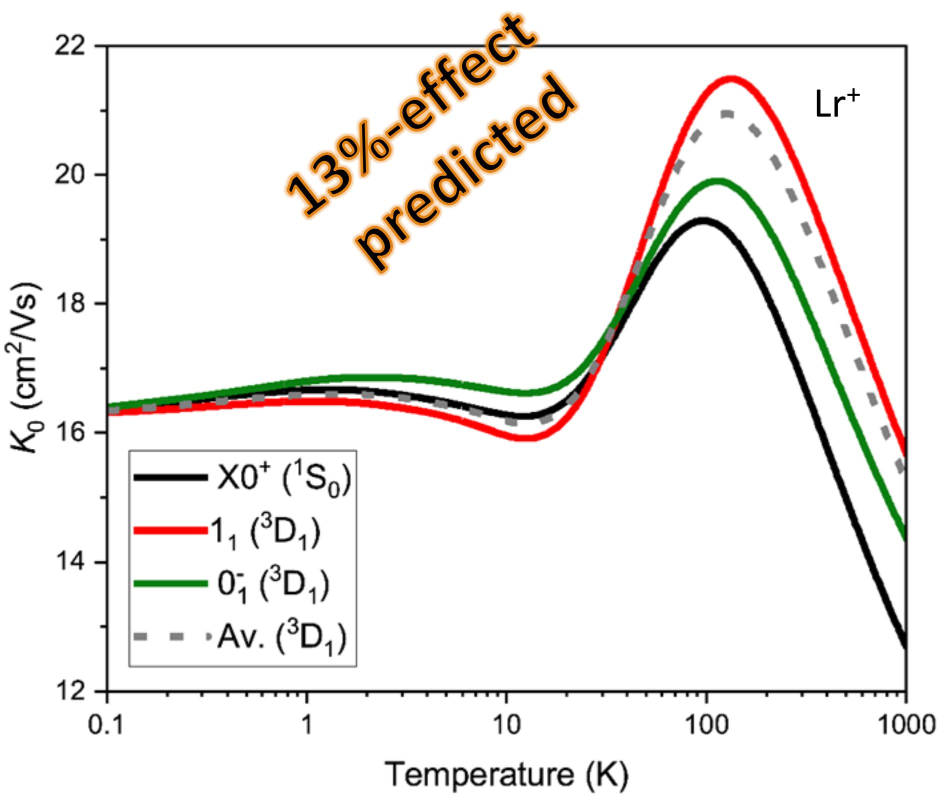


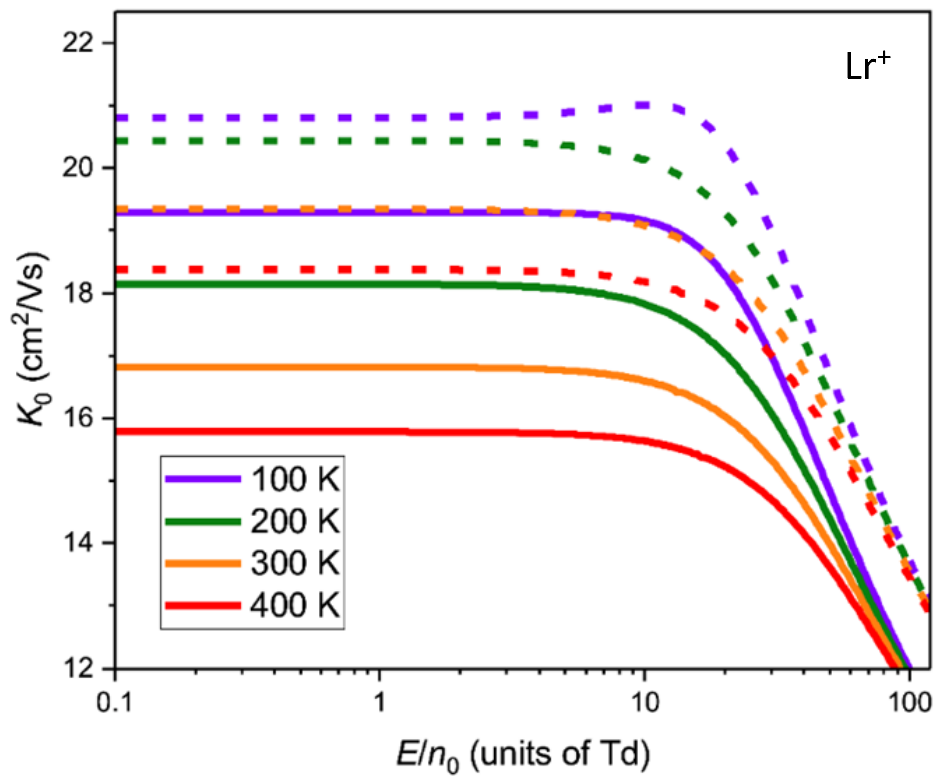
E. Kahl et al.,
PRA 100 (2019) 062505

H. Ramanantoanina et al.,
Atoms 10(2) (2022) 48

Mobilities for Lr^{+*}

- Interaction potentials from *ab-initio* (MRCI) calculations
  - → Good agreement with SRCC and IHFSCC
  - → "Anisotropic spin-orbit coupled approximation"





H. Ramanantoanina et al.,
PRA 108 (2023) 012802

Summary & Outlook

- ✓ LRC setup developed and successfully commissioned
- ✓ LRC proof-of-principle established on $^{175}Lu^+$
- ✓ Hyperfine spectroscopy on Lu^+ has been also carried out
- ✓ Bunching & transmission efficiency of the LRC setup sufficiently high

- ✓ Predictions of electronic structure and transport properties of Lr^+ look quite promising
- ✓ Queued experiments:
  - → optimizing bunch-mode operation
  - → offline LRC on actinium-225 (sensitivity test)
  - → online experiments Lu^+ & Lr^+… (stay tuned)

Thank you!