Laser spectroscopy on heavy ions

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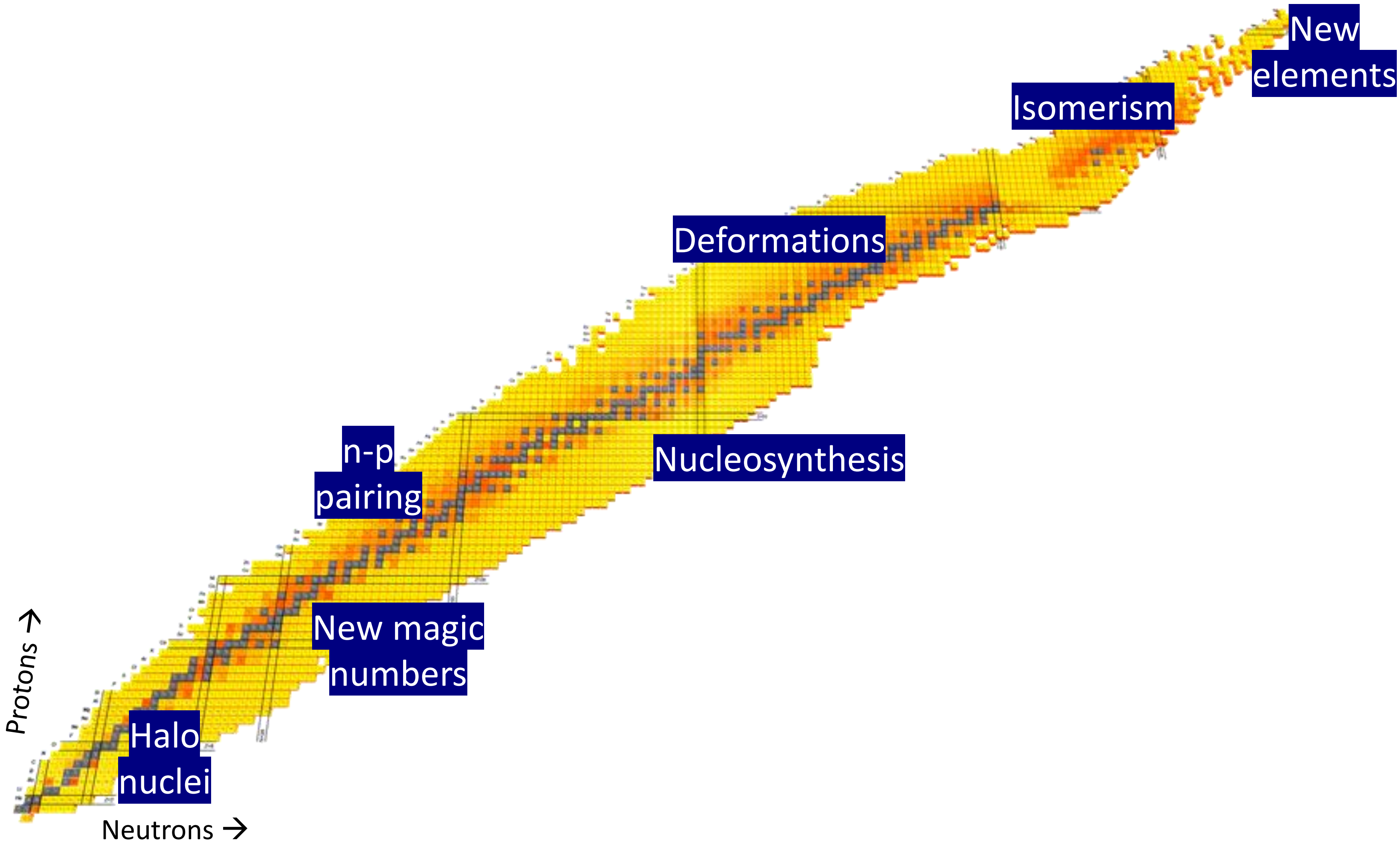
Outline

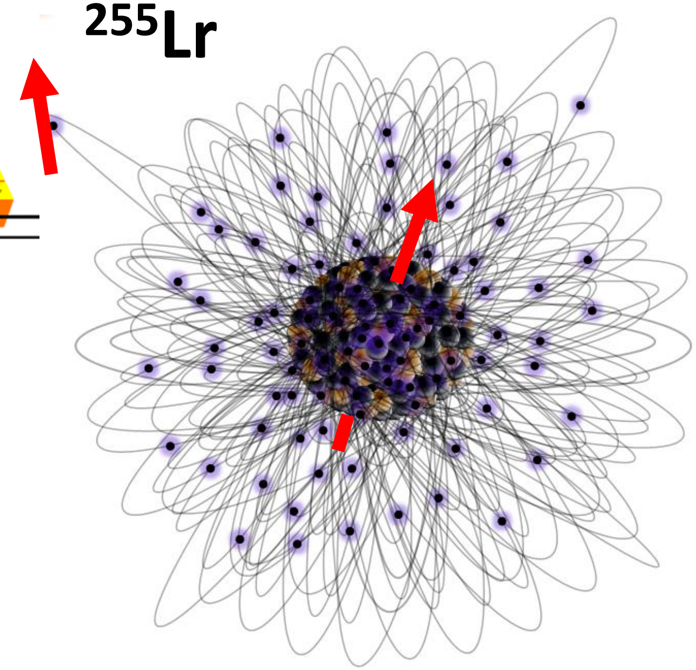
- Motivation
- Experimental challenges
- Laser Resonance Chromatography (LRC)
    - The method & setup
    - First results from inauguration experiments (Lu^+)
- Prospects for LRC on lawrencium (Z=103) and beyond
- Summary & Outlook

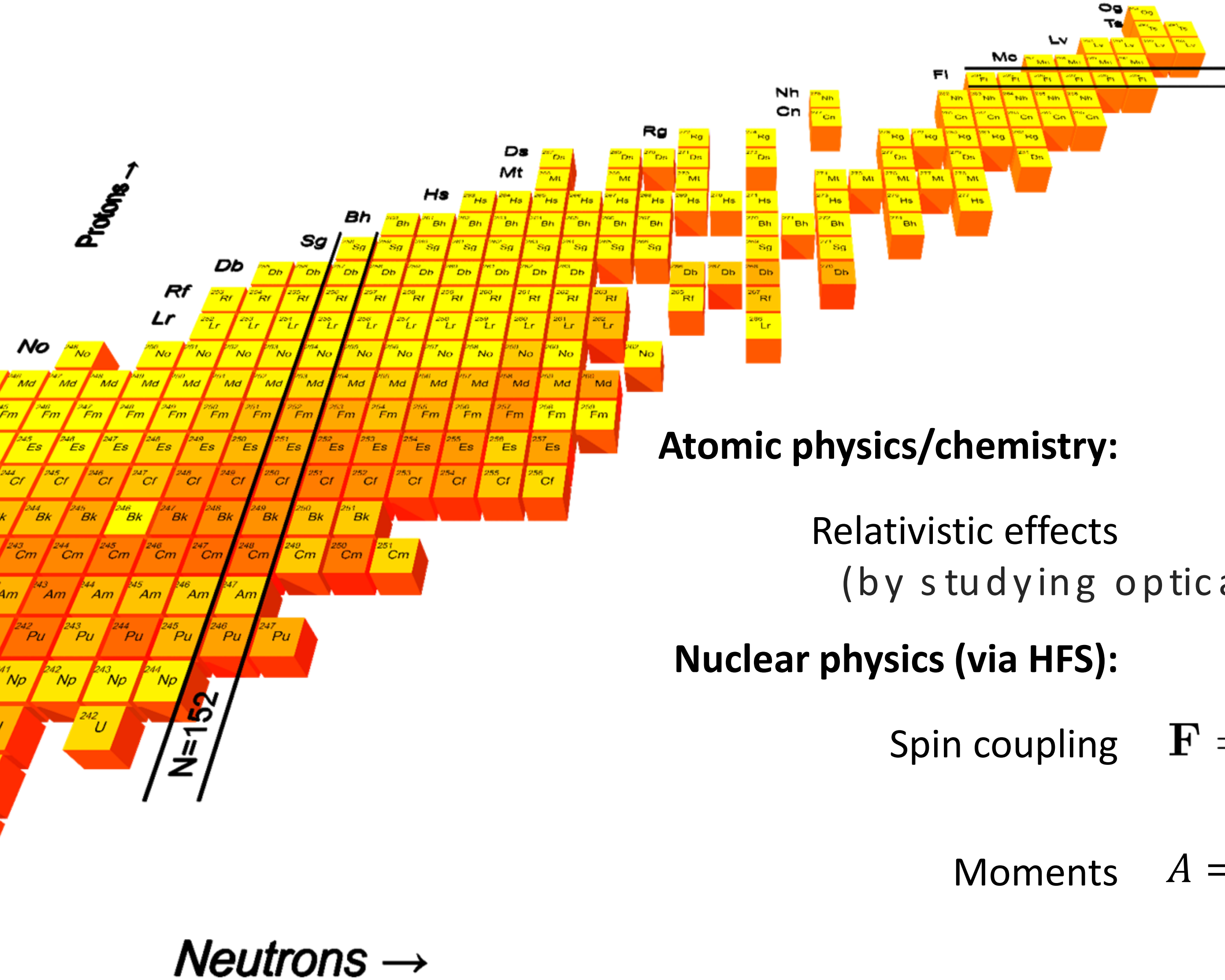
Motivation

Modern alchemists



Motivation





Atomic physics/chemistry:

Relativistic effects
(by studying optical transitions & ionization potentials)

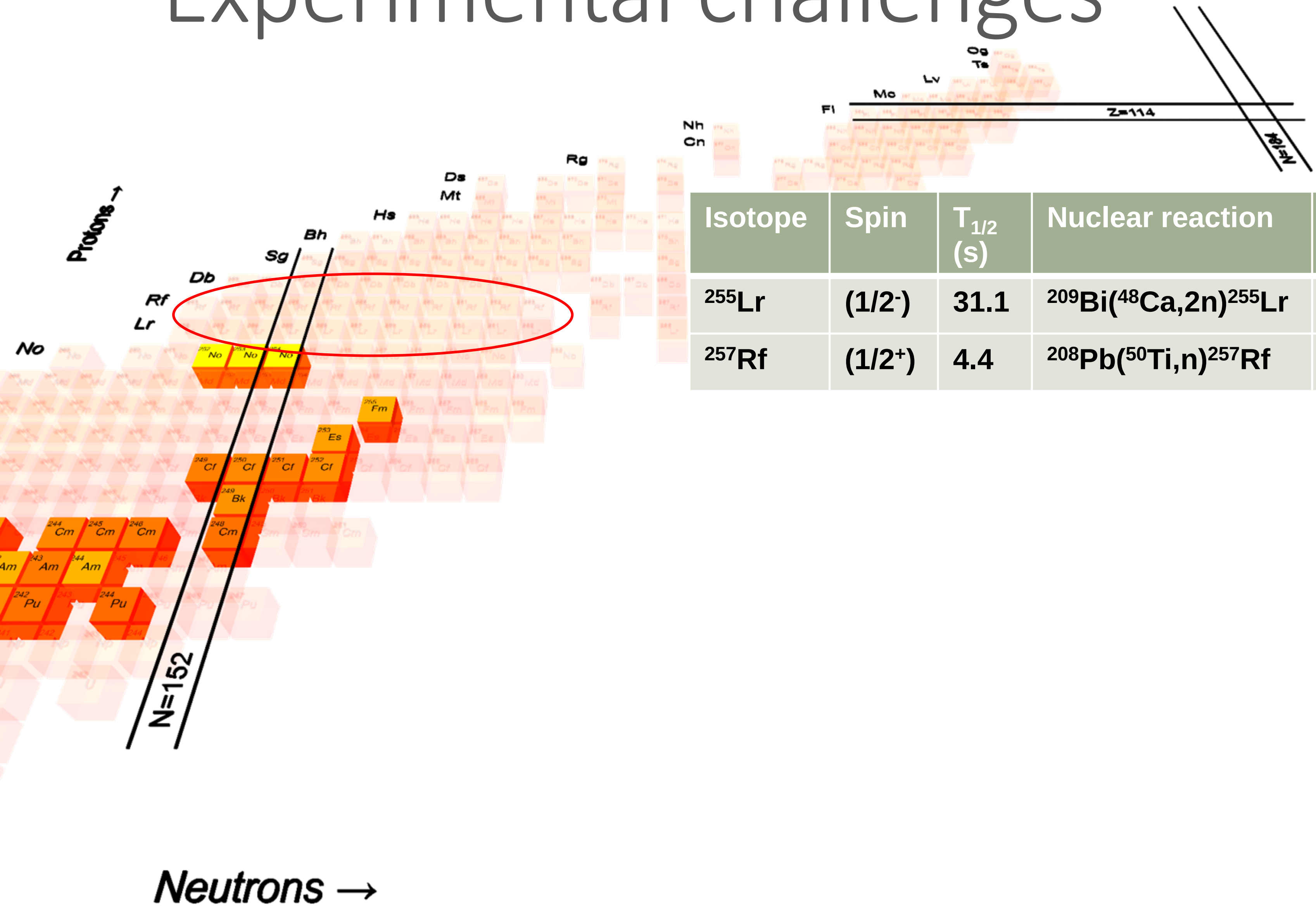
Nuclear physics (via HFS):

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

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

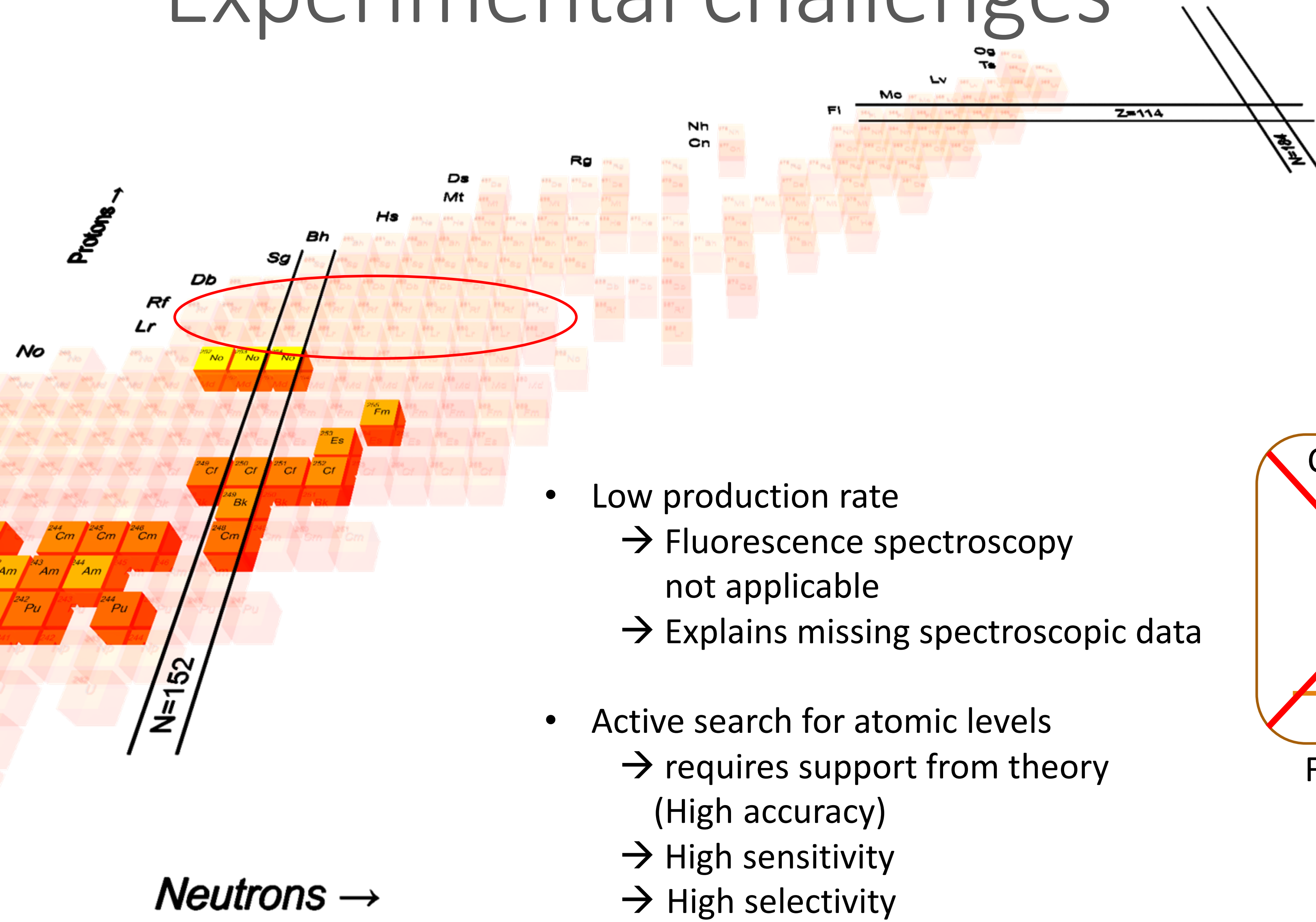
Charge radii $\boldsymbol{\delta \langle r^2 \rangle^{AA'}} = \left(\Delta\nu^{AA'} - \frac{A - A'}{AA'} M \right) \frac{1}{F}$

Experimental challenges



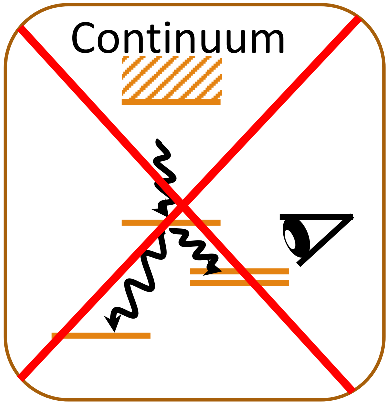
Isotope	Spin	$T_{1/2}$ (s)	Nuclear reaction	Production rate (1/s)
^{255}Lr	$(1/2^-)$	31.1	^{209}Bi(^{48}Ca,2n)^{255}Lr	3.4
^{257}Rf	$(1/2^+)$	4.4	^{208}Pb(^{50}Ti,n)^{257}Rf	0.1

Experimental challenges



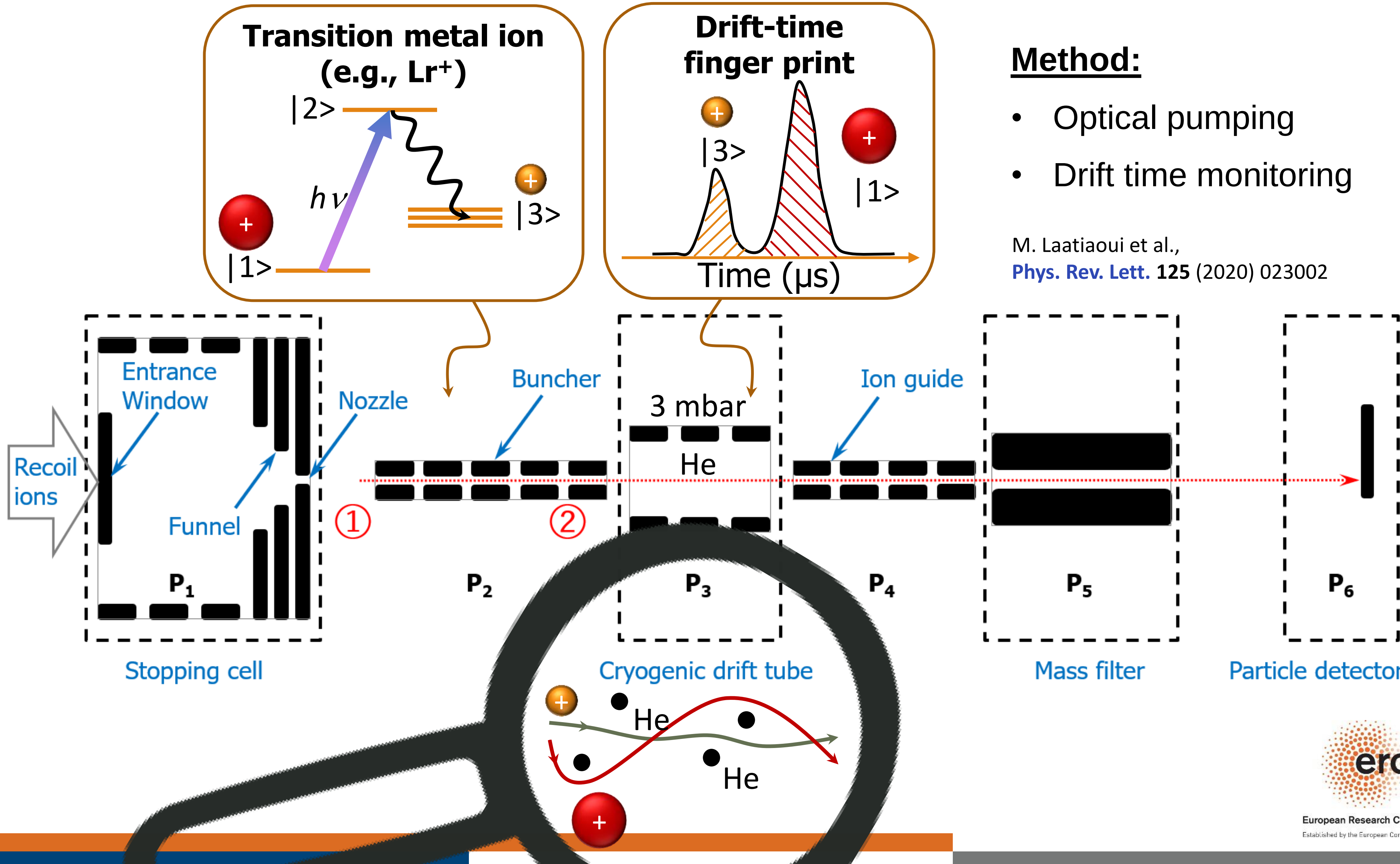
- Low production rate
  → Fluorescence spectroscopy not applicable
  → Explains missing spectroscopic data

- Active search for atomic levels
  → requires support from theory (High accuracy)
  → High sensitivity
  → High selectivity
  → High efficiency



Fluorescence

Laser Resonance Chromatography (LRC)



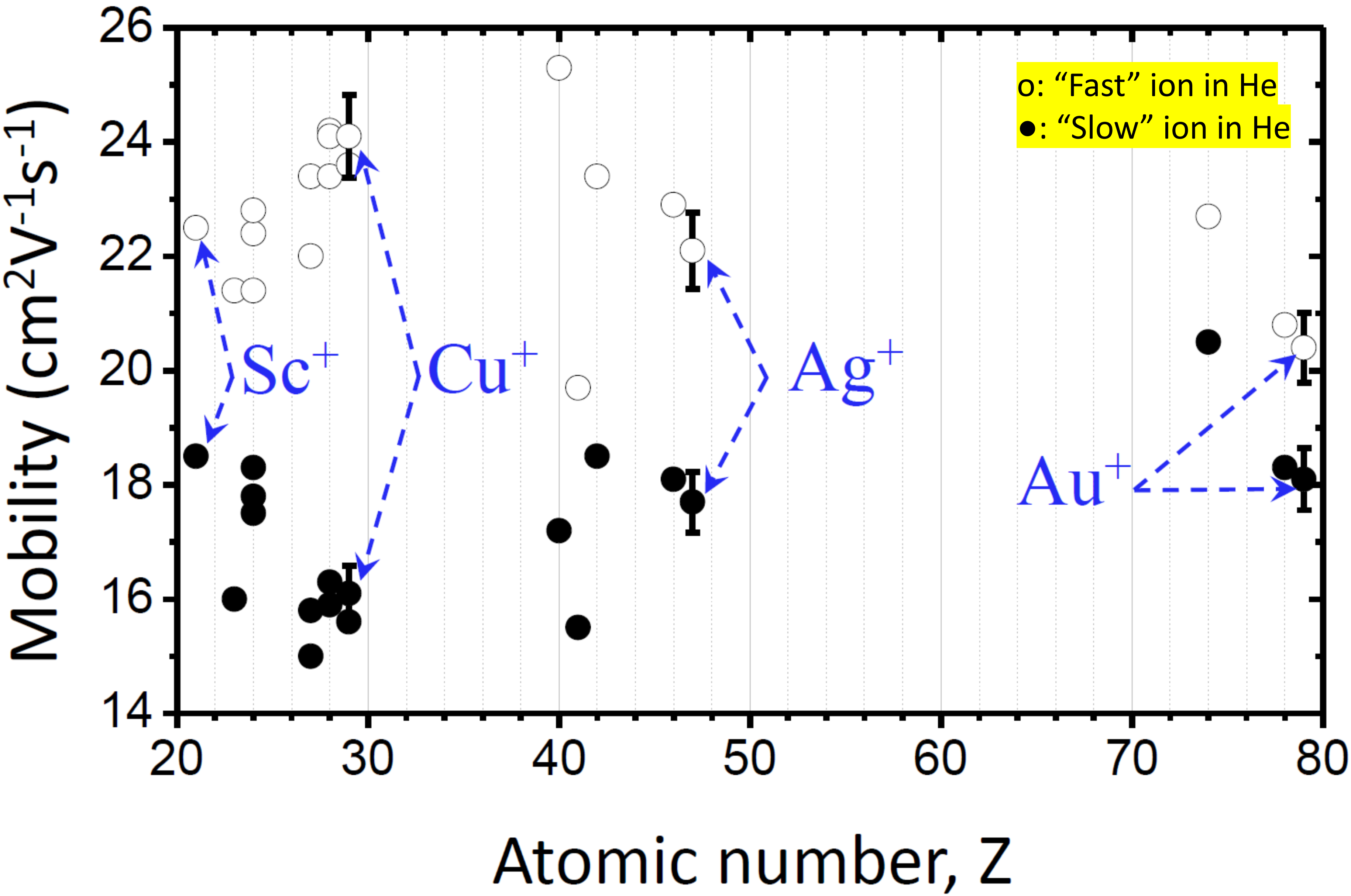
Method:

- Optical pumping
- Drift time monitoring

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

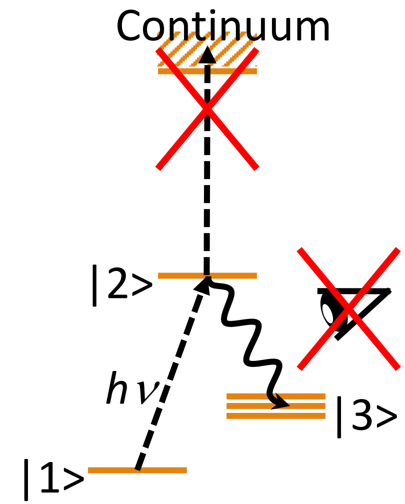
European Research Council
Established by the European Commission

Distinct ion mobilities (K_0)

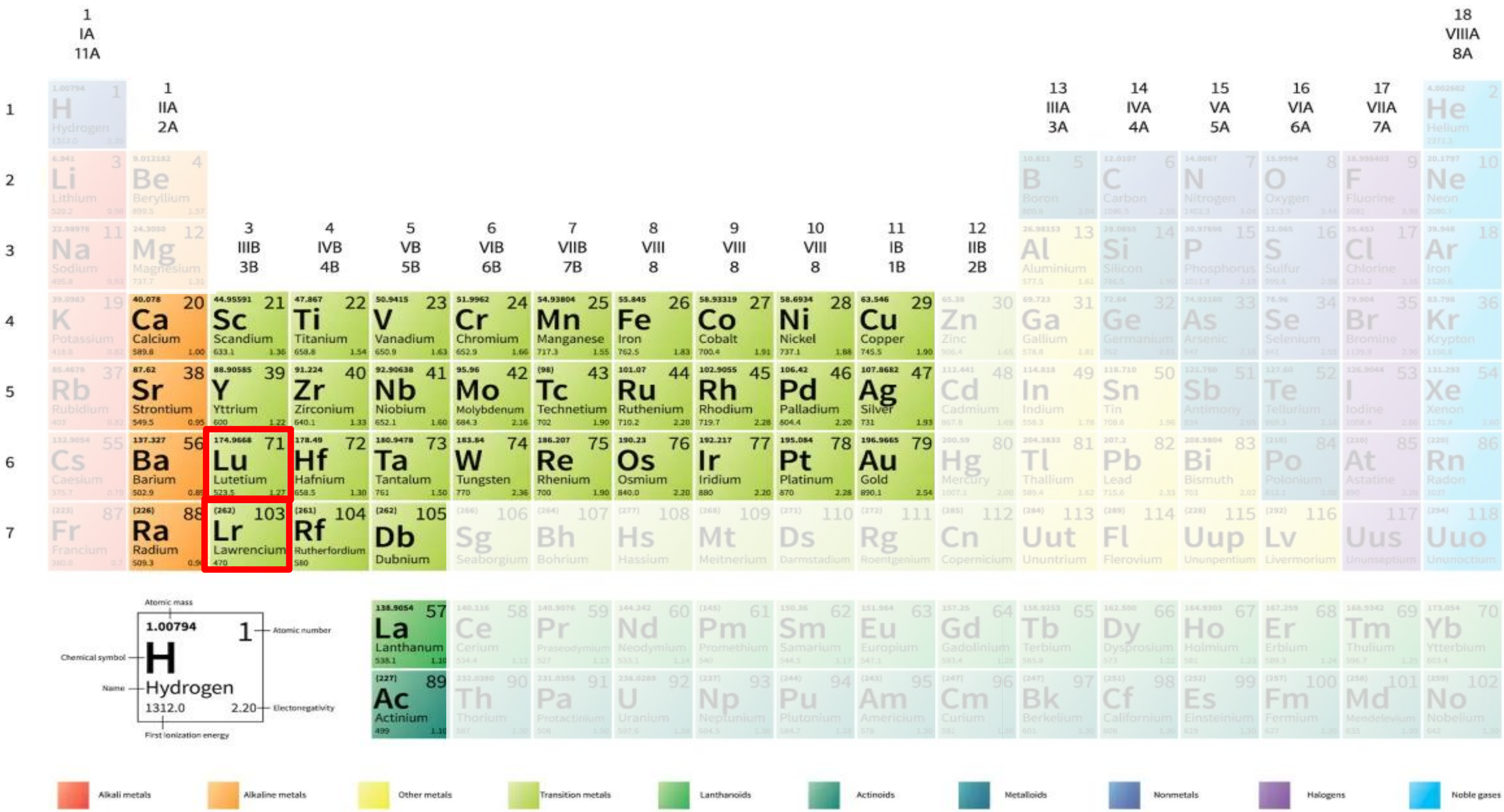


General features

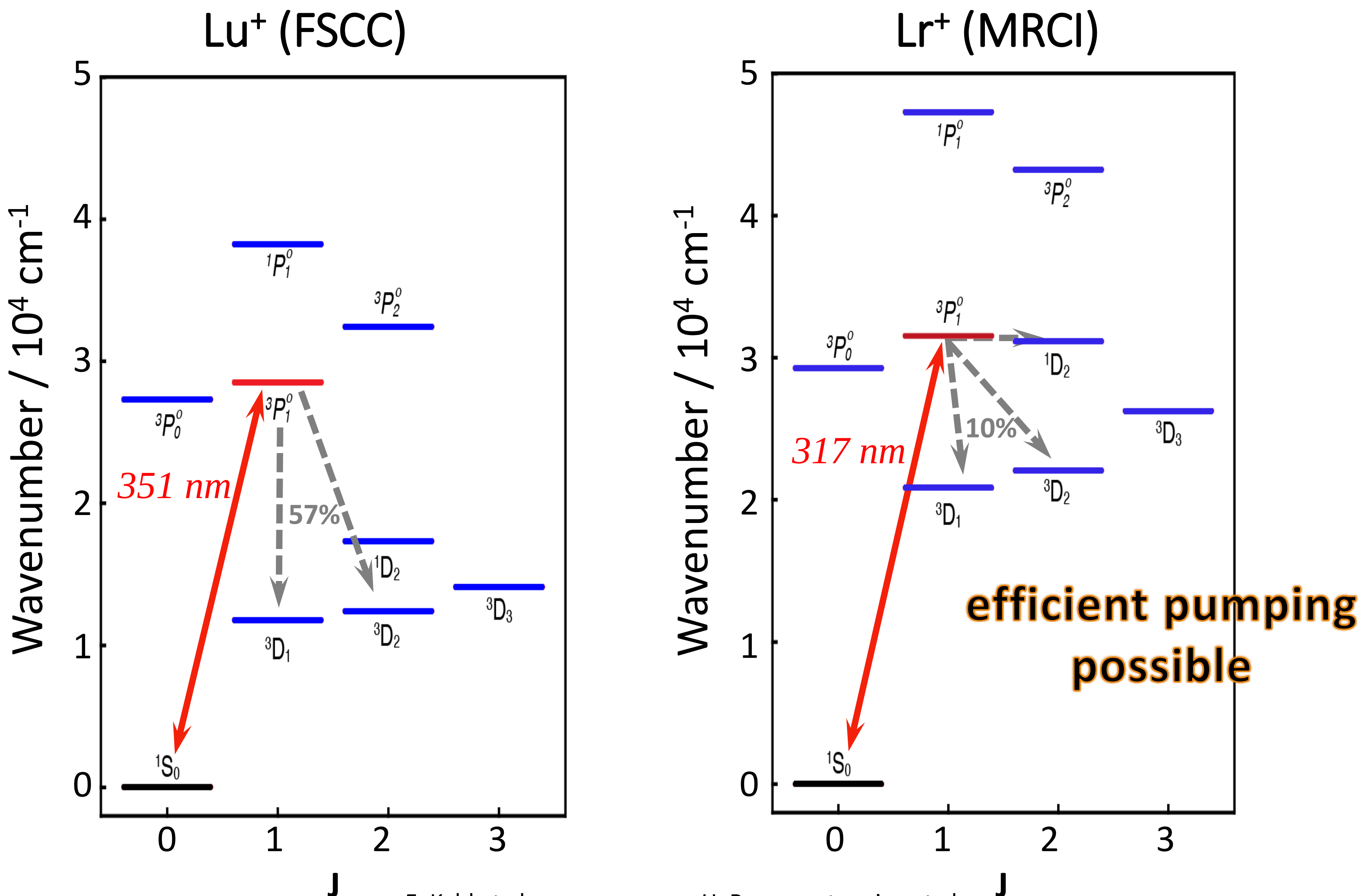
- Fast (milliseconds)
  → No need for neutralization/evaporation of sample atoms
- Sensitive
  → No need for fluorescence detection
  → No need for photoionization
- Suitable for d-block elements
  → Insensitive to physicochemical properties
- Efficient
  → No cycle losses
  → Permanent monitoring of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



Accessible elements



Excitation schemes for Lu^+ and Lr^+

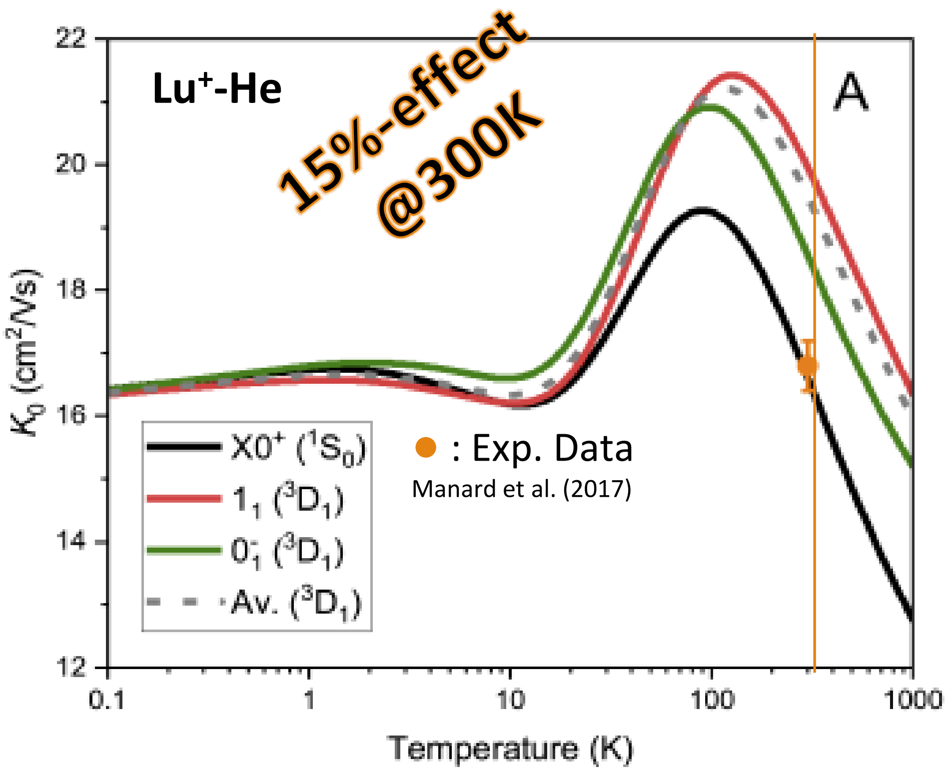


E. Kahl et al., **PRA 100** (2019) 062505

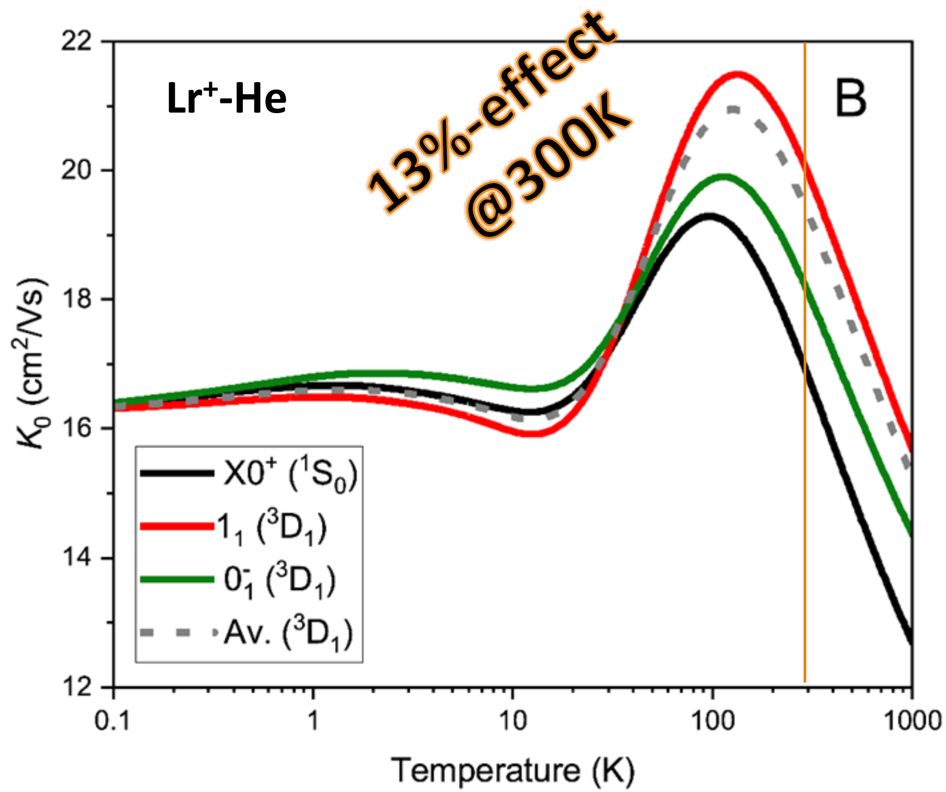
H. Ramanantoanina et al., **Atoms 10(2)** (2022) 48

Ion mobilities (K_0) for Lu^+ and Lr^+

- Interaction potentials from *ab-initio* (MRCI) calculations
  - → Good agreement with SRCC and IHFSCC
  - → "Anisotropic spin-orbit coupled approximation"
- Predictions accurate within 3% for the $Lu^+(^1S_0)$–He

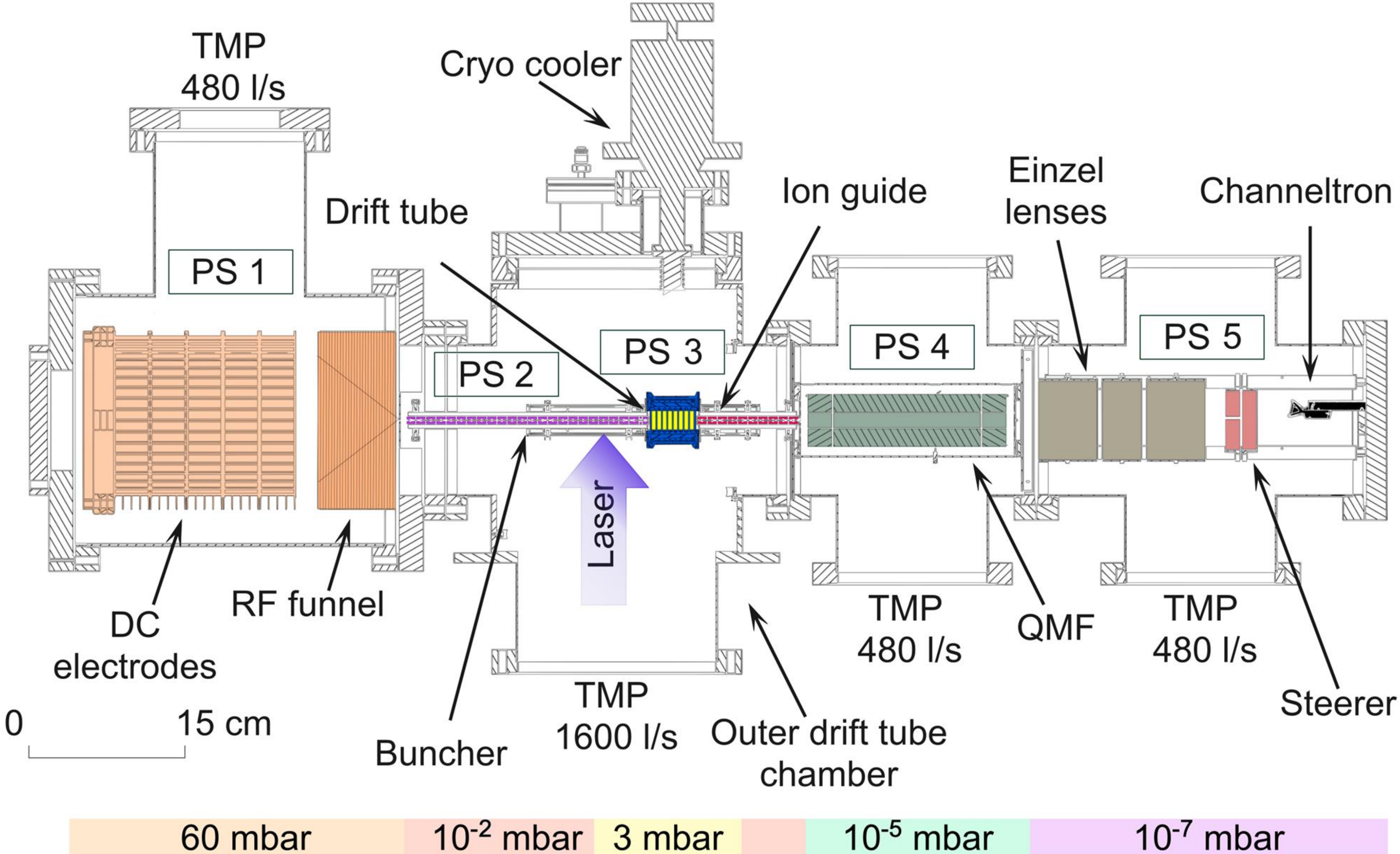


M. Laatiaoui et al.,
PRA 102 (2020) 013106



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

The LRC setup

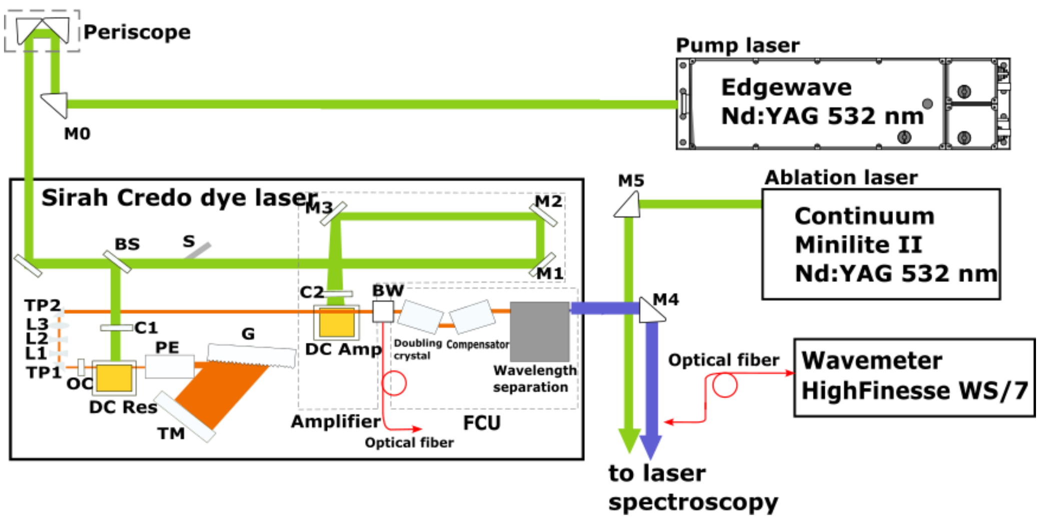


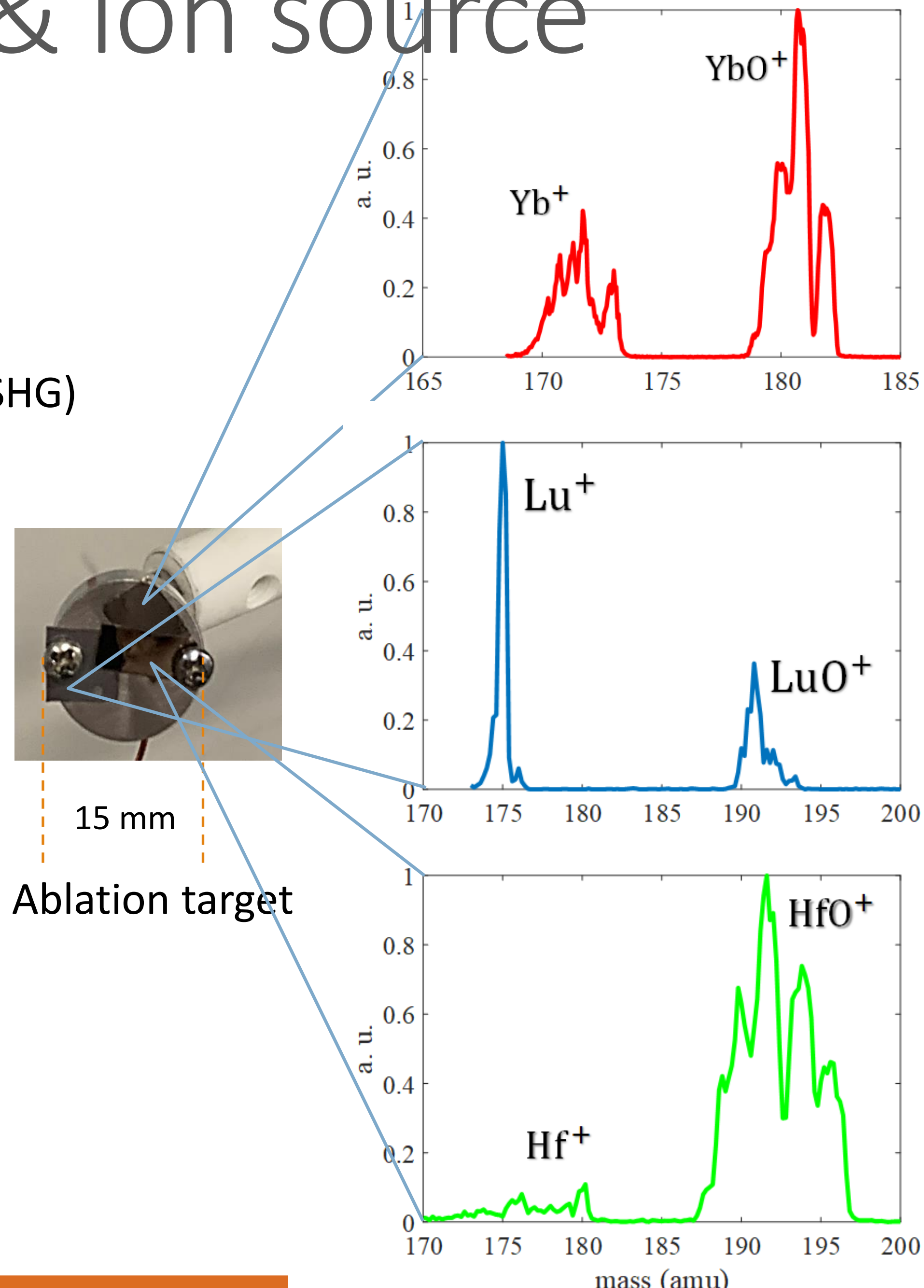
The laser system & ion source

Ablation: Minilite II (~10 W @ 532 nm)
in cell or in vacuum

LRC: Credo Dye Laser

- 430 – 760 nm (250 – 380 nm with SHG)
- Bandwidth: 4.5 GHz @ 350 nm

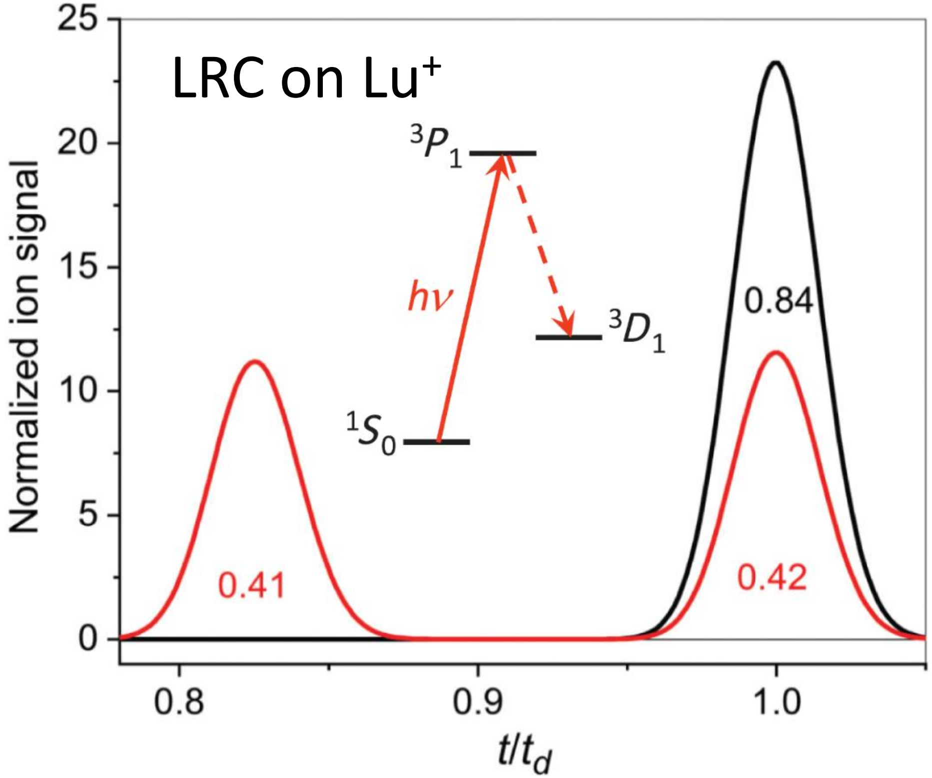




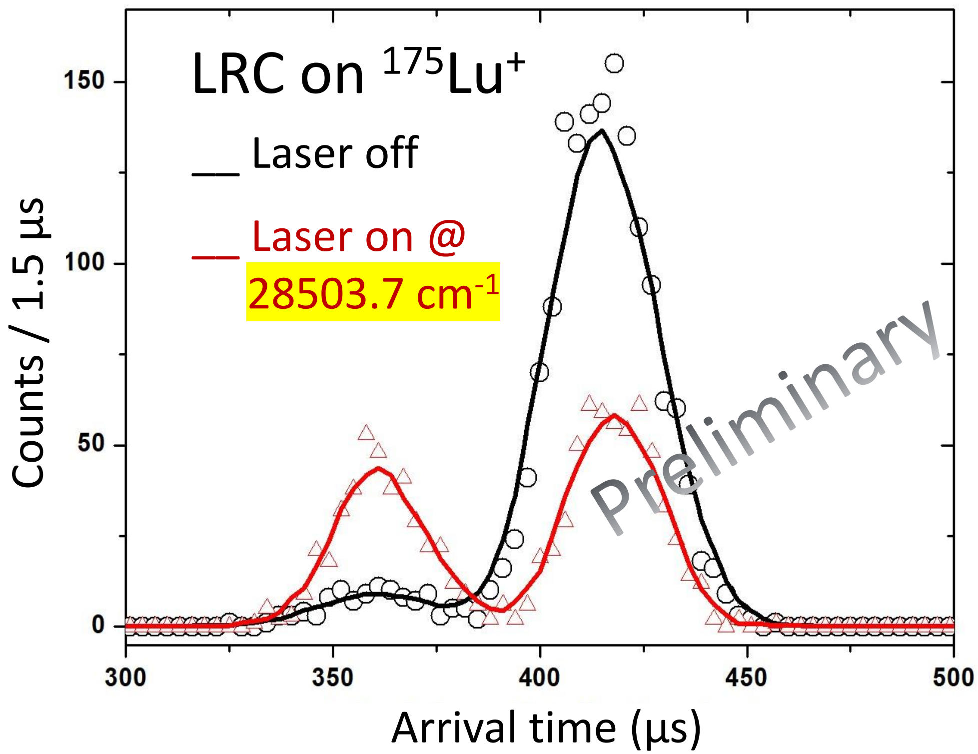
E. Romero Romero et al.,
Atoms 10(3) (2022) 87

The first LRC shot

With resonant laser excitation



Theo. 2020

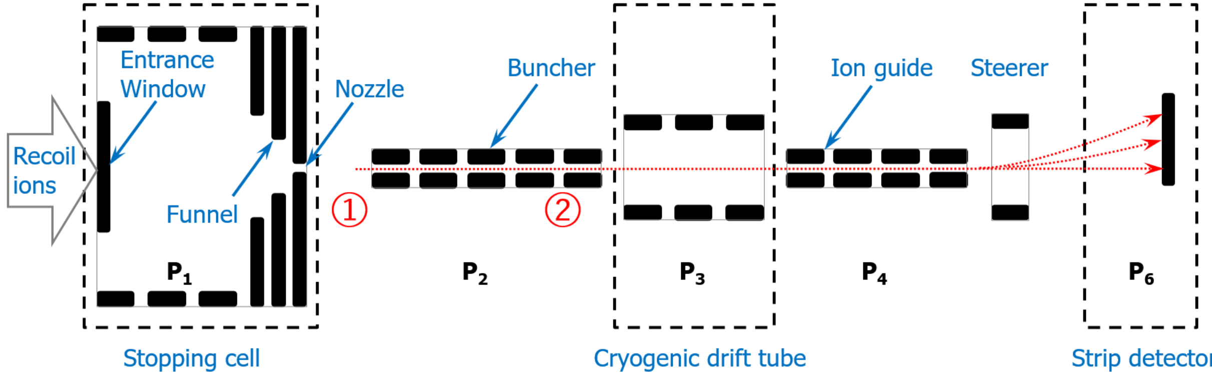


Exp. (05/2023)

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

LRC towards Lr^+ and Rf^+

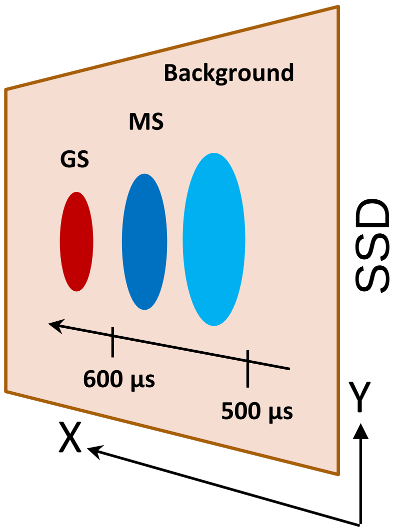
- Requirements: Radioactive-decay detection (using SSD)



- Increased sensitivity by registering alpha- (beta, fission) decays
  → Deflection of ions at the right moment
  → Centroids correspond to distinct arrival times

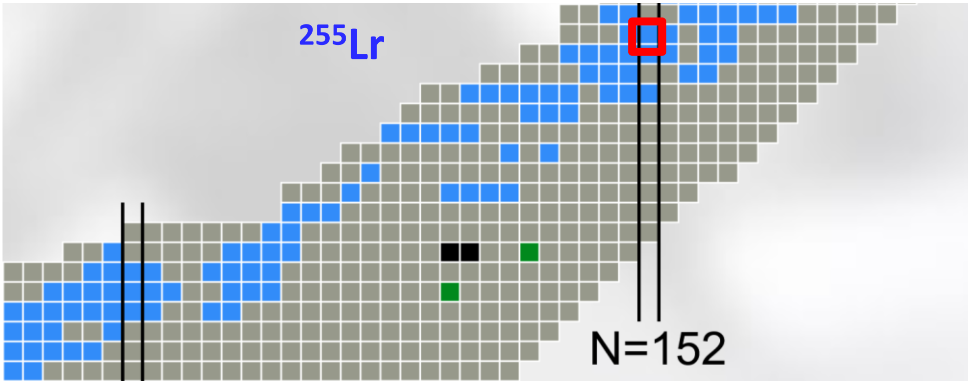
- Molecules need much more time
  → No mass filter required for alpha emitters
  → higher sensitivity & efficiency

- Level search with $<10^6$ atoms in total and HFS measurements with $<10^5$ atoms in total shall be possible



Lr^+ & beyond

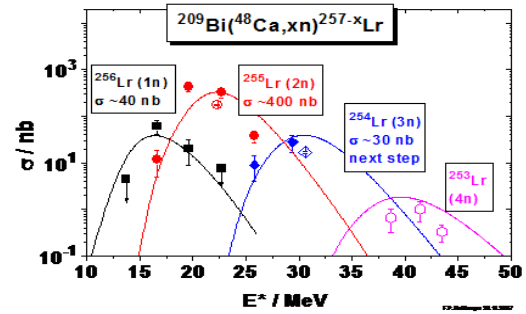
Far from stability

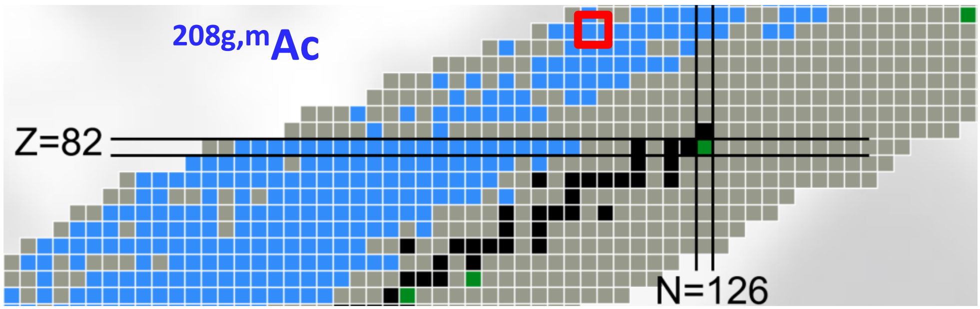


Evaporation residue:
^{208}Bi + ^{48}Ca → ^{255}Lr
(0.4 pps)

Has long-lived K-isomer!

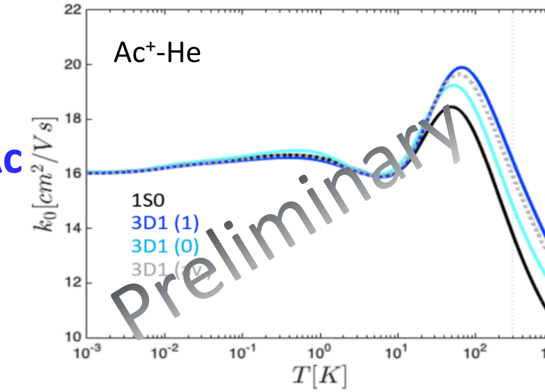
Lr^+

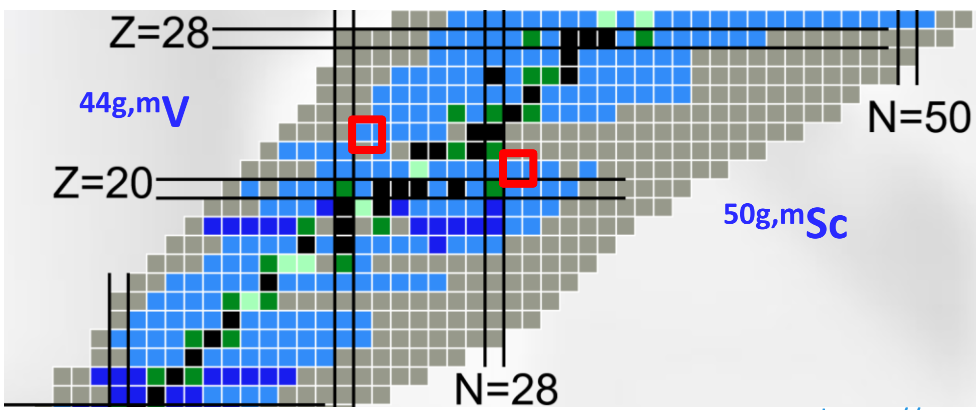




Evaporation residue:
^{197}Au + ^{20}Ne → ^{208g,m}Ac
(2 pps)

Ac^+

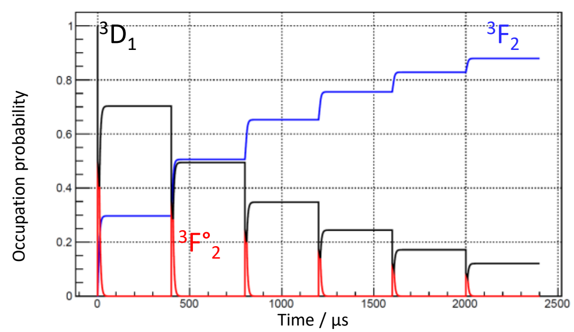




Evaporation residue:
^{40}Ca + ^{6}Li → ^{44g,m}V
(2500 pps)

Projectile fragments:
^{86}Kr on C → ^{50g,m}Sc
(190 pps; $T_{1/2}$ > 0.3 s)

Sc^+



https://u.ganil-spiral2.eu/chartbeams/

Summary/next steps

- ✓ Laser spectroscopy is a versatile tool for investigating atomic & nuclear properties
- ✓ LRC setup developed & proof-of-principle experiments established on $^{175,176}Lu^{+}$
- ✓ 0.6% overall efficiency → improvements possible

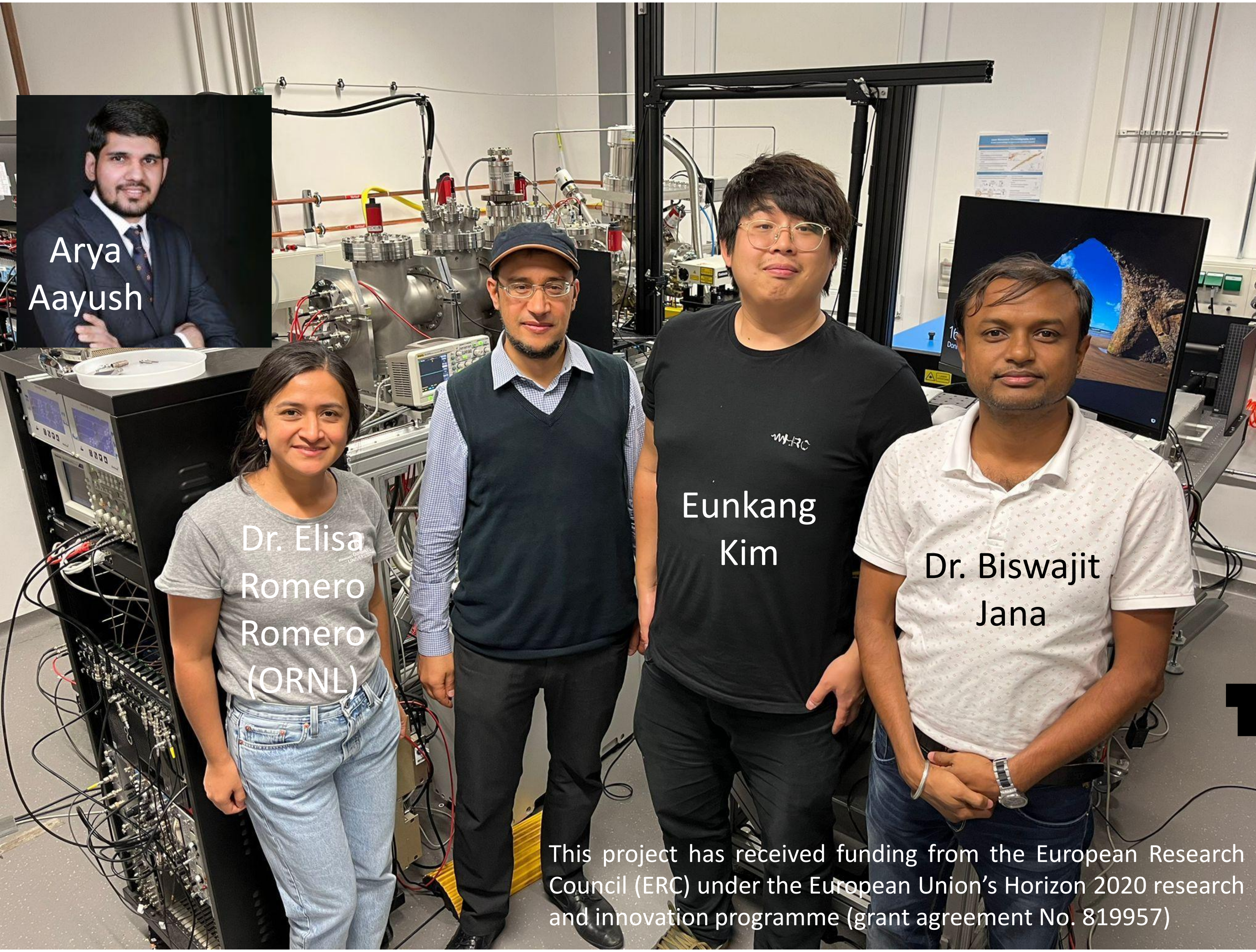
LRC roadmap:

→ Investigation of states lifetimes and impact of collisional quenching

→ Optimizing efficiency & resolution

→ Online experiments on Lu^{+} and Lr^{+}

The chromatography team



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