

AXIS 1: NUCLEAR PHYSICS CENTER

Scientific Advisory Board: meeting n°1



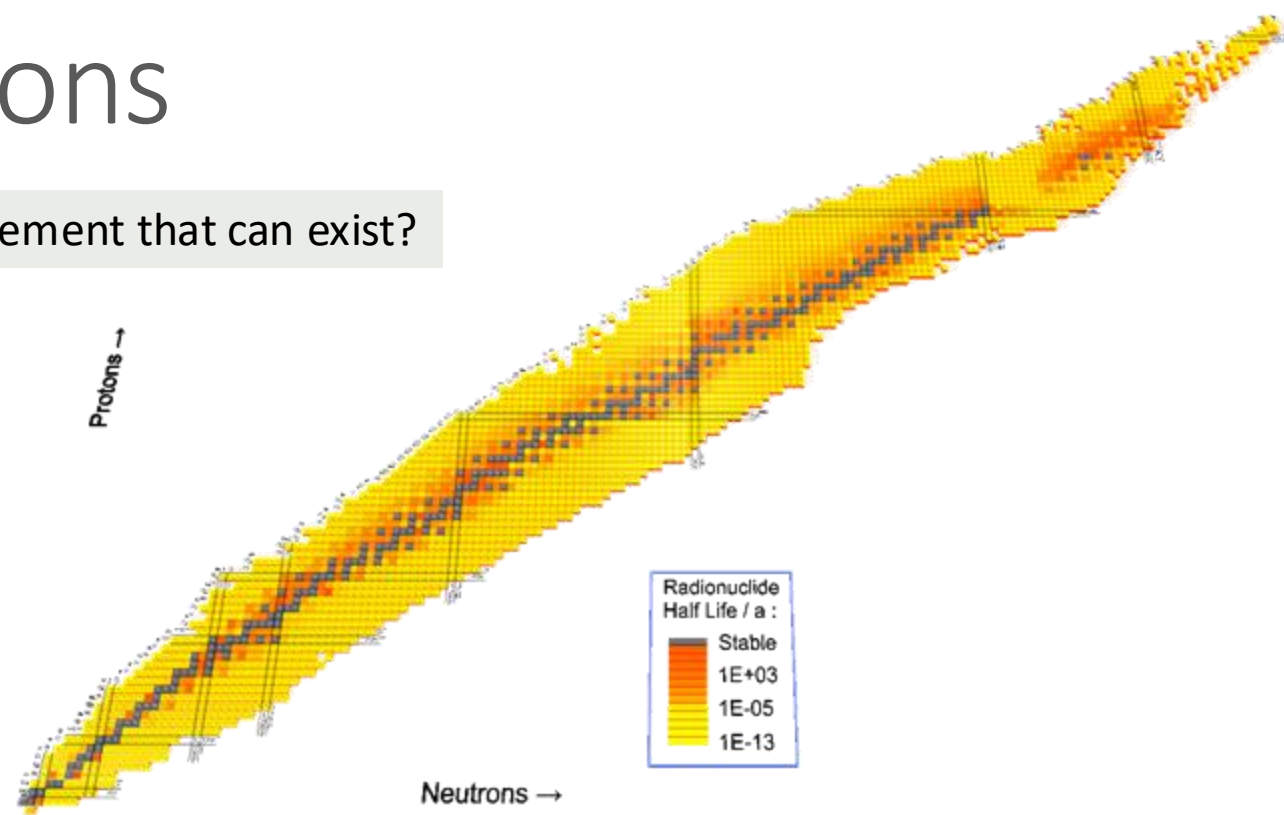
WP3: *Laser Resonance Chromatography @ S³*

M. Laatiaoui



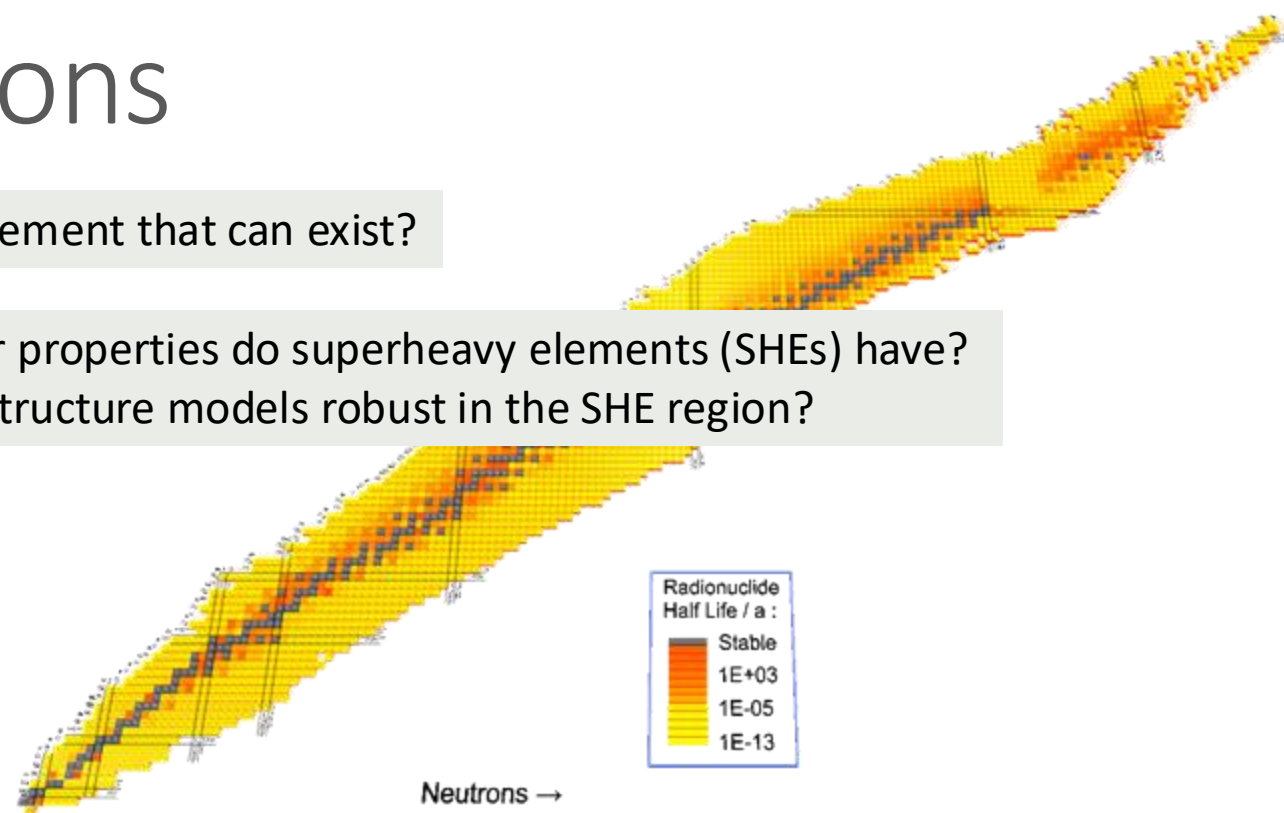
Key questions

- What is the heaviest element that can exist?



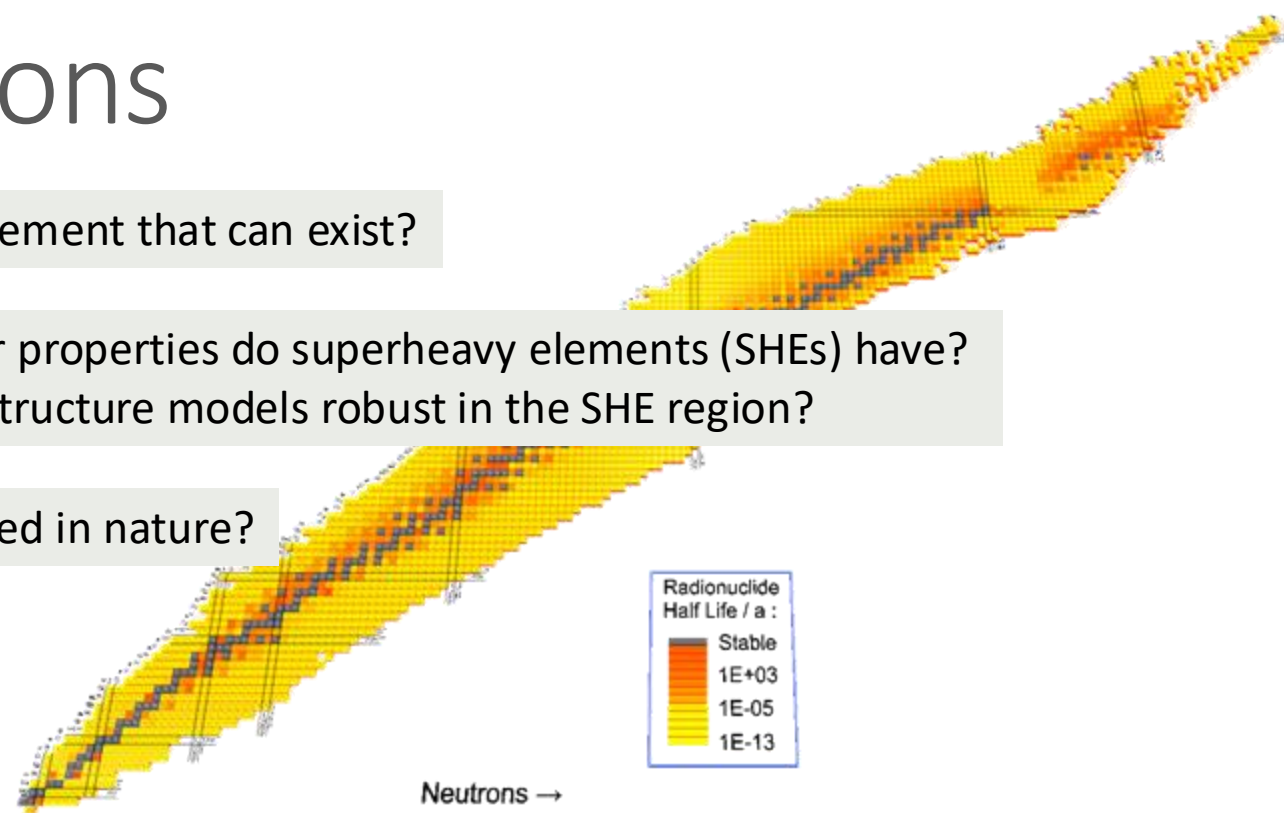
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- What is the heaviest element that can exist?
- What atomic & nuclear properties do superheavy elements (SHEs) have?
- Are atomic & nuclear structure models robust in the SHE region?



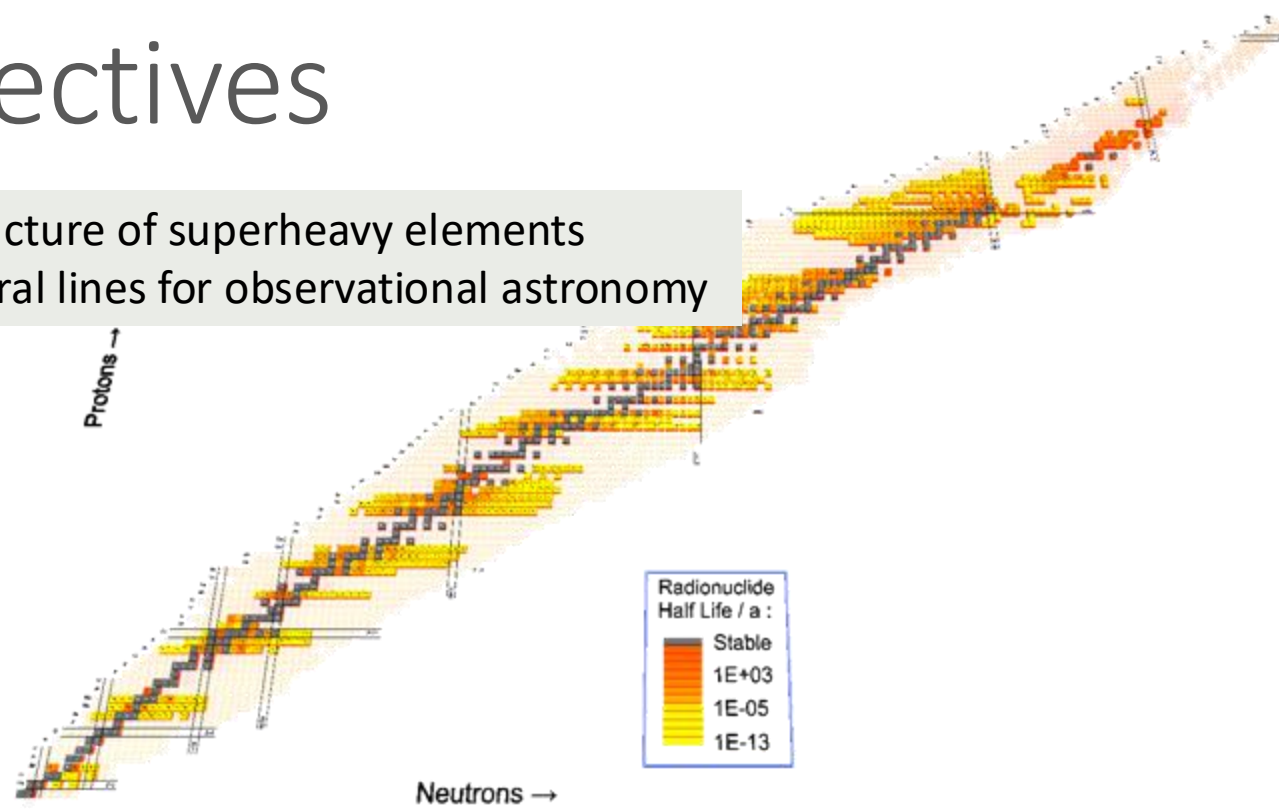
Key questions

- What is the heaviest element that can exist?
- What atomic & nuclear properties do superheavy elements (SHEs) have?
- Are atomic & nuclear structure models robust in the SHE region?
- Are SHEs being produced in nature?



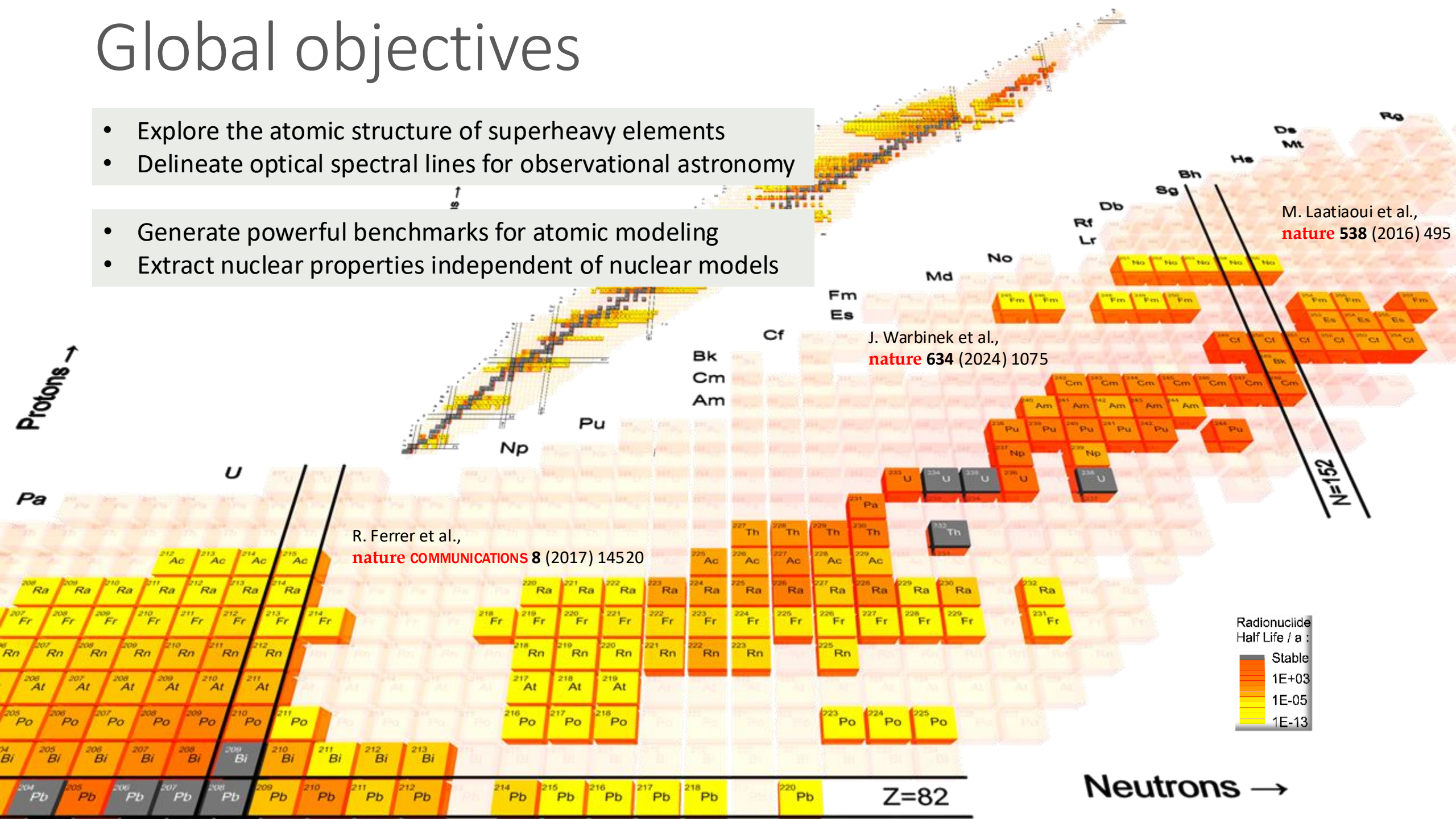
Global objectives

- Explore the atomic structure of superheavy elements
- Delineate optical spectral lines for observational astronomy



Global objectives

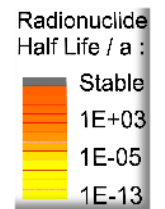
- Explore the atomic structure of superheavy elements
- Delineate optical spectral lines for observational astronomy
- Generate powerful benchmarks for atomic modeling
- Extract nuclear properties independent of nuclear models



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

J. Warbinek et al.,
nature 634 (2024) 1075

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

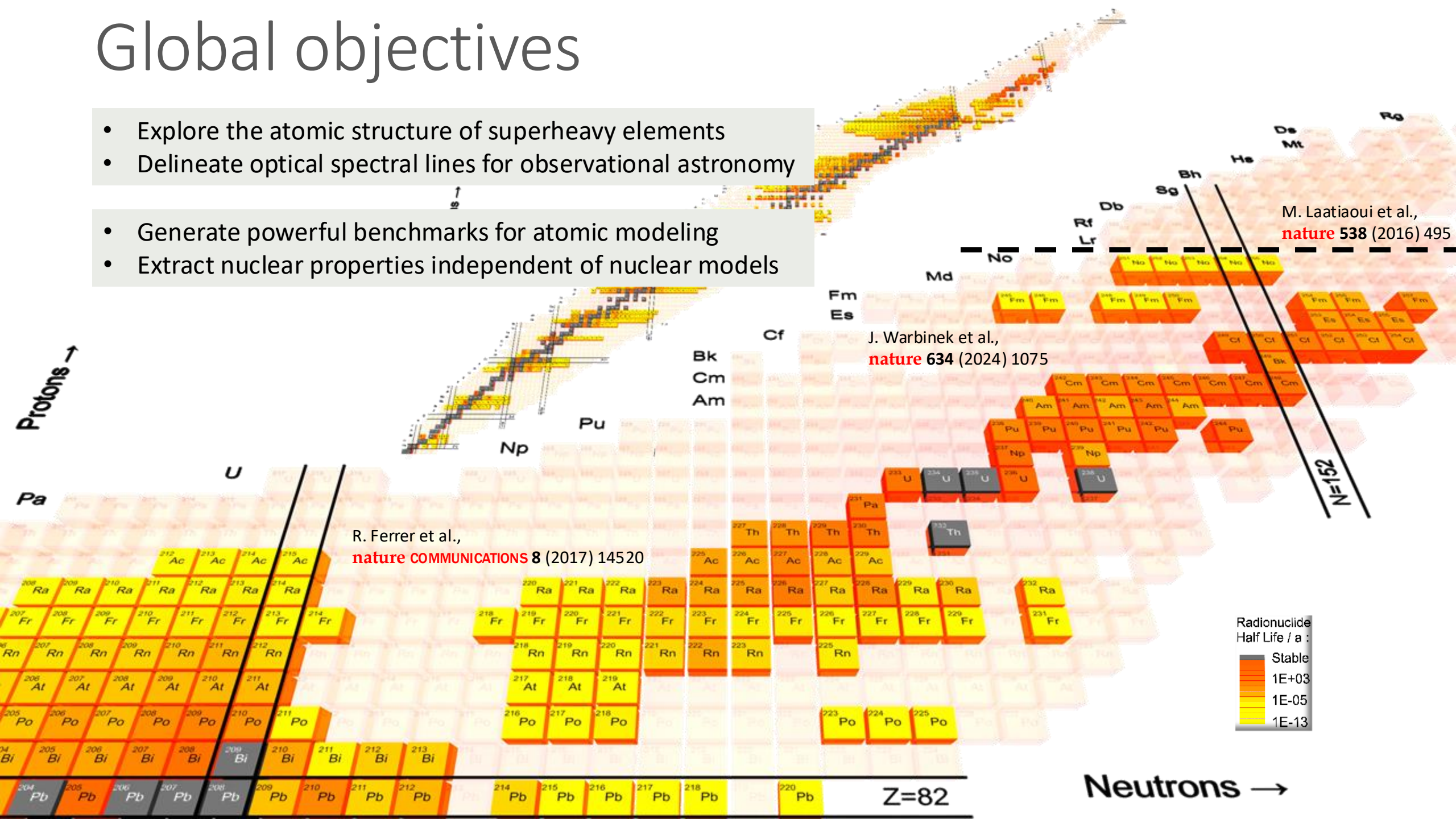


Z=82

Neutrons →

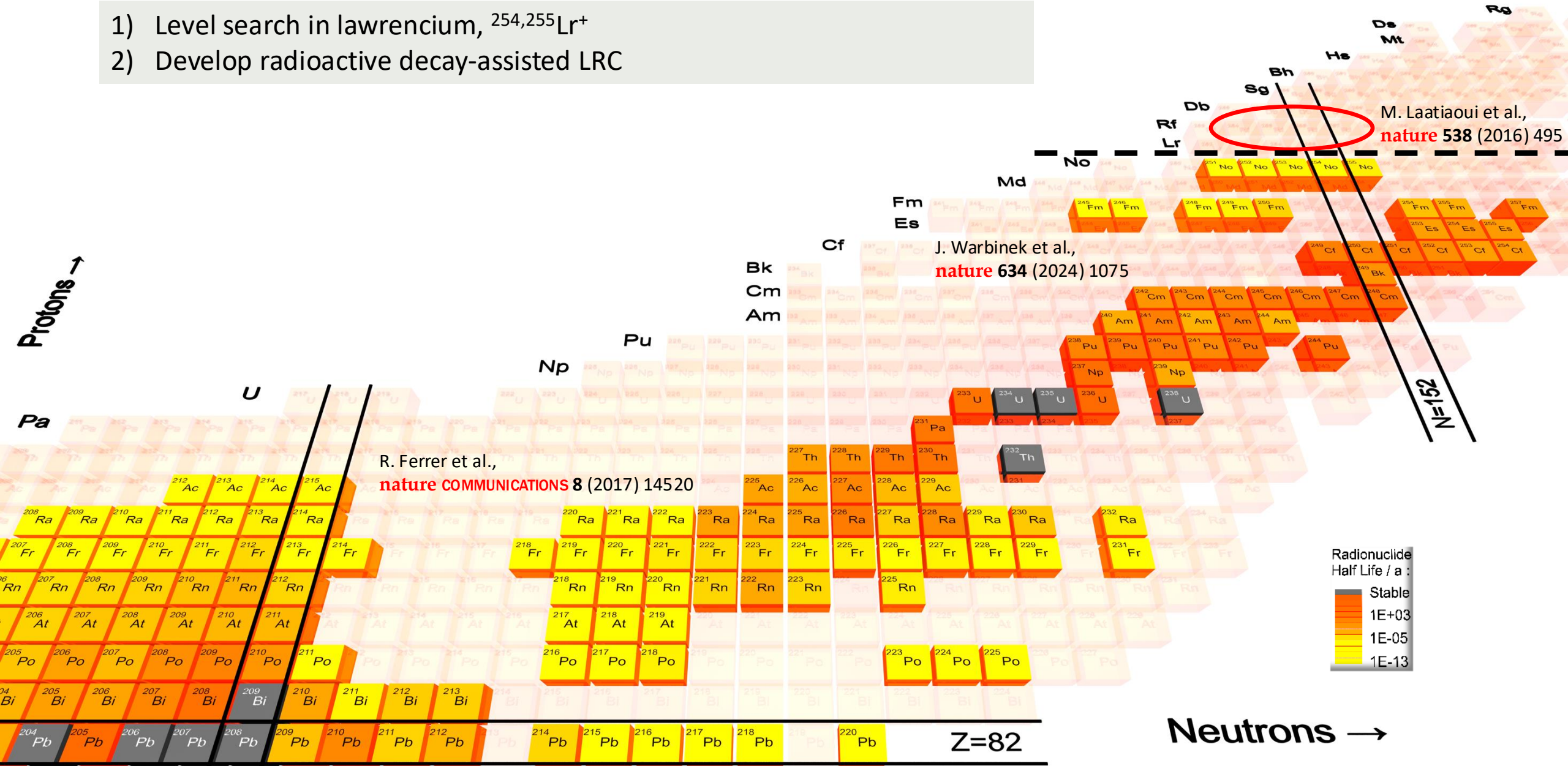
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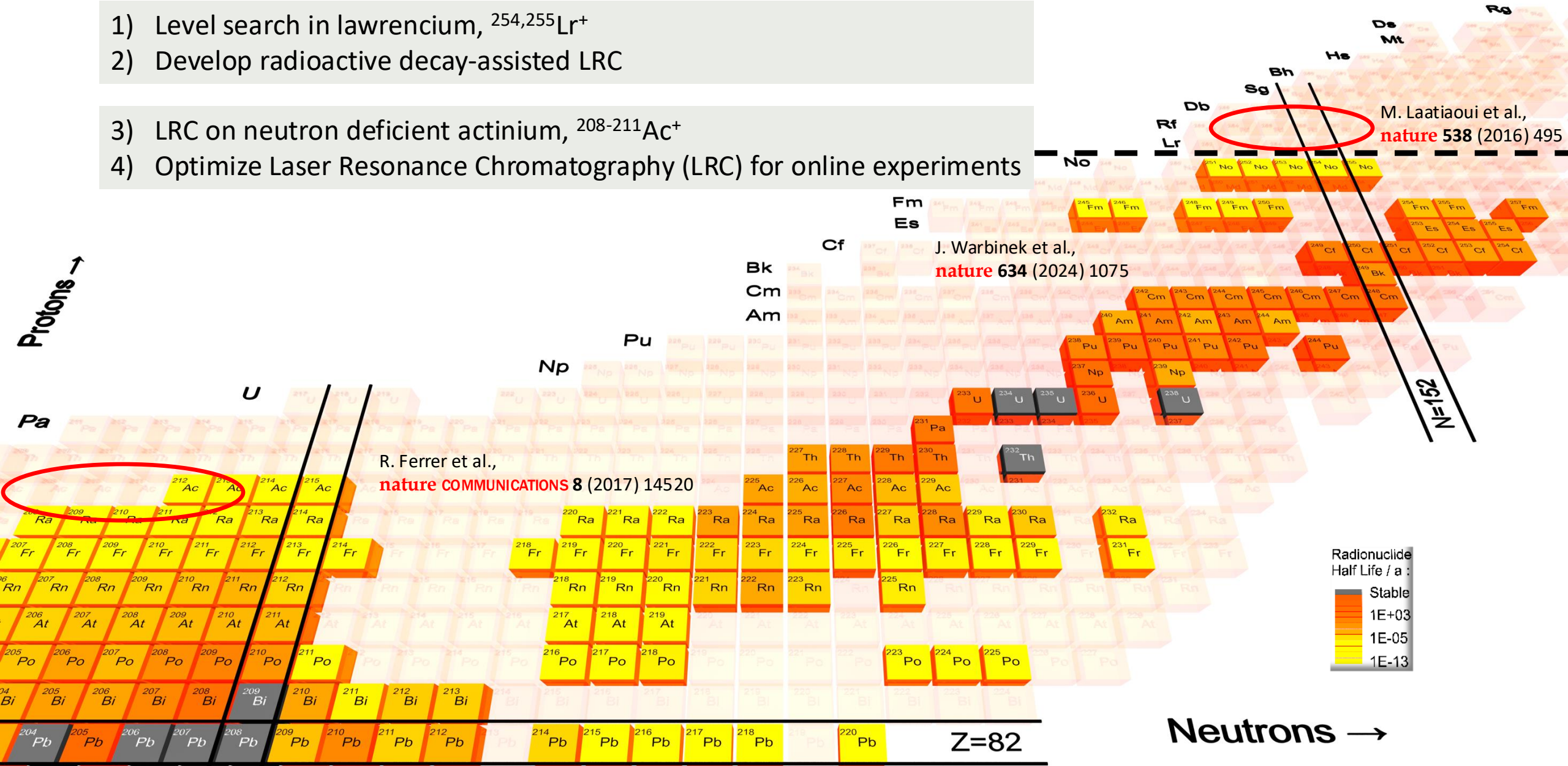
Specific objectives

- 1) Level search in lawrencium, $^{254,255}\text{Lr}^+$
- 2) Develop radioactive decay-assisted LRC

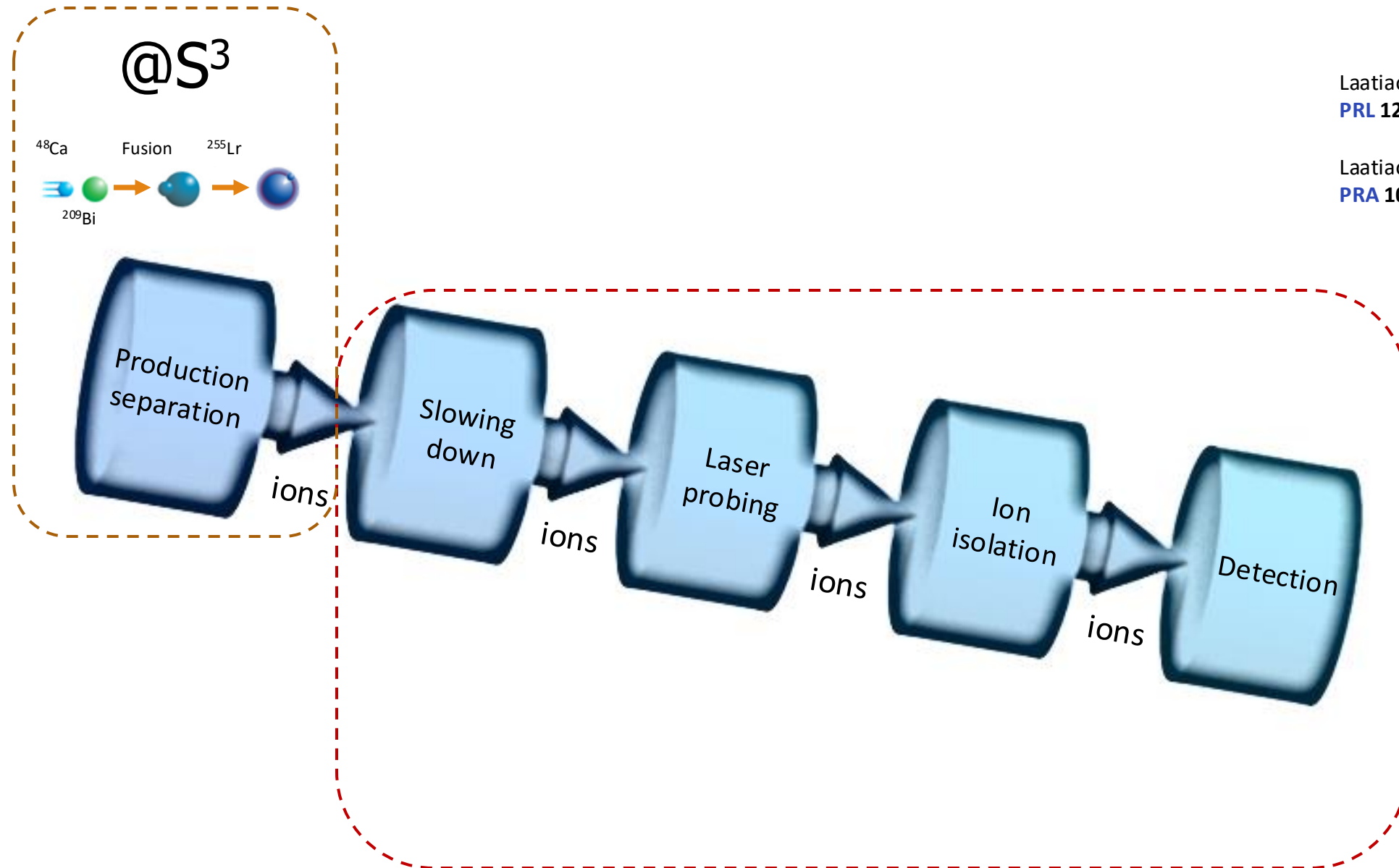


Specific objectives

- 1) Level search in lawrencium, $^{254,255}\text{Lr}^+$
- 2) Develop radioactive decay-assisted LRC
- 3) LRC on neutron deficient actinium, $^{208-211}\text{Ac}^+$
- 4) Optimize Laser Resonance Chromatography (LRC) for online experiments



Laser Resonance Chromatography (LRC)



European Research Council
Established by the European Commission

Laatiaoui *et al.*,
PRL 125 (2020) 023002

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

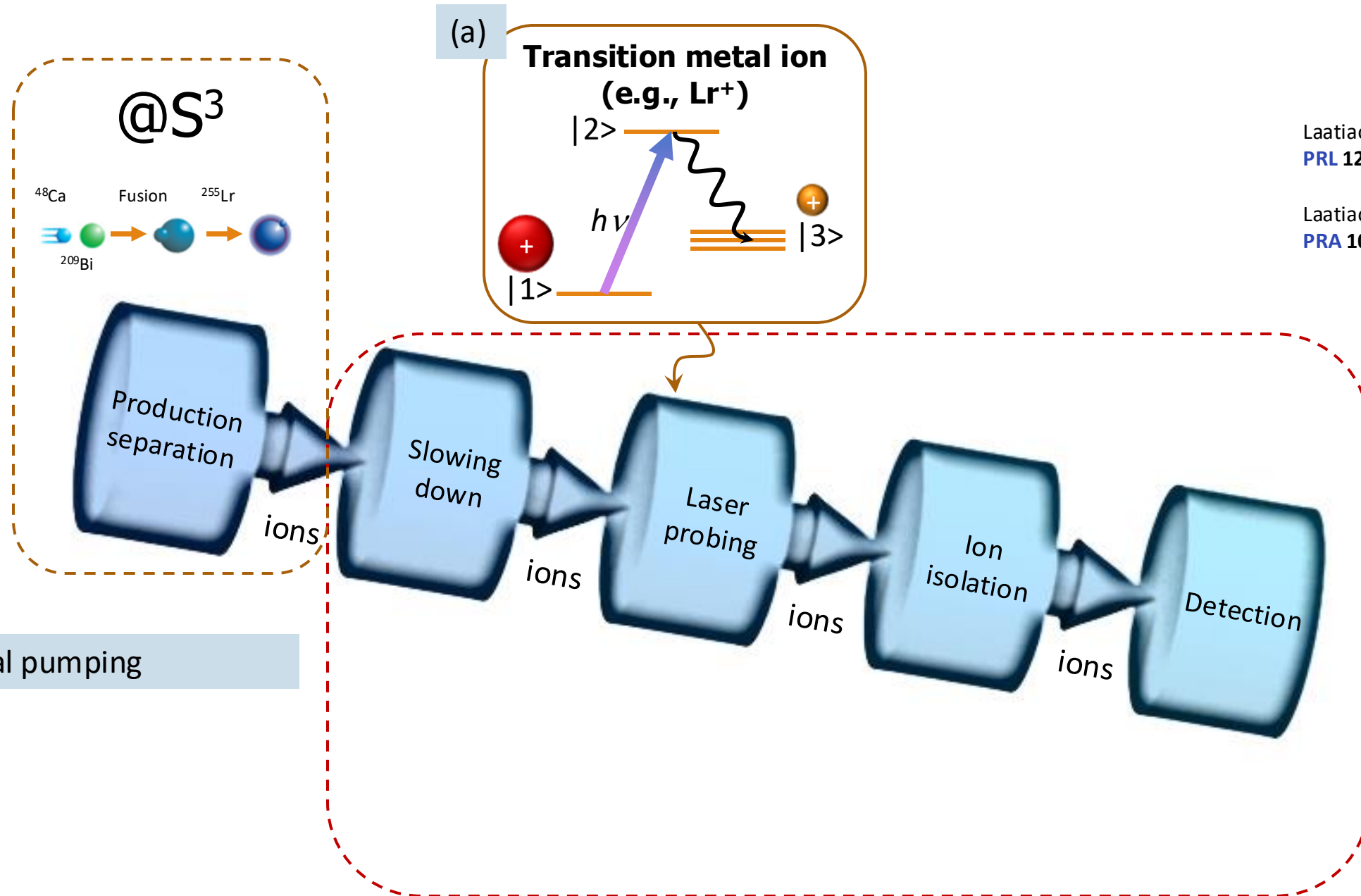
Laser Resonance Chromatography (LRC)



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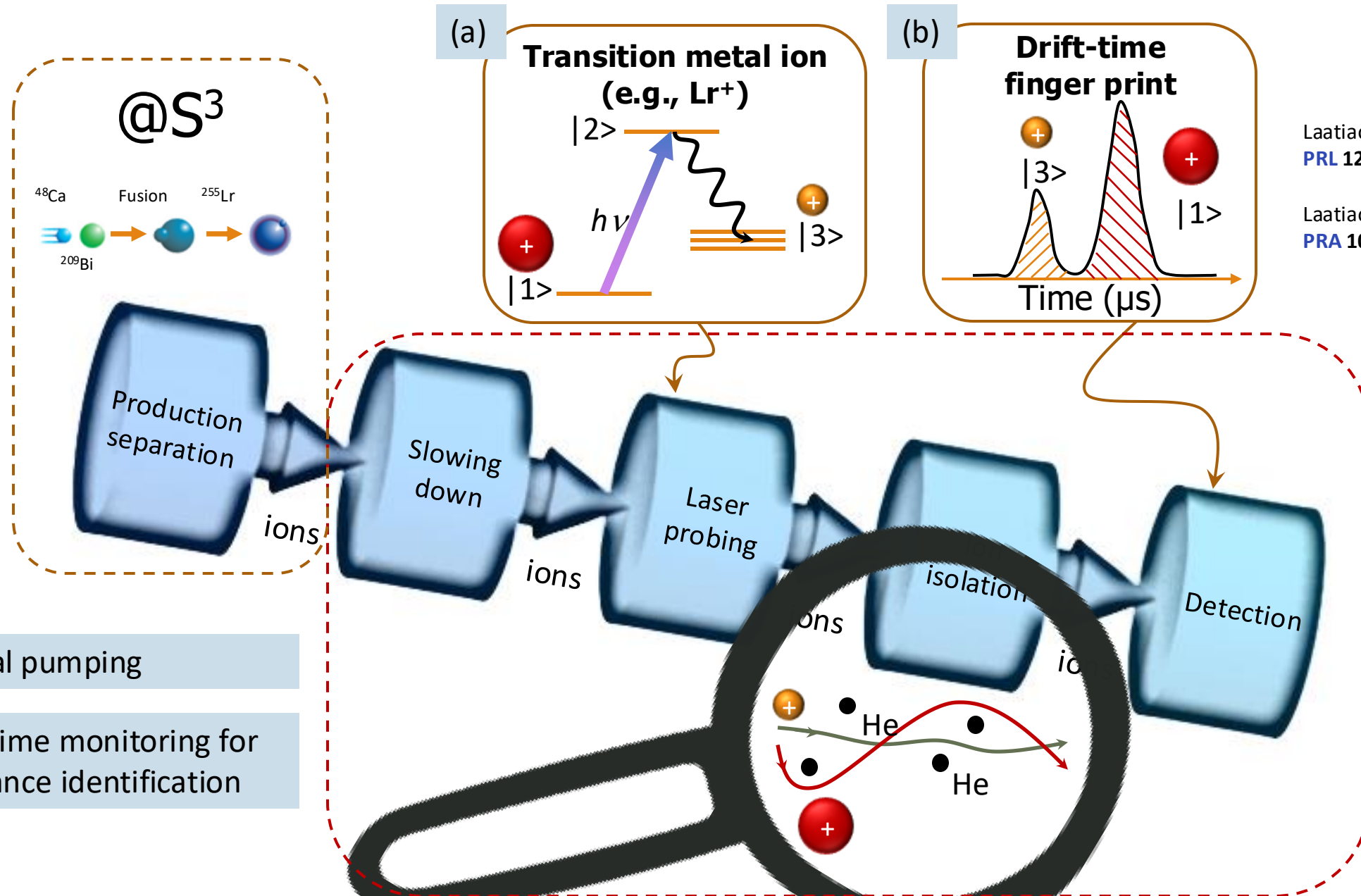
Laatiaoui *et al.*,
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(a) Optical pumping

Laser Resonance Chromatography (LRC)



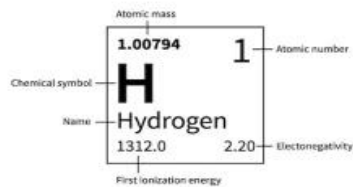
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Laatiaoui *et al.*,
PRL 125 (2020) 023002

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Accessible elements

1	1 IA 11A	1 H Hydrogen 1.00794 1.008	2 IIA 2A	3	4	5	6	7	8	9	10	11	12	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A	
2		3 Li Lithium 6.941 6.941	4 Be Beryllium 9.012182 9.012											5 B Boron 10.811 10.811	6 C Carbon 12.0107 12.011	7 N Nitrogen 14.0067 14.007	8 O Oxygen 15.9994 15.999	9 F Fluorine 18.998403 18.998	10 Ne Neon 20.1797 20.180	
3		11 Na Sodium 22.98976 22.990	12 Mg Magnesium 24.3040 24.304	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminium 26.98153 26.982	14 Si Silicon 28.0855 28.086	15 P Phosphorus 30.97306 30.973	16 S Sulfur 32.065 32.065	17 Cl Chlorine 35.453 35.453	18 Ar Argon 39.948 39.948	
4		19 K Potassium 39.0983 39.098	20 Ca Calcium 40.078 40.078	21 Sc Scandium 44.95591 44.956	22 Ti Titanium 47.867 47.867	23 V Vanadium 50.9415 50.942	24 Cr Chromium 51.9962 51.996	25 Mn Manganese 54.93804 54.938	26 Fe Iron 55.845 55.845	27 Co Cobalt 58.93319 58.933	28 Ni Nickel 58.6934 58.693	29 Cu Copper 63.546 63.546	30 Zn Zinc 65.38 65.38	31 Ga Gallium 69.723 69.723	32 Ge Germanium 72.64 72.64	33 As Arsenic 74.92160 74.922	34 Se Selenium 78.96 78.96	35 Br Bromine 79.904 79.904	36 Kr Krypton 83.796 83.796	
5		37 Rb Rubidium 85.4678 85.468	38 Sr Strontium 87.62 87.62	39 Y Yttrium 88.90585 88.906	40 Zr Zirconium 91.224 91.224	41 Nb Niobium 92.90638 92.906	42 Mo Molybdenum 95.96 95.96	43 Tc Technetium [98] [98]	44 Ru Ruthenium 101.07 101.07	45 Rh Rhodium 102.9055 102.906	46 Pd Palladium 106.42 106.42	47 Ag Silver 107.8682 107.868	48 Cd Cadmium 112.411 112.411	49 In Indium 114.818 114.818	50 Sn Tin 118.710 118.710	51 Sb Antimony 121.760 121.760	52 Te Tellurium 127.60 127.60	53 I Iodine 126.9044 126.904	54 Xe Xenon 131.293 131.293	
6		55 Cs Caesium 132.9054 132.905	56 Ba Barium 137.327 137.327	57 Lu Lutetium 174.9668 174.967	71 Hf Hafnium 178.49 178.49	72 Ta Tantalum 180.9478 180.948	73 W Tungsten 183.84 183.84	74 Re Rhenium 186.207 186.207	75 Os Osmium 190.23 190.23	76 Ir Iridium 192.217 192.217	77 Pt Platinum 195.084 195.084	78 Au Gold 196.9665 196.967	79 Hg Mercury 200.59 200.59	80 Tl Thallium 204.3833 204.383	81 Pb Lead 207.2 207.2	82 Bi Bismuth 208.9804 208.980	83 Po Polonium [210] [210]	84 At Astatine [210] [210]	85 Rn Radon [222] [222]	
7		87 Fr Francium [223] [223]	88 Ra Radium [226] [226]	89 Lr Lawrencium [262] [262]	103 Rf Rutherfordium [261] [261]	104 Db Dubnium [262] [262]	105	106	107	108	109	110	111	112	113	114	115	116	117	118

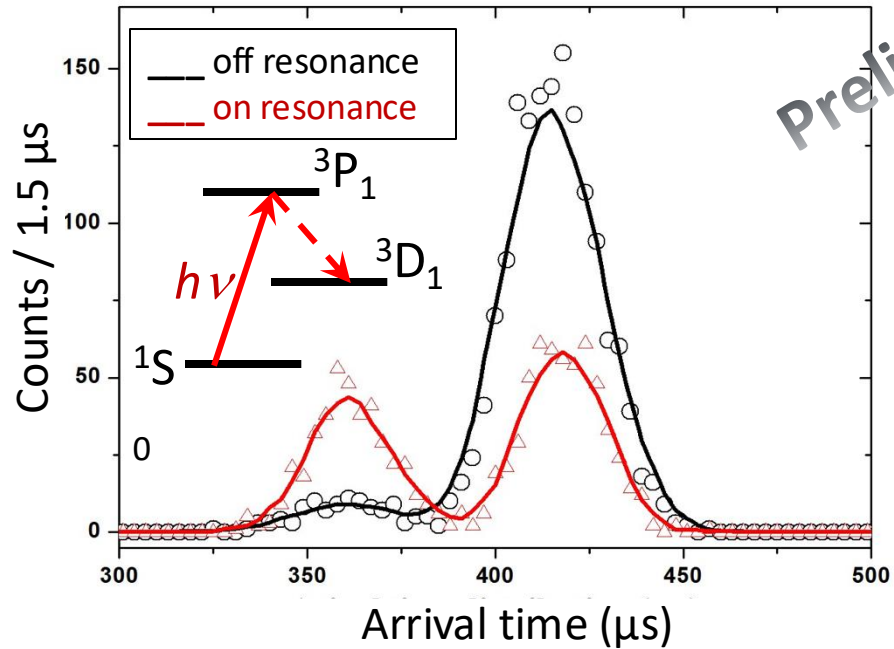


57 La Lanthanum 138.9054 138.905	58 Ce Cerium 140.116 140.116	59 Pr Praseodymium 140.9076 140.908	60 Nd Neodymium 144.242 144.242	61 Pm Promethium [145] [145]	62 Sm Samarium 150.36 150.36	63 Eu Europium 151.964 151.964	64 Gd Gadolinium 157.25 157.25	65 Tb Terbium 158.9253 158.925	66 Dy Dysprosium 162.500 162.500	67 Ho Holmium 164.9303 164.930	68 Er Erbium 167.259 167.259	69 Tm Thulium 168.9342 168.934	70 Yb Ytterbium 173.054 173.054
89 Ac Actinium [227] [227]	90 Th Thorium 232.0380 232.038	91 Pa Protactinium 231.0368 231.037	92 U Uranium 238.0289 238.029	93 Np Neptunium [237] [237]	94 Pu Plutonium [244] [244]	95 Am Americium [243] [243]	96 Cm Curium [247] [247]	97 Bk Berkelium [247] [247]	98 Cf Californium [251] [251]	99 Es Einsteinium [252] [252]	100 Fm Fermium [257] [257]	101 Md Mendelevium [258] [258]	102 No Nobelium [259] [259]

- Alkali metals
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- Other metals
- Transition metals
- Lanthanoids
- Actinoids
- Metalloids
- Nonmetals
- Halogens
- Noble gases

Proof of principle for ^{175}Lu

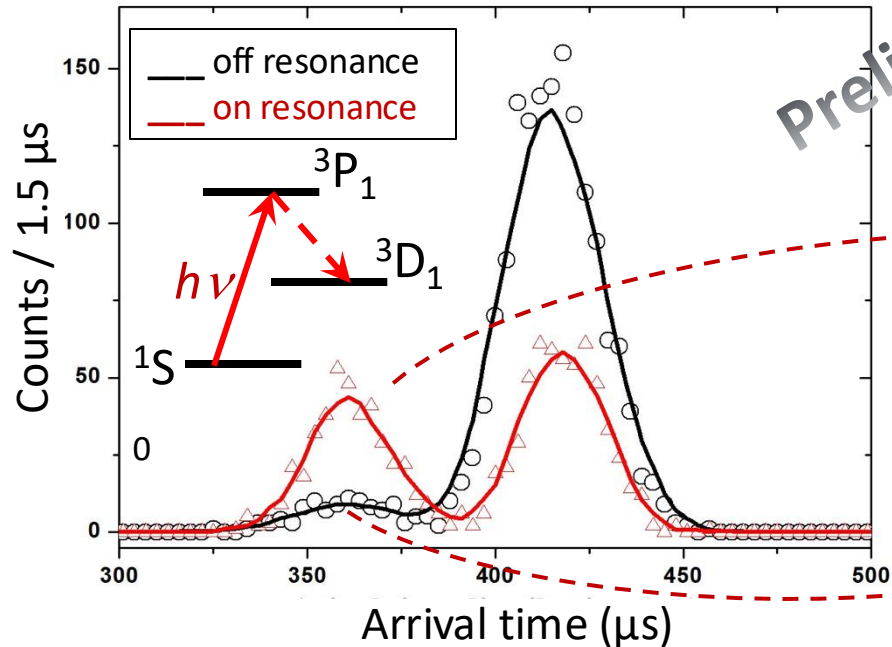
137.327	56	174.9668	71	178.49	72
Ba		Lu		Hf	
Barium		Lutetium		Hafnium	
502.9	0.89	573.5	1.27	658.5	1.30



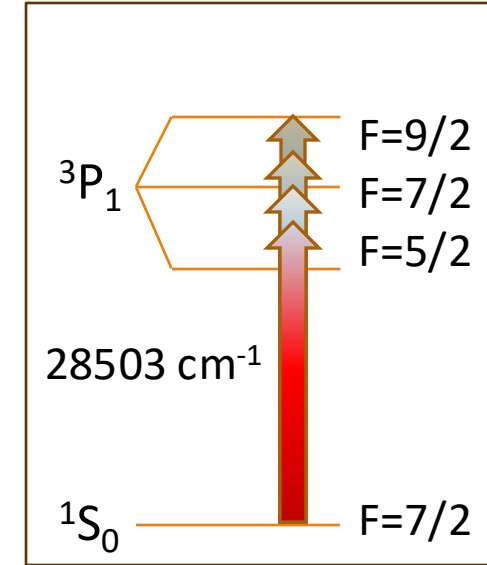
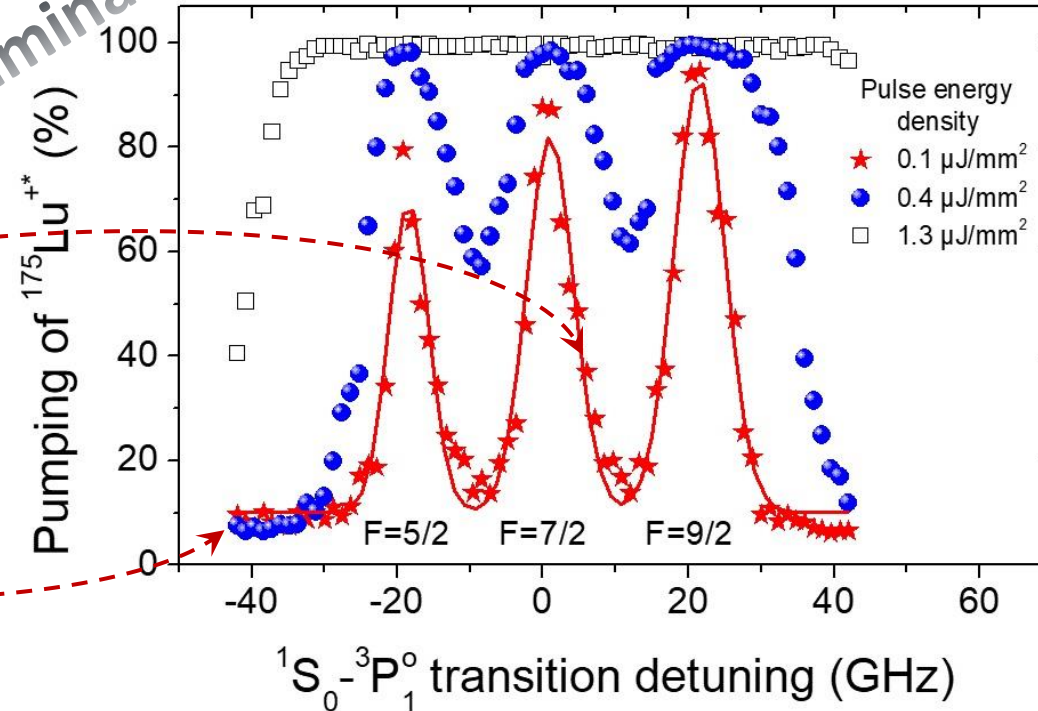
- E. Kahl et al., **PRA** **100** (2019) 062505
Laatiaoui et al., **PRL** **125** (2020) 023002
Laatiaoui et al., **PRA** **102** (2020) 013106
Ramanantoanina et al., **PRA** **104** (2021) 022813
Ramanantoanina et al., **Atoms** **10** (2022) 48
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Kim et al., **NIMB** **555** (2024) 165461

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Preliminary

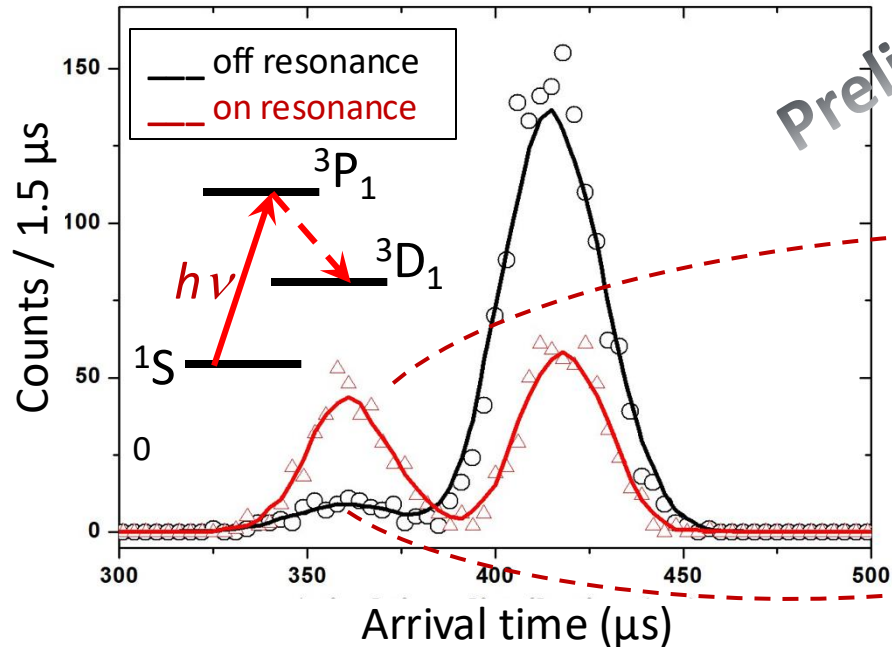


- Hyperfine structure studies possible at low laser power
-

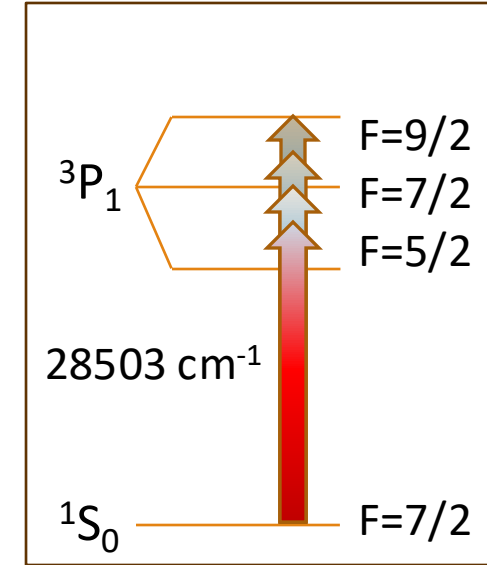
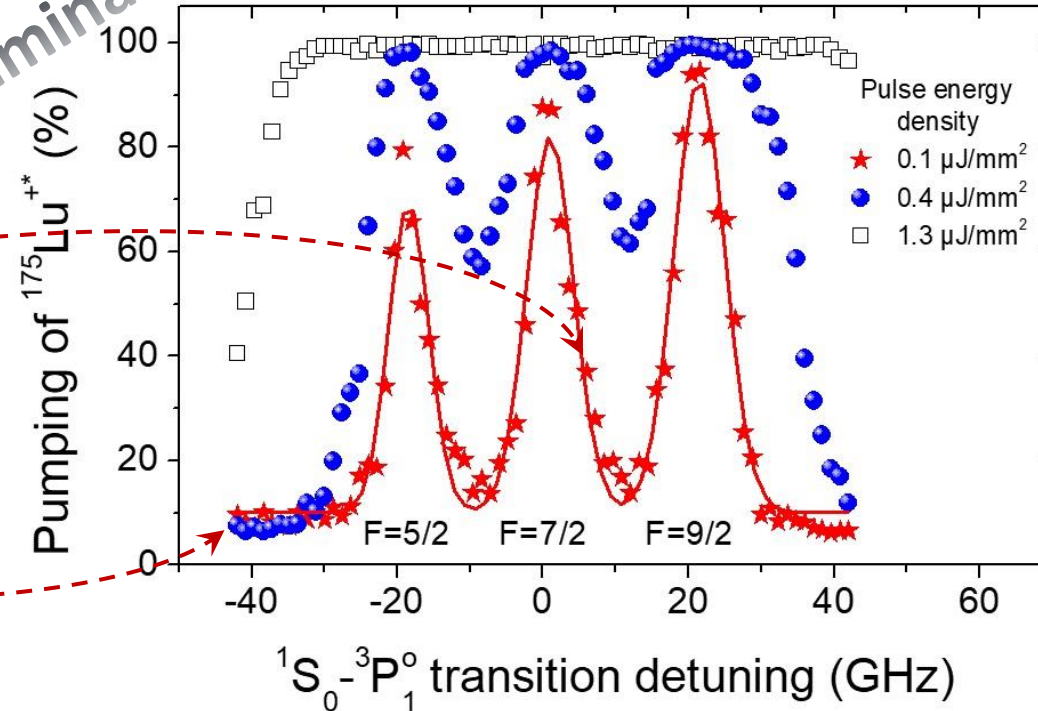
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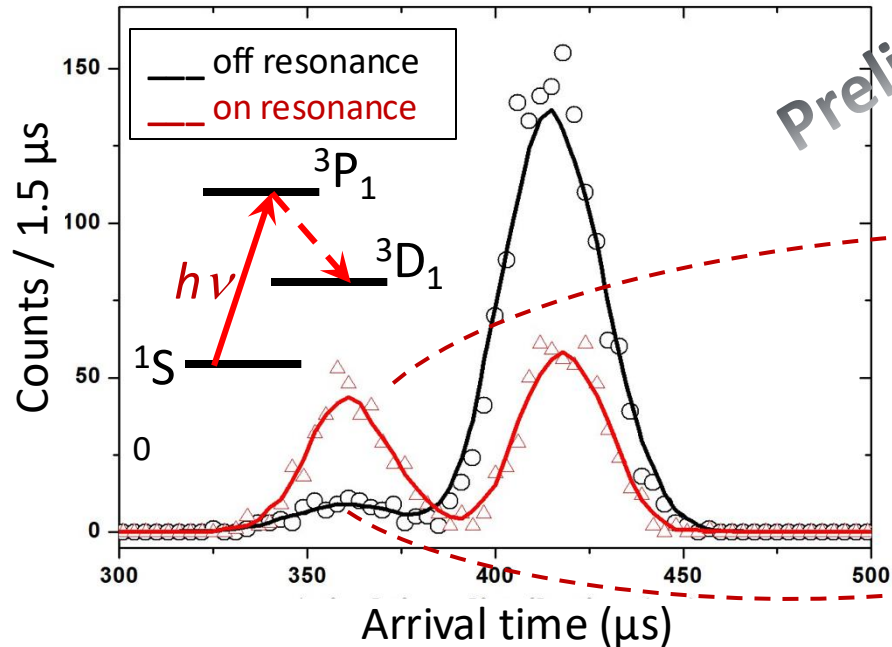


- Hyperfine structure studies possible at low laser power
- Power broadening beneficial for faster level search

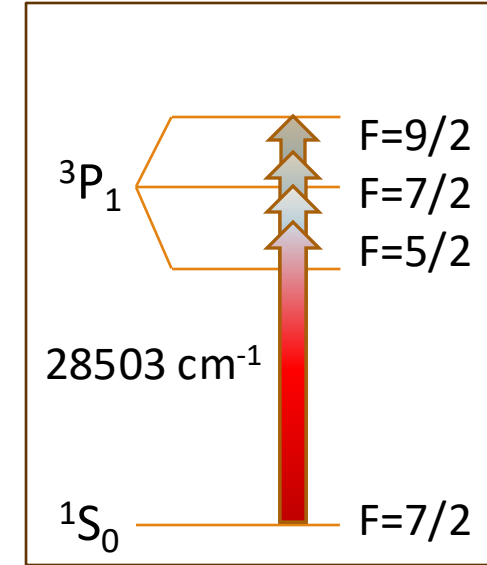
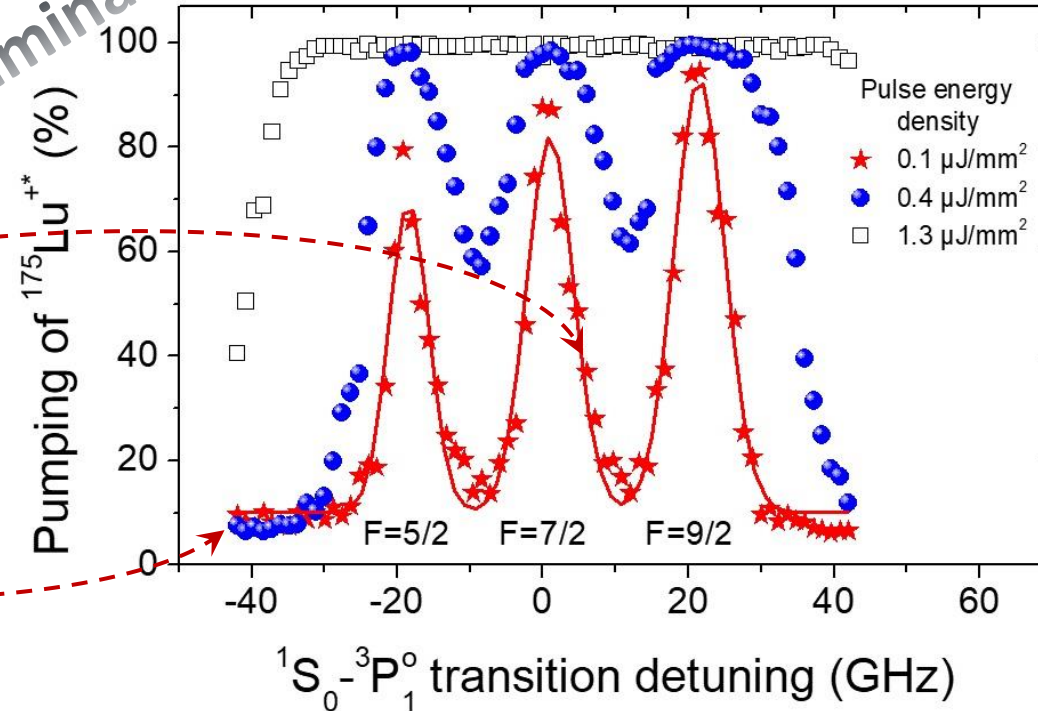
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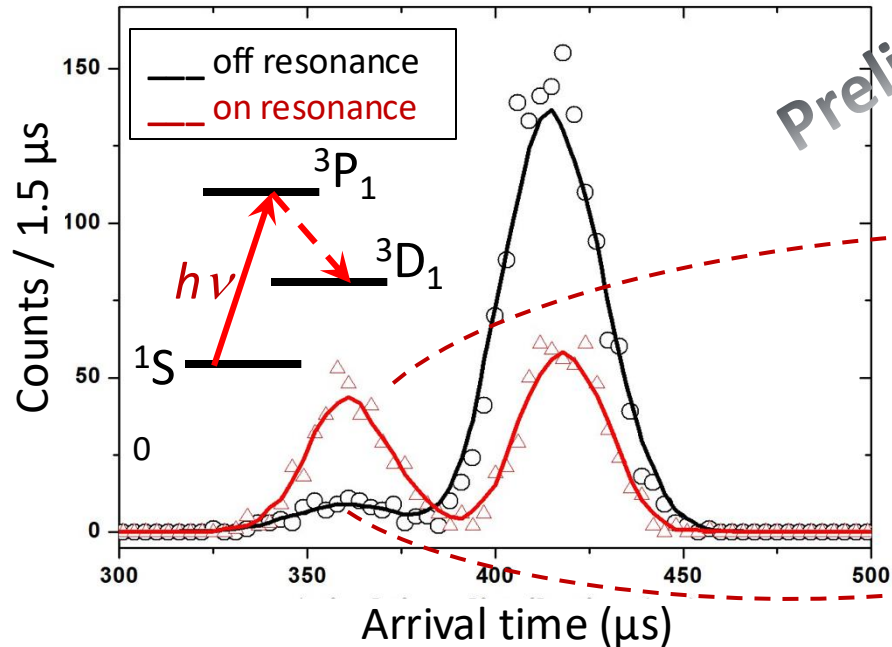
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• Measured overall-efficiency: 0.6%

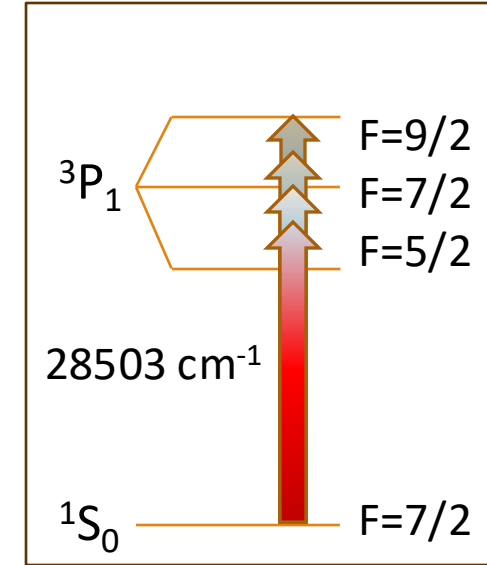
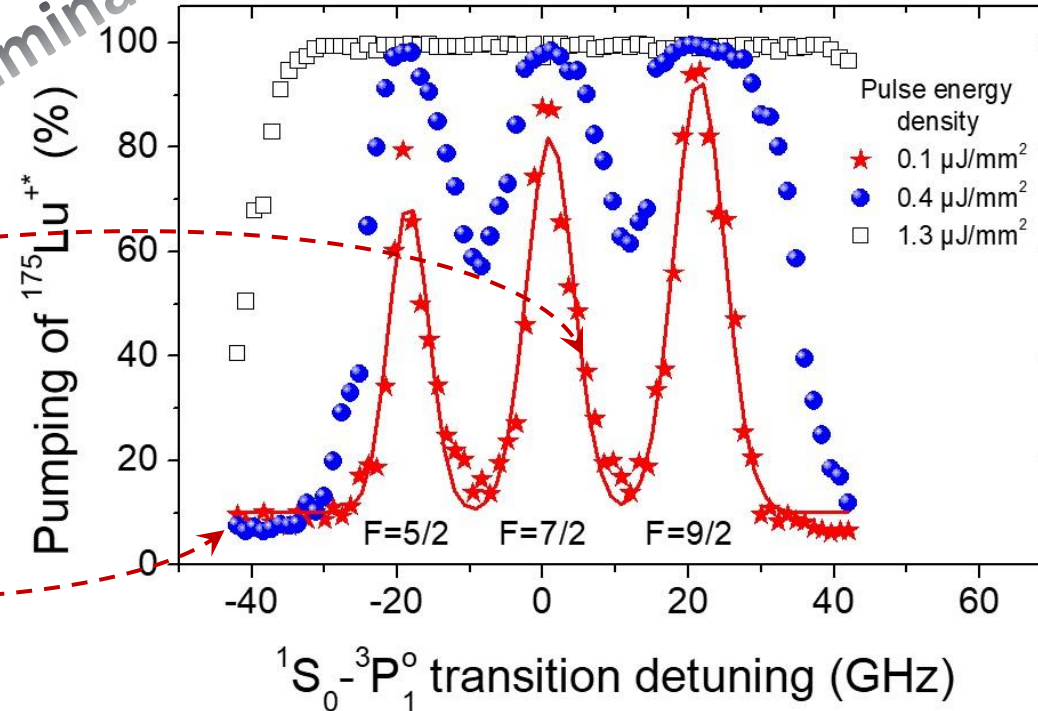
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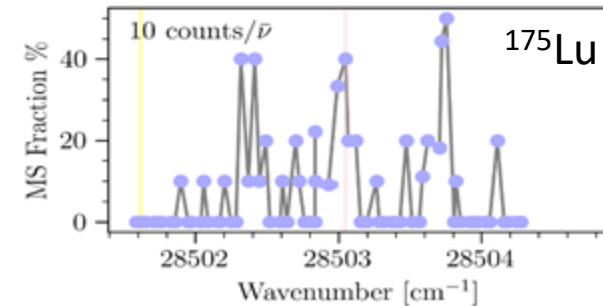
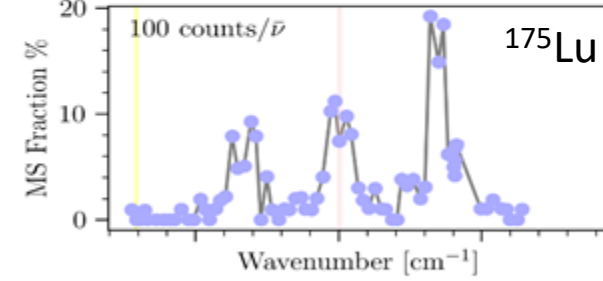
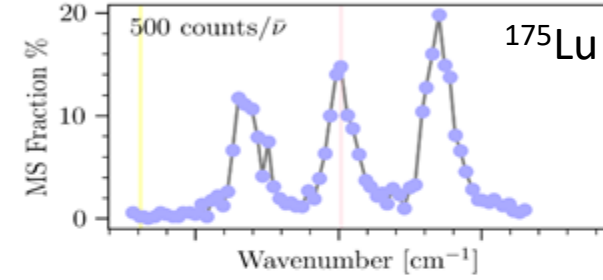
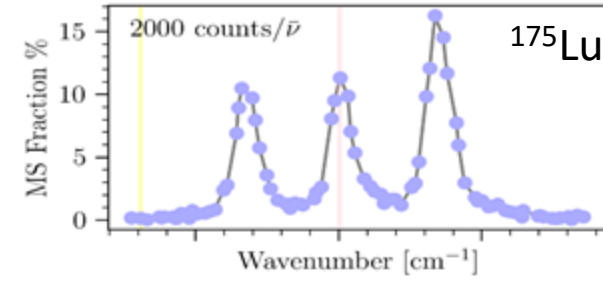
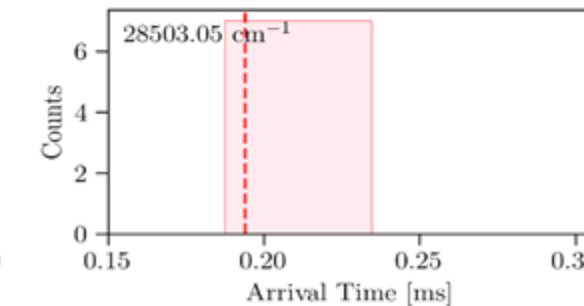
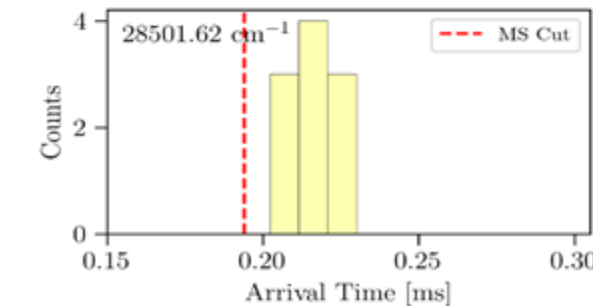
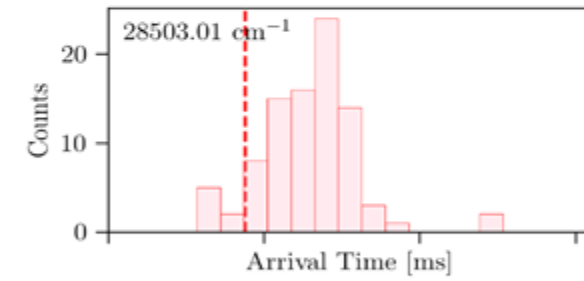
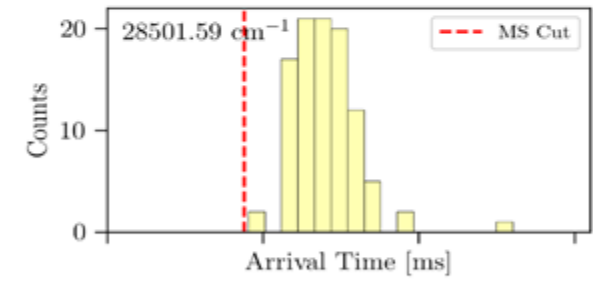
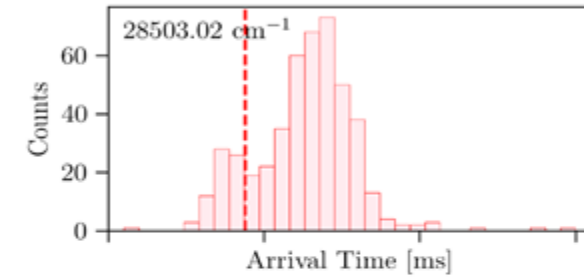
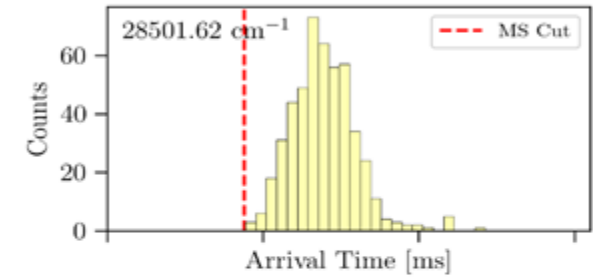
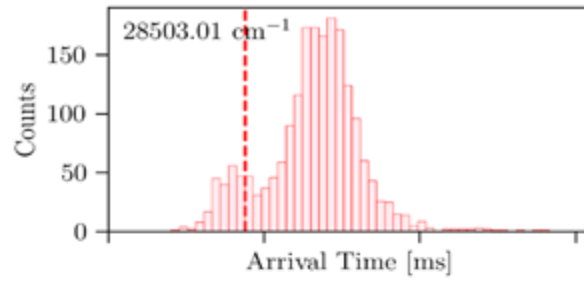
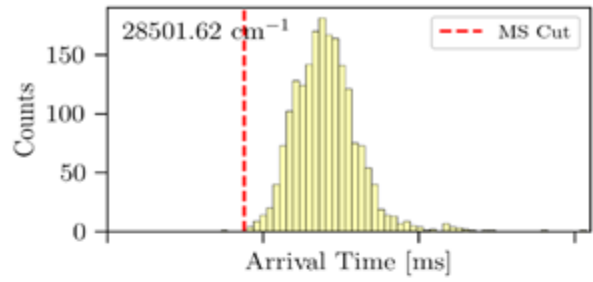
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➤ Postdoc #1 / T-3.1: LRC offline optimization -- (start 03/2025)

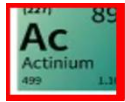
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LRC sensitivity



Aayush Arya,
Master thesis,
JGU Mainz,
September 2024

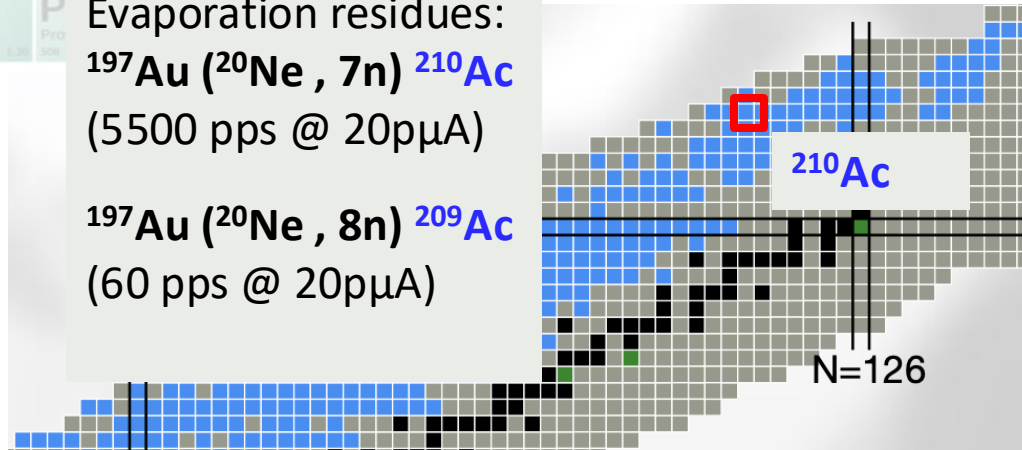
LRC on Ac^+



Evaporation residues:

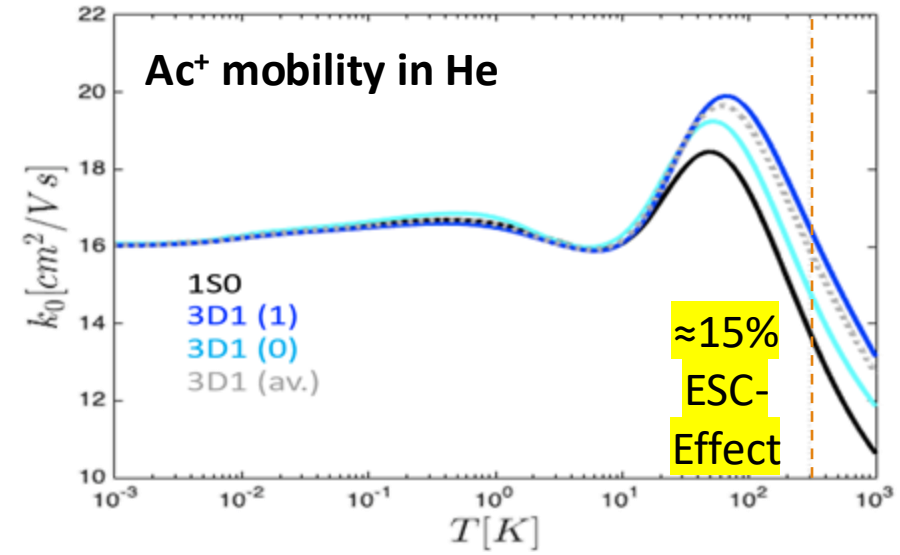
$^{197}\text{Au} (^{20}\text{Ne}, 7n) ^{210}\text{Ac}$
(5500 pps @ $20\mu\text{A}$)

$^{197}\text{Au} (^{20}\text{Ne}, 8n) ^{209}\text{Ac}$
(60 pps @ $20\mu\text{A}$)

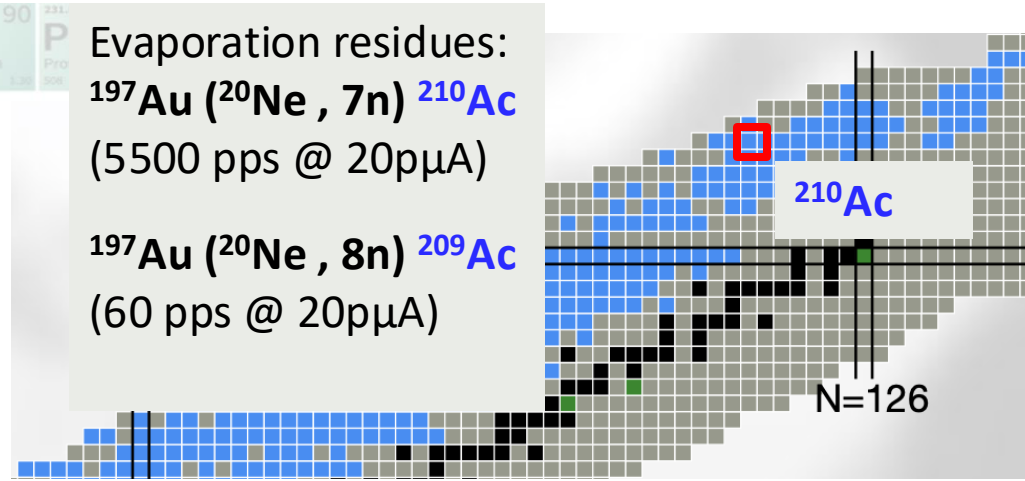
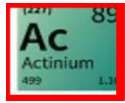


<https://u.ganil-spiral2.eu/chartbeams/>

Courtesy H. Ramanantoanina

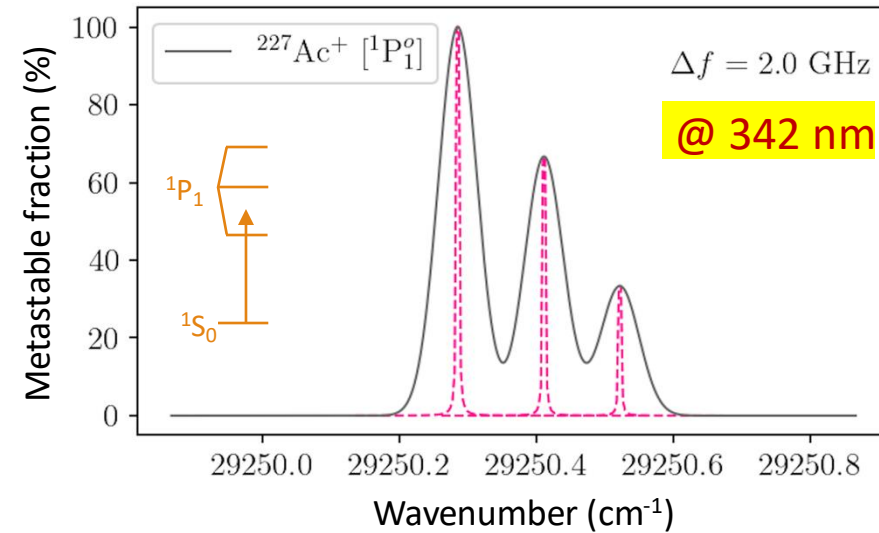
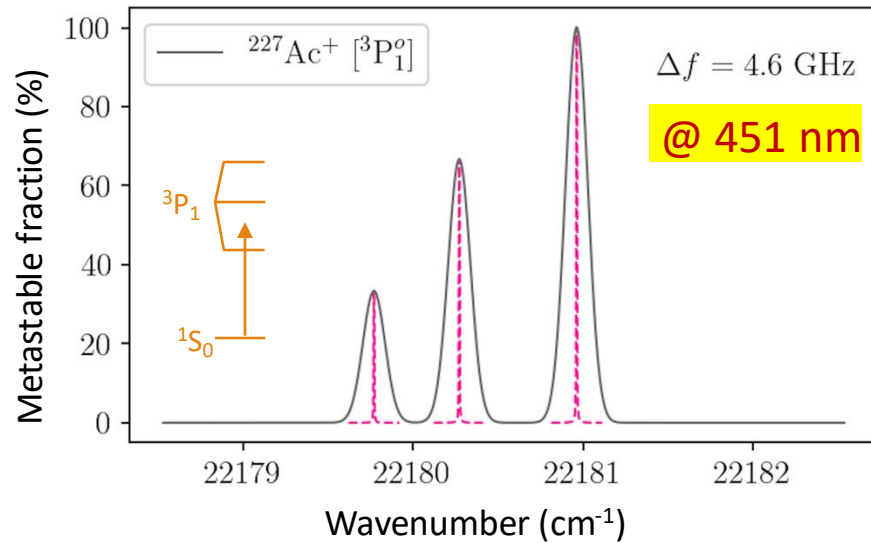
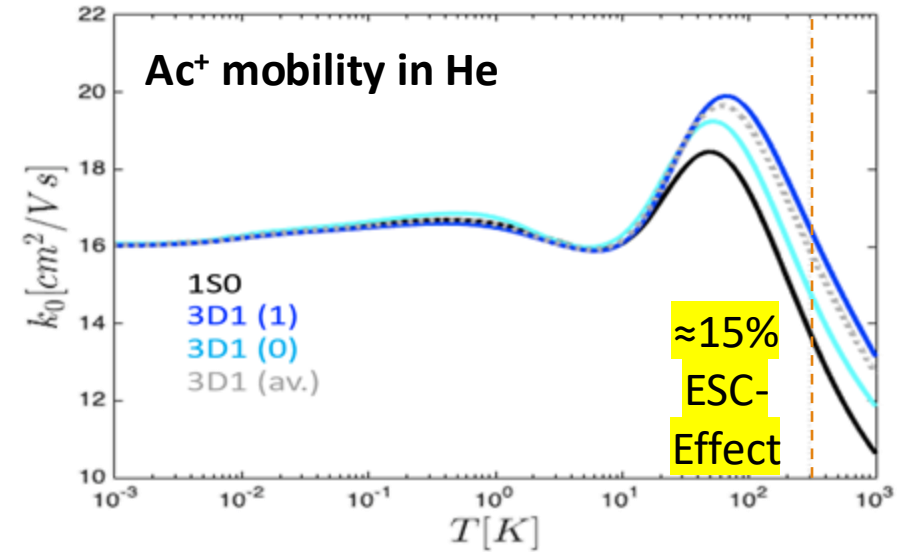


LRC on Ac^+



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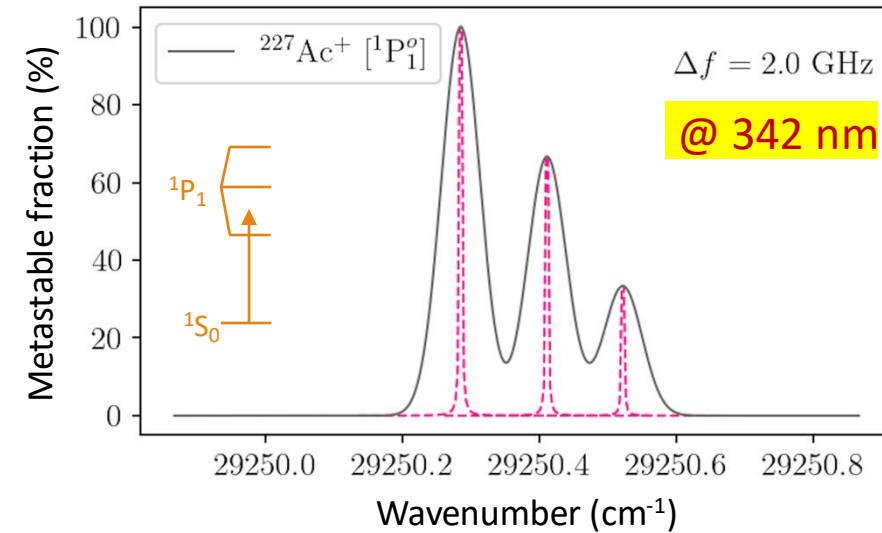
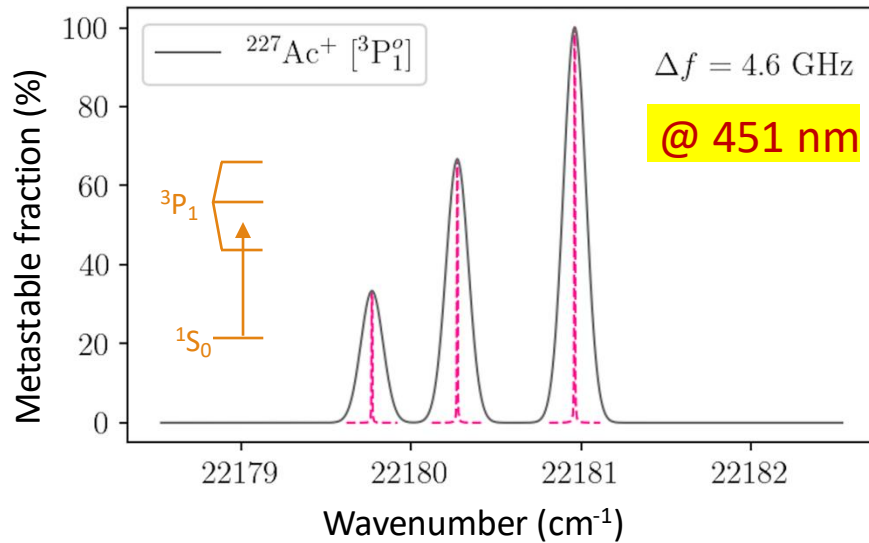
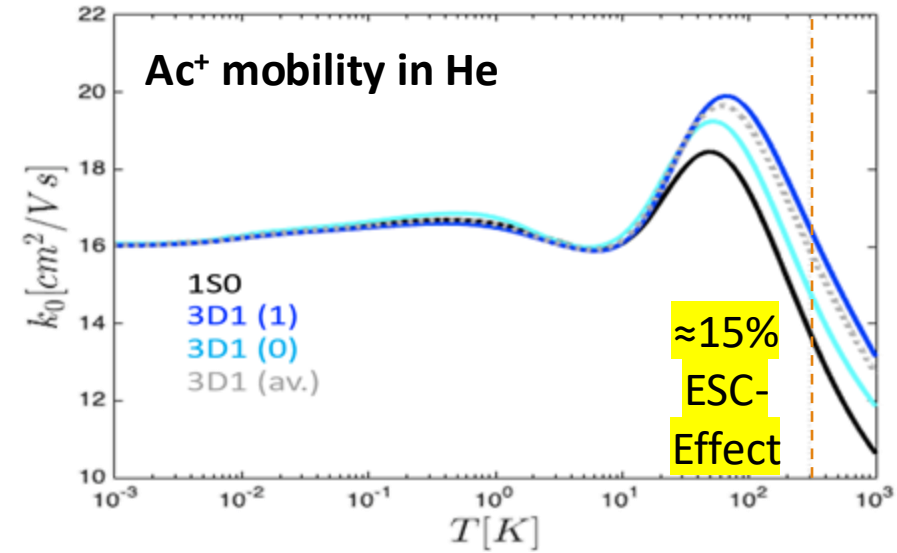
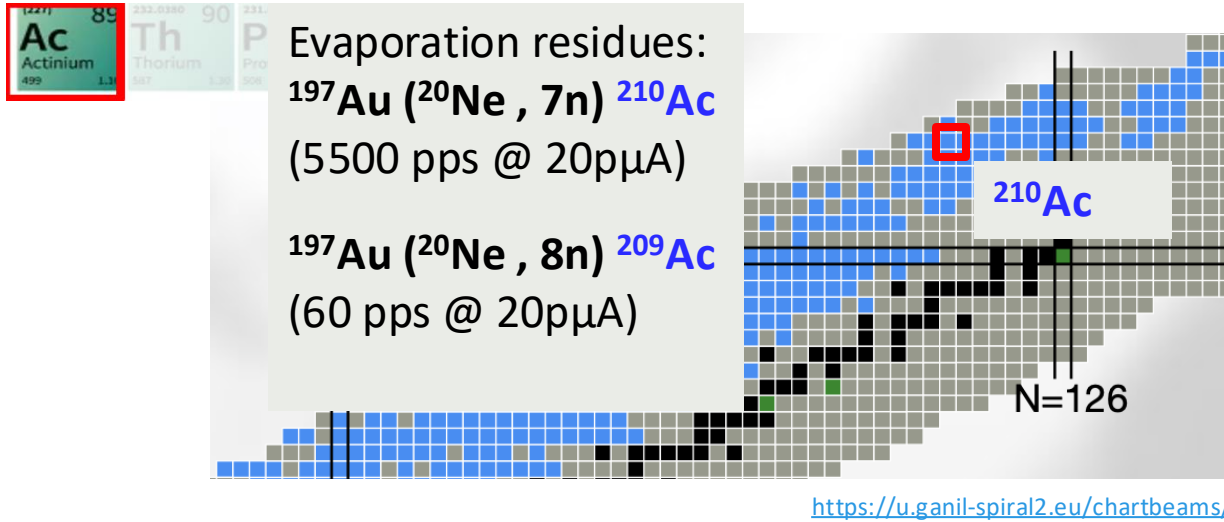
Courtesy H. Ramanantoanina



Aayush Arya,
 Master thesis,
 JGU Mainz,
 September 2024

LRC on Ac^+

Courtesy H. Ramanantoanina

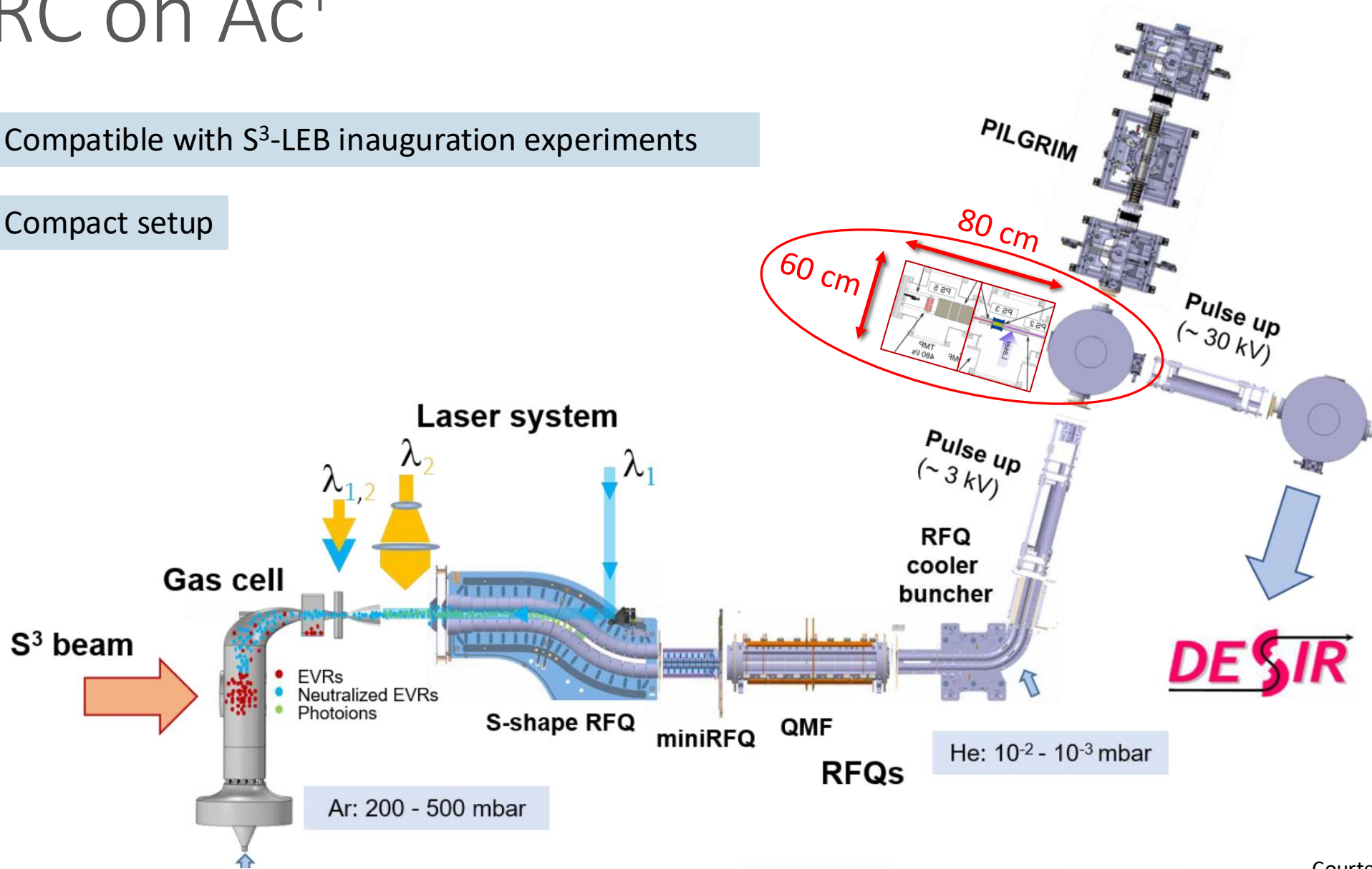


Aayush Arya,
Master thesis,
 JGU Mainz,
 September 2024

➤ Postdoc #1 / T-3.2: LRC on neutron deficient actinium, $^{208-211}\text{Ac}^+$

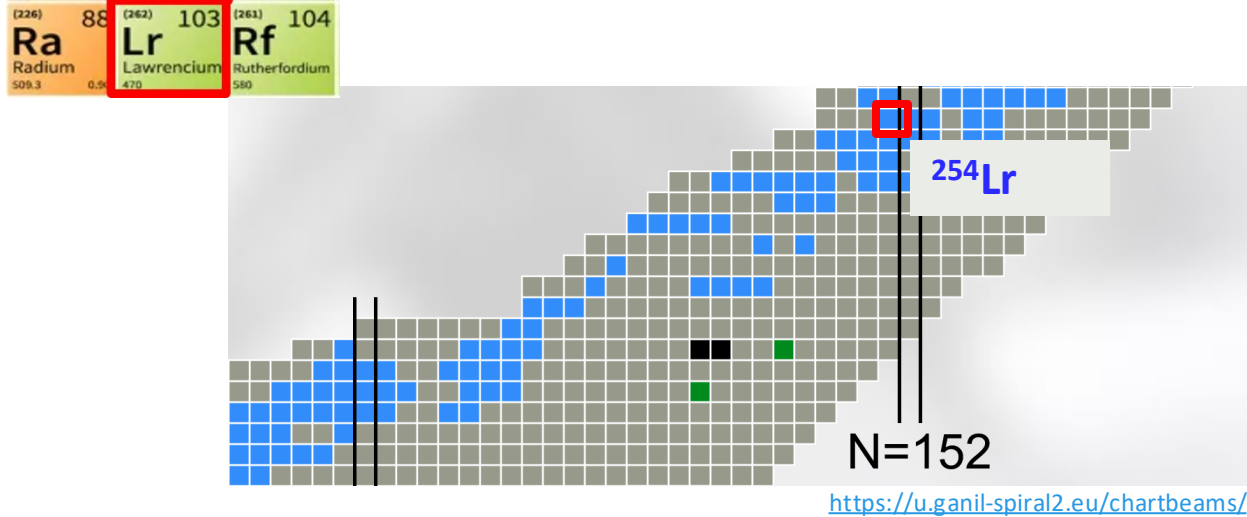
LRC on Ac^+

- Compatible with S^3 -LEB inauguration experiments
- Compact setup



Courtesy V. Manea

LRC on Lr^+



Evaporation residues:

^{208}Pb (^{48}Ti , pn) ^{254}Lr

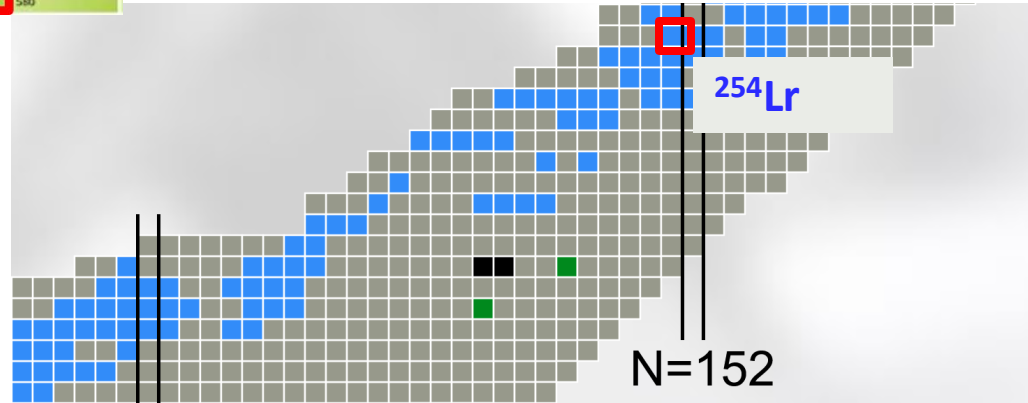
(3.2 pps @ $3\text{p}\mu\text{A}$)

^{209}Bi (^{48}Ca , 2n) ^{255}Lr

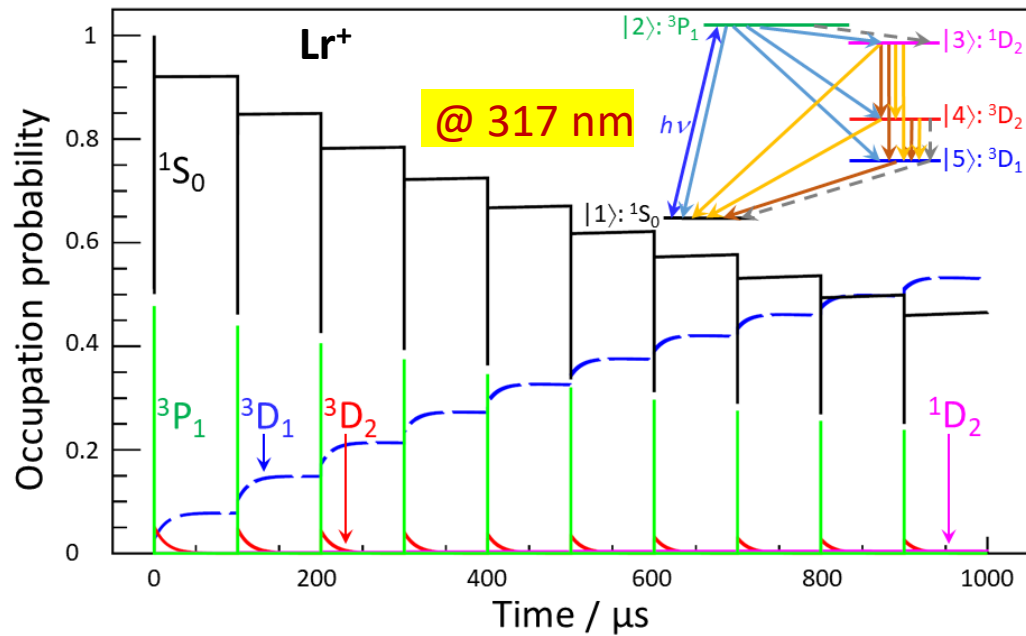
(0.4 pps @ $3\text{p}\mu\text{A}$)

LRC on Lr^+

(226) 88 Ra Radium 226.0254	(262) 103 Lr Lawrencium 262.1093	(261) 104 Rf Rutherfordium 261.1088
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<https://u.ganil-spiral2.eu/chartbeams/>



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(3.2 pps @ $3 \mu\text{A}$)

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

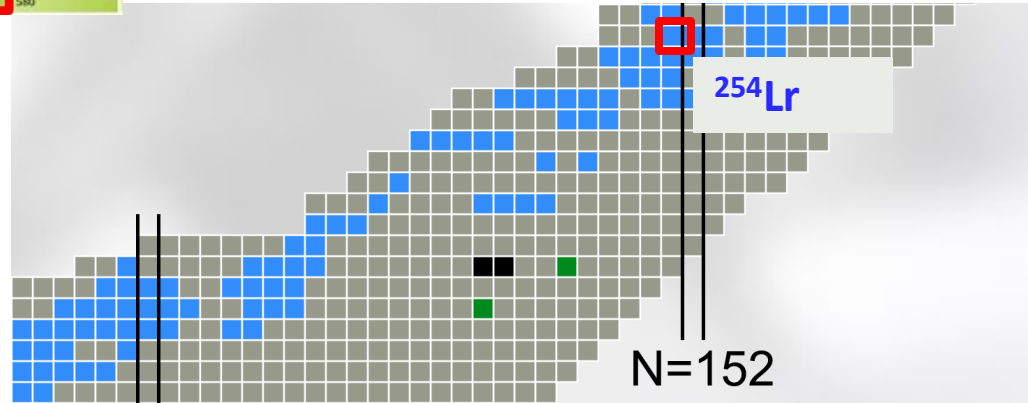
Laatiaoui et al., *PRL* **125** (2020) 023002

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

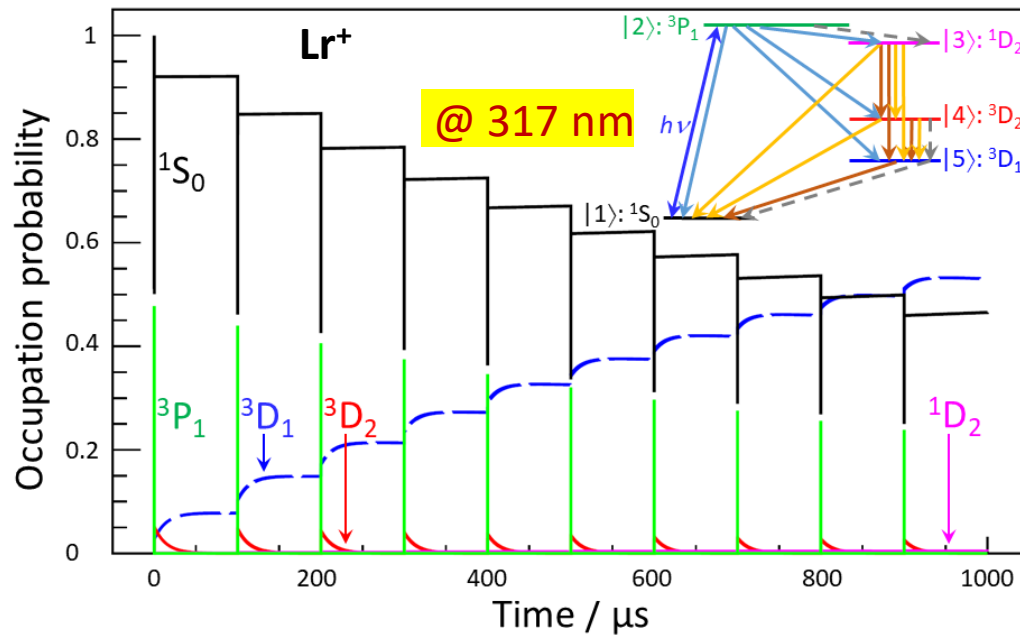
Ramanantoanina et al., *PRA* **108** (2023) 012802

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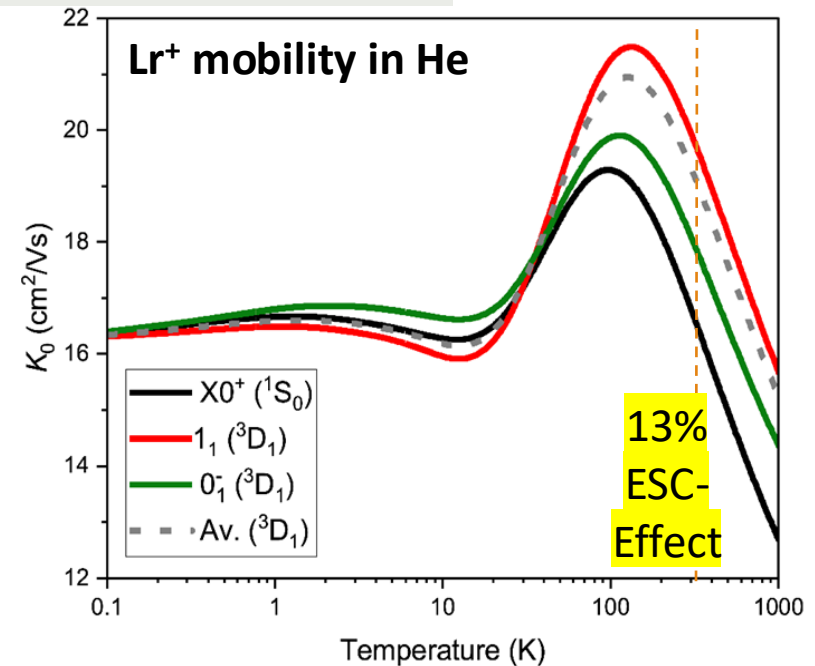
(0.4 pps @ $3\text{p}\mu\text{A}$)

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

Laatiaoui et al., *PRL* **125** (2020) 023002

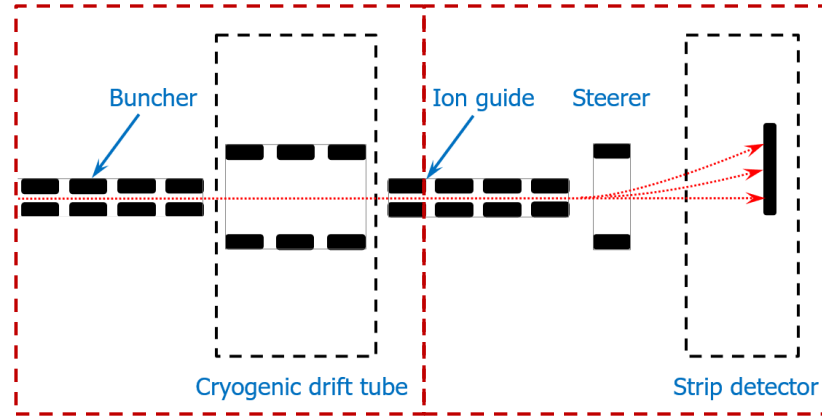
Ramanantoanina et al., *Atoms* **10** (2022) 48

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

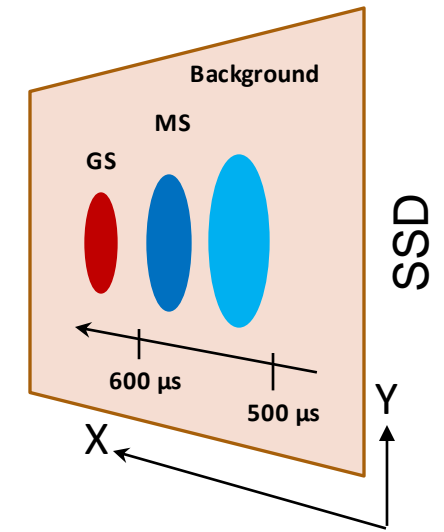


LRC on Lr^+

- Radioactive decay-assisted LRC (using SSD detector)

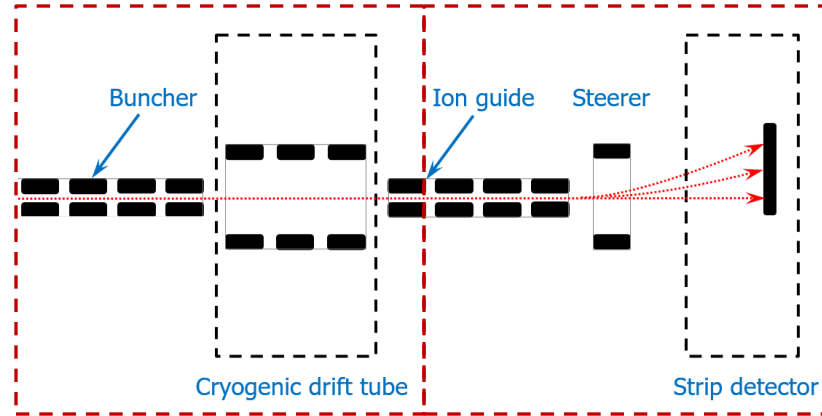


- Increased sensitivity by registering alpha decay events
 - Deflection of ions at the right moment
 - Centroids of radioactivity hotspots correspond to distinct arrival times

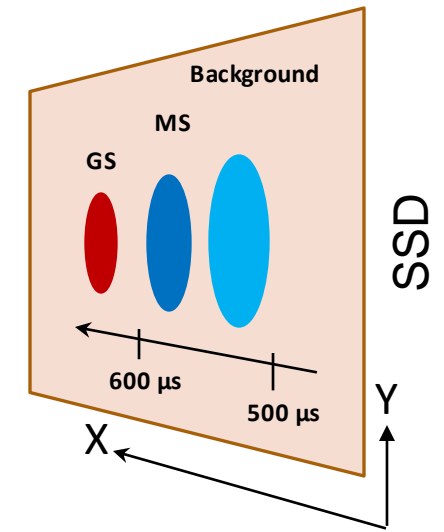


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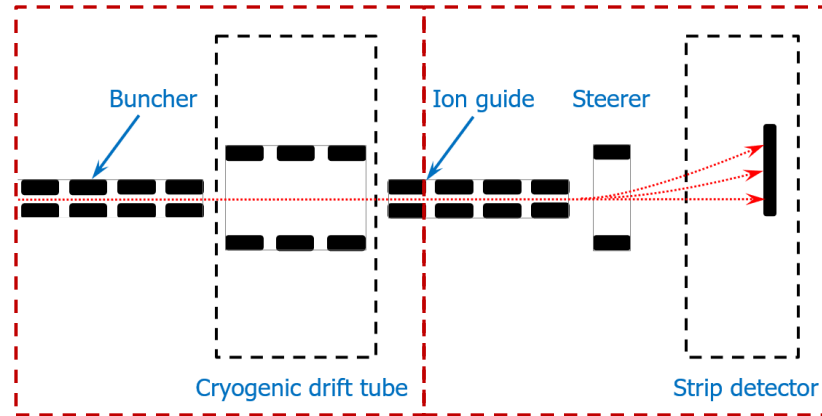


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- Level search in Lr^+ with $<10^6$ atoms in total shall be possible



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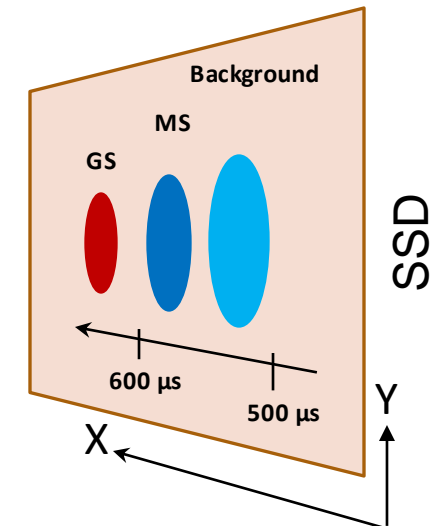


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➤ PhD #1 / T-3.4: Develop radioactive decay-assisted LRC -- (start 10/2025)

➤ PhD #1 / T-3.5: Level search in lawrencium, $^{254,255}\text{Lr}^+$



LRC@S³ roadmap

Postdoc #1:

✓ T-3.1: Optimize LRC efficiency & spectral resolution
(LRC proof of principle on Lu⁺ promising)

(start 03/2025)

✓ T-3.2: LRC on neutron deficient actinium, ²⁰⁸⁻²¹¹Ac⁺

(start ≈ 03/2026)

PhD #1:

✓ T-3.4: Develop radioactive decay-assisted LRC

(start 10/2025)

✓ T-3.5: Level search in lawrencium, ^{254,255}Lr⁺

(Predicted electronic structure and transport properties of Lr⁺ promising)