

GANIL SCIENTIFIC COUNCIL 2025

FEBRUARY 4TH, 2025

Laser Resonance Chromatography @ GANIL

*M. Laatiaoui (GANIL)
on behalf of the LRC project & collaboration*

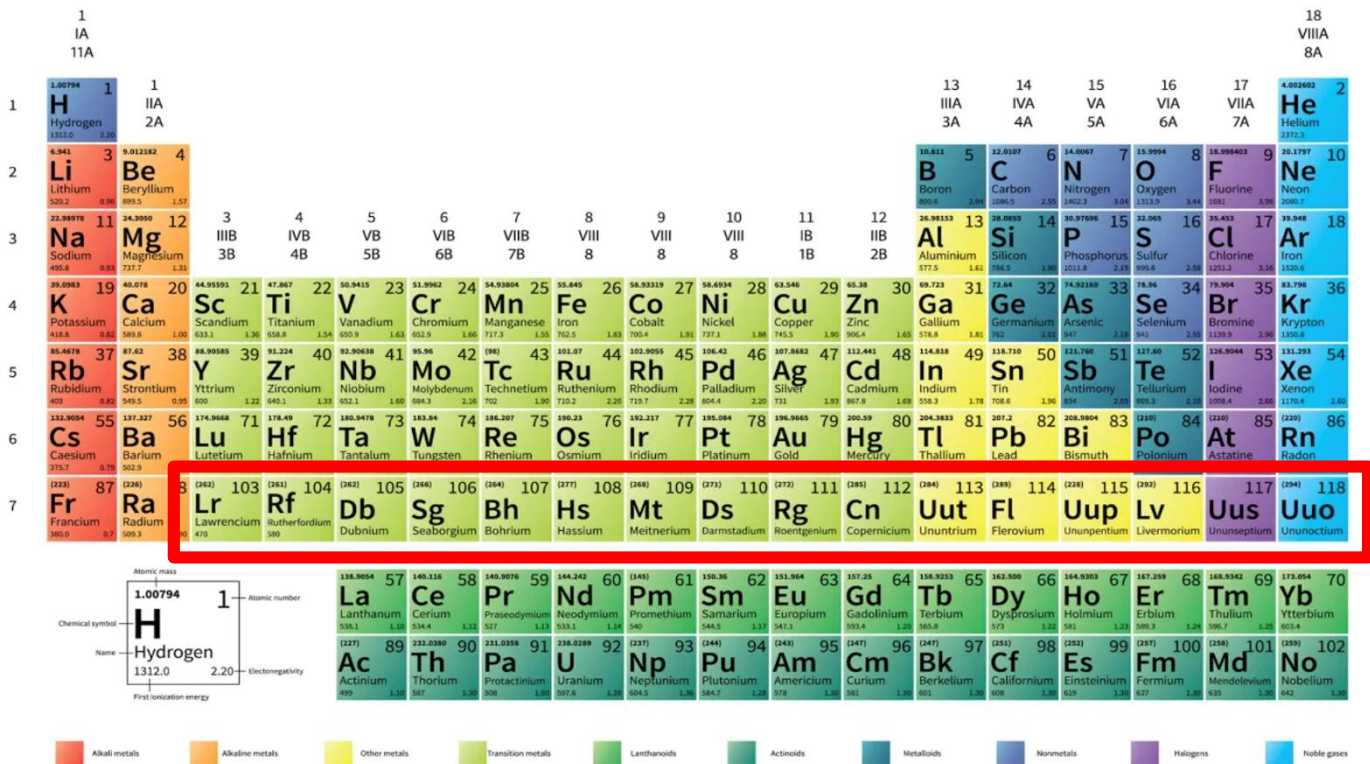


The LRC project has received funding for the period 2019-2024 from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 819957)

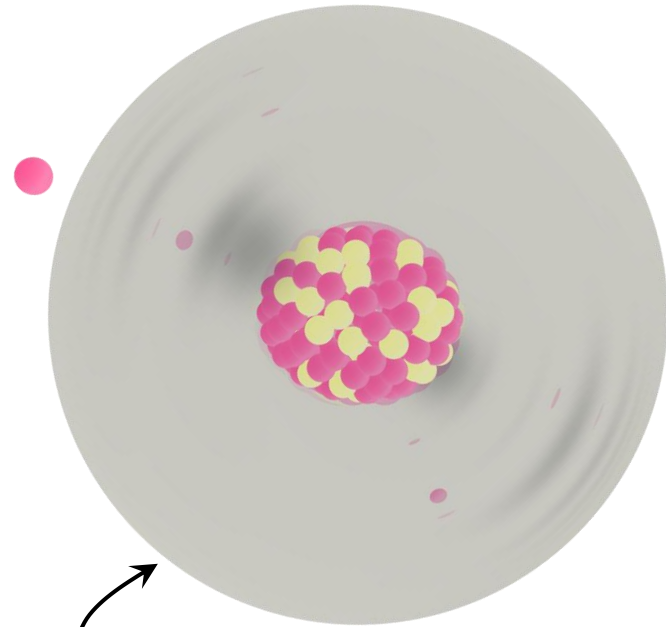
Outline

- Motivation
- Objectives
- Laser Resonance Chromatography (LRC)
 - The LRC technique
 - Proof-of-principle results
- Towards LRC on actinium & lawrencium
- Start-up phase program

Motivation



^{255}Lr



^{209}Bi



^{48}Ca



Which radionuclides can exist?

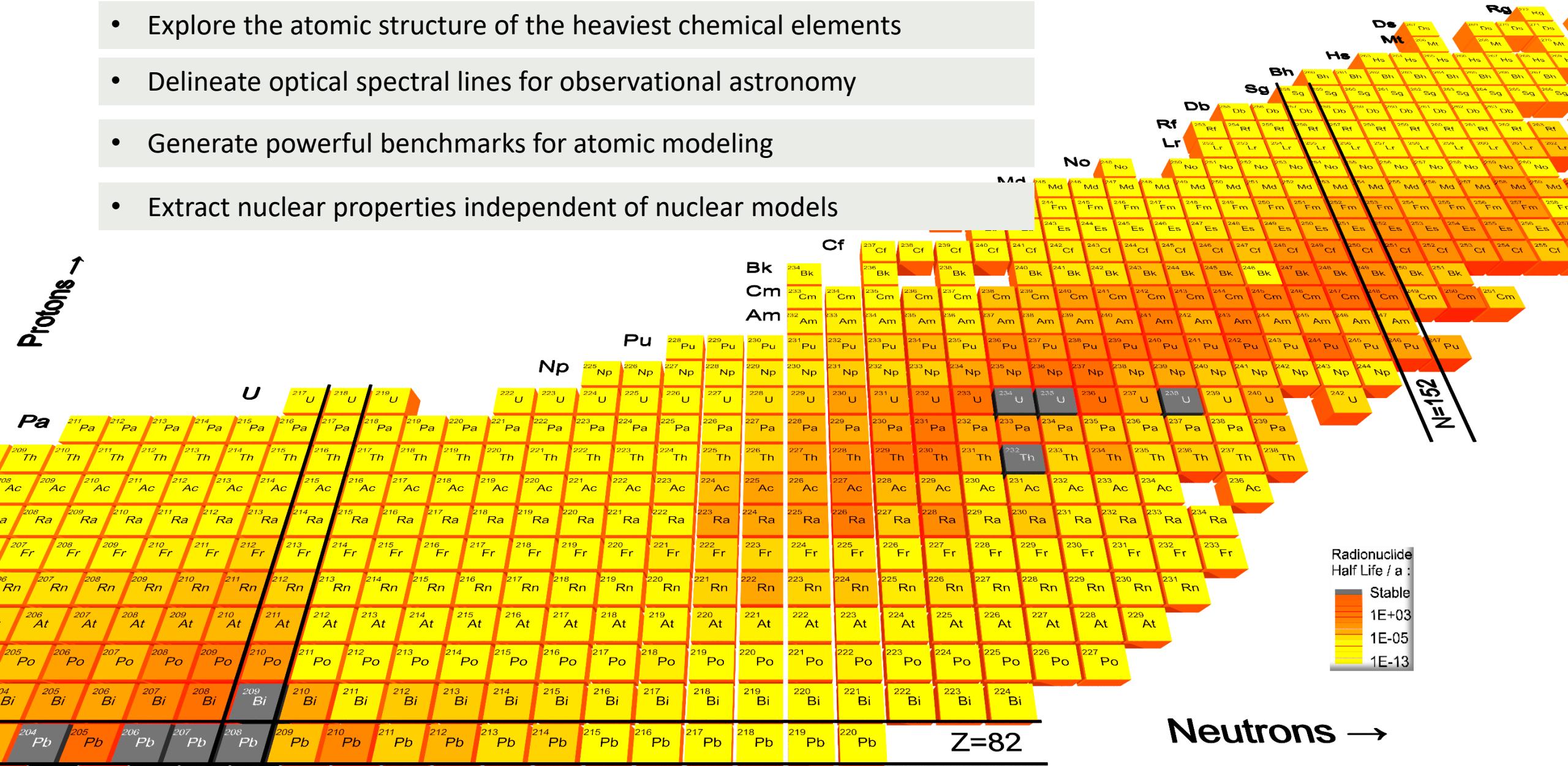
What chemical, atomic & nuclear properties do they have?

How robust is our understanding of atomic & nuclear structure?

Are these radionuclides being produced in the universe?

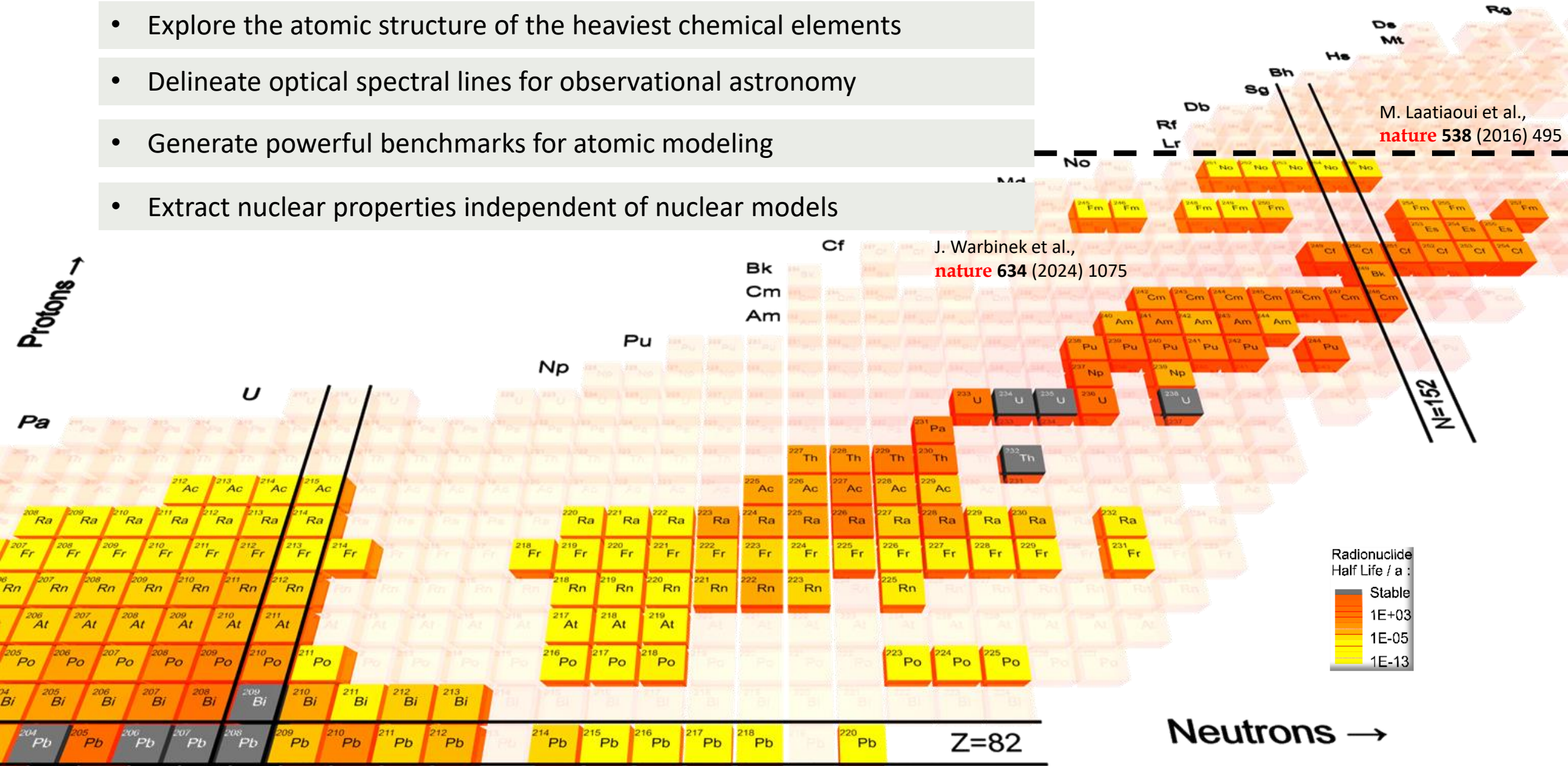
Main objectives

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



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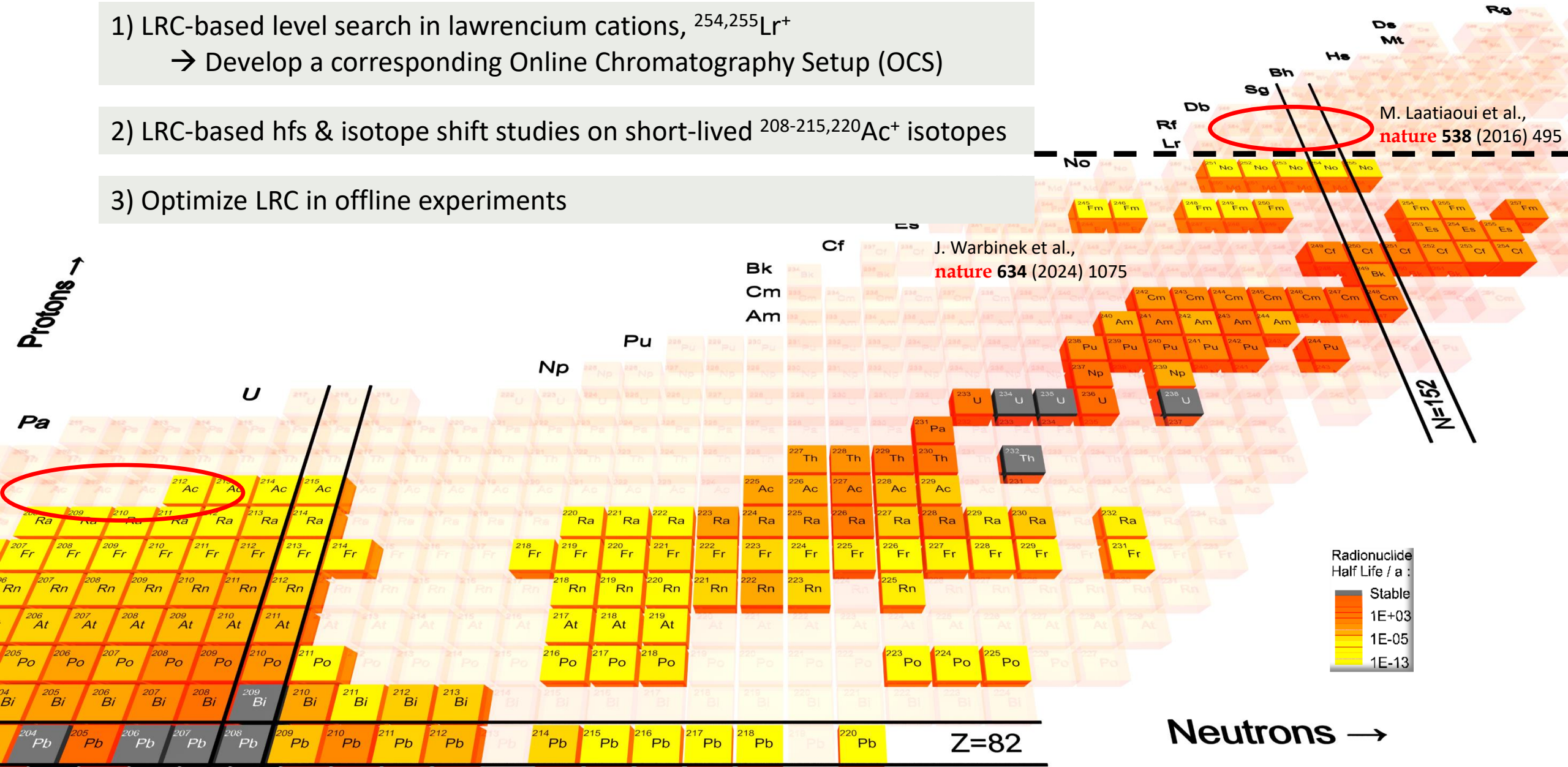


More specific

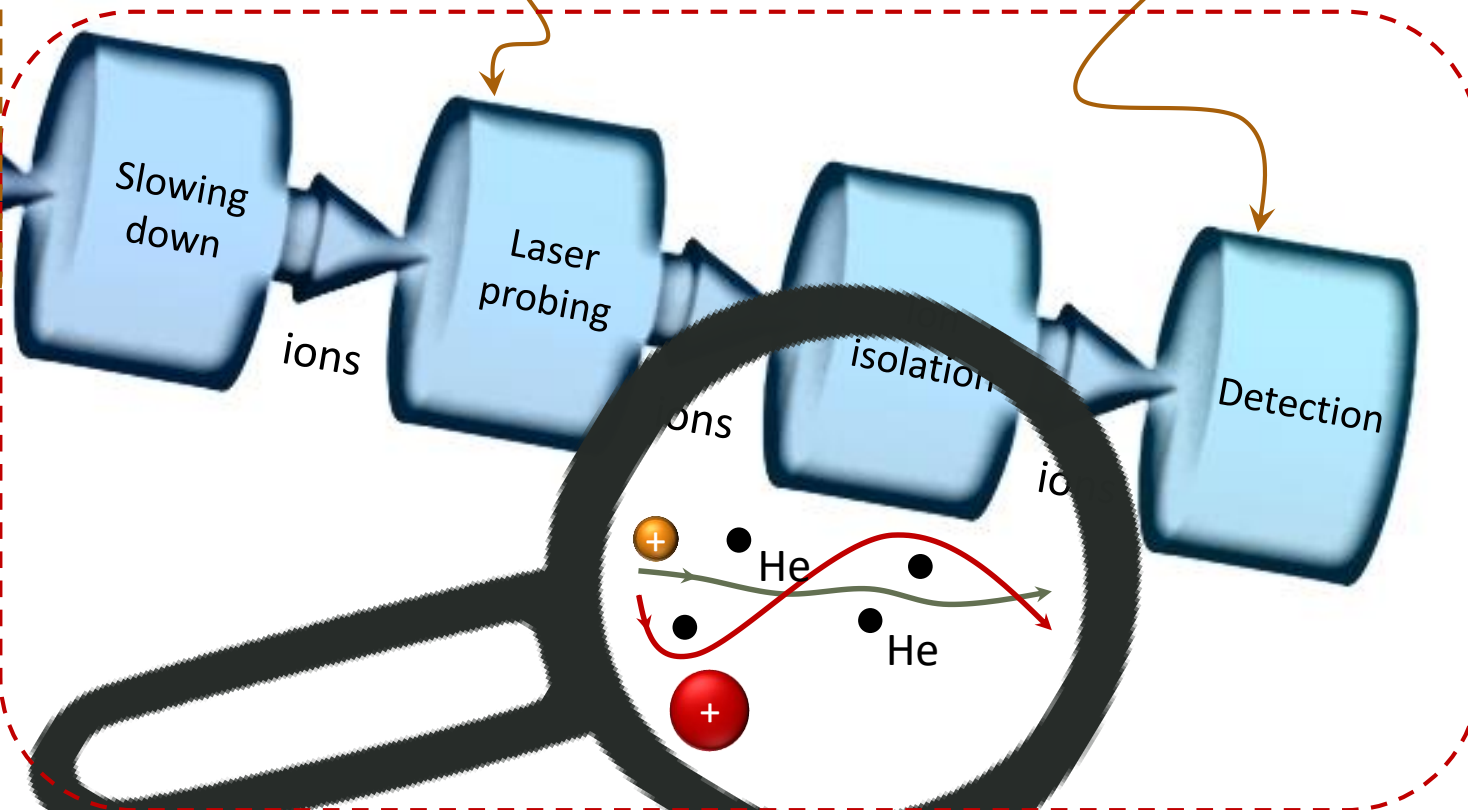
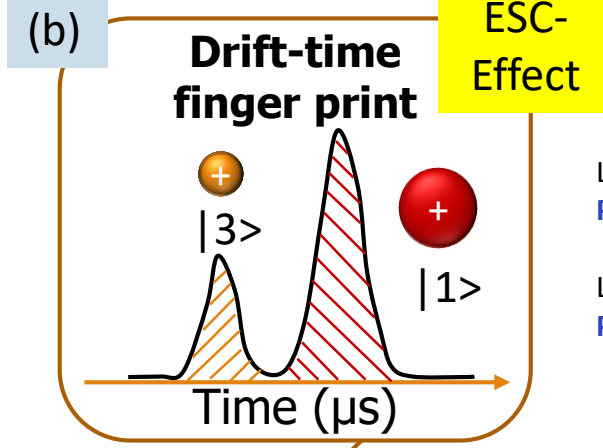
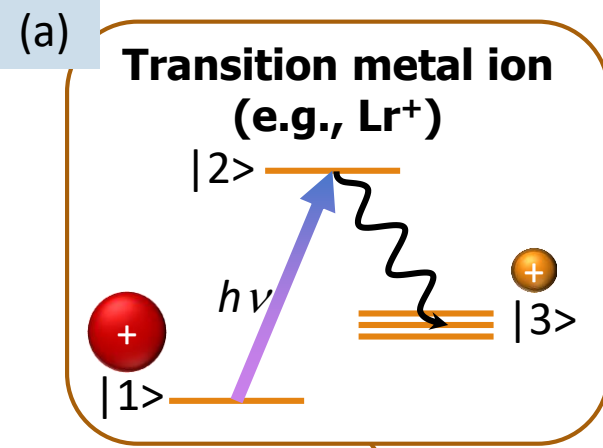
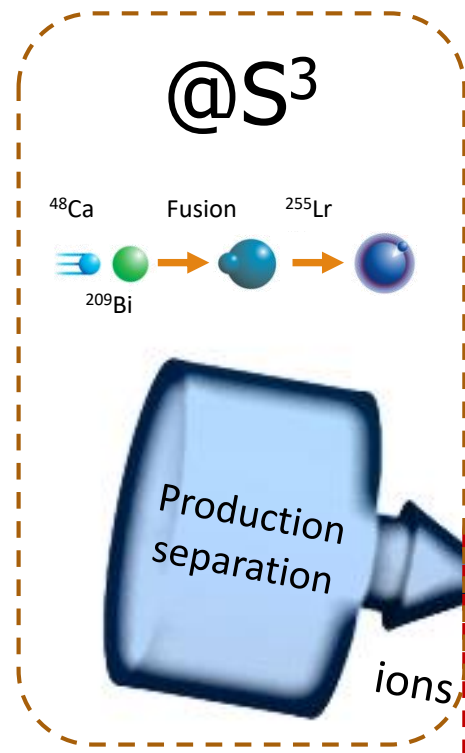
1) LRC-based level search in lawrencium cations, $^{254,255}\text{Lr}^+$
→ Develop a corresponding Online Chromatography Setup (OCS)

2) LRC-based hfs & isotope shift studies on short-lived $^{208-215,220}\text{Ac}^+$ isotopes

3) Optimize LRC in offline experiments



Laser Resonance Chromatography (LRC)



(a) Optical pumping

(b) Drift time monitoring for resonance identification

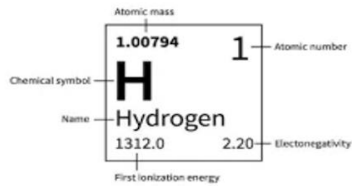


Laatiaoui *et al.*,
PRL 125 (2020) 023002

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

Accessible elements

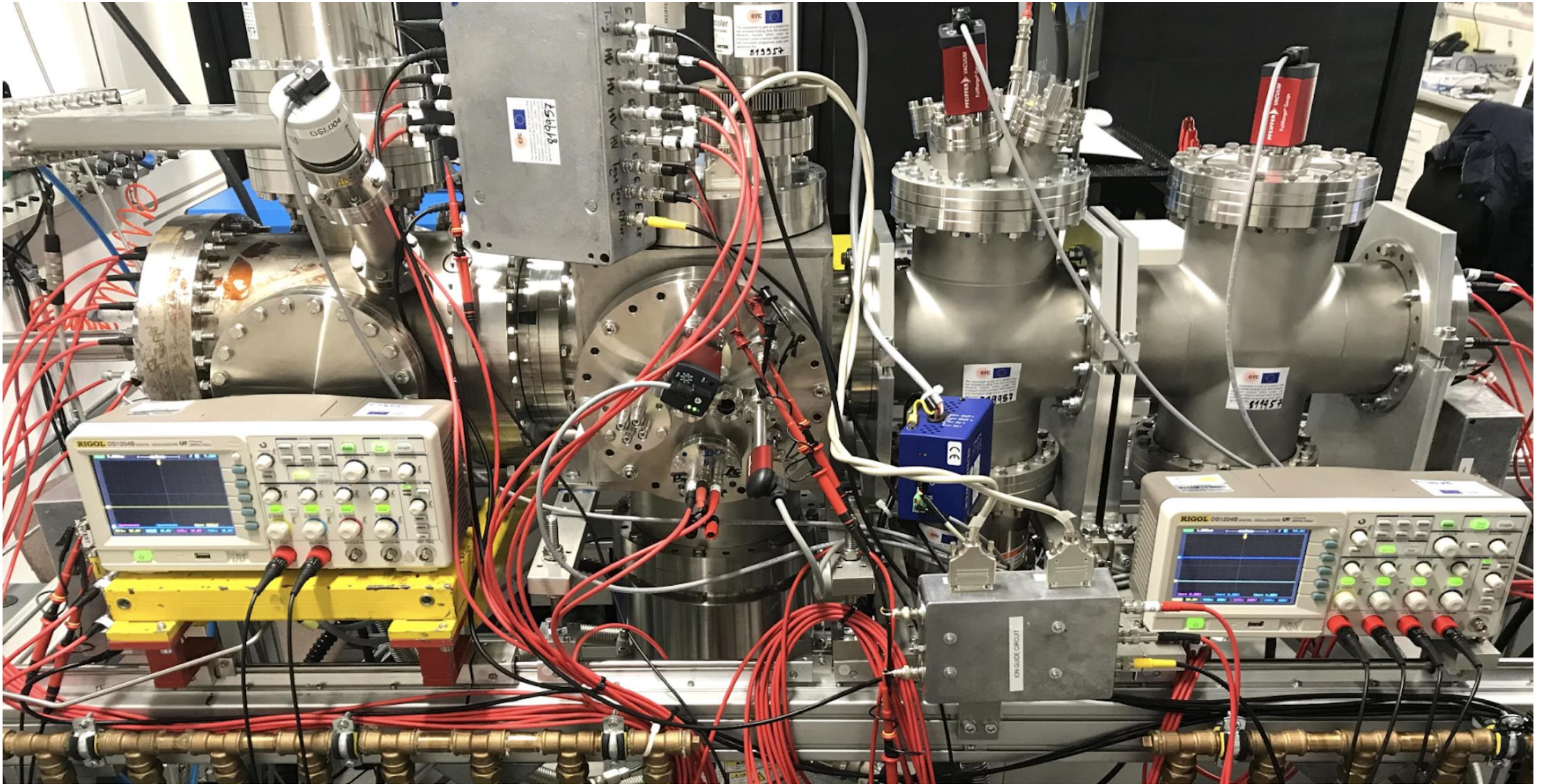
1 IA 11A																	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1	H 1 Hydrogen 1.00794 1.012 2.20											He 2 Helium 4.002602 2372.3										
2	Li 3 Lithium 6.941 320.3 0.98	Be 4 Beryllium 9.012182 899.5 1.57											B 5 Boron 10.811 1080.6 2.04	C 6 Carbon 12.0107 1200.5 2.35	N 7 Nitrogen 14.0067 1402.3 3.04	O 8 Oxygen 15.9994 1599.9 3.44	F 9 Fluorine 18.998403 1882 3.98	Ne 10 Neon 20.1797 2000.7				
3	Na 11 Sodium 22.98976 498.8 0.93	Mg 12 Magnesium 24.3050 731.7 1.31	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	8 VIII 8	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	Al 13 Aluminium 26.98153 577.5 1.61	Si 14 Silicon 28.0855 786.5 1.90	P 15 Phosphorus 30.97306 3091.4 2.19	S 16 Sulfur 32.065 399.5 2.58	Cl 17 Chlorine 35.453 3545.3 3.16	Ar 18 Argon 39.948 3520.6		
4	K 19 Potassium 39.0983 418.8 0.82	Ca 20 Calcium 40.078 589.8 1.00	Sc 21 Scandium 44.95591 633.1 1.36	Ti 22 Titanium 47.867 658.8 1.54	V 23 Vanadium 50.9415 650.9 1.63	Cr 24 Chromium 51.9962 652.9 1.66	Mn 25 Manganese 54.93804 717.3 1.55	Fe 26 Iron 55.845 762.5 1.83	Co 27 Cobalt 58.93319 700.4 1.91	Ni 28 Nickel 58.6934 737.1 1.88	Cu 29 Copper 63.546 745.5 1.90	Zn 30 Zinc 65.38 906.4 1.49	Ga 31 Gallium 69.723 978.8 1.81	Ge 32 Germanium 72.64 762 2.05	As 33 Arsenic 74.92160 967 2.18	Se 34 Selenium 78.96 941 2.55	Br 35 Bromine 79.904 1329.8 2.96	Kr 36 Krypton 83.798 1996.8				
5	Rb 37 Rubidium 85.4678 403 0.82	Sr 38 Strontium 87.62 549.5 0.95	Y 39 Yttrium 88.90585 640.1 1.33	Zr 40 Zirconium 91.224 640.1 1.33	Nb 41 Niobium 92.90638 652.1 1.60	Mo 42 Molybdenum 95.96 684.3 2.16	(98)	Tc 43 Technetium 101.07 702 1.90	Ru 44 Ruthenium 102.9055 710.2 2.20	Rh 45 Rhodium 106.42 719.7 2.28	Pd 46 Palladium 107.8682 804.4 2.20	Ag 47 Silver 107.8682 731 1.93	Cd 48 Cadmium 112.411 907.8 1.49	In 49 Indium 114.818 558.3 1.78	Sn 50 Tin 118.710 708.6 1.96	Sb 51 Antimony 121.760 584 2.05	Te 52 Tellurium 127.60 908.3 2.55	I 53 Iodine 126.9044 1008.4 2.66	Xe 54 Xenon 131.293 1170.4 2.60			
6	Cs 55 Caesium 132.9054 375.7 0.79	Ba 56 Barium 137.327 502.9 0.89	Lu 71 Lutetium 174.9668 589.5 1.30	Hf 72 Hafnium 178.49 589.5 1.30	Ta 73 Tantalum 180.9478 761 1.50	W 74 Tungsten 183.84 770 2.36	Re 75 Rhenium 186.207 770 1.90	Os 76 Osmium 190.23 840.0 2.20	Ir 77 Iridium 192.227 890 2.20	Pt 78 Platinum 195.084 870 2.28	Au 79 Gold 196.9665 890.3 2.54	Hg 80 Mercury 200.59 1007.1 2.00	Tl 81 Thallium 204.3833 589.4 1.82	Pb 82 Lead 207.2 703 2.33	Bi 83 Bismuth 208.9804 703 2.02	Po 84 Polonium (209)	At 85 Astatine (210)	Rn 86 Radon (210)				
7	Fr 87 Francium (223)	Ra 88 Radium (226)	Lr 103 Lawrencium (262)	Rf 104 Rutherfordium (261)	Db 105 Dubnium (262)	Sg 106 Seaborgium (264)	Bh 107 Bohrium (264)	Hs 108 Hassium (277)	Mt 109 Meitnerium (268)	Ds 110 Darmstadtium (271)	Rg 111 Roentgenium (272)	Cn 112 Copernicium (285)	Uut 113 Ununtrium (284)	Fl 114 Flerovium (289)	Uup 115 Ununpentium (288)	Lv 116 Livermorium (292)	Uus 117 Ununseptium (292)	Uuo 118 Ununoctium (294)				



138.9054 57 La Lanthanum 538.1 1.10	140.116 58 Ce Cerium 534.4 1.13	140.9076 59 Pr Praseodymium 527 1.13	144.242 60 Nd Neodymium 589 1.14	(145)	150.36 62 Sm Samarium 544.5 1.17	151.964 63 Eu Europium 547.3 1.20	157.25 64 Gd Gadolinium 593.8 1.24	158.9253 65 Tb Terbium 589.8 1.25	162.500 66 Dy Dysprosium 573 1.25	164.9303 67 Ho Holmium 589.1 1.25	167.259 68 Er Erbium 589.3 1.24	168.9342 69 Tm Thulium 589.7 1.25	173.054 70 Yb Ytterbium 603.4				
(227)	231.036 90 Th Thorium 589 1.30	231.036 91 Pa Protactinium 500 1.30	238.0289 92 U Uranium 507.6 1.30	(237)	244 94 Pu Plutonium 584.7 1.28	(243)	247 95 Am Americium 579 1.30	(247)	247 96 Cm Curium 601 1.30	(247)	251 98 Cf Californium 600 1.30	(252)	257 99 Es Einsteinium 627 1.30	(258)	101 Md Mendelevium 635 1.30	(259)	102 No Nobelium 624 1.30

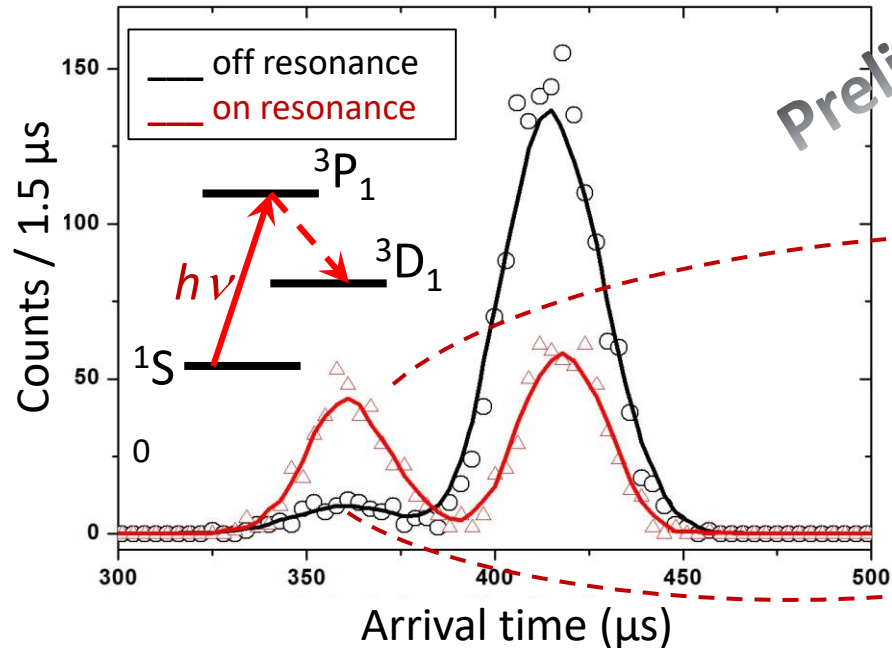
- Alkali metals
- Alkaline metals
- Other metals
- Transition metals
- Lanthanoids
- Actinoids
- Metalloids
- Nonmetals
- Halogens
- Noble gases

LRC offline setup

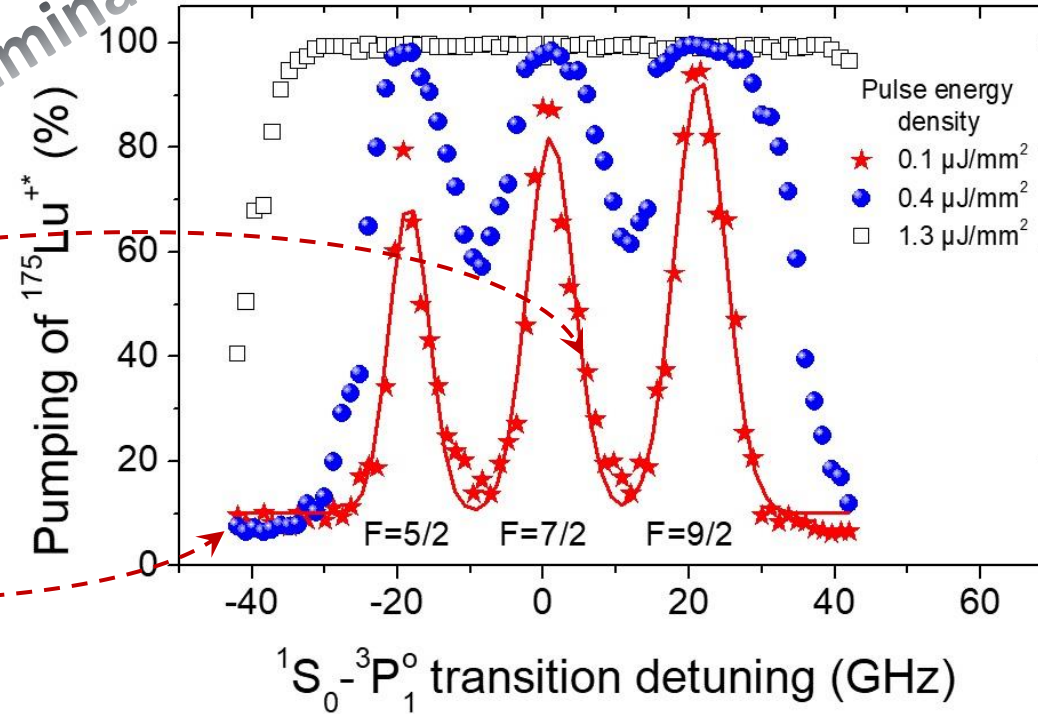


Proof of principle for ^{175}Lu

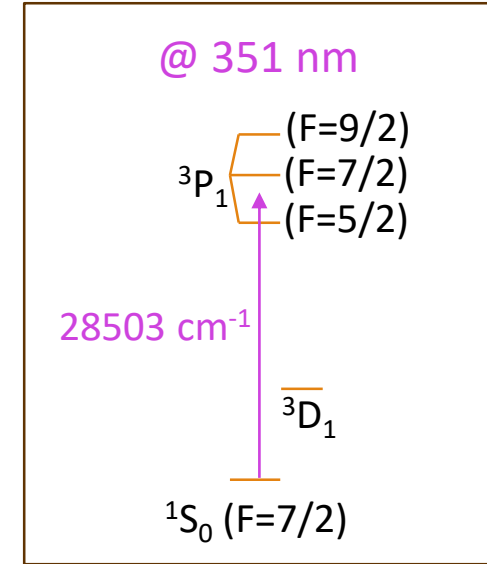
137.327 Ba Barium 502.9	56	174.9668 Lu Lutetium 523.5	71	178.49 Hf Hafnium 658.5	72
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Preliminary



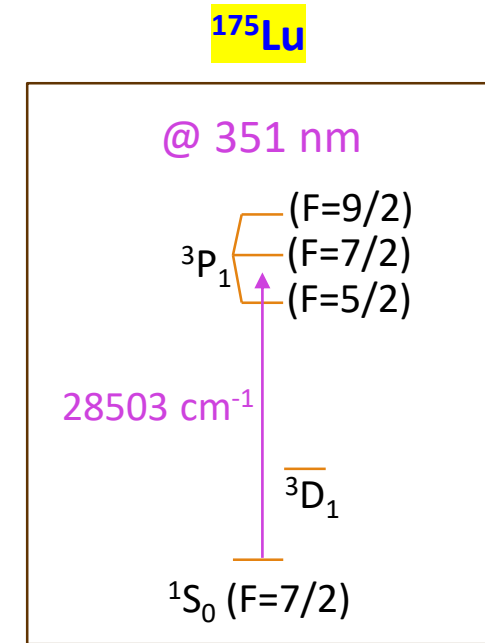
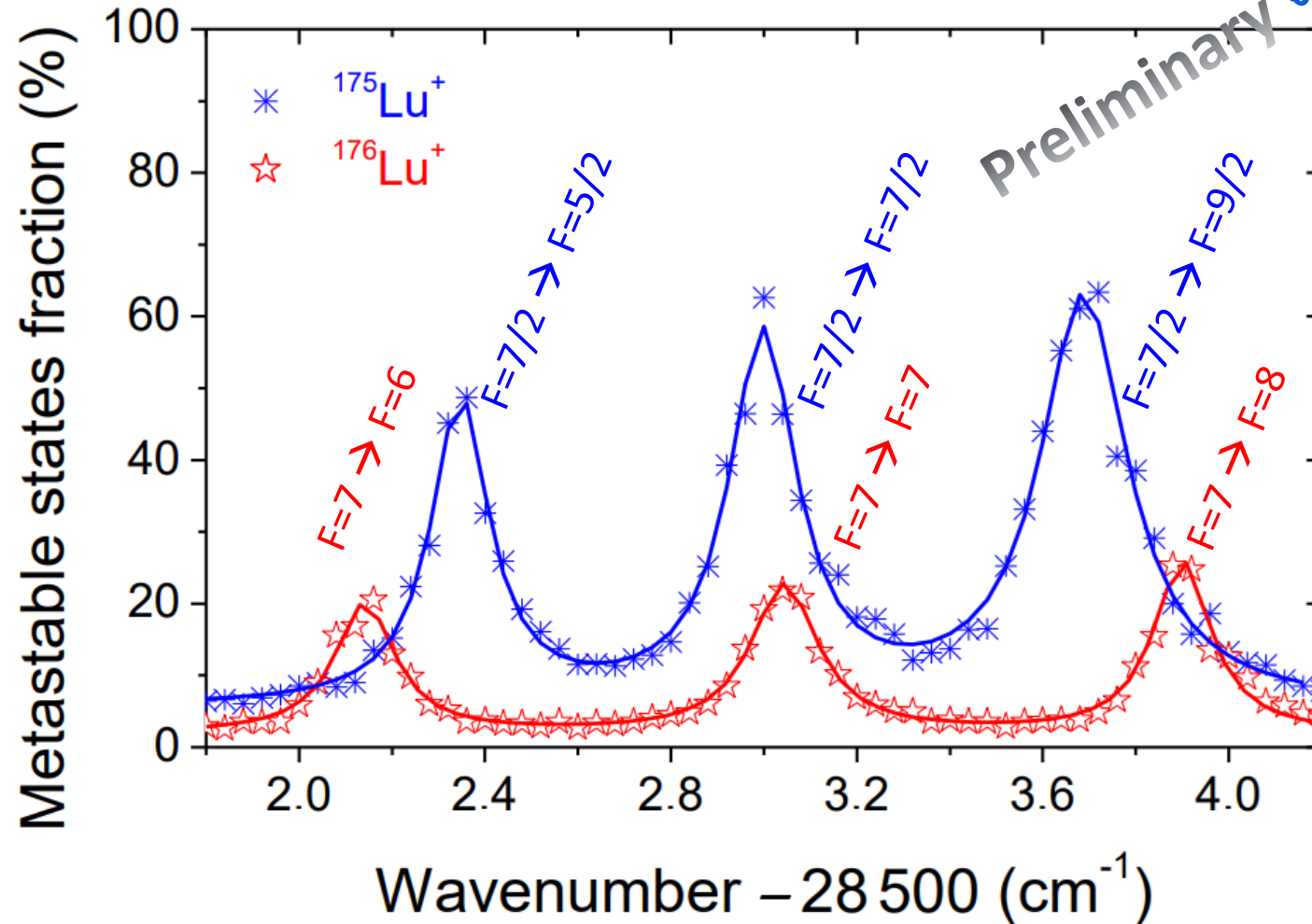
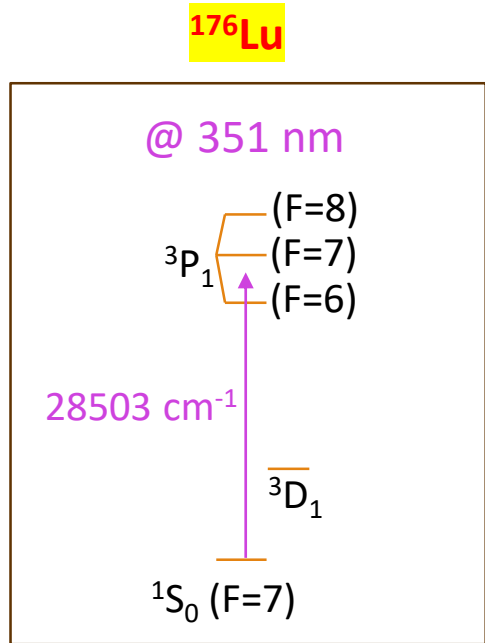
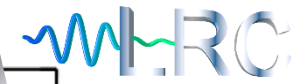
^{175}Lu



- Hyperfine structure studies possible at low laser power
- Power broadening beneficial for faster level search
- Measured overall-efficiency for ion transport: 0.6%

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
 Romero-Romero et al., *Atoms* **10** (2022) 87
 Ramanantoanina et al., *PRA* **108** (2023) 012802
 Visentin et al., *PRA* **110** (2024) 012805
 Kim et al., *NIMB* **555** (2024) 165461

HFS & isotope shift studies



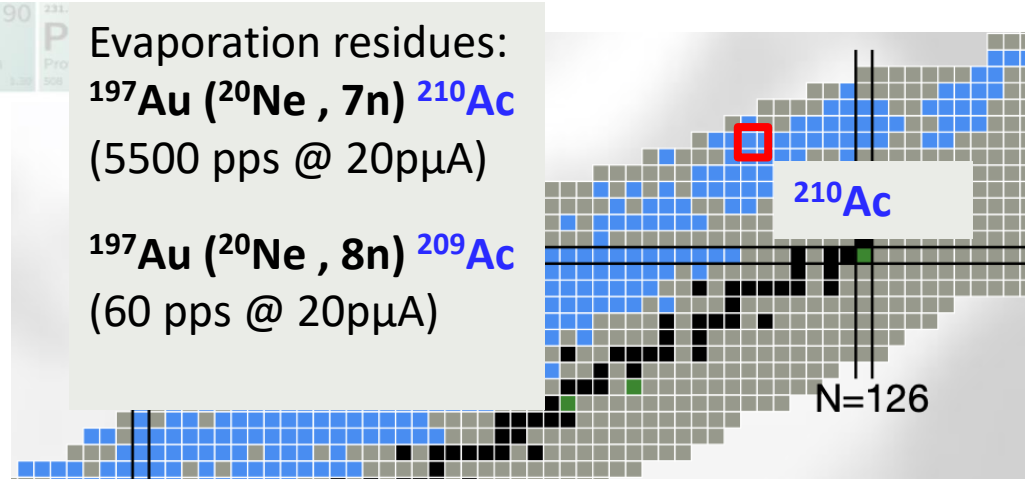
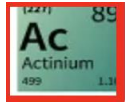
Aayush Arya,
Master thesis,
JGU Mainz,
September 2024

Species	A [MHz]		B [MHz]	
	this work	literature	this work	literature
¹⁷⁵ Lu	+4,952 ± 16	+4,964 ± 9 ^a	-1,962 ± 94	-1,871 ± 30 ^a
¹⁷⁶ Lu	+3,494 ± 8	3,502.6838 ± 0.0017 ^b	-2,604 ± 115	-2,602.291 ± 0.024 ^b

^a: Hartog D. *et al.*,
AJSS **248** (2020) 10

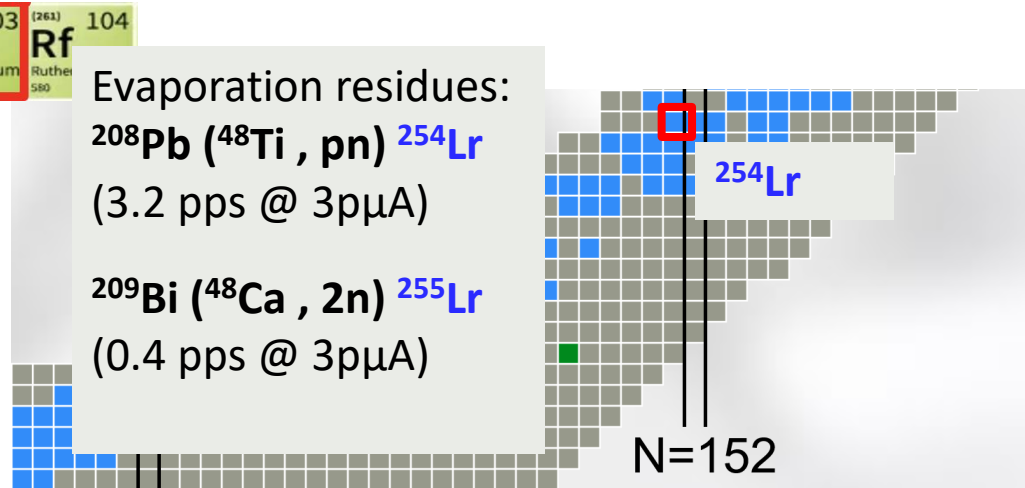
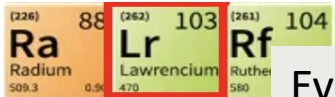
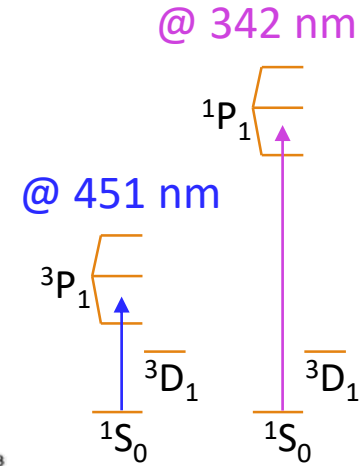
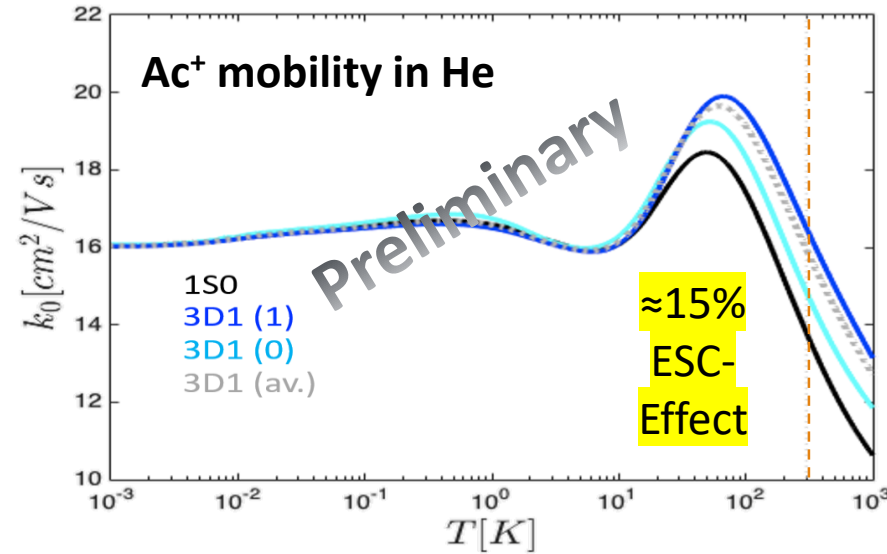
^b: Kaewuam R. *et al.*,
JMO **65** (2018) 592

LRC on Ac^+ and Lr^+

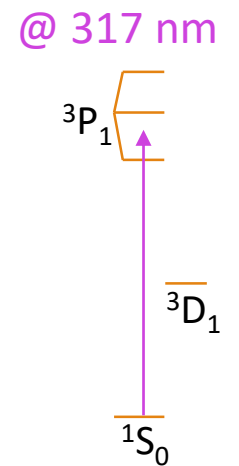
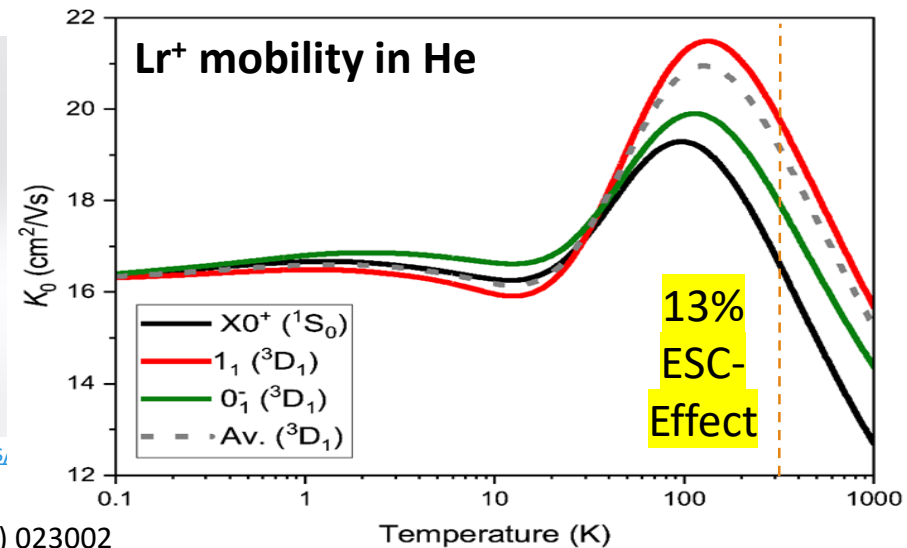


<https://u.ganil-spiral2.eu/chartbeams/>

Courtesy H. Ramanantoanina



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



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

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

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

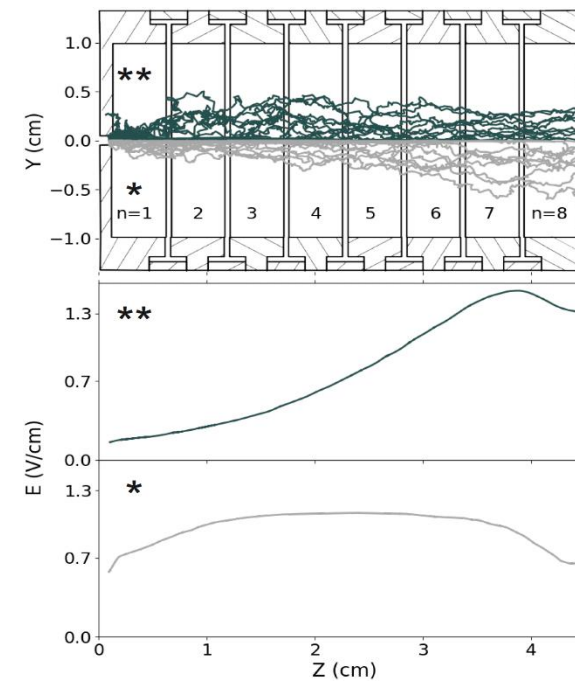
Ramanantoanina et al., *PRA* **108** (2023) 012802

Start-up phase @GANIL

Enhancing the efficiency

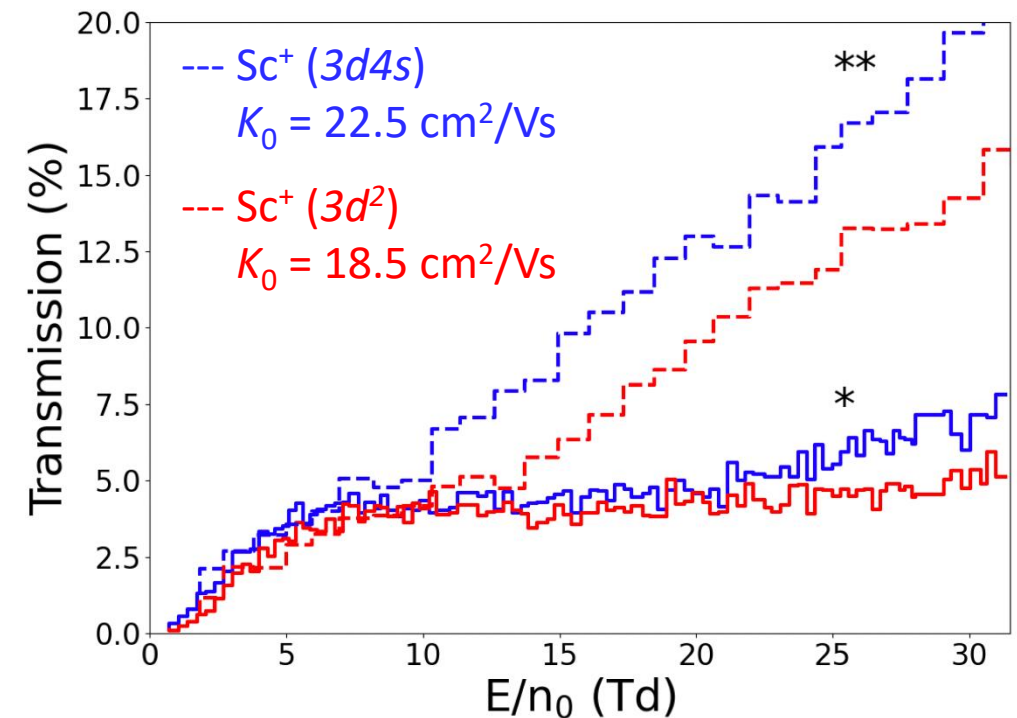
- Optimization of the drift field & pressure
 - while preventing electric discharge
 - & suppressing collisional quenching

- Exploiting synergies with GISELE/FRIENDS3 (Hall D)



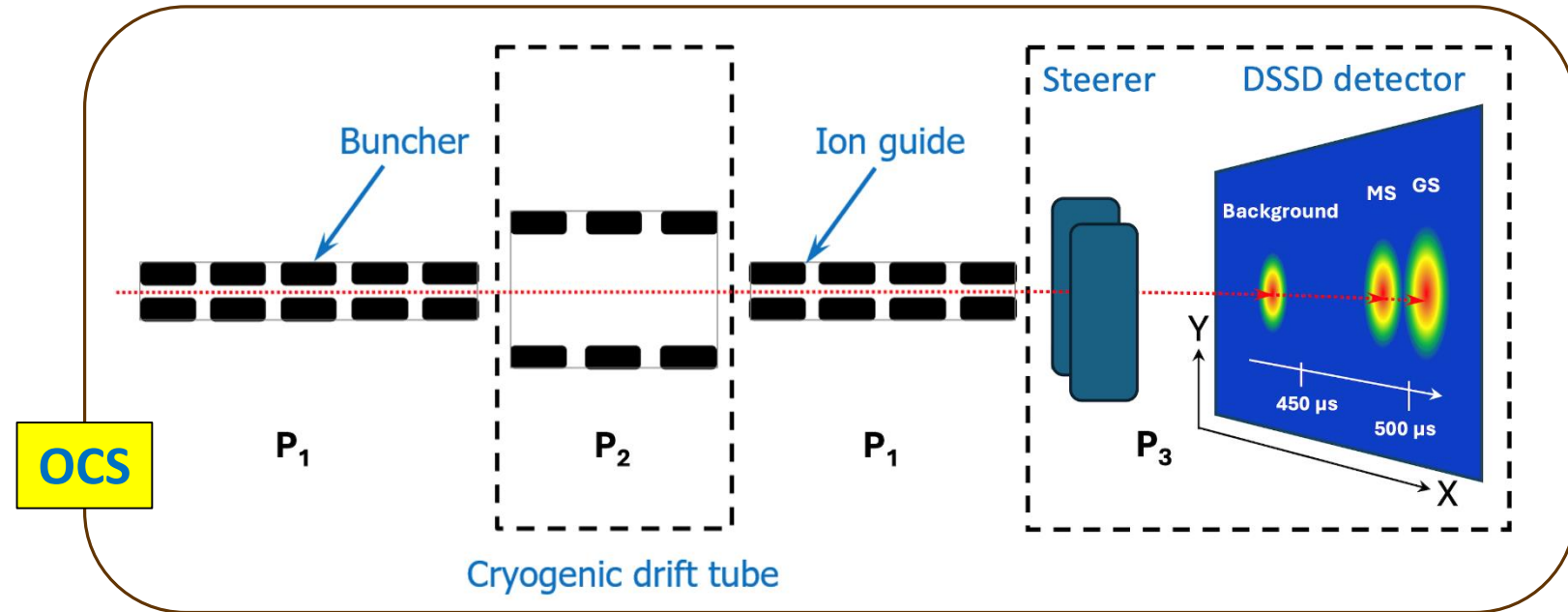
SIMION simulations
(SDS model) for
Sc⁺ drifting in He

Romero-Romero *et al.*,
Atoms **10** (2022) 87



Enhancing the sensitivity

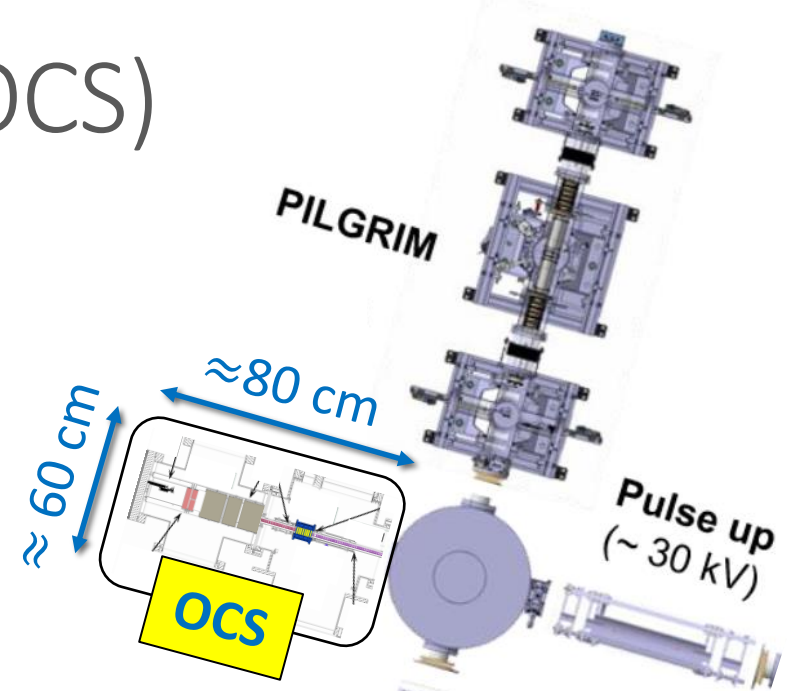
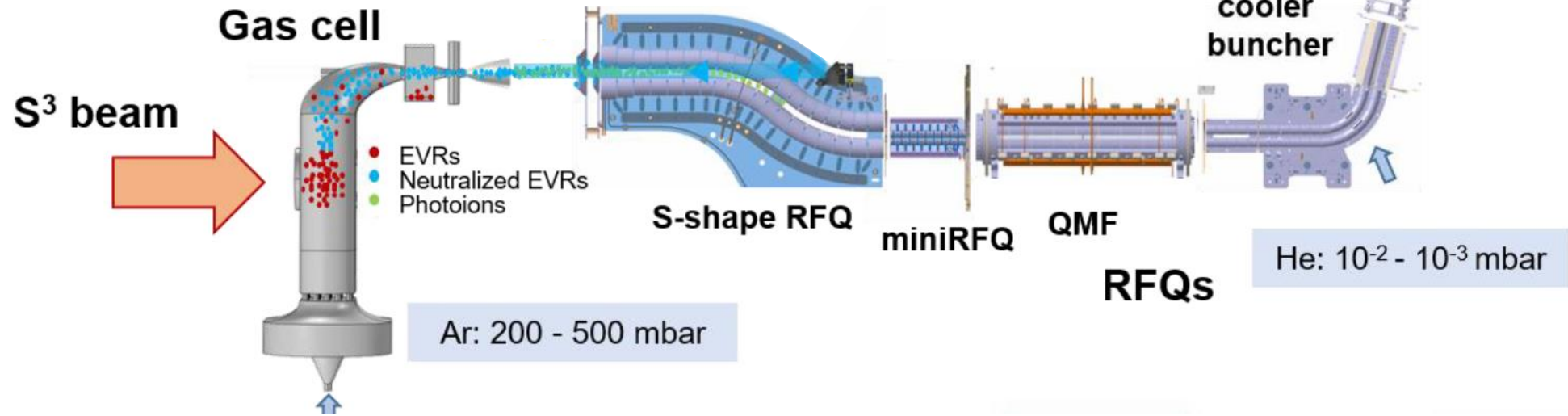
- Development of an Online Chromatography Setup (OCS)



- Increased sensitivity by registering alpha decay events
 - Deflection of ions at the right moment
 - Centroids of radioactivity hotspots correspond to distinct arrival times
- Bulky molecules are slow-moving, thus easy to discriminate
 - No mass filter required for alpha emitters

Online Chromatography Setup (OCS)

- First phase: Integration behind Q-deflector @ S3-LEB
- Compact setup (≈ 80 cm length)
- Inauguration in parasitic mode ($^{214}\text{Ac}^+$)



Start-up phase program (overview)

- Work packages (2025-2028):
 - (WP1): Online experimental program including the development of the OCS
[CaeSAR PhD]

- (WP2): Offline experimental program with the existing LRC setup
[CNRS Postdoc]

- (WP3): Proof-of-concept activities for grant applications
[Prepare funding application for a new stopping cell]
[Prepare funding application for LRC setup @DESIR]

Description	2025												2026												2027												2028																				
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12									
WP1: Online experimental program																																																									
Task-1.1 Simulations, design, & construction	x	x										x	x	x	x	x	x	x	x	x	x	x	x																																		
Task-1.2 Equipment procurement		x	x	x								x	x																																												
Task-1.3 DAQ inauguration																																																									
Task-1.4 Offline calibration/optimization																																																									
Task-1.5 Online inauguration with Ac isotopes (parasitic)																																																									
Task-1.6 Beamtime proposals																																																									
Task-1.7 Level search in lawrencium																																																									
Task-1.8 Online HFS of Lr isotopes																																																									
Task-1.9 Online HFS of Ac isotopes																																																									
WP2: Offline experimental program																																																									
Task-2.1 LRC setup transport and storage																																																									
Task-2.2 Setup installation in HALL D																																																									
Task-2.3 Study transition strengths & quenching effects																																																									
Task-2.4 Enhance ion transmission efficiency																																																									
Task-2.5 Enhance LRC spectral precision																																																									
WP3: Proof-of-concept activities																																																									
Task-3.1 Simulations & design of the cryogenic stopping cell																																																									
Task-3.2 Gas dynamic simulations for the nozzle																																																									
Task-3.3 Ion trajectory simulations for collinear LRC																																																									
Task-3.4 Preparation of grant applications																																																									

Cost category	Total (kEUR)
Online Chromatography Setup (Tab. A.1)	131
Carrying amount for LRC equipment (Tab. A.2)	45
Resumption of LRC operation at GANIL (Tab. A.3)	45
Total costs	221

Duties	FTE
Technical referent for OCS	0.2
Support for the OCS at S ³ -LEB	0.7
Technical referent for the offline setup (coordination)	0.2
Support for the offline setup in Hall D	1.2
Support for the cryogenic buffer-gas stopping cell (design)	0.2
Total	2.5

Distinct ion mobilities (K_0)

