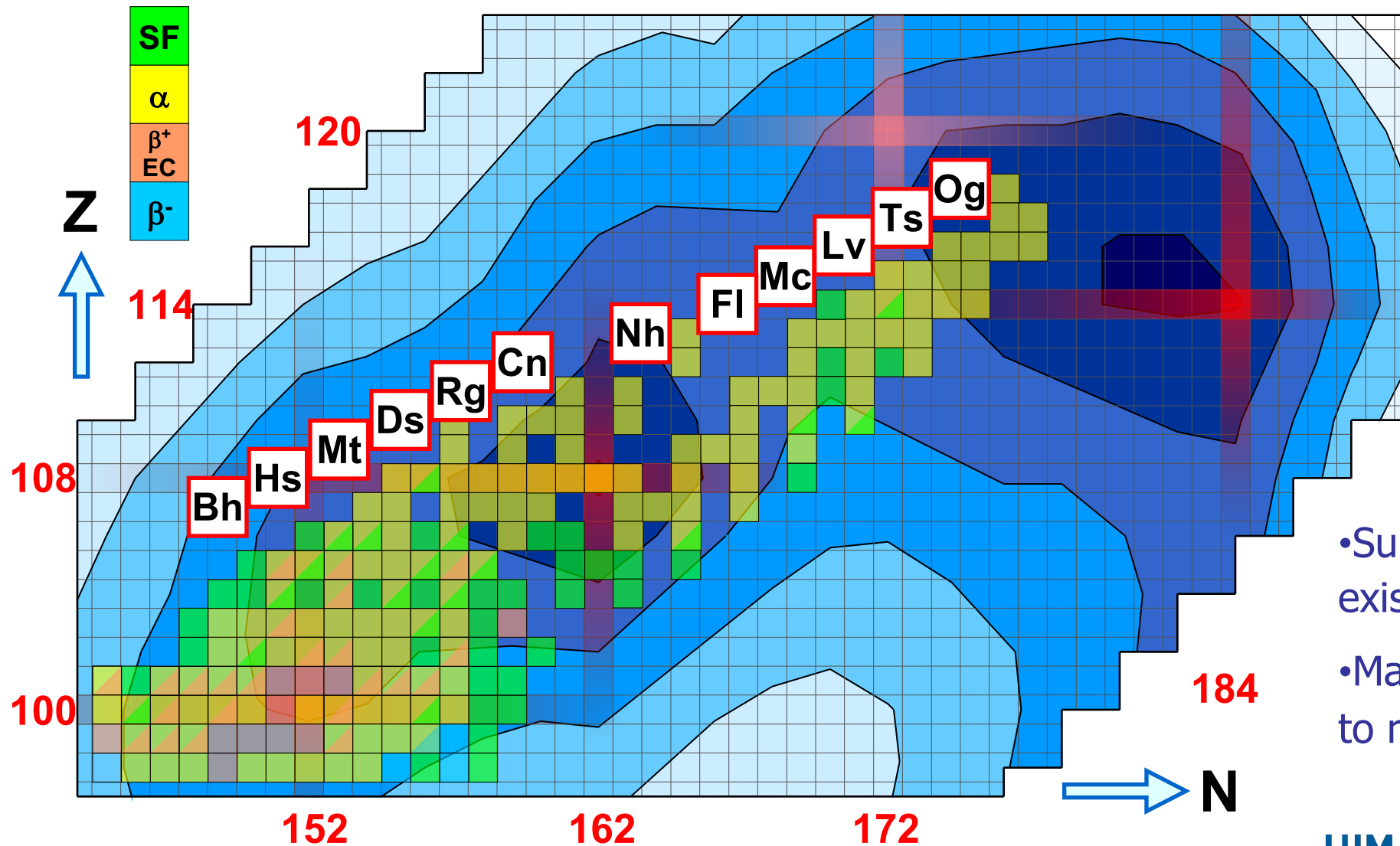


Status and Perspectives for Mass Spectrometry and Laser Spectroscopy of the Heaviest Elements

Michael Block

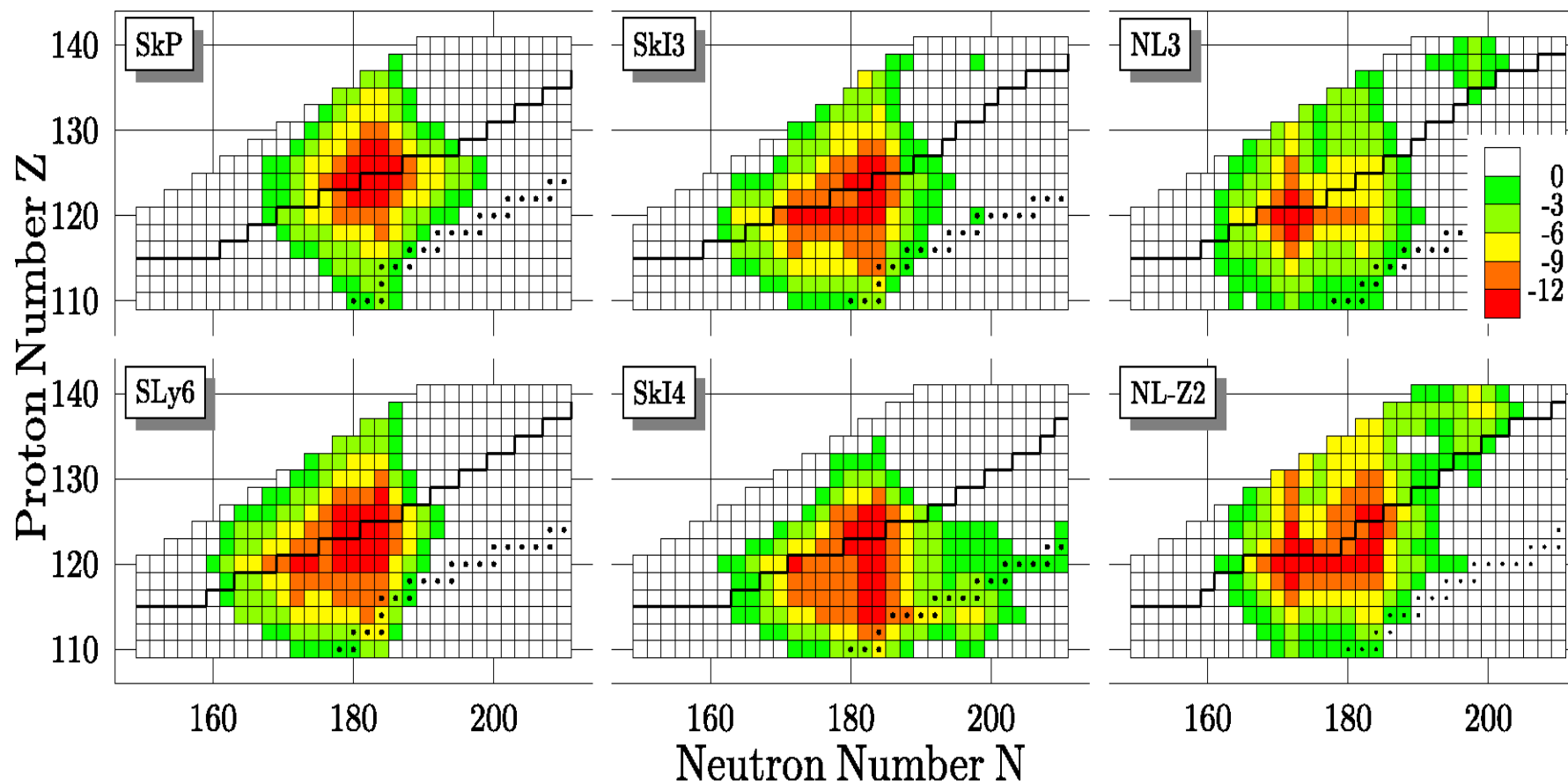
**GSI Darmstadt
Helmholtz-Institut Mainz
Department Chemie, Universität Mainz**

Superheavy Element Landscape

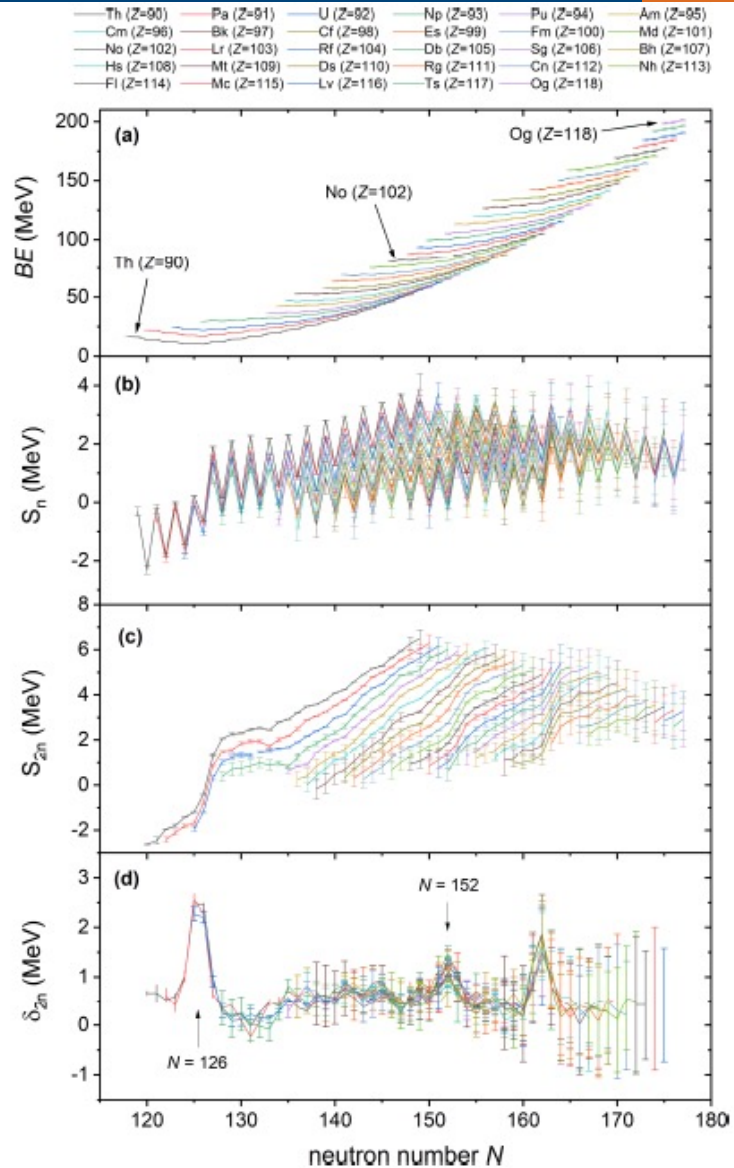


- Superheavy elements owe existence to nuclear shell effects
- Mass measurements give access to nuclear shell structure

Distinct Magic Numbers in SHE?

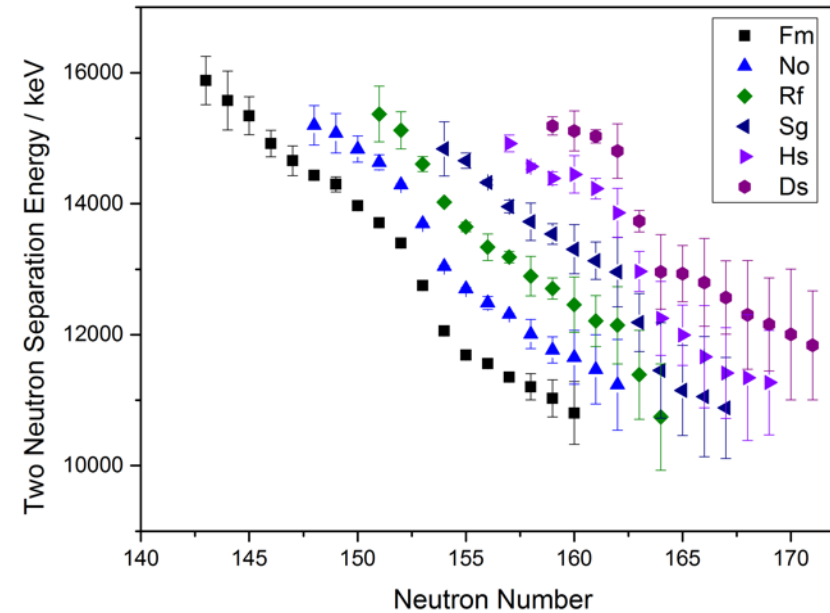
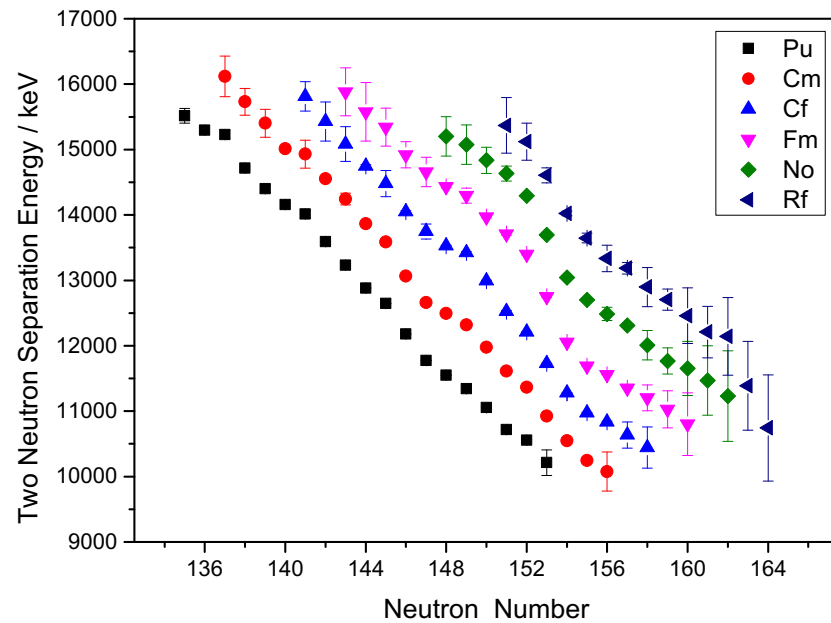


Mass differences reveal nuclear structure



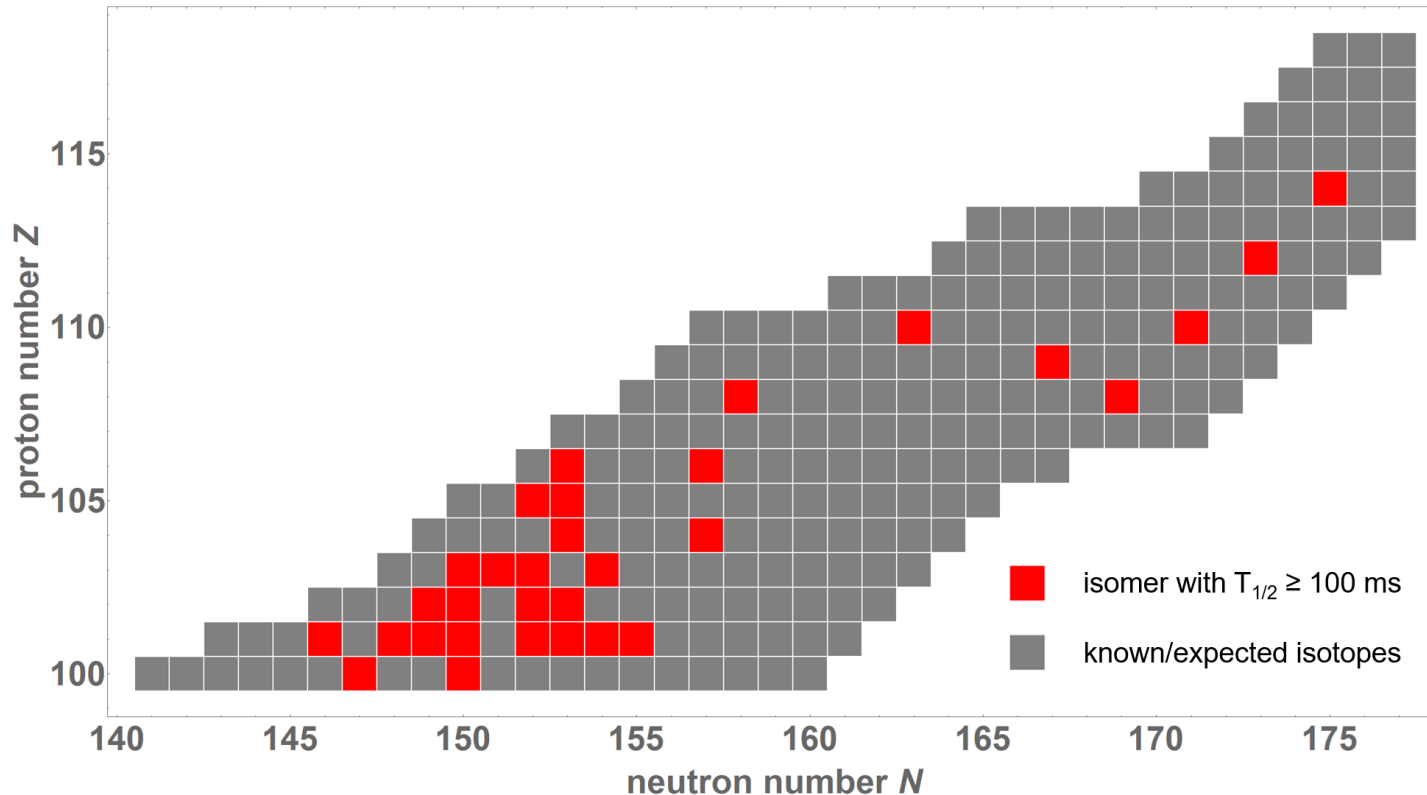
- nuclear mass differences such as one/two-nucleon-separation energies reflect nuclear structure effects
- signatures of shell closures, pairing, and the onset of deformation
- comparison of data to nuclear models provides valuable information

Nuclear Shell effects from Separation Energies



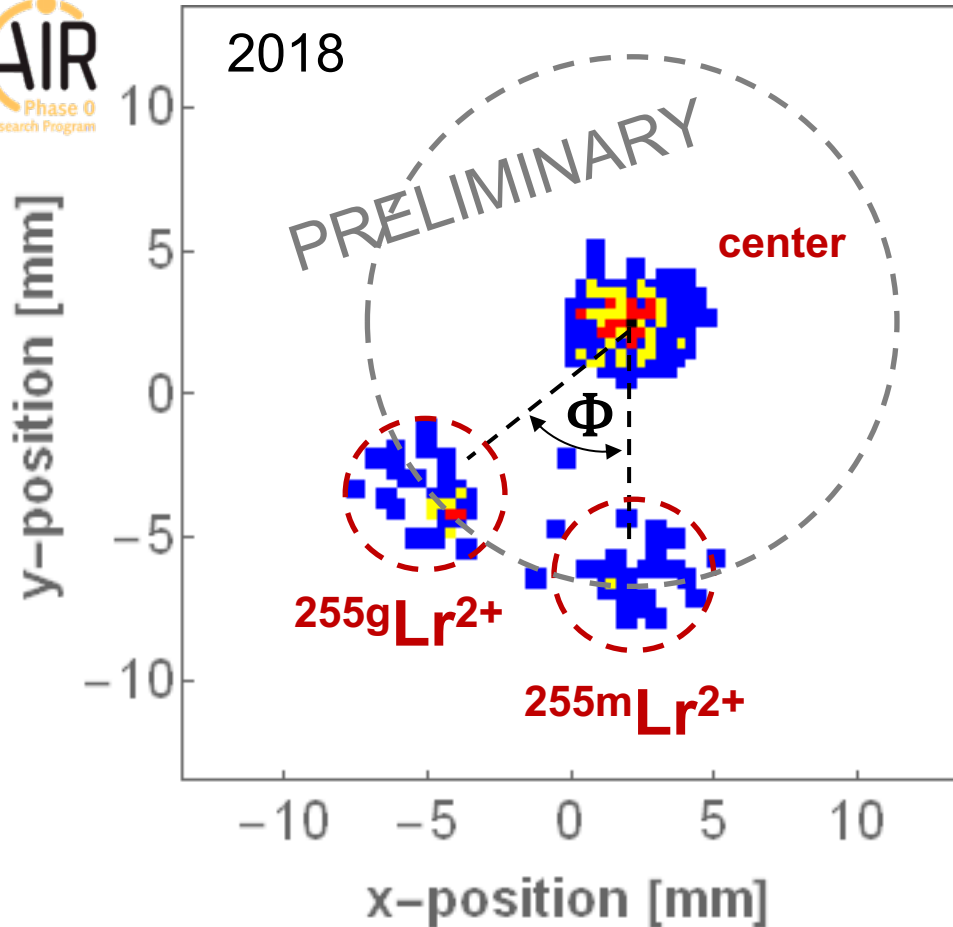
neutron separation energies derived from masses and Q_{α} -values show signatures of nuclear shell effects at $N = 152$ and $N = 162$

Long-Lived Isomers in the Heaviest Elements

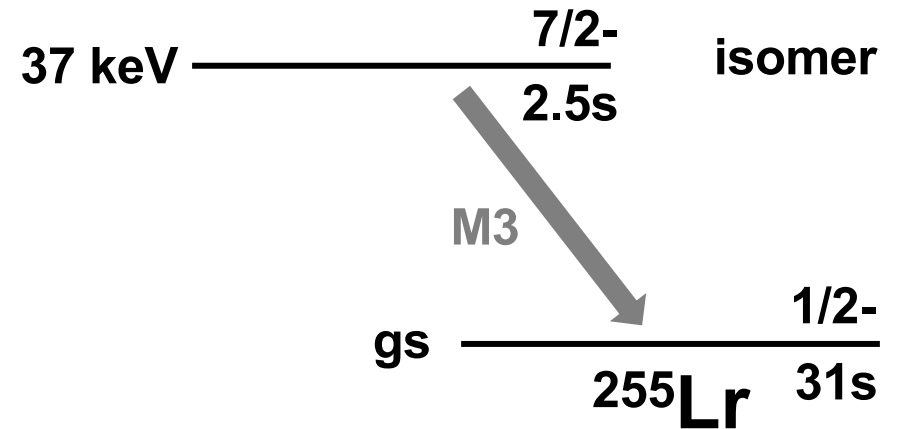


- several (long-lived) isomeric states known, further may exist
- many of these are difficult to observe experimentally
- Penning-trap mass spectrometry well suited to locate low-energy and long-lived isomers
- laser spectroscopy can provide information on isomer's structure

SHIPTRAP Results - Example $^{255(m)}\text{Lr}^{2+}$



- mass resolving power $m/\Delta m \approx 10^7$
- long-lived isomer with $E^* \approx 37$ keV was resolved from ground state



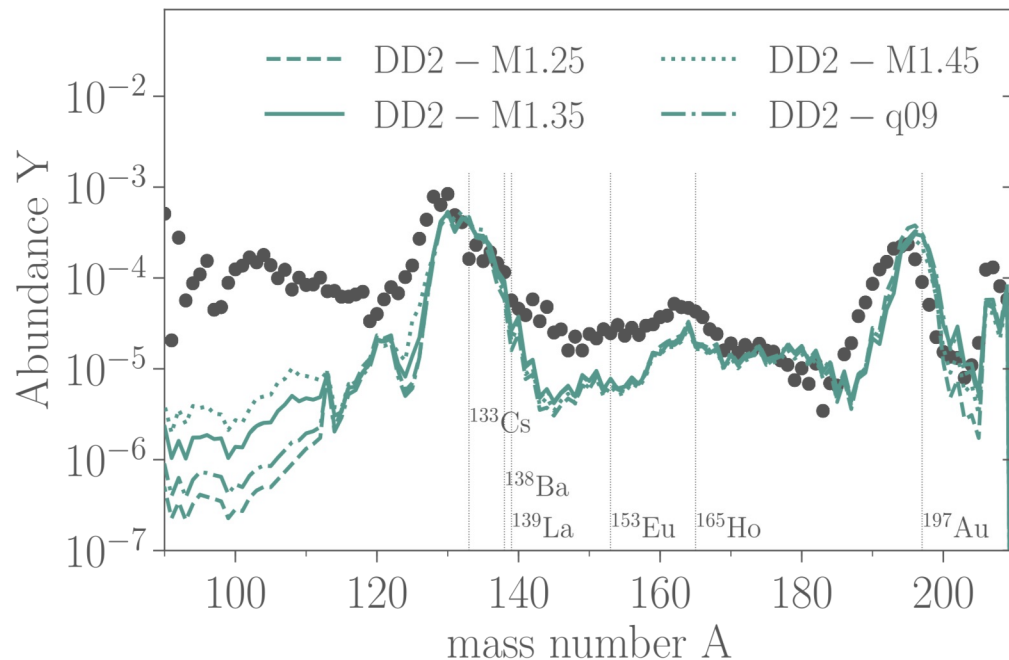
$Z=103, N=152$

- figure shows part of data taken in 10 hours
- 1200 ms phase-evolution time

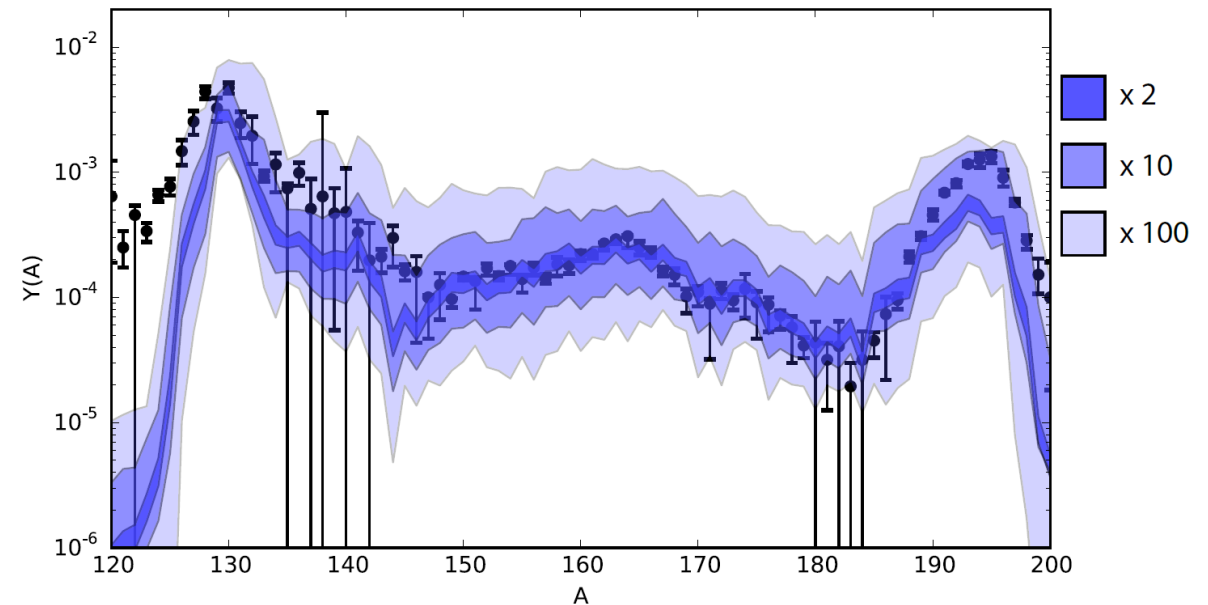
Einfluss Neutron-induzierter Reaktionen im r-Prozess

Impact of masses and (n, γ)-rates on the elemental abundances in r process can be studied by model predictions

Masses

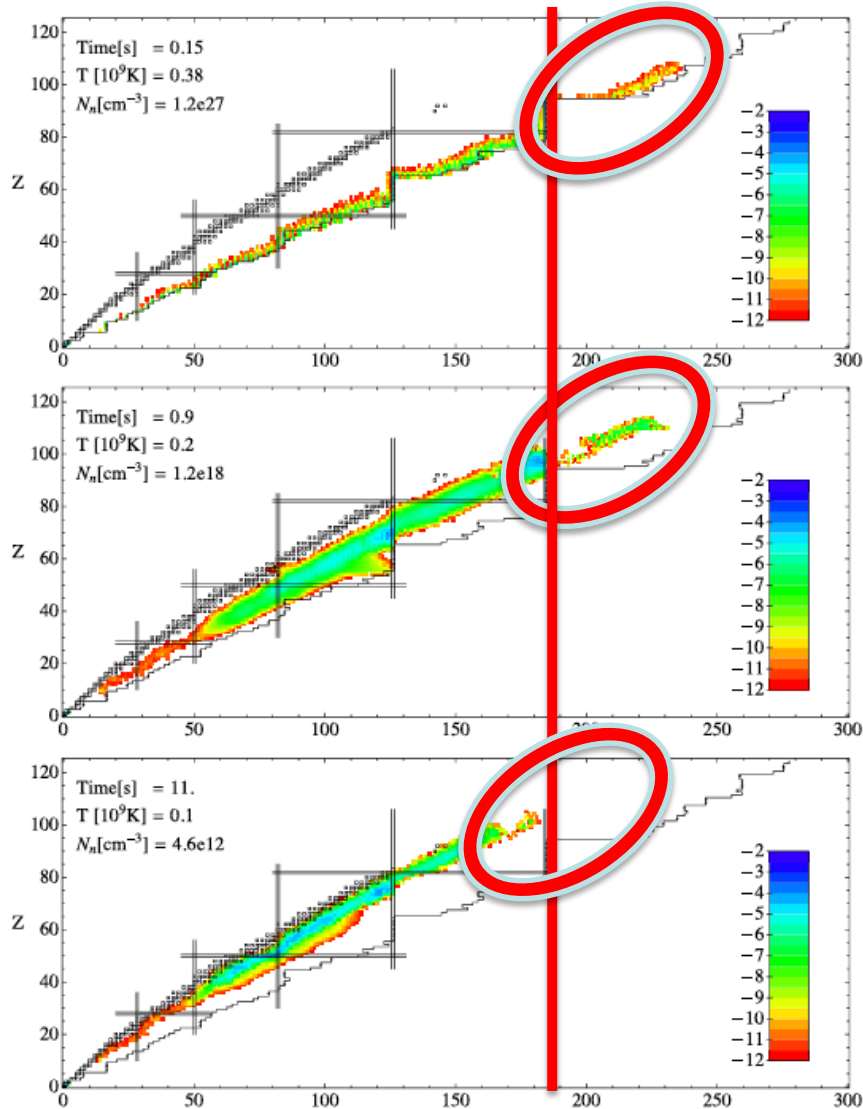


(n, γ)-Rates



Nikas et al (2020) PRC, submitted, arxiv

Are superheavy elements produced in the r process?

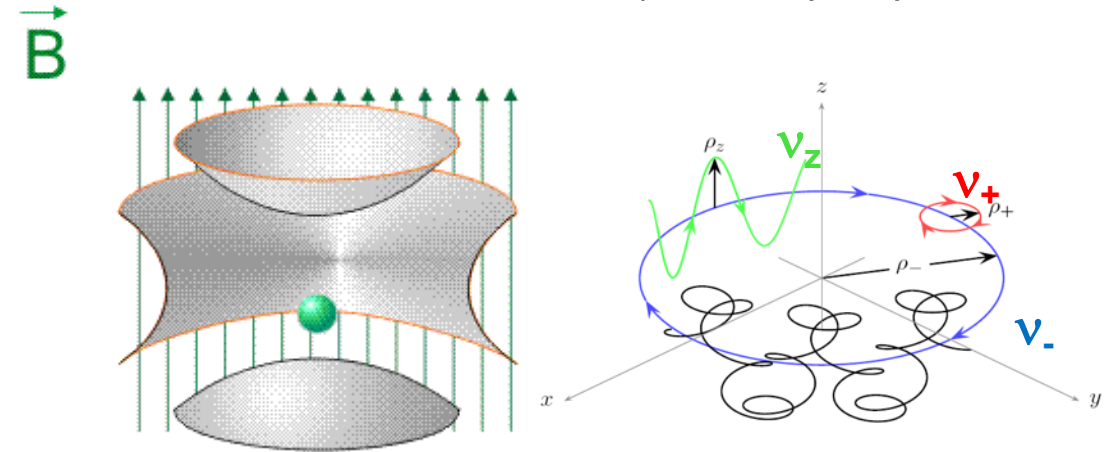


- r process path towards heaviest elements terminated by fission (fission recycling)
- fission barrier heights strongly model dependent, thus accurate description of fission is crucial
- impact of shell structure, e.g., $N = 184$
- isomers play a role
- limited experimental data for relevant nuclei

Mass Measurement Techniques

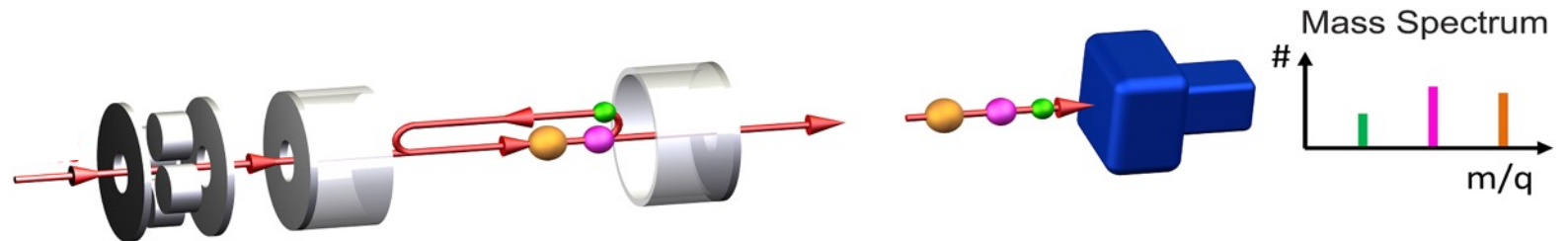
Frequency-based mass measurements,
mainly in Penning traps

cyclotron motion $\omega_c = qB/m$



L. S. Brown and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233
G. Gabrielse, Int. J. Mass Spectr. 279, (2009) 107

Time-of-flight
mass spectrometry,
nowadays with MR-ToF



H. Wollnik et al., Int. J. Mass Spectrom.
Ion Processes 96 (1990) 267

Both techniques require similar beam preparation

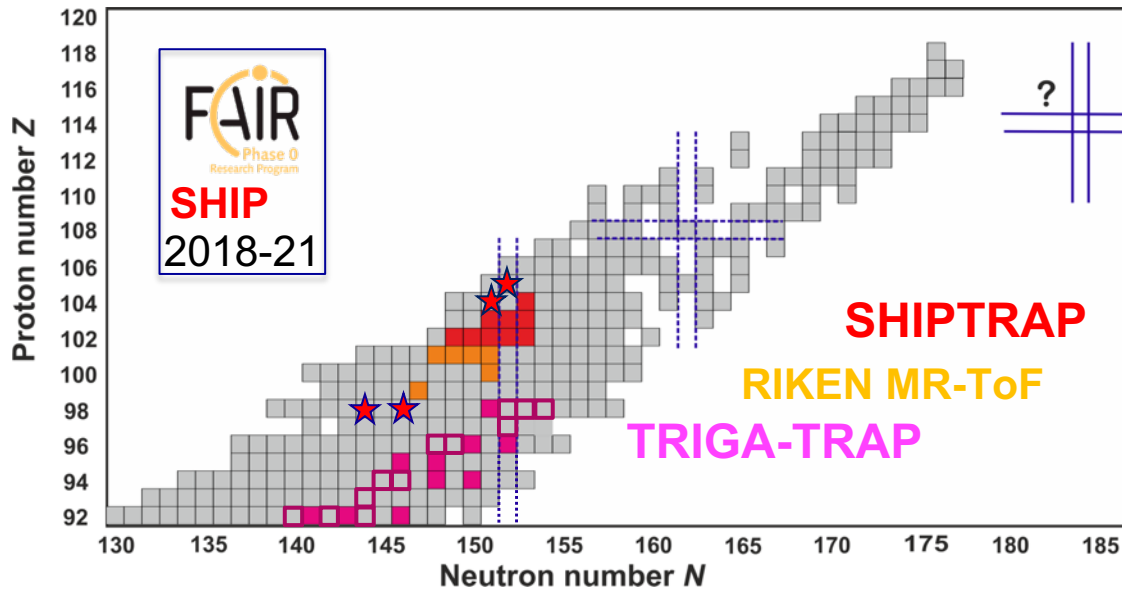
Typical Performance and Reach for Rare Isotopes



- required yield: \approx few particles per hour (SHIPTRAP 1 / day)
- accessible half-life \approx 10 ms - stable
- relative mass uncertainty $\approx 10^{-8}$ or better, in particular for mass doublets and certain cases $\approx 10^{-9}$
- required number of ions for a measurement 5-10

Yield often not the limiting factor but contaminants / background

Mass measurements of Actinides and Transactinides



- mass spectrometry beyond $Z = 100$ established since 2008
- measurements with rates of $\approx 0.00002/s$ and 5 detected ions in total performed
- rel. mass uncertainty on the order of 10^{-8}
- Mass resolving power up to $m/\Delta m = 11,000,000$ with Penning traps
- unambiguous identification of low-lying isomers with tens of keV

- O. Kaleja, F. Giacoppo et al., in preparation
- O. Kaleja, PhD thesis Uni Mainz 2020
- B. Andelic, PhD thesis Uni Groningen 2021
- E. Minaya Ramirez et al. Science 337, 1207 (2012)
- M. Block et al., Nature 463, 785 (2010)
- Y. Ito et al., Phys. Rev. Lett. 120, 152501 (2018)
- J. van de Laar et al., in preparation
- M. Eibach et al., Phys. Rev. C 89, 064318 (2014)

General Motivation for Laser Spectroscopy

- Atomic physics & chemistry

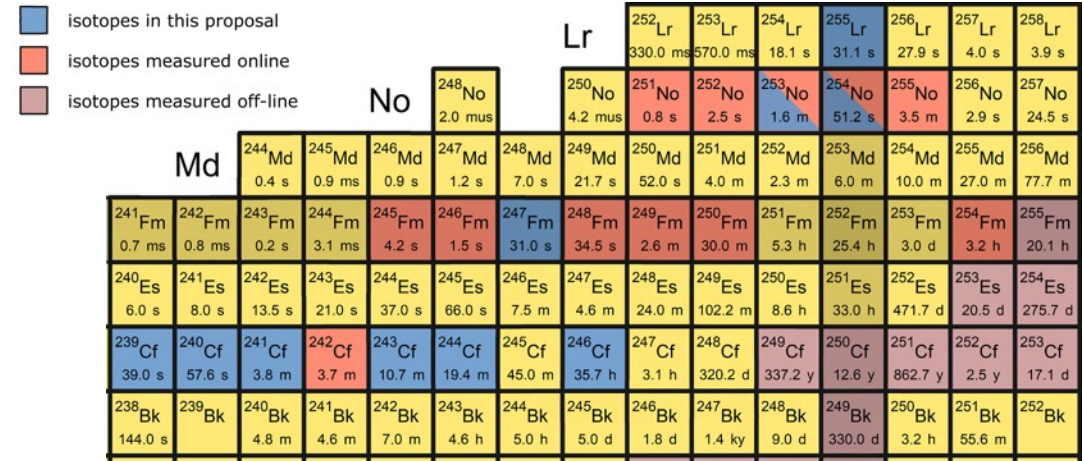
- Experimental identification of atomic transitions
- Study relativistic effects
- Benchmark theoretical models

- Nuclear physics

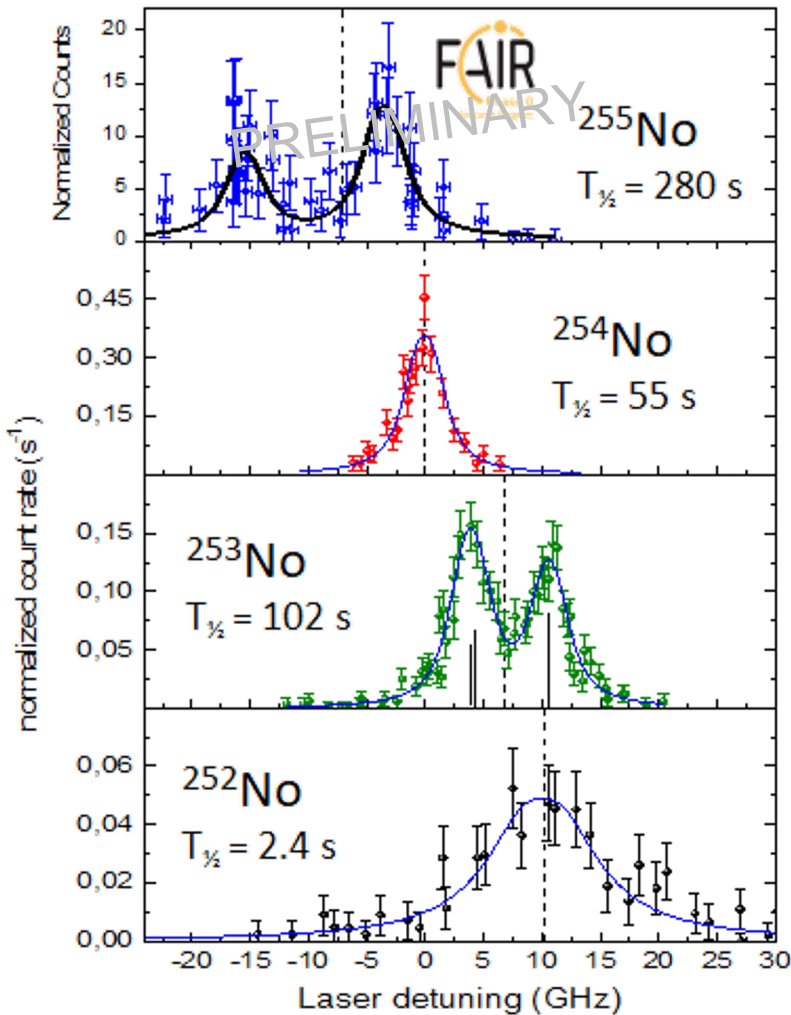
- Differential charge radii via isotope shift measurements across multiple isotopes
- Spin coupling and nuclear moments (single-particle and collective properties) via HFS spectroscopy
- Improvement of nuclear models

- Astrophysics

- Provide spectroscopic data for the search of superheavy elements in the universe



Laser Spectroscopy of Nobelium (Z=102) Isotopes



- first laser spectroscopy spectroscopy beyond Z=100
- yield as low as 0.05 atoms / second
- isotope shift allowed determining changes in mean-square charge radii around $N = 152$
- magnetic dipole and electric quadrupole moment of ^{253,255}No obtained from hyperfine splitting

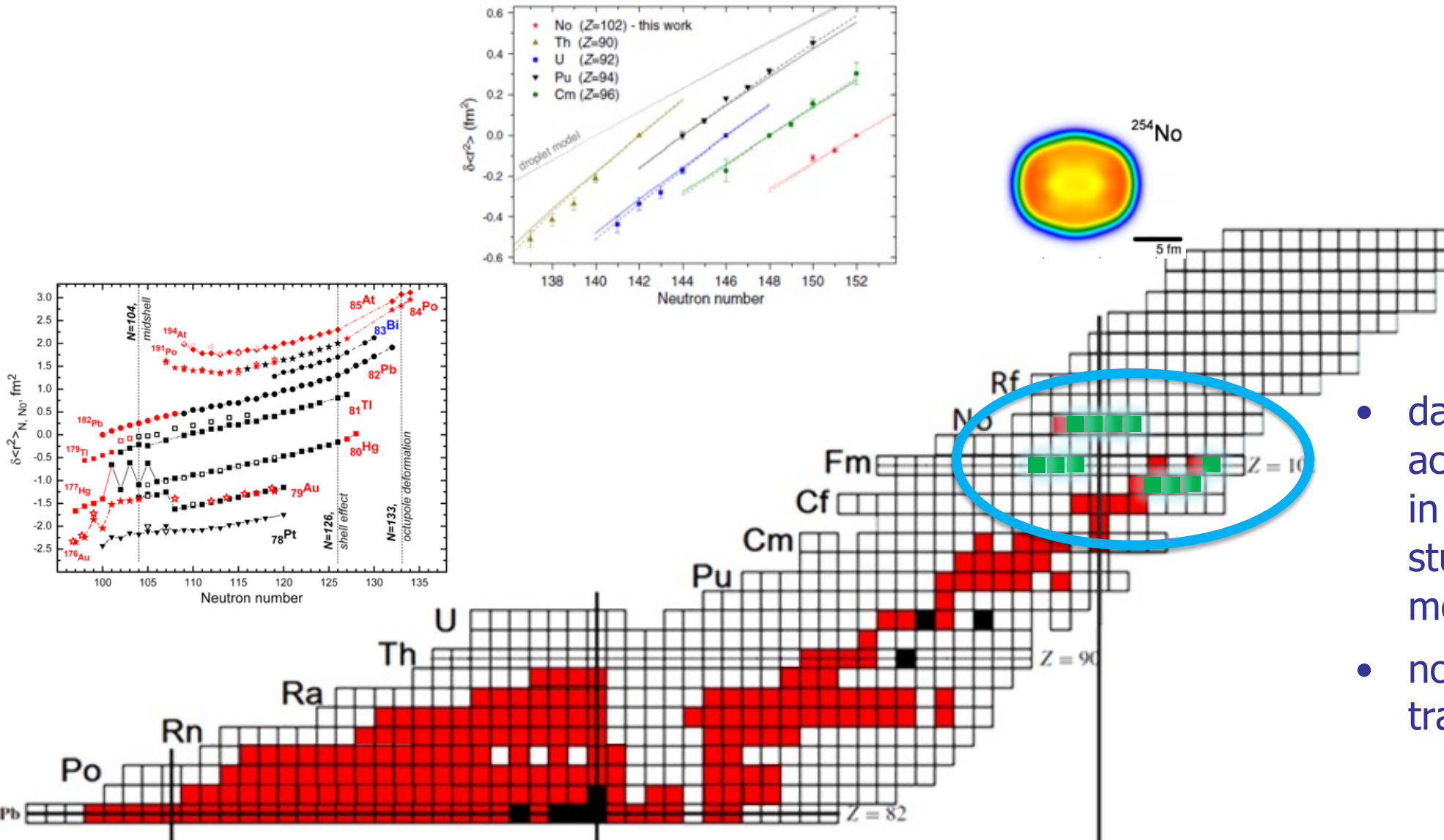
Experiment: S. Raeder, M. Laatiaoui *et al.*

Theory: A. Borschevsky V. Dzuba, S. Fritzsche,
B. Schütrumpf, W. Nazarewicz *et al.*

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

S. Raeder *et al.*, Phys. Rev. Lett. 120 (2018) 232503

Status of Laser Spectroscopy in Heavy Elements



- data for some long-lived actinide isotopes available in quantities for offline studies with conventional methods
- no experimental data for transactinides

Summary and Conclusions

- Many fundamental questions from LRP 2017 remain open and still motivate our future research activities
- New techniques such as mass spectrometry and laser spectroscopy enhanced our possibilities for nuclear structure studies in heavy nuclei (electromagnetic moments, mean-square charge radii, mass filters, ...)
- Technical and methodological developments extended reach towards more exotic and ever heavier nuclei with high precision – needs to continue
- Combine different measurements techniques for comprehensive nuclear structure studies: obtain more observables from one experiment

Future Directions

- High-intensity stable beams are still crucial
- Go more neutron-rich in known elements not only up in Z
- Exploit different production schemes including radioactive decays to extend the reach toward additional nuclides
- Extending reach of measurements goes along with technical and methodological developments to improve performance
- Combine different techniques more extensively, e.g. laser ionization, laser cooling, trap-assisted decay spectroscopy, ...

Future Directions

- exploit upgraded and new next-generation facilities to utilize different production schemes to access more exotic nuclides
- close collaboration with theory crucial
- foster and increase interdisciplinary activities, e.g., collaboration with atomic physics and fundamental symmetries communities
- intensify collaboration on technical and methodological developments and large-scale infrastructures
- Support the facility efforts to assure availability of user beamtime