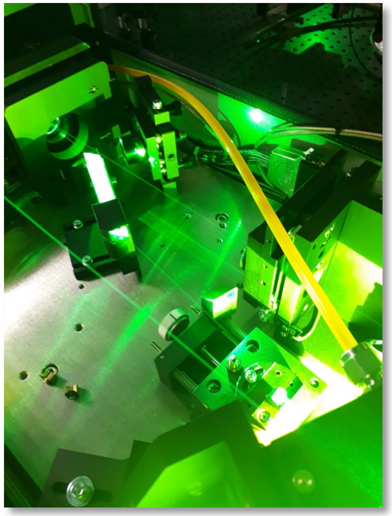
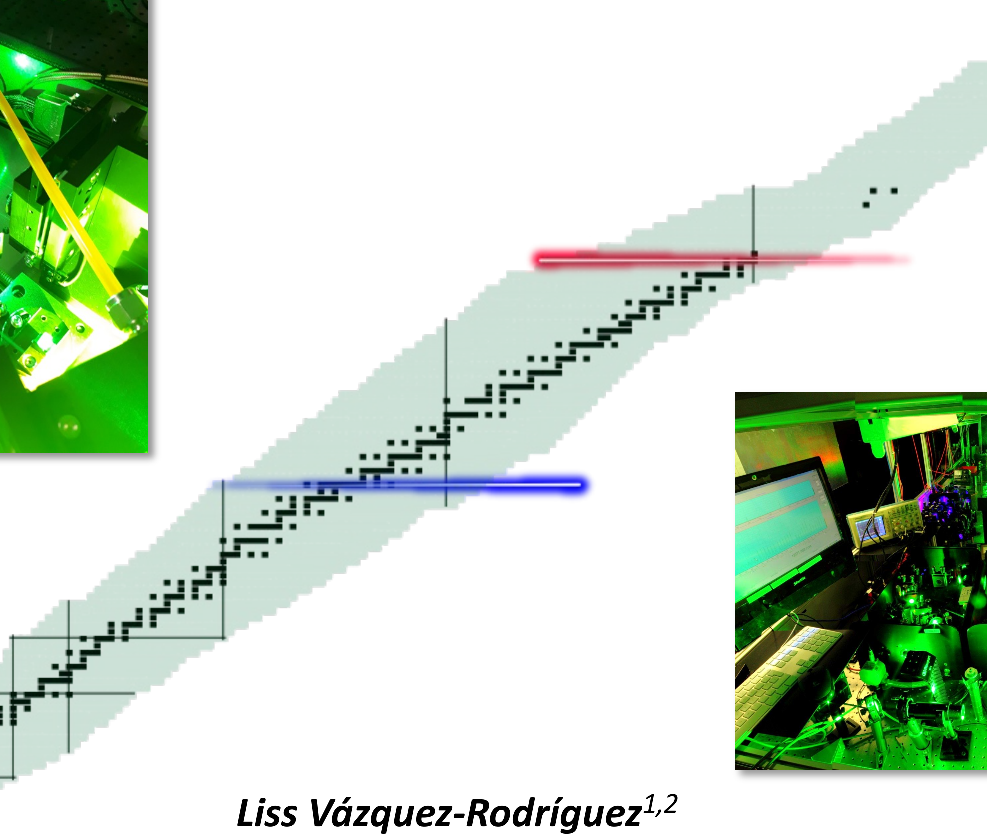
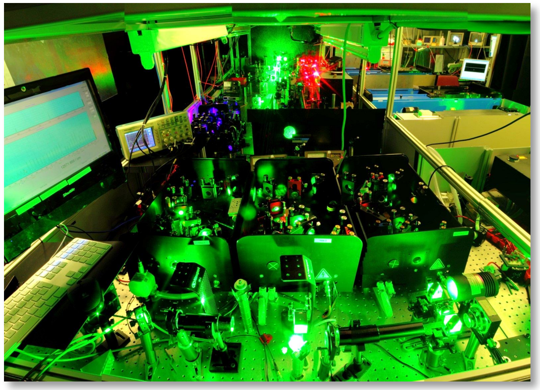
“High-resolution laser spectroscopy: a powerful tool to unravel the mysteries of the atomic nucleus"







Liss Vázquez-Rodríguez[1,2]

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Outline

Introduction

Fundamentals of laser spectroscopy and hyperfine structure

Experimental set-up, COLLAPS at ISOLDE/CERN

Recent results, from Sn to Pb

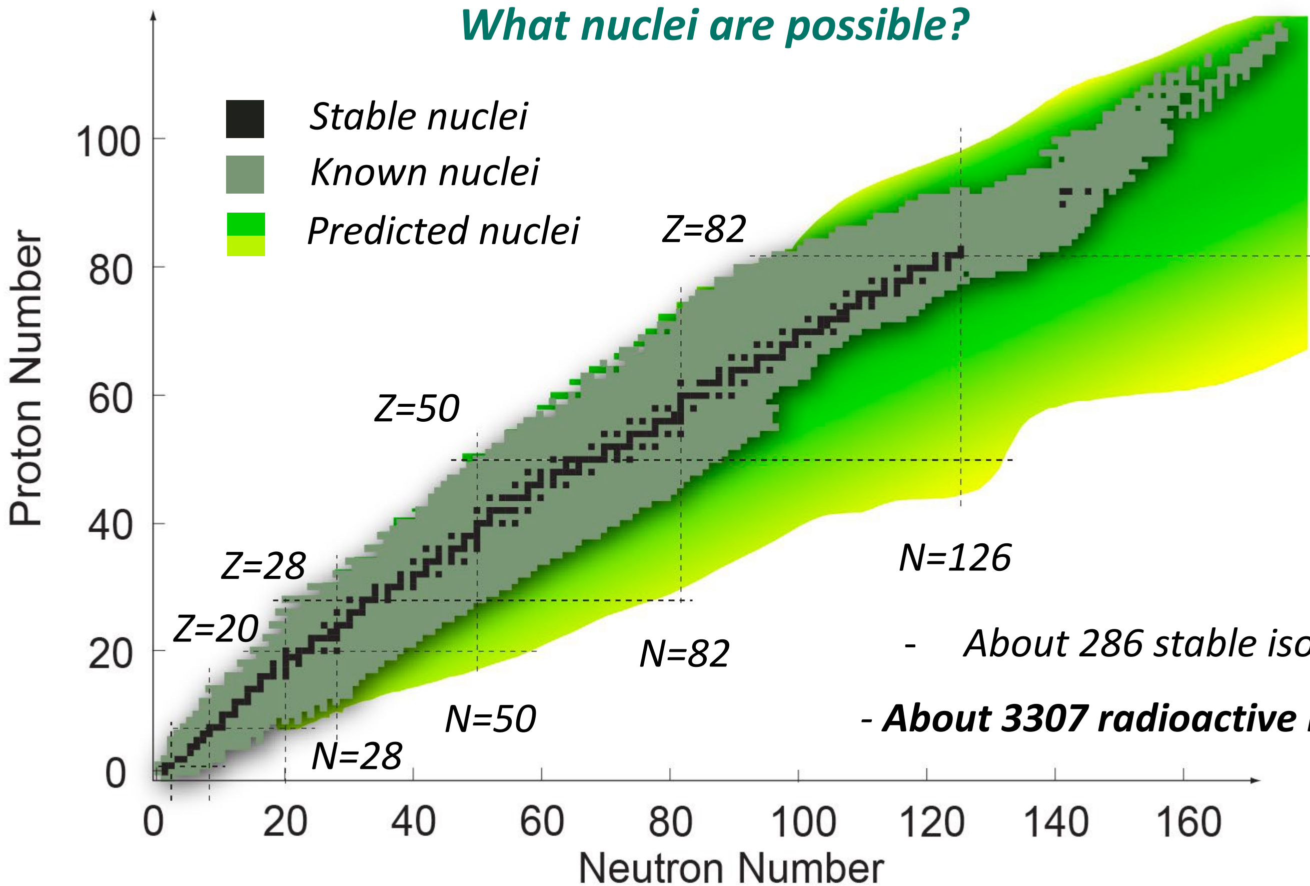
Perspectives

Main topics and goals of this meeting:

- *…*

- *What should be EFT and many-body priorities in nuclear structure research in light of the advent of new experimental facilities for the study of exotic nuclei?*

Introduction



- About 286 stable isotopes

- **About 3307 radioactive isotopes**

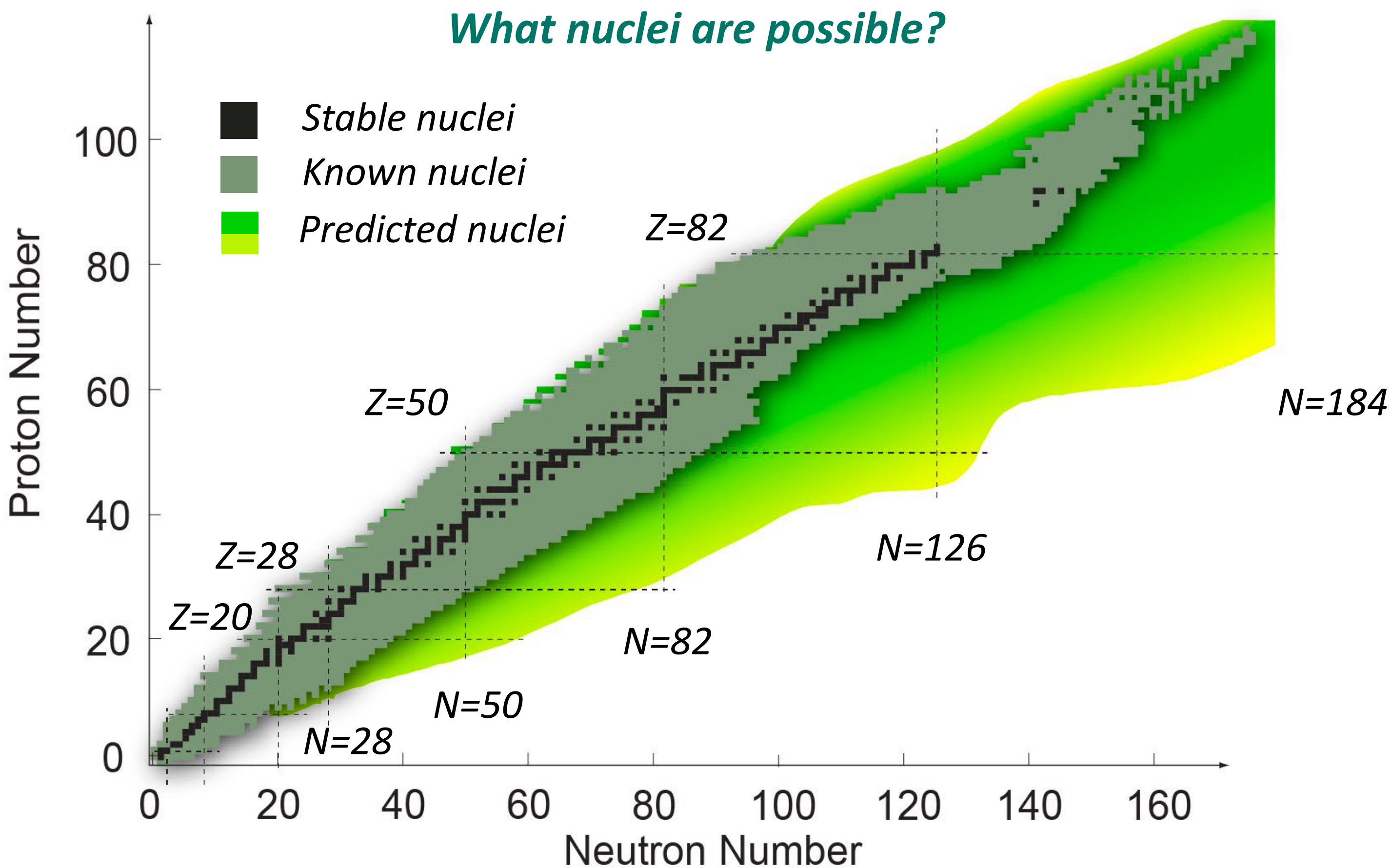
Nuclear Physics Research Aim

- Unravel the fundamental properties of nuclei from their basic constituents

Lofty goal: Find a comprehensive and quantified model of atomic nuclei

Picture taken from A. Gade, FRIB Science

Introduction



Open questions

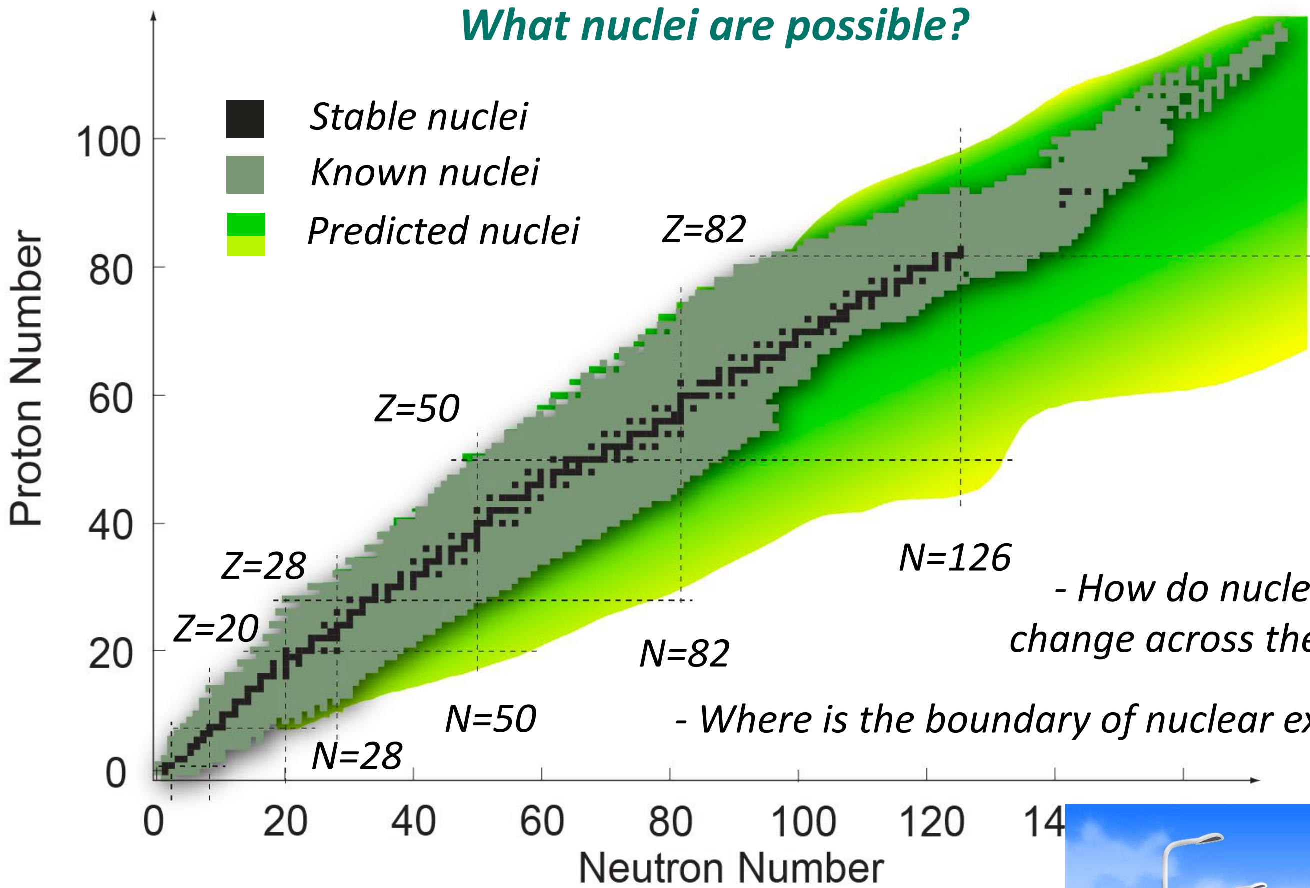
- How do nuclear properties change across the nuclear chart?

- Where is the boundary of nuclear existence?

Picture taken from A. Gade, FRIB Science

Introduction

What nuclei are possible?

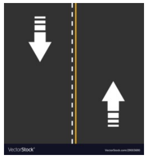


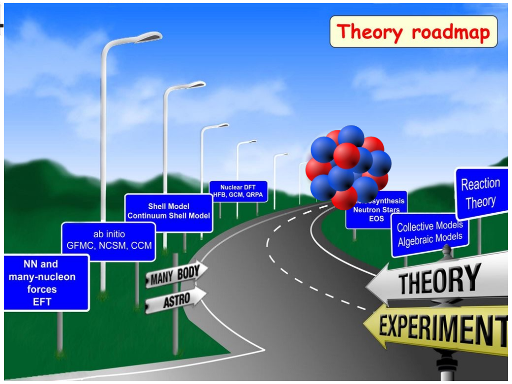
- How do nuclear properties change across the nuclear chart?

- Where is the boundary of nuclear existence?

Experiment: access key regions of the nuclear chart to constrains models and identify missing physics

Theory: identifies key nuclei and properties to be studied

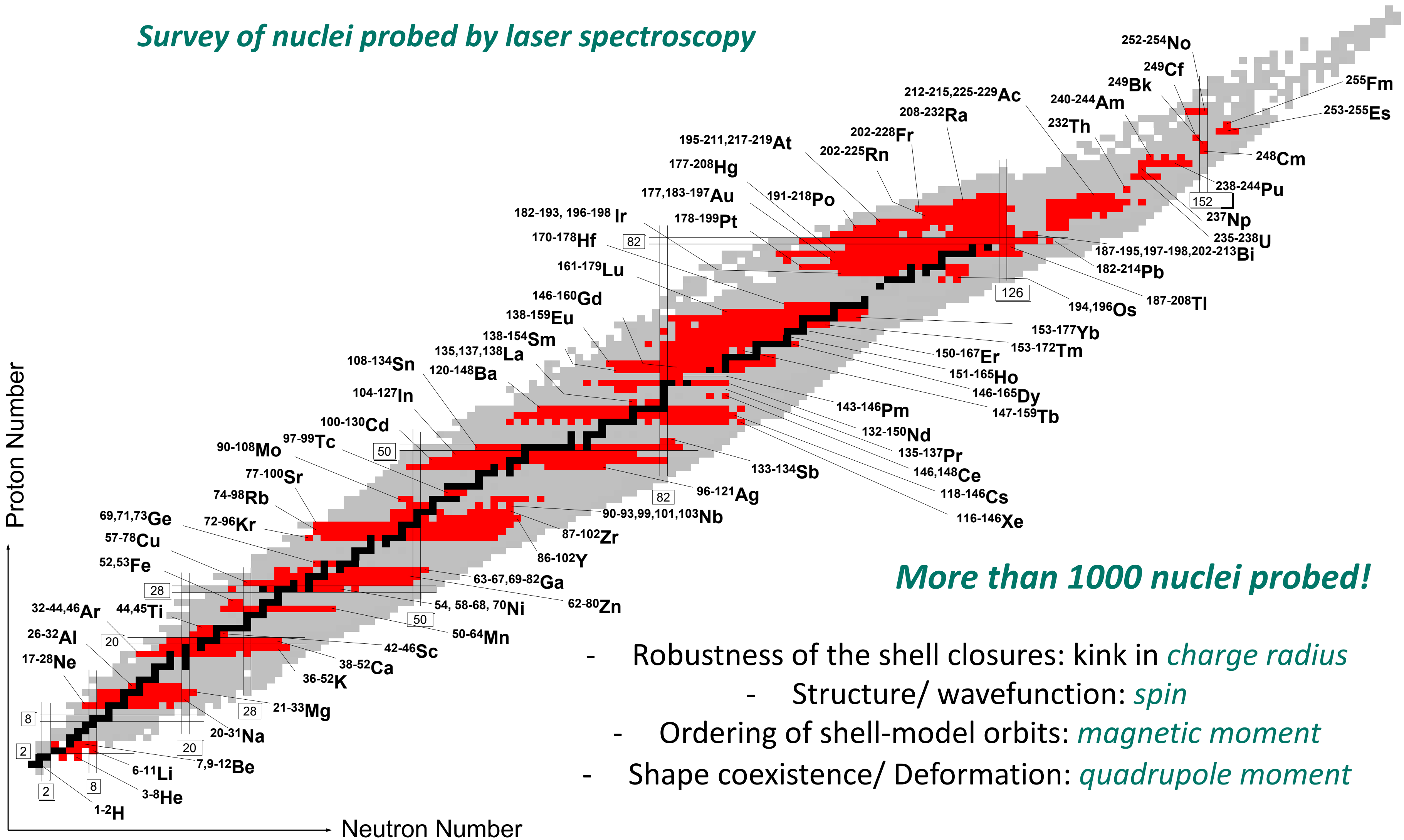




Introduction

Laser spectroscopy: a powerful tool to study the atomic nucleus

Survey of nuclei probed by laser spectroscopy

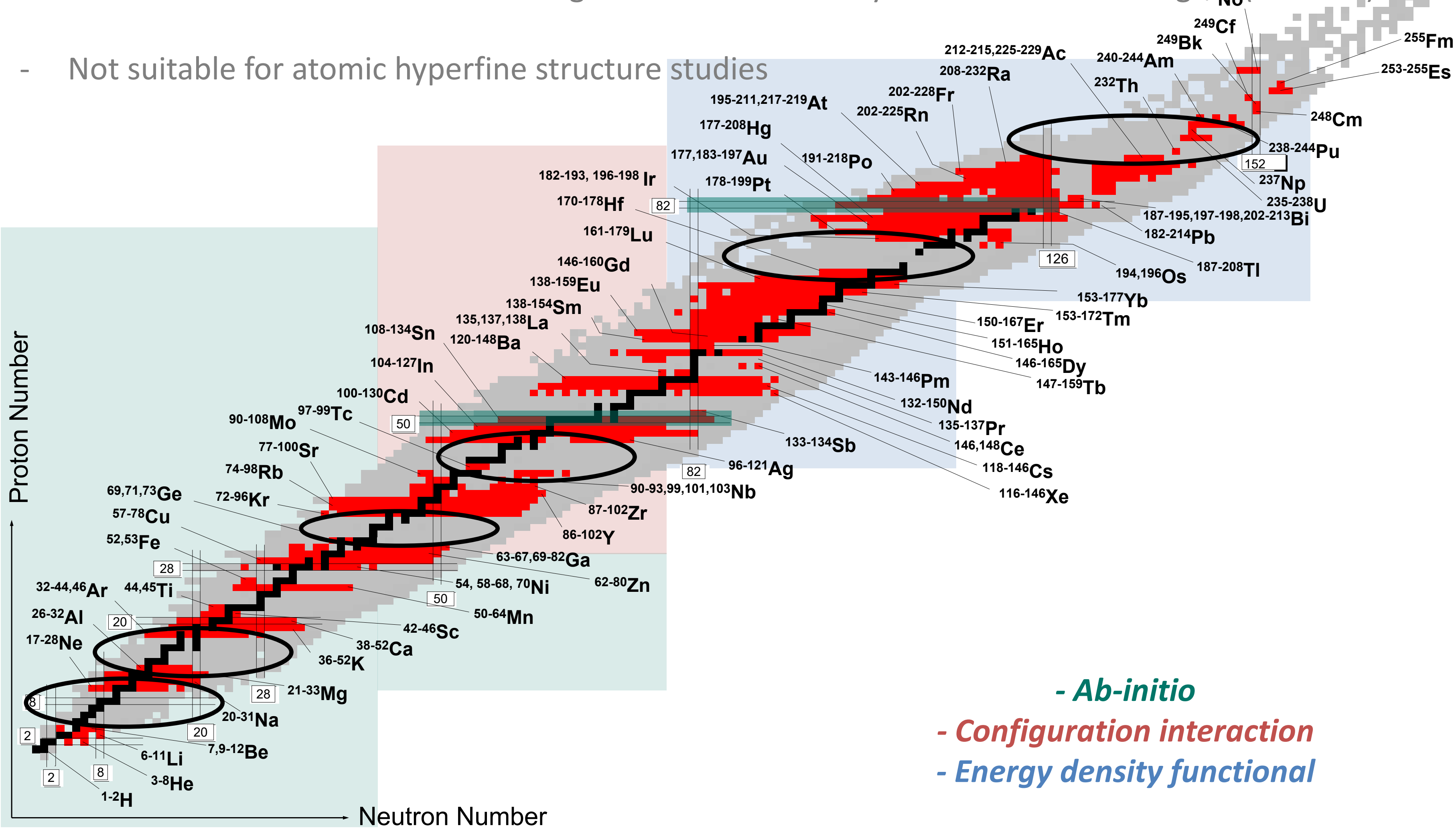


More than 1000 nuclei probed!

- Robustness of the shell closures: kink in *charge radius*
  - Structure/ wavefunction: *spin*
- Ordering of shell-model orbits: *magnetic moment*
- Shape coexistence/ Deformation: *quadrupole moment*

Introduction

- Not yet available as ISOL-beams
- Atomic or ionic transitions from the ground state lie mainly in the vacuum UV region (< 90 nm)
- Not suitable for atomic hyperfine structure studies



- Ab-initio

- Configuration interaction

- Energy density functional

Introduction

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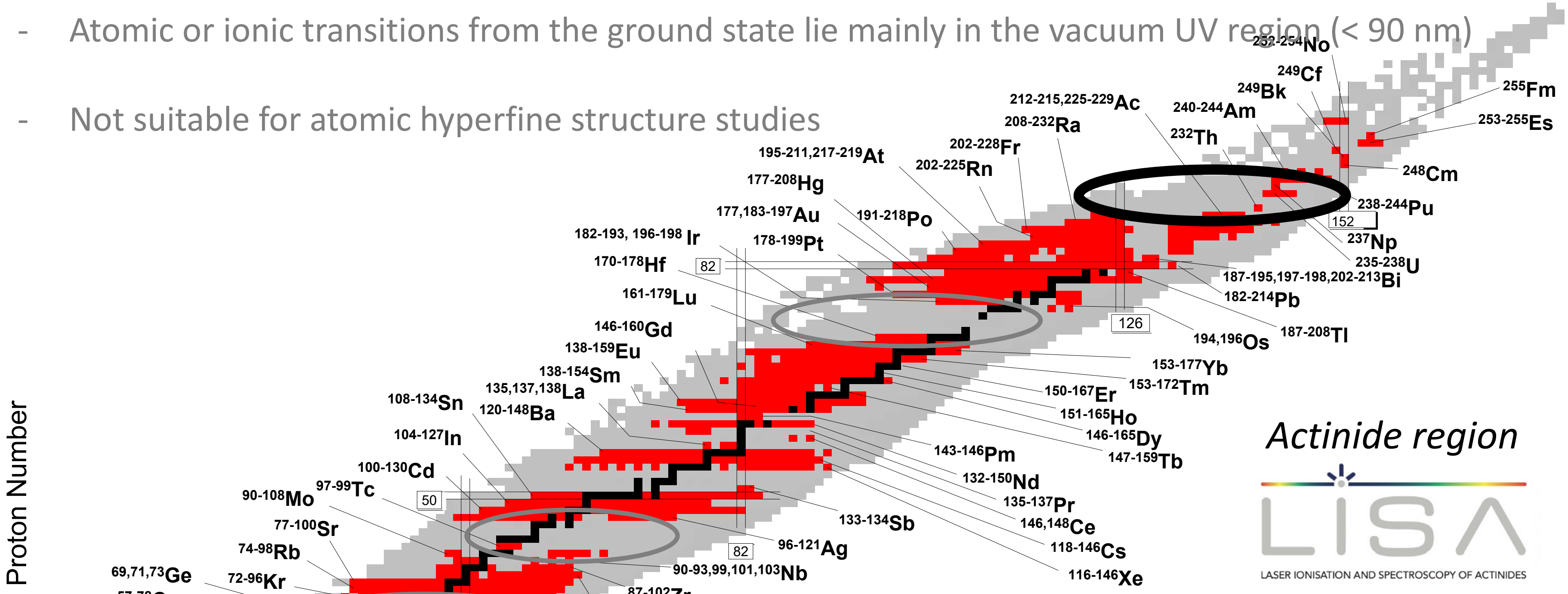
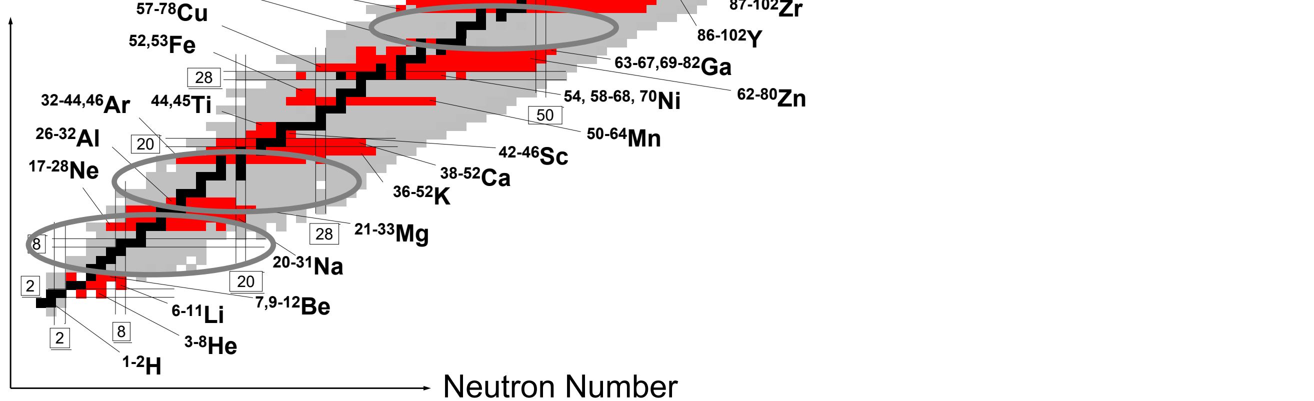

Actinide region

LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

Introduction

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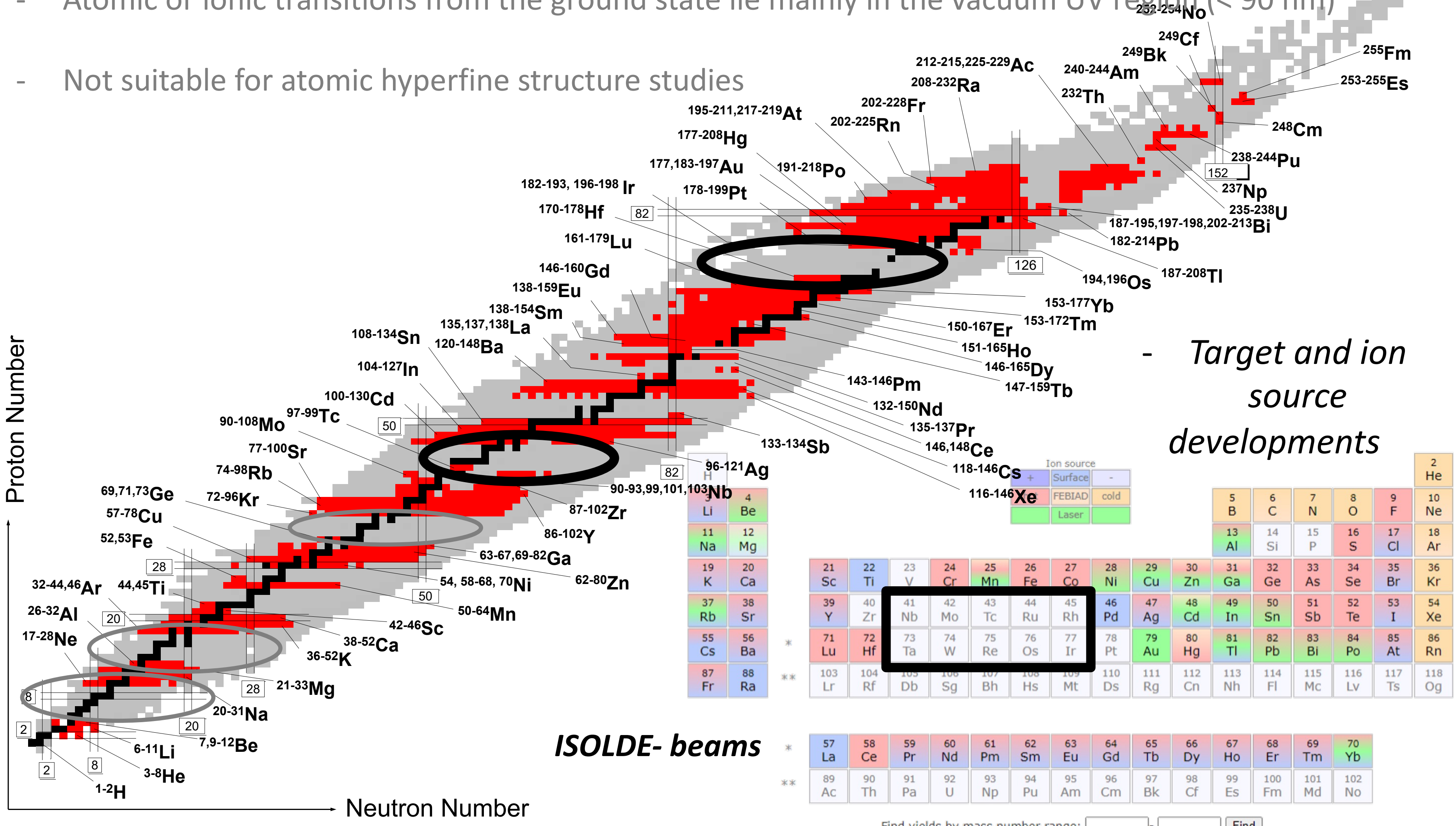

- *Target and ion source developments*

ISOLDE- beams

Introduction

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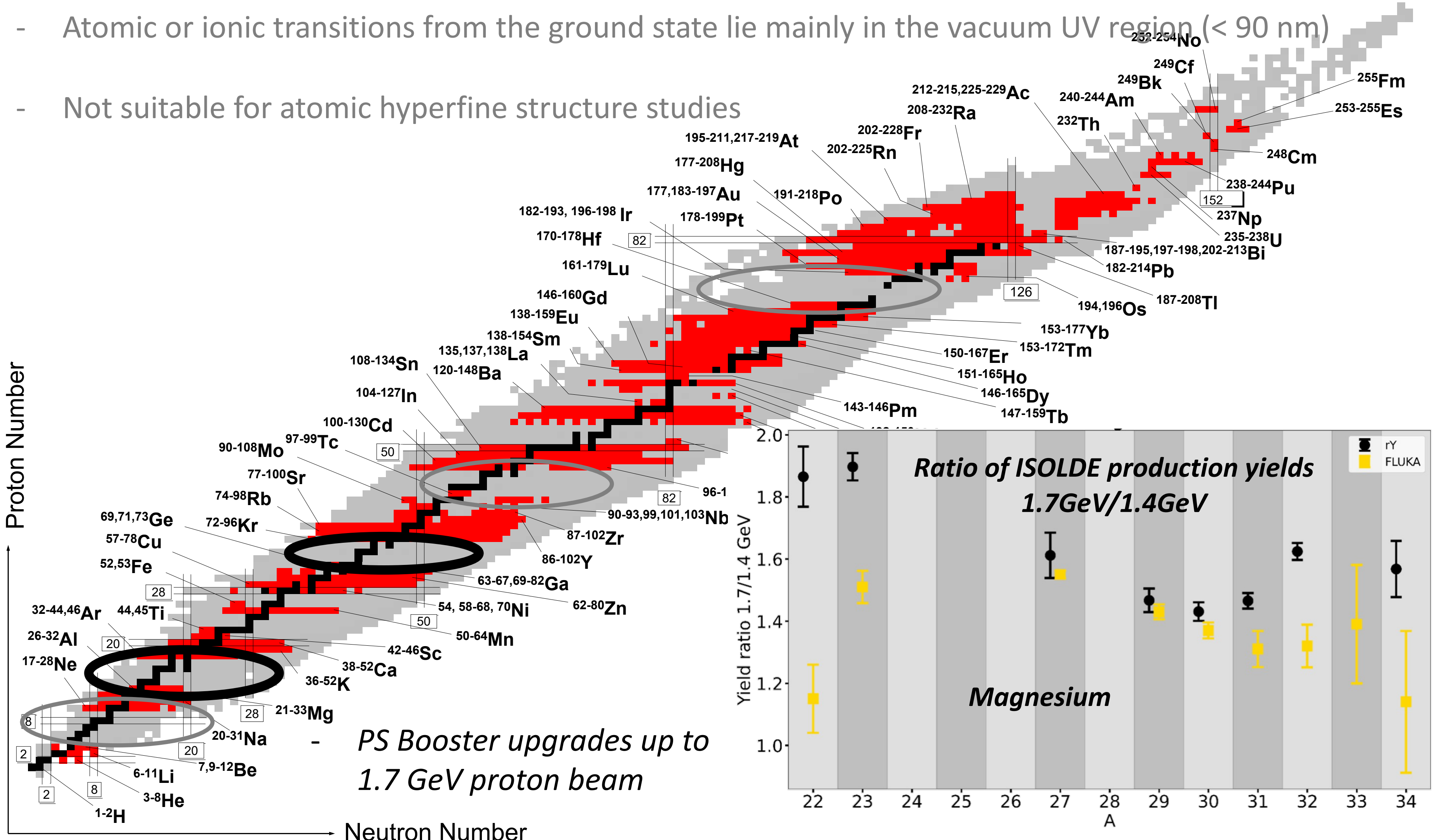

- *PS Booster upgrades up to 1.7 GeV proton beam*

Courtesy of Simon Stegemann, ISOLDE workshop 2022

Introduction

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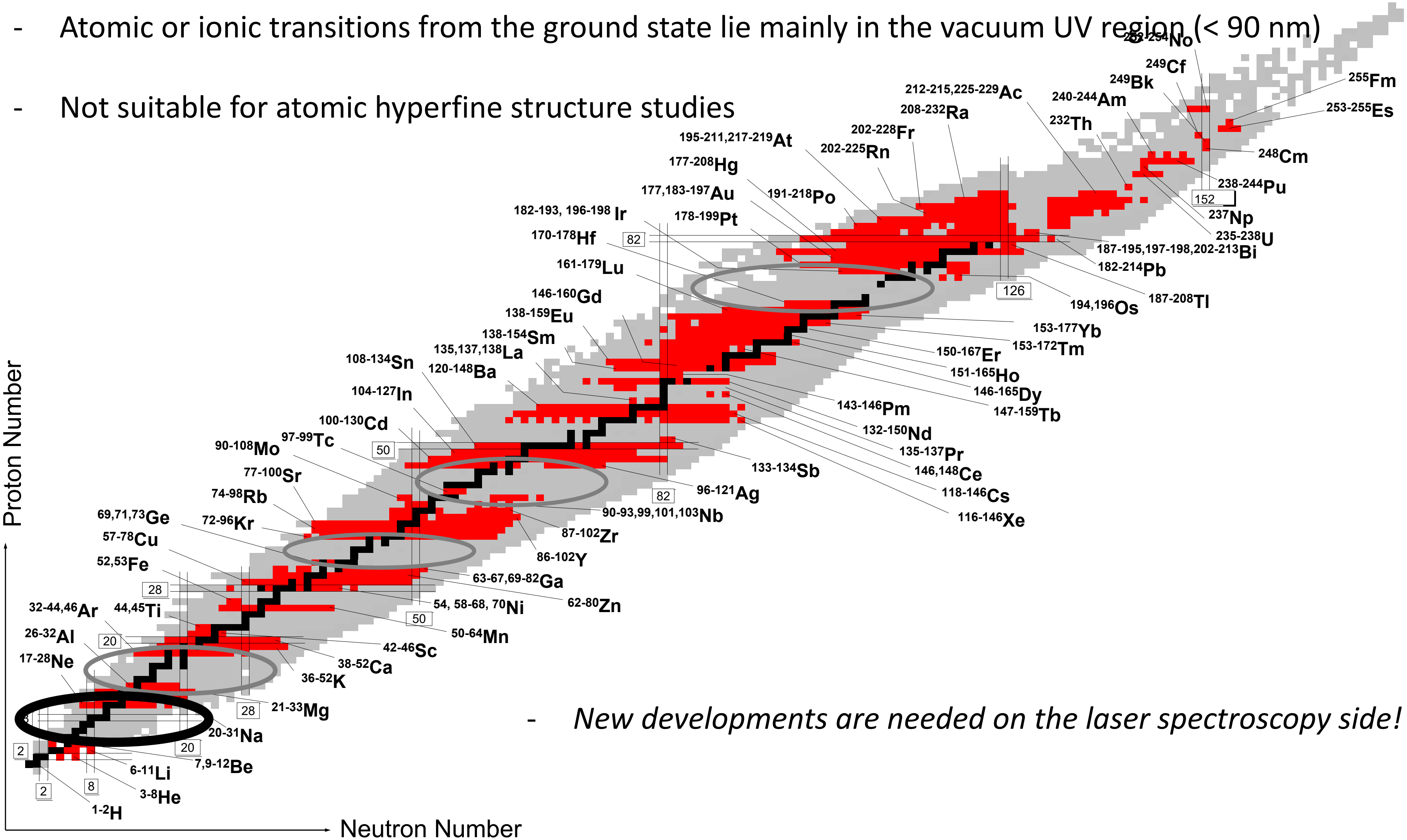


- *New developments are needed on the laser spectroscopy side!*

Fundamentals of laser spectroscopy and hyperfine structure

What can we learn from laser spectroscopy?

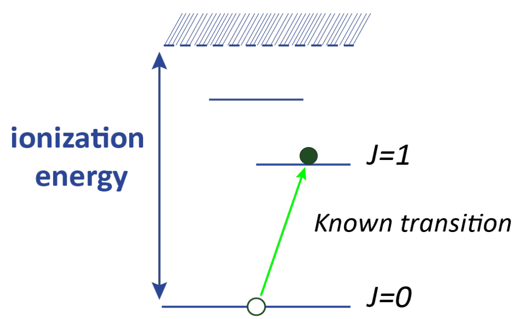
↓

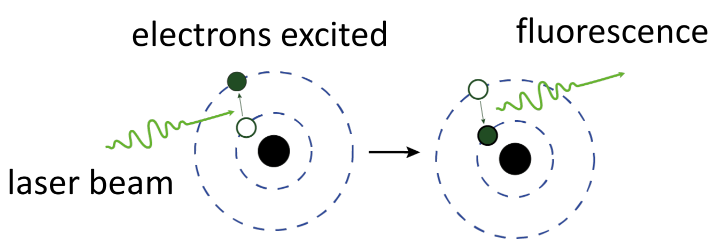
Model (nuclear) independent

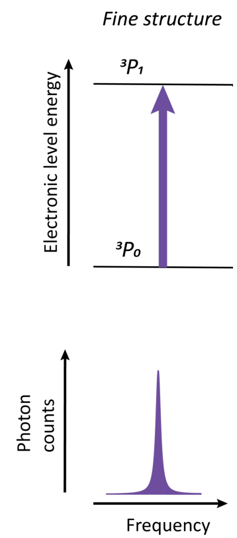
↓

Nuclear properties (**spin, μ, Q, charge radius**)

Atomic laser spectroscopy: a fruitful marriage of atomic and nuclear physics

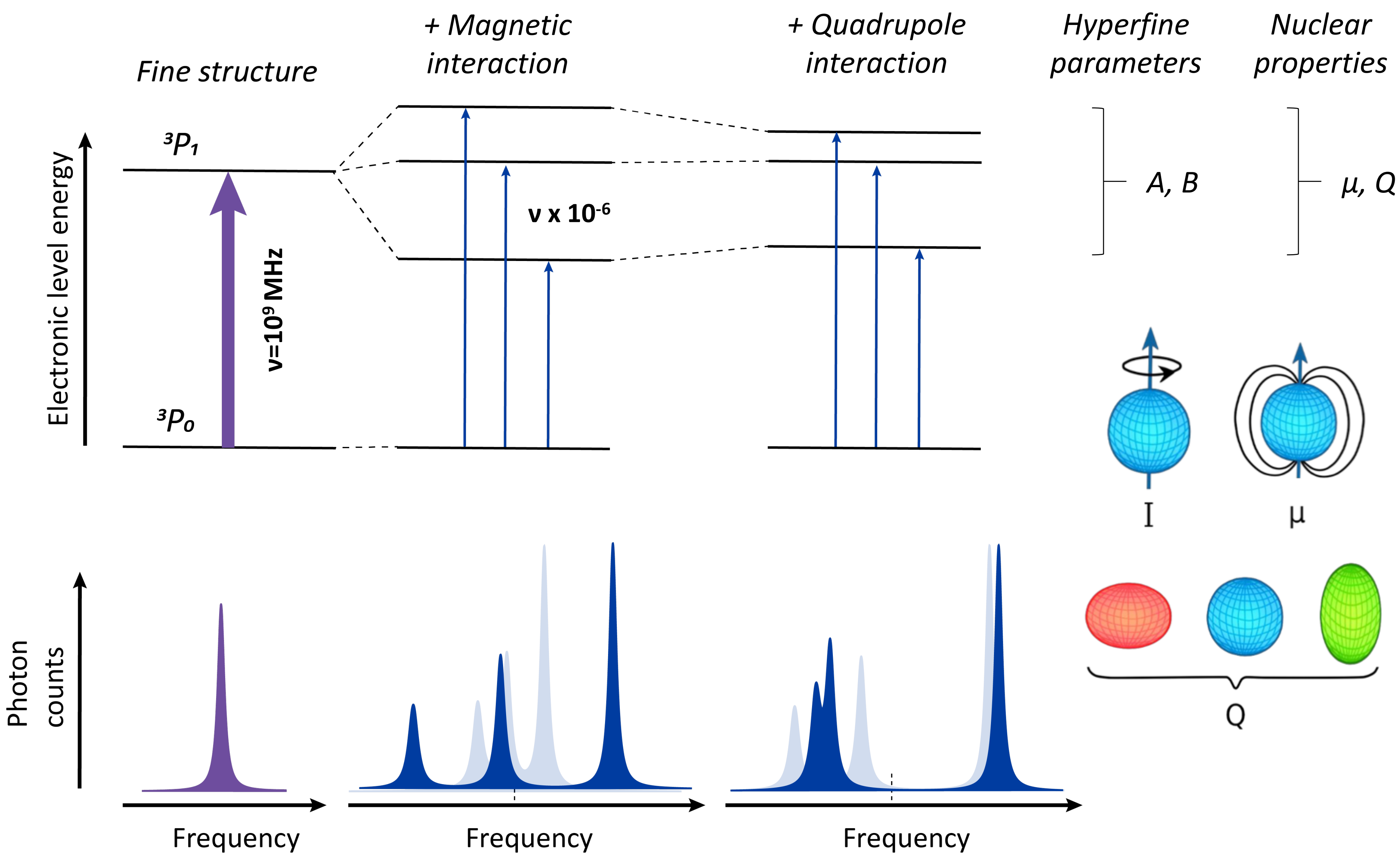






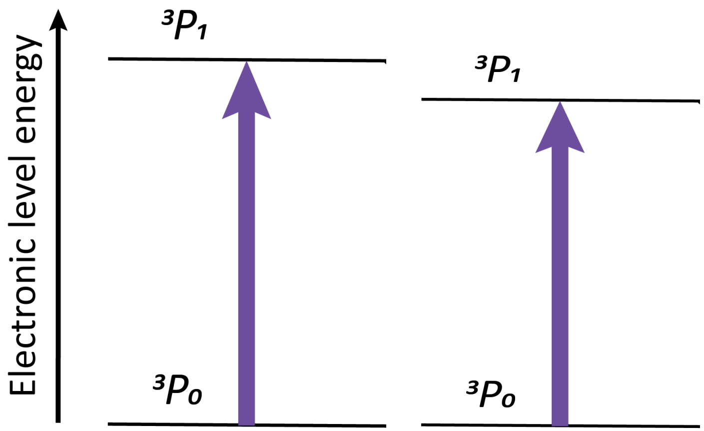
Fundamentals of laser spectroscopy and hyperfine structure

Hyperfine structure



Fundamentals of laser spectroscopy and hyperfine structure

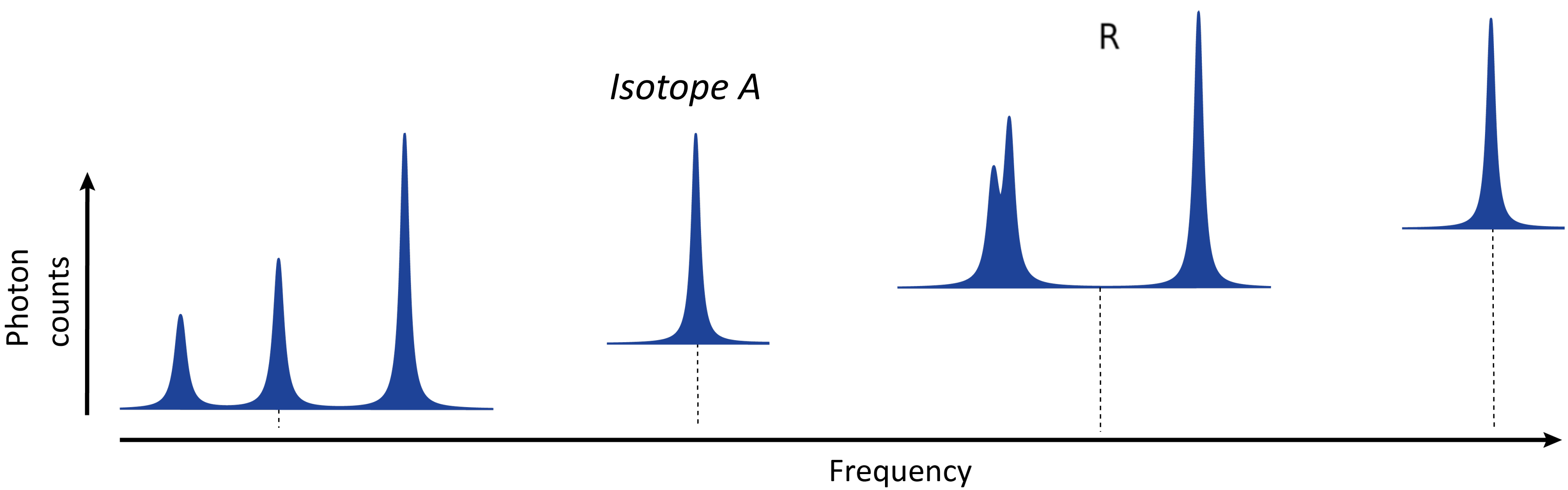
Fine structure



Isotope shift

$$\delta\nu_i^{A,A'} \propto \delta\langle r^2\rangle^{A,A'}$$

Differences in mean square charge radii



Fundamentals of laser spectroscopy and hyperfine structure

Nuclear properties from laser spectroscopy

$$A\frac{\boldsymbol{I}}{\boldsymbol{\mu}} = \text{const}$$

$$\frac{B}{\boldsymbol{Q}} = \text{const} = eV_{jj}$$

Isotope shift $\propto$ ***ms charge radii***

Fundamentals of laser spectroscopy and hyperfine structure

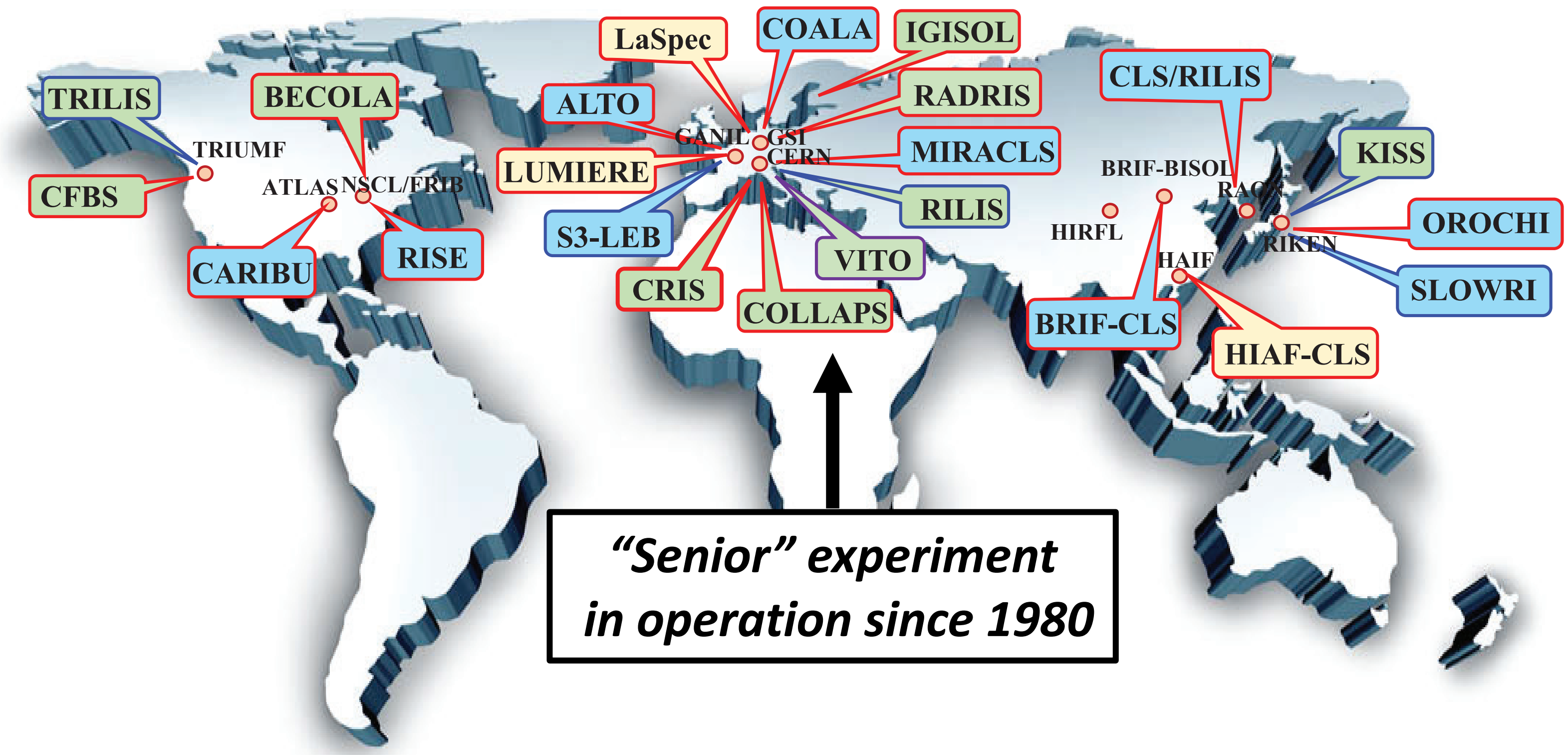
Distribution of laser spectroscopy experiments

Operational | Commissioning | Planning

- About 8 operational experimental setup for the study of nuclear properties (high-resolution)
- About another 8 in commissioning (in the last 20 years)

Fundamentals of laser spectroscopy and hyperfine structure

Distribution of laser spectroscopy experiments



Operational | Commissioning | Planning

- *About 8 operational experimental setup for the study of nuclear properties (high-resolution)*
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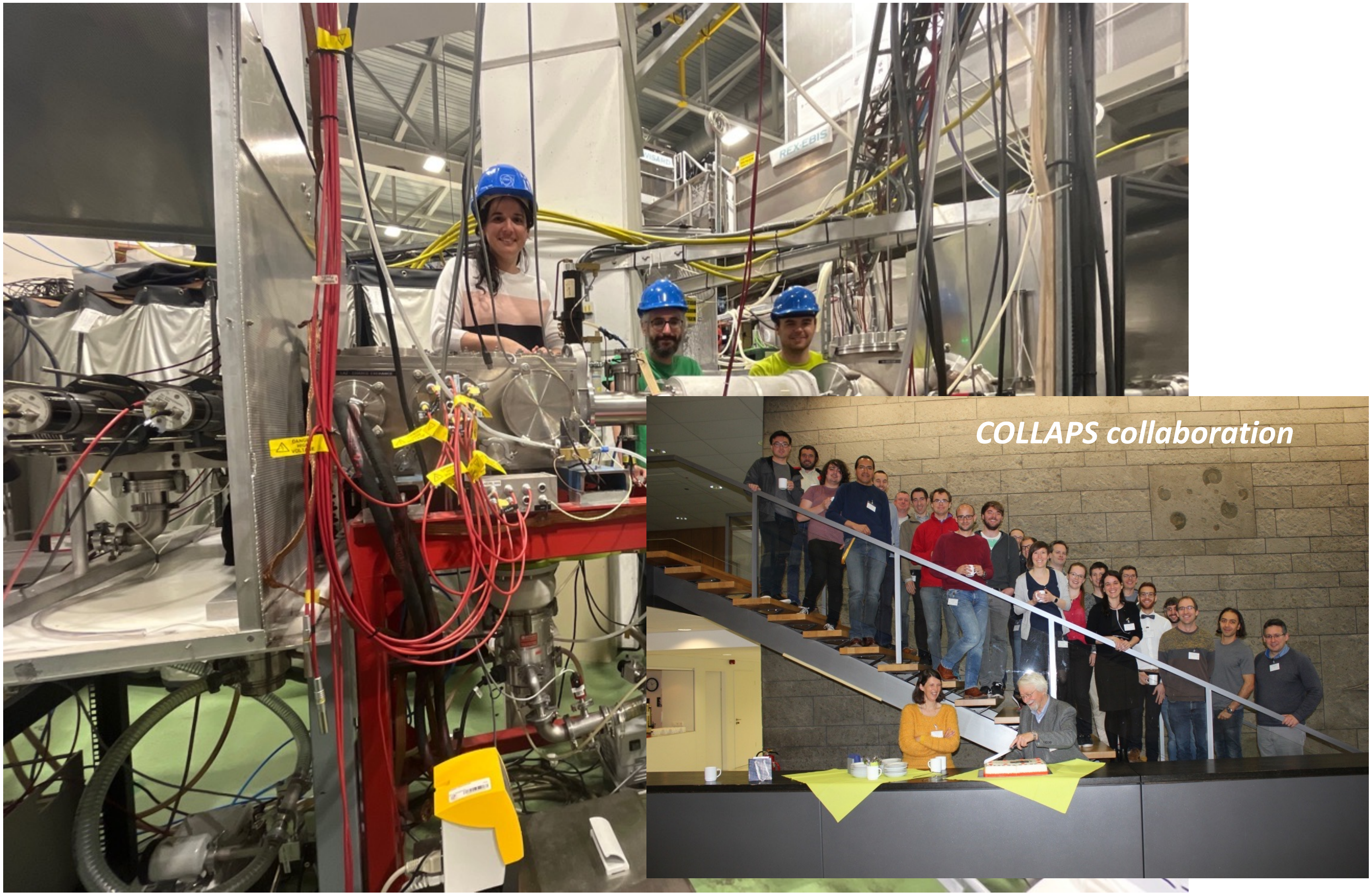
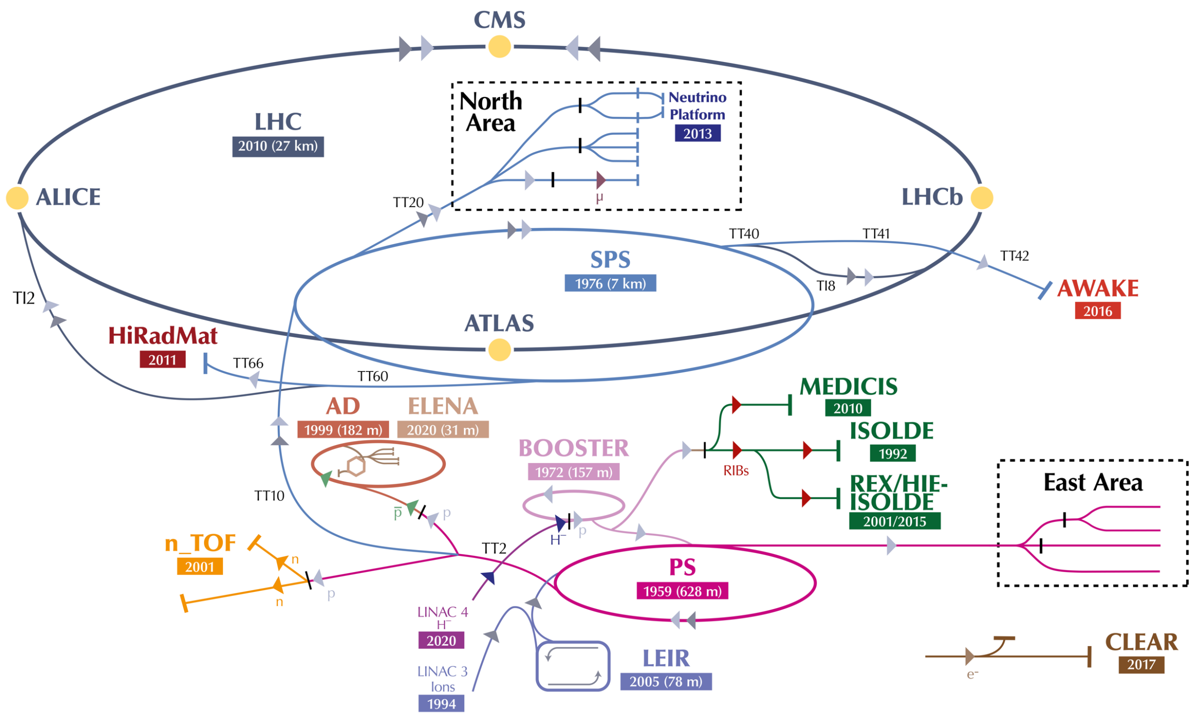
Experimental set-up, COLLAPS at ISOLDE/CERN

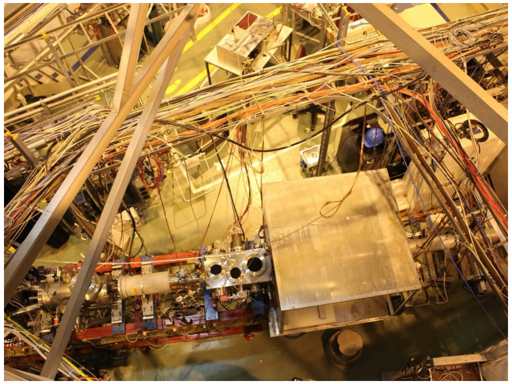


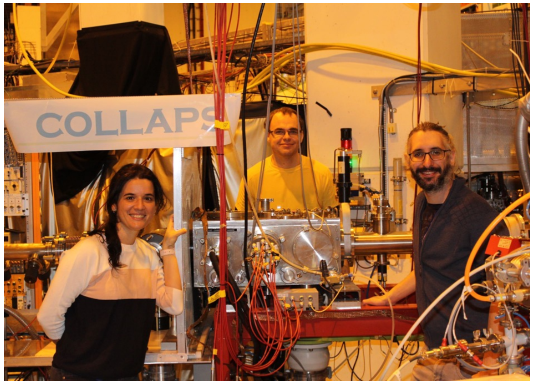
Photographic service CERN, 20-04-2020

Experimental set-up, COLLAPS at ISOLDE/CERN

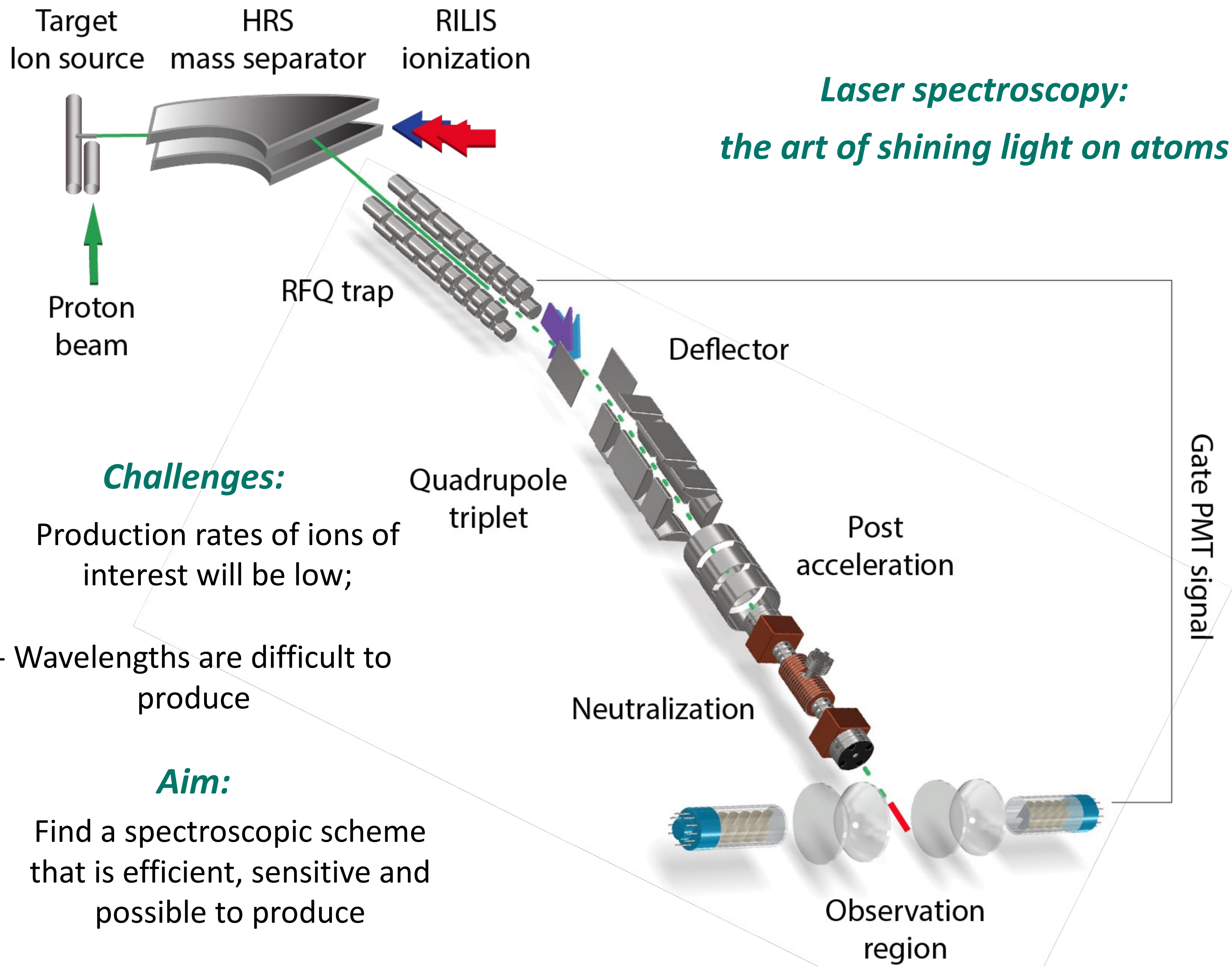
The CERN accelerator complex







Experimental set-up, COLLAPS at ISOLDE/CERN



Laser spectroscopy:
the art of shining light on atoms

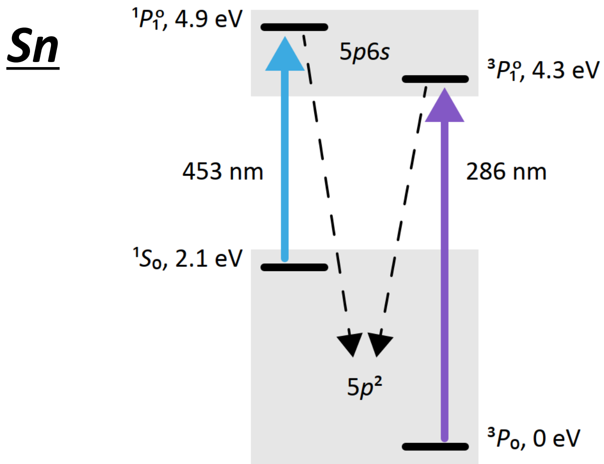
Challenges:

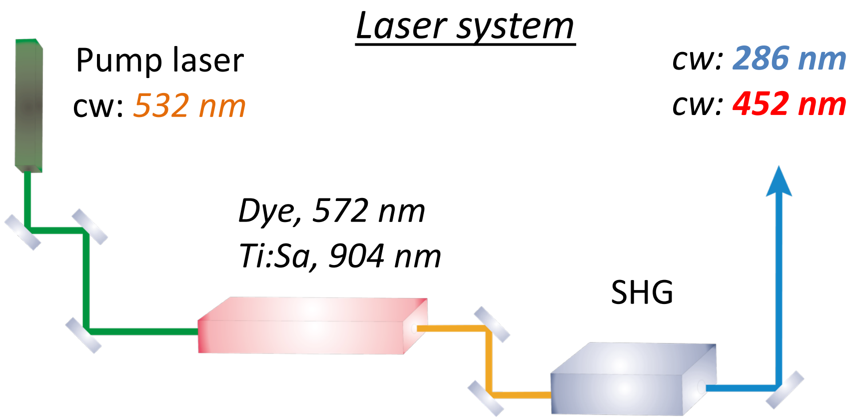
- Production rates of ions of interest will be low;
- Wavelengths are difficult to produce

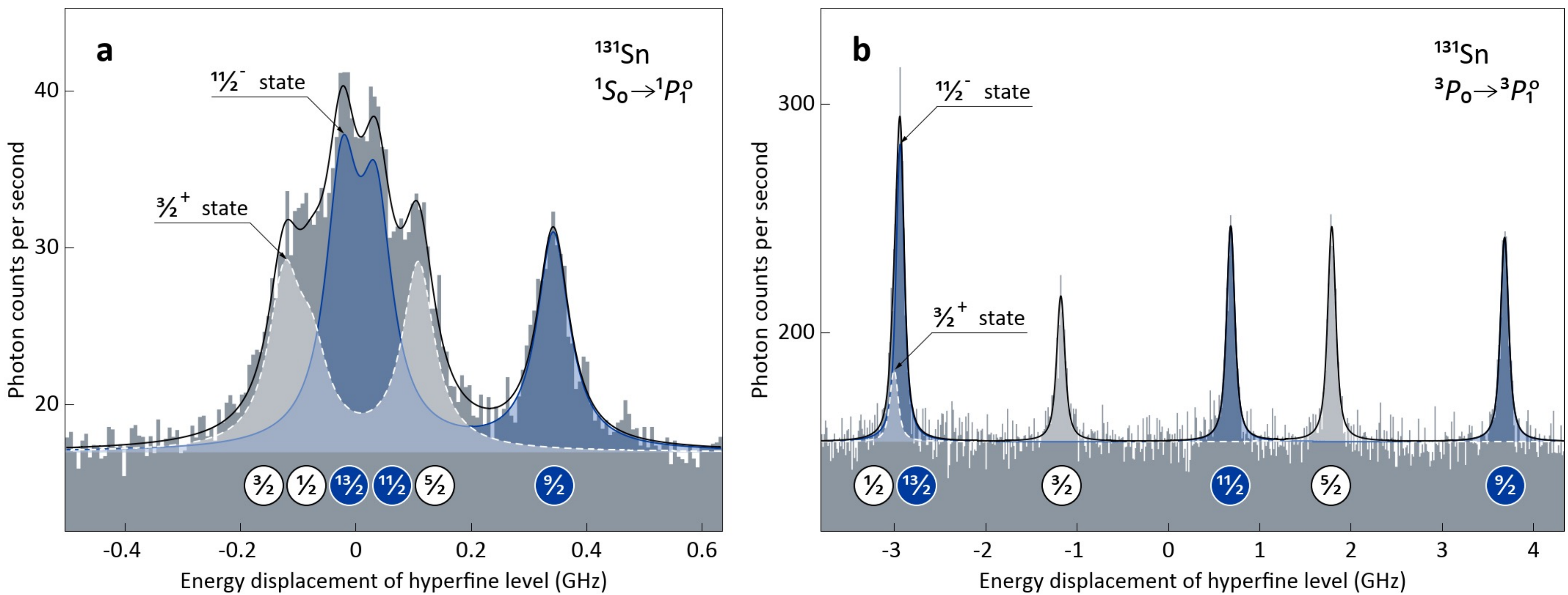
Aim:

- Find a spectroscopic scheme that is efficient, sensitive and possible to produce

Experimental set-up, COLLAPS at ISOLDE/CERN

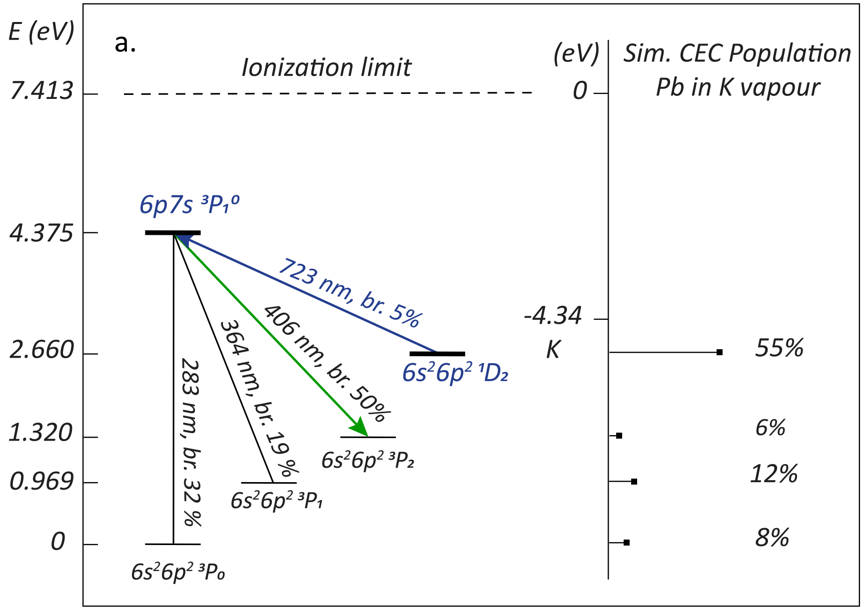






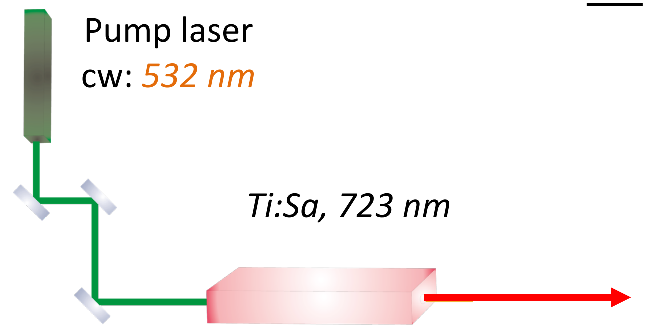
D. T. Yordanov, L. V. Rodríguez, et al. Commun. Phys. ***3****, 107 2020*

Experimental set-up, COLLAPS at ISOLDE/CERN

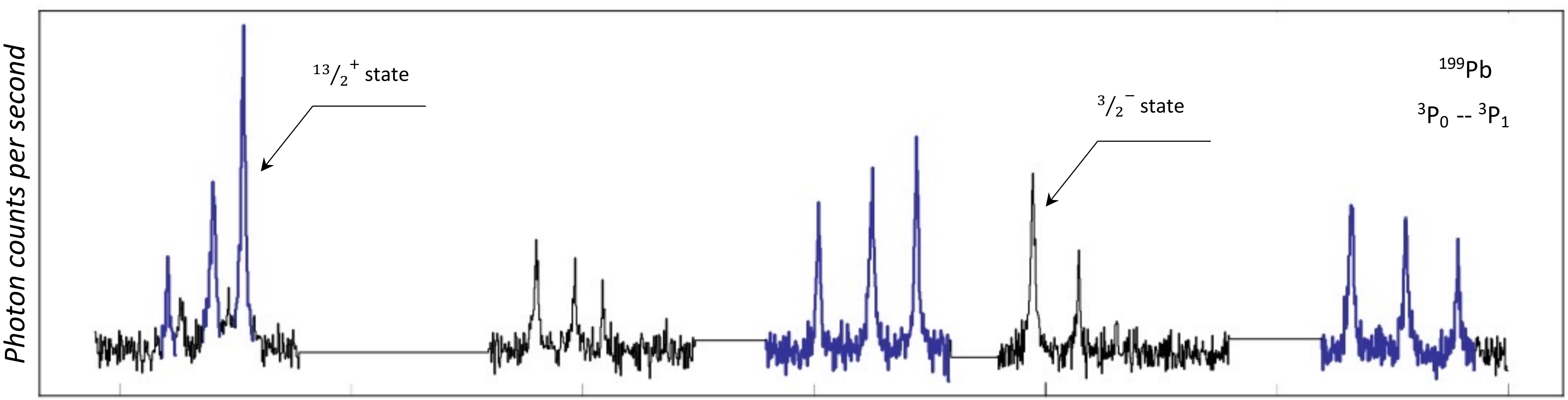


Laser system

Pb



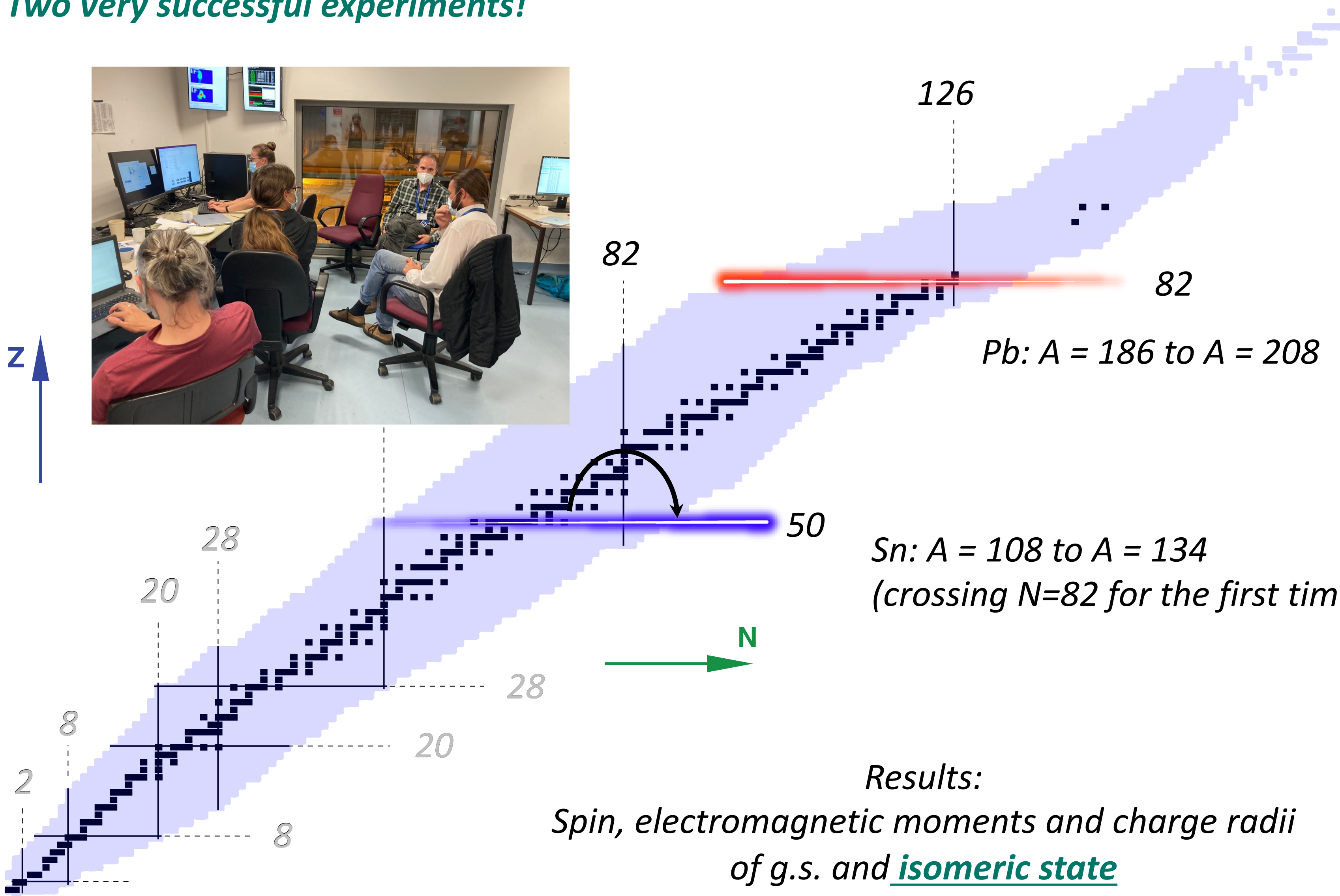
Example HFS spectra of ^{201}Pb in the 723nm transition



L. V. Rodríguez, et al. INTC-CERN, 2021

Recent results, from Sn to Pb

Two very successful experiments!



Pb: A = 186 to A = 208

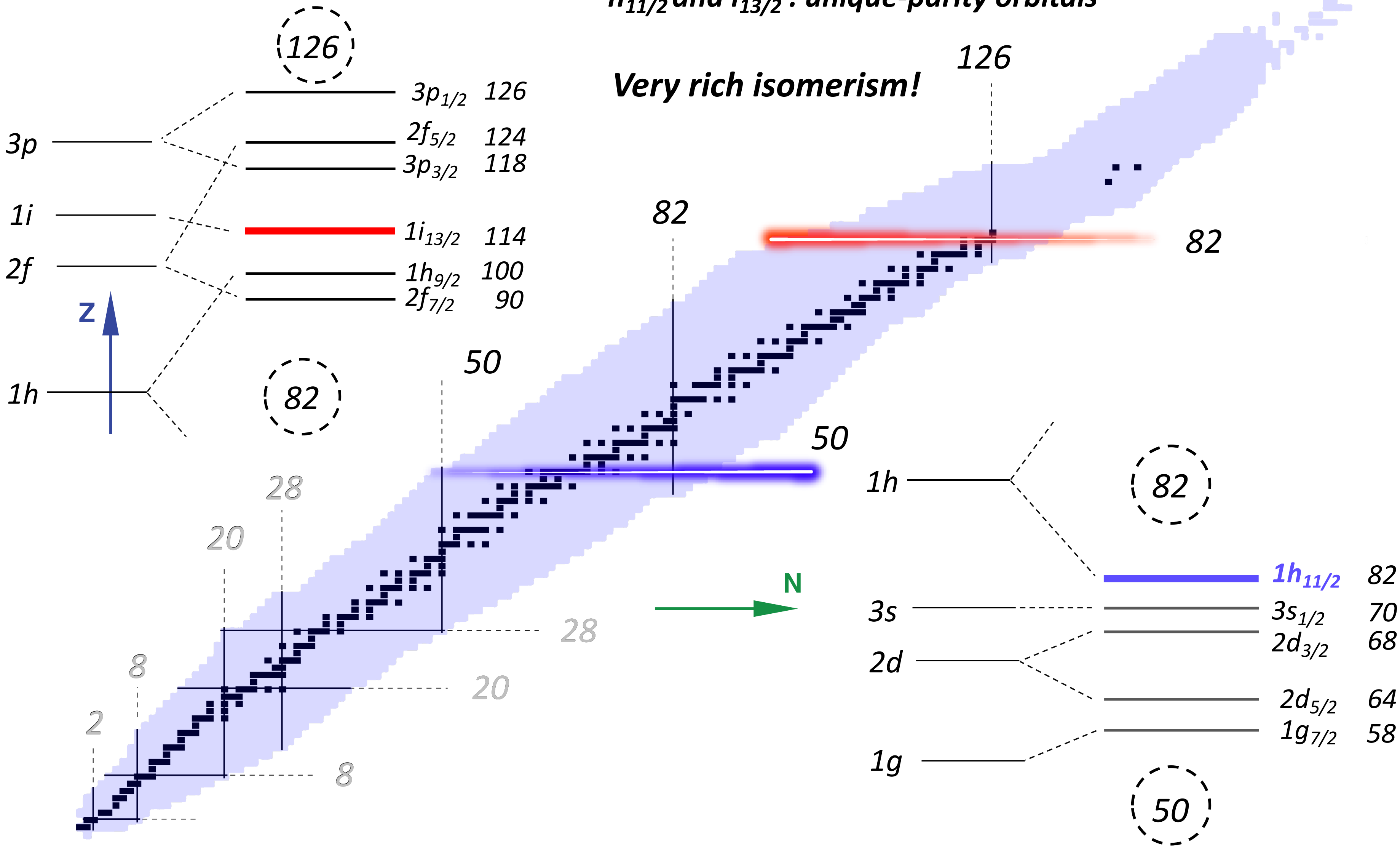
Sn: A = 108 to A = 134
(crossing N=82 for the first time)

Results:
*Spin, electromagnetic moments and charge radii of g.s. and **isomeric state***

Recent results, from Sn to Pb

Spherical shell model
Neutron orbitals (blue: Sn, red: Pb)

Isomeric states:
$h_{11/2}$ and $i_{13/2}$: unique-parity orbitals



Recent results, from Sn to Pb

Linear trends in Q observed in Cd (Sn-2p)

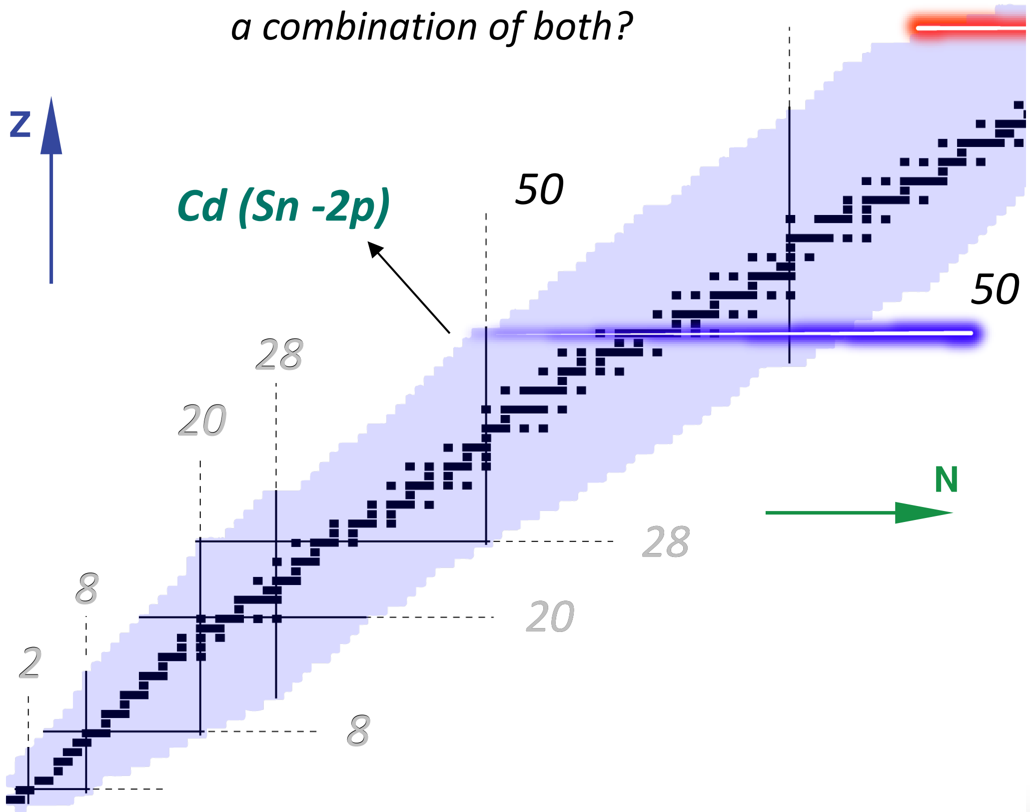
Produced by the neutrons (seniority)

or

by the two p-holes

or

a combination of both?



Selected for a Viewpoint in *Physics*
PRL **110,** 192501 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Spins, Electromagnetic Moments, and Isomers of $^{107-129}$Cd

D. T. Yordanov,[1,2,*] D. L. Balabanski,[3] J. Bieroń,[4] M. L. Bissell,[5] K. Blaum,[1] I. Budinčević,[5] S. Fritzsche,[6] N. Frömmgen,[7] G. Georgiev,[8] Ch. Geppert,[6,7] M. Hammen,[7] M. Kowalska,[2] K. Kreim,[1] A. Krieger,[7] R. Neugart,[7] W. Nörtershäuser,[6,7] J. Papuga,[5] and S. Schmidt[6]

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[7]*Institut für Kernchemie, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany*
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(Received 28 January 2013; published 6 May 2013)

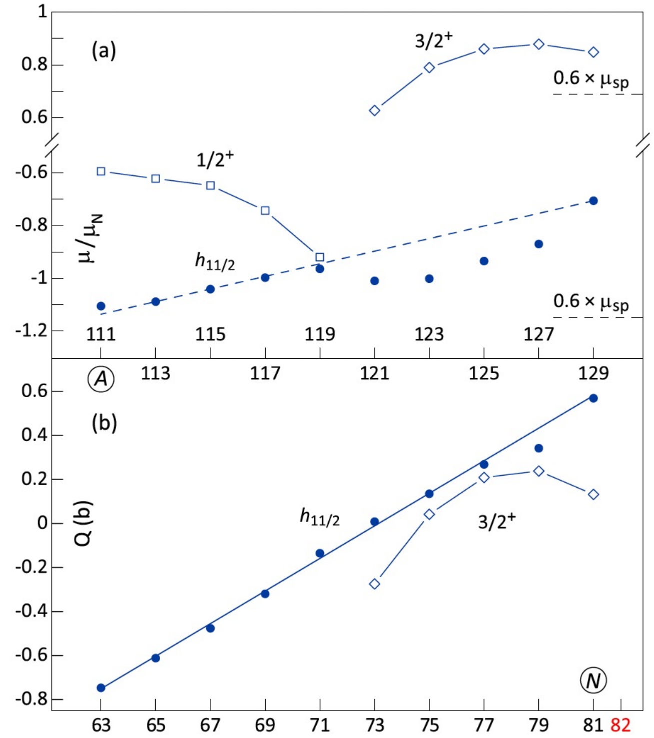
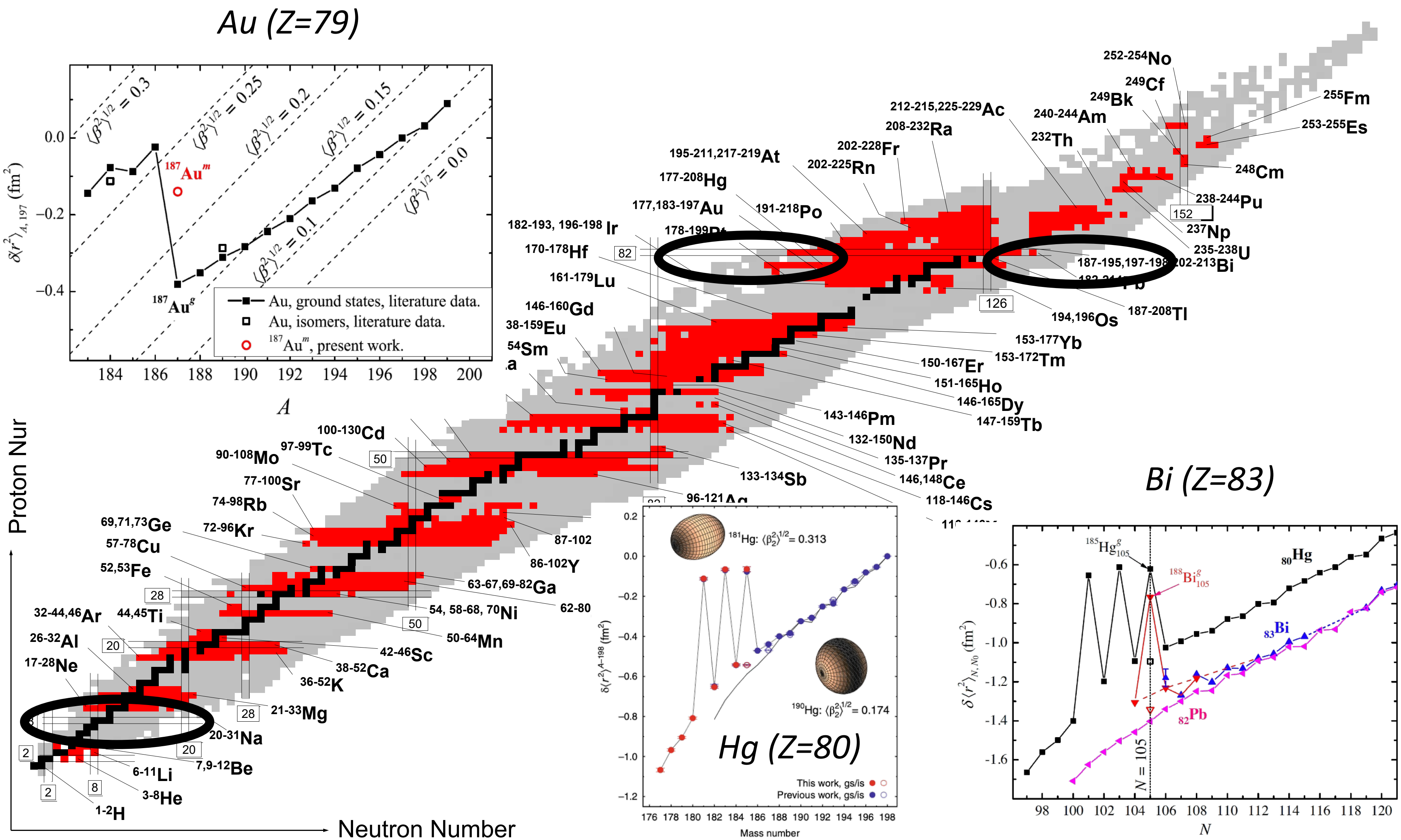


FIG. 2 (color online). Magnetic (a) and quadrupole (b) moments of $^{111-129}$Cd from this work. The experimental error bars are smaller than the markers. A straight line is fitted through the $h_{11/2}$ quadrupole moments, consistent with Eq. (2). The dashed line indicates the effect of core polarization.

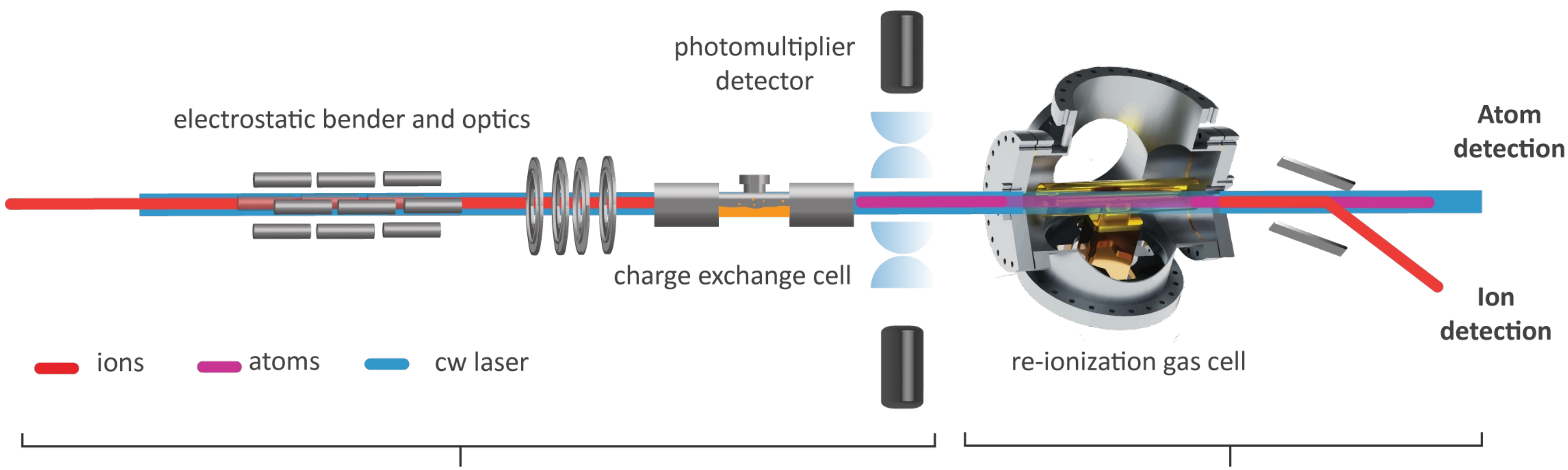
Perspectives

Motivation: Pushing COLLAPS to the limit

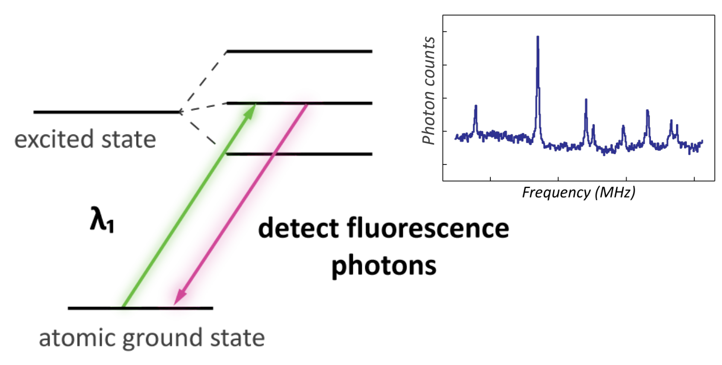


Perspectives

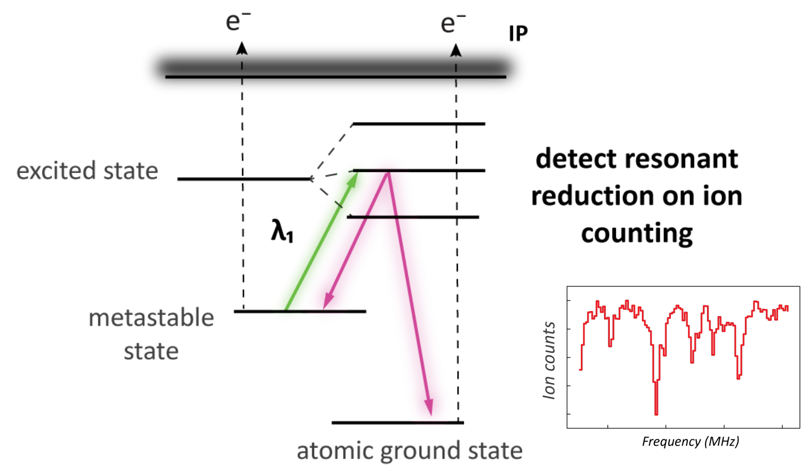
Ultra-high sensitive set-up for collinear laser spectroscopy



a. resonant excitation and photon detection



b. state selective re-ionization and atom/ion detection

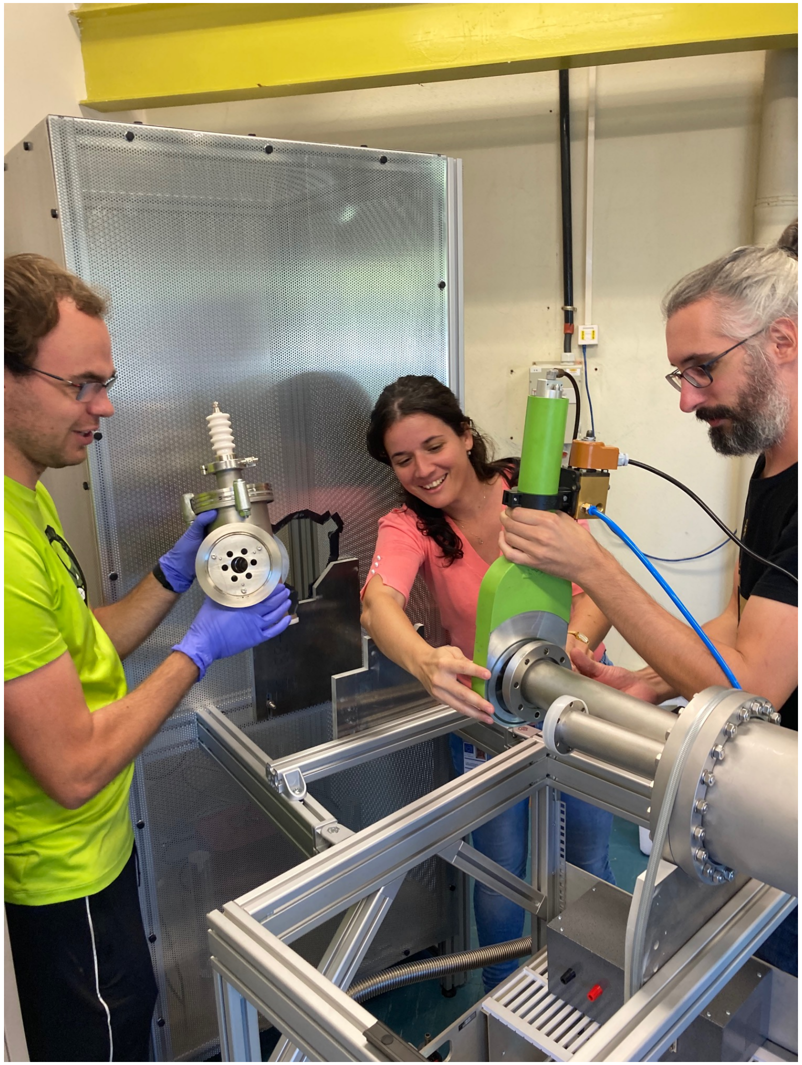


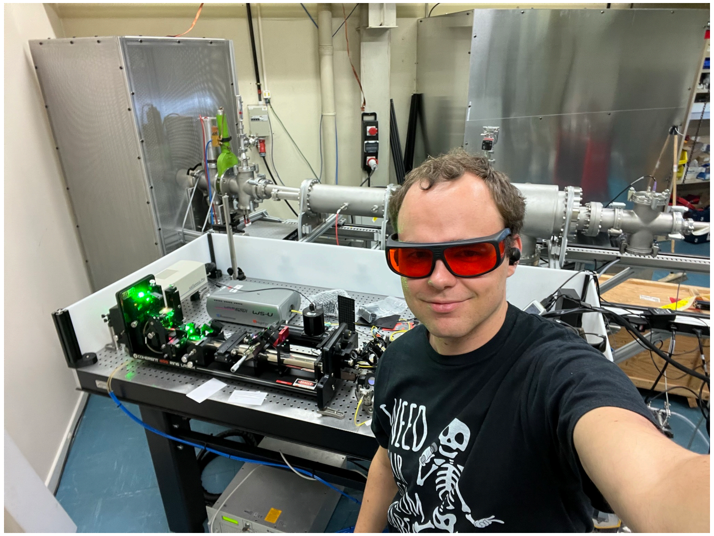
COLLAPS: 10^4 ions/s bunched beam

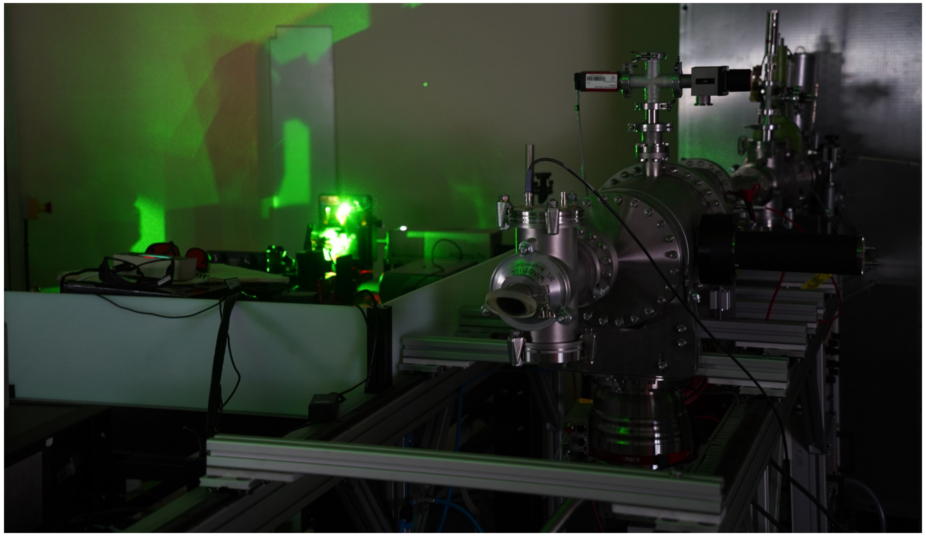
COLLAPS+ re-ionization: 10 - 100 ions/s, continuous beam

Perspectives

Work in progress …







Thank you for your attention!