

In-Gas Laser Ionization and Spectroscopy: A quest for the atomic and nuclear structure of very exotic nuclei

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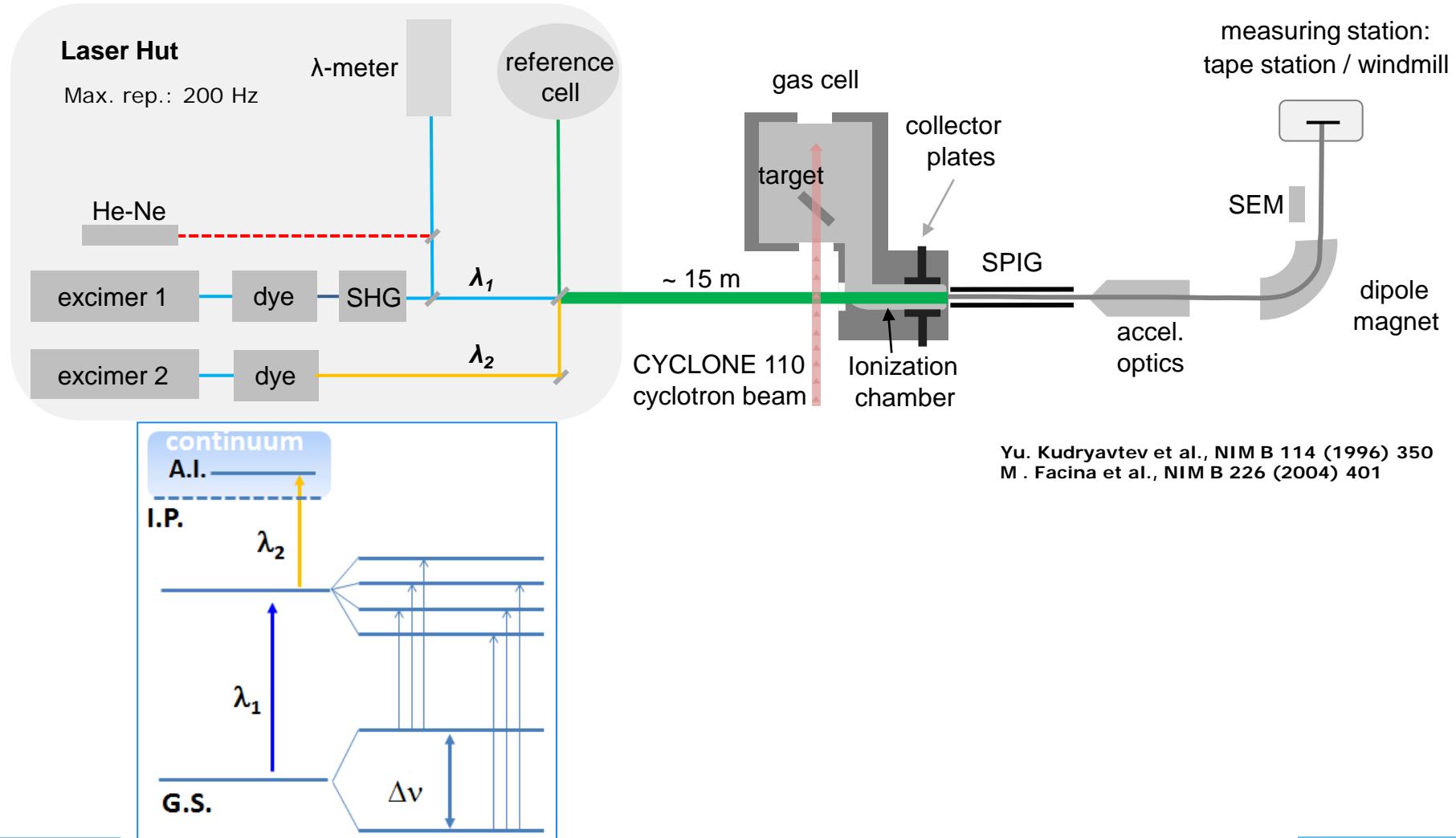


Outline

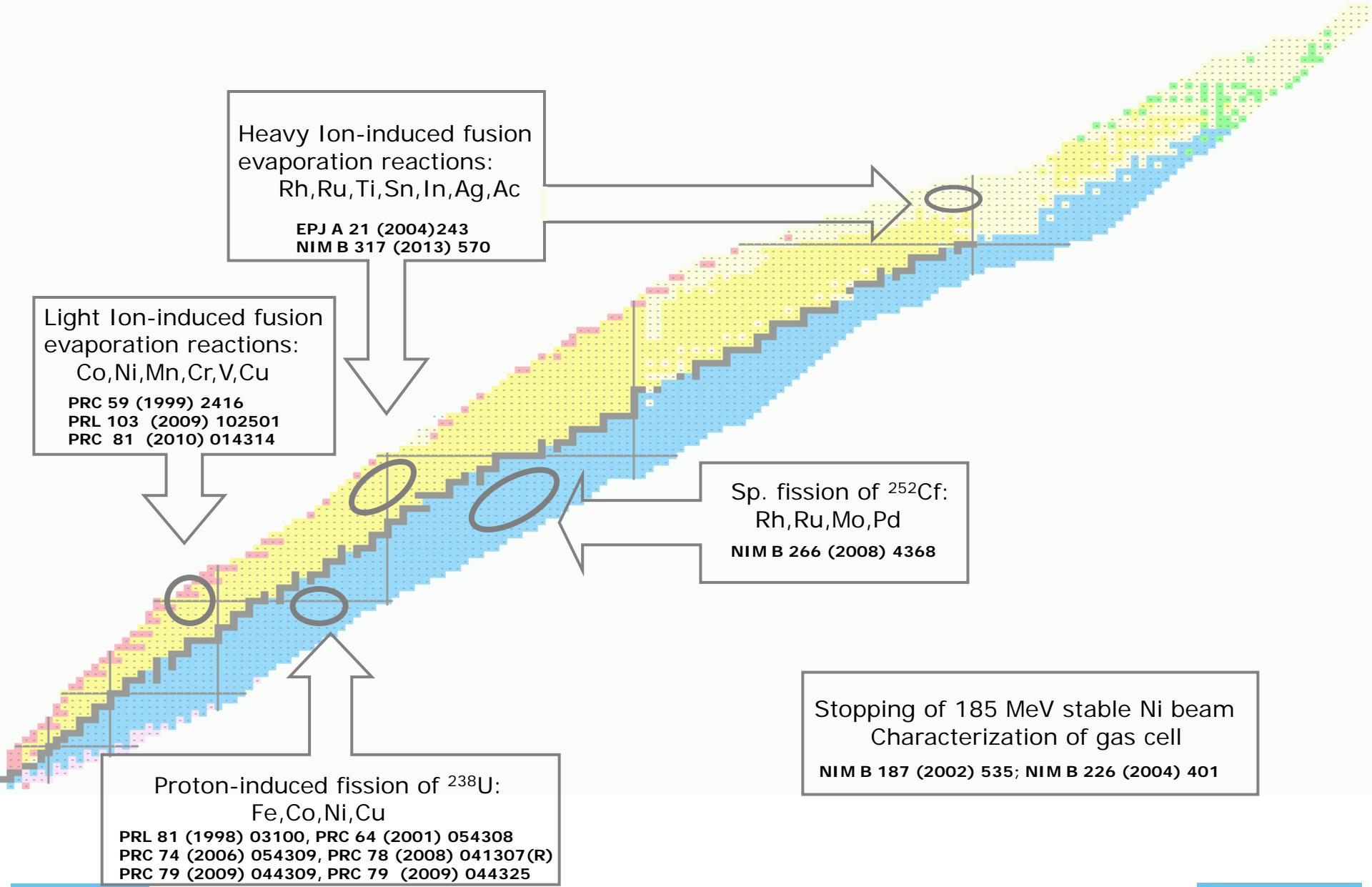
- Production of radioactive beams by RILIS
- Laser spectroscopy at the LISOL facility
- Towards high-resolution in-source laser spectroscopy
- Outlook

Resonance Ionization Laser Ion Source – Gas Cell

- Leuven Isotope Separator On-Line (LISOL) facility:
In-Gas Laser Ionization and Spectroscopy of RIBs

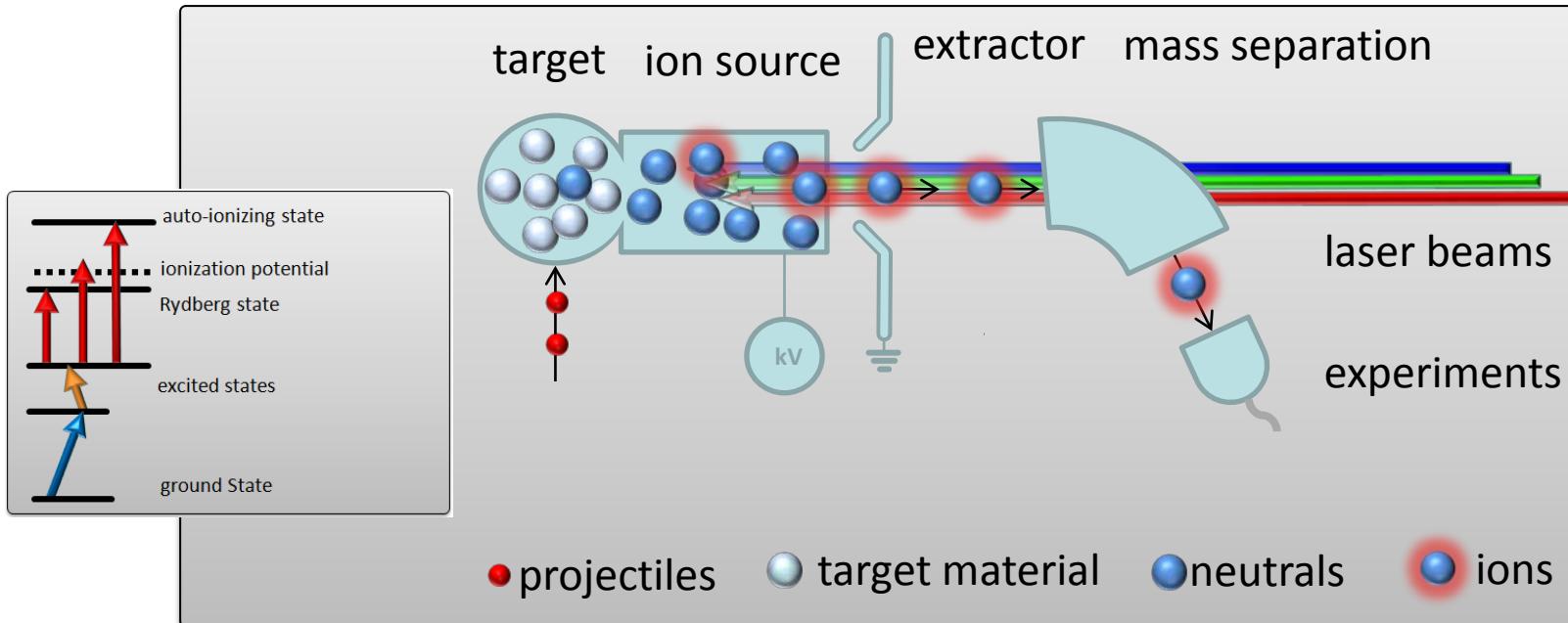


LISOL Beams since 1994

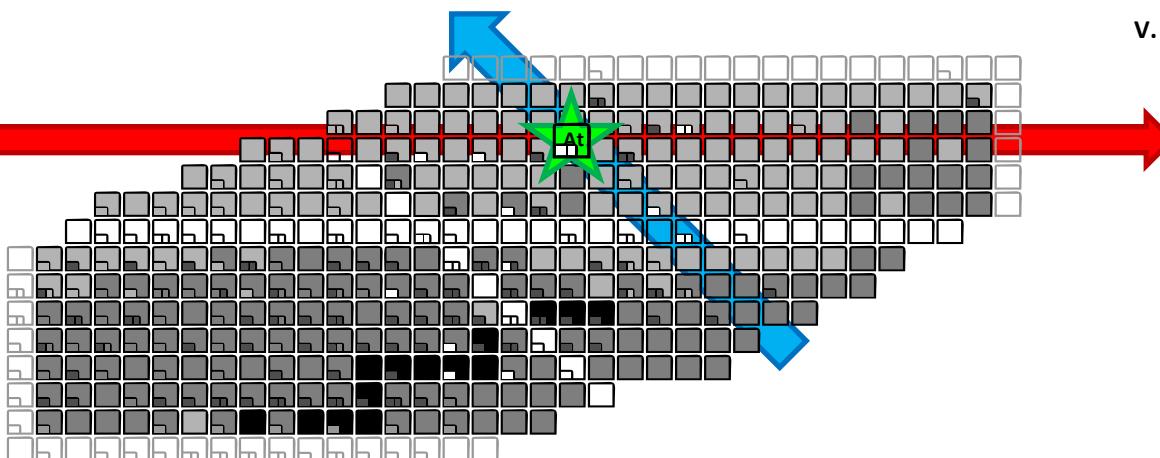


Resonance Ionization Laser Ion Source – Hot Cavity

- Production of RIBs with the Hot Cavity RILIS-ISOLDE



V. Mishin et al., NIM B73 (1993) 550



courtesy of S. Rothe

Hot Cavity vs Gas Cell RILIS

- SELECTIVE PRODUCTION OF EXOTIC NUCLEI

➤ Hot Cavity

- No refractory elements
- $T_{1/2}$ element dependent
- Sensitivity 1 ion/s (^{182}Pb)
- Resol~ 4 GHz (^{59}Cu) (Doppler)
- Produced Ion beams ~30 elements

G.D. Alkhazov et al., NIM A 280 (1989) 141

V. Mishin et al., NIM B73 (1993) 550

V.N. Fedosseev et al., Hyp. Int. 127 (2000) 409

U. Koester, Nucl. Phys. A 701 (2002) 441c

➤ Gas Cell

- All elements available
- $T_{1/2}$ cell evacuation time
- Sensitivity < 1 ion/s (^{97}Ag)
- Resol. ~ 4 GHz (^{59}Cu) (Pressure)
- Produced Ion beams ~15 elements

L. Vermeeren et al., PRL 73 (1994) 1935

Yu. Kudryavtsev et al. NIM B114 (1996) 350

Yu. Kudryavtsev et al. NIM B267 (2009) 2908

- SPECTROSCOPY

Hot Cavity @ IRIS & RILIS-ISOLDE

G.D. Alkhazov et al., NIM A 69 (1992) 517

A.E. Barzakh et al., PRC 61 (2000) 034304

U. Koester, et al., NIM B160 (2000) 528

V.N. Fedosseev et al., NIM B204 (2003) 353

In-Gas Cell @ LISOL

T. E. Cocolios et al., PRL 103 (2009) 102501

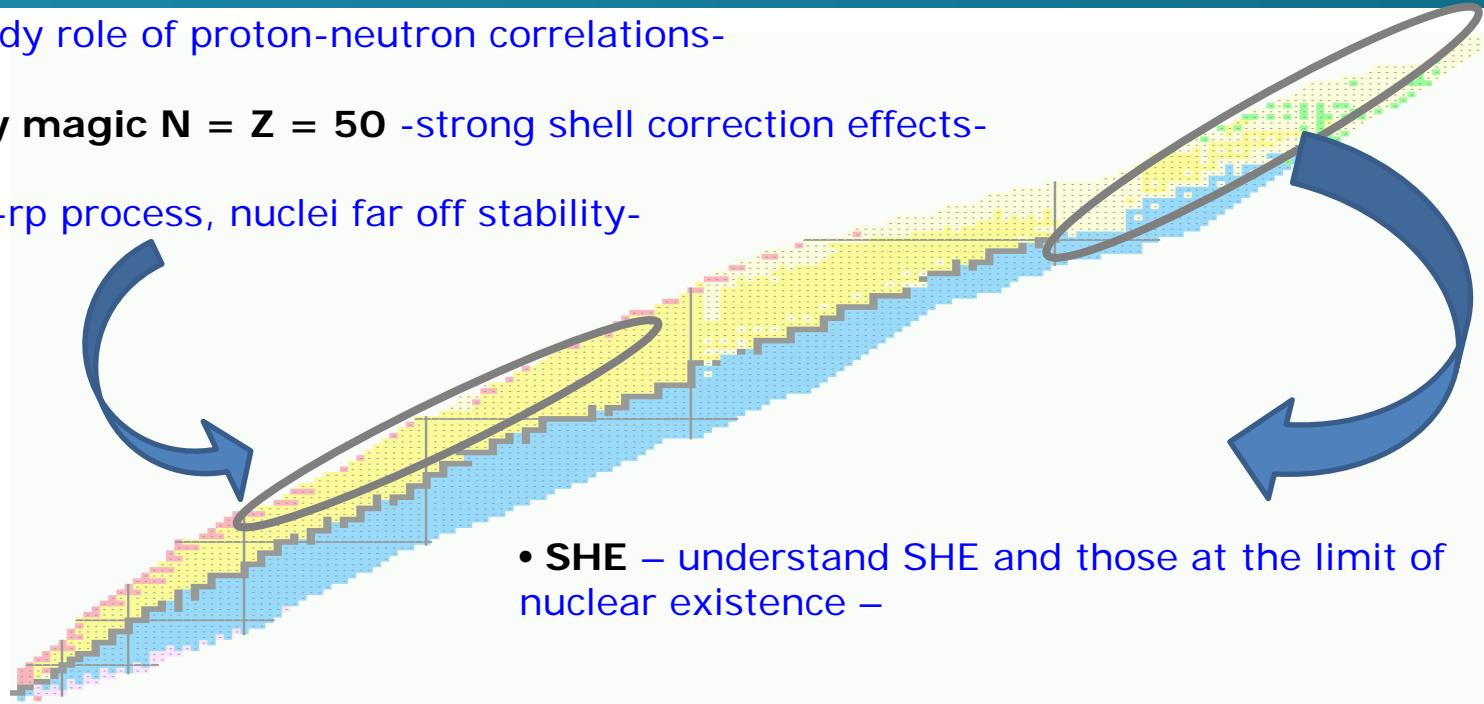
T. E. Cocolios et al., PRC 81 (2010) 014314

R. F. et al., PLB 728 (2014) 191



Physics program

- **$N = Z$ nuclei** -Study role of proton-neutron correlations-
- **Proximity doubly magic $N = Z = 50$** -strong shell correction effects-
- **Proton drip line** -rp process, nuclei far off stability-



→ test nuclear and atomic models and guide new theoretical developments

- In-Gas-Cell Laser Spectroscopy of neutron deficient Ag and Ac isotopes
- Towards high resolution In-Gas-Jet Laser Spectroscopy of rare isotopes

Laser spectroscopy & nuclear ground- and isomeric-state properties

Measured:

Isotope shifts

Isomer shifts

Hyperfine splitting

Deduced observables:
(model independent)

Sizes

Quadrupole Mom.

Dipole Mom.

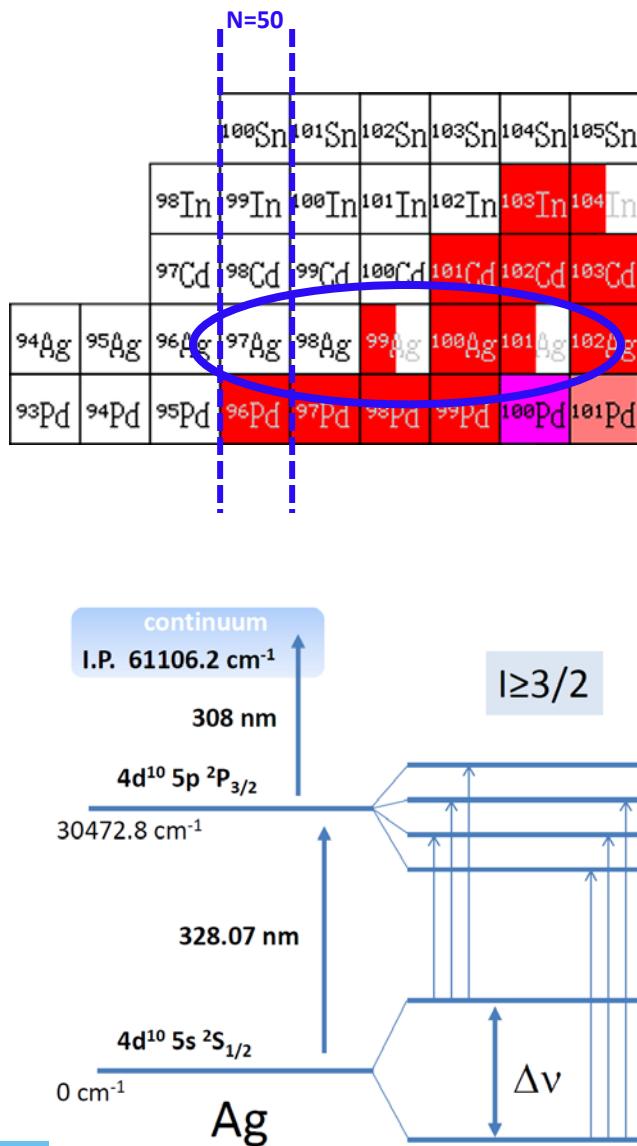
Spins

Inferred information:
(model dependent)

Shapes/deform. parameters

Single/few particle configurations

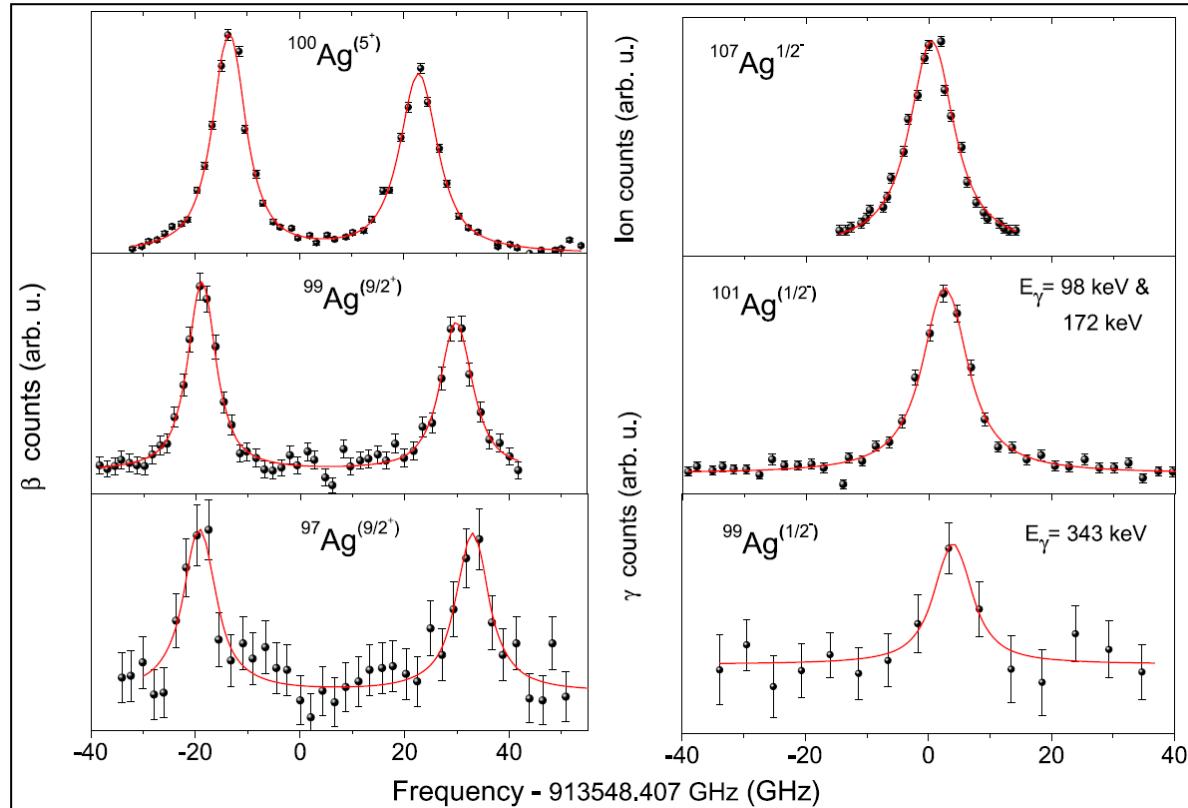
In-Gas-Cell Laser Spectroscopy of Ag



⁹²Mo(¹⁴N – 130 MeV, 2pxn) ^{104-x}Ag

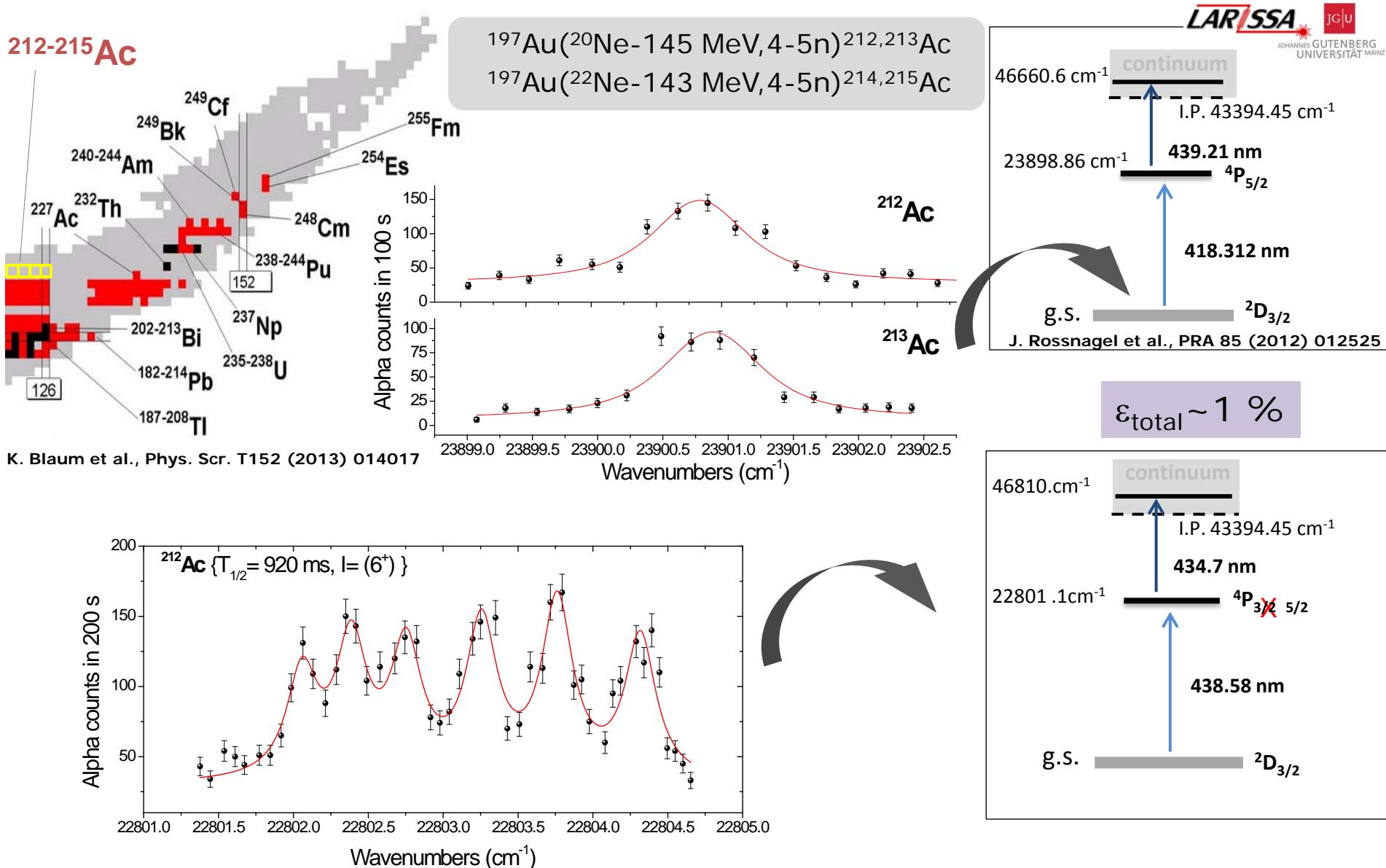
$^{64,\text{nat}}\text{Zn}(\text{Ar} - 125 \text{ MeV}, \text{pxn})^{101-\text{x}}\text{Ag}$

R.F. et al., Phys. Lett. B 728 (2014) 191

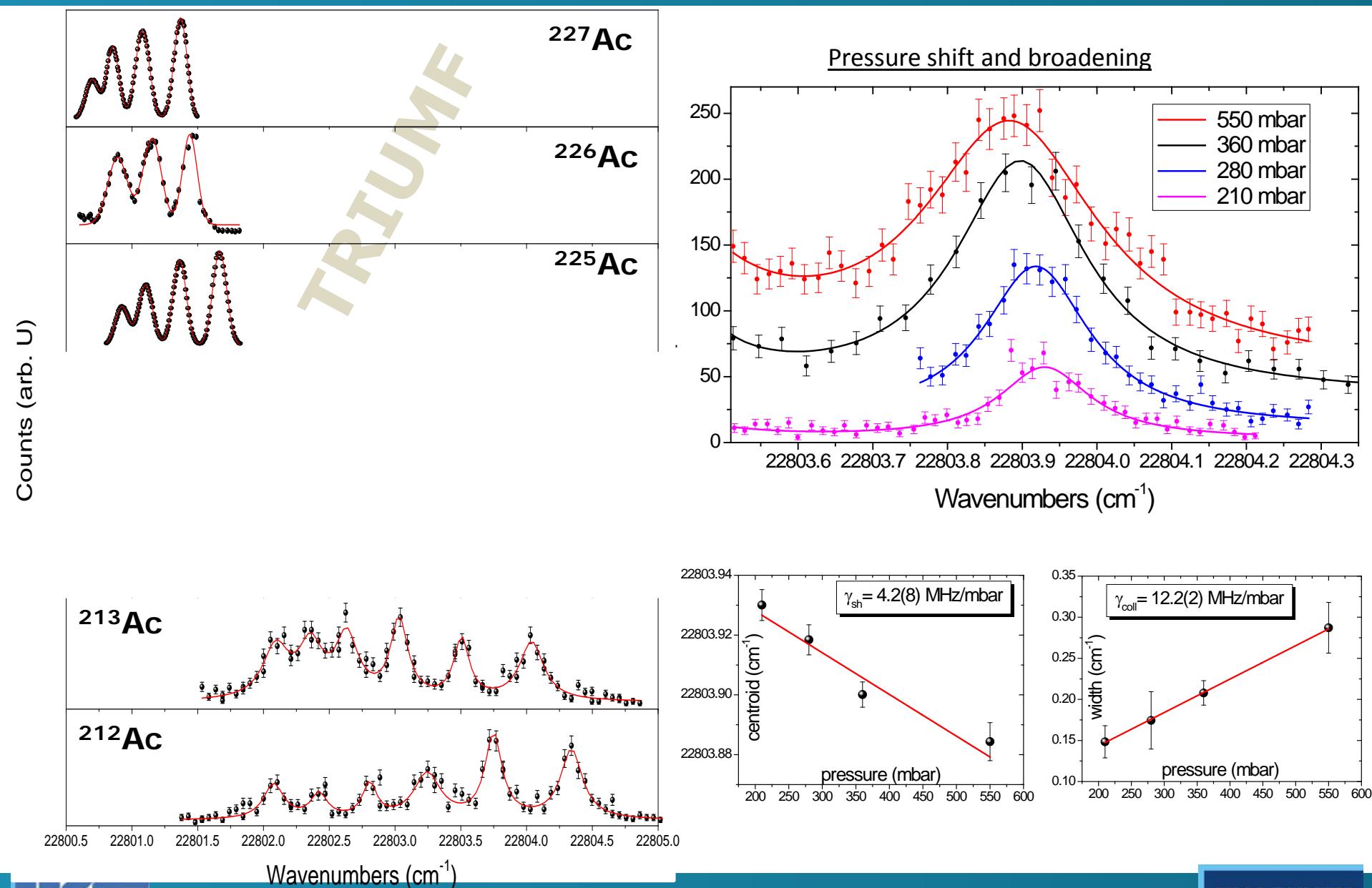


count rates: $^{101}\text{Ag}=2.3 \text{ pps}$, $^{97}\text{Ag}=0.9 \text{ pps}$
 $\varepsilon_{\text{total}} \sim 2 \%$

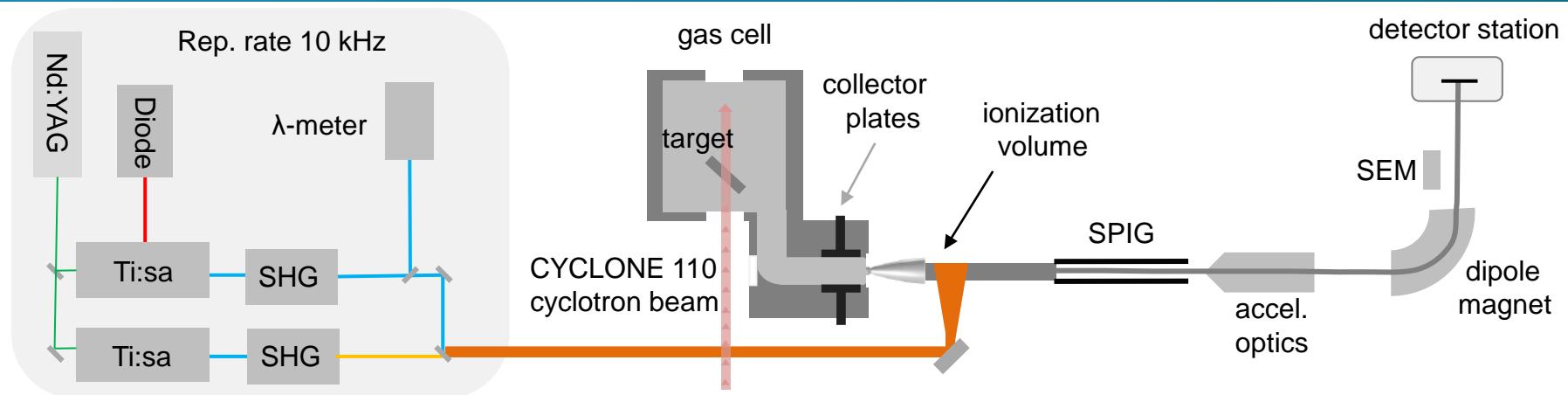
Production & First Spectroscopy of Ac



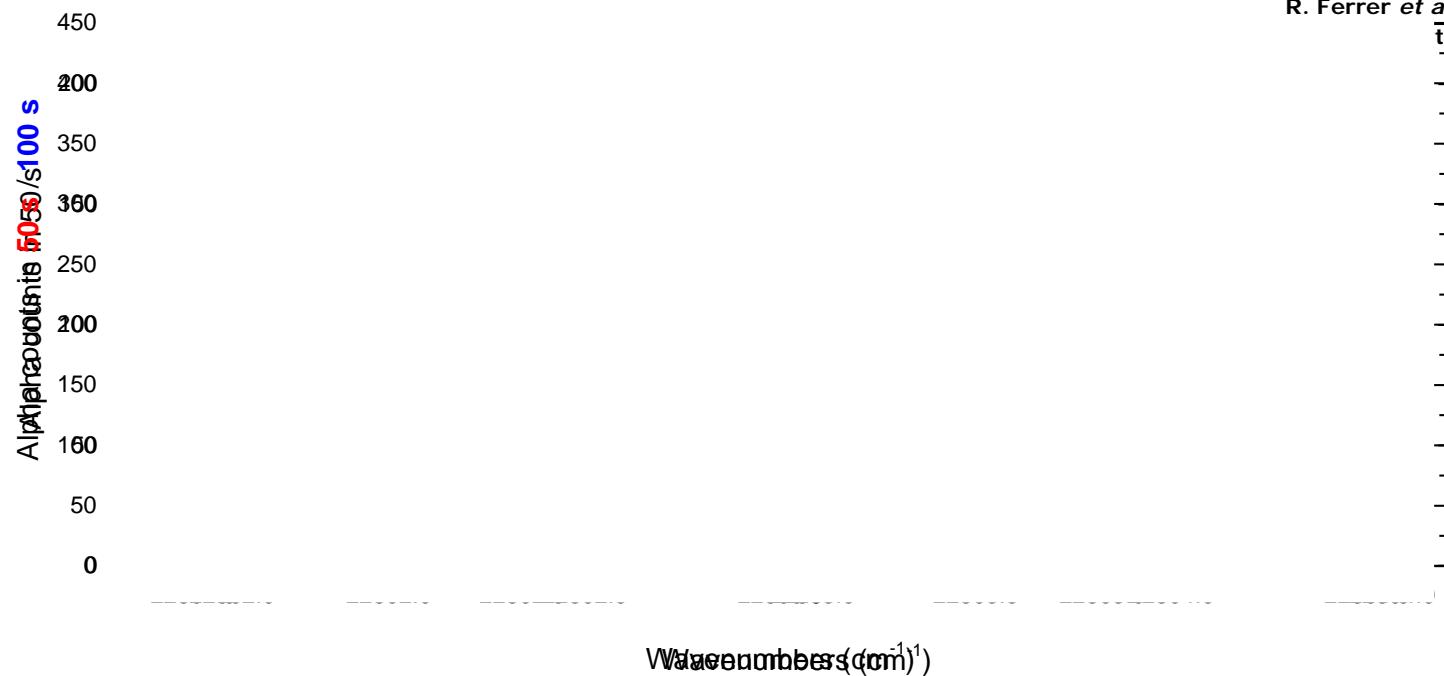
HFS of $^{212-215}\text{Ac}$ - 438 nm transition -



In-Gas Raman Spectroscopy of $^{24,25}\text{Ac}$



T. Sonoda *et al.*, NIM B267 (2009) 2918
R. Ferrer *et al.*, NIM B 291 (2012) 29
Isev *et al.*, NIM B 297 (2013) 7



Figures of merit:

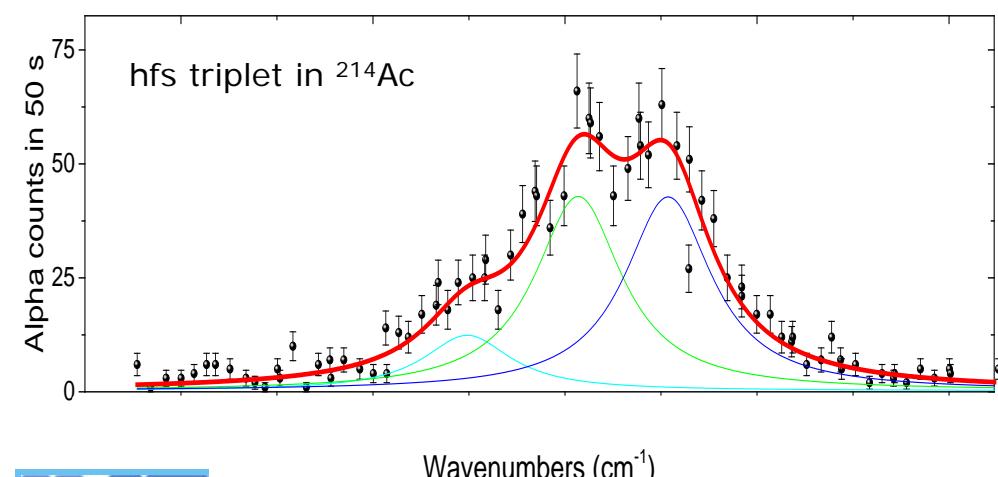
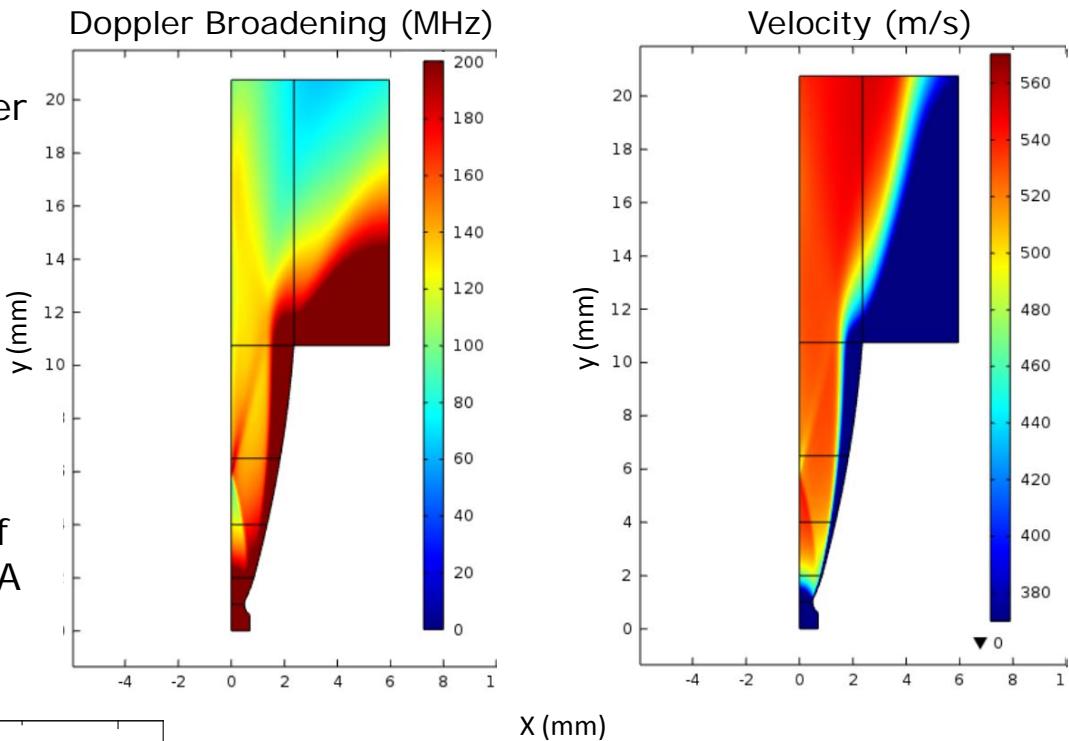
- ✓ Resolution ~ 5e-7 (FWHM = 400 MHz)
- ✓ Selectivity ~ 200
- ✓ Efficiency ~ 0.5%

In-Gas-Jet Spectroscopy of $^{214,215}\text{Ac}$

- Observed spectral widths → jet T and jet divergence, and laser power
- Reduction energy up to 80 nJ → singlet FWHM~300 MHz, mainly Gaussian contribution

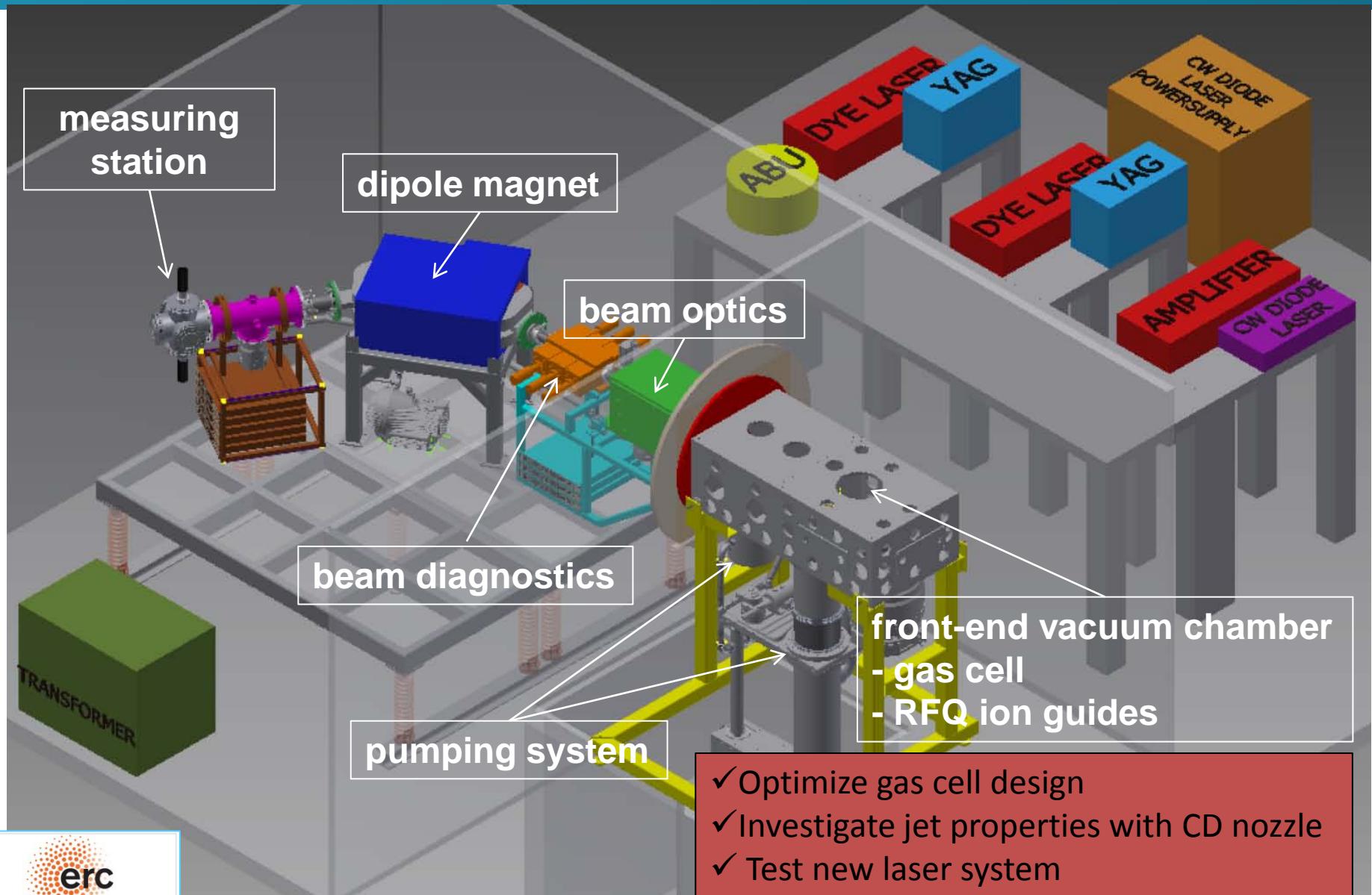
In-jet spectroscopy results in:

- 25-fold improvement in uncertainties of isotope shifts and magnetic hf constant A
- access to quadrupole moments as well



- Improve temporal overlap to increase efficiency → 1/10 to 10/10
- Design of a better nozzle and characterization of gas jets → **Jet visualization by PLIF**

HELIOS @ KU Leuven

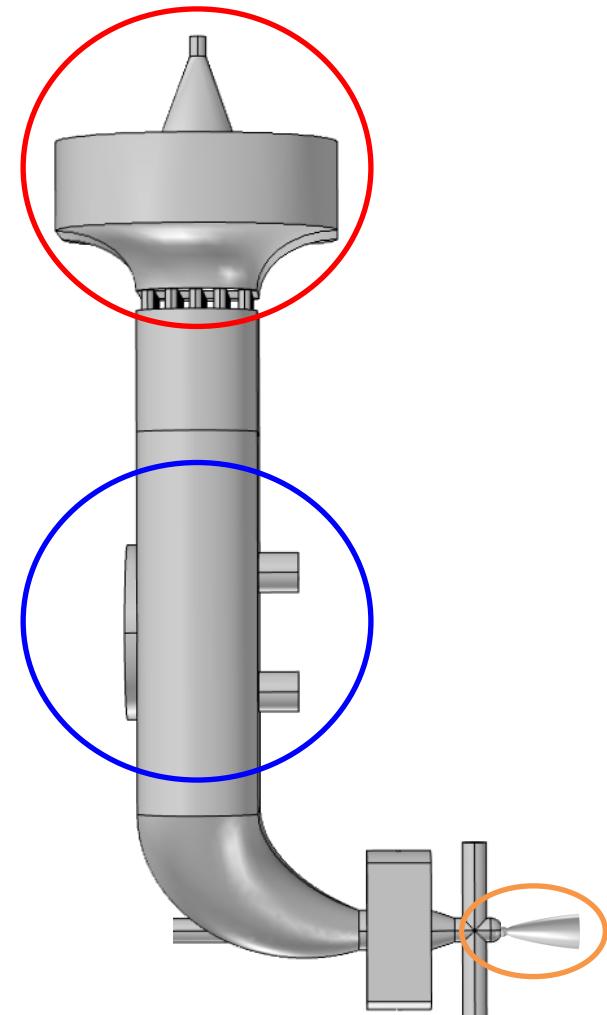


New Gas Cell Design

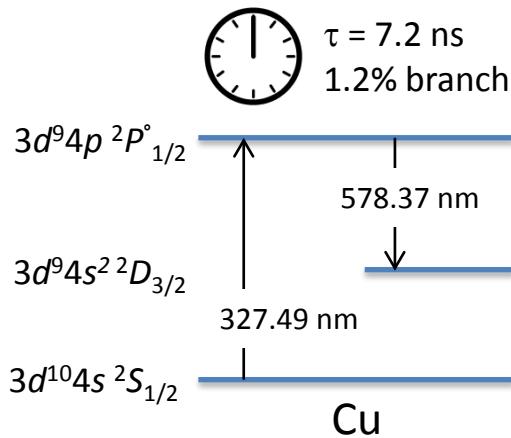
- The gas inlet
 - Obstacle to stop gas and reduce vortices
 - Honeycomb tube structure to produce a homogeneous flow through the cell

- The entrance window
 - Accept full beams

- The 'de Laval' nozzle
 - Produce a uniform quasi-parallel supersonic jet

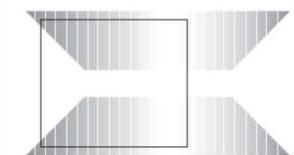
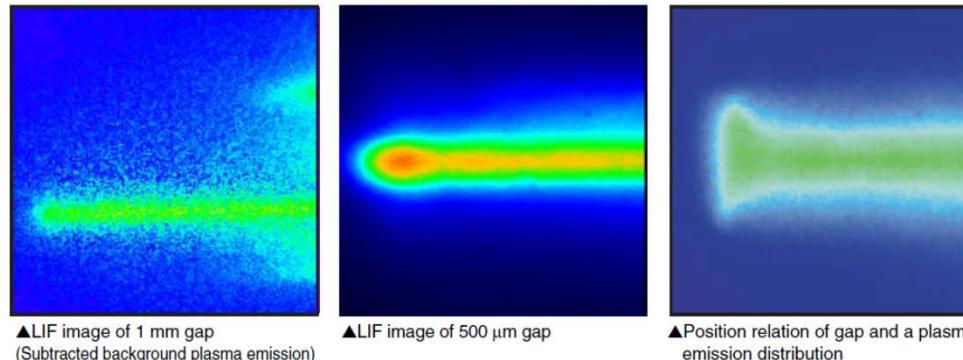


Jet visualization: PLIF Principle



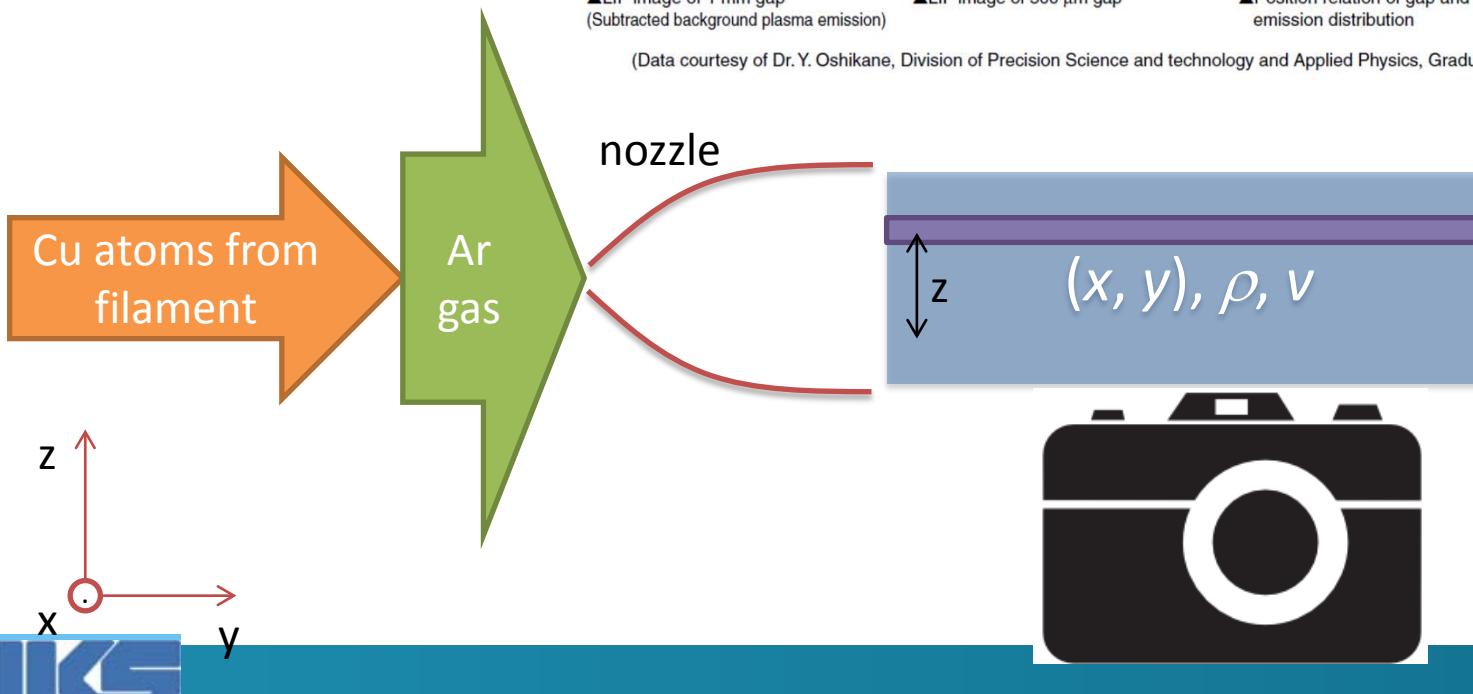
■ Visualization of CF₂ by LIF in a high frequency plasma

A plasma is generated by applying high frequency waves of 150 MHz to 6 mm in diameter alumina electrodes placed at a gap of 1 mm in a gas mixture (1 atm pressure) of He (99 %) and CF₂ (1 %).
(Excitation wavelength: 261.77 nm, gate width: 50 ns, optical filter spectral transmittance: 280 nm to 370 nm)



▲The illustration which saw the electrode from the side. Left figure is ultraviolet light image in square region. Green region shows plasma of 500 μm gap.

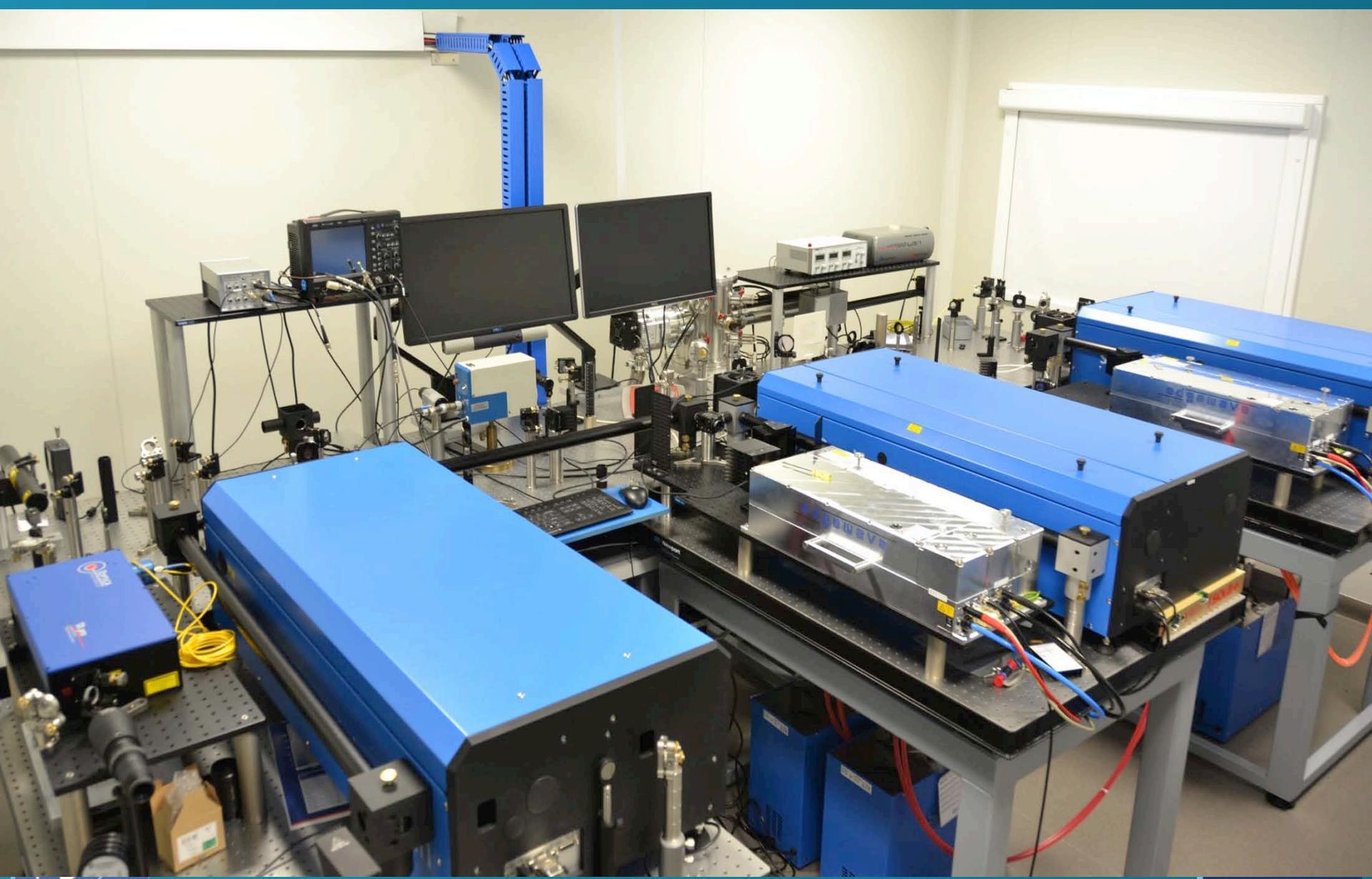
(Data courtesy of Dr. Y. Oshikane, Division of Precision Science and technology and Applied Physics, Graduate School of Engineering, Osaka University, Japan)



HELIOS –Jet Room–

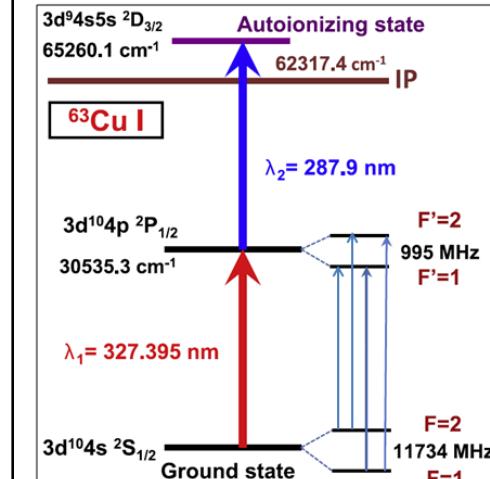
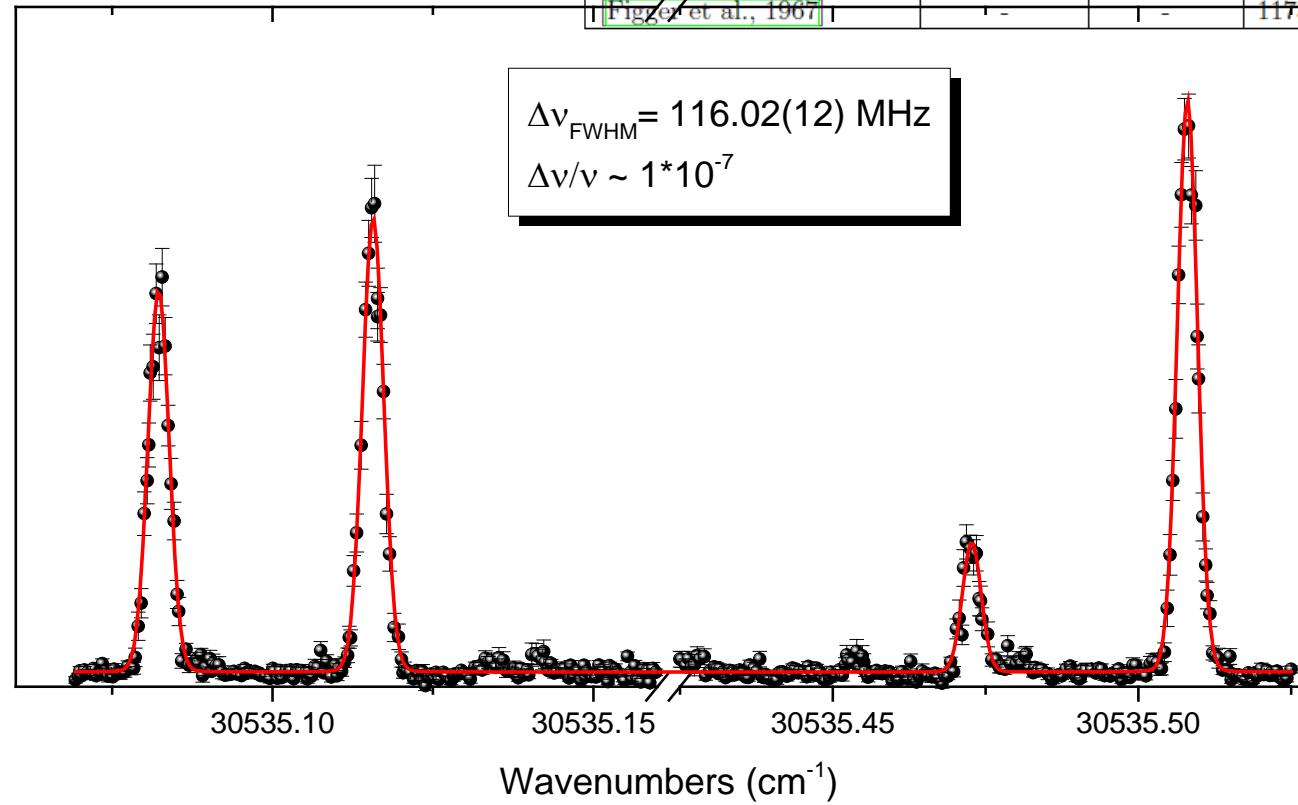


HELIOS –Laser Room–



HFS ^{63}Cu @ HELIOS

	HS _{ex} (MHz)	A _{ex} (MHz)	HS _{gs} (MHz)	A _{gs} (MHz)
HELIOS	1042(22)	521(11)	11726(23)	5863(12)
Kudryavtsev et al., 2013	995(30)	498(15)	-	-
Bergström et al., 1989	1013.2(20)	506.6(10)	-	-
Ting and Lew, 1957	-	-	11733.83(1)	5869.15(5)
Sonnenschein et al., 2014	-	-	11774(40)	5887(20)
Cocolios et al., 2010	-	-	11716(20)	5858(10)
Figge et al., 1967	-	-	11733.817412(40)	5866.908706(20)



→ Further optimization of amplified diode laser radiation in progress

REGLIS³ @ SPIRAL2

^{94}Ag

High-spin isomerism ($J=21^+$)
 β,β -delayed p, 1p-, and 2-p! emission

^{80}Zr

Shape coexistence and single-particle behavior



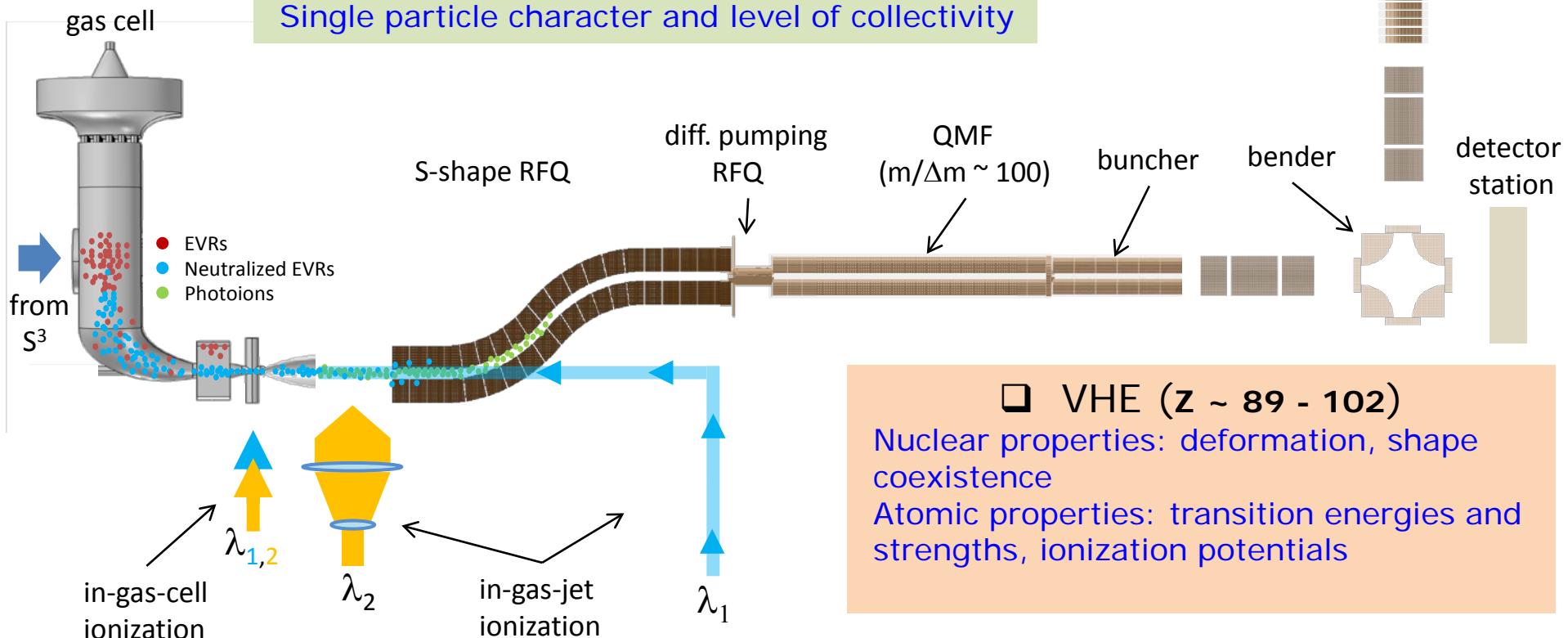
$^{107-101}\text{Sn}$

Test validity of shell-model predictions
Single particle character and level of collectivity

MR ToF
 $(m/\Delta m \sim 10^5)$



detector station



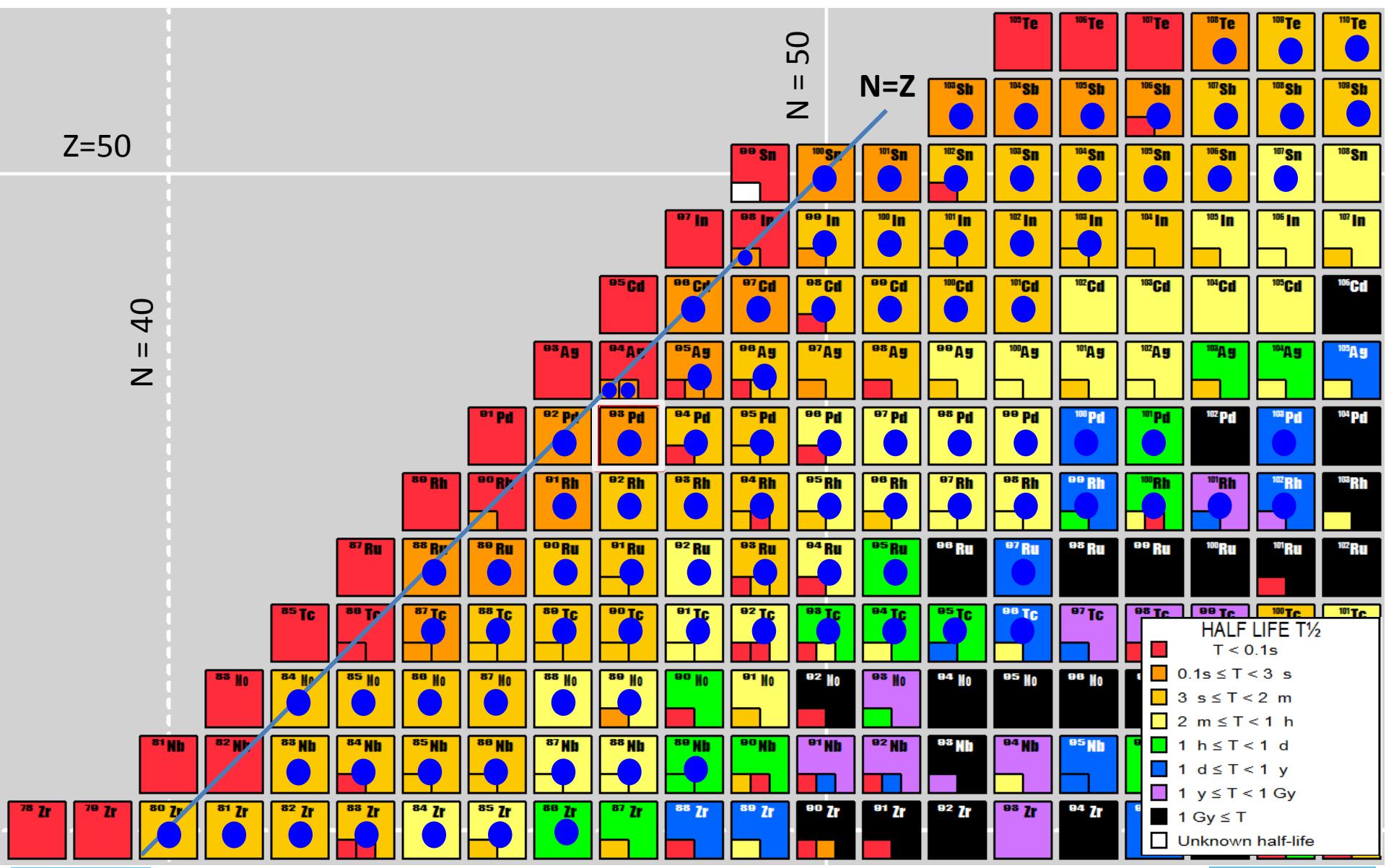
VHE ($z \sim 89 - 102$)

Nuclear properties: deformation, shape coexistence
Atomic properties: transition energies and strengths, ionization potentials

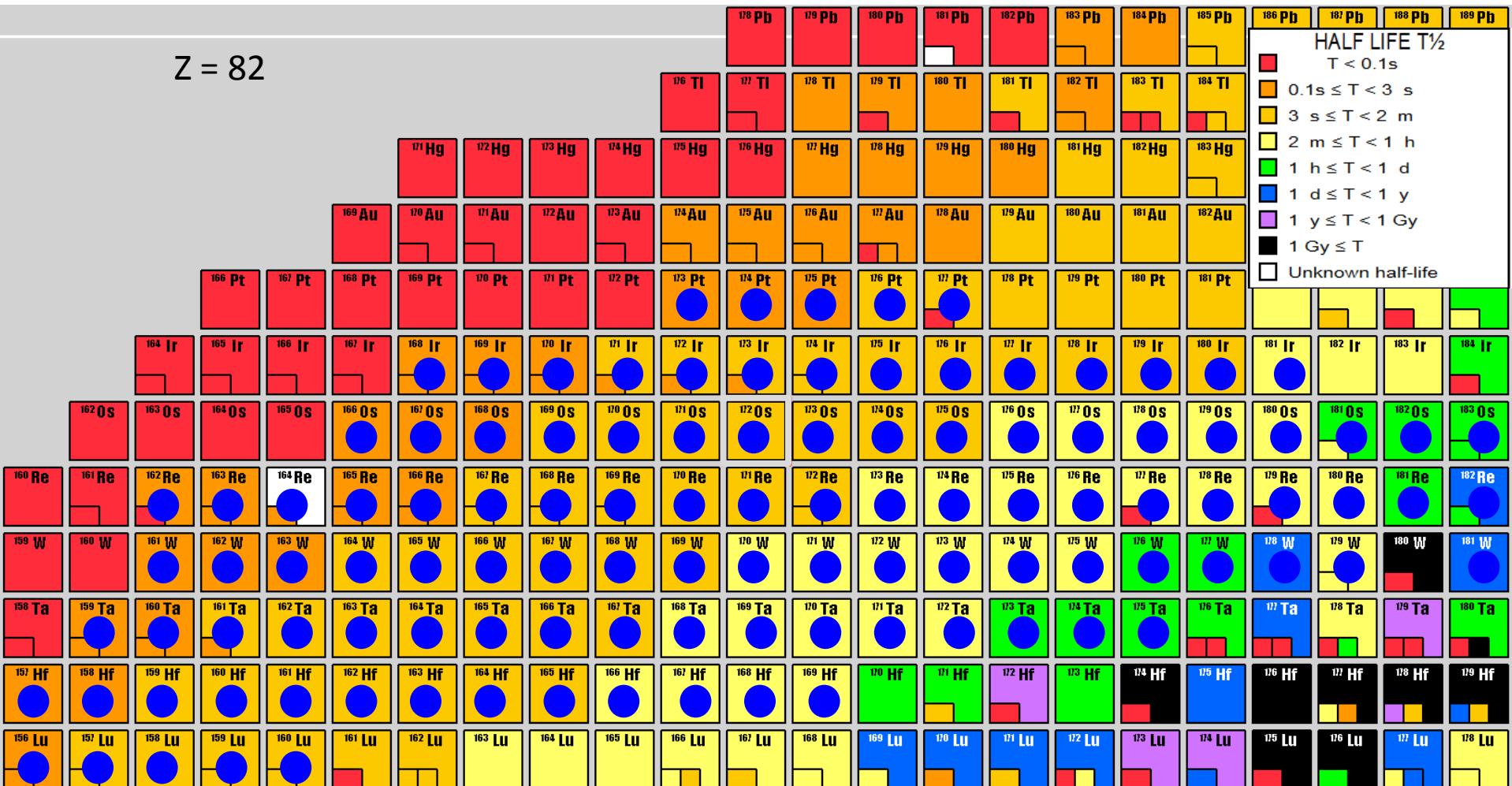
R. F. et al., NIM B 317 (2013) 570



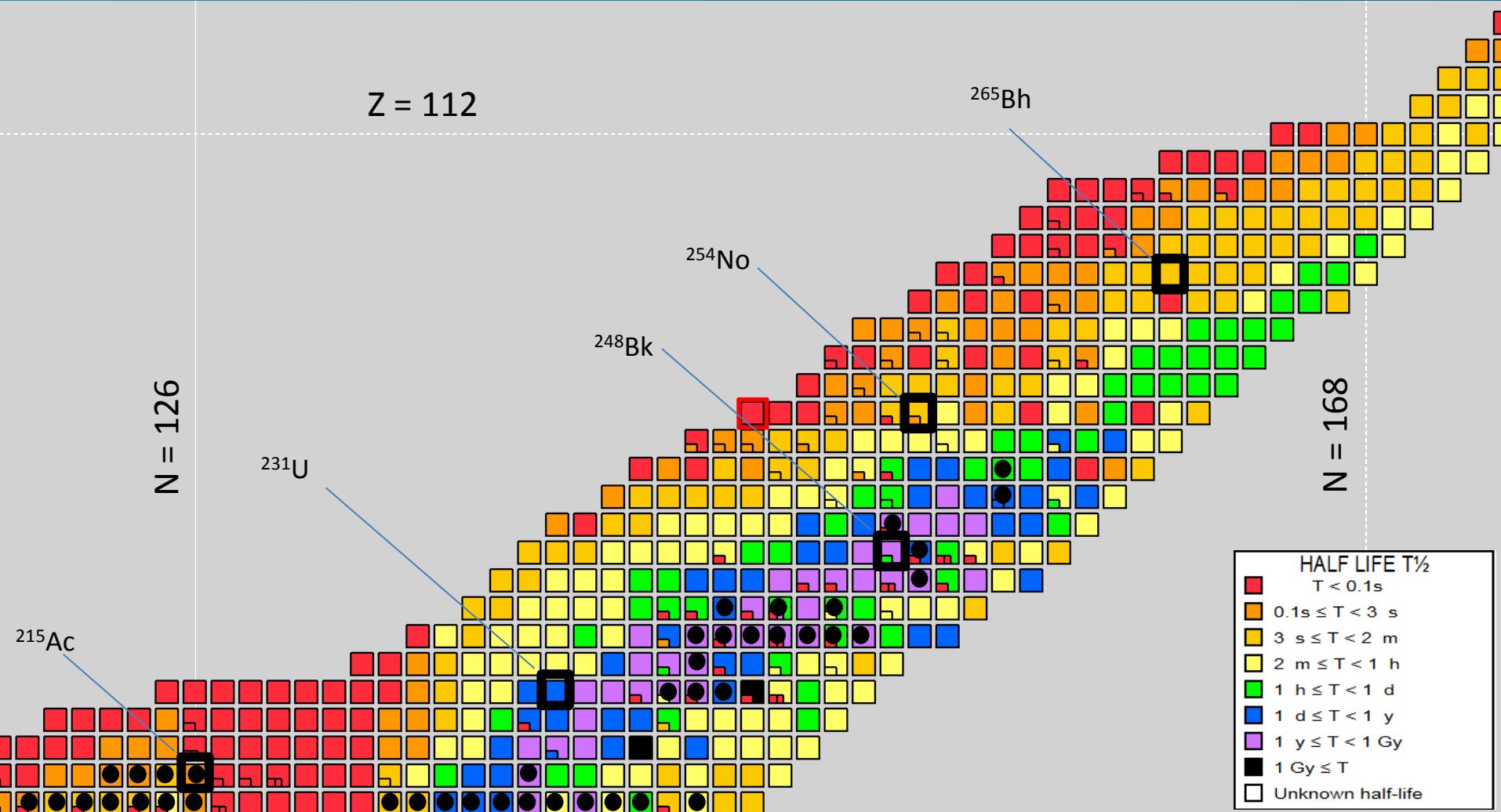
Candidates for IGLIS in the ^{100}Sn region



IGLIS on refractory elements



Candidates for IGLIS in the SHE region



- Atomic transitions need to be found prior to laser spectroscopy studies
- Interplay between theory and experiments is required to extract nuclear ground- and isomeric-state properties

Acknowledgments

LISOL team

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A. Zadvornaya

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JYFL University of Jyväskylä: I. Moore, V. Sonnenschein

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KU LEUVEN