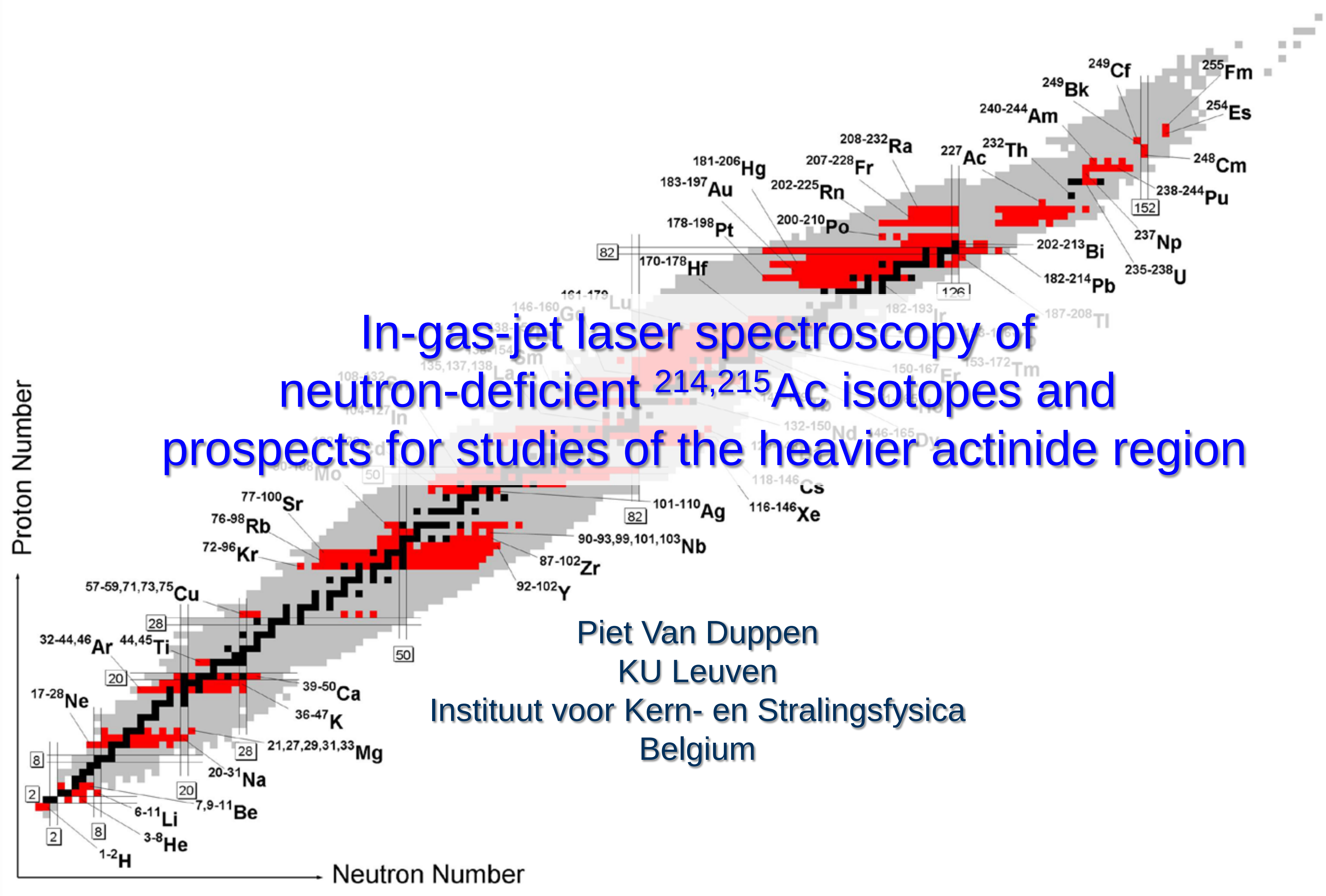



# In-gas-jet laser spectroscopy of neutron-deficient $^{214,215}$Ac isotopes and prospects for studies of the heavier actinide region


Piet Van Duppen
KU Leuven
Instituut voor Kern- en Stralingsfysica
Belgium


KU LEUVEN

K. Blaum,- Phys. Scr. T152 (2013) 014017

# Outline

• The Heavy Element Laser Ionization Spectroscopy (HELIOS) project:
Motivation →

**EPJ Web of Conferences**
**Volume 131 (2016)**

**Nobel Symposium NS 160 – Chemistry and Physics of Heavy and Superheavy Elements**

**Bäckaskog Castle, Sweden, May 29 – June 3, 2016**
D. Rudolph (Ed.)

• Laser ionization spectroscopy of $^{212-215}$Ac at the Leuven Isotope Separator On Line (LISOL) facility

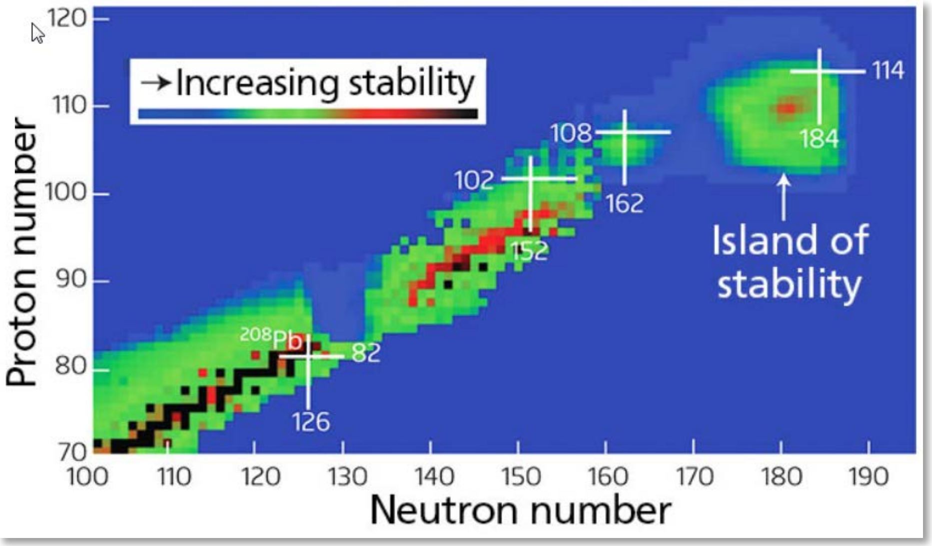
• Off-line characterization studies

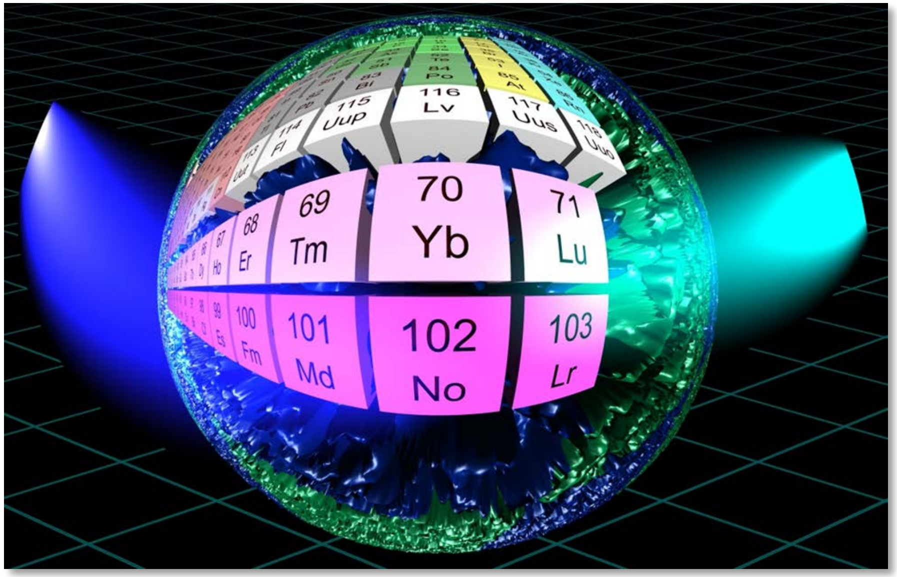
• Conclusion and prospects for heavy element studies

# • Heavy and super-heavy elements

## Nuclear physics

- Competition of the short-range nuclear and long-range Coulomb force
- Role of shell effects and deformation
- Microscopic understanding of fission




## Atomic physics

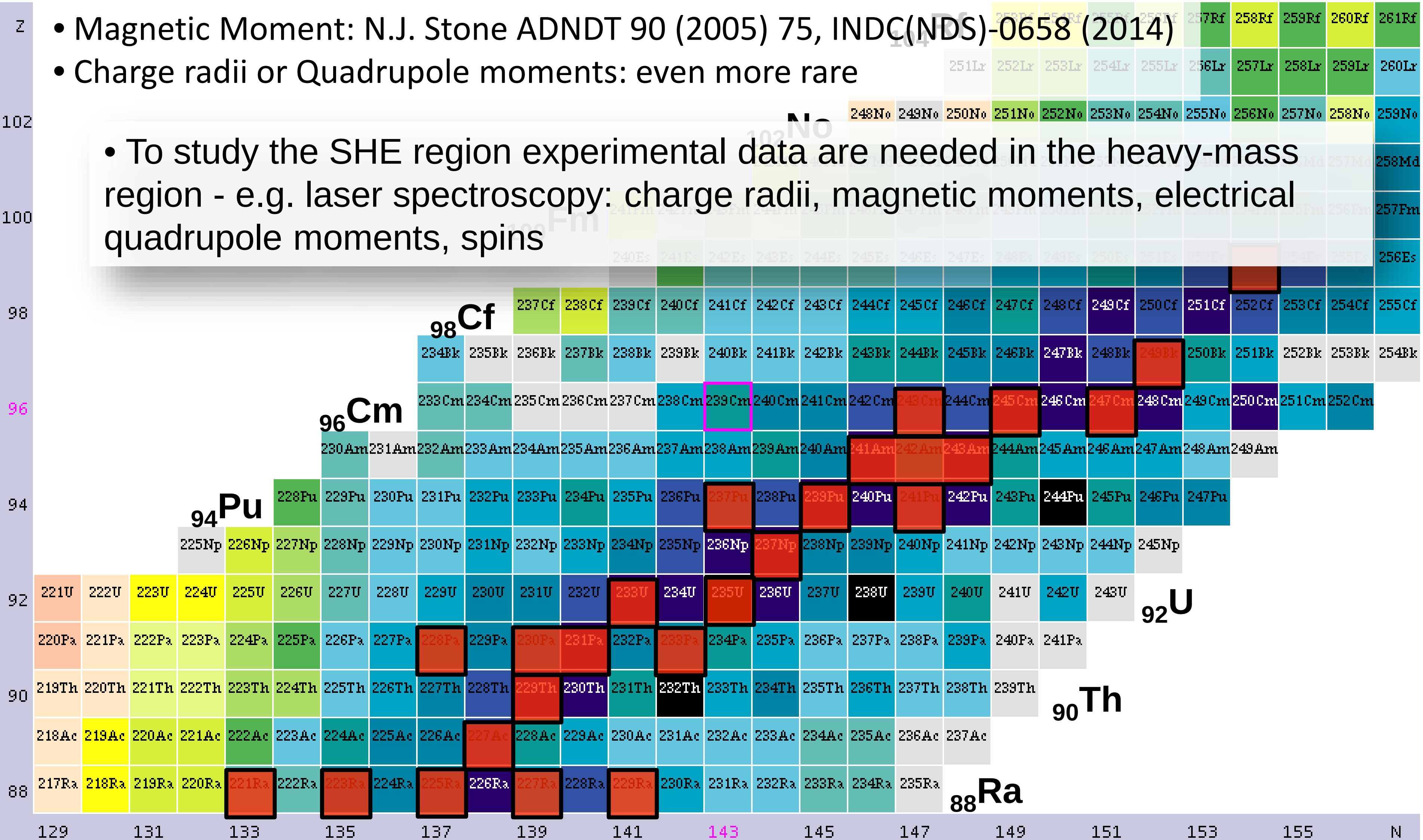
- Relativistic effects and electron correlations in the atomic structure

KU LEUVEN

# Reported Magnetic Moments

- Magnetic Moment: N.J. Stone ADNDT 90 (2005) 75, INDC(NDS)-0658 (2014)
- Charge radii or Quadrupole moments: even more rare

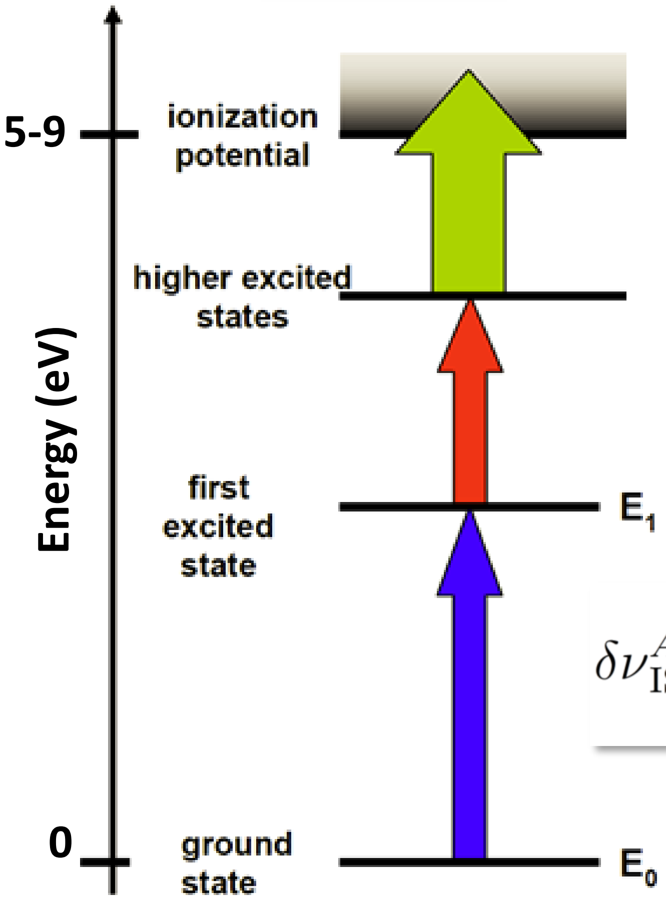
- To study the SHE region experimental data are needed in the heavy-mass region - e.g. laser spectroscopy: charge radii, magnetic moments, electrical quadrupole moments, spins



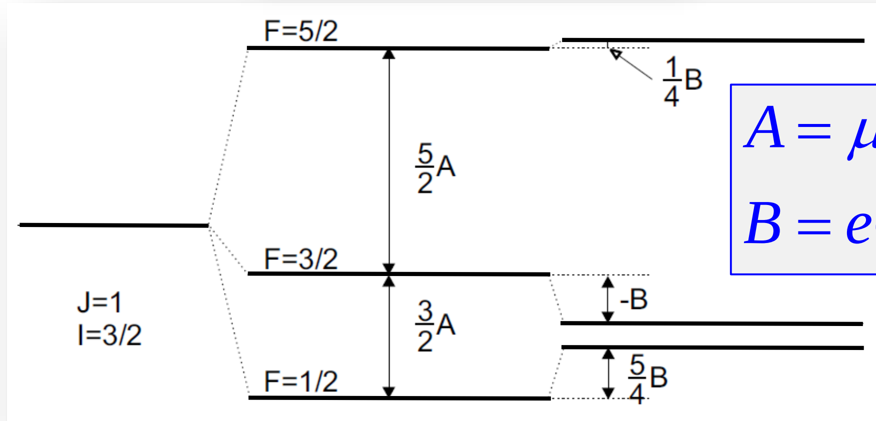

KU LEUVEN

# Laser Ionization Spectroscopy: basics

## Sensitivity




## Hyperfine Splitting




$$A = \mu_I B_e(0) / (IJ)$$

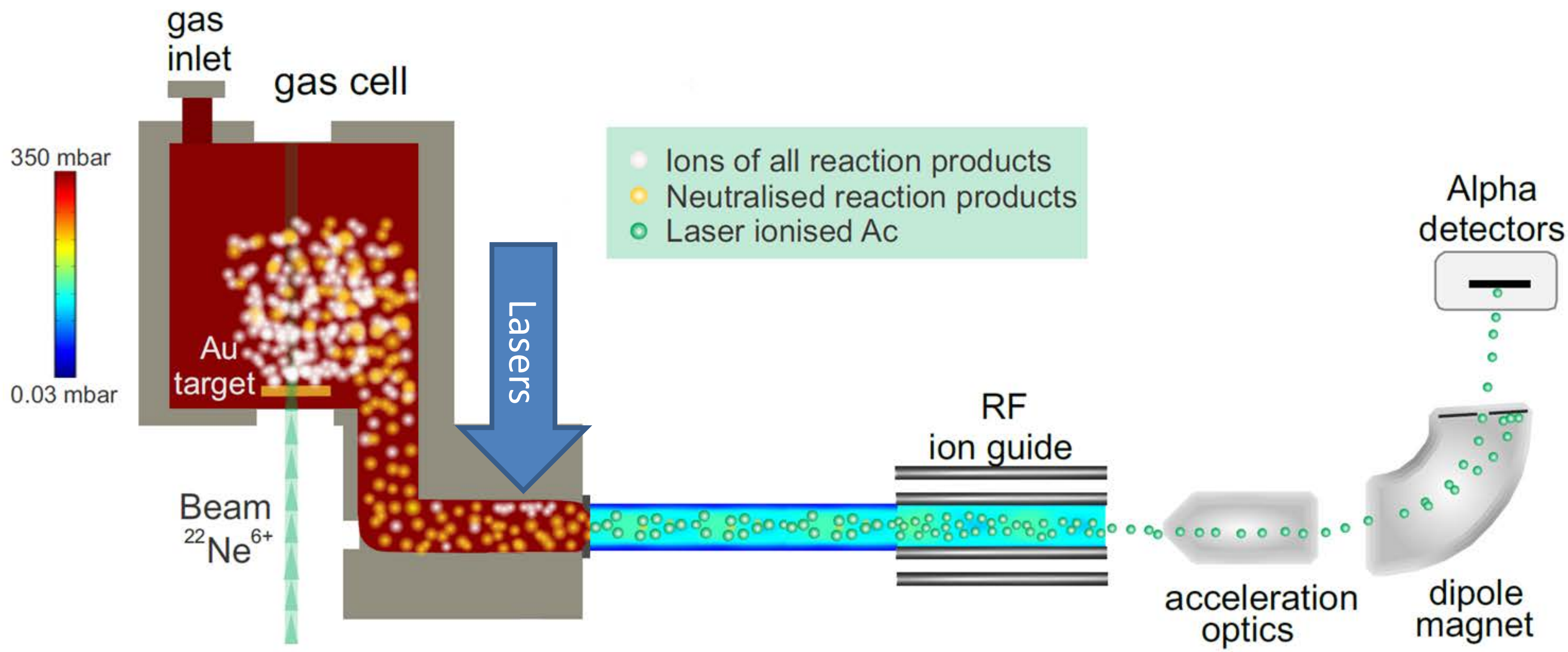
$$B = eQ_S V_{ZZ}(0)$$

## Isotope Shift

$$\delta\nu_{\mathrm{IS}}^{AA'} = K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + \frac{2\pi Z e}{3} \Delta |\Psi(0)|^2 \; \delta \left\langle r^2 \right\rangle^{AA'}$$

$$\delta \left\langle r^2 \right\rangle^{A,A'}$$

# Laser Ionization Spectroscopy @ LISOL: in-gas cell




Limitations:

- Pressure shift and broadening
- Doppler broadening
- Atom and Ion-gas interactions

$^{57}$Cu(Z=29, N=28, $T_{1/2}$=196 ms)
Cocolios,- PRL 103 (2009) 102501
$^{97}$Ag (Z=47, N=50, $T_{1/2}$= 26 s))
Ferrer,- PLB 728 (2014) 191

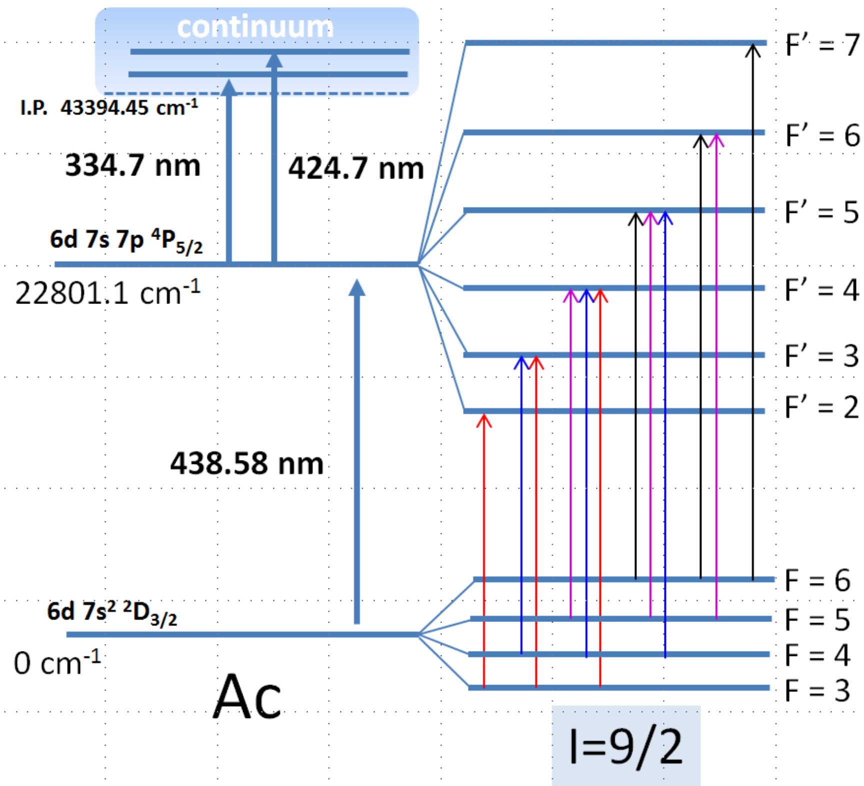
# HFS of $^{212-215}$Ac - 439 nm transition

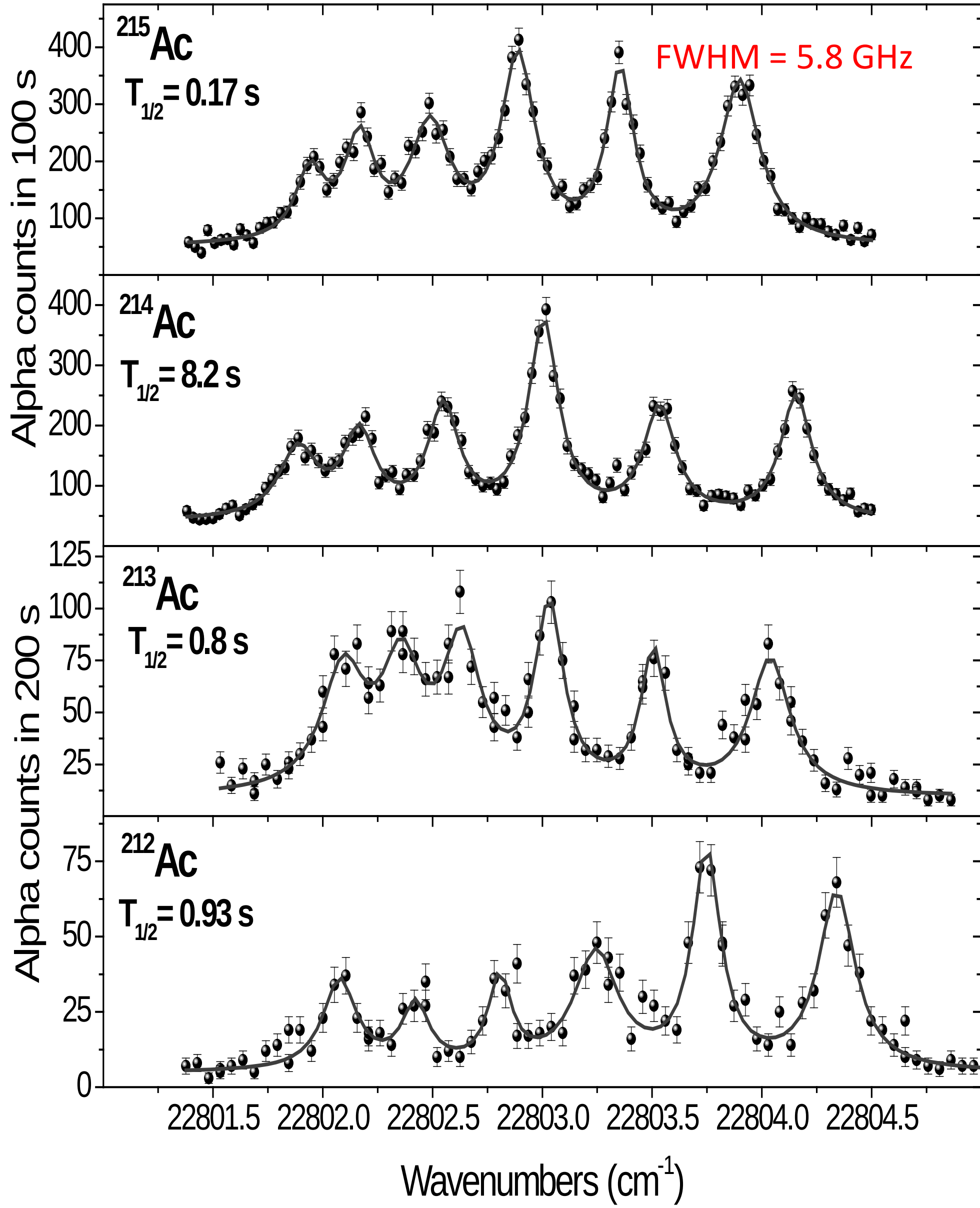
N=126

LARISSA JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

$^{227}$Ac ($T_{1/2}$=21.7 y)

J. Rossnagel et al., PRA 85 (2012) 012525



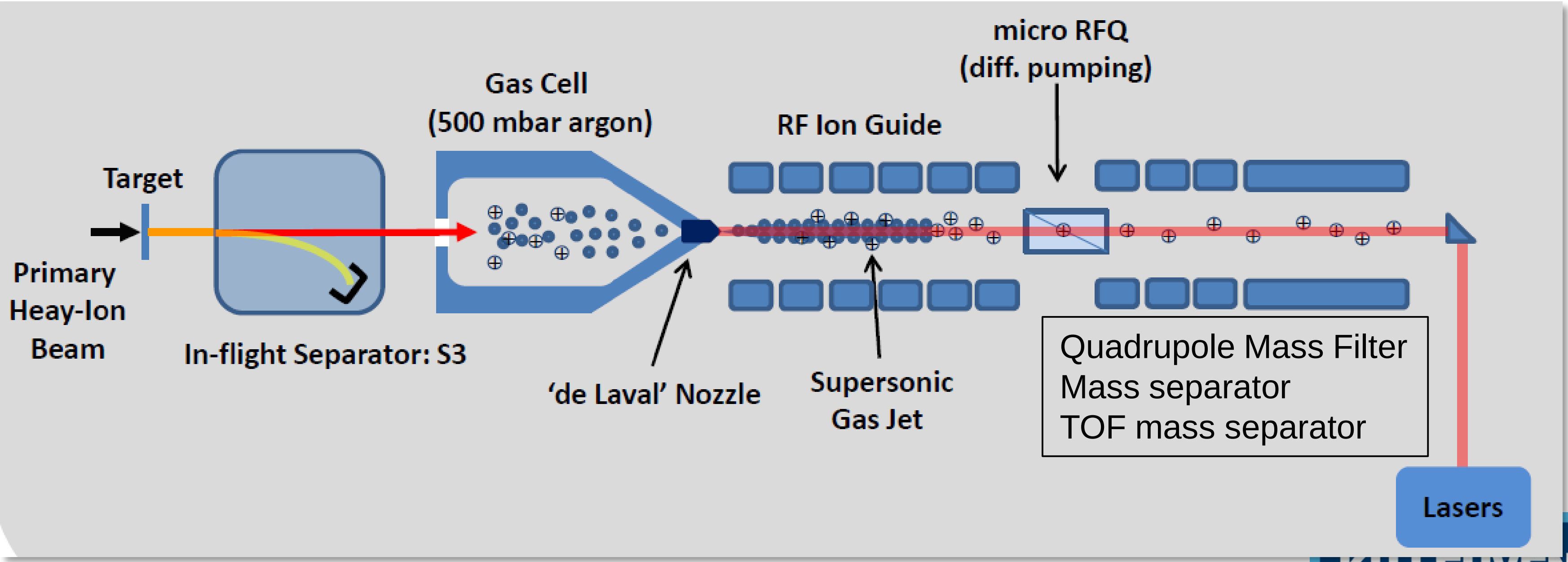




$^{197}$Au($^{20}$Ne-145 MeV,4-5n)$^{212,213}$Ac

$^{197}$Au($^{22}$Ne-143 MeV,4-5n)$^{214,215}$Ac

# The HELIOS concept

- Production of the heavy elements (or neutron deficient isotopes):
  heavy-ion fusion evaporation reactions
- Separation of the primary and secondary beam: e.g. S3-GANIL, MARA@JYFL
- Thermalization in the gas cell
- Repelling unwanted ions
- Formation of a cooled atomic beam through e.g. a 'de Laval' nozzle (gas jet)
- Resonant laser ionization: high-repetition rate laser system (>10 kHz)
- Ion capture and transport in the RF Ion Guide followed by mass separation
- Detection of the ions: radioactivity / ion counting



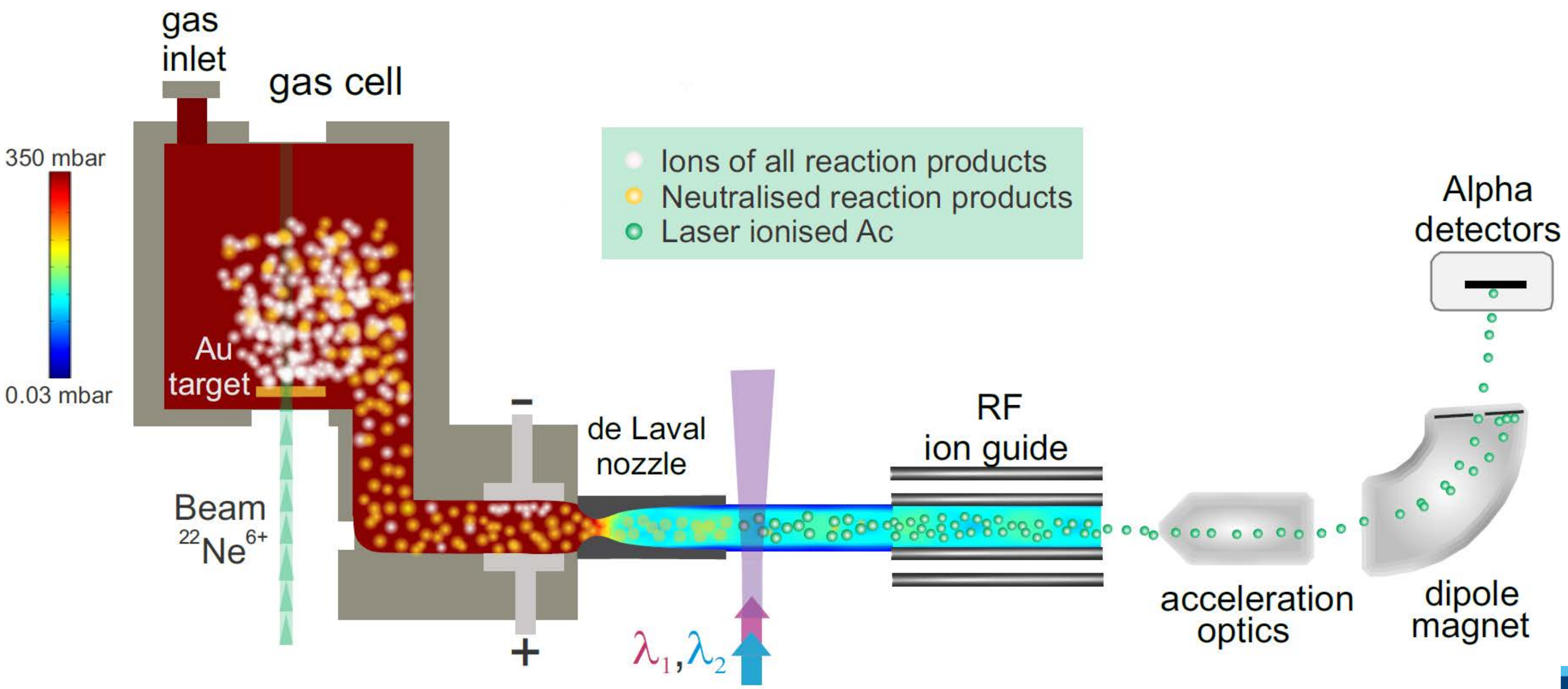

KU LEUVEN

Y. Kudryavtsev et al., NIM B297 (2013) 7, R. Ferrer et al, NIM B 291 (2012) 29
K. Blaum et al., NIM B 204 (2003) 331, I. Moore et al., AIP Conf. Proc. 831 (2006) 51

# The HELIOS concept

- Total expected efficiency: 4%
- Strategy
  - In-gas cell laser ionization spectroscopy (broadband – 5 GHz): rough laser scans, search for atomic transitions
  - In-gas jet laser ionization spectroscopy (narrow band – 100 MHz)

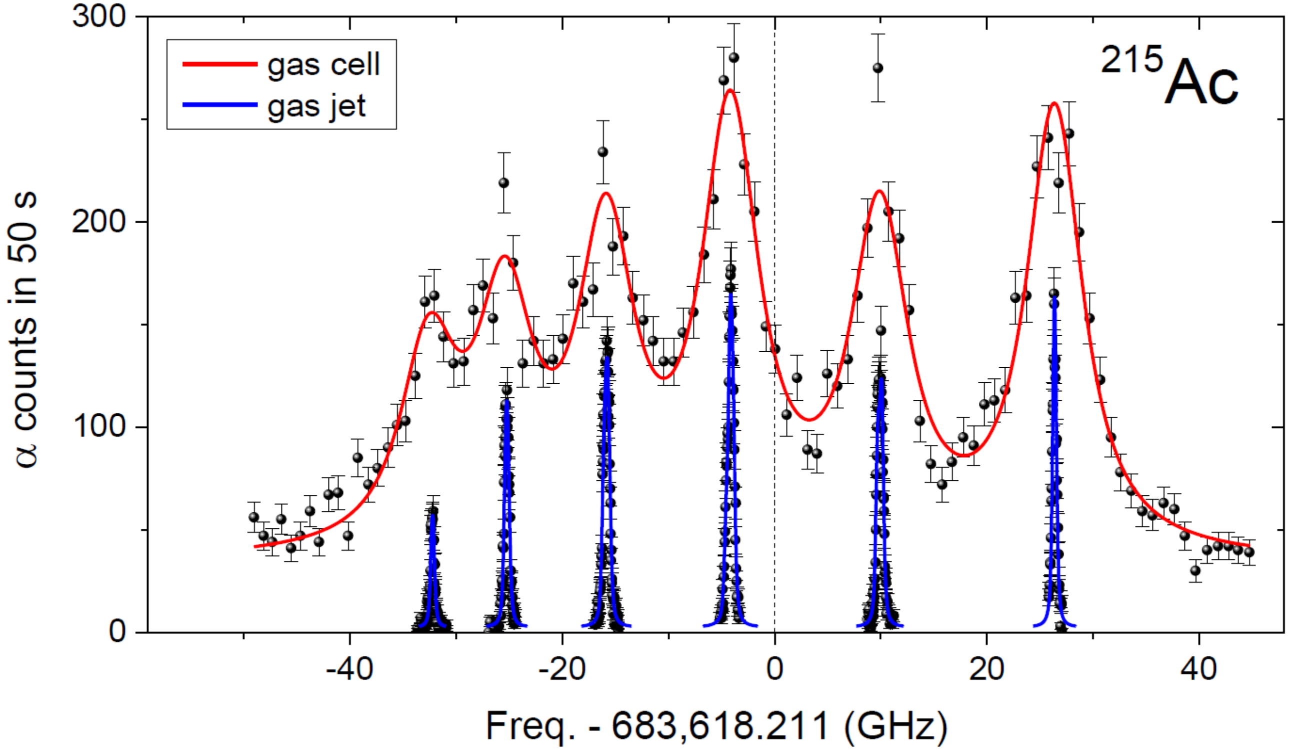
## From 'in-gas cell' to 'in-gas jet' laser spectroscopy




KU LEUVEN

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

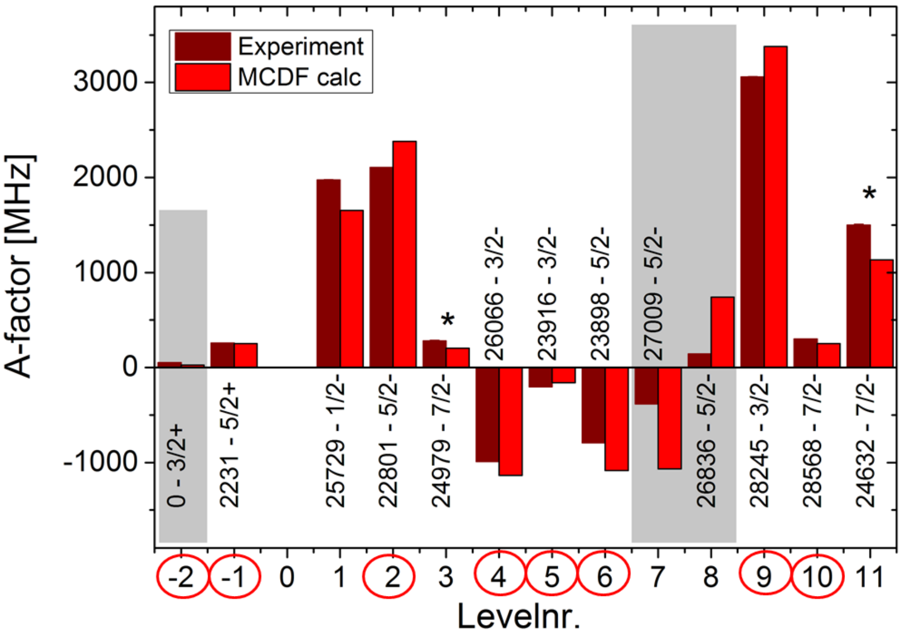
# $^{215}$Ac $T_{1/2}$ = 0.17 s $J_\pi$ = 9/2$^-$

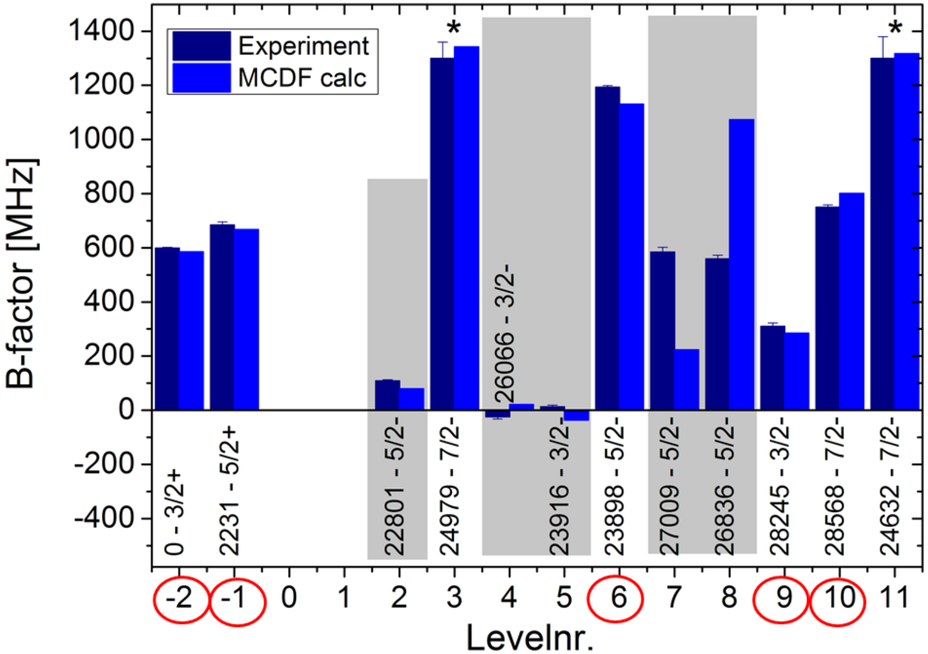



<u>Figures of merit</u>:

- ✓ Resolution - FWHM= 394(18) MHz
- ✓ Selectivity = 121(27)
- ✓ Efficiency = 0.42(13) % (duty cycle 1/14)

# Multi-Monfiguration Dirac Fock atomic physics calculations: $^{227}$Ac



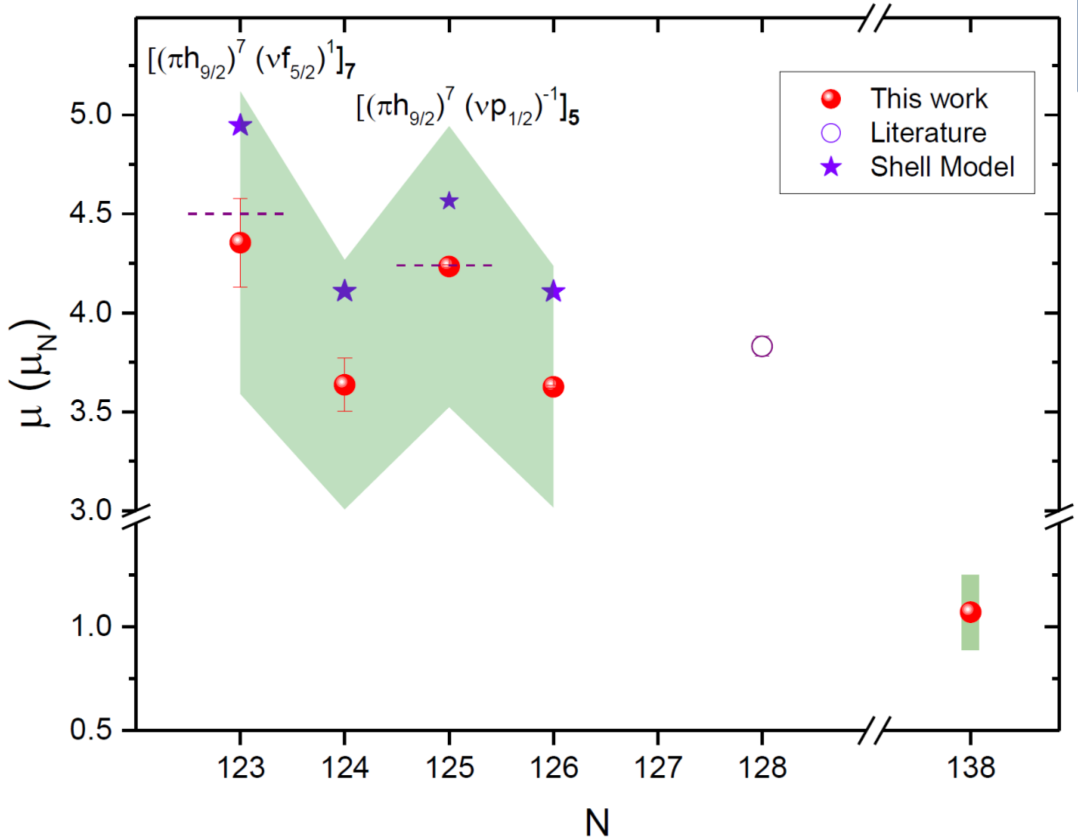



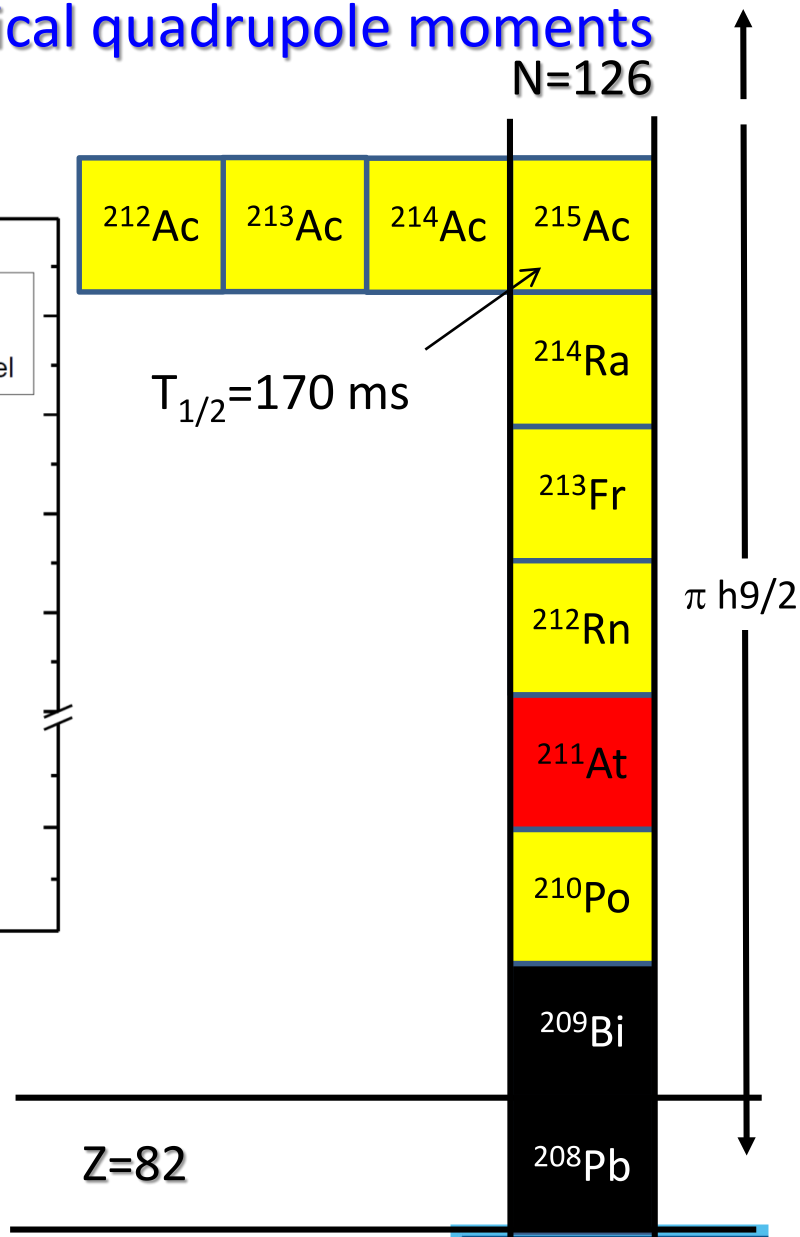

| Fred,- Phys. Rev. 98 (1955) $^{227}$Ac | MCDF calculations + experimental data on $^{227}$Ac |
|---|---|
| $\mu_{lit.} = 1.1(1)\ \mu_N$ | $\mu_{calc.} = 1.07(18)\ \mu_N$ |
| $Q_{lit.} = 1.7(2)$ eb | $Q_{calc.} = 1.74(10)$ eb |

KU LEUVEN

# Magnetic dipole moments and electical quadrupole moments

$$\mu^{exp.} = \frac{A^{exp} \cdot I^{exp}}{A^{227} \cdot 3/2} \cdot \mu^{227}_{calc.}$$

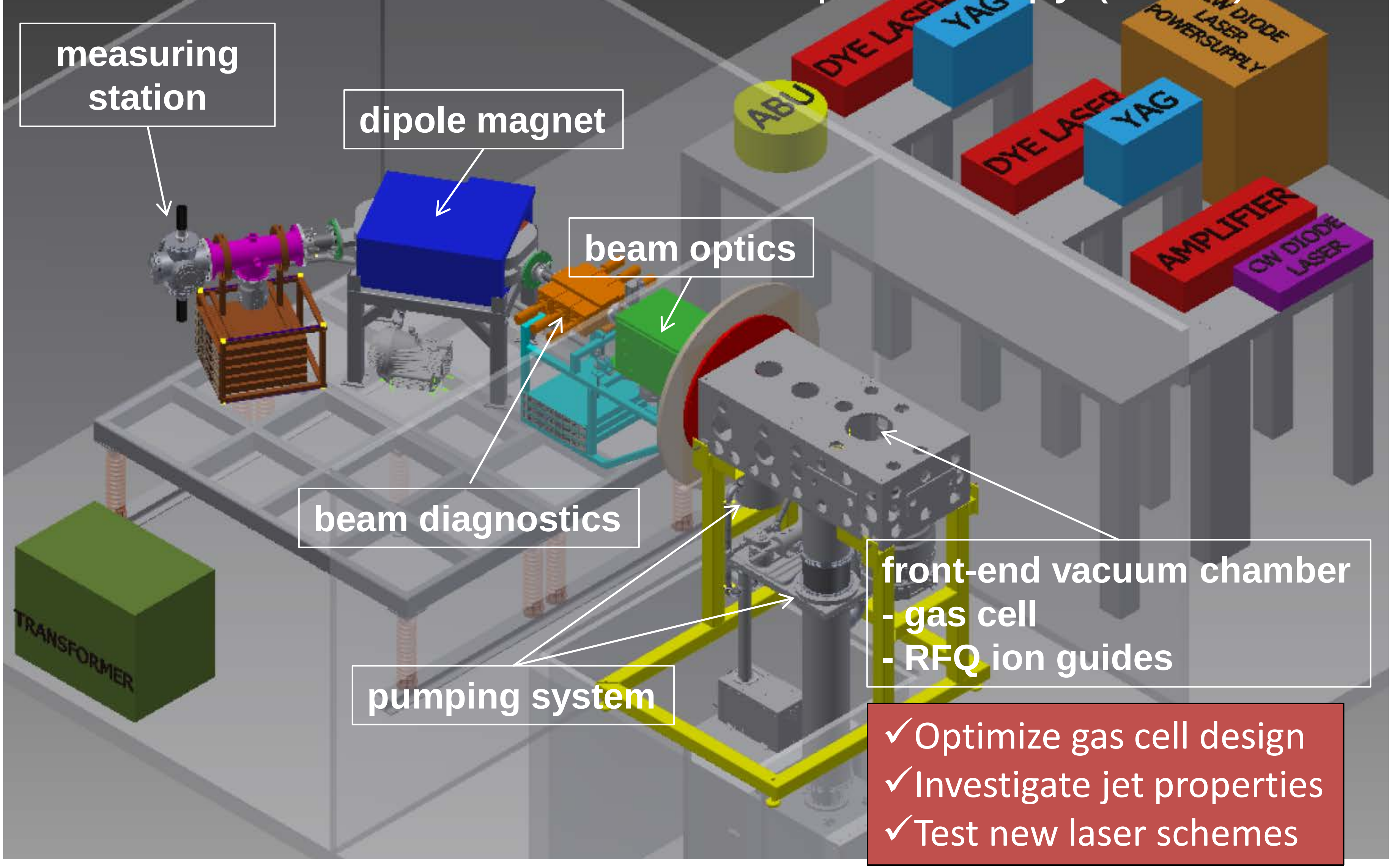



R. Ferrer *et al,* Nature Communications 8 (2017) 14520,
Shell-model calculations: H. Grawe (Caurier, - PRC67 (2003) 054310)

KU LEUVEN

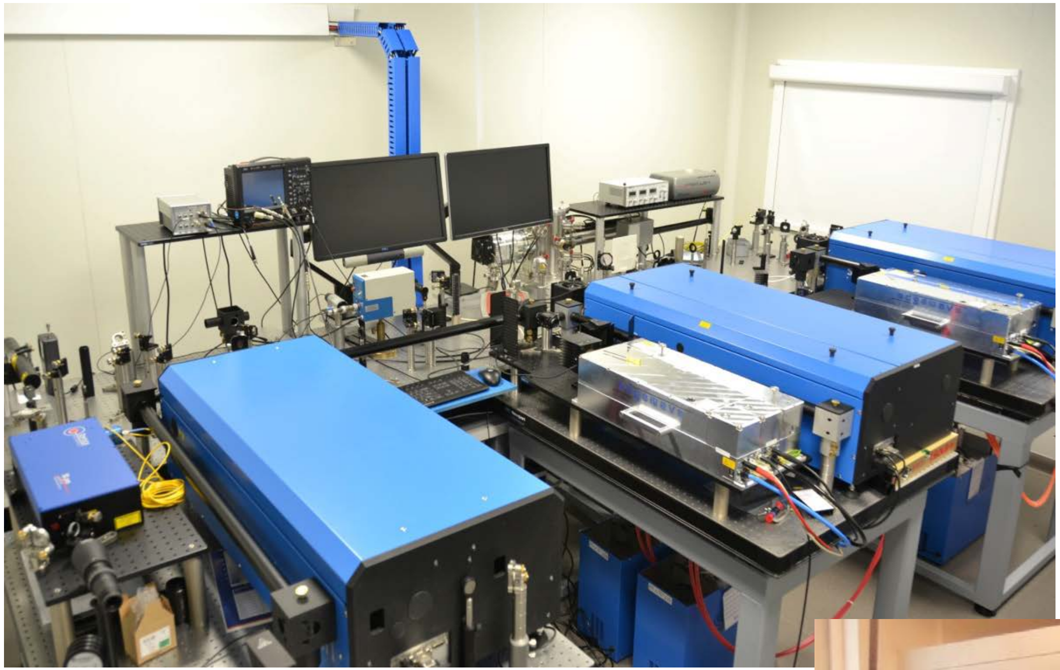
# In Gas Laser Ionization and Spectroscopy (IGLIS)



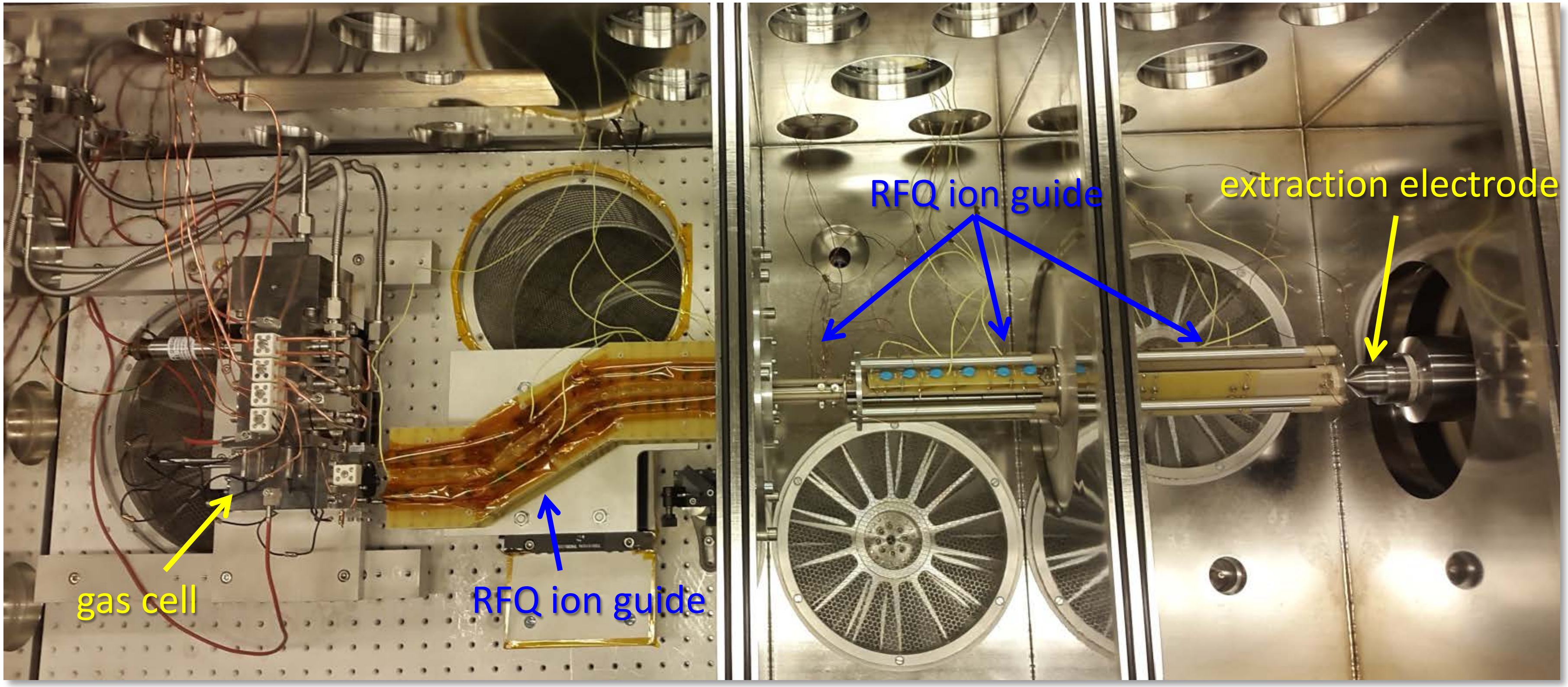

- ✓Optimize gas cell design
- ✓Investigate jet properties
- ✓Test new laser schemes

Y. Kudryavtsev,- NIM B 376 (2016) 345–352

KU LEUVEN



IGLIS @ KU Leuven

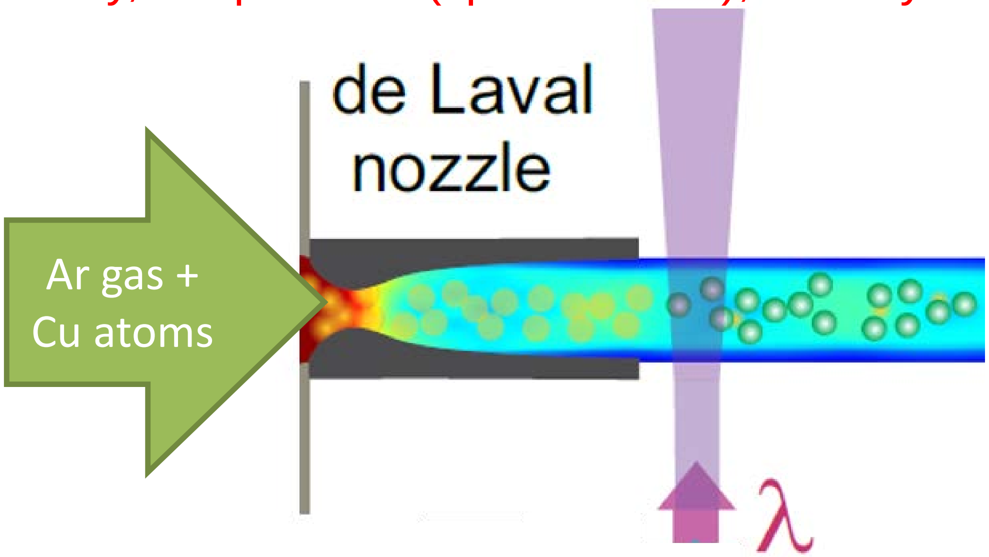

RFQ ion guide
extraction electrode
gas cell
RFQ ion guide

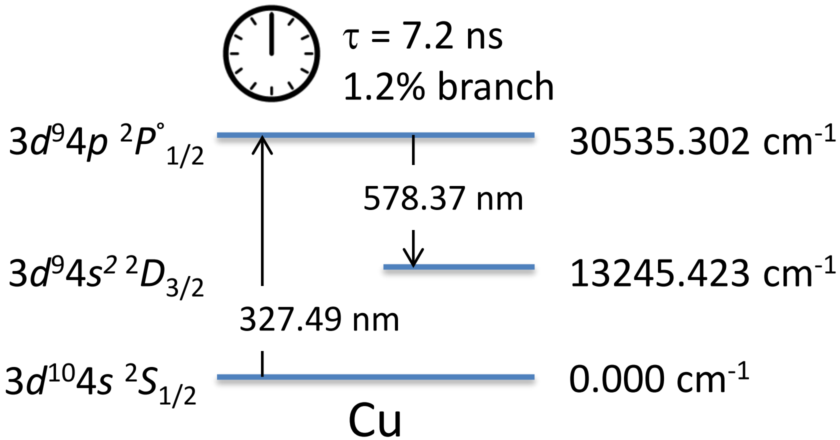

Prototype gas cell for GANIL (S3-LEB)

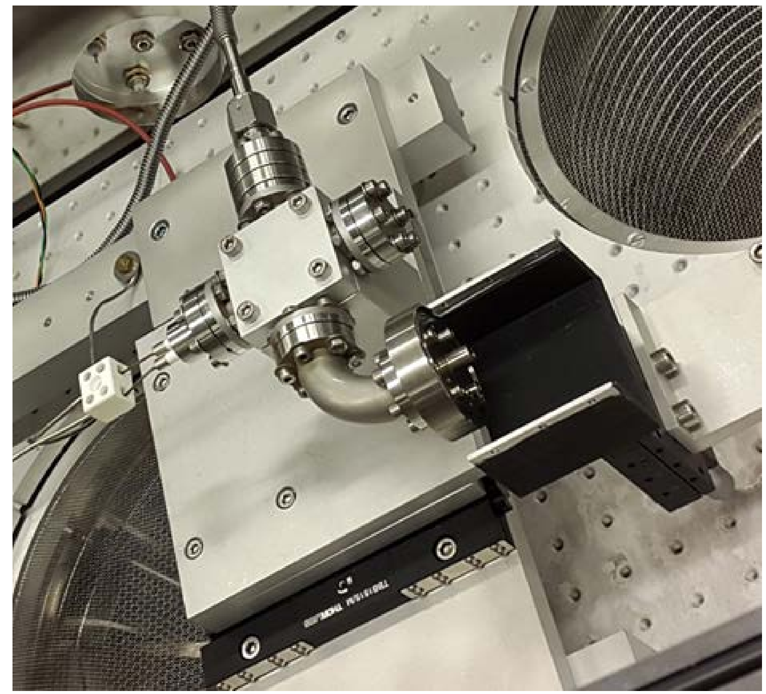
KU LEUVEN

# Gas Flow Simulation and Validation

- Visualisation and characterization of the
gas jet with planar-laser induced fluorescence (PLIF):
density, temperature (spectral lines), velocity



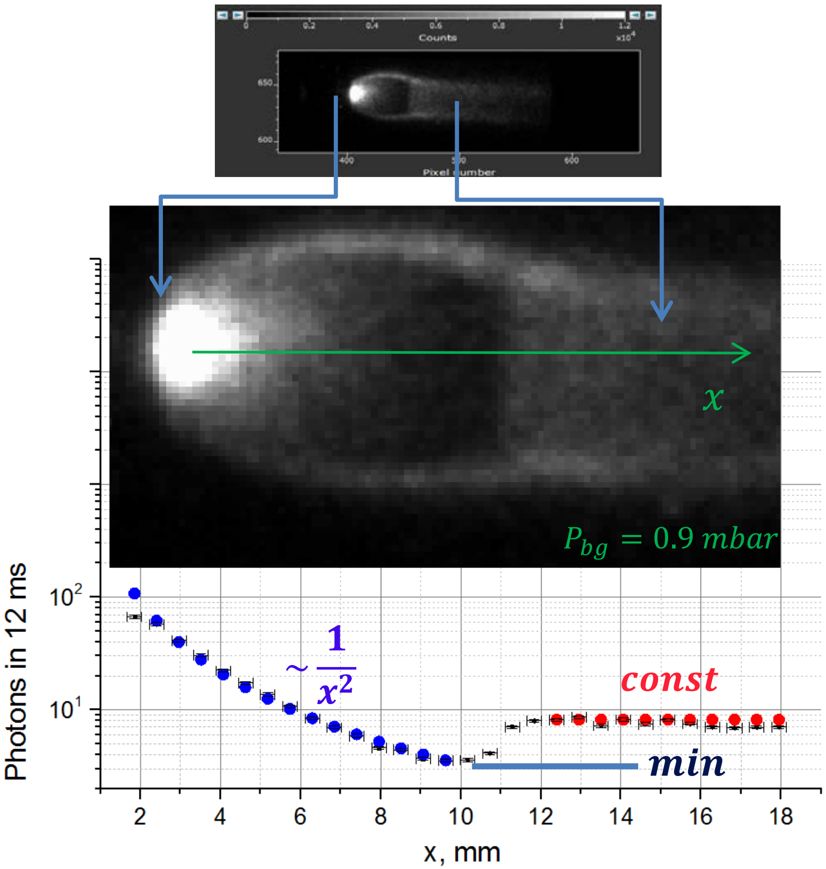



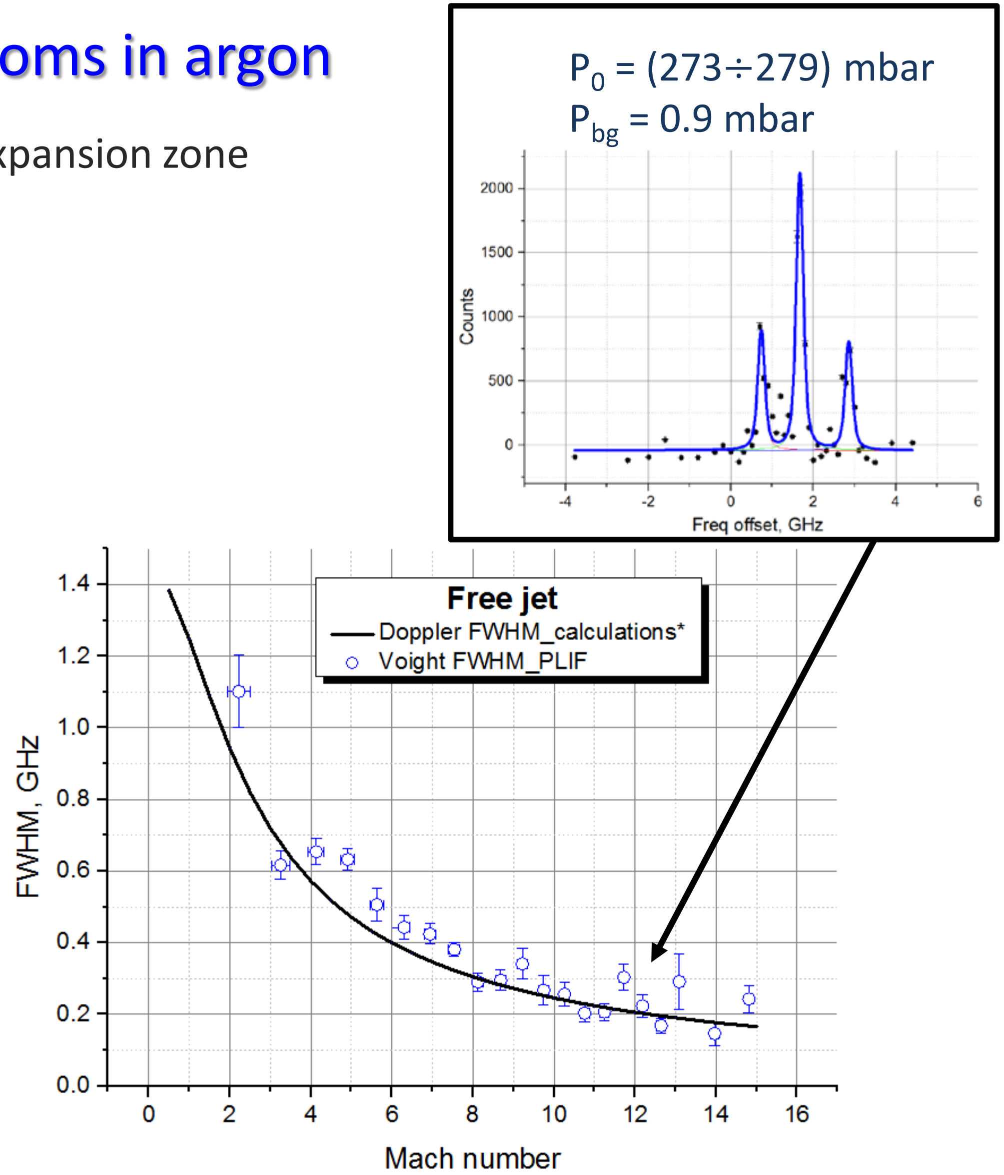



Noel T. Clemens, Encyclopedia of Imaging Science and Technology, pp. 390 – 419, 2002

# Free jet expansion – Cu atoms in argon

- Mach disk position and density drop in the expansion zone
- Temperature → FWHM

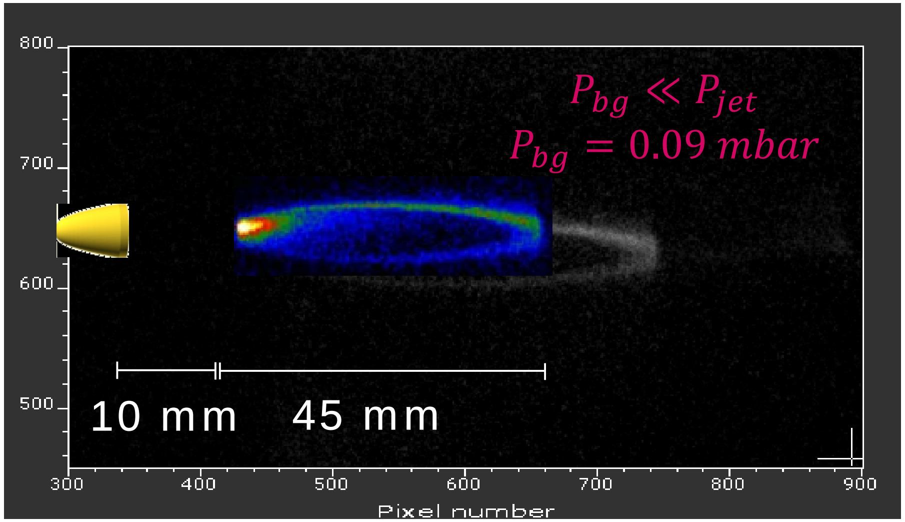


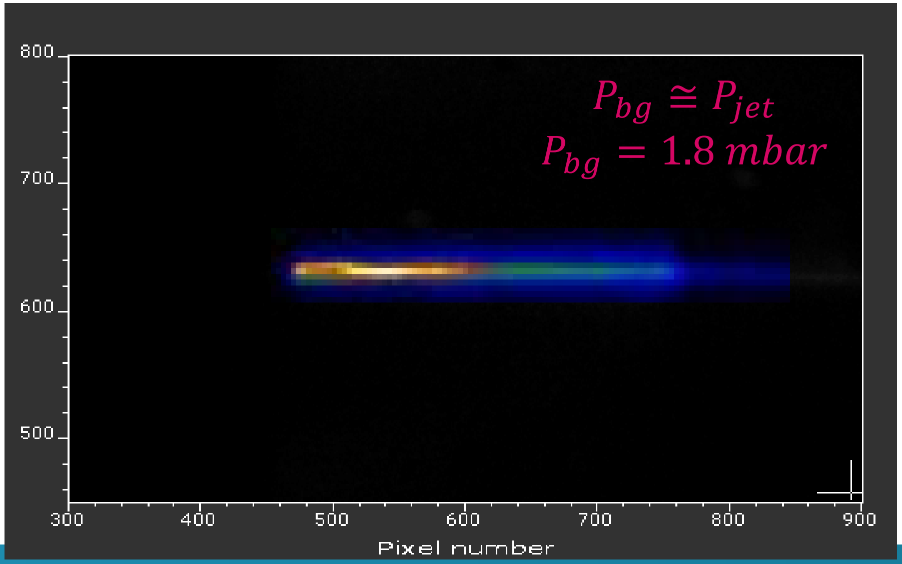



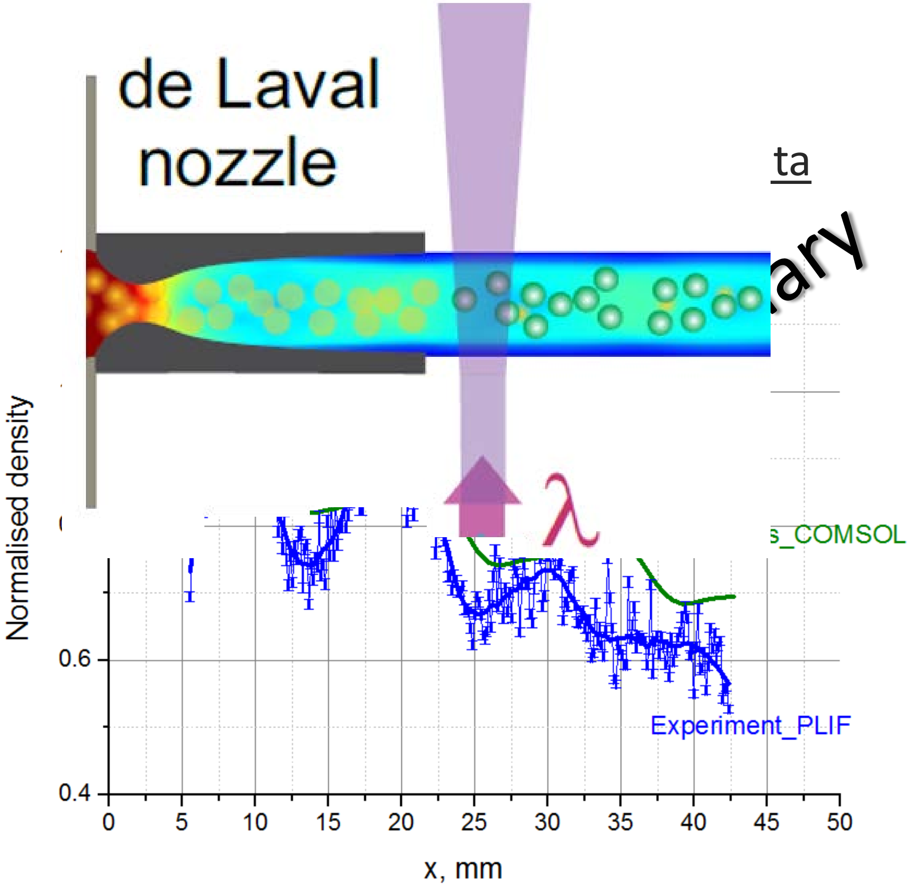

KU LEUVEN

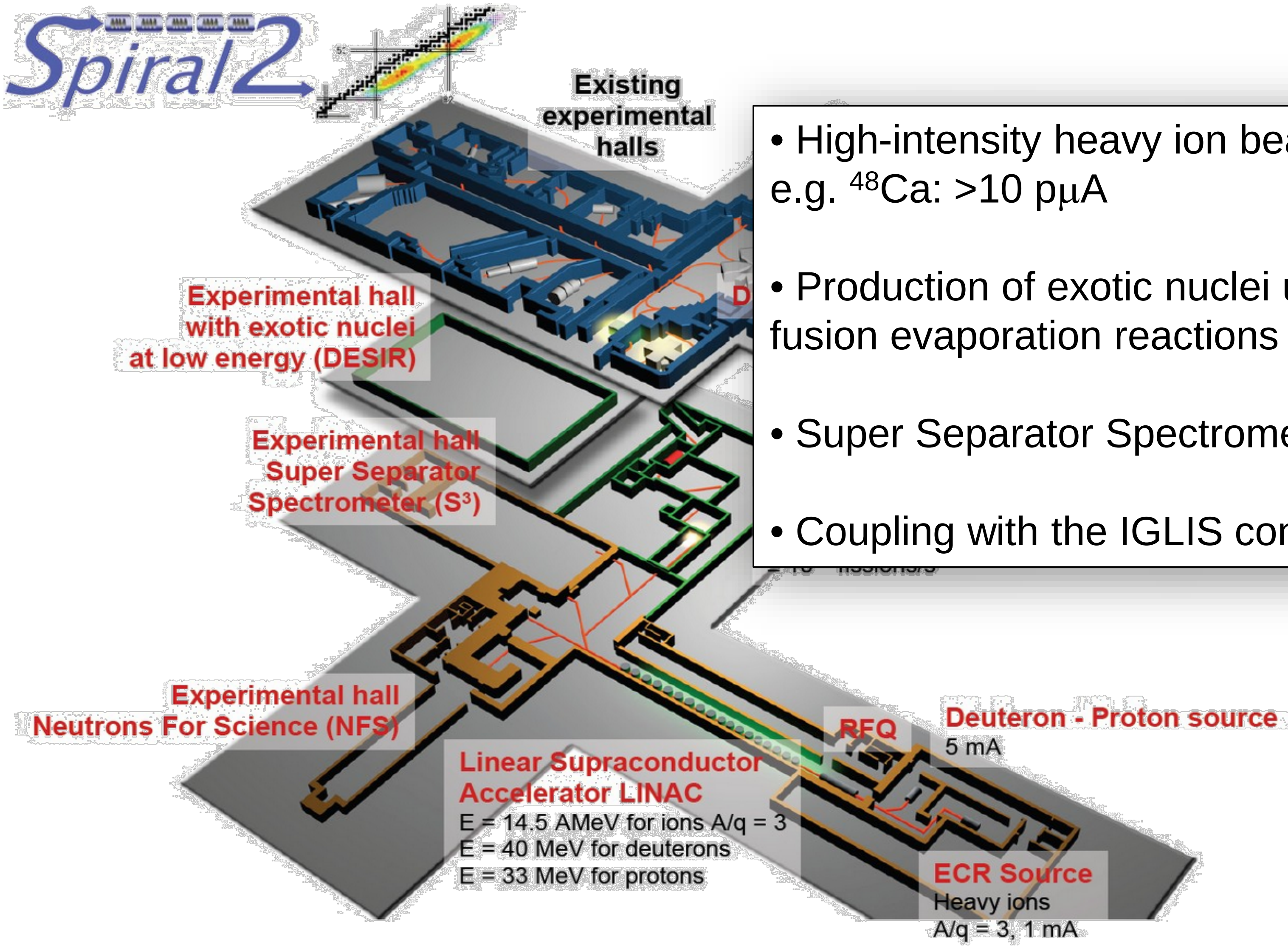
# ‘de Laval’ nozzle

Stagnation pressure 290 mbar, $P_{jet}$~ 1 mbar, Mach 5.5





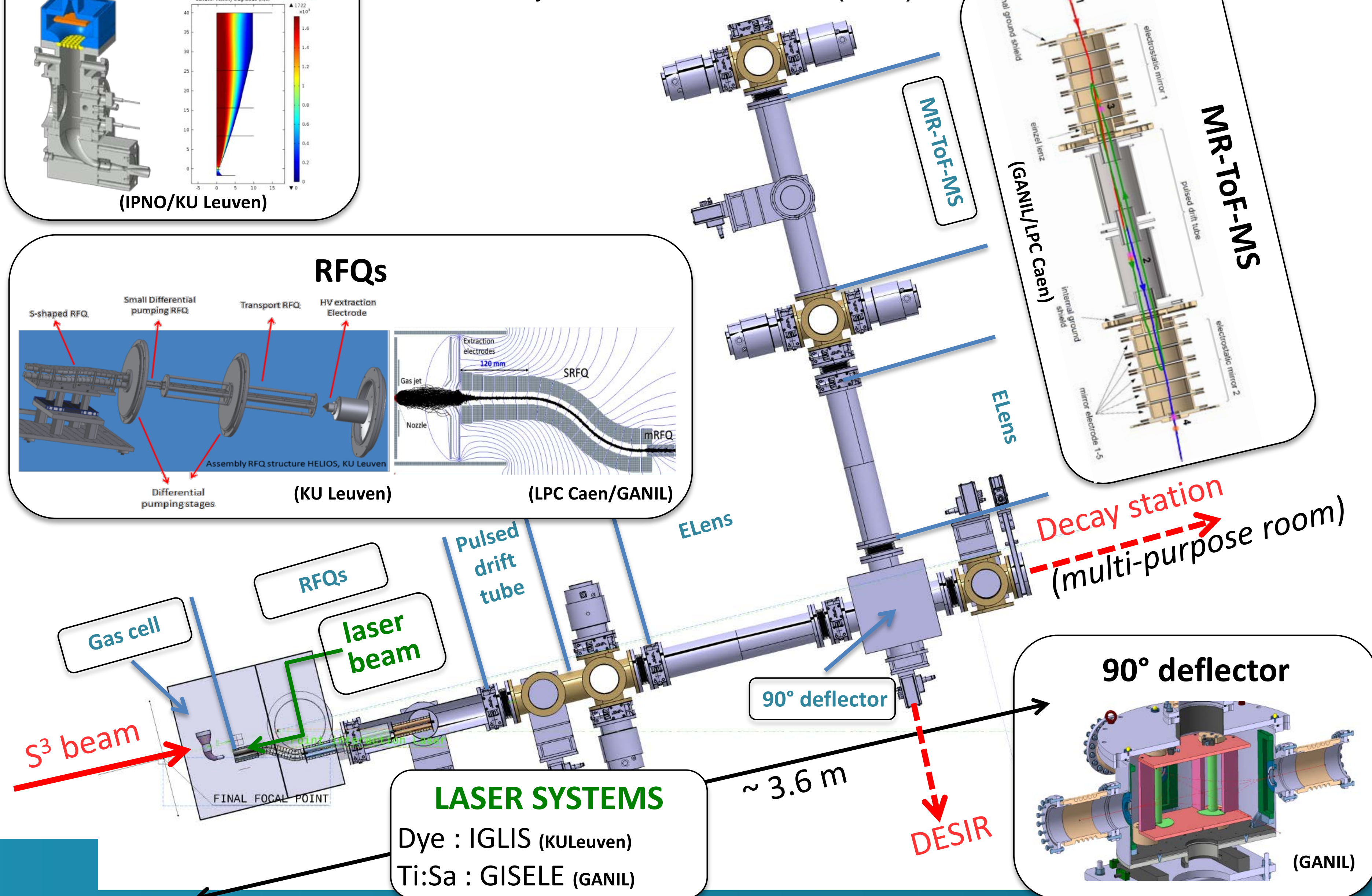

- High-intensity heavy ion beams: e.g. $^{48}$Ca: >10 pμA
- Production of exotic nuclei using heavy-ion fusion evaporation reactions
- Super Separator Spectrometer: S3
- Coupling with the IGLIS concept

IGLIS @ S3LEB - SPIRAL2 - GANIL
IGLIS @ MARA - JYFL

KU LEUVEN

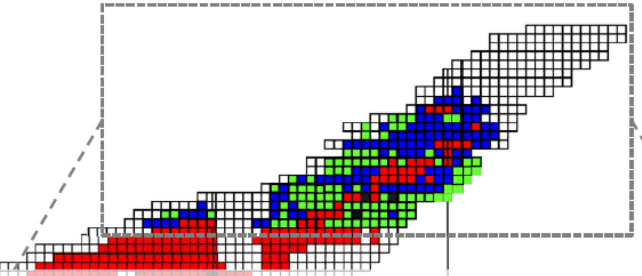
# $S^3$-LEB general layout

R. Ferrer et al., NIM B 317 (2013) 570
Y. Kudryavtsev et al., NIM B297 (2013) 7



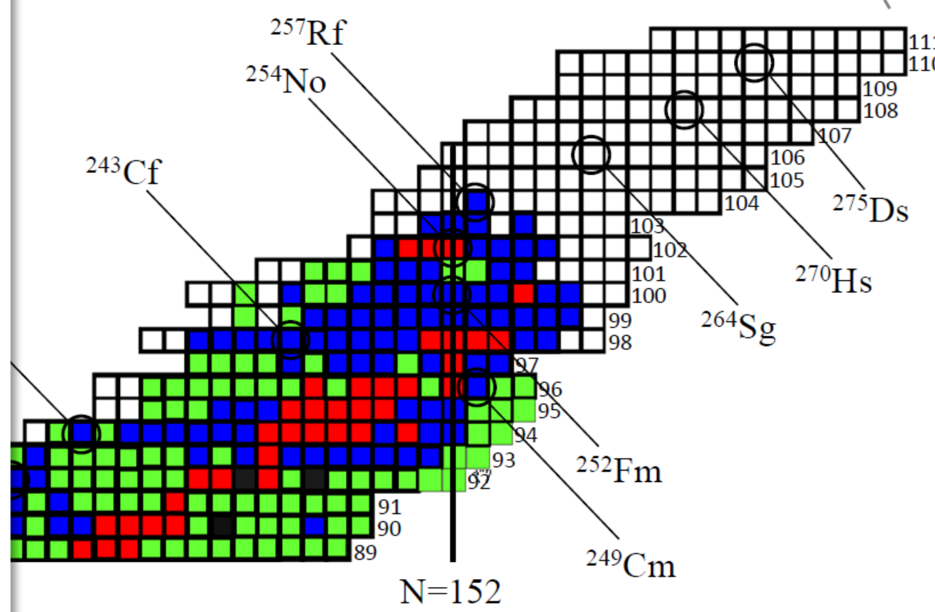
# New opportunities with IGLIS

- Stable
- Species studied by laser spectroscopy
- Reach of IGLIS based on experimental cross sections
- Reach of IGLIS based on estimated cross sections




- Heavy element region: including K-isomers (e.g. $^{254}$No - K isomer $T_{1/2}$ = 275 ms)
- N = Z nuclei around $^{100}$Sn
- Very neutron deficient regions between Z=50 and 82)

| | gas jet (projected) |
|---|---|
| **Ionisation volume** | |
| Pressure (mbar) | $\sim 0.05$ |
| Temperature (K) | $\sim 9$ |
| Jet divergence (deg.) | $< 1$ |
| **Linewidth (FWHM)** | |
| Total (MHz) | $\sim 100$ |
| Lorentz$^{\flat}$(MHz) | $< 10$ |
| Gauss$^{\Vert}$(MHz) | $\sim 100$ |
| **Selectivity**$^{\sharp}$ | $> 3{,}000$ |
| **Efficiency**$^{\natural}$(%) | $> 10$ |



# Conclusion and outlook

- Feasibility for in-gas jet laser ionization spectroscopy of actinium is proven
  - good efficiency (5.6 % duty factor corrected) and spectral resolution (~400 MHz)

- Further off-line characterization will be performed at the IGLIS lab at KU Leuven

- Opens new route for precision laser spectroscopy measurements of neutron-deficient isotopes and study of pure isomeric beams produced in heavy-ion fusion evaporation reactions
  - N=Z line around and below $^{100}$Sn
  - neutron-deficient deformed region A~150
  - very heavy element region

- On-line experiments at S3 (SPIRAL2 - GANIL) starting in 2018/2019

KU LEUVEN

**KU Leuven LISOL team**

P. Creemers, R. de Groote, L.P. Gaffney, L. Ghys, C. Granados, M. Huyse, Yu. Kudryavtsev, Y. Martínez, E. Mogilevskiy, S. Raeder, S. Sels, P. Van den Bergh, P. Van Duppen, A. Zadvornaya

**GANIL- IPN Orsay – LPC Caen:**
B. Bastin, D. Boilley, Ph. Dambre, P. Delahaye, P. Duchesne, X. Fléchard, S. Franchoo, N. Lecesne, H. Lu, F. Lutton, Y. Merrer, B. Osmond, J. Piot , O. Pochon, H. Savajols , J. C. Thomas, E. Traykov

**University of Mainz:**
R. Heinke, T. Kron, P. Nauberreit, P. Schoenberg, K. Wendt

**GSI:** M. Laatiaoui, M. Block, H. Grawe

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

**RILIS-ISOLDE:** S. Rothe

erc BriX EQUIPEx S3 INVESTISSEMENT D'AVENIR

KU LEUVEN