# Radioactive Ion Beam & Lasers

## The Use of Lasers for Radioactive Ion Beam Production and Research

Piet Van Duppen
KU Leuven, Belgium

- Why do we use radioactive ion beams?
- How are radioactive ion beams produced?
  - production mechanisms
  - Isotope Separator On-Line versus In-Flight
  - ISOLDE – CERN
- Laser Resonance Ionization
  - Basic principle
  - What can we learn from it?
  - Properties and limitations: selectivity, spectral broadening
- Selected examples of laser spectroscopy studies
- Conclusion and outlook

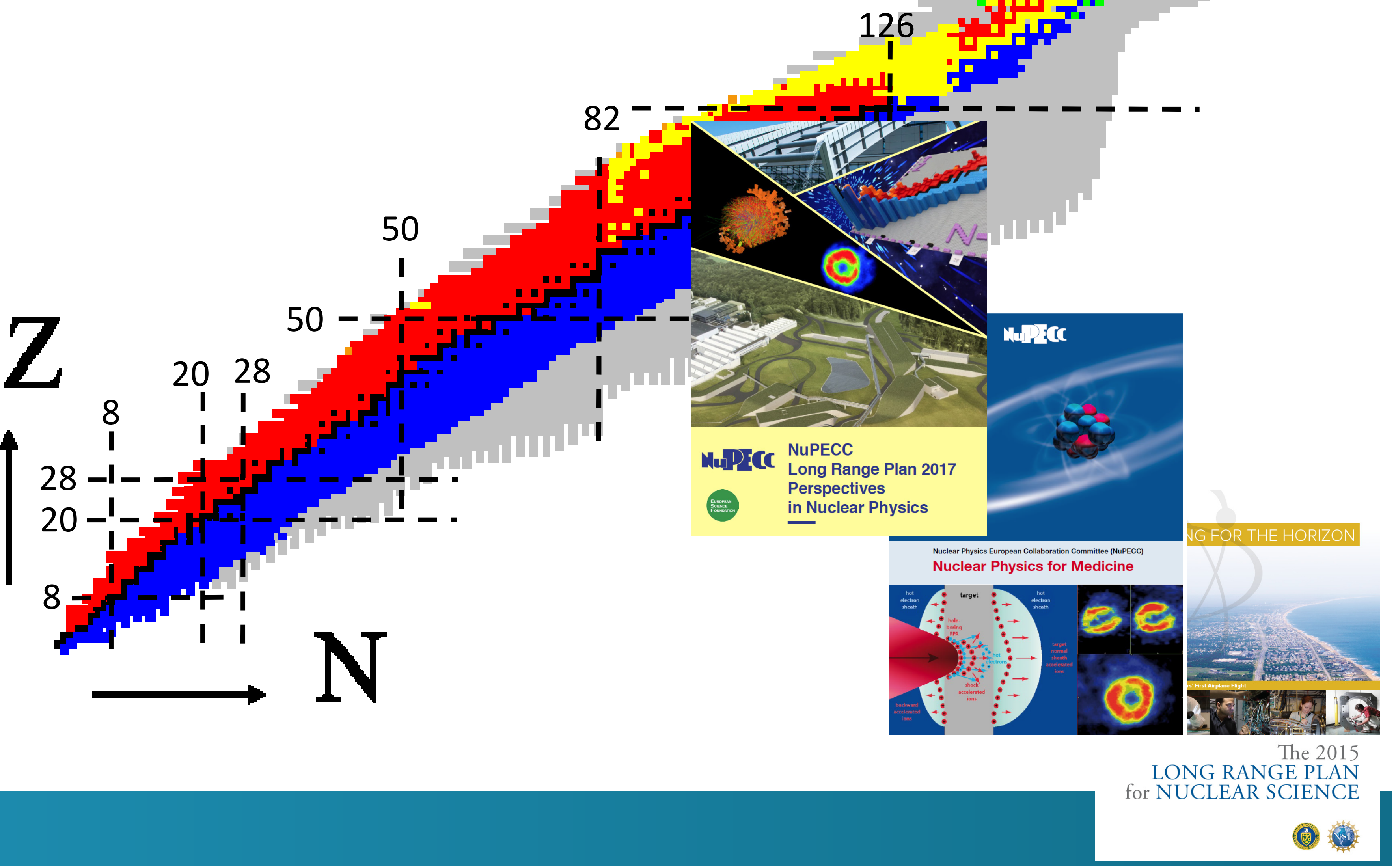
<u>Literature:</u>

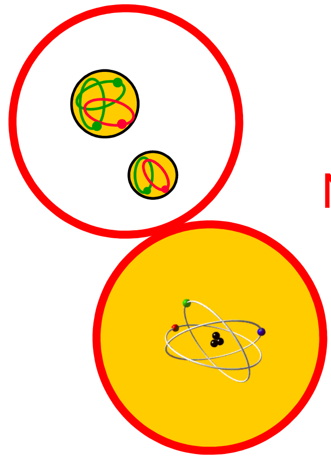
- Euroschool Lecture Notes (www.euroschoolonexoticbeams.be)

“Nuclear Moments” R. Neugart and G. Neyens (2006)
“Isotope Separation On Line and Post Acceleration” PVD (2006)
“Nuclear Charge Radii of Light Elements and Recent Developments in Collinear Laser Spectroscopy”
W. Nörtershäuser and Ch. Geppert (2014)

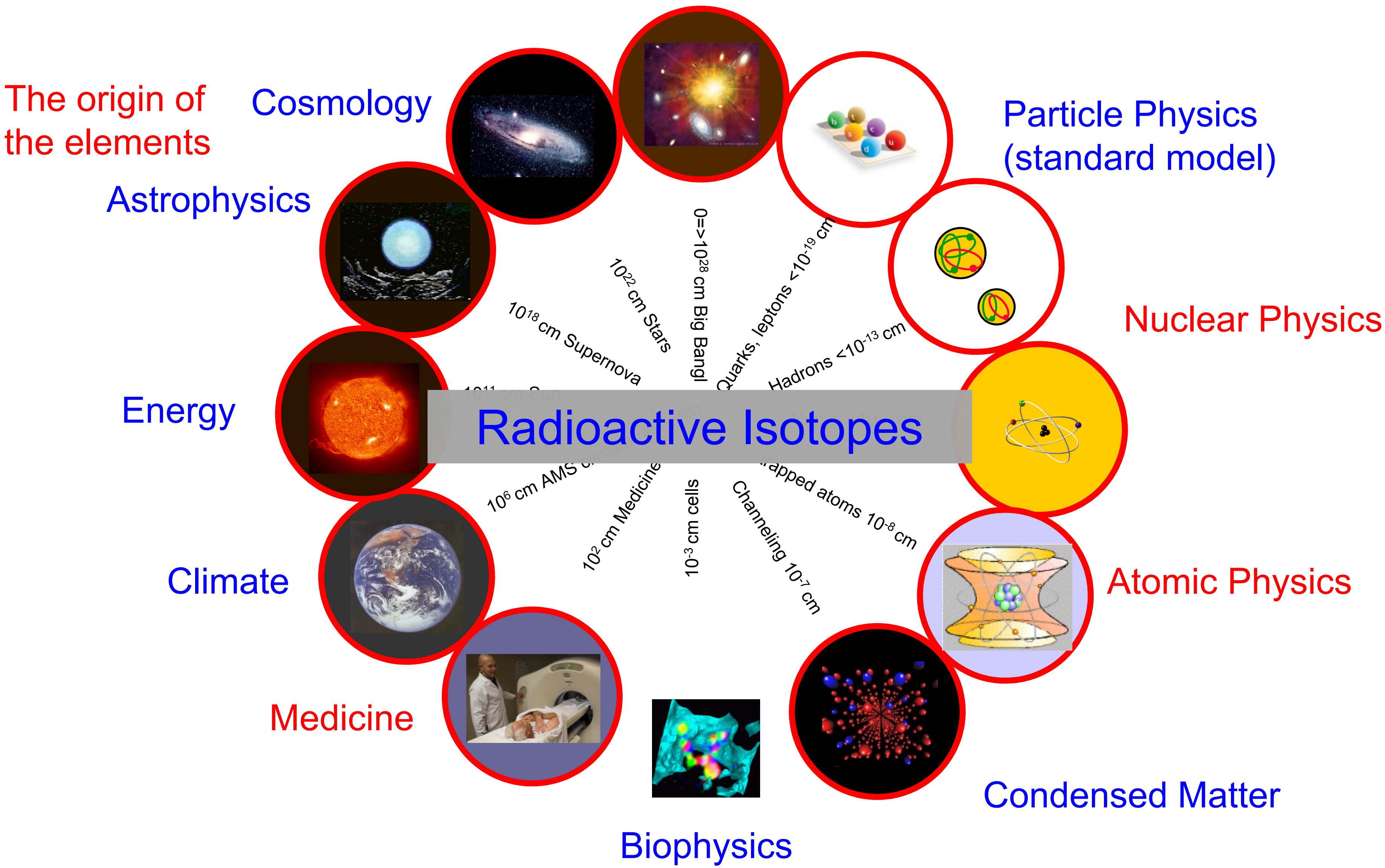
- Research with Radioactive Ion Beams

- To answer fundamental questions in nuclear physics, nuclear astrophysics, fundamental interactions and atomic physics
- Applications (e.g. radioisotopes, trace analysis, ...)





Nuclear Physics


The origin of the elements
Cosmology
Astrophysics
Energy
Climate
Medicine
Biophysics
Condensed Matter
Atomic Physics
Nuclear Physics
Particle Physics (standard model)
Radioactive Isotopes
0=>10^28 cm Big Bang!
10^22 cm Stars
10^18 cm Supernova
Quarks, leptons <10^-19 cm
Hadrons <10^-13 cm
apped atoms 10^-8 cm
Channeling 10^-7 cm
10^-3 cm cells
10^2 cm Medicine
10^6 cm AMS

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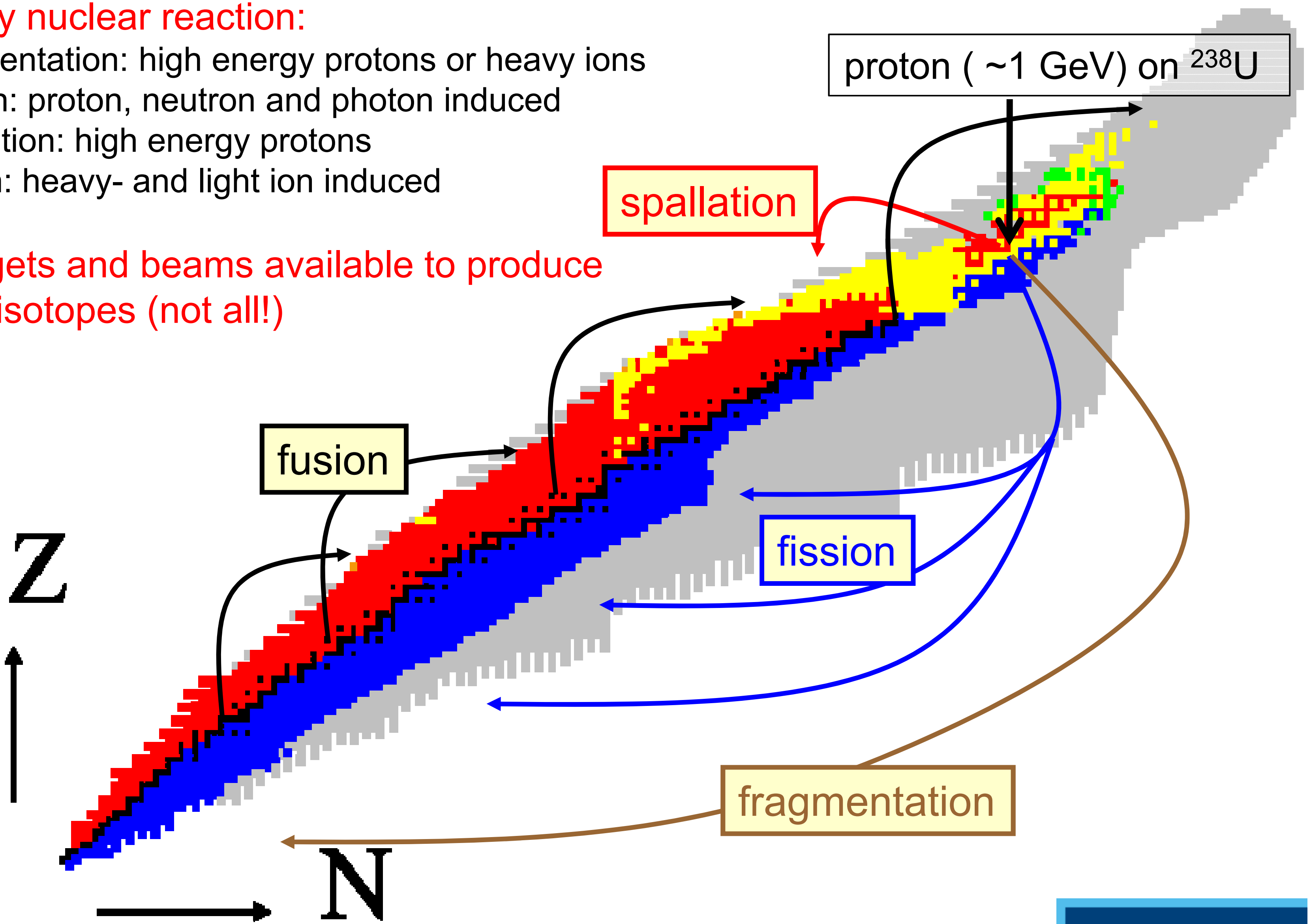
# Production of Radioactive Isotopes

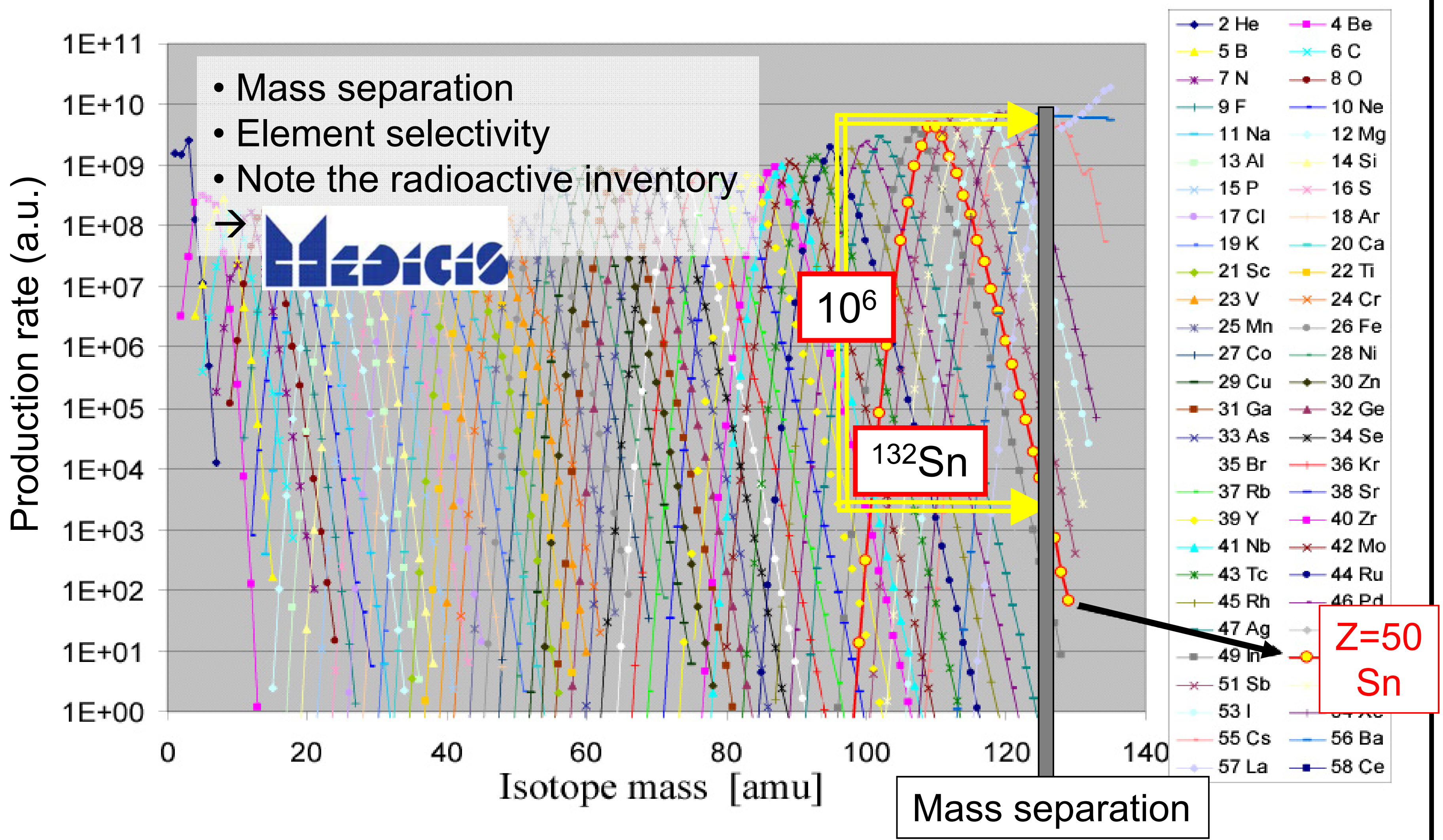
- Primary nuclear reaction:
  - fragmentation: high energy protons or heavy ions
  - fission: proton, neutron and photon induced
  - spallation: high energy protons
  - fusion: heavy- and light ion induced

⇒ targets and beams available to produce many isotopes (not all!)



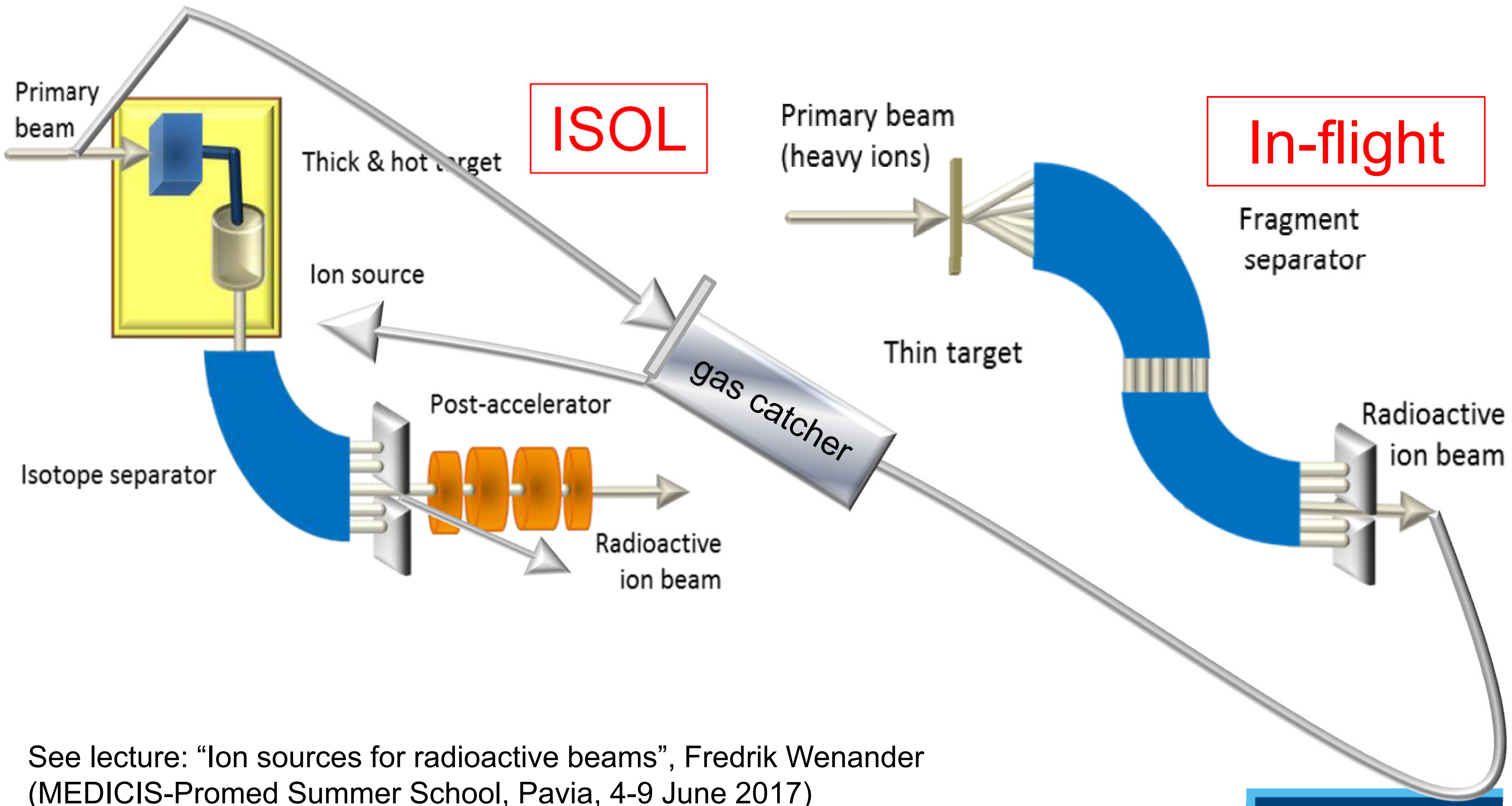
# Production of PURE Radioactive Ion Beams

- 1 GeV proton beam on a lanthanum (La) target




J. Lettry, V. Fedoseev (CERN)

- Radioactive Ion Beams are produced using two complementary ways
  - Isotope Separator On Line method (ISOL)
  - In-flight method



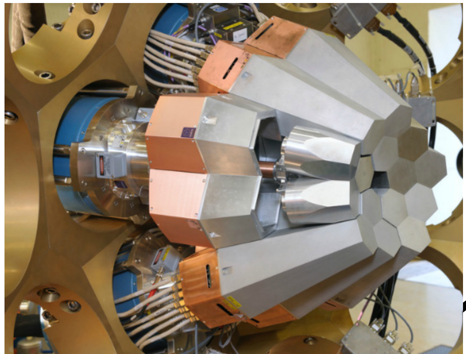

See lecture: "Ion sources for radioactive beams", Fredrik Wenander (MEDICIS-Promed Summer School, Pavia, 4-9 June 2017)
See lecture: "Target material for radioisotope production" J. Pedro Ramos

# Experimental RIB research

- HIE ISOLDE

Energy

- Primary beam
- Production cross section
- Efficiency



Intensity

- Beam purification

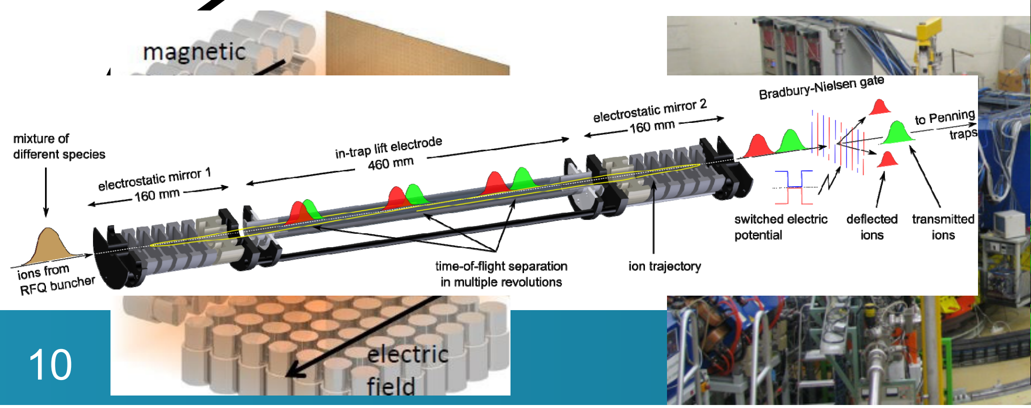
(laser ion source, MR-TOF, High Resolution Separator)

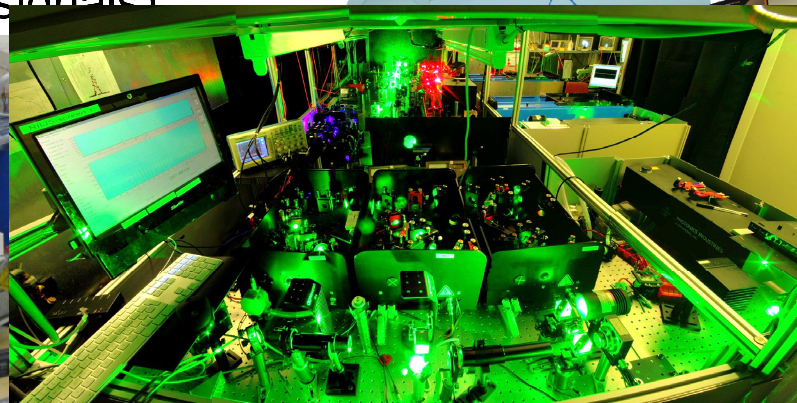
see lecture "Radioactive Ion Beam Manipulation" P. Delahaye

- Adapted Instrumentation

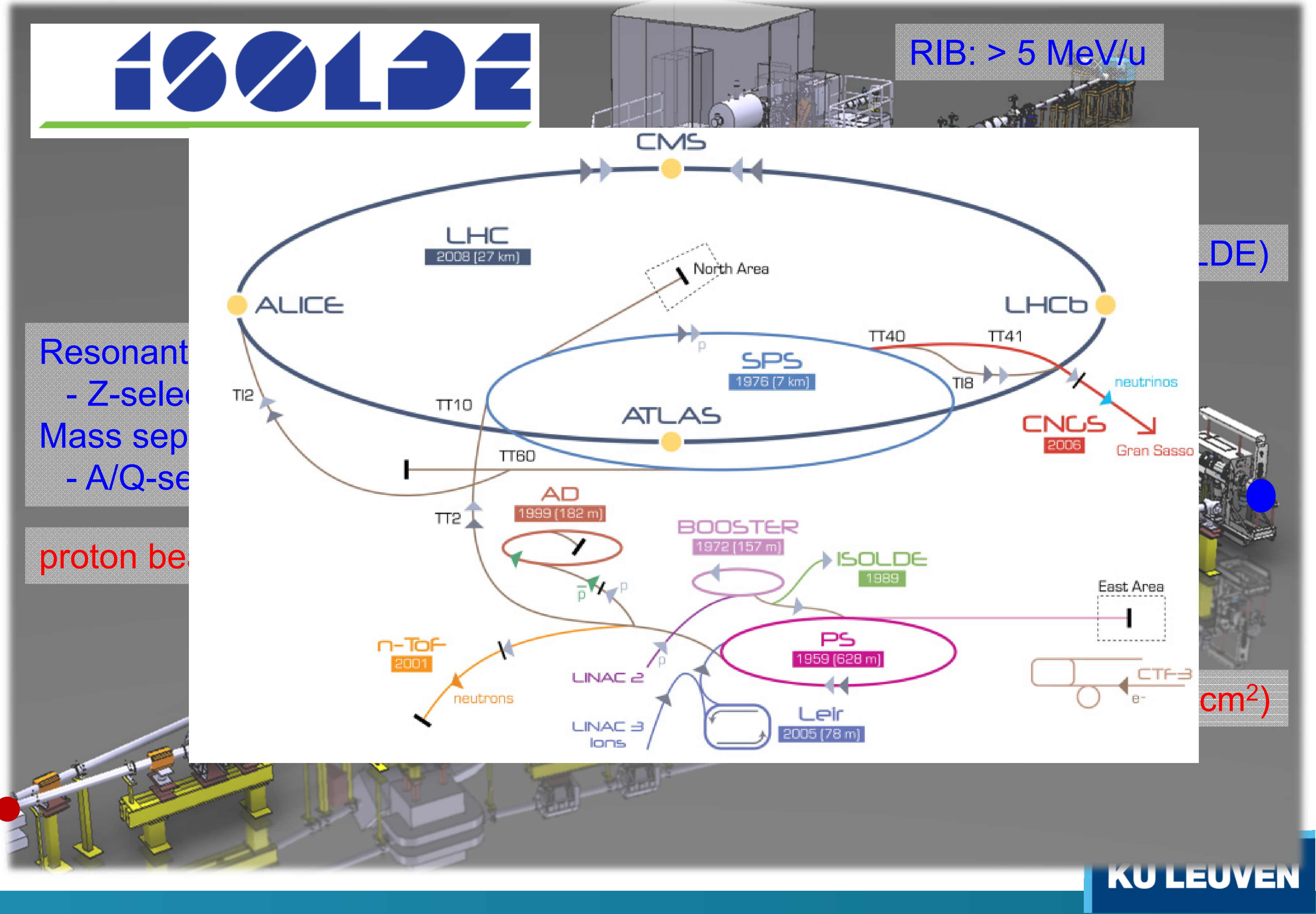
(identification of reaction products, detection of weak signals)

Selectivity/sensitivity



# Radioactive Ion Beams from ISOLDE at CERN




 PVD and K. Riisager J.Phys.G: 38 (2011) 024005

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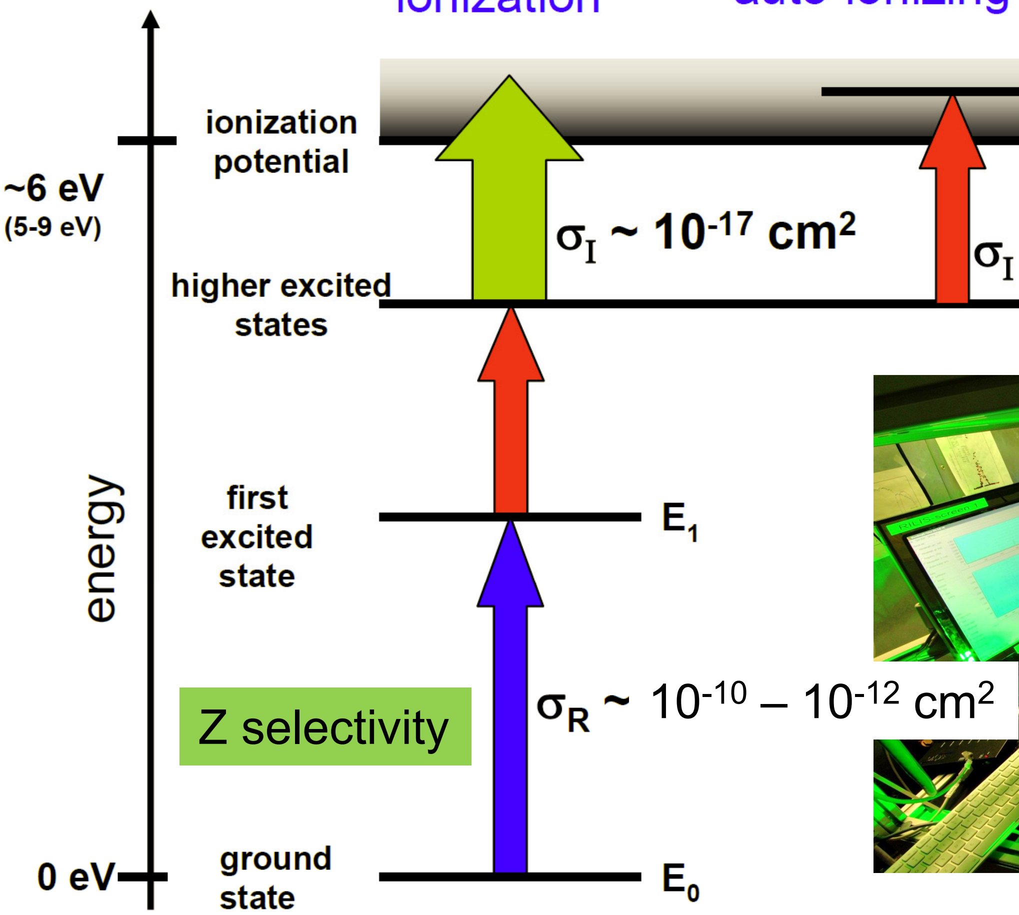
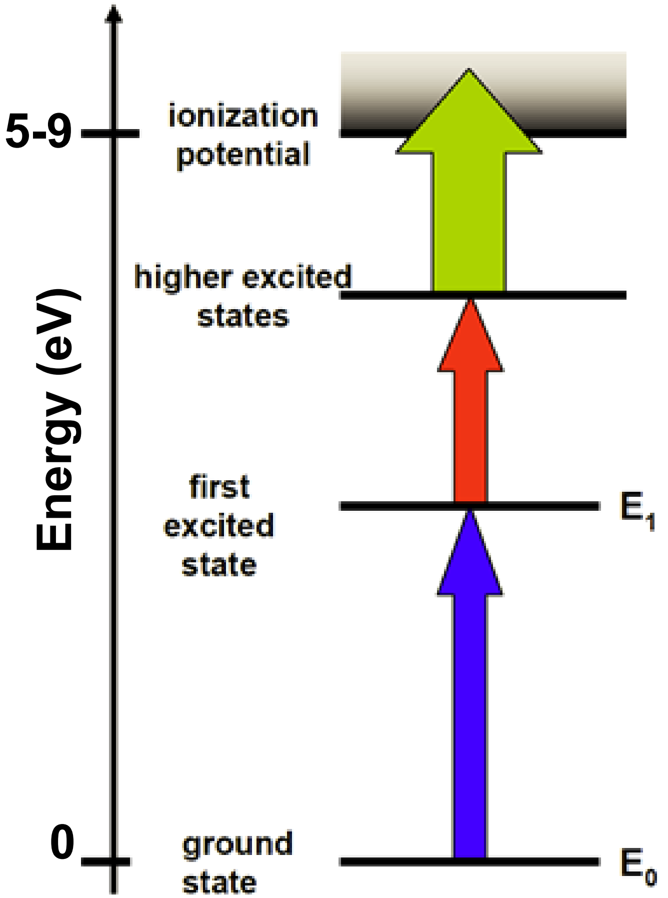
# Laser Resonance Ionization




- saturation: ~ 10 mW/cm$^2$ ~ $10^{16}$ photons/s cm$^2$

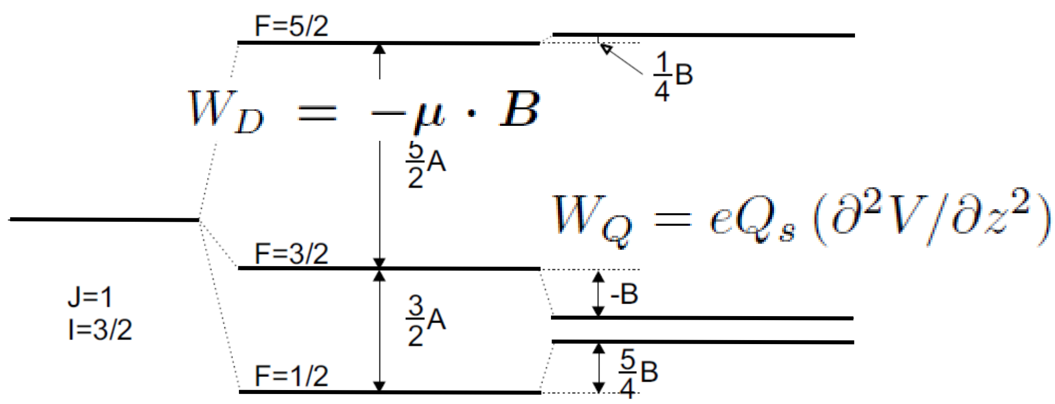

Otten E.W., Treatise on Heavy Ion Science vol 8 (1989) 517
Billowes J and Campbell P, J. Phys. G21 (1995) 707
Kluge H-J., Nörtershäuser, W. Spectrochim. Acta B 58 (2003) 1031
Kluge H-J., Hyperfine Interact. 196 (2010) 295
Cheal B.and Flanagan K., J. Phys. G. 37 (2010) 113101

- Laser Spectroscopy: basics




$$\vec{F} = \vec{I} + \vec{J} \quad \left(|I - J| \leq F \leq I + J\right)$$

Hyperfine Splitting




$$W_F = \frac{1}{2}AC + B\,\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

$$C = F(F+1) - I(I+1) - J(J+1).$$

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

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

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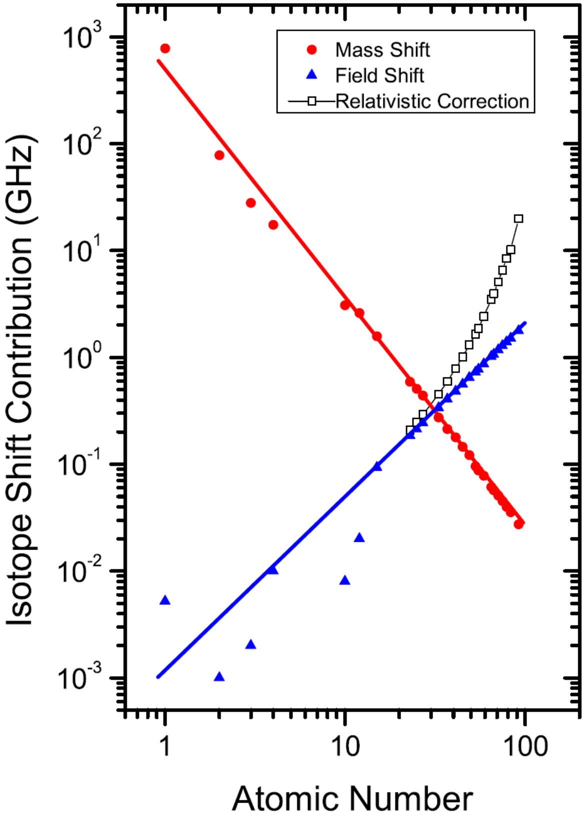
## • Laser Spectroscopy: basics

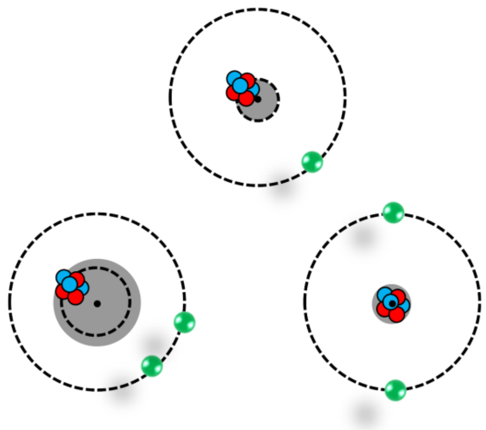

**Isotope Shift**

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

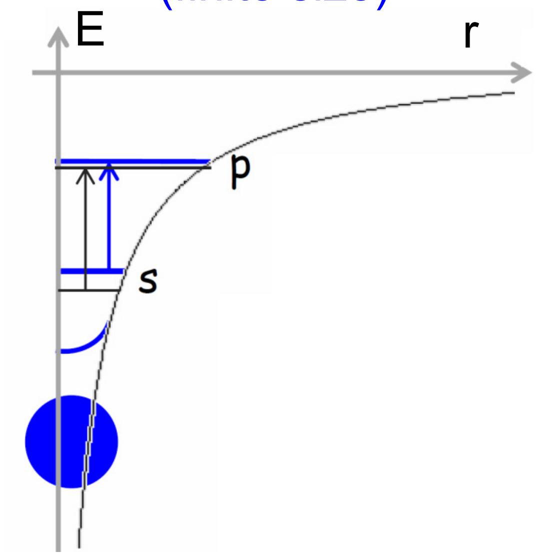



Blaum, Dilling, Nörtershäuser
Phys. Scr. T152 (2013)

Mass shift
(center of mass motion)



Field shift
(finite size)

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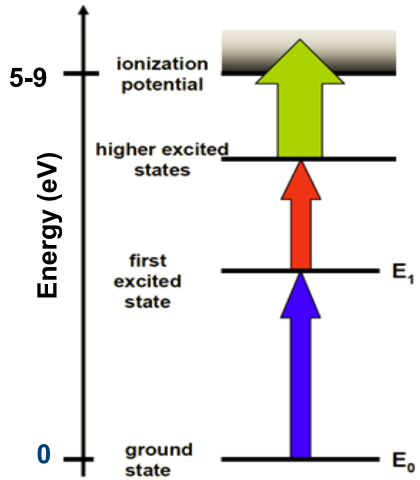



Laser Spectroscopy Experiments: requirements

- High spectral resolution
- High accuracy
- High efficiency/sensitivity (weak production)
- Fast measurement cycle (short-lived radioactive isotopes)

Measured: Isotope shifts Isomer shifts Hyperfine splitting

Atomic Theory

Deduced observables: **(nuclear-model independent)**

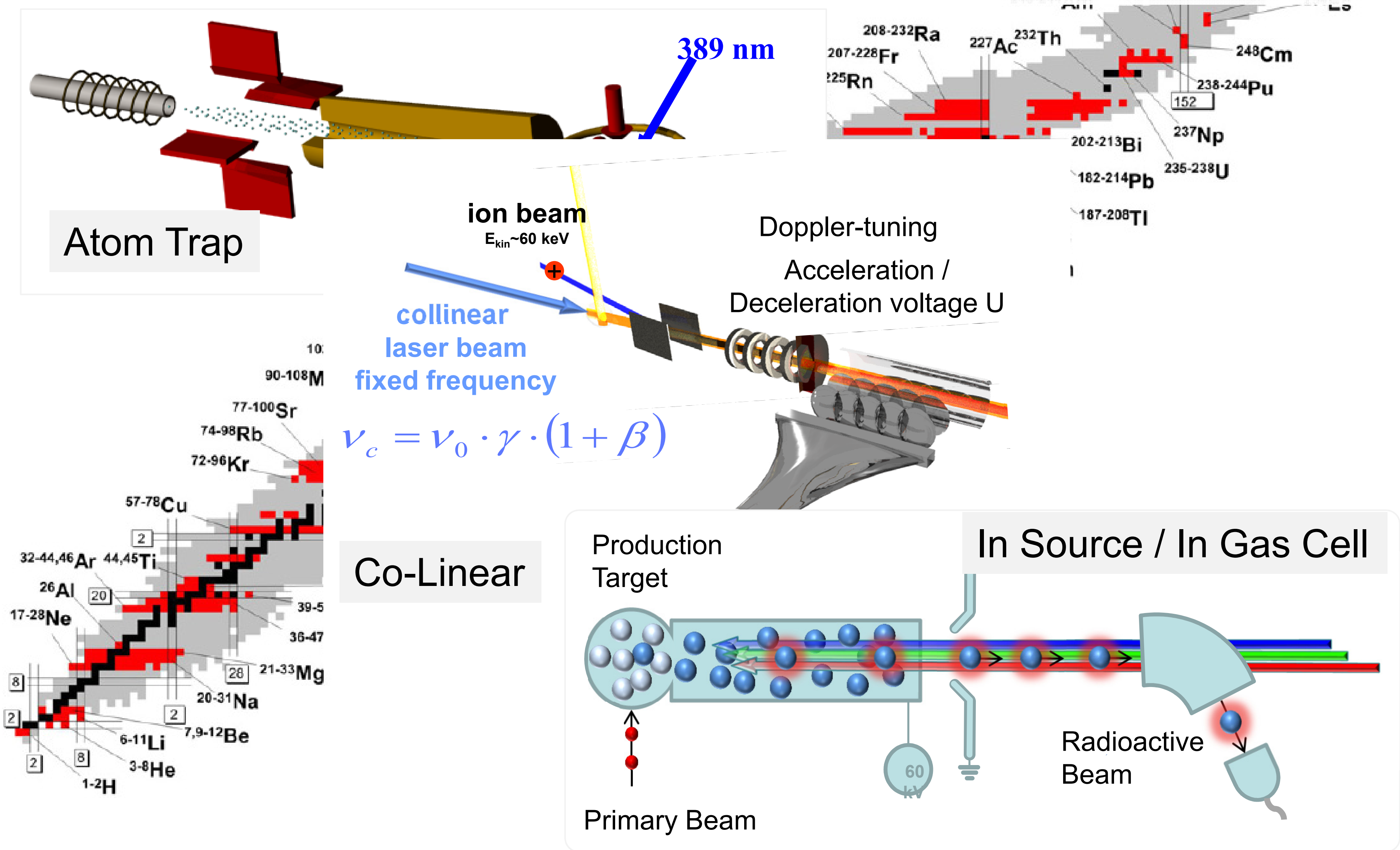
Sizes Quadrupole Mom. Dipole Mom. Spins / Parities

Inferred information: **(nuclear-model dependent)**

Static/dynamic deformation Single-particle configurations

# Chart of Nuclei - Laser Spectroscopy of exotic nuclei

Progress is driven by innovative developments of instrumentation



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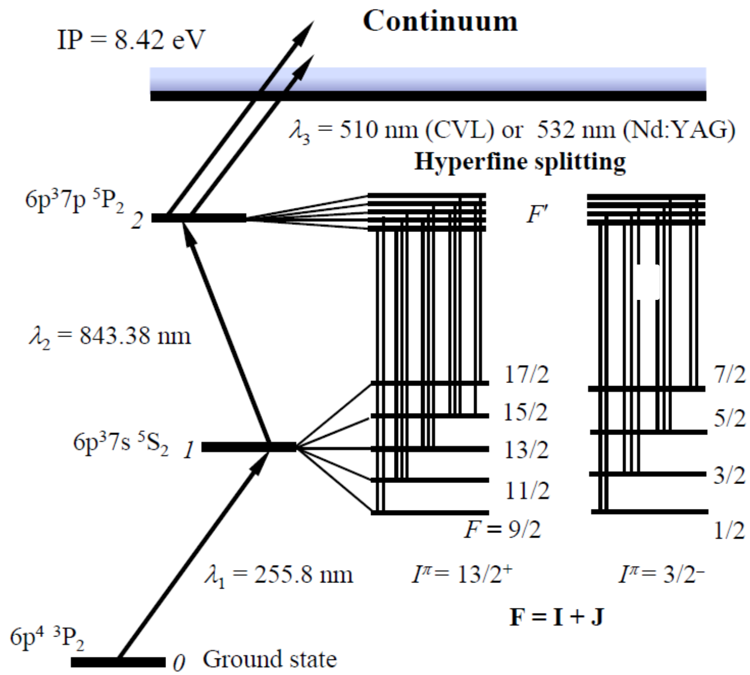
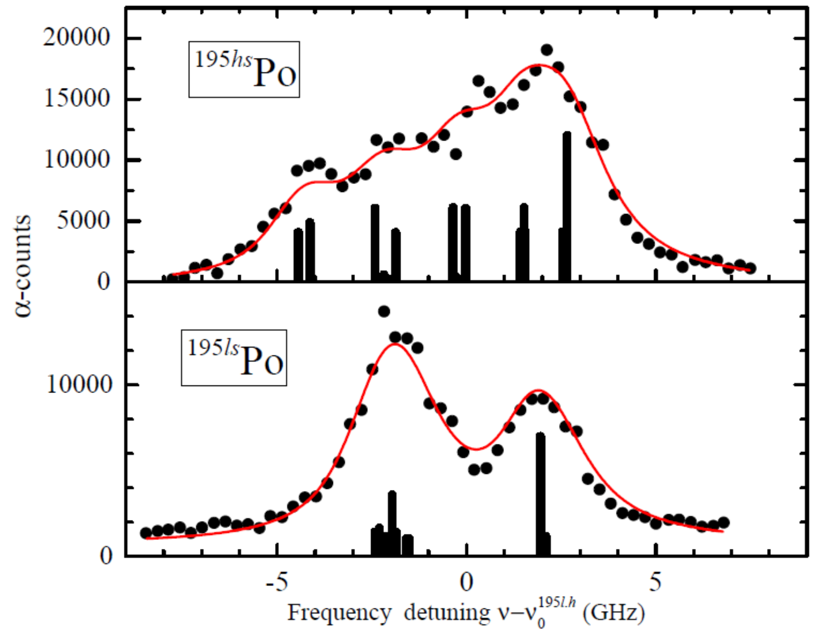
# Broadening mechanisms of the spectral lines

- Natural line width $$\delta\nu_n = 1/(2\pi\tau)$$ τ: life time of atomic state
- Doppler width – thermal movement: $$\delta\nu_D = \frac{\nu_0}{c}\sqrt{8kT\ln 2/m}$$
  T: temperature (K)
  m: mass of the atom
  k: Boltzmann's constant
  c: velocity of light
- Other broadening mechanism (e.g. buffer gas collisions)
- Laser line width



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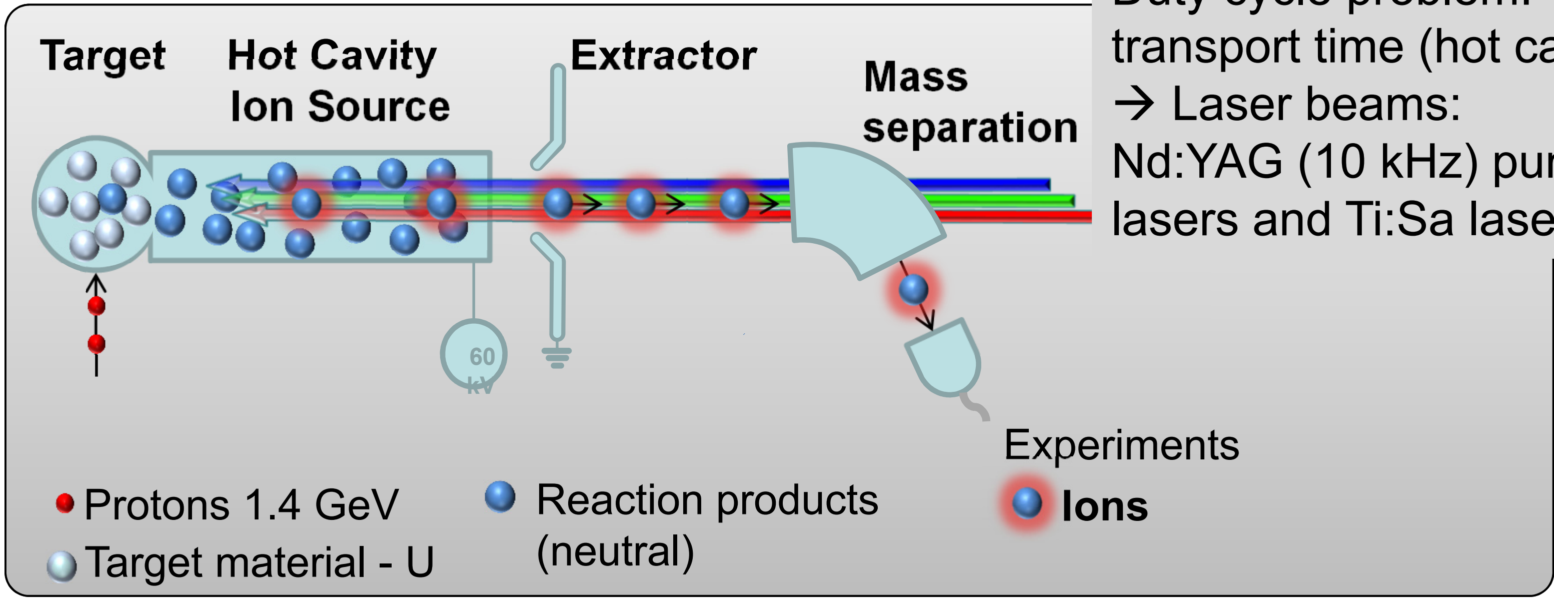
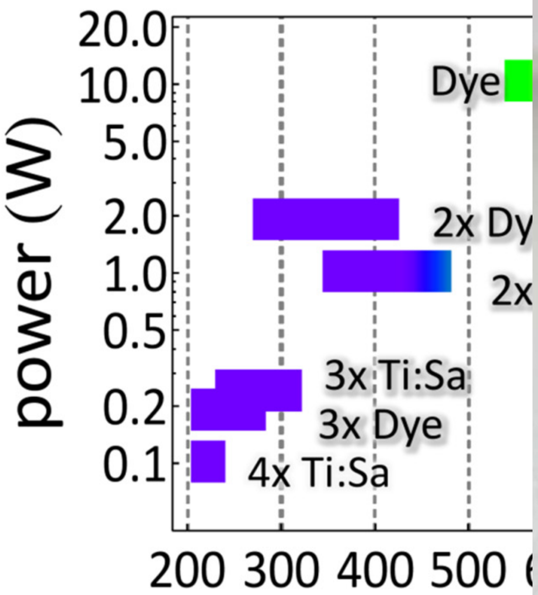
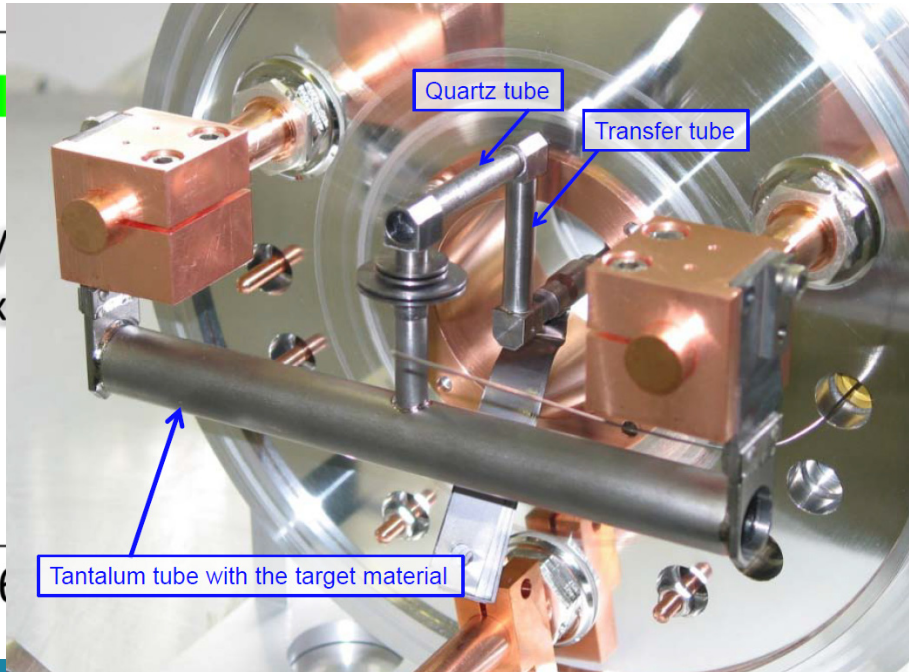
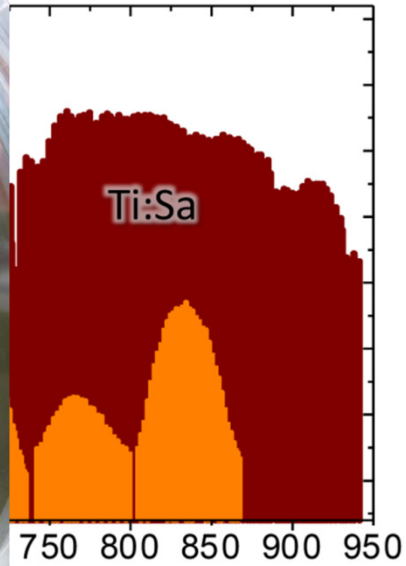
Duty cycle problem:
transport time (hot cavity) ~ 100 μs
→ Laser beams:
Nd:YAG (10 kHz) pumped dye lasers and Ti:Sa lasers



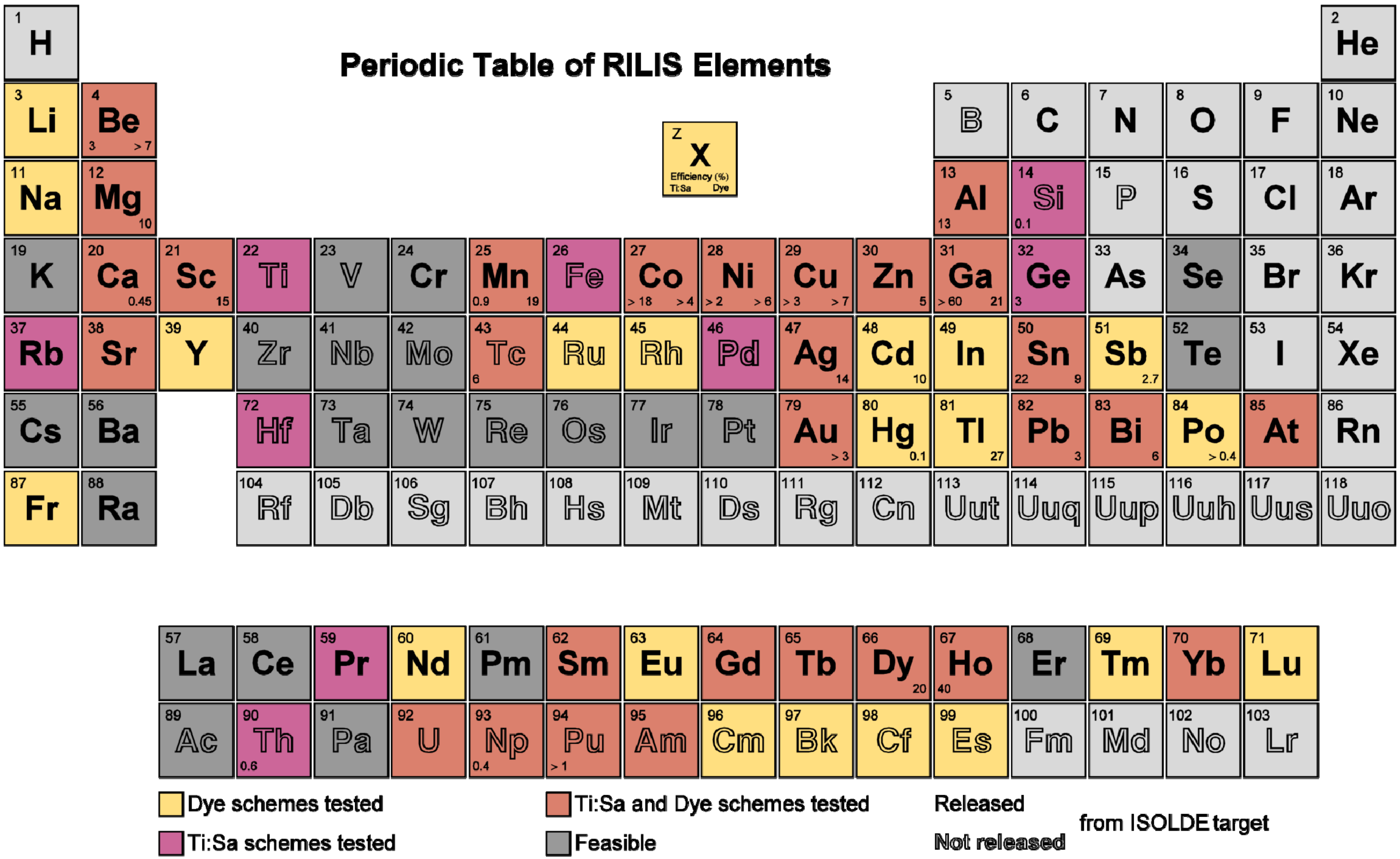





See: J. Pedro Ramos and Th. Stora

# Resonance Ionization for Radioactive Isotopes

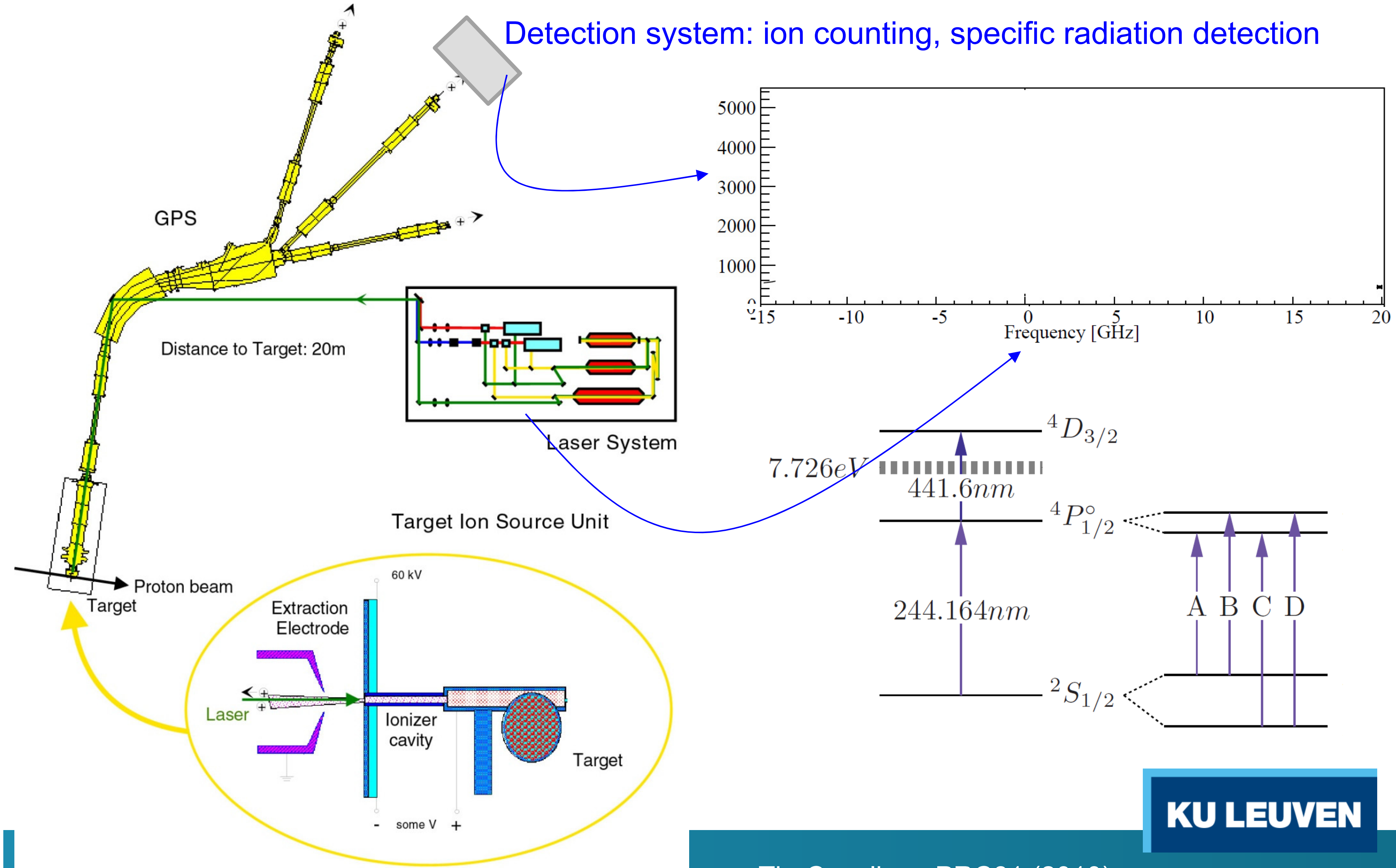



ISOLDE, LISOL, JYFL, TRIUMF, HRIBF-ORNL, GSI - developments at GANIL, RIKEN,…



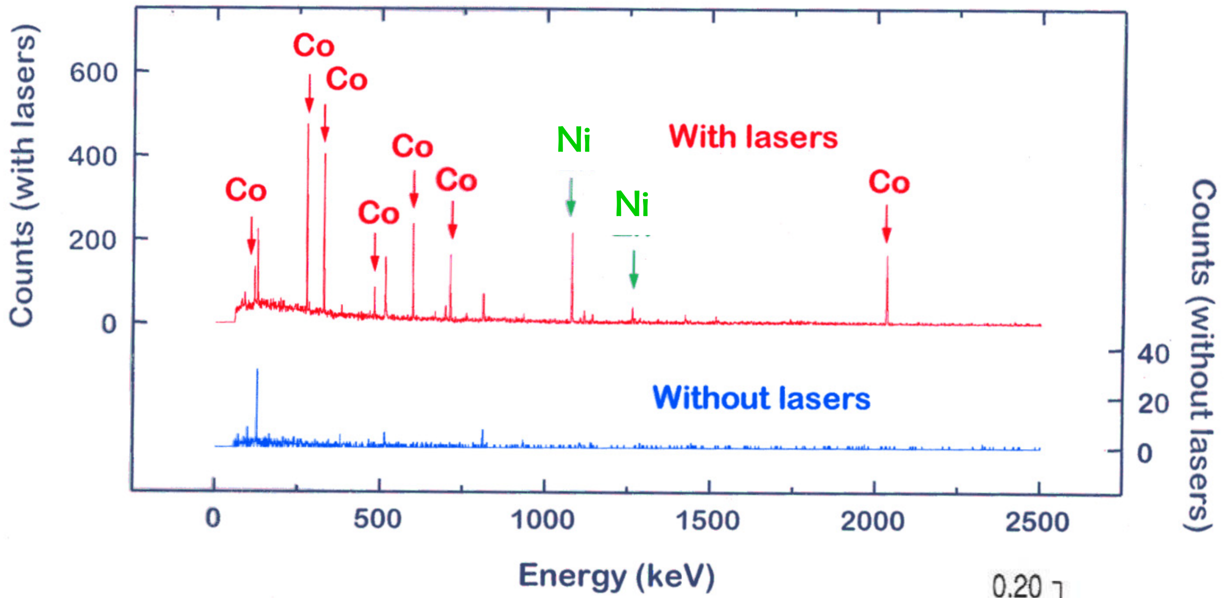
courtesy B. Marsh

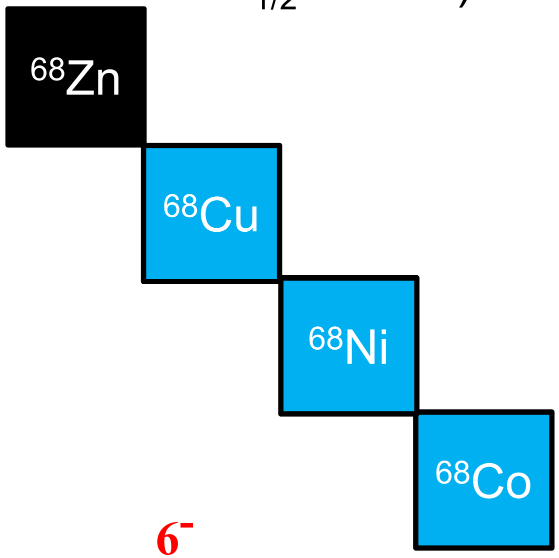
- In-source laser spectroscopy - generic



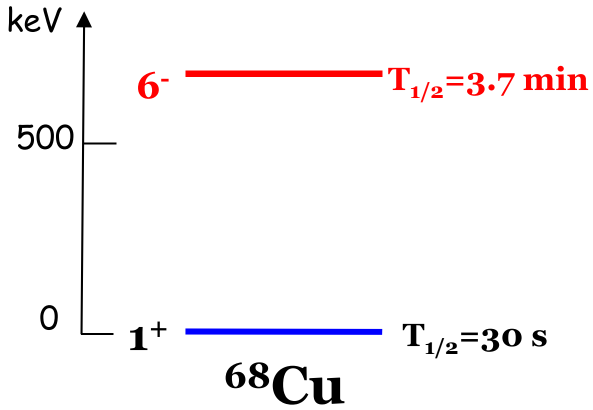
- Element selectivity

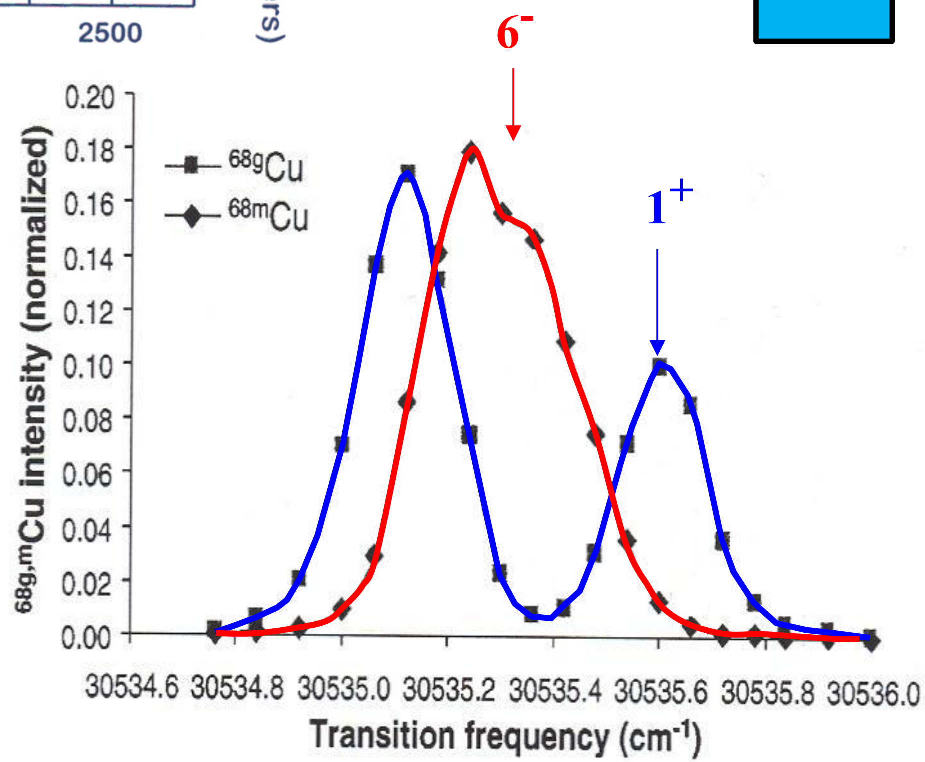
p + $^{238}U$ → fission – ($^{68}Co$ isomer and ground state: $T_{1/2}$ = 1.6 s and $T_{1/2}$ = 0.2 s)




- Isomer selectivity




 Mueller,- PRC61 (2000), Koster,- Hyp. Int. 127 (2000)

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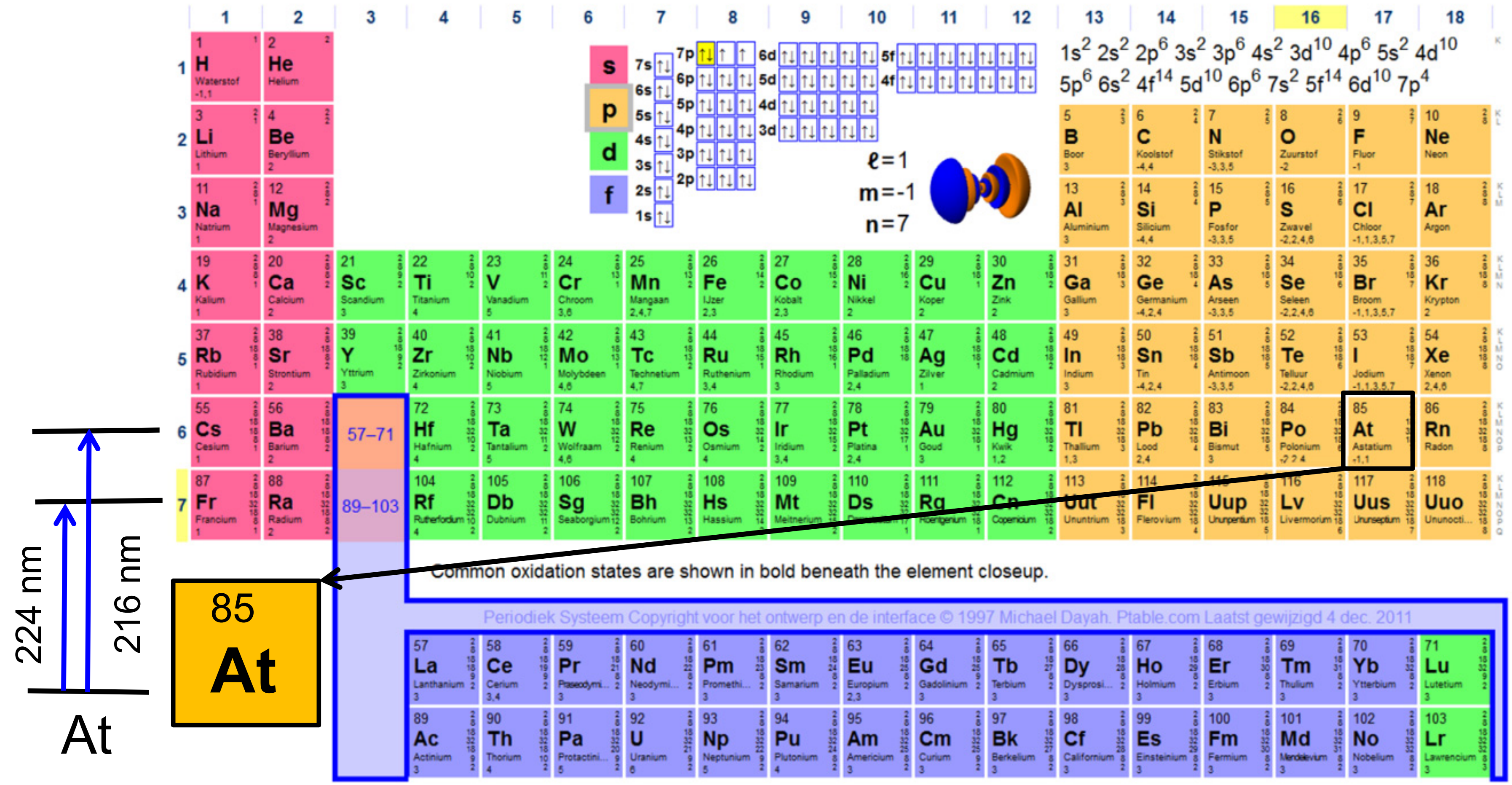
- Laser Ionization of Astatine (At)






ARTICLE

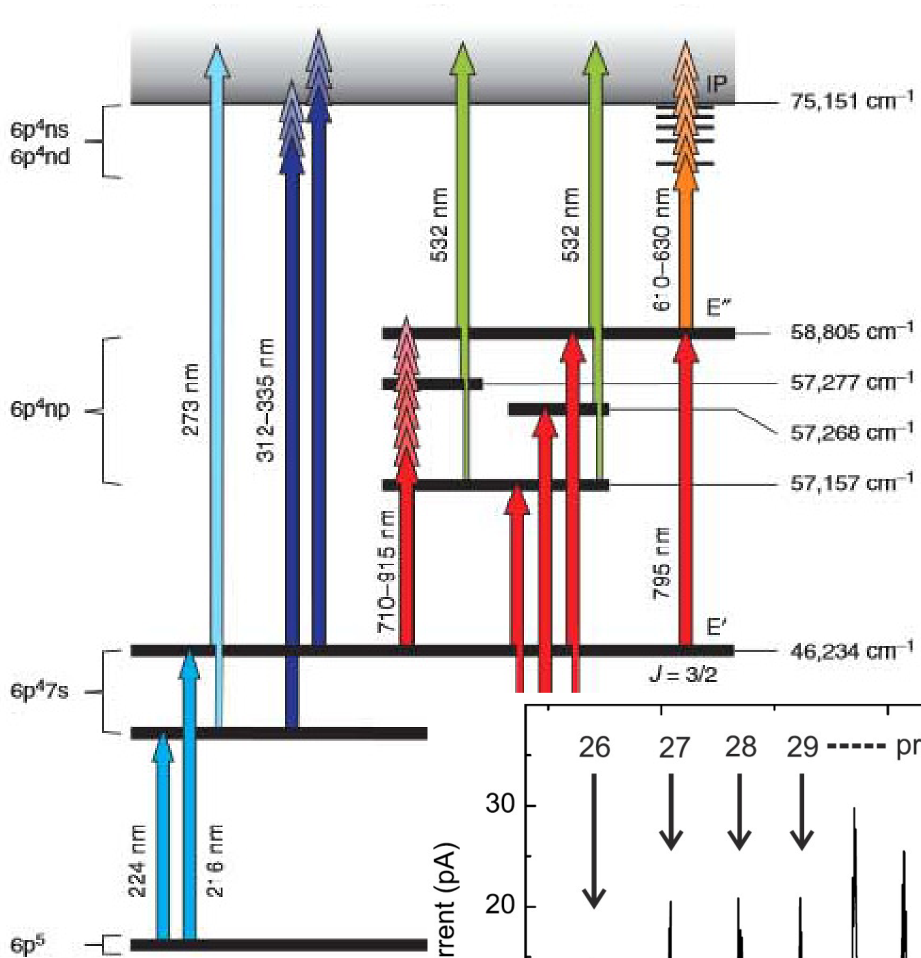

Received 21 Aug 2012 | Accepted 27 Mar 2013 | Published 14 May 2013 DOI: 10.1038/ncomms2819 OPEN


Measurement of the first ionization potential of astatine by laser ionization spectroscopy

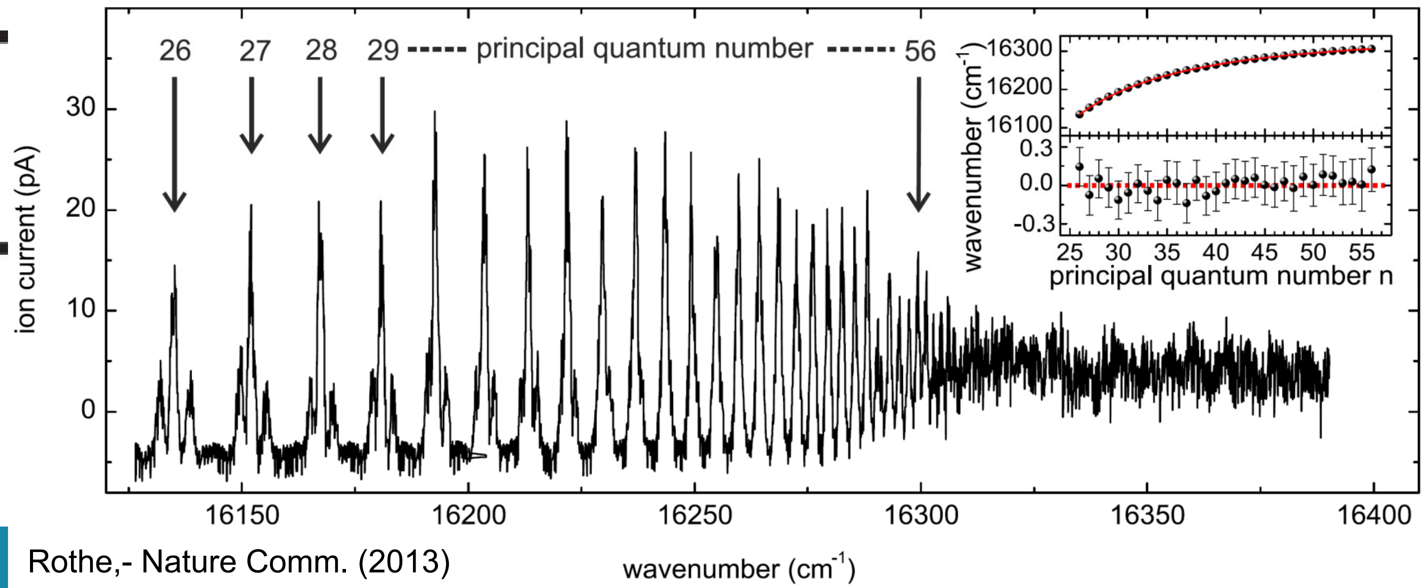


McLaughlin J. Opt. Soc. Am. 54 (1964)

# The Ionization Scheme of Astatine

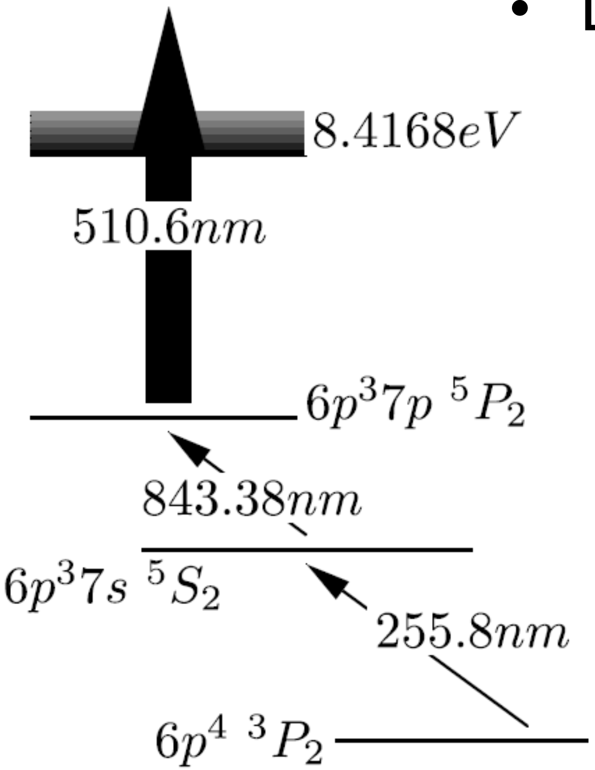


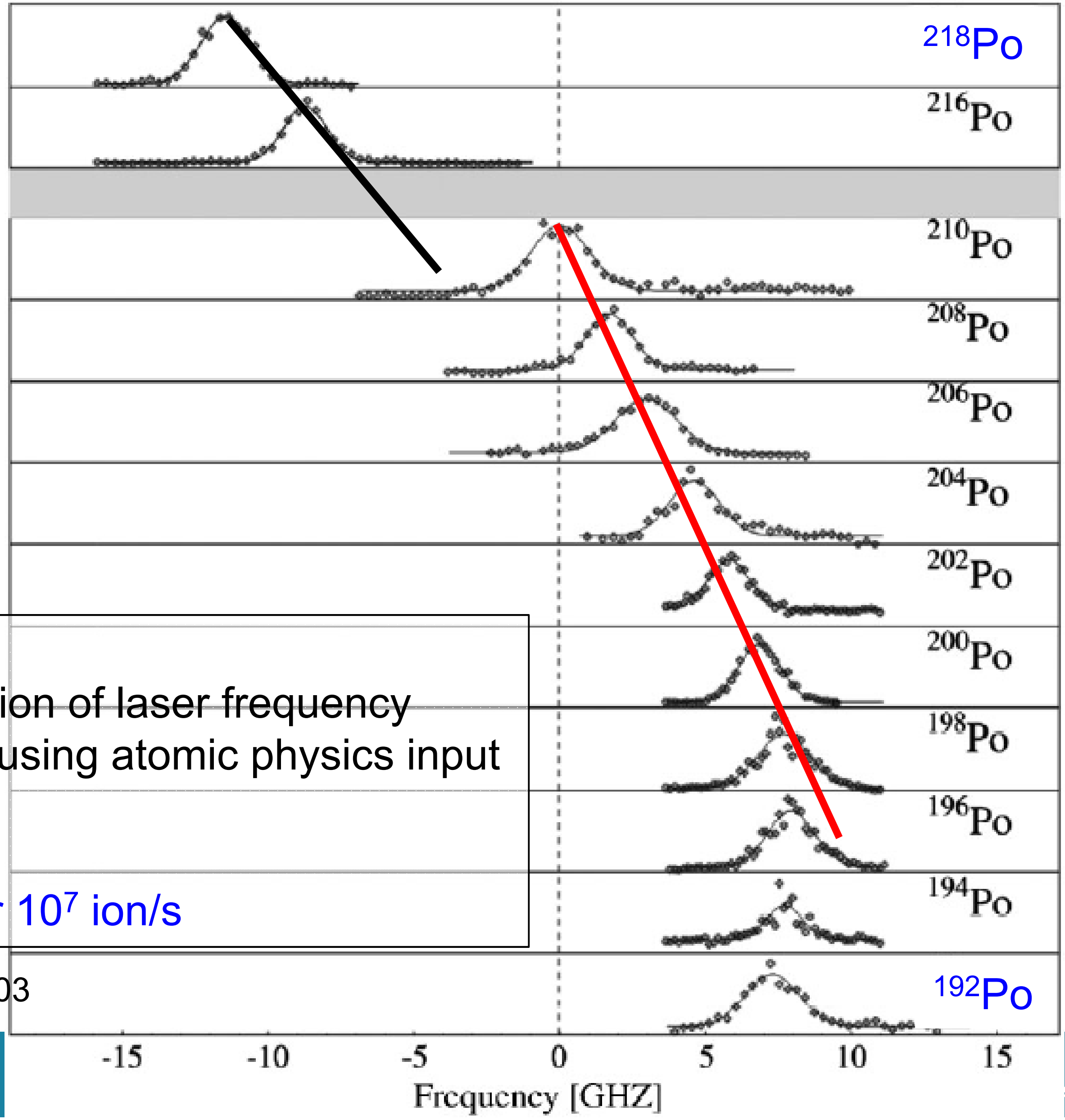

- ISOLDE (CERN) and TRIUMF (Canada)
- IP(At) = 9.31751(8) eV
- Atomic theory
  - MCDF: 9.24 (15) eV (Fritzsche)
  - CCSD: 9.307 (25) eV (Pershina)
- Benchmark for the prediction of the chemical properties of astatine e.g. $^{211}At$ for targeted alpha-particle therapy




Rothe,- Nature Comm. (2013)

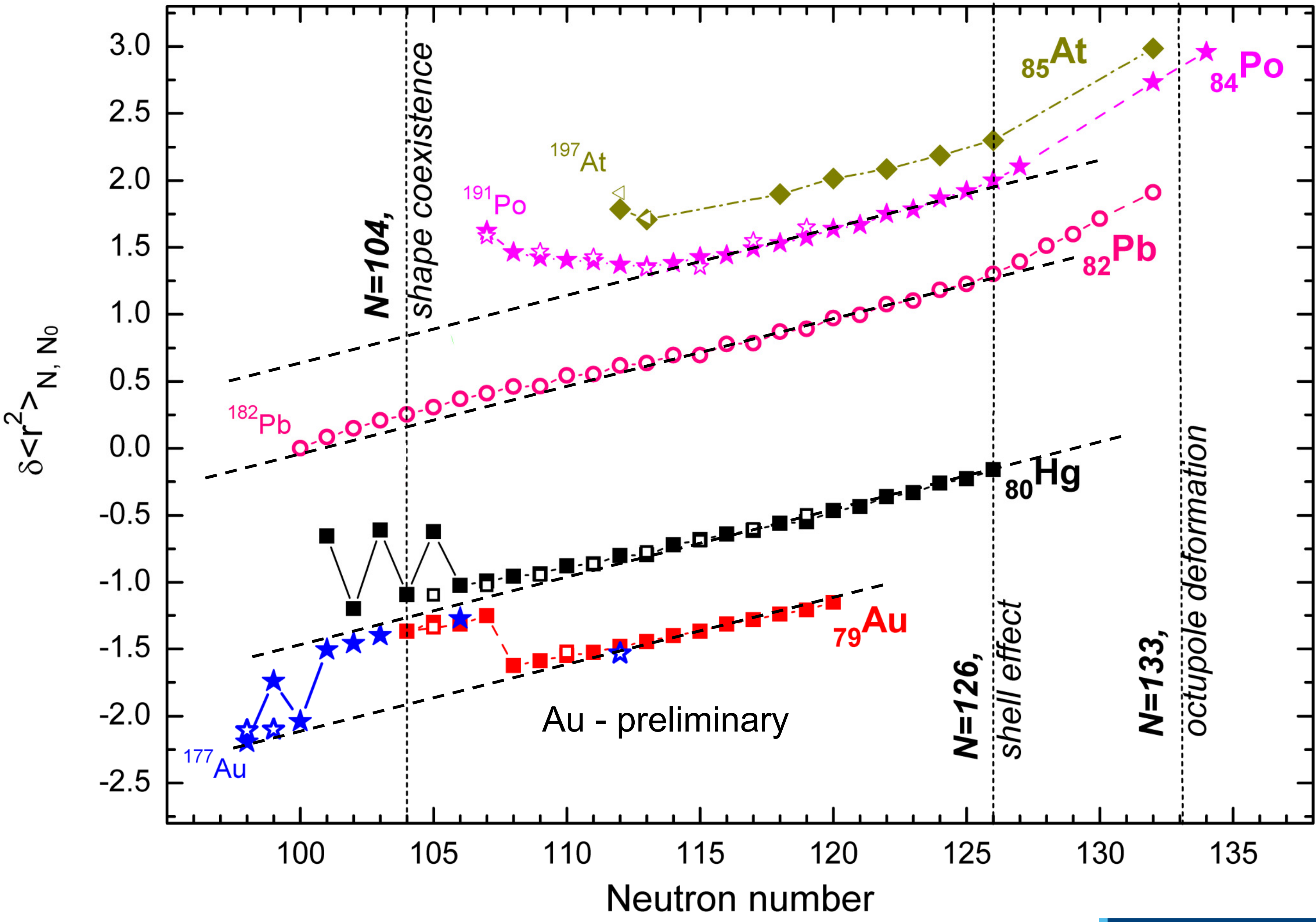
- Laser spectroscopy of Po




- In-source laser spectroscopy :
    - production rate as a function of laser frequency
    - deduction of charge radii using atomic physics input
- A=218 to 192
- $T_{1/2}$ = 3 yr to 33 ms
- Intensity form 0.3 ion/s to over $10^7$ ion/s

Th. Cocolios et al., PRL106 (2011) 052503

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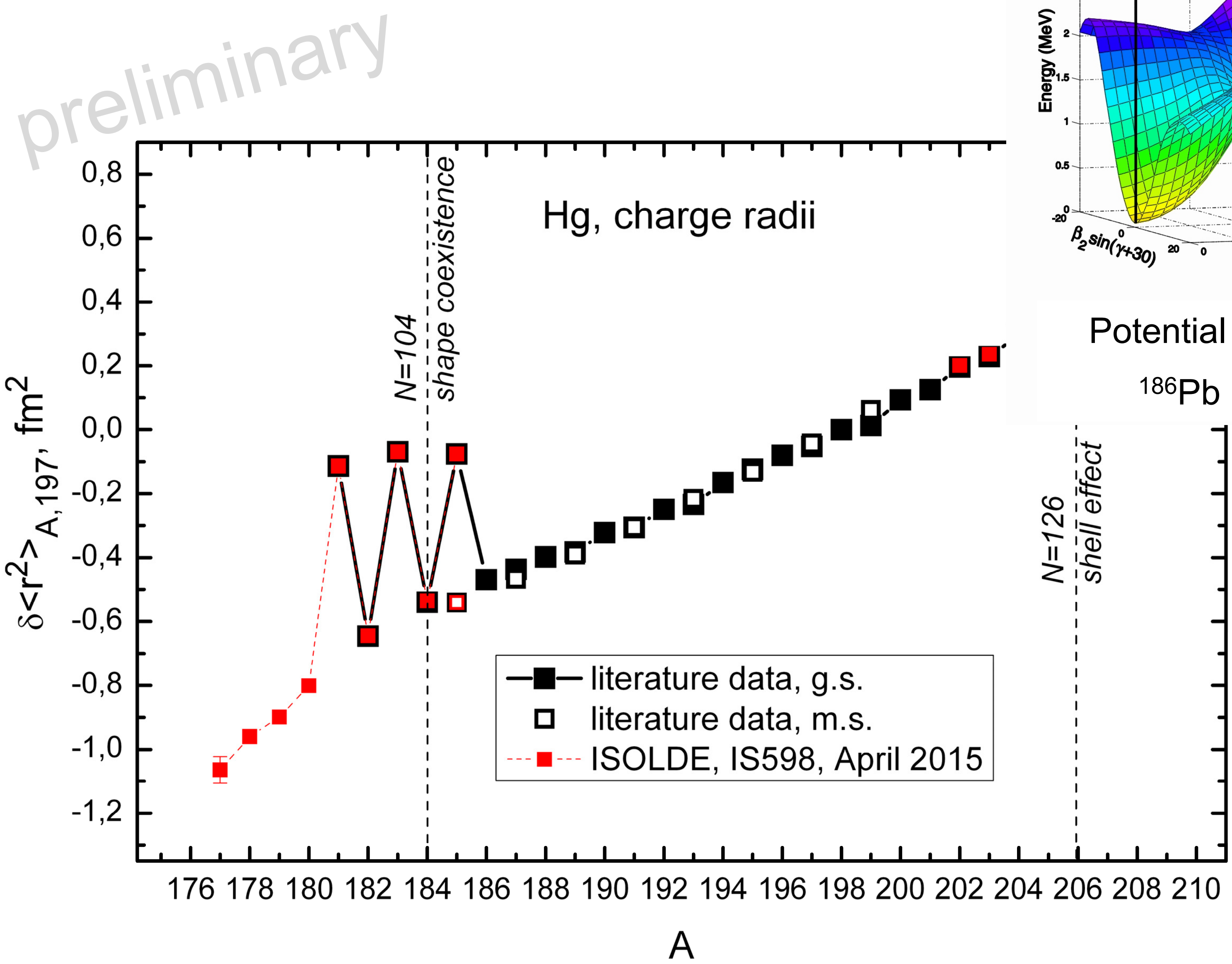
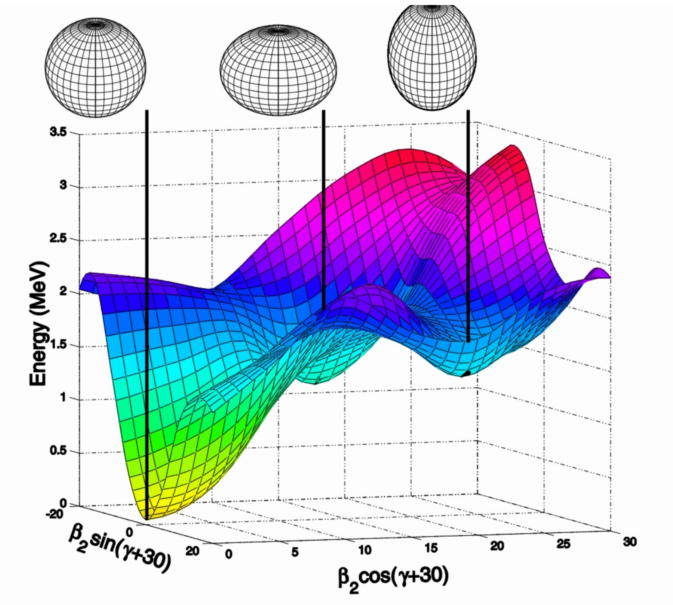
De Witte,- PRL (2007), Cocolios,- PRL (2011), Seliverstof PLB (2013)

# Shape Coexistence in the Lead Region




Potential energy surface of $^{186}$Pb (Z=82, N=104)

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## Reducing the spectral line width

- Narrow-band laser light
- Lower temperature (e.g. super sonic gas jets)
- Atom/ion beam co-linear with laser light
  - Velocity after acceleration: $v = \sqrt{2eU/m}$
  - Spread in energy: $\delta E = \delta\left(\frac{1}{2}mv^2\right) = m\,v\,\delta v$
  - Doppler shift: $\Delta\nu_D = \nu_0\beta = \nu_0(v/c)$
  - Doppler broadening: $\delta\nu_D = \nu_0\,\delta\beta = \nu_0(\delta v/c)$

$$\delta\nu_D = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}}$$

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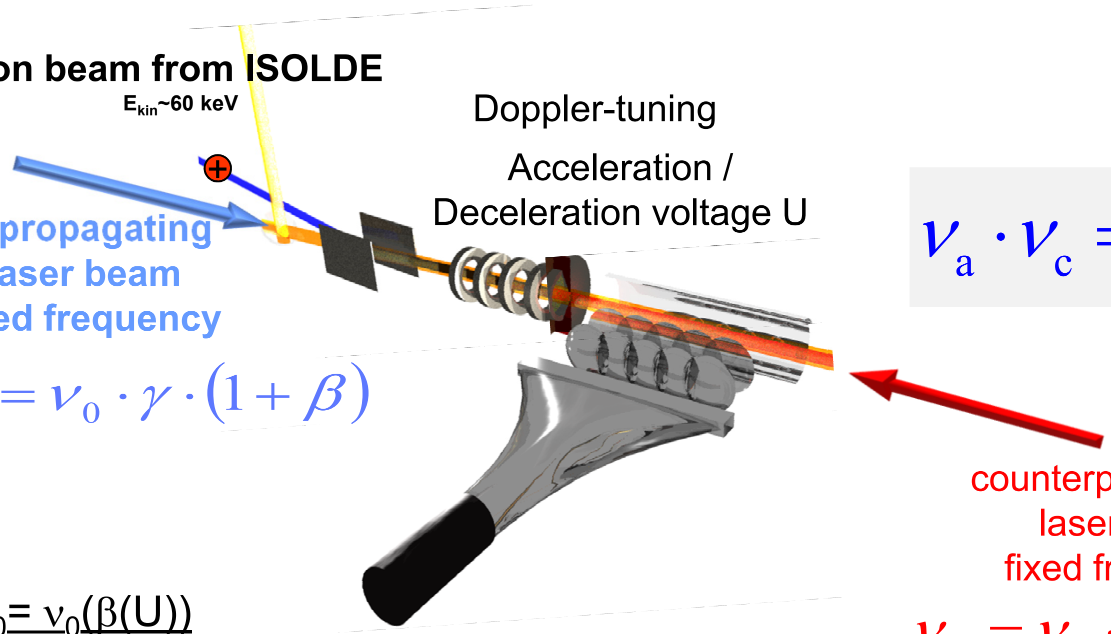
- Halo Nuclei - Laser Spectroscopy of Short-Lived Be isotopes: Copropagating and Counterpropagating Laser Beams.




$$\nu_a \cdot \nu_c = \nu_0^2 \cdot \gamma^2 \cdot \left(1 - \beta^2\right) = \nu_0^2$$

$$\nu_c = \nu_0 \cdot \gamma \cdot (1 + \beta)$$

$$\nu_a = \nu_0 \cdot \gamma \cdot (1 - \beta)$$

$\nu_0 = \nu_0(\beta(U))$

- acceleration voltage $\Delta U/U = 10^{-4}$

Requirements:

- Measure absolute frequencies: Accuracy: $\Delta\nu/\nu < 10^{-9}$
- High sensitivity: 8000 ions per second $^{12}Be(T_{1/2} = 21ms)$

Courtesy: W. Nörtershäuser

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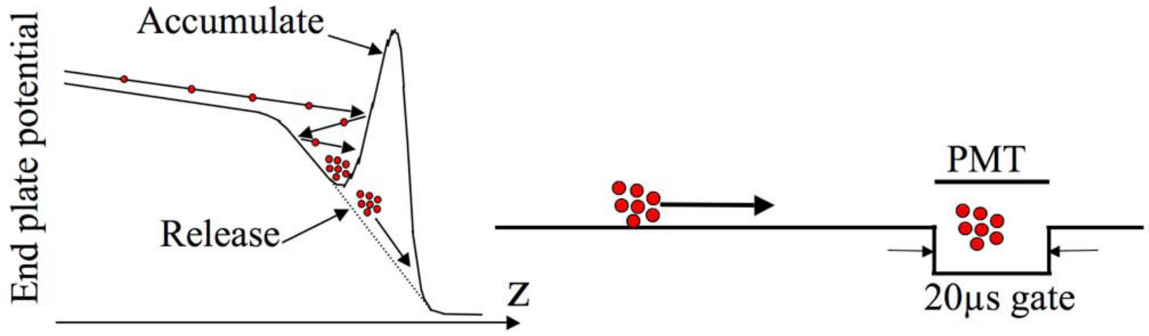
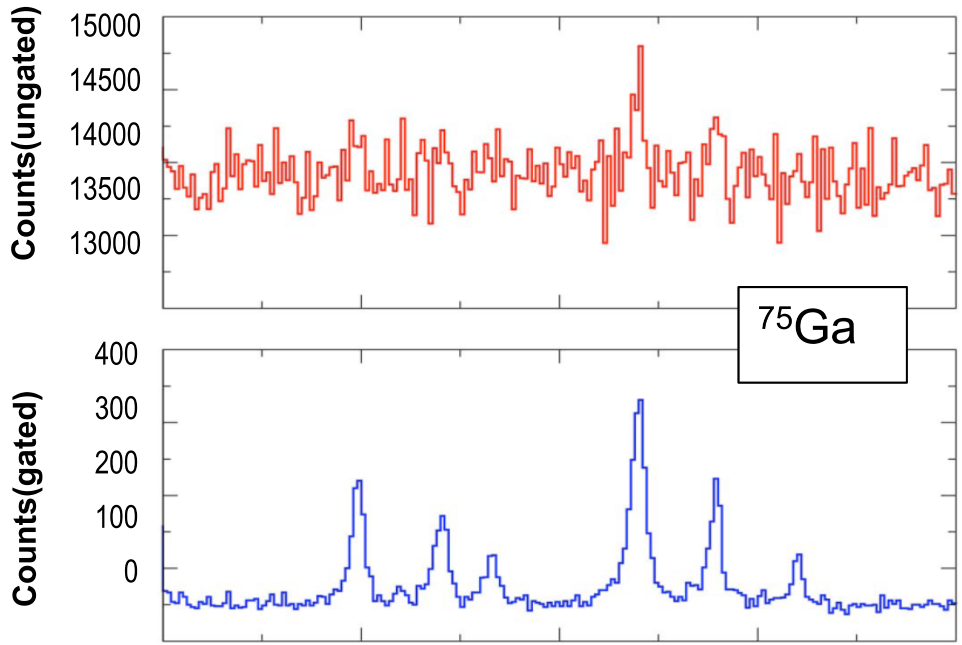
- Improving sensitivity for optical detection by a factor 100 using ion bunching



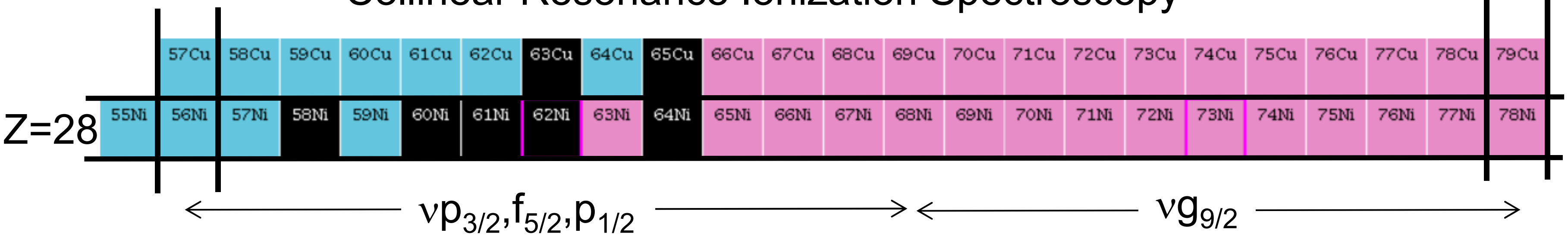

JYFL: Nieminen NIMA 469 (2001)
ISOLTRAP: Herfurth,-NIMA 469 (2001).
Niemenem ,- PRL 88, 094801 (2002)
Cheal,- PRL104, 252502 (2010)

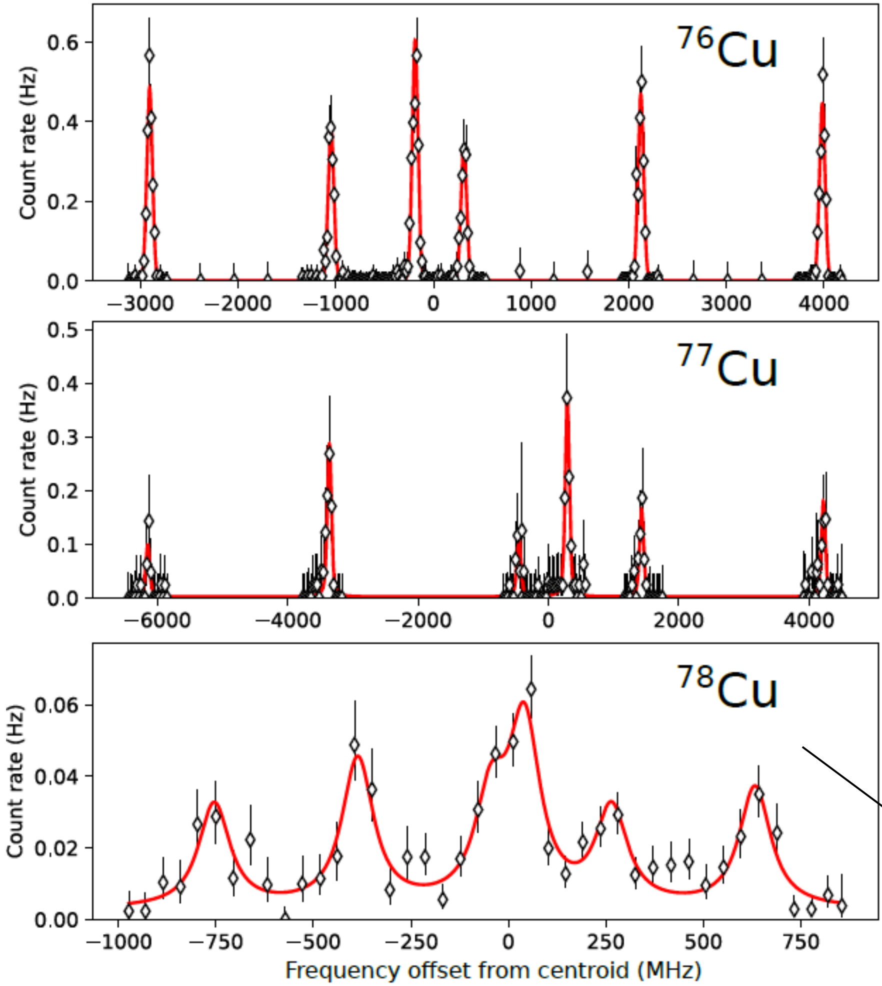
Continuous photon detection

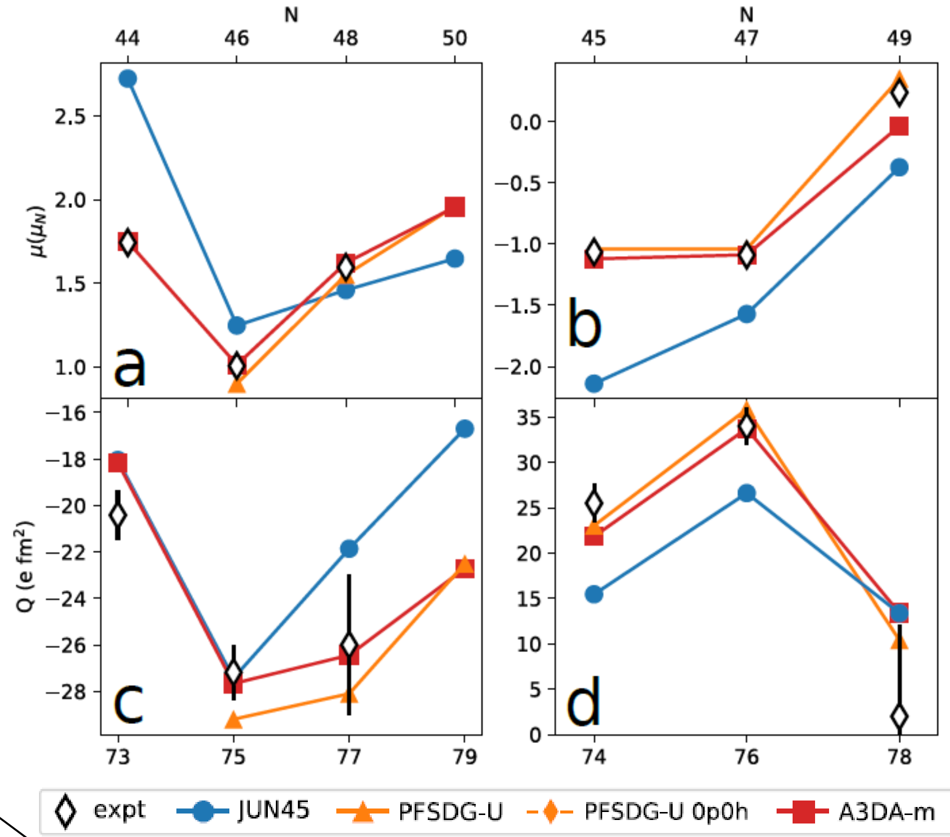



Photon detection with 20 μs time gate

- Collinear Resonance Ionization Spectroscopy




Count rate: 0.05 /s (8 h measuring time)

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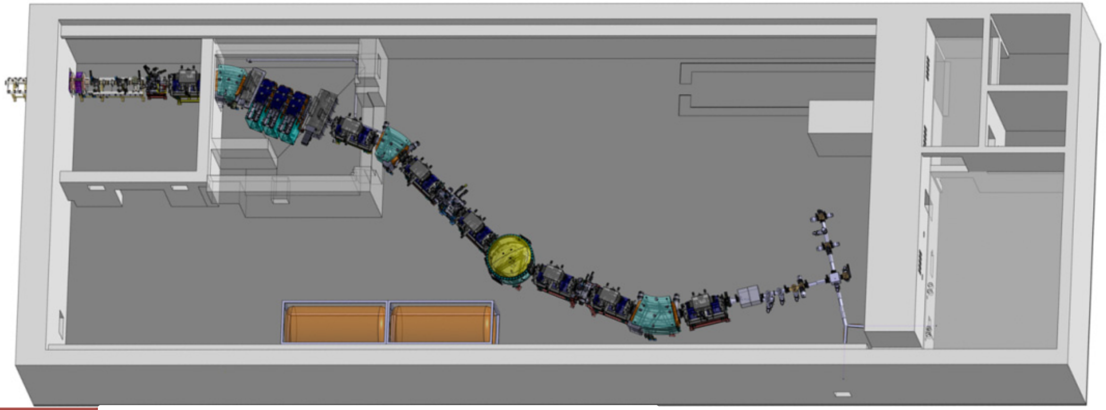
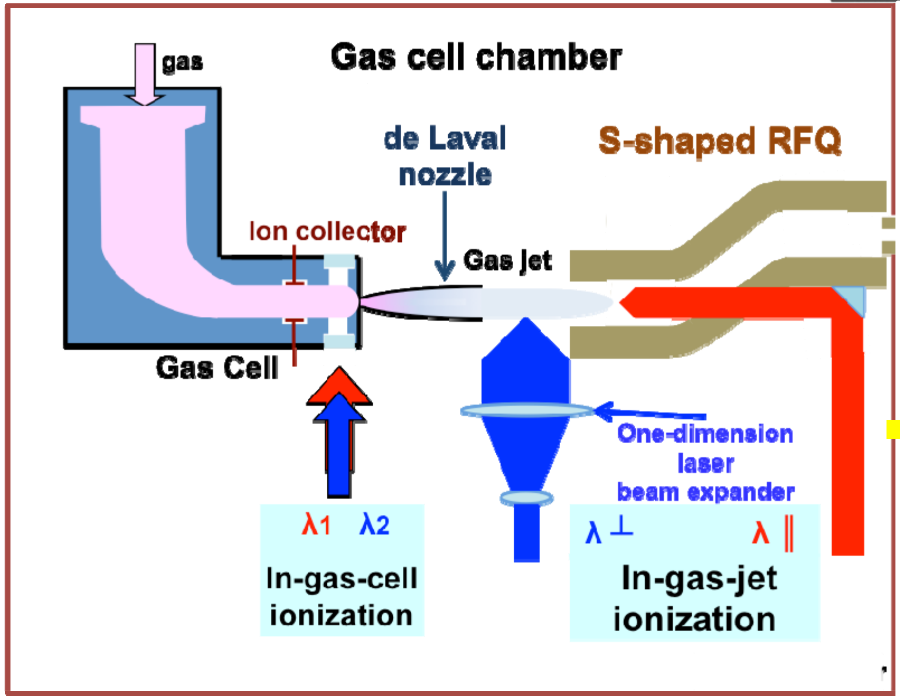
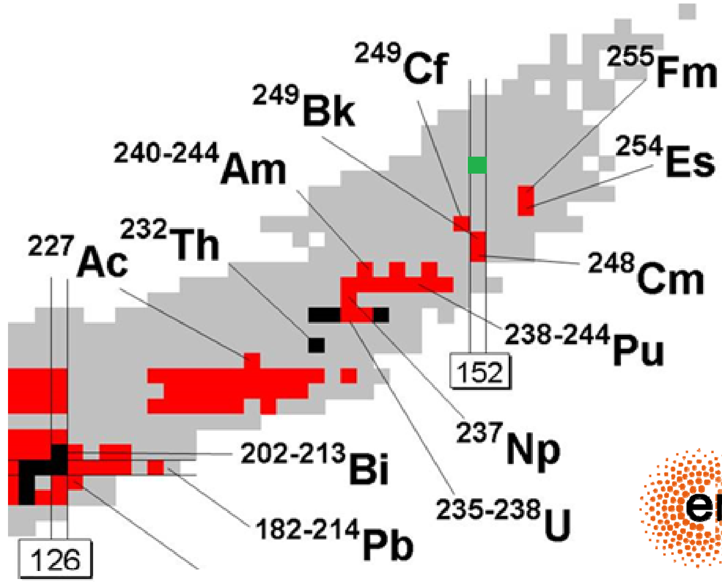
- In Gas Laser Ionization and Spectroscopy (IGLIS)
  - ➢ High intensity heavy-ion LINAC: >10 pμA
  - ➢ Super Separator Spectrometer

GANIL spiral2 laboratoire commun CEA/DSM CNRS/IN2P3

Super Separator Spectrometer - S3



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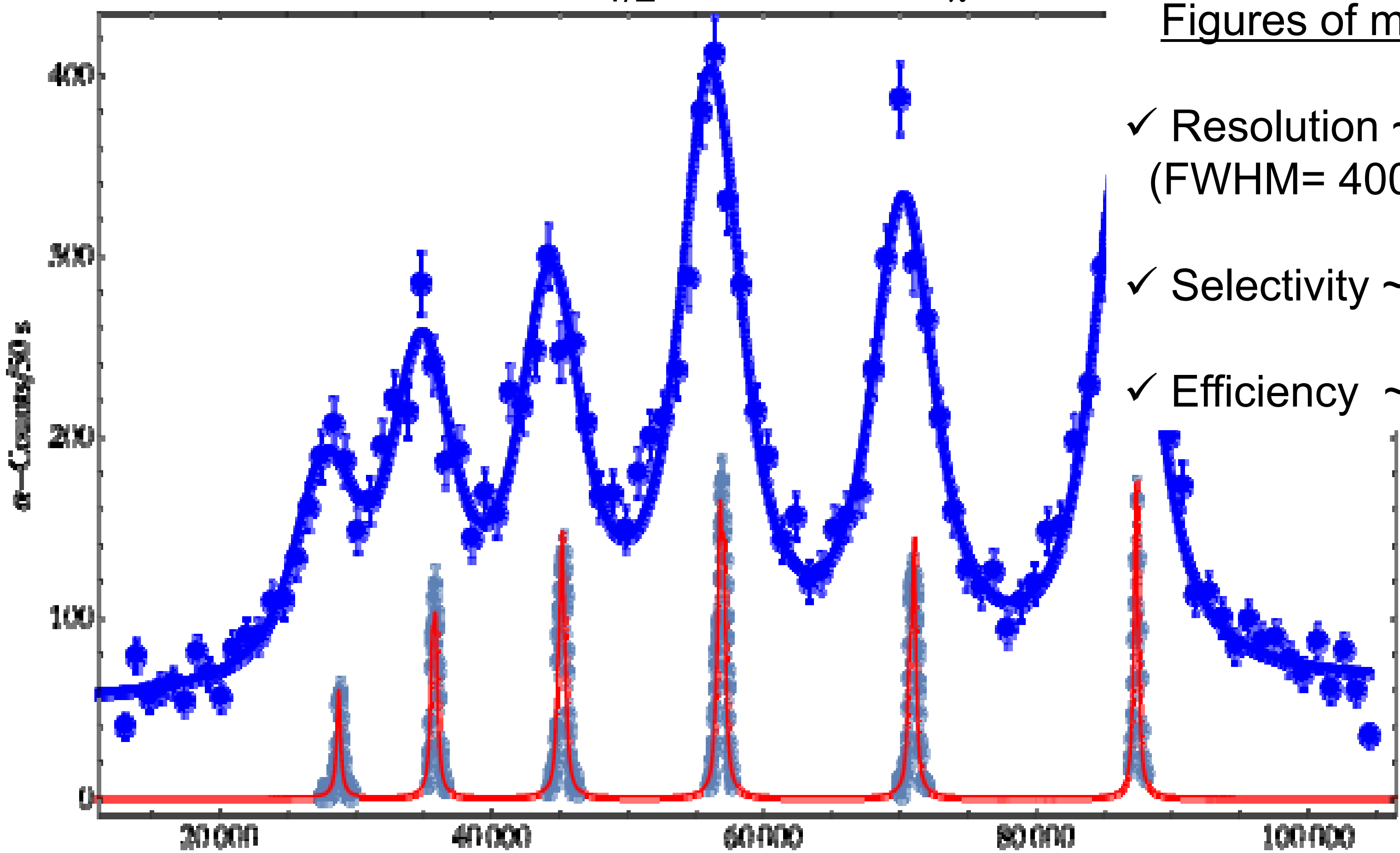
Kudryavtsev NIM B297 (2013), Ferrer NIMB317 (2014) and Nat. Comm. (2017)

# LISOL's famous last action (*)

## * 1/5/1974 - † 6/12/2014

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




Figures of merit:

- ✓ Resolution ~ 5 $10^{-7}$ (FWHM= 400 MHz)
- ✓ Selectivity ~ 200
- ✓ Efficiency ~ 0.5%

**- in gas cell** **- in gas jet**

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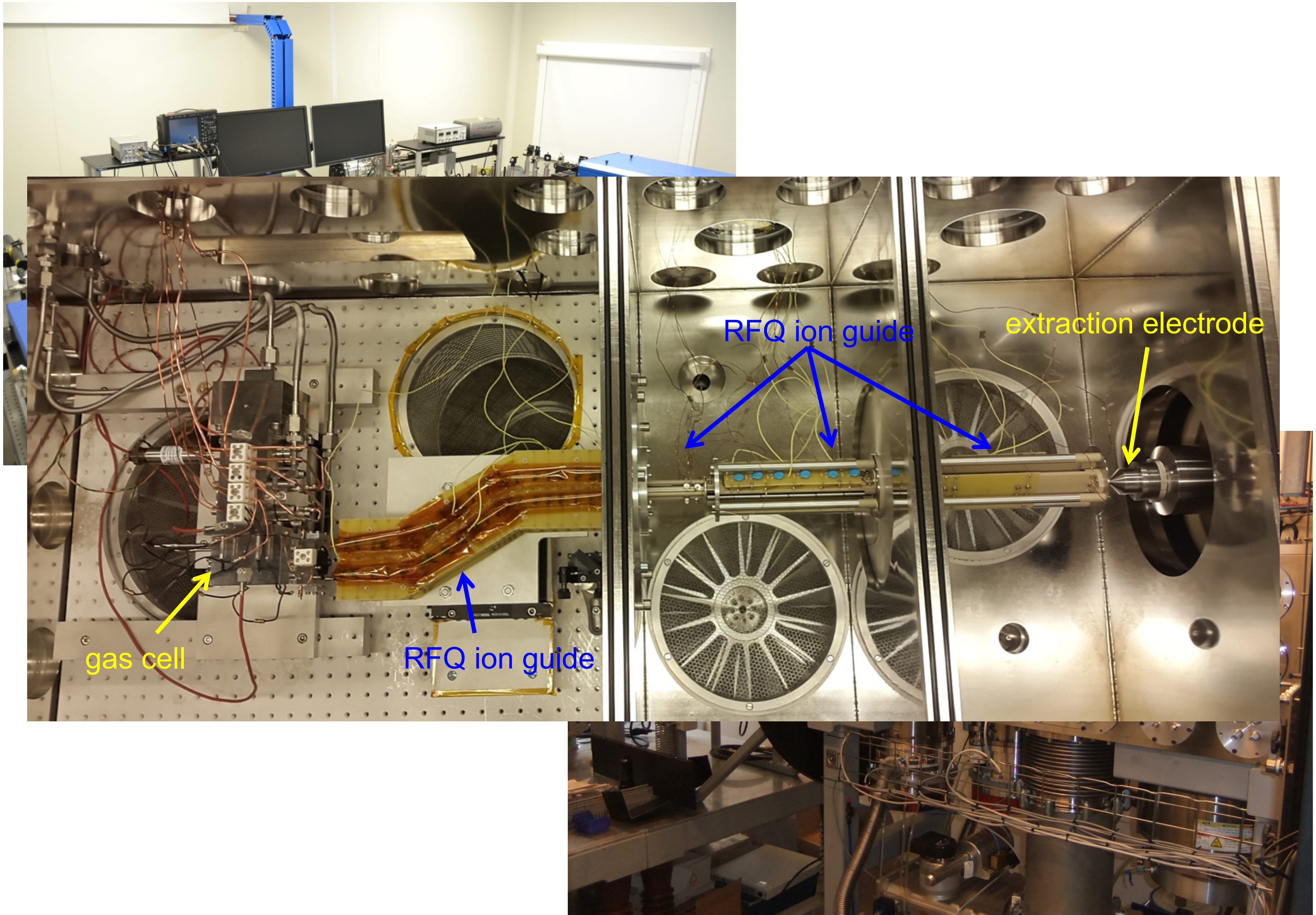


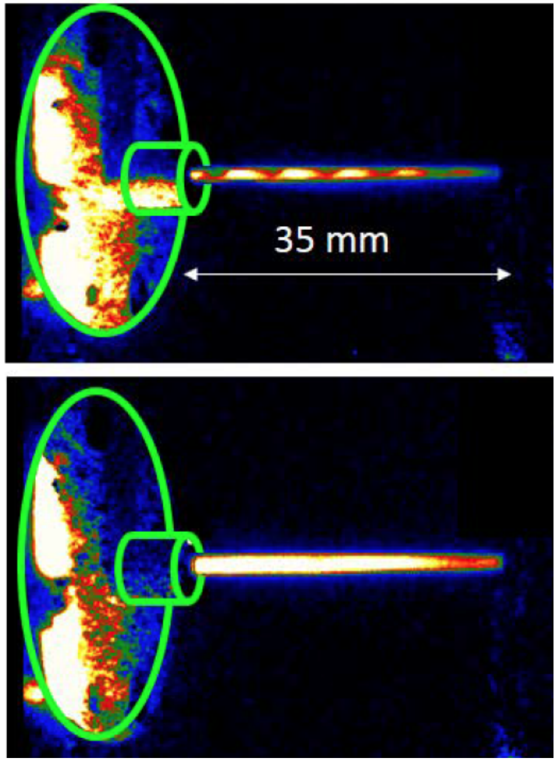

# IGLIS @ KU Leuven

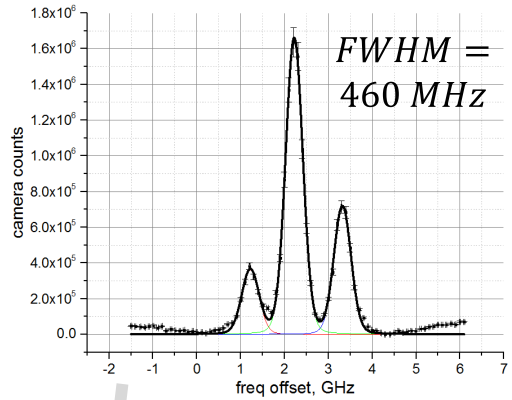
Piet Van Duppen

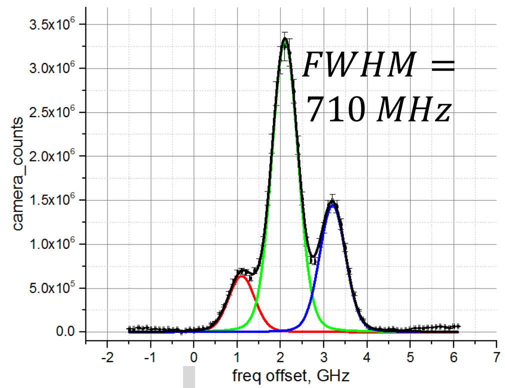
- Laser and gas-cell based mass separator lab at KU Leuven

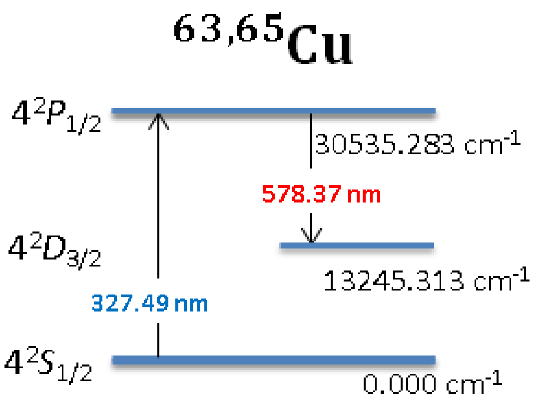
$T_{avg}$ > 150 K
Eff. << 10 %
Res. > 1100 MHz

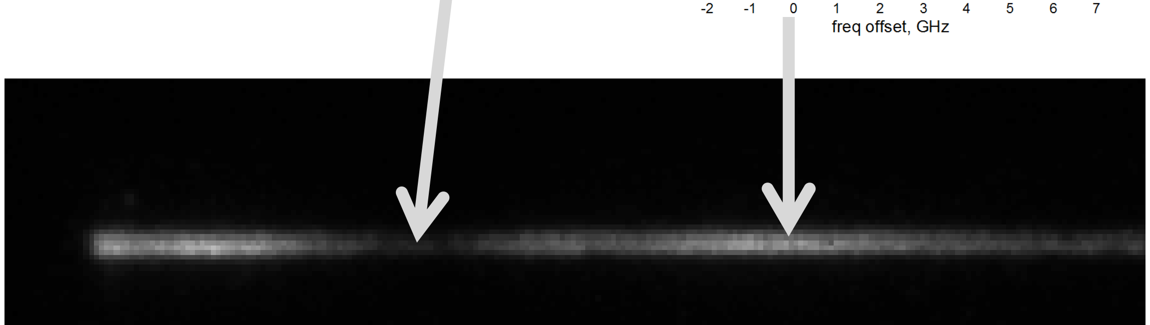
T~ 30 K
Eff. > 10 %
Res. ~ 400 MHz



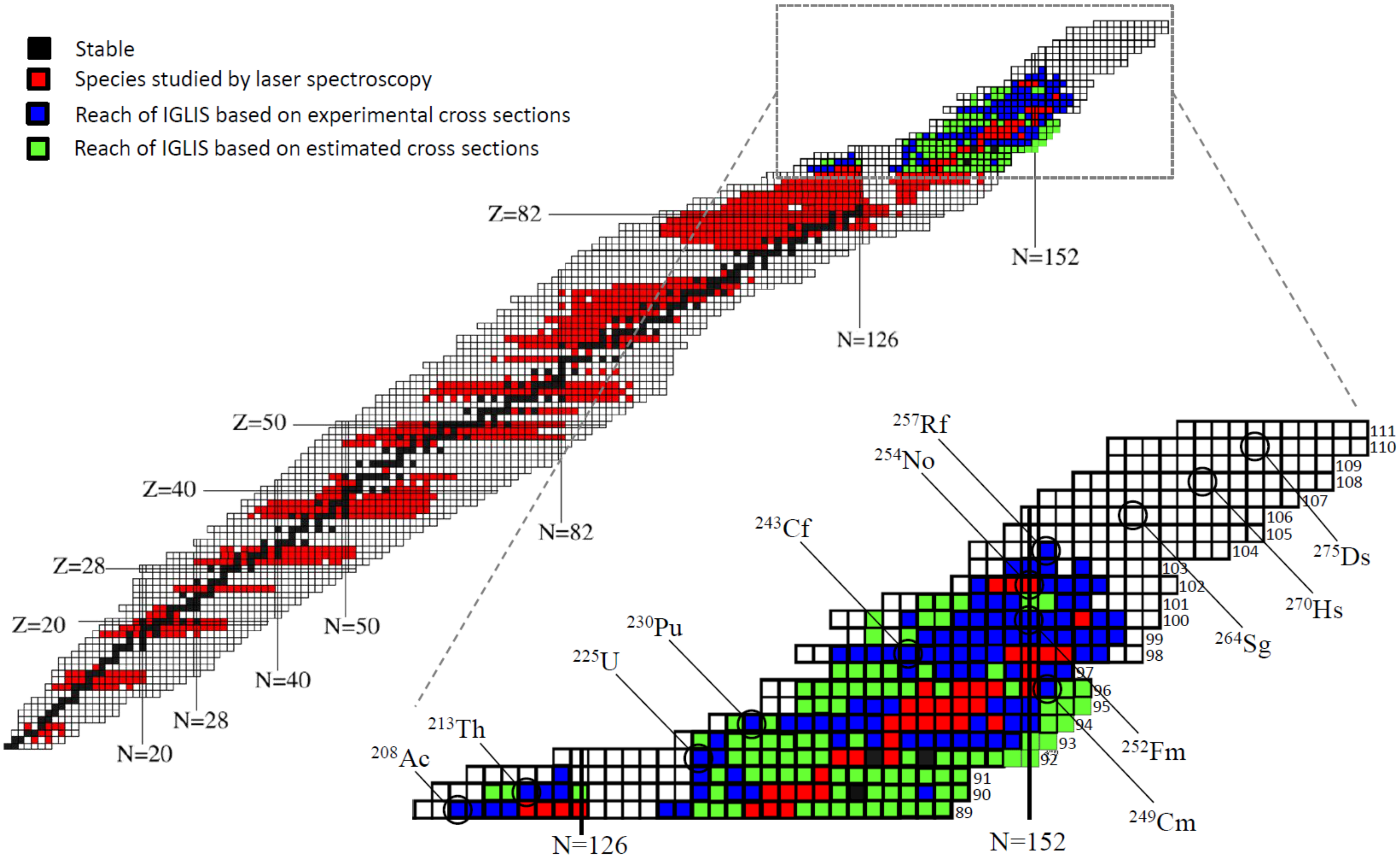



- New opportunities with IGLIS

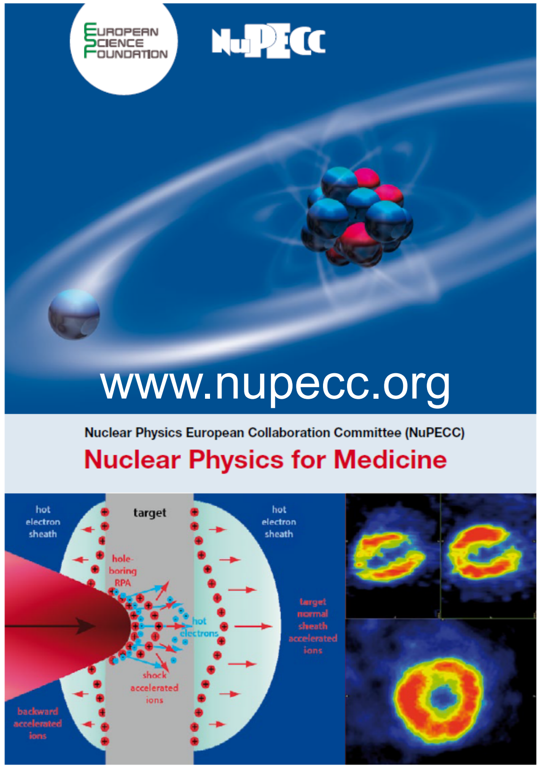



 R. Ferrer,- Nature Comm. (2017)

KU LEUVEN

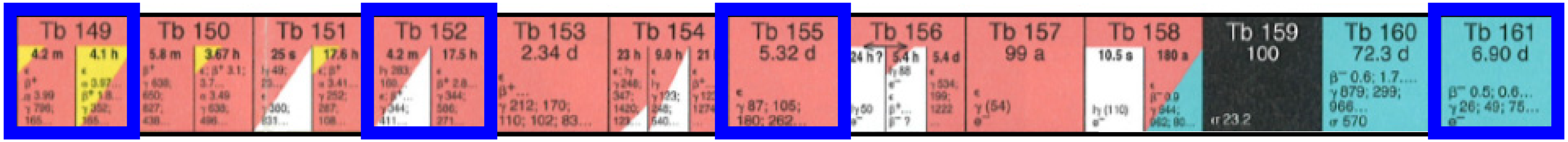
Piet Van Duppen

- Innovative radioisotopes for Medicine
  - Terbium: a unique element for nuclear medicine produced with laser resonance ionization


α ($T_{1/2}$=4.1 h)

γ ($T_{1/2}$=5.32 d)




β⁺/EC($T_{1/2}$=17.5 h)

β⁻ ($T_{1/2}$=6.9 d)

ISOLDE

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courtesy U. Köster

# Conclusion and Outlook

- Lasers are an important tool for Radioactive Beam studies:
  - for the production of pure (isomeric) beams (> 50% beam time at ISOLDE)
  - for fundamental research (nuclear physics, atomic physics, nuclear astrophysics, condensed matter, fundamental interaction studies…)
  - for applications (trace analysis, future medical radioisotope production)

- Substantial progress has been made on different fronts:
  - laser developments (necessary power, stability, ruggedized, towards turn-key systems)
  - implementation of laser ionization (hot cavity, gas jet, CRIS, LIST-Fink,- PRX5 (2015))

- Worldwide efforts for production of RIB
  - facilities under construction and major upgrades

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- Radioactive Ion Beams Factories

GANIL spiral2 laboratoire commun CEA/DSM CNRS/IN2P3

ISOLDE

EURISOL

FRIB

SPES exotic beams for science

TRIUMF

GSI FAIR

RIKEN NISHINA CENTER

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