# Laser-assisted Nuclear Spectroscopy Studies at ISOLDE-CERN

## Or, is $R=r_oA^{1/3}$? (as it is said in all textbooks)

Andrei Andreyev
University of York(UK), JAEA(Tokai, Japan), CERN-ISOLDE
on behalf of RILIS-Windmill-ISOLTRAP collaboration

- **Reminder on Isotope Shift(IS) and Hyperfine Splitting (HFS)**
- **ISOLDE and our detection tools**
- **In-source laser spectroscopy with RILIS (Au, Hg, Bi chains)**
- **Collinear laser spectroscopy with COLLAPS and CRIS (Ca, In chains)**
- **Conclusions**

Special thanks to Ronald Garcia Ruiz (CRIS-COLLAPS Collaboration)

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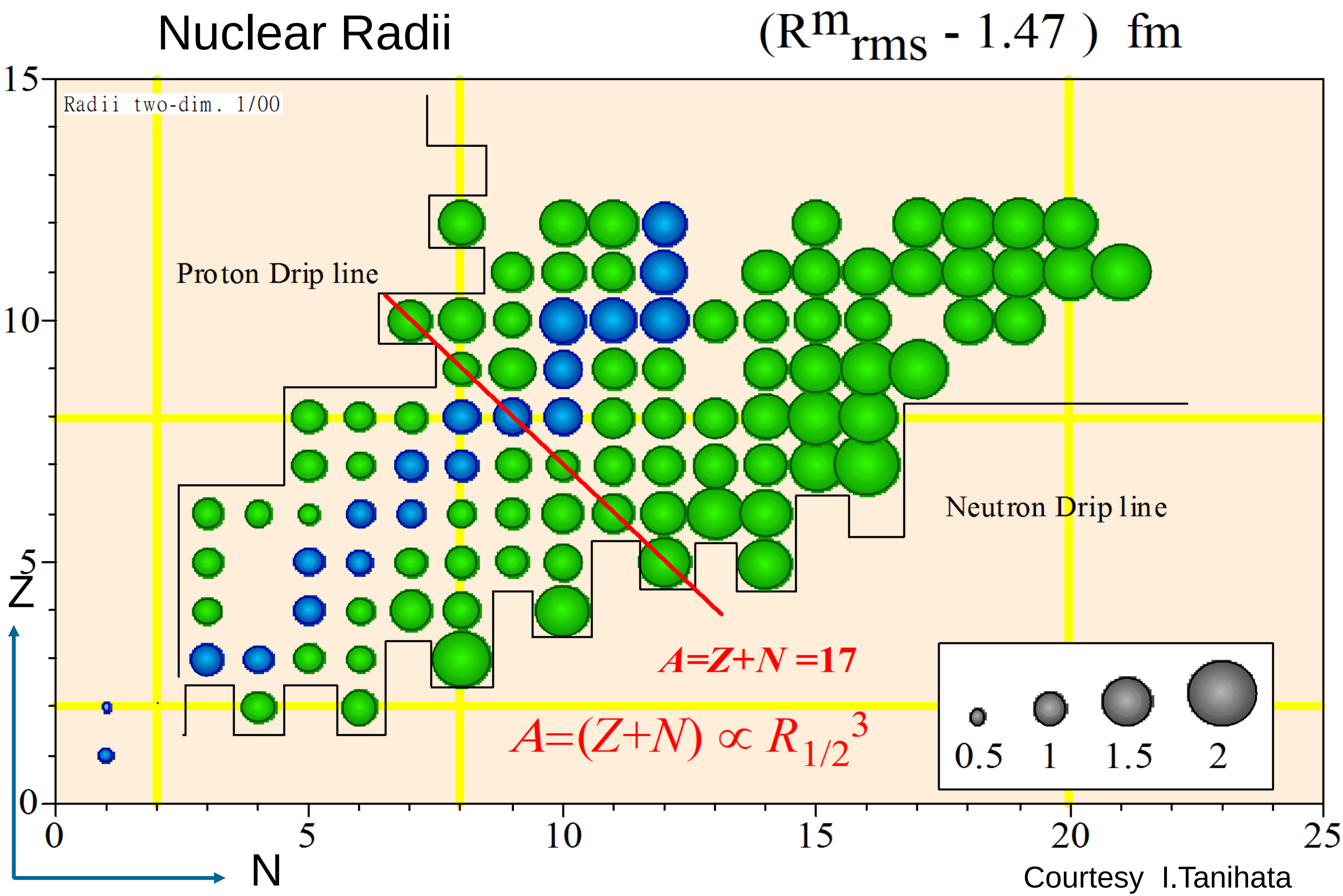
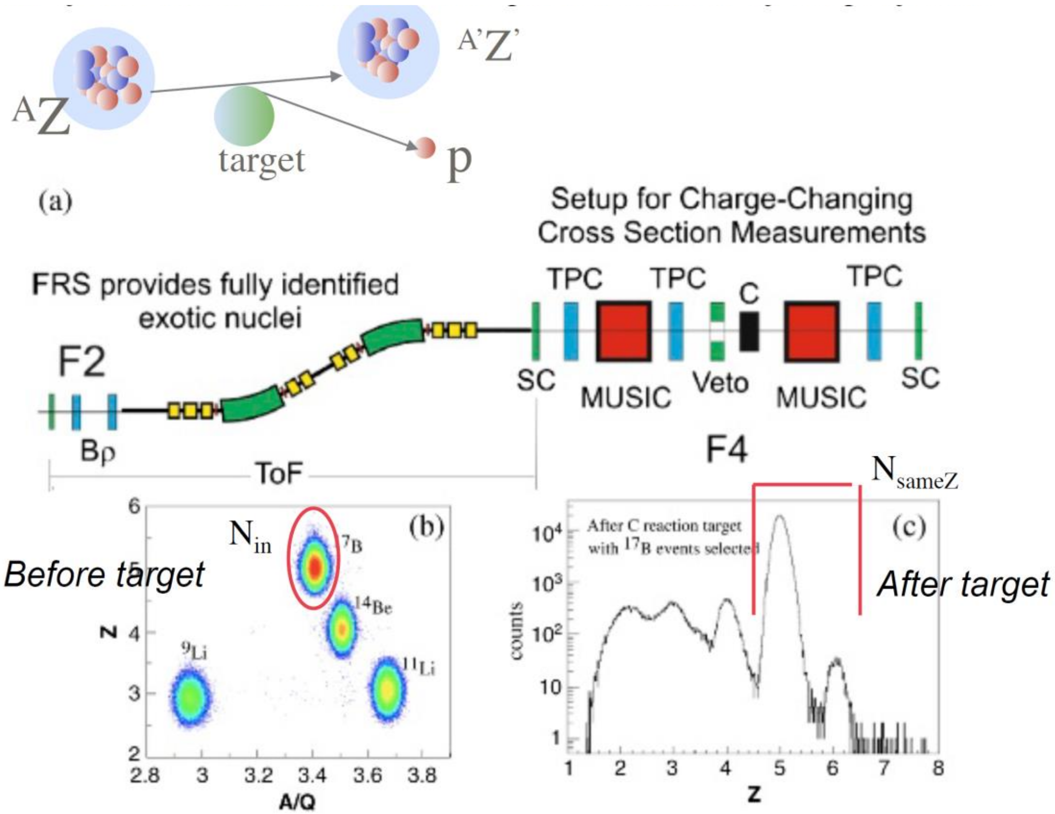
# RIBs: Breaking Old Rules in Nuclear Physics: is $R=r_0A^{1/3}$ ?

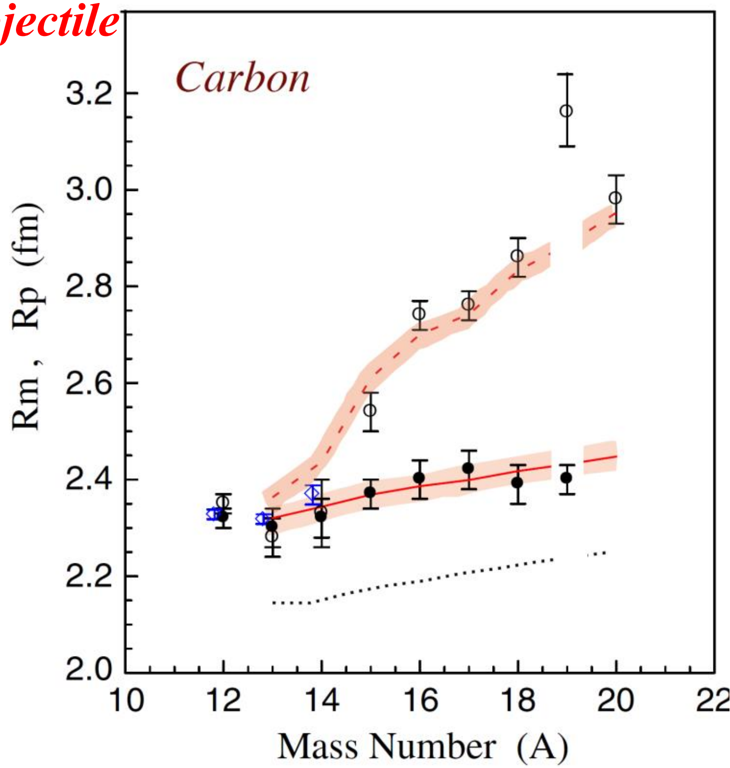



Courtesy I.Tanihata

# An example: Charge radii from Charge Changing Cross Sections with RIBs

***Sum of all reactions that decrease proton number of the projectile***




- Consistent with Rp from electron scattering

TABLE I. Secondary beam energies, measured $\sigma_{CC}$ and the root-mean-square proton and matter radii derived from the data for the carbon isotopes.

| Isotope | $E/A$ (MeV) | $\sigma_{CC}^{ex}$ (mb) | $R_p^{ex}$ (fm) | $R_p^{(e^-,\mu)}$ (fm) | $R_m^{ex}$ (fm) |
|---|---|---|---|---|---|
| $^{12}C$ | 937 | 733(7) | 2.32(2) | 2.33(1) | 2.35(2) |
| $^{13}C$ | 828 | 726(7) | 2.30(4) | 2.32(1) | 2.28(4) |
| $^{14}C$ | 900 | 731(7) | 2.32(4) | 2.37(2) | 2.33(7) |
| $^{15}C$ | 907 | 743(7) | 2.37(3) | | 2.54(4) |
| $^{16}C$ | 907 | 748(7) | 2.40(4) | | 2.74(3) |
| $^{17}C$ | 979 | 754(7) | 2.42(4) | | 2.76(3) |
| $^{18}C$ | 895 | 747(7) | 2.39(4) | | 2.86(4) |
| $^{19}C$ | 895 | 749(9) | 2.40(3) | | 3.16(7) |

*Carbon* R. Kanungo et al., Phys. Rev. Lett. 117 (2016) 102501

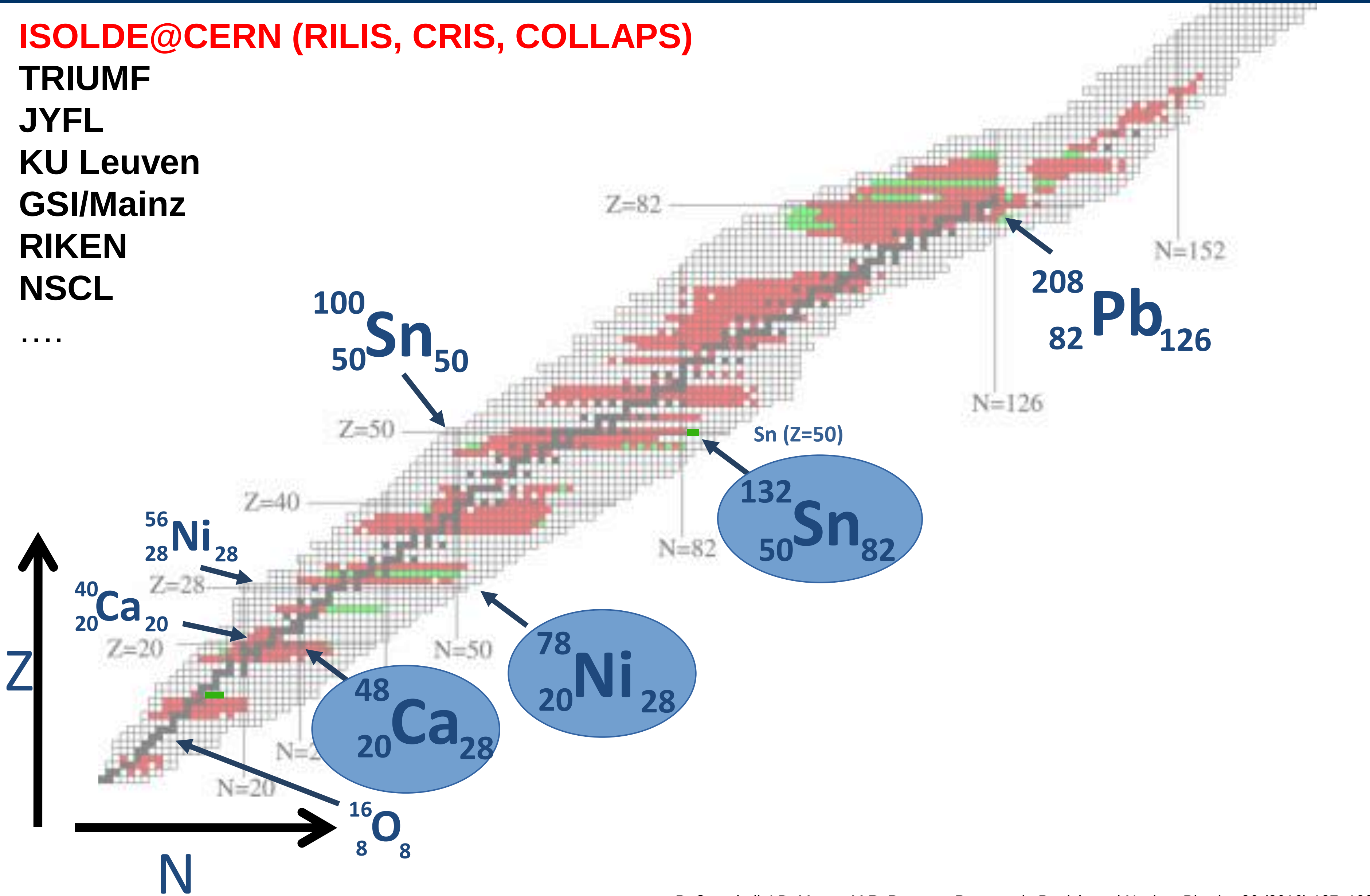
*Boron* A. Estrade et al., Phys. Rev. Lett. 113 (2014) 132501

*Beryllium* S. Terashima et al., Prog. Theor. Exp. Phys. (2014) 101D02

Courtesy R. Kanungo

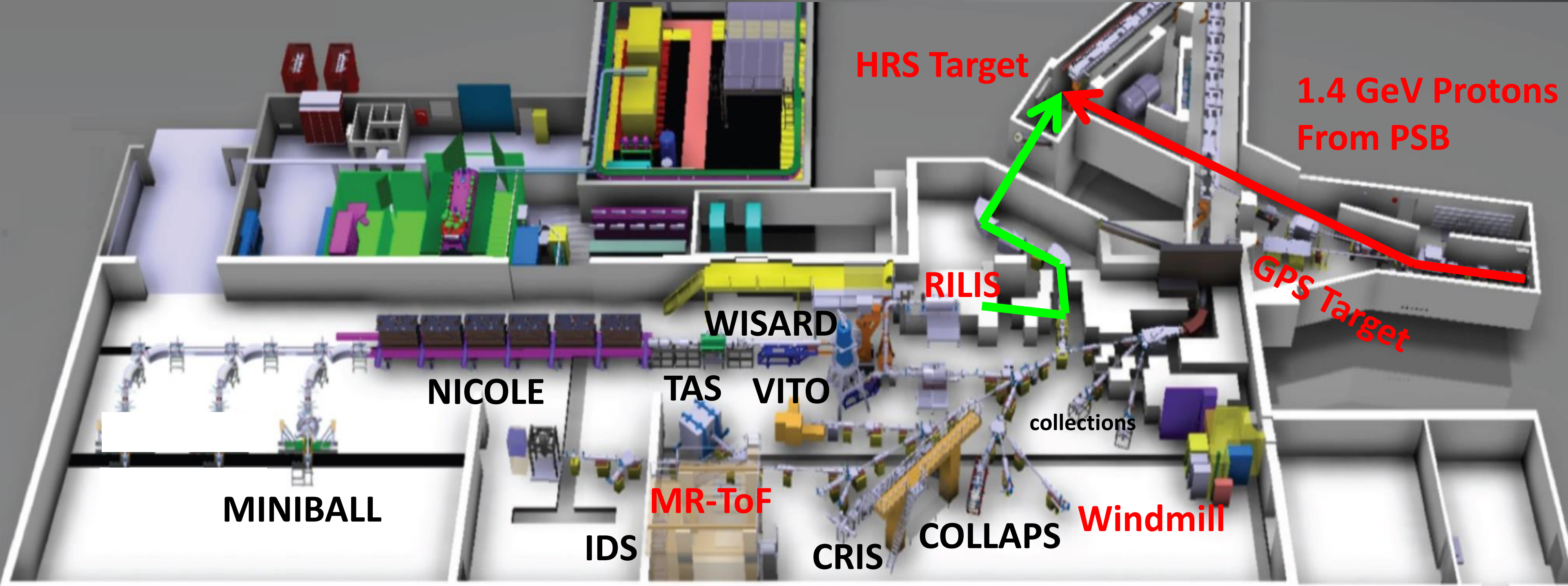
# Charge Radii from Laser-Assisted studies 2016' status

**ISOLDE@CERN (RILIS, CRIS, COLLAPS)**
**TRIUMF**
**JYFL**
**KU Leuven**
**GSI/Mainz**
**RIKEN**
**NSCL**
….

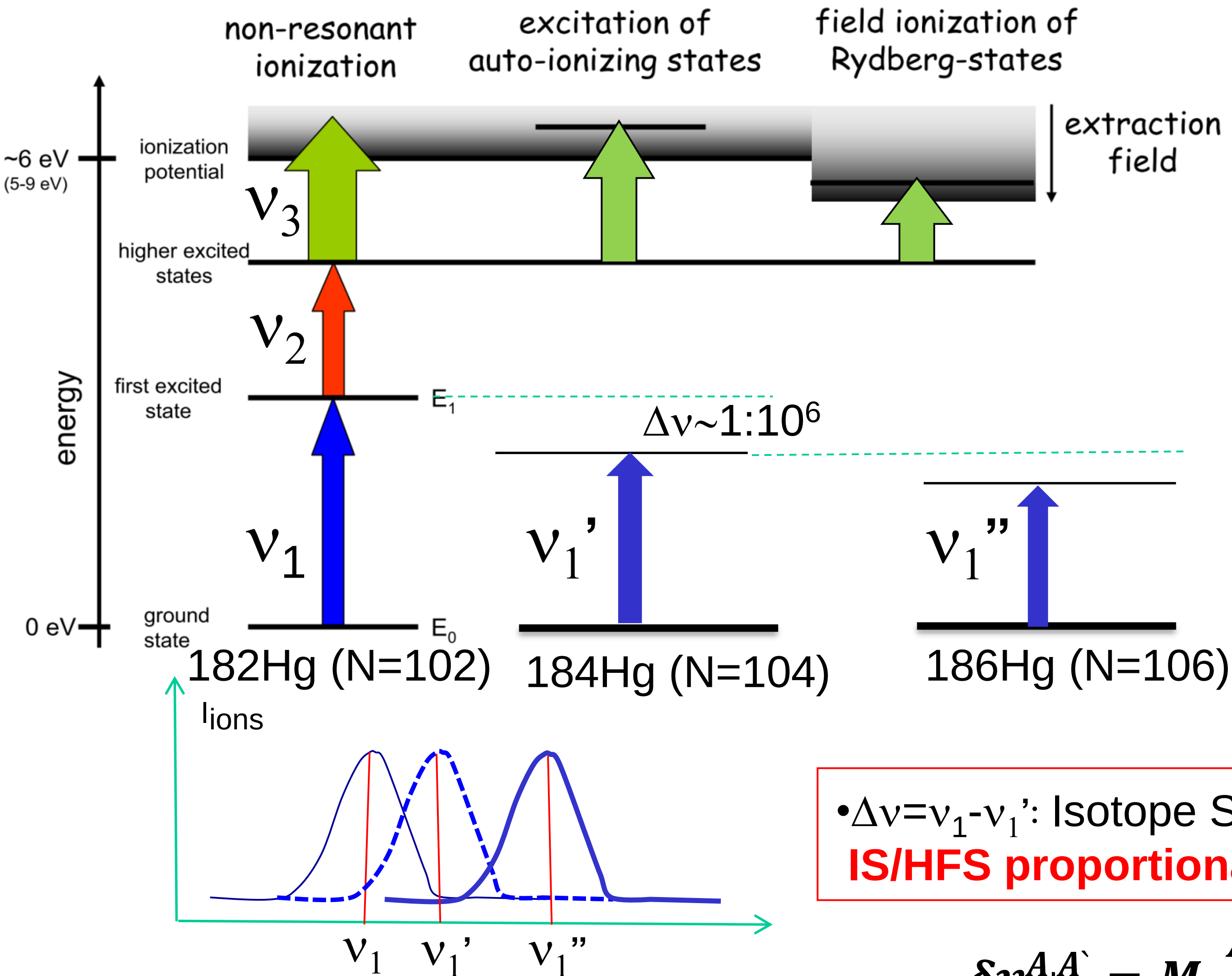



P. Campbell, I.D. Moore, M.R. Pearson, Progress in Particle and Nuclear Physics 86 (2016) 127–180

# The ISOLDE facility at CERN



# Resonance Laser Spectroscopy of an Atom



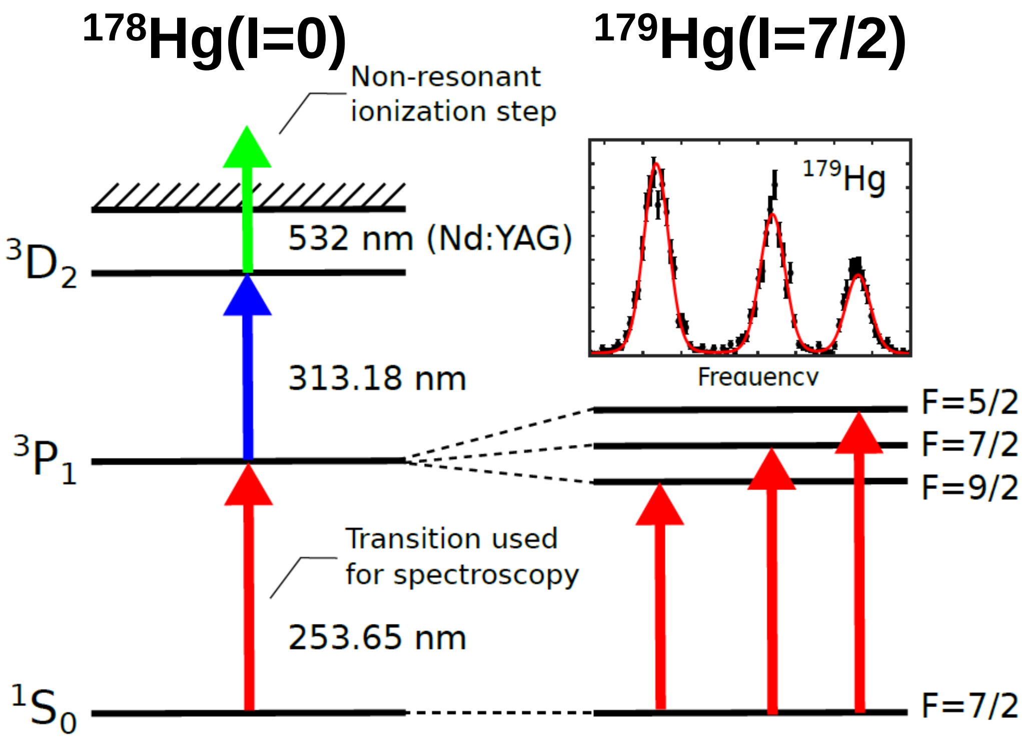

- $\Delta\nu = \nu_1 - \nu_1'$: Isotope Shift (IS) or HFS

**IS/HFS proportional to the charge radius**

$$\delta\nu^{A,A'} = \underbrace{M_i \frac{A' - A}{AA'}}_{\text{Mass shift}} + \underbrace{F_i\,\delta\langle r^2\rangle^{A,A'}}_{\text{Field shift}}$$

# Resonance Laser Spectroscopy of an odd-A nucleus

- More complex in odd-A (odd-odd-A) cases
- Needs to consider HFS splitting, due to coupling of nuclear I and electron spin J, resulting in total atomic spin F=I+J




$$\boldsymbol{F}_{atom} = \boldsymbol{I}_{nuclear} + \boldsymbol{J}_{electron}$$

$$\Delta \boldsymbol{F} = 0, \pm 1$$

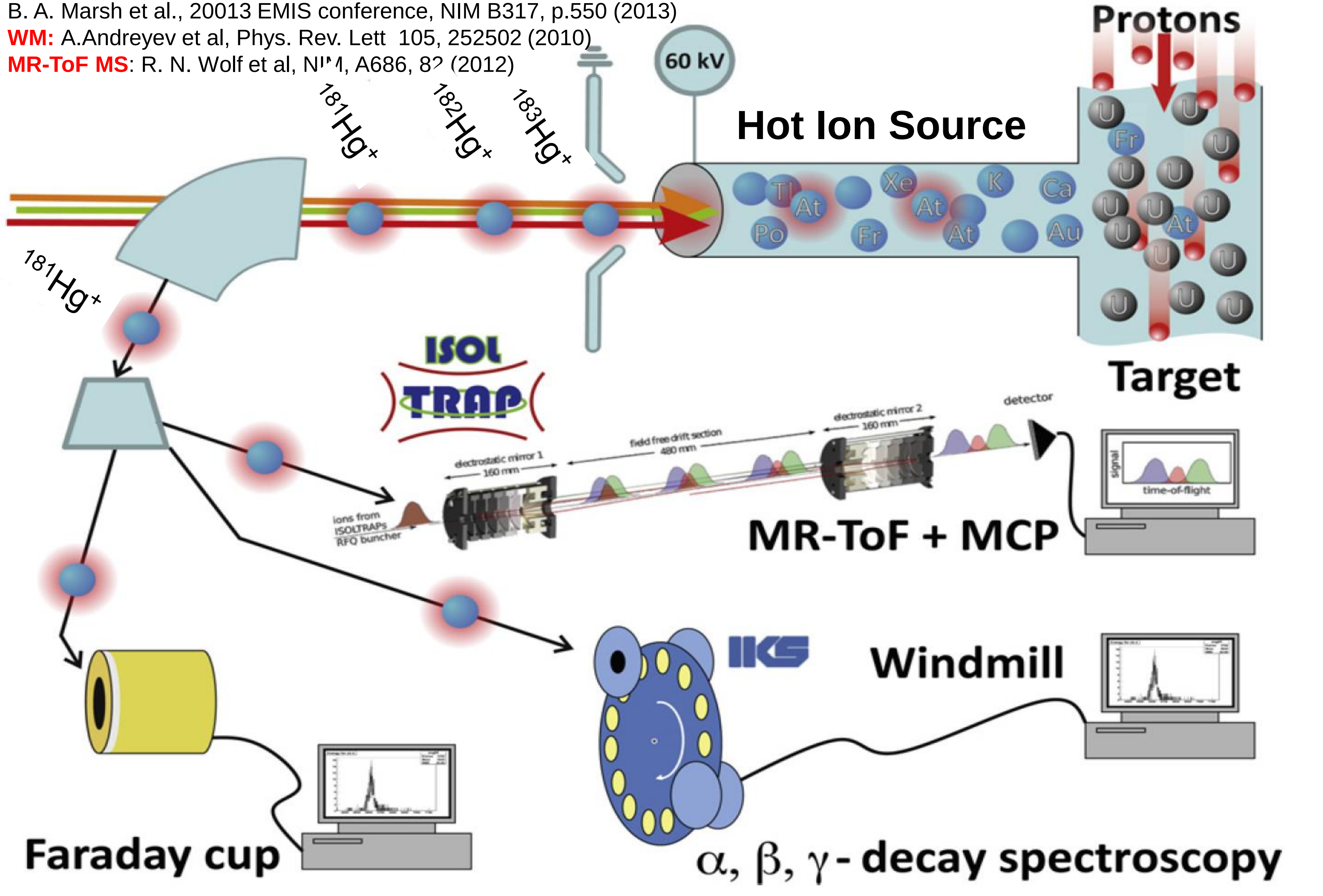
$$\Delta\nu^F = A\frac{C}{2} + B\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)IJ}$$

$$A = \frac{\mu_I B_e(0)}{IJ}$$

$$B = eQ_s \frac{\partial^2 V}{\partial^2 z}$$

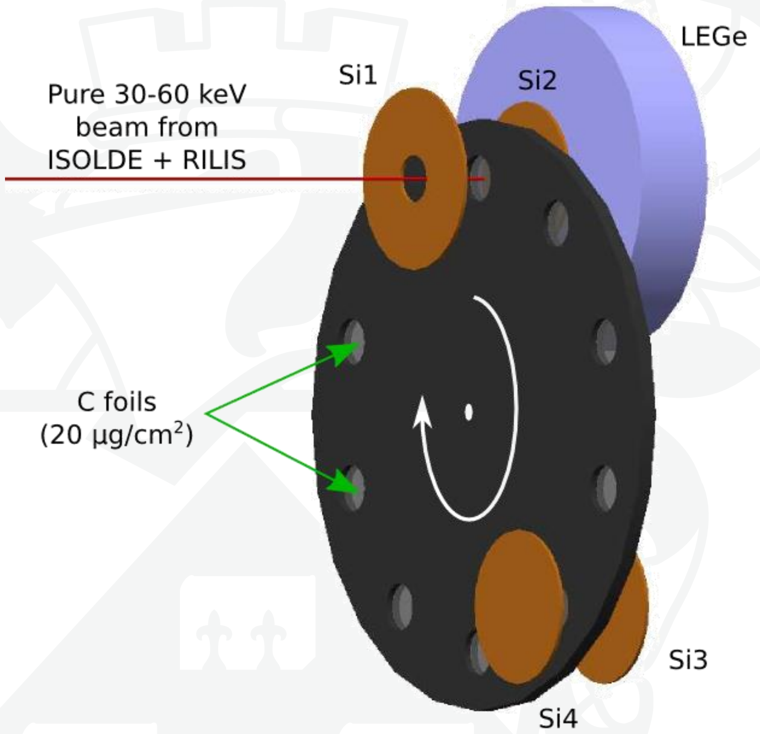
# Case 1: In-source Laser Spectroscopy with RILIS

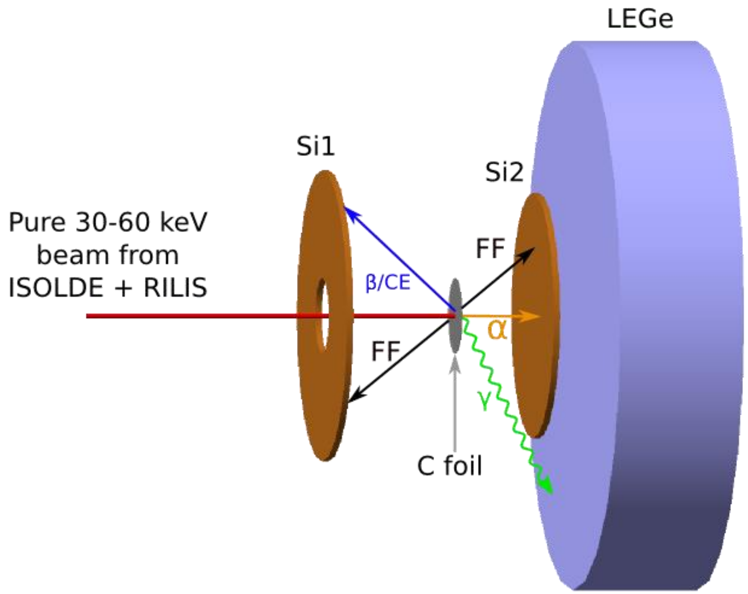
B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)
**WM:** A.Andreyev et al, Phys. Rev. Lett 105, 252502 (2010)
**MR-ToF MS**: R. N. Wolf et al, NIM, A686, 82 (2012)

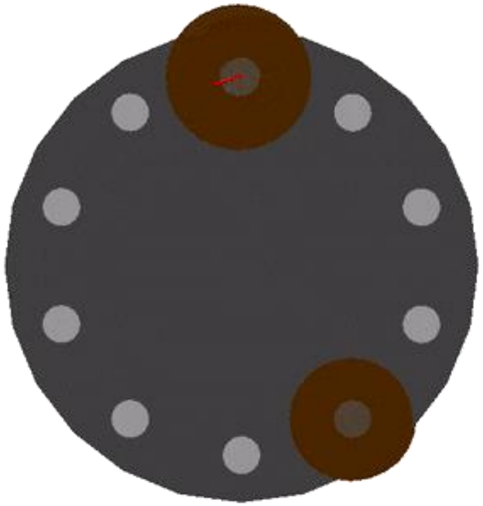


# Windmill Detection System

A. Andreyev et al., PRL 105, 252502 (2010)



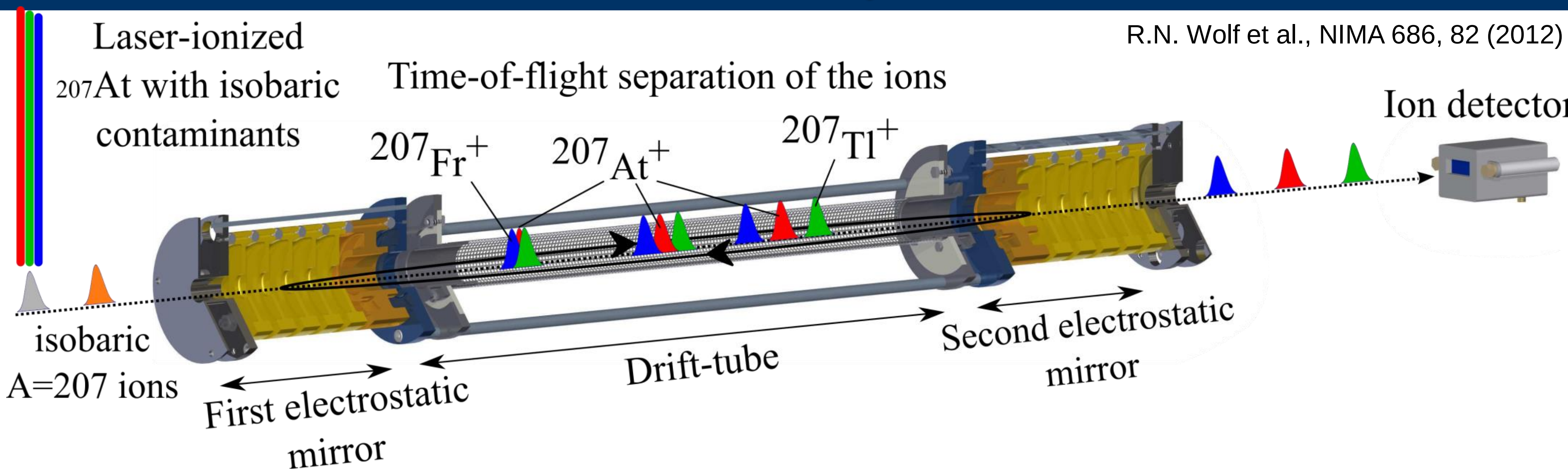



## Setup: Si detectors both sides of the C-foil

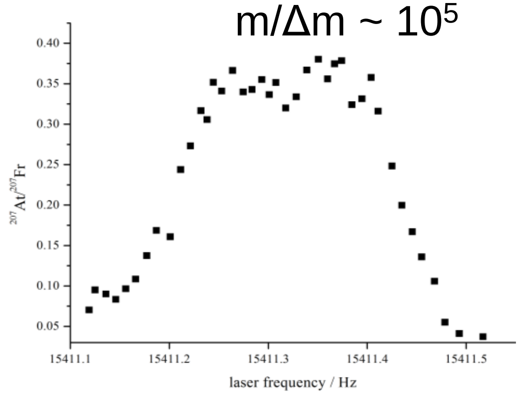
- Simple setup & DAQ: 2 Surface barrier detectors (1 of them – annular) and 2 PIPS detectors.
- 34% geometrical efficiency at implantation site.
- Alpha-gamma coincidences
- Digital electronics

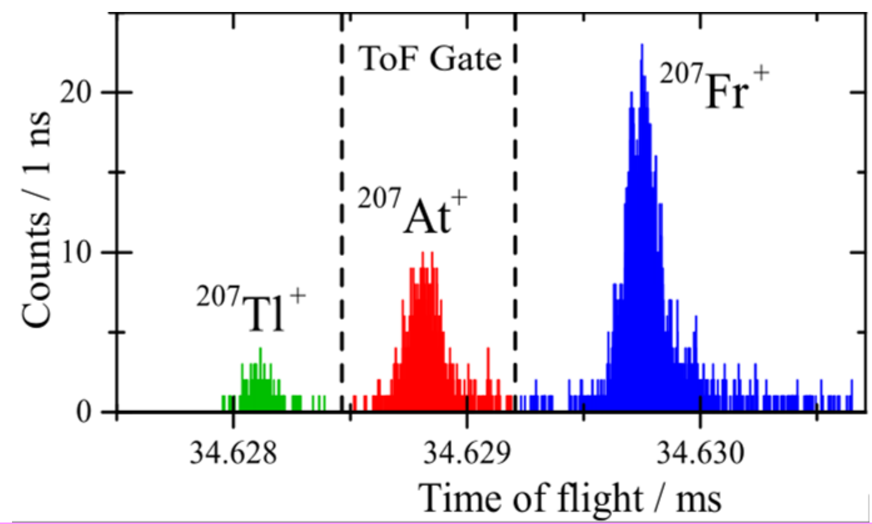
# MR-ToF Mass Spectrometer

R.N. Wolf et al., NIMA 686, 82 (2012)




~1000 revolutions, ~35 ms,
$m/\Delta m \sim 10^5$



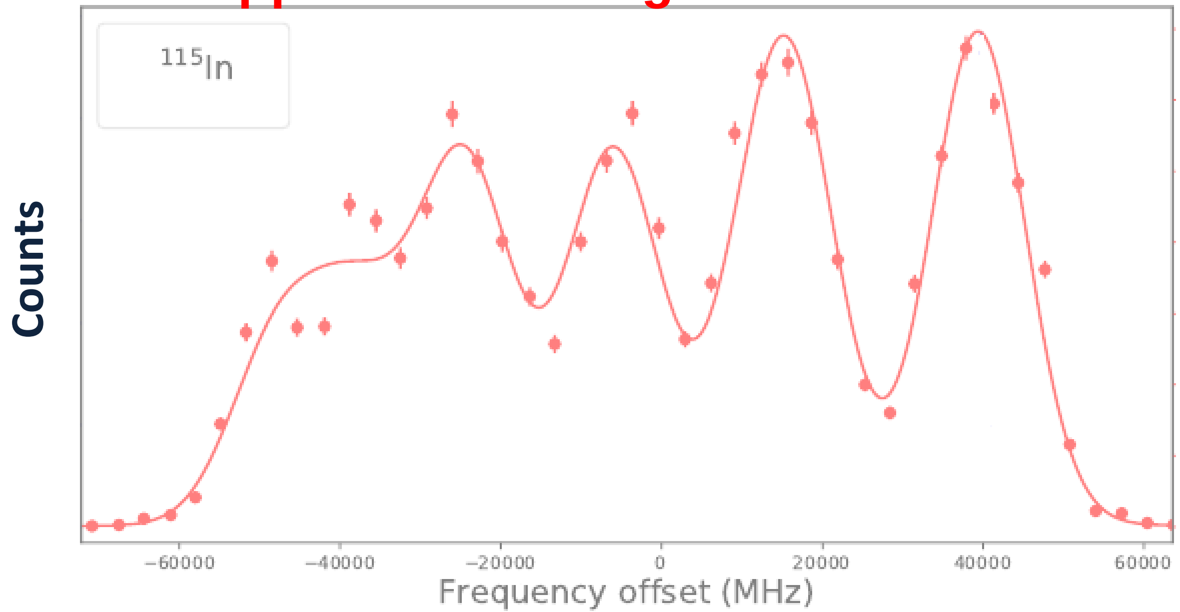



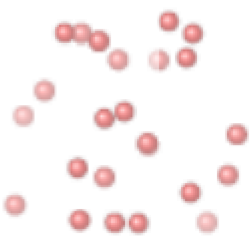

- MR-ToF MS counts ions, thus is not limited by decay scheme or long half-lives
- MR-ToF MS offers a way to separate background for direct single-ion detection using MCP (time scale: tens of ms).

# Resolution for In-source Laser Spectroscopy with RILIS

Main limitation for the resolution:

**Doppler broadening due to hot ion source configuration**



**Doppler Broadening**

$$\Delta\nu_D = \frac{2\nu_0}{c}\sqrt{\frac{2\ln 2\, k\, T}{m}}$$

**Source temperature**

**Velocity**

**Ion mass**

**Room Temp. 300 K~ 25 meV**

→ $\Delta\nu_D$ **> GHz**

# Laser-assisted Nuclear Spectroscopy Studies in the Lead Region at ISOLDE-CERN

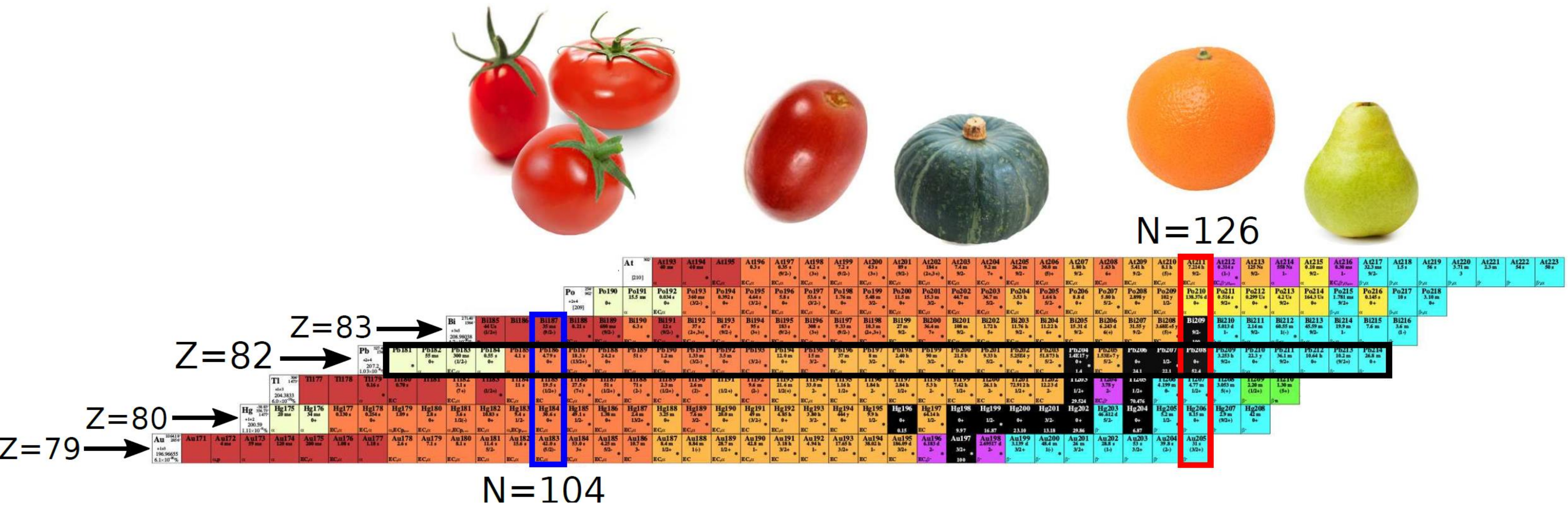
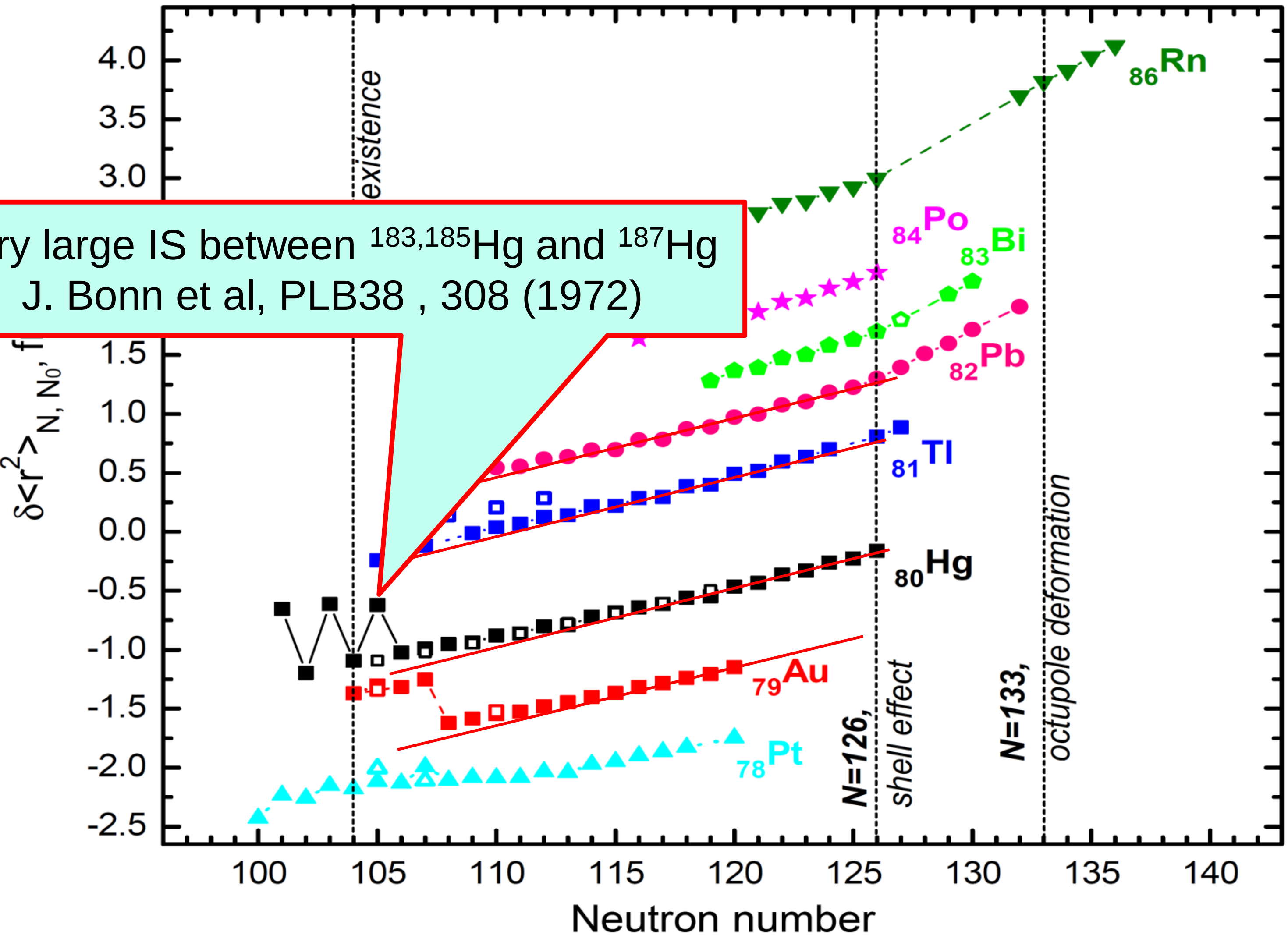



Image courtesy J.Cubiss

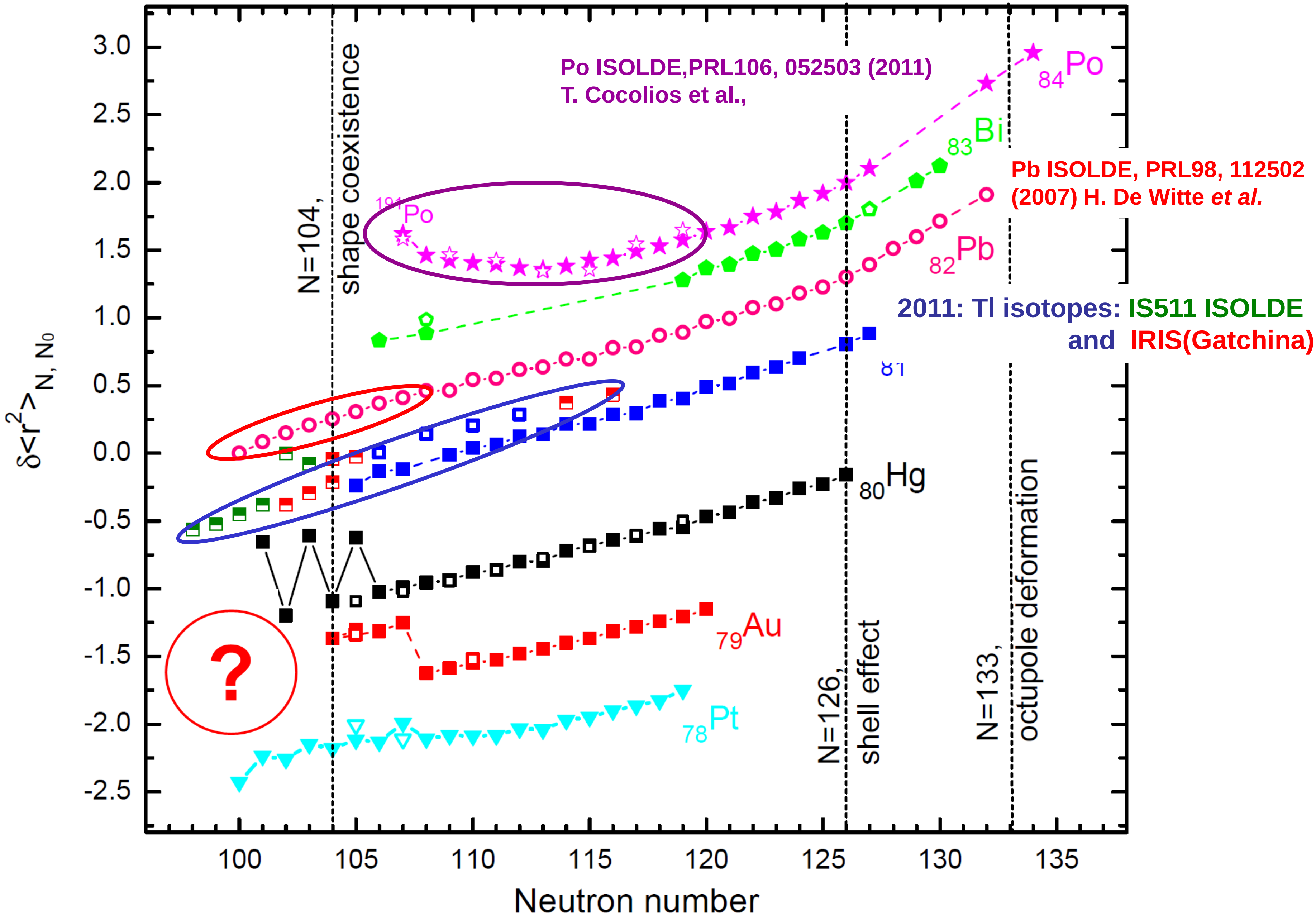
UNIVERSITY of York

# Pre-2003: Charge Radii in the Lead Region



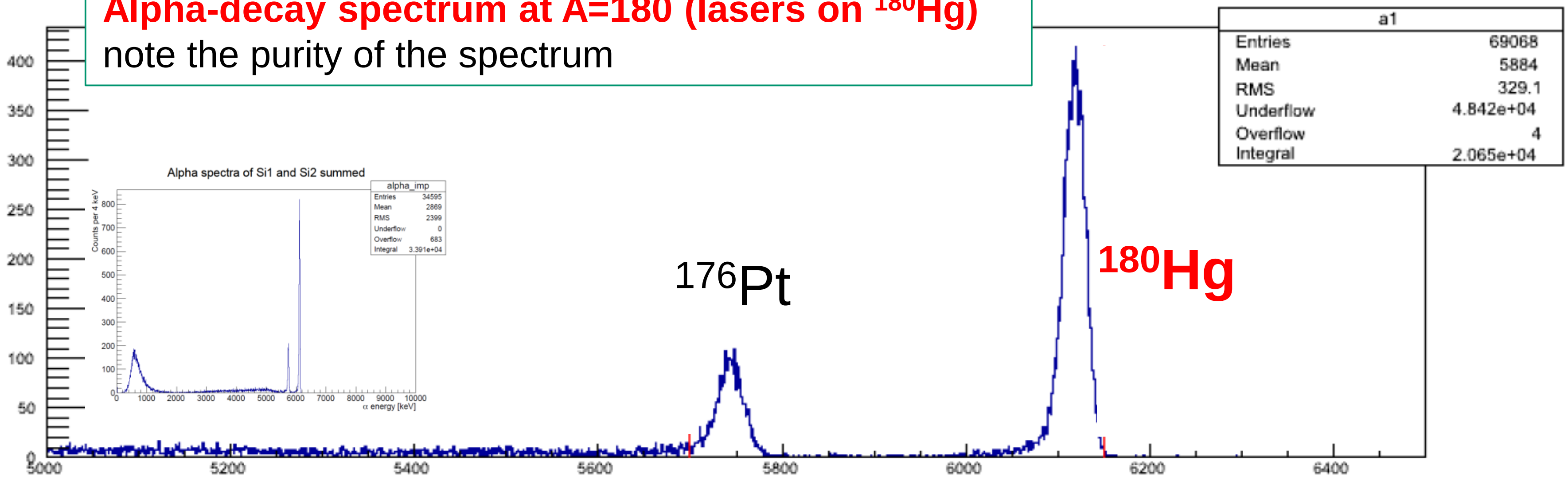

- Shape coexistence around N~104
- Sphericity around N=126, kink in radii, high-spin isomers
- Octupole effects around N~132, inverse odd-even radii staggering

# 2003-2011: Charge Radii in the Lead Region

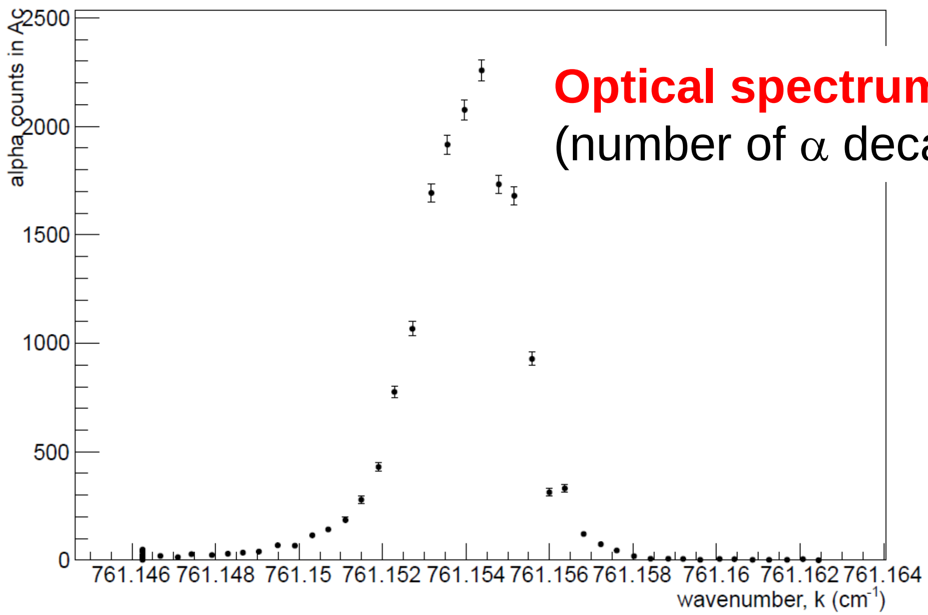


# $^{180}$Hg@Windmill

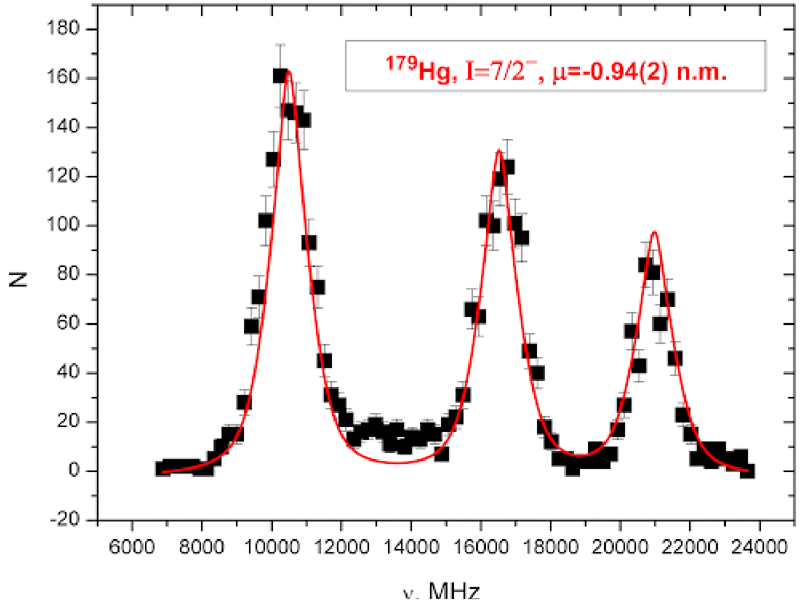
**Alpha-decay spectrum at A=180 (lasers on $^{180}$Hg)**
note the purity of the spectrum



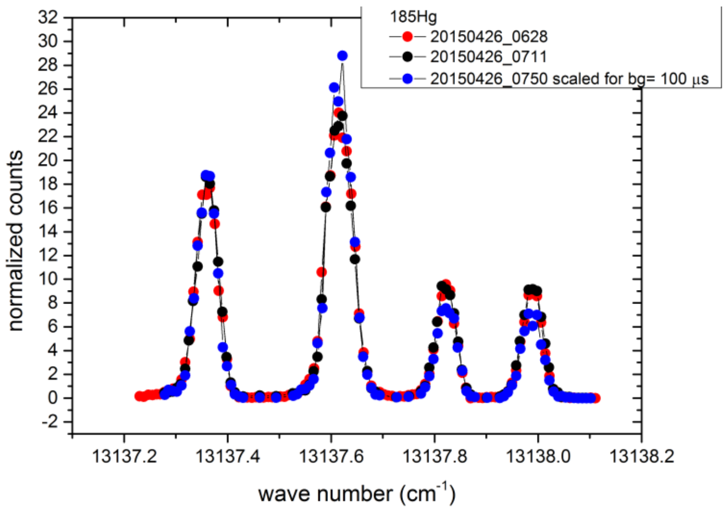

**Optical spectrum (even-even case, I=0$^+$)**
(number of $\alpha$ decays as a function of laser frequency)



# $^{179,185,207,208}Hg$



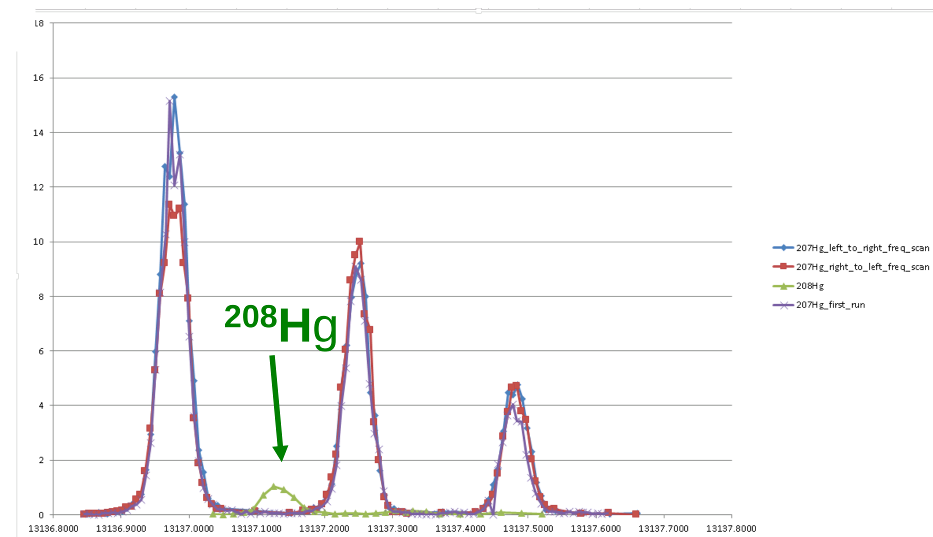

**$^{185}Hg$ HFS spectrum@MR-ToF, gs+is**




**Isotopes with N>126**

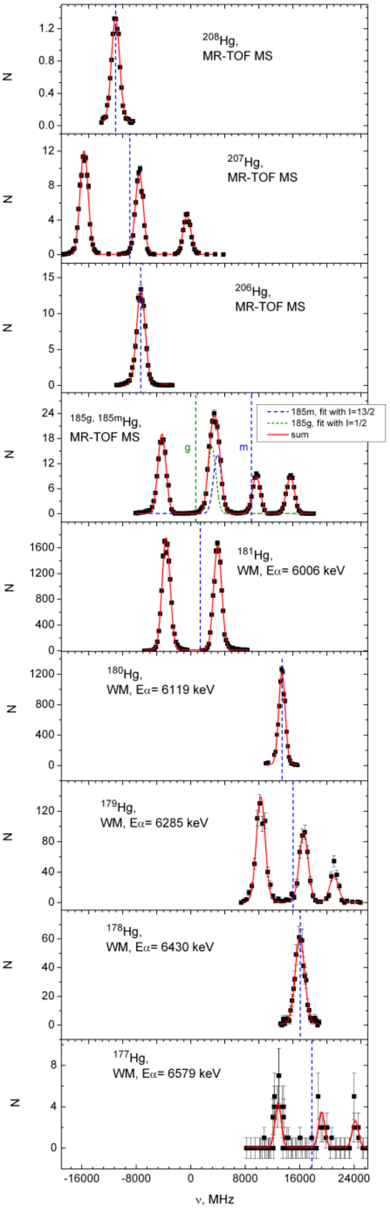
**$^{207}Hg$ HFS spectra@MR-ToF, I=9/2**

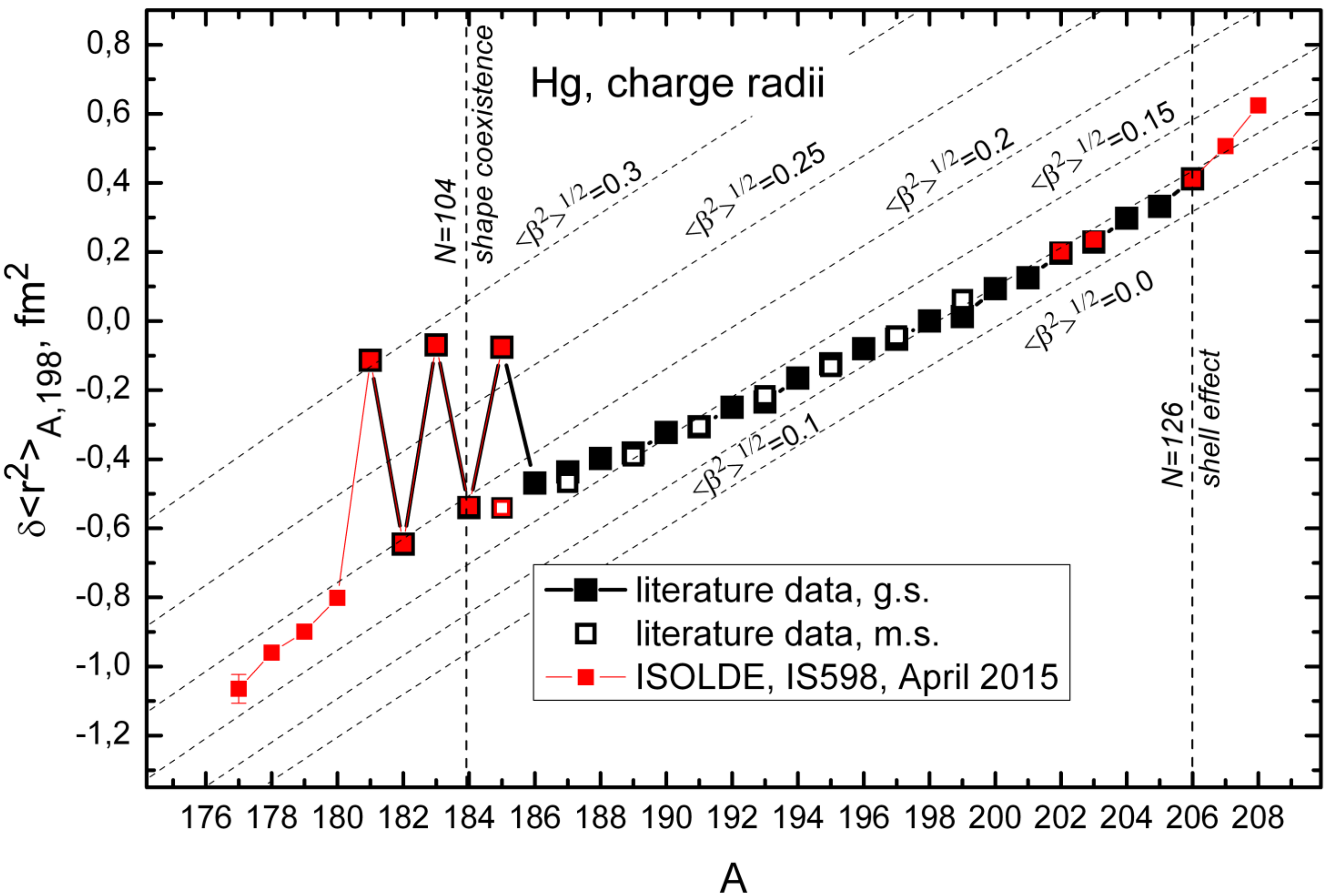
**also $^{208}Hg$! I=0**



# HFS spectra and Charge radii for Hg isotopes

(S.Sels et al, Nature Physics, Oct 2018)




$^{181,183,185}$Hg- confirmation of earlier data on staggering for ½$^-$ gs

**$^{177,178,179,180}$Hg (new) – trend towards sphericity**

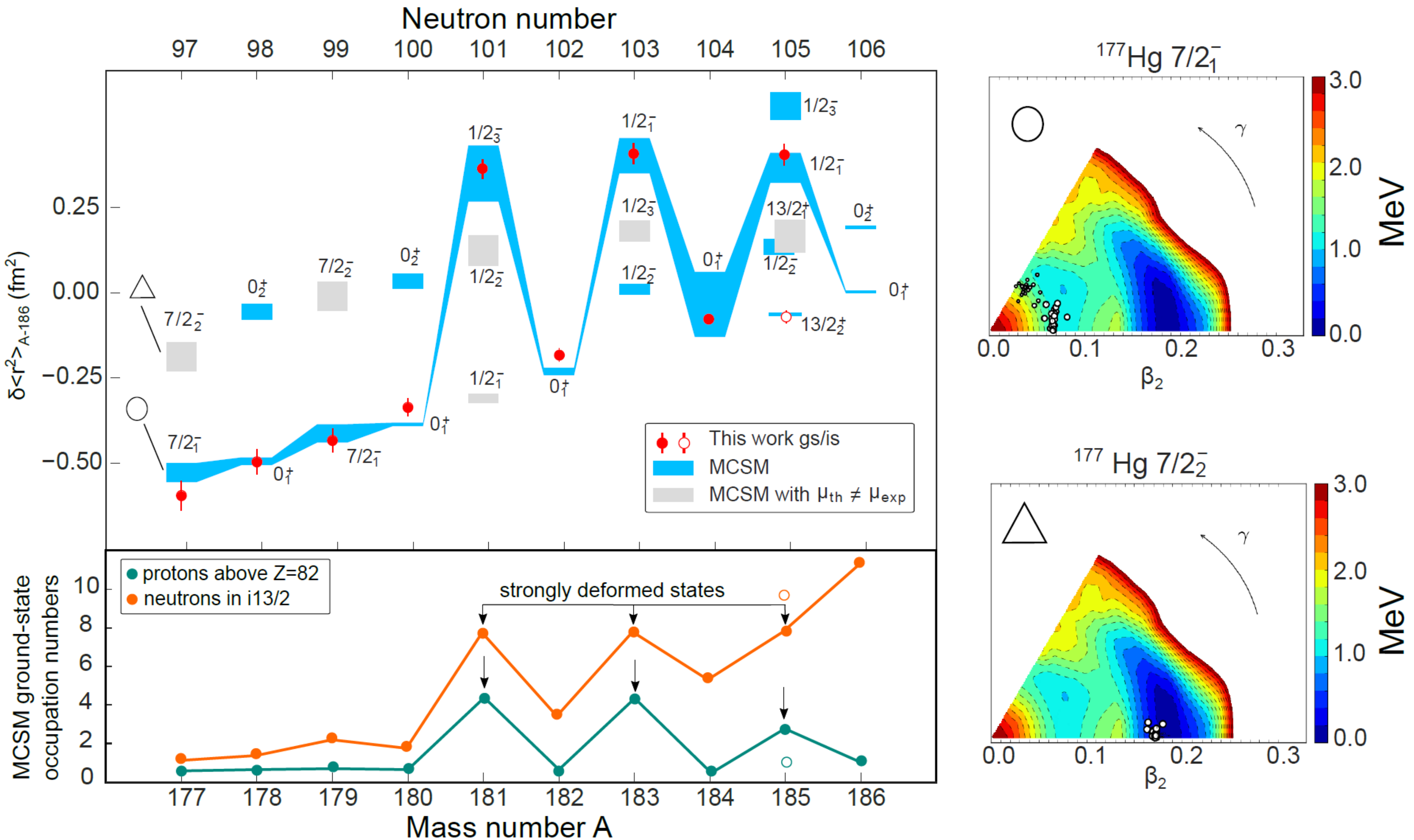
**$^{207,208}$Hg (new): kink beyond N=126**

# MCSM for Hg isotopes (Y. Tsunoda, T.Otsuka et al)

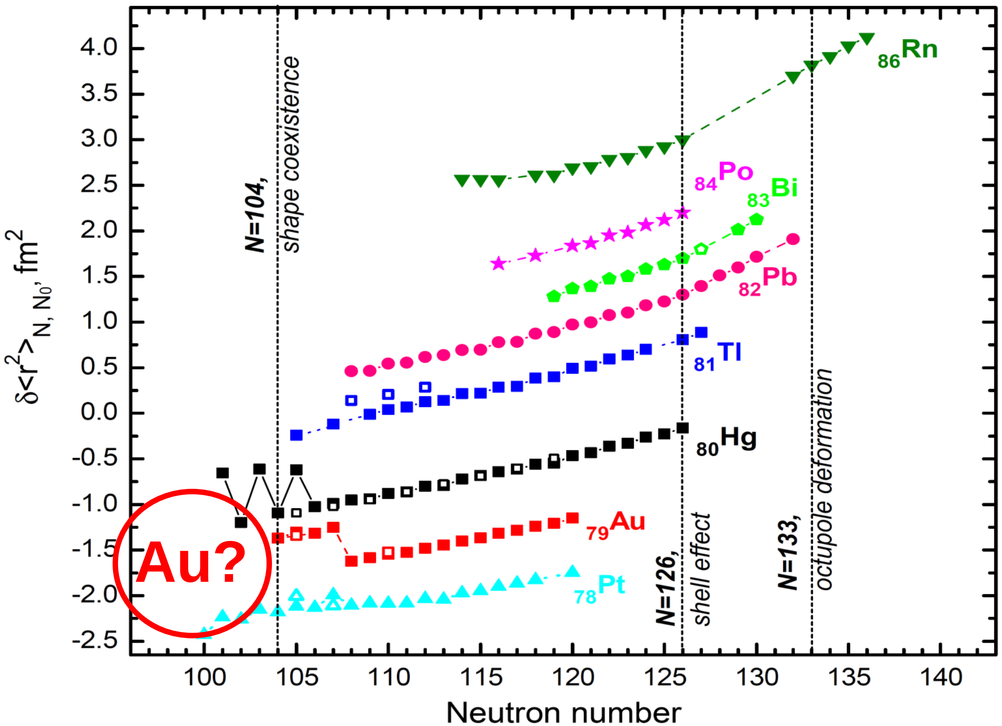
(S.Sels et al, Nature Physics, Oct 2018)

Performed by Takaharu Otsuka's team

- Largest calculation of its kind, avoids diagonalization of >2x$10^{42}$-dimensional H matrix
- Radii are well reproduced.
- Results show an increase of >2 protons promoted into the h9/2 intruder state.



# IS534@ISOLDE: Charge radii of Au isotopes




- Are the light gold isotopes deformed, A(Au)<183?
- What are the spins of ground and isomeric states?

Previous radii data (ISOLDE)

$^{185\text{-}190}$Au : K. Wallmeroth et al, NPA493,224 (1989)

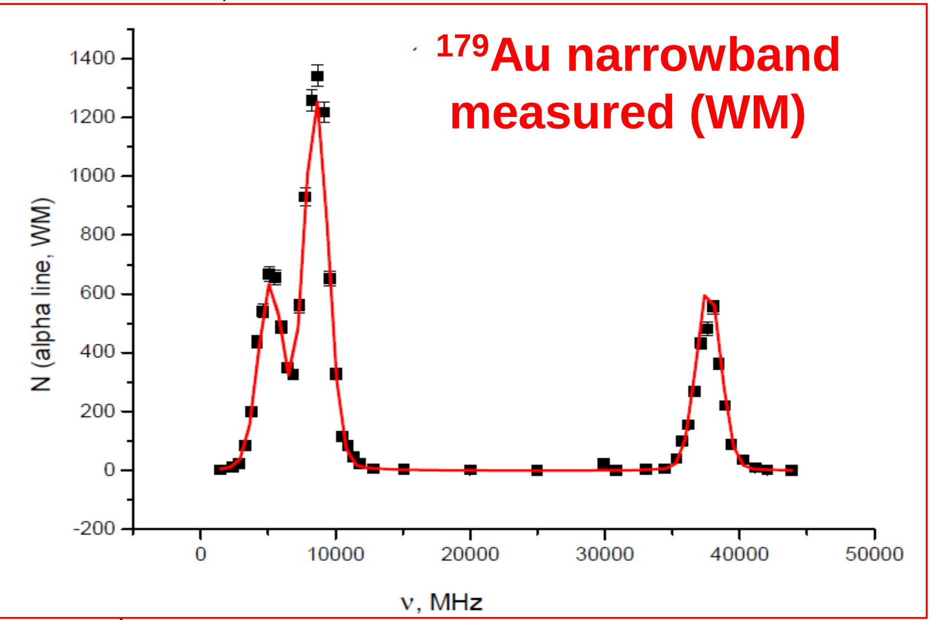
$^{183,184}$Au: U. Kronert  et al, Z.Phys. A331, 521 (1988)

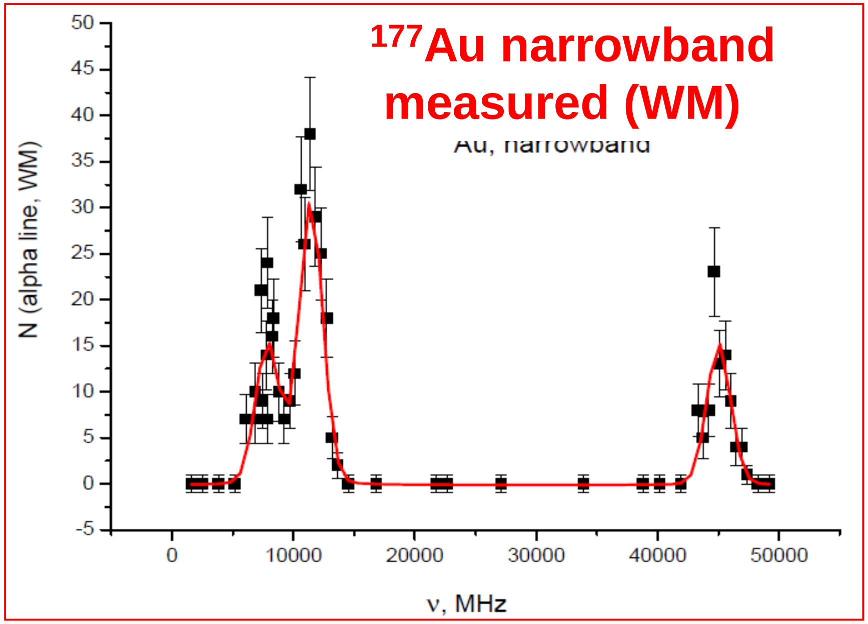
$^{184mg}$Au: F. Le Blanc et al. PRL79, 2213 (1997)

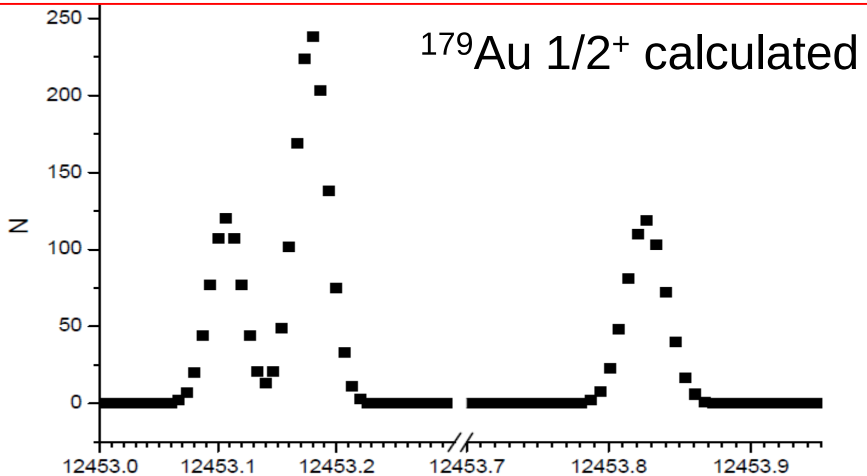
# IS534: Hyperfine Splitting Scans (HFS) for $^{177,179}Au$

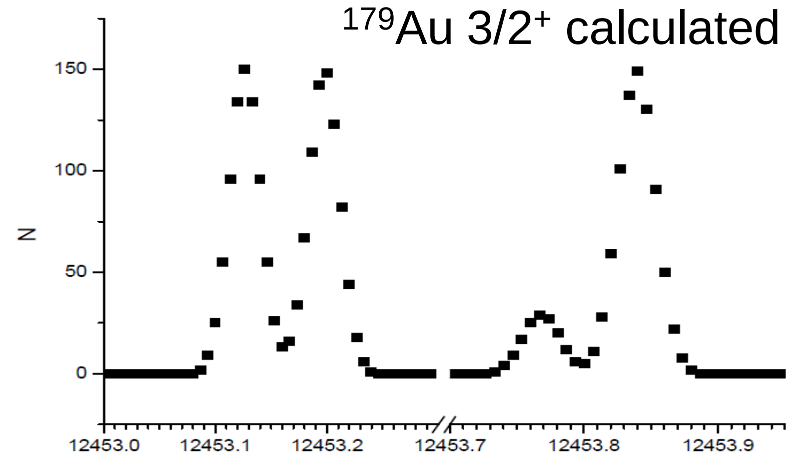
(number of alpha decays as a function of laser frequency)

J. Cubiss et al, PLB 2018



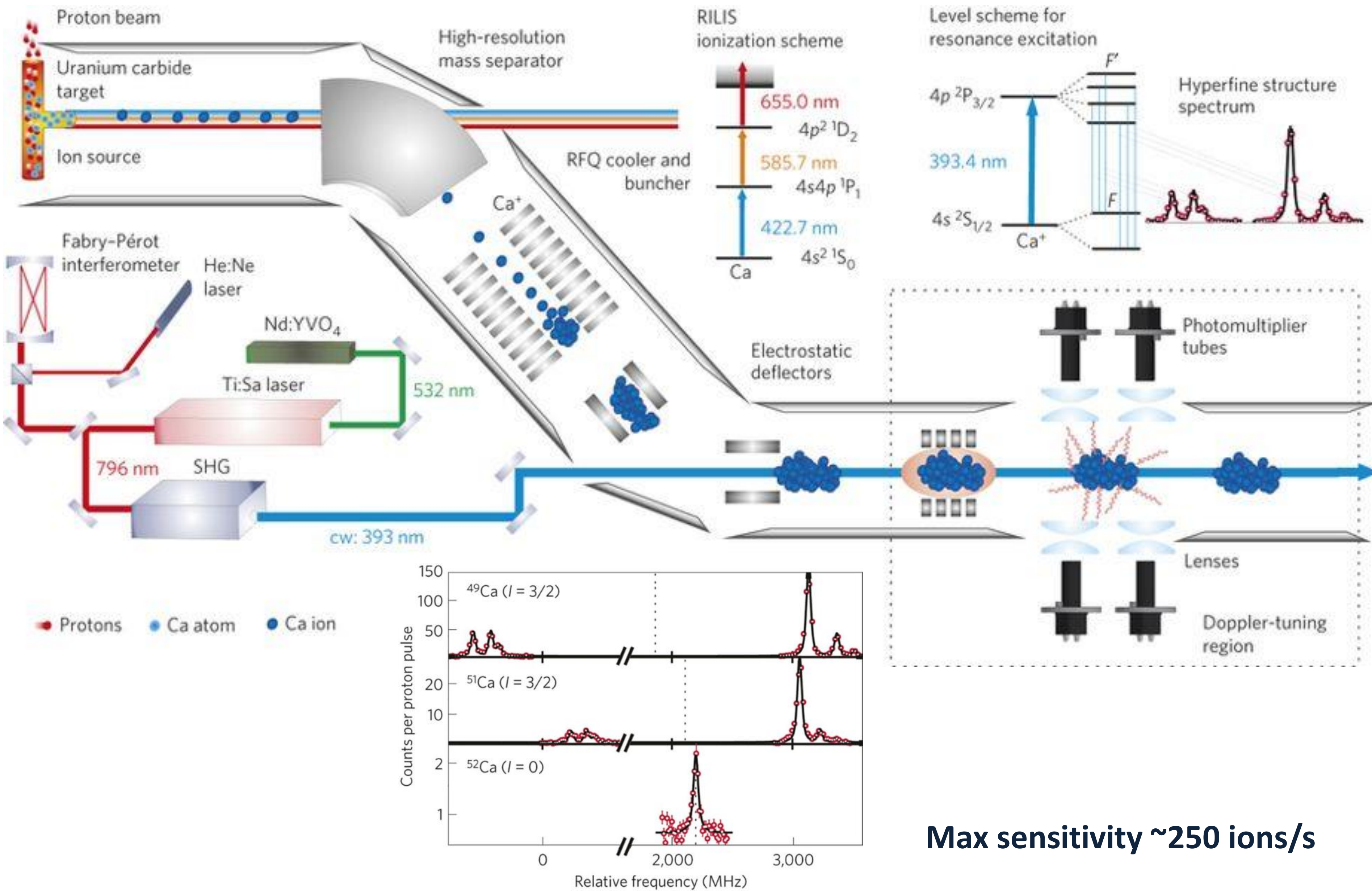




**Based on the number of HFS components and their intensity ratio, the gs spins of $^{177,179}Au$ are experimentally determined as 1/2**

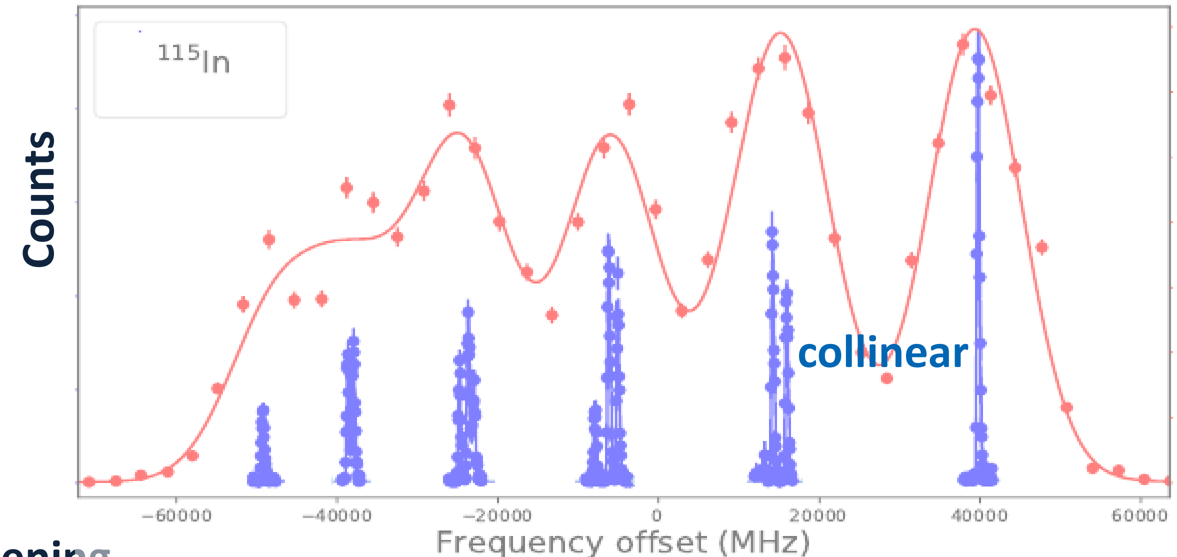
# Case 2: COLlinear LAser SPectroscopy at ISOLDE (COLLAPS) for charge radii of n-rich $^{49,51,52}$Ca isotopes

R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)

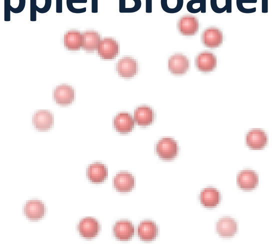



**Max sensitivity ~250 ions/s**

# Resolution in Collinear Laser Spectroscopy




**Doppler Broadening**



$$\Delta\nu_D = \frac{2\nu_0}{c}\sqrt{\frac{2\ln 2\, kT}{m}}$$

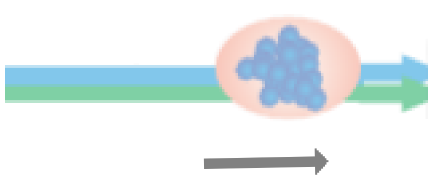
Ion mass

**Room Temp. 300 K~ 25 meV**

→ $\Delta\nu_D$ **> GHz**

**Fast beams**

**Collinear laser spectroscopy**




**Energy spread**

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

Ion beam energy

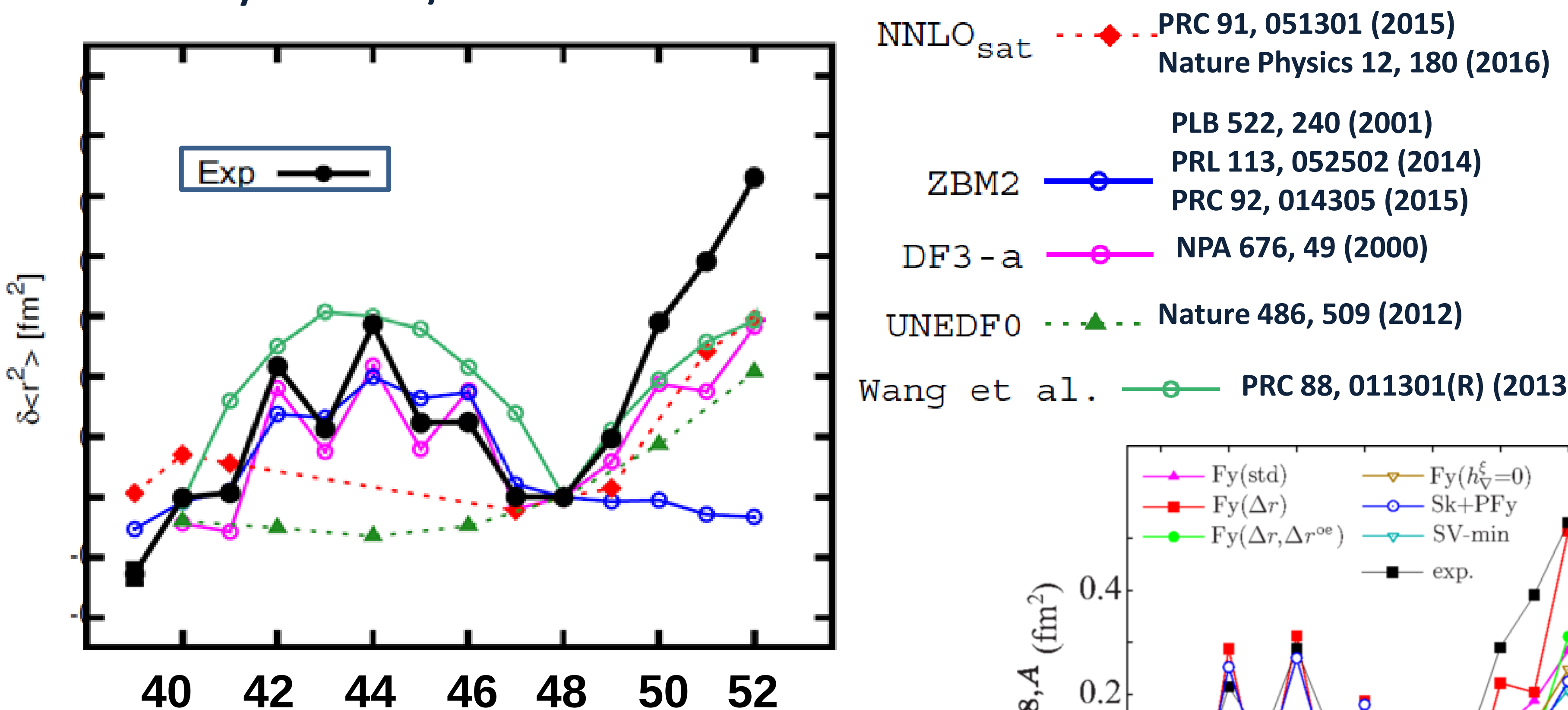
- High precision/resolution (~MHz)
- High efficiency (<100 ions/s)
- High selectivity (>1/10$^6$)
- Short time scales (< 1 s)

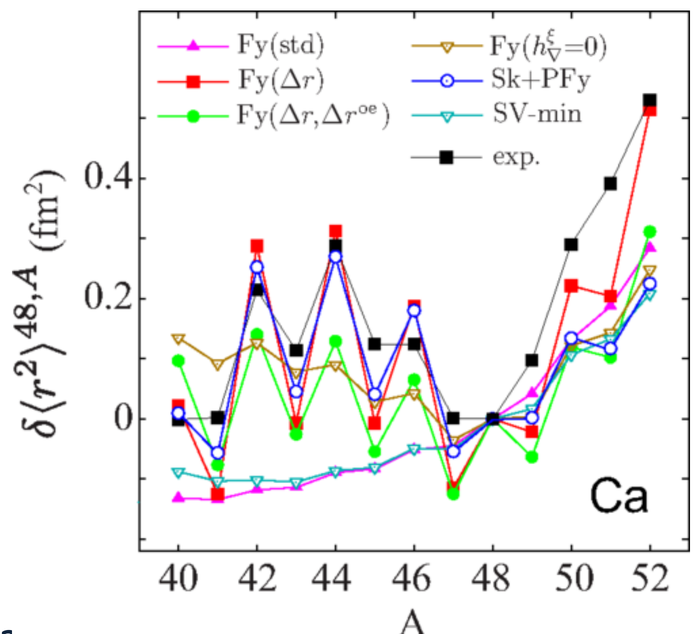
**→ at *eU*=40 keV**

$\Delta\nu_D$ **~ MHz**

# Ca (Z=20) Charge Radii

**R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)**
**Max sensitivity ~250 ions/s**



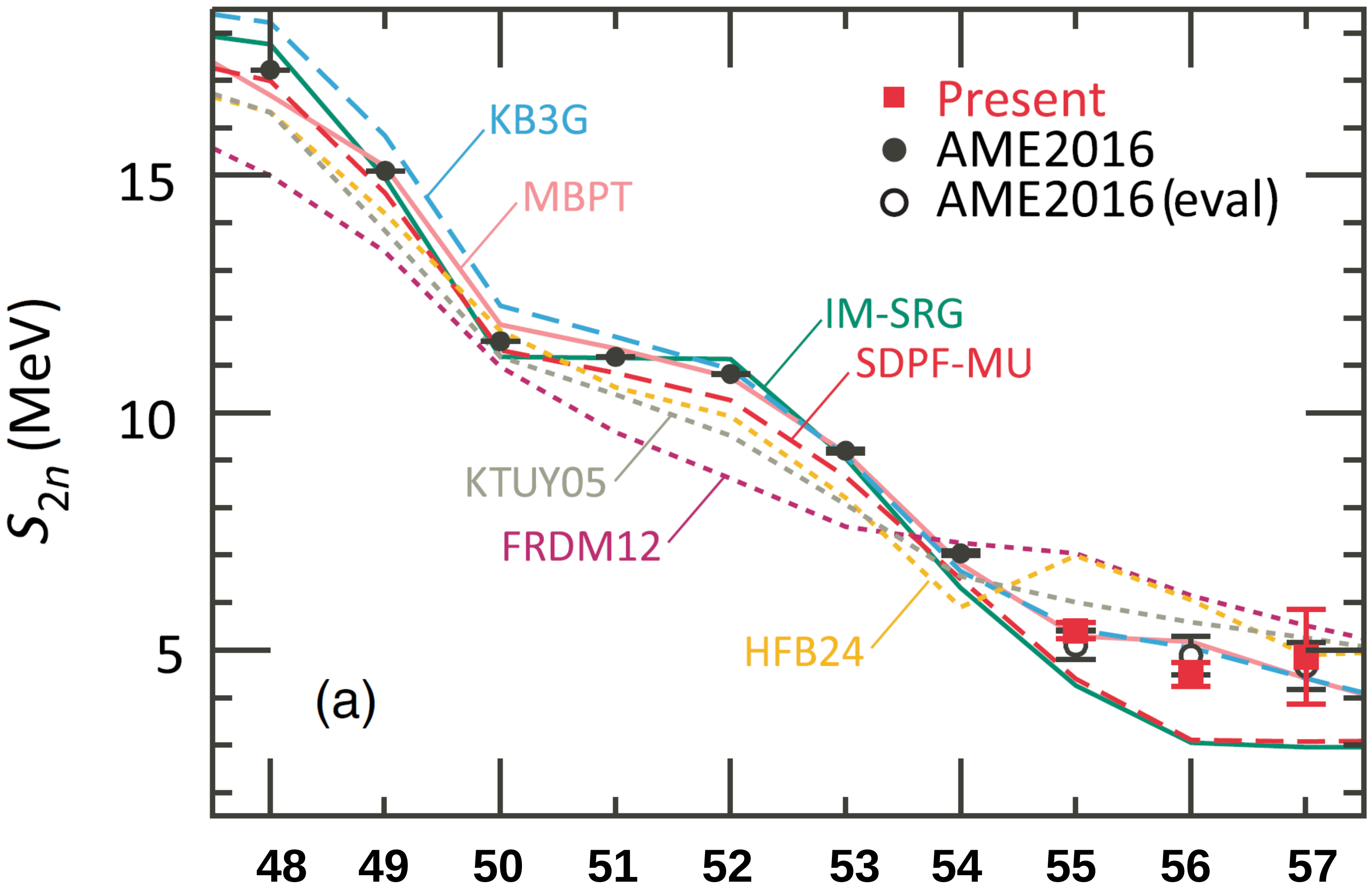




P.-G. Reinhard and W. Nazarewicz
Phys. Rev. C **95**, 064328

**Beyond $^{52}$Ca: Sensitivity -> ~1 ion/s**

**Radioactive detection of Collinear-laser optical pumping after Charge exchange**
**[R.F. Garcia Ruiz *et al.* J. Phys. G. 44, 044003 (2017)]**

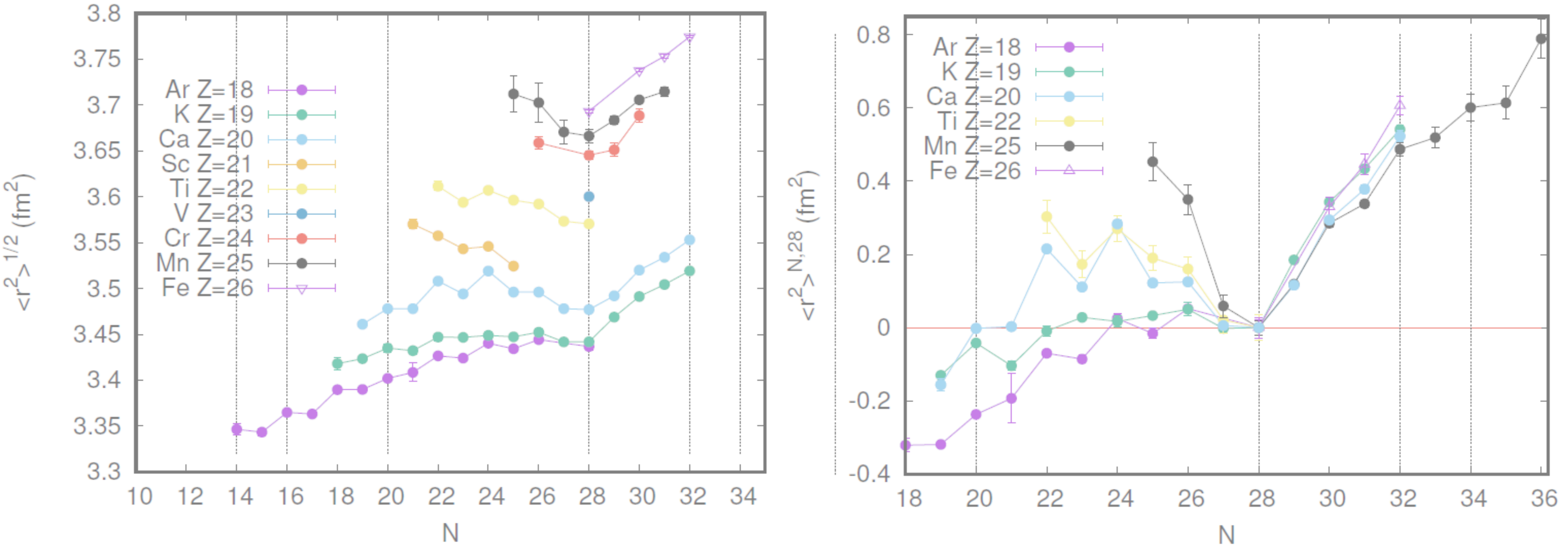
# 48-57Ca Masses




$^{53,54}$Ca, ISOLDE, F.Wienholz, Nature, 2013

$^{54-57}$Ca, RIKEN, S. Michimasa et al, PRL121, 2018

# Charge Radii Systematics around Ca



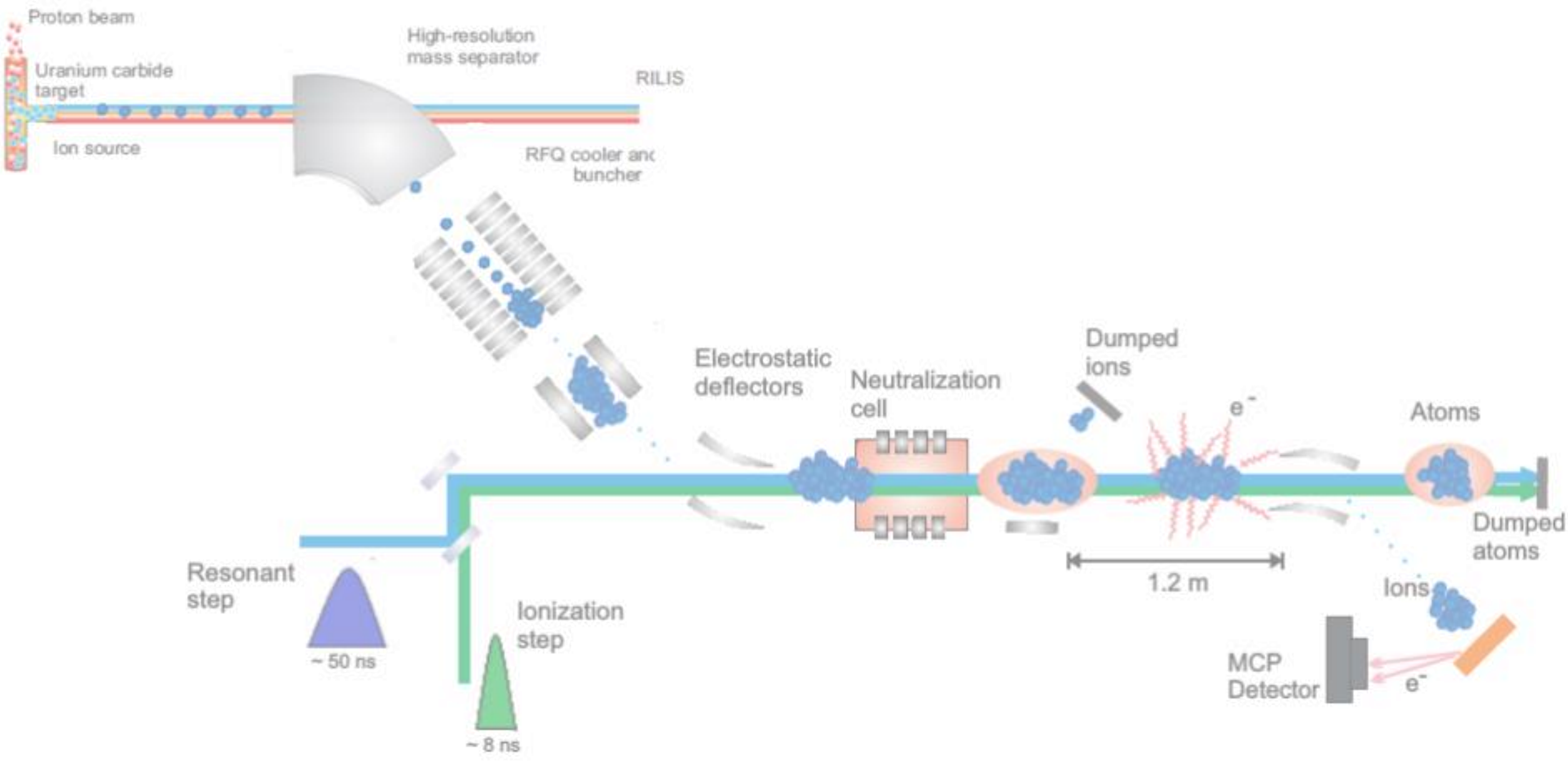

$^{50-61}$Mn (Z=25) → [H. Heylen et al, Phys. Rev. C 94, 054321(2016)]
$^{40-52}$Ca (Z=20) → [R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]
$^{38-51}$K (Z=19) → [K. Kreim et al, Phys. Lett. B 731, 97 (2014)]
$^{44-50}$Sc (Z=21) → [In preparation (2018)]

COLLAPS/ISOLDE

$^{48-52}$K(Z=19) → [In preparation (2018)]

CRIS/ISOLDE

# Case 3: Collinear Resonance Ionisation Spectroscopy (CRIS@ISOLDE)




- Resonance ionization in a collinear geometry, often after charge neutralisation
- Detection of particles, rather than of photons

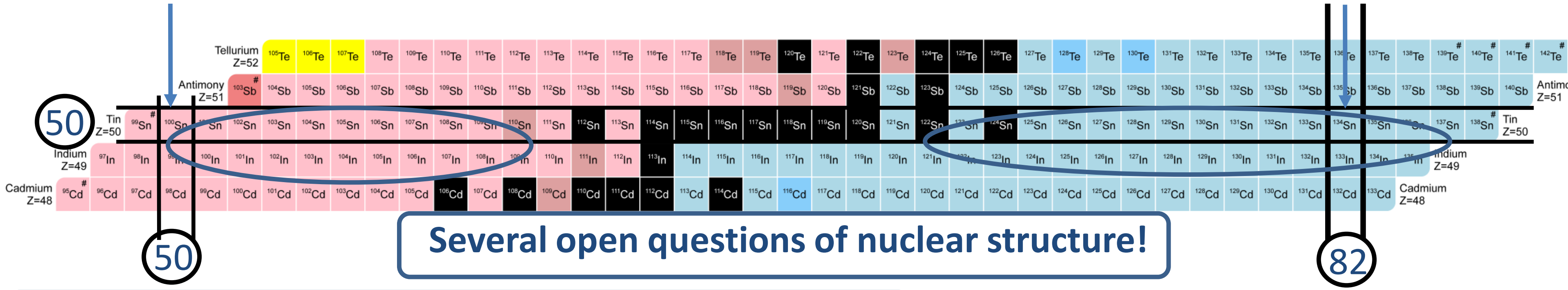
# Nuclear Structure around In-Sn chains

**Doubly "magic" $^{100}$Sn**

[Hinke *et al.* Nature 486, 341 (2012)]

**Doubly "magic" $^{132}$Sn**

[Jones *et al.* Nature 465, 454 (2010)]




**Several open questions of nuclear structure!**

$^{111-131}$In (Z=49): Garcia Ruiz et al. CERN-INTC-2017-025 (2017)
$^{100-111}$In (Z=49): Garcia Ruiz et al. CERN-INTC-2017-055 (2017)
$^{103-121}$Sn (Z=50): Garcia Ruiz et al. CERN-INTC-2016-037 (2016)

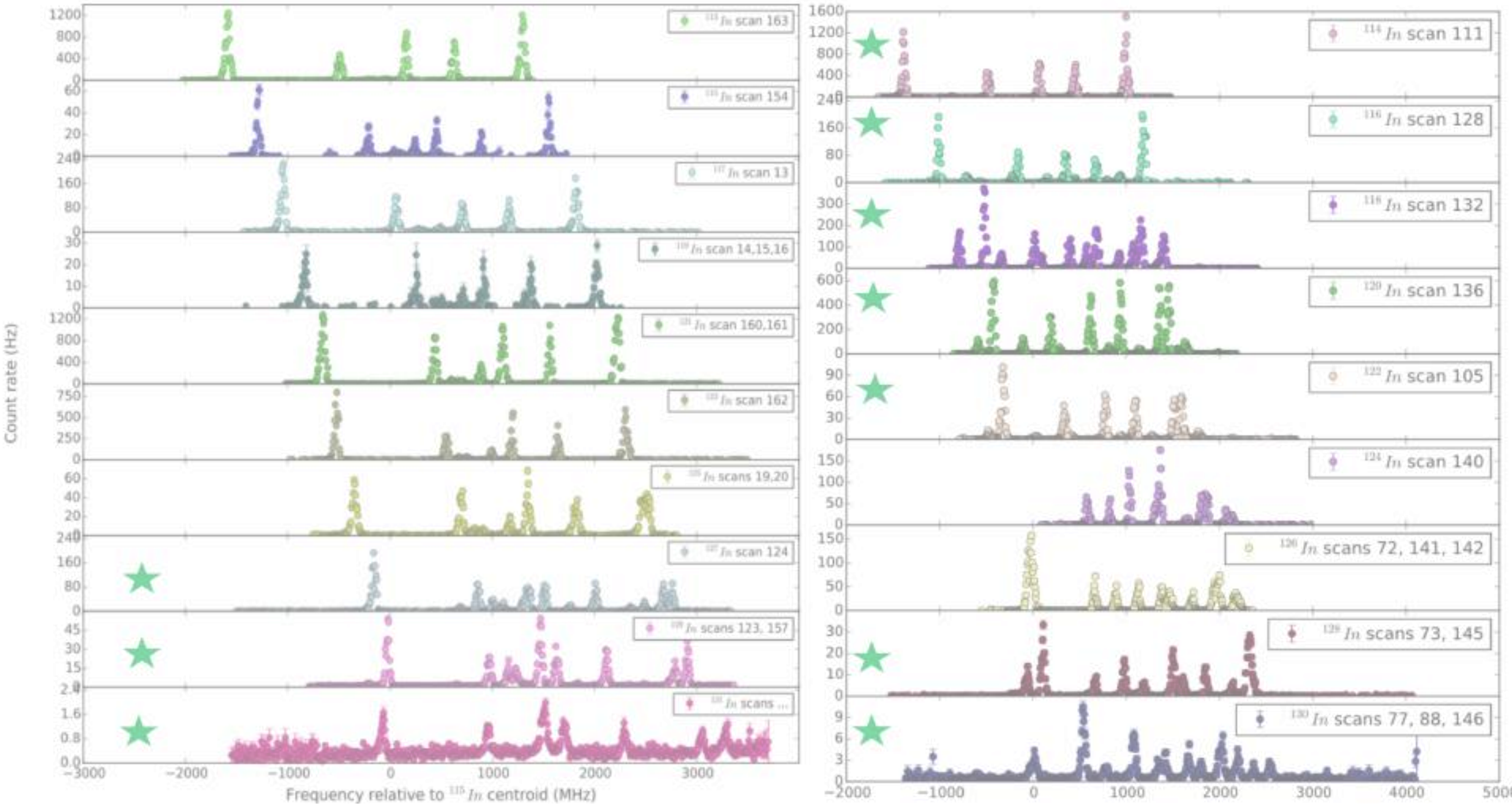
- Shell evolution towards N=Z=50 ?
- Ordering of shell model orbits ?
- Robustness of N=Z=50 shell closures?
- Proton-neutron correlations?

CC and IMSRG → [T. Morris et al. Phys. Rev. Lett. 120, 152503 (2018)]
LSSM → [Togashi et al. Phys. Rev. Lett. 121, 062501 (2018)]
….

# Indium chain with CRIS

## Measurements from $^{101}$In (N=52) up to $^{131}$In (N=82)

( New results★ )



# Summary of Recent Results with CRIS and COLLAPS

- High precision/resolution (~20-60 MHz)
- High efficiency (<100 ions/s)
- High selectivity (>1/$10^6$)
- Short time scales (< 1 s)

Laser spectroscopy → $I \quad \delta\langle r^2\rangle \quad \mu_I \quad Q_s$

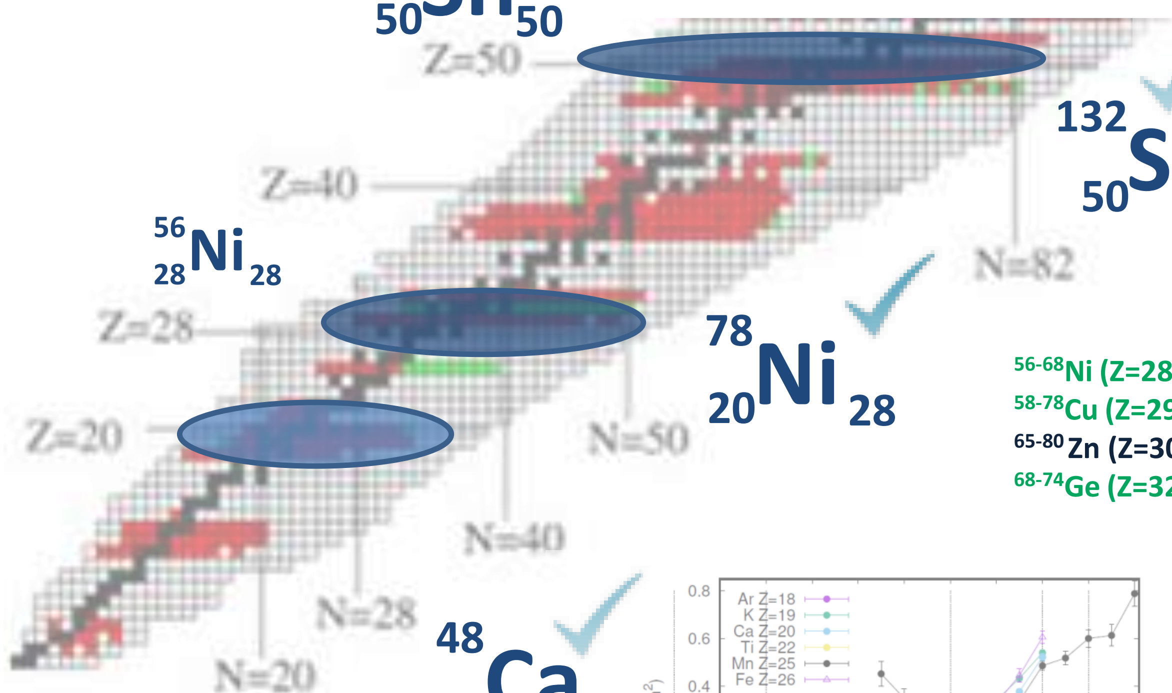
$^{100}_{50}Sn_{50}$

$^{132}_{50}Sn_{82}$

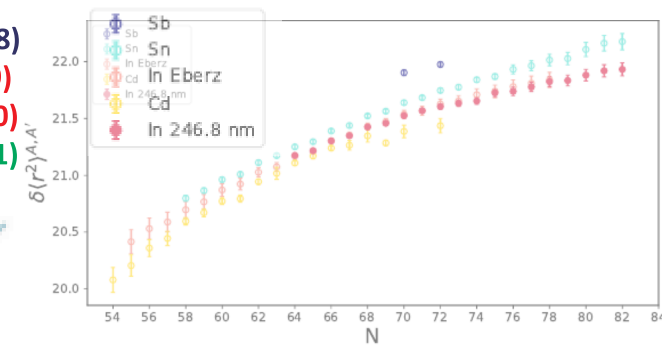
$^{56}_{28}Ni_{28}$

$^{78}_{20}Ni_{28}$

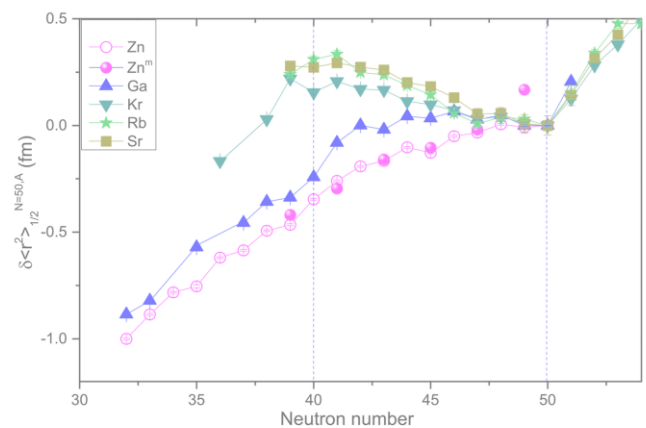
$^{48}_{20}Ca_{28}$



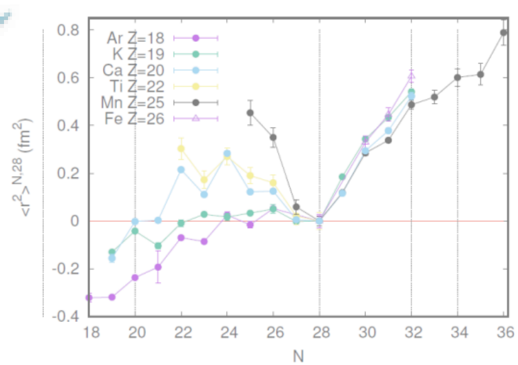

$^{100-130}$Cd (Z=48)
$^{101-131}$In (Z=49)
$^{103-134}$Sn (Z=50)
$^{112-134}$Sb (Z=51)




$^{56-68}$Ni (Z=28)
$^{58-78}$Cu (Z=29)
$^{65-80}$Zn (Z=30)
$^{68-74}$Ge (Z=32)




$^{38-52}$K (Z=19)
$^{40-52}$Ca (Z=20)
$^{44-50}$Sc (Z=21)
$^{50-61}$Mn (Z=25)




Published
CRIS (unpublished)
COLLAPS (unpublished)

# Summary: Prolific recent results from laser spectroscopy at ISOLDE and very bright Future across the whole Nuclear Chart

**ISOLDE@CERN (RILIS, CRIS, COLLAPS)**

**TRIUMF**

**JYFL**

**KU Leuven**

**GSI/Mainz**

**RIKEN**

**NSCL**

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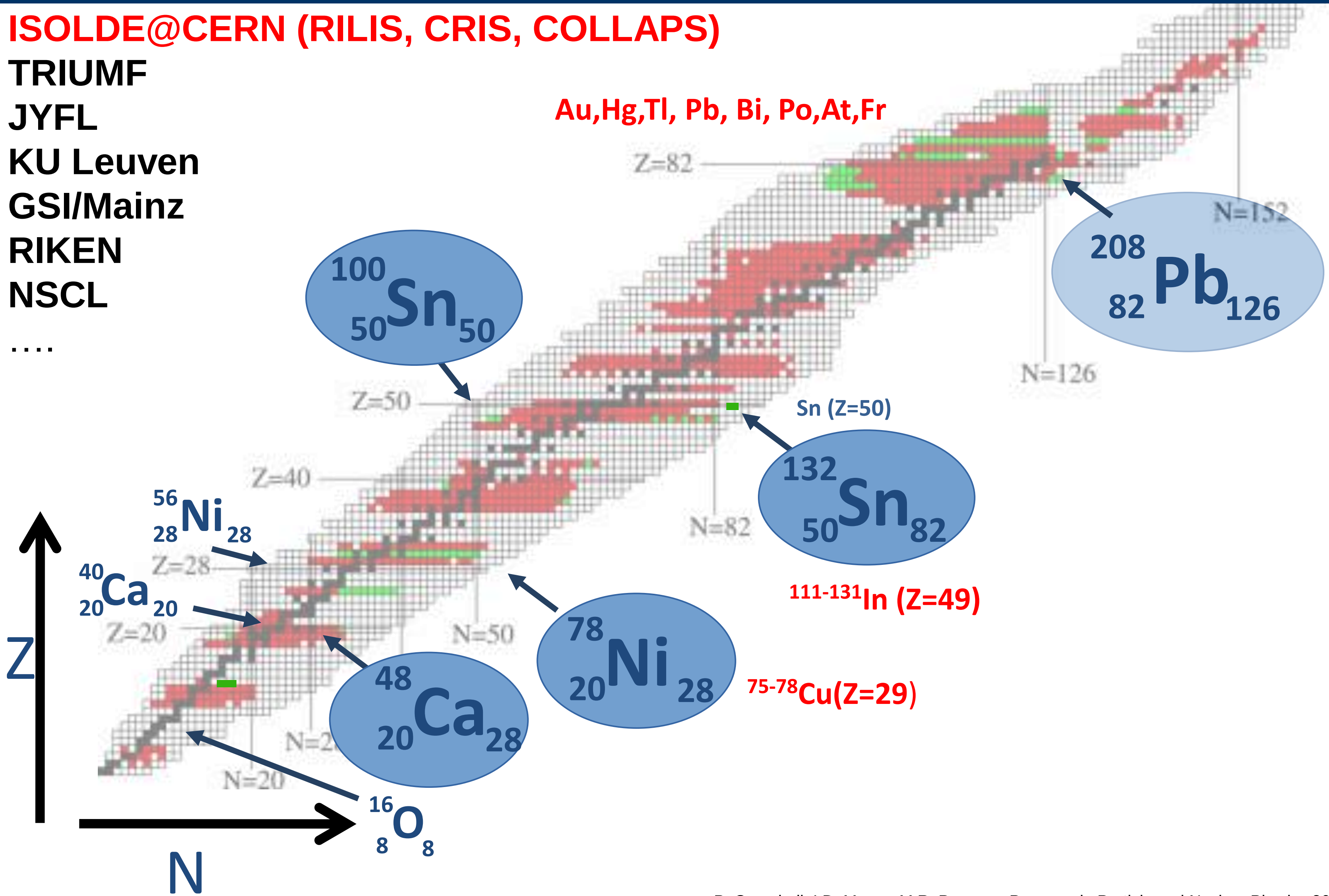


P. Campbell, I.D. Moore, M.R. Pearson, Progress in Particle and Nuclear Physics 86 (2016) 127–180