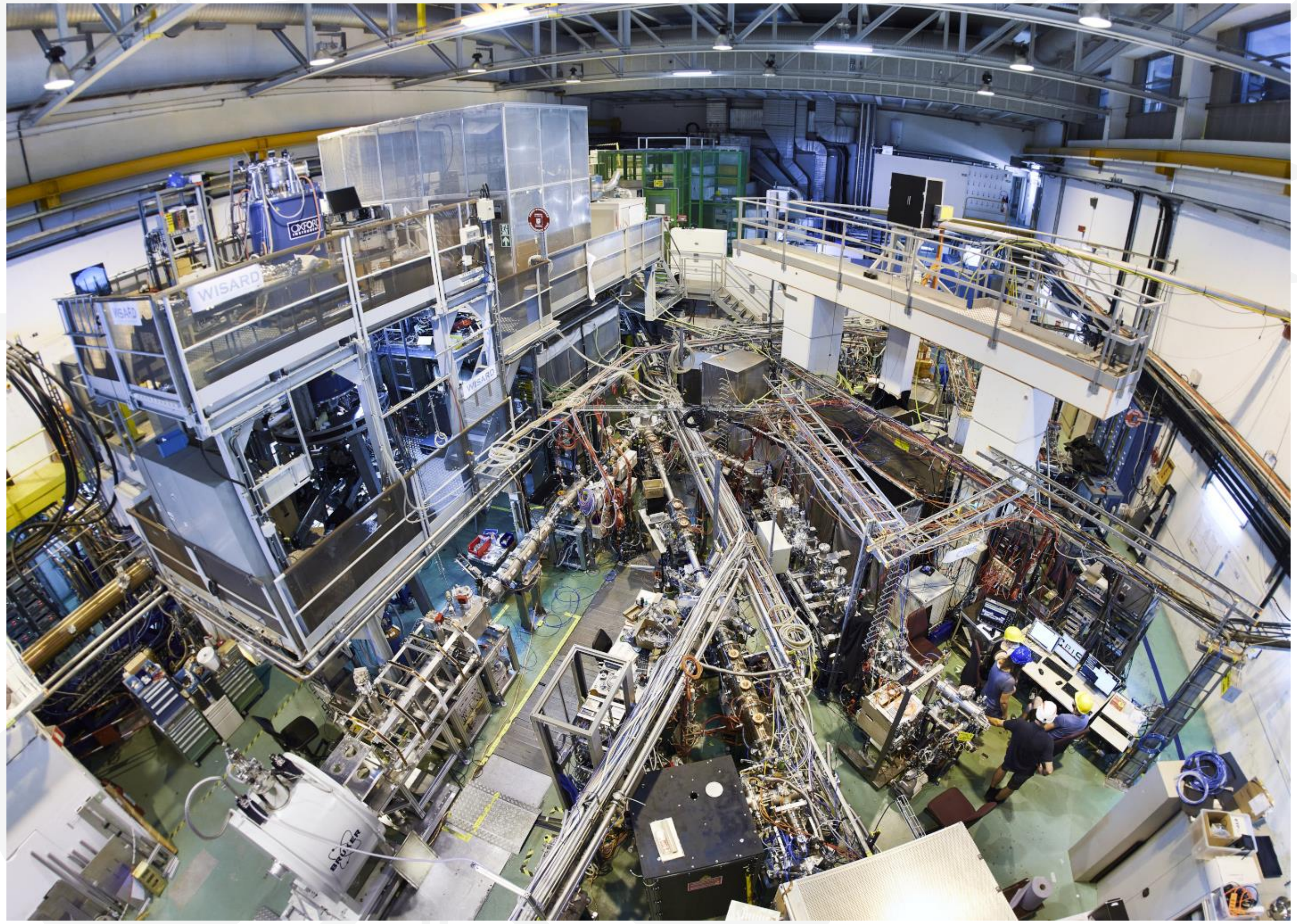
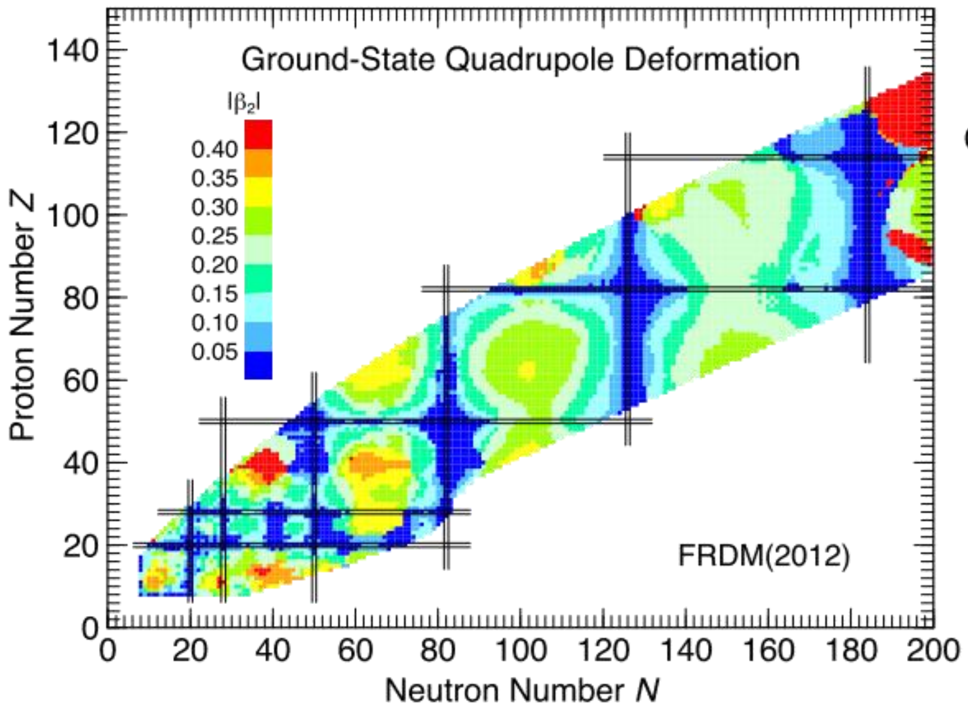
In-source laser spectroscopy @ ISOLDE

James Cubiss – University of York – james.cubiss@york.ac.uk
On behalf of the RILIS–Windmill–ISOLTRAP–IDS–Paris–Bruxelles collaboration

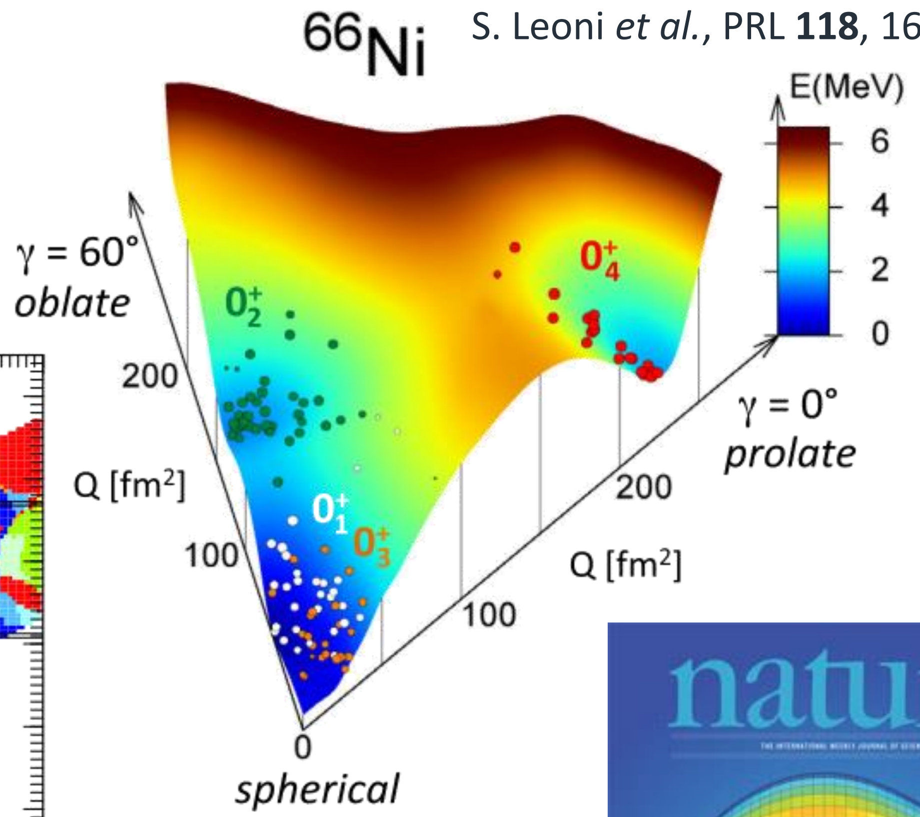


Nuclear shapes & configurations

- Fundamental and characteristic property
- Provides insight into governing interactions
- Rich variety of phenomena to describe
  - Evolution across landscape
  - Coexistence within same nucleus
  - Exotic octupole (pear) shapes



Moller *et al.*, Atom. Data Nucl. Data **109-110**, (2016)



S. Leoni *et al.*, PRL **118**, 162502 (2017)

Gaffney *et al.*, Nature **497**, (2013)

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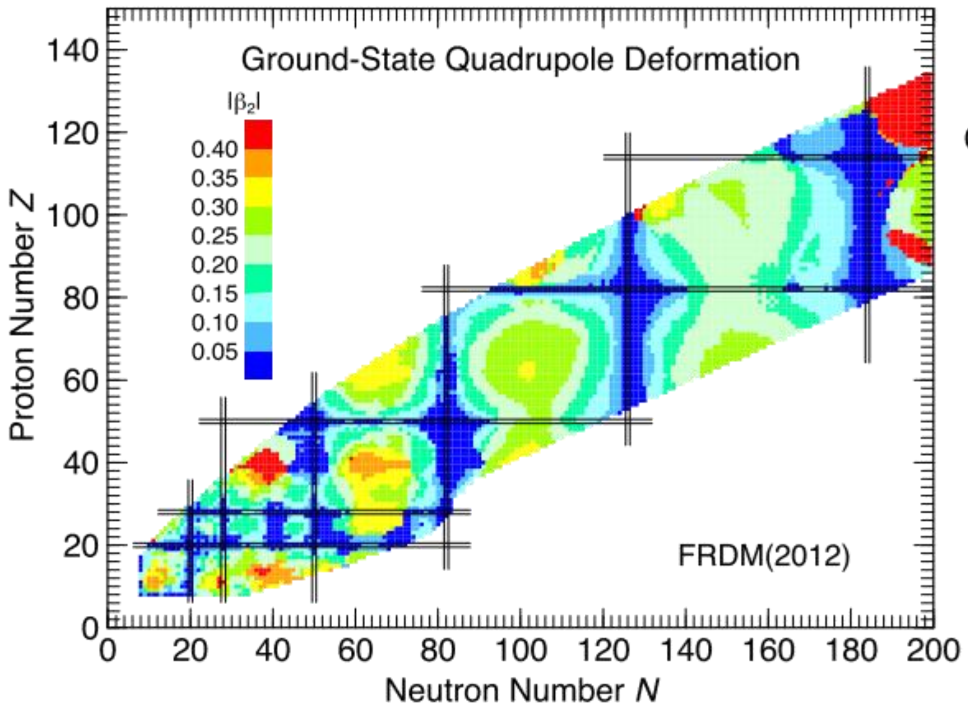

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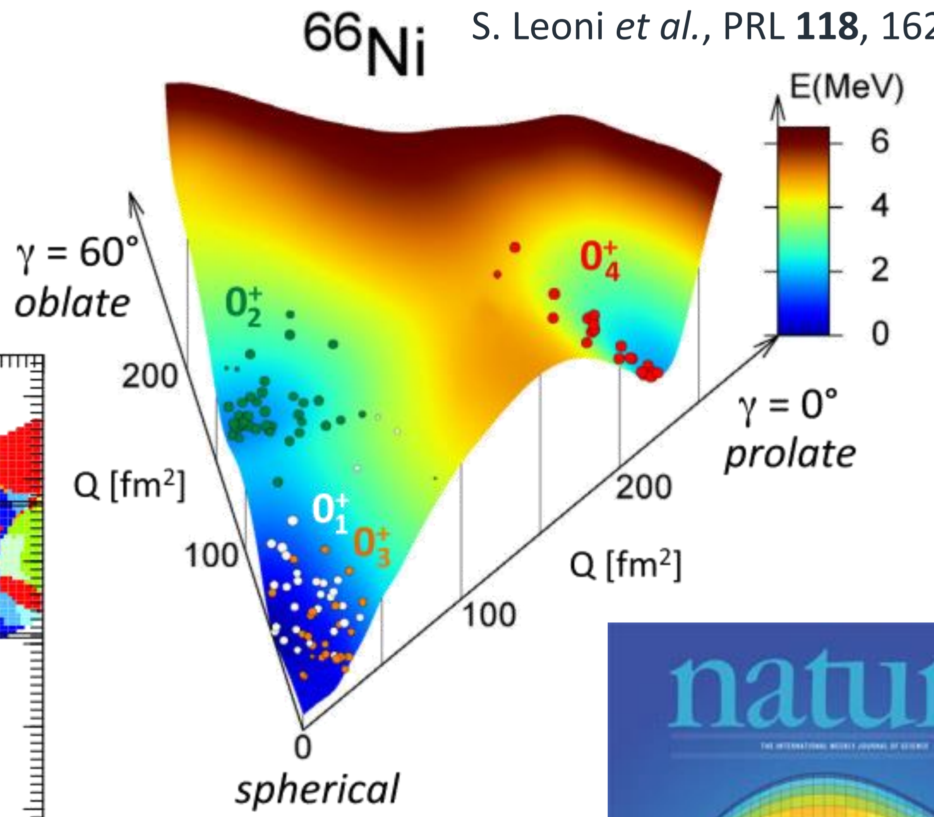

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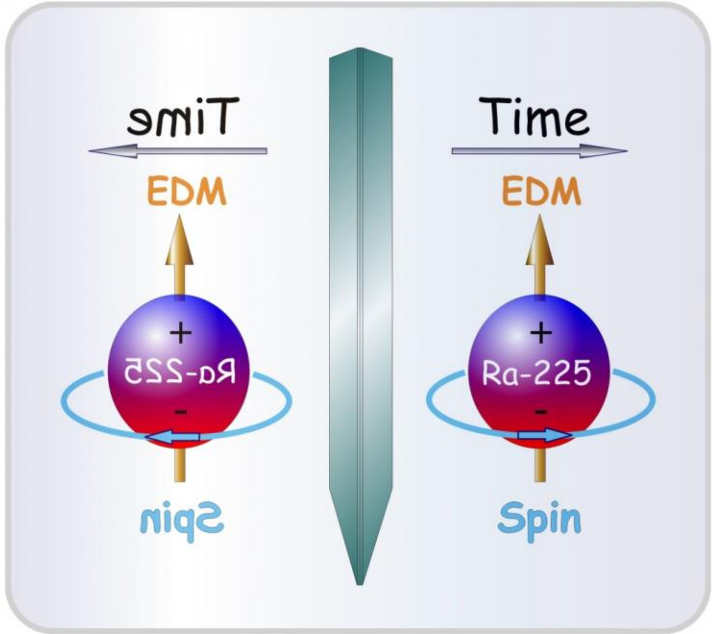
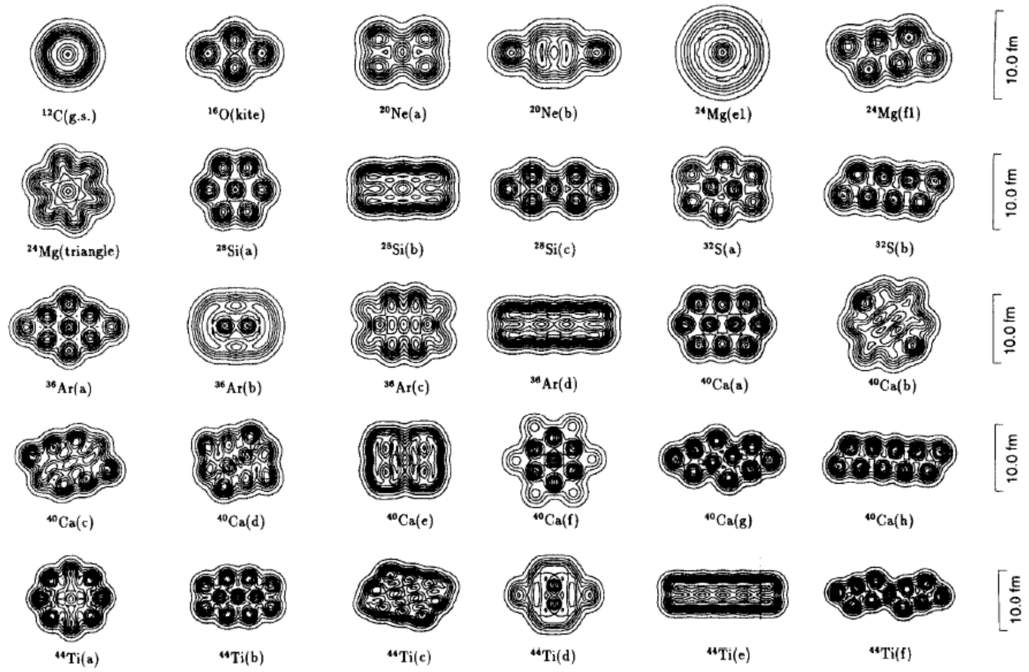


P. Mueller ANL – physics highlight for Parker *et al.*, PRL **114**, 233002 (2015)

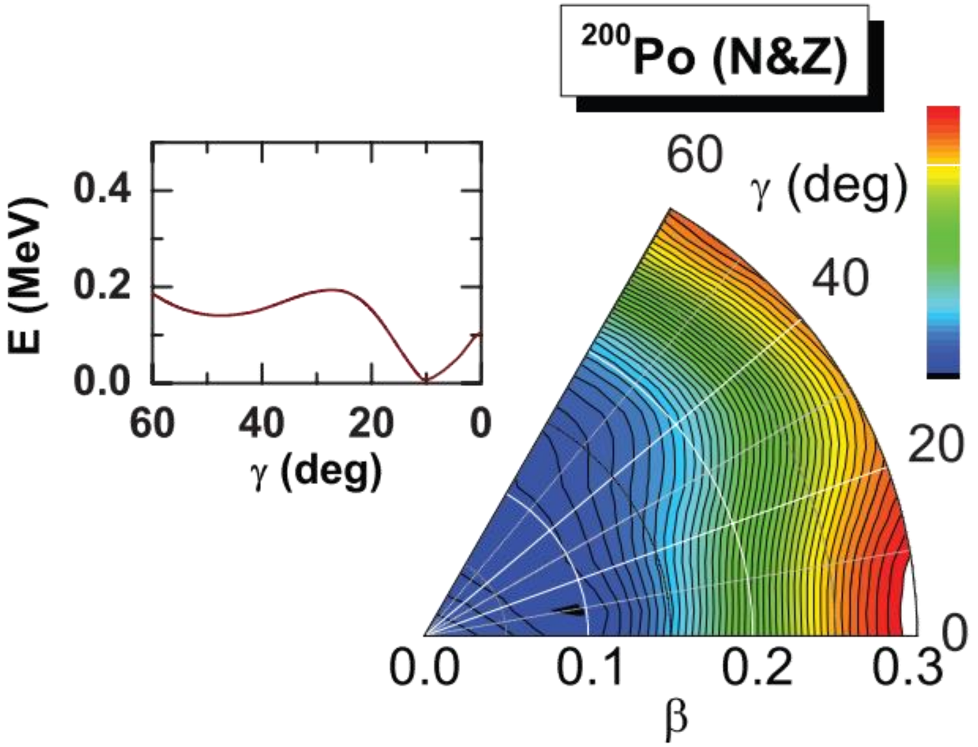
Zhang & Rae, Nucl. Phys. A **564**, (1993)

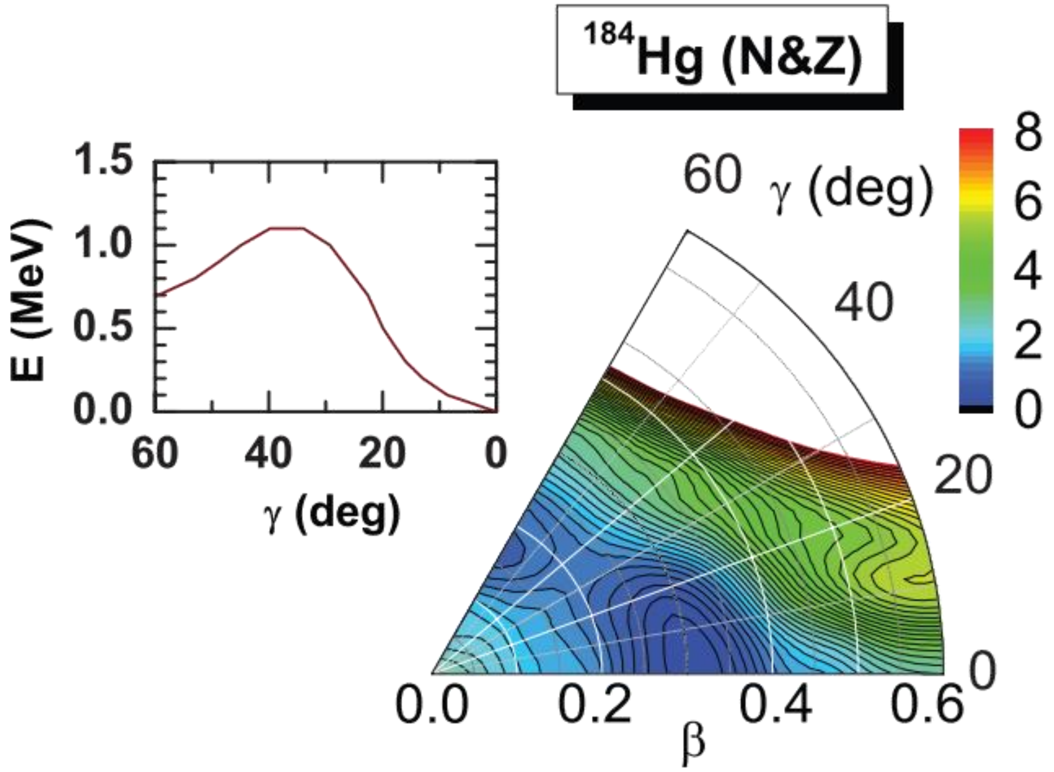


- BSM studies:
  - Enhanced Schiff moments in Octupole Nuclei
  - Amplify signature of eEDMs by $>10^3$
- Astrophysics:
  - Cluster states
  - Shape isomers

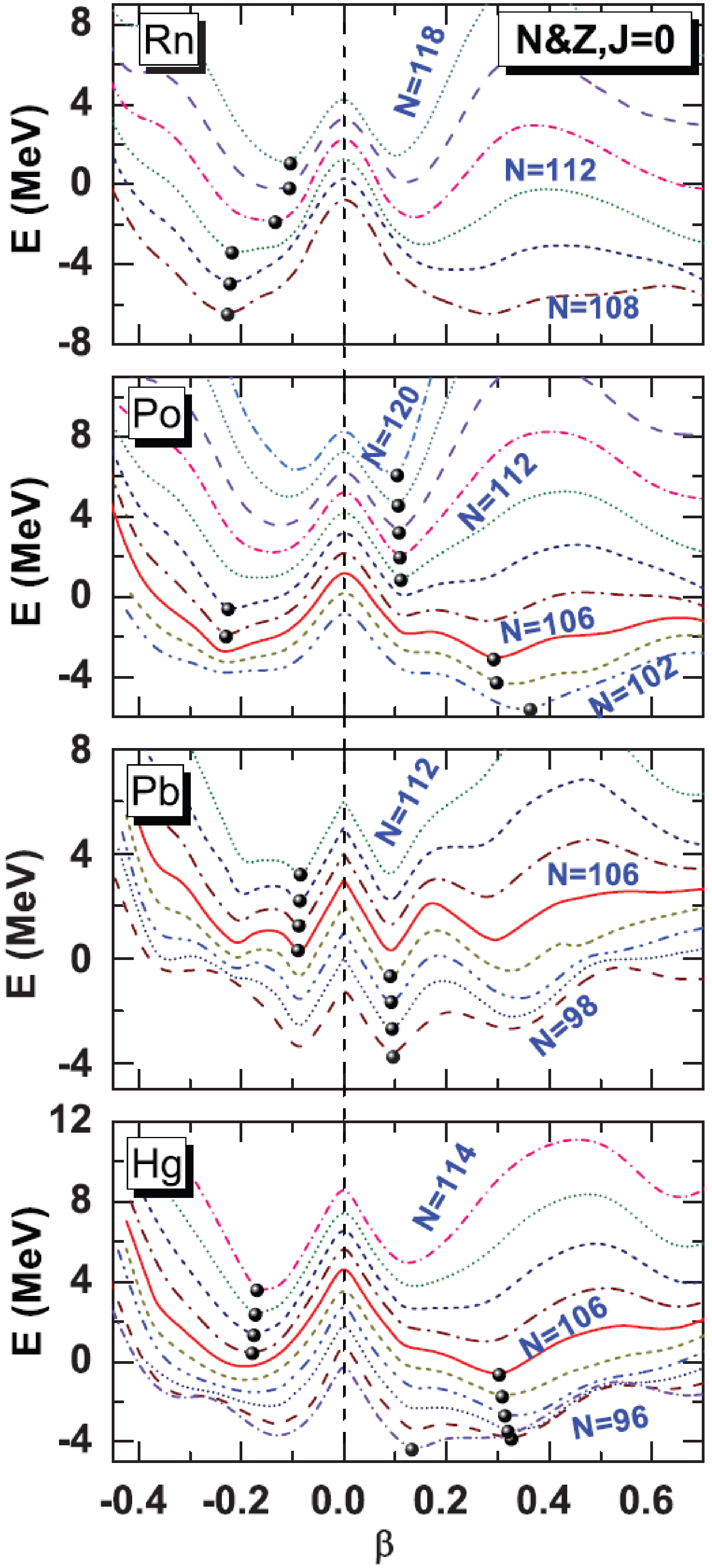
Nuclear shapes & configurations

- Multiple minima in nuclear potential energy surfaces all at different deformations
- Small changes in neutron number may lead to rapid changes in nuclear shape
- Experimental input vital for constraining our models

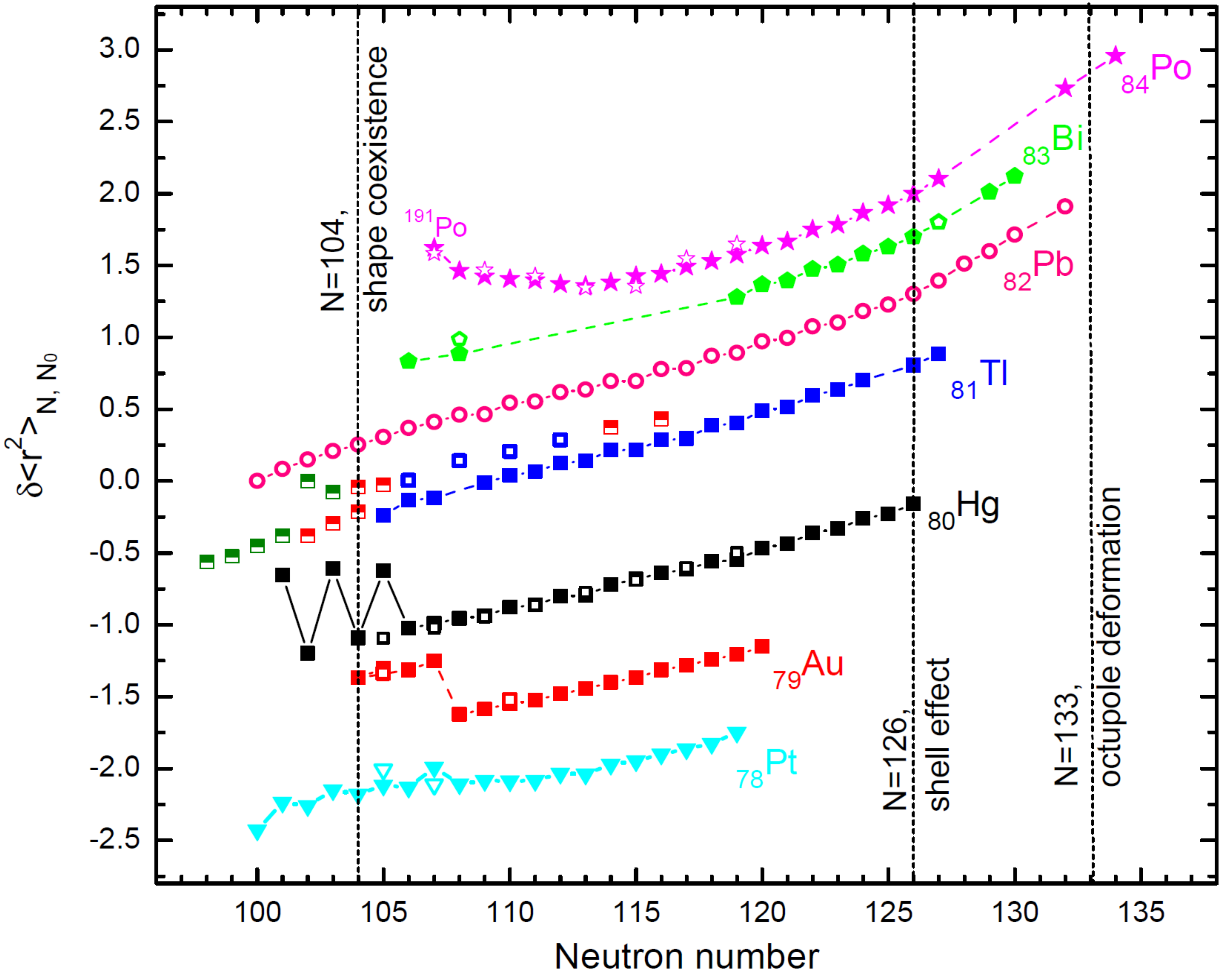




Yao, Bender & Heenen, PRC **87**, 034322 (2013)



Charge radii in region near "magic" Pb (Z=82)



Charge radii in region near “magic” Pb (Z=82)

Rapid onsets of deformation

Cocolios *et al.*, PRL **106**, 052503 (2011)

Isomer shifts show shape coexistence

Barzakh *et al.*, PRC **88**, 1 (2013)

Barzakh *et al.*, PRC **95**, 014324 (2017)

Large jumps and staggers, competition in ground state

Bonn *et al.*, PLB **38**, 308 (1972)

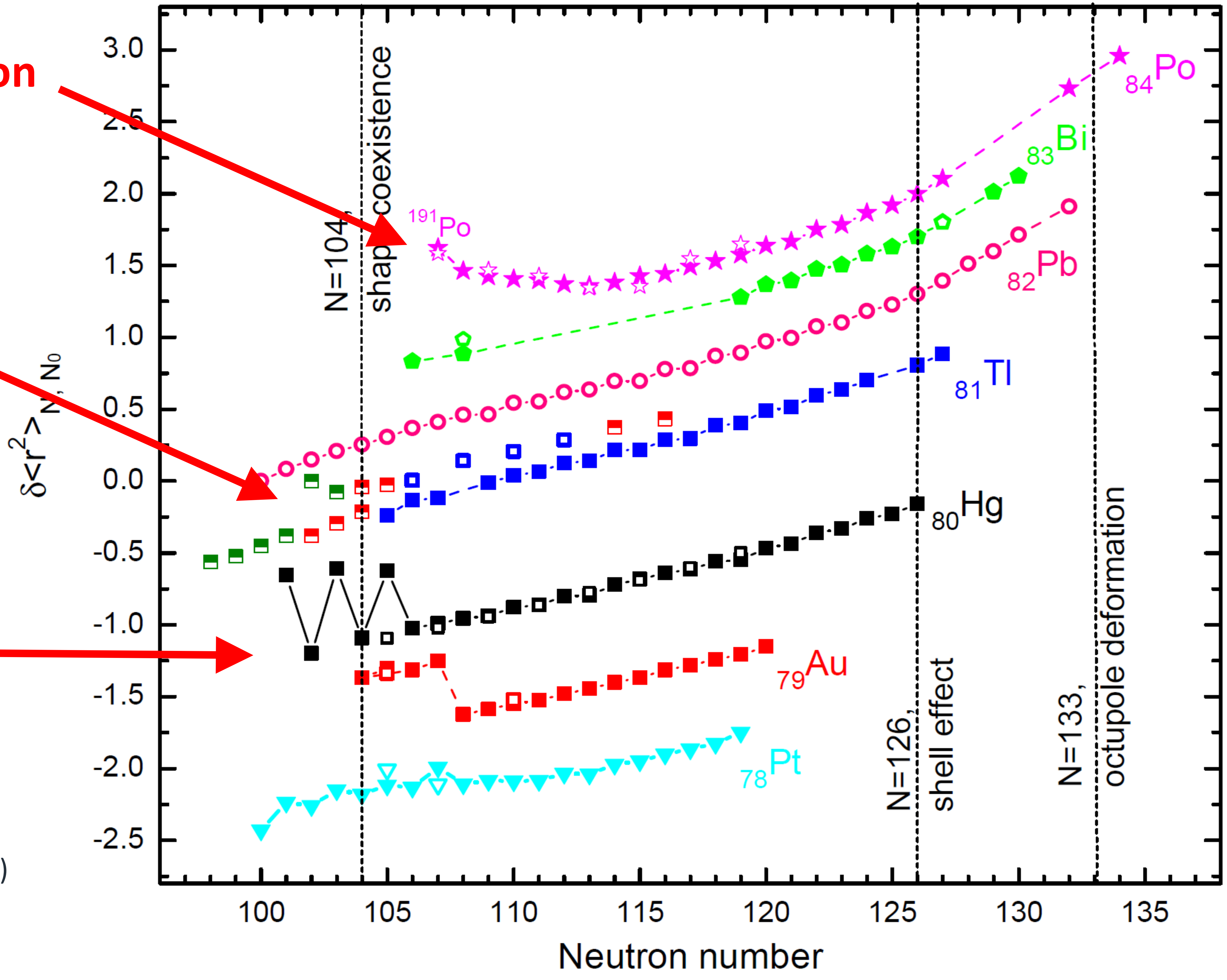
Kuhl *et al.*, PRL **39**, 180 (1977)

Ulm *et al.*, Z. Phys. A **325**, 247 (1986)

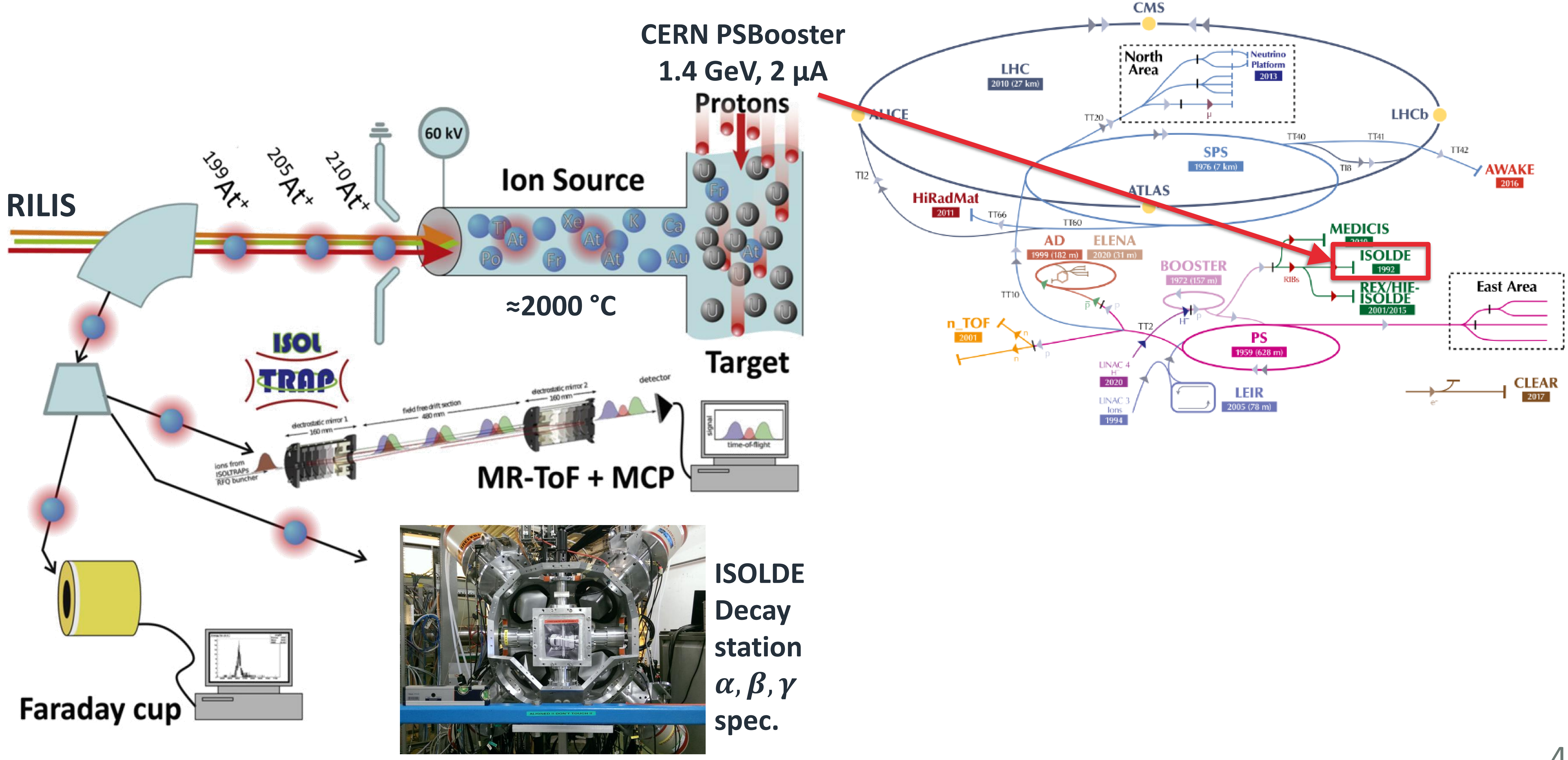
Wallmeroth *et al.*, Nuc. Phys. A **449**, 224 (1989)

Ekstrom *et al.*, Nuc. Phys. A **348**, 25 (1980)

Kronert *et al.*, Z. Phys. A **331**, 521 (1988)



Our tools – In-source spectroscopy



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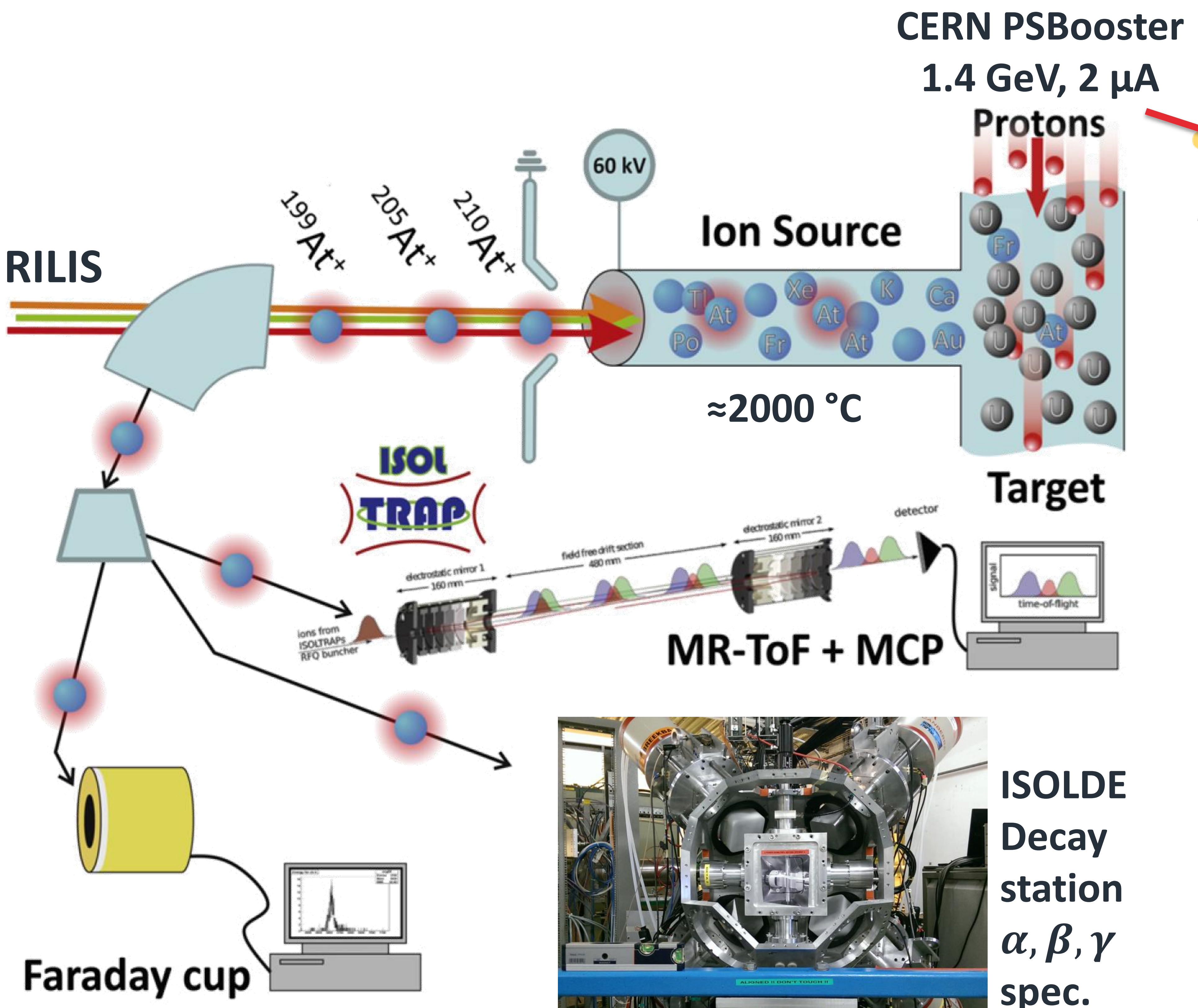
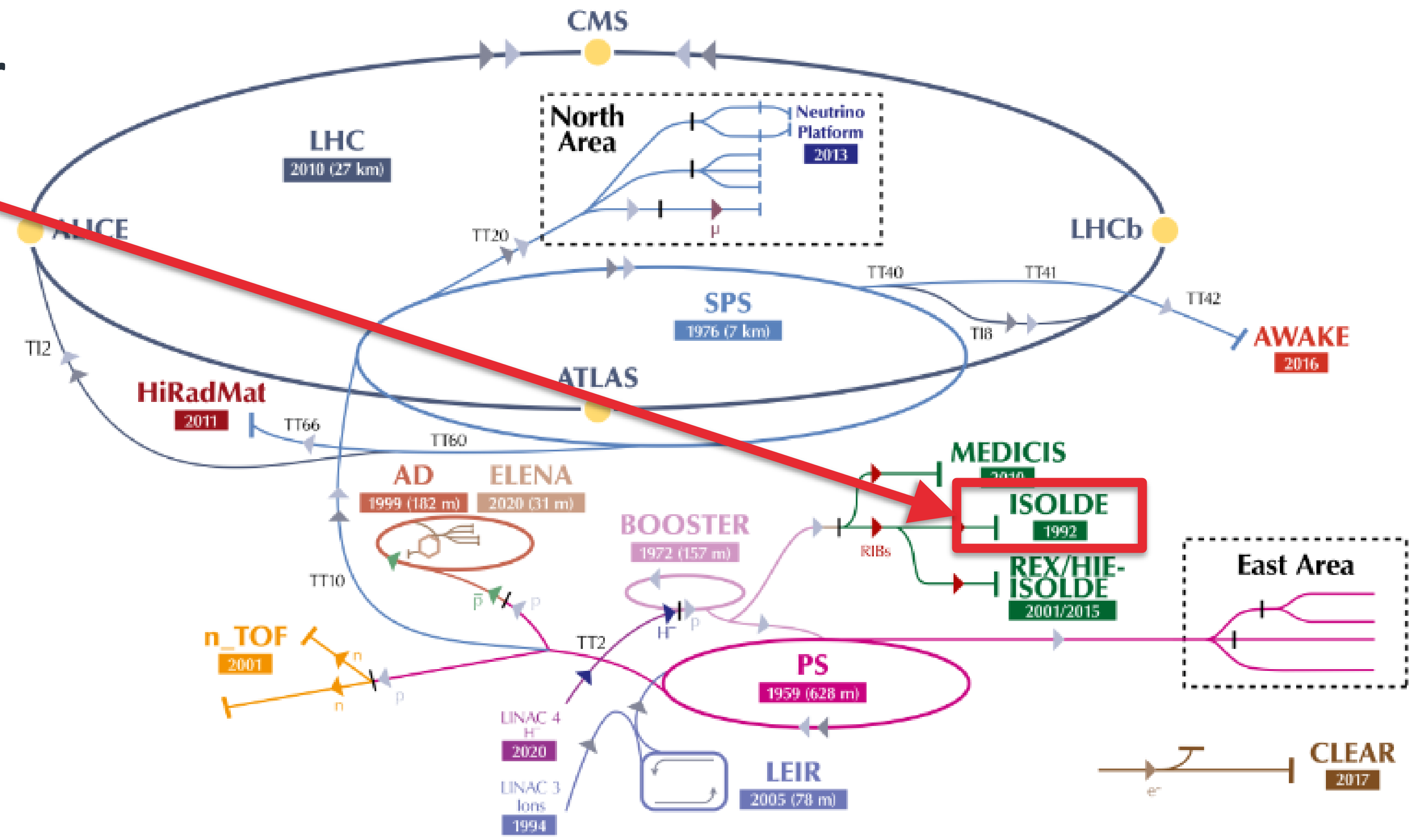




ISOLDE Decay station α, β, γ spec.

Highly efficient: (>0.01 ions/s)
Low resolution observables:

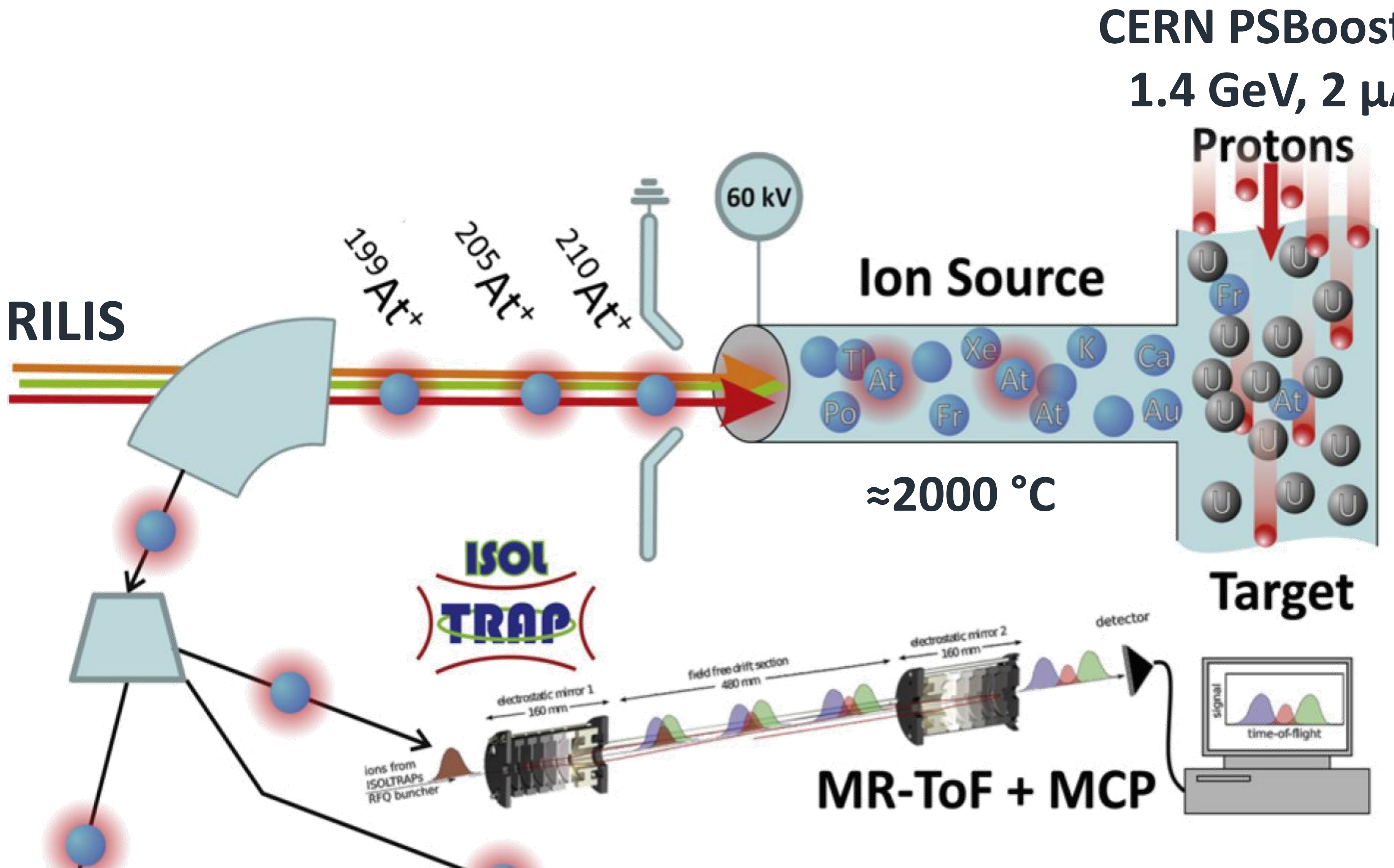
$\delta\langle r^2\rangle^{A,A'}$ **– mean-squared charge radius**
Radial extent of proton wavefunction

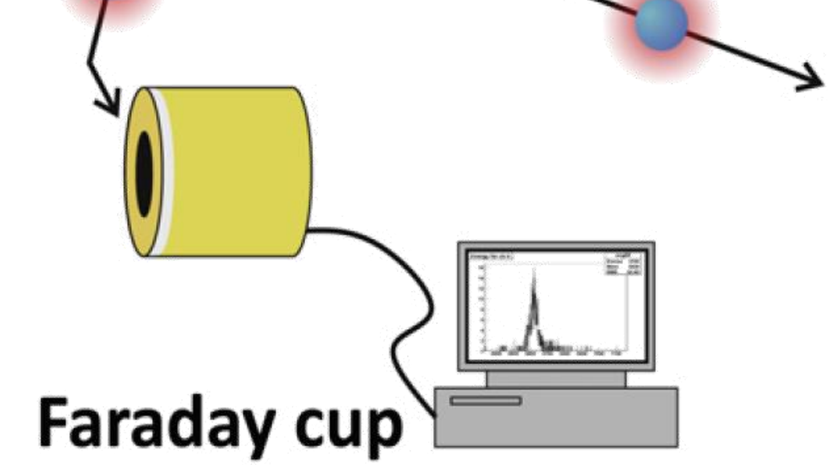
μ **– mag. dipole moment**
Config. of unpaired nucleons

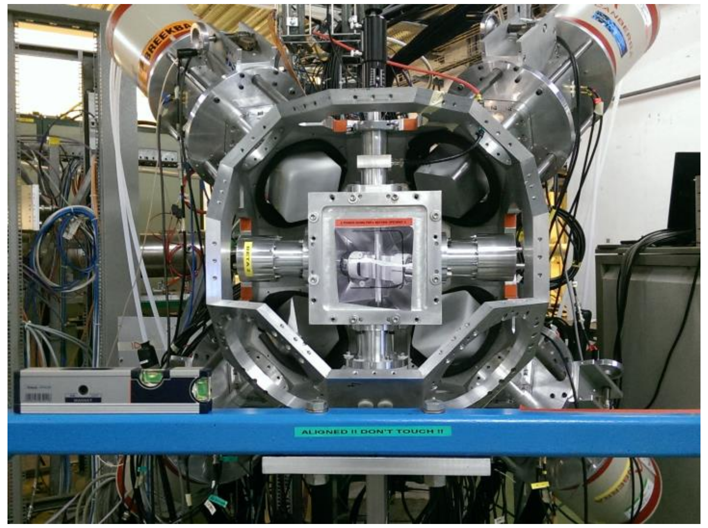
~~Q – **electric quad. moment**~~
~~Probes shape of the nucleus~~

~~I – **Nuclear Spin**~~

Our tools – In-source spectroscopy







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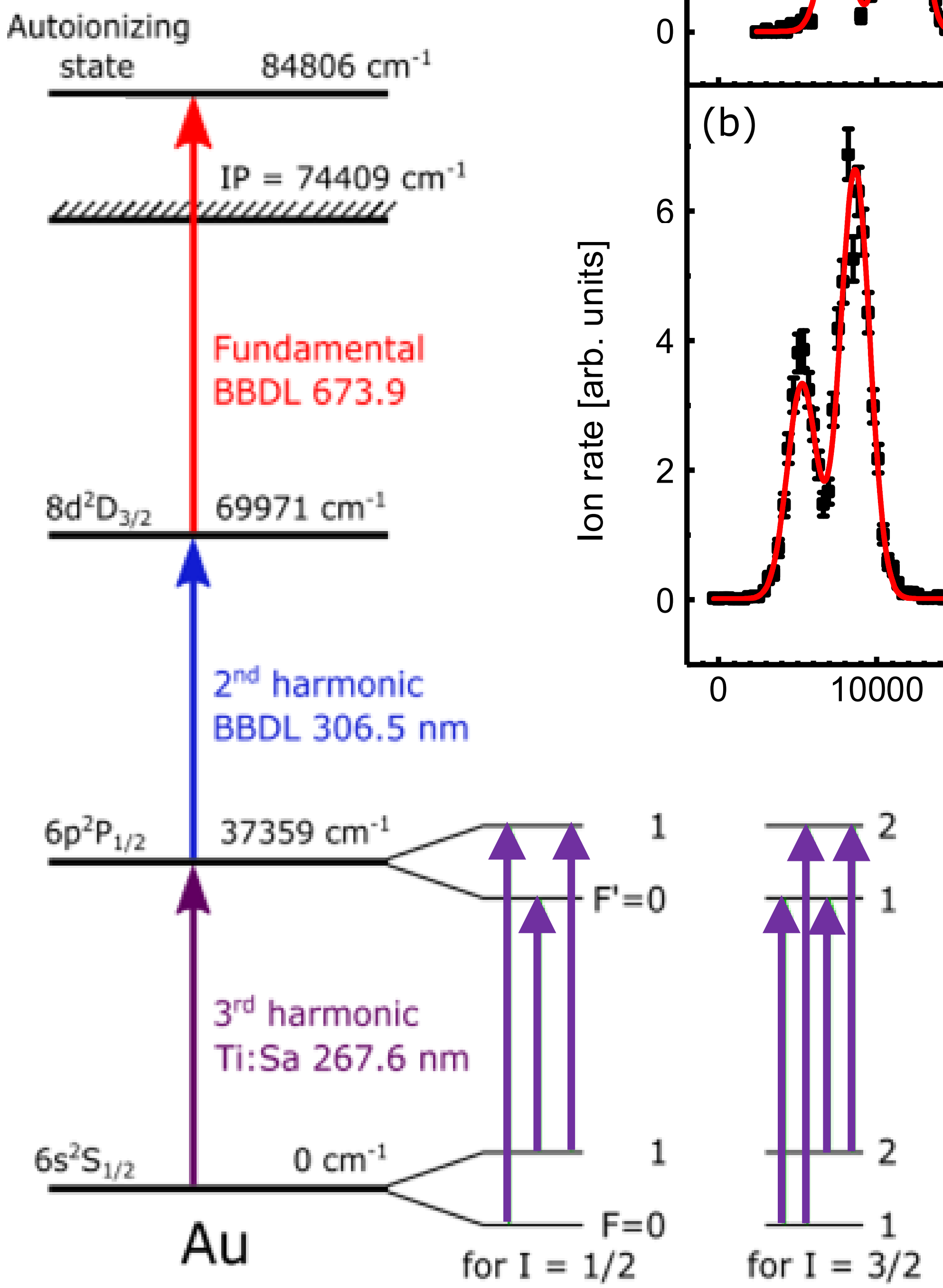

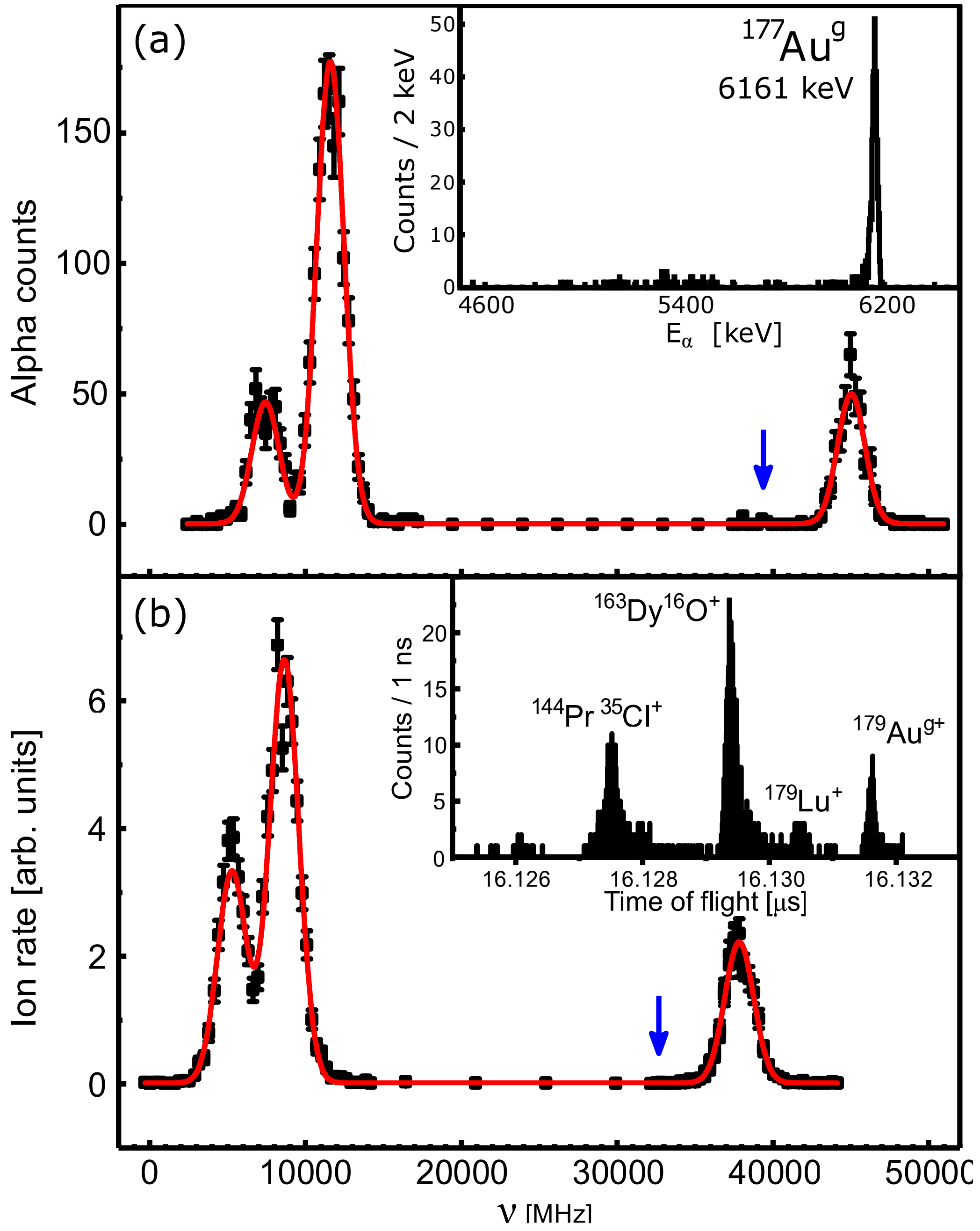

Gold (Z=79) and bismuth (Z=83) radii

PHYSICAL REVIEW LETTERS **131**, 202501 (2023)

Editors' Suggestion

Deformation versus Sphericity in the Ground States of the Lightest Gold Isotopes

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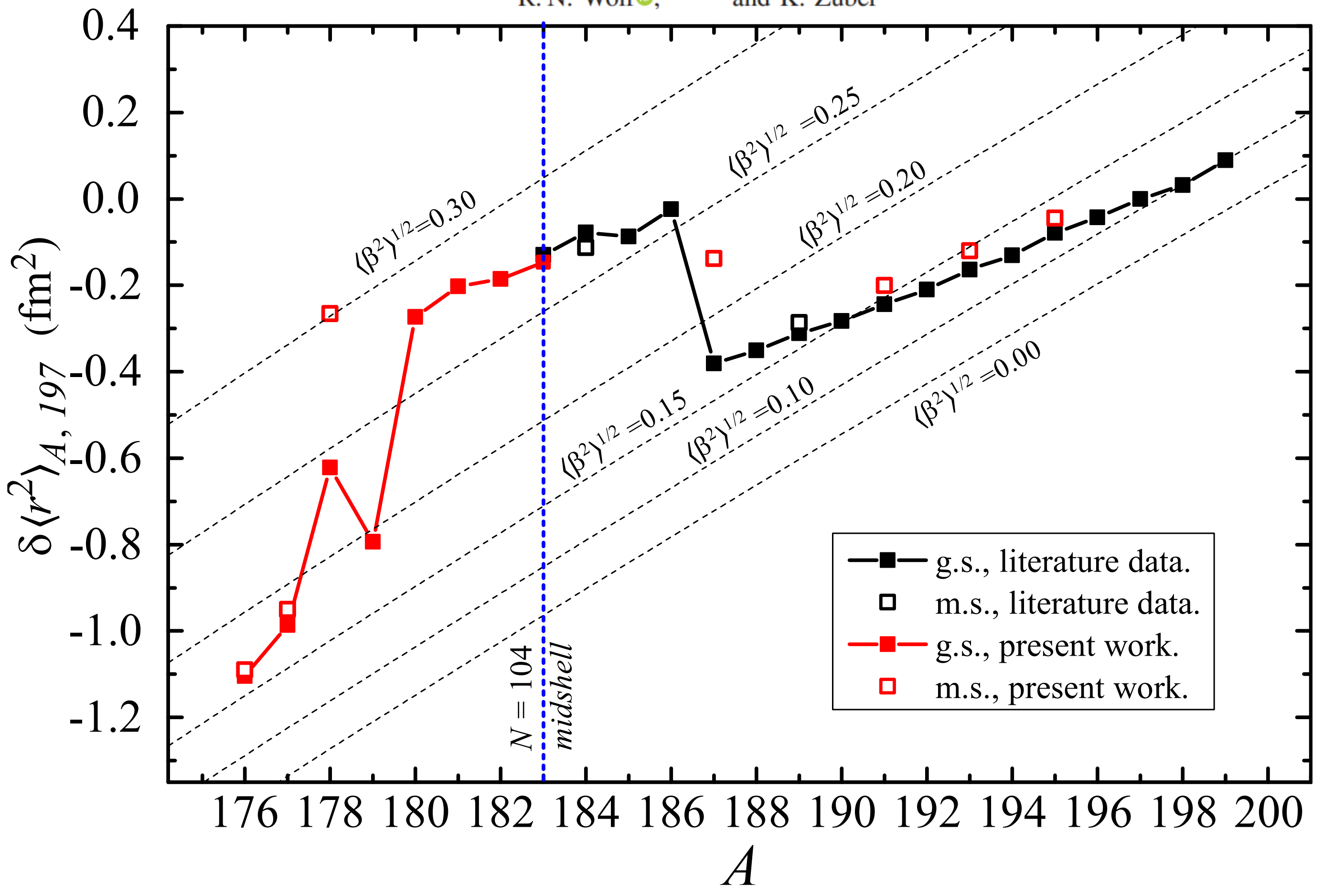

^{187}Au shape coexistence

A. E. Barzakh *et al.*, PRC **101**, 064321 (2020)

$^{180-182}$Au- stay strongly deformed

^{176g,m,177m,g,179}Au – trend towards sphericity

^{178g,m}Au – both isomers are deformed

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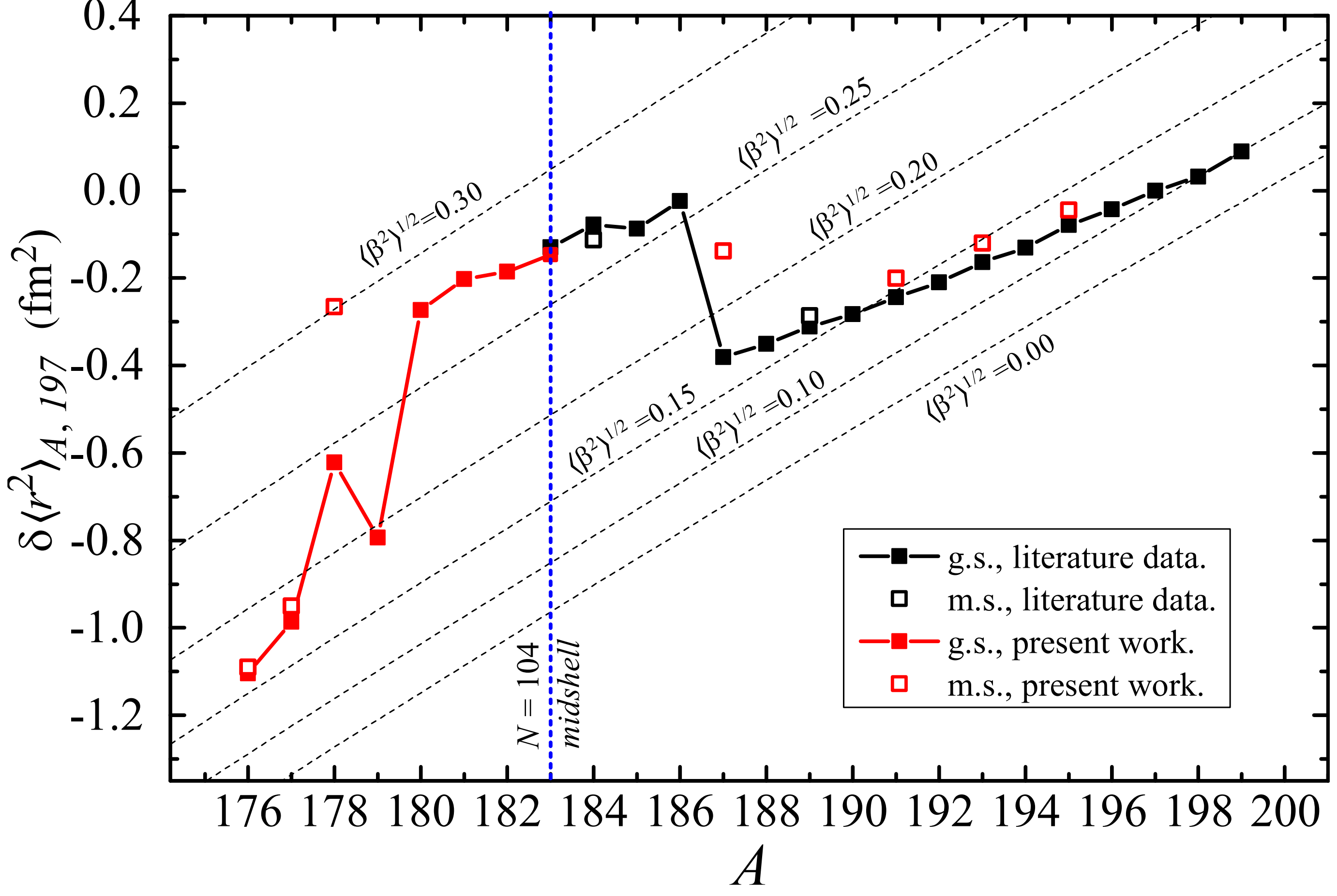

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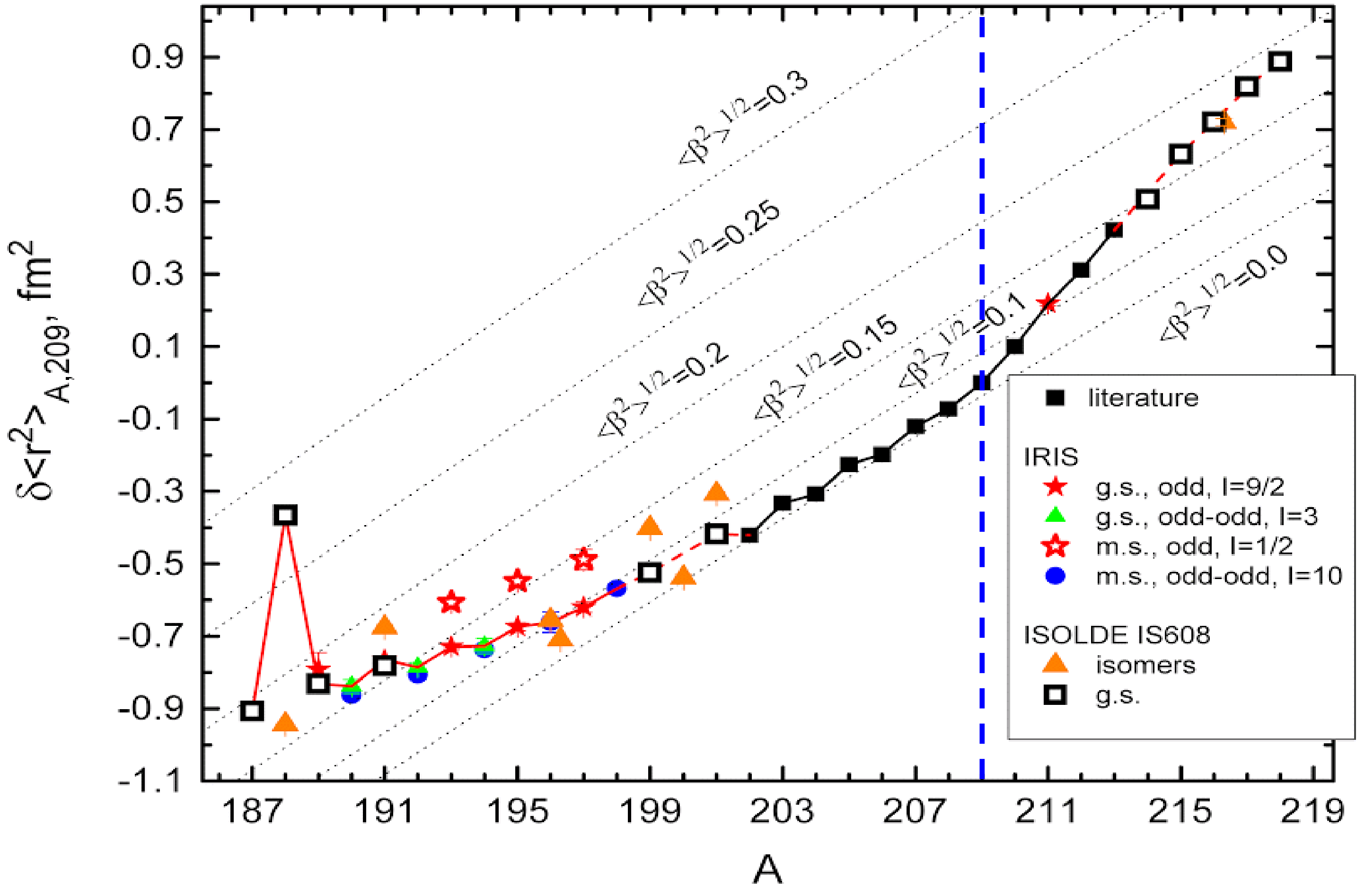

$^{189-209}$Bi – follow the spherical Pb trend

Large isomer shifts in odd-A nuclei – coexistence.

^{188}Bi (N=105) – Large stagger!

Kink at N=126 – shelf effect.

A.E. Barzakh *et al.*, PRL **127**, 192501 (2021)

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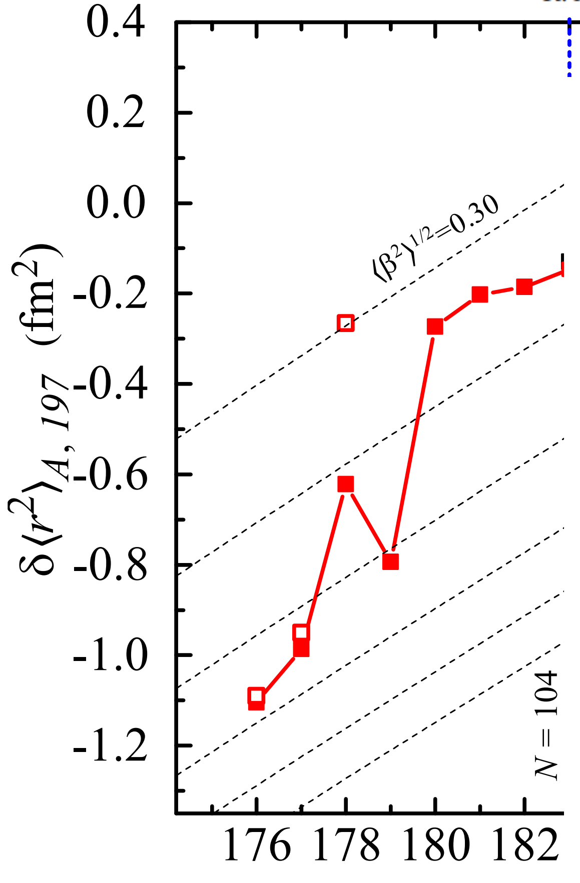

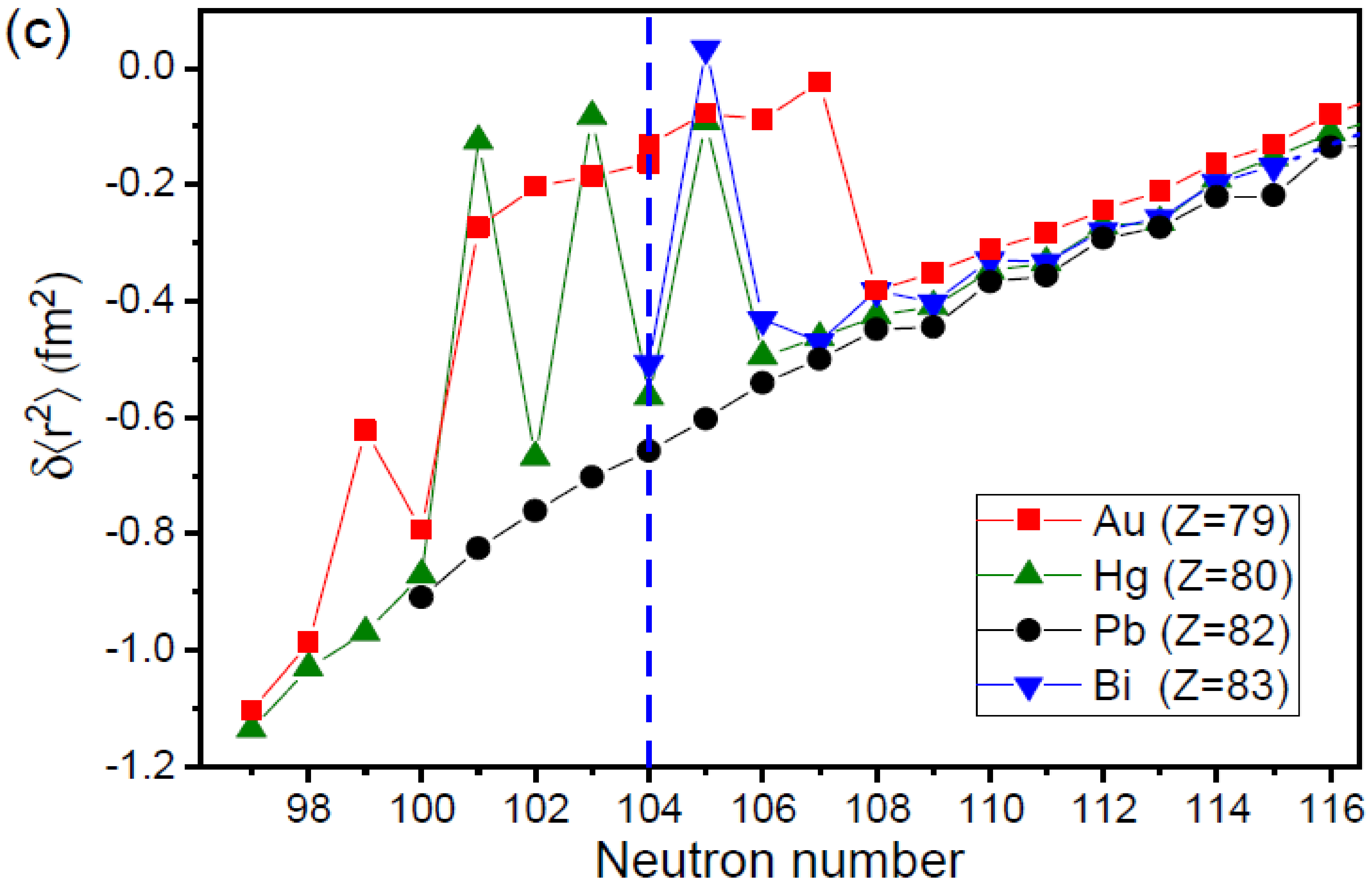

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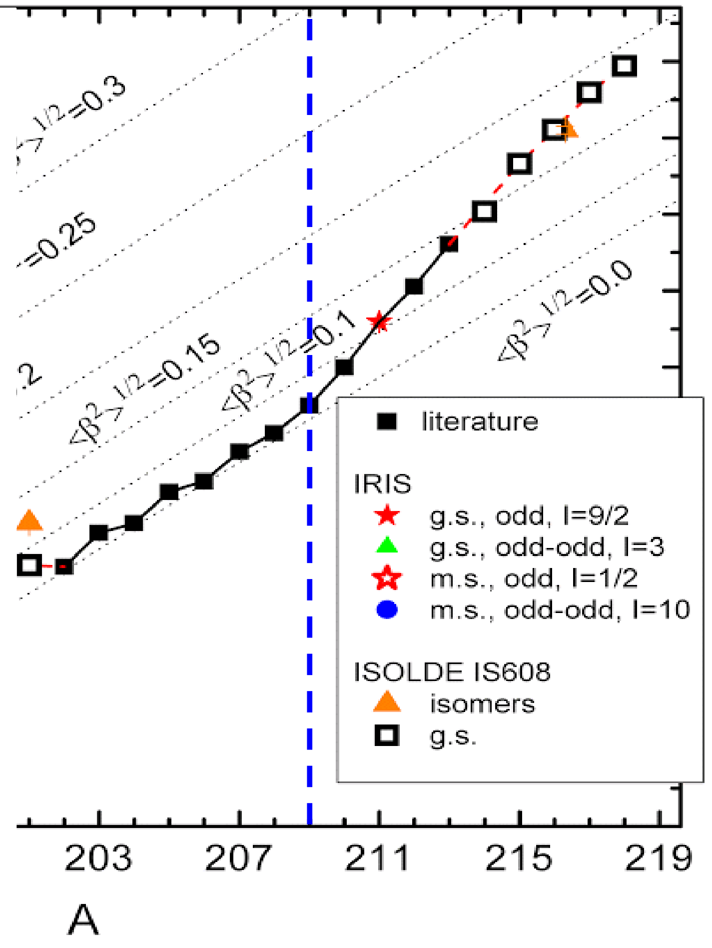

^{187}Au shape coexis

A. E. Barzakh *et al.*

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J. G. Cubiss *et al.*, I

ierical Pb trend

dd-A nuclei – coexistence.

agger!

fect.

127, 192501 (2021)

Odd- and odd-odd HFB calculations

- Too complex for ab-initio and Monte Carlo Shell Model calculations – can "global" models be used?
- HFB using D1M-Gogny [S. Goriely *et al.*, PRL **102**, 242501 (2009)]
- Begin by selecting states with correct spin, and calculating ground state.

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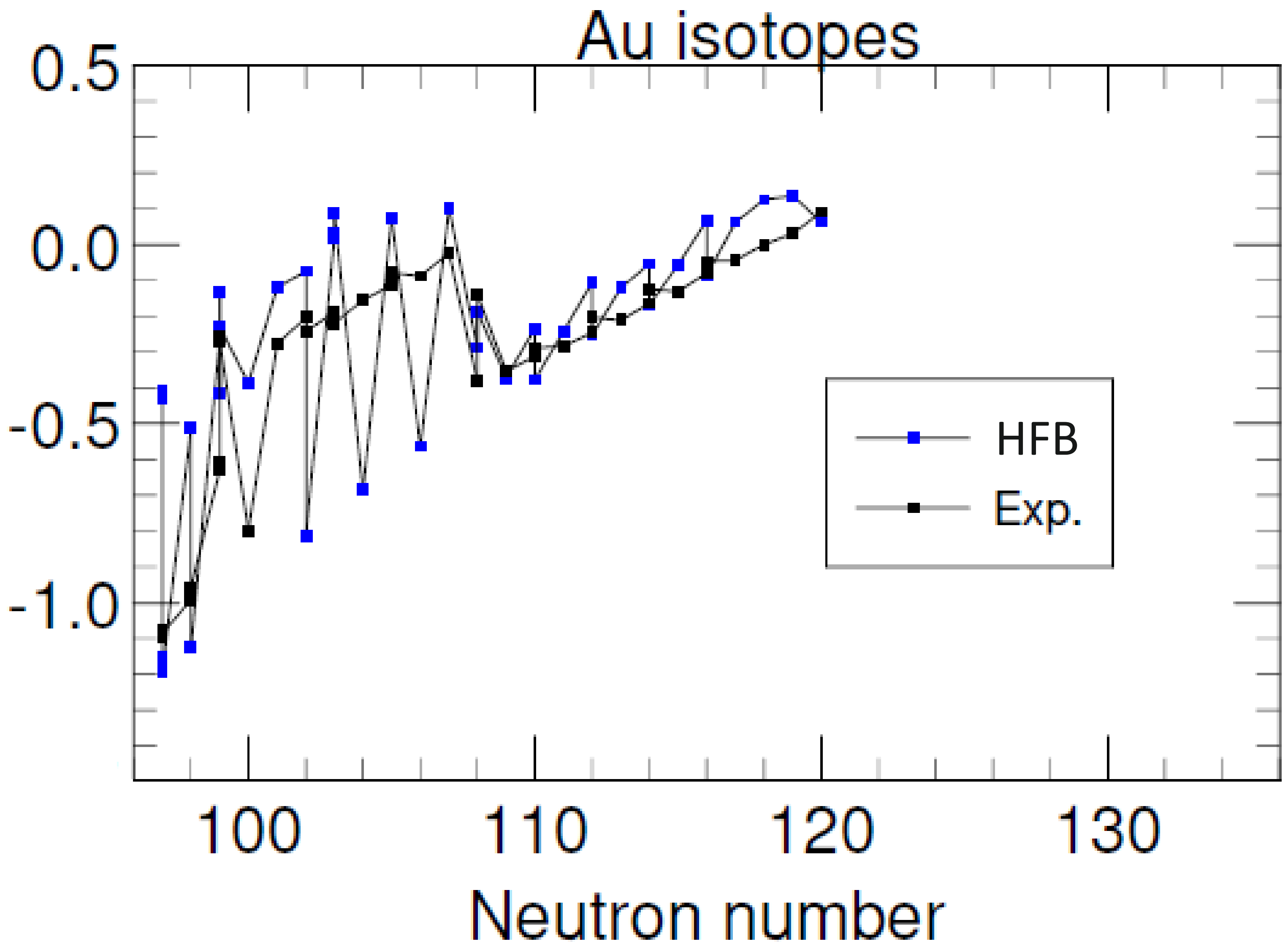
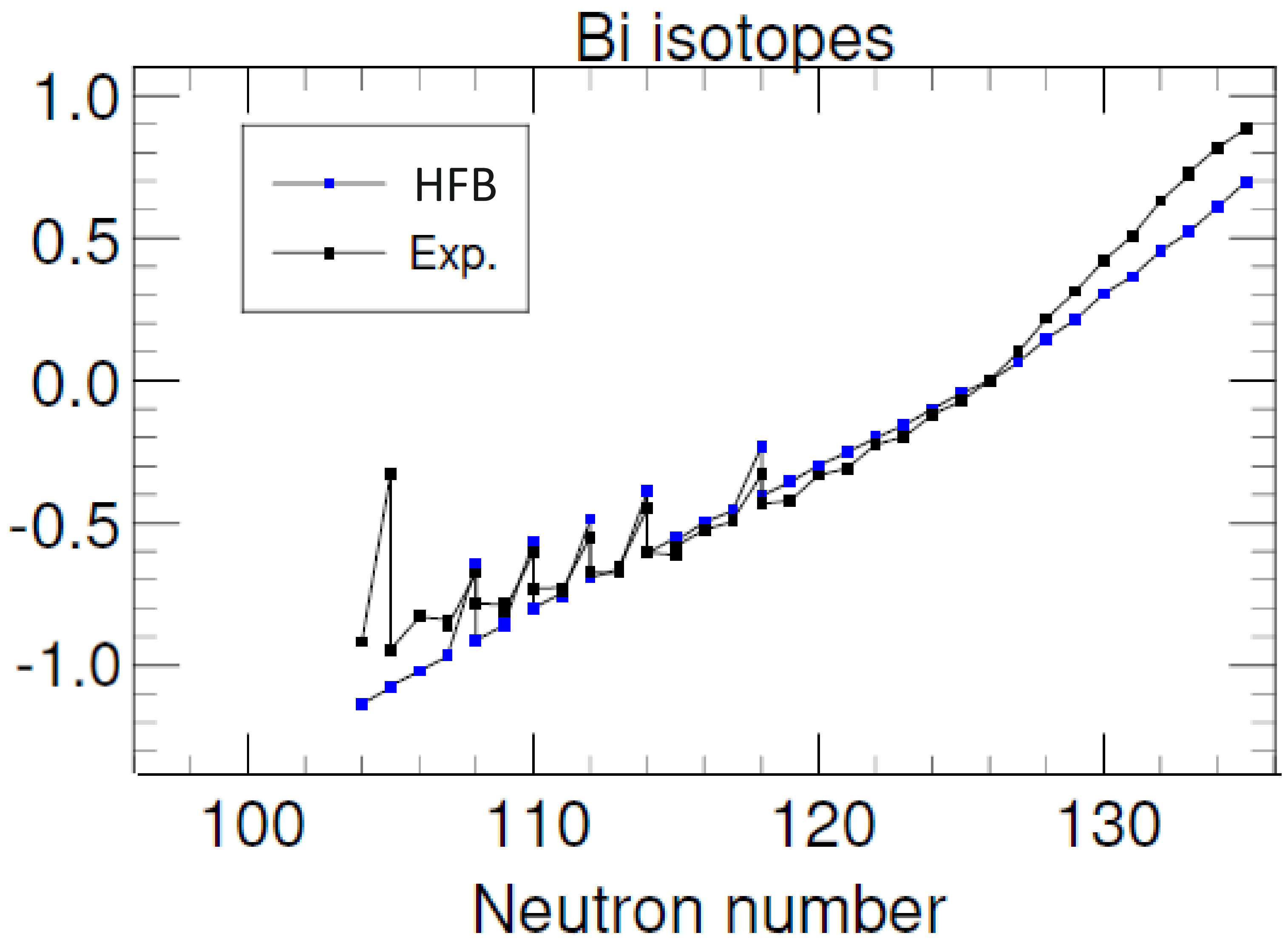
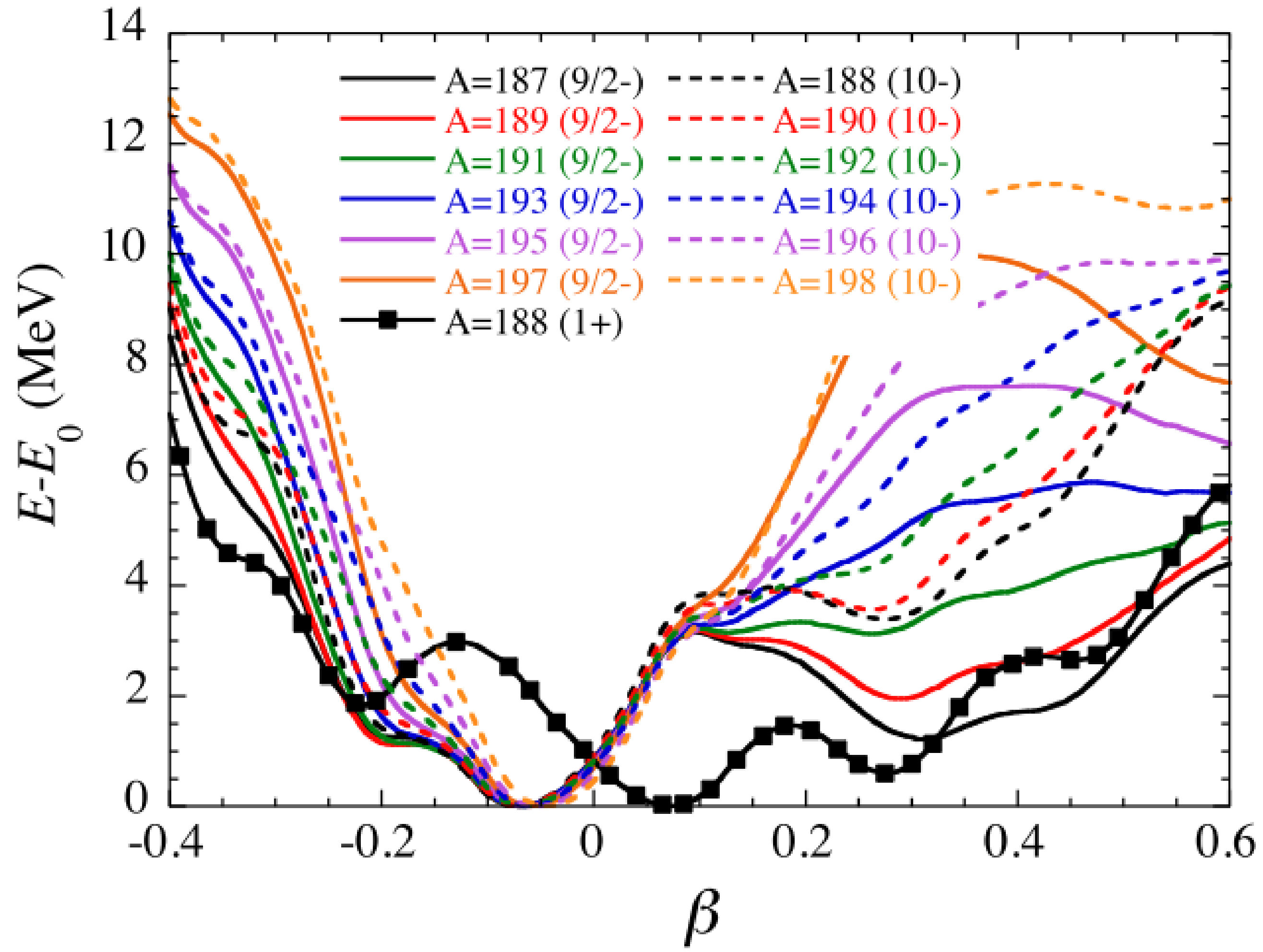
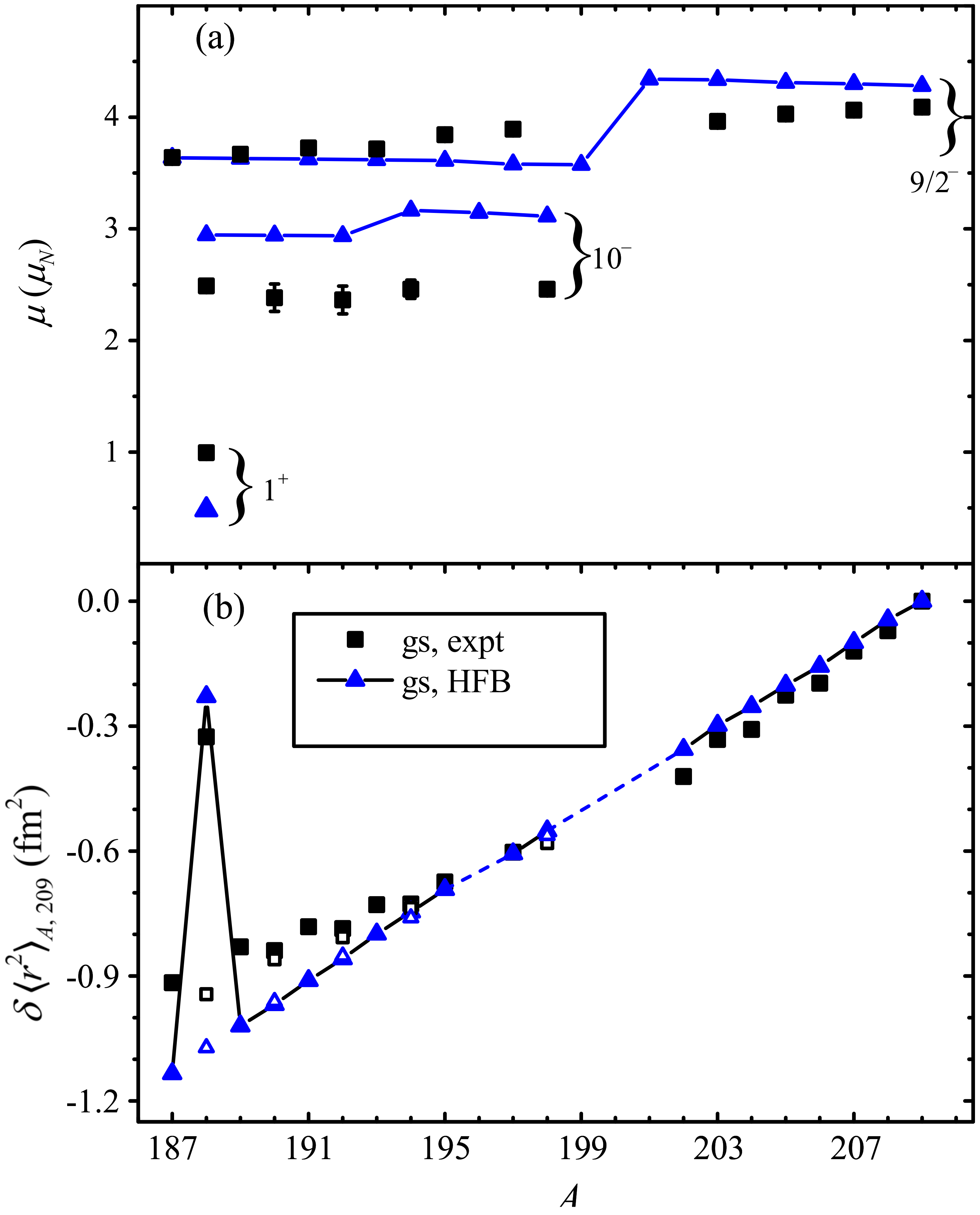




HFB for Bismuth

- HFB using D1M-Gogny. Candidate states were selected by: **Correct I^{π} for PES, agreement with μ, <1 MeV**





A.E. Barzakh *et al.*, PRL **127**, 192501 (2021)
S. Péru *et al.*, PRC **104**, 024328 (2021)

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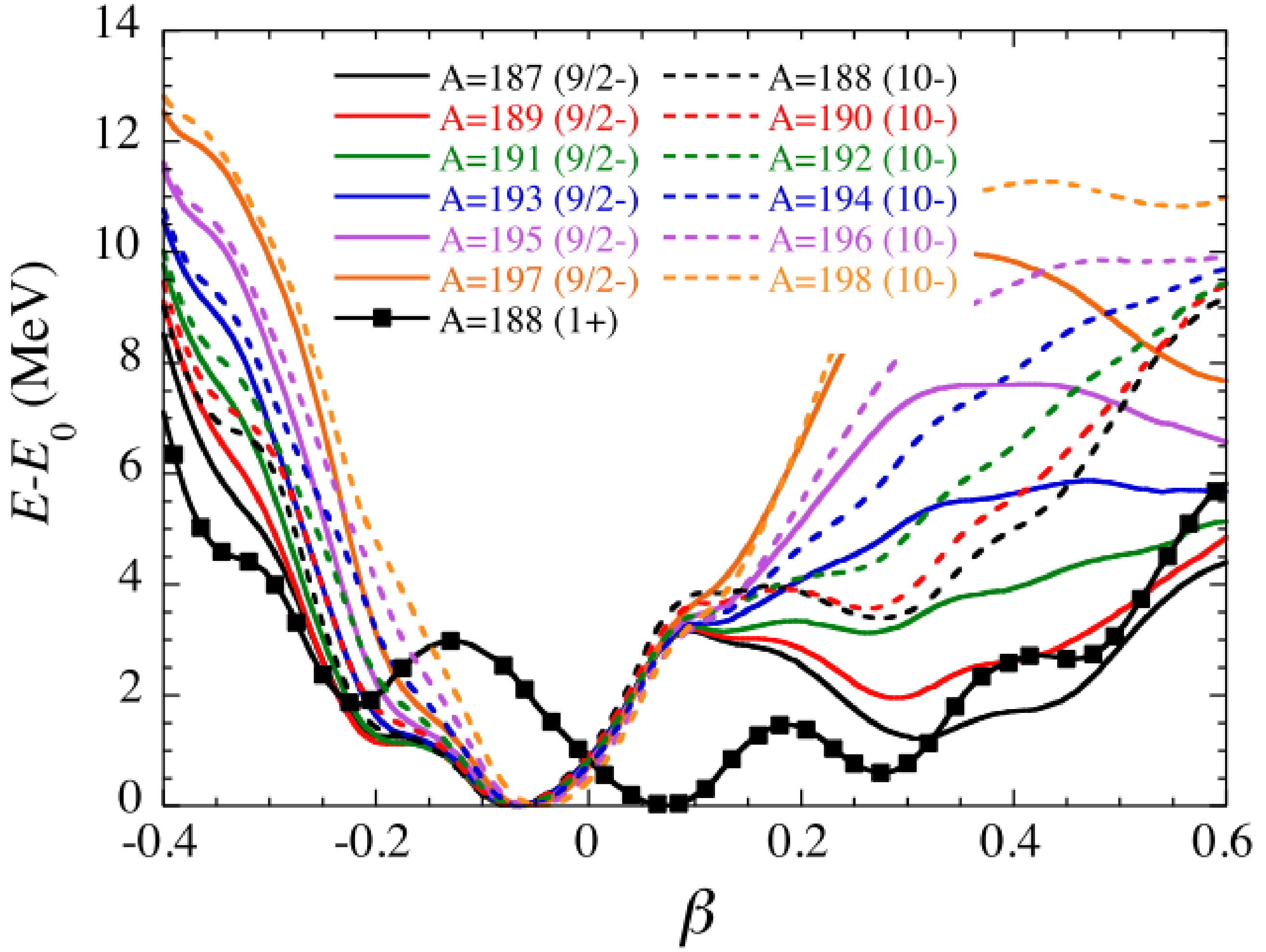
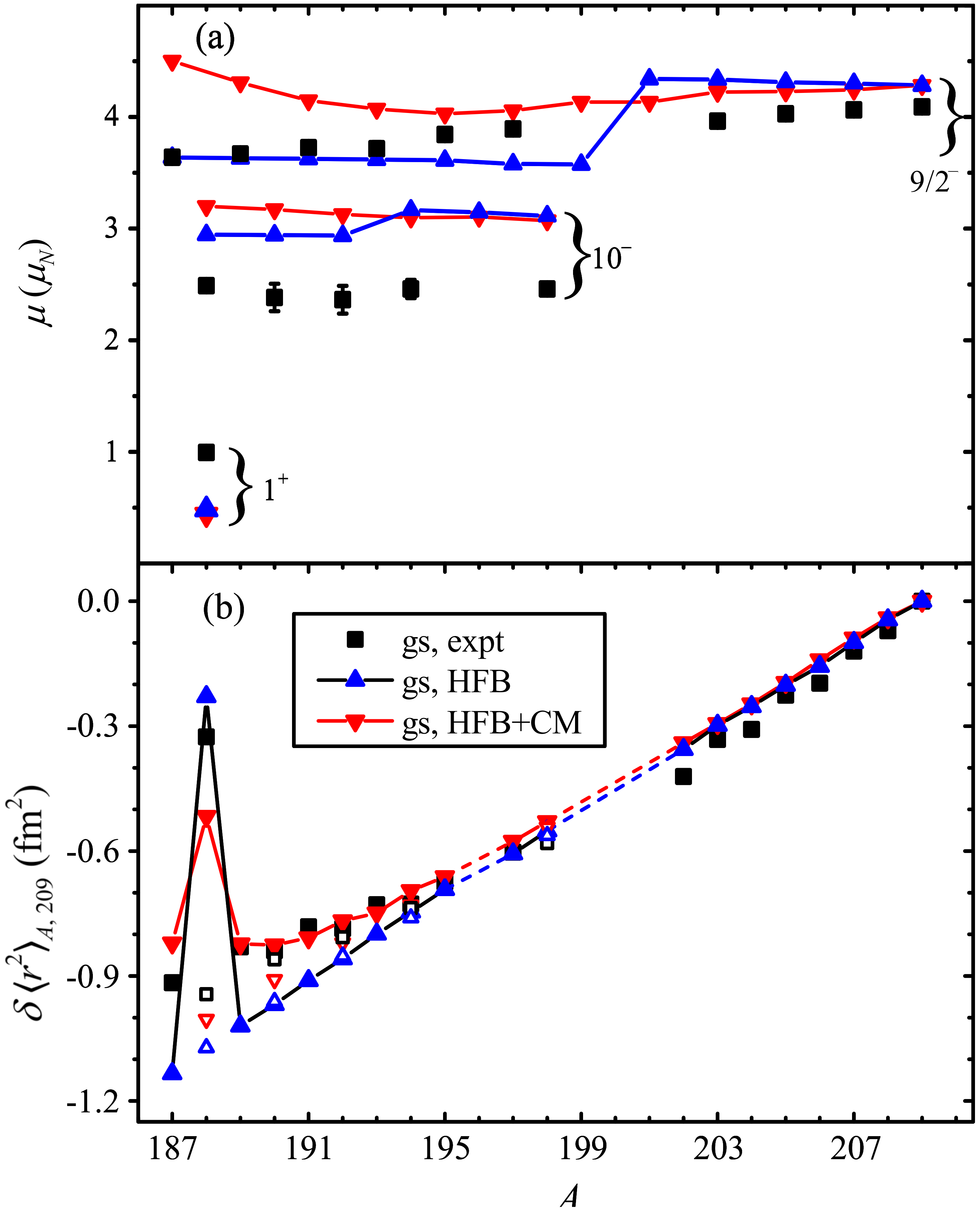
- **Configuration mixing** across deformation surface introduced:

$$\langle \mathcal{O} \rangle = \frac{\int_q \mathcal{O} \exp(-E(q)/T) dq}{\int_q \exp(-E(q)/T) dq}$$

$E(q)$ is HFB energy of PES at deformation q, and T is mixing parameter (0.5 MeV).





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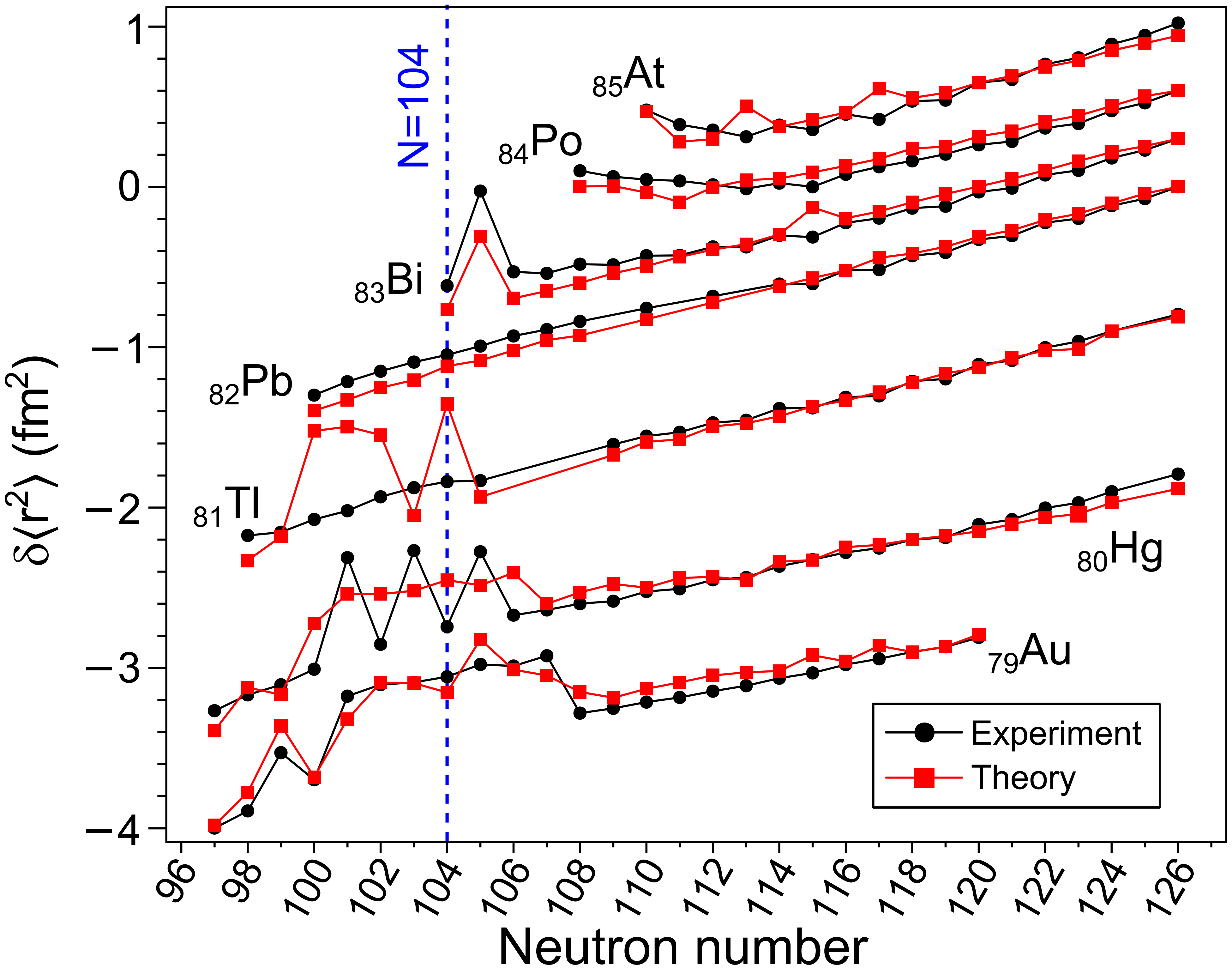
Charge-radii across the lead region, from Au to At (Z=79 to 85)

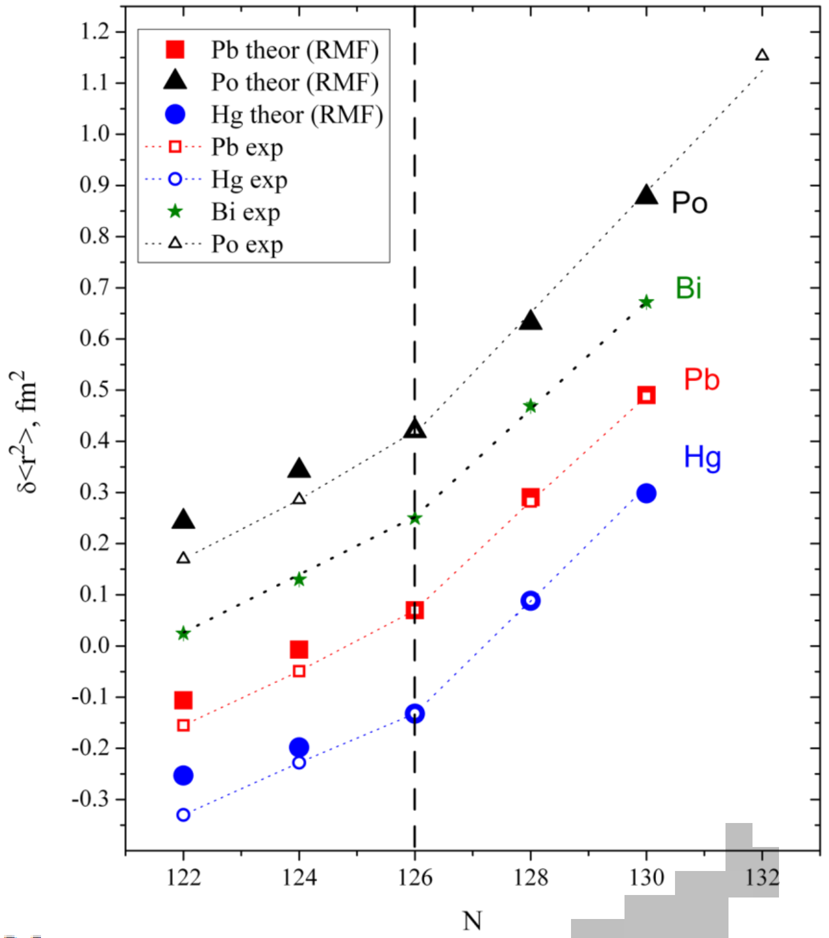
- Try applying same approach to proton-rich ground states of all chains we have measured (Z=79-85, ≈150 isotopes)
- All results here include mixing, using same statistical approach
- Exceptions in Tl and Hg chain:
  - Tl, more deformed state with better match with moment
  - Hg, only reproducible by selecting correct sign of deformation

J. G. Cubiss *et al.*, PRL **131**, 202501 (2023)



Ion sourcery @ ISOLDE

Shell effects crossing N=126



Octupole “region”

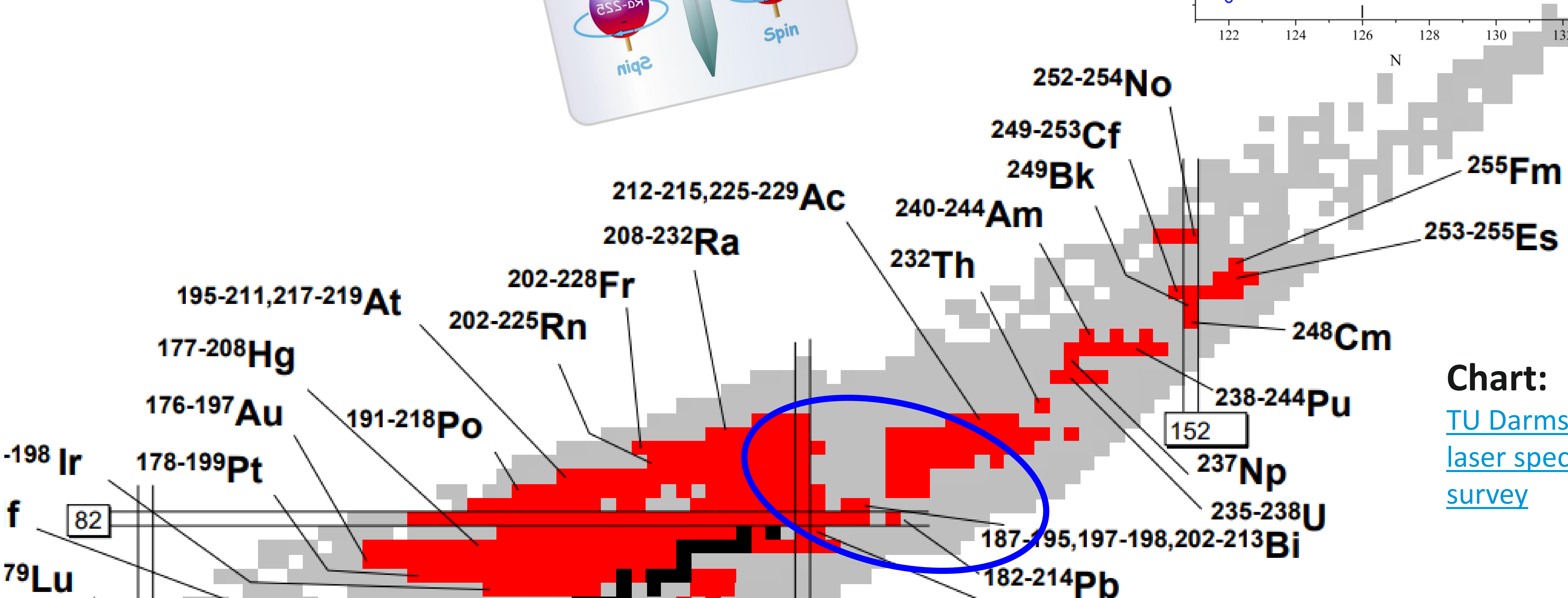


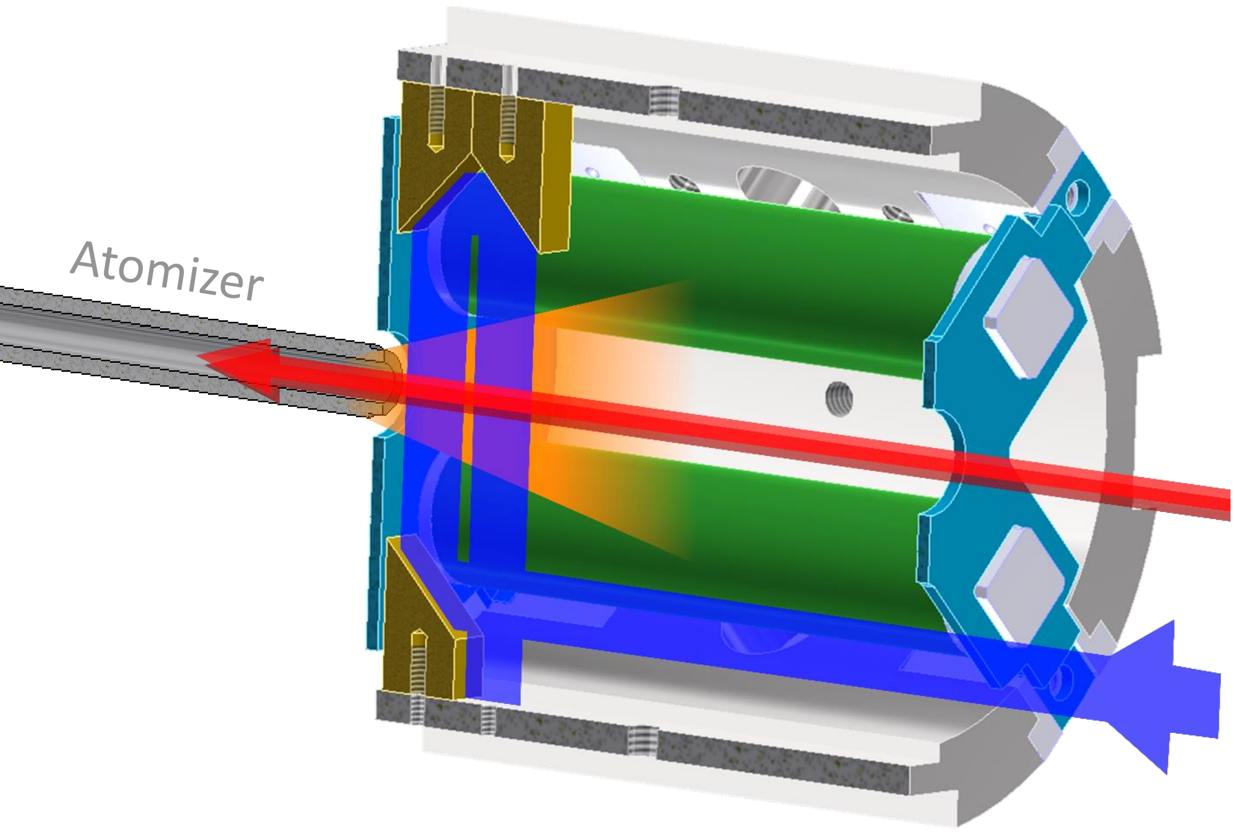
Chart: [TU Darmstadt laser spec. survey]

Ion sourcery @ ISOLDE

Laser Ion Source and Trap (LIST)

R. Heinke *et al.*, *Hyperfine Interactions* **238**, 6 (2017)

- Suppresses prohibitive contamination
- High-res. perp. Illumination mode (100s MHz)



Octupole "region"

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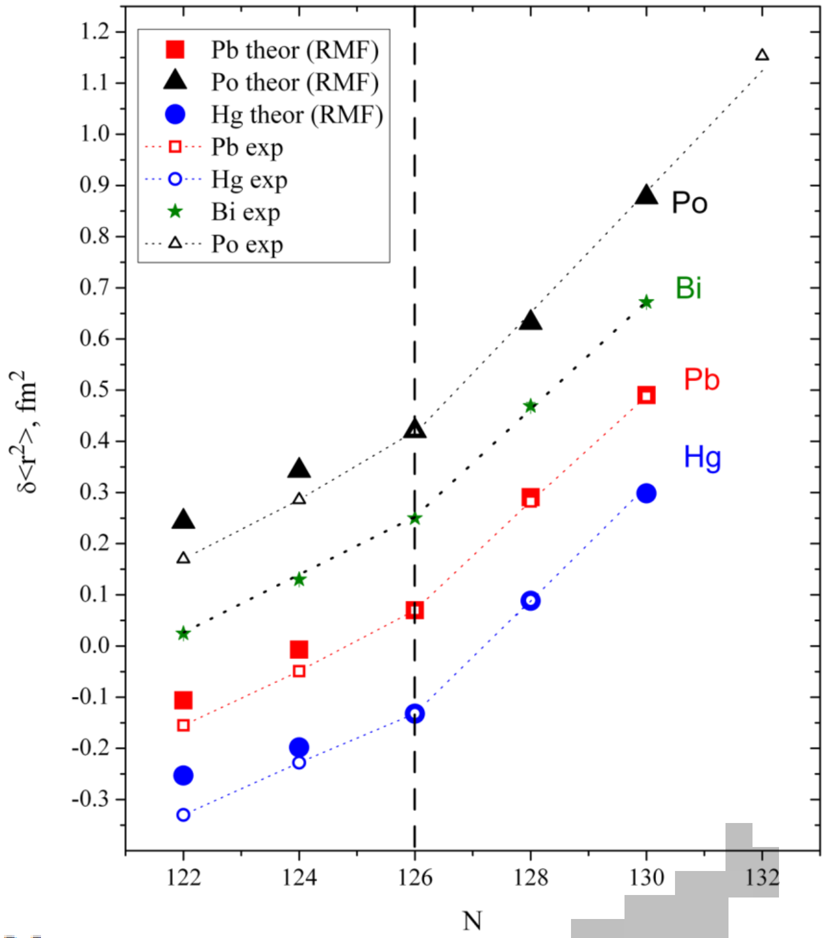


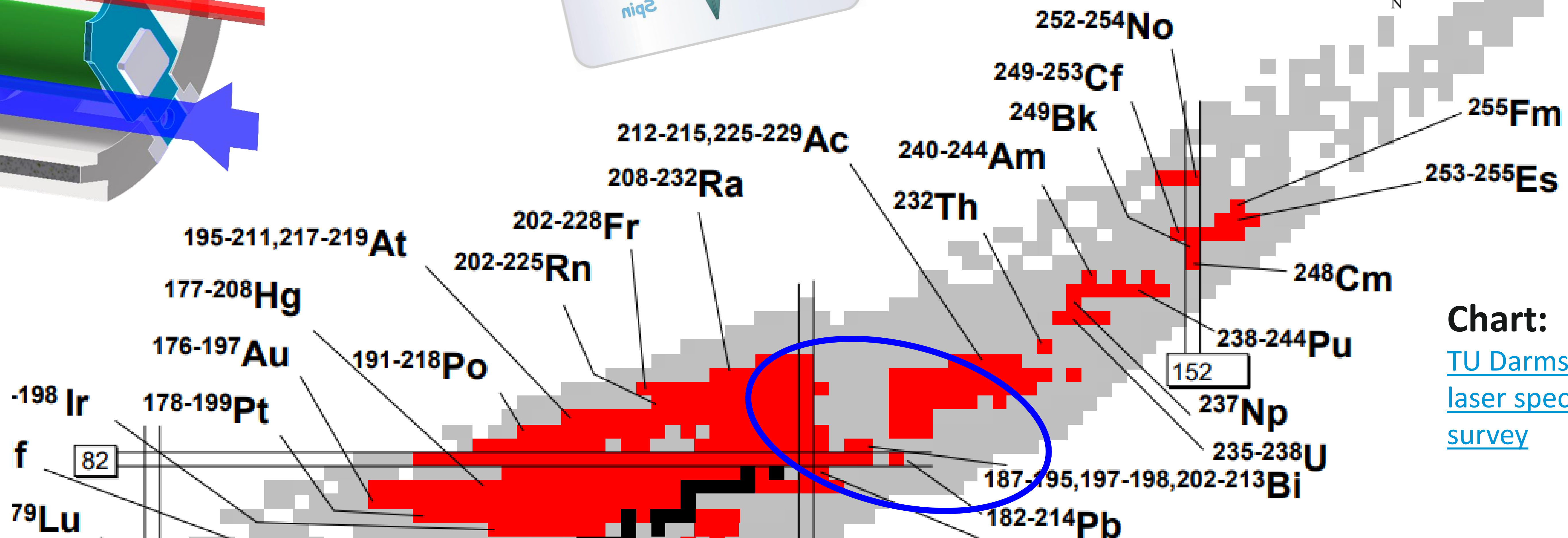
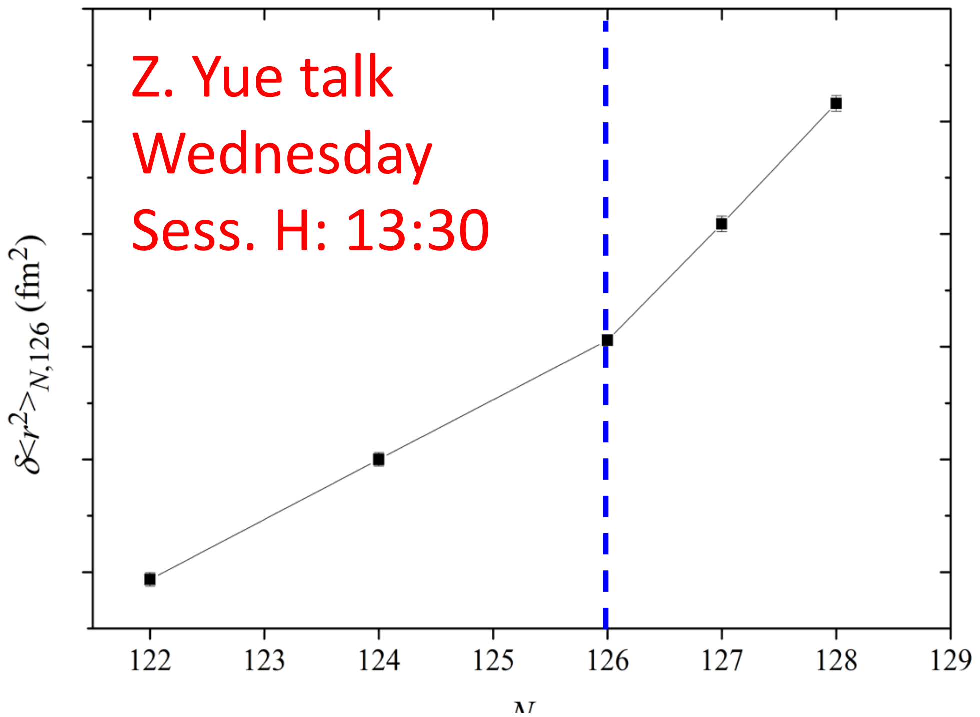


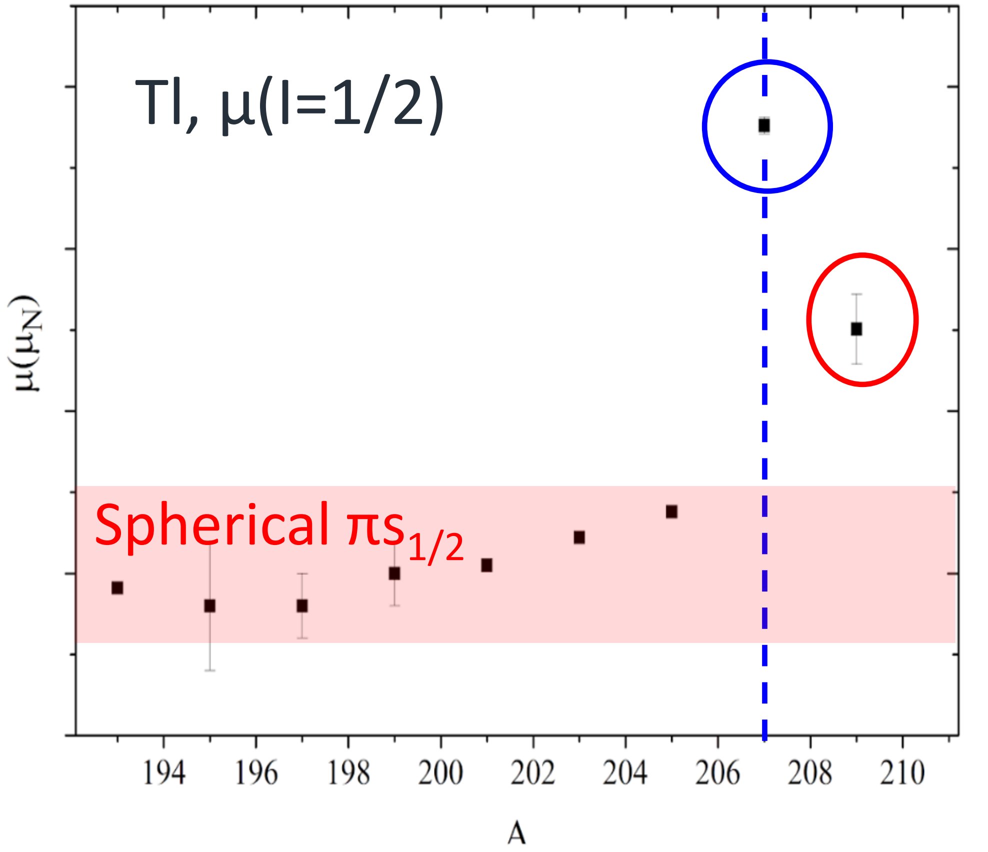
Chart:

[TU Darmstadt laser spec. survey]

The Laser Ion Source and Trap

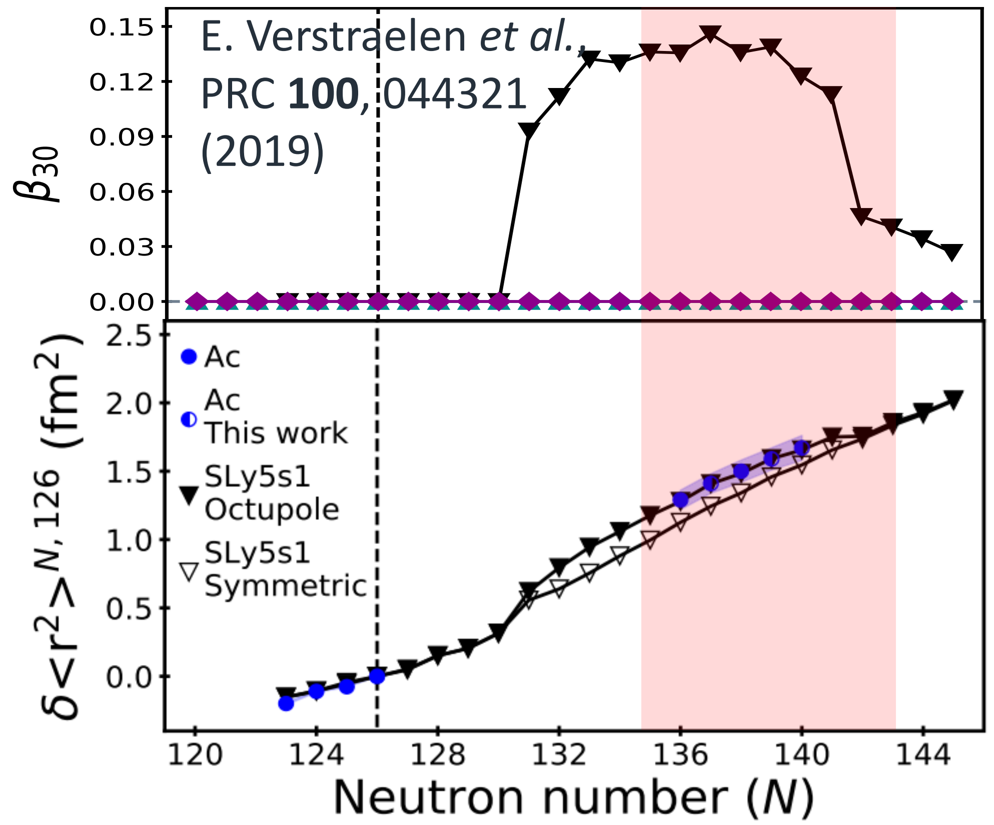
Neutron-rich Tl isotopes

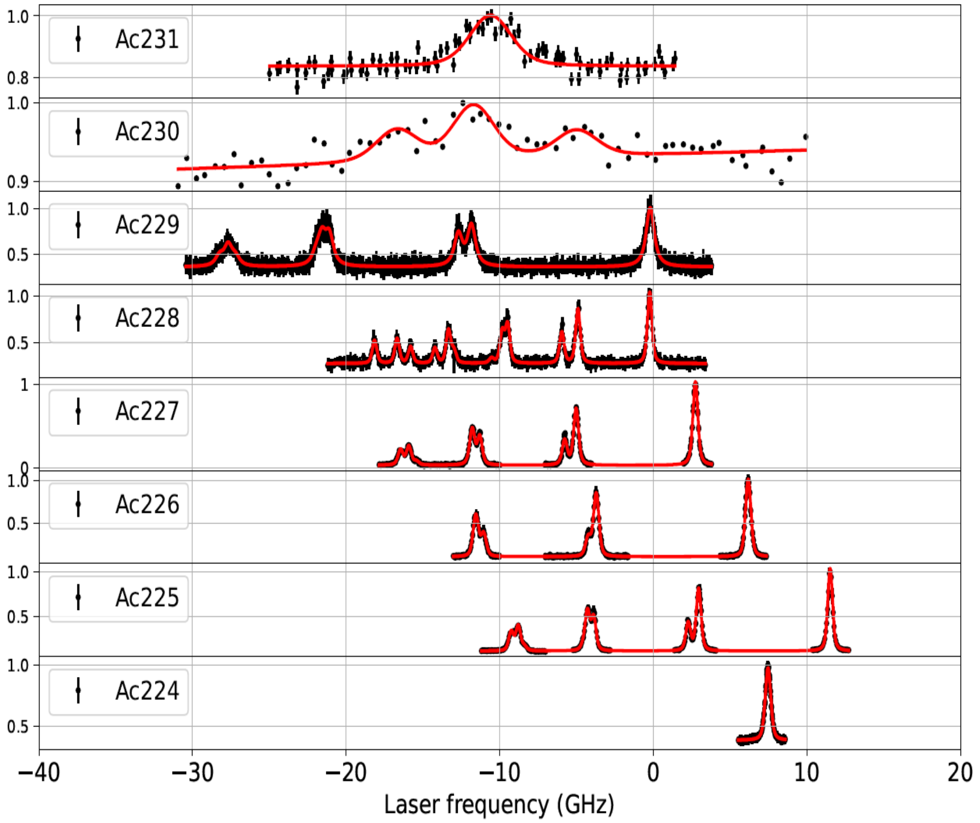




Z. Yue *et al.*, PLB **849**, 138452 (2024)

Neutron-rich Actiniums

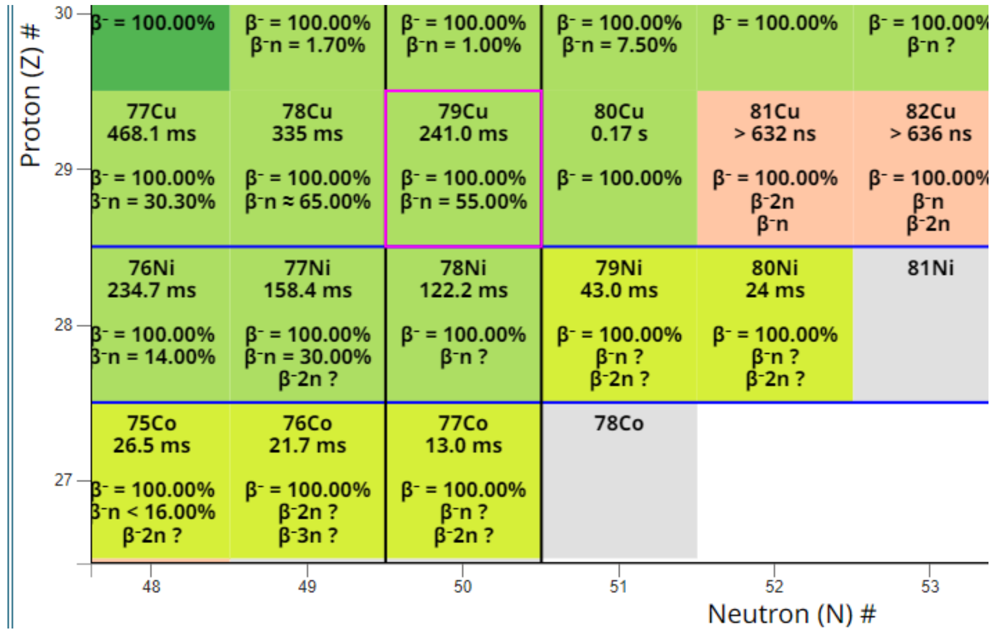




Coming soon:

- Evolution in neutron-rich Hg
- Probing the "kink" in neutron-rich Bi with high-spin isomers

- Laser spec. of ^{79,80}Cu



Summary

- Wide ranging campaign of ground and isomeric state property studies across the Pb region

- **“Global” models do well across the region**
  - Magnetic moments powerful selection tool
  - Functionals need further development

- **Laser Ion Source and Trap (LIST):**
  - Opens access to new regions of chart
  - Perp. Illum. mode brings in-source into precision regime

- **Still much to learn and plenty of fun to be had along the way ☺!**

Summary

- Wide ranging campaign of ground and isomeric state property studies across the Pb region

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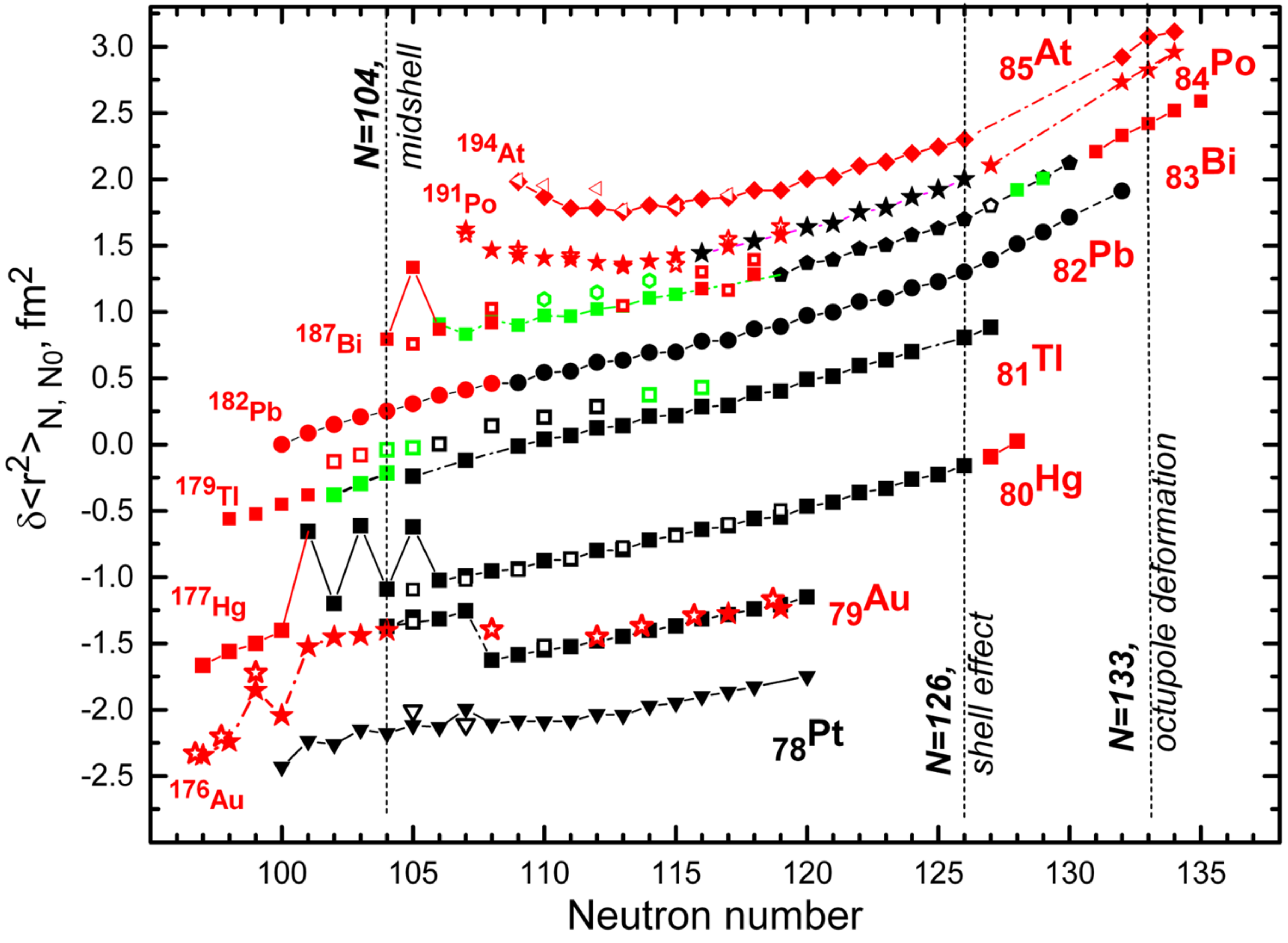


Red data = our data from ISOLDE

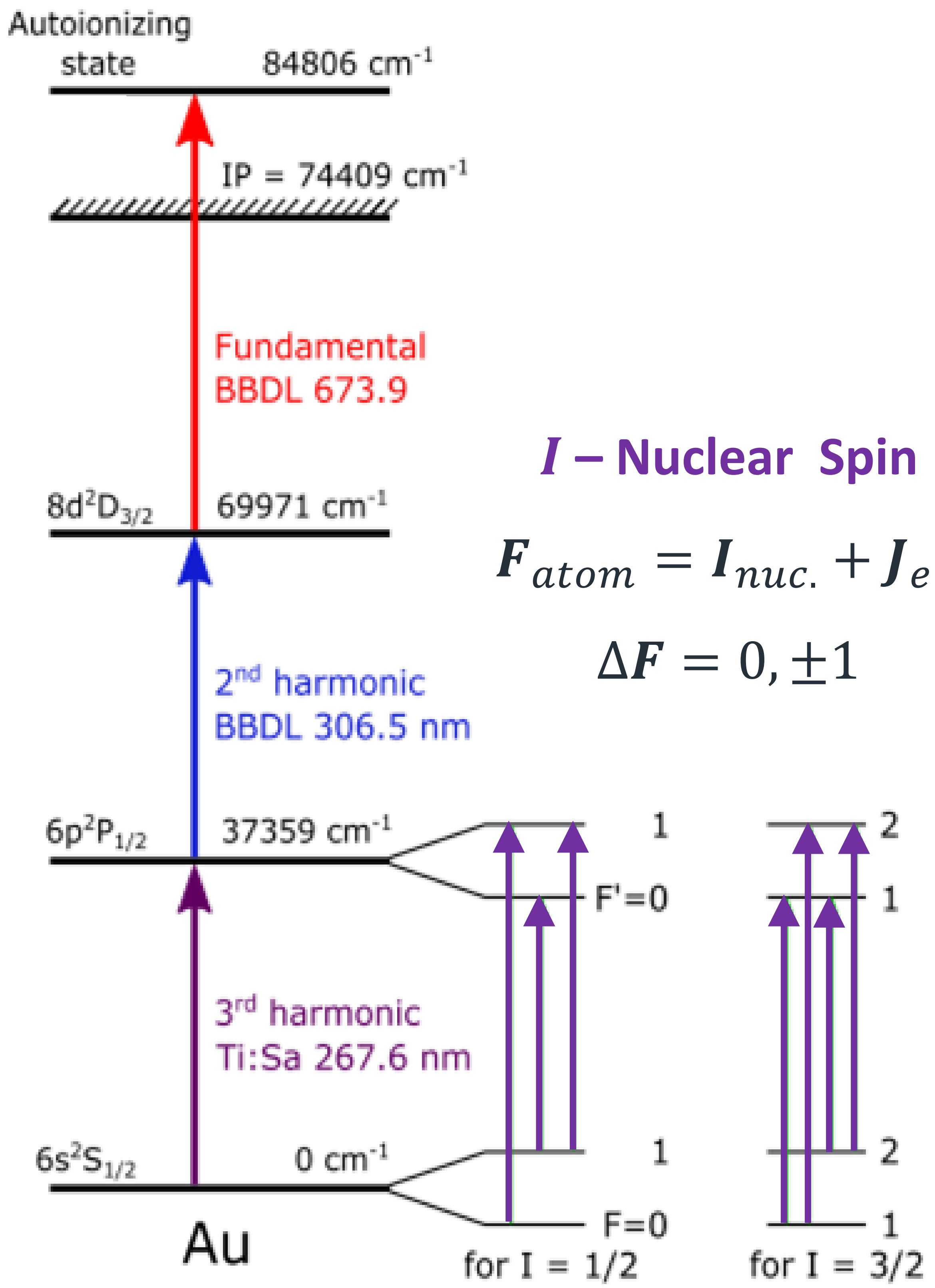
Green points = Gatchina

Black points = literature

Thank you for listening

Additional slides

Basic laser spec.



***I* – Nuclear Spin**

$$\boldsymbol{F}_{atom} = \boldsymbol{I}_{nuc.} + \boldsymbol{J}_{e^-}$$

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

Isotope or isomer shift:

$$\delta\nu^{A,A`} = M_i \frac{A' - A}{AA'} + F_i\, \delta\langle r^2\rangle^{A,A'}$$

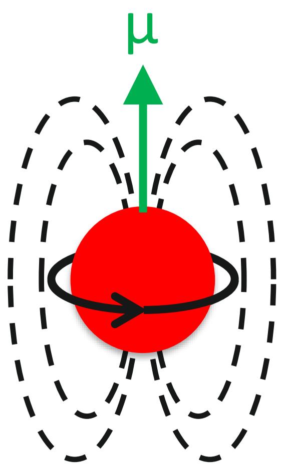
Mass shift — Field shift

$\delta\langle r^2\rangle^{A,A'}$ – mean-squared charge radius

Radial extent of proton wavefunction

Hyperfine structure:

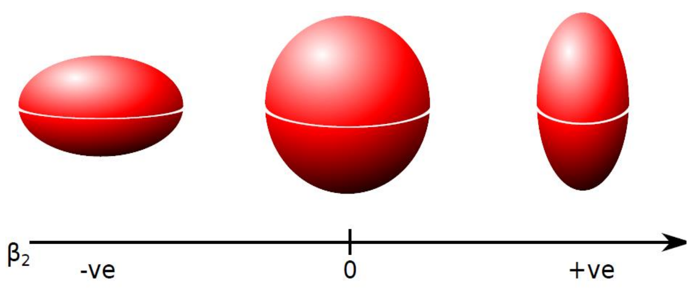
$$\Delta \mathrm{E_{hfs}} = A\frac{K}{2} + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I\cdot J} + \cdots$$



μ – mag. dipole moment

Config. of unpaired nucleons

$$A = \frac{\mu B_e(0)}{I\cdot J}$$



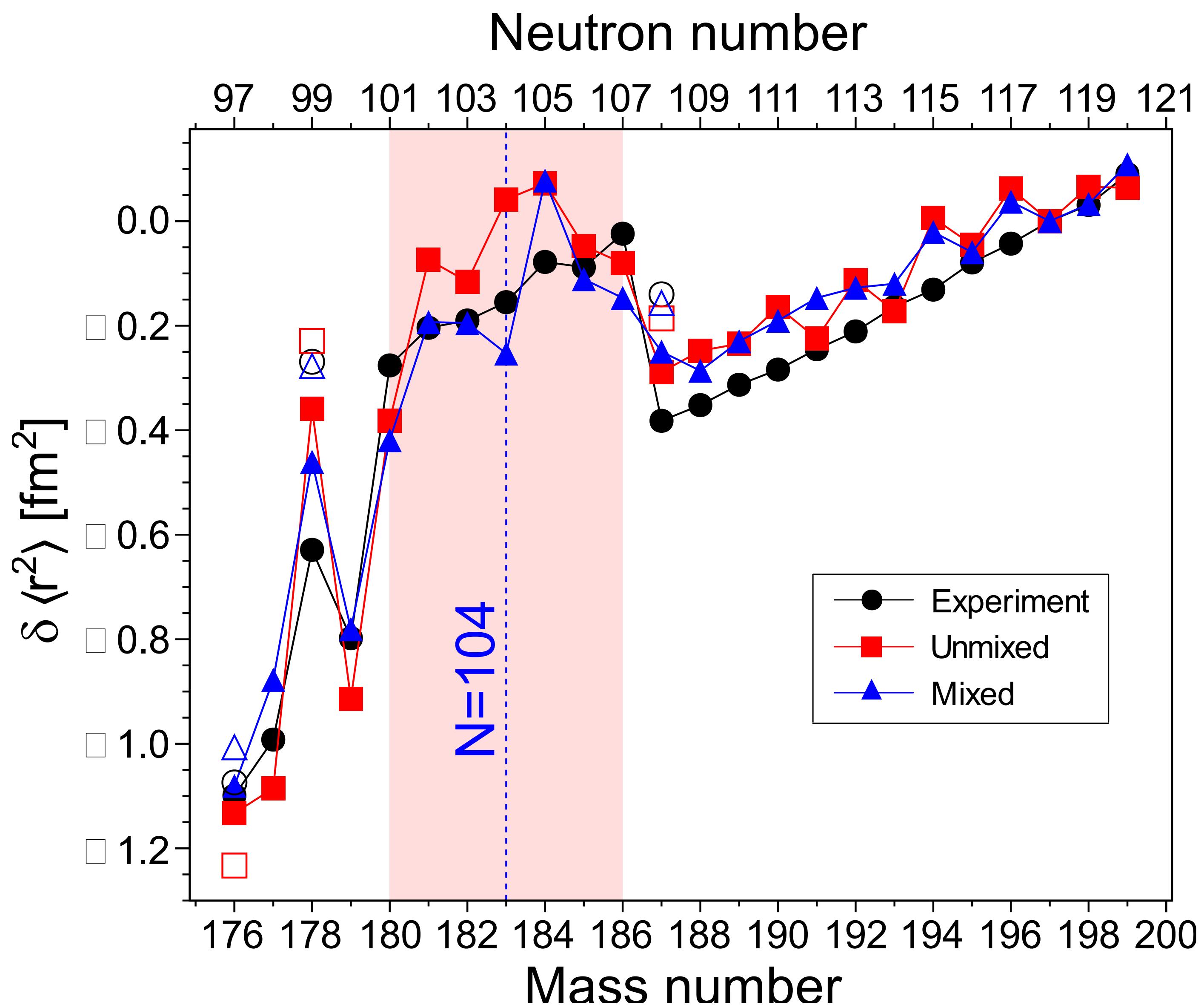
Q – electric quad. moment

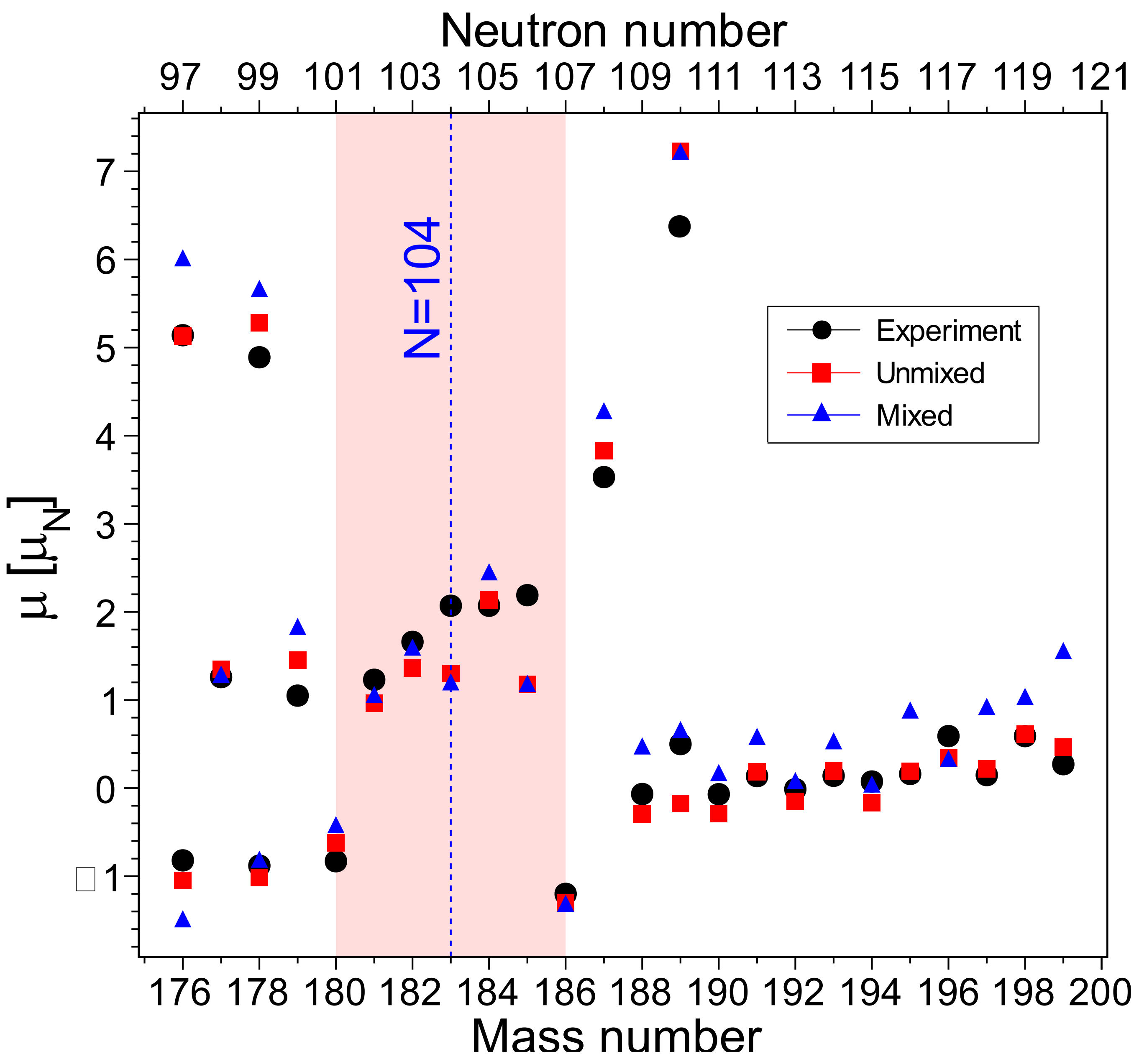
Probes shape of the nucleus

$$B = eQ\left\langle \frac{\delta^2 V}{\delta z^2}\right\rangle$$

HFB for Au isotopes

- Try applying same approach as used in Bi isotopes both for **unmixed** and **mixed** cases
  States selected by spin, and dipole moment



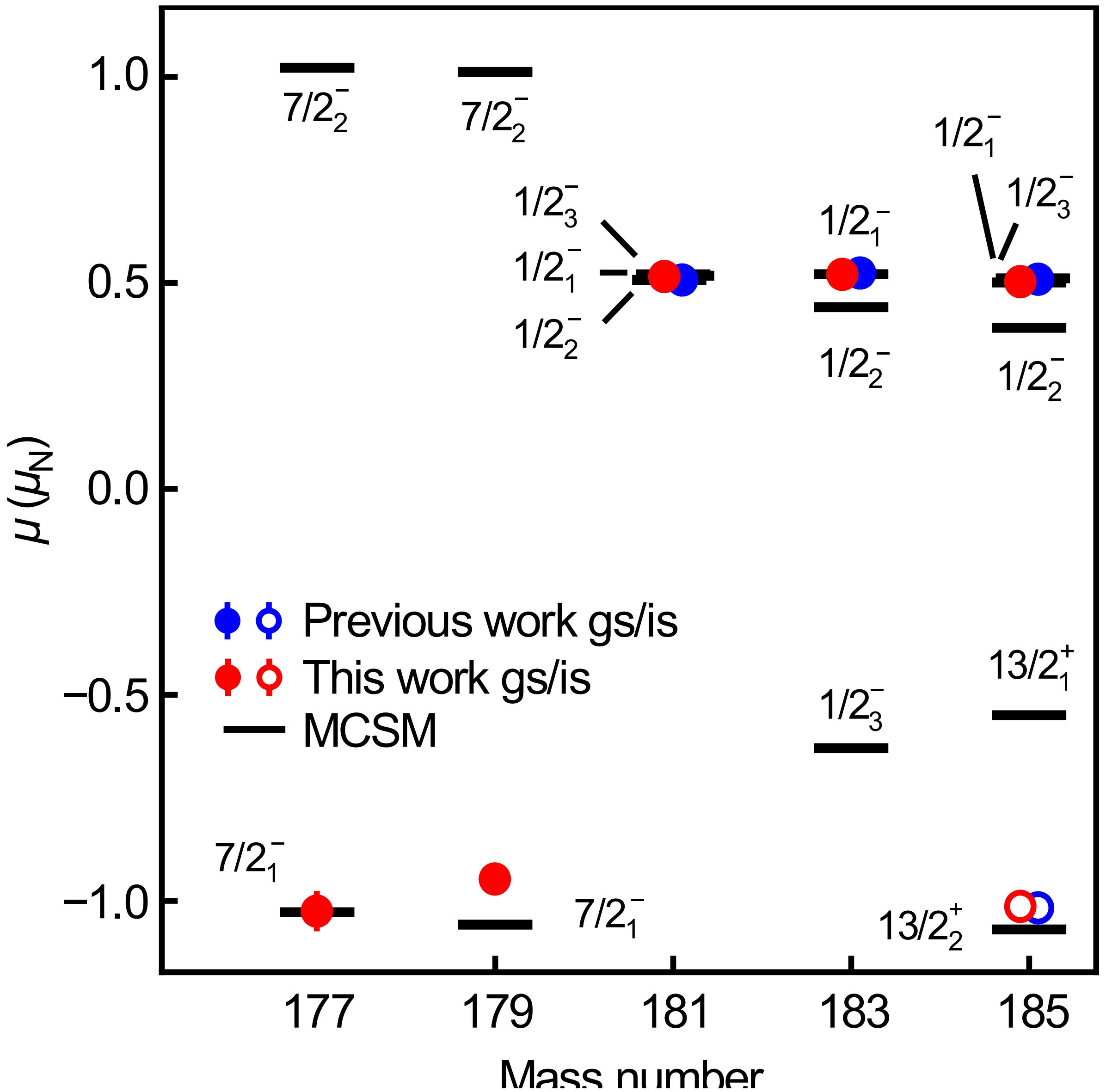


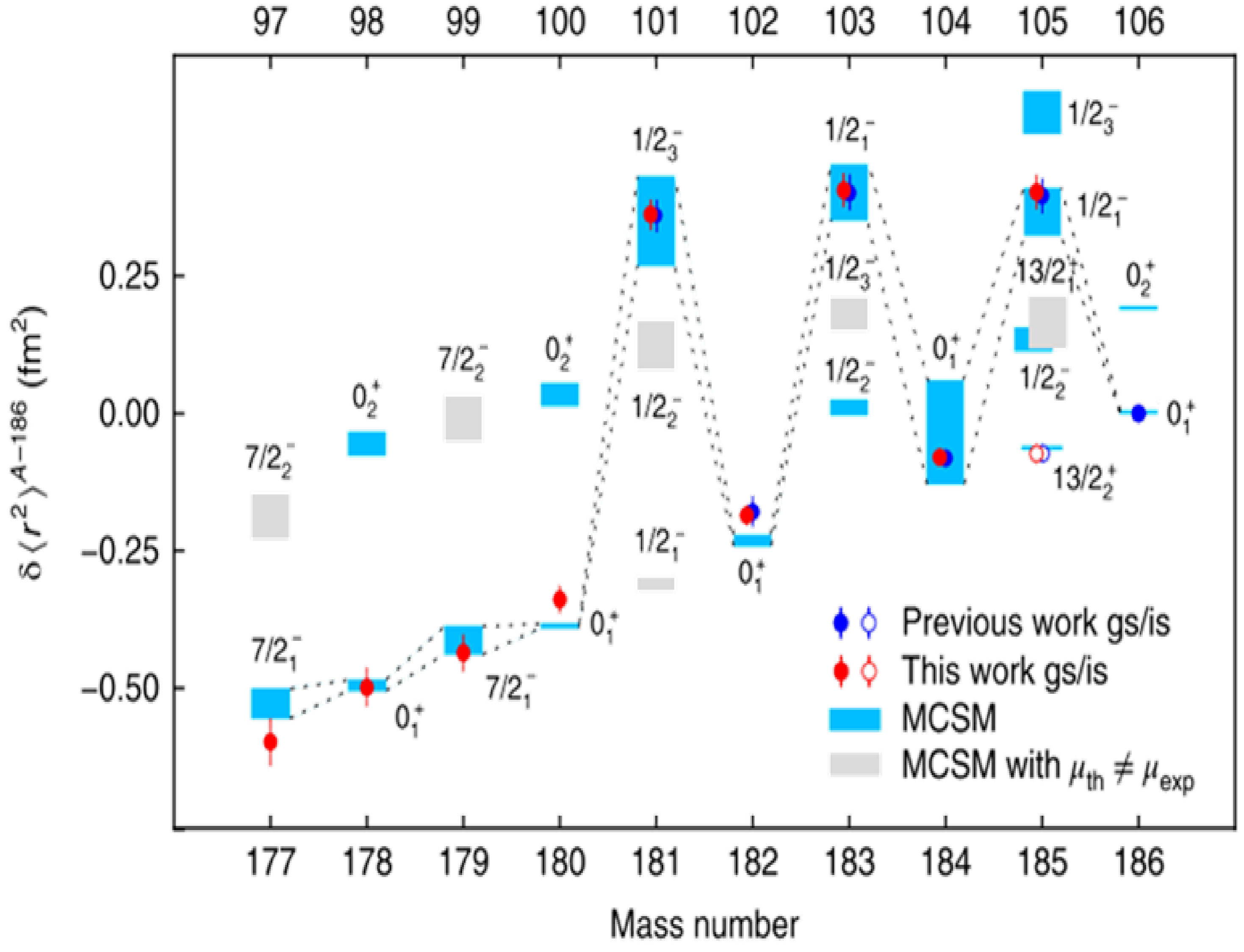
- A good agreement with experiment is seen
- Inclusion of mixing gives comparable results

MCSM description of Hg

- Largest calculation of its kind at the time:
  ^{132}Sn core - **30π**, $1g_{7/2}$ to $1i_{13/2}$,
  24ν, $1h_{9/2}$ to $1j_{15/2}$
  Avoids diagonalization of >10^{42} dimensional H matrix

- Only possible using magnetic dipole moments





B.A. Marsh *et al.*, Nature Physics **14**, 1163-1167 (2018)
S. Sels *et al.*, PRC **99**, 044306 (2019)

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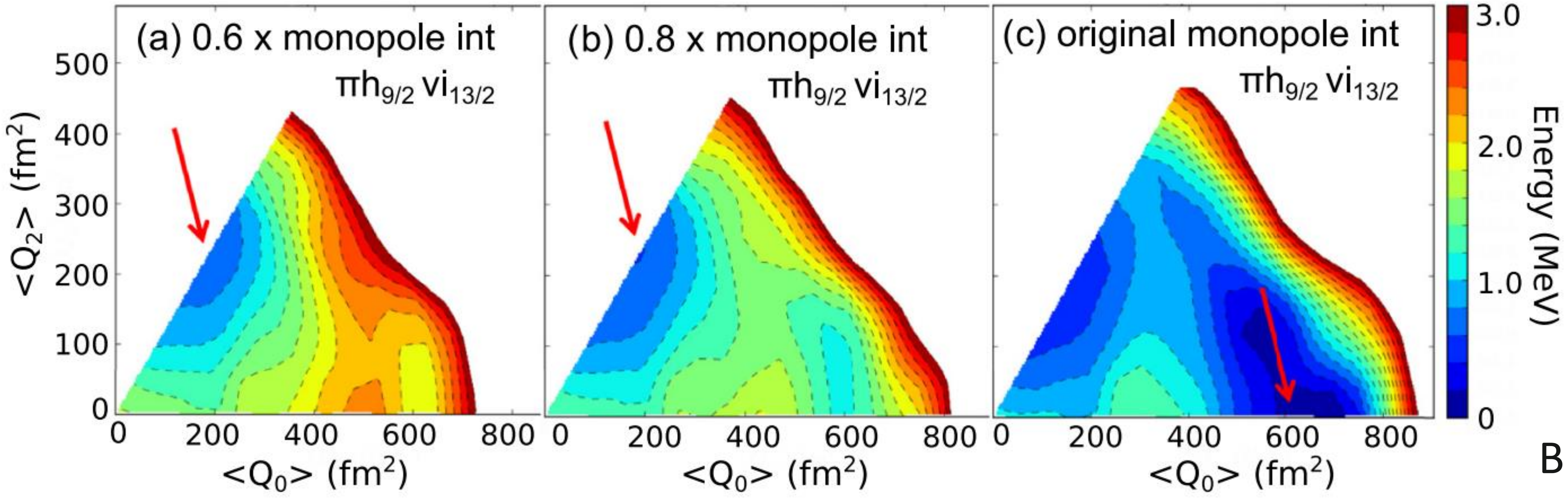
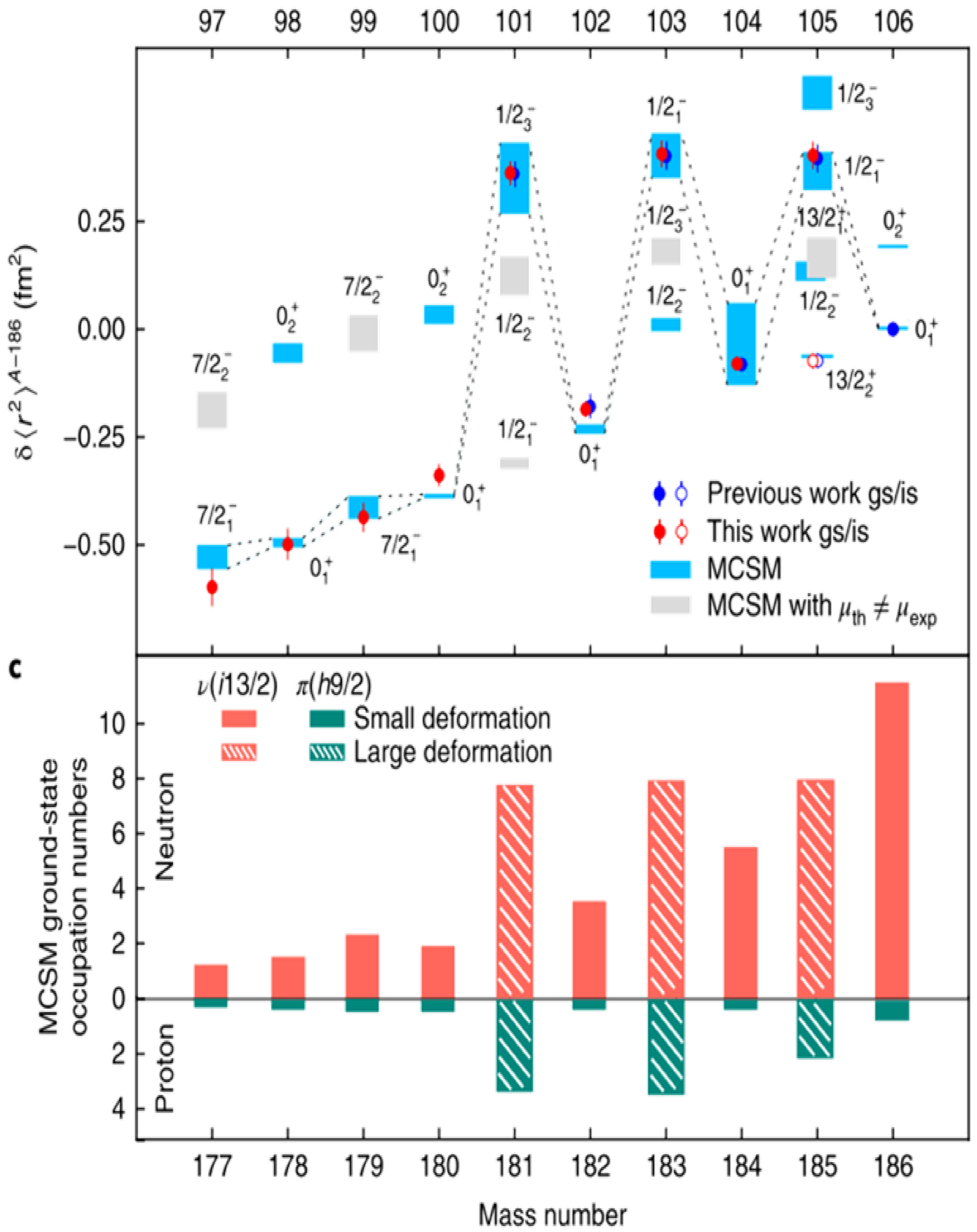
- Only possible using magnetic dipole moments

- Large sensitivity to monopole interaction between:
  >2 protons in $\pi h_{9/2}$ intruder state
  Large occupation of $\nu i_{13/2}$





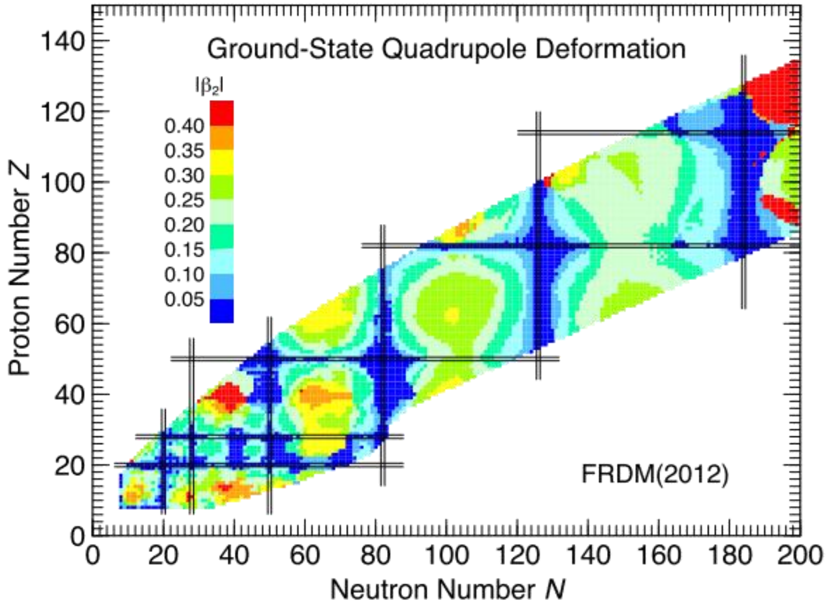
B.A. Marsh *et al.*, Nature Physics **14**, 1163-1167 (2018)
S. Sels *et al.*, PRC **99**, 044306 (2019)

Nuclear shape coexistence

- Shell closures -> Spherical
  Open shells -> Deformed shapes

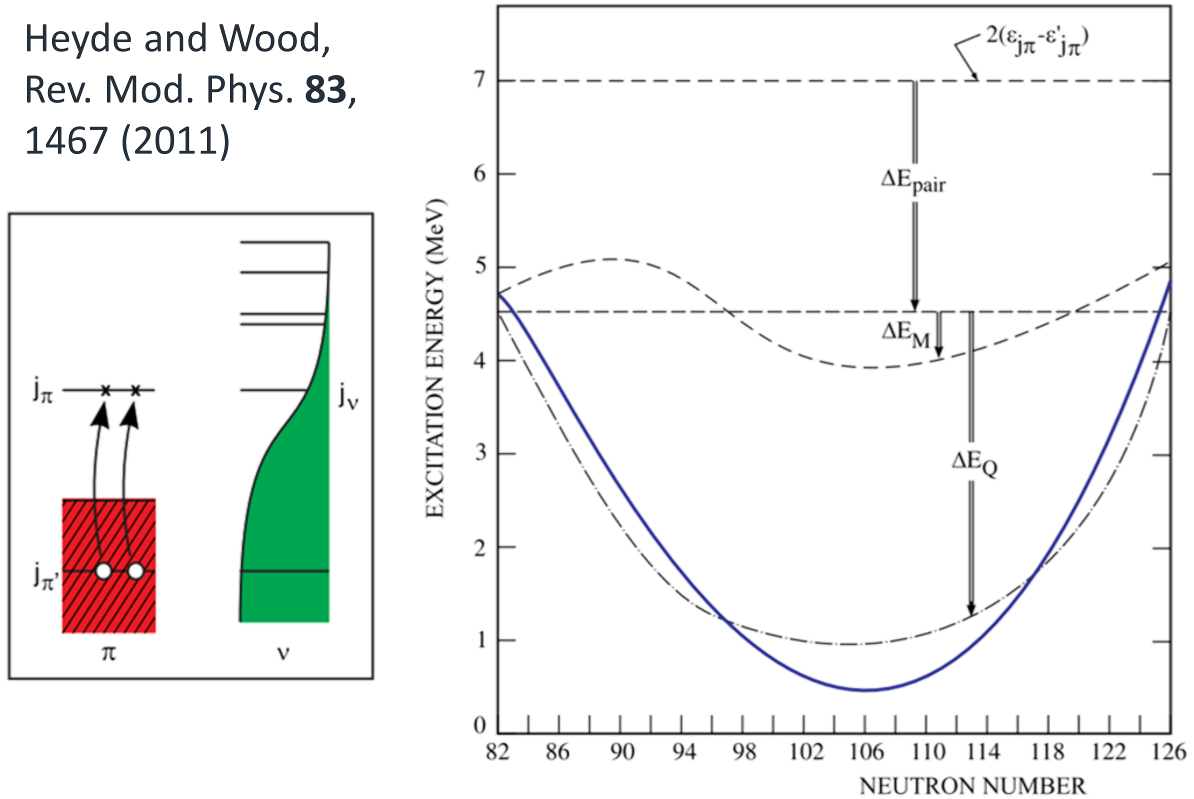
- Open-closed shell region?
  Shape coexistence: States with different deformations, within the same nucleus

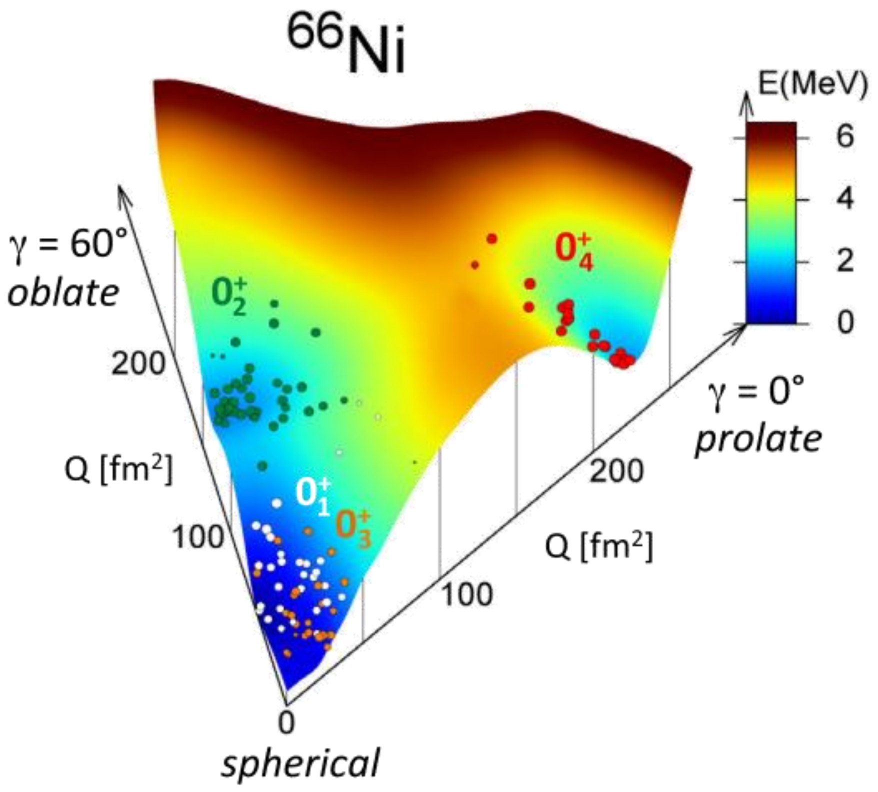
- “Classical” description particle-hole excitations across shell gaps, populating “intruder” states - energies of which reduced by residual interactions between nucleons



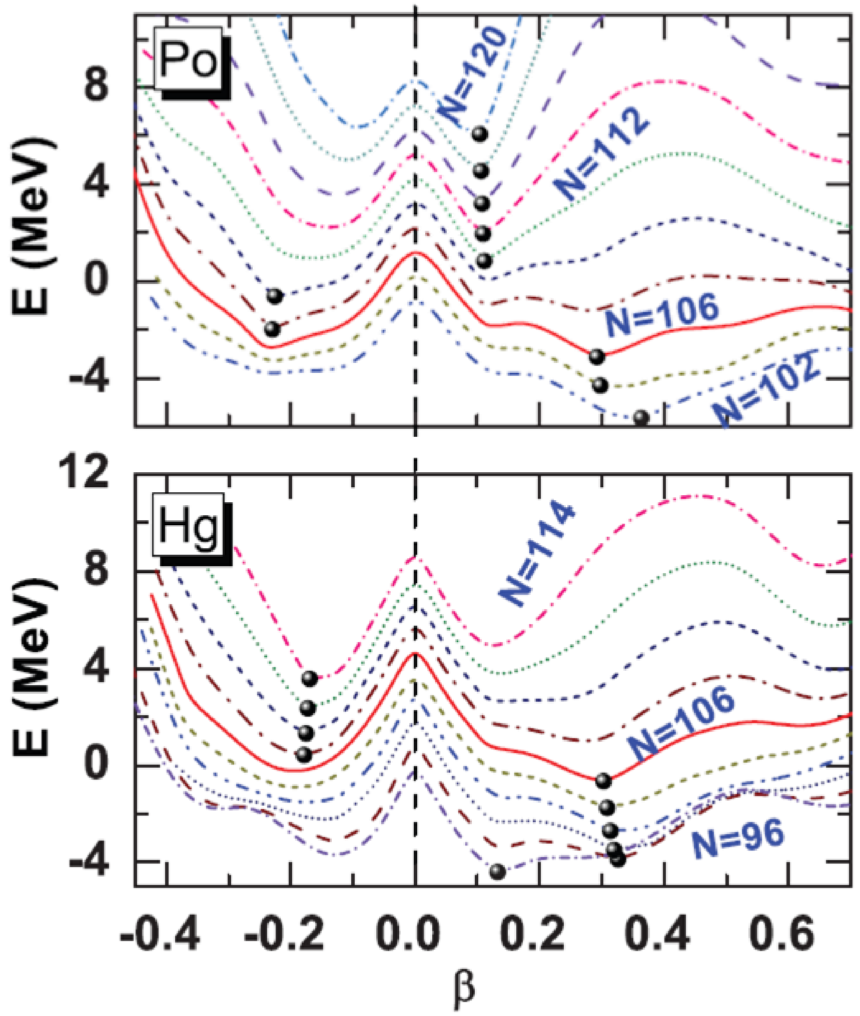
Moller *et al.*, Atom. Data Nucl. Data **109-110**, (2016)

Heyde and Wood, Rev. Mod. Phys. **83**, 1467 (2011)



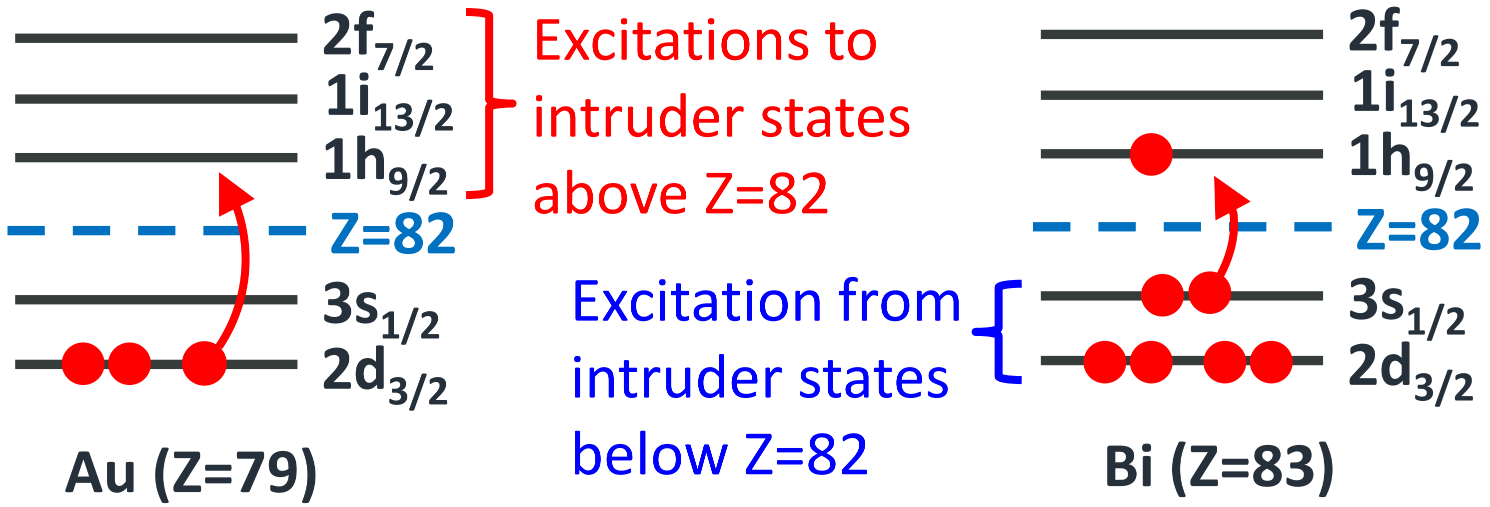


S. Leoni *et al.*, PRL **118**, 162502 (2017)



Yao, Bender & Heenen, PRC **87**, 034322 (2013)

Intruders in the Pb region:



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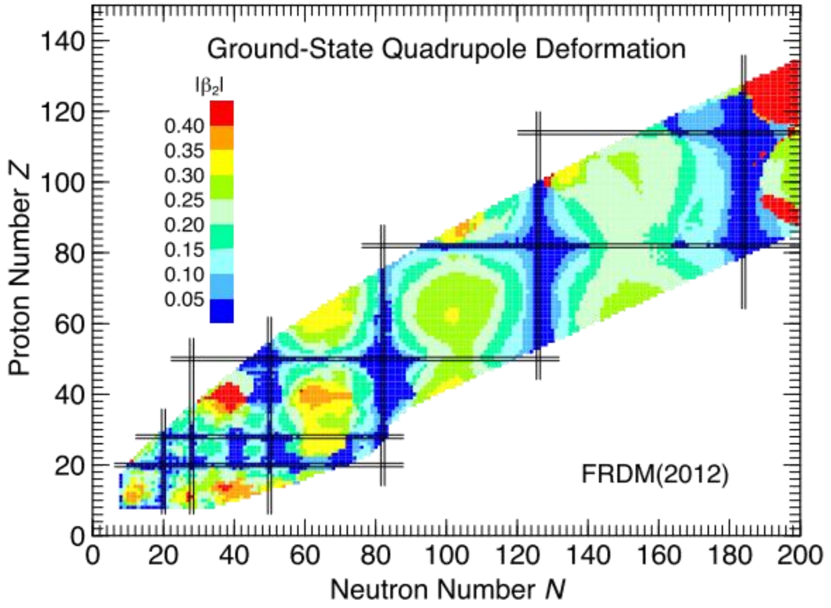

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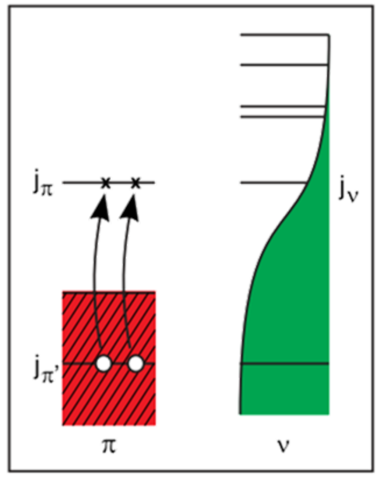
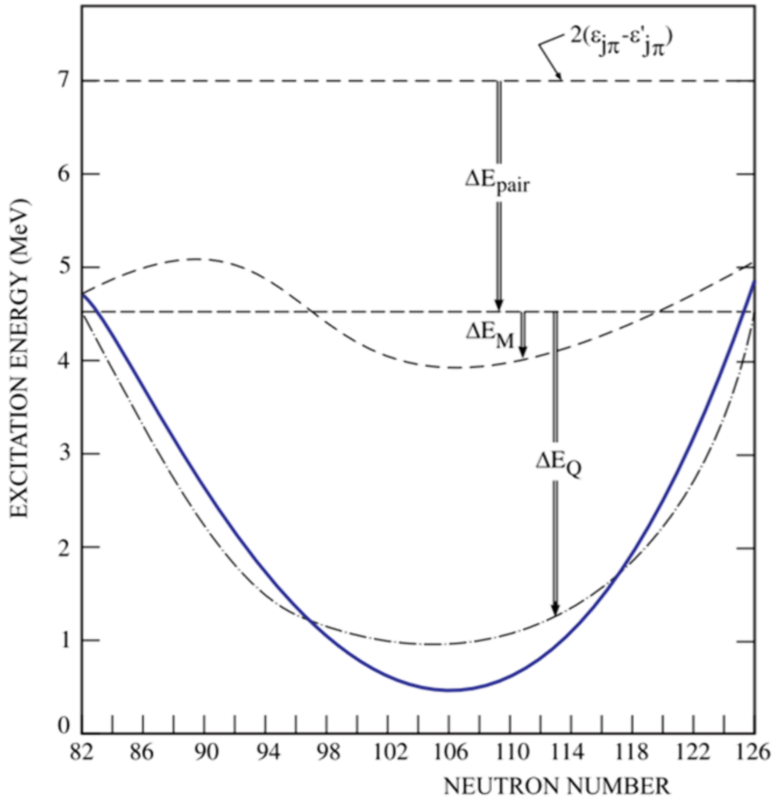
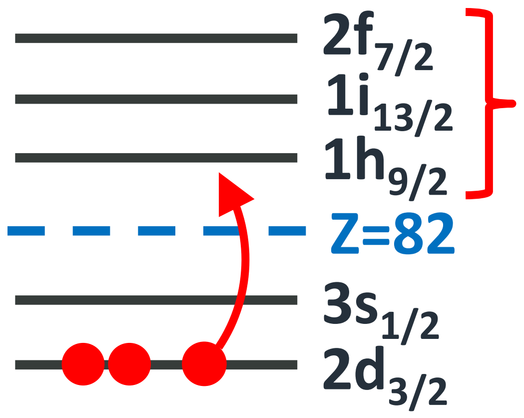


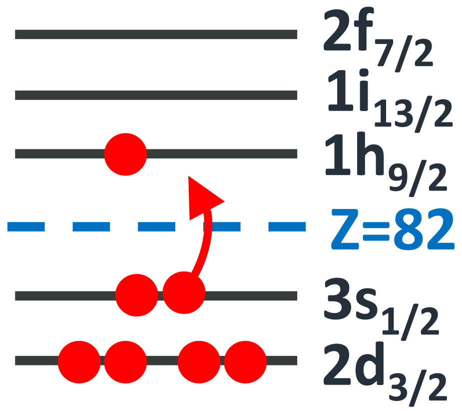


Intruders in the Pb region:



Excitations to intruder states above Z=82

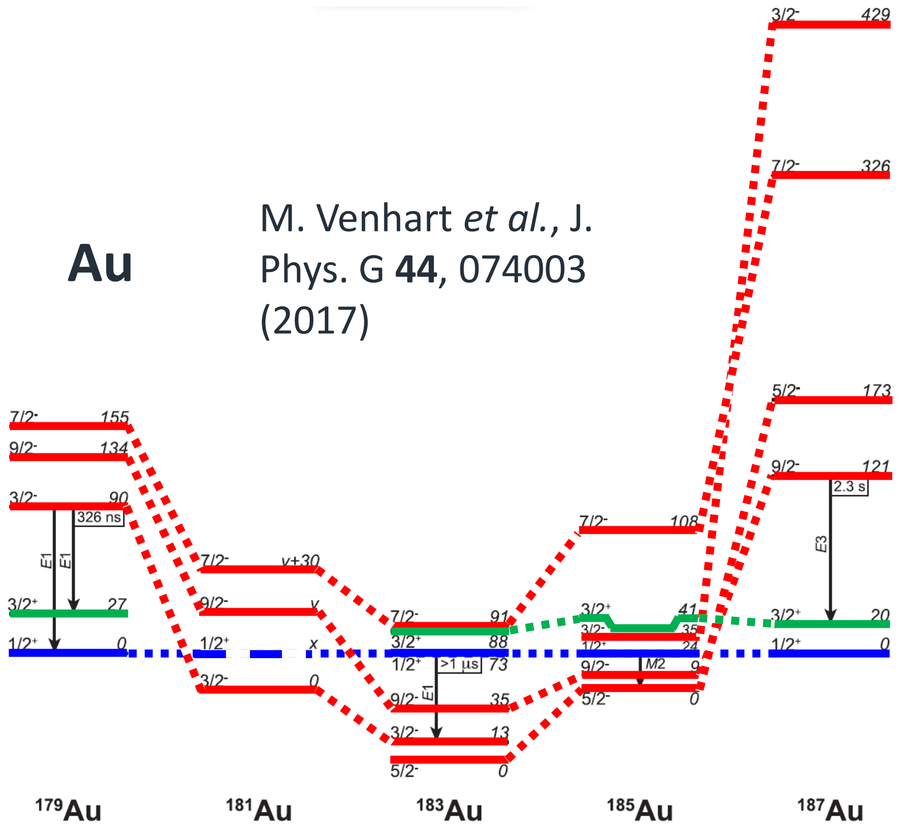
Excitation from intruder states below Z=82

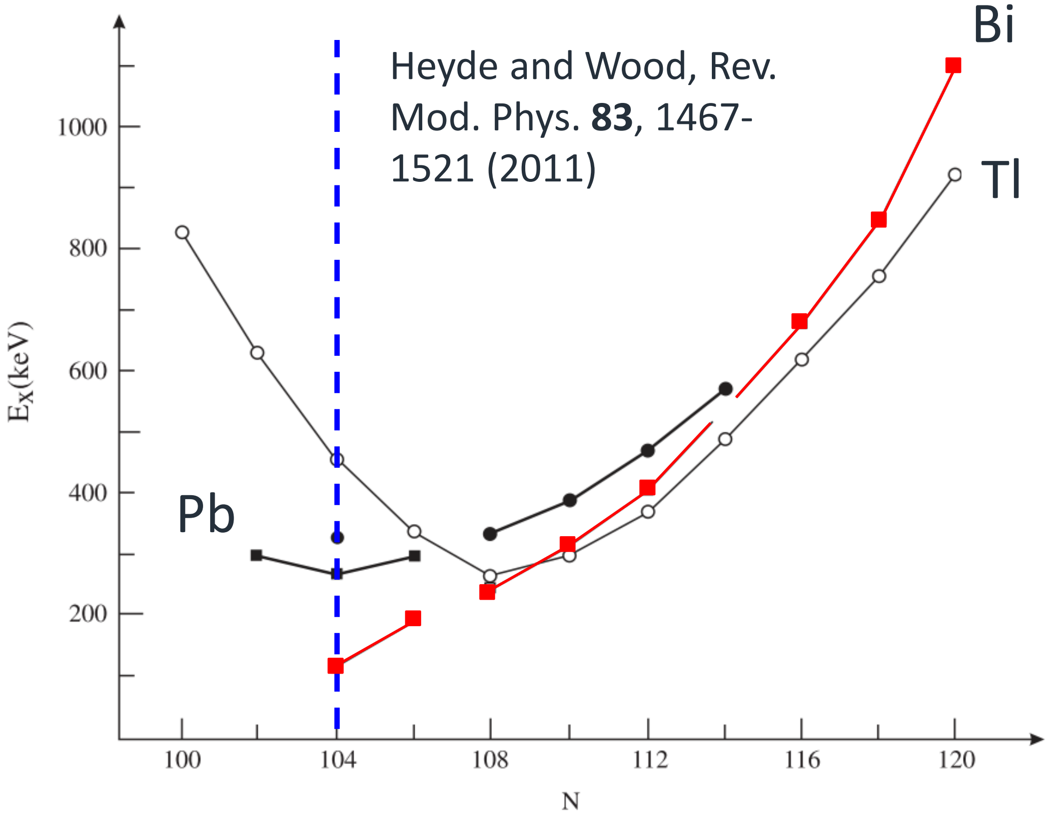


Au (Z=79)

Bi (Z=83)

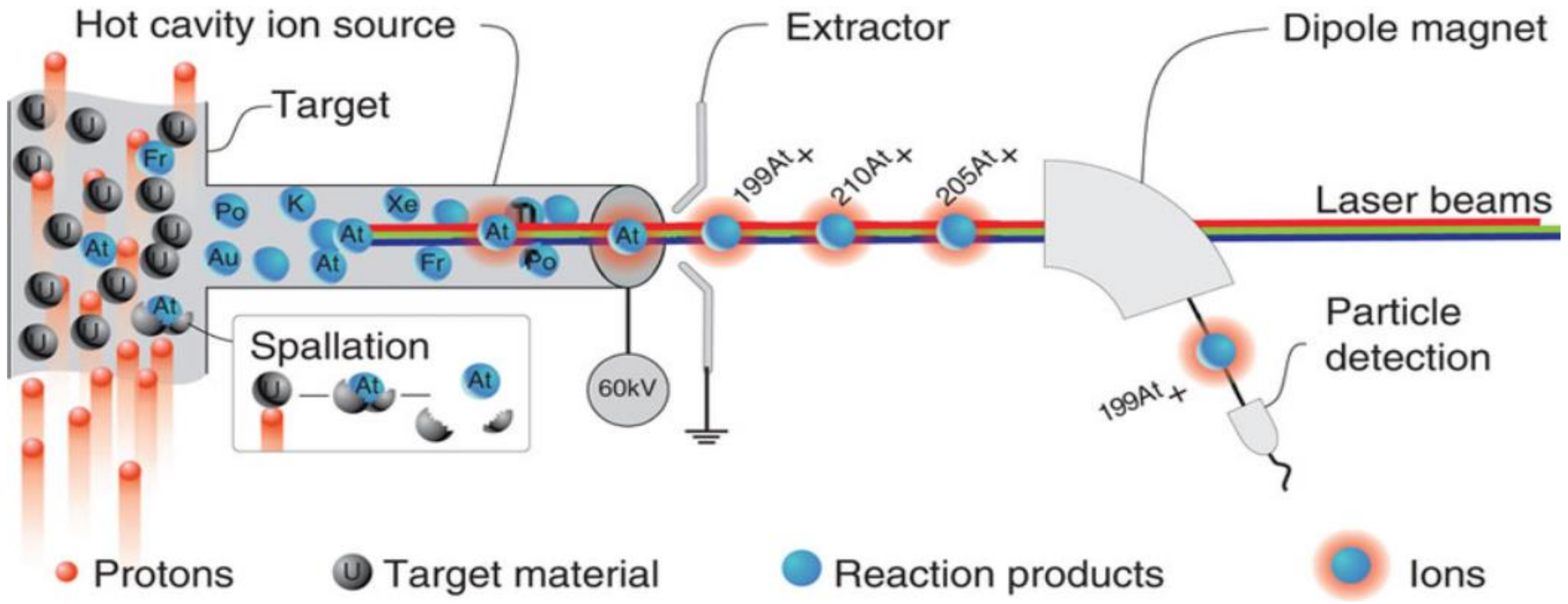
M. Venhart *et al.*, J. Phys. G **44**, 074003 (2017)

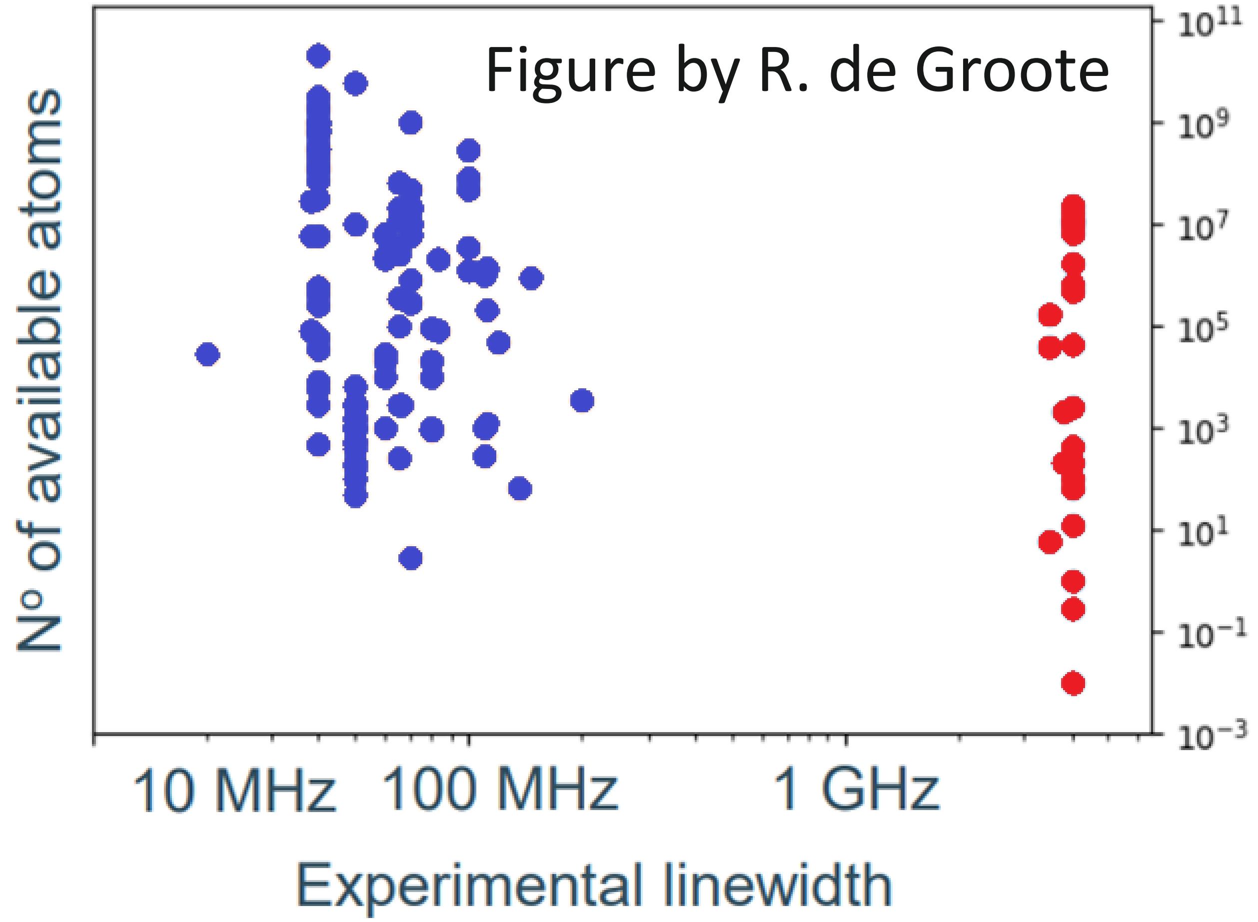




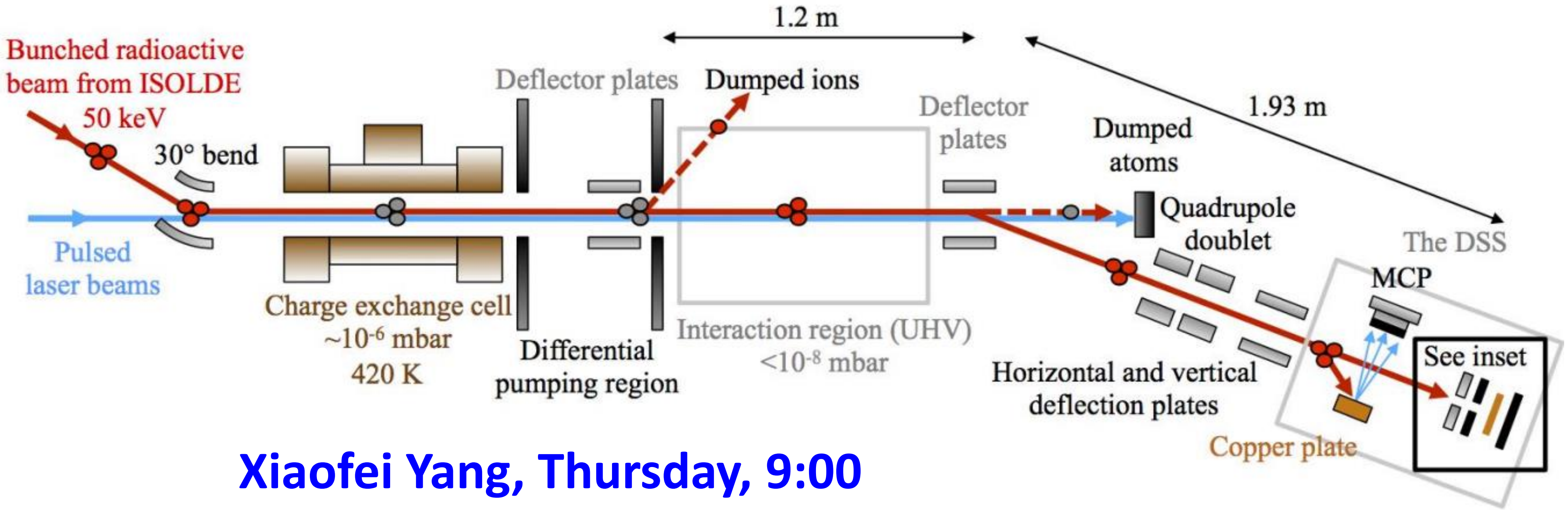
Types of laser spectroscopy

In-source
(RILIS/TRILIS)

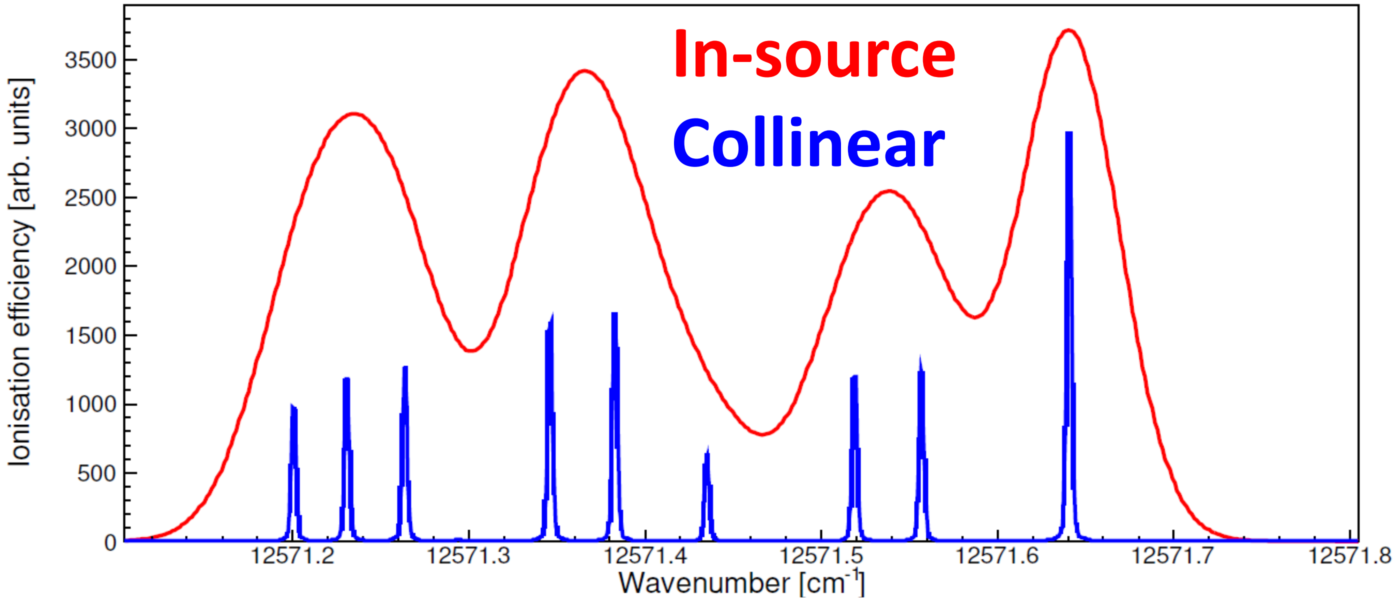




Collinear,
Resonant ionisation spectroscopy (CRIS)
Fluorescence spectroscopy (COLLAPS)



Xiaofei Yang, Thursday, 9:00



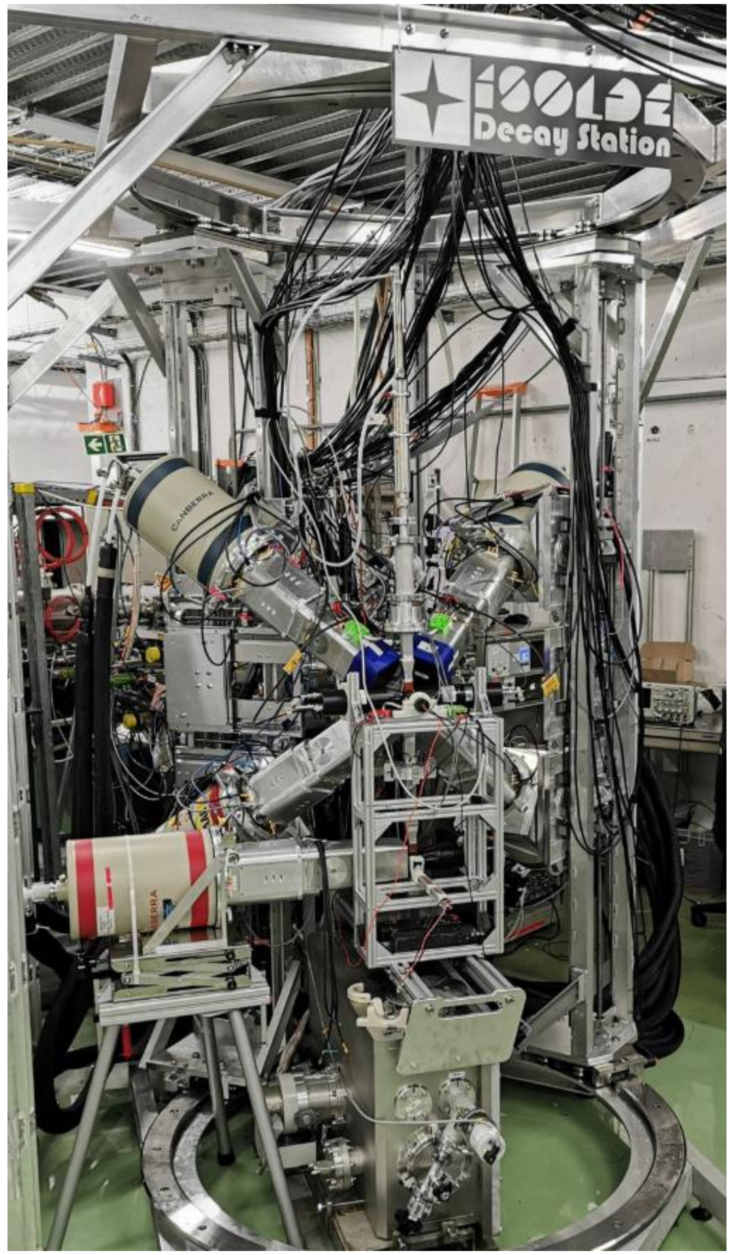
In-source: Low resolution, high efficiency
Collinear: High resolution, low efficiency
Collinear pushing resolution frontier – probed magnetic octupole (^{45}Sc)
R.P. de Groote *et al.*, PLB **827**, 136930 (2022)

Sensitivity boost

Past - Windmill

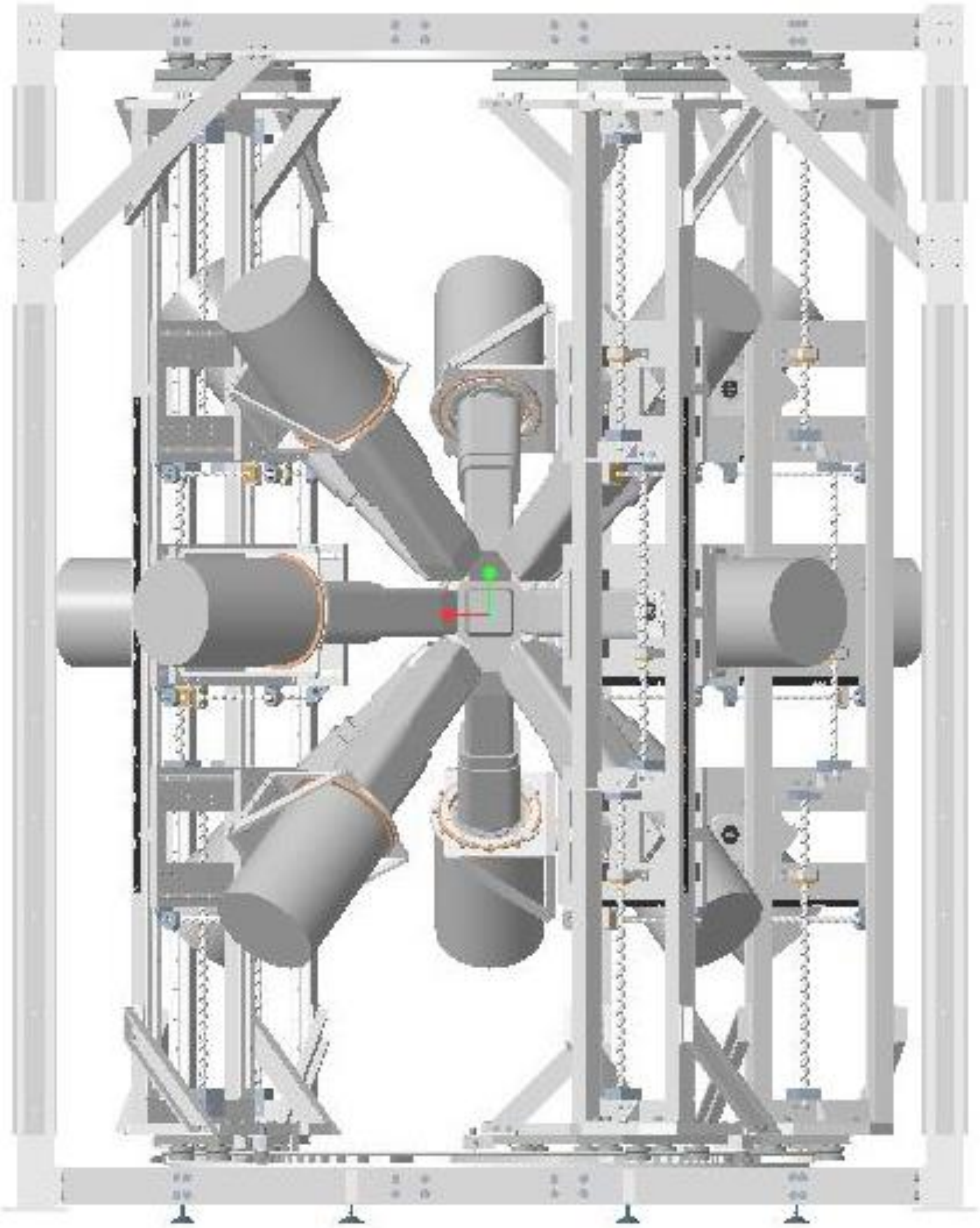
- **1 planar germanium**
- 2(+2) Silicons

Present - IDS



- **6 germanium clovers (24 crystals)**
- Plastics for beta tagging ($\varepsilon = 30 - 40\%$)

Future – "more" IDS



- **12(+3) clovers (up 60 crystals)**
- Even more plastic… (ε up to 70%)

Nuclear shape coexistence

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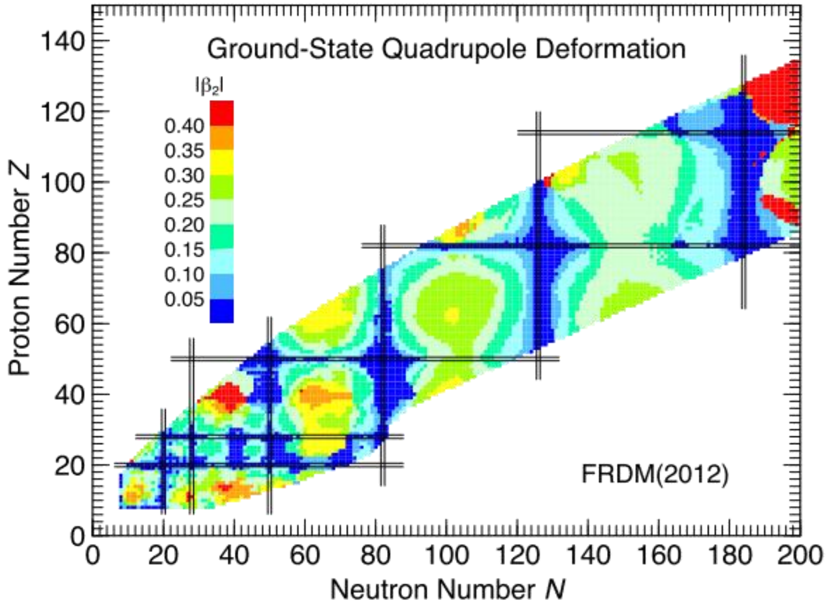
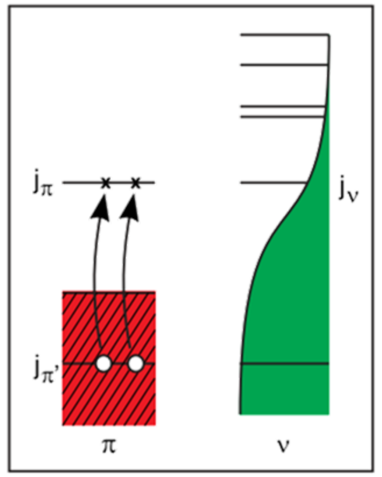
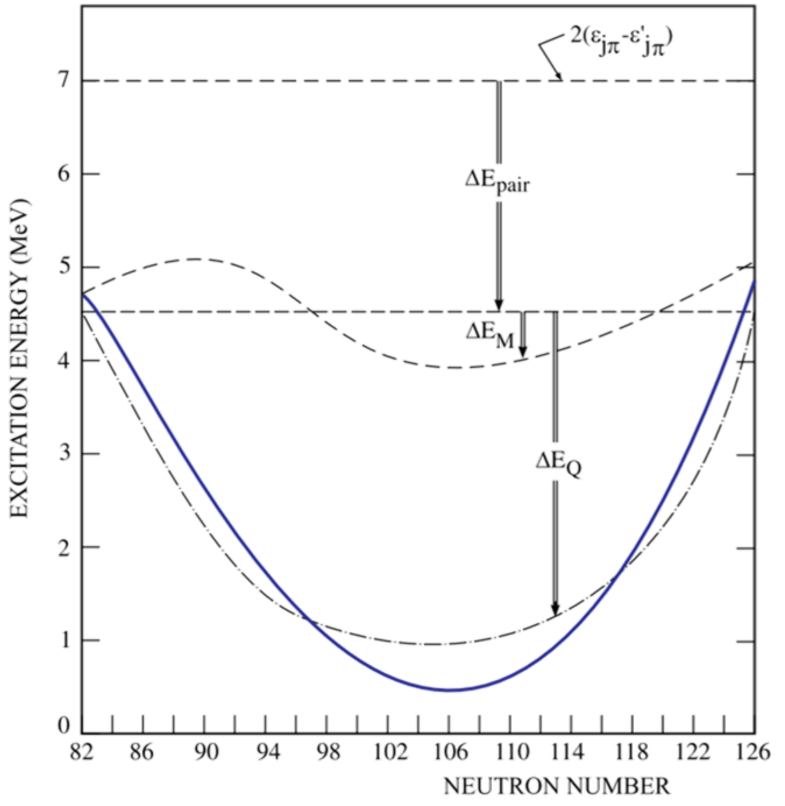


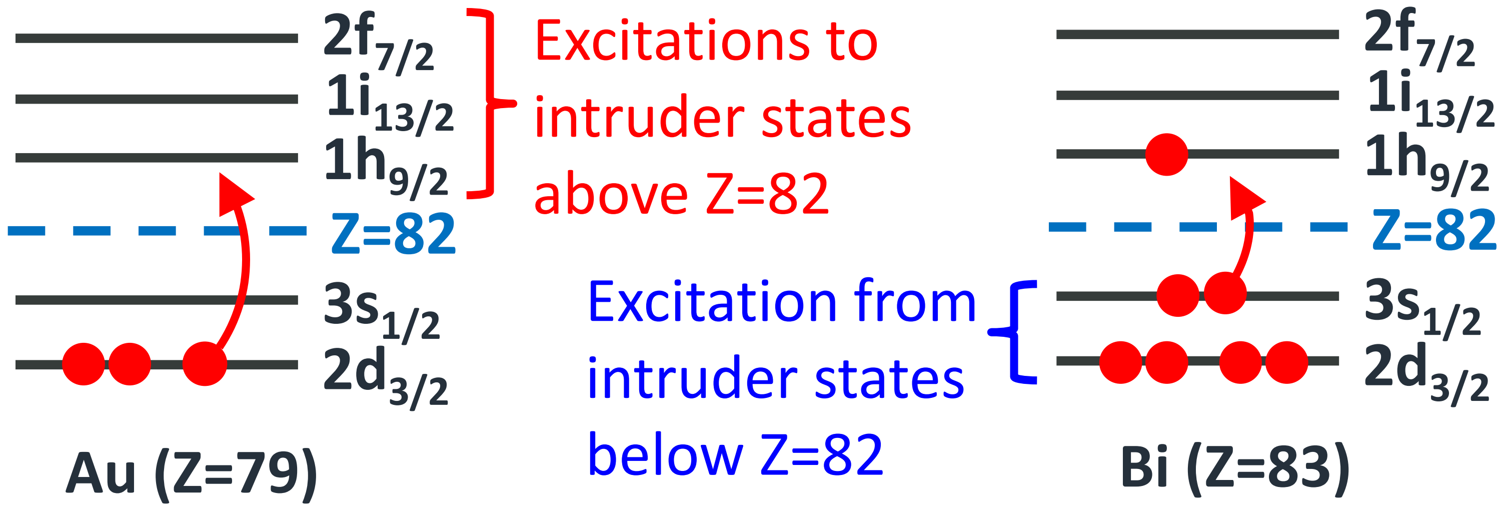
Moller *et al.*, Atom. Data Nucl. Data **109-110**, (2016)

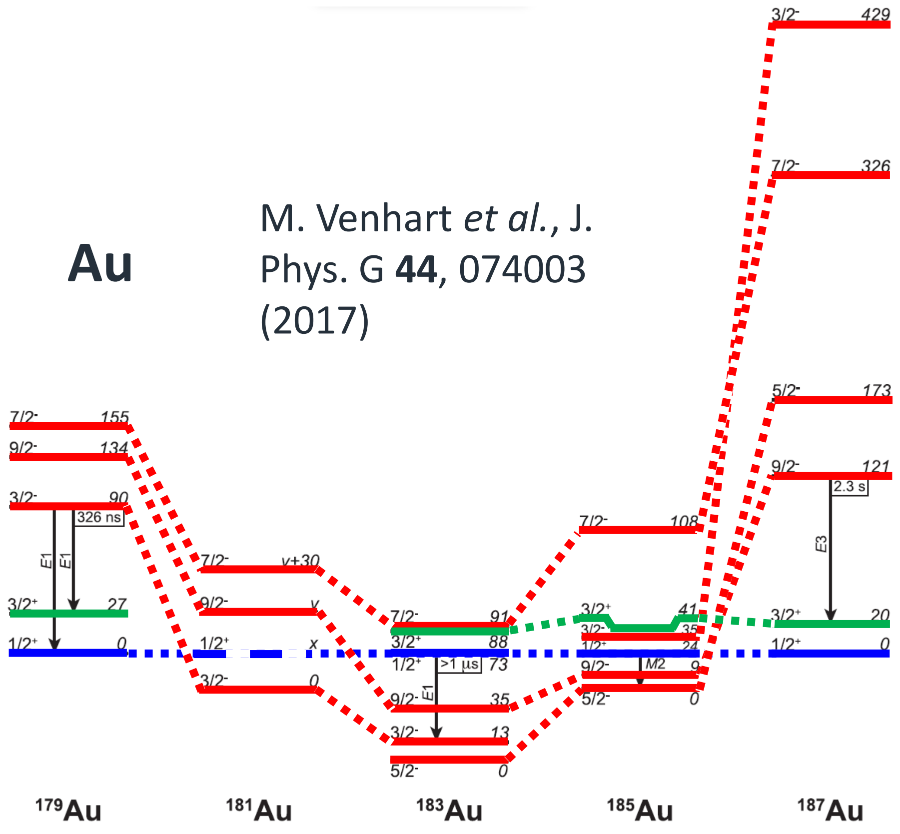
Heyde and Wood, Rev. Mod. Phys. **83**, 1467 (2011)



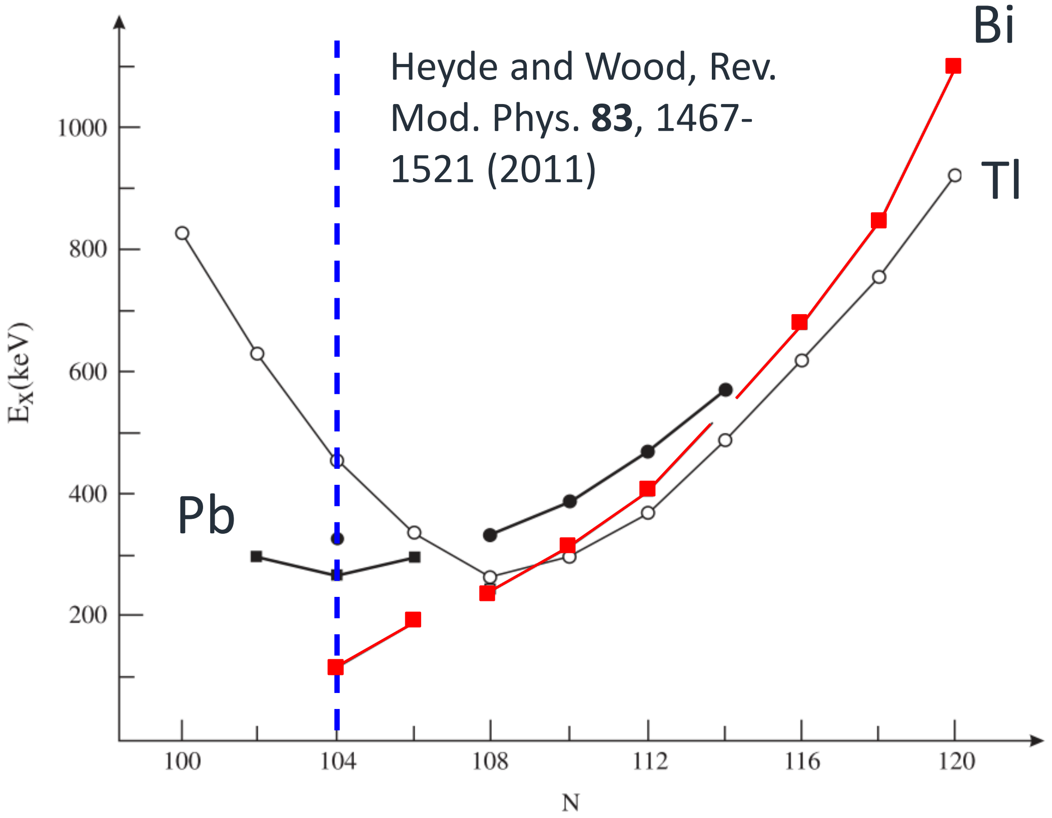


Culprits in the Pb region:



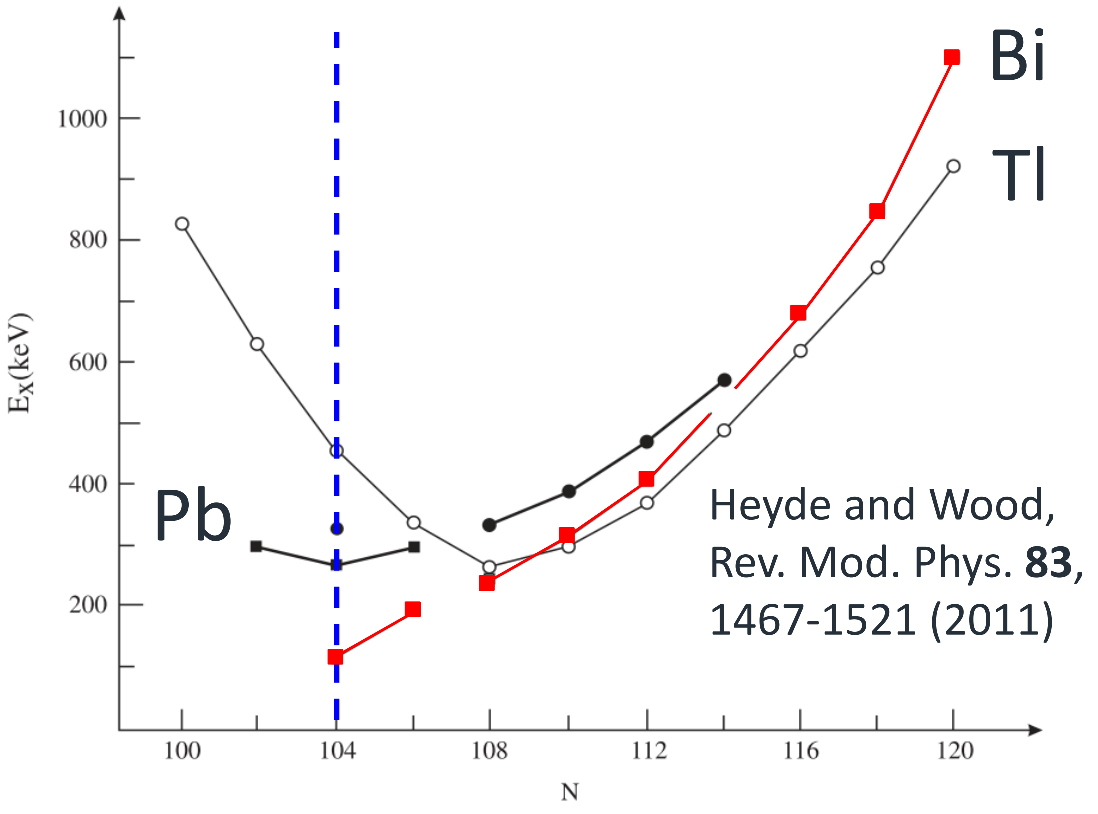


M. Venhart *et al.*, J. Phys. G **44**, 074003 (2017)

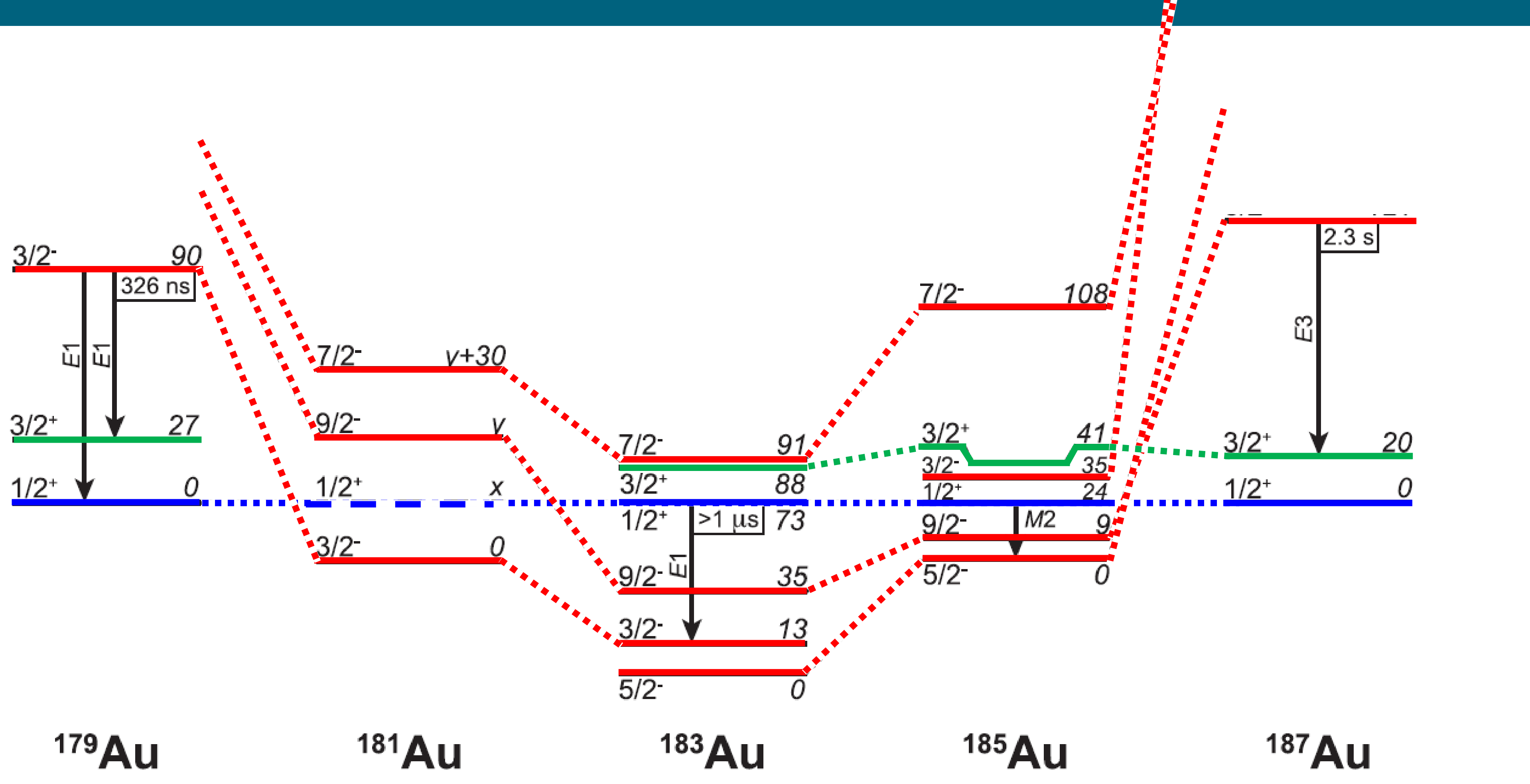


Heyde and Wood, Rev. Mod. Phys. **83**, 1467-1521 (2011)

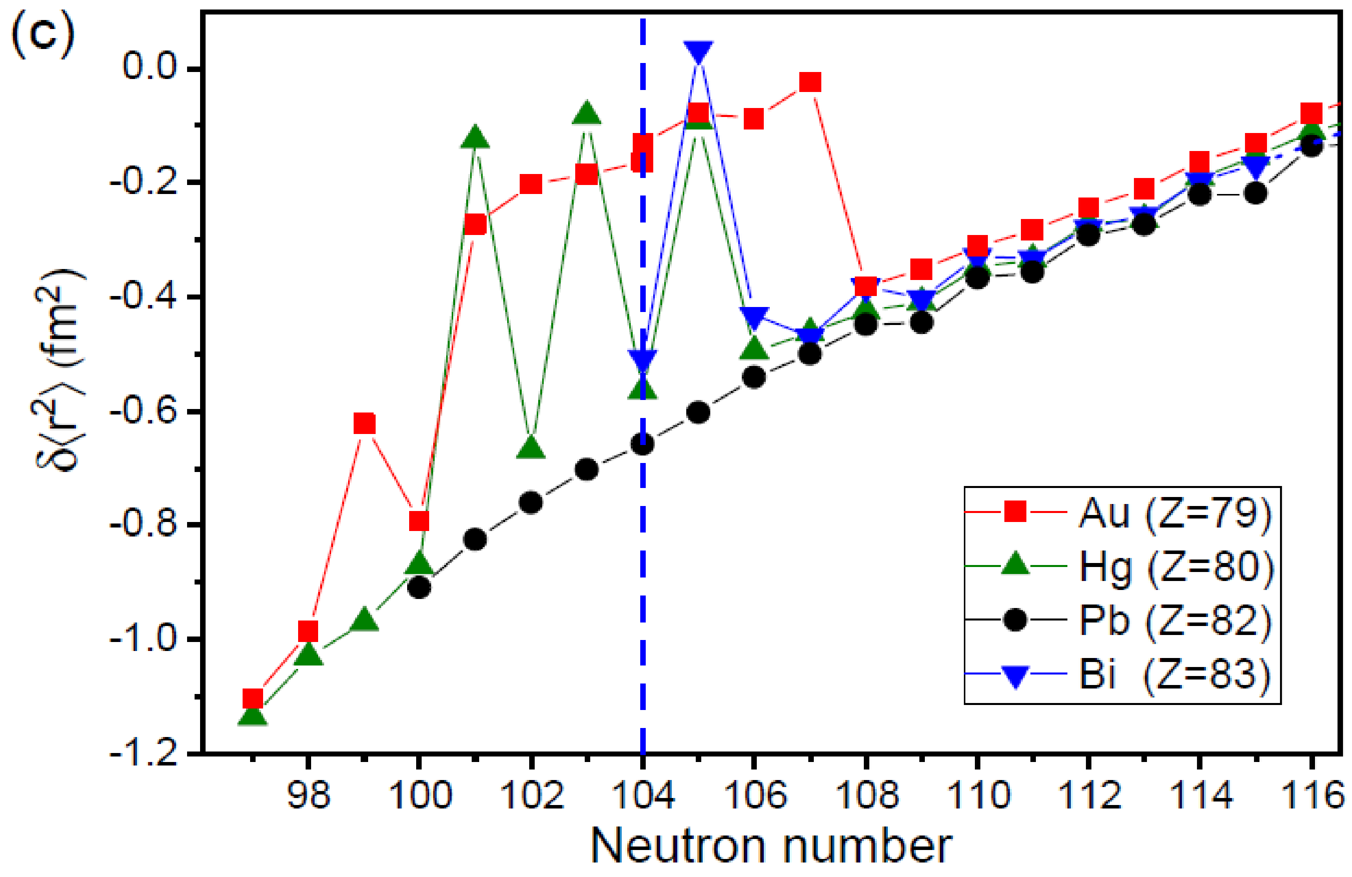
Comparing systematics



Heyde and Wood, Rev. Mod. Phys. **83**, 1467-1521 (2011)

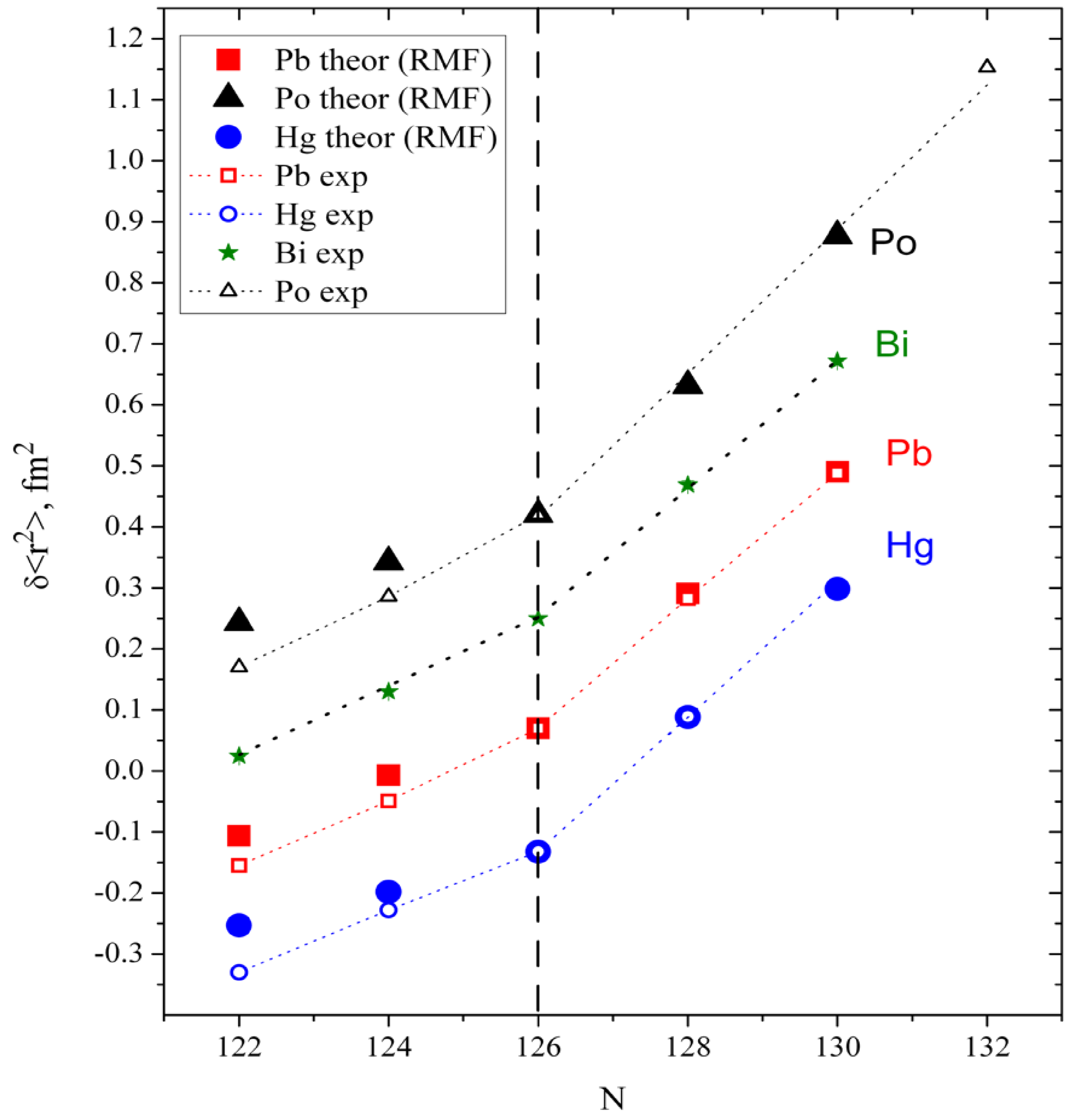


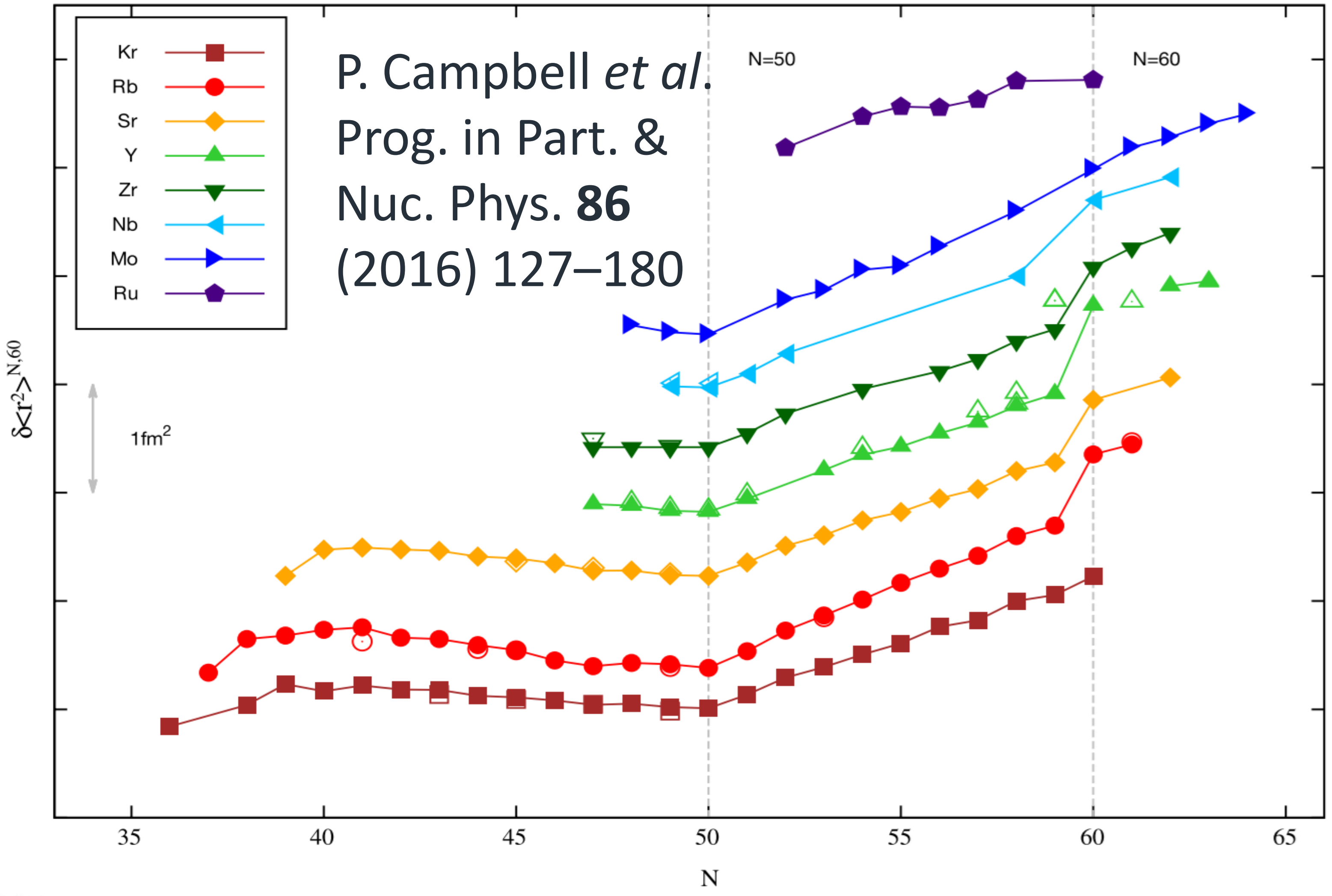
M. Venhart *et al.*, J. Phys. G **44**, 074003 (2017)

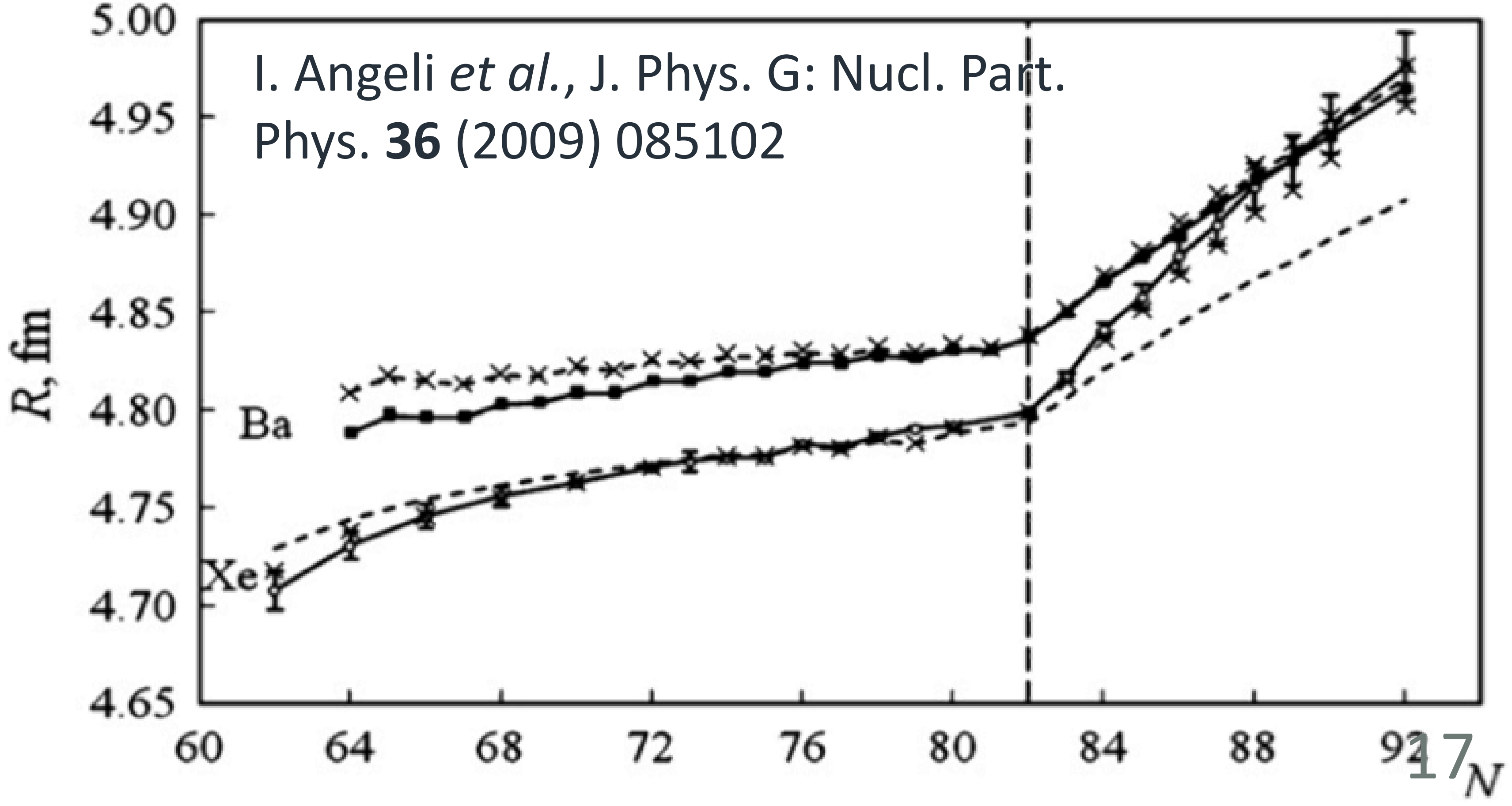


Shell effects in radii - Kink

- Shell effect in radii, known as the kink:
  Slope in $\delta\langle r^2\rangle$ increases when crossing a shell closure
  Seen in elements above and below proton shell closures







Describing the kink

- Involve scattering neutrons into large ℓ orbitals with n=1 – attractive proton-neutron interaction increases charge radius.
- Near Z=82, N=126 neutron pairs scatter into $\nu 1i_{11/2}$ – can probe with magnetic moments:
- μ(^{214}Fr,^{210}Bi) suggested admixture between [$\pi h_{9/2}$,$\nu g_{9/2}$] and [$\pi h_{9/2}$,$\nu i_{11/2}$] configurations.
- μ(^{209}Pb,^{211}Po) consistent with pure $\nu g_{9/2}$