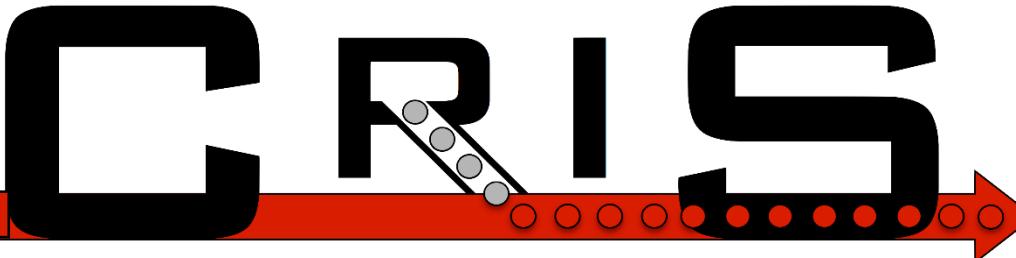


High-precision laser ionization spectroscopy towards ^{100}Sn

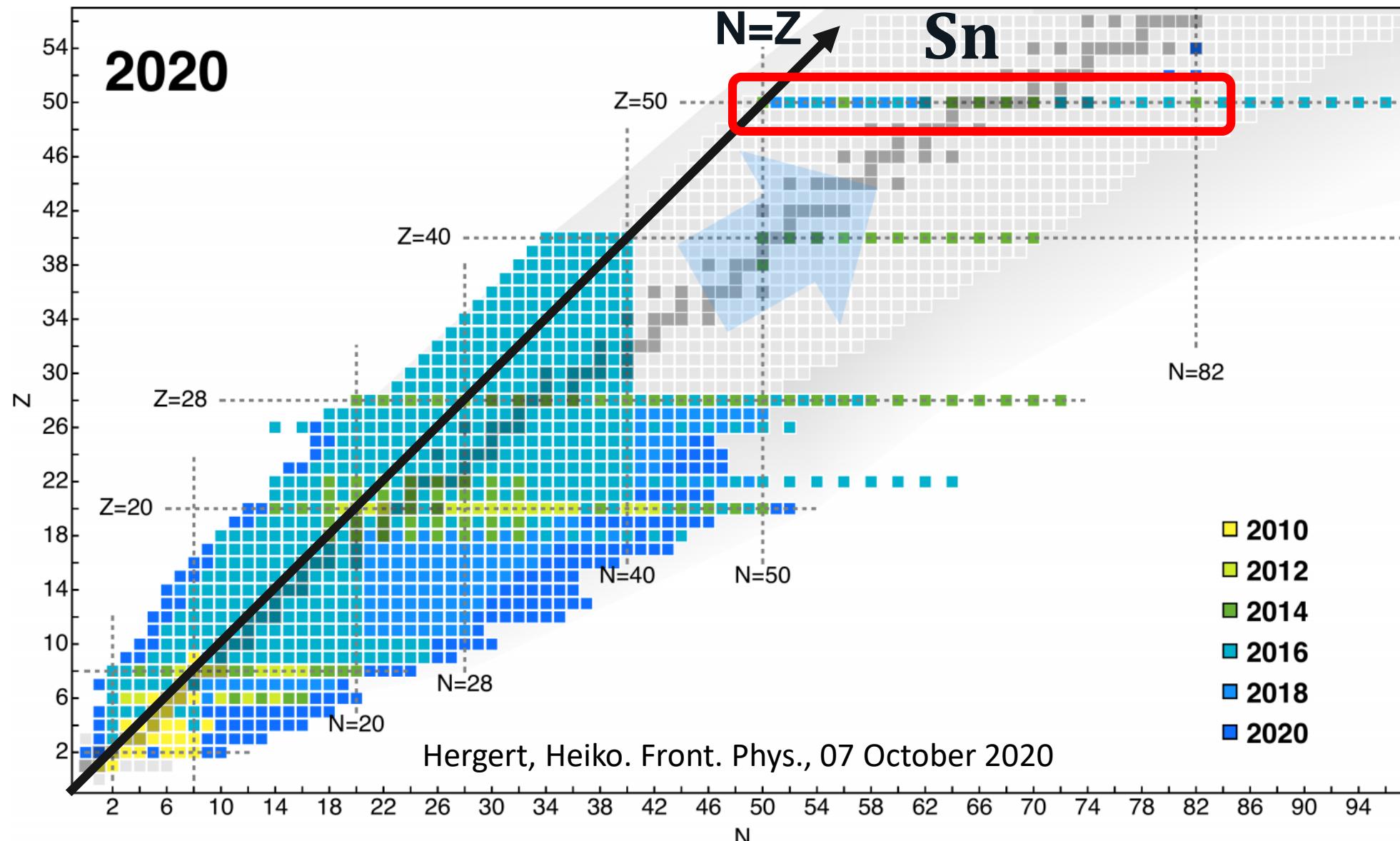
ISOLDE workshop 2020

Fredrik Parnefjord Gustafsson

27-11-2020

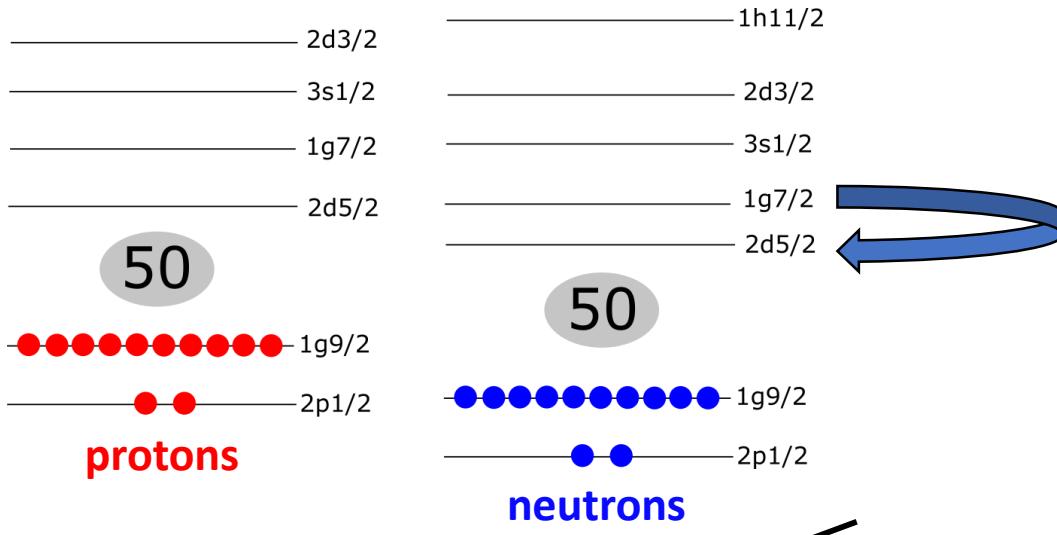


Progress of *ab-initio* theory for nuclear structure



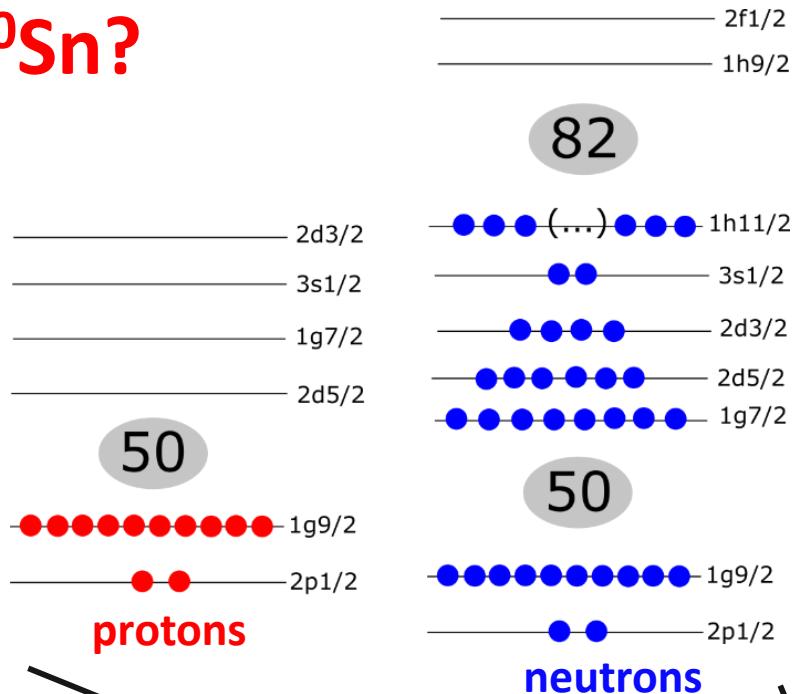
Tin isotopic chain at Z=50

$^{100}\text{Sn}_{50}^{50}$

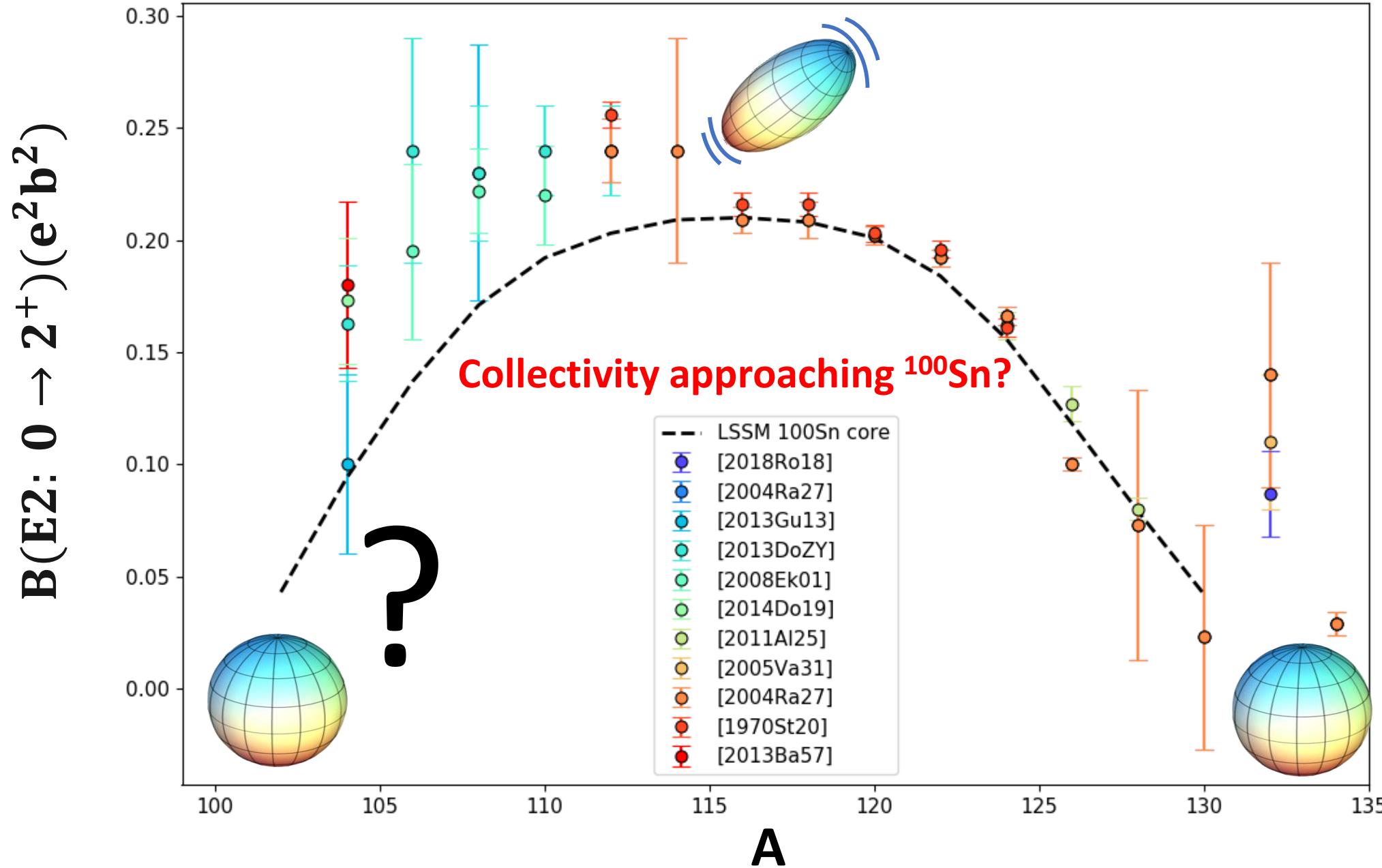


^{99}In β^+	^{100}In β^+	^{101}In β^+	^{102}In β^+	^{103}In β^+	^{104}In β^+	^{105}In β^+	^{106}In β^+	^{107}In β^+	^{108}In β^+	^{109}In β^+	^{110}In β^+	^{111}In β^+	^{112}In β^+	^{113}In β^+	^{114}In e^- -capture	^{115}In β^+	^{116}In β^+	^{117}In β^+	^{118}In β^+	^{119}In e^- -capture	^{120}In β^+	^{121}In β^-	^{122}In β^-	^{123}In β^-	^{124}In β^-	^{125}In β^-	^{126}In β^-	^{127}In β^-	^{128}In β^-	^{129}In β^-	^{130}In β^-	^{131}In β^-	^{132}In β^-	^{133}In β^-
^{100}Sn β^+	^{101}Sn β^+	^{102}Sn β^+	^{103}Sn β^+	^{104}Sn β^+	^{105}Sn β^+	^{106}Sn β^+	^{107}Sn β^+	^{108}Sn β^+	^{109}Sn β^+	^{110}Sn β^+	^{111}Sn β^+	^{112}Sn β^+	^{113}Sn β^+	^{114}Sn β^+	^{115}Sn Stable	^{116}Sn Stable	^{117}Sn Stable	^{118}Sn Stable	^{119}Sn Stable	^{120}Sn Stable	^{121}Sn Stable	^{122}Sn Stable	^{123}Sn Stable	^{124}Sn Stable	^{125}Sn Stable	^{126}Sn Stable	^{127}Sn Stable	^{128}Sn Stable	^{129}Sn Stable	^{130}Sn Stable	^{131}Sn Stable	^{132}Sn Stable	^{133}Sn Stable	
^{103}Sb β^+	^{104}Sb β^+	^{105}Sb β^+	^{106}Sb β^+	^{107}Sb β^+	^{108}Sb β^+	^{109}Sb β^+	^{110}Sb β^+	^{111}Sb β^+	^{112}Sb β^+	^{113}Sb β^+	^{114}Sb β^+	^{115}Sb β^+	^{116}Sb β^+	^{117}Sb β^+	^{118}Sb β^+	^{119}Sb e^- -capture	^{120}Sb β^+	^{121}Sb Stable	^{122}Sb Stable	^{123}Sb Stable	^{124}Sb Stable	^{125}Sb Stable	^{126}Sb Stable	^{127}Sb Stable	^{128}Sb Stable	^{129}Sb Stable	^{130}Sb Stable	^{131}Sb Stable	^{132}Sb Stable	^{133}Sb Stable				

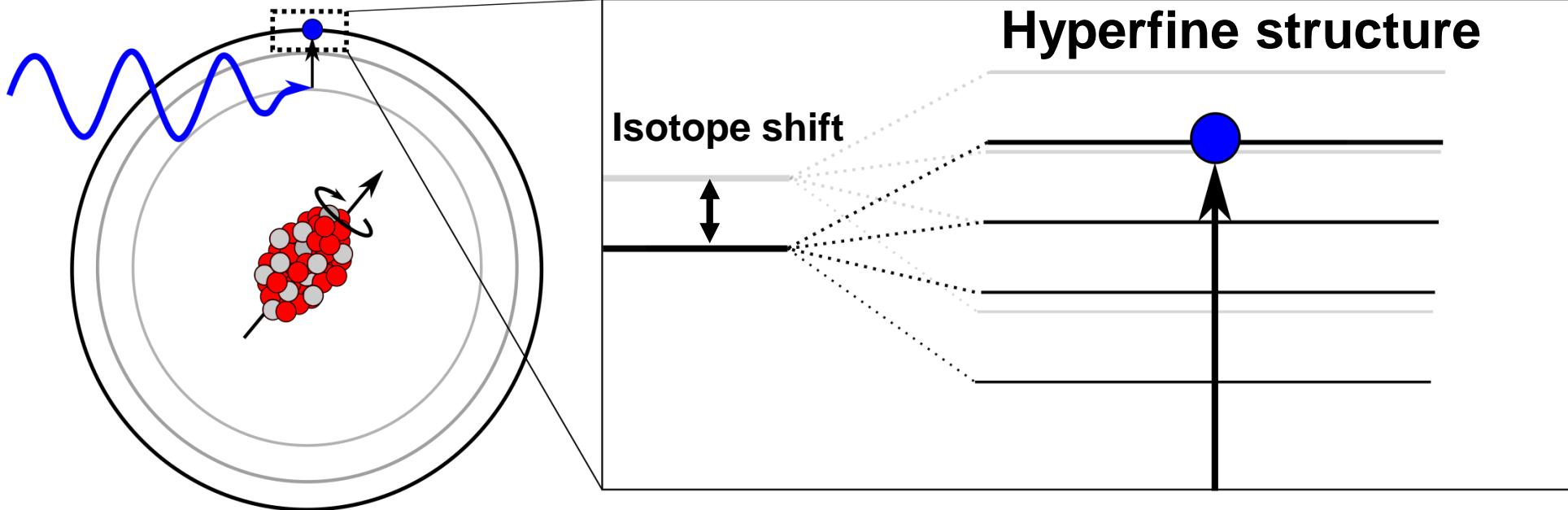
$^{132}\text{Sn}_{50}^{82}$



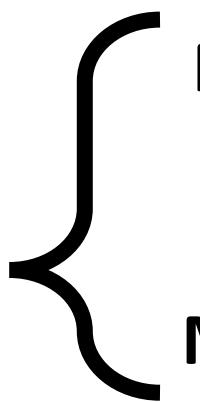
Collectivity between shell closures?



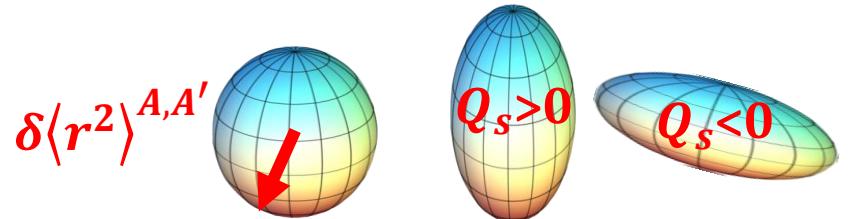
Probing the nuclear structure using bound electrons



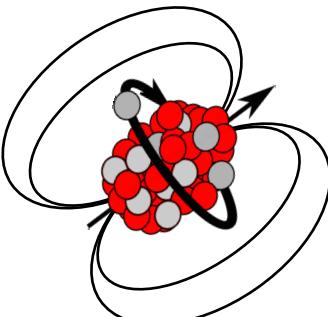
Electronic
+
Nuclear



Macroscopic:



Microscopic:



$$g = \frac{\mu_I}{I}$$

Collinear spectroscopy - **High resolution**
+
Ionization spectroscopy - **High detection efficiency**
=

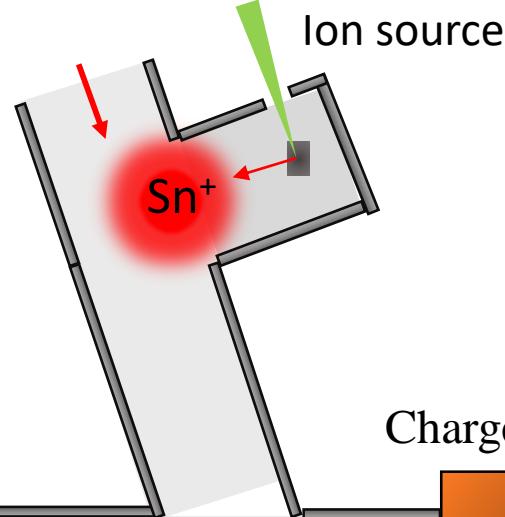
Collinear Resonance Ionisation Spectroscopy



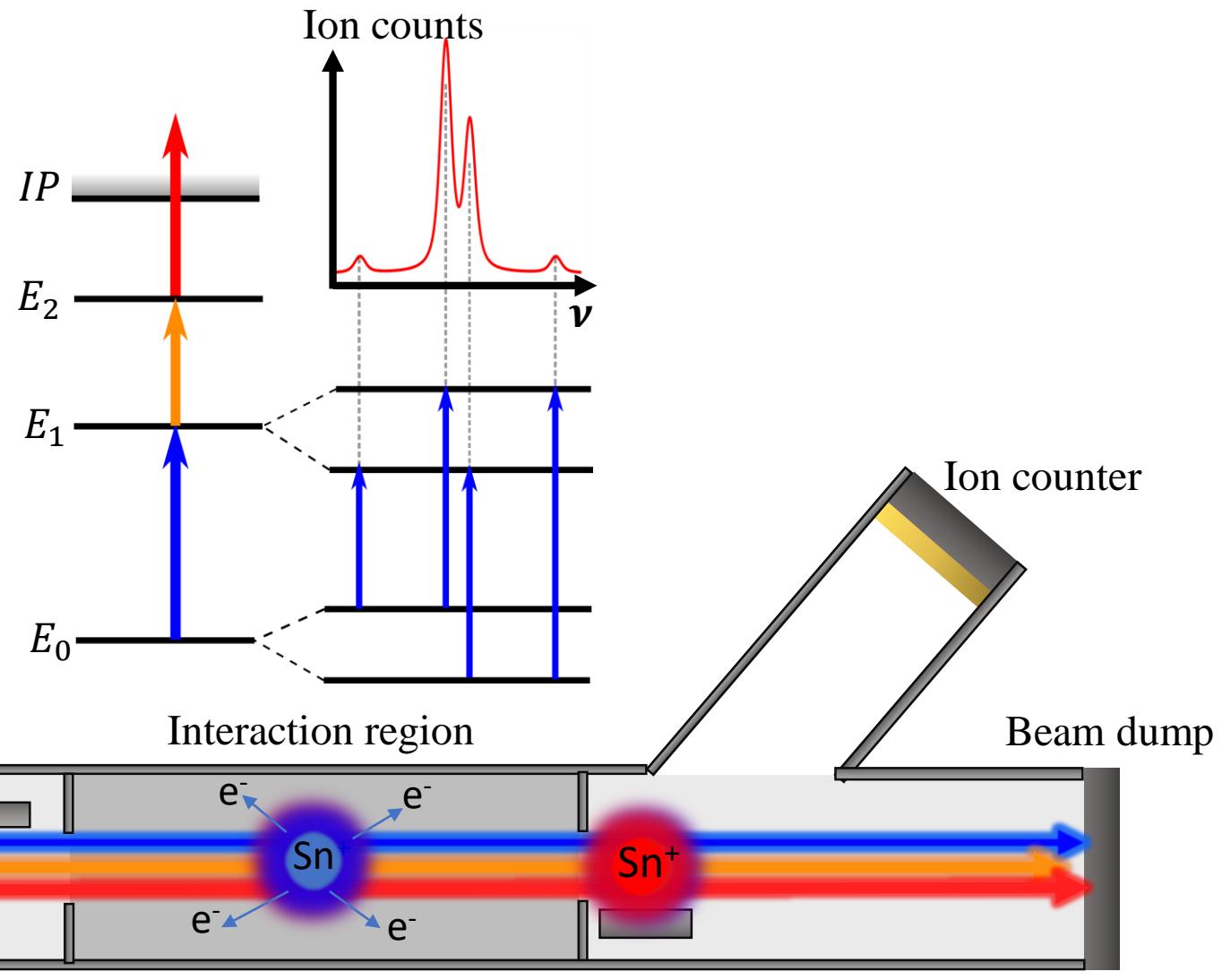
Collinear Resonance Ionization Spectroscopy

C R I S

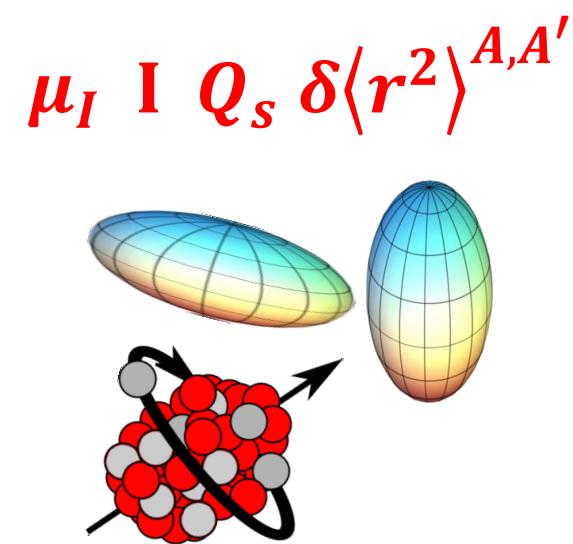
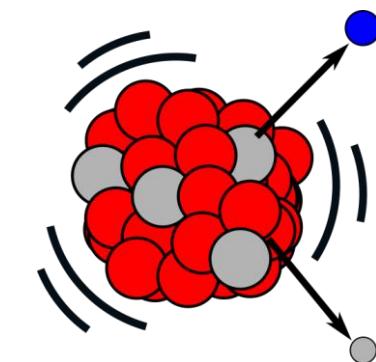
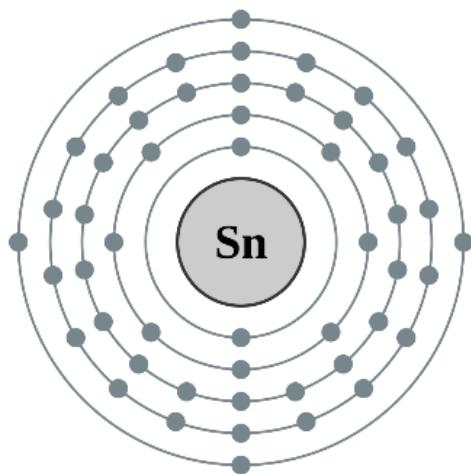
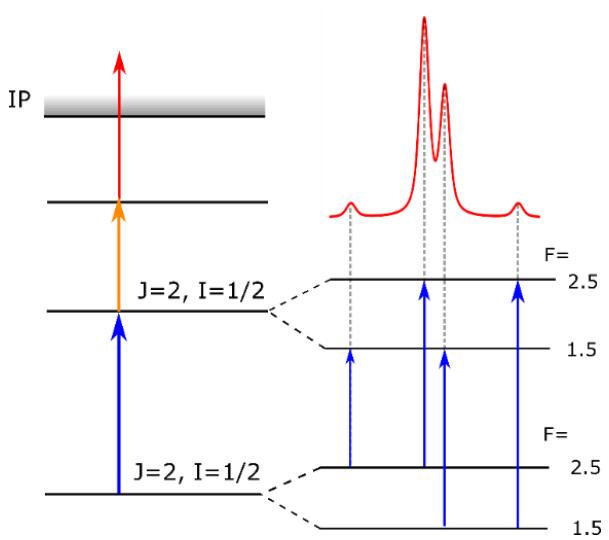
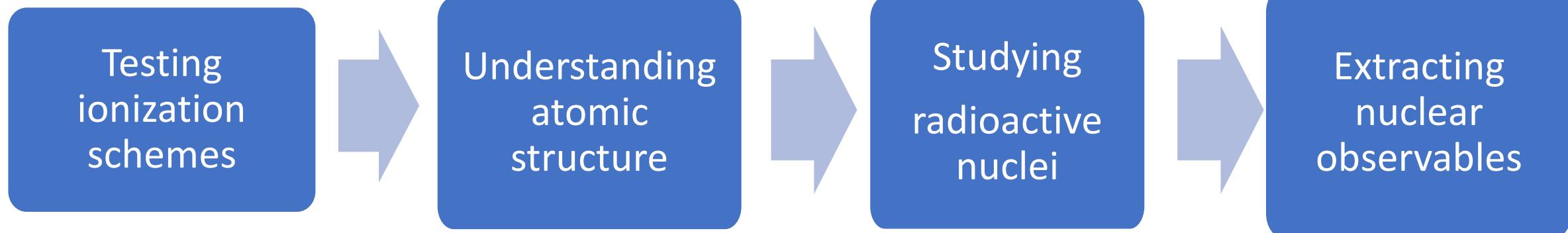
Ion beam
from ISOLDE



Charge-exchange-cell



Experimental procedure

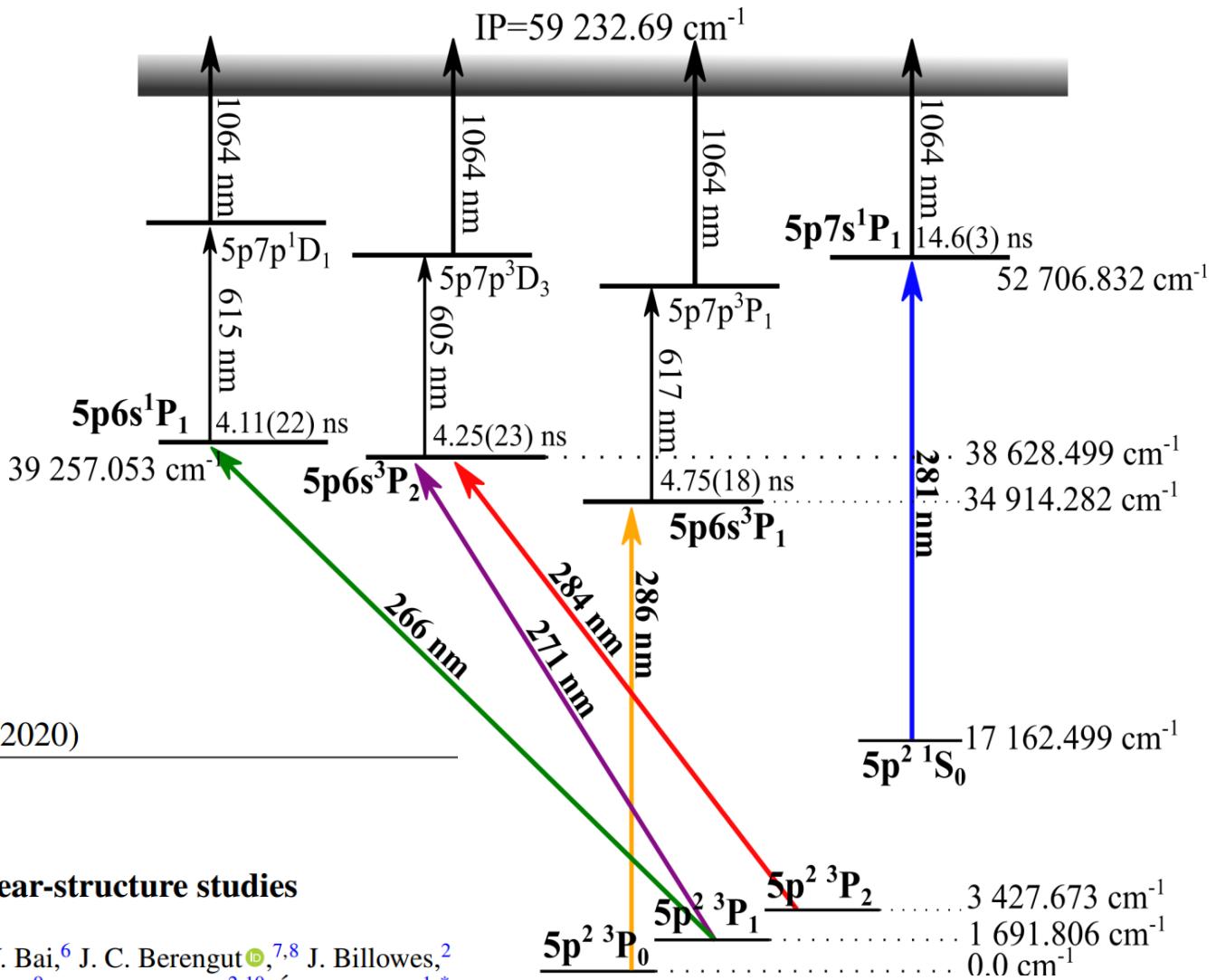


Investigating tin ionization schemes

Efficiency?

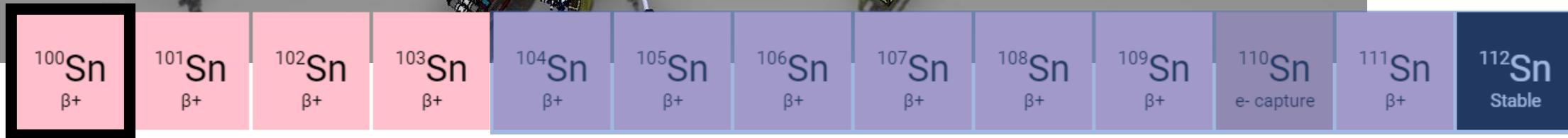
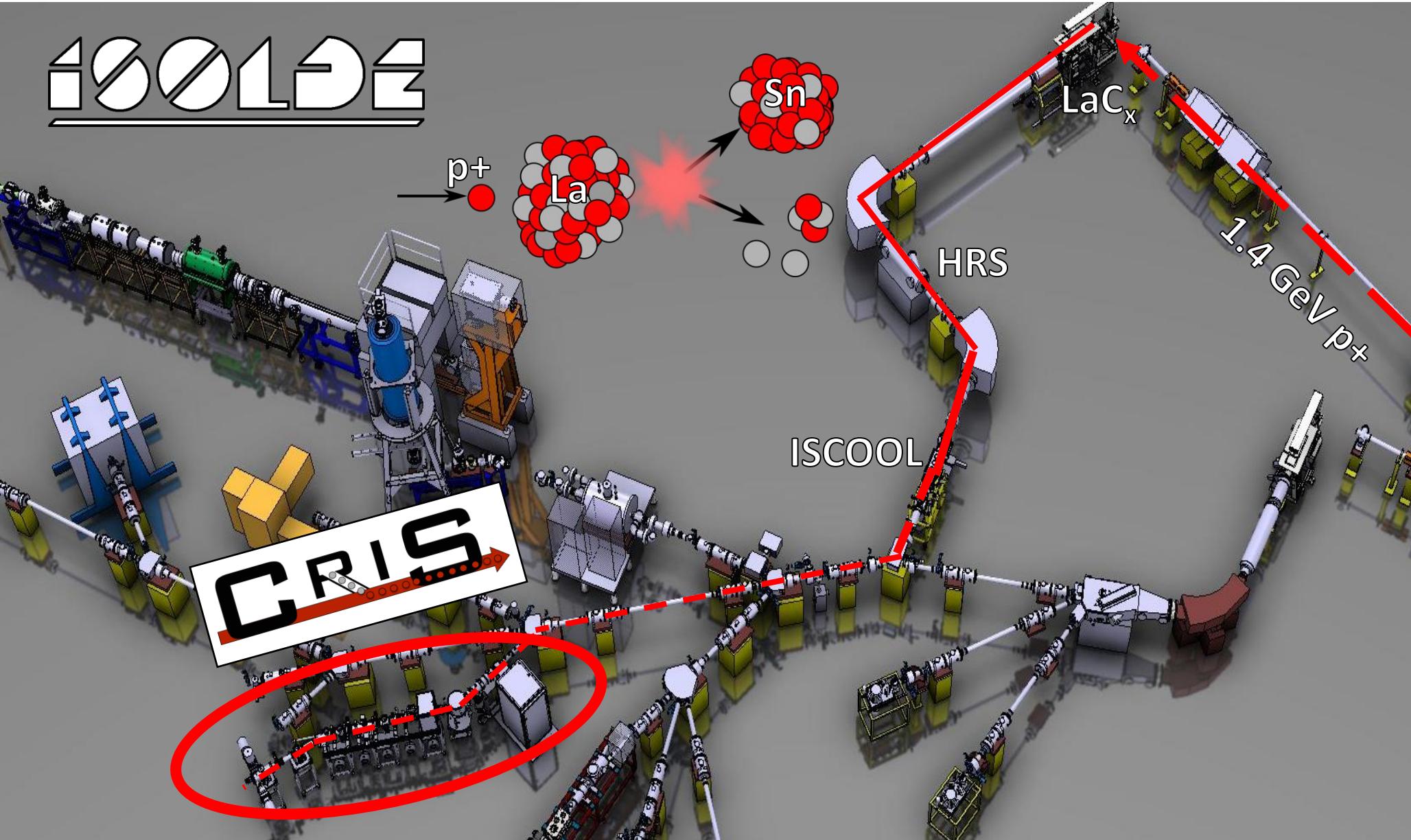
Sensitivity to nuclear structure?

PHYSICAL REVIEW A 102, 052812 (2020)

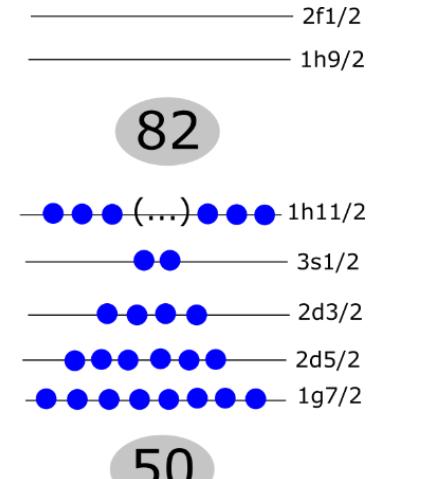
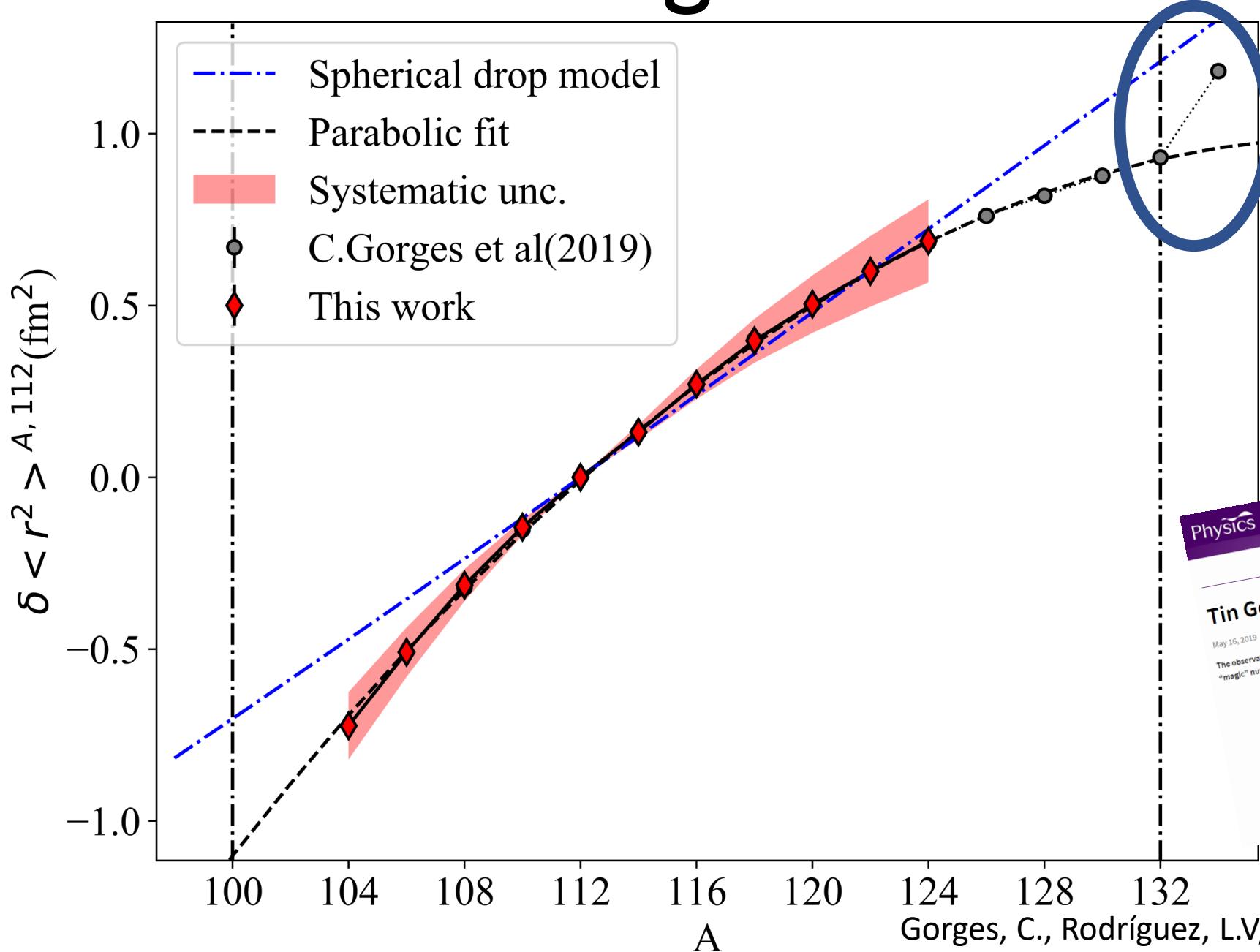


Tin resonance-ionization schemes for atomic- and nuclear-structure studies

F. P. Gustafsson^{1,5}, C. M. Ricketts^{1,2}, M. L. Reitsma^{1,3}, R. F. Garcia Ruiz^{4,5}, S. W. Bai⁶, J. C. Berengut^{1,7,8}, J. Billowes², C. L. Binnersley², A. Borschevsky^{1,3}, T. E. Cocolios¹, B. S. Cooper², R. P. de Groot⁹, K. T. Flanagan^{2,10}, Á. Koszorús,^{1,*} G. Neyens^{1,5}, H. A. Perrett², A. R. Vernon^{1,2}, Q. Wang^{5,†}, S. G. Wilkins¹¹, and X. F. Yang^{1,6}



Tin charge radii



Physics

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Tin Gets Kinky

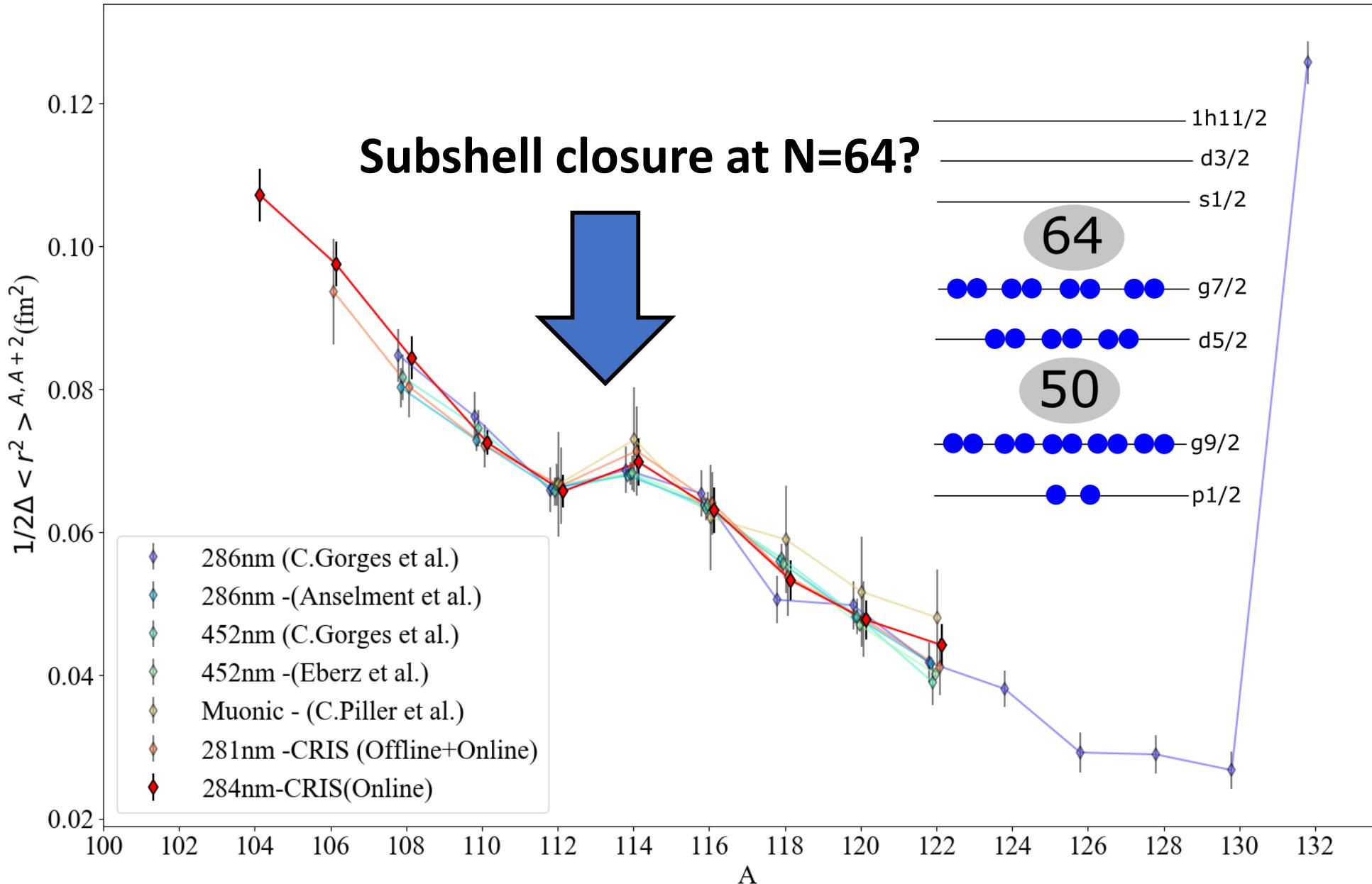
May 16, 2019 • Physics 12, §58

The observation that tin nuclei suddenly increase in size when the number of neutrons they contain reaches a "magic" number helps test models of nucleon interactions.

Neutron Proton

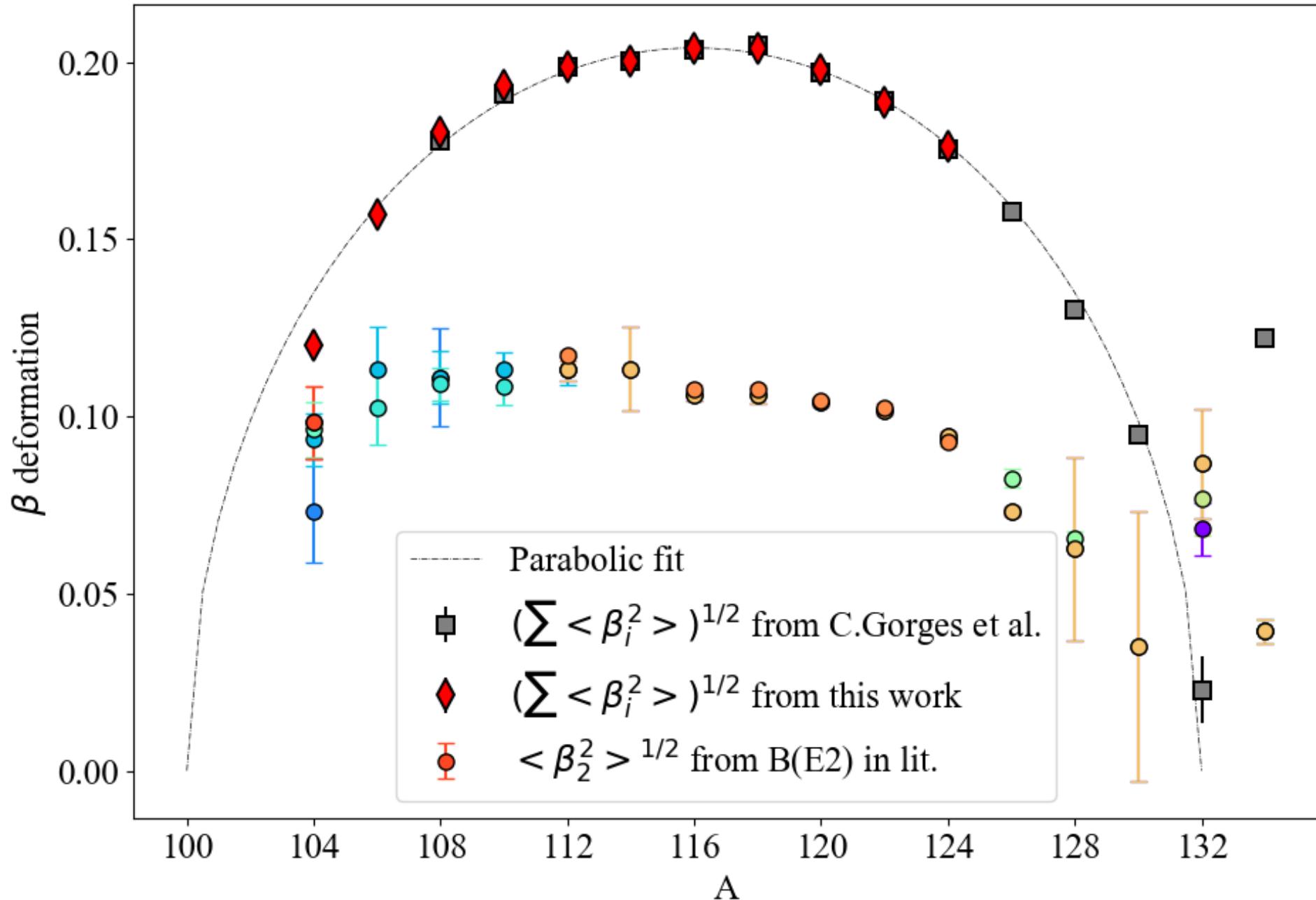
APL Alan Stonebraker

Differential charge radii:

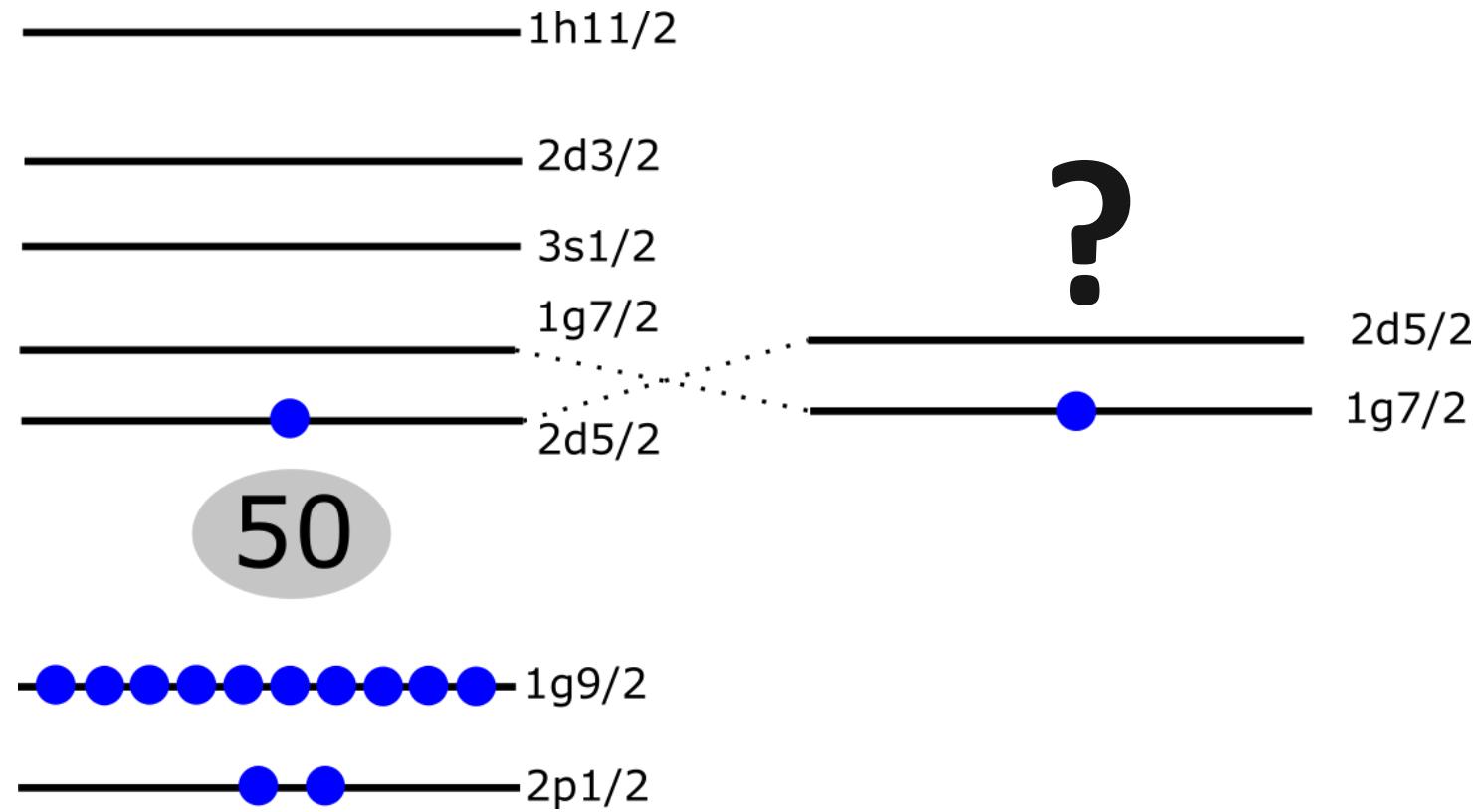


Collectivity along the tin chain

$$\begin{aligned} R_{Def} & \quad \text{[Elliptical shape with wavy lines]} \\ - & \quad \text{[Sphere]} \\ R_{Sph} & \quad \text{[Sphere]} \\ = & \quad \text{[Elliptical shape with wavy lines]} \\ \Delta R & \quad \text{[Elliptical shape with wavy lines]} \\ \left(\frac{\Delta R}{R_{Sph}}\right)^2 & \propto \sum \langle \beta_i^2 \rangle^2 \end{aligned}$$

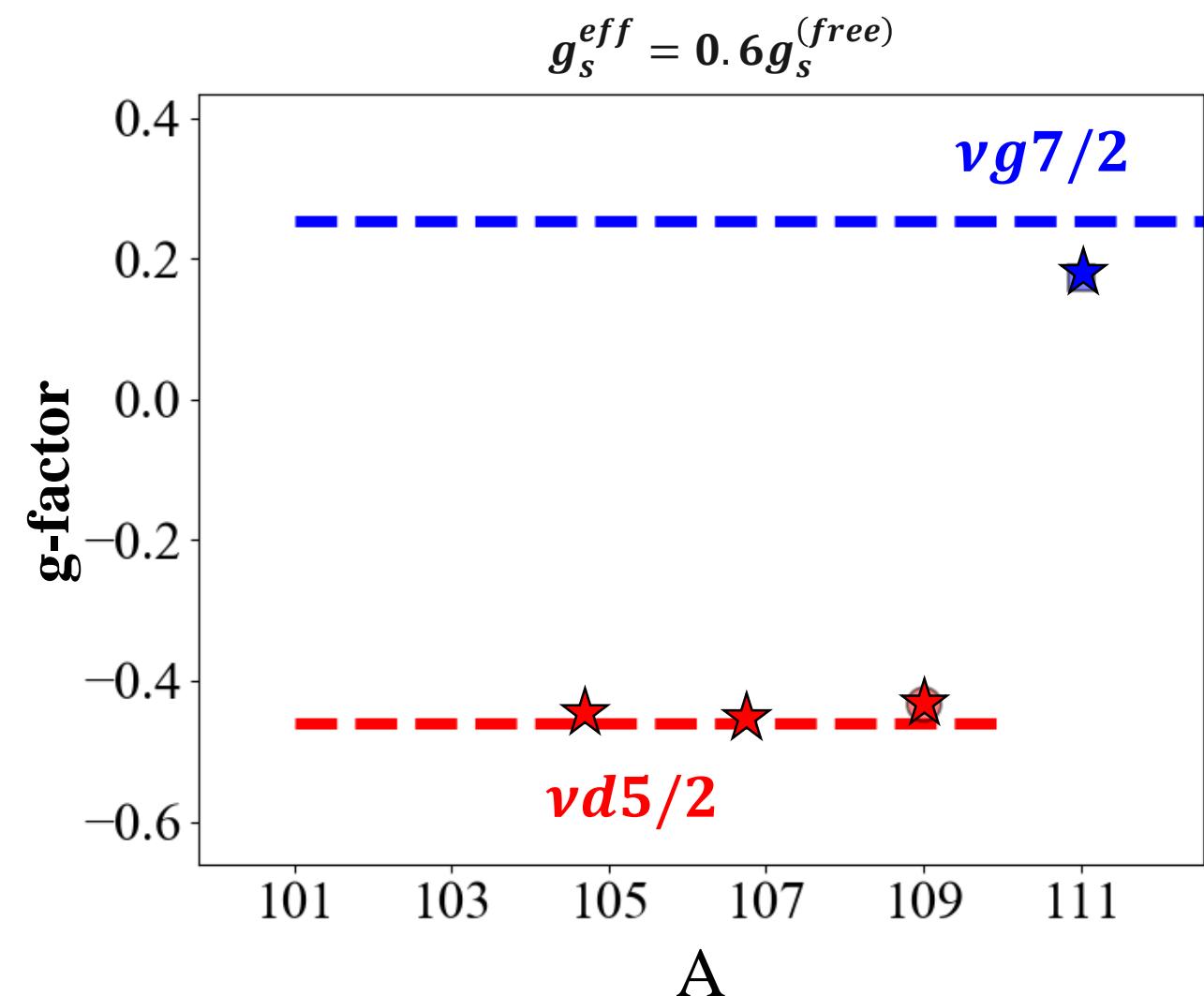
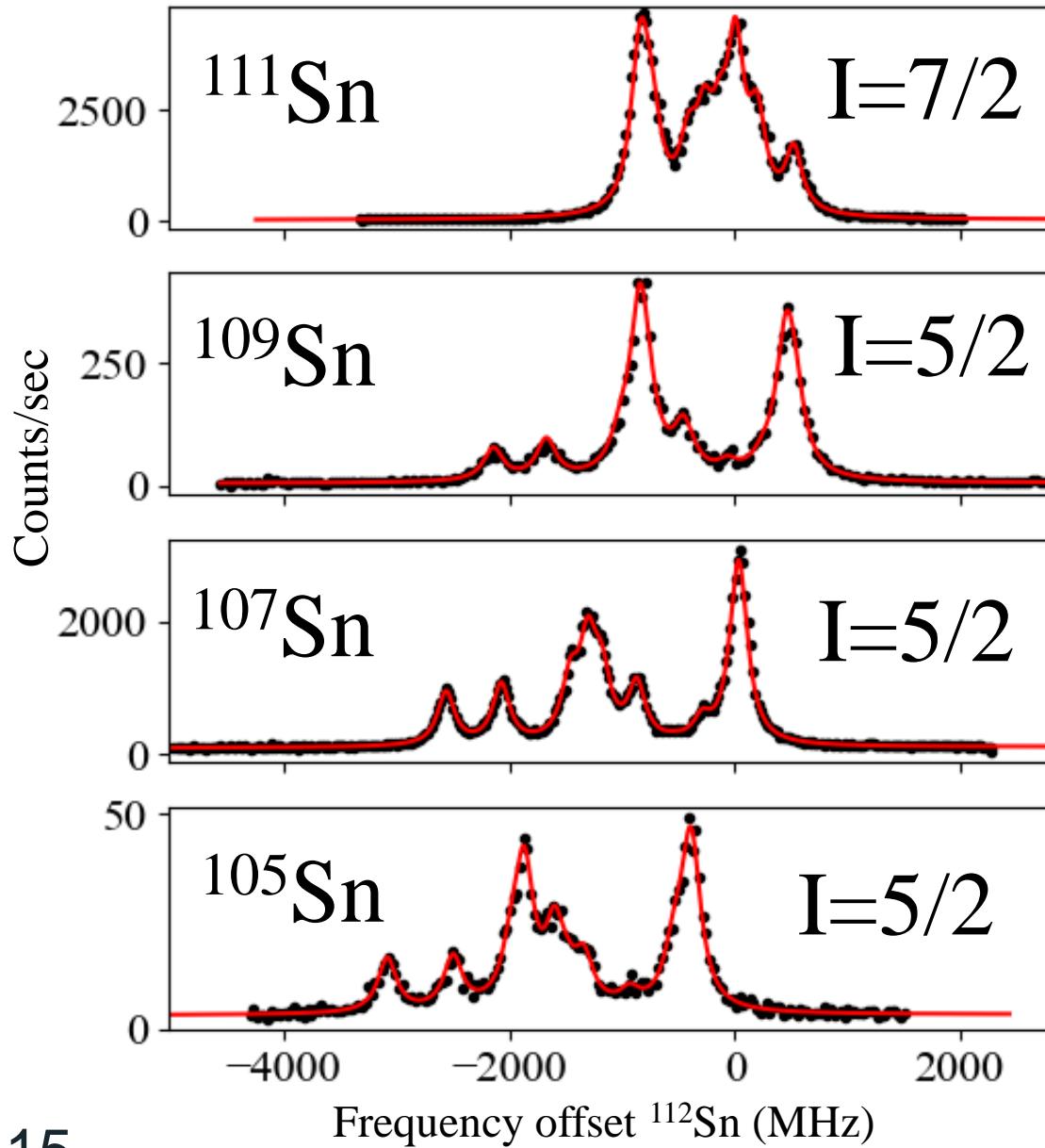


Level ordering approaching shell closure?

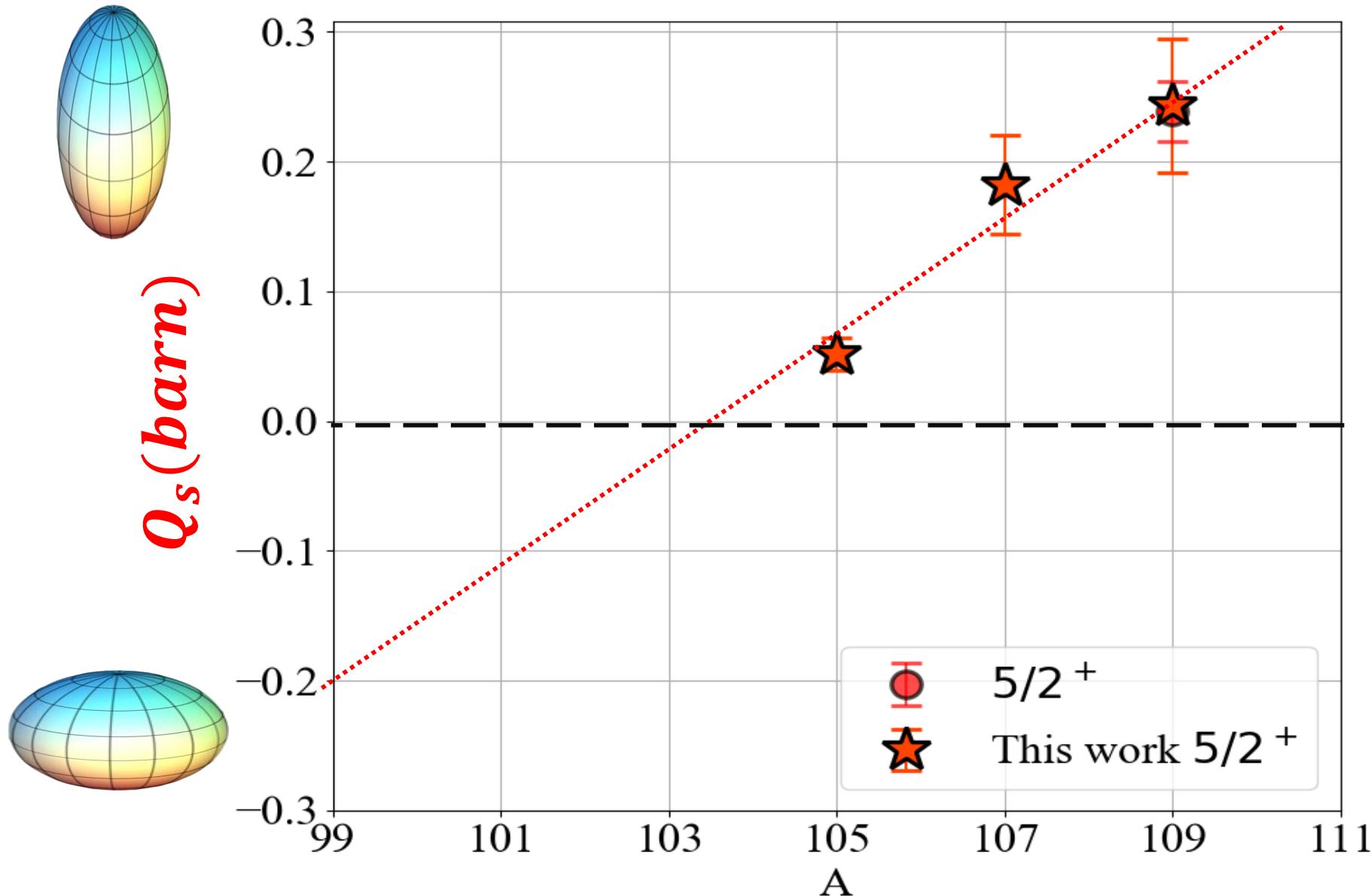


Nuclear moments are sensitive to the orbital of the unpaired nucleon

Level ordering from hyperfine structures



Spectroscopic quadrupole moments

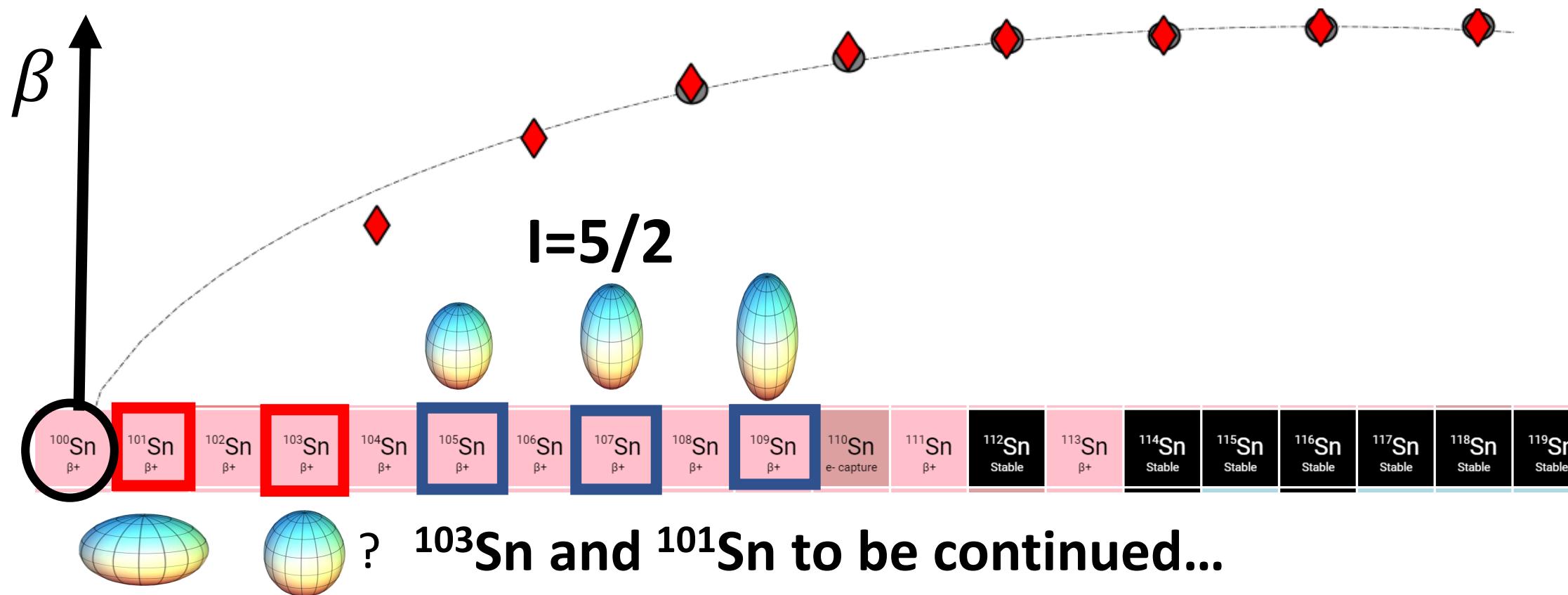


Conclusions:

Collectivity? Clearly reduced collectivity towards ^{100}Sn

Level ordering? Single particle behaviour down to ^{105}Sn occupying the $d5/2$ orbital

→ Rigid shell closure at N=50



Thanks for your attention

F.P. Gustafsson, N.Rondelez, R.F. Garcia Ruiz, S.W. Bai, J. Billowes, C.L. Binnersley, M.L. Bissell, L. Caceres, T.E. Cocolios, B.S. Cooper, G.J. Farooq-Smith, K.T. Flanagan, A. Galindo Uribarri, S. Franchoo, R.F. Garcia Ruiz, R.P. de Groote, Á. Koszorús, K. König, G. Neyens, C.M. Ricketts, E. Romero Romero, T. Tratajczyk, A.R. Vernon, S.G. Wilkins, Q. Wang and X.F. Yang



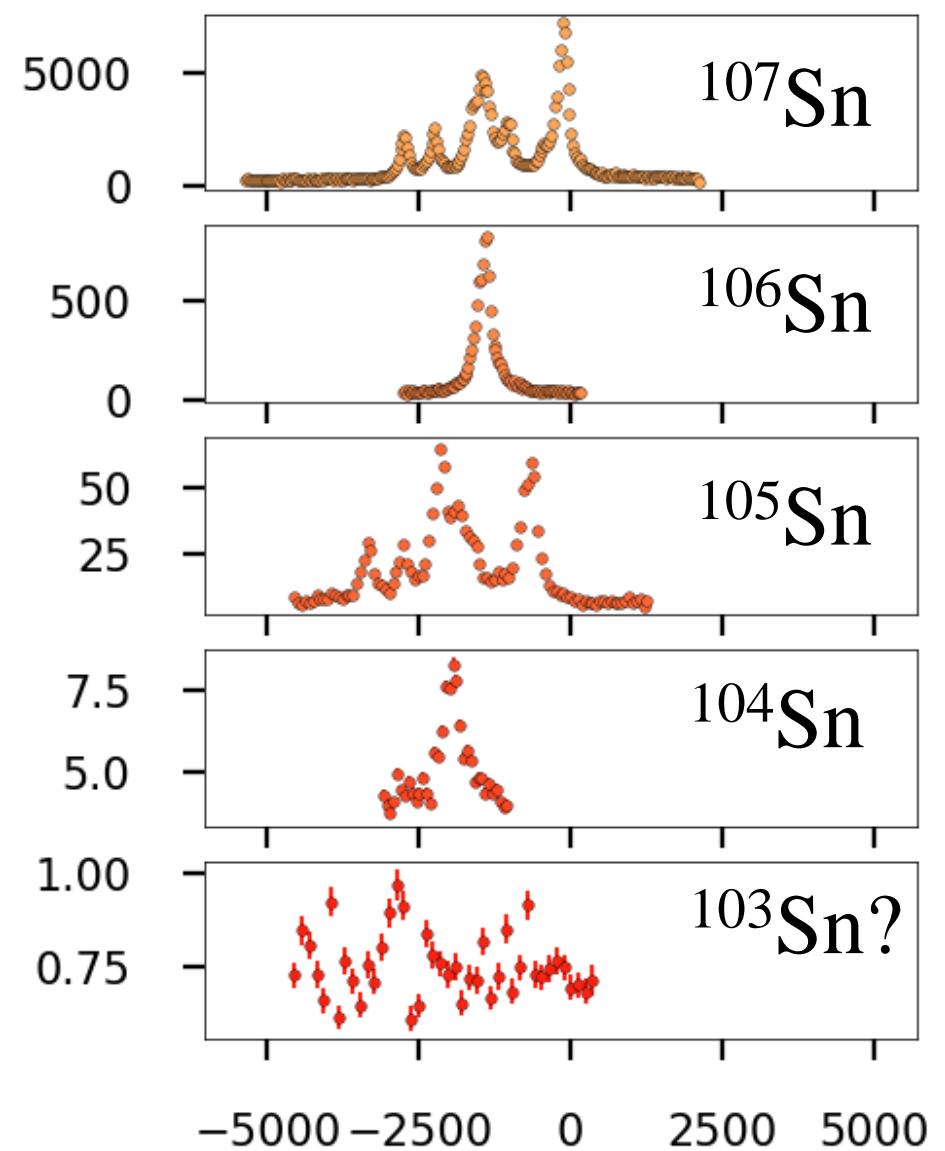
Outlook: ^{103}Sn and beyond...

Roughly 1/700 efficiency from ISCOOL

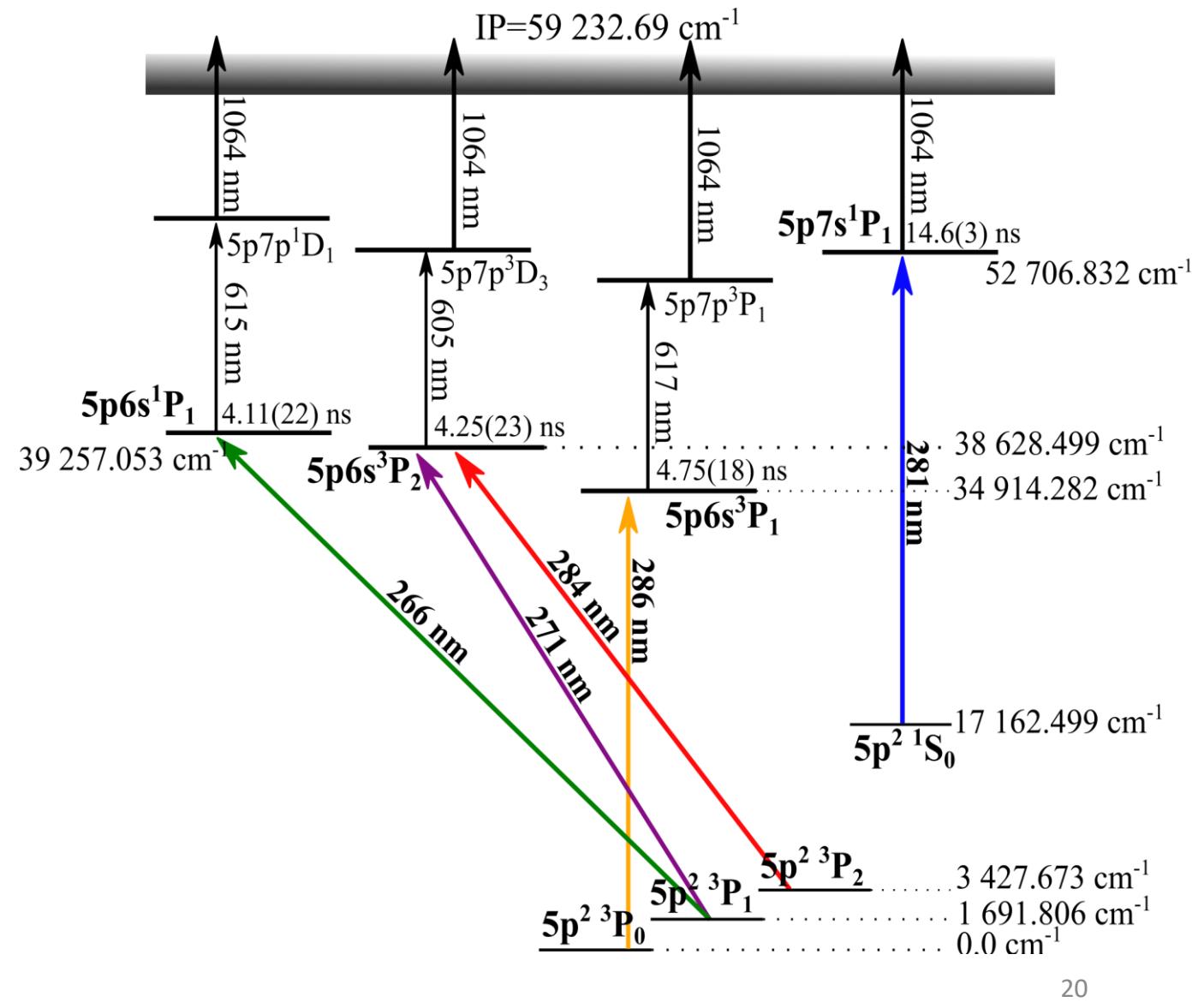
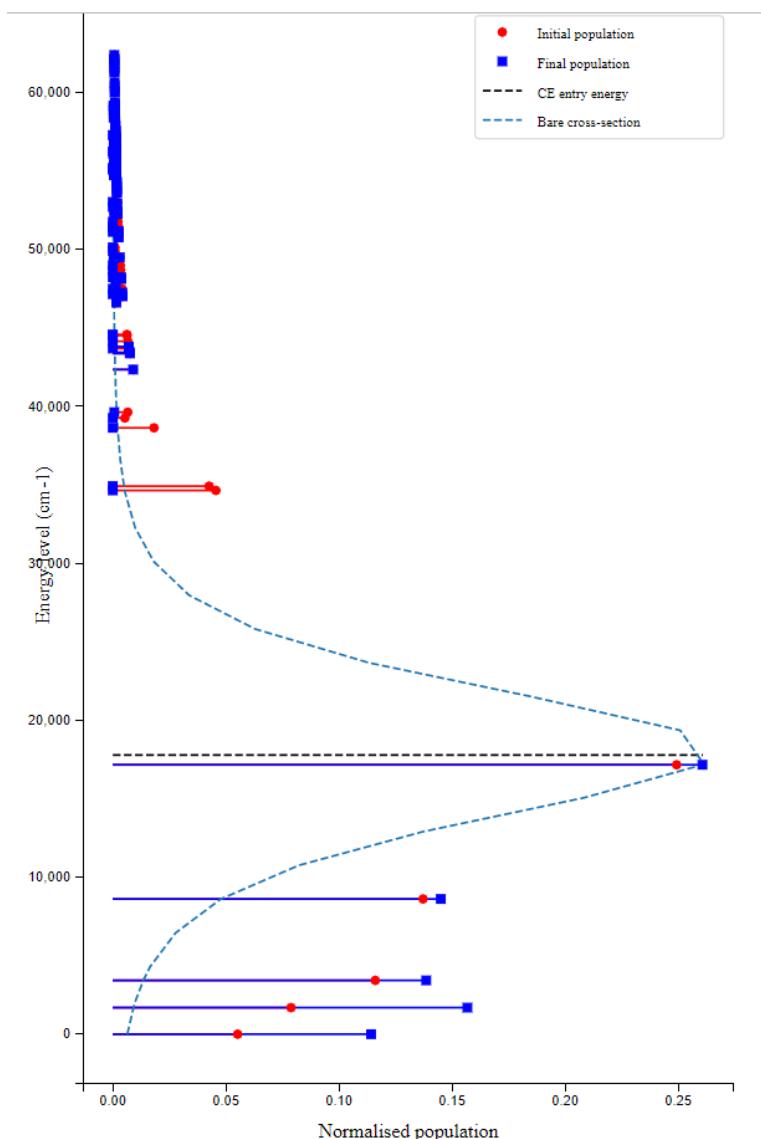
Isobaric contamination contributing to background

Options:

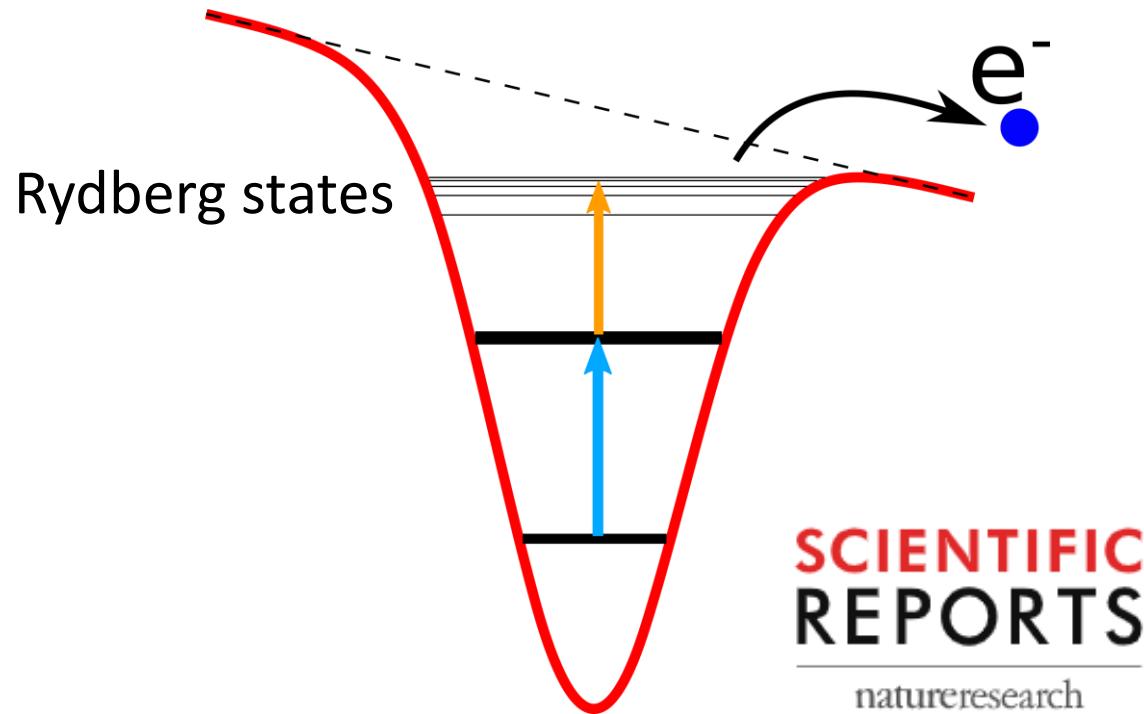
- Optical pumping, Ion-ionization, anion spectroscopy..
- Field-ionization from Rydberg states..



Population in probed atomic states



Field-ionization from rydberg states

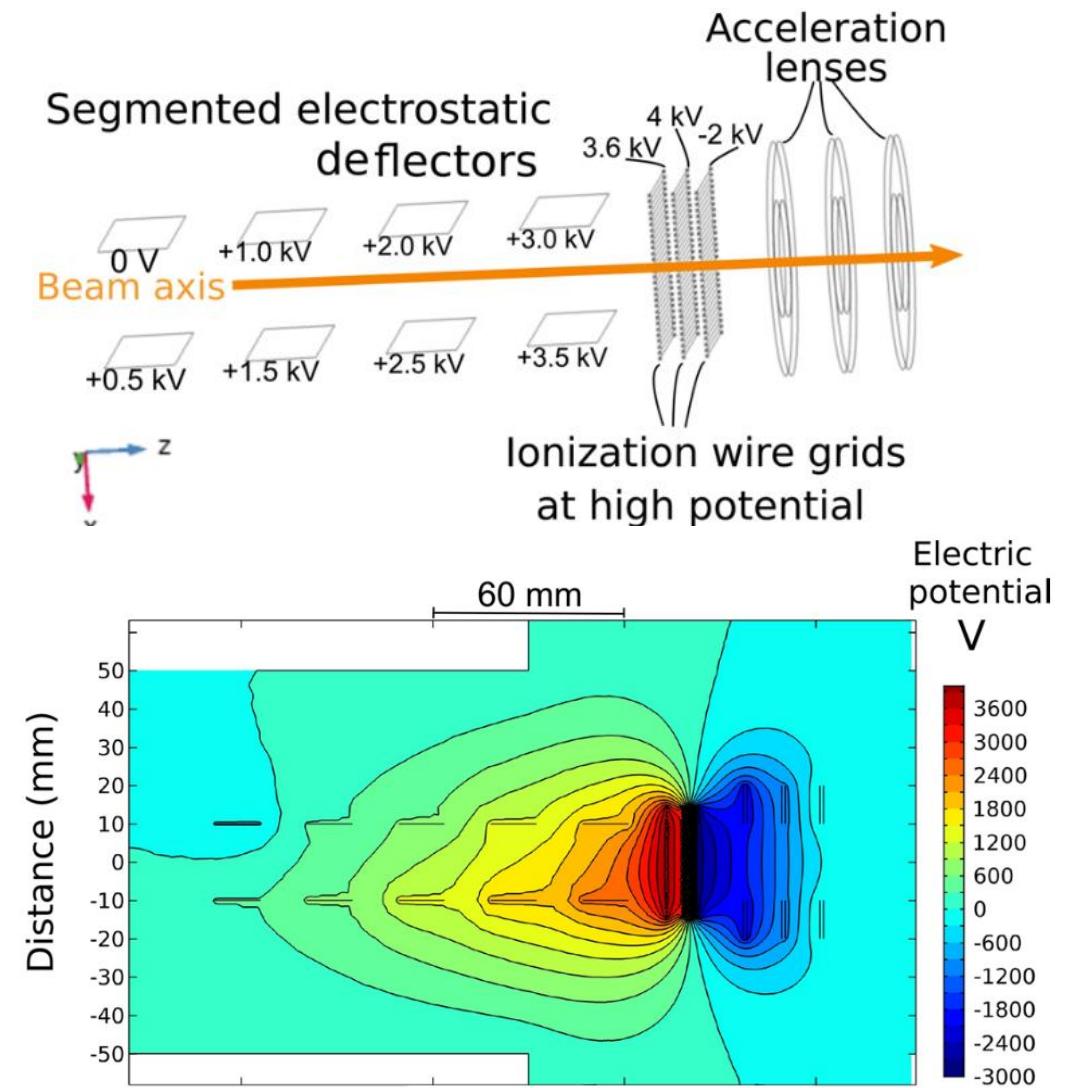


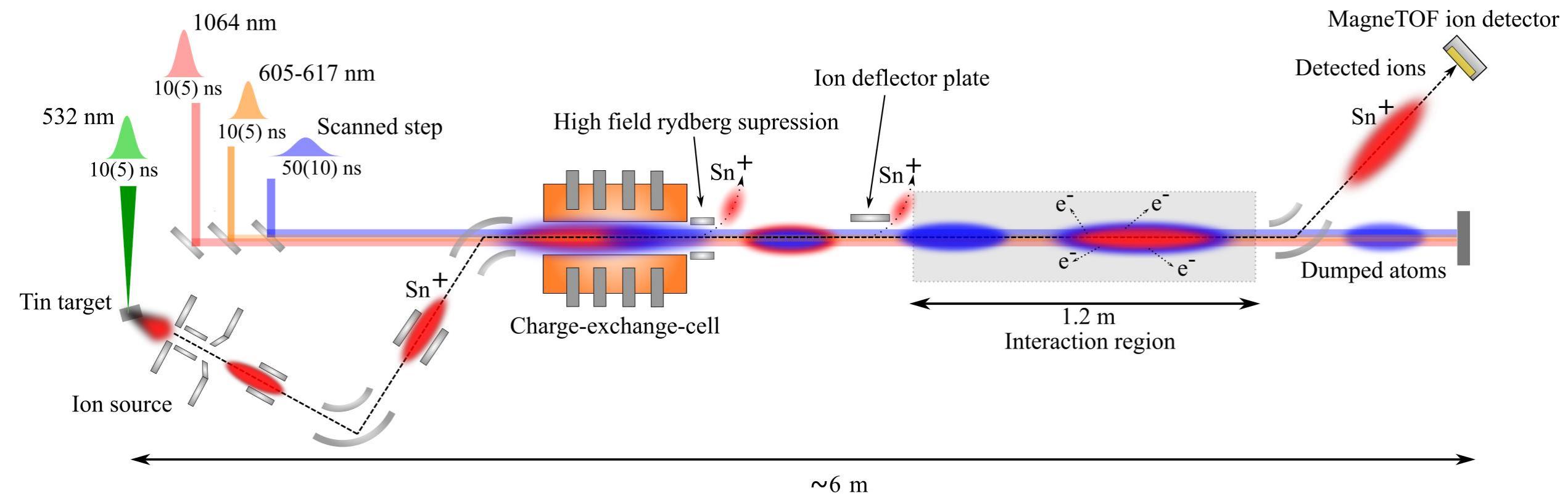
**SCIENTIFIC
REPORTS**
nature research

Check for updates

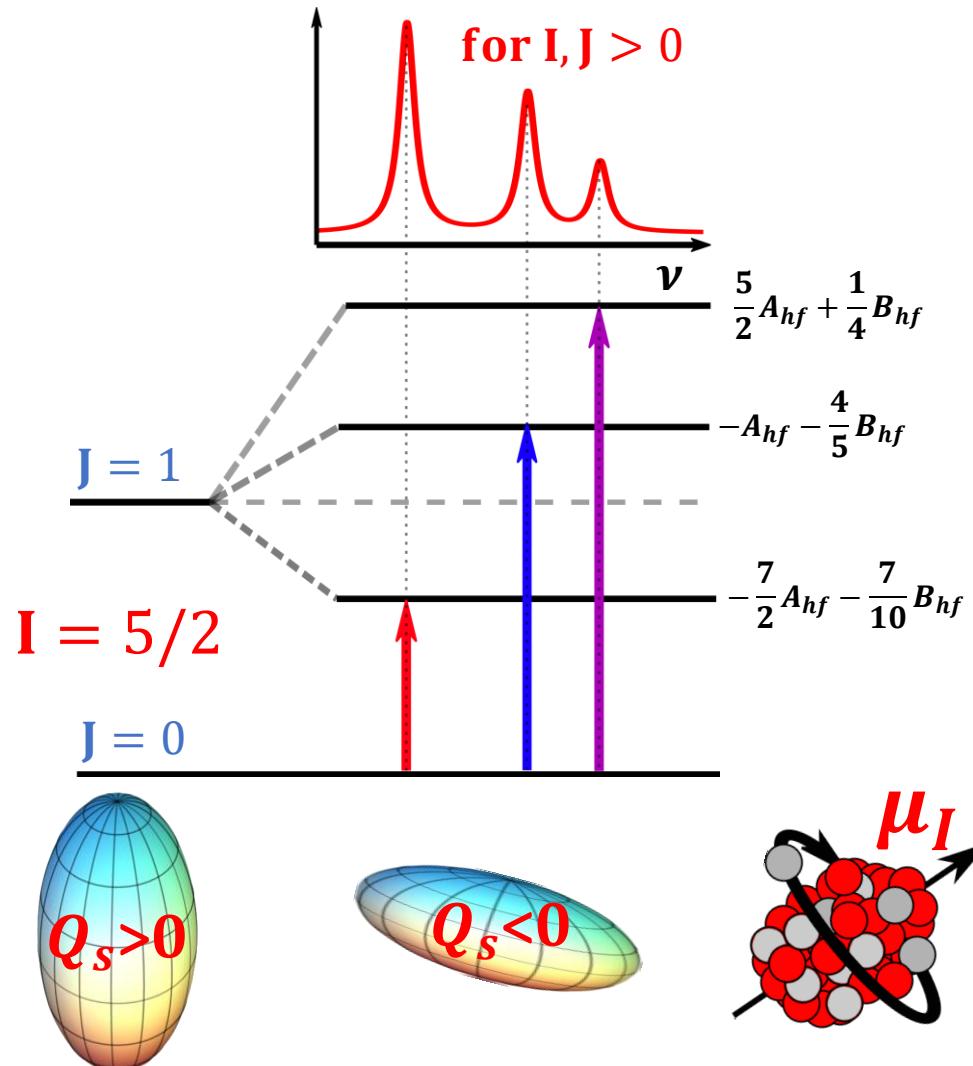
**Laser spectroscopy of indium
Rydberg atom bunches by electric
field ionization**

A. R. Vernon¹, C. M. Ricketts², J. Billowes², T. E. Cocolios¹, B. S. Cooper^{2,8}, K. T. Flanagan^{2,8}, R. F. Garcia Ruiz^{3,4}, F. P. Gustafsson¹, G. Neyens^{1,3}, H. A. Perrett², B. K. Sahoo⁵, Q. Wang⁶, F. J. Waso⁷ & X. F. Yang⁹





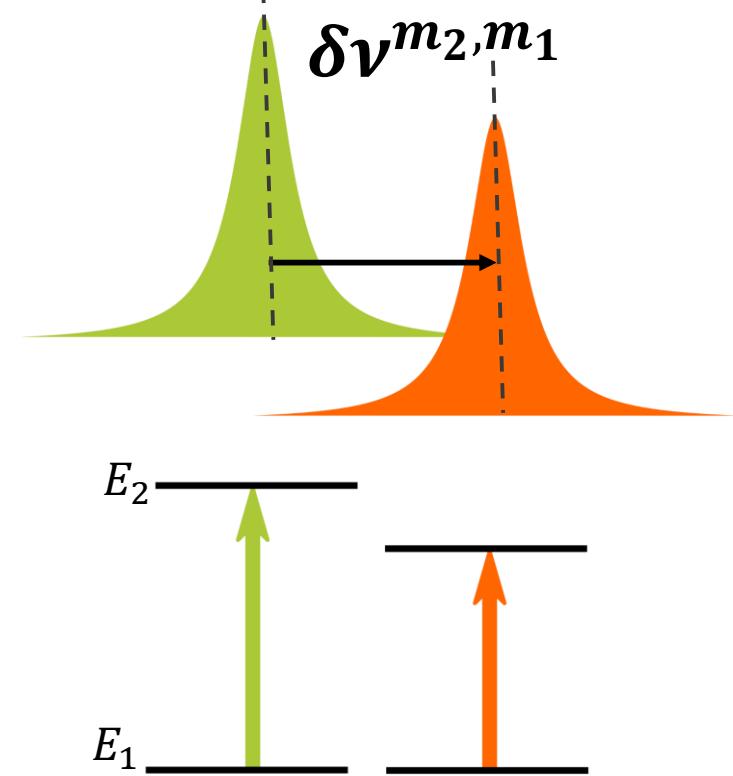
Hyperfine structure



Nuclear moments and spin: μ_I, I, Q_s

Electronic factors: A_0, q

Isotope shift

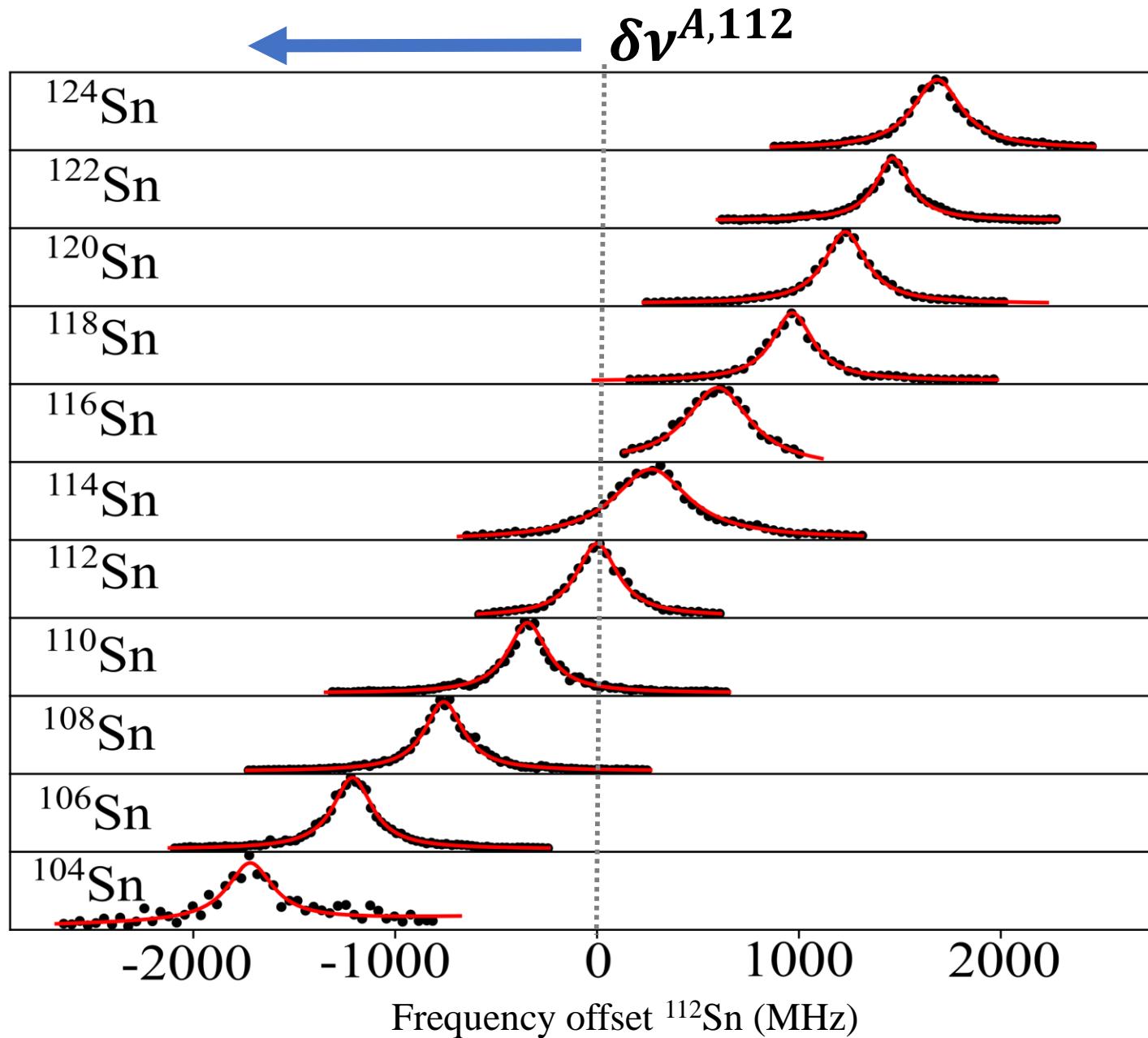


Nuclear charge radii: $\delta\langle r^2 \rangle$

Electronic factors: F_λ, k_{ms}

Dynamic deformation

Even-even tin isotopes $I=0$



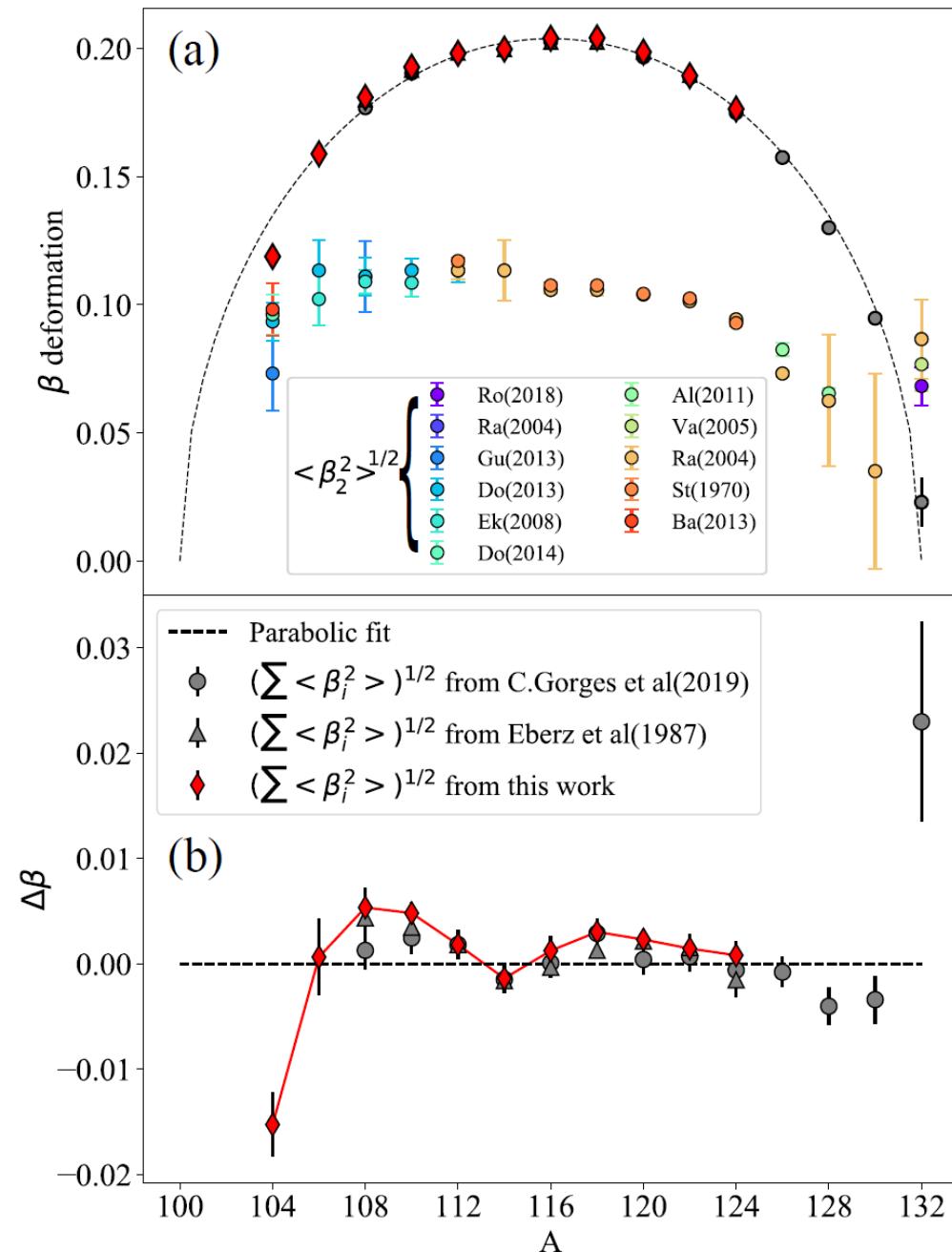
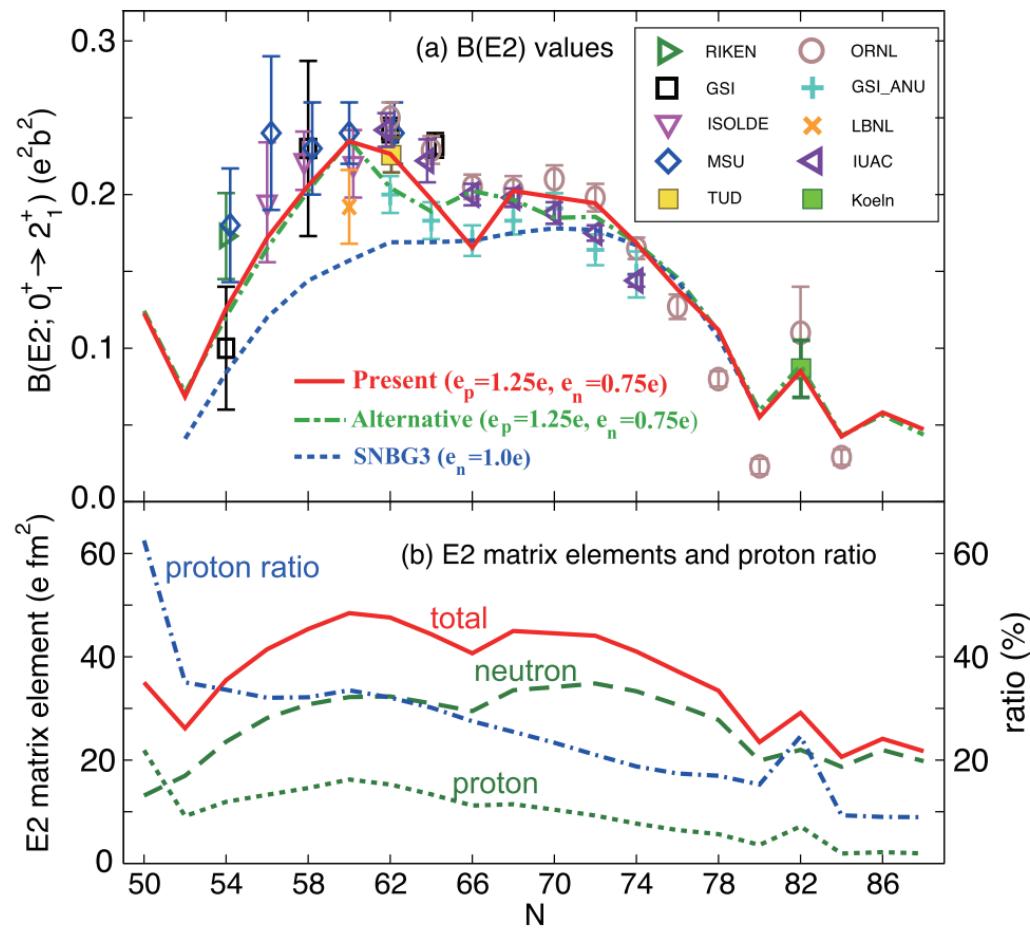
Calculated
electronic factors:

$$F_\lambda, k_{ms}$$



$$\delta\langle r^2 \rangle^{A,112}$$

Collectivity of tin



Beta deformation parameter

From IS:

From $B(E2: 0 \rightarrow 2^+)$:

$$\delta\langle r^2 \rangle_{Exp}^{A,A'} = \delta\langle r^2 \rangle_{sph}^{A,A'} + \frac{5}{4\pi} \langle r^2 \rangle_{sph}^A \sum \langle \beta_i^2 \rangle$$

$$\langle \beta_2^2 \rangle^{\frac{1}{2}} = B(E2)^{\frac{1}{2}} \left[\frac{4\pi}{5Z\langle r^2 \rangle_{ch}} \right]$$

$$\left(\sum \langle \beta_i^2 \rangle \right)^{\frac{1}{2}} = \frac{4\pi}{5\langle r^2 \rangle_{sph}^A} \left(\delta\langle r^2 \rangle_{Exp}^{A,A'} - \delta\langle r^2 \rangle_{sph}^{A,A'} \right)$$

Atomic physics

Atomic calculations:

Two theoretical approaches for calculating atomic factors:

Relativistic FSCC →

A_0, F_λ and q

CI+MBPT →

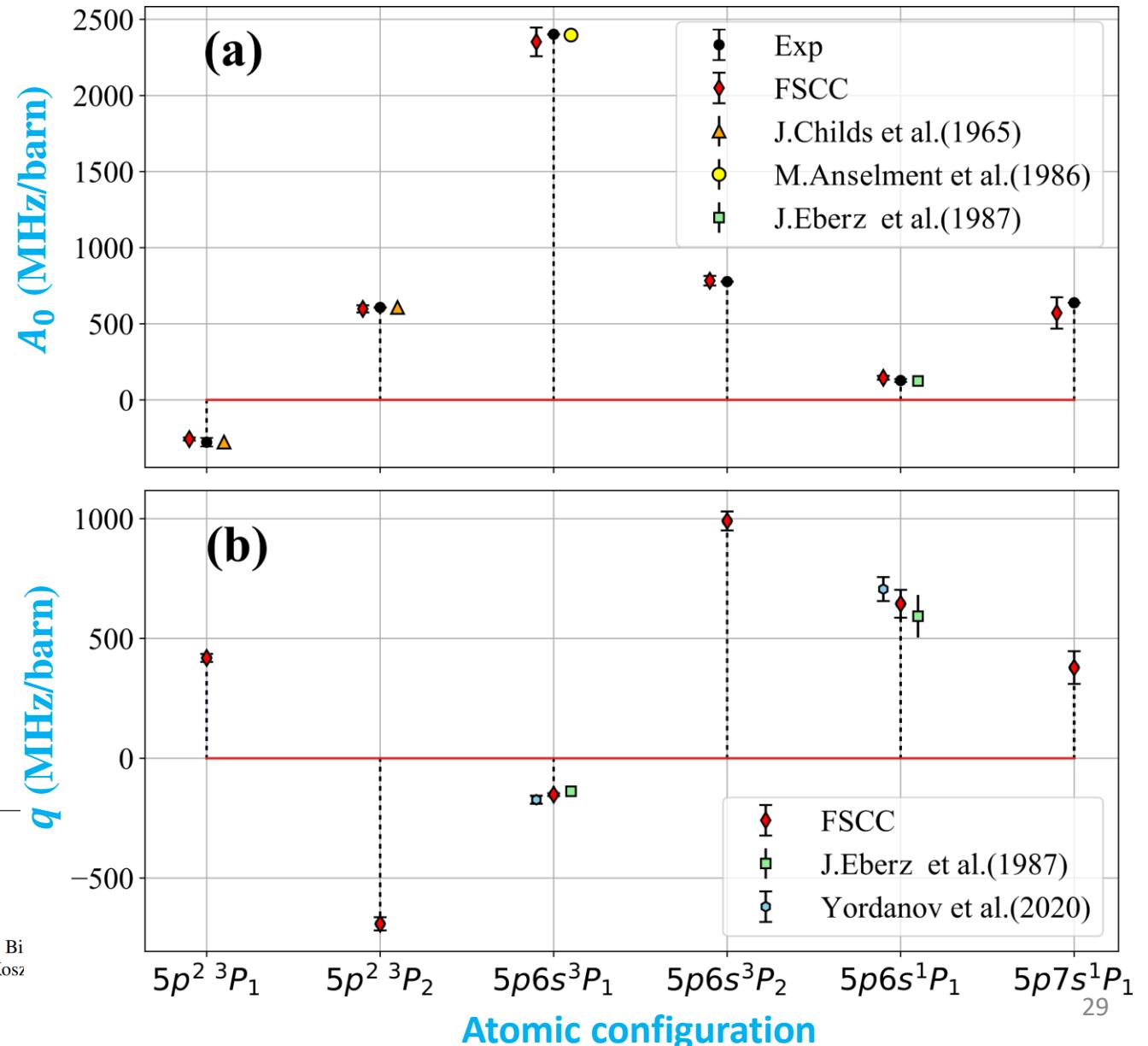
k_{ms}

Excellent agreement!

PHYSICAL REVIEW A 102, 052812 (2020)

Tin resonance-ionization schemes for atomic- and nuclear-structure studies

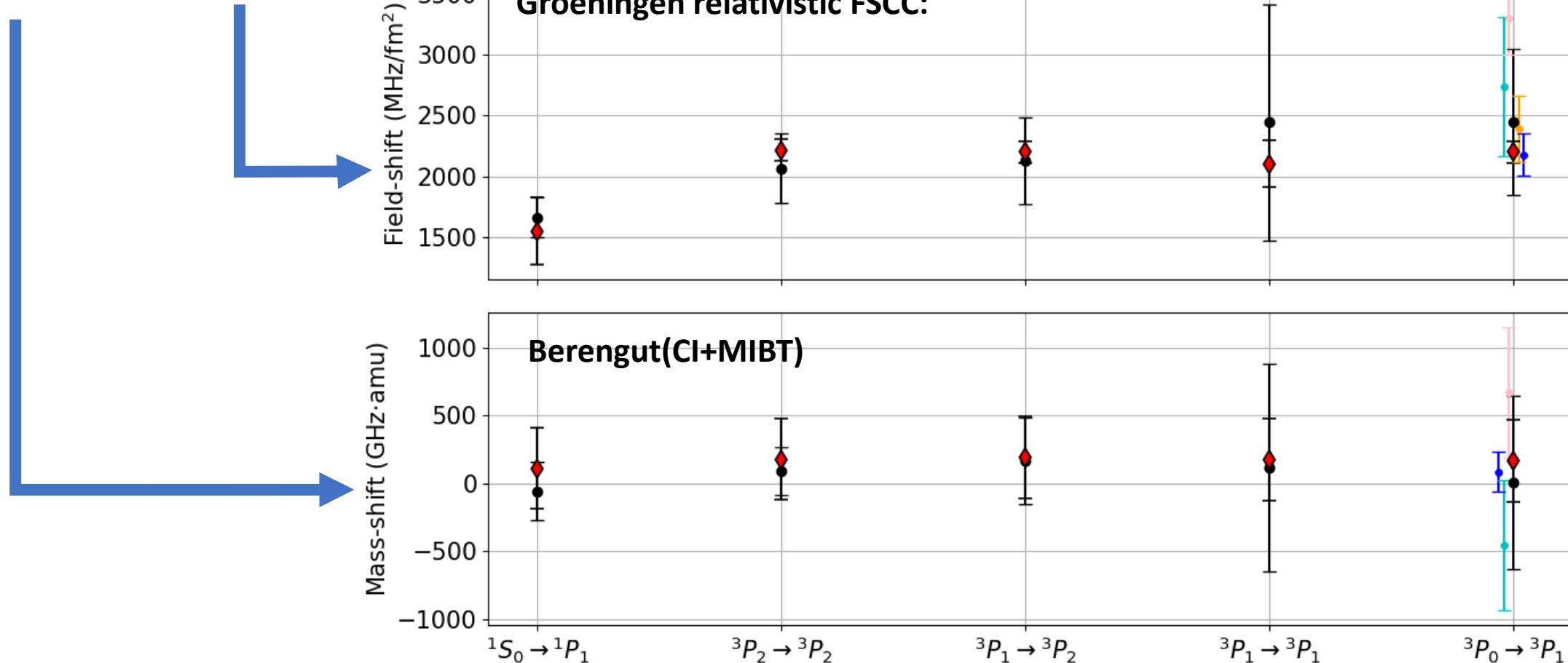
F. P. Gustafsson¹, C. M. Ricketts¹, M. L. Reitsma¹, R. F. Garcia Ruiz^{4,5}, S. W. Bai⁶, J. C. Berengut^{1,7,8}, J. Bi¹, C. L. Binningsley², A. Borschevsky^{1,3}, T. E. Cocolios¹, B. S. Cooper², R. P. de Groot⁹, K. T. Flanagan^{2,10}, Á. Koszeghy¹¹, G. Neyens¹⁰, H. A. Perrett², A. R. Vernon^{1,2}, Q. Wang^{5,†}, S. G. Wilkins¹¹, and X. F. Yang^{1,6}



Field and mass shifts:

$$\delta\nu^{A,A'} = k_{ms} \frac{A' - A}{AA'} + F_\lambda \delta\langle r^2 \rangle^{A,A'}$$

	Exp		Gorges(2019)		Ebertz(1986)
	Theory		Anselment(1986)		Landolt-Börnstein(2004)

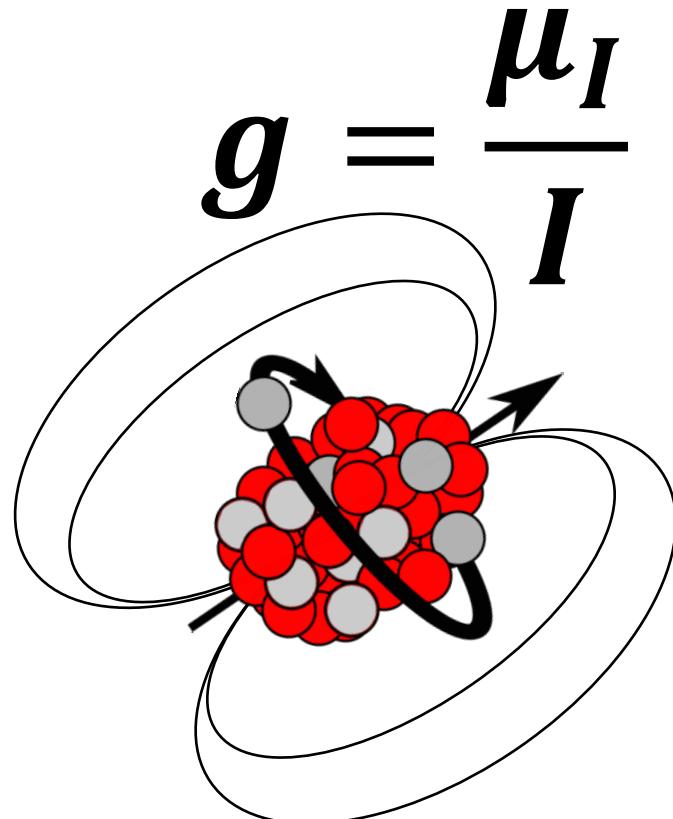


Nuclear Moments

Odd-even nuclei

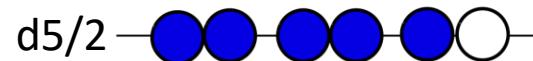
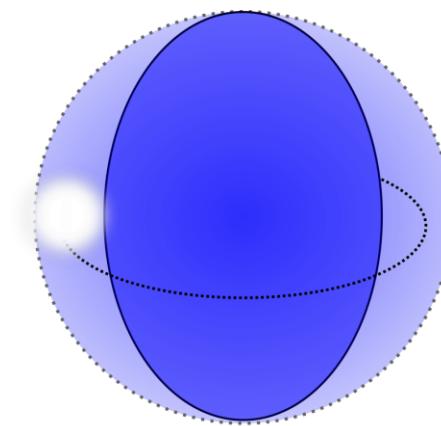
Microscopic structure from nuclear moments

Sensitivity to orbital of unpaired nucleon

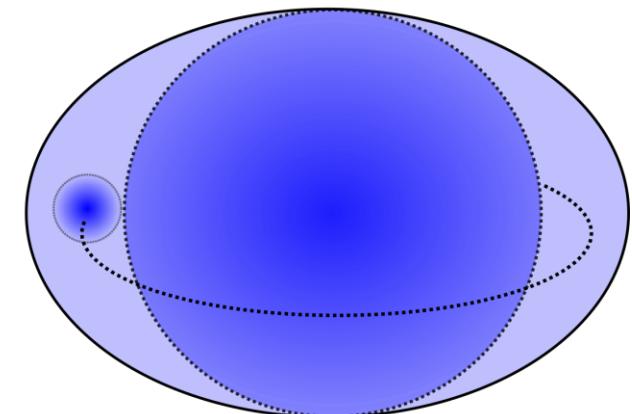


Electric quadrupole moments

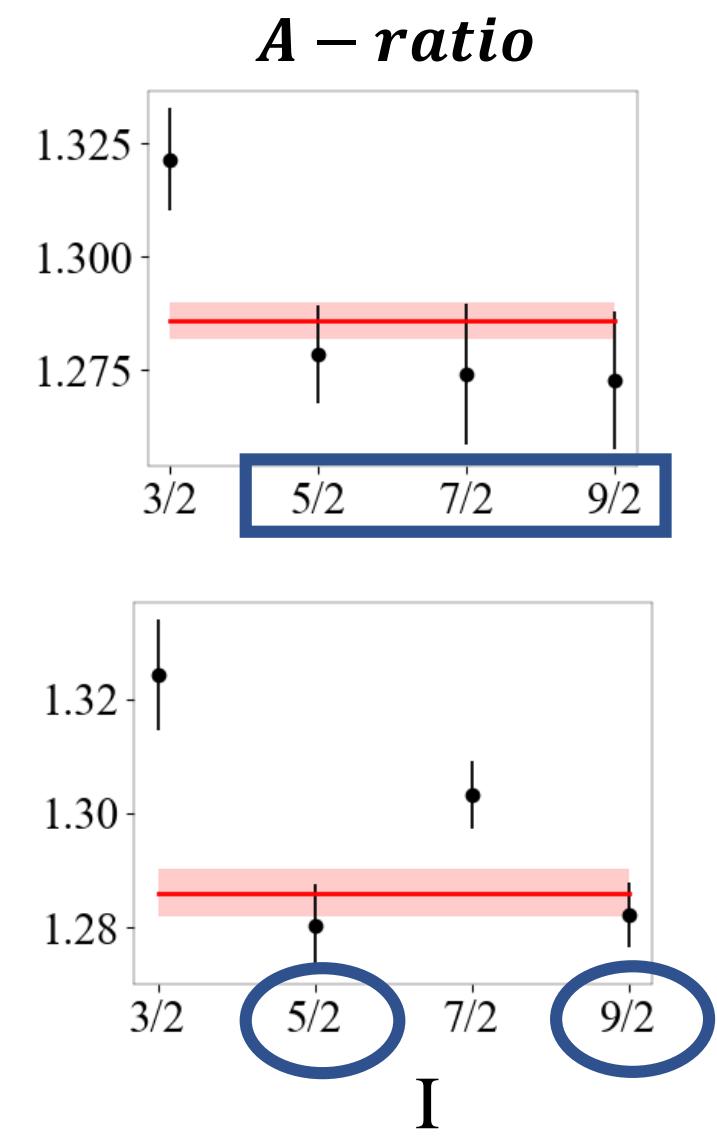
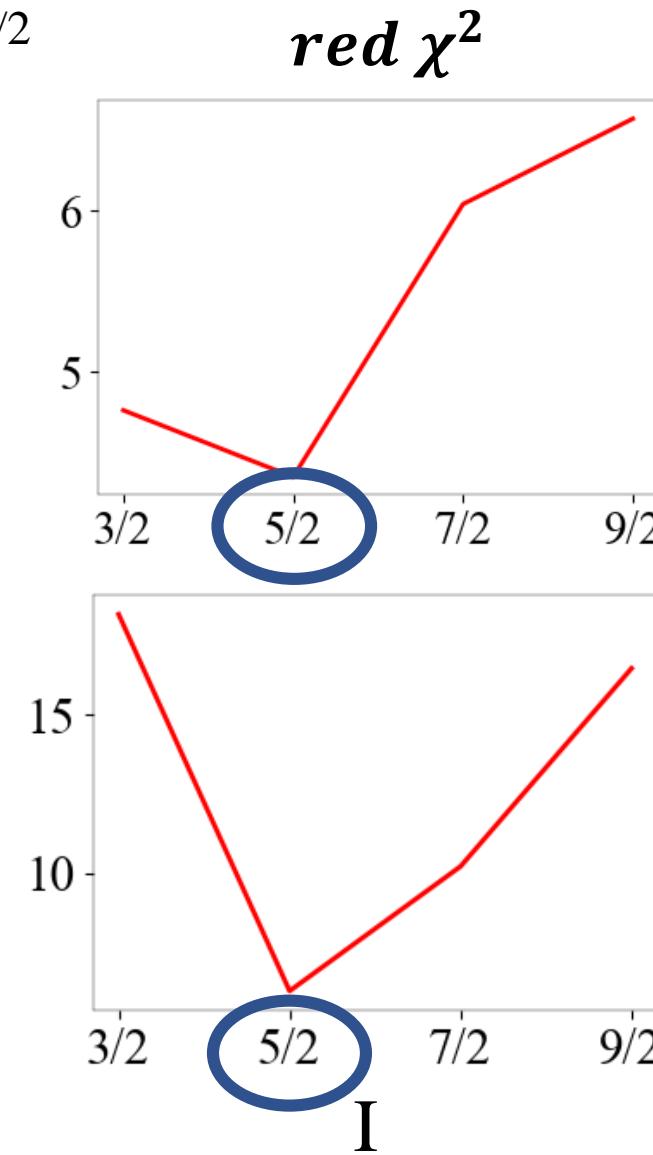
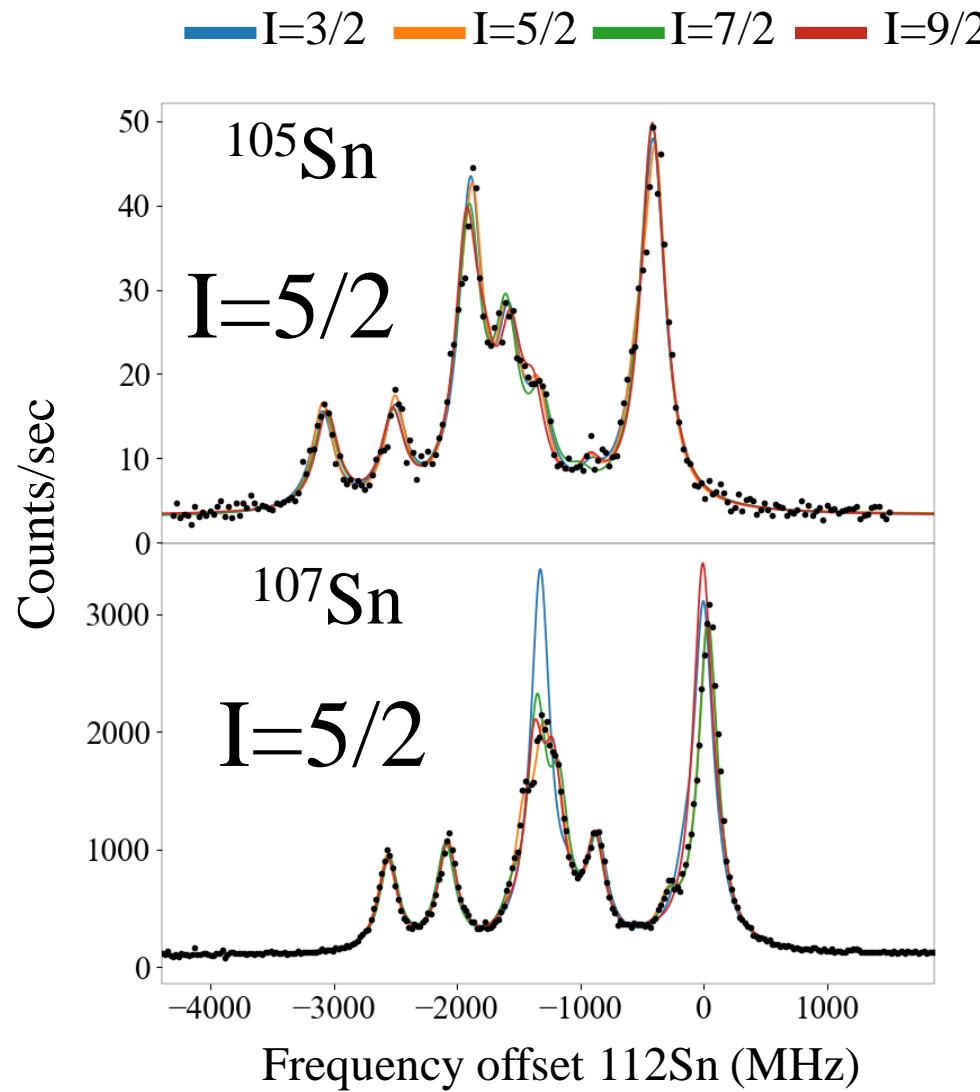
$$Q_s > 0$$



$$Q_s < 0$$

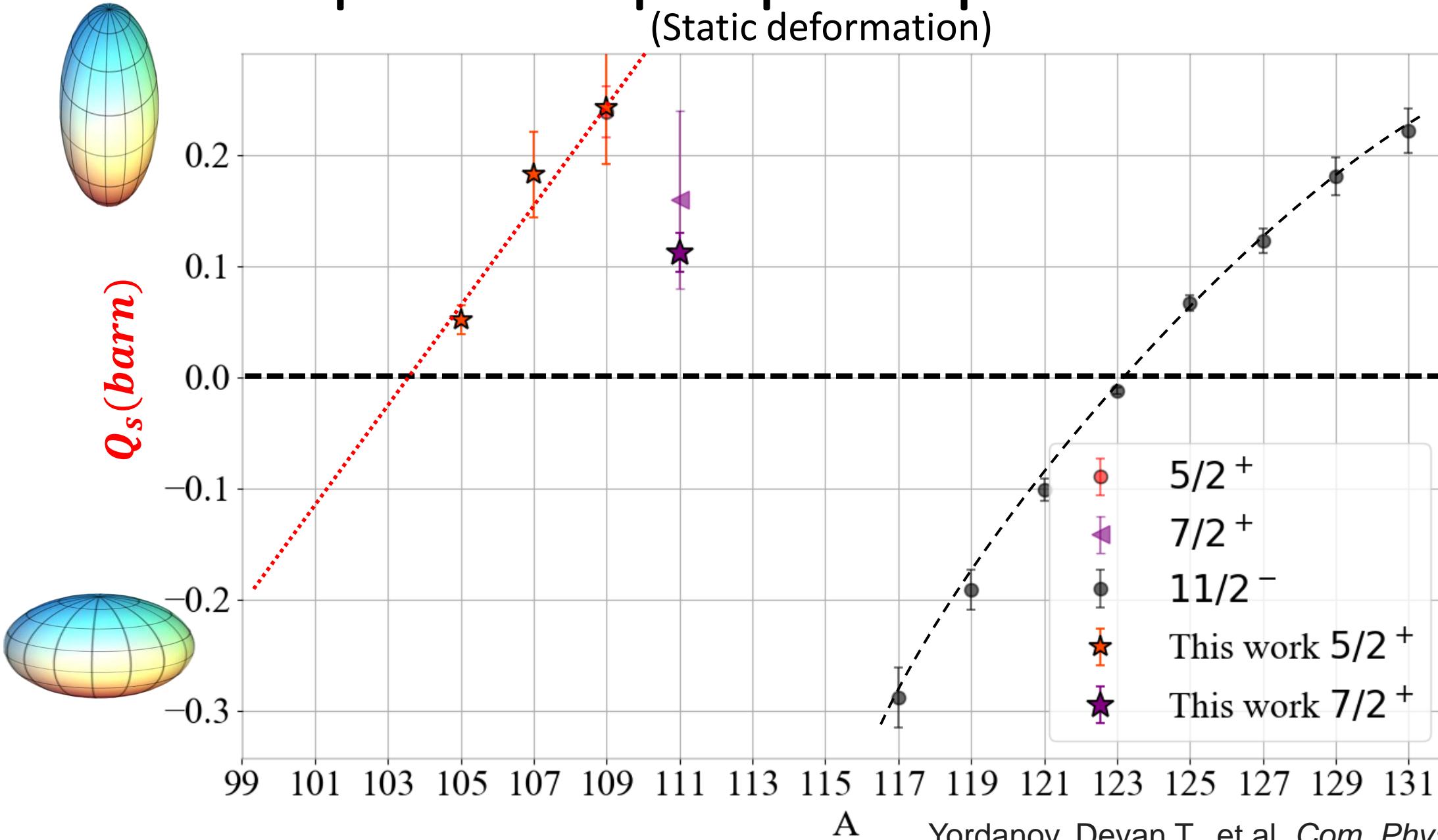


Spin assignment of $^{107,105}\text{Sn}$

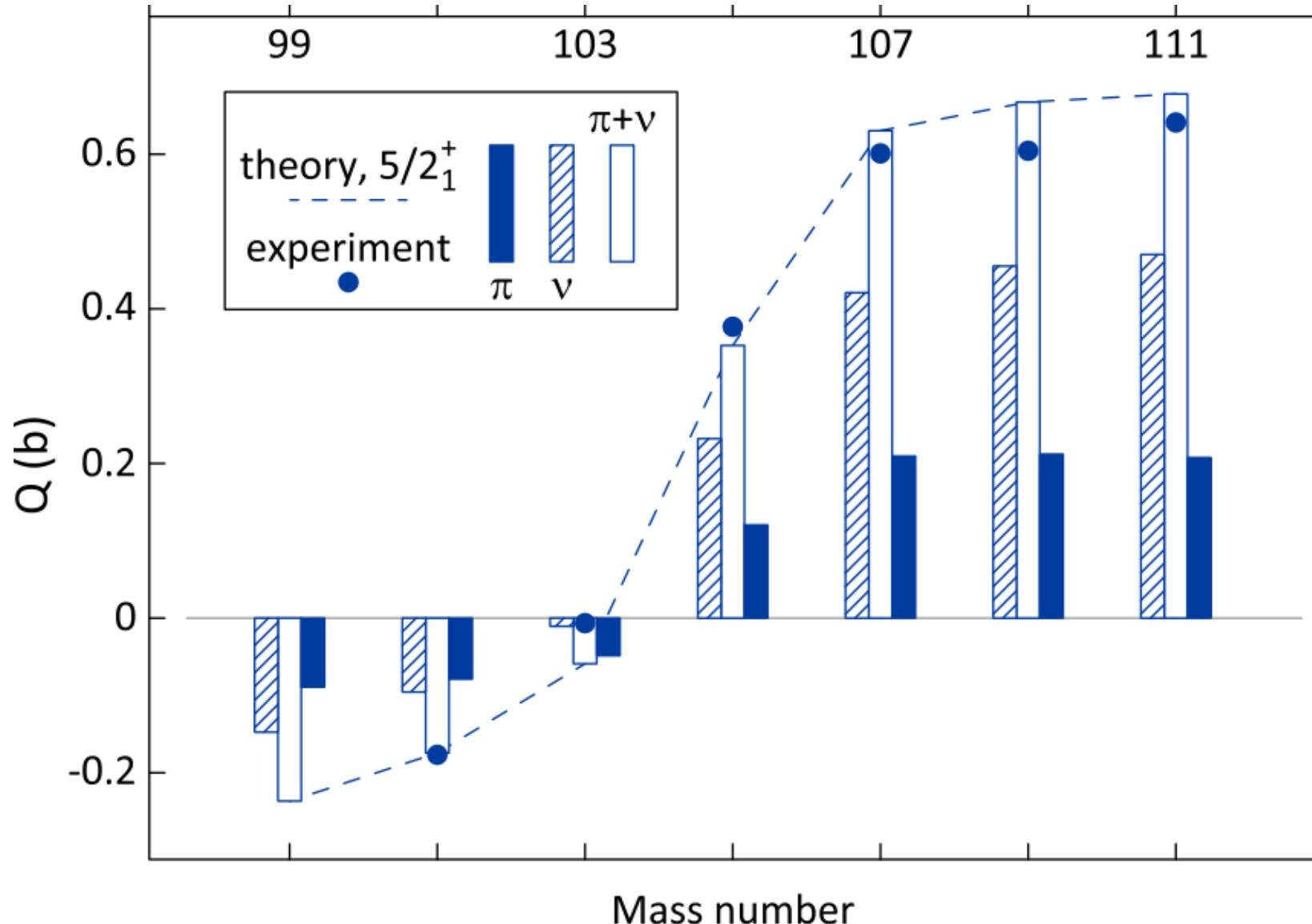


Spectroscopic quadrupole moments

(Static deformation)



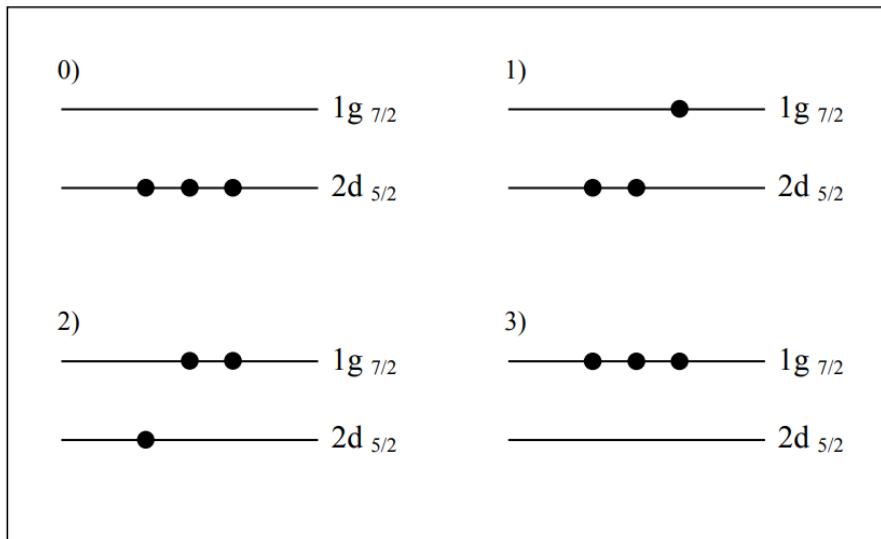
Cadmium d_{5/2}



Seniority 3 ($d5/2$)³

$j_1 = 5/2$	$j_2 = 5/2$	$j_3 = 5/2$	M	
m_1	m_2	m_3		
$5/2$	$3/2$	$1/2$	$9/2$	$I = 9/2$
		$-1/2$	$7/2$	
		$-3/2$	$5/2$	
		$-5/2$	$3/2$	
$5/2$	$1/2$	$-1/2$	$5/2$	$I = 5/2$
		$-3/2$	$3/2$	
		$-5/2$	$1/2$	
$5/2$	$-1/2$	$-3/2$	$1/2$	
		$-5/2$	$-1/2$	
$5/2$	$-3/2$	$-5/2$	$-3/2$	
$3/2$	$1/2$	$-1/2$	$3/2$	$I = 3/2$
		$-3/2$	$1/2$	
		$-5/2$	$-1/2$	
$3/2$	$-1/2$	$-3/2$	$-1/2$	
		$-5/2$	$-3/2$	
$3/2$	$-3/2$	$-5/2$	$-5/2$	
$1/2$	$-1/2$	$-3/2$	$-3/2$	
		$-5/2$	$-5/2$	
$1/2$	$-3/2$	$-5/2$	$-7/2$	
$-1/2$	$-3/2$	$-5/2$	$-9/2$	

Seniority-3 in g7/2+d5/2



configuration	1/2 ⁺	3/2 ⁺	5/2 ⁺	7/2 ⁺	9/2 ⁺	11/2 ⁺	13/2 ⁺	15/2 ⁺	17/2 ⁺
$(d_{5/2})^3$		X	X		X				
$(d_{5/2})^2_{0^+} + g_{7/2}$				X					
$(d_{5/2})^2_{2^+} + g_{7/2}$		X	X	X	X	X			
$(d_{5/2})^2_{4^+} + g_{7/2}$	X	X	X	X	X	X	X	X	
$d_{5/2} + (g_{7/2})^2_{0^+}$			X						
$d_{5/2} + (g_{7/2})^2_{2^+}$	X	X	X	X	X				
$d_{5/2} + (g_{7/2})^2_{4^+}$		X	X	X	X	X	X		
$d_{5/2} + (g_{7/2})^2_{6^+}$			X	X	X	X	X	X	X
$(g_{7/2})^3$		X	X	X	X	X		X	