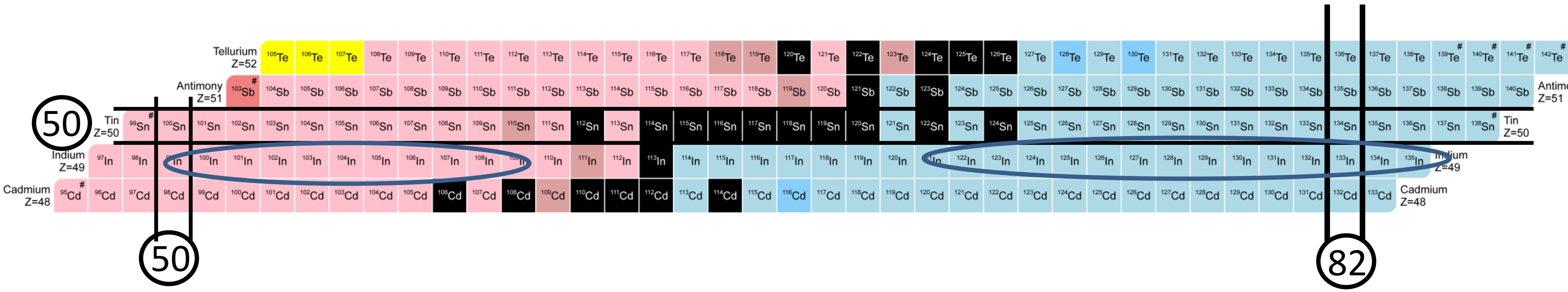
Laser Spectroscopy of exotic neutron-deficient indium (Z = 49) isotopes: approaching N = 50

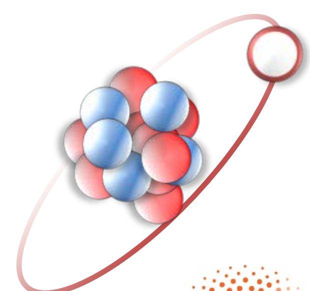


Addendum to (IS639)

Ronald Fernando Garcia Ruiz

The University of Manchester

CRIS Collaboration



MANCHESTER 1824

56th Meeting of the INTC

European Research Council
Established by the European Commission

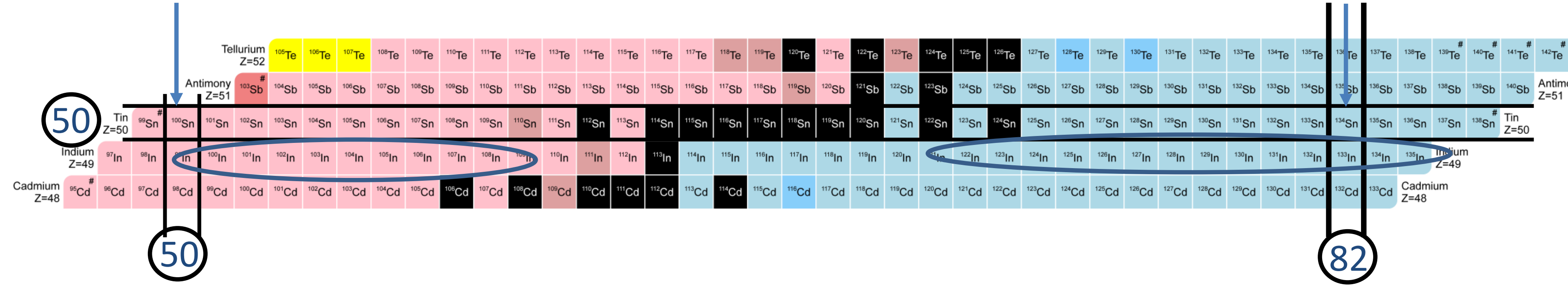
Motivation

Doubly "magic" ^{100}Sn

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

Doubly "magic" ^{132}Sn

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



Nuclear chart taken from http://people.physics.anu.edu.au/~ecs103/chart/index.php

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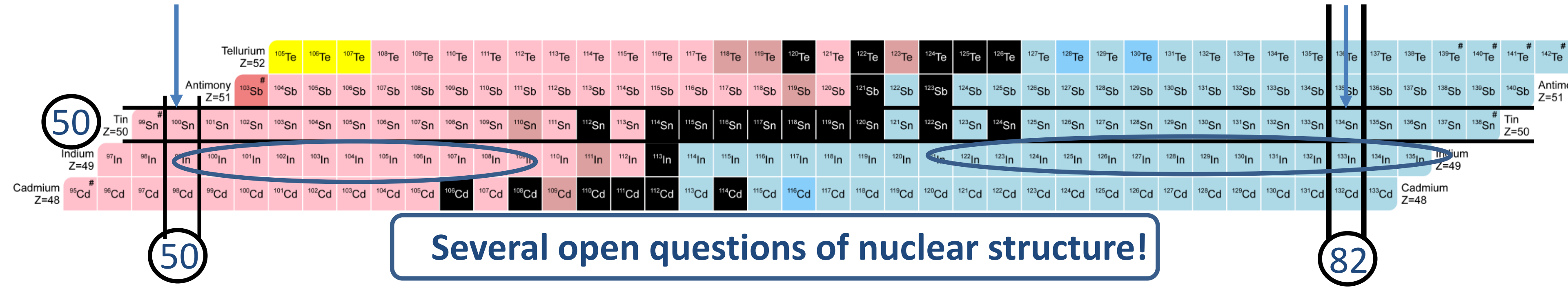

Several open questions of nuclear structure!

Nuclear chart taken from http://people.physics.anu.edu.au/~ecs103/chart/index.php

- **Evolution of collectivity / single particle approaching the N=Z=50 and N=82 shell closures?**
- **Robustness of N=Z=50 shell closures?**
  - Robust ? [Hinke *et al.* Nature 486, 341 (2012)] [Guastalla *et al.*, PRL 110, 172501 (2013)]
  - Soft? [Vaman *et al.*, PRL 99, 162501 (2007)] [Coraggio *et al.* PRC 91, 041301(R) (2015)]
- **Ordering of shell-model orbits**
  - Contradictory evidence! [Darby et al. PRL 105, 162502 (2010)] [Banu et al. PRC 72, 061305(R) (2005)] [Seweryniak et al. PRL 99, 022504 (2007)]
- **Proton-neutron interaction?**
- **Role of electro-weak currents?** [Yuan et al. PLB 762, 237 (2016)] [Rejmund et al. PLB 753, 86 (2016)]

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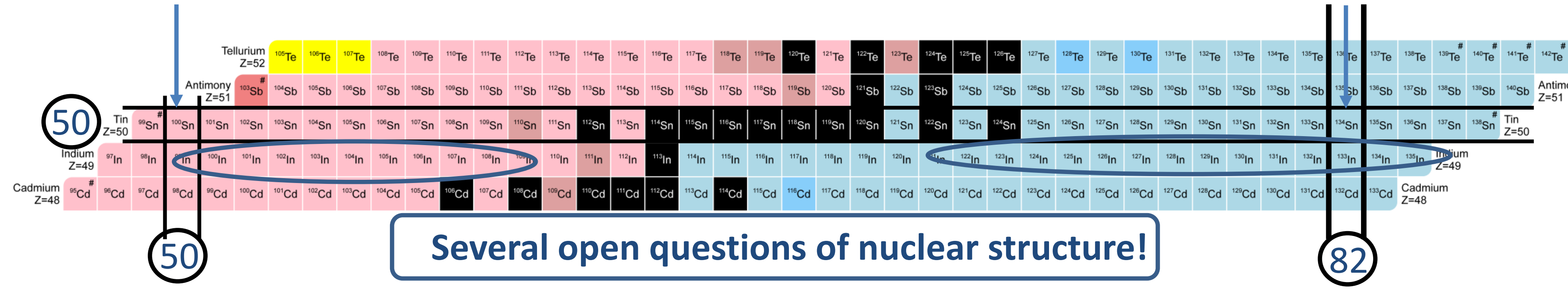

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Laser spectroscopy ⟹ I , $\Delta\langle r^2\rangle$, μ , Q

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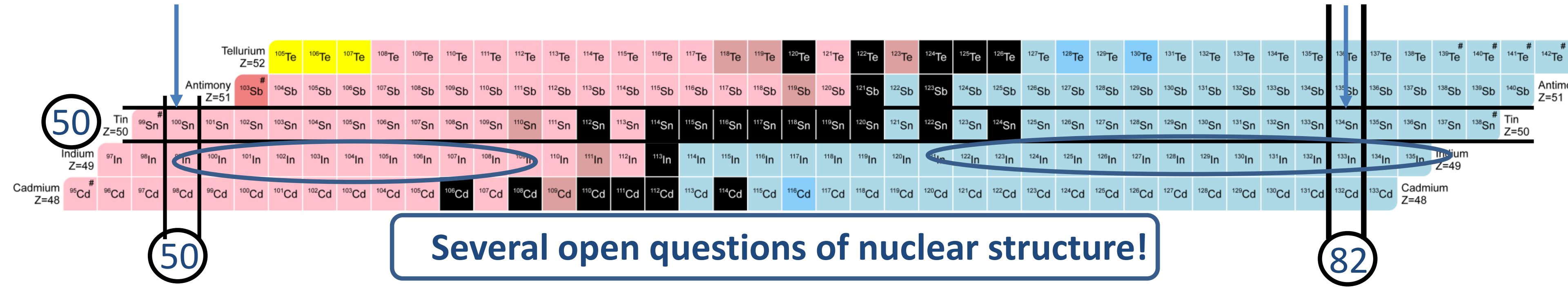

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Laser spectroscopy ⇒ I , $\Delta\langle r^2\rangle$, μ , Q

[Hagen et al, Nature Physics 12, 186 (2016)]
[Garcia Ruiz et al, Nature Physics 12, 594 (2016)]
[Stroberg et al. Phys. Rev. Lett. 118, 032502 (2017)]

Nuclear force
- Phenomenology
- Chiral effective field theory

Many-body methods
- Ab-initio
- Shell-model
- DFT

Electro-weak currents
- Effective neutron/proton charges
- Microscopic description of effective operators

Minutes of the 55th meeting of the INTC

- ✓ *The INTC clearly considers the entire proposed program of high scientific interest.*

- ✓ *Of particular interest is the study of the isotope ^{100}In for which a number of different theoretical calculations both from traditional shell model as well as ab-initio approaches are available.*

- ✓ *Since higher yields are anticipated for the most exotic cases on the neutron-rich side (as compared to the more ambitious ^{100}In) the UCx target run is considered to be the best starting point for this program.*

Main challenges: Low yields / high contamination

Mon 08-05-17 DAY

19:20

```
Yields by single beta measurement:

128In   1.7e+04 (laser on - laser off)

assuming everything else is Cs:
128Cs   3.7e+04 (laser off, 10s collection)
```

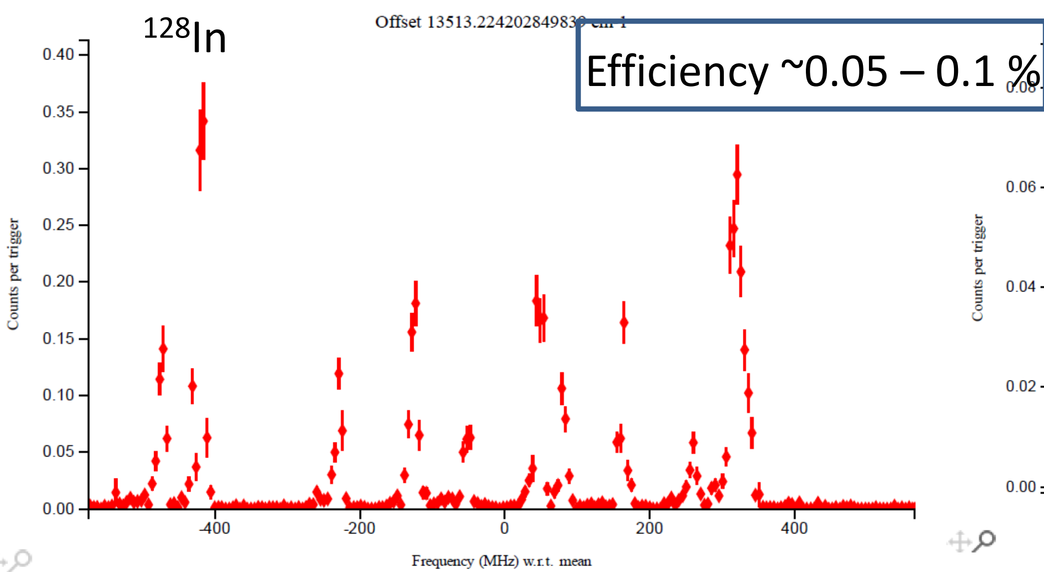
	Yield (ions/μC)		Yield (^{A}In)/^{A}Cs ratio	
A	Expected	Measured	Expected	Measured
^{128}In	$>10^5$	1.7×10^4	$>10^2$	0.45
^{129}In	$>10^4$	$\sim10^4$	$>10^2$	$1/10^3$
^{130}In	$>10^4$	5.3×10^3	$>10^2$	$<1/10^4$
^{131}In	$>10^4$	$\sim10^3$	>10	$<1/10^4$
^{132}In	$>10^4$	$\sim10^2$	$>1/10^2$	$<1/10^5$
^{133}In	$>10^{3i}$	-	$>1/10^3$	-
^{134}In	$>10^2$	-	$>1/10^4$	-

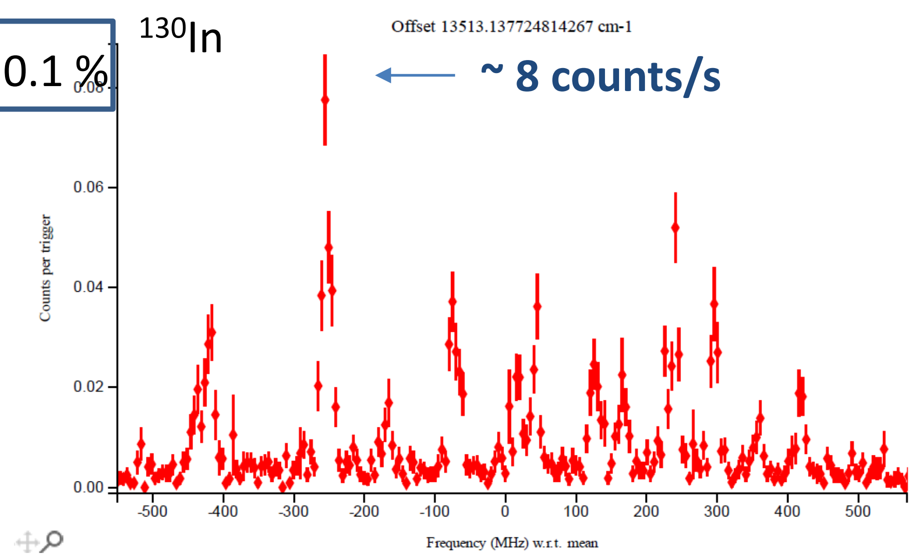
21:28

```
Estimated yields on this mass, assuming, that the 130Cs isomer with halflife of 29.21 m is detected:

130In   5.3e+03 (ppp)
130Cs   3.3e+06 (uA)

Now heating target to 2000C (550A)
```





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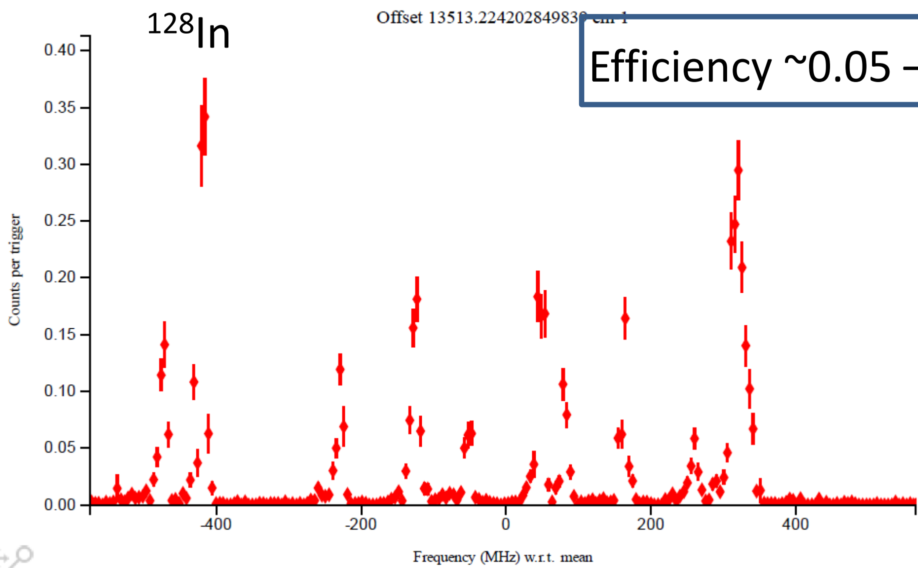
	Estimated yields on this mass, assuming, that the 130Cs isomer with halflife of 29.21 m is detected: 130In 5.3e+03 (ppp) 130Cs 3.3e+06 (uA) Now heating target to 2000C (550A)

- Yield/bck down by more than 10^3
- ^{129}In as hard as expected for ^{133}In

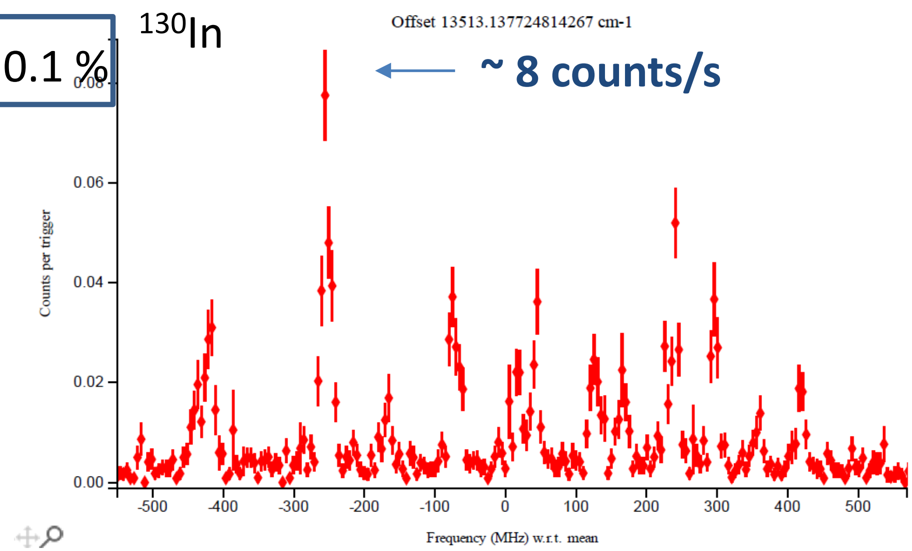
^{128}In

Efficiency ~0.05 – 0.1 %



^{130}In

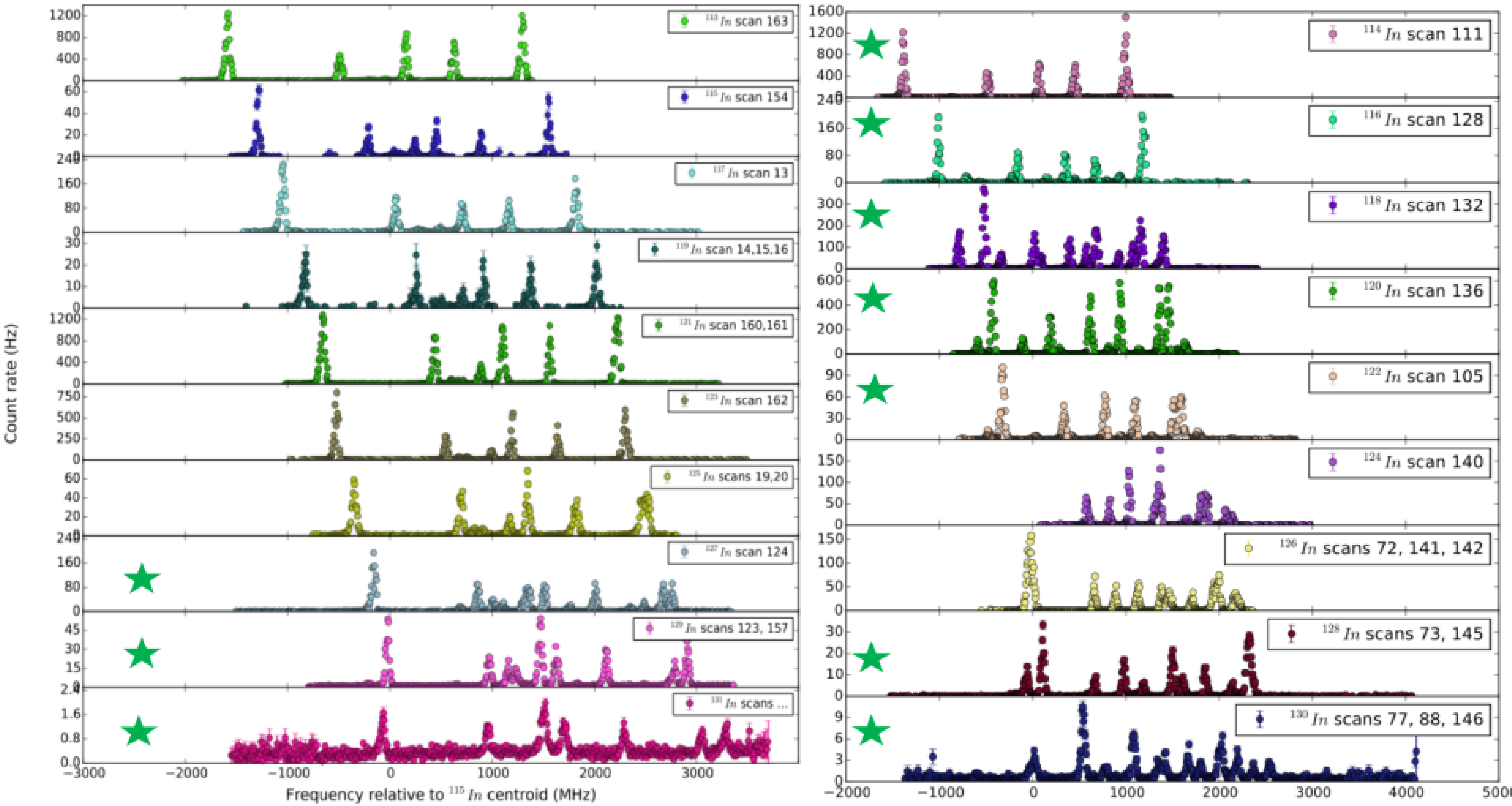
~ 8 counts/s



Results: CRIS First Experimental Campaign

Measurements from ^{113}In (N=64) up to ^{131}In (N=82)

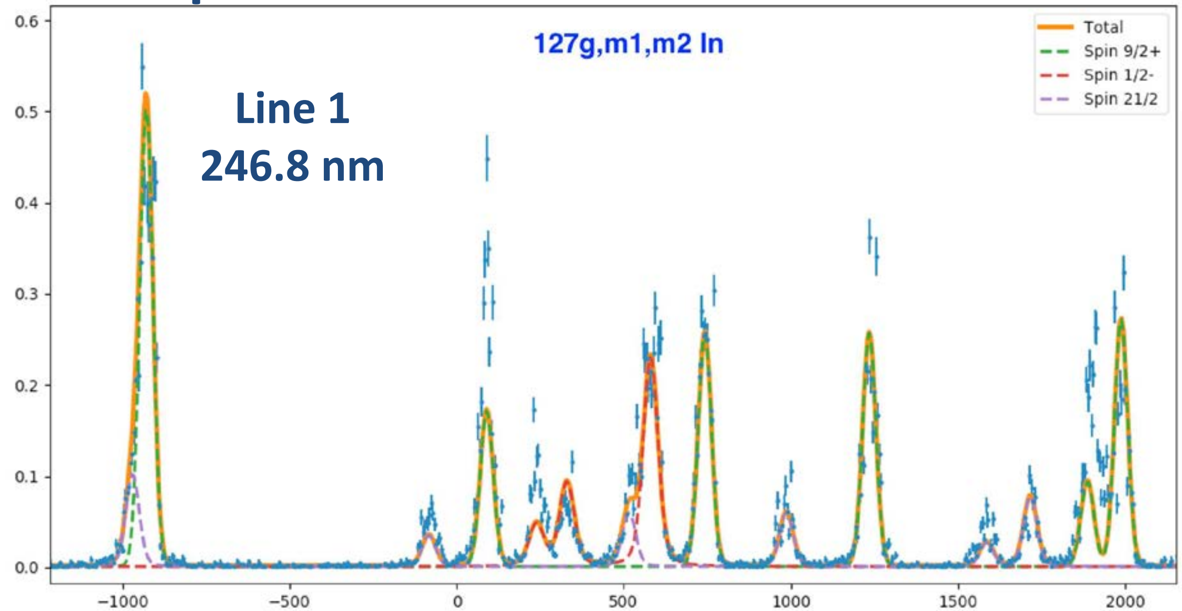
(New results ★)

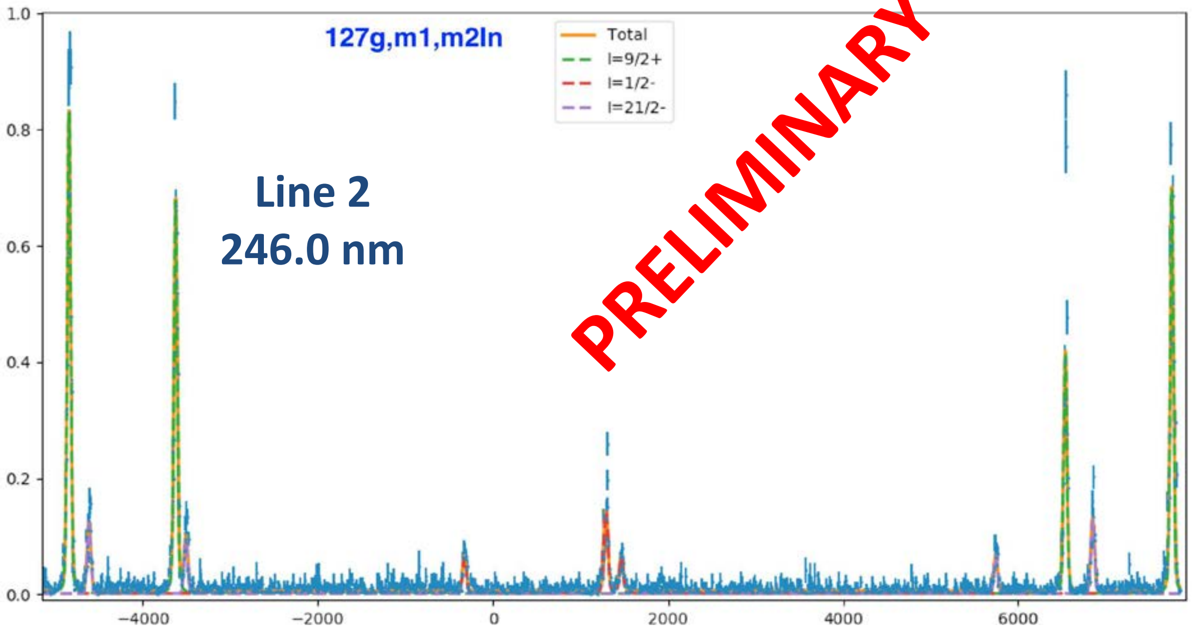


Additionally, two hyperfine structure peaks were identified for ^{132}In!

Two ionization schemes were used online

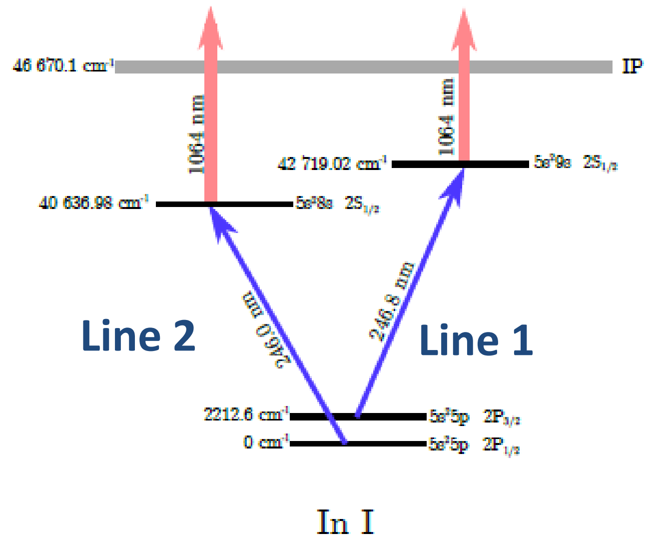
Example of ^{127}In





PRELIMINARY

(Tested for first time at CRIS)



- ✓ **Unambiguous identification of hfs peaks**
- ✓ **Further constraints to nuclear structure observables**
- ✓ **New developments fully tested:**
  - **Charge exchange chamber**
  - **Laser ionization schemes were developed offline**

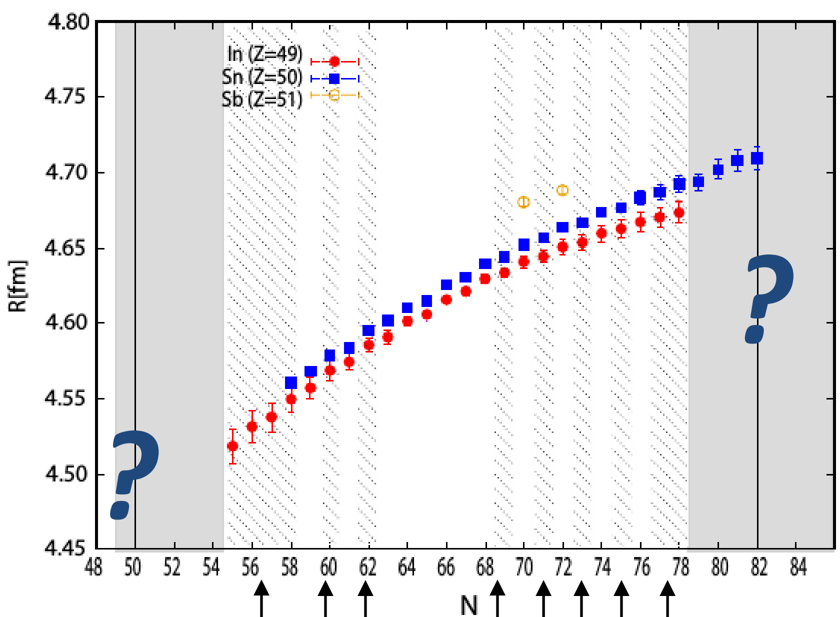
Results: CRIS First Experimental Campaign

❑ A successful experimental campaign!

Several new results for electromagnetic moments and charge radii of:

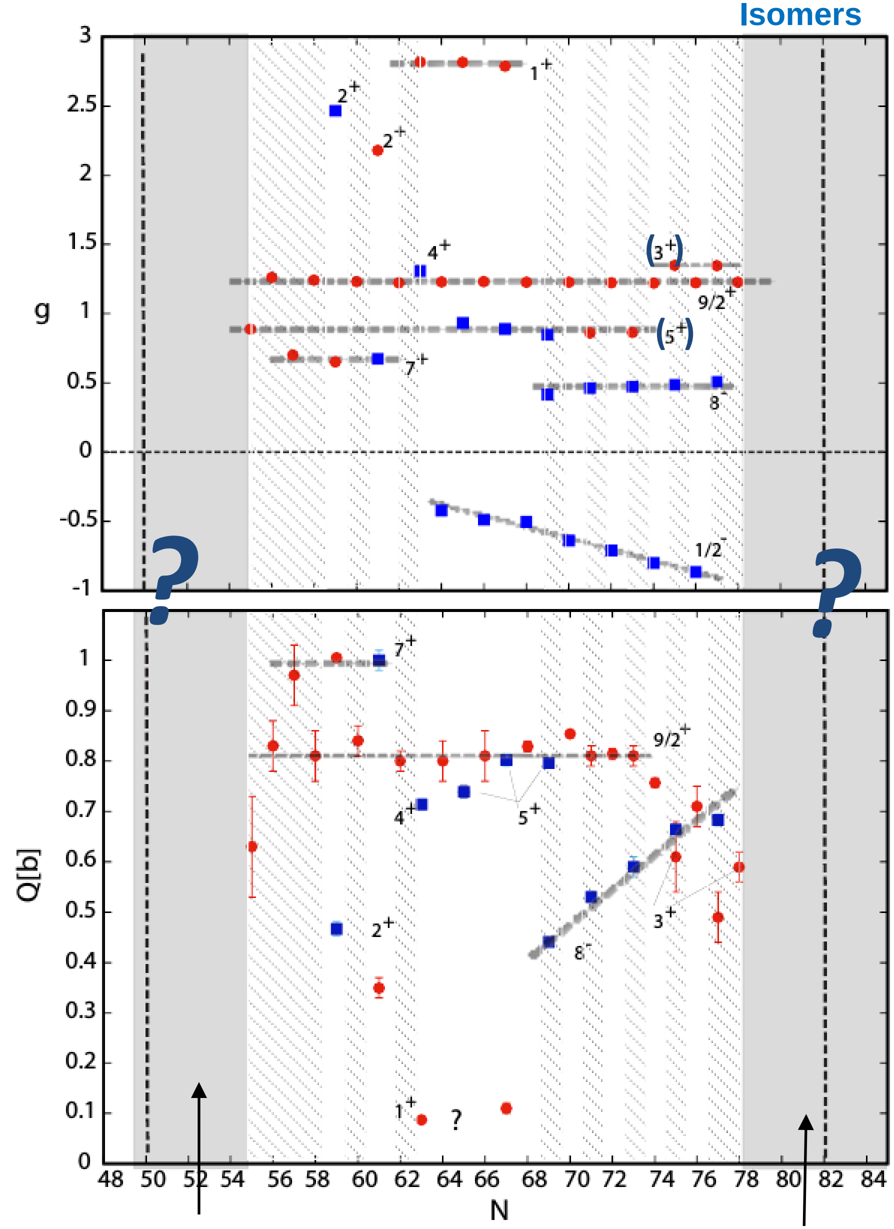
- ✓ 1+ states in 114, 116, 118, 120, 122
- ✓ 9/2 states in 129, 131
- ✓ 1/2 states in 127, 129 and 131
- ✓ high spin isomers (>21/2) in 127, 129
- ✓ ground and isomeric states in 128 3+, 8-
- ✓ ground and isomeric states in 130: 1-, 10-, 5+

High-precision isomer shifts will be obtained!



Unknown for several isomers

Ground states
Isomers



Unknown around N=50 and N=82!

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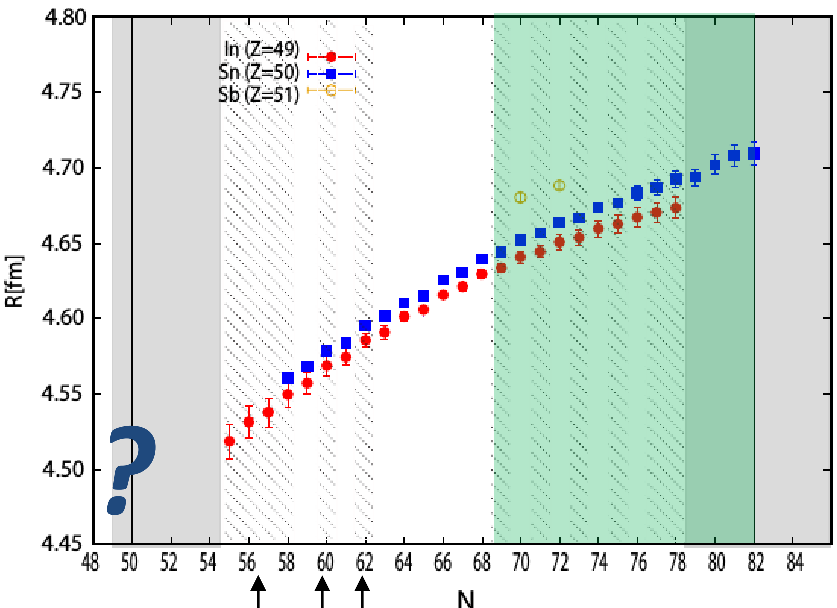

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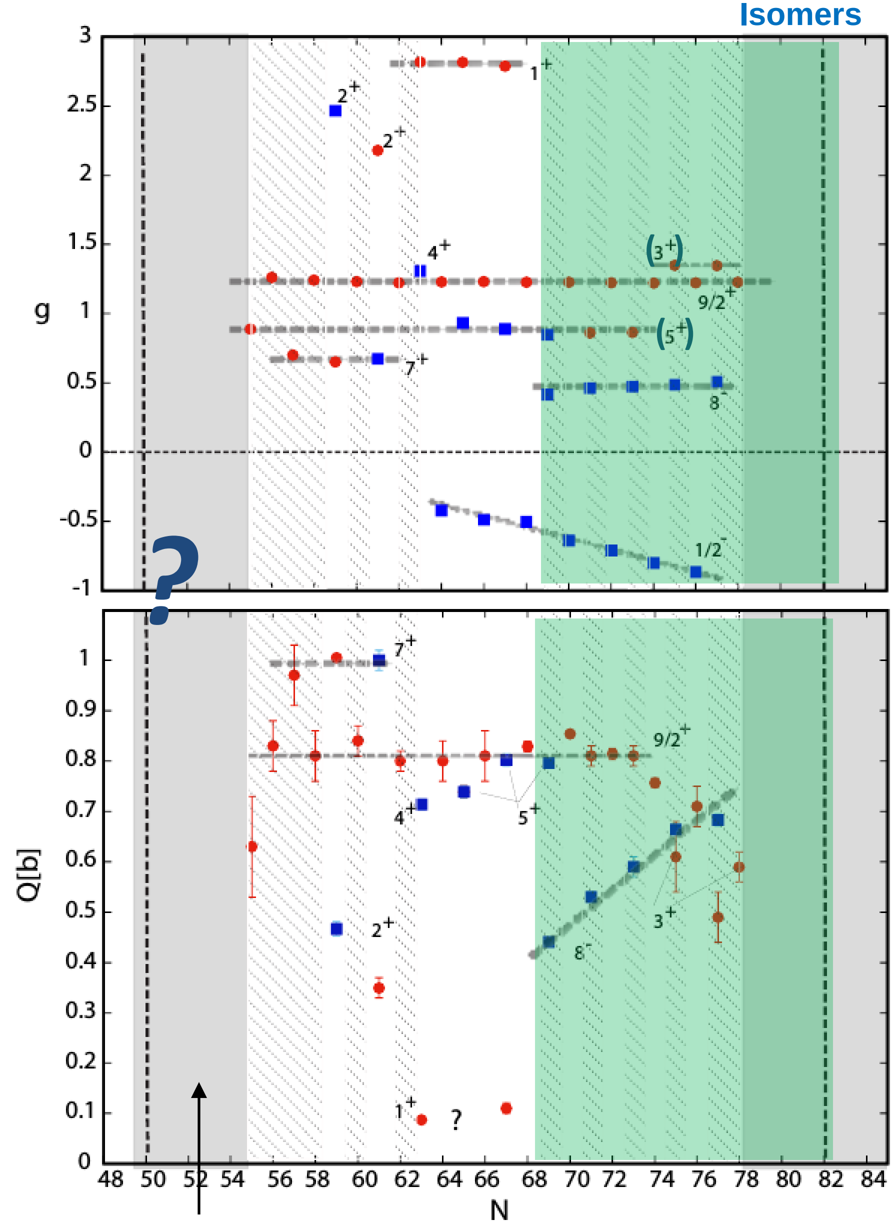

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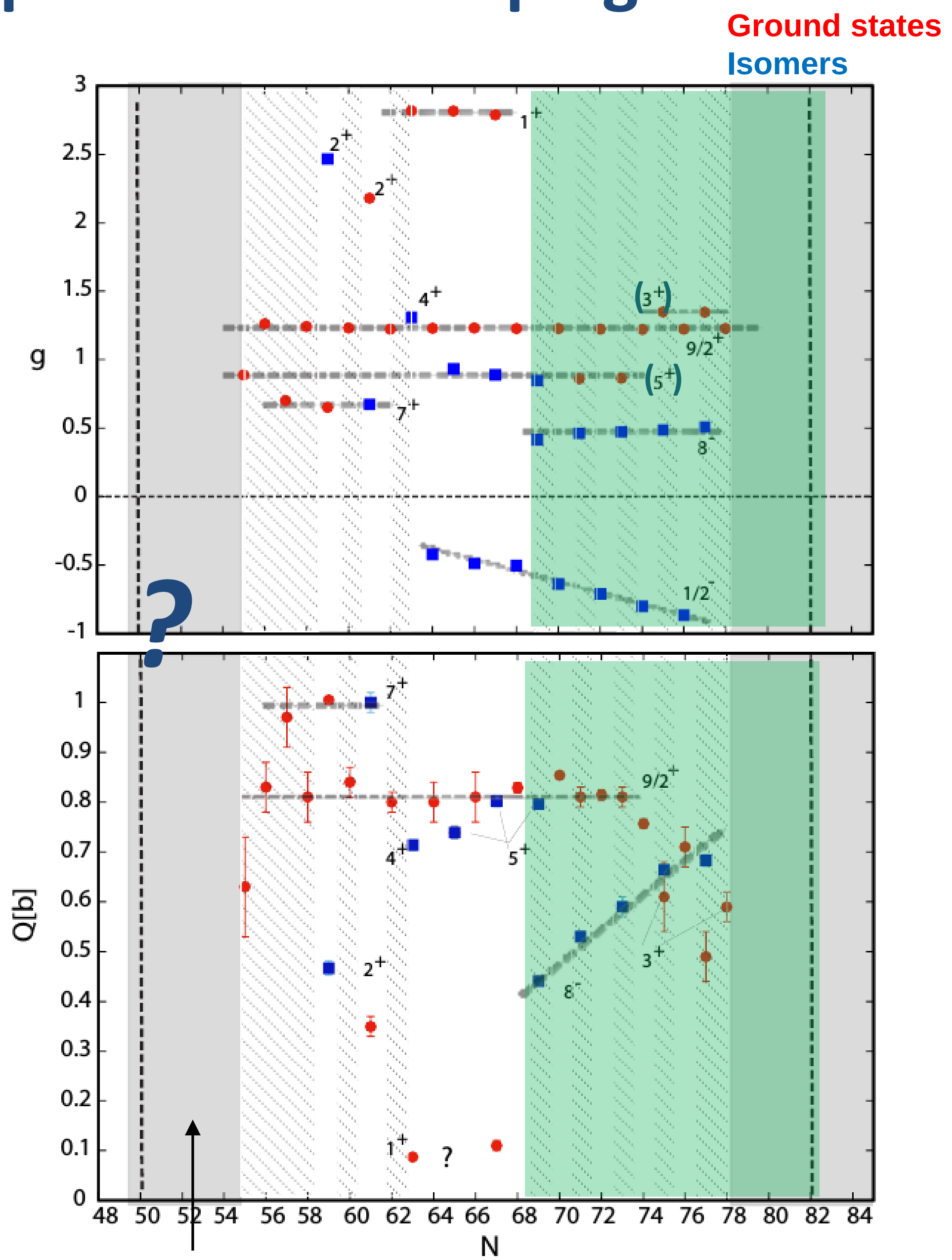
- ❑ Yields were about two orders of magnitude lower, and the contamination higher than expected -> An accidental vent of the target at high temperature occurred at the start of the run.
- ❑ The high efficiency and high selectivity of CRIS was demonstrated
- ❑ Solid bases for the extension of CRIS experiments towards ^{100}In



Unknown around N=50 and N=82!

Beam time request

Total=18 shifts

Isotope	I	Half life	Yield (ions/s)	Shifts
^{100}In	$(6^+, 7^+)$	7.0 s	16	7
^{101}In	$(9/2^+)$	15 s	380	2
^{102}In	(6^+)	22 s	8.6×10^3	0.5
^{103}In	$(9/2^+)$	65 s	8.0×10^4	0.5
^{103m}In	$(1/2^-)$	34 s	$>10^2$	1
^{104m}In	(3^+)	15.7 s	$>10^2$	1
^{105m}In	$(1/2^-)$	48 s	$>10^4$	0.3
^{106m}In	(2^+)	5.2 m	$>10^4$	0.3
^{107m}In	$1/2^-$	50.4 s	$>10^5$	0.3
^{109m_1}In	$1/2^-$	1.34 m	$>10^3$	0.3
^{109m_2}In	$(19/2^-)$	0.21 s	$>10^3$	0.3
^{111m}In	$(1/2^-)$	7.7 m	$>10^3$	0.3
$^{112-122}$In^i	–	>1 s	$\geq 10^4$	4

- ✓ **^{100}In: key physics case for our understanding of nuclear structure around N=Z=50 and the development of inter-nucleon interactions and many-body methods**

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- ✓ ***I=1/2* states: Understating of electro-weak currents in the M1 operator.**

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- ✓ ***I=9/2*** **states: Evolution of single-particle/collectivity approaching N=Z=50 and N=82**
- ✓ ***I=1/2*** **states: Understating of electro-weak currents in the M1 operator.**
- ✓ **odd-odd isotopes: Role of proton-neutron interaction and like-nucleon pairing**

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✓ *I=1/2* states: Understating of electro-weak currents in the M1 operator.

✓ odd-odd isotopes: Role of proton-neutron interaction and like-nucleon pairing

TAC (From previous INTC):

- ^{100}In 16/s :ok
  -> ☺
- NanoLaCx (not currently possible)
  -> Were not asked. Not needed
- Impurities claimed Cs:
  -> Important for neutron-rich

- LaC: fluctuations in yield possible
  -> We quoted lowest reported yields
- RILIS optimization for isomers could be needed for odd isotopes.
  -> Knowledge acquired during previous runs.

Thank you for your attention!

Acknowledgements

Thanks to all ISOLDE stuff for this great run with lots of new physics.

Experiment: CRIS Collaboration

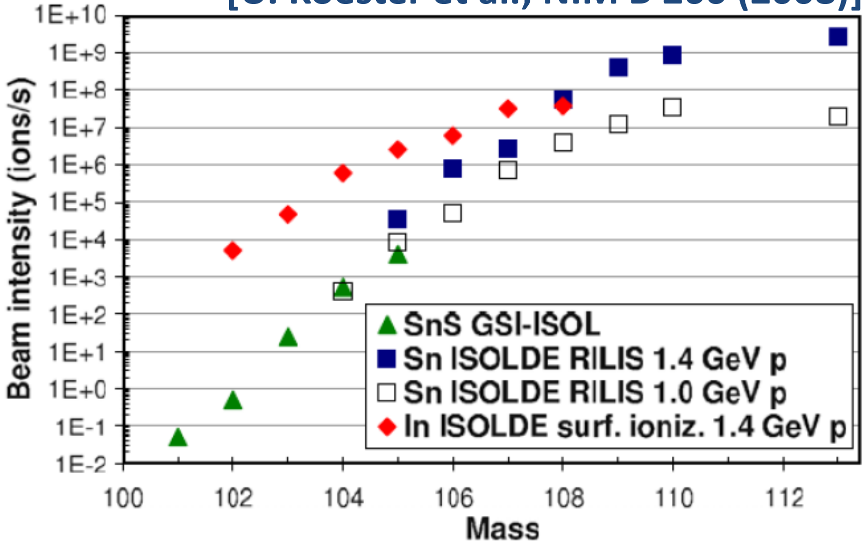
J. Billowes, C.L Binnersley, M.L. Bissell, T.E. Cocolios, R.P. de Groote, G.J. Farooq-Smith, K.T. Flanagan, S. Franchoo, R.F. Garcia Ruiz, G. Georgiev, G. Hagen, W. Gins, A. Koszorus, K.M. Lynch, B.A. Marsh, G. Neyens, H.H. Stroke, A.R. Vernon, K. Wendt, S.G Wilkins, X.F. Yang, D.T. Yordanov

Theory:

G. Hagen (ORNL)
J. Holt (TRIUMF)

Laser spectroscopy around A=100

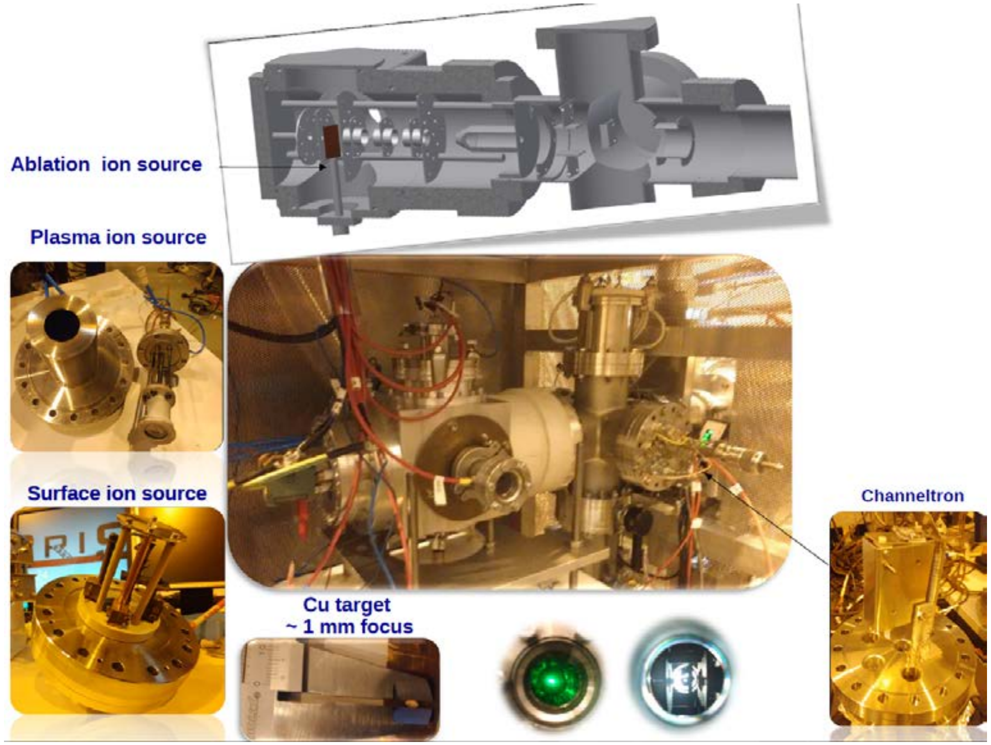
[U. Koester et al.; NIM B 266 (2008)]



- ❑ Indium isotopes provides the least risky option to start the laser spectroscopy studies around A=100
  - ✓ Ionization schemes fully tested
  - ✓ Good production yields
  - ✓ Feasibility has been demonstrated.

- ✓ New Charge exchange chamber was recently installed
- ✓ New offline ion source has been developed to produce In and Sn beams
- ✓ Neutralization tests for Sn and In have been performed
- ✓ First tests of RIS with Sn and In
- ✓ First CRIS off-line measurements of In were performed with the ablation ion source
- ❑ Developments of Sn ionization schemes are ongoing
- ❑ A new NEG pump setup will be installed in summer 2017 to improve UHV -> further background suppression.

Off-line Developments



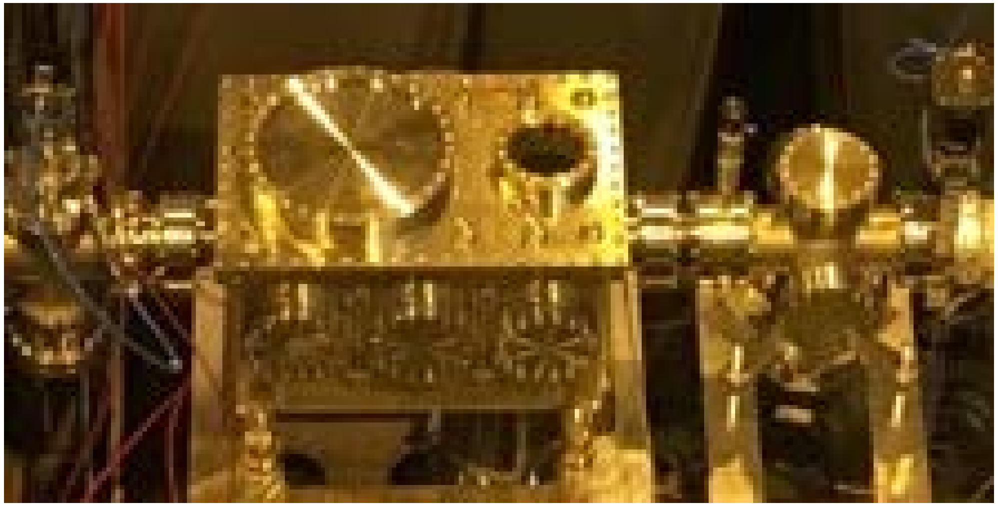
New CRIS offline Ion Source

- ✓ Ion source working up to 30 kV
- ✓ New ion beam optics allows for
  - ✓ Surface ion source
  - ✓ Plasma ion source
  - ✓ Ablation ion source
- ✓ Channeltron setup installed to be used as well as atomic beam/ laser ion source

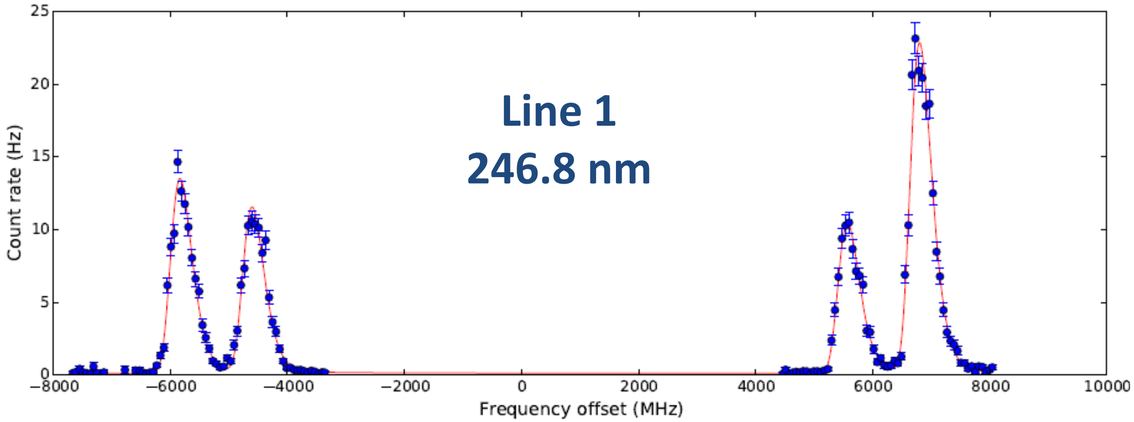
- ✓ Neutralization tests for Sn and In
- ✓ First tests of RIS with Sn and In
- ✓ First CRIS off-line measurements of In were performed with ablation ion source

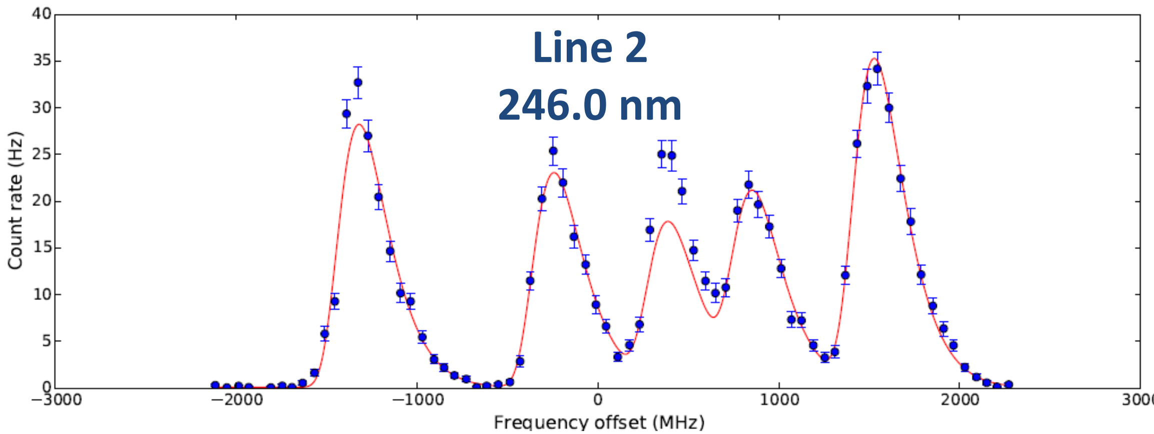
New CEC chamber at CRIS

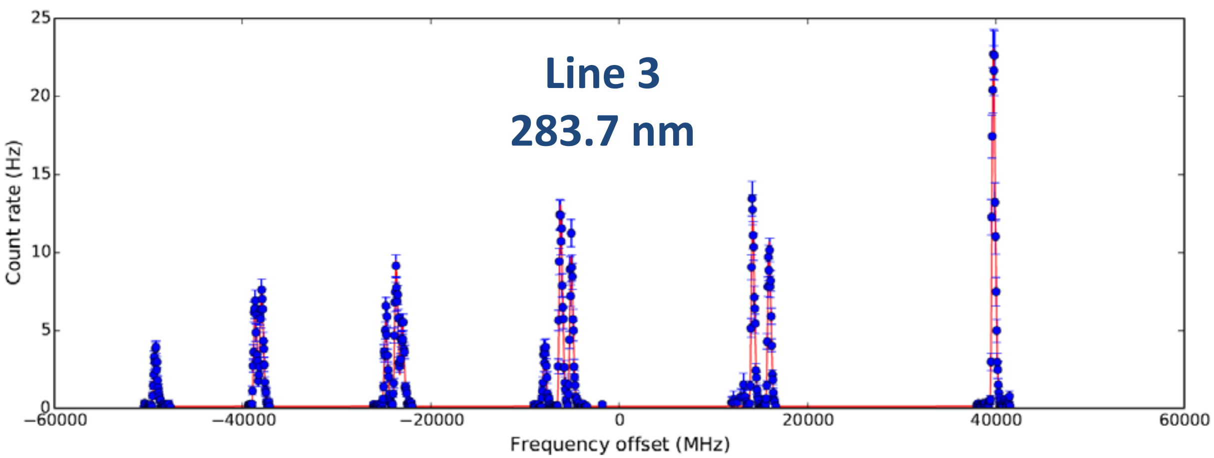
- ✓ Vacuum improved by more than x 10
- ✓ Passive cooling avoids using oil
- ✓ Higher temperatures can be reached to use different vapour gasses.

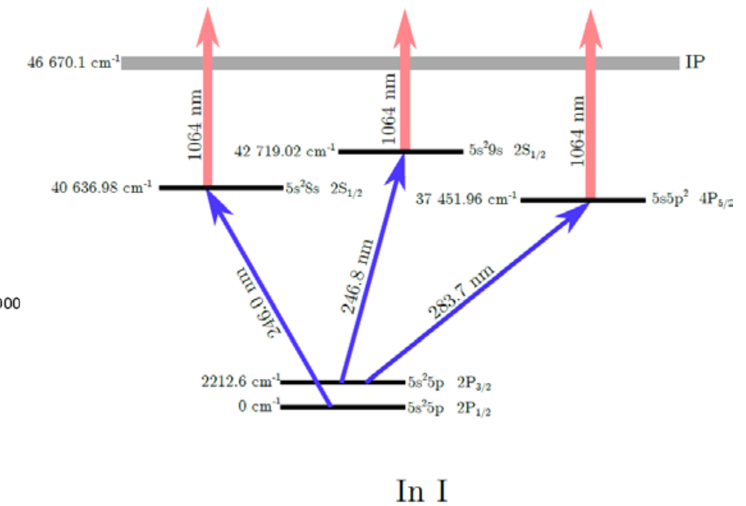


Firs CRIS off-line experiments: ^{115}In

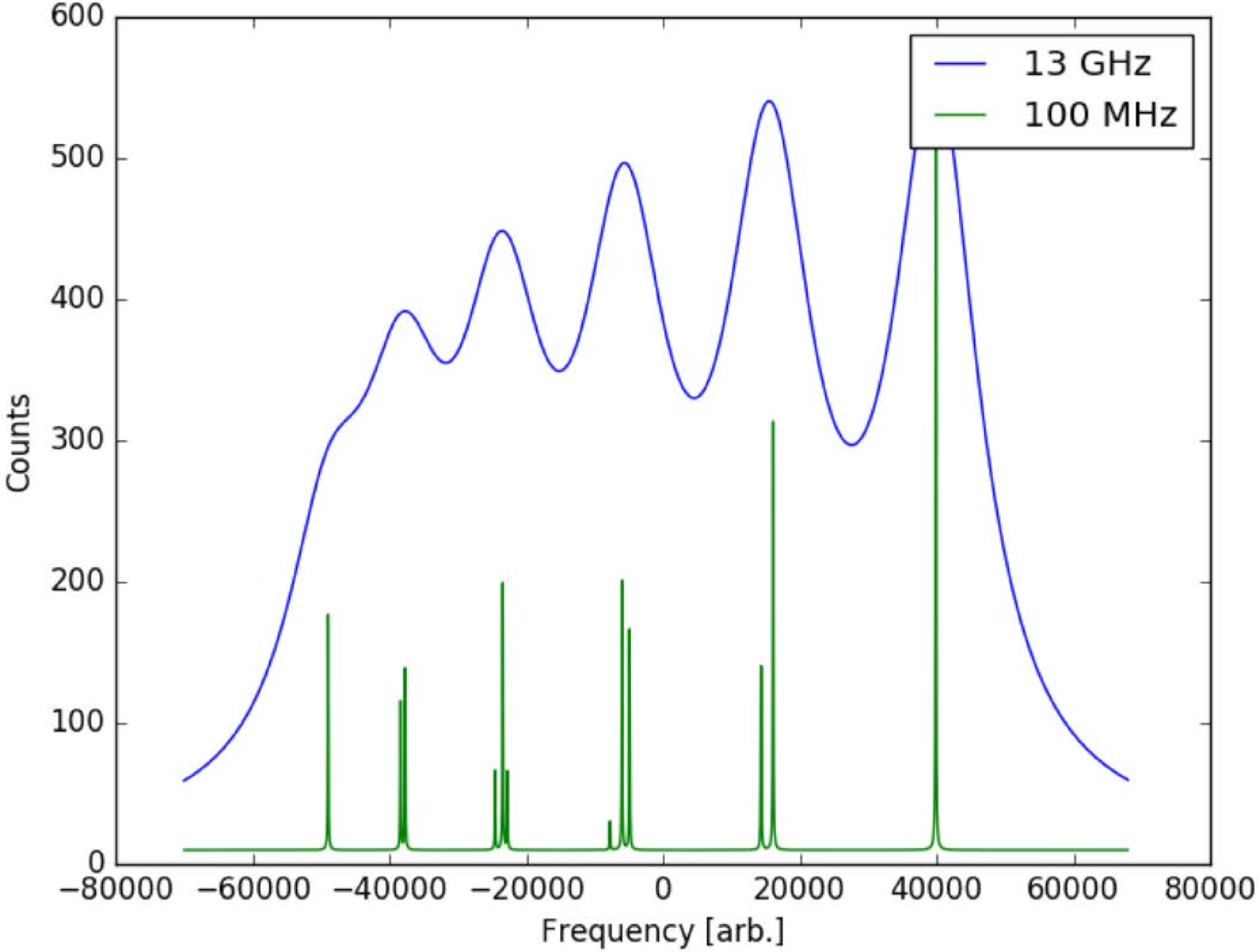






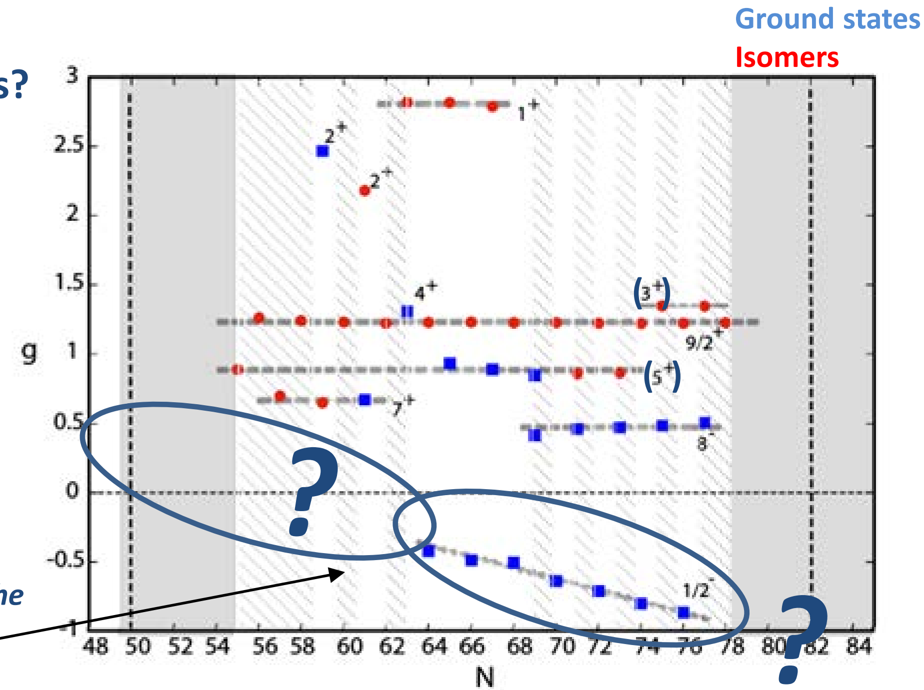


Simulations ^{115}In



Charge radii and electromagnetic moments

- Evolution of collectivity / single particle approaching the N=Z=50 and N=82 shell closures?
- Role of correlations across N=Z=50 and N=82?
- Proton-neutron interaction?
- High-spin isomers / exotic decays
- Role of electro-weak currents?
- Microscopic origin of effective operators? Effective charges and g-factors



"..Still, the unusual magnetic moments of the I=1/2 isomeric states represent an unresolved puzzle and may require a reconsideration of the overall nuclear structure of these isotopes"
[J. Eberz Nucl. Phys A 464 (1987) Q-28]

$$\mu \equiv \langle I, m=I \mid \mathbf{M}_1 \mid I, m=I \rangle$$

Evolution of $p_{1/2}$ moments
→ Sensitive to many-body currents (?)
→ $p_{1/2}$ moments insensitive to first-order core polarisation

odd proton	$l+1/2$	$-\frac{(l+2)\,l_1}{(2l+3)\,(2l_1+1)} \times \{ \ldots$
	$l-1/2$	$\frac{(l-1)\,l_1}{(2l+1)\,(2l_1+1)} \times \{ \ldots$

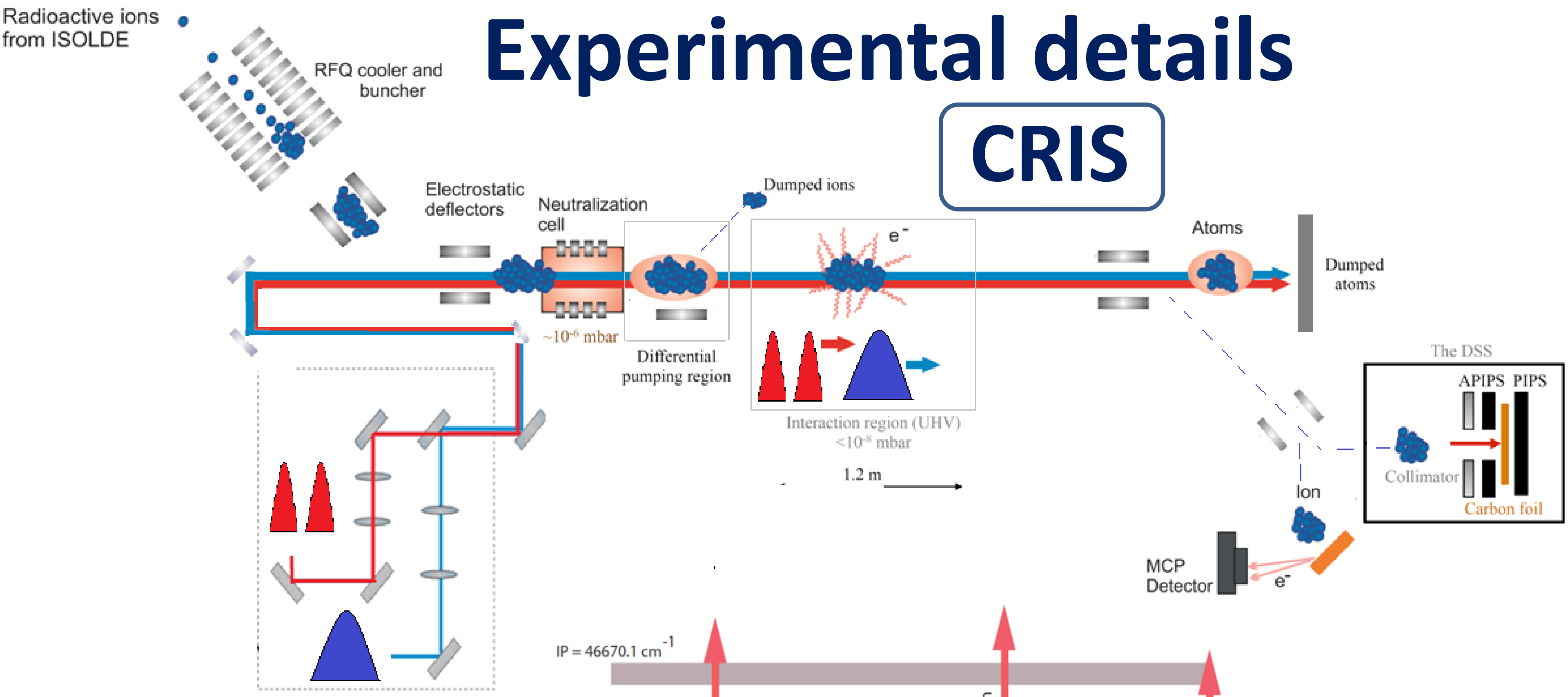
[Arima and H. Horie, Prog. Theor. Phys. 12, 623 (1954)]

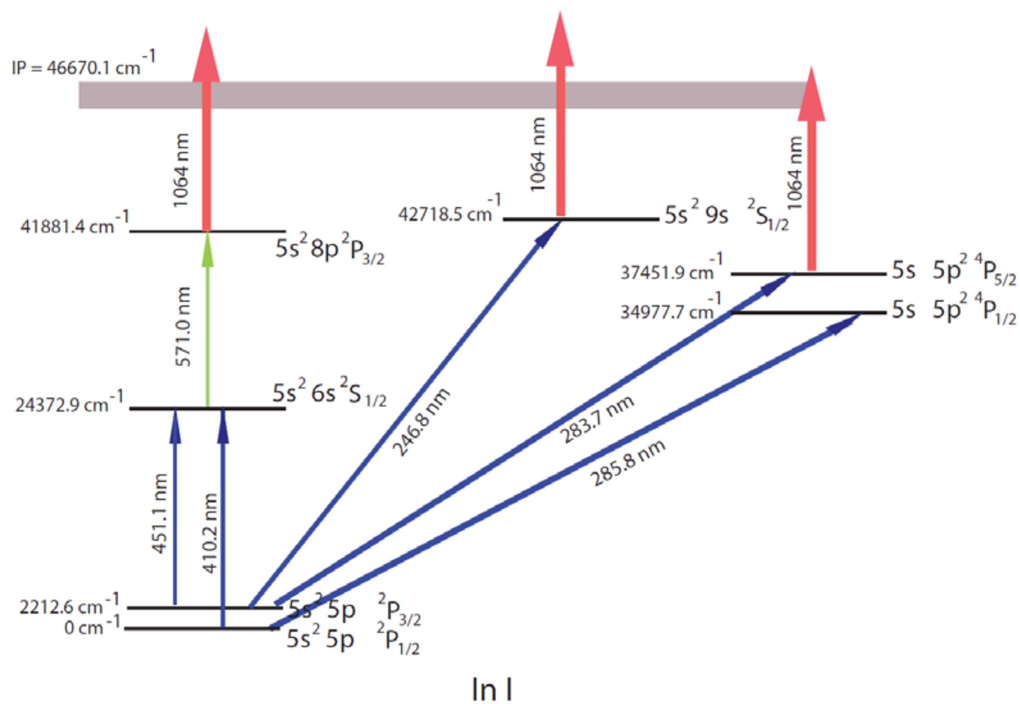
→ Sensitive to many-body currents (?)

- ❑ ***Electromagnetic moments are sensitive probes to the role of electro-weak currents***

Experimental details

CRIS





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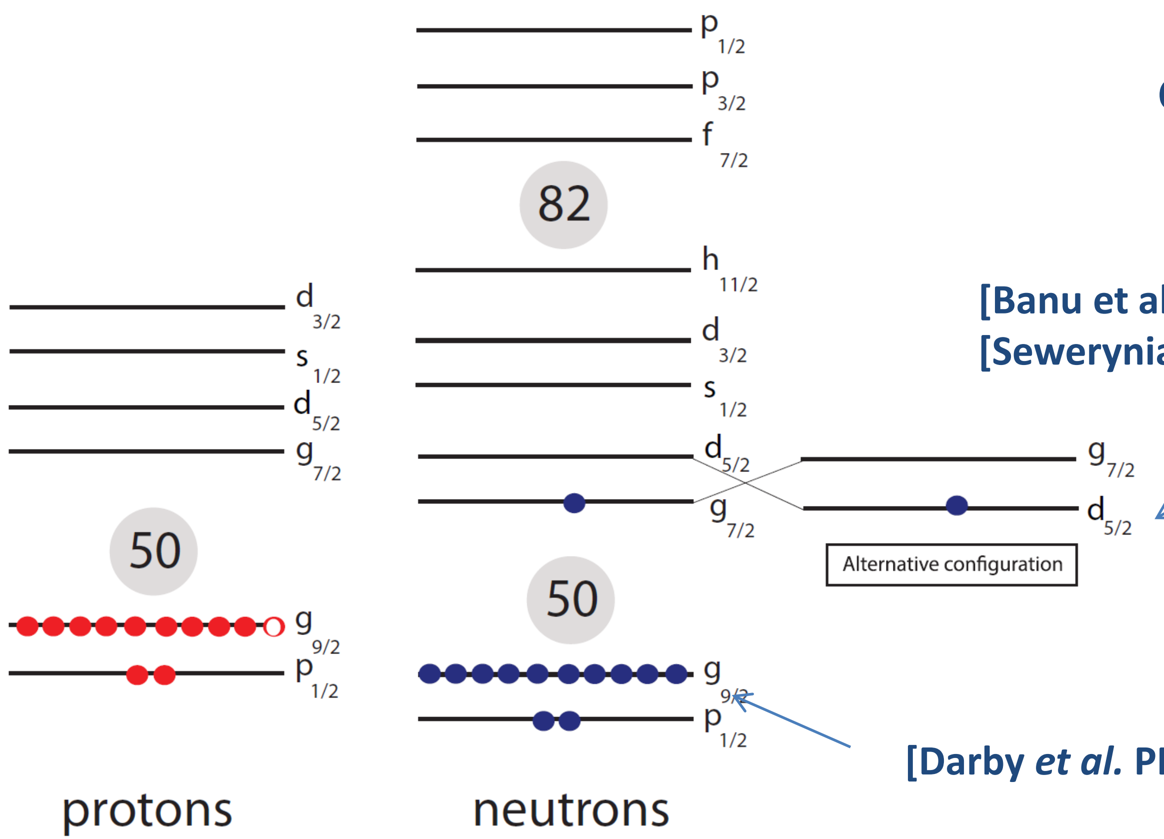
Ground-state spins

- Shell evolution towards N=Z=50 and N=82?
- Ordering of shell-model orbits towards ?

Contradictory evidence!



[Banu et al. PRC 72, 061305(R) (2005)]
[Seweryniak *et al*. PRL 99, 022504 (2007)]

[Darby *et al.* PRL 105, 162502 (2010)]

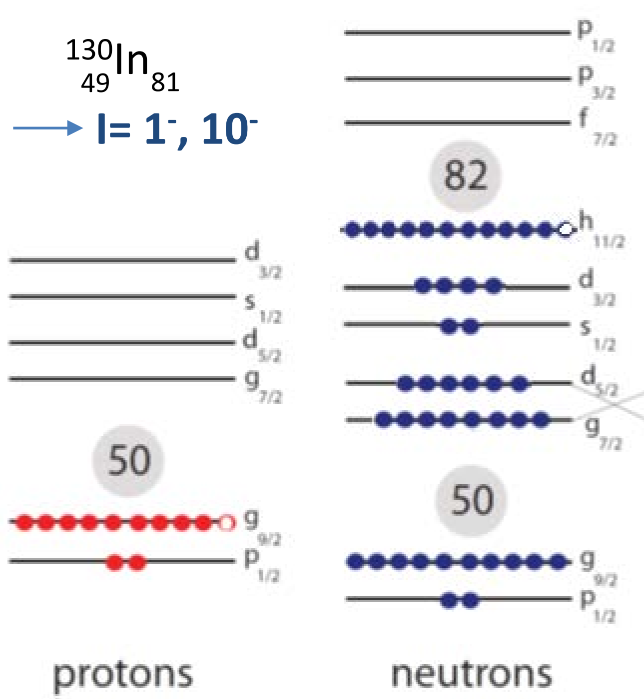
- ***Ground-state spins are essential observables for our understanding of nuclear structure***

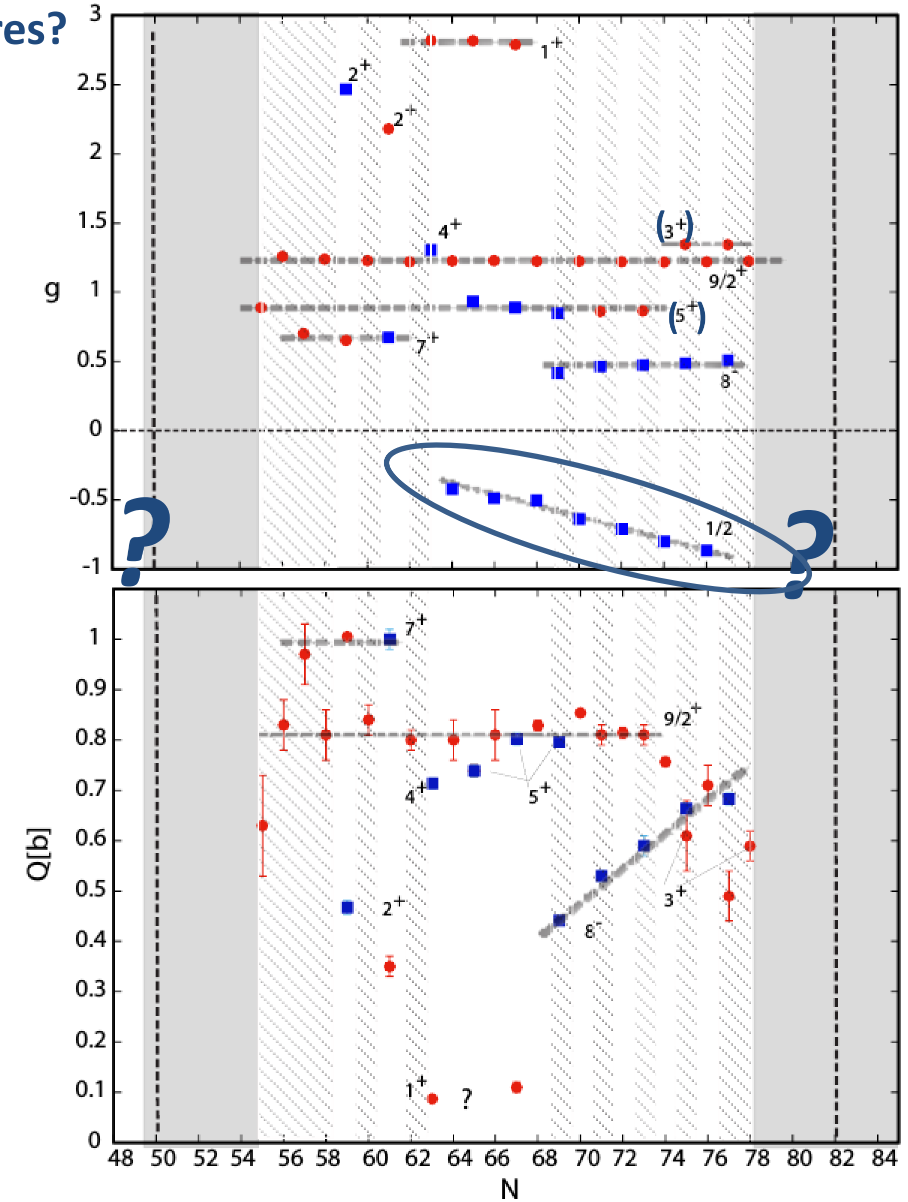
Charge radii and electromagnetic moments

- Evolution of collectivity / single particle approaching the N=Z=50 and N=82 shell closures?
- Role of correlations across N=Z=50 and N=82?
- Role of electro-weak currents?
- Proton-neutron interaction?

$^{130}_{49}In_{81}$

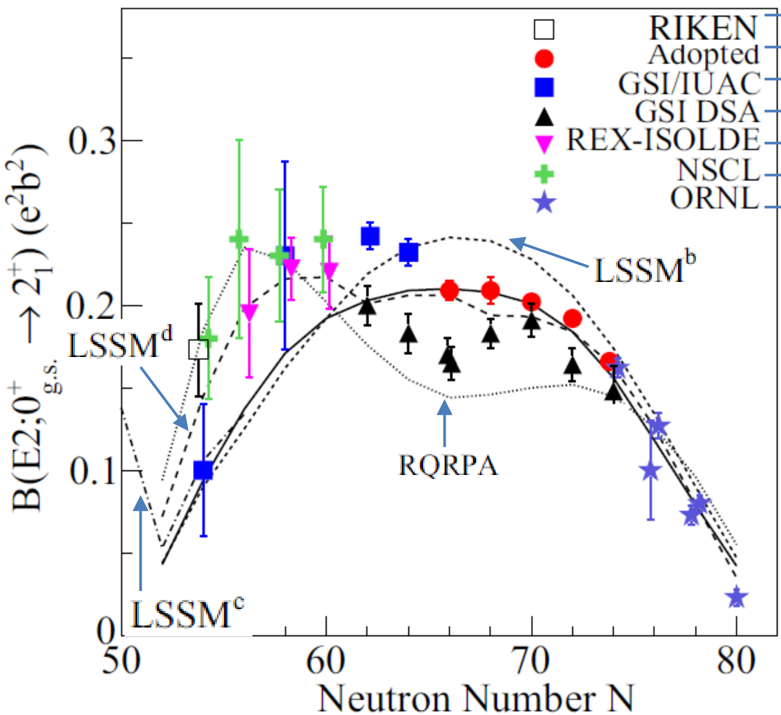
→ I= 1^-, 10^-





Open questions

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



- RIKEN → [Doornenbal *et al.* PRC 90, 061302(R) (2014)]
- Adopted → [Raman *et al.* ADNDT 78, 1 (2001)]
- GSI/IUAC → [Guastalla *et al.* PRL 110, 172501 (2013)]
- GSI DSA → [Jungclaus *et al.* PLB 695, 110 (2011)]
- REX-ISOLDE → [Ekstrom *et al.* PRL 101, 012502 (2008), Cederkall *et al.* PRL 98, 172501 (2007)]
- NSCL → [Vaman *et al.* PRL 99, 162501 (2007), Bader *et al.* PRC 88, 021301(R) (2013)]
- ORNL → [Allmond *et al.* PRC 84, 061303 (2011)]

^{100}Sn core { — LSSM[a]

^{90}Zr core { LSSM[b], LSSM[c] — Different truncations; LSSM[d] — Only neutron across N=50.

^{88}Sr core { Mainly protons across Z=50.

[Coraggio *et al.* PRC 91, 041301(R) (2015)]

Figure adapted from Doornenbal *et al.* PRC 90, 061302(R) (2014).

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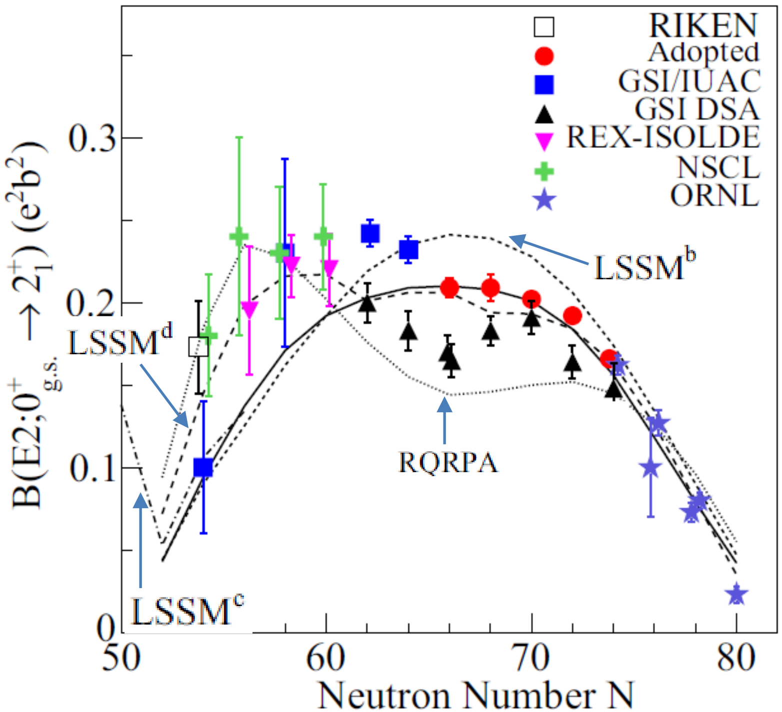
Open questions

- o Shell evolution towards N=Z=50 ?
- o Ordering of shell model orbits ?
- o Robustness of N=Z=50 shell closures?
- o Proton-neutron correlations?
- o Correlations across N=Z=50
- o Effective operators?
  Effective charges and g-factors



Inconsistent use of effective charges!

Different conclusions on the robustness of N=Z=50

^{100}Sn core { LSSM[a] e_n= 1.0 e

^{90}Zr core { LSSM[b] e_n= 0.5 e, e_p= 1.5 e
LSSM[c] e_n= 0.5 e, e_p= 1.5 e
LSSM[d] Only neutron across N=50. Isospin-dependent effective charges e_n>1.0 (e_n<1.0) e below (above) ^{110}Sn

^{88}Sr core { Mainly protons across Z=50. Theoretical effective charges. e_n>0.8, e_p>1.6

[Coraggio *et al.* PRC 91, 041301(R) (2015)]

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[Doornenbal et al. PRC 90, 061302(R) (2014)]

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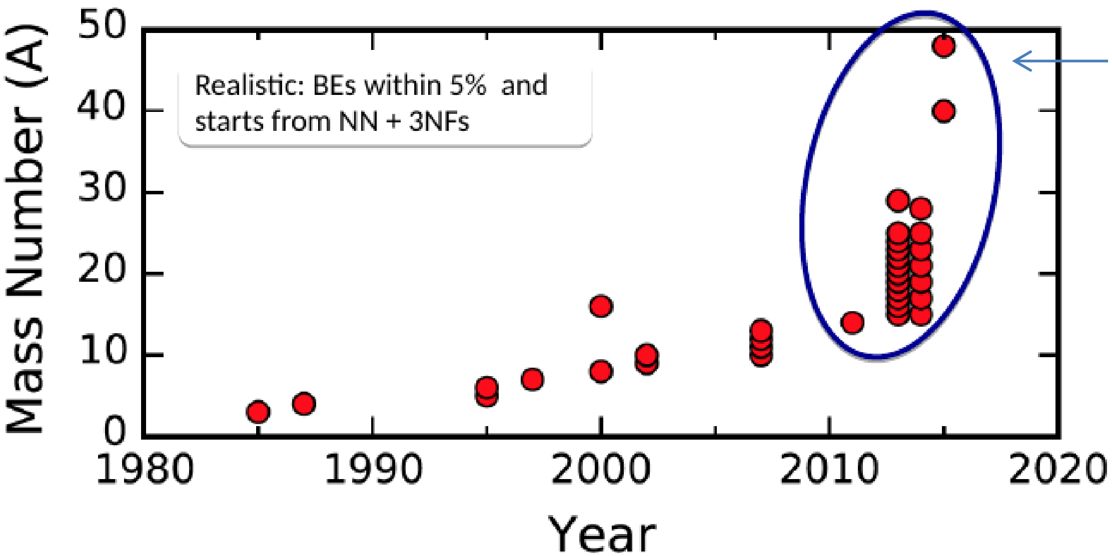
Motivation

Laser spectroscopy ➡ I , $\Delta\langle r^2\rangle$, μ , Q

Nuclear force
- Phenomenology
- Chiral effective field theory

Many-body methods
- Ab-initio
- Shell-model
- DFT

Electro-weak currents
- Effective neutron/proton charges
- Microscopic description of effective operators



Status of ab-initio calculations (2016)

✓ **Ca region**

[Hagen et al, Nature Physics 12, 186 (2016)]
[Garcia Ruiz et al, Nature Physics 12, 594 (2016)]

✓ **Ni region**

[Stroberg et al. Phys. Rev. Lett. 118, 032502 (2017)]
[Hagen et al , Phys. Rev. Lett 117, 172501 (2016)]

o **Sn region ?**

New developments in EFT + Normalization group + many-body methods:

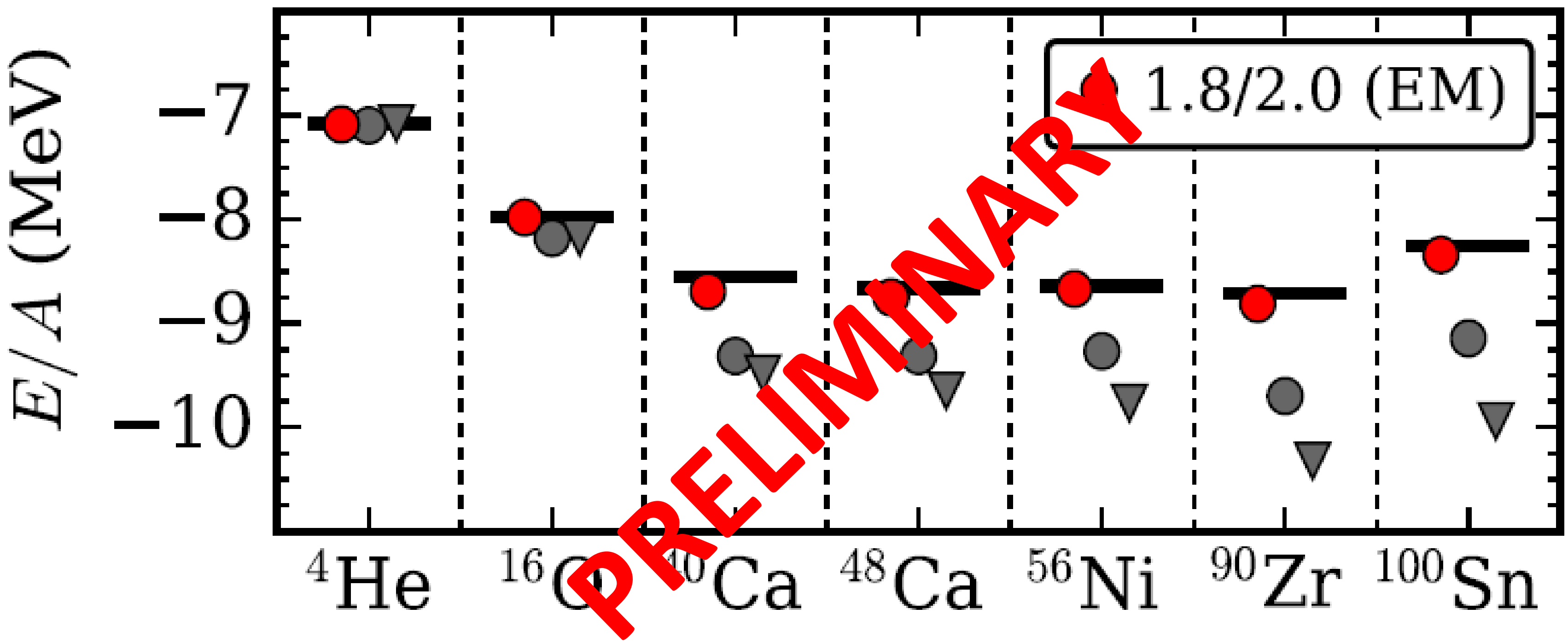
Coupled clusters [Hagen et al. Phys. Rev. Lett 117, 172501 (2016)]

In-Medium SRG [Phys. Rev. Lett 118, 032502 (2017)]

Gorkov-Green Function [Phys. Rev. Lett 117, 052501 (2016)]

…

Ab-initio calculations of heavy-nuclei (CC)

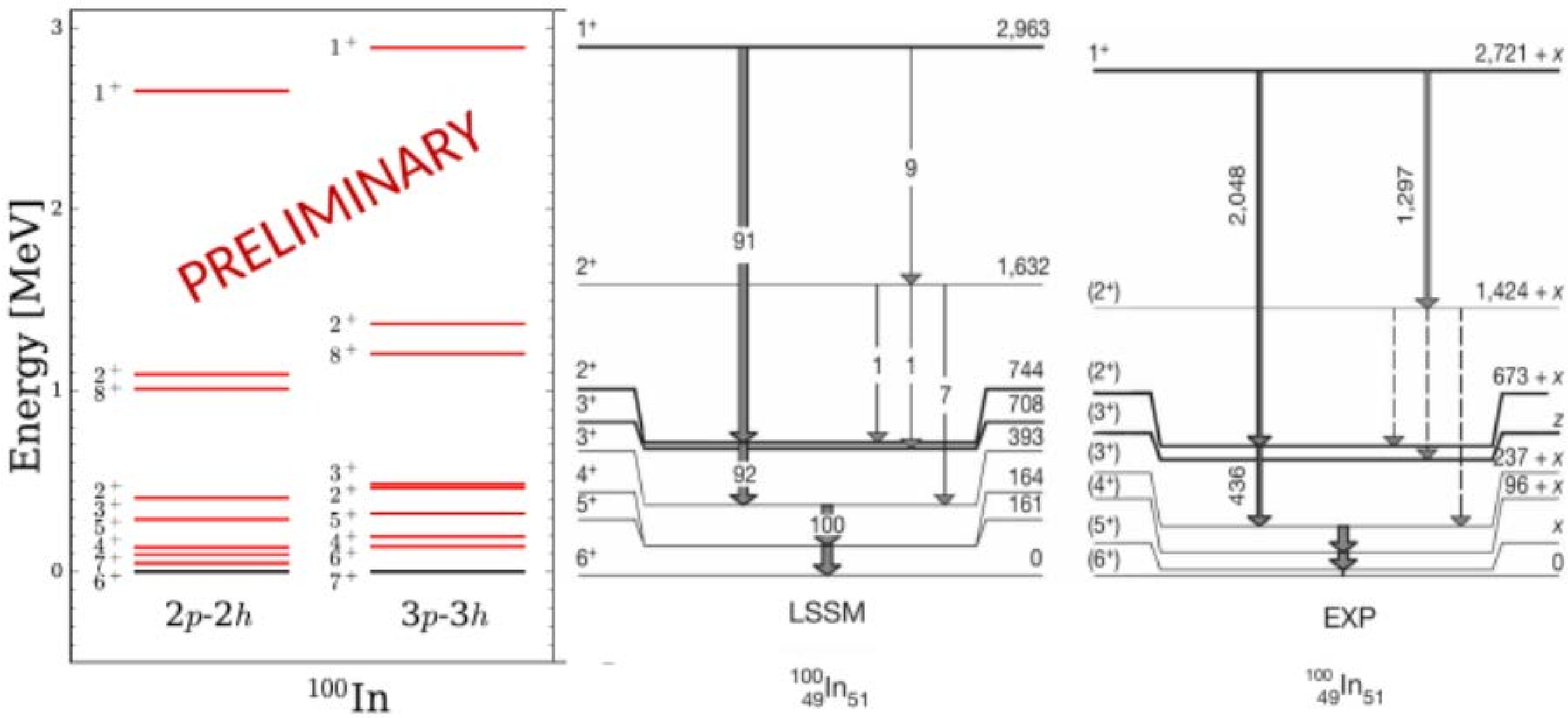


1.8/2.0(EM): Accurate BEs
Soft interaction: SRG NN from Entem& Machleidt with 3NF from chiral EFT

1.8/2.0 (EM) from K. Hebeler *et al* PRC (2011). The other chiral NN + 3NFs are from Binder et al, PLB (2014)

[Hagen et al. In preparation (2017)]

Ab-initio results around ^{100}In



Ab-initio calculations
[Hagen et al. In preparation (2017)]

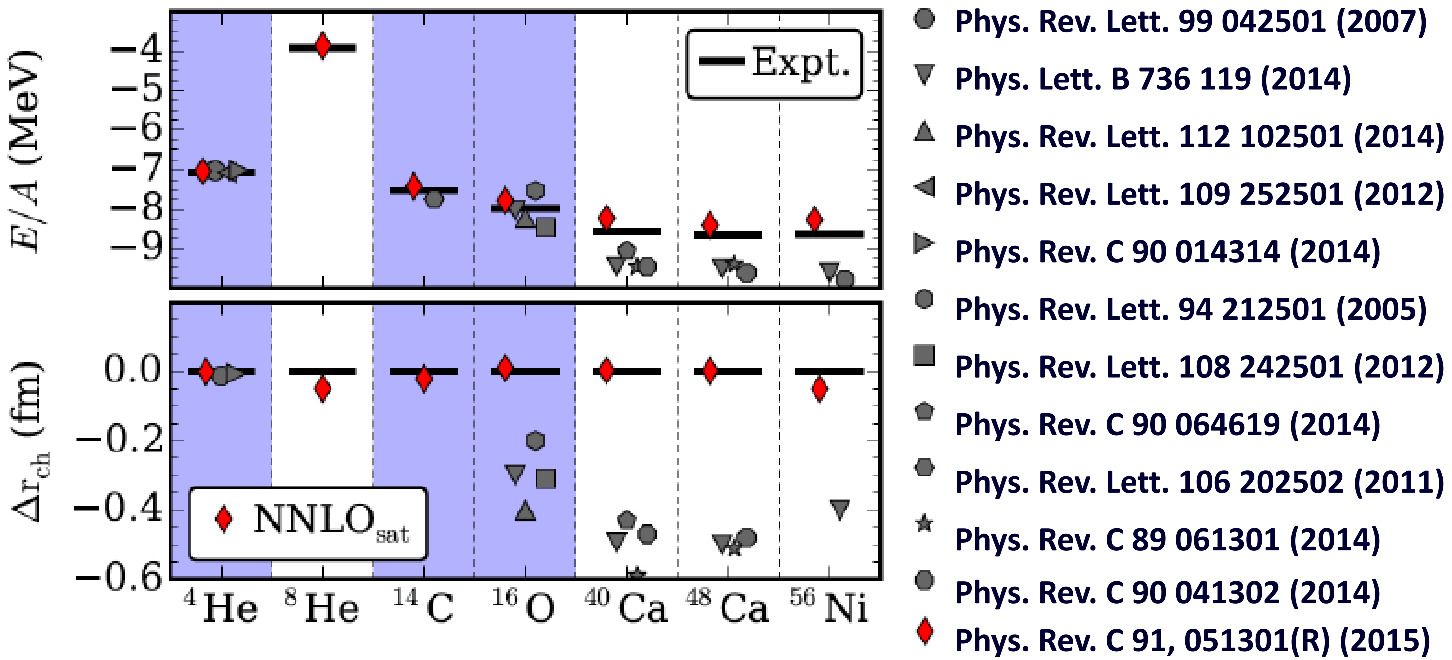
[Hinke et al. Nature 486, 341 (2012)]

- *Ground-state spins are essential observables for our understanding of nuclear structure*

Charge radii

Laser spectroscopy ⇒ I , $\langle r^2 \rangle$, μ , Q

Simultaneous reproduction of charge radii and binding energies has been a long-standing challenges for nuclear theory.



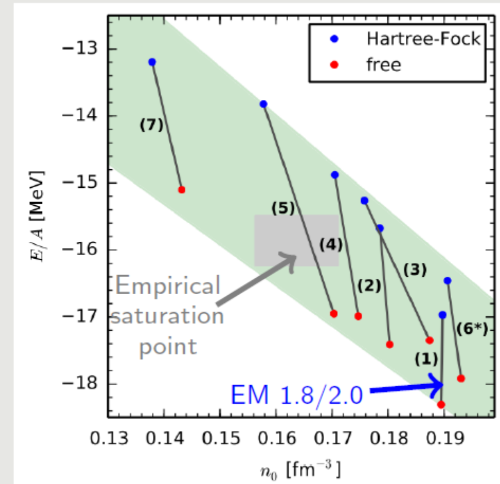
Nature Physics 12, 186 (2016)

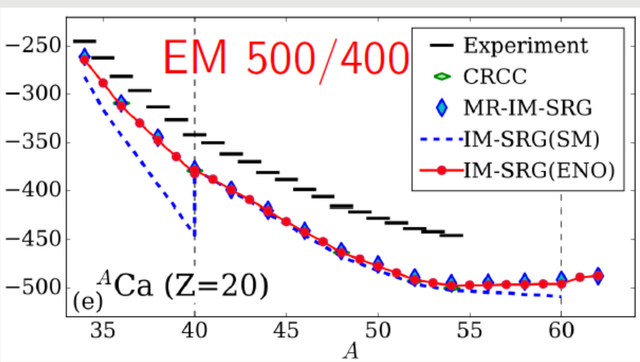
Extension to the Sn region is underway! [Hagen et *al.* In preparation (2017)] [J. Holt. Private commun. (2017)]

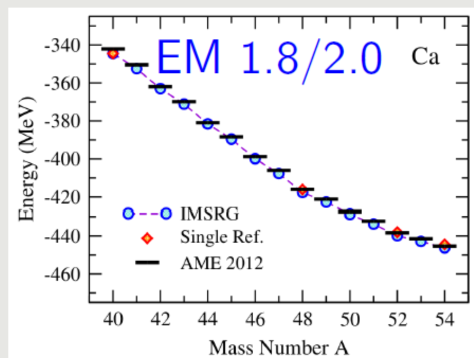
- ***Ground-state spin are essential observables for our understanding of nuclear structure***
- ***Charge radii provides a test to inter-nucleon interactions and many-body methods***

VS-IMSRG

	EM 500/400	EM 1.8/2.0
NN	N^3LO	same
	$\Lambda_{2N} = 500$ MeV	same
	non-local regulator	same
	fit to NN scattering, ^{2}H	same
	$\lambda_{SRG} = 1.88\ \text{fm}^{-1}$	≈ same
3N	N^2LO	same
	$\Lambda_{3N} = 400$ MeV	≈ same
	local regulator	**non-local regulator**
	fit to ^{3}H BE, $t_{1/2}$	**fit to ^{3}H BE, ^{4}He r_{ch}**
	consistently SRG evolved	**no SRG for 3N**







- Neither interaction is fully consistent

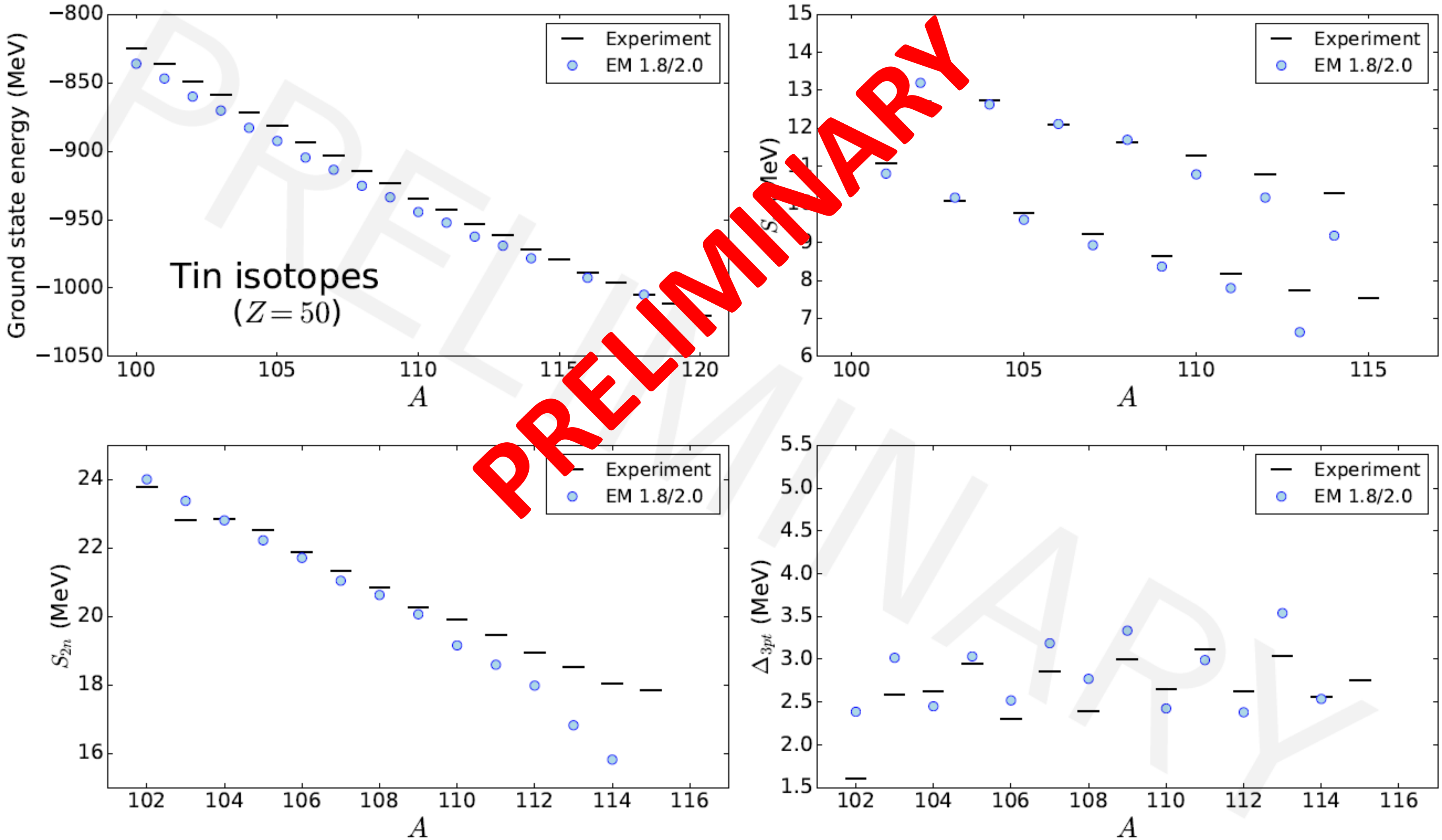
  however. . .

- Saturation properties appear important for finite nuclei

[J. Holt, R. Stroberg. Private communication (2017)]

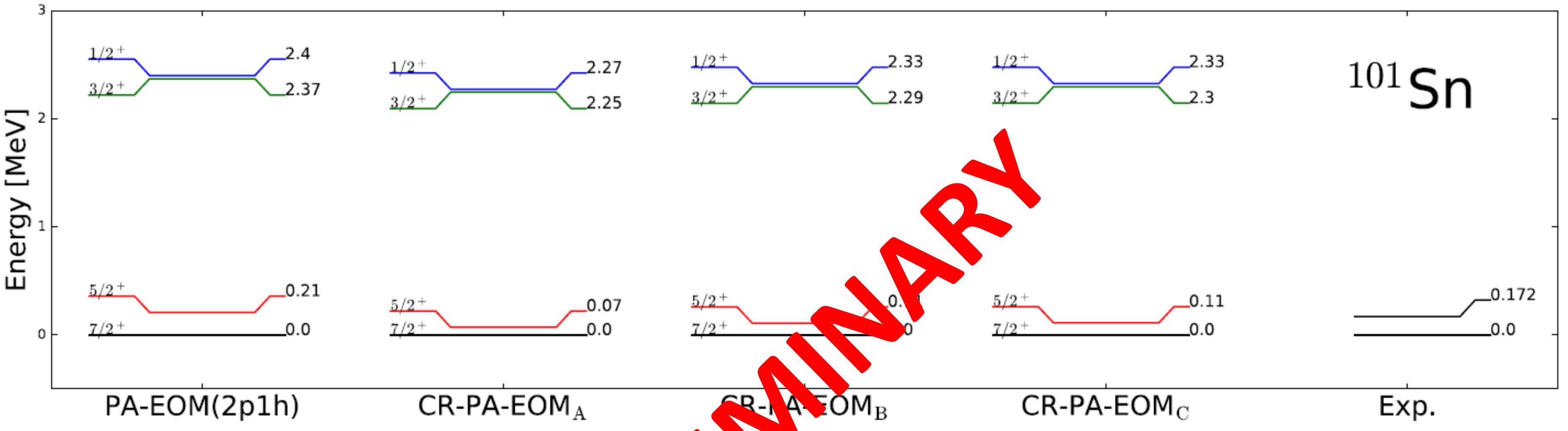
VS-IMSRG

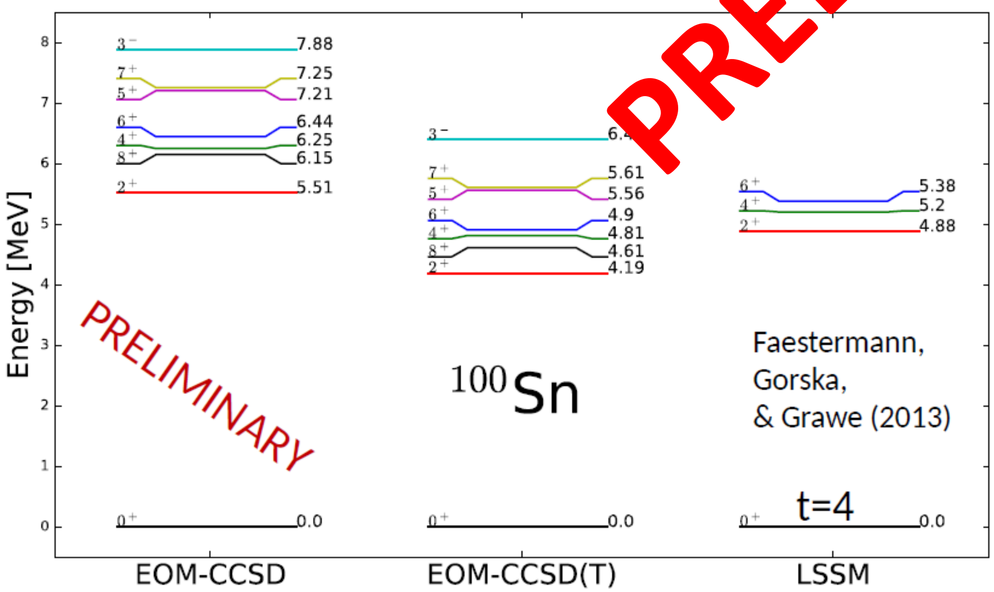
Isotopic chain with $\hbar\omega = 16$, $e_{max} = 14$, $E3_{max} = 16$



[J. Holt, R. Stroberg. Private communication (2017)]

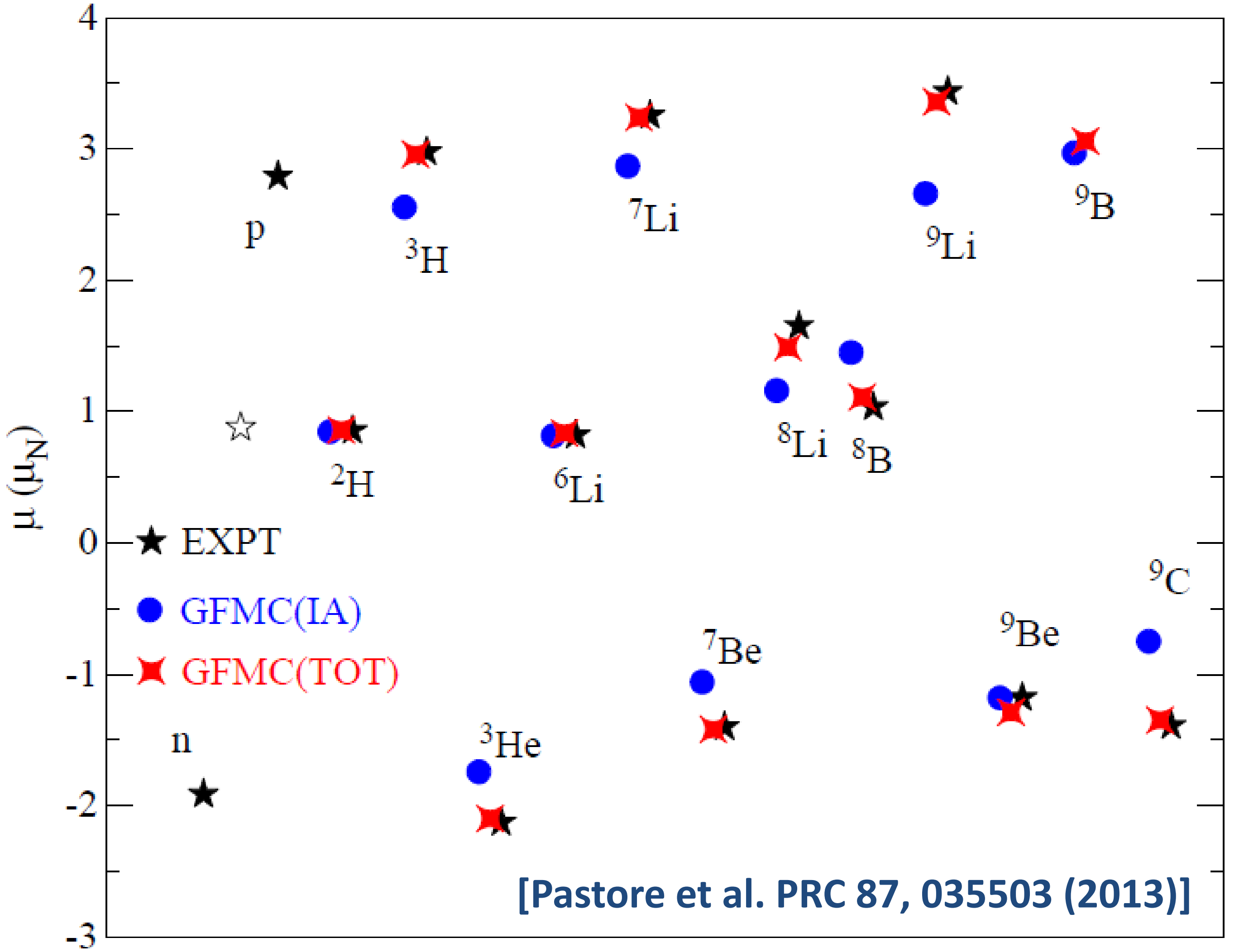
Structure of the ligthest tin isotopes





[Hagen et al. In preparation (2017)]

Electromagnetic moments and many-body currents



Quantum Monte Calculations + up to two-body currents (MEC) derived from chiral EFT

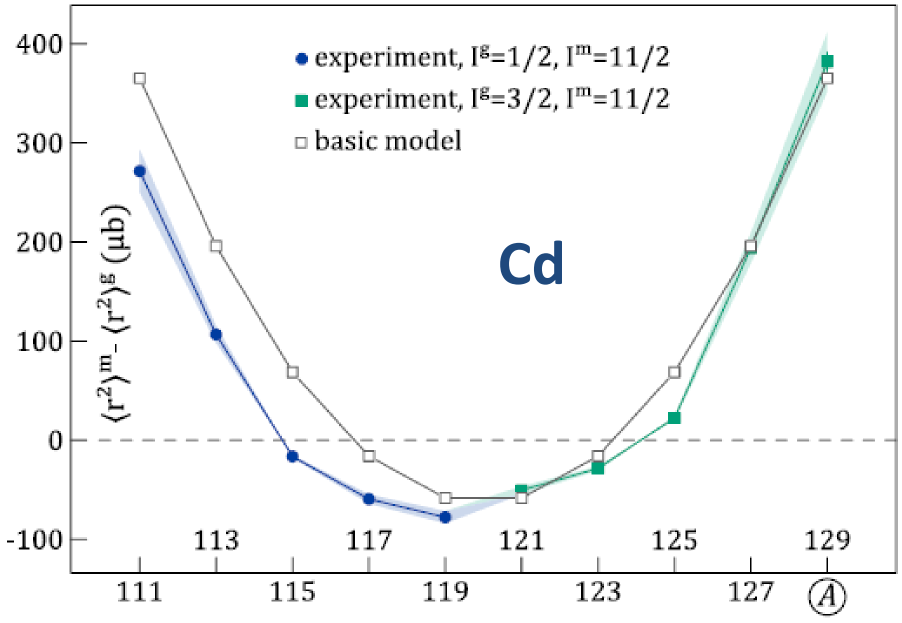
-> Magnetic moments are highly sensitive: changes up to MEC ~40% for ^{9}C

Work in progress to include MEC in medium mass nuclei [A. Ekstrom et al. PRL 113, 262504 (2014)]

Isomer shifts

[Yordanov *et al.* PRL 116, 032501 (2016)]

-> "Rms charge-radii changes from ground states to isomers of Cd isotopes follow a distinct parabolic dependence as a function of the atomic mass number"



Population of states after CEC