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# Laser spectroscopy on neutron-rich Ca isotopes

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*The University of Manchester*
*KU Leuven*

*Nuclear Structure 2016*
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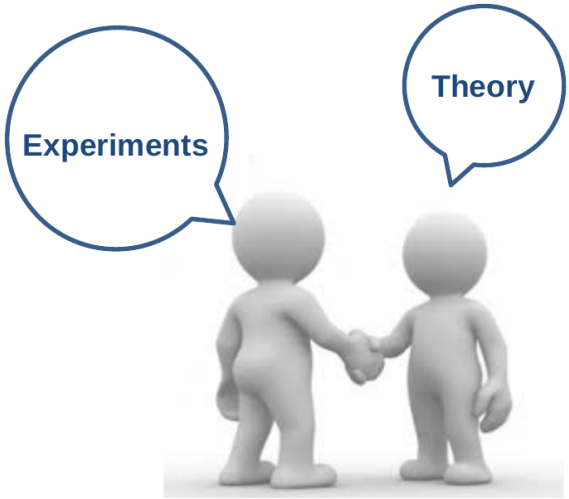
# Thanks to

**COLLLAPS Collaboration**
M. Bissell, K. Blaum, N. Frommgen, W. Gins, C. Gorges, M. Hammen, H. Heylen, M. Kowalska, K. Kreim, S. Malbrunot-Ettenauer, R. Neugart, G. Neyens, W. Nortershauser, J. Papuga, X. Yang, D.Yordanov




**NN+3N Calculations**
J.D. Holt, J. Menendez, A. Schwenk, J. Simonis

**Charge radii calculations**
A. Ekstrom, G. Hagen, K. Hebeler, G. R. Jansen, W. Nazarewicz, T. Papenbrock, K. A. Wendt

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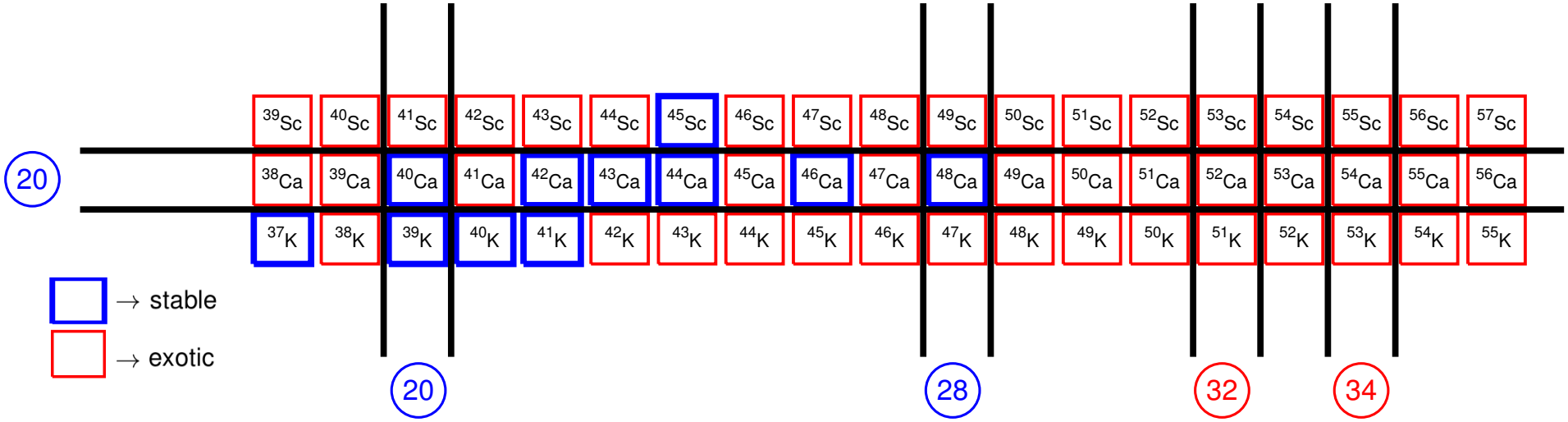
# Multiple shell structures in the Ca(Z=20) isotopes

→ Two doubly-magic stable isotopes: $^{40,48}$Ca



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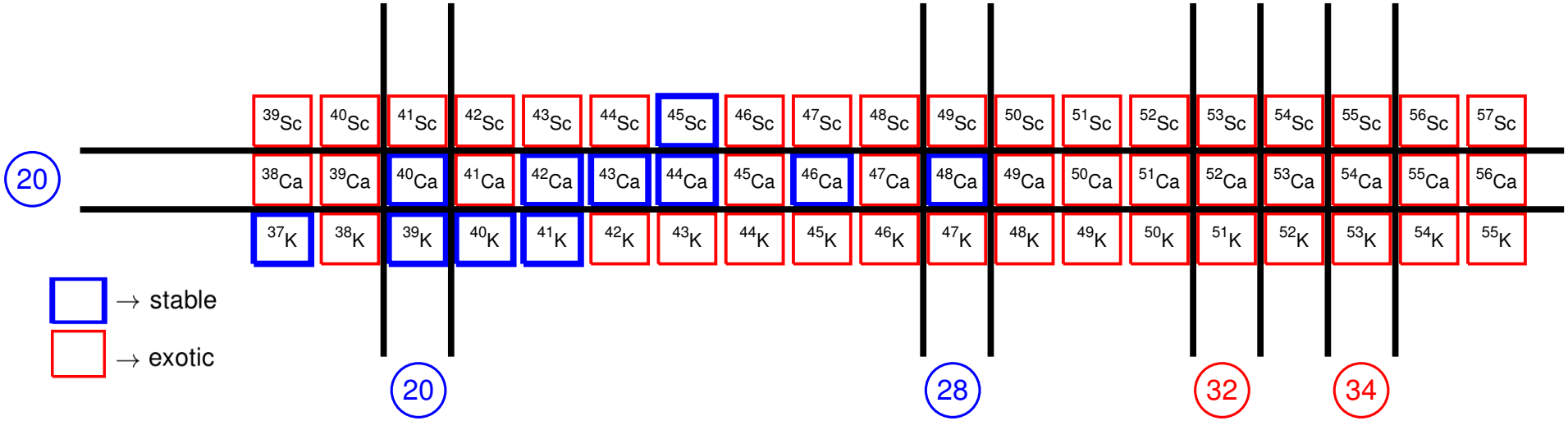
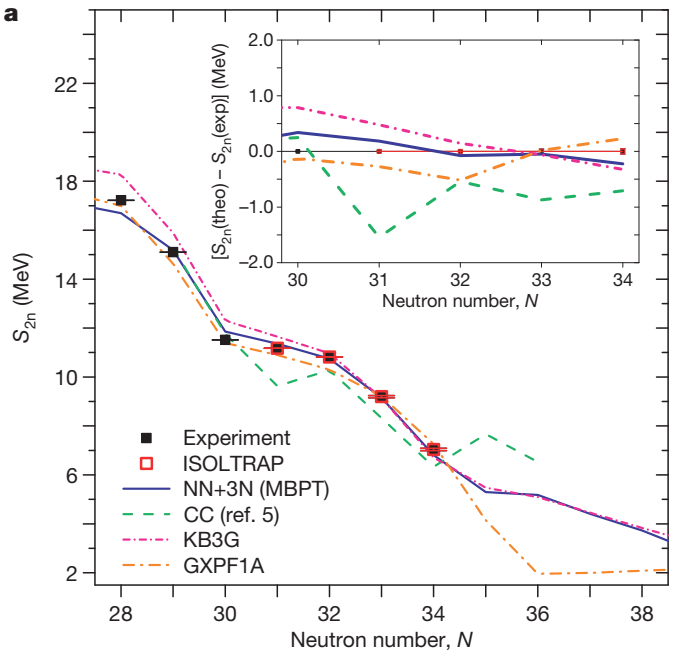



→ Possibly two doubly-magic exotic isotopes: $^{52,54}$Ca

# Multiple shell structures in the Ca(Z=20) isotopes



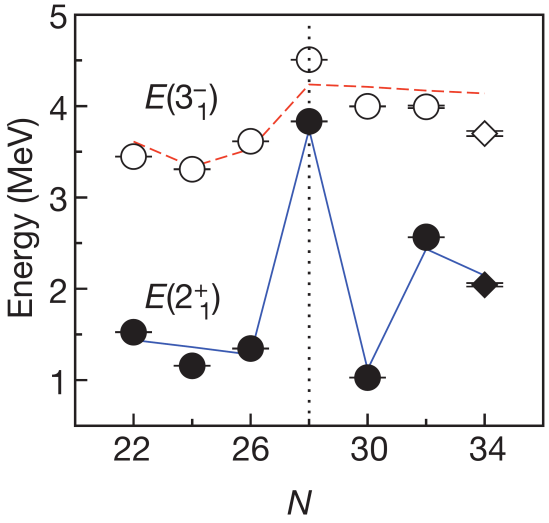

LETTER

doi:10.1038/natur

## Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

[Nature 346, 498 (2013)]




LETTER

doi:10.1038/nature12522

## Evidence for a new nuclear 'magic number' from the level structure of $^{54}$Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

[Nature 207, 502 (2013)]

# Calcium, the nuclear force and the many-body problem

$\rightarrow I$ , $\langle r^2 \rangle$, $\mu$, $Q$

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**The nuclear force**

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- Shell-model
- Ab-initio
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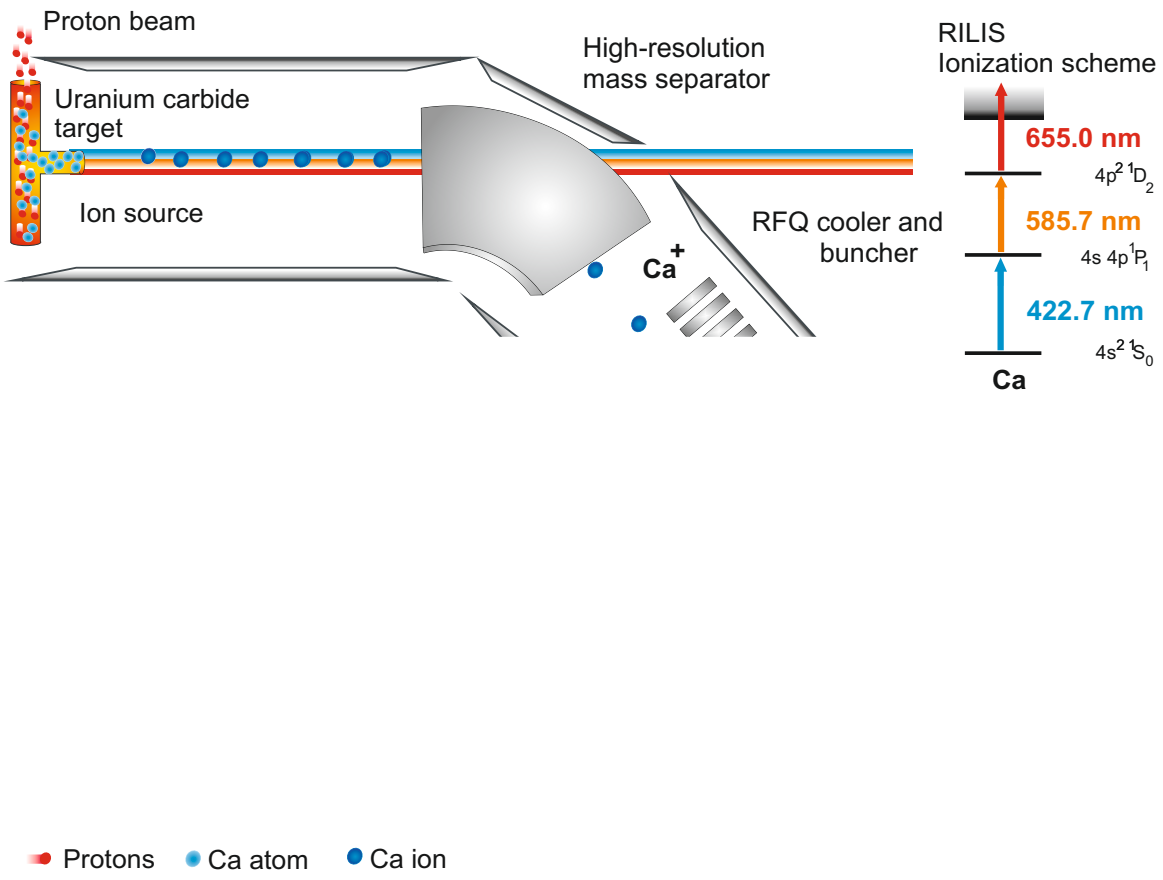
**Electro-weak currents**

- role of many-body currents
- effective operators

# COLLAPS Beam line at ISOLDE



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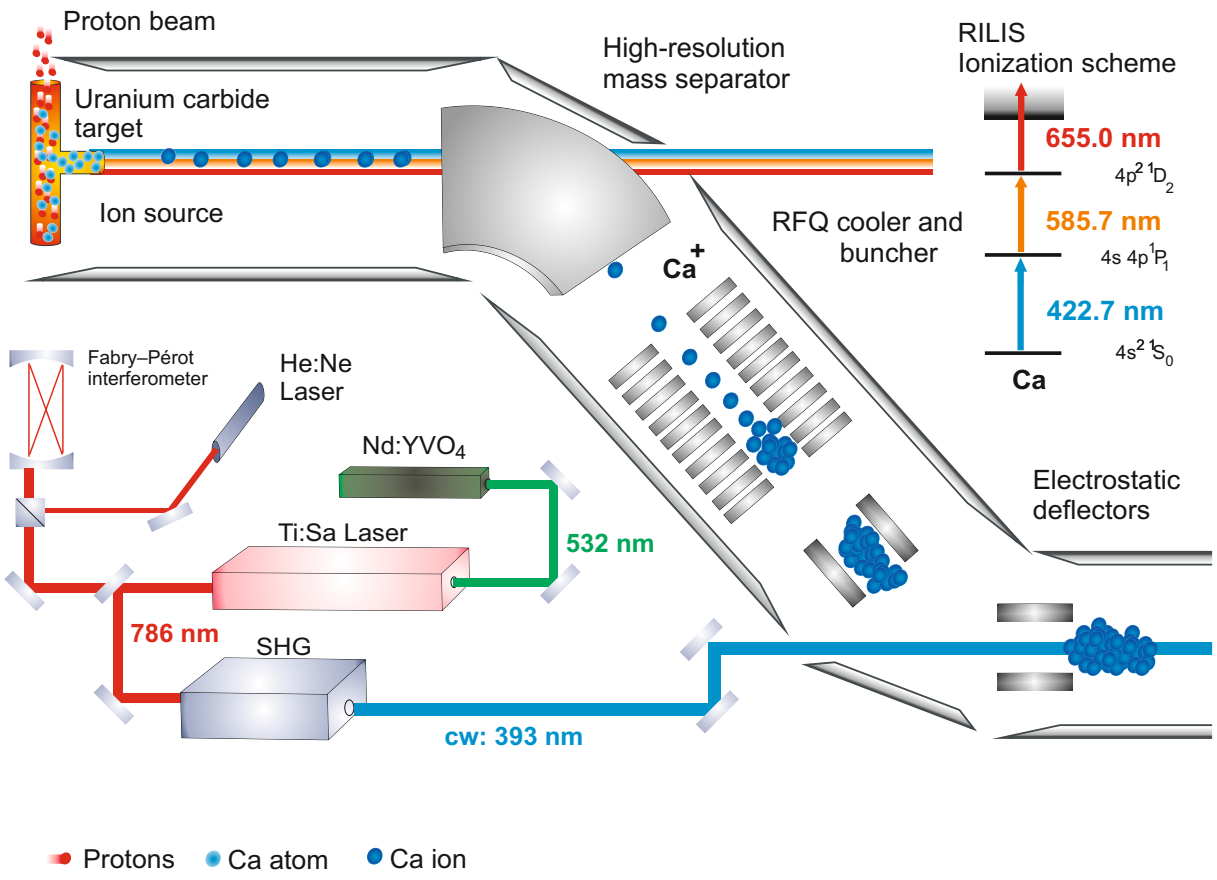

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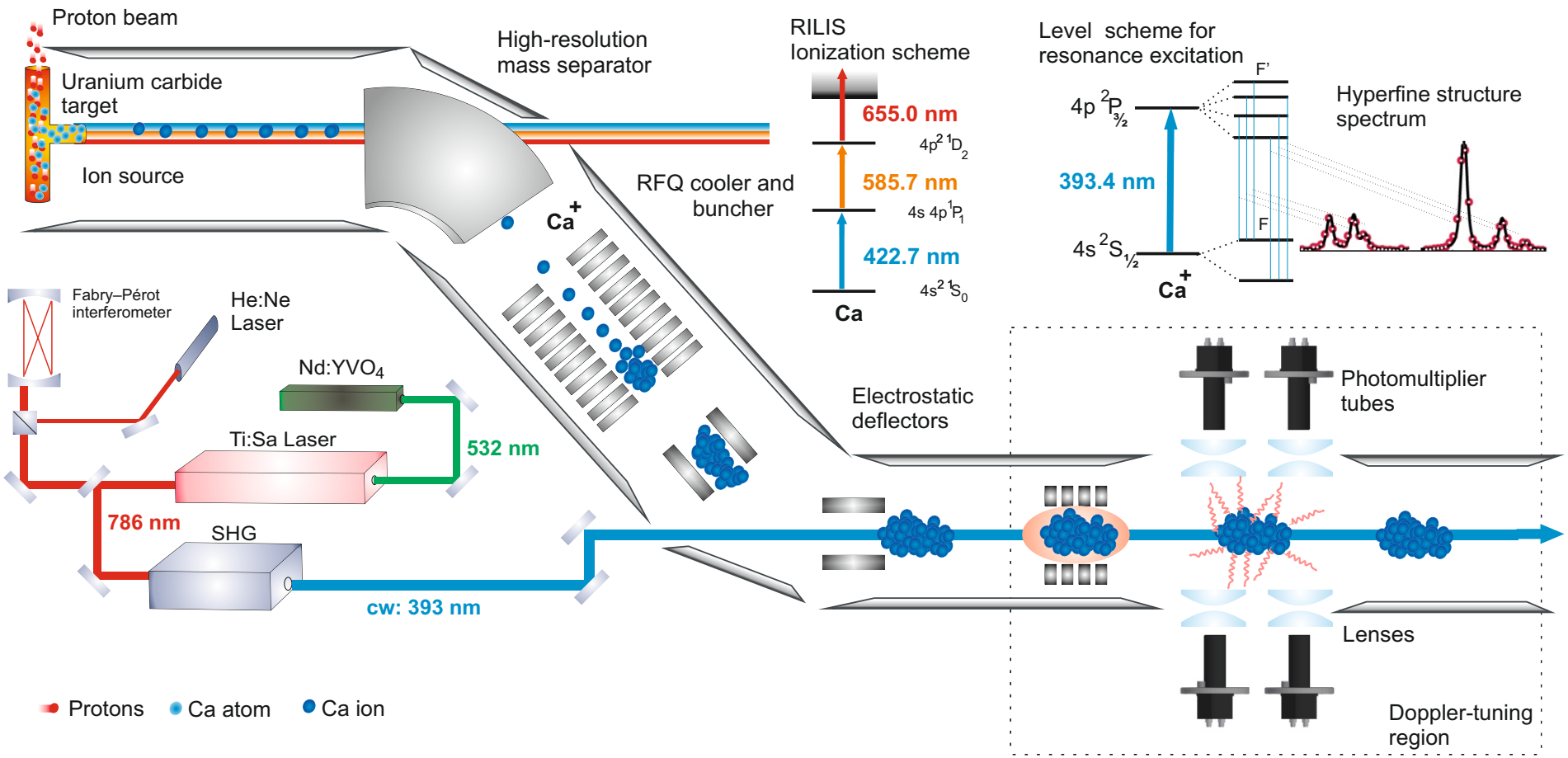
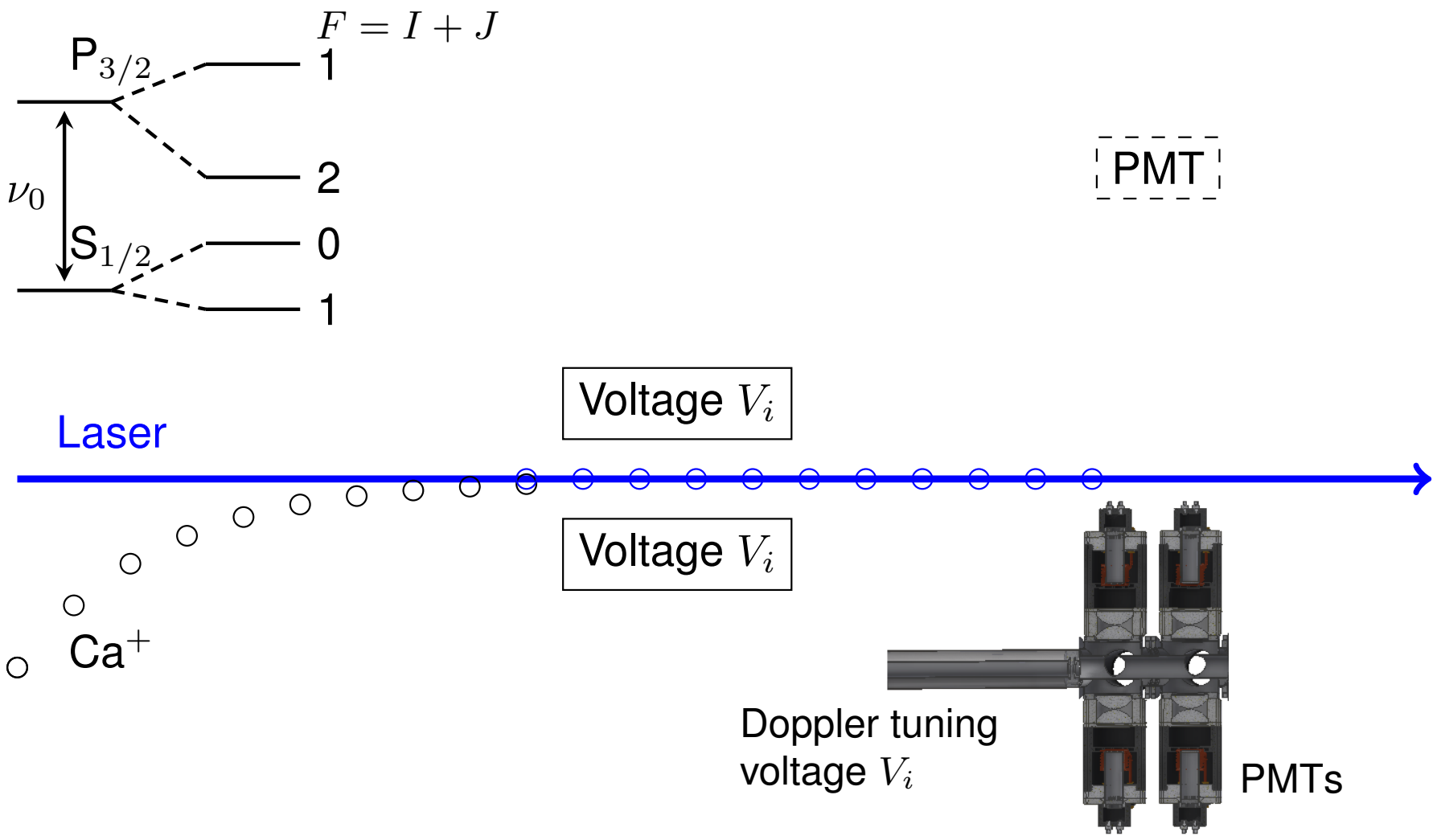
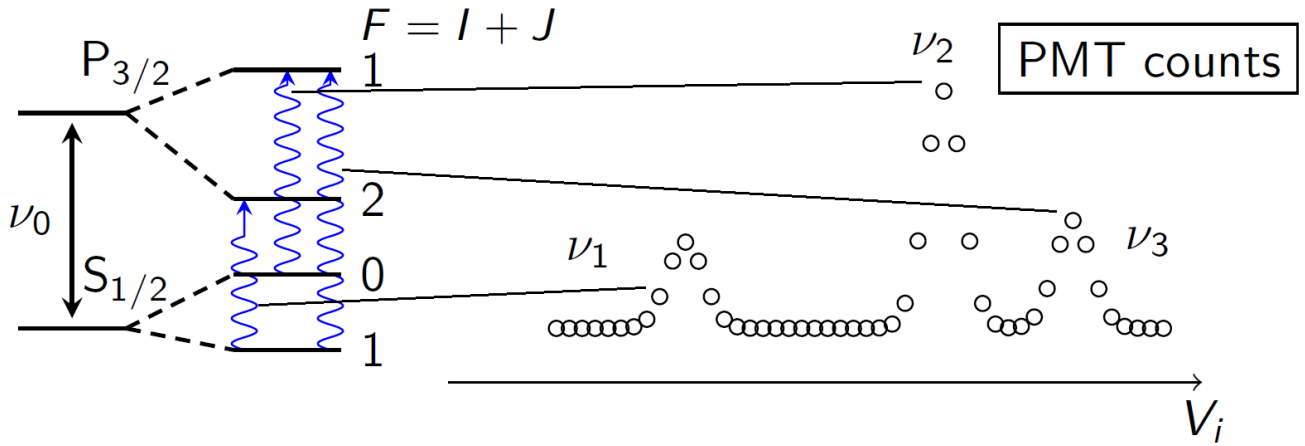


# Collinear Laser Spectroscopy



# Hyperfine structure $\rightarrow I$, $\delta\langle r^2\rangle$, $\mu_I$, $Q_s$




For a given nuclear spin $I$, with $C = [F(F+1) - I(I+1) - J(J+1)]$

$$h\nu = \nu_0 + A\frac{C}{2} + B\frac{1}{4}\frac{(3/2)C(C+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)}$$

- Isotope shifts: $\delta\langle r^2\rangle^{A,A'} = \frac{\delta\nu^{A,A'}}{F} - \frac{K_{MS}}{F}\frac{M_{A'} - M_A}{(M_{A'} + m_e)M_A}$ $\begin{cases} K_{MS}, & \text{Mass shift constant} \\ F, & \text{Electric field factor} \\ M_A & \text{Nuclear mass} \end{cases}$

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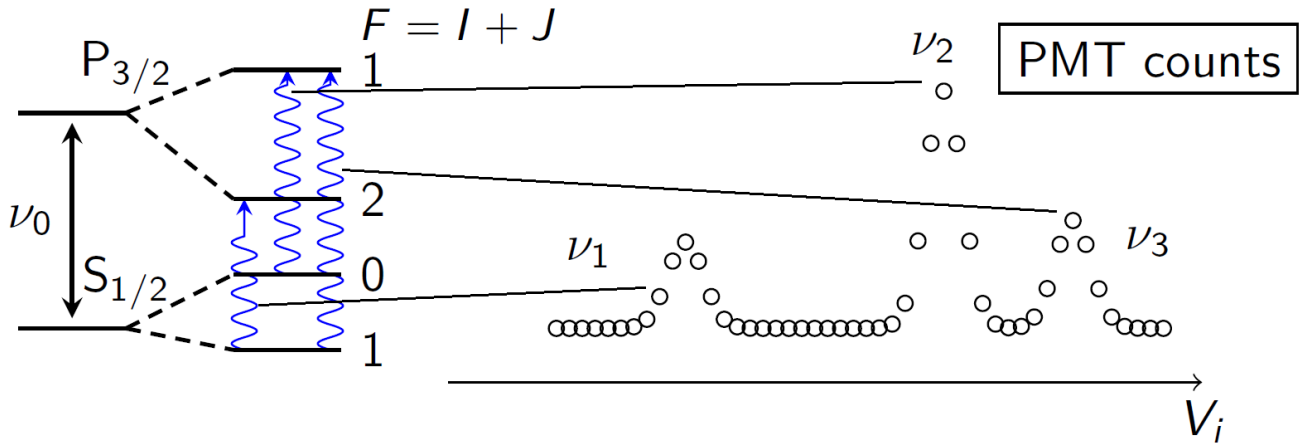


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- Magnetic dipole: $A = \frac{B_I \mu_I}{IJ} \rightarrow \mu_I = AI\left(\frac{B_I}{J}\right)^{-1}$

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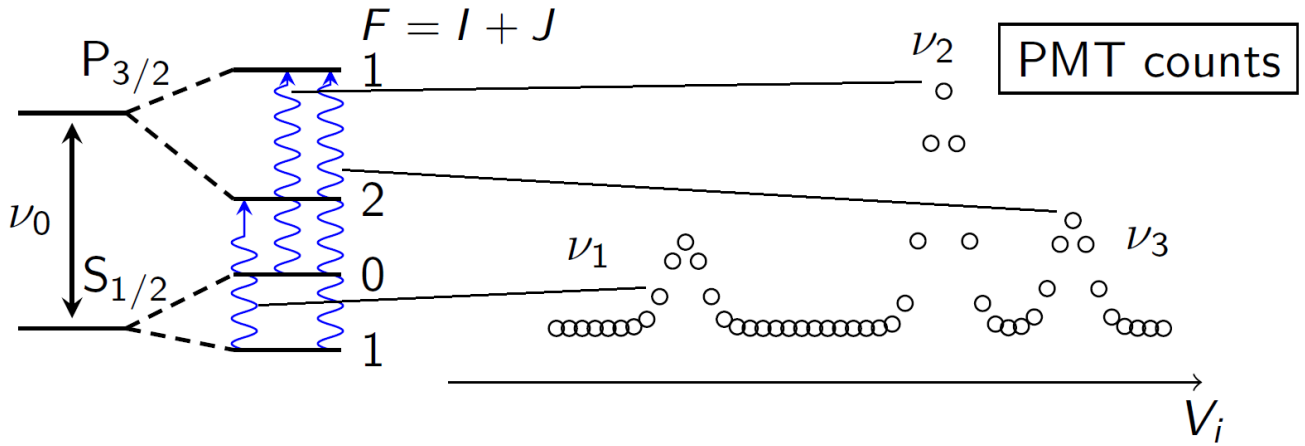


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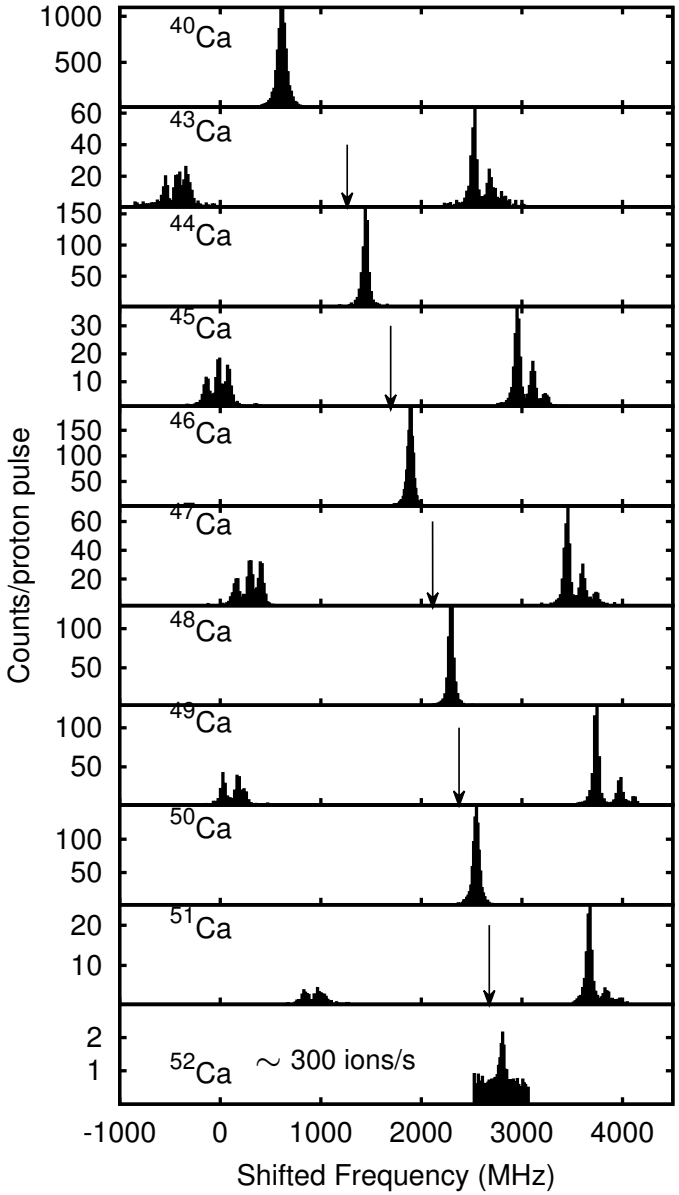
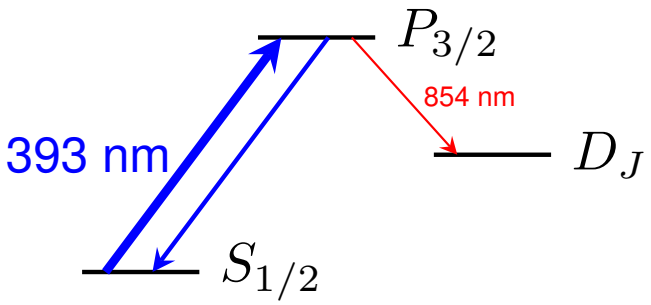
- Electric quadrupole: $B = e\frac{\partial^2 V}{\partial^2 z}Q_s \rightarrow Q_s = B\left(e\frac{\partial^2 V}{\partial^2 z}\right)^{-1}$

# Measured HFS spectra



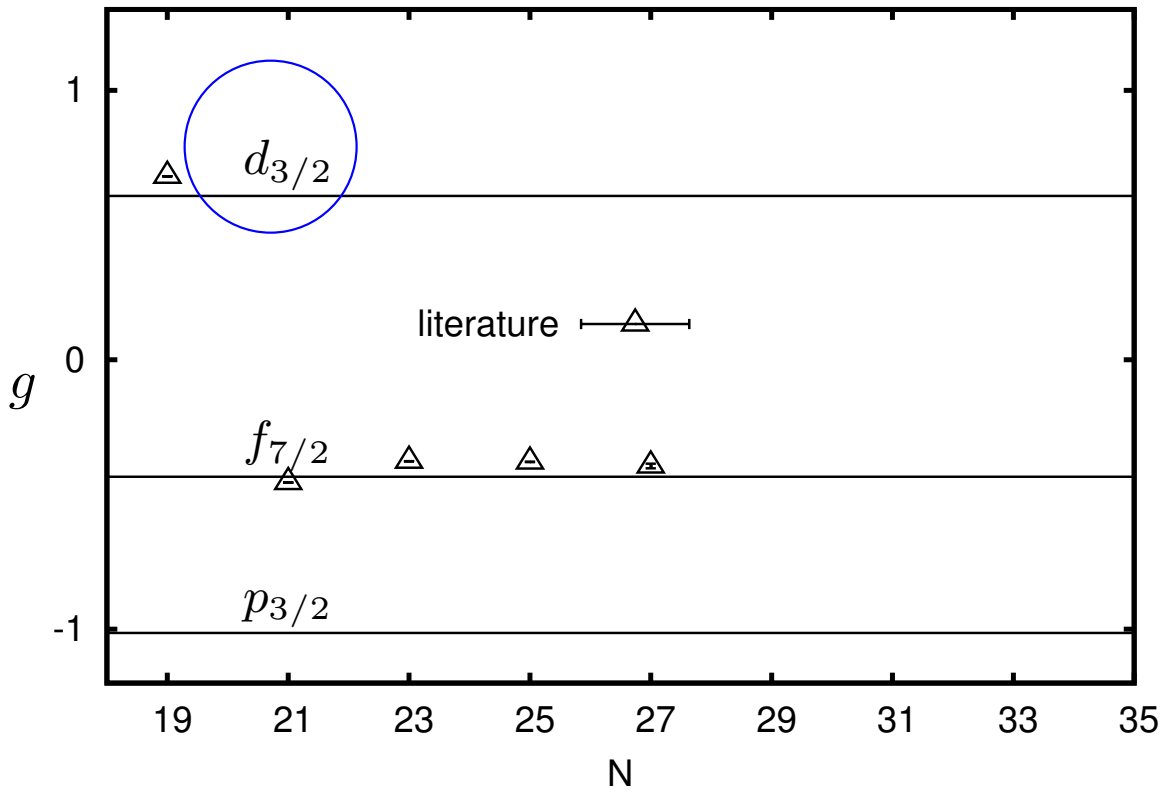



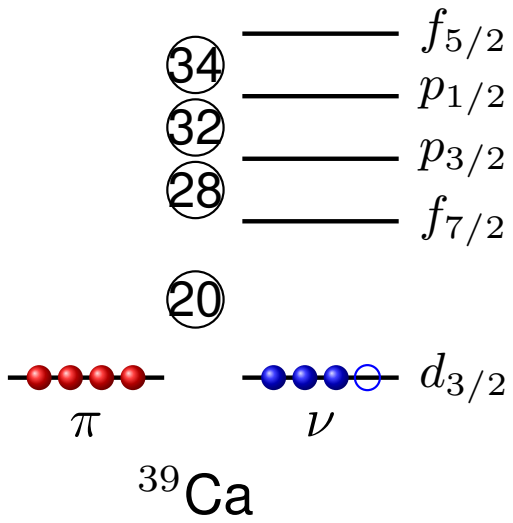

High resolution, high sensitivity
$\rightarrow$ Up to $^{52}$Ca ($\sim$ 300 ions/s)

- Spin determination:
  $A(S_{1/2})/A(P_{3/2})$
- Charge radii:
  $\delta\nu^{A,A'} \rightarrow \delta\langle r^2\rangle^{A,A'}$
- Magnetic moments:
  $A \rightarrow \mu_I$
- Quadrupole moments:
  $B \rightarrow Q_s$

# Results: $g$-factors

[R.F. Garcia Ruiz et al., PRC 91, 041304(R) (2015)]



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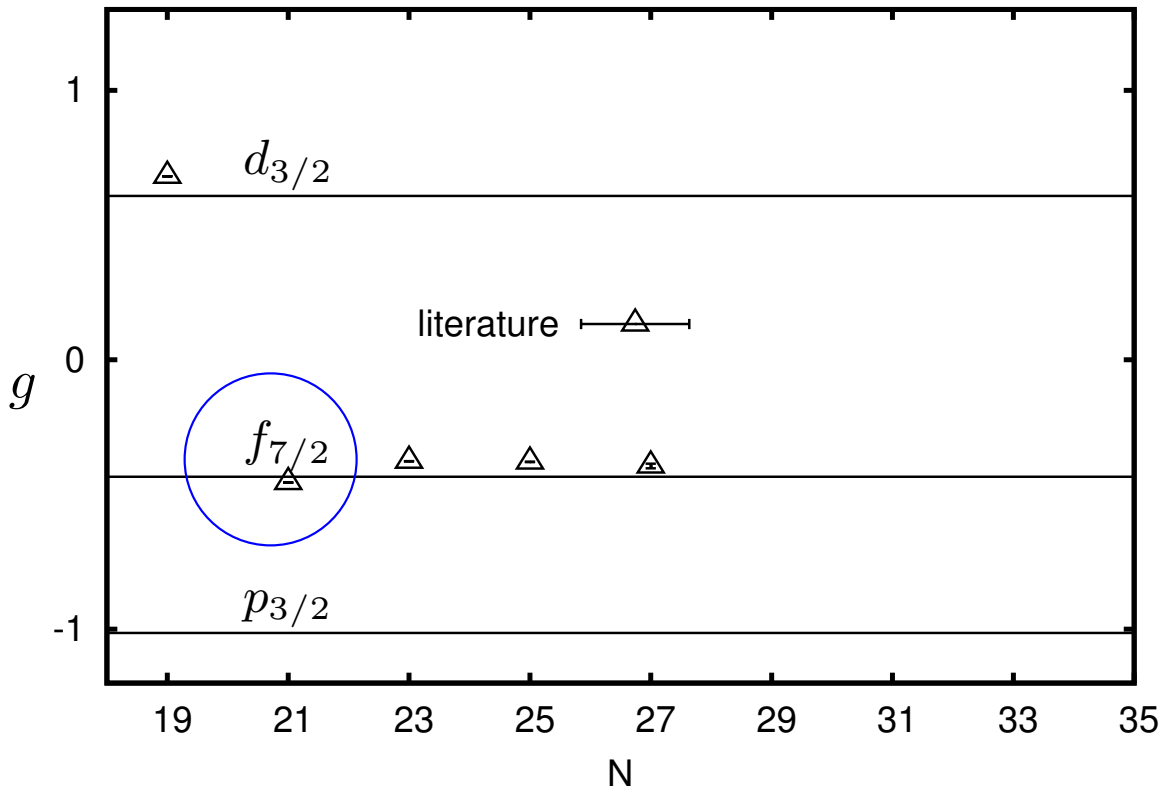


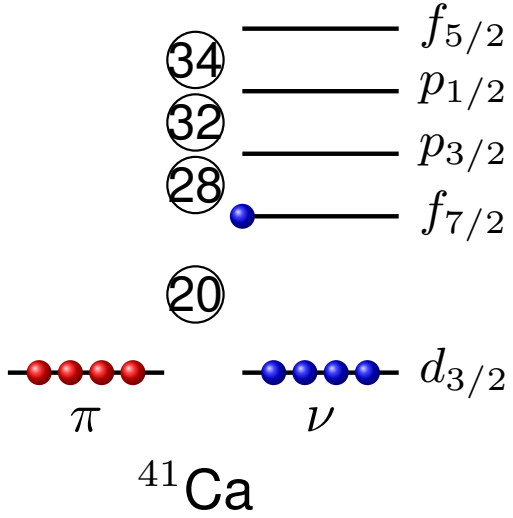

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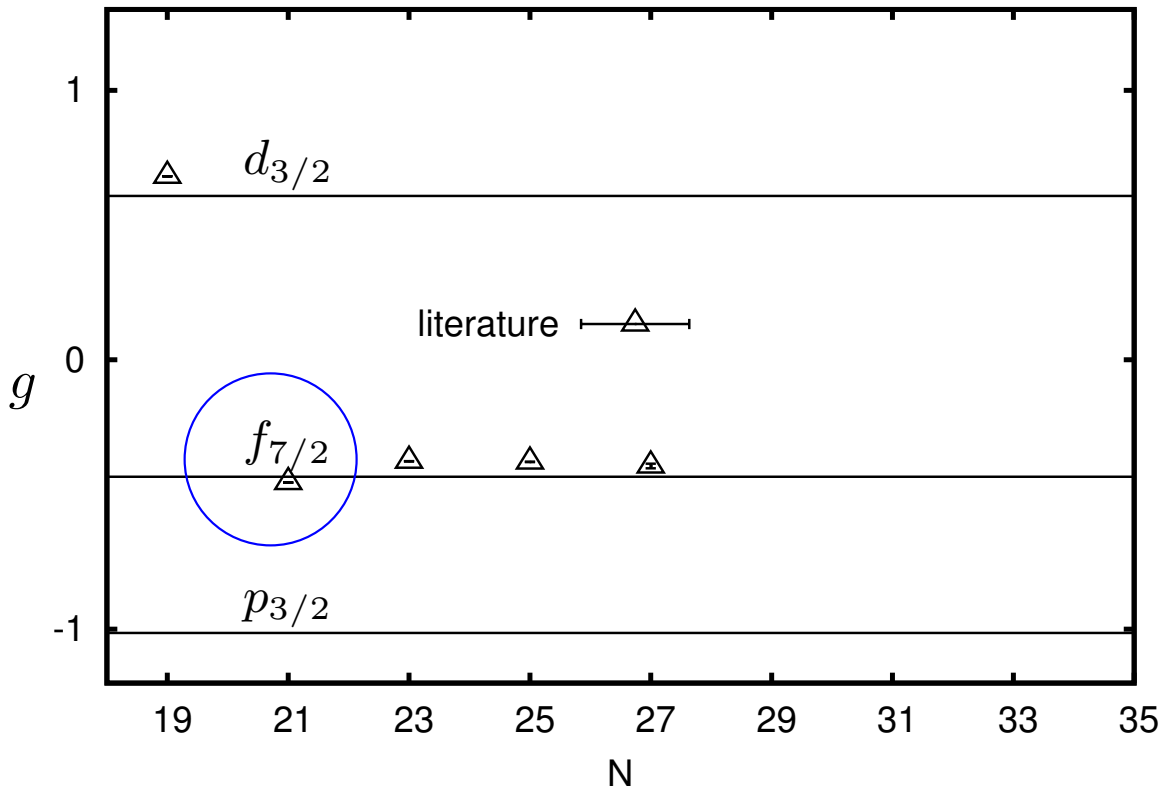


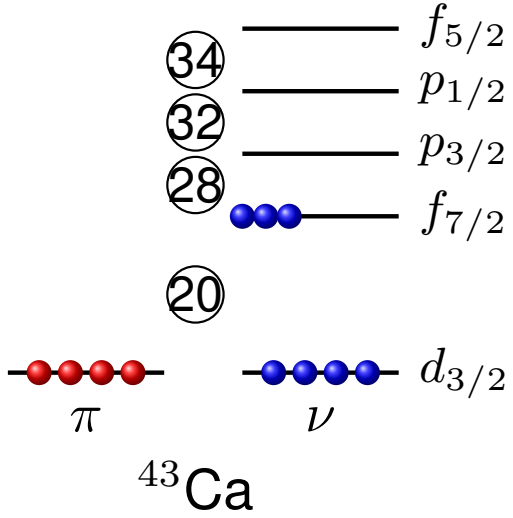

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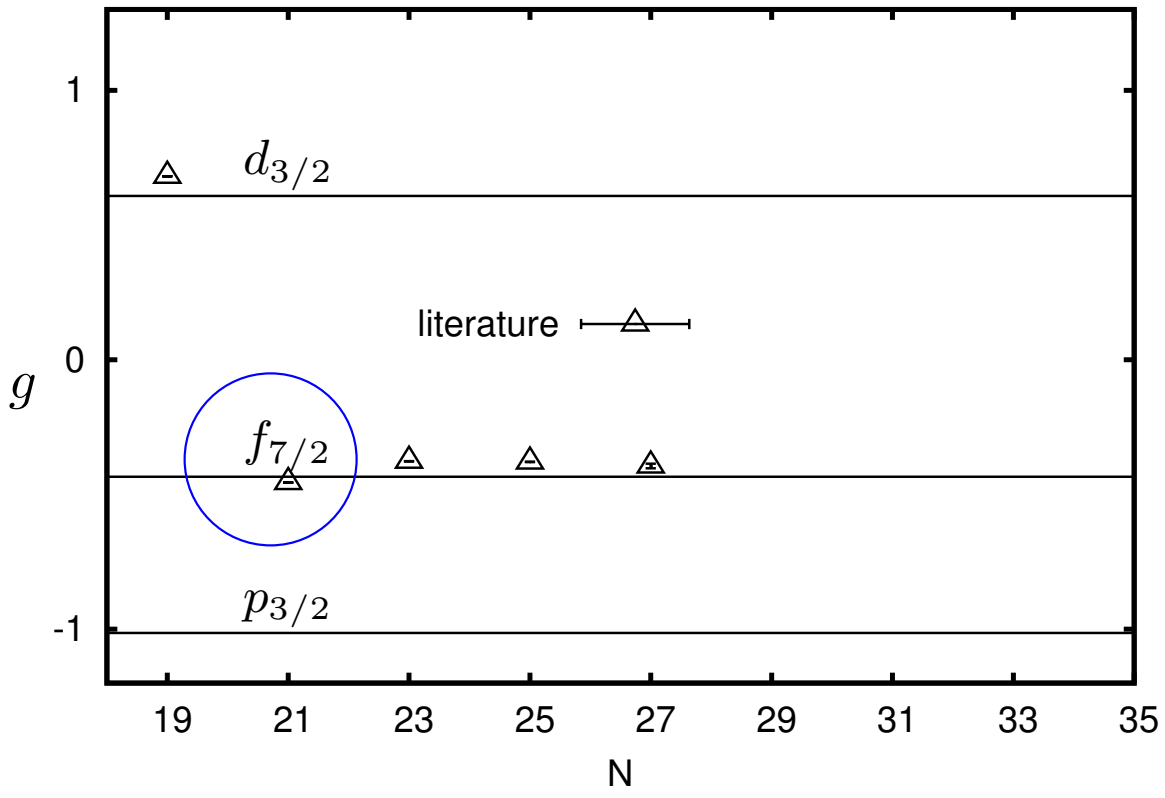


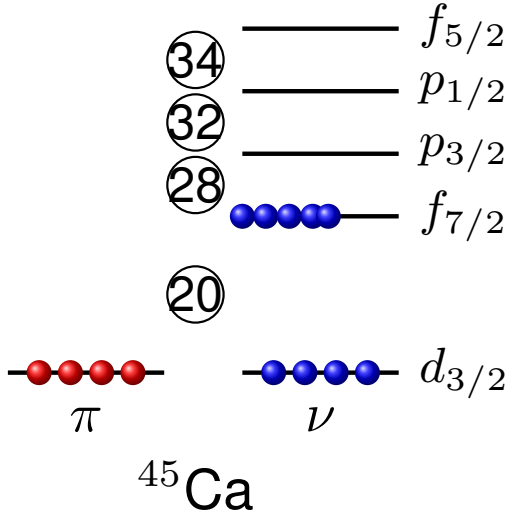

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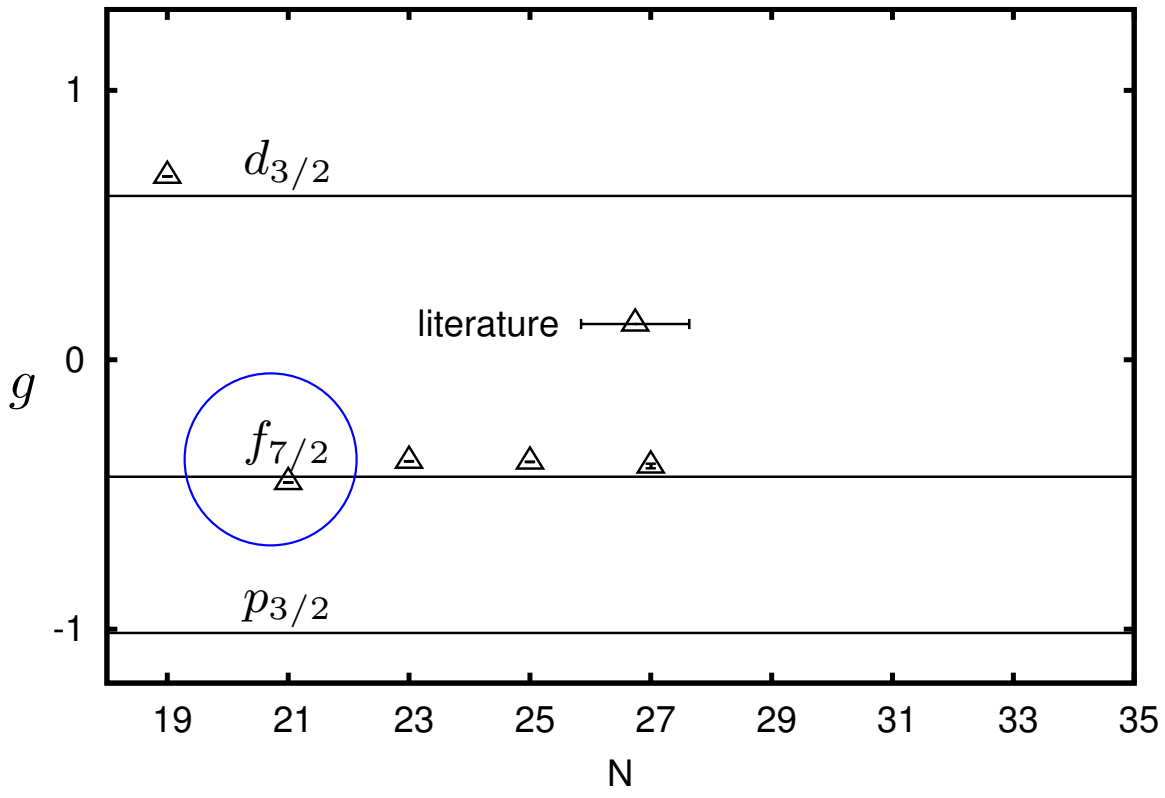


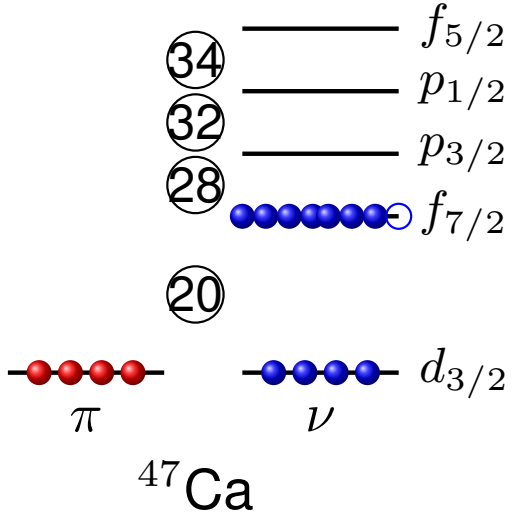

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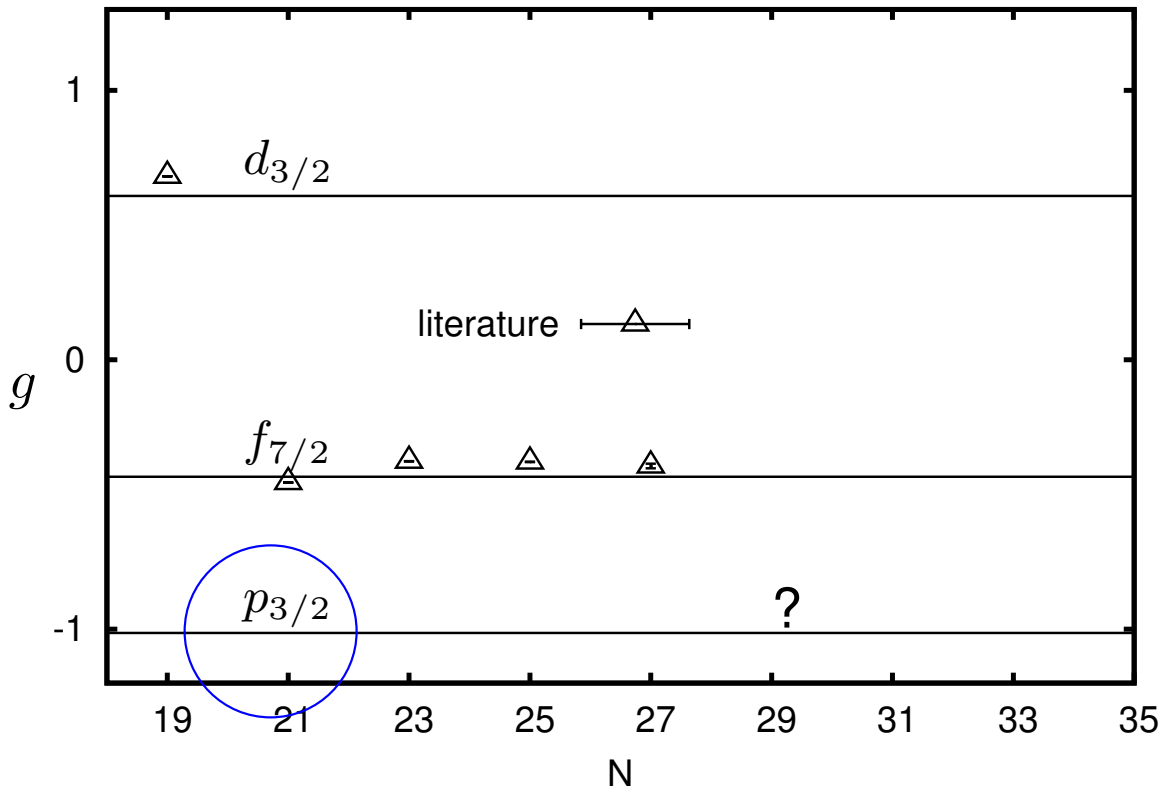


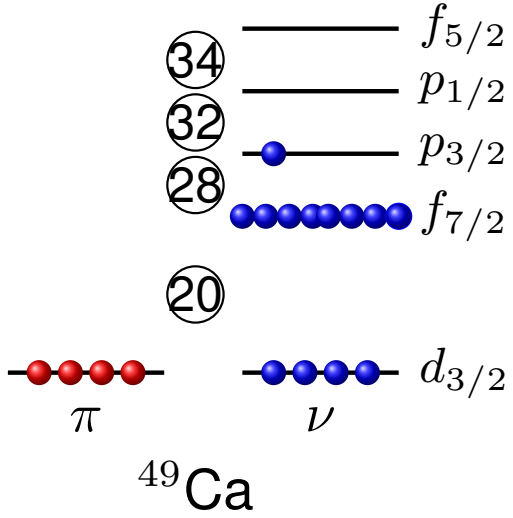

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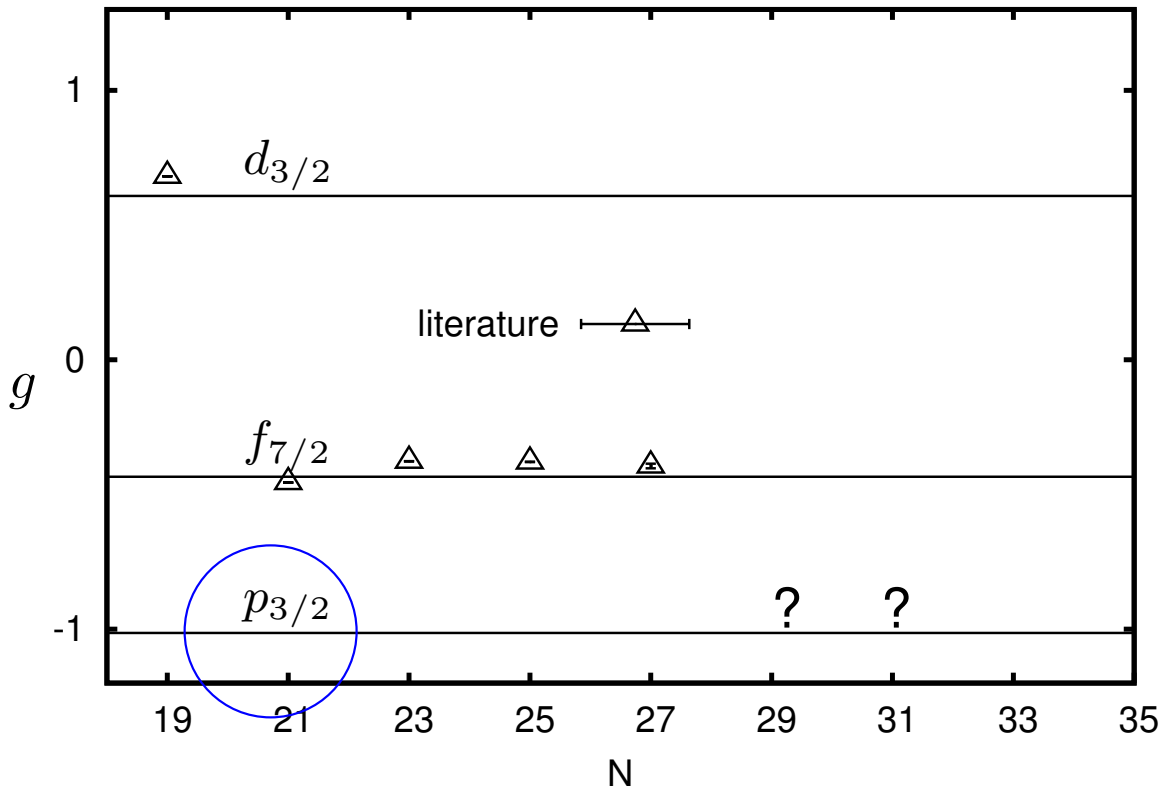


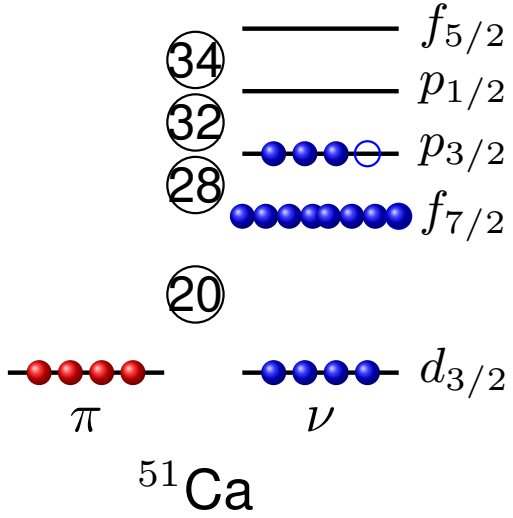

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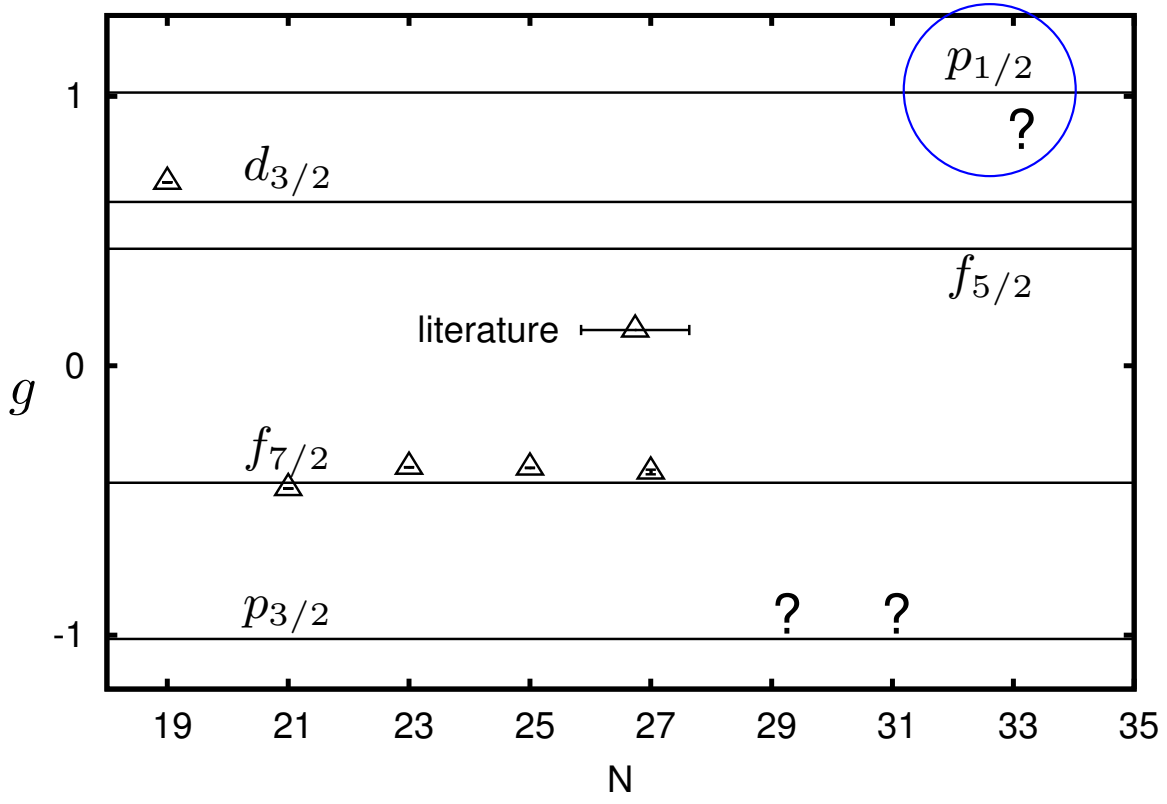


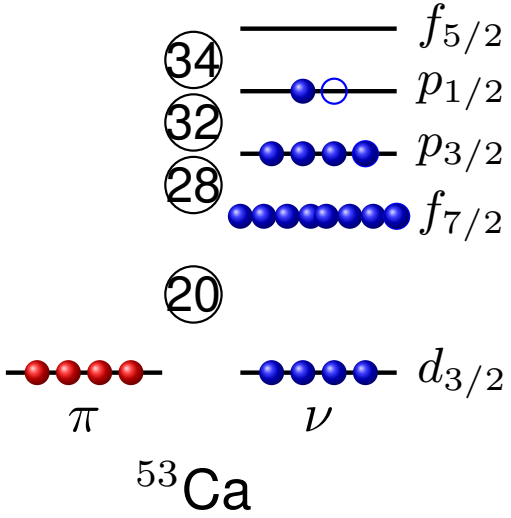

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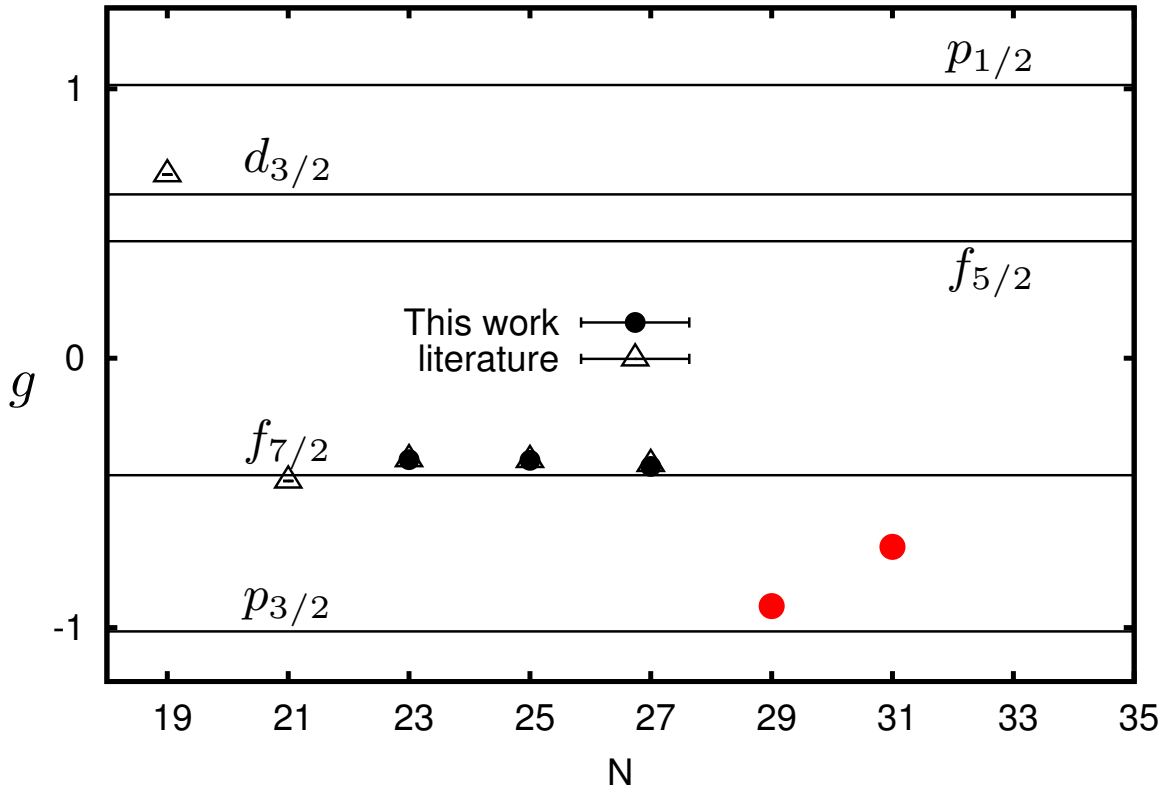
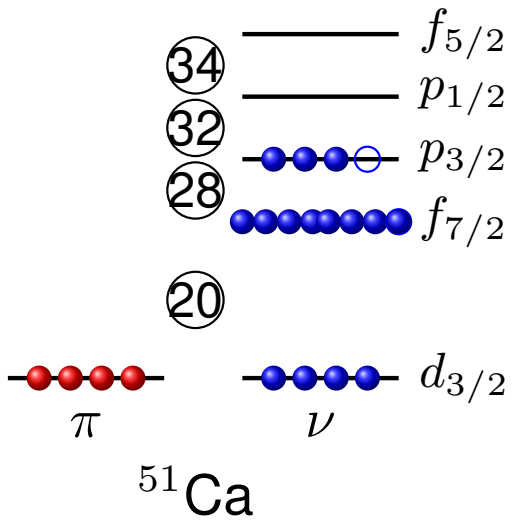
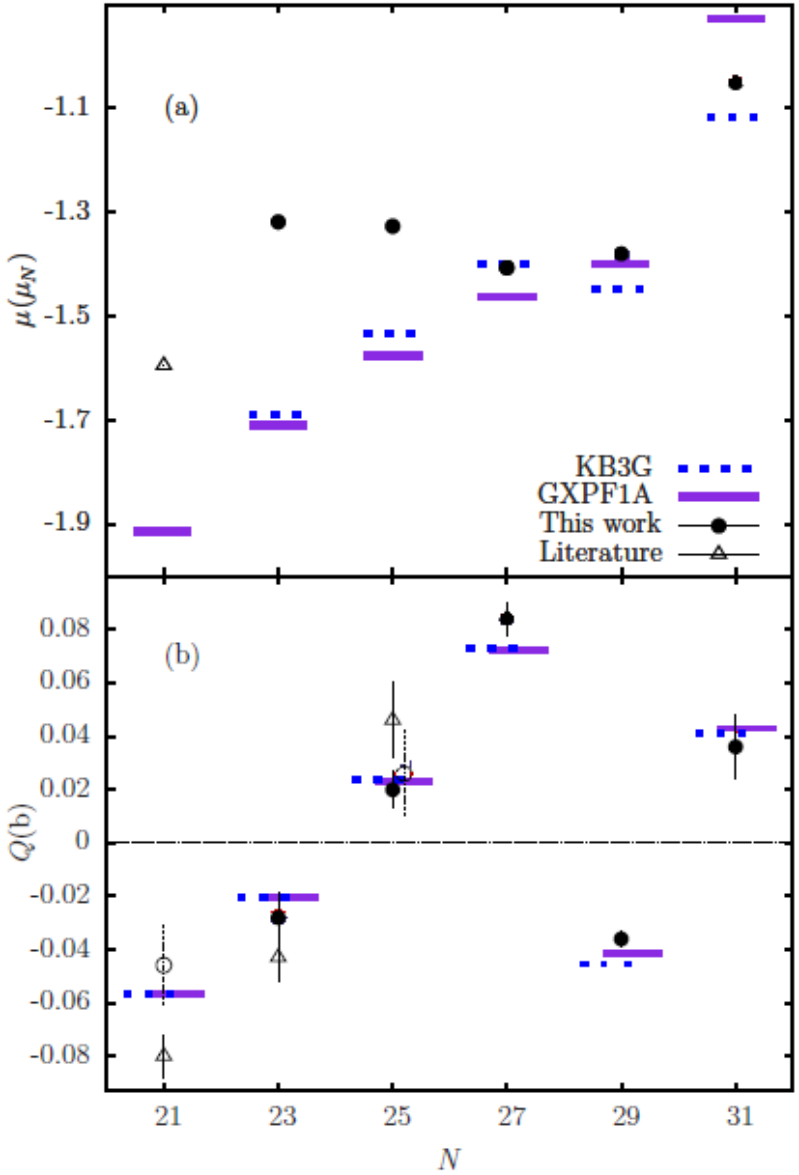



Neeed of cross-shell excitations across $N = 32$!

# Results: Electromagnetic moments

[R.F. Garcia Ruiz et al., PRC 91, 041304(R) (2015)]




→ Valence space interactions ($^{40}$Ca core)
NN interactions fitted to the Ca region

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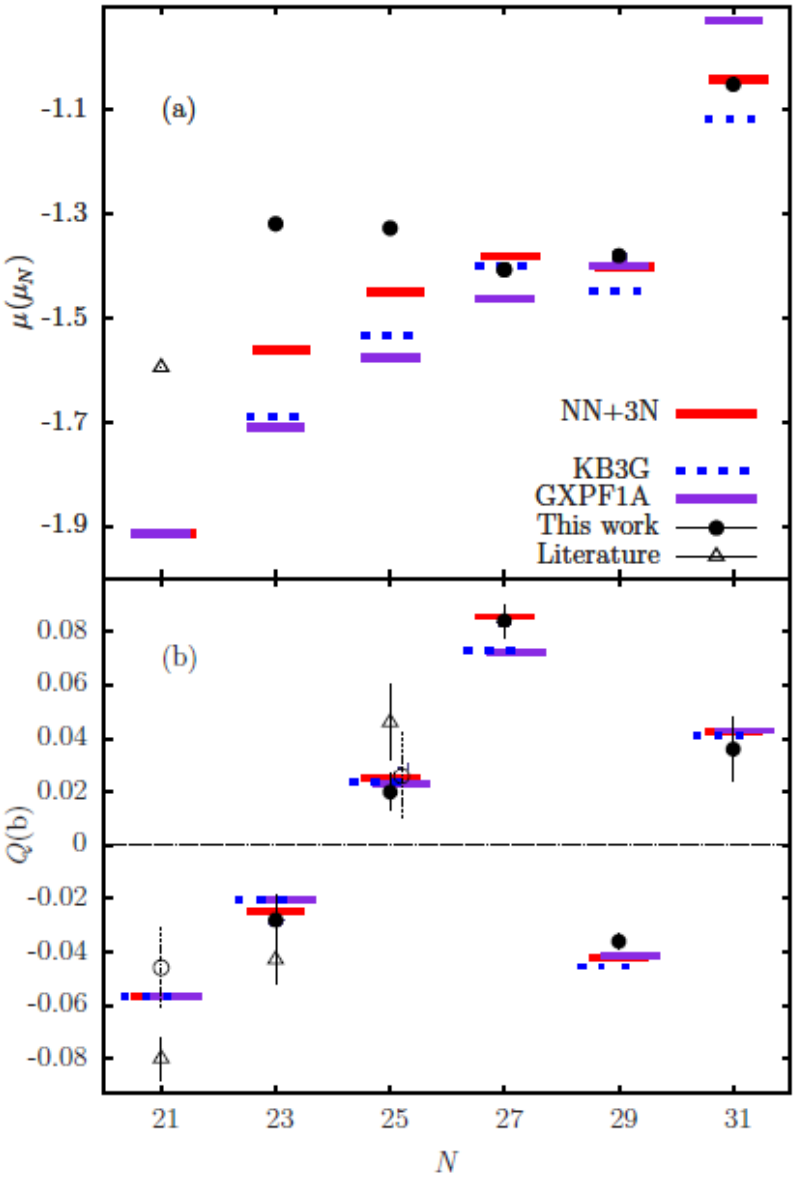


→ 3N+NN → "Microscopic interactions". Fitted up to A=3 system. Derived from chiral effective field theory. ($^{40}$Ca core)

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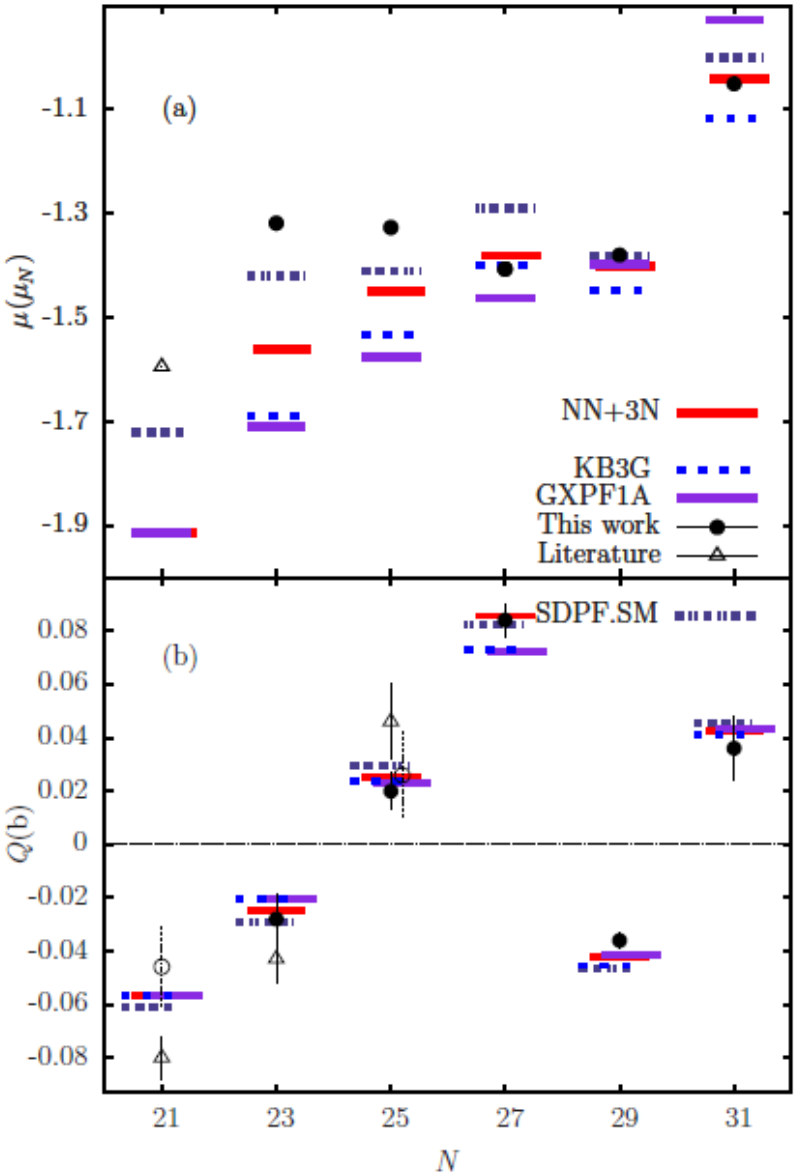


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Large scale shell model calculations.($^{28}$Si core)
NN interactions fitted to $sdpf$ nuclei.

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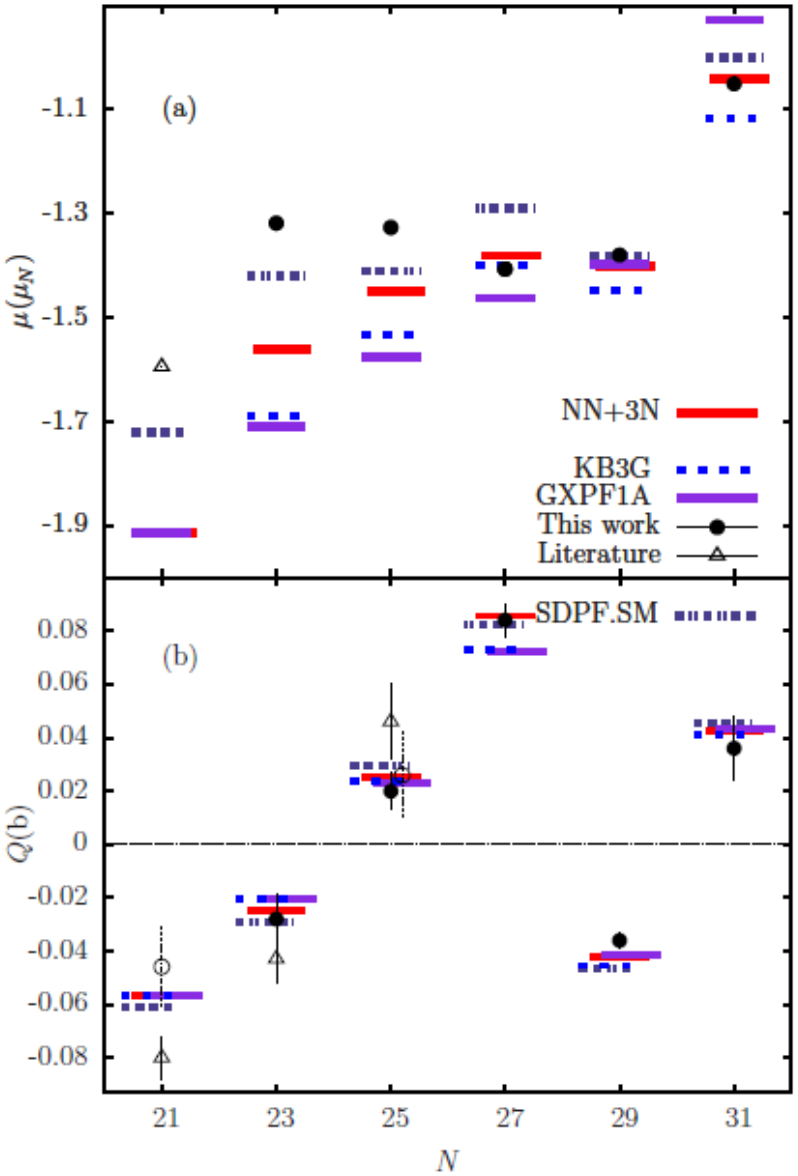


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Need of cross-shell excitations across $Z, N = 20$. Consistent with:

→ $g(2^+)$ values
[Schielke et al. PLB 571, 29 (2003)] [Taylor et al. PLB 605, 265 (2005)]
→ $B(E2)$ values
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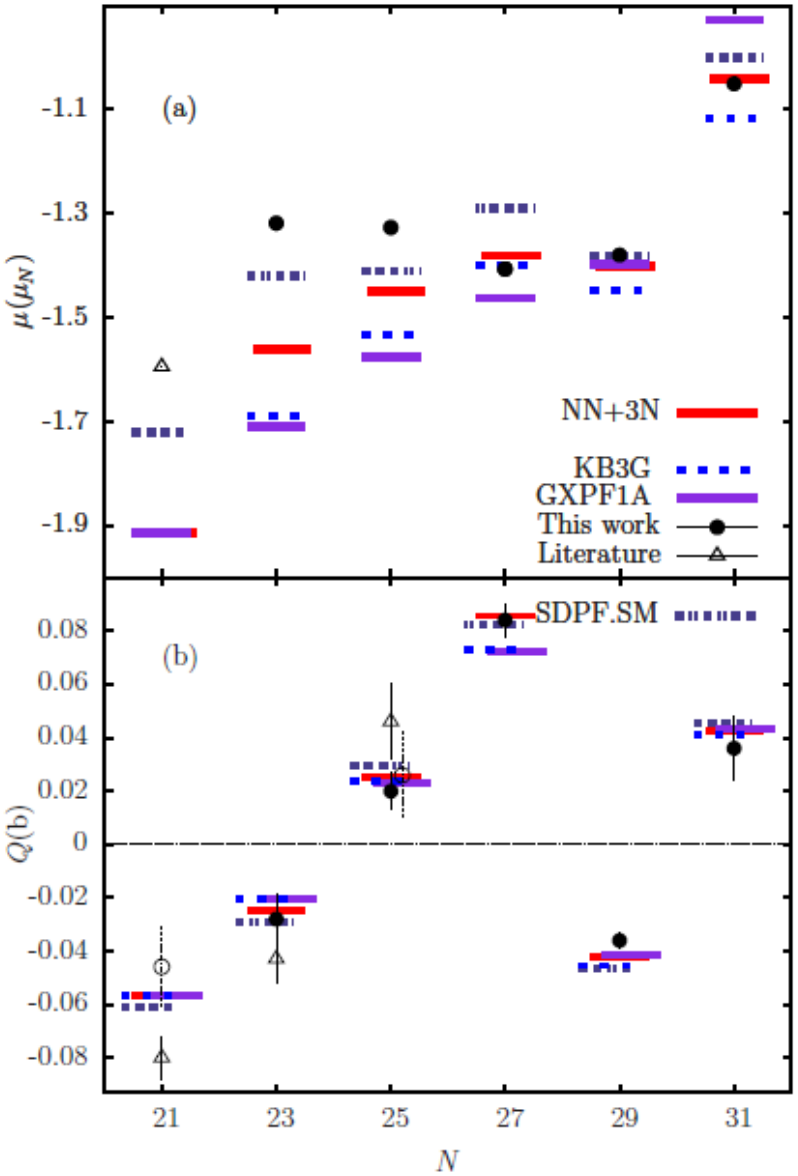


Good agreement with theory using free $g$-factor and effective charges $e_n = 0.5e, e_p = 1.5e$

In contrast with $B(M1)$ values for $^{48}$Ca
$\rightarrow g_{eff} = 0.75 g_{free}$
[Neumann-Cosel et al, PLB 443, 1 (1998) ]

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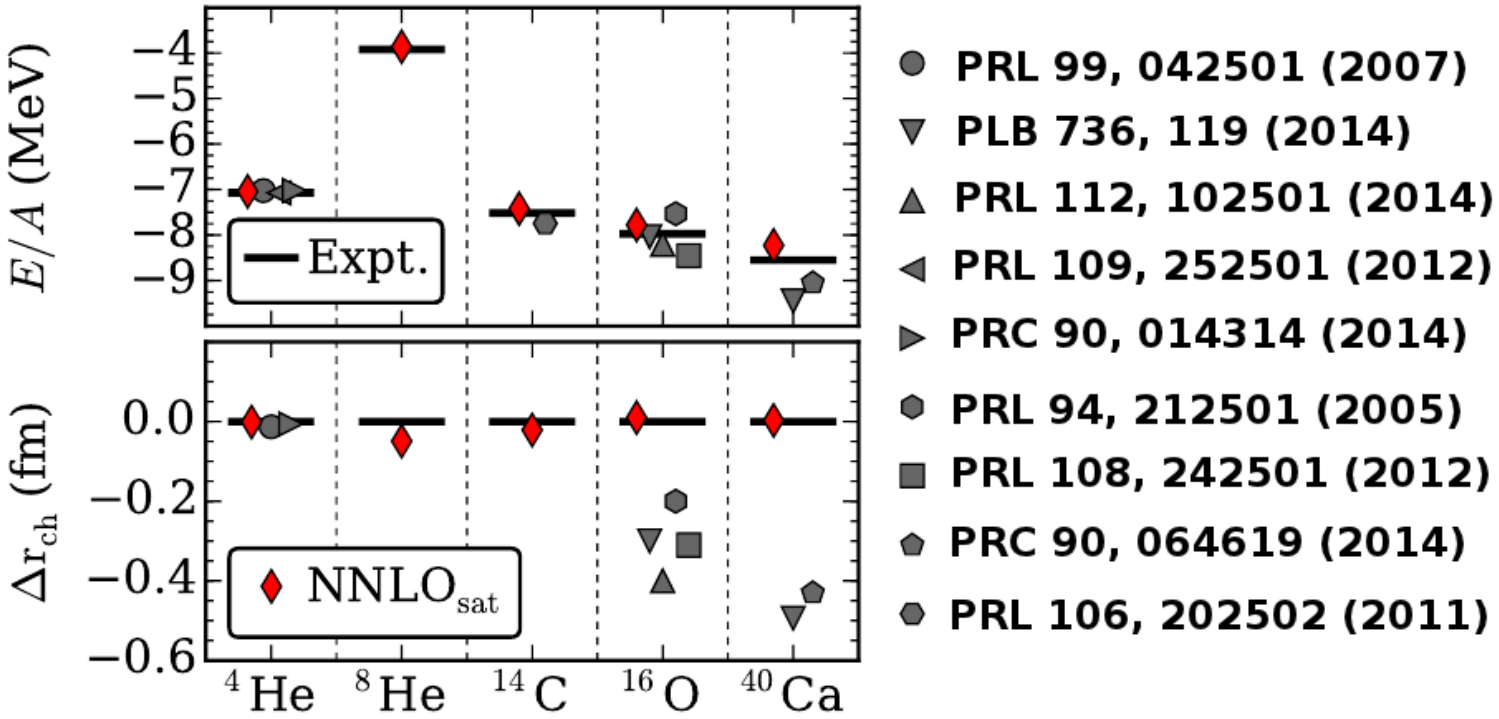
[Caurier et al. PLB 522, 240 (2001)]

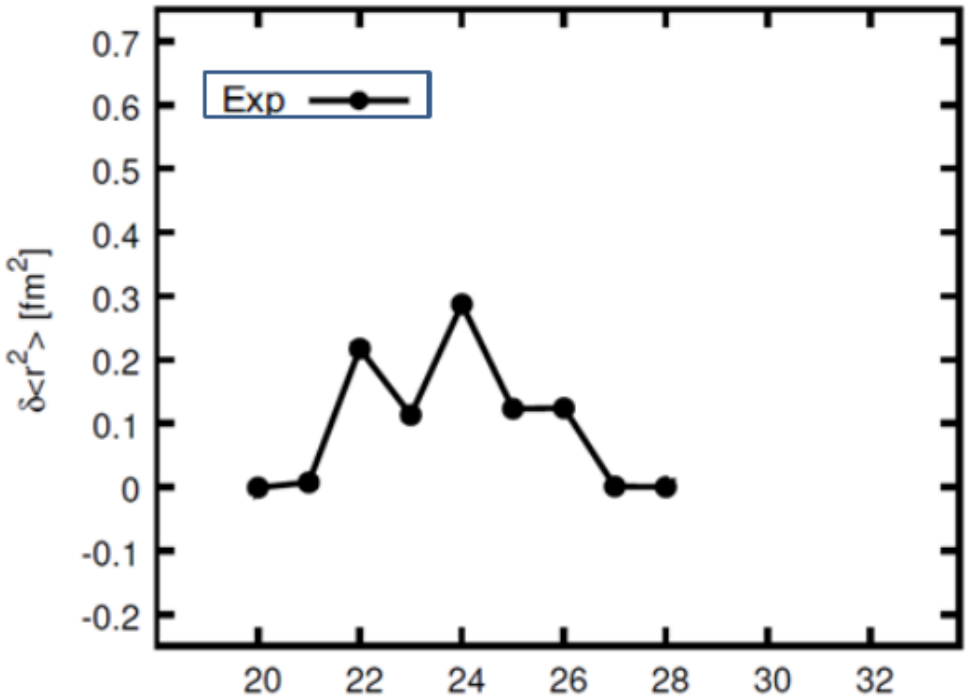
# Nuclear radii and binding energies from chiral interactions

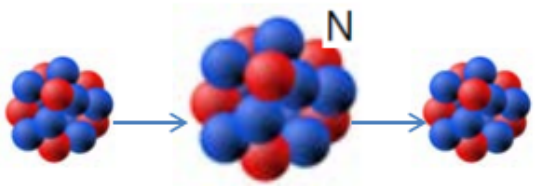
*"The accurate reproduction of nuclear radii and binding energies of medium-mass nuclei is a long-standing challenge in nuclear theory"*
[A. Ekstrom *et al* PRC 91 (2015)]



# Results: Charge radii

The charge radii of Ca isotopes present additional challenges
[R.F. Garcia Ruiz *et al.* Nature Physics (2016)]



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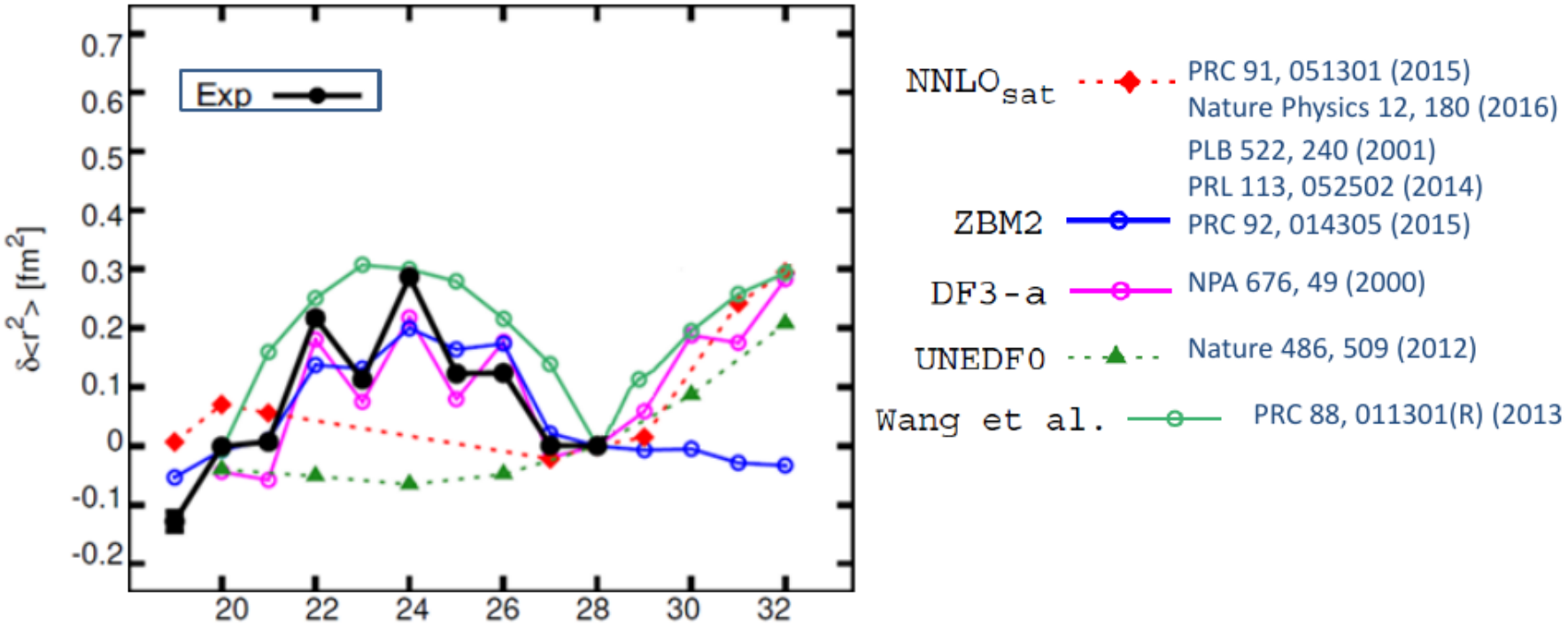


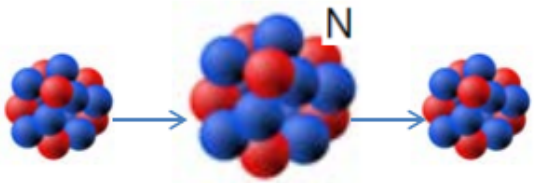

# Results: Charge radii

ARTICLES
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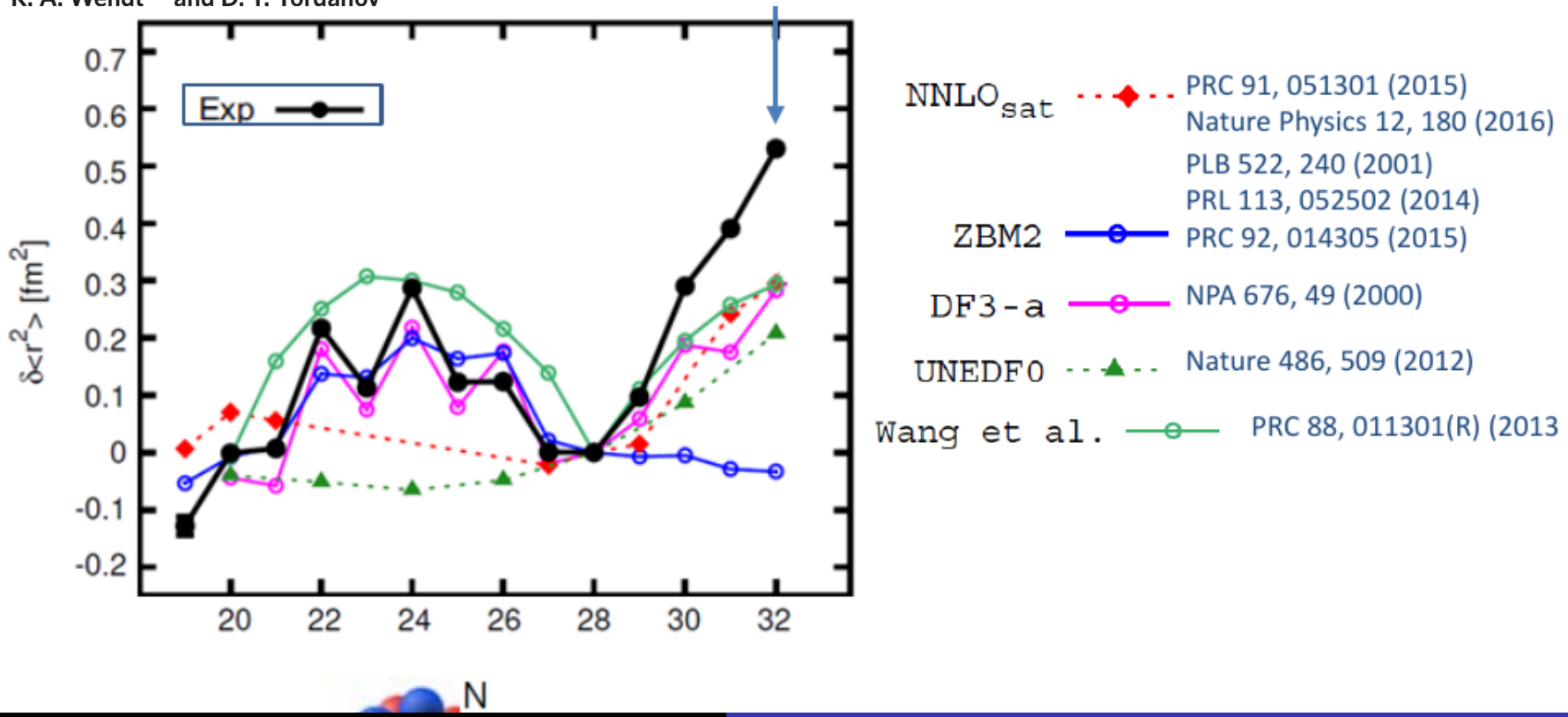
nature physics

## Unexpectedly large charge radii of neutron-rich calcium isotopes

R. F. Garcia Ruiz[1*], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]



# The Limit of Optical Detection

Very low production yield beyond $^{52}$Ca

| Isotope | Yield |
|---|---|
| $^{53}$Ca | $\sim 100$ ions/s |
| $^{54}$Ca | $\sim 10$ ions/s |

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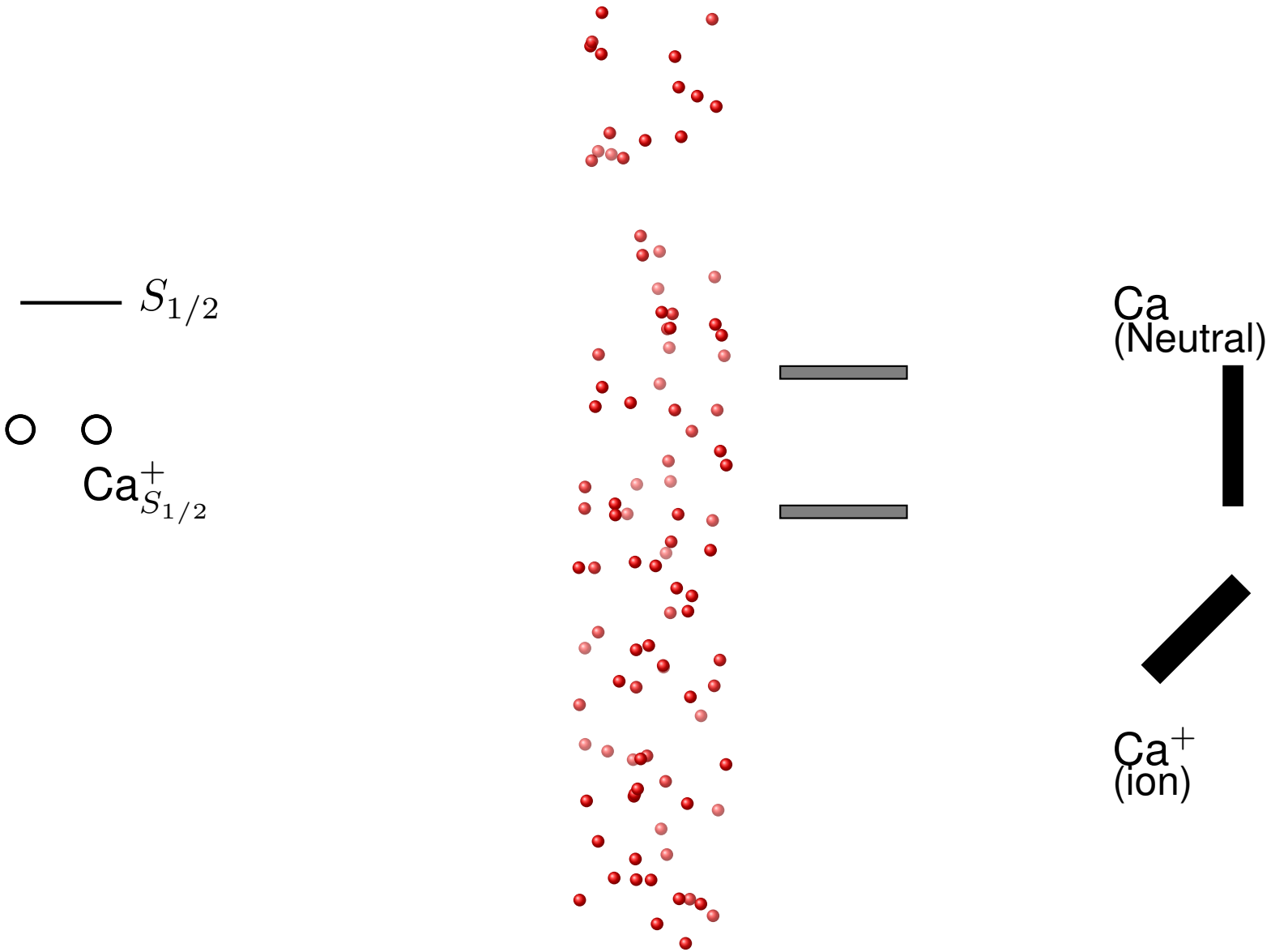
Non optical techniques need to be implemented to obtain higher sensitivity.
Particle detection $> 10^2$ photo detection sensitivity.
*Ultrasensitive Radioactive Detection of Collinear-Laser Optical Pumping*
[*Vermeeren et al.* PRL 68 (1992) 1679]

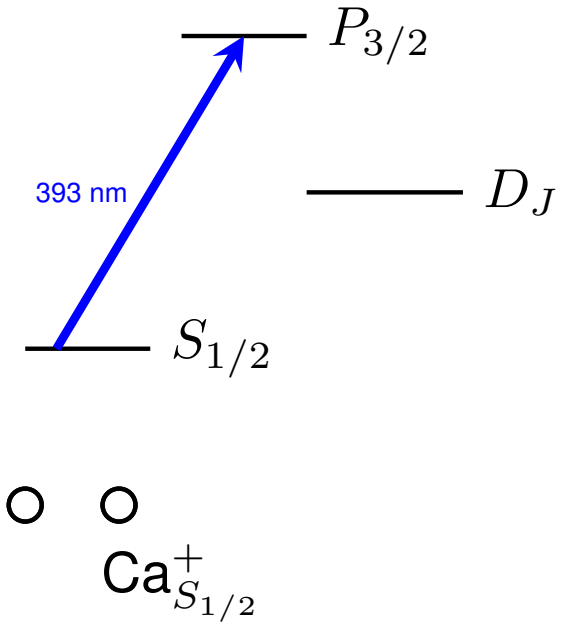
# Ultra-sensitivity: Atom/ion detection

Charge exchange cell (CEC)



# Optical pumping and state-selective neutralization

Charge exchange cell (CEC)

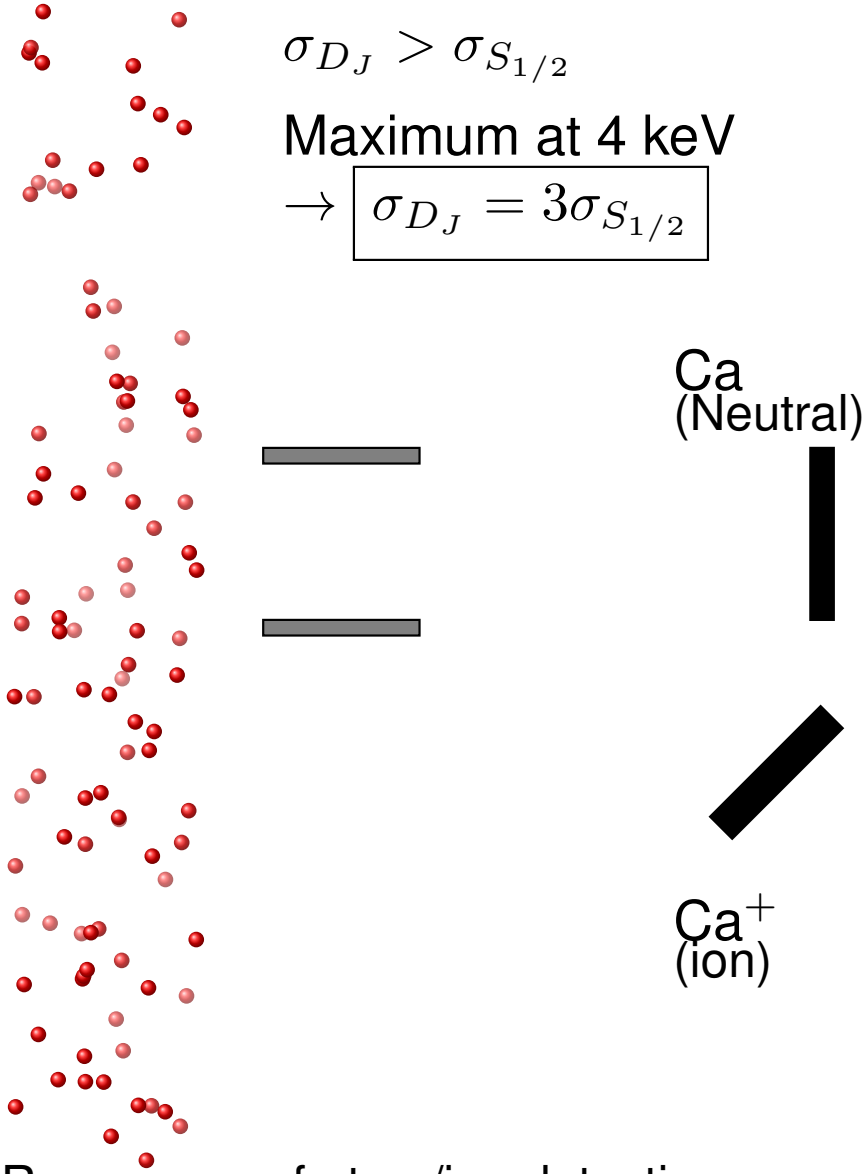



Neutralization cross section

$\sigma_{D_J} > \sigma_{S_{1/2}}$

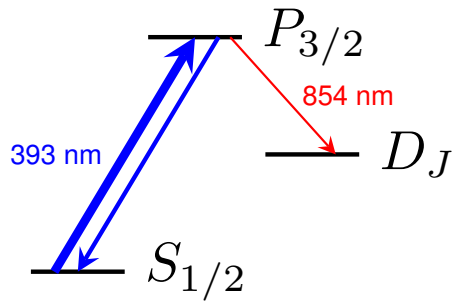
Maximum at 4 keV

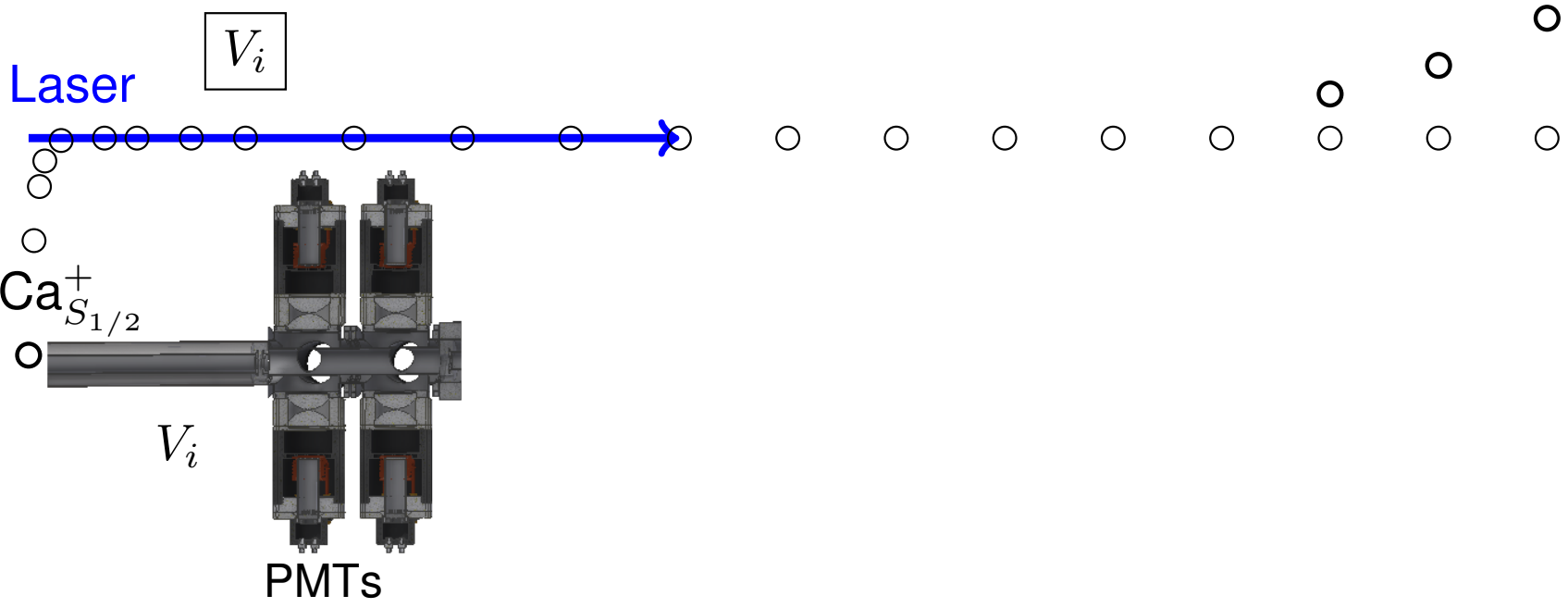
$\rightarrow \boxed{\sigma_{D_J} = 3\sigma_{S_{1/2}}}$




Resonant excitation $\rightarrow$ Resonance of atom/ion detection

# New Beam Line Design



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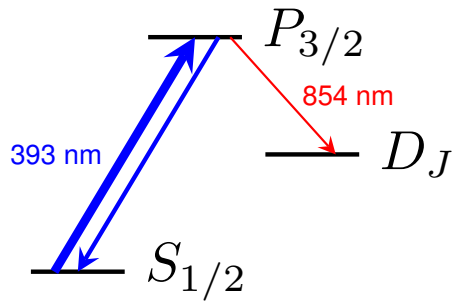


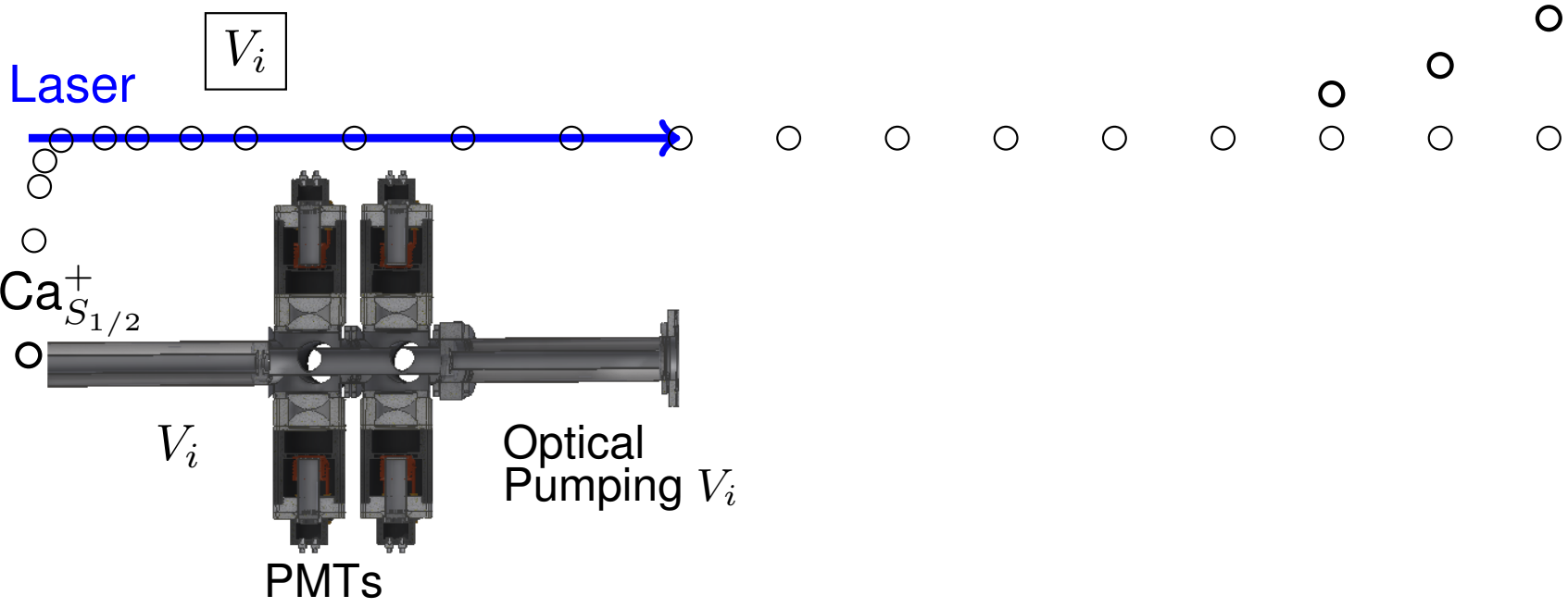

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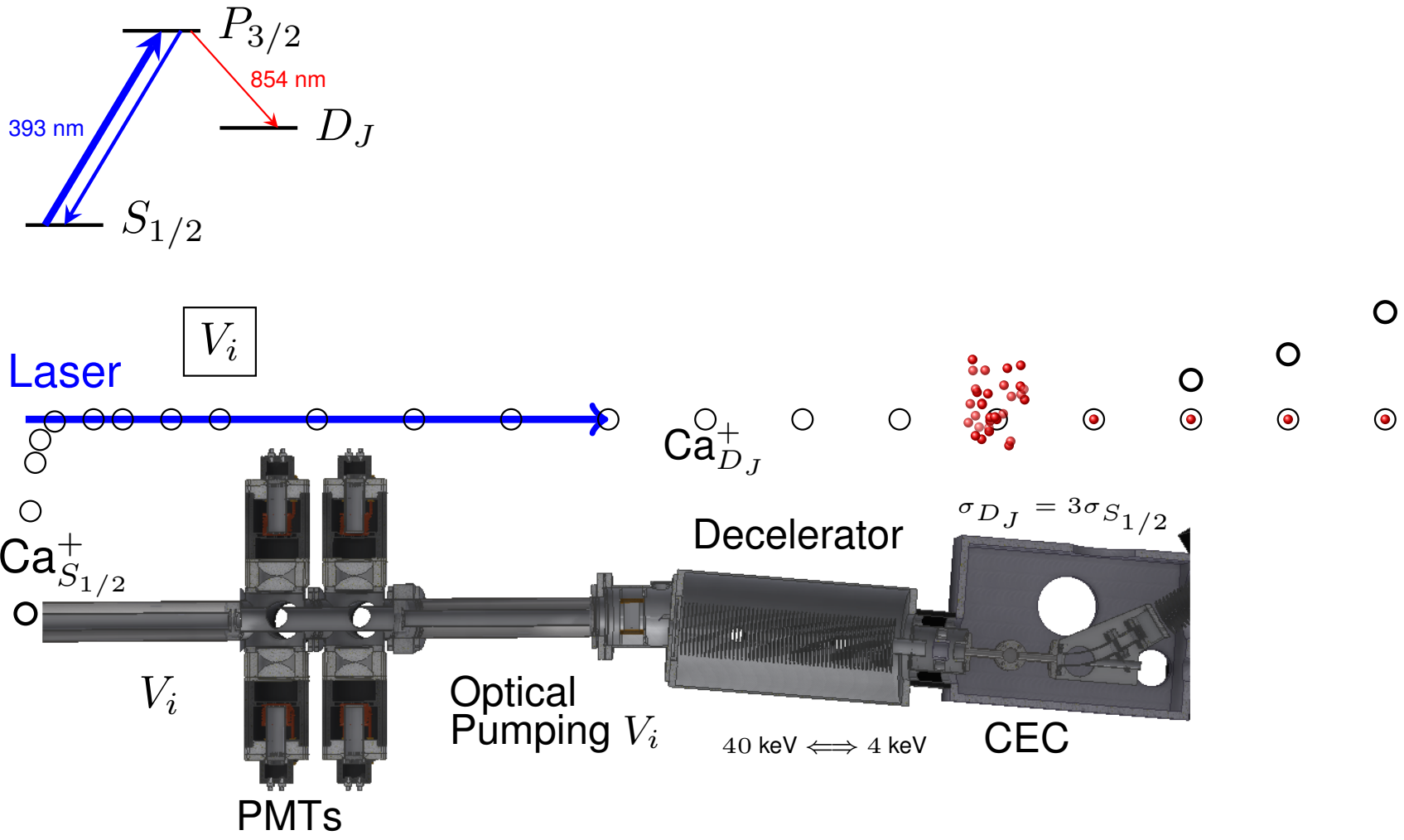

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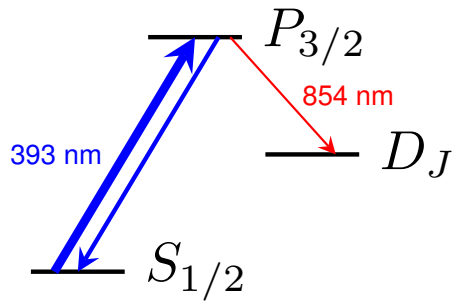


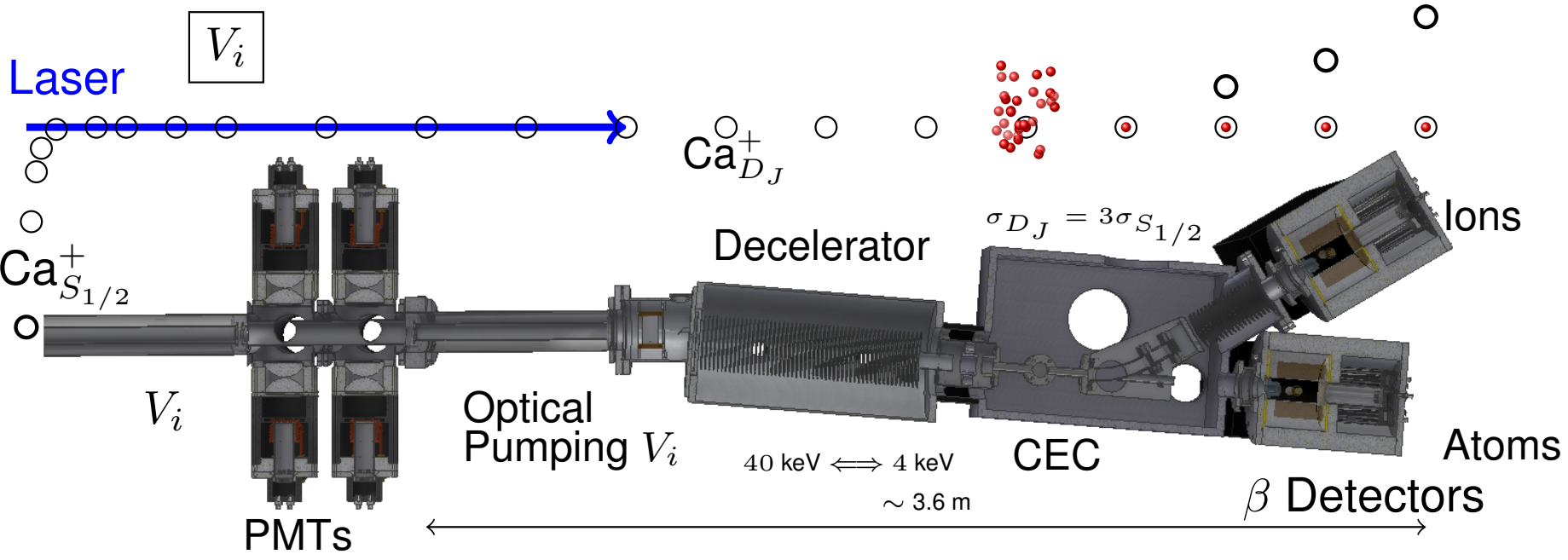

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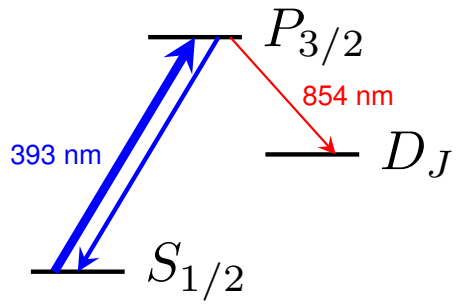
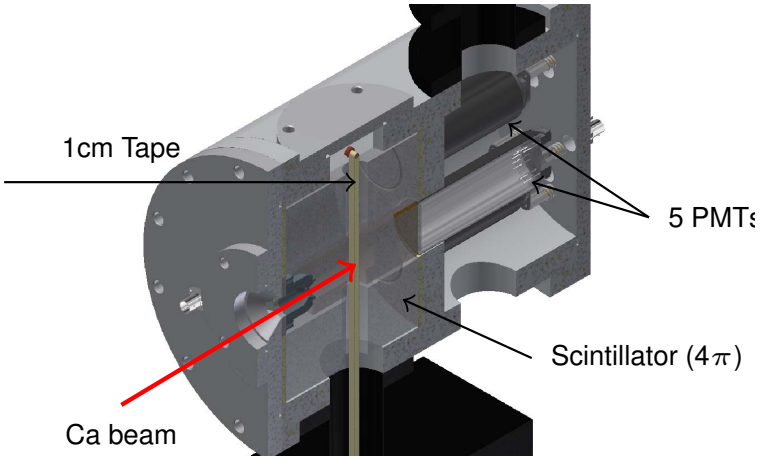
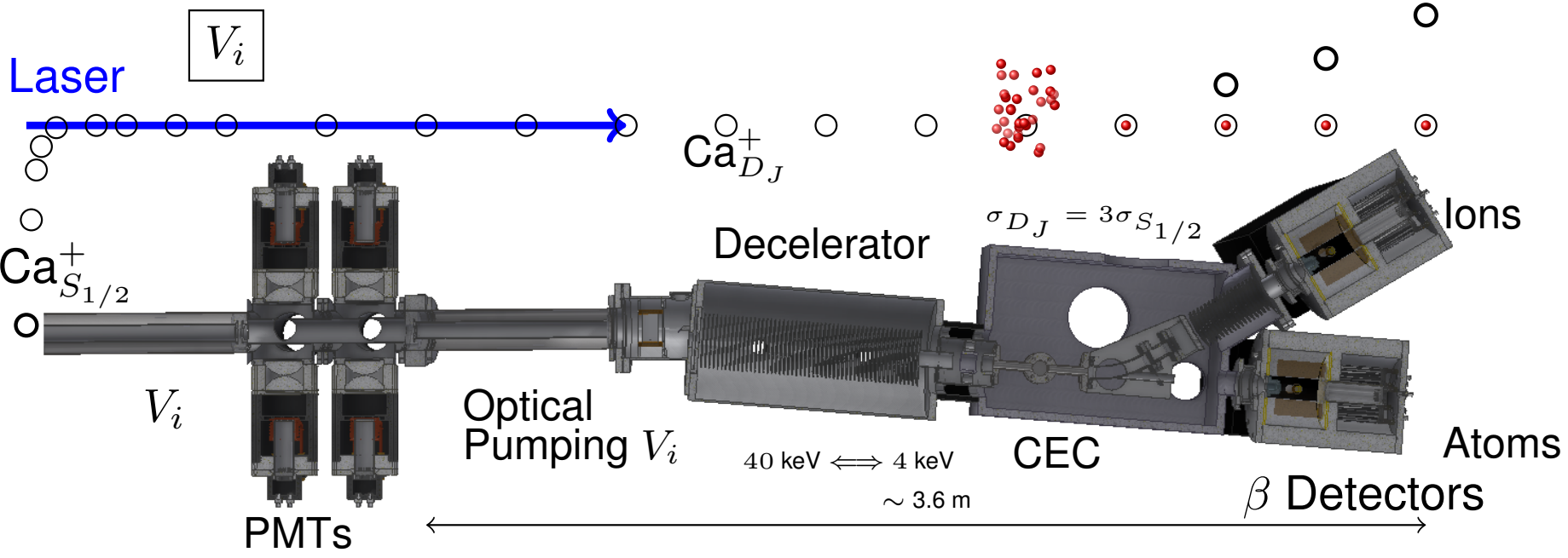
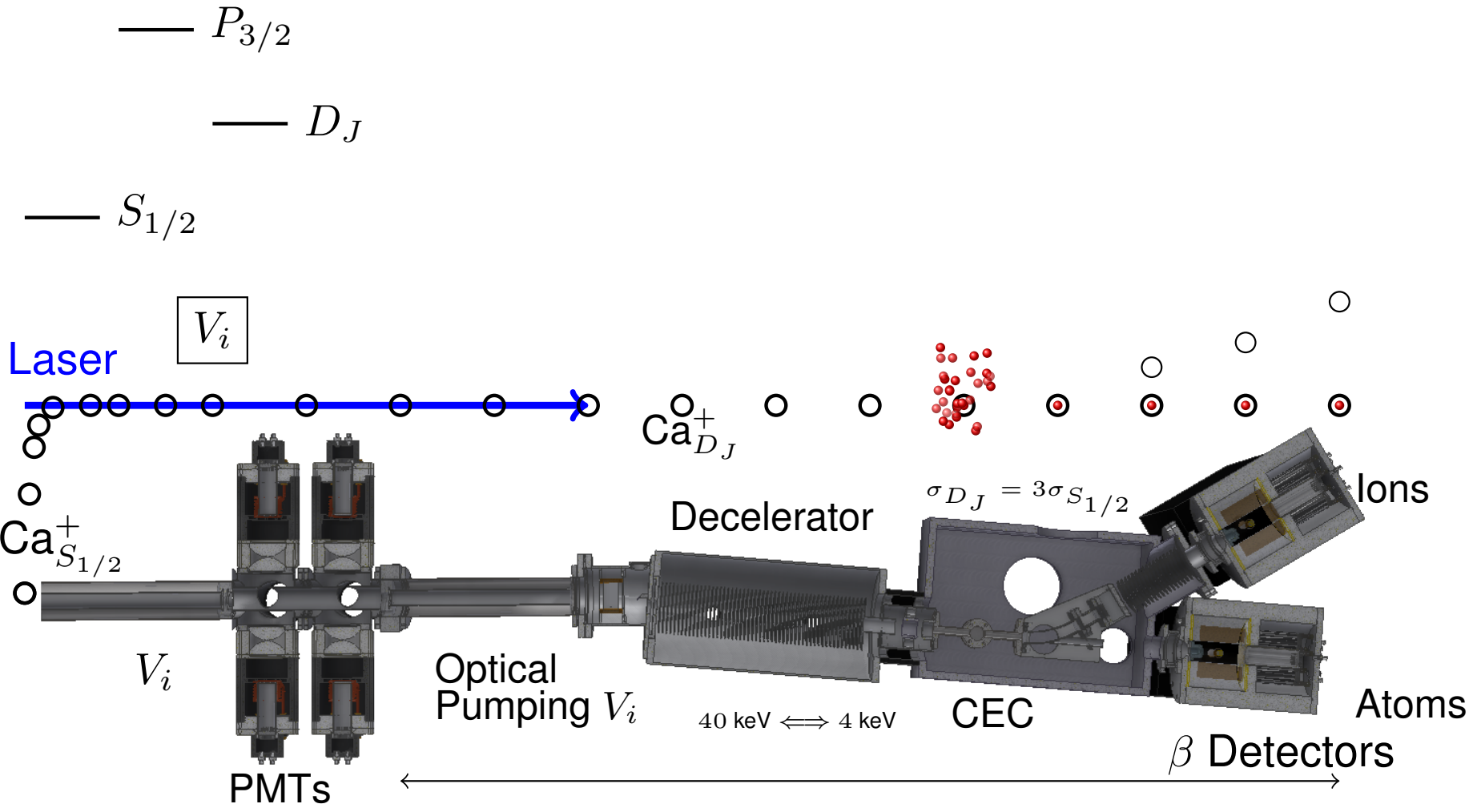


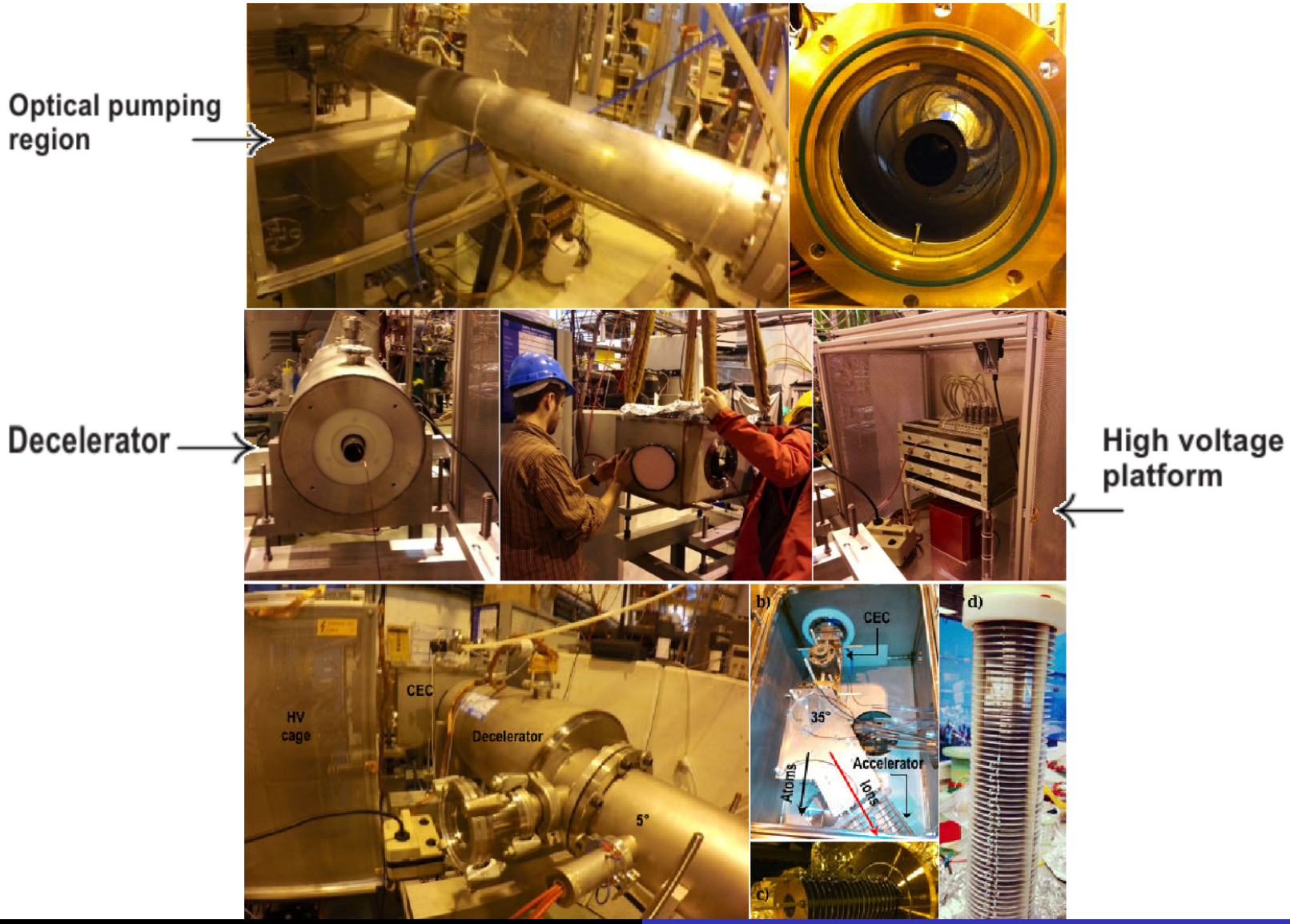



# Optical pumping + State-selective neutralization + Radioactive detection

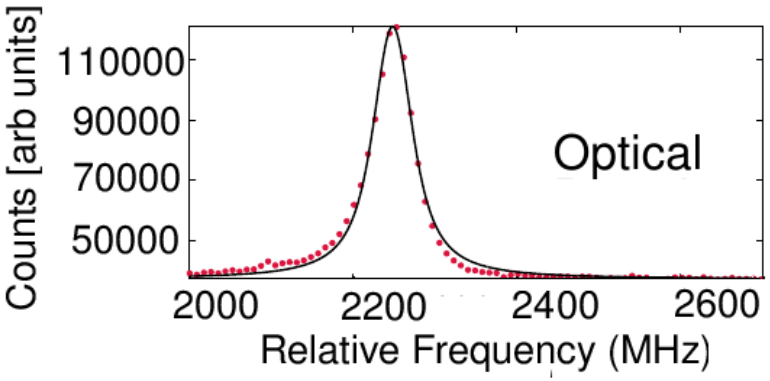


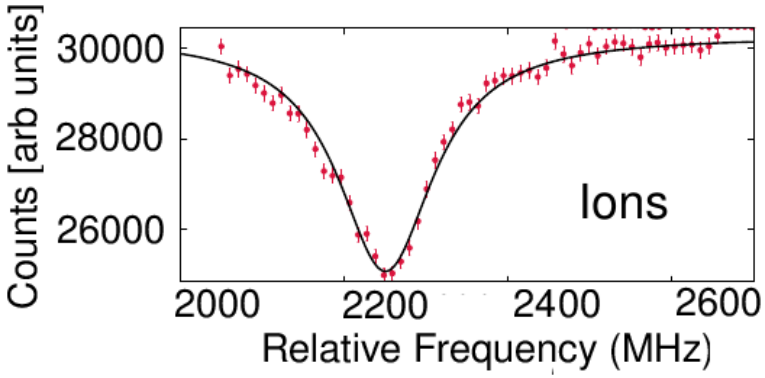
# Commissioning the beam line (2015)

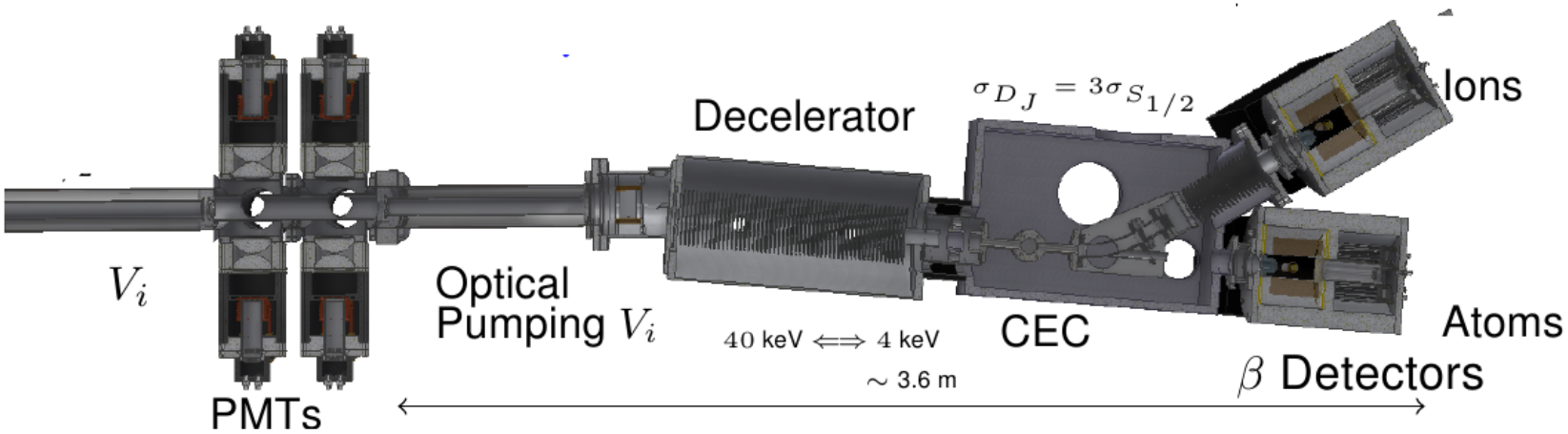
Ion beam transmission successfully tested >90 % (April 2015)



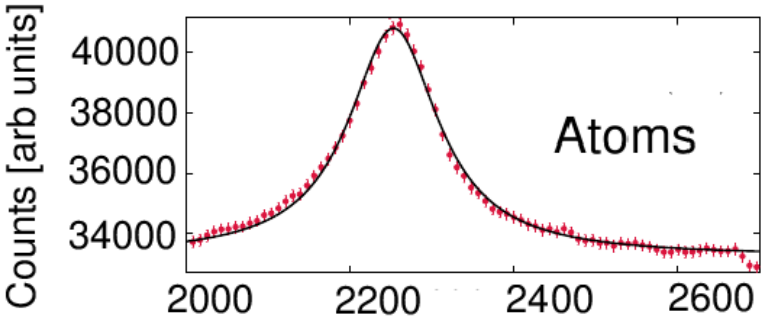
# First offline tests: August 2015



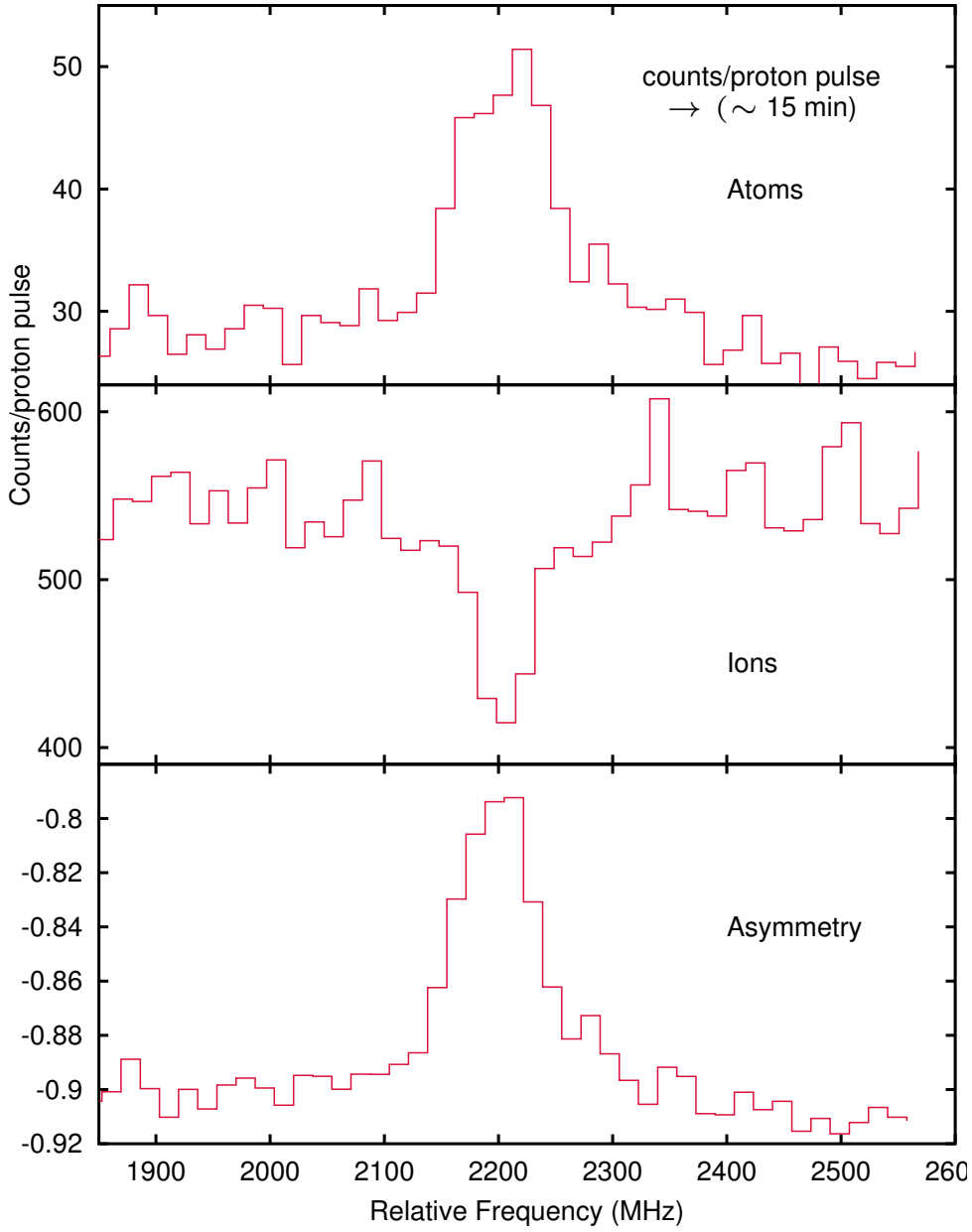




$^{40}$Ca



# Results: Proof of sensitiviy with $^{52}$Ca



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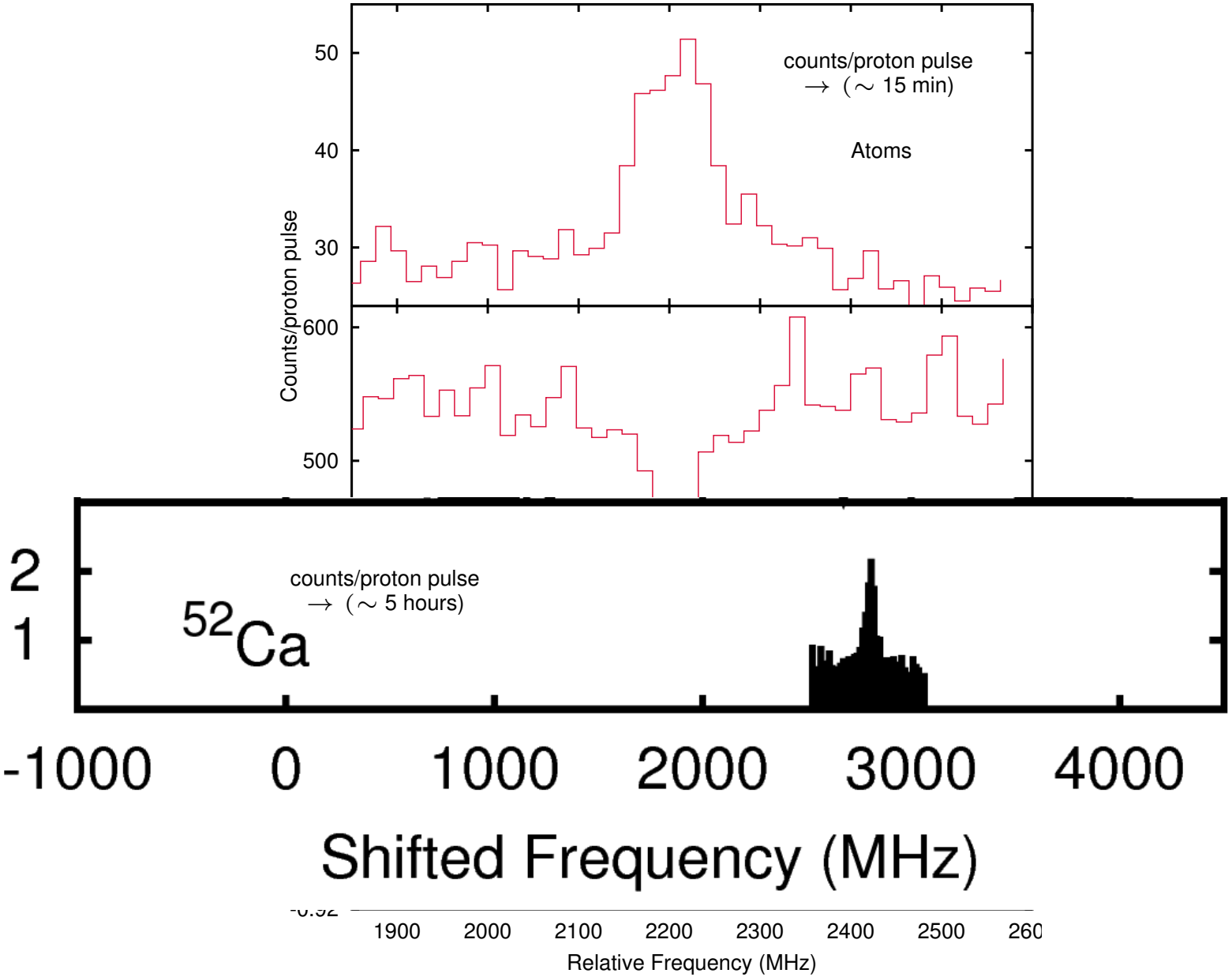


# Summary and Outlook

**Ground-state spin and electromagnetic moments of $^{47\text{-}51}$Ca** $I \quad Q_s \quad \mu_I$

**Charge radii measurements up to $^{52}$Ca (N=32)**
**-> New challenges for nuclear structure theory** $\delta\langle r^2\rangle^{A,A'}$

**Unanswered question regarding the use of effective operators, importance of MEC currents?**

**[Ekstrom et al. PRL 113, 262504 (2014)]**
**[Carlson et al. RMP 87, 1067 (2015)]**
**[Pastore et al. PRC 87, 035503 (2013)]**

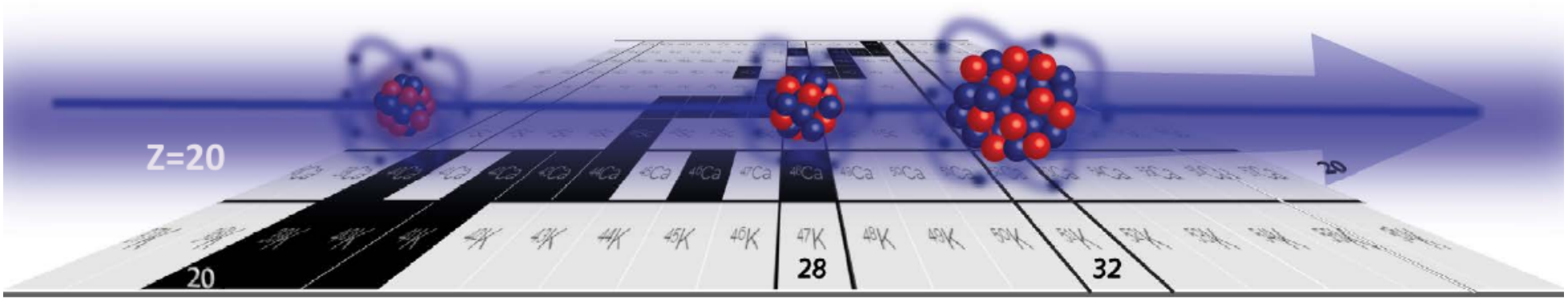
**The nuclear force**
- Phenomenology
- Chiral Effective field theory

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

**Electro-weak currents**
- role of many-body currents
- effective operators

# Summary and Outlook

Need of further developments of experiments and theory!



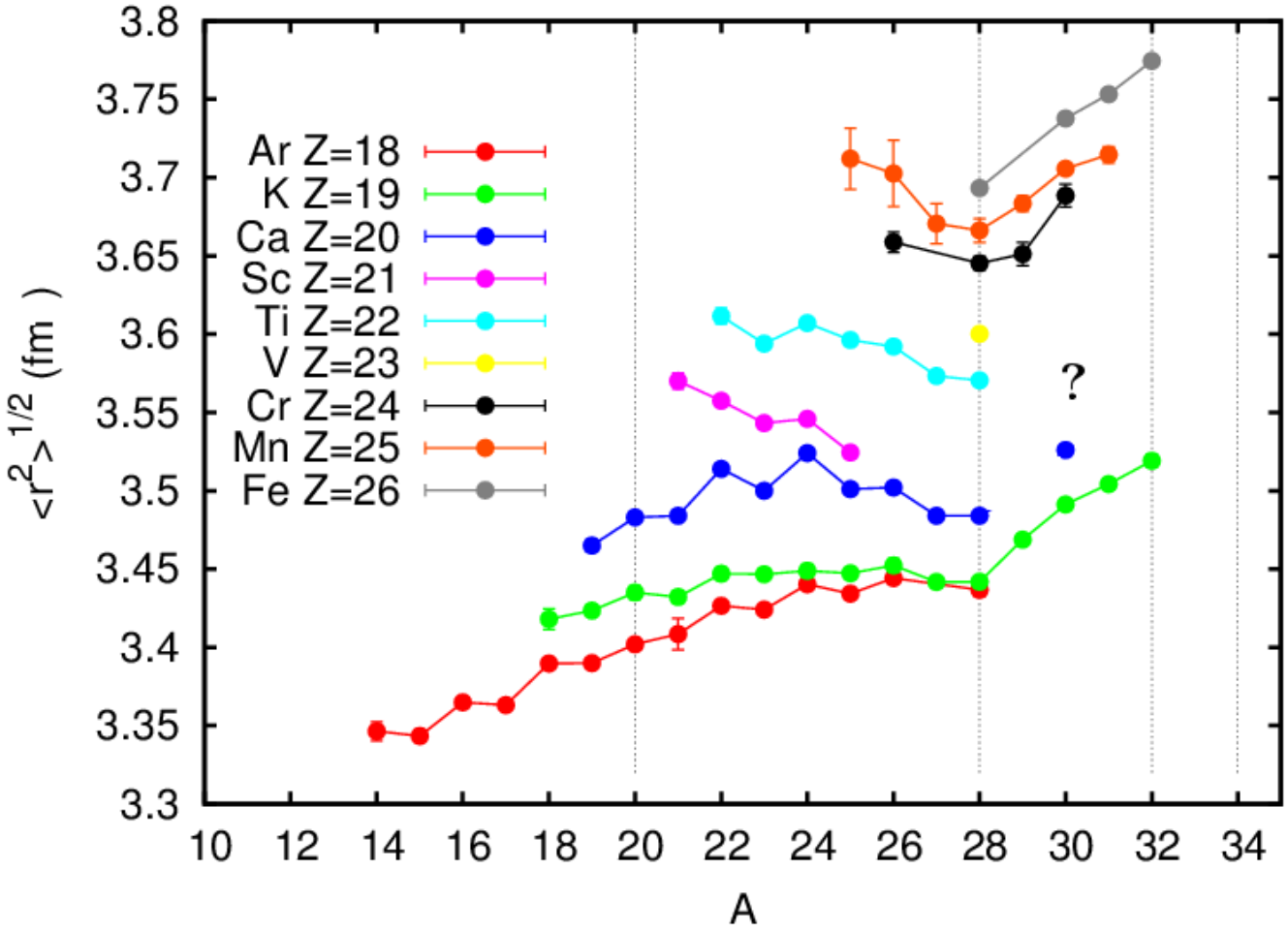

$\rightarrow$ Higher sensitivity to study $^{53,54}$Ca

<u>...there is still much more to learn...</u>

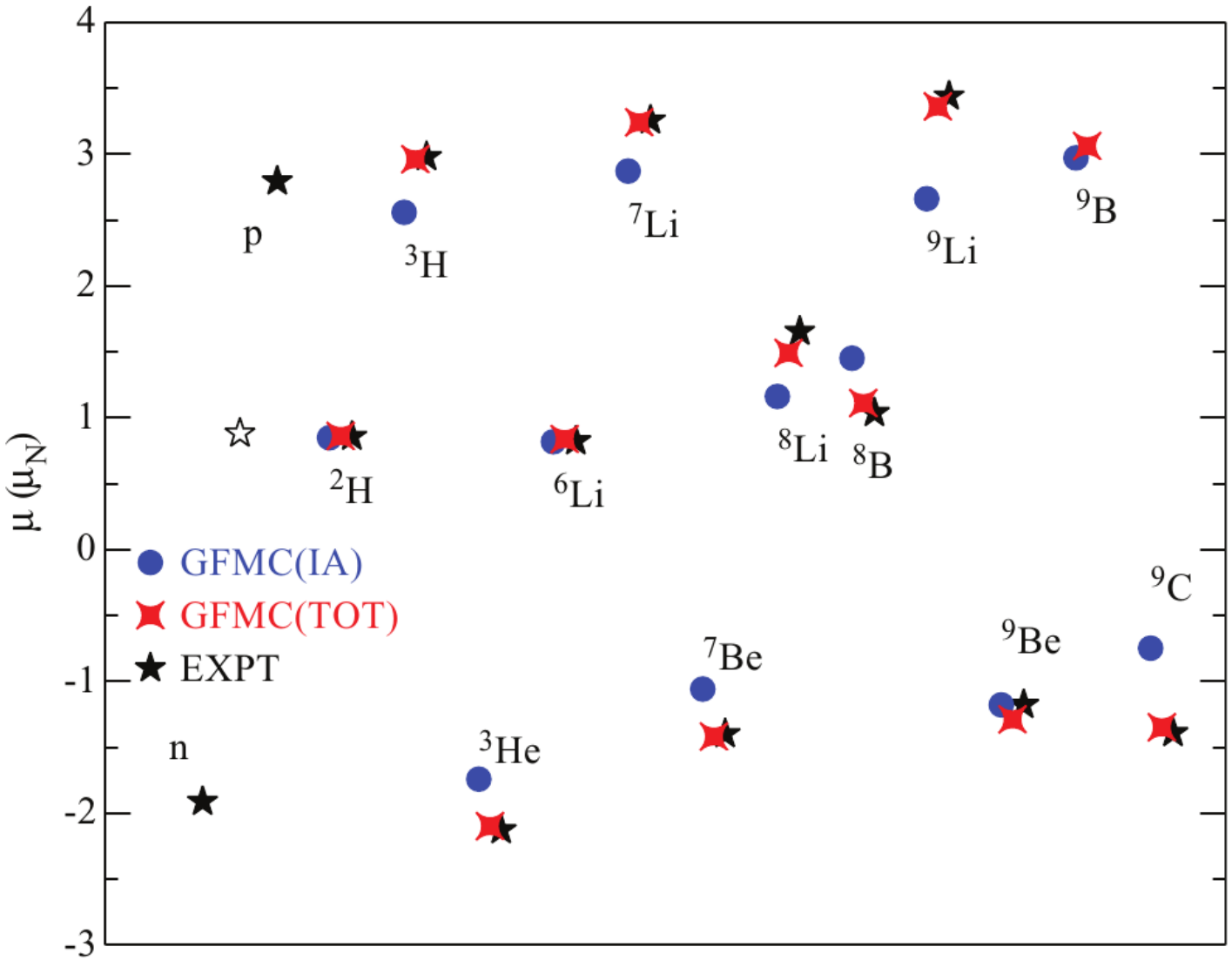
# Summary and Outlook

Thanks for your attention

# Ca region

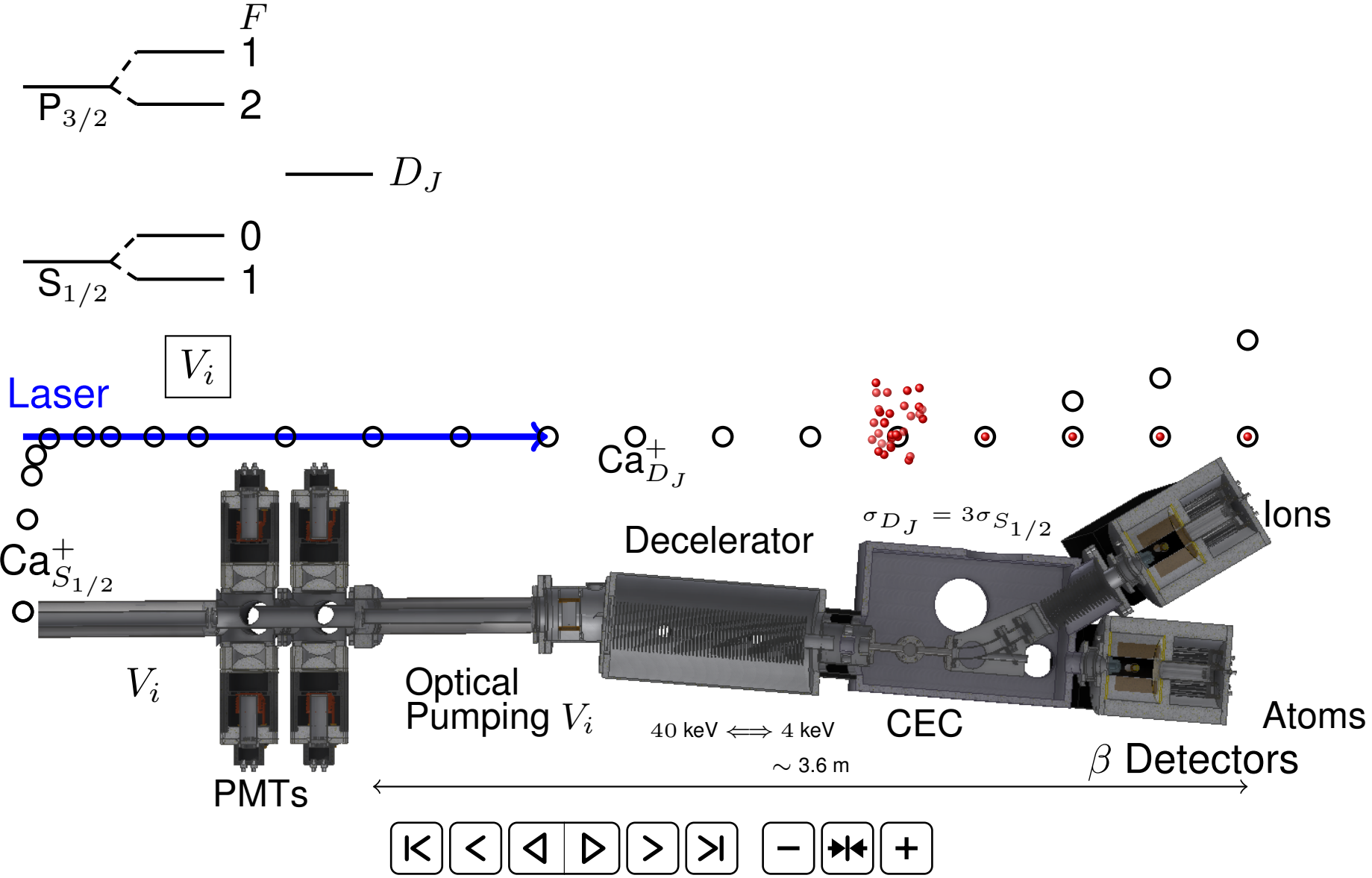

Ar Z=18
K Z=19
Ca Z=20
Sc Z=21
Ti Z=22
V Z=23
Cr Z=24
Mn Z=25
Fe Z=26
?
<r2>1/2 (fm )
A
3.8
3.75
3.7
3.65
3.6
3.55
3.5
3.45
3.4
3.35
3.3
10
12
14
16
18
20
22
24
26
28
30
32
34

# Ca region

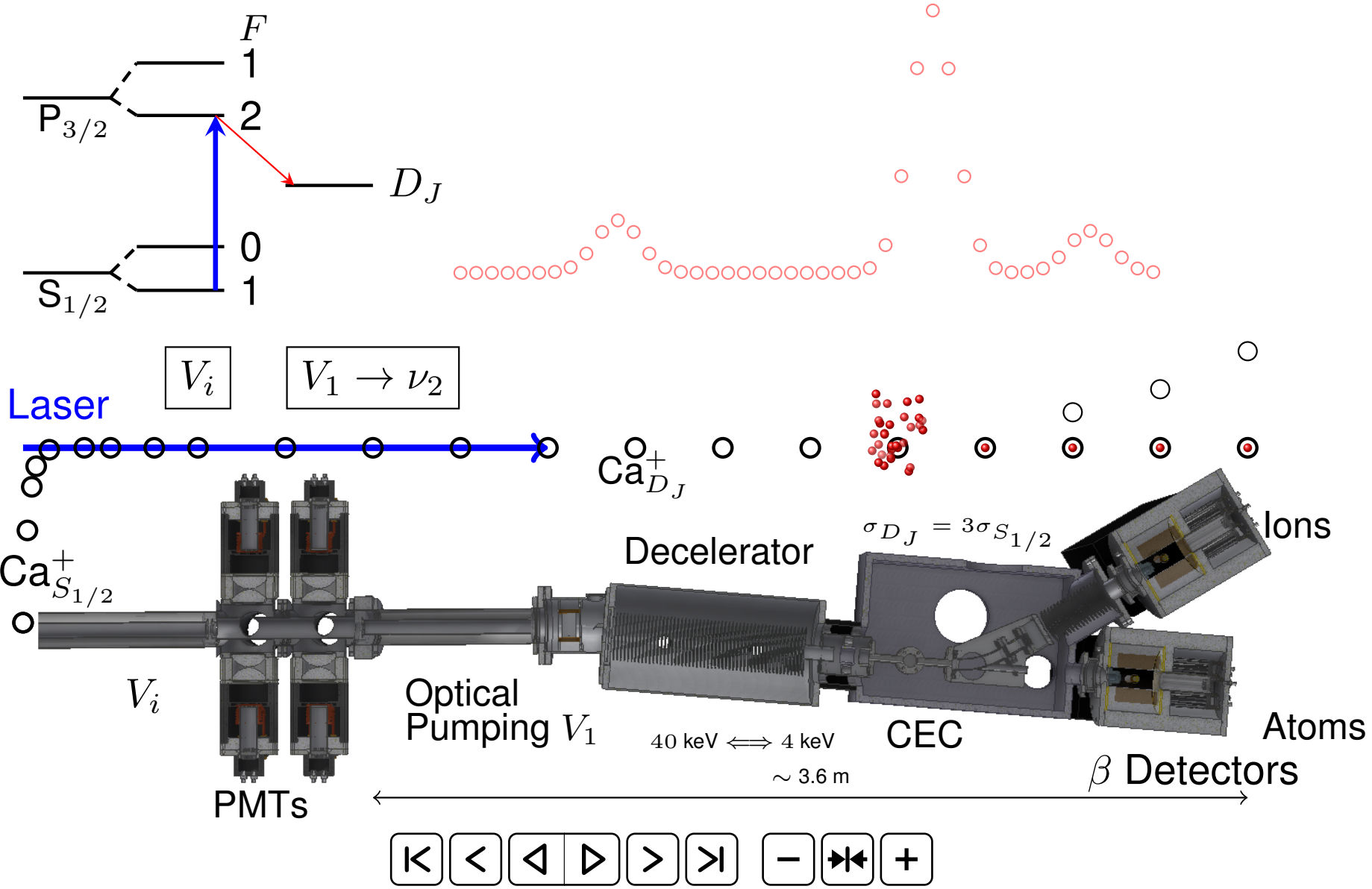



[S. Pastore et al. PRC 87, 035503 (2013)]

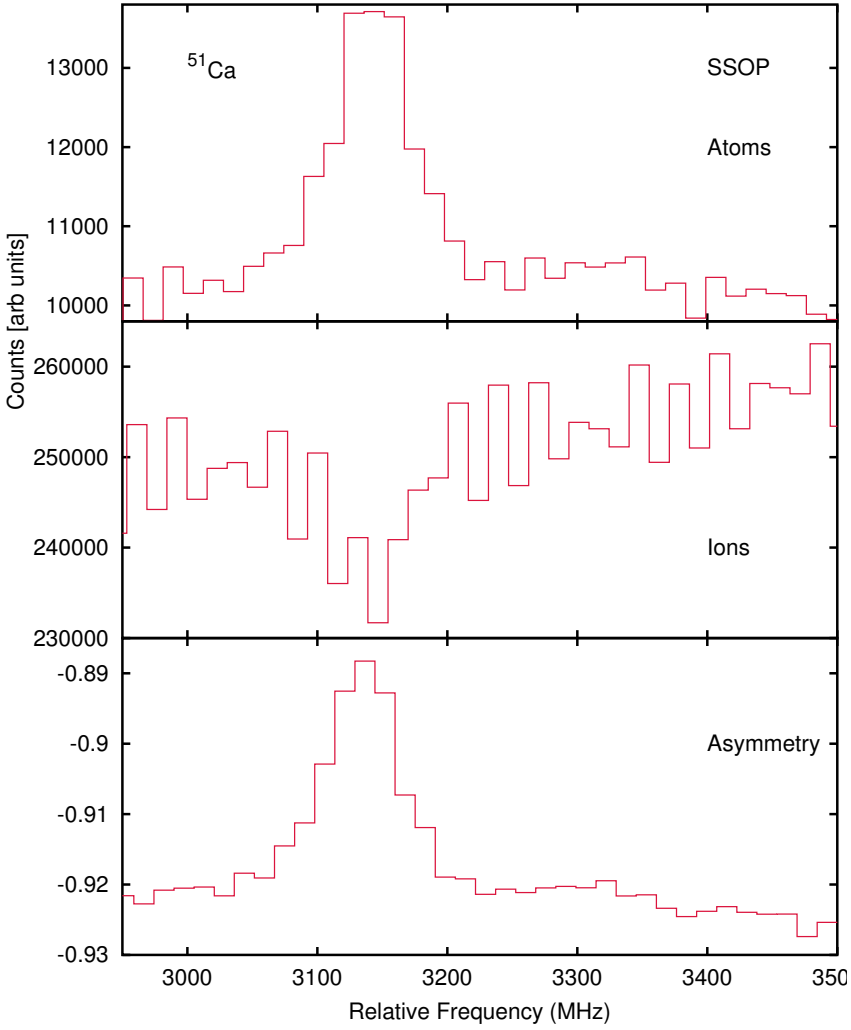
# Spin $I = 1/2$ ($^{53}$Ca)

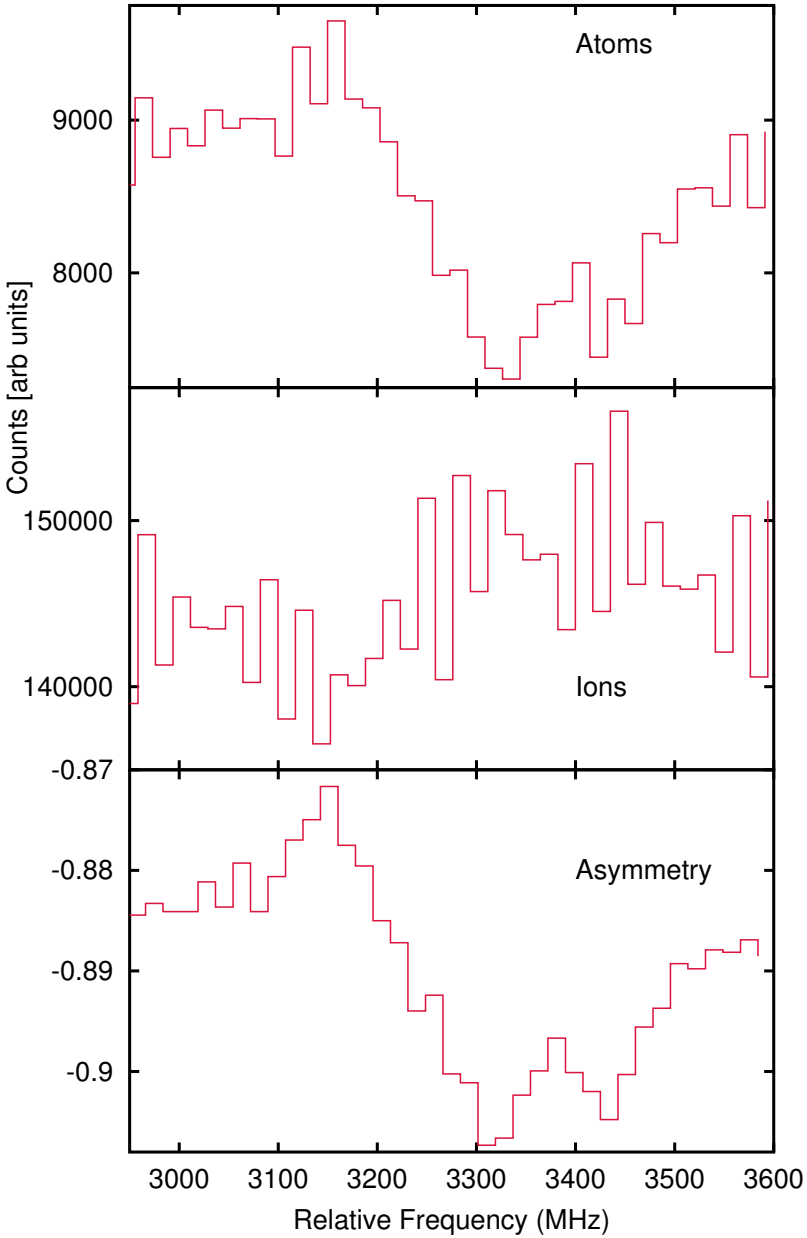


# Multi-step Optical Pumping (Spin $I = 1/2$)

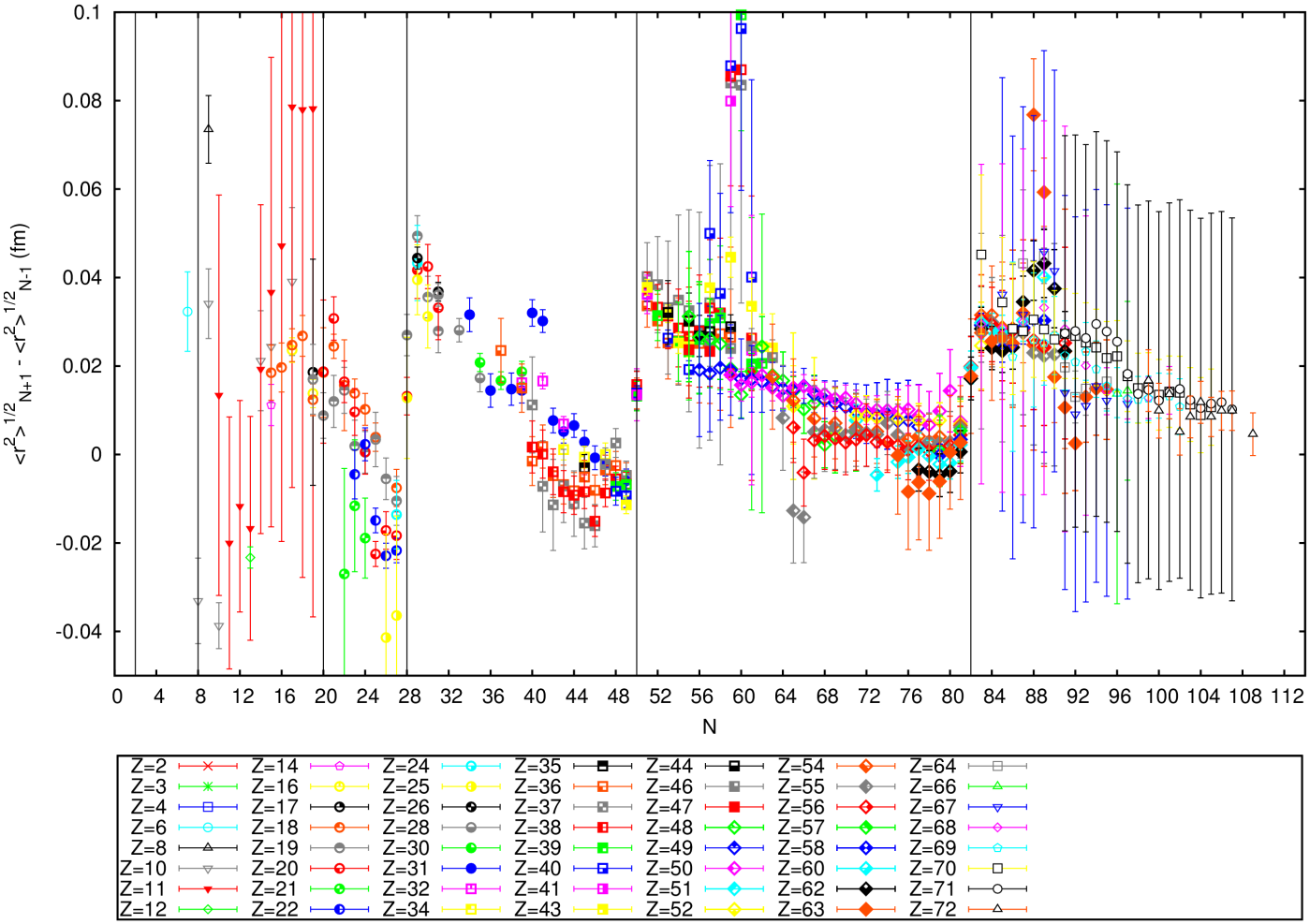


# Results: $^{51}$Ca

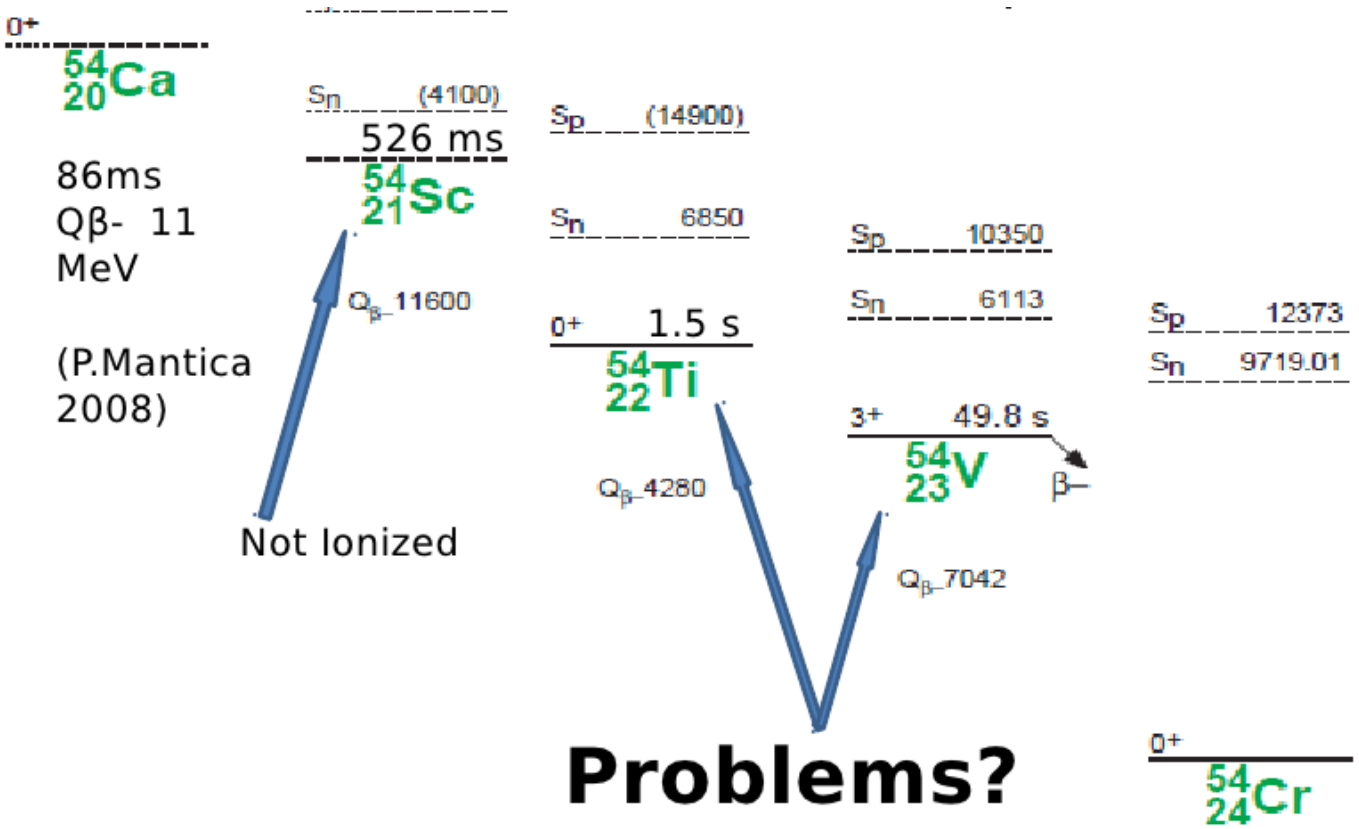


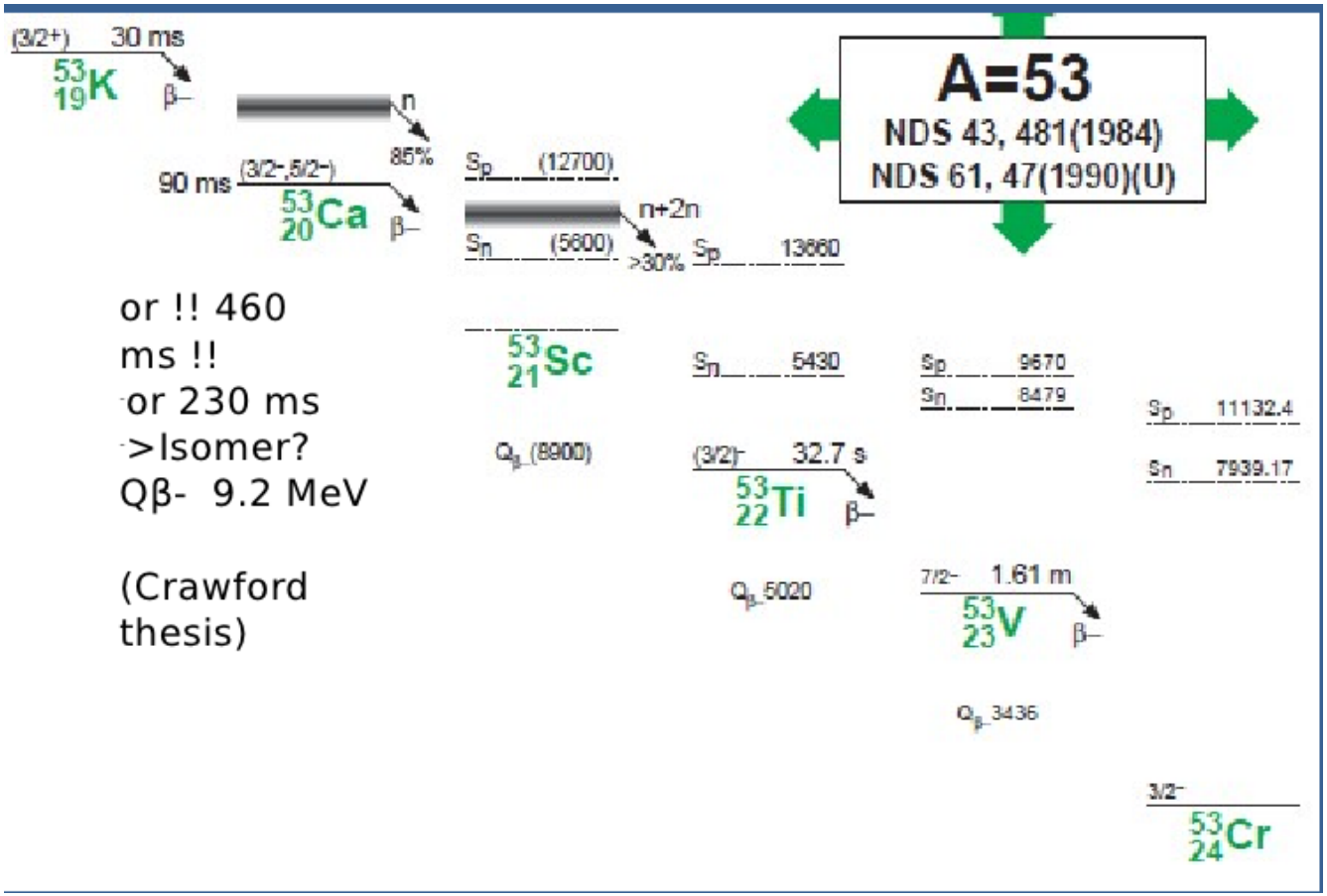
# Charge Radii Systematic



# Beam Contamination

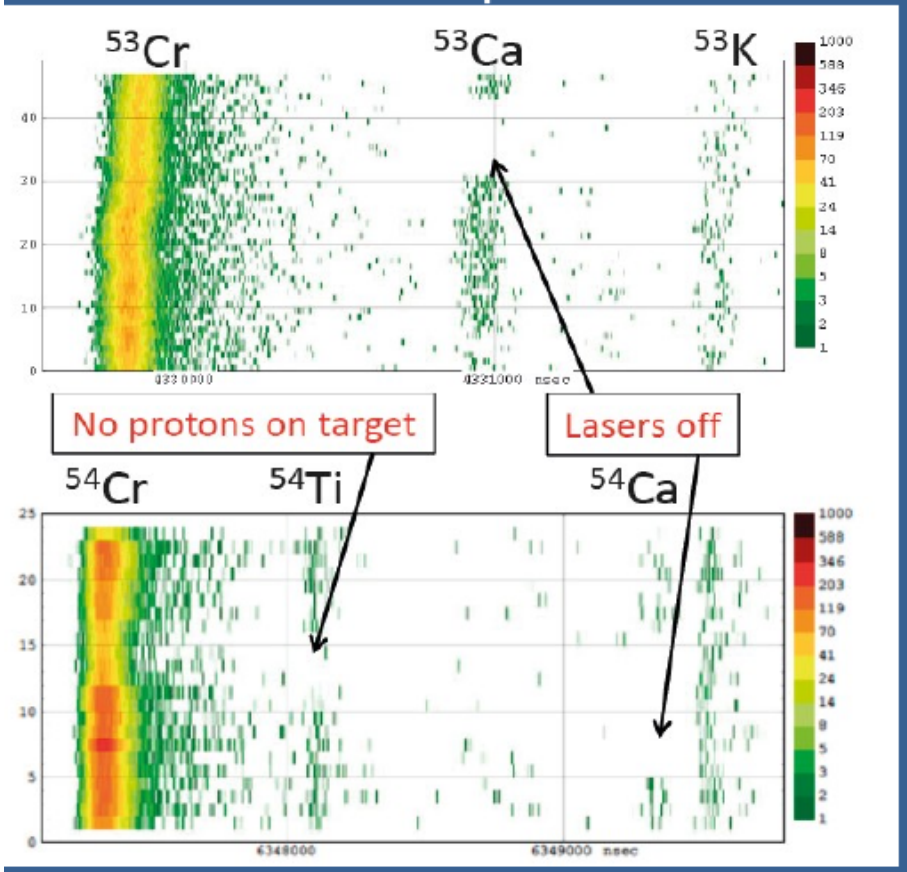


# Beam Contamination



# Beam Contamination

## ISOLTRAP experience:




| Contamination ratio | 54Ca | 53Ca |
|---|---|---|
| 54Cr (Stable) | 928 | |
| 54Ti(1.5s) | 3 | |
| 54 Stable (Molecule?) | 2 | |
| 53Cr (Stable) | | 300 |
| 53Ti(33s) | | ~0 |
| 53K(30ms) | | >0.3 |

| | Yield |
|---|---|
| 53Ca | ~100 ions/s |
| 54Ca | ~10 ions/s |

Considering τ1/2 of 54Ti and 54Ca
Only 10% of total β's.

***Thanks to Frank Wienholtz.***