Max Planck Institute for Nuclear Physics

EMMI Program, GSI Darmstadt 2012

"Precision Measurements of Ground-State Properties for Nuclear Structure Studies"

Max-Planck-Institut für Kernphysik

EMMI

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May 02, 2012

Johannes Gutenberg Universität Mainz

Max-Planck-Gesellschaft

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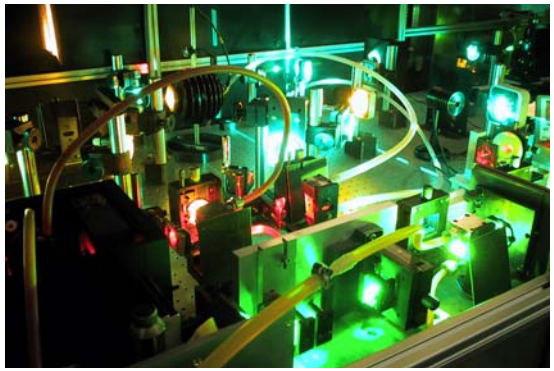
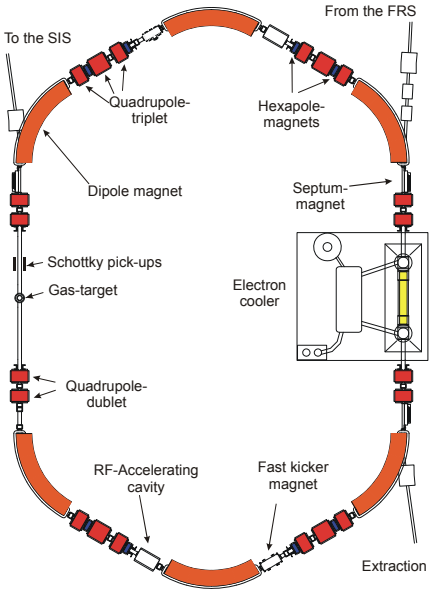
Outline





- **Introduction and motivation**
- **Principle of laser spectroscopy and mass spectrometry**
- **Recent results**
- **Summary and outlook**

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Nuclear ground state properties

What do we learn?

Charge Radii	nuclear structure: nuclear charge distribution, deformation
Spins, Moments	microscopic nuclear structure: wave functions, coupling of nucleons, configuration mixing, shell structure macroscopic nuclear structure: deformation
Masses	nuclear binding energy basic test of nuclear models nuclear structure: shell closures, pairing, onset of deformation, drip lines, halos

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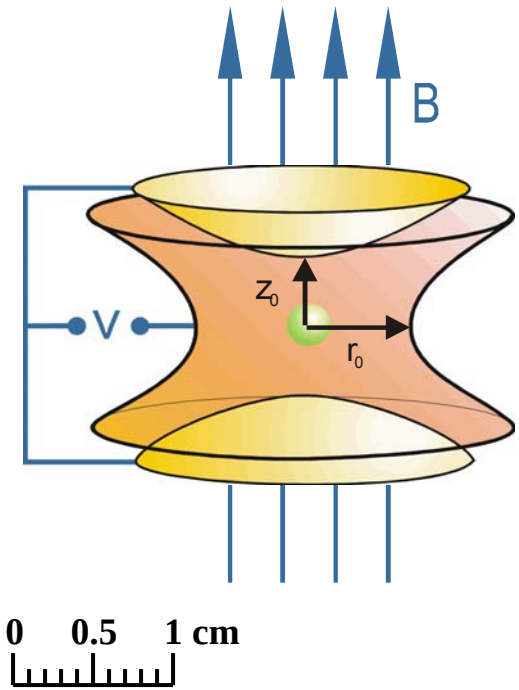
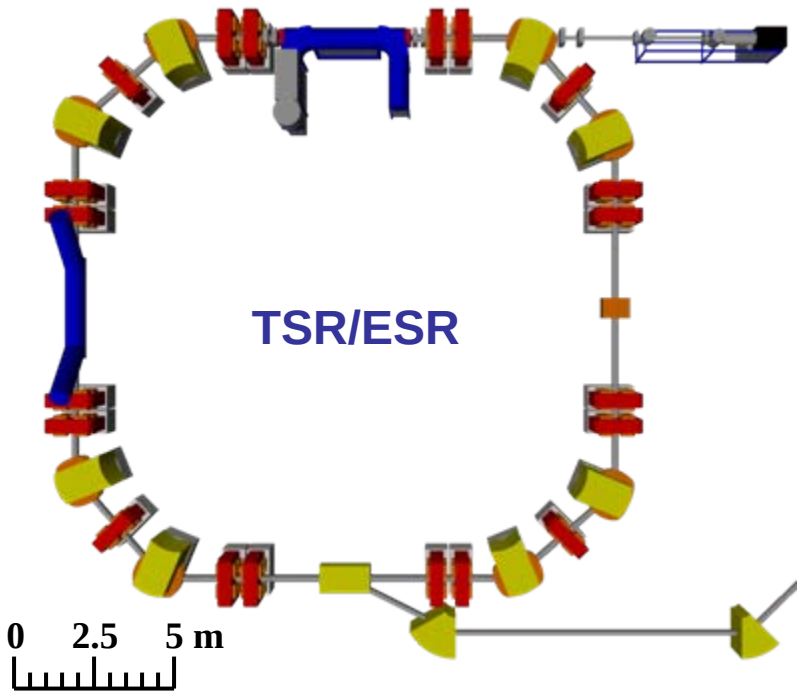
Storage and cooling techniques

Penning trap



Storage ring



particles at nearly rest in space

relativistic particles

- ion cooling
- long storage times
- single-ion sensitivity
- high accuracy

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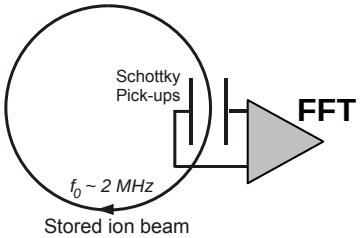
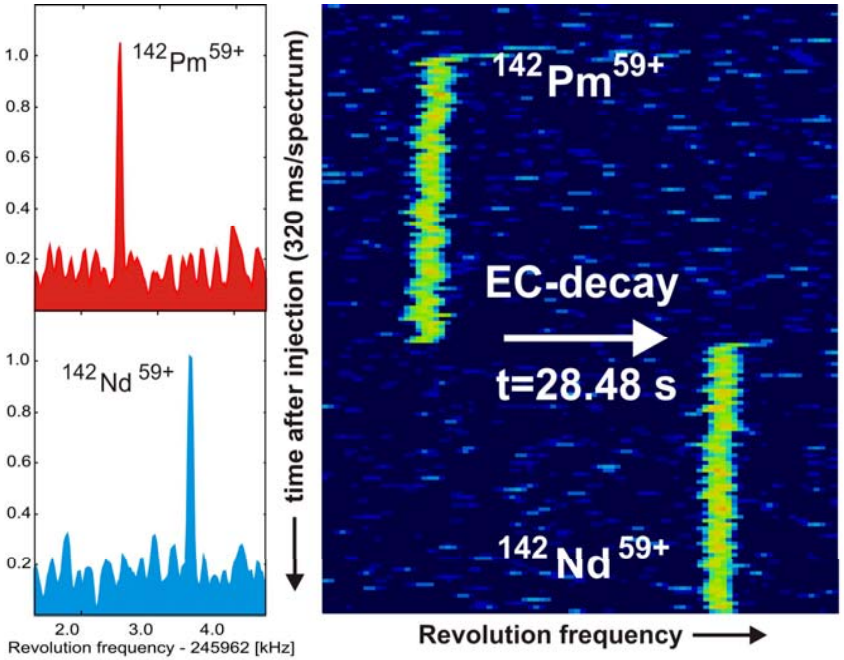
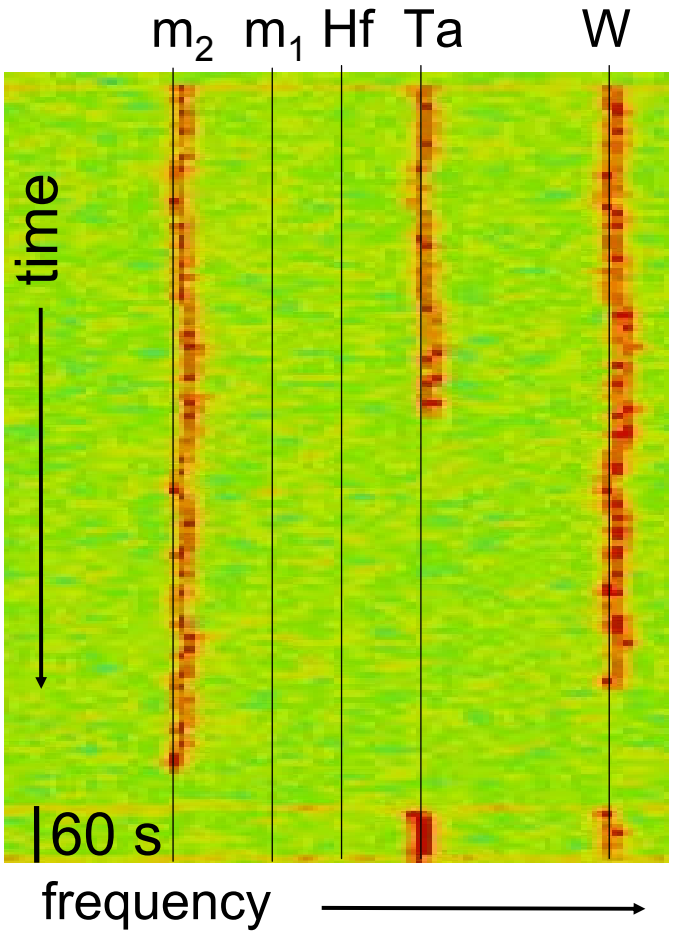
Single ion sensitivity

Schottky detection in a storage ring







Discovery of new isotopes and isomers.

Hf: Phys. Rev. Lett. 105 (2010) 172501

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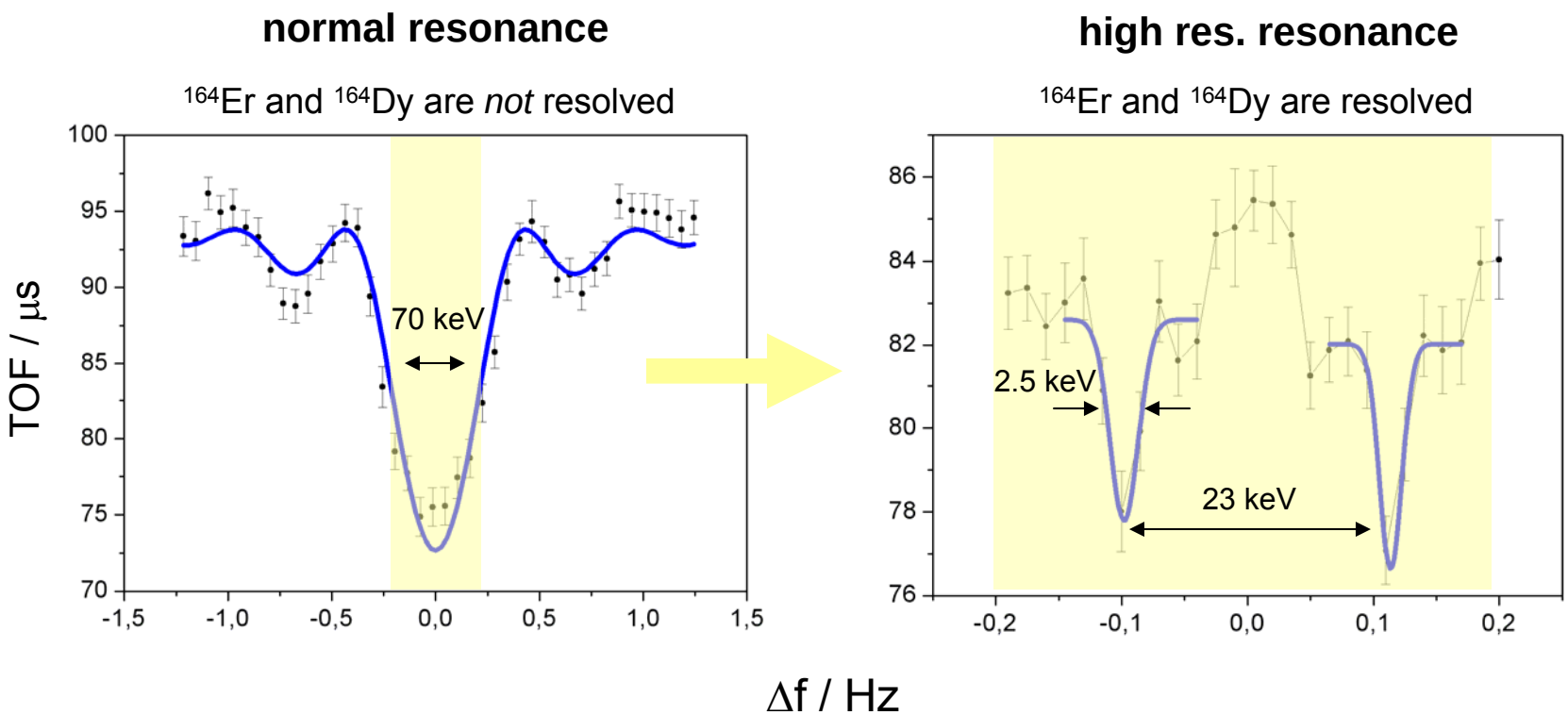
Ultra-high resolving power



A resolving power of 10^8 has been demonstrated in a Penning trap.

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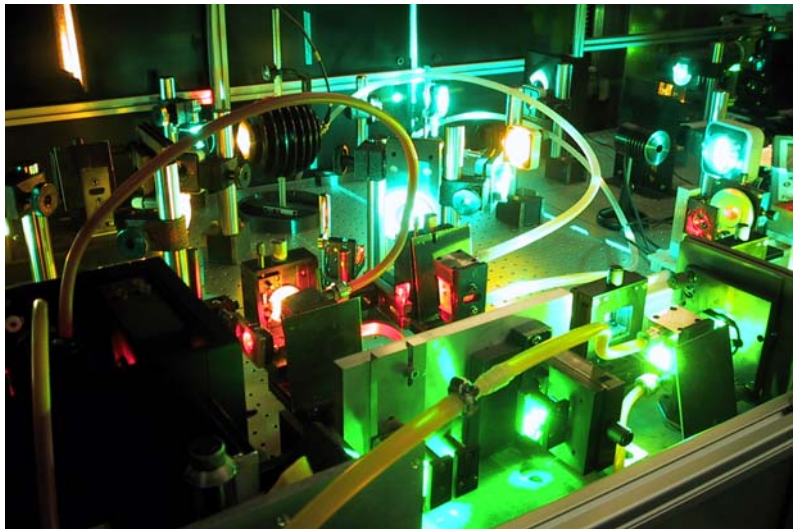
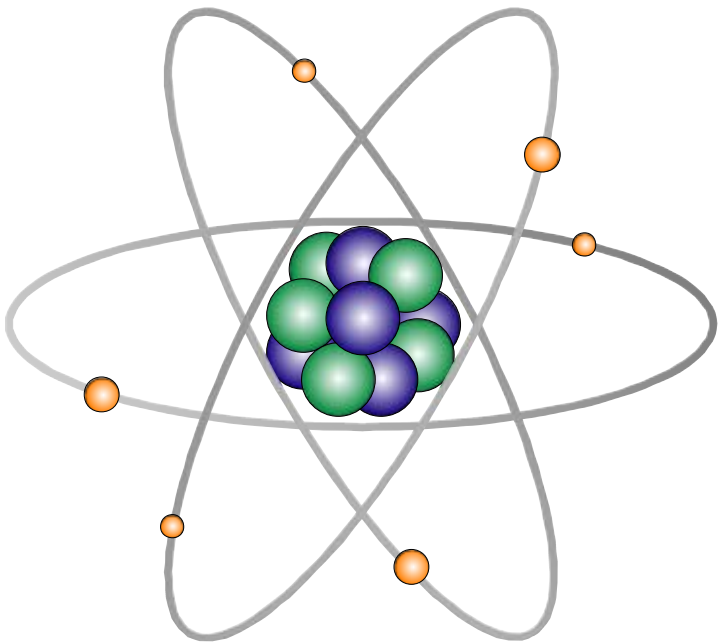
High-precision
Penning trap and laser experiments

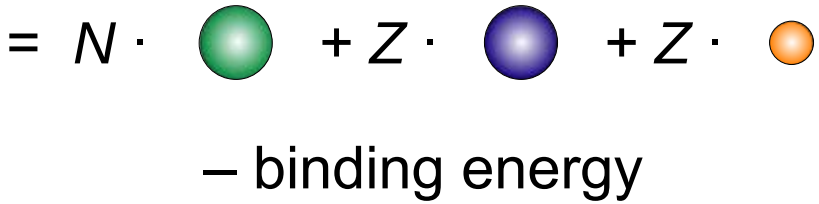


Determination of atomic and nuclear ground state properties: masses, binding energies, *g*-factors, nuclear moments, radii

Applications of precision masses

High-accuracy mass measurements allow one to determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.





$$M_{\text{Atom}} = N \cdot m_{\text{neutron}} + Z \cdot m_{\text{proton}} + Z \cdot m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

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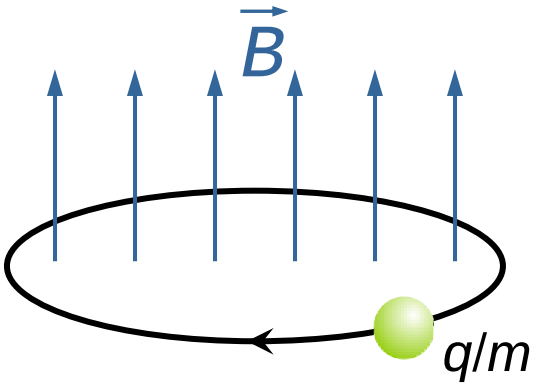
Principle of Penning trap mass spectrometry

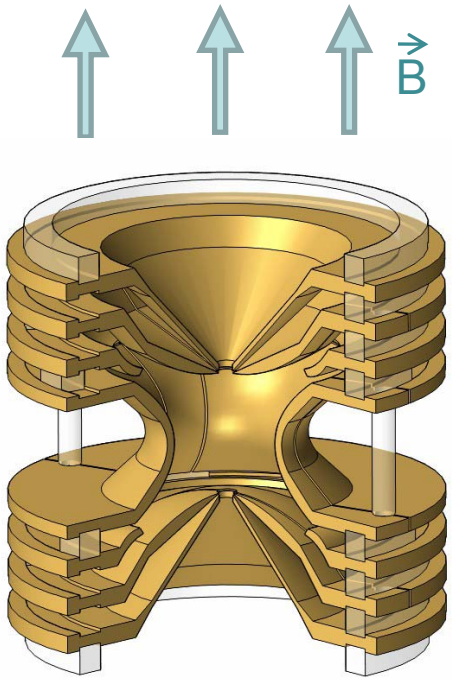


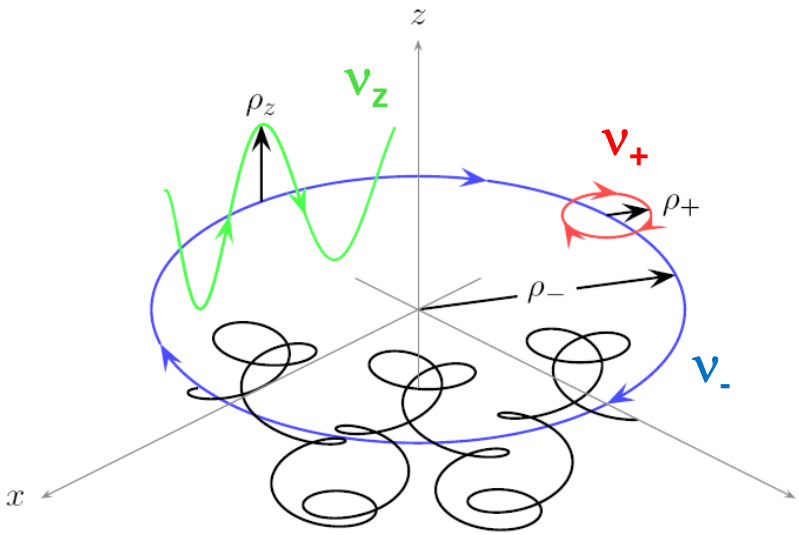
Cyclotron frequency:

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

PENNING trap

- Strong homogen. magnetic field
- Weak electric 3D quadrupole field





Typical freq.
q = e
m = 100 u
B = 6 T

$\Rightarrow$ $f_- \approx$ 1kHz
$f_+ \approx$ 1MHz

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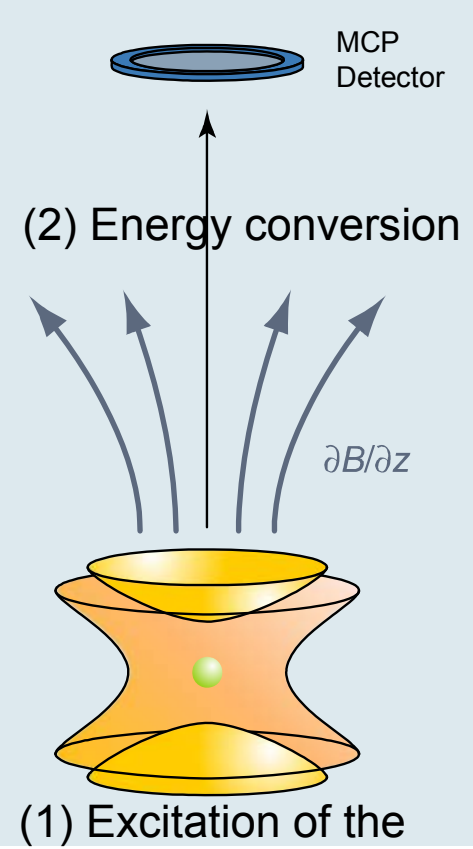
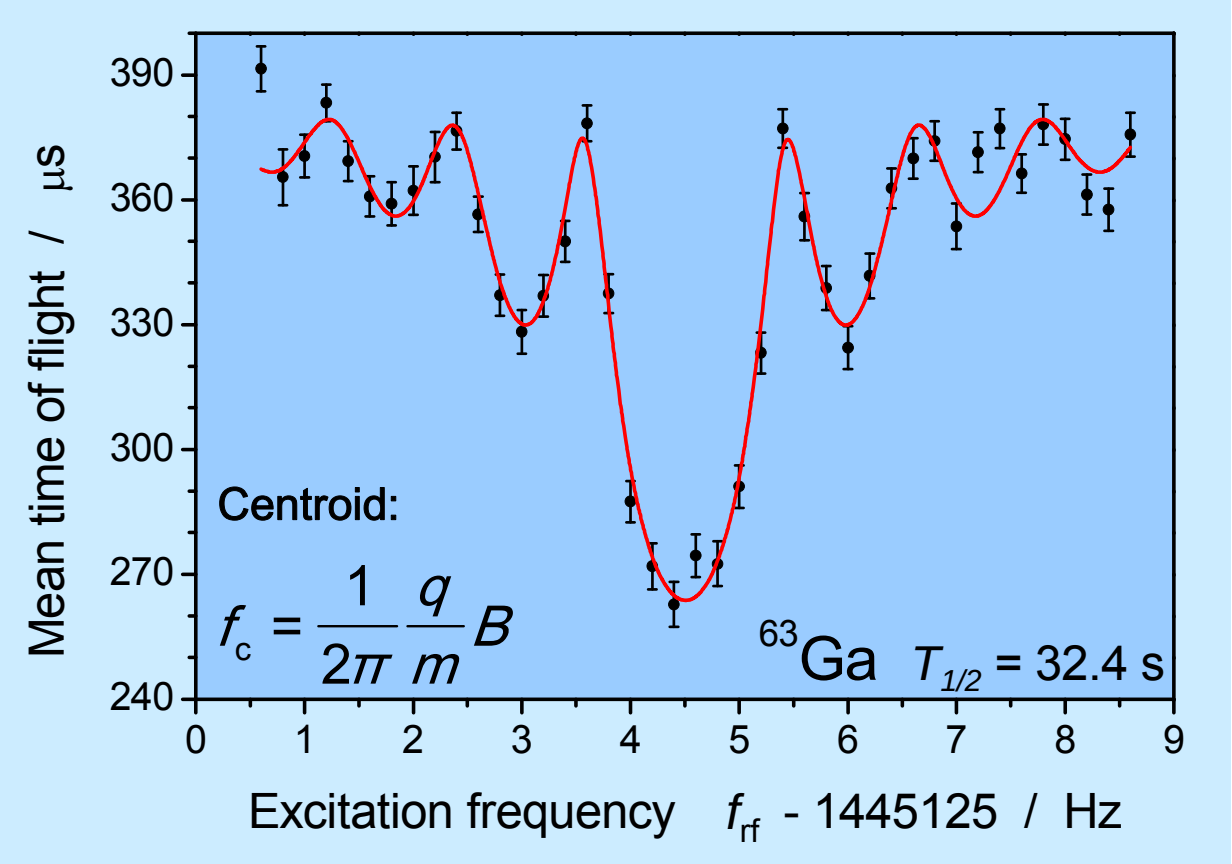
TOF cyclotron resonance detection

(3) TOF measurement





Determine atomic mass from frequency ratio with a well-known "reference mass".

$$\frac{f_{c,ref}}{f_c} = \frac{m - m_e}{m_{ref} - m_e}$$

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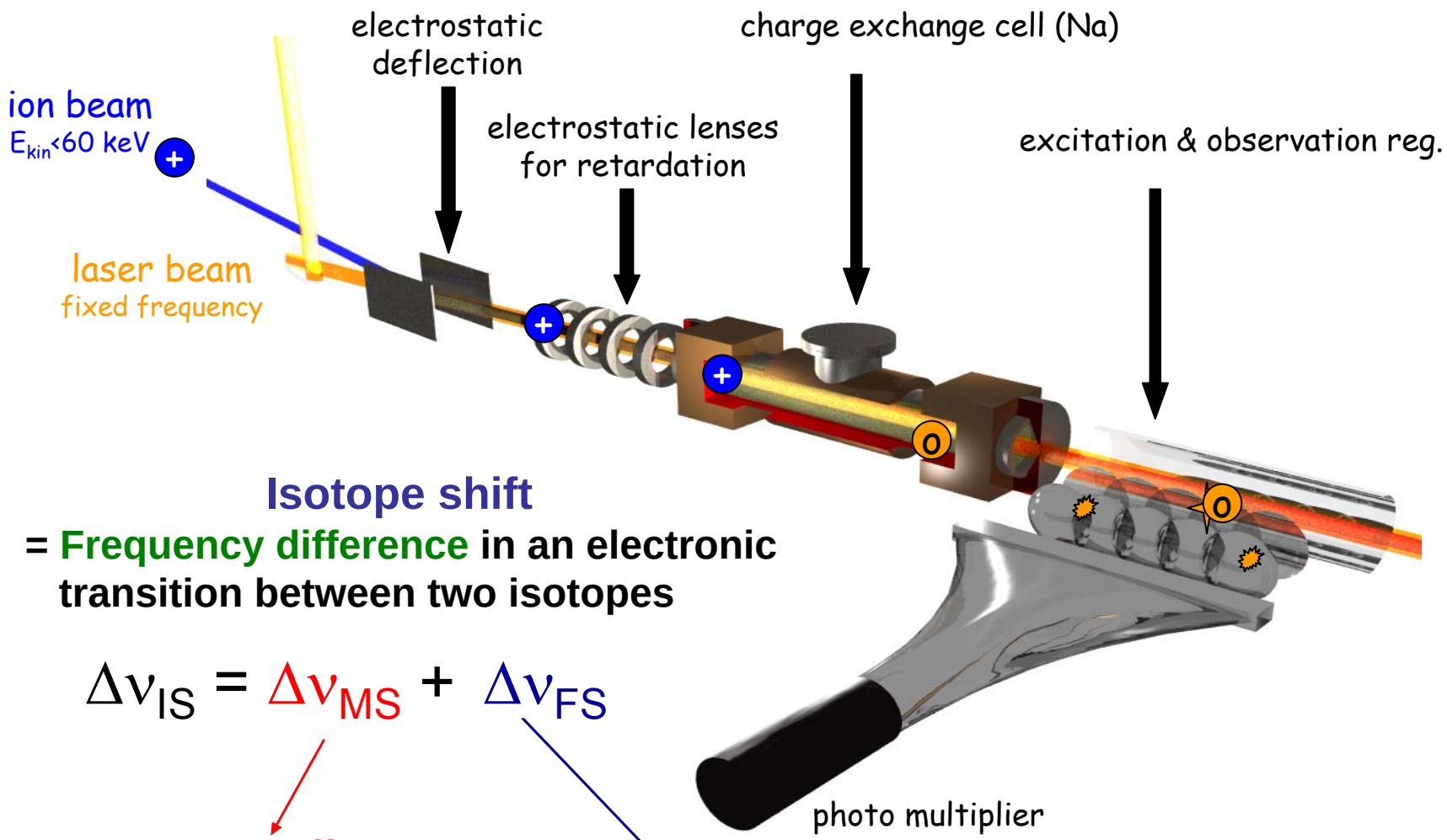
Principle of collinear laser spectroscopy



Isotope shift

= Frequency difference in an electronic transition between two isotopes

$$\Delta\nu_{IS} = \Delta\nu_{MS} + \Delta\nu_{FS}$$

Mass Effect

$\Delta\nu_{MS} \sim (A-A')/AA'$

$\frac{2\pi Z}{3} |\psi(0)|^2 \delta\langle r^2\rangle$ **Field Shift**

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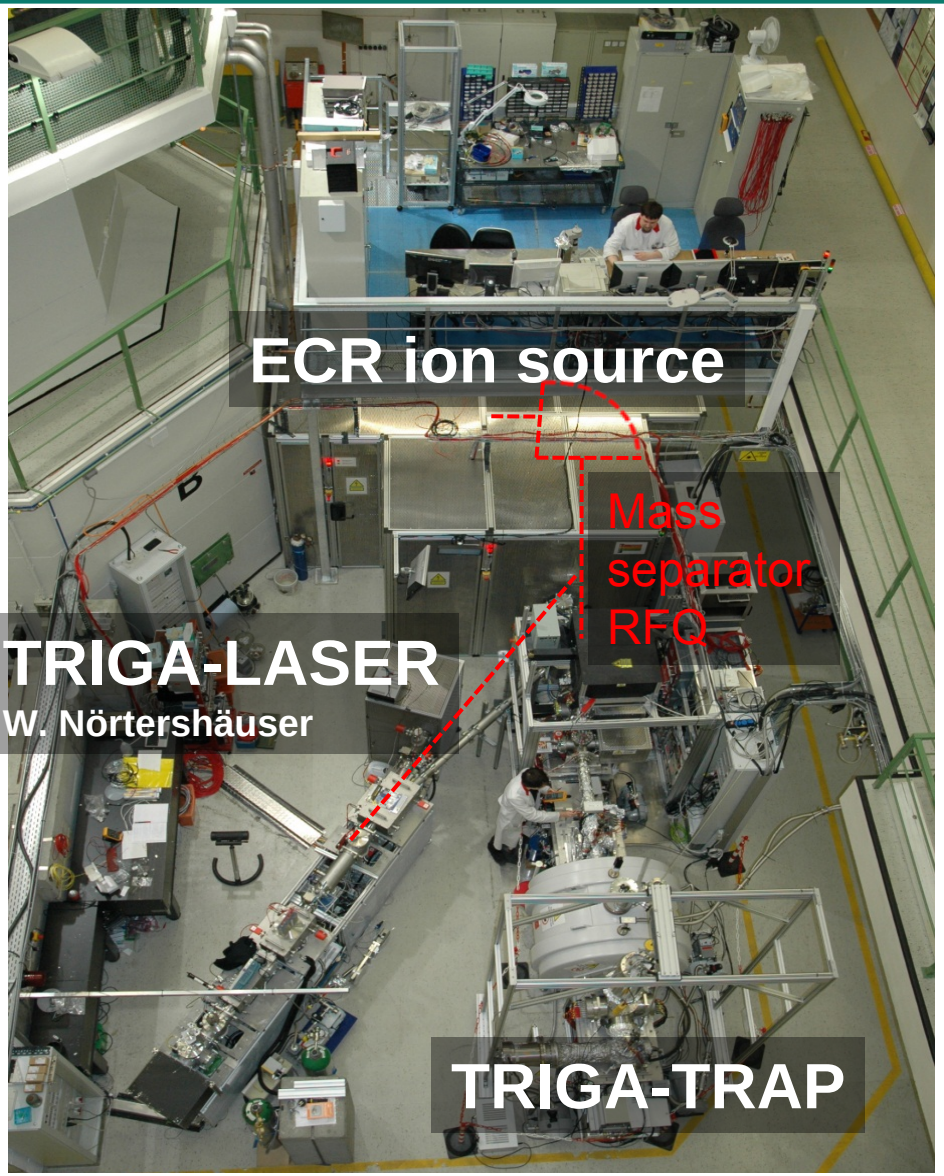
TRIGA-SPEC: TRIGA-LASER + TRIGA-TRAP

project start @ TRIGA: 01/08
start off-line data taking: 05/09

steady 100 kW,
pulsed 250 MW,
neutron flux 1.8×10^{11} / $cm^2 s$

Nucl. Instrum. Meth. A 594, 162 (2008)



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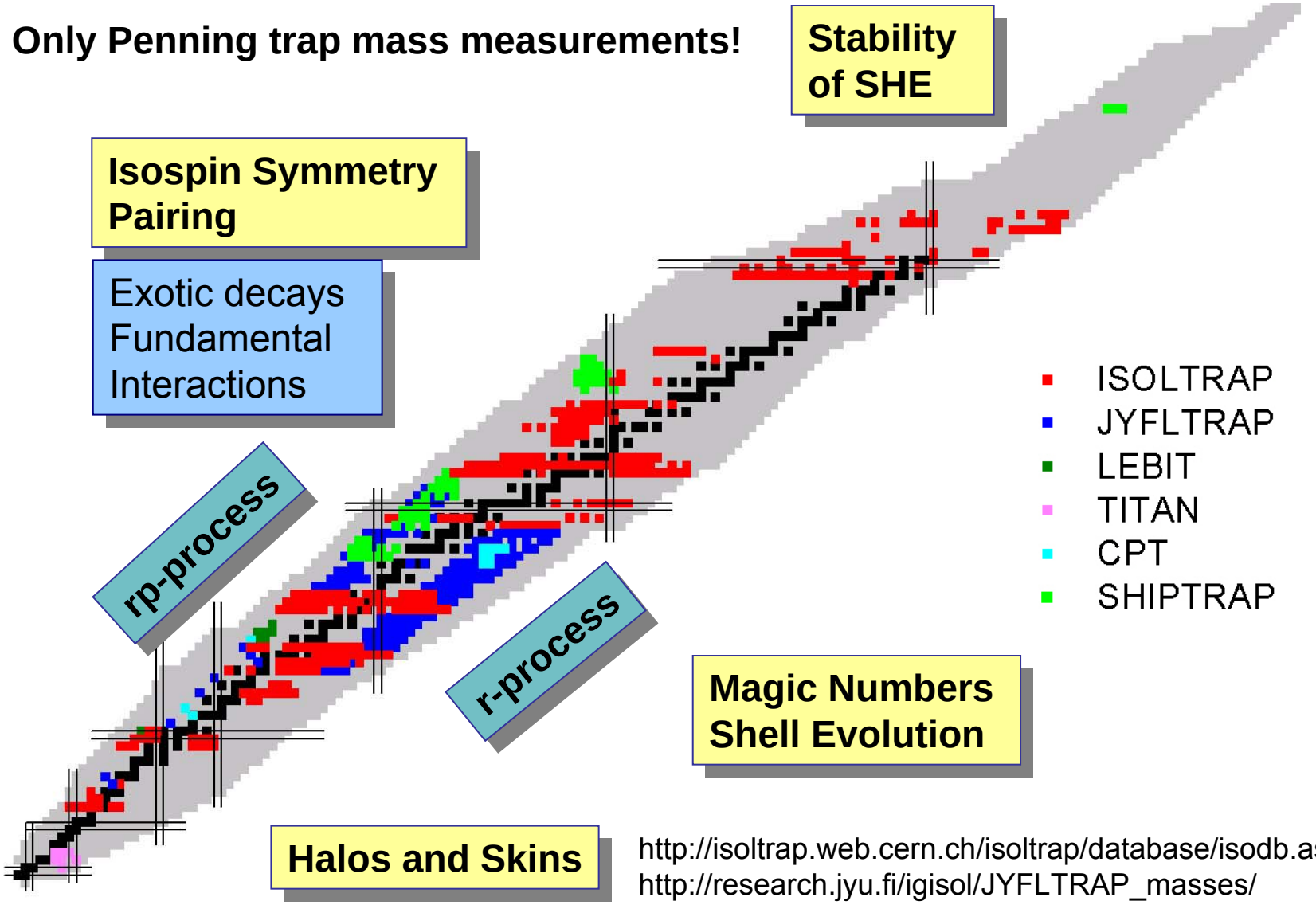
Nuclear structure studies

Only Penning trap mass measurements!

Stability of SHE

Isospin Symmetry
Pairing

Exotic decays
Fundamental
Interactions



Magic Numbers
Shell Evolution

Halos and Skins

http://isoltrap.web.cern.ch/isoltrap/database/isodb.asp
http://research.jyu.fi/igisol/JYFLTRAP_masses/

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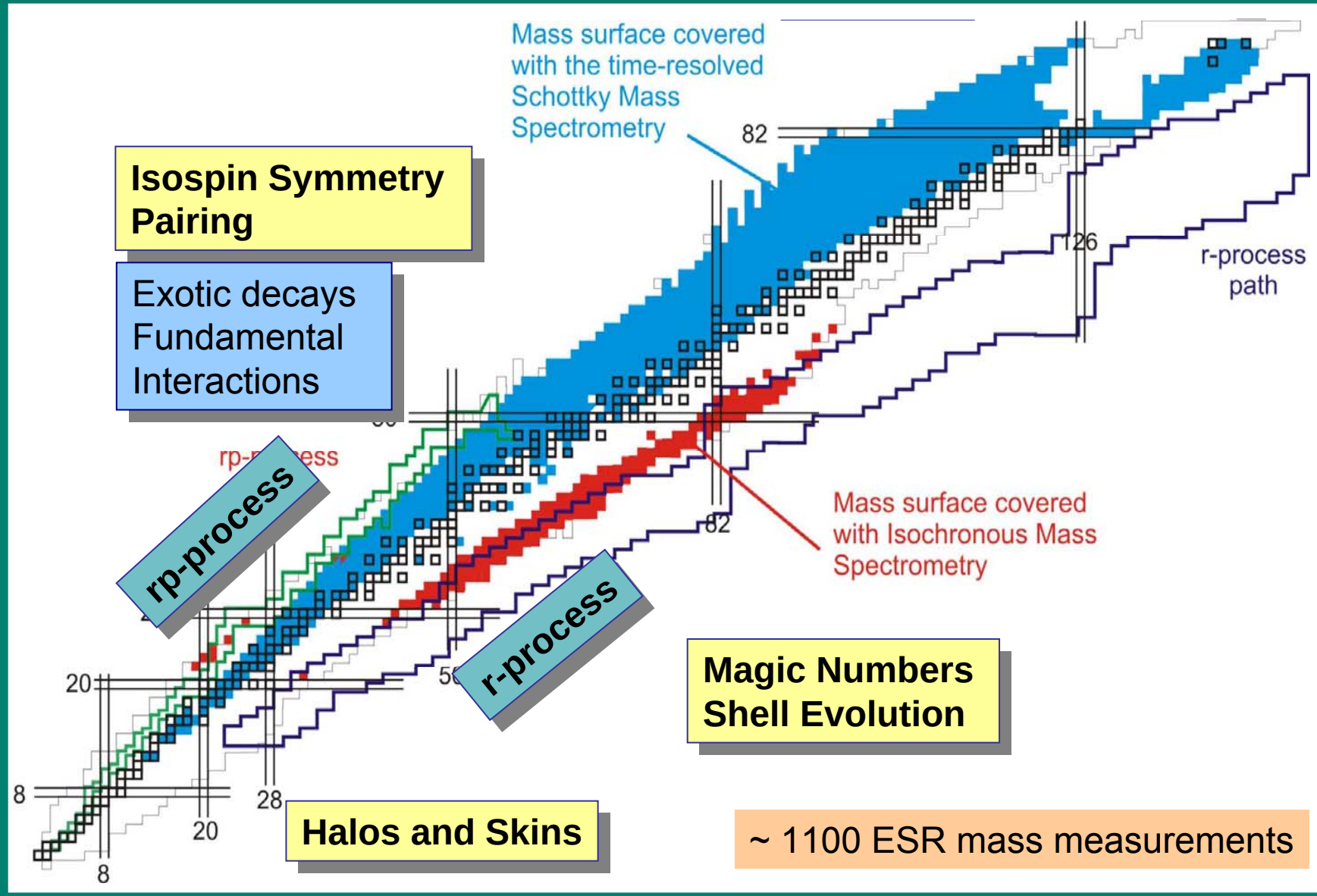
Nuclear structure studies



Isospin Symmetry
Pairing

Exotic decays
Fundamental
Interactions

rp-process

r-process

Magic Numbers
Shell Evolution

Halos and Skins

~ 1100 ESR mass measurements

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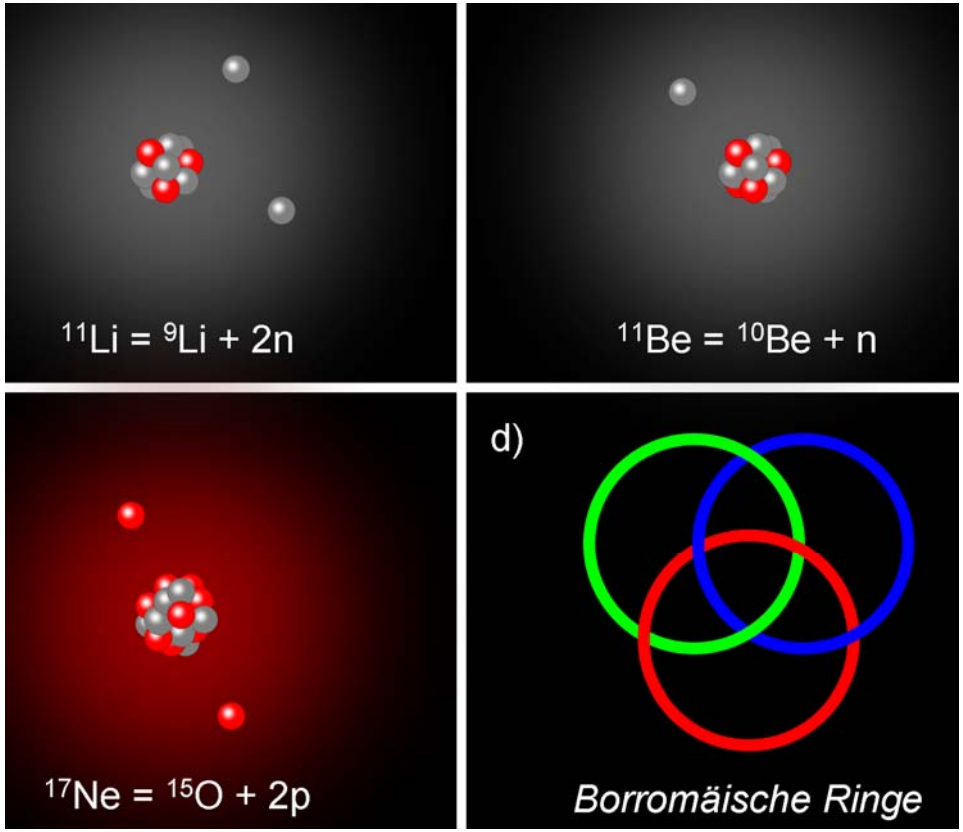
Investigation of nuclear halos

… via nuclear mass (binding energy) and charge radii measurements!



^{6,8}He

P. Mueller *et al.*, PRL 99, 252501 (2007)
V.L. Ryjkov *et al.*, PRL 101, 012501 (2008)

^{9,11}Li:

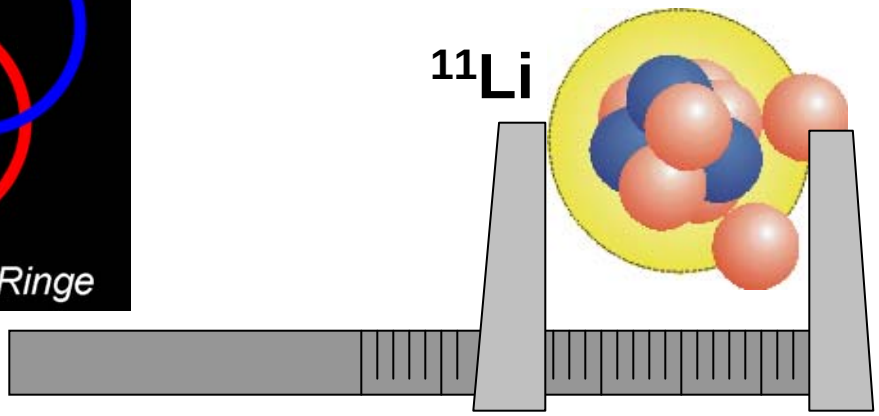
R. Neugart *et al.*, PRL 101, 132502 (2008)
M. Smith *et al.*, PRL 101, 202501 (2008)

^{11}Be:

W. Nörtershäuser *et al.*, PRL102, 062503 (2009)
R. Ringle *et al.*, PLB 675, 170 (2009)

^{17}Ne:

W. Geithner *et al.*, PRL102, 252502 (2008)



Argonne, GANIL, GSI, ISOLDE, TRIUMF

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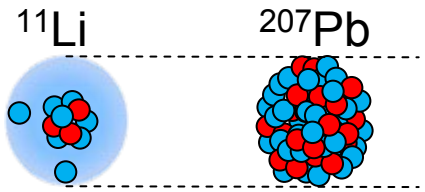
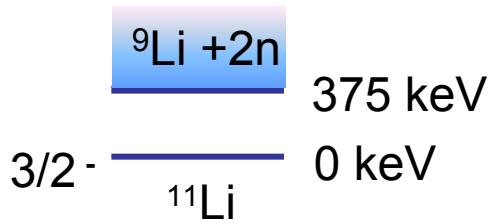
Beryllium: nuclear charge radii

characteristic properties of nuclear halos

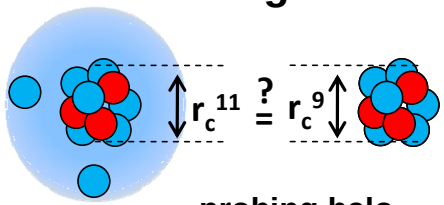
large matter radius



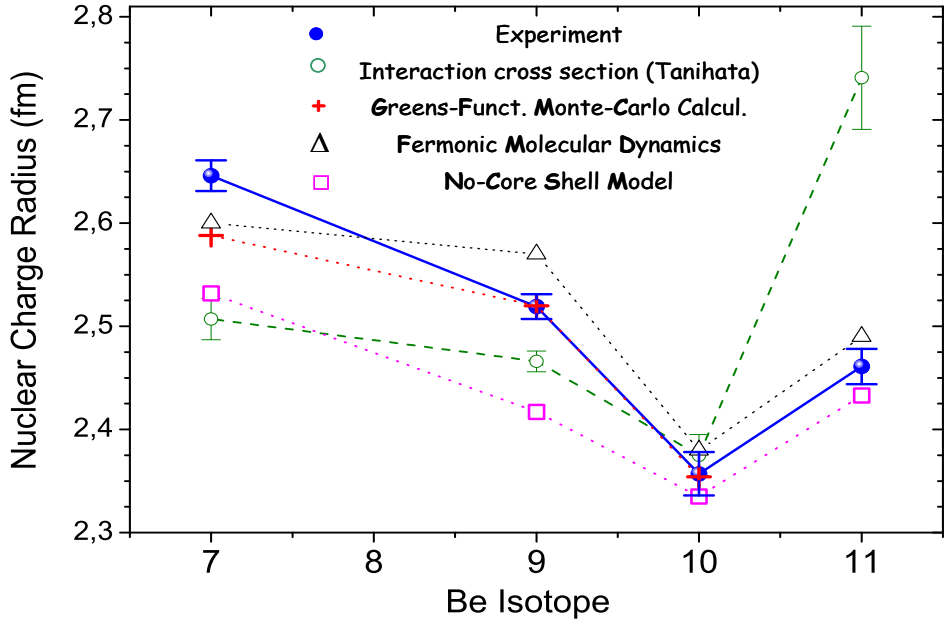
weakly bound

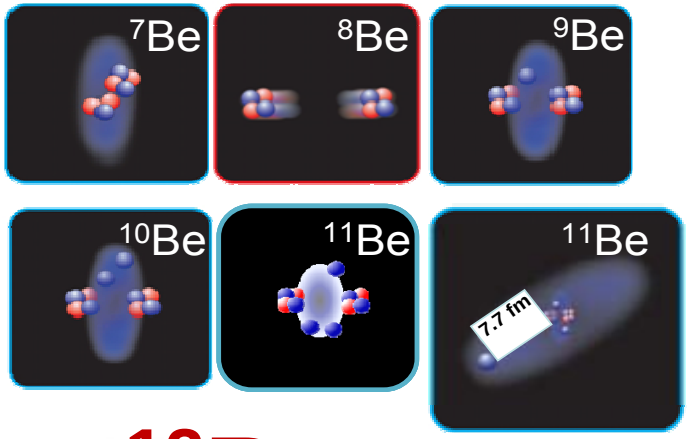


increased charge radius



probing halo neutron – nucleus interaction





^{12}Be

^{11}Be: Phys. Rev. Lett. 102, 062503 (2009)

„Size“ and structure determination of the neutron halos in ^{11,12}Be

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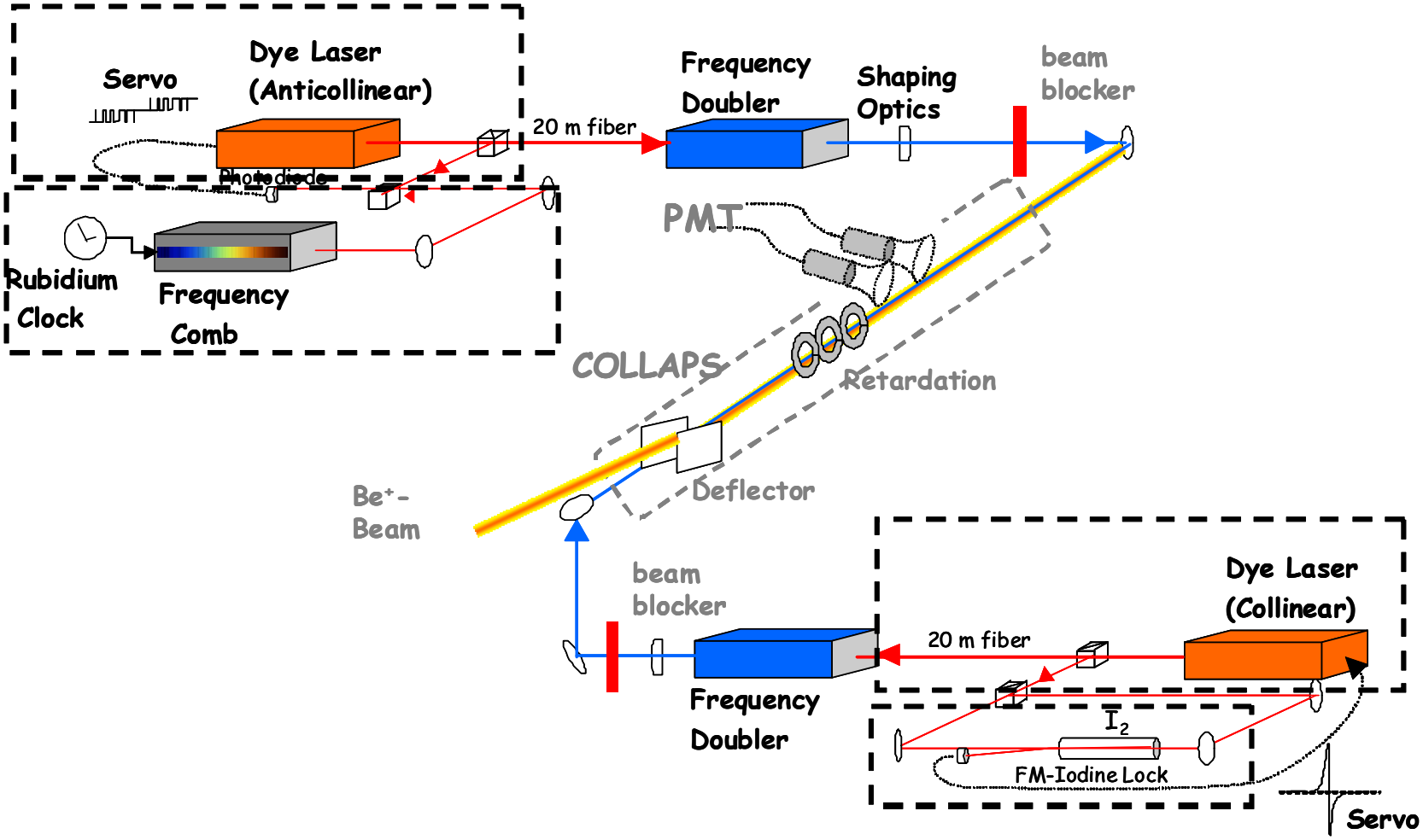
Be spectroscopy – laser system



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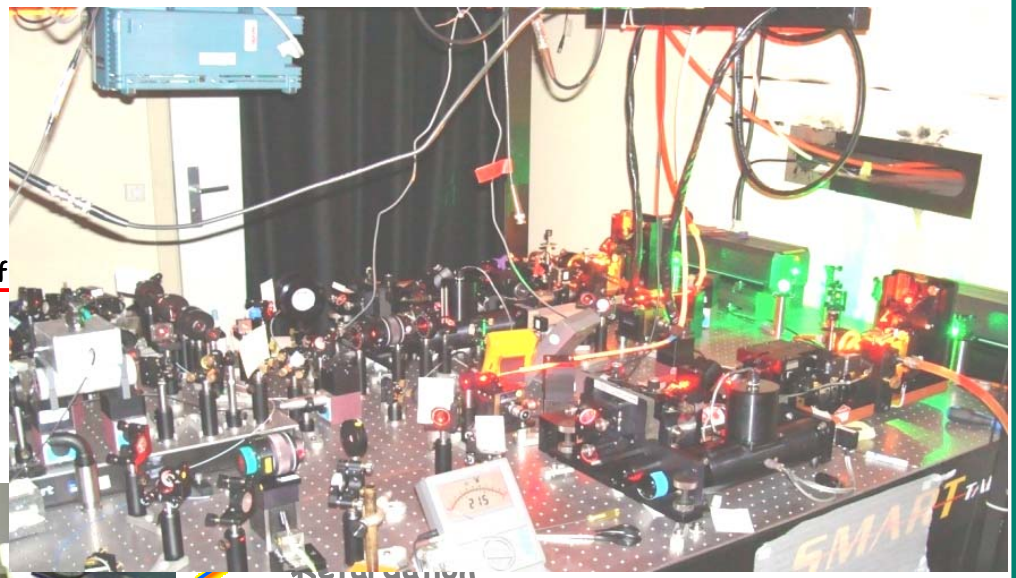
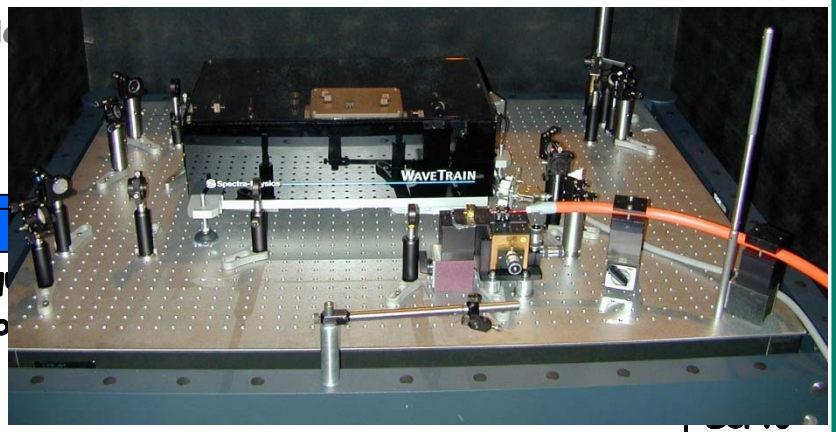
Be spectroscopy – laser system





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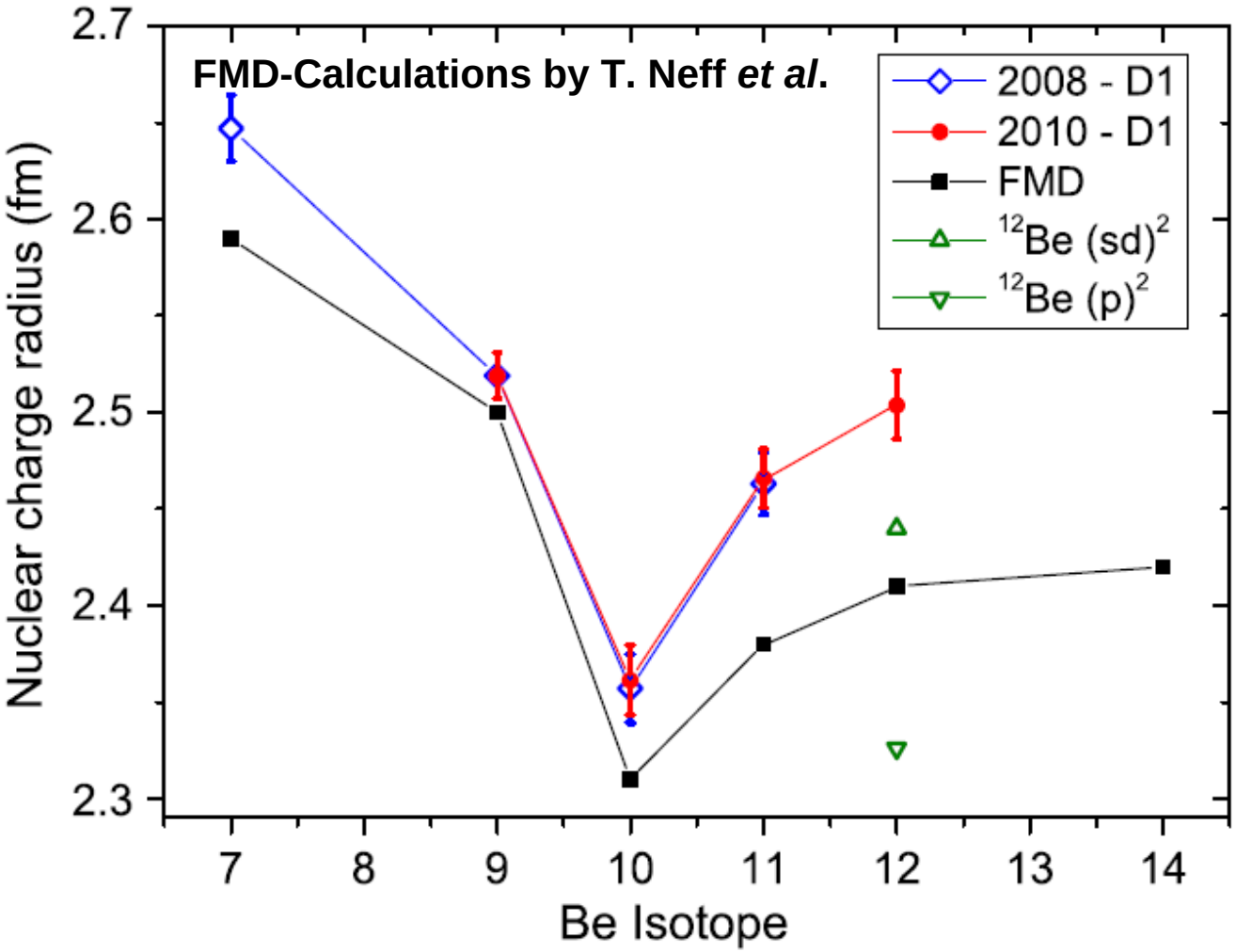
Beryllium: Nuclear Charge Radii



COLLAPS (ISOLDE)

A. Krieger *et al.*, Phys. Rev. Lett. 108, 142501 (2012).

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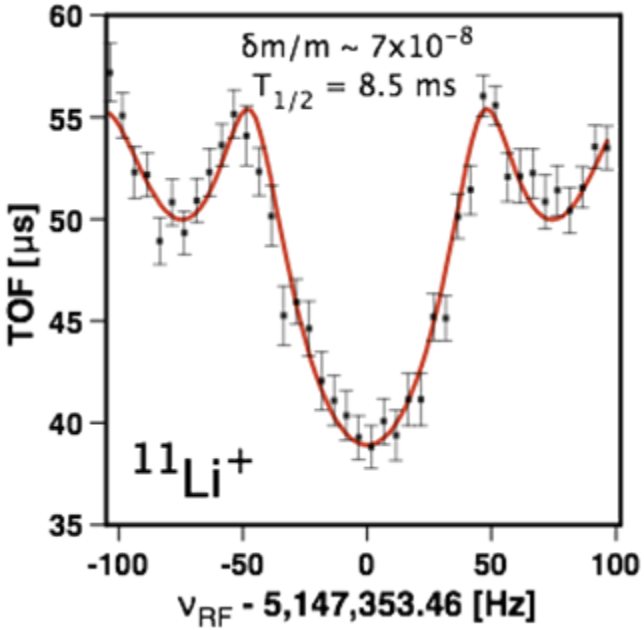
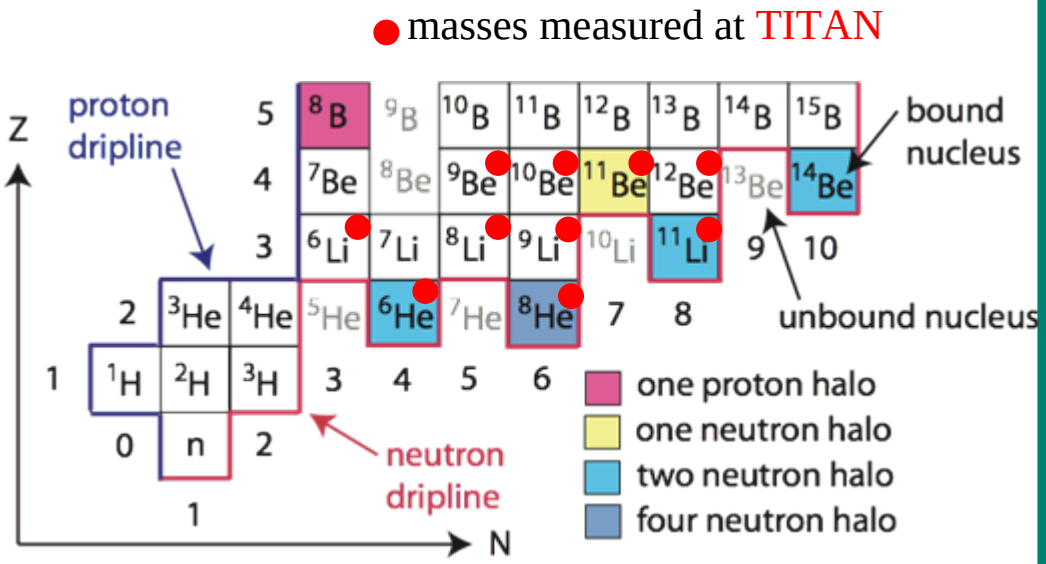
Halo mass mass measurements

Motivations:

1) guide nuclear theory and refine our understanding of the nucleus
2) mass is the major contribution to the charge radius error





Ab-initio methods points to the need of 3-body interactions in order to explain both the binding energy and charge radius of halo nuclei.

TITAN (TRIUMF)

e.g. V.L. Ryjkov *et al.*, PRL 101, 012501 (2008), M. Smith *et al.*, PRL 101, 202501 (2008)

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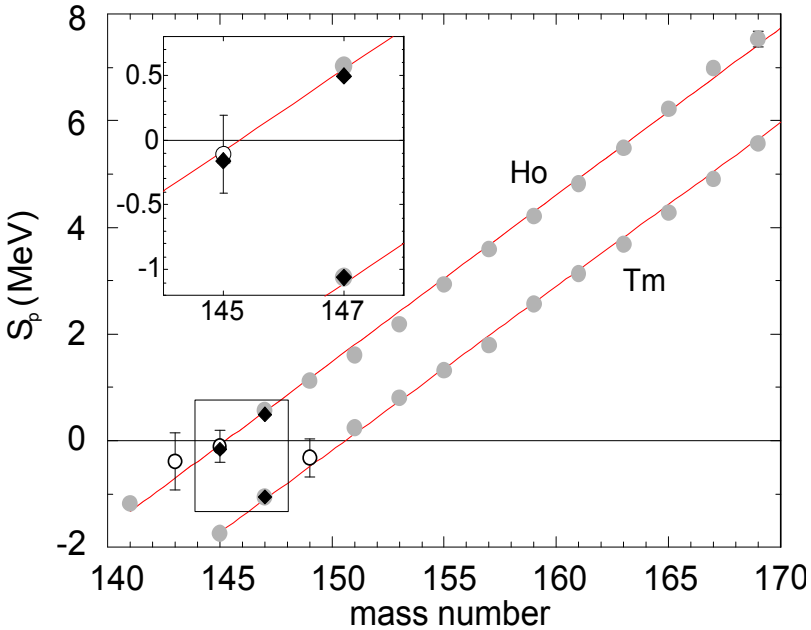
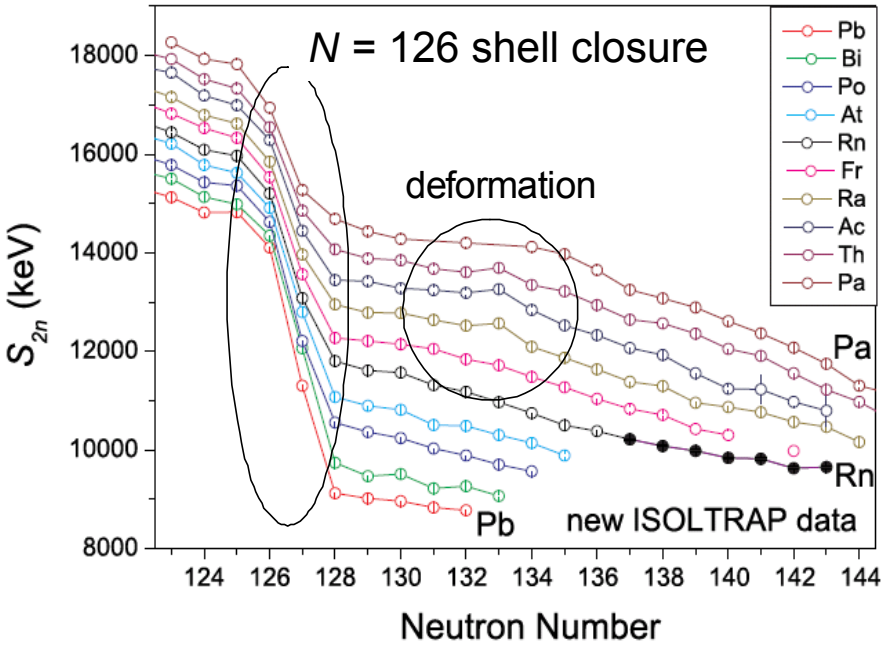
Nuclear structure studies

$S_p = B(Z,N) - B(Z\text{-}1,N)$



$S_{2n} = B(Z,N) - B(Z,N\text{-}2)$



SHIPTRAP: First direct mass measurement beyond the proton dripline.

CPT/ISOLTRAP/JYFLTRAP/LEBIT/TITAN: Investigation of shell closures, halos, …

C. Rauth *et al.*, Phys. Rev. Lett. 100, 012501 (2008)
M. Dworschak *et al.*, Phys. Rev. Lett. 100, 072501 (2008)
W. Geithner *et al.*, Phys. Rev. Lett. 101, 252502 (2008)

B. Cakirli *et al.*, Phys. Rev. Lett. 102, 082501 (2009)
D. Neidherr *et al.*, Phys. Rev. Lett. 102, 112501 (2009)
S. Naimi *et al.*, Phys. Rev. Lett. 105, 032502 (2010)

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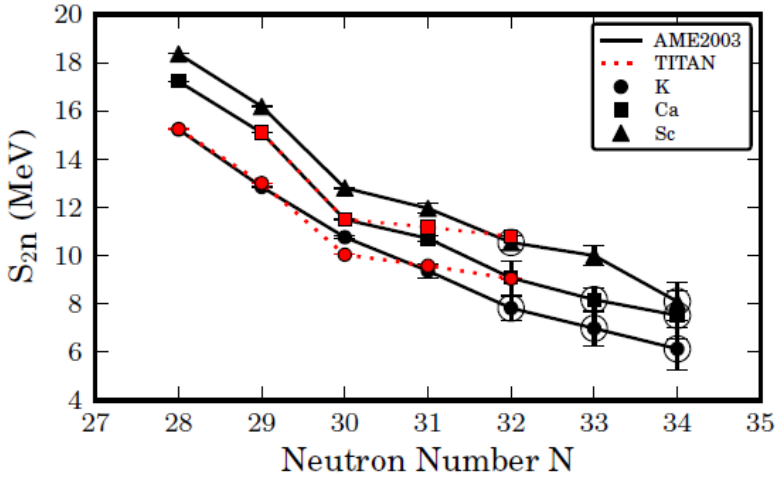
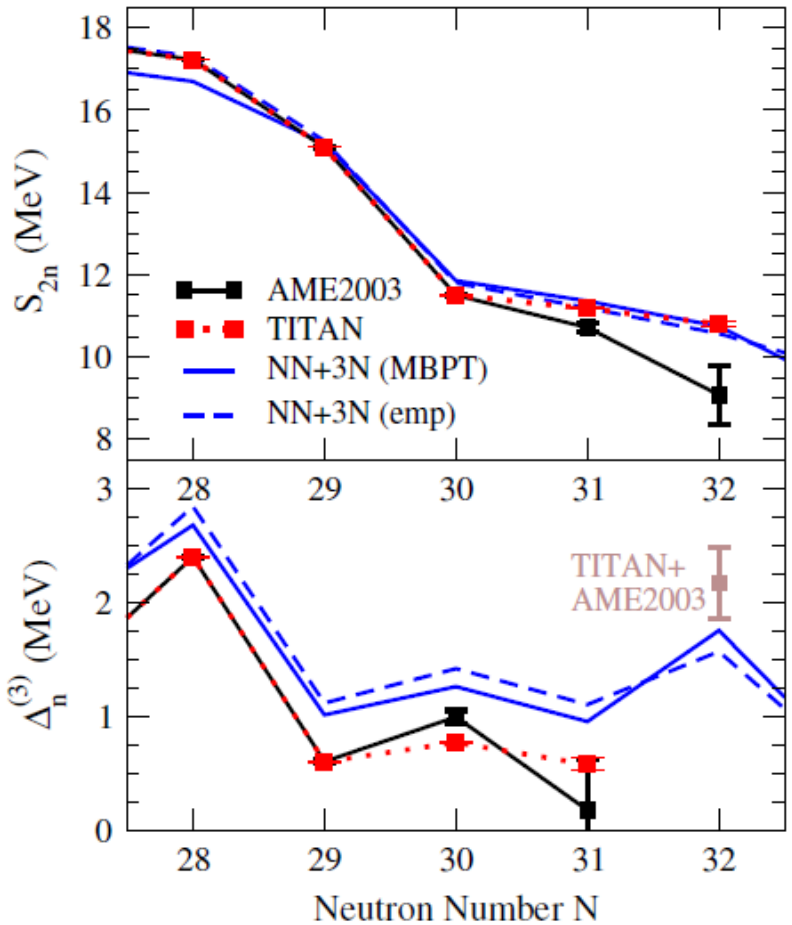
Nuclear masses and 3N-forces

New neutron-rich Ca and K masses.



^{52}Ca is more bound by 1.74 MeV.

Calculations including three-nucleon (3N) forces by A. Schwenk *et al*.



TITAN (TRIUMF)

A.T. Gallant *et al.*, ArXiv 1204.1987v1 (2012).

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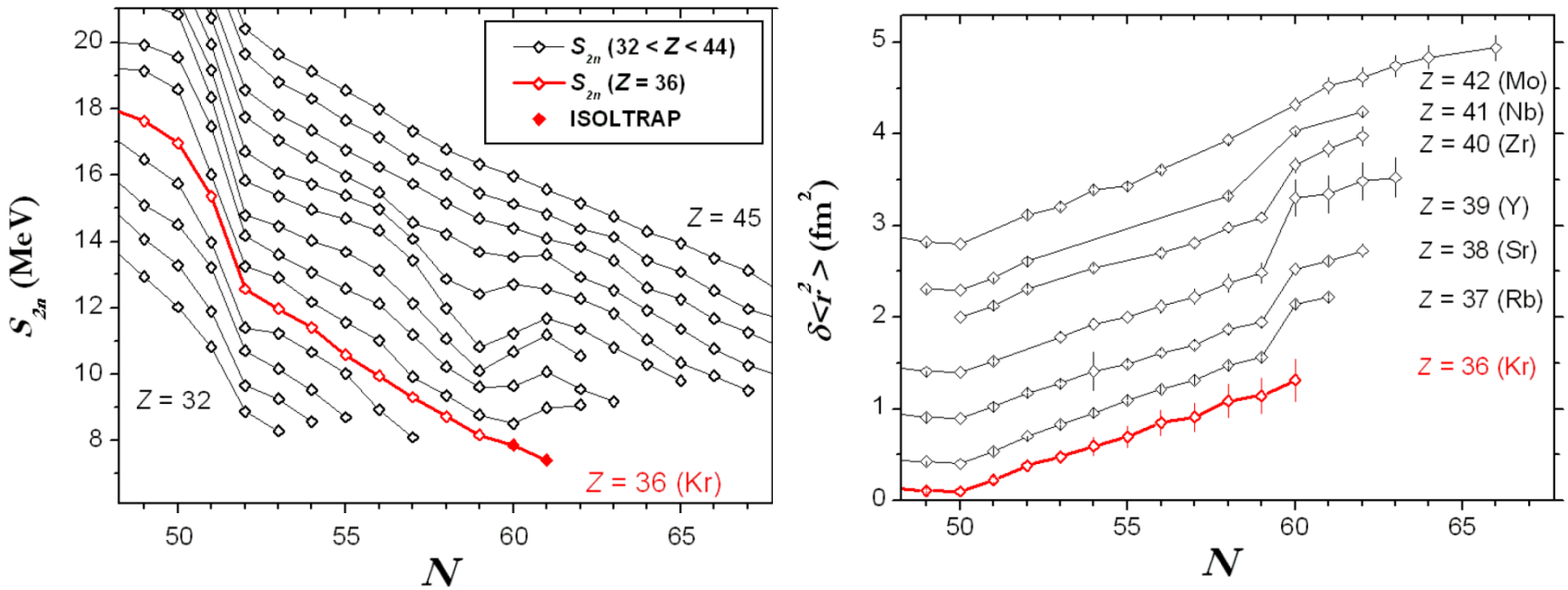
Quantum phase transition



- **End of phase transition region reached: critical-point boundary**
- **Supported by charge radii measurements**

ISOLTRAP (ISOLDE) **IGISOL (Jyväskylä)**

S. Naimi *et al.*, Phys. Rev. Lett. 103, 032502 (2010)
B. Cheal et al., Phys. Rev. Lett. 102, 222501 (2009)

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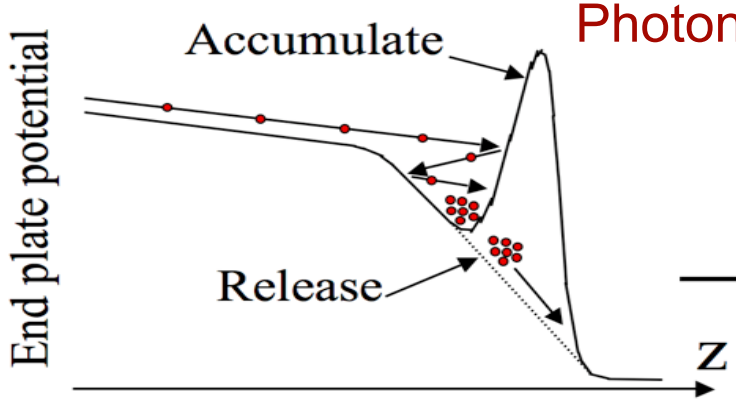
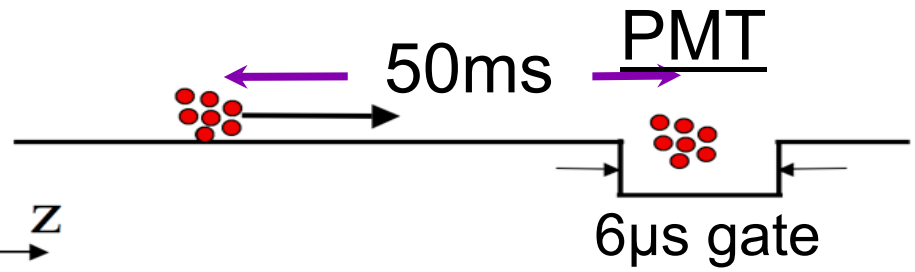
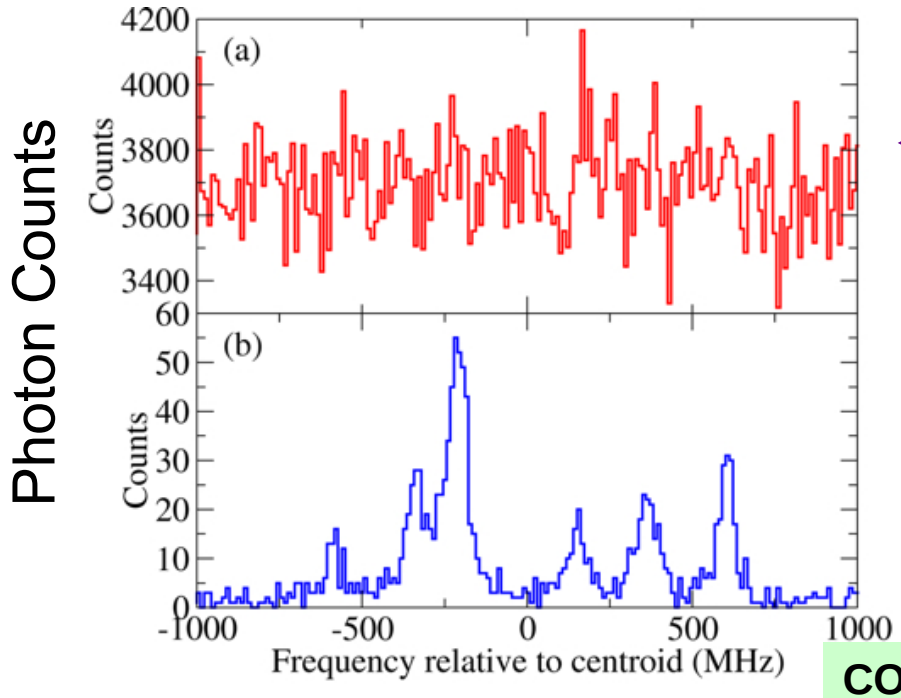
Laser spectroscopy with ISCOOL



Photon background dominated by continuous laser scatter → bunched beams



Idea: A. Nieminen *et al.*, PRL 88 (2002)



Ungated

Gated (64μs - 70μs)

Background suppression

50ms / 6μs = ~10^4

COLLAPS (ISOLDE) **IGISOL (Jyväskylä)**

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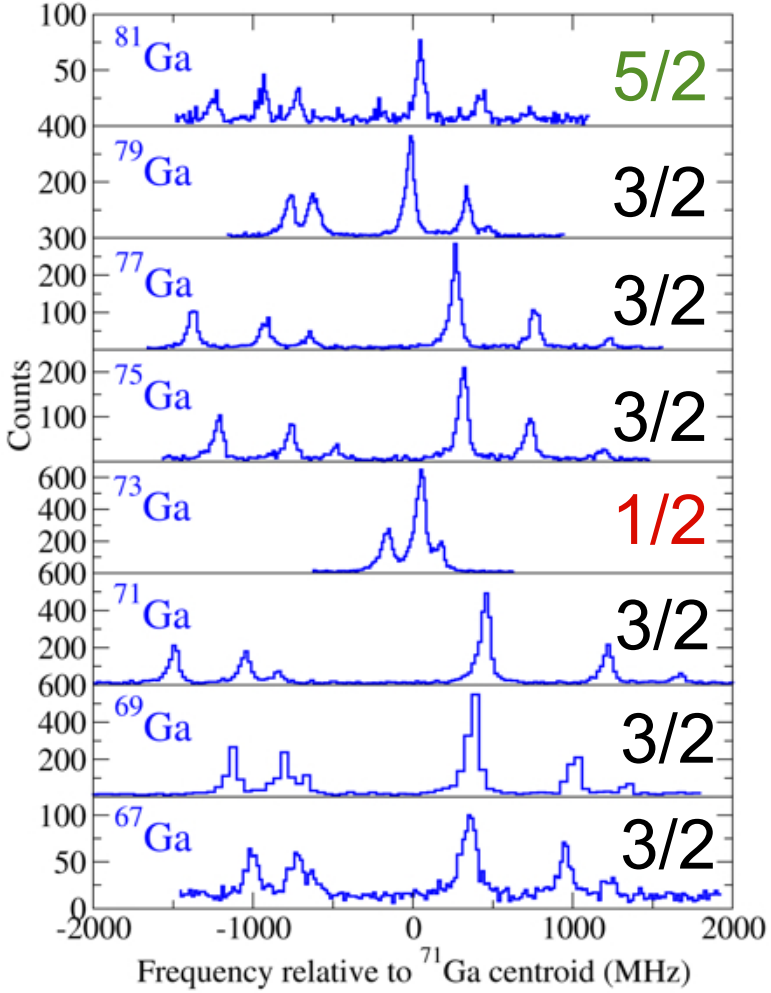
Isotope shifts in Cu and Ga

$\pi\ p_{3/2}(f_{5/2})^2$

Emptying of $p_{3/2}$

$\pi\ (p_{3/2})^3$



Spin 3/2, 5/2 inversion

Spin 1/2 col.

Sudden nuclear structure changes between *N*=40 and *N*=50

^{71,73,75}Cu: Phys. Rev. Lett. 103, 142501 (2009); $^{67\text{-}81}$Ga: Phys. Rev. Lett. 104, 252502 (2010)

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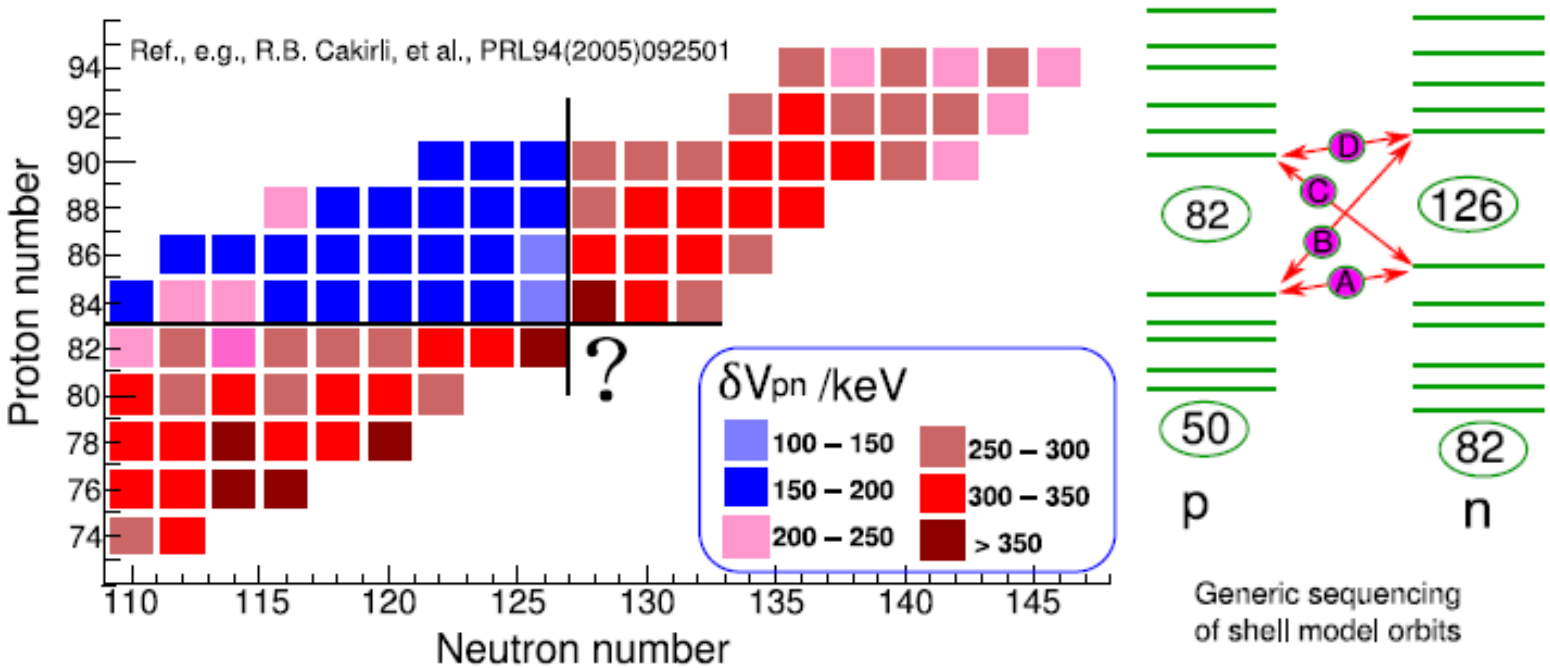
Experimental proton-neutron interaction



For even-even nuclei

$$\delta V_{pn}(Z,N) = \frac{1}{4}[\{B(Z,N)-B(Z,N-2)\}-\{B(Z-2,N)-B(Z-2,N-2)\}]$$

p-n interactions are sensitive to the spatial overlaps of the proton and neutron wave functions

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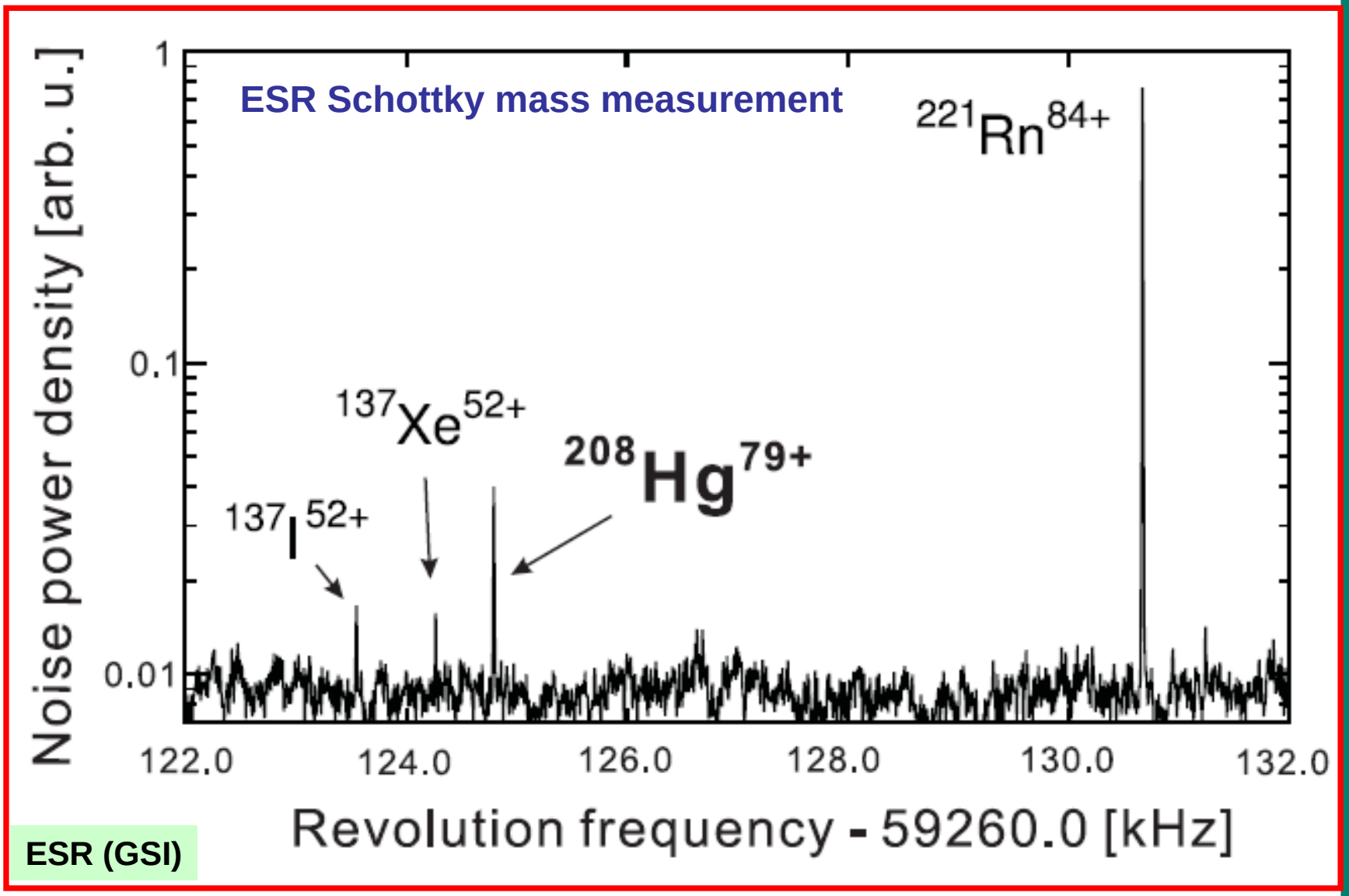
Experimental proton-neutron interaction



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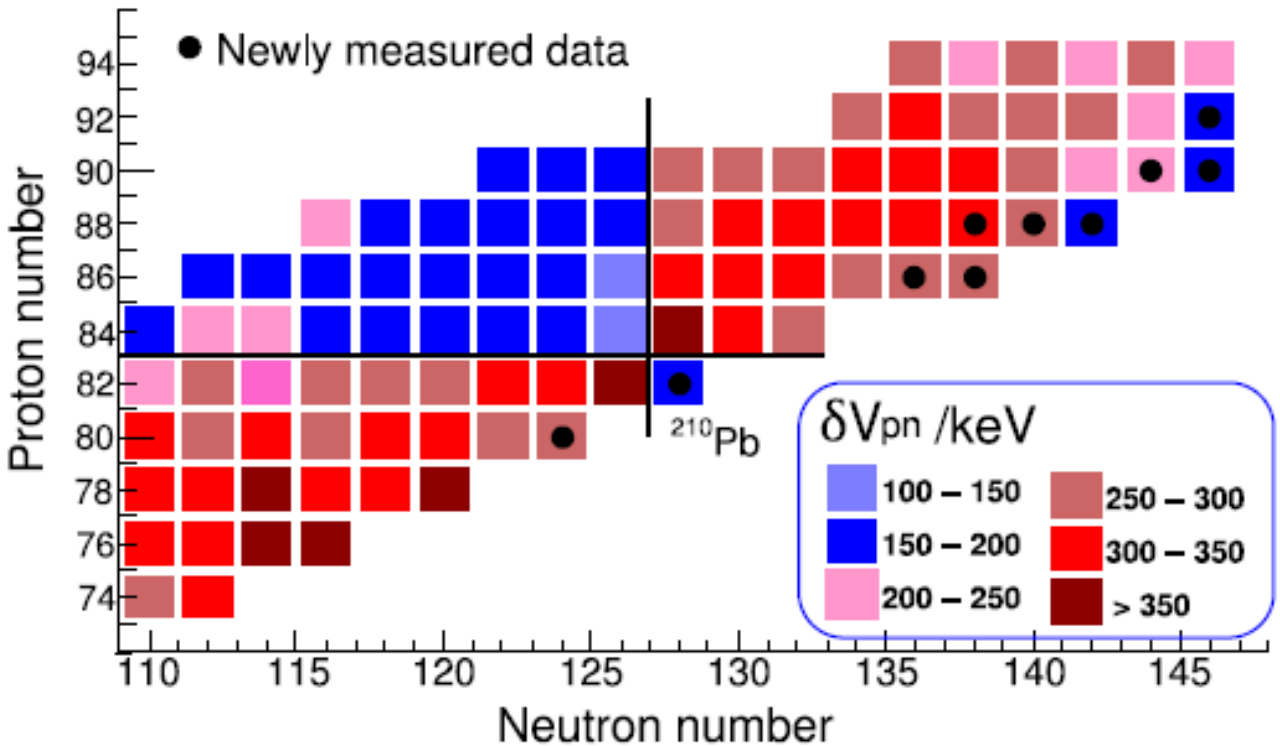
Masses reveal the p-n interaction strength



For even-even nuclei

$$\delta V_{pn}(Z,N) = \frac{1}{4}[\{B(Z,N)-B(Z,N-2)\}-\{B(Z-2,N)-B(Z-2,N-2)\}]$$

$^{223\text{-}229}$Rn: Phys. Rev. Lett. 102, 112501 (2009)

^{208}Hg: Phys. Rev. Lett. 102, 122503 (2009)

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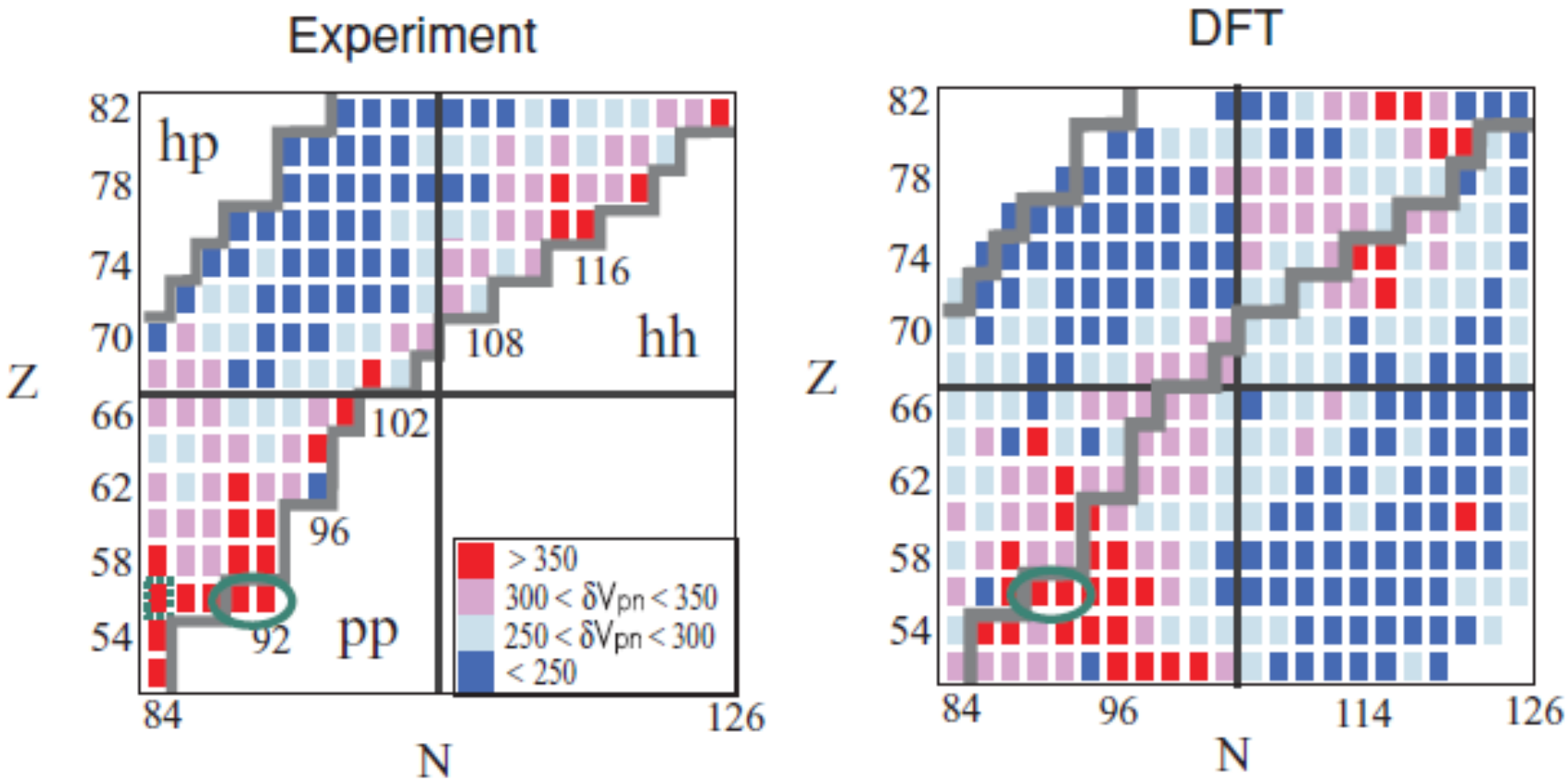
Experiment – Theory (DFT)



Excellent agreement on a few 10 keV level!

ISOLTRAP (ISOLDE)

D. Neidherr *et al.*, PRC 80, 044323 (2009)
M. Stoitsov *et al.*, PRL 98, 132502 (2007)

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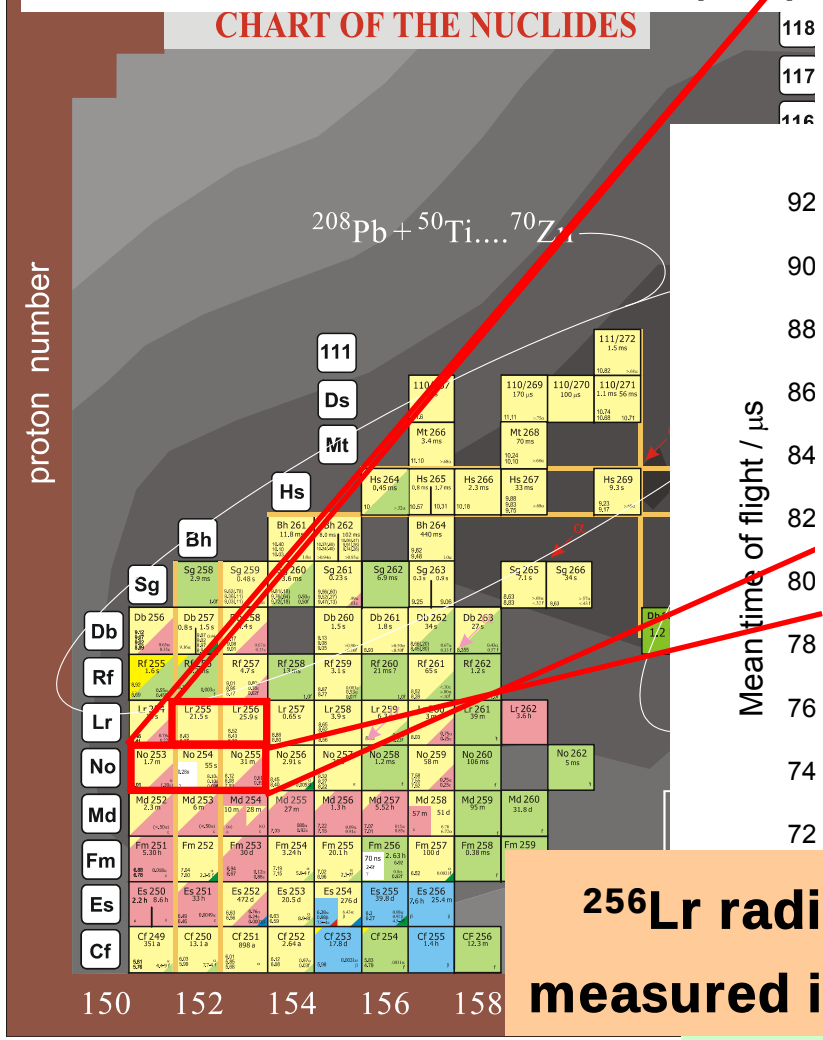
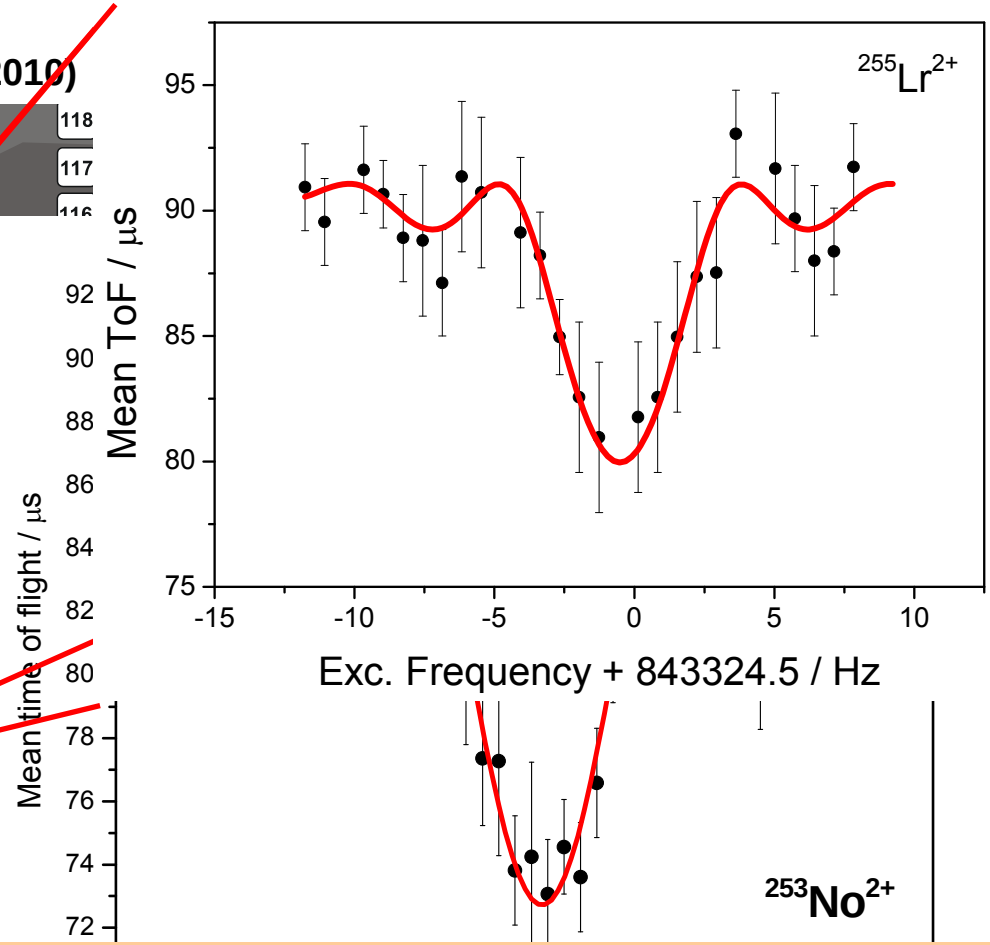
Direct mass measurements on No and Lr

M. Block et al., Nature 463, 785 (2010)
M. Dworschak et al., PRC 81, 064312 (2010)





^{256}Lr radionuclide with lowest yield ever measured in a Penning trap (2 ions / minute)

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Summary

Atomic physics techniques are an ideal tool for the precise determination of nuclear ground state properties for nuclear structure studies!

- Tools: lasers, Penning traps and storage rings
- Observables: charge radii, masses, moments, spins
- Nuclear structure:
  - Halos and skins
  - Magic numbers and shell evolution
  - Pairing, onset of deformation
  - Stability of superheavy elements

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Thanks

Thanks a lot for the invitation and your attention!

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WWW: www.mpi-hd.mpg.de/blaum/

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