*Reflections, Liverpool 2015*

# Precision Measurements of Nuclear Ground-state Properties for Nuclear Structure, Astrophysics and Fundamental Studies

- Motivation for precision nuclear data
- Atomic physics techniques in nuclear physics
- Applications of nuclear ground state data


**Klaus Blaum**

**July 29th, 2015**

Max-Planck-Institut für Kernphysik

Max Planck Institute for Nuclear Physics

Klaus.blaum@mpi-hd.mpg.de

Max Planck Institute for Nuclear Physics

# Characteristics of a (radioactive) nucleus

**its weight**

**its size**

**its life-time/decay**

**its shape**

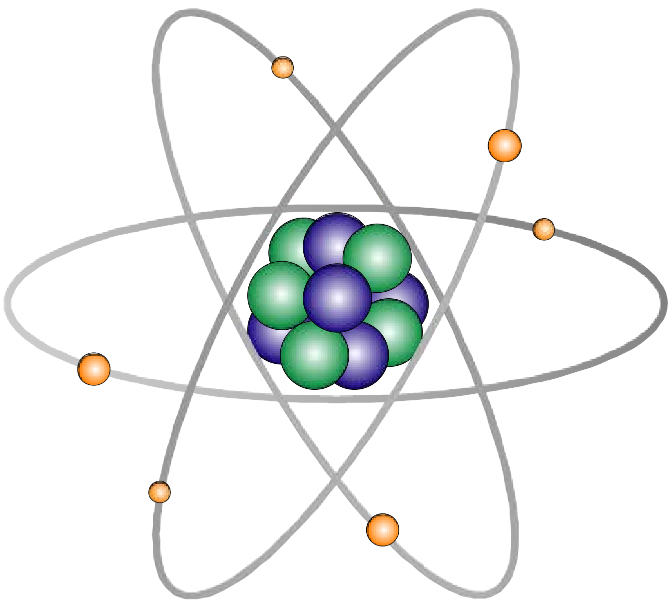
**its e.m. properties**

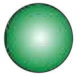
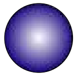
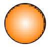
**its mood (state)**

In recent years unique tools have been developed to determine experimentally and to describe theoretically these characteristics.

# Atomic and nuclear masses

**Masses determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.**



= $N$ ·  + $Z$ ·  + $Z$ · 

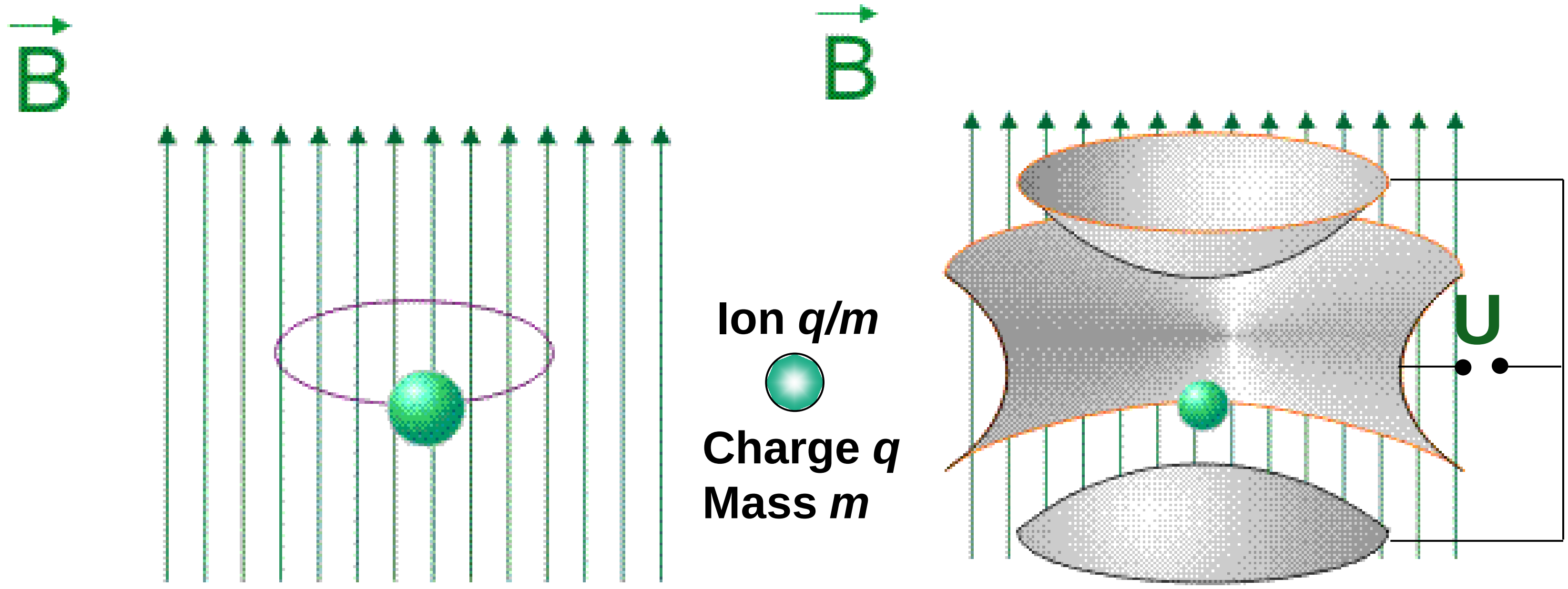
– binding energy

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

$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} - 10^{-8}$

# Storage of ions in a Penning trap




The free cyclotron frequency is inverse proportional to the mass of the ions!

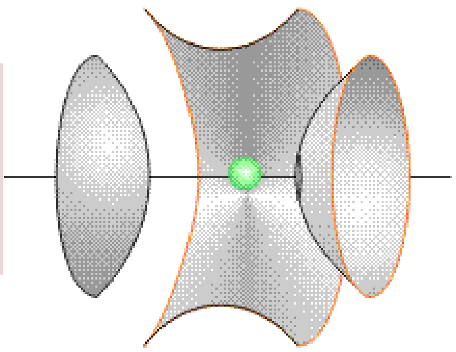
$$\omega_c = qB / m$$

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986).
K. Blaum, J. Dilling, W. Nörtershäuser, Phys. Scr. T152, 014017 (2017).

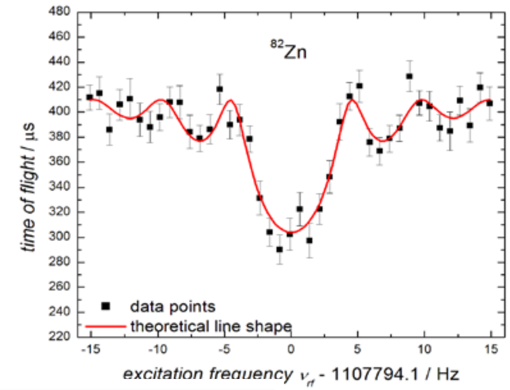
MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

# Cyclotron frequency detection techniques

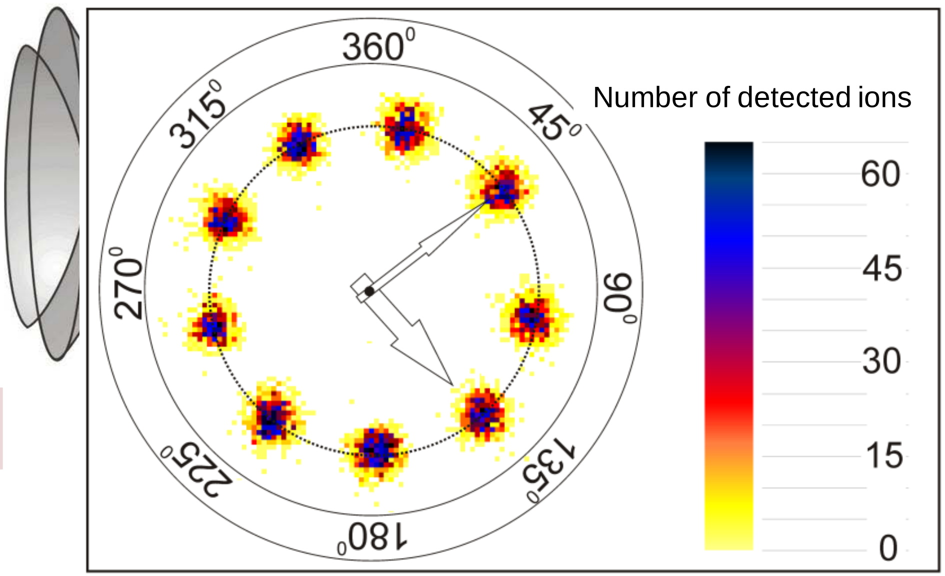
*Destructive time-of-flight detection*



**$R \propto 1/T_{obs}$**




*Space/ Phase resolving detection*

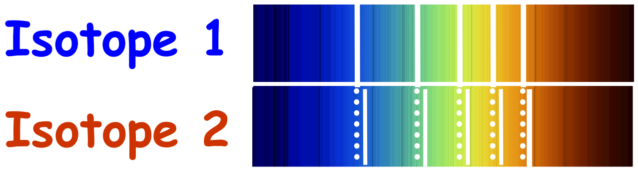



**$R \propto 1/T_{obs} \cdot \Delta\phi/2\pi$**

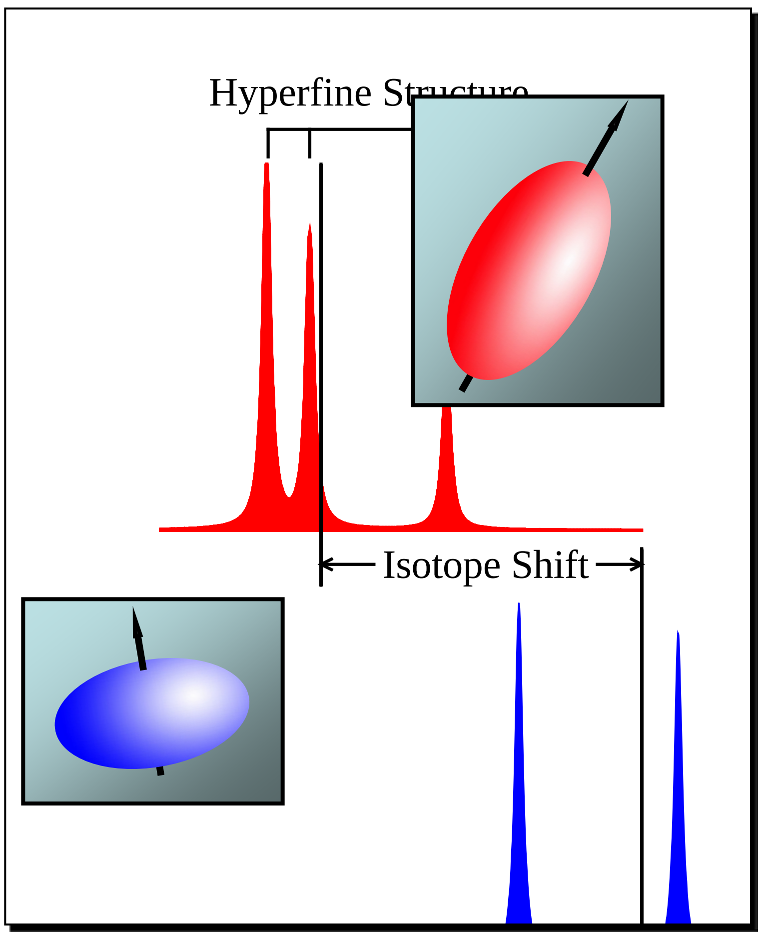
**Mass accuracy of $\delta m/m = 10^{-10}$ demonstrated!**

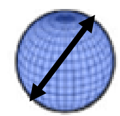
S. Eliseev *et al.*, Phys. Rev. Lett. 110, 082501 (2013)

# Laser spectroscopy and nuclear structure



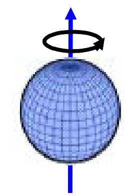

Isotope Shift := Frequency difference in an electronic transition between two isotopes



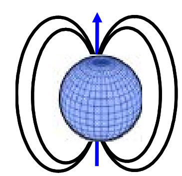
$\langle r^2 \rangle$

its size

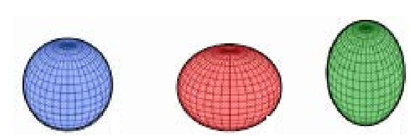


$\mathbf{F} = \mathbf{I} + \mathbf{J}$

its e.m. property



$A = \mu_I \frac{\langle B(0) \rangle}{\mathbf{I} \cdot \mathbf{J}}$

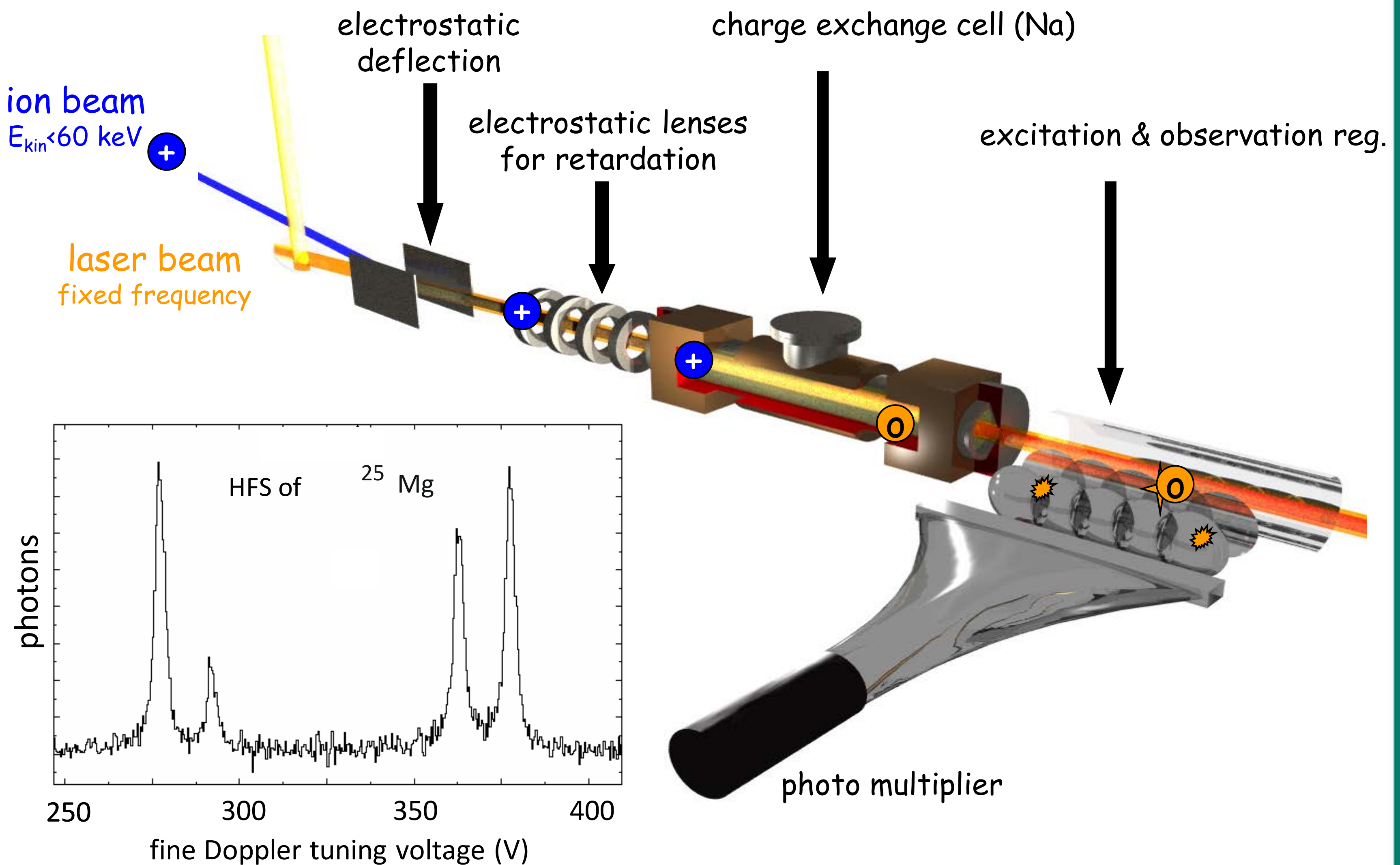


$B = e\, Q_S\, \langle \varphi_{zz}(0) \rangle$

its shape

B. Cheal, K.T. Flanagan, J. Phys. G 37, 113101 (2010).
K. Blaum, J. Dilling, W. Nörtershäuser, Phys. Scr. T152, 014017 (2017).

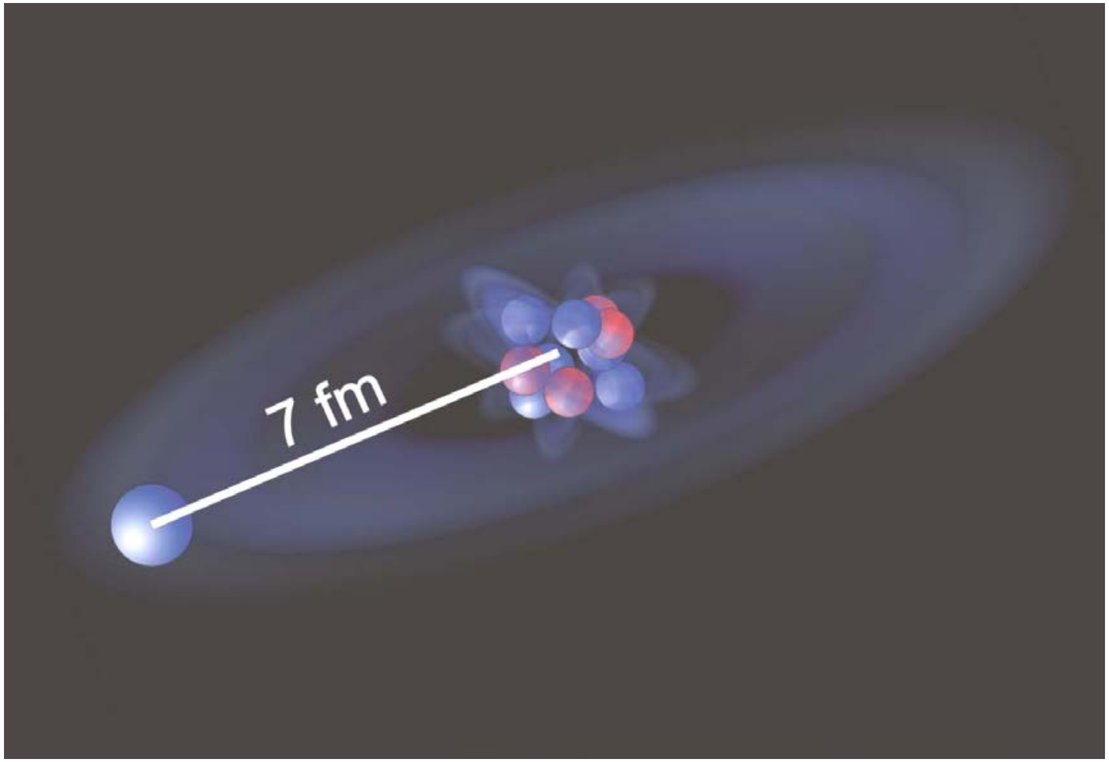
# Basics of (collinear) laser spectroscopy




MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

# Masses and radii

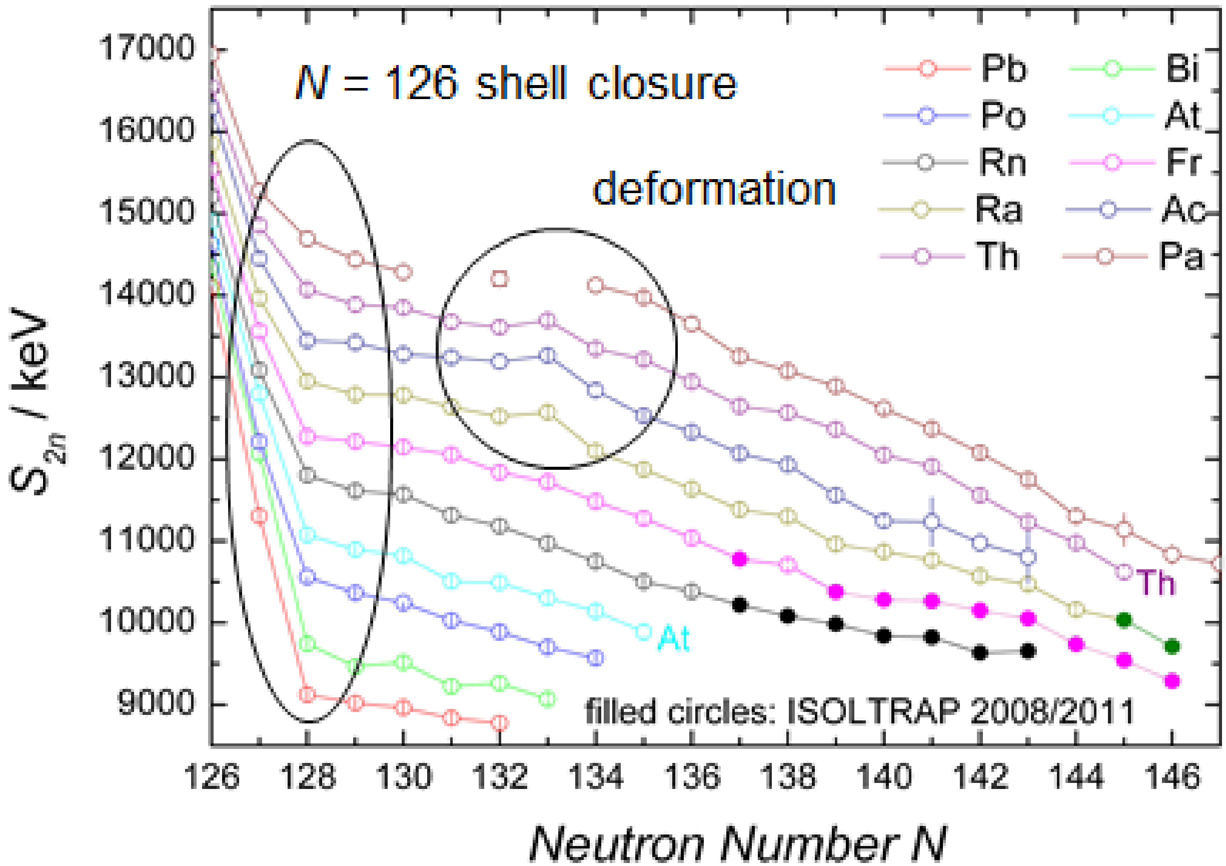
## Nuclear structure studies




**COLLAPS, CRIS, ESR, ISOLTRAP, JYFLTRAP, SHIPTRAP, TITAN**

# Nuclear structure studies

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



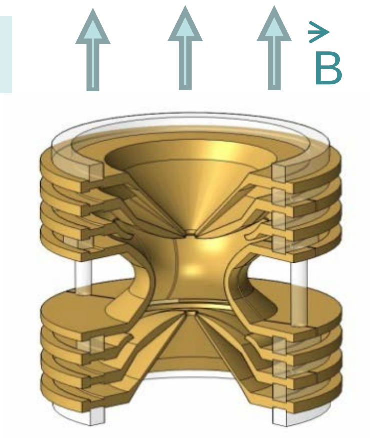


D. Yordanov *et al.*, Phys. Rev. Lett. 110, 192501 (2013)
M.L. Bissell *et al.*, Phys. Rev. Lett. 113, 052502 (2014)
Z. Meisel *et al.*, Phys. Rev. Lett. 114, 022501 (2015)
J. Papuga *et al.*, Phys. Rev. Lett. 110, 172503 (2013)
R.F. Casten *et al.*, Phys. Rev. Lett. 113, 112501 (2014)
M. Rosenbusch *et al.*, Phys. Rev. Lett. 114, 202501 (2015)

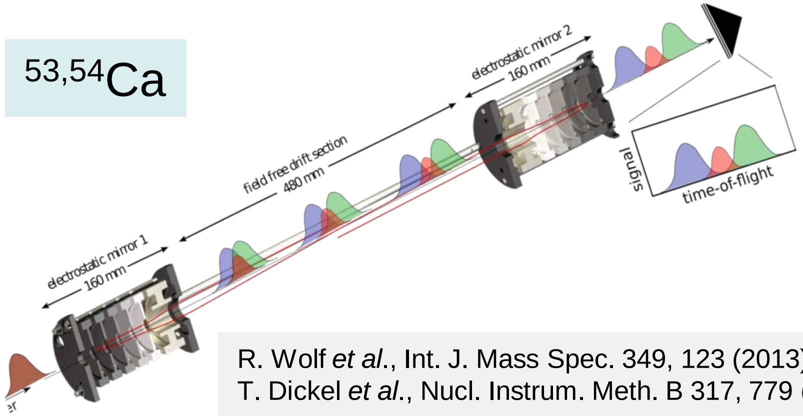
# Ca masses pin down nuclear forces

Multi-reflection time-of-flight and Penning-trap mass spectrometry

$^{51,52}$Ca



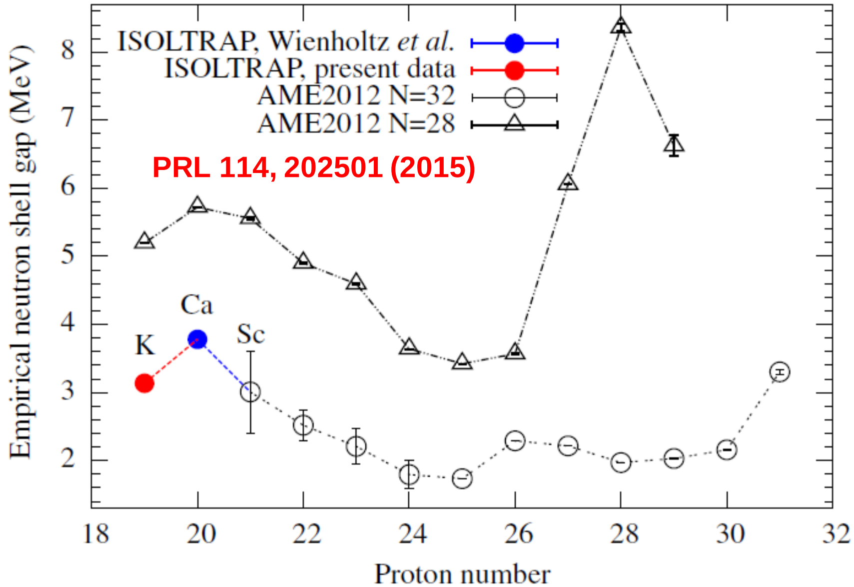

$^{53,54}$Ca




R. Wolf *et al.*, Int. J. Mass Spec. 349, 123 (2013)
T. Dickel *et al.*, Nucl. Instrum. Meth. B 317, 779 (2013)

- Production rates of ~10 ions/s
- Mass measurements via $S_{2n}$ establish new magic number at $N = 32$
- Correct prediction from 3N-forces (A. Schwenk *et al.*, TUD)

F. Wienholtz *et al.*, Nature 498, 346 (2013)



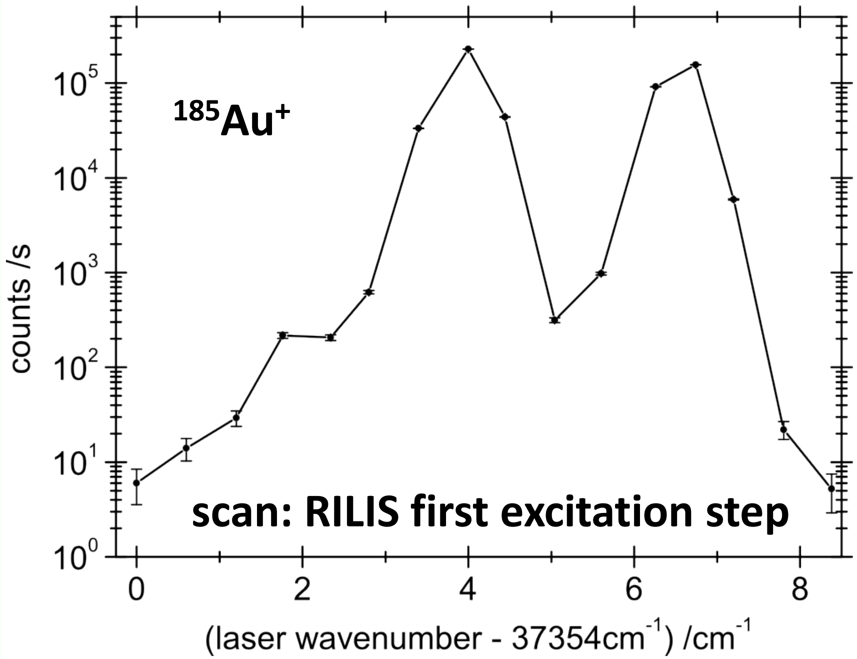

ISOLTRAP (CERN), TITAN (TRIUMF)

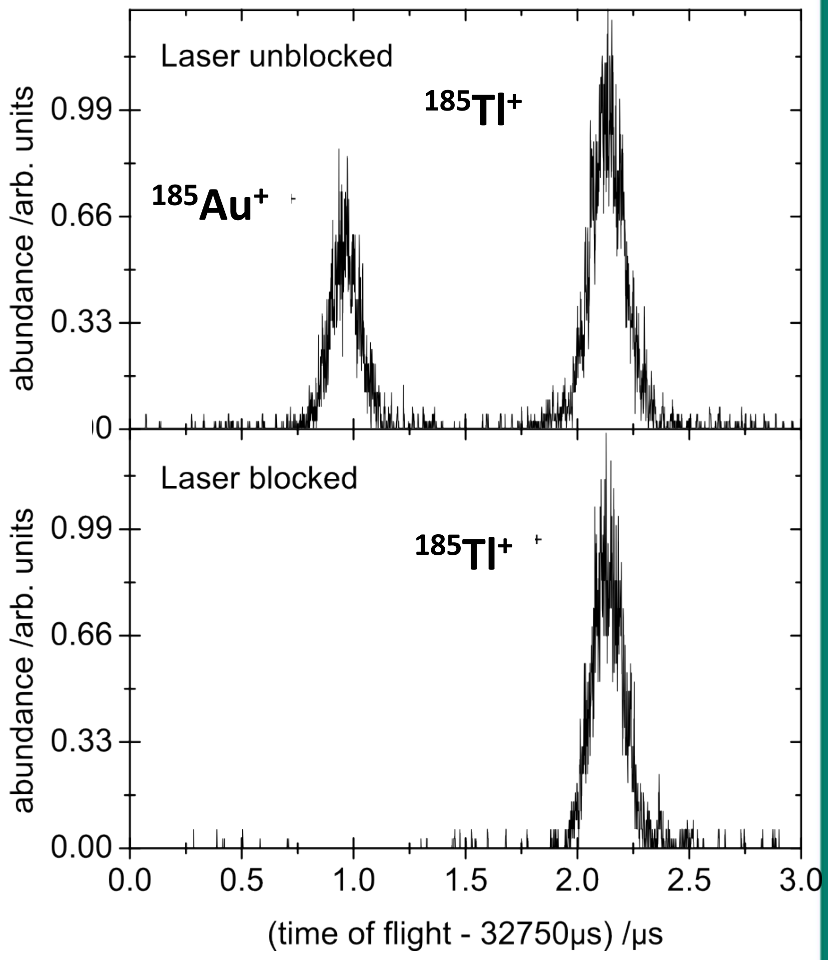
Max Planck Institute
for Nuclear Physics

# MR-ToF ion beam analysis

**MR-ToF analyzer to investigate resonant laser ionization of radionuclides**

- fast, high sensitivity to improve ioniz. eff.
- high dynamic range: 1-1e5 counts/s
- counts free from bg contamination
- provides isomerically pure beams




Wolf *et al.*, IJMS 349-350, 123 (2013); Kreim *et al.*, NIM B 317, 492 (2013); Marsh *et al.*, NIM B 317, 550 (2013)

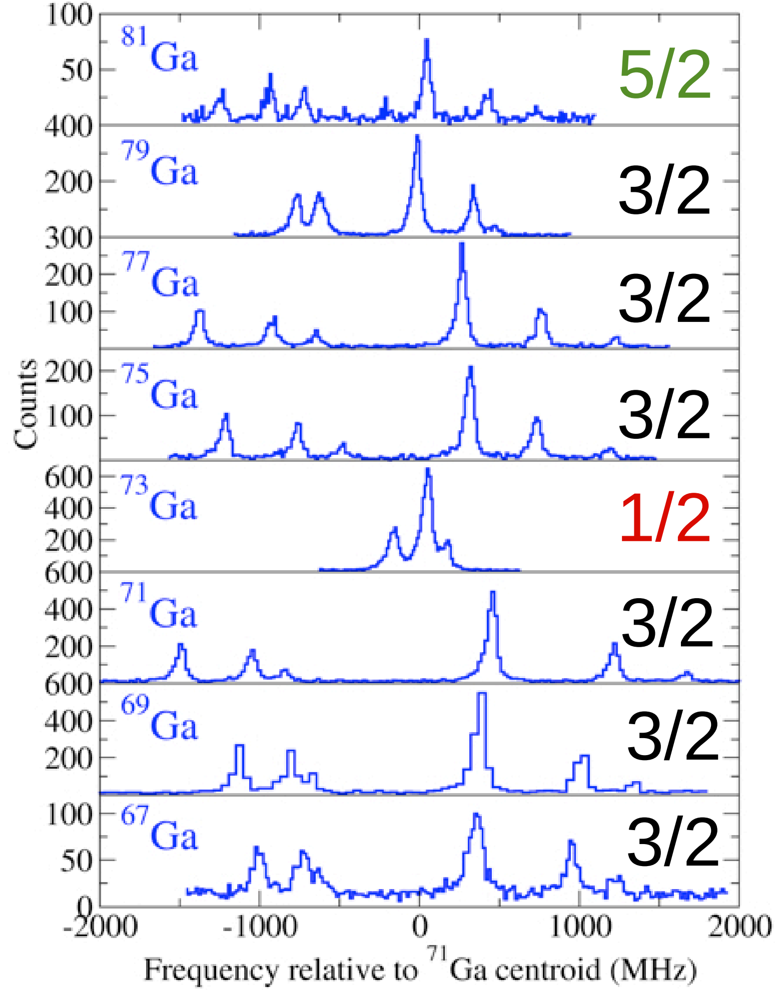

Max Planck Institute for Nuclear Physics

# Isotope shifts in Cu,Ga and Cd

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

Emptying of $p_{3/2}$

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



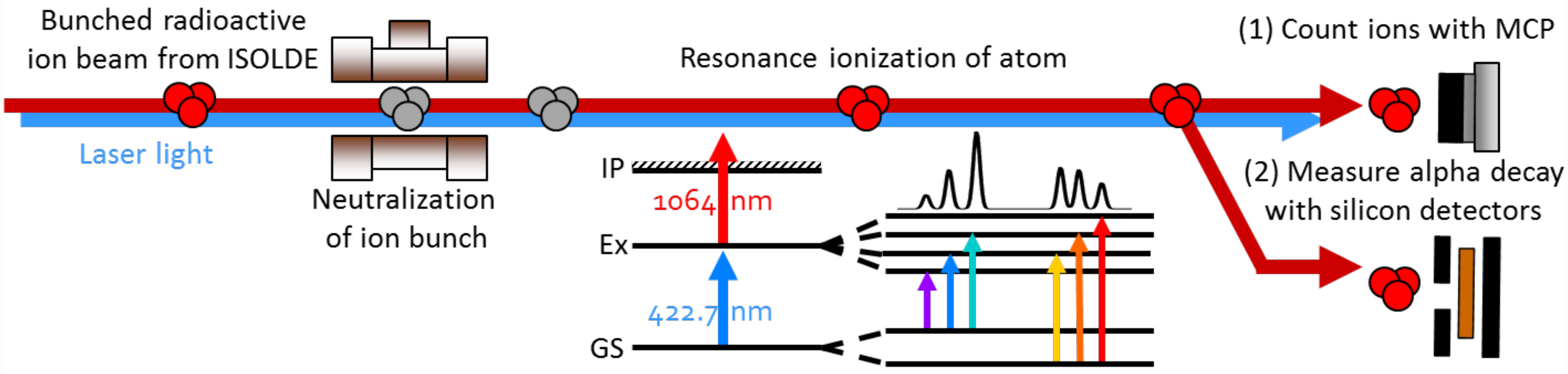

Spin 3/2, 5/2 inversion

Spin 1/2 col.

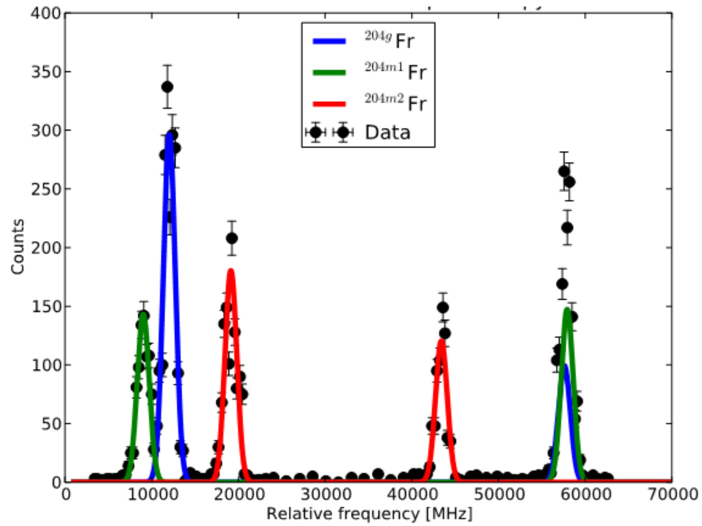
**Sudden nuclear structure changes between *N*=40 and *N*=50**

**[71,73,75]Cu: PRL 103, 142501 (2009); [67-81]Ga: PRL 104, 252502 (2010); [102-132]Cd: PRL 110, 192501 (2013)**

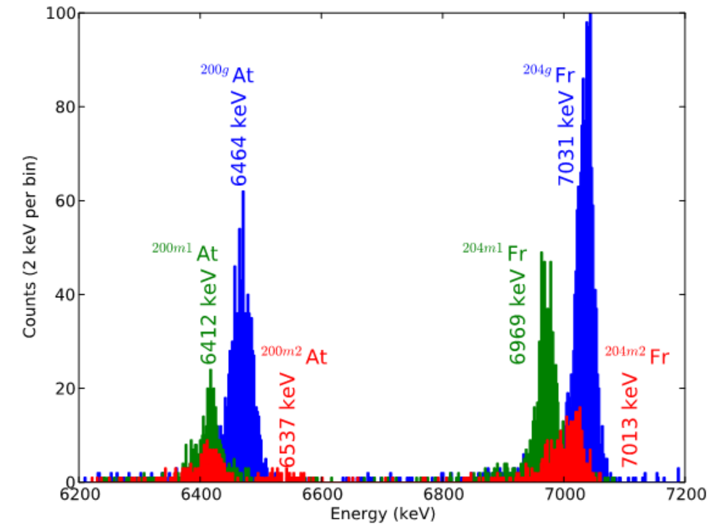
# CRIS at $^{202-231}$Fr




(1) Study of the hyperfine structure with CRIS



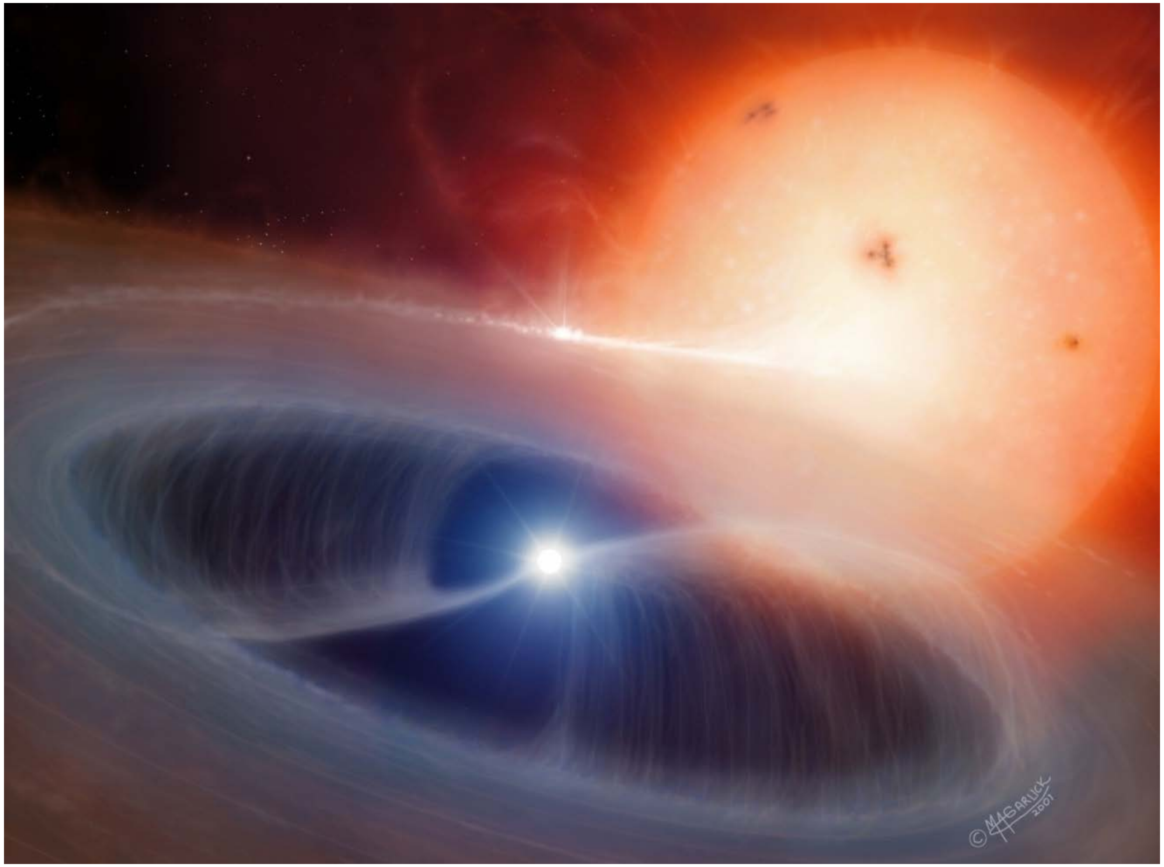

(2) Identification of nuclear states with the DSS




K.M. Lynch *et al.*, Phys. Rev. X **4** 011055 (2014) K.T. Flanagan *et al.*, Phys. Rev. Lett. **111** 212501 (2013)

# Masses

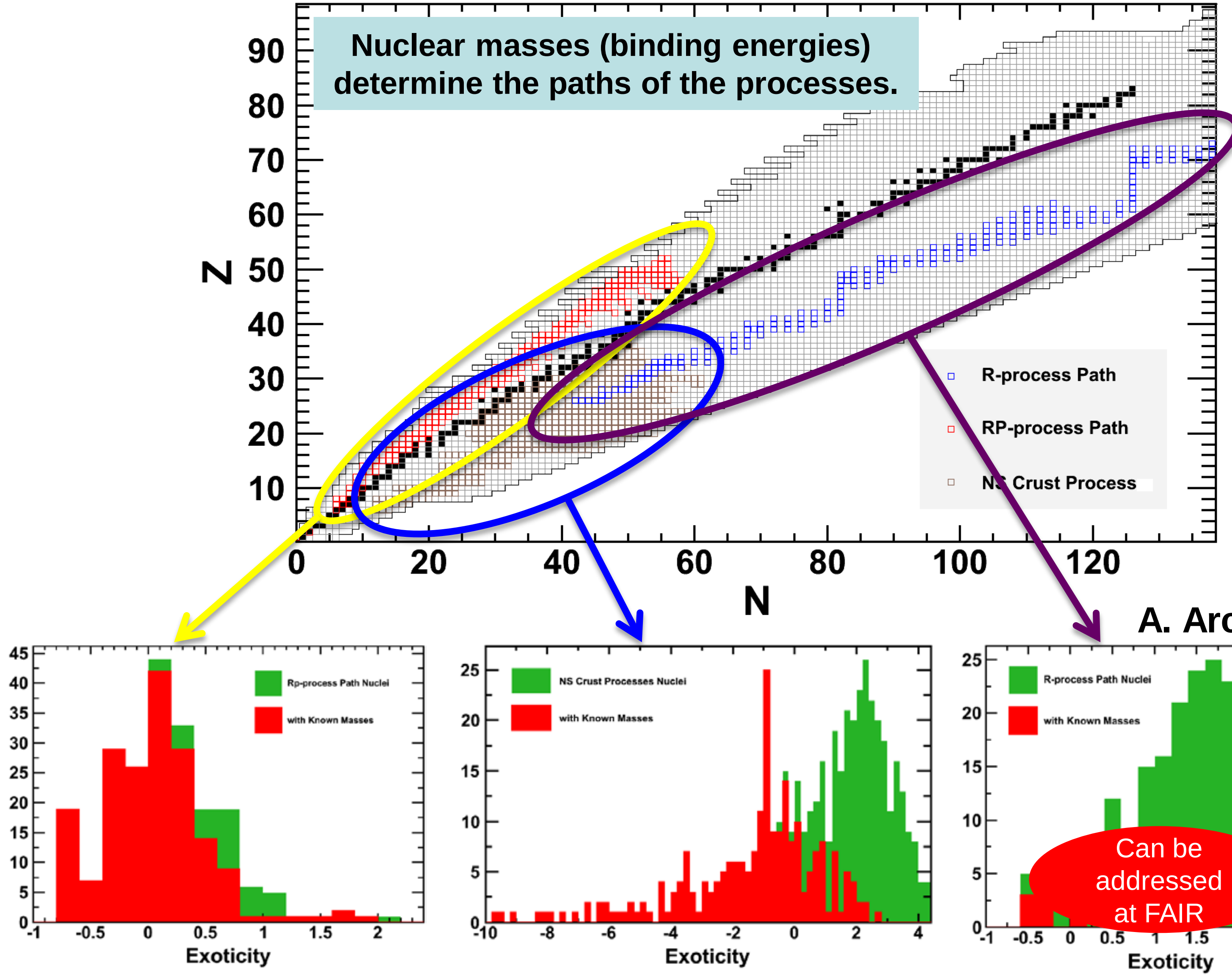
## Nuclear astrophysics studies



**CPT, CSRe, ESR, ISOLTRAP, JYFLTRAP, LEBIT, SHIPTRAP, TITAN**

Max Planck Institute for Nuclear Physics

# Mass spectrometry for nucleosynthesis

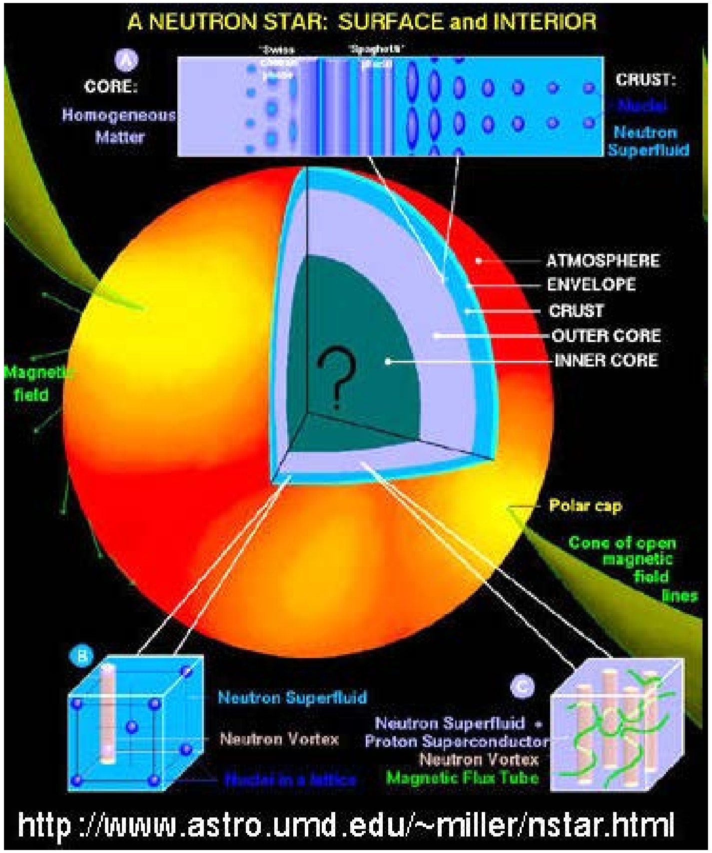


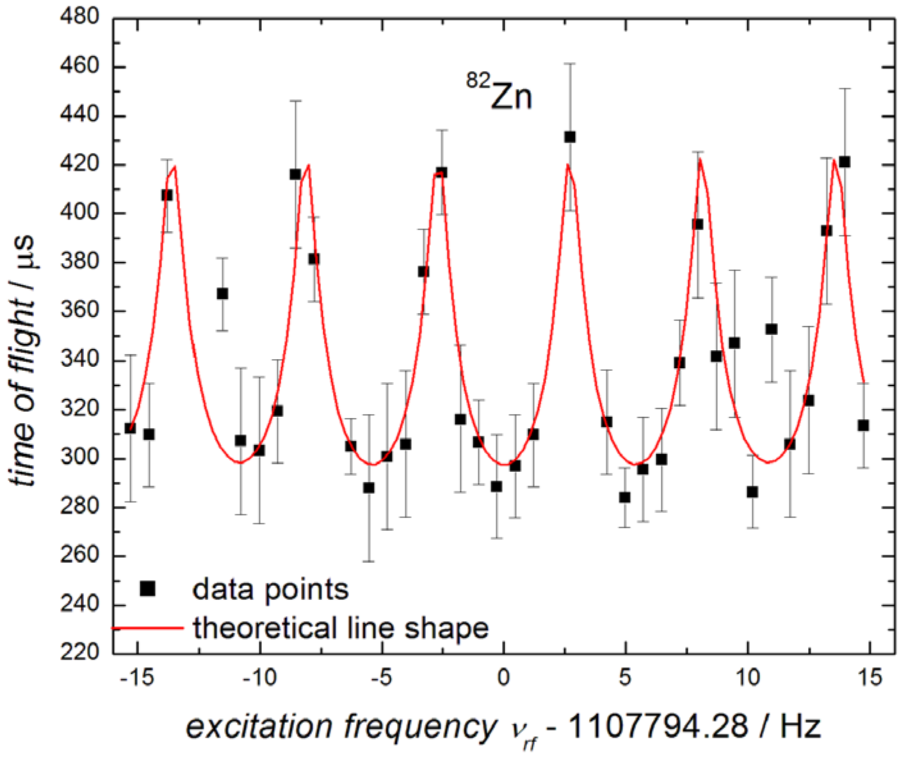

A. Arcones et al.

MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

# Nuclear astrophysics

## Composition of the outer crust of a neutron star



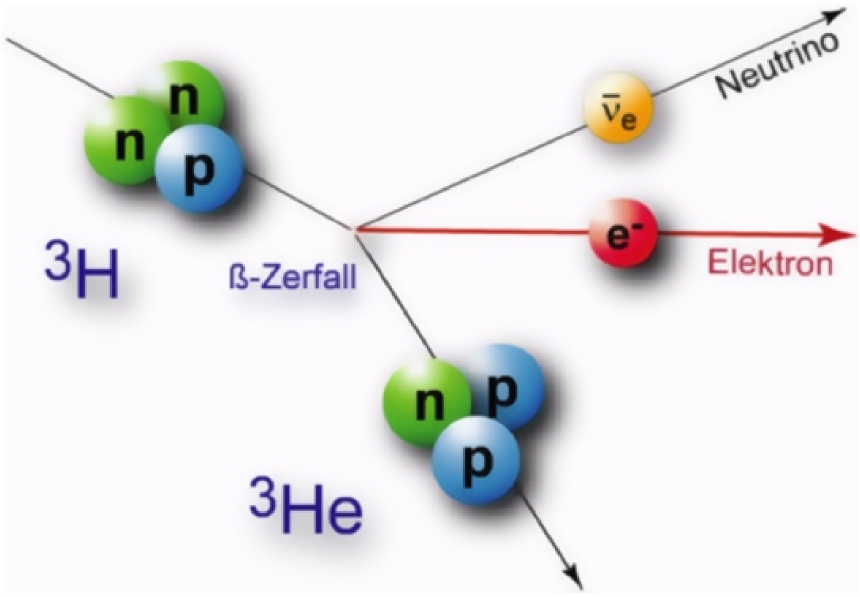

***80 ions in 35 minutes!***

***$\delta m/m = 4 \cdot 10^{-8}$***

R. Wolf *et al.*, Phys. Rev. Lett., 110, 041101 (2013)

# Towards highest precision

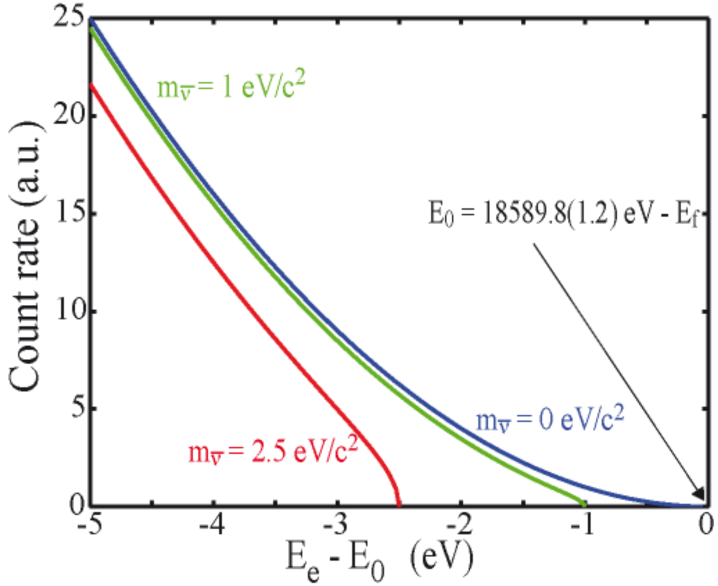
Nuclear masses for fundamental studies




**FSU, ISOLTRAP, JYFLTRAP, SHIPTRAP, THe-TRAP, TRIGATRAP**

# THe-TRAP for KATRIN

## A high-precision $Q(^3T\text{-}^3He)$-value measurement




$$^3_1H \rightarrow ^3_2He + e^- + \overline{\nu}$$

$Q_{lit}$ =18 589.8 (1.2) eV

$Q_{lit}$ =18 592.01(7) eV [E. Myers, PRL (2015)]

We aim for: $\delta Q(^3T \rightarrow ^3He)$ = 20 meV

$\delta m/m = 7 \cdot 10^{-12}$

$\Delta T$ < 0.2 K/d at 24°C

$\Delta B/B$ < 100 ppt / h $\Delta x \leq 0.1\ \mu m$

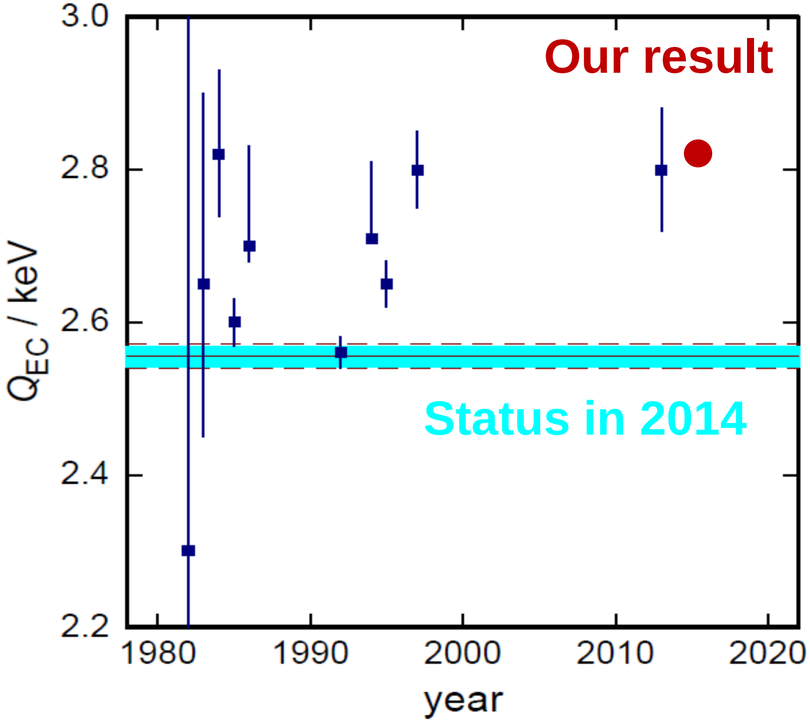
First $^{12}C^{4+}/^{16}O^{6+}$ mass ratio measurement at $\delta m/m = 1.4 \cdot 10^{-11}$ performed.

# The ECHo ($^{163}$Ho) project

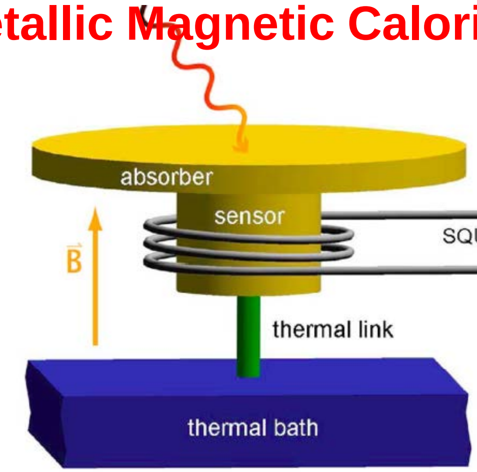
$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

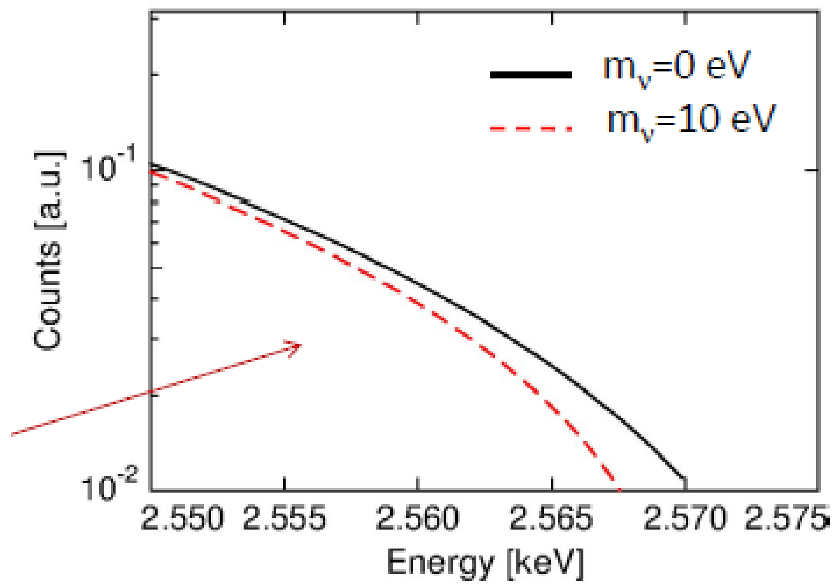
$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

## *Q*-value of EC in $^{163}$Ho




## Metallic Magnetic Calorimetry




S. Eliseev *et al*., Phys. Rev. Lett. in print (2015)

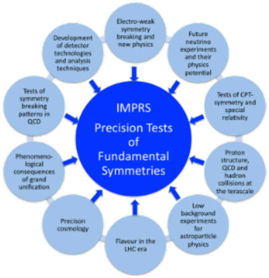
# Summary

***Breath-taking results in the precise determination of nuclear ground-state properties using atomic physics techniques have been achieved!***

**Thank you for the invitation and your attention!**

**Email:** klaus.blaum@mpi-hd.mpg.de

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




*Max Planck Society* | *IMPRS-PTFS* | *Adv. Grant MEFUCO* | *Helmholtz Alliance*