MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

Stockholm University, Physics Colloquium

"High-precision Penning trap experiments with exotic ions"

Klaus Blaum

19.02.2009

Max-Planck-Institut für Kernphysik

HELMHOLTZ GEMEINSCHAFT

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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Outline

- Introduction, history and methods
- Principle of Penning traps
- Setup and measurement procedure
- Precision mass and *g*-factor measurements

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Part I

High-precision mass measurements

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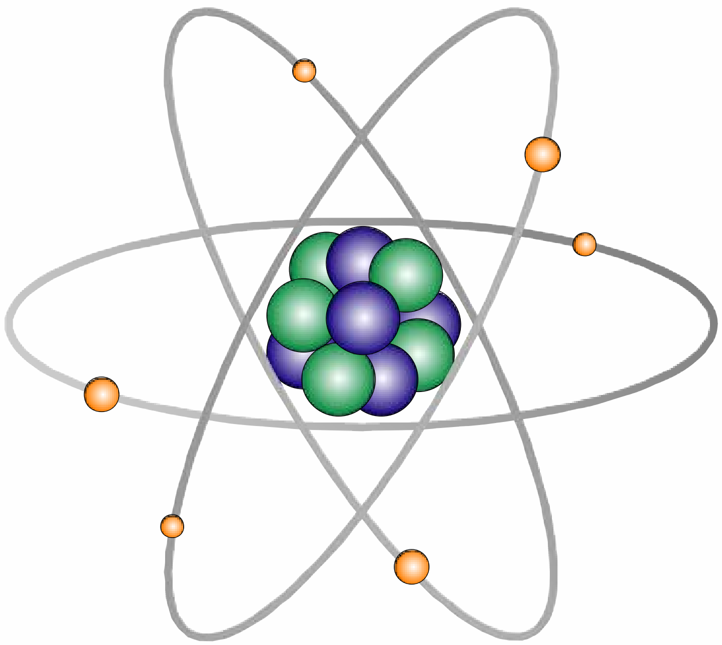
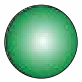
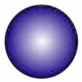
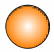
Applications of precision masses

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



$= N \cdot$  $+ Z \cdot$  $+ Z \cdot$ 

– binding energy

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

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Requirements for mass spectrometry

K. B., Phys. Rep. 425, 1-78 (2006)	$\delta m/m$
General physics & chemistry	$\leq 10^{-5}$
Nuclear structure physics - separation of isobars	$\leq 10^{-6}$
Astrophysics - separation of isomers	$\leq 10^{-6}$
Weak interaction studies	$\leq 10^{-8}$
Metrology - fundamental constants	$\leq 10^{-9}$
CPT tests	$\leq 10^{-10}$
QED in highly-charged ions - separation of atomic states	$\leq 10^{-11}$

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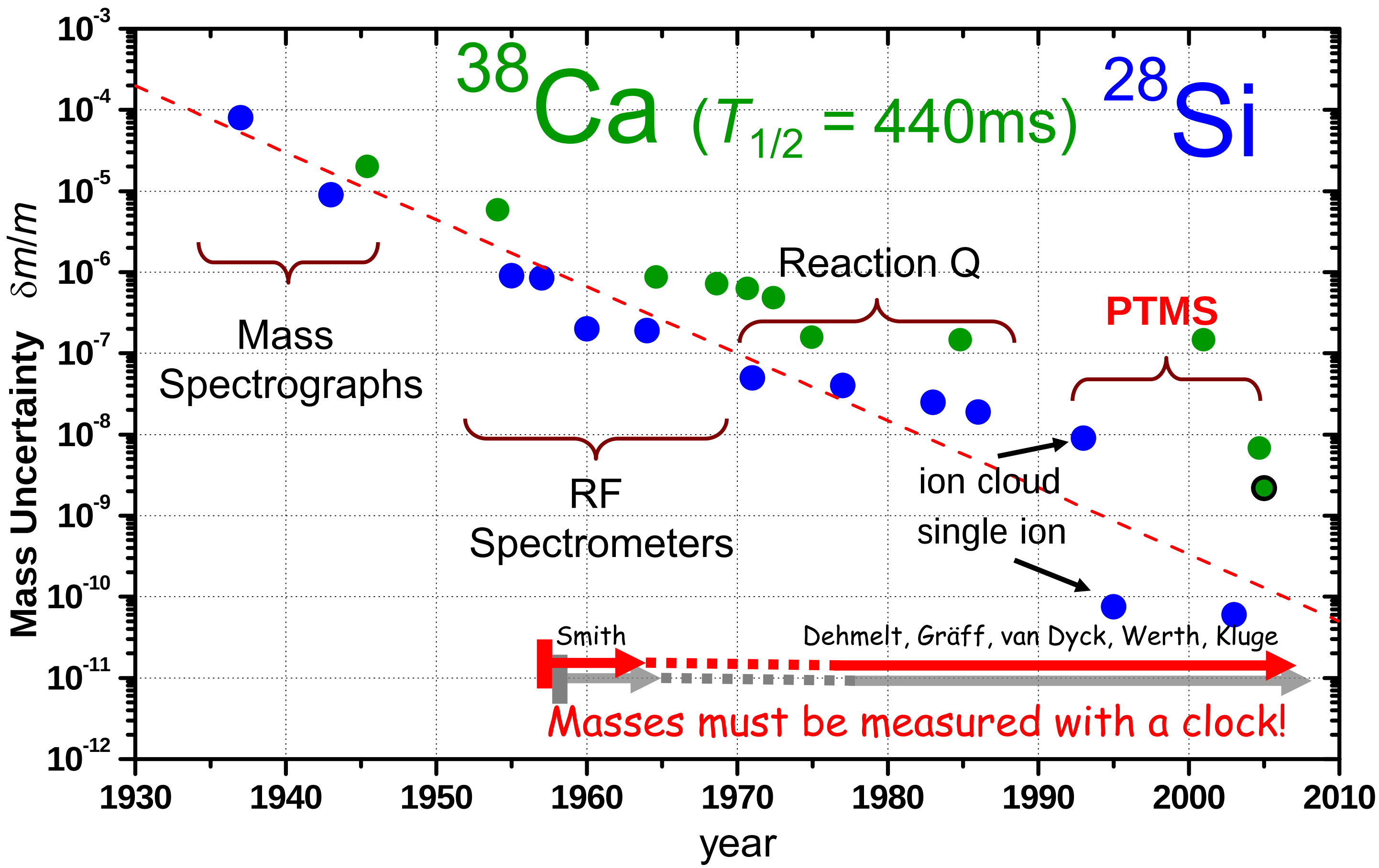
A brief history of mass spectrometry



SMILETRAP, MIT-TRAP (now at FSU), Seattle-TRAP, HD-TRAP

CPT, ISOLTRAP, JYFLTRAP, LEBIT, SHIPTRAP

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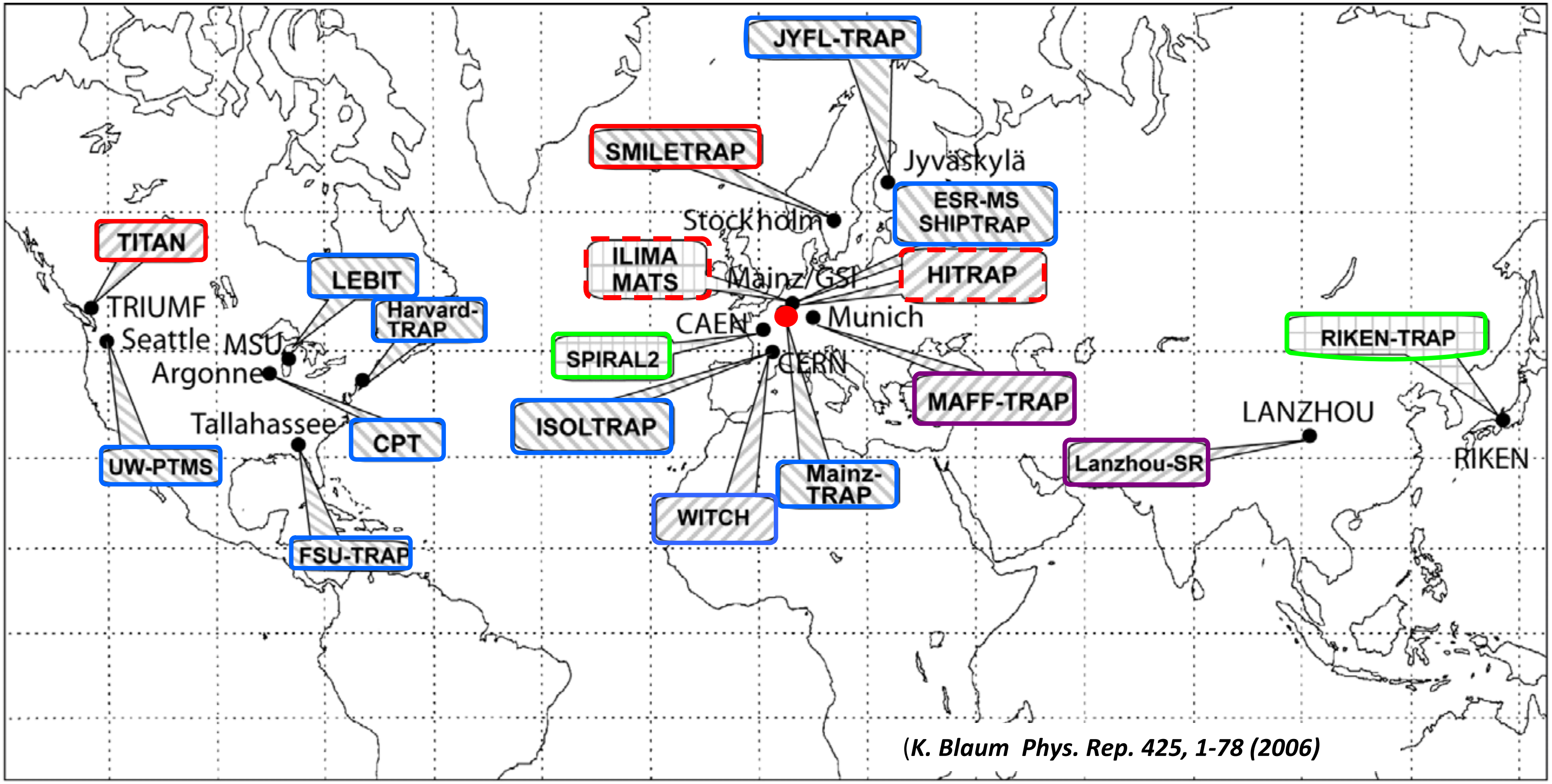
Facilities for mass spectrometry



operating facilities

facilities under construction or test

planned facilities

facilities using HCI

under construction

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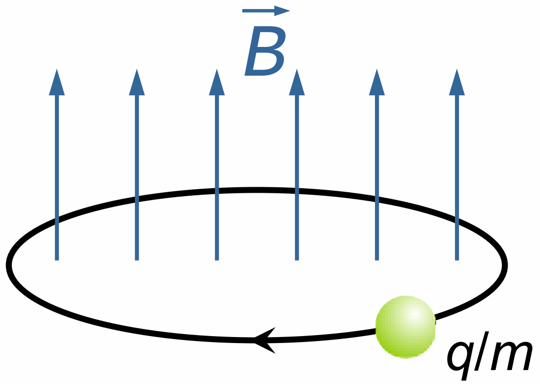
Principle of Penning trap mass spectrometry

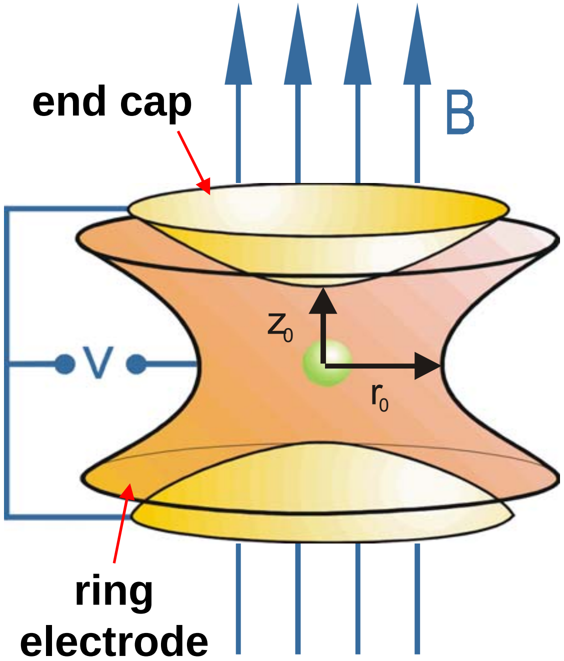


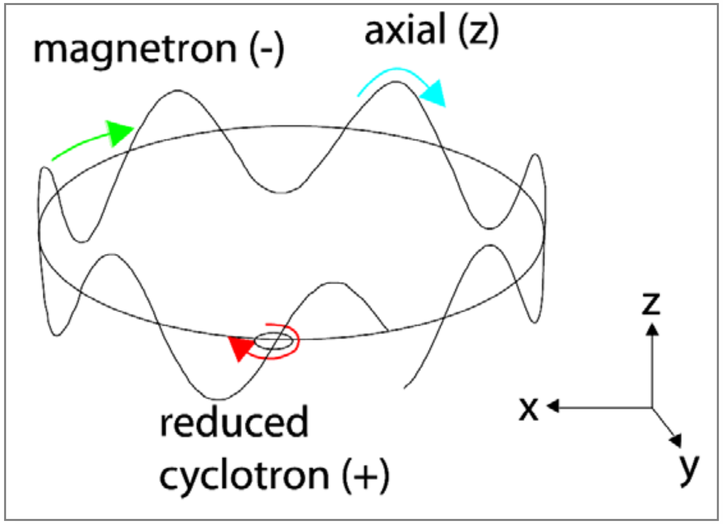
Cyclotron frequency:

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

PENNING trap

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





Brown & Gabrielse, Rev. Mod. Phys. 58, 233 (1986)

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

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

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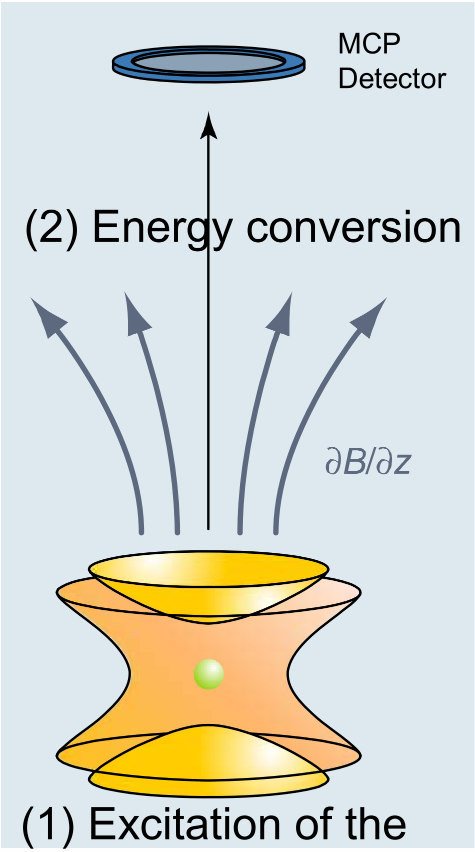
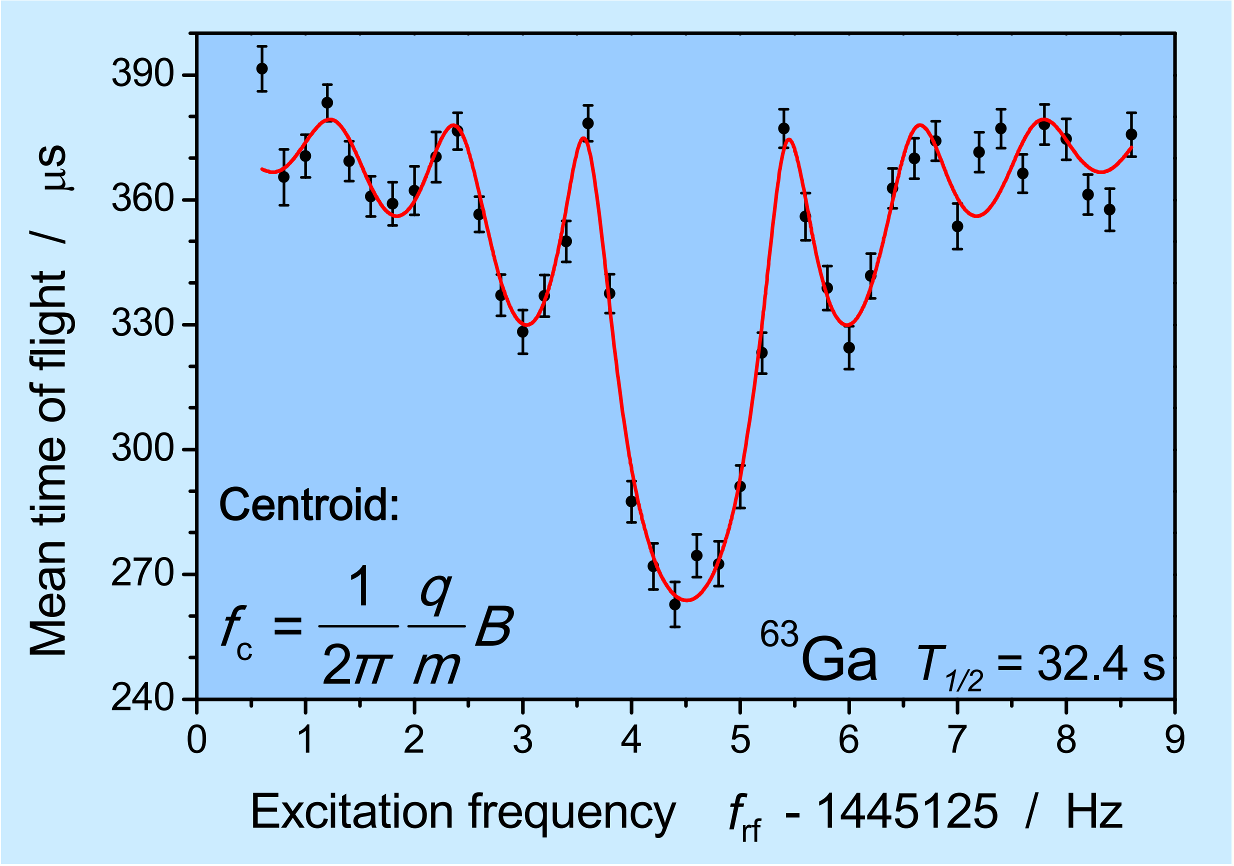
TOF cyclotron resonance detection

(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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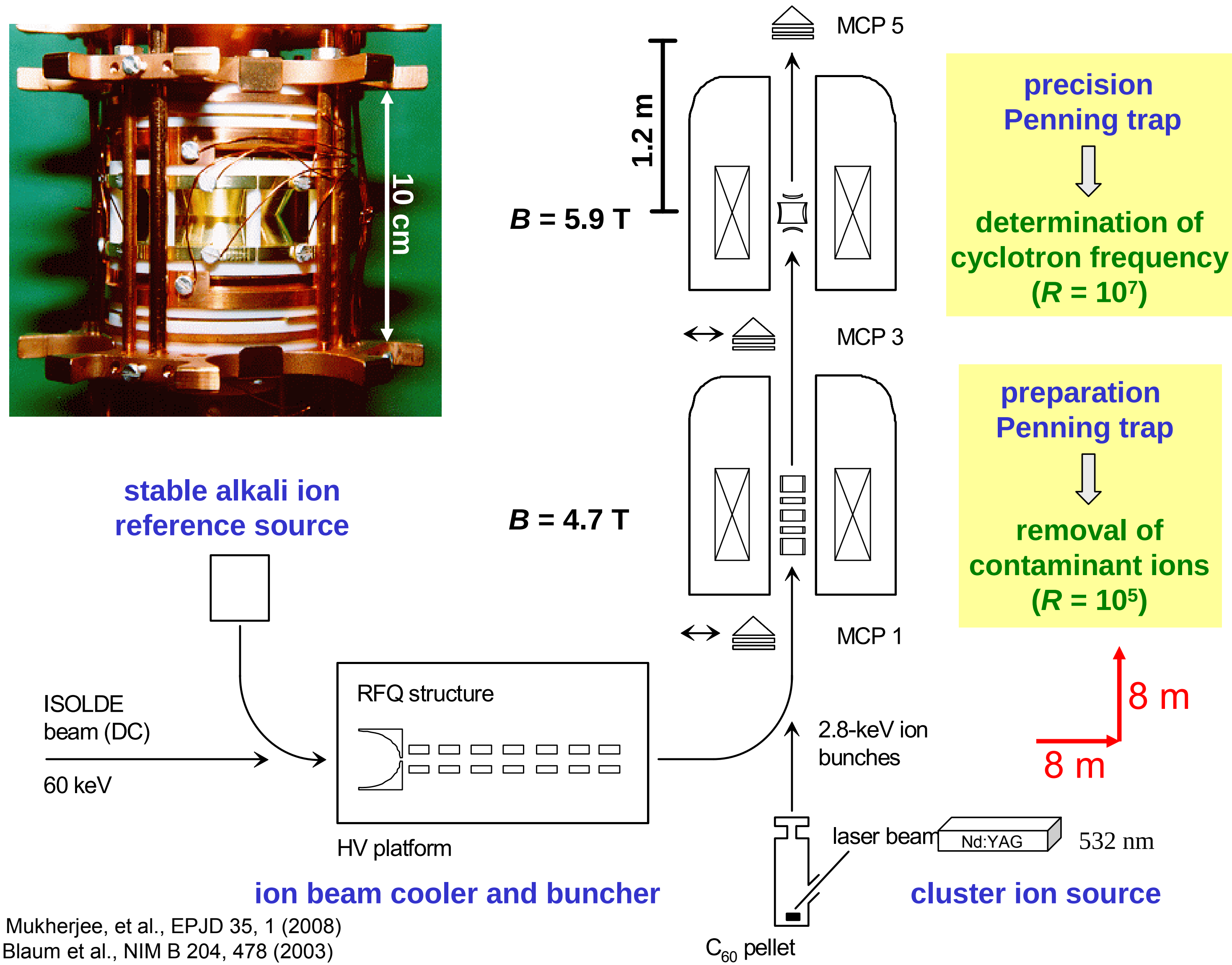
The ISOLTRAP experiment



M. Mukherjee, et al., EPJD 35, 1 (2008)
K. Blaum et al., NIM B 204, 478 (2003)

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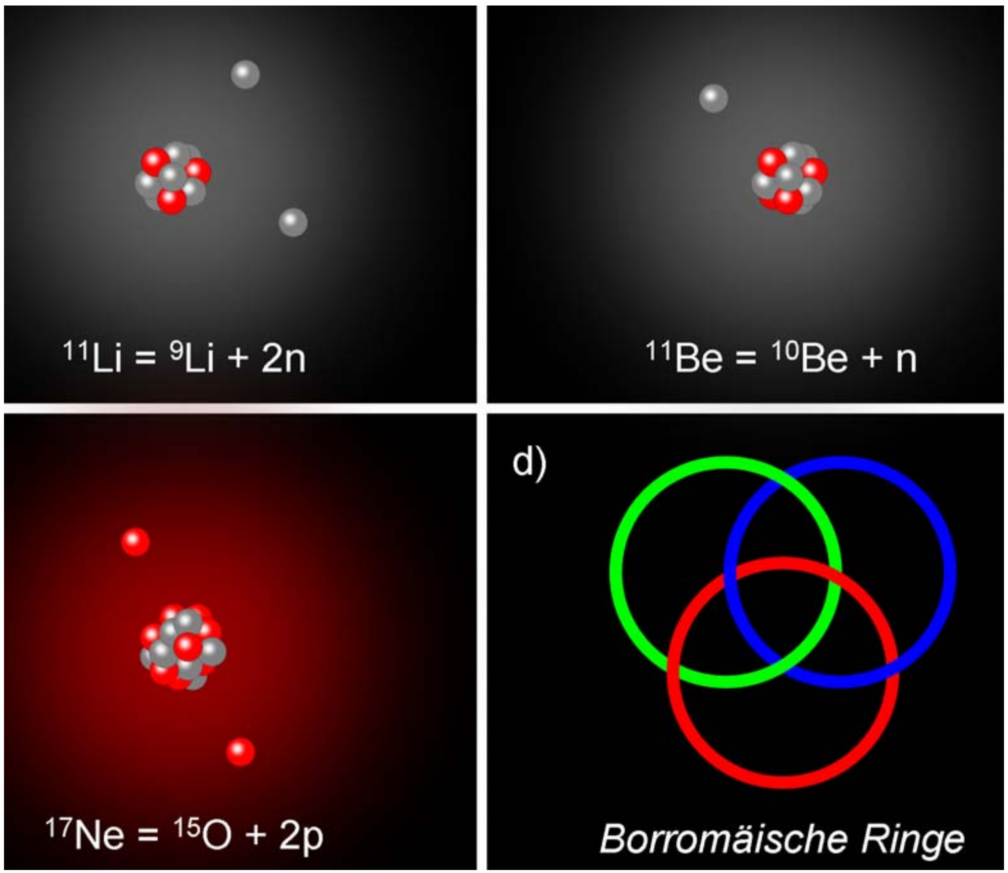
Investigation of nuclear halos

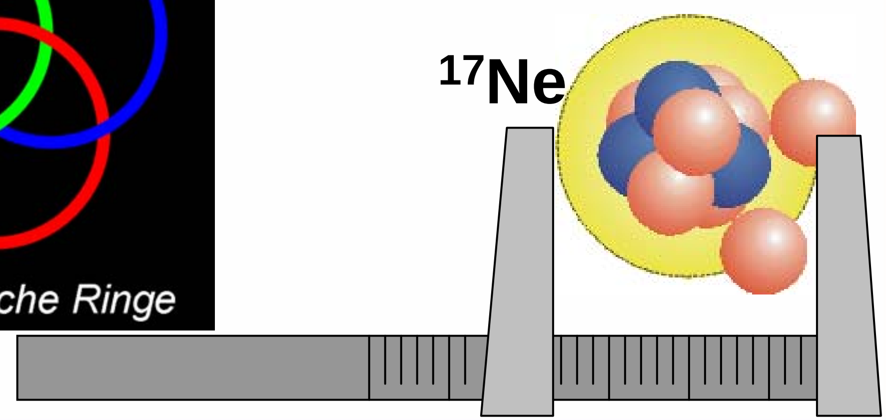
… via nuclear mass (binding energy) and charge radii measurements!



^{11}Li:
R. Neugart *et al*., PRL 101, 132502 (2008)

^{11}Be:
W. Nörtershäuser *et al*., PRL 102, 062503 (2009)

^{17}Ne:
W. Geithner *et al*., PRL 101, 252502 (2008)



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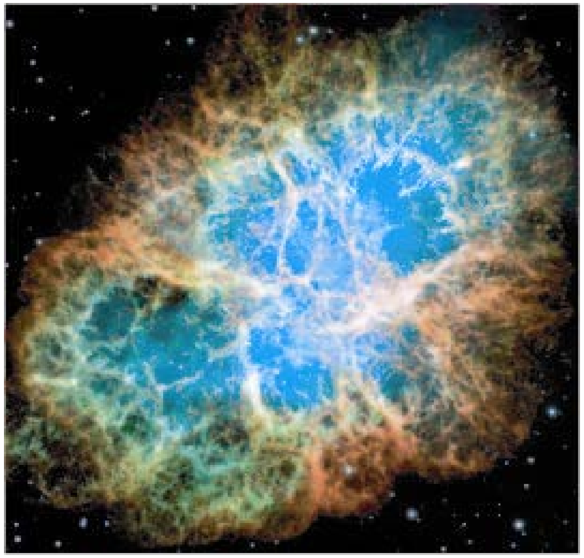
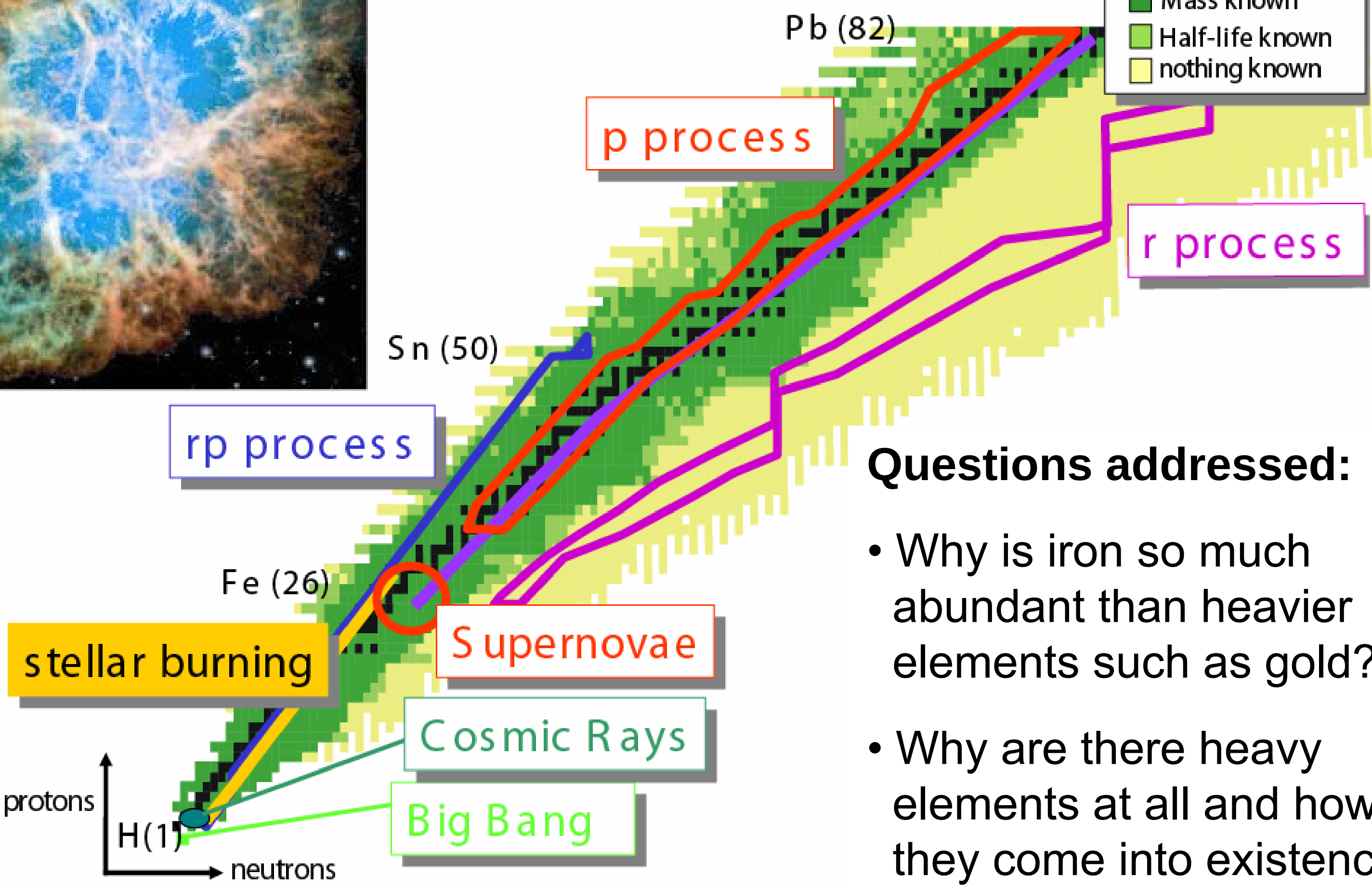
Applications in astrophysics



K. Blaum *et al.*, Phys. J. 5, 35 (2006); H. Schatz *et al.*, Europhys. News 37, 16 (2006)



Questions addressed:

- Why is iron so much abundant than heavier elements such as gold?
- Why are there heavy elements at all and how did they come into existence?

M. Mukherjee *et al.*, Phys. Rev. Lett. 93, 150801 (2004)
J. Clark *et al.*, Phys. Rev. Lett. 92, 192501 (2004)

D. Rodríguez *et al.*, Phys. Rev. Lett. 93, 161104 (2004)
S. Baruah *et al.*, Phys. Rev. Lett. 101, 262501 (2008)

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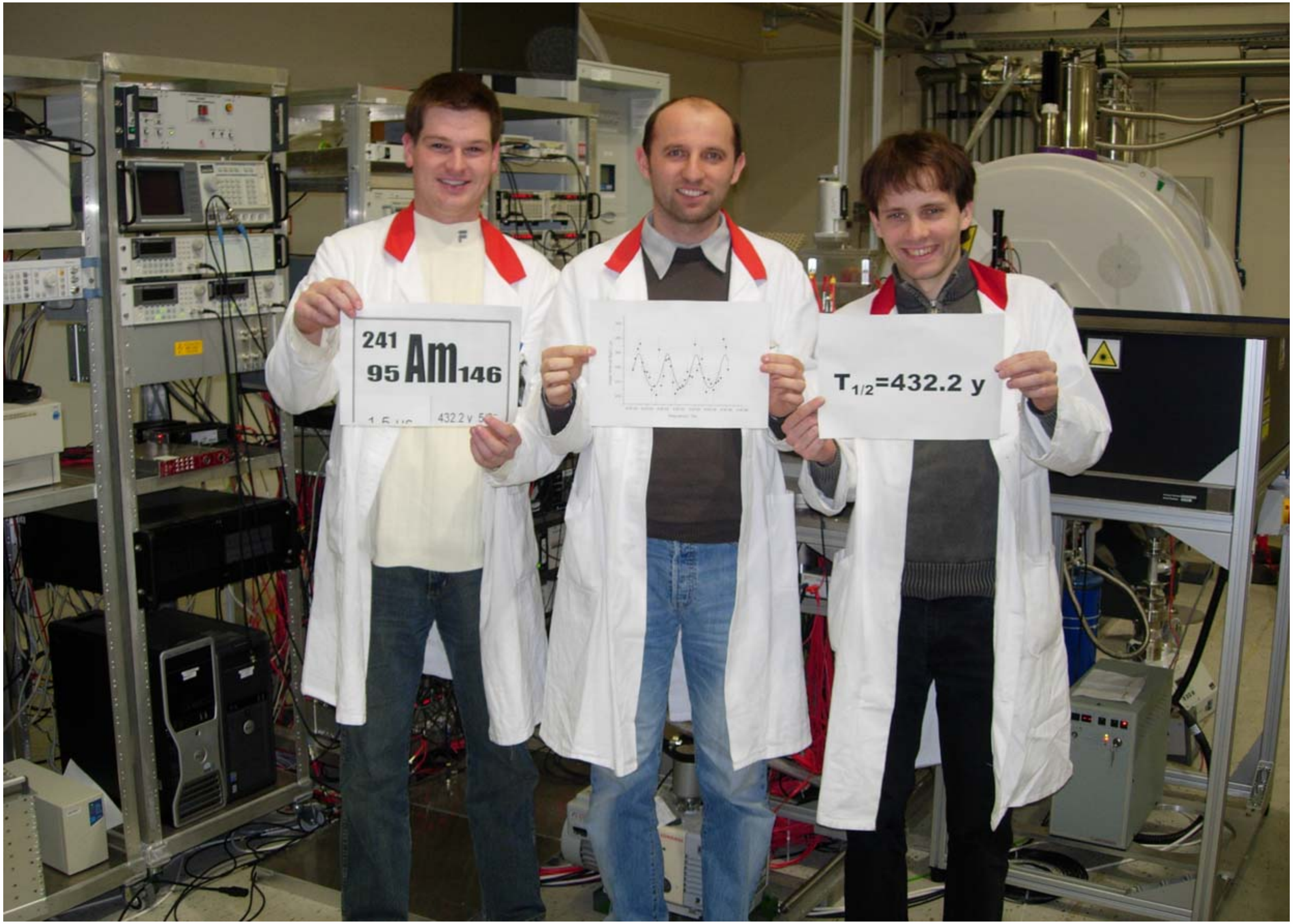
First results from TRIGA-TRAP



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*I*sobaric *M*ultiplet *M*ass *E*quation

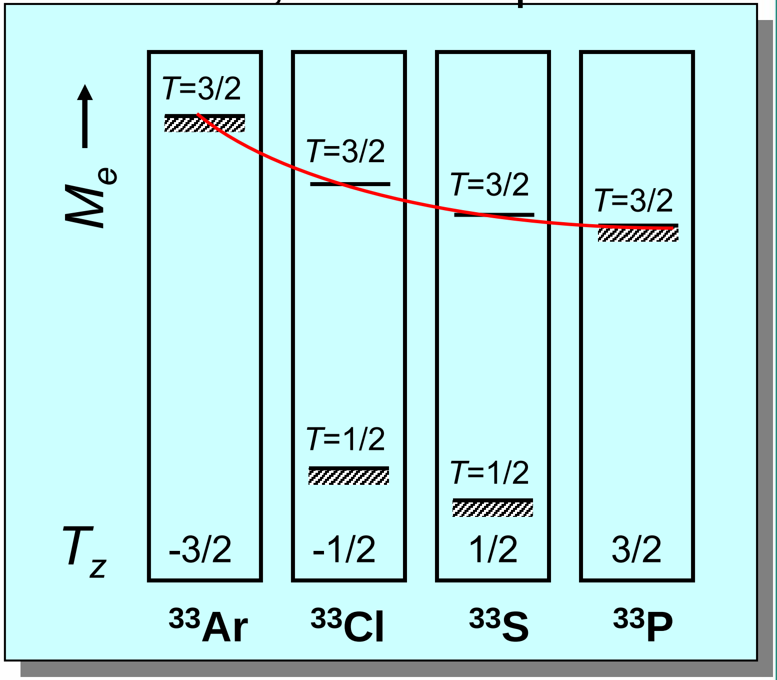
Mass formula for multiplets of nuclear states with same mass and isospin

$$M = a + bT_z + cT_z^2 \quad + dT_z^3$$

Commonly used quadratic form

?

A = 33, *T* = 3/2 quartet:



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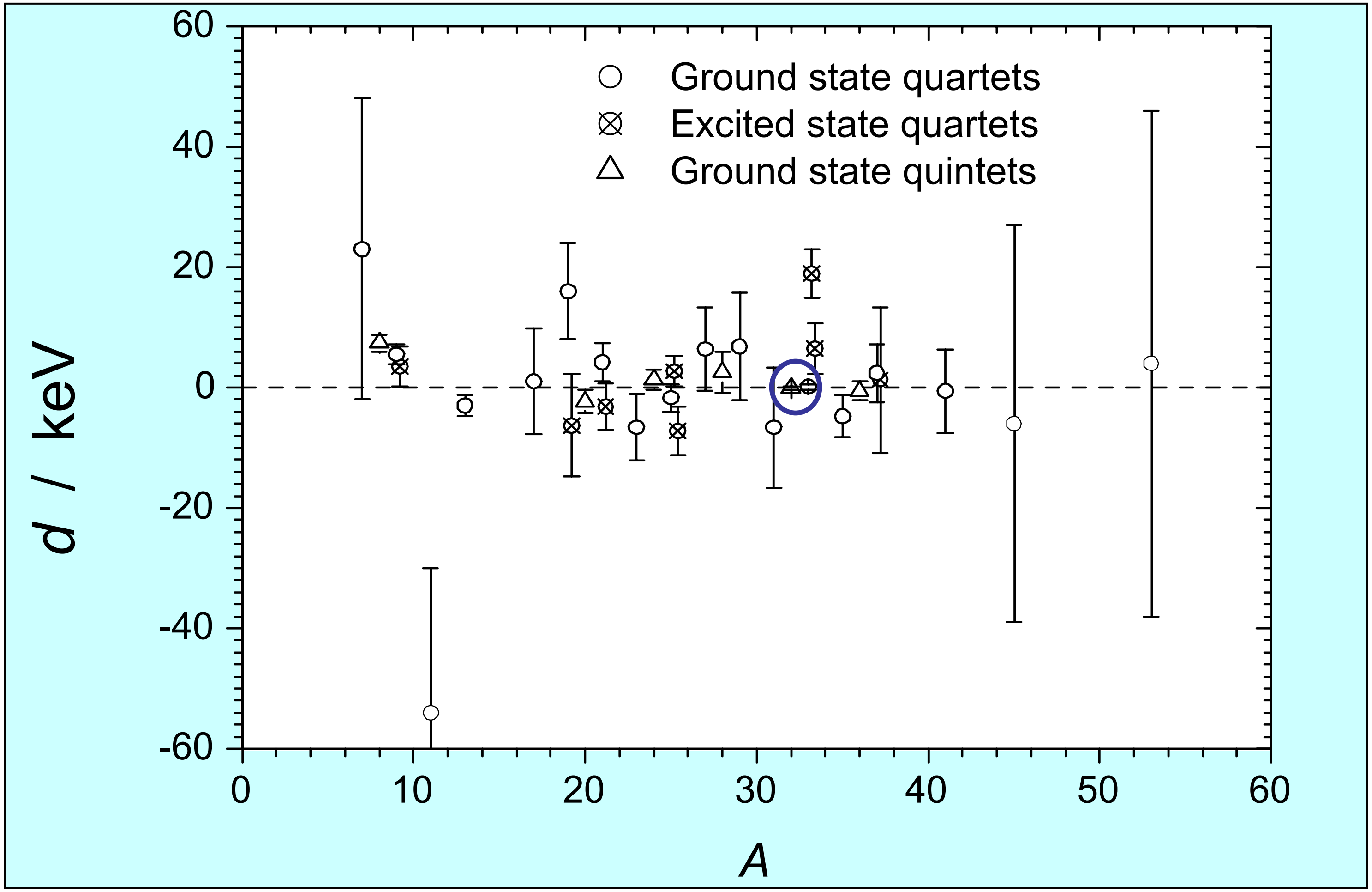
Most stringent test of IMME



ISOLTRAP measurements 2002:

– ^{33}Ar with $u(m)$ = 0.44 keV

– ^{32}Ar with $u(m)$ = 1.8 keV

New status: K. B. *et al.*, Phys. Rev. Lett. 91, 260801 (2003).

A = 33, T = 3/2 quartet: d = -0.13(45) keV

A = 32, T = 2 quintet: d = -0.11(30) keV

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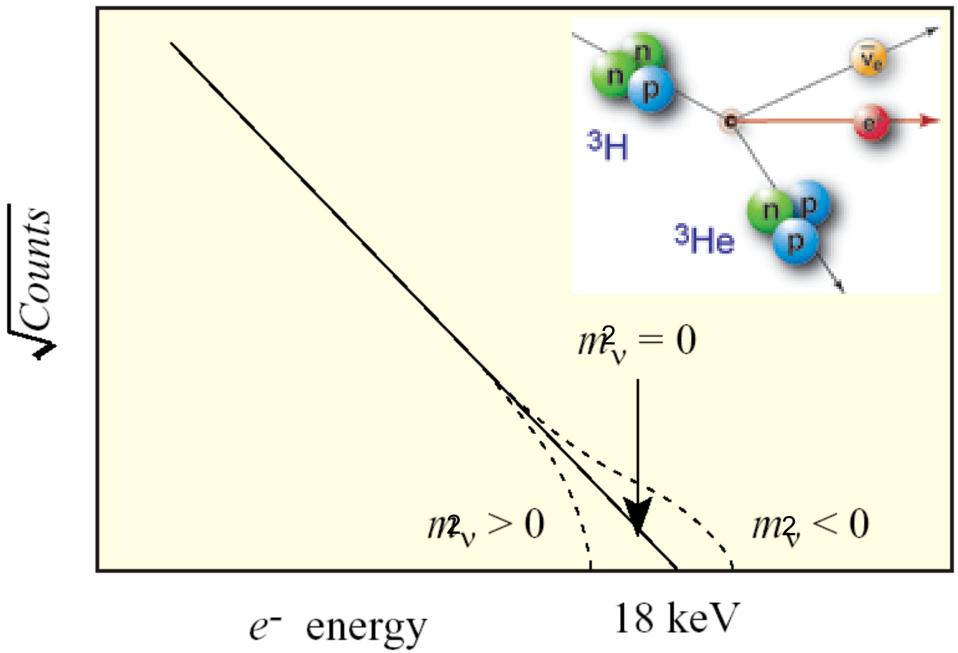
Determination of the $^3T \rightarrow {}^3He$ *Q*-value

Important parameter for the determination of the electron neutrino rest mass.

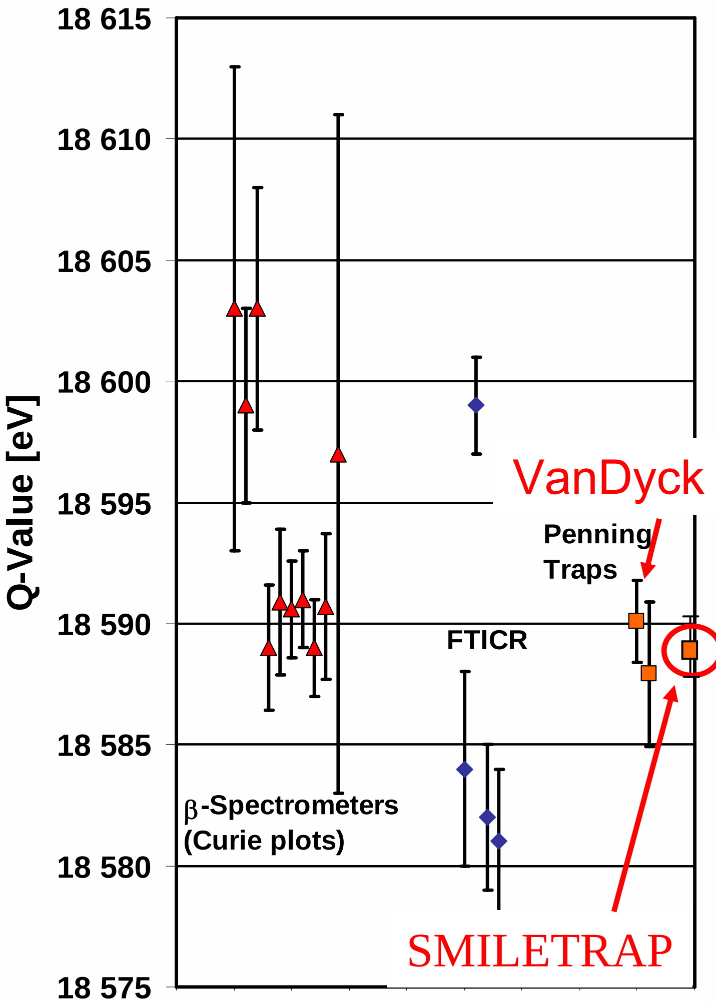


- Q-value of Tritium beta decay

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

Q=18 589.8 (1.2) eV

SMILETRAP: Sz. Nagy *et al.*, Europhys.Lett. 74, 404 (2006)



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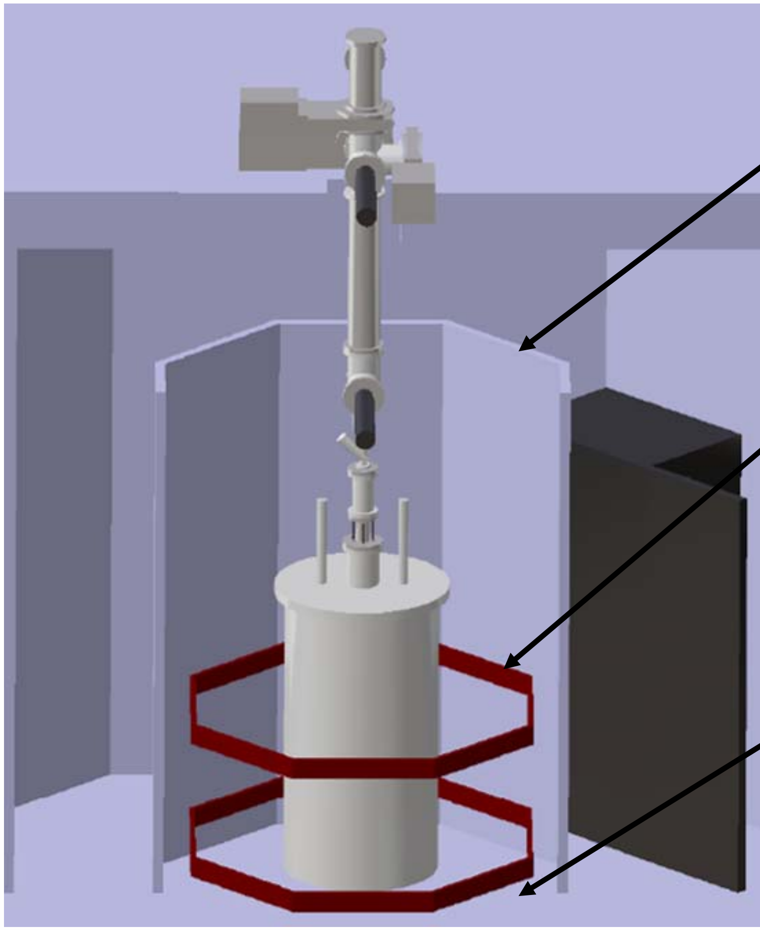
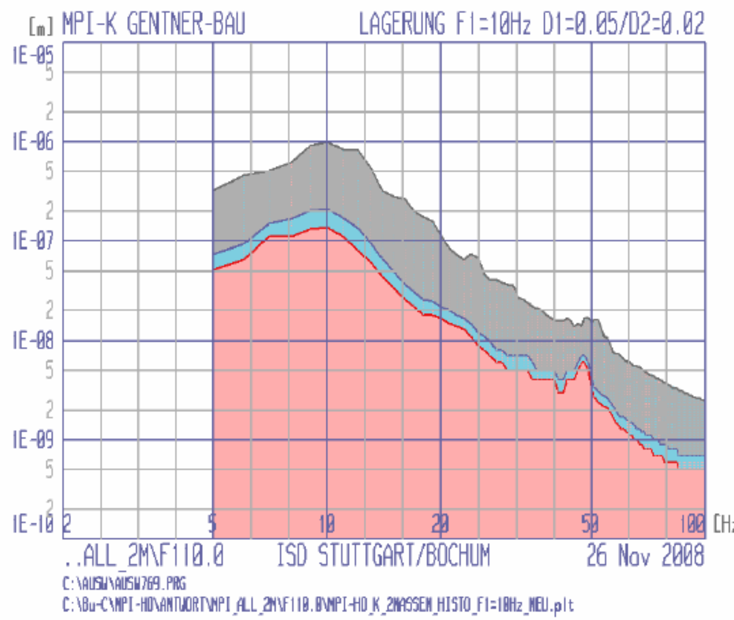
… in the new lab at MPIK



Temperature stabilized room:
$\Delta T < 0.1$ K

Magnetic field stability:
$\Delta B/B < 17$ ppt / h

Vibrationally isolated floor:
$\Delta x \leq 0.1\ \mu$m



We aim for:
$\delta Q(^3\text{T} \rightarrow {}^3\text{He}) = 20$ meV
$\delta m/m = 7\cdot10^{-12}$

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The KATRIN spectrometer

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The KATRIN spectrometer

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Recent results of fundamental studies

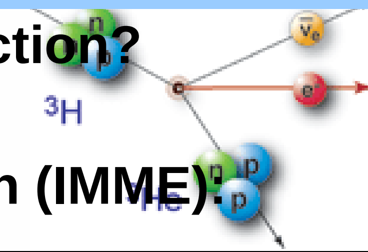
V_{ud} – is unitarity violated in quark mixing?

F. Herfurth *et al*., Eur. Phys. J. A 15, 17 (2002)
A. Kellerbauer *et al*., Phys. Rev. Lett. 93, 072502 (2004)
M. Mukherjee *et al*., Phys. Rev. Lett. 93, 150801 (2004)
S. George *et al*. Phys. Rev. Lett. 98, 162501 (2007)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Are there scalar currents present in the Weak Interaction?

K. Blaum *et al*., Phys. Rev. Lett. 91, 260801 (2003)



Stringent test of the isobaric multiplet mass equation (IMME):

F. Herfurth *et al*., Phys. Rev. Lett. 87, 142501 (2001)
K. Blaum *et al*., Phys. Rev. Lett. 91, 260801 (2003)

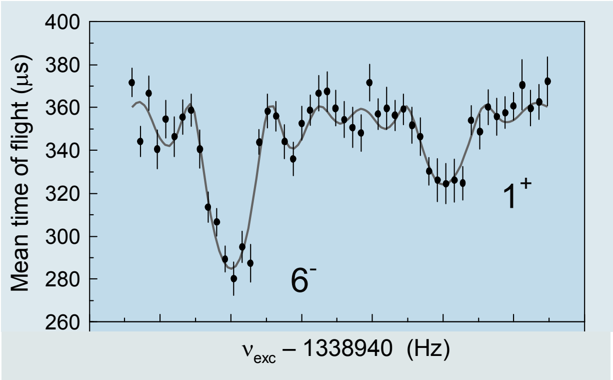
$$M = a + bT_z + cT_z^2 \quad + dT_z^3$$

Commonly used form

?

Population inversion of nuclear states, nuclear halos, and drip lines:

J. Van Roosbroeck *et al*., Phys. Rev. Lett. 92, 1112501 (2004)
Sz. Nagy *et al*., Phys. Rev. Lett. 96, 163004 (2006)
C. Rauth *et al*., Phys. Rev. Lett. 100, 012501 (2008)
M. Dworschak *et al*., Phys. Rev. Lett. 100, 072501 (2008)
R. Neugart *et al*., Phys. Rev. Lett. 101, 132502 (2008)
W. Geithner *et al*., Phys. Rev. Lett. 101, 252502 (2008)
S. Baruah *et al*., Phys. Rev. Lett. 101, 262501 (2008)



Does QED fail in strong fields?

I. Bergström *et al*., Eur. Phys. J. D 22, 41 (2003)

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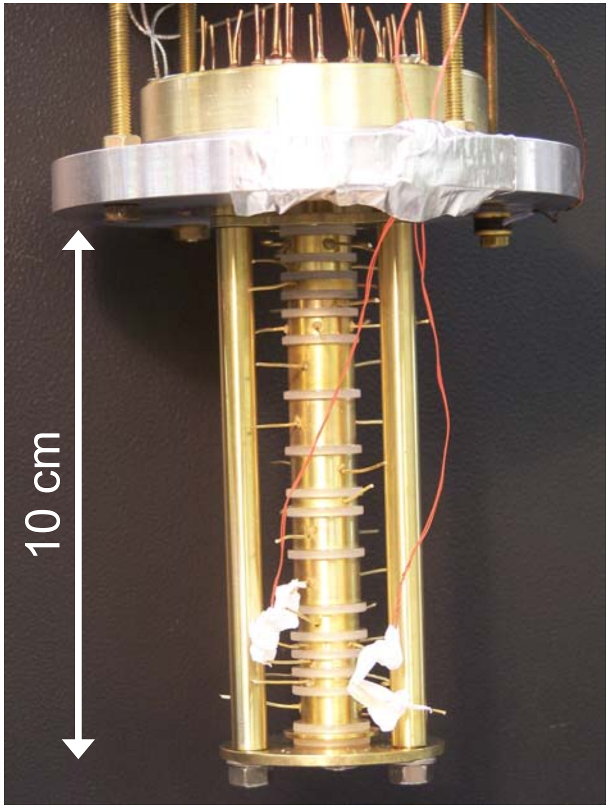
Part II

High-precision *g*-factor measurements



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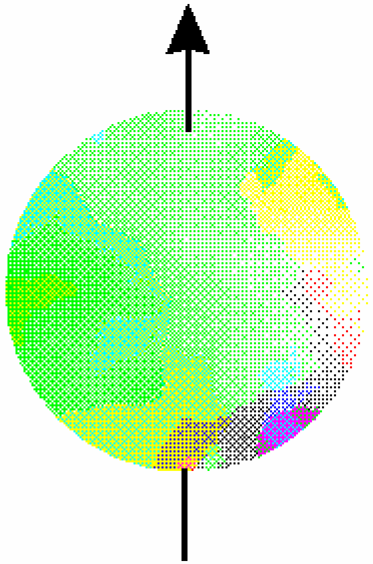
The *g*-factor



relation between magnetic dipole moment and angular momentum

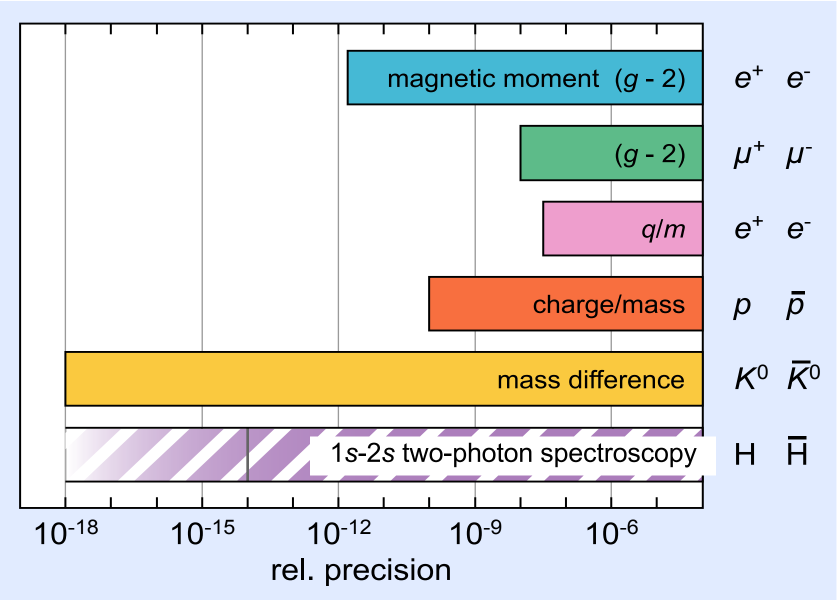
$$\boxed{\vec{\mu} = g_J \, \frac{|q|}{2\,m} \, \hbar \, \vec{J}}$$

free lepton: g_s = *g*-factor of the spin

g-factor of the proton and antiproton

Test of CPT invariance

- Currently believed to hold
- CPT transforms particle into its antiparticle (P. Dirac 1928)



$$g_p = 2 \cdot \frac{\omega_L}{\omega_c}$$

ω_c: cyclotron frequency
ω_L: Larmor frequency

PDG: $g_p = 2\times2.792847337(29)$ $g_{\bar{p}} = 2\times2.800(8)$

With our double Penning-trap technique we aim for $\delta g/g = 10^{-9}$.

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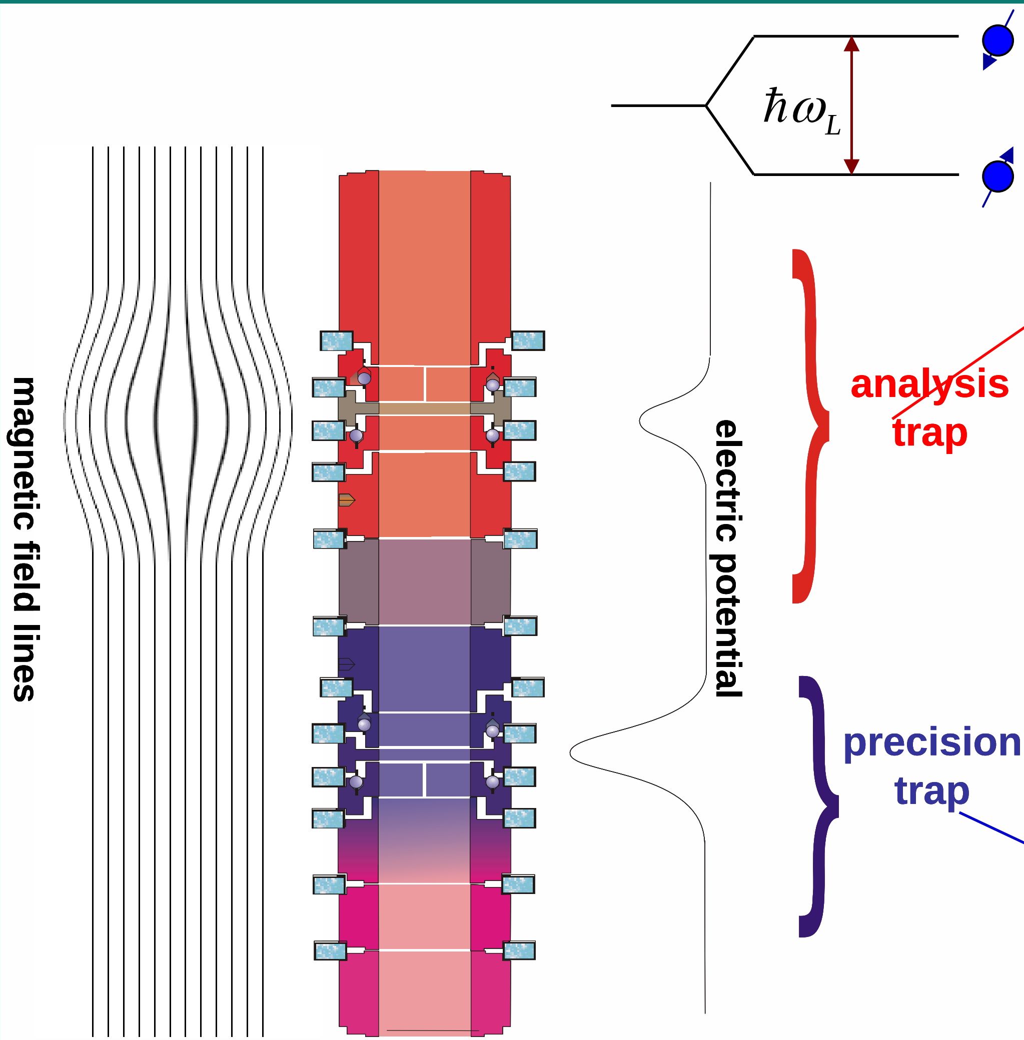
Measurement principle



Zeeman splitting in the spin eigenstates → Larmor frequency

$$\omega_L = \frac{2\mu \cdot B}{\hbar} = g\,\frac{e}{2m_p}B$$

$$\Downarrow$$

$$g = 2\,\frac{\omega_L}{\omega_c}\,\frac{m_p/e}{m_p/e}$$

$$\Uparrow$$

$$\omega_c = \frac{e}{m_p}B$$

Eigenmotions of the particle → cyclotron frequency

We aim for $\delta g/g < 10^{-9}$.

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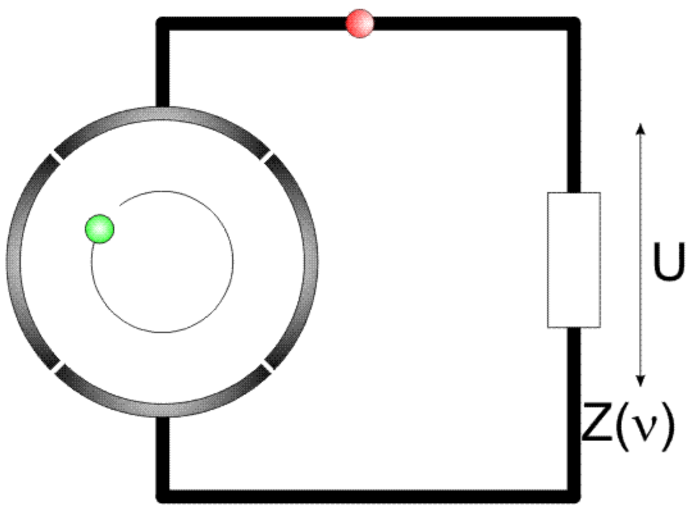
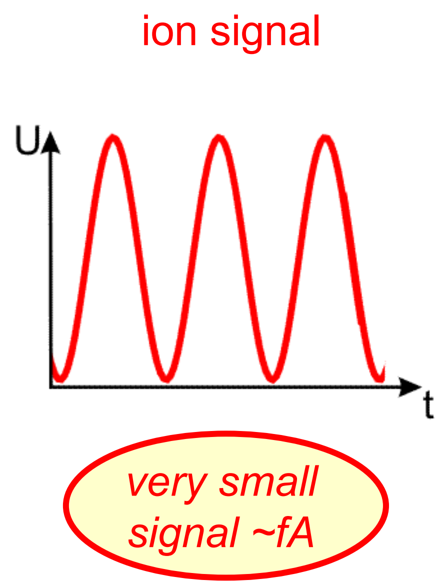
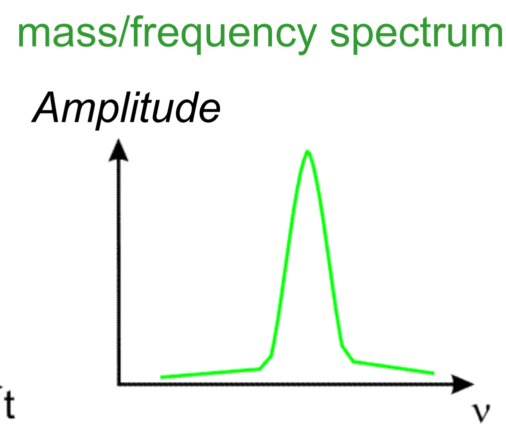
Non-destructive ion detection







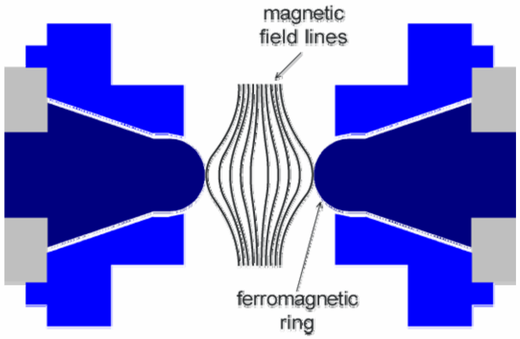
„FT-ICR“
Fourier-**T**ransform-
Ion **C**yclotron **R**esonance

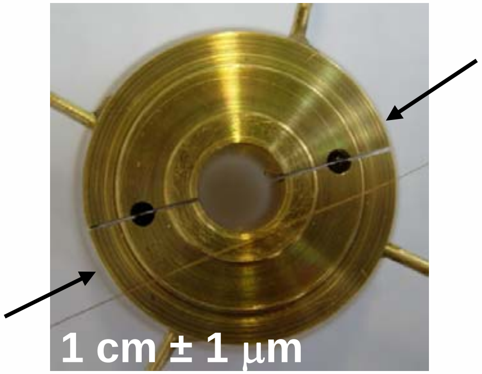
Operation of traps and electronics at **cryogenic** (4 K) temperature.

C. Weber, PhD thesis, University of Heidelberg (2004) and C. Weber *et al.*, Eur. Phys. J A 25, 65 (2005)

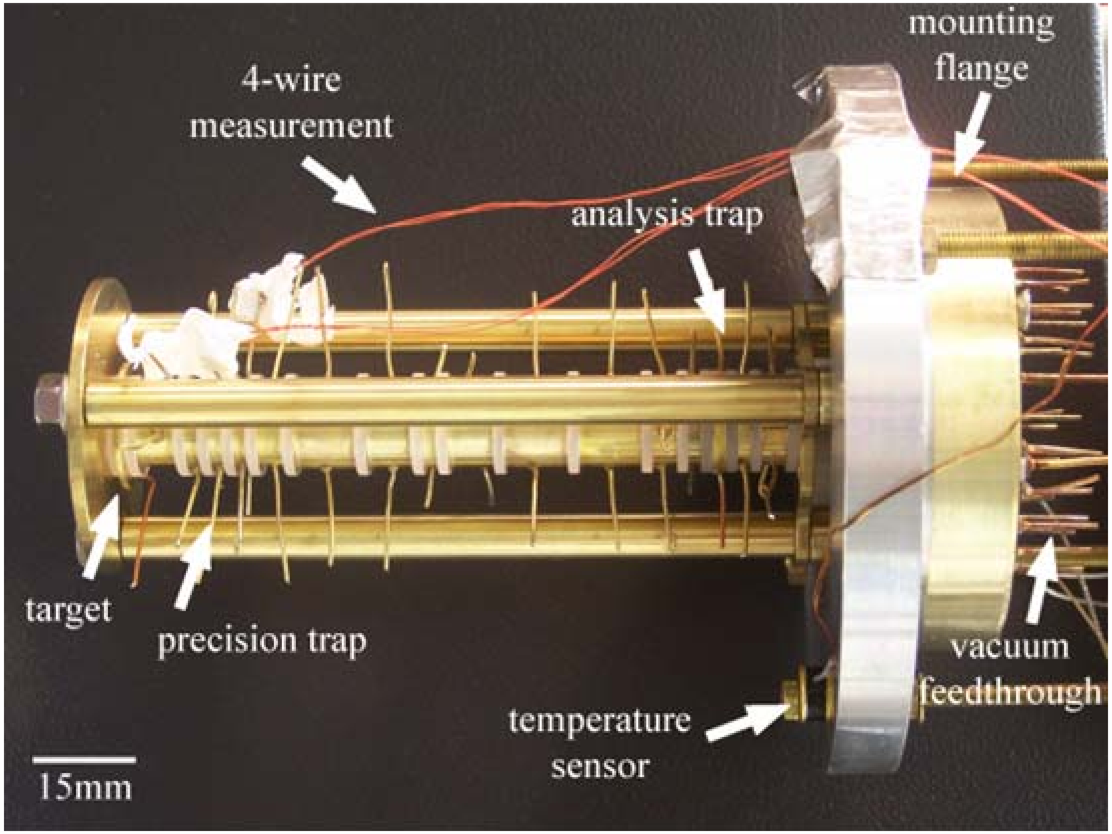
Status of the *g*-factor (anti)proton exp.

Hybrid analysis trap





Manufactured at the
Institute for **M**icrotechnique
Mainz (IMM).



J. Verdú *et al*., AIP Conference Proceedings 796, 260-265 (2005)

J. Verdú *et al*., New J. Phys. 10, 103009 (2008)

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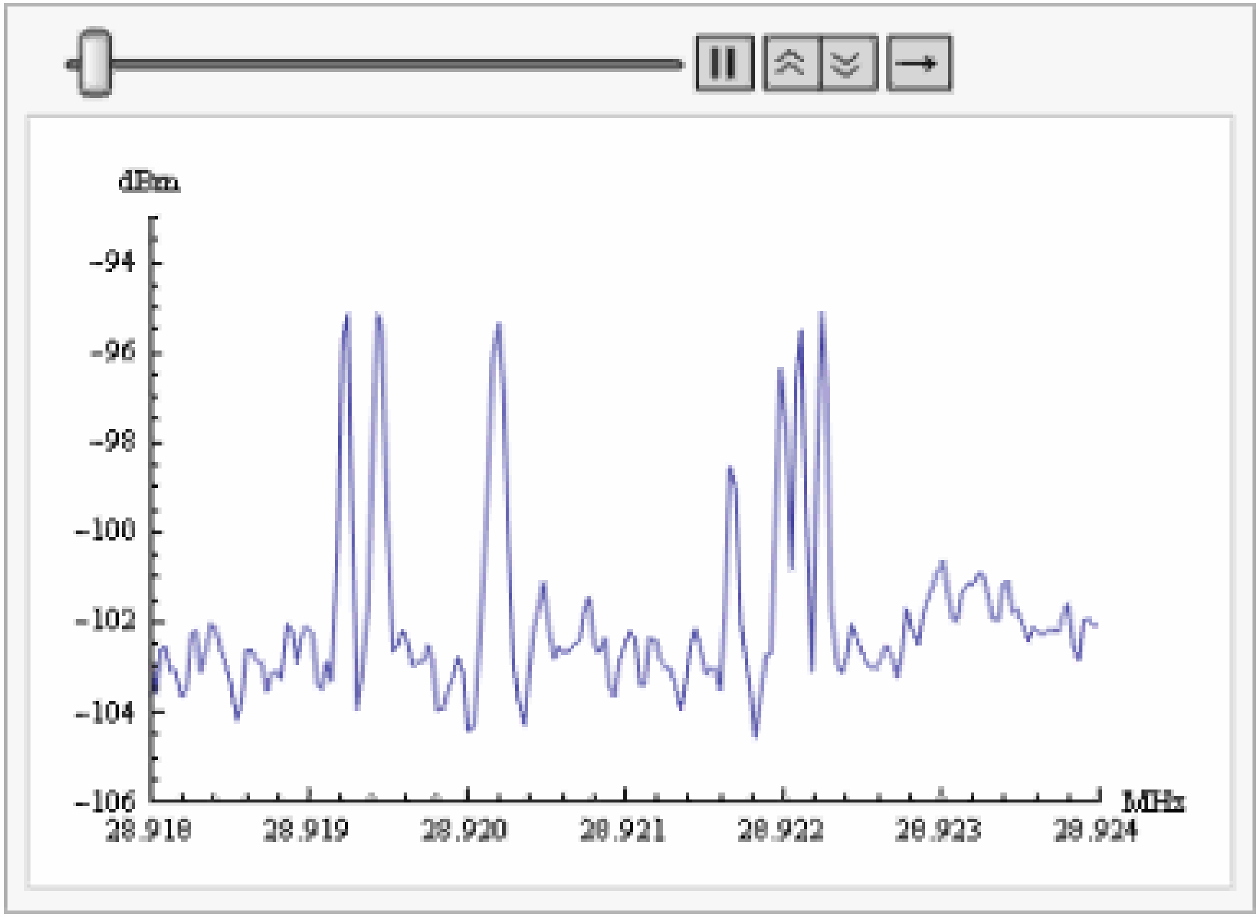
Single proton signals



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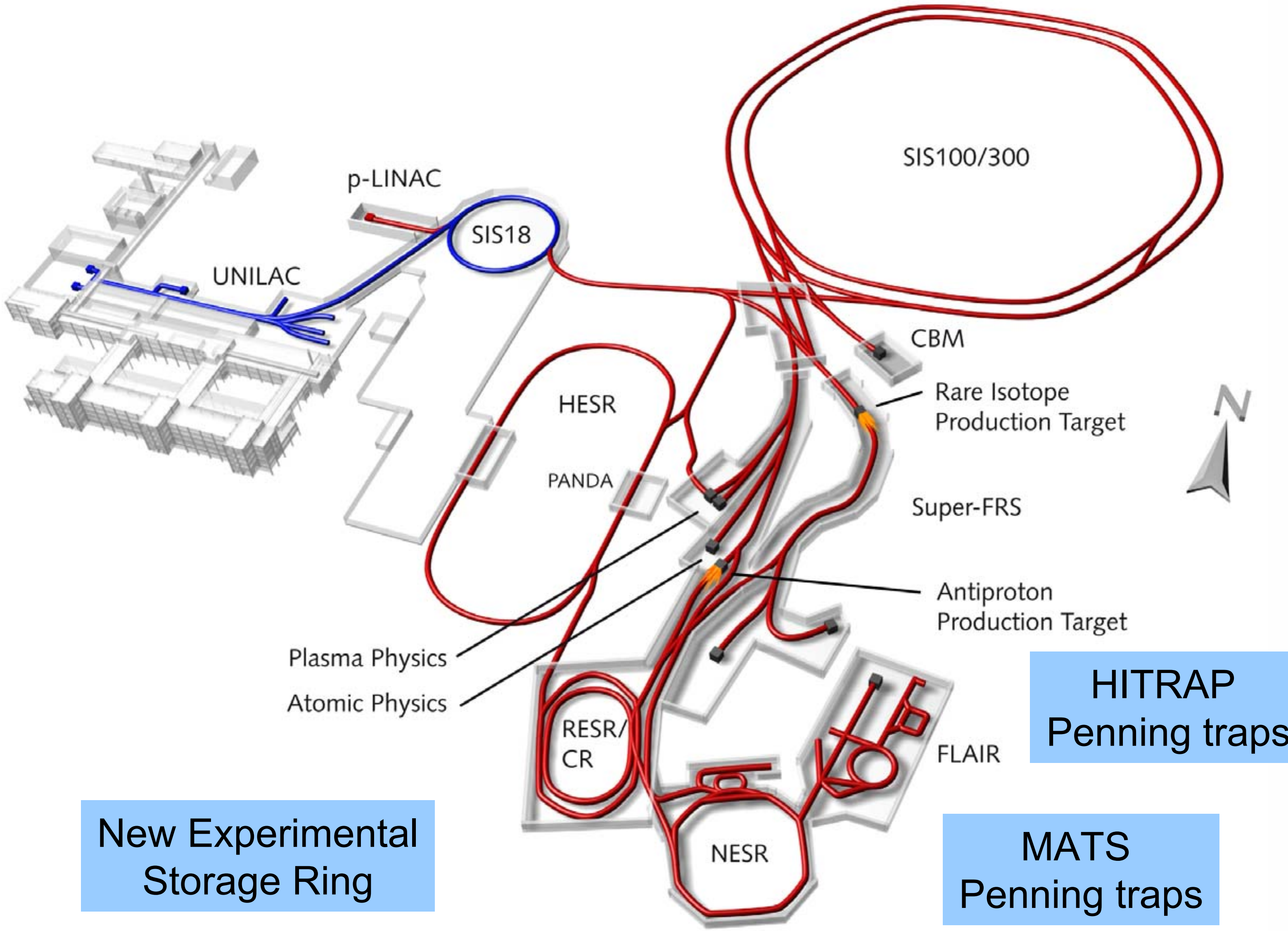
Future Penning trap facilities at FAIR



HITRAP
Penning traps

New Experimental
Storage Ring

MATS
Penning traps

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Summary

High-accuracy experiments with stored ions in Penning traps have a broad range of applications!

- Fundamental tests:
  - Unitarity test of the CKM quark-mixing matrix
  - Test of weak interaction
  - Test of CPT invariance
  - Test of bound-state QED
- Determination of fundamental constants:
  m_e, m_p, α, $N_a h$, μ, …

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The Mainz-MPIK Penning trap team

In collaboration with:

D. Beck, M. Block, J. Crespo, R. van Dyck, S. Eliseev, F. Herfurth, A. Kellerbauer, **H.-J. Kluge**, M. Kretzschmar, Yu. Novikov, D. Pinegar, W. Quint, **R. Schuch**, L. Schweikhard, N. Trautmann, J. Walz, Ch. Weinheimer, G. Werth, and the ISOLTRAP and SHIPTRAP Collaboration ...

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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/