Penning trap **PENTATRAP** for fundamental physics

Max-Planck Institute for Nuclear Physics

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

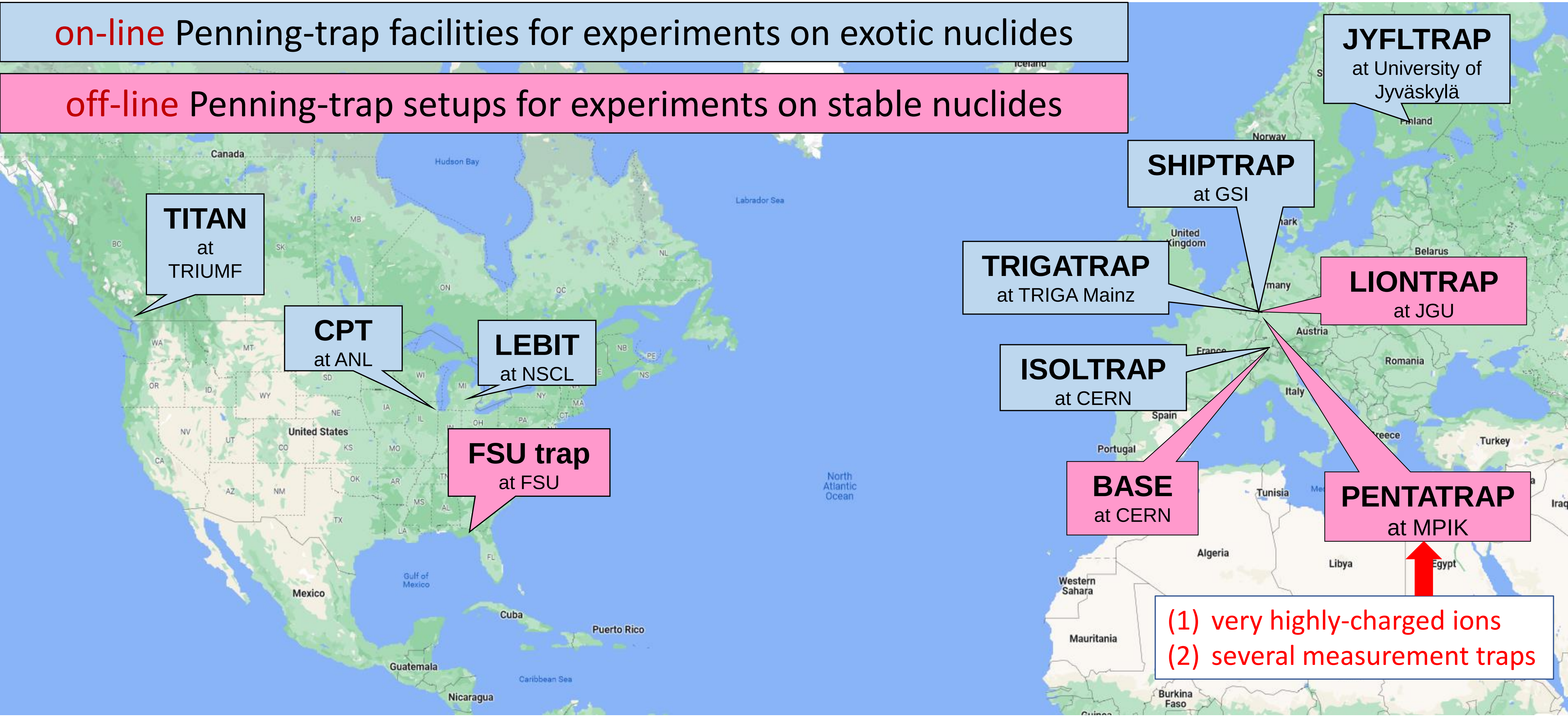
Pavel Filianin
Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany

FFK, Wien, May 22-26, 2023

High-Precision Penning Traps Worldwide

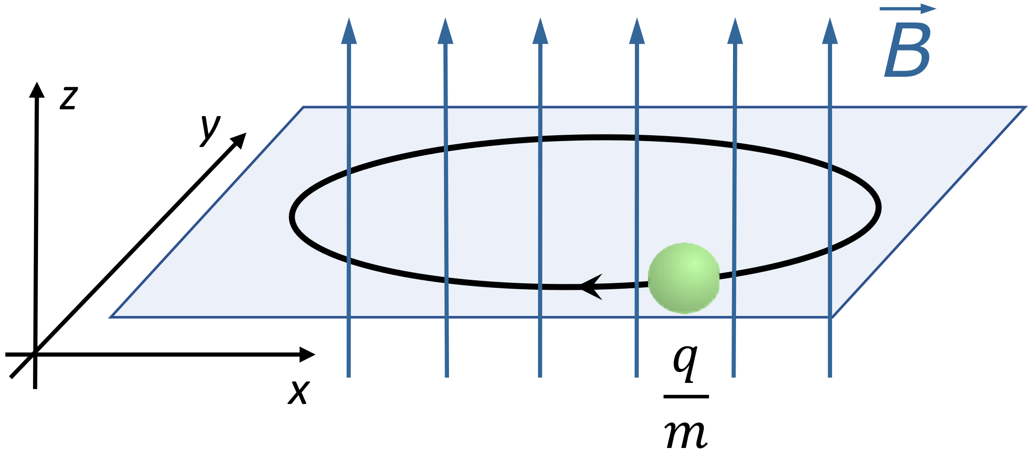
on-line Penning-trap facilities for experiments on exotic nuclides

off-line Penning-trap setups for experiments on stable nuclides



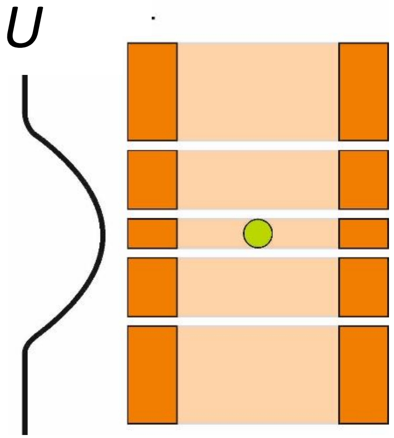
Penning Trap

strong uniform magnetic field



+

harmonic electrostatic potential



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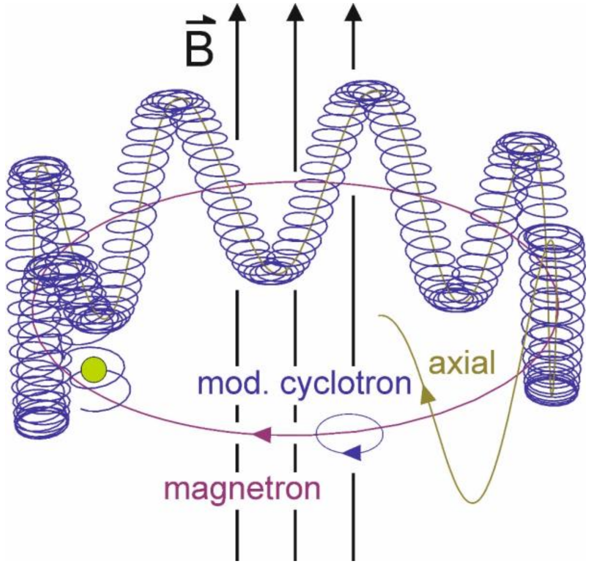
3 eigenmotions in trap



cyclotron frequency

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

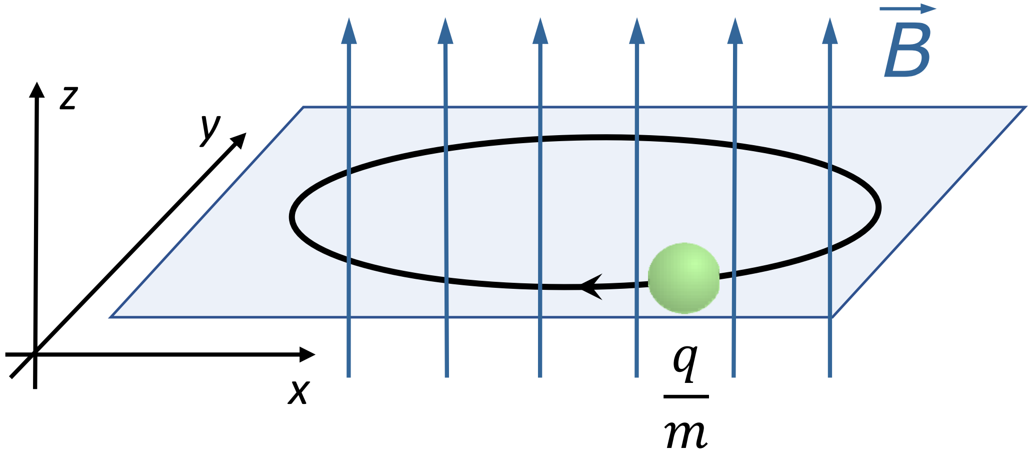
cyclotron motion: $\nu_+ = \nu_c \cdot \left(\frac{1}{2} + \frac{1}{2}\sqrt{1 - 2\nu_z^2}\right)$

axial motion: $\nu_z = \frac{1}{2\pi}\sqrt{\frac{q}{m} \cdot \frac{U}{d^2}}$

magnetron motion: $\nu_- = \nu_c \cdot \left(\frac{1}{2} - \frac{1}{2}\sqrt{1 - 2\nu_z^2}\right)$

Penning Trap

strong uniform magnetic field



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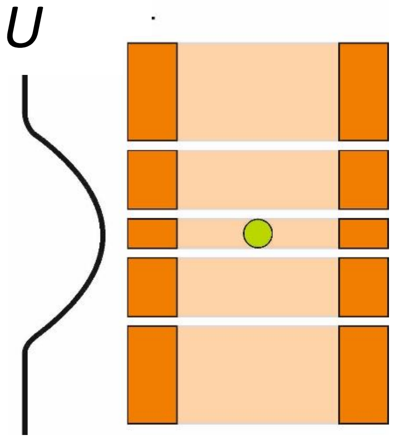

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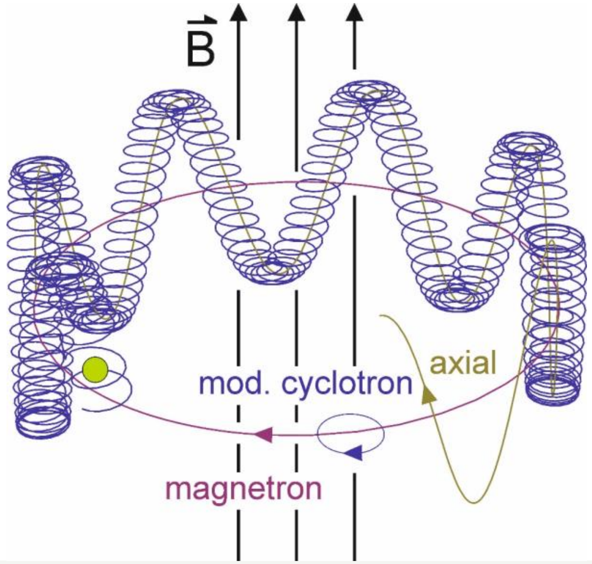


cyclotron frequency

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

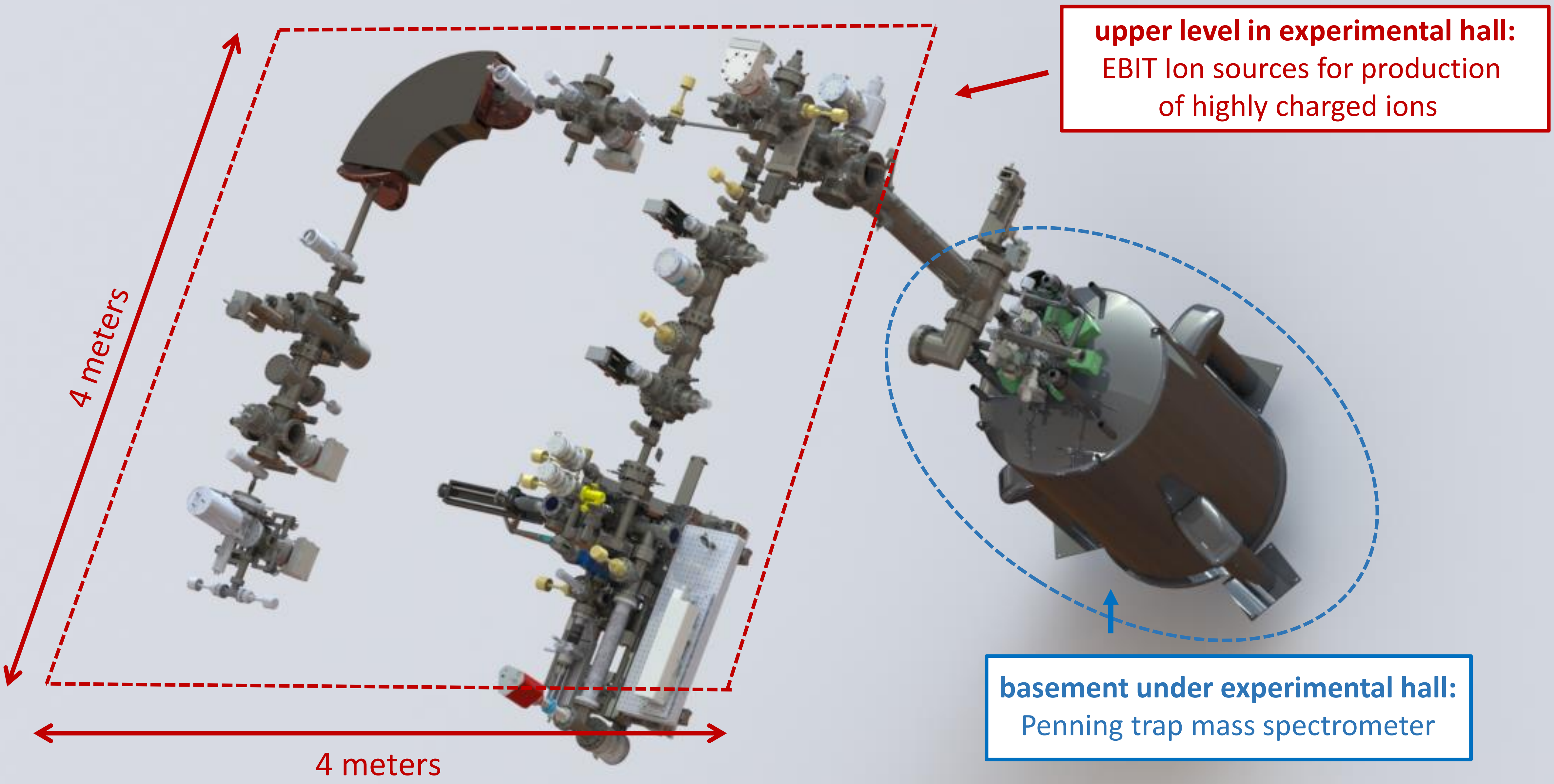
L.S. Brown, G. Gabrielse, Phys. Rev. A 25 (1982) 2423.

$^{172}Yb^{42+}$

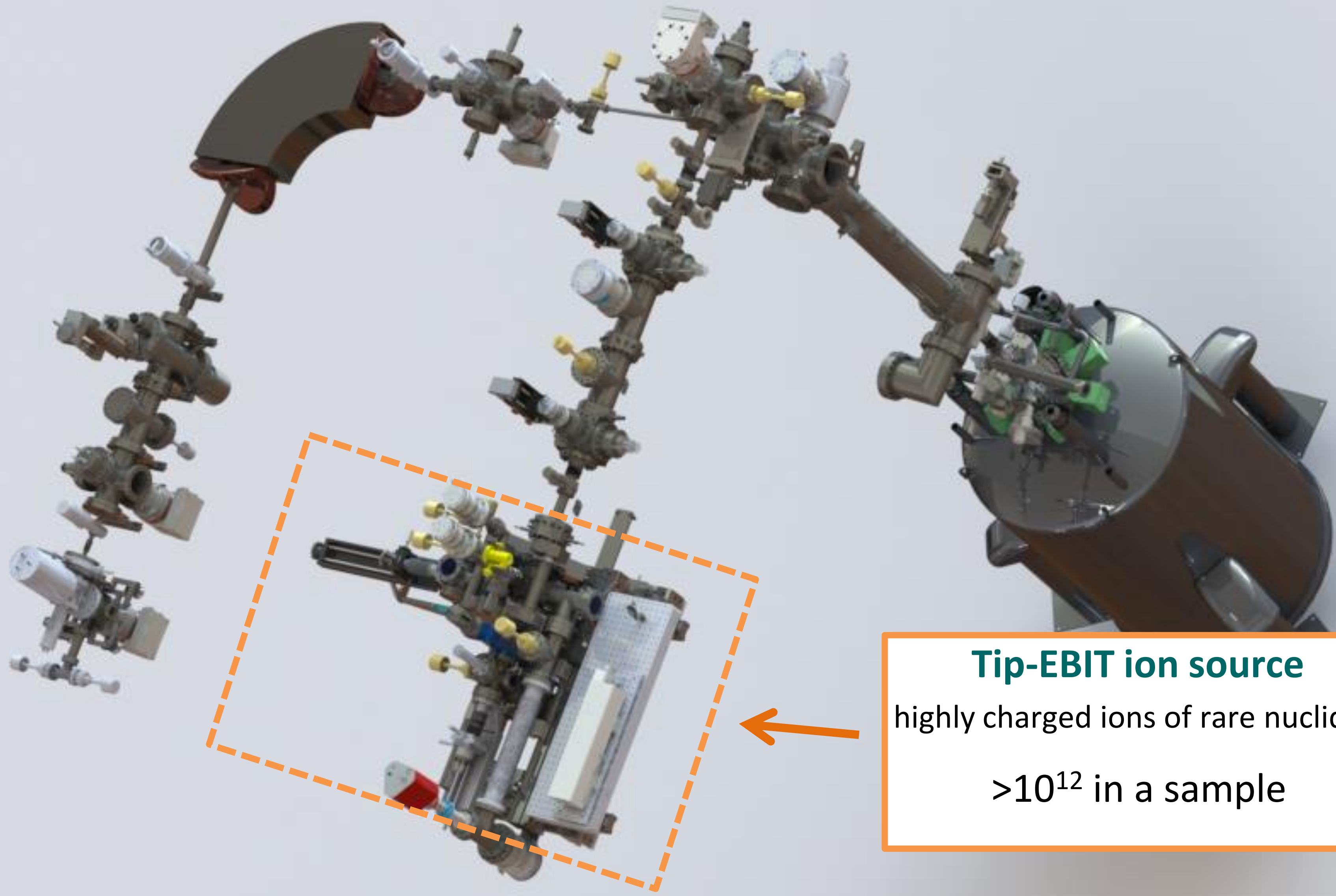
$\nu_+ \approx 26$ MHz	PnP technique
$\nu_z \approx 500$ kHz	dip technique
$\nu_- \approx 4$ kHz	double-dip technique

D. J. Wineland and H. G. Dehmelt, J. of Appl. Phys. 46 (1975) 919
E. A. Cornell *et al.*, Phys. Rev. Letter 63 (1989) 1674

PENTATRAP


upper level in experimental hall:
EBIT Ion sources for production of highly charged ions
4 meters
4 meters
basement under experimental hall:
Penning trap mass spectrometer

PENTATRAP

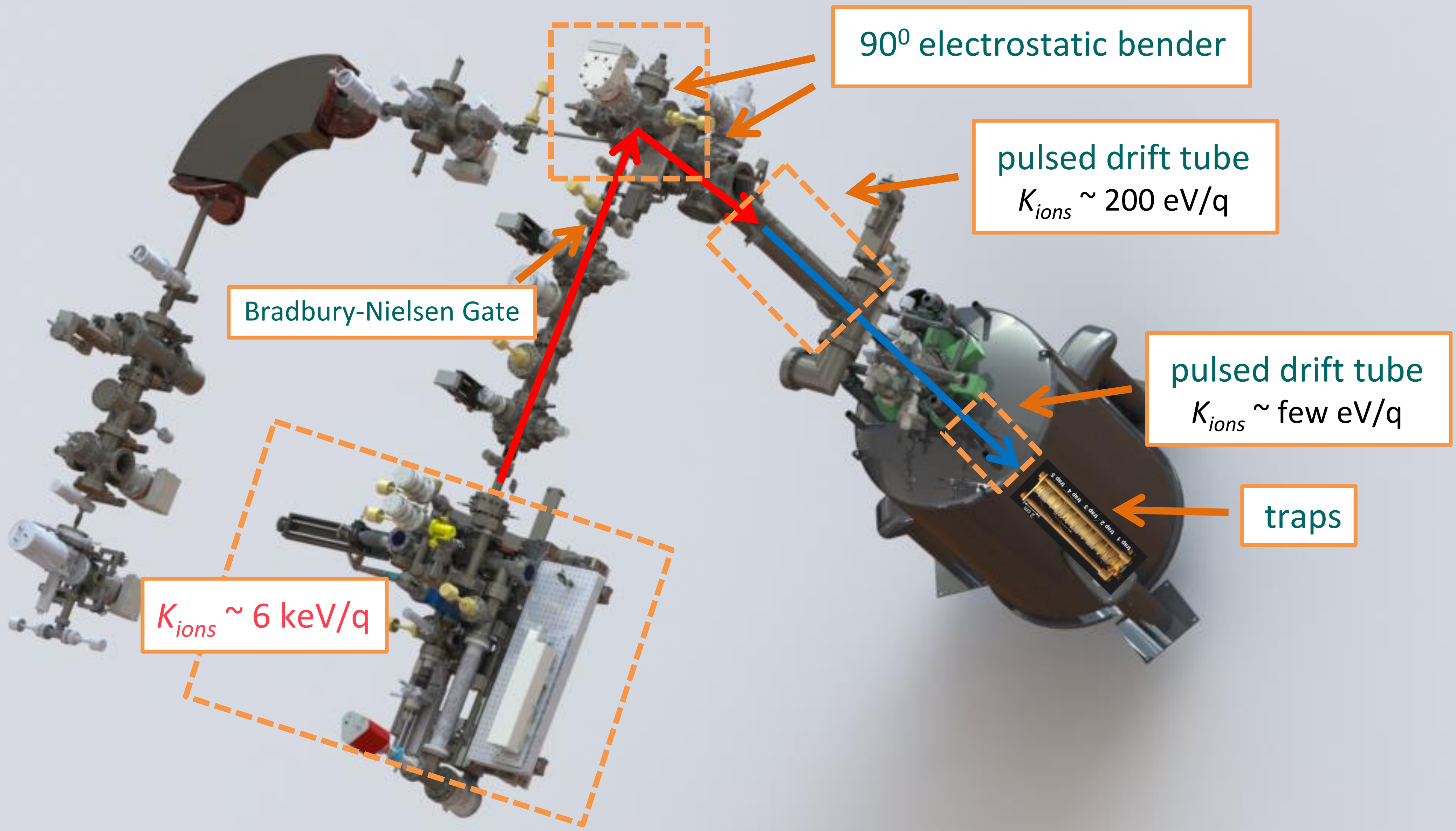


Tip-EBIT ion source

highly charged ions of rare nuclides

$>10^{12}$ in a sample

PENTATRAP

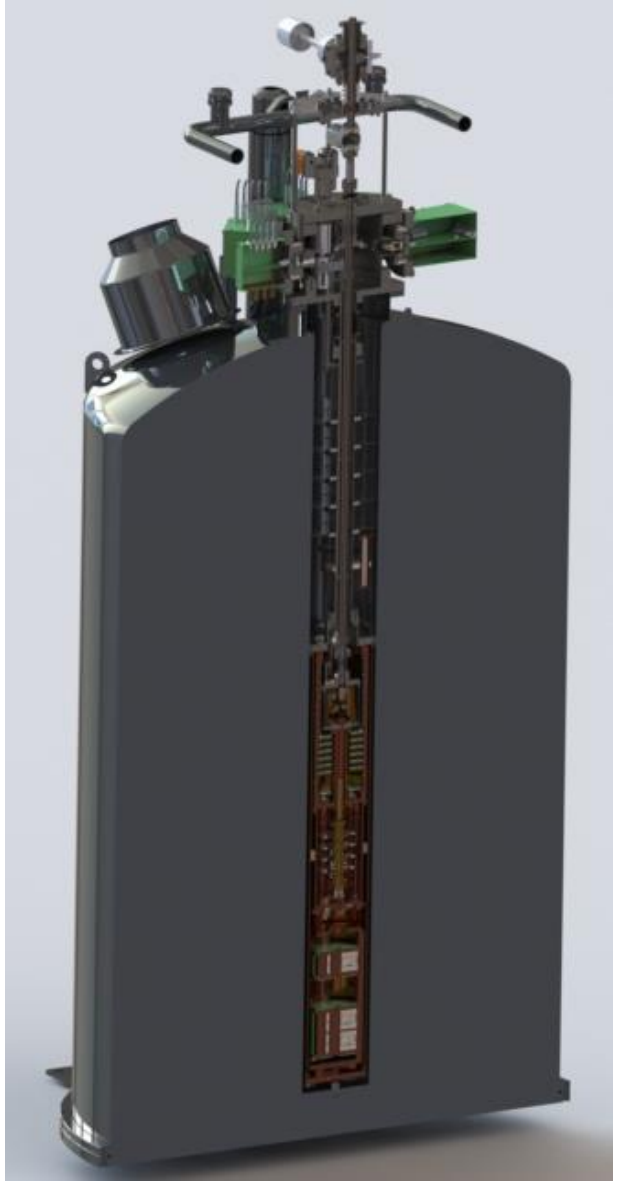


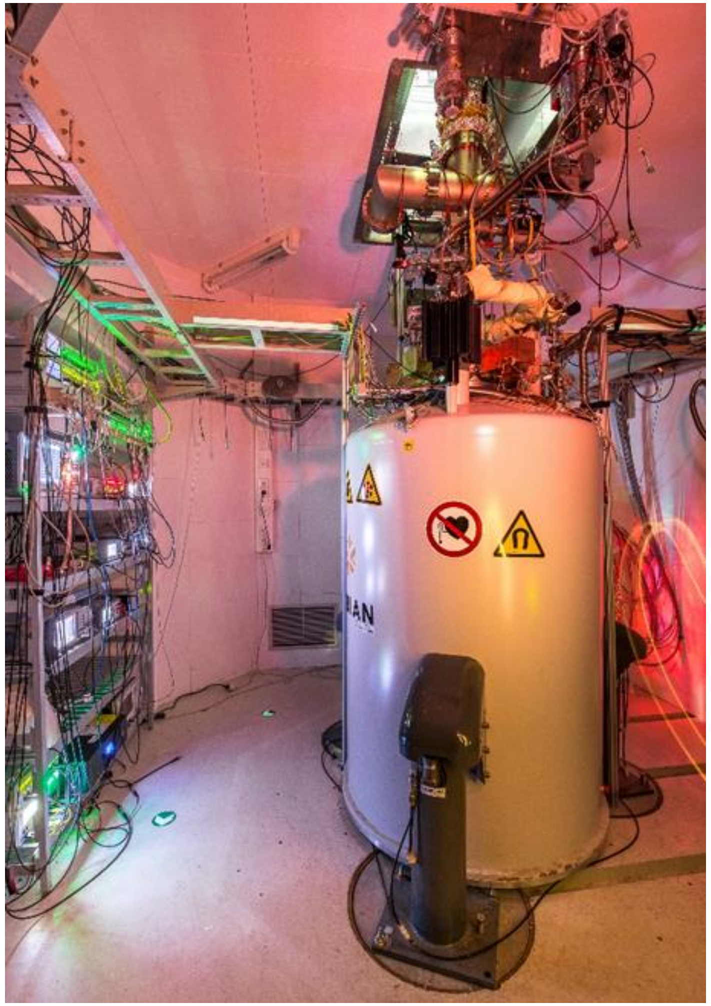
90^0 electrostatic bender
pulsed drift tube
K_{ions} ~ 200 eV/q
pulsed drift tube
K_{ions} ~ few eV/q
traps
Bradbury-Nielsen Gate
K_{ions} ~ 6 keV/q

PENTATRAP

unique features of PENTATRAP:

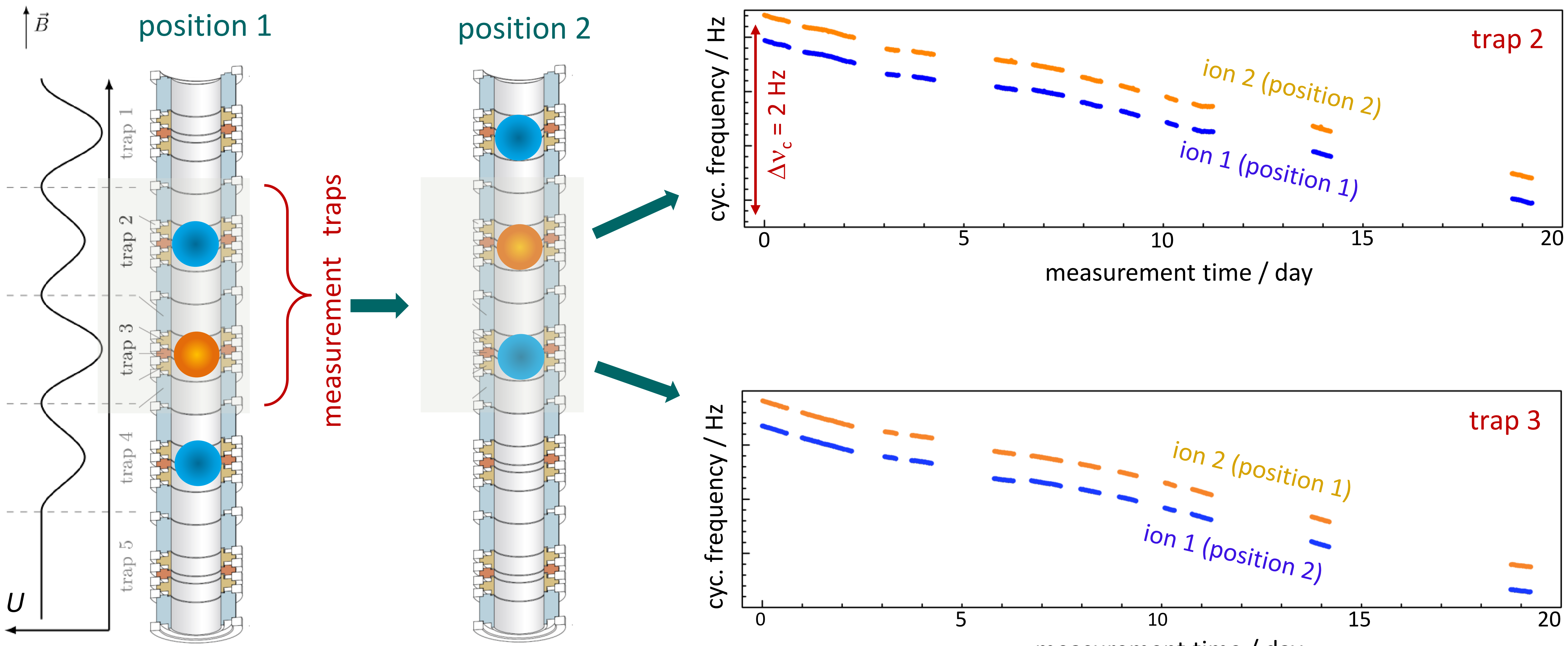
- Stack of five Penning traps
- Cryogenic environment (4.2 K)
- 7 T superconducting magnet with vertical ***cold*** bore
- Temperature in the lab is stabilized: ± 0.05 K/day
- LHe-level in the bore is stabilized: ± 50 μm
- He-pressure in the bore is stabilized: ± 2 μbar
- Relative stability of *B*-field: 10^{-10} / hour
- Ultra-stable voltage source: $\Delta U/U < 10^{-7}$ / 100 s
- Highly charged ions





Repp, J. et al., Appl. Phys. B 107, 983 (2012)
Roux, C. et al., Appl. Phys. B 107, 997 (2012)
Böhm, C. et al., Nucl. Instrum. Meth. A 828, 125 (2016)

Measurement of trap frequencies with PENTATRAP



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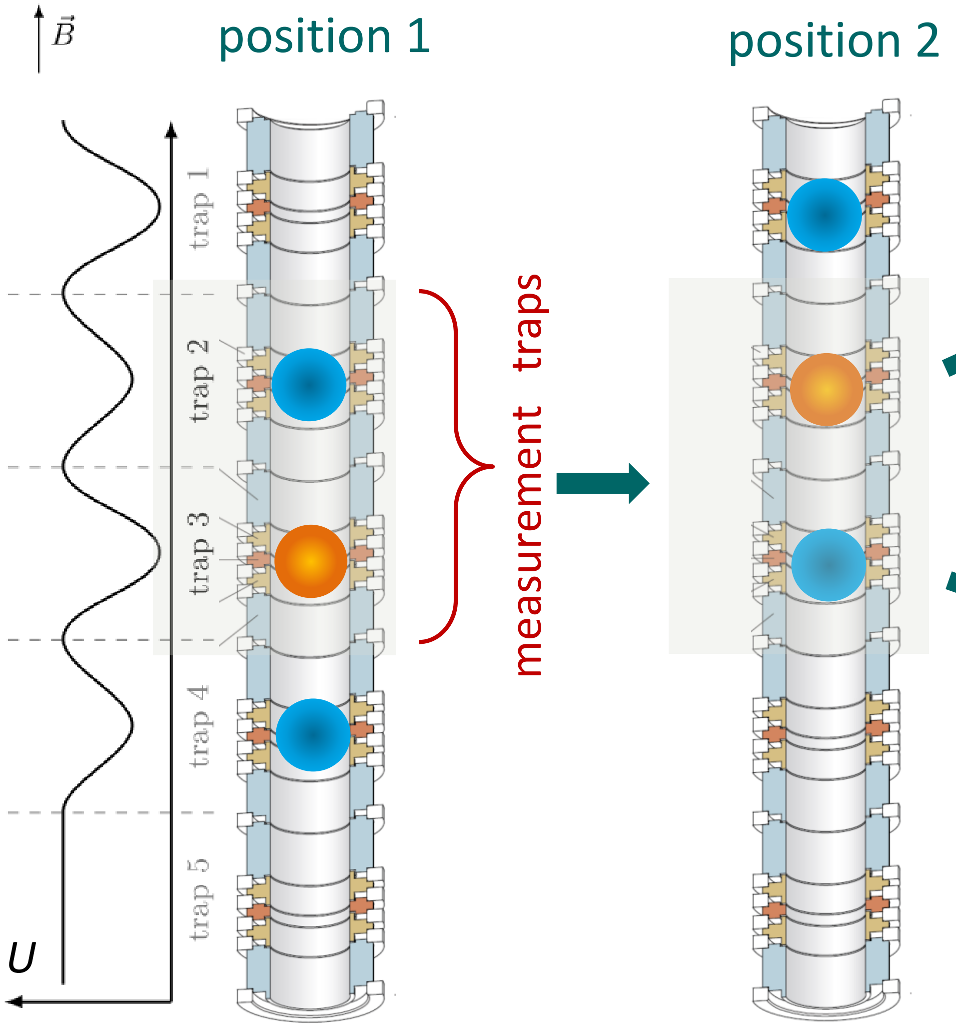

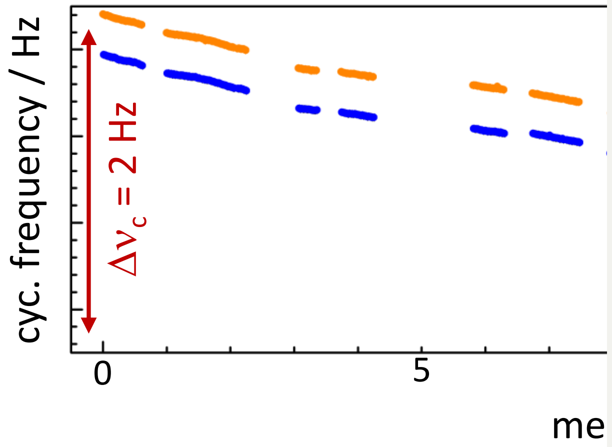

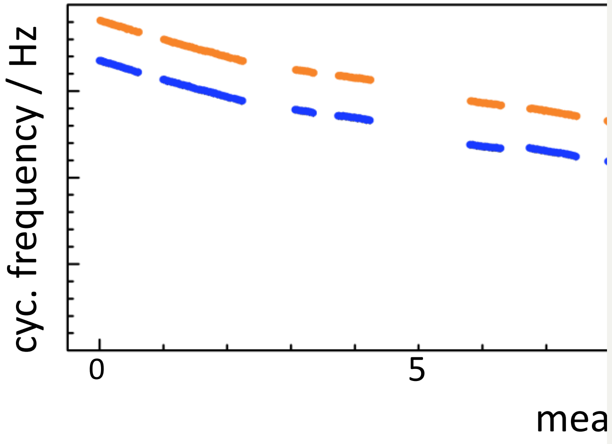

various methods of ratio calculations to compensate for B-field drift:

- interpolation
- polynomial
- cancelation
- polycancel

⬇

reliability of results

Physics at PENTATRAP

Neutrino mass:	$^{187}Re \longrightarrow {}^{187}Os + e^{-} + \nu_e$	**Filianin, P. *et al.*, Phys. Rev. Lett. 127, 072502 (2021)**
	$^{163}Ho + e^{-} \longrightarrow {}^{163}Dy + \nu_e$	**In preparation, Schweiger, Ch. et al.**
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	chain of even Ca isotopes	**Measurement campaign just started**

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Neutrino mass

β^--decay of tritium

$$m_{\overline{\nu}_e} < 0.9\ \mathrm{eV}/c^2\ (90\%\ C.L.)$$

$$Q_\beta = 18\,592.01(7)\ eV$$

KATRIN experiment

The KATRIN Collaboration., Nature Phys. 18 (2022) 160.

FSU trap

E. G. Myers *et al.*, PRL 114 (2015) 013003.

PROJECT 8

β^--decay of ^{187}Re

MINEBA

&

MANU

$$m_{\overline{\nu}_e} < 15\ \mathrm{eV}/c^2\ (90\%\ C.L.)$$

$$Q_\beta = 2466.7(1.6)\ \mathrm{eV}$$

M. Sisti et al., Nucl. Inst. Meth. A520, 125 (2004).

C. Arnaboldi et al., PRL 91, 161802 (2003).

electron capture (EC) in ^{163}Ho

ECHo

HOLMES

$$m_{\nu_e} < 225\ \mathrm{eV}/c^2\ (95\%\ C.L.)$$

$$Q_{EC} = 2858\ (51)\ \mathrm{eV}$$

P. Springer et al., Phys. Rev. A 35, 679 (1987).

P. Ranitzsch *et al.*, PRL 119, 122501 (2017).

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β⁻-decay of tritium

$$m_{\overline{\nu}_e} < 0.9\ \mathrm{eV}/c^2\ (90\%\ C.L.)$$

$$Q_\beta = 18\,592.01(7)\ eV$$

Talk at 14:15 by Edmund Myers: "Measurement of the mass difference between tritium and helium-3"

β⁻-decay of ^{187}Re

MINEBA

&

MANU

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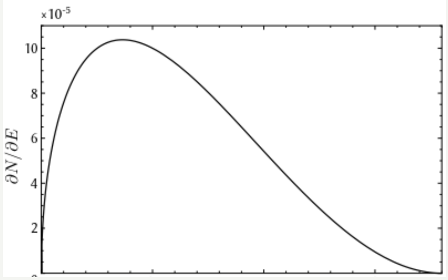
Neutrino mass

MINEBA & MANU

$^{187}Re \longrightarrow ^{187}Os + e^- + \nu_e$



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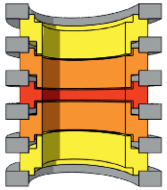
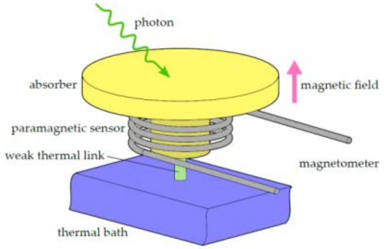
Step 1) Q_{β_187Re} → mutual test of two techniques:



Penning-trap mass spectrometry & cryogenic microcalorimetry



Q-value as M(^{187}Re) – M(^{187}Os)

Q-value as endpoint energy

Determination of Q-value of β^--decay of ^{187}Re

^{187}Re: $T_{1/2} \approx 4\cdot10^{10}$ years; abundance ≈ 63%; a few mg of volatile $C_8H_5O_3Re$

^{187}Os: stable; abundance = 1.6%; a few mg of volatile $C_{10}H_{10}Os$

$$\frac{M[^{187}\mathrm{Re}] - M[^{187}\mathrm{Os}]}{M[^{187}\mathrm{Re}]} \approx 10^{-8}$$

we measure:

$$R = \frac{\nu_c[^{187}\mathrm{Os}^{29+}]}{\nu_c[^{187}\mathrm{Re}^{29+}]}$$

we want to determine:

$$Q = M[^{187}\mathrm{Re}] - M[^{187}\mathrm{Os}] = M[^{187}\mathrm{Os}^{29+}]\cdot[R-1]+\Delta B$$

optimal charge state for Re/Os ions is 29+:

- easy to achieve an uncertainty < 10^{-11} in R-measurement
- easy to produce 29+ Re/Os ions with our EBIT
- "easy" electron configurations: $^{187}Re^{29+}$ - $[Kr]4d^{10}$; $^{187}Os^{29+}$ - $[Kr]4d^{10}4f^1$

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Heidelberg University Institute for Theoretical Physics

Zoltan Harman
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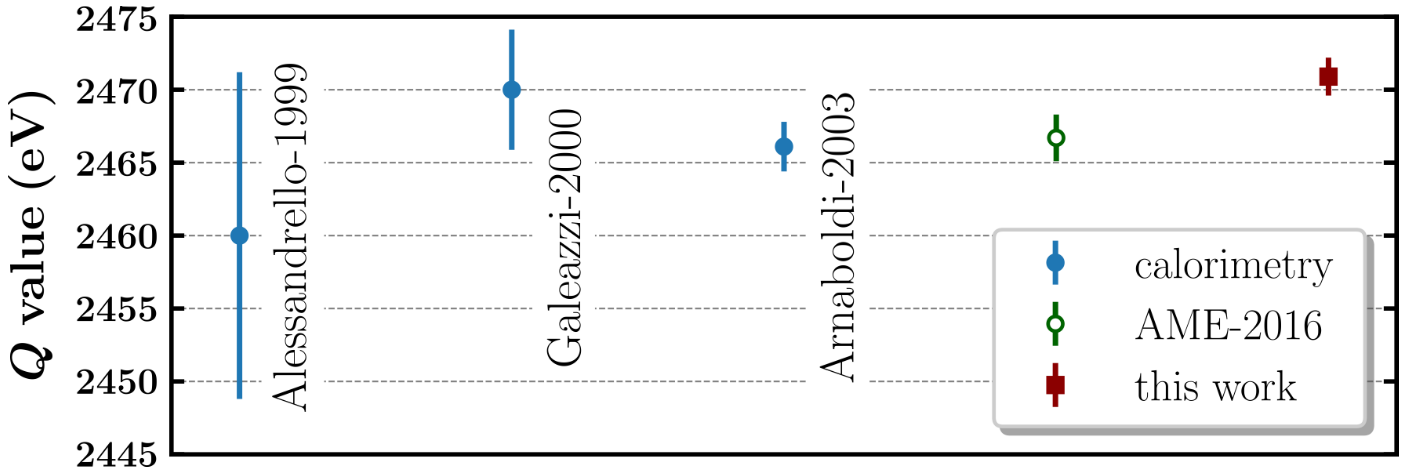

Filianin P. *et al.*, PRL 127, 072502 (2021).

uncertainty in determination of ***R***

$5 \cdot 10^{-12}$

53.5(1.0) eV

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Neutrino mass

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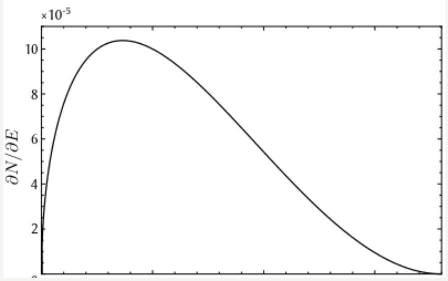
$^{187}Re \longrightarrow {}^{187}Os + e^- + \nu_e$



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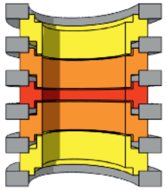
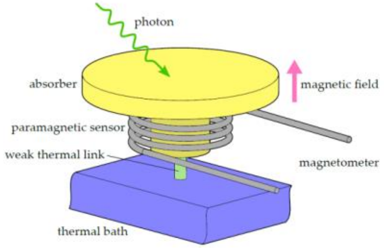


Penning-trap mass spectrometry & cryogenic microcalorimetry

Q-value as $M(^{187}Re) - M(^{187}Os)$

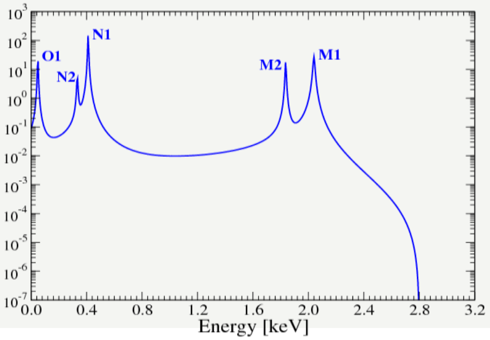
Q-value as endpoint energy



ECHo

HOLMES

$^{163}Ho + e^- \longrightarrow {}^{163}Dy + \nu_e$



$Q_{EC} = 2858\ (51)\ eV$

P. Ranitzsch *et al.*, PRL 119, 122501 (2017)

Step 2) Q_{EC_163Ho} → determination of neutrino mass (ECHo experiment)

Determination of Q-value of EC in ^{163}Ho

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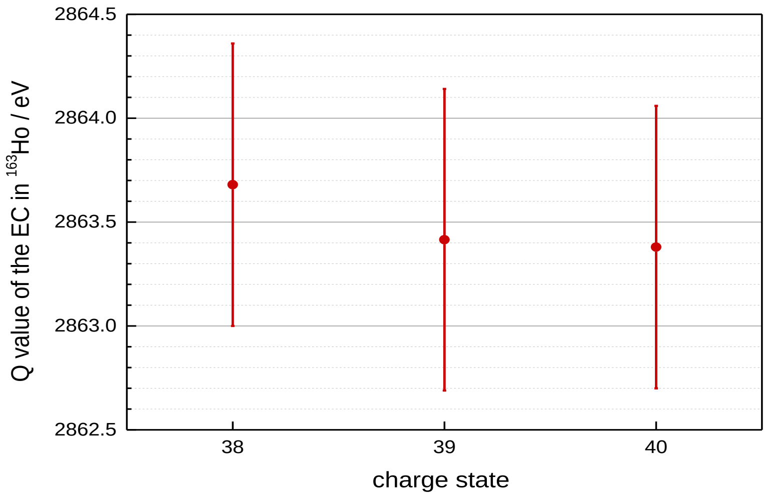
We have measured cyc. freq ratios of Dy and Ho in 3 charge states: 38+, 39+ and 40+

charge state	cyc. frequency ratio, R
38+	$1.0000000186233 \pm 3.0\cdot10^{-12}$
39+	$1.0000000113075 \pm 4.0\cdot10^{-12}$
40+	$1.0000000115156 \pm 3.5\cdot10^{-12}$

preliminary final uncertainty:

$\delta Q \sim 0.8\ eV$



$$Q = M[^{163}\text{Ho}] - M[^{163}\text{Dy}] = M[^{163}\text{Dy}^{n+}]\cdot[R-1]+\Delta B$$

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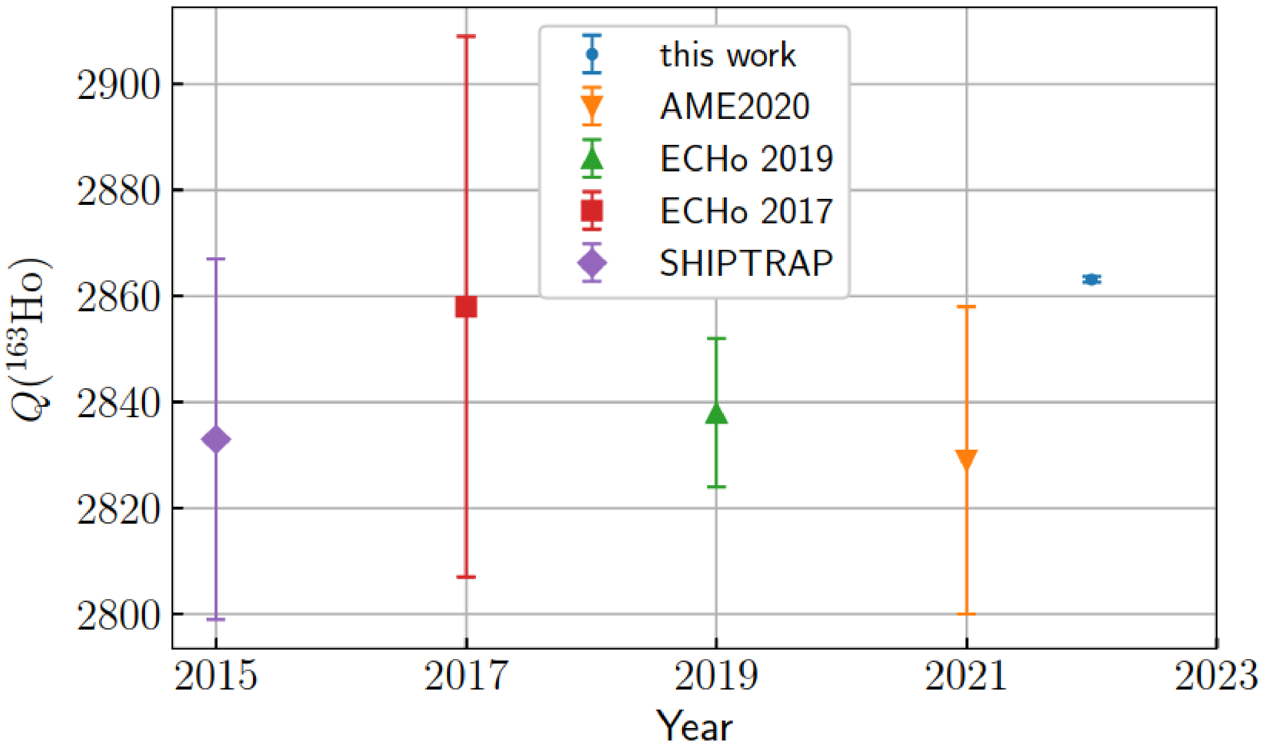
PRELIMINARY



Neutrino mass

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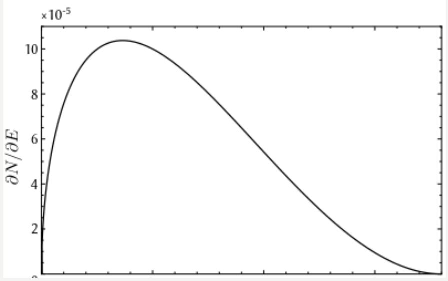

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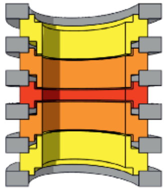

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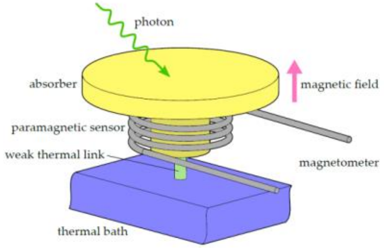

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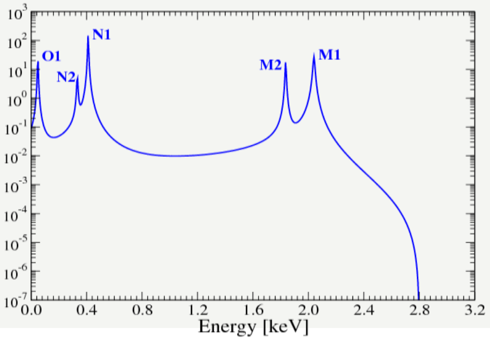

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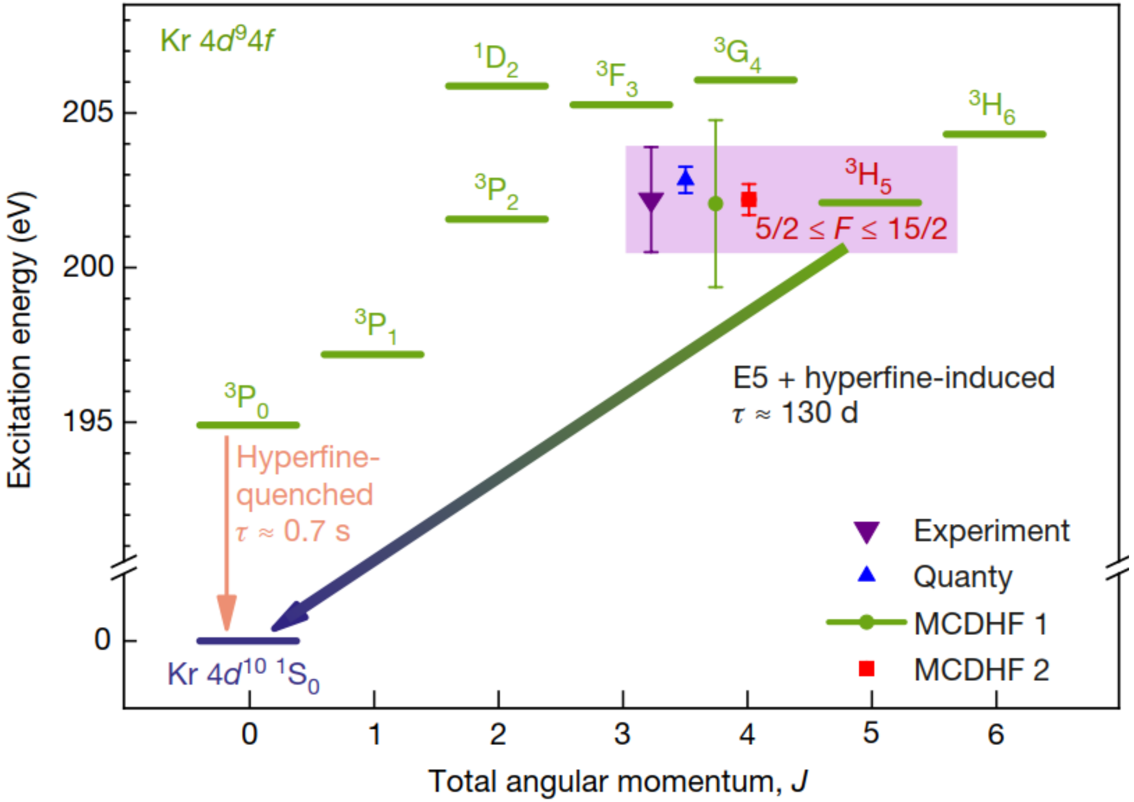
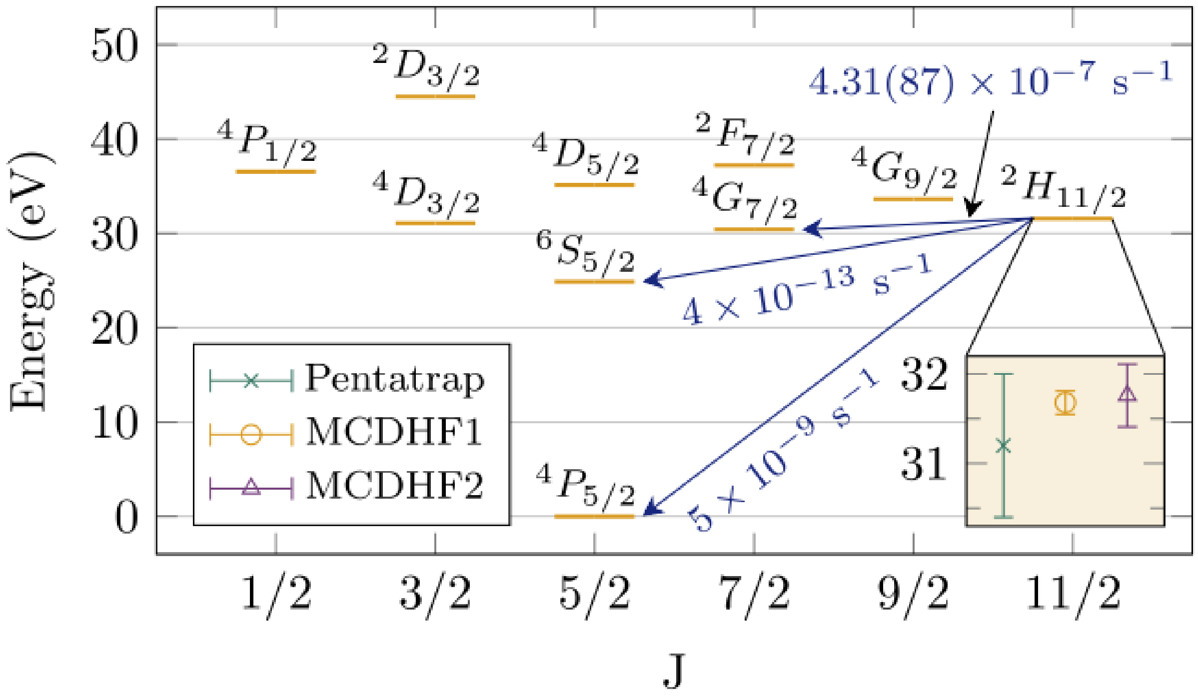
excitation energies of atomic metastable states

$^{187}Re^{29+}$ R. Schüssler et al., *Nature* 581, 42 (2020)



$E_{exc\_experimental}$ **= 202.2(17) eV**

$^{208}Pb^{41+}$ Kromer, K. et al. Submitted to PRL



$E_{exc\_experimental}$ **~ 31.2(8) eV**

excitation energies of atomic metastable states

Previous talk by Chunhai Lyu: "Ultrastable clock transitions in highly charged ions"

Possible application: search for suitable clock transitions

Table 1. Summary of metastable state in highly charged ions.

isoelectron	ion	metastable state	energy (eV)	lifetime
23V-like	U^{69+}	$[Ar]3d^5\ ^2H_{11/2}$	197.0	12.6 hours
23V-like	Th^{67+}	$[Ar]3d^5\ ^2H_{11/2}$	176.3	25.3 hours
41Nb-like	U^{51+}	$[Kr]4d^5\ ^2H_{11/2}$	57.5	8.3 days
22Ti-like	U^{70+}	$[Ar]3d^4\ ^3H_4$	205.9	46.3 days
22Ti-like	Xe^{32+}	$[Ar]3d^4\ ^5D_4$	17.9	3.0 hours
22Ti-like	Ba^{34+}	$[Ar]3d^4\ ^5D_4$	21.1	10.3 hours
22Ti-like	Ce^{36+}	$[Ar]3d^4\ ^5D_4$	24.8	54.5 hours
40Zr-like	U^{52+}	$[Kr]4d^5\ ^2H_{11/2}$	59.8	10.9 years
40Zr-like	Gd^{24+}	$[Kr]3d^4\ ^5D_4$	9.0	5.3 hours
40Zr-like	Dy^{26+}	$[Kr]3d^4\ ^3F_4$	10.6	16.3 hours

next goal:

Xe^{32+}, Gd^{24+}, Dy^{26+}

Physics at PENTATRAP

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Neutrino mass:	$^{187}Re \longrightarrow {}^{187}Os + e^- + \nu_e$	**Filianin, P. *et al.*, Phys. Rev. Lett. 127, 072502 (2021)**
	$^{163}Ho + e^- \longrightarrow {}^{163}Dy + \nu_e$	**In preparation, Schweiger, Ch. et al.**
Excitation energies of atomic metastable states:	$^{m}Re^{29+}$, $^{m}Os^{30+}$	**Schuessler, R. *et al.*, Nature 581, 42 (2020)**
	$^{m}Pb^{41+}$	**Submitted to PRL, Kromer, K. *et al.***
Test of QED in strong electromagnetic fields (g-factors):	$M(^{20}Ne^{10+})$ vs $M(^{12}C^{6+})$	**Submitted to PRL, Heiße, F. *et al.***
	$M(^{9}Be^{3+})$ vs $M(^{12}C^{4+})$	**Data analysis is ongoing**
Dark matter and 5th force (King plot)	$M(^{168,170,174,176}Yb)$ vs $M(^{172}Yb)$	**In preparation, Door, M. *et al.***
	chain of even Ca isotopes	**Measurement campaign just started**

Test of QED in strong electromagnetic fields

Measurement with Alphatrap of the g-factor of an electron in $^{20}Ne^{9+}$

$$g_{\text{exp}} = 2\,\frac{\nu_L}{\nu_c}\,\frac{m_e}{m(^{20}\text{Ne}^{9+})}\,\frac{q}{e}$$

Alphatrap

from Atomic Mass Evaluation (AME)

Talk today at 15:25 by C.Konig: "High precision measurements of single ions in the ALPHATRAP Penning trap setup"

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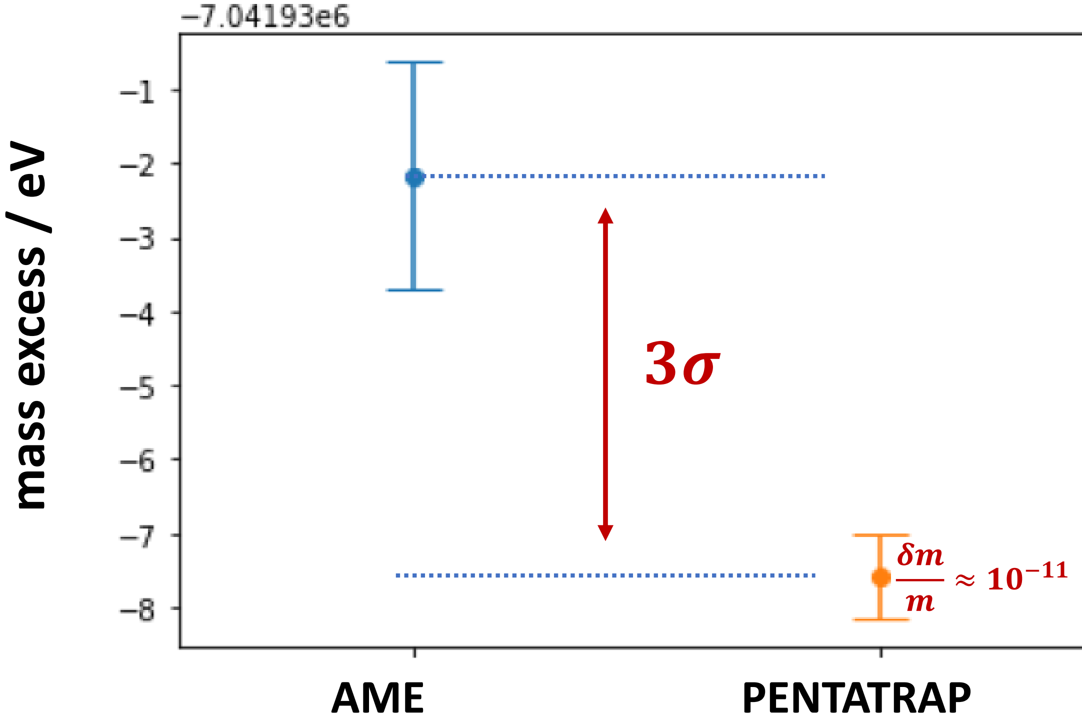
$$g_{\mathrm{exp}} \neq g_{\mathrm{theory}}$$

(discrepancy of about 3σ)

$^{20}Ne^{10+}$ vs $^{12}C^{6+}$



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dark matter and 5th force

If Light Dark Matter particles exist: bosons, they couple quarks and leptons (5th force)

↓

interraction of atomic electrons with a nucleus is altered,
atomic-electron binding energies & transition frequencies are changed

transition frequencies depend on nuclear mass

Penning traps ↗

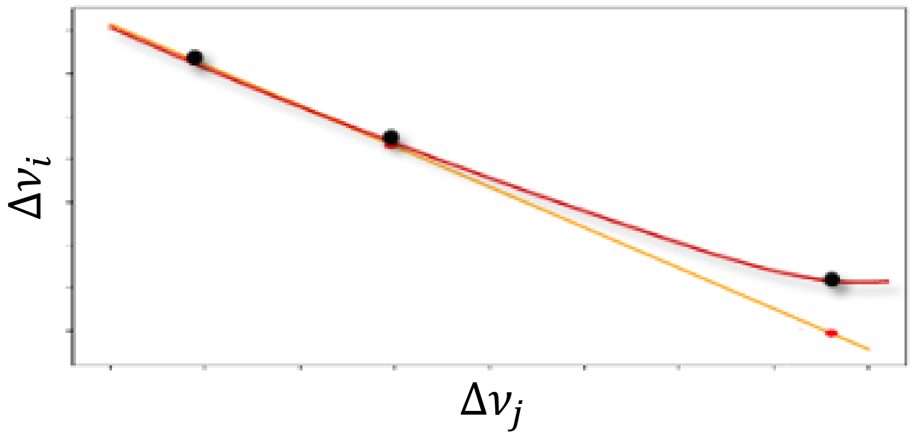
dark matter and 5th force

Talk on Monday by A.Viatkina: "Calculation of isotope shifts and King plot nonlinearities in Ca+"

$$\Delta\nu_i = C_1 \cdot \frac{m_1 - m_2}{m_1 m_2} + C_2 \cdot \Delta\nu_j + \text{[higher–order SM effects + LDM bosons]}$$

$$\nu_i(\text{isotope}_1) - \nu_i(\text{isotope}_2) \equiv \Delta\nu_i$$

King plot



one needs elements with many even-even isotopes
and quadrupole/octupole (narrow optical) transitions:

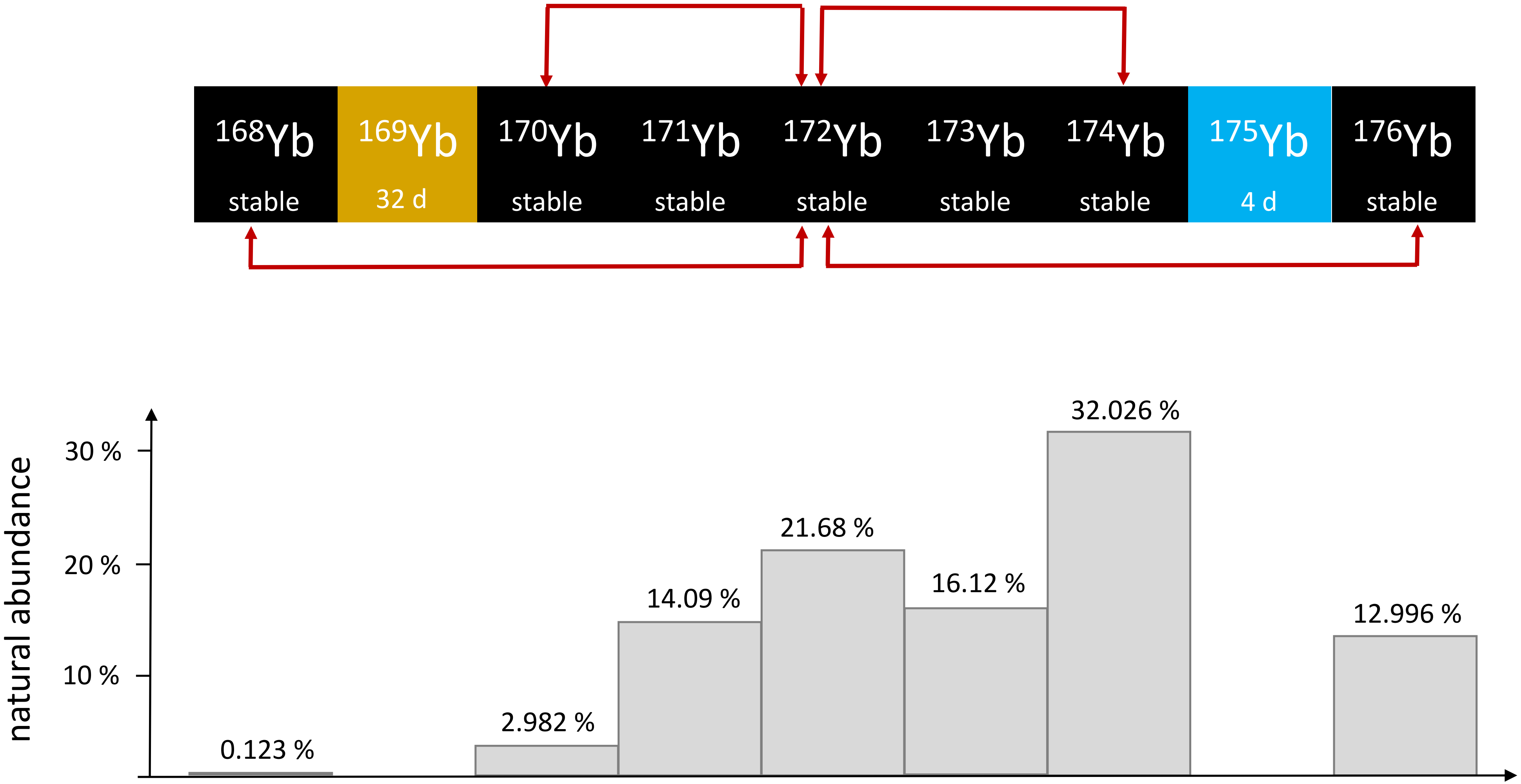
^{168,170,172,174,176}Yb	I. Counts et al., PRL 125, 123002 (2020) K. Ono et al., arXiv: 2110.13544v2 J. Hur et al., arXiv: 2201.03578v2 N.L. Figueroa et al., PRL 128, 073001 (2022)
^{40,42,44,46,48}Ca	C. Solaro et al., PRL 125, 123003 (2020) F.W. Knollmann et al., PRA 100, 022514 (2019)
^{84,86,88,90}Sr	T. Manowitz et al., PRL 123, 203001 (2019) H. Miyake et al., PRR 1, 033113 (2019)

FUTURE:

$$\delta(\Delta\nu_i) \approx 10 \text{ mHz}$$

$$\delta\left(\frac{m_1}{m_2}\right) \approx 5 \cdot 10^{-12}$$

Yb mass-ratio measurements



Yb mass-ratio data analysis is ongoing!

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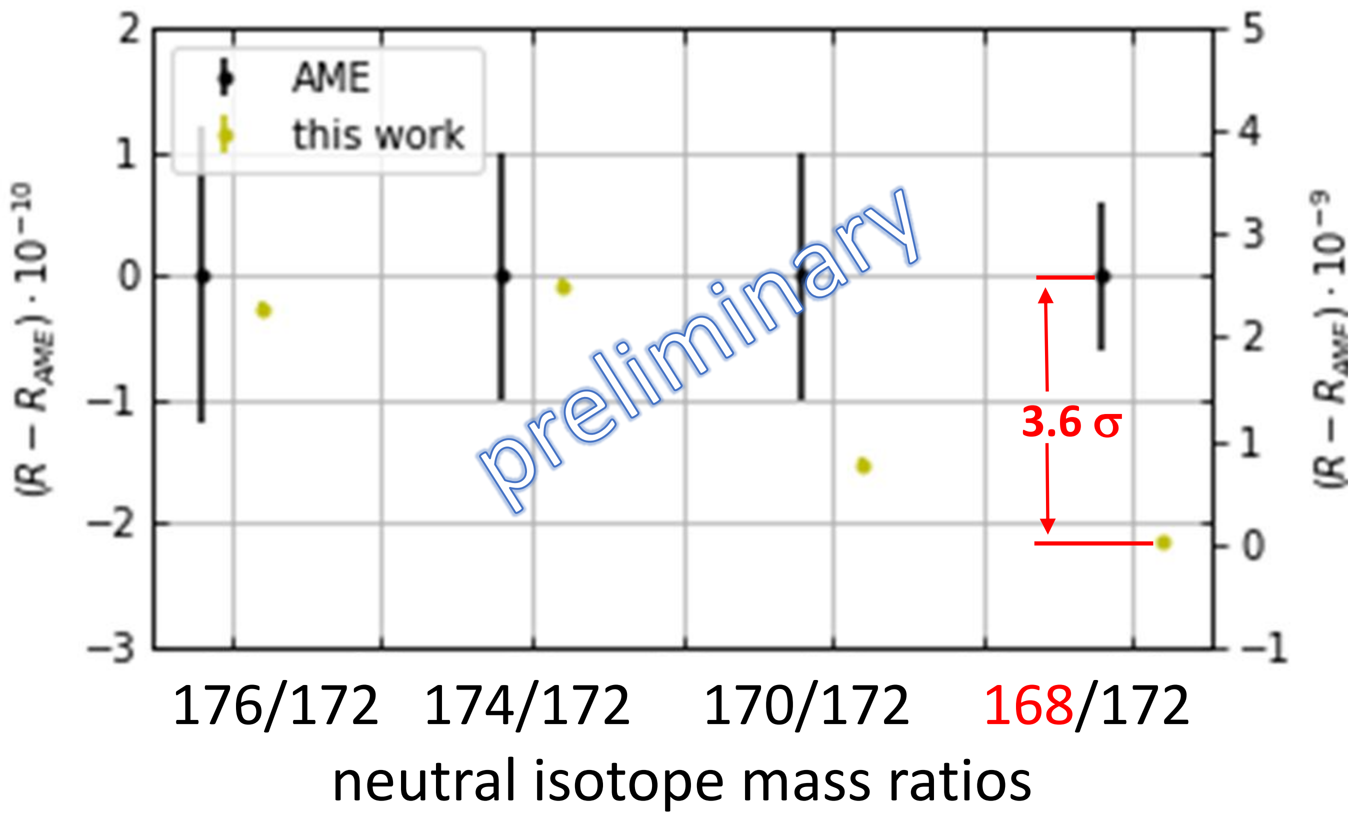
cyclotron-frequency ratio of	statistical uncertainty
$^{172}Yb^{42+}$ / $^{168}Yb^{42+}$	< $2 \cdot 10^{-12}$
$^{172}Yb^{42+}$ / $^{170}Yb^{42+}$	< $2 \cdot 10^{-12}$
$^{172}Yb^{42+}$ / $^{174}Yb^{42+}$	< $2 \cdot 10^{-12}$
$^{172}Yb^{42+}$ / $^{176}Yb^{42+}$	< $2 \cdot 10^{-12}$

error budget	
statistics	< $2 \cdot 10^{-12}$
relativistic shift	~ $2 \cdot 10^{-12}$
axial fit	~ $2 \cdot 10^{-12}$
binding energy	< 10^{-12}
total uncertainty $\sim 5 \cdot 10^{-12}$	



Planned measurements with PENTATRAP

dark matter and 5th force: even isotopes of Ca

atomic metastable states: Xe^{32+}, Gd^{24+}, Dy^{26+}

α-constant variation: $^{133,135,137}Cs$ & ^{87}Rb vs ^{12}C

Max-Planck-Institut für Kernphysik

Max-Planck Institute for Nuclear Physics

Thank you for your attention!

FOR 2202 ECHo

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isoQuant SFB1225

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erc European Research Council

ERC AdG 832848 - FunI

IMPRS Precision Tests of Fundamental Symmetries

IMPRS-PTFS

Present and former PENTATRAP members:

Christine Böhm, Menno Door, Andreas Dörr, Sergey Eliseev, Pavel Filianin, Daniel Lange, Kathrin Kromer, Yuri N. Novikov, Julia Repp, Alexander Rischka, Christian Roux, Christoph Schweiger, Rima Schüssler, and Klaus Blaum