MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

High-precision nuclear mass measurements to search for new physics

- Motivations for high precision mass measurements
- The Pentatrap mass spectrometer
- 5th force search and electron neutrino mass

Menno Door

Max Planck Institute for Nuclear Physics in Heidelberg / Germany

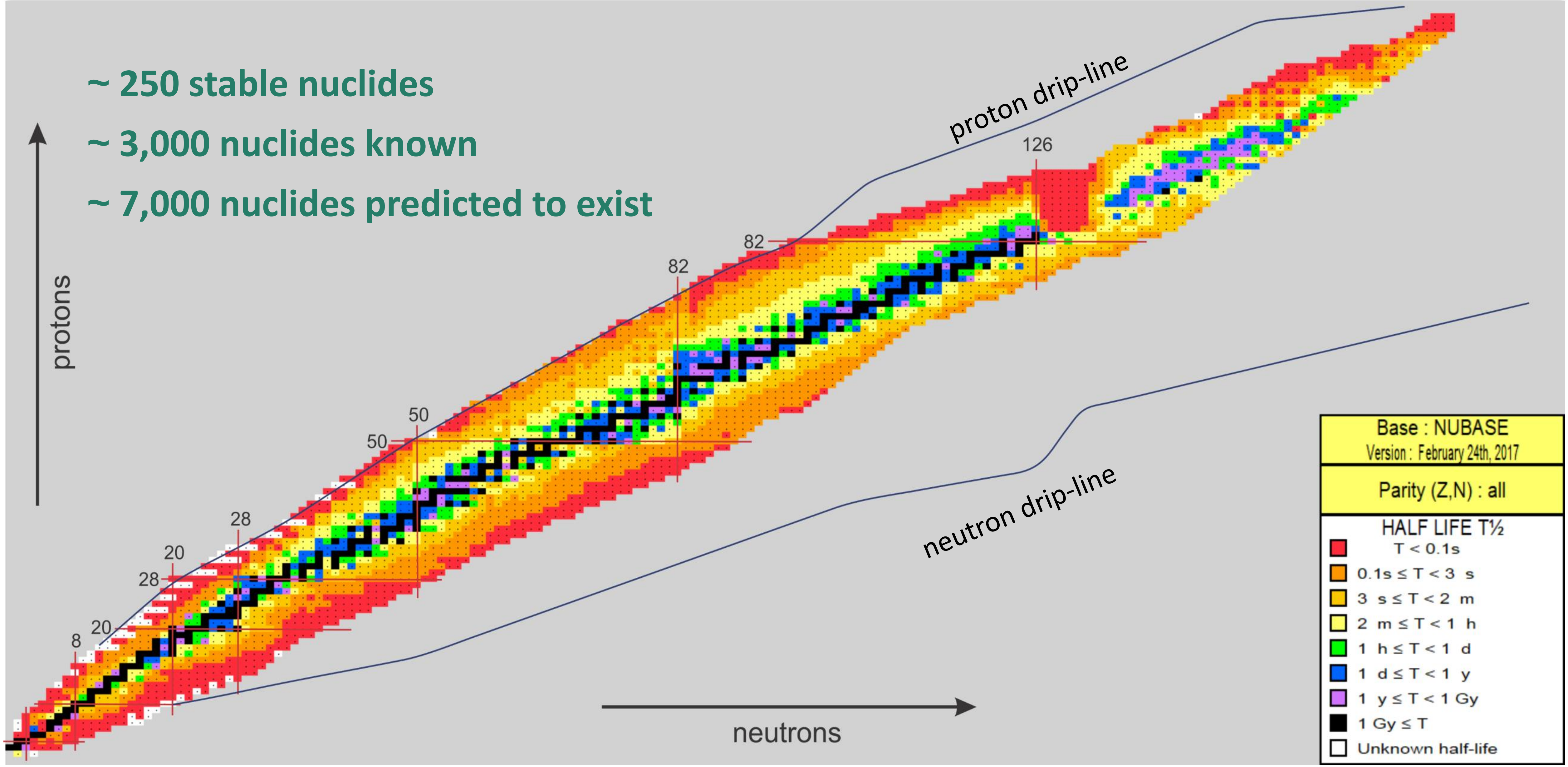
2023/10/12

@ NUSTAR Week 2023

Max Planck Society *IMPRS-PTFS* *DFG FOR 2202* *ERC AdG 832848 - FunI* *DFG SFB 1225*

Nuclear chart

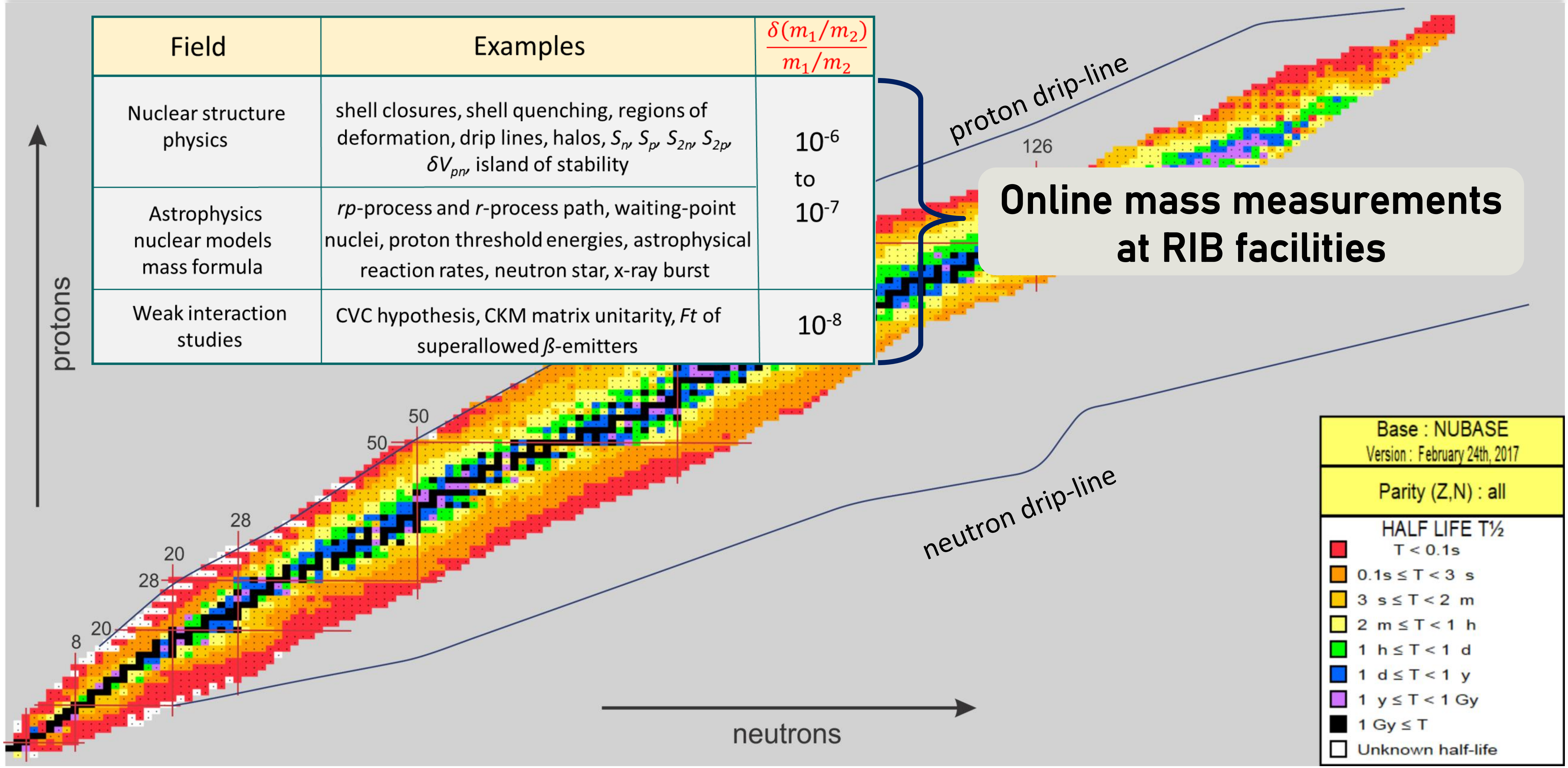
- ~ 250 stable nuclides
- ~ 3,000 nuclides known
- ~ 7,000 nuclides predicted to exist



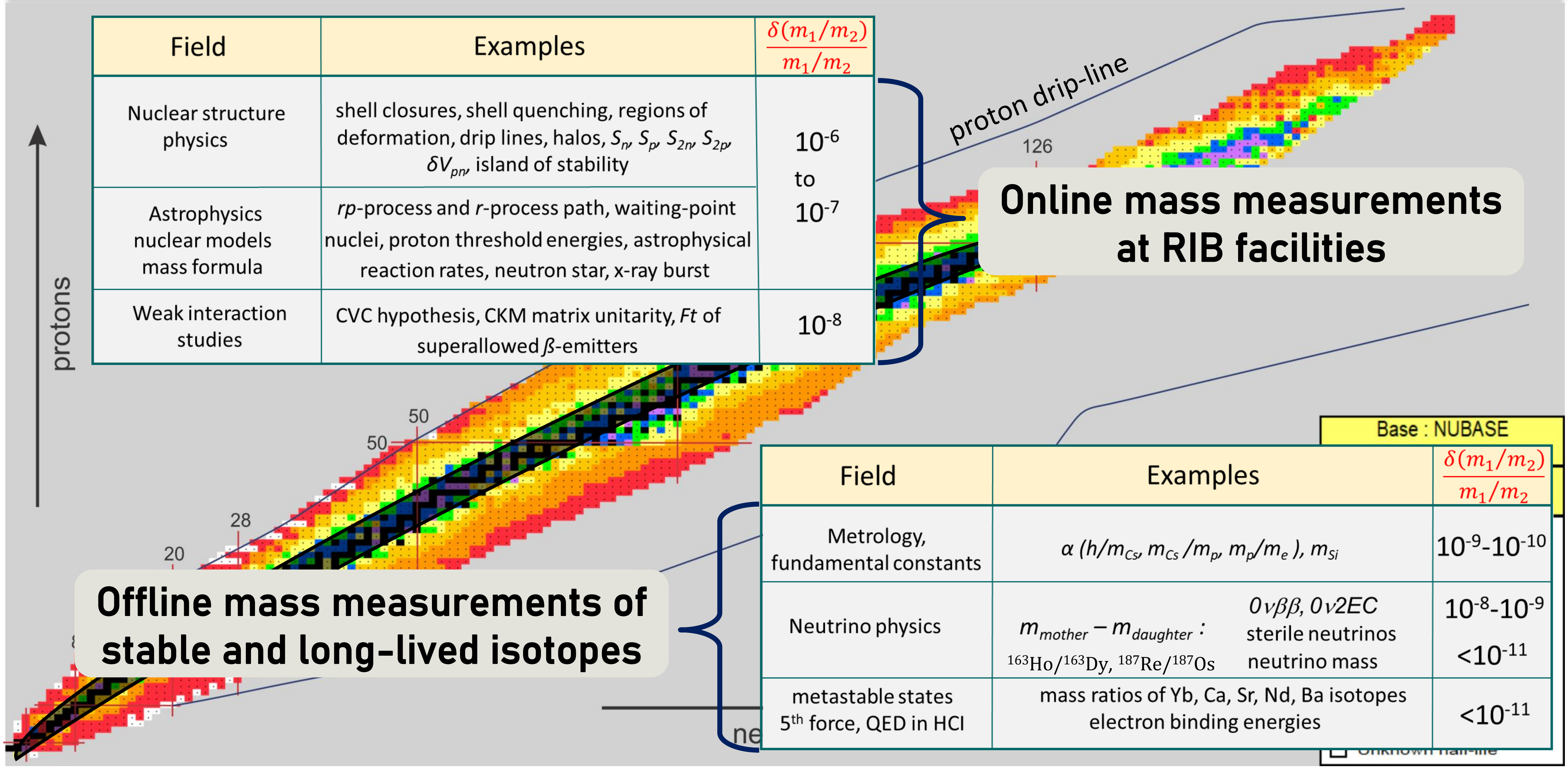
Mass measurement motivations

Field	Examples	$\frac{\delta(m_1/m_2)}{m_1/m_2}$
Nuclear structure physics	shell closures, shell quenching, regions of deformation, drip lines, halos, S_n, S_p, S_{2n}, S_{2p}, δV_{pn}, island of stability	10^{-6} to 10^{-7}
Astrophysics nuclear models mass formula	*rp*-process and *r*-process path, waiting-point nuclei, proton threshold energies, astrophysical reaction rates, neutron star, x-ray burst	
Weak interaction studies	CVC hypothesis, CKM matrix unitarity, *Ft* of superallowed *β*-emitters	10^{-8}

Online mass measurements at RIB facilities



Mass measurement motivations



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Weak interaction studies	CVC hypothesis, CKM matrix unitarity, *Ft* of superallowed *β*-emitters	10^{-8}

Online mass measurements at RIB facilities

Offline mass measurements of stable and long-lived isotopes

Field	Examples	$\frac{\delta(m_1/m_2)}{m_1/m_2}$
Metrology, fundamental constants	α $(h/m_{Cs}, m_{Cs}/m_p, m_p/m_e)$, m_{Si}	10^{-9}-10^{-10}
Neutrino physics	$m_{mother} - m_{daughter}$: ^{163}Ho/^{163}Dy, ^{187}Re/^{187}Os — $0\nu\beta\beta$, $0\nu 2EC$ sterile neutrinos neutrino mass	10^{-8}-10^{-9} $<10^{-11}$
metastable states 5[th] force, QED in HCI	mass ratios of Yb, Ca, Sr, Nd, Ba isotopes electron binding energies	$<10^{-11}$

Pentatrap Motivation: Applications of mass-ratios $\delta m/_m \leq 10^{-11}$

Neutrino physics

$$^{187}\text{Re} \rightarrow {}^{187}\text{Os} + e^- + \overline{\nu_e} + \boldsymbol{Q_{\beta^-}}$$

$$^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy} + \nu_e + \boldsymbol{Q_{EC}}$$

Gastaldo, L. et al., Eur. Phys. J. ST 226, 1623 (2017)

Filianin, P. et al., Phys. Rev. Lett. 127, 072502 (2021) $\delta Q = 1.3\ \text{eV}$

Schweiger, Ch. et al., Submitted, Nature Physics (2023) $\delta Q = 0.8\ \text{eV}$

Meta-stable states for HCI clocks

$$\Delta m({}^{208}\text{Pb}^{41+} - {}^{208}\text{Pb}^{*41+})$$

$$\Delta m({}^{187}\text{Re}^{29+} - {}^{187}\text{Re}^{*29+})$$

Kozlov, M. G. et al., Rev. Mod. Phys. 90, 045005 (2018)

Kromer, K. et al., Submitted, PRL (2023) $\delta E = 0.8\ \text{eV}$

Schuessler, R. X. et al., Nature 581, 42 (2020) $\delta E = 1.7\ \text{eV}$

Test of QED

Binding energies: $\boldsymbol{E_B}(\textbf{Xe}^{17+}) = \Delta m(\text{Xe}^{17+} - \text{Xe}^{18+})c^2 - m_e c^2$

g-factor: $g = 2\frac{\nu_L}{\nu_c}\frac{m_e}{\boldsymbol{m}(^{20}\textbf{Ne})}\frac{q}{e}$

Shabaev, V. M. et al., Int. J. of Mass Spec. 251, 109, (2006)

Rischka, A. et al., Phys. Rev. Lett. 124, 113001 (2020) $\delta E = 4\ \text{eV}$

Heisse, F. et al., Accepted, PRL (2023) $\delta m = 9 \times 10^{-11}\ \text{amu}$

5th force search: Isotope shift

$$\nu_i^{AA'} = K_i\, \boldsymbol{\mu_{AA'}} + F_i\, \delta\langle r^2\rangle_{AA'} + \alpha_{NP} X_i \gamma_{AA'}$$

Flambaum, V. V. et al., Phys. Rev. A 79, 032510 (2018)

Yb isotope mass-ratios done and Analysis/Paper in preparation
Ca isotopes currently being measured

$$\frac{\delta(\mathbf{m}_A/\mathbf{m}_B)}{\mathbf{m}_A/\mathbf{m}_B} \leq 7 \times 10^{-12}$$

Determination of fine structure constant α

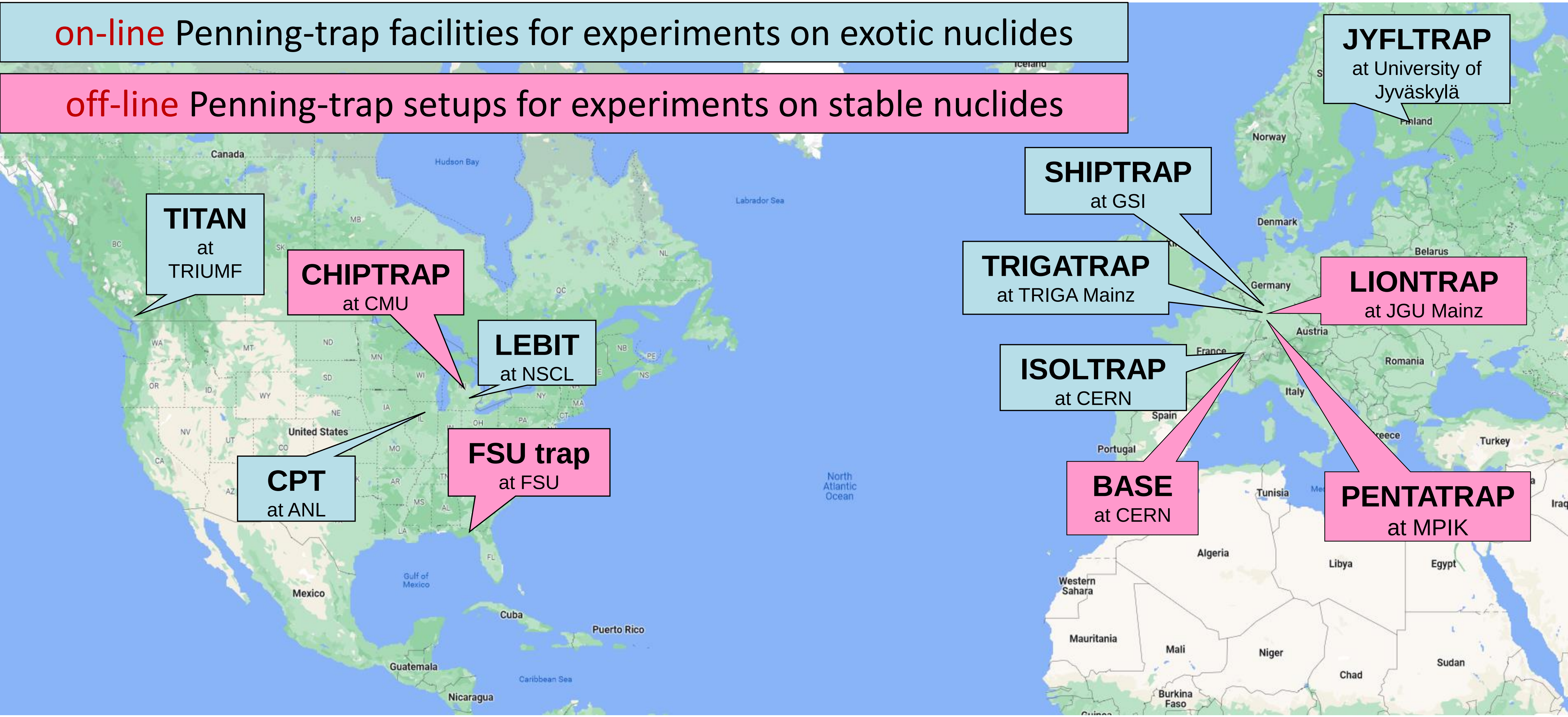
$$\alpha^2 = \frac{2R_\infty}{c}\frac{\boldsymbol{m_{Rb}}}{m_e}\frac{h}{m_{Rb}}$$

Morel, L., et al., *Nature* **588**, 61–65 (2020)

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



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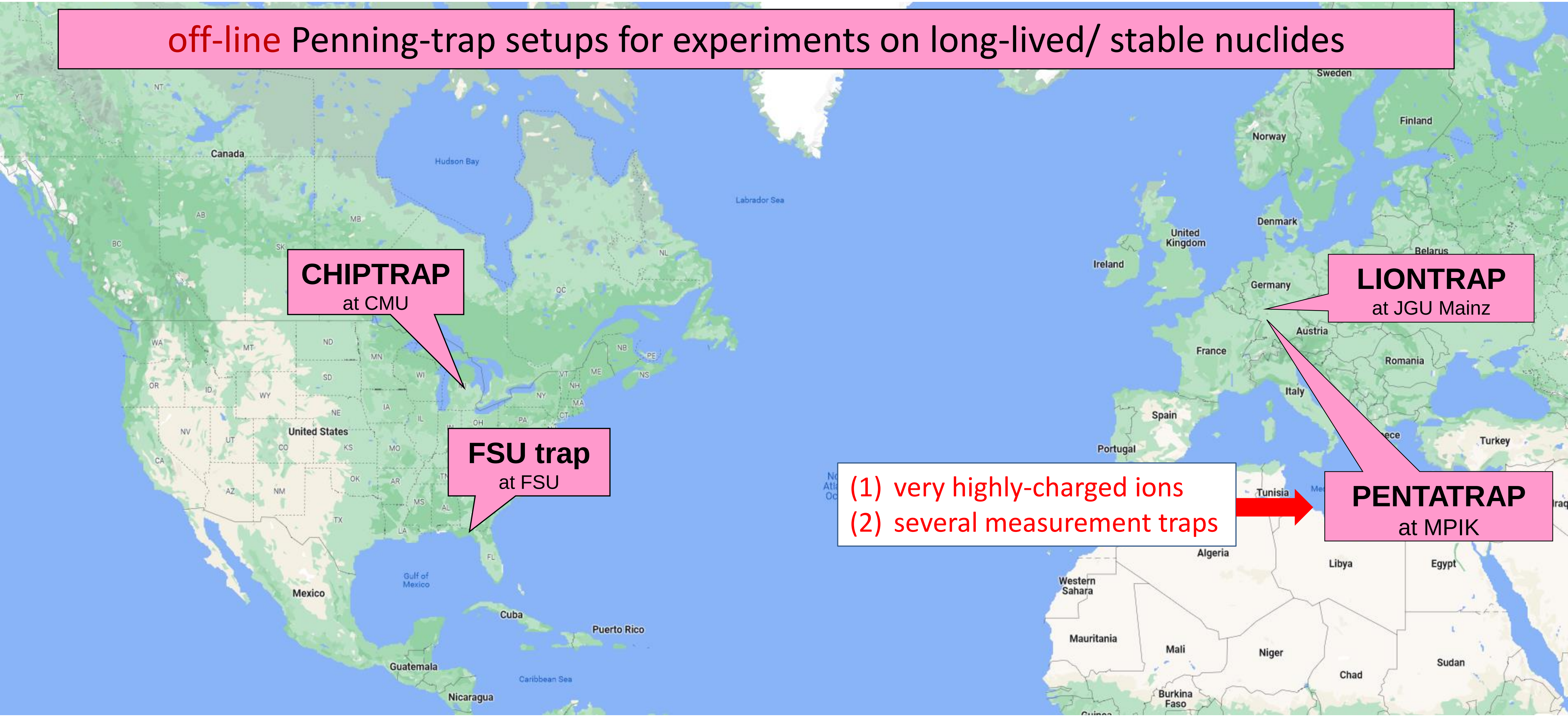
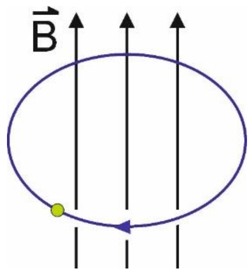


Where we measure masses:

Max Planck Institute for Nuclear Physics (Heidelberg)
Division “Stored and Cooled Ions” (Prof. Klaus Blaum)

Pentatrap (part of MATS section)

Penning trap



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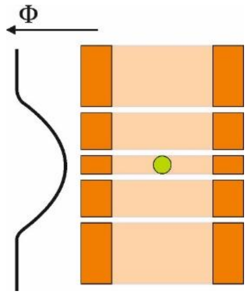

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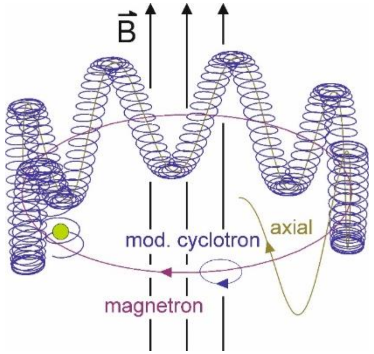


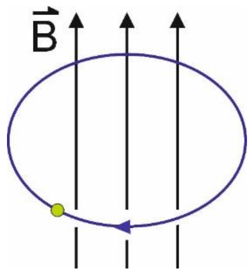
Free-space
cyclotron frequency

$$\omega_c = \frac{qB}{m}$$

Harmonic electrical potential

3 Eigenmotions in trap

Penning trap



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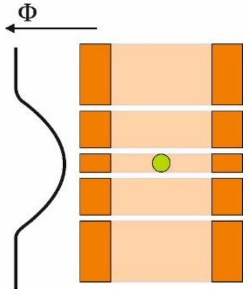

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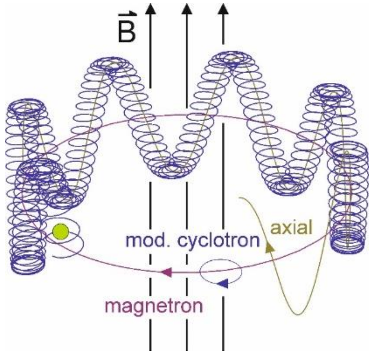

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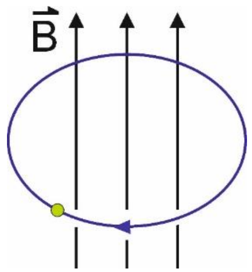
$$\omega_z = \sqrt{\frac{2qC_2}{md^2}U}$$

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

Penning trap



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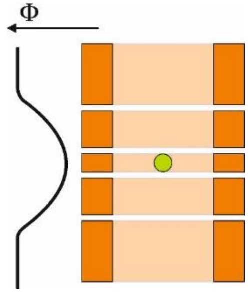

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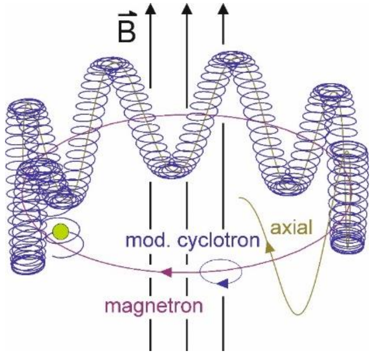

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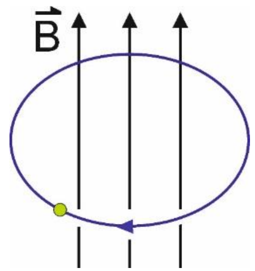
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

Measurement of all Eigenfrequencies

$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$

Rev. Mod. Phys. 58, 233 (1986)

Penning trap



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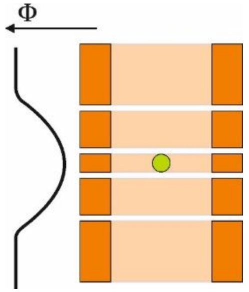

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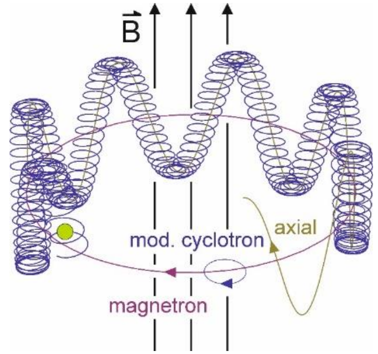


Free-space
cyclotron frequency

$$\omega_c = \frac{q\boldsymbol{B}}{m}$$

Magnetic field drops out in the ratio

Harmonic electrical potential

3 Eigenmotions in trap

$$\omega_z = \sqrt{\frac{2qC_2}{md^2}U}$$

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

Measurement of all Eigenfrequencies

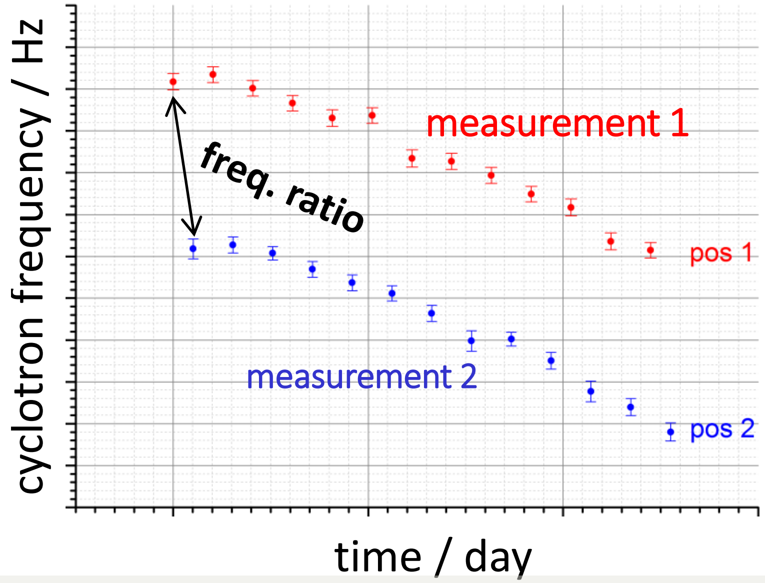
$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$

Rev. Mod. Phys. 58, 233 (1986)

Mass Spectrometry

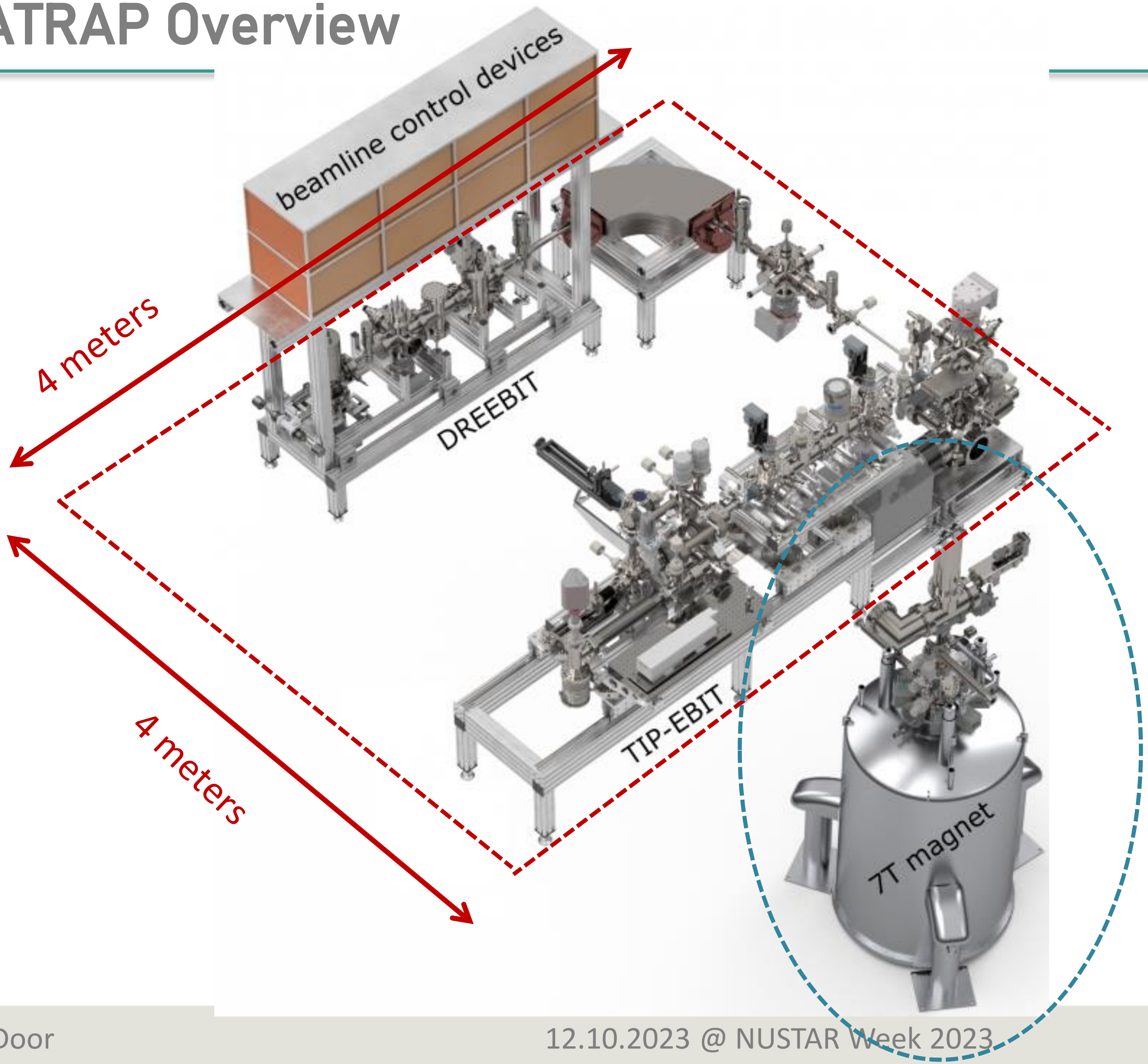
$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$ Ion A

Ion B $$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$



Ion Mass ratio: $$R = \frac{\omega_c^A}{\omega_c^B} = \frac{q^A m^B}{q^B m^A}$$

PENTATRAP Overview



upper level in experimental hall:
EBIT Ion sources for production of highly charged ions

basement under experimental hall:
Penning trap mass spectrometer

PENTATRAP Overview

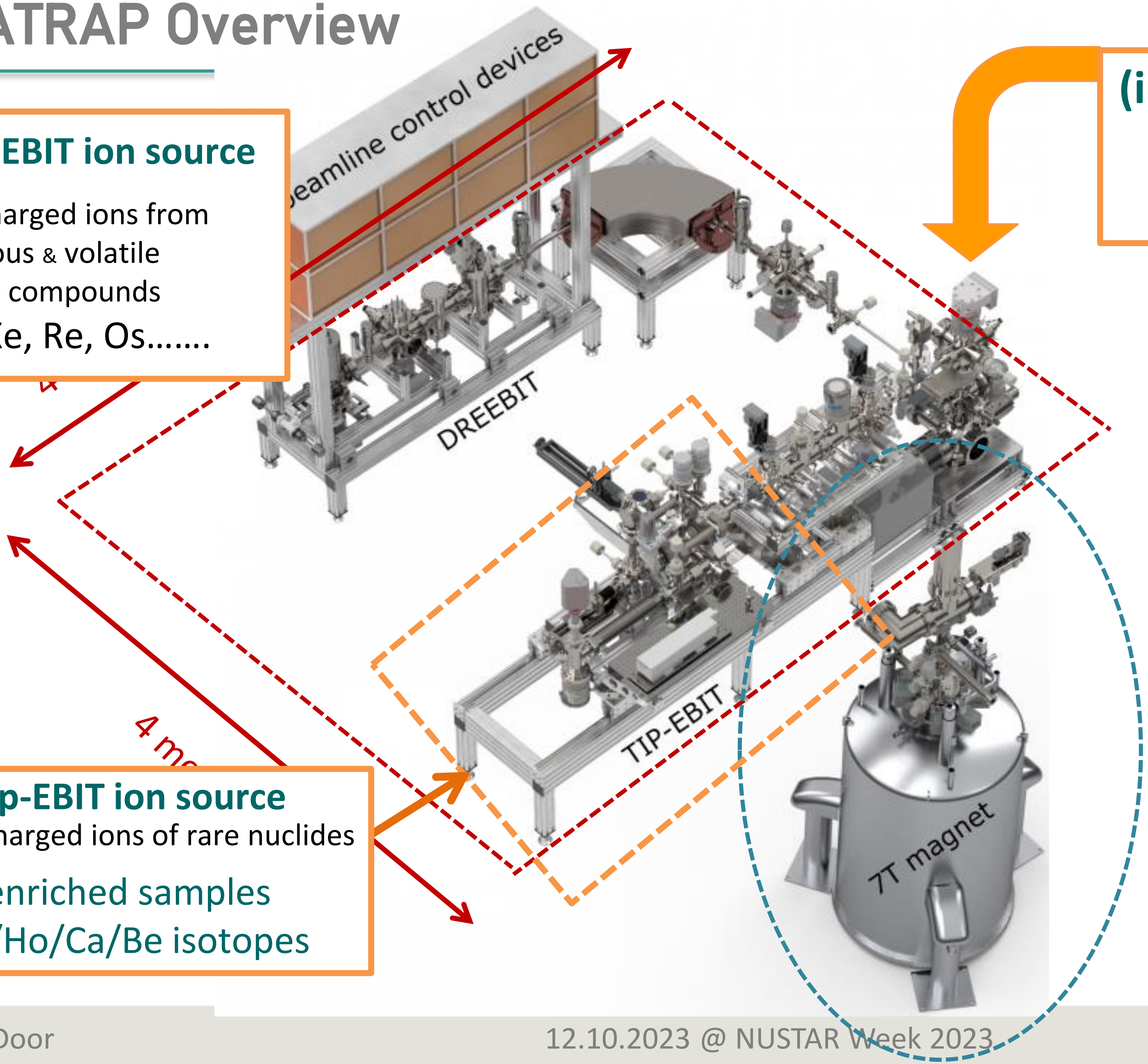
Dresden-EBIT ion source

highly charged ions from gaseous & volatile chem. compounds

Ar, Xe, Re, Os…….

(in future) HD-EBIT / Hyper-EBIT

Pb^{82+}, Pb^{81+}



upper level in experimental hall:
EBIT Ion sources for production of highly charged ions

basement under experimental hall:
Penning trap mass spectrometer

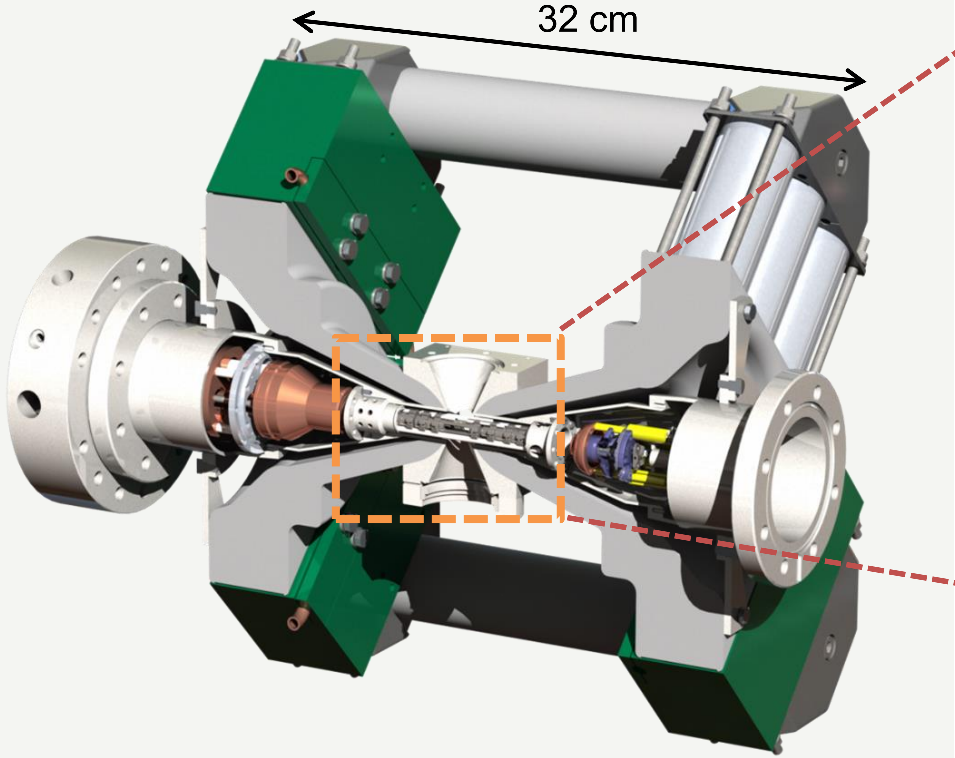
Tip-EBIT ion source
highly charged ions of rare nuclides

enriched samples
Yb/Ho/Ca/Be isotopes

Electron Beam Ion Trap (EBIT) → Tip-EBIT

Mini-EBIT developed in J.R. Crespo‘s group

Micke, P. et al., Rev. Sci. Instr. 89, 063109 (2018)



compact room temperature

permanent magnet, 0.85 T

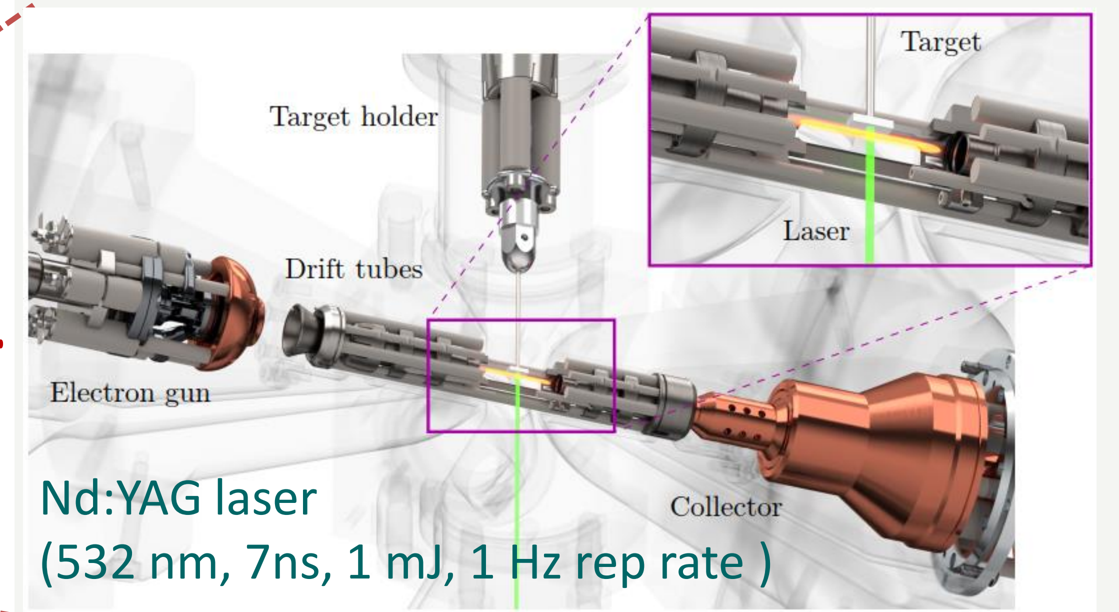
max. electron current = 80 mA

max. electron energy = 10 keV

+

Laser “ablation“

Schweiger, Ch. et al., Rev. Sci. Instr. 90, 123201 (2019)

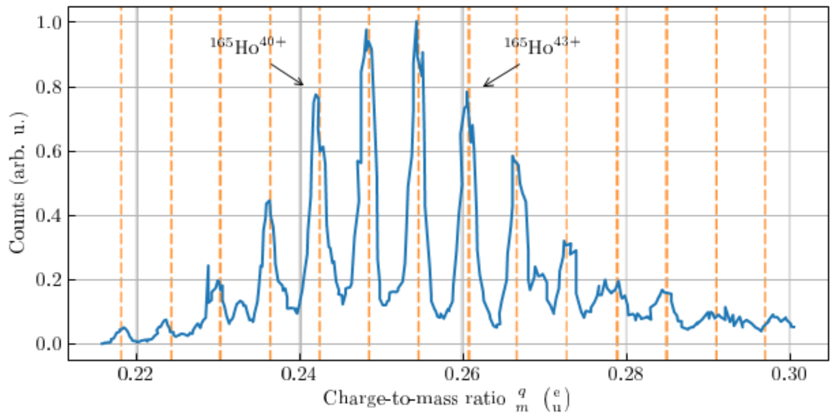


Nd:YAG laser

(532 nm, 7ns, 1 mJ, 1 Hz rep rate)

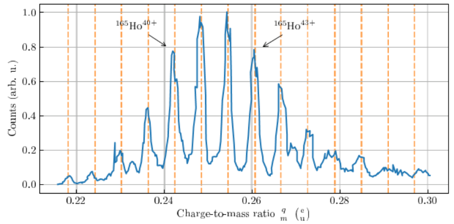
smallest sample: 10^{12} atoms

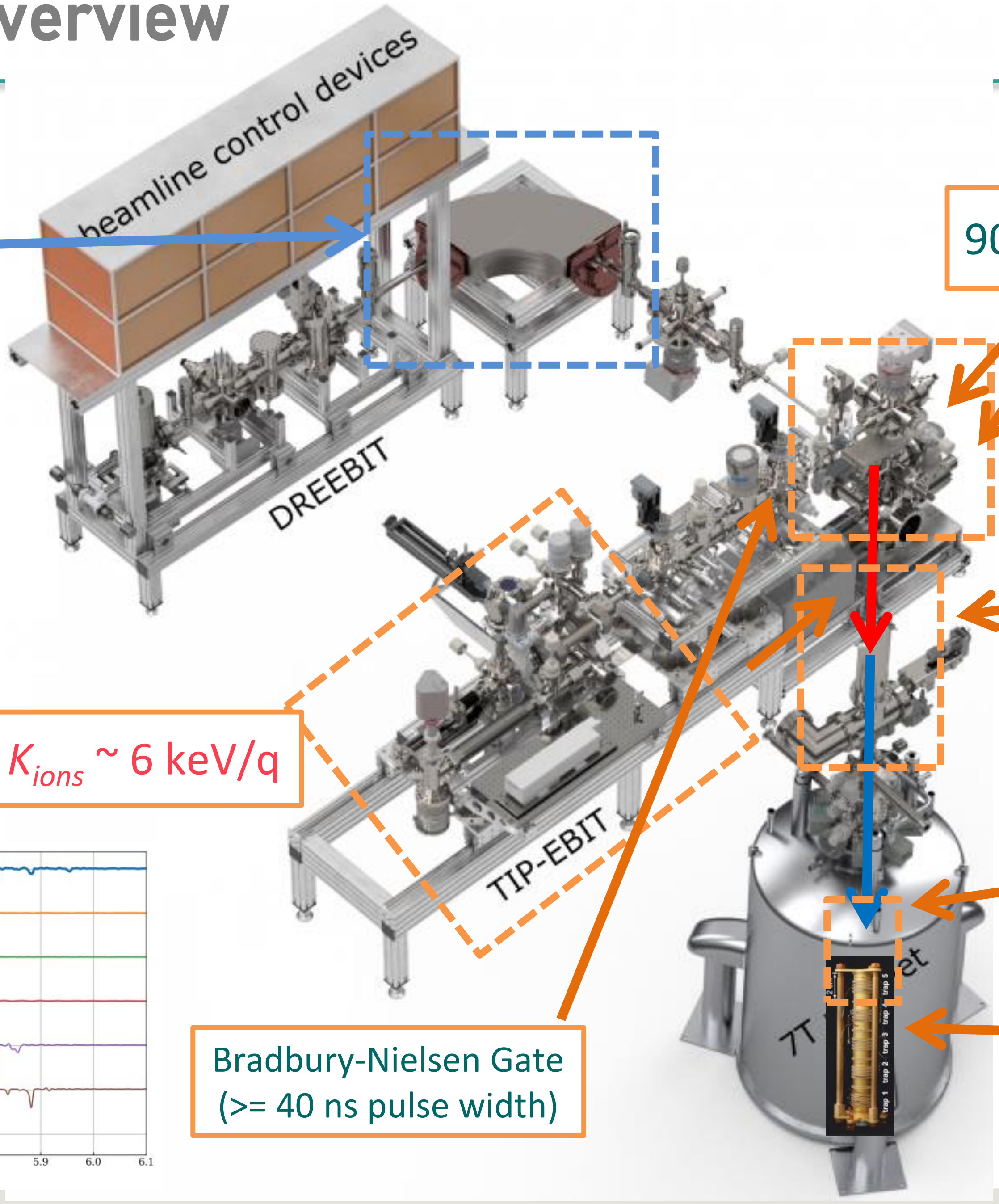
life time: 20000 laser shots



PENTATRAP Overview

90⁰ dipole magnet





90⁰ electrostatic benders

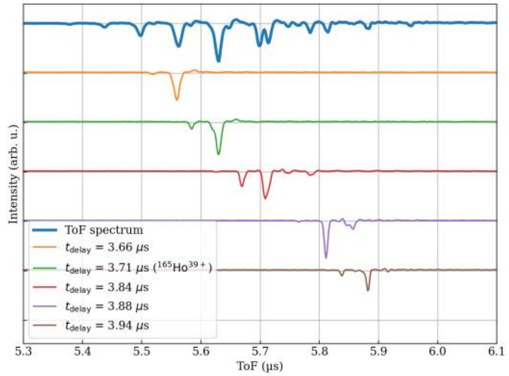
pulsed drift tube
K_{ions} ~ 200 eV/q

K_{ions} ~ 6 keV/q

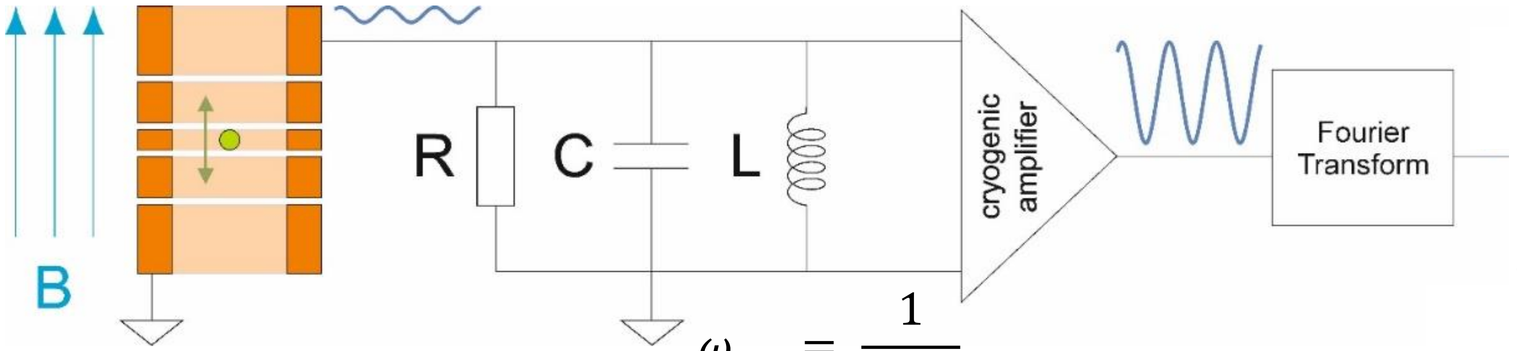
pulsed drift tube
K_{ions} ~ few eV/q

traps

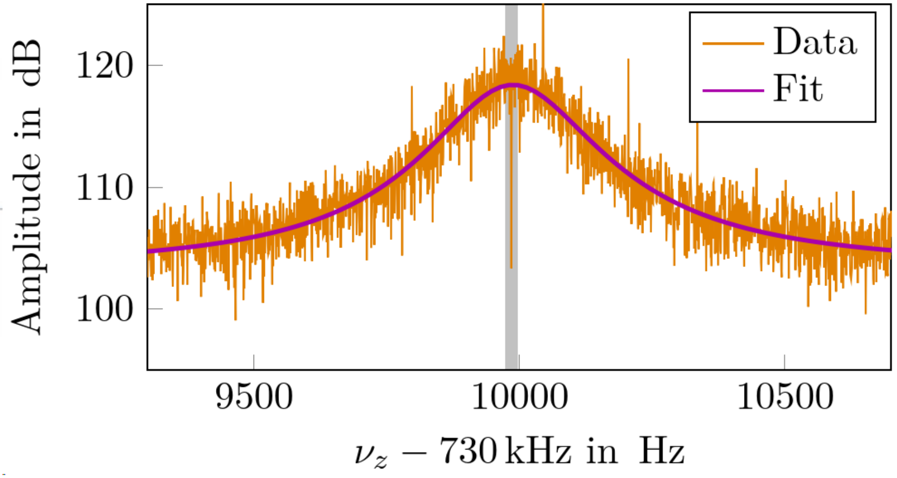
Bradbury-Nielsen Gate
(>= 40 ns pulse width)



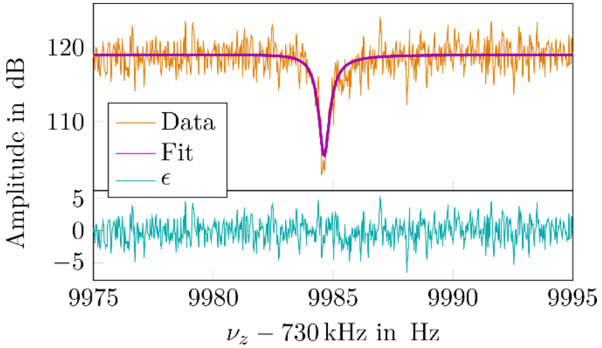
Fourier transform ion cyclotron resonance – FT-ICR



$$\omega_{res} = \frac{1}{\sqrt{LC}}$$

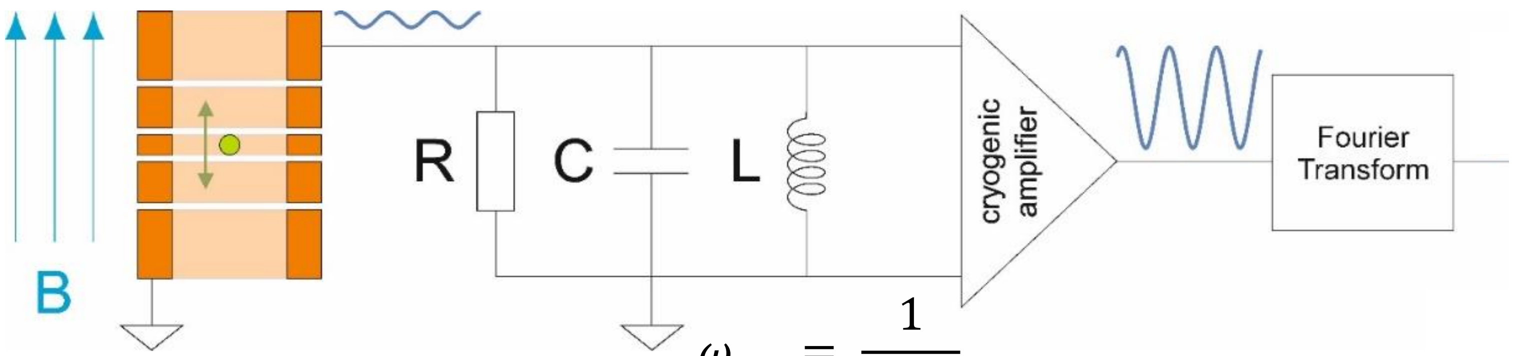


Direct measurement of ω_z by dip method



$$\omega_z = \sqrt{\frac{2qC_2U}{m}} = \omega_{res}$$

Fourier transform ion cyclotron resonance – FT-ICR



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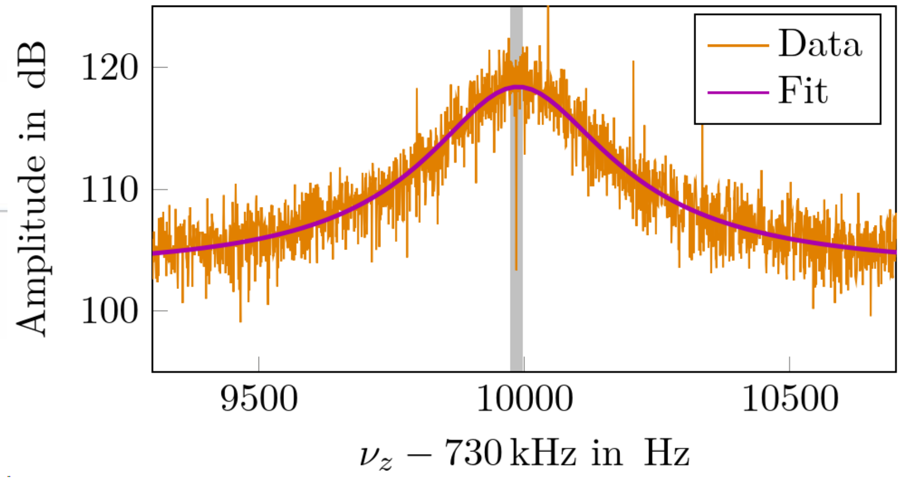

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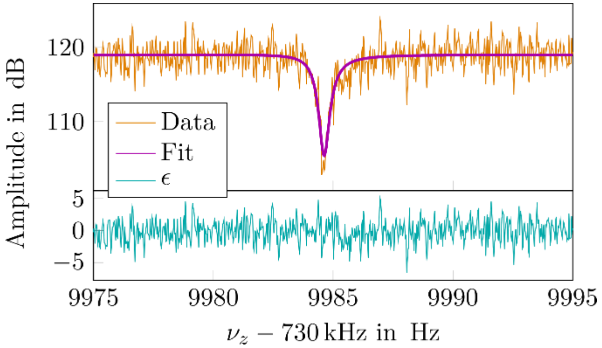
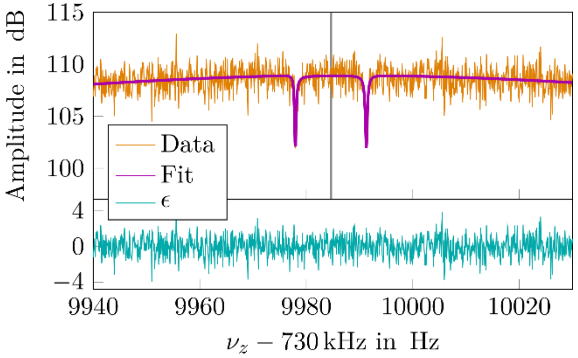


$$\omega_z = \sqrt{\frac{2qC_2U}{m}} = \omega_{res}$$

Indirect measurement of $\omega_{+/-}$ by double dip method



Sideband coupling ω_- to ω_z

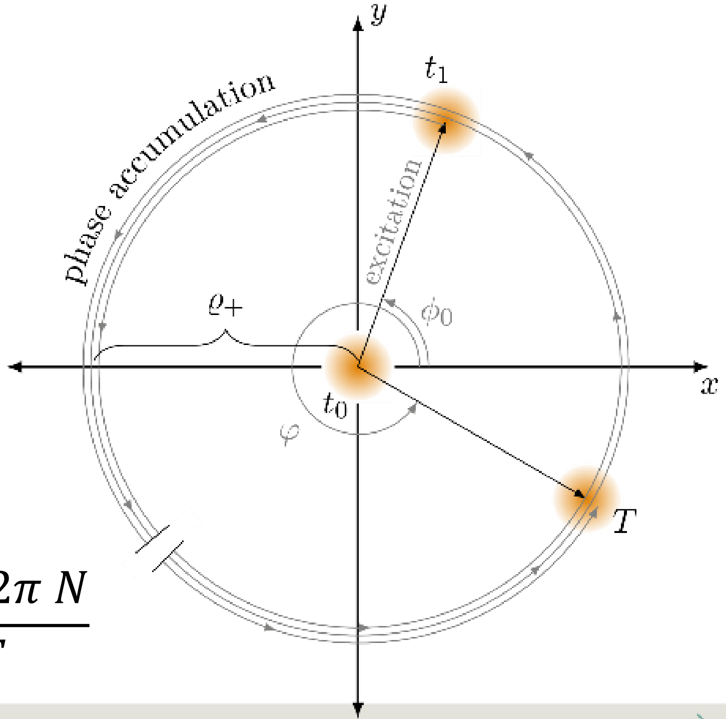
coupling the eigenmotions – harmonic oscillators – to exchange energy

ω_+: phase sensitive method „**Pulse and Phase / PnP**"

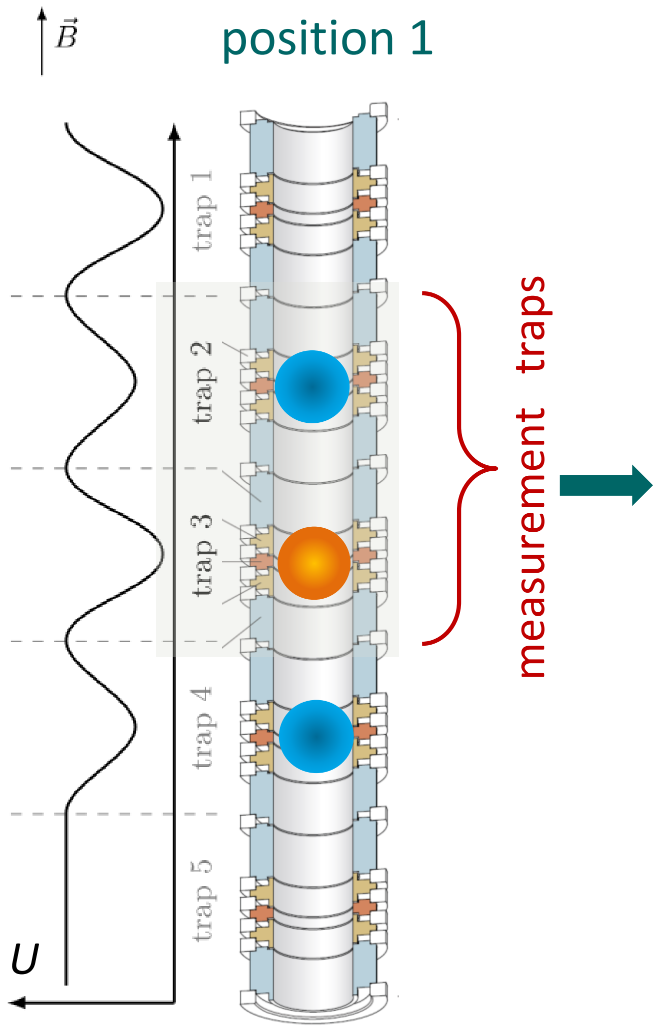
Far more precise then double dip method

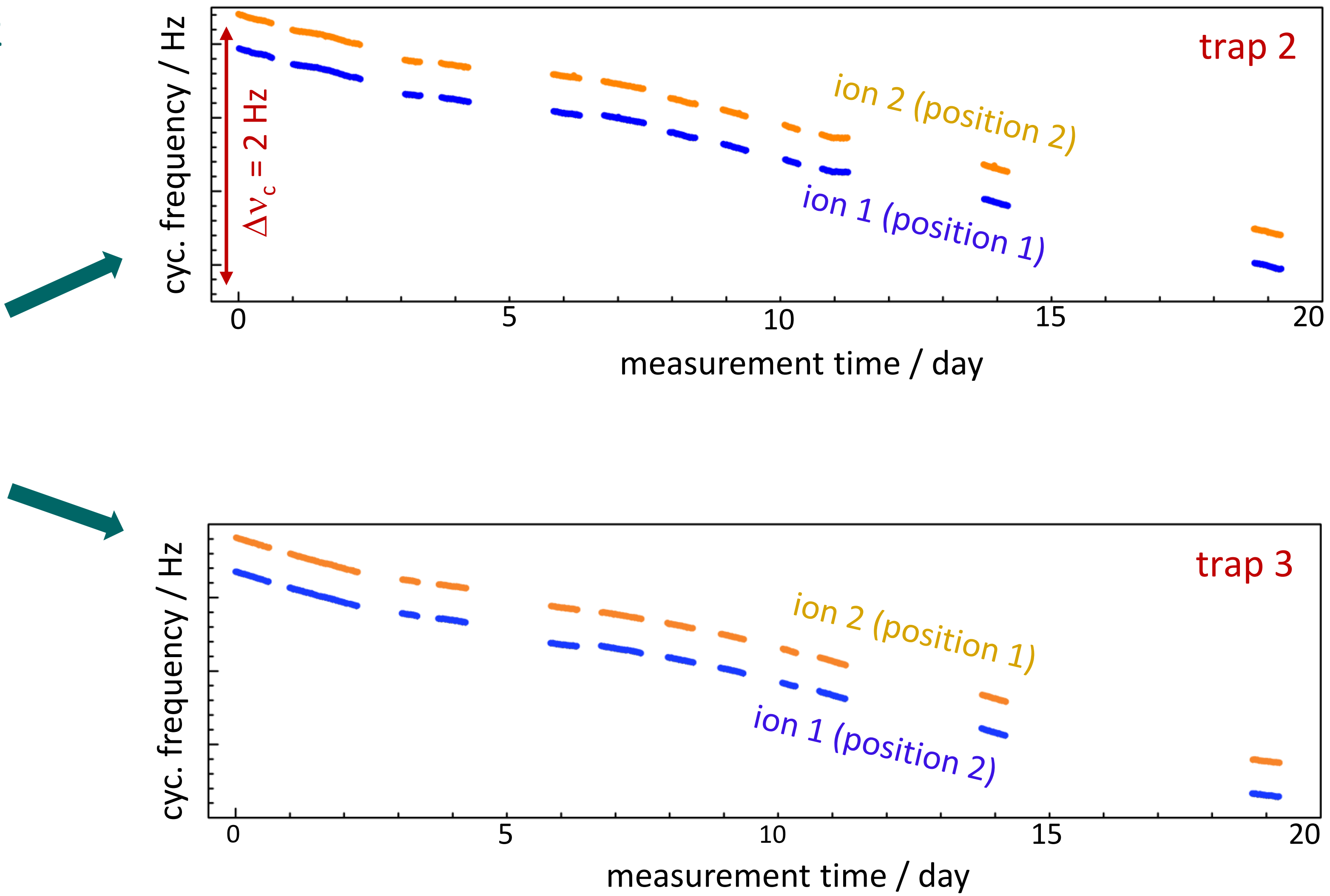
Ramsey type measurement

$$\omega_+ = \frac{\Delta\varphi + 2\pi\, N}{\Delta T}$$



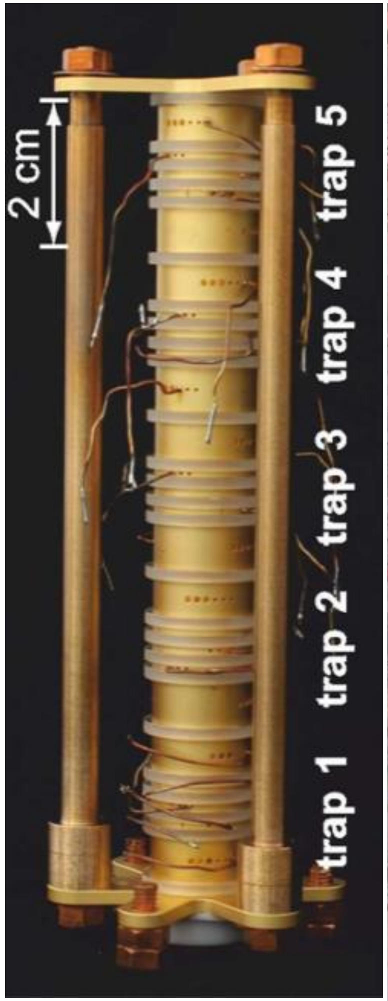
Simultaneous measurement in two traps – nice to check systematics

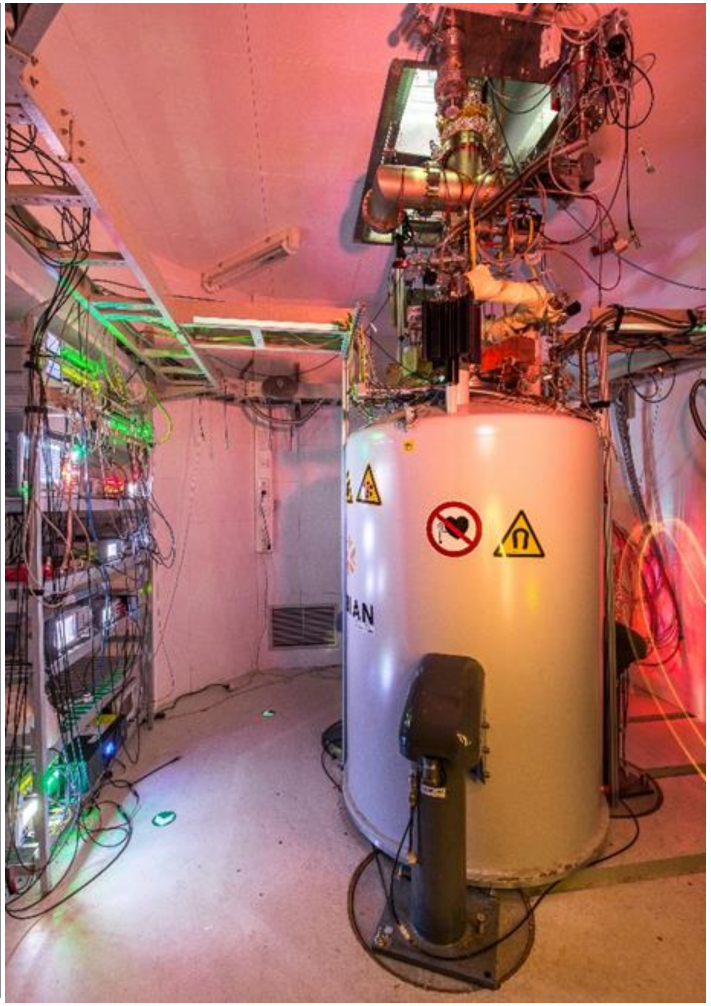




Pentatrap's unique features

- Stack of five identical Penning traps
- Cryogenic detection systems: 4.2 K
- Superconducting magnet with vertical cold bore: 7 T
- 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: $\omega_c \geq 20\ MHz$**
- **Simultaneous measurement of ω_+ and ω_z**
- **Tunable detection system, $\omega_{res} \pm 6\ kHz$**





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)

Pentatrap Motivation: Applications of mass-ratios $\delta m/m \leq 10^{-11}$

Neutrino physics

$^{187}\text{Re} \rightarrow {}^{187}\text{Os} + e^- + \overline{\nu_e} + Q_{\beta^-}$ → Filianin, P. et al., Phys. Rev. Lett. 127, 072502 (2021) — $\delta Q = 1.3$ eV

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Kozlov, M. G. et al., Rev. Mod. Phys. 90, 045005 (2018)

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g-factor: $g = 2\frac{\nu_L}{\nu_c}\frac{m_e}{m({}^{20}\text{Ne})}\frac{q}{e}$ → Heisse, F. et al., Accepted, PRL (2023) — $\delta m = 9 \times 10^{-11}$ amu

Shabaev, V. M. et al., Int. J. of Mass Spec. 251, 109, (2006)

5th force search: Isotope shift

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Flambaum, V. V. et al., Phys. Rev. A 79, 032510 (2018)

Yb isotope mass-ratios done and Analysis/Paper in preparation
Ca isotopes currently being measured

$\frac{\delta(m_A/m_B)}{m_A/m_B} \leq 7 \times 10^{-12}$

Determination of fine structure constant α

$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{Rb}}{m_e}\frac{h}{m_{Rb}}$

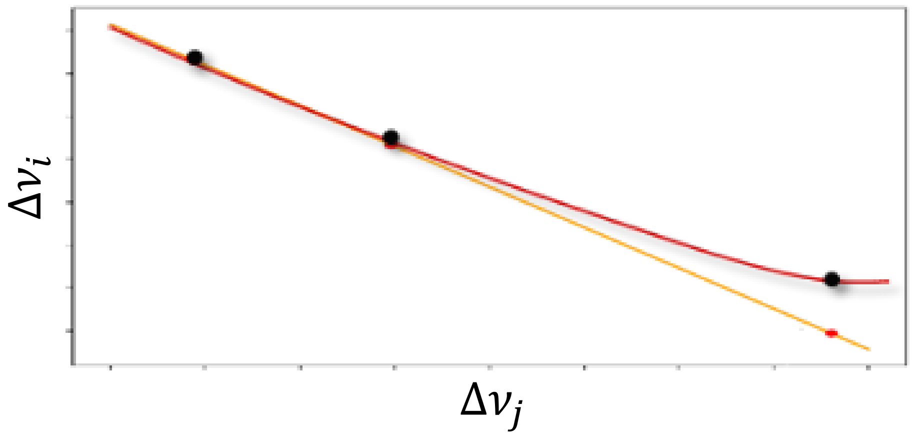
Morel, L., et al., *Nature* **588**, 61–65 (2020)

5th force search – Isotope shift King plot analysis

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

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

King's plot



5th force search – Isotope shift King plot analysis

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

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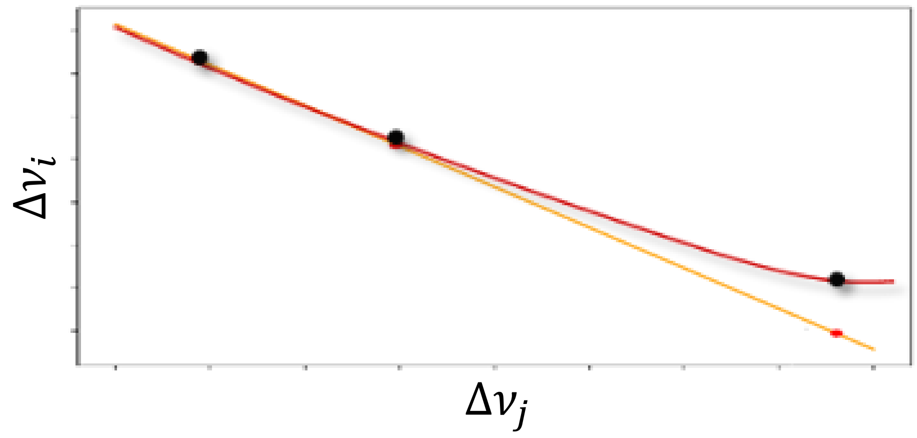

one needs elements with many even-even isotopes and quadrupole (narrow optical) transitions:

^{168,170,172,174,176}Yb	$^2S_{1/2} \leftrightarrow {}^2D_{5/2}$ (411 nm) $^2S_{1/2} \leftrightarrow {}^2D_{3/2}$ (436 nm)	I. Counts et al., PRL 125, 123002 (2020)
^{40,42,44,46,48}Ca	$4s^2S_{1/2} \leftrightarrow 3d^2D_{5/2}$ (729 nm) $4s^2S_{1/2} \leftrightarrow 3d^2D_{3/2}$ (732 nm)	C. Solaro et al., PRL 125, 123003 (2020) F.W. Knollmann et al., PRA 100, 022514 (2019)
^{84,86,88,90}Sr	$5S_{1/2} - 4D_{5/2}$ $1S_0 - 3P_1$, $1S_0 - 3P_0$	T. Manowitz et al., PRL 123, 203001 (2019) H. Miyake et al., PRR 1, 033113 (2019)

^{142,144,146,148,150}Nd	^{130,132,134,136,138}Ba
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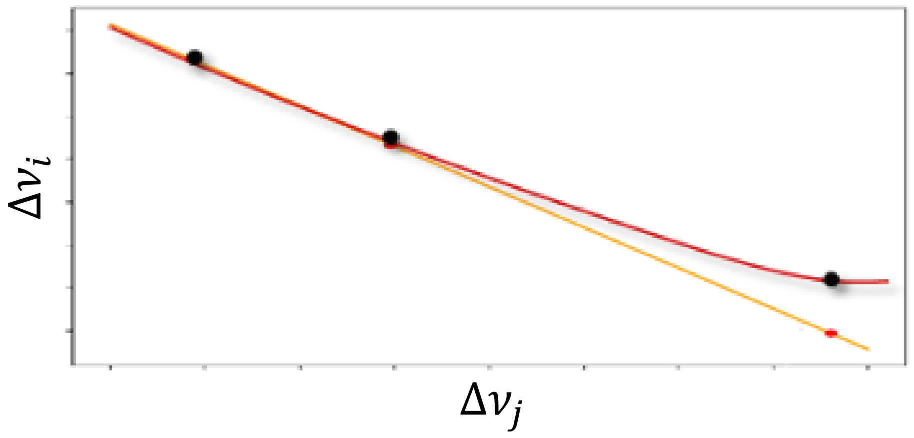

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FUTURE of IS spectroscopy:

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

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

5th force search – Isotope shift King plot analysis

$$\delta R = \frac{\omega_c(^{A}\mathrm{Yb}^{42+})}{\omega_c(^{A'}\mathrm{Yb}^{42+})} = \frac{m_{A'}}{m_A} \approx 5 * 10^{-12}$$

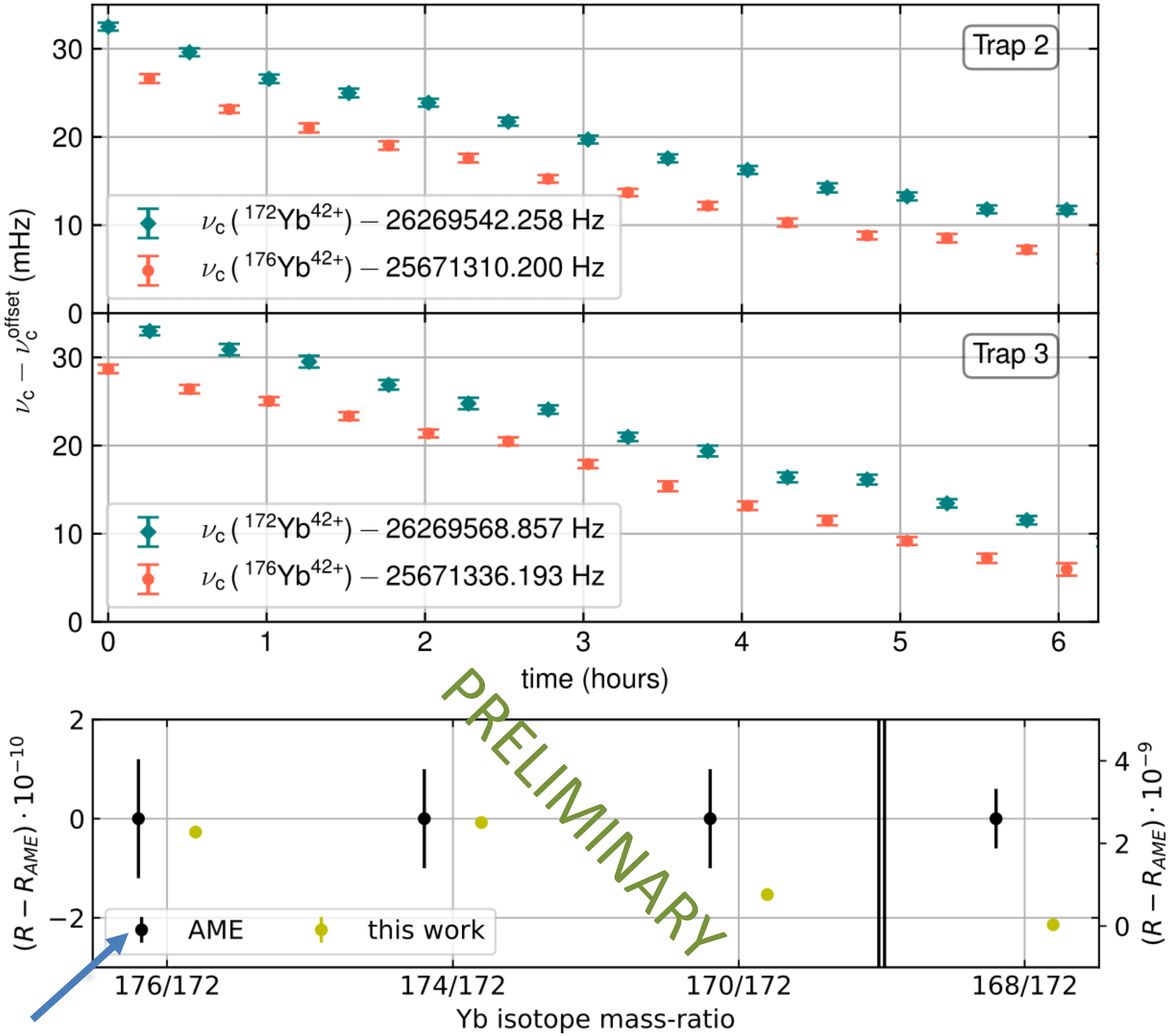
strongest systematic uncertainties:

1) dip line shape / fit
2) relativistic shifts

Measured as non-doublets:

- All isotopes at 42+ charge state
- Detection system tuned to match axial and resonator frequency
- No systematics due to trap anharmonics or magnetic field inhomogeneities!

Improved mass-ratios by at least factor of 20 compared to literature (atomic mass evaluation - AME)



5th force search – Isotope shift King plot analysis

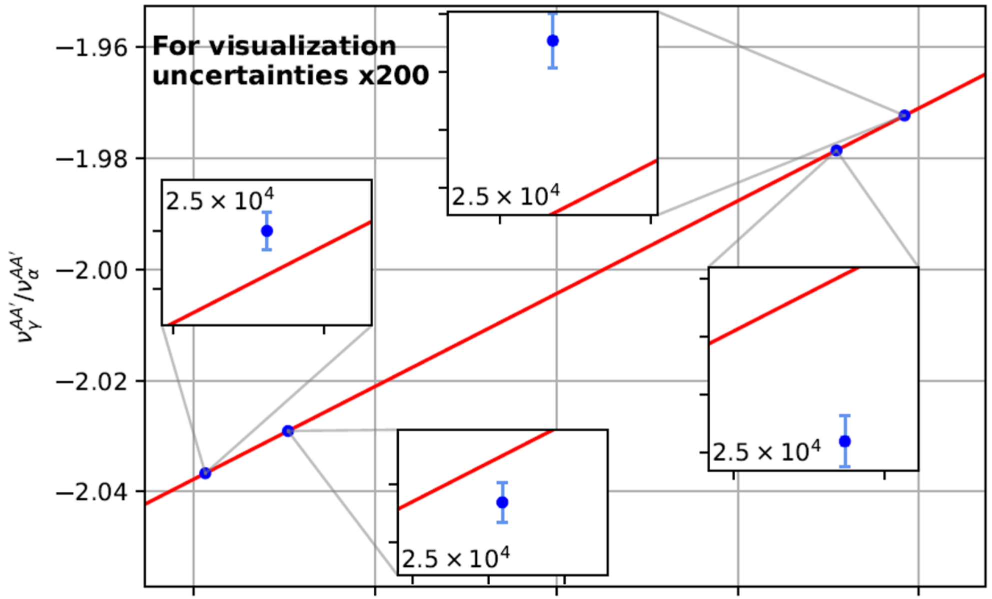
Nuclear masses needed: **Binding energies for correction** precisely calculated by Zoltan Harmans Group, Chunhai Lyu (MPIK, Heidelberg)

High precision spectroscopy data from the group of Tanja Mehlstaeubler, PhD student Chih-Han Yeh (PTB Braunschweig, Germany) + published data from other groups

Analysis is still ongoing (Julian Berengut, group of Elina Fuchs, group of Achim Schwenk):

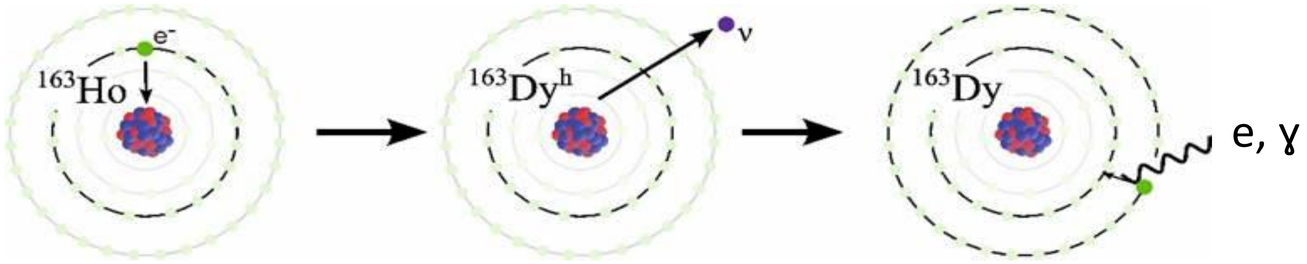
- Nuclear deformation effects are dominant source of non-linearity **(QFS)**
- Extraction of limits for 5th force carrier boson difficult

Better cases might be Calcium (less QFS) or Tin (more isotopes)

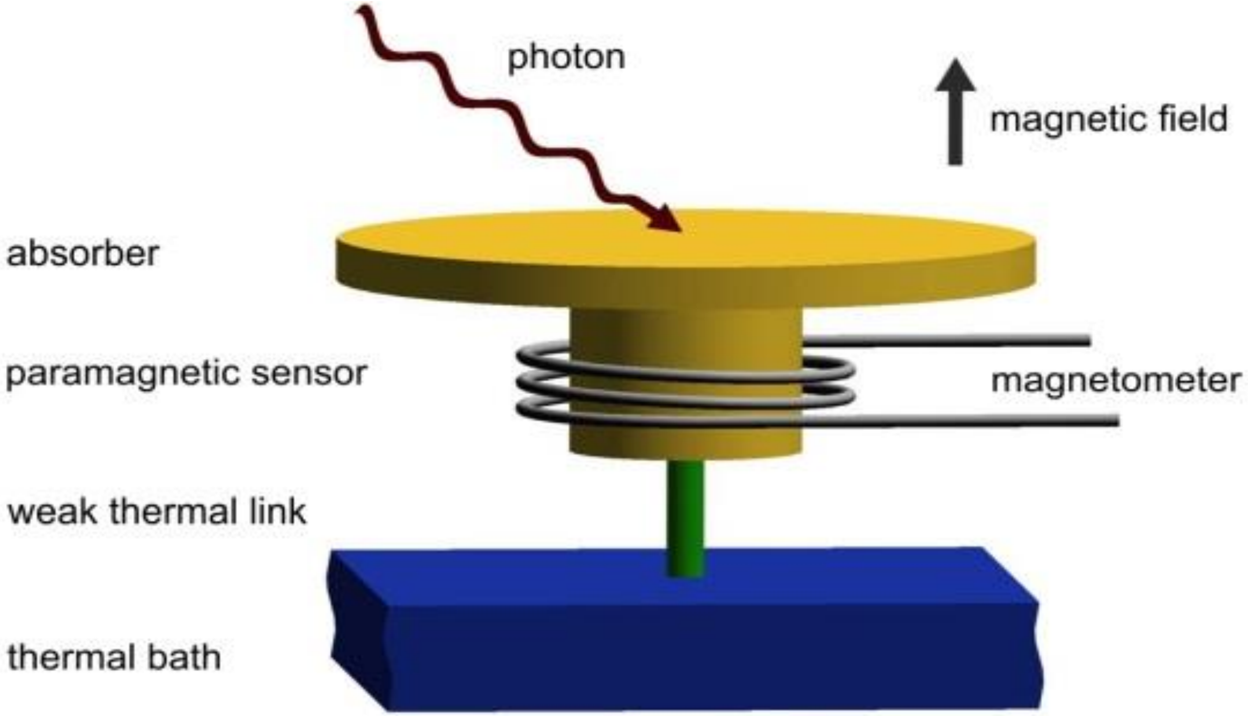


PRELIMINARY DATA
PLOT REMOVED
FOR ONLINE VERSION

The Electron Capture in Holmium experiment



$$^{163}\mathrm{Ho} + e^- \longrightarrow {}^{163}\mathrm{Dy}^{\star} + \nu_e \longrightarrow {}^{163}\mathrm{Dy} + \nu_e + Q_{EC}$$



Current best upper limits on m_{ν_e}:

Cosmology	0.12 eV/c² (95 % C.L.)
KATRIN ($\bar{\nu}_e$)	0.8 eV/c² (90 % C.L.)
ECHo (ν_e)	150 eV/c² (95 % C.L.)
ECHo aims at:	**≈ 1 eV/c²**

- m_{ν_e} via electron capture process in ^{163}Ho
- Metallic magnetic calorimeters, determining full spectrum (except neutrino)
- ^{163}Ho directly implanted in the absorber

Aghanim, N. et al., *A&A 641*, A6 (2020)
Aker, M. et al., Nat. Phys. 18, 160 (2022)
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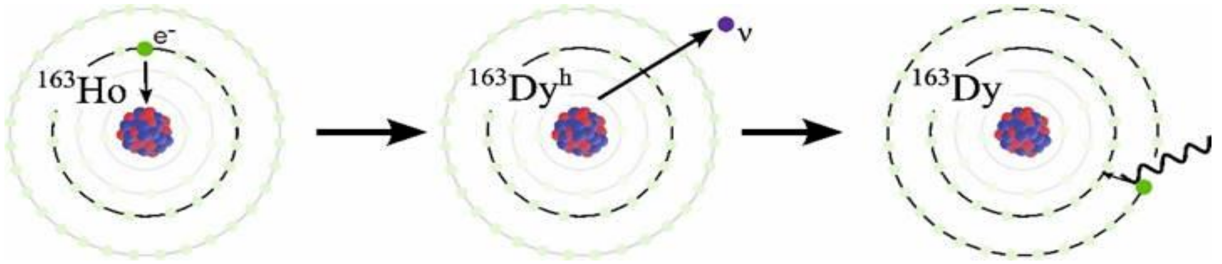

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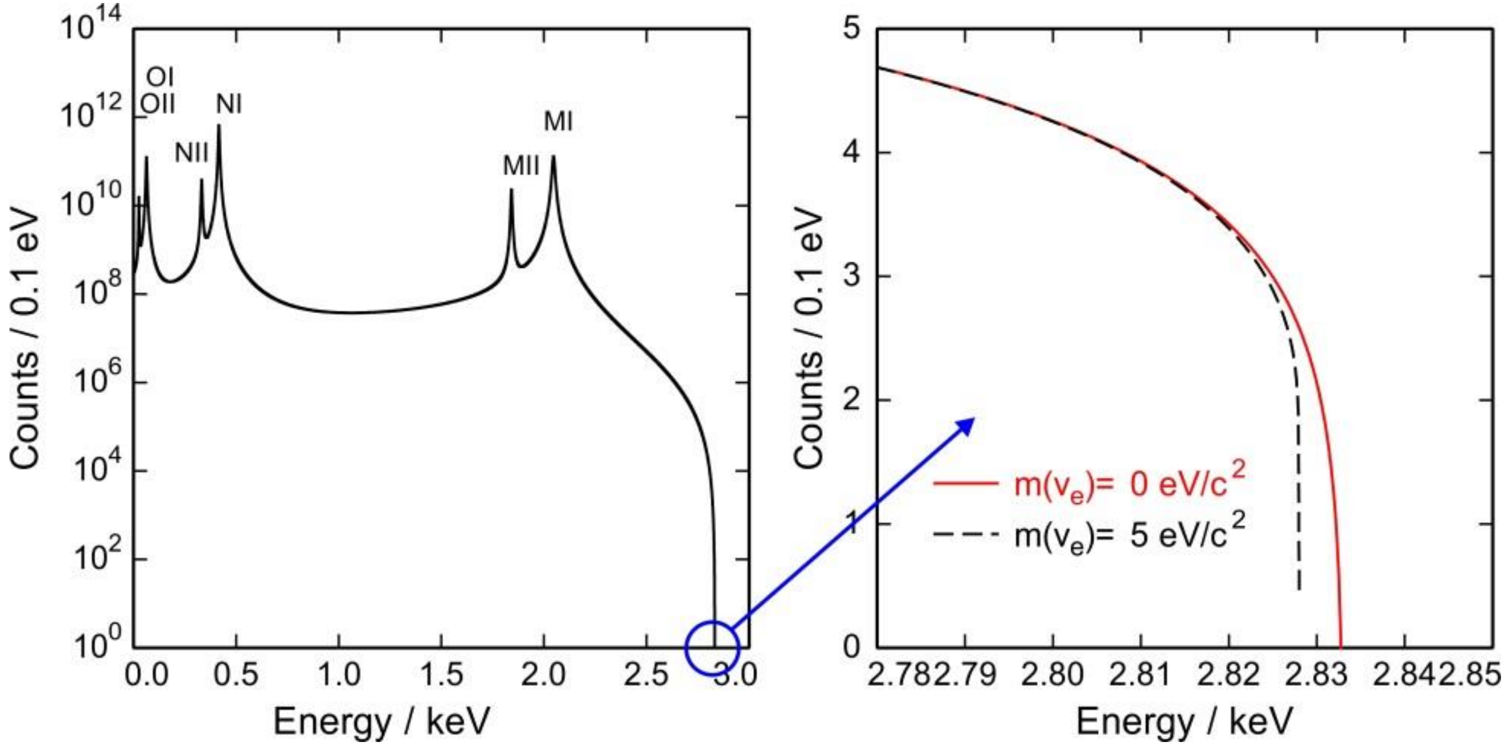

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Determination of Q-value of EC in 163Ho

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

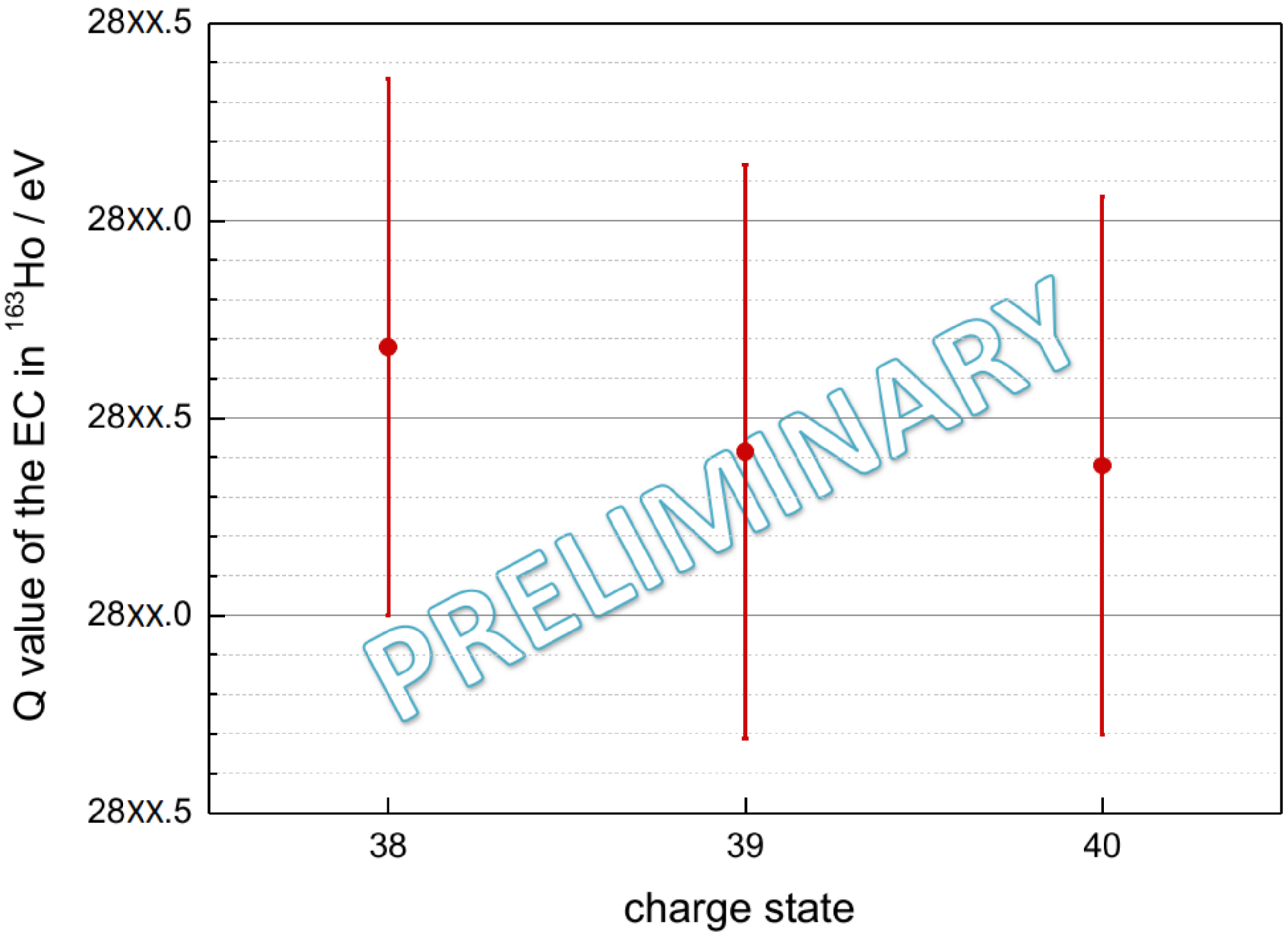
Theory groups calculating binding energies
Maurits Haverkort
Zoltan Harman
Paul Indelicato

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

charge state	cyclotron freq ratio, *R*
38+	$1.0000000186XX3 \pm 3.0\cdot10^{-12}$
39+	$1.0000000113XX5 \pm 4.0\cdot10^{-12}$
40+	$1.0000000115XX6 \pm 3.5\cdot10^{-12}$

preliminary final uncertainty:

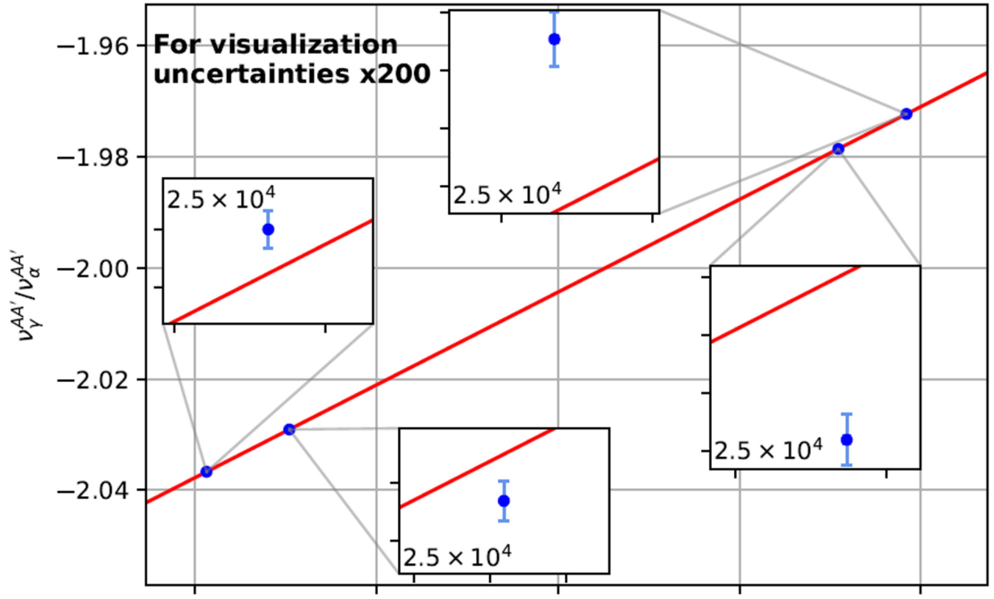
$$\delta Q \approx 0.8\ eV$$



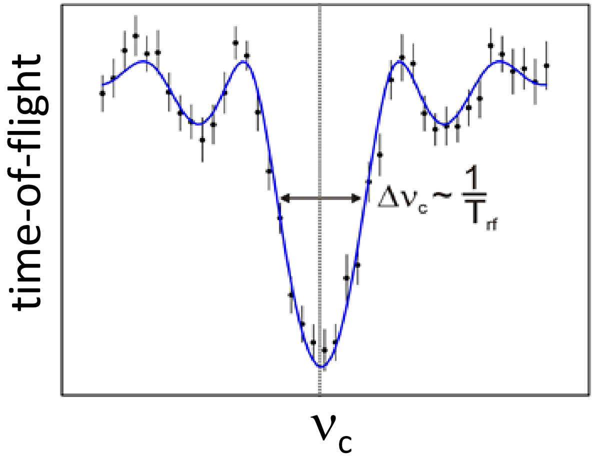
Outlook for few ppt mass ratios of stable and long-lived isotopes

Next measurements:

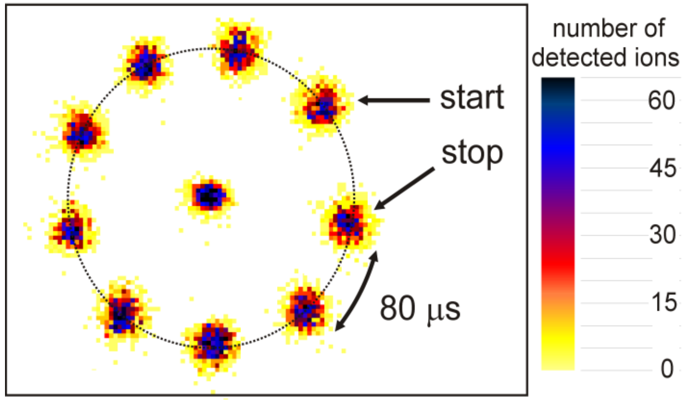
- **Calcium chain for fifth force search**
- 7-Be for sterile neutrino physics (50 days halflife)
- Rb and Cs masses, supporting atomic recoil measurements for the determination of the fine structure constant
- Meta stable states for HCI clocks
- **Reference masses for online experiments, e.g. 208-Pb (K. Kromer et al. 2022), 238-U, 249-Cf, 251-Cf**



online ToF-ICR



online PI-ICR



Thank you for your attention!

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Present and former PENTATRAP members:

Christine Böhm, Menno Door, Andreas Dörr, Sergey Eliseev, Lucia Enzmann, Pavel Filianin, Jost Herkenhoff, Daniel Lange, Kathrin Kromer, Marius Müller, Jan Nägele, Yuri N. Novikov, Julia Repp, Alexander Rischka, Christian Roux, Christoph Schweiger, Rima X. Schüssler and Klaus Blaum