

Helmholtz Investigator Group: High Precision Mass Measurements of Highly Charged Ions

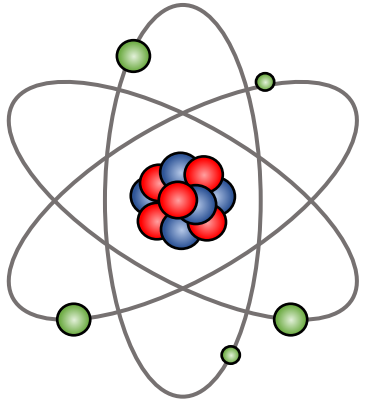
Rima Schüssler



HI JENA
Helmholtz Institute Jena



HIG: High Precision Mass Measurements

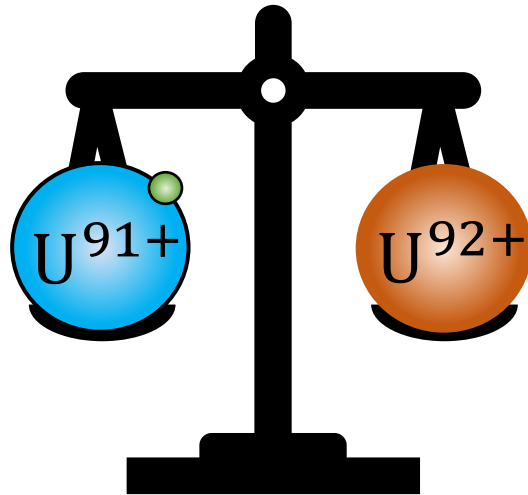


Einstein: $E = mc^2$

$$= N \cdot \text{red dot} + Z \cdot \text{blue dot} + n_{elec} \cdot \text{green dot} - B_{nucl} / c^2 - B_{elec} / c^2$$

Helmholtz Investigator Group

Test of QED in strong fields with a mass measurement



Outline

QED with mass measurements

Penning trap mass spectrometry

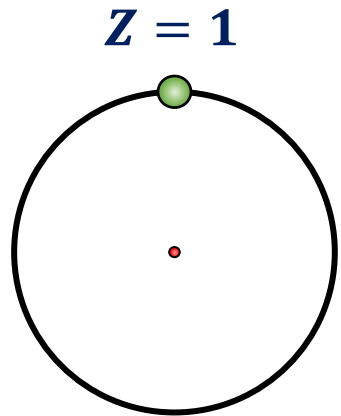
Current status

Dealing with the fire

Test of QED

Best tested theory

Light systems
e.g. Hydrogen



$\text{QED} \sim Z^4$

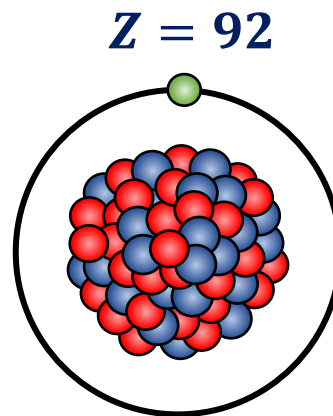
$$f_{1S-2S} = 2\,466\,061\,413\,187\,018\, (11) \text{ Hz}$$

Low energy: traps

PRL 110, 230801 (2013)

Tests not as precise

Heavy systems
e.g. U^{91+}



$$f_{Ly\alpha} = 3.35075\, (14) \times 10^{19} \text{ Hz}$$

High energy: storage rings

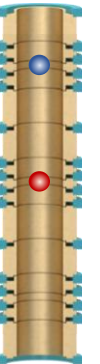
PRL 94, 223001 (2005)

Do QED calculations hold
in strong fields?

Challenging for experiment and theory

Novel approach
for testing QED in
strong fields

Ion traps
Masses

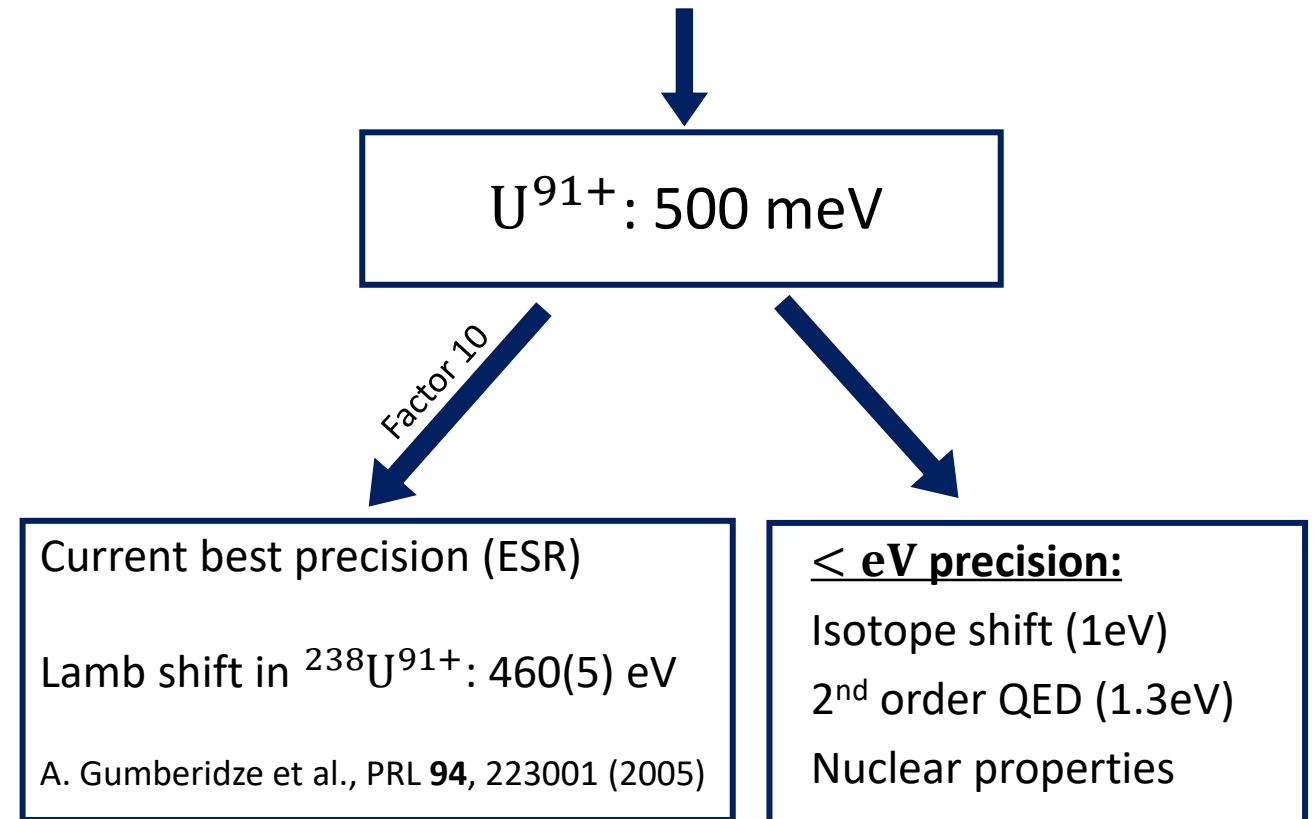
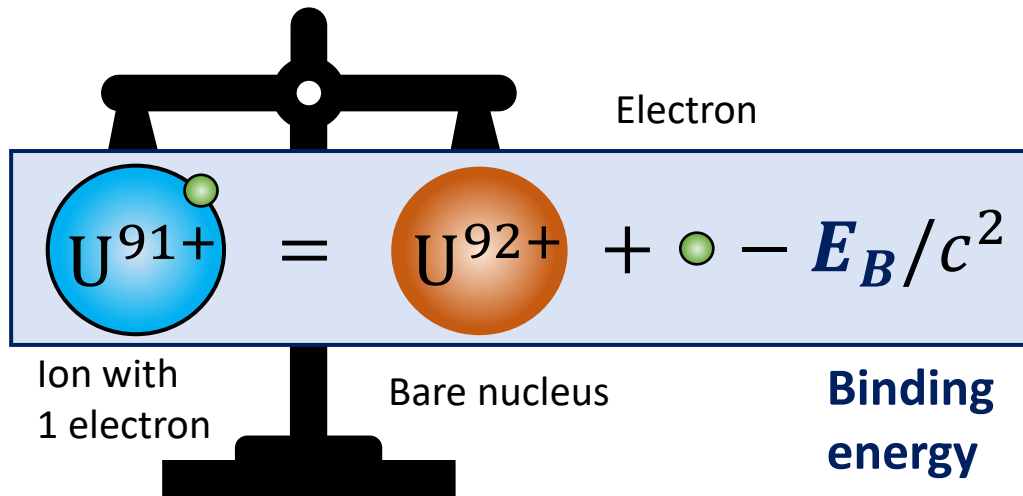


Test of QED

Binding energy via high-precision mass measurement with $\delta m/m \approx 10^{-12}$

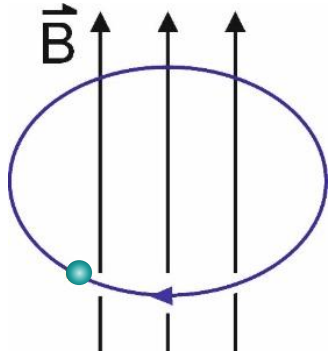
QED effect: Lamb shift

Einstein: $E = mc^2$



All charge states (He-like, Li-like...)
→ Multi-electron theories

Penning trap mass measurement

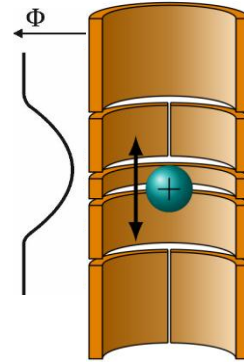


Free-space
cyclotron frequency

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

Relative measurement

$$R = \frac{\omega_{c1}}{\omega_{c2}} = \frac{q_1 m_2}{q_2 m_1} \frac{B_1}{B_2}$$



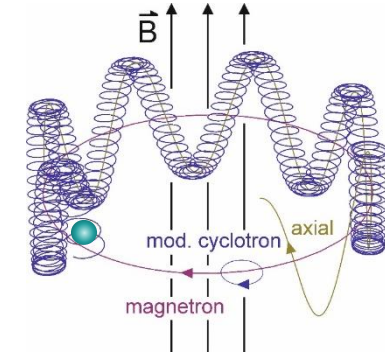
Harmonic electrical
potential

Measurement of all
Eigenfrequencies

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

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

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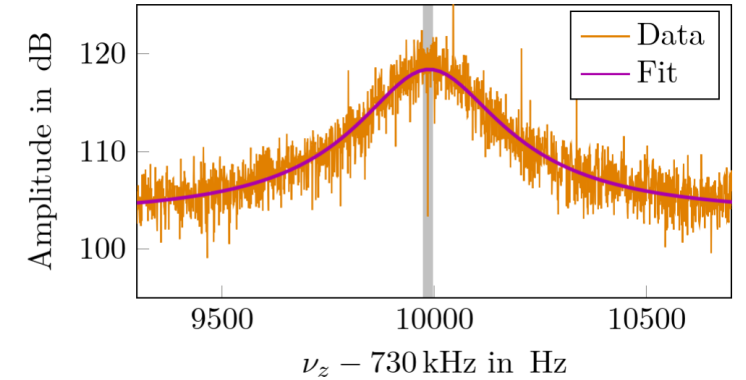
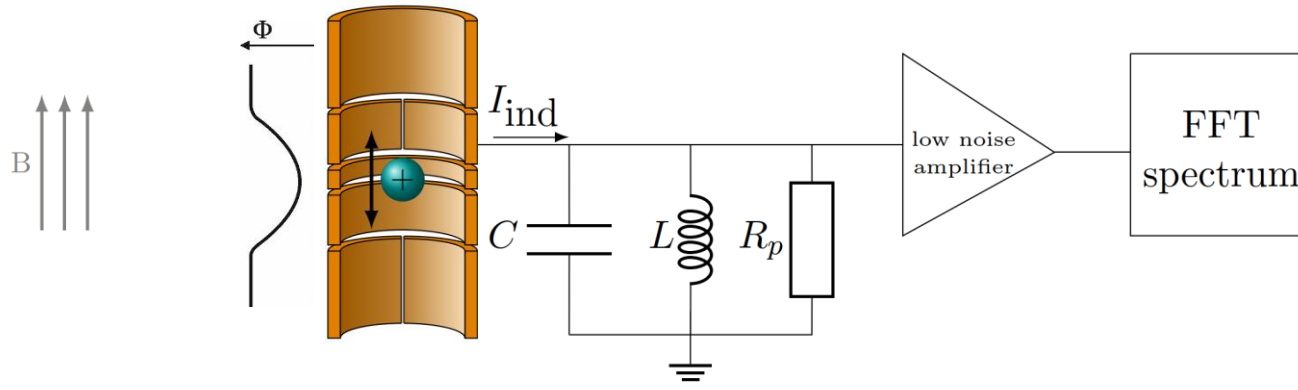
3 Eigenmotions in trap

Axial $\omega_z = \sqrt{\frac{q}{m} \cdot \frac{U}{d^2}}$ 600 kHz

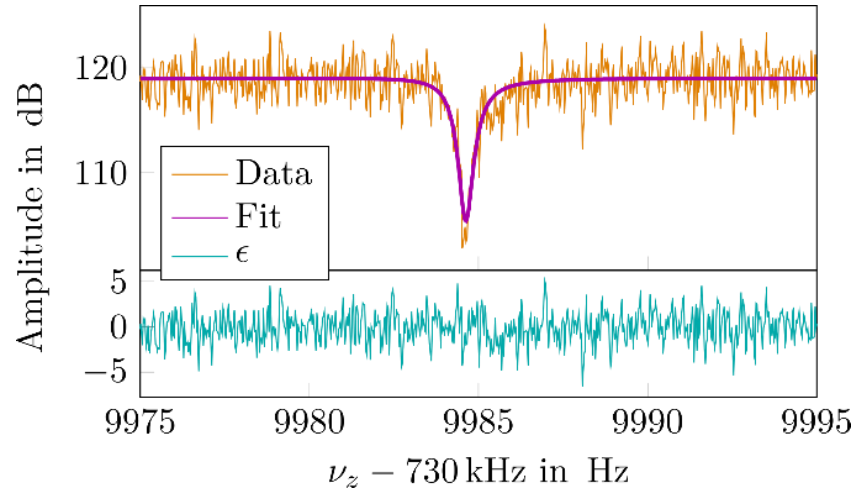
Mod. cyclotron $\omega_+ = \frac{\omega_c}{2} + \frac{\omega_c}{2} \sqrt{1 - 2\omega_z^2}$ 40 MHz

Magnetron $\omega_- = \frac{\omega_c}{2} - \frac{\omega_c}{2} \sqrt{1 - 2\omega_z^2}$ 10 kHz

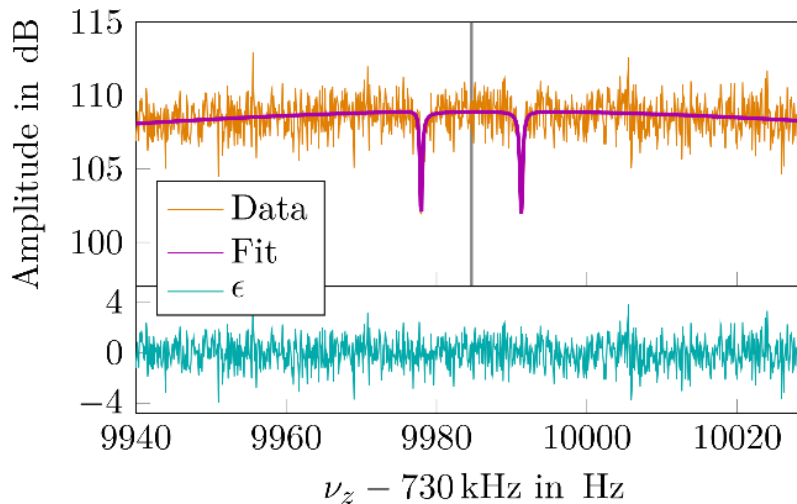
Fourier transform ion cyclotron resonance



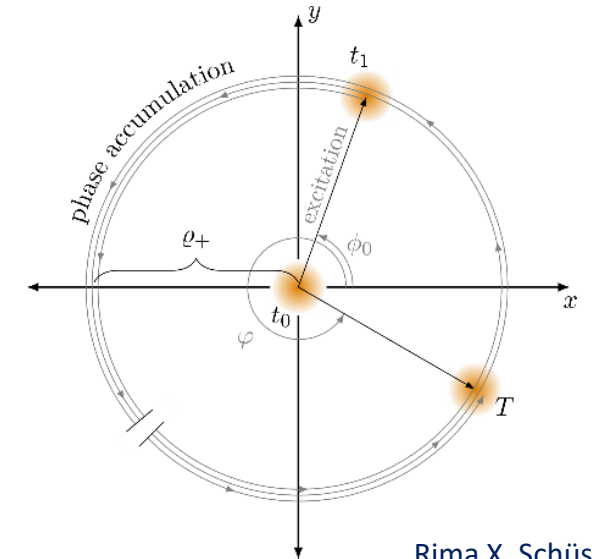
Axial ω_z :
Direct measurement



Magnetron ω_- :
Sideband coupling to ω_z



Modified cyclotron ω_+ :
phase method PnP

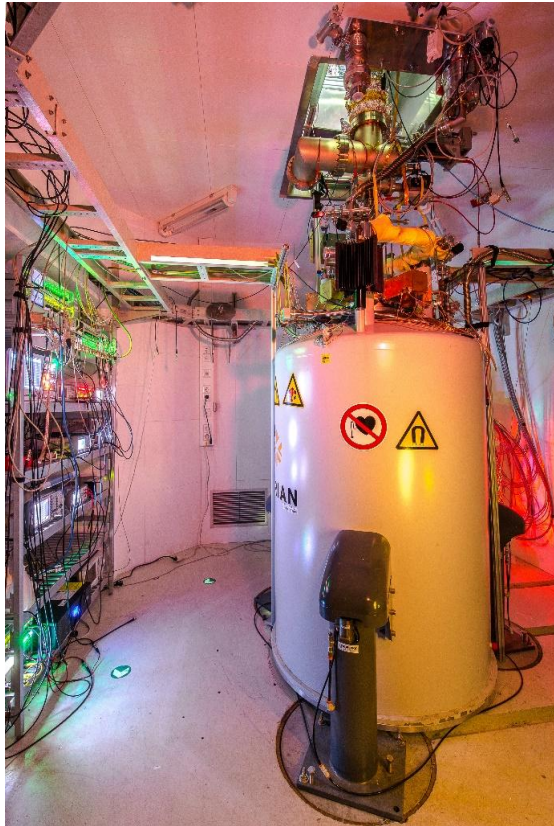


Experimental Setup

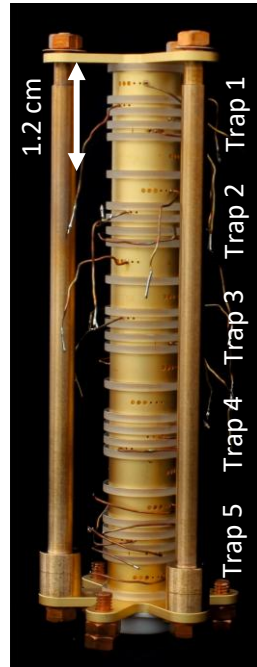
Goal: $\delta m/m \approx 10^{-12}$

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

$$\omega_z = \sqrt{\frac{q}{m} \cdot \frac{U}{d^2}}$$



Pentatrap



Stable & homogeneous magnet: **7T**

Ultra-stable voltage source (StaRep): $\frac{\Delta U}{U} < 10^{-8} / 100 \text{ s}$

Several traps

Simultaneous measurement of ω_+ and ω_z

Highly charged ions: $\omega_c \geq 10 \text{ MHz}$

Cryogenic setup: long storage, low noise

Temperature stabilized lab

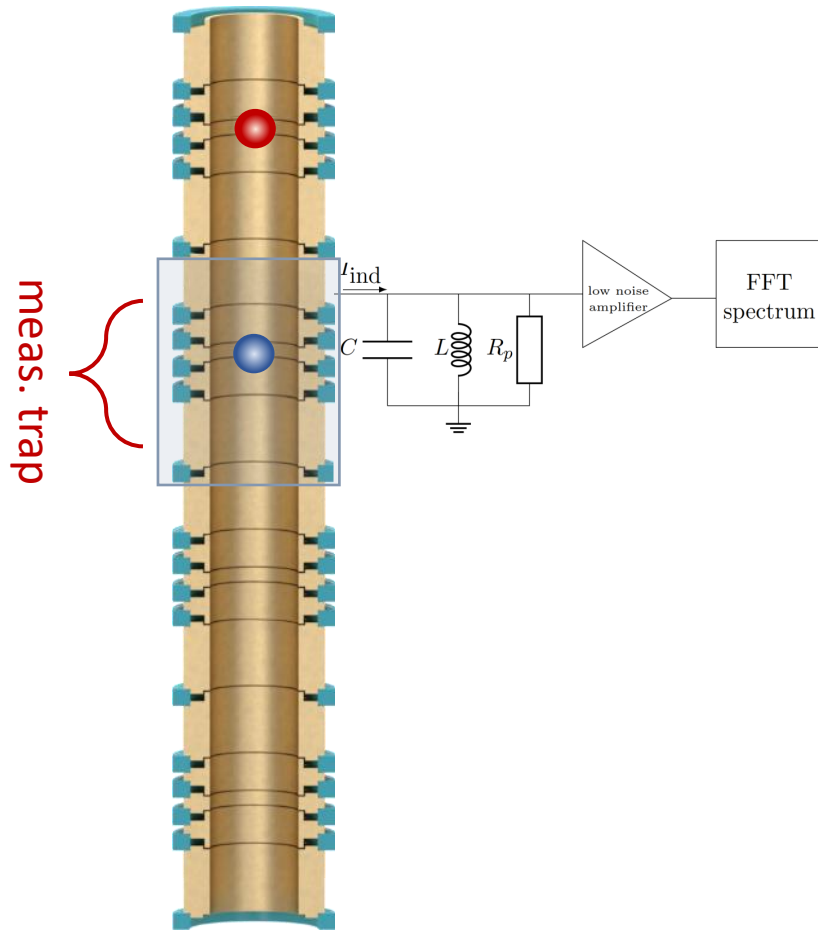
Repp, J. et al., Appl. Phys. B 107, 983 (2012)

Roux, C. et al., Appl. Phys. B 107, 997 (2012)

Böhm, C. et al., Nucl. Instrum. Meth. A 828, 125 (2016)

Herkenhoff, J. et al., Rev. Sci. Instrum. 92, 103201 (2021)

Measurement setup



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

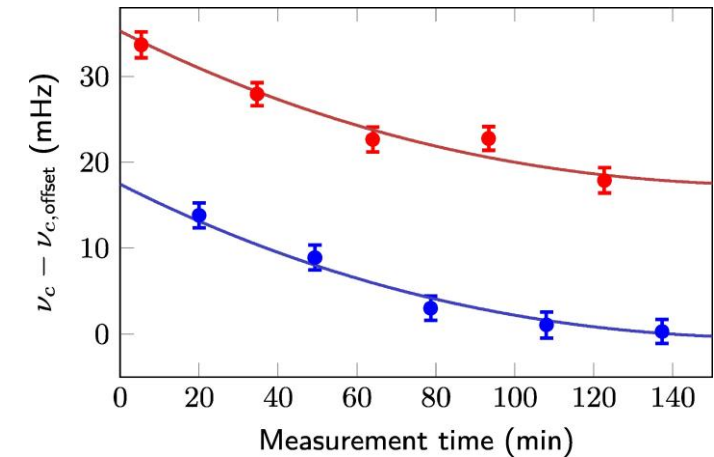
Magnetic field not known!

Mass ratio measurements:

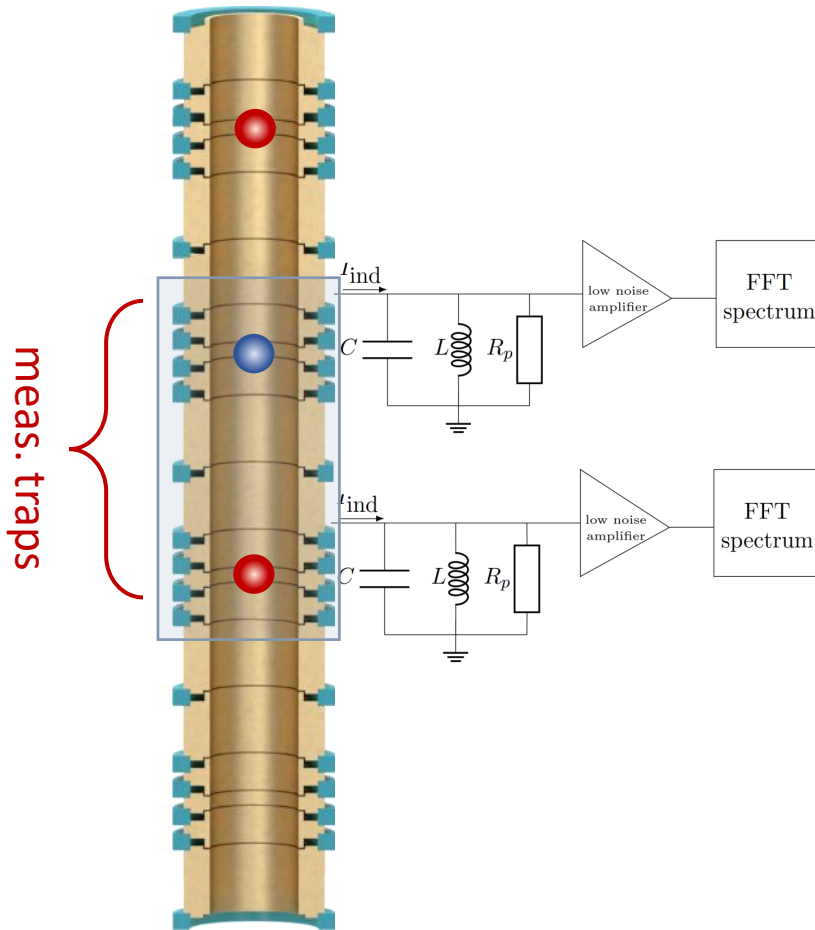
$$R = \frac{\omega_1}{\omega_2} = \frac{q_1 \cdot m_2}{q_2 \cdot m_1} \frac{B(t_1)}{B(t_2)}$$

$$f_1(t) = \mathbf{R} \cdot (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$

$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



Measurement setup



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

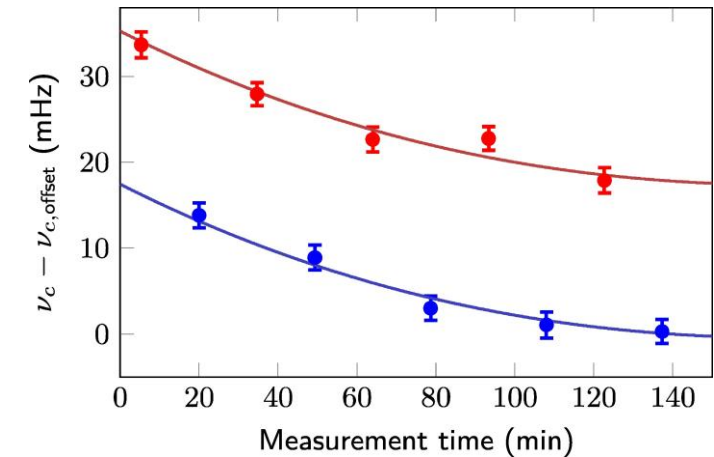
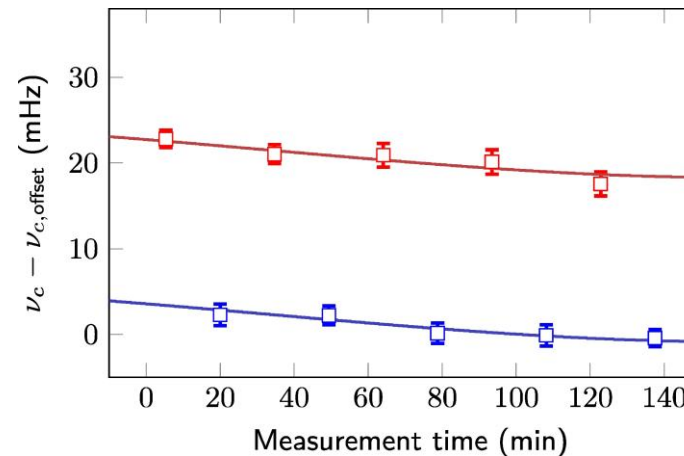
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Mass ratio measurements:

$$R = \frac{\omega_1}{\omega_2} = \frac{q_1 \cdot m_2}{q_2 \cdot m_1} \frac{B(t_1)}{B(t_2)}$$

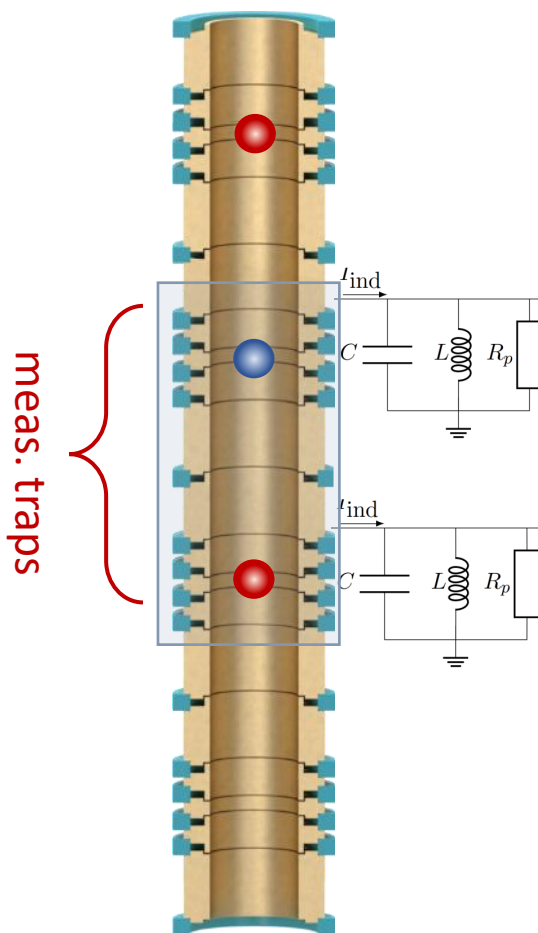
$$f_1(t) = \mathbf{R} \cdot (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$

$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



Limited to 2 measurement traps due to detection system

Measurement setup



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

Magnetic field not known

Mass ratio measurements:

$$R = \frac{\omega_1}{\omega_2} = \frac{q_1 \cdot m_2}{q_2 \cdot m_1} \frac{B(t_1)}{B(t_2)}$$

High precision mass measurements

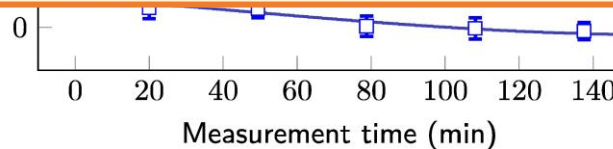
Convert to frequency:

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

Single ions

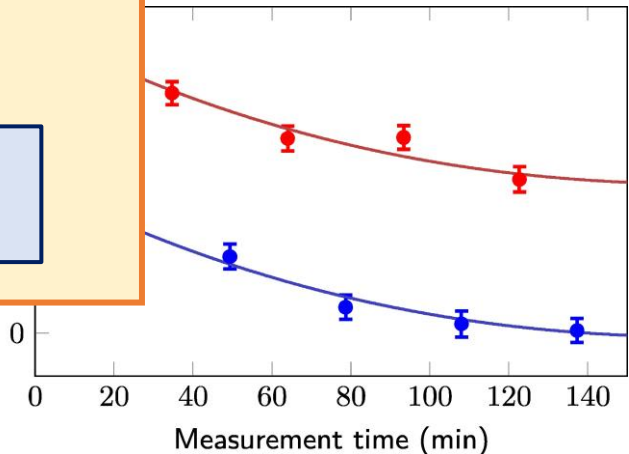
Mass ratios

Large acceptance for charge-to-mass ratios

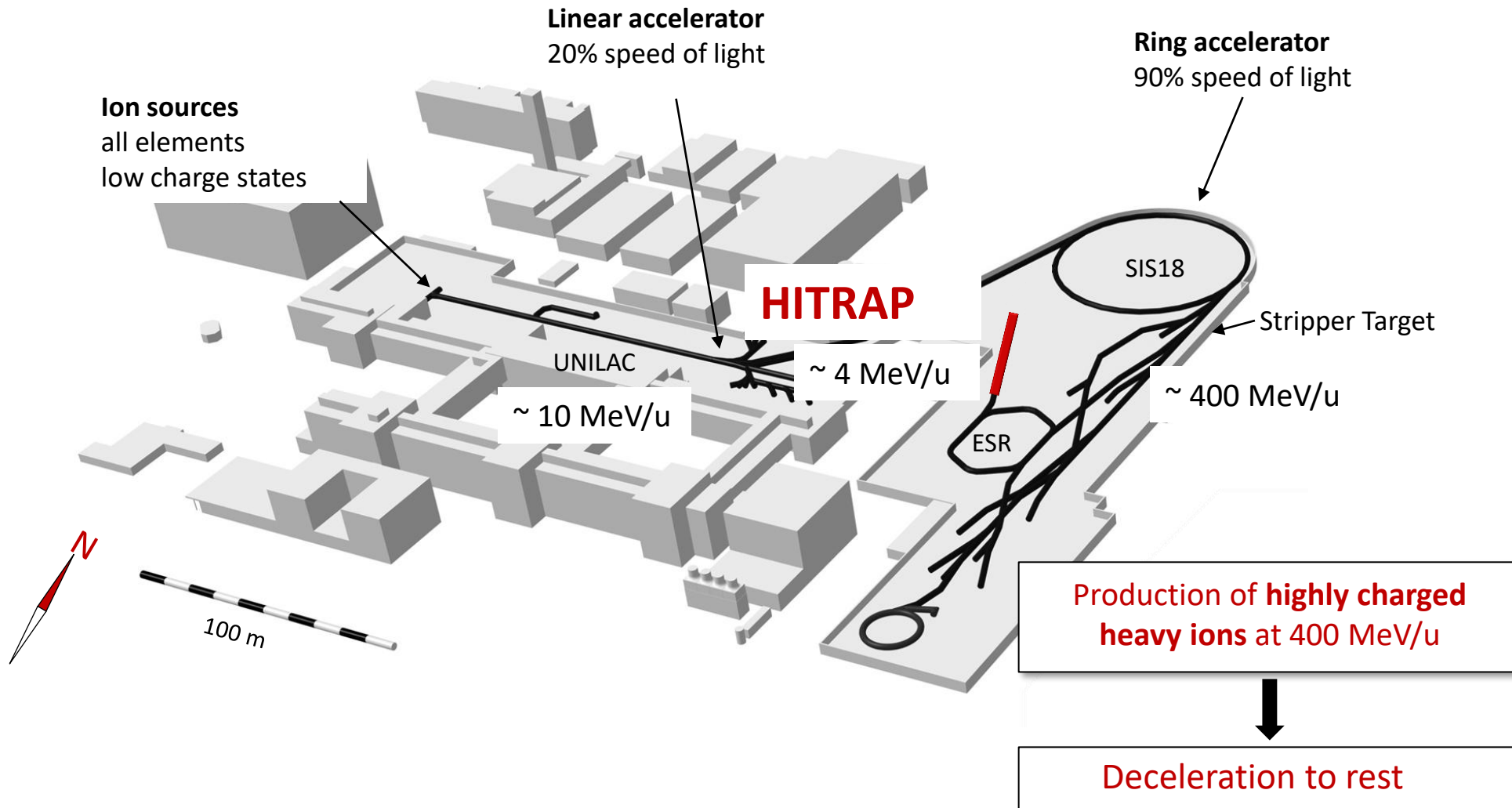


$$a + b \cdot t + c \cdot t^2 + d \cdot t^3$$

$$+ b \cdot t + c \cdot t^2 + d \cdot t^3$$



GSI Helmholtz Center for Heavy Ion Research



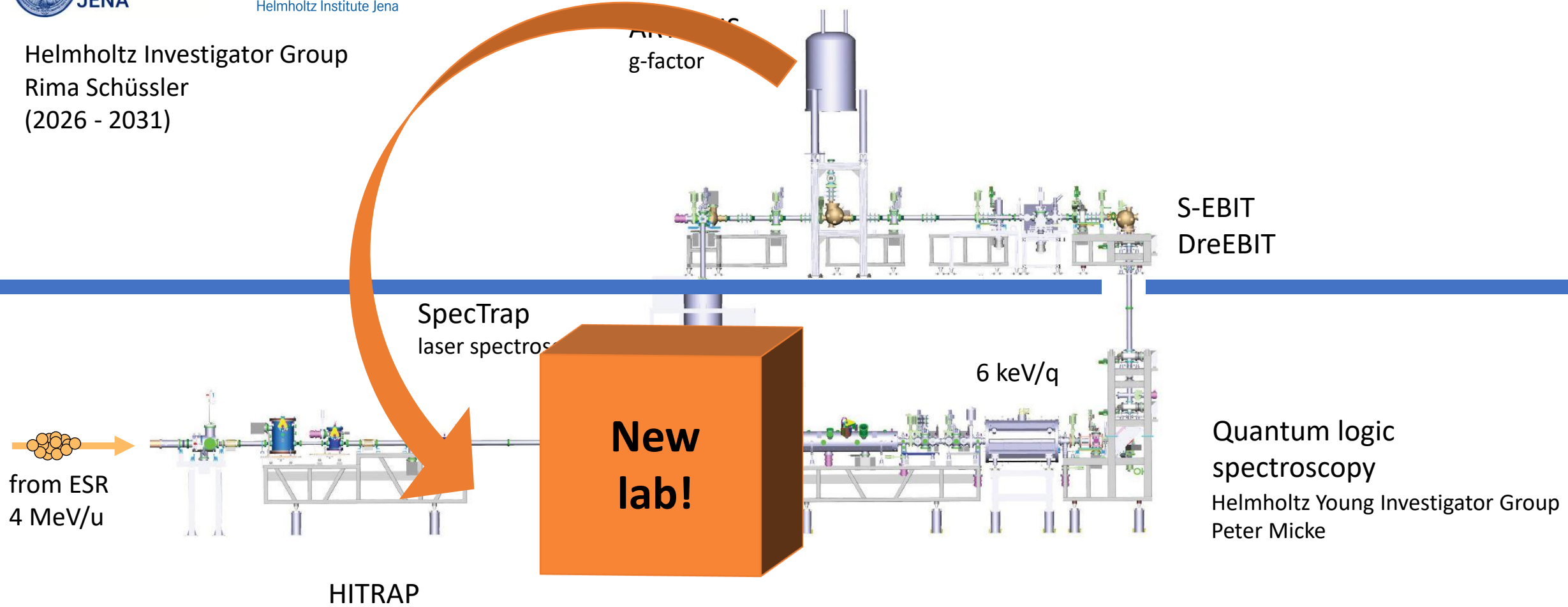
HITRAP



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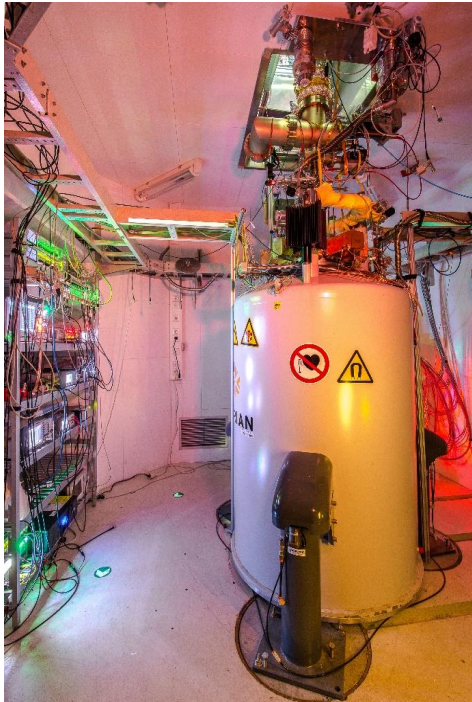
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Helmholtz Investigator Group
Rima Schüssler
(2026 - 2031)



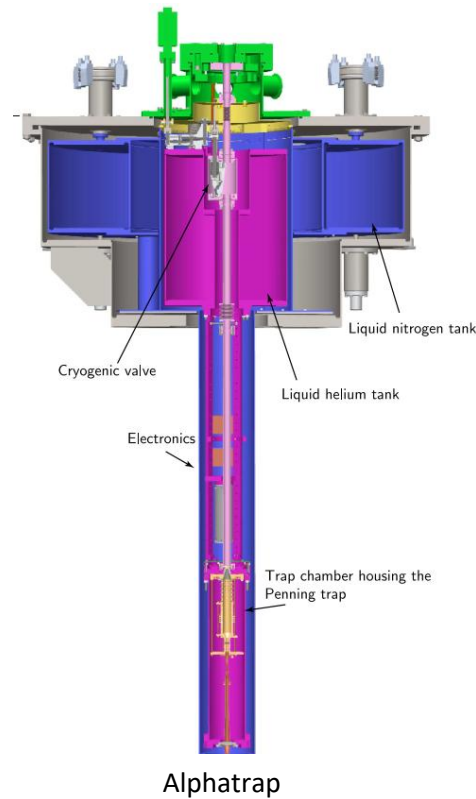
Outlook

Build Lab



Pentatrap

Build the experiment

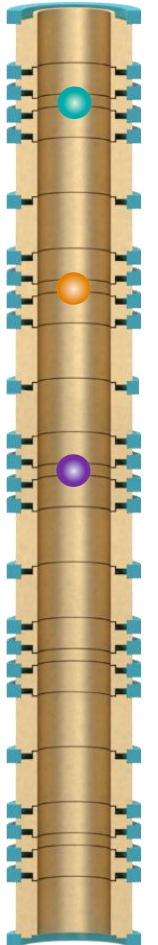


Commissioning & Characterisation

Offline Measurements:

- Isotope shift
- Neutrino Physics
- Metastable states
- Test of $E = mc^2$
- ...

Binding energy of heavy, highly charged ions!



Neutrino Mass

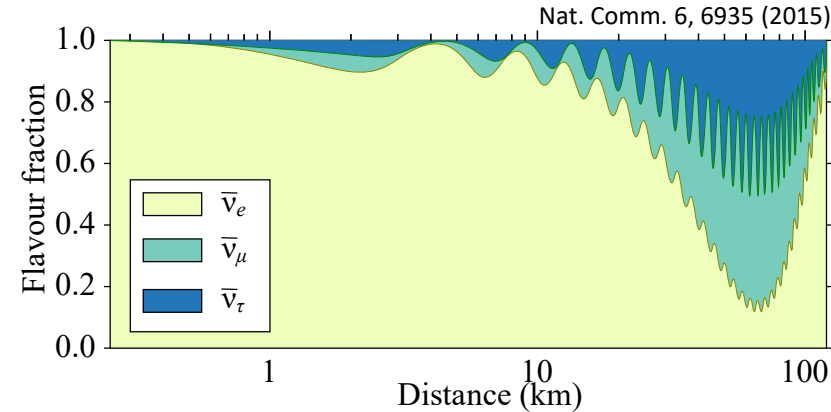
Standard Model:



3 massless Neutrinos



But: Neutrino Oscillations



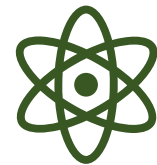
Massive Particles!

$$\begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} = \text{PMNS Matrix} \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}$$

Mass eigenstates

What is the (tiny) mass of neutrinos?

Rough Idea:



Nuclide A



Nuclide B



Neutrino



Energy

Mass measurement!

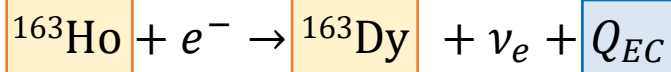
← Q value

Other experiments

Electron Capture in Holmium

Current limit: $m_{\nu_e} < 150 \text{ eV}$

Goal: $m_{\nu_e} < 1 \text{ eV}$



$$\begin{aligned} Q &= M(^{163}\text{Ho})c^2 - M(^{163}\text{Dy})c^2 \\ &= M(^{163}\text{Ho}^{q+})c^2 - M(^{163}\text{Dy}^{q+})c^2 + \Delta E_B \\ &= M(^{163}\text{Ho}^{q+})c^2 \cdot [R - 1] + \Delta E_B \end{aligned}$$

$$R = \frac{m(\text{Ho}^{q+})}{m(\text{Dy}^{q+})}$$

$q = 38, 39, 40$

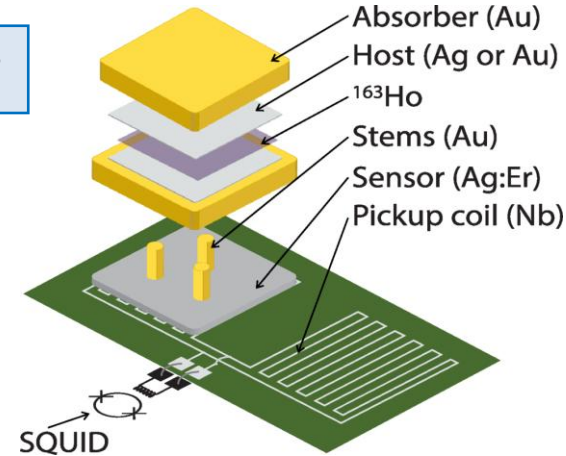
$$Q = 2863.2(6) \text{ eV}$$

Micro calorimeter

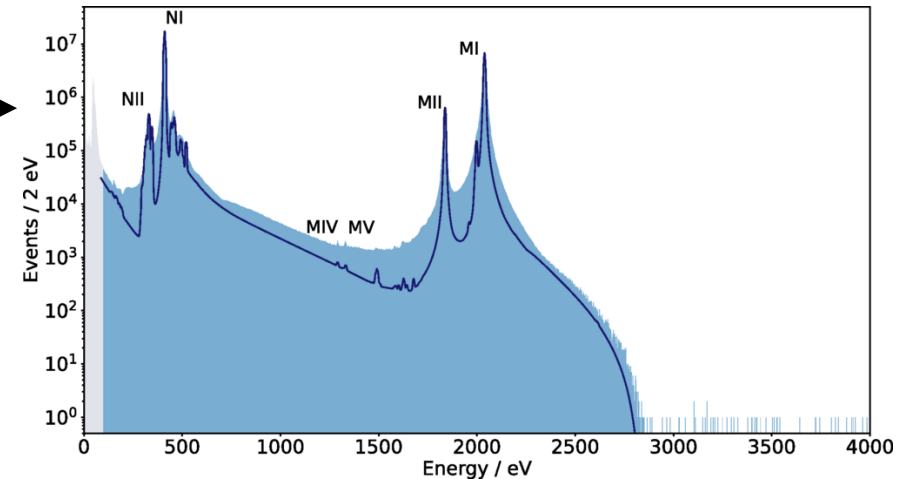
Independent
cross check!

$$Q = 2862(4) \text{ eV}$$

New limit: $m_{\nu_e} < 15 \text{ eV}$



ECHO-Collaboration



Fit to the spectrum yields (among others):

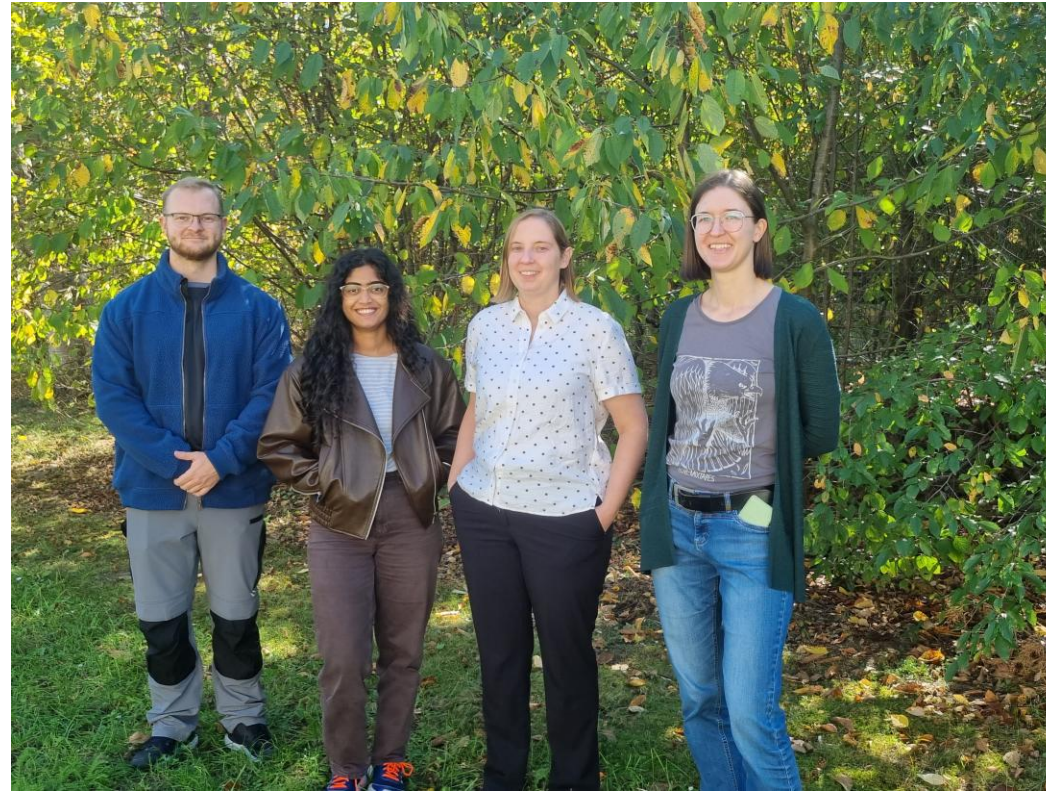
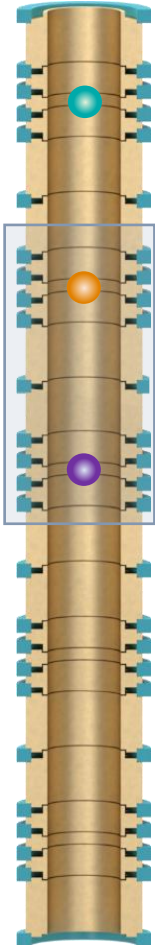
- electron neutrino mass
- Q value of transition

Thank you for your attention!

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Toni Hölzel, Sruthy Varma Koyickal, **Rima X. Schüssler**, Esther Menz

Thanks!

