# *Ultra-high precision nuclear mass measurements for fundamental studies*

- Basics of Penning-trap mass spectrometry
- Nuclear masses for neutrino physics
- Fundamental physics studies

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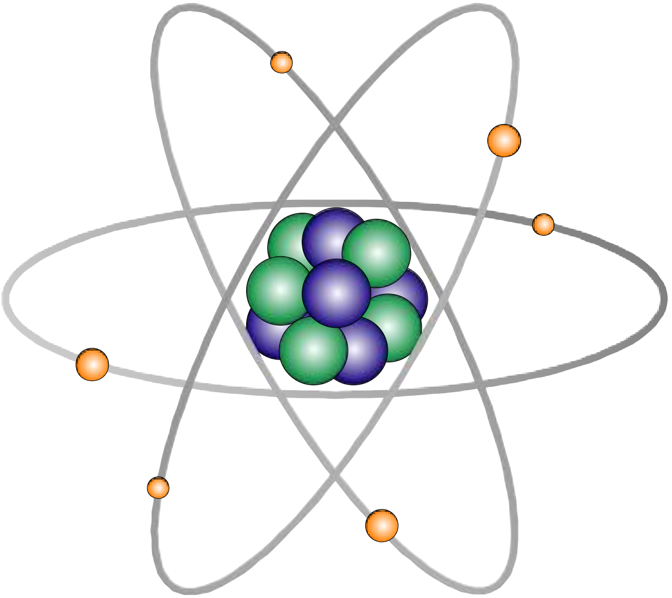
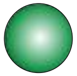
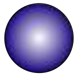
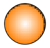
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

**CERN, Nov 29th, 2024**

European Research Council
Established by the European Commission

# The mass of an atom



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

– binding energy

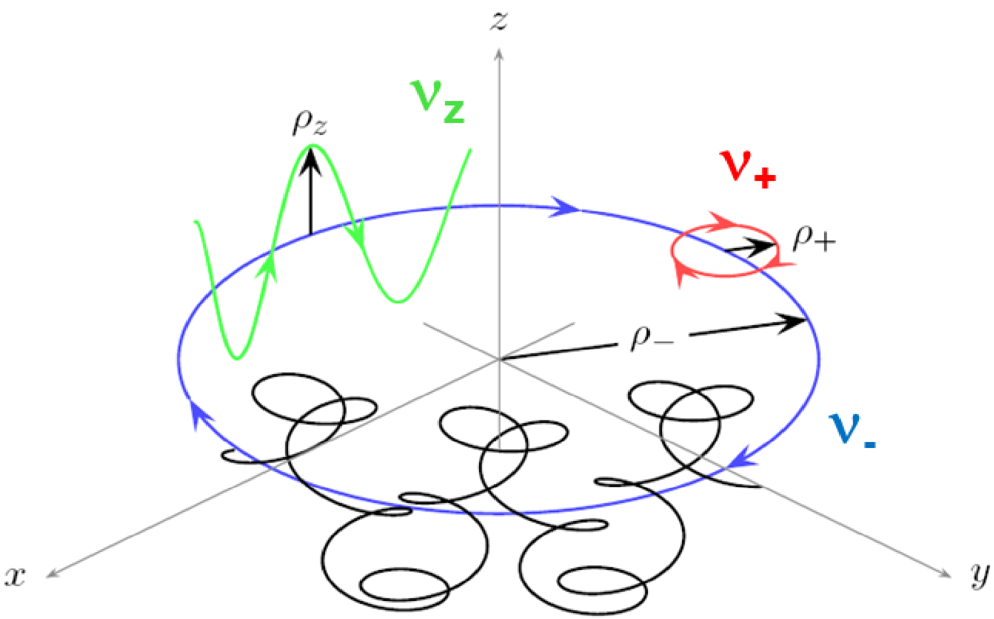
Einstein $E = mc^2$

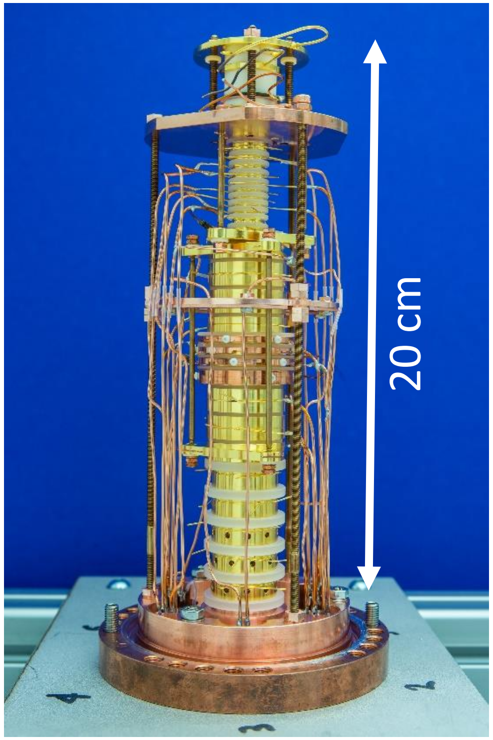
$$m_{\text{Atom}} = N \bullet m_{\text{neutron}} + Z \bullet m_{\text{proton}} + Z \bullet m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

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

$\delta m/m = 10^{-6} – 10^{-8}$

# Storage of ions in a Penning trap




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

$$\nu_c = qB/(2\pi m_{ion})$$

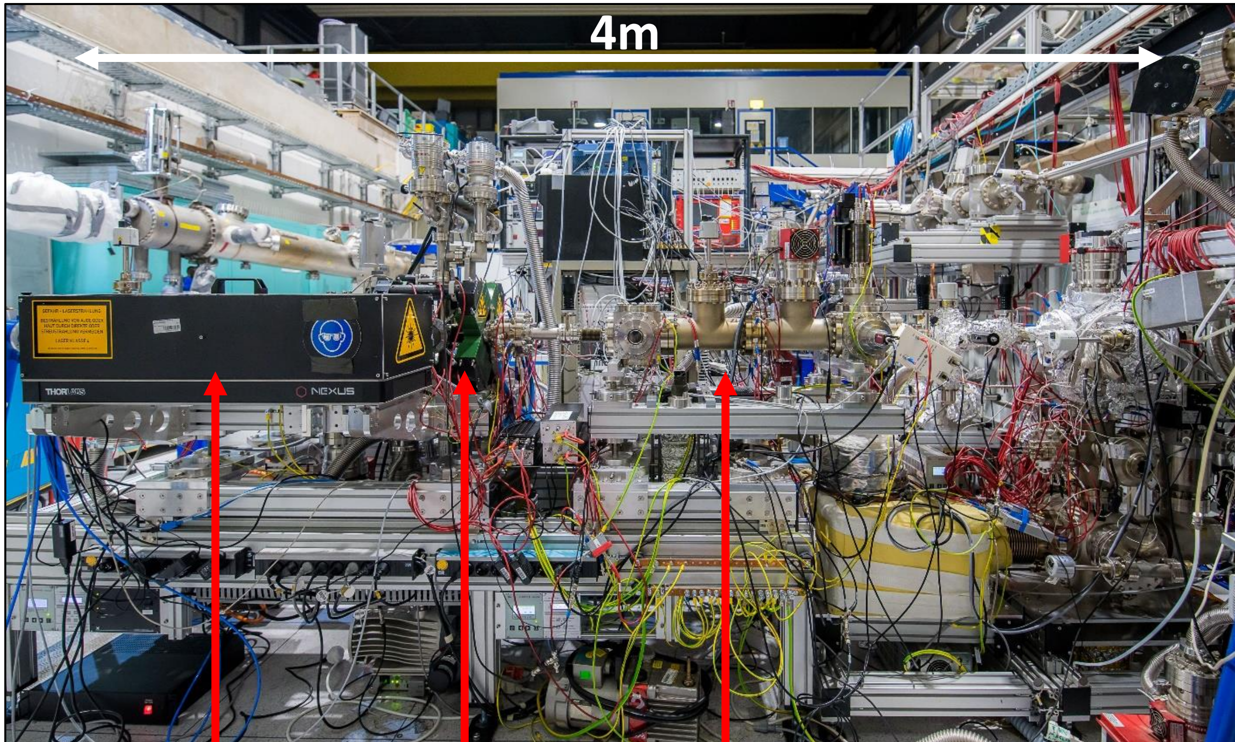
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

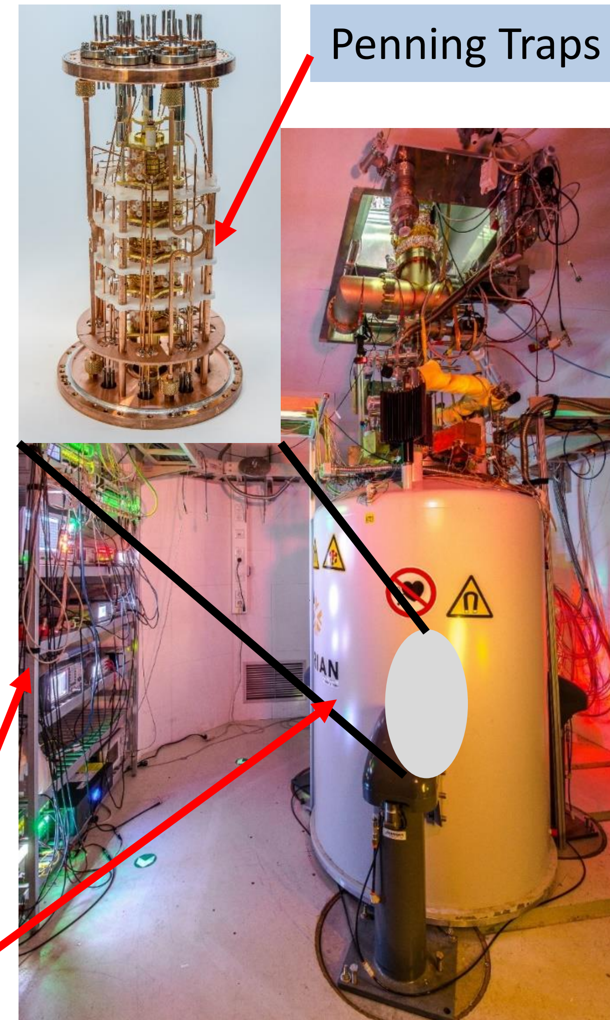
- Non-destructive FT-ICR detection technique

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. **58** (1986) 233

# PENTATRAP – A Penning-trap setup at MPIK

## A balance for highly charged ions.



Penning Traps

Laser Ion Source | EBIT | Transfer Beamline | Electronics

Superconducting Magnet

# Measurement principle at PENTATRAP

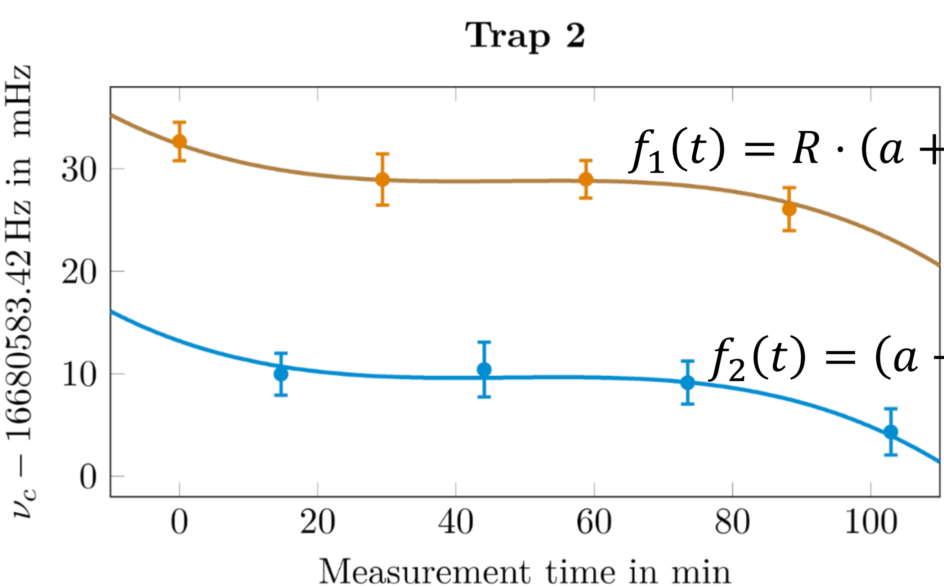
## Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

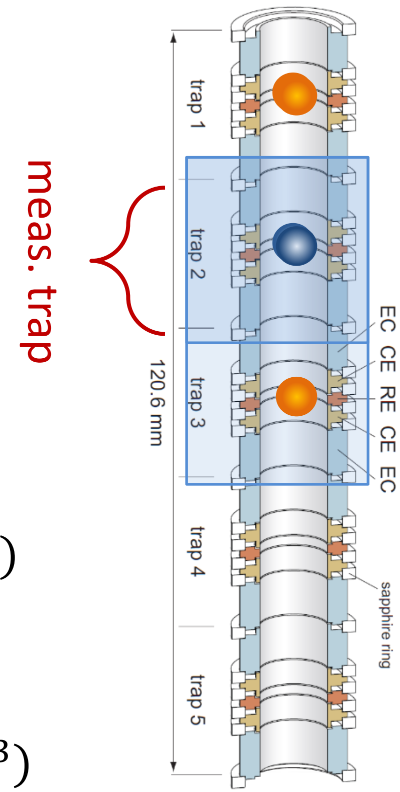
Second ion:

$$R = \frac{\omega_1}{\omega_2} = \frac{q_1 \cdot m_2}{q_2 \cdot m_1}$$




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

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




A. Rischka *et al.*, Phys. Rev. Lett. **124** (2020) 113001

# Results I

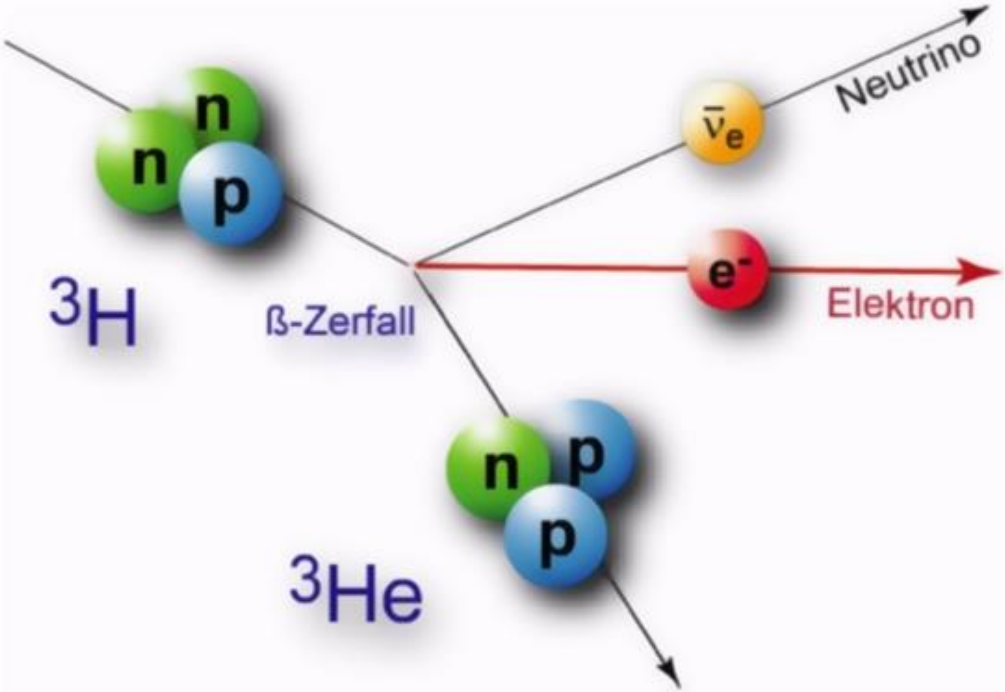
## Nuclear masses for neutrino physics

***Q*-values:**

$^{3}T \rightarrow {}^{3}He$

$^{163}Ho \rightarrow {}^{163}Dy$

$^{187}Re \rightarrow {}^{187}Os$

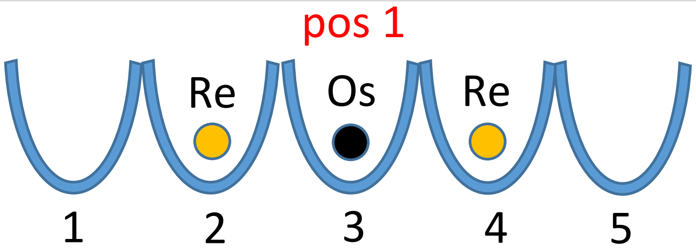



**$\beta^-$ -decay of $^{187}$Re**

$$R = \frac{\nu_c(^{187}\mathrm{Os}^{29+})}{\nu_c(^{187}\mathrm{Re}^{29+})}$$

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

# $Q$-value of $^{187}$Re-$^{187}$Os for neutrino physics




P. Filianin *et al.*, Phys. Rev. Lett. **127** (2021) 072502

**relative nuclear mass precision achieved: $6 \cdot 10^{-12}$**

**BUT**

For $Re^{29+}$ ($Z$ = 75) vs. $Os^{29+}$ ($Z$ = 76) we measure two ratios with a 50/50 probability:

$$R_1 = 1.000000013886(15)$$

$$R_2 = 1.000000015024(12)$$

# Weighing of different electron config.

Ground-state configuration of $Re^{29+}$ and $Os^{30+}$: $[_{36}Kr]\ 4d^{10}$

Metastable state $[_{36}Kr]\ 4d^9\ 4f^1$ with $E_{exc} \approx 200$ eV in $Re^{29+}$

Similar state in $Os^{30+}$ expected!

**$Re^{29+}$**

metastable state

$B_{PENTATRAP}$ = 202.2(17) eV

$B_{Harman}$ = 202.2(5) eV

$B_{Indelicato}$ = 202.1 (27) eV

$B_{Haverkort}$ = 202.8(4) eV

ground state

**$Os^{30+}$**

metastable state

$B_{PENTATRAP}$ = 207(3) eV

$B_{Haverkort}$ = 209(2) eV

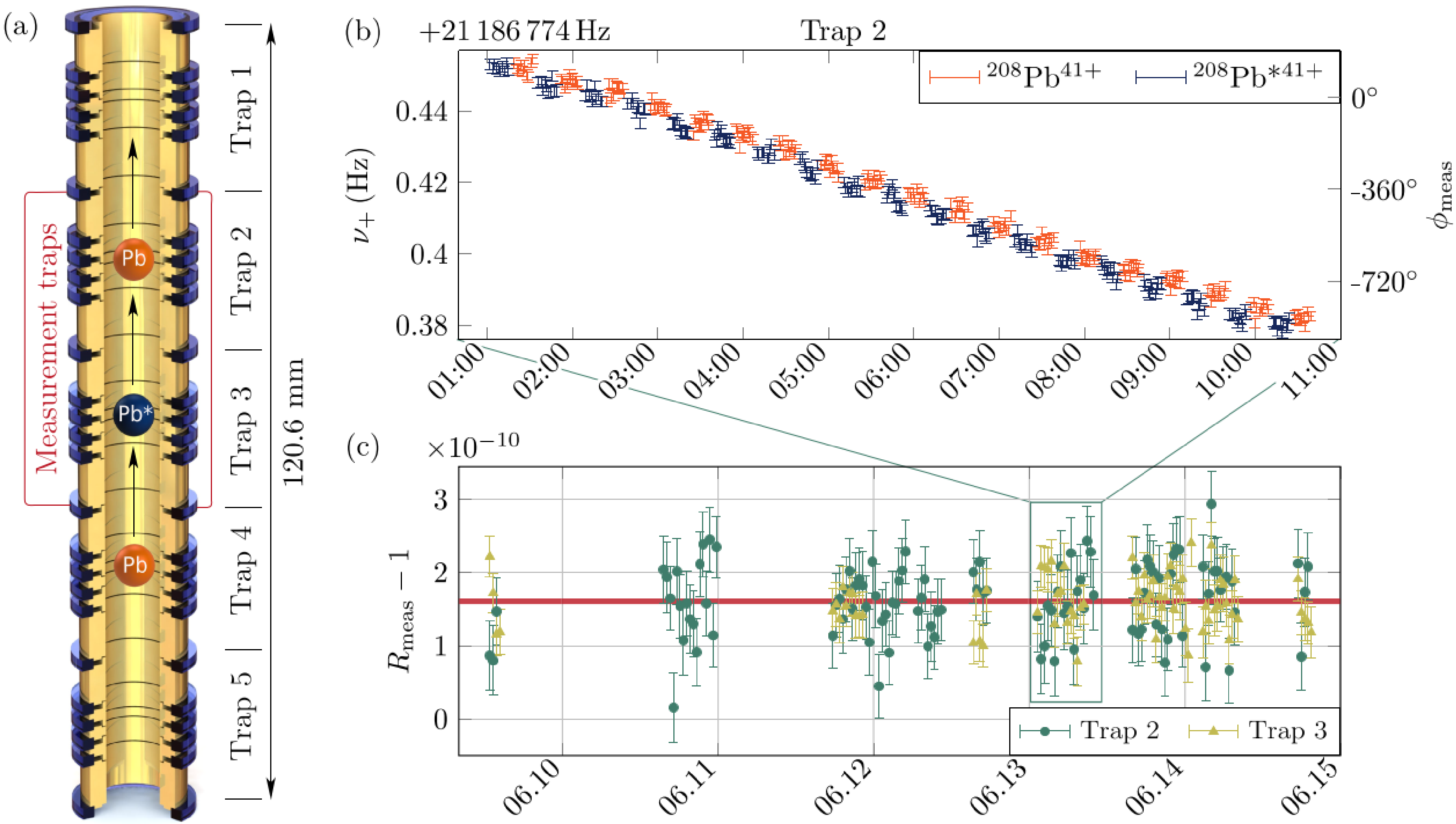
$B_{Indelicato}$ = 207(3) eV

ground state

R. Schüssler *et al.*, Nature **581** (2020) 42

**Possible application: search for suitable clock transitions**

# Search for low-lying isomeric states

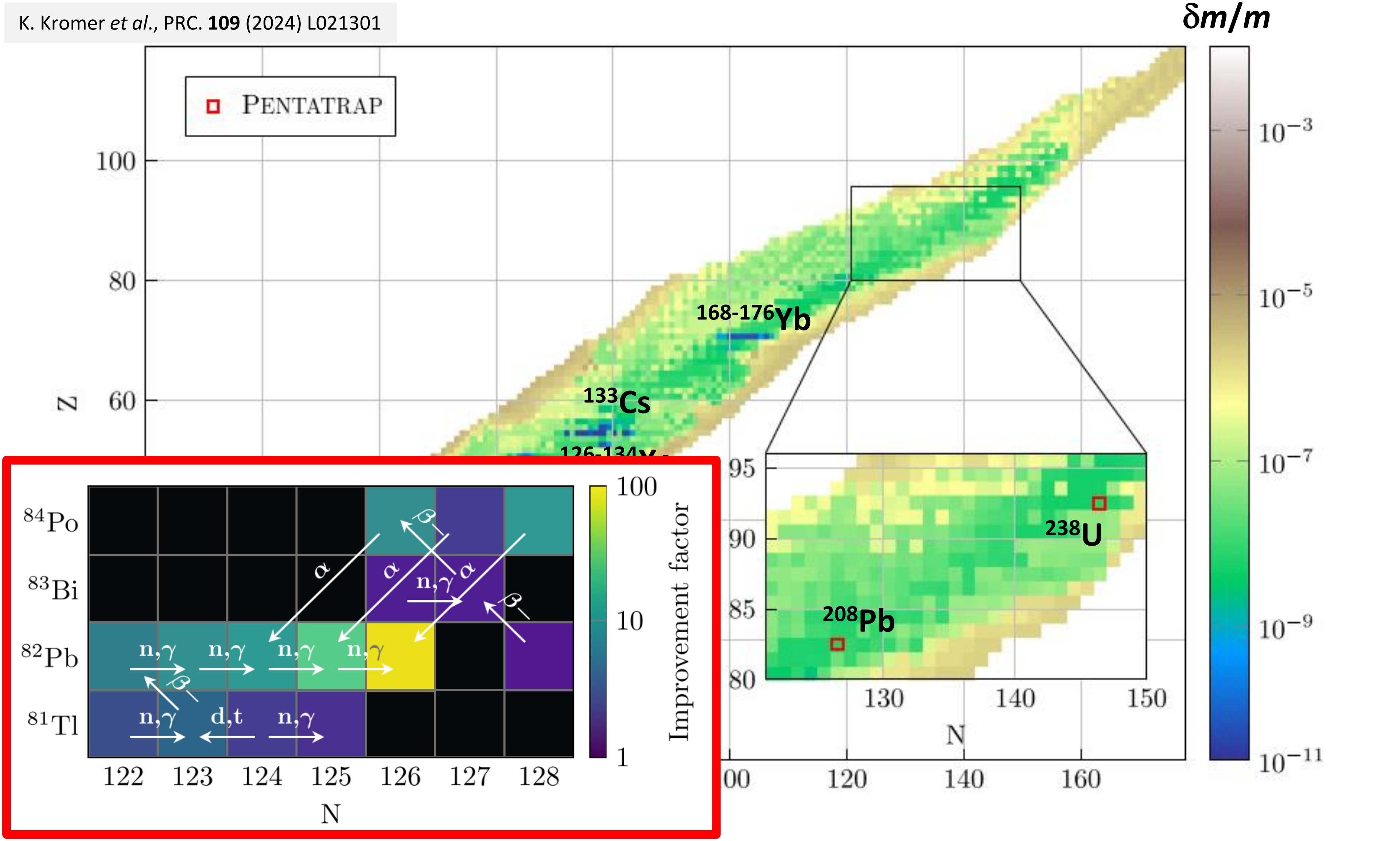



$\Delta m$ = 31.2(8) eV/c²

K. Kromer *et al.*, PRL. **131** (2023) 223002

# The AME mass backbone

K. Kromer *et al.*, PRC. **109** (2024) L021301



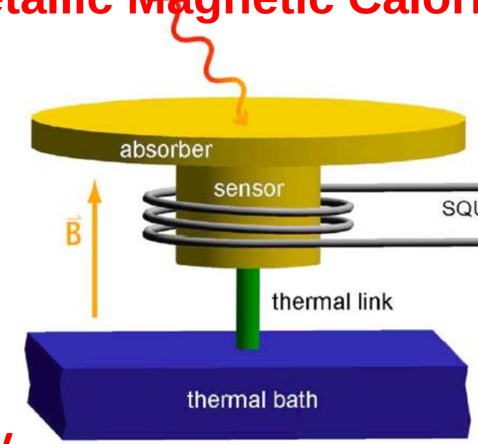
# The ECHo ($^{163}$Ho) project

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

ISOLDE

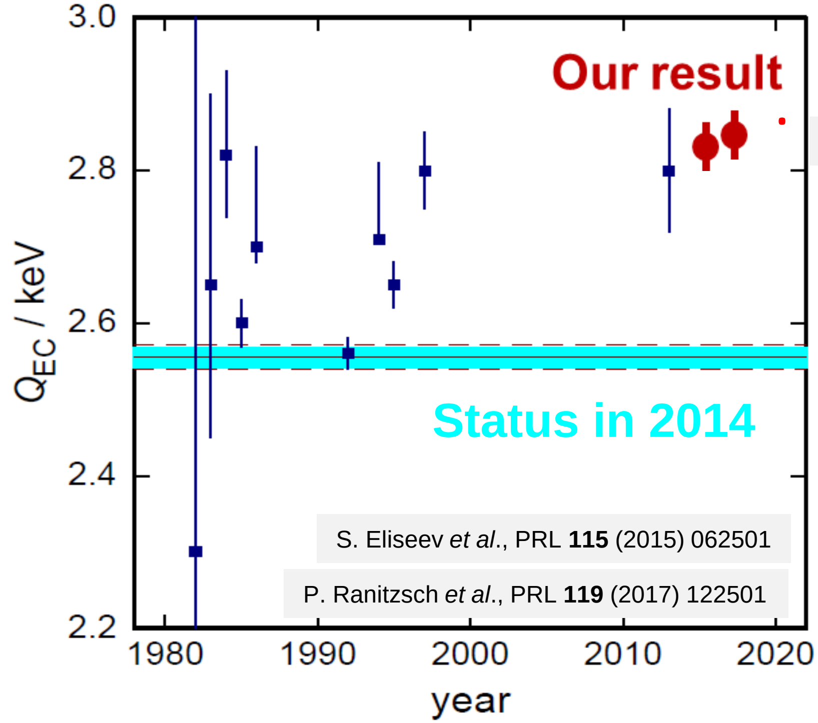
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{C}$$

## Metallic Magnetic Calorimetry

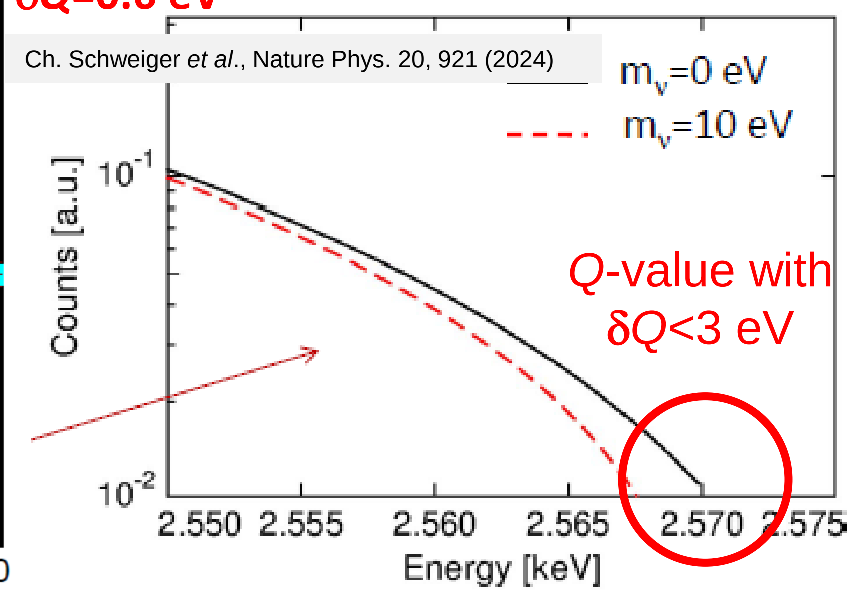



ECHo-Collaboration:
Loredana Gastaldo
Christian Enss

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

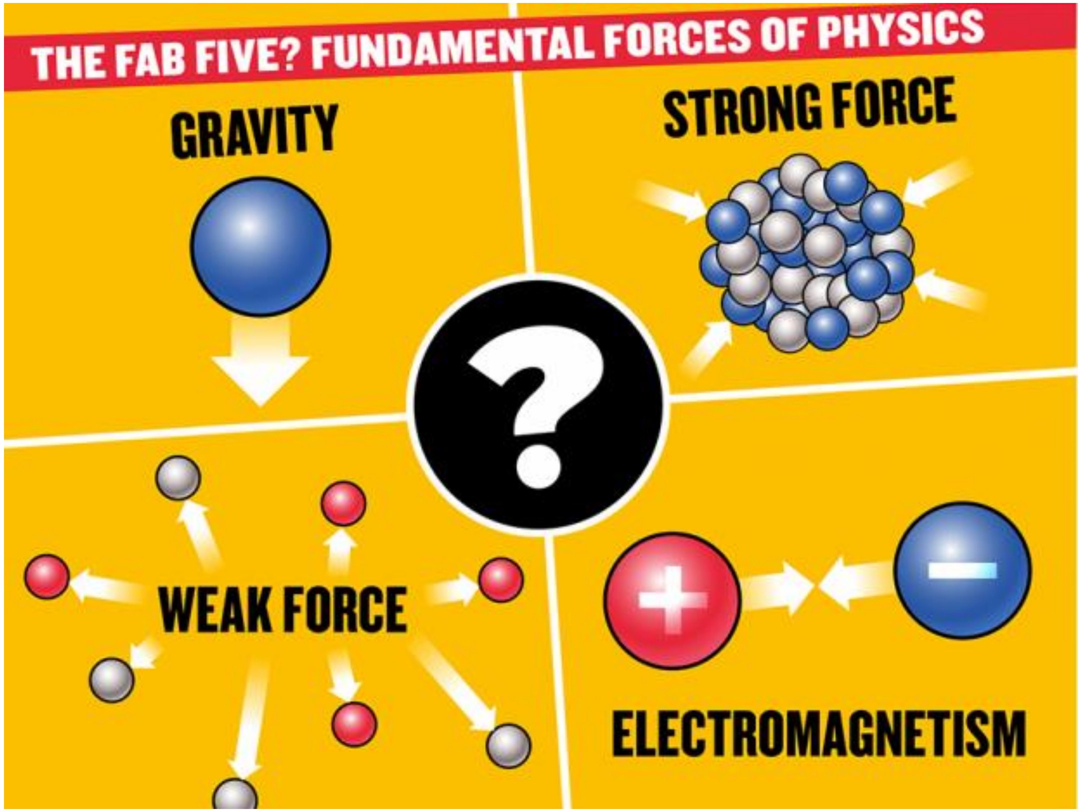



**δ*Q*=0.6 eV**



# Results II

## Nuclear masses for fifth force search

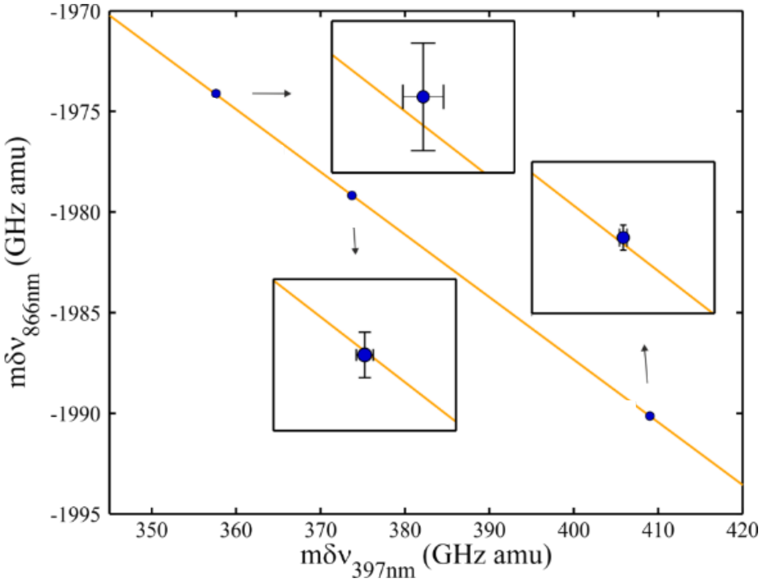



www.freedomsphoenix.com/

# Probe for new force carriers

## Isotope shift spectroscopy: 5th force?

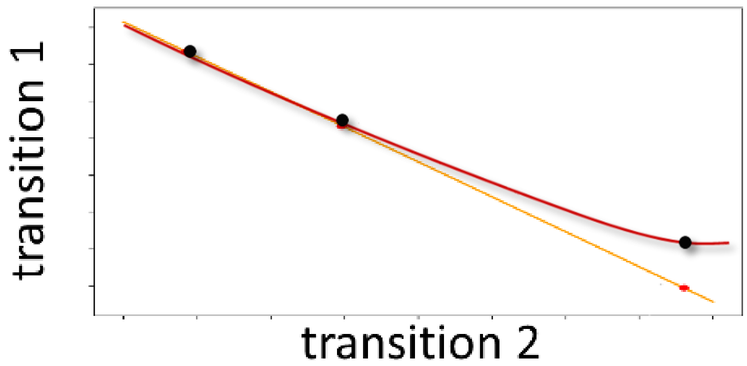
- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'}$
- use 2 transitions $i, j$
  ➔ eliminate $\delta\langle r^2\rangle_{A,A'}$




- new force mediated through scalar field with boson mass $m_\phi \rightarrow X_i$
- coupling to neutrons: $y_n$
- coupling to electrons: $y_e$

➔ nonlinearity in King's plot:

$$\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'} + $$
$$+\alpha_{NP} X_i (\mathrm{A} - \mathrm{A}')$$



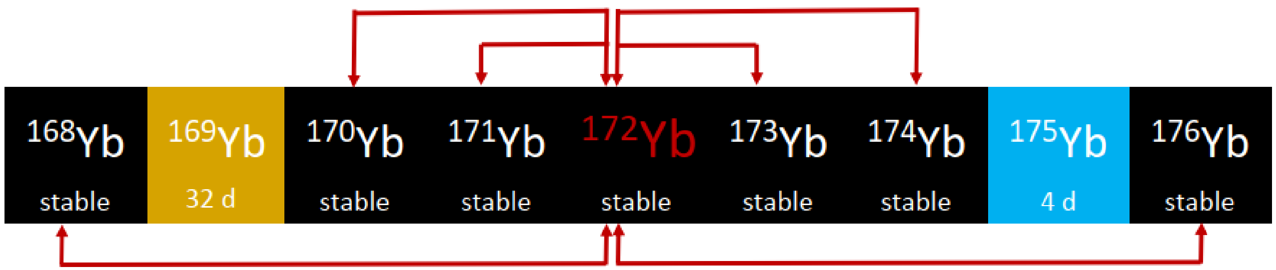

Berengut *et al.*, PRL **120**, 091801 (2018); Ozeri *et al.* (2020)

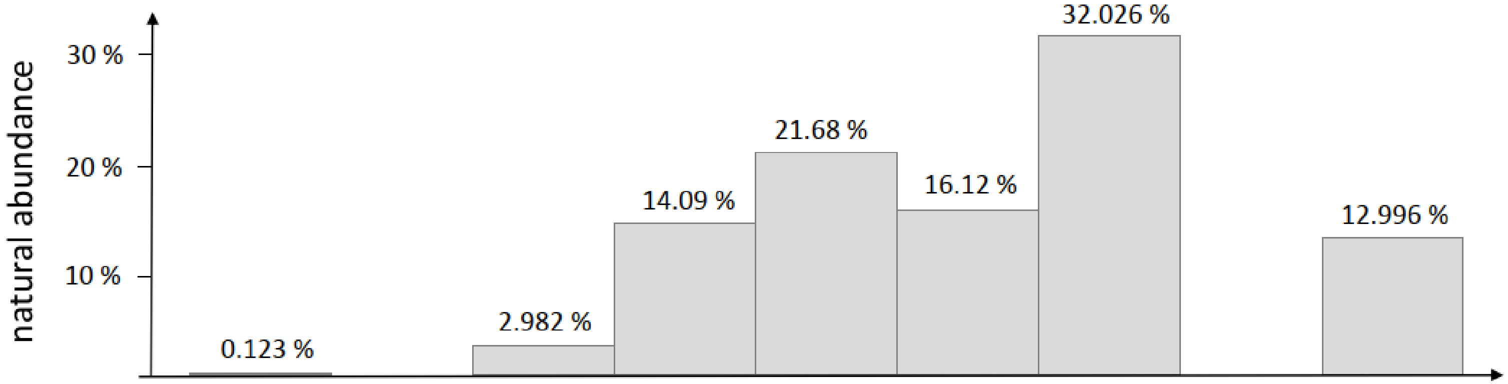
**High-precision atomic and nuclear spectroscopy measurements needed!**

# Yb mass-ratio measurements

**Motivation: 5th force search using King-plot analysis in Ca, Sr, Yb**

**Mass-ratio uncertainties of $10^{-11}$ and below required!**



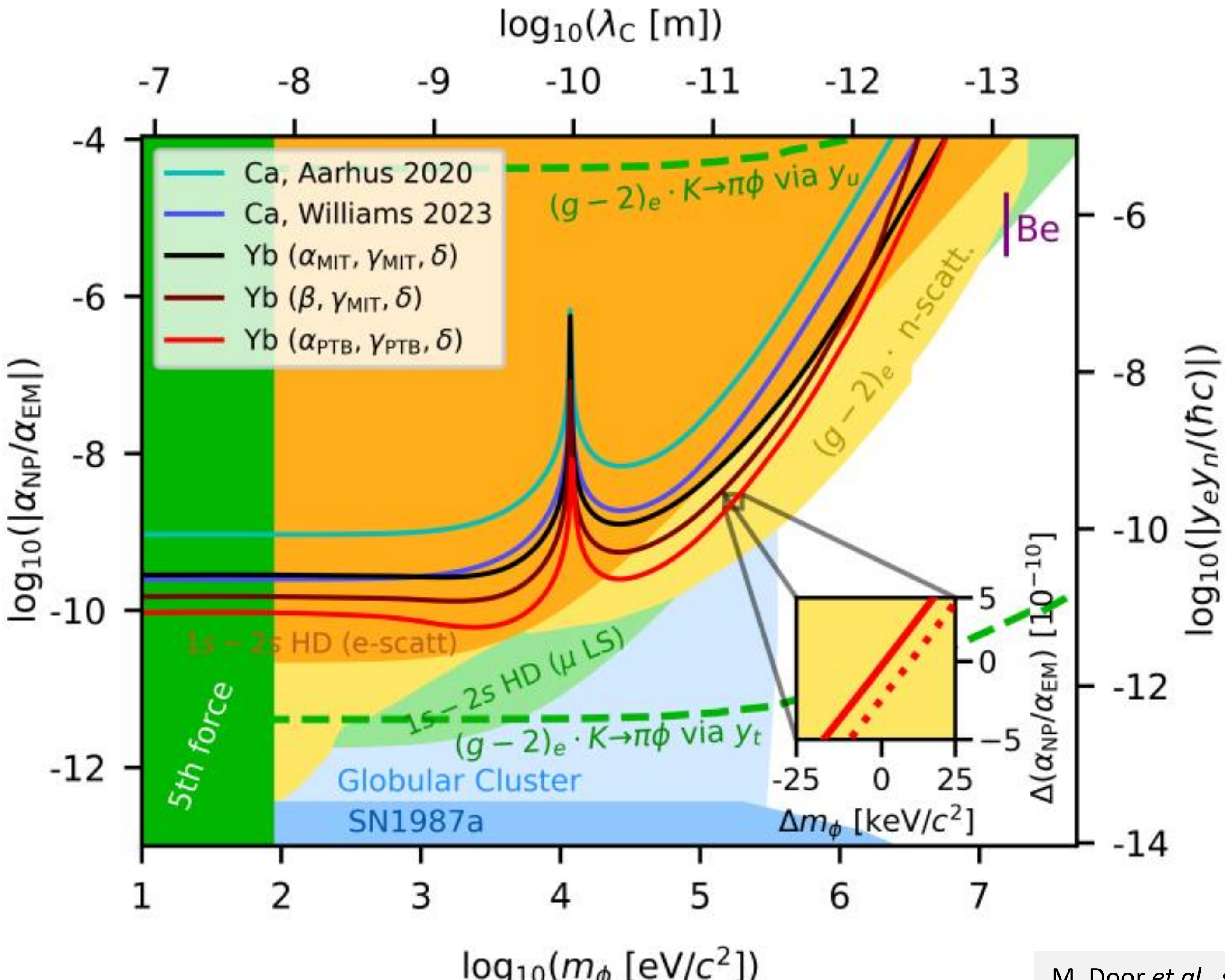




M. Door *et al.*, submitted (2024)

**All even-even mass ratios measured. ☺**

**Relative mass uncertainty: ~$4\cdot10^{-12}$, improvement factor: typically >50**

# Yb spectroscopy limits

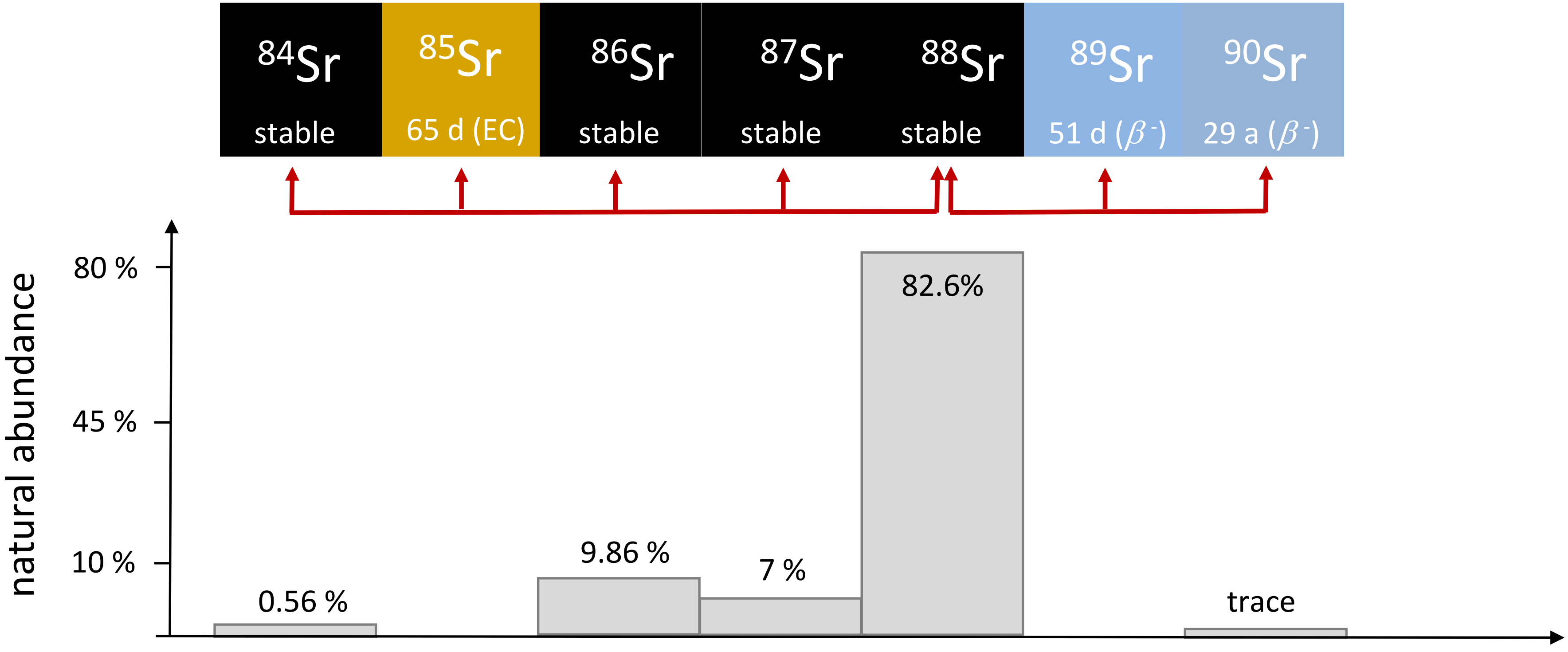



M. Door *et al.*, submitted (2024)

# Sr mass-ratio measurements

**Much more complicated, since there are only three stable even-even isotopes!**

**Mass-ratio uncertainties of $10^{-11}$ and below required!**




**Improvement factor needed:**

| | | | | | | |
|---|---|---|---|---|---|---|
| **1400** | **3000** | **10** | **10** | **10** | **100** | **1500** |

# Summary

*Precision Penning-trap mass spectrometry has reached an amazing precision even on exotic systems and has opened up many new fields of research!*

**Thanks for the invitation and your attention!**

***Max Planck Society*** ***IMPRS-PTFS*** ***IMPRS-QD*** ***ERC AdG 832848 - FunI*** ***DFG***

# Thanks …

**to all my Division members and**

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