Weighing the Nucleus: European Trapped-Ion Efforts for Astrophysics

- ❖ Introduction to trapped ion mass spectrometry
- ❖ Technical advances in mass measurements
- ❖ European efforts and some latest mass results

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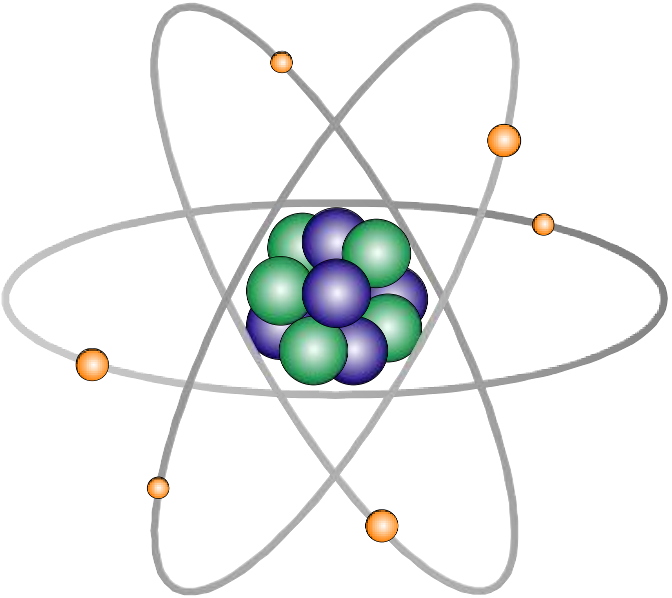
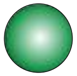
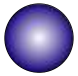
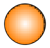
Heidelberg, May 12th, 2026

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

The mass of an atom



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

– binding energy

Einstein $E = mc^2$

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

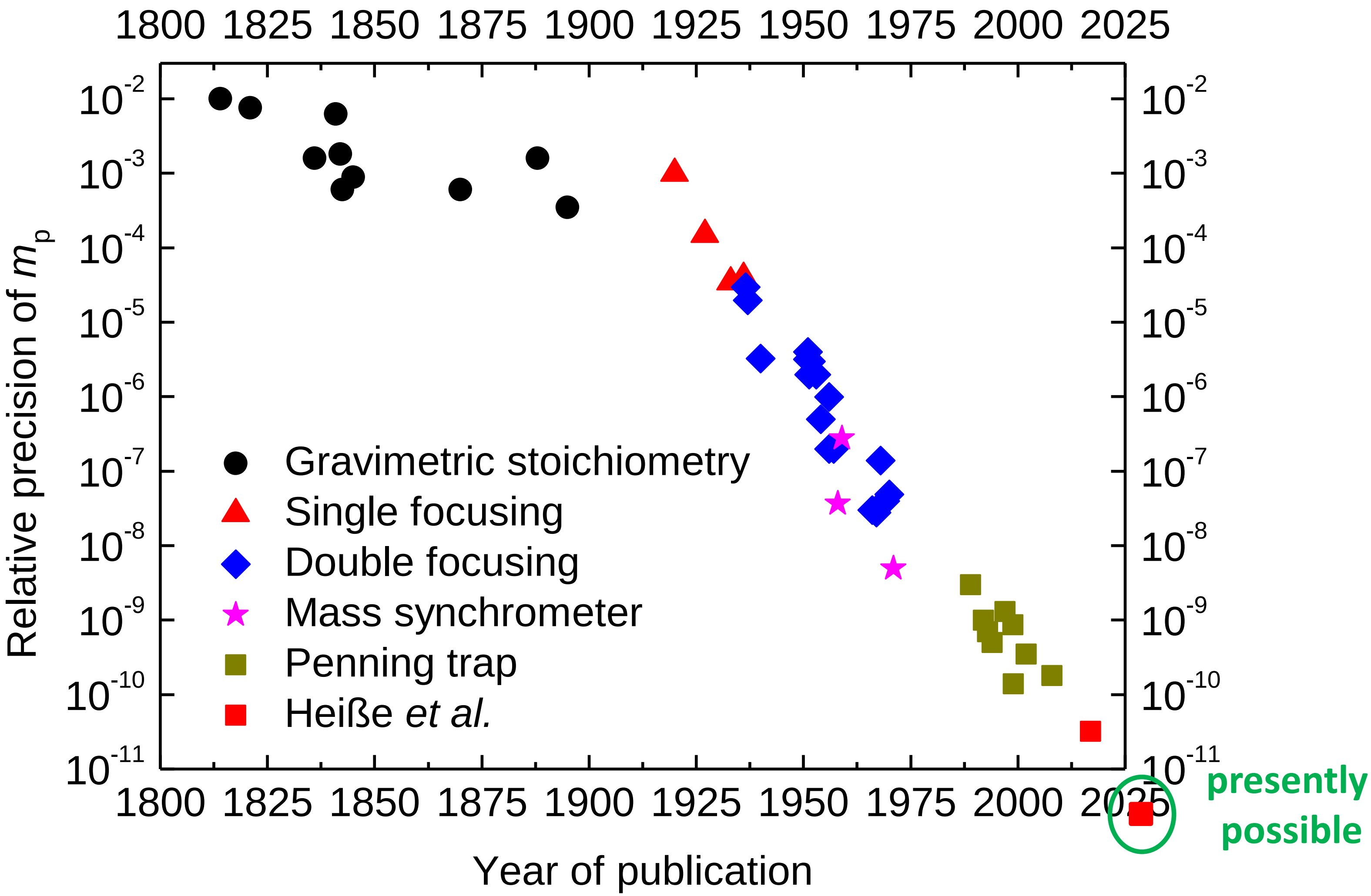
$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} - 10^{-8}$

electronic structure

nuclear structure

Precision progress: the proton mass

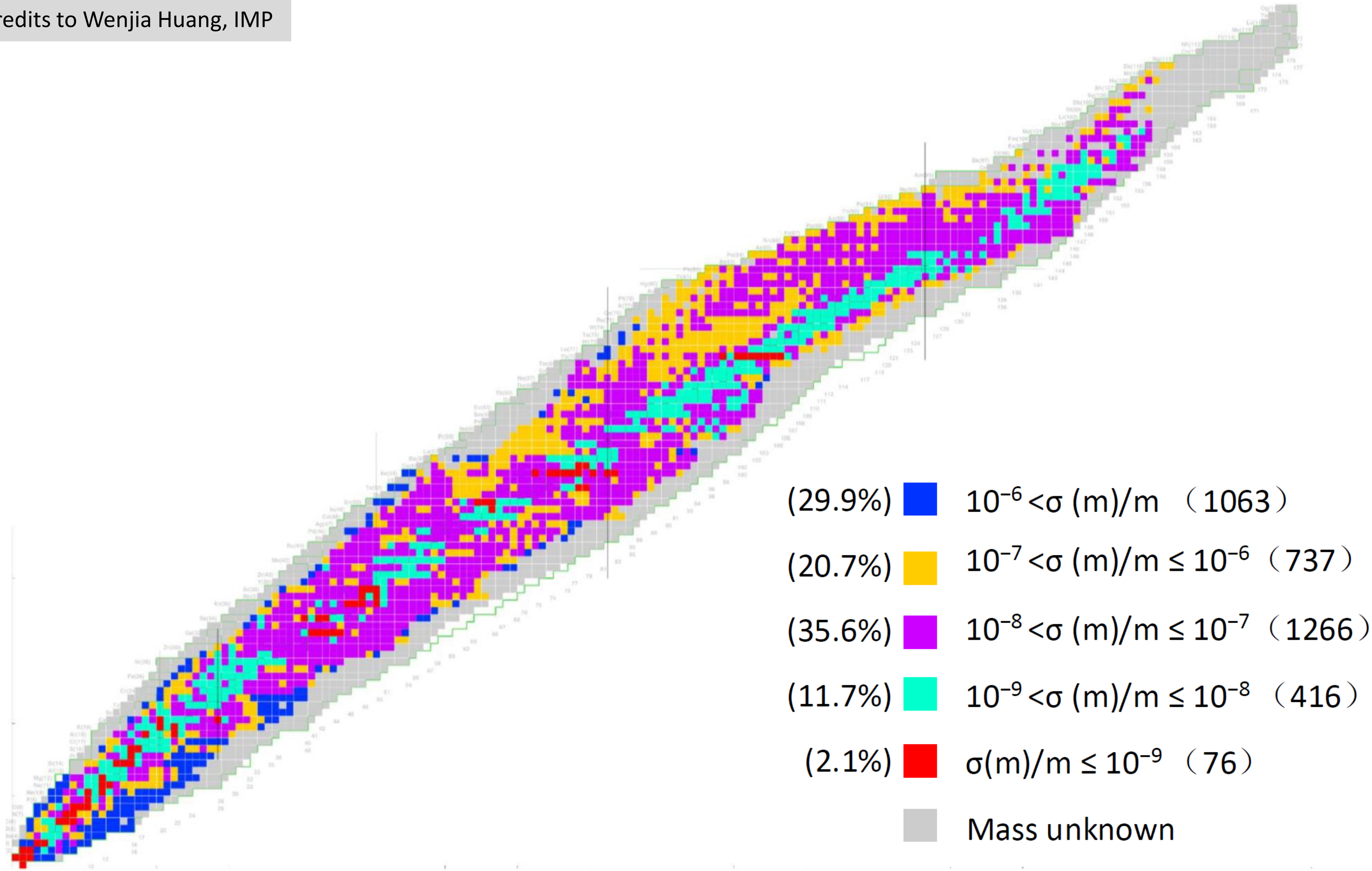


Courtesy F. Heiße

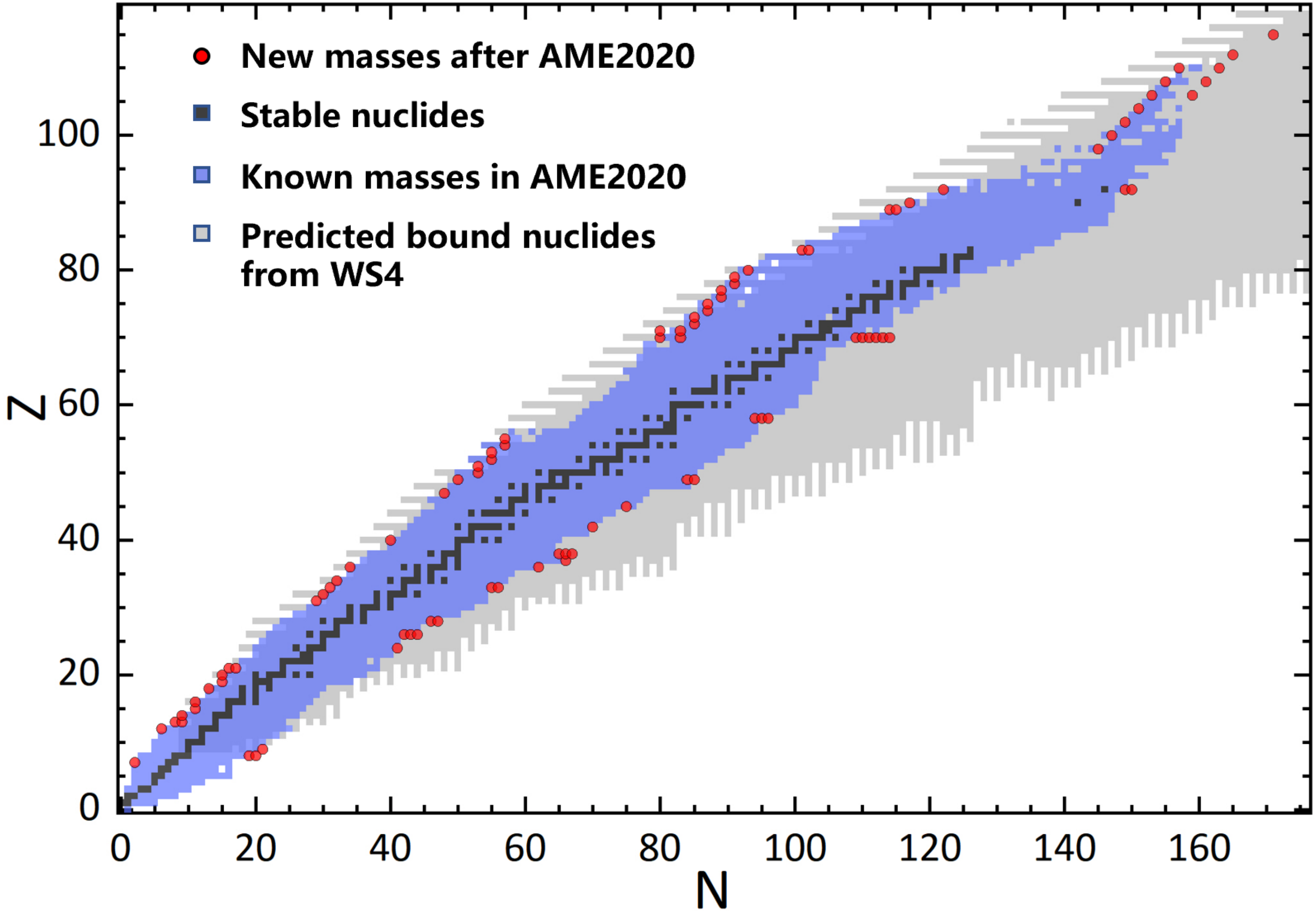
F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

Relative mass uncertainties

Credits to Wenjia Huang, IMP



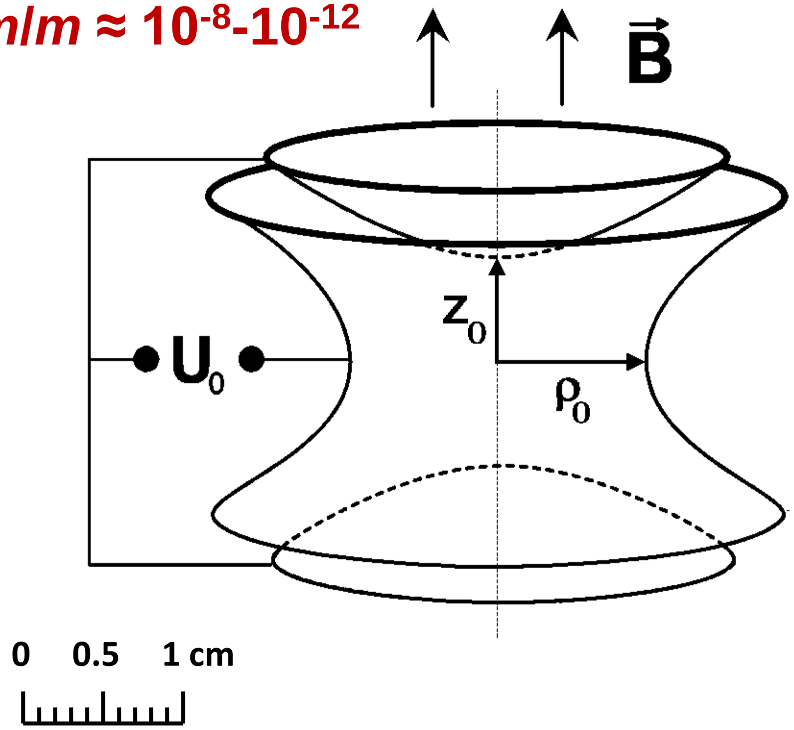
New masses measured since last AME2020



„Old“ mass spectrometry devices

Penning Trap

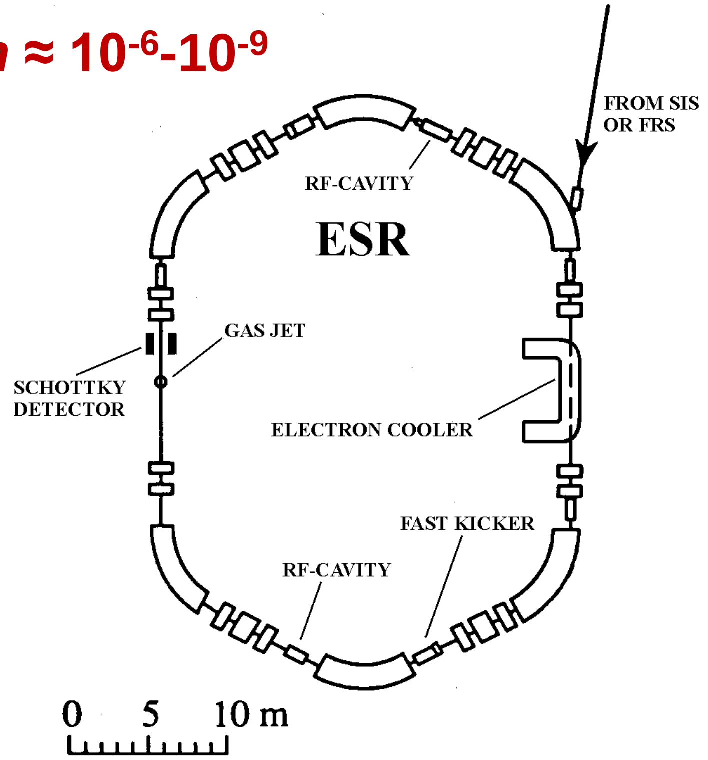
$\delta m/m \approx 10^{-8}$-$10^{-12}$



particles at nearly rest in space

Storage Ring

$\delta m/m \approx 10^{-6}$-$10^{-9}$



relativistic particles

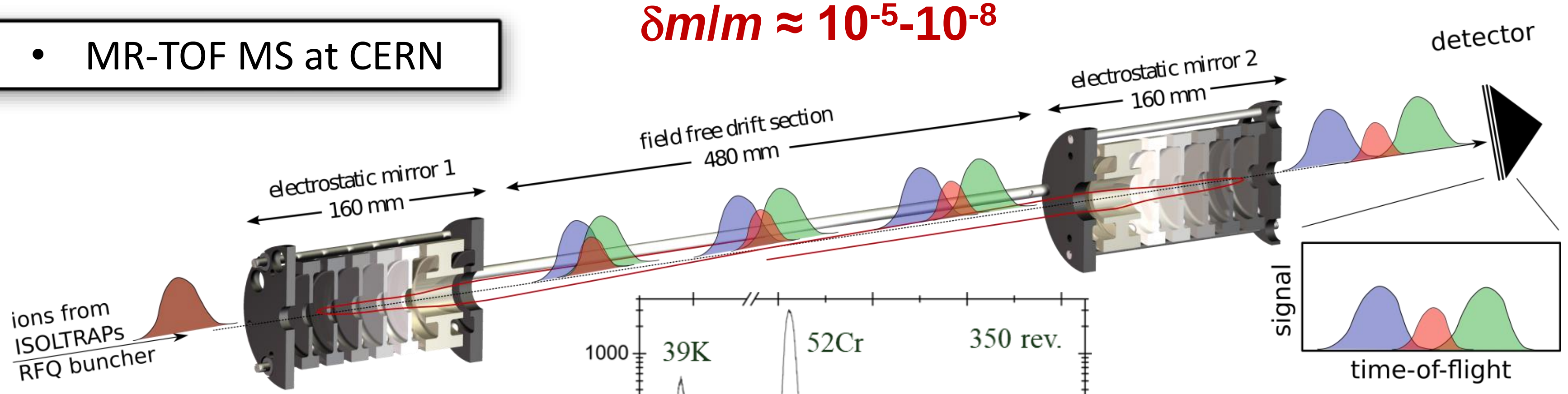
∗ ion cooling ∗ “infinite“ storage time ∗ single-ion sensitivity
∗ frequency meas. ∗ mass spectrometric capabilities ∗ high accuracy

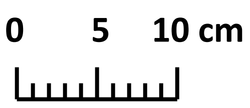
„New“ trapping device

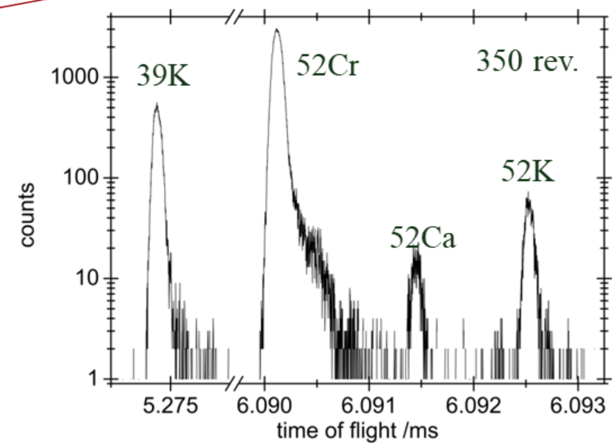
Multi-Reflection Time-of-Flight Spectrometer

- MR-TOF MS at CERN

$\delta m/m \approx 10^{-5}$-$10^{-8}$





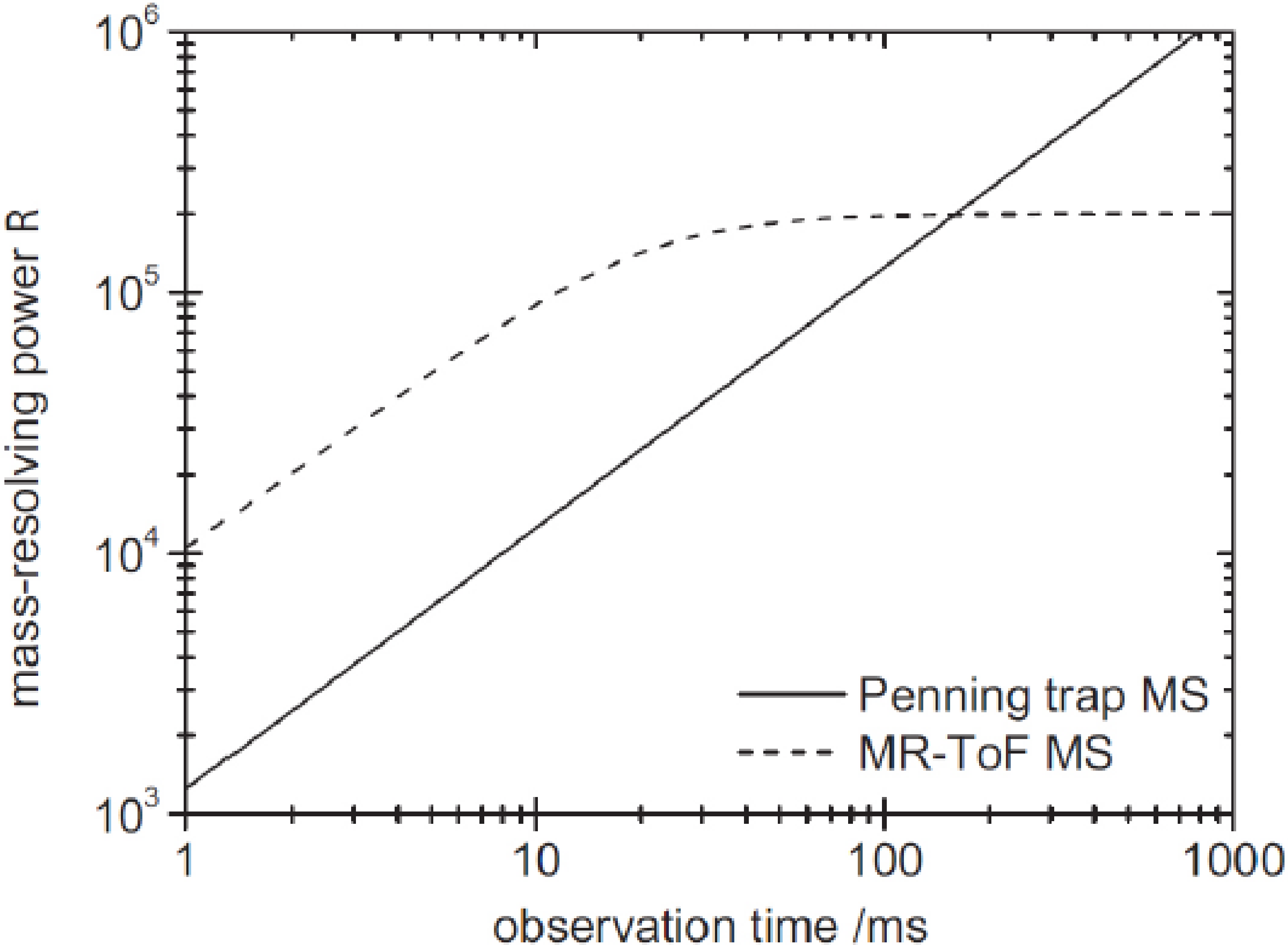


R. N. Wolf *et al.*, NIM A **686**, 82 (2012)
R. N. Wolf *et al.*, IJMS (2013)

particles at nearly rest in space

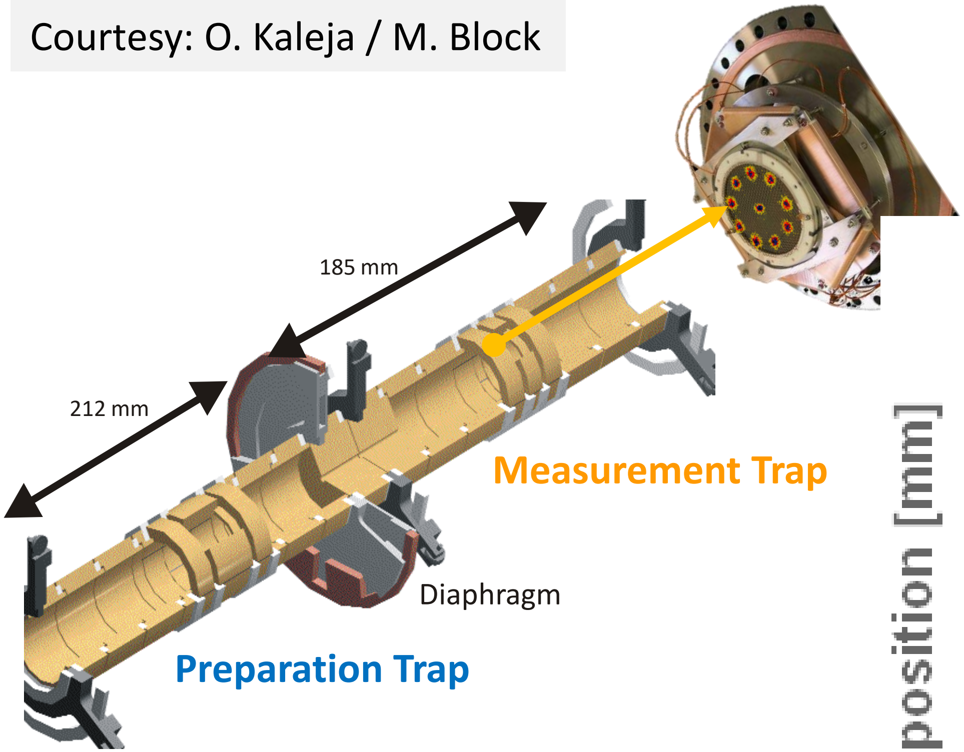
∗ “long“ storage time ∗ single-ion sensitivity ∗ time-of-flight measurement ∗ high accuracy ∗ mass spectrometric capabilities

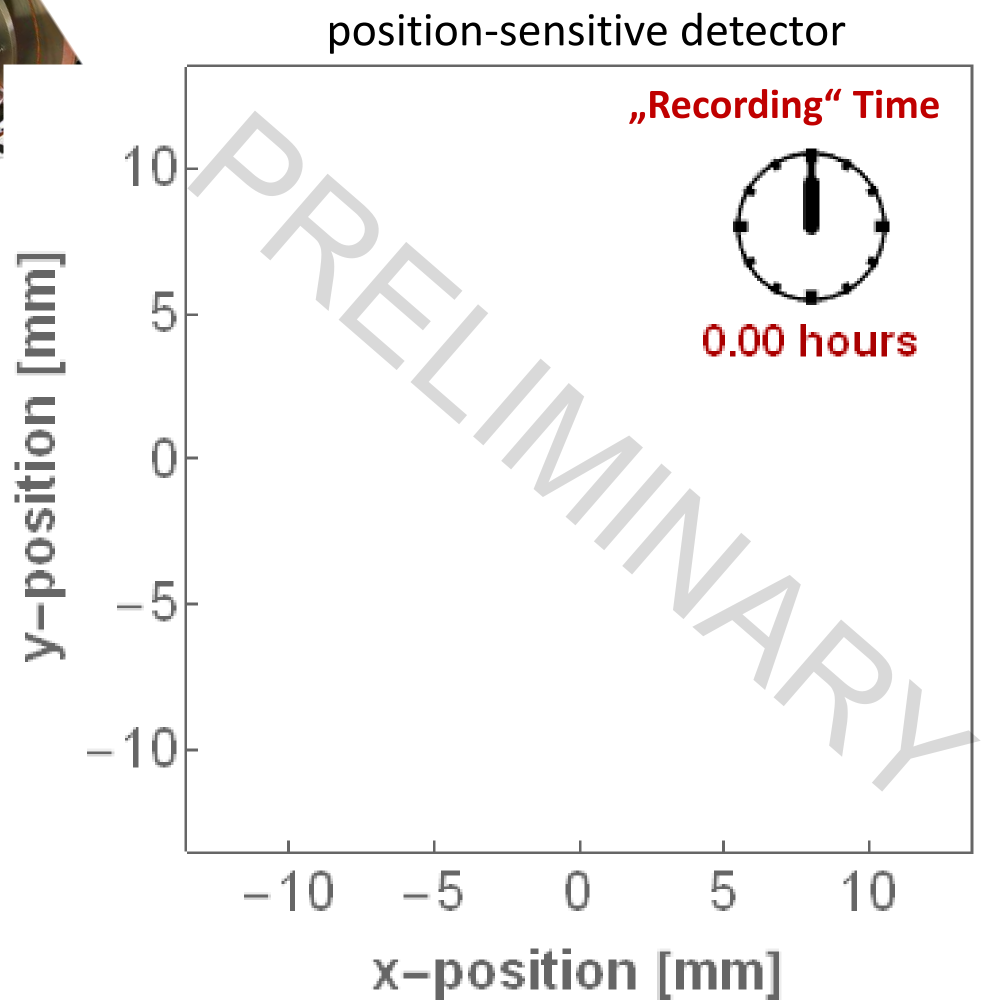
Mass resolving power



PI-ICR on $^{255(m)}Lr^{2+}$ @ SHIPTRAP

Courtesy: O. Kaleja / M. Block

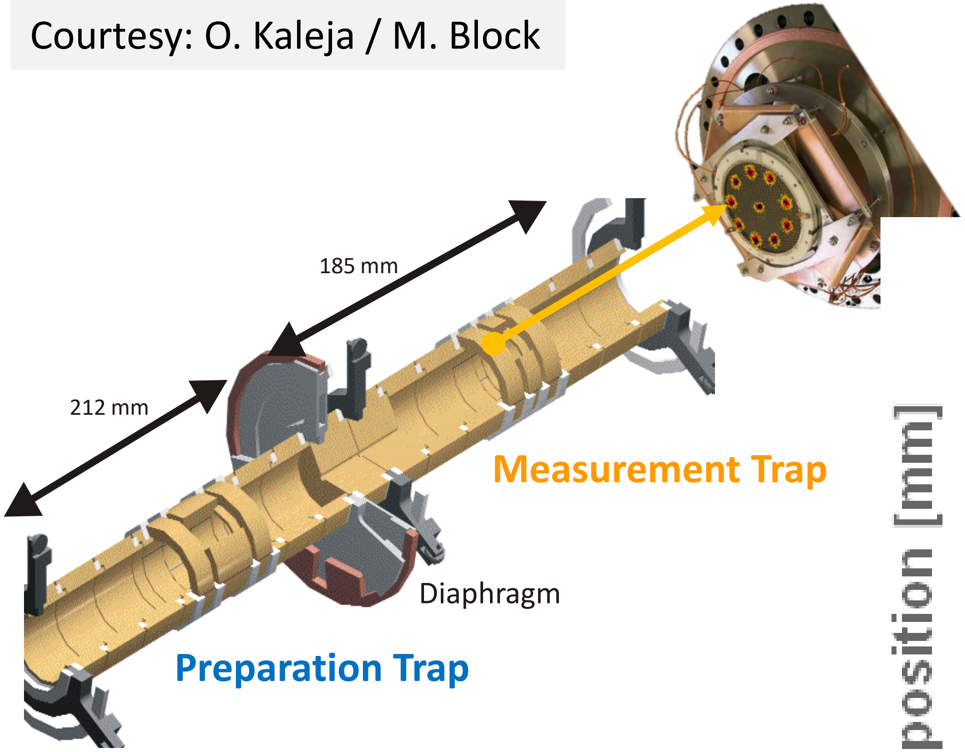


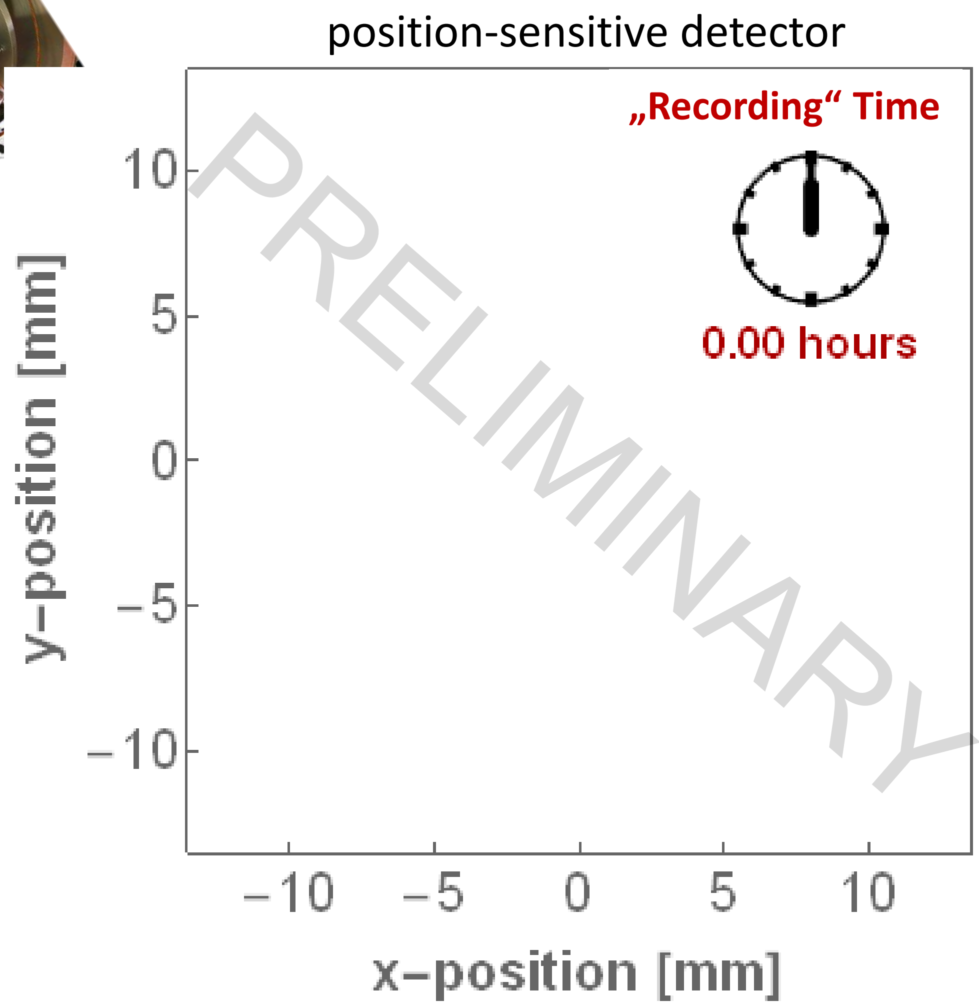


Production rate at GSI:
4 Lr ion every 1 min
Efficiency: ~5%
→ ~14 events per hour

PI-ICR on $^{255(m)}Lr^{2+}$ @ SHIPTRAP

Courtesy: O. Kaleja / M. Block





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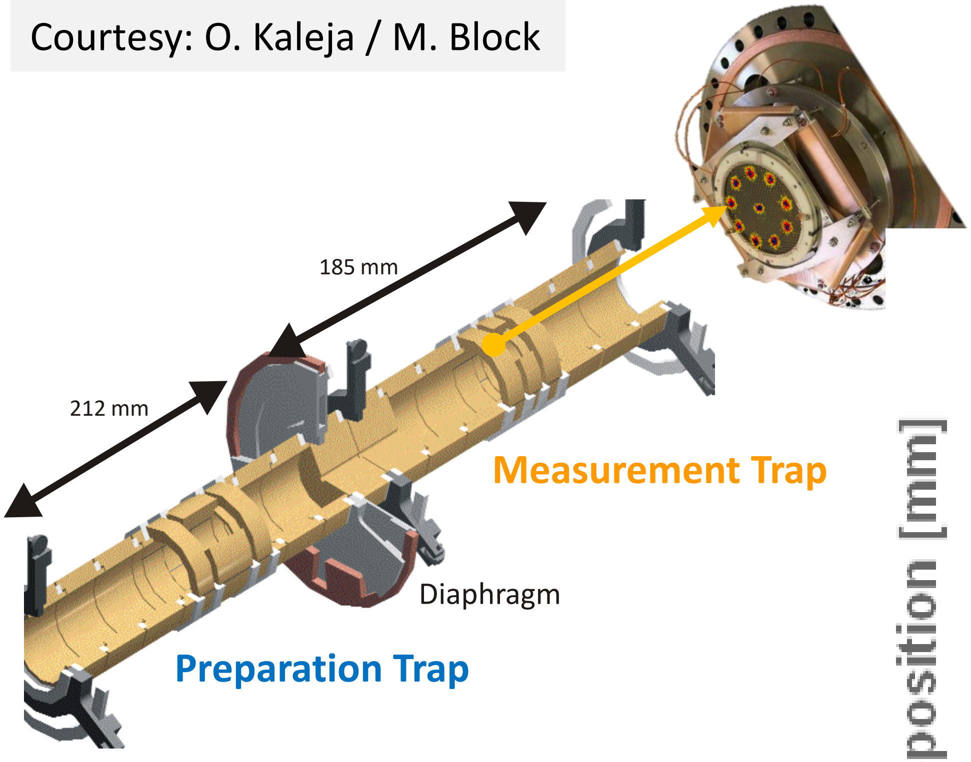
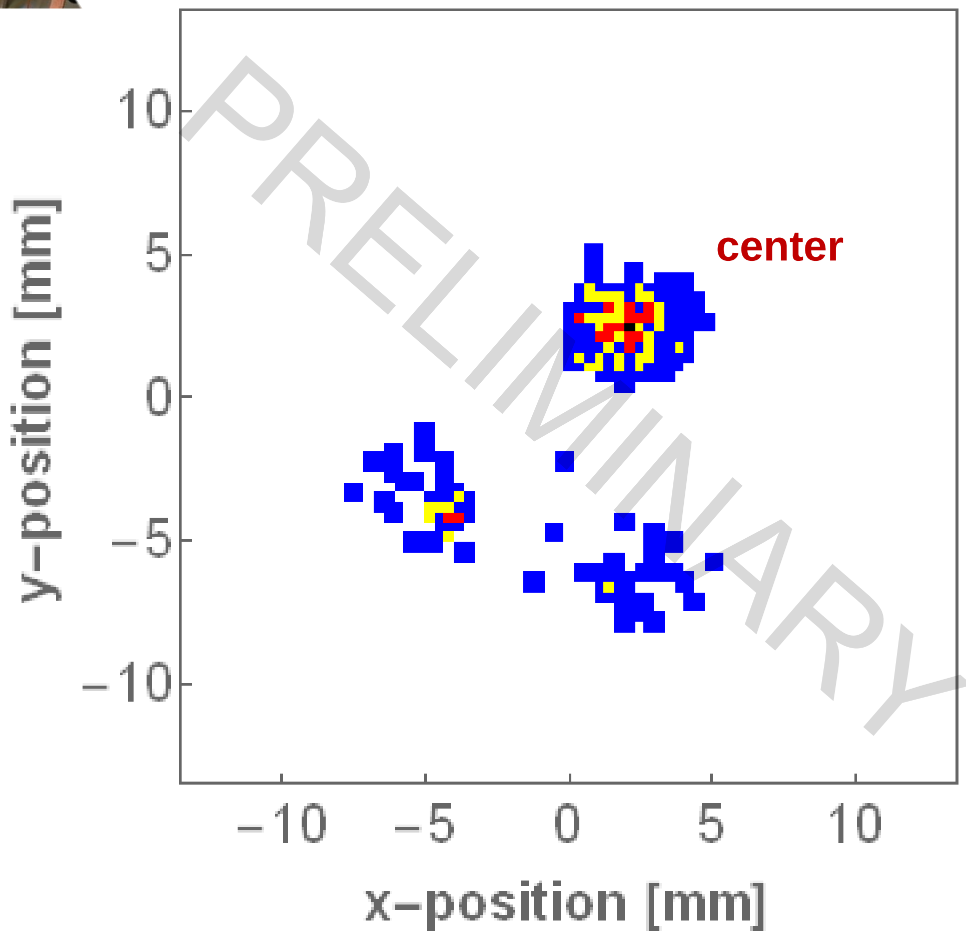
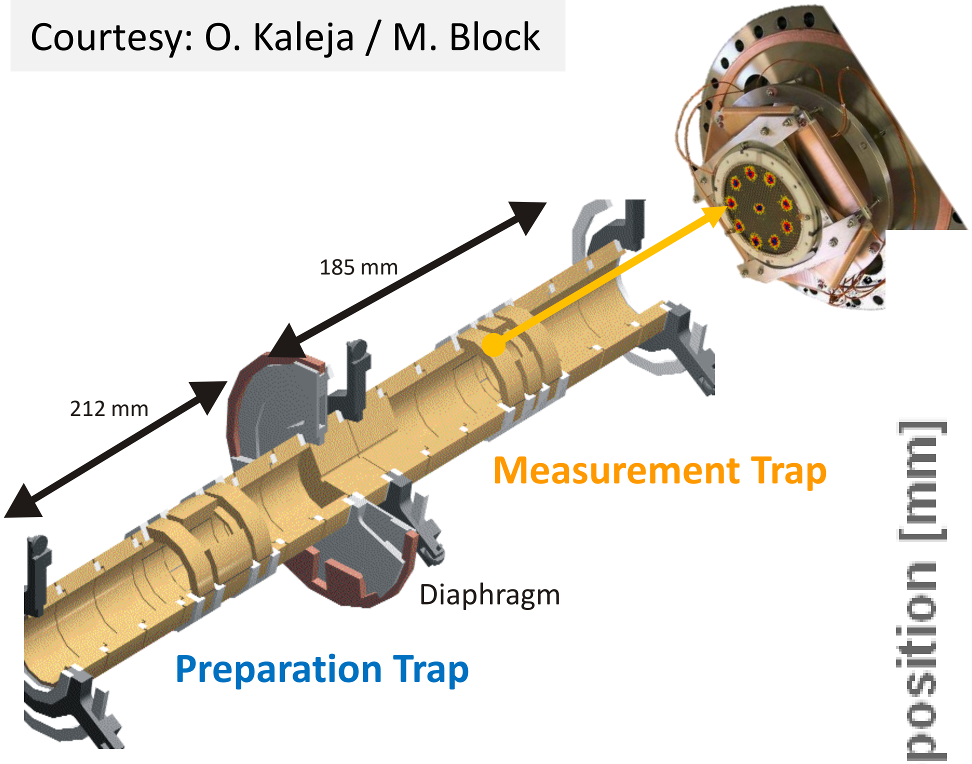


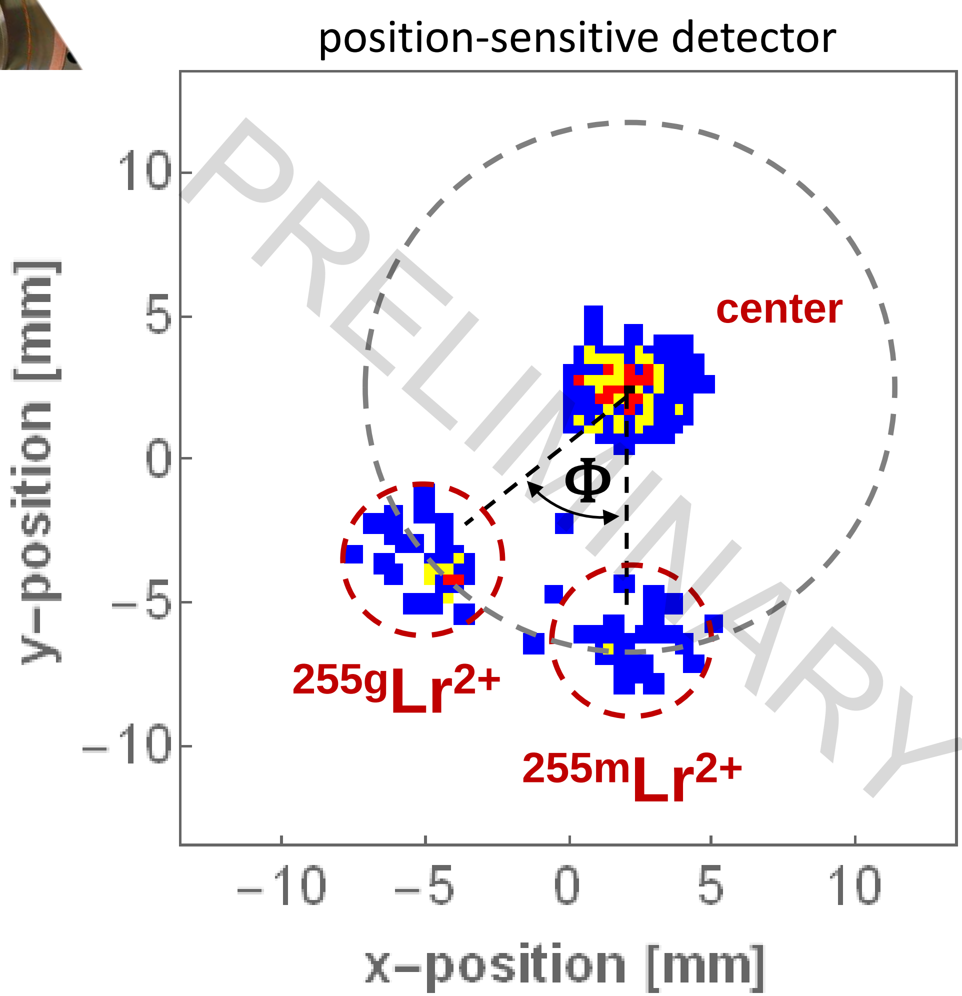
position-sensitive detector



PI-ICR on $^{255(m)}Lr^{2+}$ @ SHIPTRAP

Courtesy: O. Kaleja / M. Block





Mass resolution of 10^7

Measurement principle at PENTATRAP

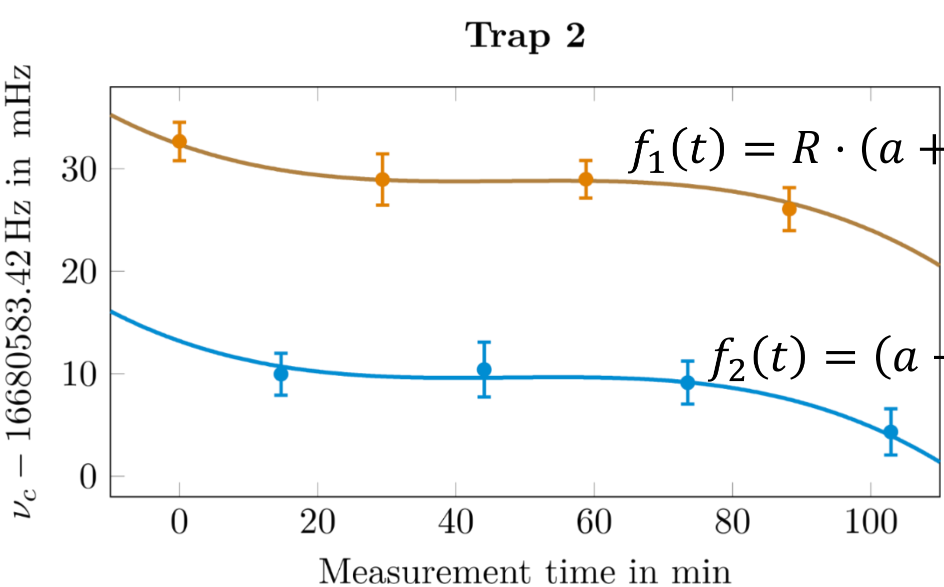
Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

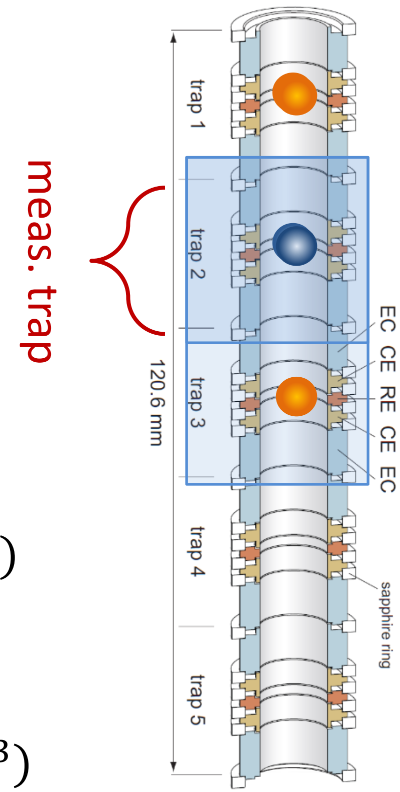
Second ion:

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



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

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



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

The ECHo (^{163}Ho) project

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

NEUTRONS FOR SCIENCE

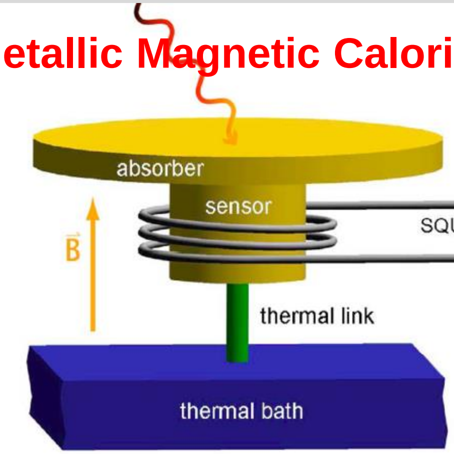
EC-Decay of ^{163}Ho

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

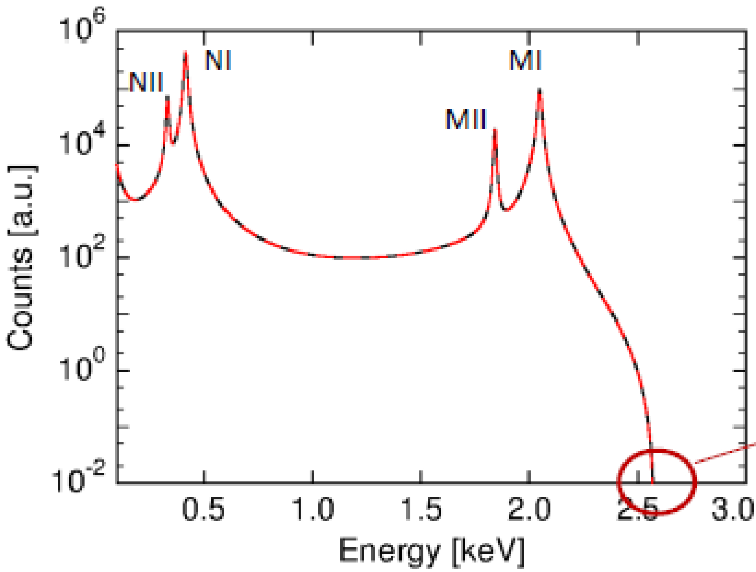
ECHo-Collaboration:
Heidelberg University

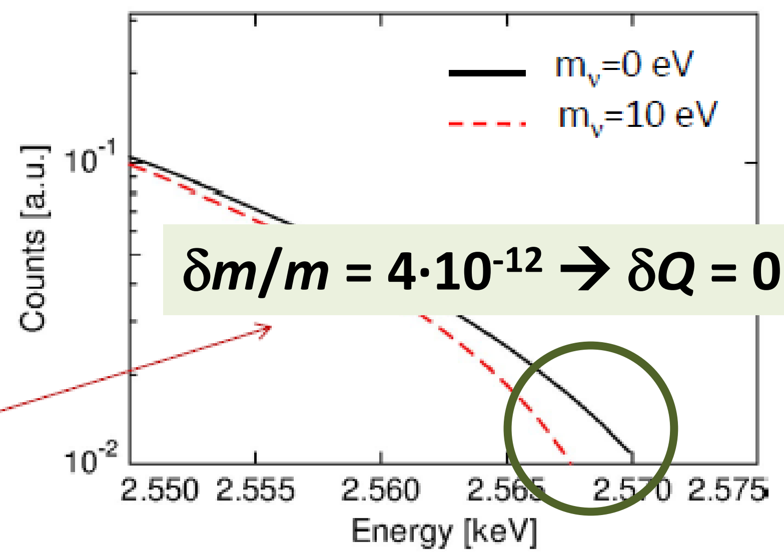
Theory

Metallic Magnetic Calorimetry



$Q = M(^{163}\mathrm{Ho}) - M(^{163}\mathrm{Dy}) = M(^{163}\mathrm{Ho}^{39+}) - M(^{163}\mathrm{Dy}^{39+}) + \Delta B_{electron}$





$\delta m/m = 4\cdot10^{-12} \rightarrow \delta Q = 0.6$ eV

Latest result: $m_\beta < 15$ eV/c² (90% c.l.) @ ECHo

Ch. Schweiger *et al.*, Nature Phys. **20**, 921 (2024)
ECHo Collab., Phys. Rev. Lett. **136,** 121801 (2026)

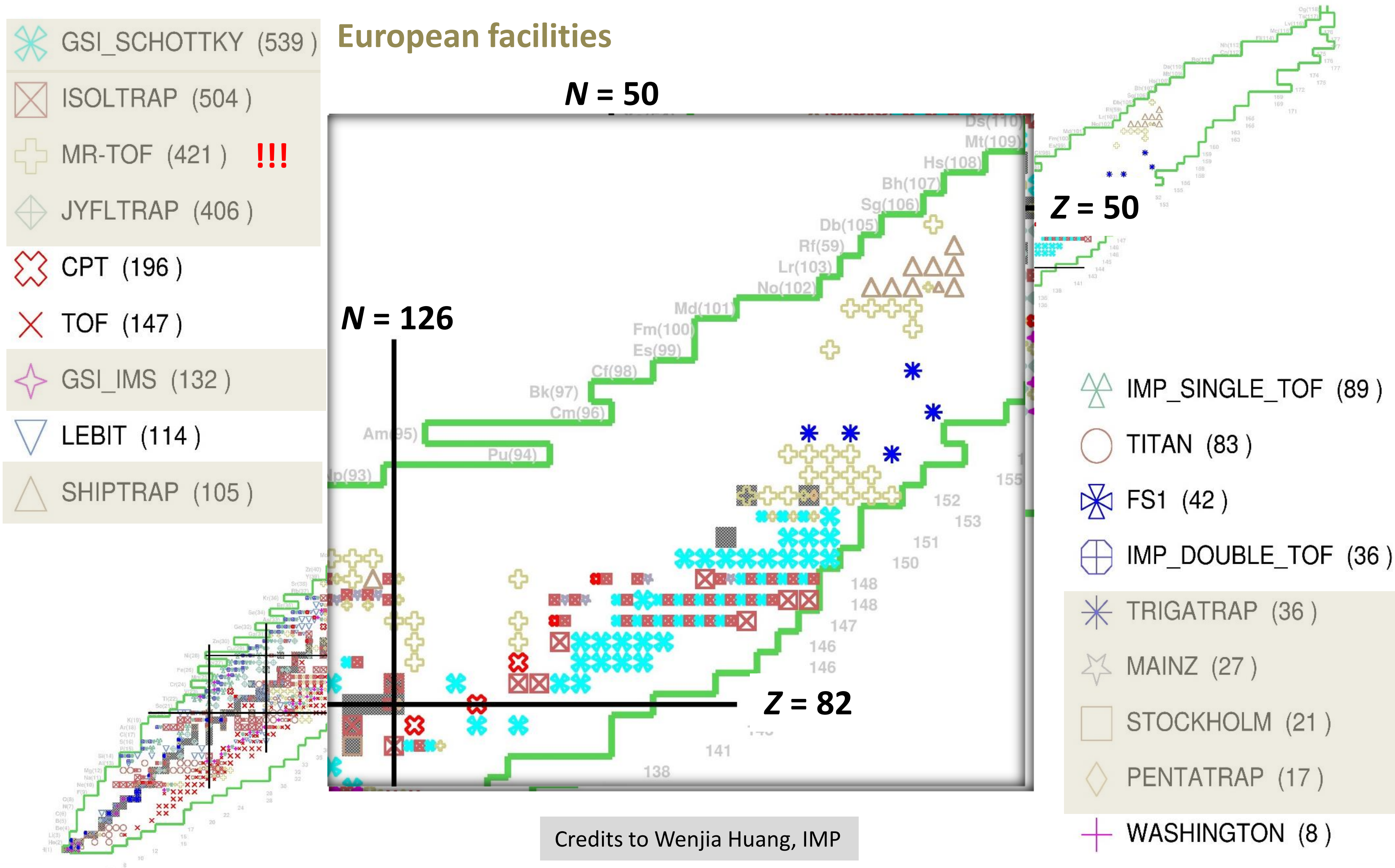
Penning traps for mass measurements

European facilities

Type of reaction	ISOL-TRAP	CPT	SHIP-TRAP	JYFL-TRAP	LEBIT	TRIGA-TRAP	TITAN	PENTA-TRAP	HITRAP
ISOL	X						X		
fusion		X	X						
IGISOL				X					
fragmen-tation					X				X
neutron-fission						X			
highly-charged							X	X	X
long-$T_{1/2}$ stable								X	X

There is a high degree of complementarity !

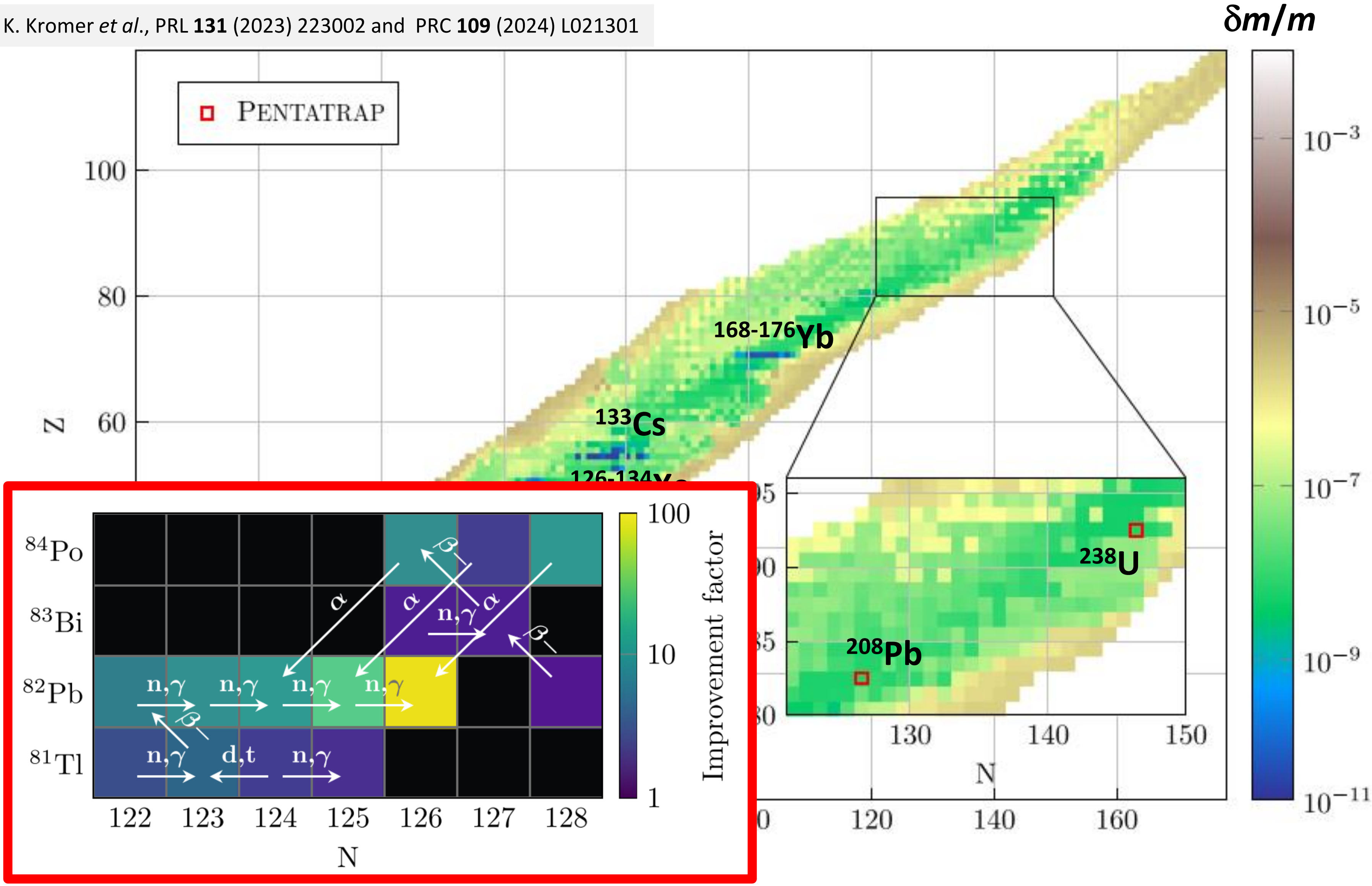
Mass summary of all facilities



Credits to Wenjia Huang, IMP

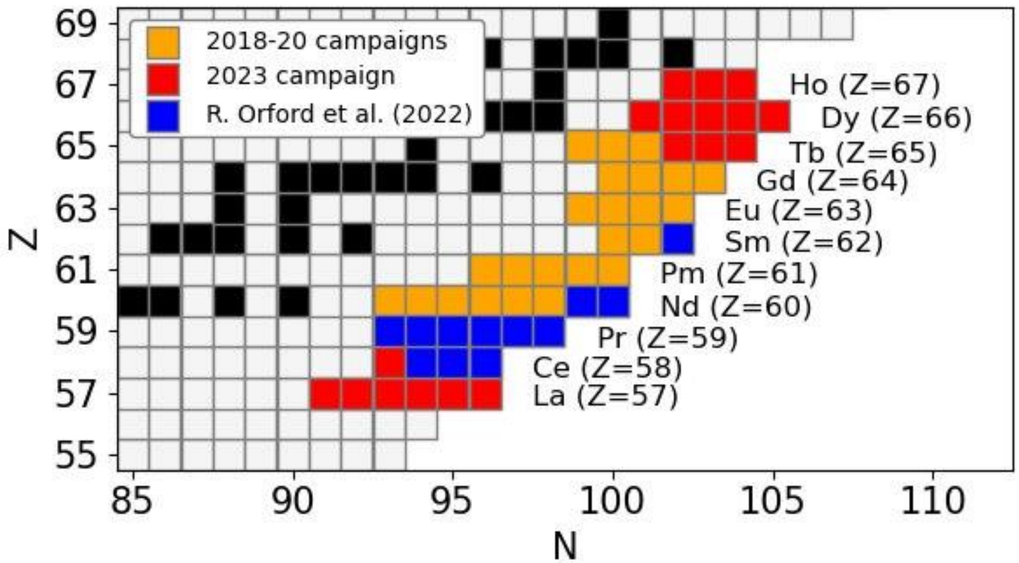
The AME mass backbone

K. Kromer *et al.*, PRL **131** (2023) 223002 and PRC **109** (2024) L021301



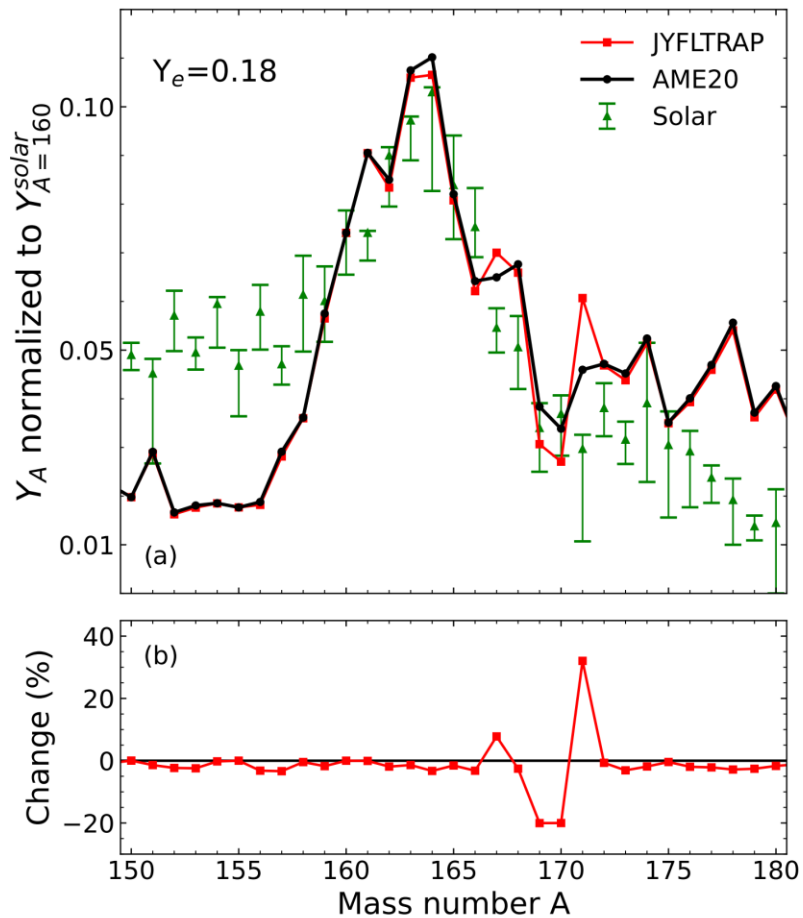
Impact of precise nuclear masses

Investigation of the rare-earth abundance peak of the r-process



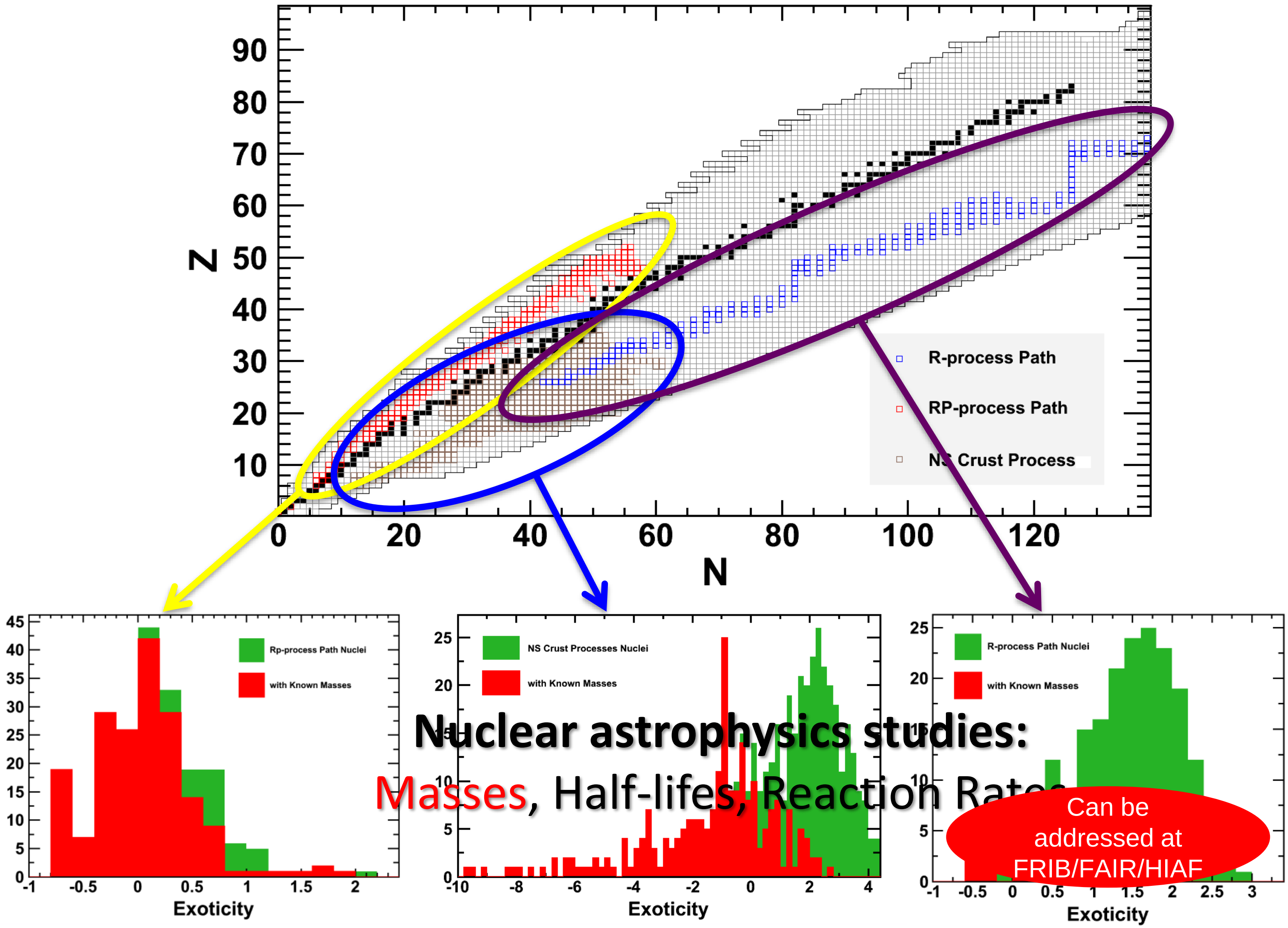
19 nuclides measured for the first time at JYFLTRAP

TALYS neutron-capture reaction rates:
changes up to 15% as compared to AME20
→ Impact on abundances at *A*=169-171



A. Jaries *et al.*, PRC **110** (2024) 045809 and A. Jaries *et al.*, PRL **134** (2025) 042501

Mass spectrometry in nuclear astrophysics



Nuclear astrophysics studies:

Masses, Half-lifes, Reaction Rates

Can be addressed at FRIB/FAIR/HIAF

Thanks …

to the entire mass spectrometry community…

and you for the invitation and your attention!

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

Spare slides

The nucleosynthesis paths

Key incredient to determine the reaction path: nuclear binding energies!