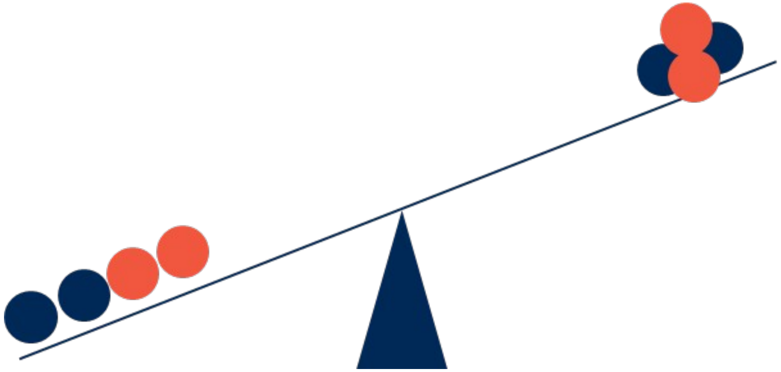
Measurement of double electron-capture Q-value with the JYFLTRAP mass spectrometer

A presicion mass measurement of Ba isotopes

Brian Kootte for the IGISOL Collaboration

Binding energy - fundamental property of the nucleus

- Nucleus weighs less than its constituents
- Difference is known as the **binding energy**



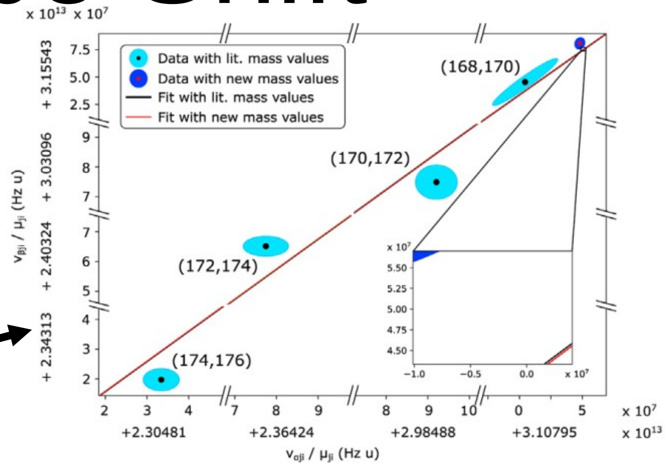
Binding energy is extracted from atomic masses and essential for:

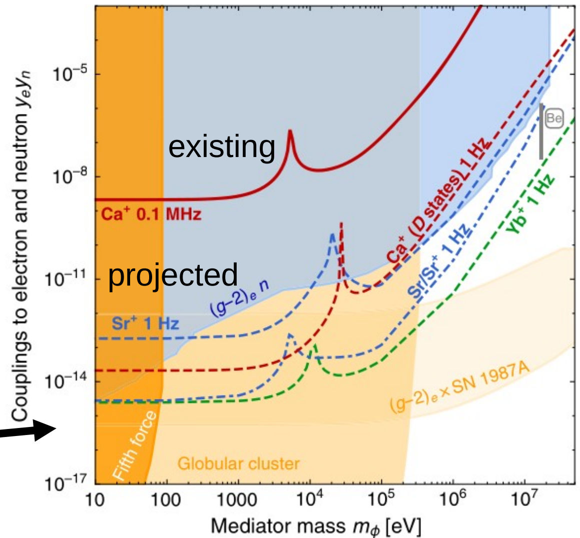
- Nuclear structure
- Nuclear astrophysics
- Fundamental physics tests

Motivation #1: Isotope Shift

- e^- interact with nucleus to shift atomic energy levels
- Isotope-dependent shifts of atomic transition: $\delta\nu = \nu - \nu_{ref}$
- **Modified isotope shifts** of two different transitions have roughly linear relationship in "King" plot $\mu\delta\nu_1$ vs $\mu\delta\nu_2$
- Mass is required for **inverse mass factor:**
- $\mu = (m_{ref} \times m_{IOI})/(m_{IOI} - m_{ref})$
  Z. Ge et al. Eur. Phys. J. A (2024) 60:147,
  D.A. Nesterenko et al. Int. J. of Mass Spec. 458 (2020) 116435
- Deviations from linearity could signal new physics

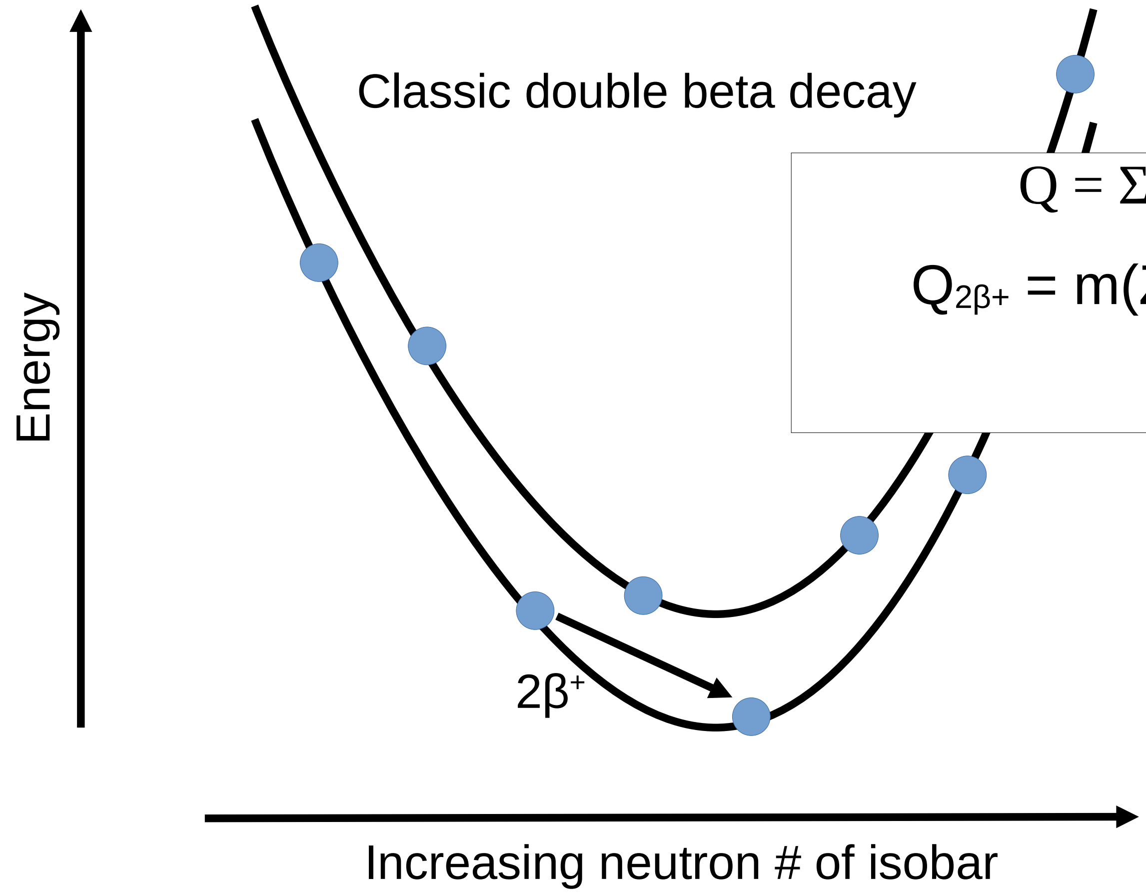
V.V. Flambaum et al. Phys. Rev. A 97, 032510 (2018),
J.C. Berengut, et al. Phys. Rev. Lett. 120, 091801 (2018)





Isotope shift limits on a hypothetical, light boson

Motivation #2: Exotic beta decay



$$Q = \Sigma \text{ initial masses} - \Sigma \text{ final masses}$$

$$Q_{2\beta+} = m(Z, N) - m(Z\text{-}2, N+2) - 2m(e^{+}) - 2m(\nu_{e})$$

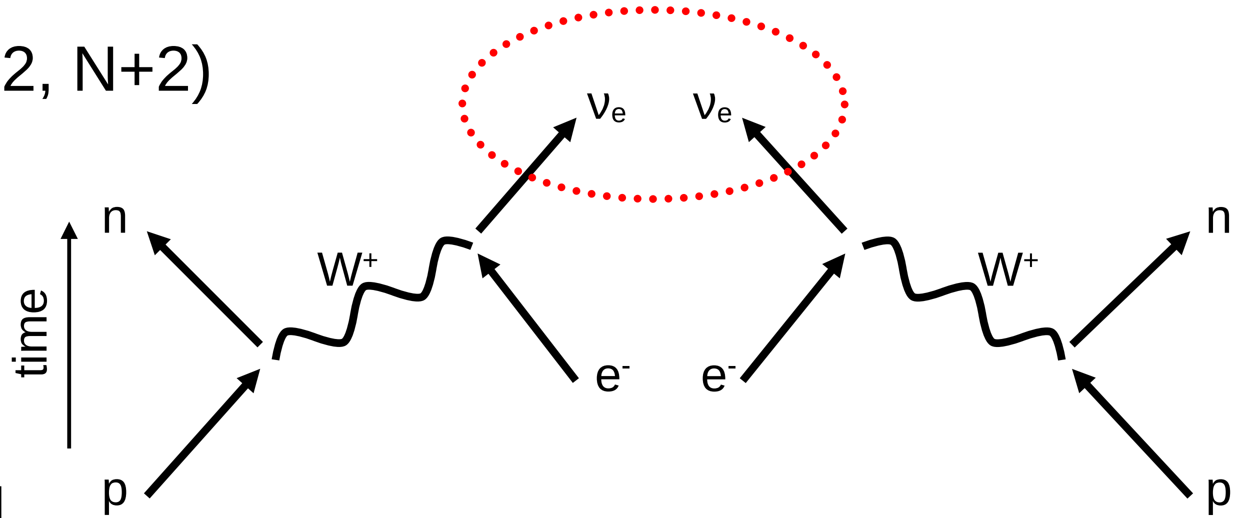
(Ignoring e^{-} binding energy)

Motivation #2: Exotic beta decay (Double orbital electron capture)

$$Q_{2\nu ECEC} = m(Z, N) - m(Z-2, N+2) - 2m(\nu_e)$$

$$Q_{0\nu ECEC} = m(Z, N) - m(Z-2, N+2)$$

Search for candidate neutrinoless decays



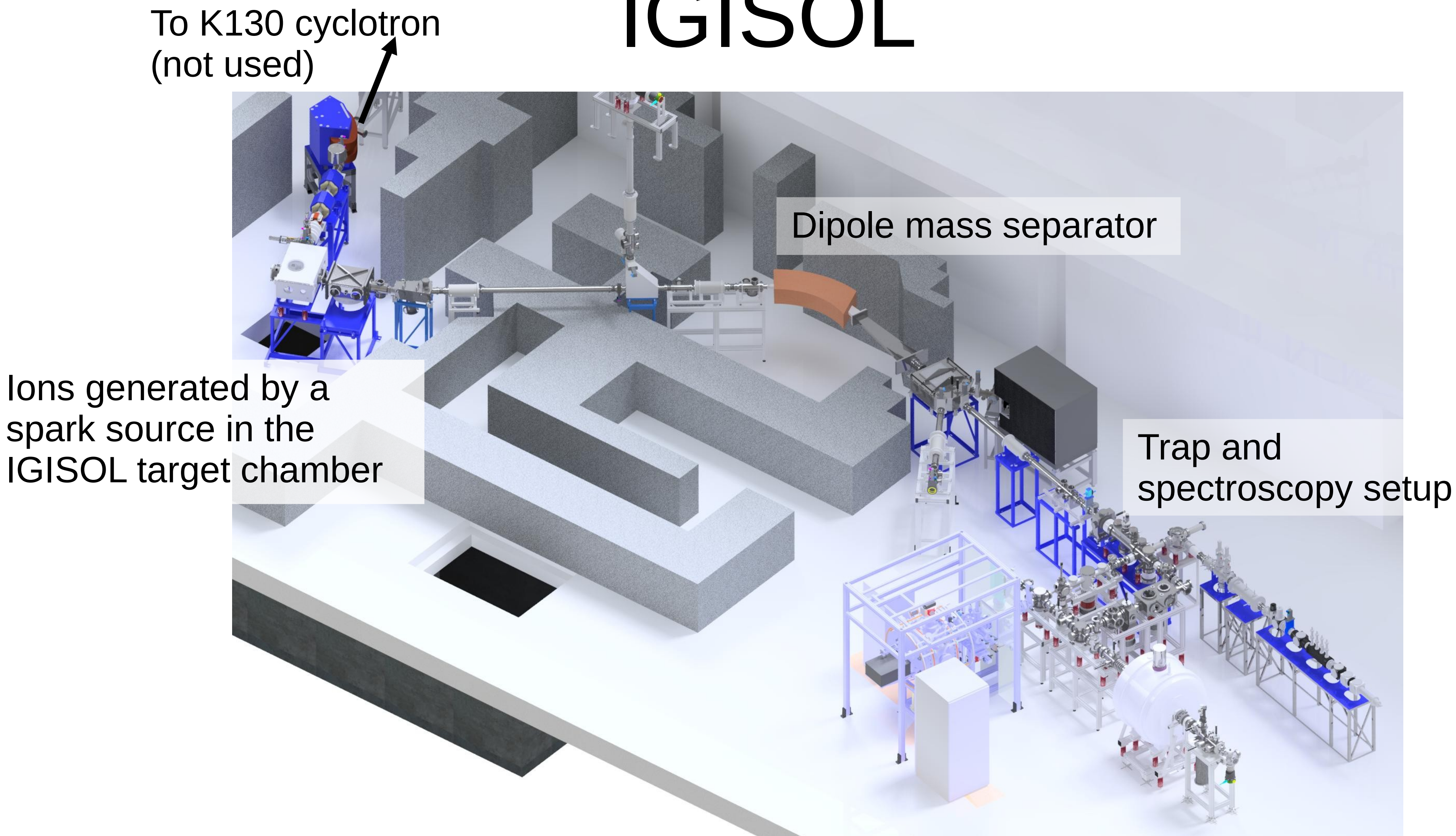
0νECEC can be enhanced significantly by resonance effects!

[Blaum et al. Rev. Mod. Phys. 92, 4, 045007 (2020)]

Need for ^{132}Ba atomic mass

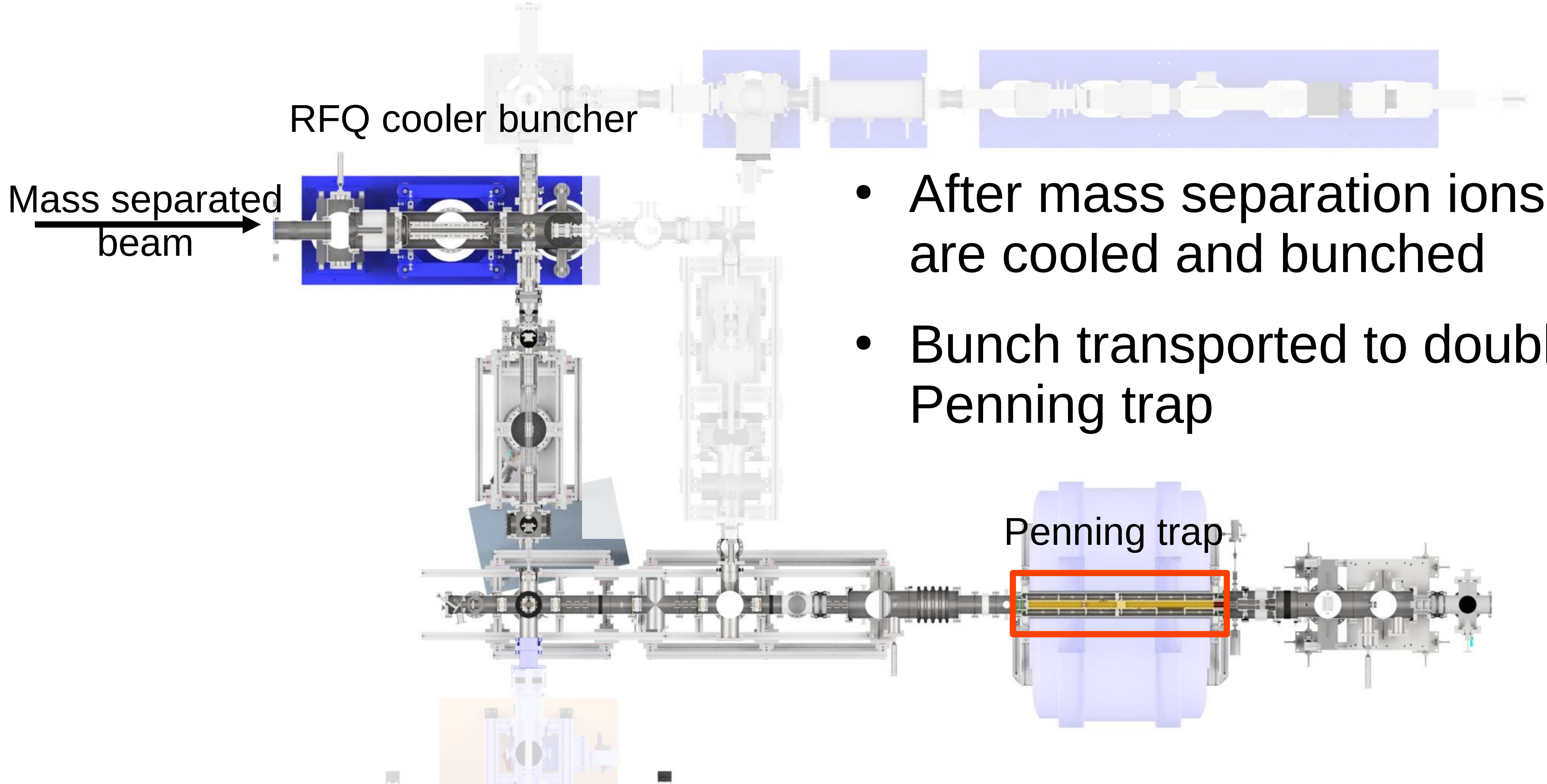
- Precise and accurate masses needed for King plot and decay Q-value
- 1-β^+ and 2-β^+ energetically forbidden
- Both EC/β^+ and ECEC modes possible
- Limit on $T_{1/2}$ from geochemical measurements of Xe in natural Barite ($BaSO_4$) [A. P. Meshik et al. Phys. Rev. C, Vol. 64, 035205 (2001)]
- $T_{1/2} > 3x10^{21}$ years (0.1% natural abundance)

IGISOL



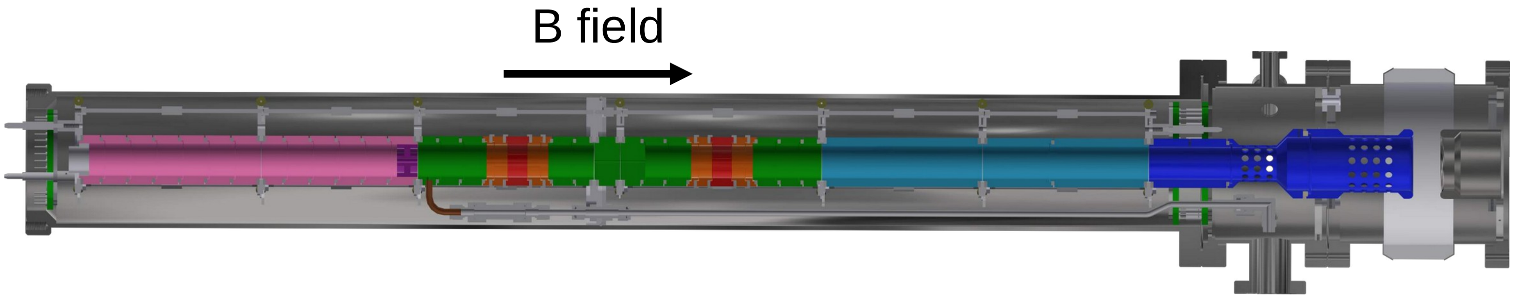
To K130 cyclotron
(not used)
Dipole mass separator
Ions generated by a
spark source in the
IGISOL target chamber
Trap and
spectroscopy setup

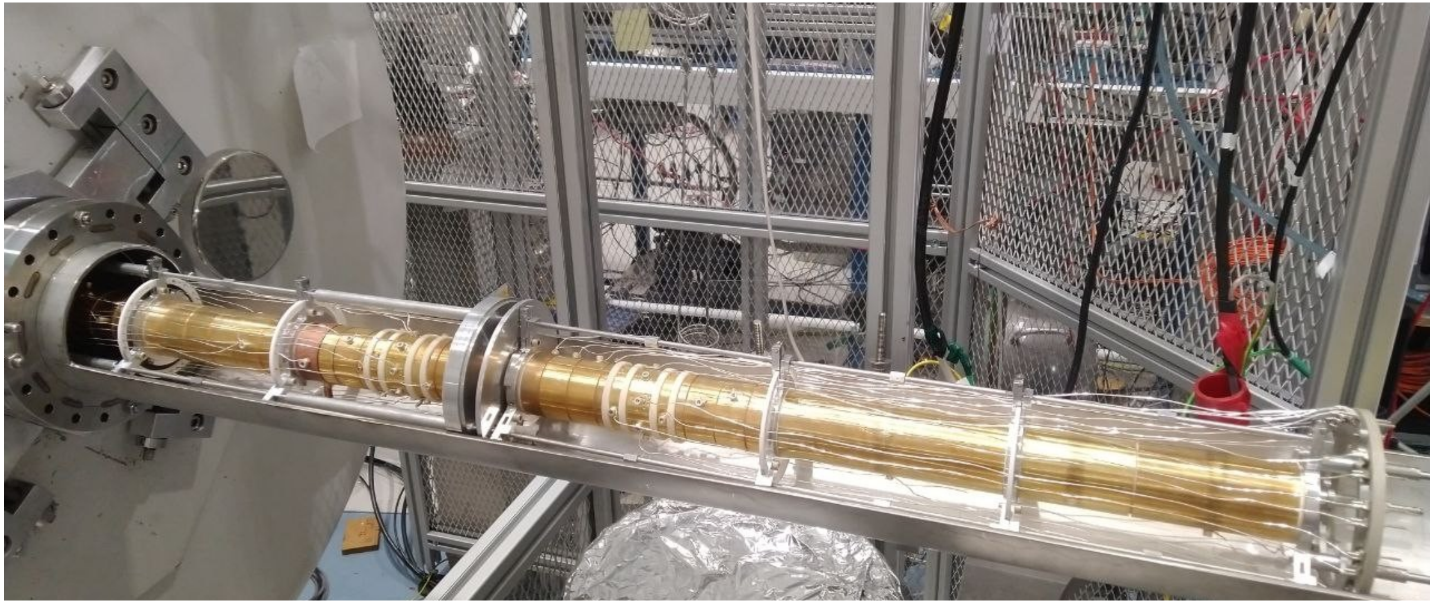
Ion trapping setup



- After mass separation ions are cooled and bunched
- Bunch transported to double Penning trap

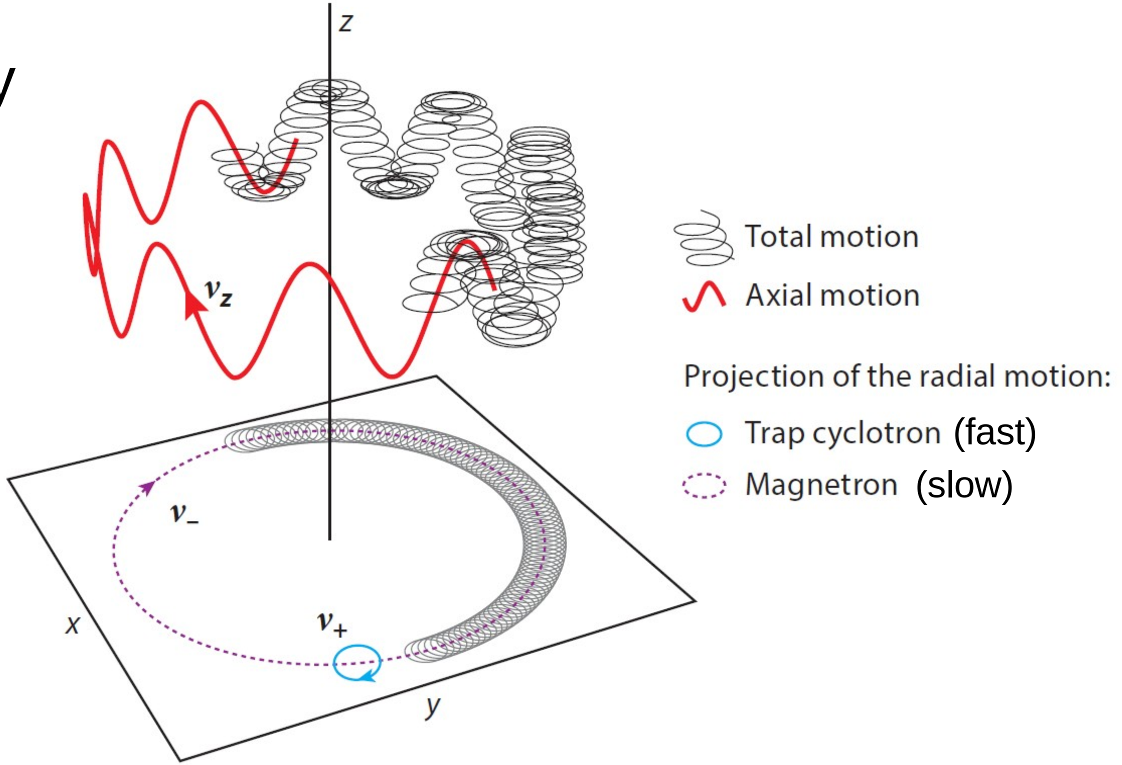
JYFLTRAP





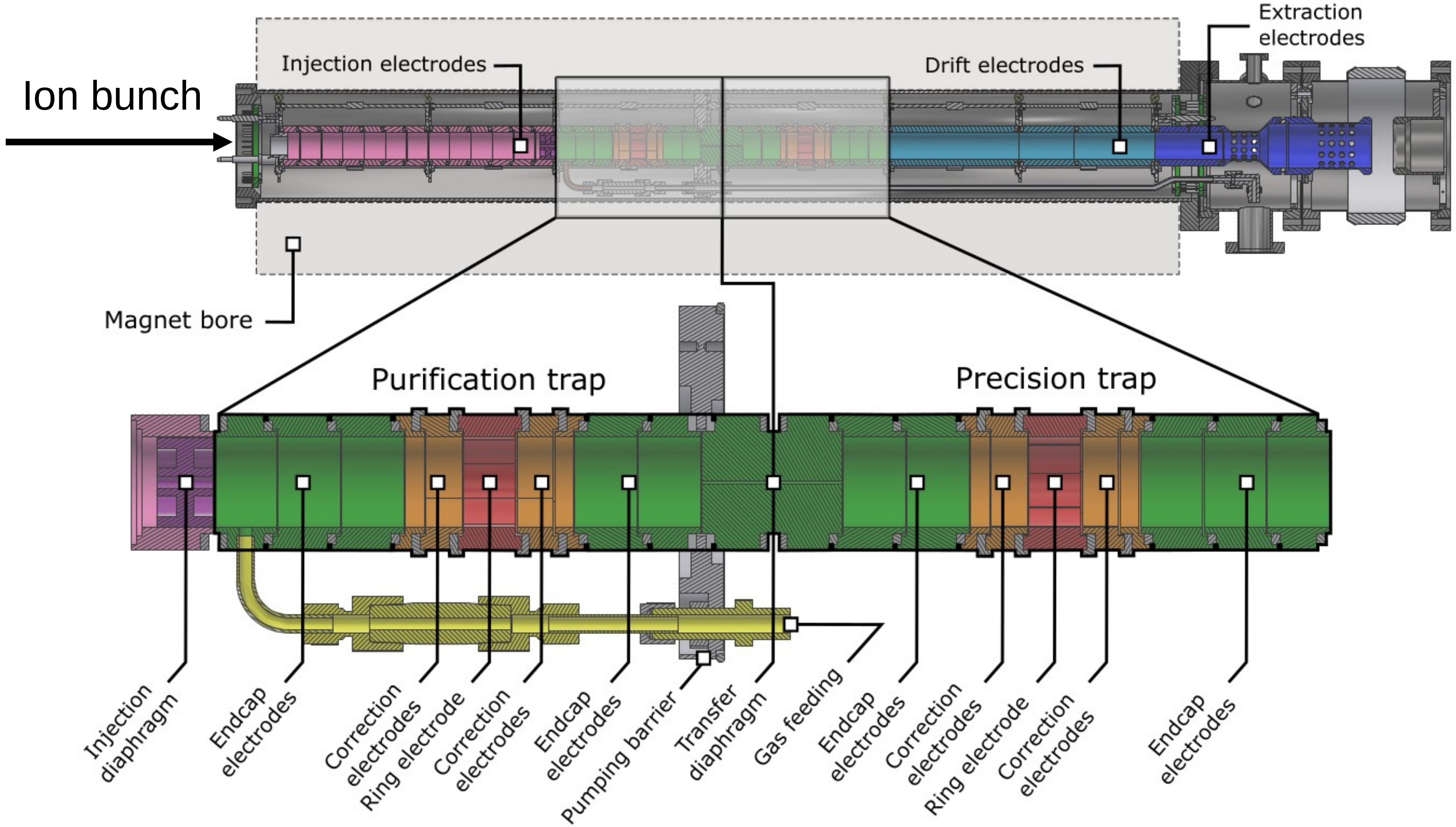
Penning trap basics

- Cyclotron frequency given by $\nu_c = qB/(2\pi m)$
- Measuring frequency provides mass
- Ion in ideal Penning trap has reduced cyclotron (ν_+) and magnetron (ν_-) eigenmodes
- Can convert from one to the other using RF electric fields
- Free space $\nu_c = \nu_+ + \nu_-$



Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74

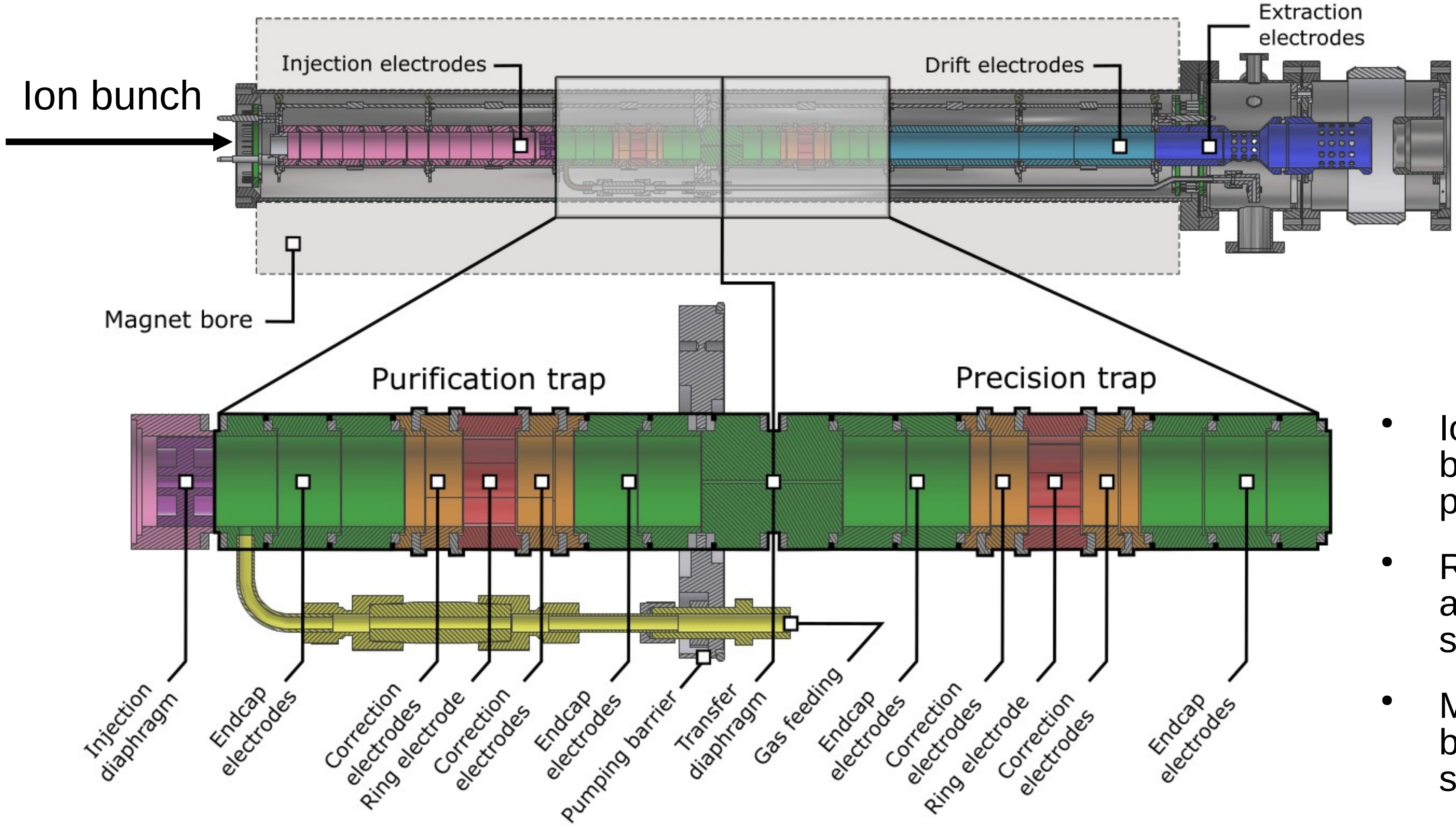
JYFLTRAP



Ion bunch
Injection electrodes
Drift electrodes
Extraction electrodes
Magnet bore
Purification trap
Precision trap
Injection diaphragm
Endcap electrodes
Correction electrodes
Ring electrode
Correction electrodes
Endcap electrodes
Pumping barrier
Transfer diaphragm
Gas feeding
Endcap electrodes
Correction electrodes
Ring electrode
Correction electrodes
Endcap electrodes

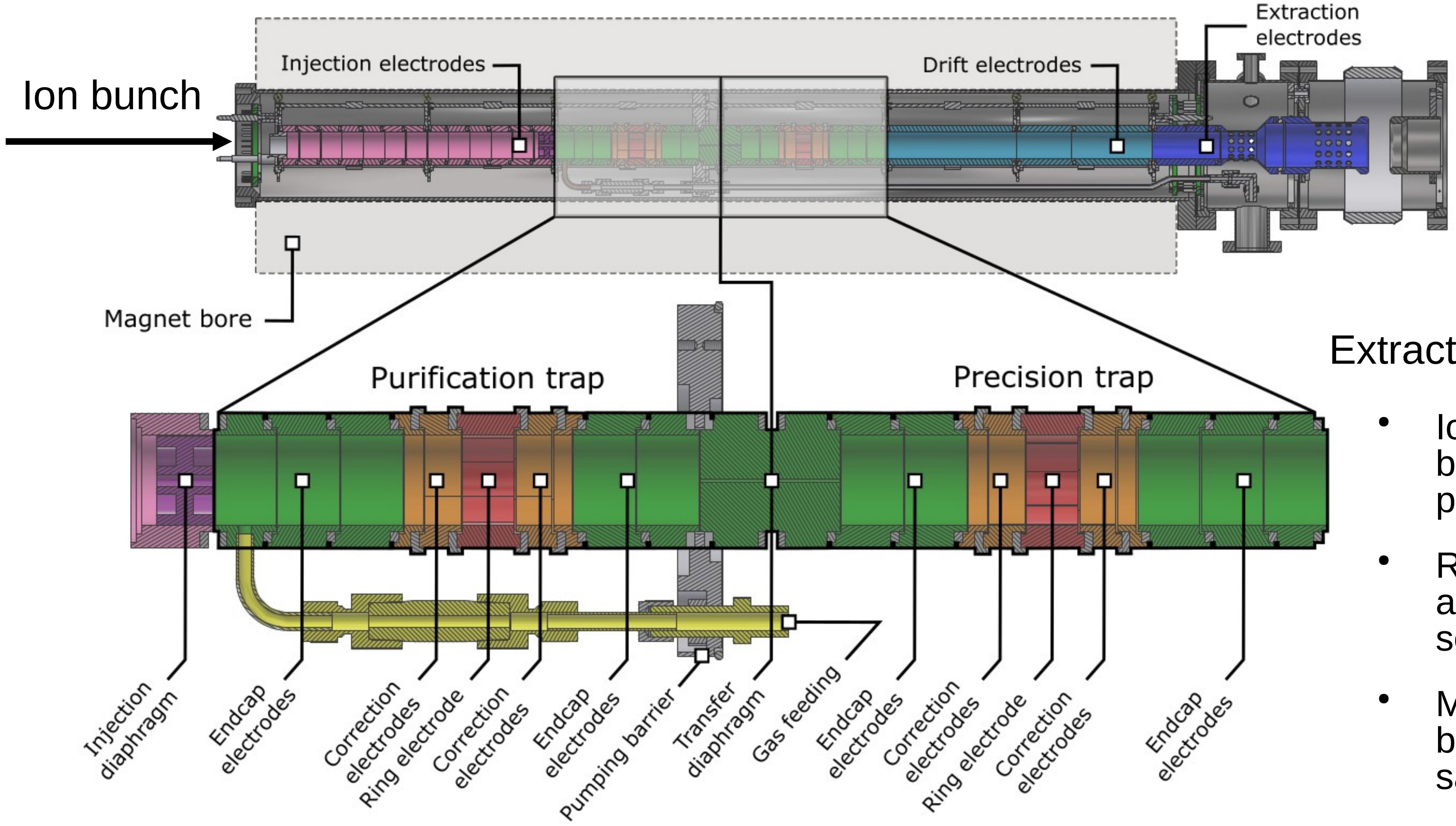
JYFLTRAP

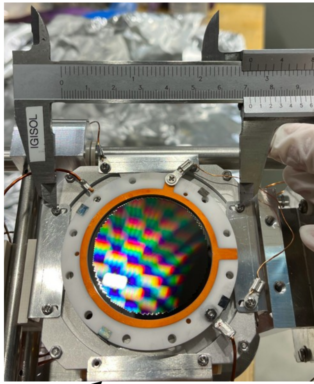
Ion bunch



- Ions cooled and bunched in preparation trap
- RF applied to achieve mass-selectivity
- Multiple cycles can be used to clean the sample

JYFLTRAP





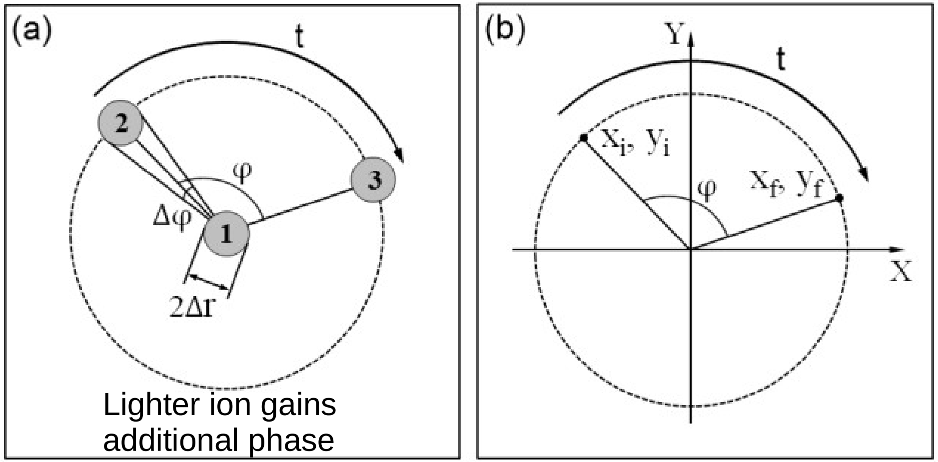
Extraction to 2D MCP

- Ions cooled and bunched in preparation trap
- RF applied to achieve mass-selectivity
- Multiple cycles can be used to clean the sample!

Phase imaging mass measurement in the precision trap

- PI-ICR can measure masses quickly and precisely
- 1) Convert ions to cyclotron mode
- 2) Ions accumulate phase (550 ms in this case)
- 3) Extract and compare angle on position-sensitive detector

see Nesterenko Eur. Phys. J. A (2018) 54: 154

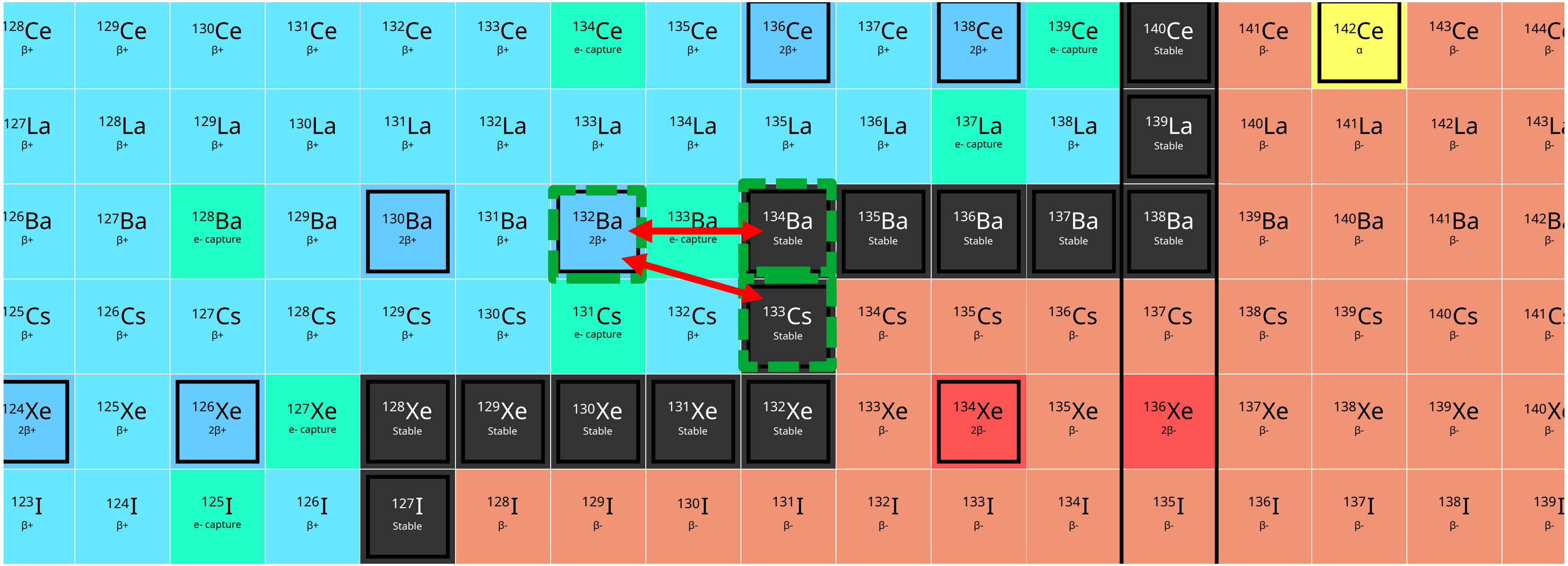


Barium Isotopes

Two frequency ratios measured in Penning trap

(evaluation ongoing)

N=82

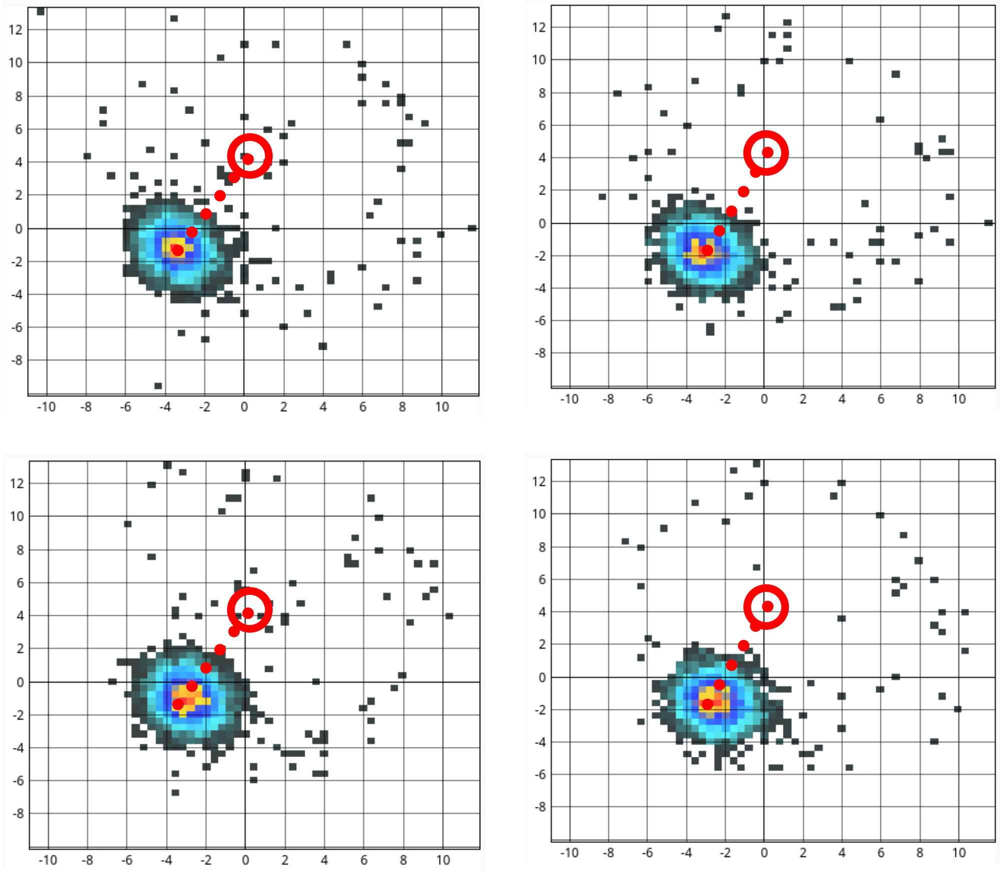


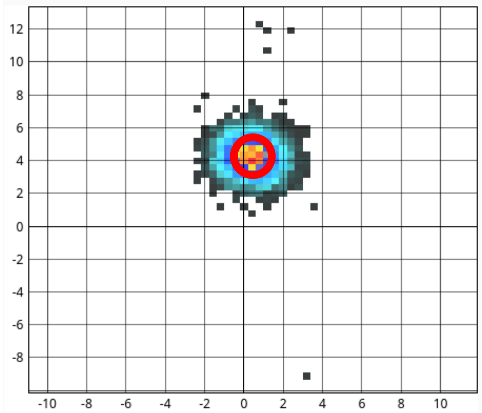
^{132}Ba vs ^{133}Cs

^{132}Ba ^{133}Cs

Magnetron

Cyclotron
(significant phase acquired)

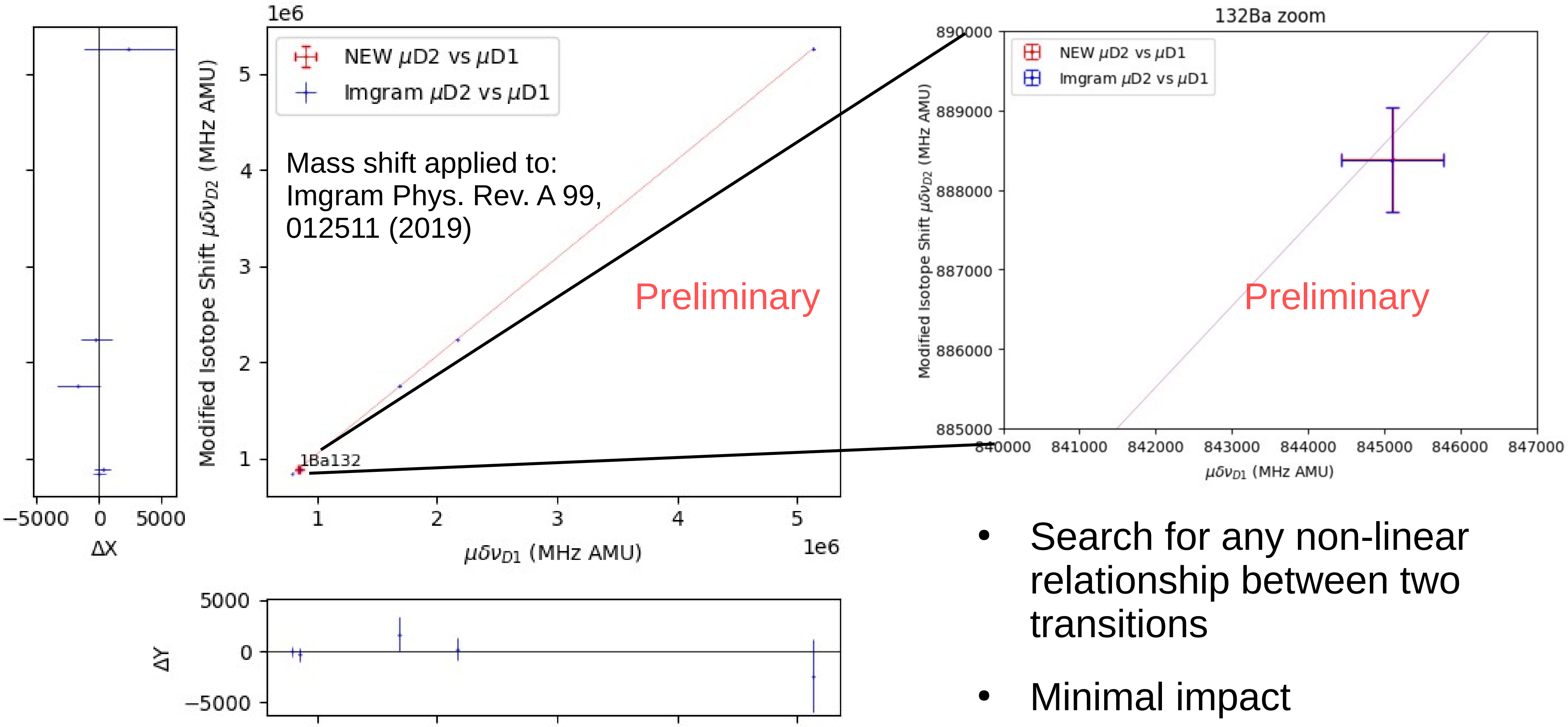




Centre

We intensionally pick a number of revolutions so the spots overlap

Effect of measurement on King Plot



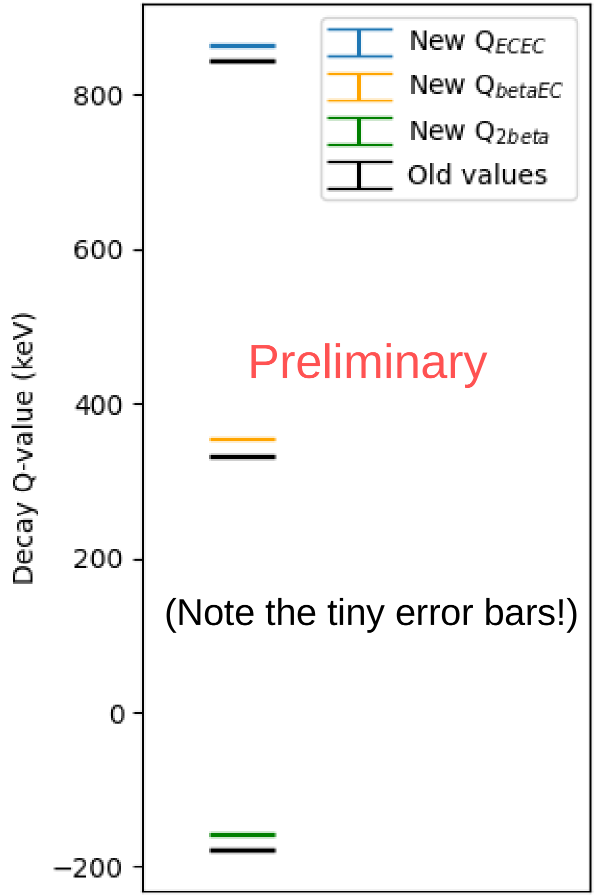
- Search for any non-linear relationship between two transitions
- Minimal impact

Shifts to decay Q-values

$$Q_{ECEC} = m(^{132}Ba) - m(^{132}Xe) - 2(\nu_e)$$

$$Q_{EC\beta+} = m(^{132}Ba) - m(^{132}Xe) - m(e^-) - 2(\nu_e)$$

$$Q_{2\beta+} = m(^{132}Ba) - m(^{132}Xe) - 2m(e^-) - 2(\nu_e)$$



Shifts to decay Q-values

$Q_{ECEC} = m(^{132}Ba) - m(^{132}Xe) - 2(\nu_e)$ →

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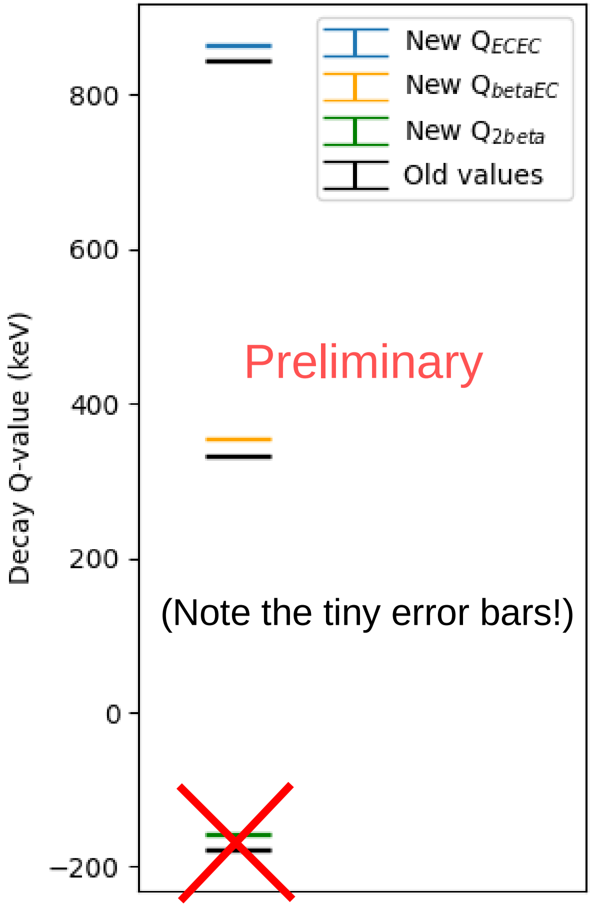

Links to 2020 Atomic Mass Evaluation

- ^{132}Ba mass is linked to ^{120}Te by 227 +/- 0.2 keV difference between ^{122}Te(p, t) and ^{132}Ba(p, t) Q-values (Munich Q3D spectrograph)
  [G. Suliman, et al. Eur. Phys. J. A 36 (3), 243-250 (2008)]

- New mass of ^{132}Ba agrees with ^{120}Te reported by Canadian Penning Trap (Argonne) using ^{120}Sn as a reference
  [N. Scielzo, et al. Phys. Rev. C 80 (2), 025501 (2009)]

Summary and Outlook

- ^{132}Ba deviates massively from the 2020 Atomic Mass Evaluation
- ^{134}Ba also deviates significantly
- Minimal effect on King plot from Imgram 2019
- Large increase in Q-value – unfortunately this likely reduces resonant ECEC
- Possible consequences for linked radioactive masses

Thank you!

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- Zhuang Ge (Academy Research Fellow)
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- Jouni Ruotsalainen
- IGISOL collaboration
- Research Council of Finland

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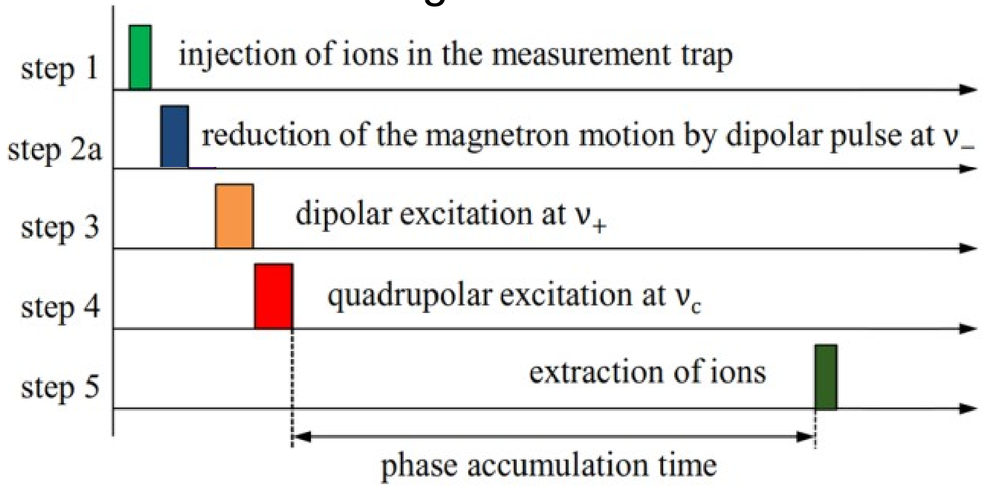
UNIVERSITY OF JYVÄSKYLÄ

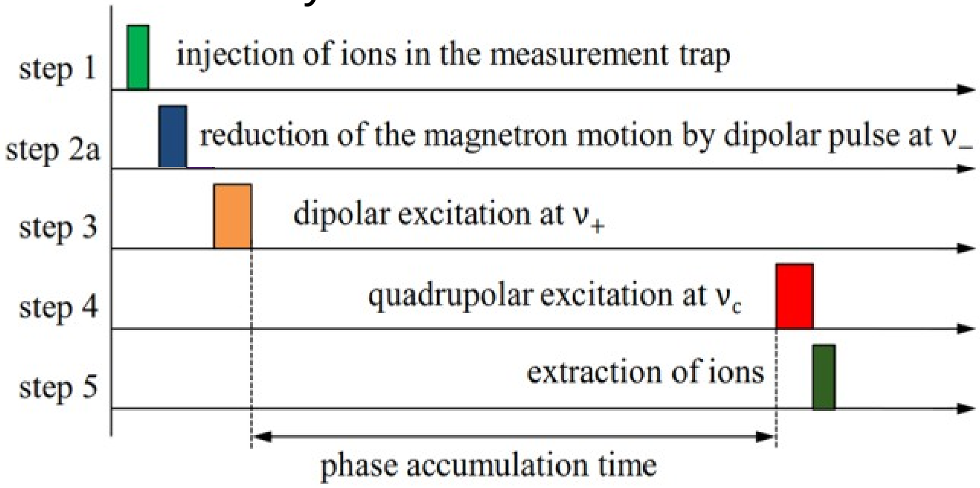
SUOMEN AKATEMIA

PI-ICR Measurement

Magnetron accumulation

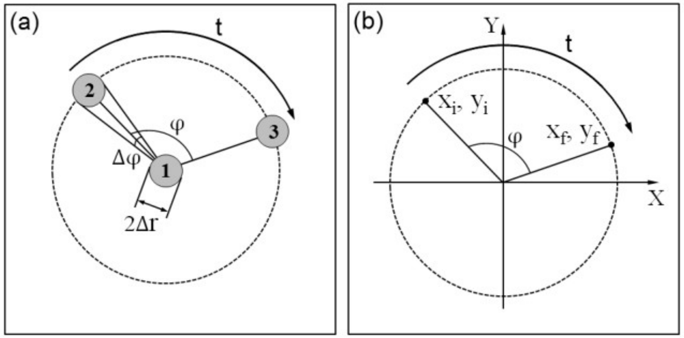


Cyclotron accumulation

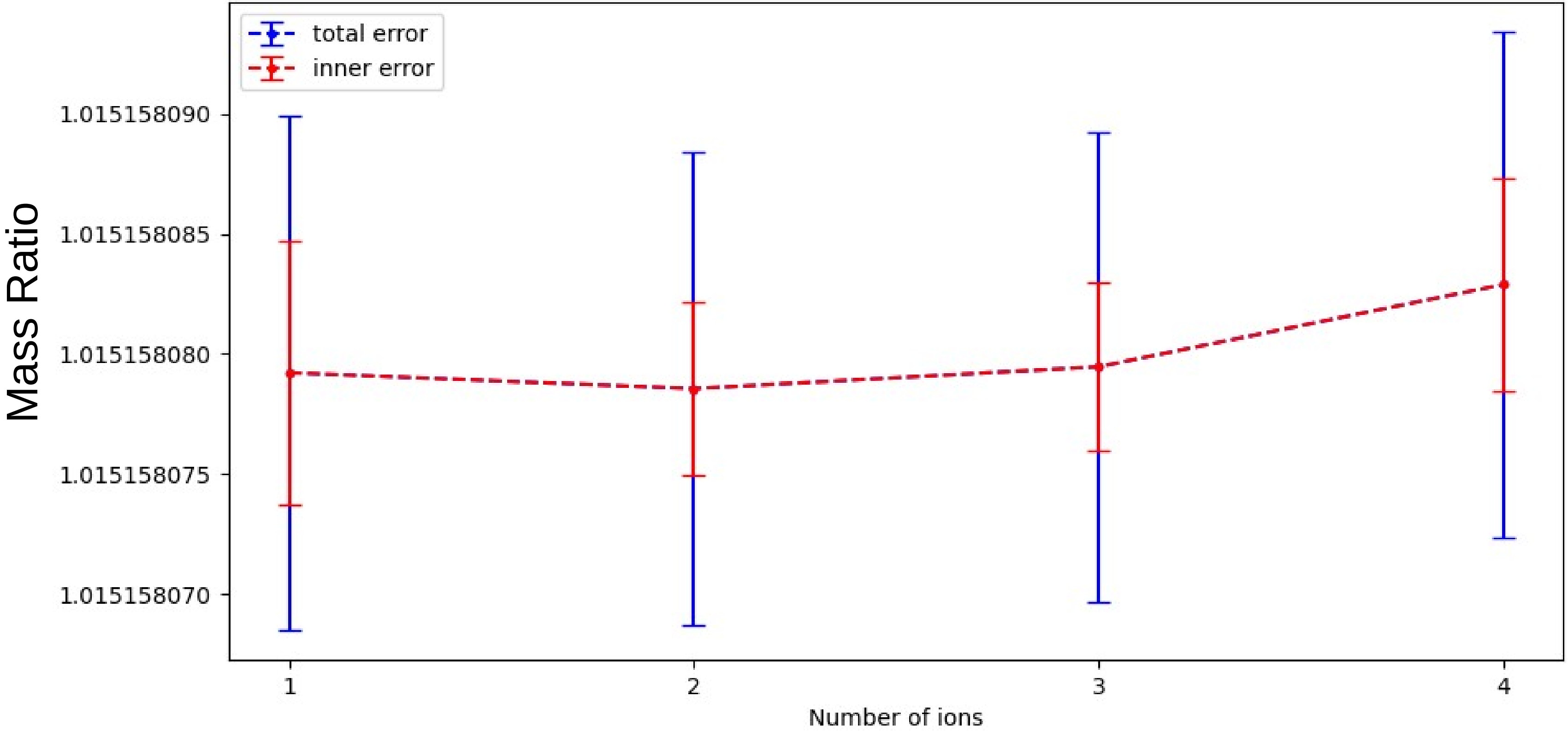


Adapted from Nesterenko Eur. Phys. J. A (2018) 54: 154

- Ions injected
- In the fast cyclotron mode, lighter ions acquire additional phase
- Extraction to 2D MCP



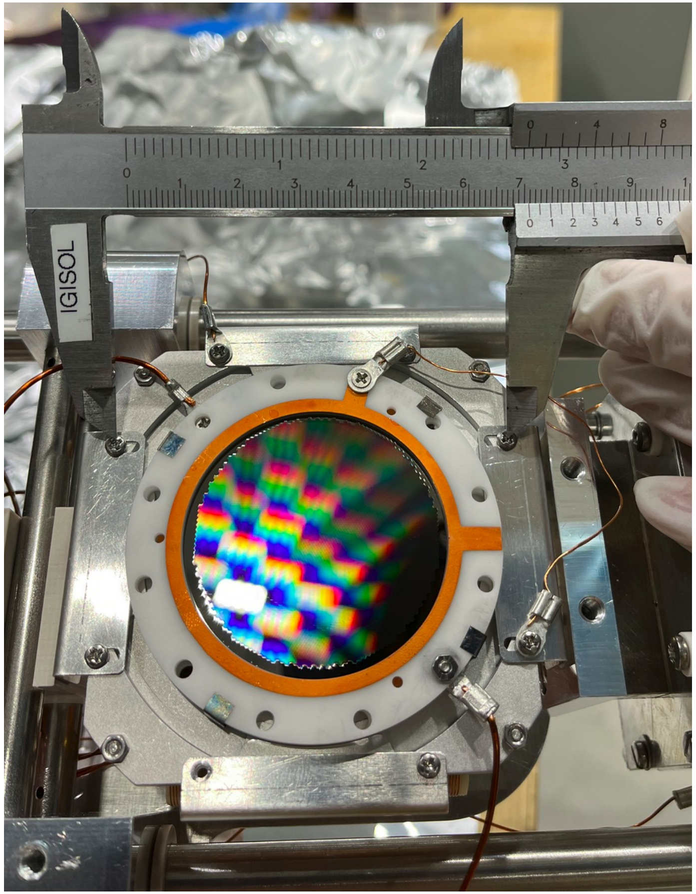
Z-class analysis; 8mm, 1-4 ions 133Cs vs 132Ba



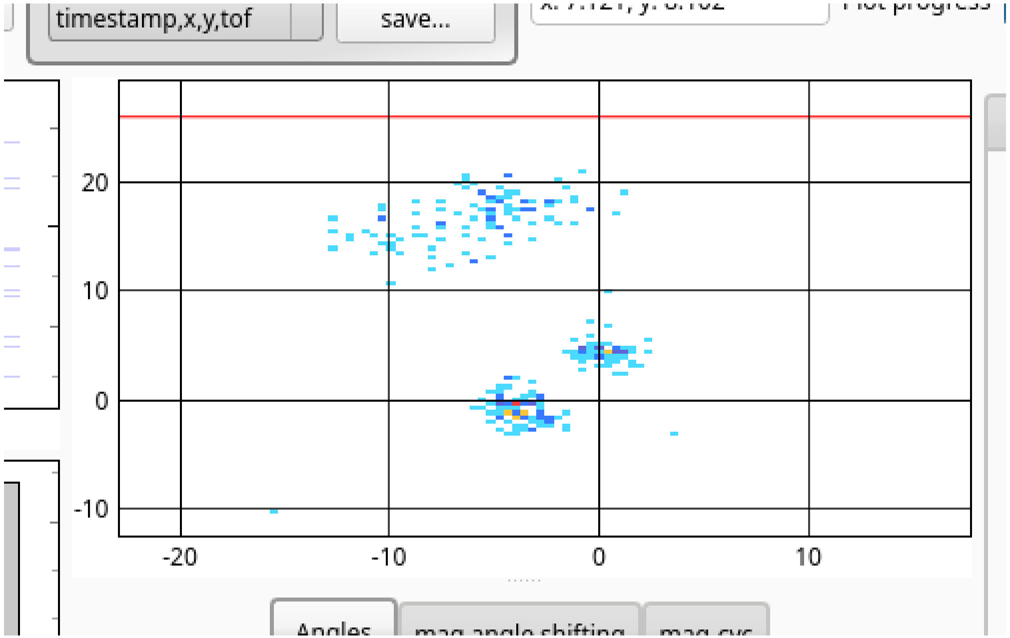
Details on Preparation and Cleaning of Ions

- Inject into Penning trap
- Store and cool for 97.431 ms
- Dipolar excitation at the magnetron frequency (11 ms)
- Quadrupolar excitation at the cyclotron frequency (150 ms)
- Transfer to 2nd trap
- “Additional cleaning step” dipolar excitation at cyclotron frequency (no timing channel?)
- Transfer back to 1st trap
- Quadrupolar excitation at the cyclotron frequency (120 ms)
- Transfer to 2nd trap for PI-ICR measurement

2D MCP



134Ba vs 132Ba



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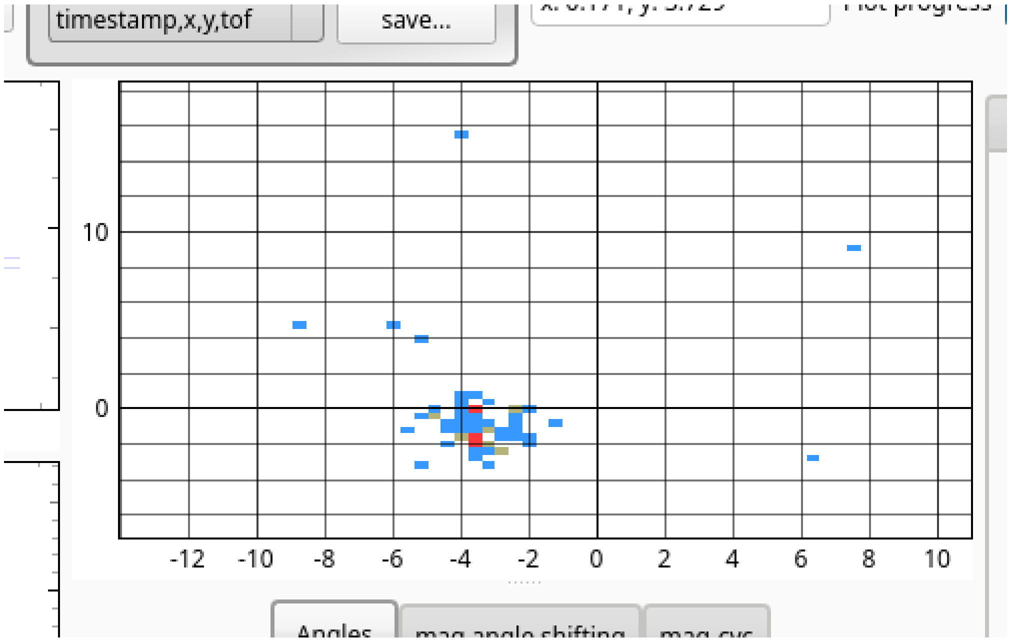

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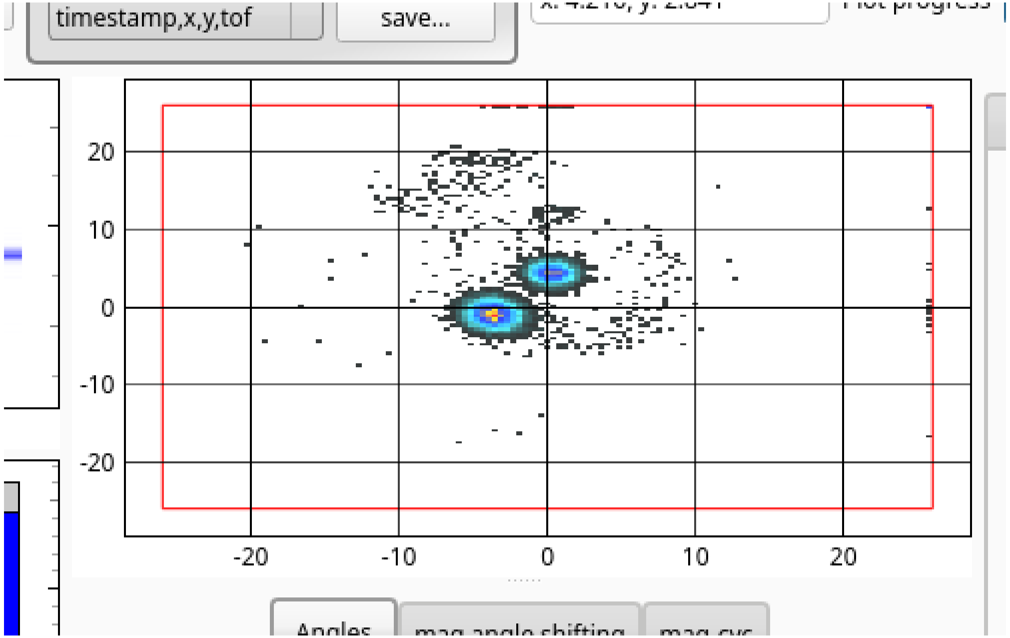
134Ba vs 132Ba



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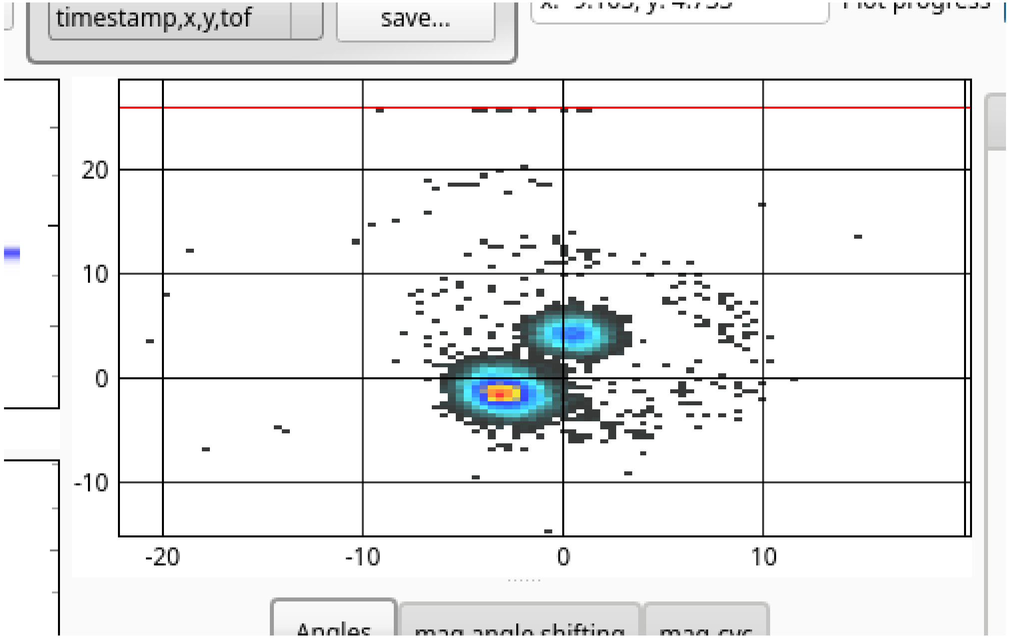
550ms_1

133Cs vs 132Ba

- Timings adjusted so both species overlap on MCP



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