# Low Q-value decays for absolute mass scale determination of the neutrino

T. Eronen, Z. Ge, J. Kostensalo, A. de Roubin, J. Suhonen

# The determination of the absolute mass scale of the neutrino

The determination of the absolute mass scale of the neutrino is one of the **burning question in physics**

Neutrino mixing experiments have revealed that neutrinos have a non-zero mass

⮡ BUT: not able to gauge the absolute mass values!
(only the difference of squared neutrino masses)

**How to pinpoint the (anti)neutrino mass?**

- Precisely
- In a model independent way

⇨

**Kinematical studies**

- $\beta^-$ decay
- Electron capture

# Direct (anti)neutrino mass measurements

**Single Electron Capture**

- Decay energy shared between:
  - Emitted neutrino
  - Atomic excitation of the daughter atom
  - (recoiling nucleus)

- Experimental approach:
  - Low temperature calorimetry measurements (ECHo, HOLMES, NuMECS)
    *L. Gastaldo et al., Eur. Phys. J. Special Topics **226**, 1623 (2017)*
    *M. Faverzani et al., J. Low Temp. Phys. **184**, 922 (2016)*
    *A. Faessler et al., Phys. Rev. C **91**, 045505 (2015)*

**Single $\beta^-$ decay**

- Energy is distributed between the decay products

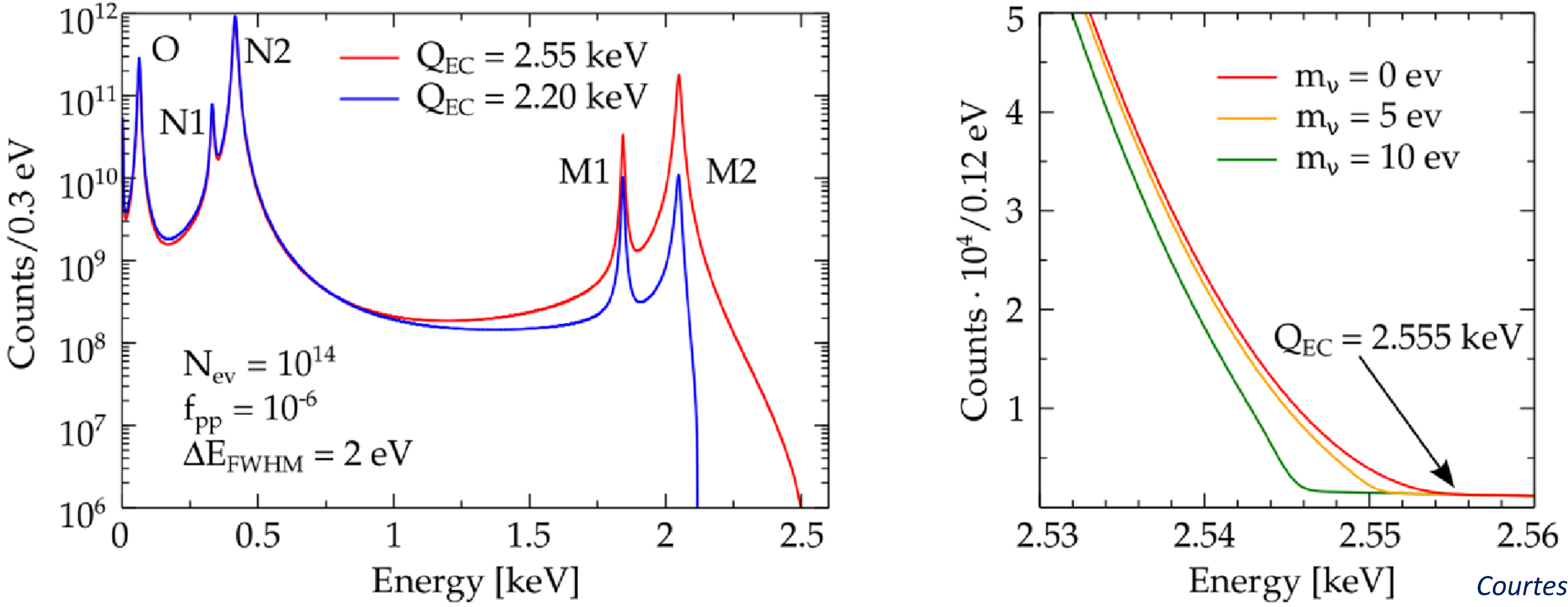
- Experimental approaches:
  - Electron spectroscopy (KATRIN)
    *C. Weinheimer, Prog. Part. Nucl. Phys., **48**, 141 (2002)*
    *KATRIN collaboration, Nat. Phys., **18**, 160 (2022)*
  - Cyclotron radiation emission spectroscopy (Super8)
    *B. Monreal et al. Mass. Phys. Rev., D **80**, 051301 (2009)*

**Interested in the endpoint of the energy spectrum!**

Need decay with a **small Q value** to maximize the sensitivity to the neutrino mass!

# Single electron capture

$^{163}Ho + e^{-} \rightarrow {}^{163}Dy^{*} + \nu_e$ ⇨ $Q_{EC} = 2.3 - 2.8$ keV



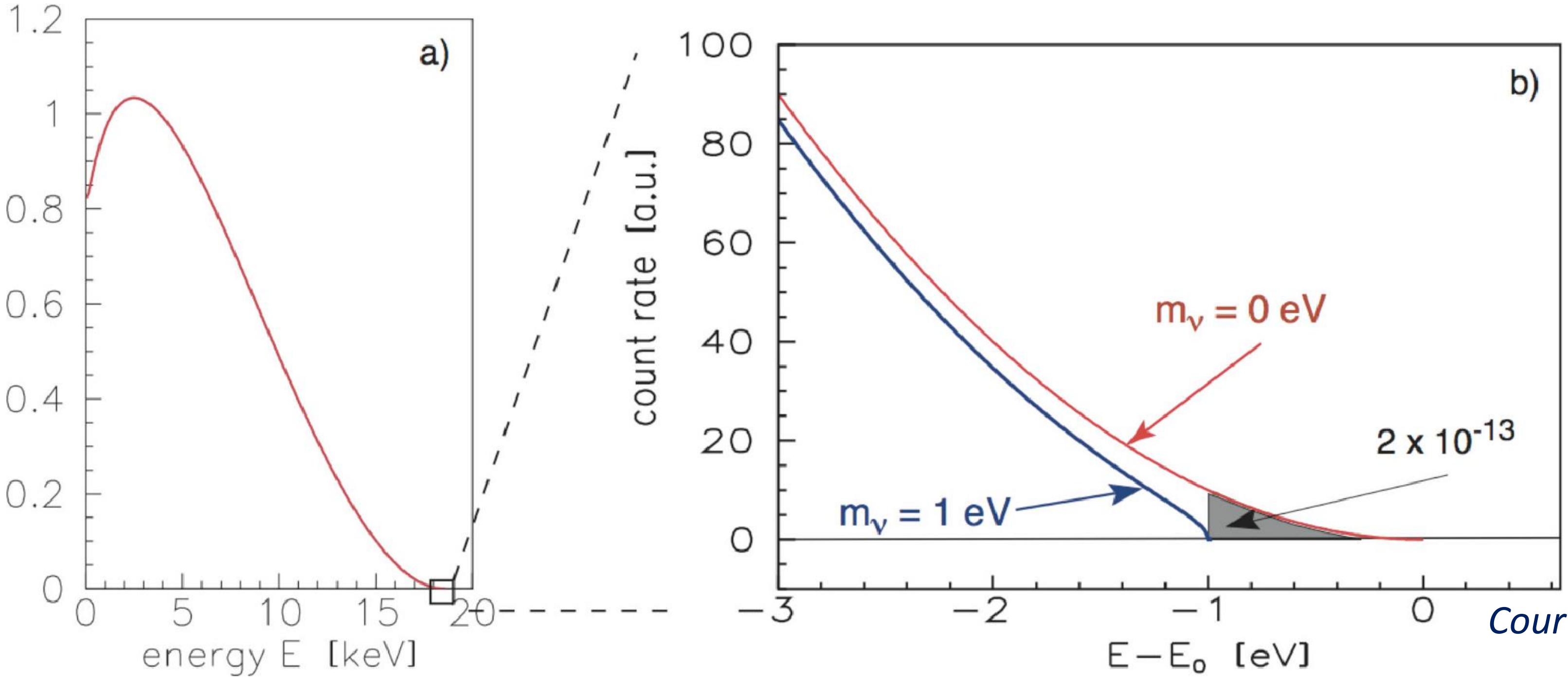
*Courtesy of C. Marquet*

- Measurement of emitted particles and their energies following the EC
- The mismatch of energy available in decay and emitted energy reveals the neutrino mass
- Upper limit of the effective electron-neutrino mass $m_{\nu_e} = 150$ eV/c$^2$ (95% confidence level)

*C. Velte et al., Eur. Phys. J. C **79**, 1026 (2019)*

# Single $\beta^-$ decay

$^3H \rightarrow {}^3He + e^- + \overline{\nu}_e$ ⇨ $Q_{EC} = 18.6$ keV



*Courtesy of C. Marquet*

- Measurement of emitted electron energy
- The maximum energy is linked to the neutrino mass
- Upper limit of the effective electron-neutrino mass $m_{\nu_e} = 0.8$ eV/c$^2$ (90% confidence level)

*KATRIN collaboration, Nat. Phys.,* ***18****, 160 (2022)*

# Ultra low Q-value $\beta$ decay for neutrino physics

**Interested in the endpoint of the energy spectrum!**

Need decay with a **small Q value** to maximize the sensitivity to the neutrino mass!

Smallest GS-to-GS Q-values around 1 keV

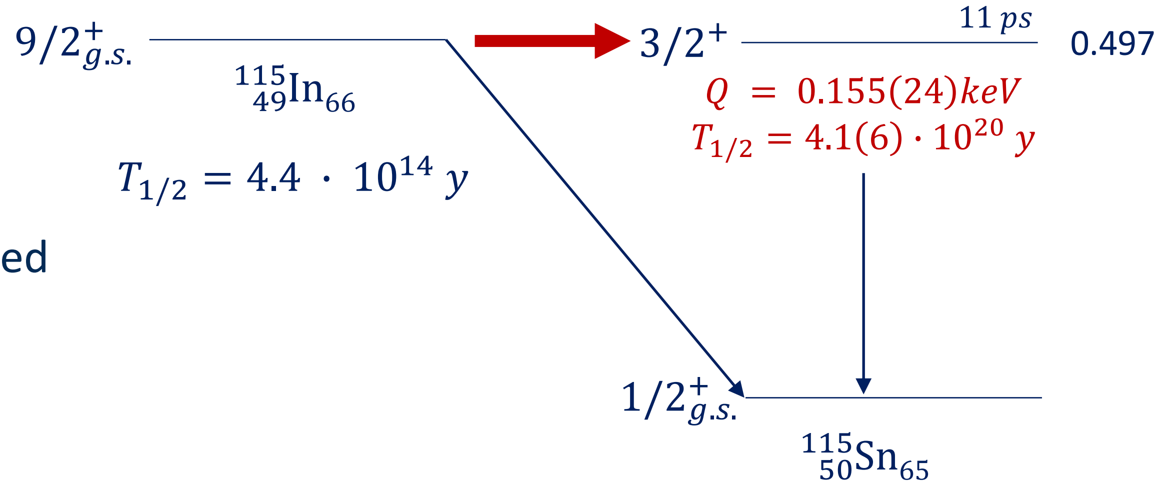
# Ultra low Q-value $\beta$ decay for neutrino physics

**Interested in the endpoint of the energy spectrum!**

Need decay with a **small Q value** to maximize the sensitivity to the neutrino mass!

Smallest GS-to-GS Q-values around 1 keV

- **Possibility to use decays with even smaller Q-values**
  - → $^{115}In(9/2^{+}) \xrightarrow{\beta^{-}} {}^{115}Sn(3/2^{+})$
  - → Q = 0.155(24) keV → smallest $\beta$ Q-value ever measured
  - → **A « detector » for the neutrino mass ?**



- **Other possible low Q-values**
  - → Many potential candidates
  - → Need to identify them with Penning traps

*B.J. Mount, M. Redshav, E.G. Myers, Phys. Rev. Lett. 103 122502 (2009)*
*J. S. E. Wieslander, Phys. Rev. Lett. 103, 122501 (2009)*
*C.M. Cattadori, Nucl. Phys. A, 748, 333-347 (2005)*

# Ultra low Q-value $\beta$ decay for neutrino physics

| **Mother( $J^{\pi}$ )**<br>*Ground state* | **Daughter ( $J^{\pi}$ )**<br>*Excited state* | **E* (keV)** | ***Q* (keV)** | **Type of decay** |
|---|---|---|---|---|
| $^{135}$Cs(7/2$^{+}$) | $^{135}$Ba(11/2$^{-}$) | 268.218(20) | 0.5(12) | $\beta^{-}$ |
| | | | | |
| $^{159}$Dy(3/2$^{-}$) | $^{159}$Tb(5/2$^{-}$) | 363.5449(14) | 1.7(12) | EC |
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| | | | | |
| $^{111}$In(9/2$^{+}$) | $^{111}$Cd(7/2$^{+}$) | 853.94(7) | 6.3(34) | EC |
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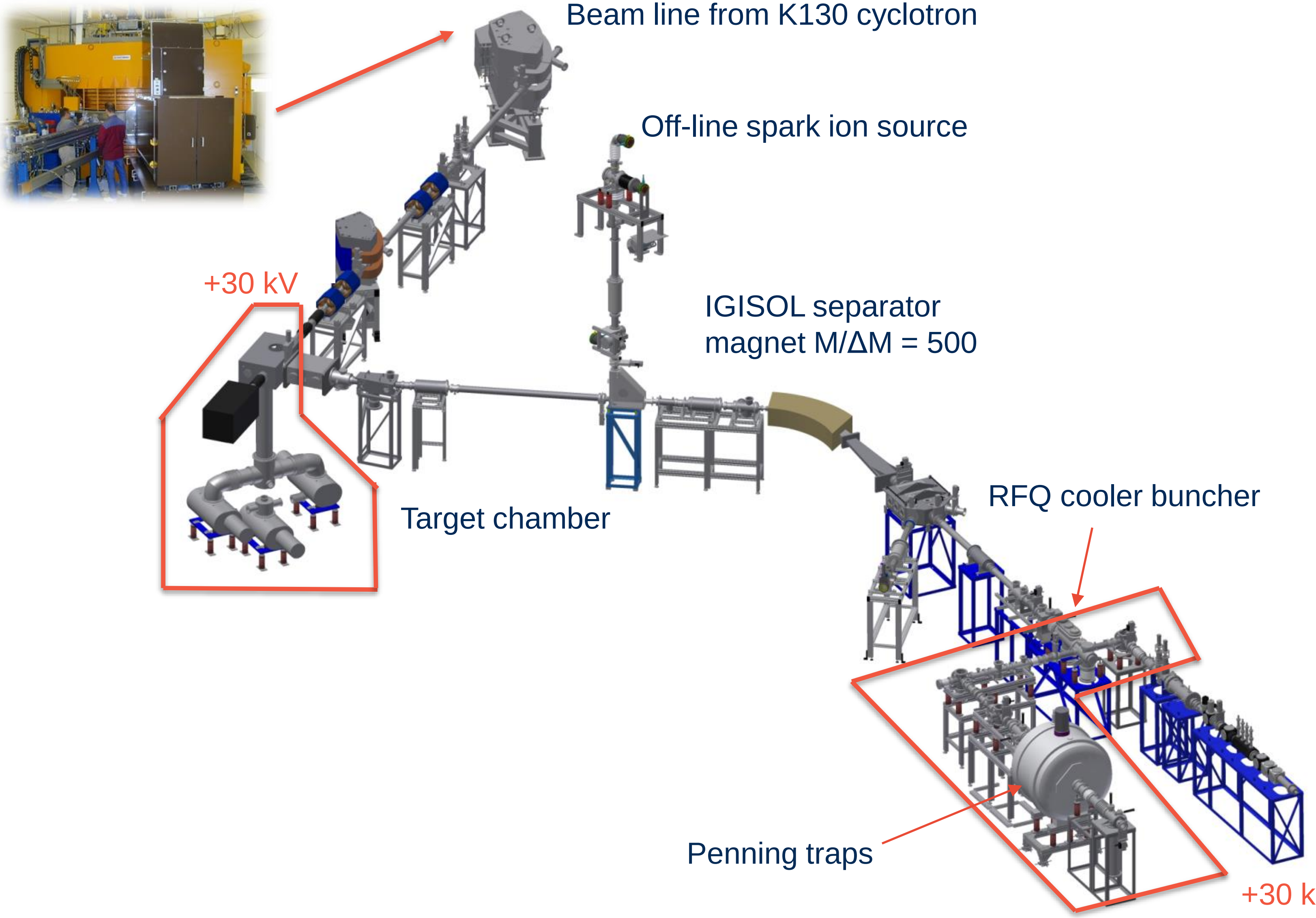
| | | | | |
| $^{131}$I(7/2$^{+}$) | $^{131}$Xe(9/2$^{+}$) | 971.22(13) | -0.42(61) | $\beta^{-}$ |

# The IGISOL-4 facility



Beam line from K130 cyclotron

Off-line spark ion source

IGISOL separator
magnet M/ΔM = 500

+30 kV

Target chamber

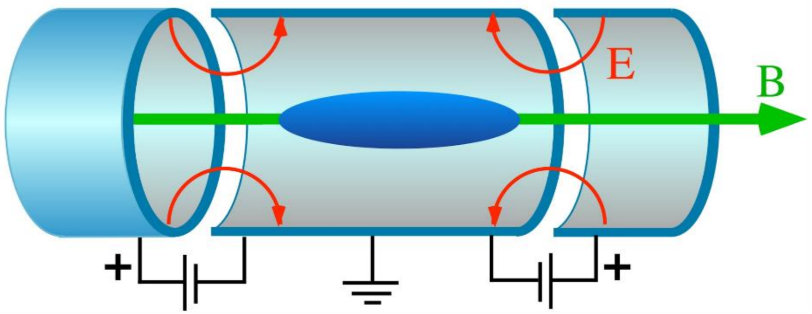
RFQ cooler buncher

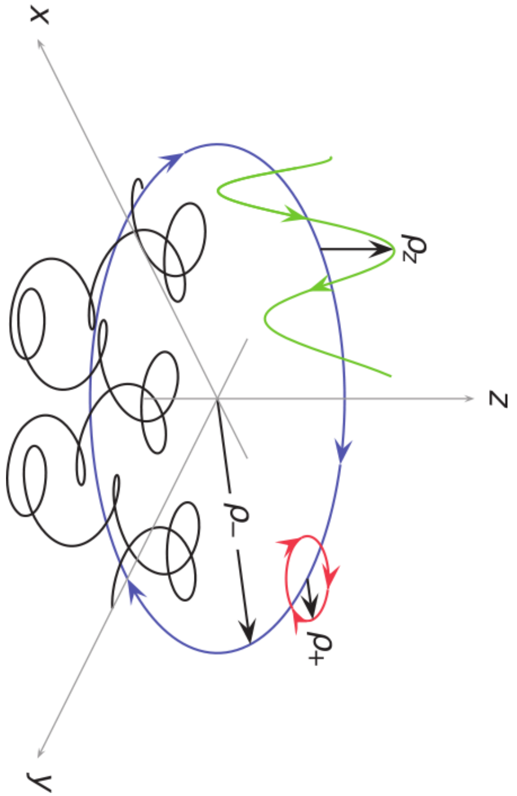
Penning traps

+30 kV

# Penning trap

- Radial confinement
  - strong homogeneous magnetic field
- Axial confinement
  - electric field





3 ion motions

- Axial
- Magnetron
- Reduced cyclotron

3 ion frequencies

- $\nu_z$
- $\nu_-$
- $\nu_+$

- Invariance theorem

$$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

- Cyclotron frequency

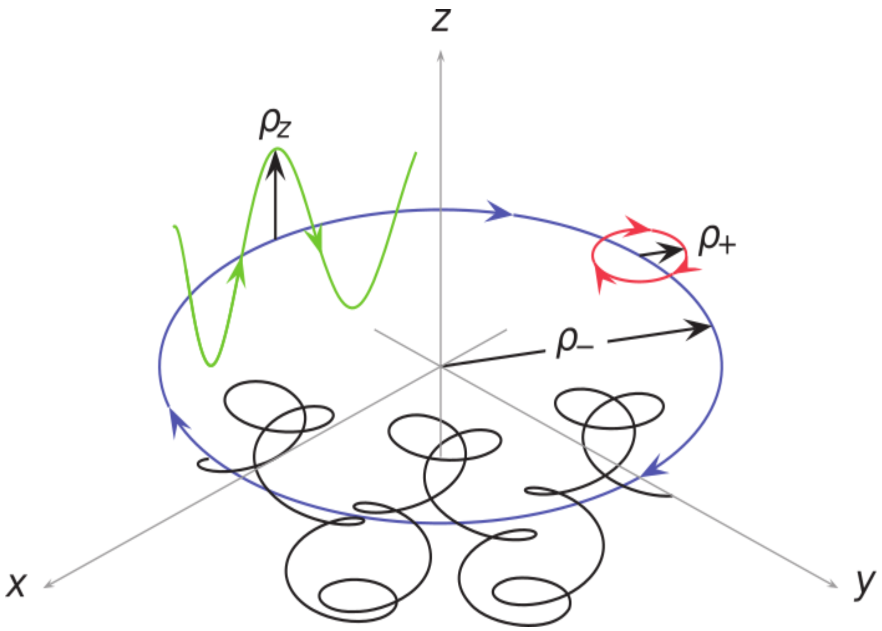
$$\nu_c = \nu_- + \nu_+$$

Cyclotron frequency

$$\boxed{\nu_c = \frac{1}{2\pi}\frac{q}{m}B}$$

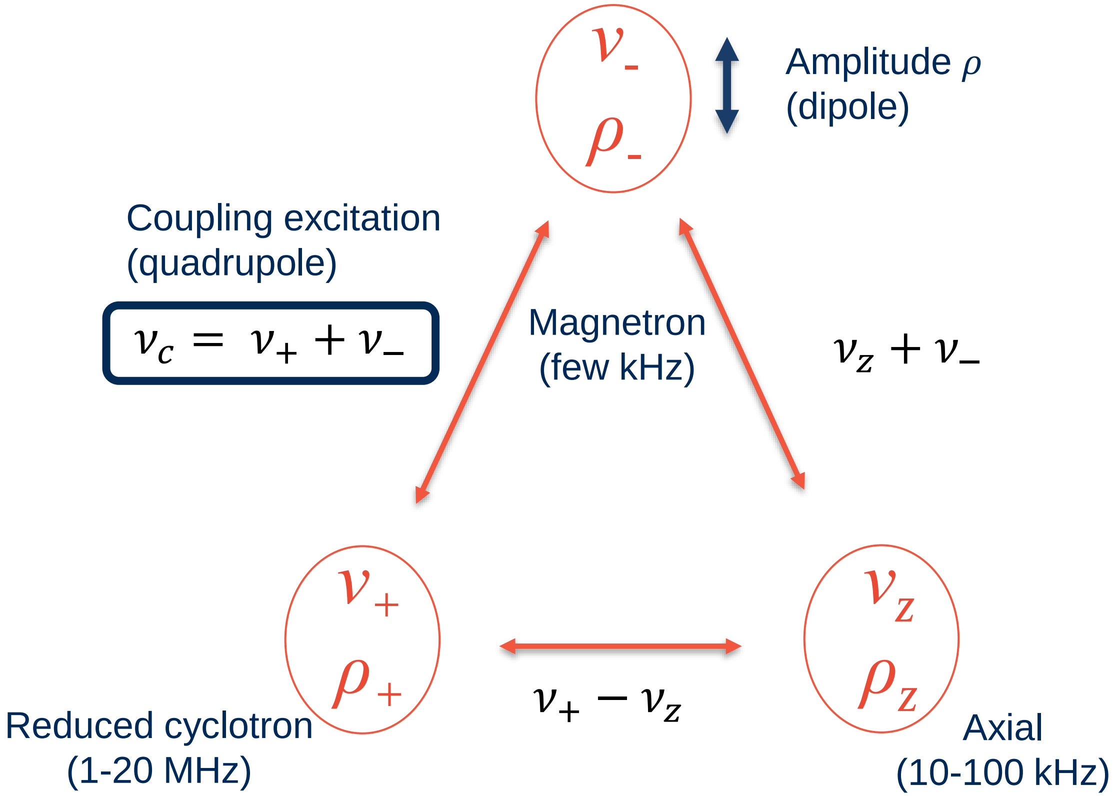
q : electric charge
B : magnetic field
m : mass

# Penning trap



Control amplitudes

Convert motions



Coupling excitation (quadrupole)

$$\boxed{\nu_c = \nu_+ + \nu_-}$$

$\nu_-$ $\rho_-$

Amplitude $\rho$ (dipole)

Magnetron (few kHz)

$\nu_z + \nu_-$

$\nu_+$ $\rho_+$

$\nu_+ - \nu_z$

$\nu_z$ $\rho_z$

Reduced cyclotron (1-20 MHz)

Axial (10-100 kHz)

---

3 ion motions

- Axial
- Magnetron
- Reduced cyclotron

↔

3 ion frequencies

- $\nu_z$
- $\nu_-$
- $\nu_+$

- Invariance theorem

$$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

- Cyclotron frequency

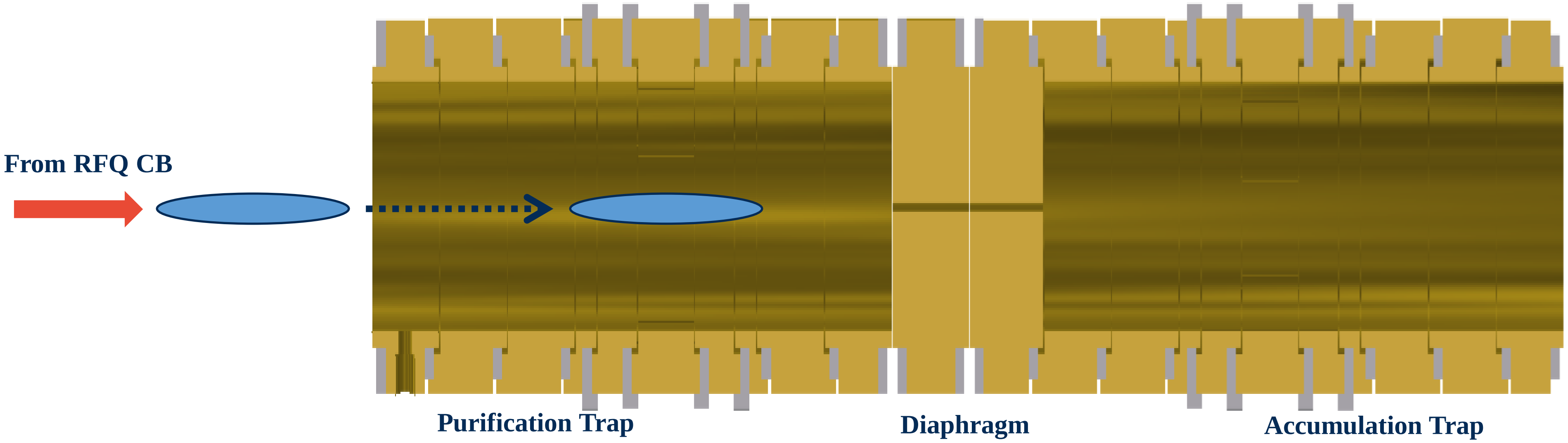
$$\nu_c = \nu_- + \nu_+$$

Cyclotron frequency

$$\boxed{\nu_c = \frac{1}{2\pi}\frac{q}{m}B}$$

q : electric charge
B : magnetic field
m : mass

# Buffer gas cooling technique

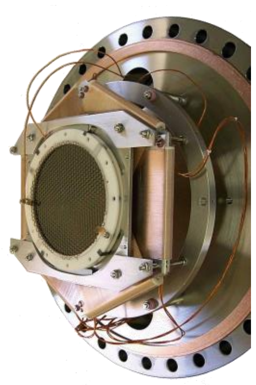


From RFQ CB

Purification Trap

Diaphragm

Accumulation Trap

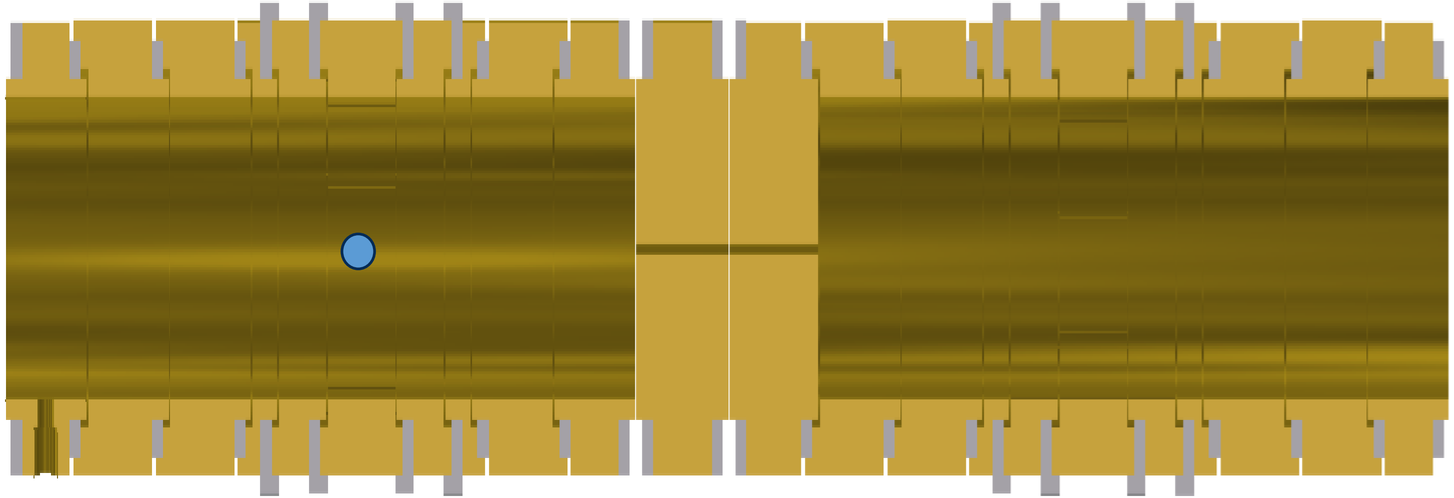


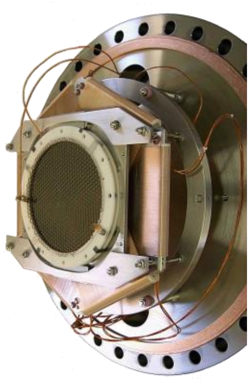
**MicroChannel Plate detector (position sensitive)**

Injection and capture of the ions

- 100 µs

# Buffer gas cooling technique

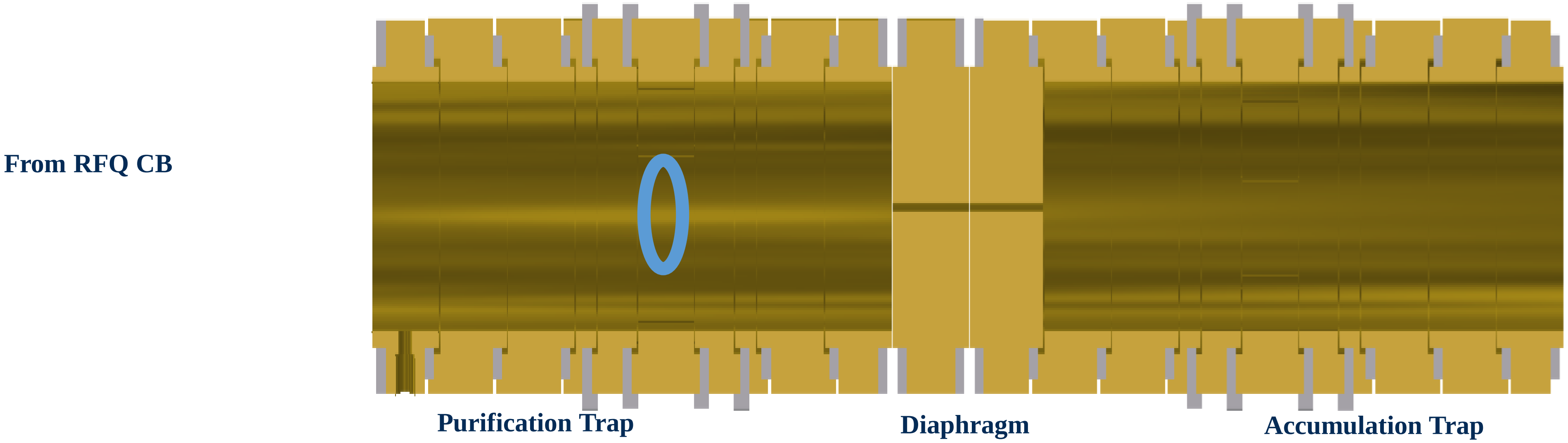


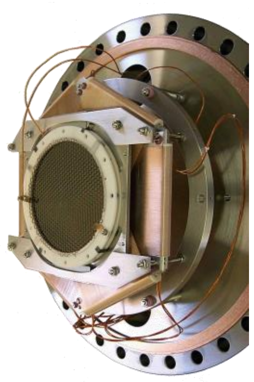


Cooling of radial and axial motions

- 30 - 100 ms

# Buffer gas cooling technique





MicroChannel Plate detector
(position sensitive)

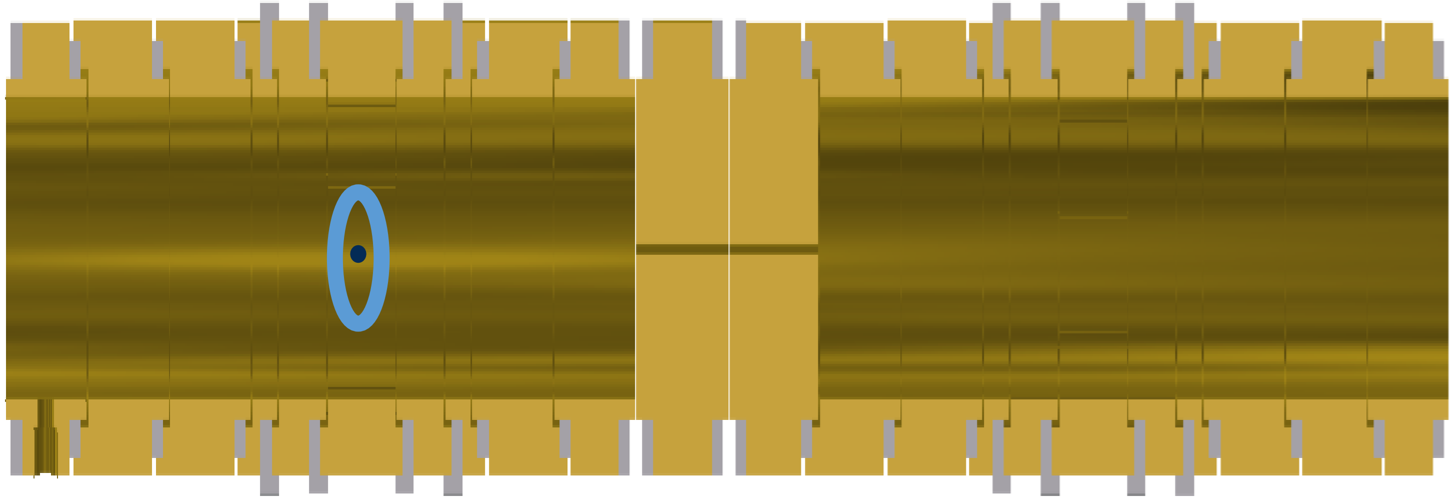
**Buffer gas cooling technique**

1. Magnetron excitation: $\nu_-$
   - 10 ms

This excitation is mass independent

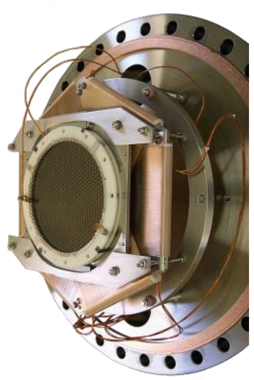
# Buffer gas cooling technique

From RFQ CB


Purification Trap

Diaphragm

Accumulation Trap

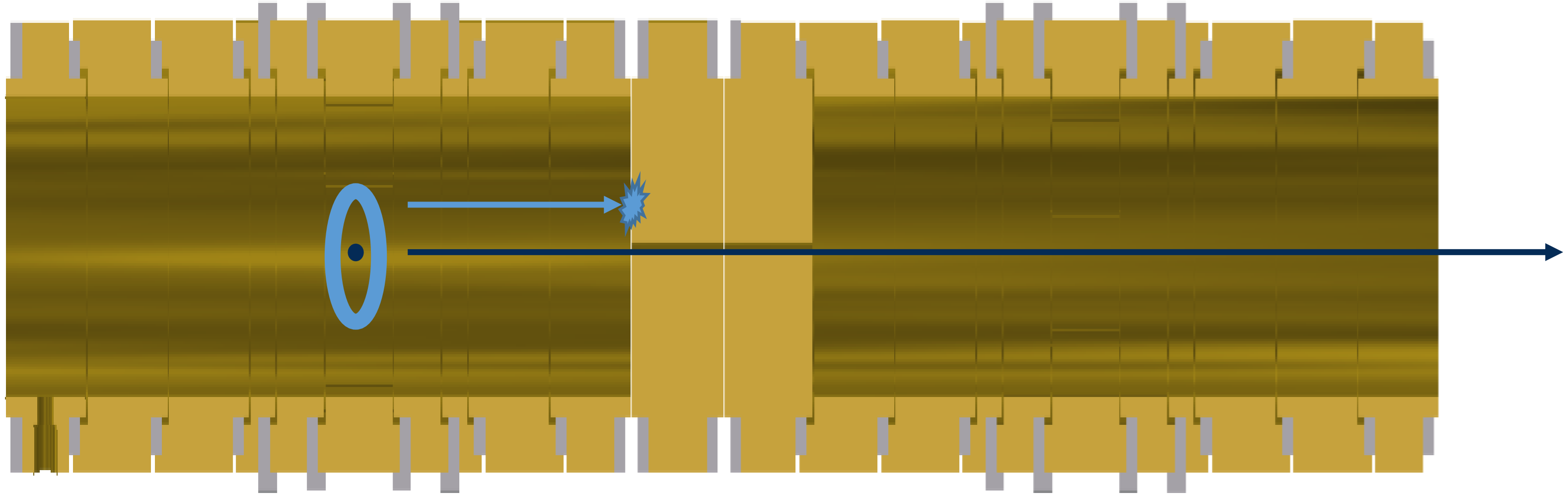

MicroChannel Plate detector
(position sensitive)

**Buffer gas cooling technique**

1. Magnetron excitation: $\boldsymbol{\nu}_-$
    - 10 ms
2. Quadrupole excitation: $\boldsymbol{\nu}_c = \boldsymbol{\nu}_+ + \boldsymbol{\nu}_-$
    - Convert the radial magnetron motion ($\boldsymbol{\nu}_-$) into modified cyclotron motion ($\boldsymbol{\nu}_+$)
    - 40 – 400 ms
    - Centering the « good guys »

\ This excitation is mass dependent !!
\ Magnetron motion is amplified
\ modified cyclotron motion is damped

# Buffer gas cooling technique

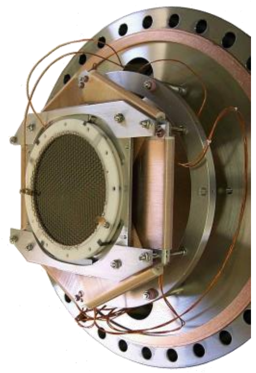


**From RFQ CB**

**Purification Trap**

**Diaphragm**

**Accumulation Trap**



**MicroChannel Plate detector**
**(position sensitive)**

## Mass resolving power of Penning trap

$$R = \frac{M}{\Delta M} = \frac{\nu_c}{\Delta\nu_c} \propto \frac{1}{\Delta\nu_c}\boxed{\frac{q}{m}B} \longrightarrow \boxed{\text{Scaling}}$$

Constant for each method 0.1 … 100 Hz

## Rule of thumb:

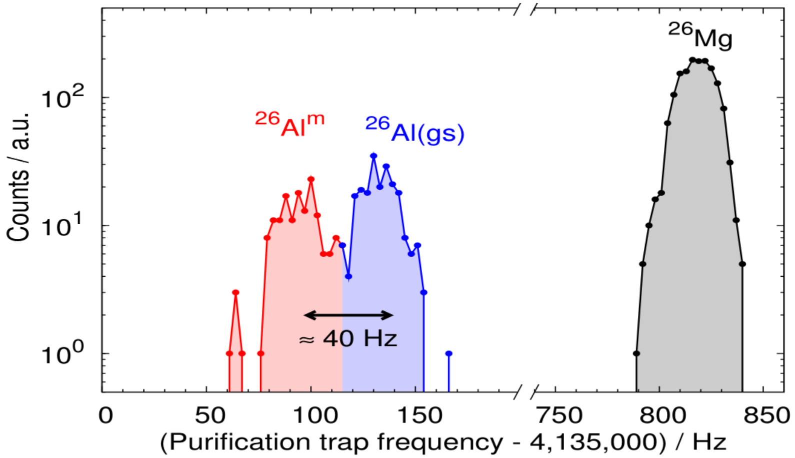
B = 7 T, q = 1e, m = 100u

$\rightarrow \nu_c \sim 1\ \text{MHz}, \quad 100\ \text{keV/Hz}$

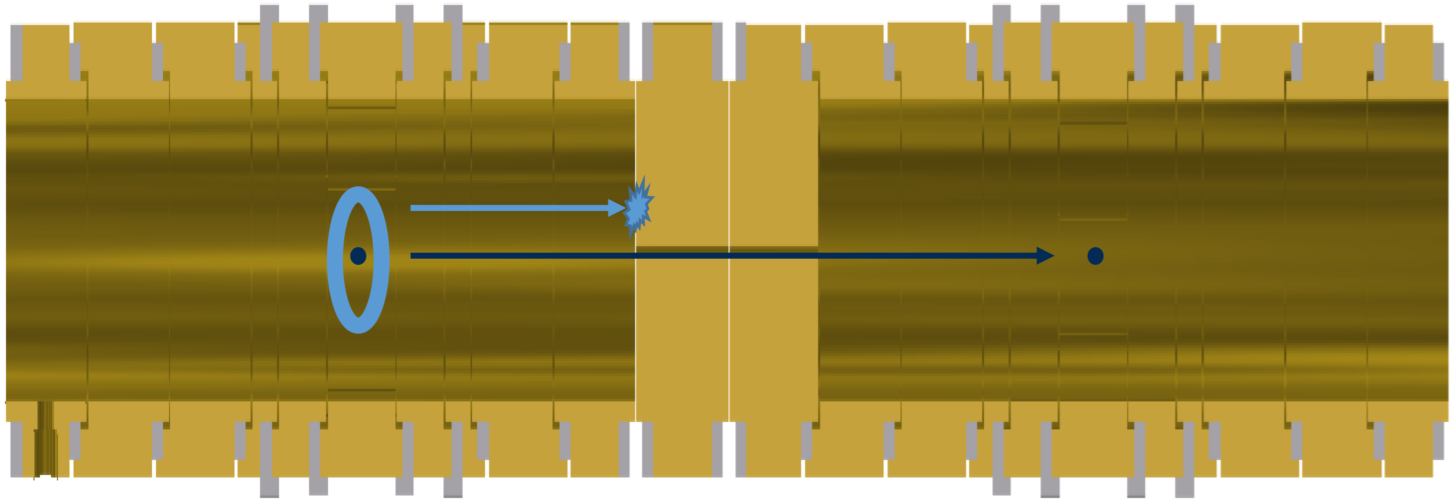
## Buffer gas cooling technique

- Gas filled purification trap
- Separation
  - 10 … 100 Hz
  - $R = 10^4 \ldots 10^5$
- Also cooling

G. Savard et al., Phys. Lett. A **158** (1991) 247—252



# Time-of-flight ion cyclotron resonance technique (ToF-ICR)

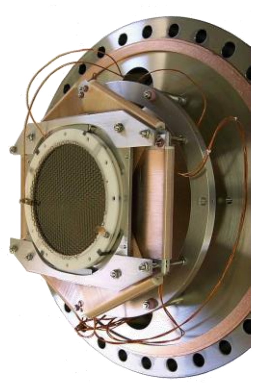


From RFQ CB

Purification Trap

Diaphragm

Accumulation Trap

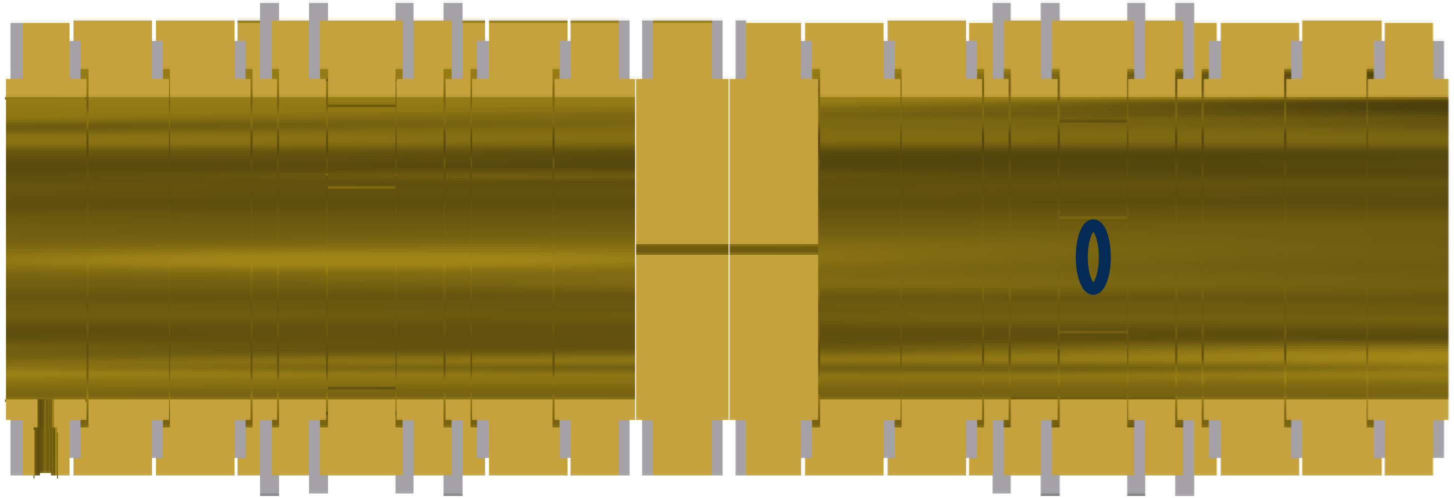


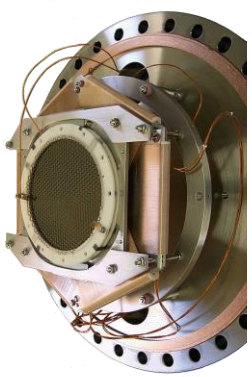
MicroChannel Plate detector
(position sensitive)

**ToF-ICR technique** (Time-of-Flight Ion Cyclotron Resonance)

Transfer of the clean ion sample to the measurement trap

# Time-of-flight ion cyclotron resonance technique (ToF-ICR)

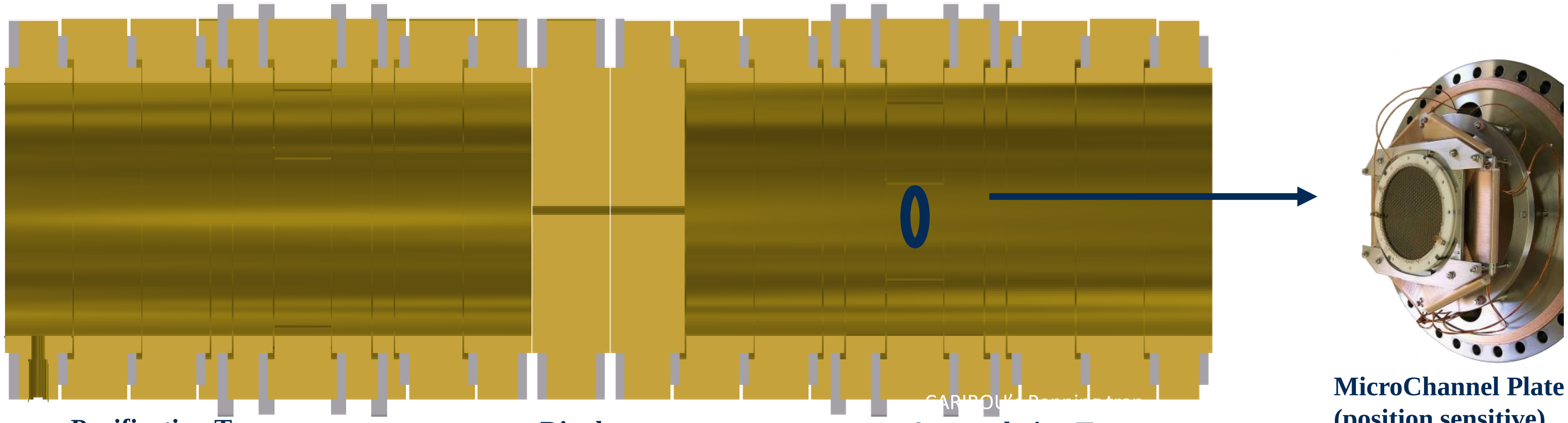



MicroChannel Plate detector
(position sensitive)

**ToF-ICR technique**

1. Magnetron excitation: $\nu_-$
   - 10 ms
   - Give a slow radial motion to the ions

# Time-of-flight ion cyclotron resonance technique (ToF-ICR)

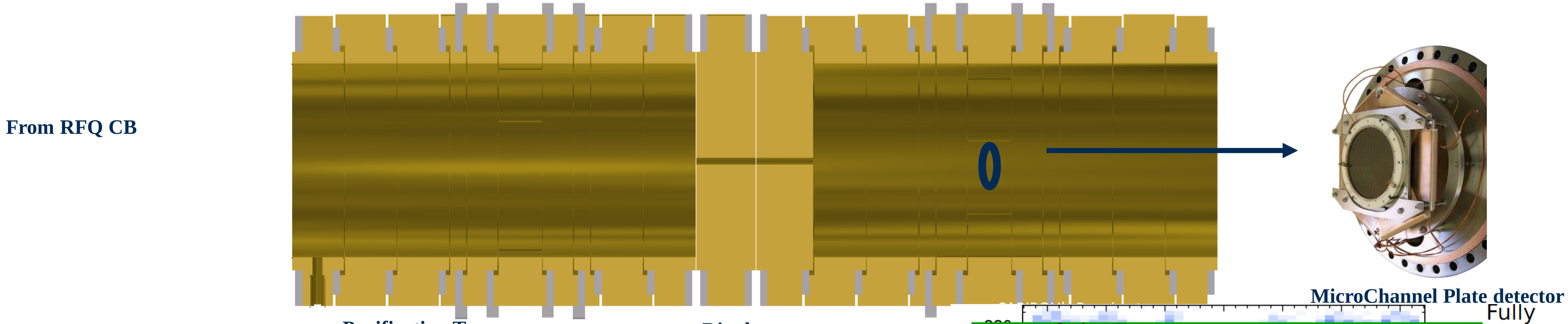


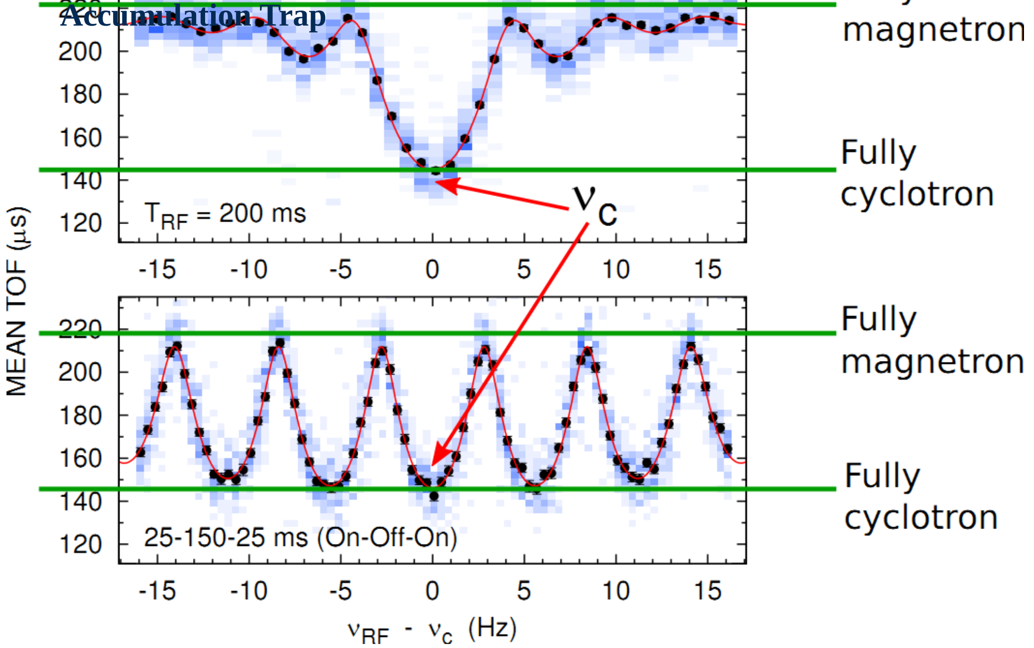
**ToF-ICR technique**

1. Magnetron excitation: $\boldsymbol{\nu}_-$
   - 10 ms
   - Give a slow radial motion to the ions
2. Quadrupole excitation: $\boldsymbol{\nu}_c = \boldsymbol{\nu}_+ + \boldsymbol{\nu}_-$
   - Convert the radial magnetron motion ($\boldsymbol{\nu}_-$) into modified cyclotron motion ($\boldsymbol{\nu}_+$)
   - 40 – 400 ms

- The modified cyclotron motion is a fast motion
- The ions are not recentered (no gas)
- Extraction towards the MCP

# Time-of-flight ion cyclotron resonance technique (ToF-ICR)





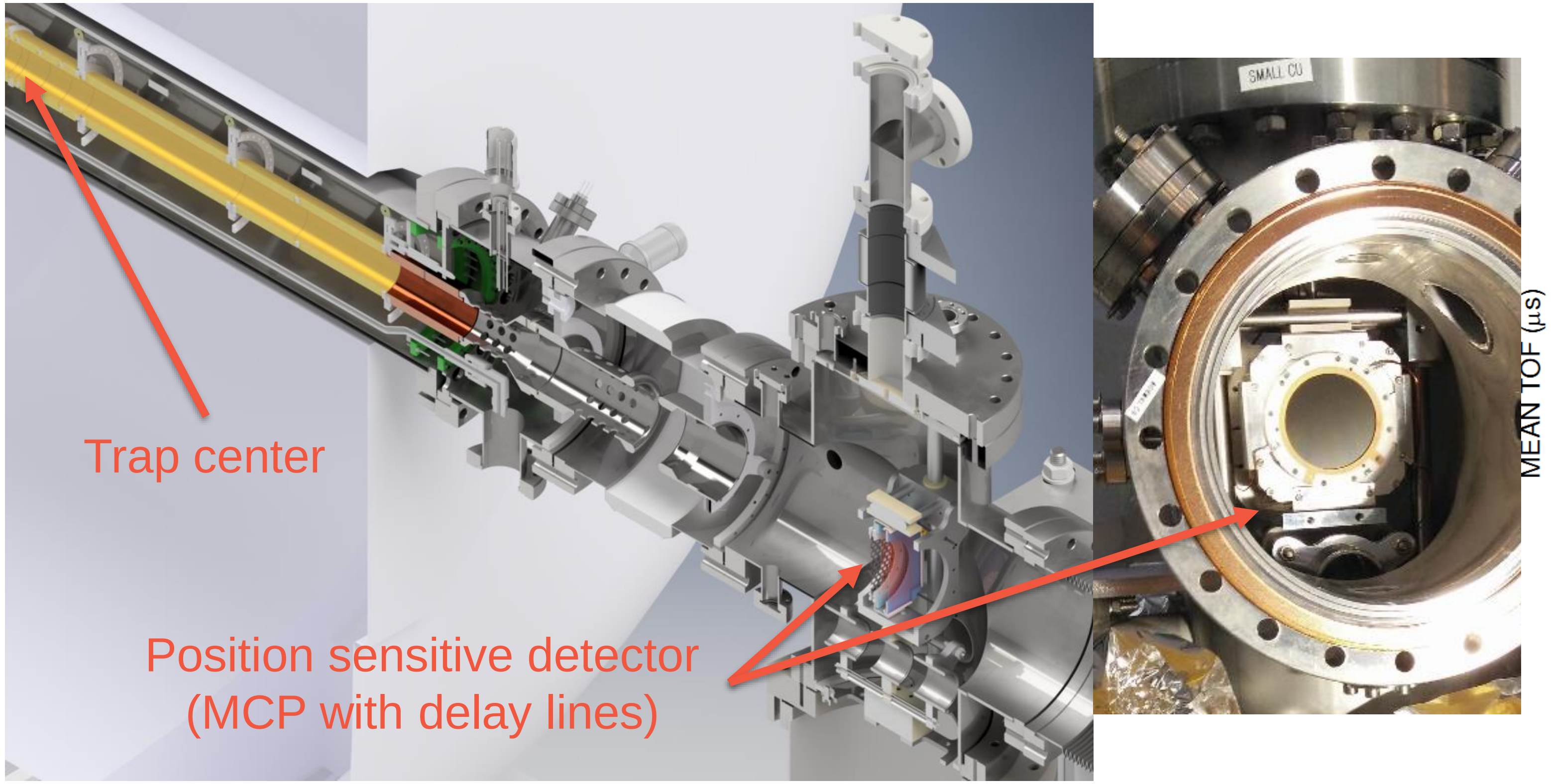
**ToF-ICR technique**

- Excitation around $\nu_c$
  - Large magnetic moment ($\nu_+$ amplitude) for resonant ions
  - $\mu \sim \omega_+^2\rho_+^2 - \omega_-^2\rho_-^2 \qquad (E_p = -\vec{\mu}\cdot\vec{B})$
- Ejection
  - Radial kinetic energy change to axial energy
- ToF is reduced

**Ramsey ToF-ICR technique**

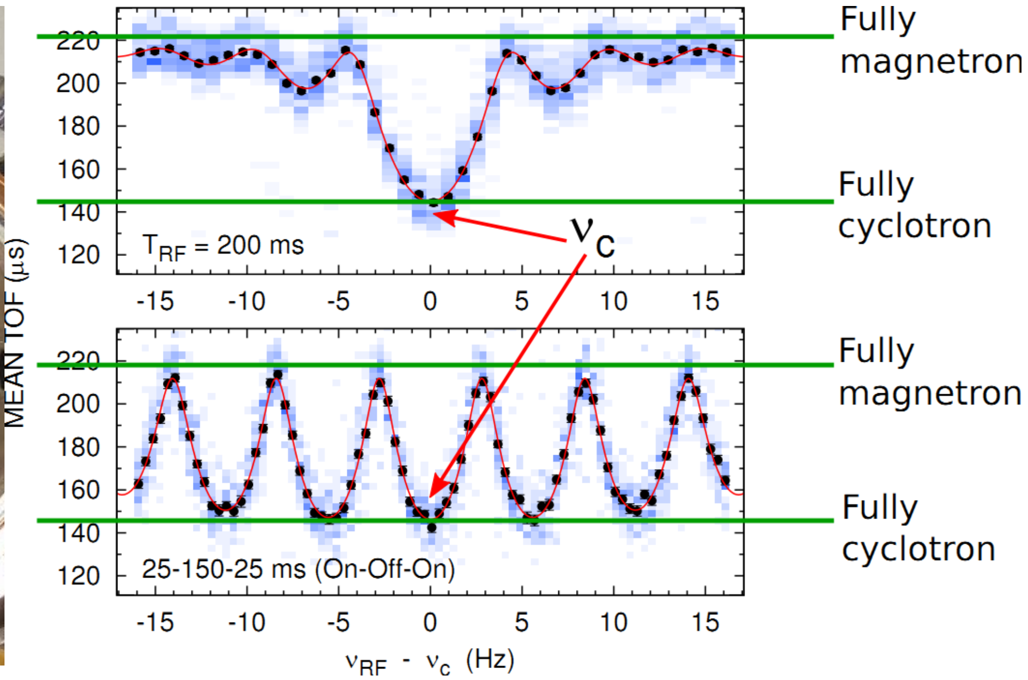
- Improves precision, reduces measurement time ~ x3

# Position sensitive detector

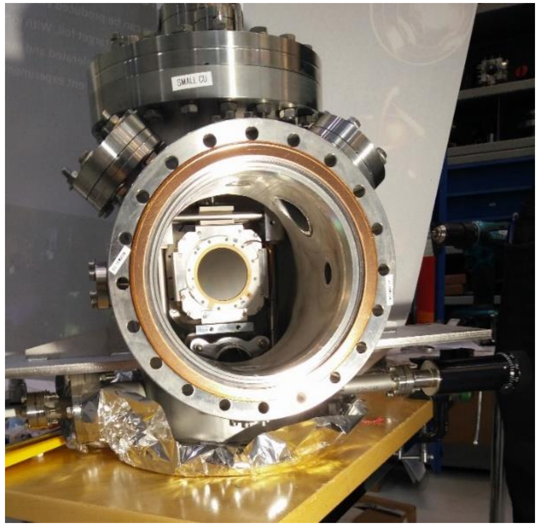


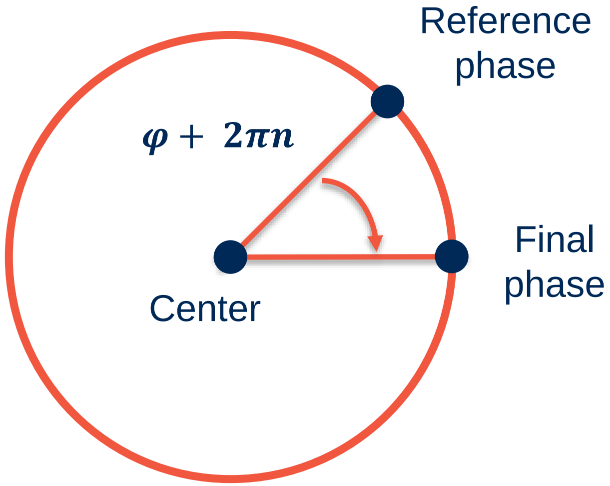
Trap center

Position sensitive detector
(MCP with delay lines)

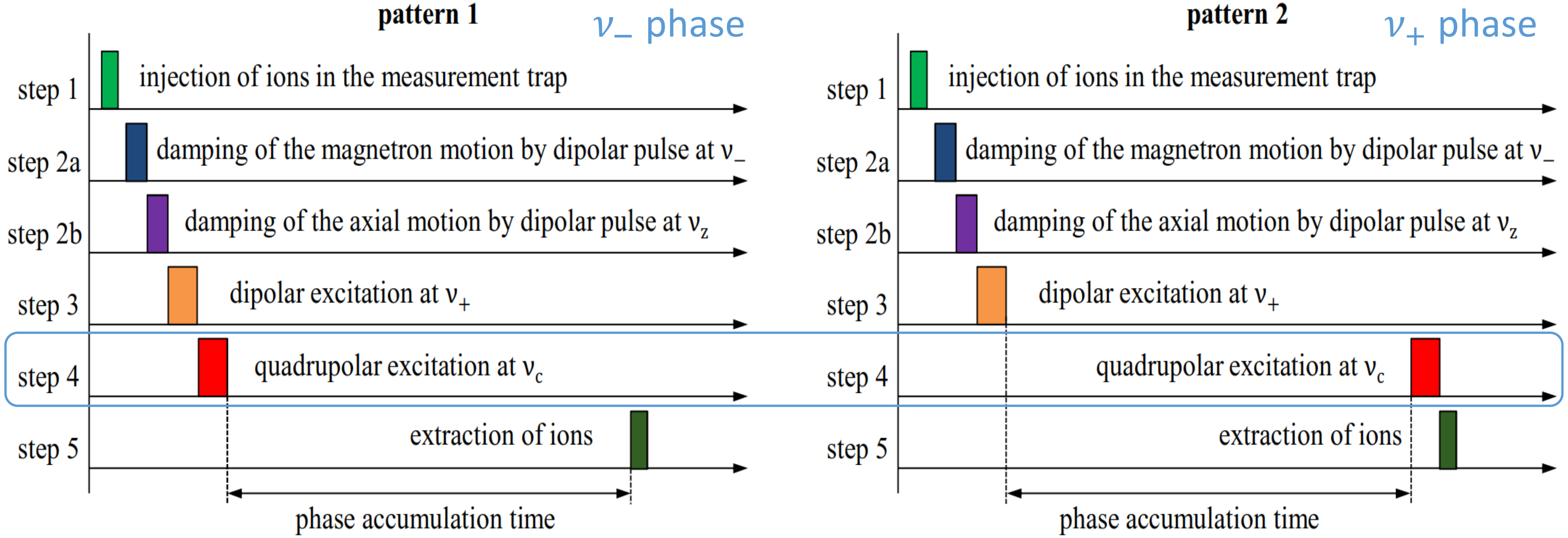


# Phase-imaging ion cyclotron resonance technique (PI-ICR)





$$\nu = \frac{\varphi + 2\pi n}{2\pi t}$$


**pattern 1** $\nu_-$ phase

step 1 injection of ions in the measurement trap

step 2a damping of the magnetron motion by dipolar pulse at $\nu_-$

step 2b damping of the axial motion by dipolar pulse at $\nu_z$

step 3 dipolar excitation at $\nu_+$

step 4 quadrupolar excitation at $\nu_c$

step 5 extraction of ions

phase accumulation time

**pattern 2** $\nu_+$ phase

step 1 injection of ions in the measurement trap

step 2a damping of the magnetron motion by dipolar pulse at $\nu_-$

step 2b damping of the axial motion by dipolar pulse at $\nu_z$

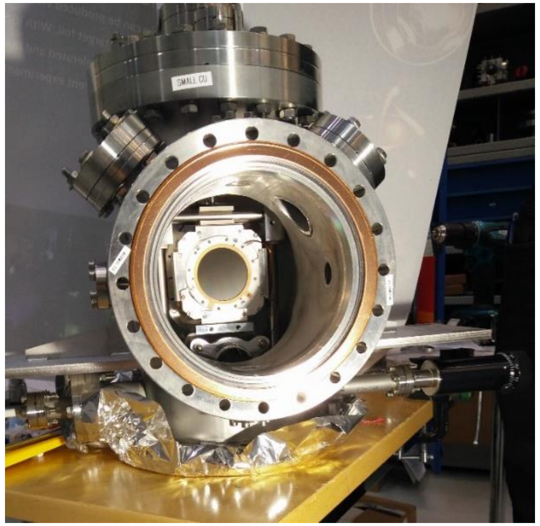
step 3 dipolar excitation at $\nu_+$

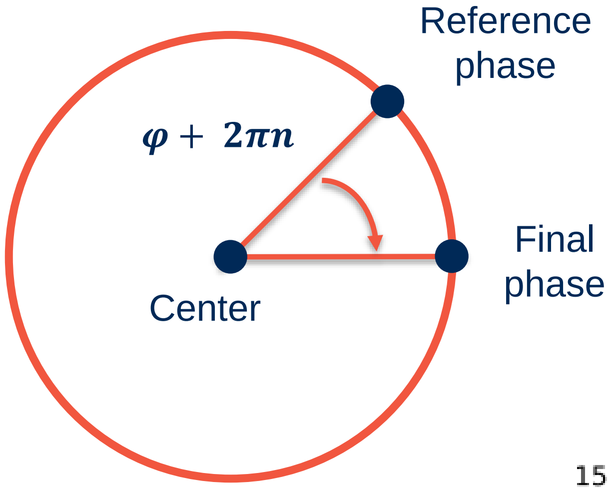
step 4 quadrupolar excitation at $\nu_c$

step 5 extraction of ions

phase accumulation time

# Phase-imaging ion cyclotron resonance technique (PI-ICR)





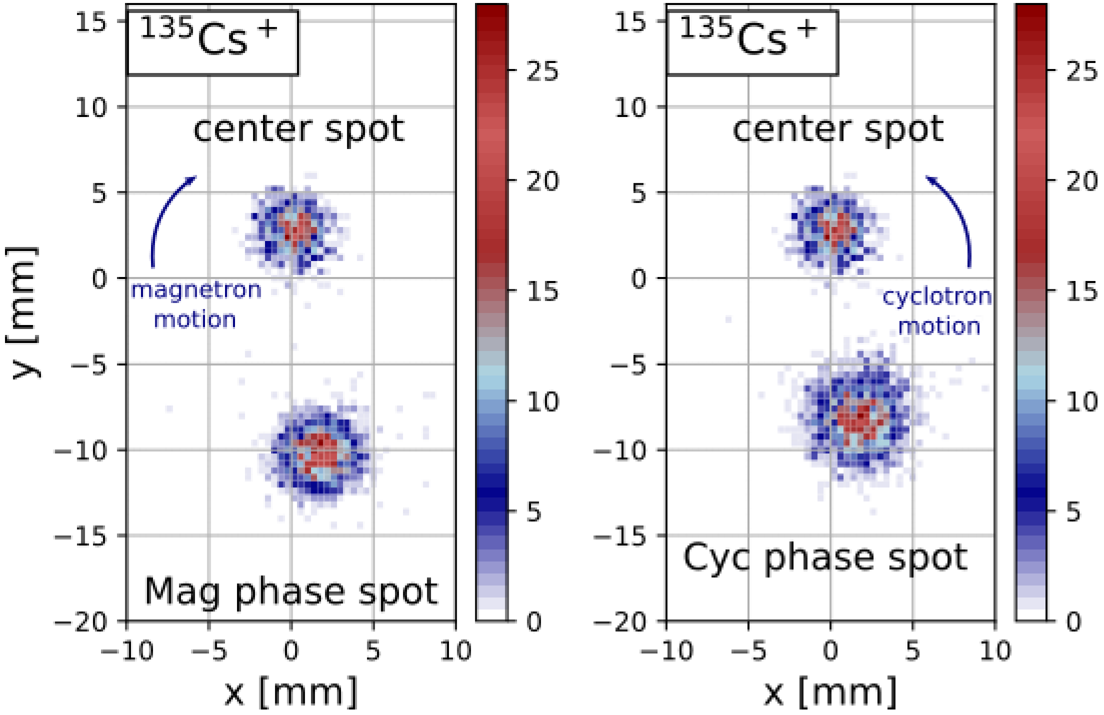
$$\nu = \frac{\varphi + 2\pi n}{2\pi t}$$

**Advantages of PI-ICR over TOF-ICR:**

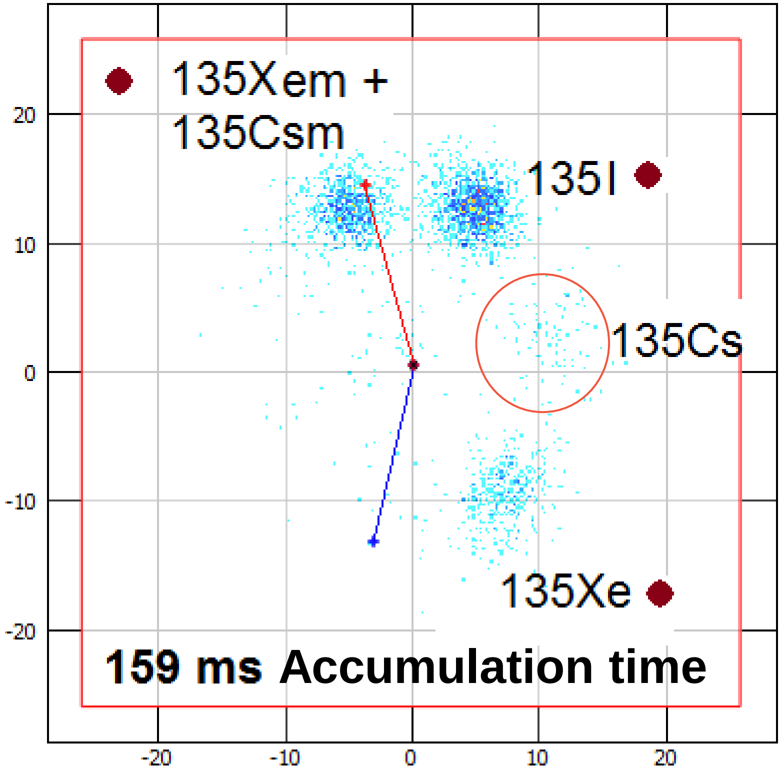
- No scanning of frequency, just data collection to one spot
- x40 faster  x5 increase in precision

**Requirements:**

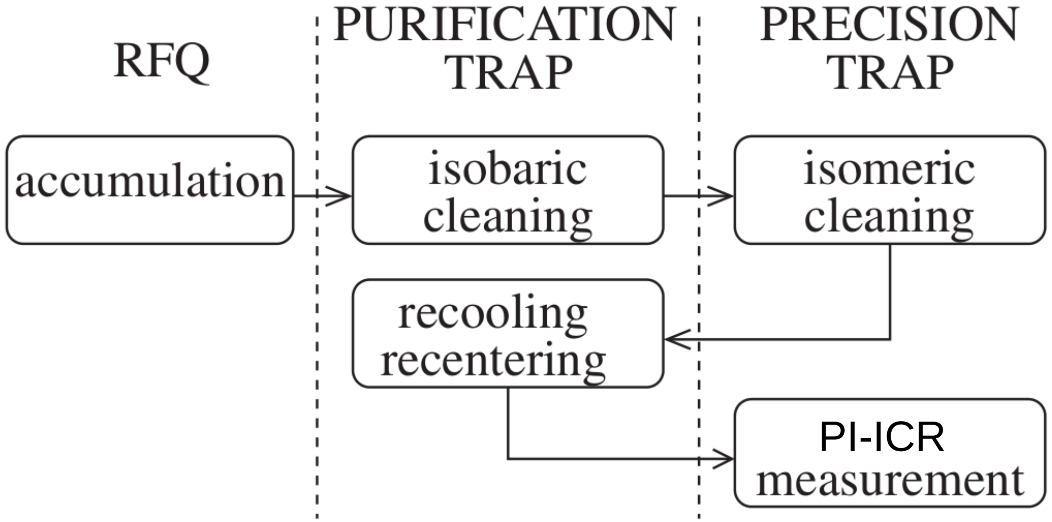
- Need to prepare the ion more carefully
- Damping of ion motions; longer setting up time
- Sensitive to voltage fluctuations



# Isomeric cleaning



Ramsey cleaning



Same cleaning processed was needed for different measurements presented here

# Ultra low Q-value $\beta$ decay for neutrino physics

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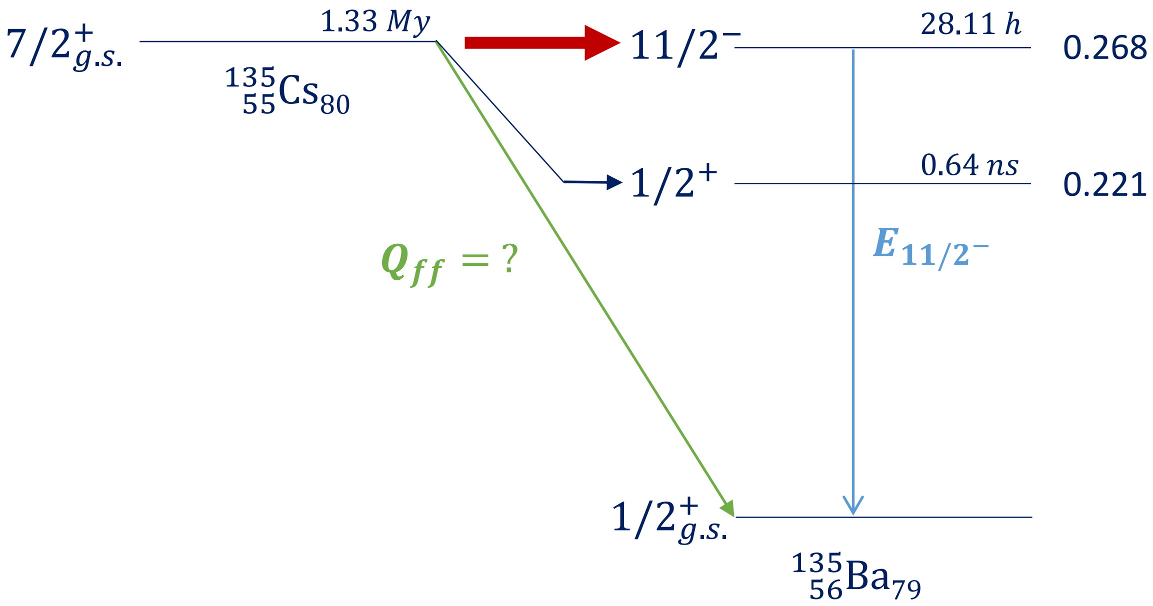
| $^{159}$Dy(3/2$^-$) | $^{159}$Tb(5/2$^-$) | 363.5449(14) | 1.7(12) | EC |
| | $^{159}$Tb(11/2$^+$) | 362.050(40) | 3.2(12) | EC |

# $^{135}$Cs(7/2$^{+}$) $\xrightarrow{\beta^-}$ $^{135}$Ba(11/2$^{-}$)

$Q_{11/2^-} = 0.5(12)\ keV$ ?



**But :** The transition is poorly known!

- Not yet proven that it is energetically possible : $Q_{11/2^-} < 0$ ?
- Decay never observed directly

To determine $Q_{11/2^-}$ we need:

- The excitation energy $E_{11/2^-} = 268.218(20)\ keV$
- The ground-state-to-ground-state Q-value $Q_{ff}$
- $Q_{ff} = 268.9(1.1)\ keV$ [1]

$$\boxed{Q_{ff} = 268.9(1.1)\ keV \rightarrow Q_{11/2^-} = 0.5(1.2)\ keV}$$

**New measurement of $Q_{ff}$ with Penning traps!!**

[1] *M. Wang et al., Chin. Phys. C 41, 030003 (2017)*

# $^{135}\text{Cs}(7/2^{+}) \xrightarrow{\beta^-} {}^{135}\text{Ba}(11/2^{-})$

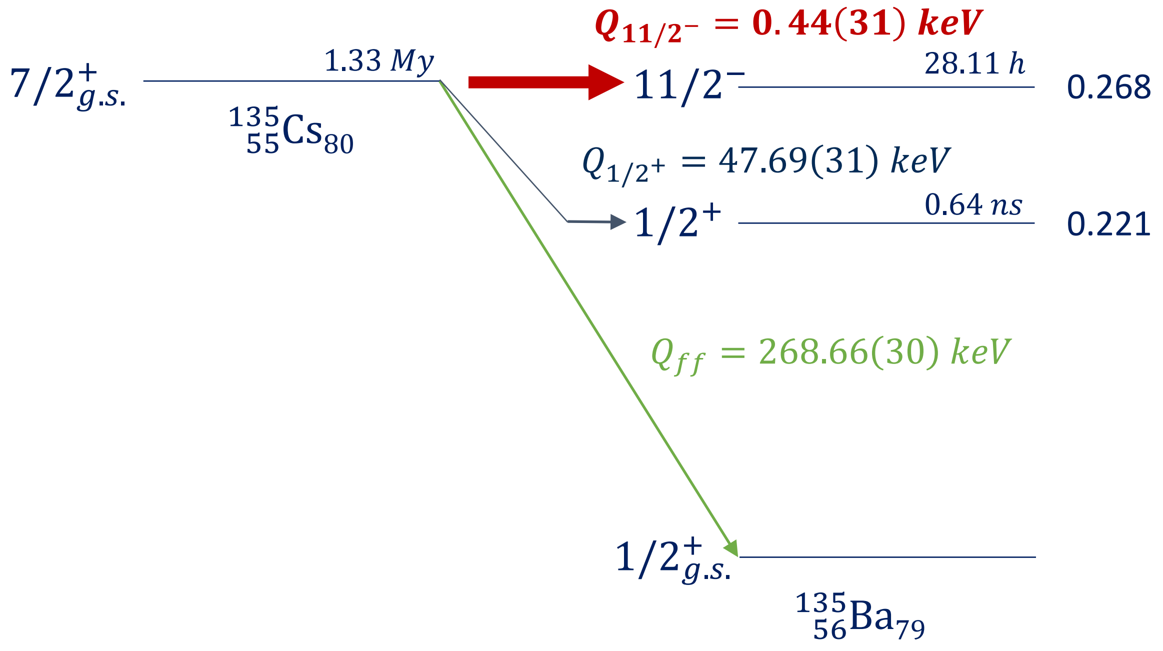
$$\boldsymbol{Q_{gs-gs} = 268.66(30)\ keV}$$
$$\boldsymbol{\rightarrow Q_{11/2^-} = 0.44(31)\ keV}$$
$$\boldsymbol{\rightarrow Q_{1/2^+} = 47.69(31)\ keV}$$

Half-lives calculations computed with NuShell@MSU

- $T_{1/2}$ ($^{135}$Ba(11/2$^-$)) = $8.2(32) \cdot 10^{11}\ y$
- $T_{1/2}$ ($^{135}$Ba(1/2$^+$)) = $6.5(17) \cdot 10^{13}\ y$

⇩

Branching ratio $(0.04 - 16) \cdot 10^{-6}$

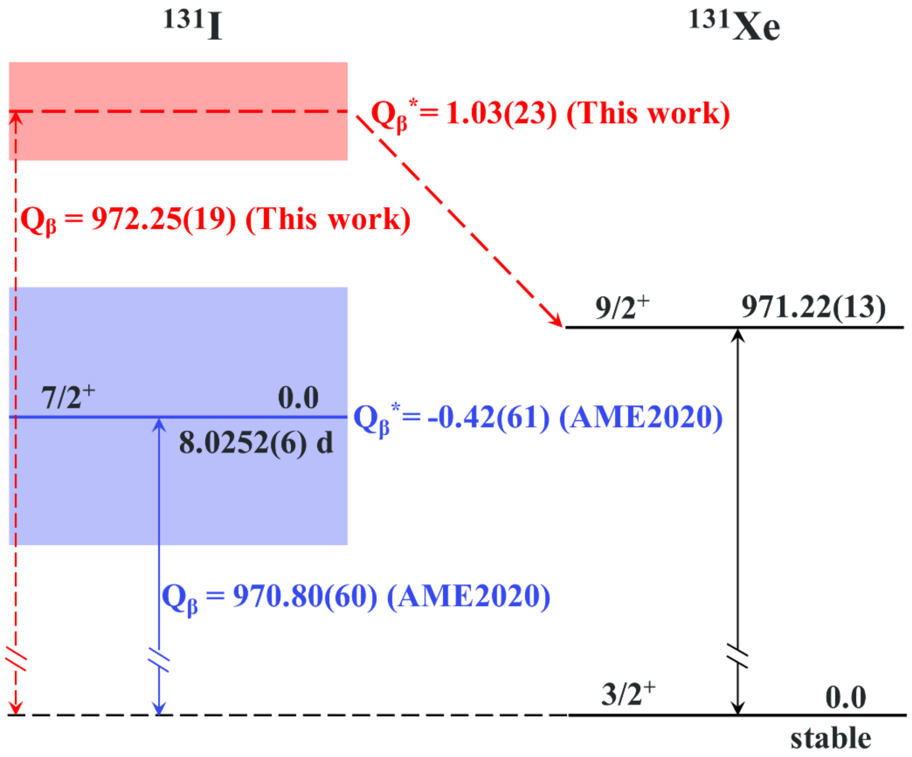


A. de Roubin et al., Phys. Rev. Lett. A **124,** 222503 (2020)

**Conclusion:**
- $^{135}Cs(7/2^{+}) \rightarrow {}^{135}Ba(11/2^{-}) > 0$
- First direct Q value measurement
- Direct measurement of the antineutrino mass?

**Expected challenges:**
- Half-live of the 11/2$^-$ state too long
- Cannot be use in coincidence

# $^{131}\mathrm{I}(7/2^+) \xrightarrow{\beta^-} {}^{131}\mathrm{Xe}(3/2^+)$

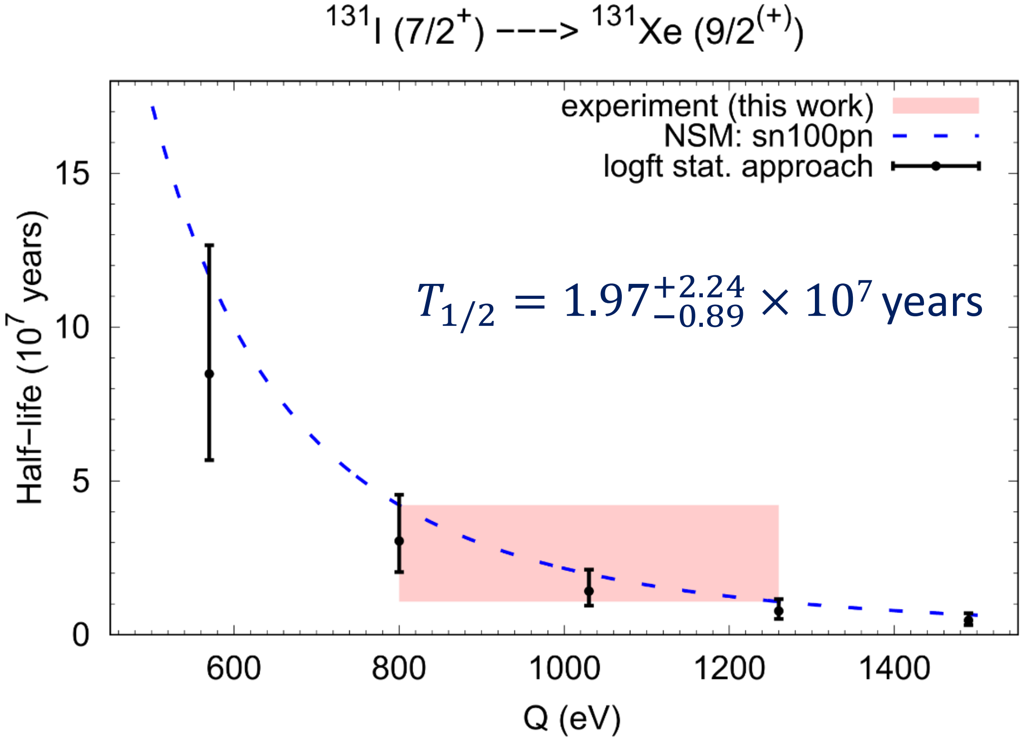


$$Q_{gs-gs} = 972.25(19)\ keV$$
$$\rightarrow\ Q_{9/2^+} = 1.03(23)\ keV$$

T. Eronen et al. accepted for publication in PLB

Half-lives calculations for this transition

- Nuclear shell model calculations with NuShellX
  *B. Brown, W. Rae, Nucl. Data Sheets **120**, 115 (2014)*
- Partial half-life is extremely sensitive to the exact value of the decay energy



$$T_{1/2} = 1.97^{+2.24}_{-0.89} \times 10^7\ \text{years}$$

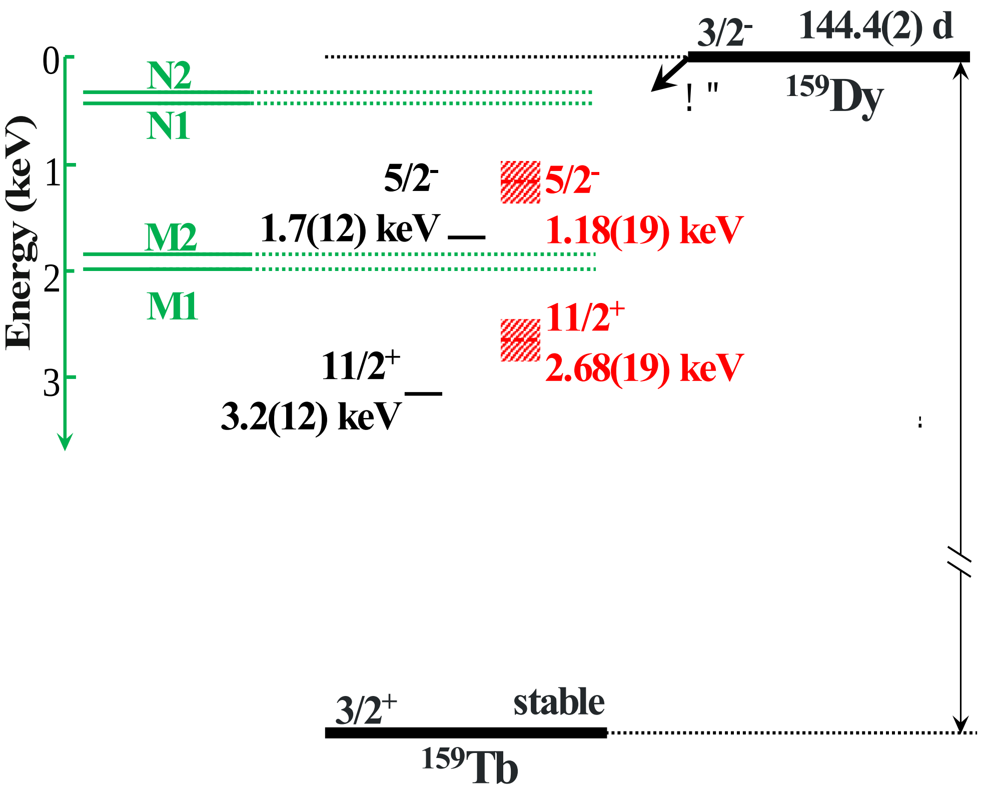
**Conclusion:**

- The decay 7/2+ → 9/2+ is of allowed type
- The transition has a simple universal shape

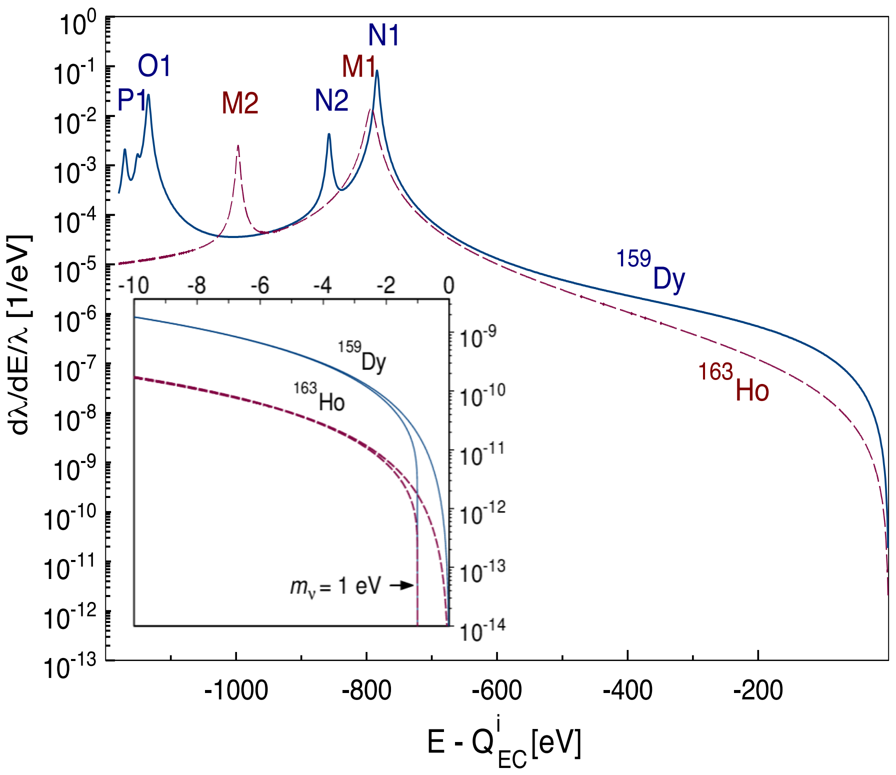
**Expected challenge:**

- The branching ratio ~ $10^{-10}$

# $^{159}\mathrm{Dy}(3/2^{-}) \xrightarrow{EC} {}^{159}\mathrm{Tb}(5/2^{-})$



**EC spectrum of $^{159}$Dy ($3/2^{-} \rightarrow 5/2^{-}$) compared to $^{163}$Ho**
**(Dirac-Hartree-Fock atomic many-body calculations)**



Courtesy of Z. Ge

*Z. Ge, T. Eronen, K. S. Tyrin et al., Phys. Rev. Lett. 127, 272301 (2021)*

# $^{159}\mathrm{Dy}(3/2^-) \xrightarrow{EC} {}^{159}\mathrm{Tb}(5/2^-)$

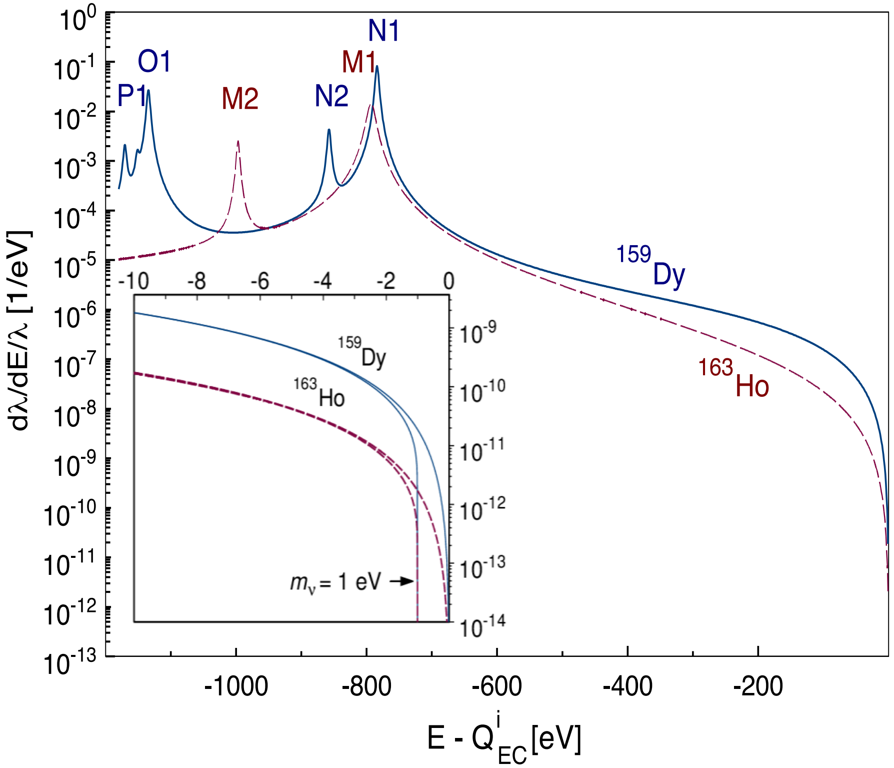
**EC spectrum of $^{159}$Dy ($3/2^- \rightarrow 5/2^-$) compared to $^{163}$Ho**
(Dirac-Hartree-Fock atomic many-body calculations)

$Q_{EC}^{\ *}$ = 1.18(19) keV

- Lowest EC Q value
- Lower than the GS-to-GS $Q_{EC}$ of $^{163}$Ho, utilized in presently running or planned direct neutrino mass experiments

- allowed transition
- known branching ratio 1.9(5) × $10^{-6}$
- Smallest EC Q value

⇨ The most promising gs-to-excited state transition for future calorimetric experiment



Courtesy of Z. Ge

*Z. Ge, T. Eronen, K. S. Tyrin et al., Phys. Rev. Lett. 127, 272301 (2021)*

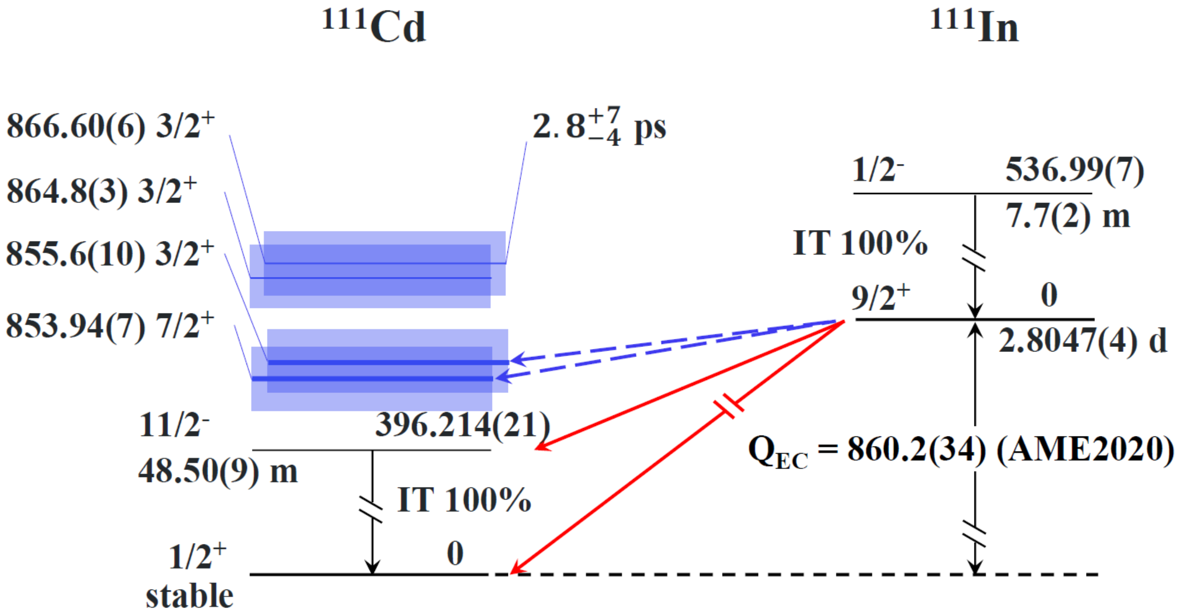
# $^{111}\mathrm{In}(9/2^+) \xrightarrow{EC} {}^{111}\mathrm{Cd}(7/2^+)$

$$\boxed{Q_{gs-gs} = 857.63(17)\ keV}$$

| **Mother( $J^\pi$ )**<br>*Ground state* | **Daughter ( $J^\pi$ )**<br>*Excited state* | **E* (keV)** | ***Q* (keV)** | **Decay type** |
|---|---|---|---|---|
| $^{111}$In(9/2$^+$) | $^{111}$Cd(7/2$^+$) | 853.94(7) | 3.69(19) | allowed |
| | $^{111}$Cd(3/2$^+$) | 855.6(10) | 2.0(10) | 2$^{nd}$ FU |
| | ~~$^{111}$Cd(3/2$^+$)~~ | ~~864.8(3)~~ | ~~-7.17(35)~~ | |
| | ~~$^{111}$Cd(3/2$^+$)~~ | ~~866.60(6)~~ | ~~-8.97(18)~~ | |

Estimated half-life for 9/2$^+$ → 3/2$^+$ transition $t_{1/2} = 5.6 \times 10^{17}$

- ➢ Transition excluded!

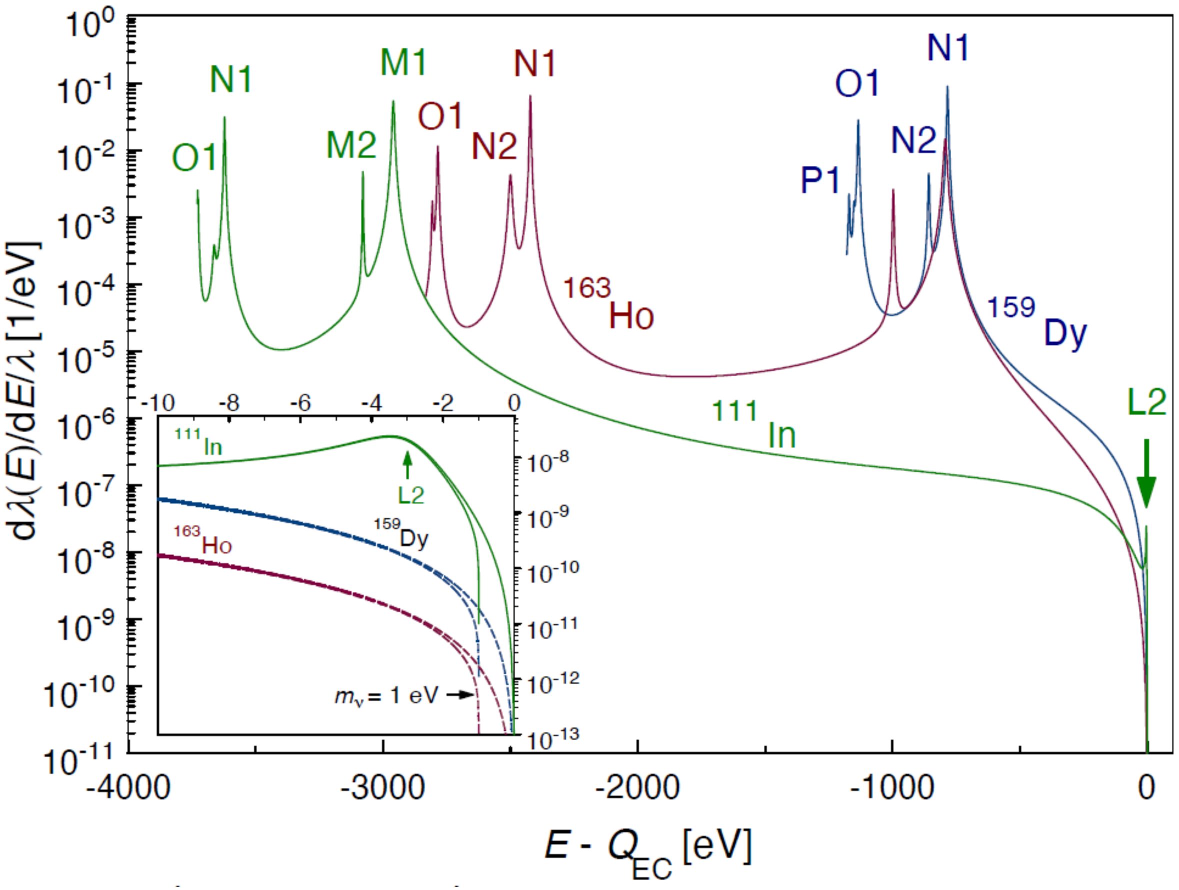


*Z. Ge et al., submitted to Elsevier*

*Z. Ge et al., arXiv:2201.12573v1*

# $^{111}\mathrm{In}(9/2^{+}) \xrightarrow{EC} {}^{111}\mathrm{Cd}(7/2^{+})$

EC spectrum of $^{111}$In($9/2^{+} \rightarrow 5/2^{-}$) compared to $^{163}$Ho and $^{159}$Dy



- EC spectrum shape investigated with atomic Dirac-HF many-body calculations
- Presence of a L2 resonance near the end point (3 eV)
- Increases significantly the counting rate in the ROI

$$Q = 2.0(10)\ \mathrm{keV}$$

**Need more precise excitation energy measurement !**

*Z. Ge et al., arXiv:2201.12573v1*

# Summary of the measured Q-values of potential candidates

- List of measured promising low Q-value decay candidates for neutrino mass determination

| Parent | T1/2 | Daughter | E∗ (keV) | decay type | Q*（keV） | Decay | $Q_0$ (keV) | $dQ_0$ (keV) |
|---|---|---|---|---|---|---|---|---|
| 146Pm(3−) | 5.53(5) y | 146Nd(2+) | 1470.63(6) | 1st FNU | 1.3(4.2) | EC | 1472.000 | 4.000 |
| 149Gd(7/2−) | 9.28(10) dy | 149Eu(5/2+) | 1312(4) | 1st FNU | 2(6.4) | EC | 1314.100 | 4.000 |
| 155Tb(3/2+) | 5.32(6) dy | 155Gd{3/2+} | 815.731(3) | Allowed{?} | 4.2(10.1) | EC | 820.000 | 10.000 |
| 159Dy(3/2−) | 144.4(2) dy | 159Tb(5/2−) | 363.5449(14) | Allowed | 1.7(1.2) | EC | 365.200 | 1.200 |
| | | 159Tb(11/2+) | 362.050(40) | 3rd FU | 3.2(1.2) | EC | 365.200 | 1.200 |
| 161Ho(5/2−) | 18.479(4) hr | 161Dy{7/2+} | 858.502(7) | 1st FNU | 1.0(2.2) | EC | 858.500 | 2.200 |
| | | 161Dy{3/2-} | 858.7919(18) | Allowed | −0.3(2.2) | EC | 858.500 | 2.200 |
| 72As(2−) | 26.0(1)h | 72Ge{1} | 4358.7(3) | Allowed{?} | −2.8(4.0) | EC | 4356.000 | 4.000 |
| | | 72Ge(3−) | 3325.01(3) | Allowed | 8.9(4.0) | β+ | 4356.000 | 4.000 |
| | | 72Ge(2+) | 3327(3) | 1st FNU | 6.9(5.0) | β+ | 4356.000 | 4.000 |
| | | 72Ge{1+} | 3338.0(3) | 1st FNU{?} | −4.1(4.0) | β+ | 4356.000 | 4.000 |
| | | 72Ge{2−} | 3341.76(4) | Allowed{?} | −7.9(4.0) | β+ | 4356.000 | 4.000 |
| 159Gd(3/2−) | 26.24(9) h | 159Tb{1/2+} | 971 | 1st FNU{?} | 0.0(1.8) | β- | 970.900 | 0.800 |
| 77As(3/2−) | 38.79(5) h | 77Se(5/2+) | 680.1035(17) | 1st FNU | 3.1(1.7) | β- | 683.200 | 1.700 |
| 76As(2−) | 26.24(9) h | 76Se{2−} | 2968.4(7) | Allowed{?} | −7.8(1.1) | β- | 2960.600 | 0.900 |
| 153Tb(5/2+) | 2.34(1)dy | 153Gd(5/2−) | 548.7645(18) | 1st FNU | −1.2(4.0) | β+ | 1569.000 | 4.000 |
| | | 153Gd{5/2} | 551.092(19) | Allowed{?} | −3.5(4.0) | β+ | 1569.000 | 4.000 |
| 111In(9/2+) | 3dy | 111Cd(3/2+) | 864.8(3) | 2nd FU | −6.6(3.0) | EC | 860.2 | 3.4 |
| | | 111Cd(3/2+) | 864.8(3) | 2nd FU | −4.6(3.0) | EC | 860.2 | 3.4 |
| | | 111Cd(3/2+) | 855.6(1.0) | 2nd FU | 4.6(3.2) | EC | 860.2 | 3.4 |
| | | 111Cd(7/2+) | 853.94(7) | Allowed | 6.3(3.0) | EC | 860.2 | 3.4 |
| 131I(7/2+) | 8dy | 131Xe{9/2+} | 971.22(13) | Allowed{?} | −0.42(0.61) | β- | 970.80 | 0.60 |
| | | 131Xe(7/2+) | 973.11(14) | Allowed | −2.31(0.62) | β- | 970.80 | 0.60 |
| 155Eu(5/2+) | 5yr | 155Gd(9/2−) | 251.7056(10) | 1st FU | 0.1(1.8) | β- | 252.00 | 2.40 |

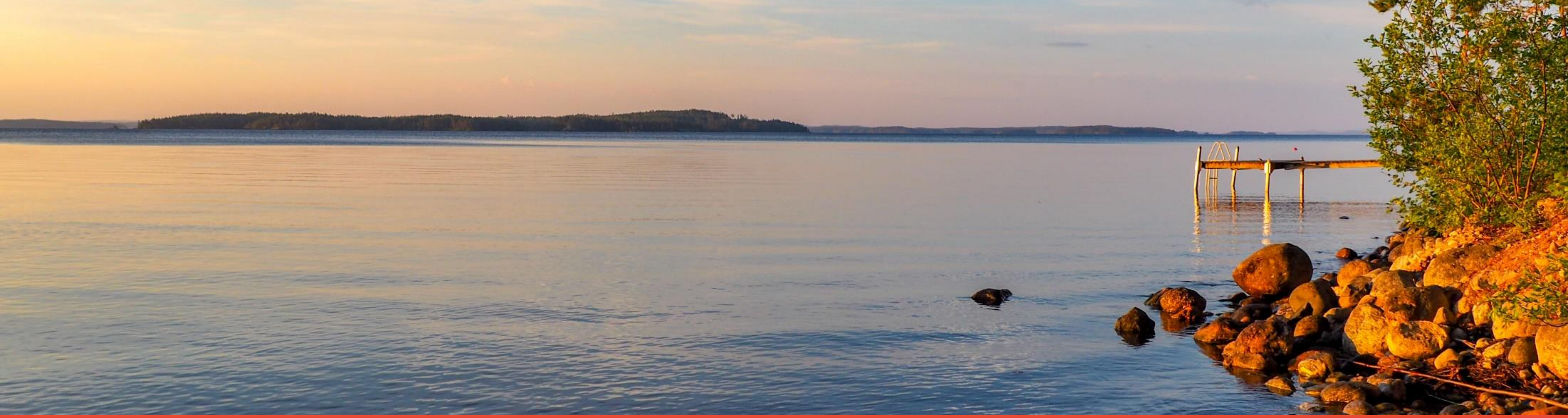
*Z. Ge, T. Eronen et al.*, Phys. Rev. Lett. 127, 272301

*Z. Ge, T. Eronen et al., PHYSICAL REVIEW C 103, 065502 (2021)*

Submitted

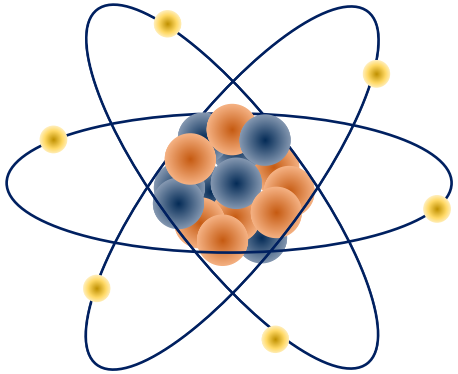
$Q_0$ from: *M. Wang et al. , Chinese Physics C 45, 030003 (2021)*
$E^*$ from: *National nuclear data center, Available at https://www.nndc.bnl.gov*

Courtesy of Z. Ge



# Thanks a lot for your attention

# Binding energy



$$M_{Nuclei} = N \times M_{Neutron} + Z \times M_{Proton} - B(N,Z)/c^2$$

$\hookrightarrow$ $E = mc^2$ → The binding energy corresponds to the missing mass

**Measuring $B(N,Z)$**

- $\delta M/M$ = $10^{-7}$ – $10^{-9}$ (For $A = 100\ u \rightarrow 100\ GeV$)
- Nuclear deformation → $\delta M/M$ = $10^{-7}$ → 10 keV
- Neutrino physic → $\delta M/M$ = $10^{-9}$ → 100 eV

# Ion traps

**Ion traps**

**Nuclear structure**

- Nucleosynthesis
- Nuclear deformation
- Shell effects

Plasma physic

Molecular and cluster physics

**Tests of Standard Model**

- CVC
- Symmetry C, P, T
- Neutrino physic

Metrology

Chemistry

**Ion manipulation**

- Cooling
- Bunching
- Accumulation
- Mass purification

# The ECHo experiment

Electron capture of $^{163}$Ho with $Q_{EC} = 2.8$ keV

163Ho source is enclosed in large array of magnetic calorimeters
- → Deposition of energy
- → Temperature increased
- → Change the magnetization of a paramagnetic temperature sensor
- → Change the magnetic flux of a voltage convertor
- → The output voltage signal is proportional to the deposited energy

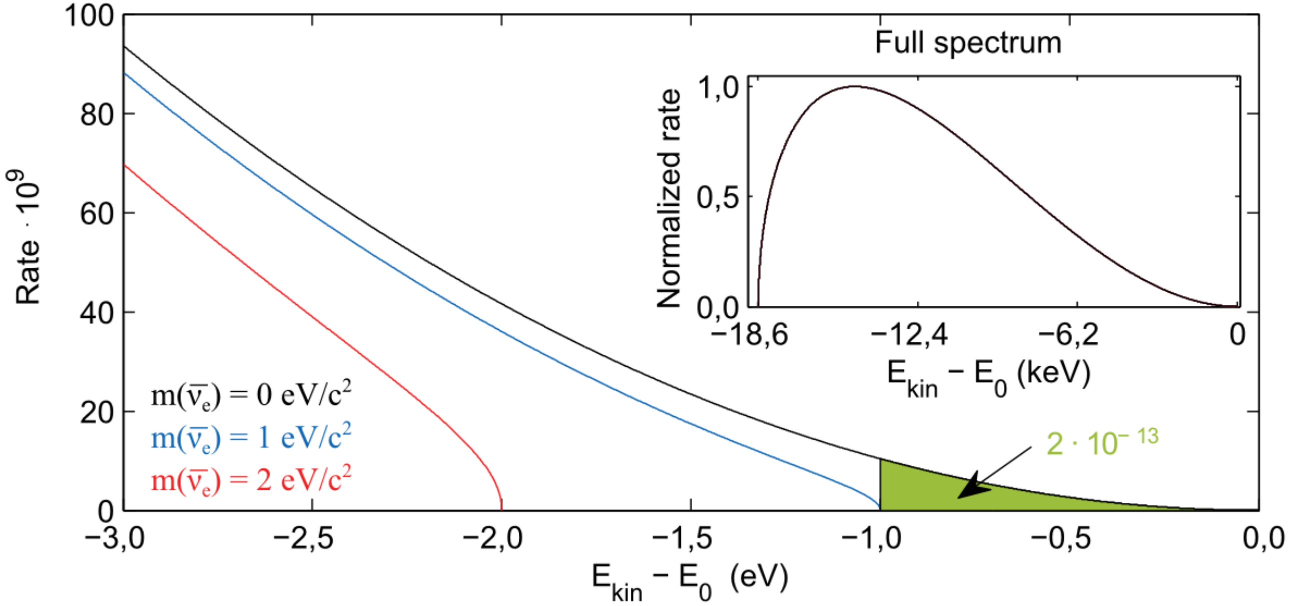
# The KATRIN experiment

- $\beta$ decay via the mass of the electron antineutrino
  - → A slight distortion of the $\beta$ decay spectrum relates directly to the electron-neutrino mass

- KATRIN [1] experiment
  - → ${}^{3}H(1/2^{+}) \xrightarrow{\beta^{-}} {}^{3}He(1/2^{+})$
  - → Allowed decay
  - → $Q = 18.5920(3)\ keV$

- Low $Q$ → higher sensitivity

Tritium $\beta$ decay electron spectrum

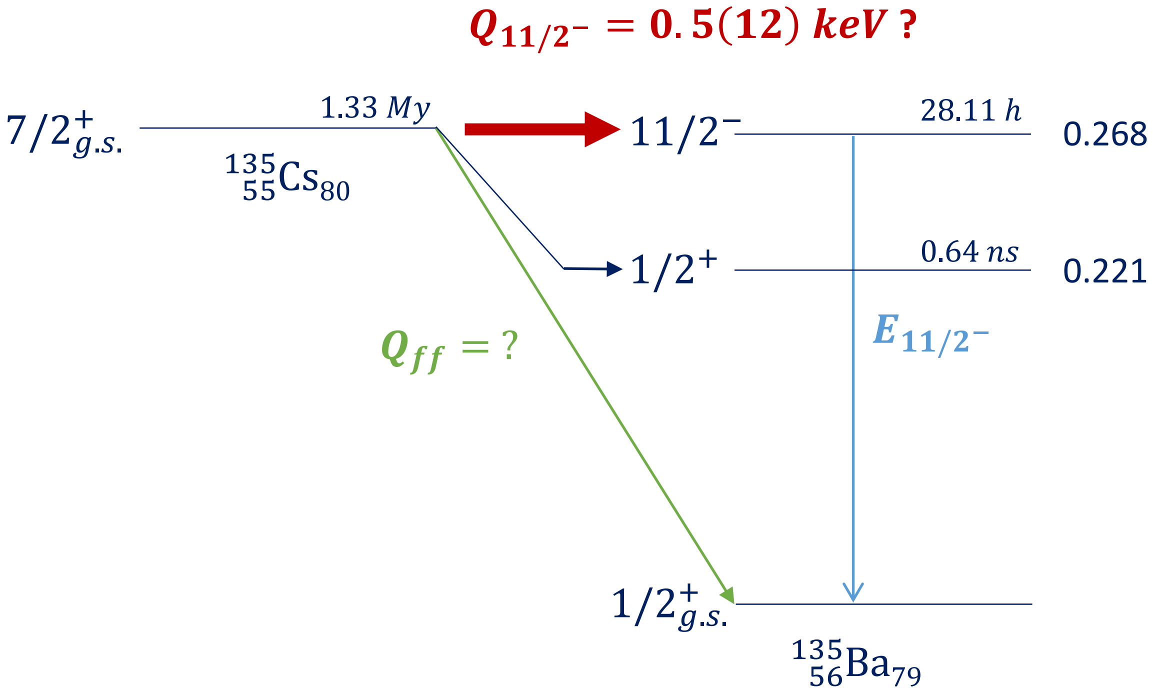


[1] *C. Weinheimer, Prog. Part. Nucl. Phys.* ***48****, 141 (2002)*

$$^{135}Cs(7/2^+) \xrightarrow{\beta^-} {}^{135}Ba(11/2^-)$$

**But :** The transition is poorly known!

- Not yet proven that it is energetically possible : $Q_{11/2^-} < 0$ ?
- Decay never observed directly



To determine $Q_{11/2^-}$ we need:

- The excitation energy $E_{11/2^-} = 268.218(20)\ keV$
- The ground-state-to-ground-state Q-value $Q_{ff}$
- $Q_{ff} = 268.9(1.1)\ keV$ [1]

$$\boxed{Q_{ff} = 268.9(1.1)\ keV \rightarrow Q_{11/2^-} = 0.5(1.2)\ keV}$$

**New measurement of $Q_{ff}$ with Penning traps!!**

[1] *M. Wang et al., Chin. Phys. C 41, 030003 (2017)*

# PI-ICR measurements

- Pure sample of $^{135}$Cs sent in the measurement trap
- Every few rounds, switched between $^{135}$Cs from IGISOL and $^{135}$Ba from the off-line spark source
- Measurement of the GS-to-GS *Q*-value performed with
  - TOF-ICR Ramsey technique
  - PI-ICR technique