Mass Measurements with Ion Traps

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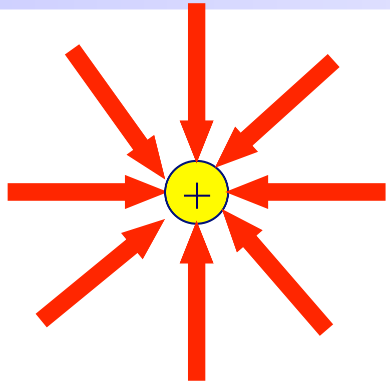
Outline

1. Confinement of charged particles
2. Mass measurements
    - Importance of the mass
    - Physics goals & mass uncertainty
    - Existing facilities
3. Penning-Trap Techniques
4. The TRAPSENSOR laboratory in Granada
    - Physics motivation
    - The QS concept
    - The QS project

CONFINEMENT OF CHARGED PARTICLES

Introduction
Confinement of charged particles



- Required:
  3-dimensional potential minimum.
  Force acting towards a center.

- Convenience:
  a) *F* ~ -*r* (Harmonic oscillator)
  b) Rotational symmetry

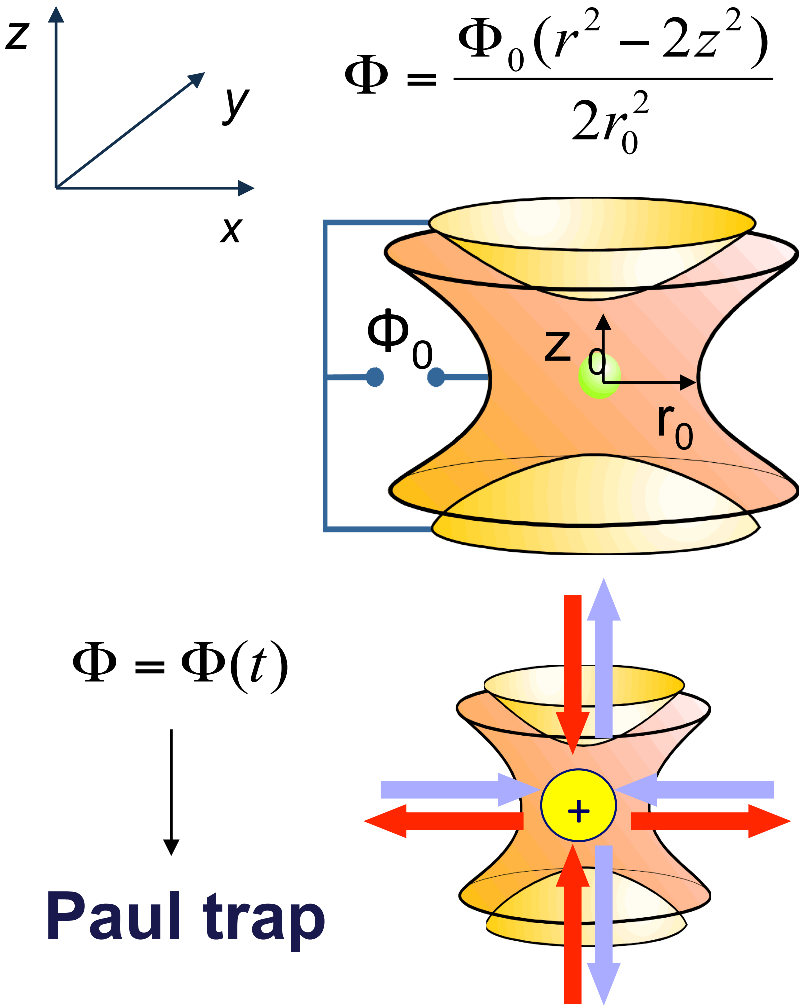
- Consequences:
  From a) $\vec{F} = -e\nabla\Phi \propto -\vec{r}$

$$\Rightarrow \quad \Phi = ax^2 + by^2 + cz^2$$

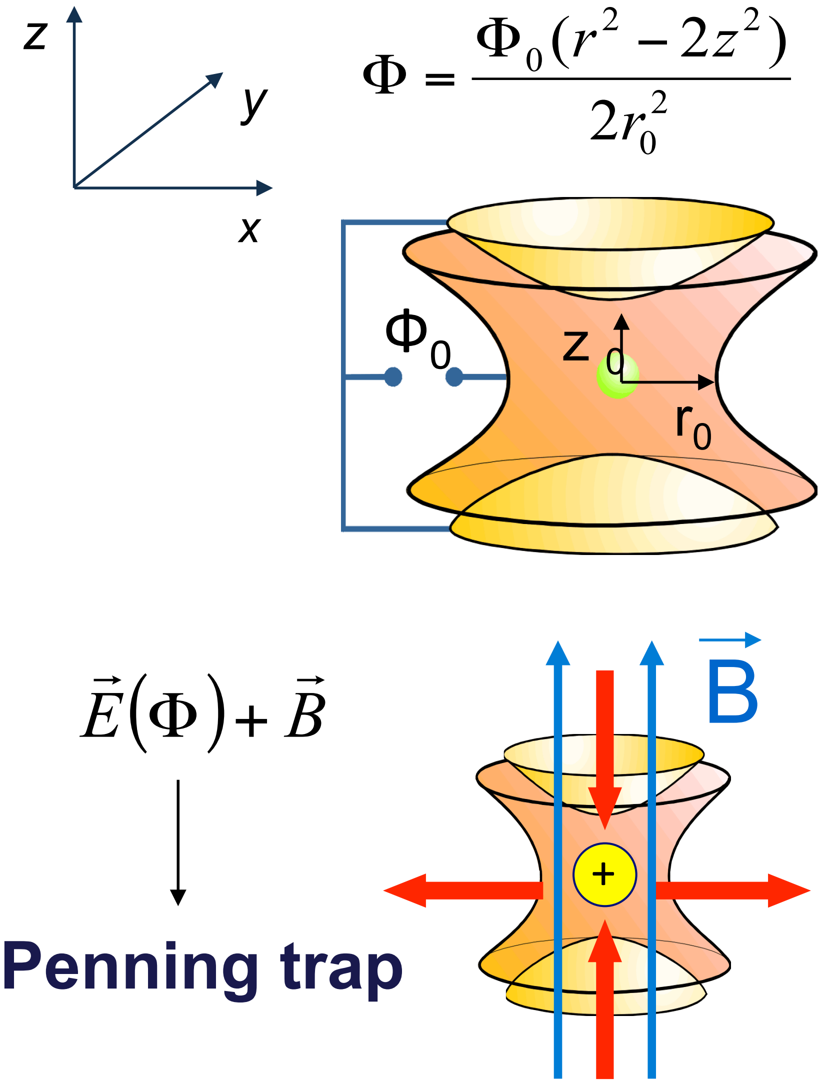
  Laplace equation
  Rotational symmetry around *z*-axis

- THERE IS NOT 3-DIMENSIONAL CONFINEMENT WITH ELECTROSTATIC FIELDS

Introduction
Confinement of charged particles

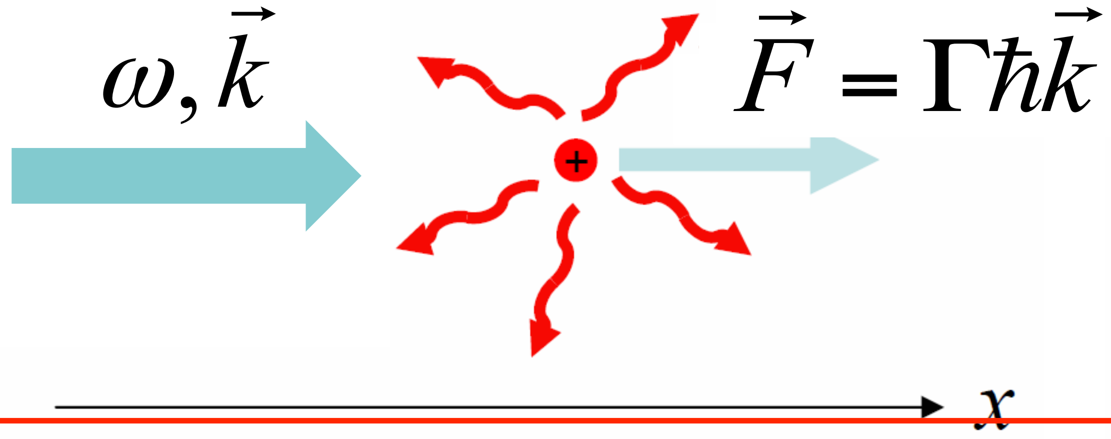


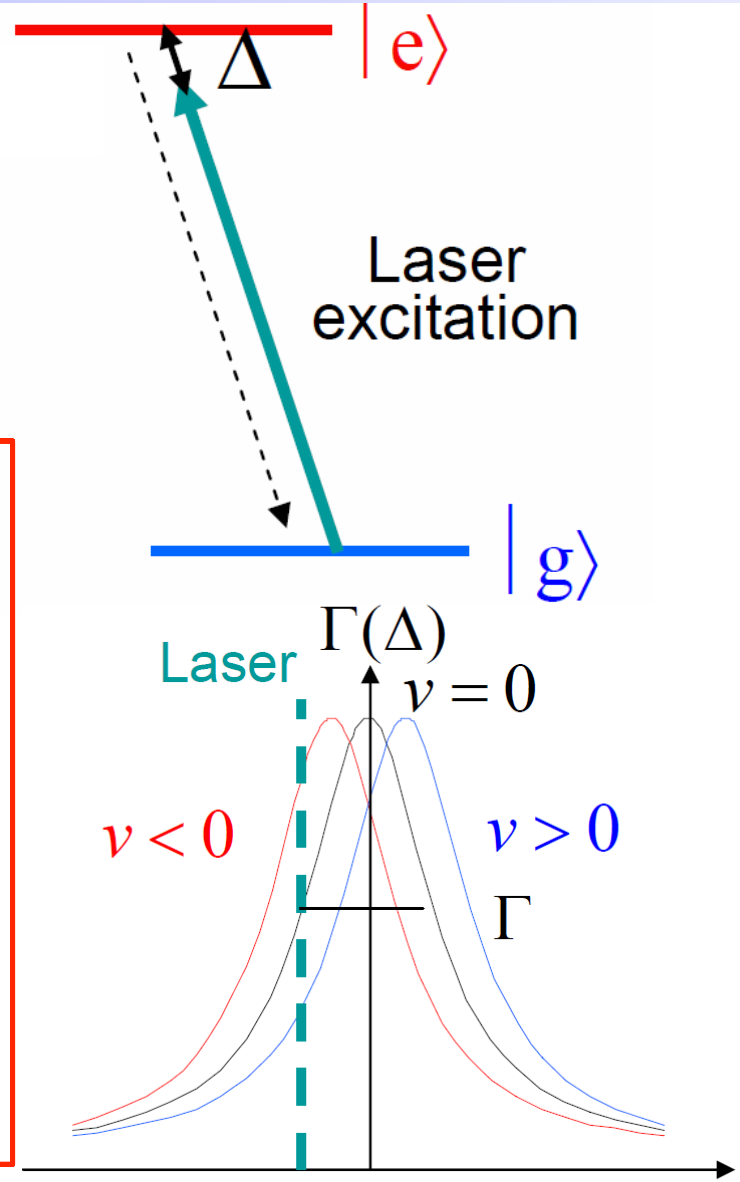
Paul trap



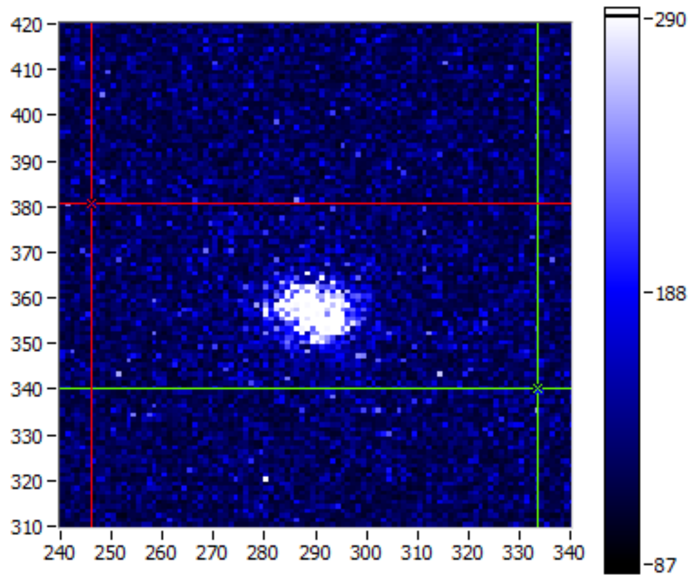
Penning trap

Cooling in Penning traps
Doppler cooling





- Cooling until the Doppler limit is reached



$$T_{\text{limit}} = \frac{\hbar \Gamma}{2 k_B}$$

$$T_{\text{limit}} \approx 1\,\text{mK}$$

Confinement of charged particles

Trapping

Increase of luminosity
Effective use
Easy manipulation
q/m-separation
Extended observation time
Accumulation & bunching

Cooling

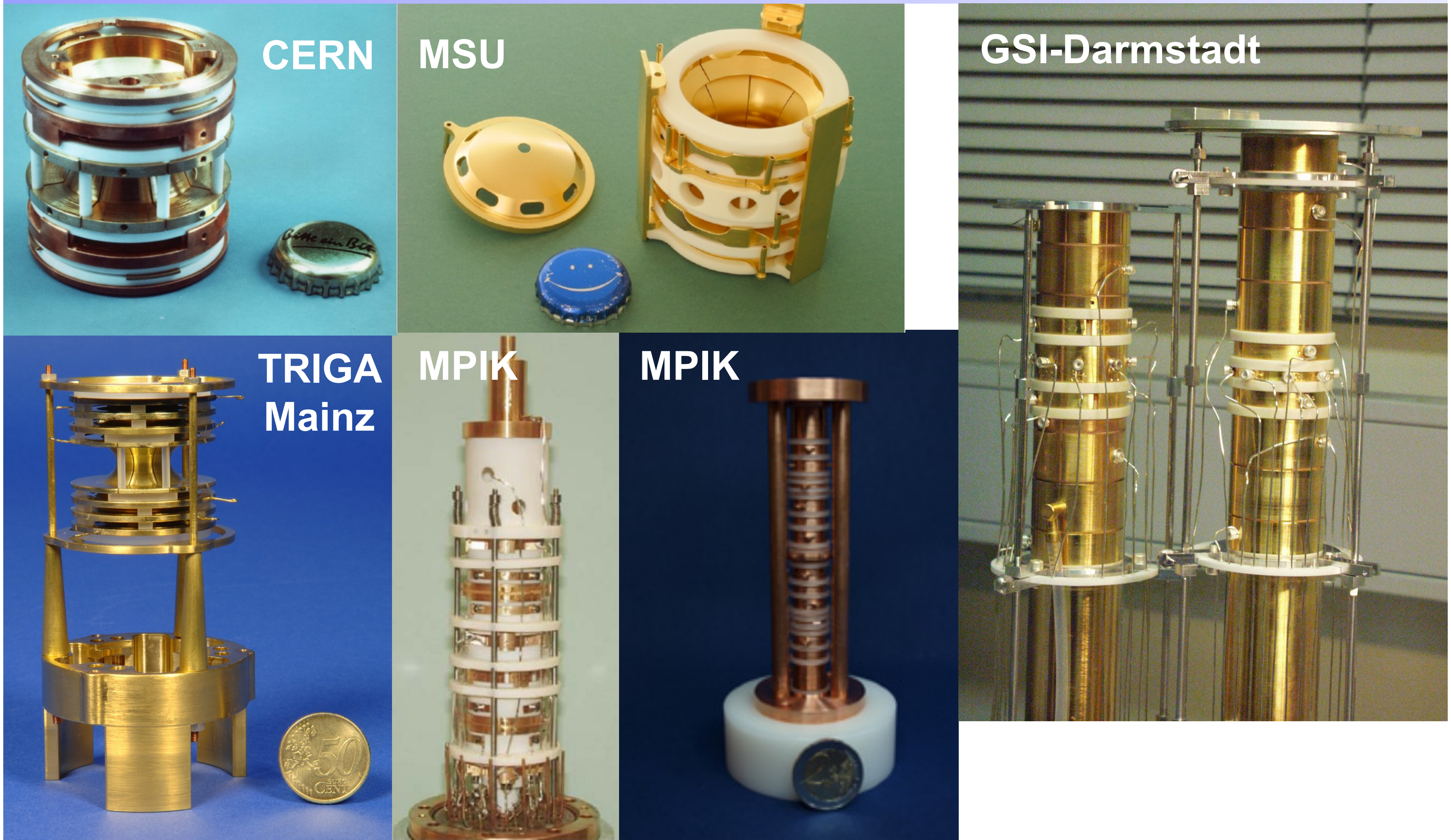
Increase of luminosity
Small amplitudes
q/m-separation
Emittance improvement
Doppler width reduction
Doppler effect elimination

ACCURACY
SENSITIVITY
EFFICIENCY

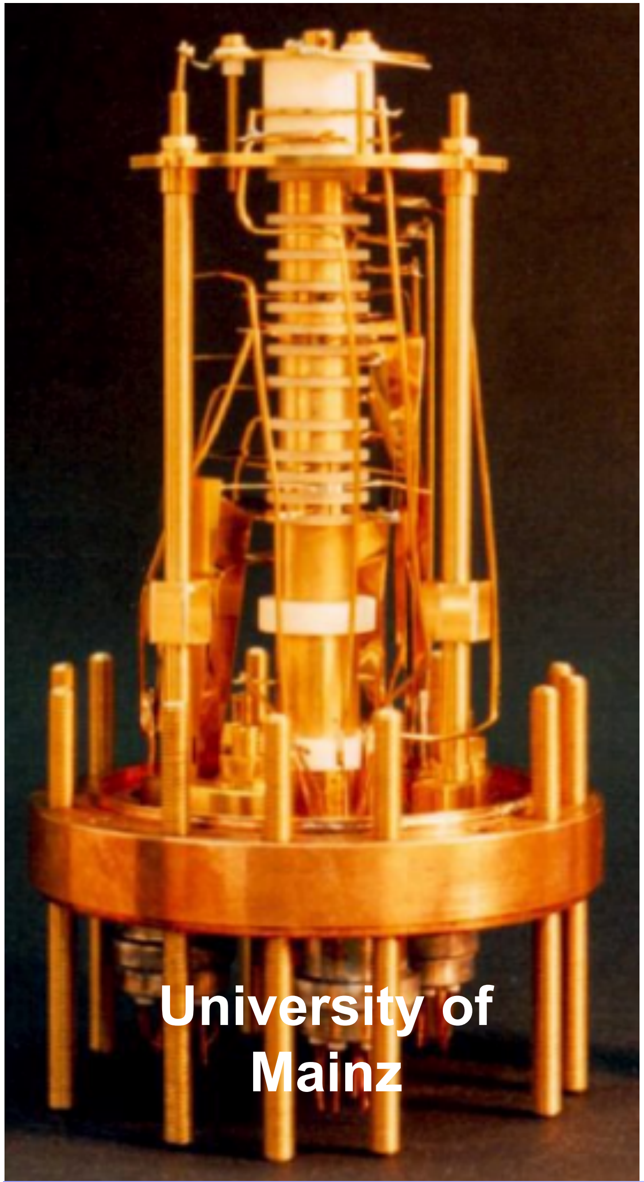
Examples

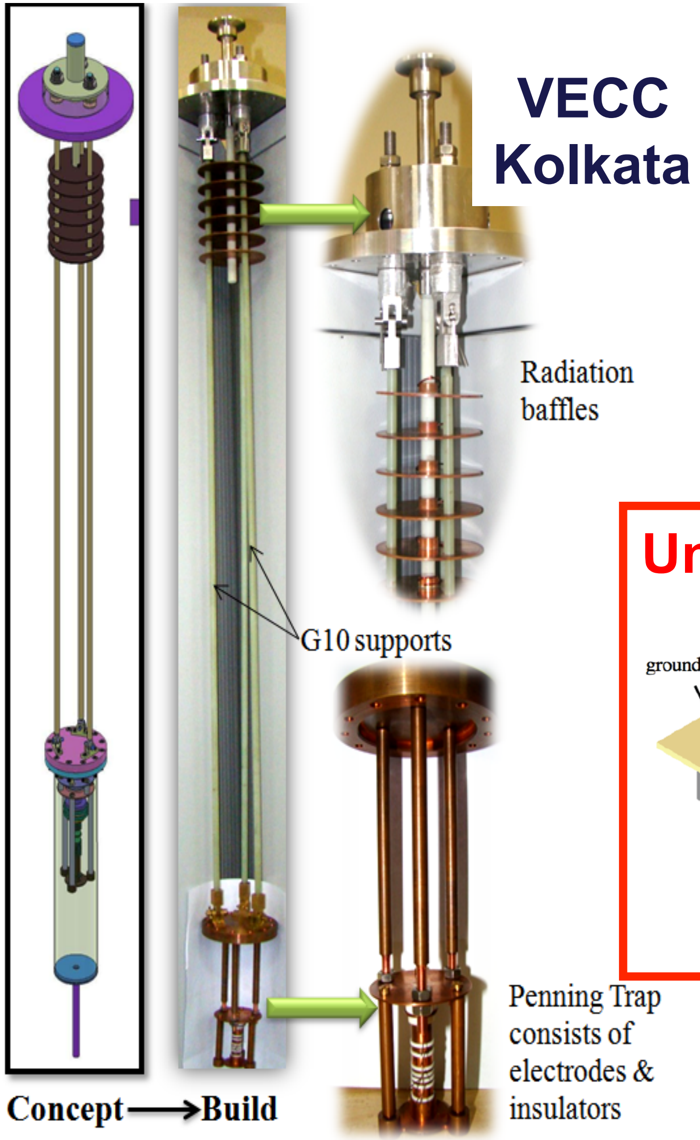
- Experiments with rare species (radioactive isotopes, HCI, antiprotons, anti-H,....)
- Ultra-high accuracy (mass, *g*-factor, α, optical clocks, relativity)
- Single-particle detection and observation (quantum logic spectroscopy)
- Quantum simulations and quantum computing
- Fundamental interactions (EDM, PV, search for non *V-A* interaction,.....)
- Accelerator device (accumulator, charge breeder, isomer separation, buncher,....)

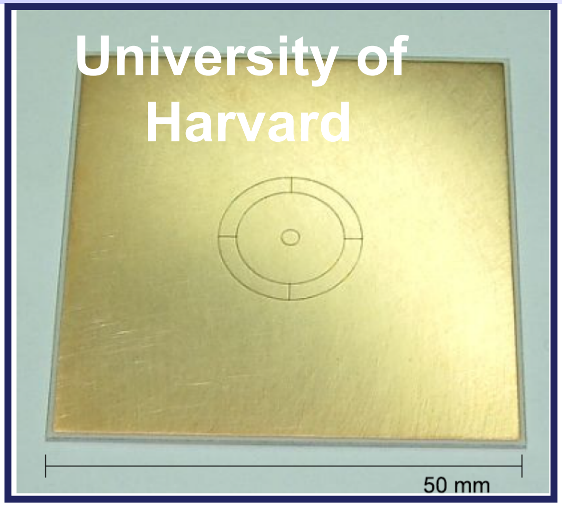
Penning traps
Different geometries (heavy-ion masses)

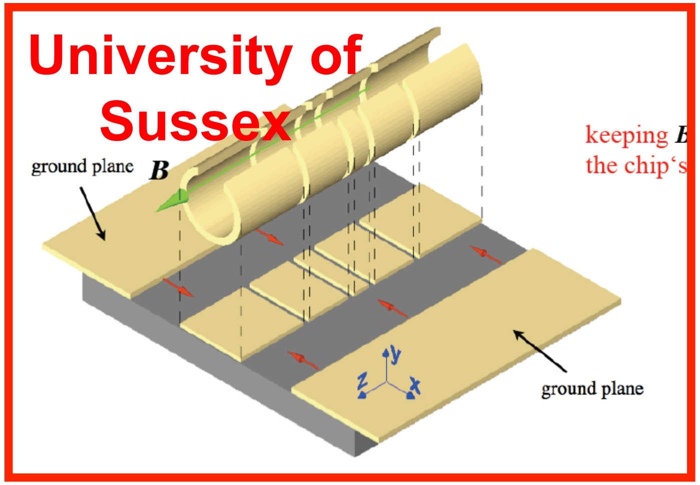


Penning traps
Different geometries (HCI, electrons)

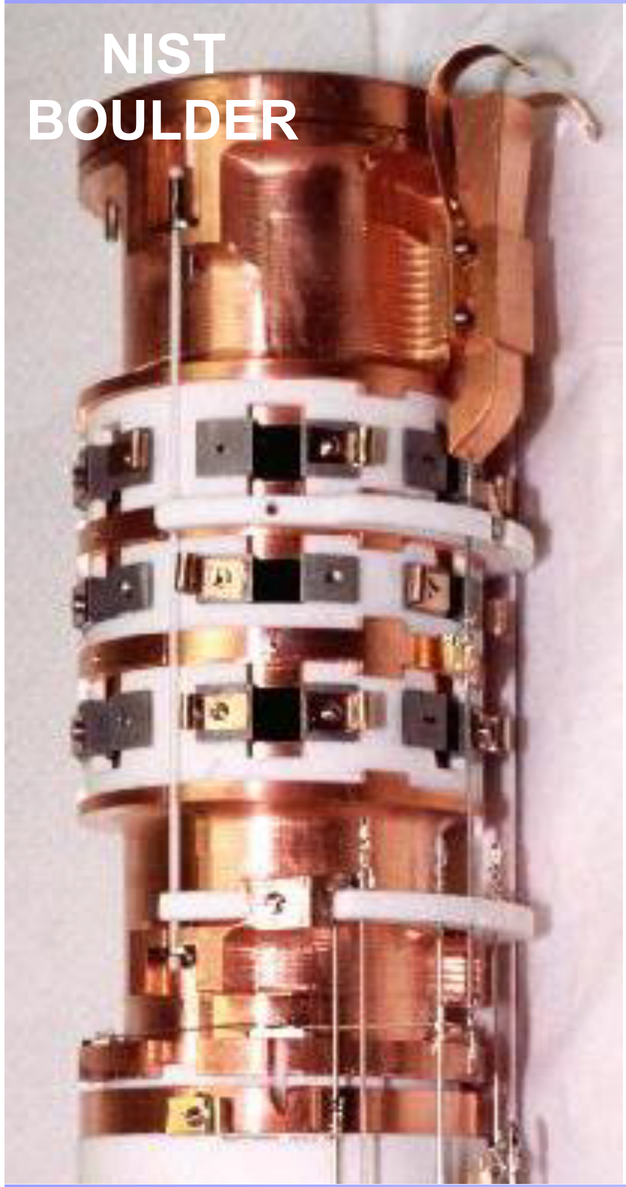


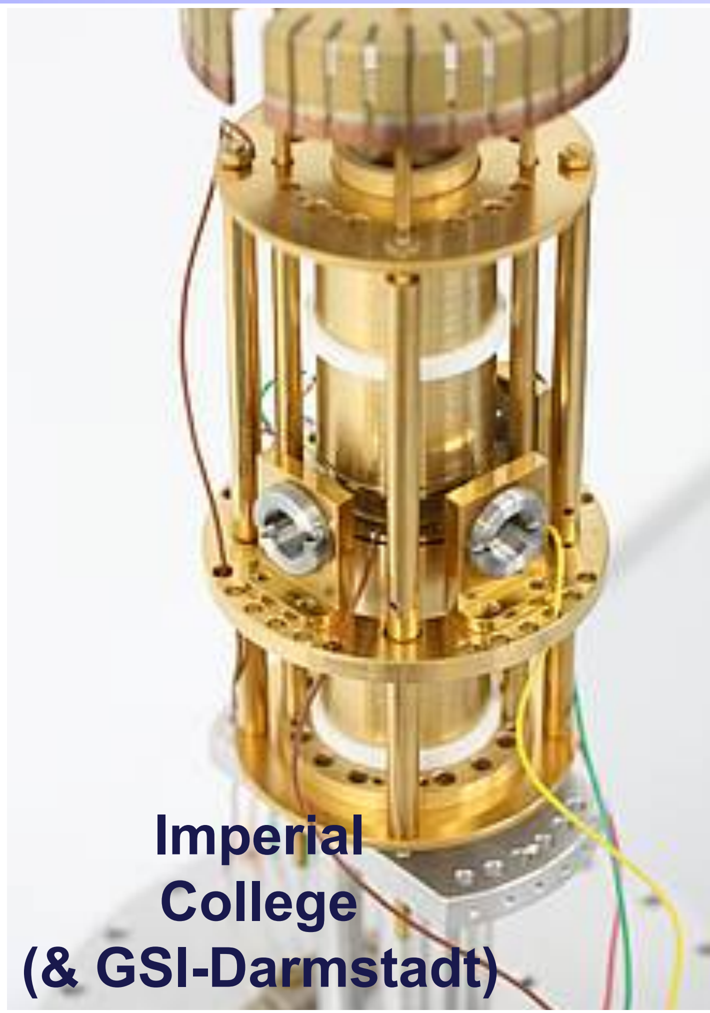


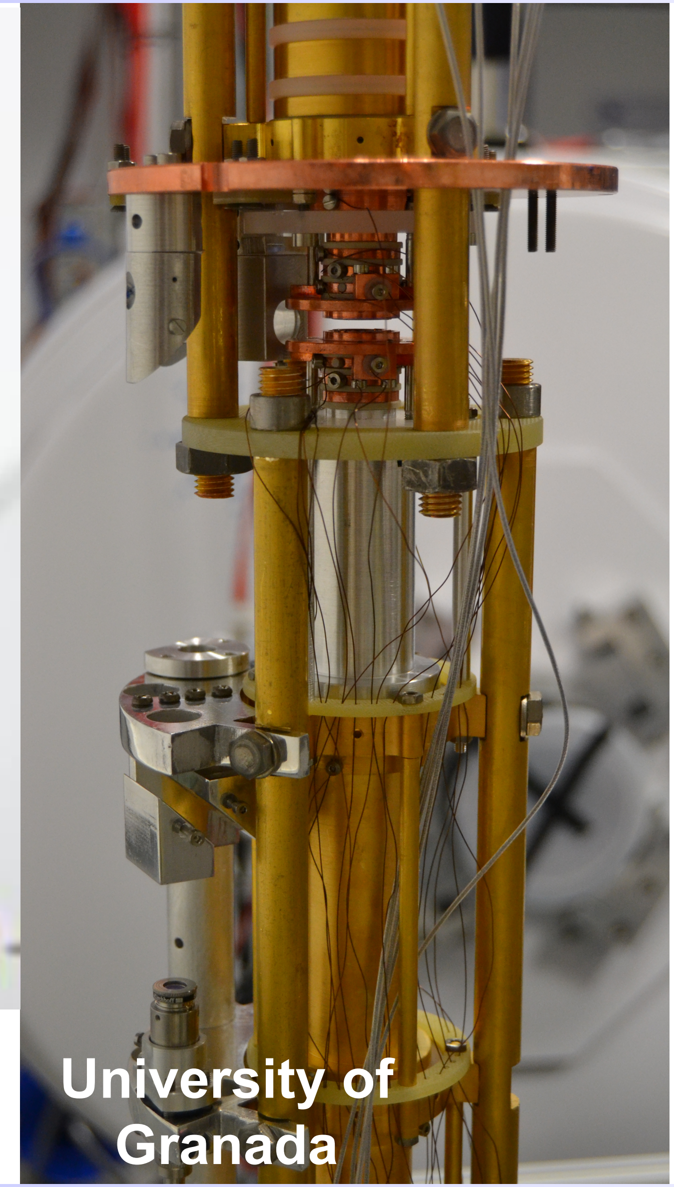




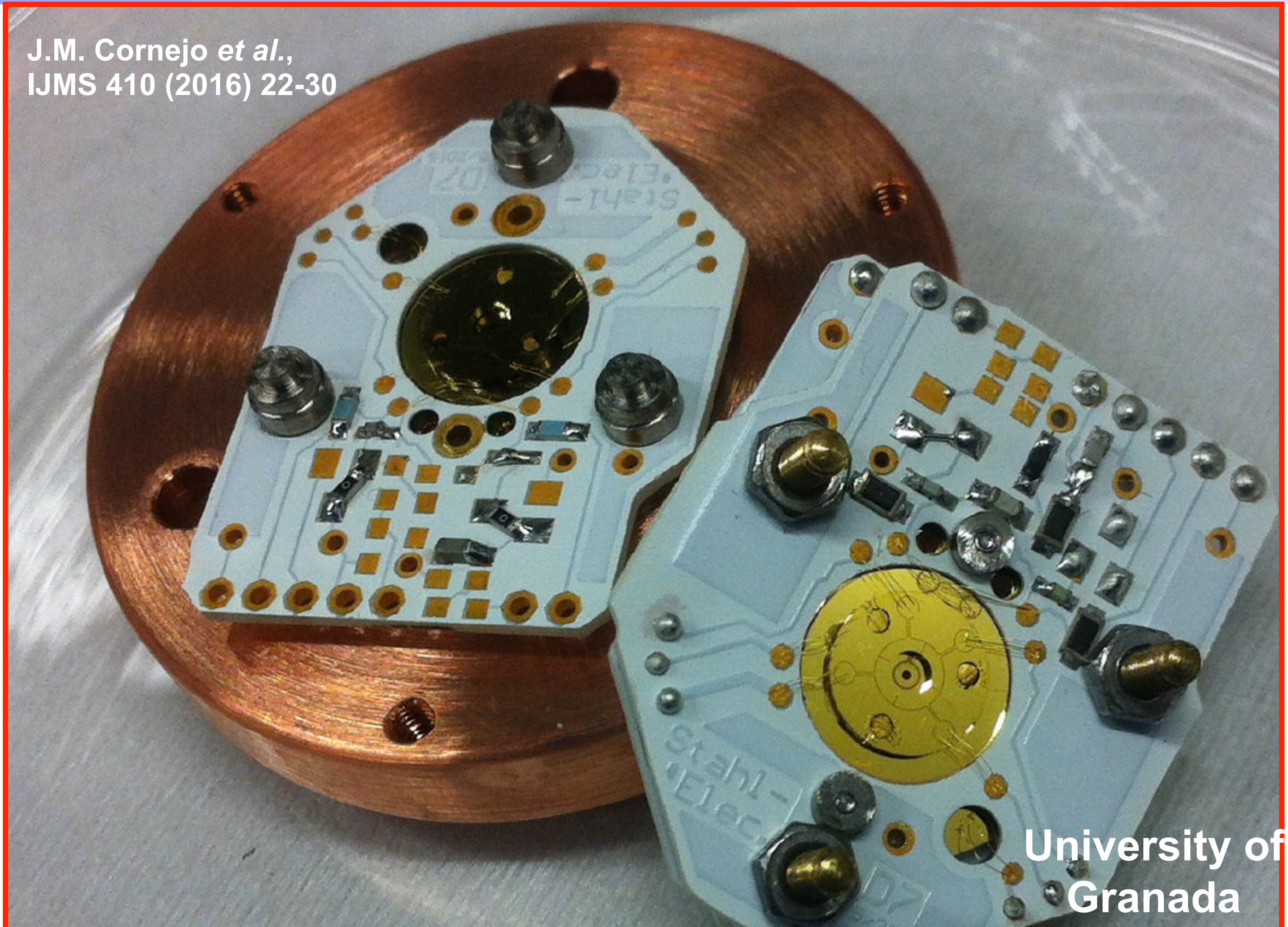
Penning traps
Different geometries (fluorescence collection)







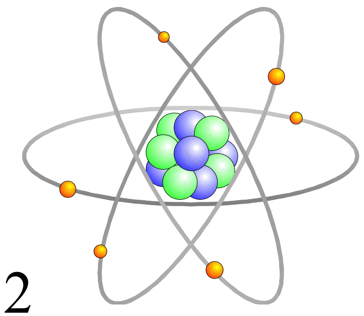
Penning traps
Different geometries (miniaturization)



MASS MEASUREMENTS

Importance of the mass
The nuclear binding energy (*B*)

The nuclear binding energy reflects all forces acting in a nucleus



$$B(N,Z) = \left\{ Zm_p + Nm_n - M(N,Z) \right\} \cdot c^2$$

Nuclear mass

$$B(N,Z) = \left\{ Zm_p + Nm_n - \left[m(^{A}X) - Zm_e - \sum_i B_i^e \right] \right\} \cdot c^2$$

Atomic mass

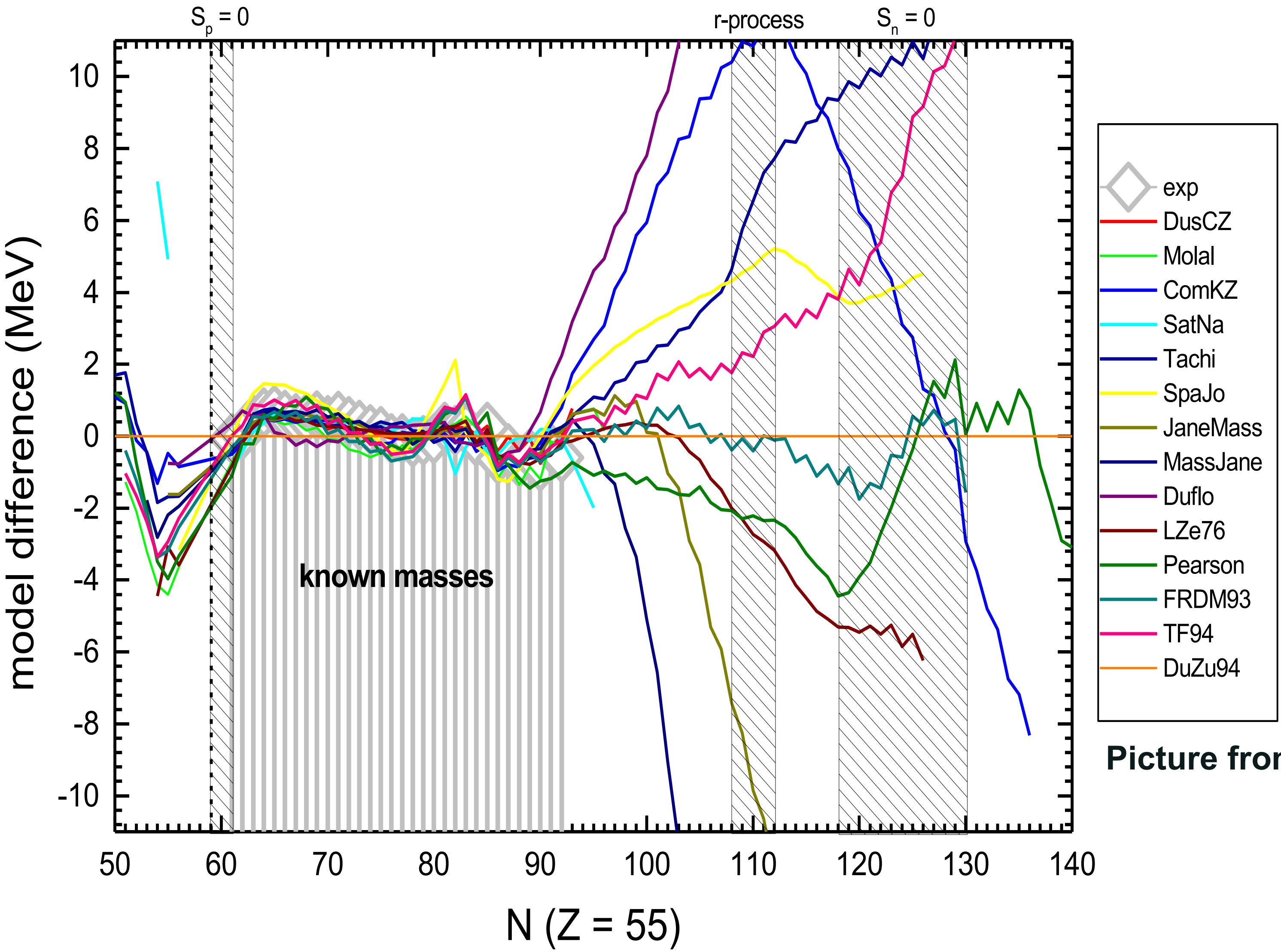
$$ME(N,Z) = m(^{A}X) - A \cdot u$$

$$\boxed{1\,\mathrm{keV} \rightarrow \frac{\delta m}{m} \approx 10^{-8}}$$

Mass excess (keV)

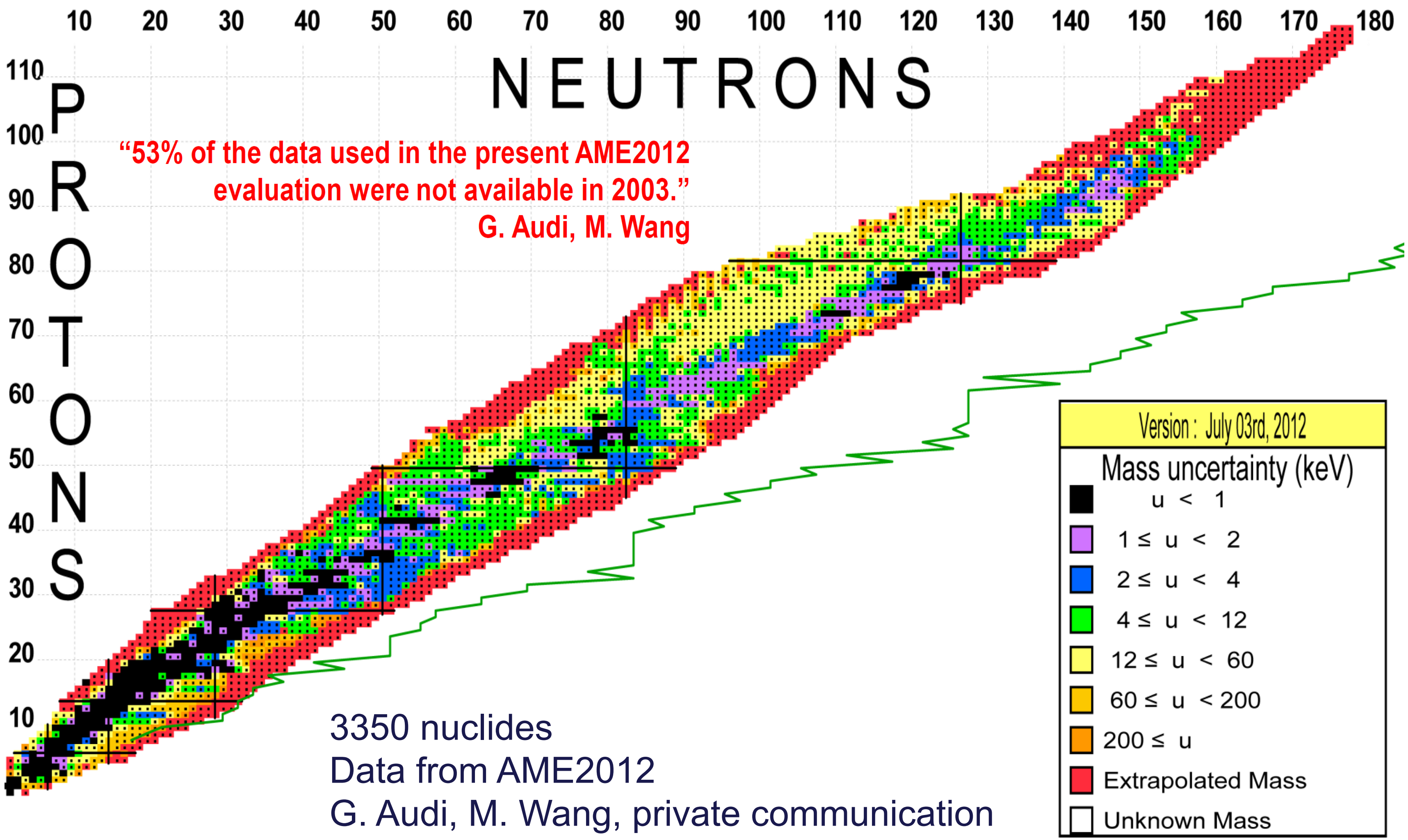
Importance of the mass

Discrepancies between the models



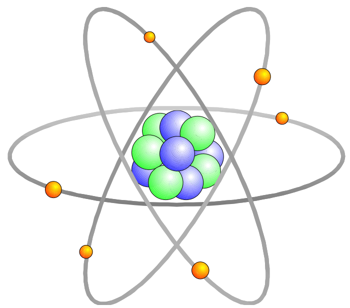
Picture from D. Lunney

Mass measurements in the last decade
The 2012 Atomic Mass Evaluation



Importance of the mass

Nucleon separation energies (S_n, S_p, S_{2n}, S_{2p})



Nuclear Structure & astrophysics

$$S_{2n} = B(N,Z) - B(N-2,Z)$$

$$S_{2p} = B(N,Z) - B(N,Z-2)$$

$$S_n = B(N,Z) - B(N-1,Z)$$

$$S_p = B(N,Z) - B(N,Z-1)$$

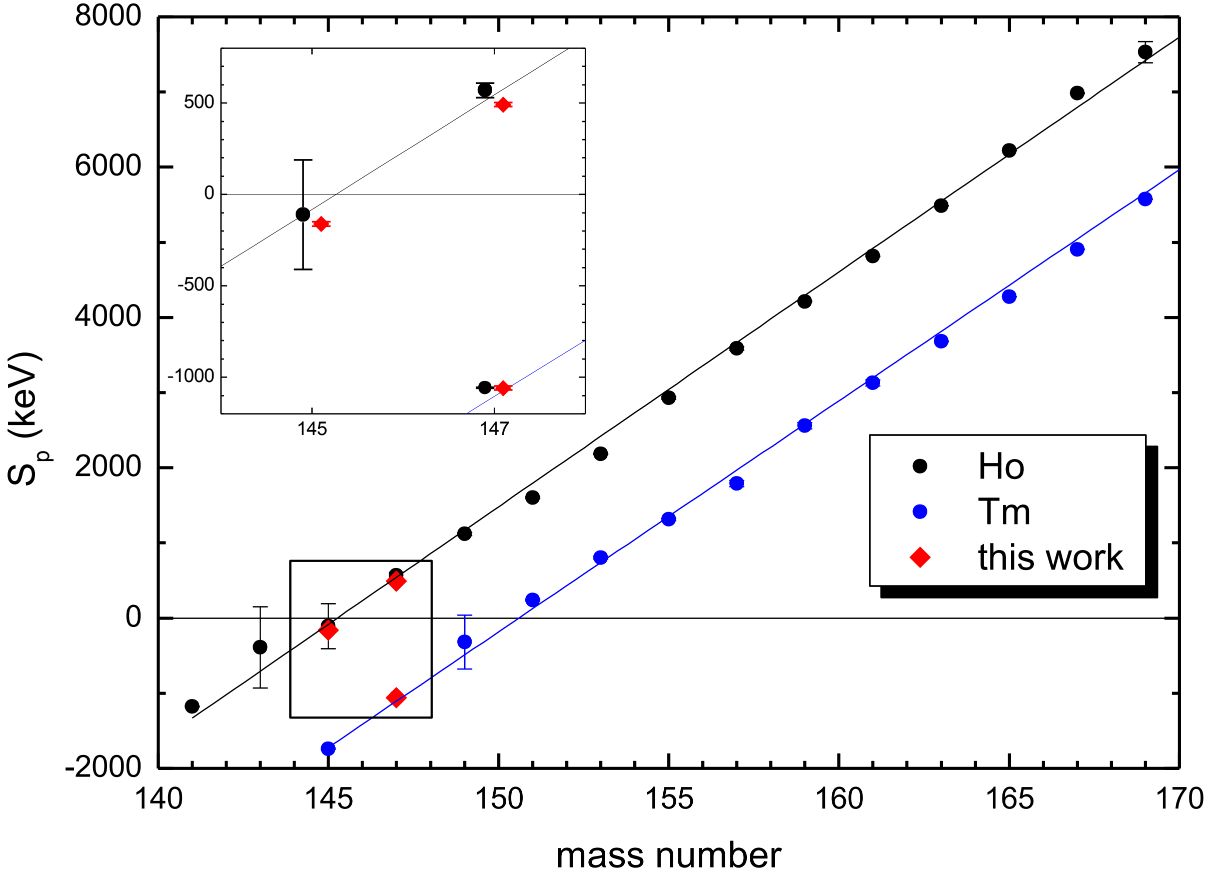
Other quantities are also important for nuclear structure, all of them obtained from nuclear binding energies

Importance of the mass

Nucleon separation energies (S_n, S_p, S_{2n}, S_{2p})

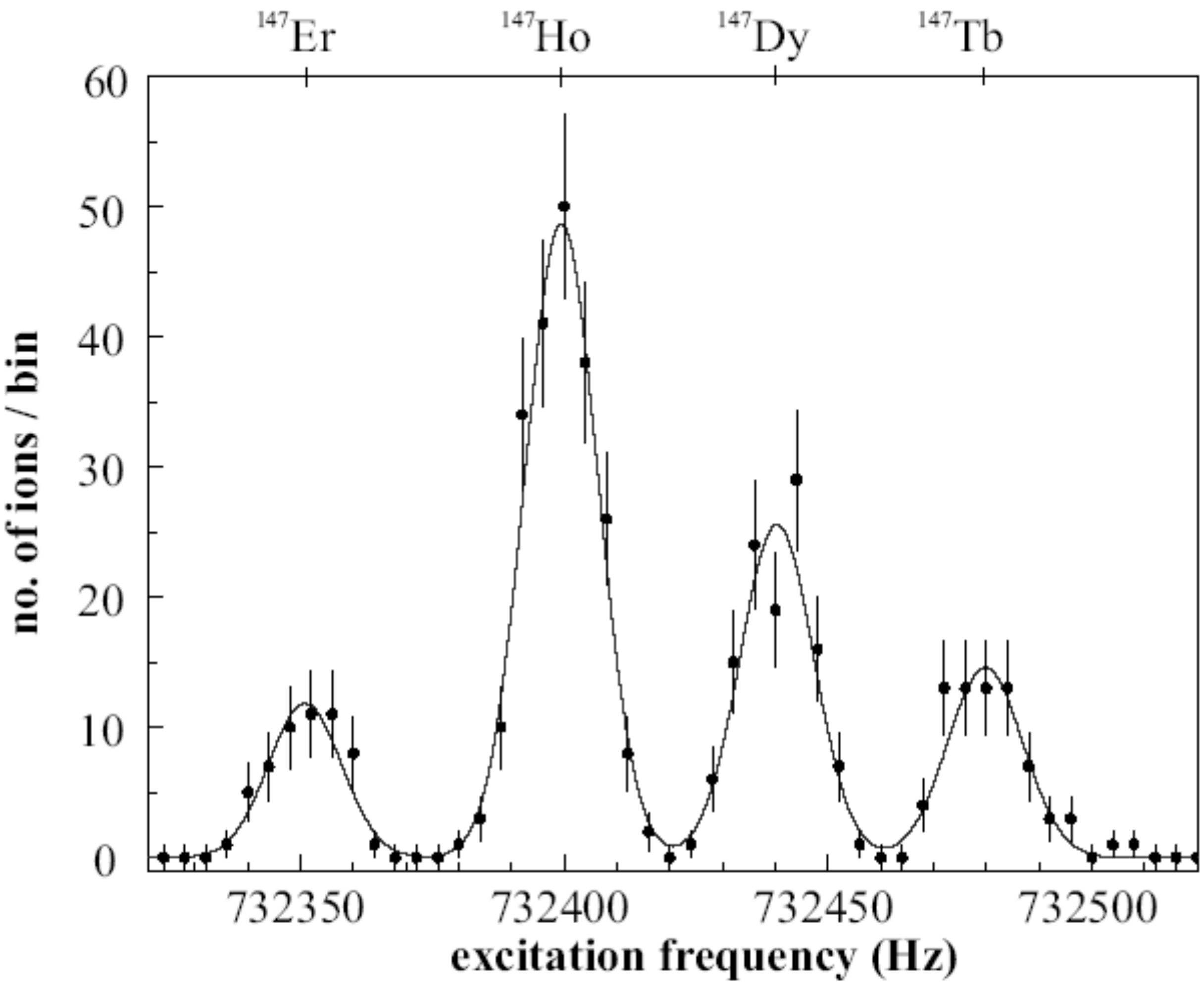
- Location of the proton-drip line

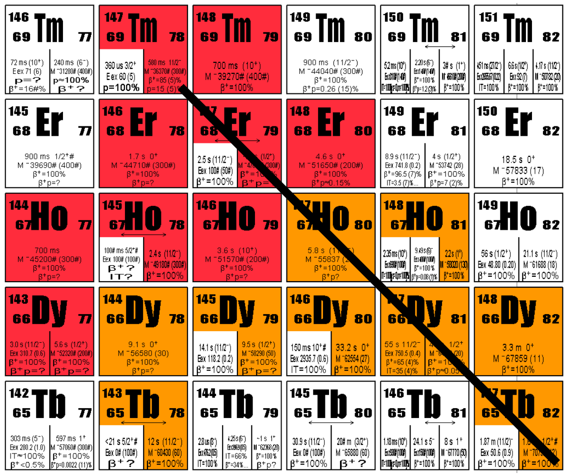
- One-proton separation energy for odd-*A* (even-*N*) isotopes of Ho (*Z*=67) and Tm (*Z*=69):



C. Rauth *et al.*, PRL 100 (2008) 012501

Importance of the mass
A remark





Importance of the mass
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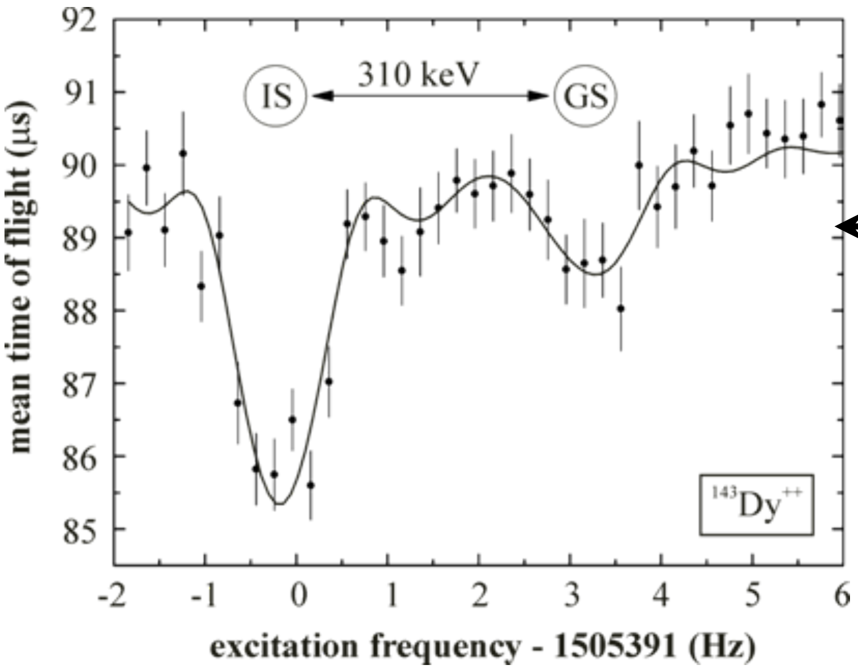
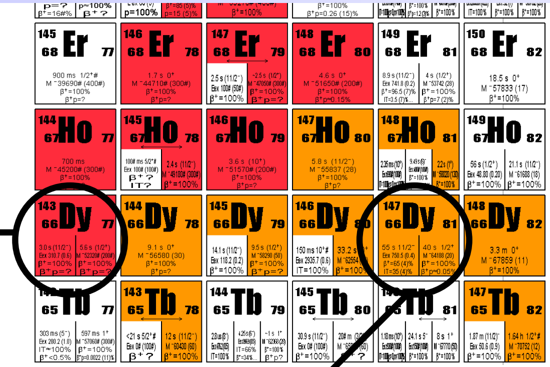
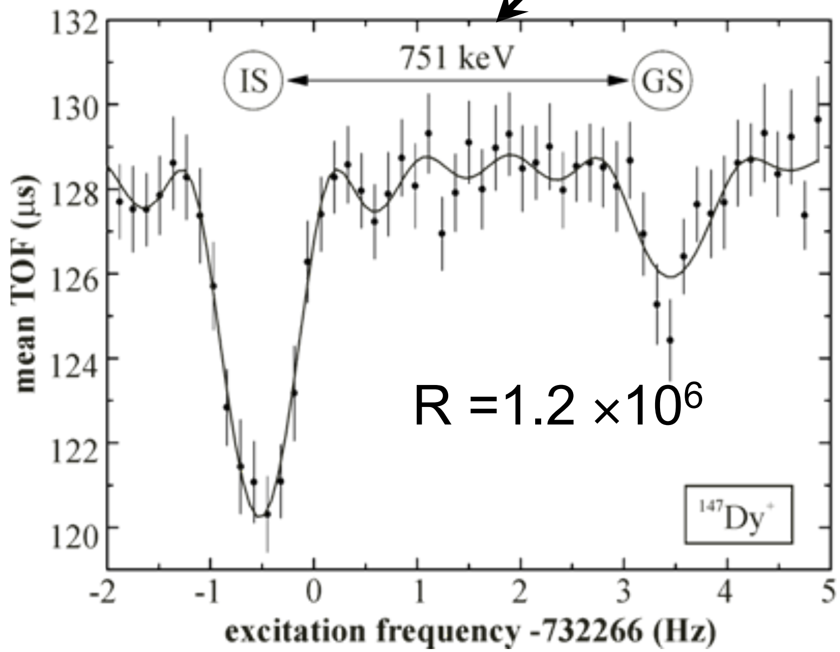






C. Rauth *et al.*, Eur. Phys. J ST 150 (2007) 329

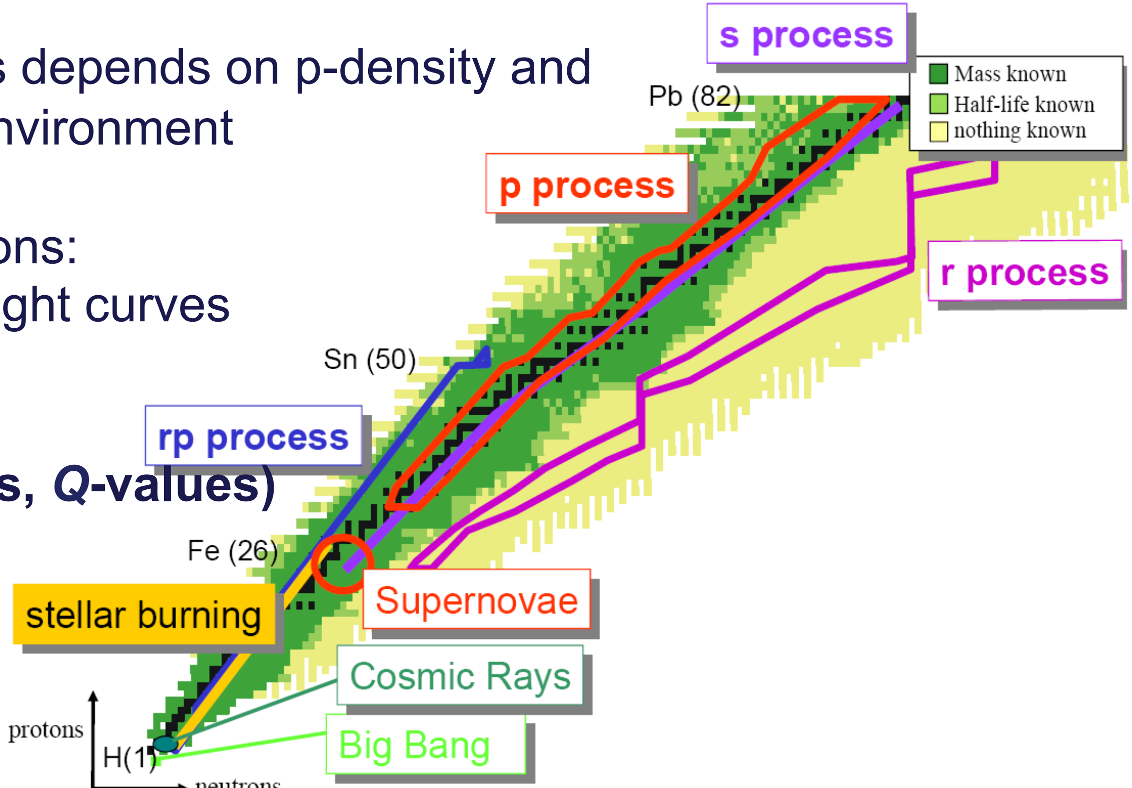
Importance of the mass
Astrophysics

- Nucleosynthesis e.g. on accreting neutron stars
- Explosive hydrogen burning (X-ray bursts)
- Steady-state burning

Evolution of the process depends on p-density and temperature in stellar environment

Astrophysical observations:
elemental abundance, light curves

Required nuclear data:
- **Masses (sep. energies, *Q*-values)**
- β decay half-lives
- Reaction rates

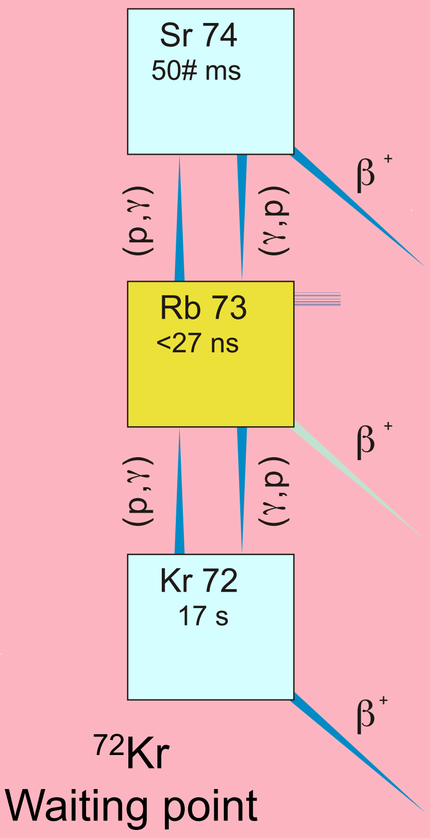


Picture from H. Schatz

Importance of the mass
Nucleon separation energies (S_n, S_p, S_{2n}, S_{2p})

$$Q_{i(p,\gamma)j} = S_j - S_i$$

ucture **& astrophysics**



$$N,Z) - B(N-2,Z)$$

$$N,Z) - B(N,Z-2)$$

$$N,Z) - B(N-1,Z)$$

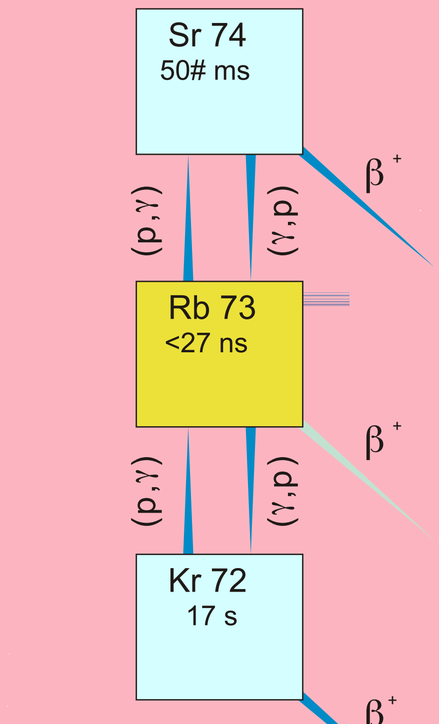
$$N,Z) - B(N,Z-1)$$

$$\lambda_{j(\gamma,p)i} = F \cdot \left(\frac{\mu kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{Q_{i(p,\gamma)j}}{kT}\right)\langle\sigma v\rangle_{i(p,\gamma)j}$$

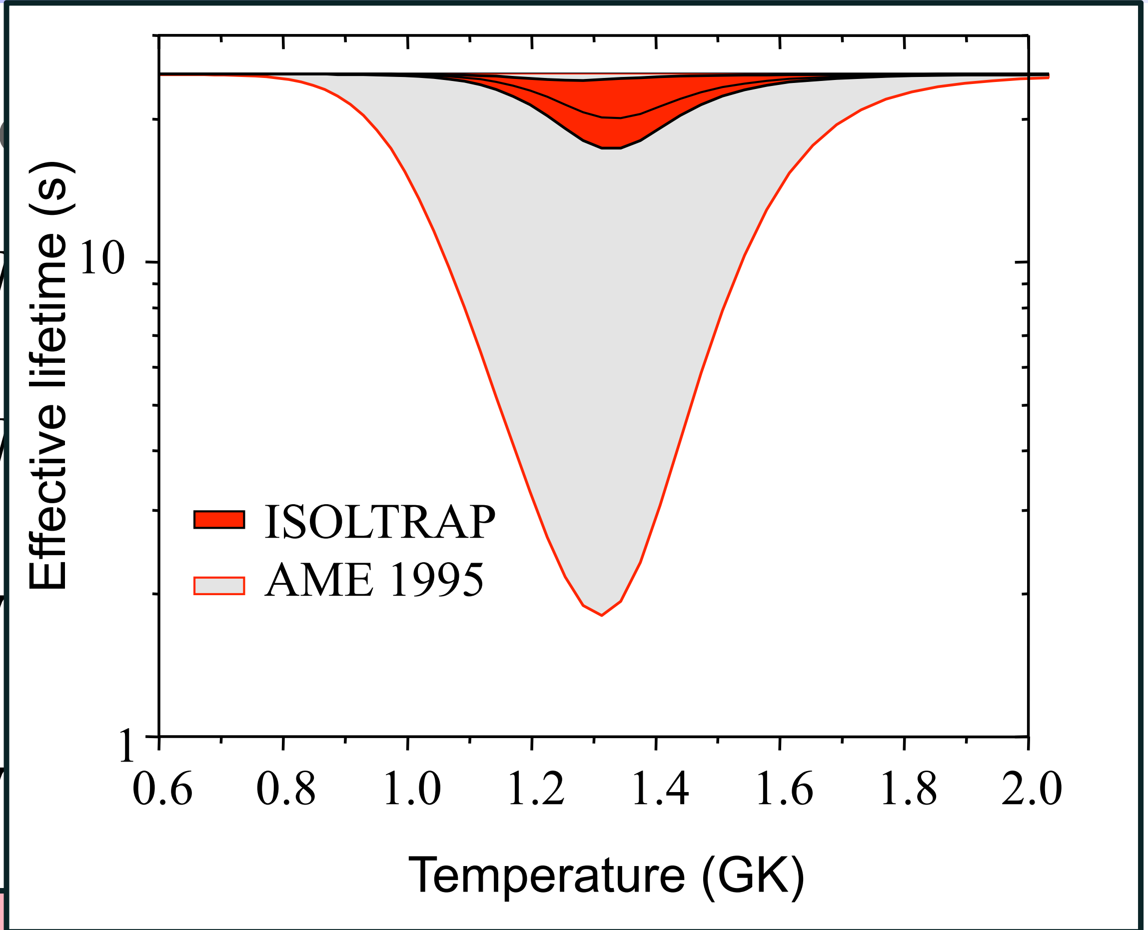
Importance of the mass

Nucleon separation energies (S_n, S_p, S_{2n}, S_{2p})

$$Q_{i(p,\gamma)j} = S_j - S_i$$



^{72}Kr
Waiting point



$$\lambda_{j(\gamma,p)i} = F \cdot \left(\frac{\mu kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{Q_{i(p,\gamma)j}}{kT}\right) \langle\sigma v\rangle_{i(p,\gamma)j}$$

PRL 93 (2004) 161104

Importance of the mass
Q-values from β-decay

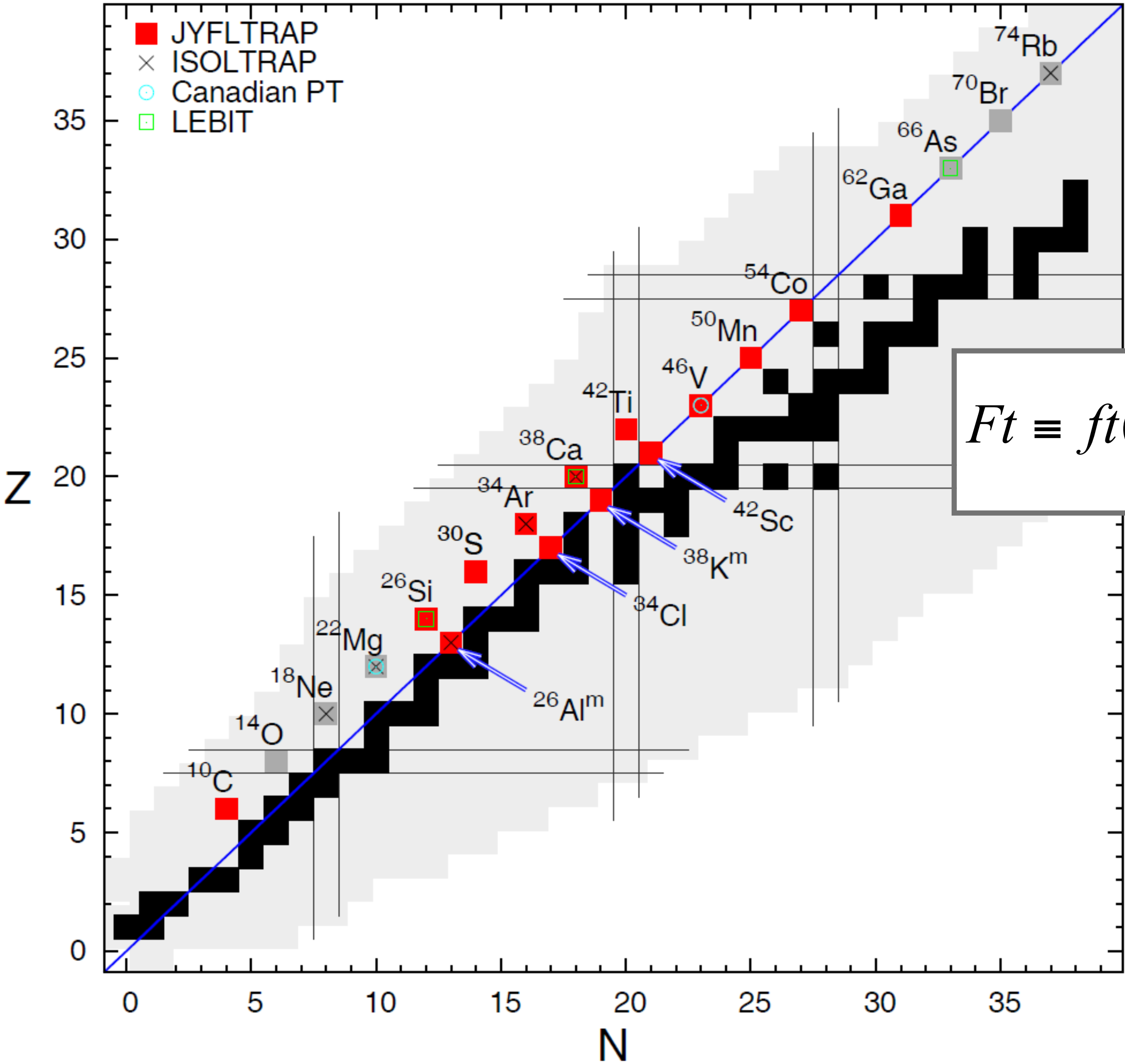
Fundamental symmetries & Neutrino-related physics

$$Q_{EC} = ME(Z,N) - ME(Z-1,N+1)$$

$$Q_{\beta^+} = ME(Z,N) - ME(Z-1,N+1) - 2m_e$$

$$Q_{\beta^-} = ME(Z,N) - ME(Z+1,N-1)$$

Importance of the mass
Q-values from β-decay



CVC hypothesis
Superallowed
β emitters
$0^+ \rightarrow 0^+$

$$Ft \equiv ft(1+\delta_R)(1-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

f *(Q^5)* statistical rate function
t *($t_{1/2}$, 1/R)* partial half-life

$$V_{ud}^2 = G_V^2 / G_\mu^2$$

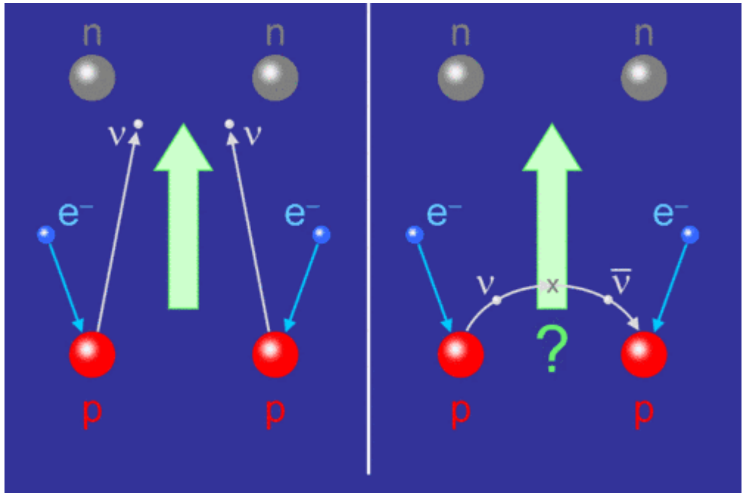
$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 1 - \Delta$$

Importance of the mass
Q-values from EC-decay

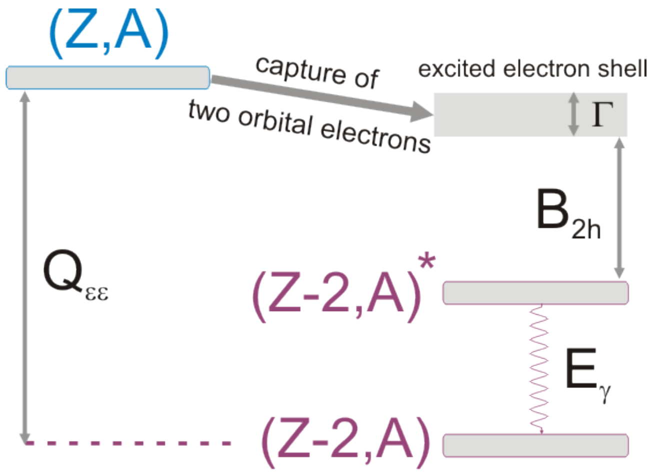
Is the neutrino a Majorana or Dirac particle?

2ν2EC ($T_{1/2}$>10^{24} y) *0ν2EC* ($T_{1/2}$>10^{30} y)

$$\frac{1}{T_{1/2}} = C \times m_\nu^2 \times |M|^2 \times |\Psi_{1e}|^2 \times |\Psi_{2e}|^2 \times \frac{\Gamma}{\left(Q - B_{2h} - E_\gamma^2\right)^2 + \frac{1}{4}\Gamma^2}$$



0ν2EC might be resonantly enhanced ($T_{1/2}$~10^{25}y)



Search for nuclides with $D=(Q_{ee}-B_{2h}-E_g) < 1$ keV

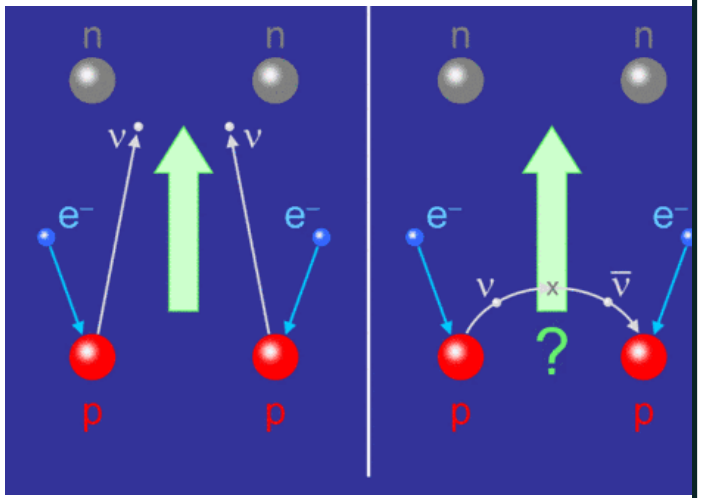
Importance of the mass
Q-values from EC-decay

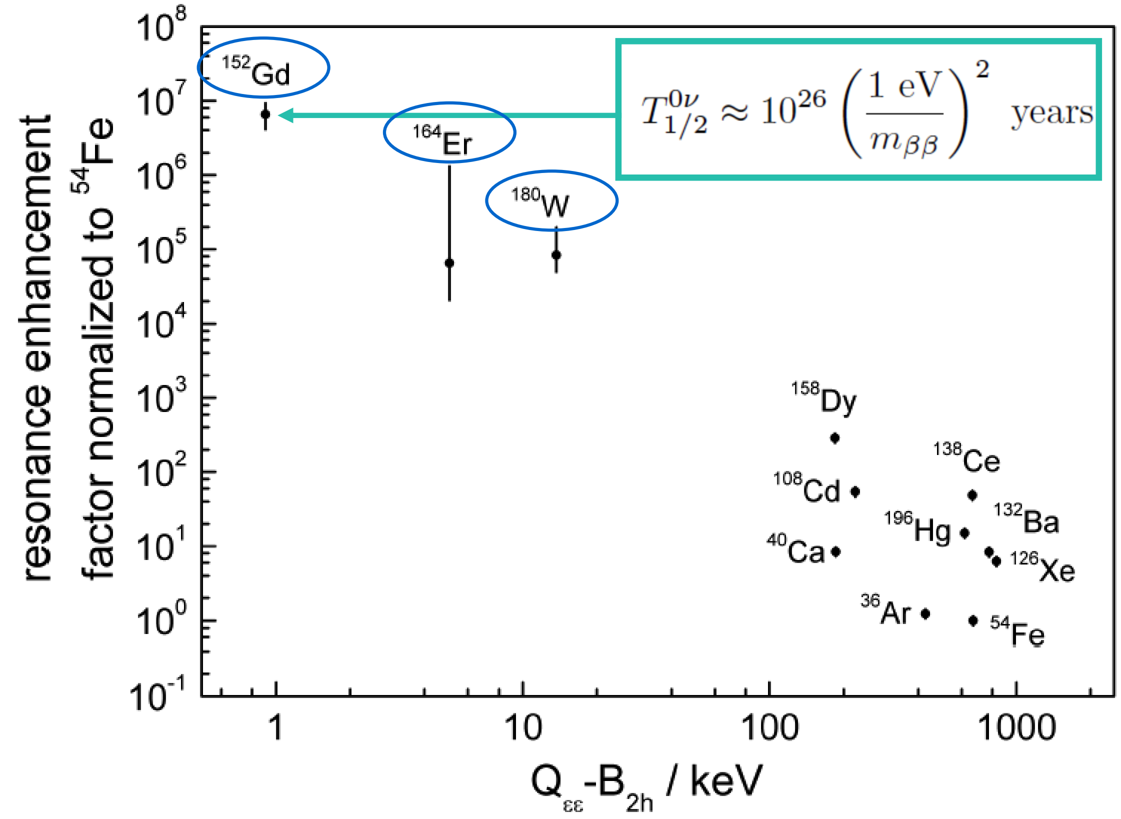
Is the neutrino a Majorana or Dirac particle?

2ν2EC **($T_{1/2}$>10^{24} y)**

0ν2EC ($T_{1/2}$>10^{30} y)

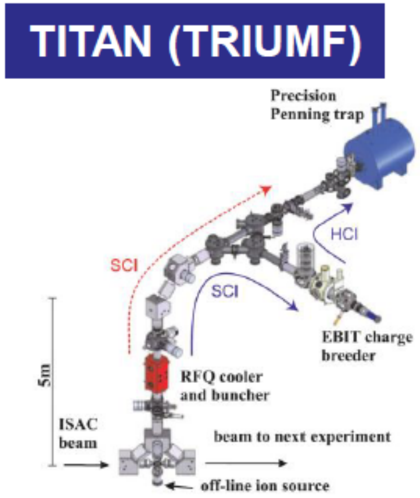
$$\frac{1}{T_{1/2}} = C \times m_\nu^2 \times |M|^2 \times |\Psi$$

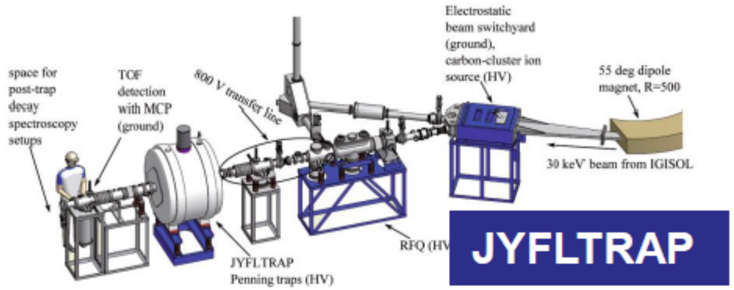


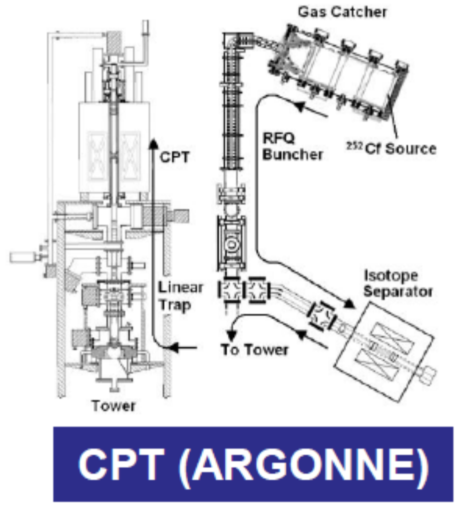


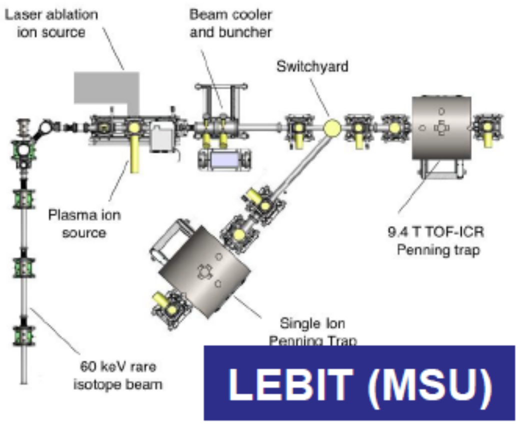
^{152}Gd: S. Eliseev *et al.*, Phys. Rev. Lett. 106 (2011) 052504

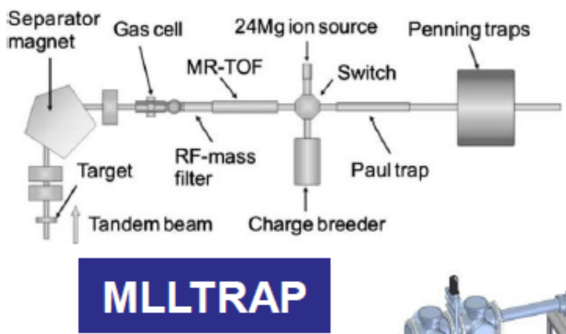
Growing  facilities

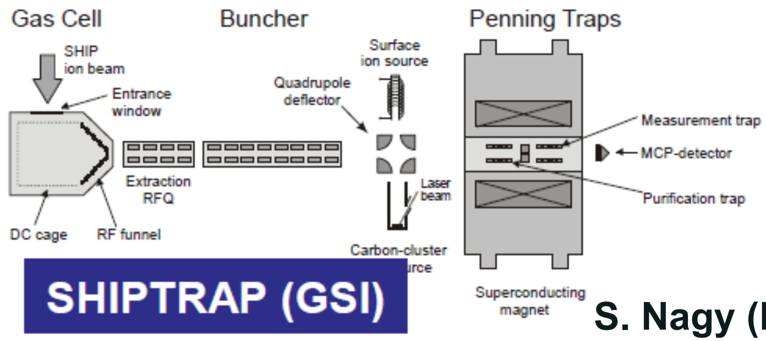


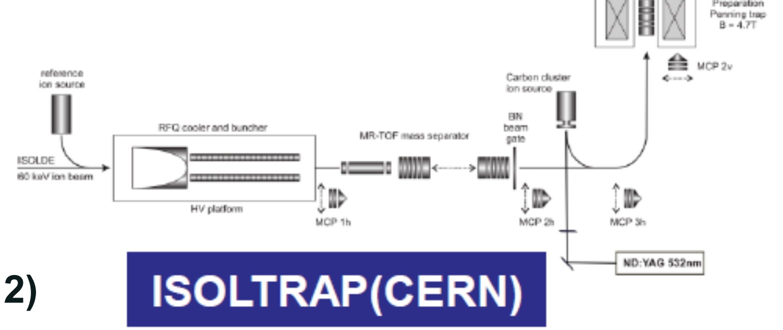






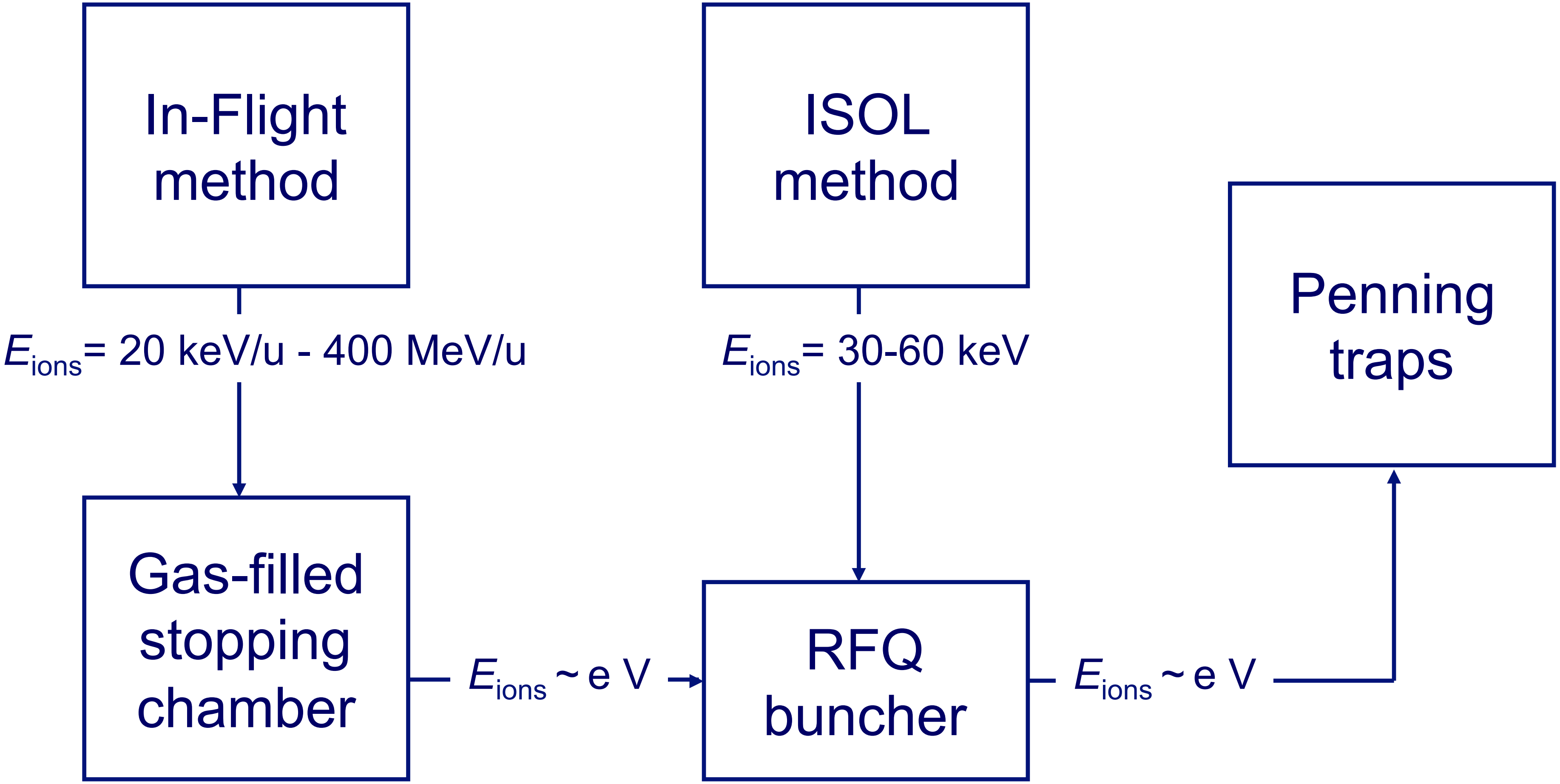






S. Nagy (EMIS2012)

Coupling Penning traps to RIB facilities

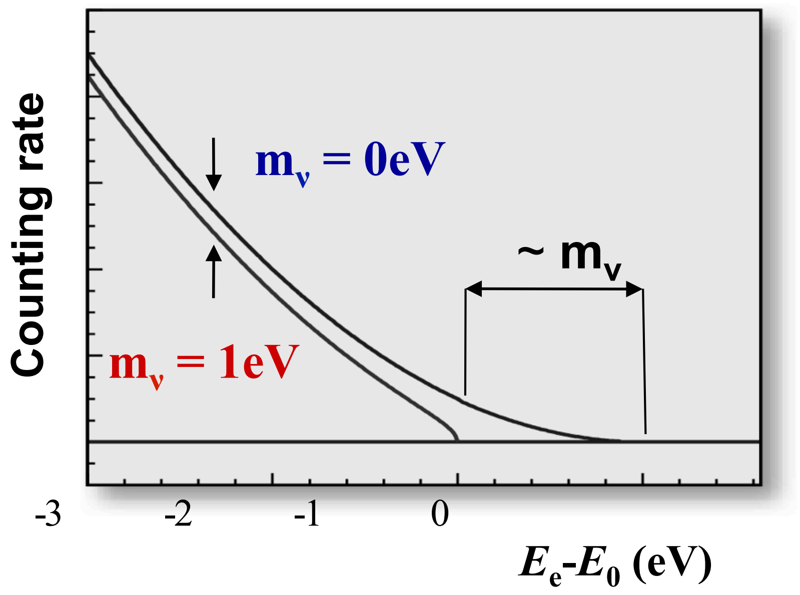


Coupling Penning traps to RIB facilities

Importance of the mass
Q-values from β-decay

What is the mass of the electron (anti)neutrino?

$$\frac{dN}{dE} = k \times F(E,Z) \times p \times E_{total} \times \left(E_0 - E_e\right)^2 \times \left[\left(E_0 - E_e\right)^2 - m_\nu^2\right]^{1/2}$$



$$F(\delta E) = \int_{-\delta E}^{0} N\left(E_\beta\right) dE \approx 2\left(\frac{\delta E}{E_0}\right)^3$$

- **The best candidates will be decaying nuclei with low *end-point energies***
- **Tritium**: $T_2 \rightarrow \left({}^3\mathbf{HeT}\right)^+ + e^- + \bar{\nu}_e$

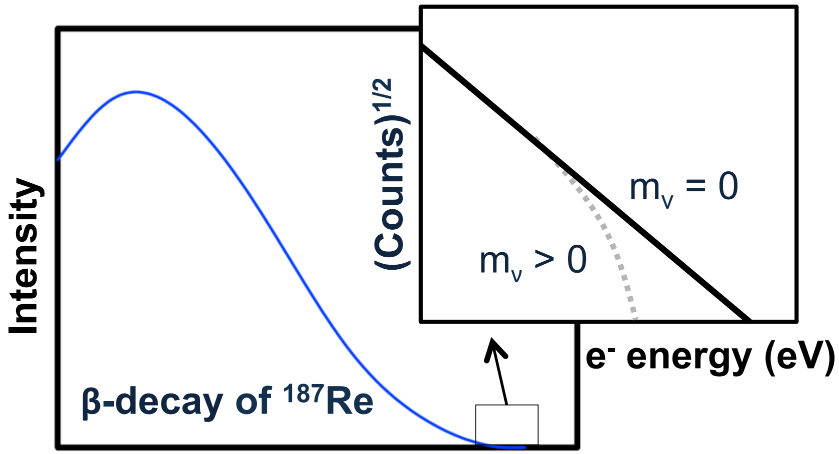
  $Q = 18.6$ **keV** $\quad T_{1/2} = 12.3$ **y**
- **^{187}Re**: ${}^{187}\mathrm{Re} \rightarrow {}^{187}\mathbf{Os} + e^- + \bar{\nu}_e$

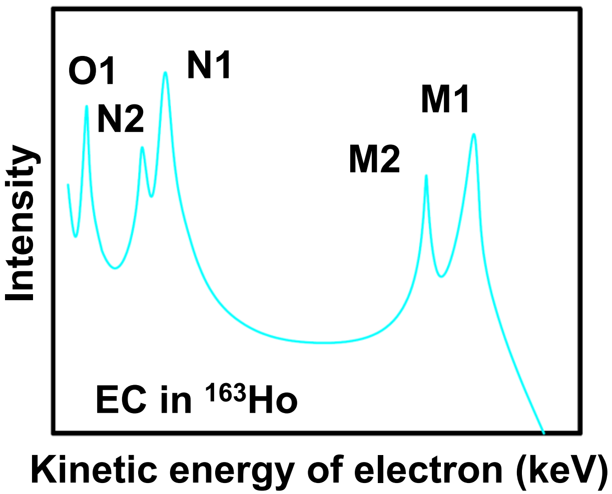
  $Q = 2.5$ **keV** $\quad T_{1/2} = 43.2 \times 10^9$ **y**

Q **has to be unambiguously determined (with δ*m*/*m* of at least 10^{-11}) from the mass difference using a Penning trap**

Importance of the mass
Q-values from β-decay and EC-decay

What is the mass of the electron (anti)neutrino?





- β-decay of ^{187}Re - The MARE project

  $^{187}Re \rightarrow {}^{187}Os + e^- + \bar{\nu}_e$

  $E_Q = 2.4653(17)$ keV **M. Sisti *et al.*, NIMA (2004)**

- EC in ^{163}Ho - The ECHo, HOLMES and NuMECS projects

  $^{163}Ho + e^- \rightarrow {}^{163}Dy + \nu_e$

  $E_Q = 2.80(5)$ keV **L. Gastaldo *et al.*, JLTP (2014)**

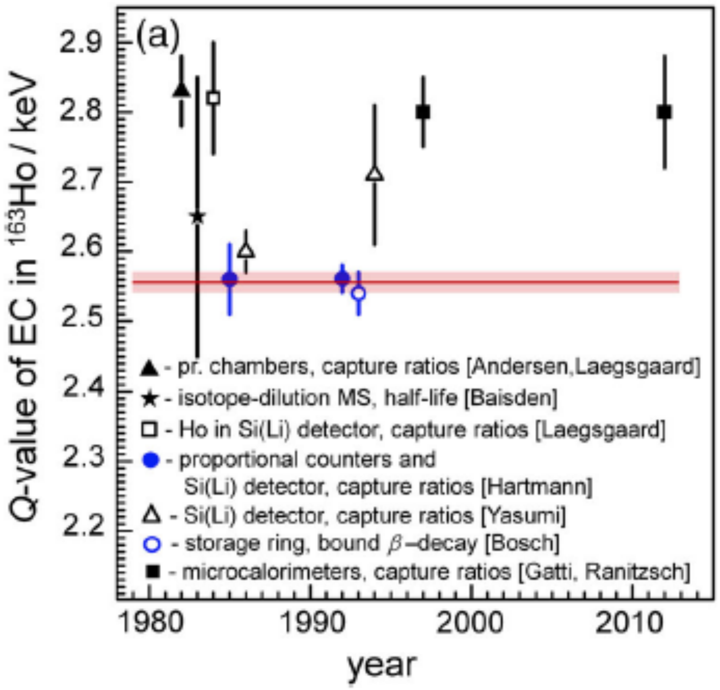
  $$\Delta m = 2833(30_{stat})(15_{sys})\ \mathrm{eV/c^2}$$

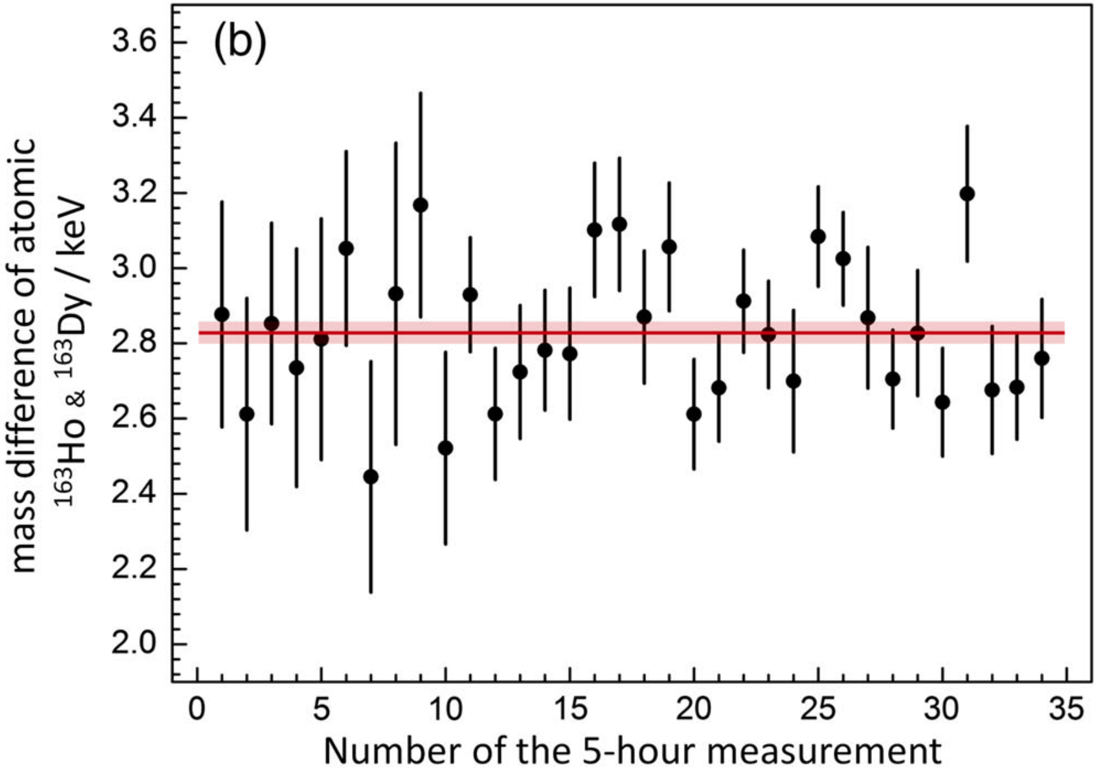
  S. Eliseev *et al.*, PRL 115, (2015) 062501

- Ultra-precise masses provide accurate *Q*-values

Recent highlights
Penning-trap *Q*-value for neutrino physics at GSI

$$\Delta m = 2833(30_{\mathbf{stat}})(15_{\mathbf{sys}})\ \mathbf{eV/c^2}$$





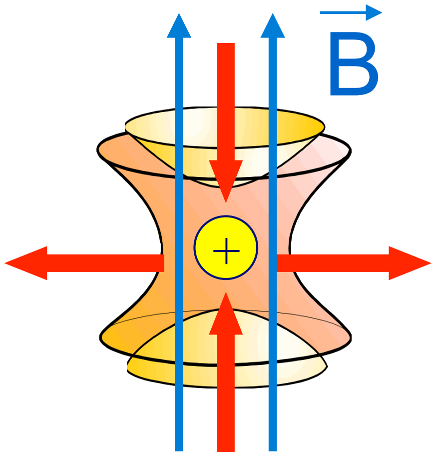
Pictures from S. Eliseev *et al.*, PRL 115, (2015) 062501

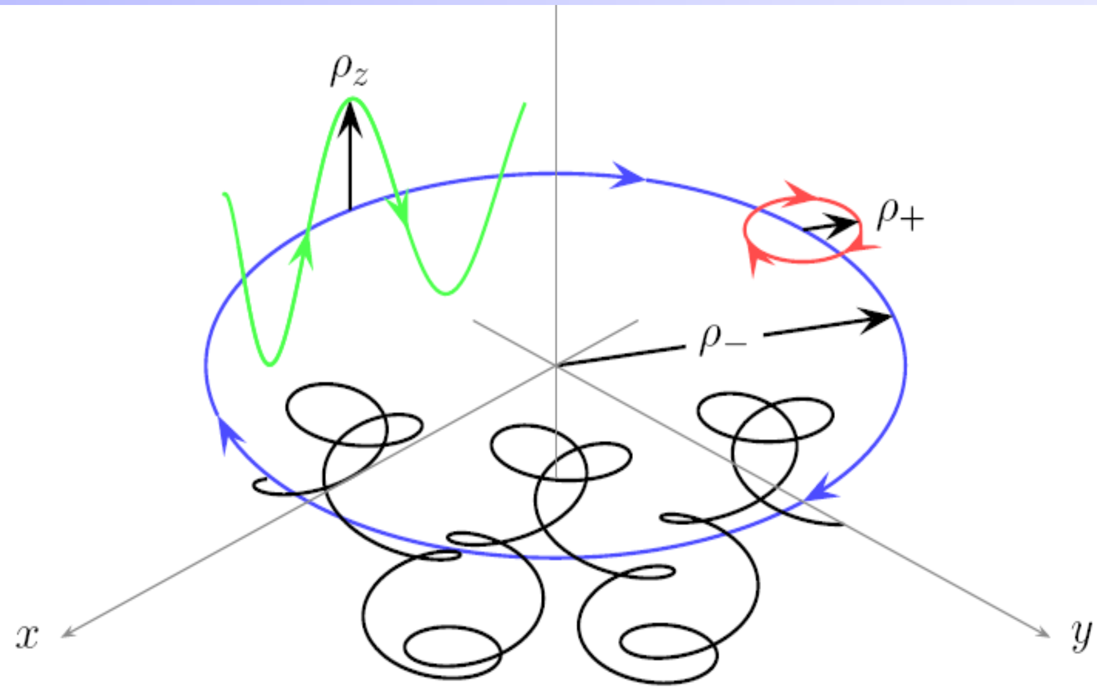
Physics goals
Mass uncertainty required

Field	Topic	Mass uncertainty
Nuclear structure physics	Shell and sub-shells, deformations, halos, S_{2p}, S_{2n}, **SHEs**	10^{-6} - 10^{-8}
Nuclear models and mass formulas	Nuclear models and mass formulas	10^{-6} - 10^{-8}
Astrophysics	(r)-process, (rp)-process, waiting point nuclides	10^{-7}
Weak interactions studies	CVC hypothesis, CKM matrix unitary	10^{-8}
Fundamental constants	Fine-structure constant	10^{-9}
Metrology	Silicon mass	$< 10^{-9}$
Neutrino physics	0νββ, 0ν2EC **Neutrino mass**	10^{-8} -10^{-9} $< 10^{-11}$
CPT Test	m_p and m_p	$< 10^{-11}$

Penning traps
Fundamentals

Magnetic + Electrostatic field





Axial motion $$\omega_z = \sqrt{\frac{q\Phi_0}{md^2}}$$

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

Reduced cyclotron motion $$\omega_+ = \frac{1}{2}\left[\omega_c + \sqrt{(\omega_c^2 - 2\omega_z^2)}\right]$$

Magnetron motion $$\omega_- = \frac{1}{2}\left[\omega_c - \sqrt{(\omega_c^2 - 2\omega_z^2)}\right]$$

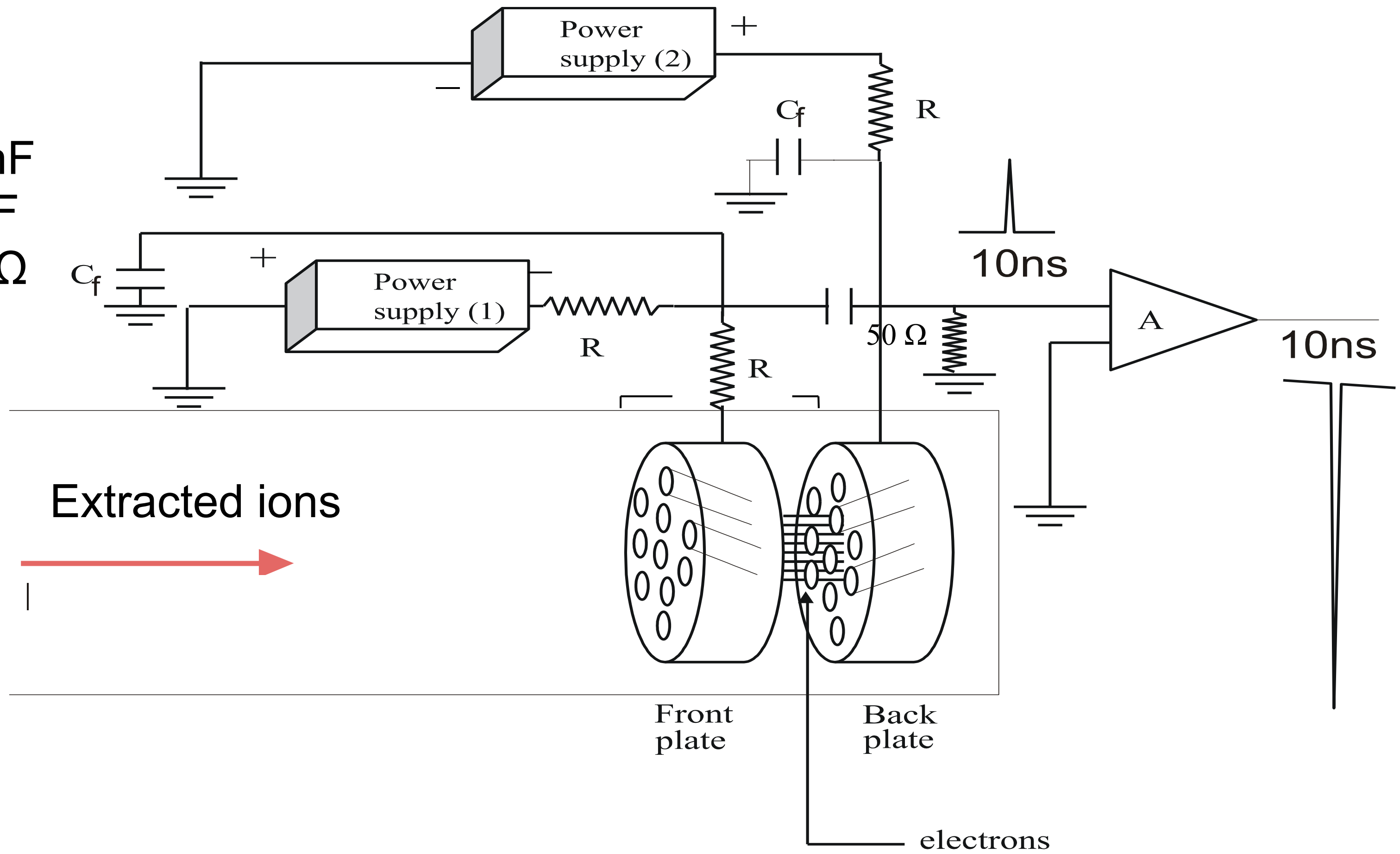
$$\omega_c = \omega_+ + \omega_-$$

$$\omega_+ > \omega_z > \omega_-$$

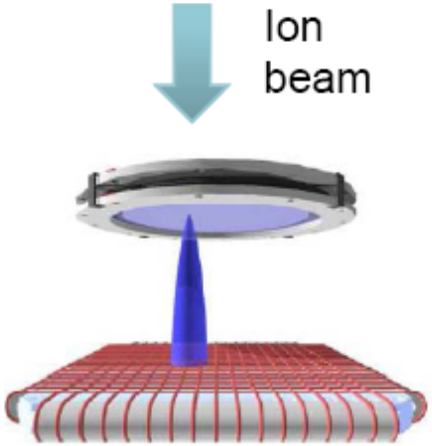
$$\omega_+^2 + \omega_z^2 + \omega_-^2 = \omega_c^2$$

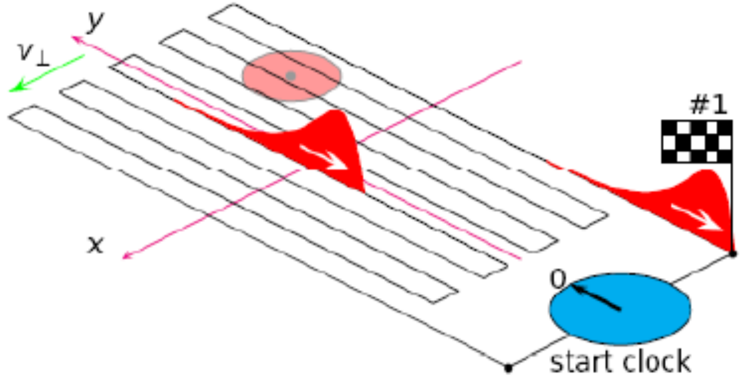
Penning traps
Detection

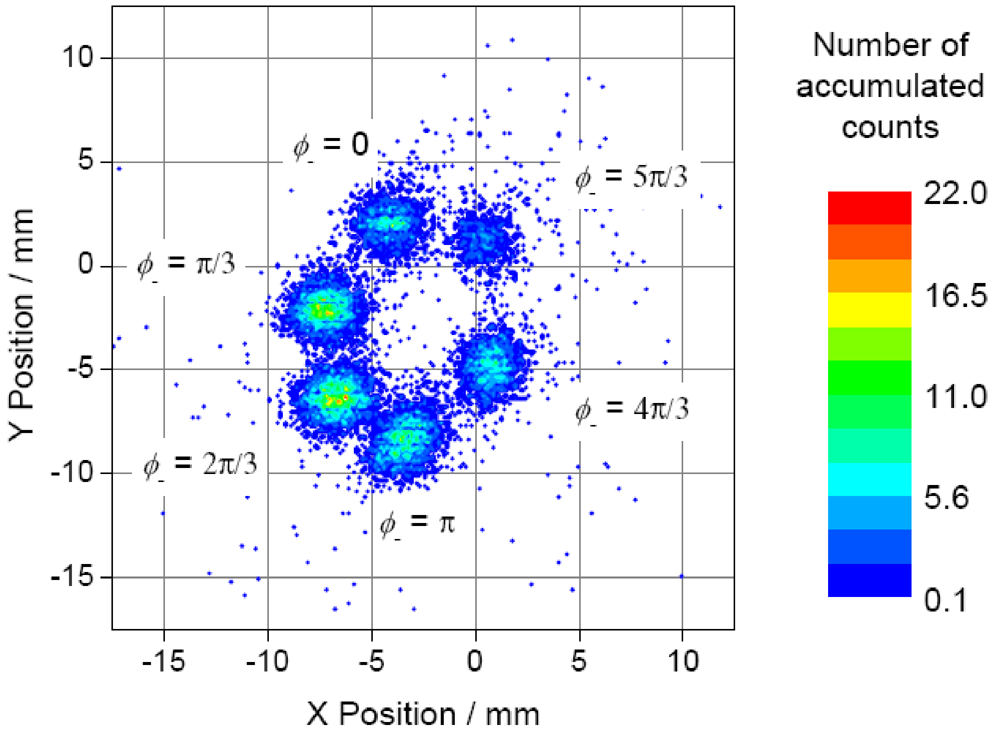
C_f = 10 nF
C = 1 nF
R = 1 MΩ



Penning traps
Detection

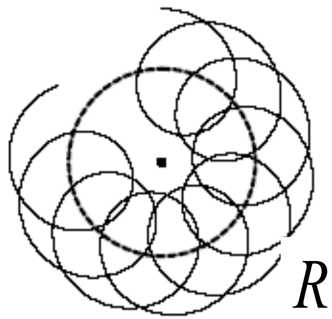




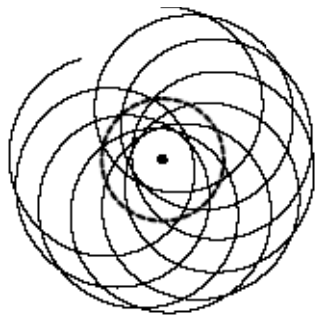


G. Eitel *et al.*, Nucl. Instrum. Methods A, 606, (2009) 475

$R_+ < R_-$

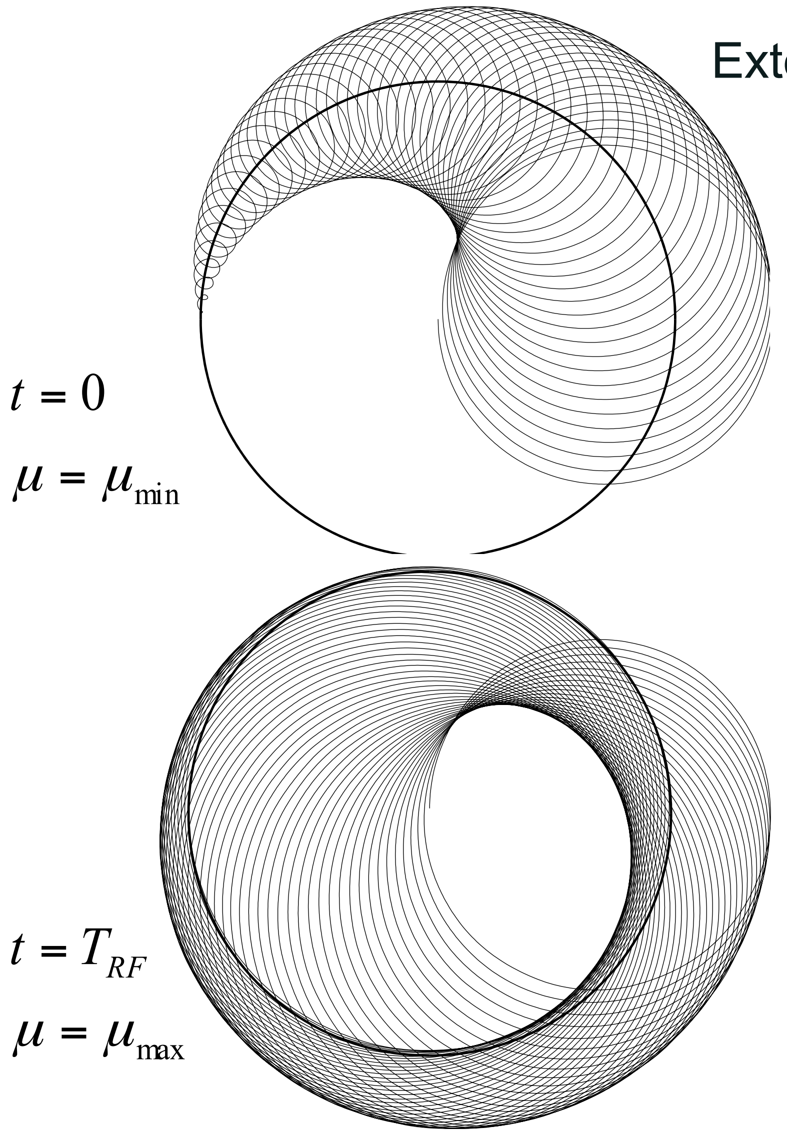


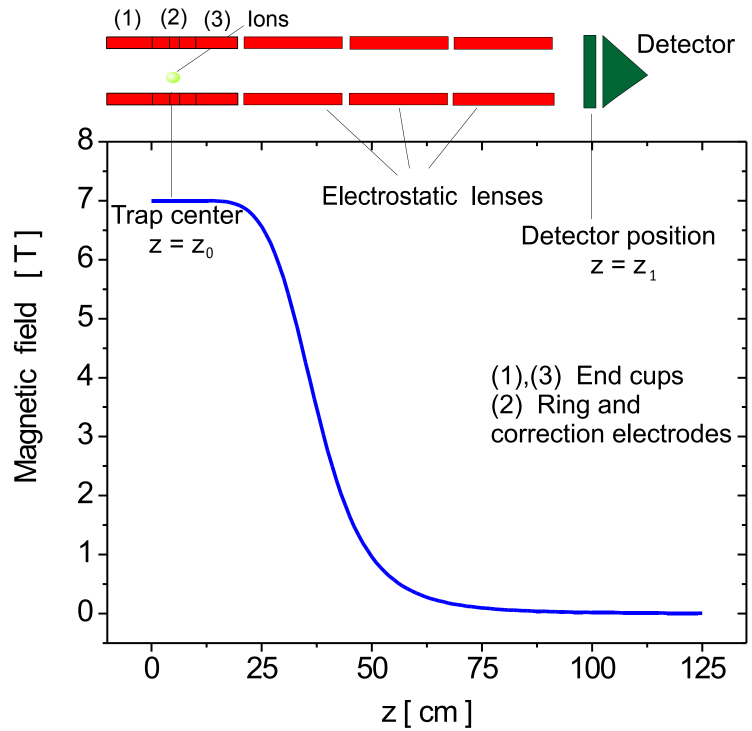
$R_+ > R_-$



Penning-trap techniques
Time-of-Flight Ion Cyclotron Resonance (TOF-ICR)

External RF quadrupole field with $\omega_{RF} = \omega_c \, (= \omega_+ + \omega_-)$



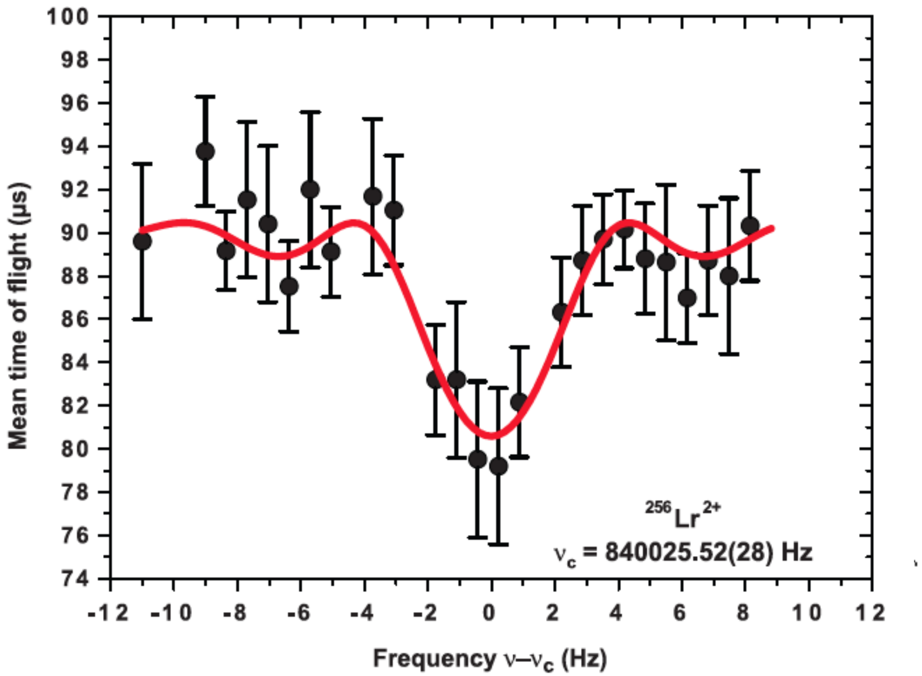


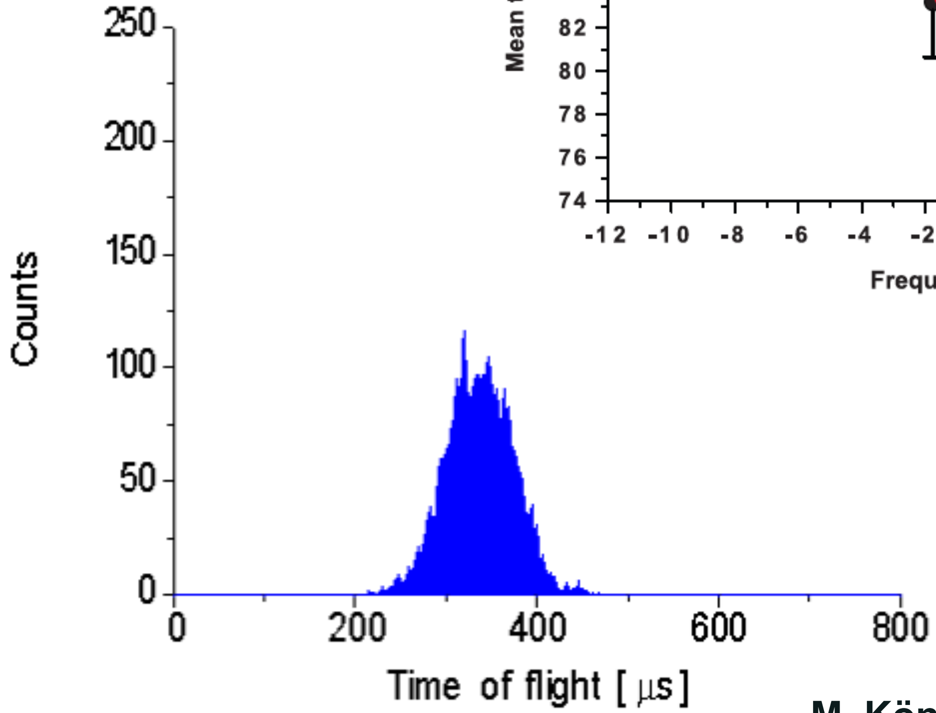
$$F_z = \mu \frac{\partial B}{\partial z}$$

$$TOF_{\min} \Leftrightarrow \mu_{\max} \Leftrightarrow \omega_{RF} = \omega_c$$

G. Gräff *et al.*, Z. Phys. A 297 (1980) 35

Time-of-Flight Ion Cyclotron Resonance (TOF-ICR)

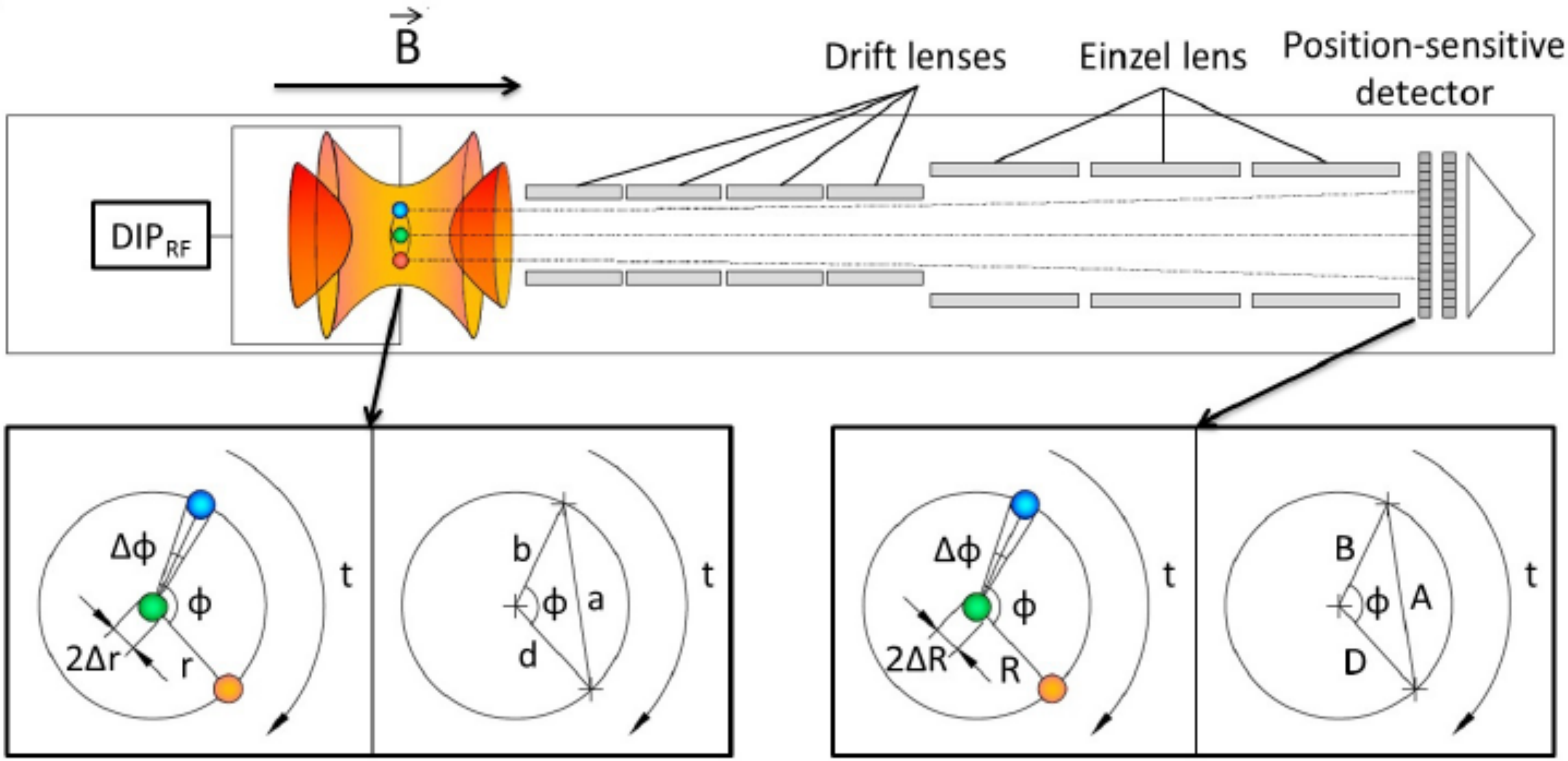




- Ion beam energy: ~ 1 eV
- Mass Resolving Power: 1×10^6
- Measurement Uncertainty: 10^{-8}-10^{-9}
- Sensitivity: ~ 40 ions
- Minimum half-life: 8 ms

M. König *et al.*, Int. J. Mass Spectrom. 142 (1995) 95

Penning-trap techniques
Phase-Imaging Ion Cyclotron Resonance (PI-ICR)



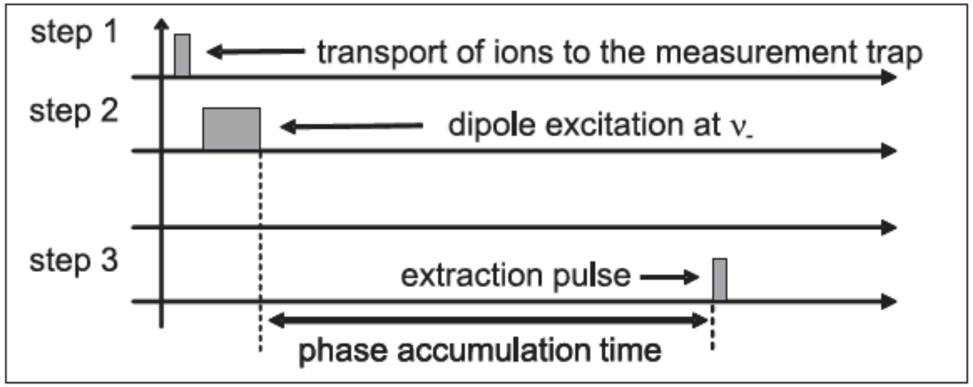
- Ion beam energy: ~ 1 eV
- Mass Resolving Power: 1×10^{7}
- Measurement Uncertainty: 10^{-9}-10^{-10}

- Sensitivity: ~ 10-20 ions
- Minimum half-life: ~ 1 ms

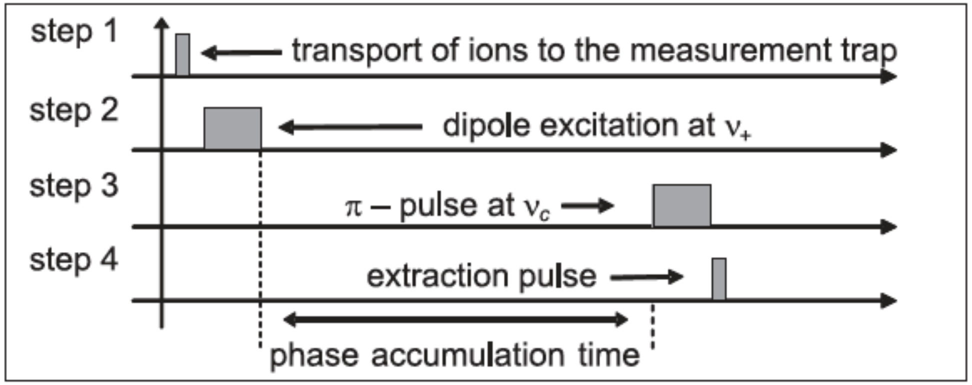
S. Eliseev *et al.*, PRL 110, (2013) 082501

Phase-Imaging Ion Cyclotron Resonance (PI-ICR)

magnetron frequency



modified cyclotron frequency



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

$$\boxed{\delta\nu = \frac{\delta k}{2\pi t\sqrt{1-k^2}},}$$

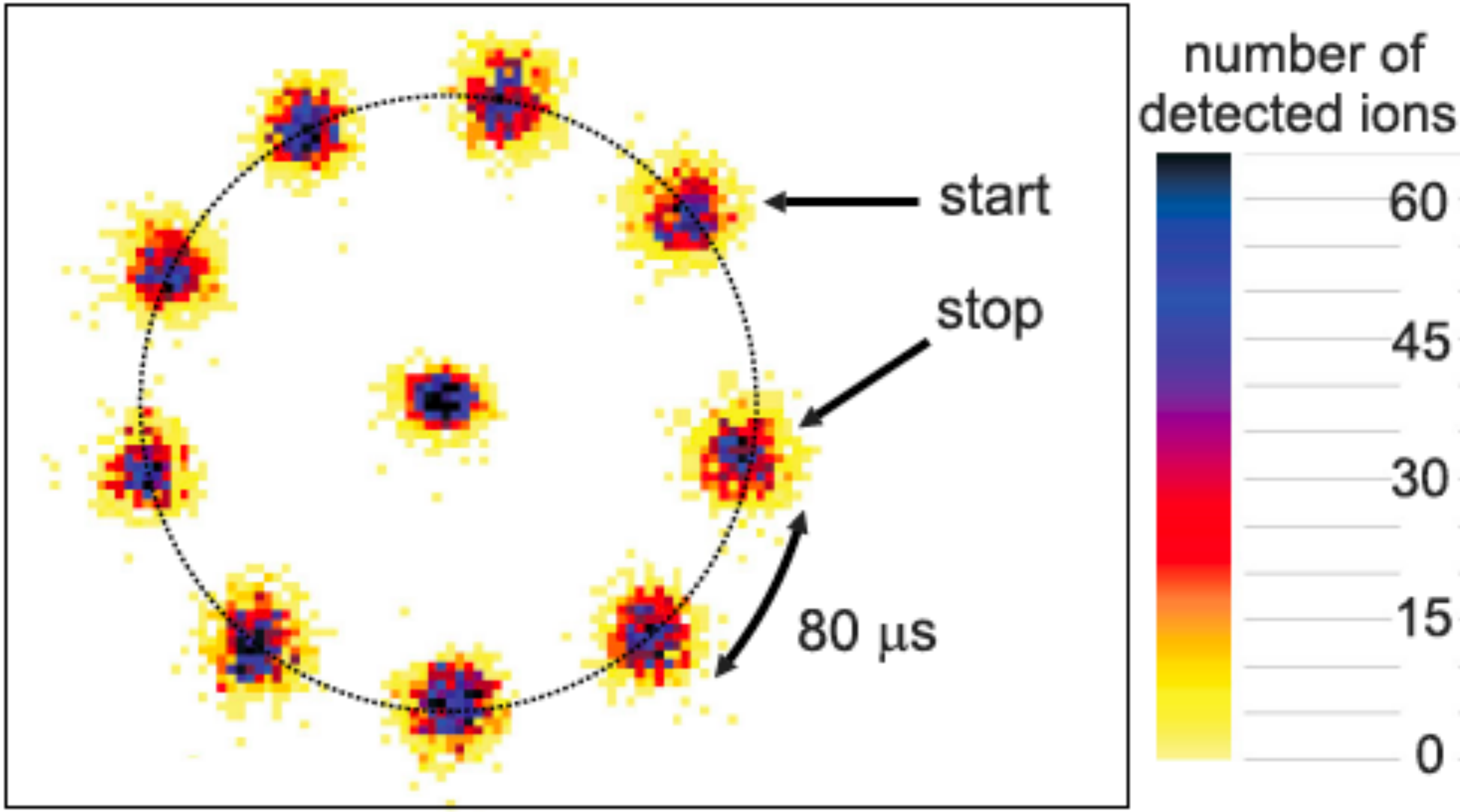
$$\boxed{\frac{\nu_c}{\Delta\nu_c} \approx \frac{\nu_+}{\Delta\nu_+} = \frac{\phi + 2\pi n}{\Delta\phi} = \frac{\pi\nu_+ t R_+}{\Delta R_+}.}$$

$$\delta\nu_c \approx \frac{1}{\pi t\sqrt{N}} \times \frac{\Delta R}{R}$$

S. Eliseev *et al.*, PRL 110, (2013) 082501

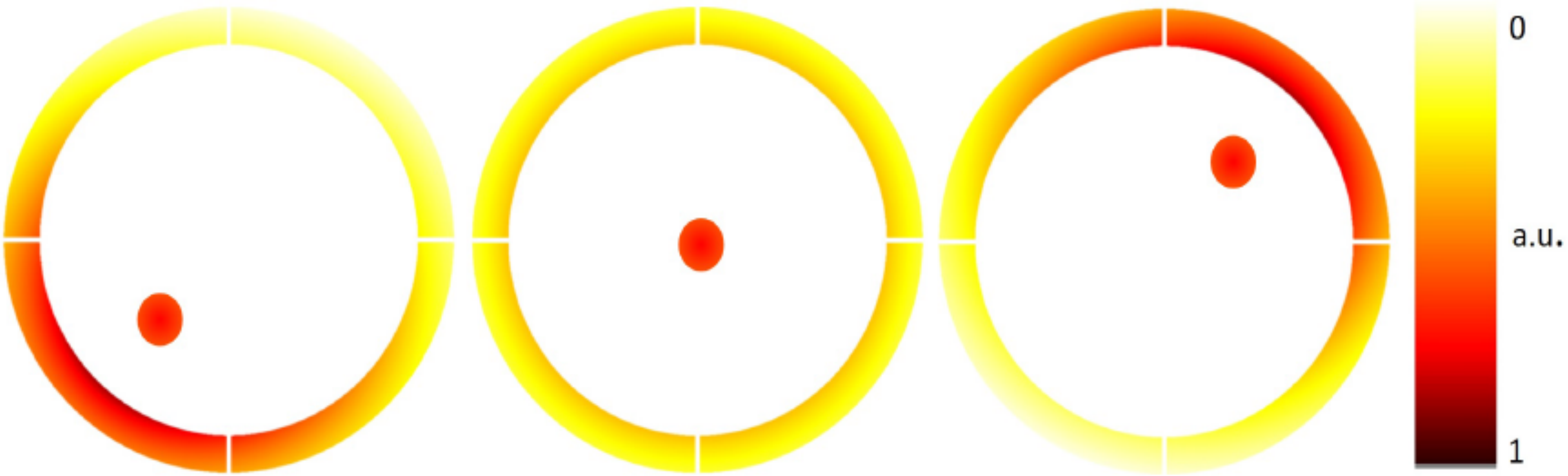
Mass measurements in nuclear physics

Mass measurements techniques: PI-ICR



S. Eliseev *et al.*, PRL 110, (2013) 082501

Induced-image current detection

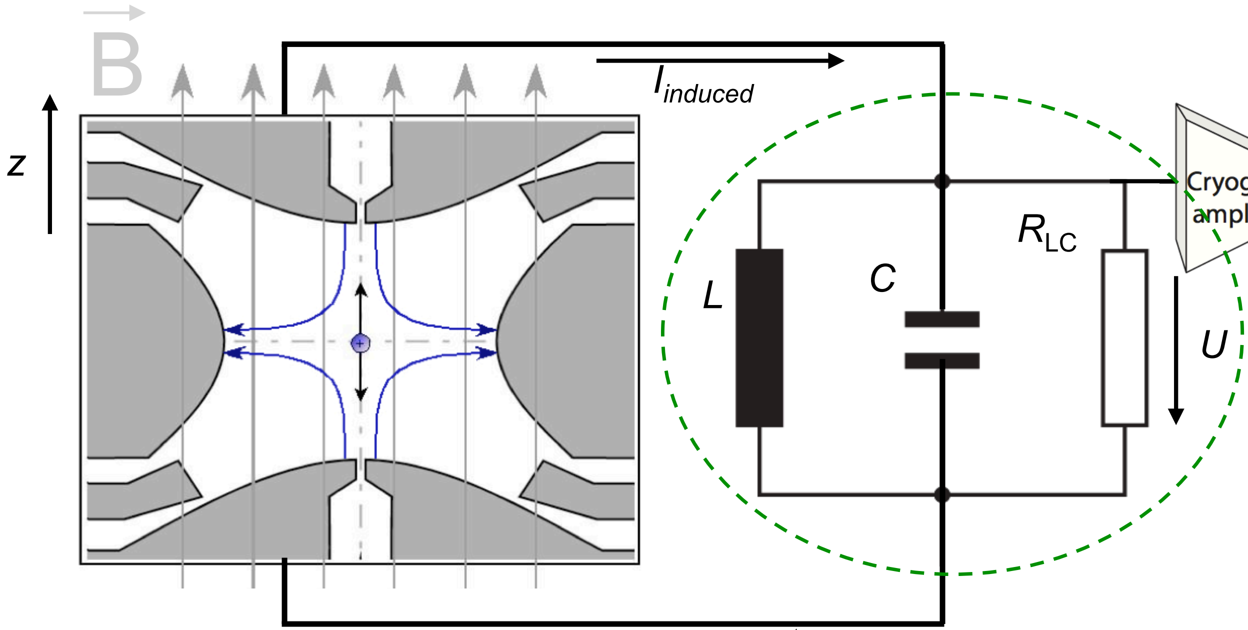


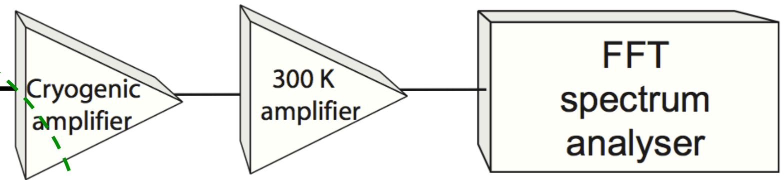
$$Q_{\rm i}(x) = -q\frac{\Delta\psi(x)}{\Delta U}$$

$$Q_{\rm i}(x) = -q\frac{x}{d}$$

$$i = \frac{dQ_{\rm i}(x,t)}{dt} = -\frac{q}{d}\frac{dx}{dt} = 2\pi q\frac{x(t)\nu}{d}$$

Penning-trap techniques
Induced-image current detection



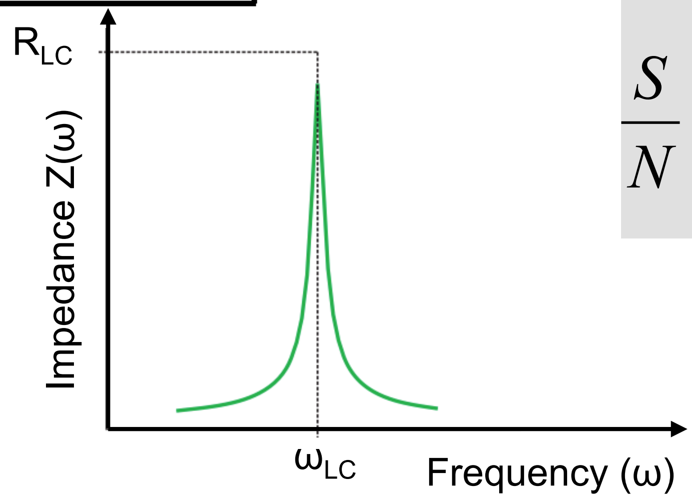


Alternative:
use a DC SQUID at 4 K

$$I_{induced} \propto q \cdot \frac{\nu_z}{z_0} \cdot z$$

$$\frac{S}{N} \propto q \cdot \frac{z}{z_0} \cdot \sqrt{\frac{\nu_z}{\Delta\nu}} \cdot \sqrt{\frac{Q}{TC}}$$

This technique was originally developed mainly at:
- -Univ. of Harvard ($\bar{p}$,p)
- -Univ. of Washington (low *m/q*) (now at MPIK in Heidelberg)
- -MIT (*m/q* up to ~50) (now at Florida State Univ.)
- -University of Mainz (now also at MPIK)



$$Z = \frac{Q}{2\pi\nu C}$$

THE TRAPSENSOR LABORATORY IN GRANADA

Laboratorios
Singulares
UGR

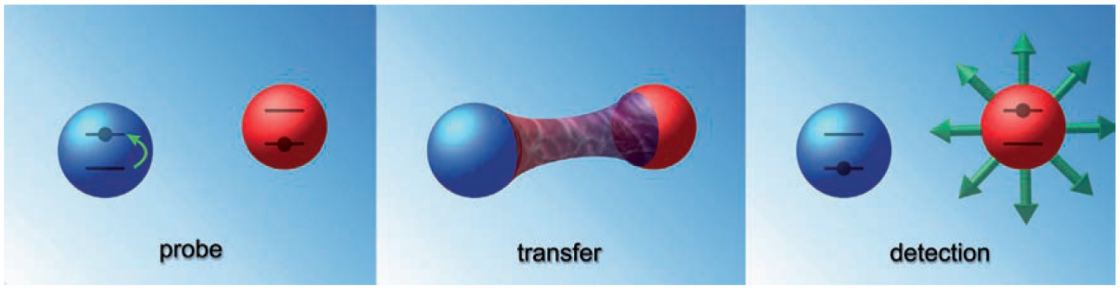
Physics Motivation
Precision sensing and metrology with a single ion

- **Two techniques in the framework of quantum-optics experiments**

→ Ions stored in the same trap

- Quantum-logic spectroscopy (Same potential well)

P. O. Schmidt *et al.,* Science 309 (2005) 749-752 (Wineland's group)

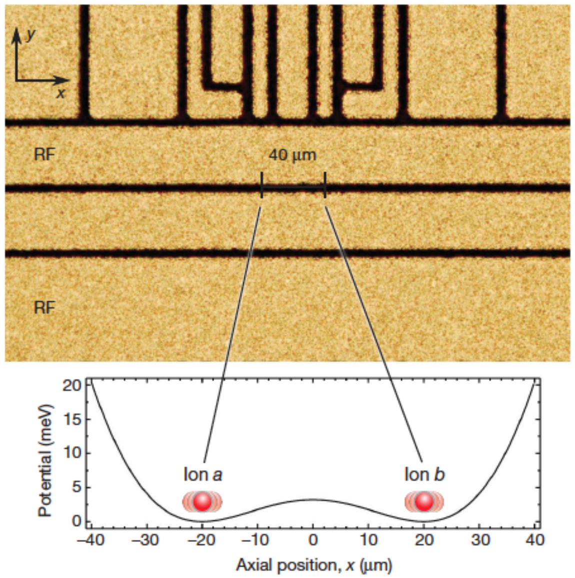


Picture from P.O. Schmidt *et al.*, Special Issue / PTB-Mitteilungen 119 (2009), No. 2

- Extension to molecular ions

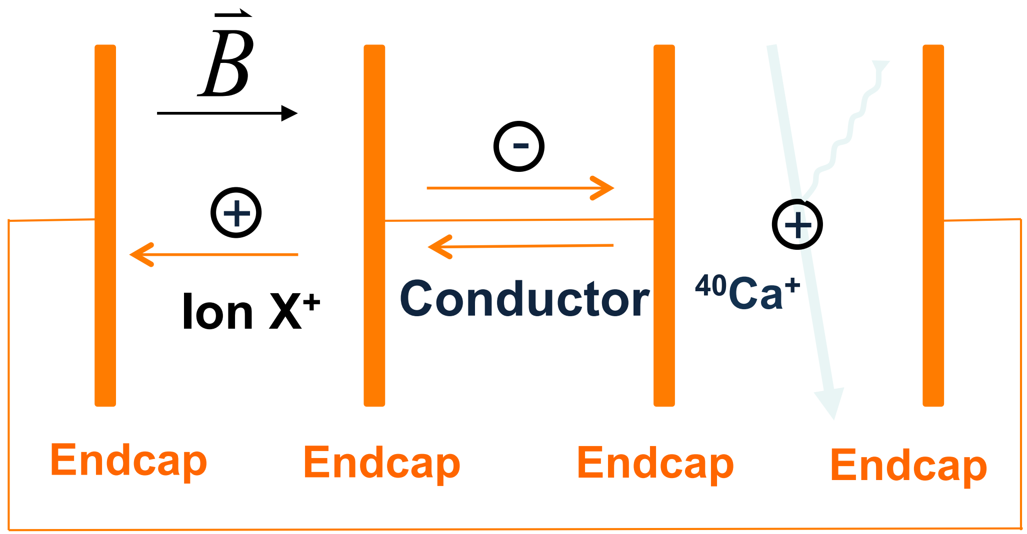
F. Wolf *et al.*, Nature 530 (2016) 457 (Schmidt 's group)

- Coupled quantized mechanical oscillators (Different potential well)



K.E. Brown *et al.*, Nature 471 (2016) 196-199 (Wineland 's group)

The QS technique
The principle of the stored ion calorimeter



D. J. Heinzen & D. J. Wineland, Phys. Rev. A 42(5) (1990) 2977-2994

1. **COOLING**

   Conductor ON

2. **PROBING THE ION X^+**

   Conductor OFF

3. **ION-ION INTERACTION**

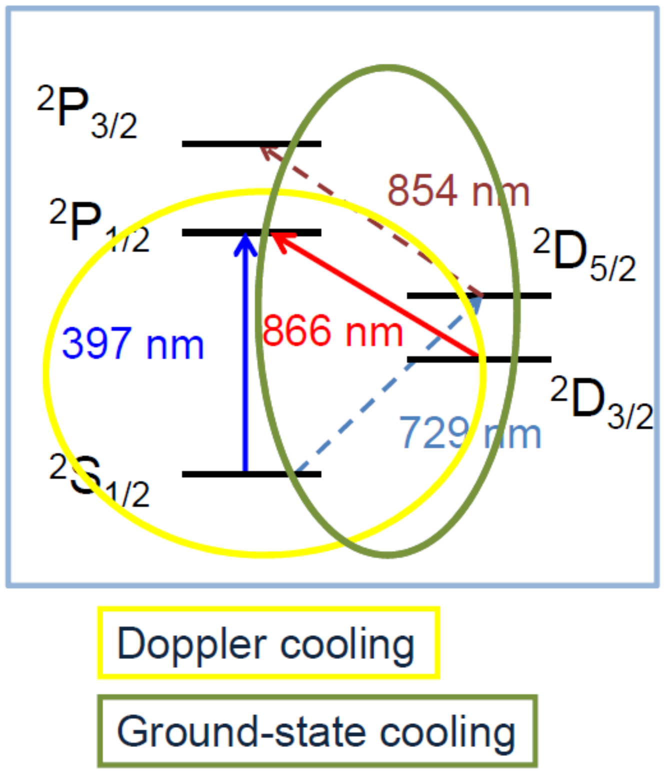
   Conductor ON/ Lasers OFF

4. **DETECTION**

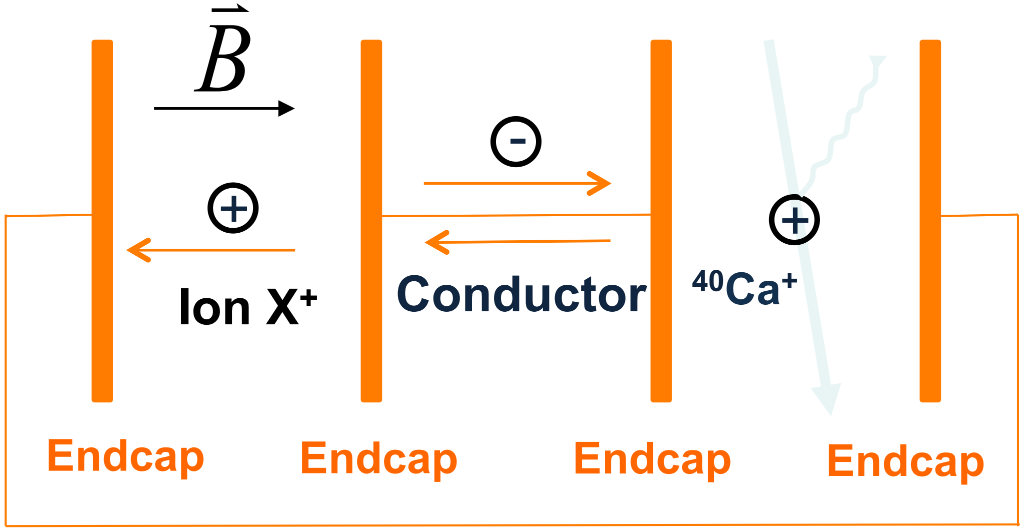
   Conductor ON

$T\ (^{40}Ca^+) \approx 1$ mK

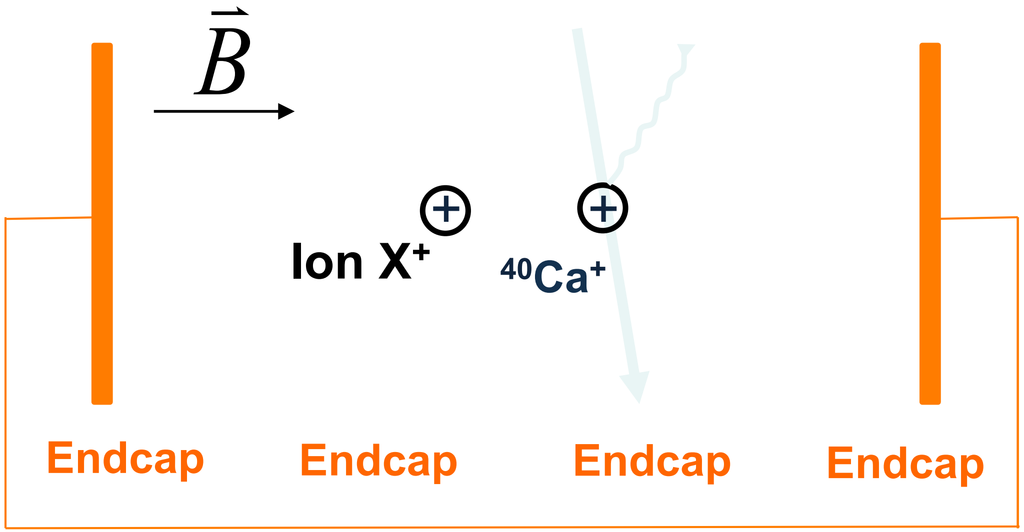
$T\ (^{40}Ca^+)$ <<; <n>~0



The QS technique
The principle of the stored ion calorimeter

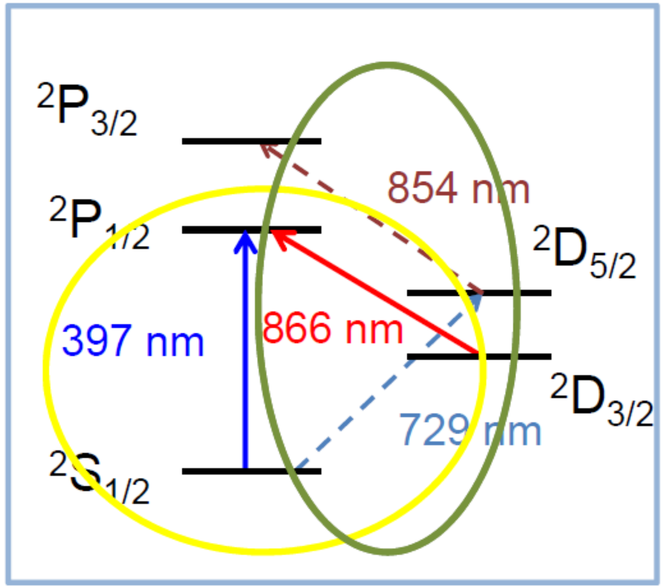


D. J. Heinzen & D. J. Wineland, Phys. Rev. A 42(5) (1990) 2977-2994



$T\,(^{40}Ca^{+}) \approx 1$ mK

$T\,(^{40}Ca^{+})$ <<; $\langle n \rangle \sim 0$

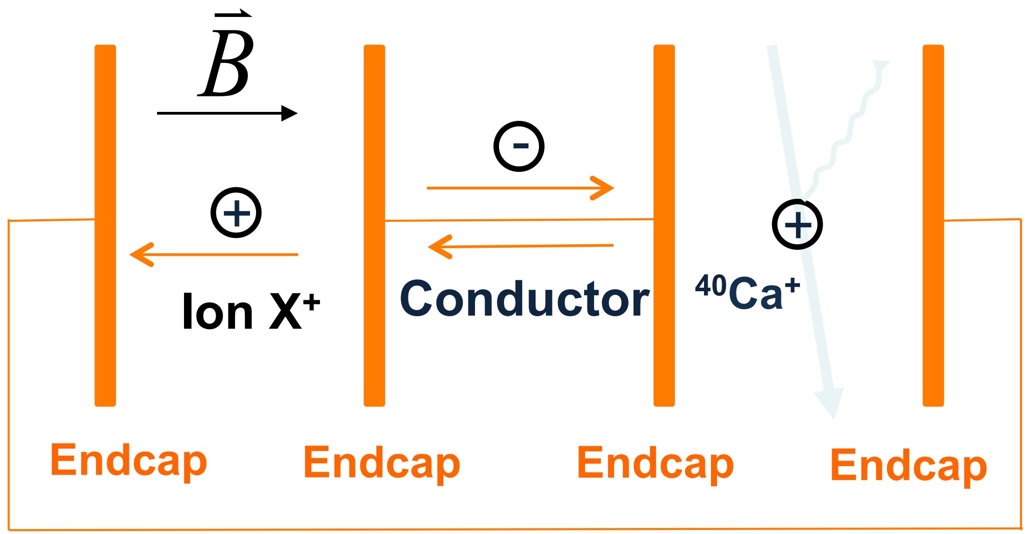


Doppler cooling

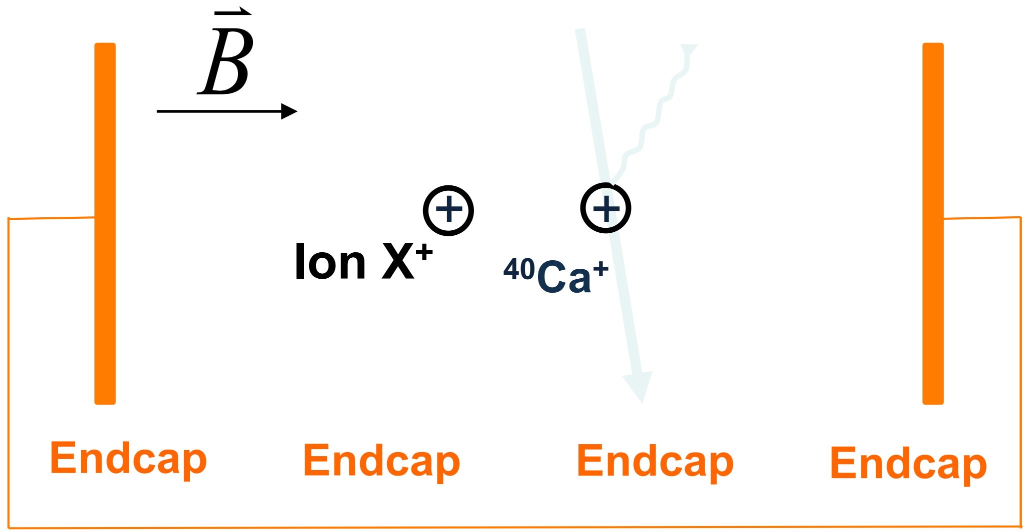
Ground-state cooling

The QS technique

The principle of the stored ion calorimeter



D. J. Heinzen & D. J. Wineland, Phys. Rev. A 42(5) (1990) 2977-2994

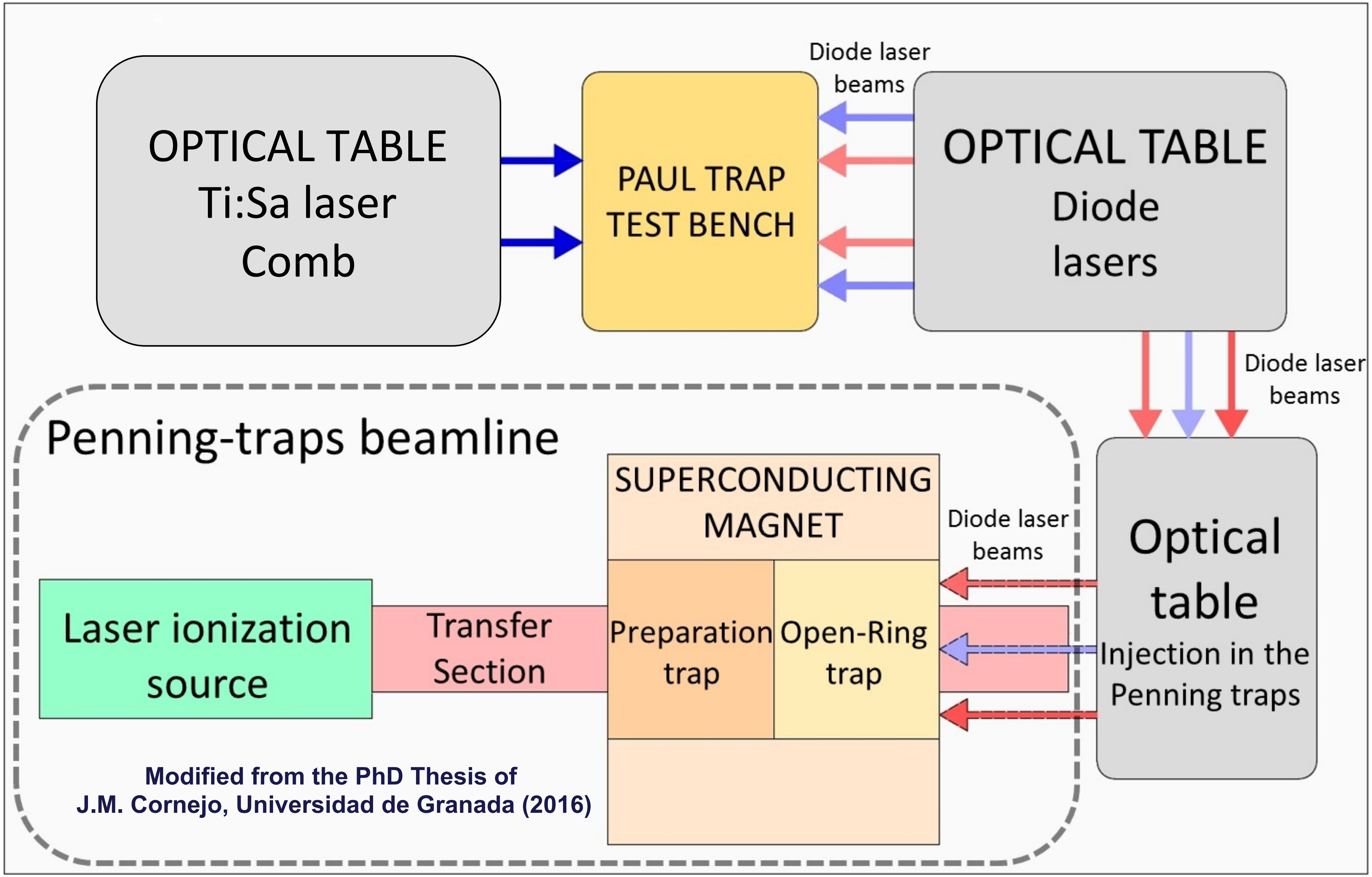


$T\,(^{40}Ca^+) \approx 1$ mK

- Ion X^+ can be any ion regardless of its mass, charge and polarity.
- Very small oscillation amplitudes can be detected → **highest sensitivity as sensor & highest precision.**

FOR SUPERHEAVY ELEMENTS AND/
OR NEUTRINO MASSES

The QS project
Layout (TRAPSENSOR laboratory)



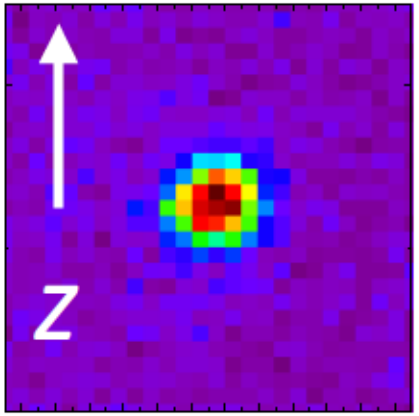
The QS Project
Single ion

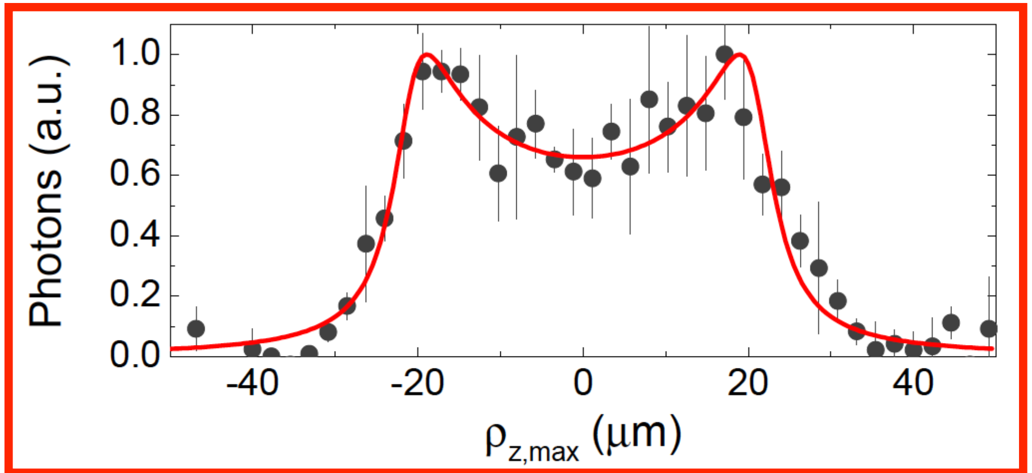
F. Domínguez, *et al.*, Scientific Reports 7, 8336 (2017)

Thermal equilibrium

$$\nu_z \approx 100\,\mathrm{kHz}$$

$$\rho_z^{\max} \approx 2.6\,\mu\mathrm{m}$$

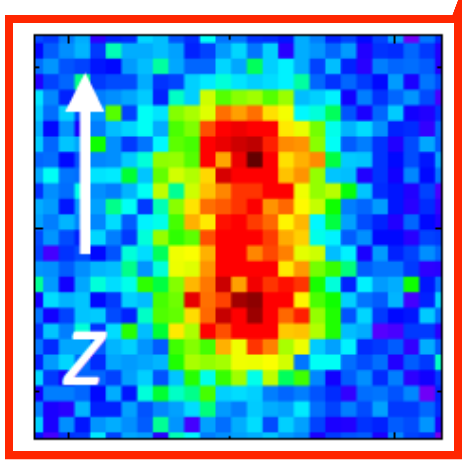


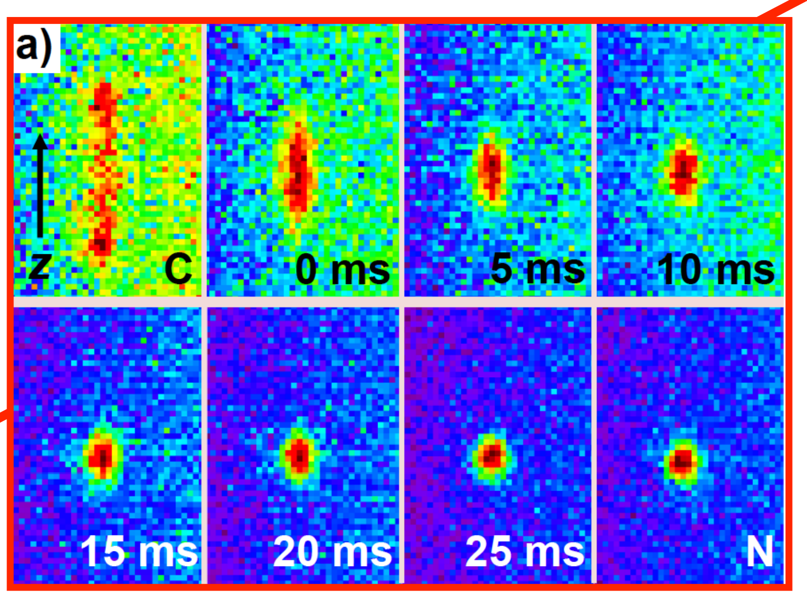


External RF field

$$\nu_z \approx 100\,\mathrm{kHz}$$

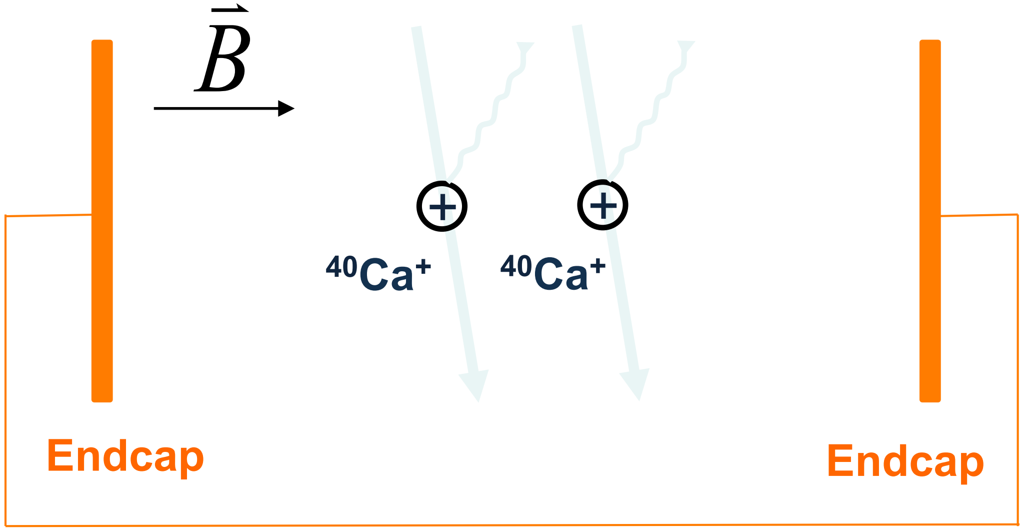
$$\rho_z^{\max} \approx 21\,\mu\mathrm{m}$$





In a trap with characteristics dimensions of about 1 cm.

The QS Project
Two-ion crystal

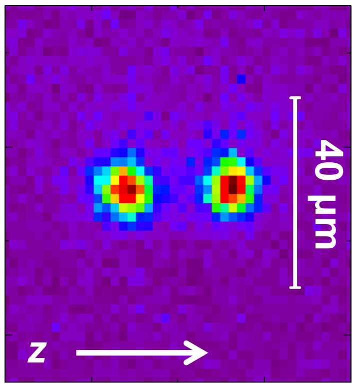


- Use different ions (e.g. *m/q* = 187) and monitor the ion of interest through the $^{40}Ca^+$ ion.

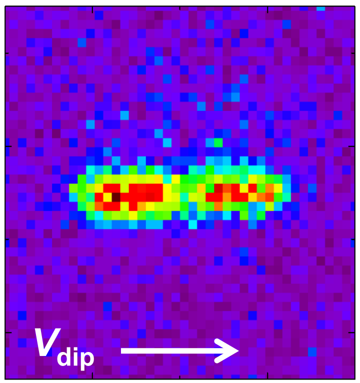
$$M, M = \mu m \rightarrow \text{Axial frequency shift}$$
$$\mu = 4.675$$

$$\Omega_{\pm}^{2} = \omega_{\text{trap}}^{2}\left(1+\frac{1}{\mu} \pm \sqrt{1+\frac{1}{\mu^{2}}-\frac{1}{\mu}}\right)$$

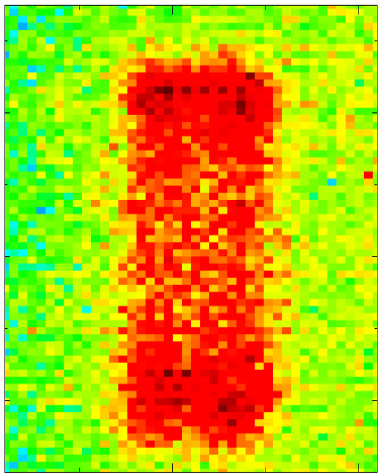
$$\rightarrow \Omega_{-} = 0.55 \times \omega_{\text{trap}}$$



No excitation



Axial excitation
Axial orientation

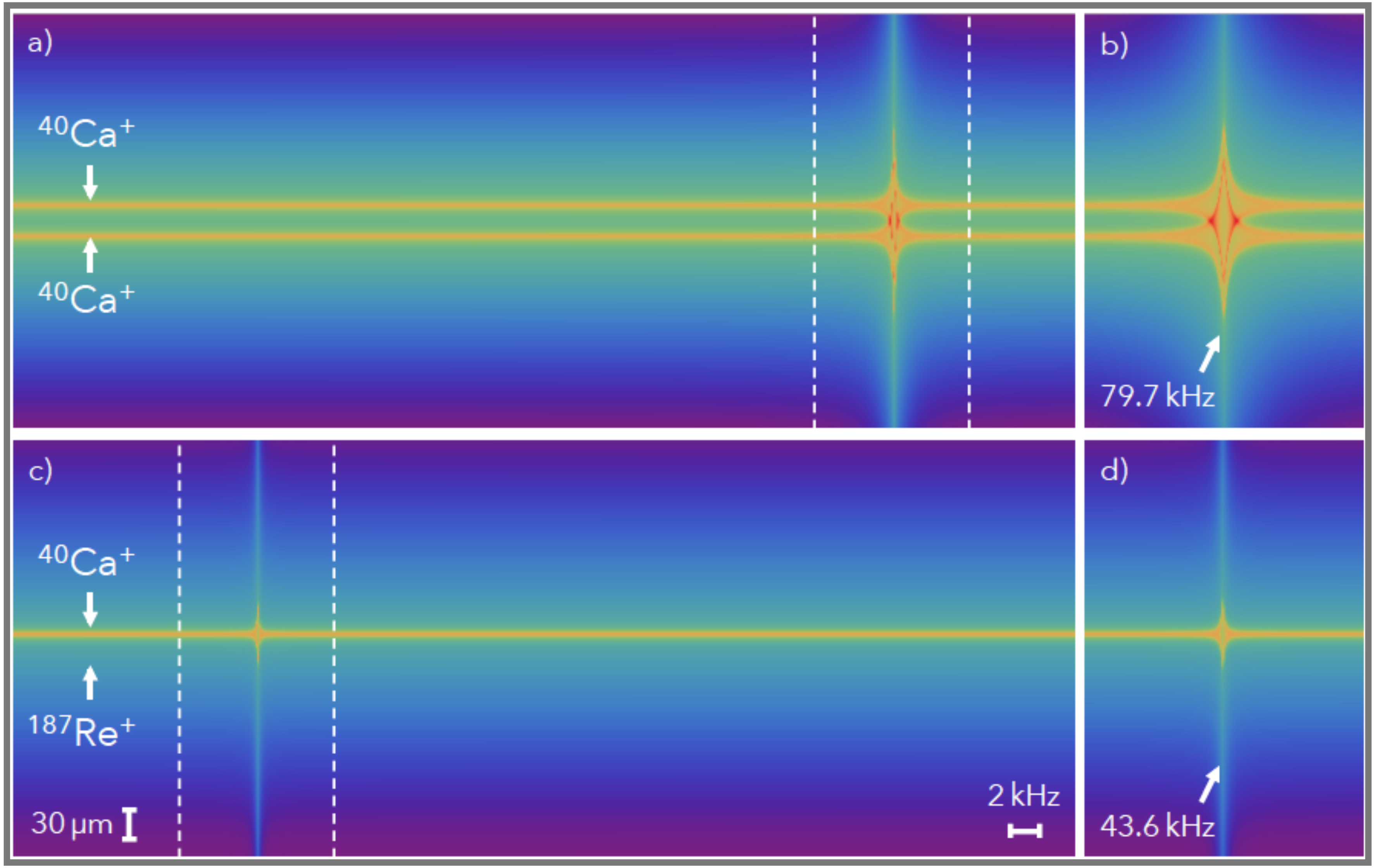


Axial excitation
Radial orientation

G. Morigi and H. Walter, *Eur. Phys. J. D* 13(2) 261-269 (2001)

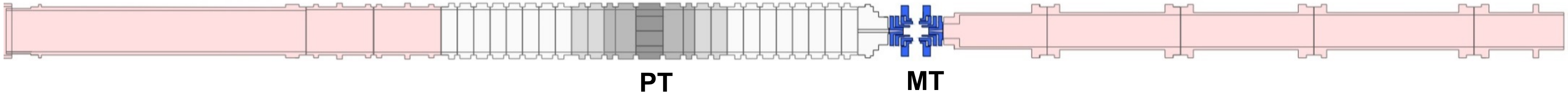
M. Drewsen *et al*, Phys. Rev. Lett. 93 243201 (2004)

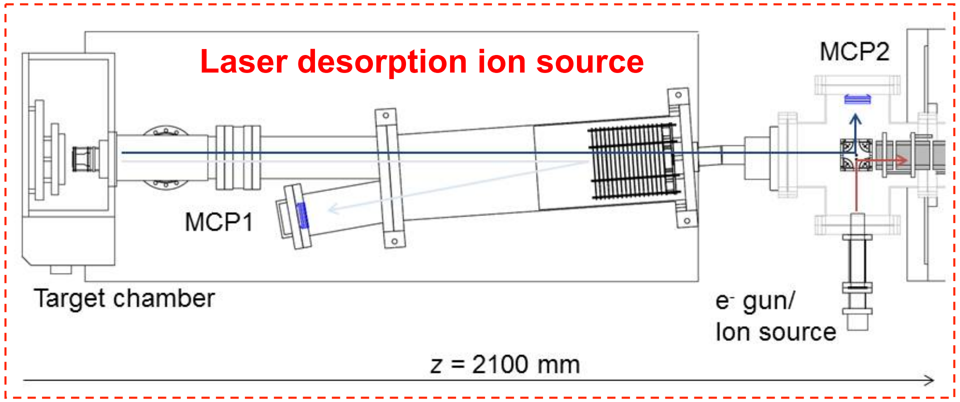
The QS Project
Two-ion crystal

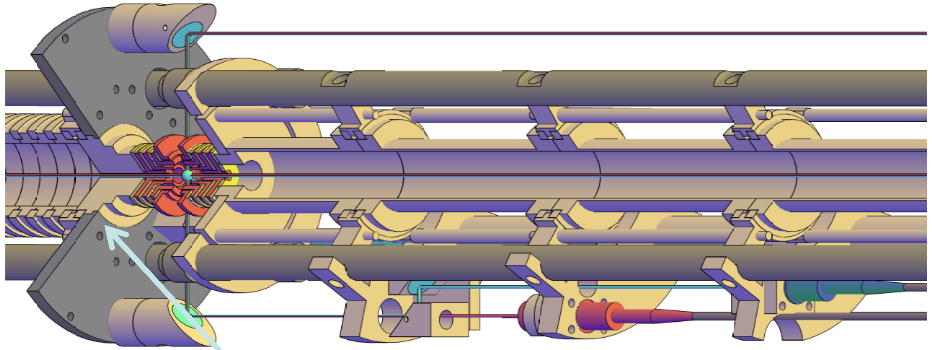


F. Domínguez, M.J. Gutiérrez *et al.*, Journal of Modern Optics (2017)

The QS Project
The Penning-traps beamline

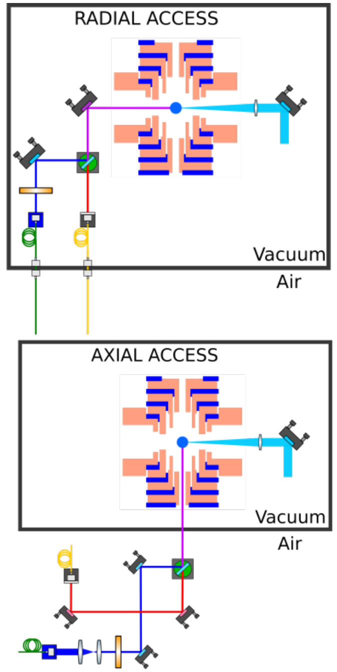






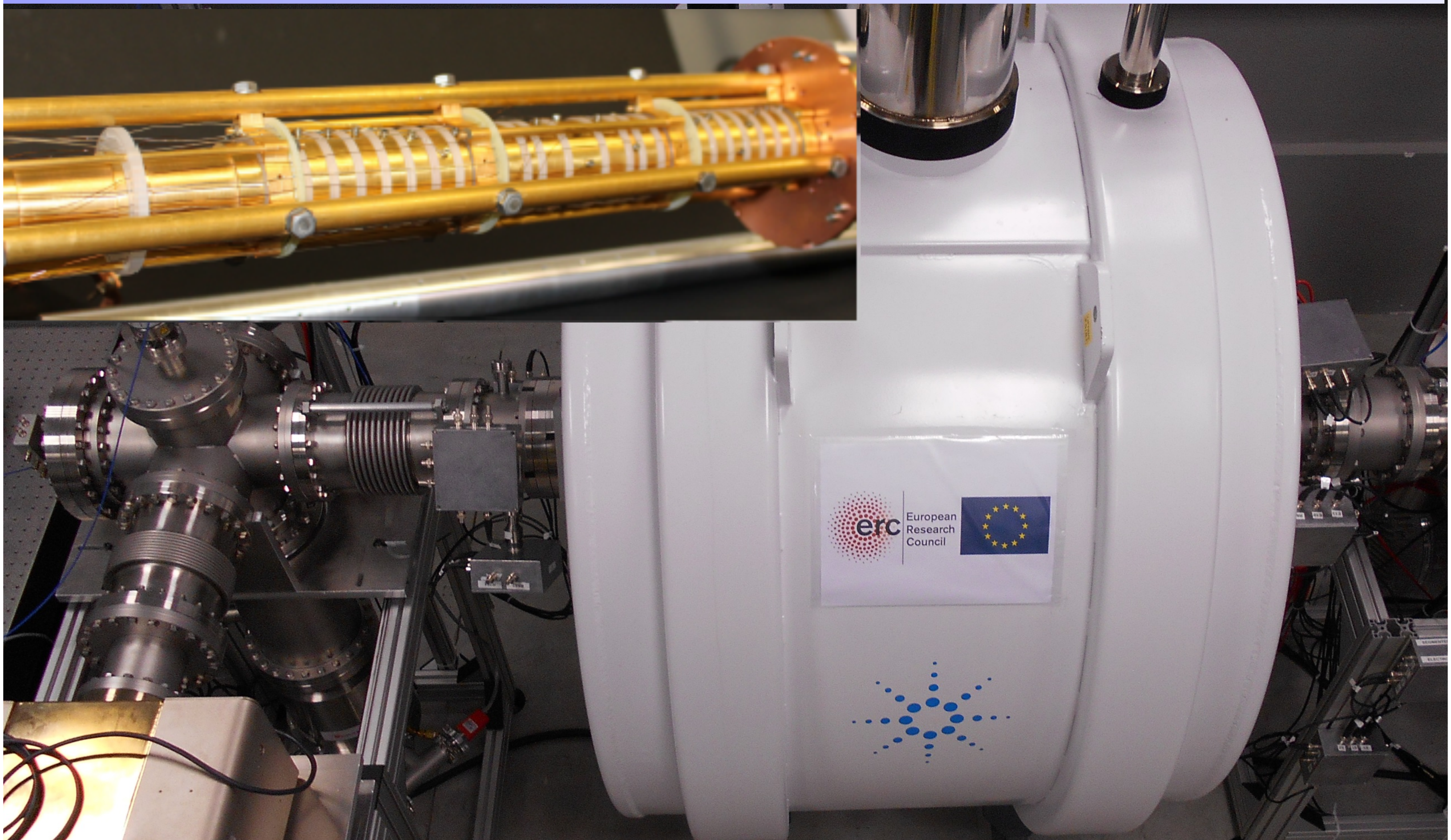
Universal ion source → Transfer → Ion preparation, separation and cooling → Precision trap + laser cooling

Ion preparation, separation and cooling → Novel cooling mechanisms → Vacuum improvement → Precision trap + laser cooling



The QS Project

The Penning-traps beamline



The QS Project
The Penning-traps beamline