Mass Measurements with Ion Traps for Nuclear Physics

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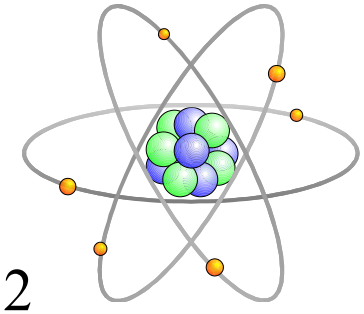
Outline

1. General remarks
    - Importance of the mass
    - Physics goals & mass uncertainty
2. The Penning trap
    - Fundamentals
    - Techniques for exotic nuclei
    - Existing facilities & physics survey
    - Mass uncertainty & half-life
    - Recent highlights
3. The project TRAPSENSOR in Granada
    - The technique
    - Implementation
    - First results

GENERAL REMARKS

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

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

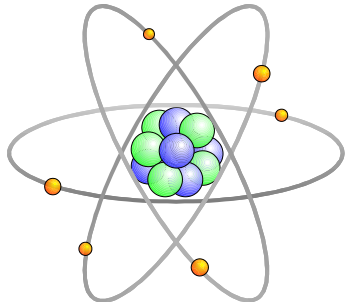
Atomic mass

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

Mass excess (keV)

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

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



Nuclear Structure & astrophysics

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

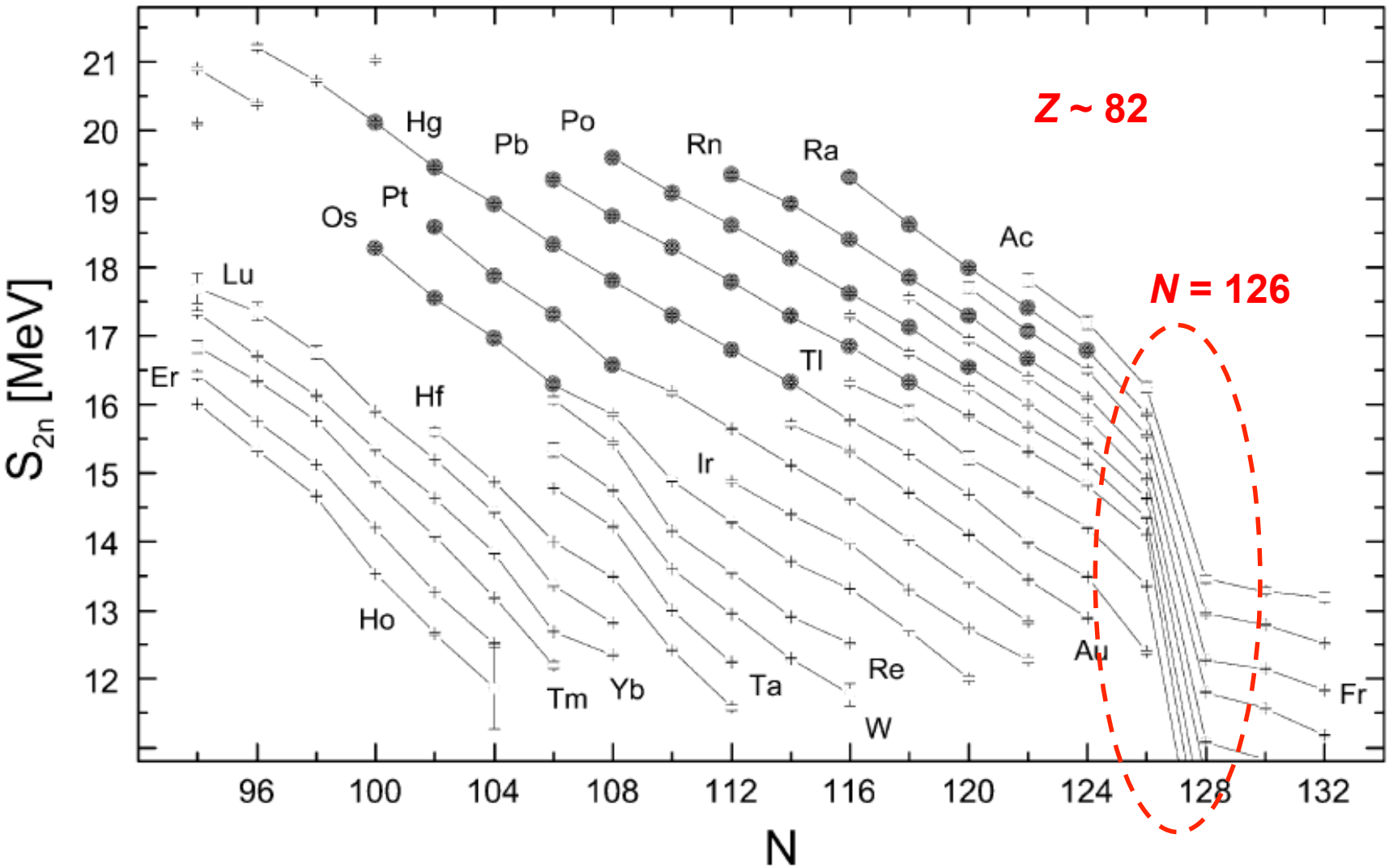
$$S_{2p} = B(N,Z) - B(N,Z-2)$$

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

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

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})

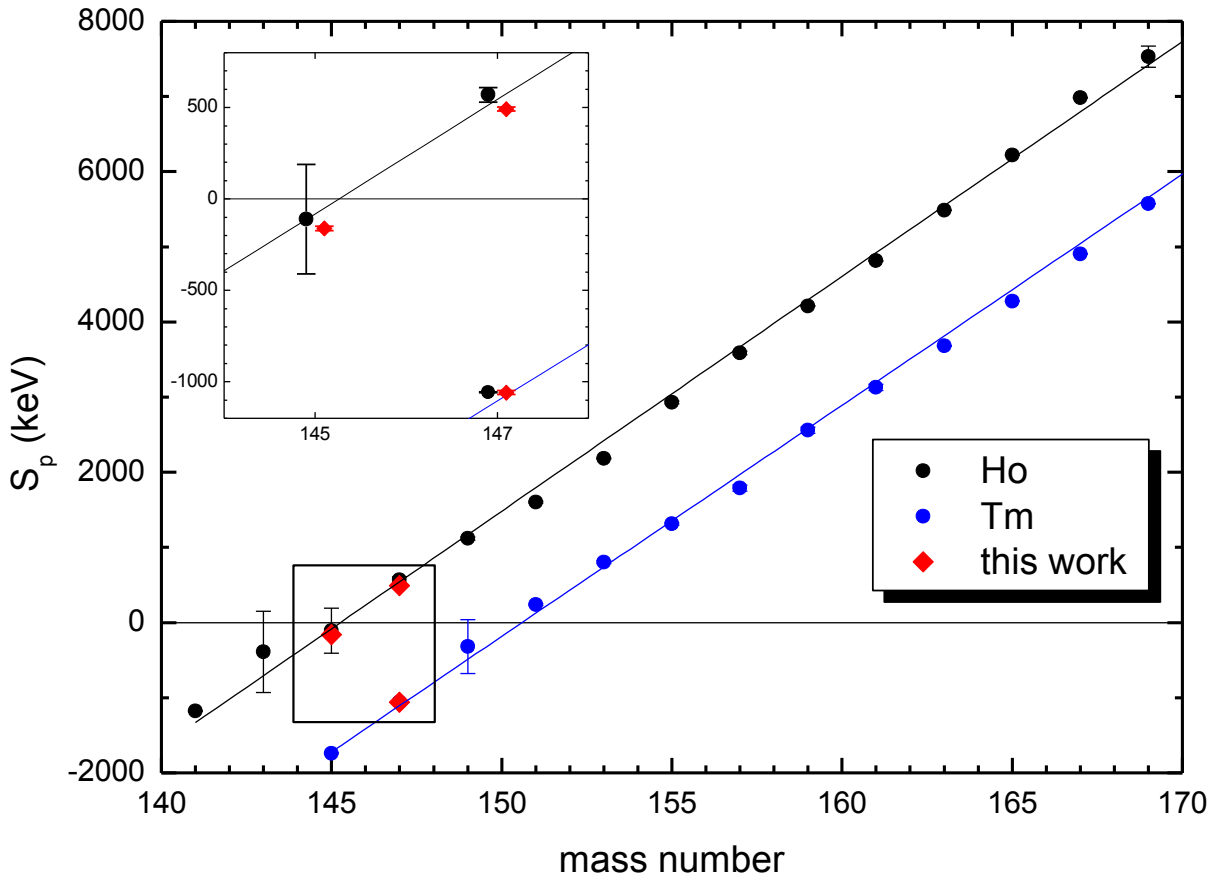


S. Schwarz *et al.*, Nucl. Phys. A 693 (2001) 533

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

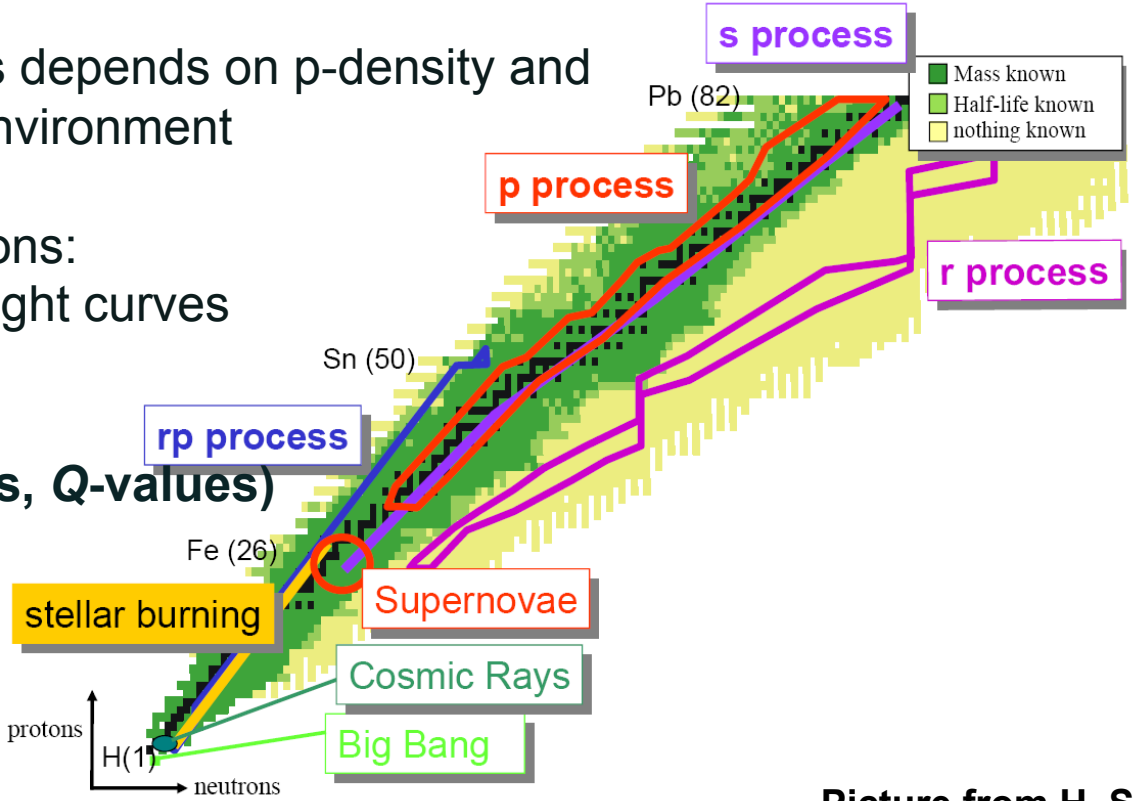
Importance of the mass
Astrophysics

- 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})

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

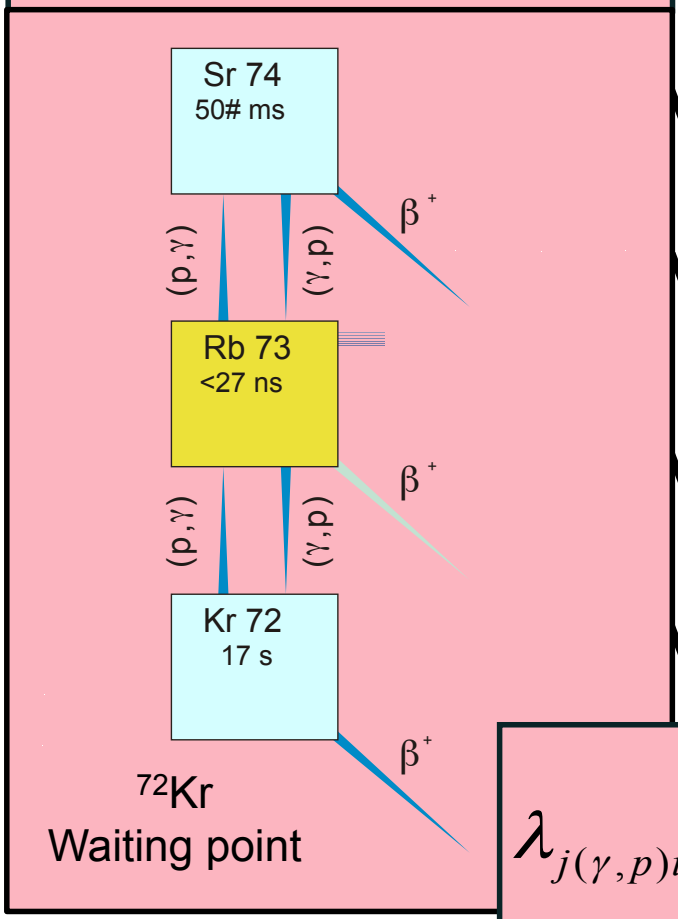
ucture **& astrophysics**

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

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

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

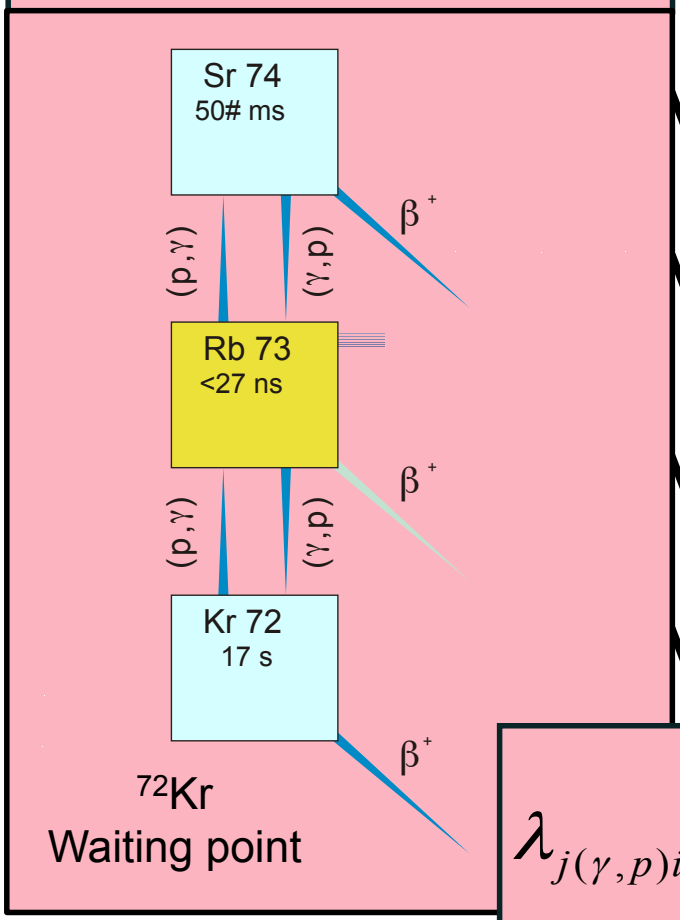
$$N,Z) - B(N-1,Z)$$

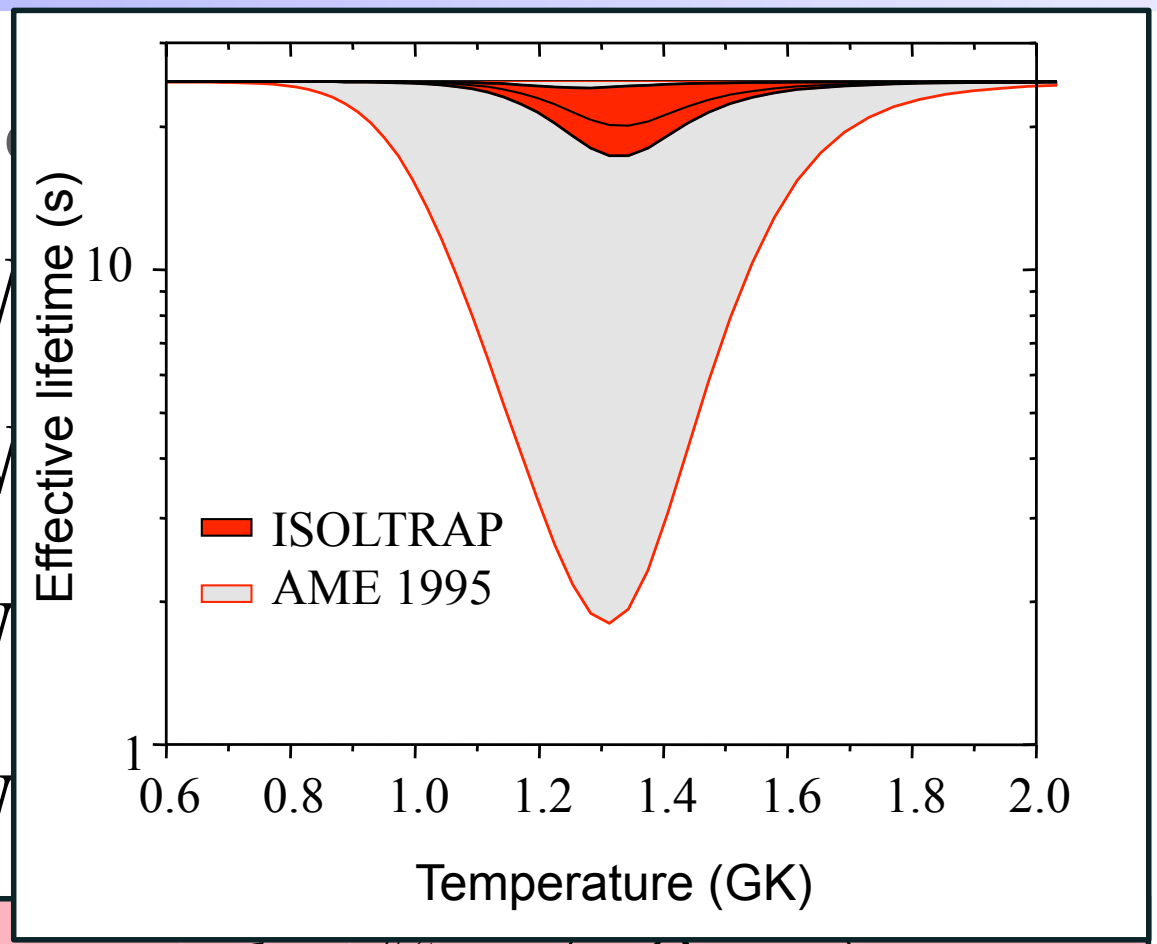


$$\lambda_{j(\gamma,p)i} = F \cdot \left(\frac{\mu kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{Q_{i(p,\gamma)j}}{kT}\right) \langle \sigma \upsilon \rangle_{i(p,\gamma)j}$$

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

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





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

D. Rodríguez *et al.*, PRL 93 (2004) 161104

Q-values from β-decay

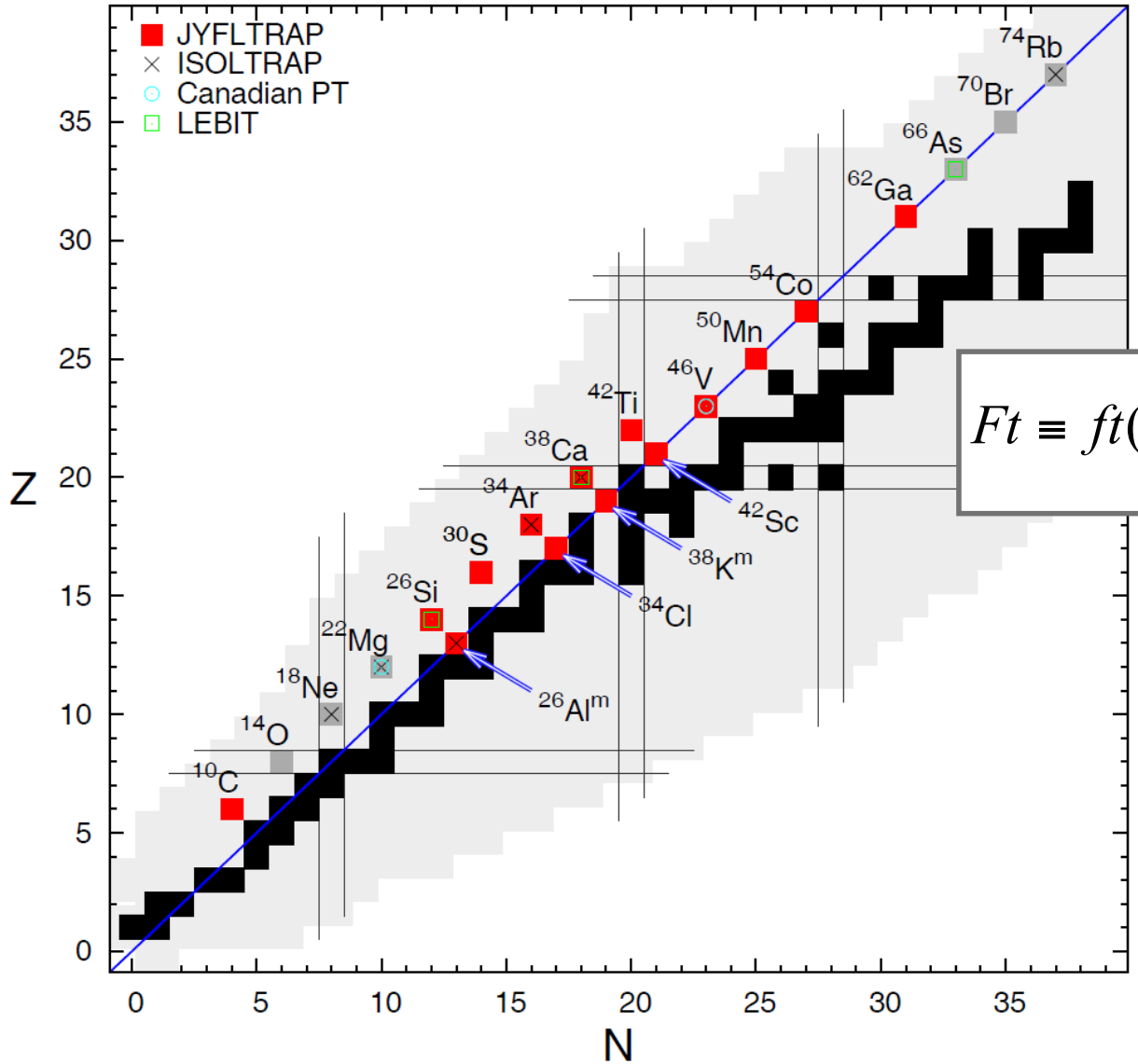
Fundamental symmetries &
Neutrino-related physics

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

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

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

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

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

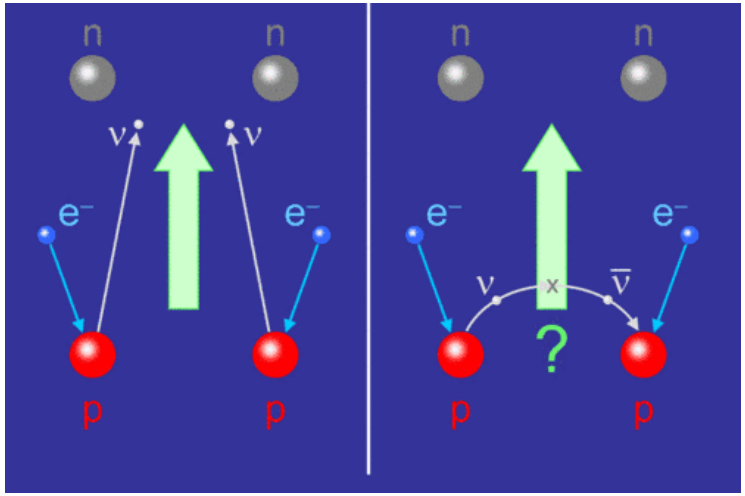
$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 1 - \Delta$$

Importance of the mass
Q-values from EC-decay

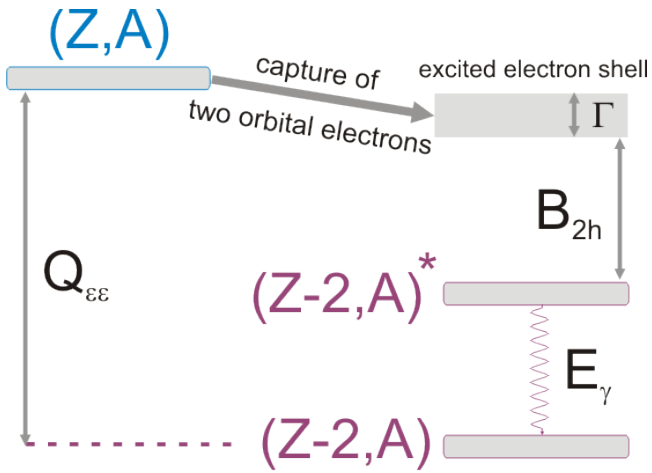
Is the neutrino a Majorana or Dirac particle?

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)



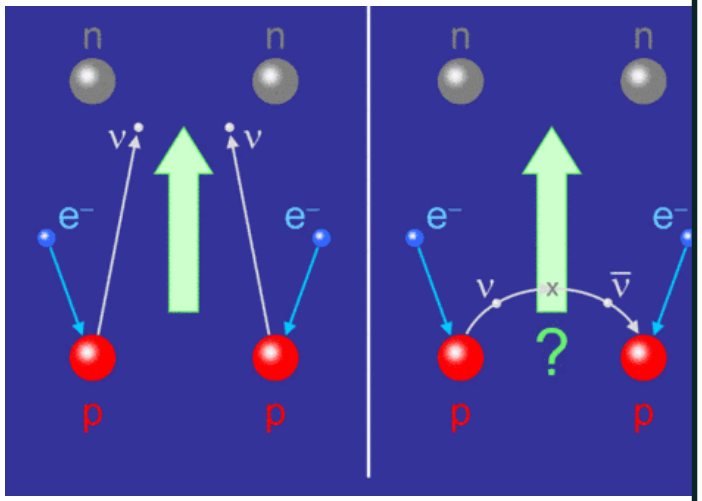
Search for nuclides with D=(Q_{ee}-B_{2h}-E_g) < 1 keV

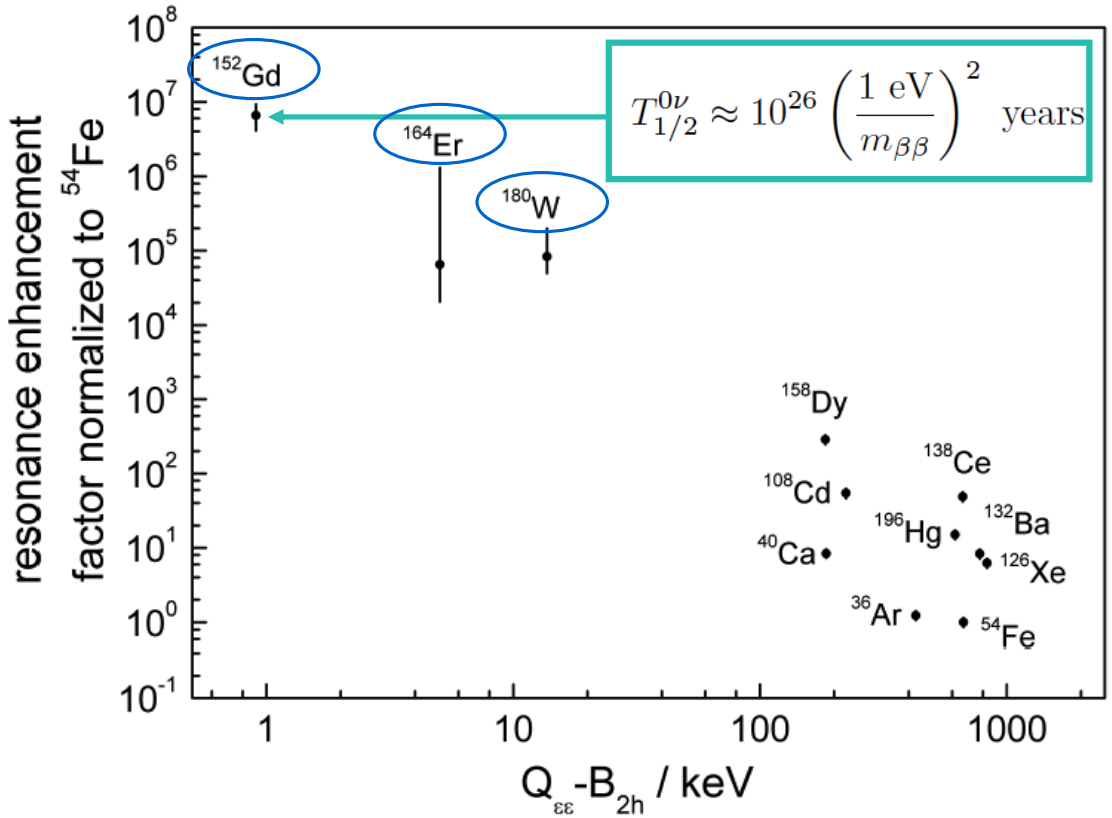
Importance of the mass
Q-values from EC-decay

Is the neutrino a Majorana or Dirac particle?

2ν2EC **($T_{1/2}$>10^{24} y)**

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





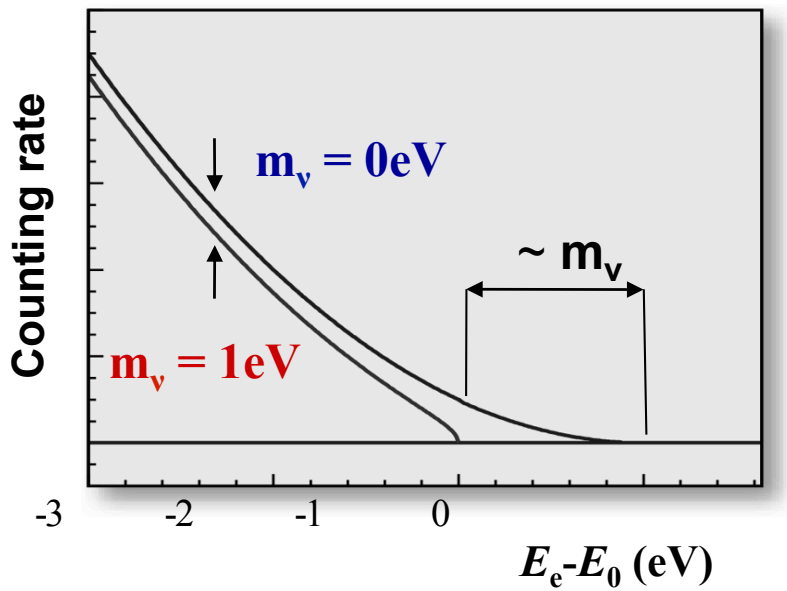
^{152}Gd: S. Eliseev *et al.*, Phys. Rev. Lett. 106 (2011) 052504

Importance of the mass
Q-values from β-decay

- Direct measurement of the mass by analyzing the end of the β-decay spectrum independent whether the neutrino is a Majorana or a Dirac particle

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

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



- **The best candidates will be decaying nuclei with low *end-point energies***
- **Tritium:** $\mathbf{T}_2 \rightarrow \left({}^3\mathbf{HeT}\right)^+ + e^- + \bar{\nu}_e$

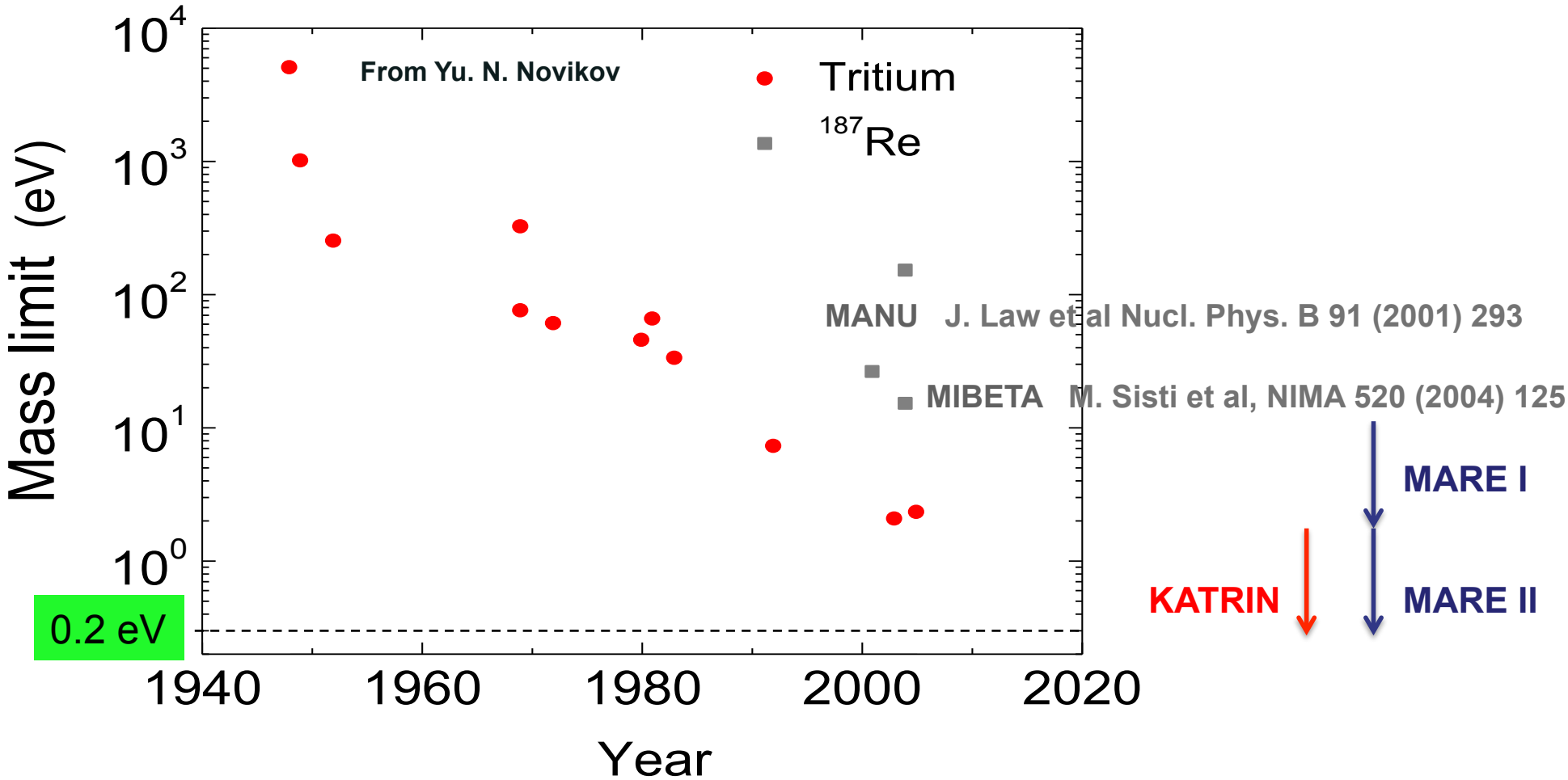
  $Q = 18.6\ \mathbf{keV} \qquad T_{1/2} = 12.3\ \mathbf{y}$

- **^{187}Re:** ${}^{187}\mathrm{Re} \rightarrow {}^{187}\mathbf{Os} + e^- + \bar{\nu}_e$

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

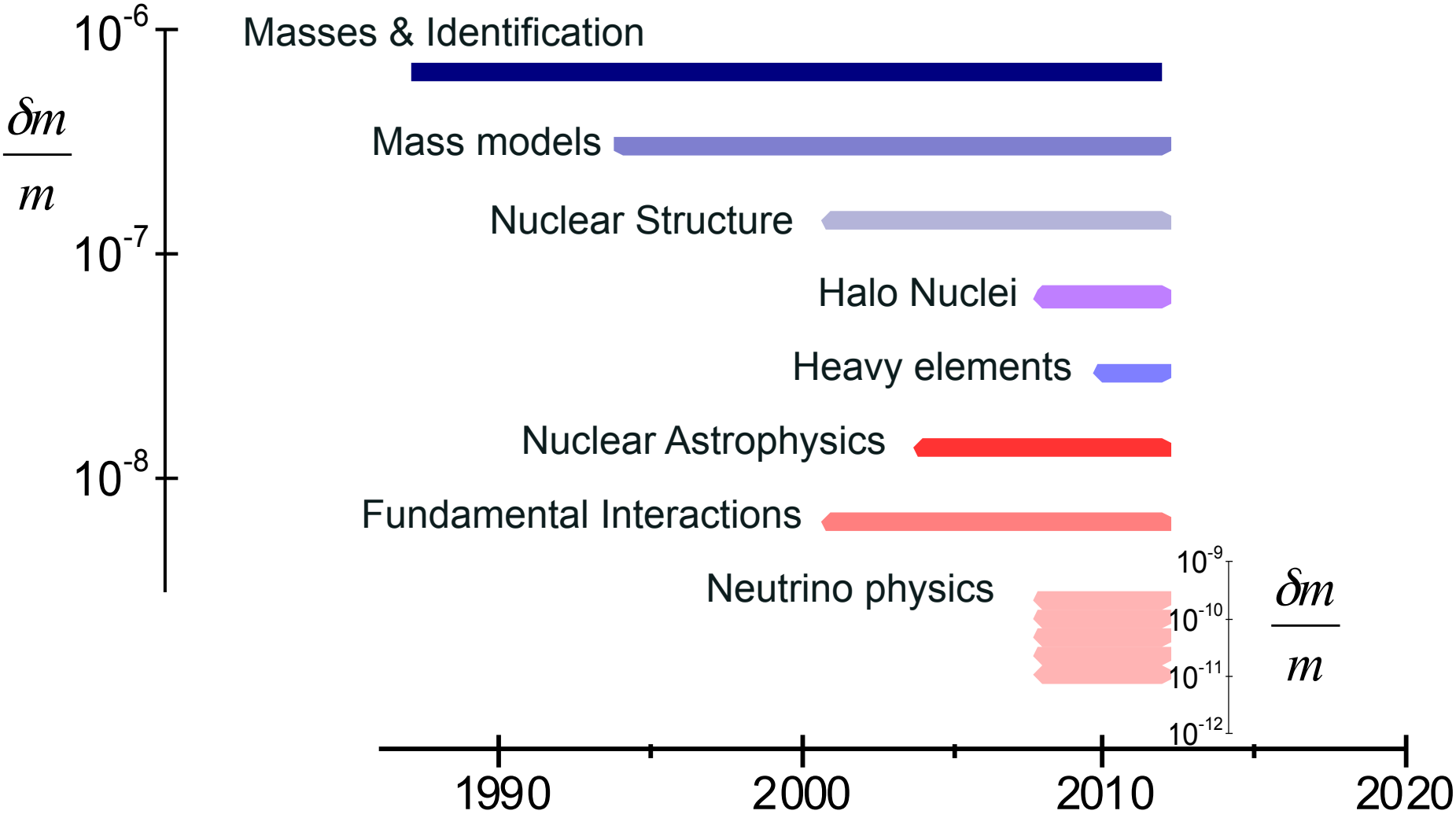
***Q* has to be unambiguously determined (with δ*m*/*m* of at least 10^{-11}) from the mass difference using a Penning trap**

History of antineutrino mass measurements
Tritium and ^{187}Re



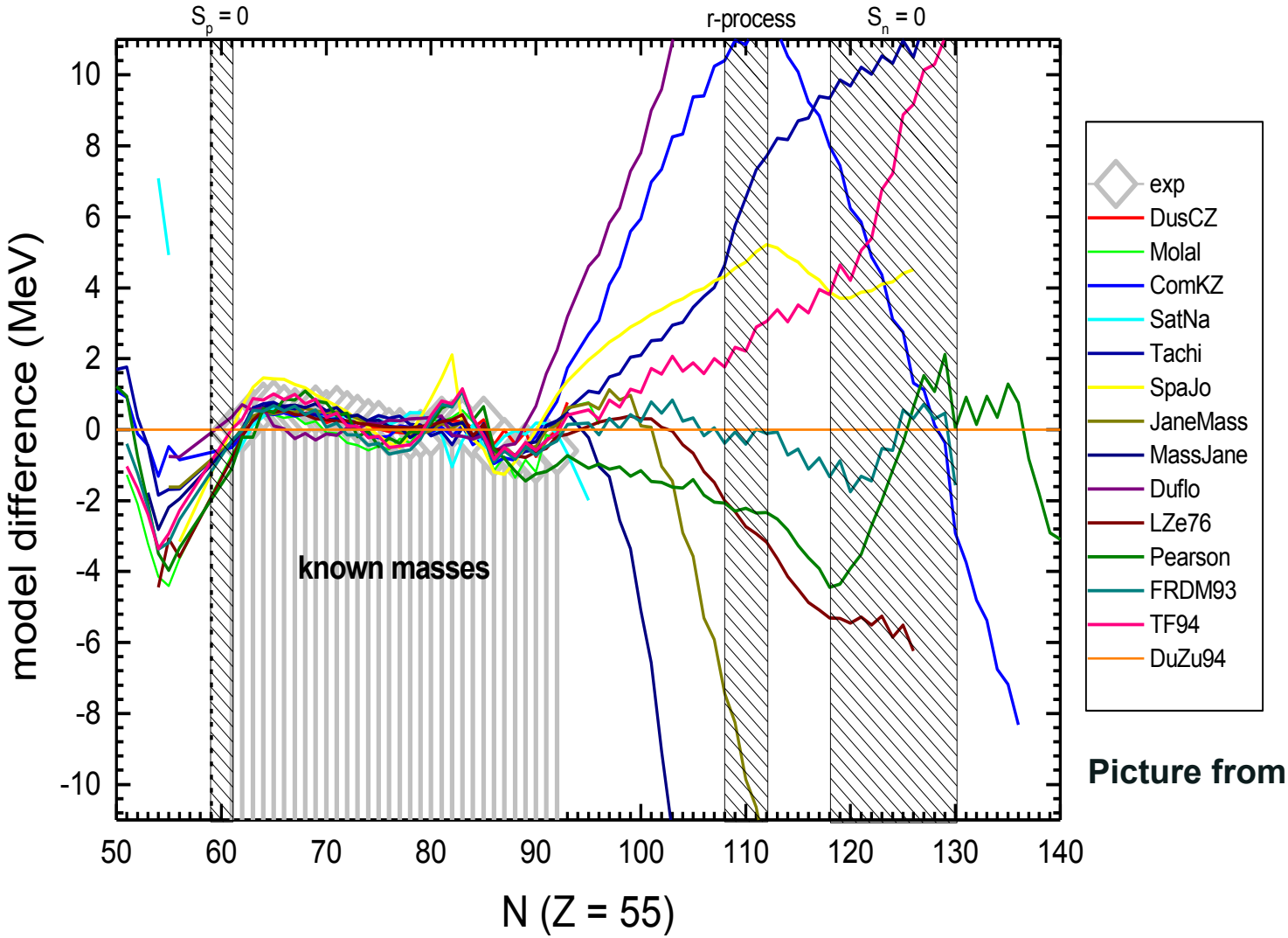
- There are two International collaborations aiming at measuring with a sensitivity of about 0.2 eV/c^2: KATRIN (KArlsruhe TRItium Neutrino experiment) and MARE (Micro calorimeter Array for a Rhenium Experiment)

Physics goals
Mass uncertainty required



Time scale for direct mass measurements using Penning traps

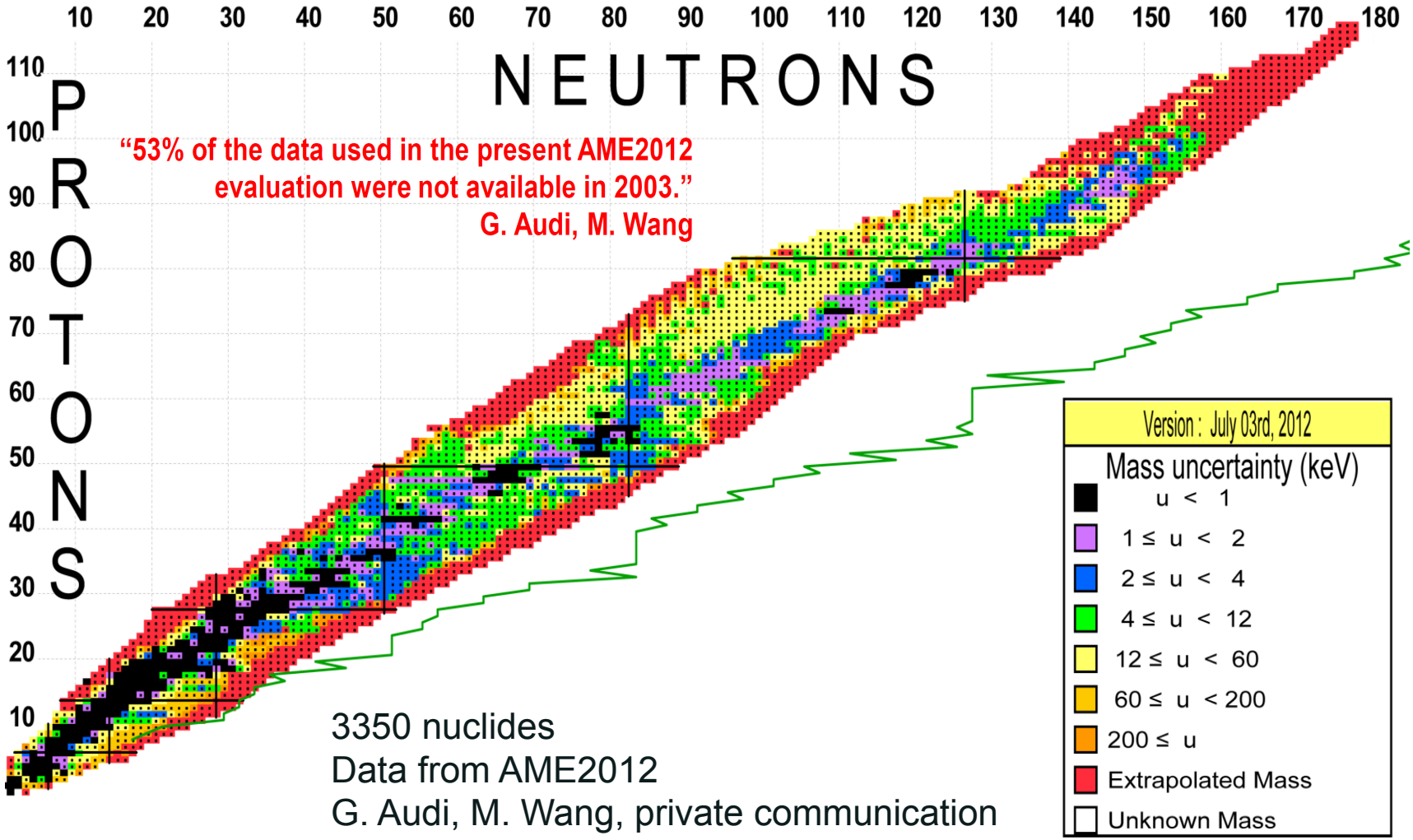
Experimental results and models
Discrepancies between the models



Picture from D. Lunney

Particularly relevant in the region of Superheavy Elements

Mass measurements in the last decade
The 2012 Atomic Mass Evaluation



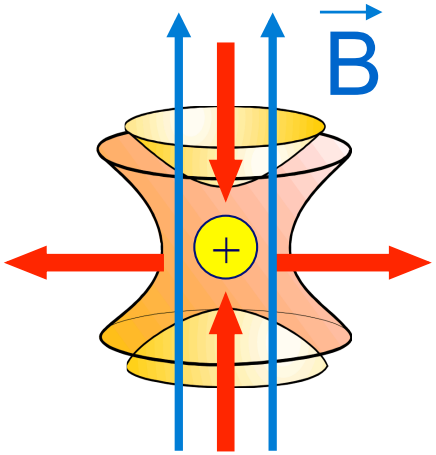
"53% of the data used in the present AME2012 evaluation were not available in 2003."
G. Audi, M. Wang

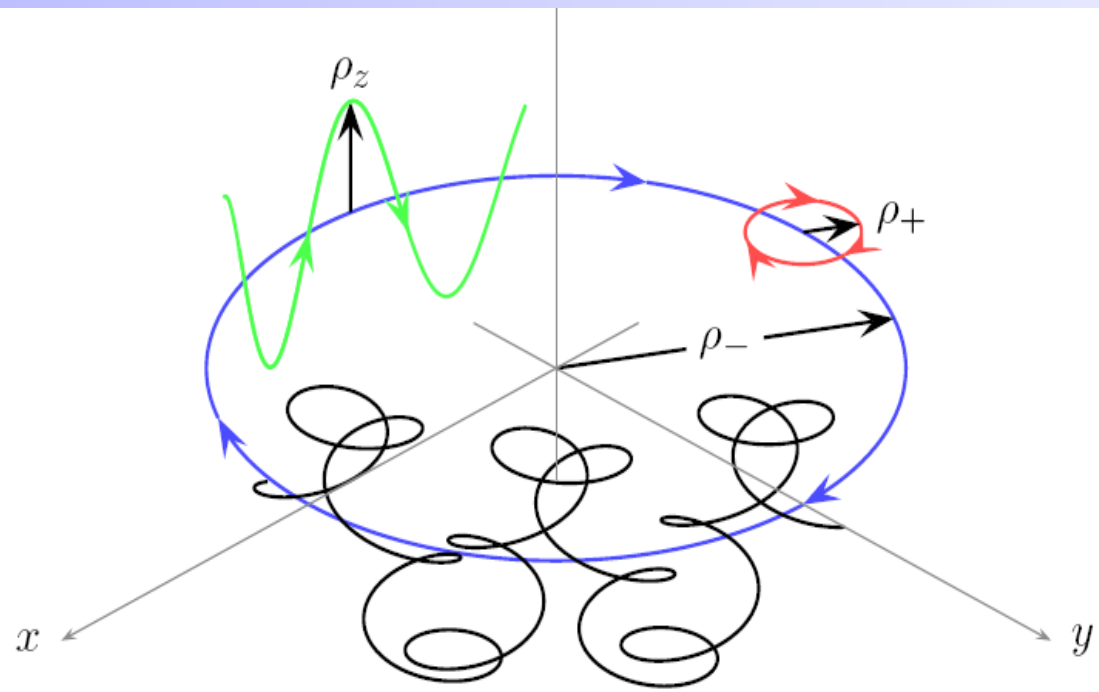
3350 nuclides
Data from AME2012
G. Audi, M. Wang, private communication

THE PENNING TRAP

Penning traps
Fundamentals

Magnetic + Electrostatic field





Axial motion

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

Reduced cyclotron motion

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

Magnetron motion

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

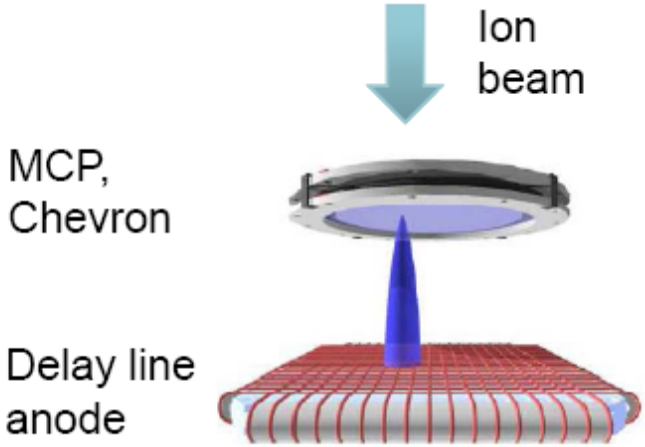
$$\omega_c = \frac{q}{m}B$$

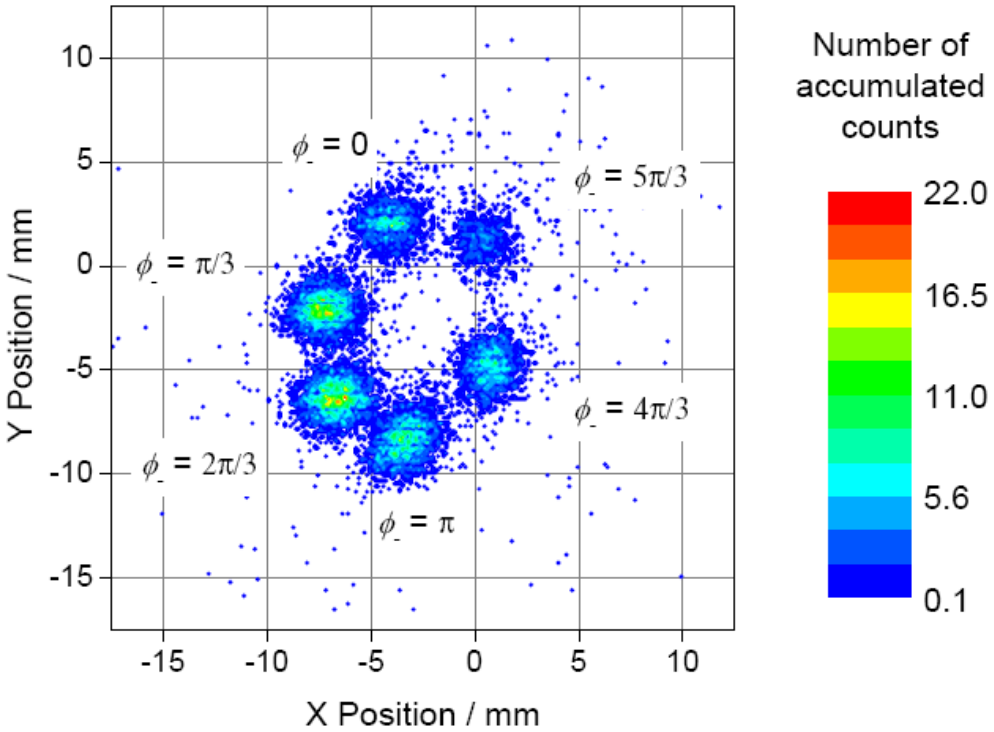
$$\omega_c = \omega_+ + \omega_-$$

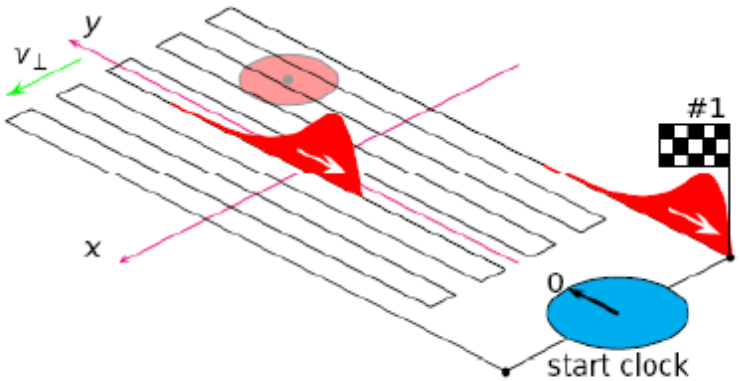
$$\omega_+ > \omega_z > \omega_-$$

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

Penning traps
Fundamentals

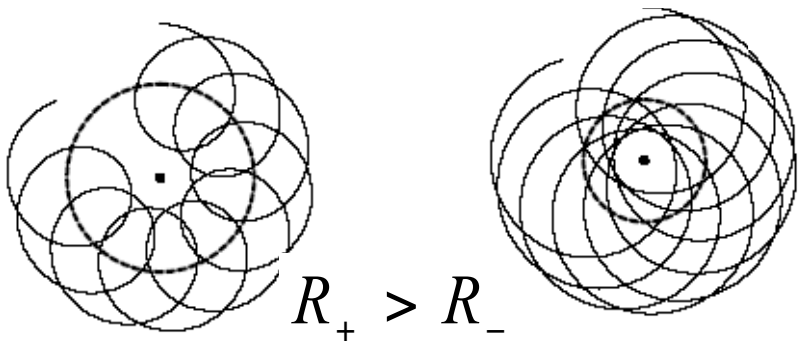






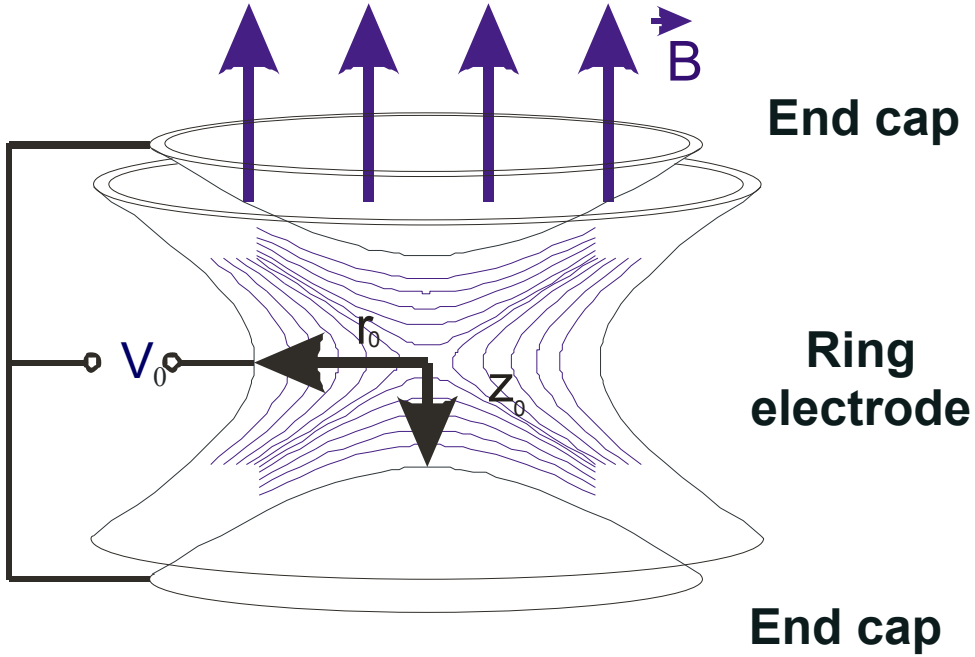
G. Eitel *et al.*, Nucl. Instrum. Methods A, 606, (2009) 475

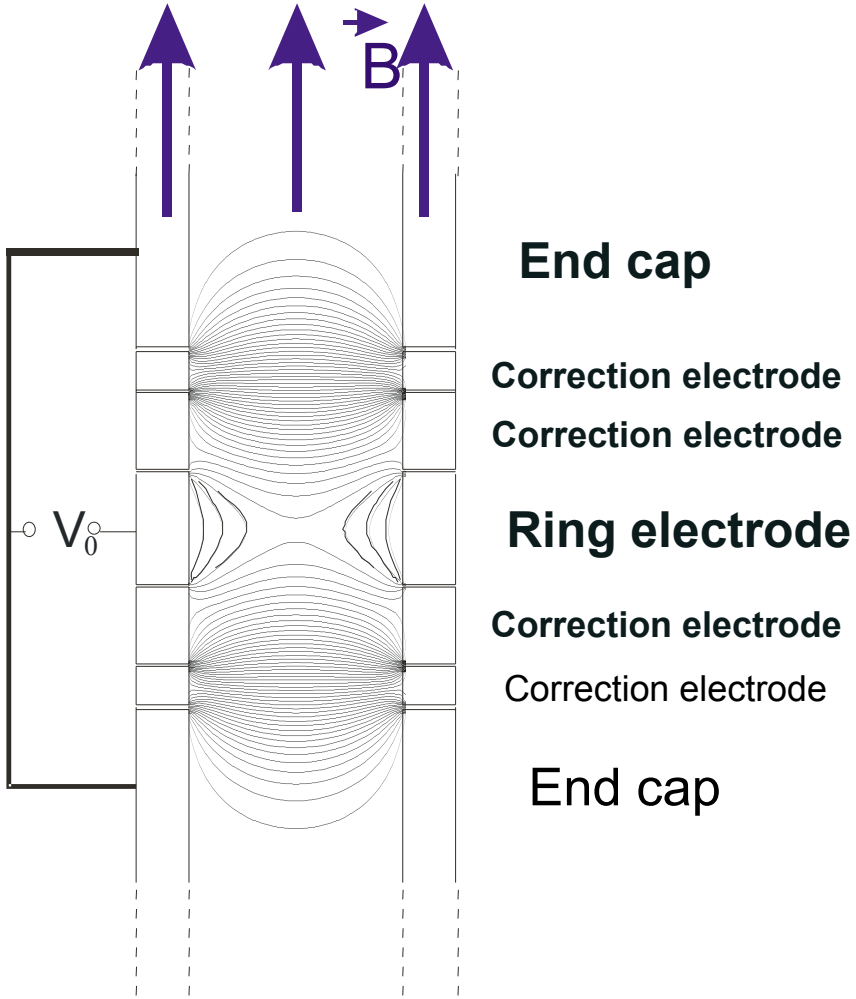
$R_+ < R_-$



$R_+ > R_-$

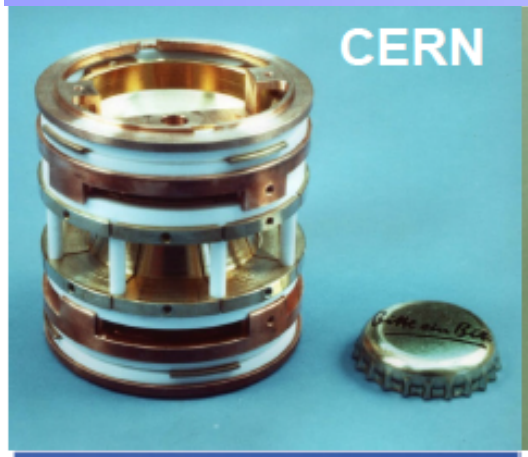
Penning traps
Different geometries

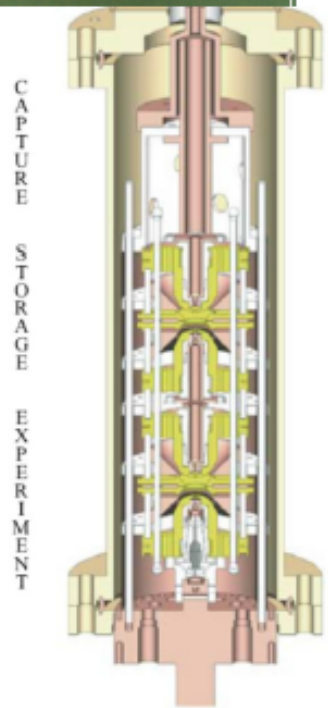




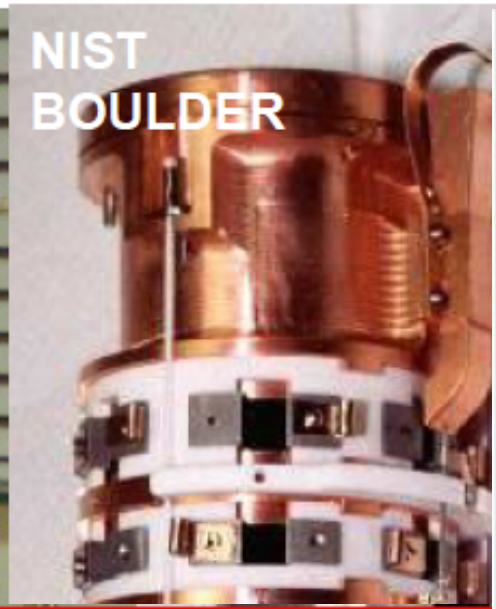
L.S. Browm and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233

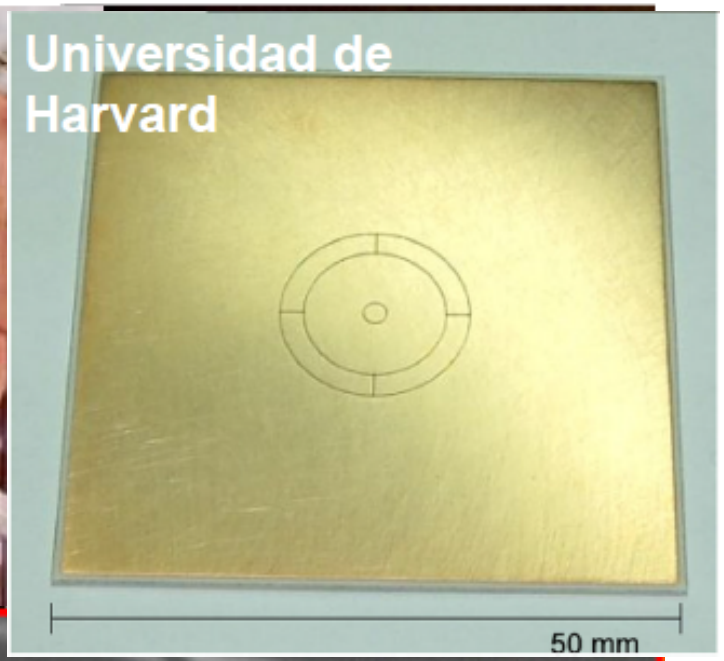
Penning traps
Different geometries



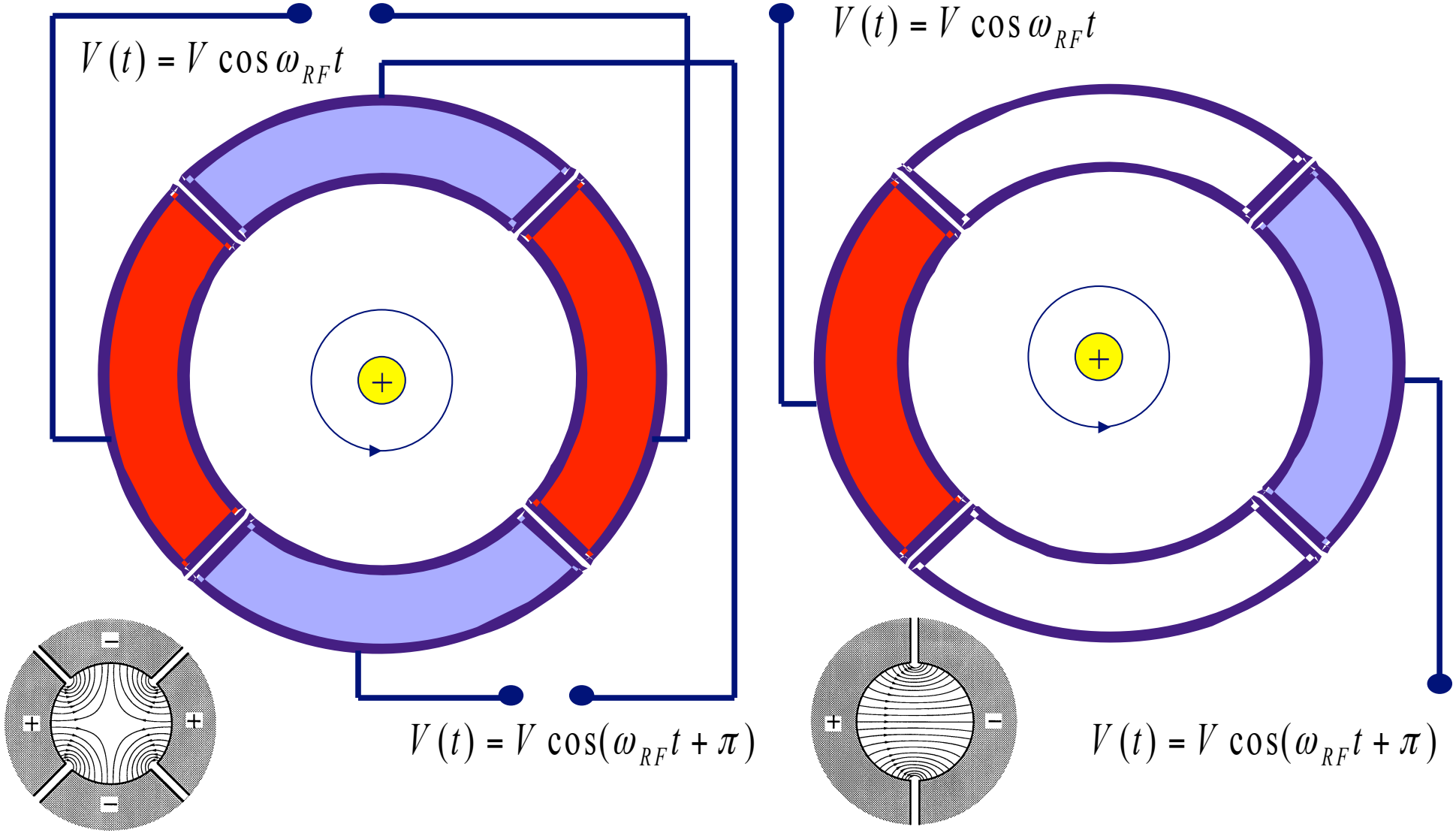


Penning traps
Different geometries

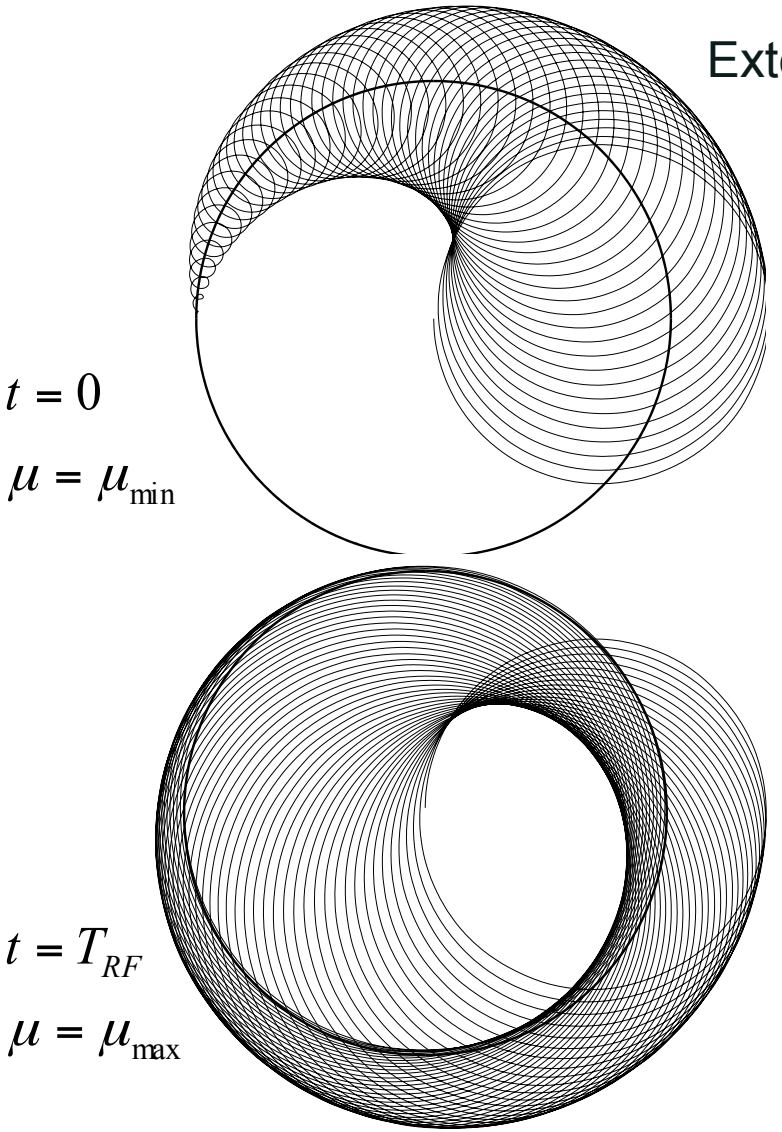




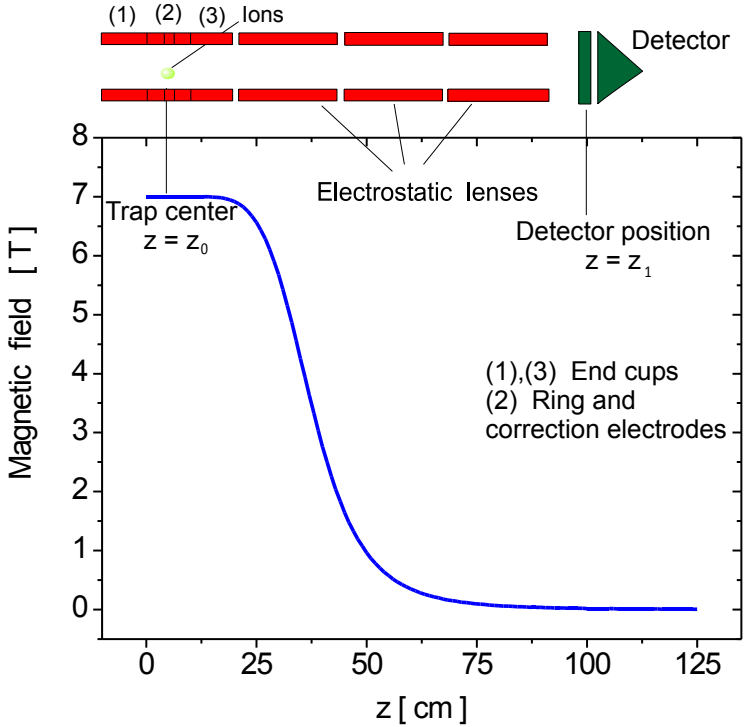
Penning-trap techniques
External Fields



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



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

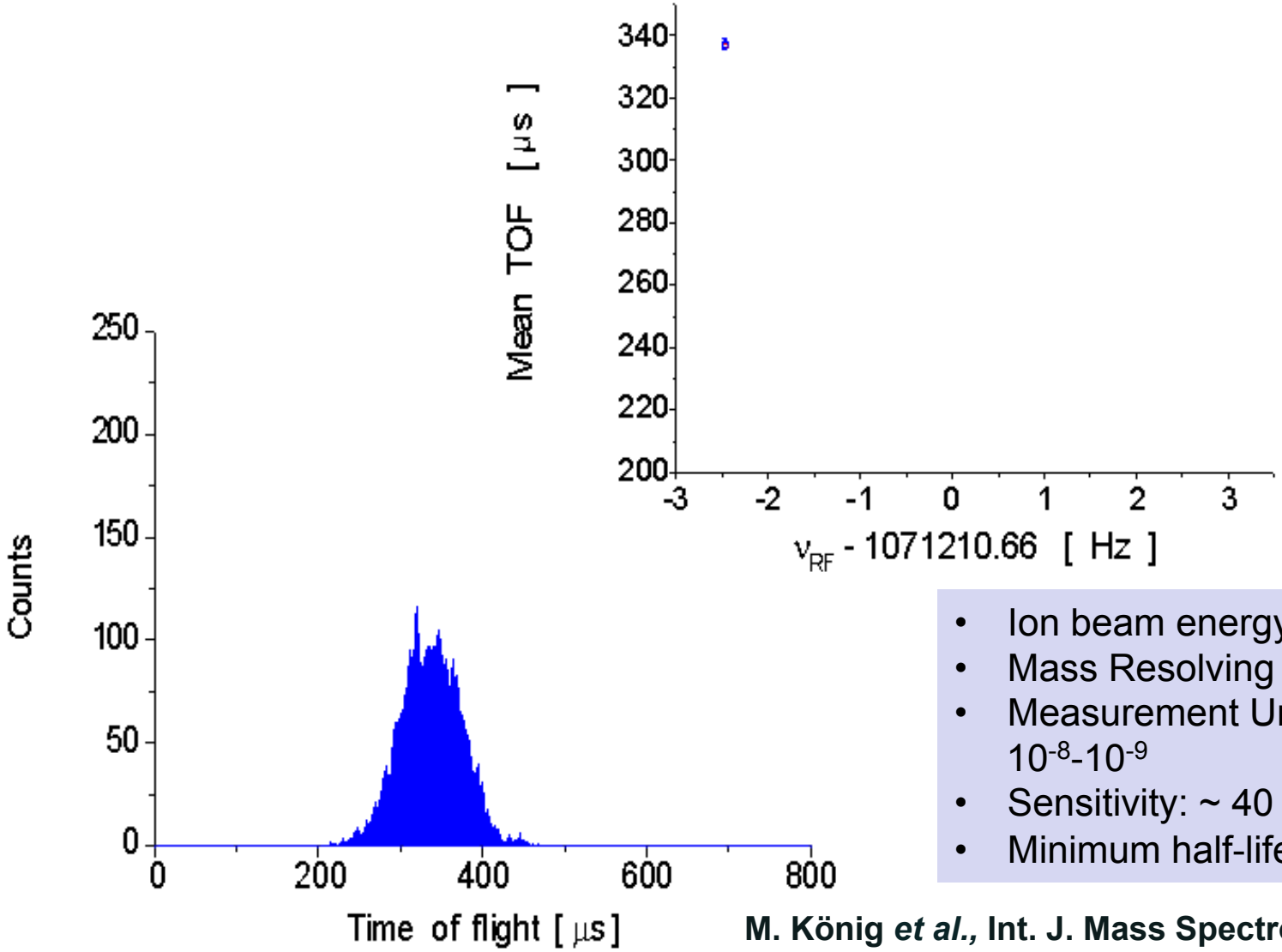


$$F_z = \mu \frac{\partial B}{\partial z}$$

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

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

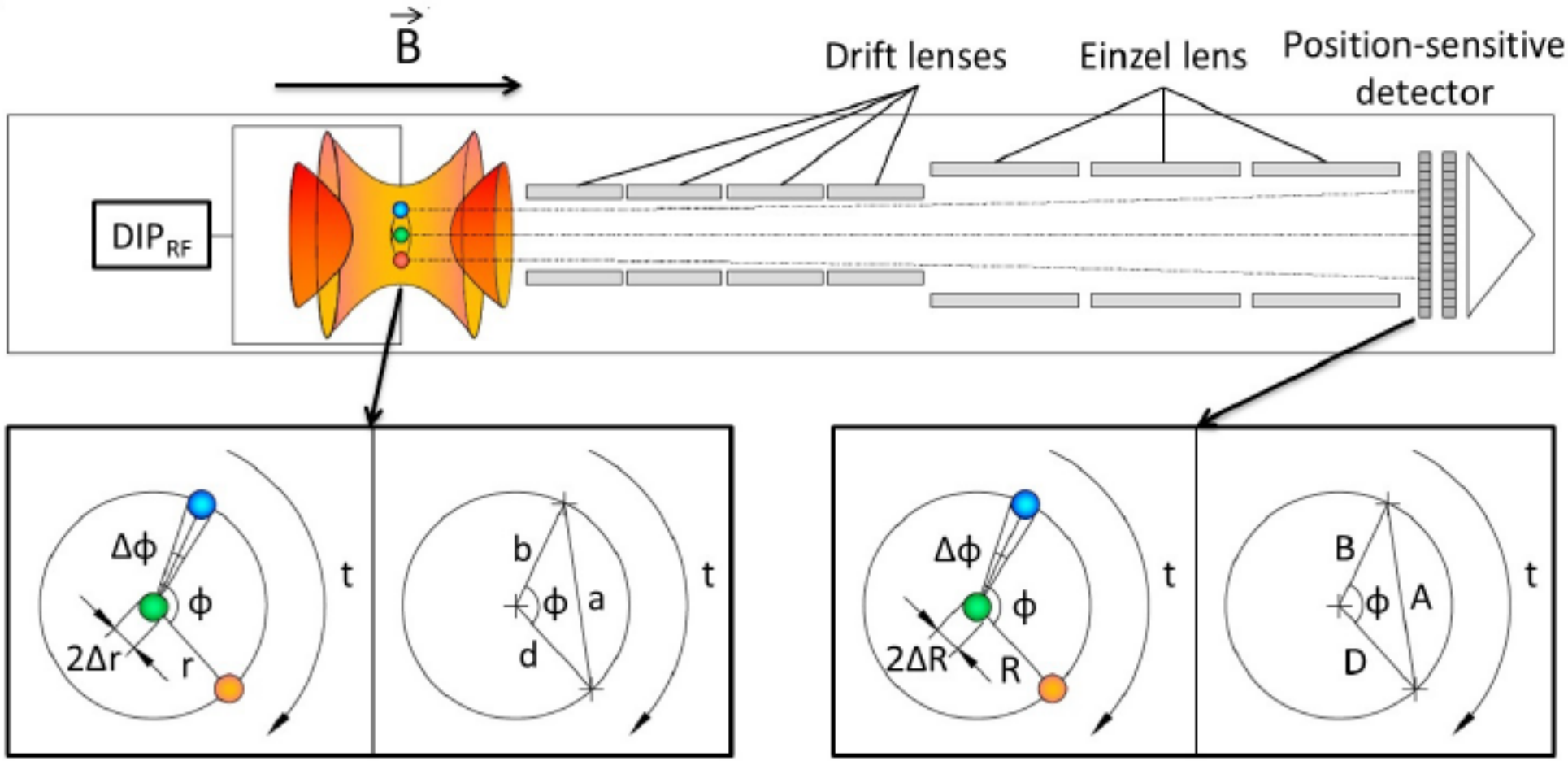
Penning-trap techniques
Time-of-Flight Ion Cyclotron Resonance (TOF-ICR)



- 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)

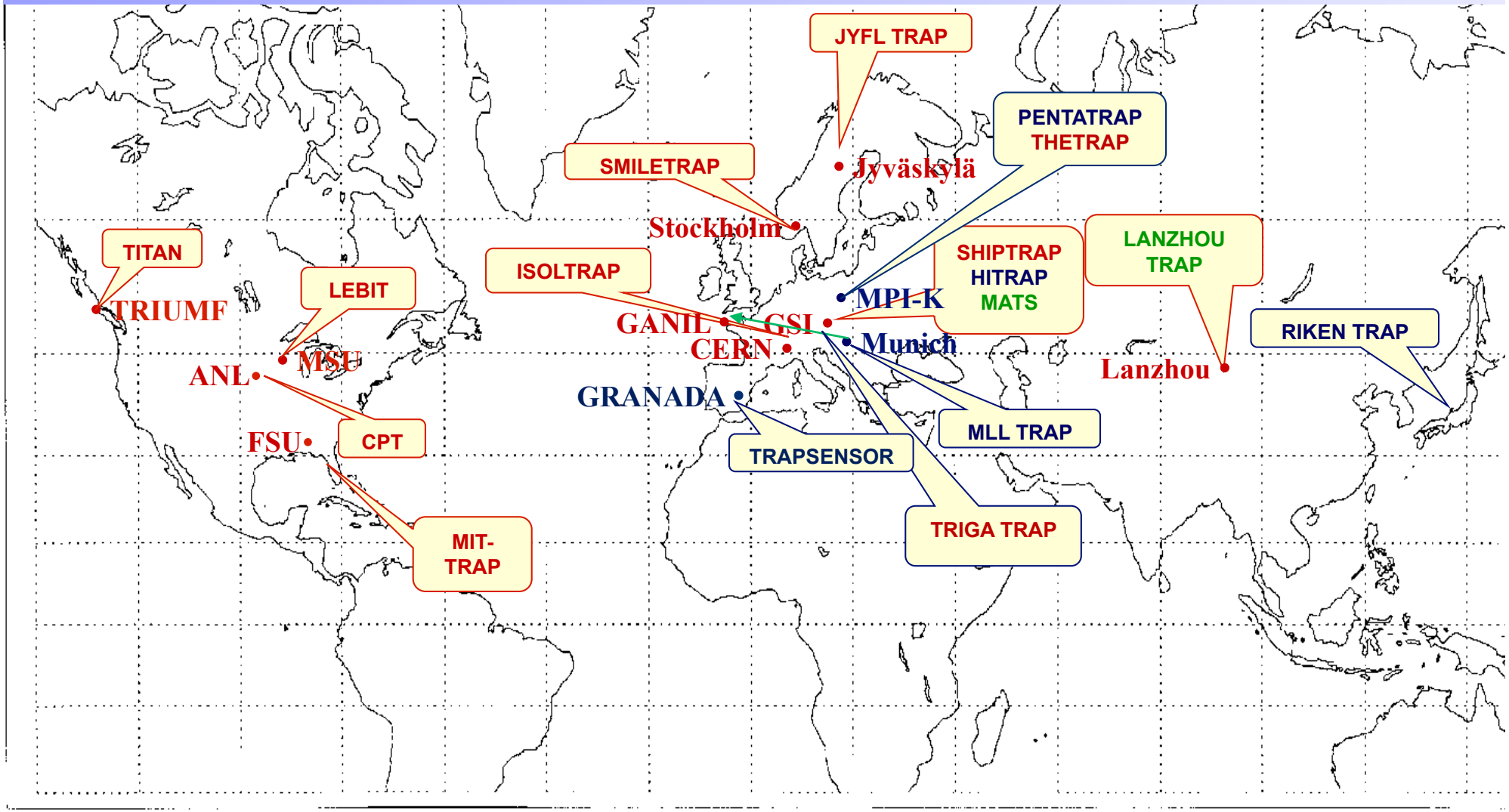


- Ion beam energy: ~ 1 eV
- Mass Resolving Power: 1×10^{7}
- Measurement Uncertainty: 10^{-9}-10^{-10}

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

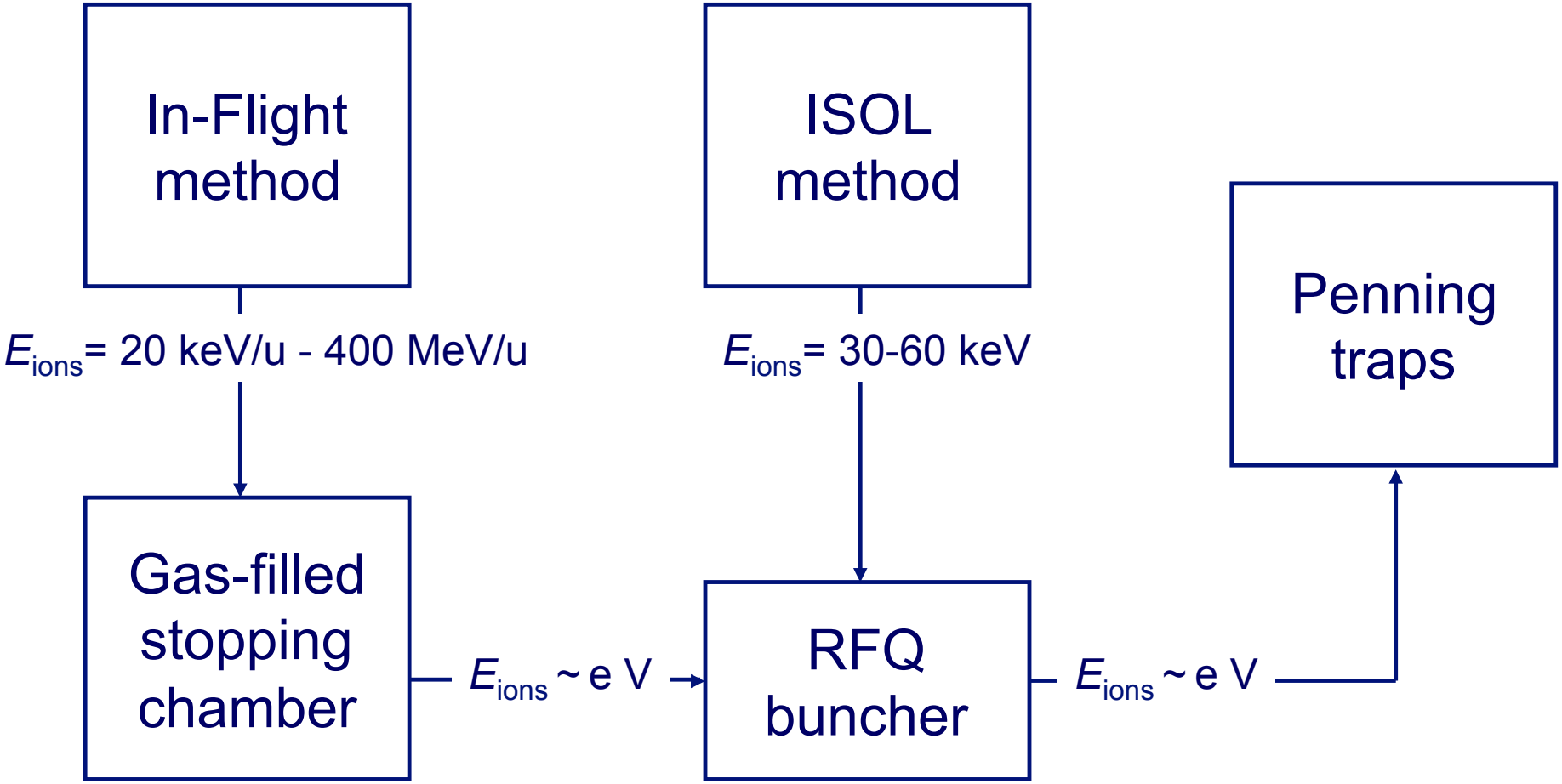
S. Eliseev *et al.*, PRL 110, (2013) 082501

Existing Penning-trap facilities
Mass spectrometry of atomic nuclei



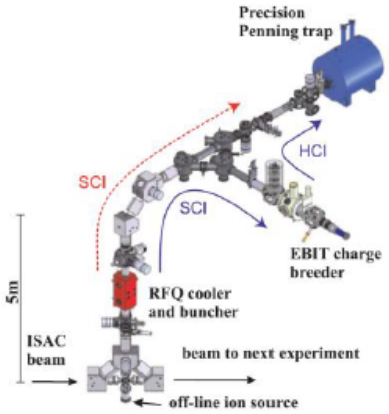
• Running facilities • Under construction • Future facilities

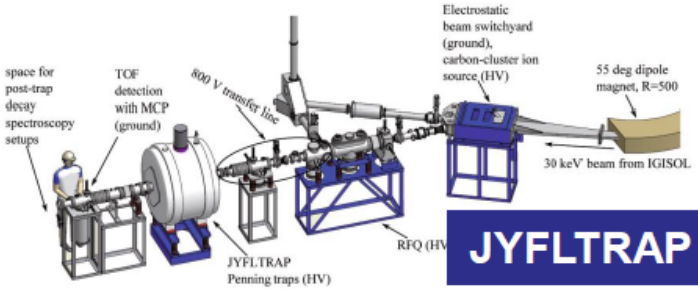
Coupling Penning traps to RIB facilities



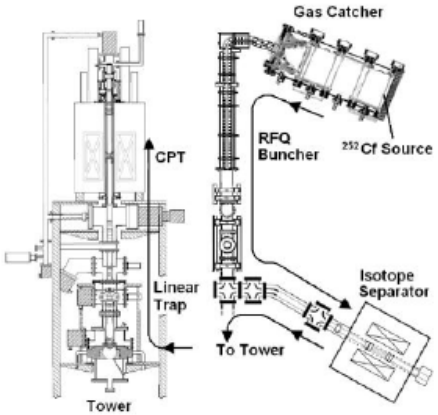
Growing facilities

TITAN (TRIUMF)

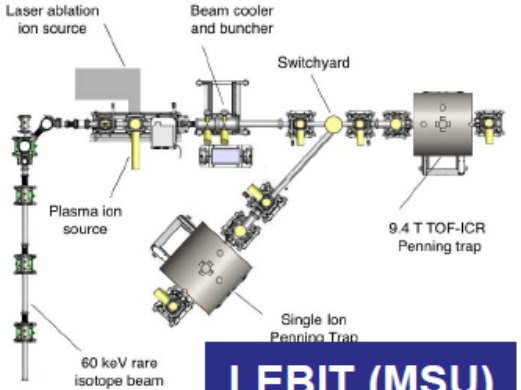




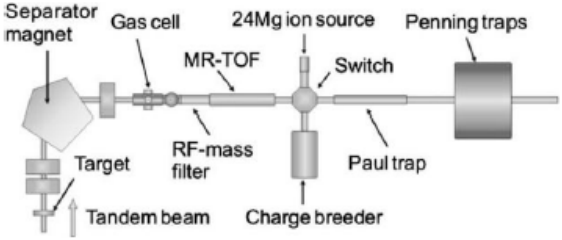
JYFLTRAP



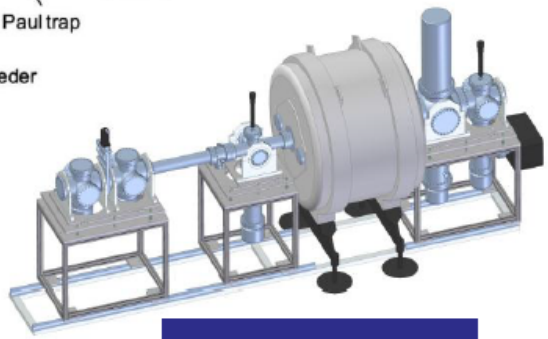
CPT (ARGONNE)



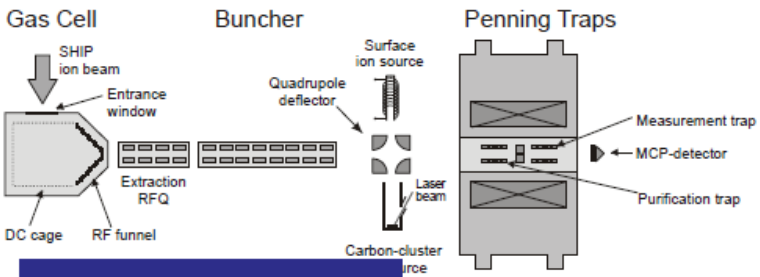
LEBIT (MSU)



MLLTRAP

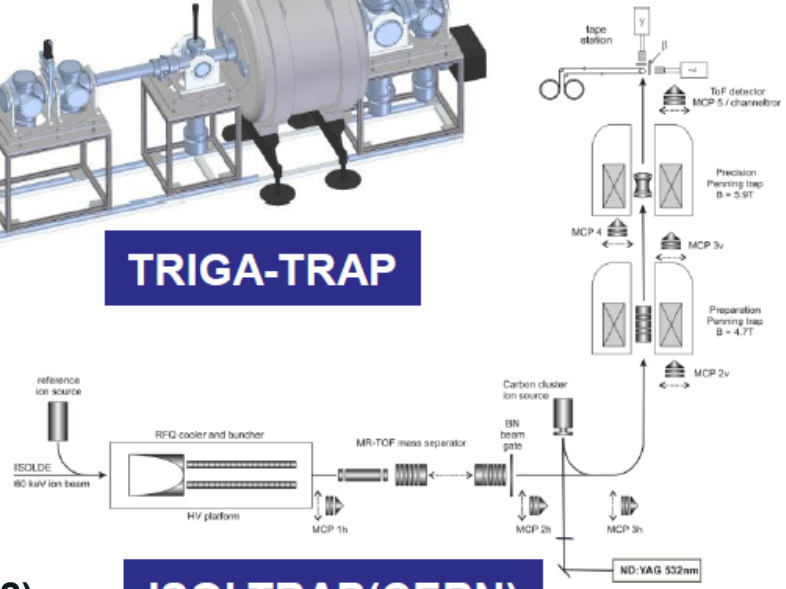


TRIGA-TRAP



SHIPTRAP (GSI)

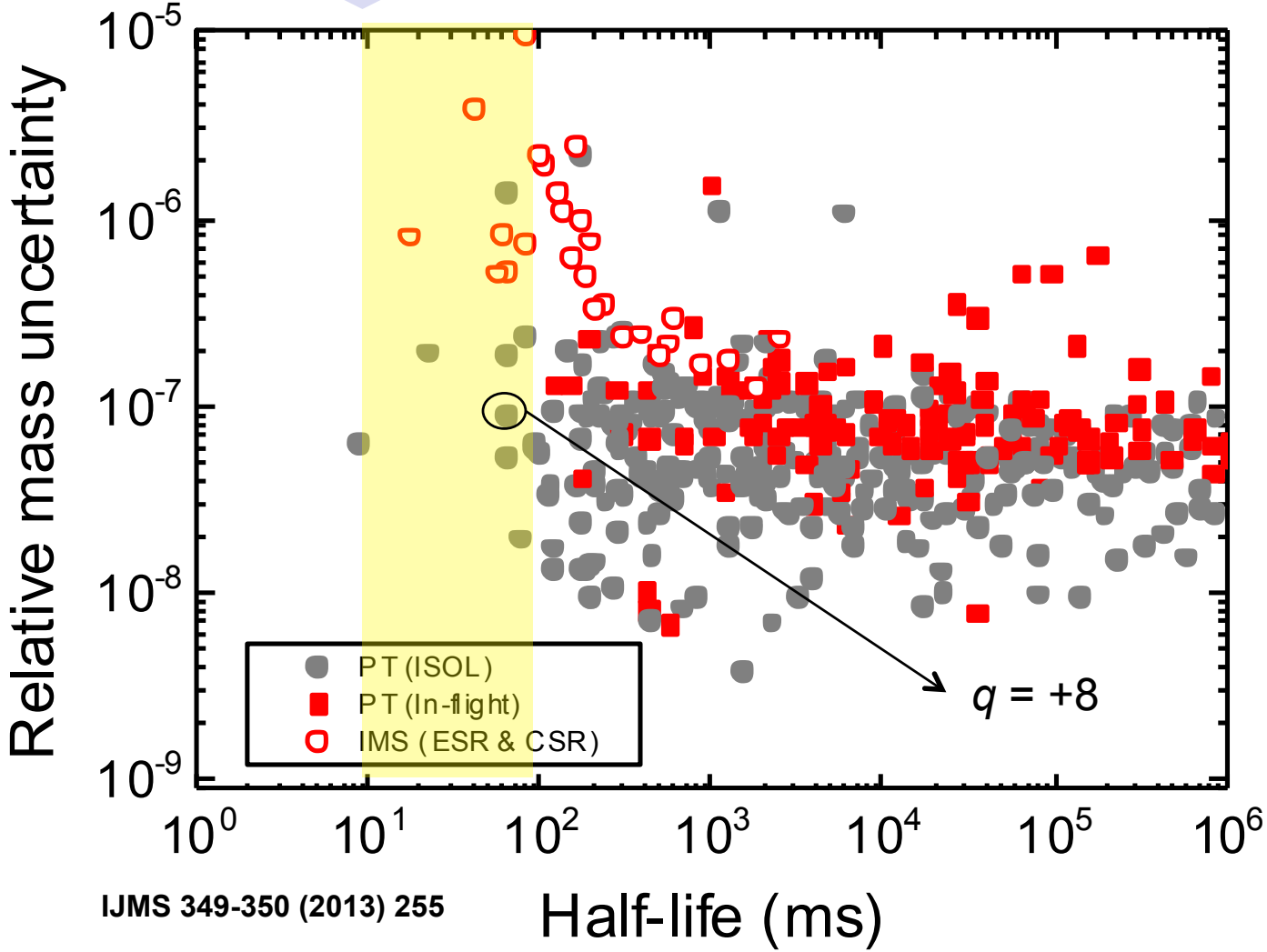
S. Nagy (EMIS2012)



ISOLTRAP(CERN)

Physics survey
Penning-trap mass measurements at RIB

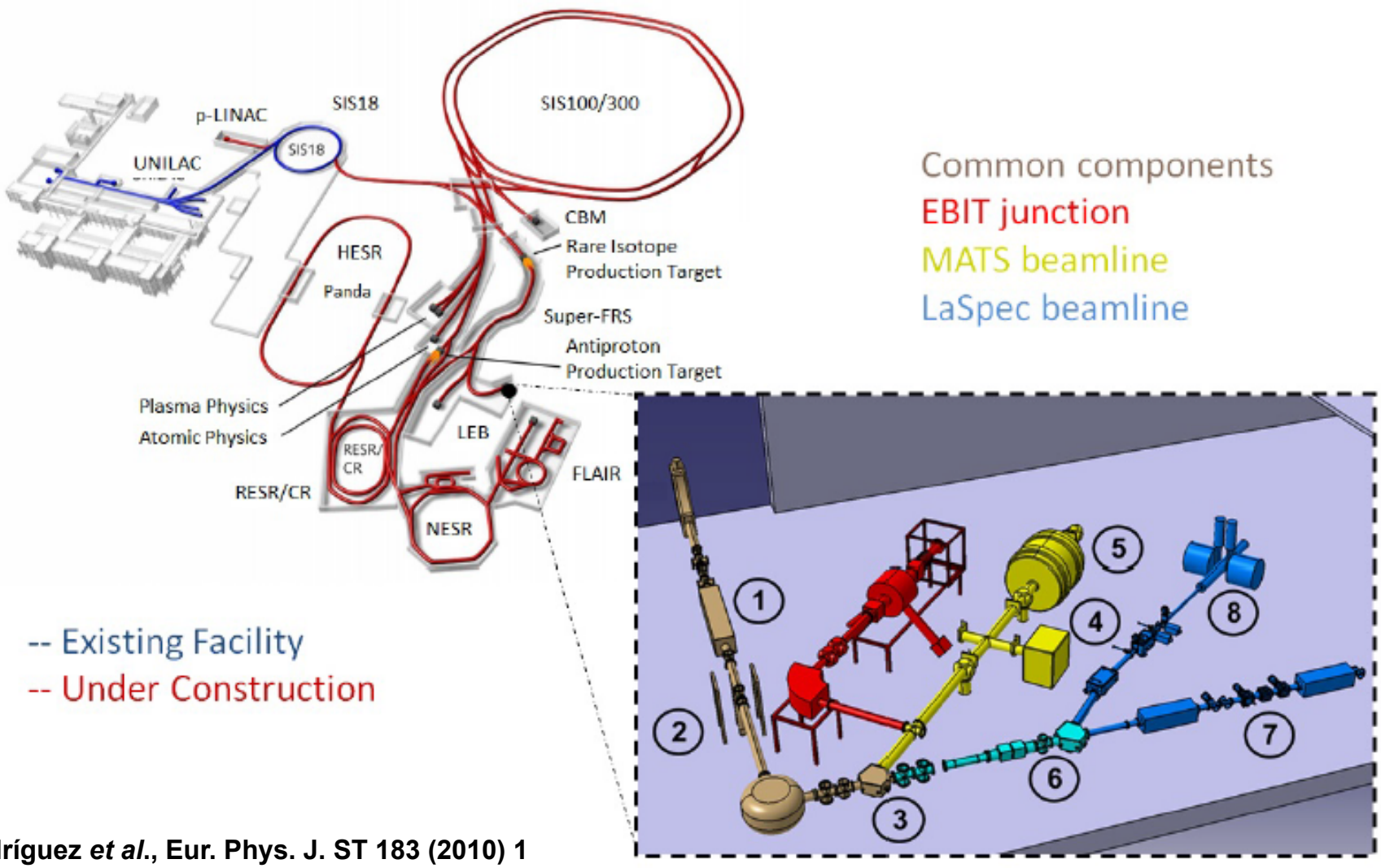
Practicable with higher production rates → MATS at FAIR



IJMS 349-350 (2013) 255

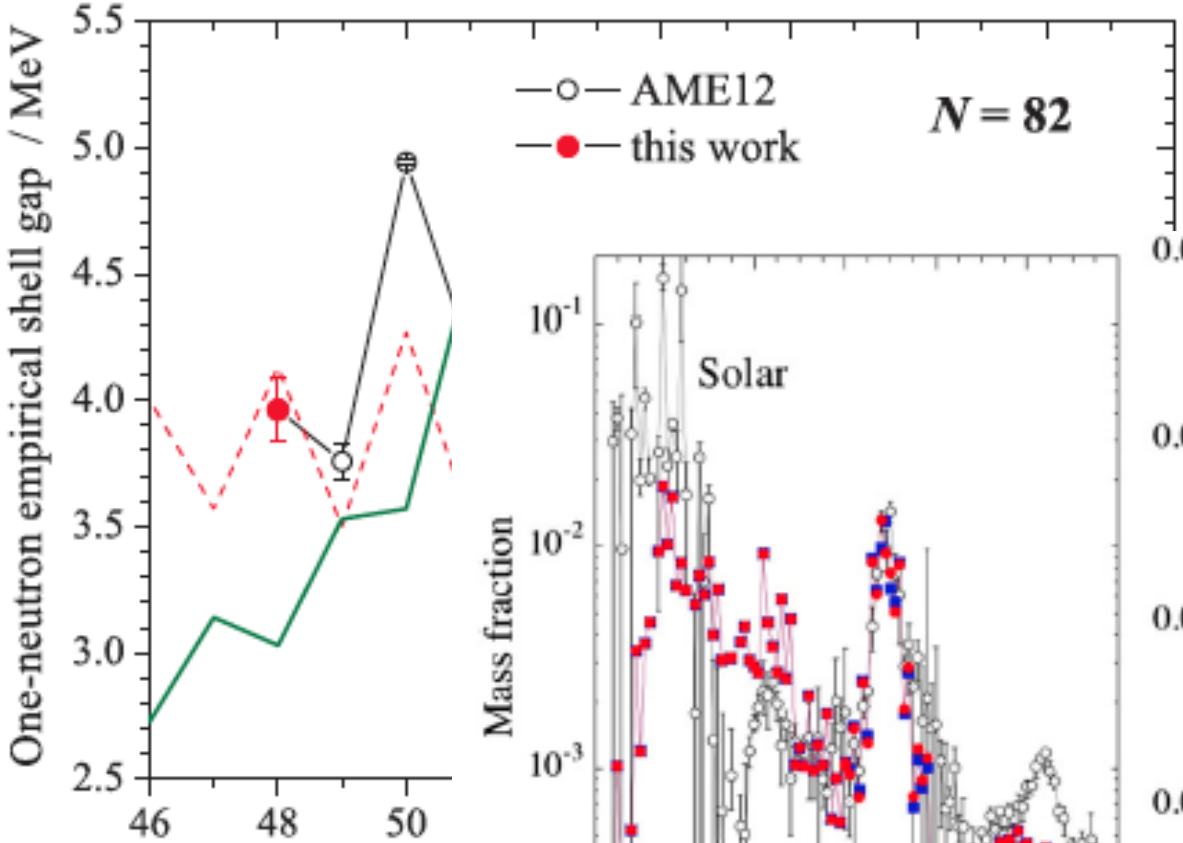
Most of the PT measurements performed with the TOF-ICR technique on 1+ or 2+ ions

Physics survey
Penning-trap mass measurements at RIB

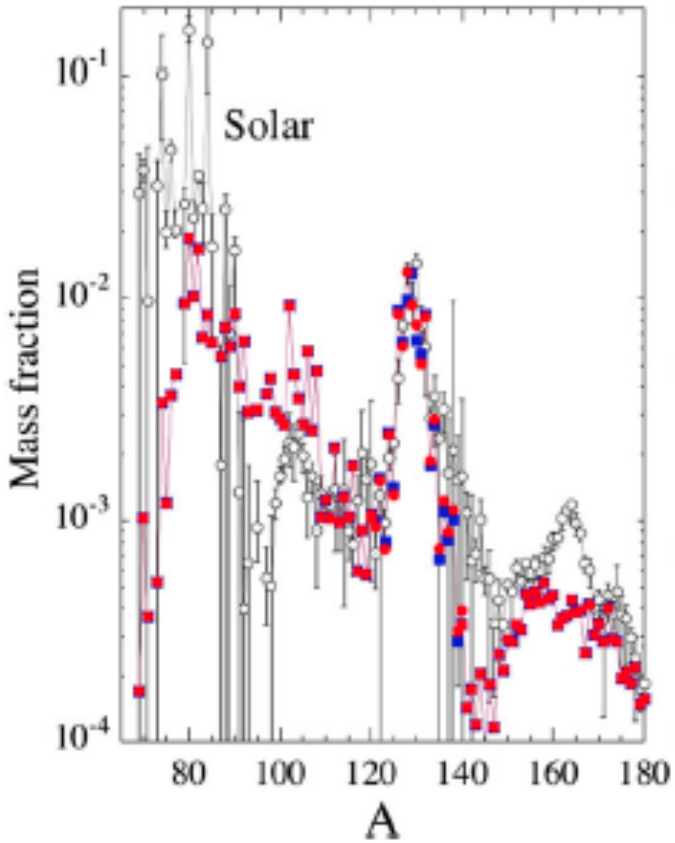


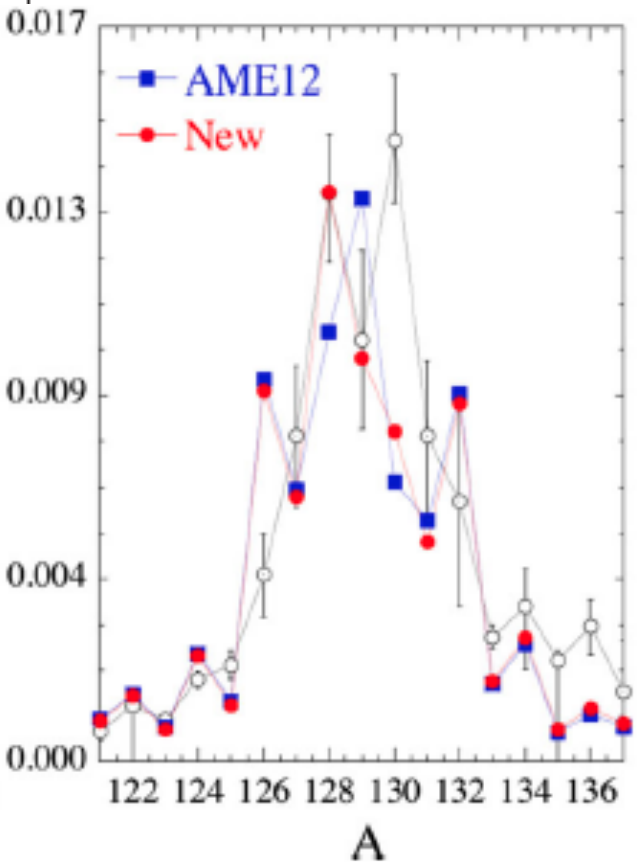
D. Rodríguez *et al.*, Eur. Phys. J. ST 183 (2010) 1

Recent highlights
Nuclear (Penning-trap) astrophysics at ISOLDE (2015)

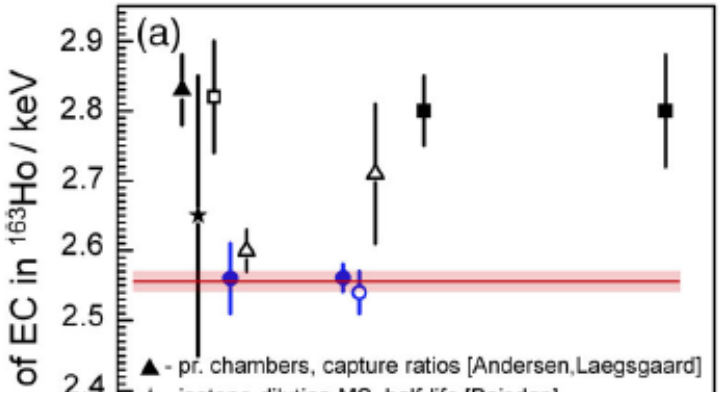


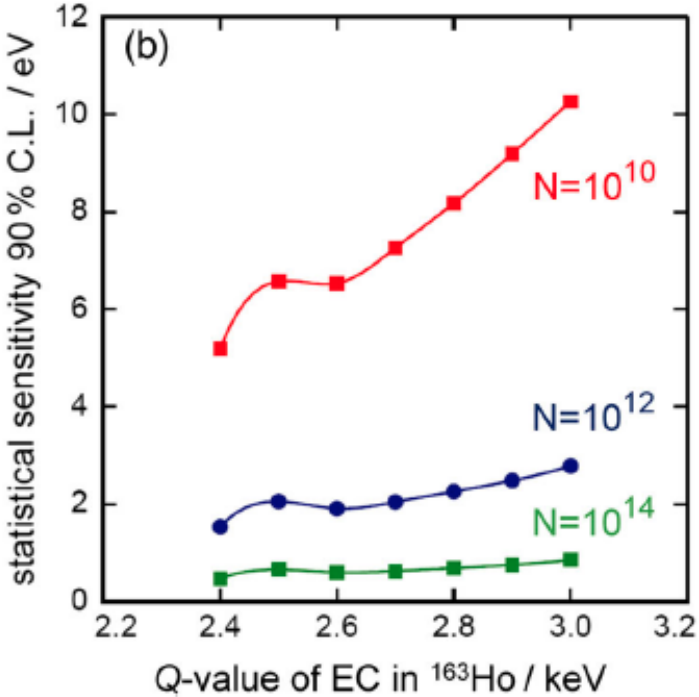
Pictures from
S. Eliseev *et al.*, PRL 115, (2015) 232501



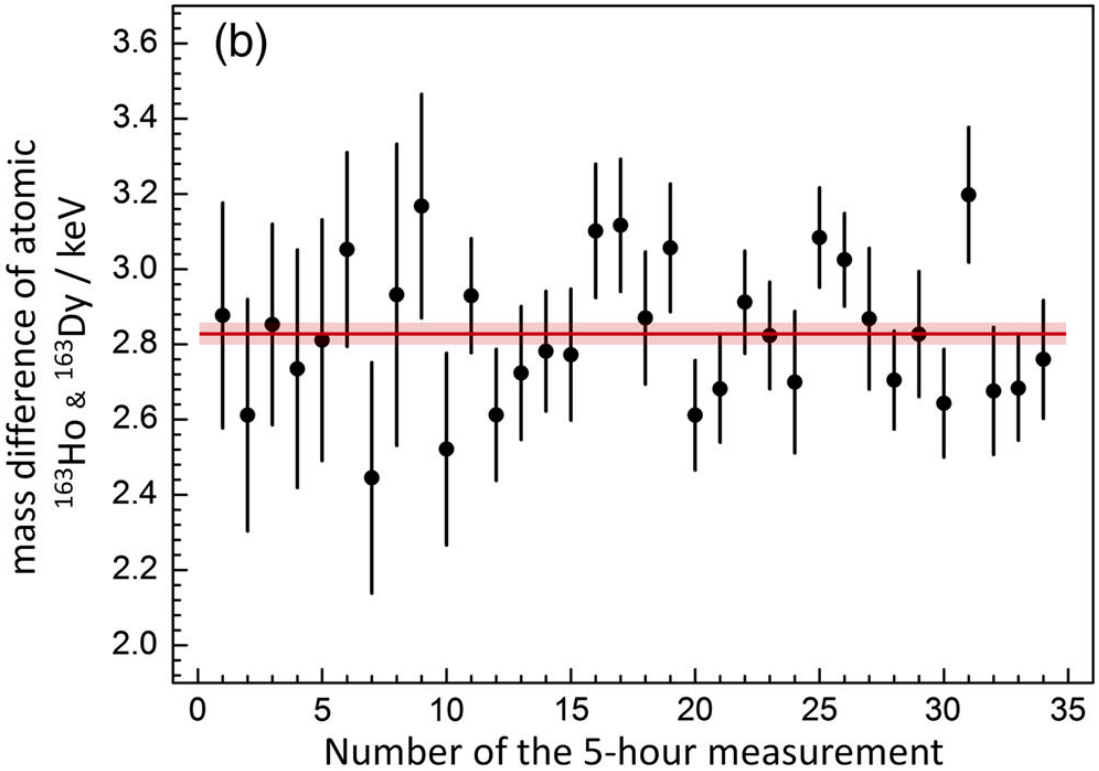


Recent highlights
Penning-trap *Q*-value for neutrino physics at GSI (2015)





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

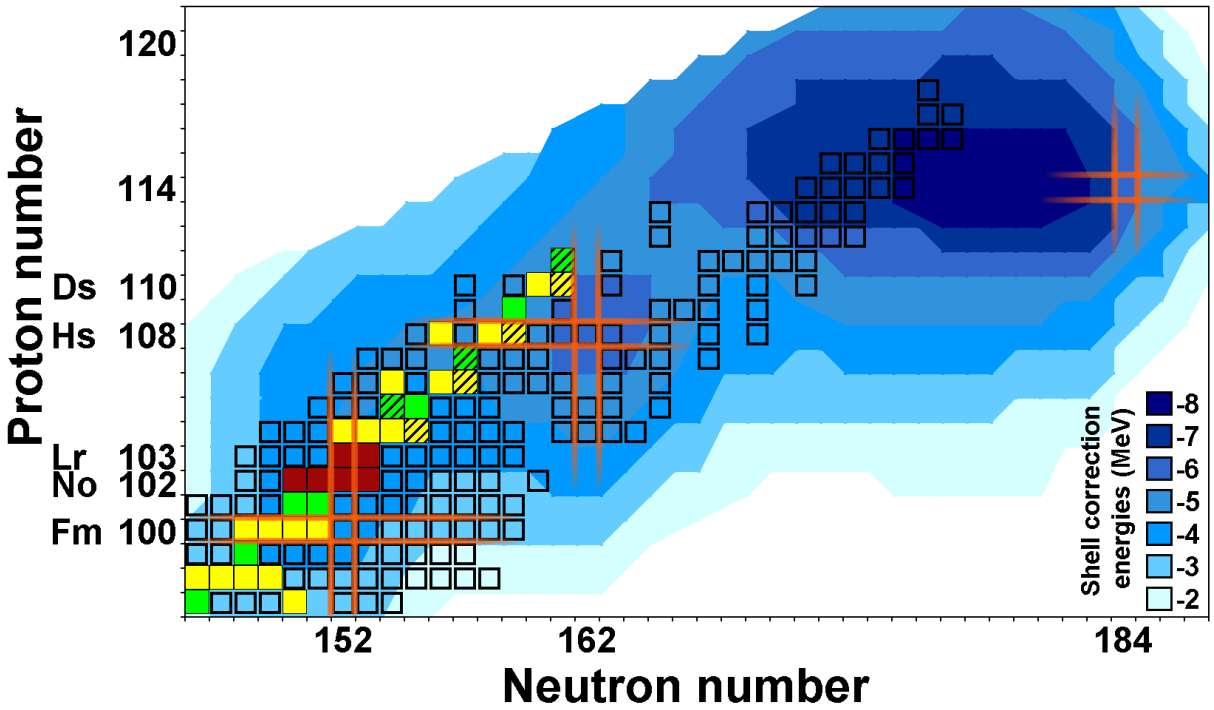


Pictures from S. Eliseev *et al.*, PRL 115, (2015) 062501

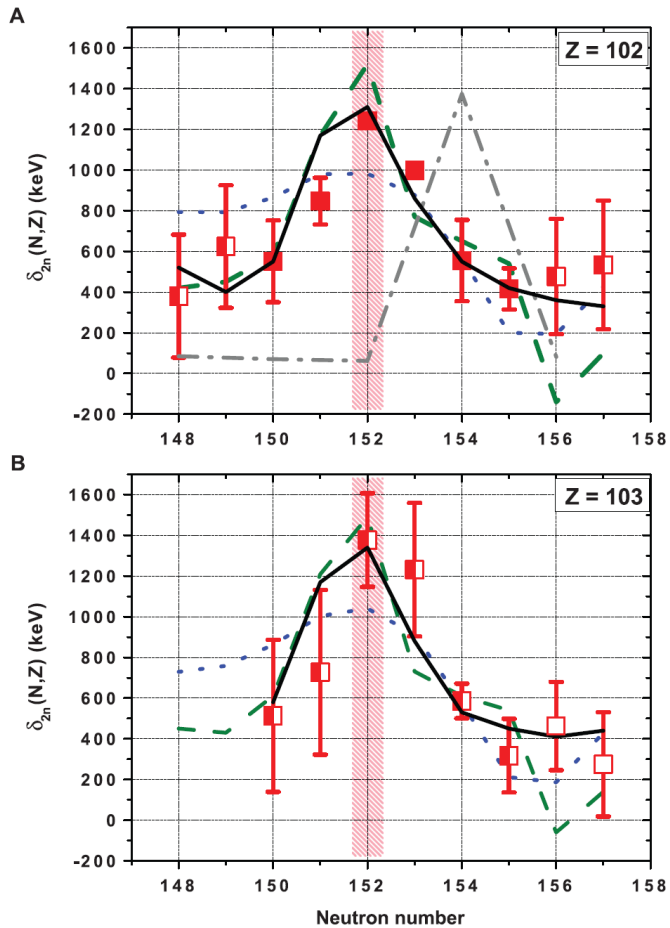
THE PROJECT TRAPSENSOR IN GRANADA

The TRAPSENSOR project
The technique

Nuclear Structure (minute production)



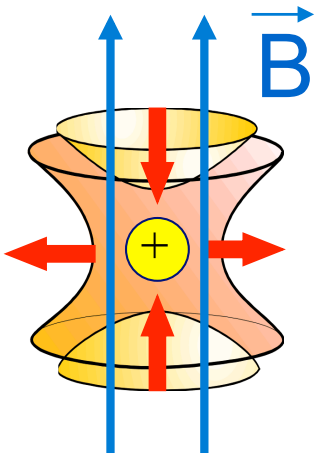
$$\delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$
$$= -2M_{exc}(N,Z) + M_{exc}(N-2,Z) + M_{exc}(N+2,Z),$$

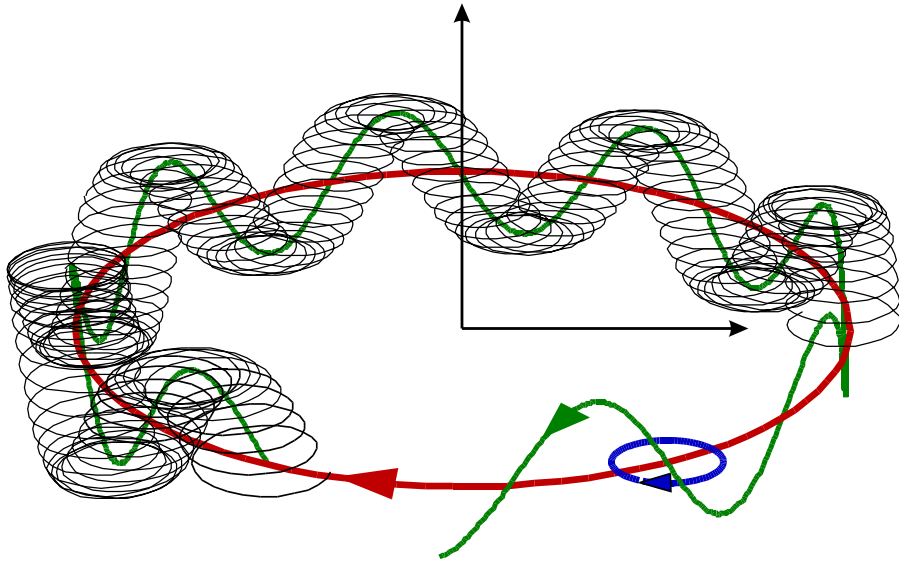


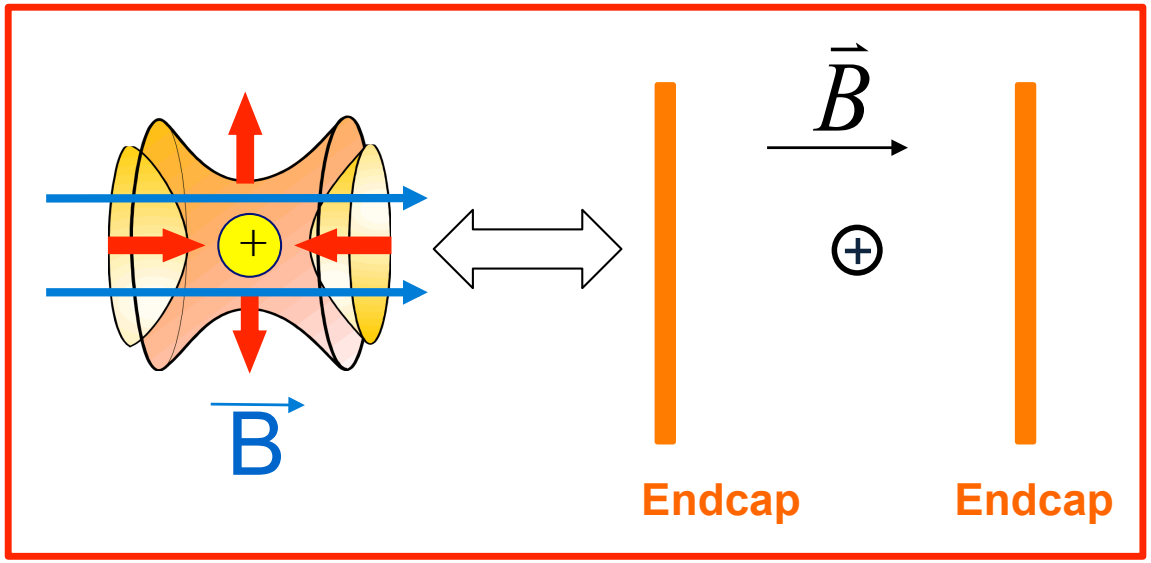
- The isotope with lowest production rate ever measured in a Penning trap (^{256}Lr, 60(18) nb)
  →48 ions detected in 93 hours !!!

E. Minaya Ramirez *et al.*, Science 337 (2012) 1207

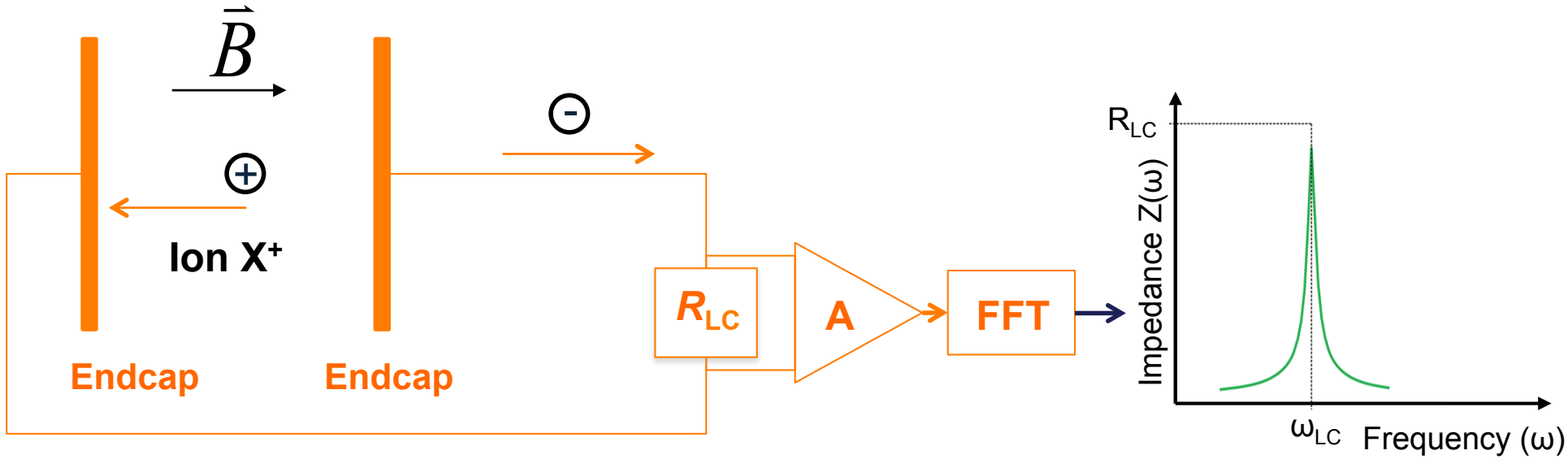
The TRAPSENSOR project
The technique







The TRAPSENSOR project
The technique



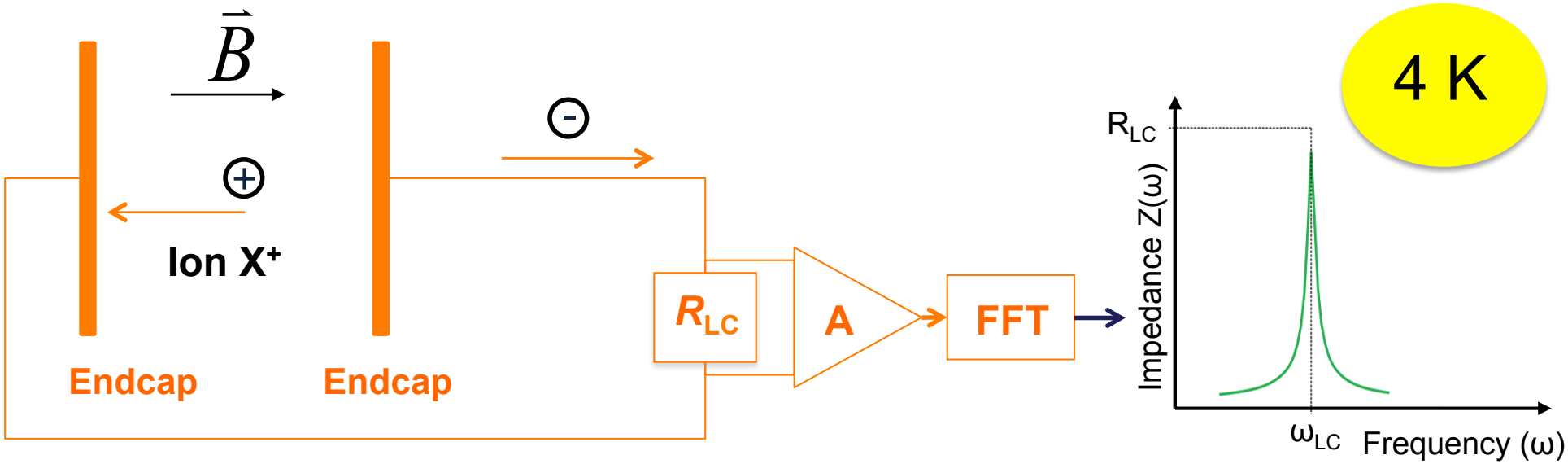
Induced image-current → Oscillation frequency → *m/q*

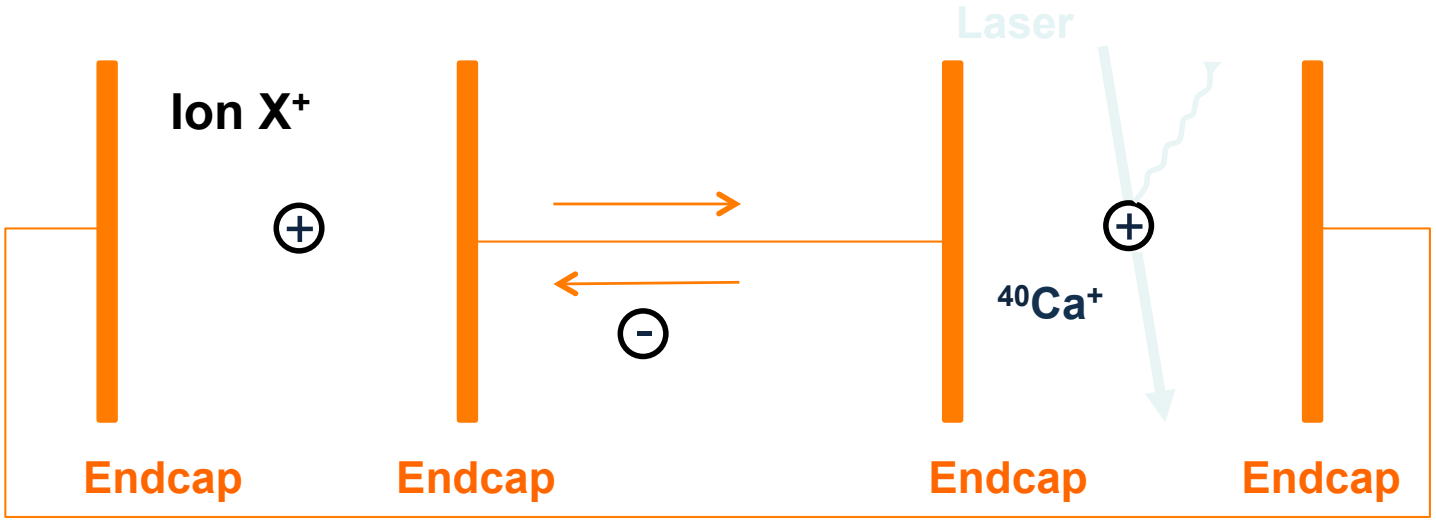
$$\omega_+^2 + \omega_z^2 + \omega_-^2 = \omega_c^2$$

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

It has been demonstrated for low or medium *m/q*

The TRAPSENSOR project
The technique





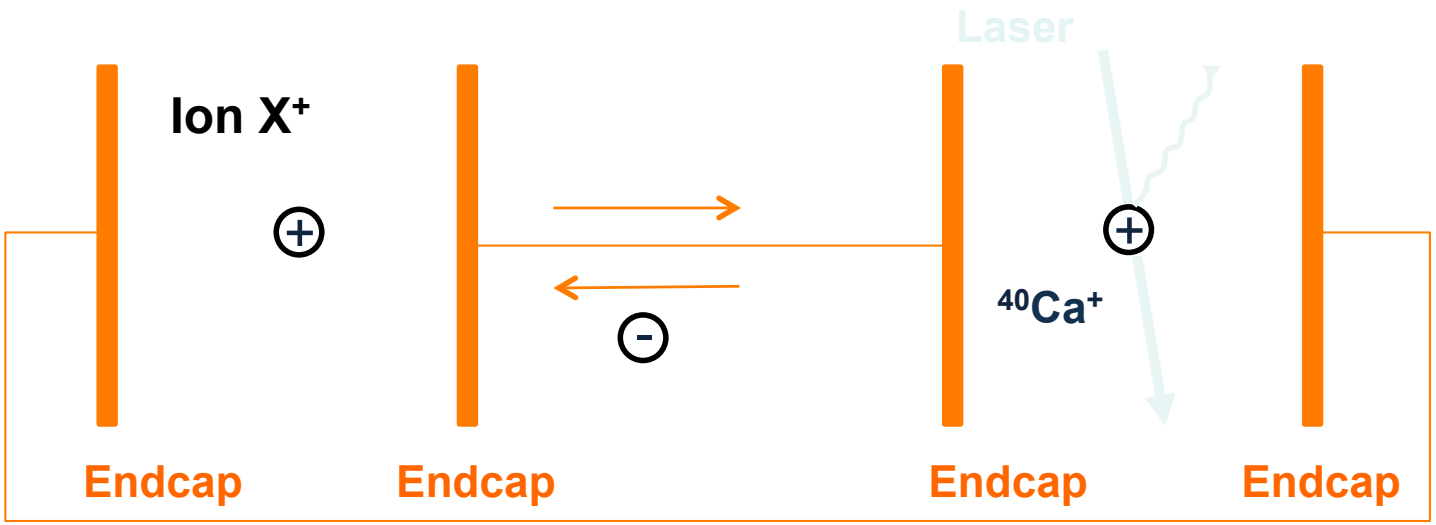
1 mK

D. J. Heinzen and D. J. Wineland, Phys. Rev. A 42(5) 2977 (1990)

The TRAPSENSOR project
The technique

1. Ion X^+ is probed with a radiofrequency field and will be detected in the optical regime.
2. Ion X^+ can be any ion regardless of its mass, charge and polarity.

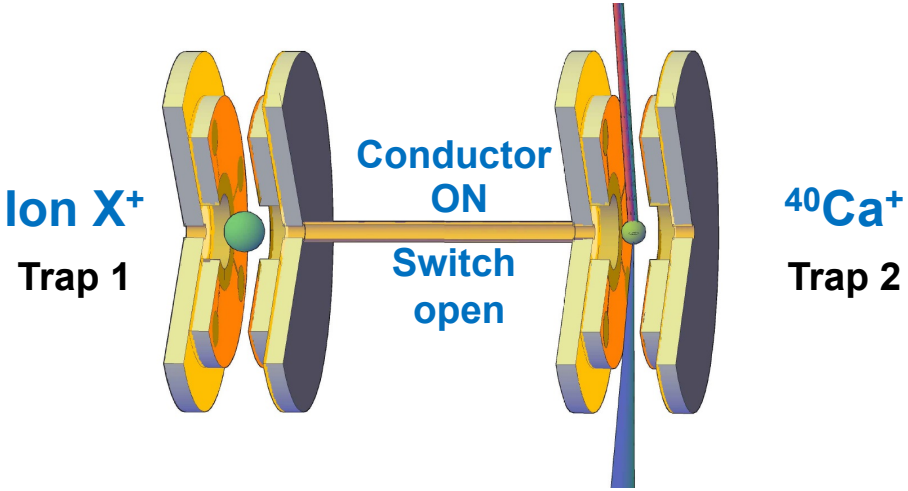
MICRO-TRAPS + LASERS + EXTERNAL ION SOURCE + PENNING TRAP BEAMLINE



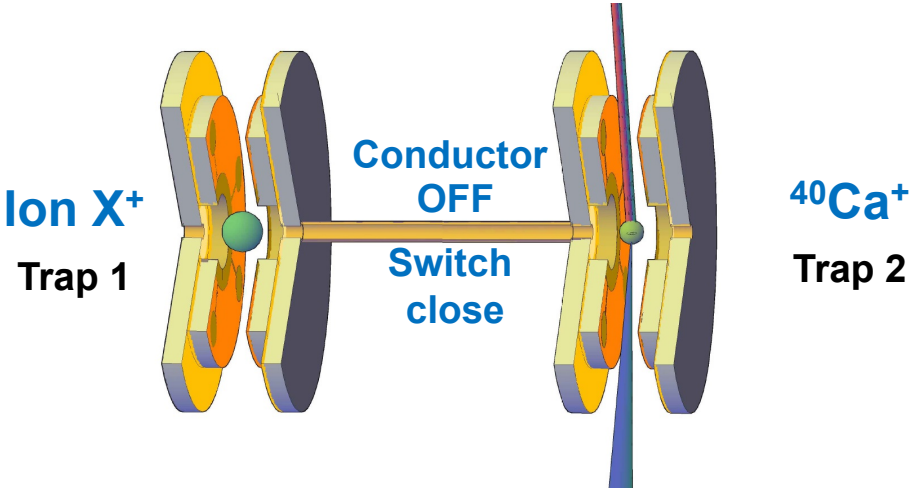
D. J. Heinzen and D. J. Wineland, Phys. Rev. A 42(5) 2977 (1990)

The project TRAPSENSOR
The technique

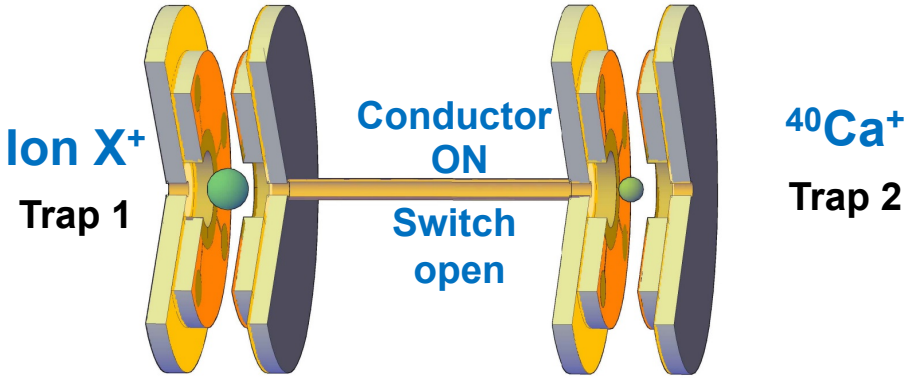
1. COOLING



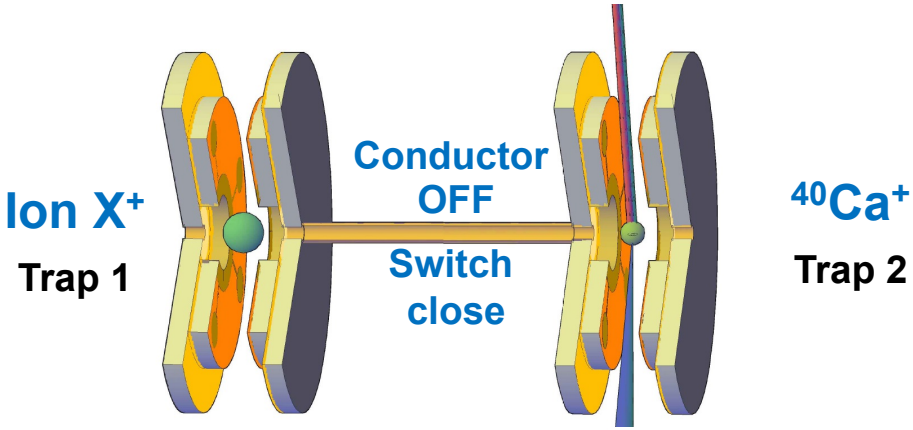
2. PROBING ION X+



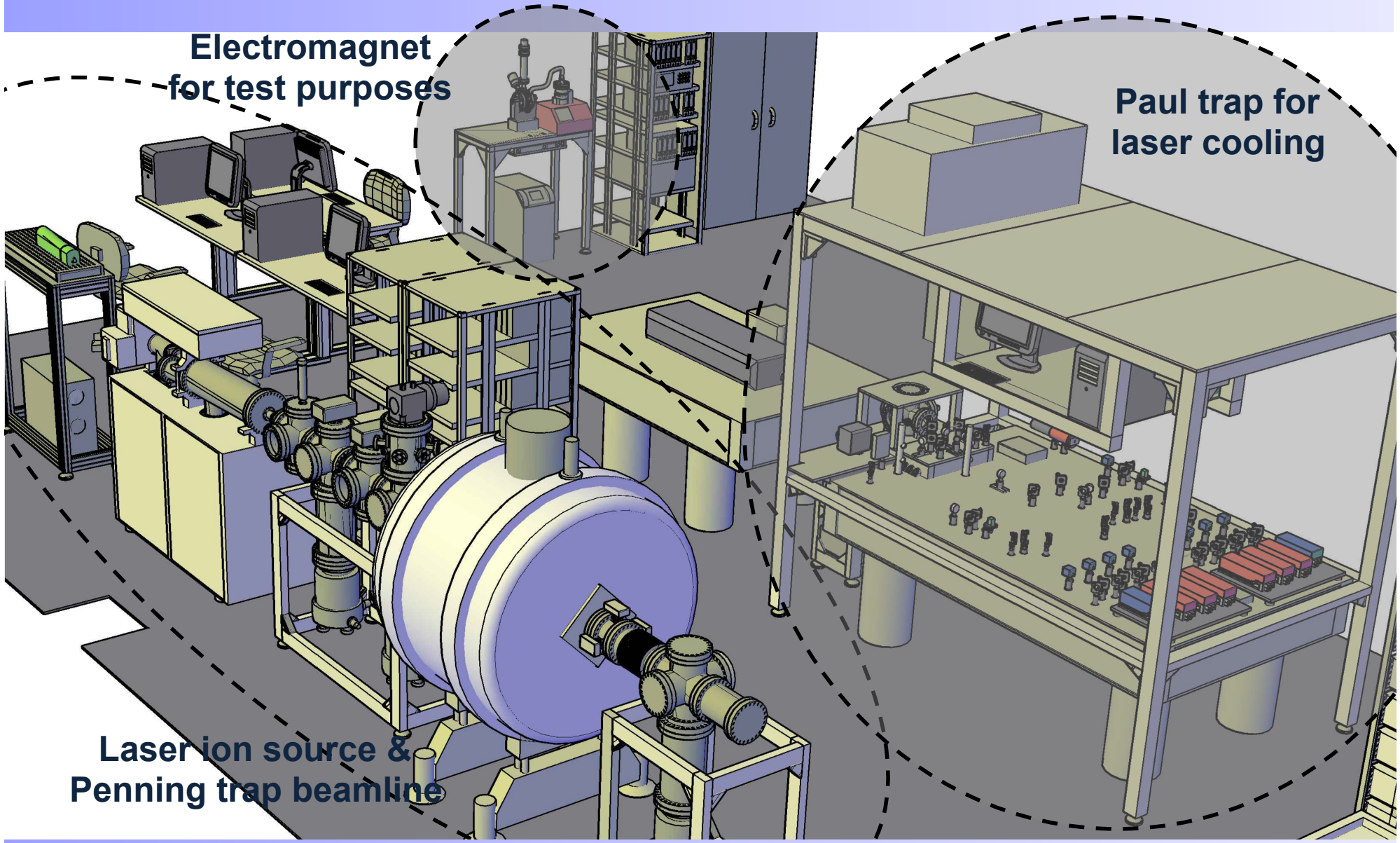
3. ION-ION INTERACTION



4. INTERROGATION

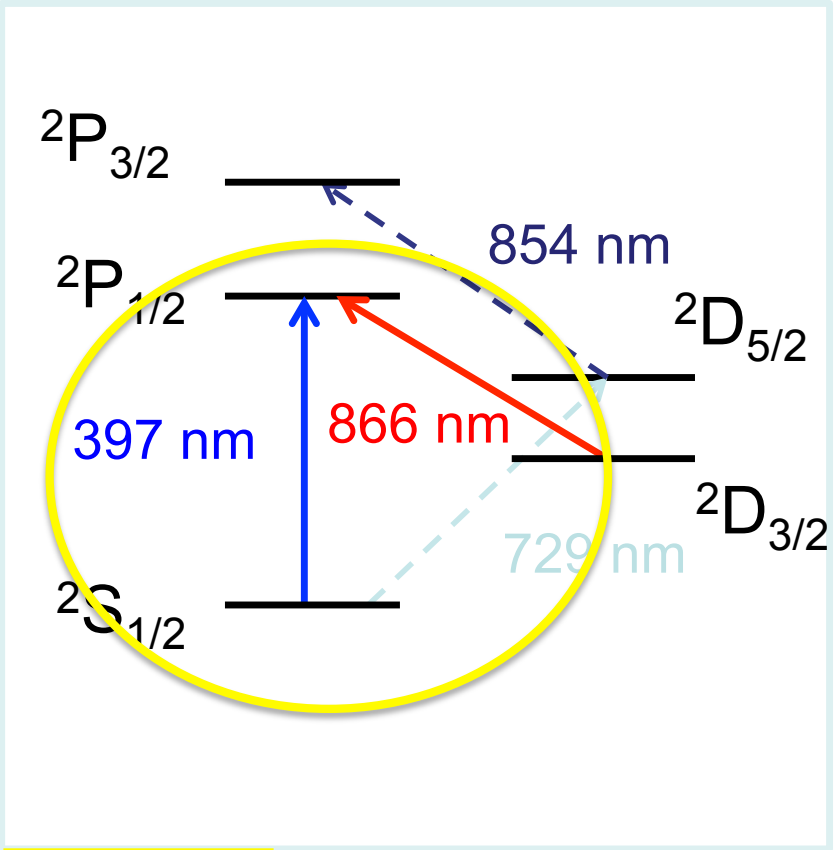


The project TRAPSENSOR
An overview of a Penning-trap beamline



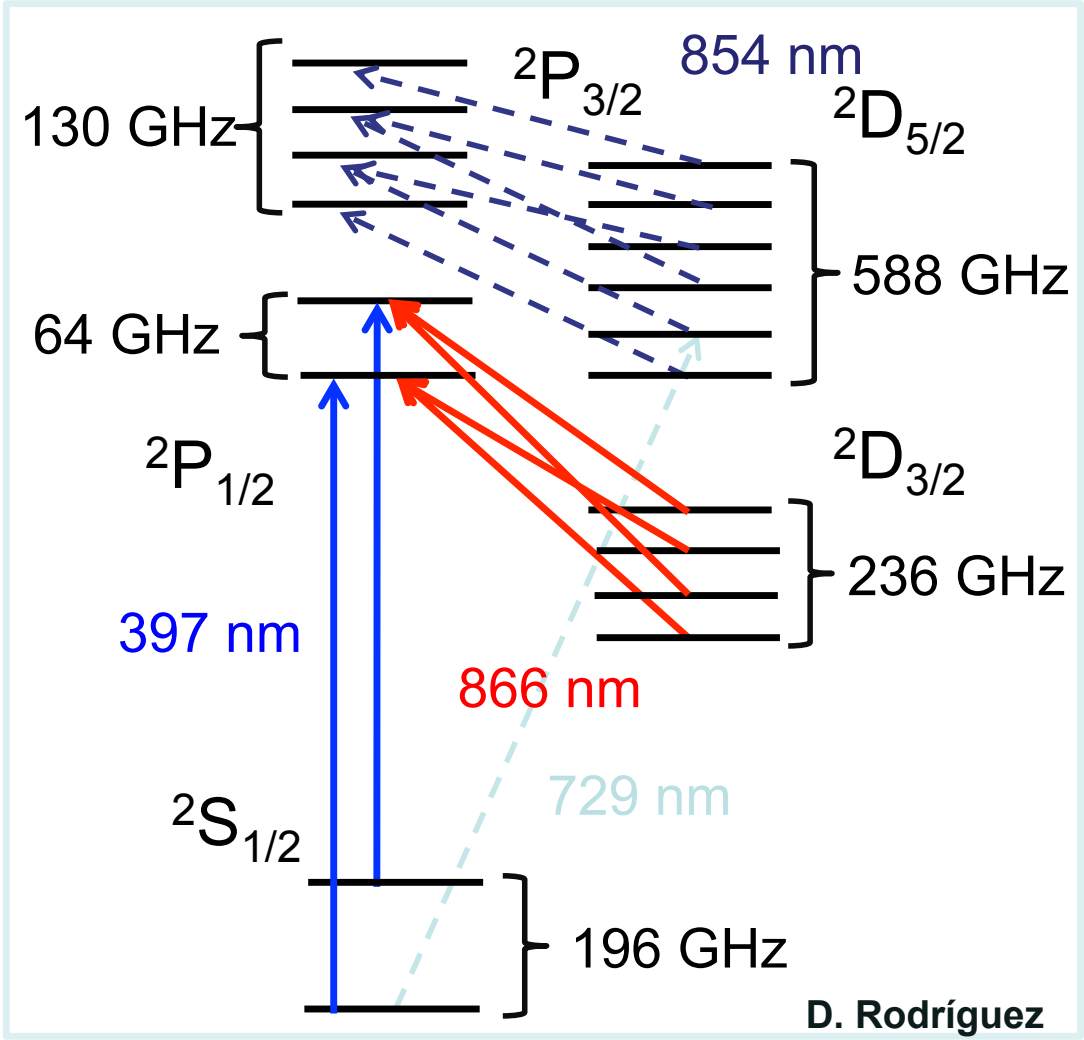
The project TRAPSENSOR
Laser system

1. Level scheme for a $^{40}Ca^{+}$ ion in a Paul trap

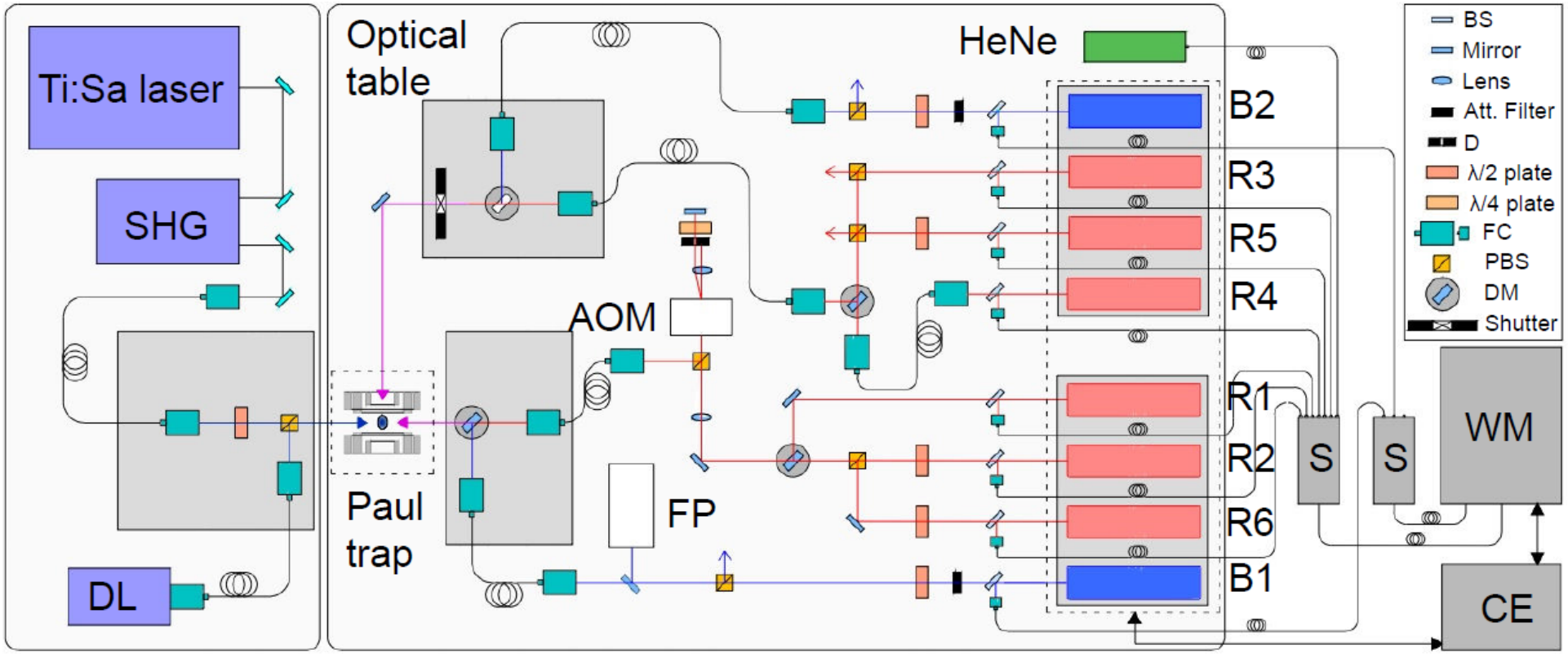


Doppler cooling

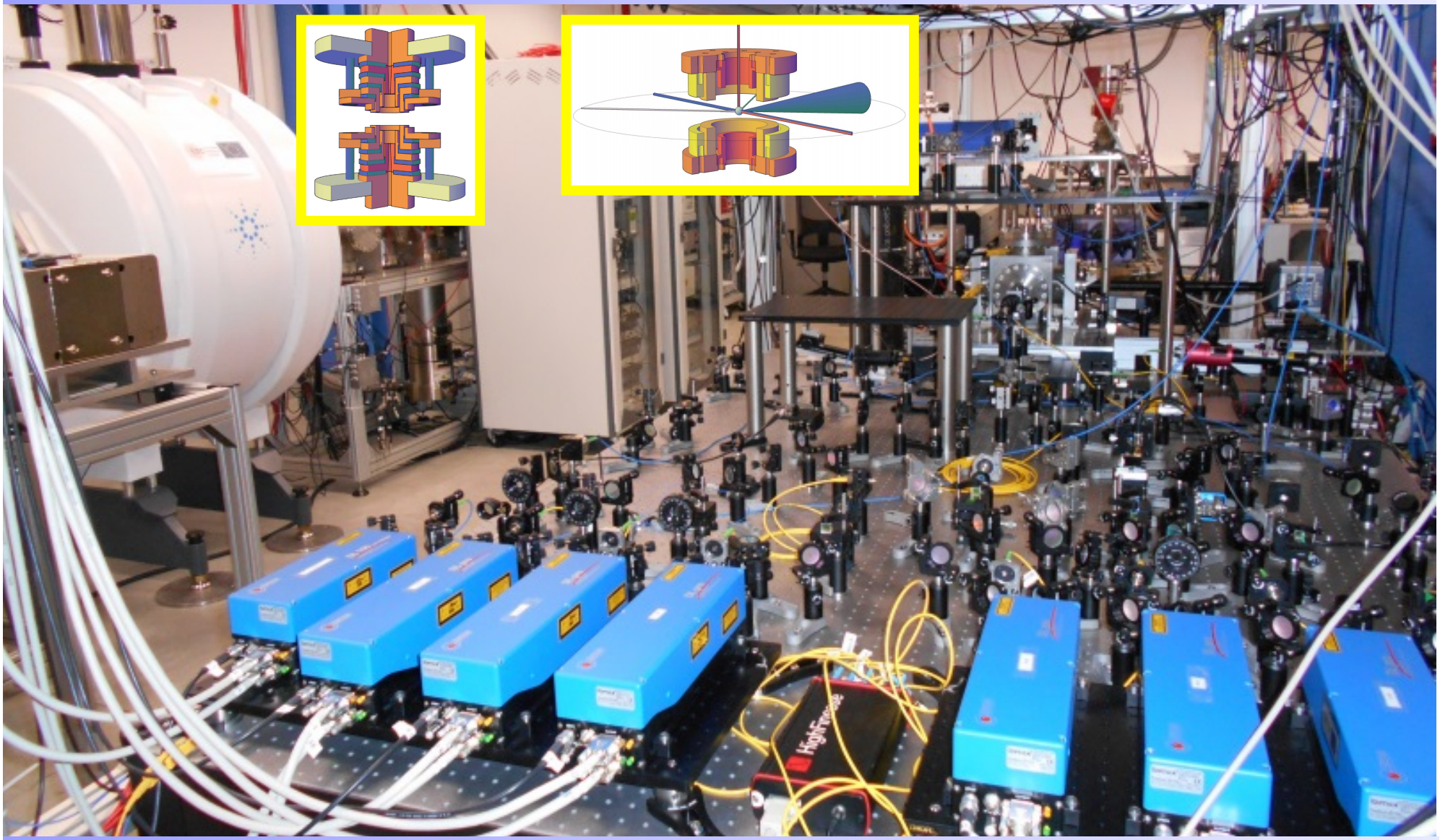
2. Level scheme for a $^{40}Ca^{+}$ ion in a 7-T magnetic field



The project TRAPSENSOR
Laser system

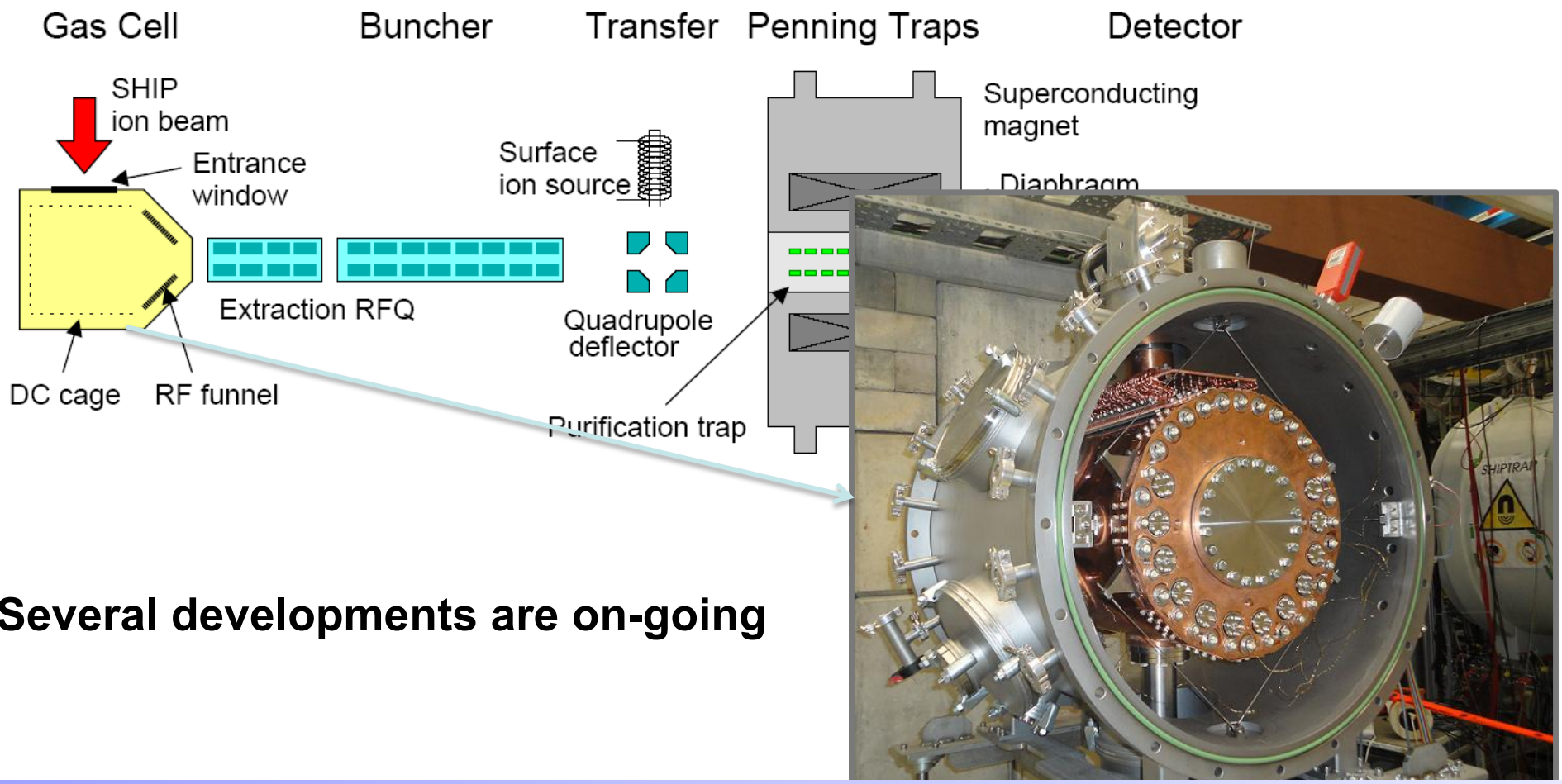


The project TRAPSENSOR
Laser system



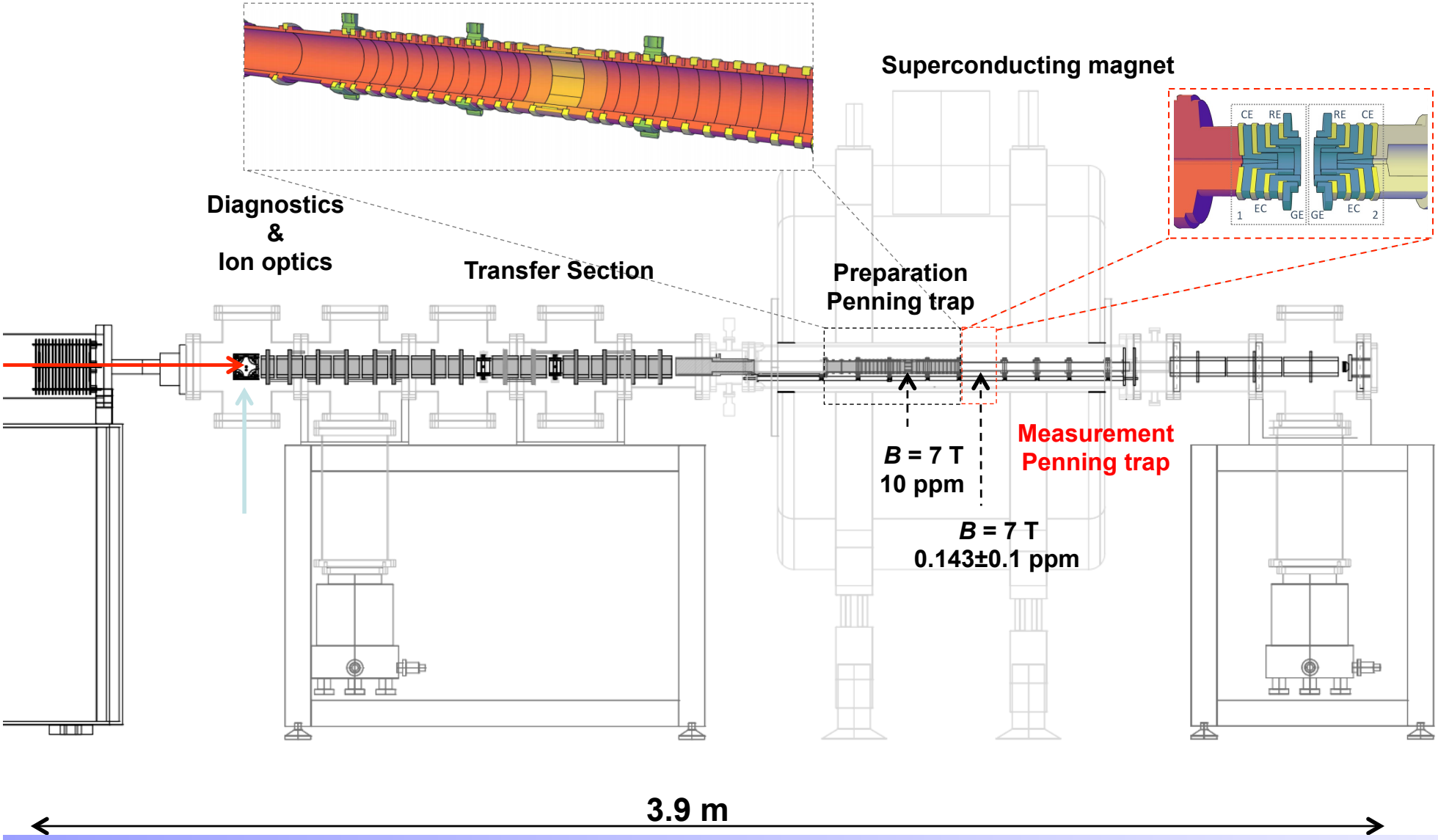
The project TRAPSENSOR
SHIPTRAP beamline

≈ 50 MeV ⟶ ≈ 1 eV

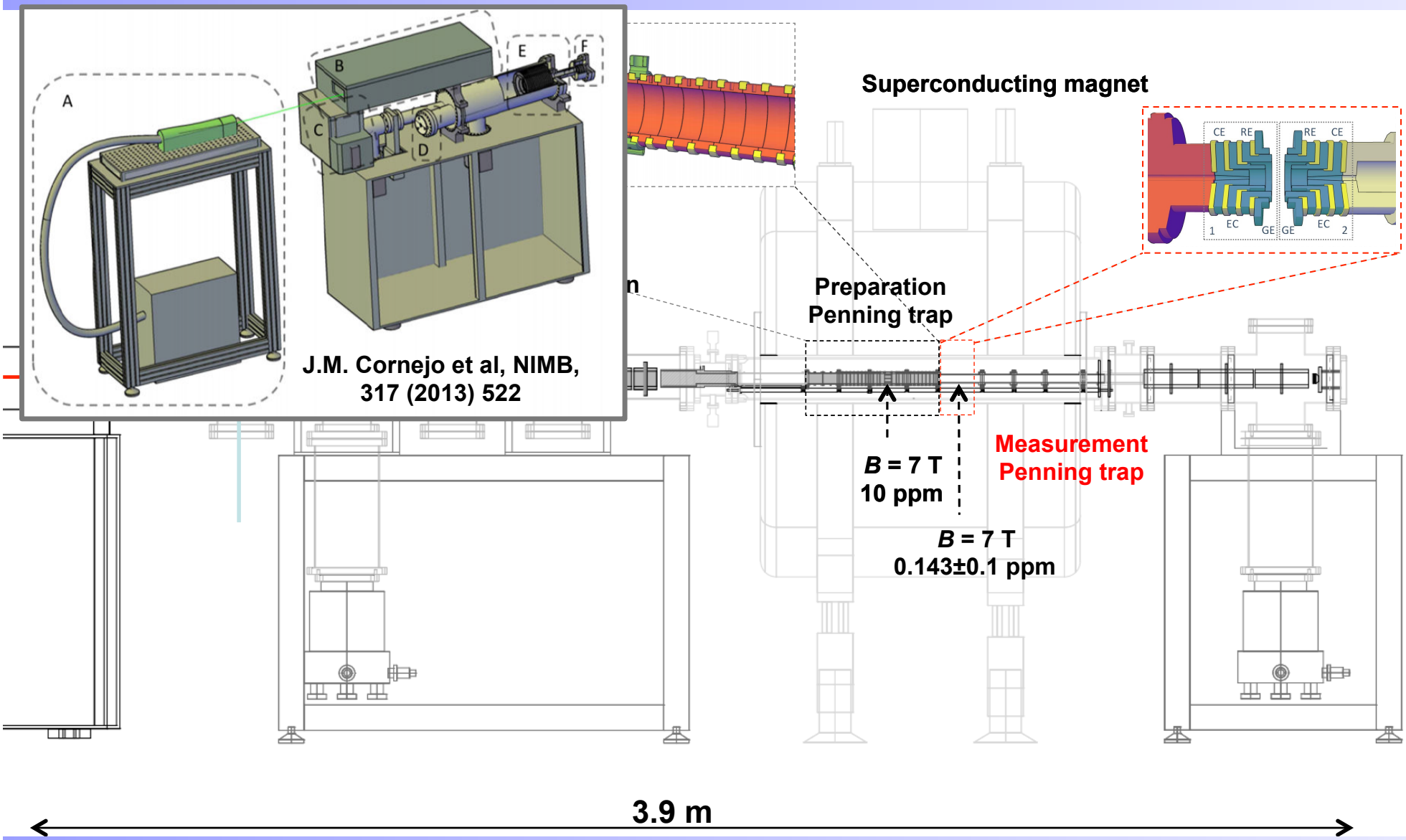


Several developments are on-going

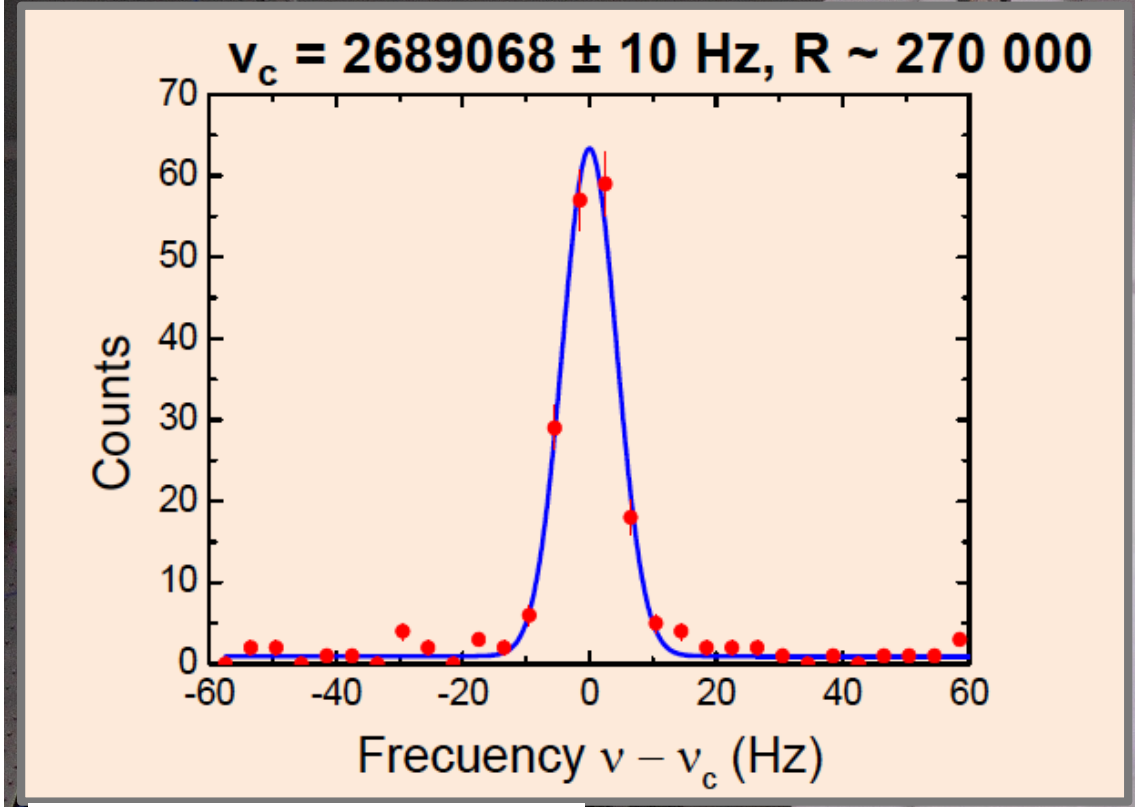
The project TRAPSENSOR
The Penning-traps beamline



The project TRAPSENSOR
The Penning-traps beamline

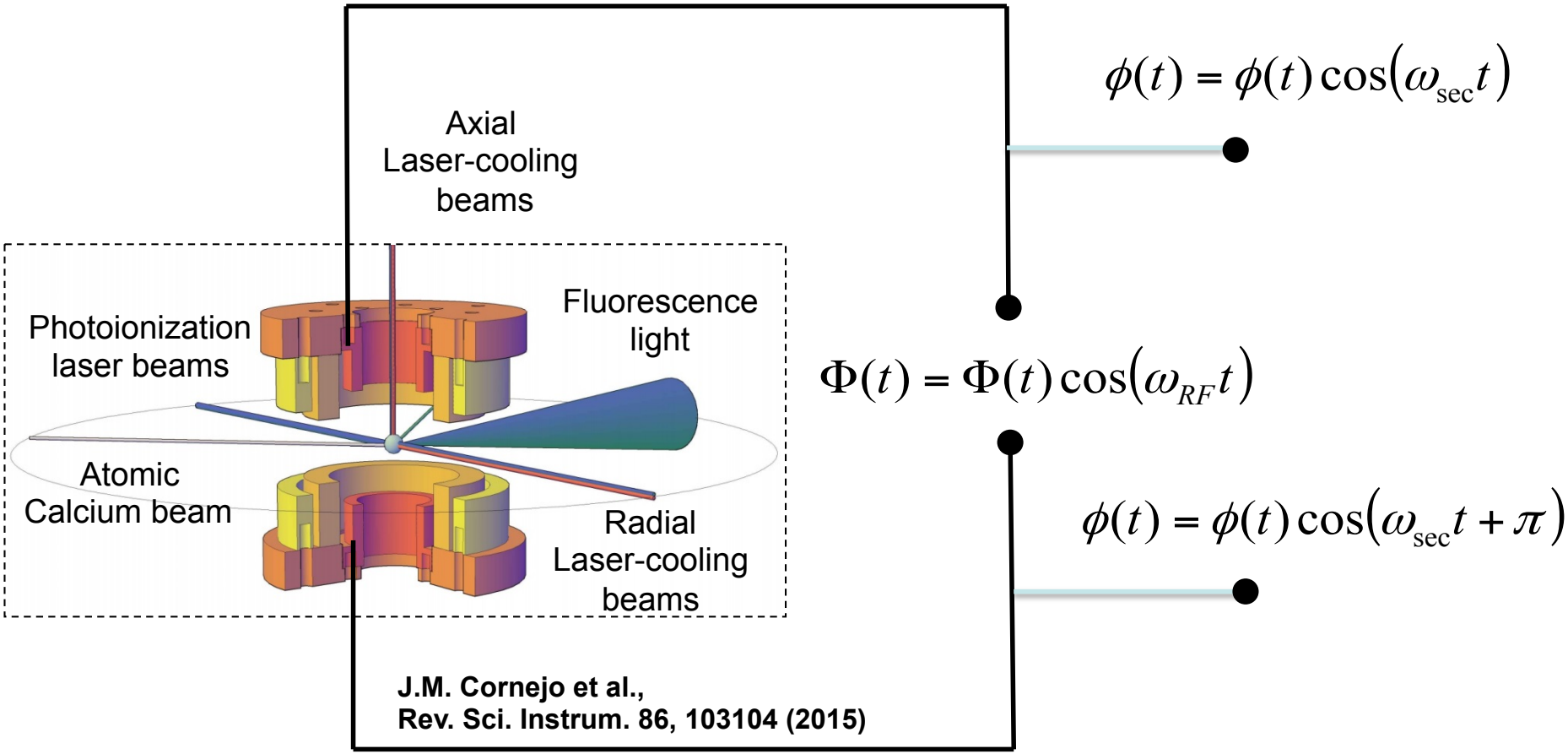


The project TRAPSENSOR
The preparation Penning trap



J.M. Cornejo and D. Rodríguez, NIMB, in press, corrected proofs

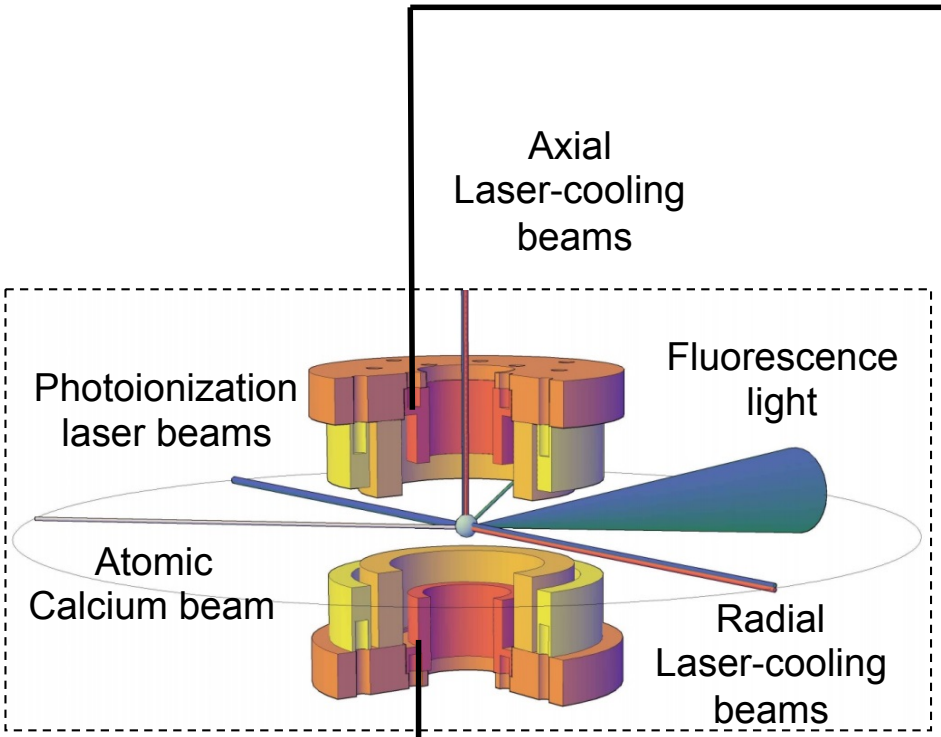
The project TRAPSENSOR
First experiment (laser cooling)



J.M. Cornejo et al.,
Rev. Sci. Instrum. 86, 103104 (2015)

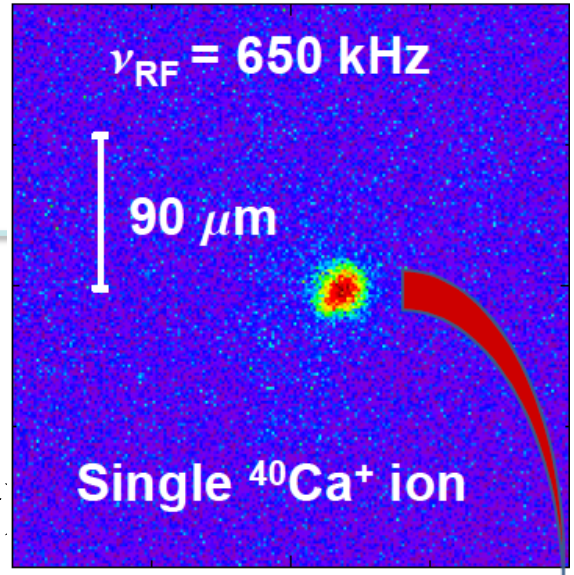
Measuring the sensitivity of the laser-cooled $^{40}Ca^{+}$ ion using an external RF field

The project TRAPSENSOR
First experiment (laser cooling)

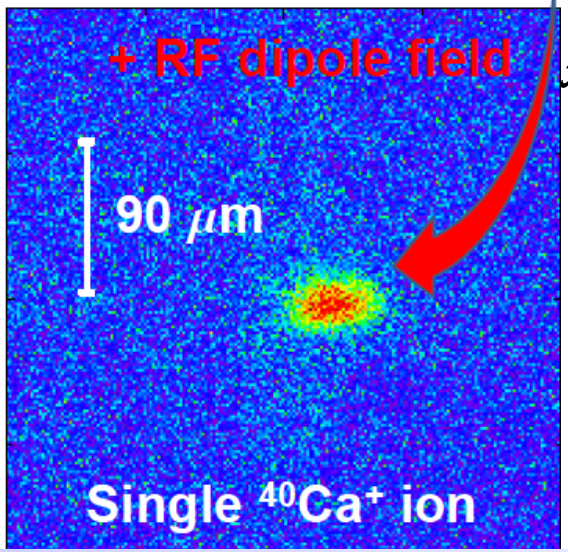


J.M. Cornejo et al.,
Rev. Sci. Instrum. 86, 103104 (2015)

$\Phi(t) = \Phi(t$



$\pi)$

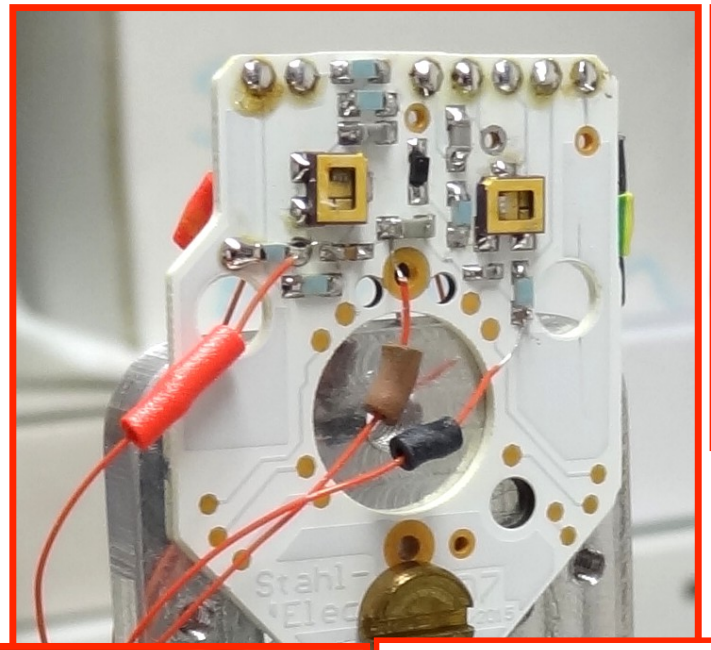


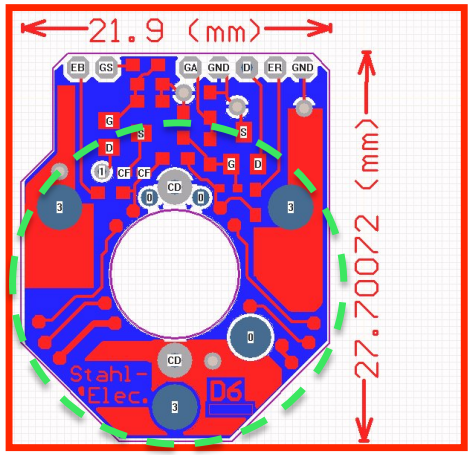
Measuring the sensitivity of the laser-coole
using an external RF field

The project TRAPSENSOR
On-going work

I. Micro-trap operation at room temperature

- The final geometry was decided in September 2014.
- The electrodes have been fabricated by TRANSLUME (May 2015).
- Electrodes are now in the US for coating and electroplating
- The electronics has been built by Stahl electronics.
- A new vacuum chamber is ready for the commissioning of the system.





II. Laser cooling in the 7-T magnetic field

- A new trap has been built to study laser cooling in the 7-T magnetic field.
- We have all the lasers and we have recently got the microwave generator to drive the EOM to generate the remaining 4 laser beams.