High-Precision Mass Measurements of Atomic (Exotic) Nuclei

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Outline

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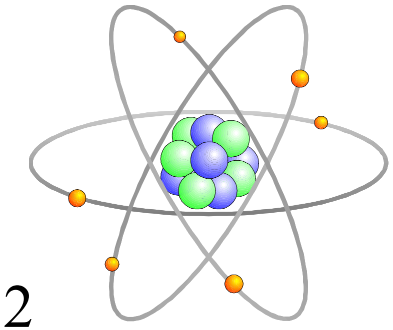
    - Importance of the mass
    - Physics goals & mass uncertainty
    - Evolution in mass uncertainty
2. Mass-spectrometry techniques for exotic nuclei
    - Time-of-flight measurements
    - Frequency measurements
3. The Penning trap
    - Fundamentals
    - Techniques for exotic nuclei
    - Existing facilities & physics survey
    - Mass uncertainty & half-life
4. Outlook: ass measurements on exotic nuclei in the future

Overview

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

The nuclear binding energy reflects all forces acting in a nucleus



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

Nuclear mass

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

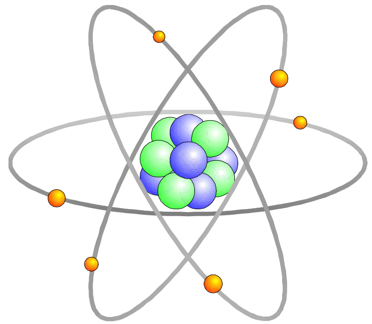
Atomic mass

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

Mass excess (keV)

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

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



Nuclear Structure & astrophysics

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

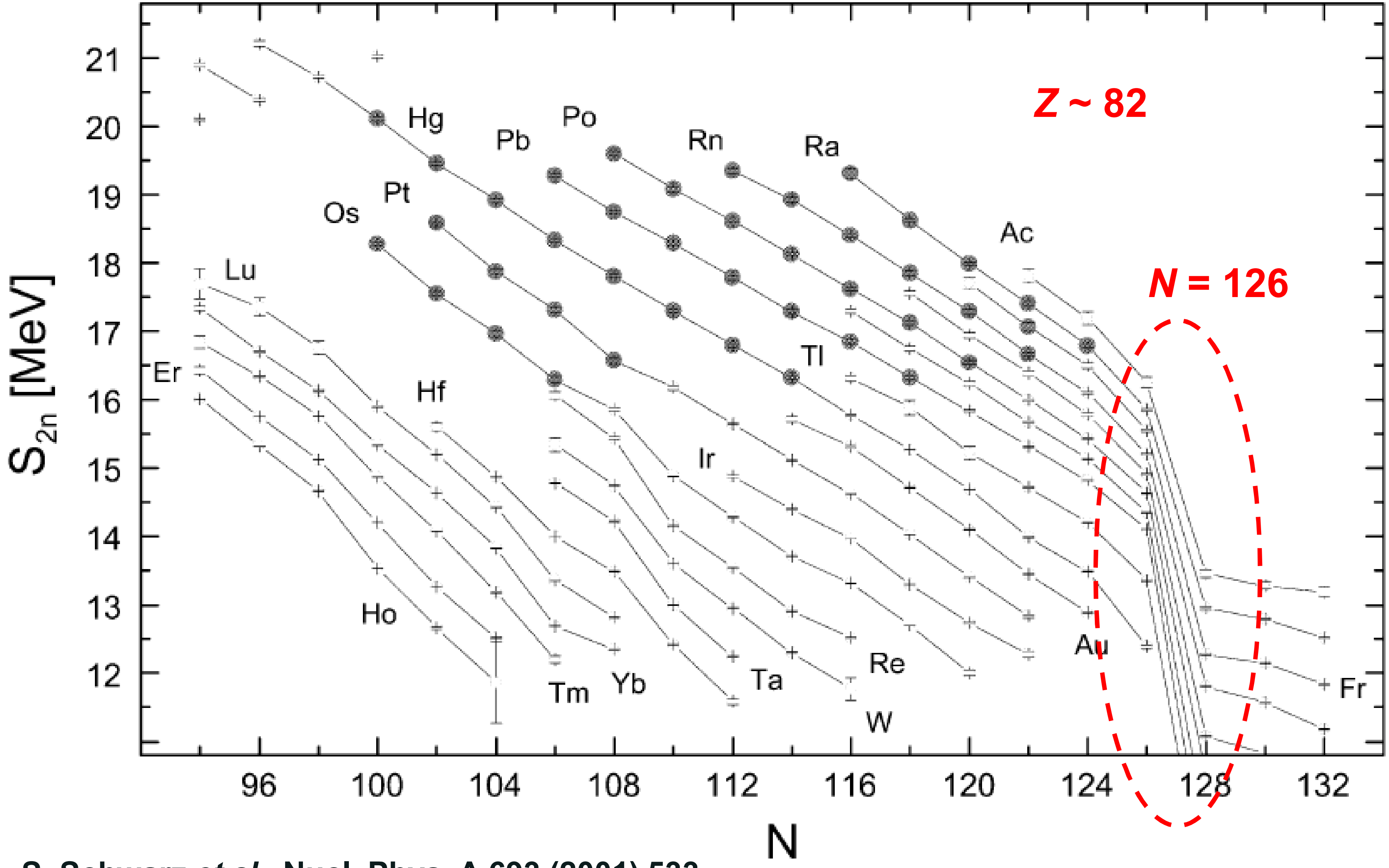
$$S_{2p} = B(N,Z) - B(N,Z-2)$$

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

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

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})

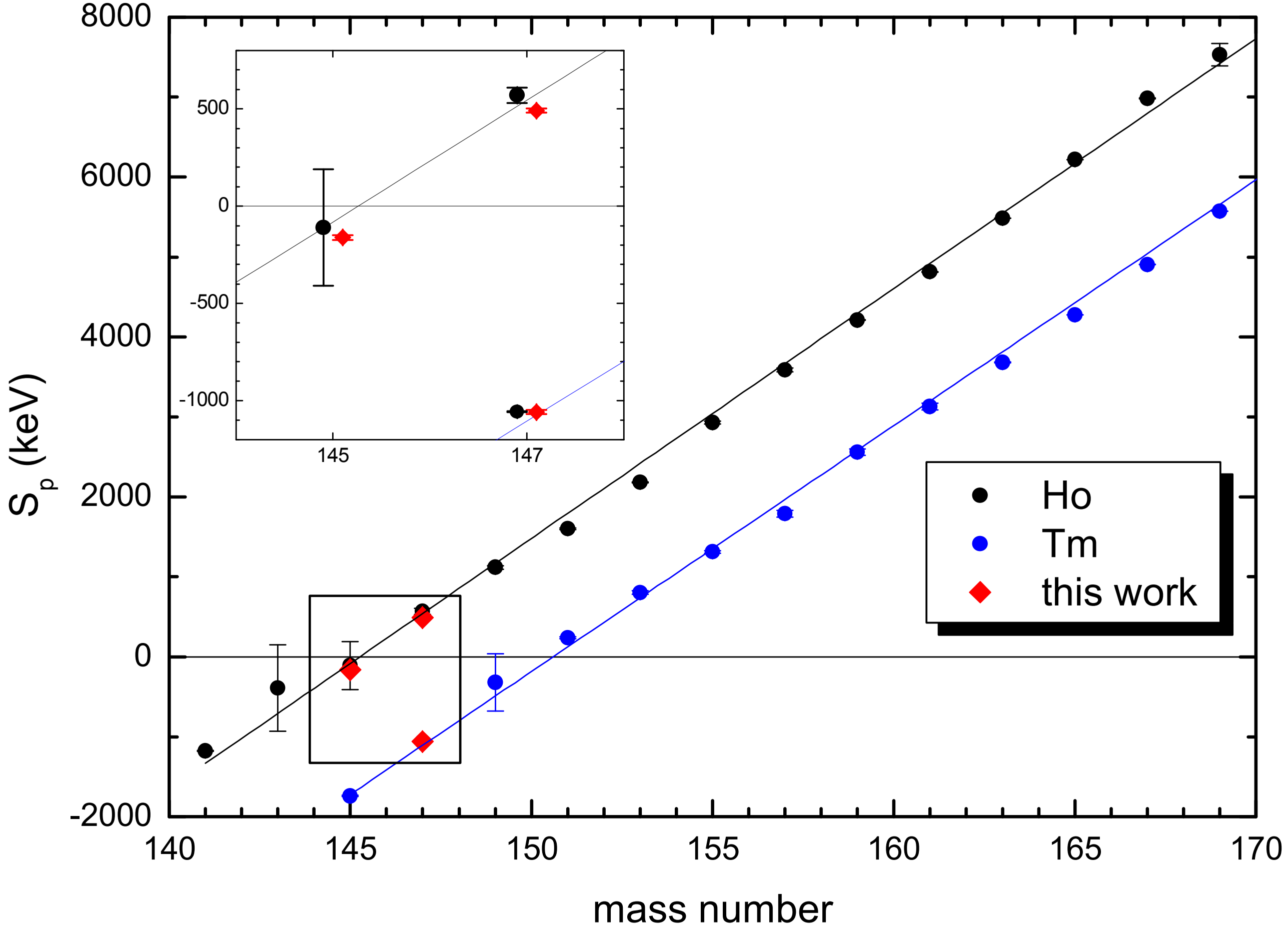


S. Schwarz *et al.*, Nucl. Phys. A 693 (2001) 533

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

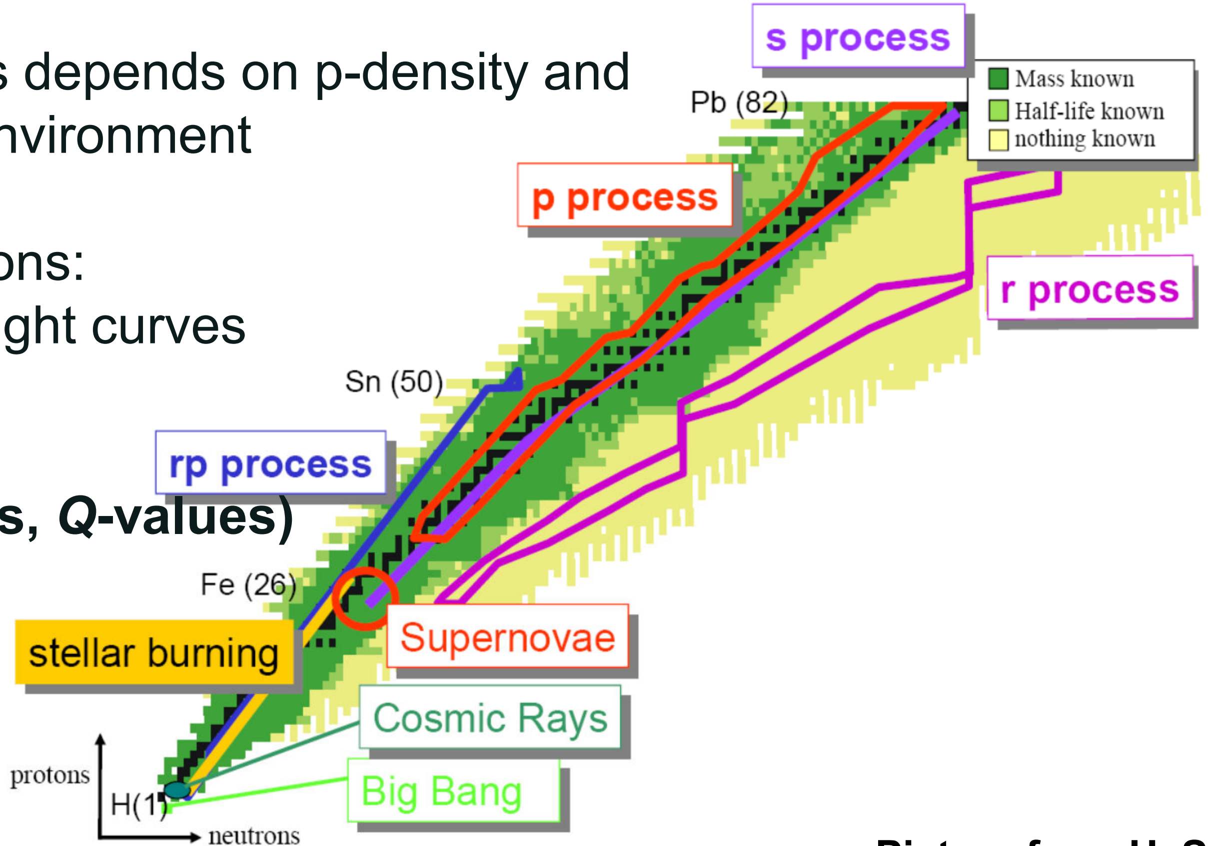
Importance of the mass
Astrophysics

- 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

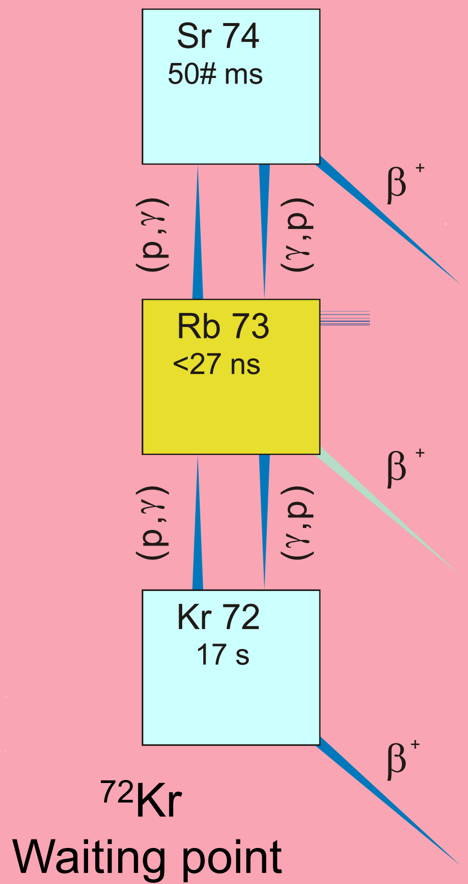
Required nuclear data:
- **Masses (sep. energies, *Q*-values)**
- β decay half-lives
- Reaction rates



Picture from H. Schatz

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

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



...cture **& astrophysics**

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

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

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

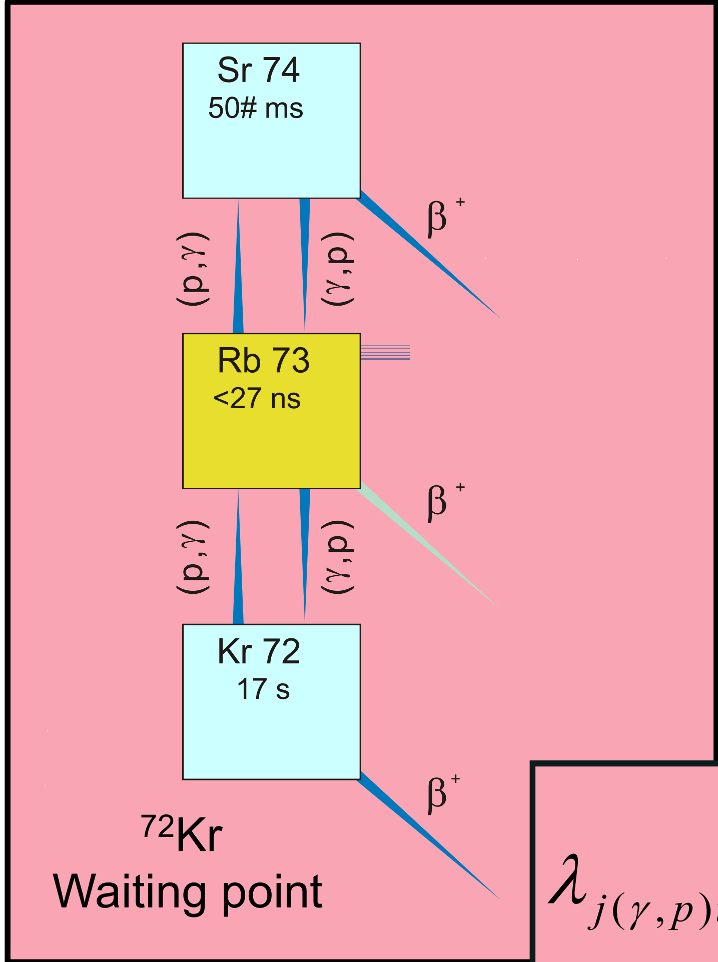
$$\ldots N,Z) - B(N-1,Z)$$

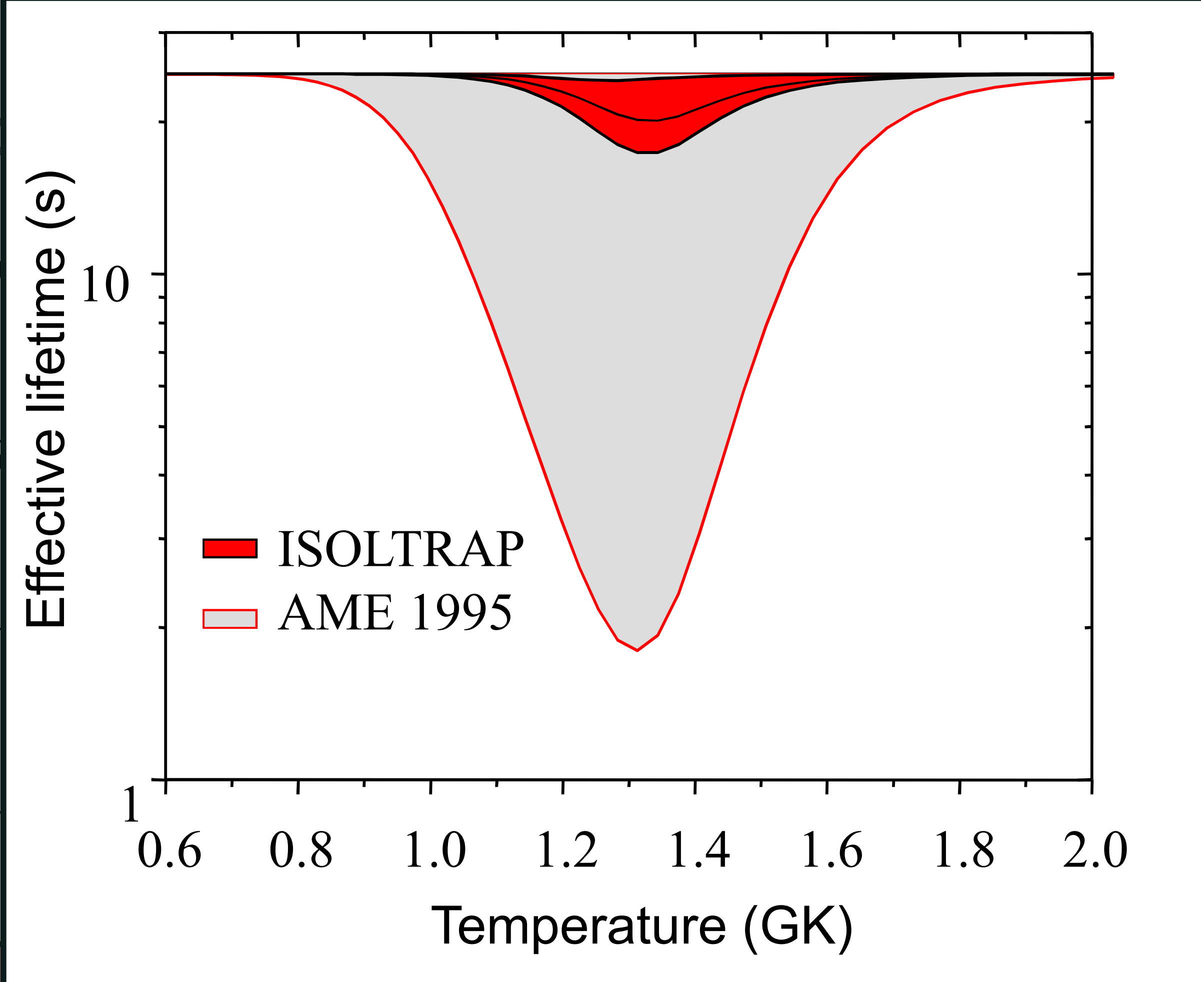
$$\lambda_{j(\gamma,p)i} = F \cdot \left(\frac{\mu kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{Q_{i(p,\gamma)j}}{kT}\right) \langle\sigma\upsilon\rangle_{i(p,\gamma)j}$$

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

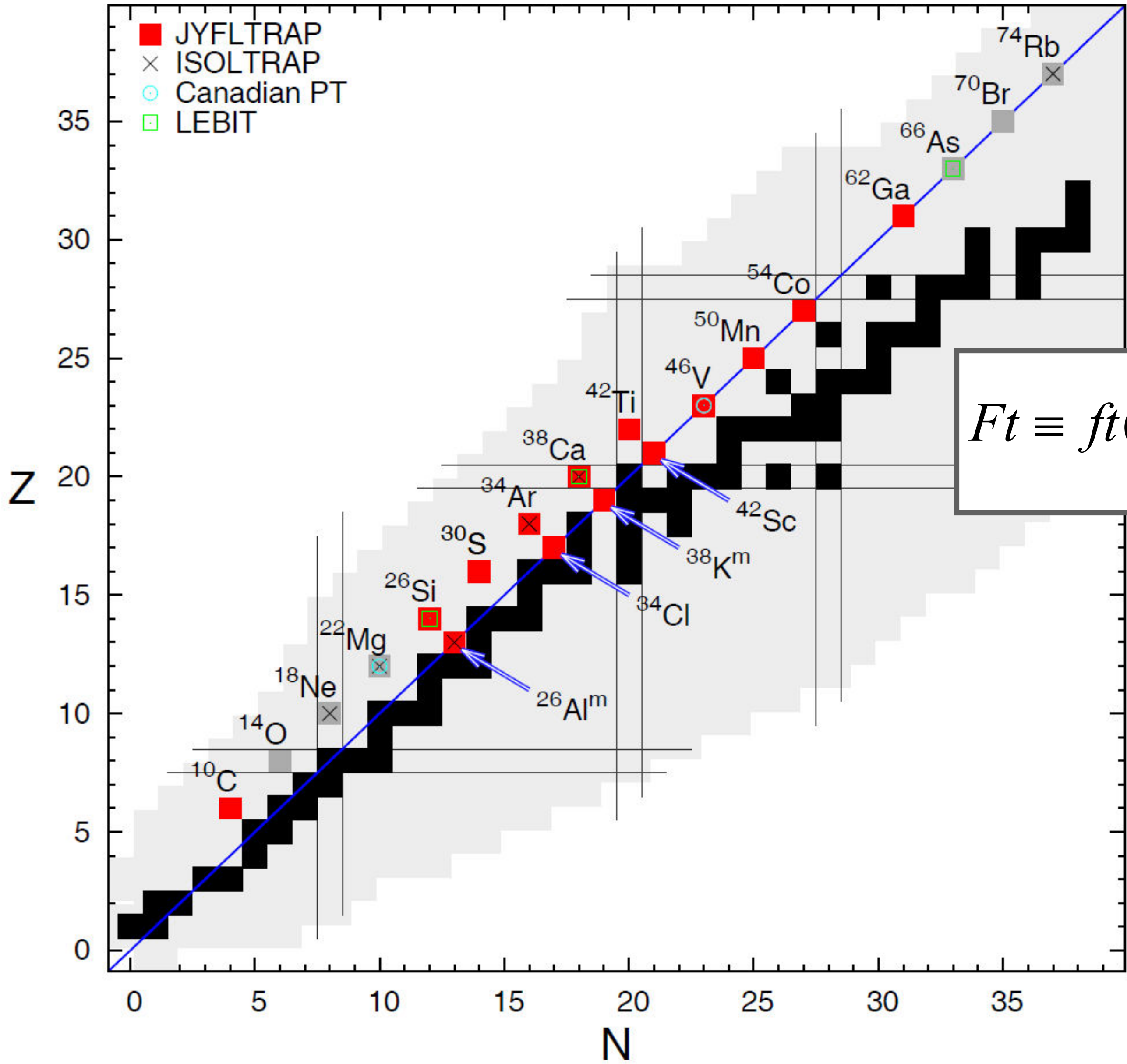
Fundamental symmetries & Neutrino-related physics

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

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

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

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

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

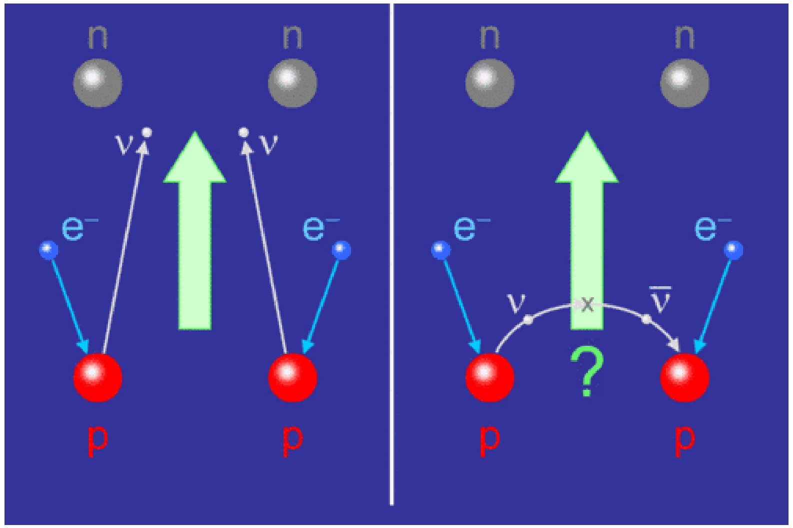
$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 1 - \Delta$$

Importance of the mass
Q-values from *EC*-decay

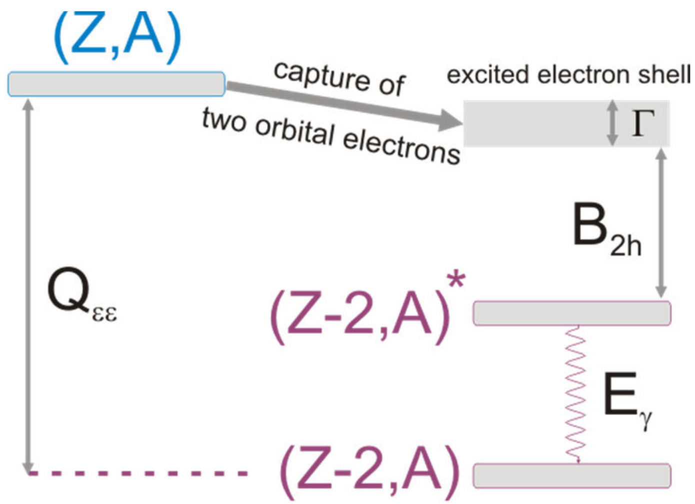
Is the neutrino a Majorana or Dirac particle?

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)

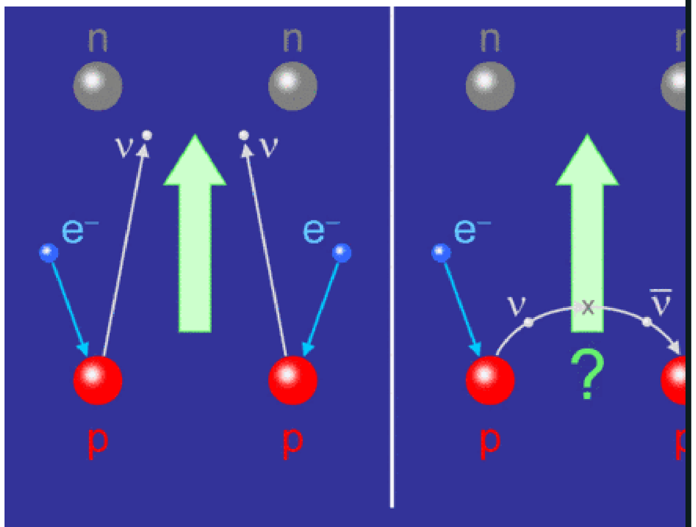


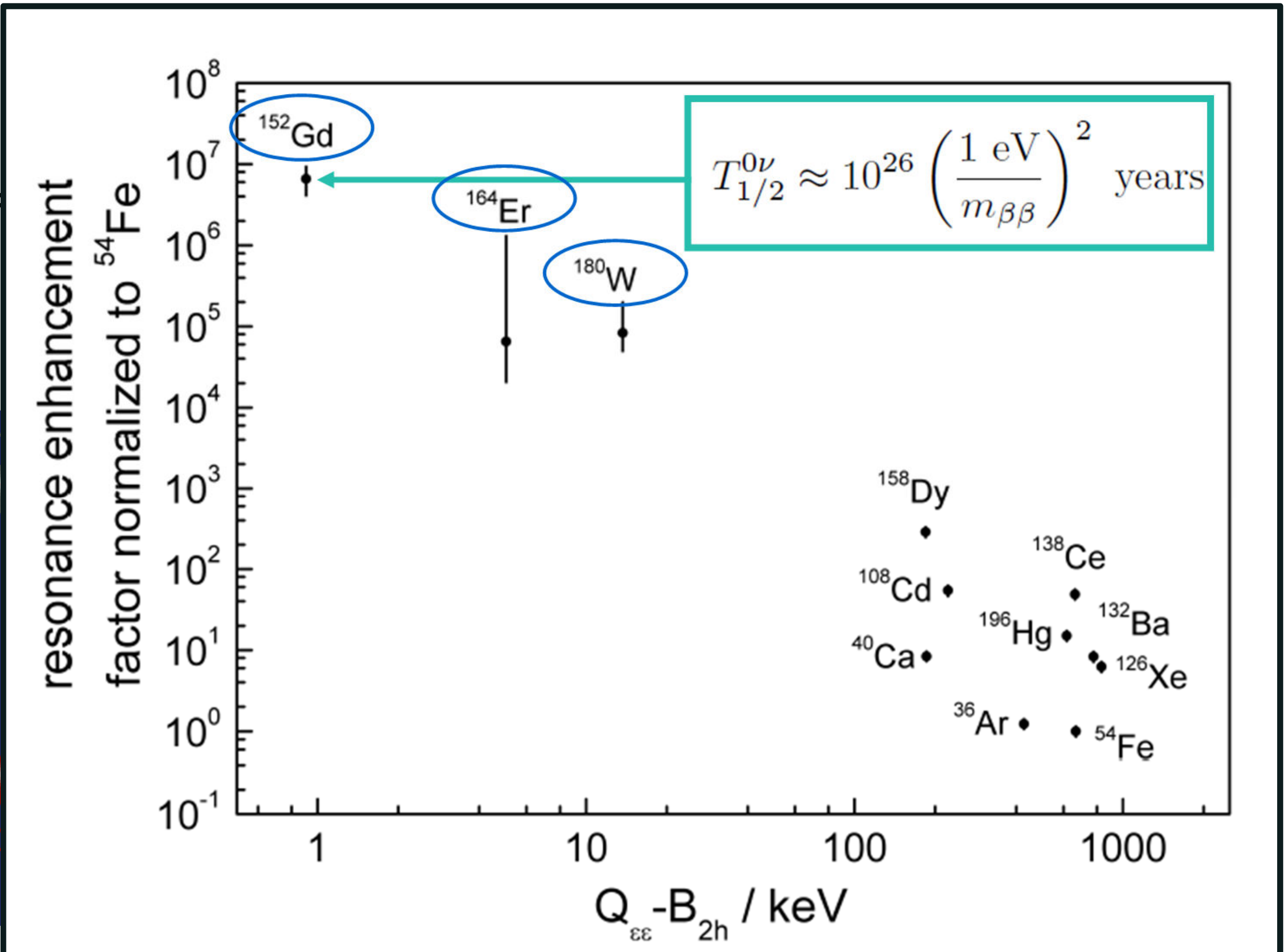
Search for nuclides with $D=(Q_{ee}-B_{2h}-E_g)$ < 1 keV

Is the neutrino a Majorana or Dirac particle?

2ν2EC **($T_{1/2}$>10^{24} y)**

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



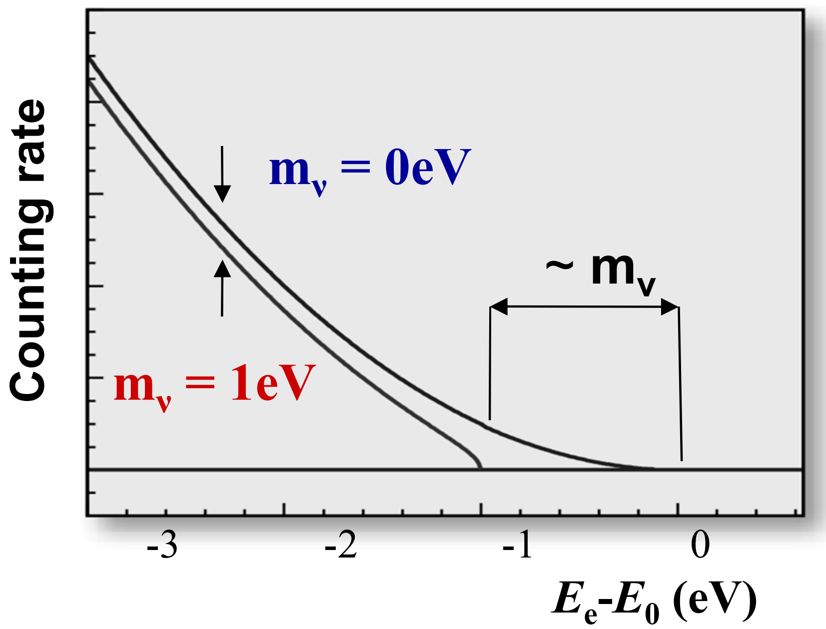


^{152}Gd: S. Eliseev *et al.*, PRL 106 (2011) 052504

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

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



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

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

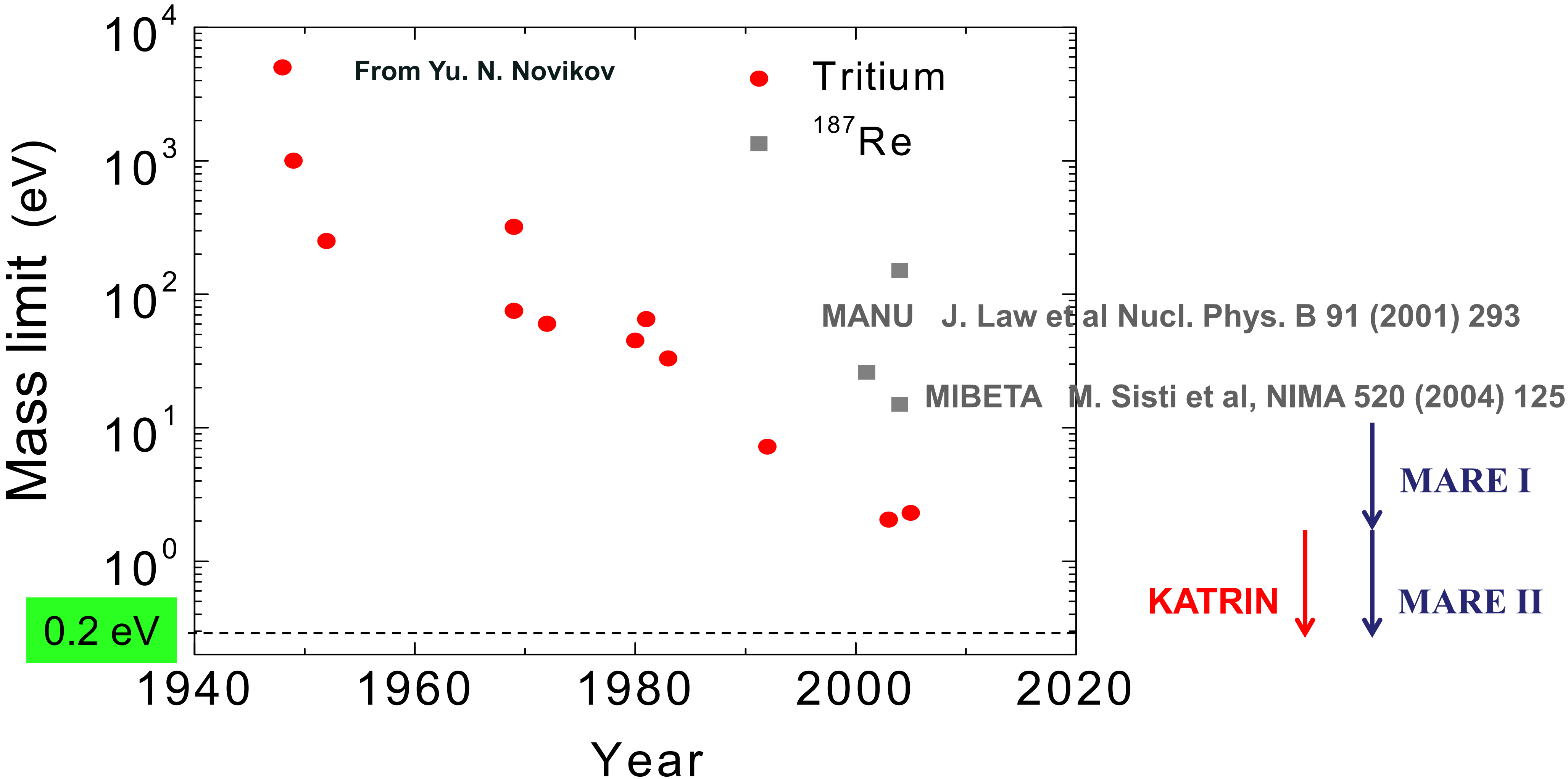
  $Q = 18.6\ \mathbf{keV} \qquad T_{1/2} = 12.3\ \mathbf{y}$

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

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

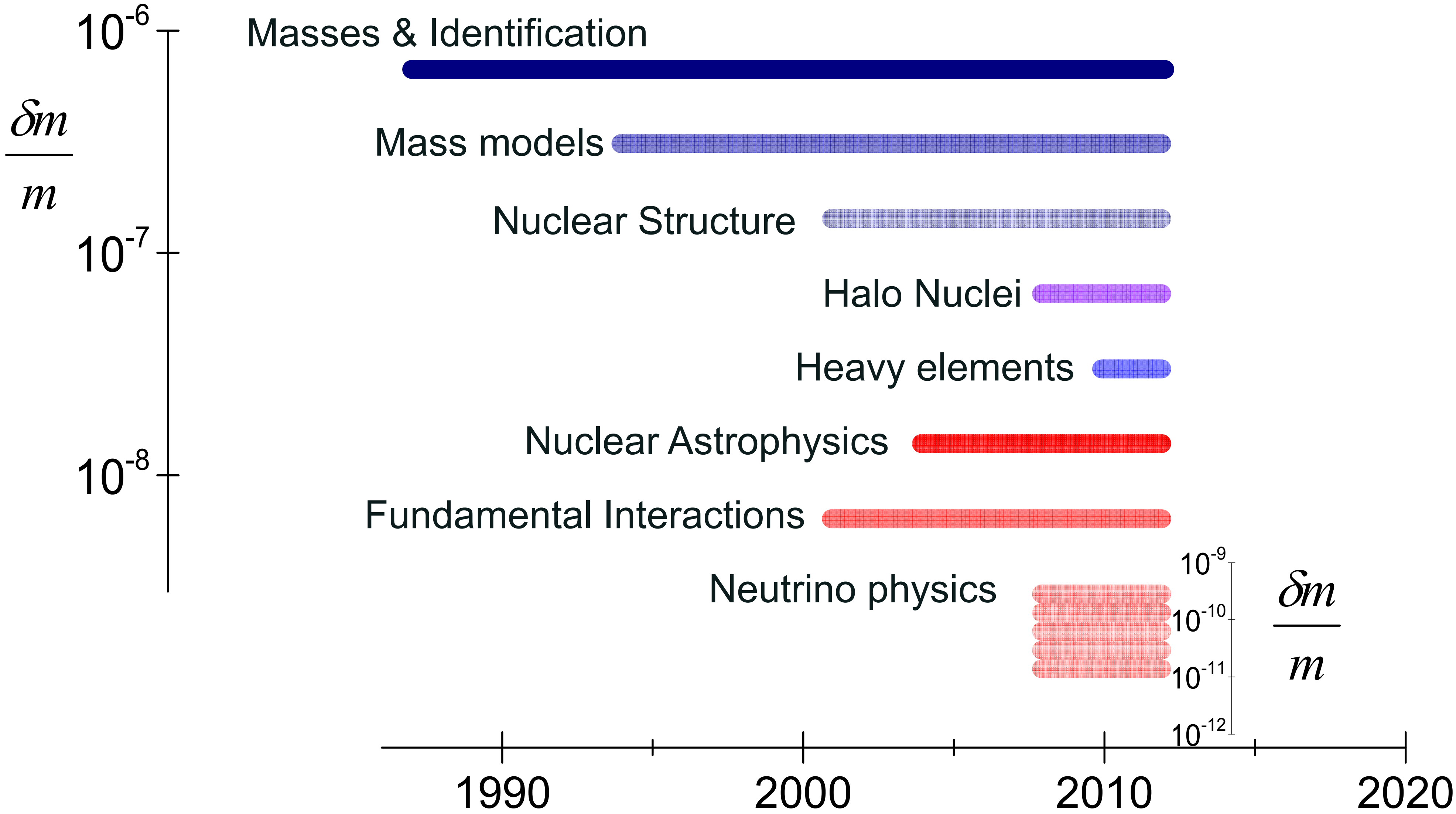
***Q* has to be unambiguously determined (with δ*m*/*m* of at least 10^{-11}) from the mass difference using a Penning trap**

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



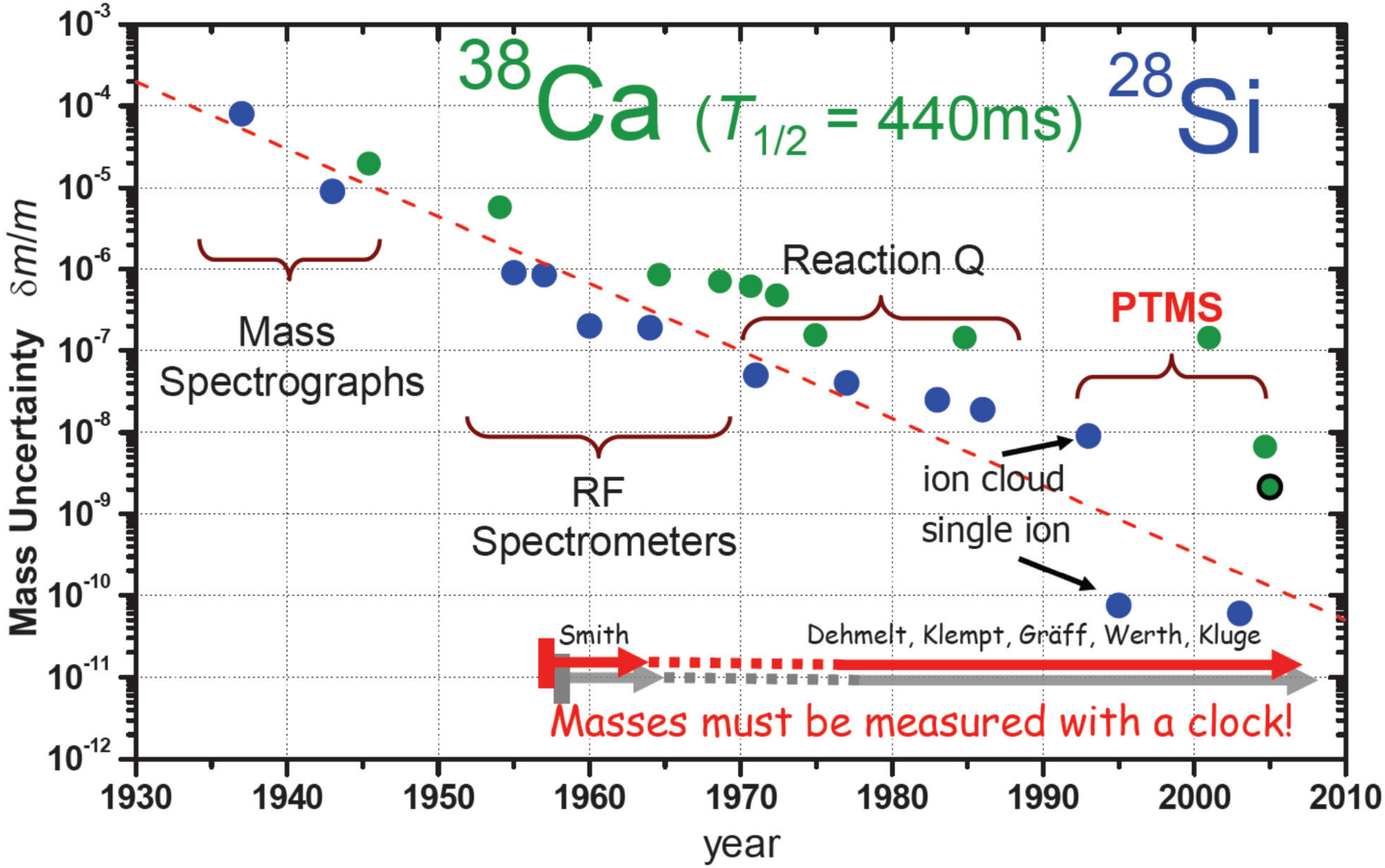
- There are two International collaborations aiming at measuring with a sensitivity of about 0.2 eV/c^2: KATRIN (KArlsruhe TRItium Neutrino experiment) and MARE (Micro calorimeter Array for a Rhenium Experiment)

Physics goals
Mass uncertainty required



Time scale for direct mass measurements using Penning traps

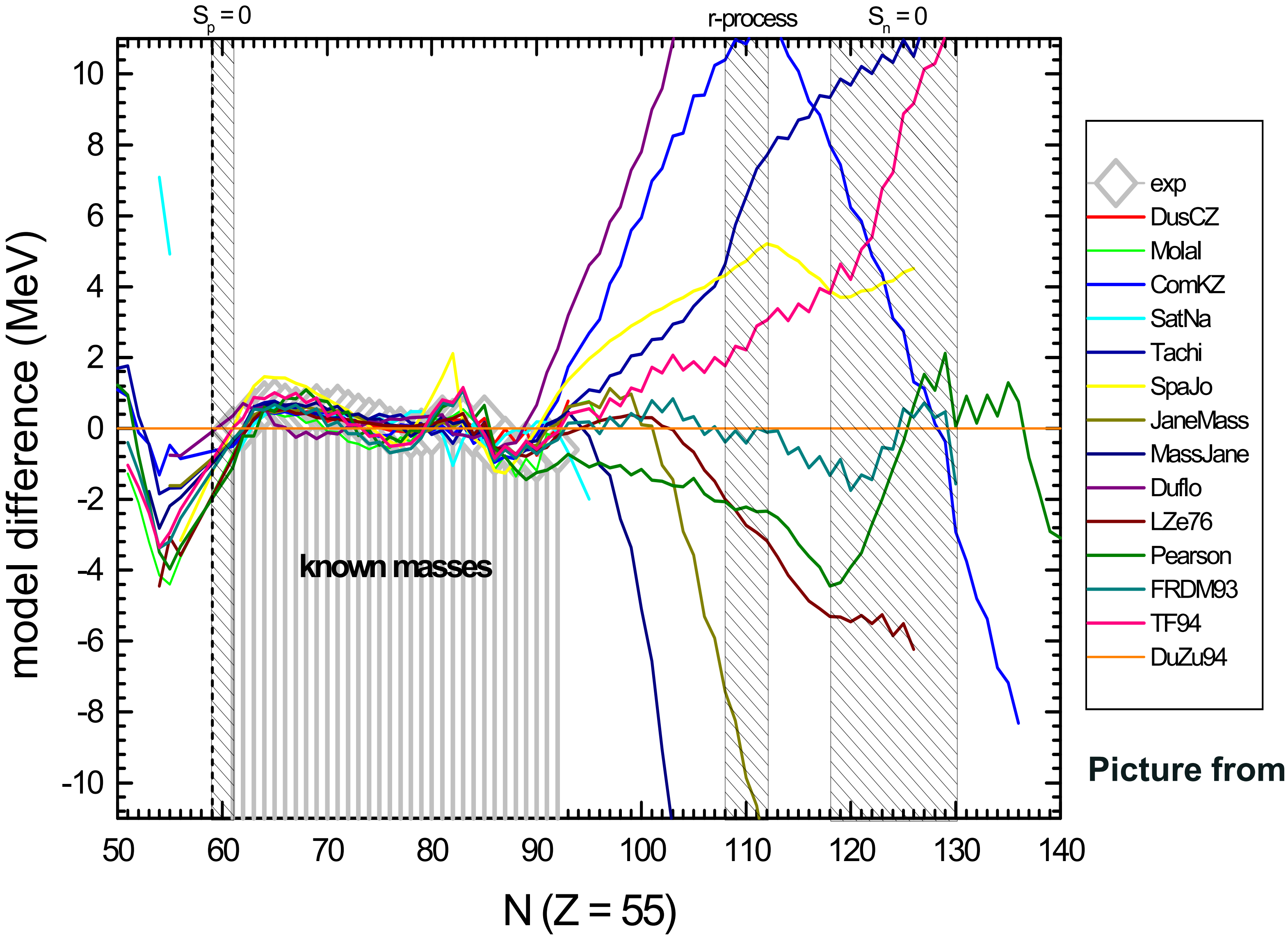
Mass uncertainty
Evolution in history



Picture from H.-J. Kluge

Experimental results and models

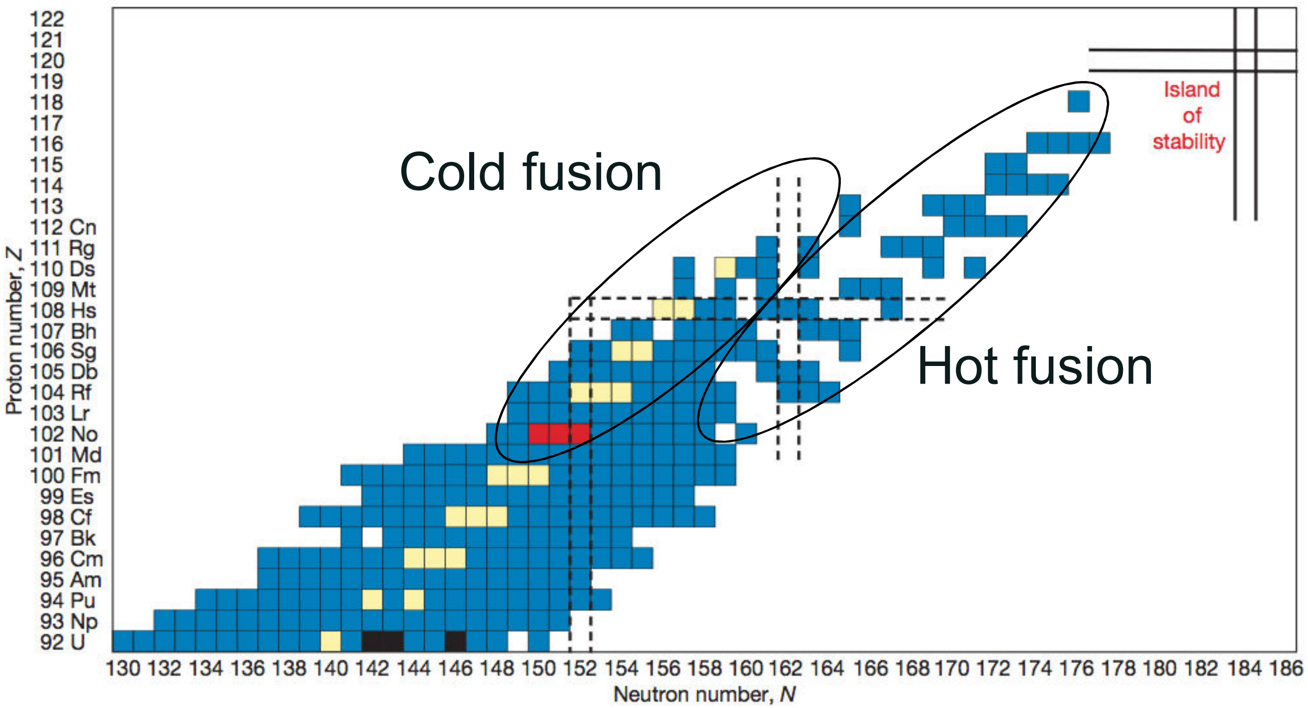
Discrepancies between the models



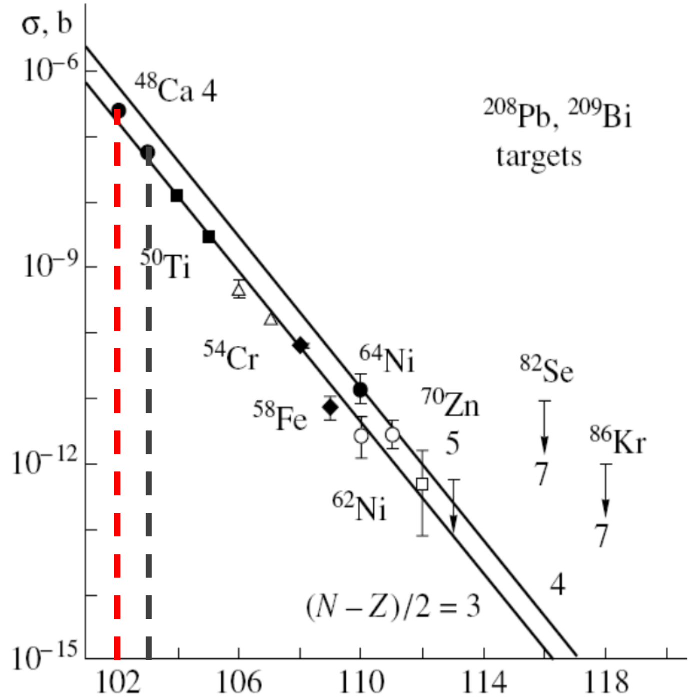
Picture from D. Lunney

Particularly relevant in the region of Superheavy Elements

Experimental results
Influence in the atomic mass evaluation

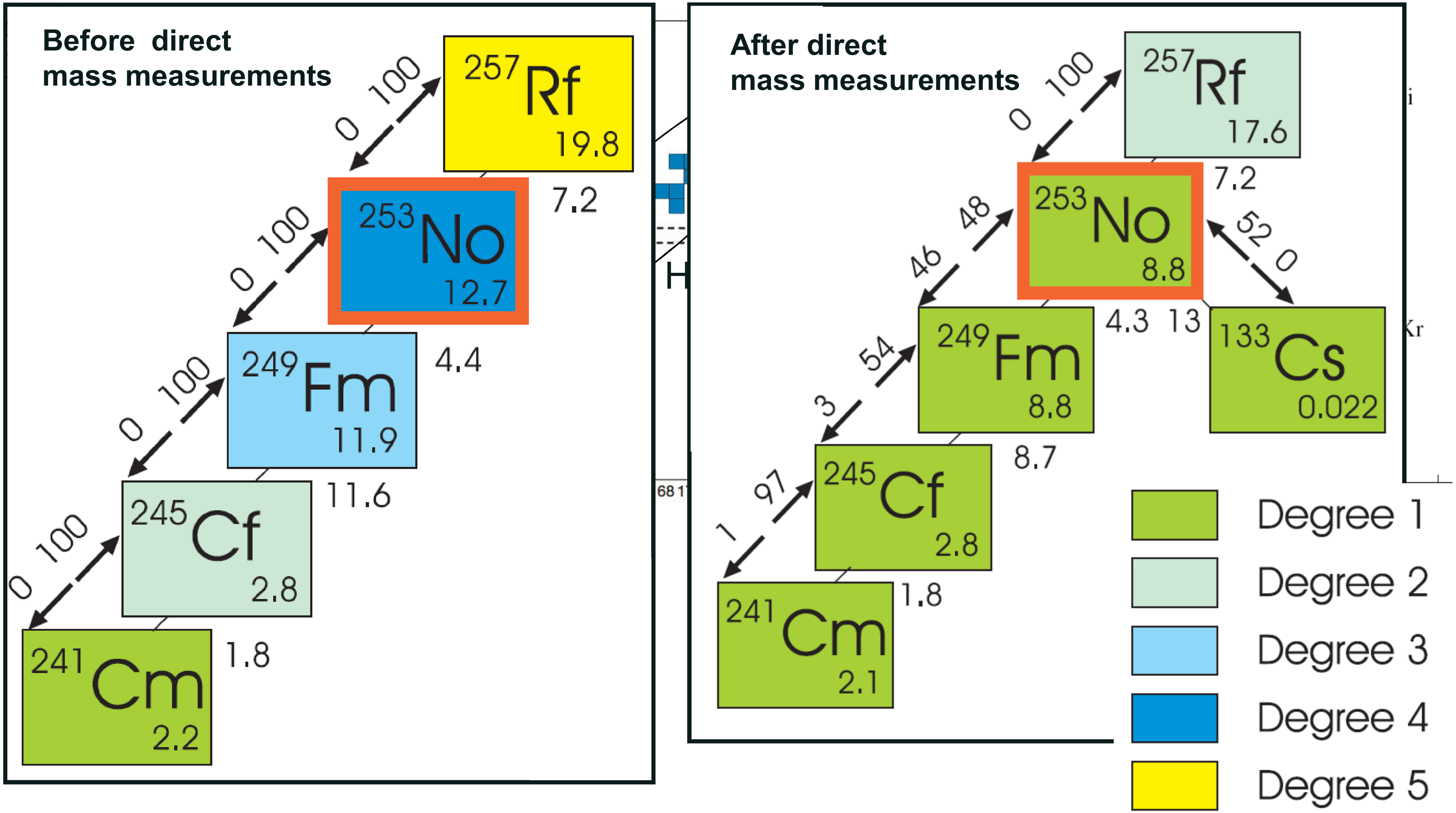


M. Block et al, Nature 463 (2010) 785



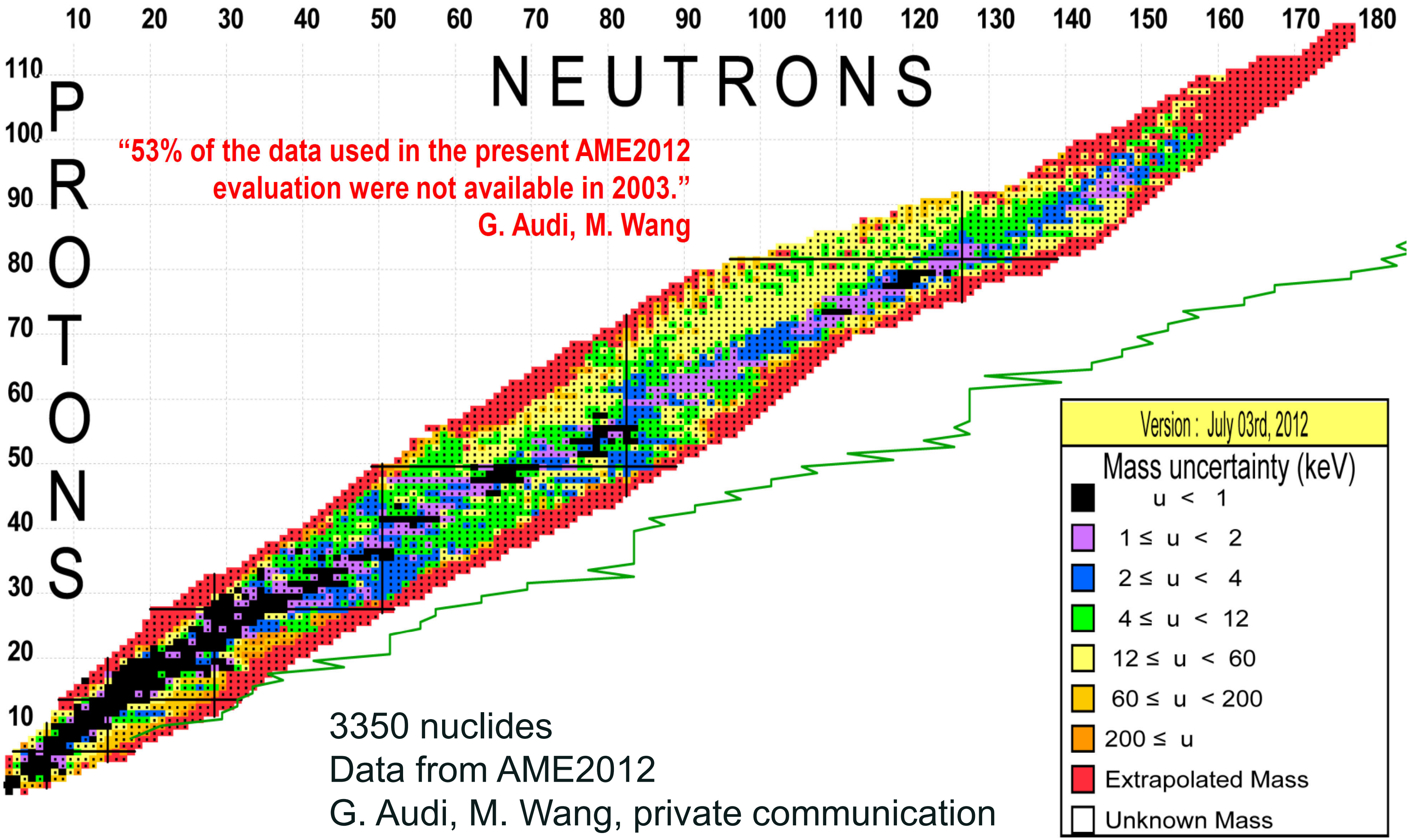
Very low production cross section

Experimental results
Influence in the atomic mass evaluation



M. Dworschak *et al.* Phys. Rev. C 81 (2010) 064312

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

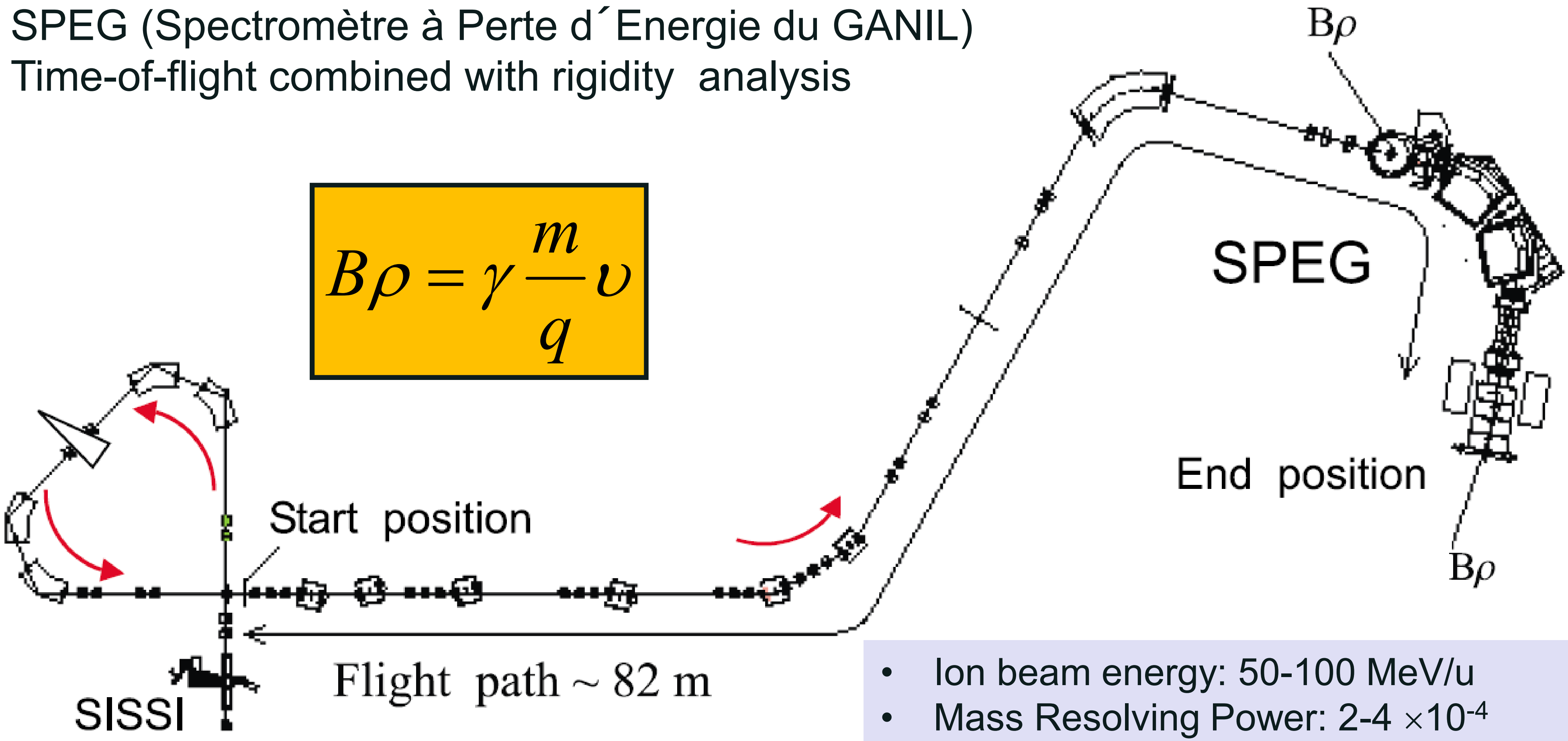
3350 nuclides
Data from AME2012
G. Audi, M. Wang, private communication

MASS SPECTROMETRY TECHNIQUES FOR EXOTIC NUCLEI

Time-of-flight measurements
Large Spectrometers (an example)

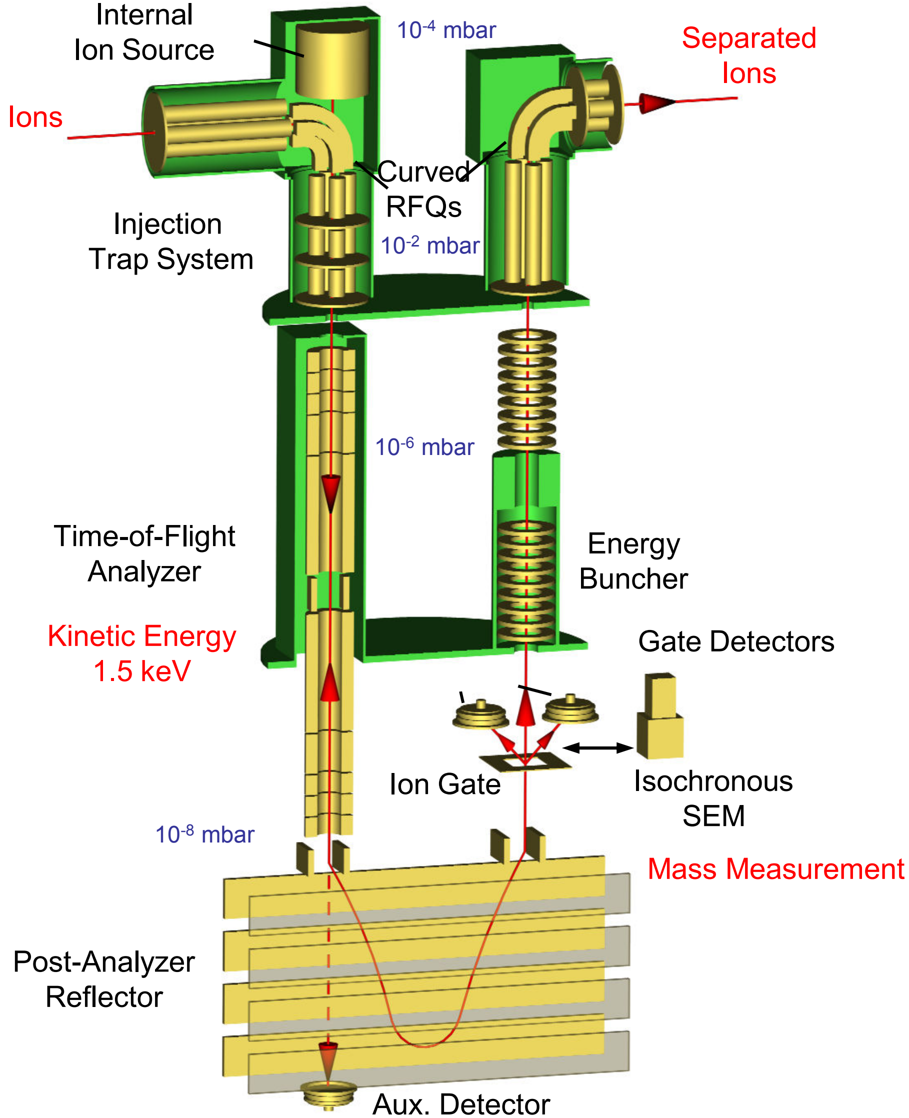
SPEG (Spectromètre à Perte d´Energie du GANIL)
Time-of-flight combined with rigidity analysis

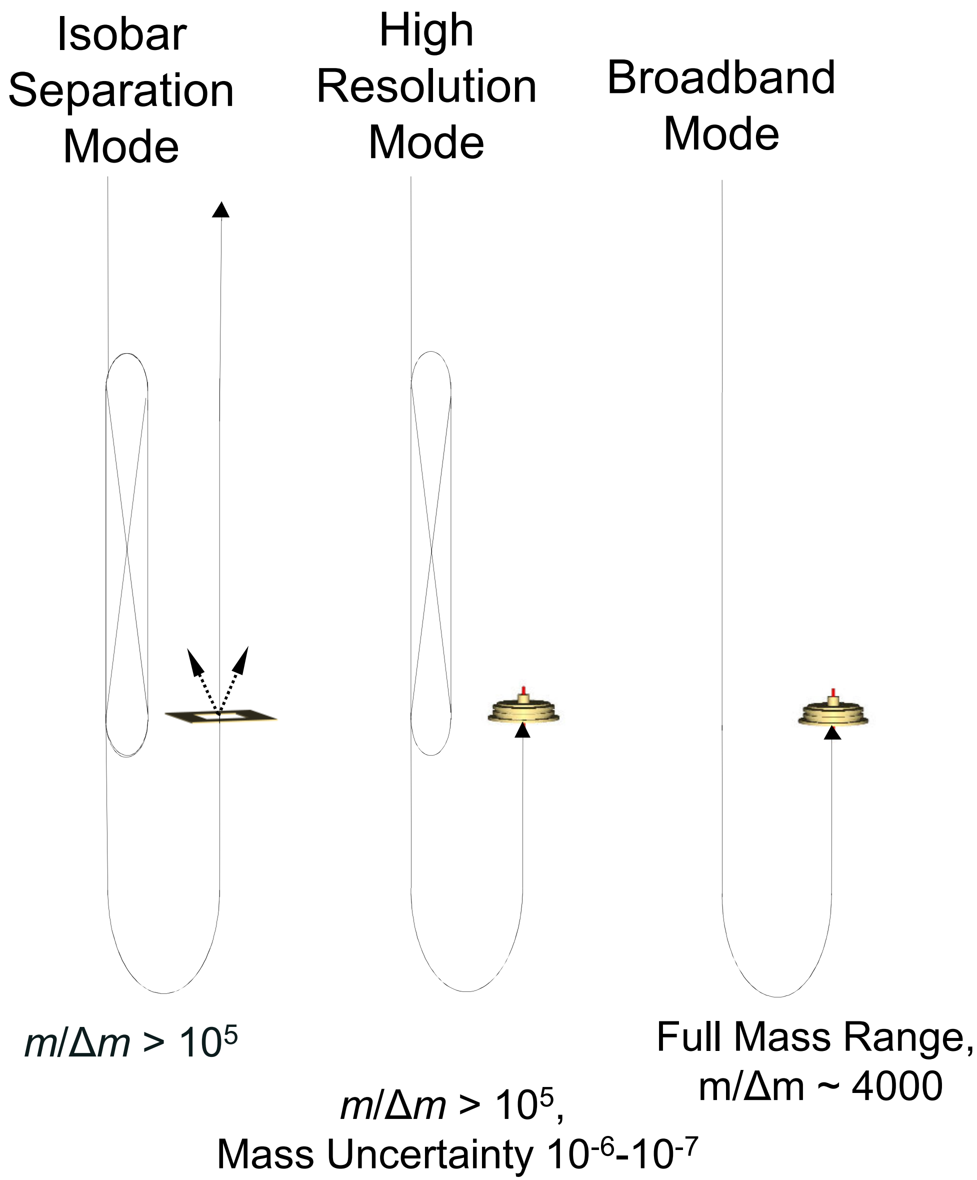
$$B\rho = \gamma \frac{m}{q} \upsilon$$



- Ion beam energy: 50-100 MeV/u
- Mass Resolving Power: 2-4 $\times 10^{-4}$
- High sensitivity and very short-lived nuclei
- Masses up to *A* ~70

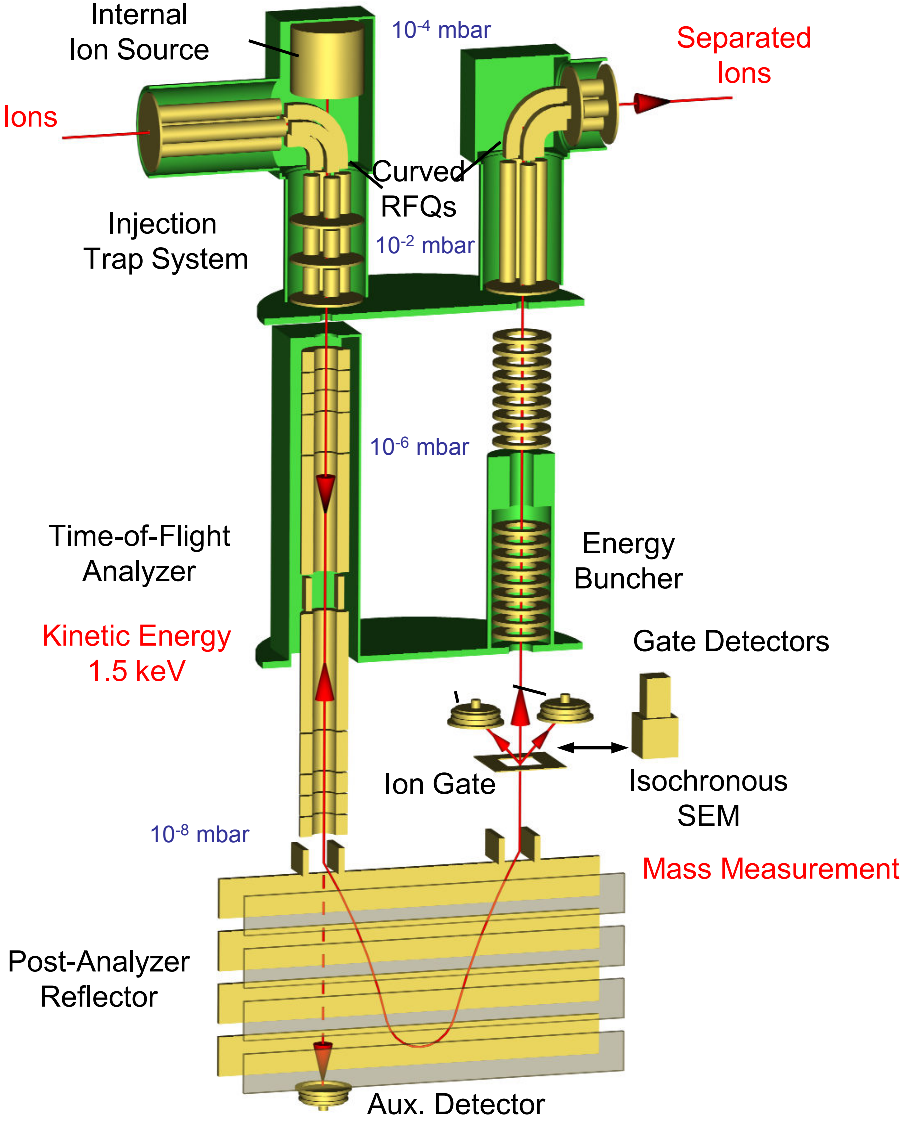
Time-of-flight measurements
Compact devices (MR-TOF-MS)



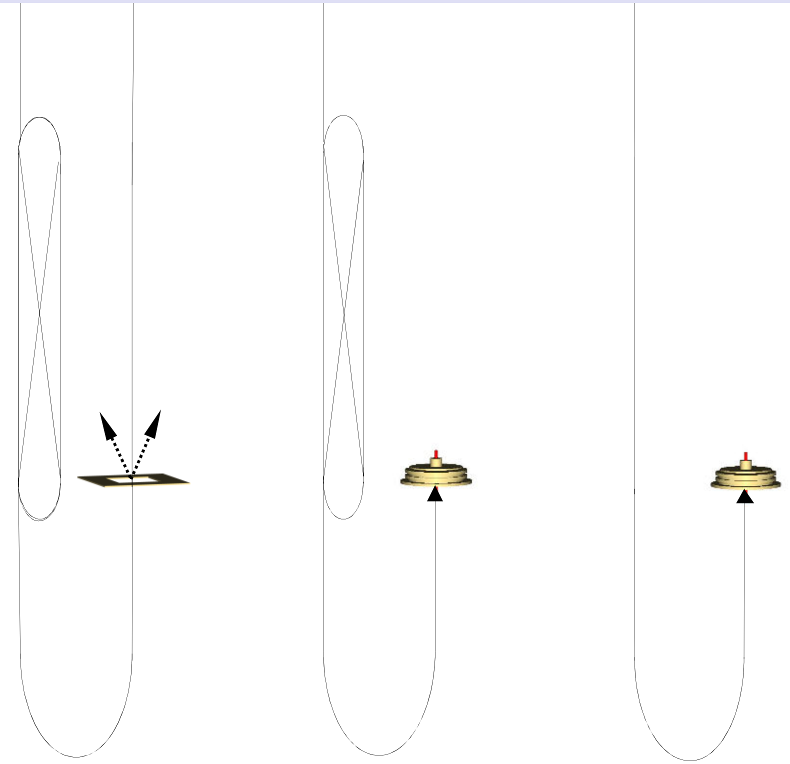


W.R. Plaß *et al.*, NIMB 266 (2008) 4560

Time-of-flight measurements
Compact devices (MR-TOF-MS)



- Ion beam energy: 1-2 keV
- Mass Resolving Power: 600,000
- Mass Measurement Uncertainty:~10^{-7}
- Sensitivity: ~10 ions



m/Δ*m* > 10^5

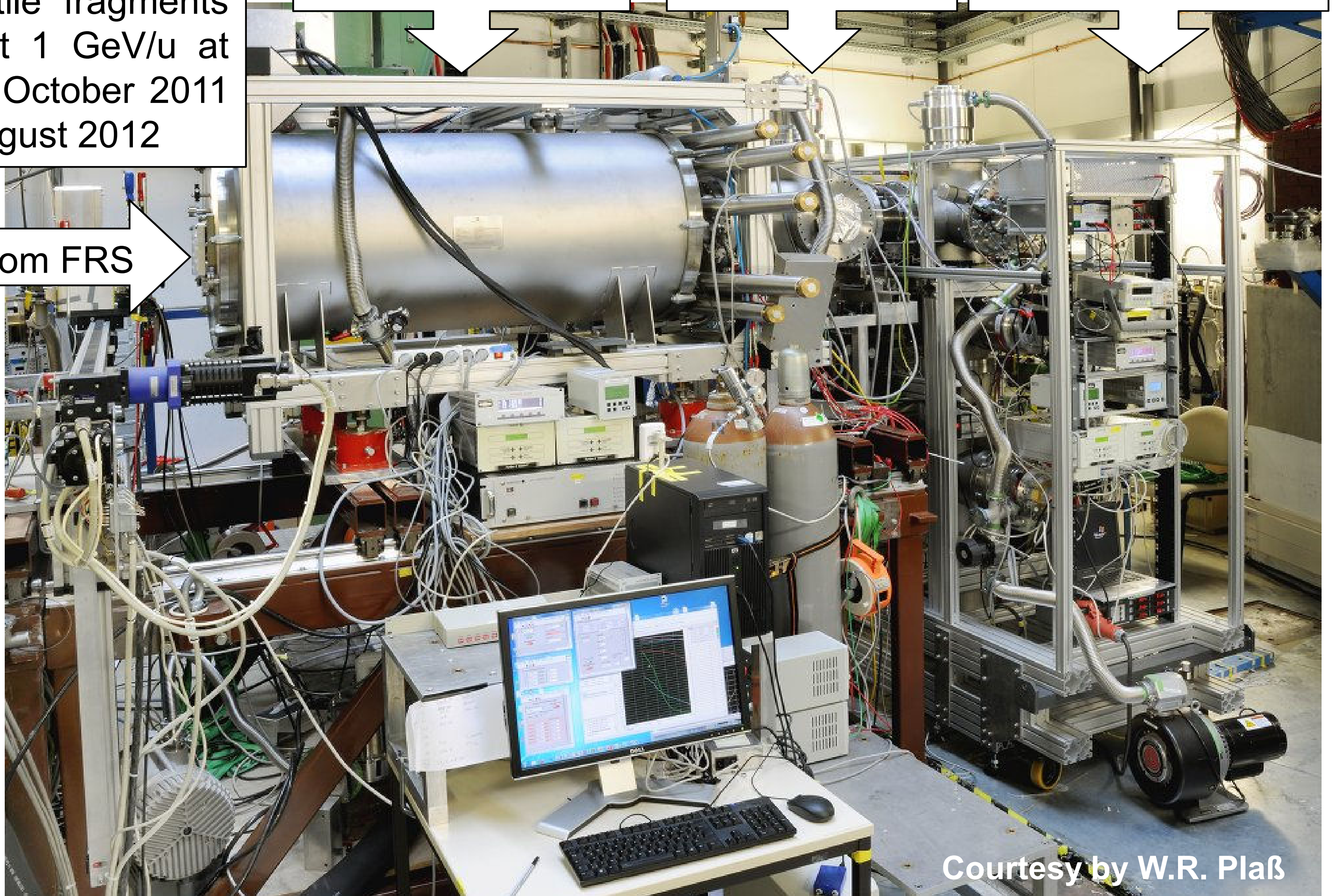
m/Δ*m* > 10^5,
Mass Uncertainty 10^{-6}-10^{-7}

Full Mass Range,
m/Δm ~ 4000

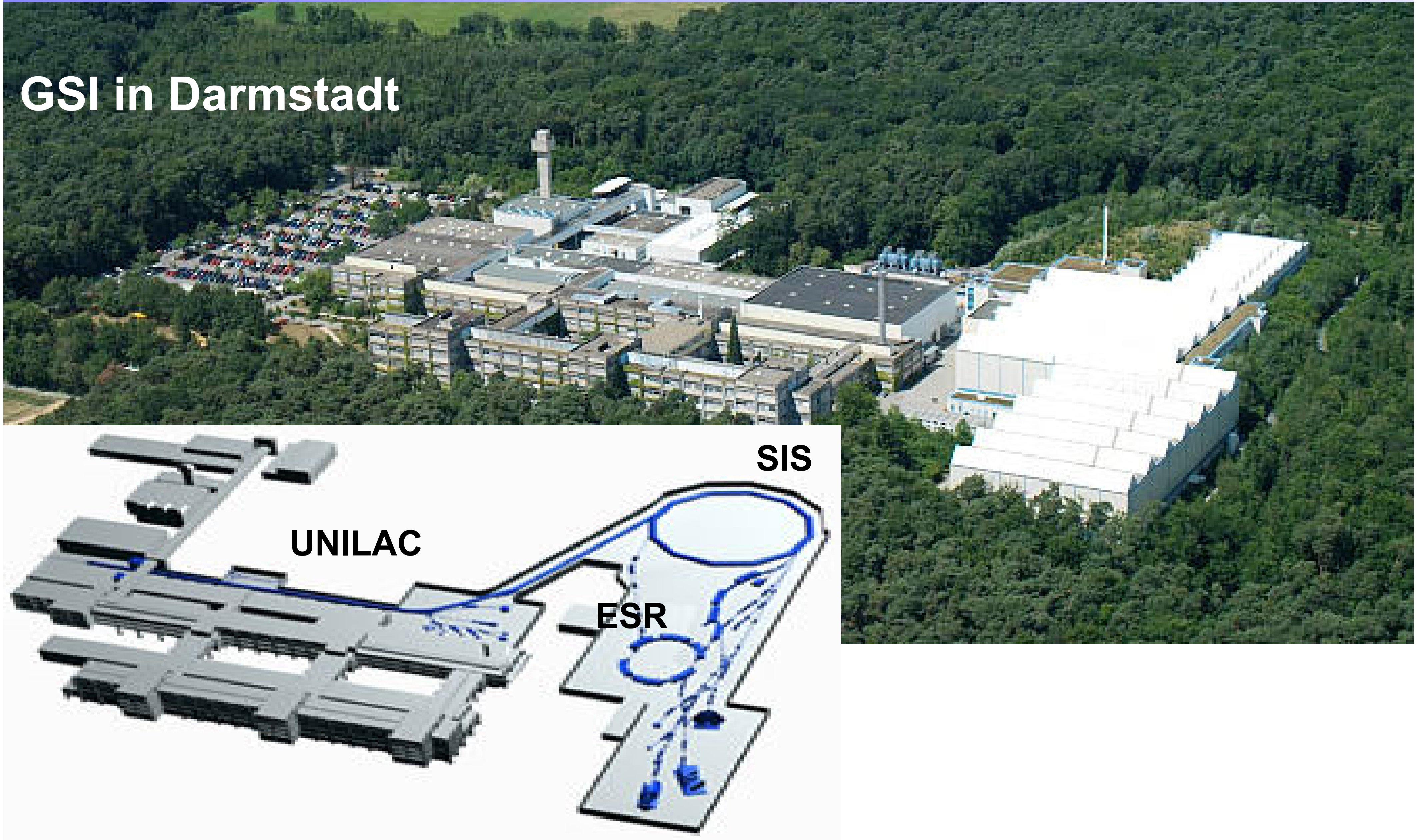
W.R. Plaß *et al.*, NIMB 266 (2008) 4560

MR-TOF-MS at accelerators
FRS at GSI

On-line test of the with ^{238}U projectile fragments produced at 1 GeV/u at the FRS in October 2011 and July/August 2012

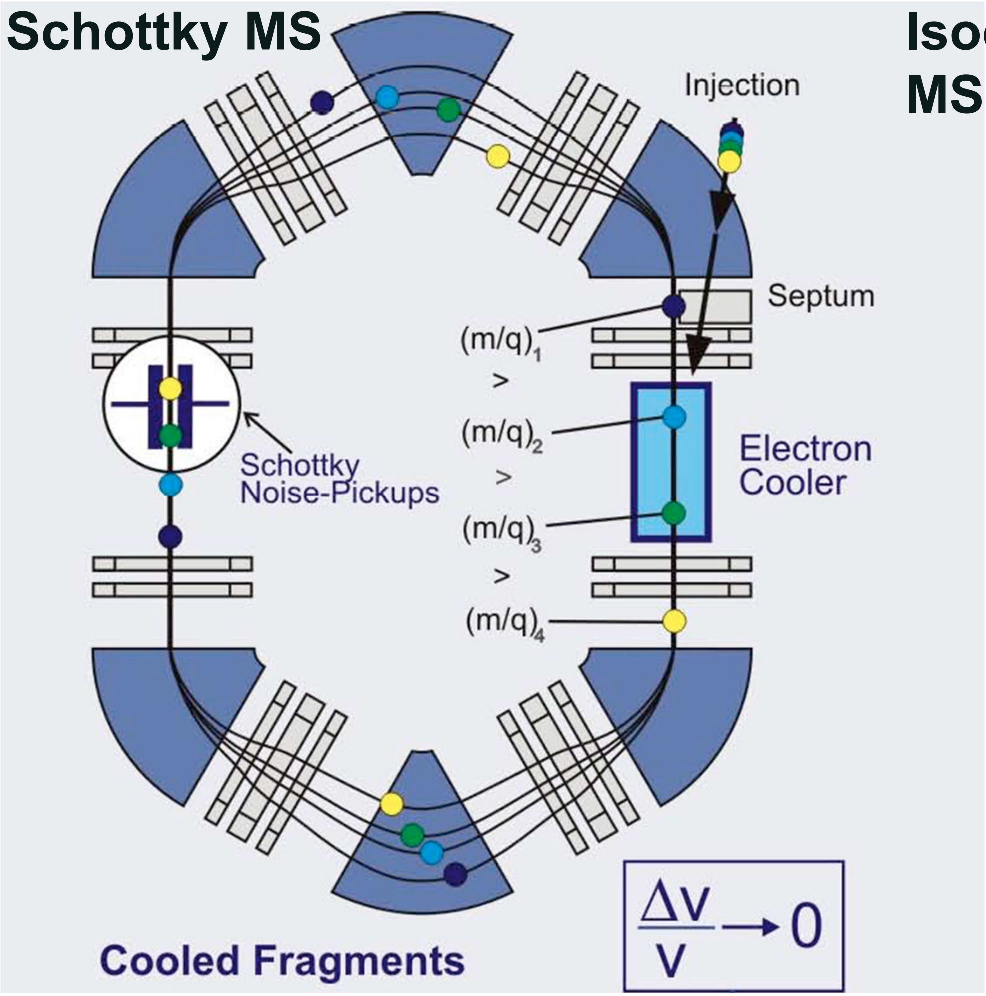


Revolution frequency measurements
Experimental storage ring (ESR)

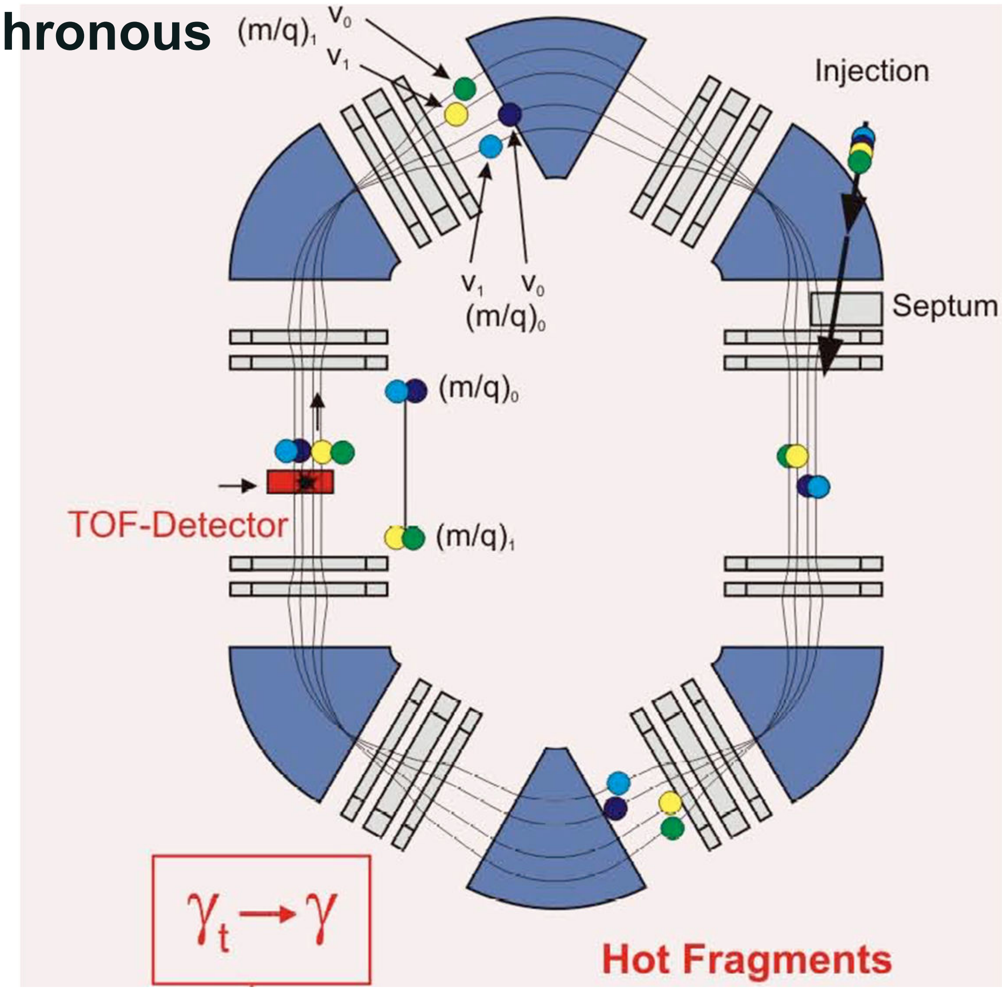


Revolution frequency measurements
Experimental storage ring (ESR)

Schottky MS



Isochronous MS



Stochastic &
Electron cooling

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta V}{V}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

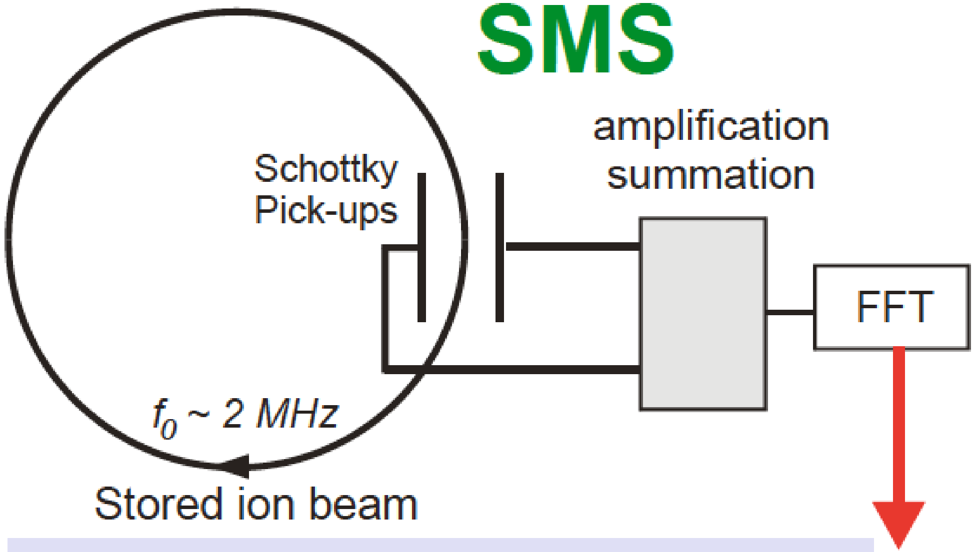
Revolution frequency measurements
Experimental storage ring (ESR)

More than 1000 masses measured

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta\left(m/q\right)}{m/q} + \frac{\Delta V}{V}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

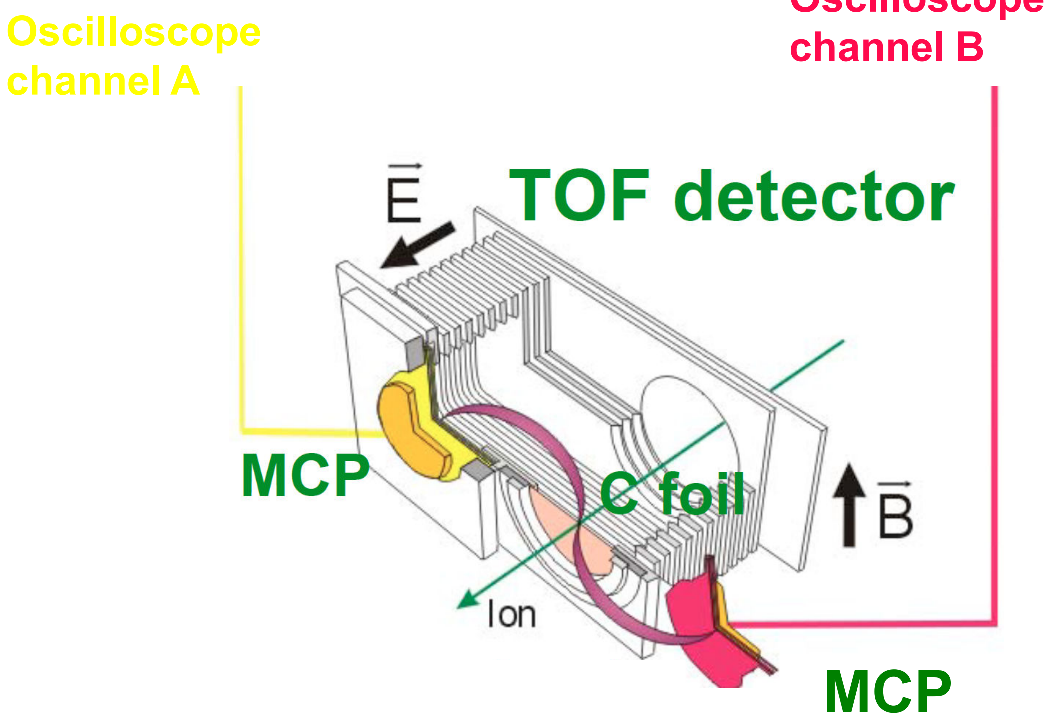
Revolution frequency measurements
Detectors and performance

Schottky MS



- Ion beam energy: ~ 10 MeV/u
- Mass Resolving Power: 2×10^6
- Measurement Uncertainty: 1.5×10^{-7}
- Sensitivity: ~1 ion
- Half-life: above 10 s

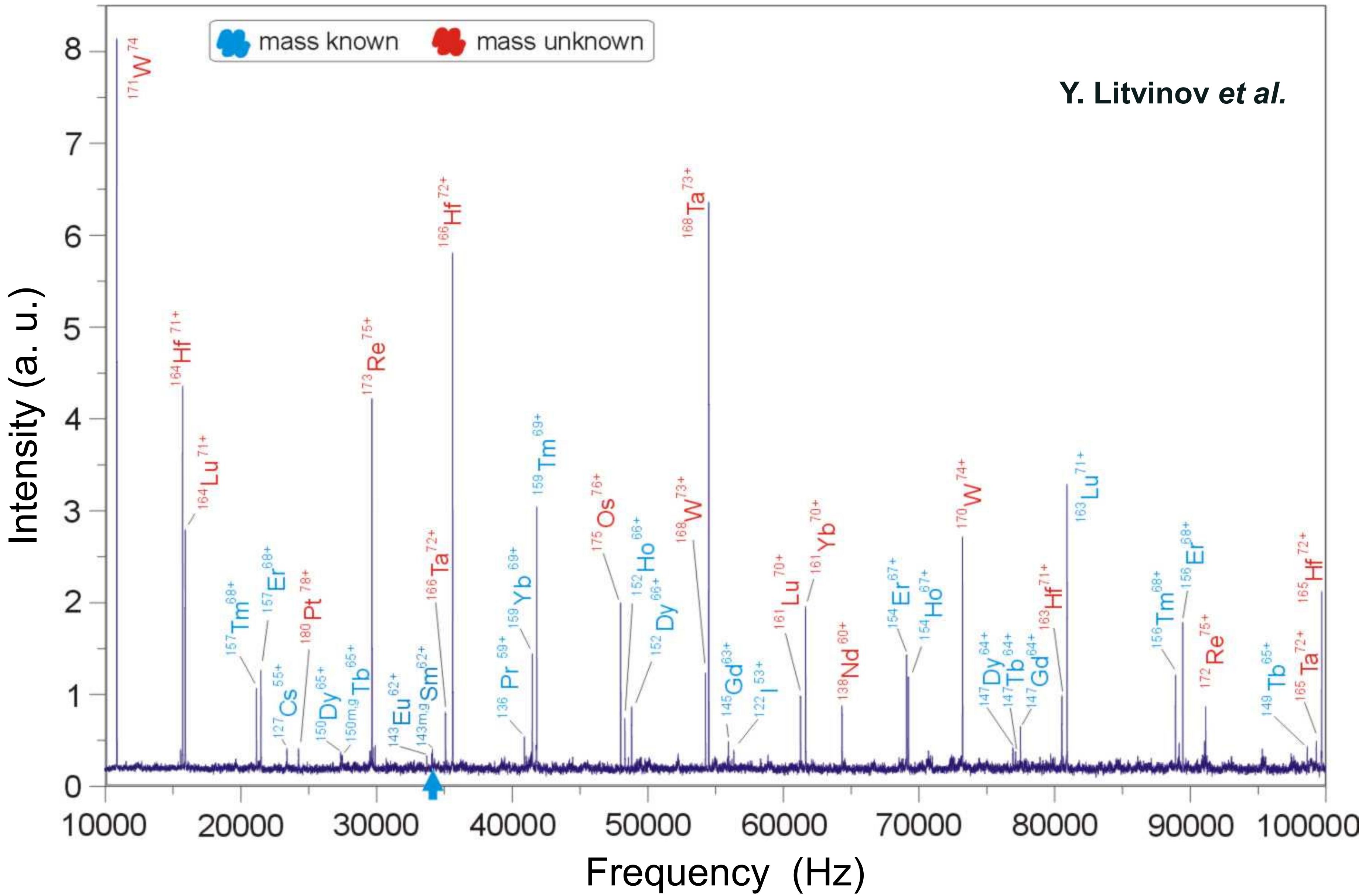
Isochronous MS



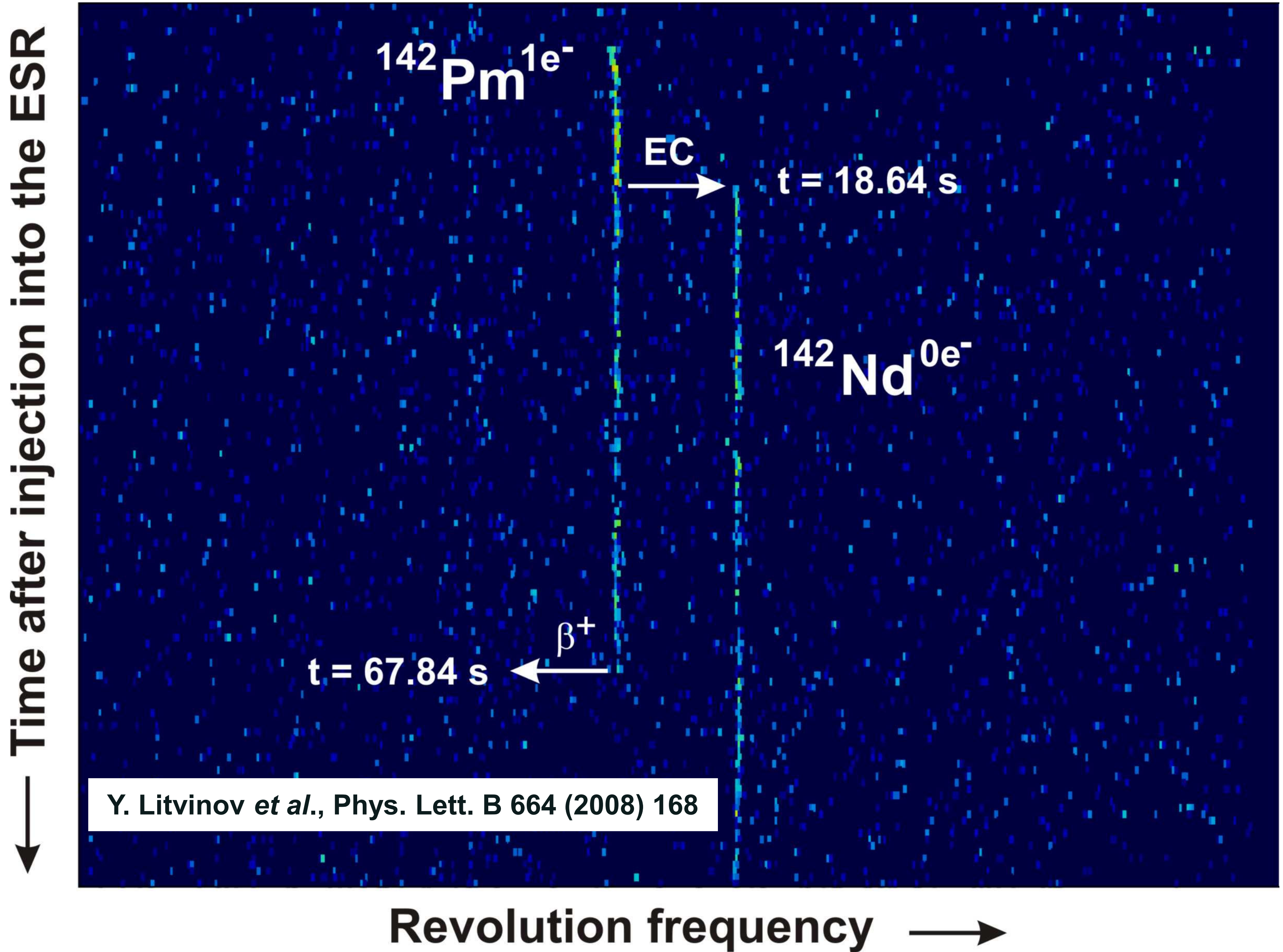
- Ion beam energy: ~ 10 MeV/u
- Mass Resolving Power: 3×10^5
- Measurement Uncertainty: 10^{-5}-10^{-6}
- Sensitivity: ~1 ion
- Half-life: above 100 μs

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta V}{V}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

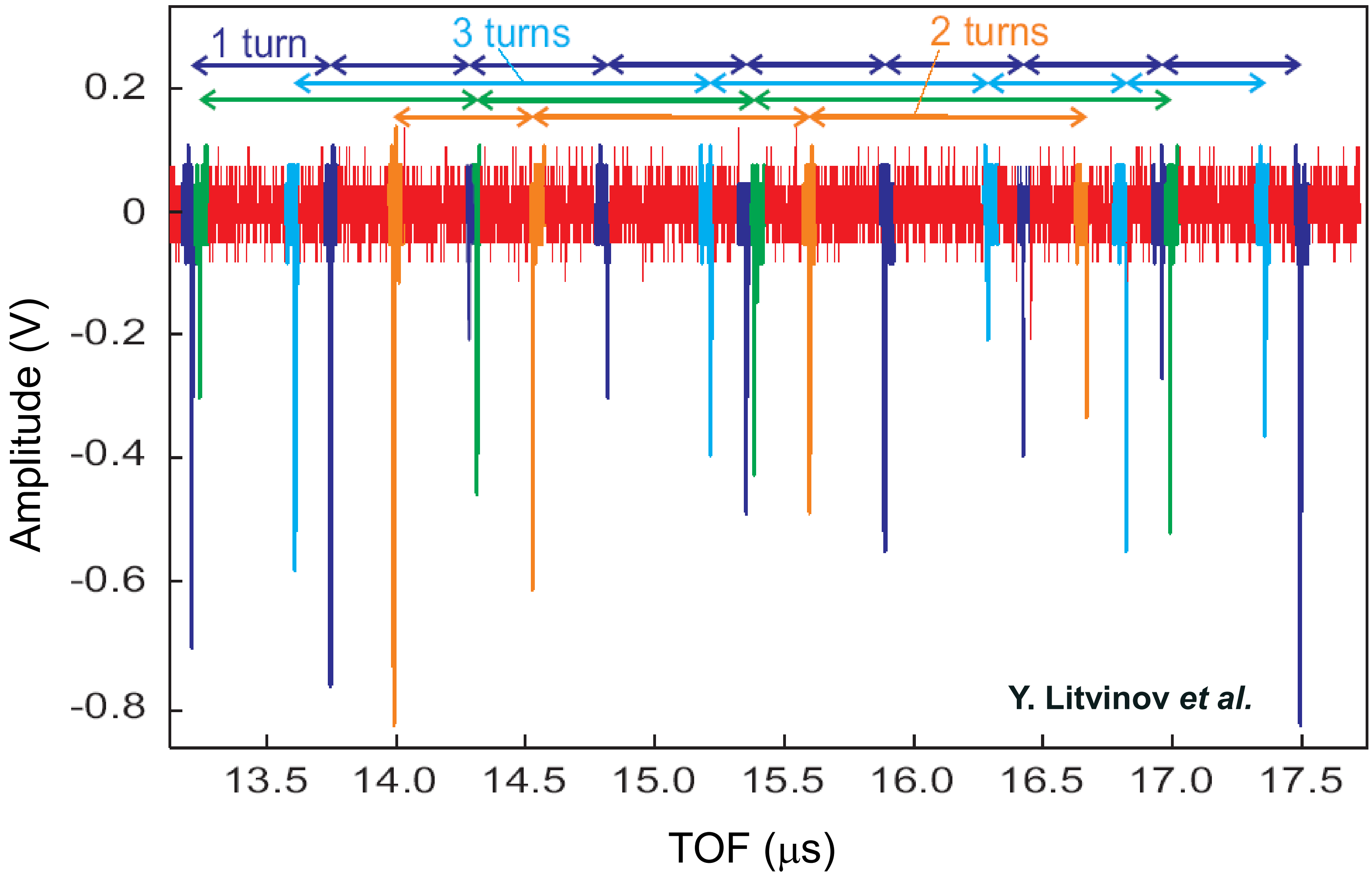
Revolution frequency measurements at ESR
SMS spectrum



A prominent result of SMS at ESR
Decay of two hydrogen-like promethium ions of $^{142}Pm^{60+}$



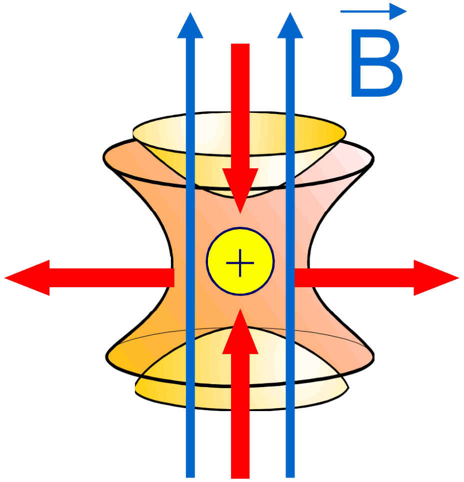
Revolution frequency measurements at ESR
IMS spectrum

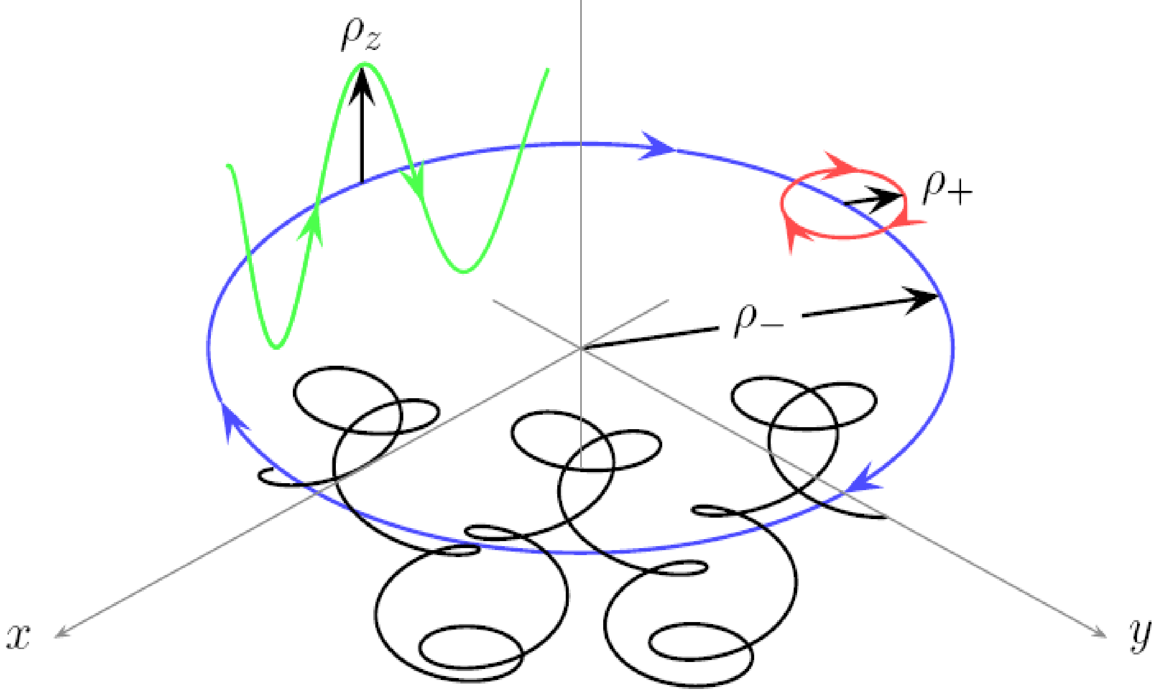


THE PENNING TRAP: CYCLOTRON FREQUENCY MEASUREMENTS

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

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

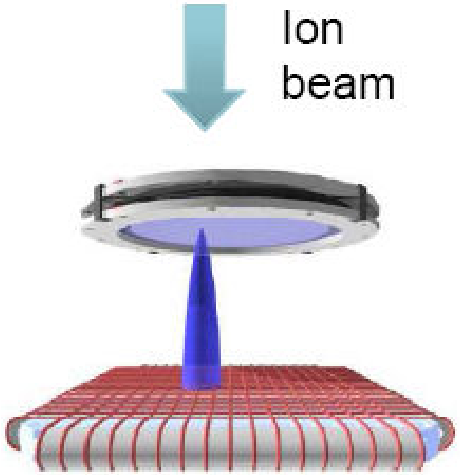
$$\omega_c = \frac{q}{m}B$$

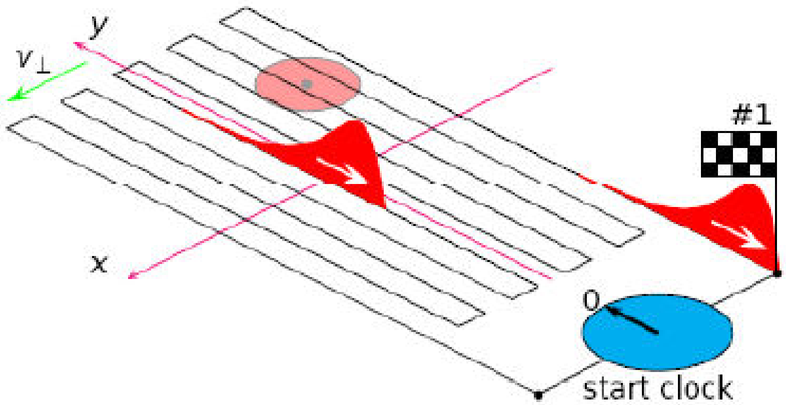
$$\omega_c = \omega_+ + \omega_-$$

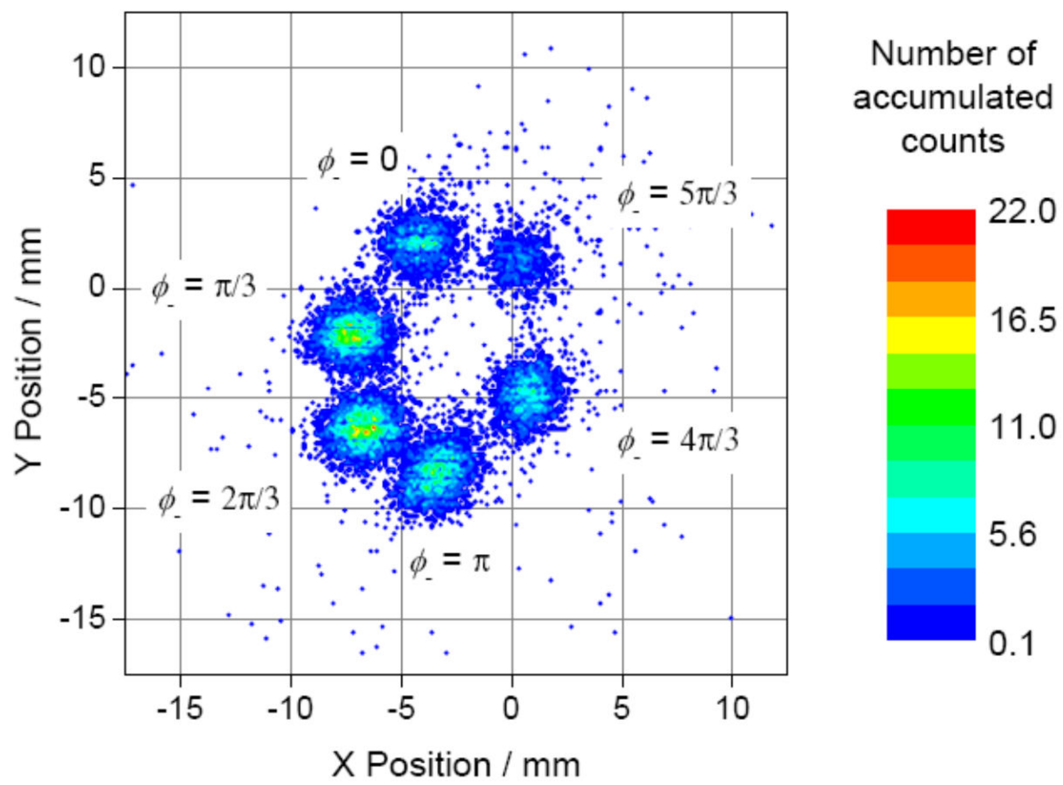
$$\omega_+ > \omega_z > \omega_-$$

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

Penning traps
Fundamentals

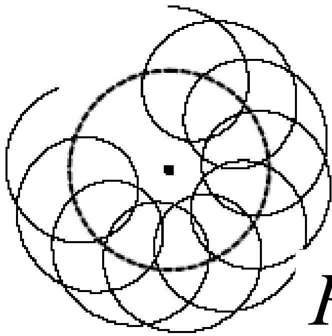




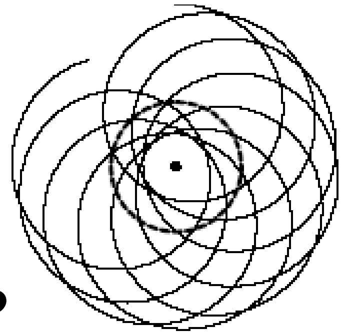


G. Eitel *et al.*, NIM A 606 (2009) 475

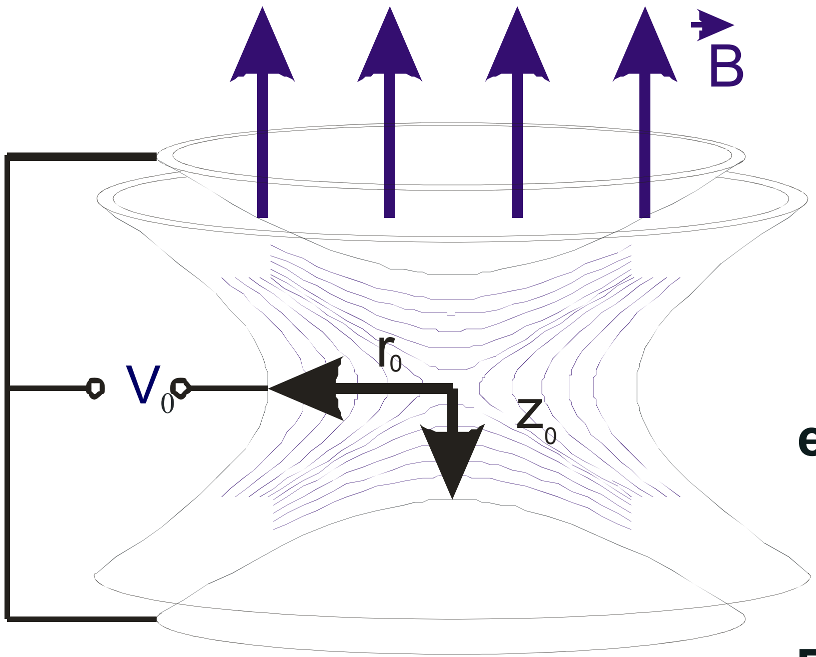
$R_+ < R_-$

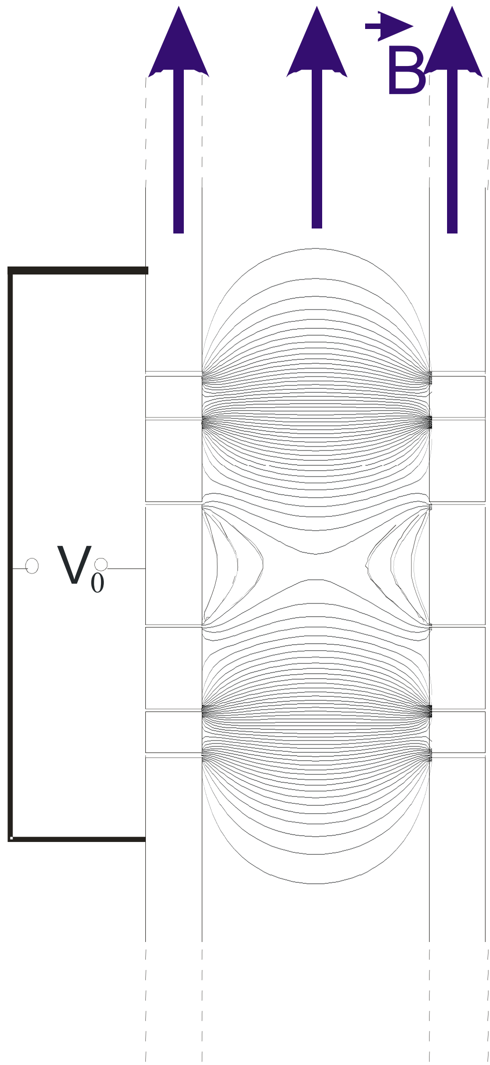


$R_+ > R_-$



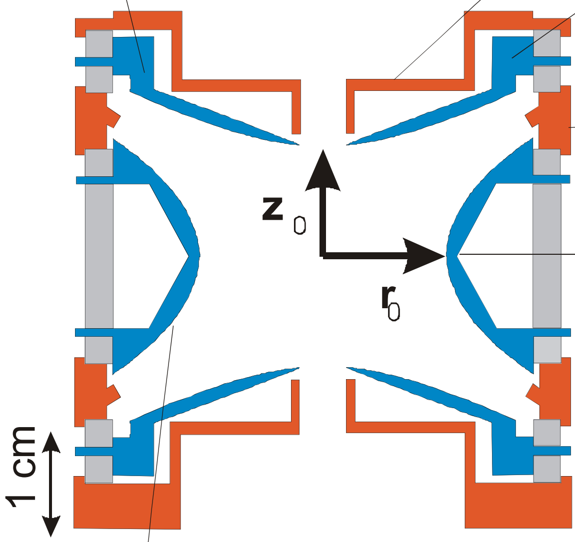
Penning traps
Different geometries

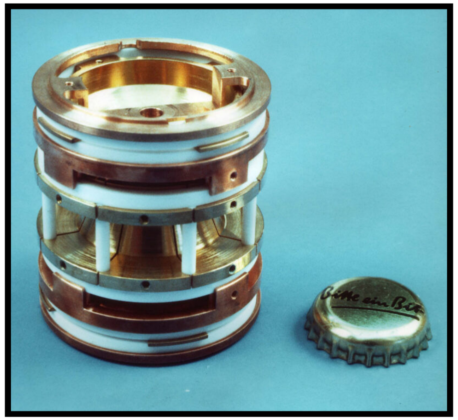


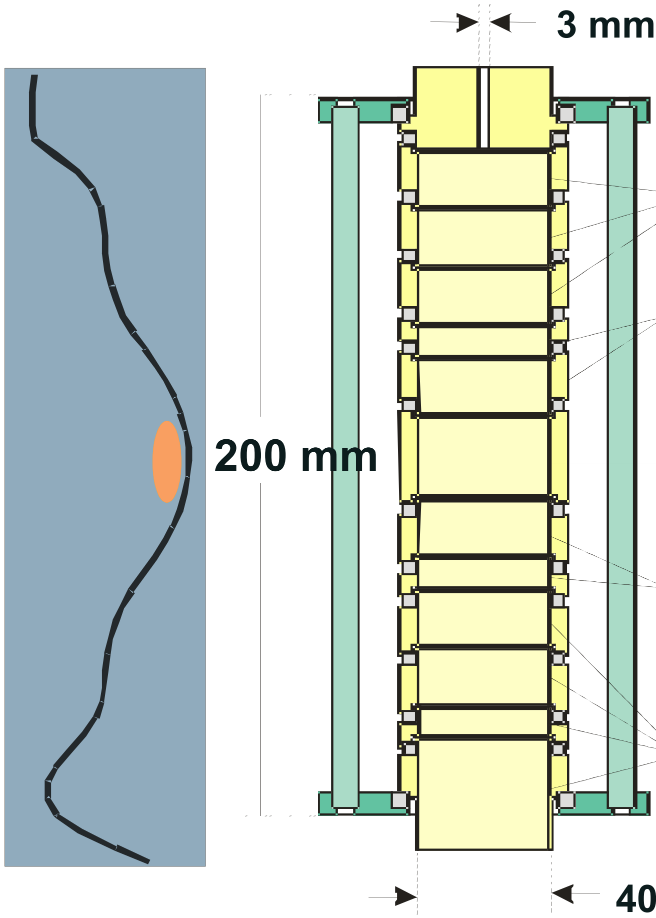


L.S. Browm and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233

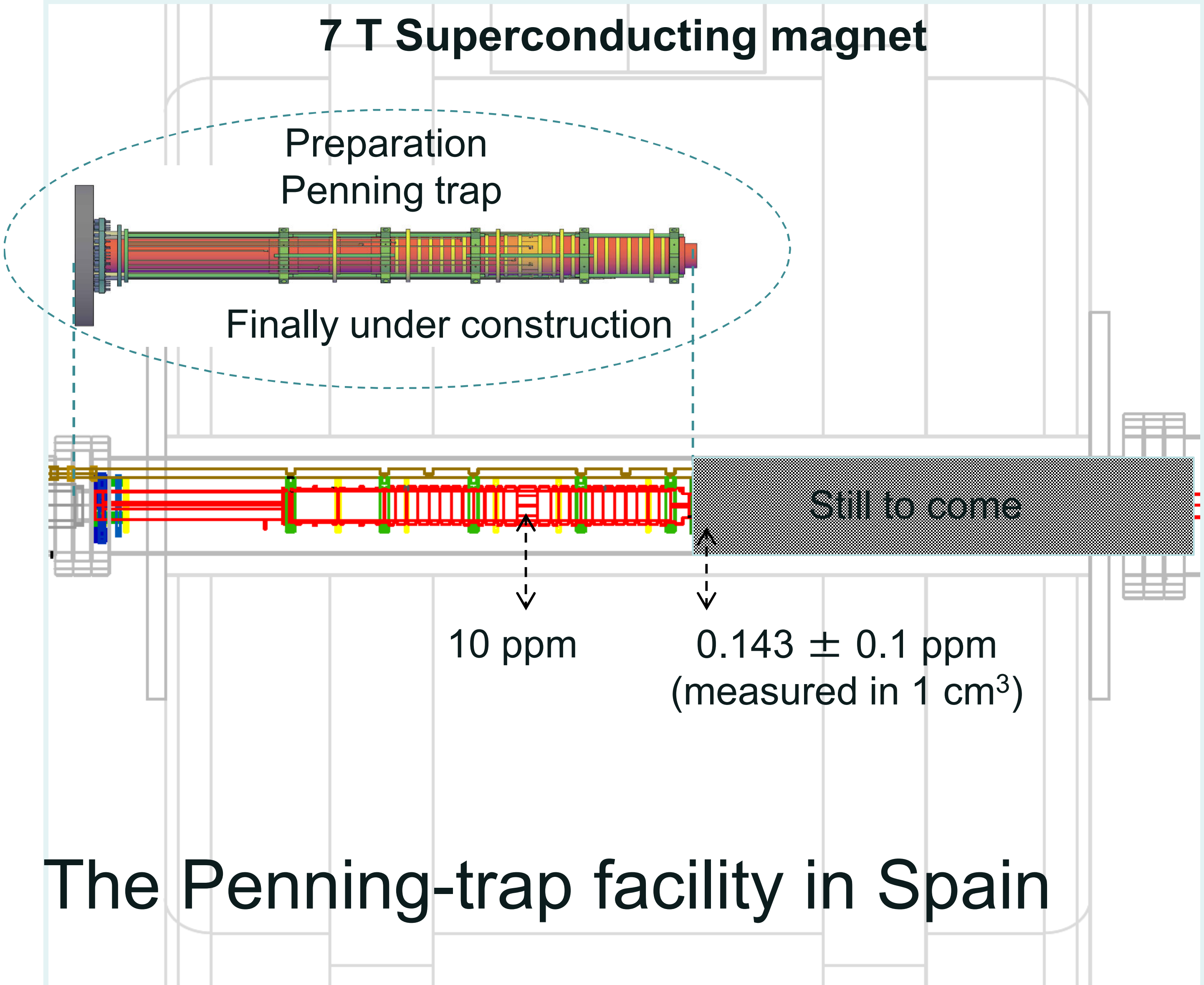
The Pioneering ISOLTRAP at ISOLDE

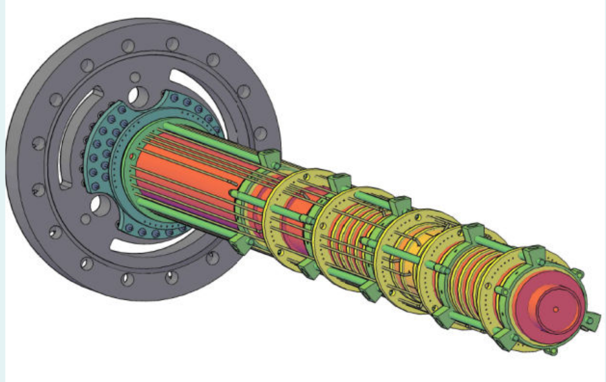


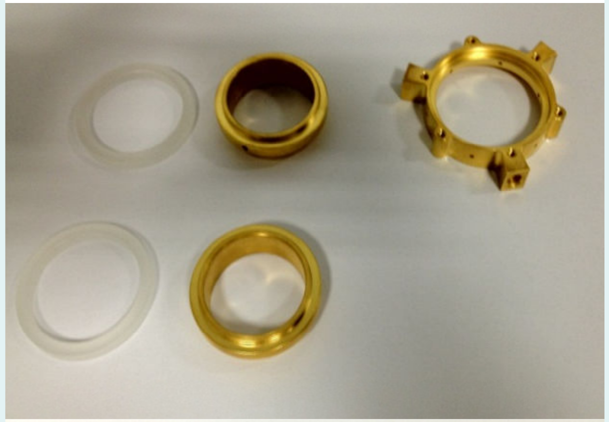




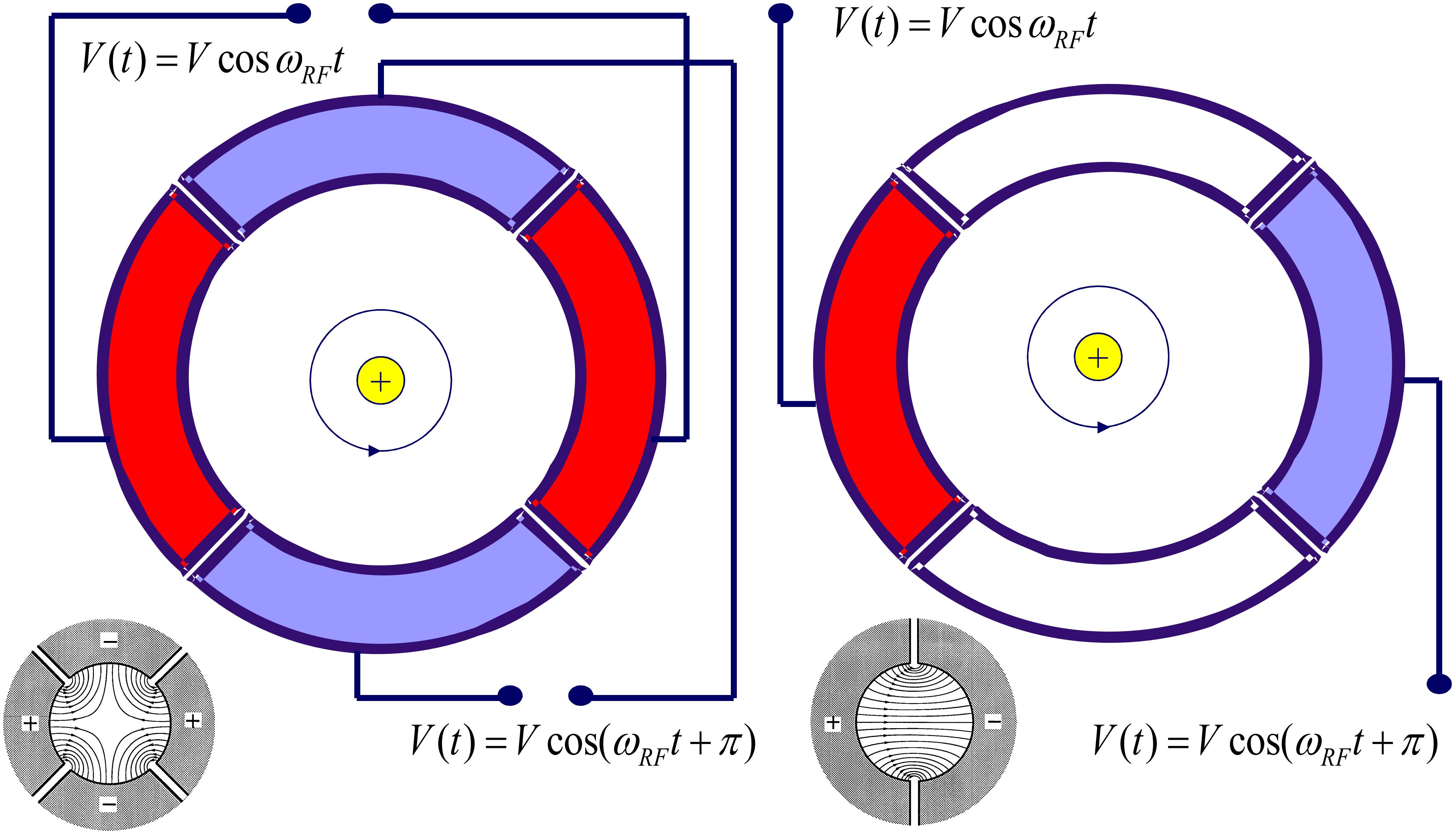
Penning traps
Different geometries



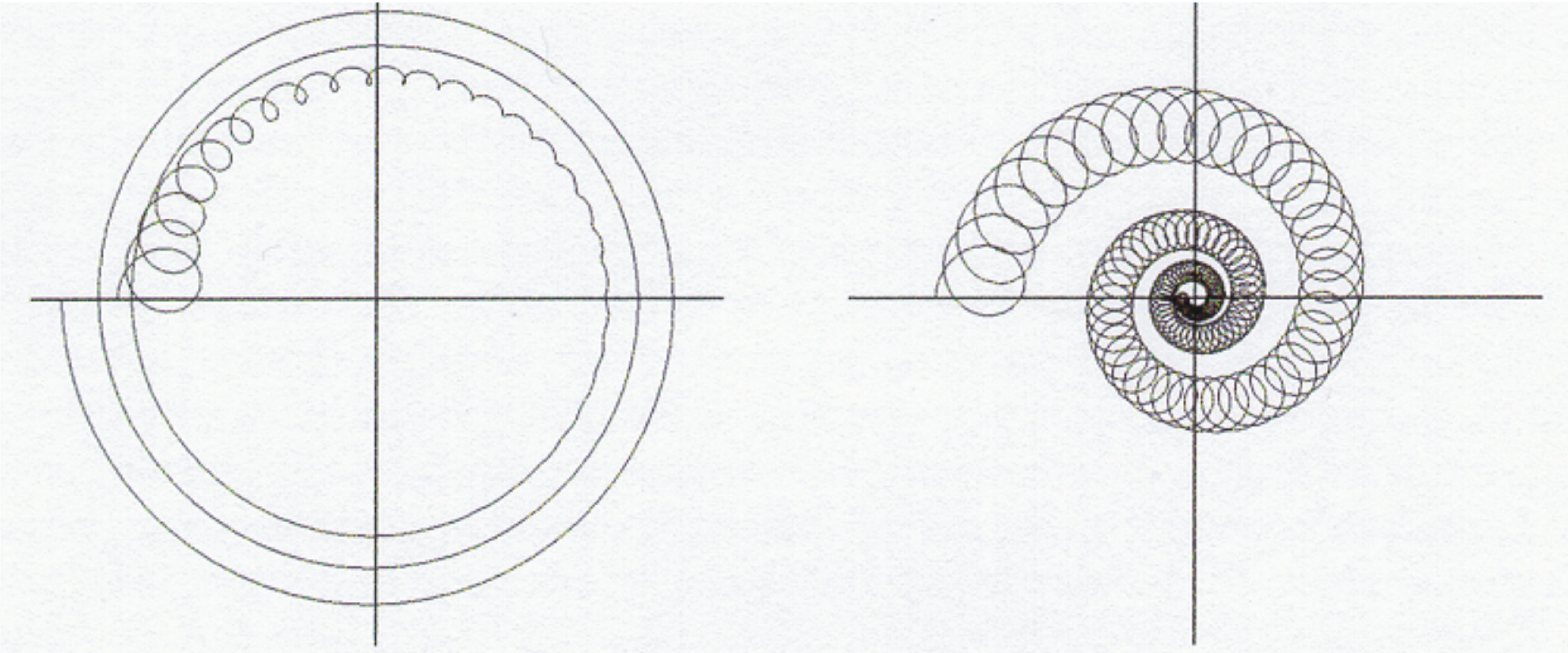




Penning-trap techniques
External Fields



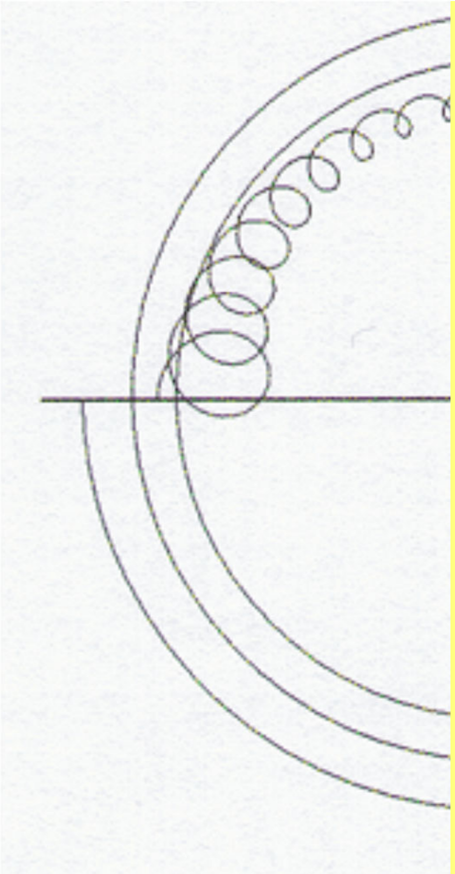
Penning-trap techniques
Isobaric separation

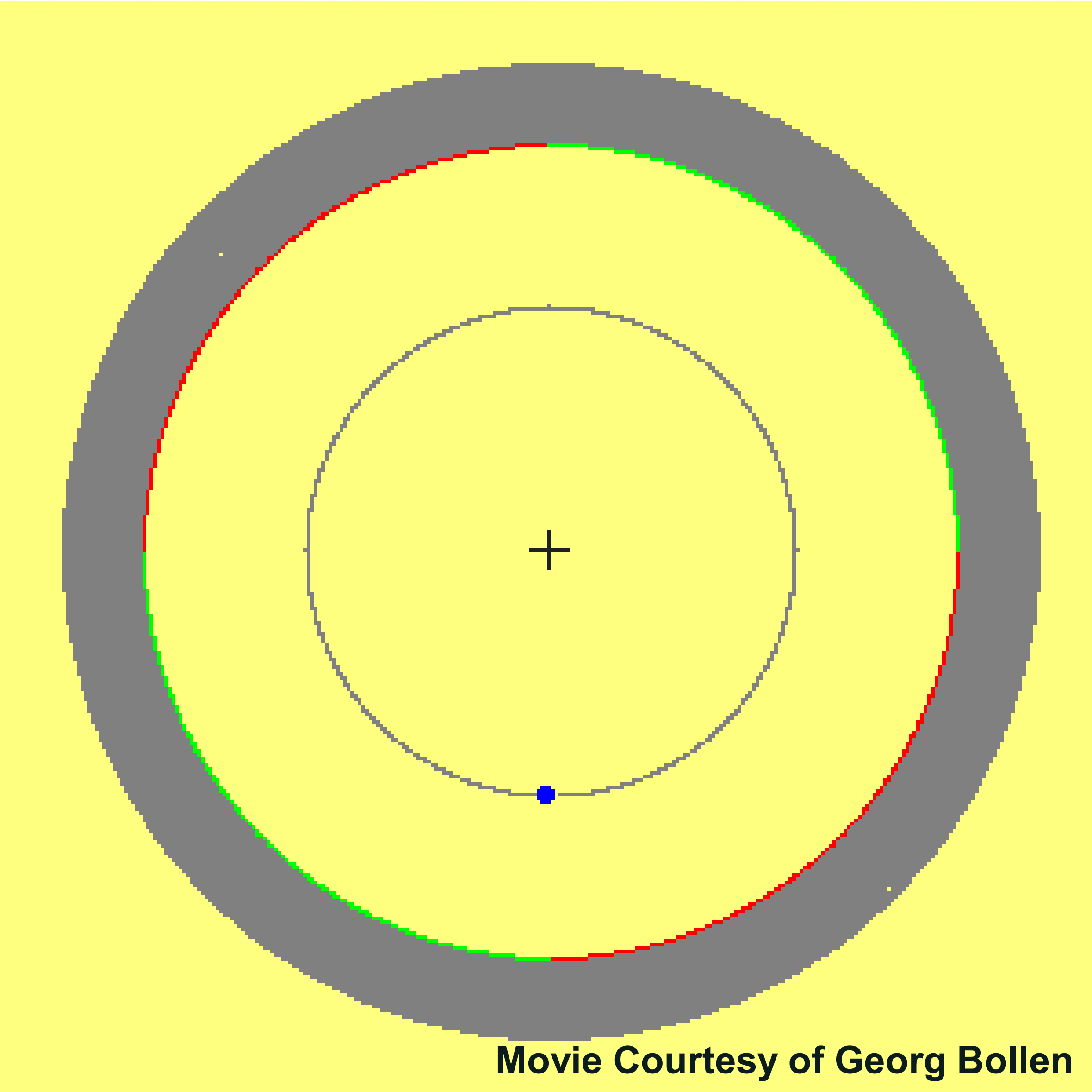


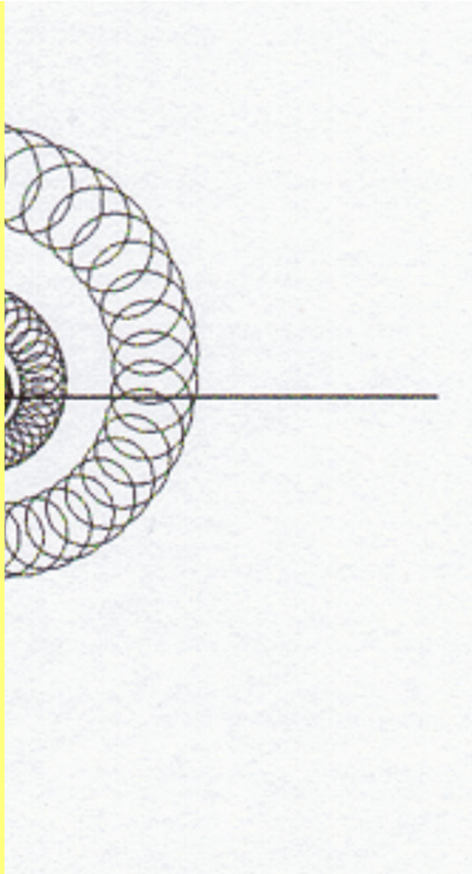
- Increase of the cyclotron radius when no excitation is applied.
- Centering of the ions after excitation at $\omega_{RF} = \omega_c$.

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

Penning-trap techniques
Isobaric separation



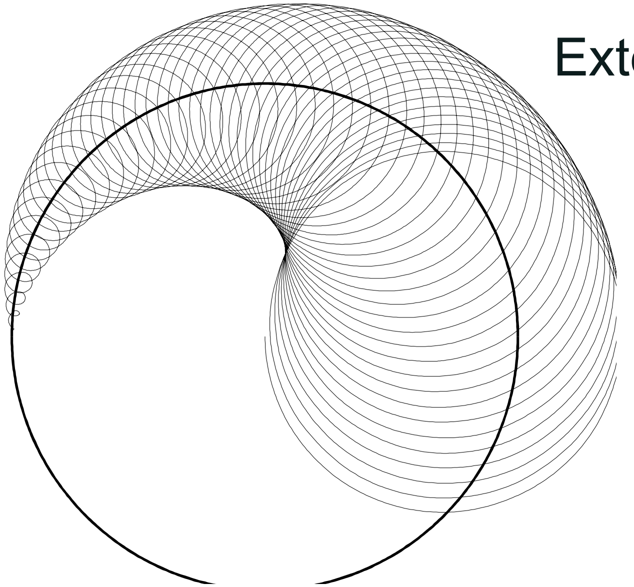




- Increase of ... ions after when no ex... ω_c.

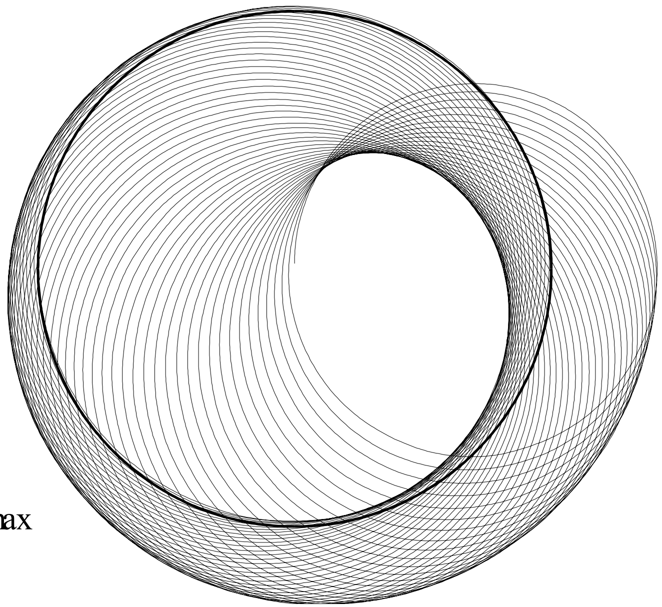
G. Savard *et al.*, I

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



$t = 0$

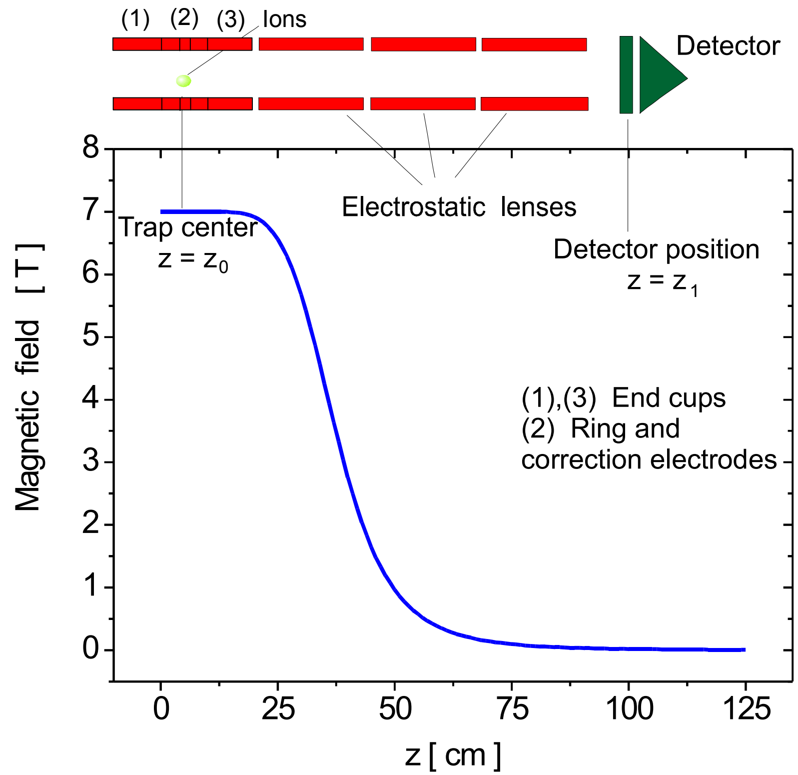
$\mu = \mu_{min}$



$t = T_{RF}$

$\mu = \mu_{max}$

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

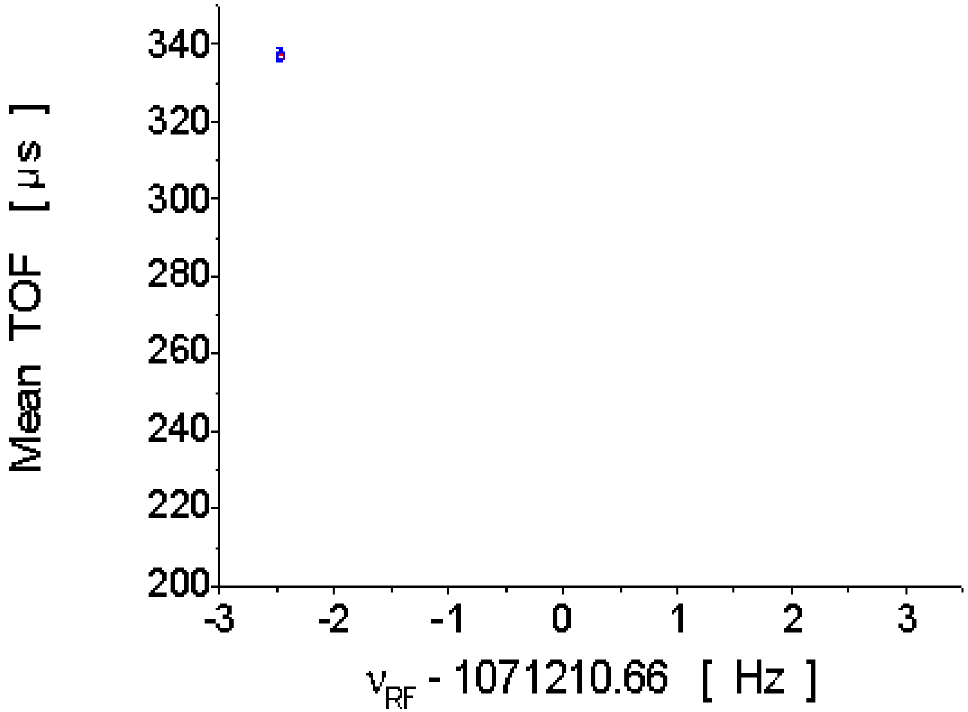


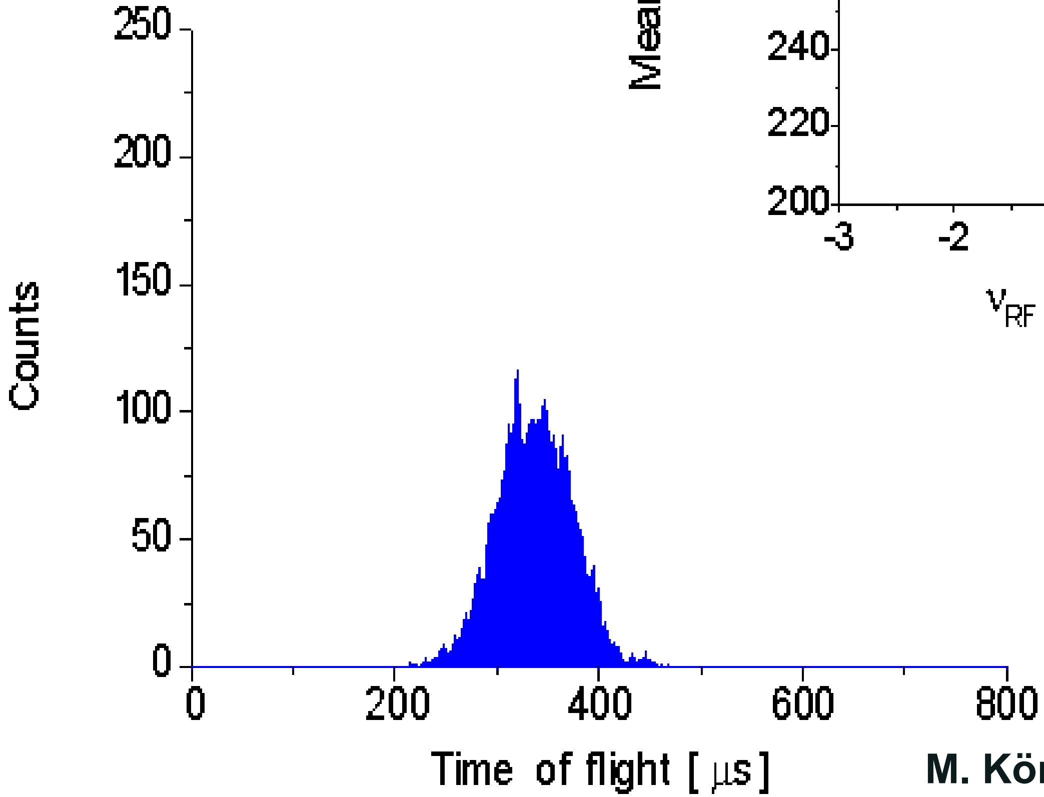
$$F_z = \mu \frac{\partial B}{\partial z}$$

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

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

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

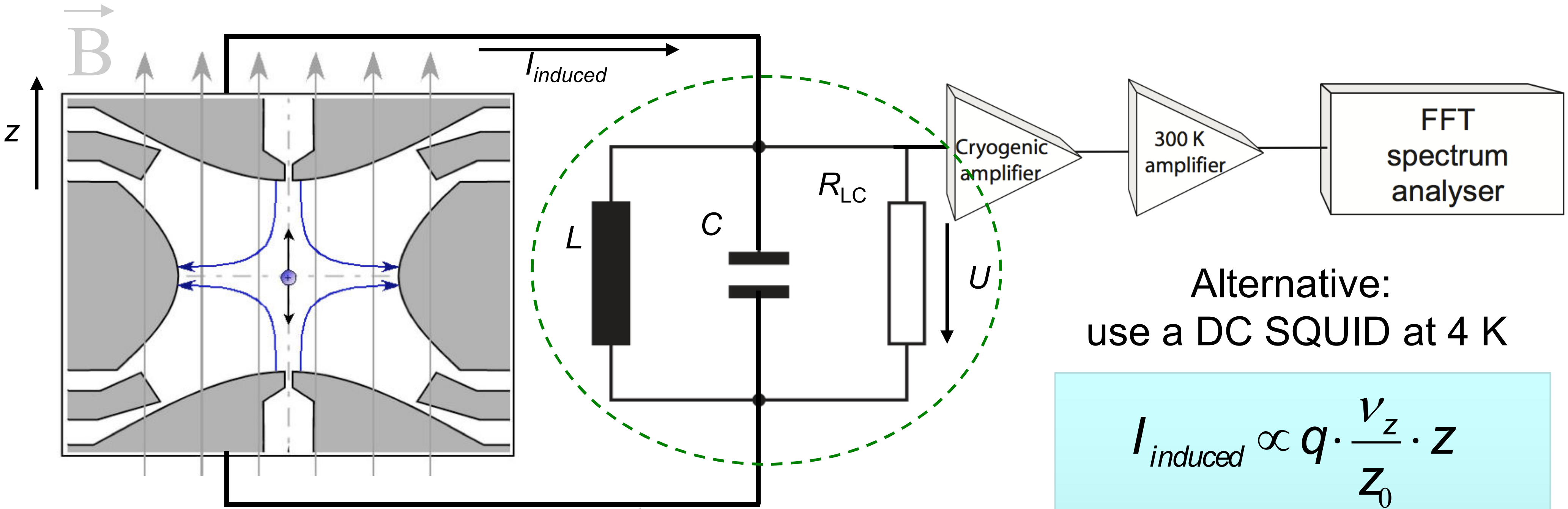




- Ion beam energy: ~ 1 eV
- Mass Resolving Power: 1×10^6
- Measurement Uncertainty: 10^{-8}-10^{-9}
- Sensitivity: ~ 40 ions
- Minimum half-life: 8 ms

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

Penning-trap techniques
Induced image current detection

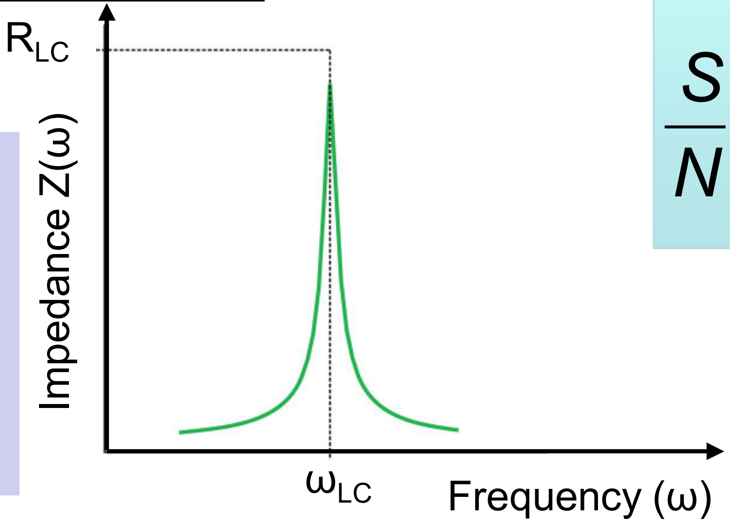


Alternative:
use a DC SQUID at 4 K

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

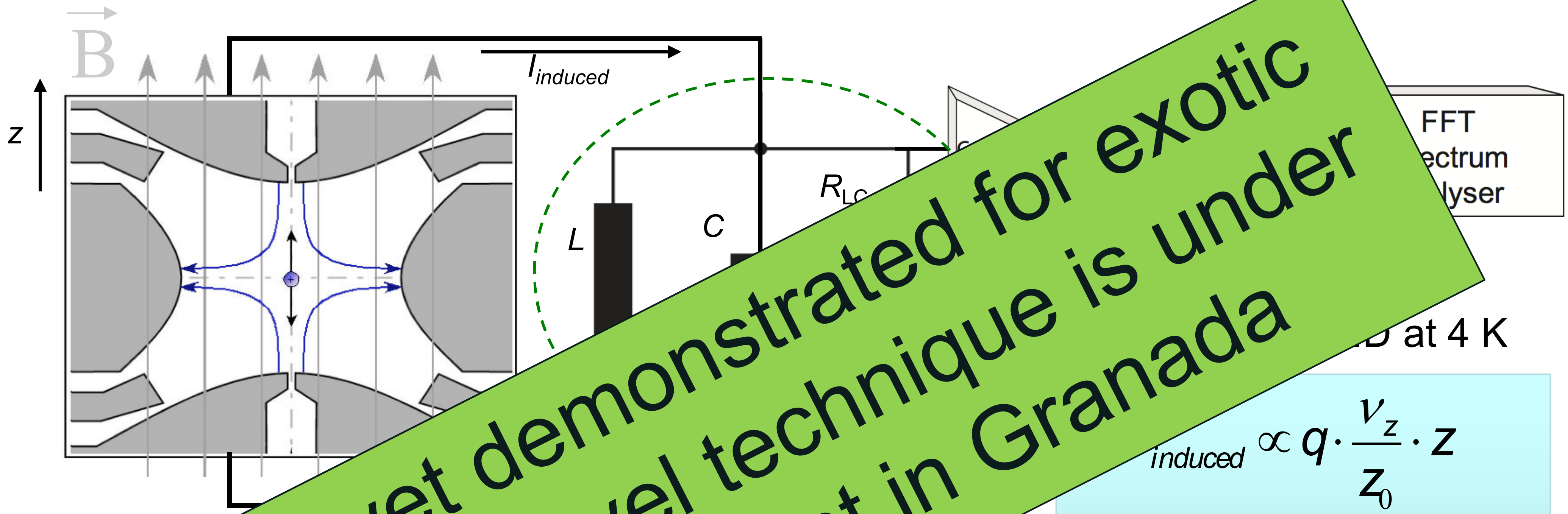
$$\frac{S}{N} \propto q \cdot \frac{z}{z_0} \cdot \sqrt{\frac{\nu_z}{\Delta \nu}} \cdot \sqrt{\frac{Q}{TC}}$$

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



- Ion beam energy: ~ 1 eV
- Measurement Uncertainty: 10^{-11}
- Sensitivity: ~ 1 ions
- Minimum half-life: (to be determined)

Penning-trap techniques
Induced image current detection

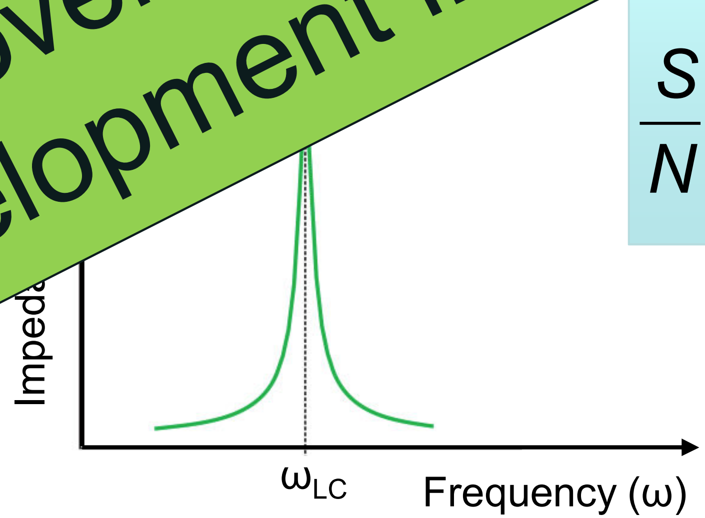


Not yet demonstrated for exotic ions. A novel technique is under development in Granada

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

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

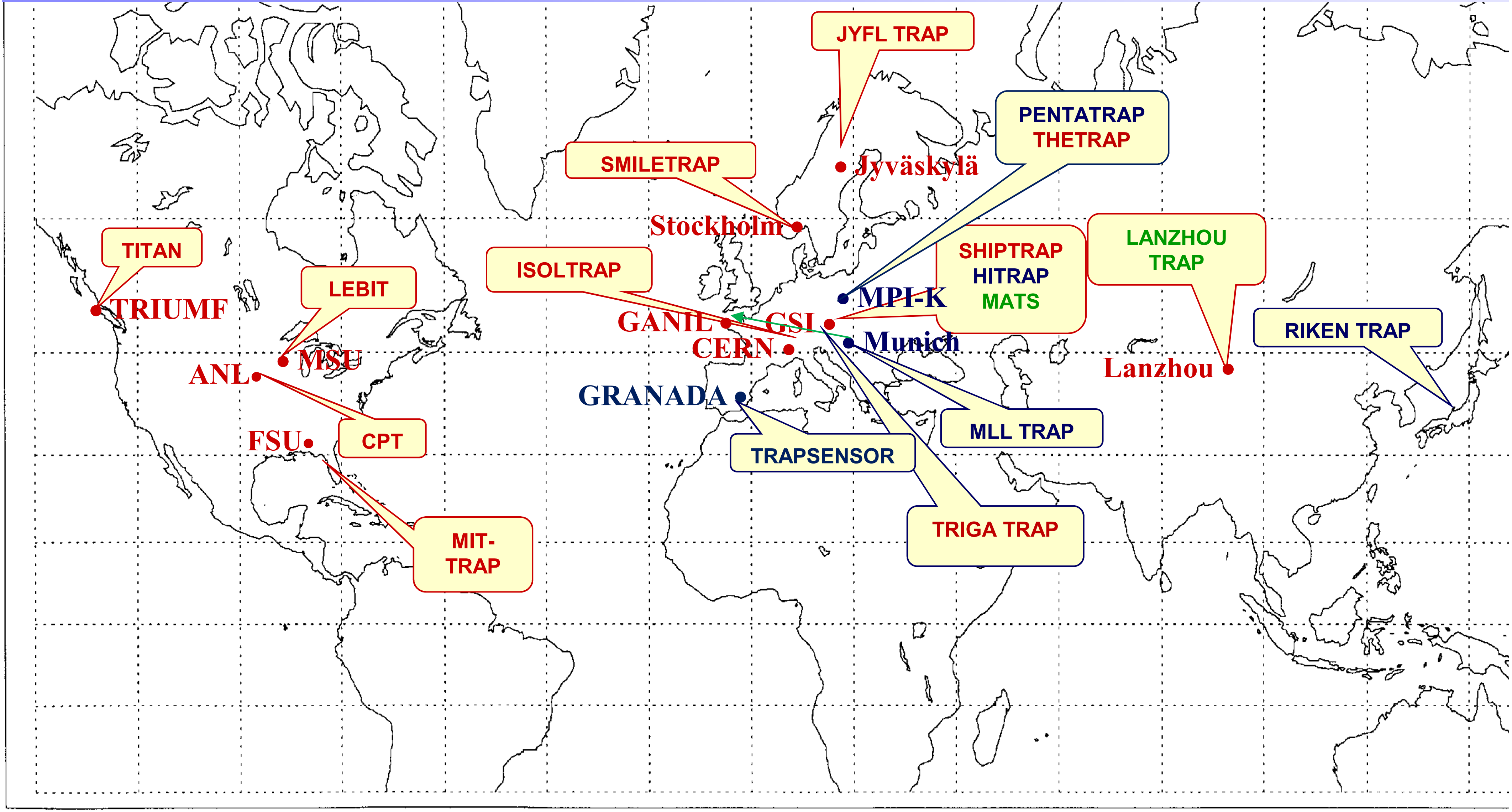
- Ion be
- Measu
  up to 10
- Sensitivity
- Minimum h
  determined)



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

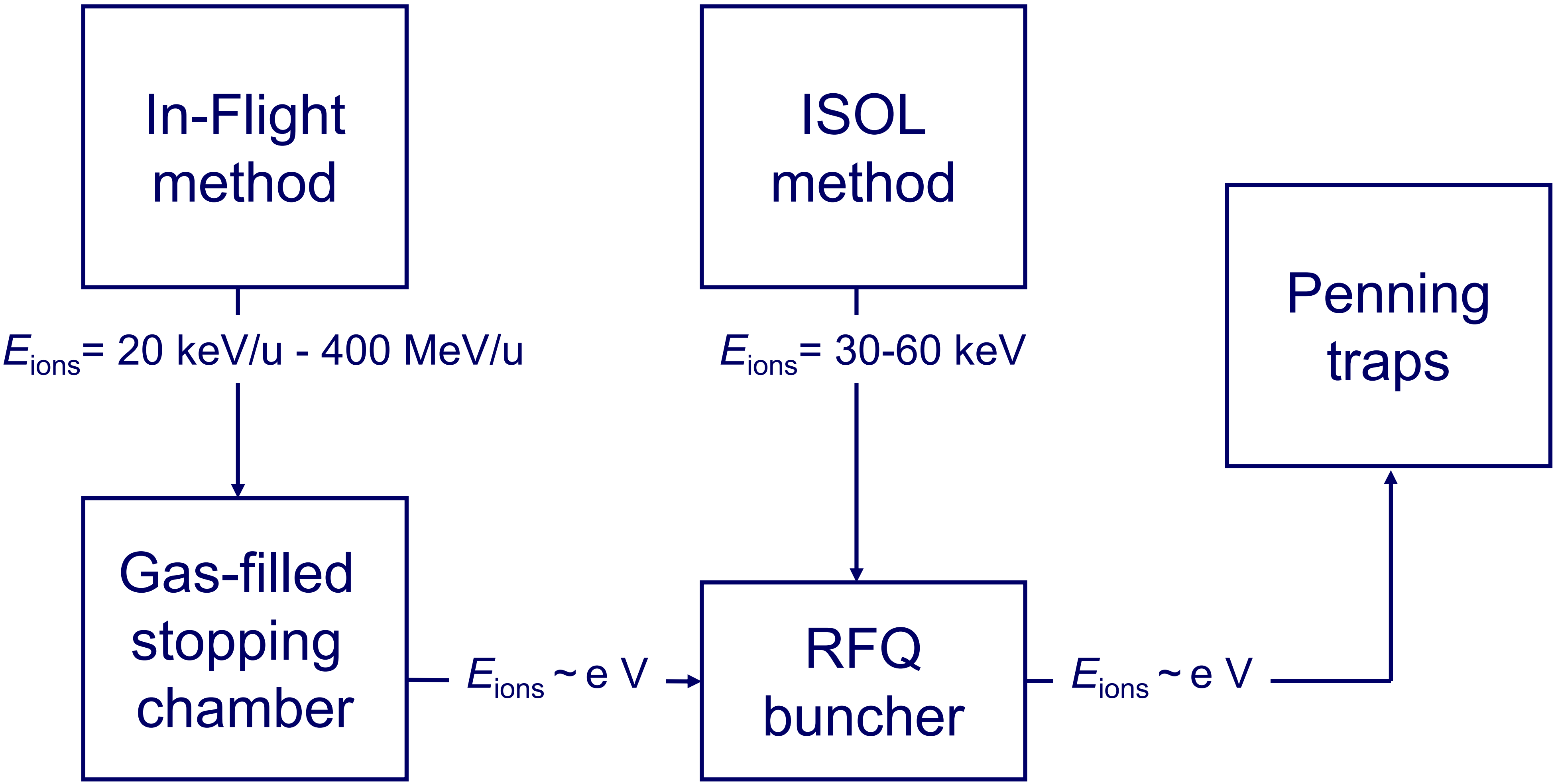
Existing Penning-trap facilities

Mass spectrometry of atomic nuclei



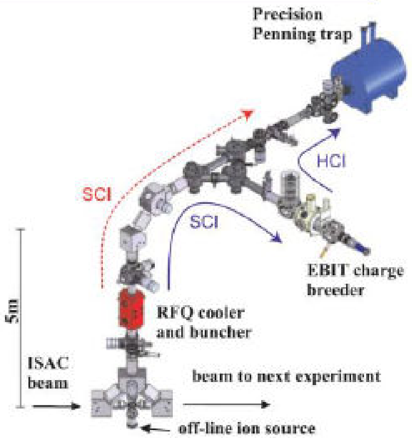
• Running facilities • Under construction • Future facilities

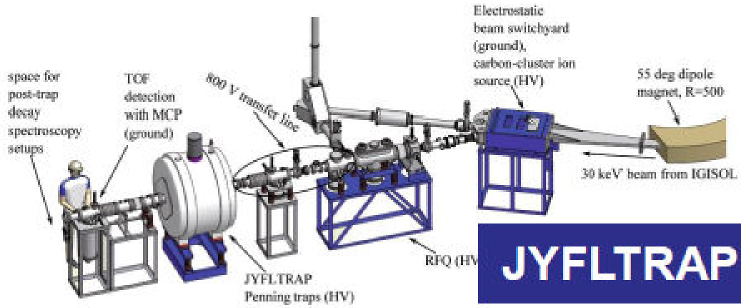
Coupling Penning traps to RIB facilities



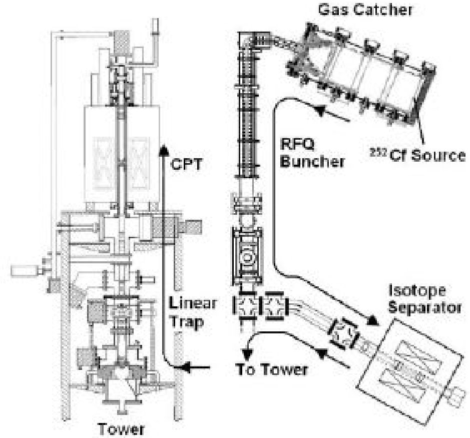
Growing  facilities

TITAN (TRIUMF)

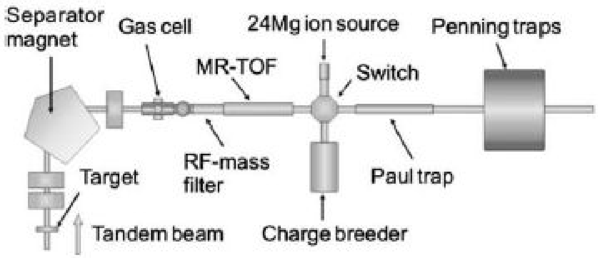




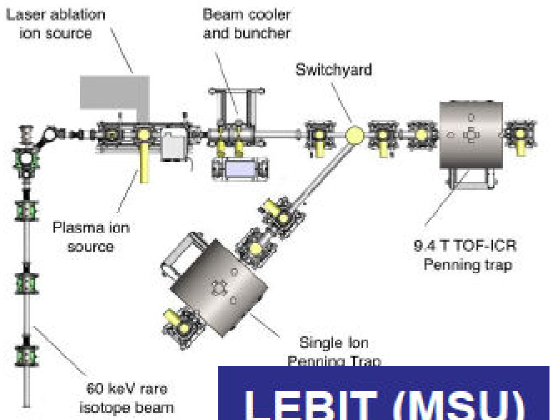
JYFLTRAP



CPT (ARGONNE)

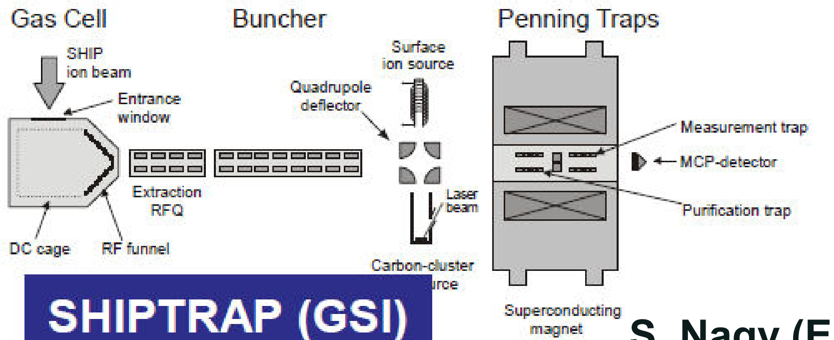


MLLTRAP



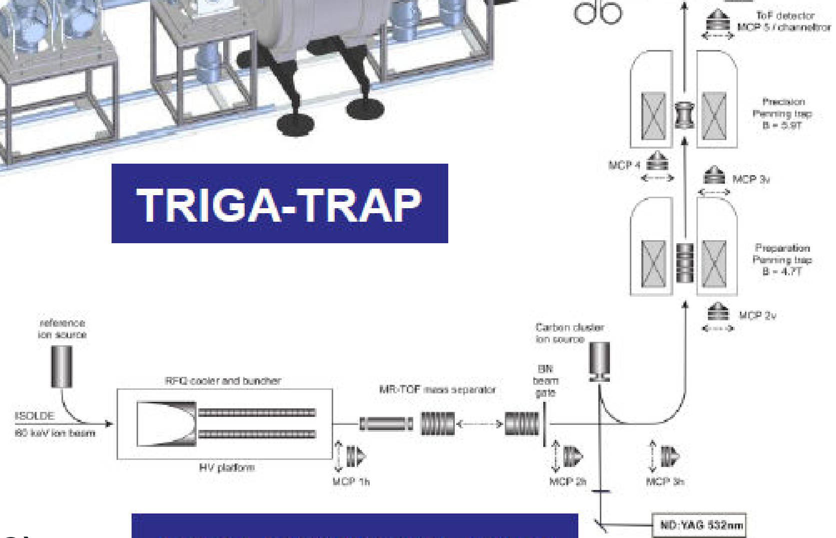
LEBIT (MSU)

TRIGA-TRAP



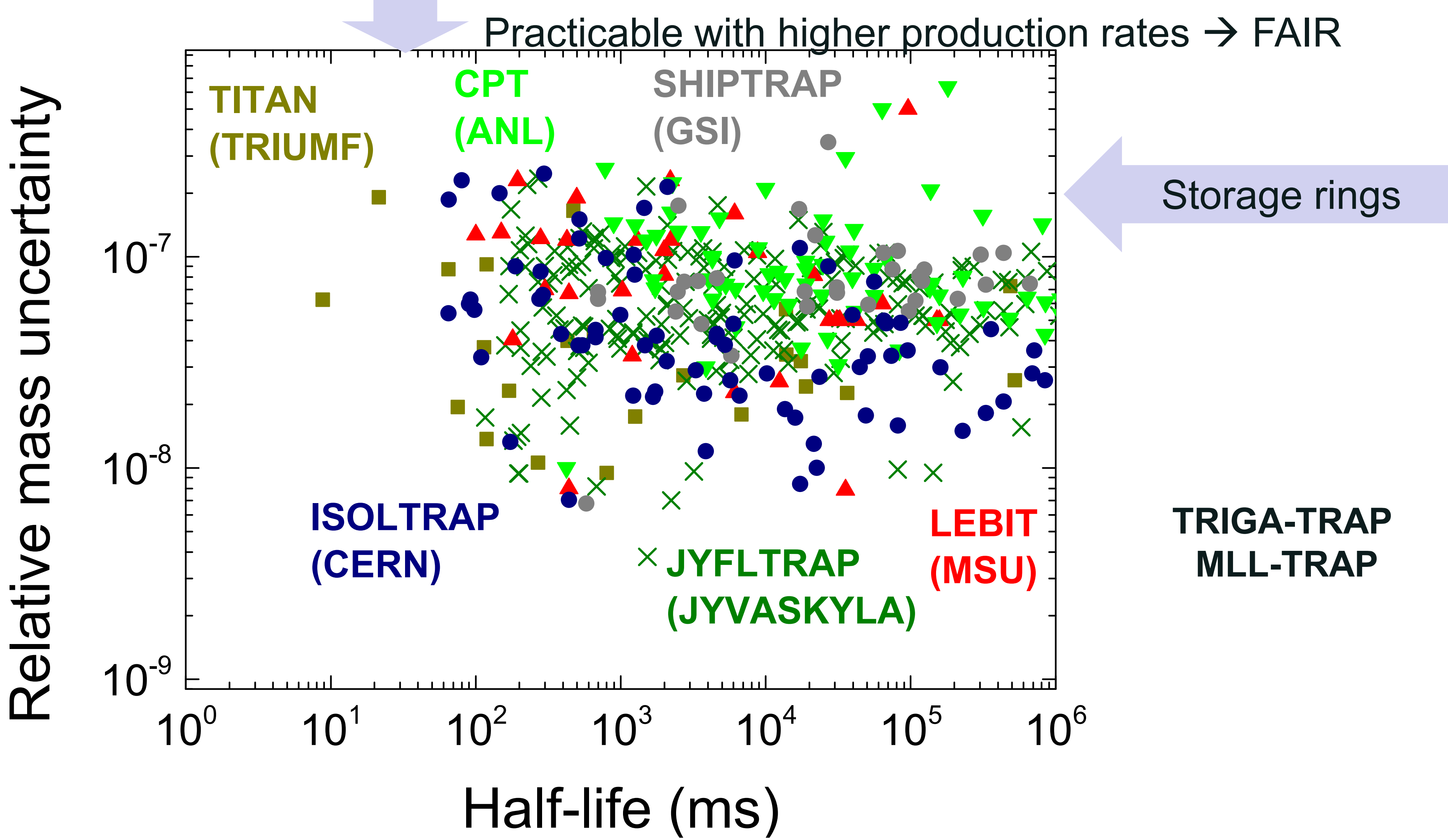
SHIPTRAP (GSI)

S. Nagy (EMIS2012)



ISOLTRAP(CERN)

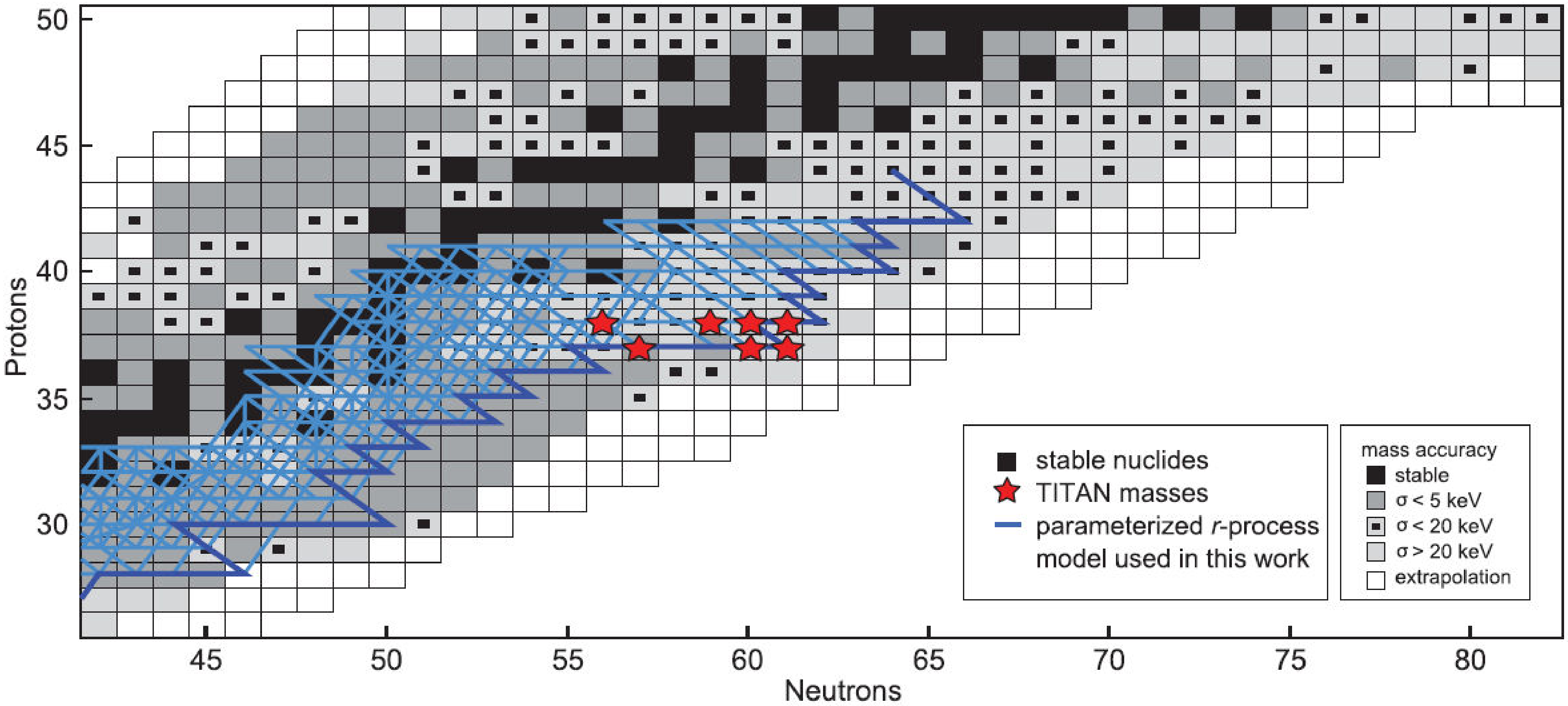
Physics survey
Penning-trap mass measurements at RIB



<u>High-lights 2011-2012</u>: S. Eliseev *et al.*, PRL 106 (2011) 052504, E. Haettner *et al.*, PRL 106 (2011) 122501, S. Eliseev *et al.*, PRL 107 (2011) 152501, S. Ettenauer et al., PRL 107 (2011) 272501, M. Brodeur *et al.*, PRL 108 (2012) 052504, D. Fink *et al.*, PRL 108 (2012) 062502, M. Brodeur *et al.*, PRL108 (2012) 212501, J. Hakala *et al.*, PRL 109 (2012) 032501, A. T. Gallant *et al.*, PRL 109 (2012) 032506, E. Minaya Ramirez *et al.*, Science 337 (2012) 1207.

Recent highlights (TITAN)
Nuclear (Penning-trap) astrophysics at TRIUMF (June 2012)

rp-process (highly-charged ions)



V. Simon *et al.*, Phys. Rev. C 85, 064308 (2012)

Recent highlights (TITAN)

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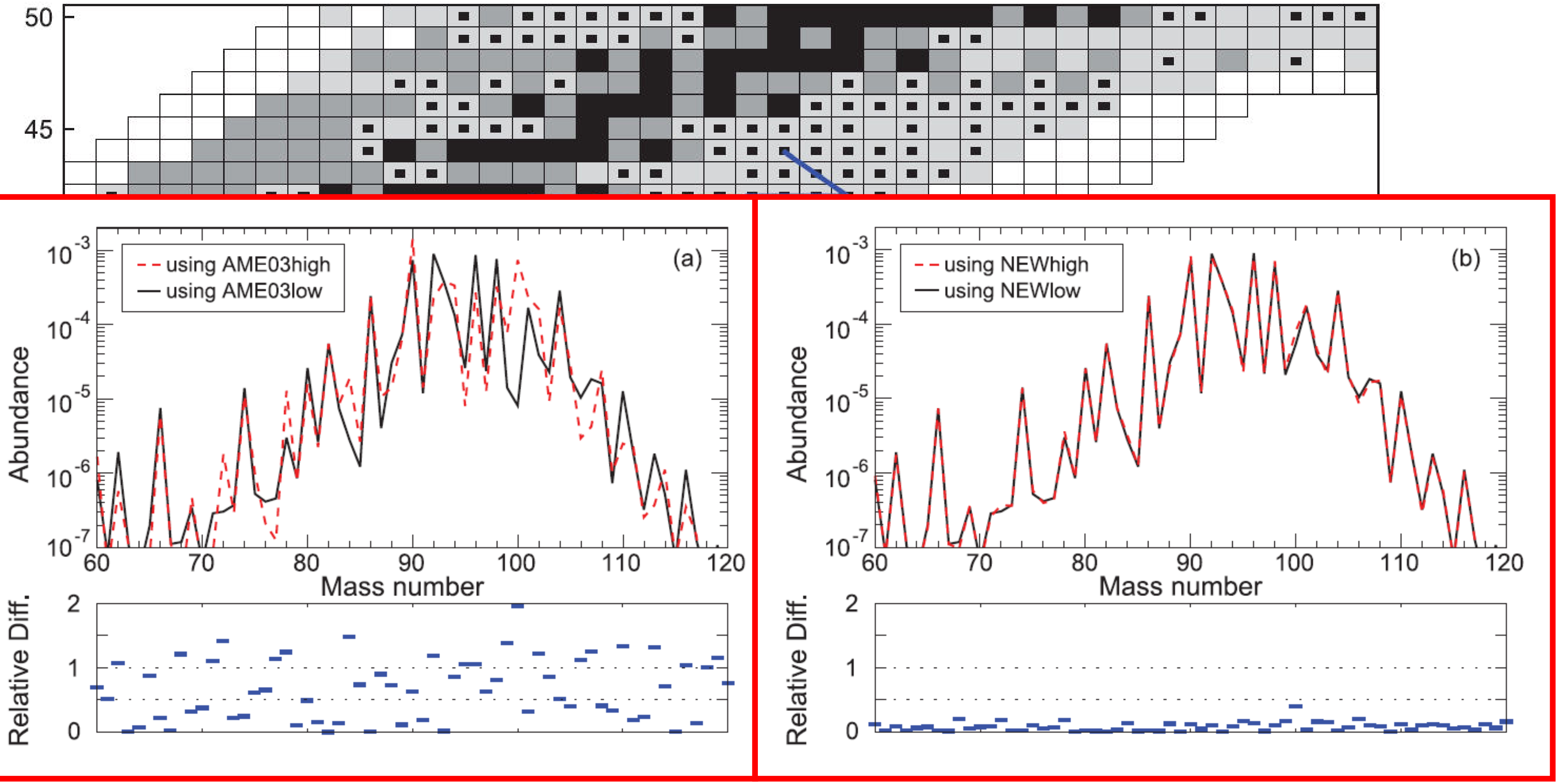
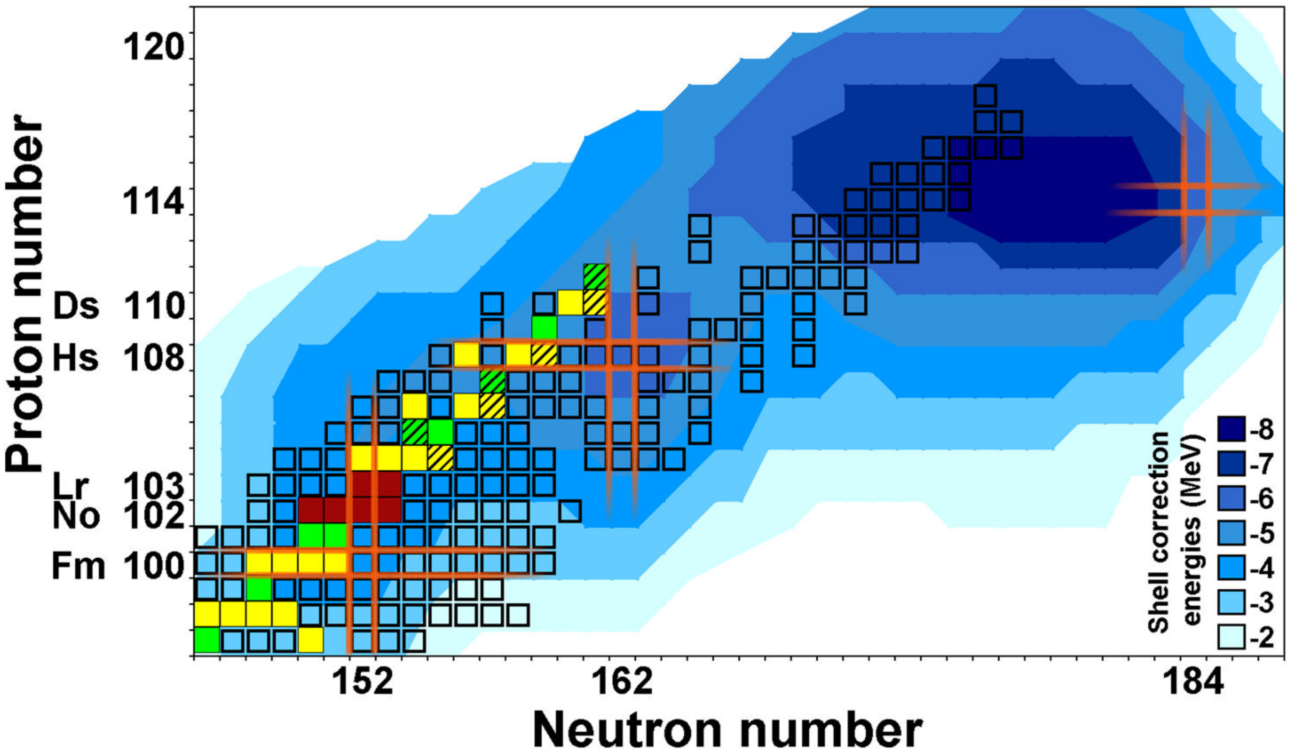


V. Simon *et al.*, Phys. Rev. C 85, 064308 (2012)

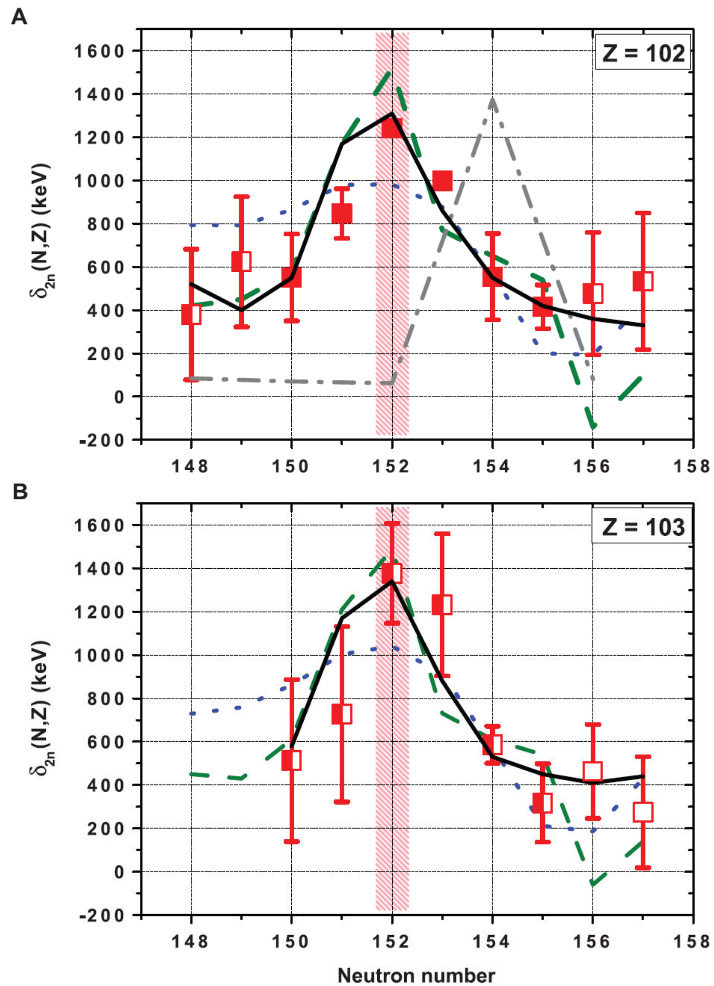
Recent highlights (SHIPTRAP)

NUSTAR (Penning-trap) experiment at GSI (September 2012)

Nuclear Structure (minute production)



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

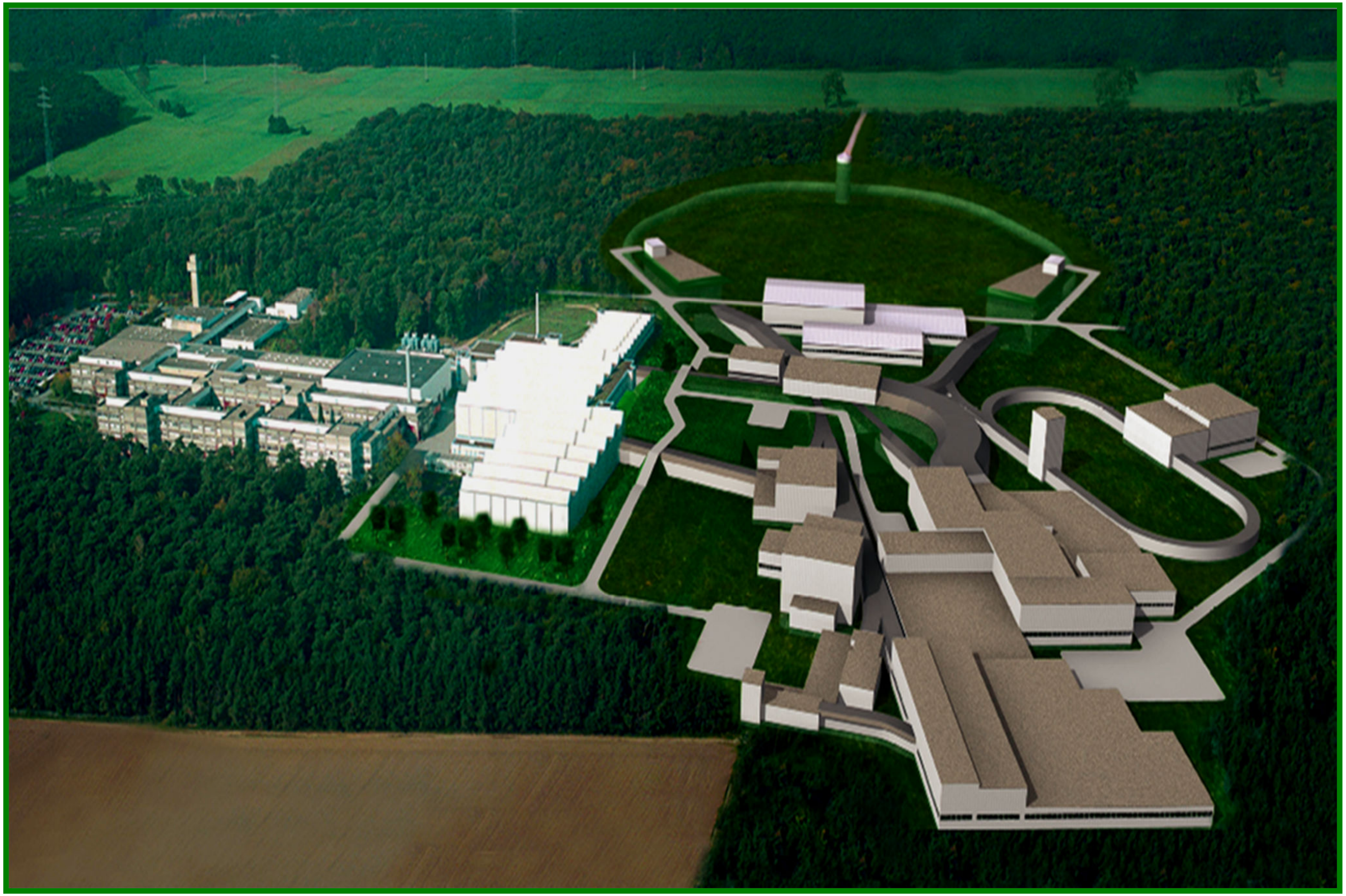


- The isotope with lowest production rate ever measured in a Penning trap (^{256}Lr, 60(18) nb) →48 ions detected in 93 hours !!!

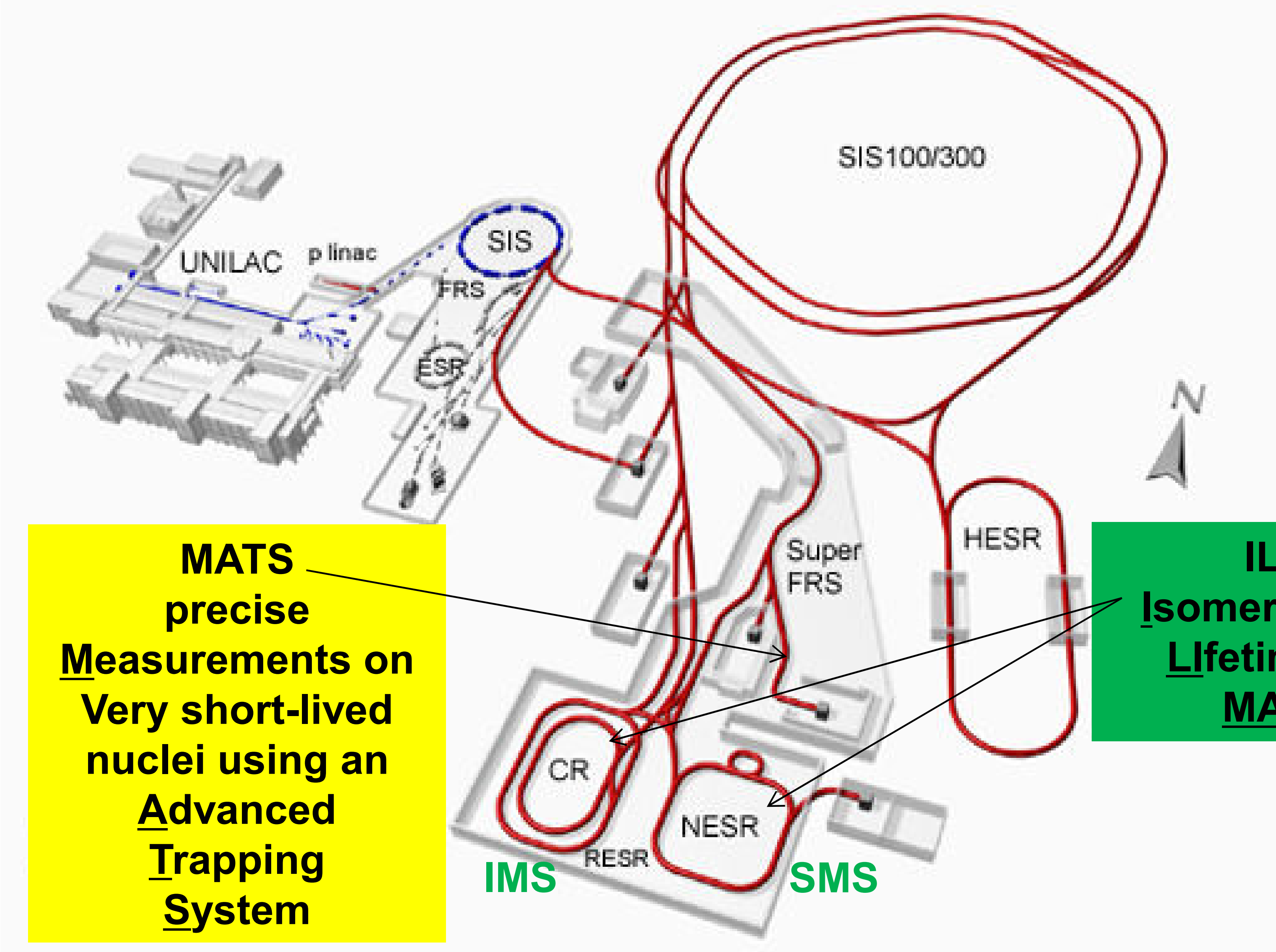
E. Minaya Ramirez *et al.*, Science 337 (2012) 1207

MASS MEASUREMENTS ON EXOTIC NUCLEI IN THE FUTURE

Future Facility for Antiprotons and Ions Research (FAIR)
Higher Production yields



Future Facility for Antiprotons and Ions Research (FAIR)
Higher Production yields



MATS
precise
Measurements on
Very short-lived
nuclei using an
Advanced
Trapping
System

ILIMA
Isomeric Beams
LIfetimes and
MAsses