FAIR Conf., Worms, Germany 2014

Nuclear Masses and their Importance for Nuclear Structure, Nuclear Astrophysics, and Fundamental Studies

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Oct 16th, 2014

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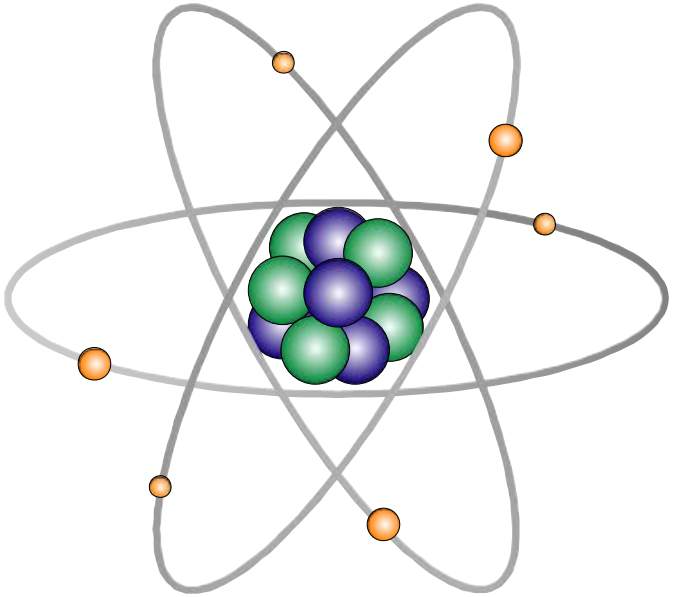
Atomic and nuclear masses

Masses determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.



$= N \cdot$  $+ Z \cdot$  $+ Z \cdot$ 

– binding energy

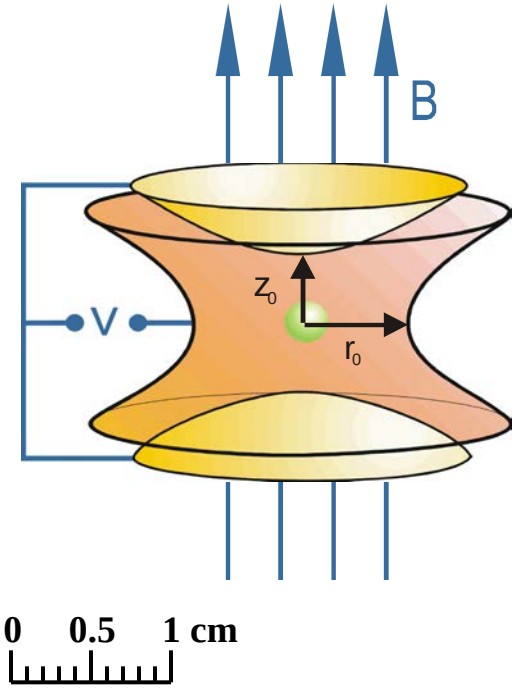
$$M_{\text{Atom}} = N \bullet m_{\text{neutron}} + Z \bullet m_{\text{proton}} + Z \bullet m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

$\delta m/m < 10^{-10}$

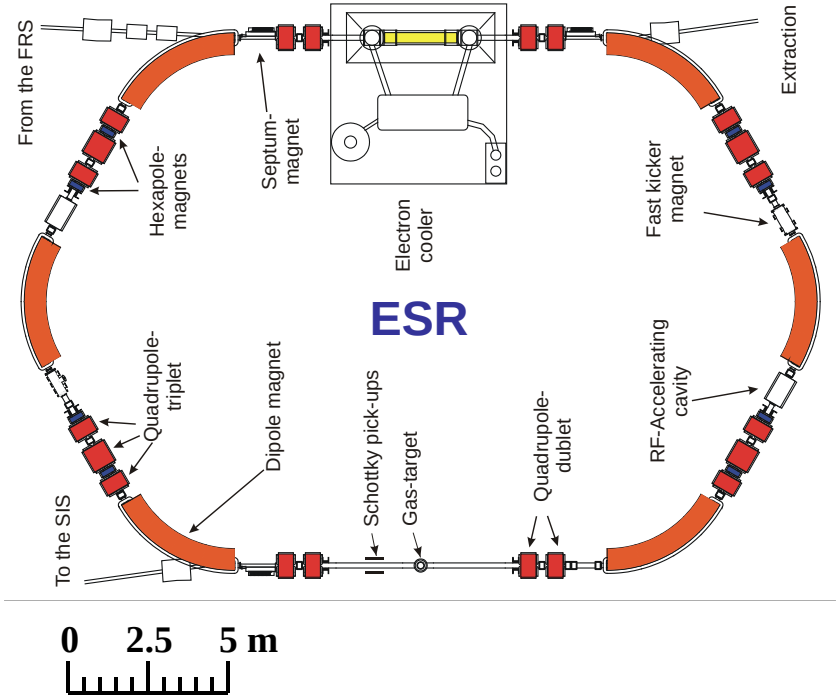
$\delta m/m = 10^{-6} – 10^{-8}$

Storage and cooling techniques

Penning trap



Storage ring



particles at nearly rest in space

relativistic particles

* ion cooling (buffer gas, resistive, electron)
* long storage times
* single-ion sensitivity
* high accuracy

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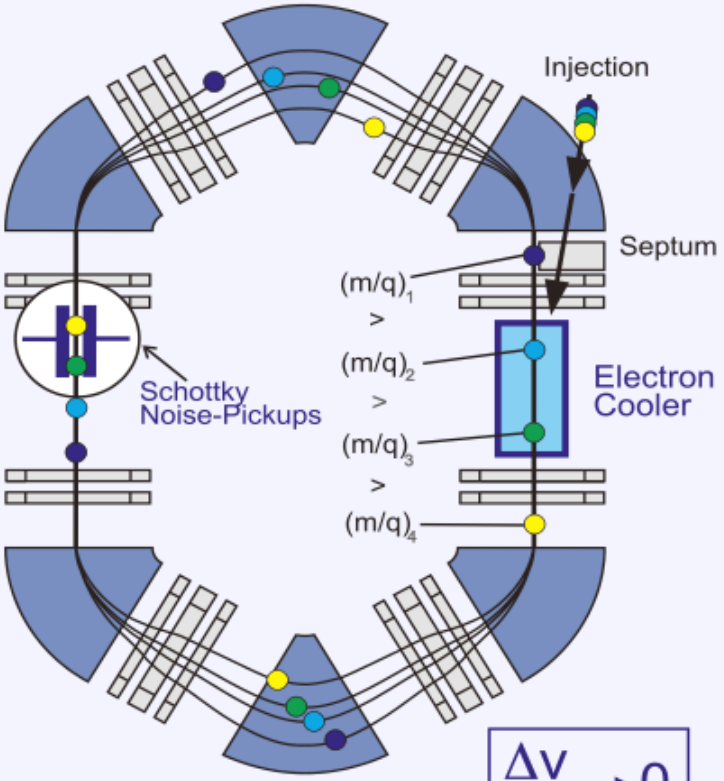
Storage ring mass spectrometry

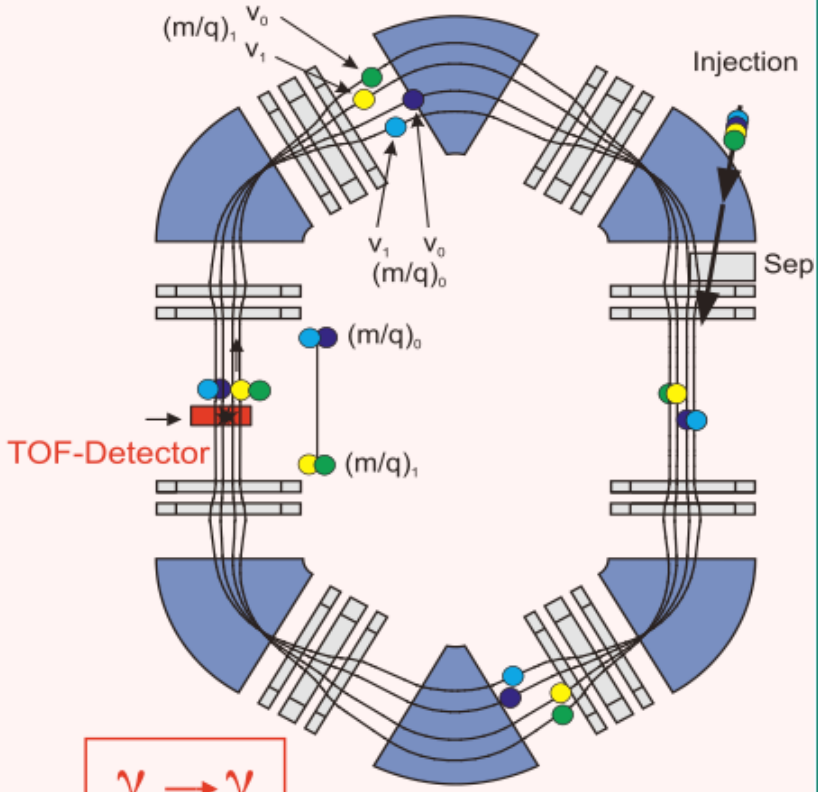
Schottky Mass Spectrometry



Cooled Fragments

$$\frac{\Delta v}{v} \rightarrow 0$$

Isochronous Mass Spectrometry



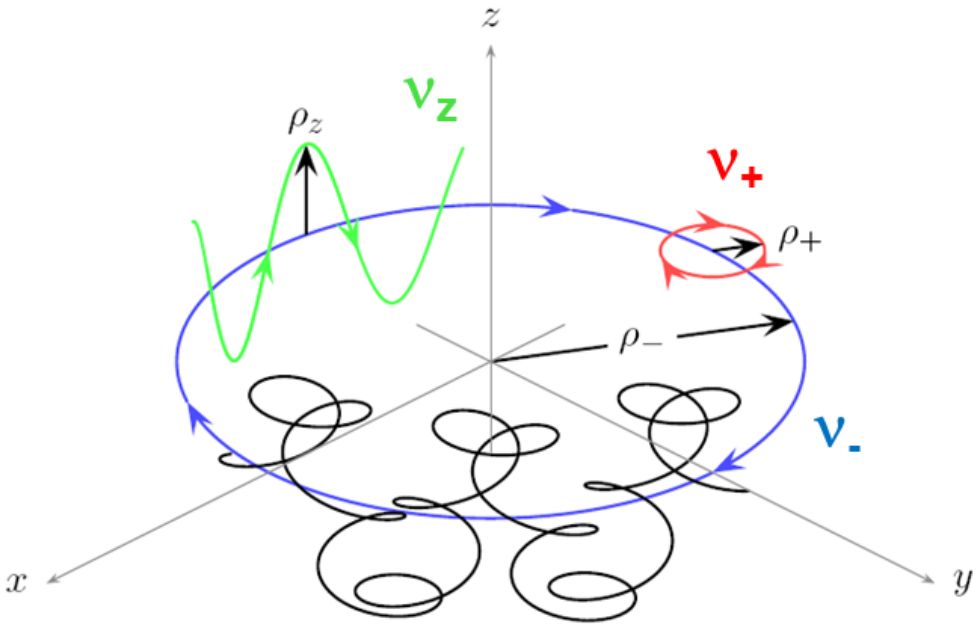
$$\gamma_t \rightarrow \gamma$$

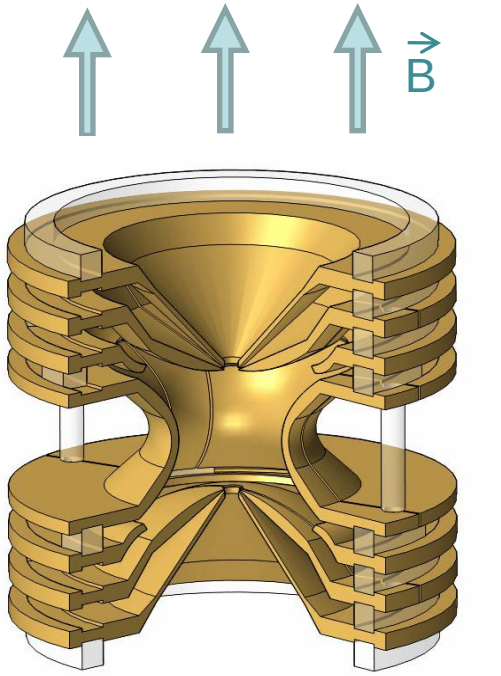
Hot Fragments

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

B. Franzke, H. Geissel & G. Münzenberg, Mass Spectrometry Reviews 27 (2008) 428

Storage of ions in a Penning trap





The free cyclotron frequency is inverse proportional to the mass of the ions!

$$\omega_c = qB/m$$

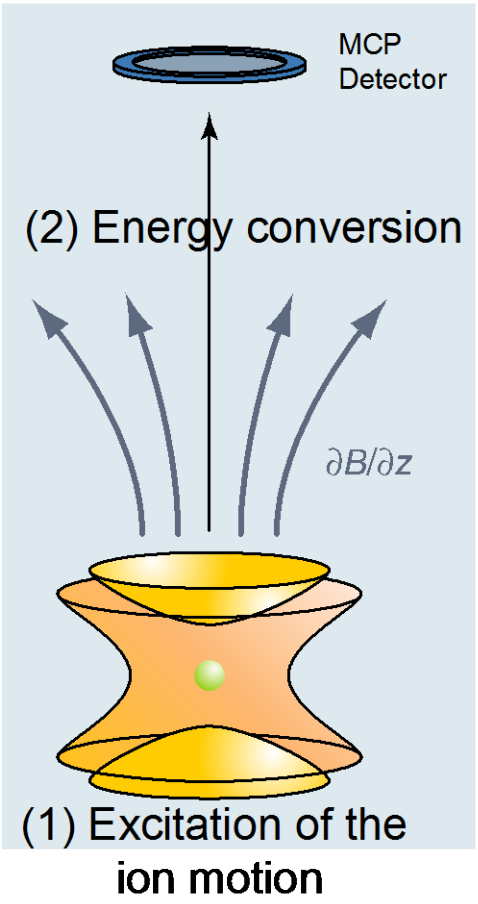
An ***invariance theorem*** saves the day:

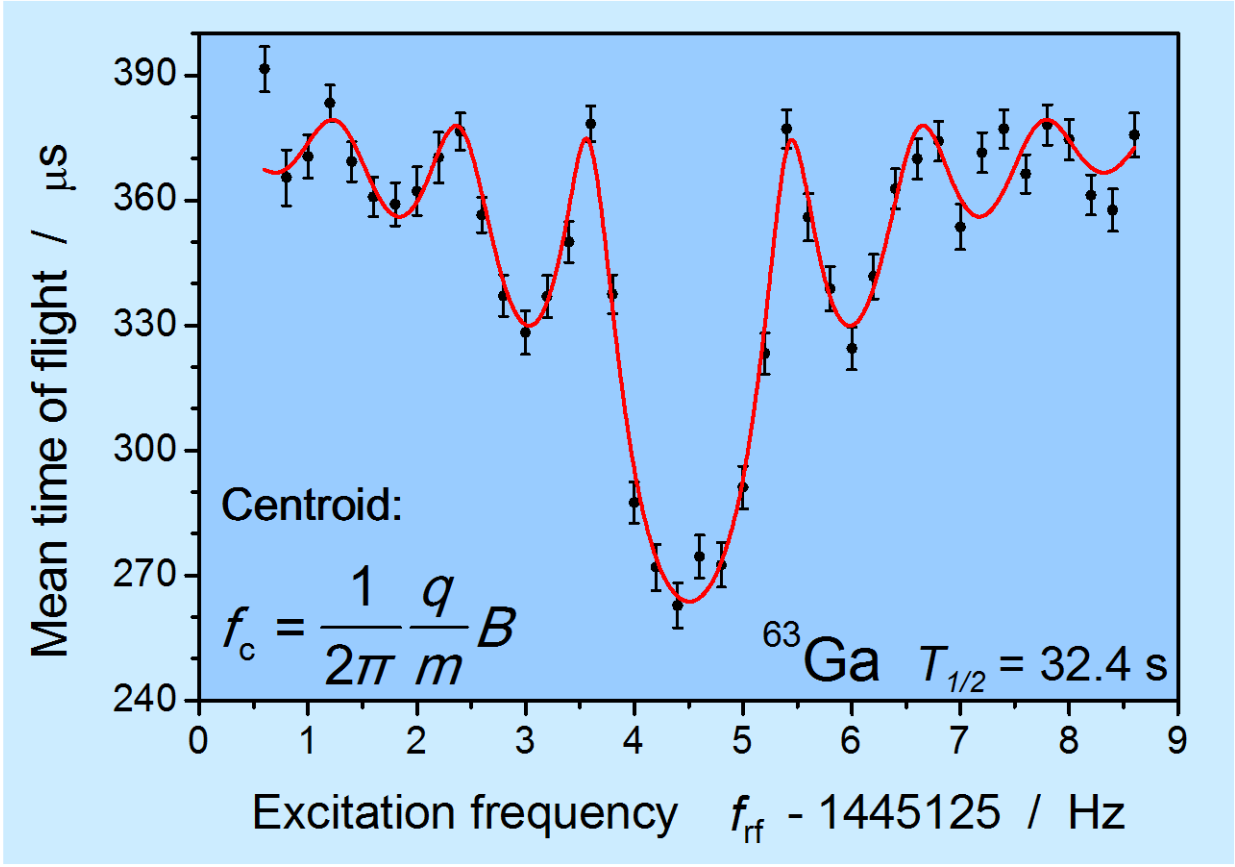
$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

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

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986).
K. Blaum, J. Dilling, W. Nörtershäuser, Phys. Scr. T152, 014017 (2017).

Penning-trap mass spectrometry





Determine atomic mass from frequency ratio with a well-known "reference mass".

$$\frac{f_{c,ref}}{f_c} = \frac{m - m_e}{m_{ref} - m_e}$$

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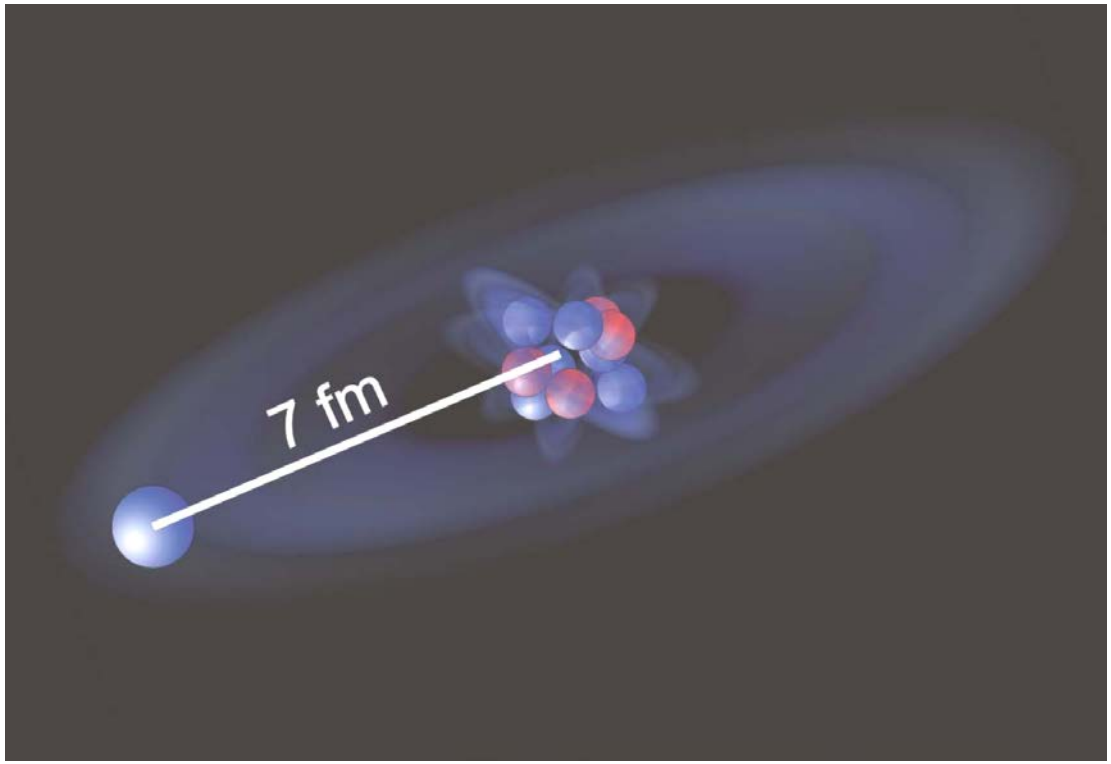
Masses

Nuclear structure studies

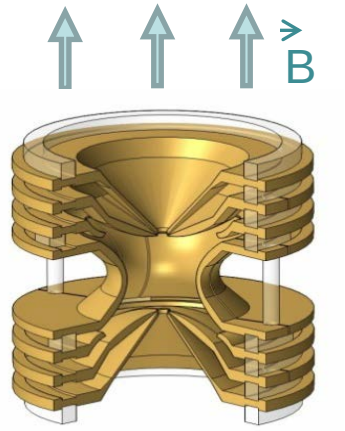


ESR, ISOLTRAP, SHIPTRAP, TITAN

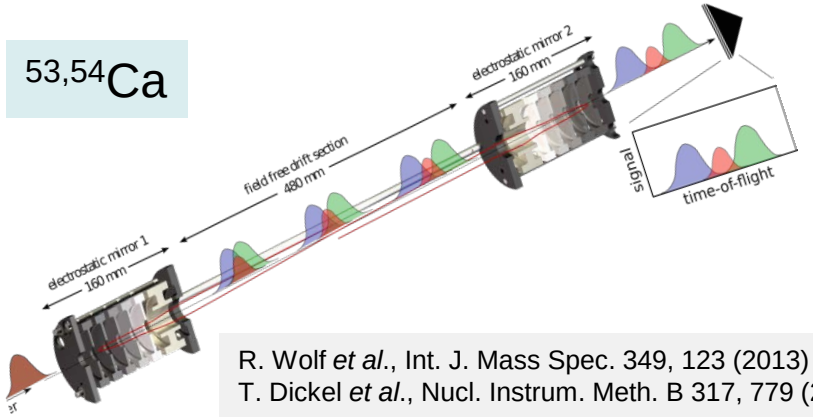
Ca masses pin down nuclear forces

Multi-reflection time-of-flight and Penning-trap mass spectrometry

^{51,52}Ca

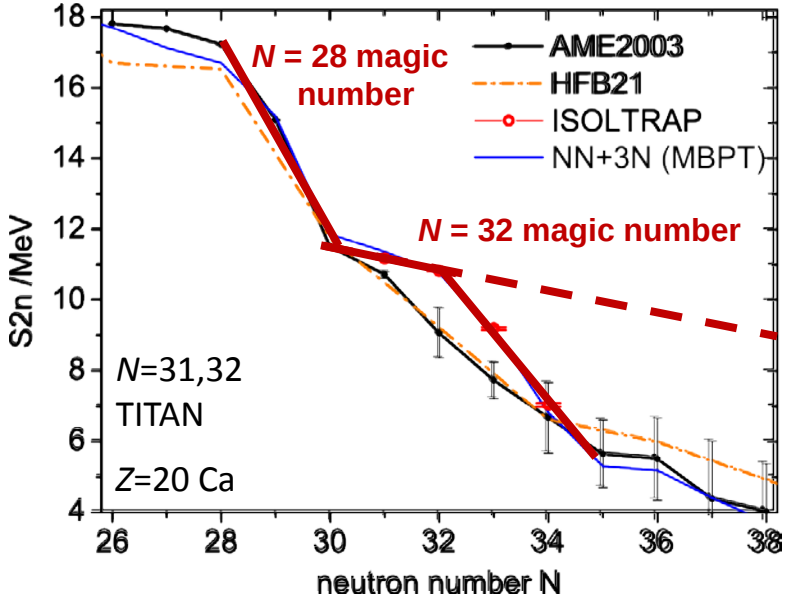


^{53,54}Ca



R. Wolf *et al.*, Int. J. Mass Spec. 349, 123 (2013)
T. Dickel *et al.*, Nucl. Instrum. Meth. B 317, 779 (2013)

- Production rates of ~10 ions/s
- Mass measurements via S_{2n} establish new magic number at N = 32
- Correct prediction from 3N-forces (A. Schwenk *et al.*, TUD)



F. Wienholtz *et al.*, Nature 498, 346 (2013)

ISOLTRAP (CERN), TITAN (TRIUMF)

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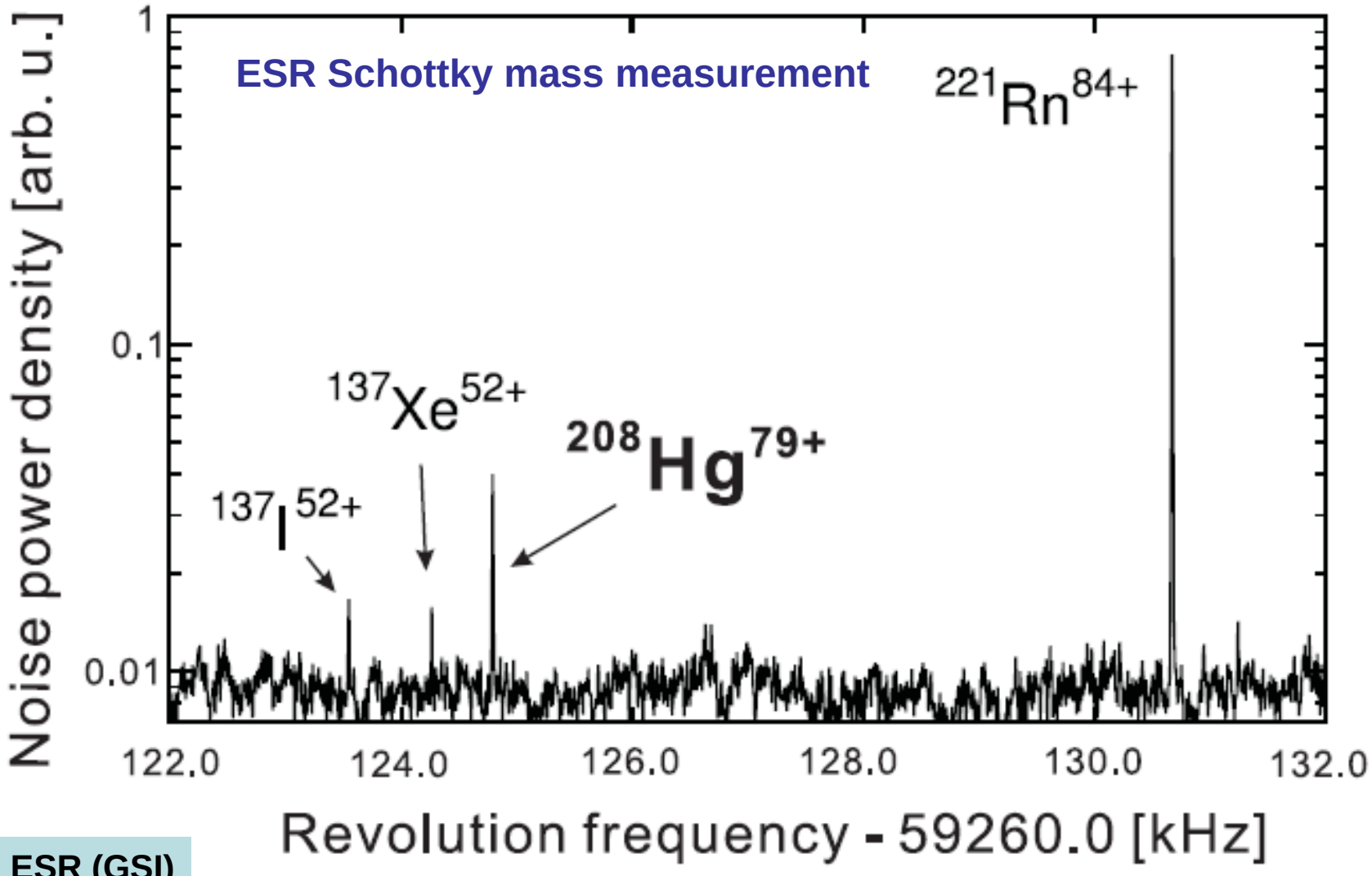
Experimental proton-neutron interaction



ESR (GSI)

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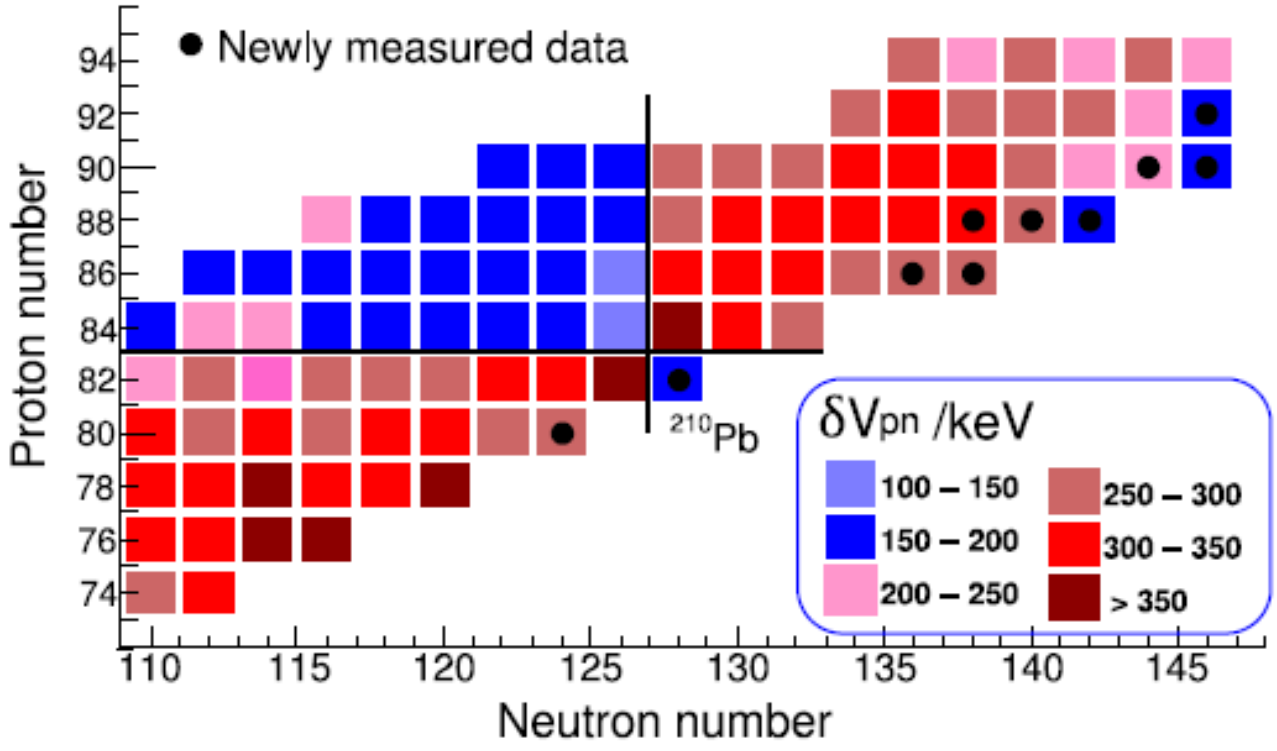
Masses reveal the p-n interaction strength

ESR (GSI)



For even-even nuclei

$$\delta V_{pn}(Z,N) = \tfrac{1}{4}[\{B(Z,N) - B(Z,N-2)\} - \{B(Z-2,N) - B(Z-2,N-2)\}]$$

$^{223\text{-}229}$Rn: Phys. Rev. Lett. 102, 112501 (2009)

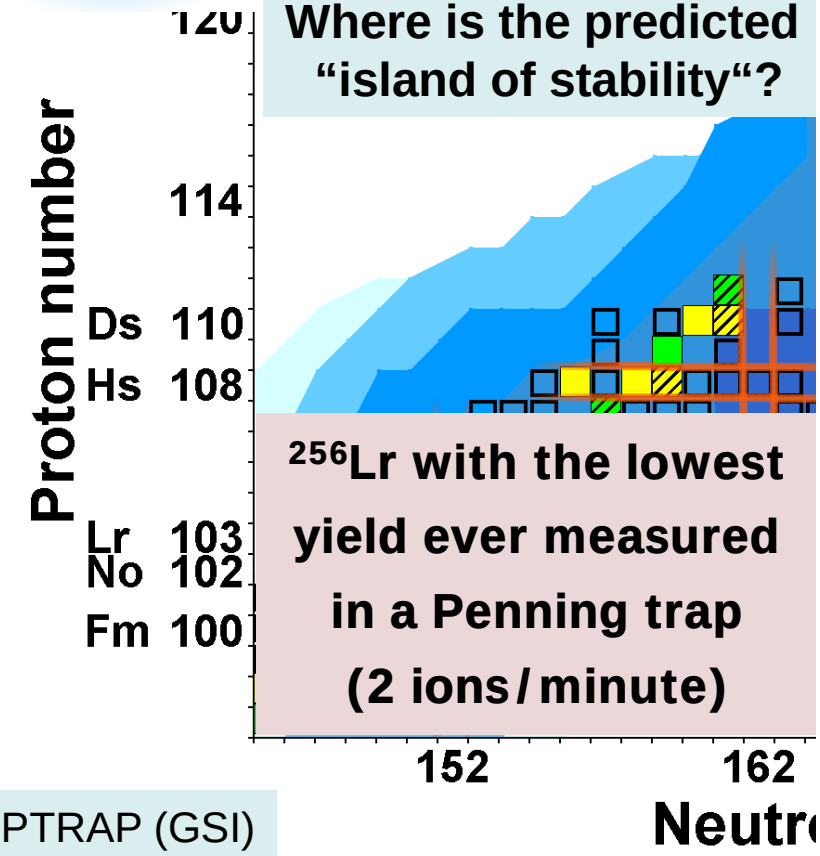
^{208}Hg: Phys. Rev. Lett. 102, 122503 (2009)

Direct Mapping of Nuclear Shell Effects

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

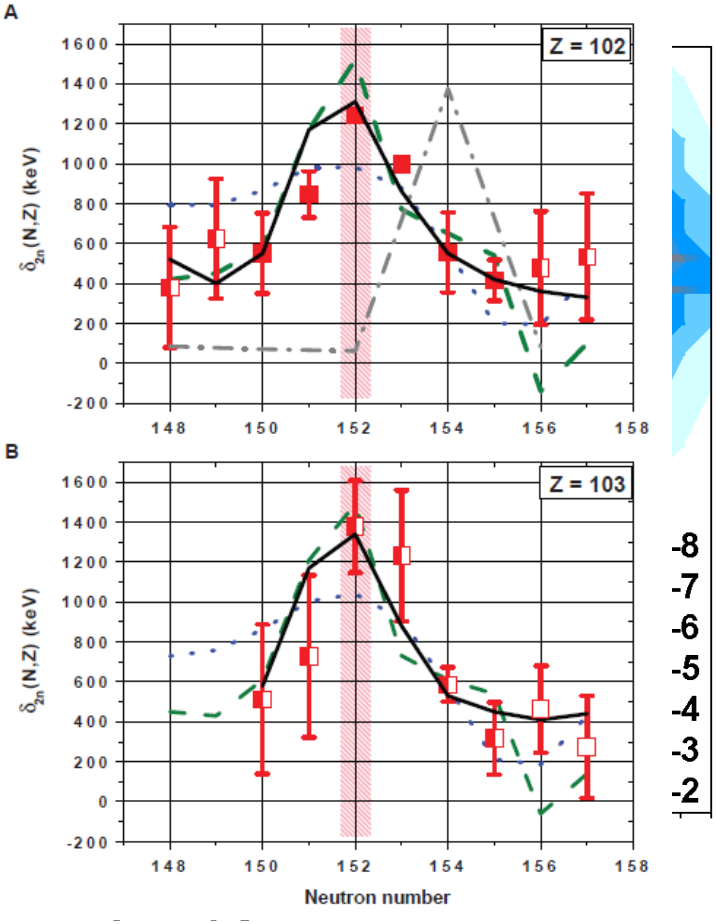
ChemistryWorld: ***Tweaked weighing scales help map the island of stability***

Where is the predicted "island of stability"?



^{256}Lr with the lowest yield ever measured in a Penning trap (2 ions / minute)

SHIPTRAP (GSI)



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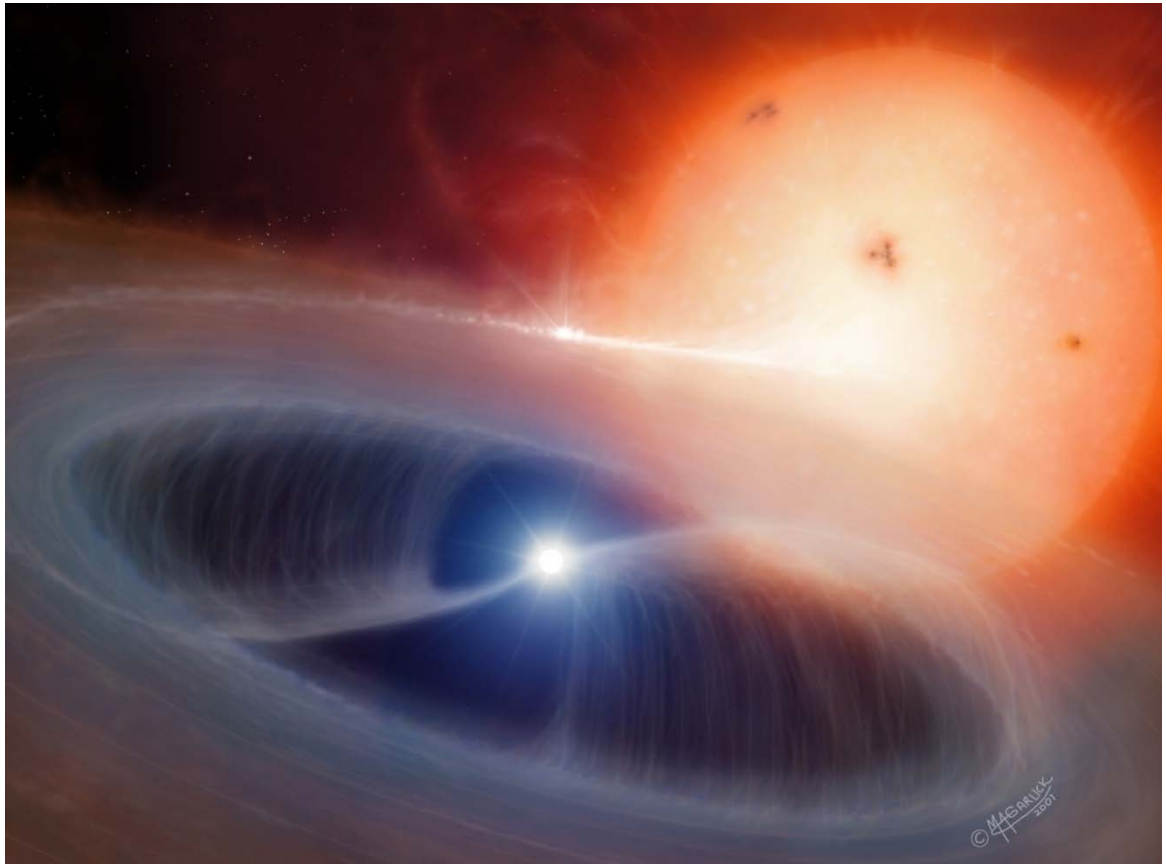
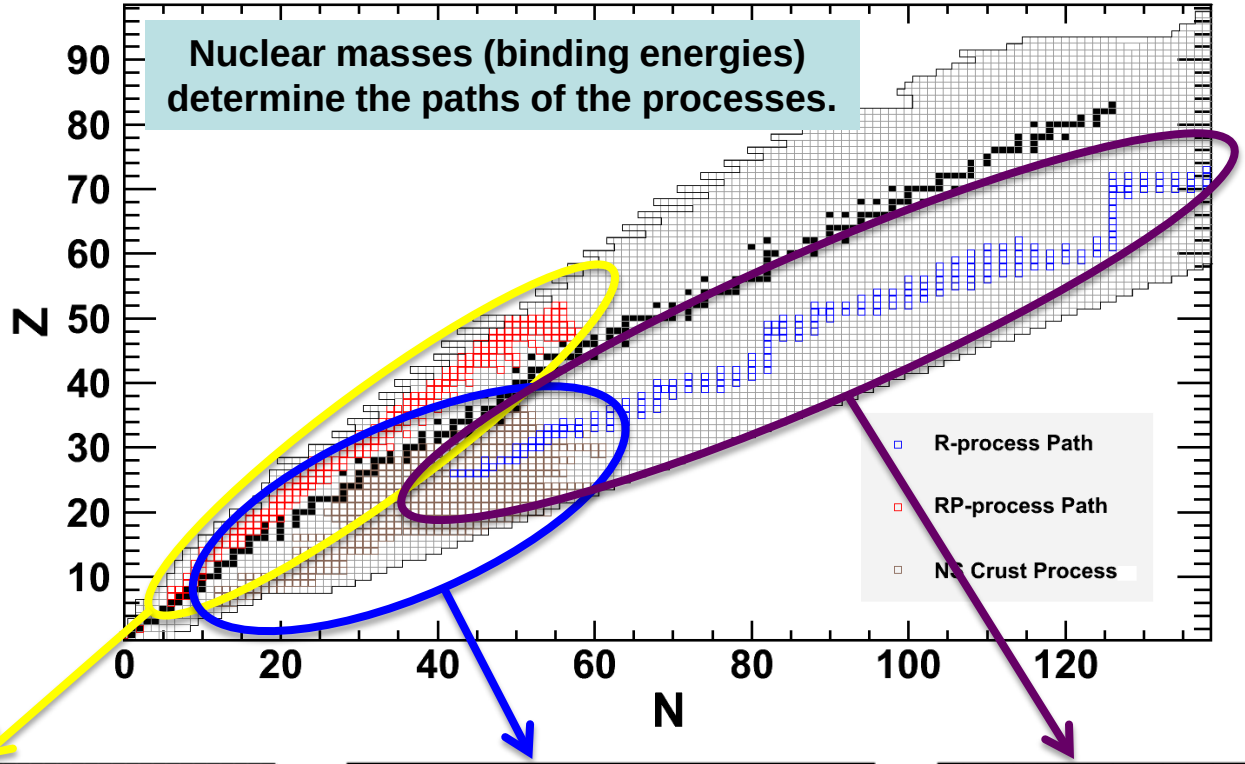
Masses

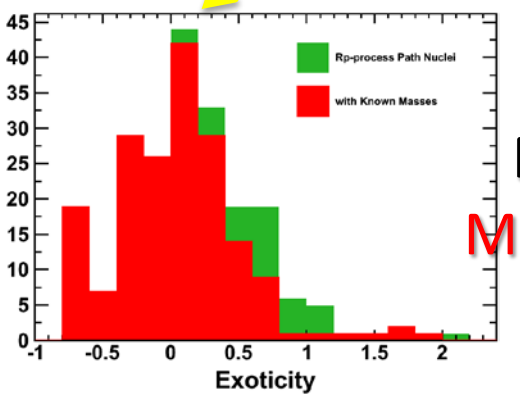
Nuclear astrophysics studies

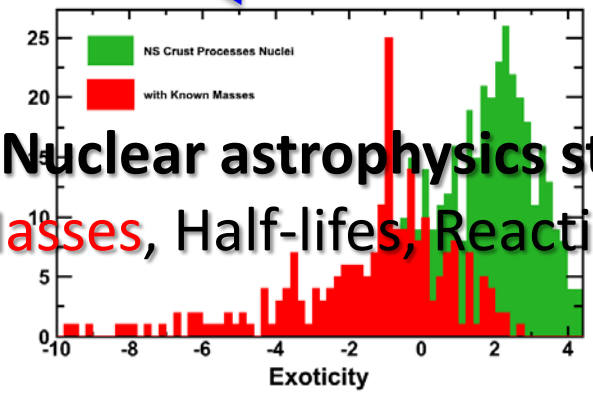


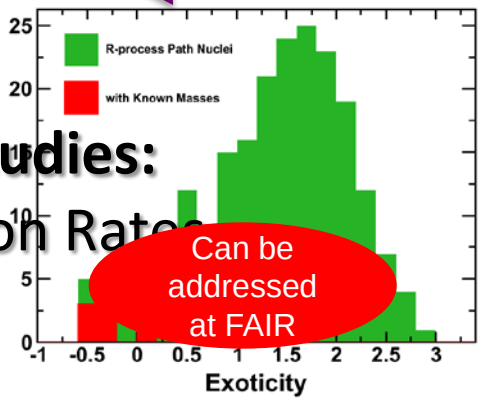
CPT, CSRe, ESR, ISOLTRAP, JYFLTRAP, LEBIT, SHIPTRAP, TITAN

Mass spectrometry for nucleosynthesis









Nuclear astrophysics studies:

Masses, Half-lifes, Reaction Rate

Can be addressed at FAIR

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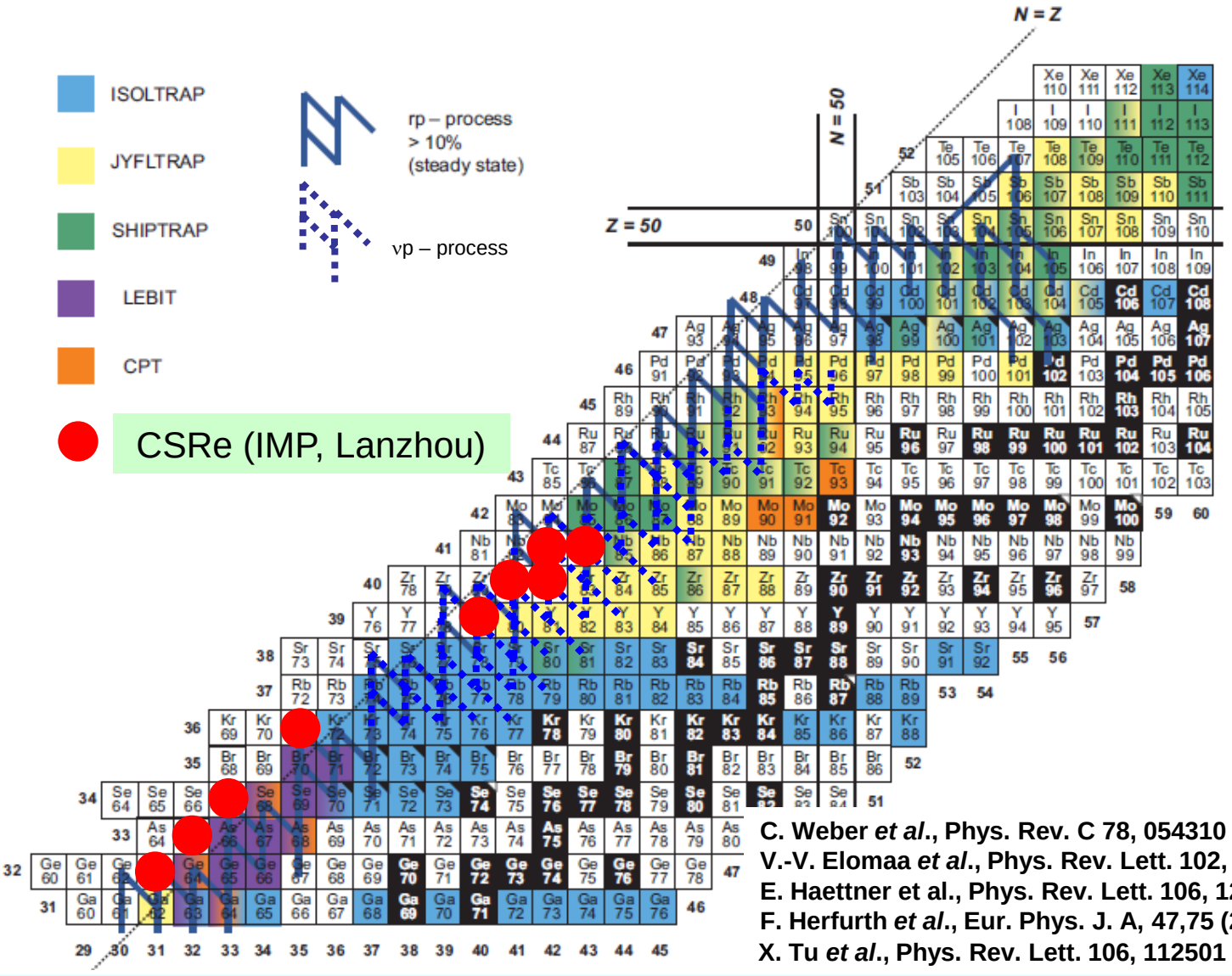
Nuclides at the rp-process path



C. Weber *et al.*, Phys. Rev. C 78, 054310 (2008)
V.-V. Elomaa *et al.*, Phys. Rev. Lett. 102, 252501 (2009)
E. Haettner et al., Phys. Rev. Lett. 106, 122501 (2011)
F. Herfurth *et al.*, Eur. Phys. J. A, 47,75 (2011)
X. Tu *et al.*, Phys. Rev. Lett. 106, 112501 (2011)

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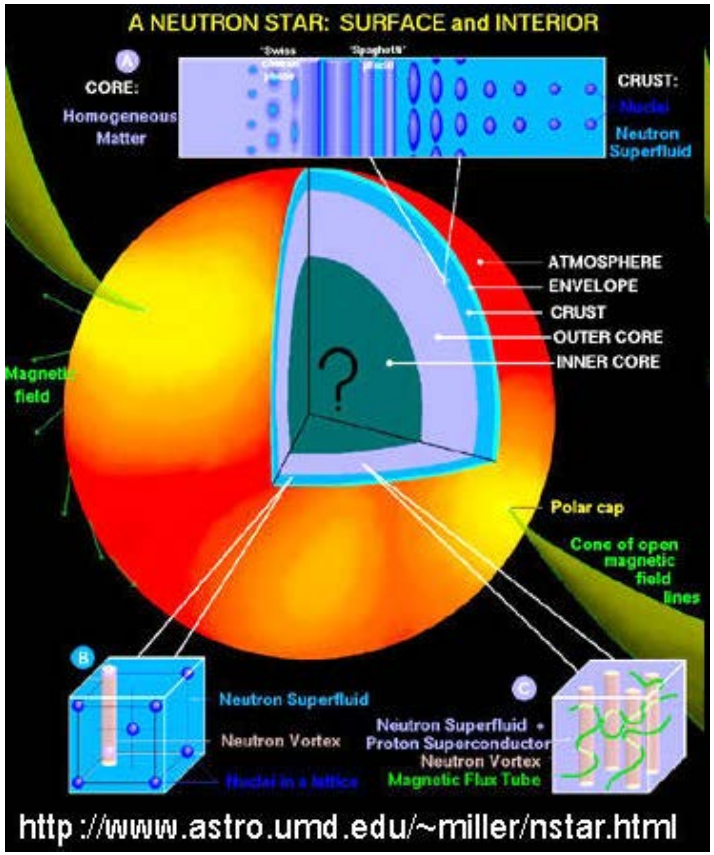
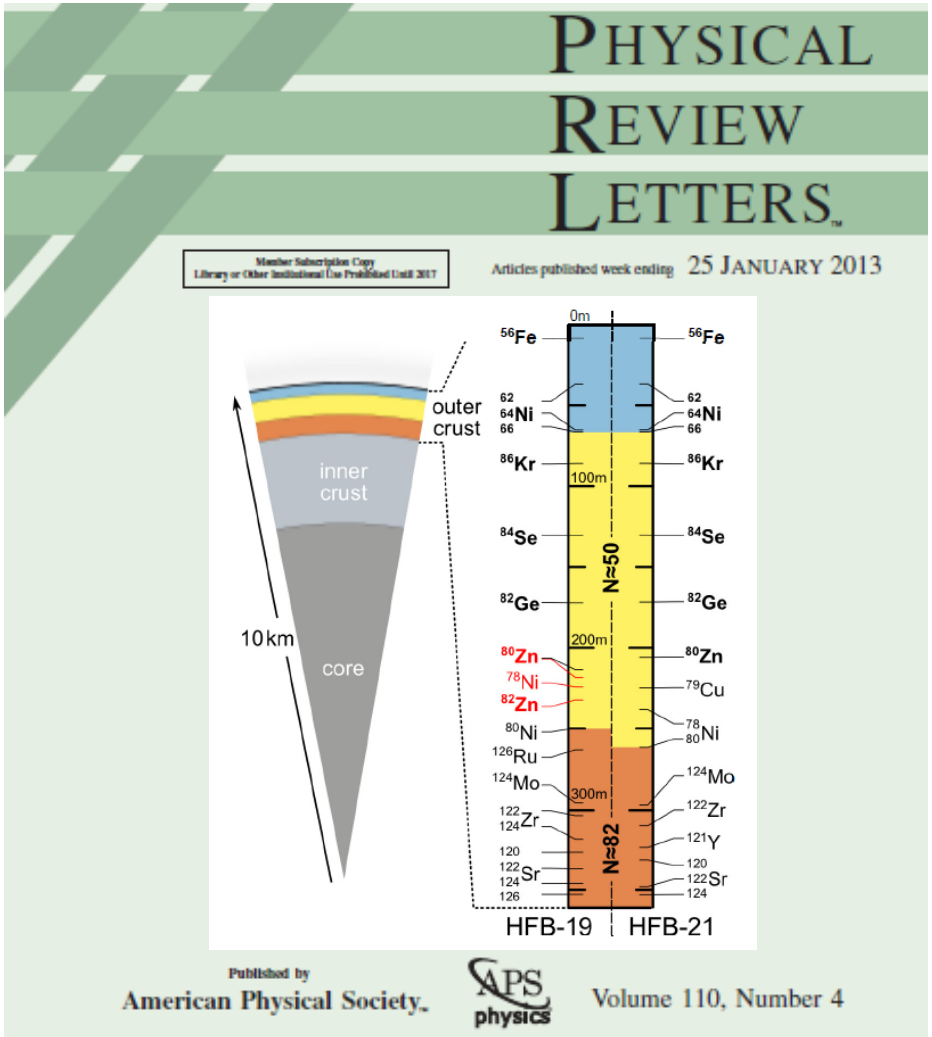
Nuclear astrophysics: Neutron star

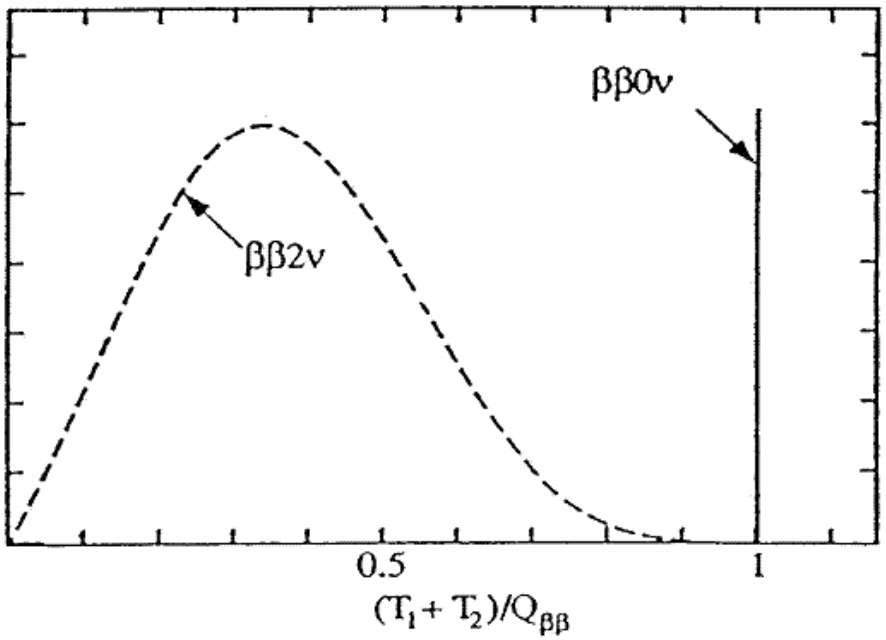
Composition of the outer crust of a neutron star

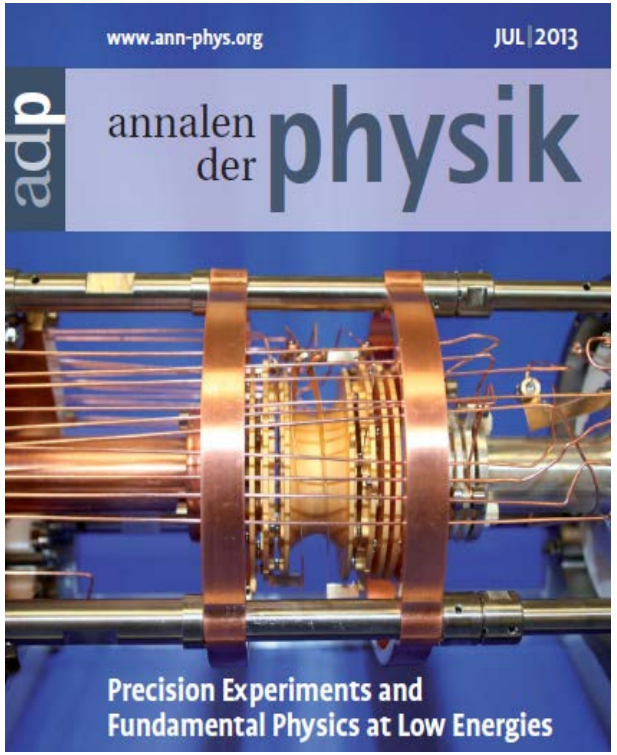




Masses

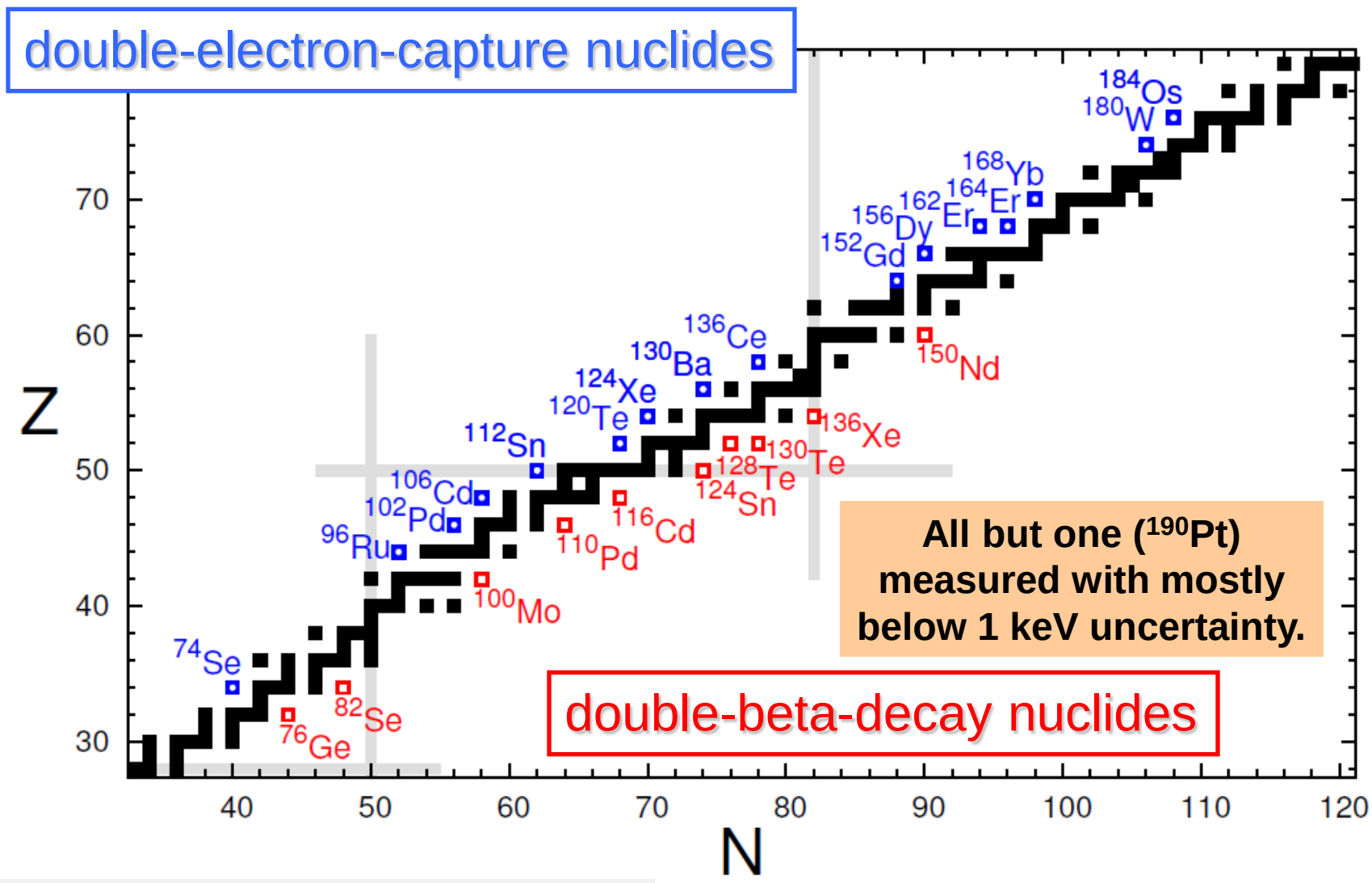
Neutrino physics studies





FSU, ISOLTRAP, JYFLTRAP, SHIPTRAP, THe-TRAP, TRIGATRAP

Results so far



S. Eliseev *et al.*, J. Phys. G, 39, 124003 (2012)

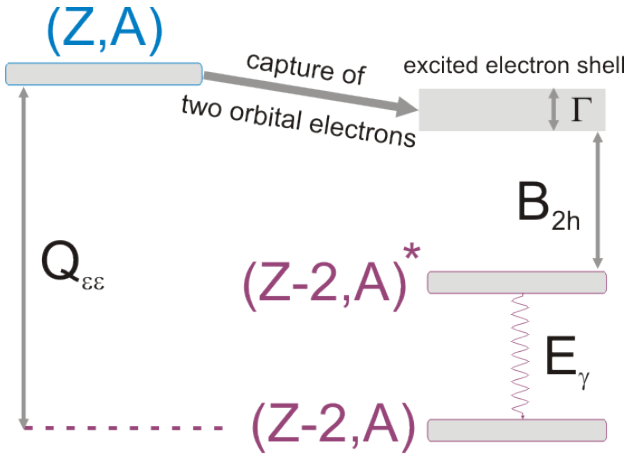
Neutrino-less double EC (0ν2*EC*)

Is 0ν2*EC* a good alternative to 0ν2ββ ?

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

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

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



Contribution of Penning traps:

Search for nuclides with $\Delta=(Q_{\varepsilon\varepsilon}-B_{2h}-E_\gamma) < 1$ keV

by measurements of $Q_{\varepsilon\varepsilon}$ –values

at ~100 eV accuracy level

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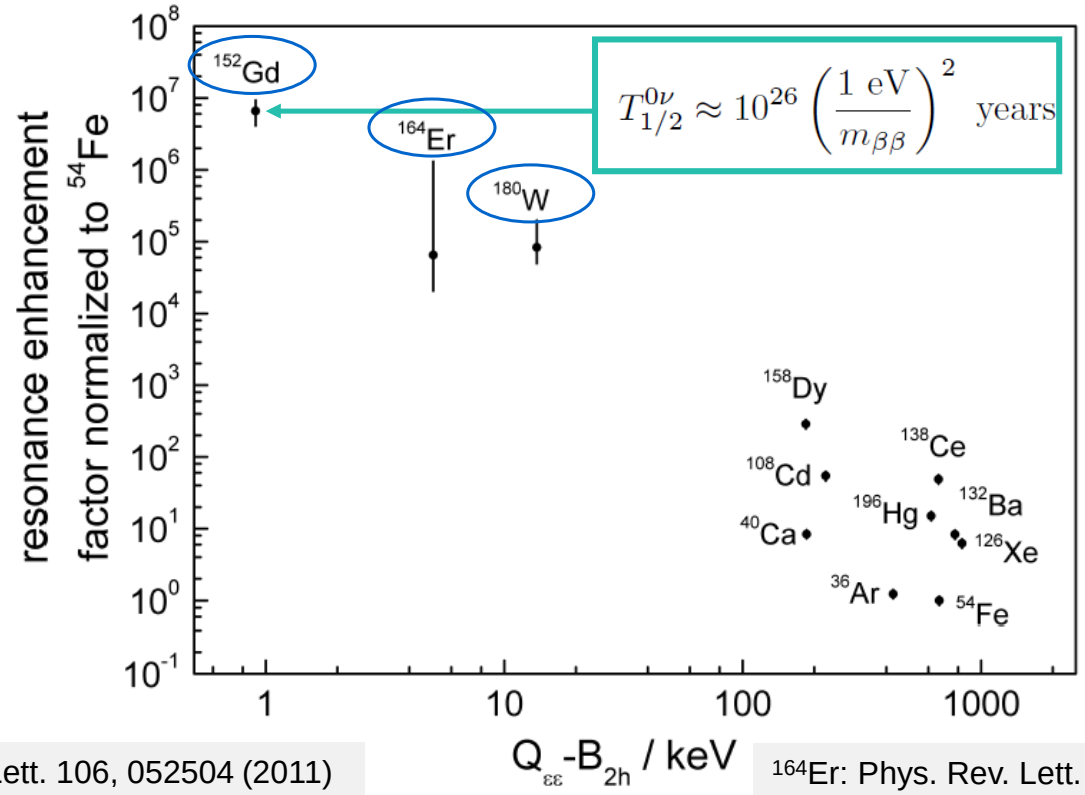
Resonance enhancement factors

JYFLTRAP (IGISOL)
SHIPTRAP (GSI)
TRIGATRAP (Mainz)

2EC - transition	*Δ* (old), keV	*Δ* (new), keV	$T_{1/2} \cdot m^2$, yr
$^{152}Gd \rightarrow {}^{152}Sm$	-0.2(3.5)	0.9(0.2)	10^{26}
$^{164}Er \rightarrow {}^{164}Dy$	5.2(3.9)	6.81(0.12)	10^{30}
$^{180}W \rightarrow {}^{180}Hf$	13.7(4.5)	12.4(0.2)	10^{27}

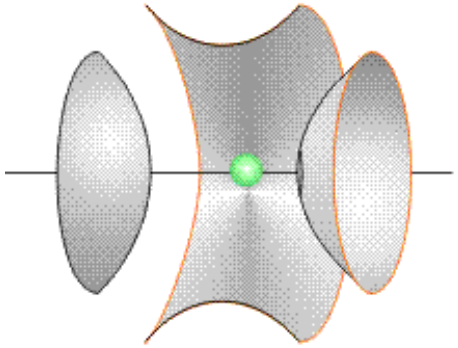


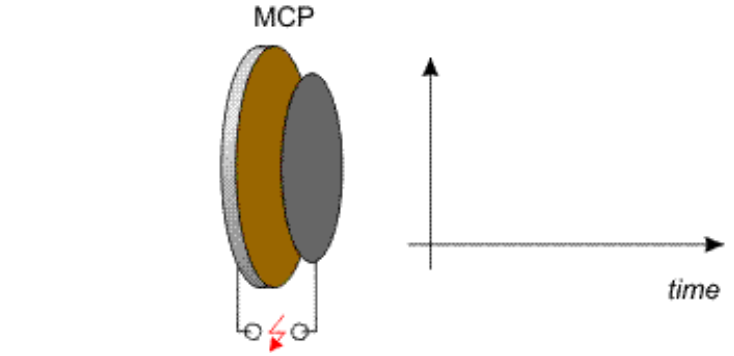
^{152}Gd: Phys. Rev. Lett. 106, 052504 (2011)

^{164}Er: Phys. Rev. Lett. 107, 152501 (2011)

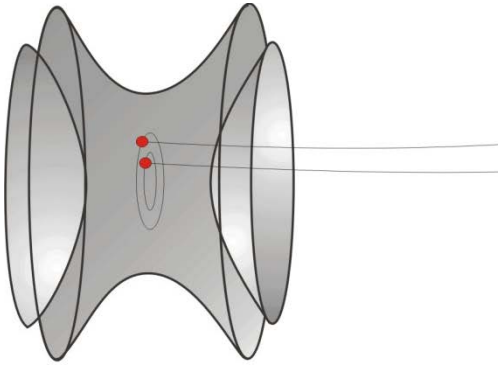
Most recent technical breakthrough

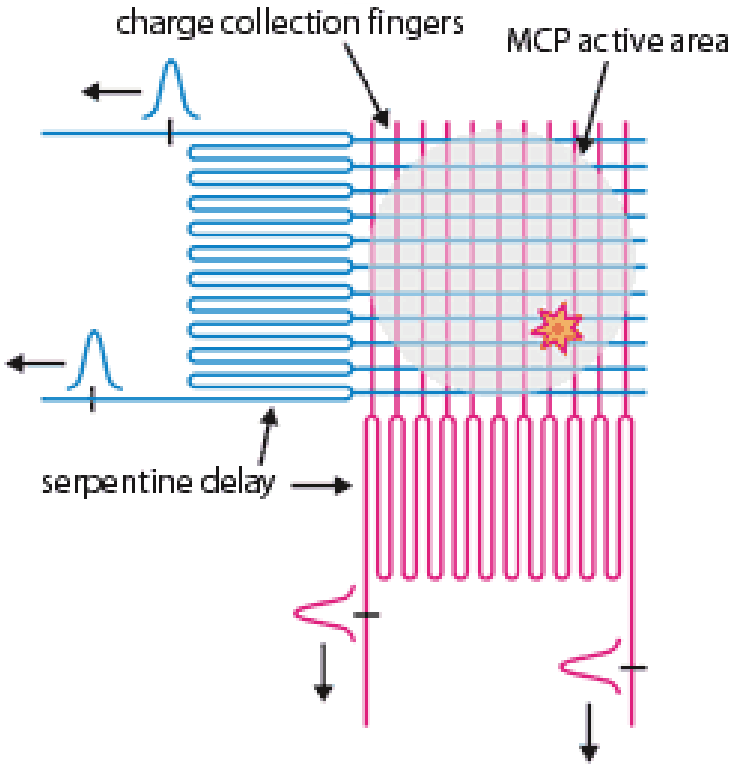
Destructive time-of-flight detection



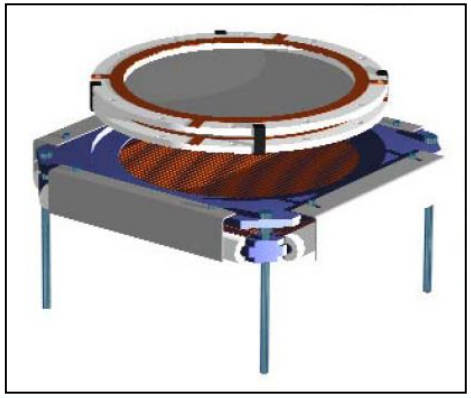


Space resolving detection





Delay-line detector



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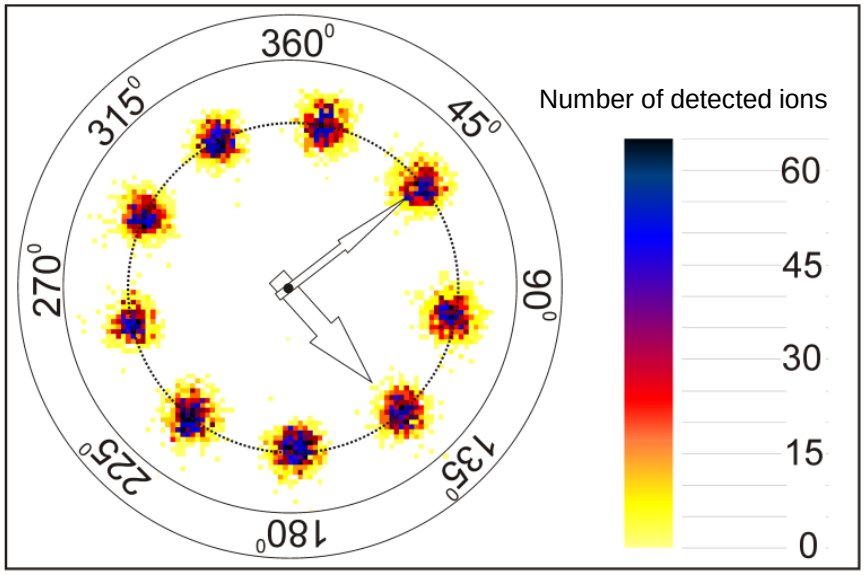
Phase-imaging magnetron measurement



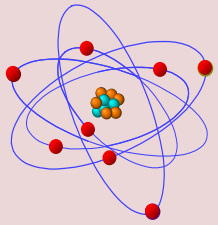
Gain of a factor of 5 in uncertainty a factor of 40 in resolution or a factor of 25 in time.

S. Eliseev *et al.*, Phys. Rev. Lett. 110, 082501 (2013)

Mass accuracy of

$$\frac{\delta m}{m} < 1 \cdot 10^{-9}$$

even for $T_{1/2} < 1$



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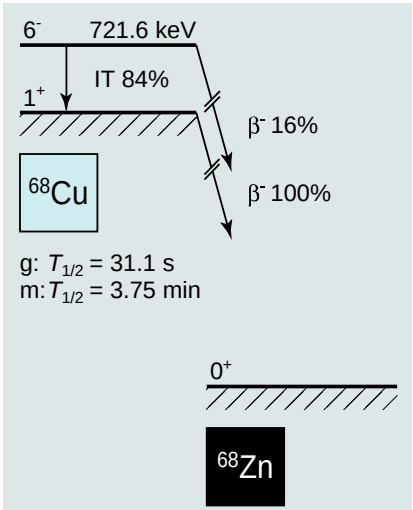
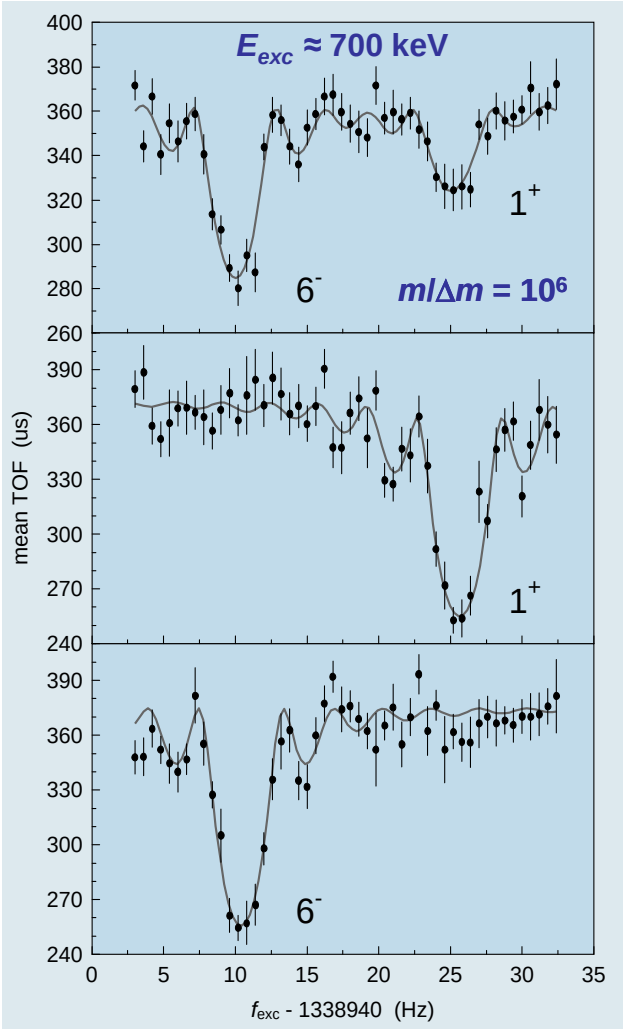
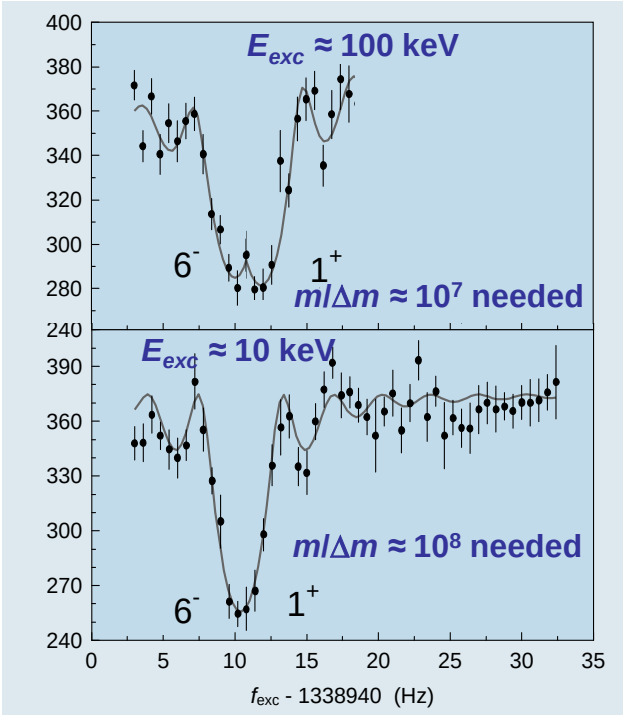
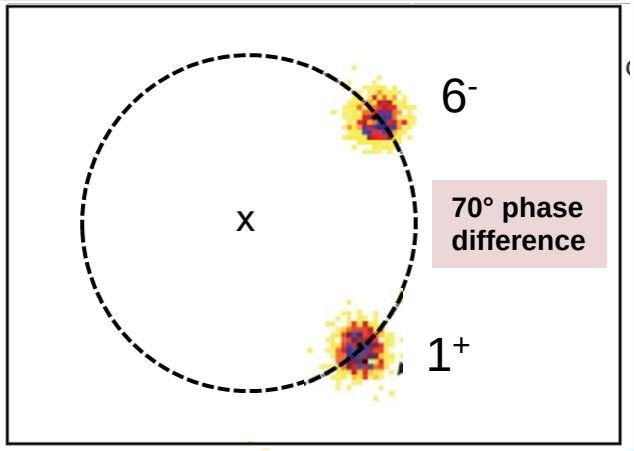
Dreams for future applications

Isomerism in ^{68}Cu:









K. Blaum *et al.*, Europhys. Lett. 67, 586 (2004)

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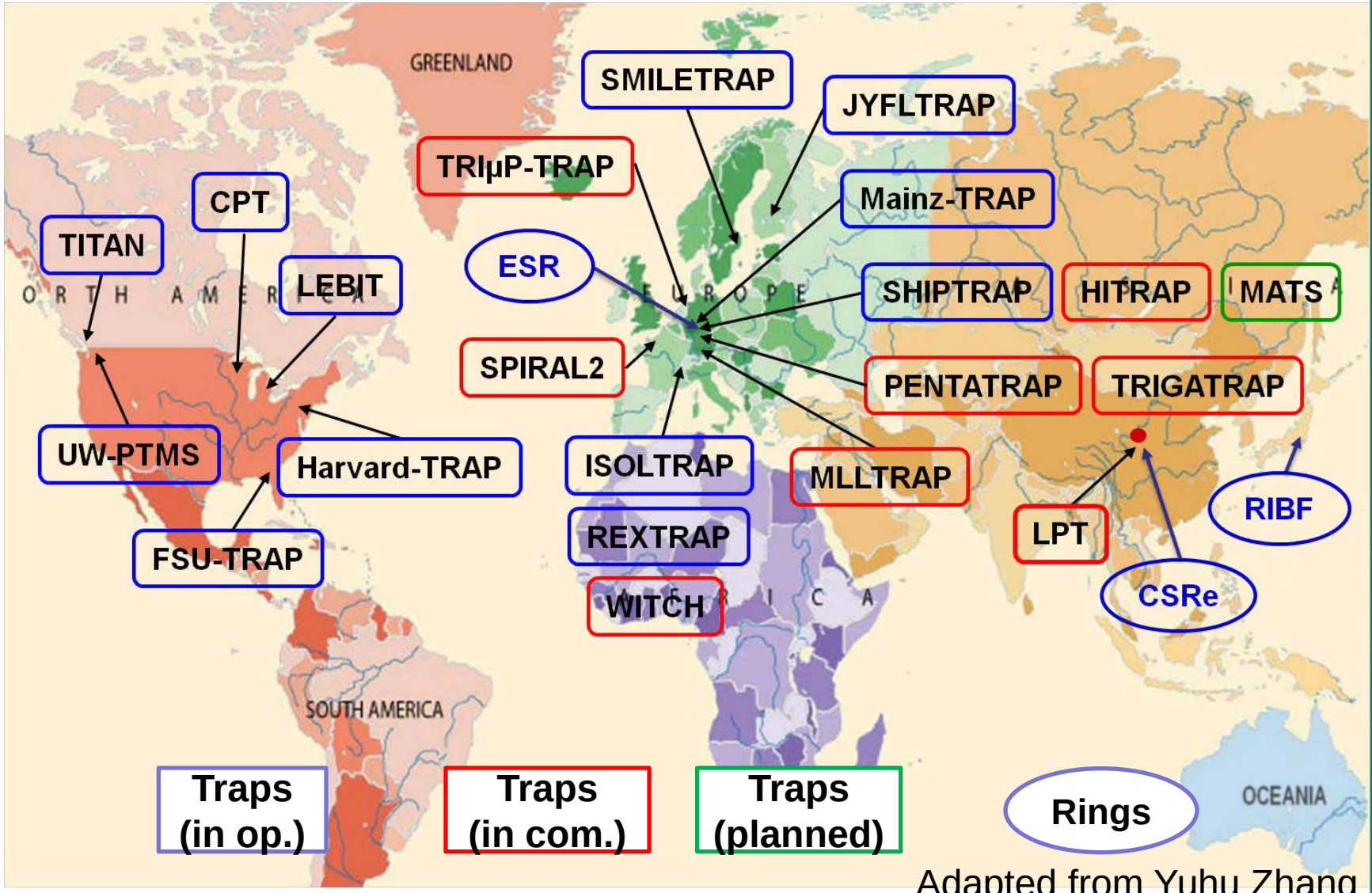
Mass measurement facilities worldwide



Adapted from Yuhu Zhang

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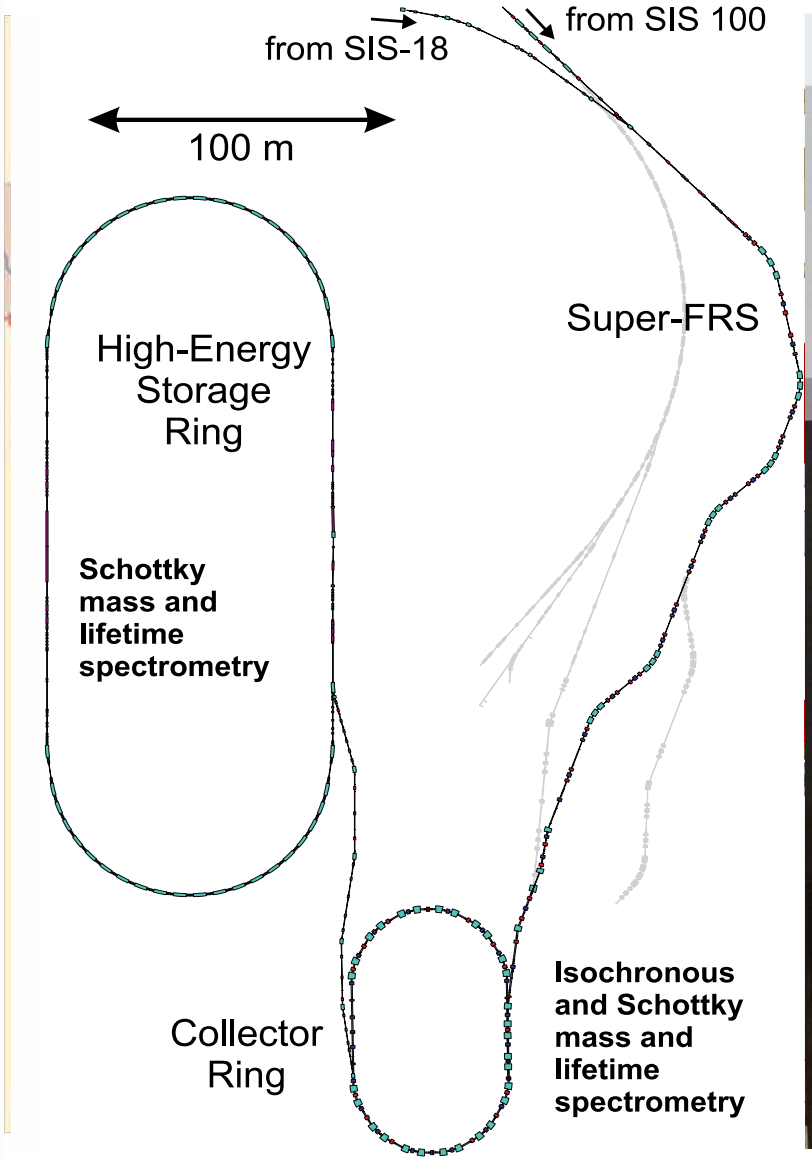
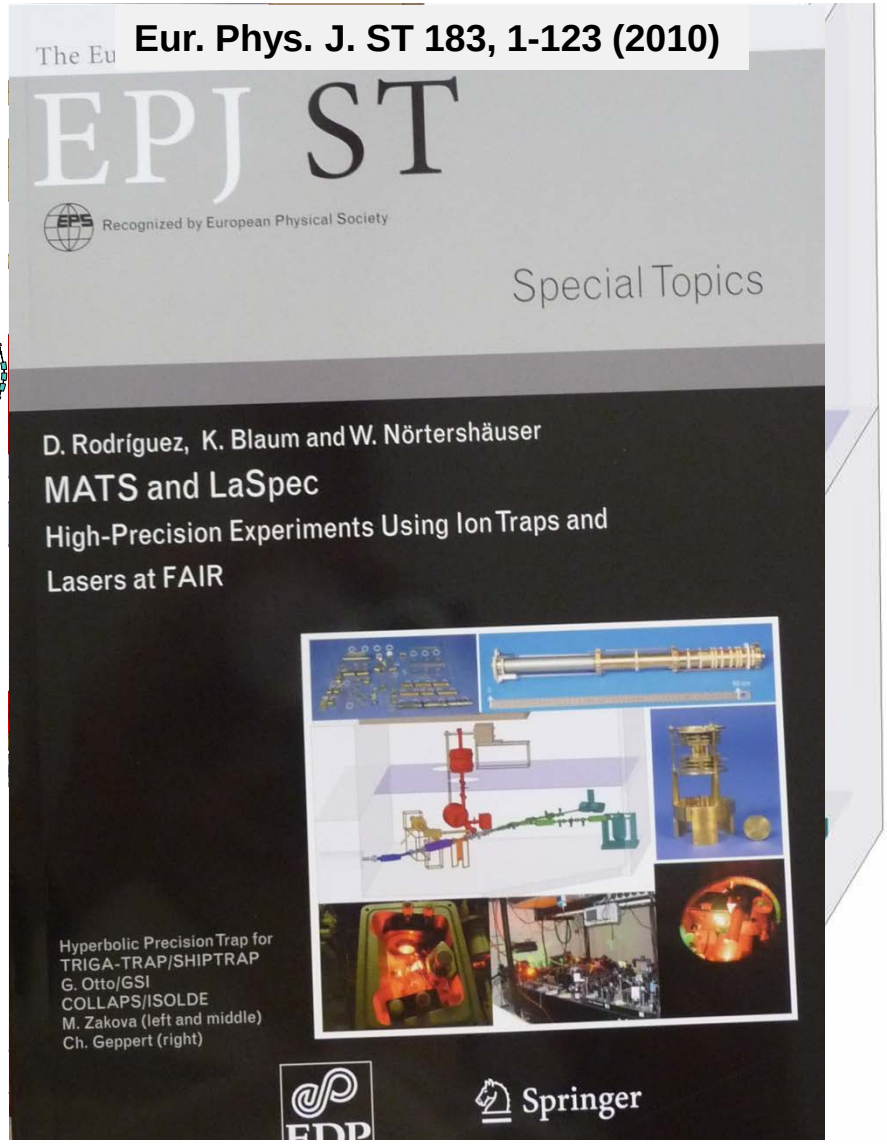
Mass measurement facilities worldwide





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Summary

Exciting results in high-precision mass spectrometry with stored and cooled exotic ions have been achieved!

Thank you all for the invitation and your attention!

Email: klaus.blaum@mpi-hd.mpg.de

WWW: www.mpi-hd.mpg.de/blaum/

Max Planck Society *Adv. Grant MEFUCO* *Helmholtz Alliance*