Rare-RI Ring Workshop, RIKEN

“High-Precision Mass Measurements in Penning Traps and Storage Rings”

Klaus Blaum

November 10, 2011

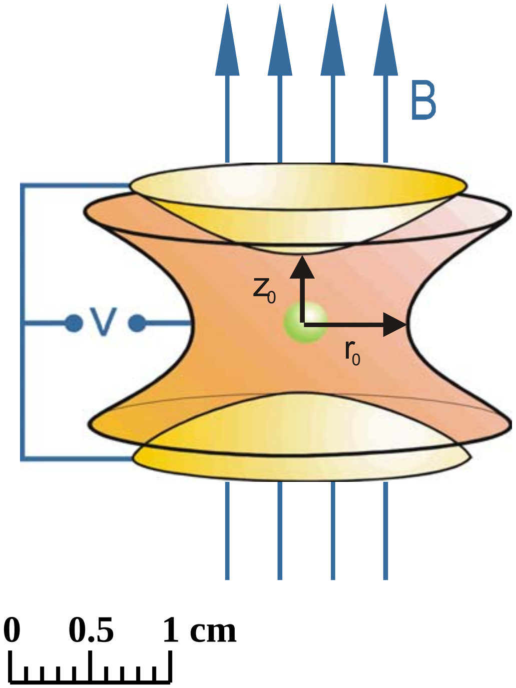
Klaus.blaum@mpi-hd.mpg.de

Outline

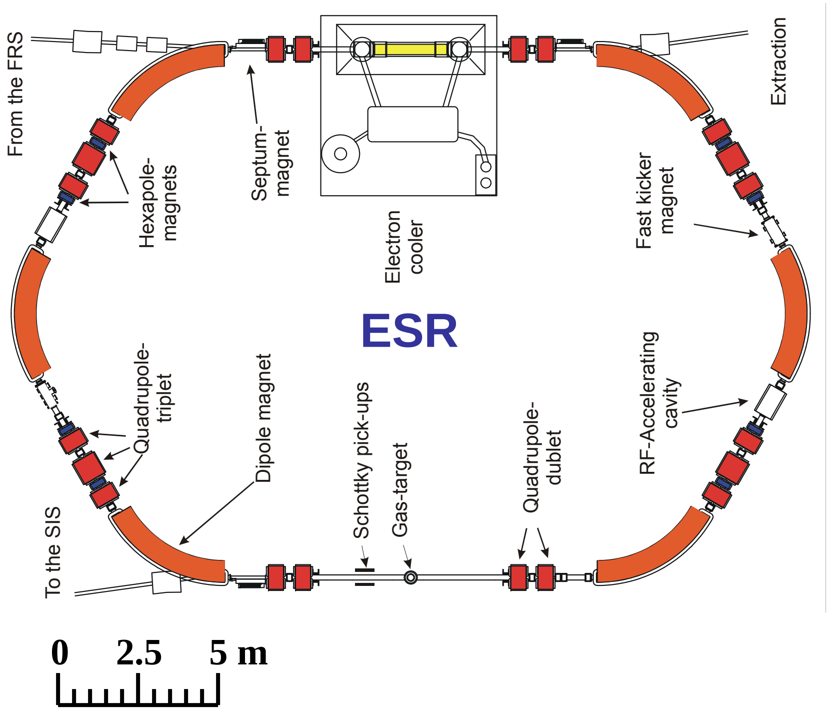
- Introduction and methods
- Principle of storage ring and Penning trap mass spectrometry
- Setup and measurement procedure
- Precision measurements of nuclear masses and their applications

Storage and cooling techniques

Penning trap



Storage ring



particles at nearly rest in space

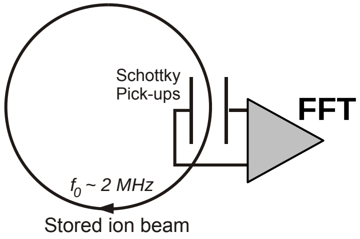
relativistic particles

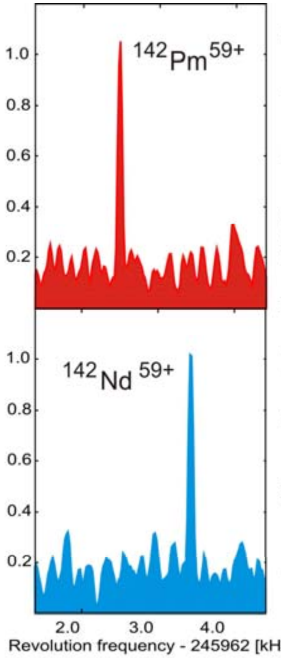
∗ ion cooling **∗ long storage times**

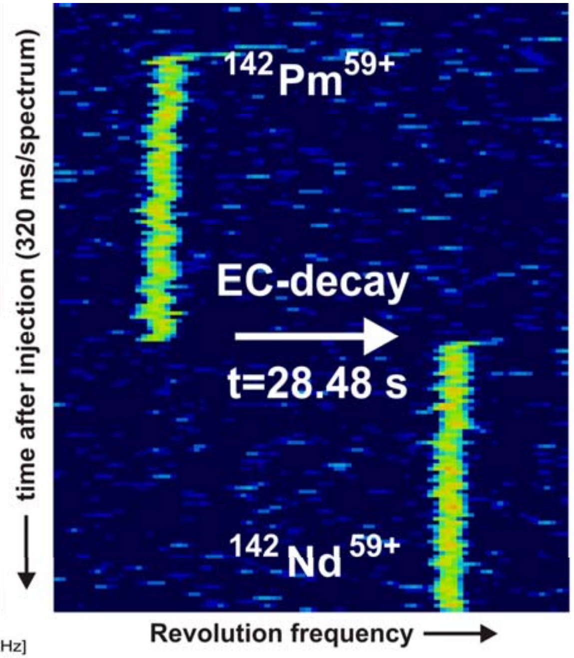
∗ single-ion sensitivity **∗ high accuracy**

Single ion sensitivity

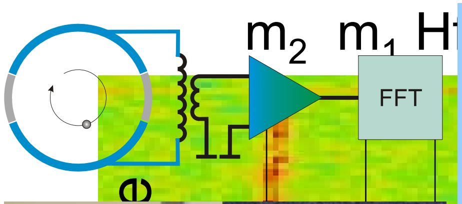
Schottky detection in a storage ring







Narrow band FT-ICR in a Penning trap



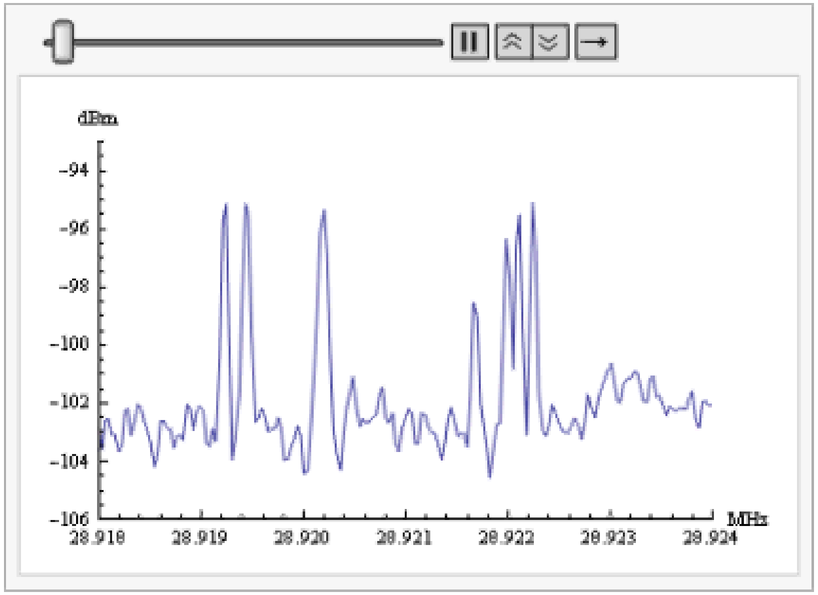
$$T = 4\ \text{K}$$

$$P = 5.5\ \text{mW}$$

$$e_n = 400\ \text{pV}/\sqrt{\text{Hz}}$$

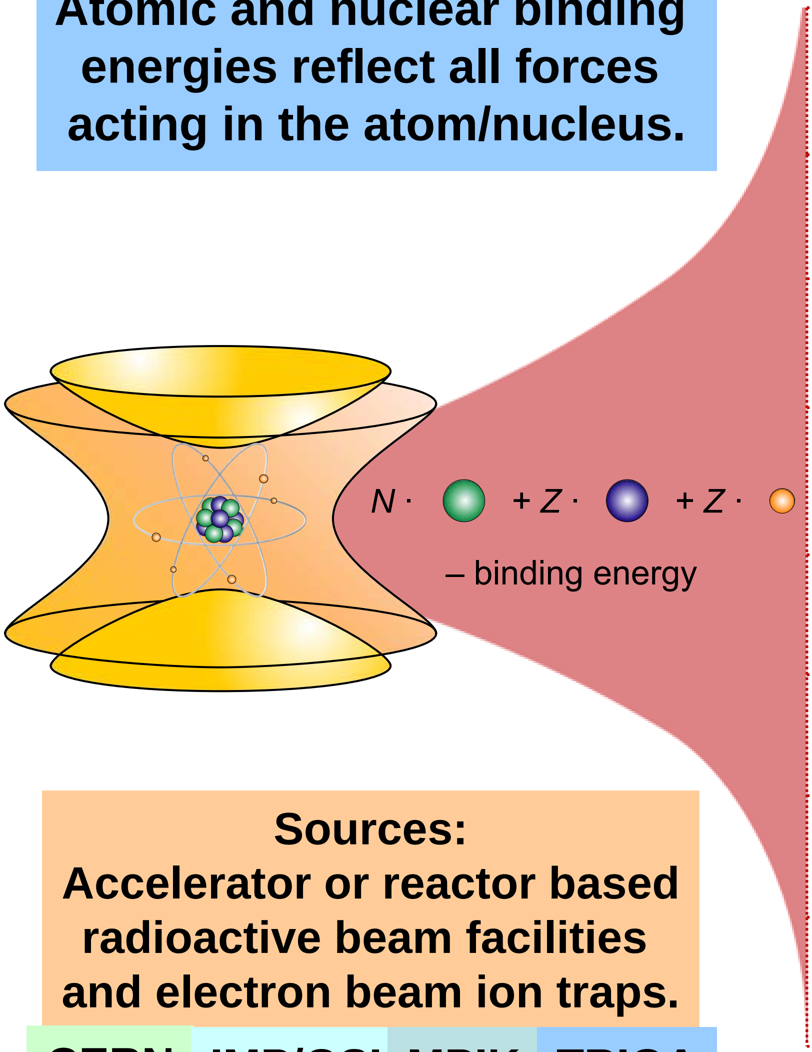
$$i_n < 2\ \text{fA}/\sqrt{\text{Hz}}$$

$$\nu_z = 600\ \text{kHz}$$



Why measuring atomic masses?

Atomic and nuclear binding energies reflect all forces acting in the atom/nucleus.



N · ● + *Z* · ● + *Z* · ●

– binding energy

General physics & chemi

Nuclear structure physics

- separat

Astrophysics

- separati

Weak interaction studies

Metrology - fundamenta

Neutrino physics

CPT tests

QED in highly-charged ior

- separation o

Experimental setups

KATRIN-TRAP

CSRe/ESR

TRIGA-TRAP

ISOLTRAP

SHIPTRAP

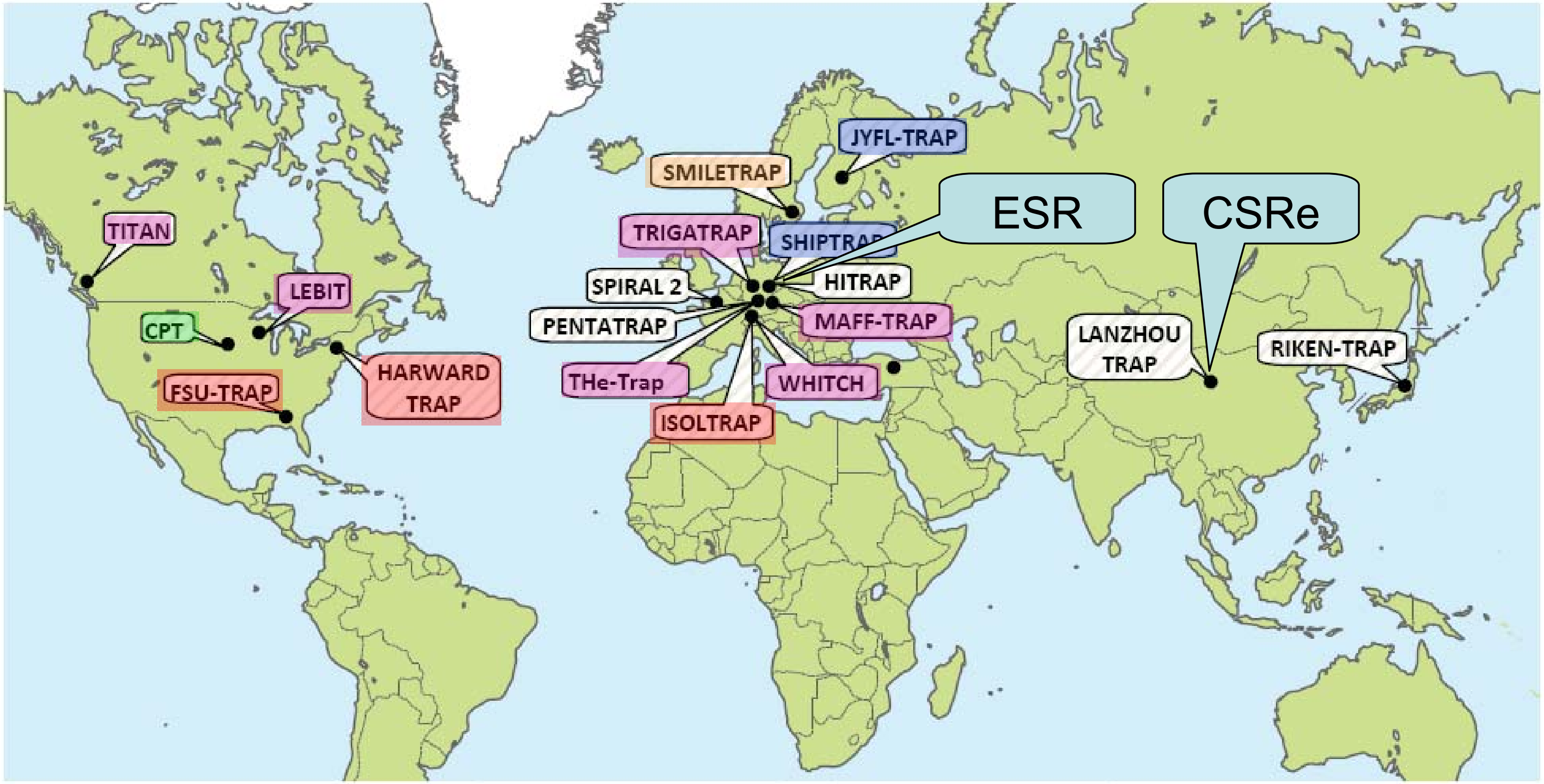
THe-TRAP

PENTA-TRAP

Sources:
Accelerator or reactor based radioactive beam facilities and electron beam ion traps.

CERN **IMP/GSI** **MPIK** **TRIGA**

Penning trap mass spectrometers worldwide



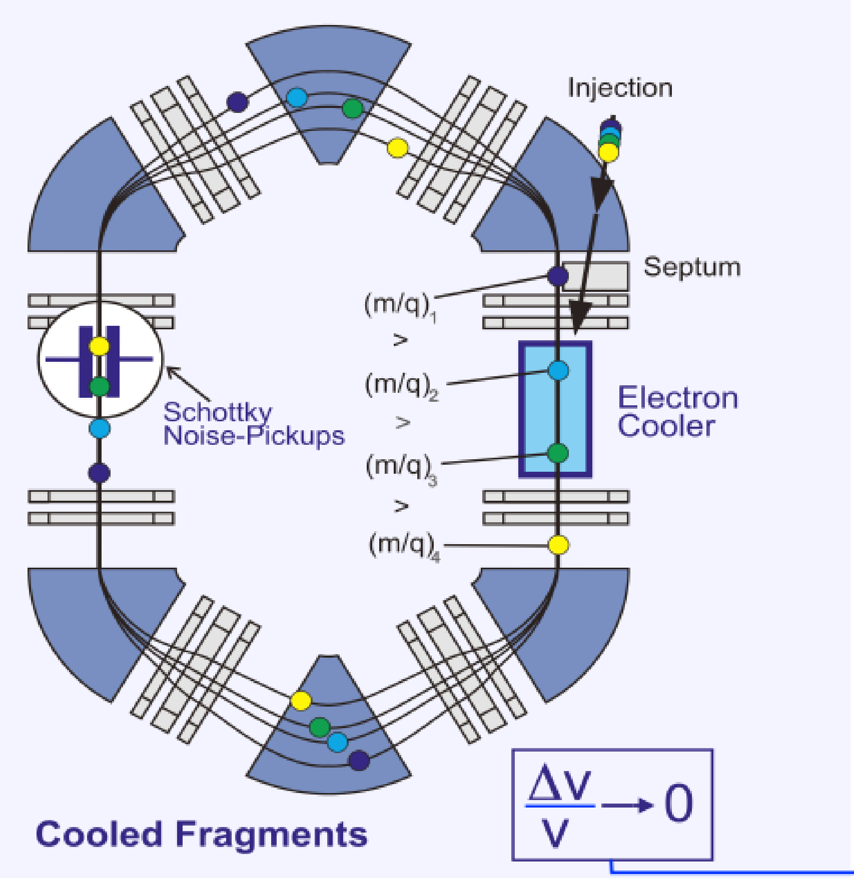
In operation since 1989 1993 1999 2004 2009

(rest under construction)

Storage rings for MS

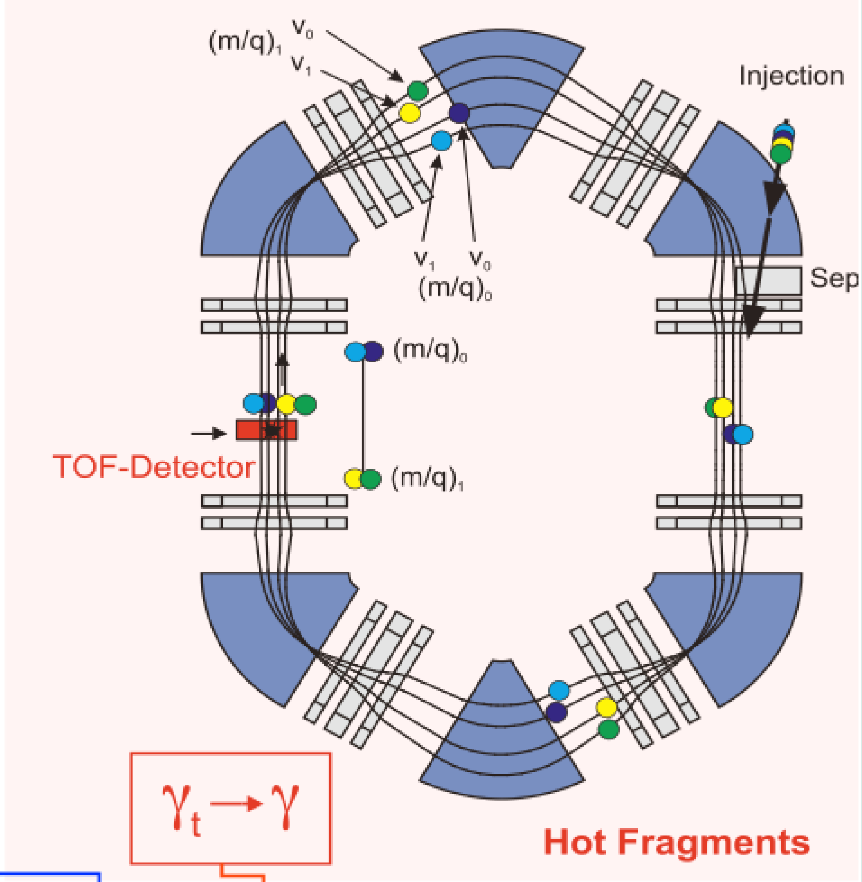
Storage ring mass spectrometry

Schottky Mass Spectrometry



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

Isochronous Mass Spectrometry

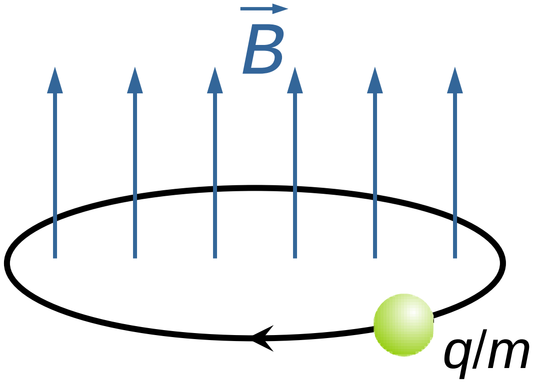


$$\boxed{\gamma_t \rightarrow \gamma}$$

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

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

Principle of Penning trap mass spectrometry

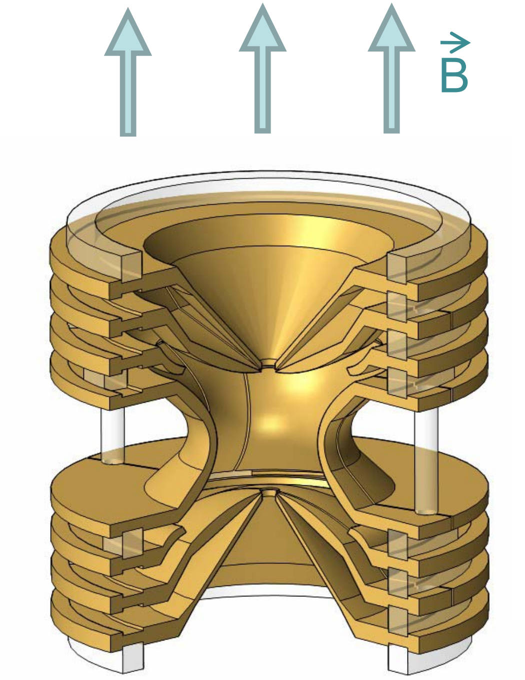


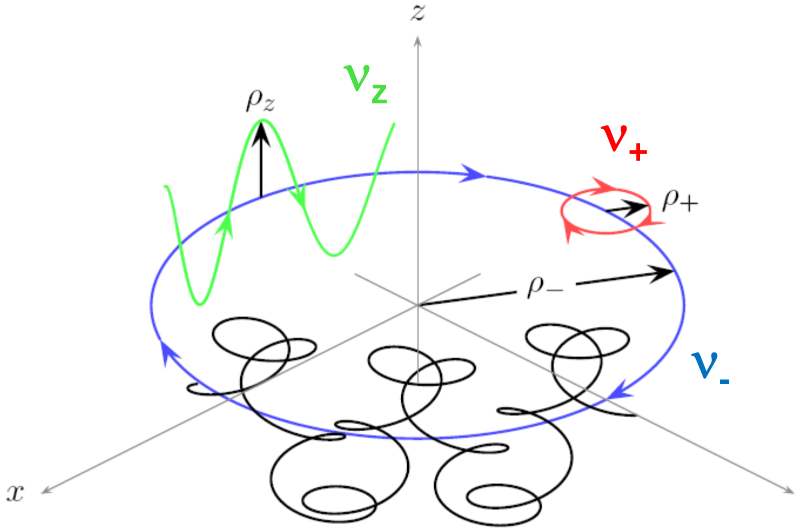
Cyclotron frequency:

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

PENNING trap

- Strong homogen. magnetic field
- Weak electric 3D quadrupole field



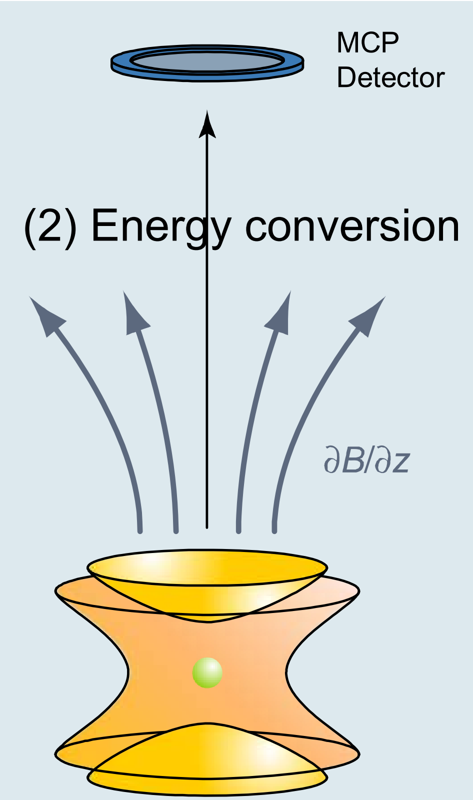


Typical freq.
q = e
m = 100 u
B = 6 T

$\Rightarrow$ f_- ≈ 1kHz
f_+ ≈ 1MHz

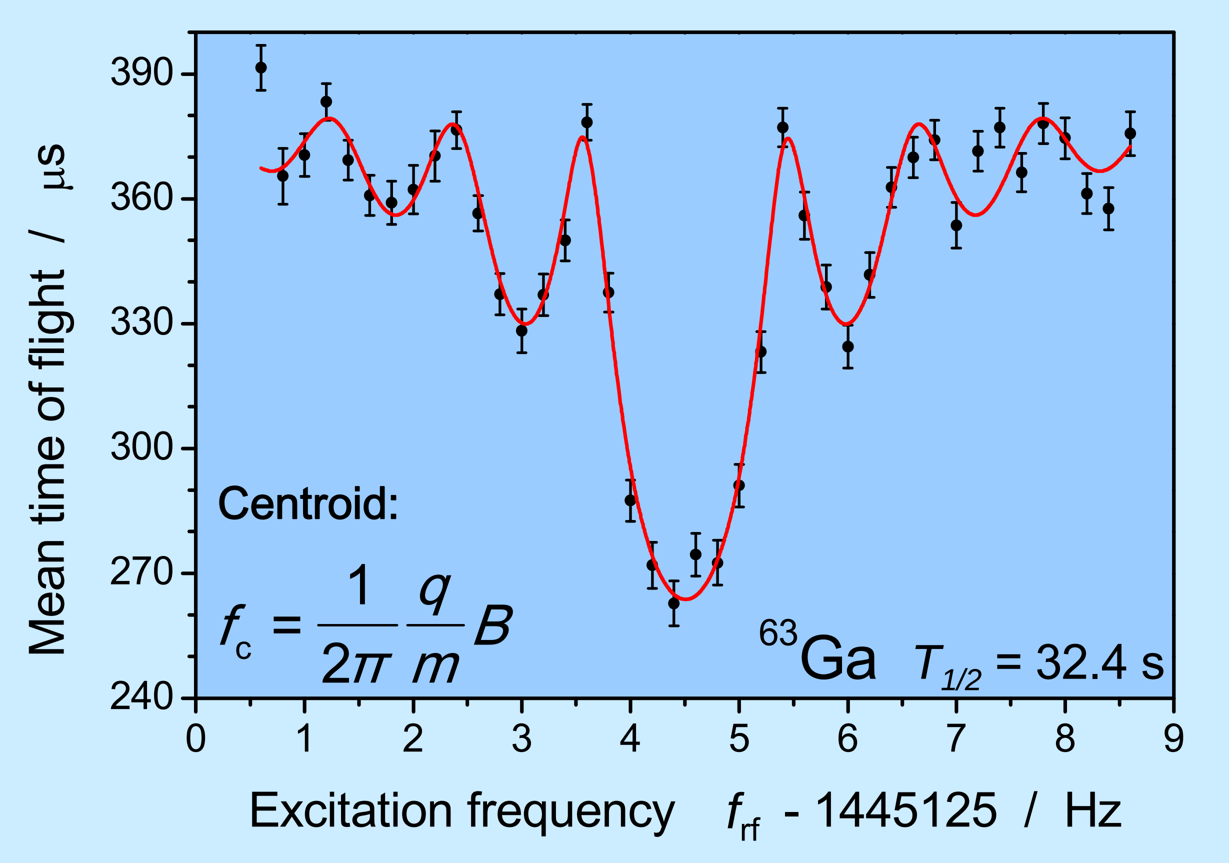
TOF cyclotron resonance detection

(3) TOF measurement



(2) Energy conversion

(1) Excitation of the ion motion



Centroid:

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

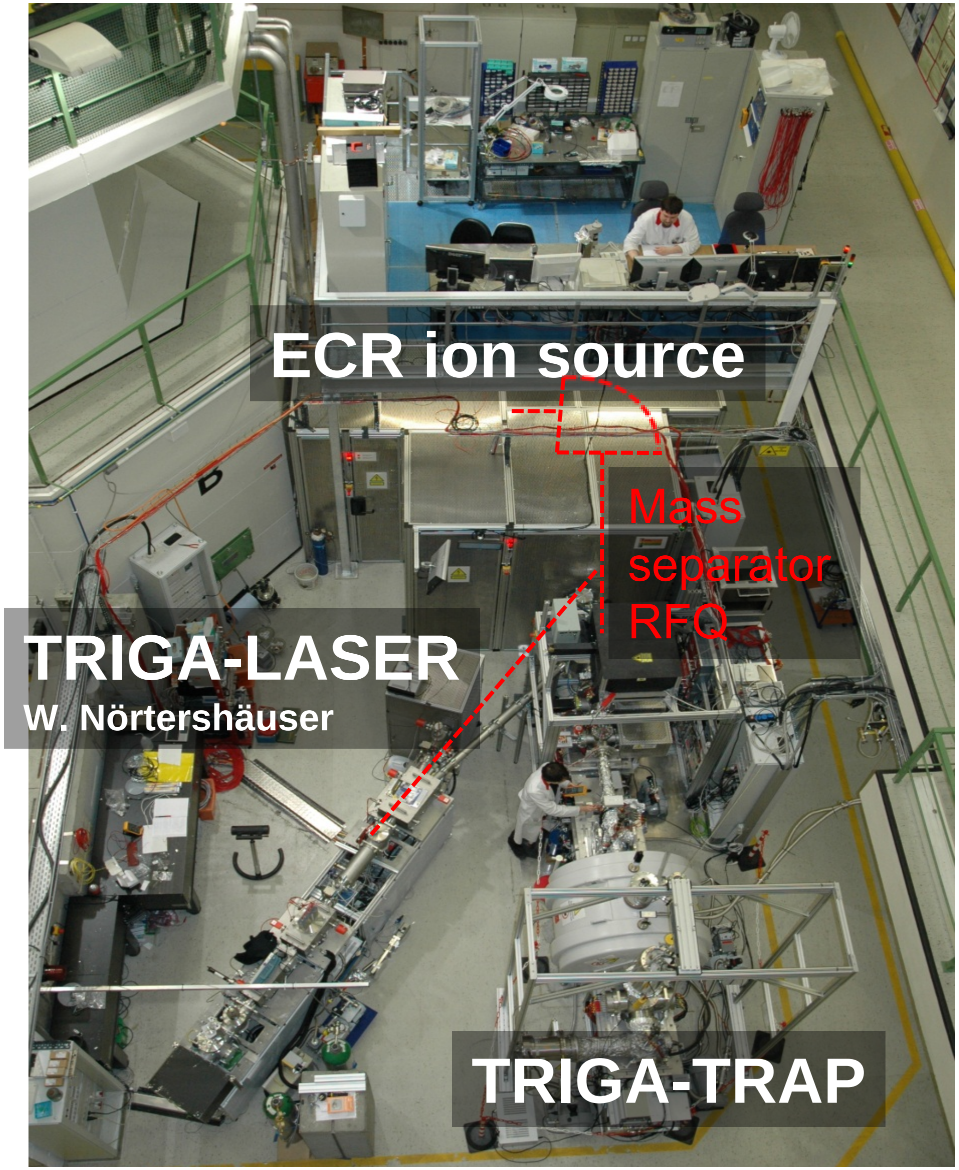
Determine atomic mass from frequency ratio with a well-known “reference mass”.

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

TRIGA-SPEC: TRIGA-LASER + TRIGA-TRAP

project start @ TRIGA: 01/08
start data taking: 05/09


TRIGA Mainz
G. Hampel
K. Eberhardt
N. Trautmann



TRIGA-LASER
W. Nörtershäuser

TRIGA-TRAP

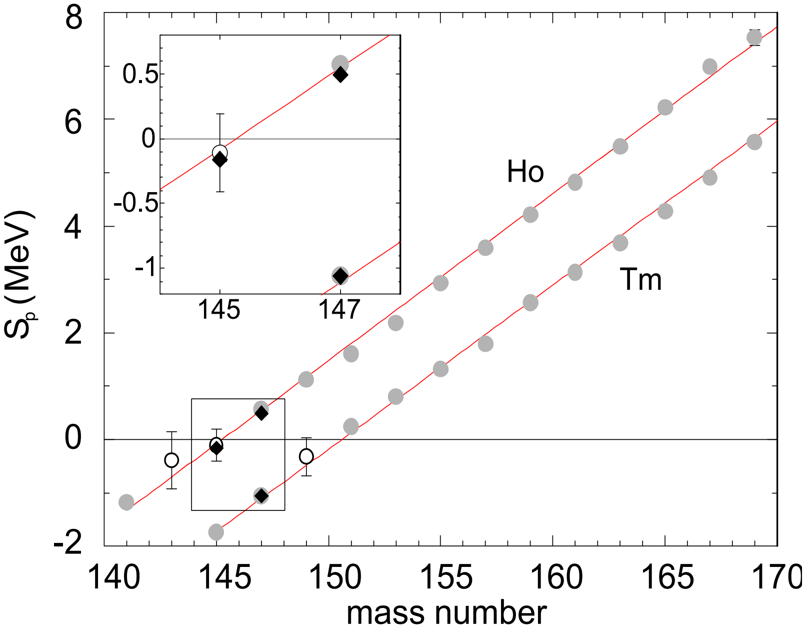
steady 100 kW,
pulsed 250 MW,
neutron flux 1.8x10^{11} / cm^2s

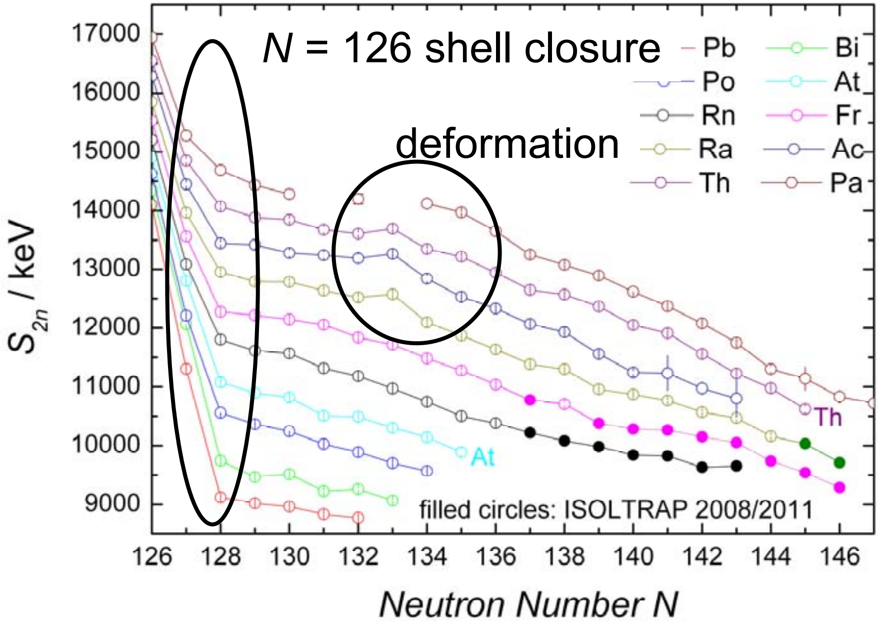
Nucl. Instrum. Meth. A 594, 162 (2008)

Nuclear structure studies

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

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





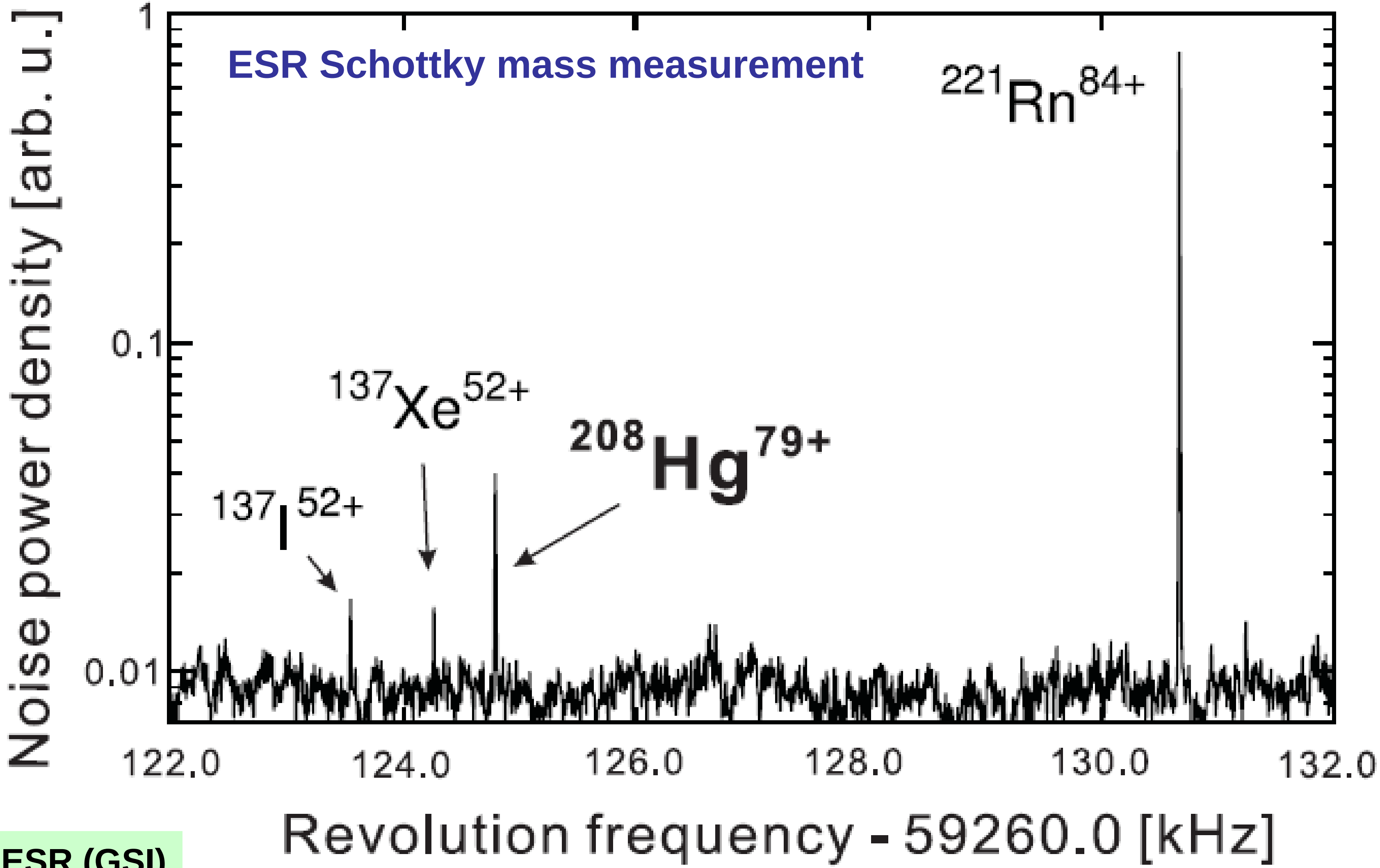
SHIPTRAP: First direct mass measurement beyond the proton dripline.

CPT/ISOLTRAP/JYFLTRAP/LEBIT/TITAN: Investigation of shell closures, halos, …

C. Rauth *et al*., Phys. Rev. Lett. 100, 012501 (2008)
M. Dworschak *et al*., Phys. Rev. Lett. 100, 072501 (2008)
W. Geithner *et al*., Phys. Rev. Lett. 101, 252502 (2008)
J. Hakala *et al*., Phys. Rev. Lett. 101, 052502 (2008)

B. Cakirli *et al*., Phys. Rev. Lett. 102, 082501 (2009)
D. Neidherr *et al*., Phys. Rev. Lett. 102, 112501 (2009)
J.S.E. Wieslander *et al*., Phys. Rev. Lett. 103, 122501 (2009)
S. Naimi *et al*., Phys. Rev. Lett. 105, 032502 (2010)

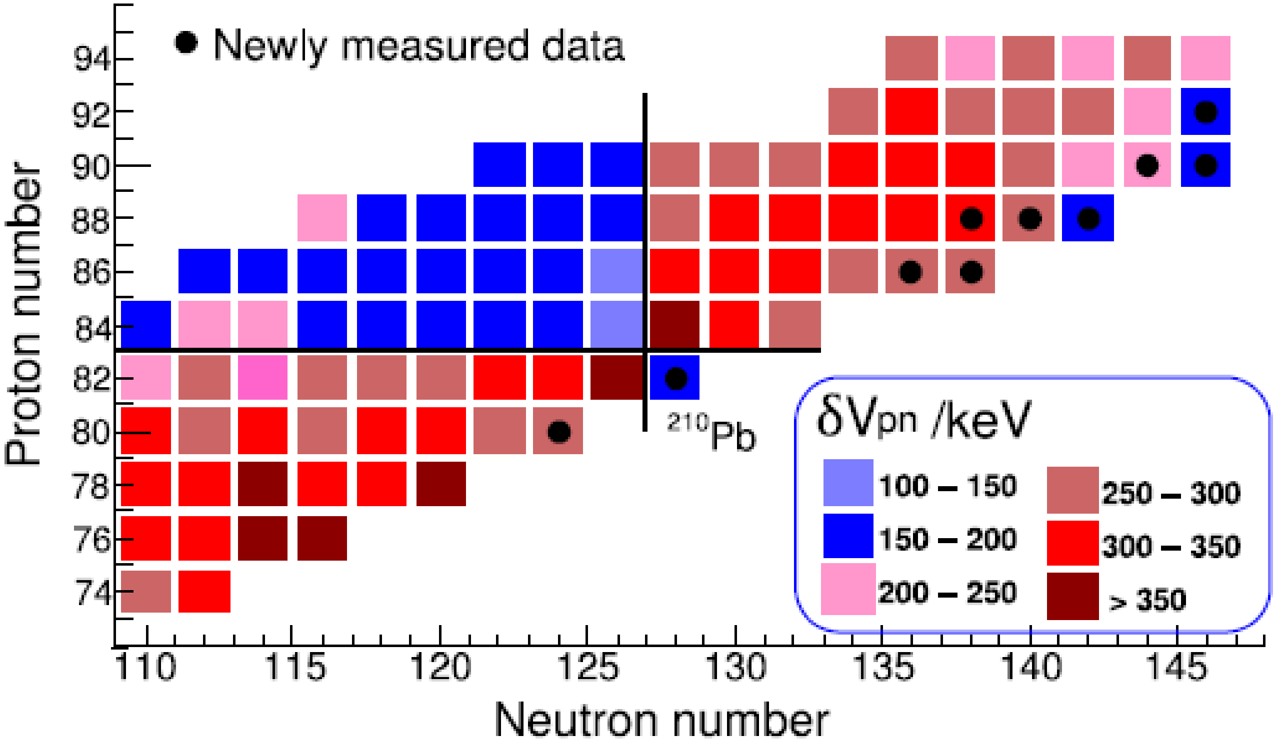
Experimental proton-neutron interaction



ESR (GSI)

Masses reveal the p-n interaction strength

ESR (GSI)



For even-even nuclei

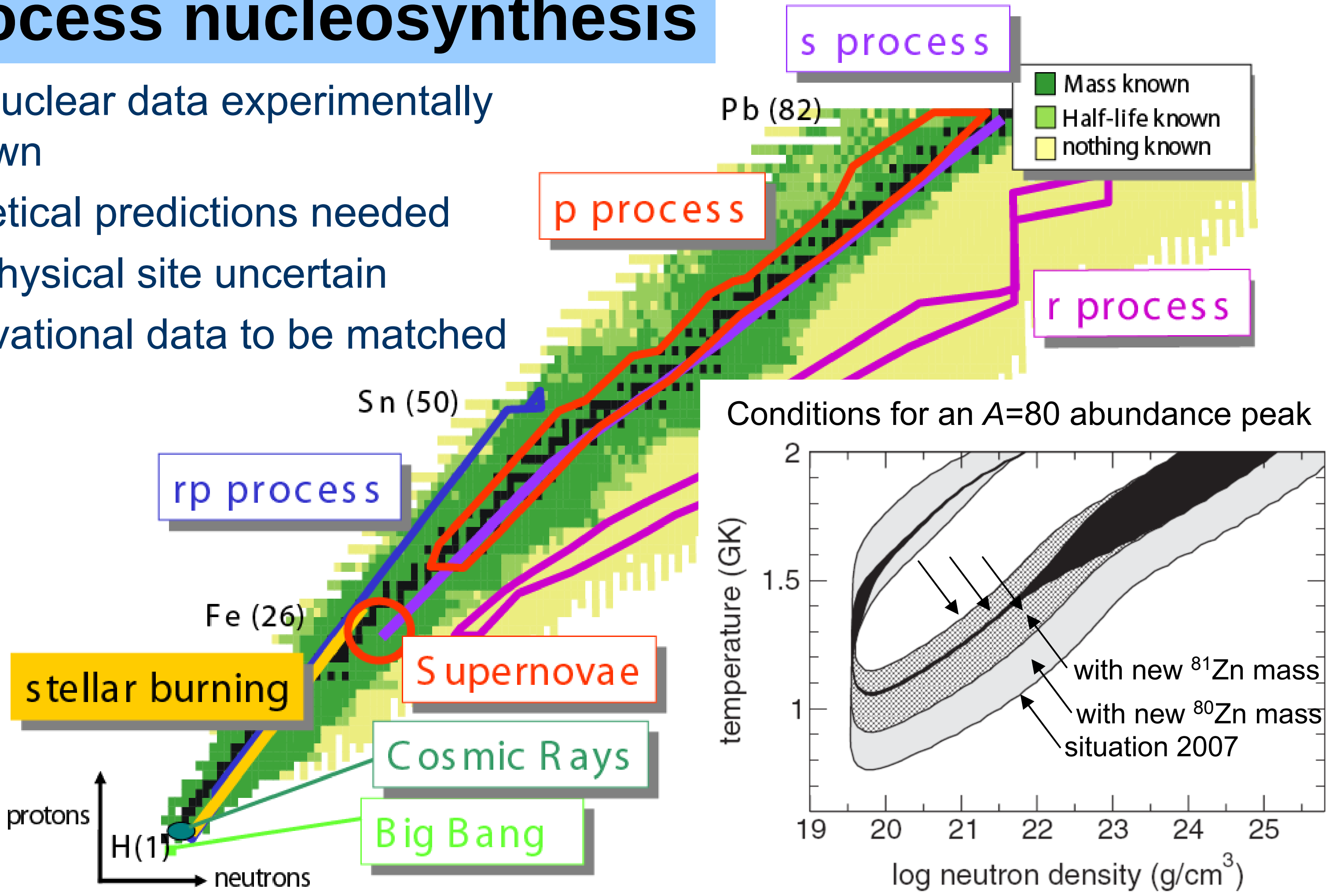
$$\delta V_{pn}(Z,N) = \tfrac{1}{4}[\{B(Z,N)-B(Z,N-2)\}-\{B(Z-2,N)-B(Z-2,N-2)\}]$$

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

Making gold in nature

r-process nucleosynthesis

- Most nuclear data experimentally unknown
- Theoretical predictions needed
- Astrophysical site uncertain
- Observational data to be matched



Conditions for an *A*=80 abundance peak

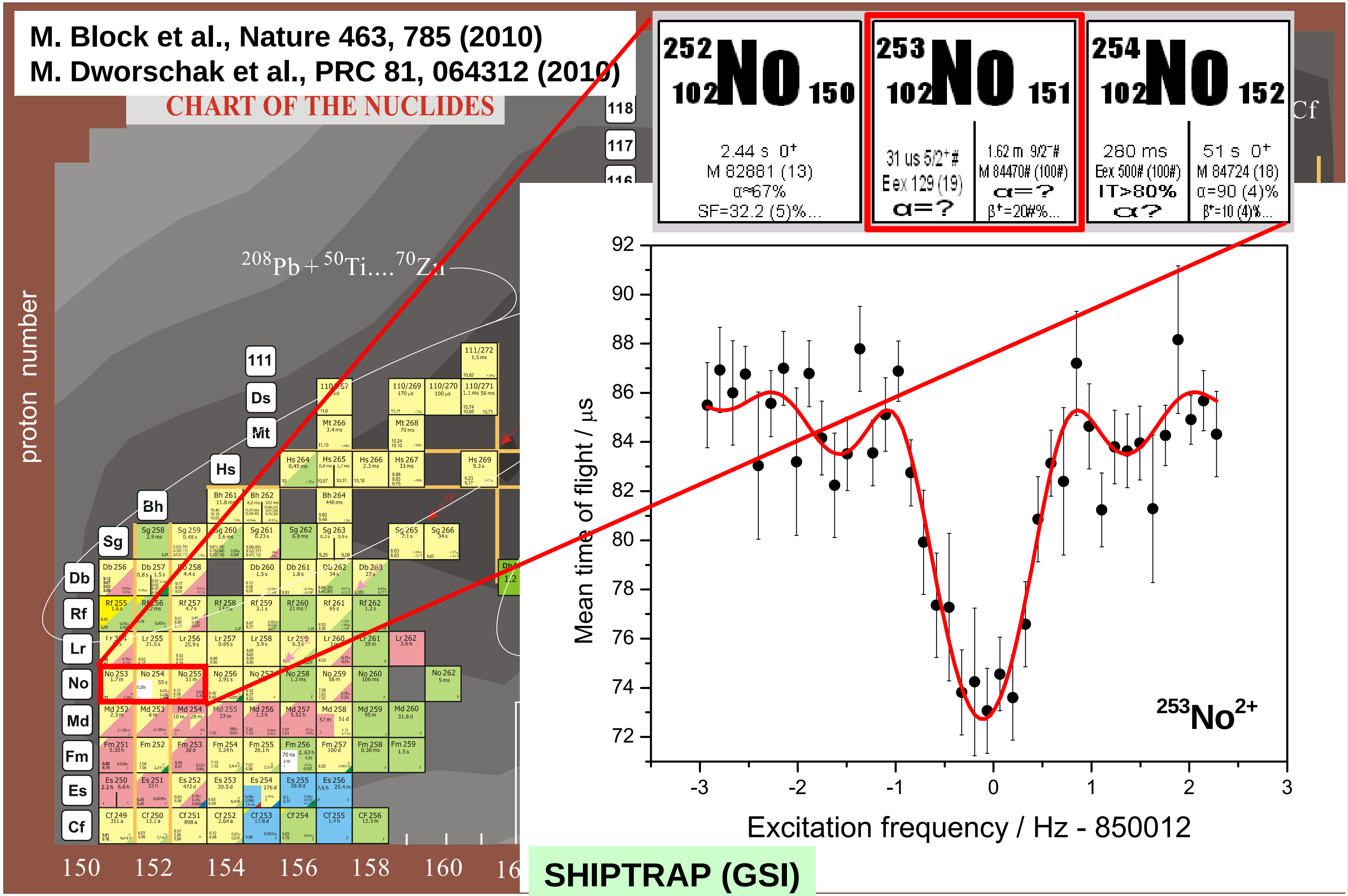
D. Rodríguez *et al.*, Phys. Rev. Lett. 93, 161104 (2004)
S. Baruah *et al.*, Phys. Rev. Lett. 101, 262501 (2008)

X.L. Tu *et al.*, Phys. Rev. Lett. 106, 112501 (2011)
E. Haettner *et al.*, Phys. Rev. Lett. 106, 122501 (2011)

MAX PLANCK INSTITUTE
FOR NUCLEAR PHYSICS

Direct mass measurements on No and Lr

M. Block et al., Nature 463, 785 (2010)
M. Dworschak et al., PRC 81, 064312 (2010)



SHIPTRAP (GSI)

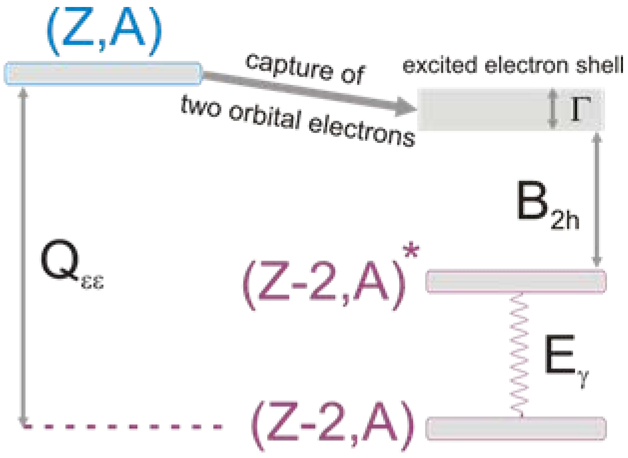
Neutrino-less double EC (0ν2*EC*)

Is the neutrino a Majorana or Dirac particle?

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

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

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



Contribution of Penning traps:

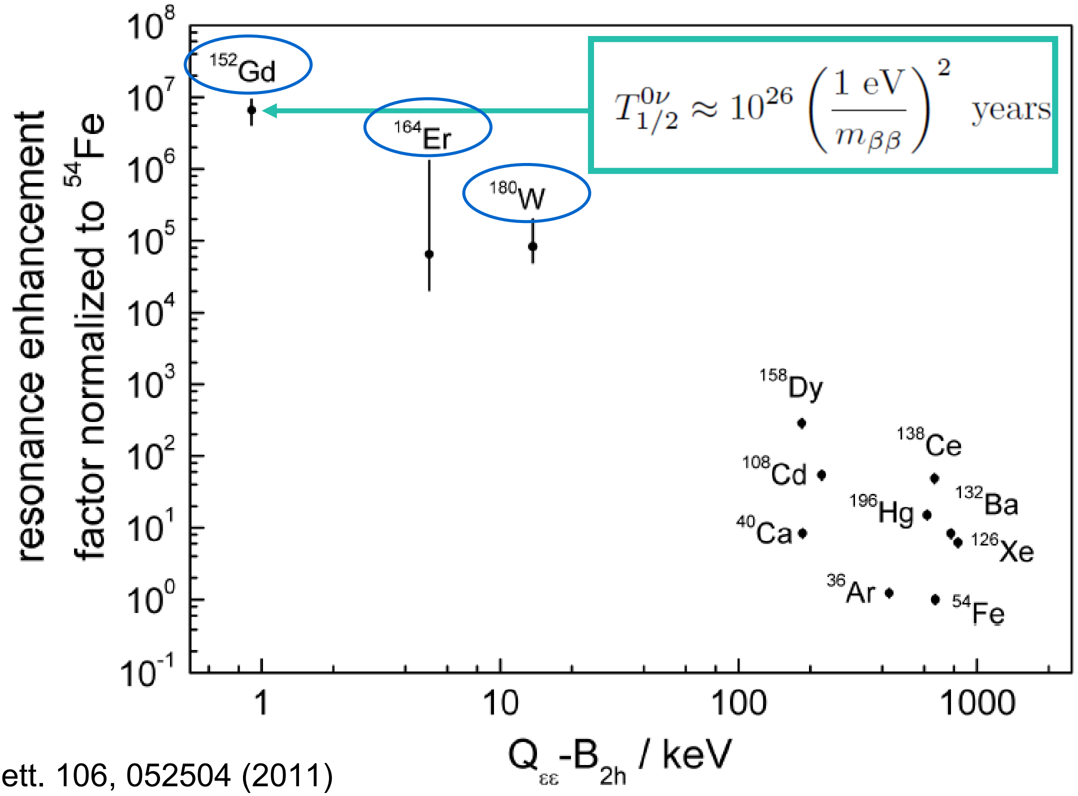
Search for nuclides with $\Delta=(Q_{\varepsilon\varepsilon}-B_{2h}-E_\gamma) < 1$ keV

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

at ~100 eV accuracy level

Resonance enhancement factors

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



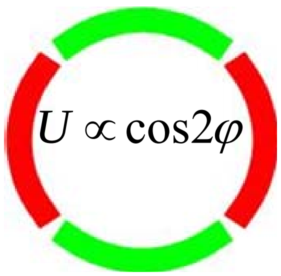
$$T^{0\nu}_{1/2} \approx 10^{26} \left(\frac{1\ \mathrm{eV}}{m_{\beta\beta}}\right)^2 \ \text{years}$$

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

107, 152501 (2011)

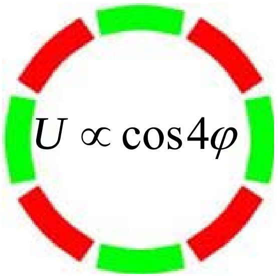
A breakthrough: Octupolar excitation

Quadrupolar excitation



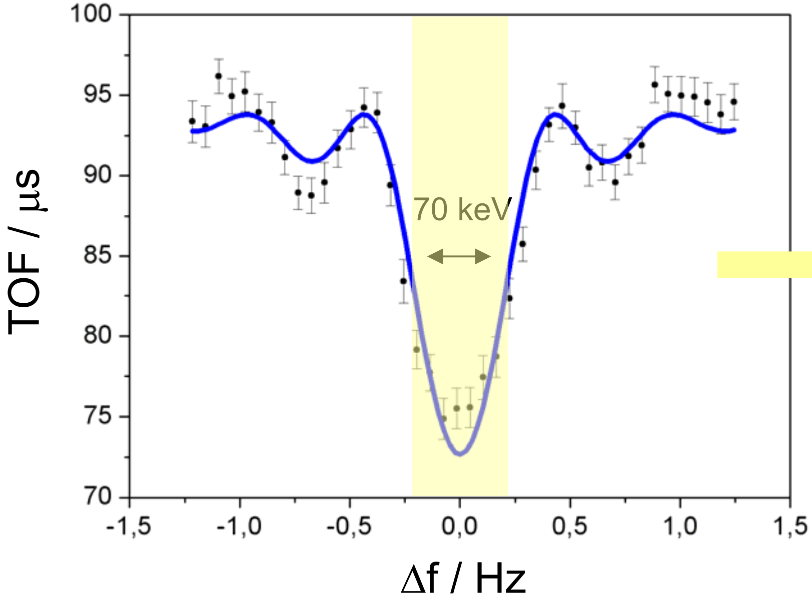
$U \propto \cos 2\varphi$

Octupolar excitation

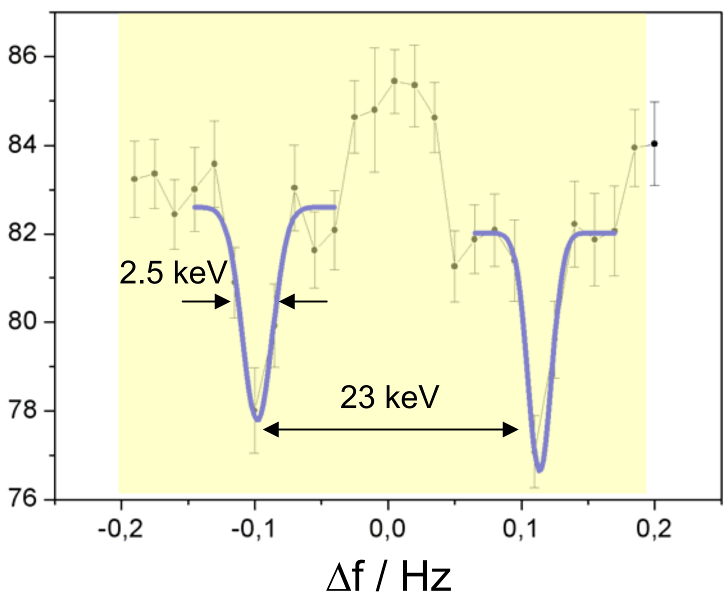


$U \propto \cos 4\varphi$

^{164}Er and ^{164}Dy are *not* resolved

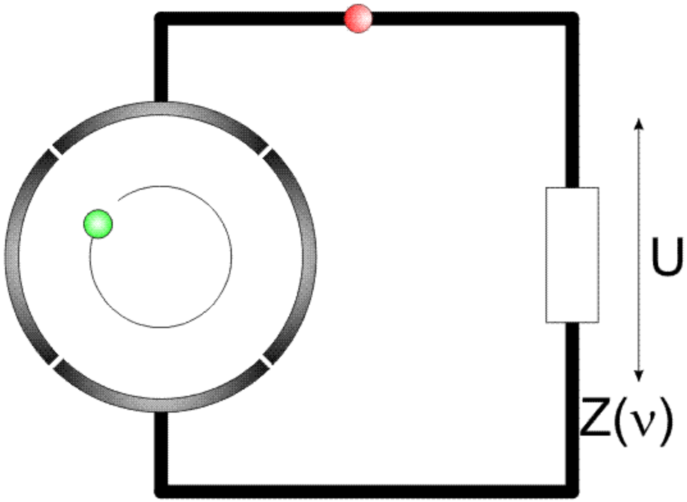


^{164}Er and ^{164}Dy are resolved

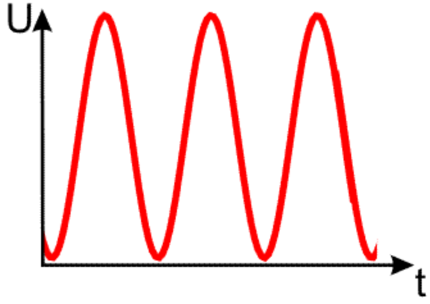


At least 20-fold improvement in resolving power!

Non-destructive ion detection

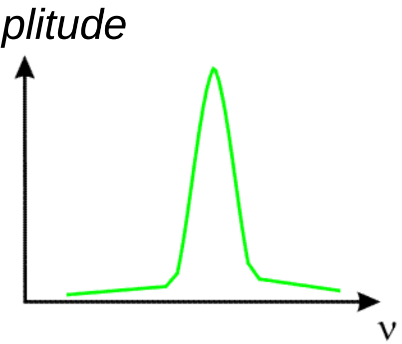


ion signal



very small signal ~fA

mass/frequency spectrum



„FT-ICR“

Fourier-**T**ransform-
Ion **C**yclotron **R**esonance

Induced current: $I_{eff} = 1/\sqrt{2} \cdot r_{ion} / D \cdot \omega \cdot q$

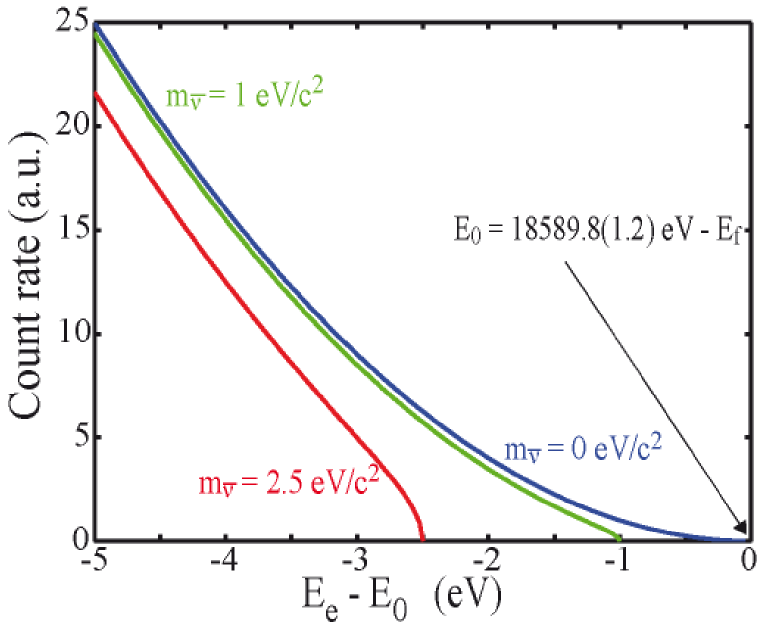
(Schottky et al. ...)

Signal / Noise $S/N \sim 1 / T^{1/2}$

Operation of traps and electronics at **cryogenic** (4 K) temperature.

THe-TRAP for KATRIN

A high-precision $Q(^3T\text{-}^3He)$-value measurement



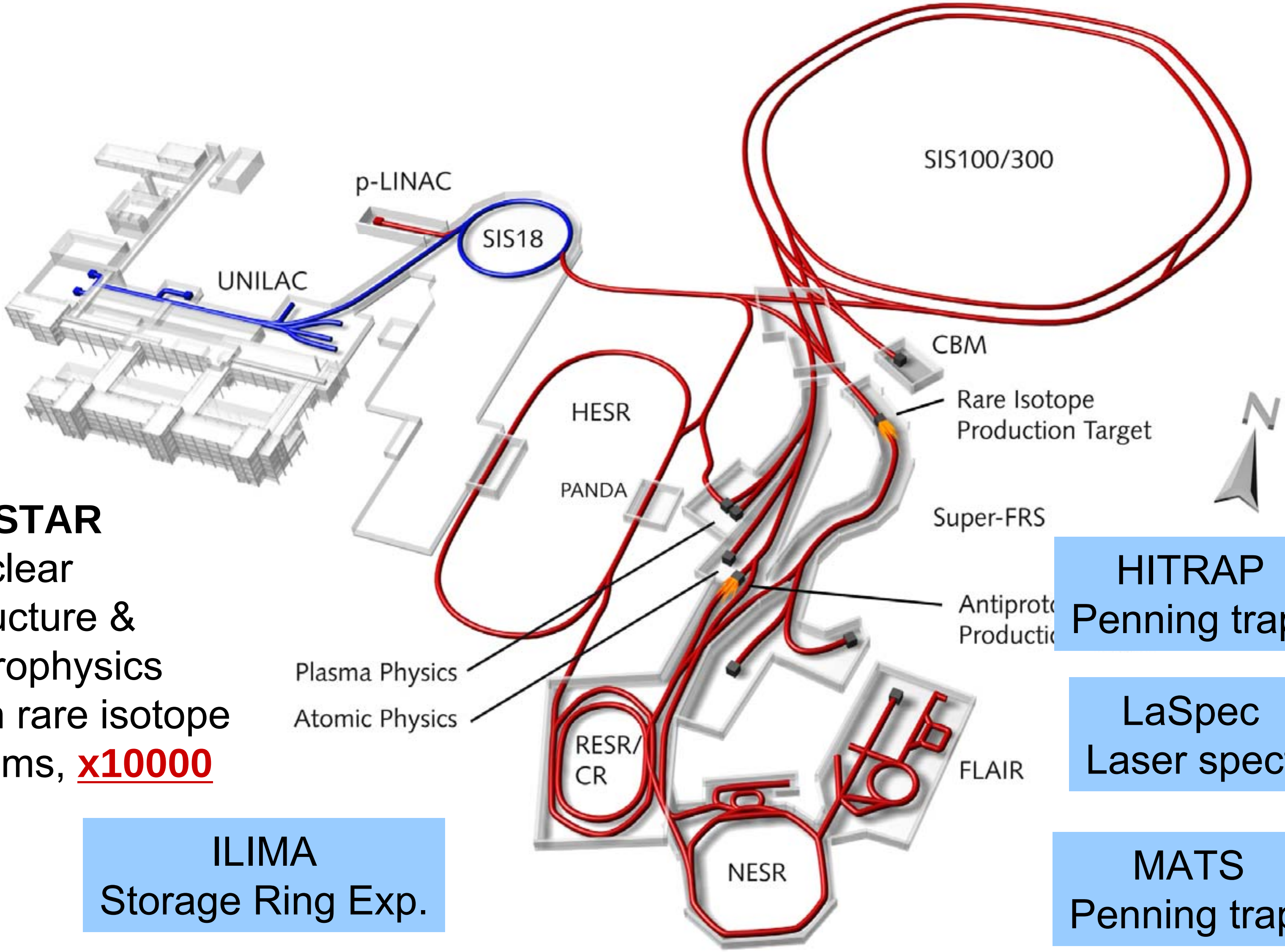
$^3_1H \rightarrow ^3_2He + e^- + \bar{\nu}$ Q_{lit} =18 589.8 (1.2) eV

We aim for: $\delta Q(^3T \rightarrow ^3He)$ = 20 meV
$\delta m/m = 7 \cdot 10^{-12}$

$\Delta T < 0.05$ K/d at 24°C
$\Delta B/B < 10$ ppt / h $\Delta x \leq 0.1\ \mu m$

First $^{12}C^{4+}/^{16}O^{6+}$ mass ratio measurement at $\delta m/m_{stat} = 4 \cdot 10^{-11}$ performed.

Future ring/trap facilities at FAIR



NUSTAR
Nuclear
Structure &
Astrophysics
with rare isotope
beams, **x10000**

ILIMA
Storage Ring Exp.

HITRAP
Penning traps

LaSpec
Laser spect.

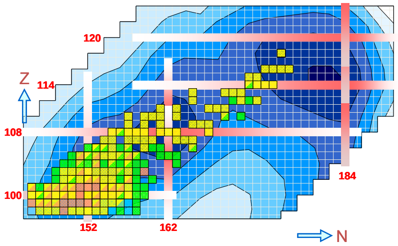
MATS
Penning traps

Summary

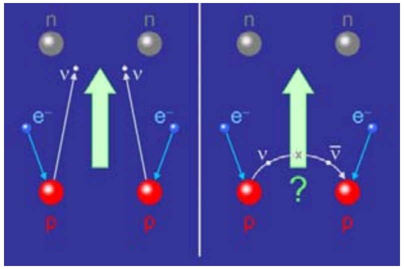
Breathtaking results in precision mass spectrometry with stored and cooled exotic ions have been achieved!

- Accurate masses have been obtained for nuclear structure studies and reliable nucleosynthesis calculations.

- First direct mass measurements above uranium bridge the gap to the island of stability.



- Discovery of a suitable candidate for 0ν2EC search.
- Development of novel and unique storage devices.
- … and many more!



Thanks

Thanks a lot for the invitation and your attention!

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

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