MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

EuNPC, Groningen 2015

Nuclear masses and their importance for nuclear structure, astrophysics, and fundamental studies

- Motivation for precision mass data
- Storage ring/Penning-trap mass spectrometry
- Applications of atomic/nuclear masses

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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August 31st, 2015

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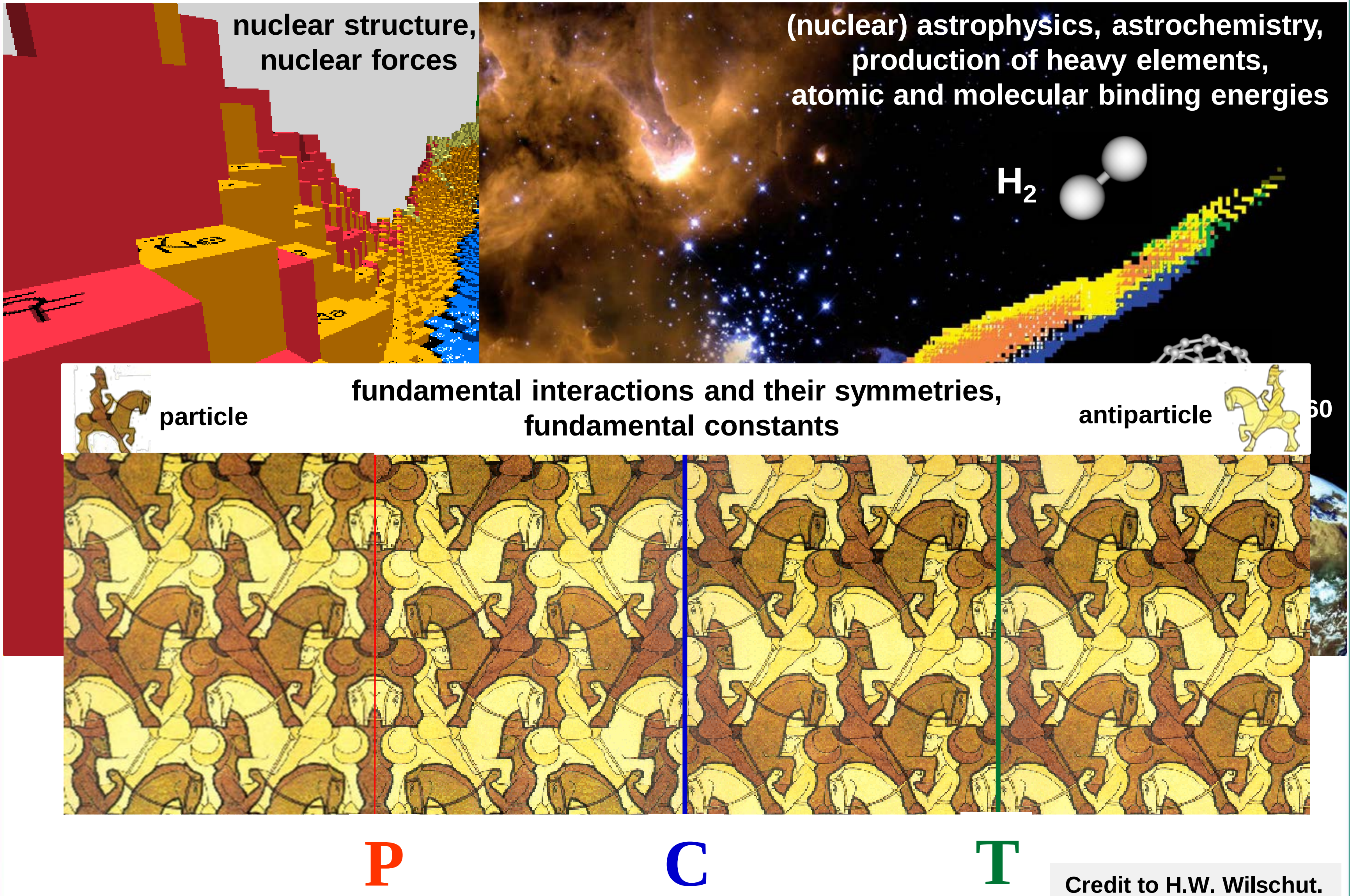
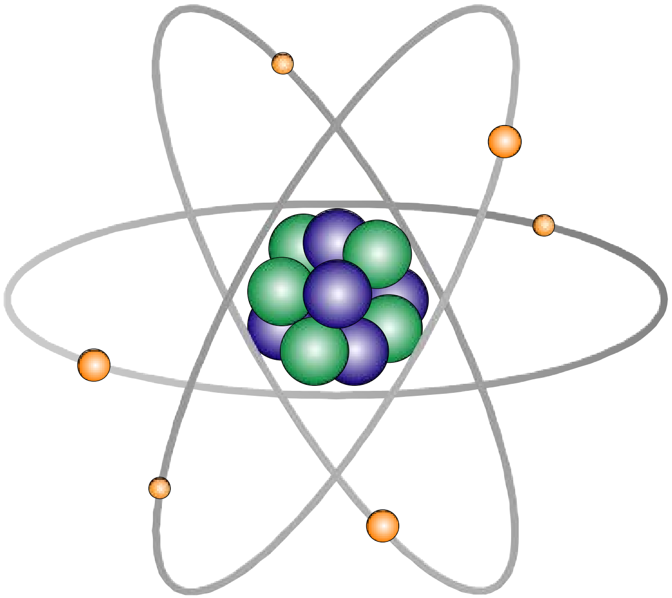
Fields of applications

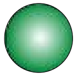
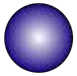
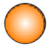


Credit to H.W. Wilschut.

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

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

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

$\delta m/m = 10^{-6} – 10^{-8}$

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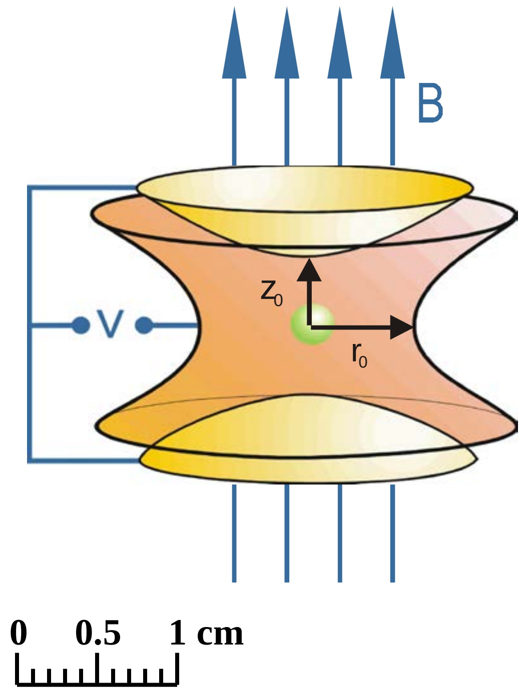
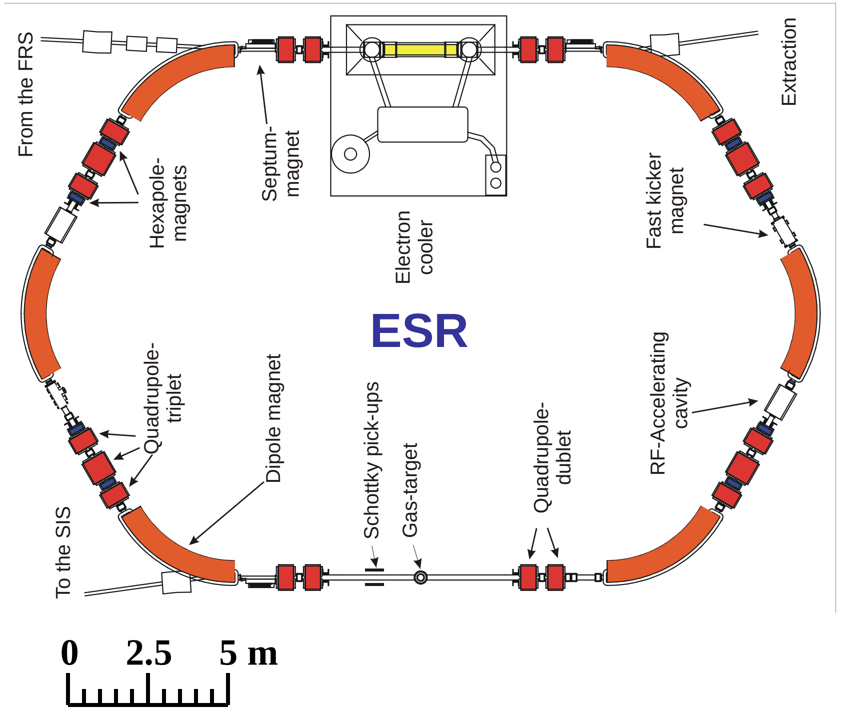
Storage and cooling techniques

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 of ions in a Penning trap

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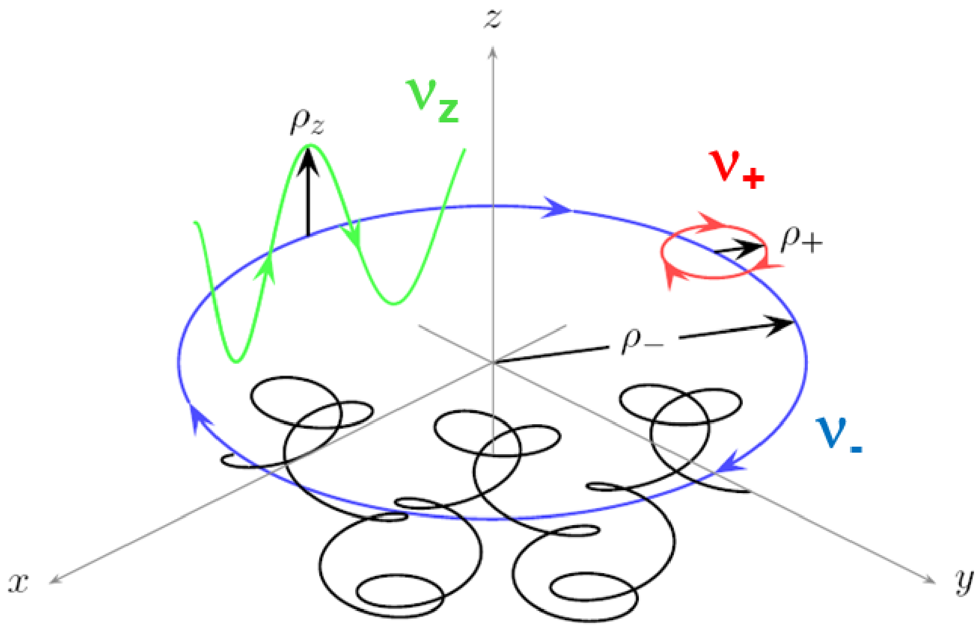

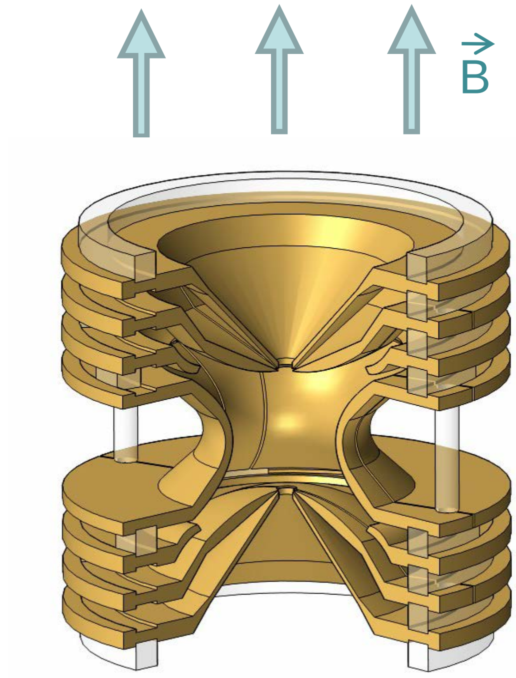

The free cyclotron frequency is inverse proportional to the mass of the ions!

$$\omega_c = qB / m$$

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).

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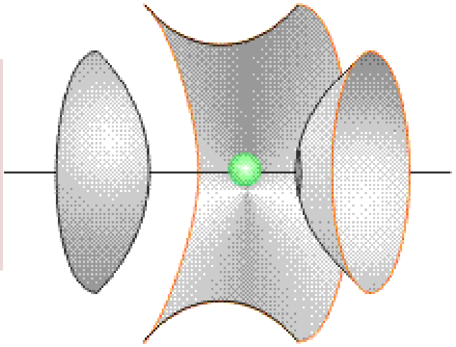
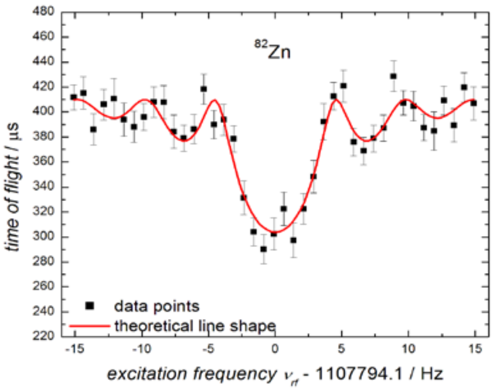
Cyclotron frequency detection techniques

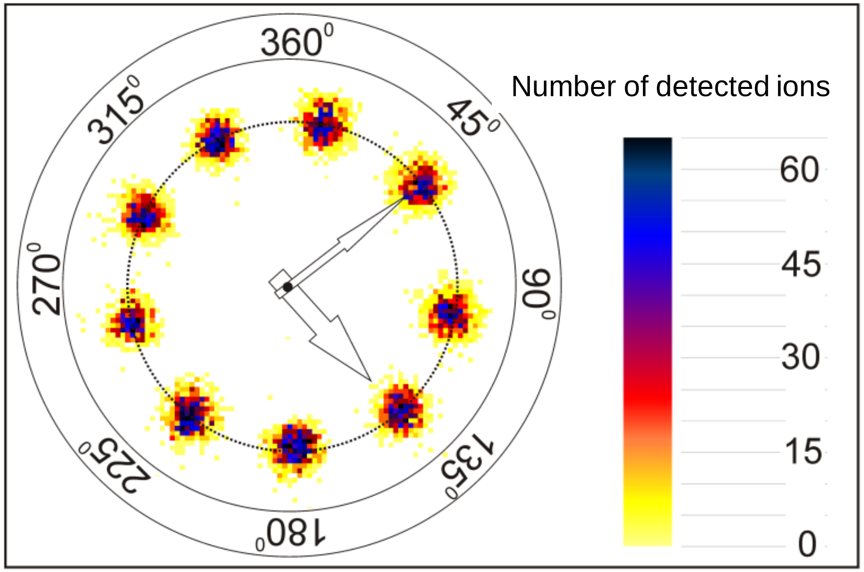
Destructive time-of-flight detection



$R \propto 1/T_{obs}$



Space/ Phase resolving detection



$R \propto 1/T_{obs} \cdot \Delta\phi/2\pi$

Mass accuracy of $\delta m/m = 10^{-10}$ demonstrated!

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

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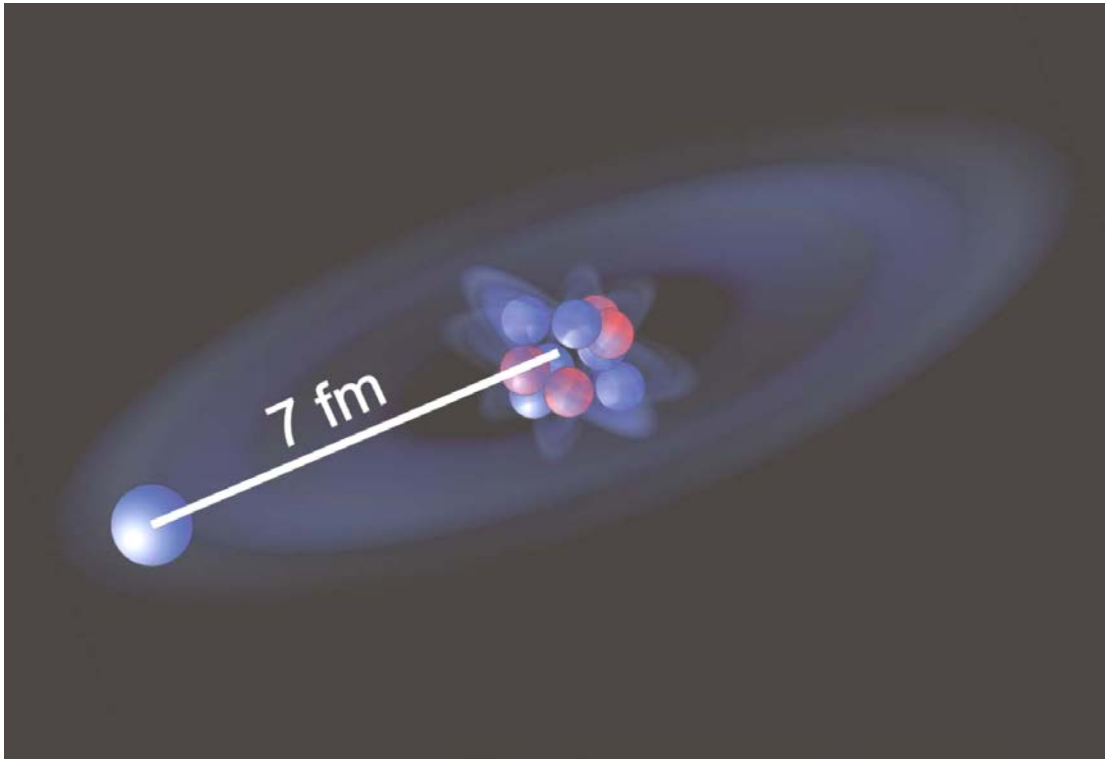
A Penning-trap setup

In collaboration with W. Nörtershäuser (TUD) and Ch. Düllmann (UMz).

Masses

Nuclear structure studies



ESR, ISOLTRAP, SHIPTRAP, TITAN

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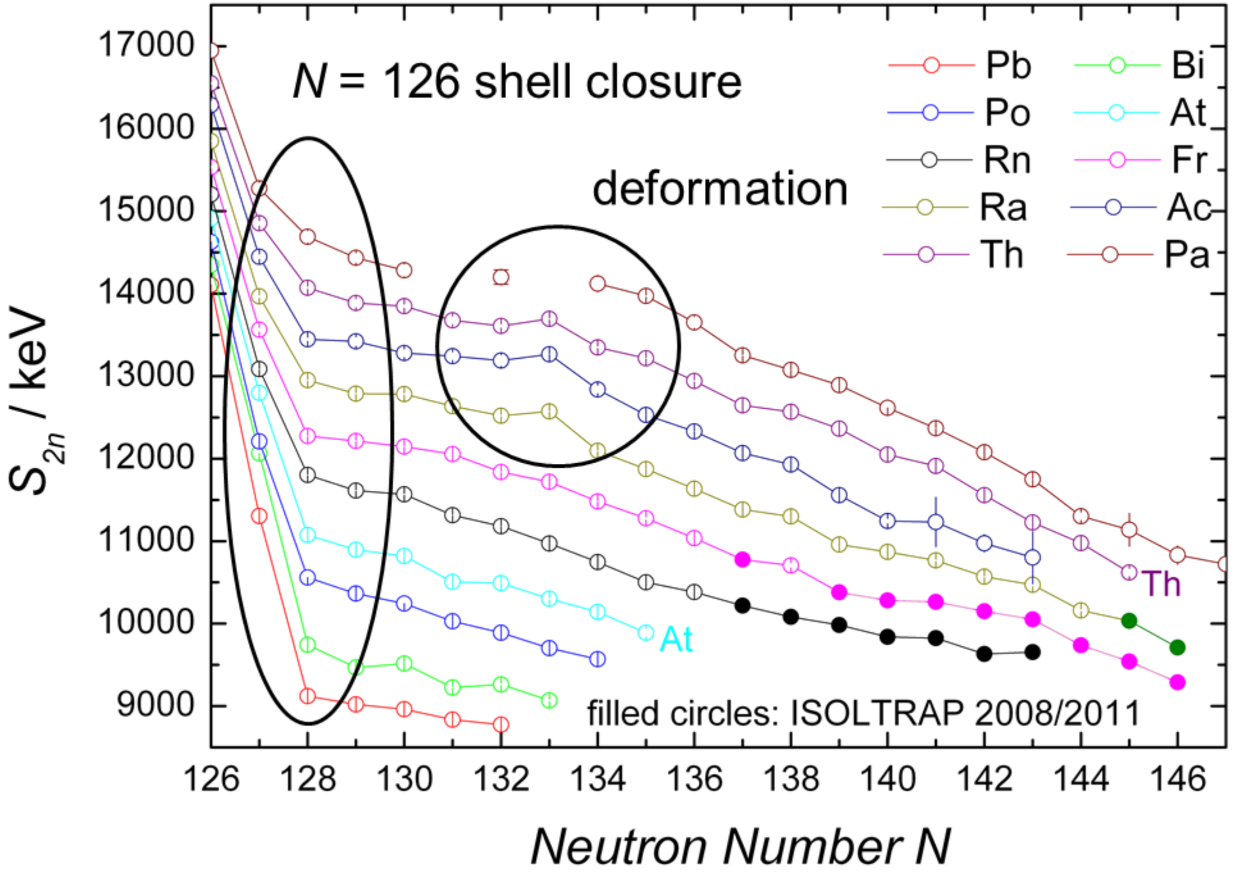
Nuclear structure studies

$$S_{2n} = B_{nucl}(Z,N) - B_{nucl}(Z,N\text{-}2)$$



D. Yordanov *et al.*, Phys. Rev. Lett. 110, 192501 (2013)
M.L. Bissell *et al.*, Phys. Rev. Lett. 113, 052502 (2014)
Z. Meisel *et al.*, Phys. Rev. Lett. 114, 022501 (2015)
J. Papuga *et al.*, Phys. Rev. Lett. 110, 172503 (2013)
R.F. Casten *et al.*, Phys. Rev. Lett. 113, 112501 (2014)
M. Rosenbusch *et al.*, Phys. Rev. Lett. 114, 202501 (2015)

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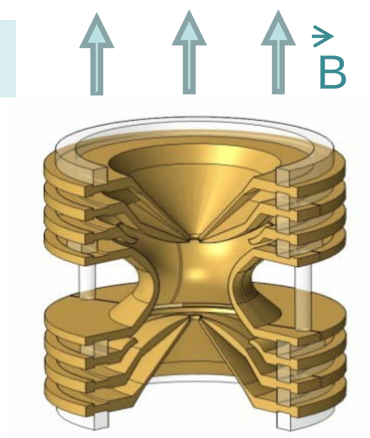
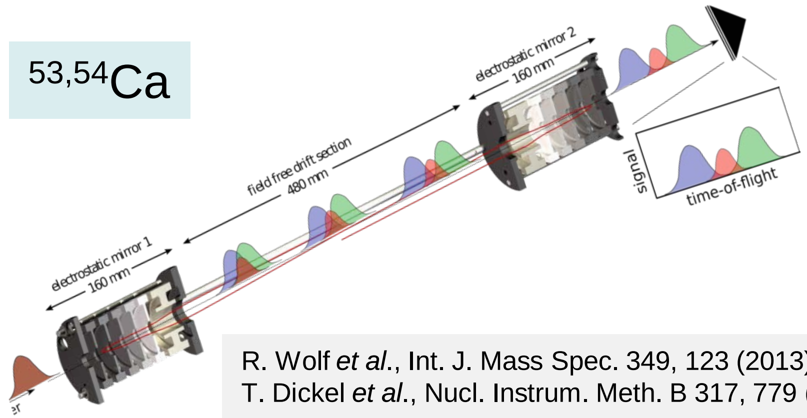
Ca masses pin down nuclear forces

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

^{51,52}Ca

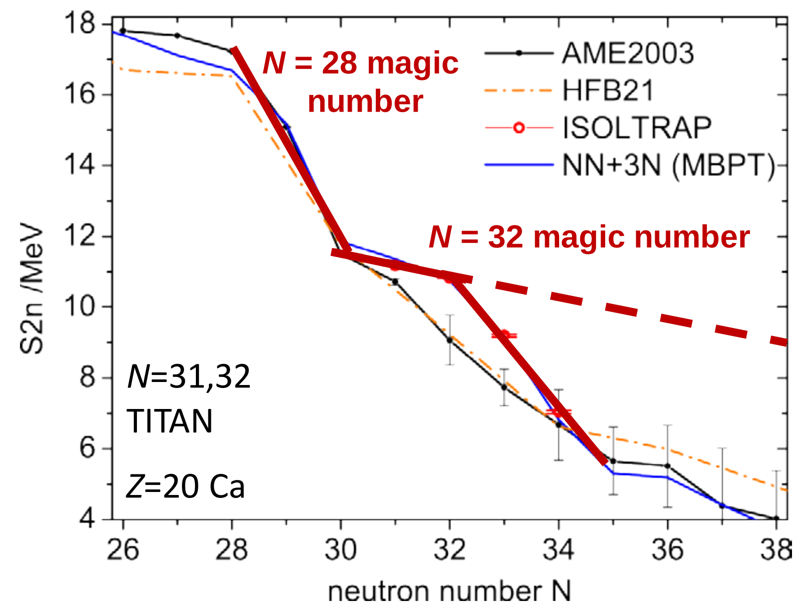


^{53,54}Ca



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)

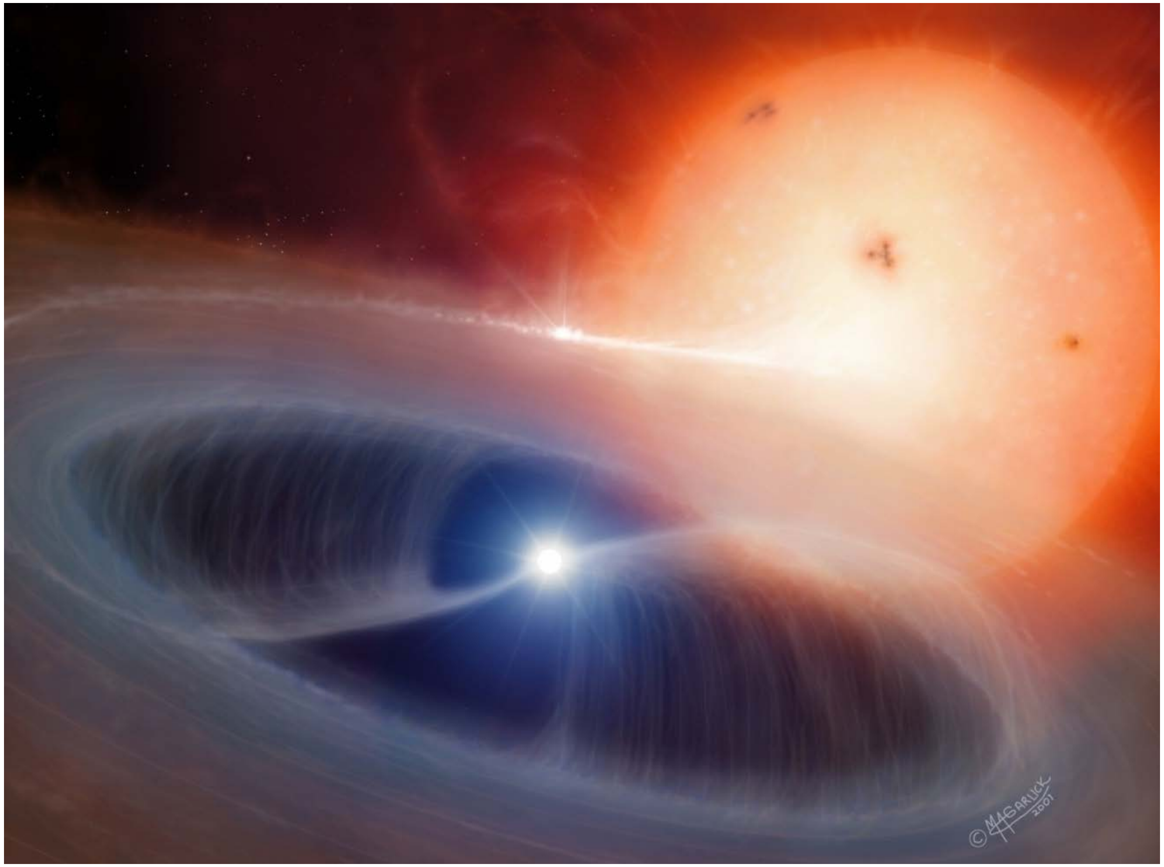


F. Wienholtz *et al.*, Nature 498, 346 (2013)

ISOLTRAP (CERN), TITAN (TRIUMF)

Masses

Nuclear astrophysics studies



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

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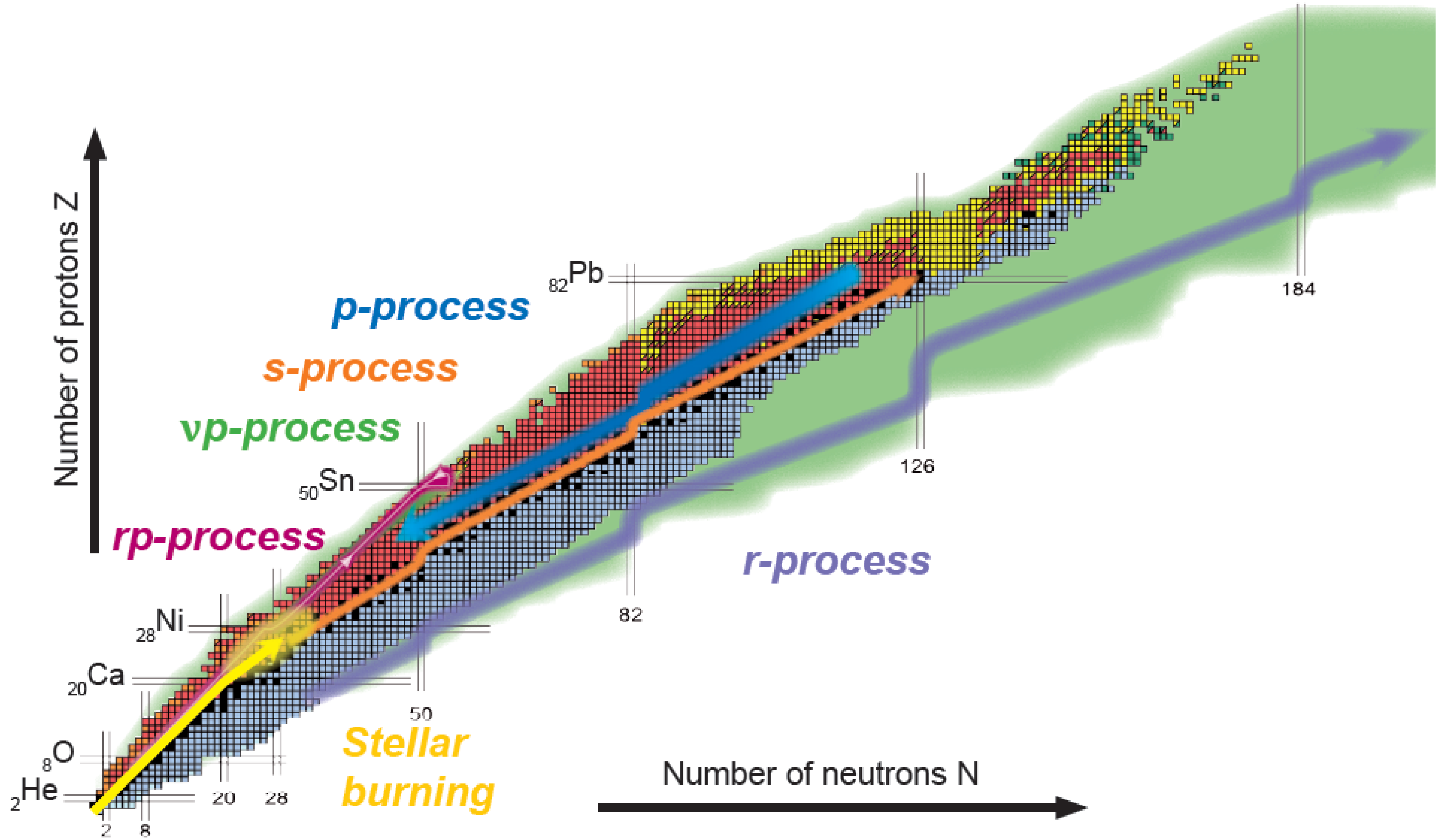
Mass spectrometry for nucleosynthesis



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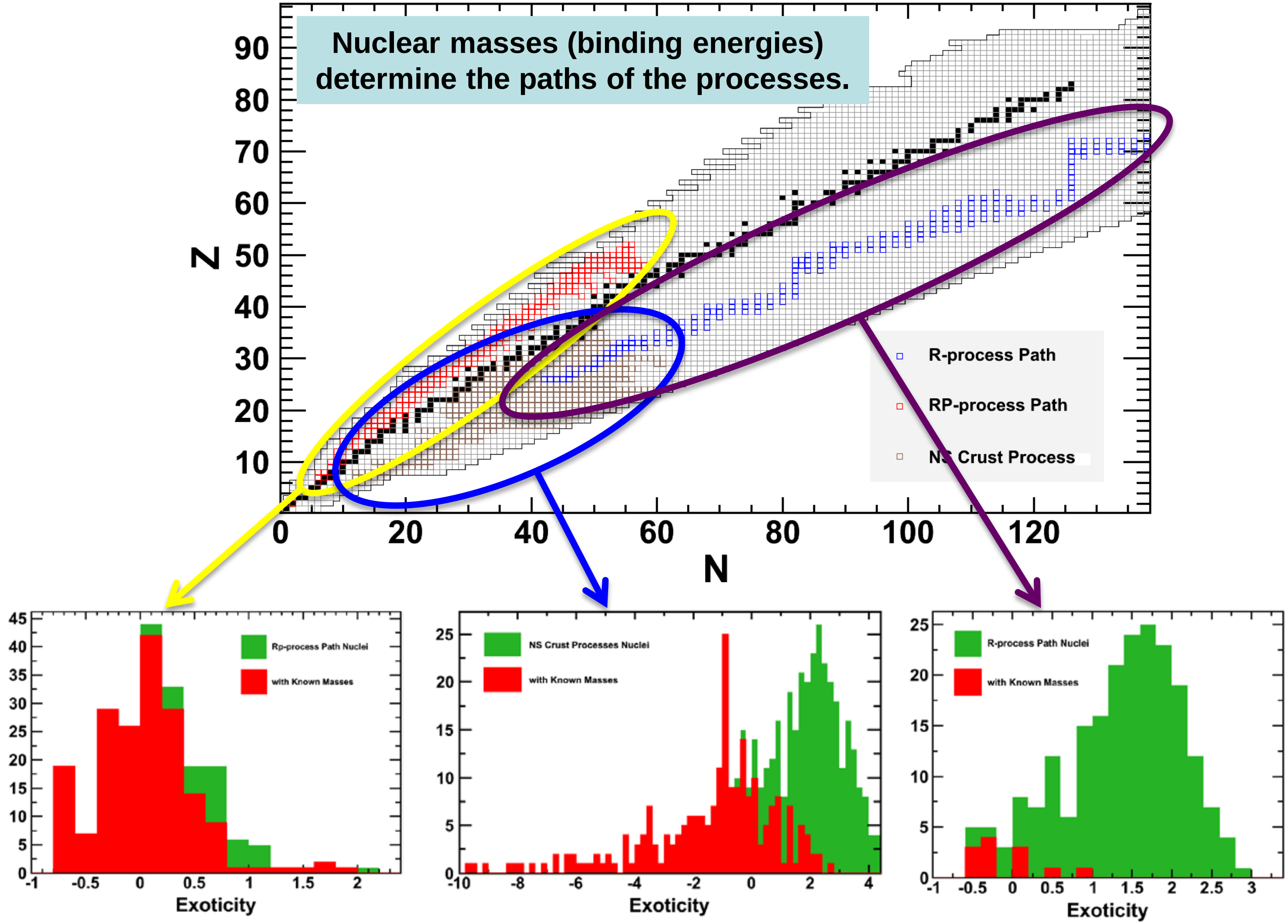
Mass spectrometry for nucleosynthesis



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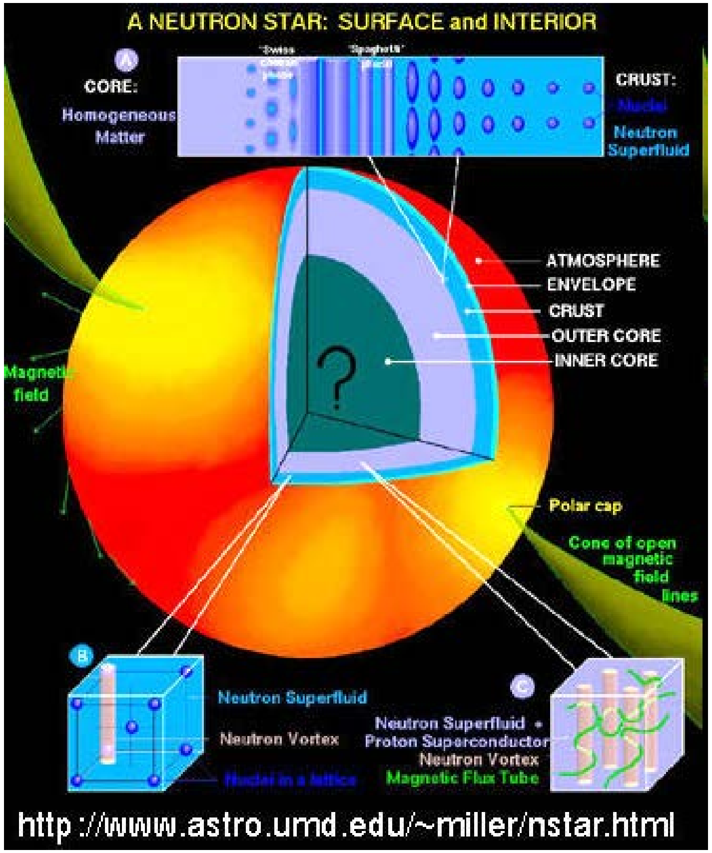
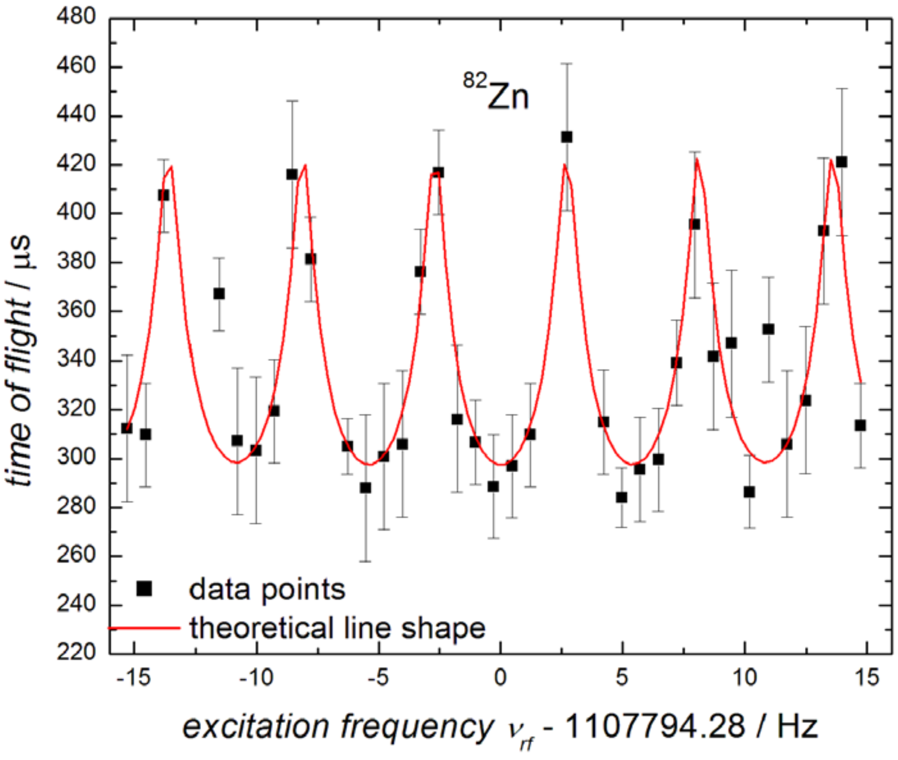
Nuclear astrophysics

Composition of the outer crust of a neutron star





80 ions in 35 minutes!

$\delta m/m = 4 \cdot 10^{-8}$

R. Wolf *et al.*, Phys. Rev. Lett., 110, 041101 (2013)

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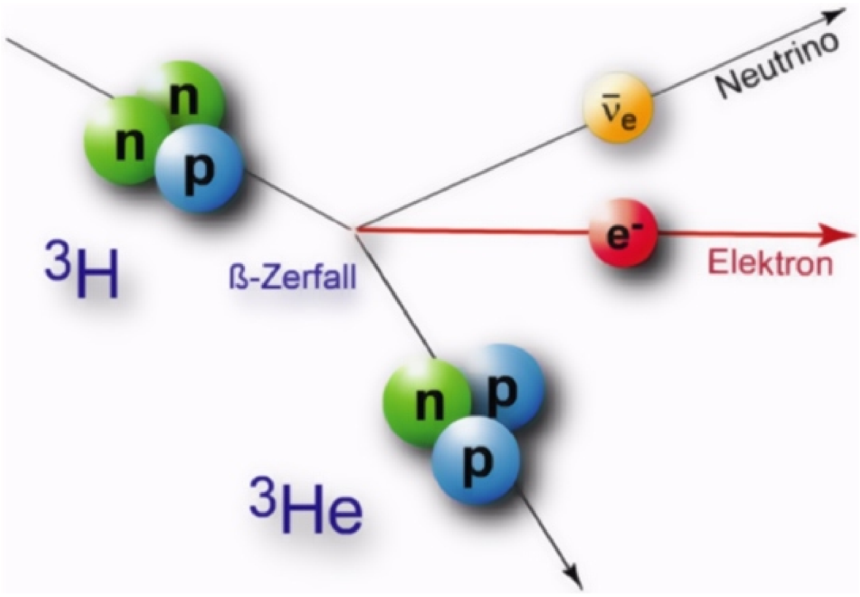
Towards highest precision

Nuclear masses for fundamental studies



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

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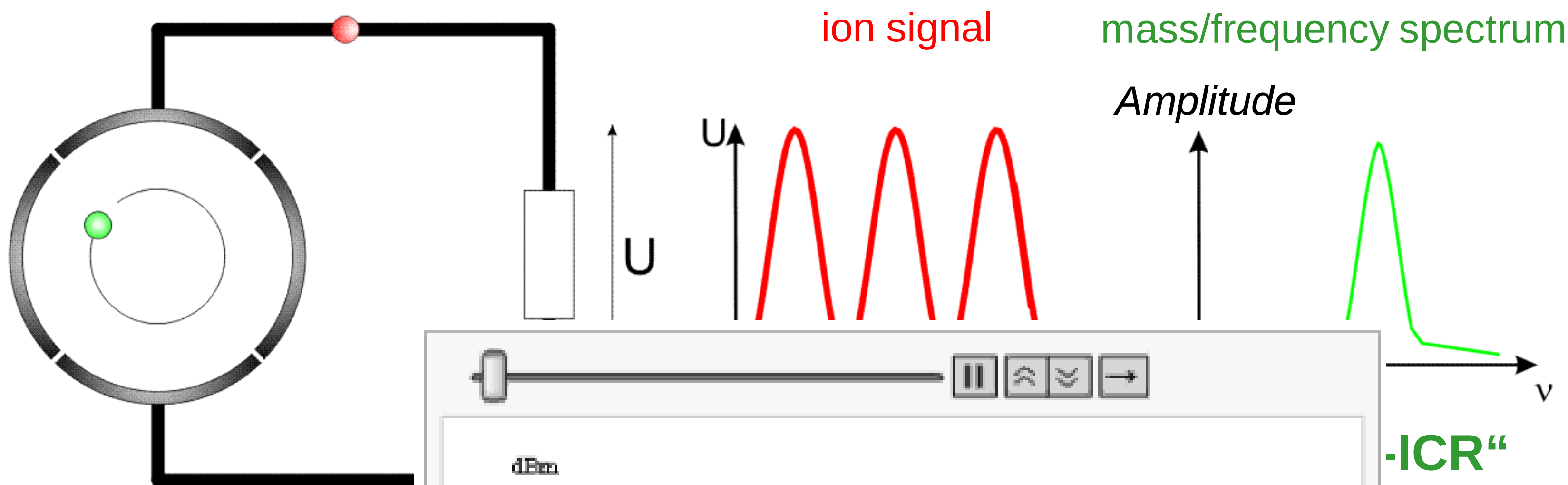
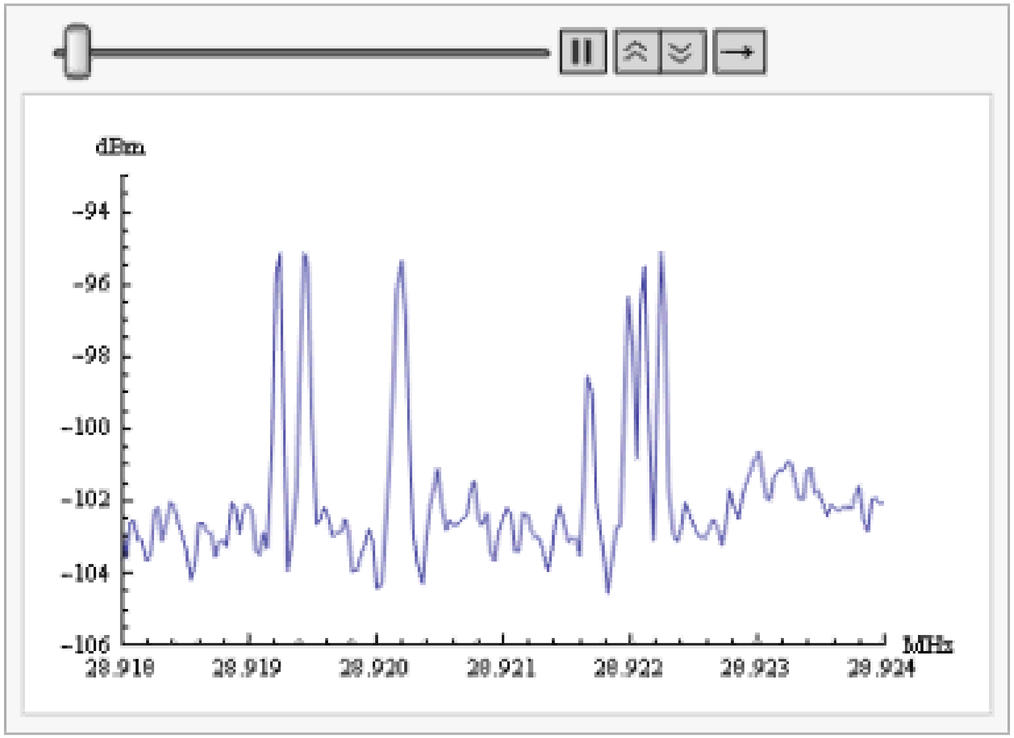
Non-destructive ion detection





-ICR“
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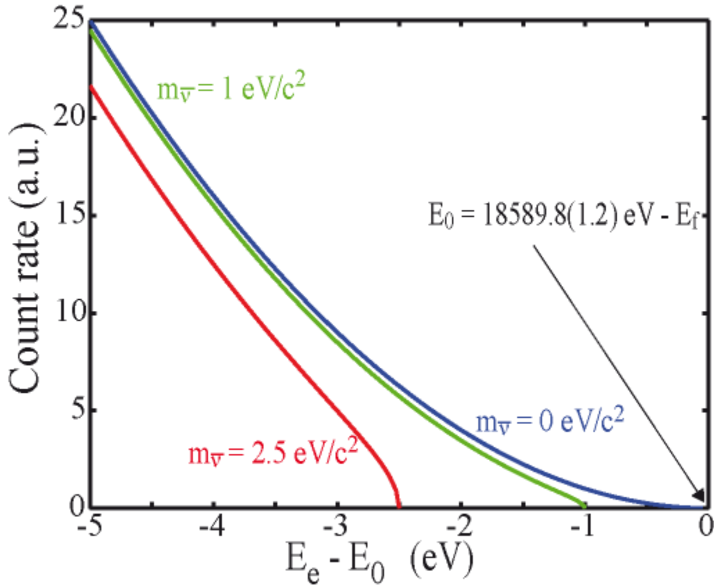
n Resonance

THe-TRAP for KATRIN

A high-precision $Q(^3T-^3He)$-value measurement



$${}^3_1H \rightarrow {}^3_2He + e^- + \bar{\nu}$$

Q_{lit} =18 589.8 (1.2) eV

Q_{lit} =18 592.01(7) eV [E. Myers, PRL (2015)]

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

$\Delta T < 0.2$ K/d at 24°C

$\Delta B/B < 100$ ppt / h $\Delta x \leq 0.1\ \mu m$

First $^{12}C^{4+}/^{16}O^{6+}$ mass ratio measurement at $\delta m/m = 1.4 \cdot 10^{-11}$ performed.

Most stringent baryonic CPT test

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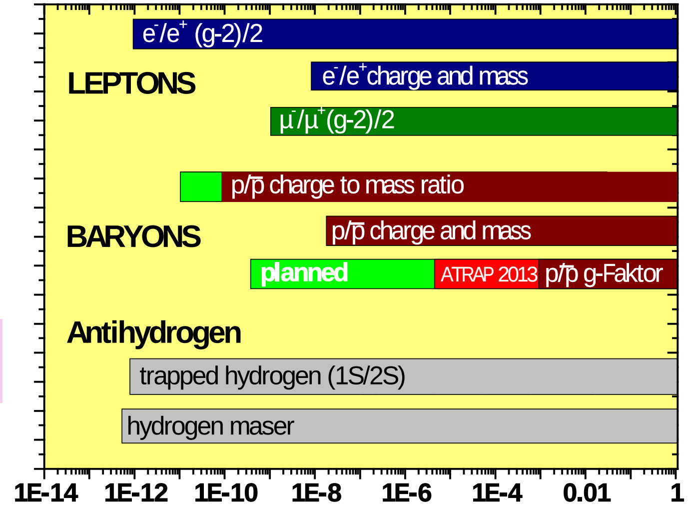
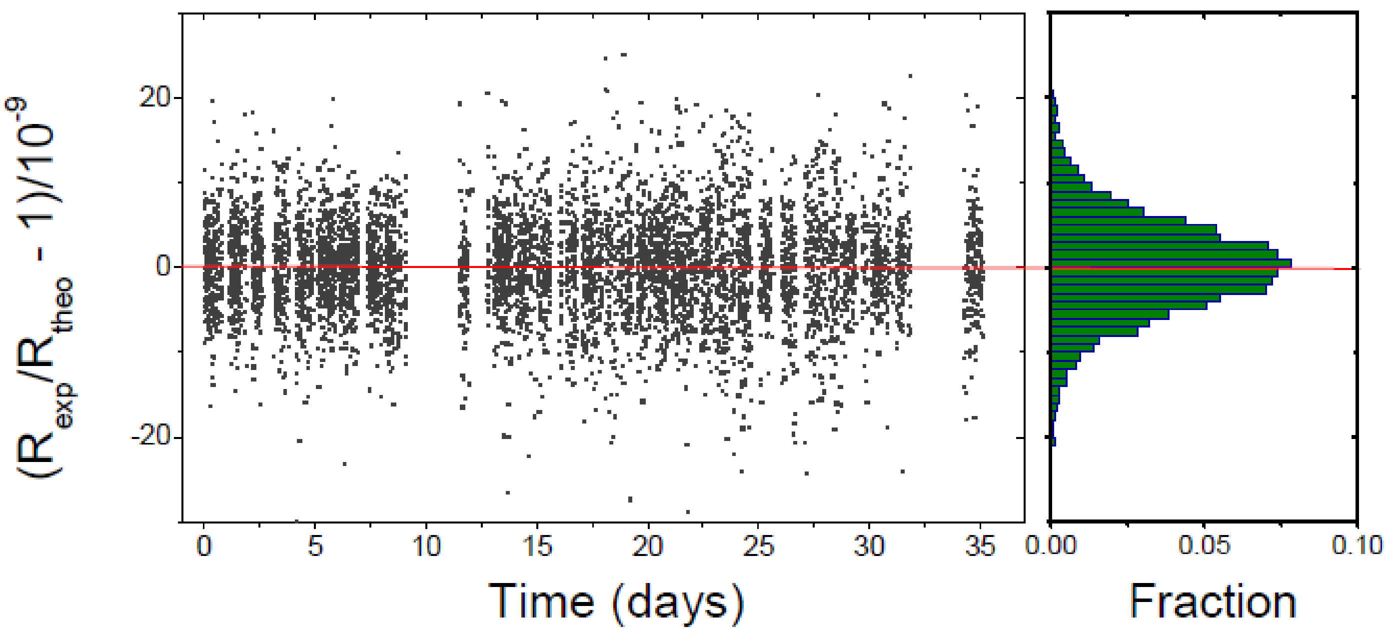


Compare charge-to-mass ratios *R* of p and $\bar{p}$:

$$(q/m)_{\bar{p}} / (q/m)_p = 1.000\,000\,000\,001\,(69)$$

S. Ulmer *et al.*, Nature 524, 196 (2015)



Summary

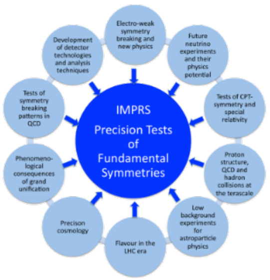
Exciting results in high-precision mass spectrometry with stored and cooled exotic ions have been achieved!

Thank you for the invitation and your attention!

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

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

Max Planck Society



IMPRS-PTFS

Adv. Grant MEFUCO

Helmholtz Alliance