Neutron Star Mergers: Hirschegg 2017

Precision mass measurements for nuclear astrophysics and neutrino physics studies

- Basics of Penning-trap mass spectrometry
- Precision atomic/nuclear masses
- Astro- and neutrino physics studies

Max Planck Institute for Nuclear Physics

Max-Planck-Institut für Kernphysik

EMMI

Klaus Blaum

Jan 18th, 2017

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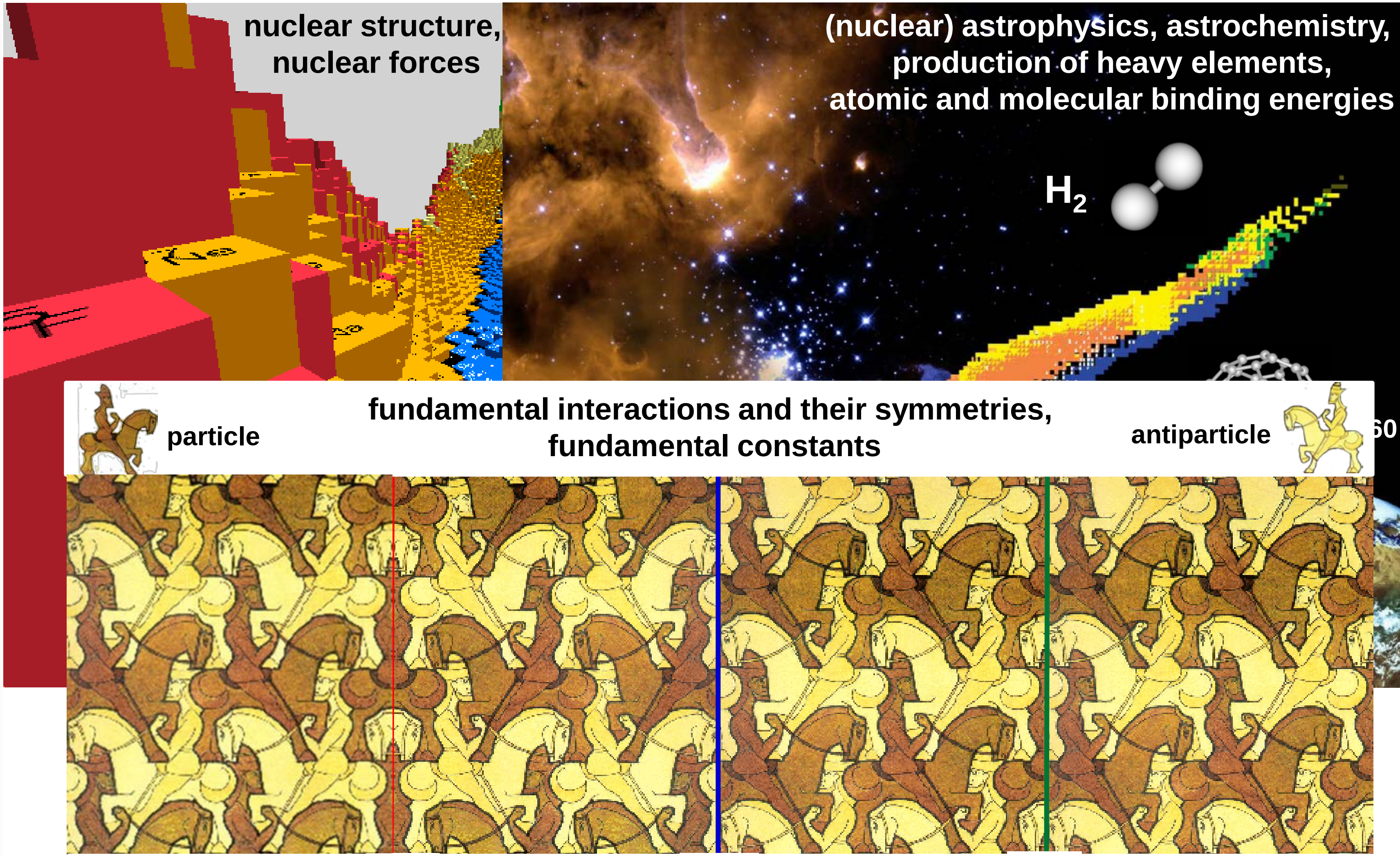
Klaus.blaum@mpi-hd.mpg.de

Fields of applications



P **C** **T**

Adapted from H. Wilschut

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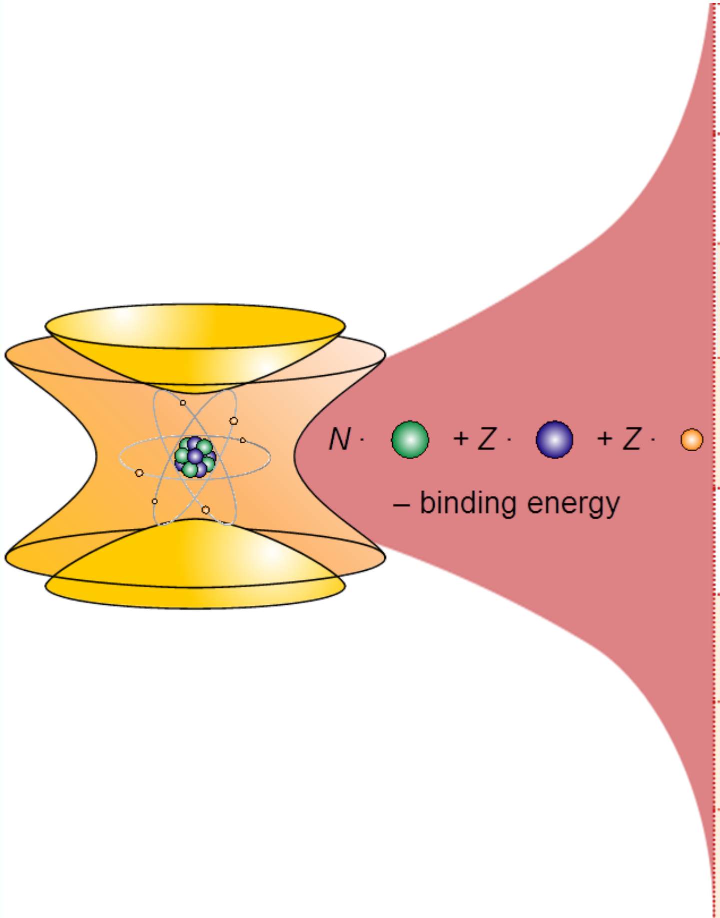
Why measuring atomic masses?

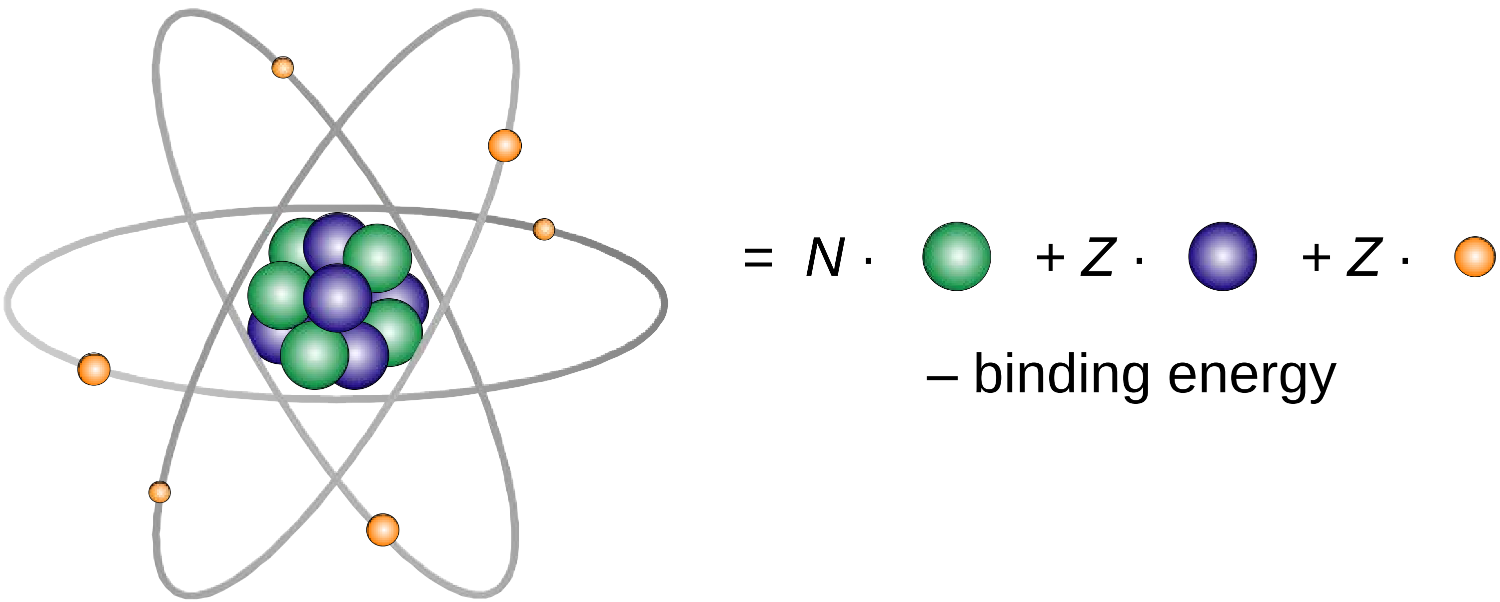


	$\delta m/m$	δE
General physics & chemistry	$\leq 10^{-5}$	1 MeV
Nuclear structure physics - separation of isobars	$\leq 10^{-6}$	100 keV
Astrophysics - separation of isomers	$\leq 10^{-7}$	10 keV
Weak interaction studies	$\leq 10^{-9}$	100 eV
Metrology - fundamental constants Neutrino physics	$\leq 10^{-10}$	eV-meV
CPT tests	$\leq 10^{-11}$	meV
QED in highly-charged ions - separation of atomic states	$\leq 10^{-11}$	eV-meV

Relative mass precision of 10^{-9} and below can presently ONLY be reached by Penning-trap mass spectrometry.

Atomic and nuclear masses

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

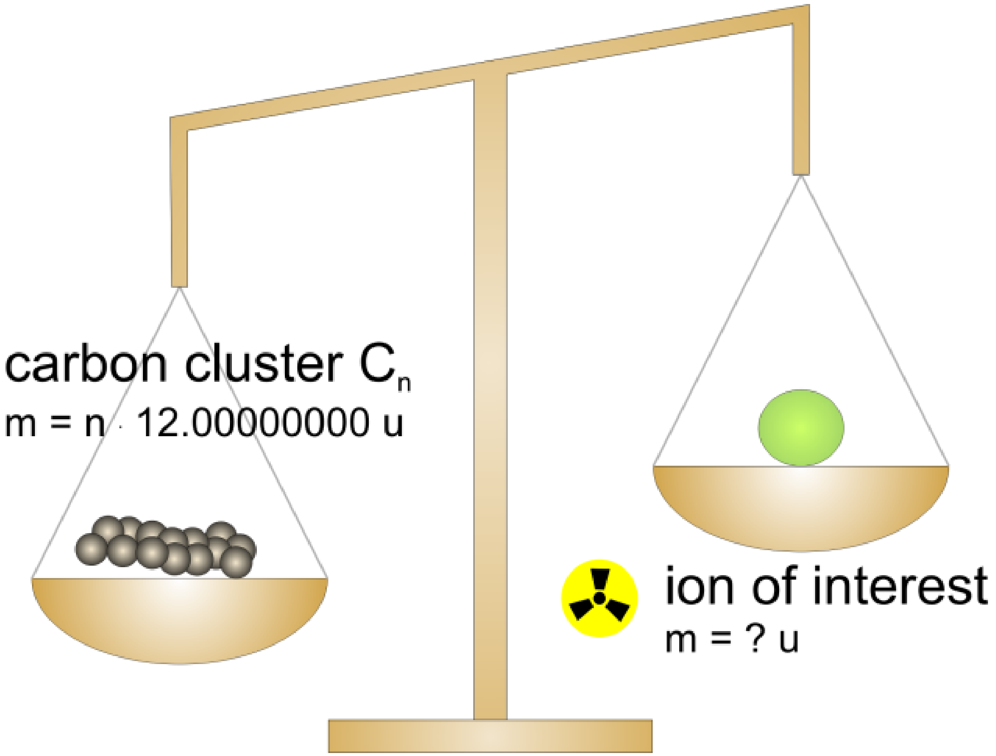


$$M_{\mathrm{Atom}} = N \bullet m_{\mathrm{neutron}} + Z \bullet m_{\mathrm{proton}} + Z \bullet m_{\mathrm{electron}} - (B_{\mathrm{atom}} + B_{\mathrm{nucleus}})/c^2$$

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

$\delta m/m = 10^{-6} - 10^{-8}$

How to weigh an atom



$\nu_{c,1}$ $\qquad$ $\nu_{c,2}$ $\Rightarrow$ $\dfrac{\nu_{c,1}}{\nu_{c,2}}$

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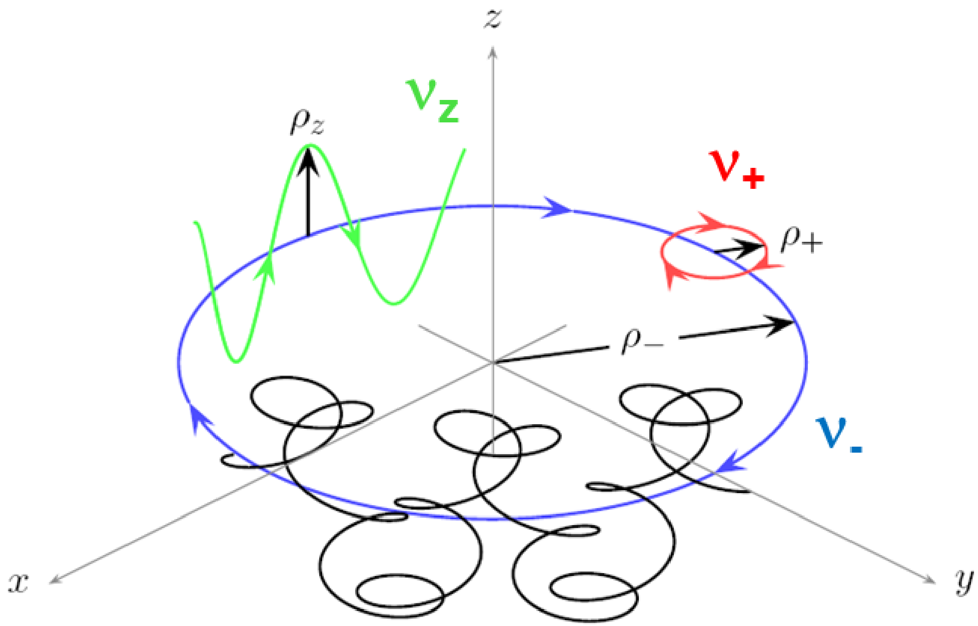
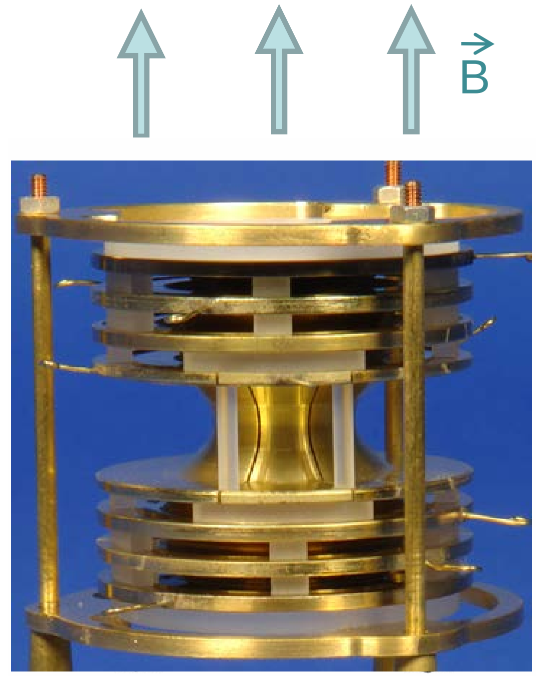
Storage of ions in a Penning trap





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

$$\omega_c = qB/m$$

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

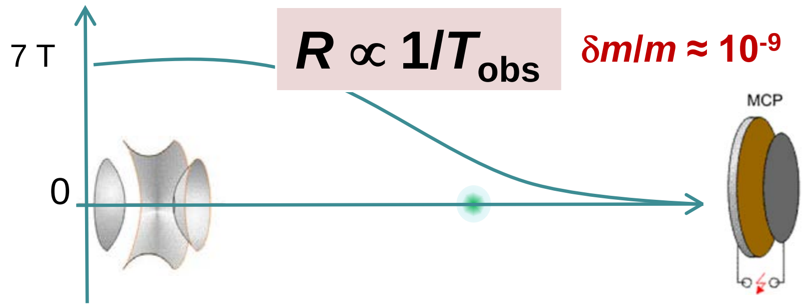
$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

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

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

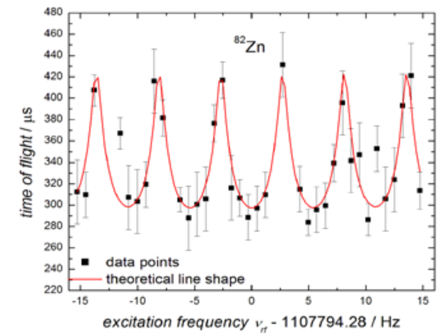
Detection techniques

Destructive time-of-Flight detection

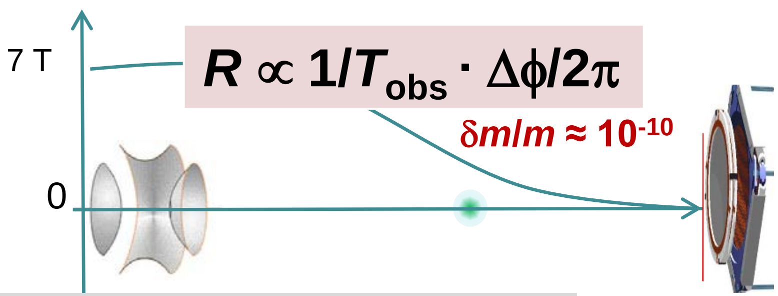


$R \propto 1/T_{obs}$

$\delta m/m \approx 10^{-9}$

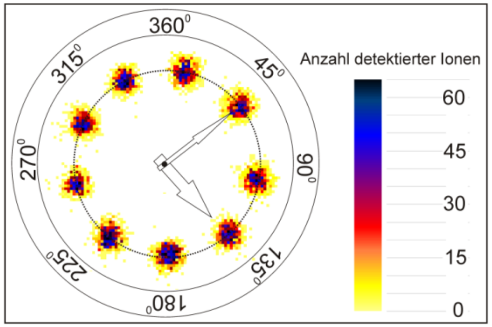


Destructive phase-imaging detection



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

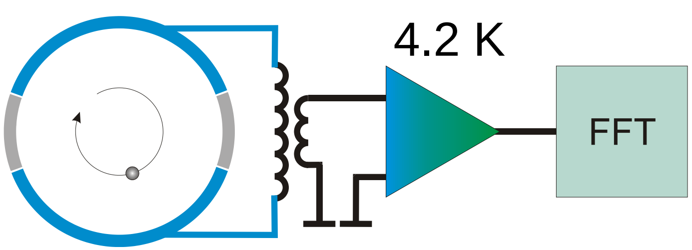
$\delta m/m \approx 10^{-10}$

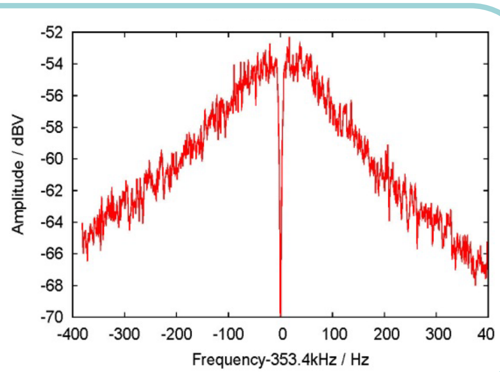


S. Eliseev *et al.*, Phys. Rev. Lett. 110, 082501 (2013)

$\delta m/m \approx 10^{-11}$

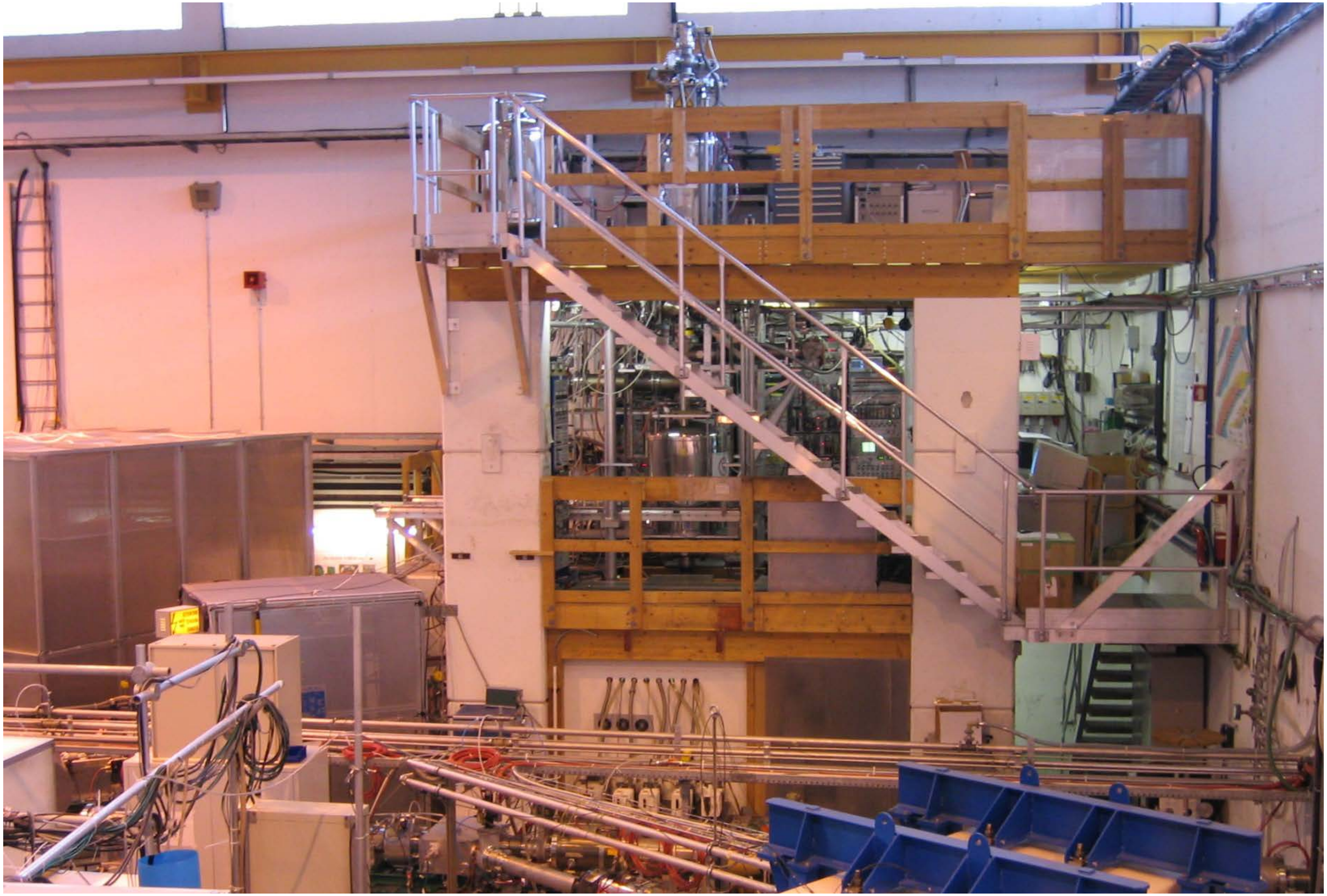
Non-destructive induced image current detection



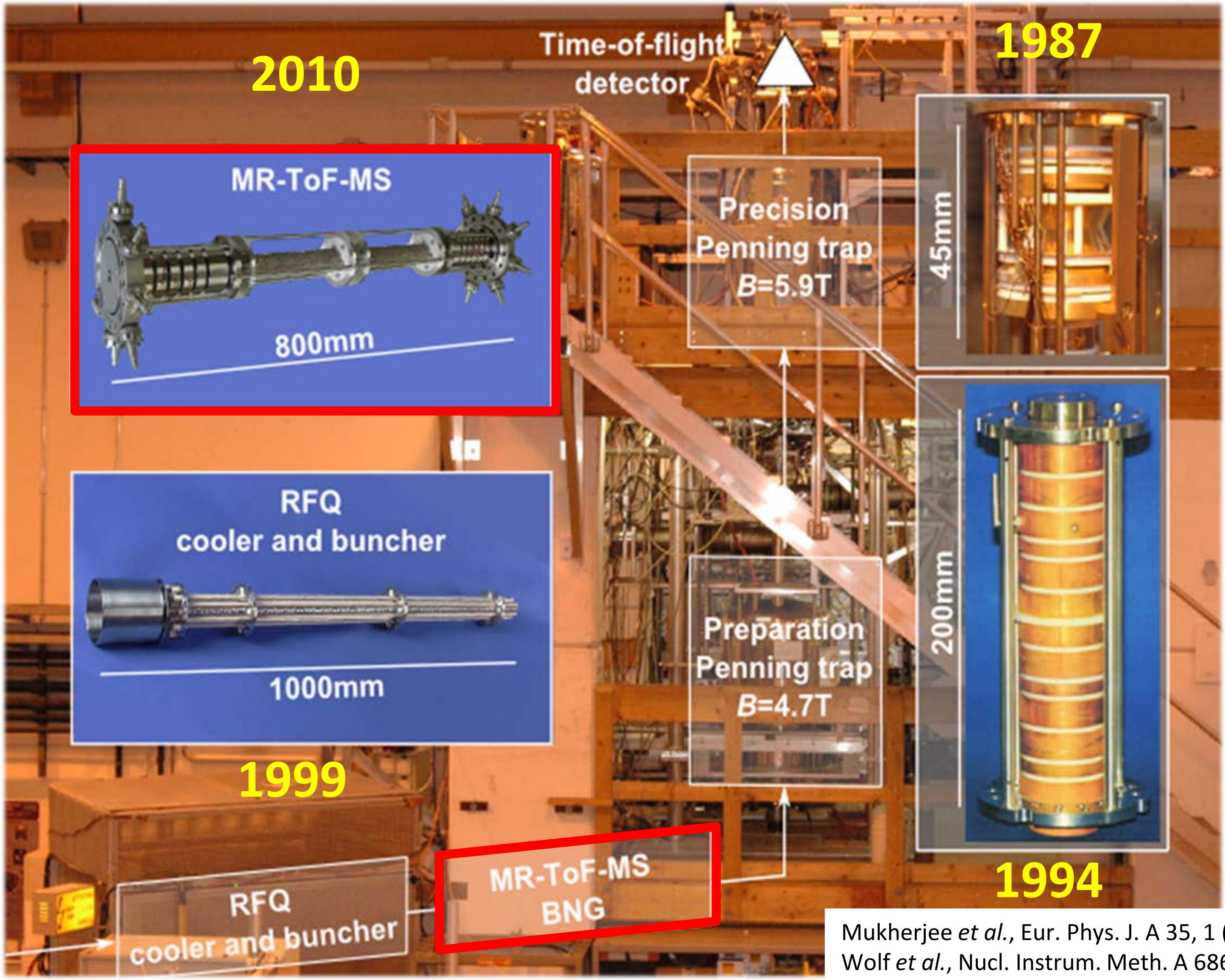


S. Sturm *et al.*, Phys. Rev. Lett. 107, 143003 (2011)

ISOLTRAP: A Penning-trap setup at CERN



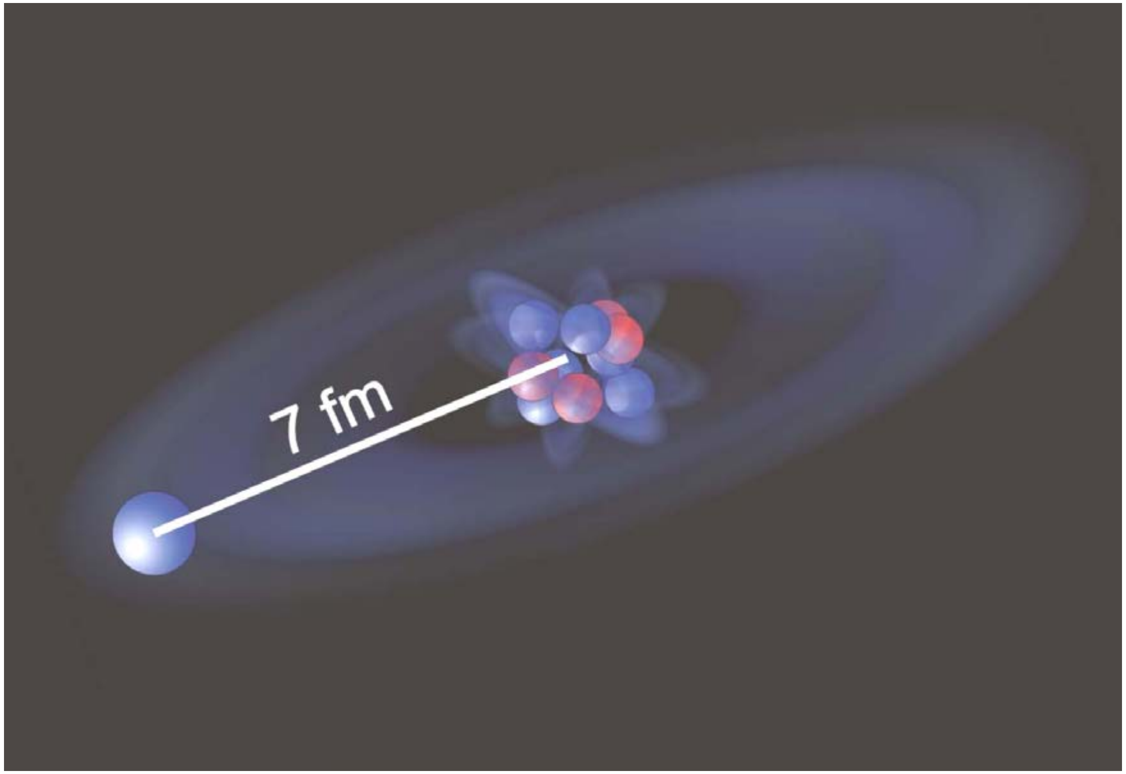
The ISOLTRAP mass spectrometer



Mukherjee *et al.*, Eur. Phys. J. A 35, 1 (2008)
Wolf *et al.*, Nucl. Instrum. Meth. A 686, 82 (2012)

Masses I

Nuclear magic numbers



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

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New magic number (*N*=32) and 3N-forces

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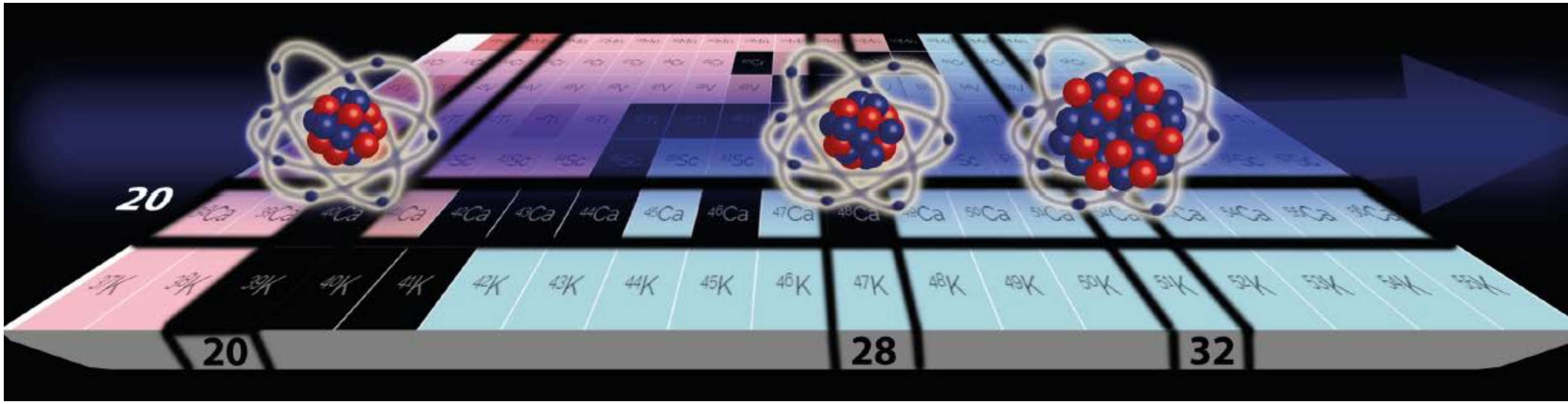
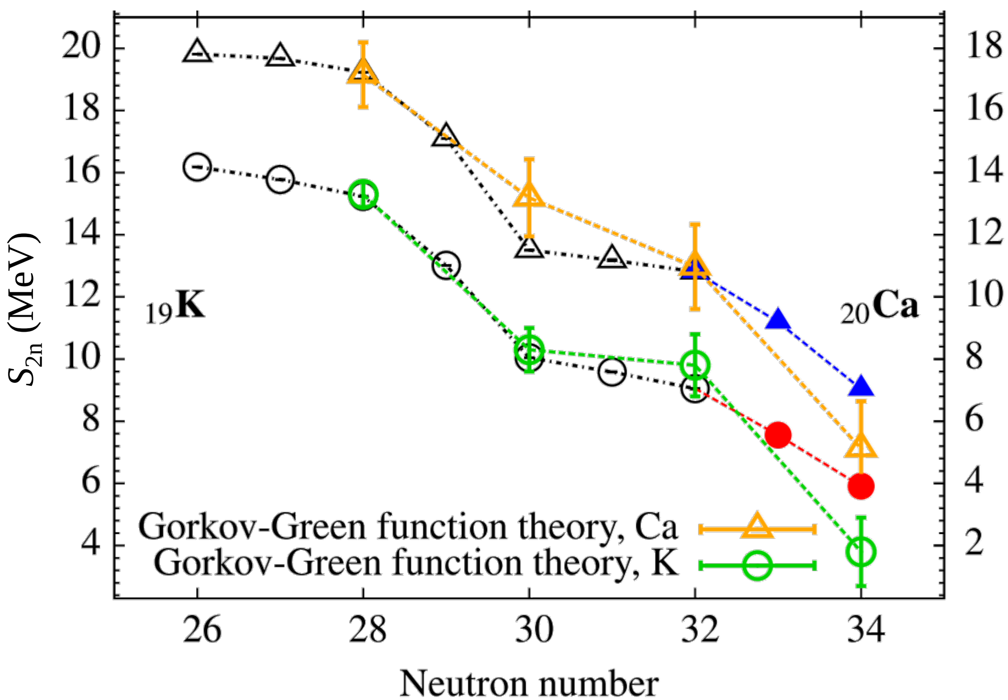
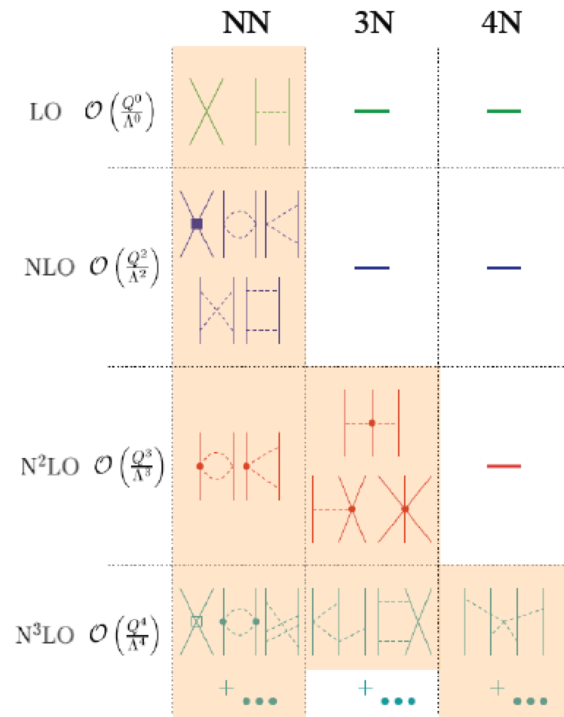
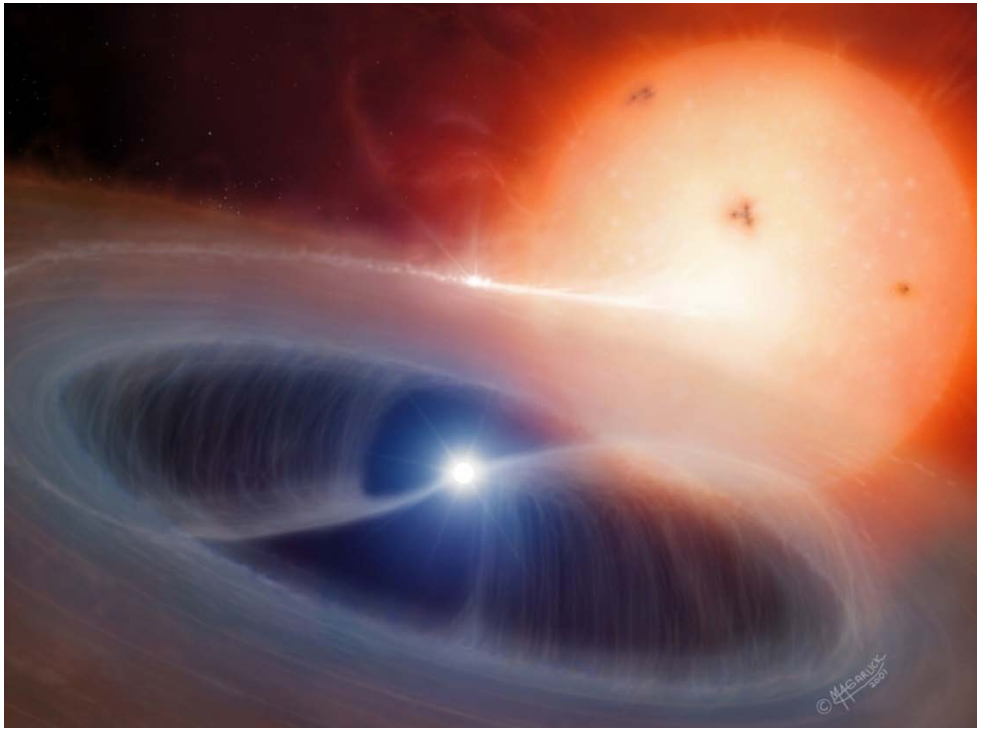






Masses II

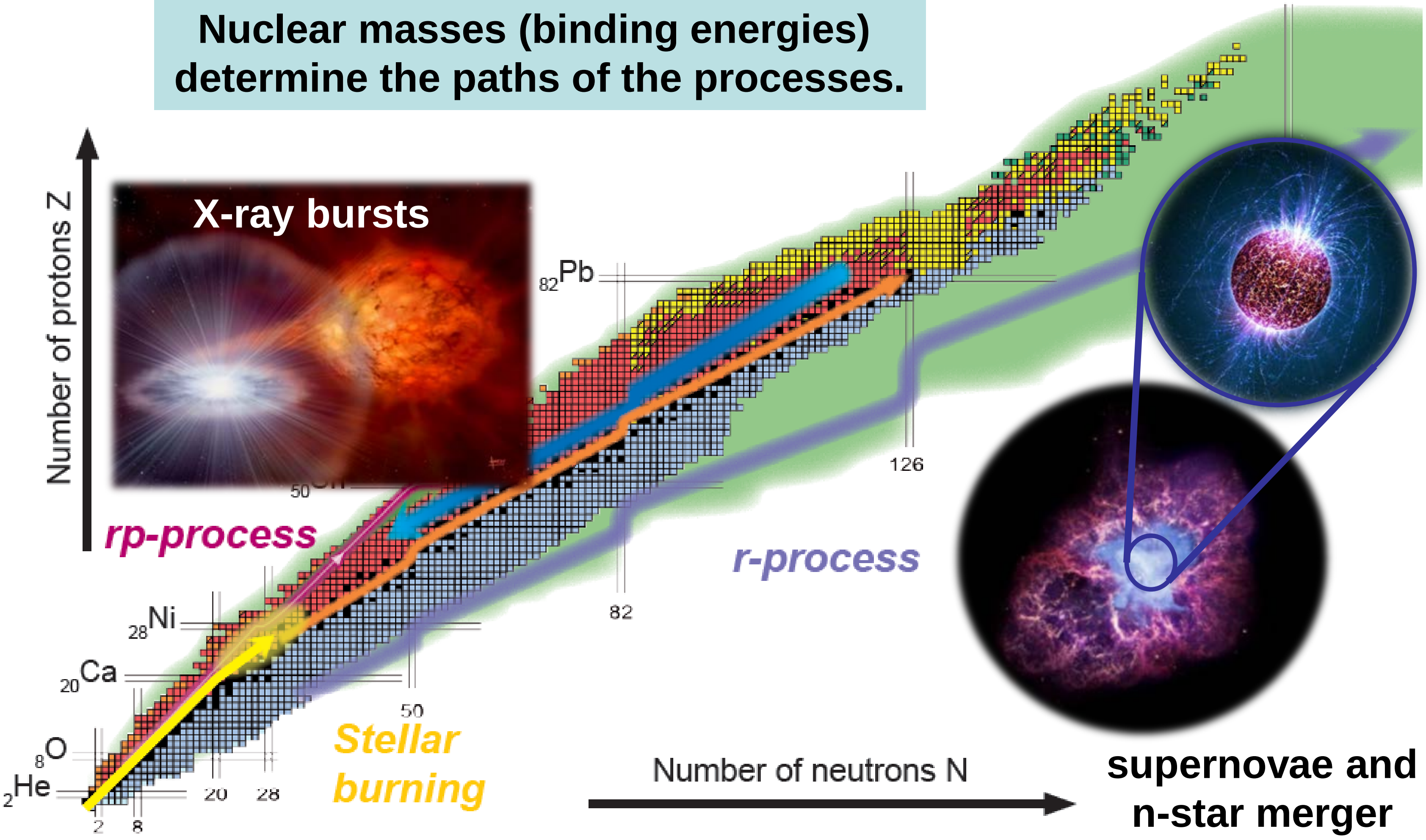
Astrophysics and nucleosynthesis



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

The nucleosynthesis paths

Nuclear masses (binding energies) determine the paths of the processes.



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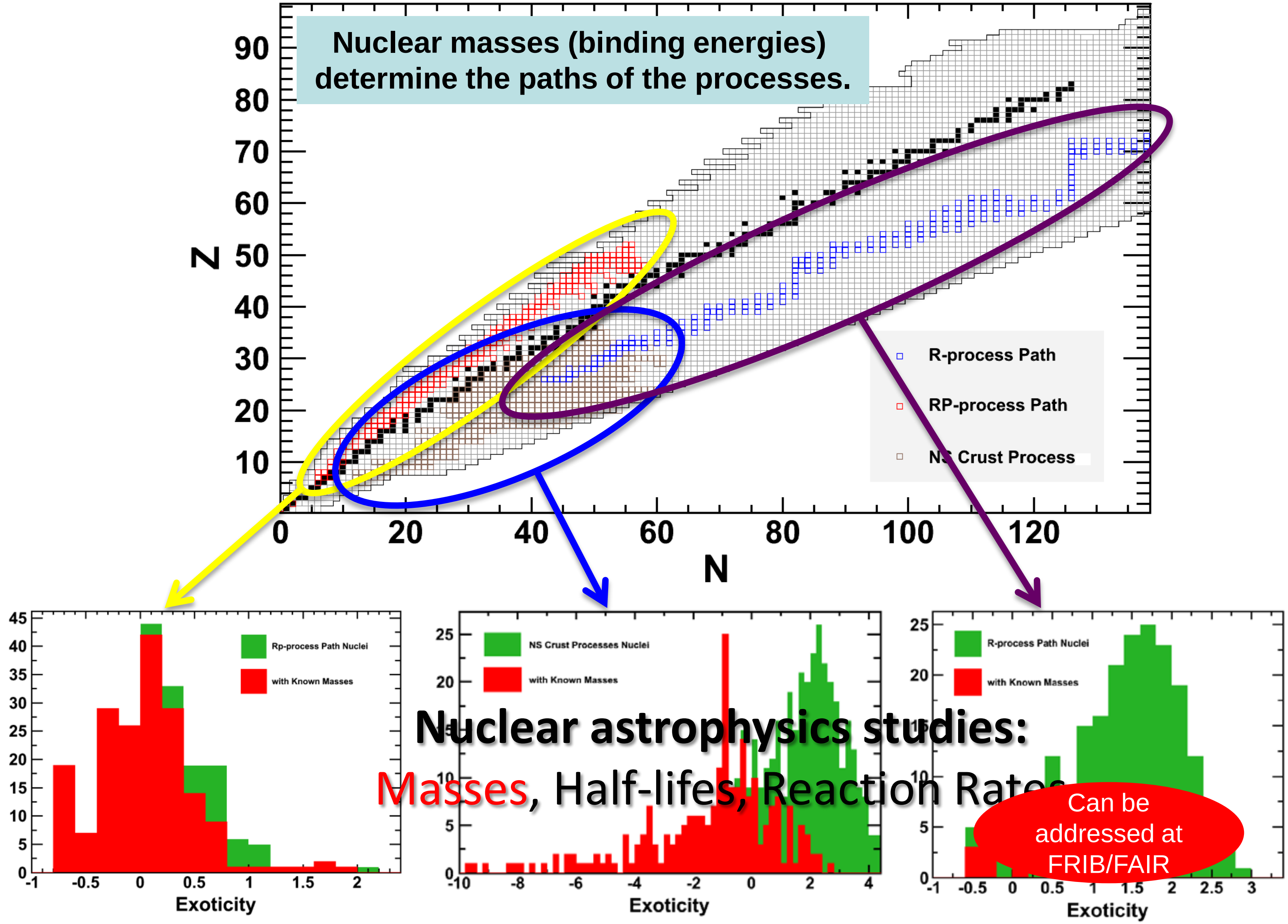
Mass spectrometry for nucleosynthesis



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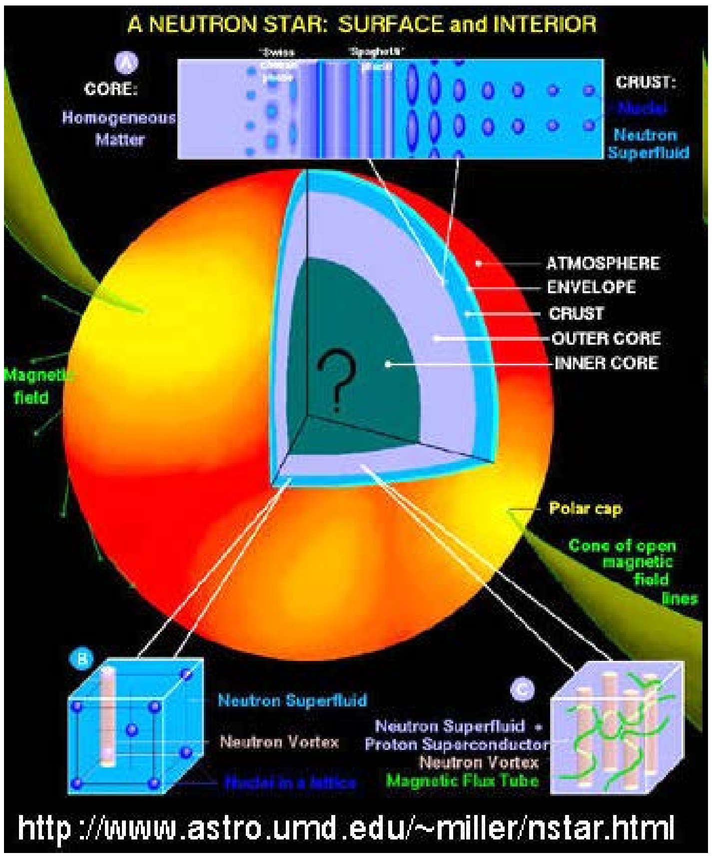
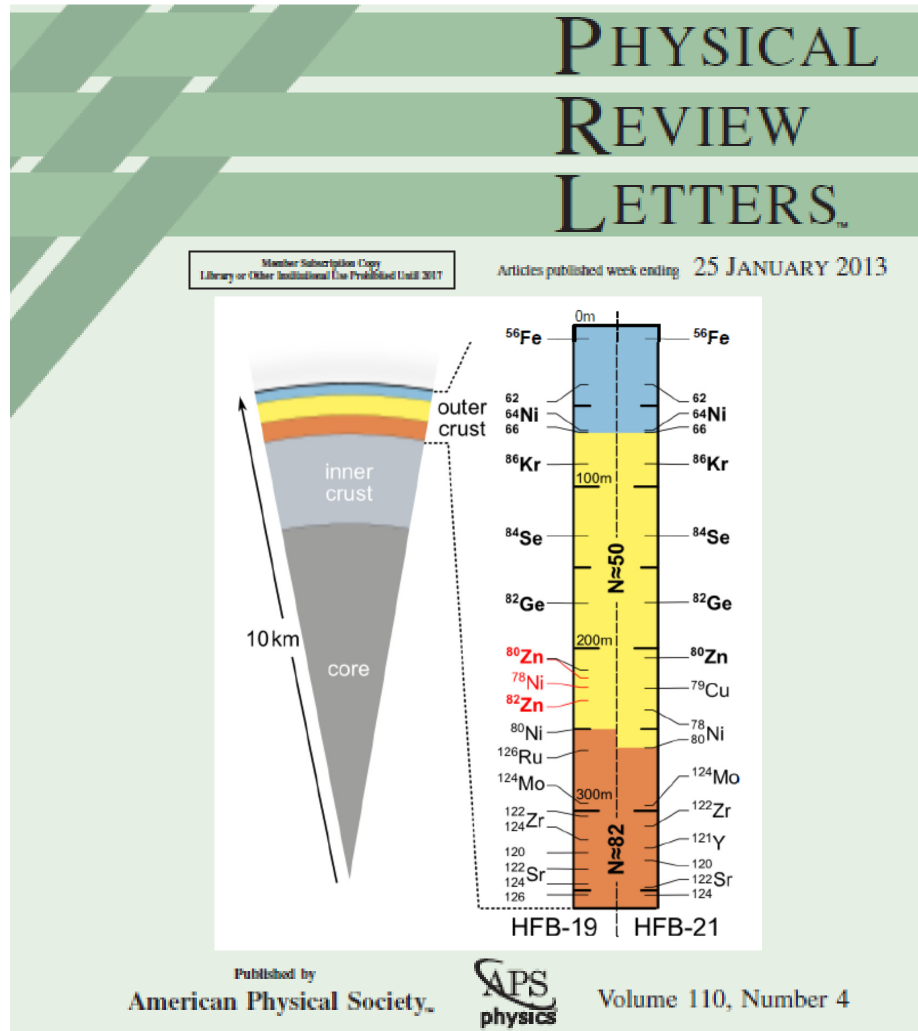
Masses for nuclear astrophysics

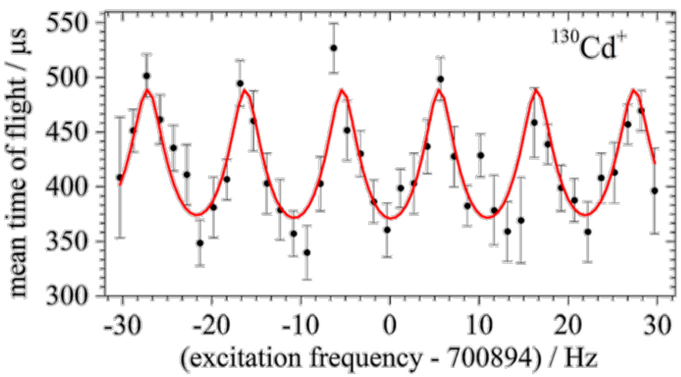
Composition of the outer crust of a neutron star

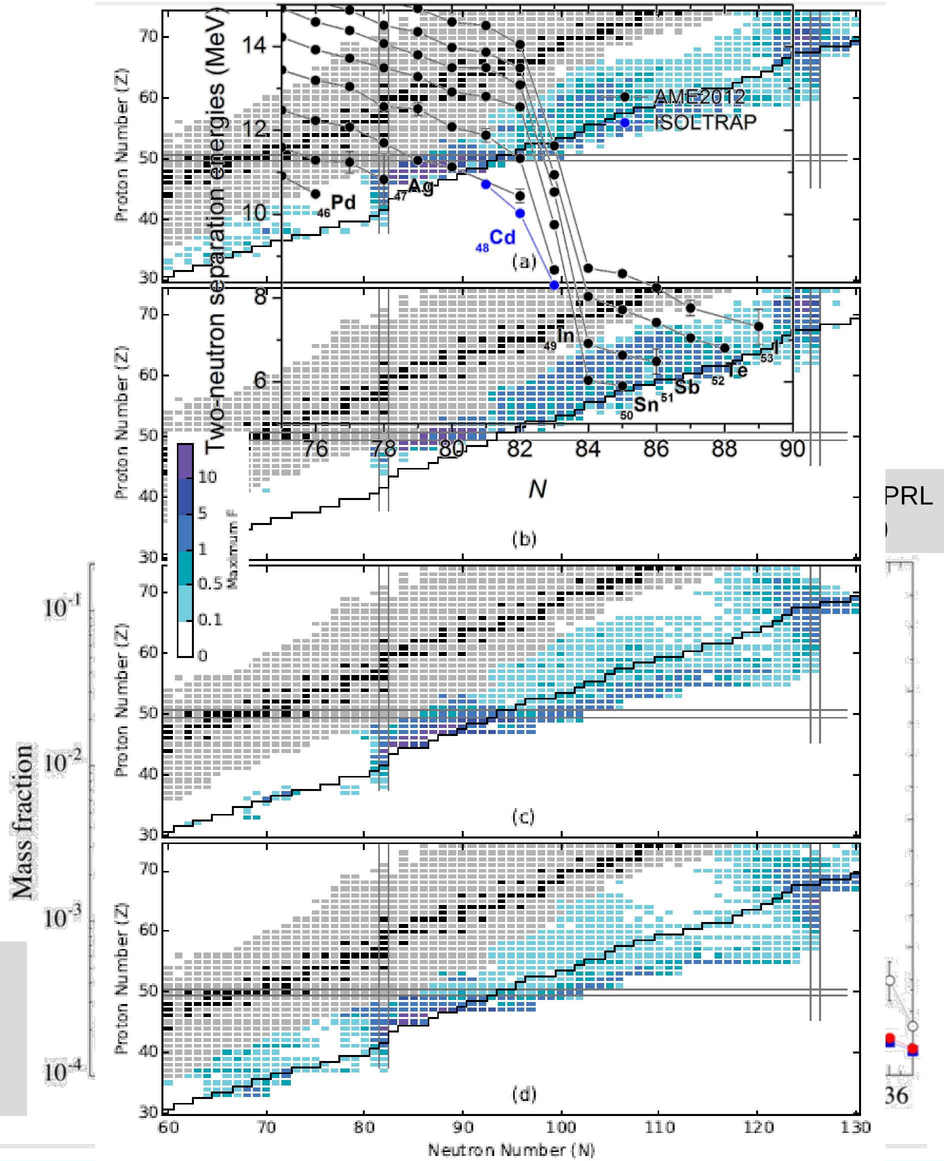




n-rich Cd masses for r-process studies

Cd	Measured with	Half life /ms	Yield /ions/uC
129	Penning trap MR-ToF-MS	(242?) (104?)	12000
130	Penning trap MR-ToF-MS	162	330
131	MR-ToF-MS	68	39





M.R. Mumpower, R. Surman, G.C. Mc-Laughlin, A. Aprahamian, *The impact of individual nuclear properties on r-process nucleosynthesis,* PPNP 86, 86-126 (2016)

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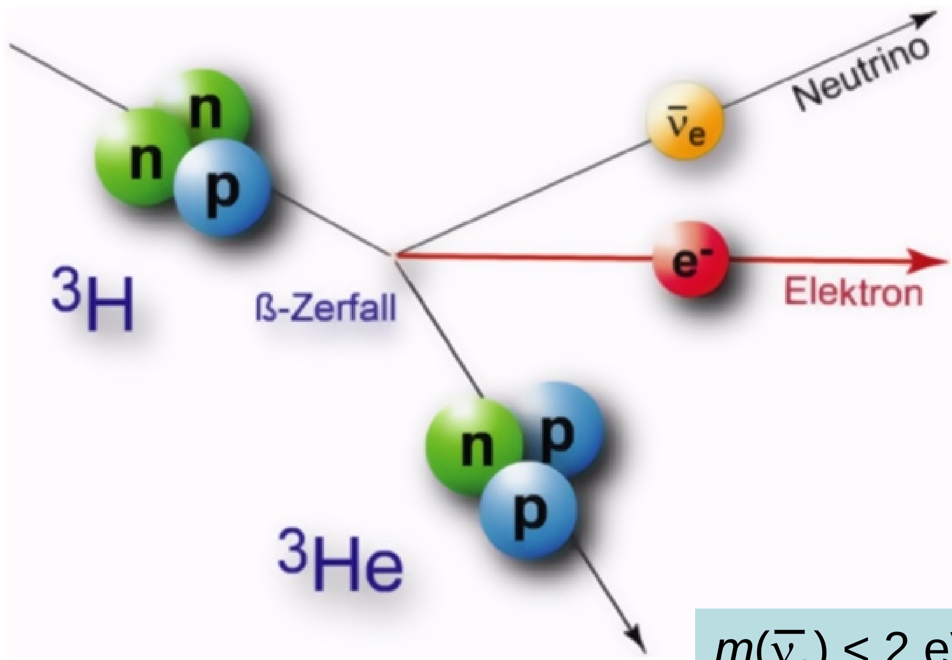
Masses III

Neutrino physics applications

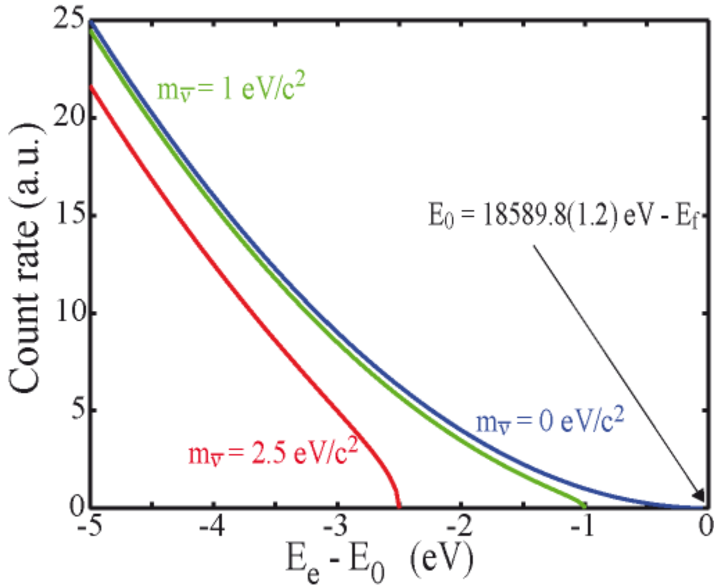


$m(\bar{\nu}_e) < 2$ eV/c^2 (95% CL)

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

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
$\delta m/m = 7\cdot10^{-12}$

$\Delta T < 0.02$ K/d at 24°C
$\Delta B/B < 10$ ppt / h $\Delta x \leq 0.1$ μm

First $^{12}C^{4+}/^{16}O^{6+}$ mass ratio measurement at $\delta m/m = 1.4\cdot10^{-11}$ performed.

The ECHo (^{163}Ho) project

$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

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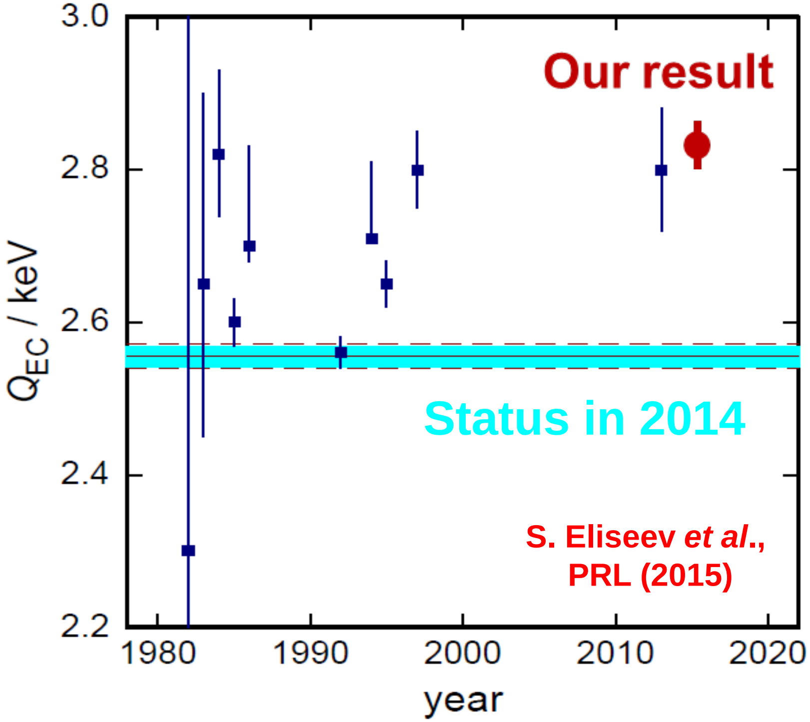
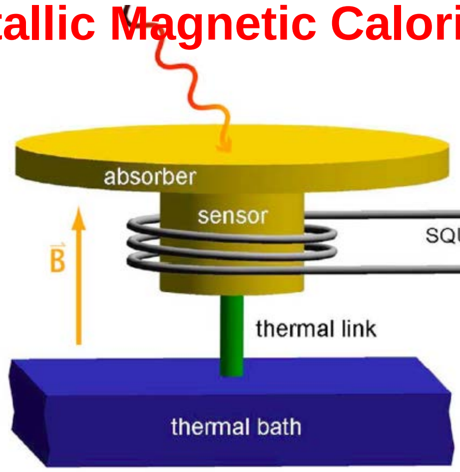
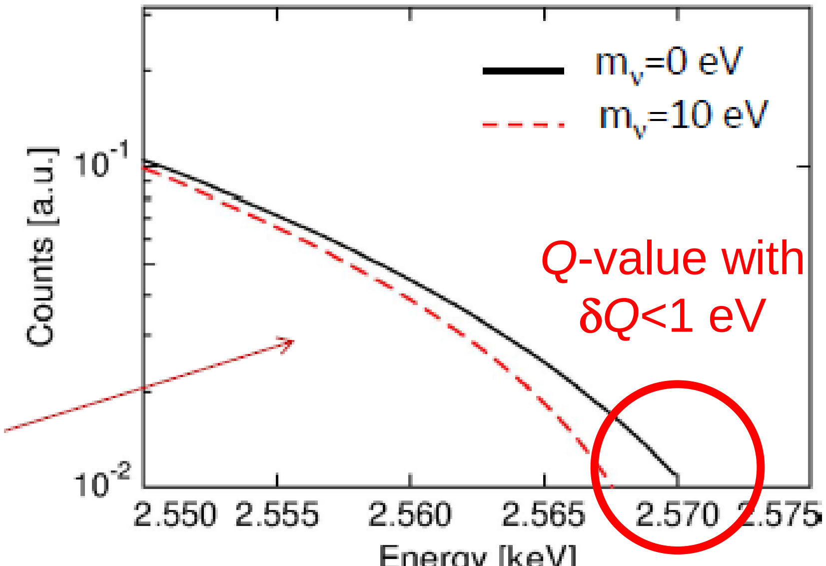
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

Q-value of EC in ^{163}Ho



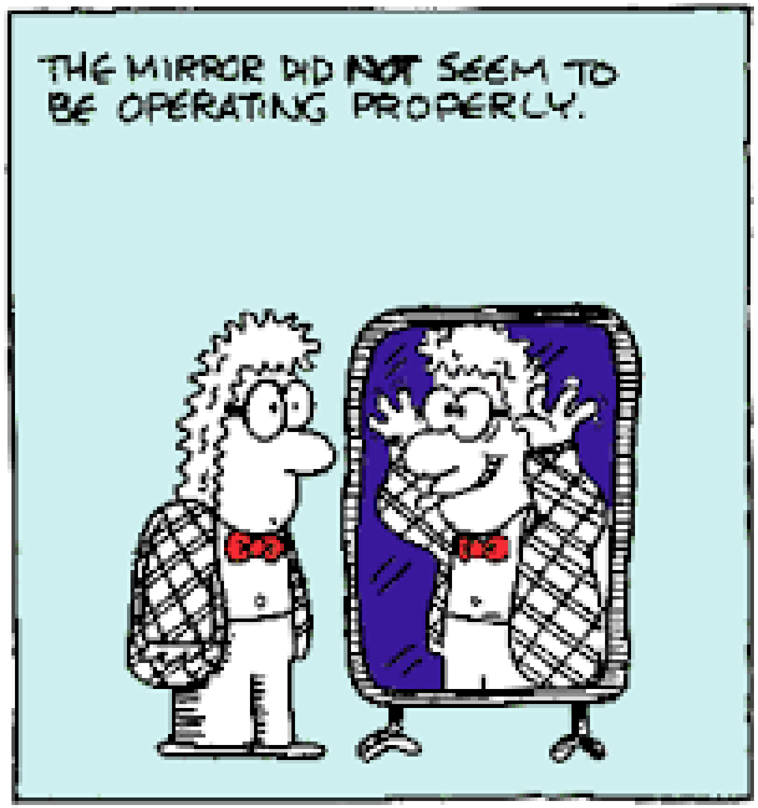
Metallic Magnetic Calorimetry





Masses IV

Test of CPT symmetry



BASE: CERN, GSI, Hannover, Mainz, MPIK, RIKEN

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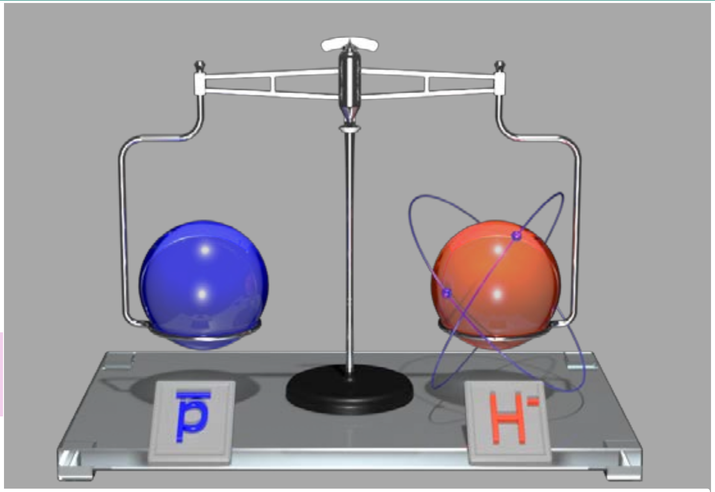
Most stringent baryonic CPT test

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

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

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



It is not that easy!

$$m_{\mathrm{H}^-} = m_p\left(1 + 2\frac{m_e}{m_p} + \frac{\alpha_{\mathrm{pol,H}^-} B_0^2}{m_p} - \frac{E_\mathrm{b}}{m_p} - \frac{E_\mathrm{a}}{m_p}\right)$$

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Thanks

Thank you all for the invitation and your attention!

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

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

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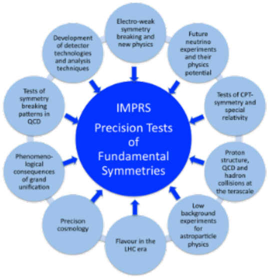

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