Max Planck Institute for Nuclear Physics

FUNTRAP, Rehovot, Israel 2012

"Precision Mass Measurements on Radioactive Ions for Nuclear Astrophysics and Fundamental Studies"

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Dec 04, 2012

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Content

	$\delta m/m$
1) Basics of Penning-trap and storage-ring mass spectrometry	
2) Nuclear astrophysics studies	≤ 10^{-7}
3) Test of the unitarity of the CKM matrix	≤ 10^{-8}
4) Nuclear masses for neutrino physics	≤ 10^{-9}

MAX-PLANCK-GESELLSCHAFT

Part I

Basics of Penning-trap and storage-ring mass spectrometry

$$E = m c^2$$

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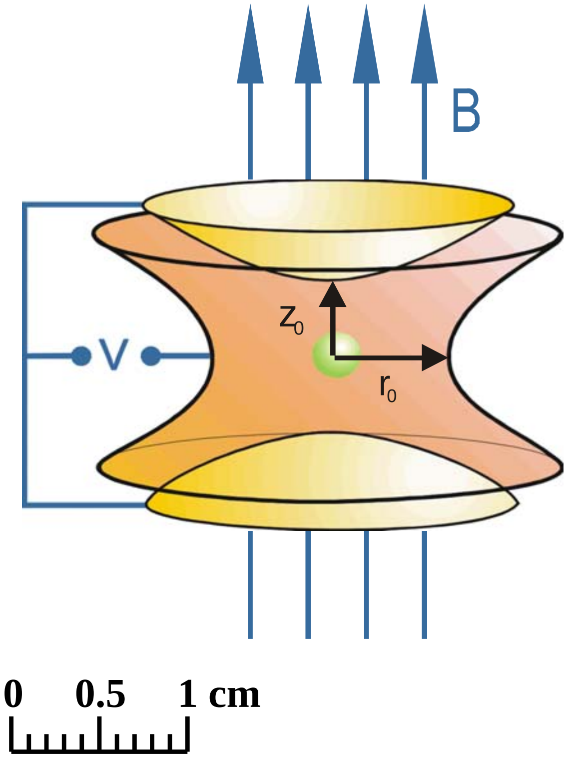
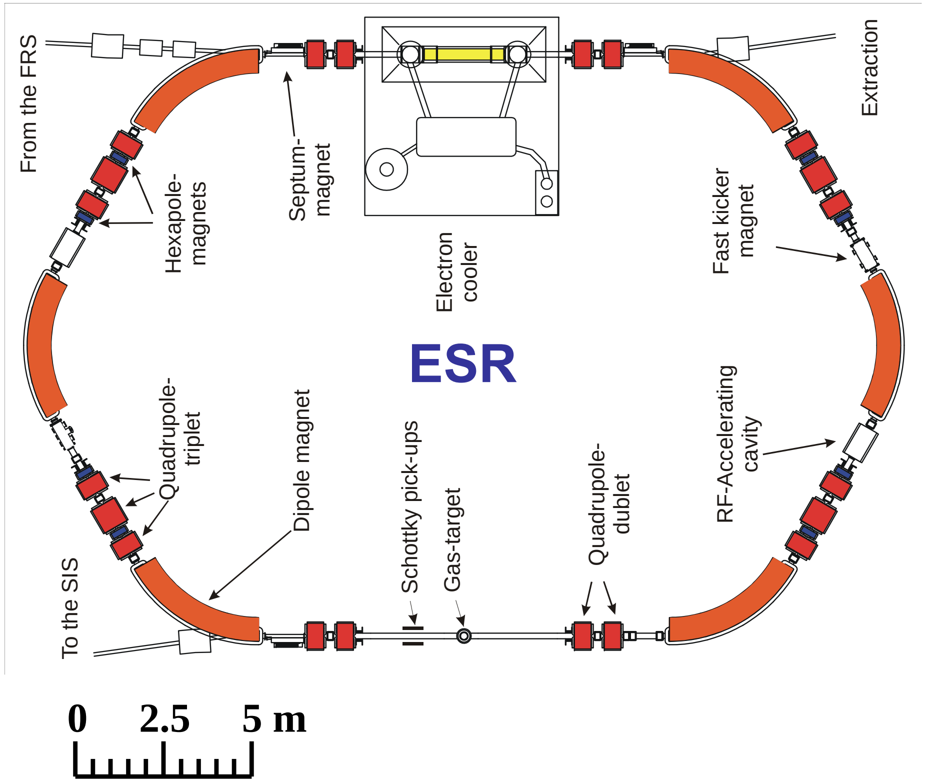
Storage and cooling techniques

Penning trap



Storage ring



particles at nearly rest in space

relativistic particles

* ion cooling
* long storage times
* single-ion sensitivity
* high accuracy

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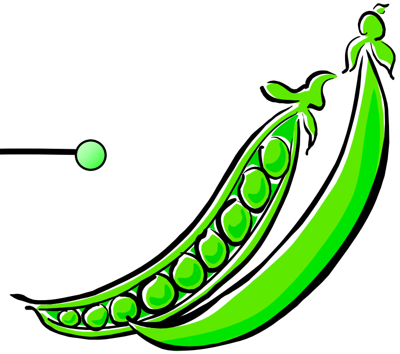
Highest accuracy

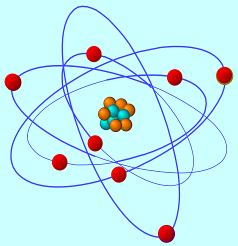


$\Delta m \approx 0.5$ g

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

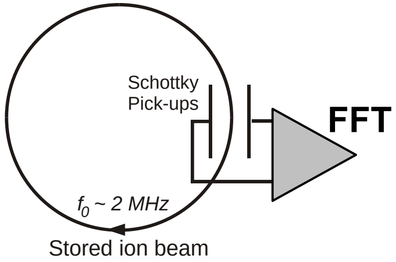
m = 516 T = 516 000 000 g $\approx 5\cdot 10^{8}$ g

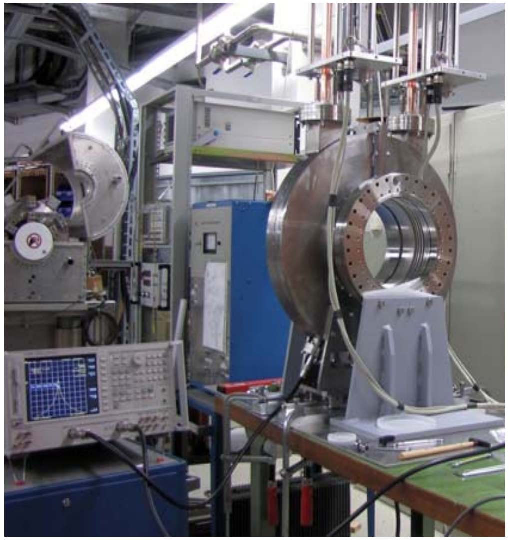
<u>However:</u> Accuracy on atomic scale and $T_{1/2}$ < 1s

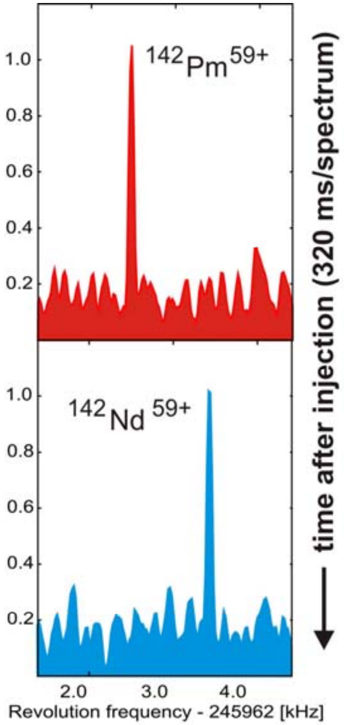


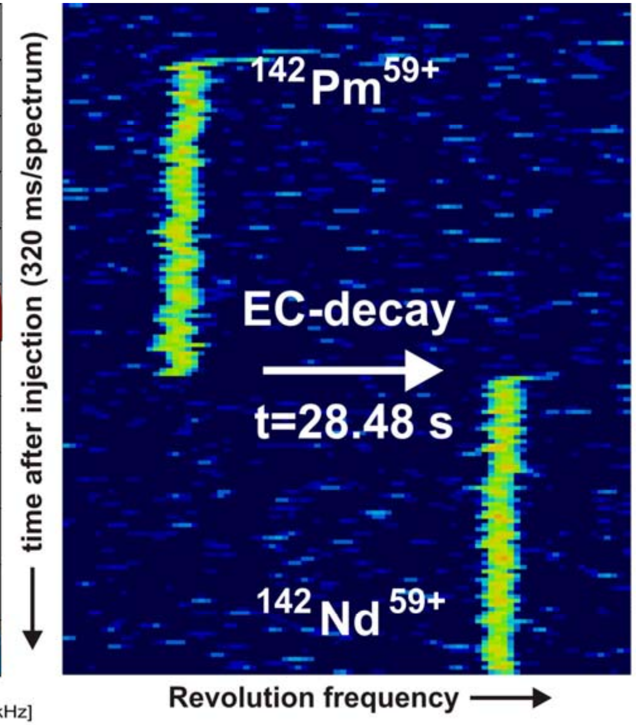
Single ion sensitivity

Schottky detection in a storage ring

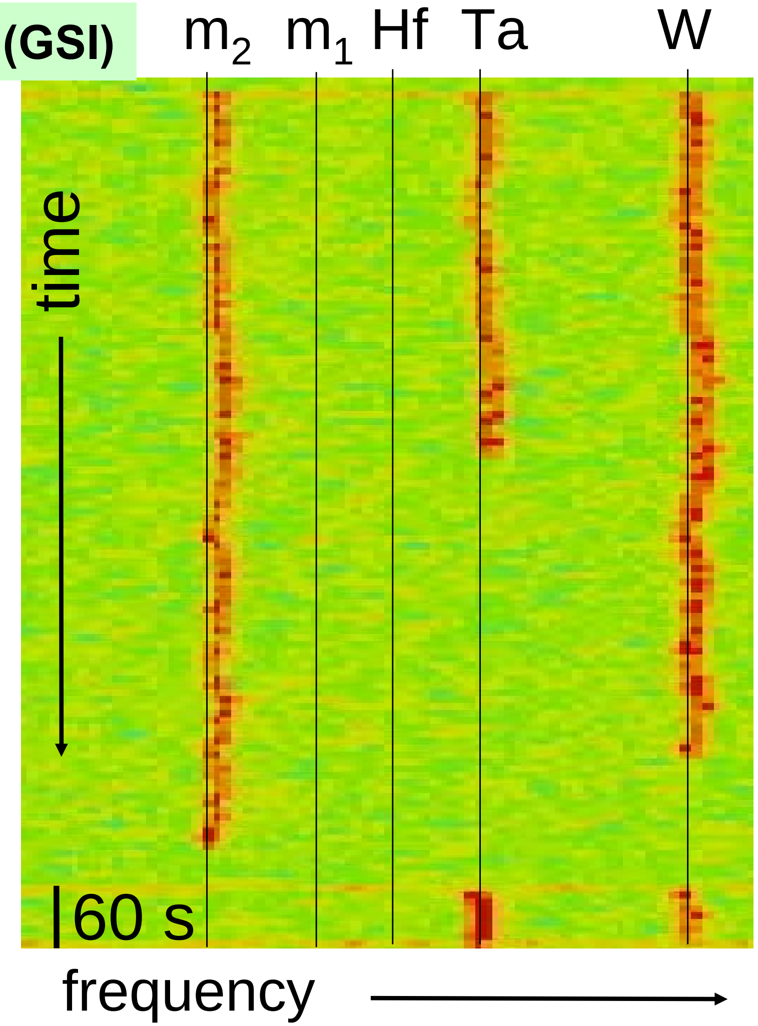








ESR (GSI)



Discovery of new isotopes and isomers.

Hf: Phys. Rev. Lett. 105 (2010) 172501

Highst resolving power

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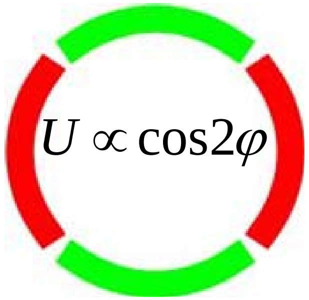
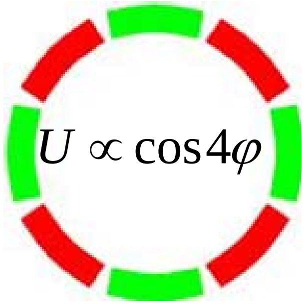
Quadrupolar excitation

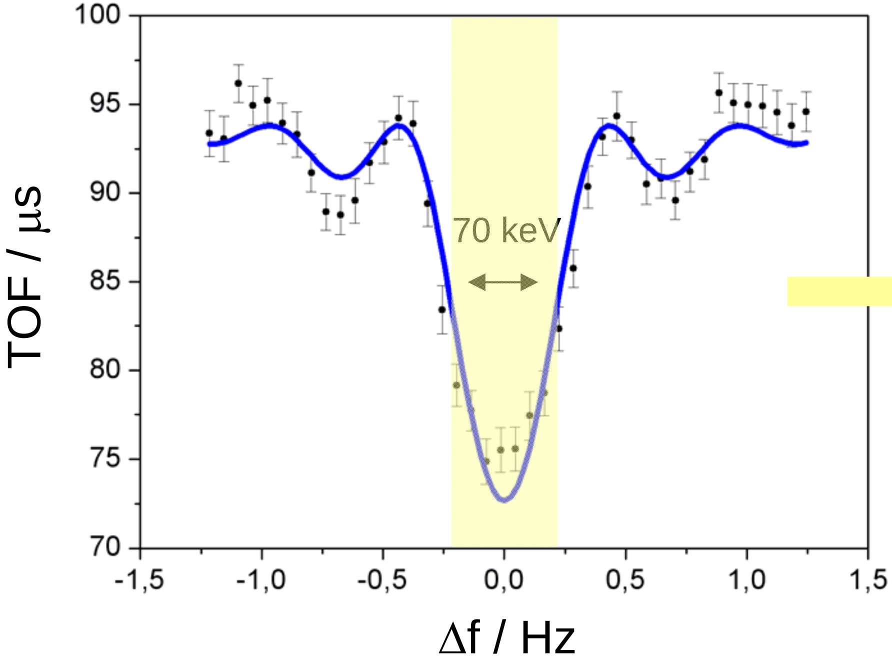


MPIK (Heidelberg)
SHIPTRAP (GSI)
LEBIT (MSU)

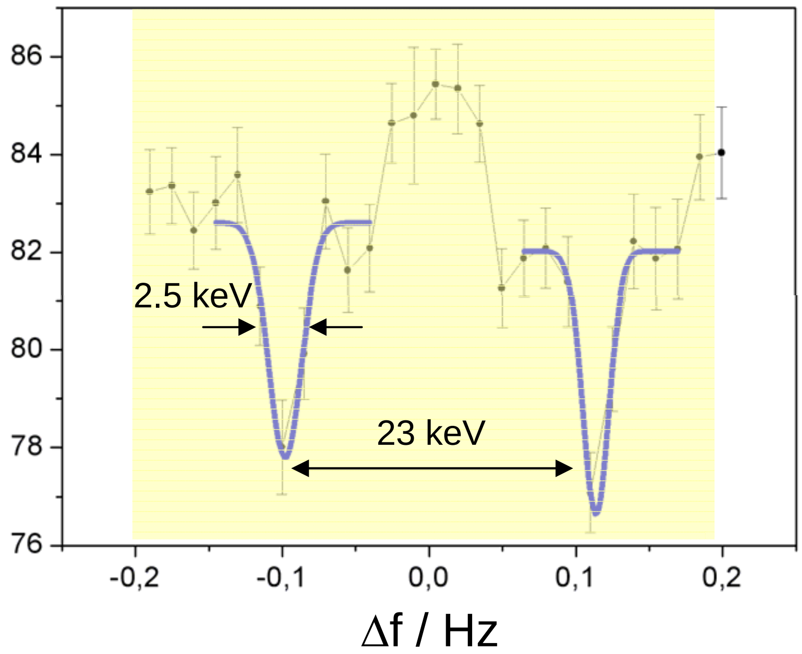


Octupolar excitation

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



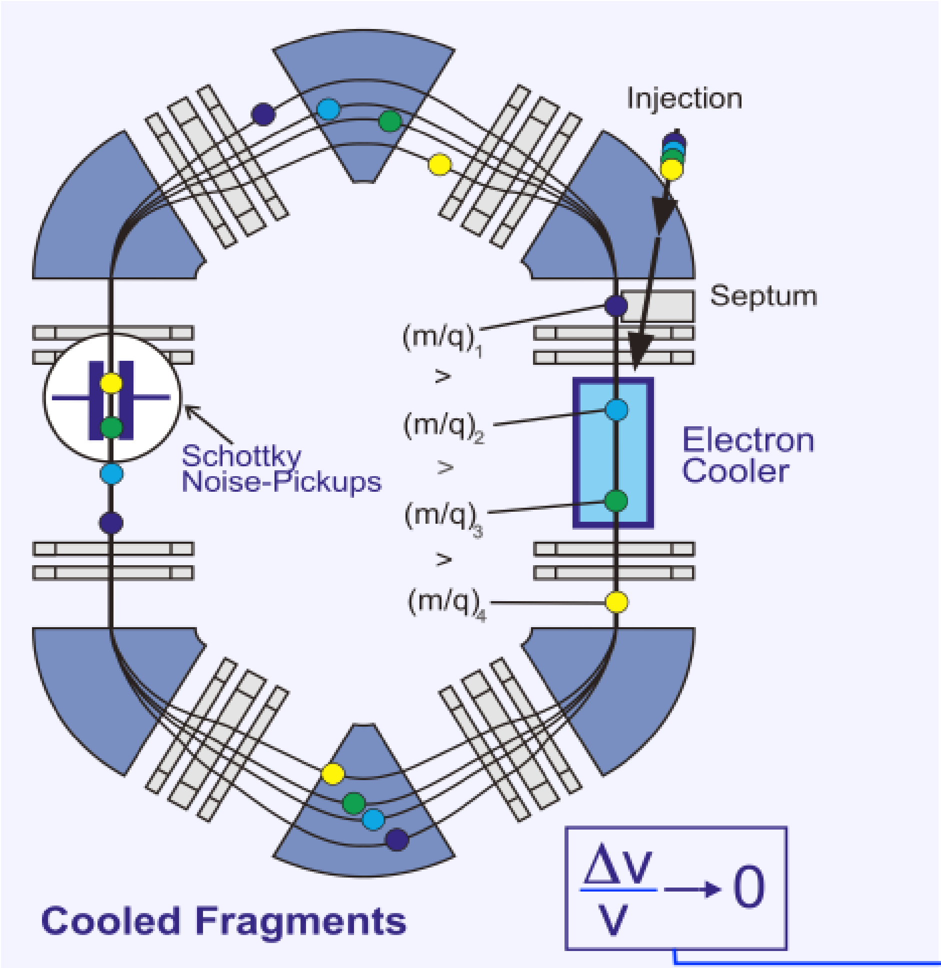
^{164}Er and ^{164}Dy are resolved



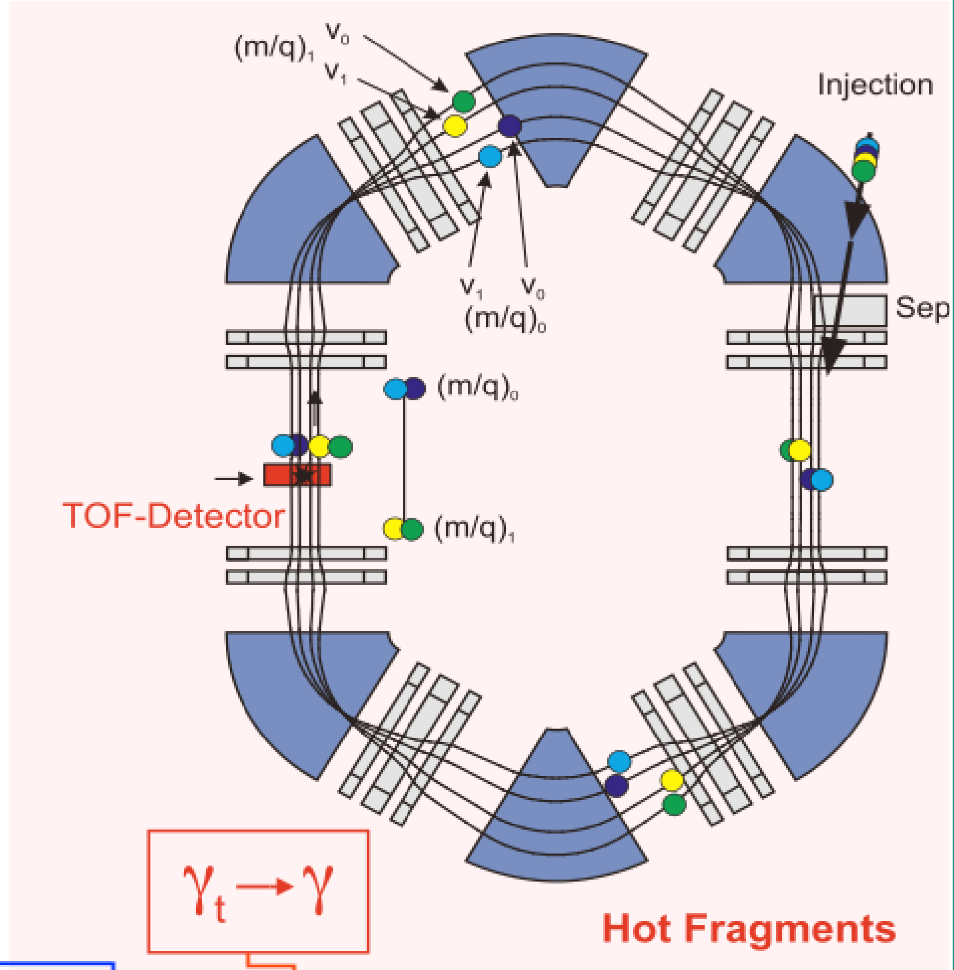
At least 20-fold improvement in resolving power!

Storage ring mass spectrometry

Schottky Mass Spectrometry



Isochronous Mass Spectrometry



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

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

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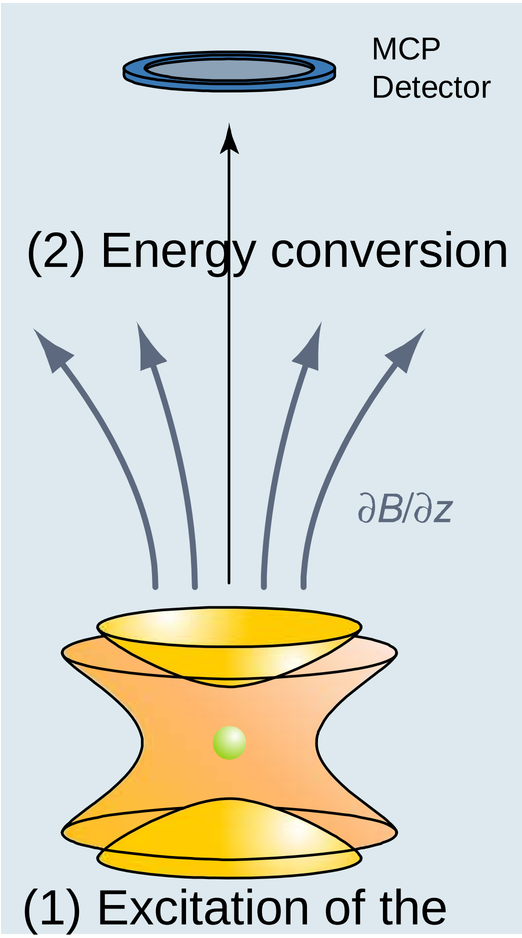
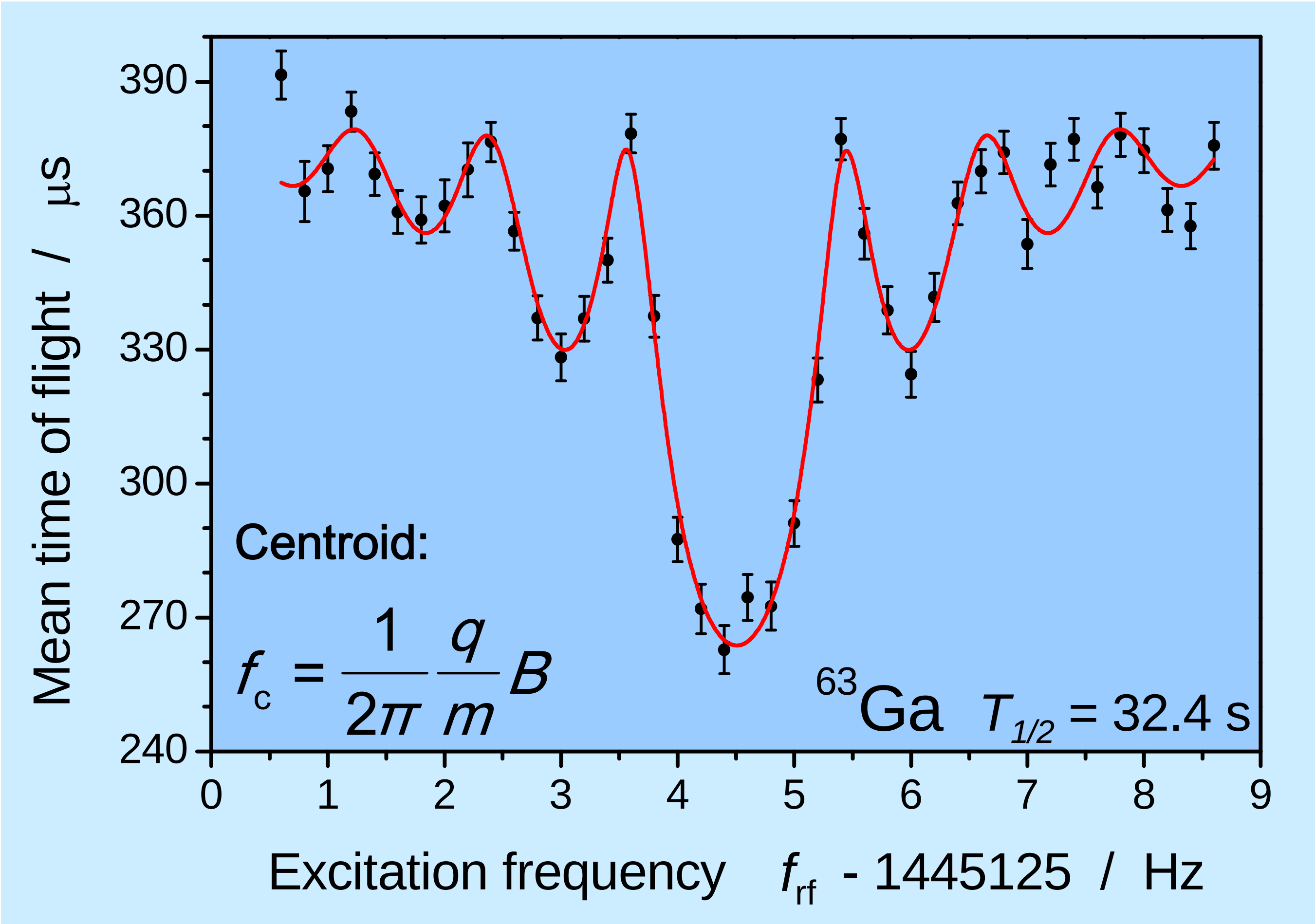
Penning-trap mass spectrometry

(3) TOF measurement





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

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

Part II

Nuclear astrophysics studies

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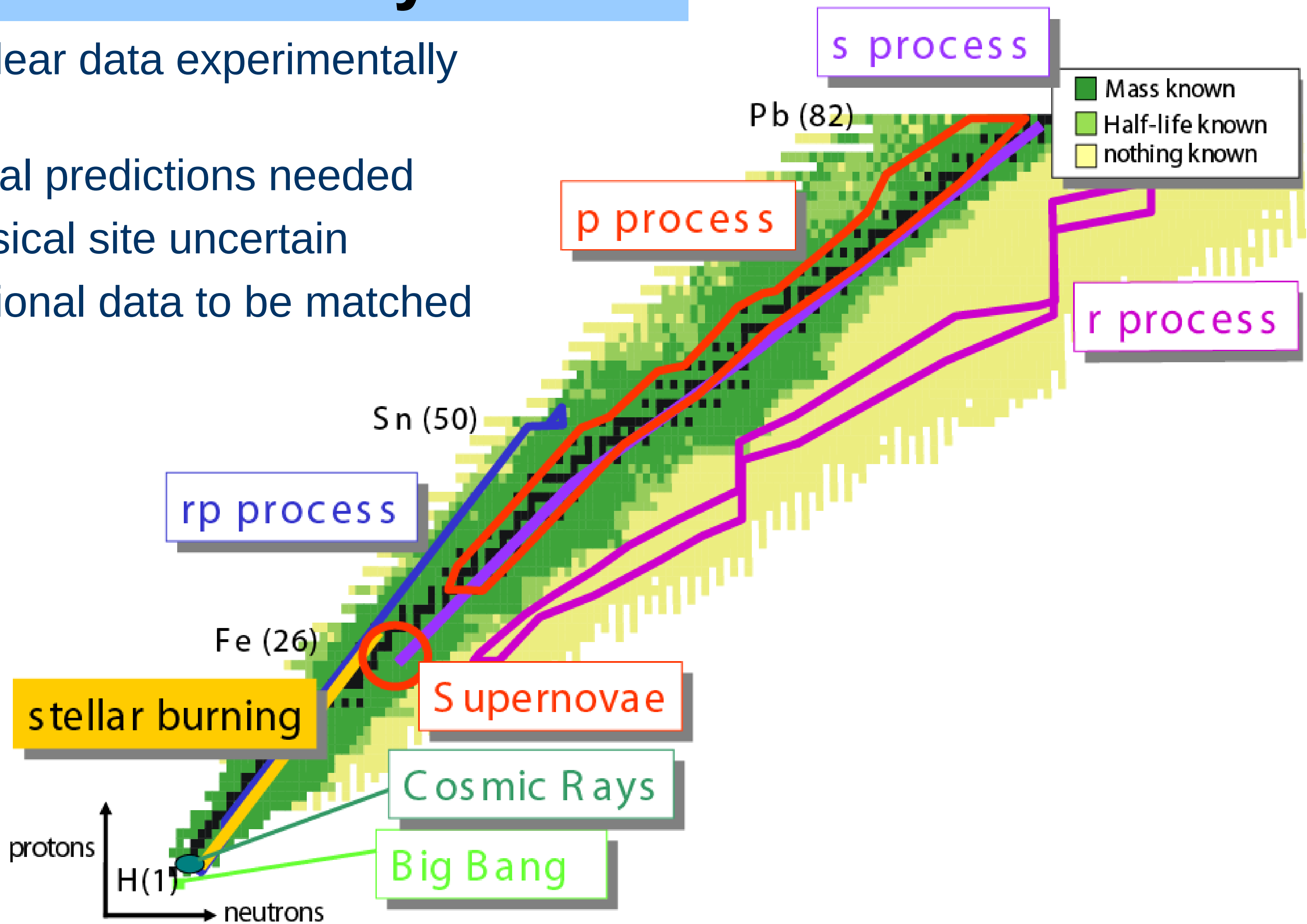
Making gold in nature

r-process nucleosynthesis

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



r-process: Impact of IMS-ESR results

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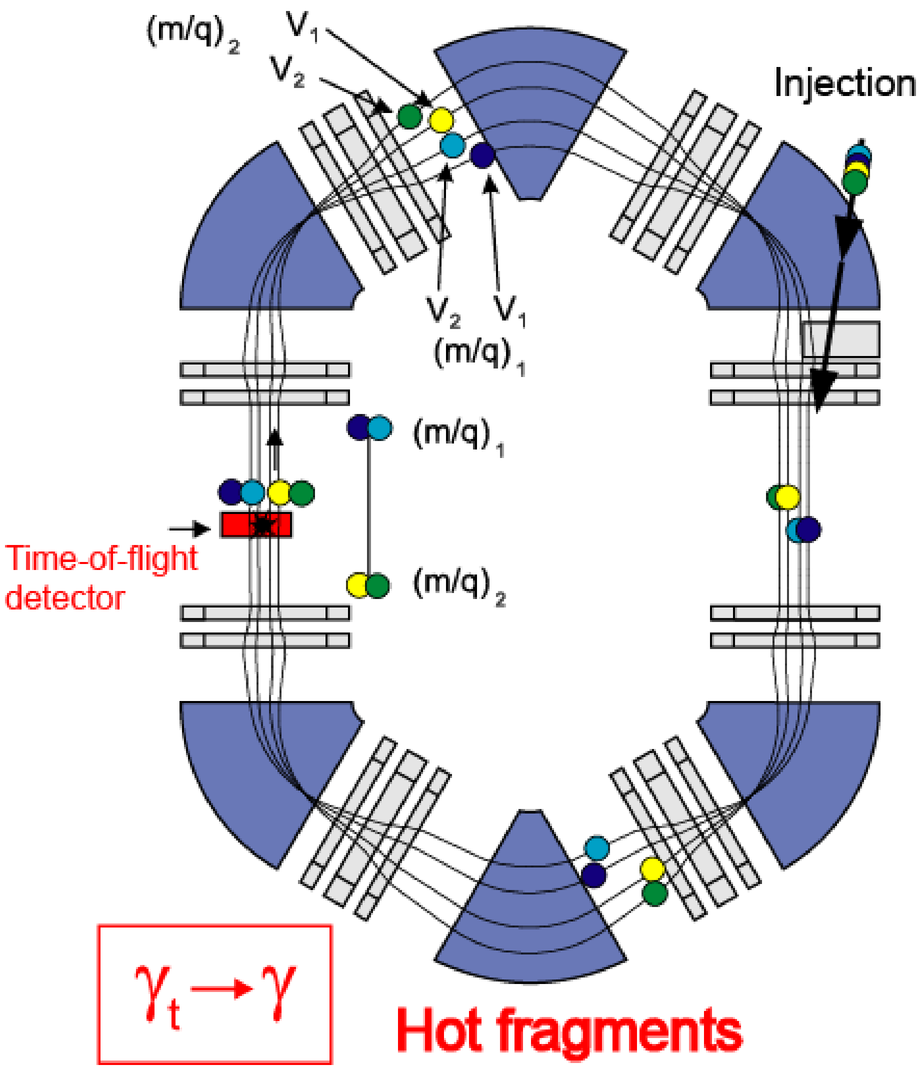
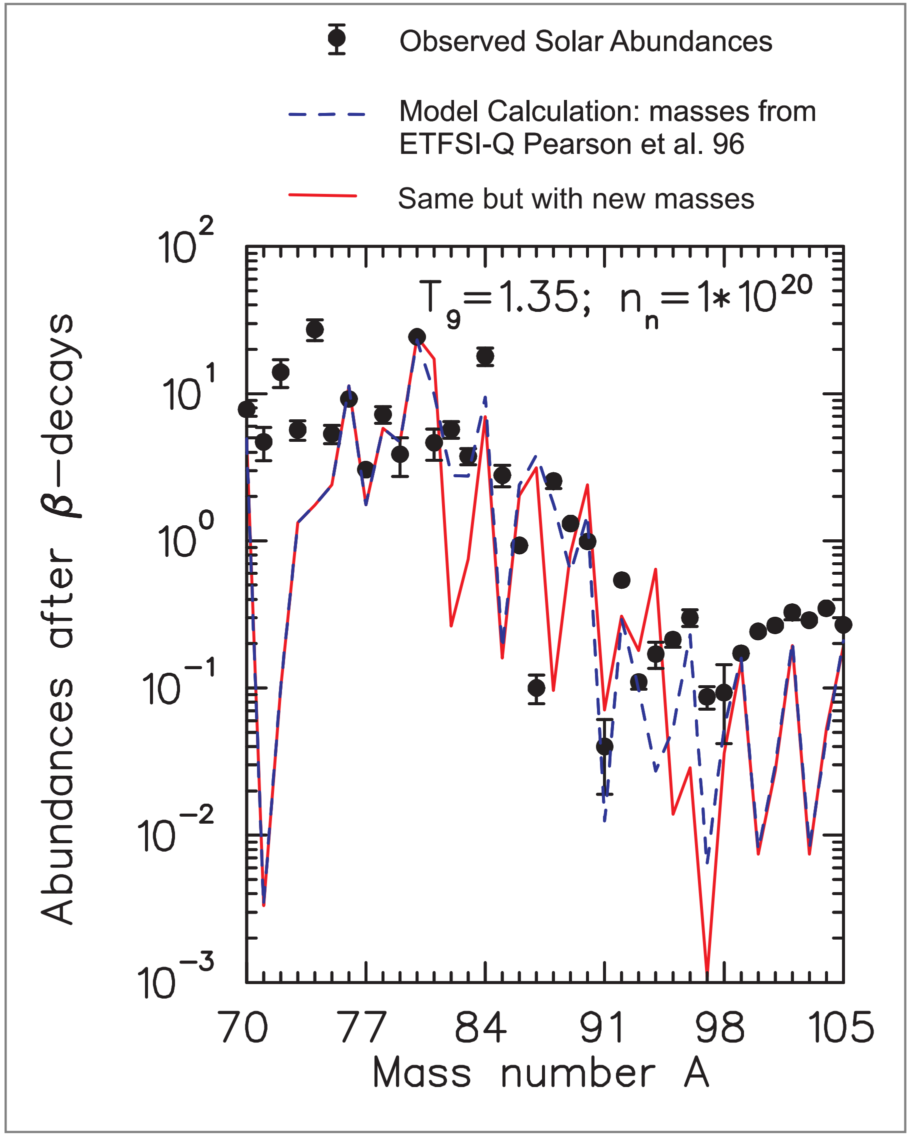
Isochronus-Mass-Spectrometry

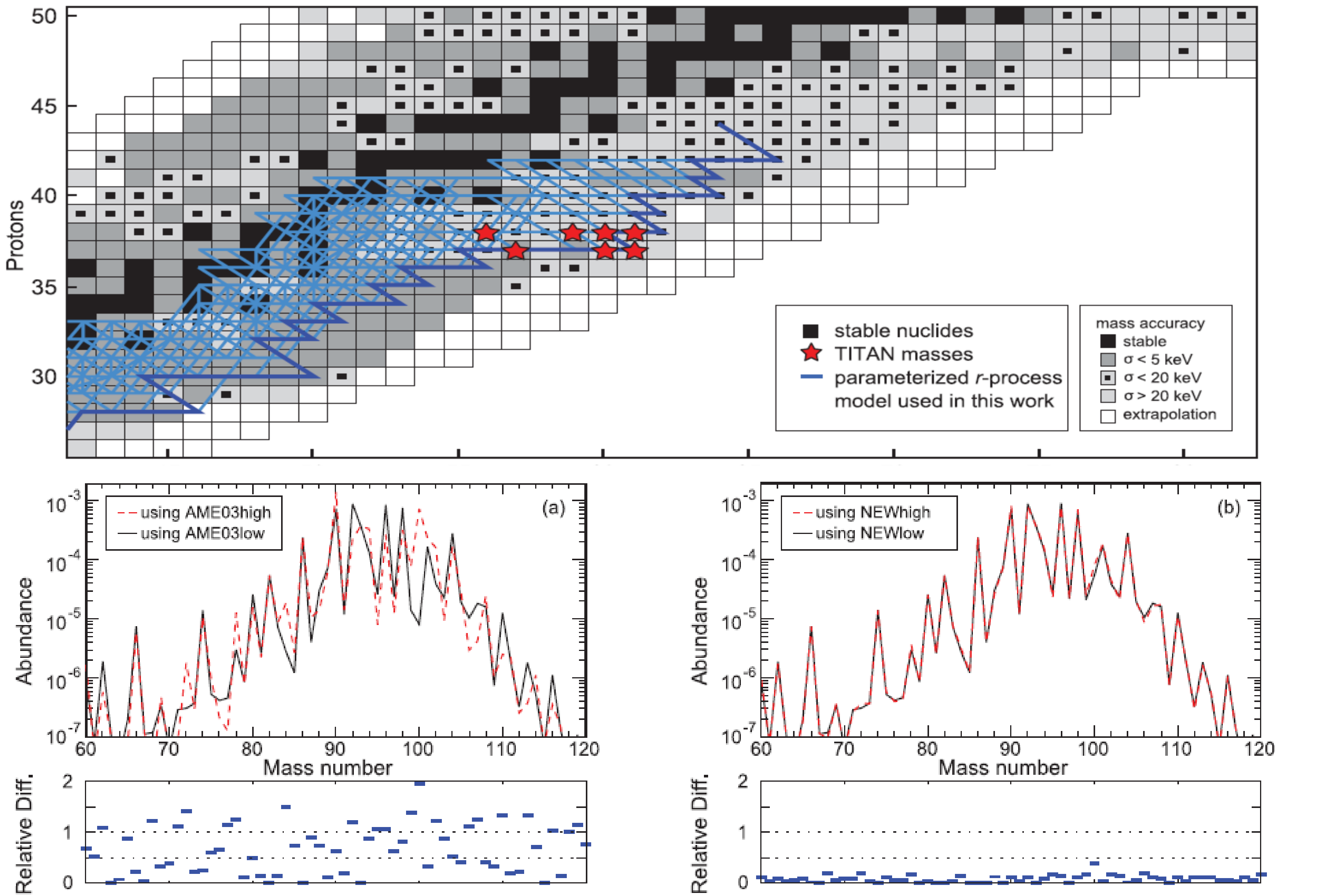




ESR (GSI)

B. Pfeiffer, GSI Report 2006-03

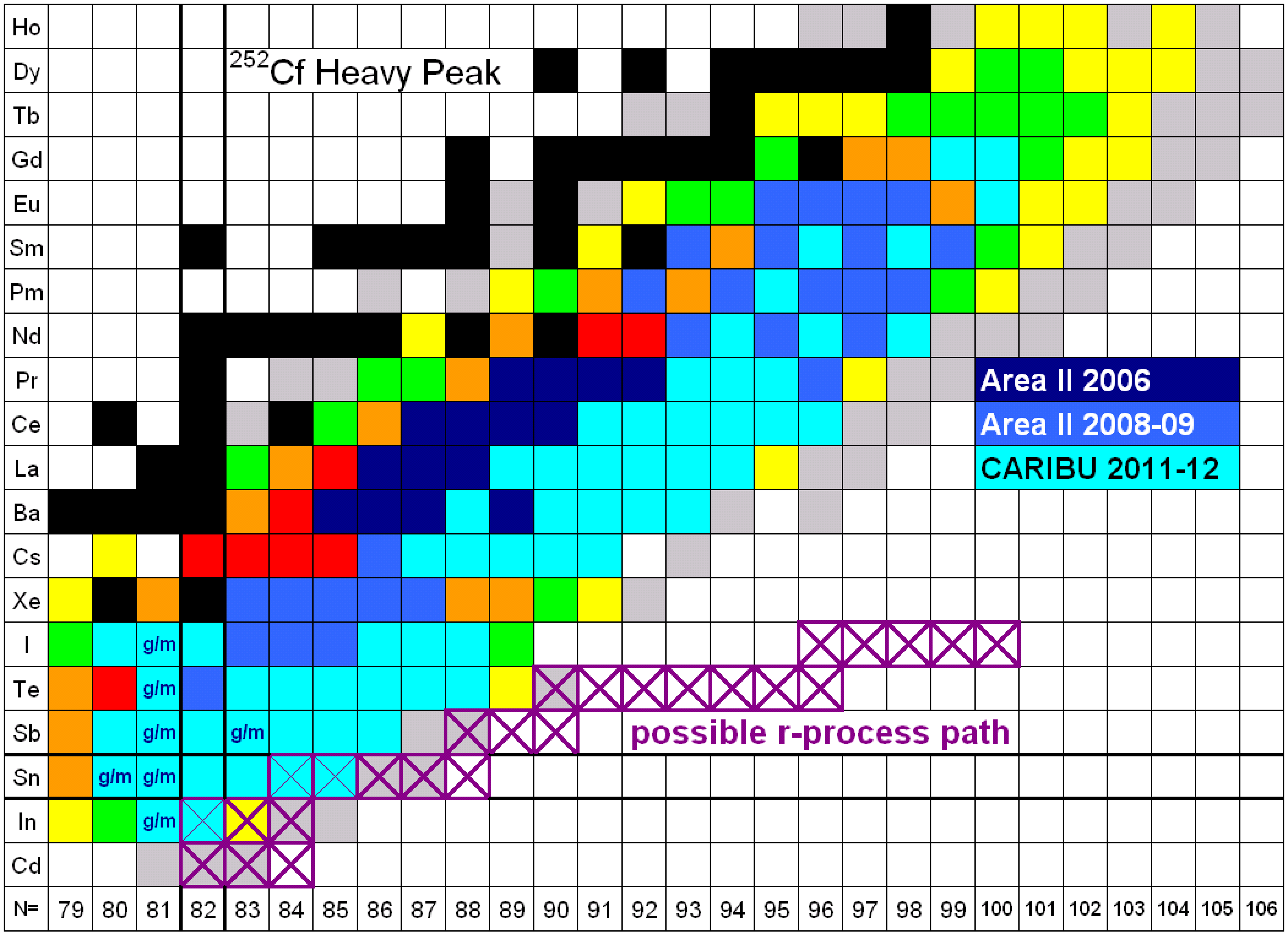
r-process: New mass results



TITAN (TRIUMF)

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

r-process: New mass results II

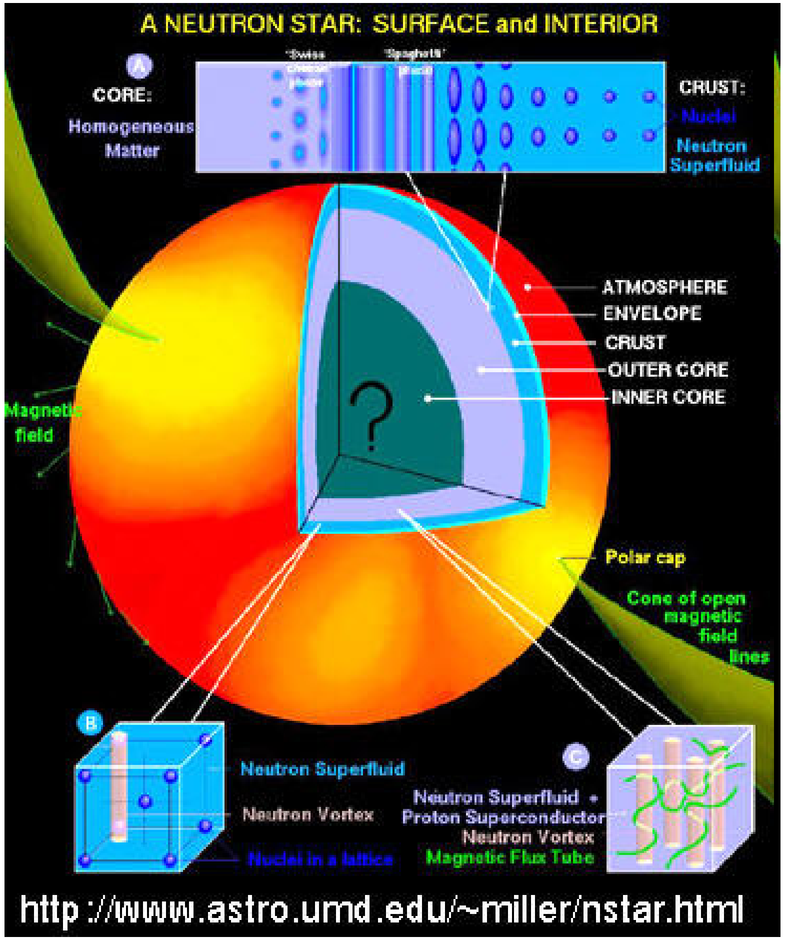


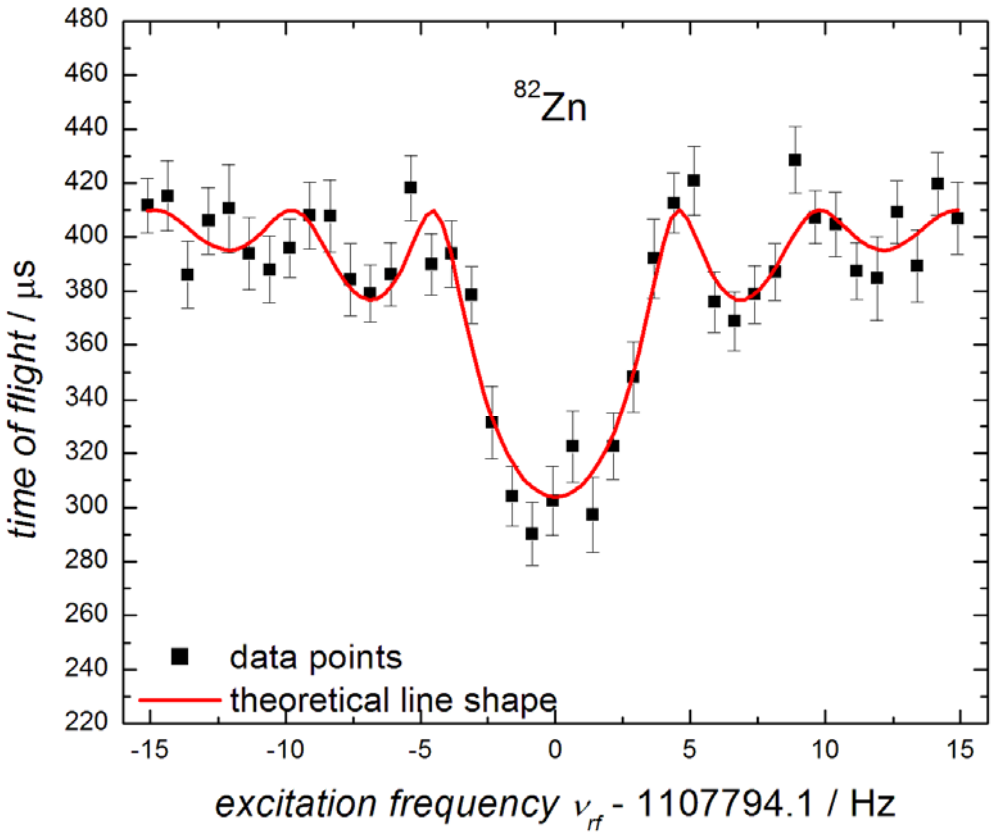
CPT (Argonne)

A large set of new mass data will be published soon!

The mass of ^{82}Zn

Composition of the outer crust of a neutron star





$\delta m/m \sim 10^{-8}$ (< 1 keV)

ISOLTRAP (ISOLDE)

R. Wolf and the ISOLTRAP Coll. (2011)

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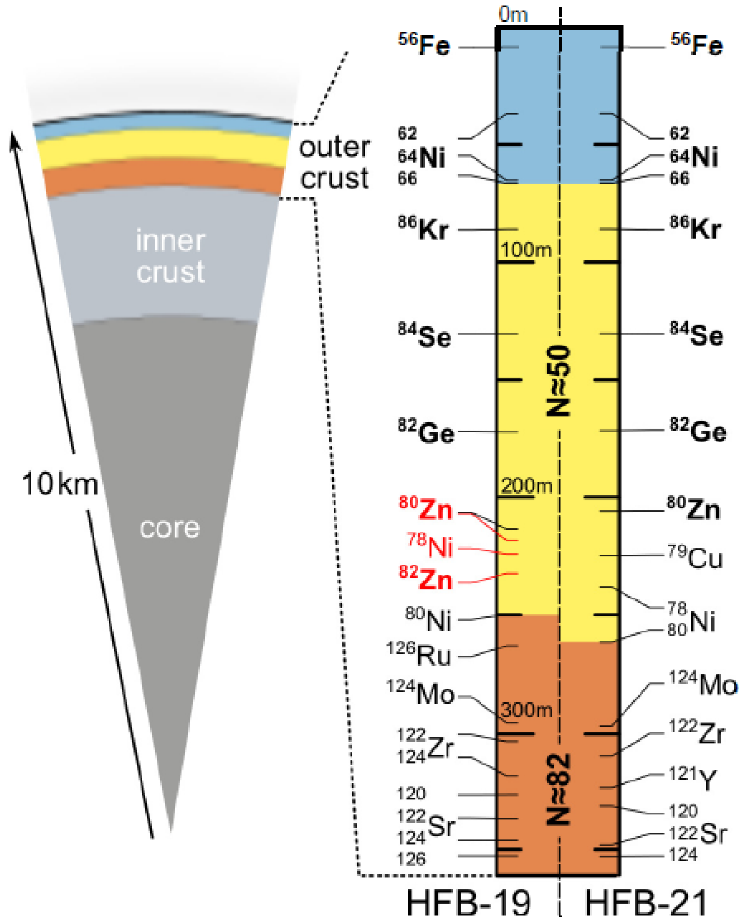
Plumbing neutron stars to new depths

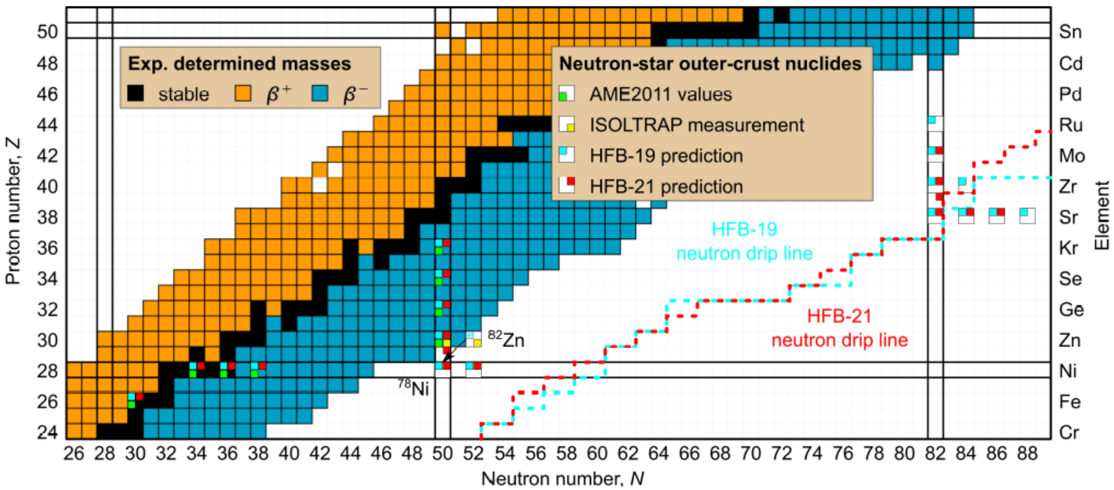
Composition of the outer crust of a neutron star

Depth profile of a neutron star



Calculations done by S. Goriely (2011)

HFB-19 and HFB-21 model calculations

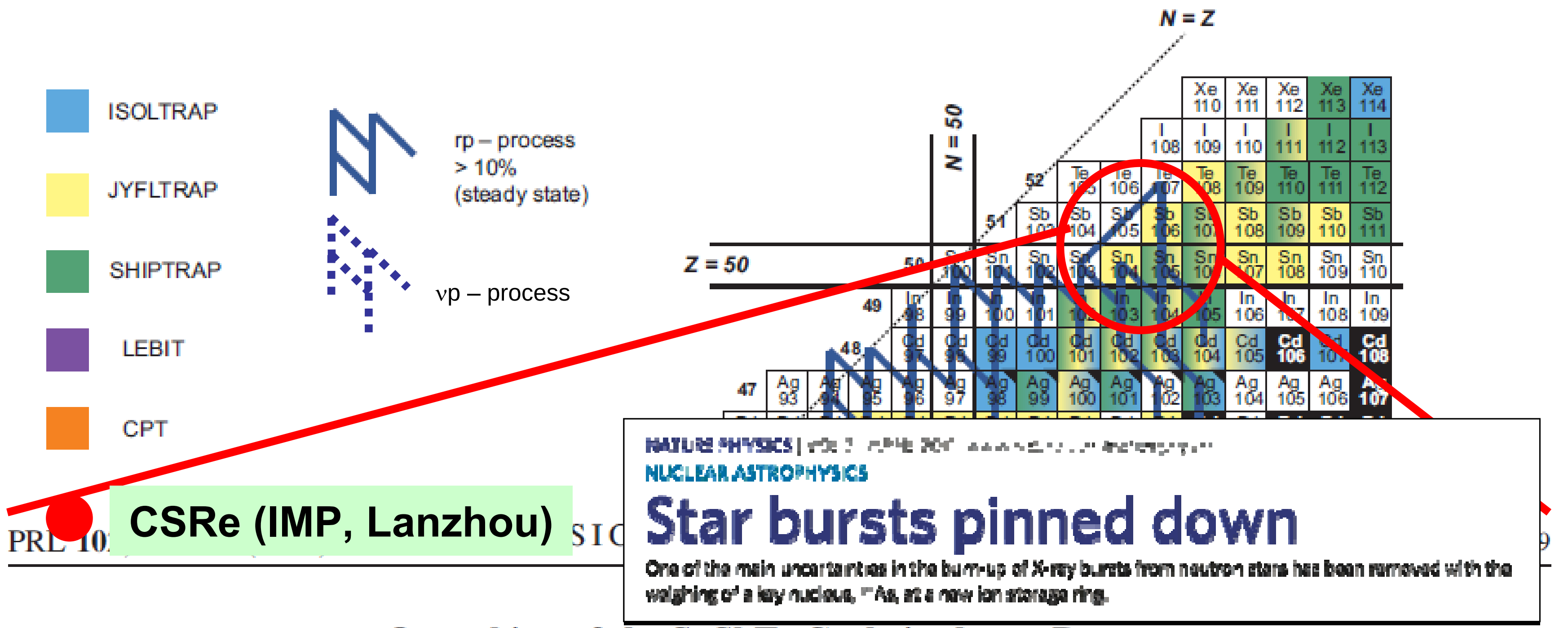


^{82}Zn: most exotic nuclide at the N=50 shell closure

Microscopic mass models predicted ^{82}Zn to be a component of the outer crust of a neutron star

→ disproved with exp. mass

Nuclides at the rp-process path

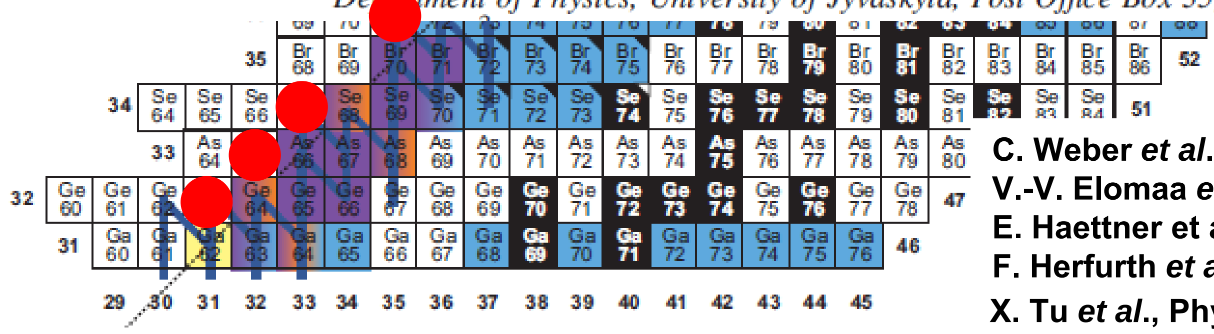


PRL

Quenching of the SnSbTe Cycle in the *rp* Process

V.-V. Elomaa,[1,*] G. K. Vorobjev,[2,3] A. Kankainen,[1] L. Batist,[2] S. Eliseev,[2,3,†] T. Eronen,[1] J. Hakala,[1] A. Jokinen,[1] I. D. Moore,[1] Yu. N. Novikov,[2,3] H. Penttilä,[1] A. Popov,[2] S. Rahaman,[1,‡] J. Rissanen,[1] A. Saastamoinen,[1] H. Schatz,[4] D. M. Seliverstov,[2] C. Weber,[1,§] and J. Äystö[1]

[1]Department of Physics, University of Jyväskylä, Post Office Box 35, FI-40014, Finland



JYFLTRAP (IGISOL)

C. Weber *et al.*, Phys. Rev. C 78, 054310 (2008)
V.-V. Elomaa *et al.*, Phys. Rev. Lett. 102, 252501 (2011)
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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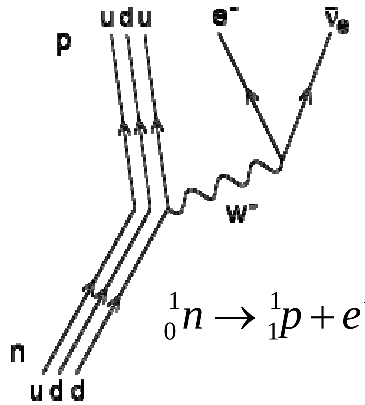
Part III

Test of the unitarity of the CKM quark mixing mtrix

Weak Interaction

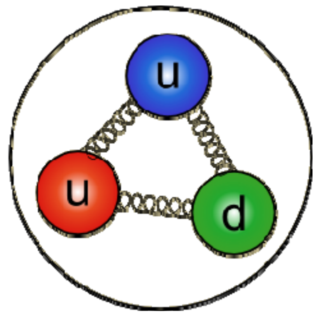
- Radioactive decay



$$^{1}_{0}n \rightarrow {}^{1}_{1}p + e^{-} + \overline{\nu}_{e}$$

Strong Interaction

- Binding between quarks within hadrons



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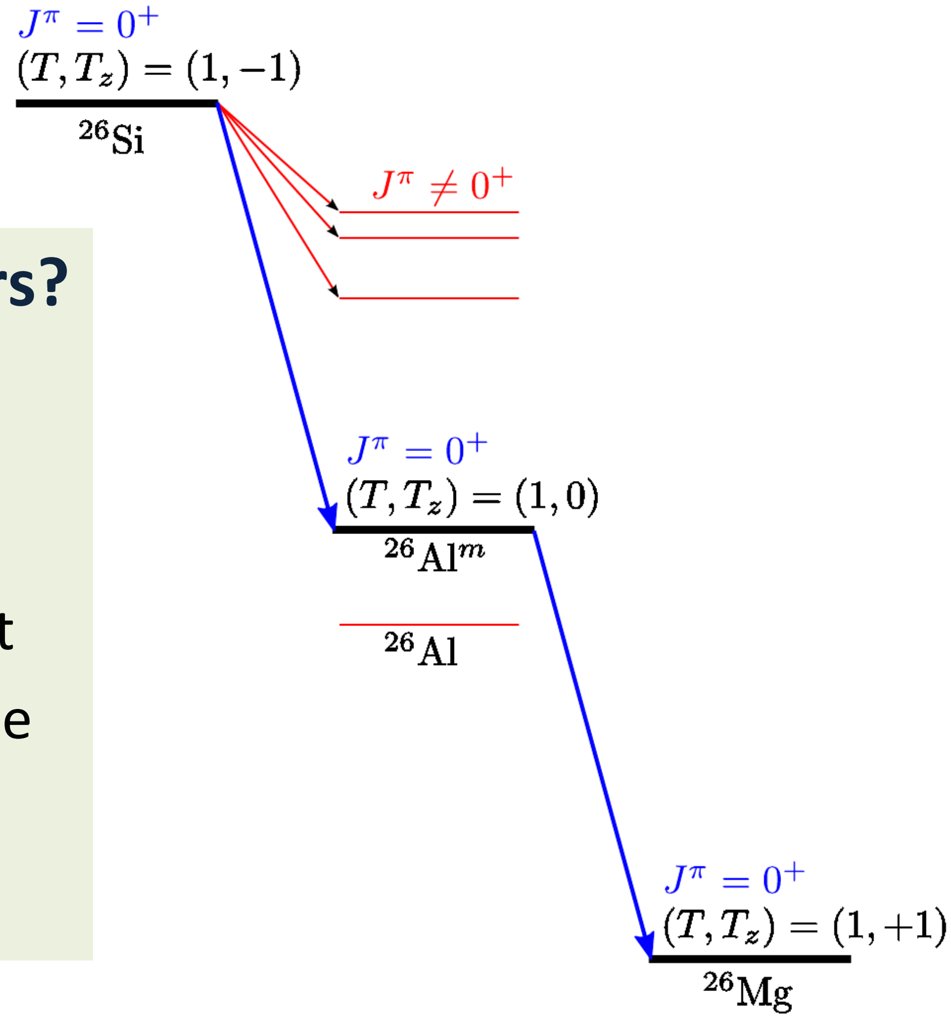
Q_{EC} values of superallowed beta emitters

Courtesy of T. Eronen

- **Superallowed beta emitters?**
  - Decays of nuclear 0^+ ? 0^+ states, *T=1*
  - Pure Fermi decays
  - Simple decay matrix element
  - Characterized with an *ft* value
    - *f* stat. rate function;($f \propto Q_{EC}^5$)
    - *t* partial half-life $t_{1/2}/b$



Q-values needed at 100-eV level

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Testing the Standard Model

- Corrected value:

$$\mathcal{F}t = ft\,(1+\delta'_R)\,(1+\delta_{\mathrm{NS}}-\delta_C) = \frac{K}{2G_V^2\,(1+\Delta_V^R)}$$

- Corrections about 1% [Towner and Hardy, Phys. Rev. C 77, 025501 (2008)]
- Cabibbo-Kobayashi-Maskawa quark mixing matrix

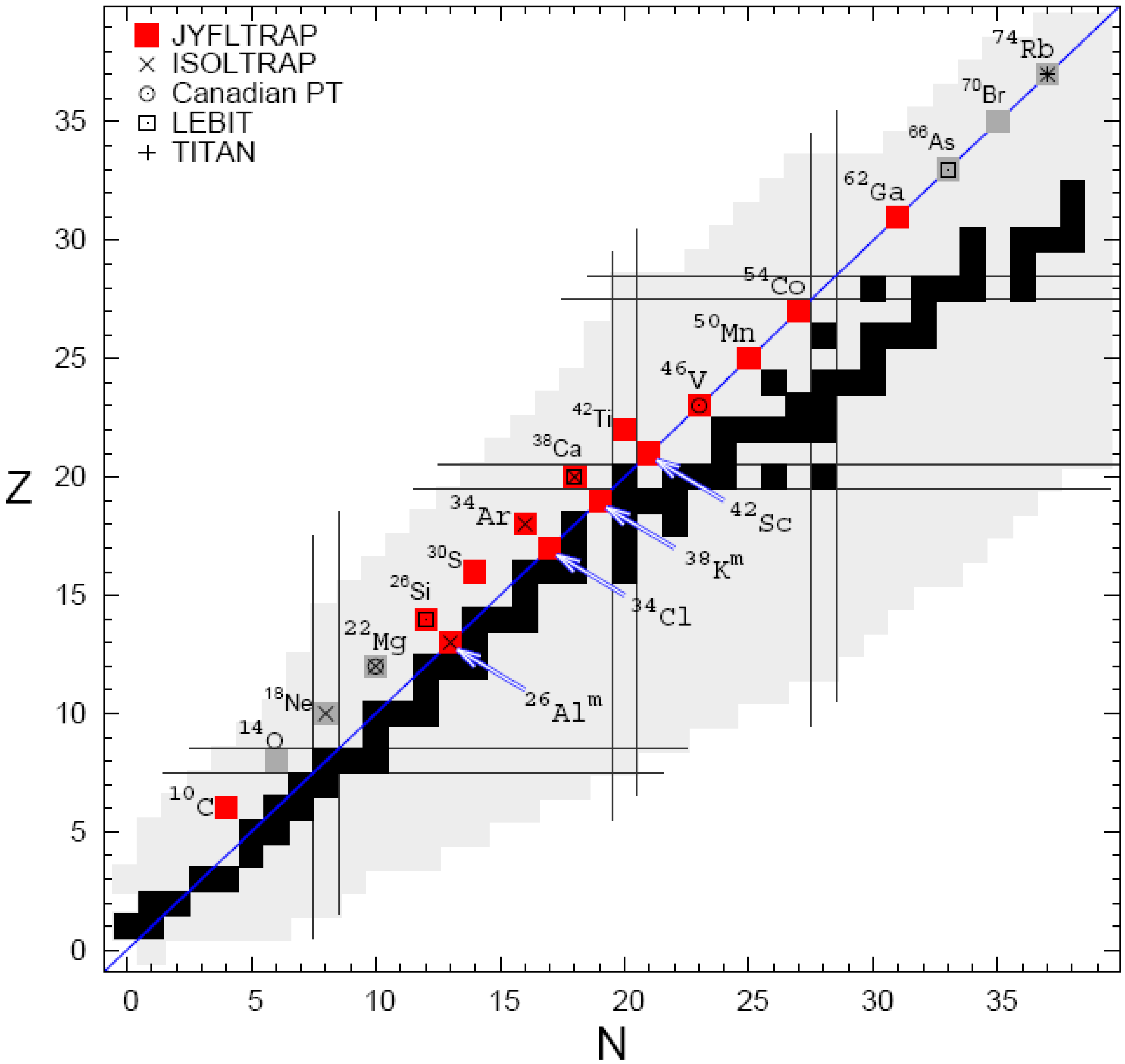
$$\begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}$$

- Quark-mass eigenstates $|x\rangle$ to weak eigenstates $|x'\rangle$

$$V_{\mathrm{ud}} = \frac{K}{2G_F^2\,(1+\Delta_R^V)\,\overline{\mathcal{F}t}}$$

Currently 13 transitions contribute

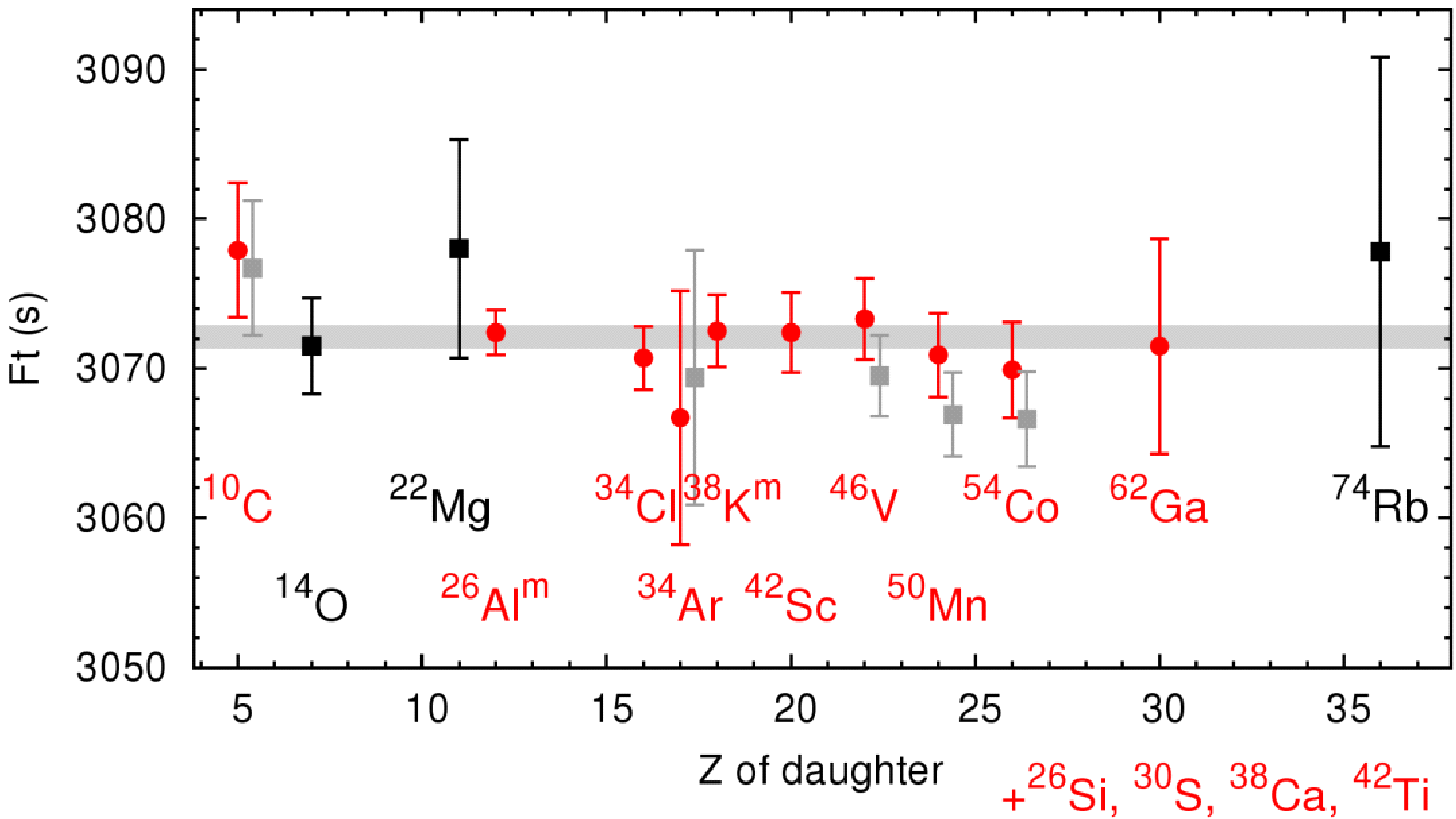
Superallowed beta-emitters – Q_{EC}



Contributes to world average value (13)

JYFLTRAP (IGISOL)
ISOLTRAP (ISOLDE)
CPT (Argonne)
LEBIT (MSU)
TITAN (TRIUMF)

The *Ft* picture



Ft = 3072.08(79) s

Towner&Hardy, Rep. Prog. Phys. 73 (2010) 046301

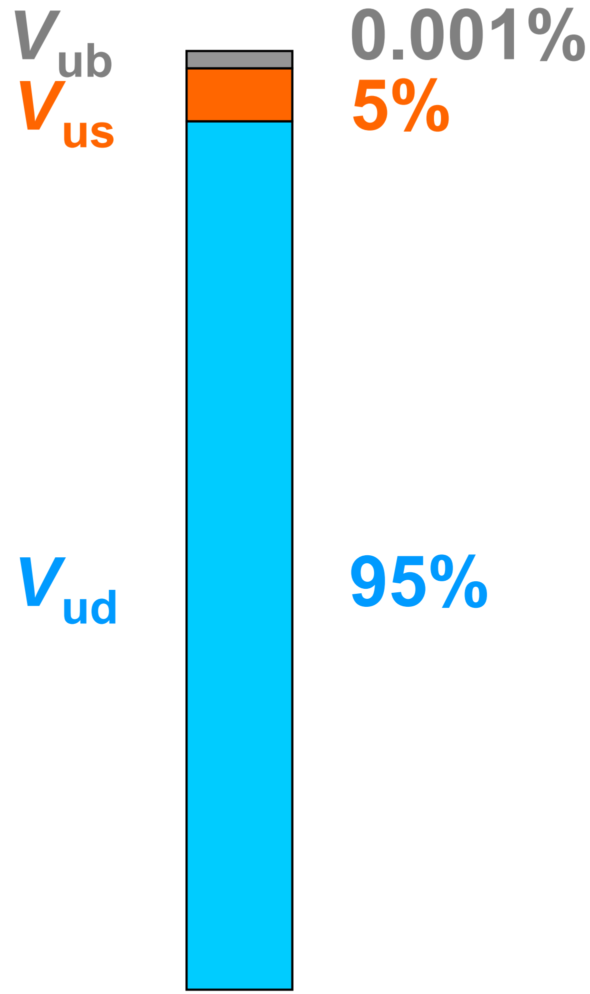
Test of the CKM unitarity

Check unitarity via first row elements:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad + \Delta$$

V_{us} and V_{ub} from particle physics data
(K and B meson decays)

Unitarity contribution:



Present status:

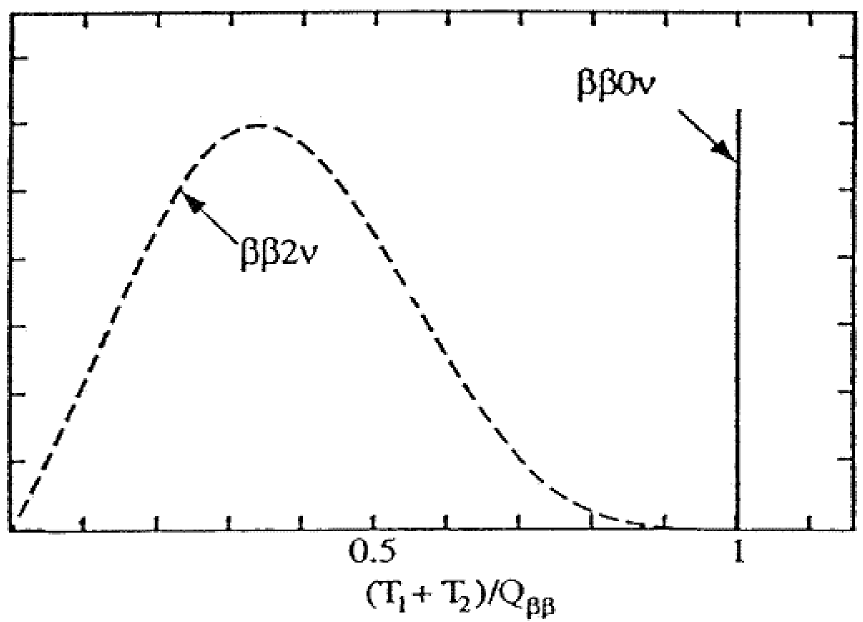
V_{ud} (nuclear β-decay) = 0.97425(22)
V_{us} (kaon-decay) = 0.22521(94)
V_{ub} (B meson decay) = 0.0037(5)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(6)$$

Towner&Hardy, Rep. Prog. Phys. 73 (2010) 046301

Part IV

Nuclear masses for neutrino physics



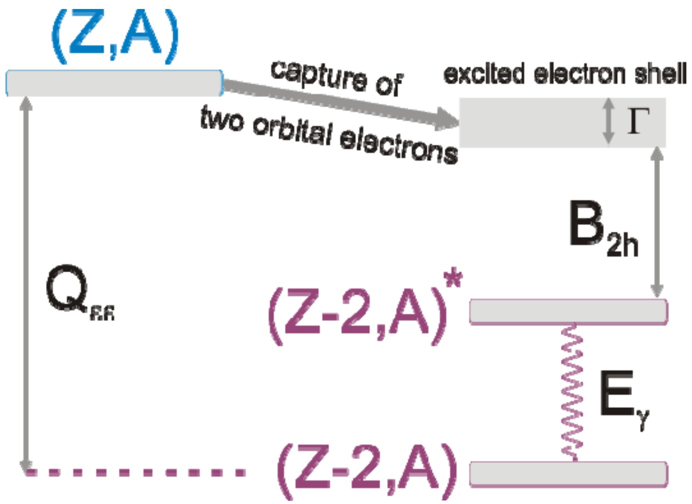
Neutrino-less double EC (0ν2*EC*)

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

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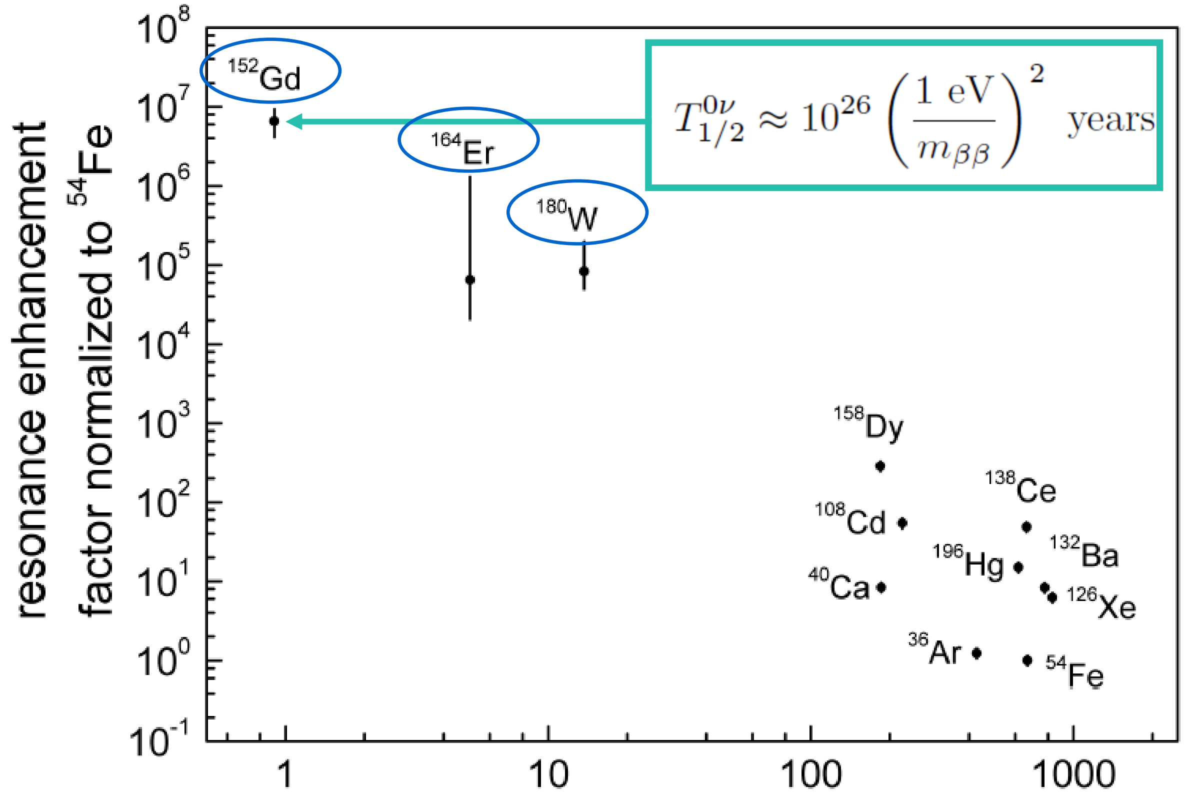
Resonance enhancement factors

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)

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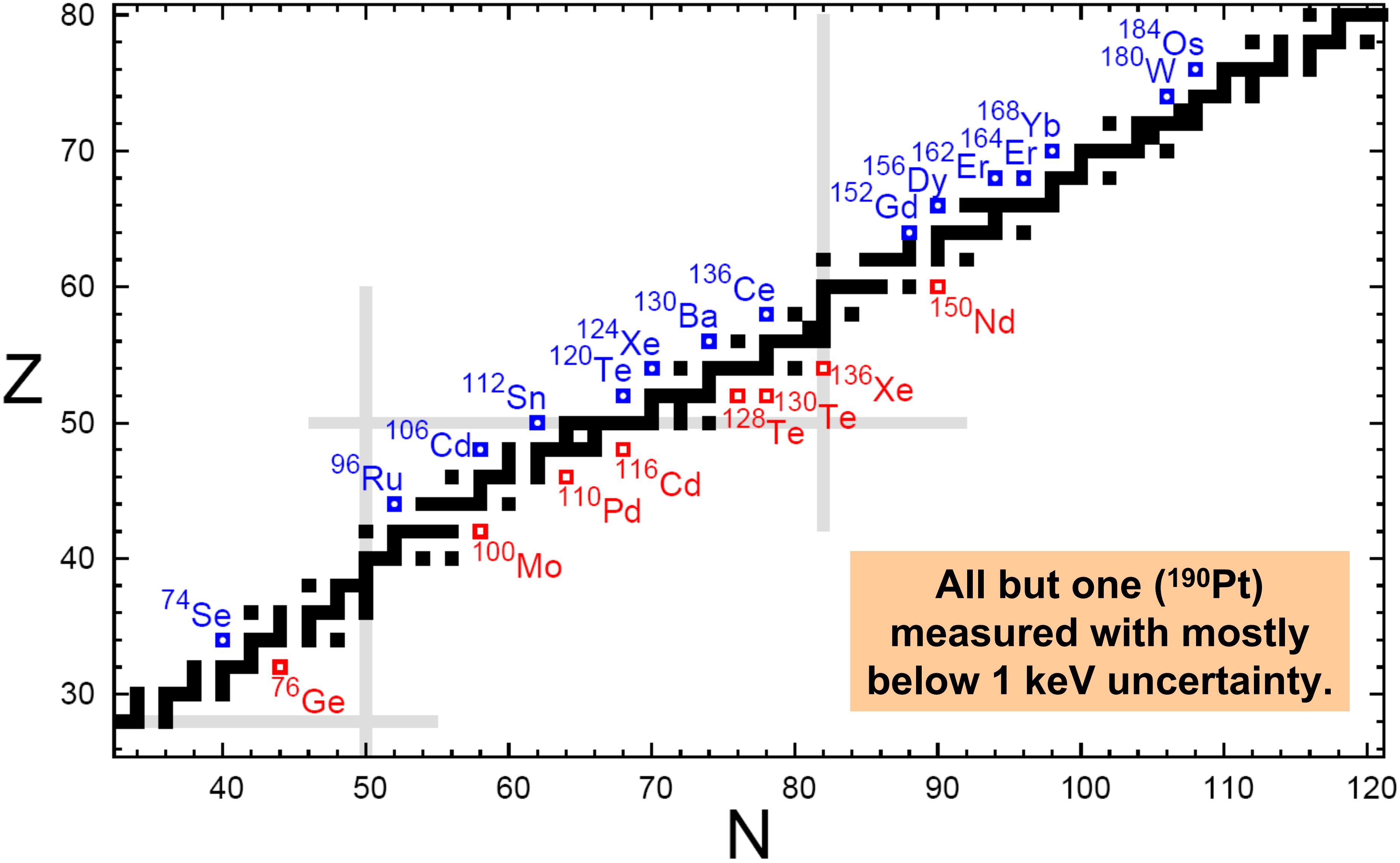
Results so far

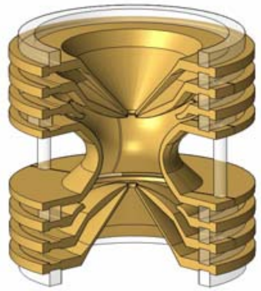


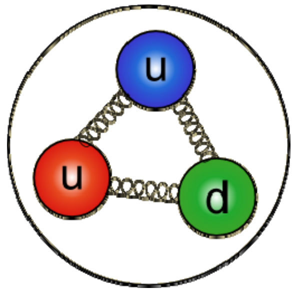
All but one (^{190}Pt) measured with mostly below 1 keV uncertainty.

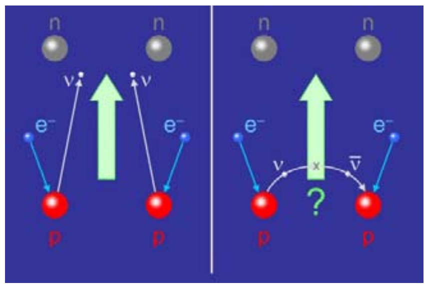
Summary

Exciting results in high-precision mass measurements for nuclear astrophysics and fundamental studies

- Basics of Penning-trap and storage-ring mass spectrometry
- Applications of precision masses for nuclear astrophysics studies
- Test of the unitarity of the CKM quark mixing matrix
- Precision masses and nuclear structure calculations for neutrino physics research
- … and many more!







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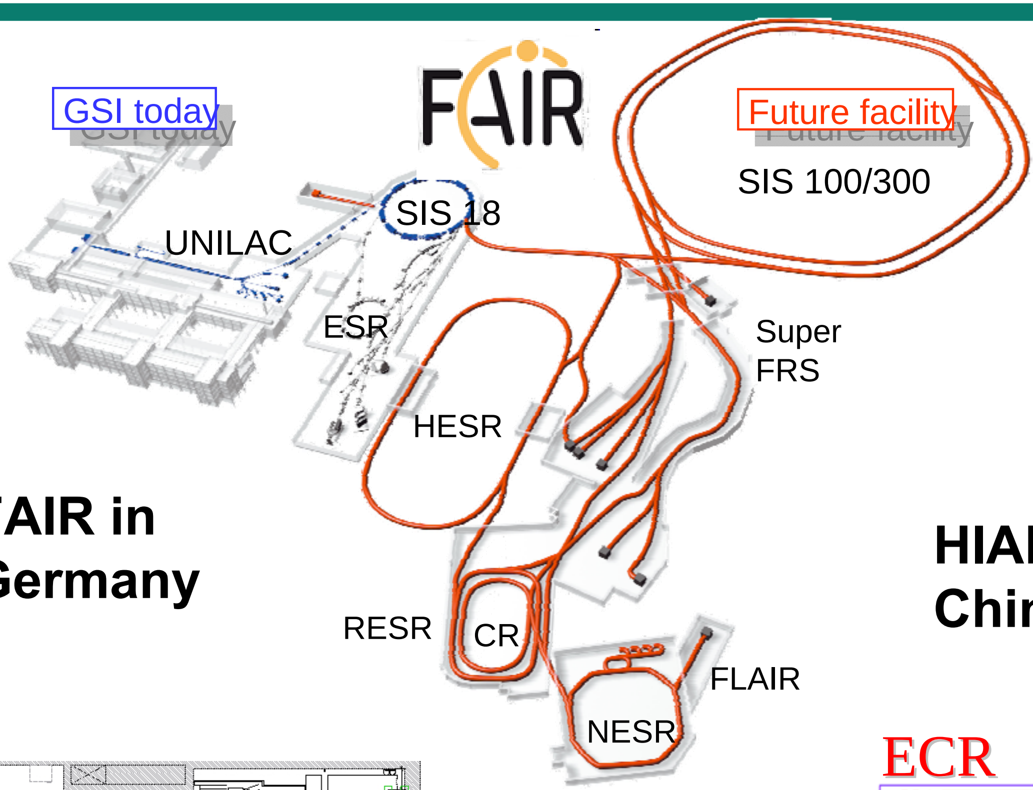
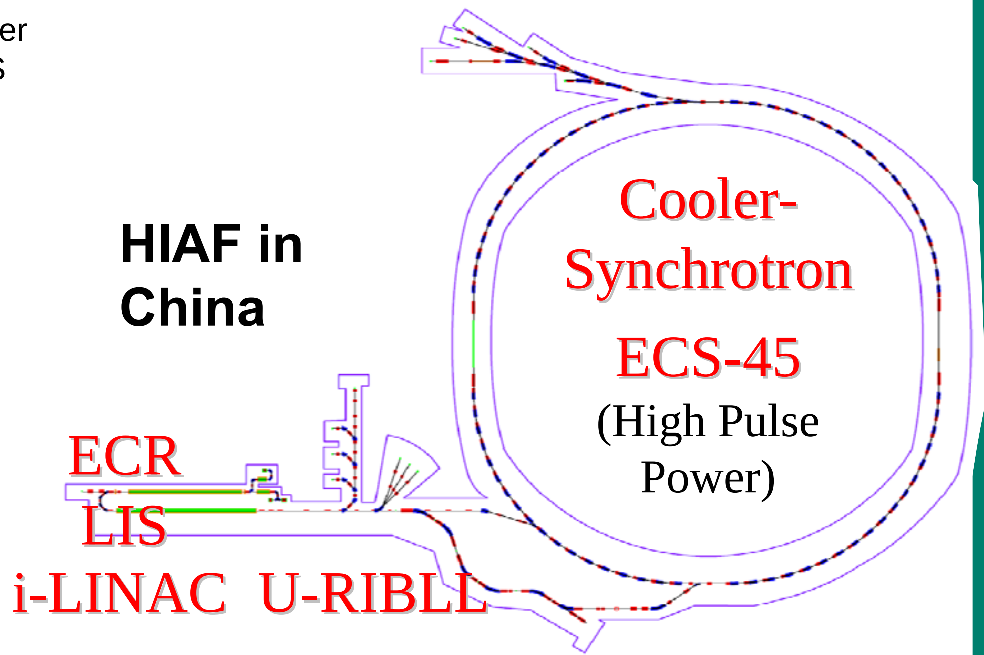
Future mass spectrometry facilities

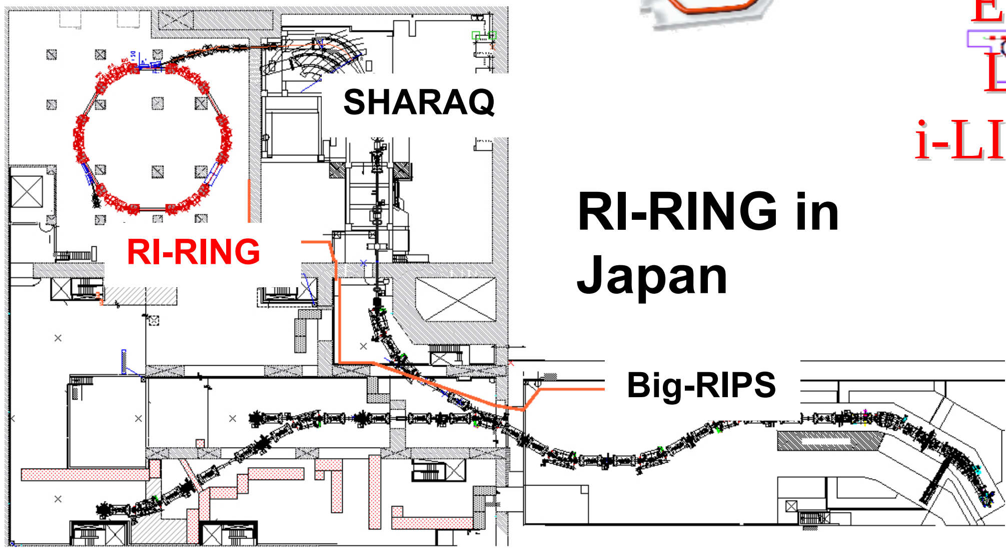


FAIR in Germany

HIAF in China



RI-RING in Japan



MLL-TRAP at DESIR
LEBIT at FRIB
CPT at CARIBU II
TRIGA-TRAP at TRIGA

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Thanks

Thanks a lot for the invitation and your attention!

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

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

Max-Planck Society

Helmholtz Alliance (HA216)

erc

Adv. Grant MEFUCO (#290870)

NAVI

Nuclear Astrophysics Virtual Institute

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