Ion traps in nuclear physics

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INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

36th Course

Nuclei in the Laboratory and in the Cosmos

Erice-Sicily, September 16-24, 2014

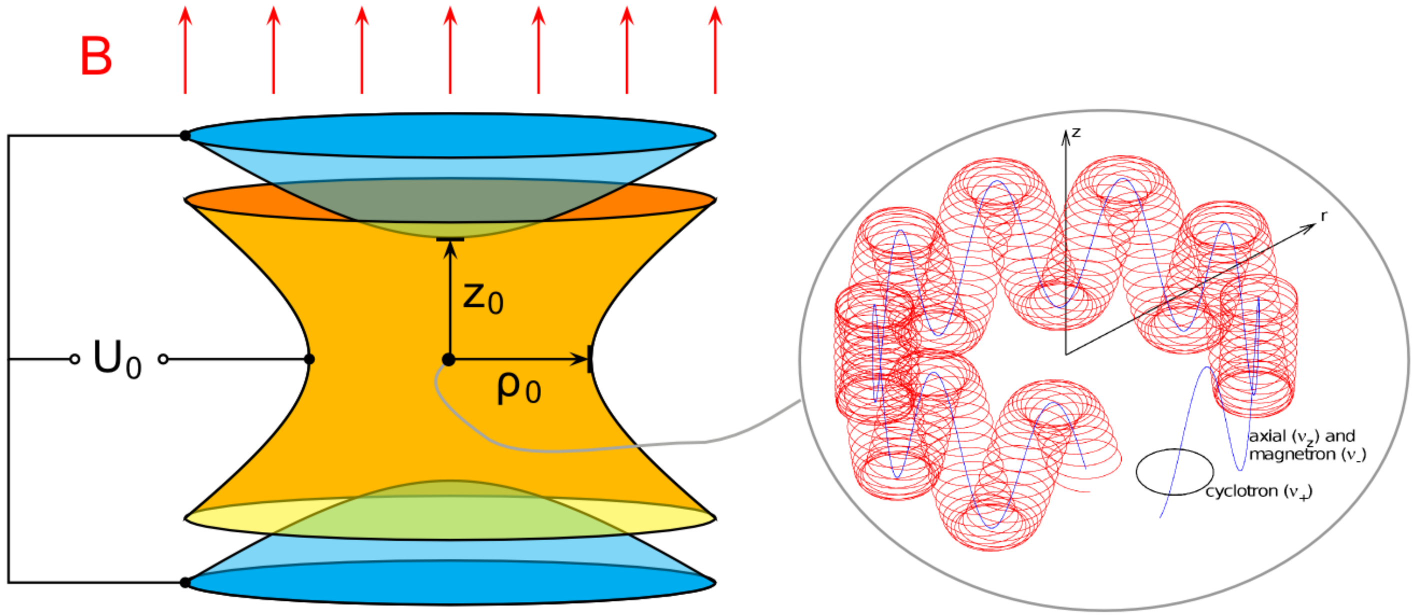
Ion traps in nuclear physics

Content

- Penning trap basics
- Mass measurements
  - Atomic masses
  - Nuclear structure
  - Nuclear astrophysics
- Trap-assisted spectroscopy
- Precision measurements
  - Superallowed beta decay
  - 0ν-$\beta\beta$, 0ν-ECEC, “ultra-low” Q-values

JYFLTRAP, CPT, ISOLTRAP, LEBIT, SHIPTRAP, TITAN, ...

Penning trap – confining charged particles



- Strong homogenous B-field
- Quadrupolar electrostatic potential

Penning trap – confining charged particles

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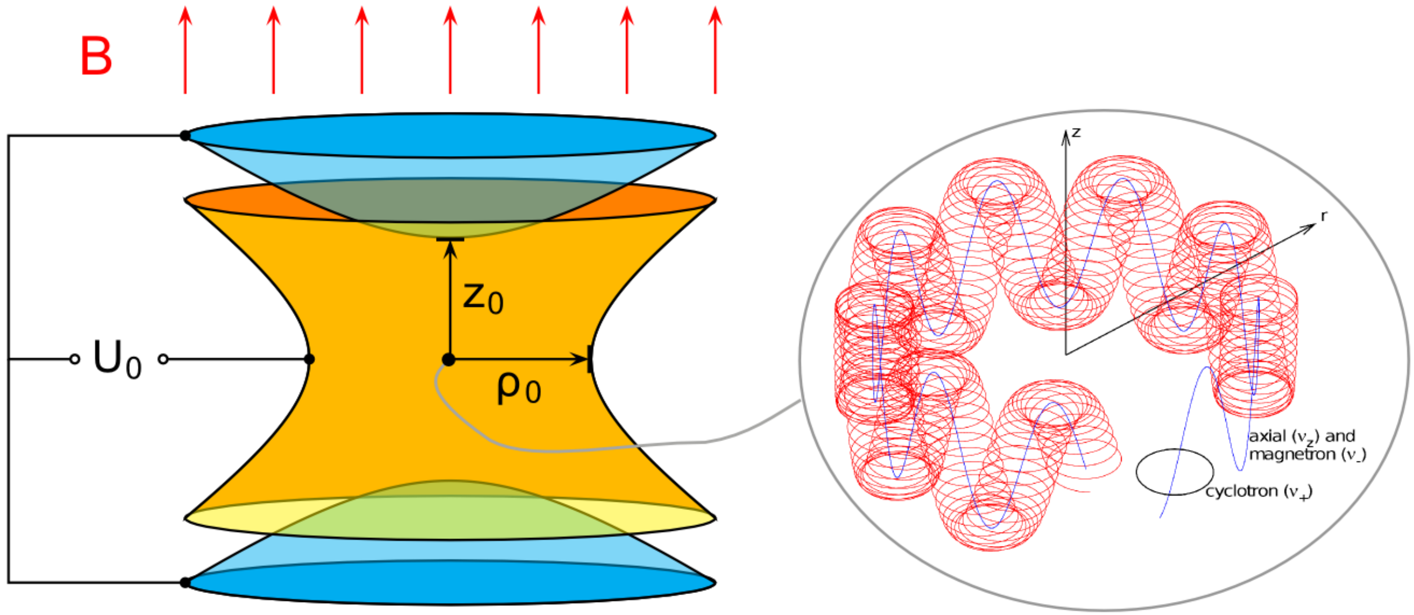


Three eigenmotions
- Axial ν_z
- Magnetron ν_-
- Modified cyclotron ν_+

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{U_0}{d^2}\frac{q}{m}}$$

$$\nu_\pm = \frac{1}{2}\left(\nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

A=100, q=1, B=7 T
- $f_+ \approx$ 1 MHz
- $f_- \approx$ 1 kHz
- $f_z \approx$ 44 kHz

Penning trap – confining charged particles

FREE-CYCLOTRON FREQUENCY: $$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

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

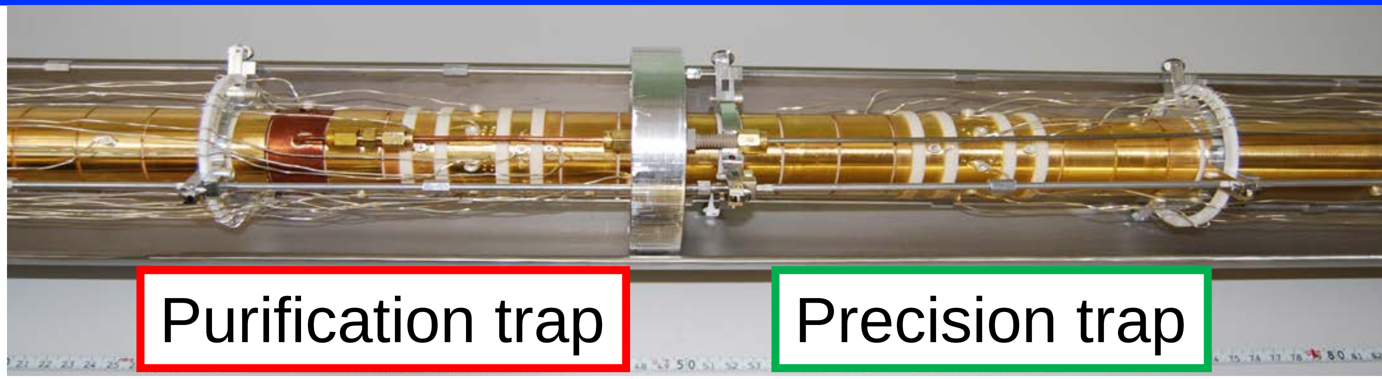
INVARIANCE THEOREM: $$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

Forgives some misalignments etc.

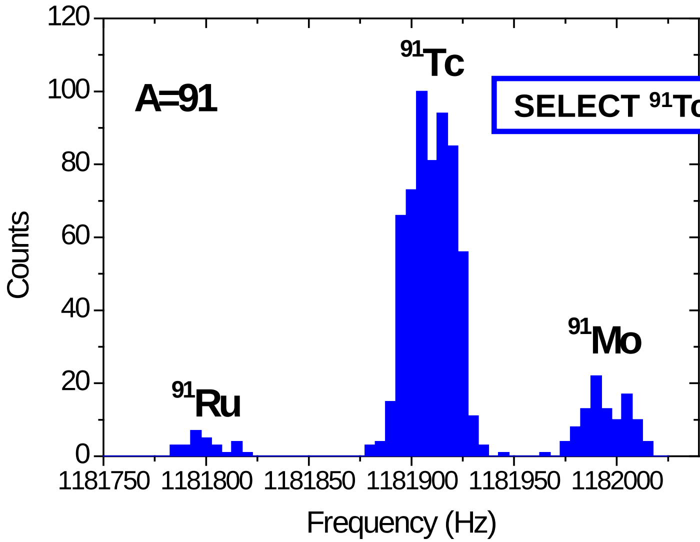
SIDEBAND FREQUENCY: $$\nu_c = \nu_- + \nu_+$$

For ideal trap but usually precise enough

Purification & measurement; JYFLTRAP

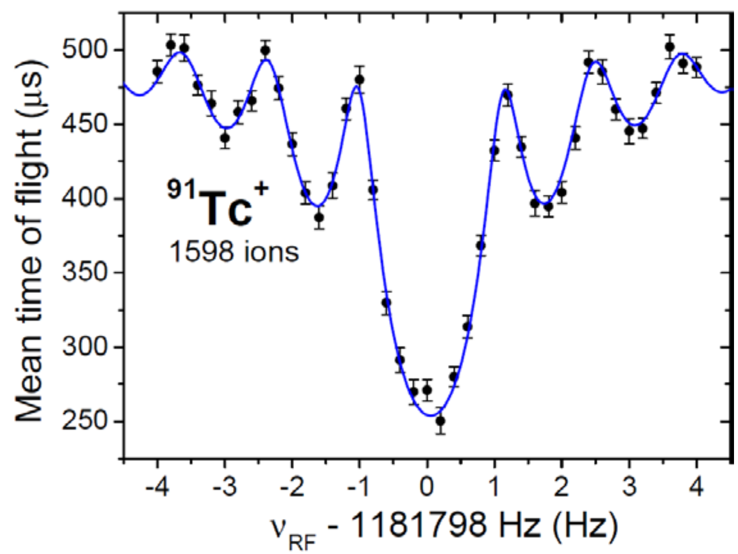


mass-selective buffer gas cooling



SELECT $^{91}Tc^{+}$

TOF-ICR method



Basic equations for mass determination

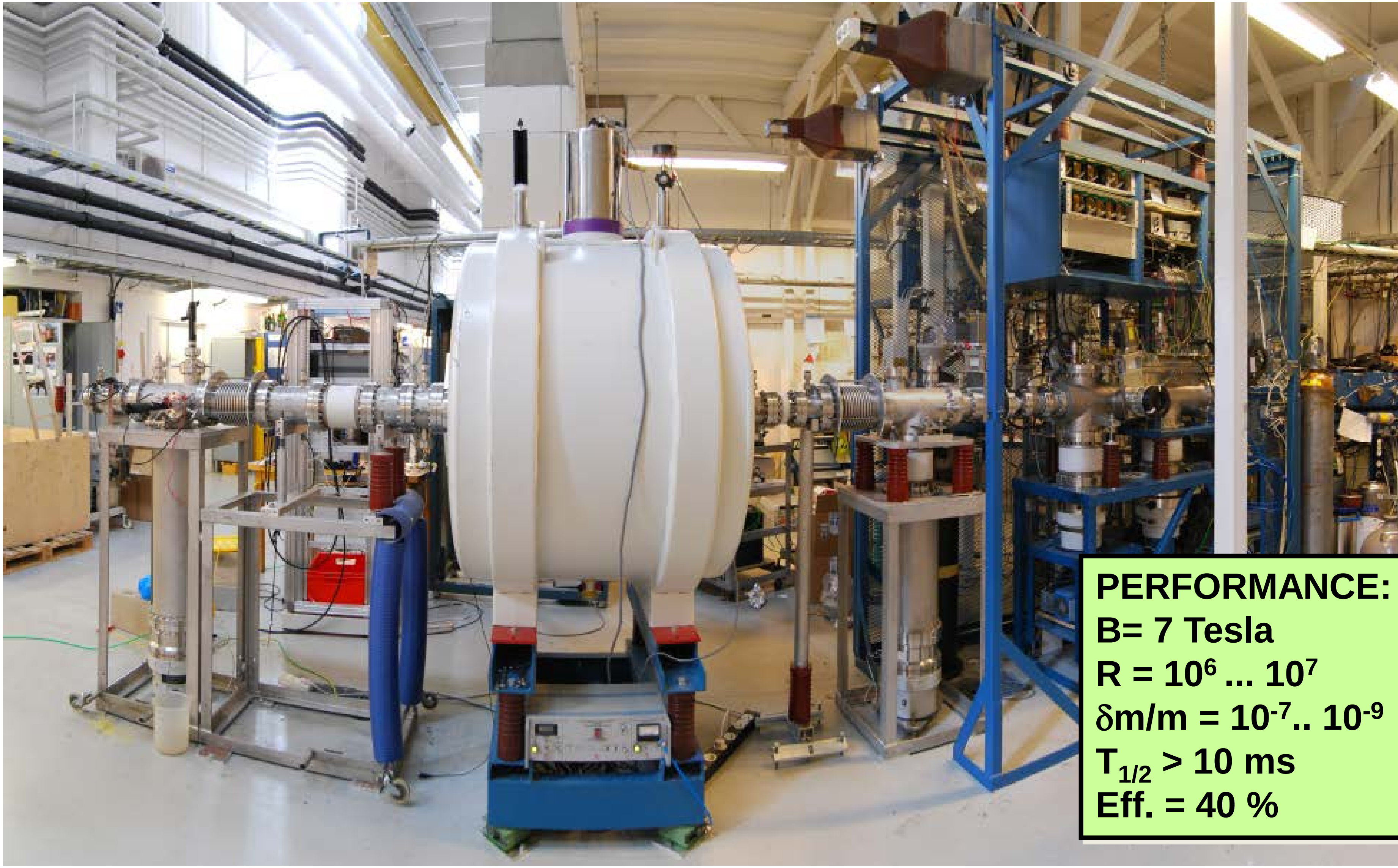
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

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

Routinely M/ΔM ~ 10^5
Space charge limit ~10^5
Good/Bad ~ 10000

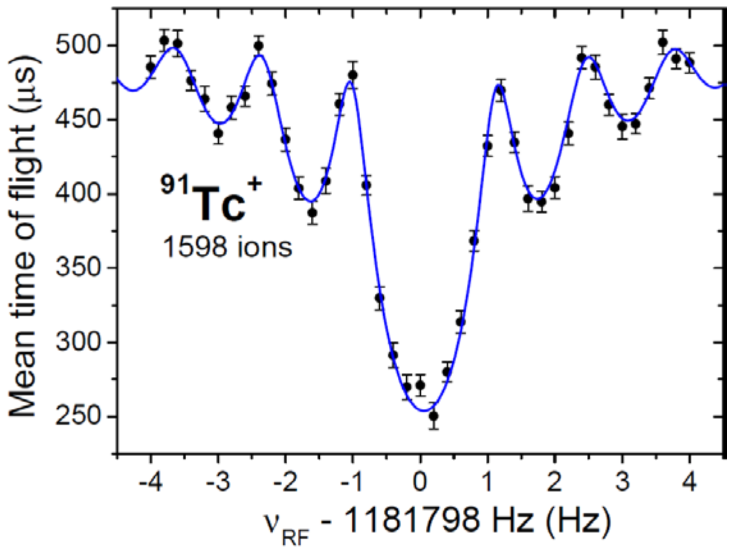
Routinely few keV
If required few tens of eV (**$\delta m/m < 1\cdot10^{-8}$**)

JYFLTRAP Mass Spectrometer at Jyväskylä

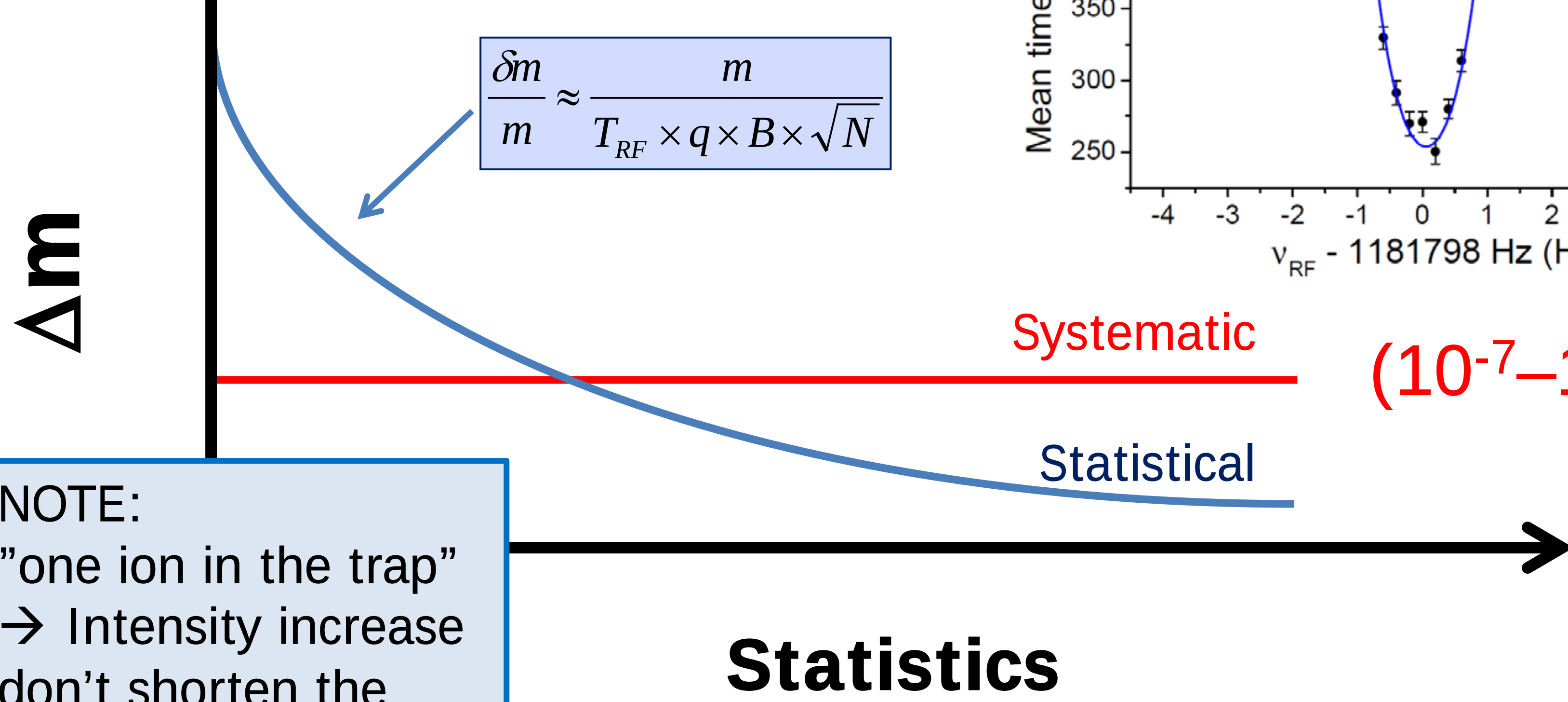


PERFORMANCE:
B= 7 Tesla
R = 10^6 ... 10^7
$\delta m/m = 10^{-7} .. 10^{-9}$
$T_{1/2} > 10$ ms
Eff. = 40 %

Statistics, systematics and ion rates



$$\frac{\delta m}{m} \approx \frac{m}{T_{RF} \times q \times B \times \sqrt{N}}$$



NOTE:
"one ion in the trap"
→ Intensity increase don't shorten the measurement time !

The role of masses in nuclear physics

Absolute mass: $\boxed{B\left({}^{A}_{Z}X_{N}\right) = Zm_{H}c^{2} + Nm_{n}c^{2} - M\left({}^{A}_{Z}X_{N}\right)c^{2}}$

High-accuracy mass measurements allow one to determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus

Mass differencies:

First order derivatives

Nucleon (s.p) binding energy (drip-line definition)
Nucleon-pair binding energy (S_{2N})
Decay energy (Q_{β}, Q_{α})
Coulomb displacement energy (Isospin multiplets)

Second order derivatives

Pairing energy (odd-even staggering)
<u>Shell-gap energy – shell survival for exotic nuclei ?</u>

Research areas and relevant precision

(atomic masses and/or Q-values)

- **Nuclear structure (10-100 keV)**
  Global correlations (100 keV)
  Local correlations (10 keV)
  - shell structure, spin-orbit interaction, pairing, collectivity

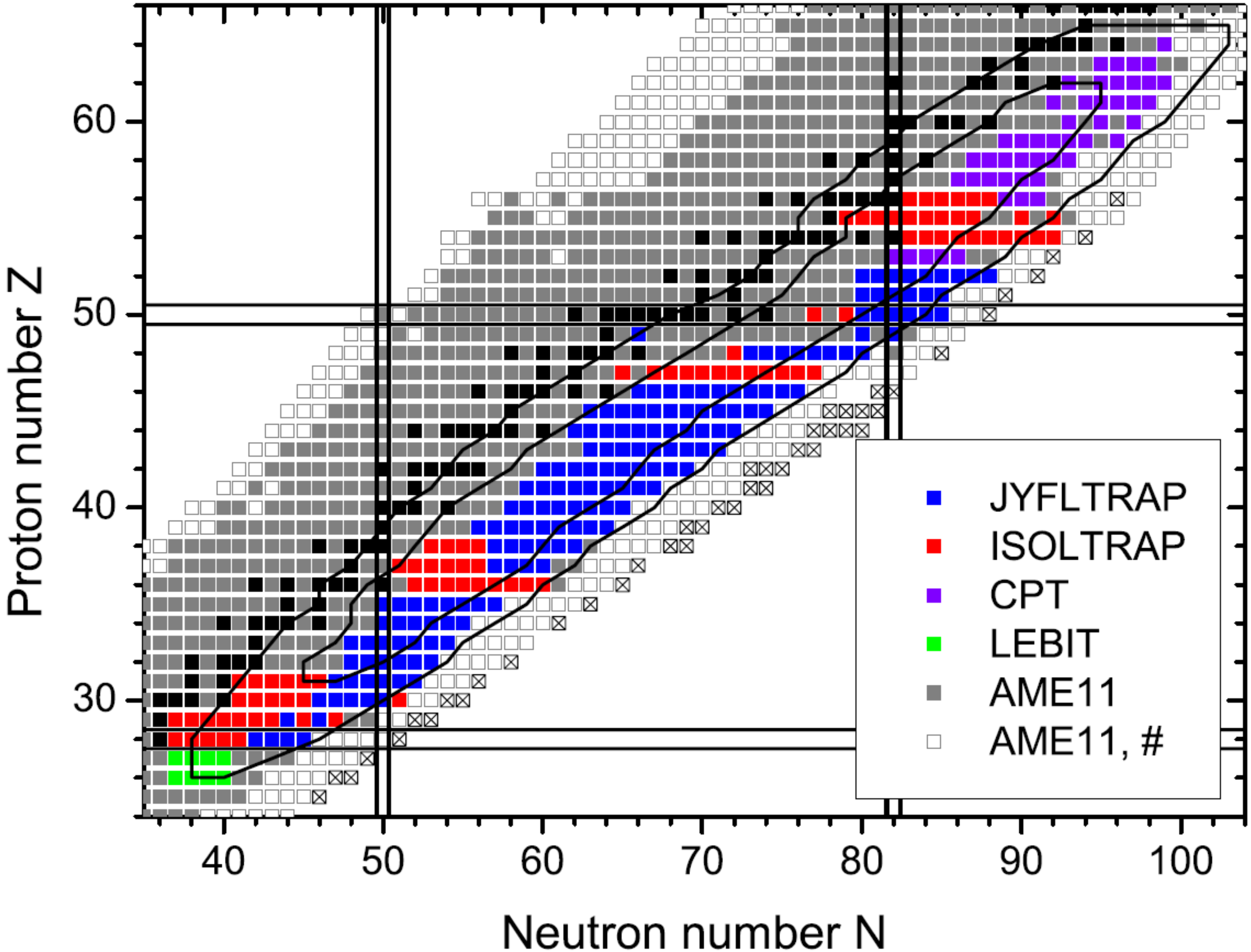
  Drip-line phenomena, halos, isomers (1 keV)

- **Nuclear astrophysics (≥ 1 keV)**

- **Charge symmetry in nuclei (≤ 1 keV)**
  Isospin multiplets
  Coulomb energy differences

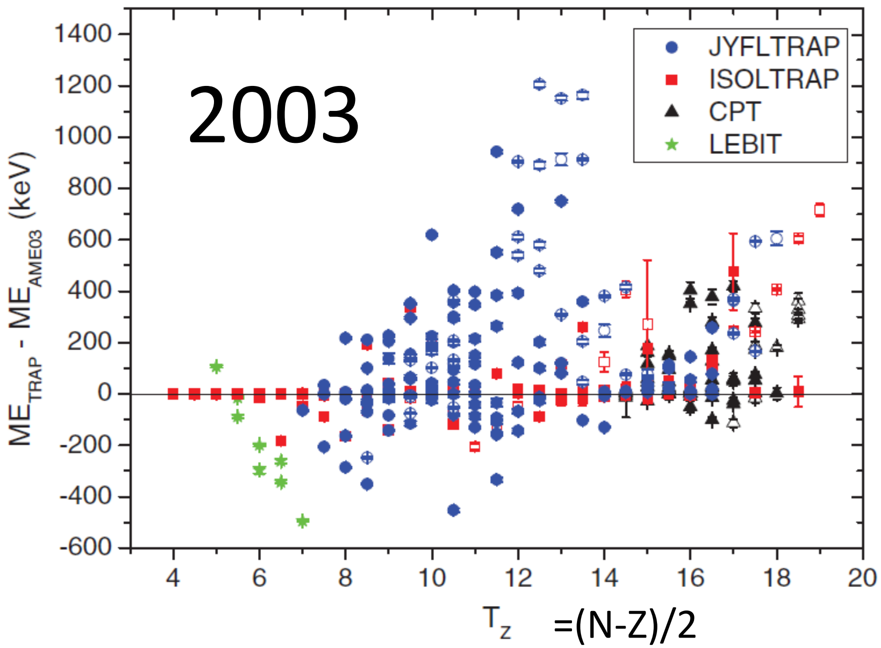
- **Test of Standard Model (≤ 100 eV)** $\delta m/m < 1\cdot10^{-9}$
  Nuclear β decay. Electroweak interaction
  - CVC theory and unitarity of CKM matrix
  - Double β decay

PT measurements of fission fragments



AME vs. PT data (n-rich nuclei)

A. Kankainen, J. Äystö and A. Jokinen, J. Phys. G 39 (2012) 093101



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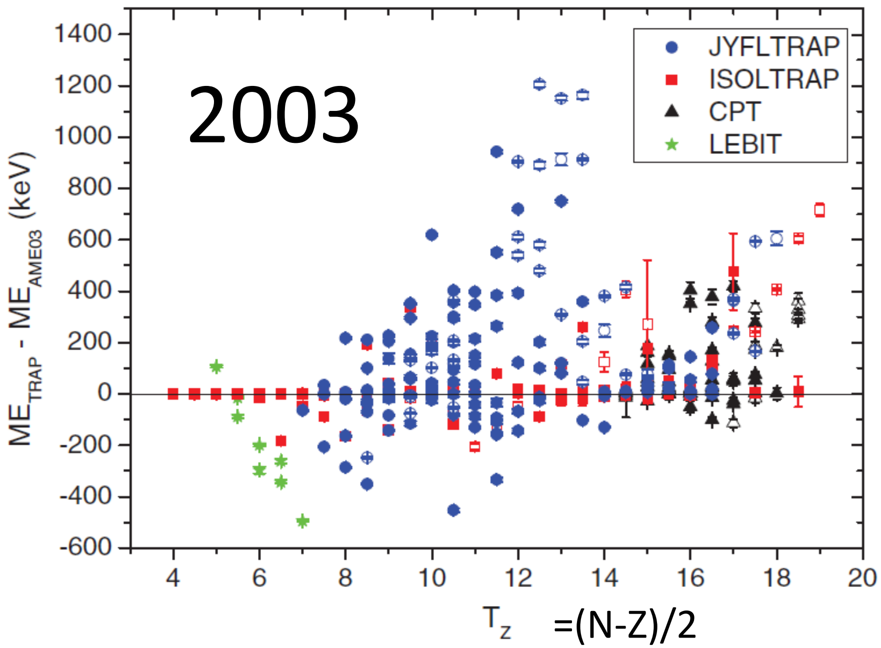
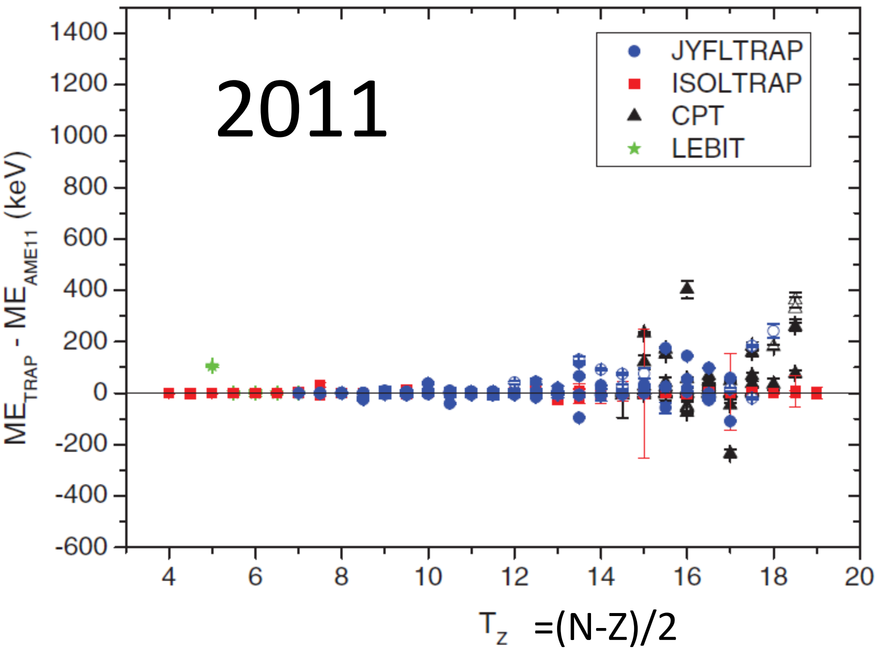
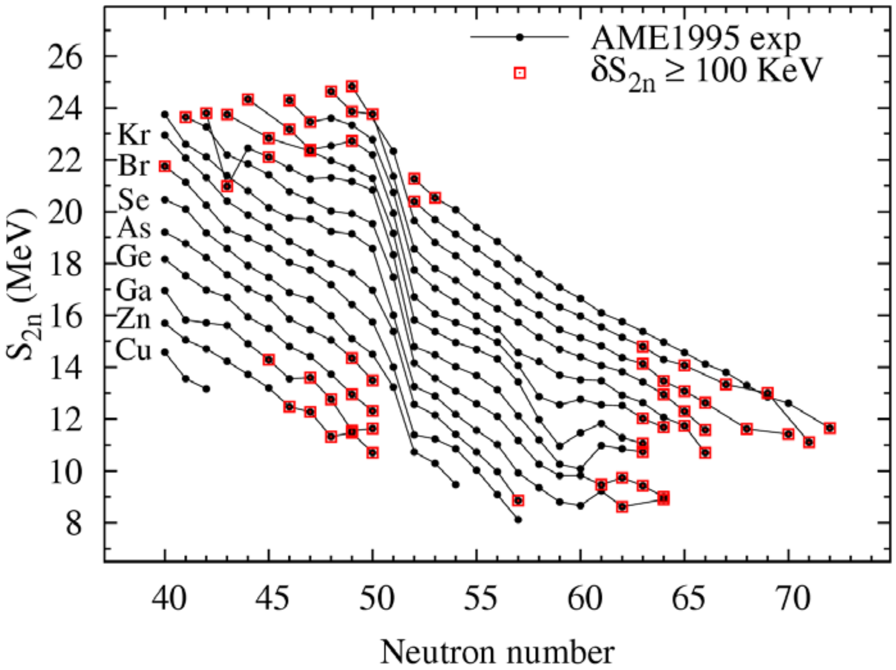




New results deviate less from the AME11 values than the Penning-trap measurements in general from the AME03.

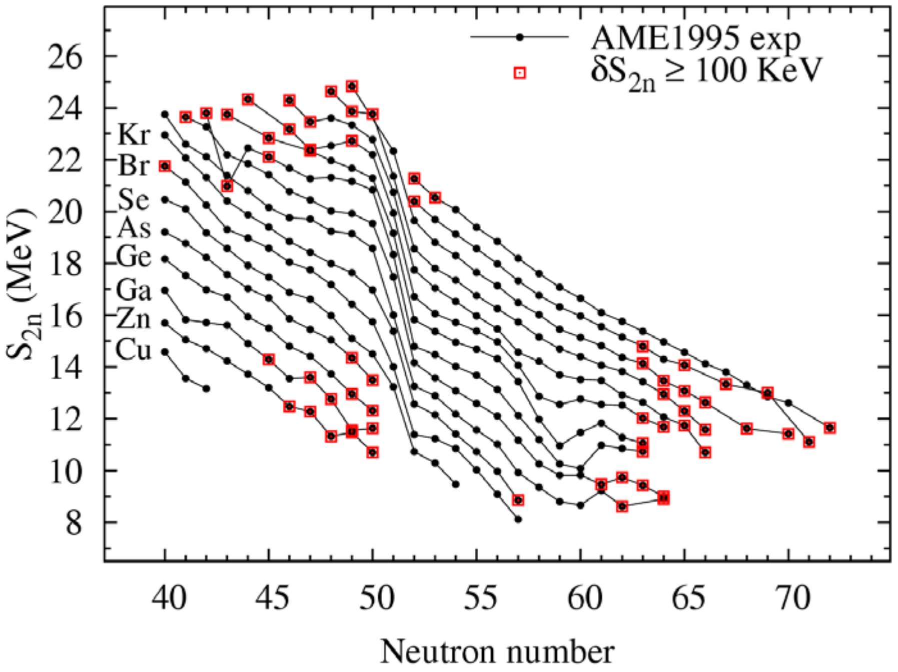
Two-neutron separation energy S_{2n}

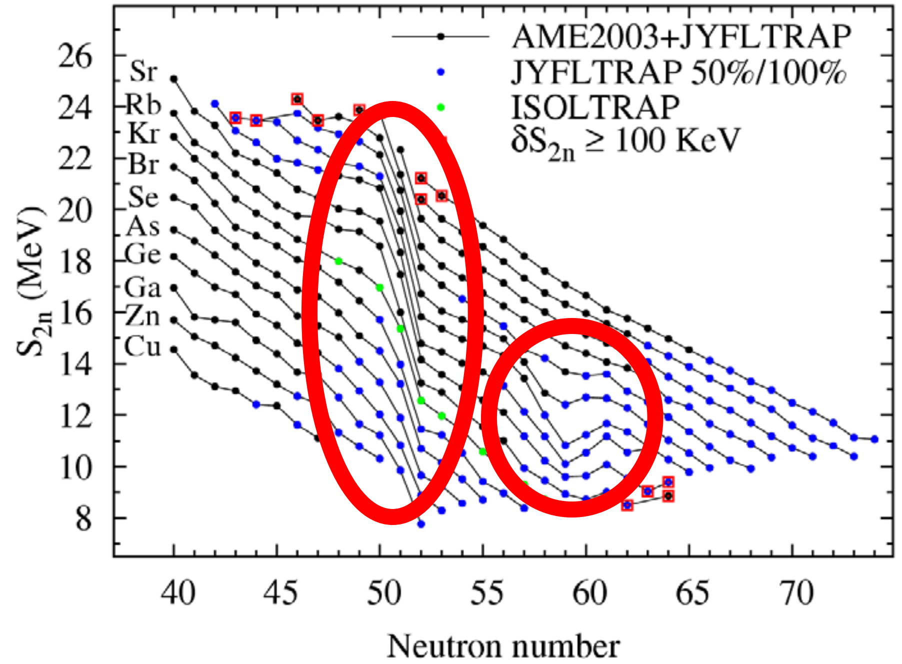
$$S_{2n}(N,Z) = B(N,Z) - B(N-2,Z)$$



Impact of the new data, e.x. S_{2n} values

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





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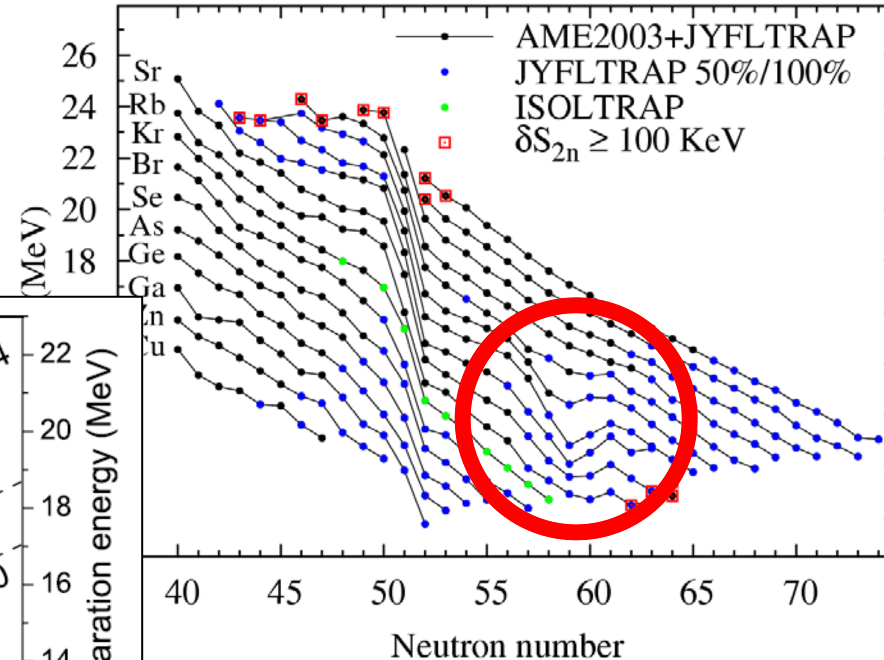
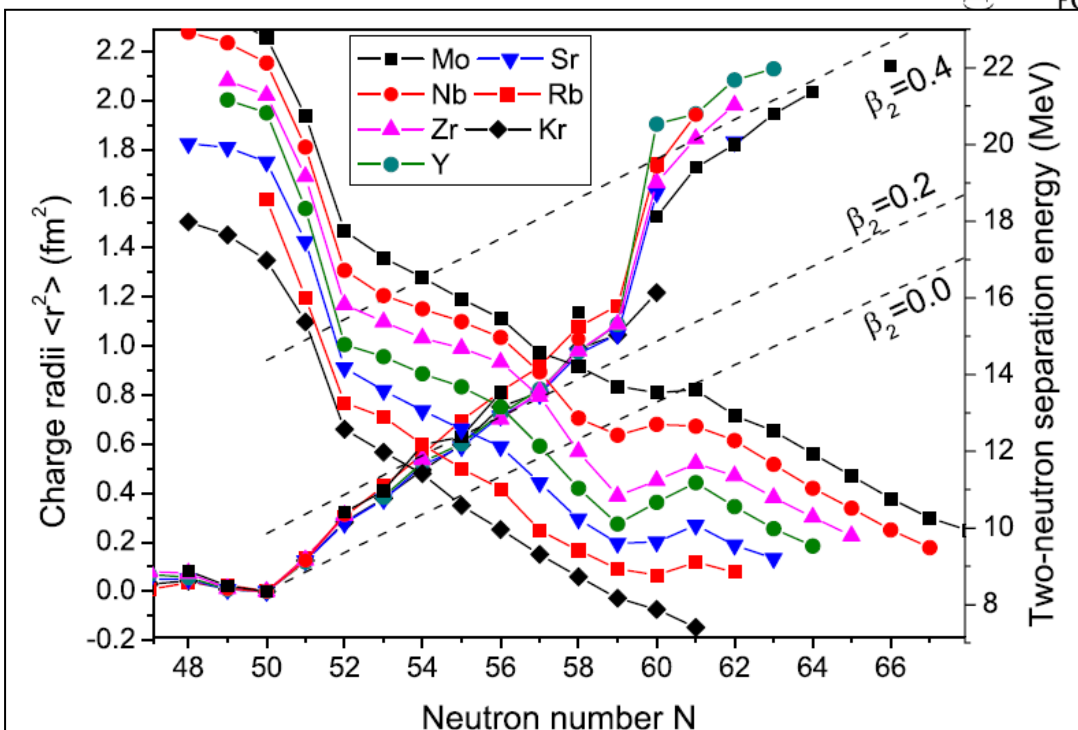
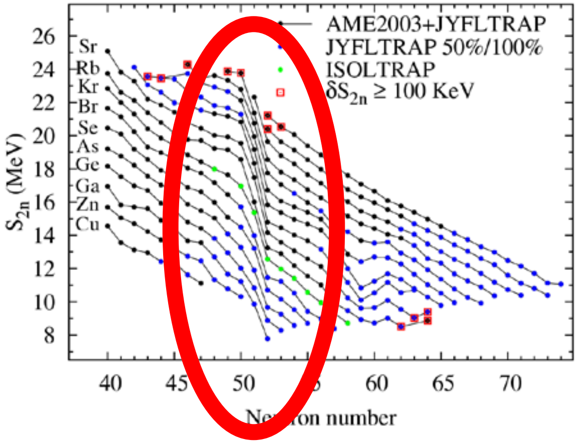


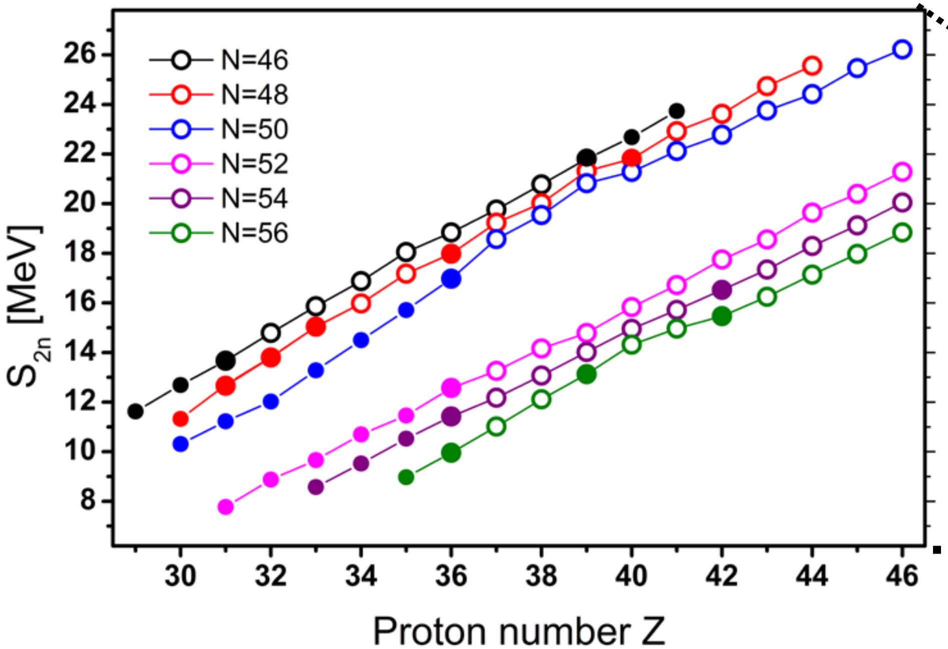


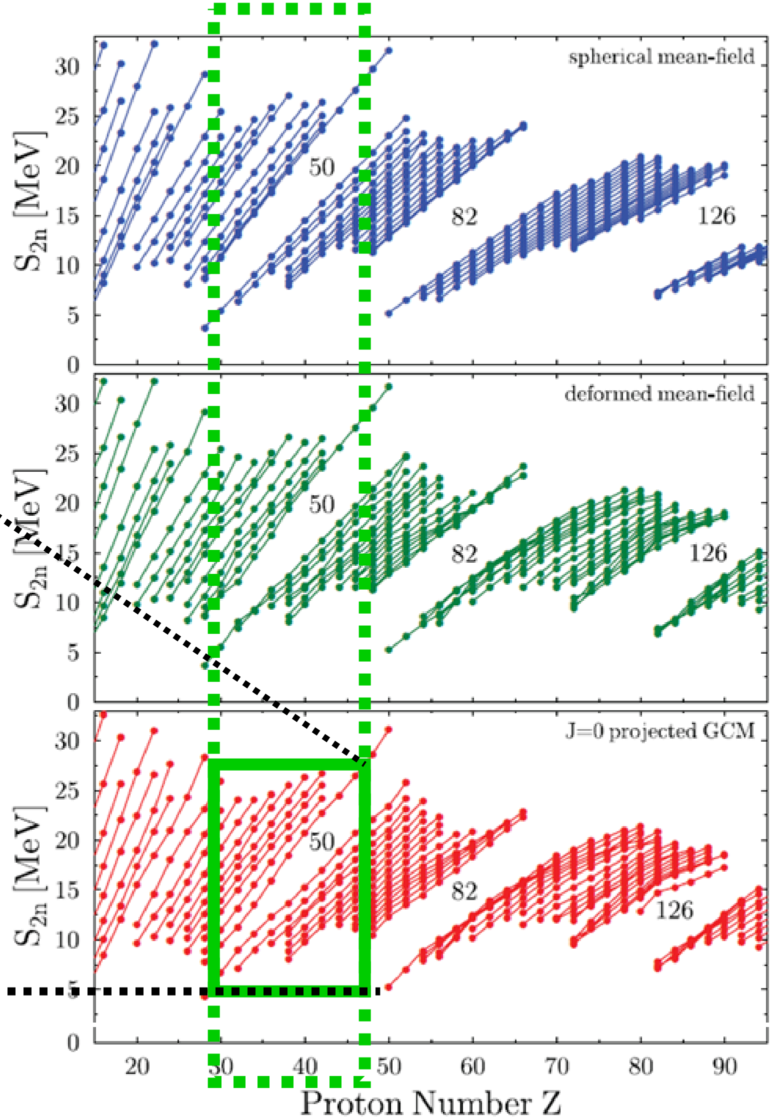
Collinear laser spectroscopy:

PRL 89 (2002) 082501
PLB 645 (2007) 133
PLB 674 (2009) 23
PRL 102 (2009) 222501

Evolution of N=50 shell gap







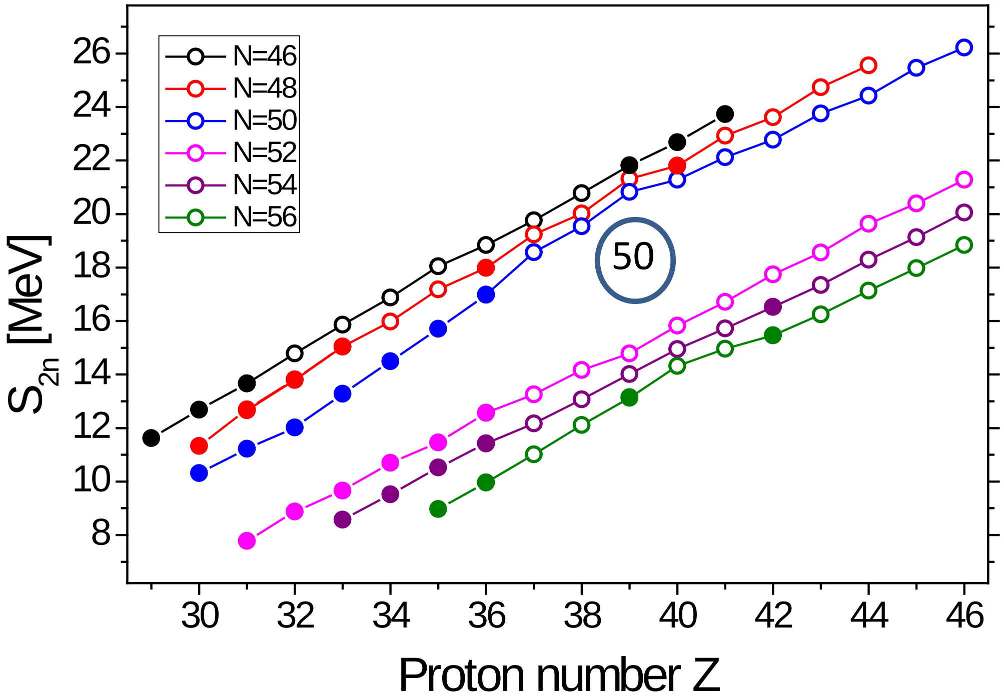
J. Hakala et al. PRL 101 (2008) 052502
+ ^{81}Zn: S. Baruah et al., PRL 101 (2008) 262501

M. Bender et al. PRC 78 (2008) 054312

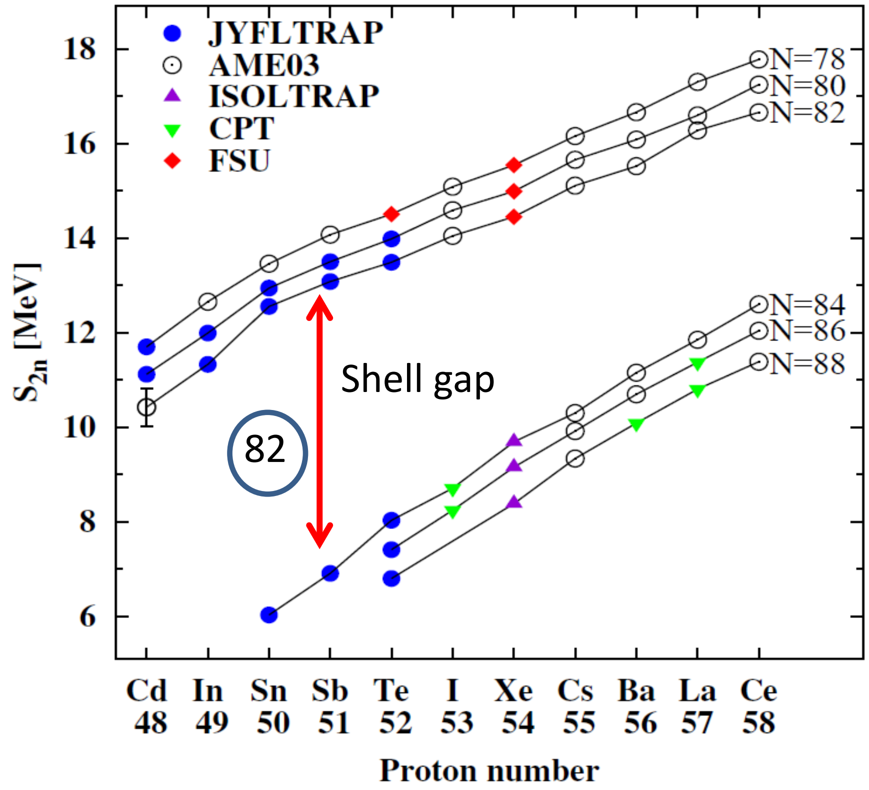
Evolution of shell gaps

$$\delta_{2n}(N_0) = S_{2n}(Z, N_0) - S_{2n}(Z, N_0 + 2)$$

Two-neutron shell gap for N=50



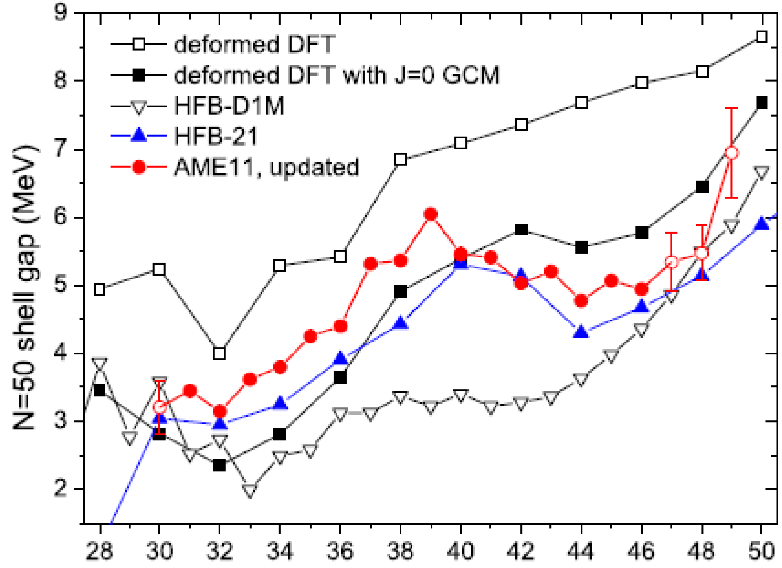
Two-neutron shell gap for N=82

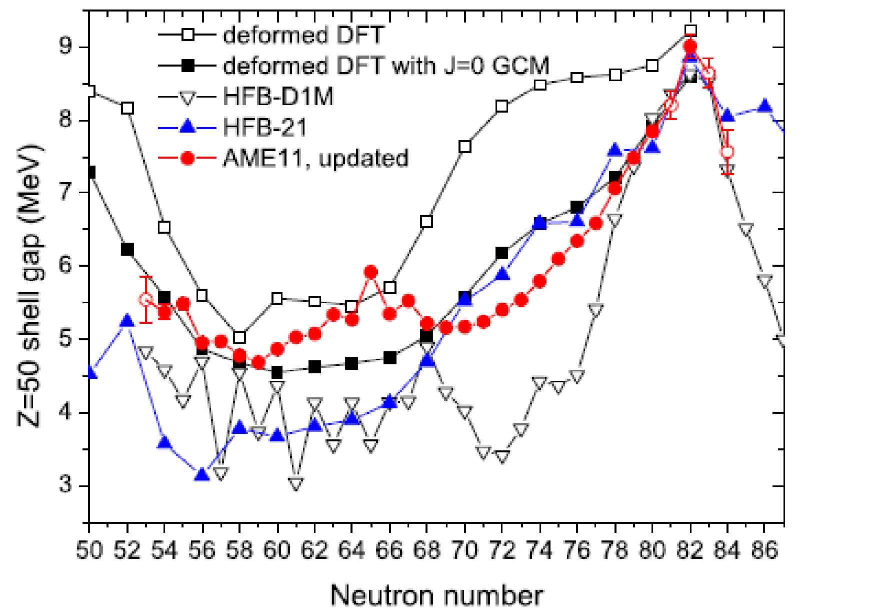


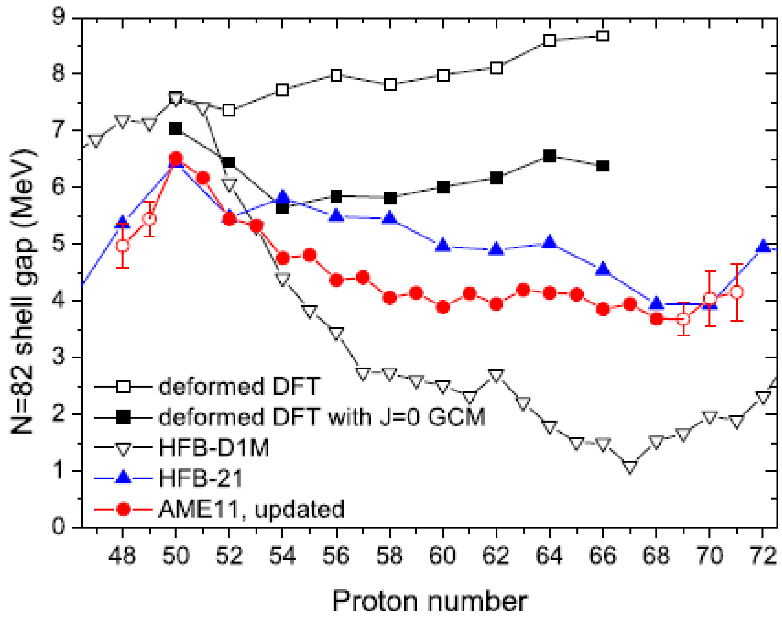
J. Hakala et al., PRL **101** (2008) 052502

J. Hakala et al., PRL **109** (2012) 032501

Shell gaps at Z=50, N=50 and N=82







Shell gap equation:

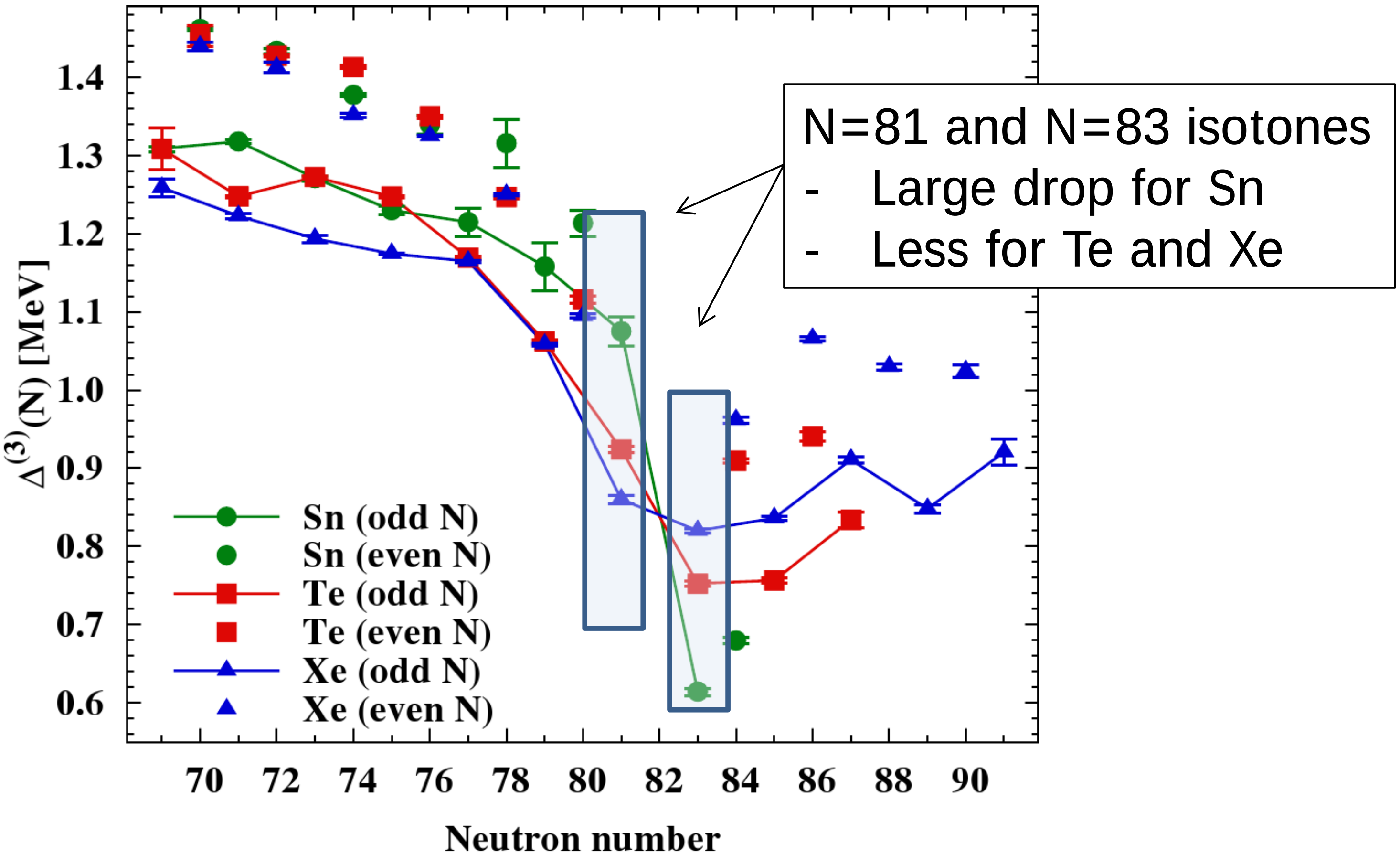
$$\delta_{2n}(N_0) = S_{2n}(Z, N_0) - S_{2n}(Z, N_0 + 2)$$

1. Persistence of N=82 shell gap
2. Reproduction of the data requires inclusion of dynamical correlations

A. Kankainen, J. Äystö and A. Jokinen, J. Phys. G 39 (2012) 093101

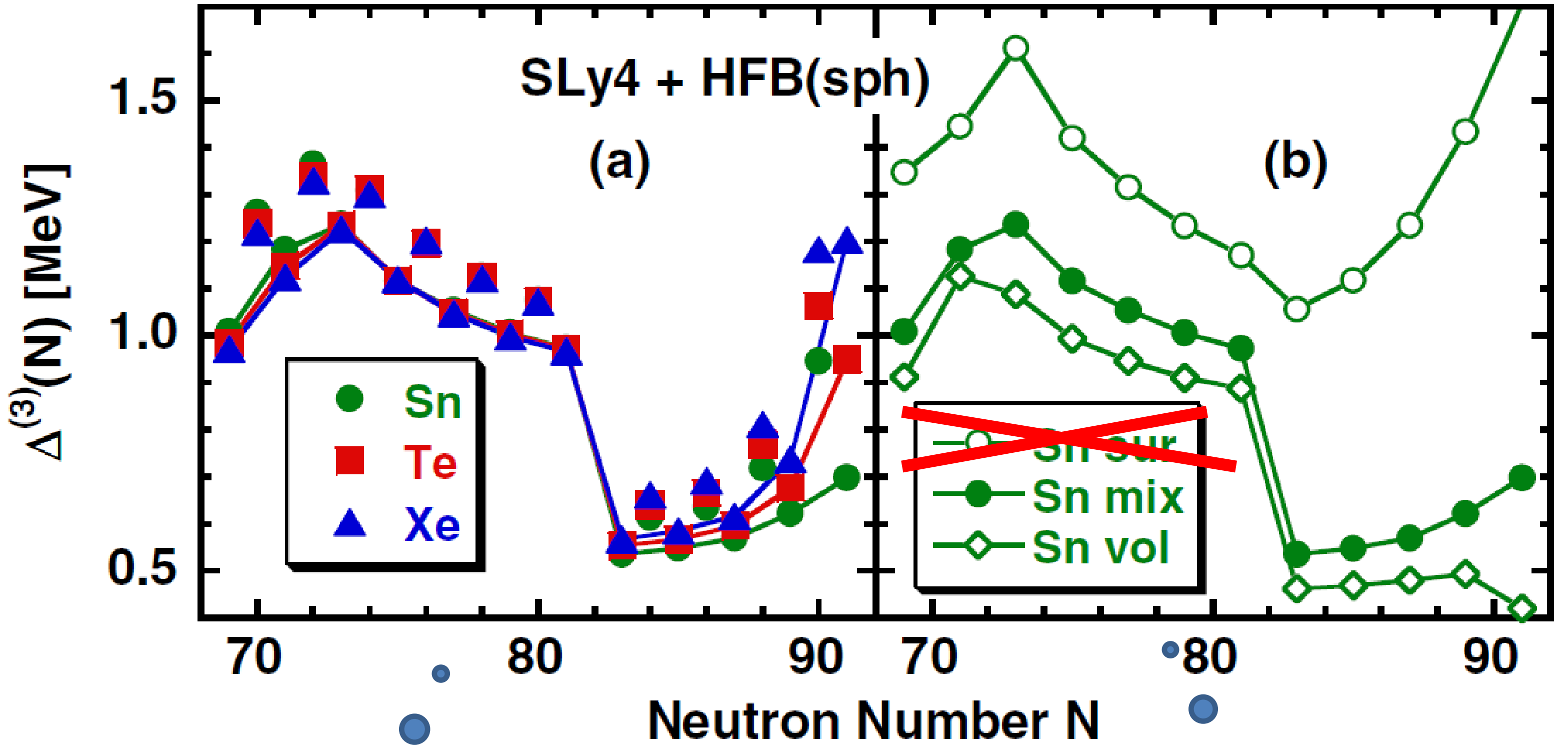
Odd-even mass staggering;
a measure of empirical pairing gap

$$\Delta^{(3)}(N) = (-1)^N [E(N+1) - 2E(N) + E(N-1)]/2$$



J. Hakala et al., PRL **109** (2012) 032501

Spherical EDF calculations around ^{132}Sn

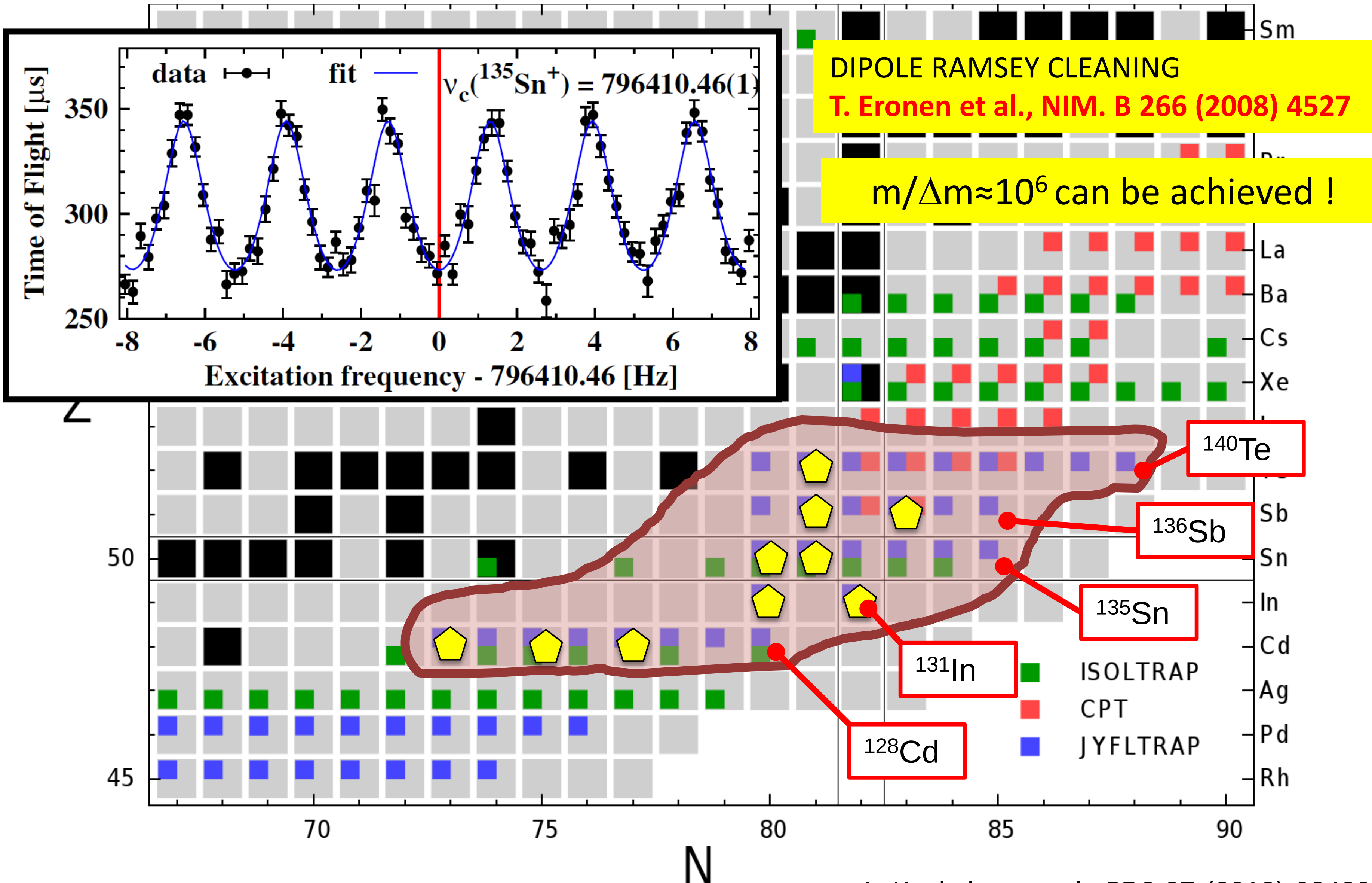


Spherical approach
→ Sn isotopes

Pairing options (Sn):
Pure surface pairing
excluded

J. Hakala et al., PRL **109** (2012) 032501

Isomeric states close to ^{132}Sn, $T_{1/2}$ > 100 ms



DIPOLE RAMSEY CLEANING

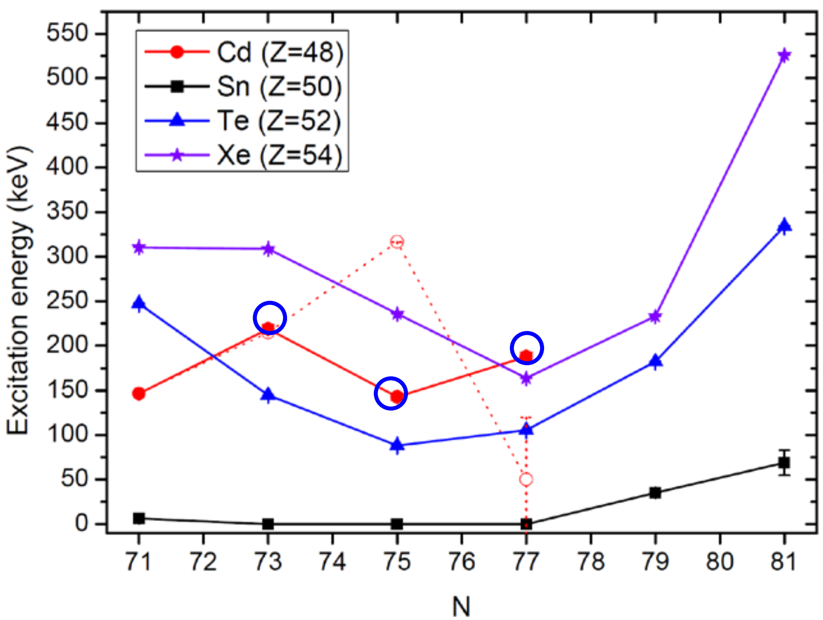
T. Eronen et al., NIM. B 266 (2008) 4527

m/Δm≈10^6 can be achieved !

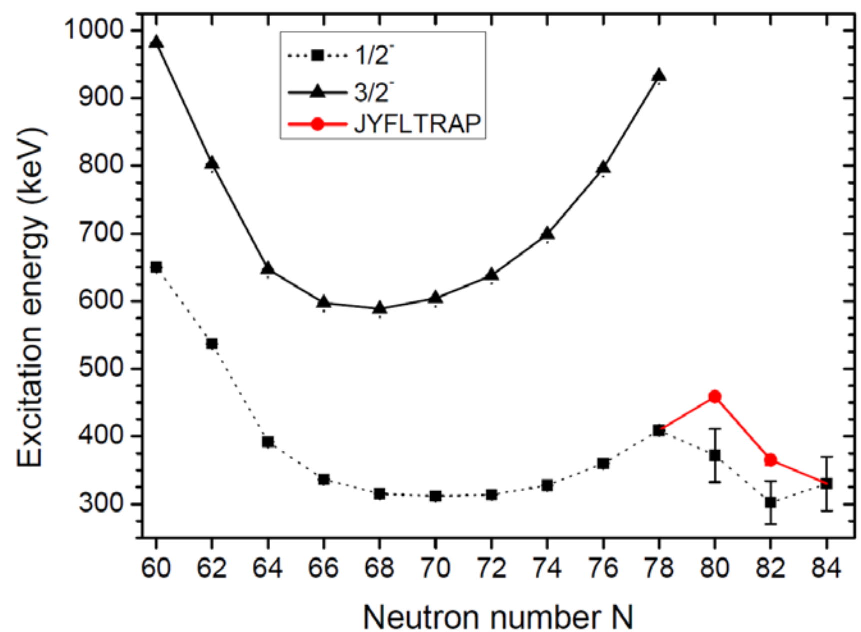
A. Kankainen et al., PRC 87 (2013) 024307

Single-particle states close to ^{132}Sn

SYSTEMATICS of the 11/2$^-$ state

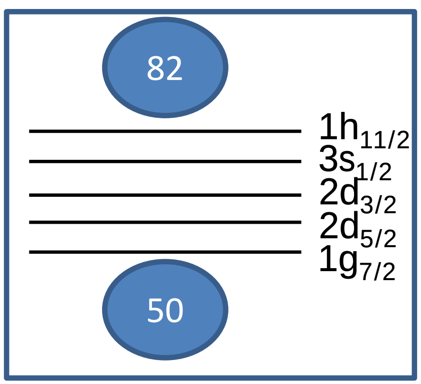


SYSTEMATICS of the 1/2$^-$ state



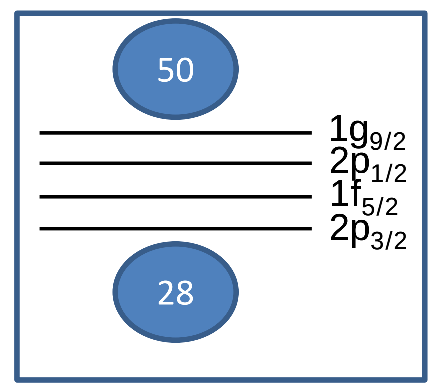
Odd neutron in the $1h_{11/2}$ shell

Cd isomers relocated → trend similar to Te isomers



In (Z=49) proton-hole in the $2p_{1/2}$ shell

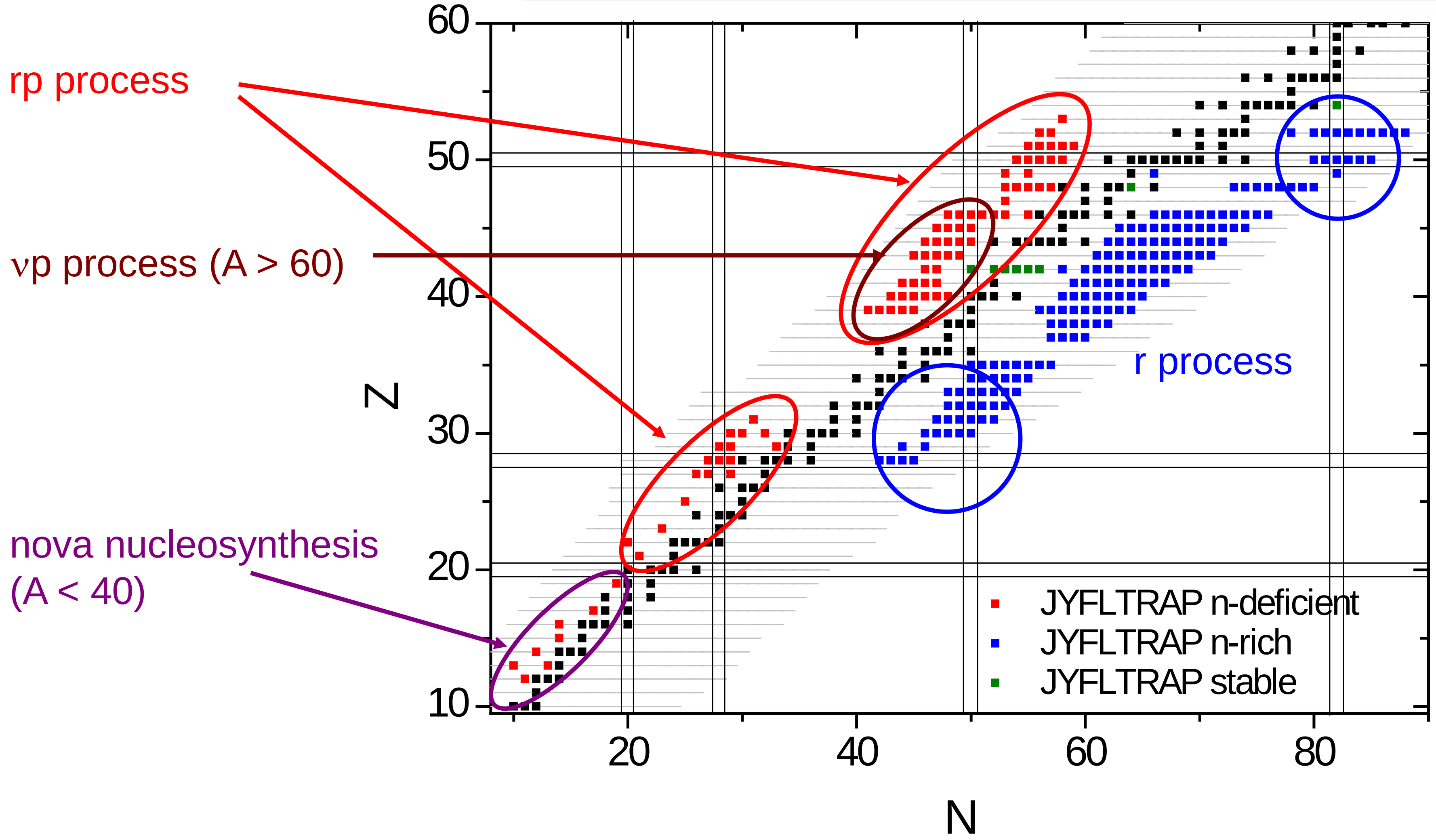
Old Q-value based energies corrected



A. Kankainen et al., PRC 87 (2013) 024307

Nuclear astrophysics at JYFLTRAP

Masses → reaction rates → path, abundance pattern,…



Masses in nuclear astrophysics

Astrophysical reaction rate for a (p,γ) resonant capture

$$N_A\langle\sigma v\rangle_r = 1.54\times 10^{11}(\mu T_9)^{-3/2}\sum_i(\omega\gamma)_i \times \exp(-11.605 E_i/T_9)\ \mathrm{cm^3 mol^{-1} s^{-1}}$$

$E_i = E_x - S_p$

Abundances (Saha-equation)

$$\frac{Y(Z+1,N)}{Y(Z,N)} \propto \exp\left(\frac{S_p(Z+1,N)}{kT}\right)$$

Beta-decay rates are strongly mass dependent

$\lambda_\beta \sim Q^5$

Reaction rate of $^{25}Al(p,\gamma)^{26}Si$

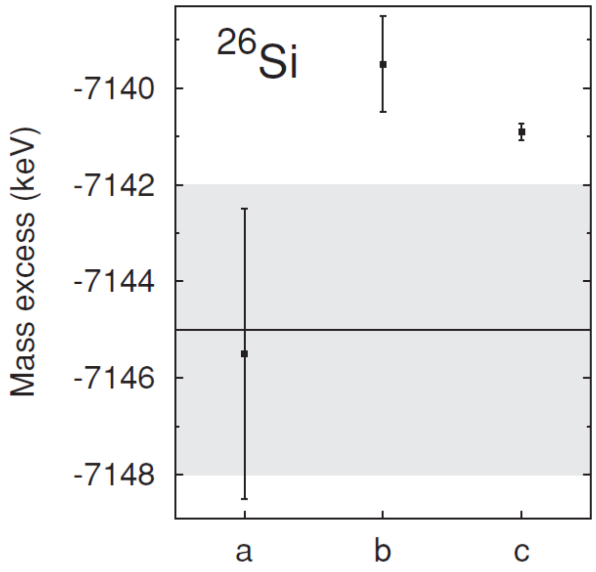
Important reaction to bypass ^{26}Al production in MgAl cycle. Resonant proton captures to excites states above proton threshold

$$N_A \langle \sigma v \rangle_r = N_A \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \sum_i (\omega\gamma)_i \exp\left[-E_{r,i}/(kT)\right]$$

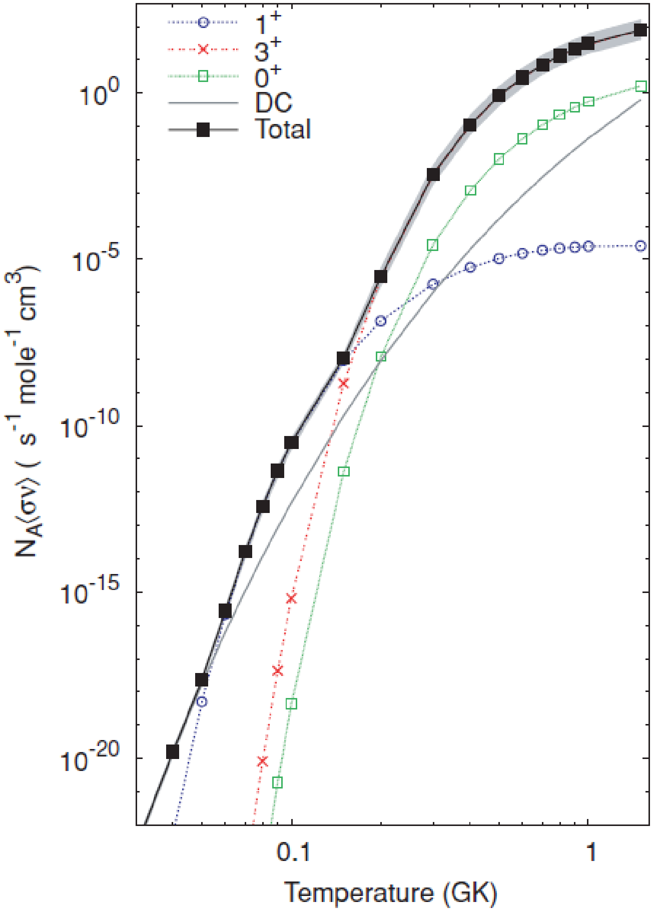
$E_r = E_x - S_p$

Need to know:

- Energies of the final states
- Width of the initial and final state
- **Proton separation energy S_p=5513.7(5) keV**



(a) J. C. Hardy et al., Phys. Rev. C 9, 252 (1974)
(b) A. Parikh et al., Phys. Rev. C 71, 055804 (2005)
(c) JYFLTRAP



T. Eronen et al., PRC 79, 032802(R) (2009)

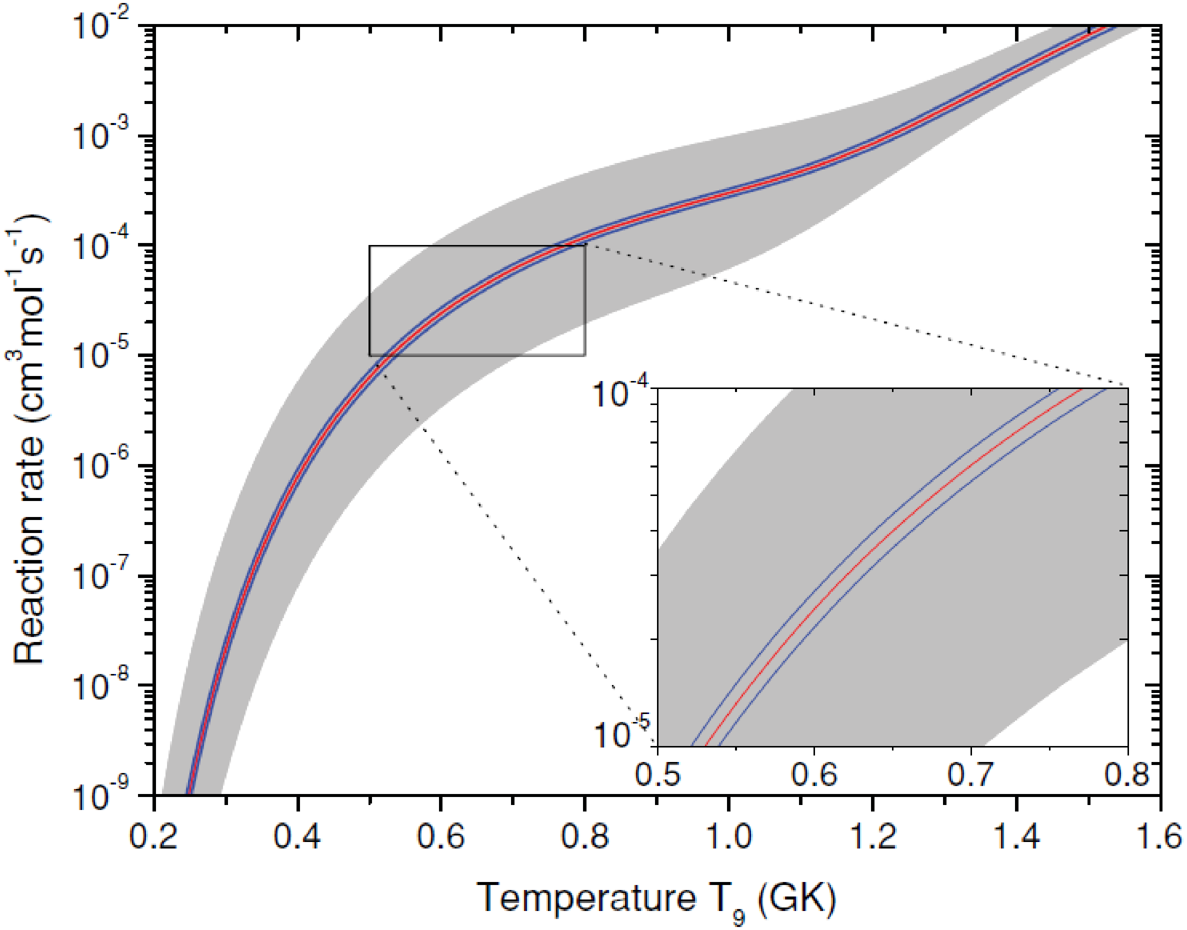
$^{56}Ni(p,\gamma)^{57}Cu$

JYFLTRAP:
$Q_{(p,\gamma)}$=689.7(5) keV

vs

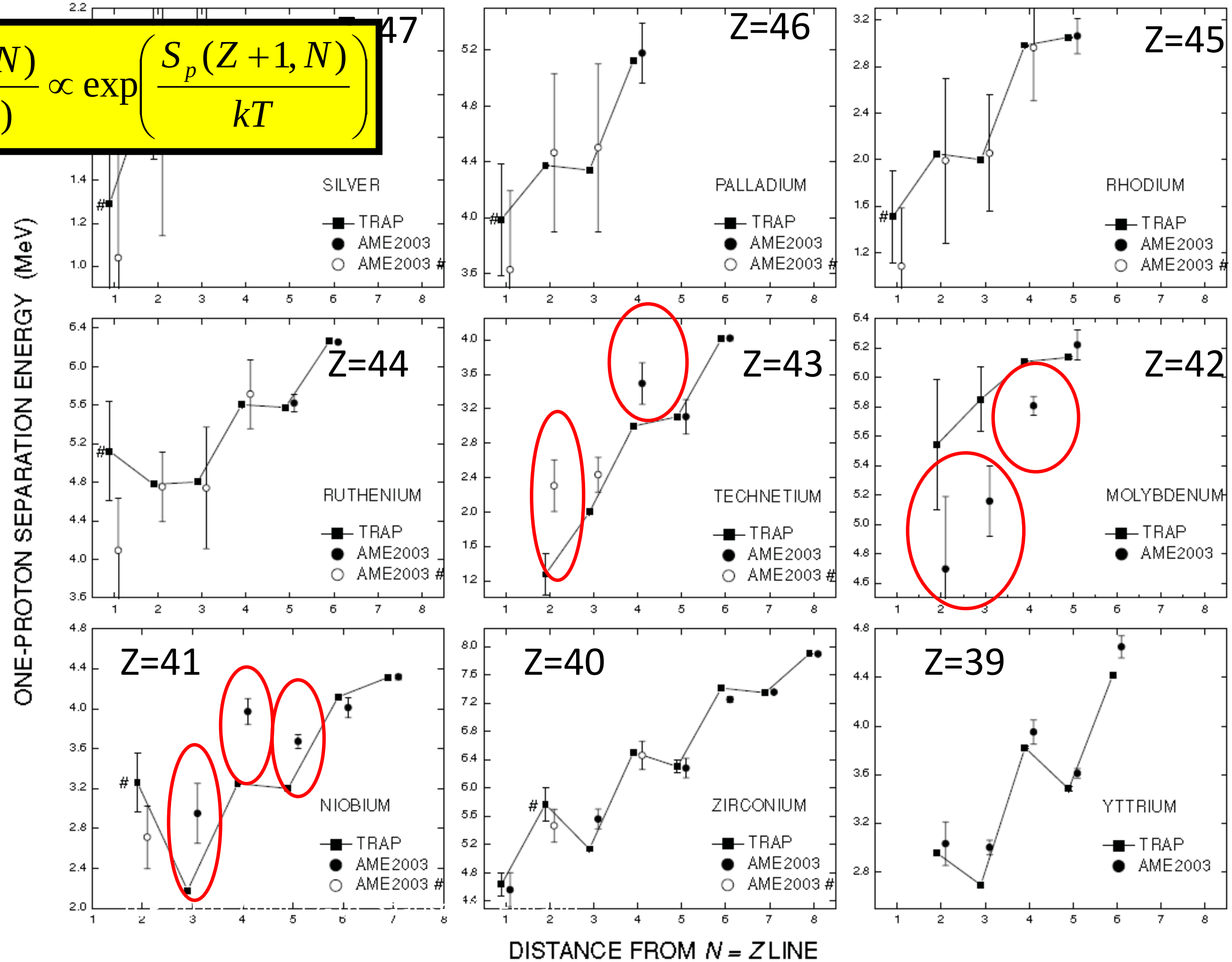
AME03:
$Q_{(p,\gamma)}$= 695(19) keV

rates very similar
but
uncertainties much smaller



Proton separation energies S_p

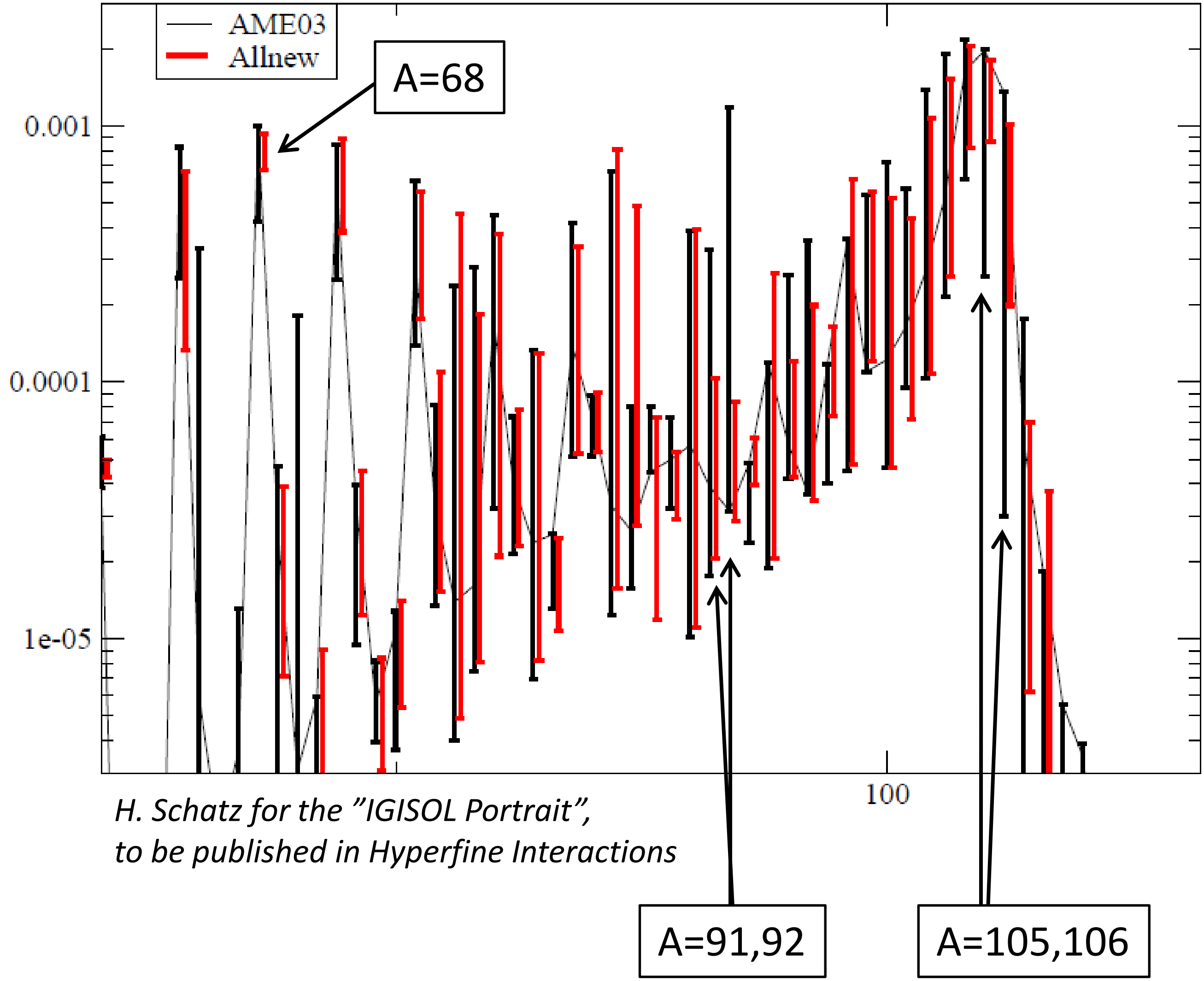
$$\frac{Y(Z+1,N)}{Y(Z,N)} \propto \exp\left(\frac{S_p(Z+1,N)}{kT}\right)$$



Rp-process abundances

Penning trap measurements

uncertainties of important most abundant isotopes at A = 68, 91, 92, 105, 106 drastically reduced



H. Schatz for the "IGISOL Portrait", to be published in Hyperfine Interactions

Effect on the νp process

$\Delta ME_{AME\text{-}TRAP}(^{88}Tc)$= -1031 keV

⬇

$^{87}Mo(n,p)^{87}Nb$
instead of
$^{87}Mo(p,\gamma)^{88}Tc$

⬇

more ^{87}Nb → more A=87

$\Delta ME_{AME\text{-}TRAP}(^{90}Tc)$=-486 keV

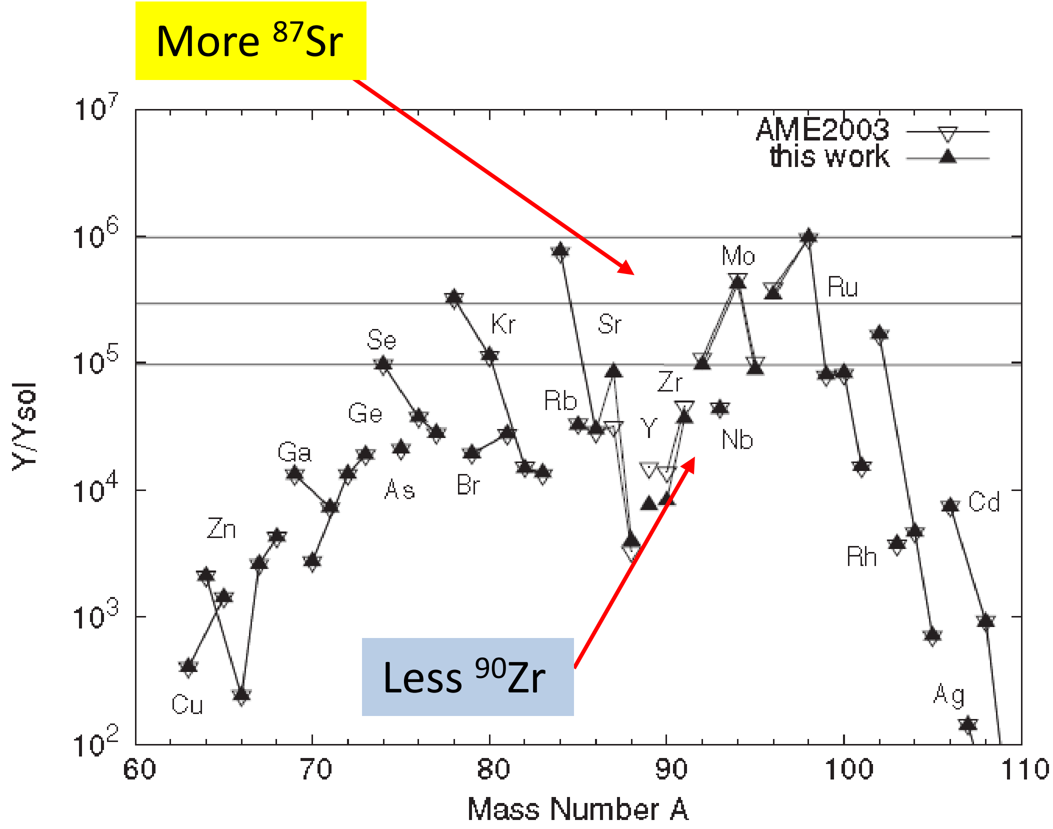
⬇

increase in $^{90}Tc(\gamma,p)^{89}Mo$

⬇

less ^{90}Tc → less A=90

Final abundances after decay to stability relative to solar abundances

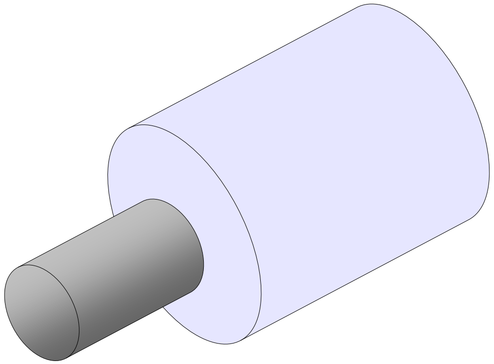


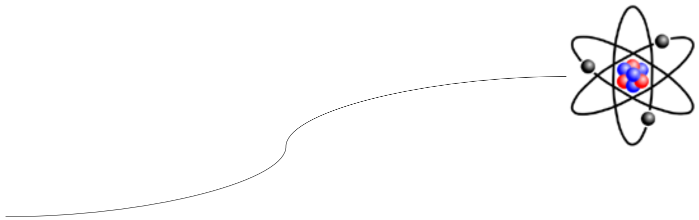
C. Weber et al. Phys. Rev. C 78, 054310 (2008)
νp calculations by C. Fröhlich et al.

Trap-assisted spectroscopy

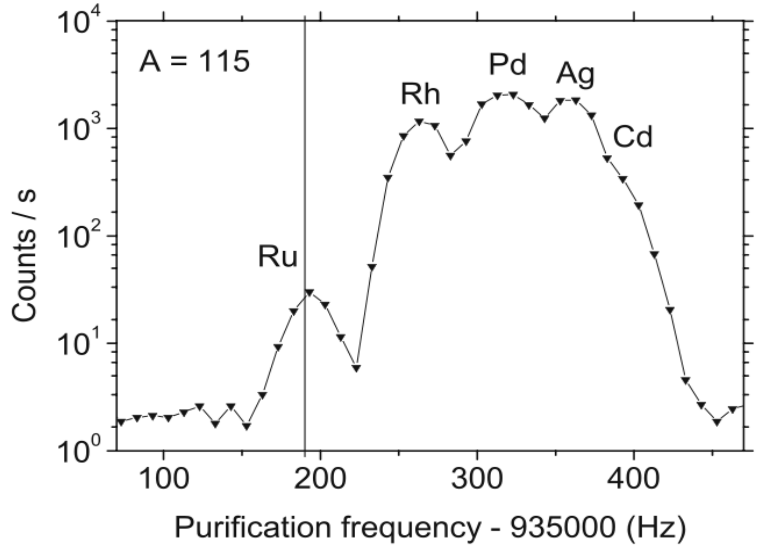
1. Precision mass measurement providing spectroscopically relevant information
2. Ion beam/cloud manipulation to improve spectroscopic measurements (**”Post-trap spectroscopy”**)
    - Change of emittance, energy spread or time structure
    - Sample **purification** (**isobaric**/isomeric**)**
    - Change of the chemical element via decay in the trap
    - Change of the ionic state
3. Spectroscopy inside the trap (”in-trap spectroscopy”)

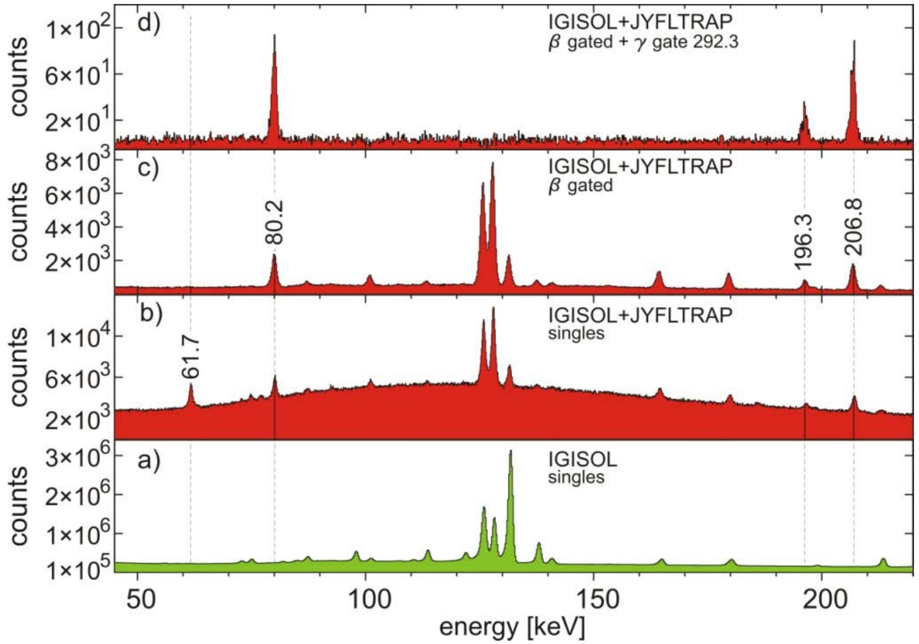
TOOLS: Paul trap and Penning trap

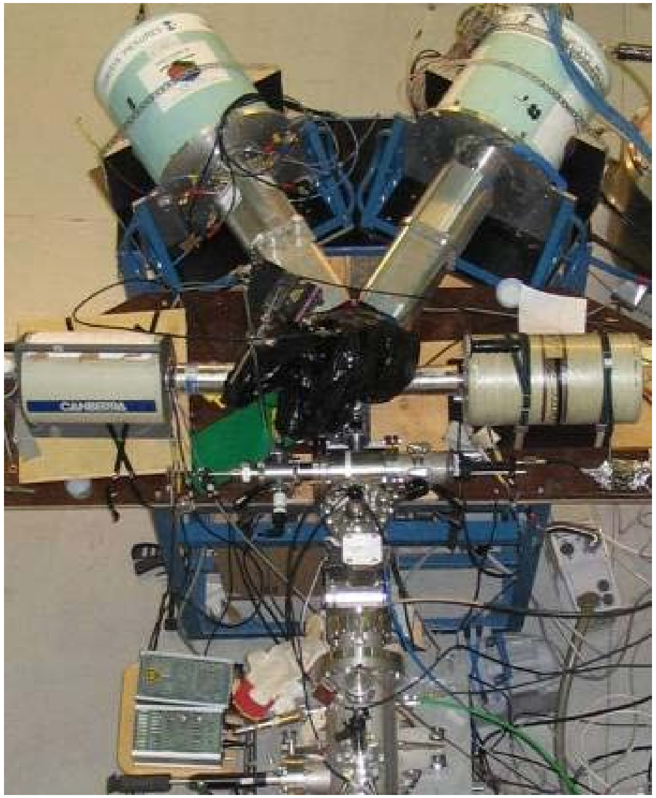




Example: Purification in A=115

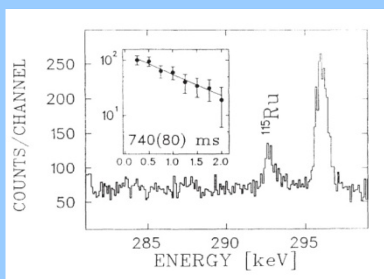




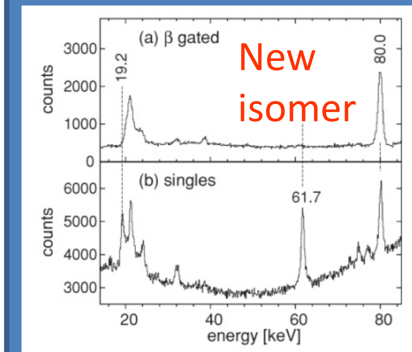


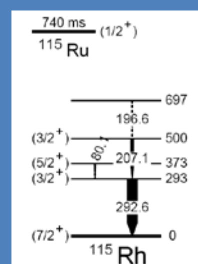
Impact of the trap: ^{115}Ru

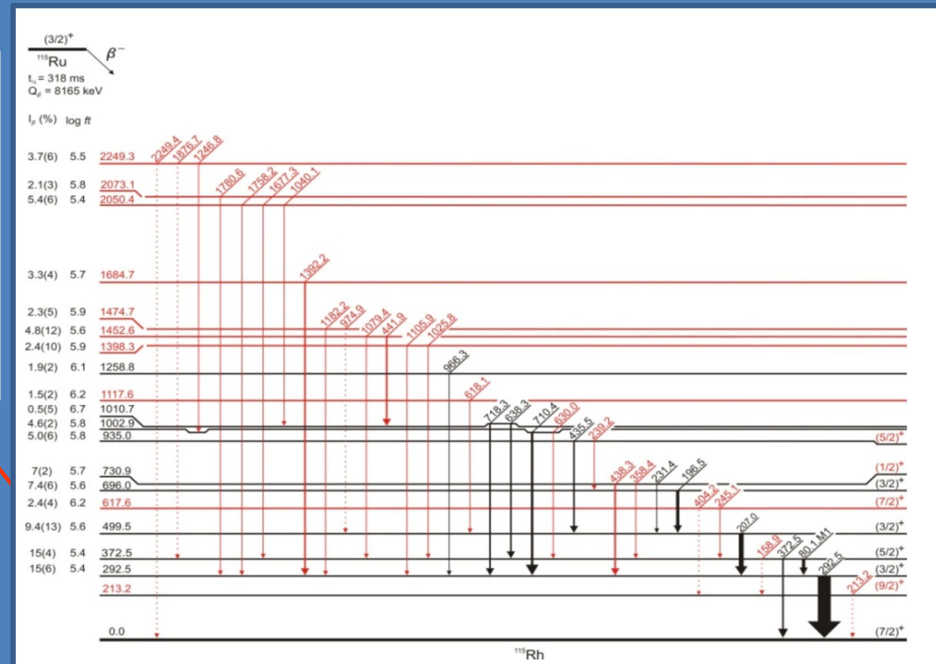
IGISOL only



IGISOL+JYFLTRAP







1992

IGISOL experiment

292.8 keV gamma line

$t_{1/2}$=740(80) ms ??

J. Äystö et al., PRL 69, 1167 (1992)

2007

Trap-assisted test experiment

First simple beta-decay scheme

J. Kurpeta et al., EPJ A 31, 263 (2007)

2010

Trap-assisted half-life measurement

-$t_{1/2}$(g.s)=318(19) ms

-$t_{1/2}$(i.s)=76(6) ms

J. Kurpeta et al., PRC 82, 064318 (2010)

2011

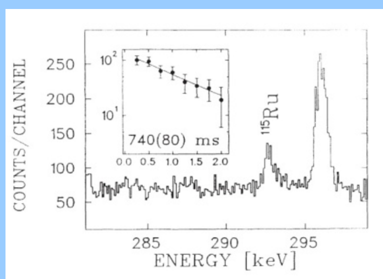
Trap-assisted beta-decay experiment

Extended beta-decay scheme

J. Rissanen et al., EPJ A 47, 97 (2011)

Impact of the trap: ^{115}Ru

IGISOL only



1992

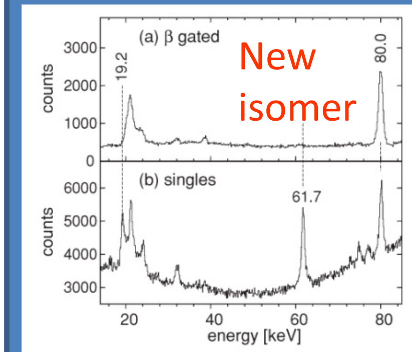
IGISOL experiment

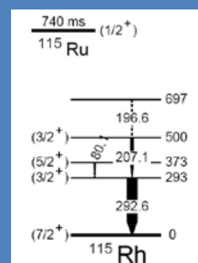
292.8 keV gamma line

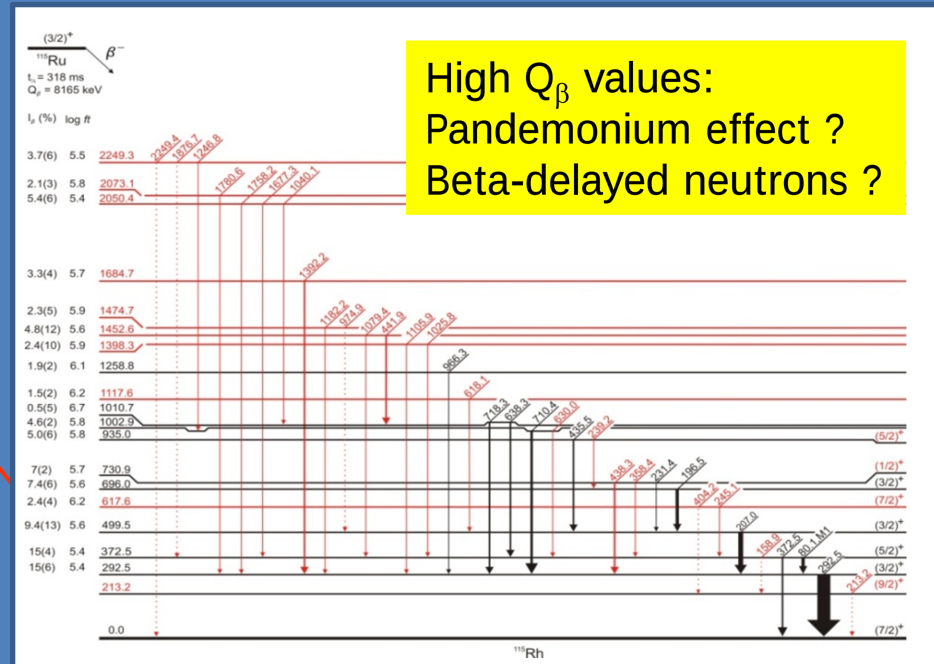
$t_{1/2}$=740(80) ms ??

J. Äystö et al., PRL 69, 1167 (1992)

IGISOL+JYFLTRAP







High Q_β values:
Pandemonium effect ?
Beta-delayed neutrons ?

2007

Trap-assisted test experiment

First simple beta-decay scheme

J. Kurpeta et al., EPJ A 31, 263 (2007)

2010

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-$t_{1/2}$(g.s)=318(19) ms

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J. Kurpeta et al., PRC 82, 064318 (2010)

2011

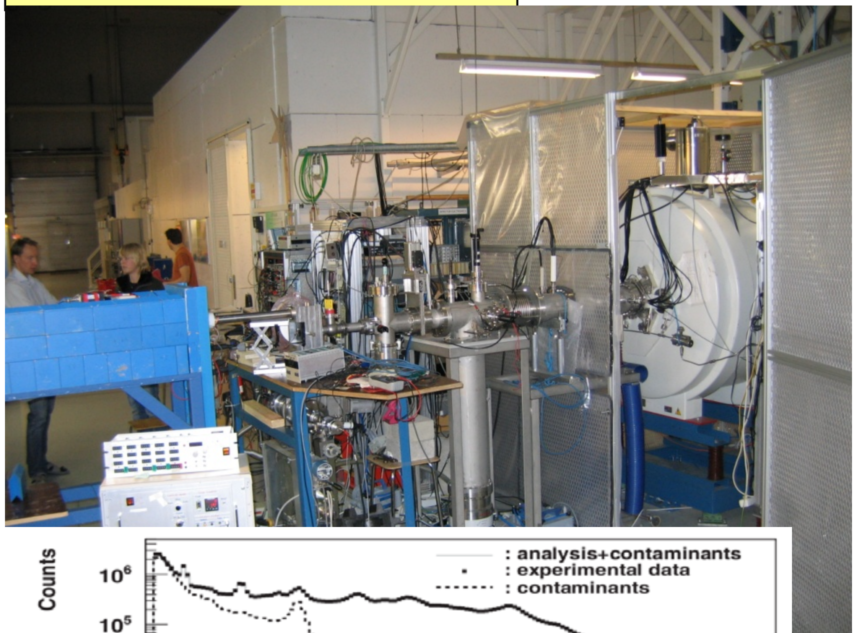
Trap-assisted beta-decay experiment

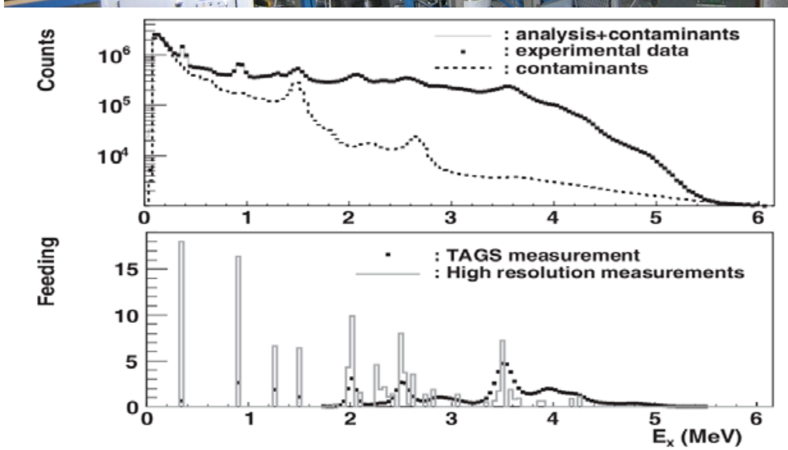
Extended beta-decay scheme

J. Rissanen et al., EPJ A 47, 97 (2011)

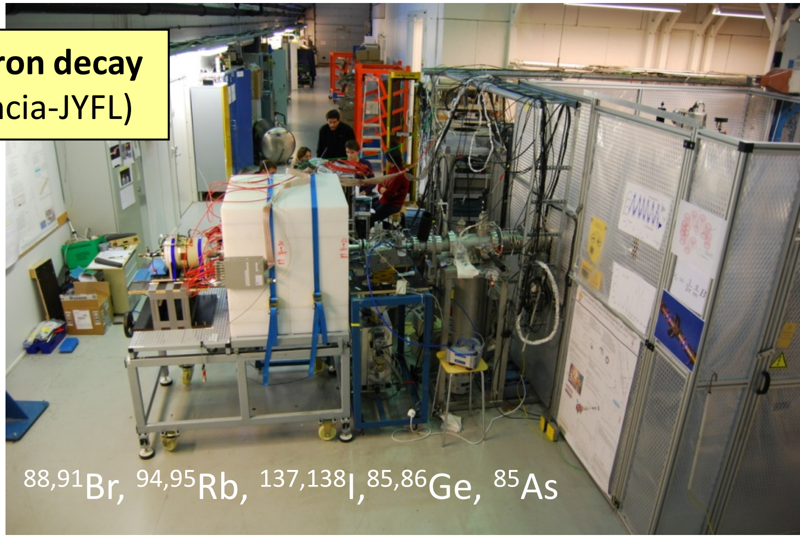
Pure samples for unselective instruments

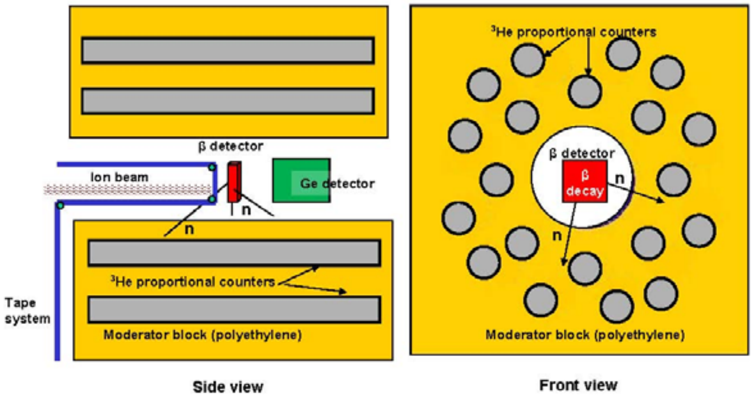
Total absorption spectroscopy
”Reactor decay heat studies”
PRL 105 (2010) 202501





Beta-delayed neutron decay
Nuclear data (Valencia-JYFL)





Collaboration:
CIEMAT (Madrid) – IFIC (Valencia) – Inst. Nucl. Res. (Debrecen) – LPC (Caen) – PNPI (St. Petersburg) – Univ. Jyväskylä (Jyvaskyla) – UPC (Barcelona) – Univ. Surrey (Surrey)

Q values from mass doublets

Parent and daughter produced simultaneously at IGISOL:

- cyclotron frequency of the parent: $\nu_{c,p}$
- cyclotron frequency of the daughter: $\nu_{c,d}$

$$\boxed{Q_{EC} = \underbrace{\left(\frac{\nu_{c,d}}{\nu_{c,p}} - 1\right)}_{< 10^{-3}} (m_d - m_e) c^2}$$

modest precision required

$$\boxed{\begin{aligned} \Delta Q_{\mathrm{EC}} &= \sqrt{(\Delta r)^2 (m_{\mathrm{daughter}} - m_e)^2 + (\Delta m_{\mathrm{daughter}})^2 (r-1)^2} \\ &\approx \Delta r \times (m_{\mathrm{daughter}} - m_e). \end{aligned}}$$

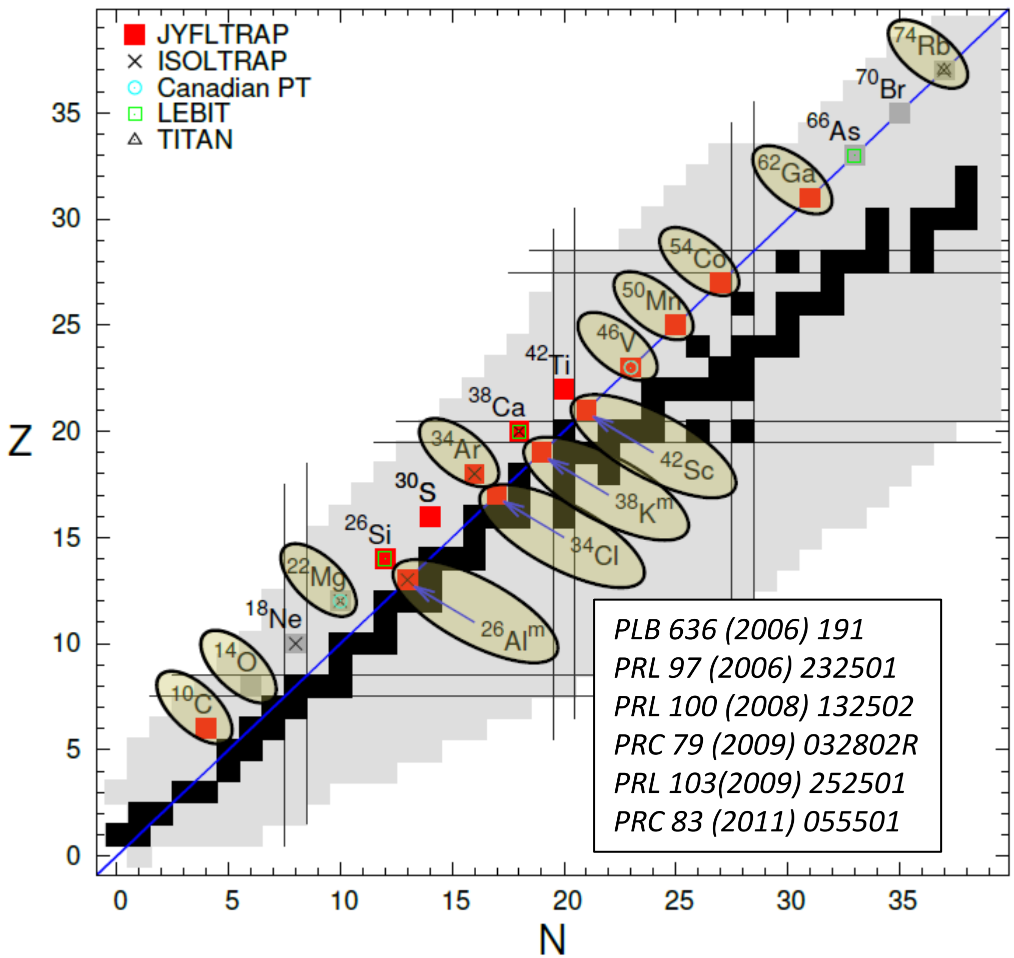
<u>In addition:</u>

Mass dependent corrections cancel out
(no external references required)

JYFLTRAP: $$\sigma_m(r)/r = 7.5(4) \times 10^{-10} \times \frac{\Delta m[\mathrm{u}]}{\mathrm{u}}$$

Superallowed Q_{EC} values

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



2005:
- ^{62}Ga

2006:
- ^{46}V, ^{42}Sc, ^{26}Al^{m}
- ^{26}Si, ^{42}Ti

2006-2007:
- ^{50}Mn, ^{54}Co

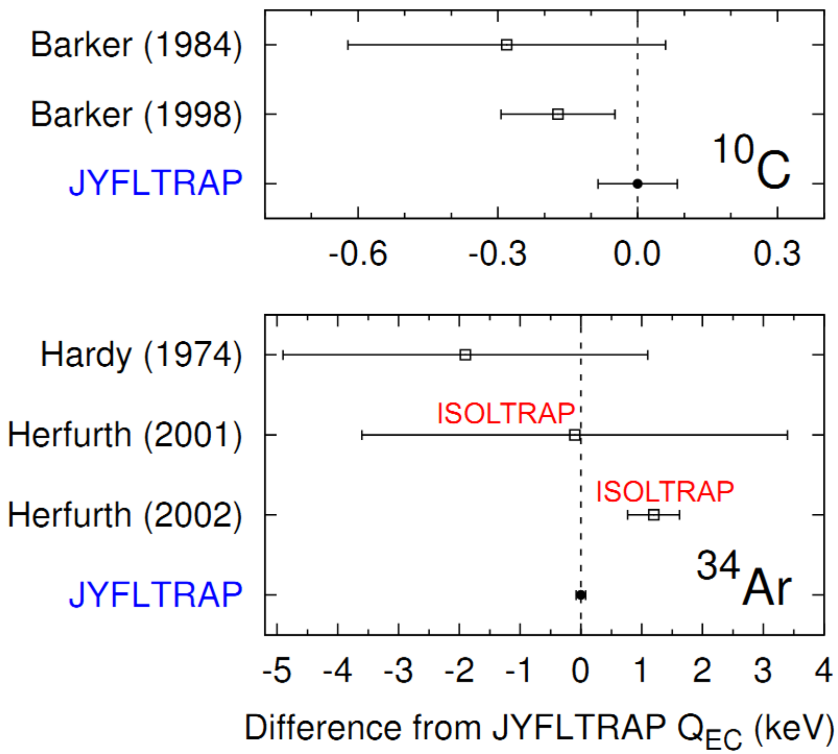
2009:
- ^{38}K^{m}, ^{34}Cl
- ^{30}S

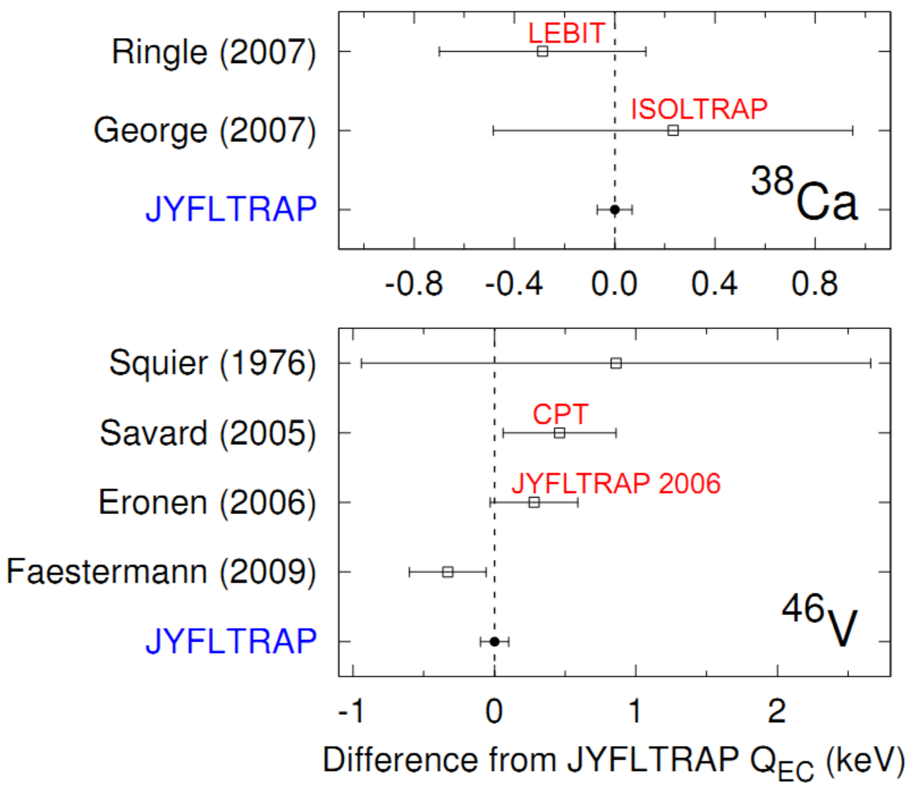
2010:
- ^{10}C, ^{34}Ar, ^{38}Ca

^{34}Ar, ^{38}K^{m} by using interleaved parent and daughter measurement !

Most recent Q_{EC} from JYFLTRAP

^{10}C, ^{34}Ar, ^{38}Ca, (revisited ^{46}V)

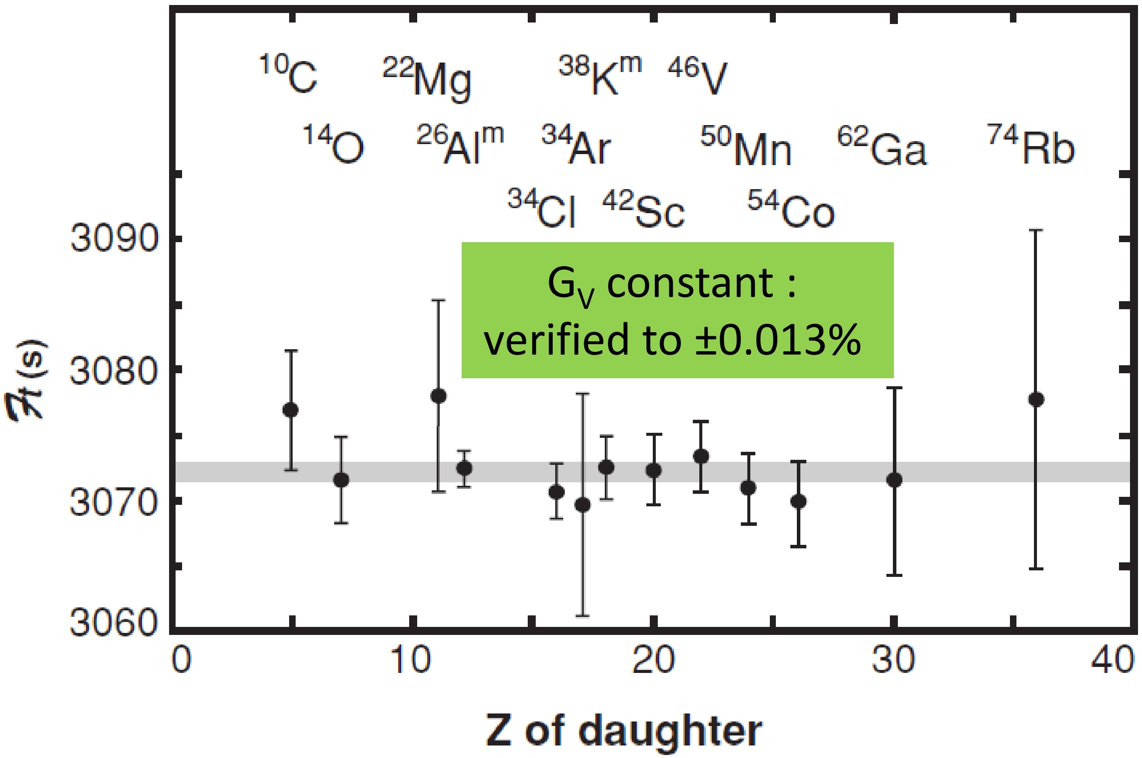




T. Eronen et al., Phys. Rev. C 83, 055501 (2011)

CVC hypothesis and the CKM unitarity

$$\overline{\mathcal{F}t} = 3071.81 \pm 0.79_{\text{stat}} \pm 0.27_{\text{syst}}\ \text{s}$$



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

Cabibbo-Kobayashi-Maskawa quark mixing matrix:

V_{ud} = 0.97425(22)

Unitarity of the CKM matrix:

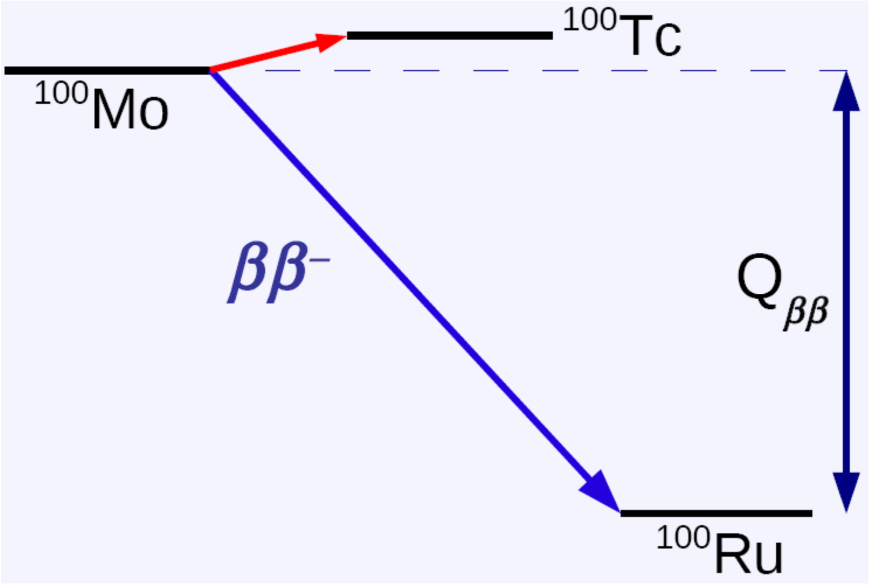
$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$ = 0.99995(61)

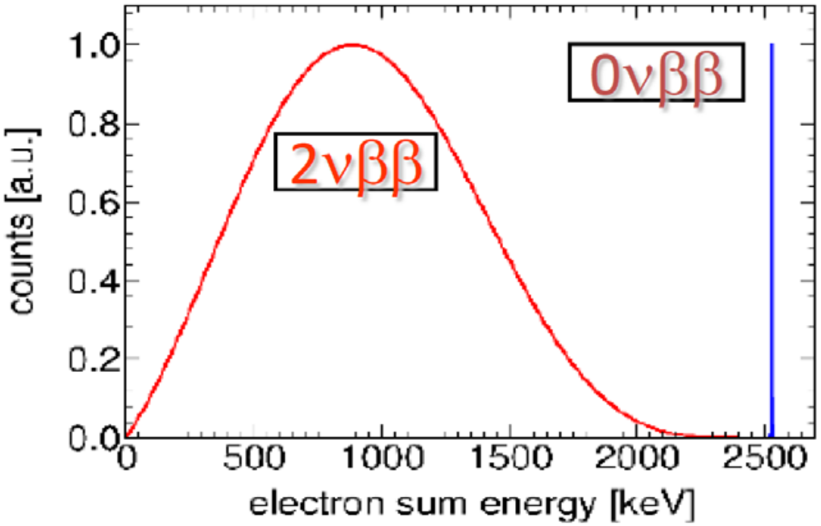
J.C. Hardy and I.S. Towner, PRC 79 (2009) 055502

Few cases to be improved/checked
Higher Z and larger theoretical corrections
Mirror transitions

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$ = 1.00008(56), J. Hardy and I. Towner, Ann. Phys. (Berlin) 525, No. 7, (2013) 443

Neutrinoless double beta-decay





2νββ : (A,Z) → (A,Z+2) + 2e$^-$ + 2ν_e

2νββ allowed in Standard Model

Observed with $t_{1/2} \sim 10^{(19\text{-}24)}$ years

$$\left[T_{1/2}^{2\nu}\right]^{-1} = G^{2\nu}\left|M^{2\nu}\right|^2$$

0νββ : (A,Z) → (A,Z+2) + 2e-

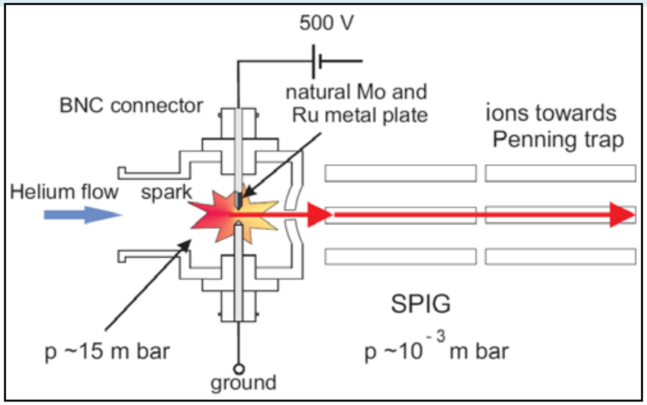
Not allowed in Standard Model

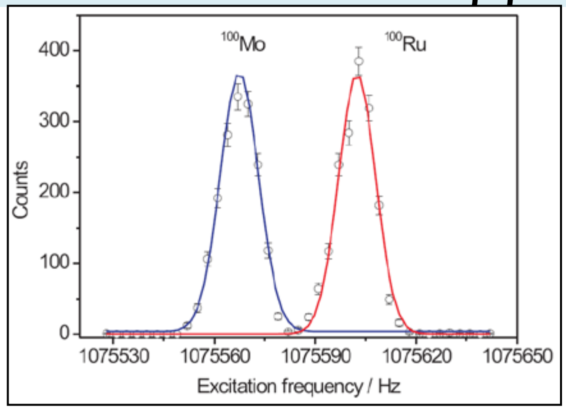
Expected with $t_{1/2} \sim 10^{(25\text{-}30)}$ years

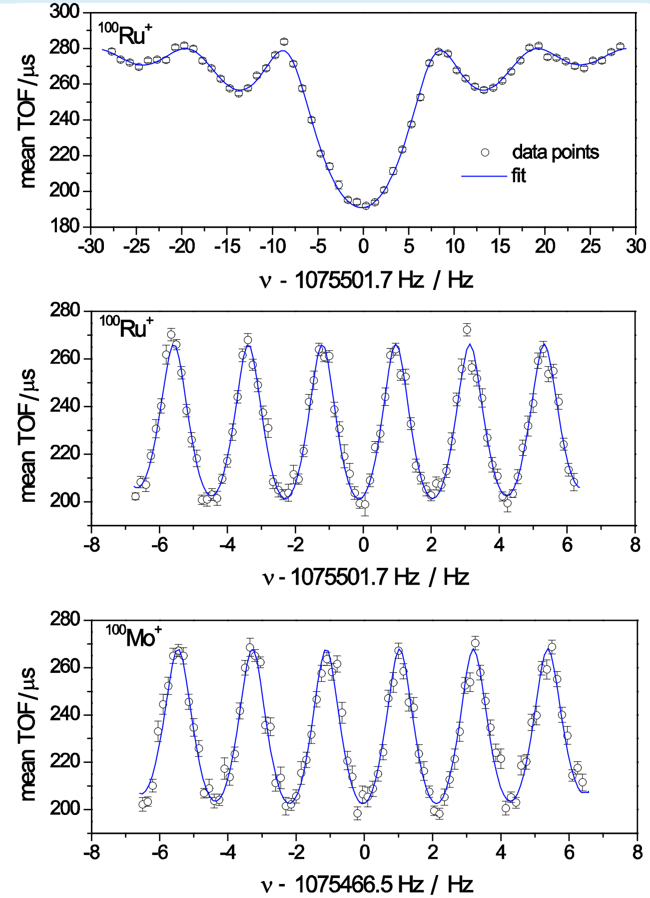
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\langle m_\nu\rangle^2$$

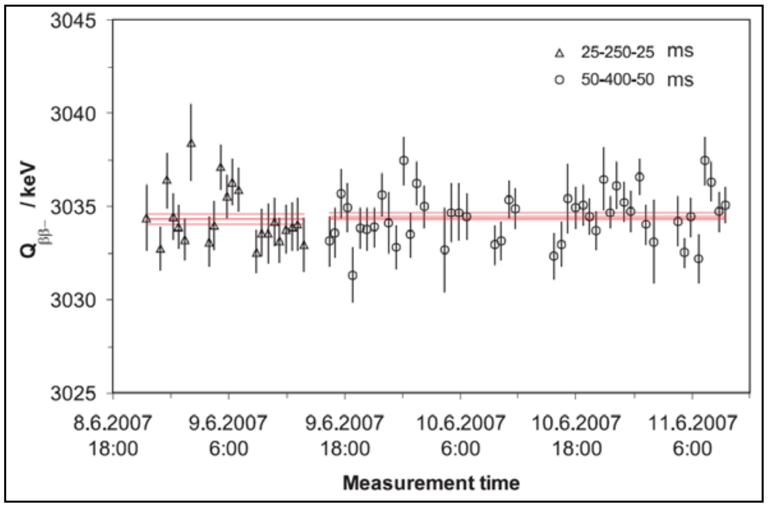
J. Suhonen *et al.*, Phys Rep. 300, 123 (1998)

Measurement of $Q_{\beta\beta}$ of ^{100}Mo









Mother	Daughter	$Q_{\beta\beta}$ [keV] (a)	$Q_{\beta\beta}$ [keV] Lit.
^{76}Ge	^{76}Se	**2039.04(16)**	2039.006(50) (b)
^{100}Mo	^{100}Ru	**3034.40(17)**	3035(6) (c)

(a) S. Rahaman *et al.*, PLB 662 (2008) 111
(b) M. Suhonen et al., J. of Instrum. 2 (2007) 06003
(c) AME2003 G. Audi et al., NPA (2003)

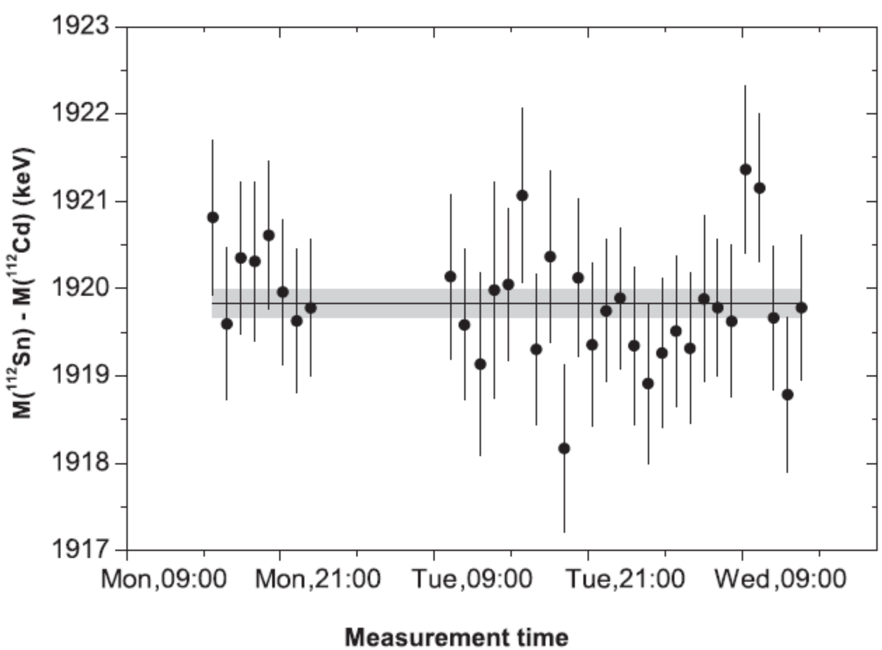
Decay of ^{112}Sn and search for ECEC-0ν decay

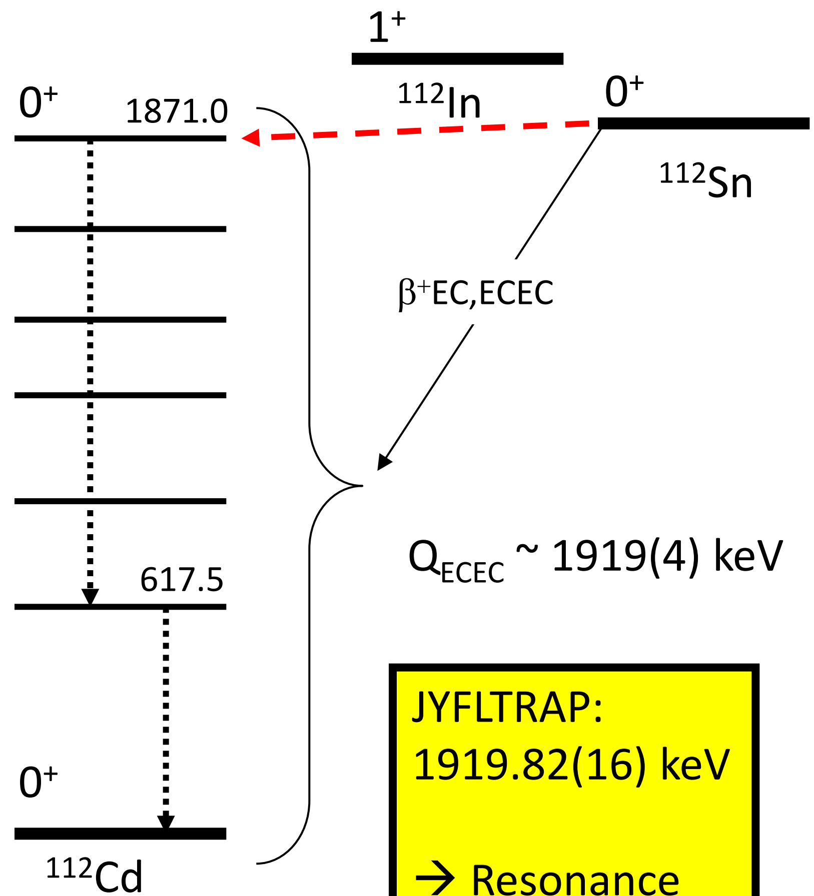
Possible decay modes:

$$e_b^- + (A,Z) \rightarrow (A,Z-2) + e^+ + X \qquad (\beta^+ EC;0\upsilon)$$
$$e_b^- + (A,Z) \rightarrow (A,Z-2) + e^+ + 2\upsilon + X \qquad (\beta^+ EC;2\upsilon)$$
$$\boxed{2e_b^- + (A,Z) \rightarrow (A,Z-2) + e^+ + 2X \qquad (ECEC;0\upsilon)}$$
$$2e_b^- + (A,Z) \rightarrow (A,Z-2) + e^+ + 2\upsilon + 2X \qquad (ECEC;2\upsilon)$$

Resonance cond. for **ECEC-0ν**

$$\boxed{\frac{1}{T_{1/2}} = \frac{(\Delta m)^2}{(Q-E)^2 + 1/4\Gamma^2}\Gamma}$$



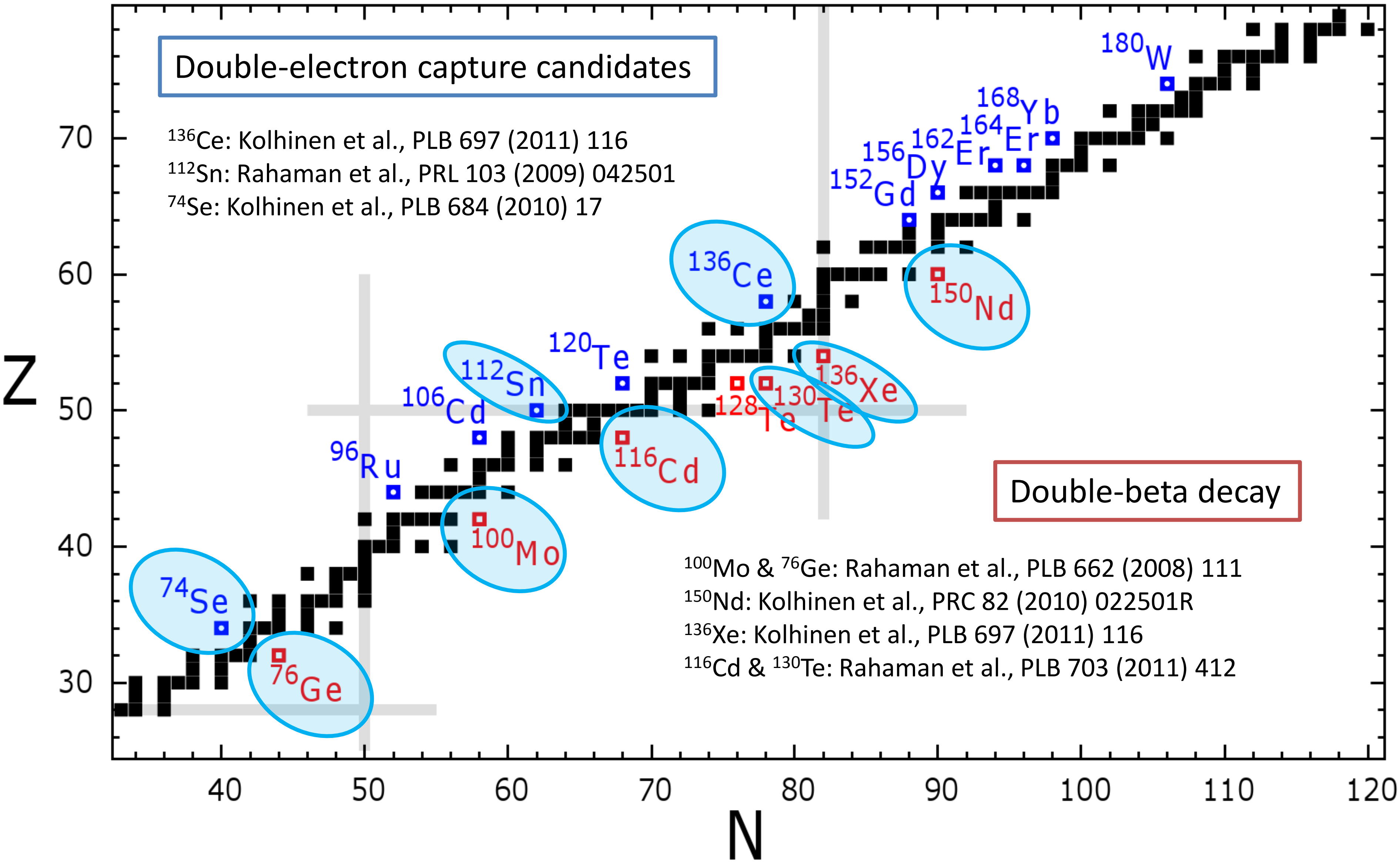


JYFLTRAP:
1919.82(16) keV

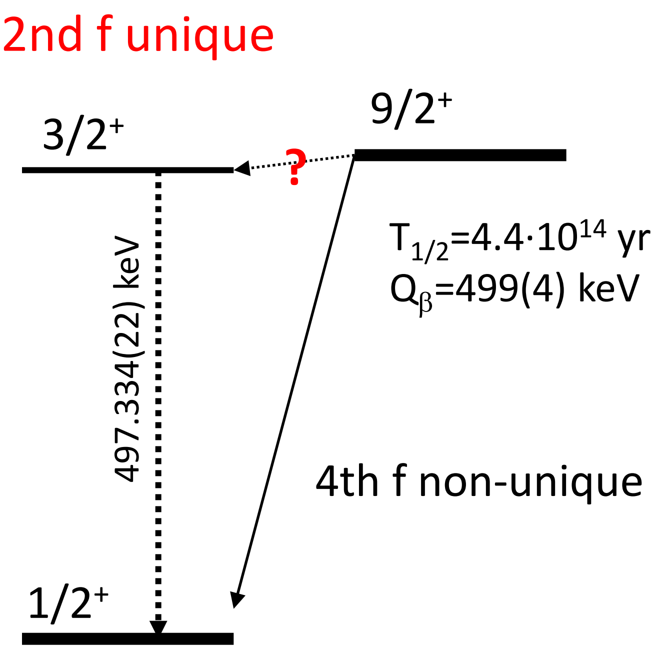
→ Resonance not favoured !!

S. Rahaman et al., PRL 103 (2009) 042501

JYFLTRAP harvest...



Rare β^- decay of $^{115}In(9/2^+) \rightarrow {}^{115}Sn(3/2^+)$



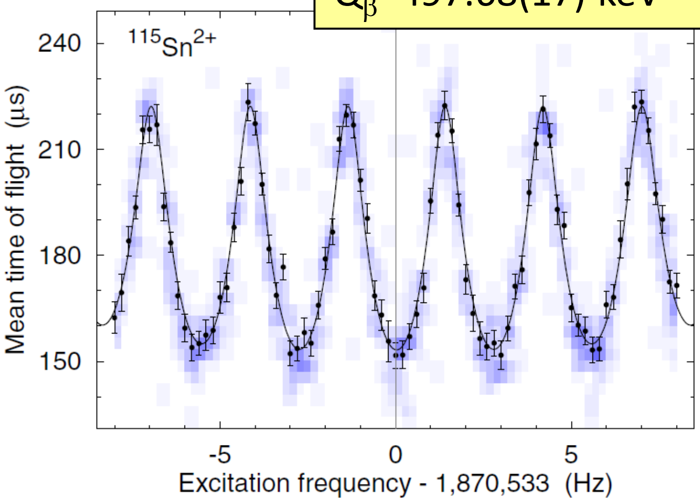
LENS neutrino project, bremstrahlung spectrum of ^{115}In in Gran Sasso
C. Cattadori et al., Nucl. Phys. A748, 333 (2005)

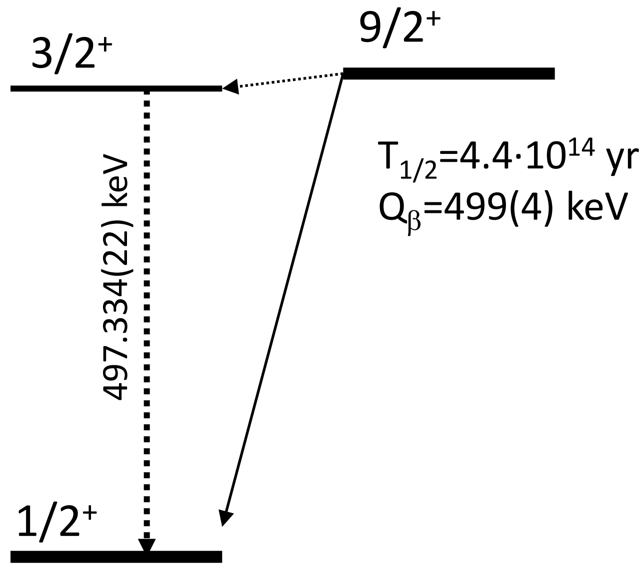
Rare β^- decay of $^{115}In(9/2^+) \rightarrow {}^{115}Sn(3/2^+)$

"Smallest Known Q Value of Any Nuclear Decay"

E. Wieslander et al., PRL 103 (2009) 122501

Q_β=497.68(17) keV

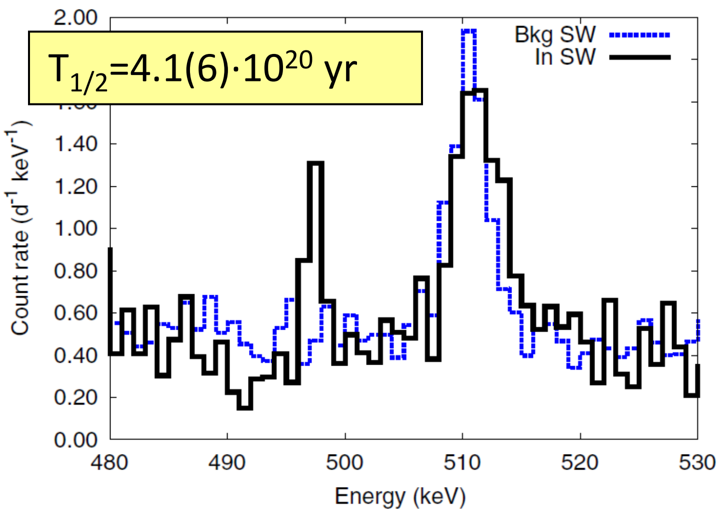




Transition to the 1st excited state
Q=350(170) eV

Low background gamma-measurement
EU-JRC-IRMM, Geel, Belgium

$T_{1/2}=4.1(6)\cdot10^{20}$ yr

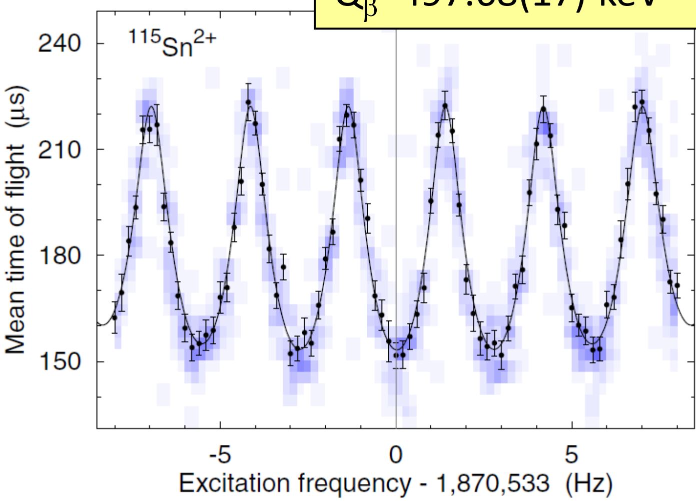


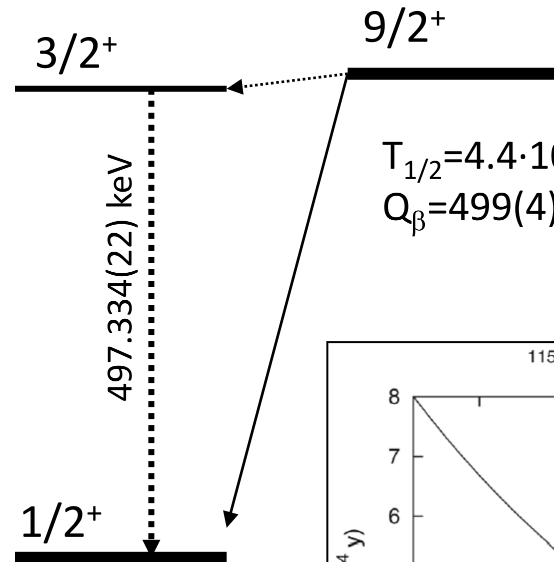
Rare β⁻ decay of ^{115}In(9/2⁺) → ^{115}Sn(3/2⁺)

"Smallest Known Q Value of Any Nuclear Decay"

E. Wieslander et al., PRL 103 (2009) 122501

Q_β=497.68(17) keV



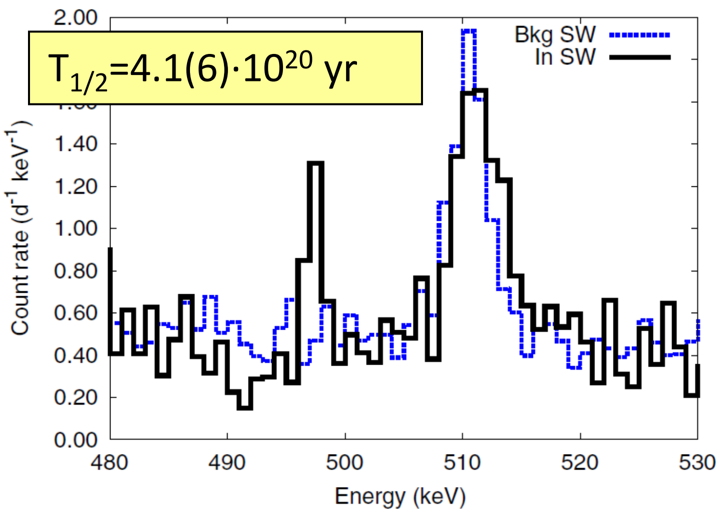


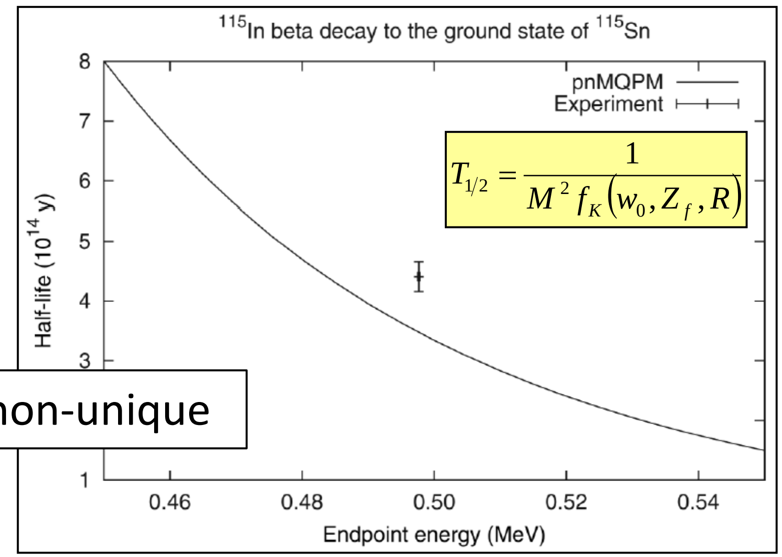
$T_{1/2}$=4.4·10^{14} yr
Q_β=499(4) keV

Transition to the 1st excited state
350(170) eV

Low background gamma-measurement
EU-JRC-IRMM, Geel, Belgium

$T_{1/2}$=4.1(6)·10^{20} yr





$$T_{1/2} = \frac{1}{M^2 f_K(w_0, Z_f, R)}$$

4th f non-unique

M from proton-neutron microscopic quasiparticle-phonon model

M.T. Mustonen and J. Suhonen, PLB 657 (2007) 38

Rare β^- decay of $^{115}In(9/2^+) \rightarrow {}^{115}Sn(3/2^+)$

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E. Wieslander et al., PRL 103 (2009) 122501

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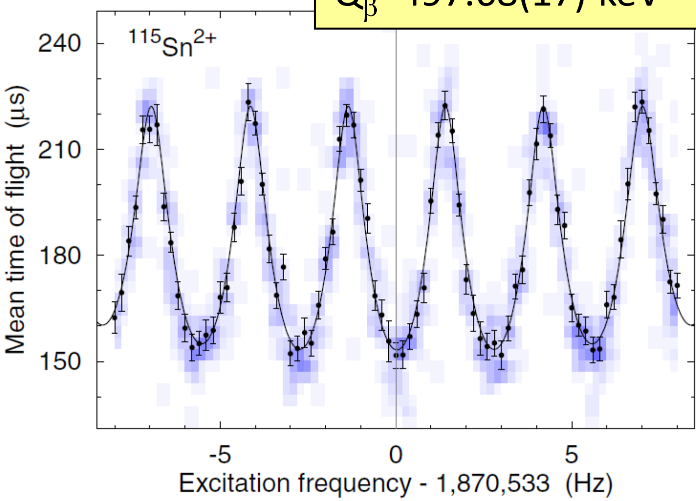
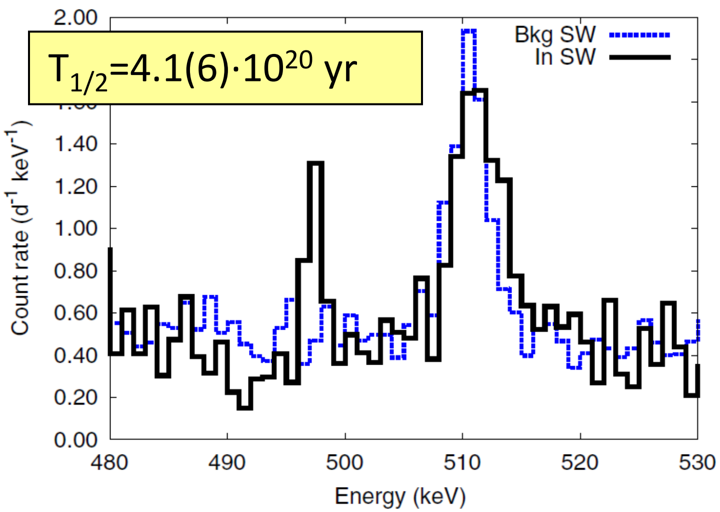
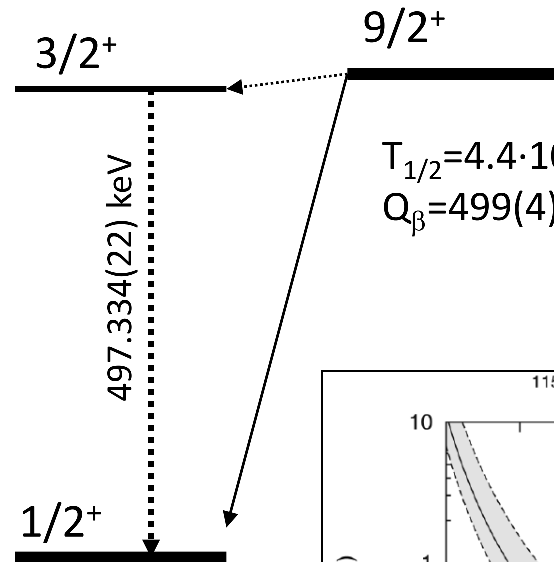


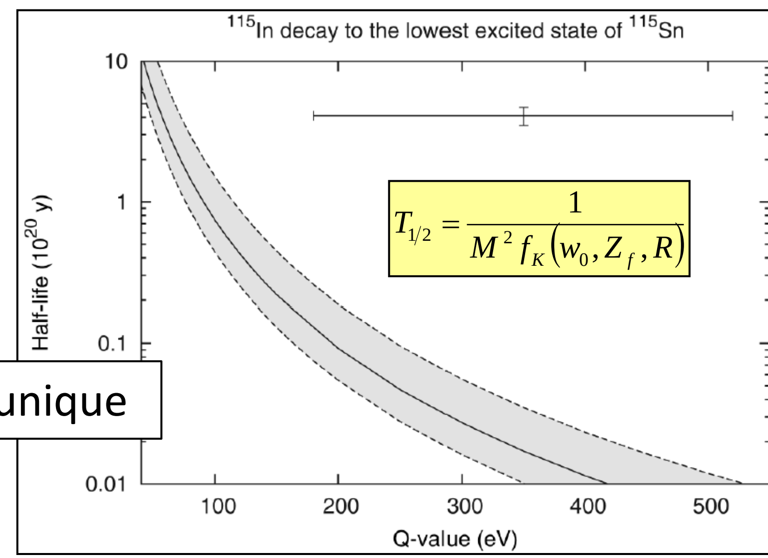
Low background gamma-measurement
EU-JRC-IRMM, Geel, Belgium

$T_{1/2}$=4.1(6)·10^{20} yr





Transition to the 1st excited state
350(170) eV



2nd f unique

M from proton-neutron microscopic quasiparticle-phonon model

M.T. Mustonen and J. Suhonen, PLB 657 (2007) 38

Summary

Mass measurements have contributed to:

- Better understanding of the structure and binding of exotic nuclei (Compare AME2003-AME2012)
- Nuclear structure studies: shell evolution, shape changes, new regions of deformation, pairing, single-particle energies
- Nuclear astrophysics
- CVC hypothesis and the unitarity of CKM
- Rare decays (Xth-forbidden beta decays, $\beta\beta$, ECEC,)
- Applications, etc

Trap-assisted spectroscopy

- Isobaric and isomeric purification
- In-trap spectroscopy
- Optical manipulation in the trap

Outlook

- Complementary information and competition: Storage rings, MR-TOF, ...
- New techniques: Ramsey and octupole excitations, phase imaging, ...
- Facility upgrades (IGISOL-4, HIE-ISOLDE, LEBIT, CARIBU, MATS@FAIR)

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J. Dobaczewski, J. Suhonen

https://www.jyu.fi/fysiikka/en/research/accelerator/igisol
http://research.jyu.fi/igisol/JYFLTRAP_masses/