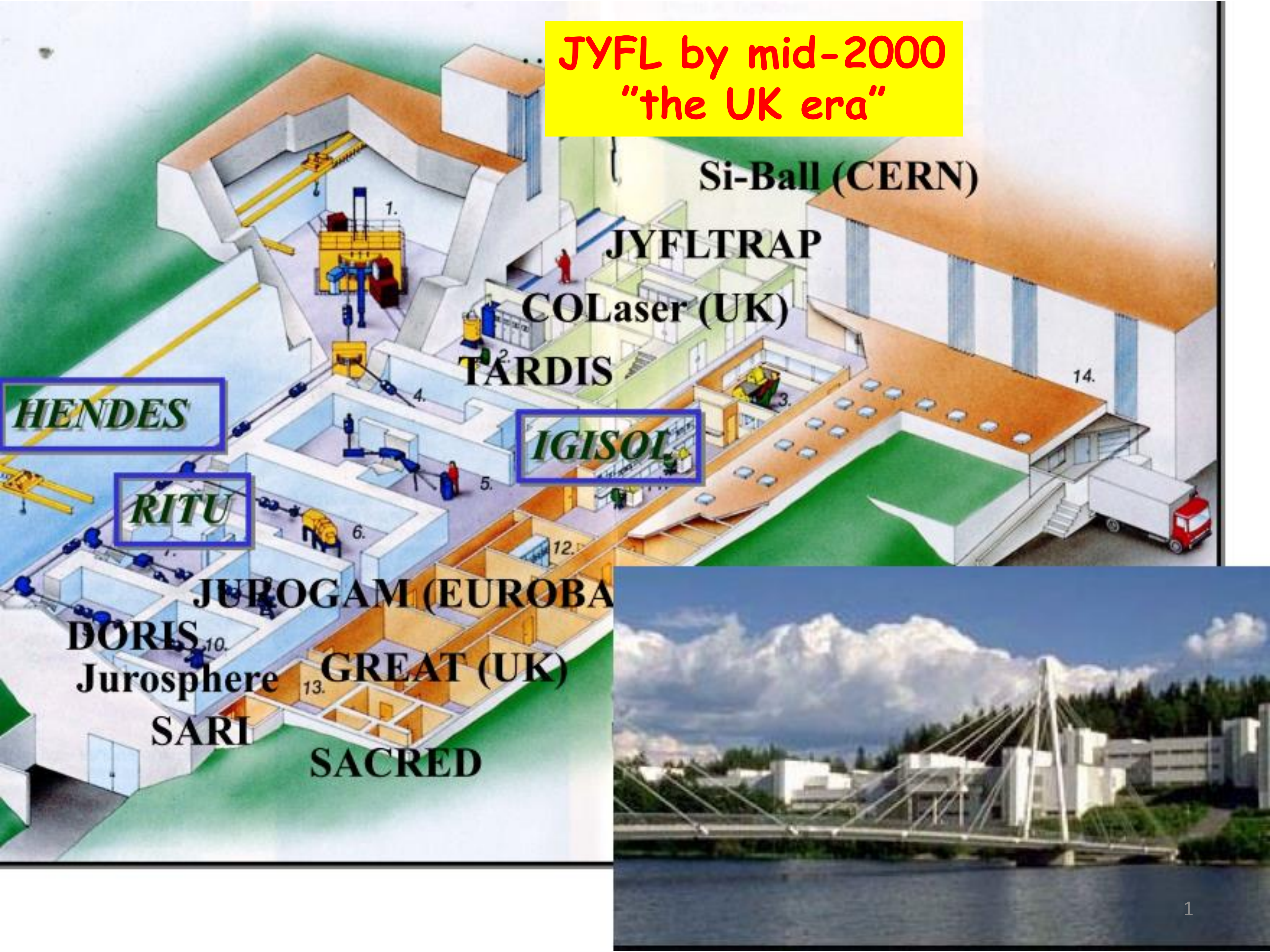
JYFL by mid-2000 "the UK era"



Si-Ball (CERN)

JYFLTRAP

COLaser (UK)

TARDIS

HENDES

IGISOL

RITU

JUROGAM (EUROBA

DORIS

Jurosphere

SARI

GREAT (UK)

SACRED


1974


1988


2005

Nuclear Physics with Ion Traps

JYVÄSKYLÄN YLIOPISTO

Juha Äystö
Helsinki Institute of Physics, Helsinki, Finland

HELSINKI INSTITUTE OF PHYSICS

Subjects:

Penning and Paul traps as a novel approach to precision studies of ground state properties of exotic nuclei.

Focus of this talk will be on
- Fermi decays and Standard Model
- structure studies of medium-mass neutron-rich nuclei by mass measurements

Relevant mass-accuracies in nuclear physics

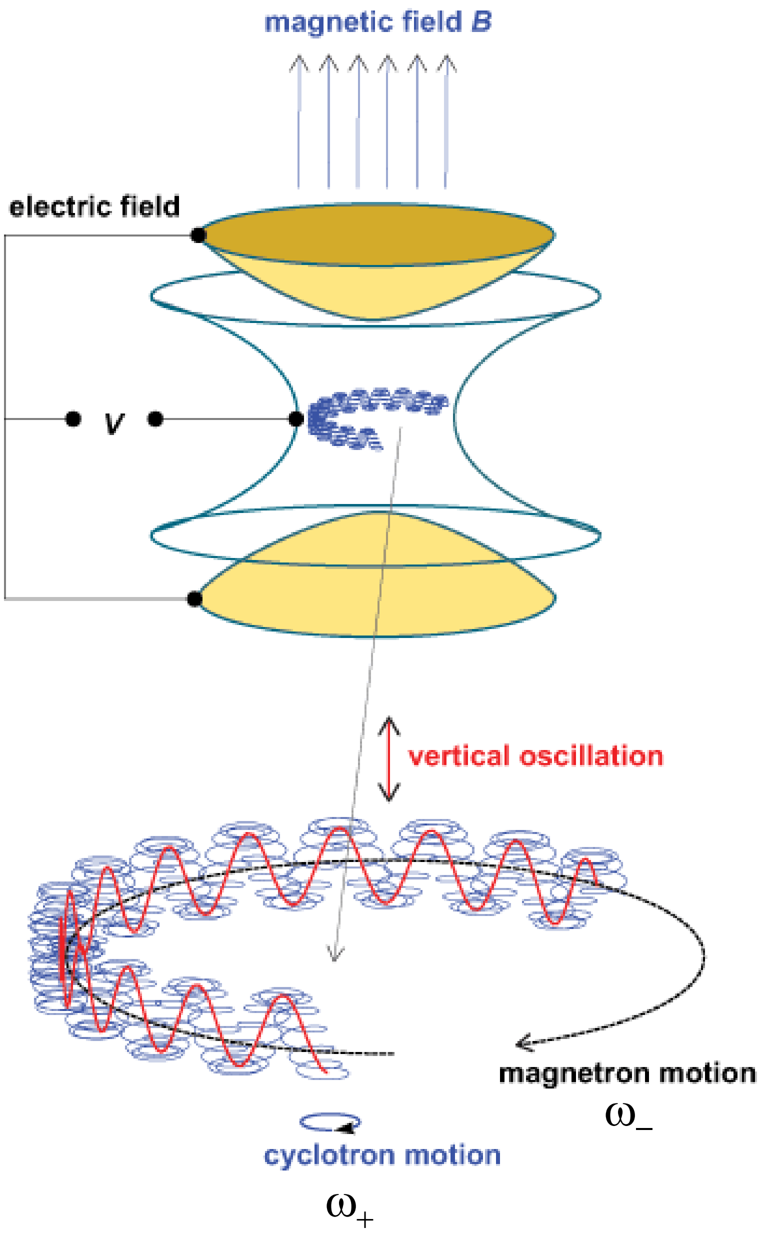
- **Nuclear structure (10-100 keV)**
  - Global correlations (100 keV)
  - Local correlations (10 keV)
    - shell structure, spin-orbit interaction, pairing, collectivity
  - Drip-line phenomena, halos, isomers (1 keV)
  - Isotope & isomer decay spectroscopy (< 0.5 MeV)

- **Nuclear astrophysics (≥ 1 keV)**

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

- **Tests of Standard Model (≤ 100 eV)** $\delta m/m < 1\cdot10^{-9}$
  - Nuclear β decay. Electroweak interaction
    - CVC theory and unitarity of the CKM matrix
    - Double β decay
    - Neutrino mass from beta decay(< 0.1 eV)

Penning trap - single ion device



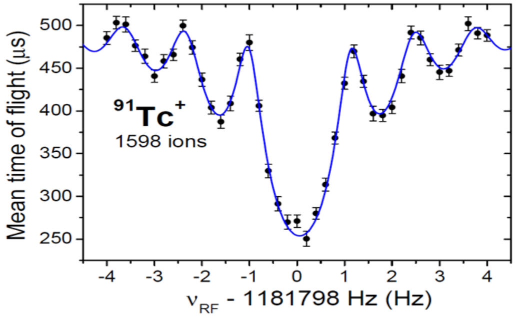
strong axial magnetic field → radial confinement

quadrupolar electric field → axial confinement

$$\omega_+^2 + \omega_-^2 + \omega_z^2 = \omega_c^2$$ ”invariance theorem”

$$\omega_+ + \omega_- \cong \omega_c$$ ”sideband frequency for ideal trap”

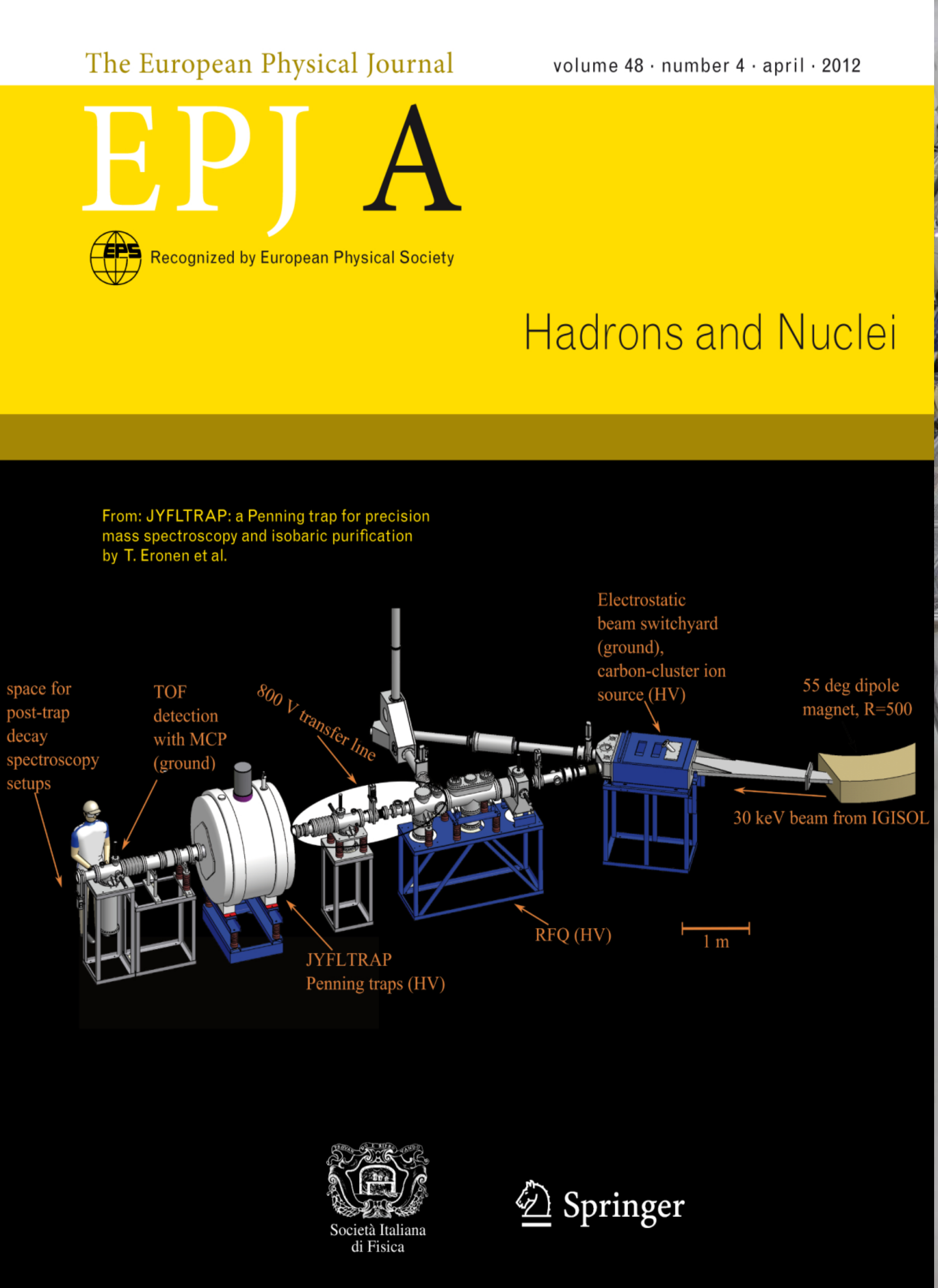
$$\boxed{\omega_c = \frac{qB}{m}}$$



Precision

Routinely few tens of keV
If required few tens of eV ($\delta m/m < 1\cdot10^{-9}$)

Special issue for IGISOL Science



The European Physical Journal

volume 48 · number 4 · april · 2012

EPJ A

Recognized by European Physical Society

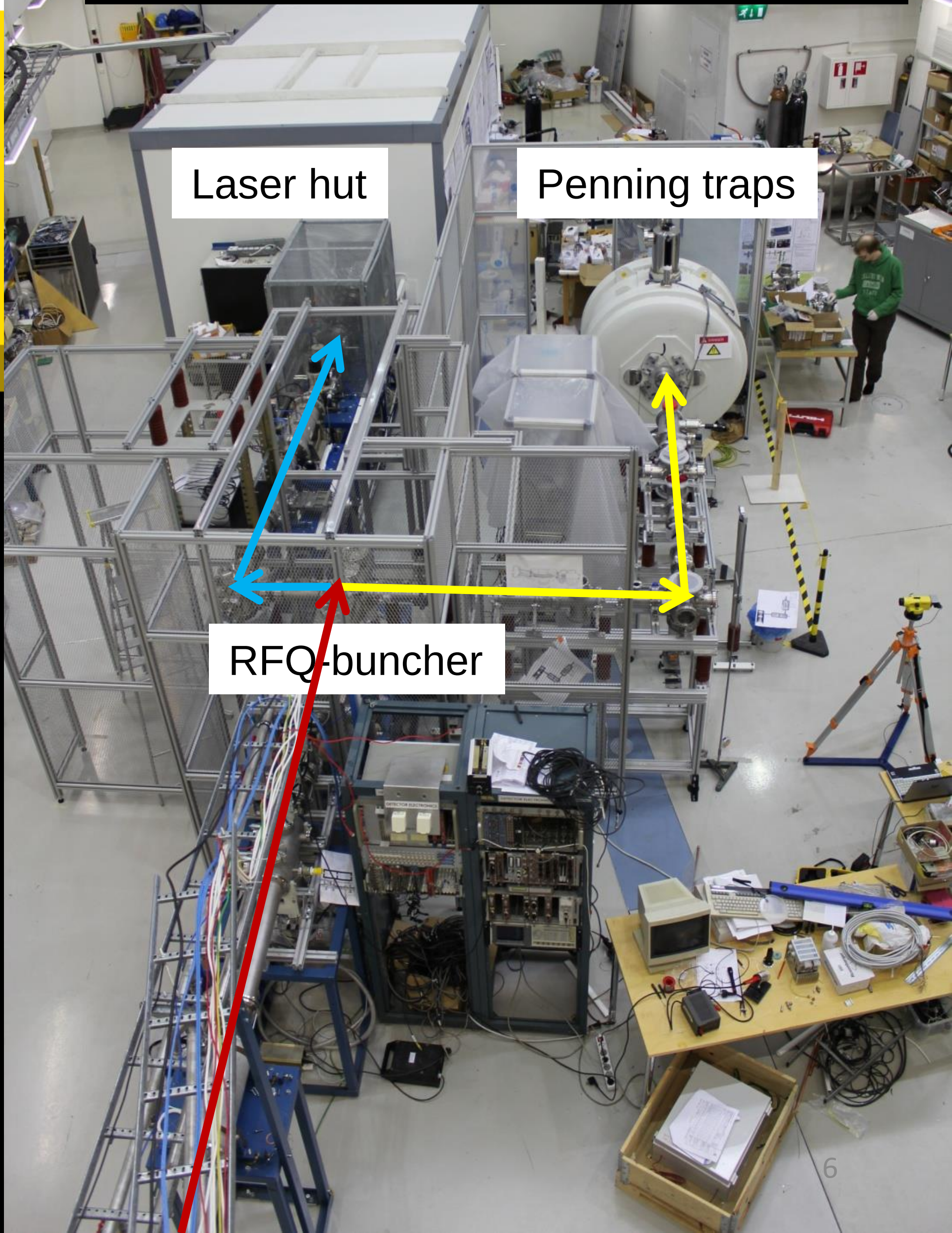
Hadrons and Nuclei

From: JYFLTRAP: a Penning trap for precision mass spectroscopy and isobaric purification by T. Eronen et al.

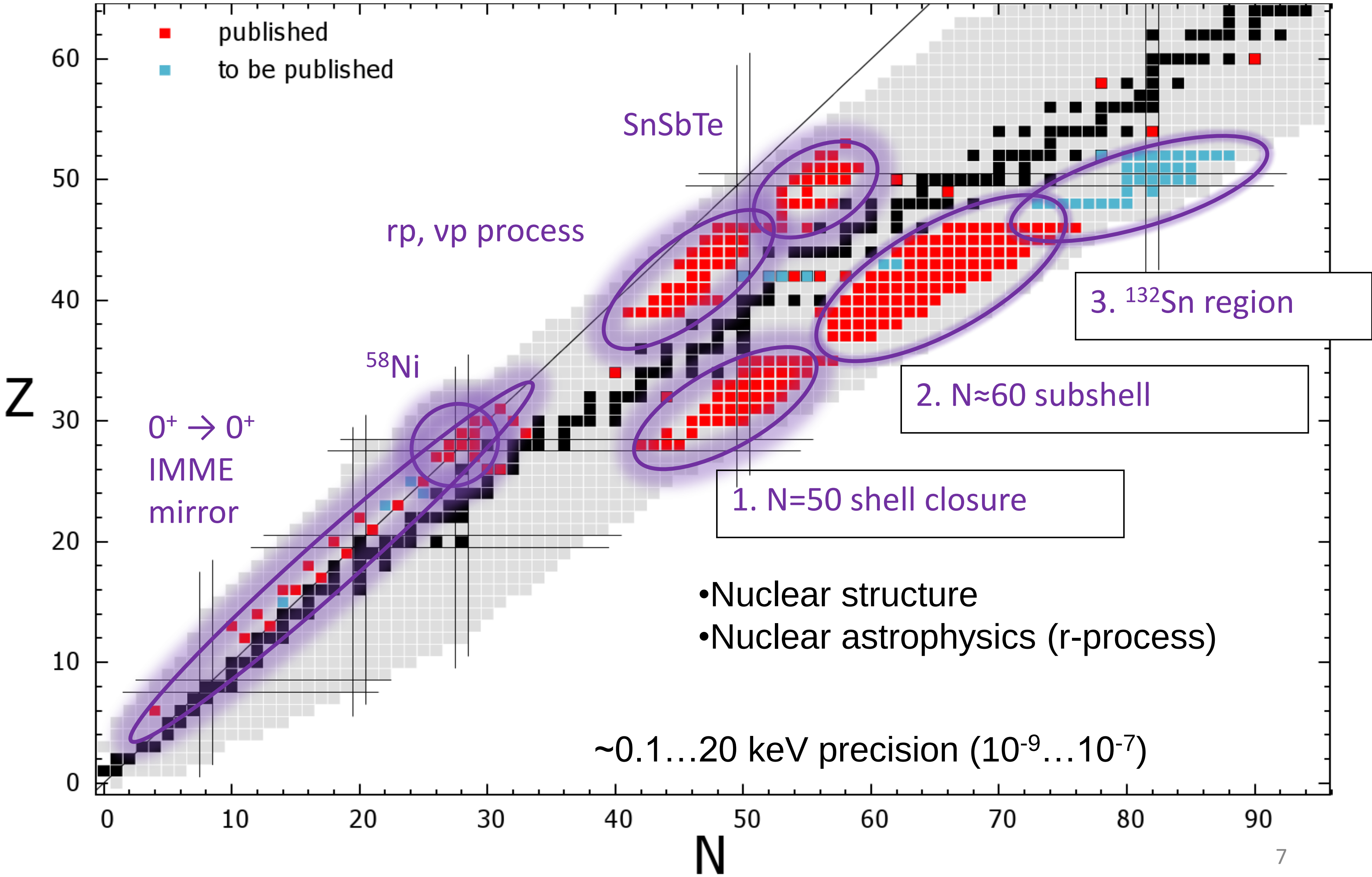
Società Italiana di Fisica

Springer

Today:
IGISOL and JYFLTRAP operate @ MCC30 & K130 cyclotrons.



JYFLTRAP mass measurements



- Nuclear structure
- Nuclear astrophysics (r-process)

~0.1…20 keV precision ($10^{-9}…10^{-7}$)

0^+ - 0^+ T=1 Fermi decays

$$Ft \equiv ft(1+\delta_R)(1-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

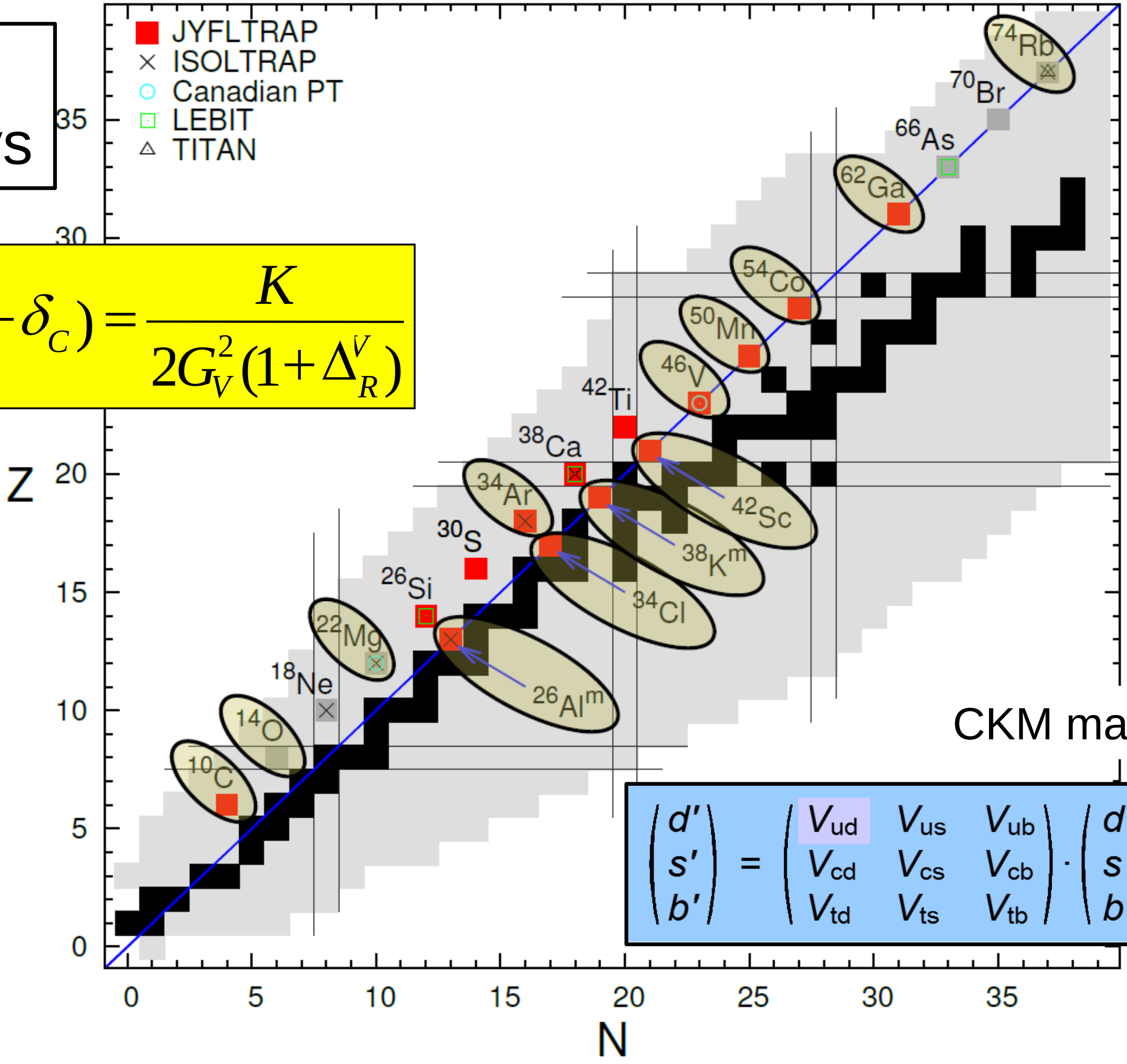


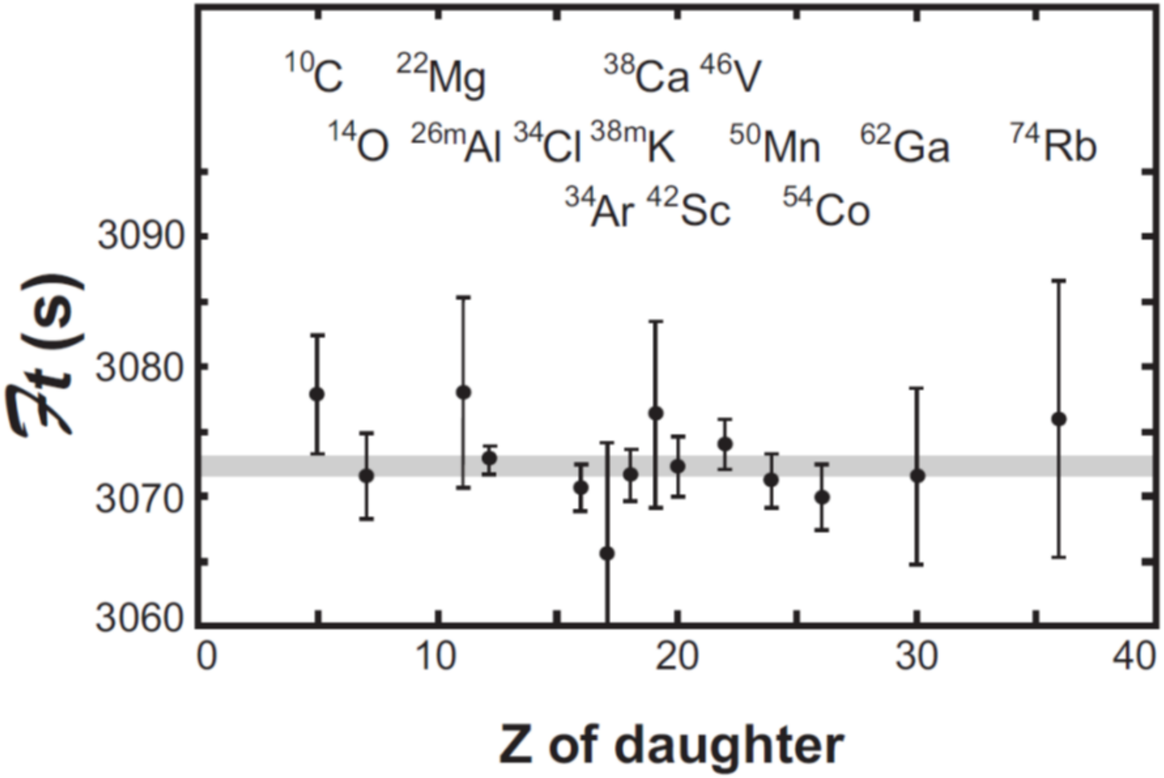
Figure 1: Nuclear chart showing the superallowed β emitters of interest. The 13 emitters that currently contribute to the world average $\mathcal{F}t$ value are circled. Emitters whose Q_{EC} values have been determined with a Penning trap are indicated.

CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ud}^2 = \frac{G_V^2}{G_\mu^2}$$

Hardy and Towner, Phys. Rev. C 91, 025501 (2015)



ISOLTRAP
CPT-Argonne
LEBIT
JYFLTRAP
Texas A&M

G_V constant : verified to ±0.013%

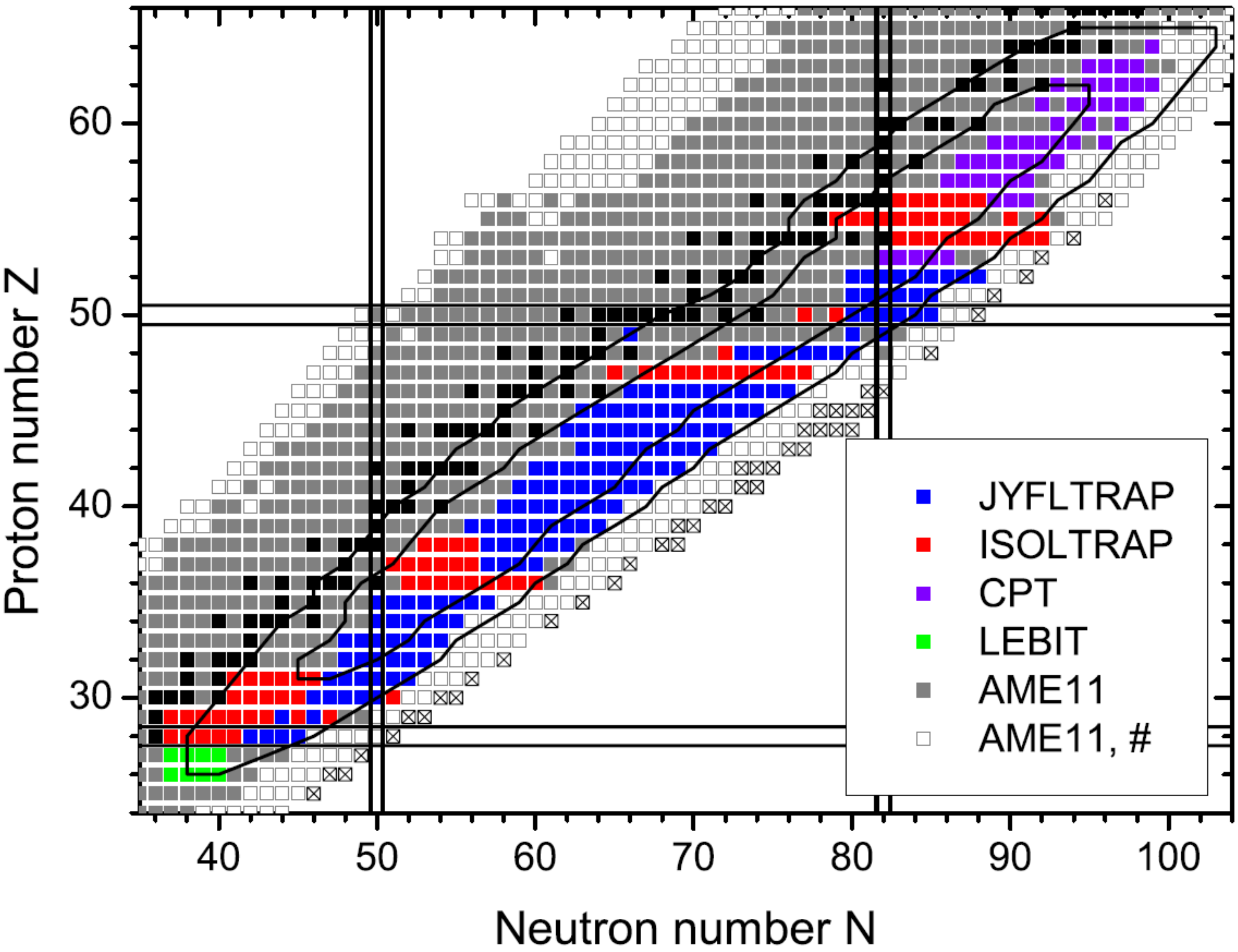
Hardy-Towner review for V_{ud} coupled with PDG 2014 for V_{us} and V_{ub}

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978 \pm 0.00055$$

Unitarity is fully confirmed by this data !

Mass measurements of neutron-rich isotopes of medium mass.

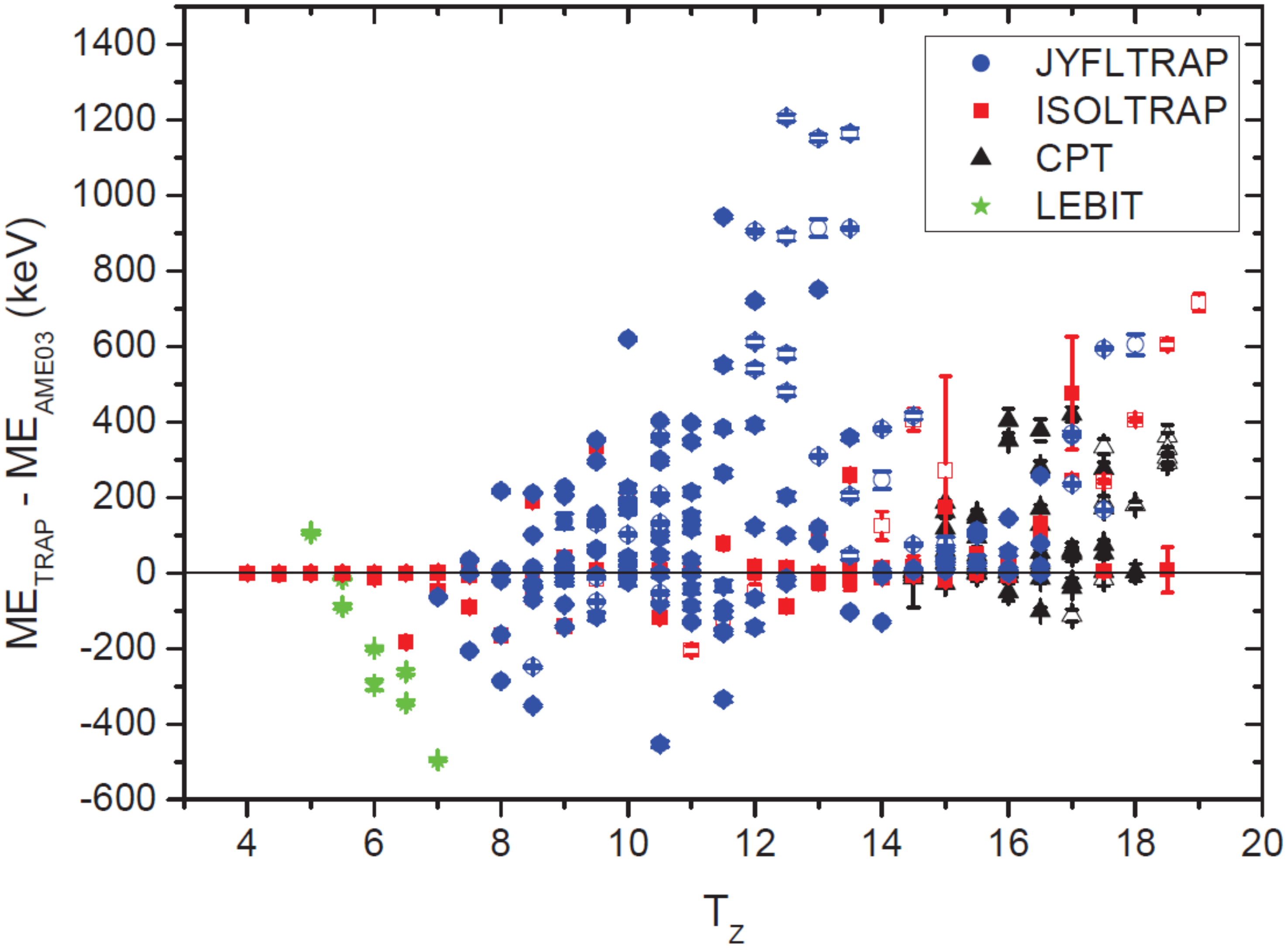
Major revision of binding energies of fission products.



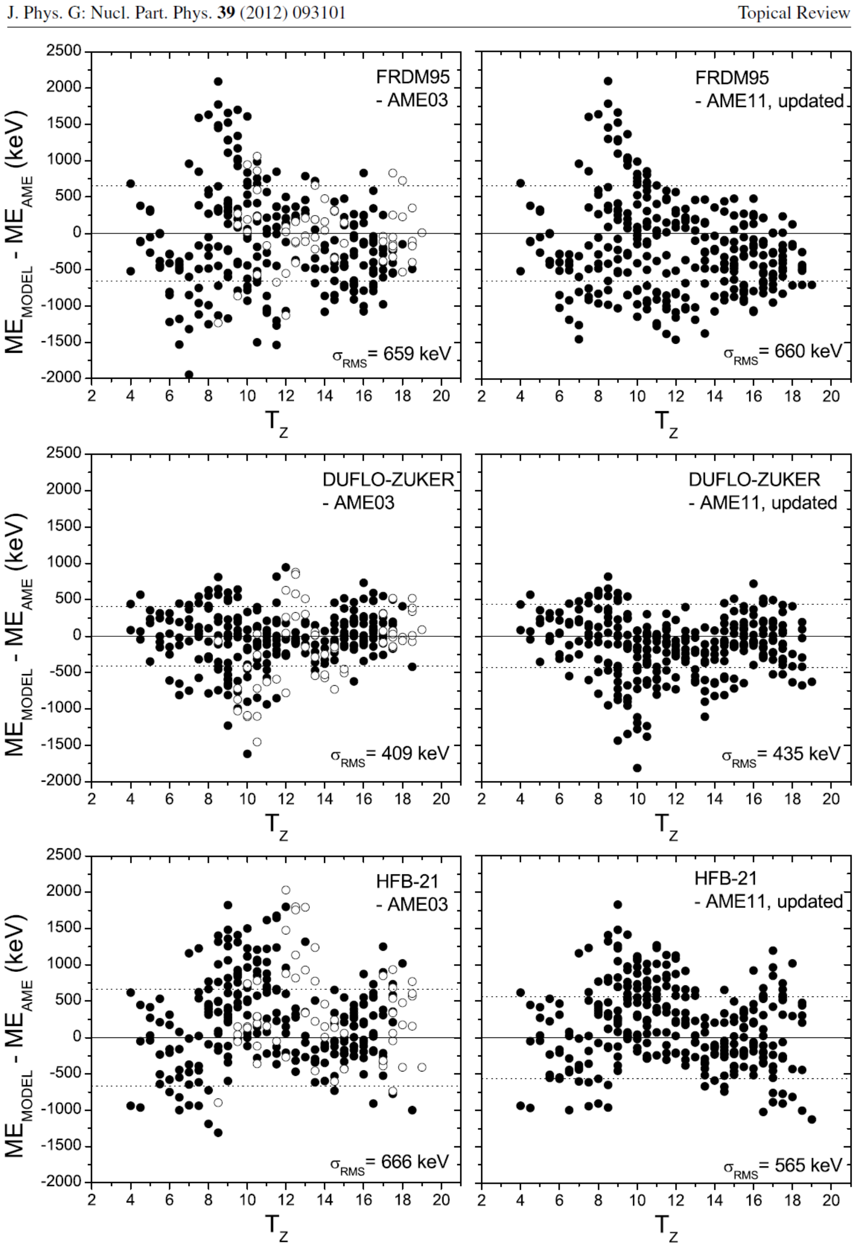
A. Kankainen, J. Äystö, A. Jokinen, J.Phys. G. Nucl. Part. Phys. 39 (2012) 093101

2003 mass evaluation and the PT data

J. Phys. G: Nucl. Part. Phys. **39** (2012) 093101

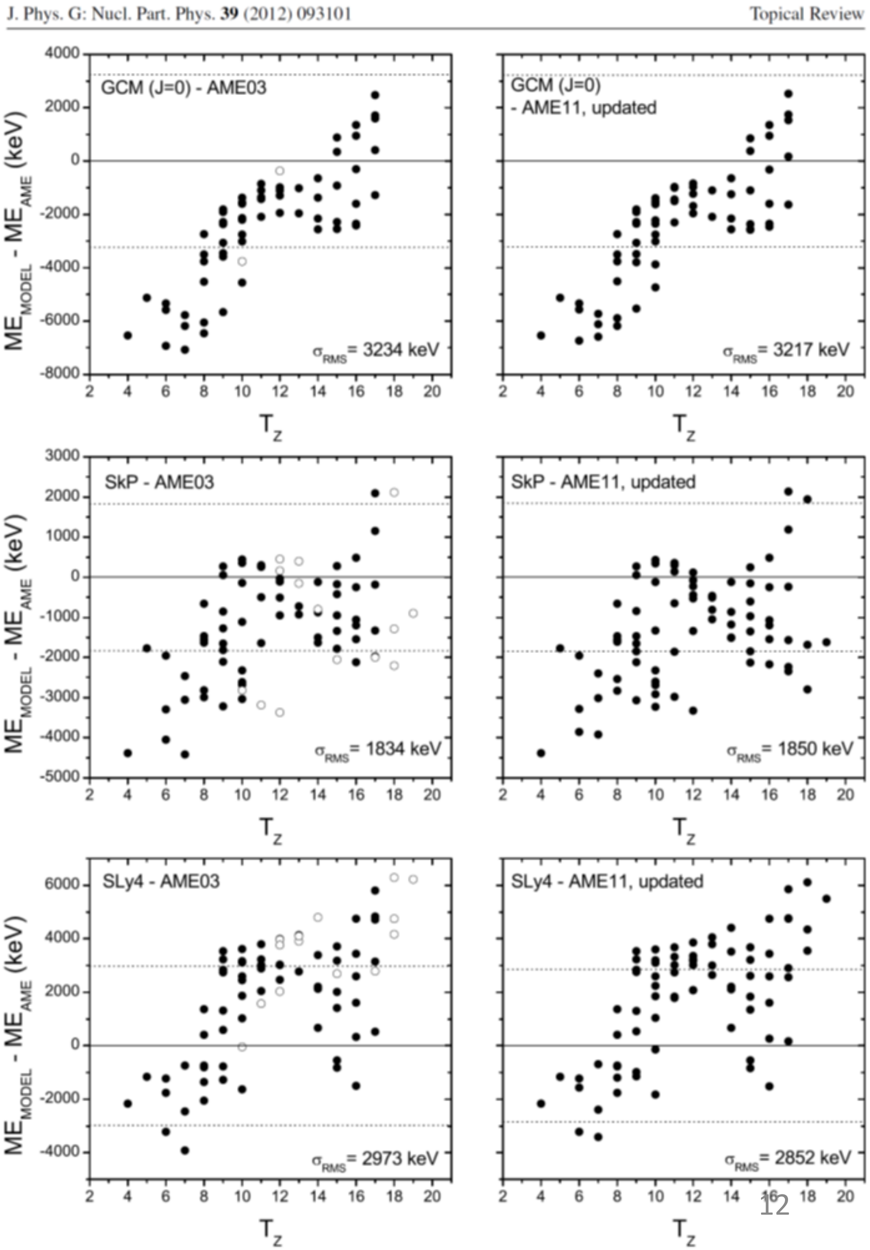


Mass models vs. improved data



J. Phys. G: Nucl. Part. Phys. **39** (2012) 093101 Topical Review

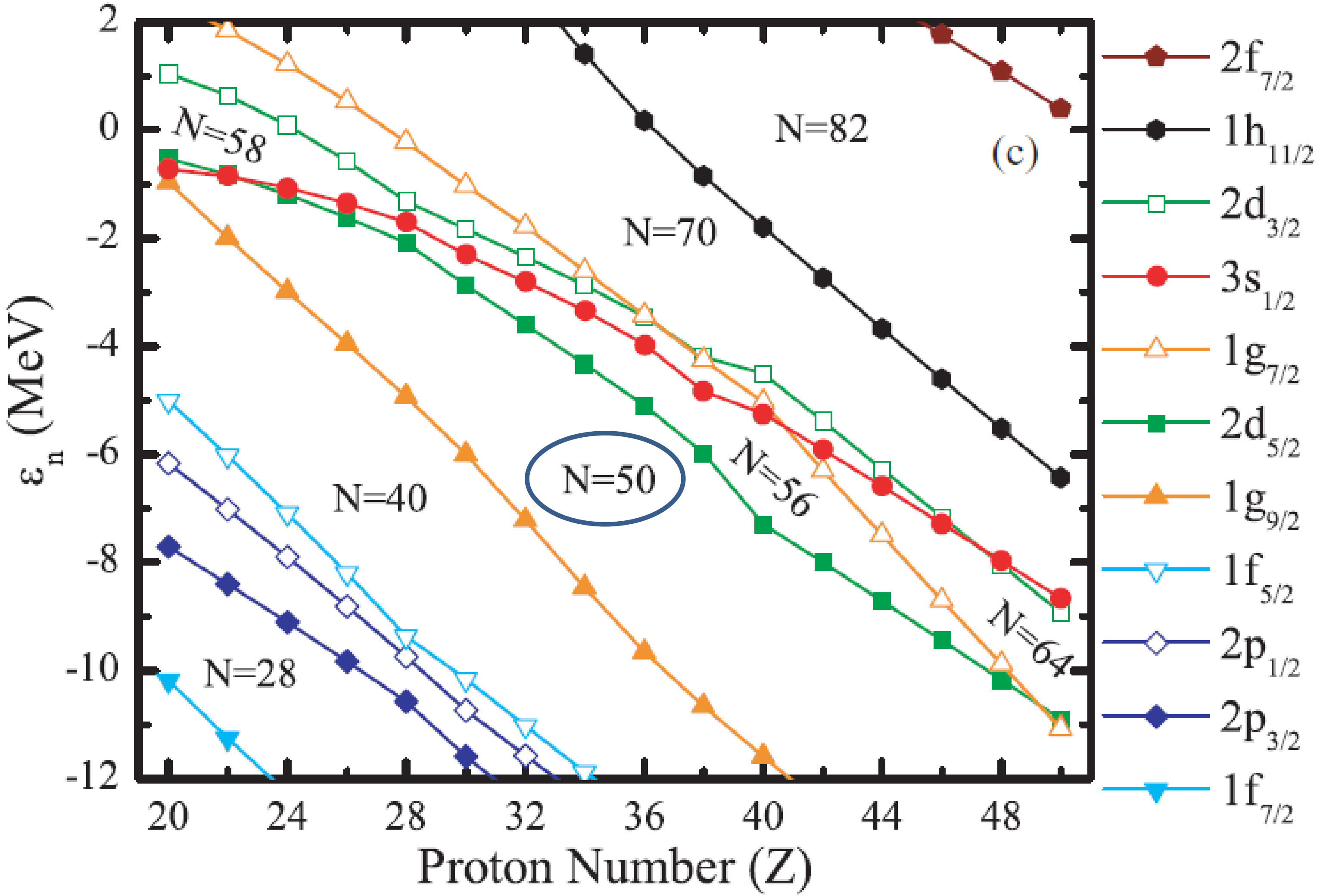
Mean-field models vs improved data



J. Phys. G: Nucl. Part. Phys. **39** (2012) 093101 Topical Review

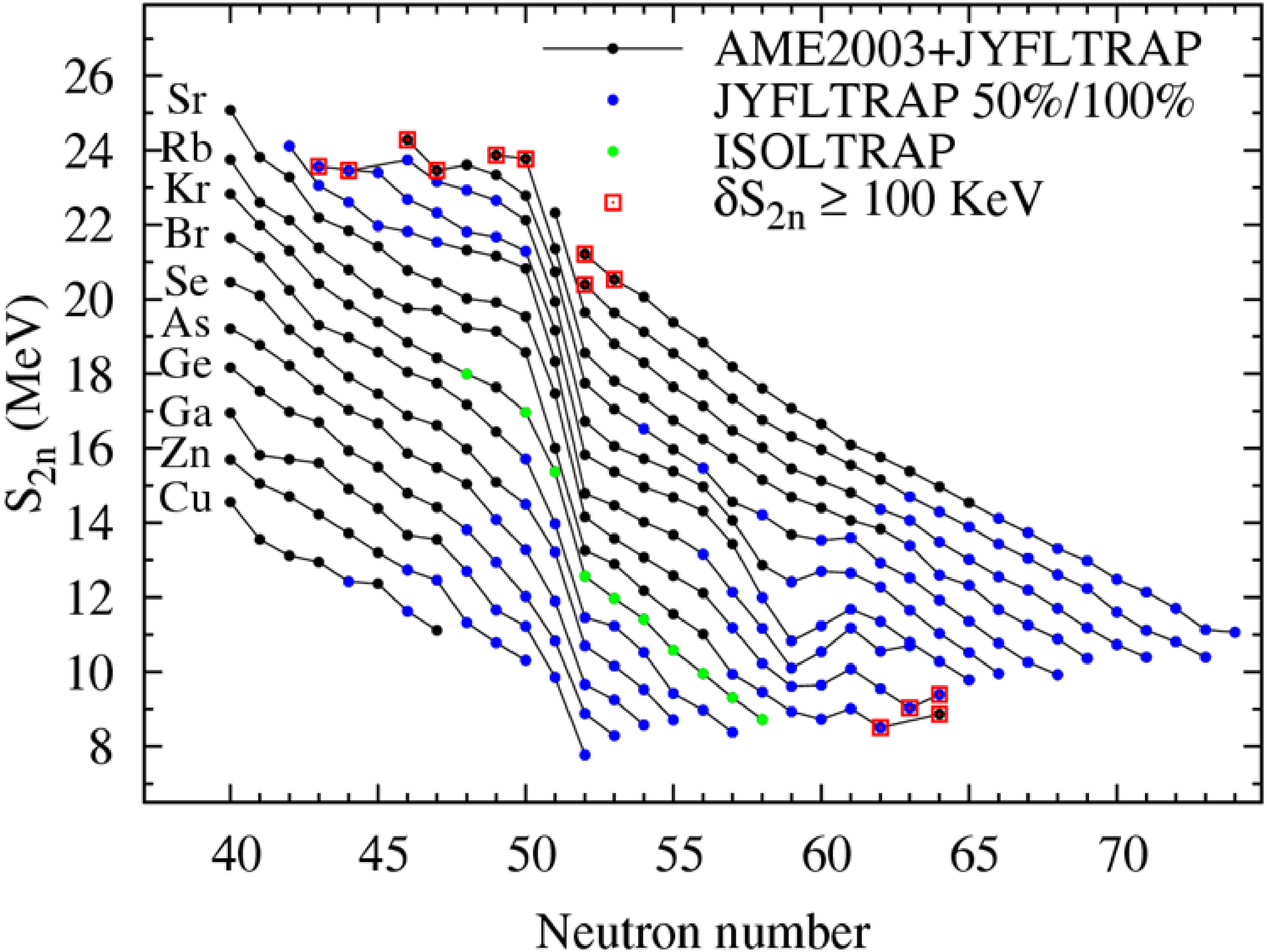
P. G. Reinhard, D. J. Dean, W. Nazarewicz, J. Dobaczewski, J. A. Maruhn, and M. R. Strayer,
Phys. Rev. C **60, 014316** (1999).

-Spherical HFB calculations with an SkO*T functional include the tensor term*

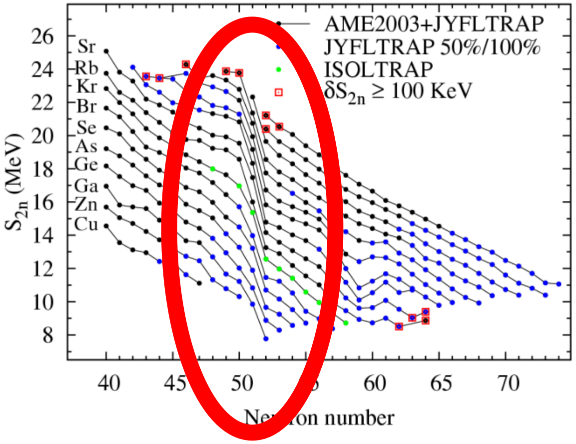


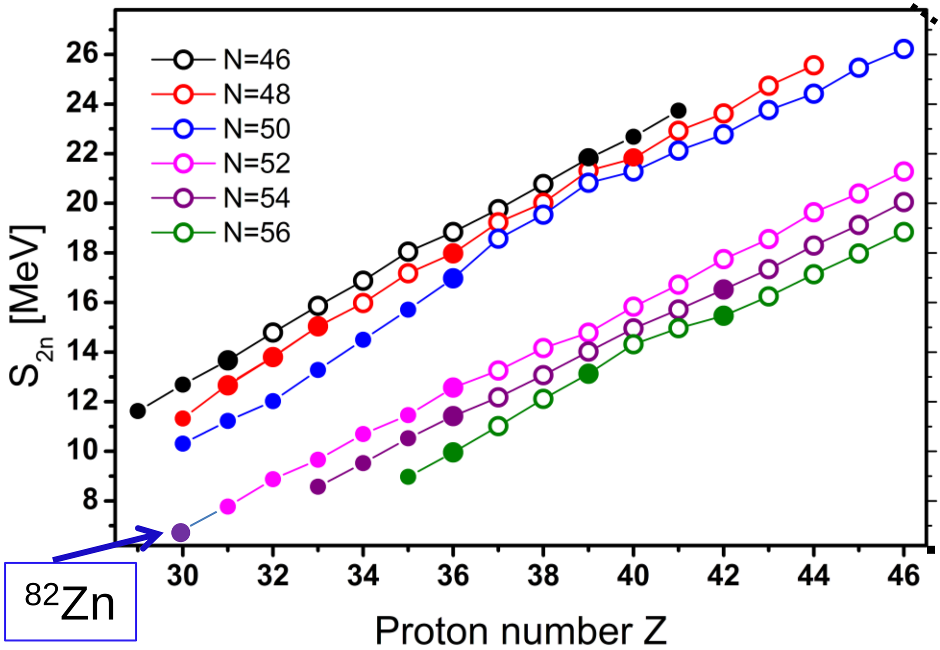
From: J. A. WINGER *et al.* PHYSICAL REVIEW C **81**, 044303 (2010)

Nucleon separation energies: reflection of s.p. energies

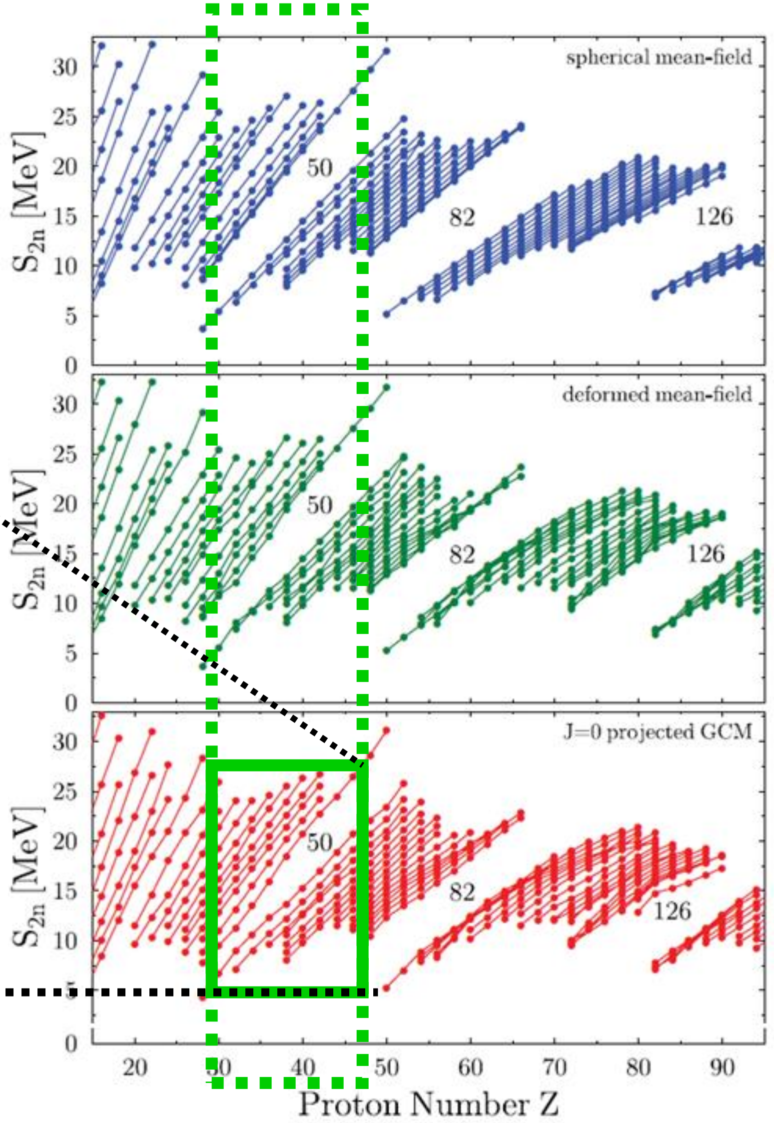


Evolution of N=50 shell gap





^{82}Zn

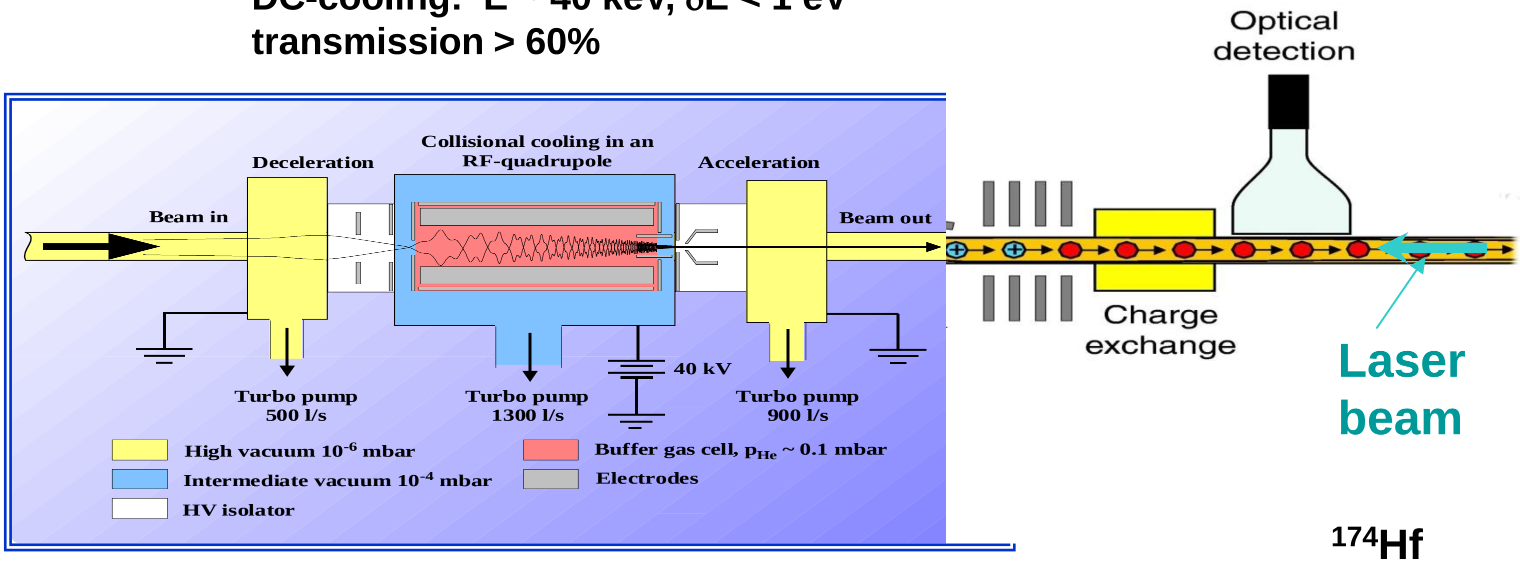


J. Hakala et al. PRL 101 (2008) 052502
R.N. Wolf et al. PRL 110 (2013) 041101

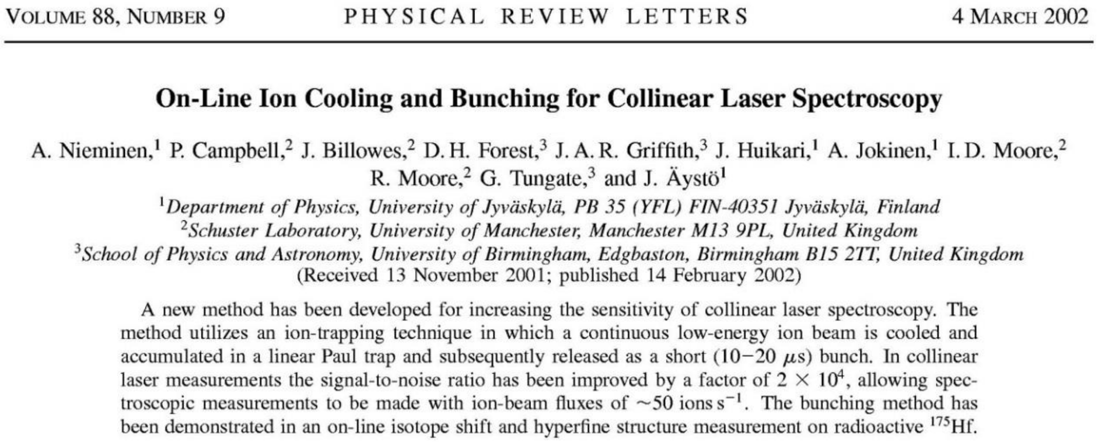
M. Bender et al. PRC 78 (2008) 054312

COLLINEAR LASER SPECTROSCOPY WITH BUNCHING

DC-cooling: E ~ 40 keV, δE < 1 eV
transmission > 60%



Bunching: from .1 μs to 10 μs
Accumulation time 10 ms - 10 s

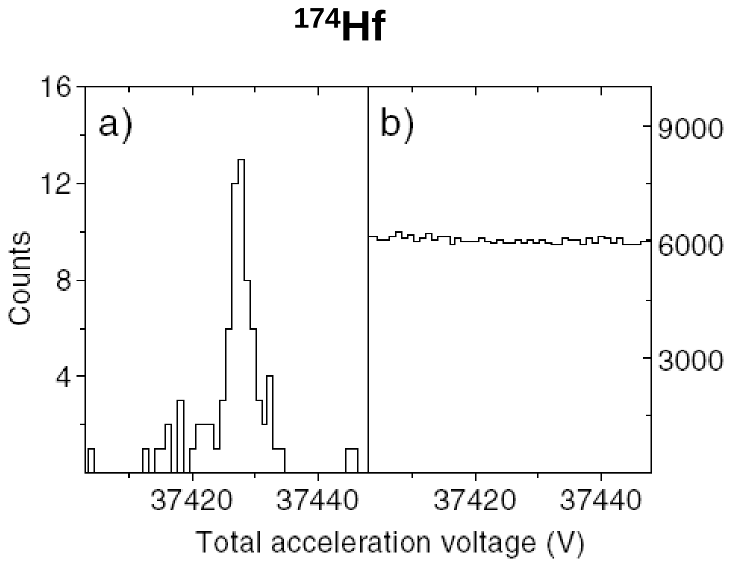


VOLUME 88, NUMBER 9 PHYSICAL REVIEW LETTERS 4 MARCH 2002

On-Line Ion Cooling and Bunching for Collinear Laser Spectroscopy

A. Nieminen,[1] P. Campbell,[2] J. Billowes,[2] D. H. Forest,[3] J. A. R. Griffith,[3] J. Huikari,[1] A. Jokinen,[1] I. D. Moore,[2]
R. Moore,[2] G. Tungate,[3] and J. Äystö[1]
[1]*Department of Physics, University of Jyväskylä, PB 35 (YFL) FIN-40351 Jyväskylä, Finland*
[2]*Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*
[3]*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*
(Received 13 November 2001; published 14 February 2002)

A new method has been developed for increasing the sensitivity of collinear laser spectroscopy. The method utilizes an ion-trapping technique in which a continuous low-energy ion beam is cooled and accumulated in a linear Paul trap and subsequently released as a short (10–20 μs) bunch. In collinear laser measurements the signal-to-noise ratio has been improved by a factor of 2×10^4, allowing spectroscopic measurements to be made with ion-beam fluxes of ~50 ions s^{-1}. The bunching method has been demonstrated in an on-line isotope shift and hyperfine structure measurement on radioactive ^{175}Hf.



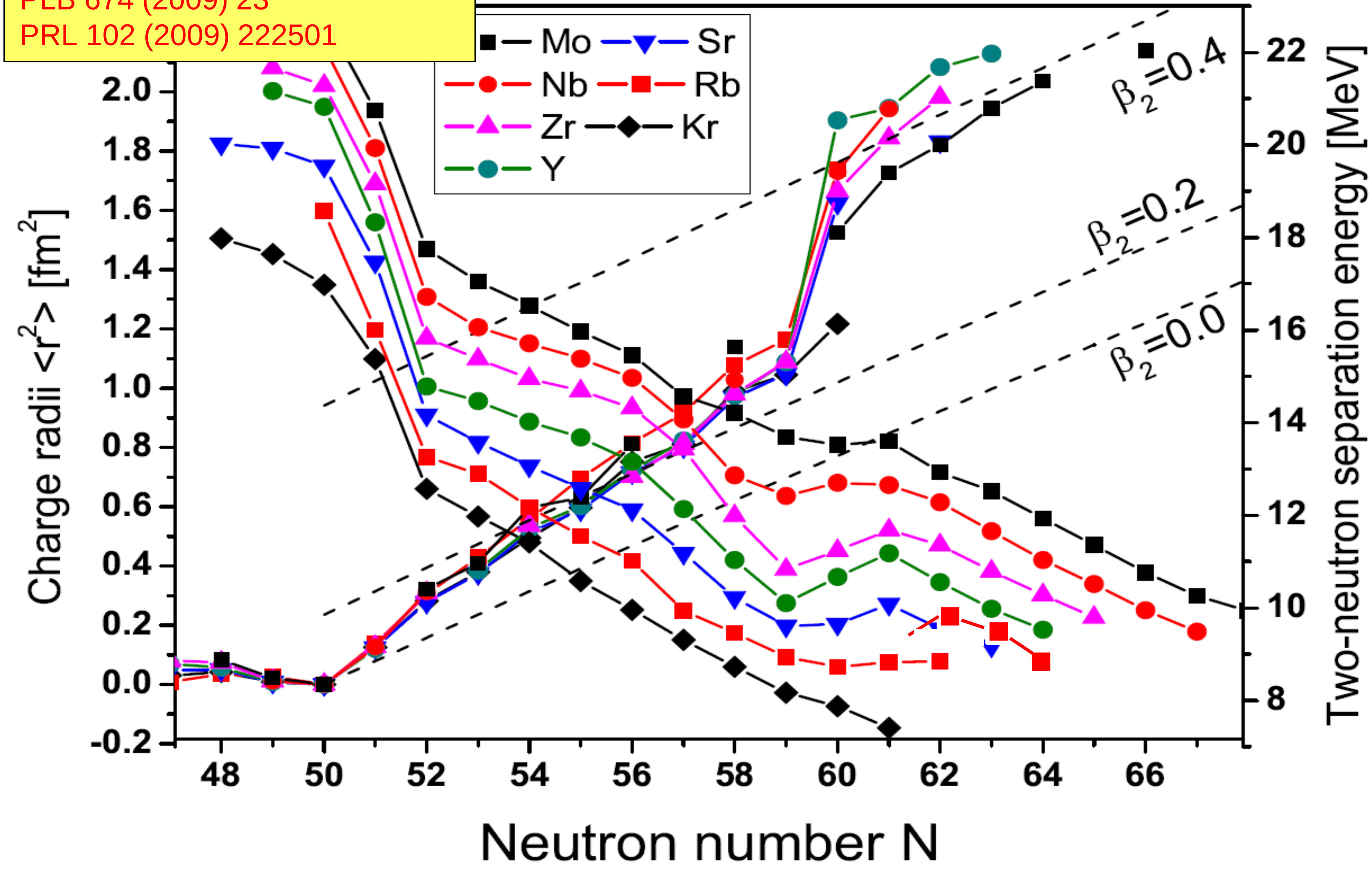
$2 \cdot 10^4$ improvement of SNR

Charge radii and two-neutron binding energies

Collinear laser spectroscopy:
PRL 89 (2002) *082501*
PLB 645 (2007) 133
PLB 674 (2009) 23
PRL 102 (2009) 222501

Newest Kr, Rb data from V. Manrea et al. (ISOLTRAP)

PHYSICAL REVIEW C **88**, 054322 (2013)

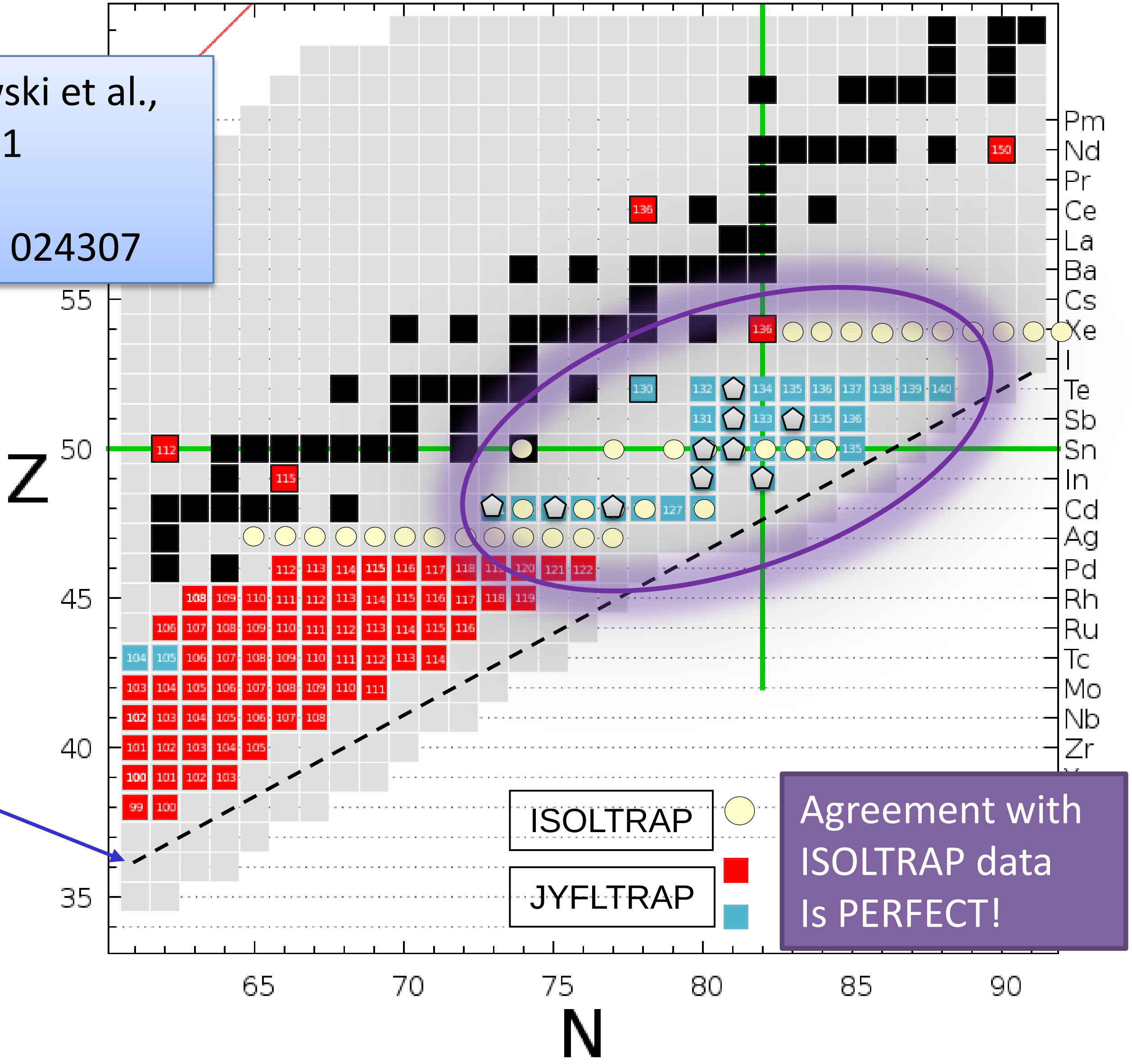


Neutron-rich masses close to ^{132}Sn

J. Hakala, J. Dobaczewski et al.,
PRL 109 (2012) 032501
A. Kankainen, et al.,
Phys. Rev. C 87 (2013) 024307

Isomers!
($T_{1/2}$ > 100 ms)

$T_{1/2}$ ≈100 ms



Agreement with
ISOLTRAP data
Is PERFECT!

Odd-even staggering (OES) in nuclear masses

a measure of empirical pairing gap

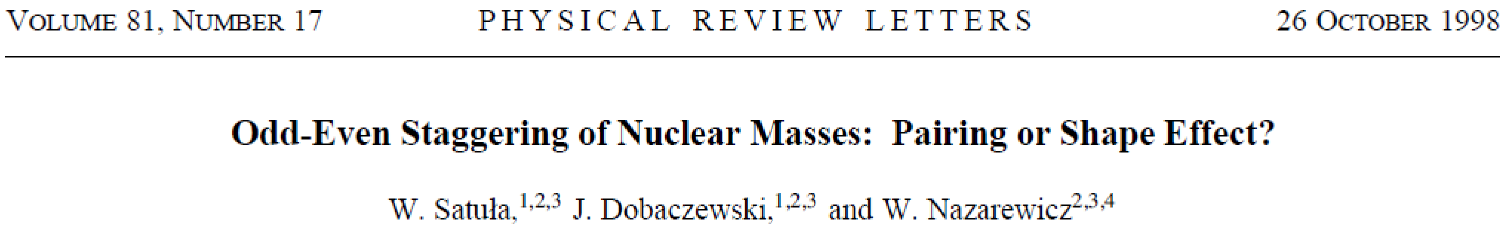
3-point formula

$$\Delta_N^{(3)} = (-1)^N \left[ME(Z,N+1) - 2ME(Z,N) + ME(Z,N-1)\right]/2$$

OES mostly depends on the intensity of nucleonic pairing correlations in nuclei but is also affected by the polarisation effects!

OES(N_{odd}) ~ measure of pairing effects

OES(N_{even}) ~ impacted by single particle states around Fermi level



VOLUME 81, NUMBER 17 PHYSICAL REVIEW LETTERS 26 OCTOBER 1998

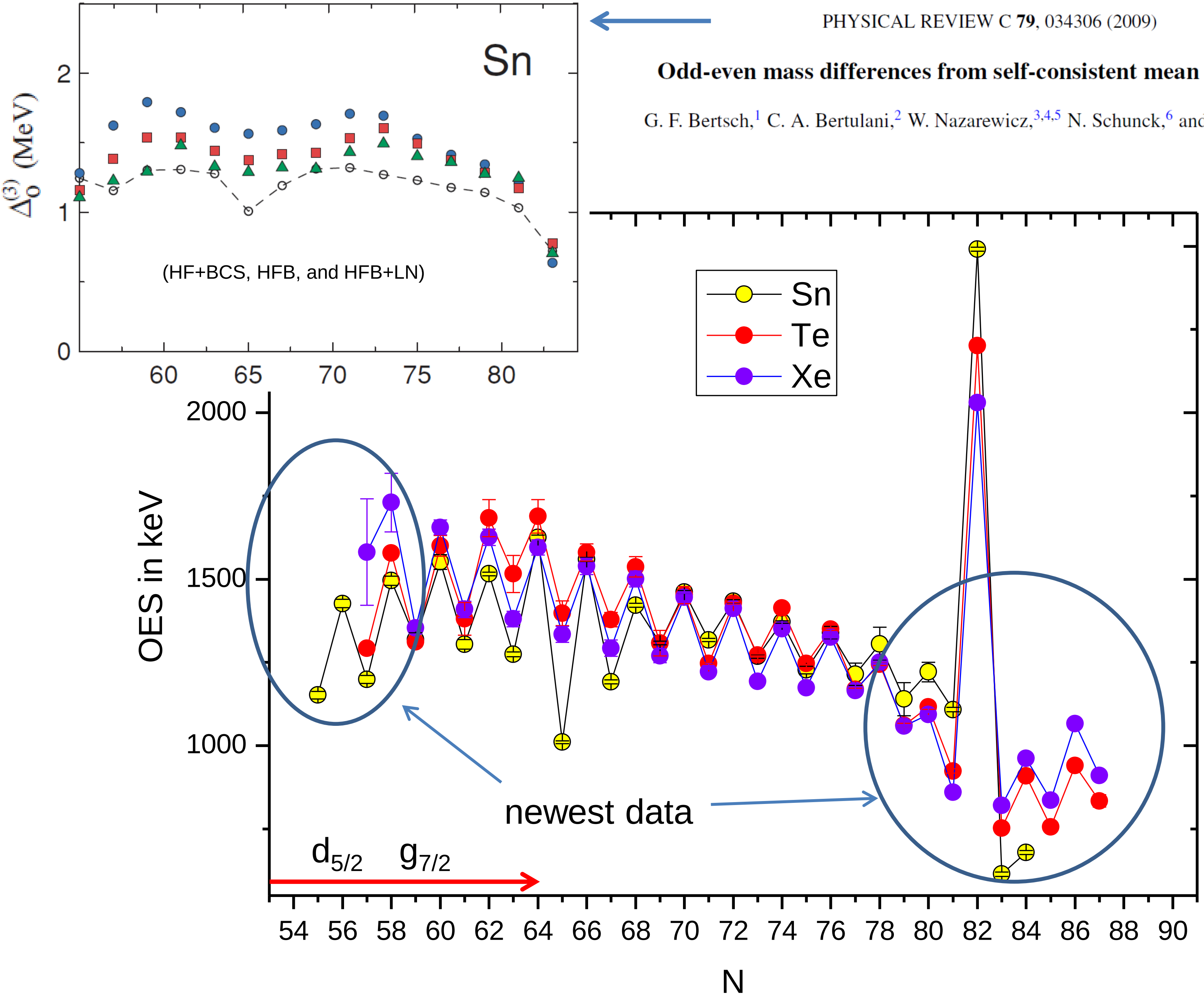
Odd-Even Staggering of Nuclear Masses: Pairing or Shape Effect?

W. Satuła,[1,2,3] J. Dobaczewski,[1,2,3] and W. Nazarewicz[2,3,4]

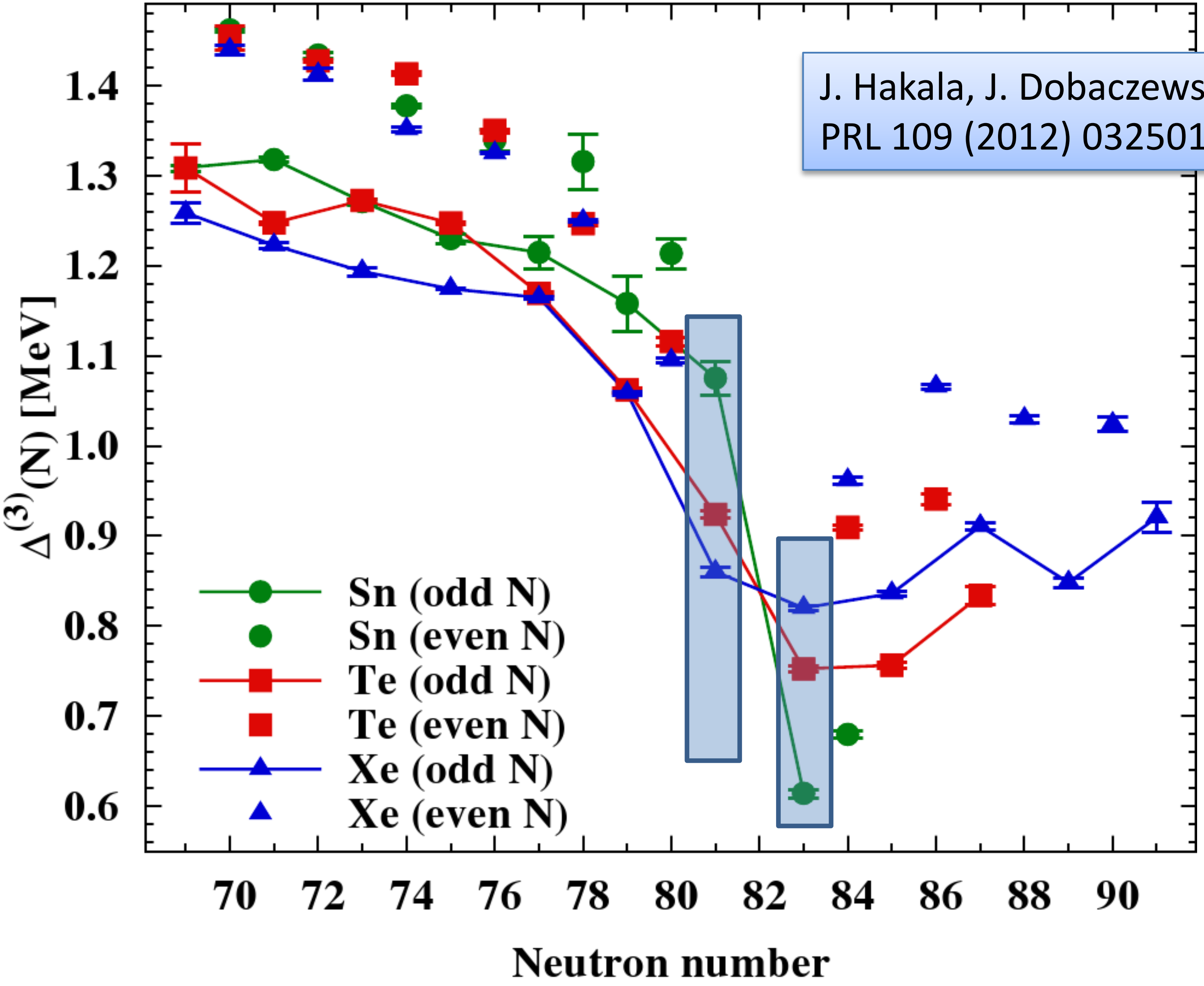
PHYSICAL REVIEW C **79**, 034306 (2009)

Odd-even mass differences from self-consistent mean field theory

G. F. Bertsch,[1] C. A. Bertulani,[2] W. Nazarewicz,[3,4,5] N. Schunck,[6] and M. V. Stoitsov[6]



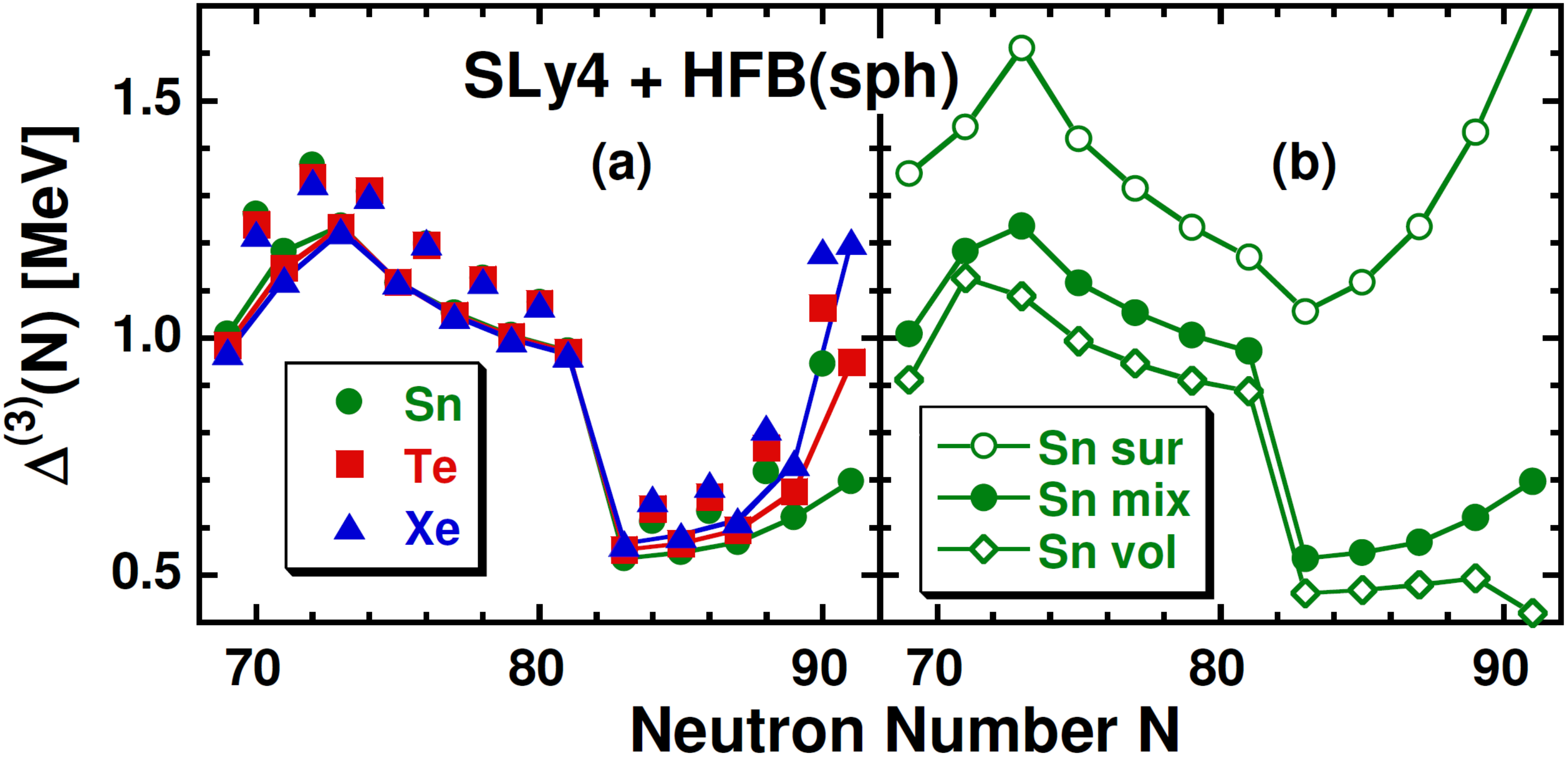
Odd-even staggering across the N=82 shell closure



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

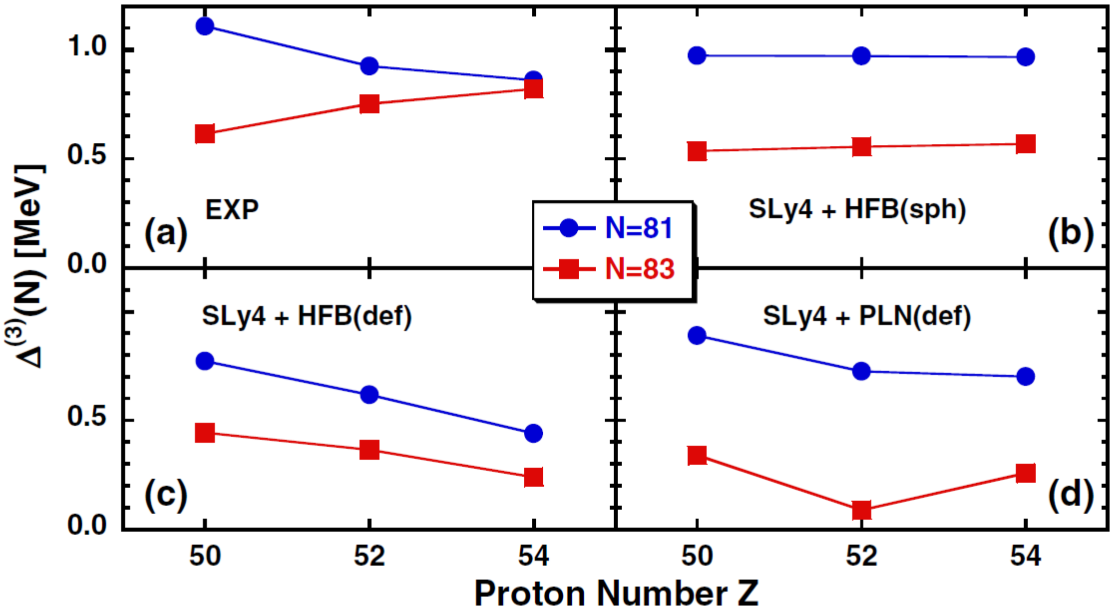
Spherical self-consistent calculation using Sly4 energy density functional plus contact pairing

Dobaczewski, Flocard, Treiner, Nucl. Phys. A **422**(1984)103



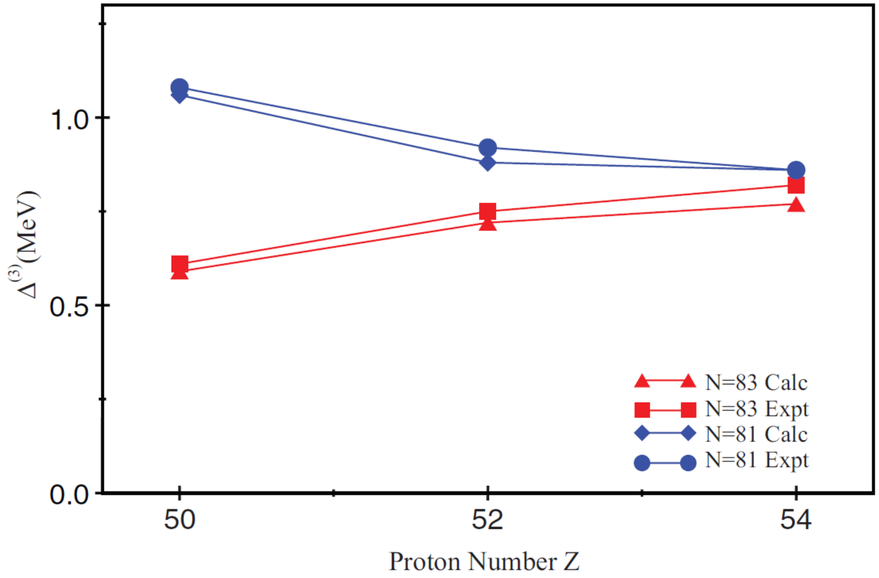
Conclusion: The N=81- 83 asymmetry in staggering indicates

- exclusion of pure surface pairing force
- significant role for polarization effects for Te and Xe !?
- same behaviour observed with Gogny interaction!
  * Robledo, Bernard, Bertsch, PRC 86(2012)064313



Mean field calculation with SLy4 functional in spherical and deformed basis.

→ No success!



L. Coraggio et al,
PRC 88(2013)041304(R)

Spherical Shell Model calculation with proton-neutron effective interaction included.

Summary

- Our knowledge of binding energies of neutron and proton -rich nuclei has experienced a major revision during the last 15 years due to Penning-trap technique applied at different accelerators.

- More than 1000 new masses have been measured with uncertainties of a few keV or less addressing a number of important (fundamental) issues for nuclear structure physics.

- The present data set provides a true challenge for future developments of mass models and nuclear structure theories when approaching the limits of nuclear stability and using nuclei as laboratories for fundamental physics.

- Future of the field will strongly be impacted by the in-flight facilities such as RIBF at RIKEN, FRIB at NSCL and FAIR.