Mass measurements and laser spectroscopy with radioactive ion beams – FAIR perspective

- **Ground-state properties (at ISOL facilities)**
- **Mass measurements**
- **Optical spectroscopy**
- **Recent highlights**
- **FAIR; MATS and LaSpec**

Ari Jokinen
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Ground-state properties

Isotope Shift → Mean Square Charge Radii $\delta\langle r^2\rangle^{AA'}$

Hyperfine Structure →
- Nuclear Spin I
- Magnetic Dipole Moment μ_I
- Electric Quadrupole Moment Q_s
- Hyperfine Anomaly

Atomic mass → Binding energy / Limits of nuclear existence

Mass differences →

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)
- Shell-gap energy (evolution of magicity)
- Valence proton-neutron interaction energy δV_{pn}

Experimental approaches on mass measurements

Indirect determination: reactions and decay

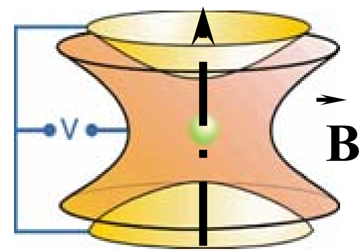
* Reactions (transfer, double pion charge exchange, invariant masses, ...)
* Decay (α, β+, β-, ...)

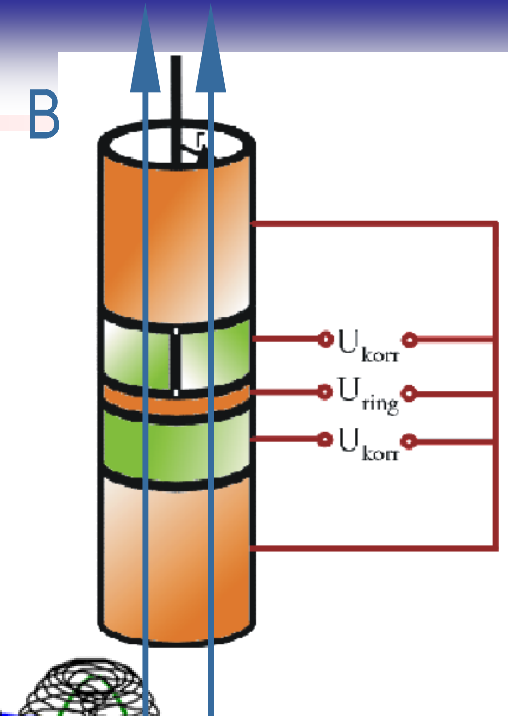
Direct measurements

* RF Spectrometers (MISTRAL)
* Bρ-TOF Spectrometers (SPEG)
* Cyclotrons (CSS2, CIME)
* Ion traps (ISOLTRAP, CPT, JYFLTRAP, SHIPTRAP, ...)
* Storage rings (FRS-ESR)
* Electrostatic mirror systems

Ion motions in Penning trap

$$\sum \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$





➢ Three harmonic eigenmotions

1. **Axial** motion:

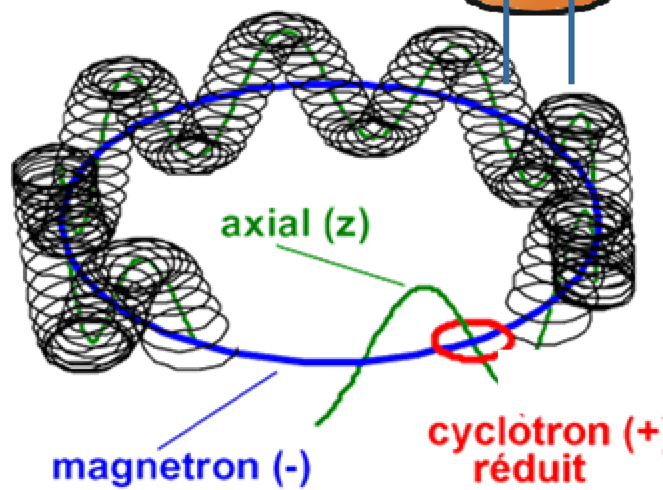
$$\omega_z = \sqrt{\frac{qV_0}{md^2}}$$

2. **Magnetron** motion (slow):

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

3. **Reduced Cyclotron** motion (fast):

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$



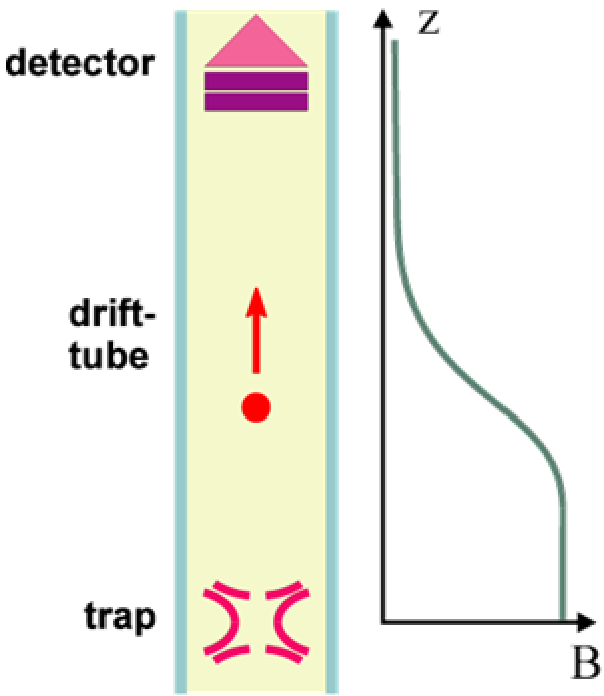
$$\omega_c = \omega_+ + \omega_- = \frac{q}{m} \cdot B$$

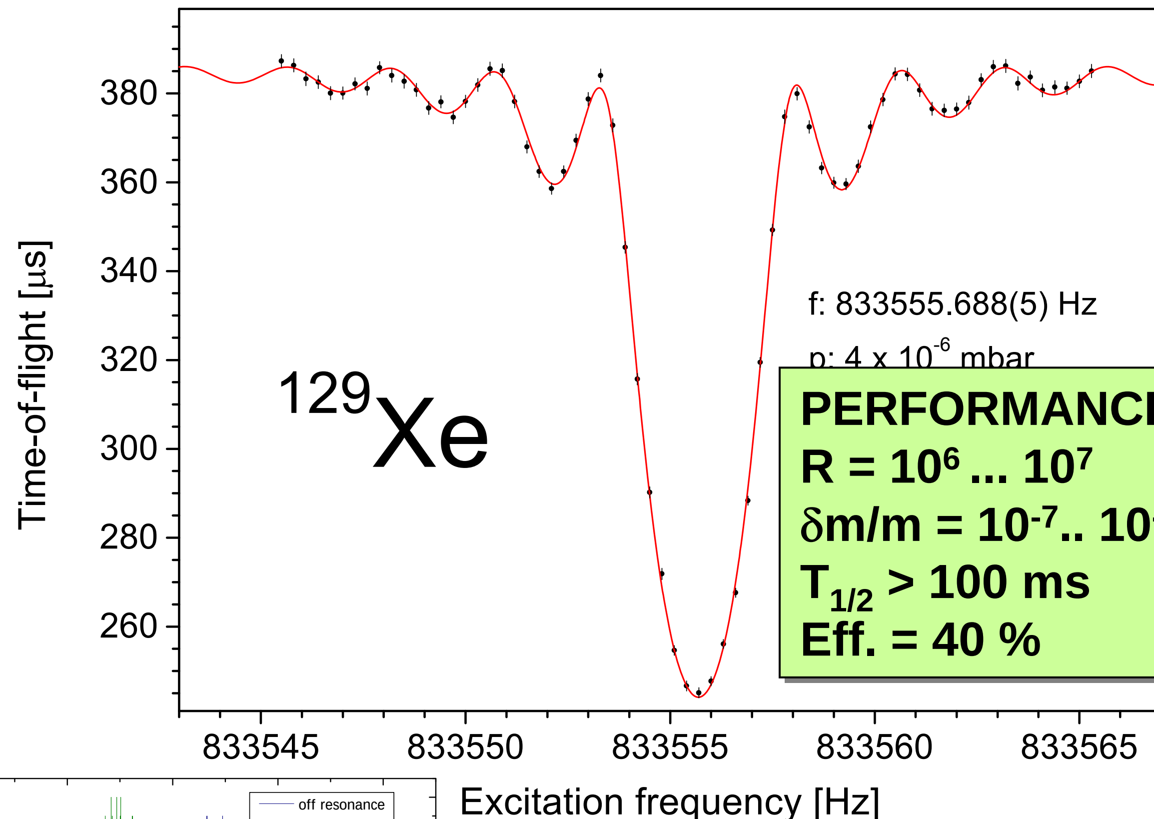
A=100, q=1, B=7 T

- $f_+ \approx$ 1 MHz
- $f_- \approx$ 1 kHz
- $f_z \approx$ 44 kHz

Resonance frequency measurement – the time-of-flight technique

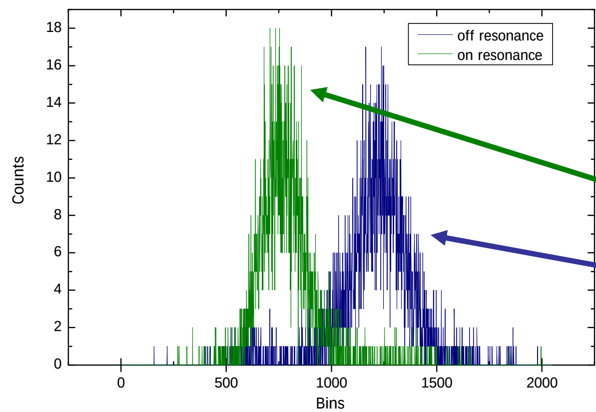
M. König et al, Int. J. Mass. Spec Ion Proc. 142 (1995) 95





PERFORMANCE:
$R = 10^6 \ldots 10^7$
$\delta m/m = 10^{-7} \ldots 10^{-8}$
$T_{1/2} > 100$ ms
Eff. = 40 %

$$\vec{F} = \vec{\mu}\ \vec{\nabla} B$$



^{129}Xe time of flight spectrum

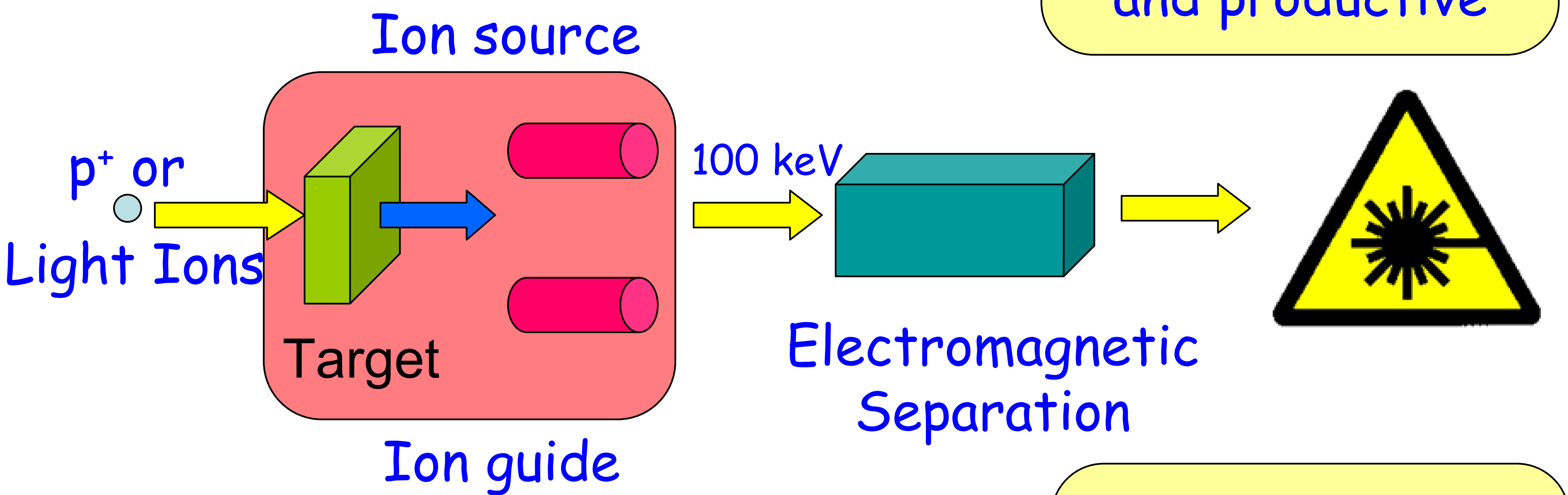
On resonance
Off resonance

ISOL approach

ISOL

$T_{1/2}$ ~ 10 ms
no reactive elements
no refractory elements

Good conditions for spectroscopy: highly successful and productive

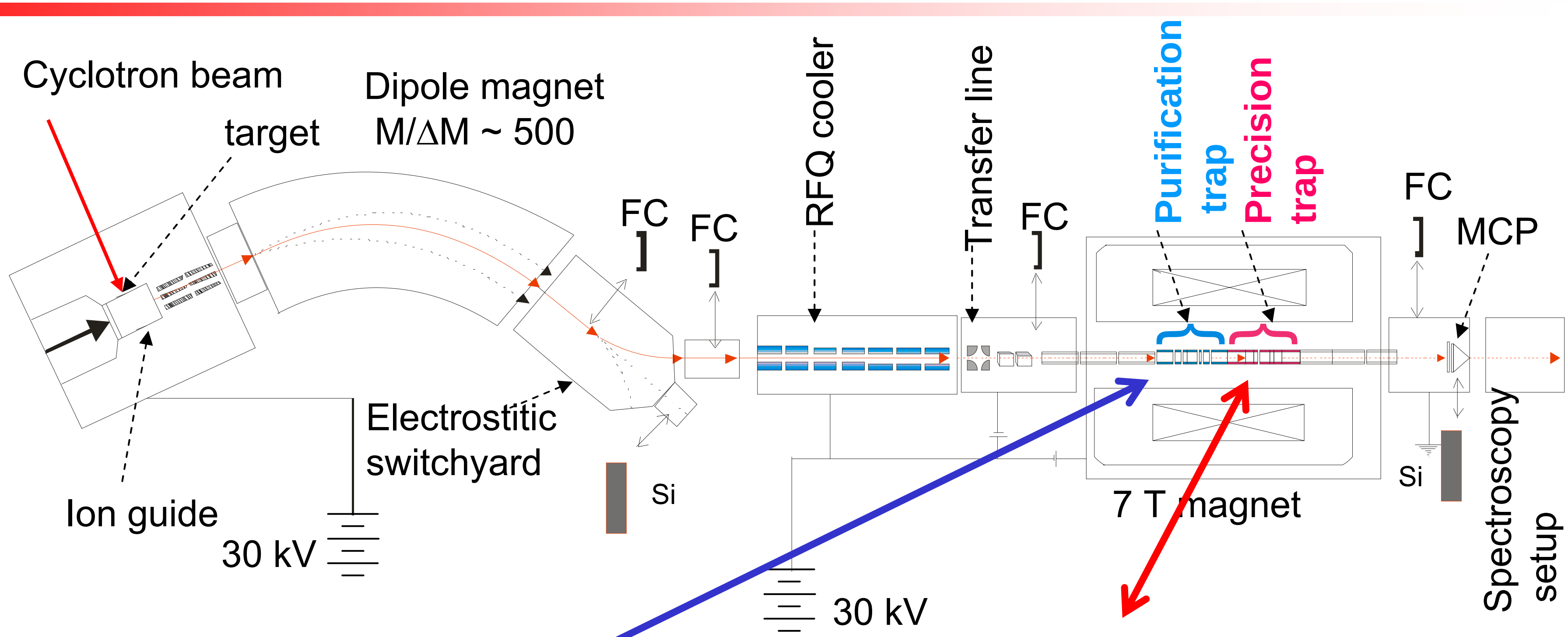


$T_{1/2}$ ~ 1 ms
reactive elements
refractory elements
very modest yields

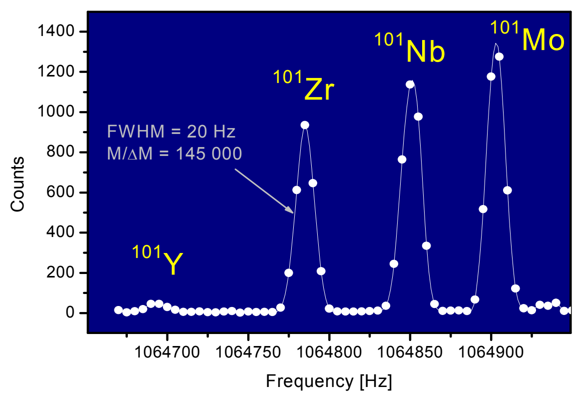
IGISOL

Good conditions for spectroscopy **only** if the beam is cooled

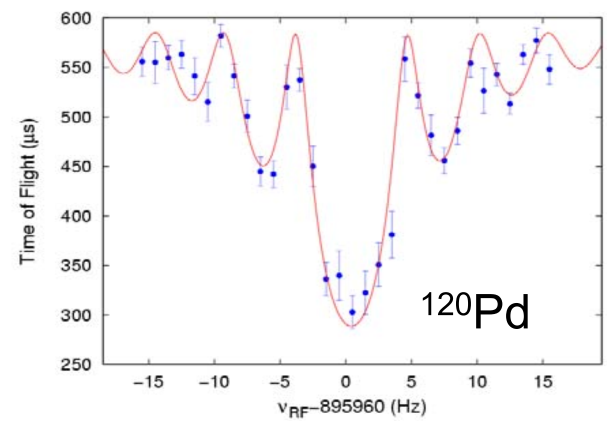
JYFLTRAP setup @ IGISOL



Purification scan



TOF-resonance in Precision trap

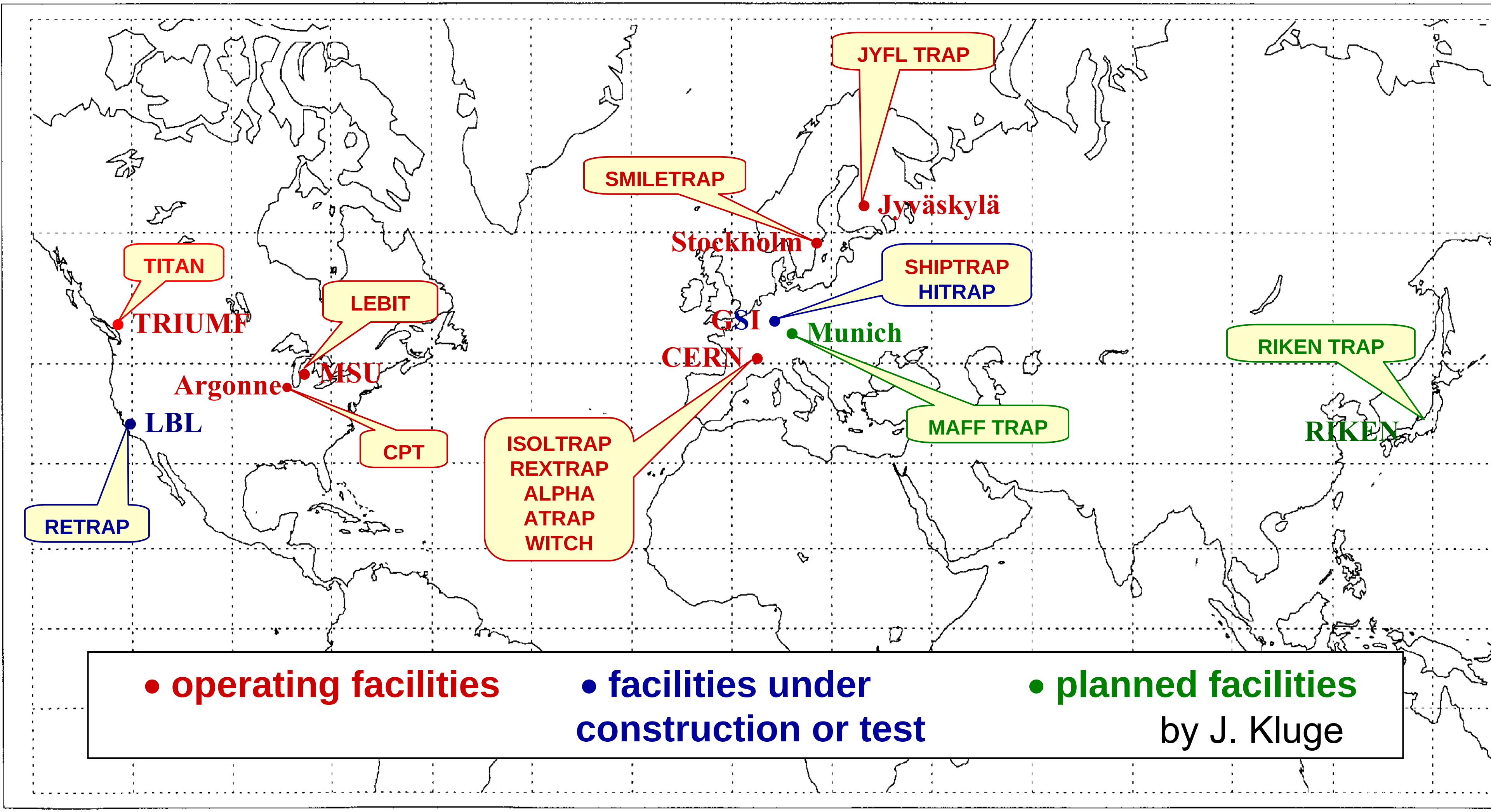


Basic equations for mass determination

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

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

Penning Traps at Accelerators

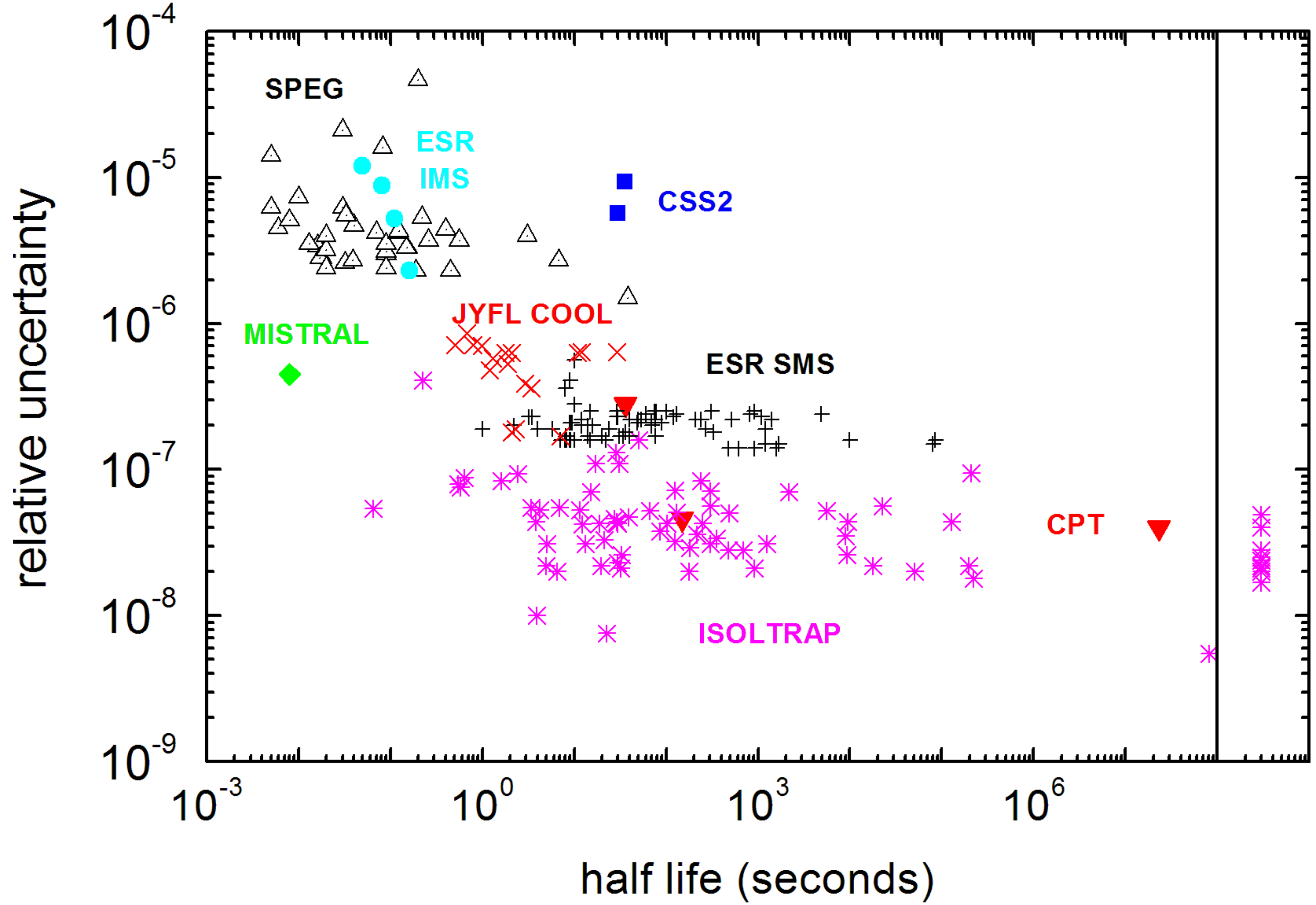


K. Blaum, Phys. Rep. 425 (2006) 1

Complementary of Penning trap projects

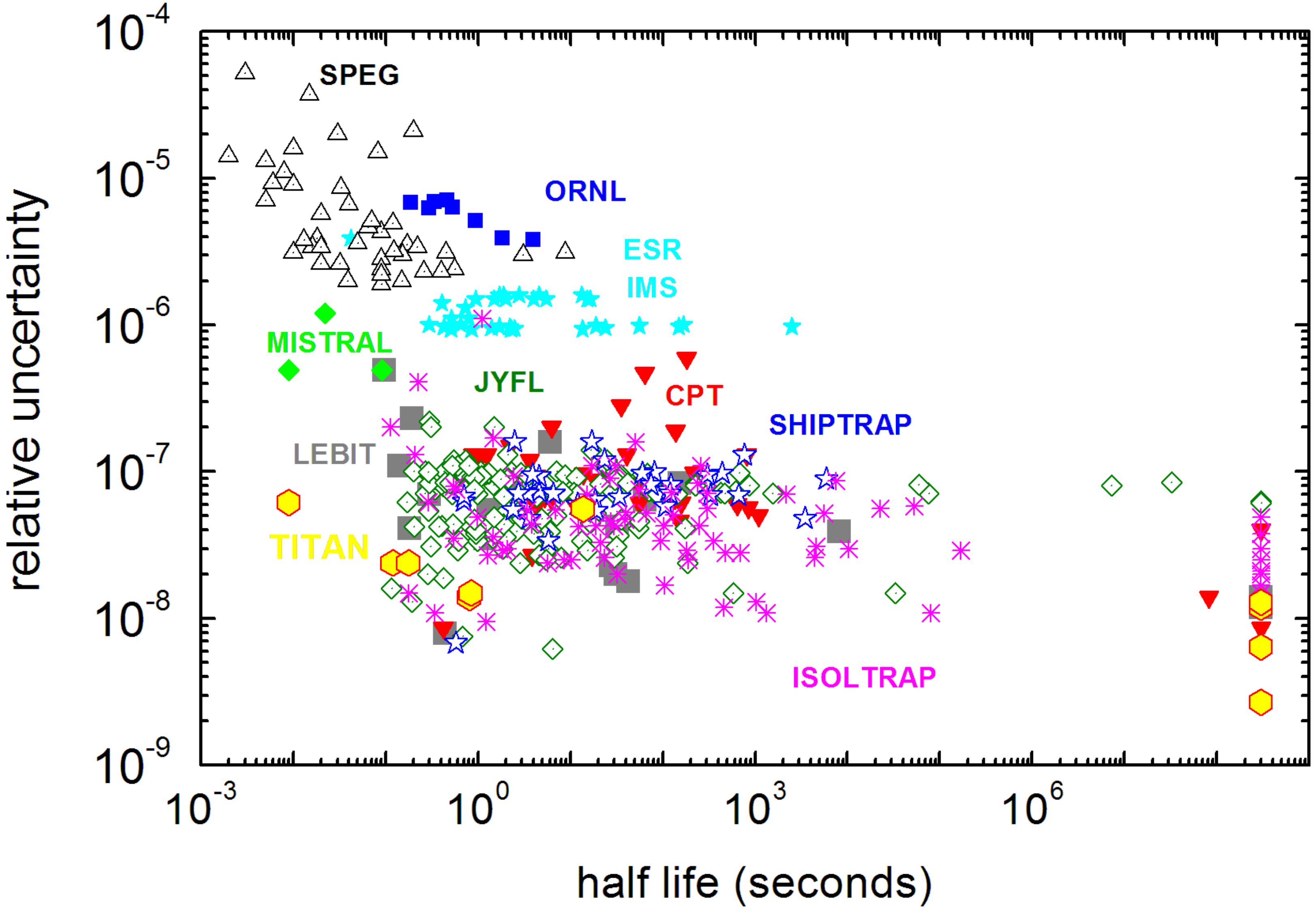
Type of reaction	ISOLTRAP	CPT	SHIPTRAP	JYFLTRAP	LEBIT	TITAN	SMILE-TRAP	MAFF-TRAP	HITRAP	MATS/FAIR
Conventional ISOL-technique	X					X				
Fusion evaporation reaction		X	X							
IGISOL				X						
Fragmentation reaction					X				X	X
neutron-induced fission								X		
Highly-charged ions						X	X		X	X
Stable ions				X			X		X	
Trap-assisted spectroscopy				X						X

Trap performance (ENAM 2004)



(D. Lunney)

Trap performance (ENAM 2008)

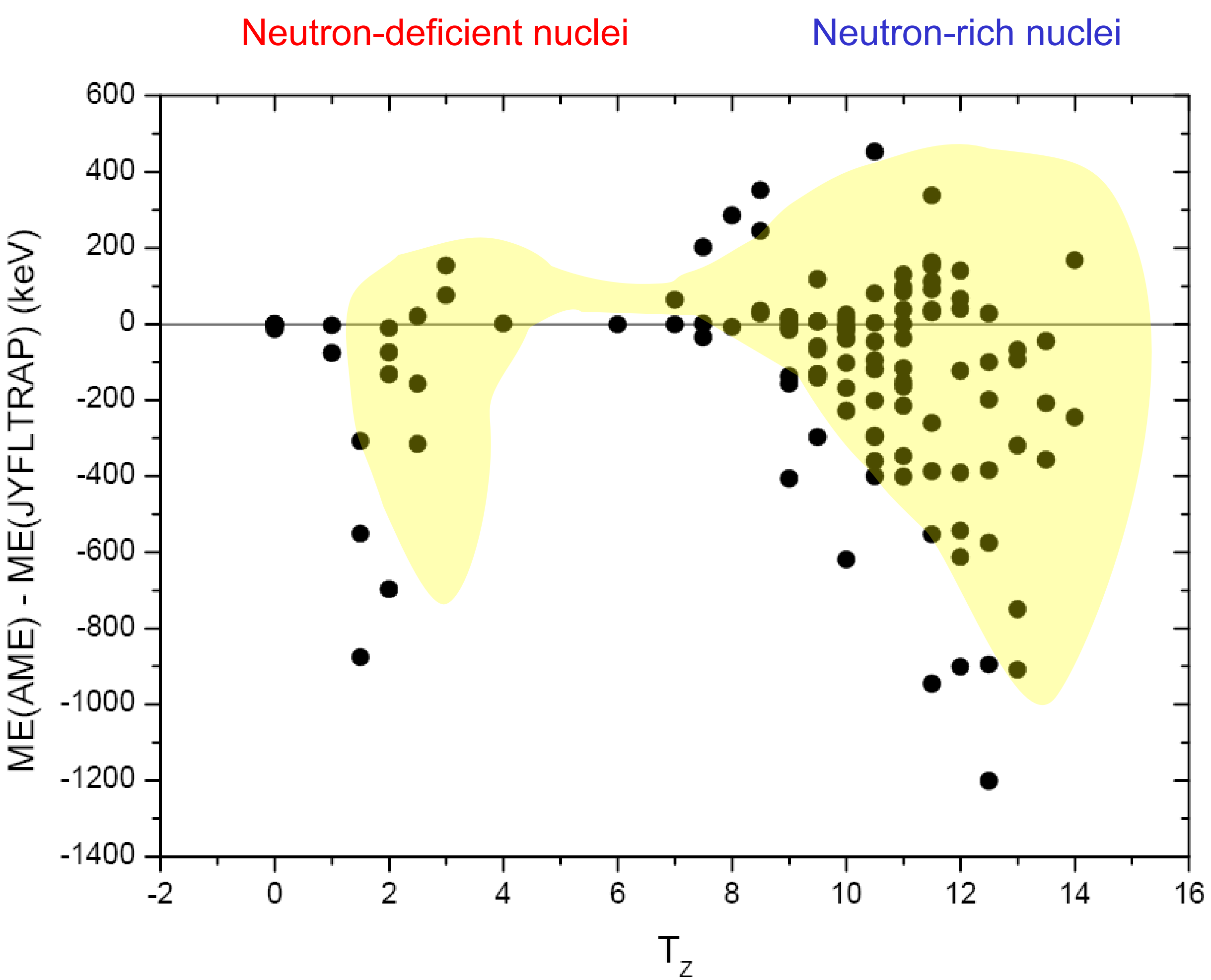


(D. Lunney)

Research areas and relevant precision

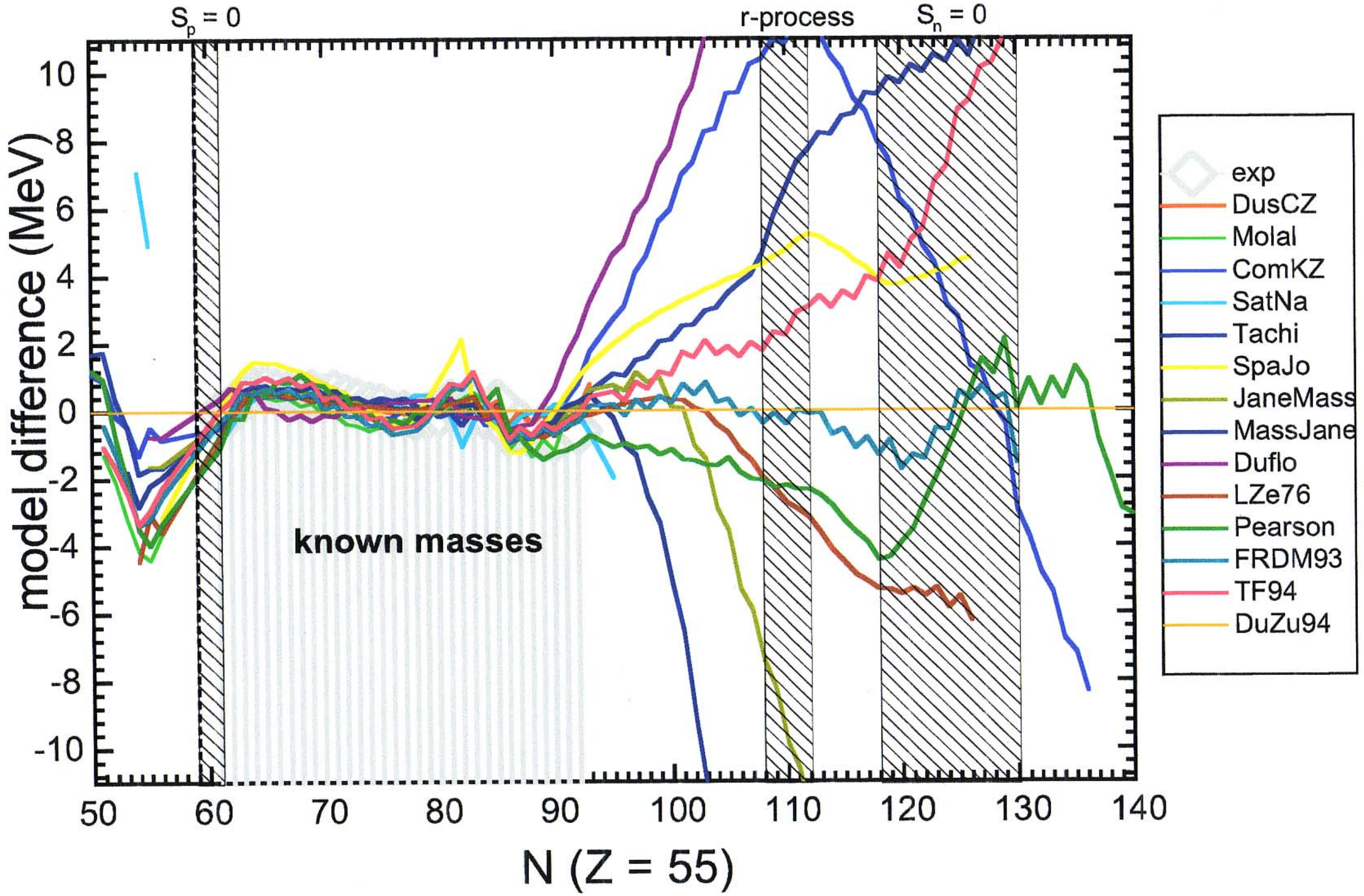
- **Nuclear structure (10-100 keV)**
  - Global correlations (100 keV)
  - Local correlations (10 keV)
    - shell structure, spin-orbit interaction, pairing, collectivity
  - Drip-line phenomena and halos (1 keV)
- **Nuclear astrophysics (1 keV)**
- **Charge symmetry in nuclei (<1 keV)**
  - Isospin multiplets
  - Coulomb energy differences
- **Test of Standard Model (< 100 eV)** $\delta m/m < 1 \cdot 10^{-9}$
  - Nuclear β decay. Electroweak interaction
    - CVC theory and unitarity of CKM matrix
    - Neutrinoless double β decay

JYFLTRAP masses and AME2003



http://research.jyu.fi/igisol/JYFLTRAP_masses/
AME2003, G. Audi et al., NPA 729 (2003) 337

Mass predictions for Z=55

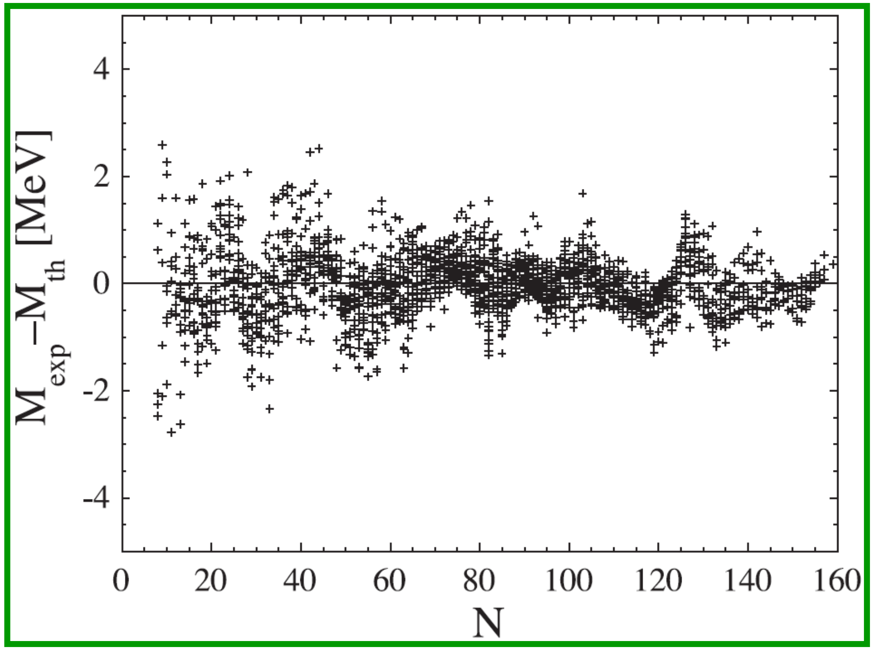


JYFLTRAP masses vs predictions

S. Goriely N. Chamel and J. M. Pearson, PRL 102 (2009) 152503
”… Crossing the 0.6 MeV accuracy threshold …”

HFB-17

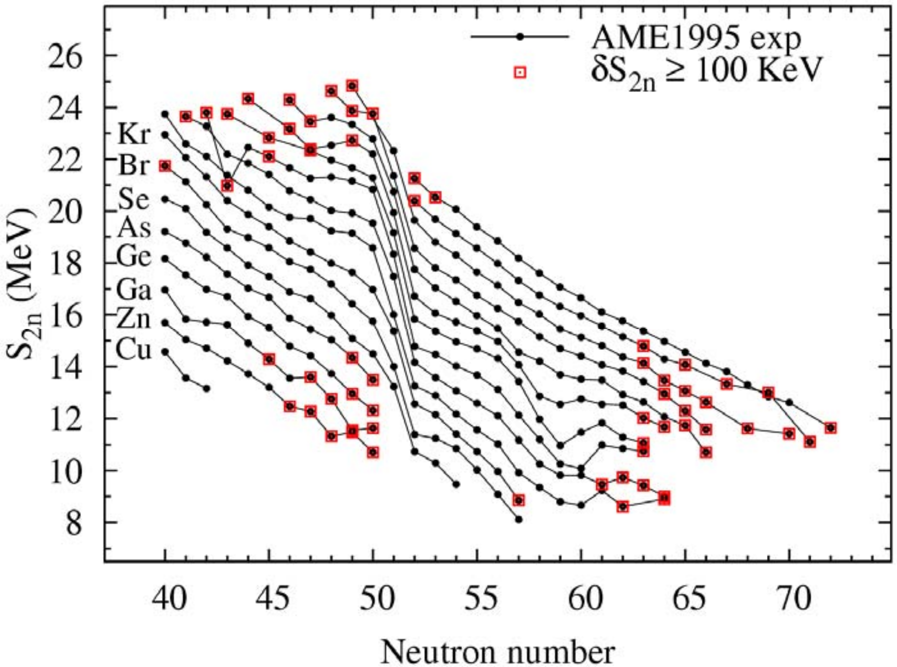
	HFB-16	HFB-17
$\sigma(2149M)$ [6]	0.632	0.581
$\bar{\epsilon}(2149M)$ [6]	−0.001	−0.019
$\sigma(M_{\mathrm{nr}})$ [6]	0.748	0.729
$\bar{\epsilon}(M_{\mathrm{nr}})$ [6]	0.161	0.119
$\sigma(S_n)$ [6]	0.500	0.506
$\bar{\epsilon}(S_n)$ [6]	−0.012	−0.010
$\sigma(Q_\beta)$ [6]	0.559	0.583
$\bar{\epsilon}(Q_\beta)$ [6]	0.031	0.022
$\sigma(434M)$ [11]	0.484	0.363
$\bar{\epsilon}(434M)$ [11]	−0.136	−0.092
$\sigma(142M)$ [12]	0.516	0.548
$\bar{\epsilon}(142M)$ [12]	−0.070	0.172
$\sigma(R_c)$ [13]	0.0313	0.0300
$\bar{\epsilon}(R_c)$ [13]	−0.0149	−0.0114
$\theta(^{208}\mathrm{Pb})$	0.15	0.15

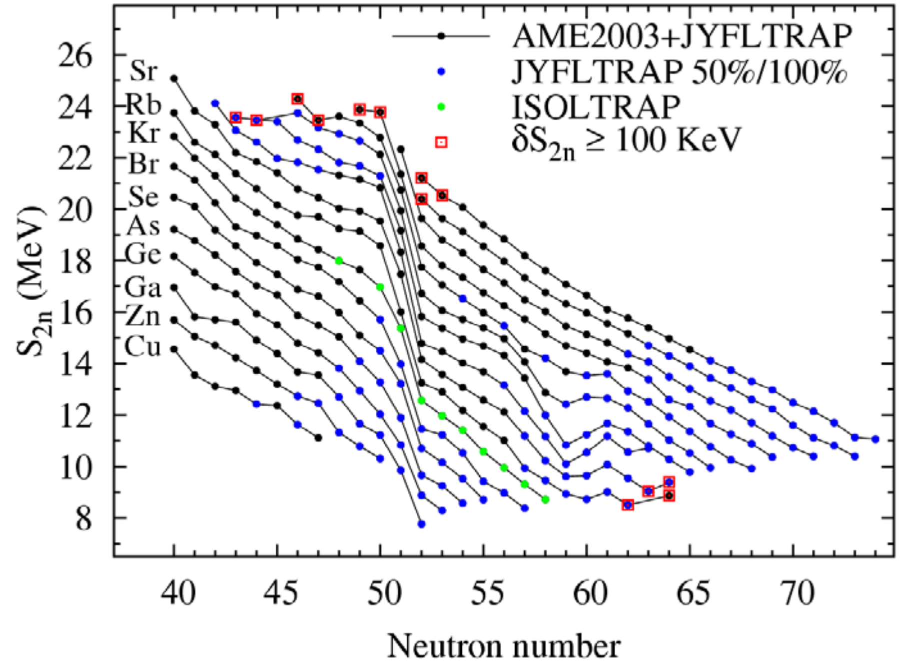


[6] G. Audi, et al. Nucl. Phys. A729, 337 (2003).
[12] http://research.jyu.fi/igisol/JYFLTRAP_masses/

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

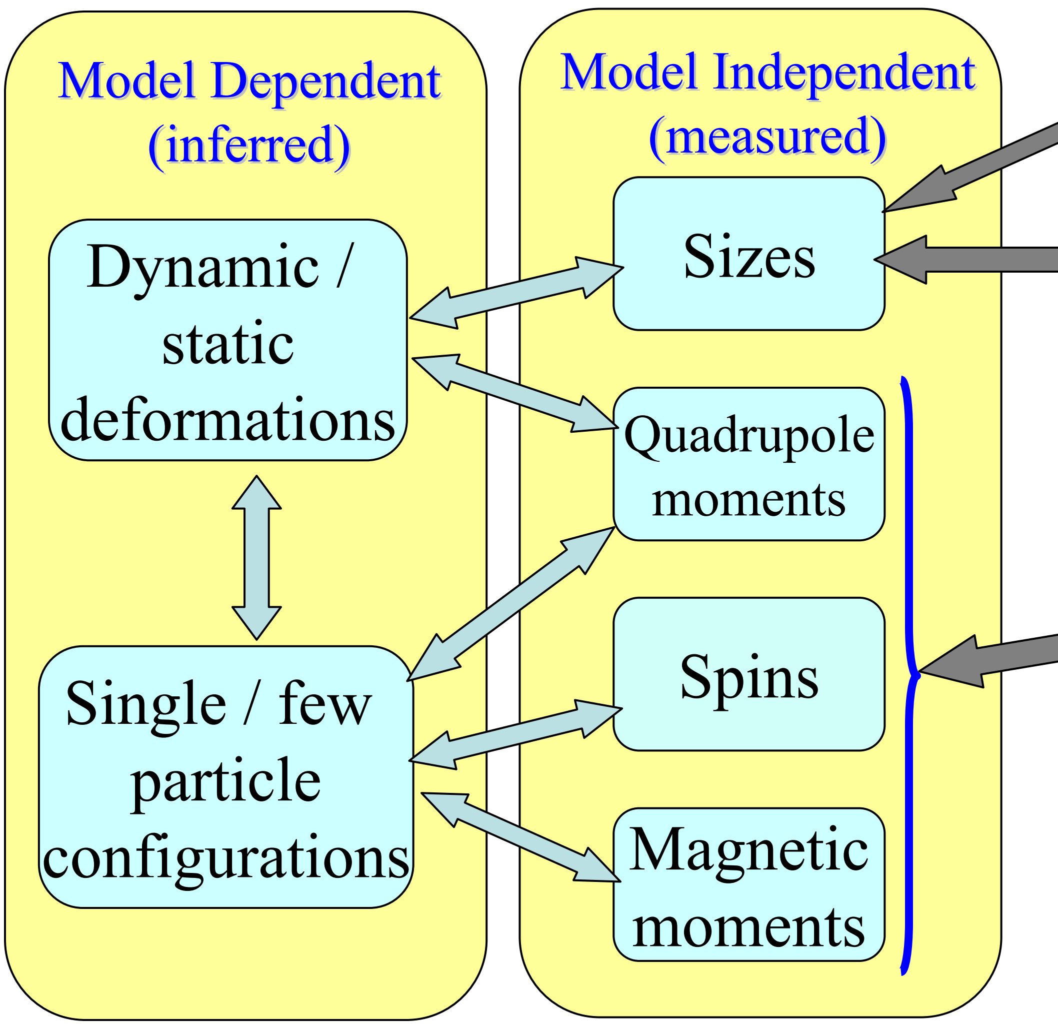
$$S_{2n}(N,Z) = B(N,Z) - B(N-2,Z)$$

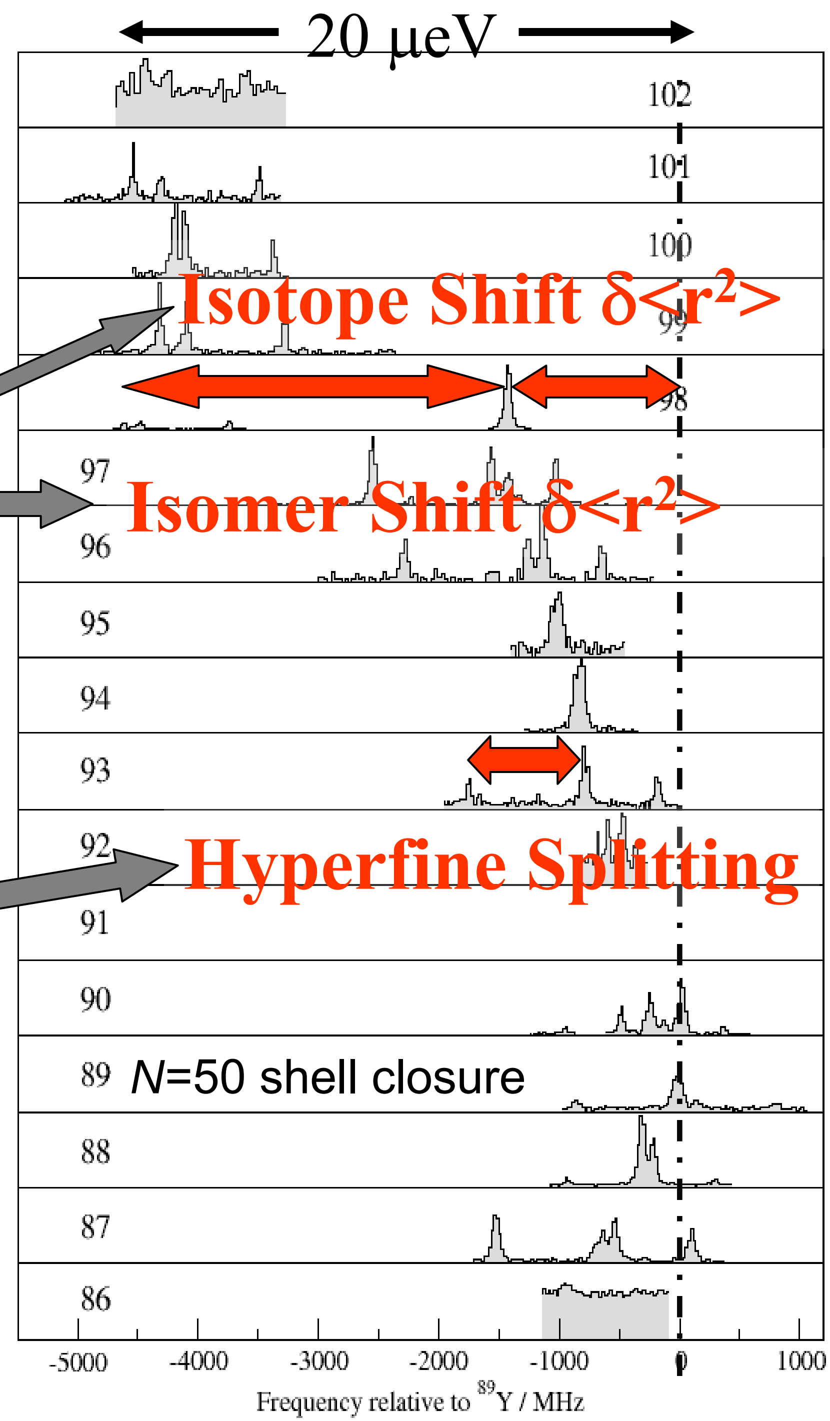




Optical spectroscopy

Measure atomic level perturbations

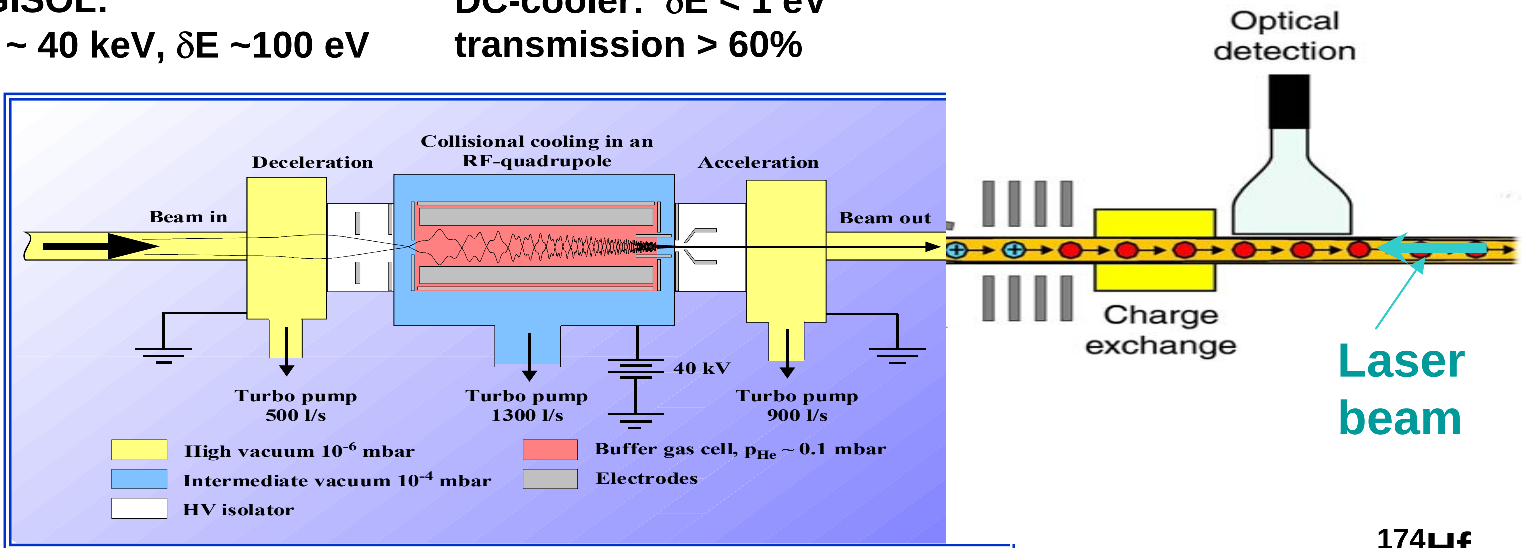




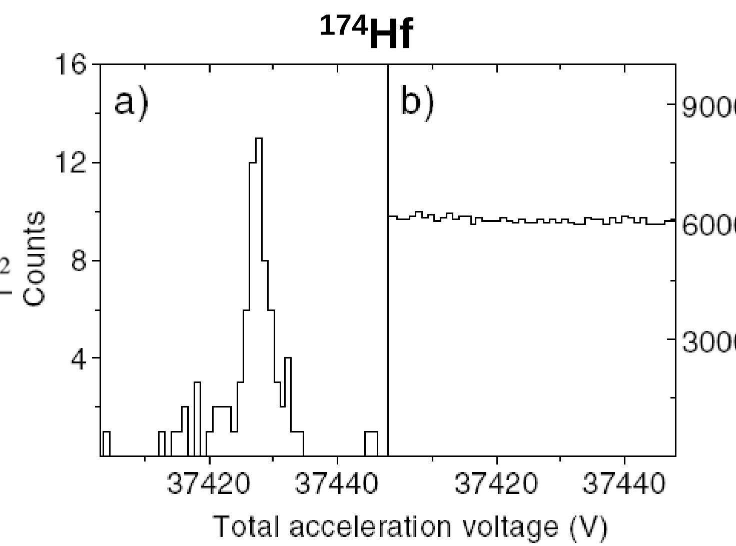
Collinear laser spectroscopy with bunching

IGISOL:
E ~ 40 keV, δE ~100 eV

DC-cooler: δE < 1 eV
transmission > 60%



Buncher:
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*
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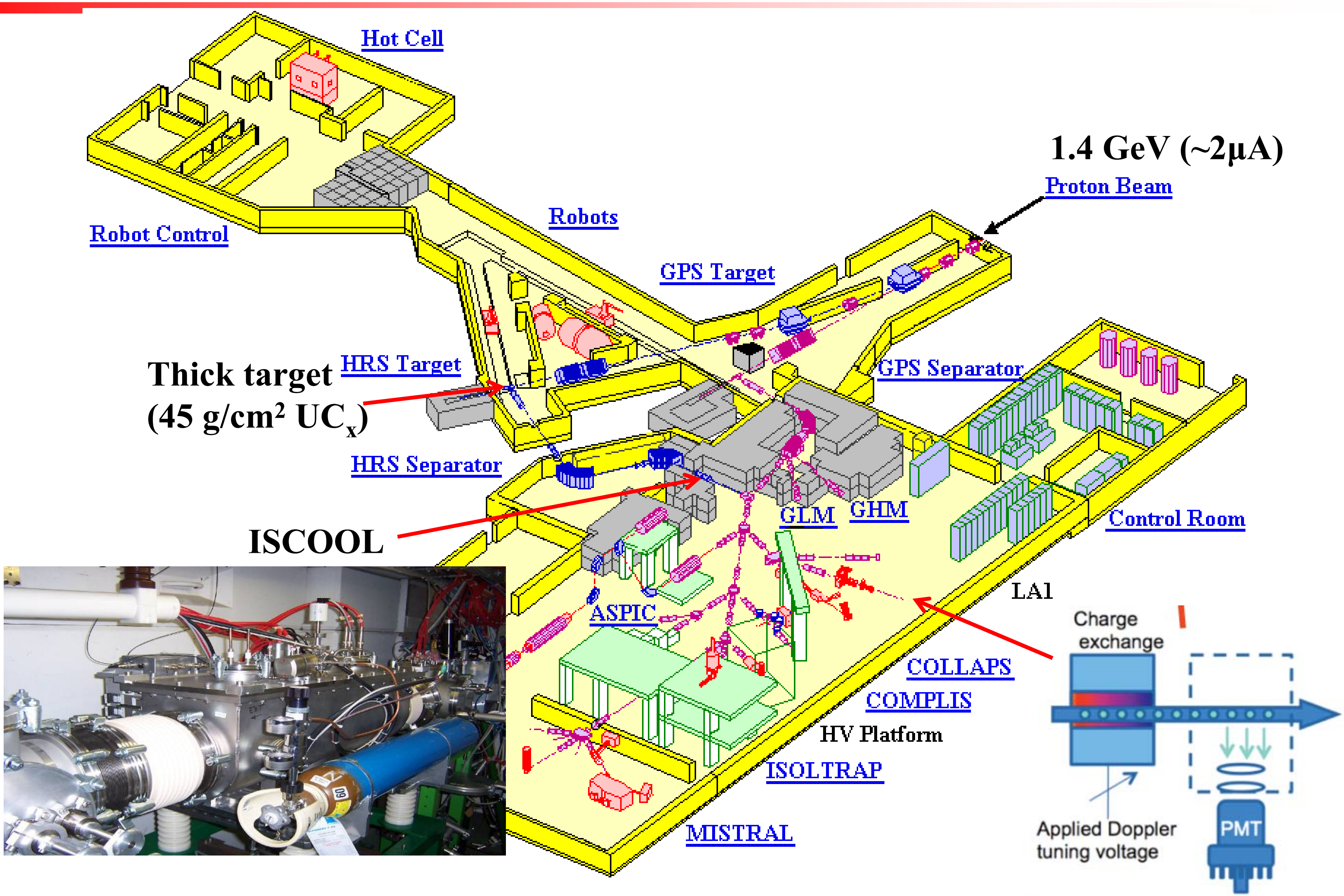
(Received 13 November 2001; published 14 February 2002)

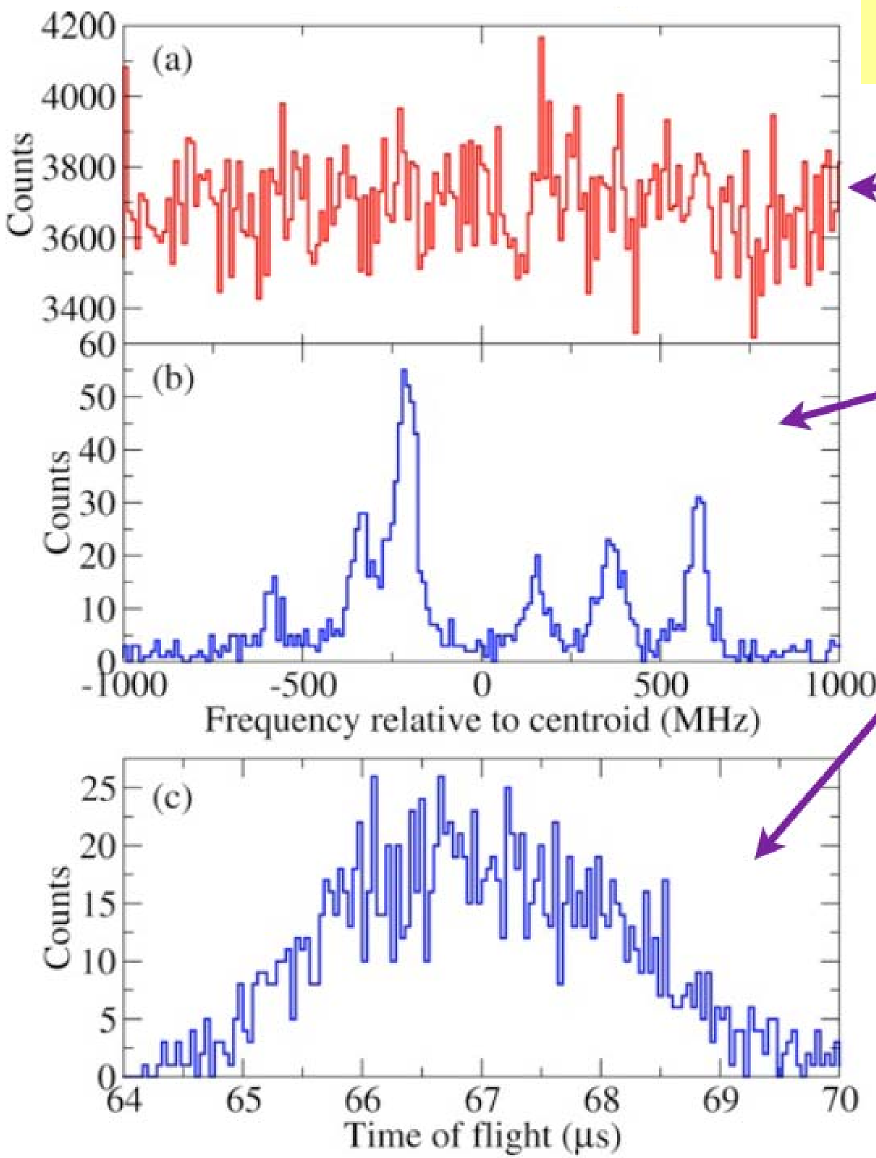
A new method has been developed for increasing the sensitivity of collinear laser spectroscopy. The method utilizes an ion-trapping technique in which a continuous low-energy ion beam is cooled and accumulated in a linear Paul trap and subsequently released as a short (10–20 μs) bunch. In collinear laser 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 !

COLLAPS & ISCOOL for Ga at ISOLDE



The power of bunching the ions with ISCOOL



^{76}Ga at 417.3 nm, $4p\ ^2P_{3/2} \rightarrow 5s\ ^2S_{1/2}$

Ungated

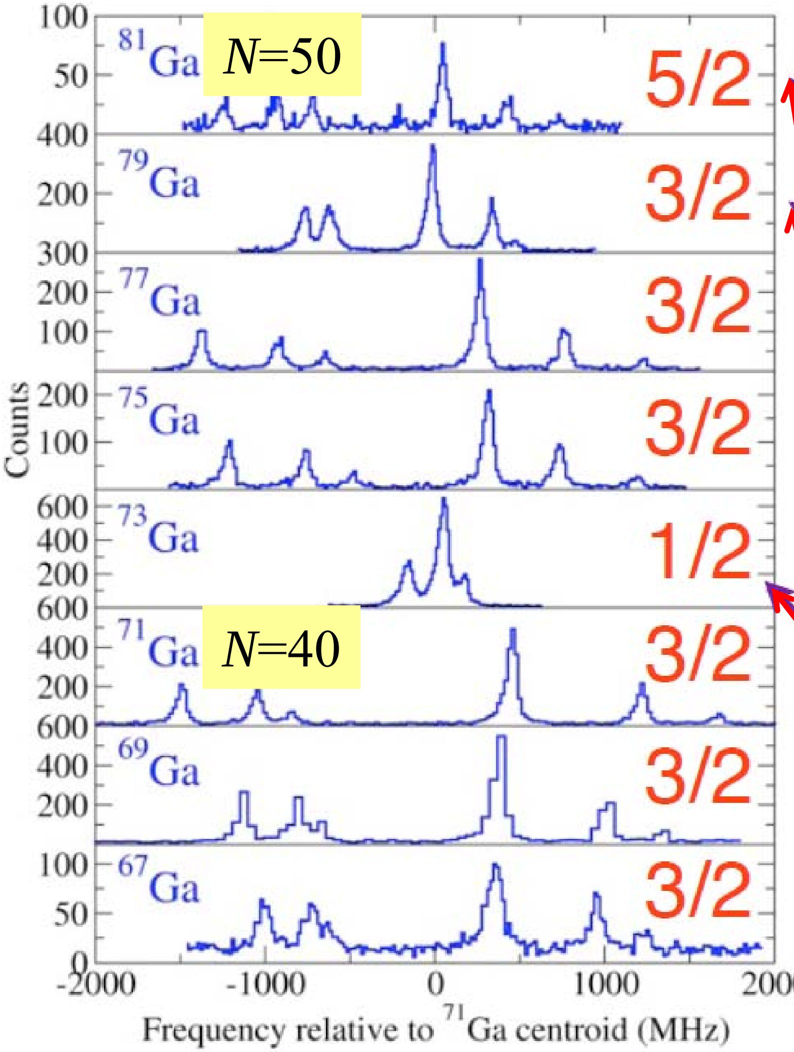
Gated (64μs - 70μs)

Time of flight
(50ms accumulation)

Background suppression

50ms / 6μs = ~10^4

Spectroscopy of Ga (Z=31) odd A isotopes



Sufficient number of peaks for μ, Q_s, $\delta\langle r^2 \rangle$ and *I*

Spin inversion
(also seen between ^{73}Cu & ^{75}Cu, K.T. Flanagan *et al.*, PRL 103 (2009) 142501)

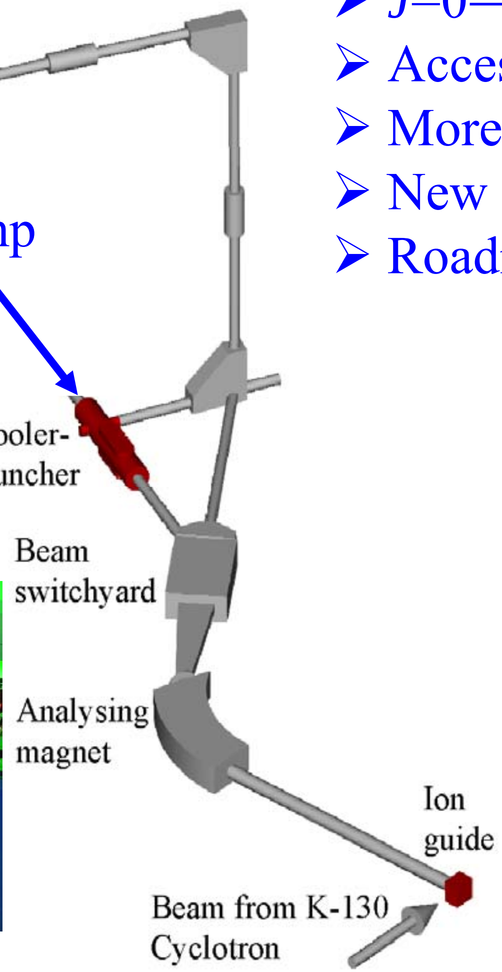
Not quantitatively predicted by any theory

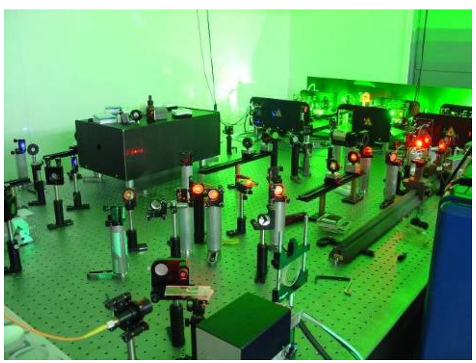
Optical pumping in the cooler

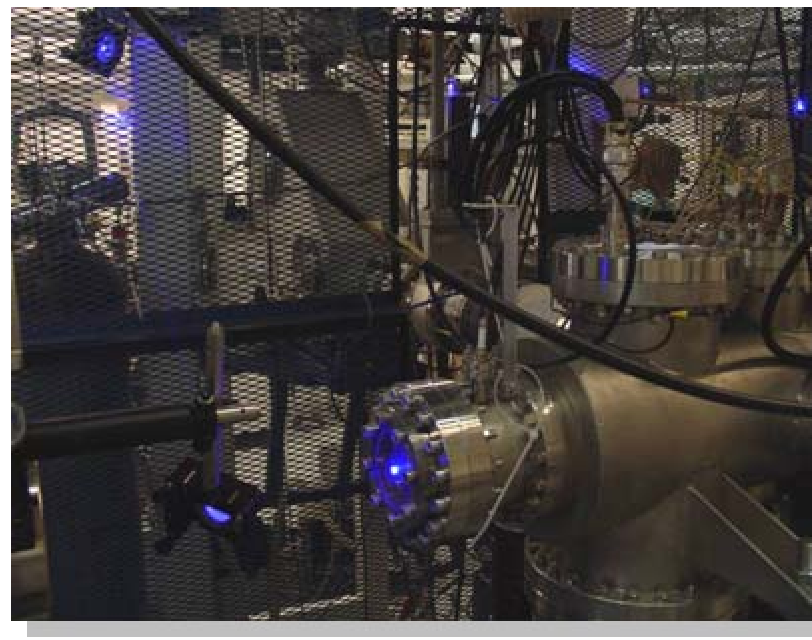
- J=0→J=1 gives μ, Q, $\delta<r^2>$, ~~I~~ (eg Y^+)
- Access to more accessible transitions (Mo)
- More efficient transitions (Nb)
- New elements to study
- Roadmap to polarization in the cooler

Ti:Sapphire
10 kHz
Γ = 4-5 GHz

pump

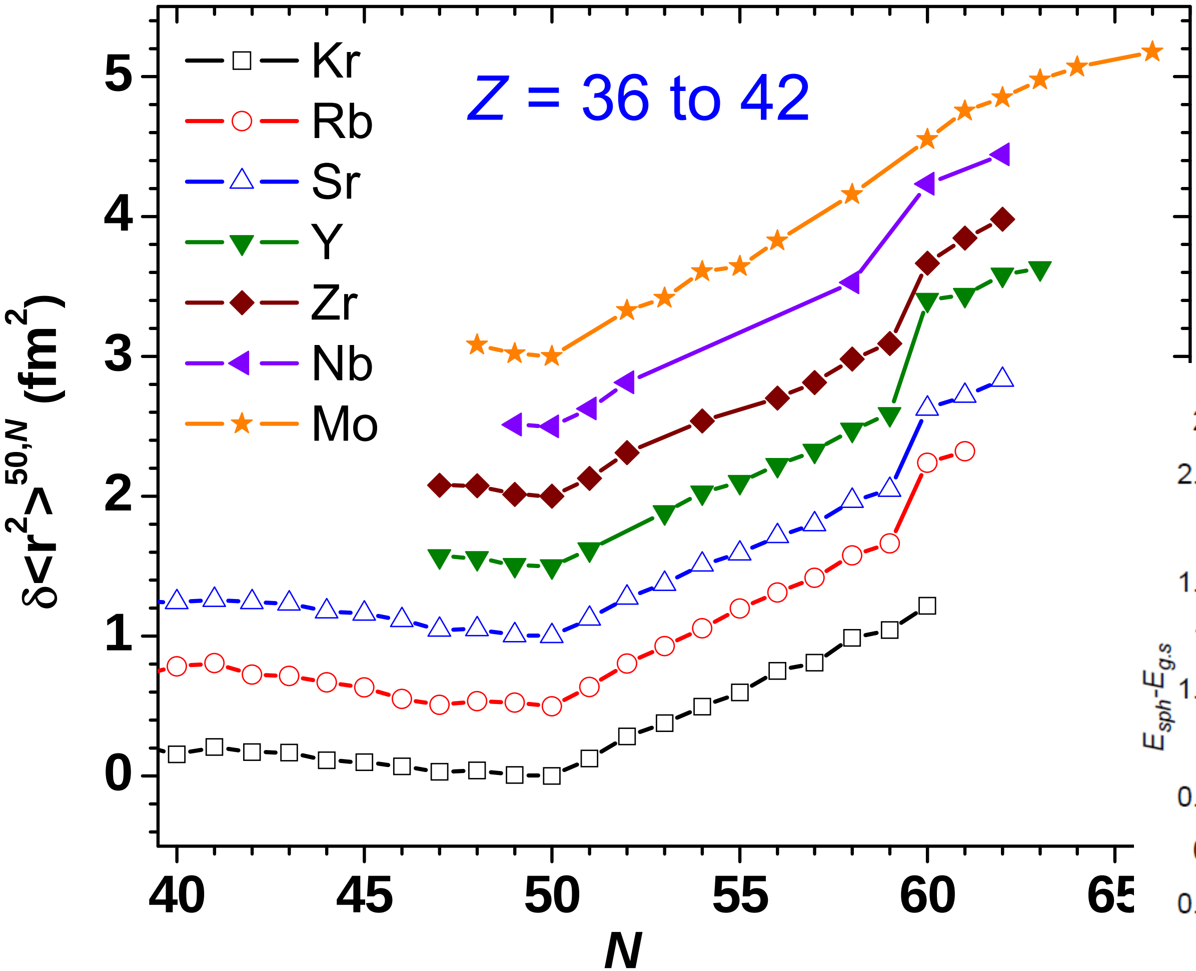






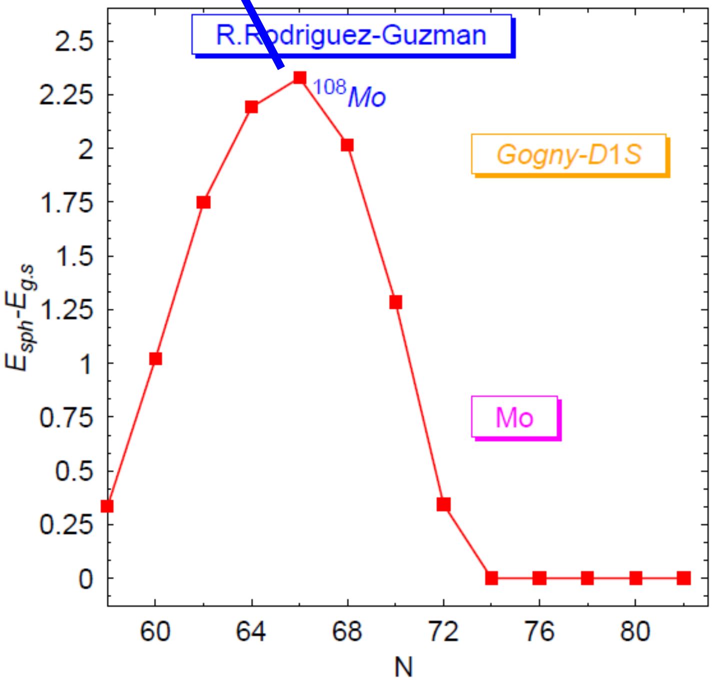
P. Campbell, Hyp. Int. 171 (2007) 143
B. Cheal, PRL 102 (2009) 222501 (Nb-case)

Nuclear structure physics around Z~40, N~60



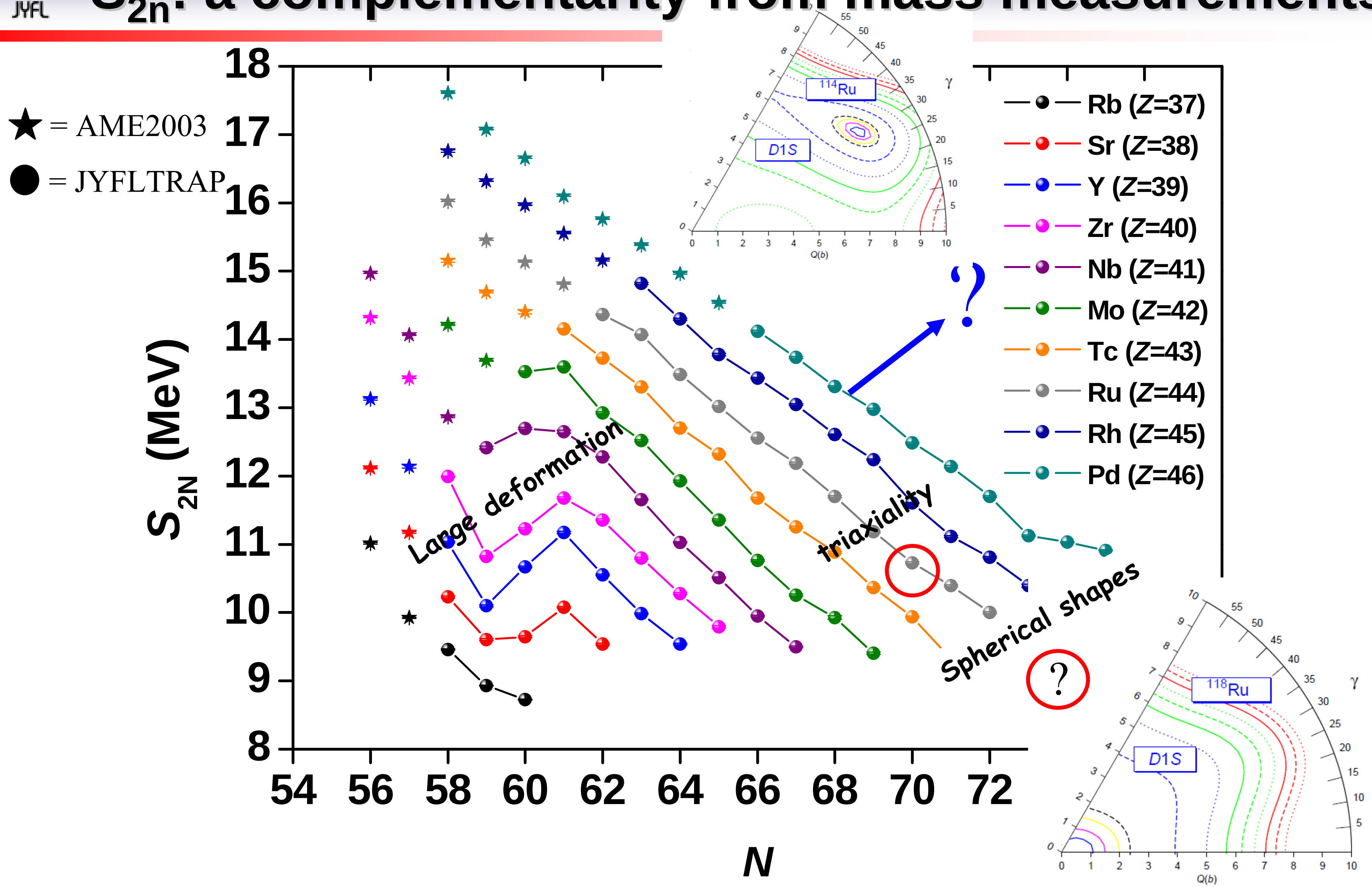
Decrease in rate of charge radius at ^{108}Mo

Energy gain due to deformation is maximised at ^{108}Mo



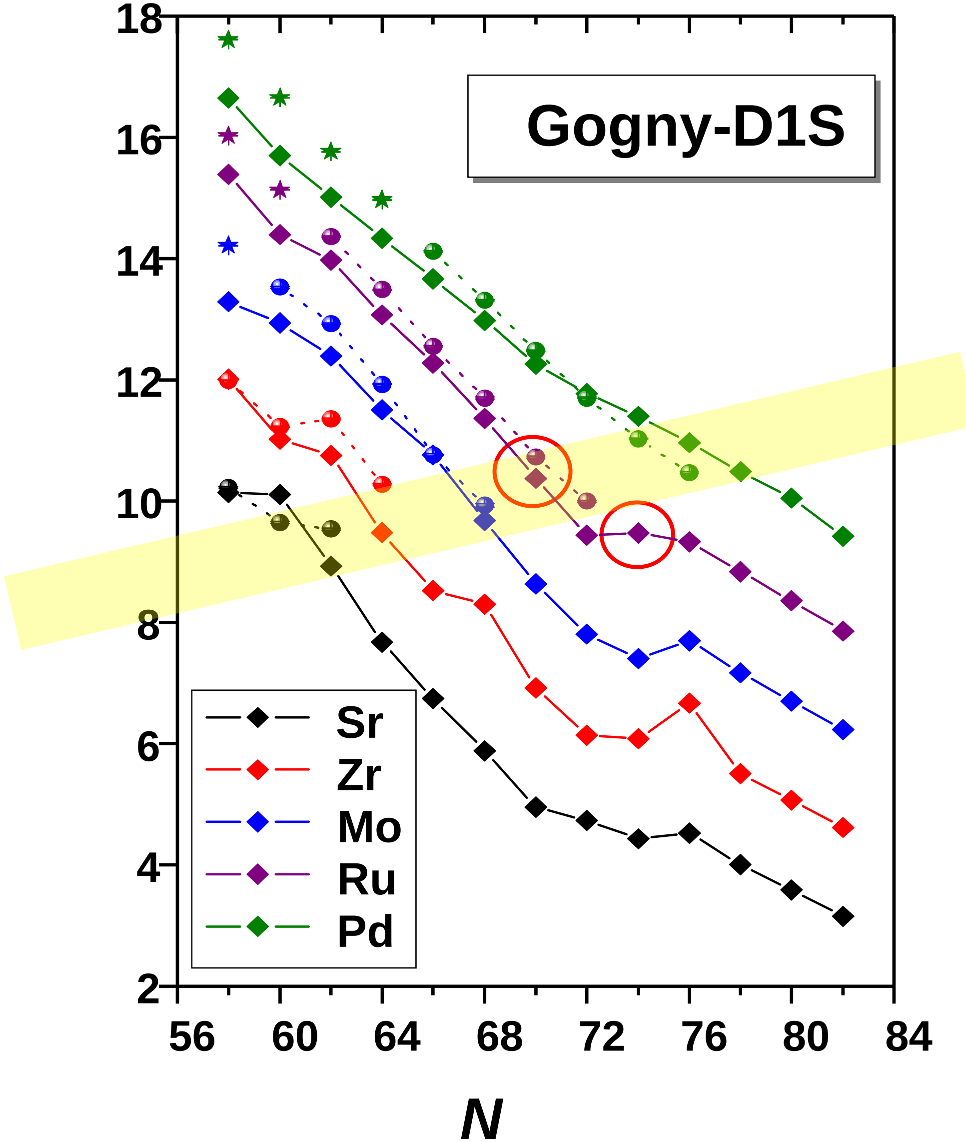
F.C. Charwood *et al.*, Phys. Lett. B 674 (2009) 23,
B. Cheal *et al.*, Phys. Rev. Lett. 102 (2009) 222501

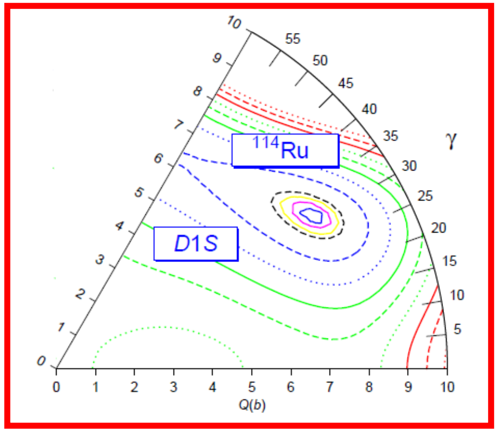
S_{2n}: a complementarity from mass measurements

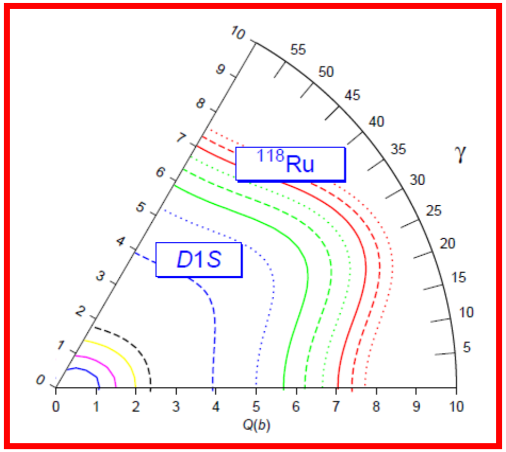


Calculations using Gogny interaction by R.R. Rodriguez-Guzman (FiDiPro)

S_{2n}: a probe of nuclear structure ?







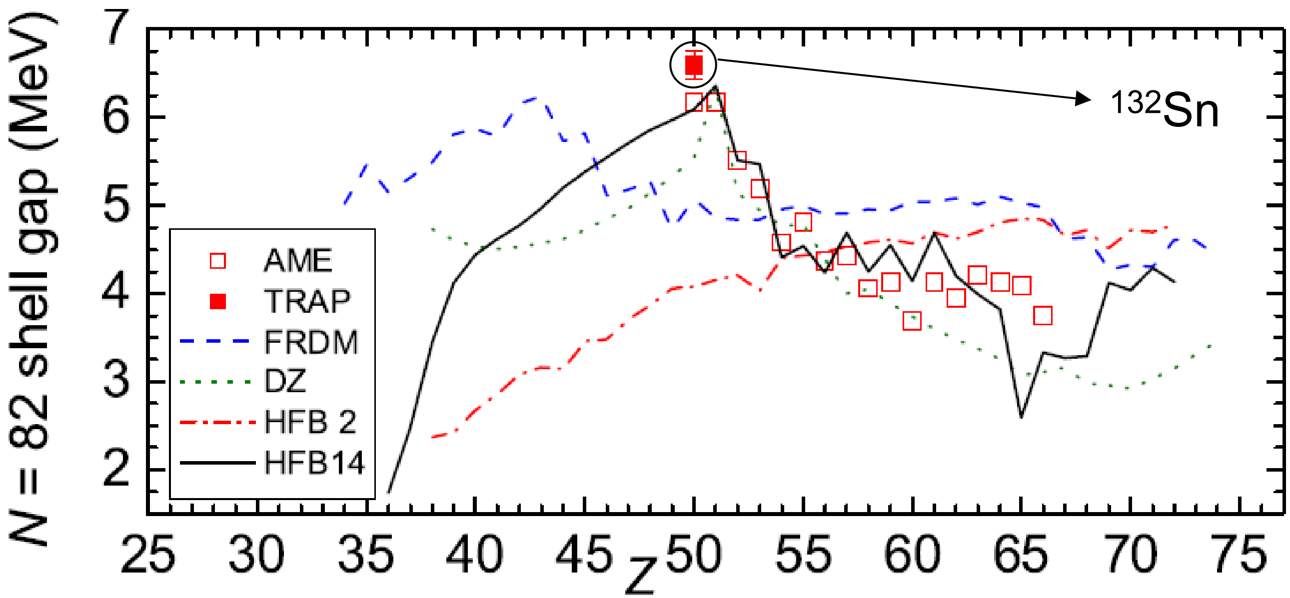
*Calculations (HFB mean field) by R.R. Rodriguez-Guzmán (April 2009)
See also: PRC 78 (2008) 034314

^{132,134}Sn and N=82 shell gap

Motivation: ^{132}Sn as r process 'waiting-point',
previous experimental evidence for N=82 shell quenching

Method: 'classical' ToF resonance
To suppress isobars: measured as molecule X+^{34}S

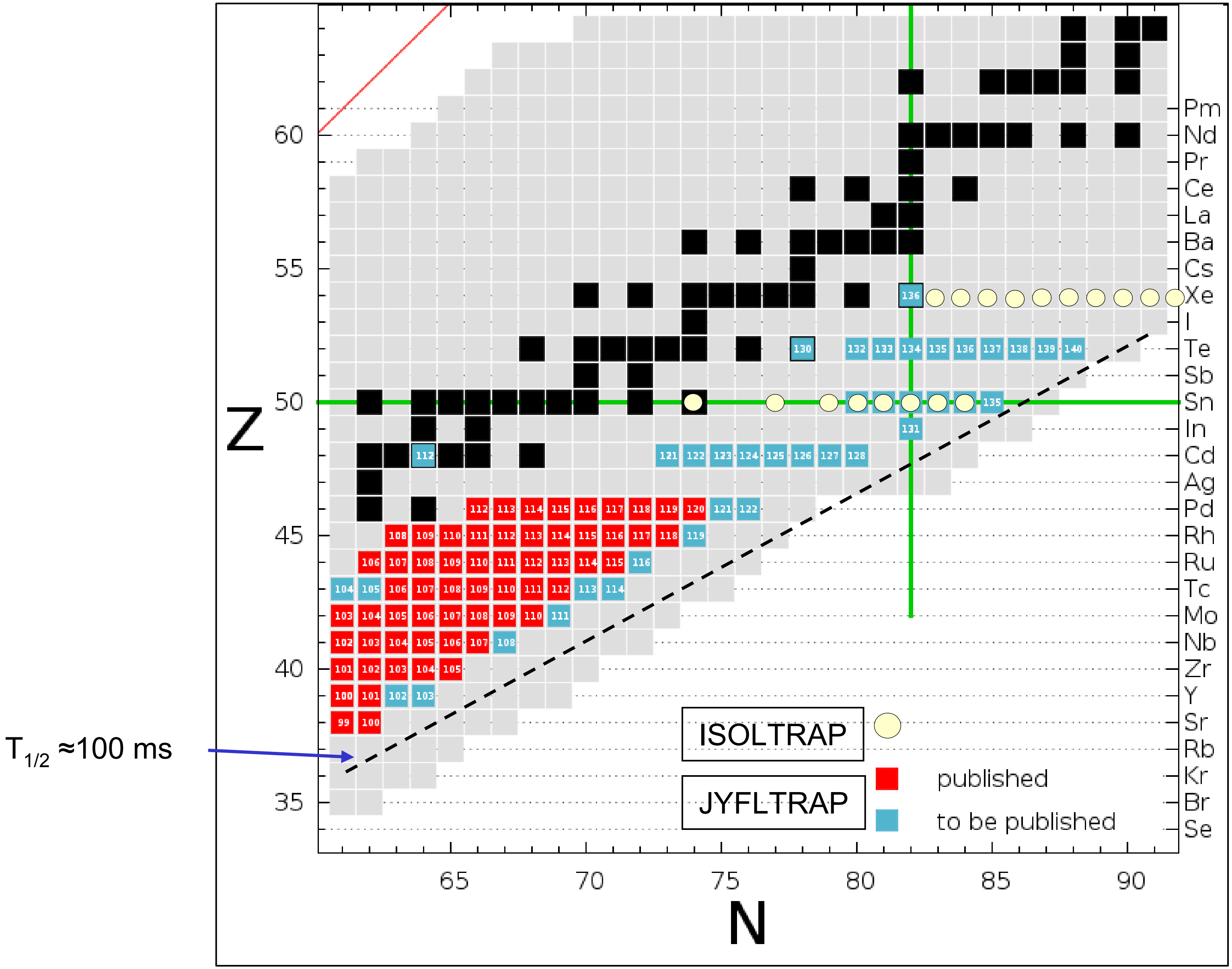
neutron shell gap $\Delta_n(N_0, Z) = S_{2n}(N_0, Z) - S_{2n}(N_0 + 2, Z)$



Restoration of N=82 gap

M. Dworschak et al., PRL 100, 072501 ('08)

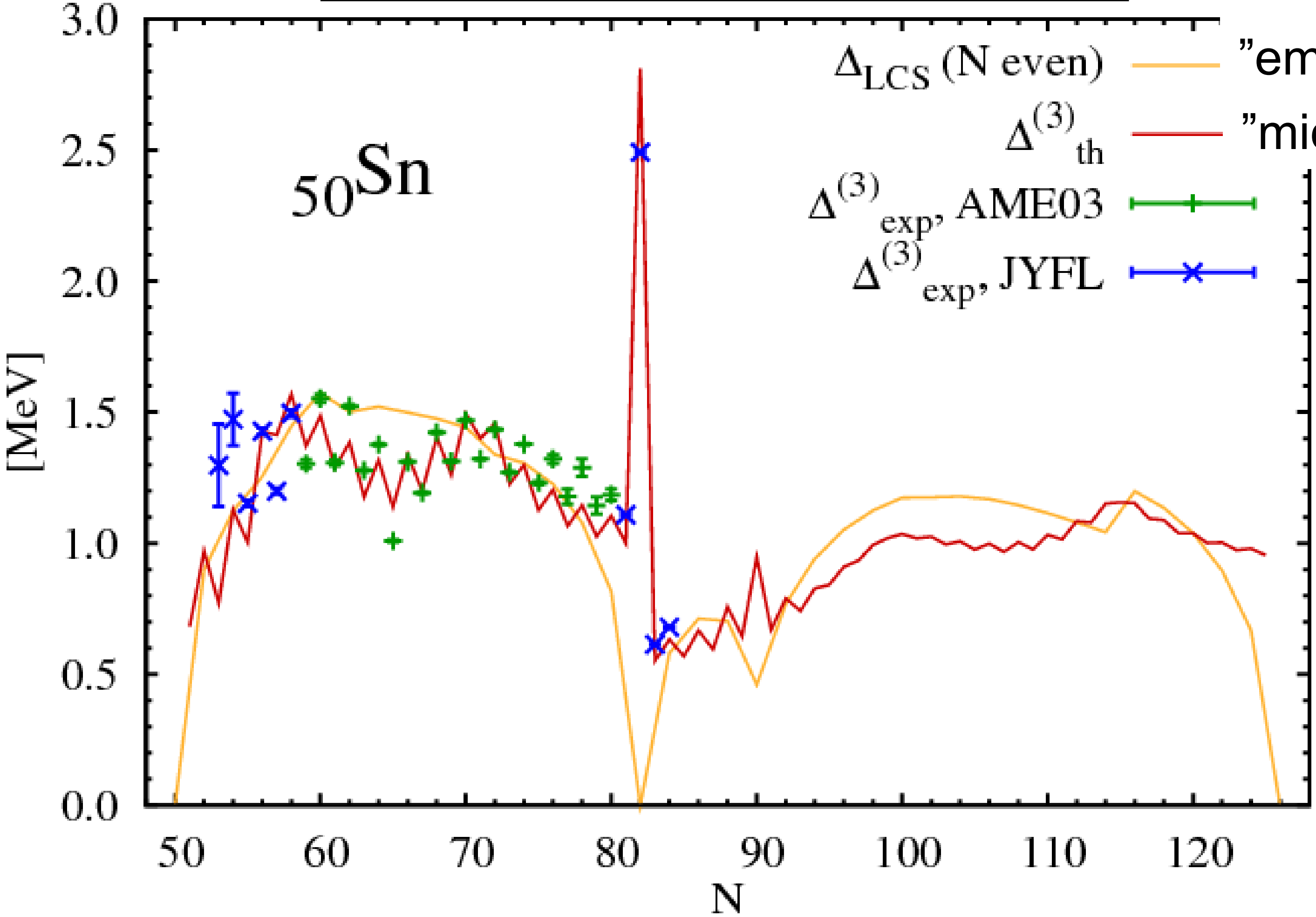
Neutron-rich masses close to ^{132}Sn



Pairing gaps close to N=82

Non-empirical nuclear energy functionals, pairing gaps and odd-even mass differences
T. Duguet and T. Lesinski, in arXiv:0907:1043v1 6 July 2009

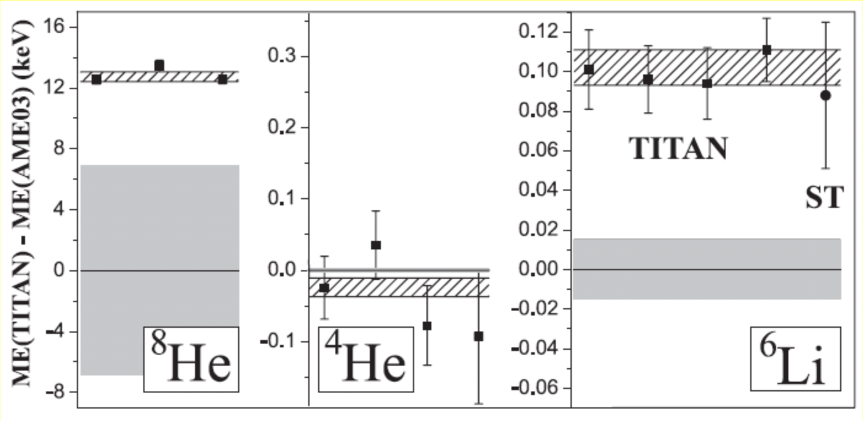
$\Delta^{(3)}(N) = (-1)^N/2\ [E(N+1) - 2\ E(N) + E(N+1)]$

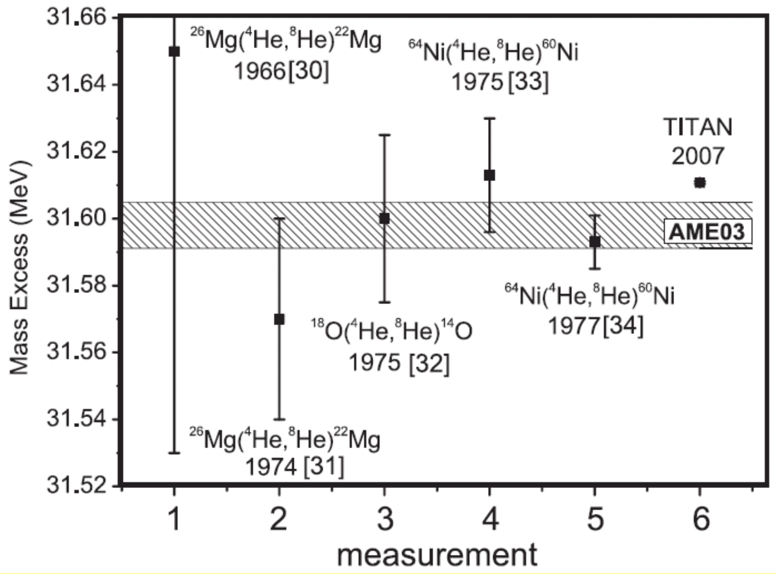


"empirical"
"microscopic"

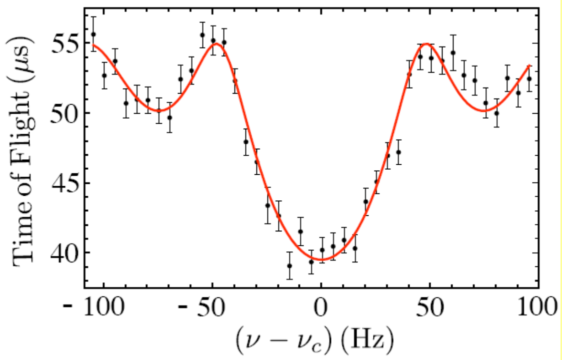
Masses of ^{11}Li and ^{8}He

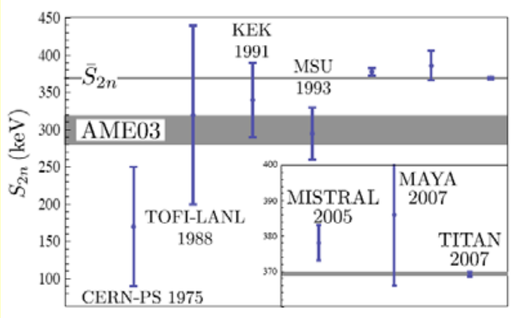
$M_e(^{8}He, T_{1/2} = 119\ ms)$
TITAN @ TRIUMF
V.L. Ryjkov et al.,
PRL 101 (2008) 012501



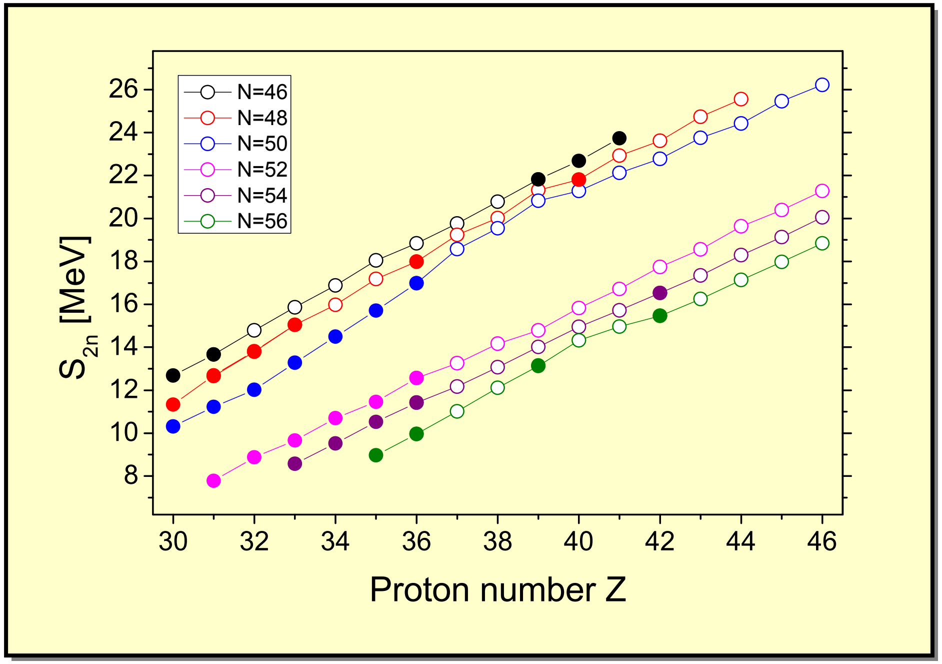


$M_e(^{11}Li, T_{1/2} = 8.8\ ms)$
TITAN @ TRIUMF
M. Smith et al.,
arXiv:0807.1260v3
[nucl-ex] 21 Jul 2008

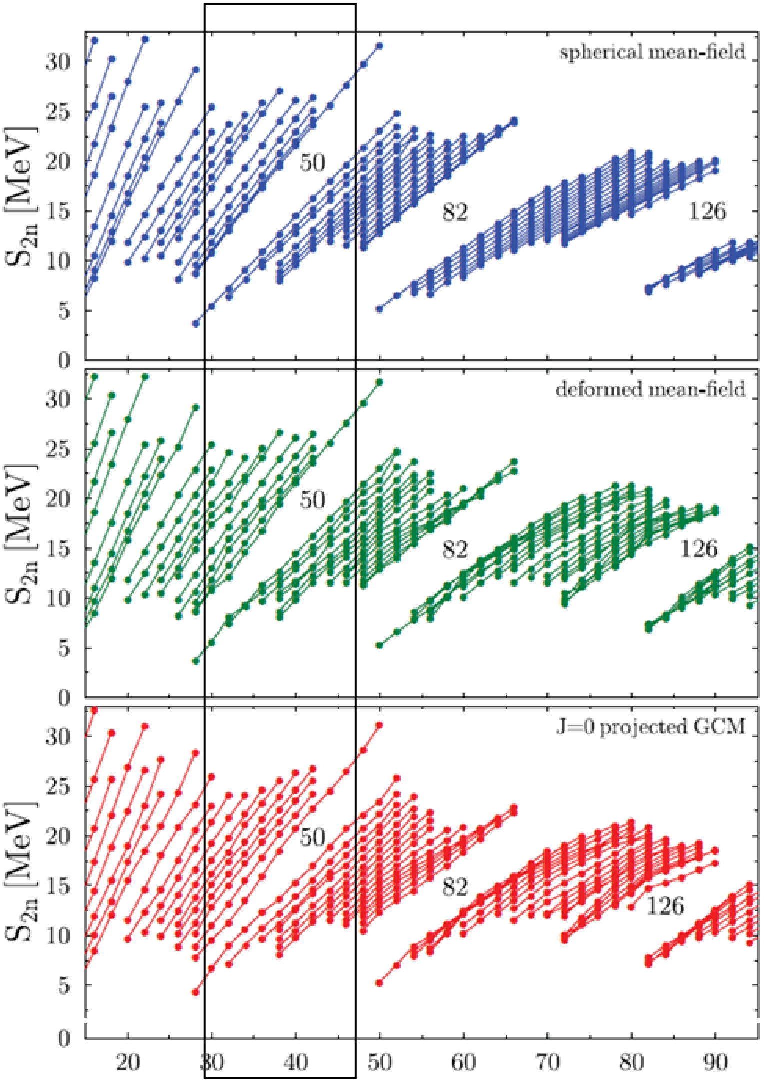




Evolution of N=50 shell gap



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

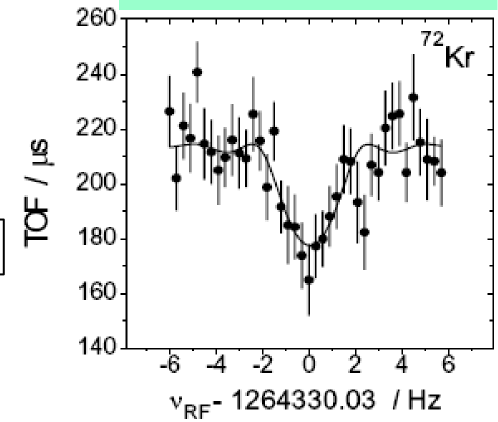
^{72}Kr – strong waiting point

VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Mass Measurement on the *rp*-Process Waiting Point ^{72}Kr

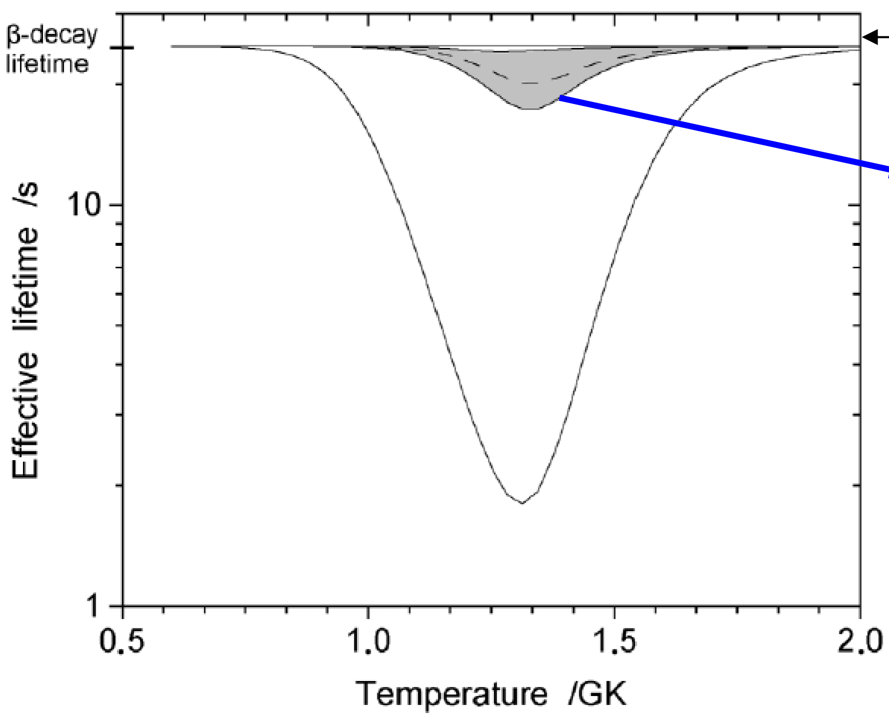
D. Rodríguez,[1,*] V. S. Kolhinen,[2] G. Audi,[3] J. Äystö,[2] D. Beck,[1] K. Blaum,[1,4] G. Bollen,[5] F. Herfurth,[1] A. Jokinen,[2] A. Kellerbauer,[4] H.-J. Kluge,[1] M. Oinonen,[6] H. Schatz,[5,7] E. Sauvan,[4,†] and S. Schwarz[5]

ISOLTRAP



$-53940.6(8.0)$

Exp. masses of ^{72}Kr, ^{73}Kr and ^{74}Kr
+ masses for ^{73}Rb and ^{74}Sr from CED



^{72}Kr ($T_{1/2} = 17.2$ s

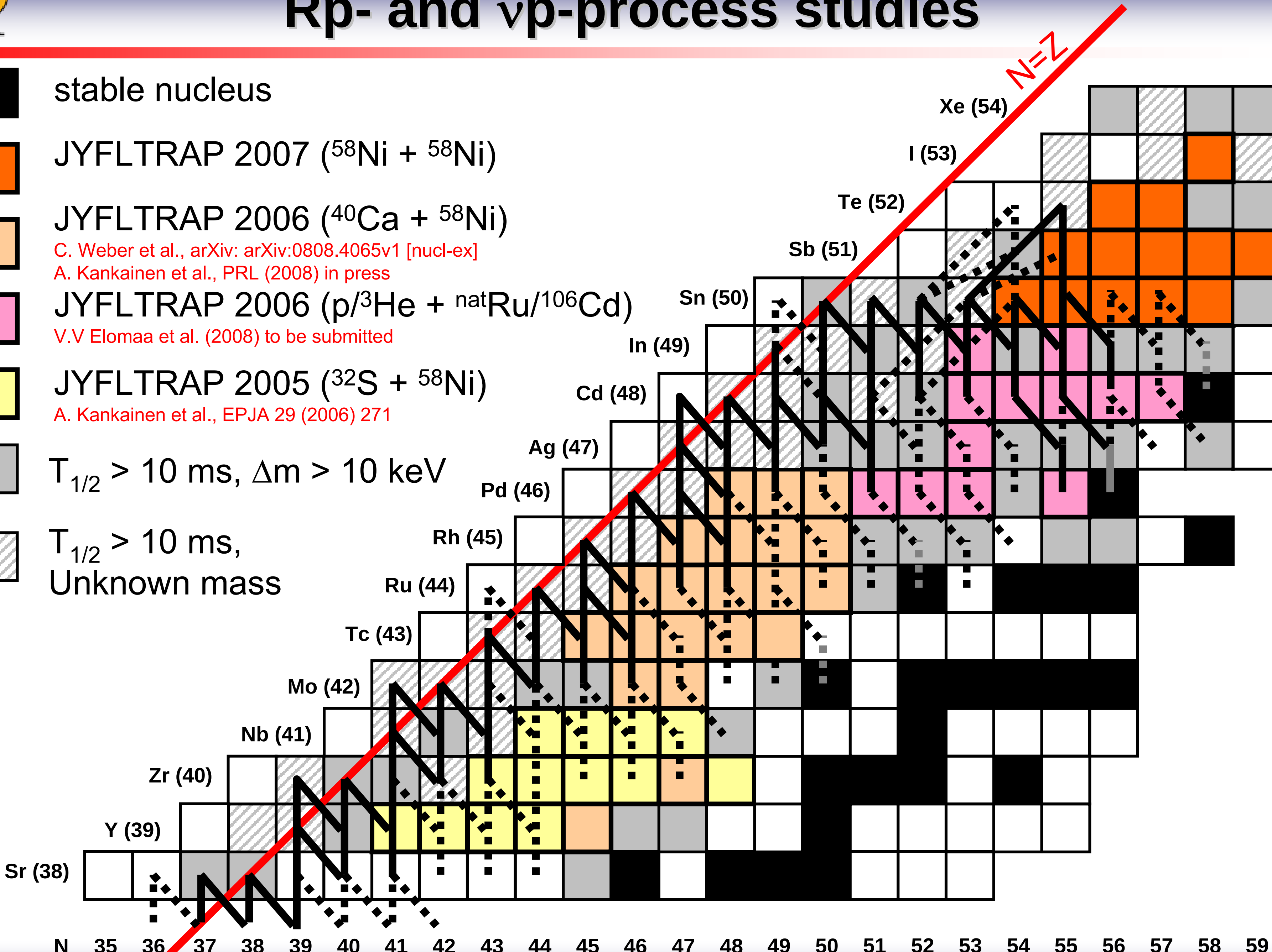
∴ Delay in rp-process > 80 % of $T_{1/2}$

^{72}Kr strong waiting point

CPT @ ANL:
^{68}Se: J. A. Clark et al., PRL 92 (2004) 192501
^{64}Ge: J. A. Clark et al., PRC75 (2007) 032801(R)

Rp- and νp-process studies

- stable nucleus
- JYFLTRAP 2007 ($^{58}Ni + {}^{58}Ni$)
- JYFLTRAP 2006 ($^{40}Ca + {}^{58}Ni$)
  C. Weber et al., arXiv: arXiv:0808.4065v1 [nucl-ex]
  A. Kankainen et al., PRL (2008) in press
- JYFLTRAP 2006 ($p/^{3}He + {}^{nat}Ru/^{106}Cd$)
  V.V Elomaa et al. (2008) to be submitted
- JYFLTRAP 2005 ($^{32}S + {}^{58}Ni$)
  A. Kankainen et al., EPJA 29 (2006) 271
- $T_{1/2}$ > 10 ms, Δm > 10 keV
- $T_{1/2}$ > 10 ms, Unknown mass

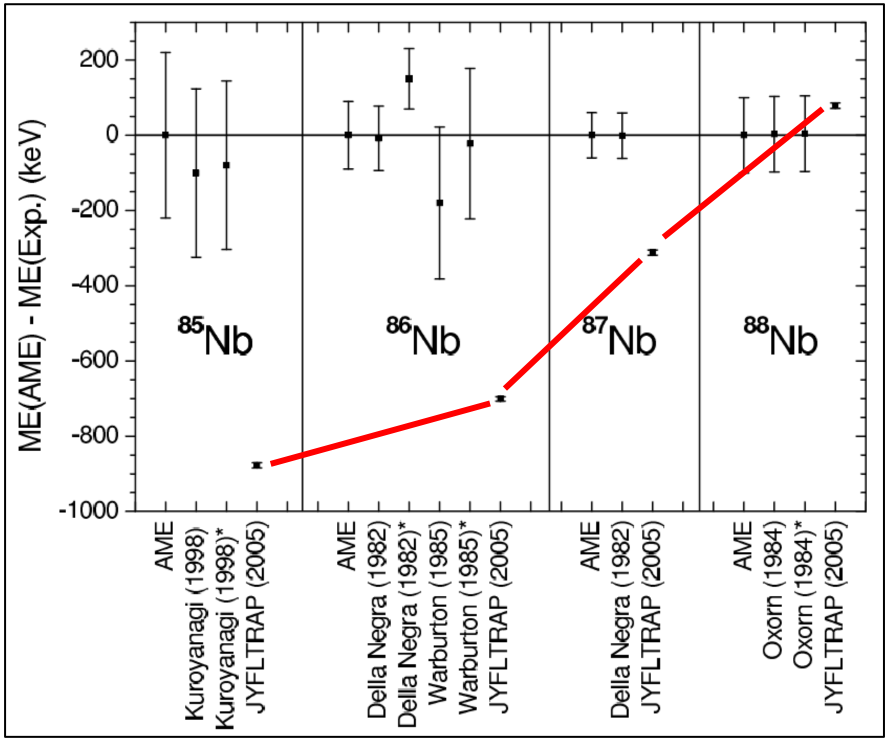


Final abundances in the np-process

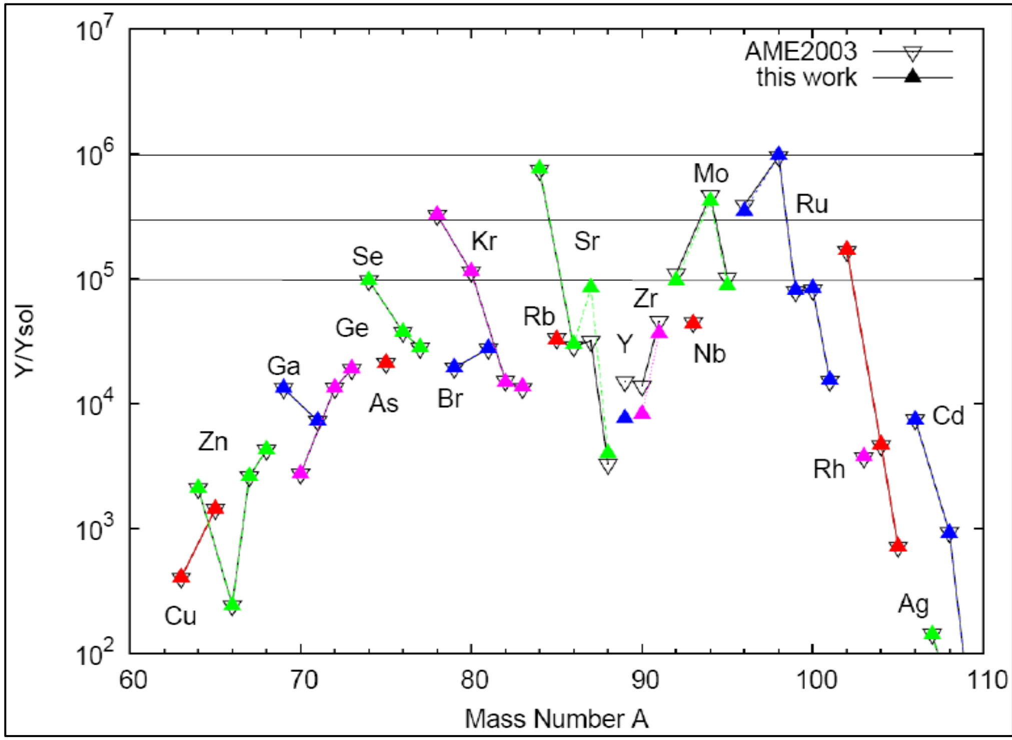
Saha equation:

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

^{88}Tc mass 1031 keV higher than in AME2003
→ $^{87}Mo(p,\gamma)^{88}Tc$ suppressed



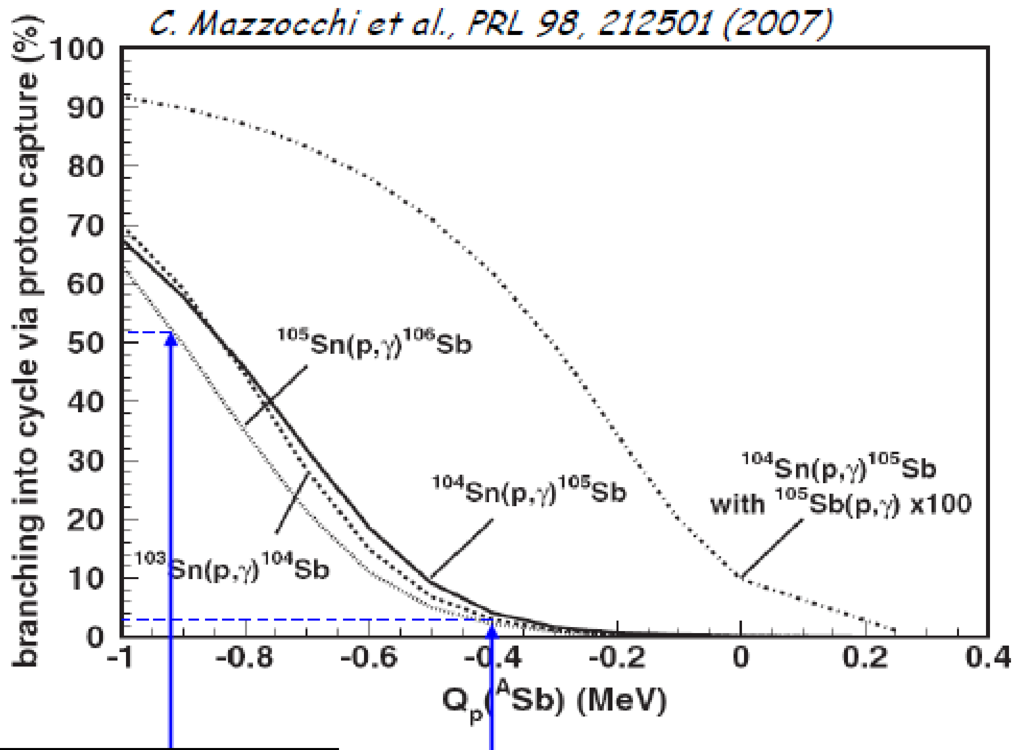
A. Kankainen et al., EPJA 29 (2006) 271



JYFLTRAP/SHPTRAP data: C. Weber et al., arXiv:0808.4065v1 [nucl-ex]

SnSbTe-cycle: End of the rp-process ?

- Branching into the cycle reduced from 50% to 3% at ^{105}Sn
- Reduces late-time He production
- Slightly longer, less luminous burst tail
- Final composition: broader distribution of ^{68}Zn, ^{72}Ge, ^{104}Pd, ^{105}Pd and residual He



S_p =930(210) keV

A. Plochocki et al., Phys. Lett. B 106, 285 (1981)

JYFLTRAP: S_p = 424(8) keV

V.-V. Elomaa, G.K. Vorobjev, A. Kankainen et al., PRL 102, 252501 (2009)

Physics of superallowed beta decay

Conserved vector current hypothesis:
ft should be constant

$$Ft \equiv ft(1+\delta_R)\left[1-(\delta_C-\delta_{NS})\right] = \frac{K}{2G_V^2(1+\Delta_R)}$$

δ_R	radiative correction $f(Z,Q_{EC})$ ~1.5 %
δ_C-δ_{NC}	isospin symmetry breaking correction f(nuclear structure), 0.3-0.7%
Δ_R	nucleus-independent radiative correction f(interactions), ~2.4%

Exp. parameters to be determined:
Beta decay half-life $T_{1/2}$
Beta decay branching ratio I_b
Decay energy Q_{EC}

Single nucleus: determination of $G_V^2(1+\Delta_R)$

Many transitions: Check if Ft is constant
→ Test of the CVC

One can deduce V_{ud} by combining beta decay and muon decay data

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

Cabibbo-Kobayashi-Maskawa quark mixing matrix:

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

Unitarity test of CKM-matrix

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

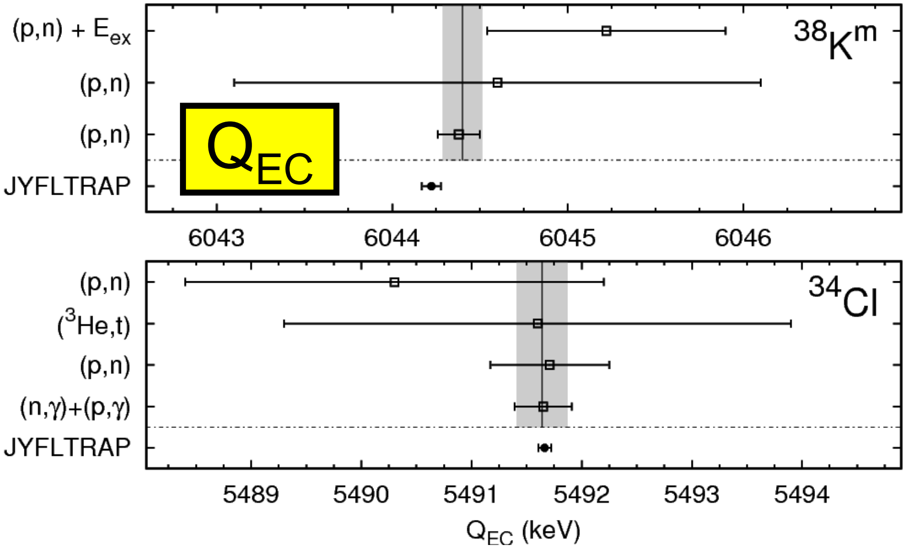
V_{ud}: > 99 % — Superallowed pure Fermi transitions, Neutron decay, Pion beta decay

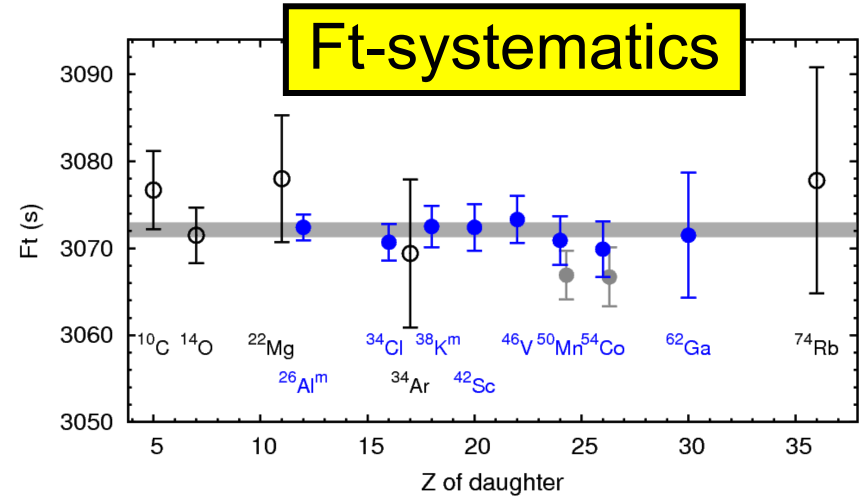
V_{us}: small — Kaon decay

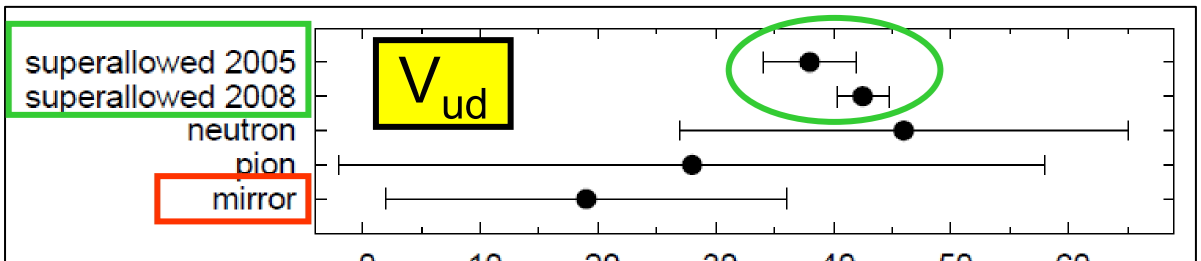
V_{ub}: very small — B meson decays

New Q_{EC}-values, V_{ud} and unitarity test

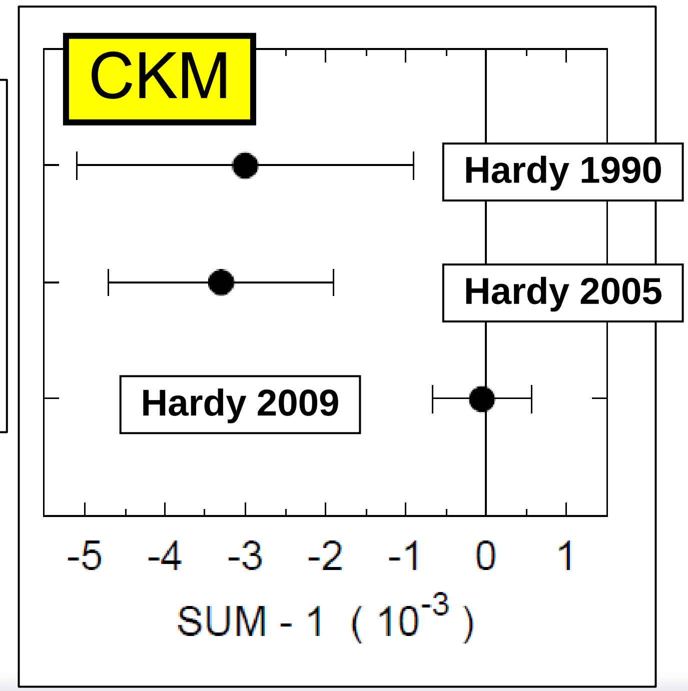
T. Eronen et al., PRL (2009) in press







Naviliat &Severijns,
PRL 102 (2009) 142302



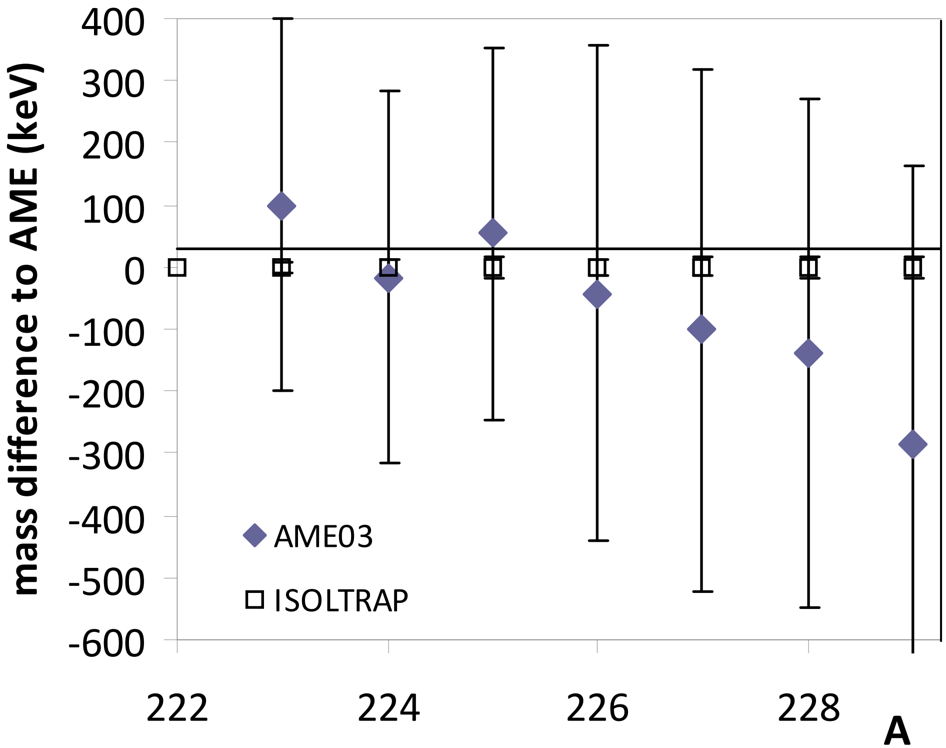
Most precise value for V_{ud}
from nuclear beta decay !!!
Its^2 contribution > 95 %

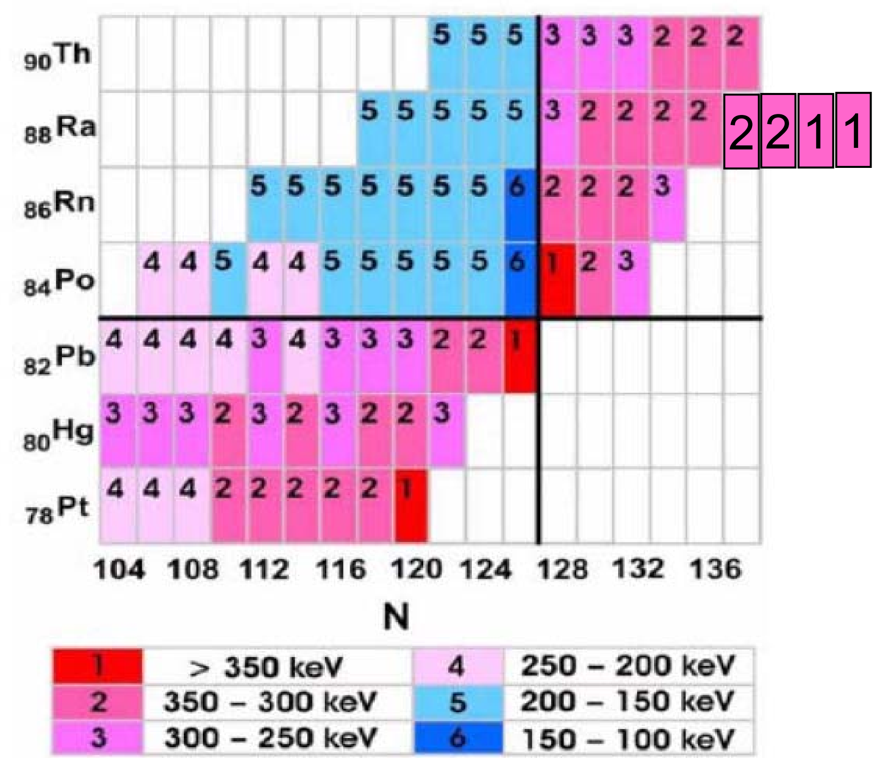
$$SUM = V_{ud}^2 + V_{us}^2 + V_{ub}^2$$

Discovery of a new isotope ^{229}Rn

Motivation: δVpn values, nuclear structure

Method: 'classical' ToF resonance for $^{223-229}$Rn





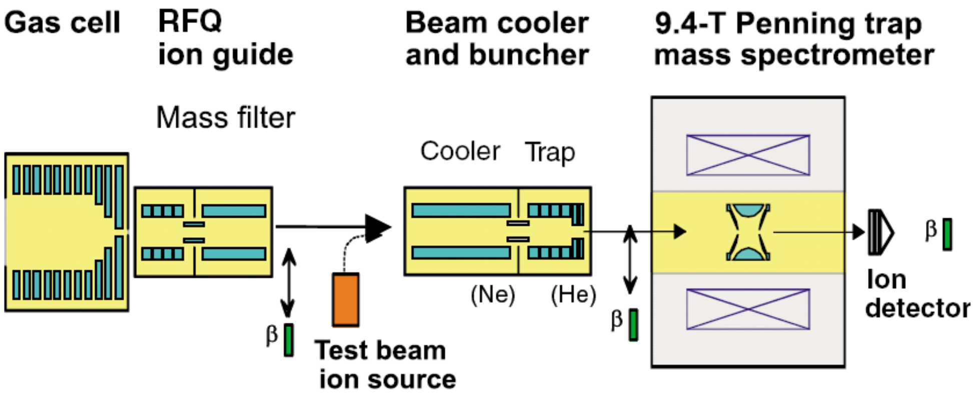
7 new masses with σ<20keV,
All never measured directly before

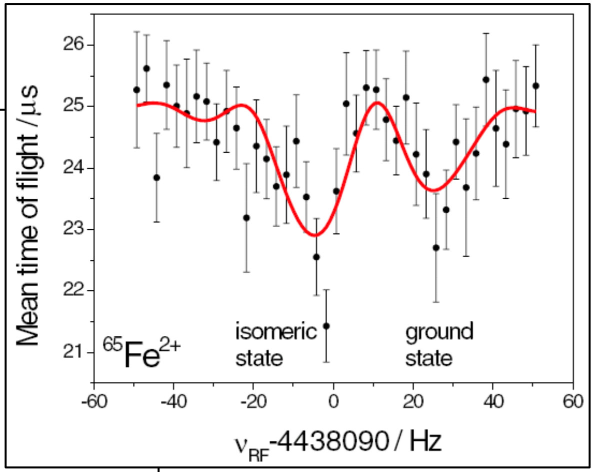
A new isotope of radon discovered: ^{229}Rn

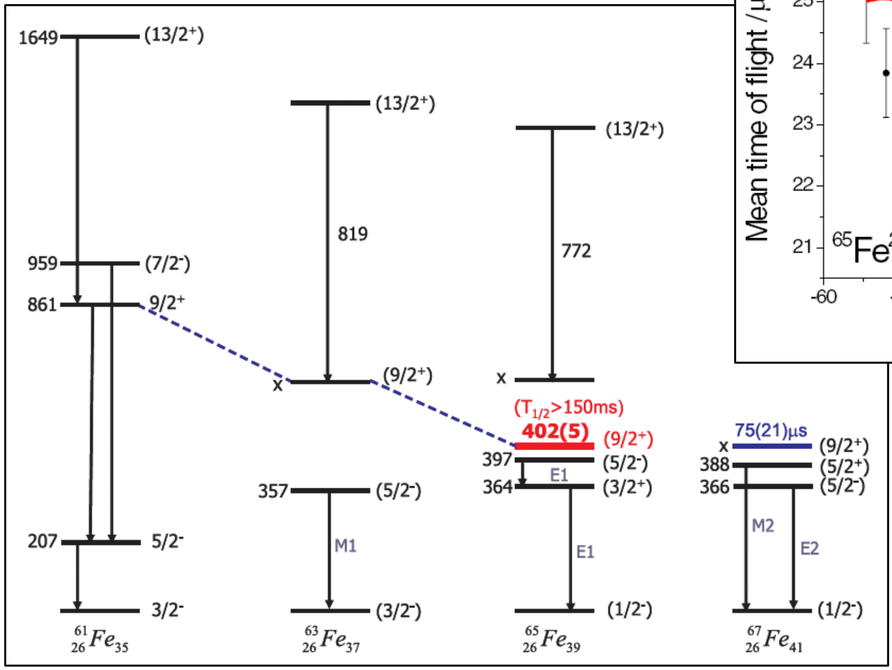
(M. Kowalska)

Discovery of nuclear isomer at LEBIT

- LEBIT at NSCL
- First trapped ions from projectile fragmentation: G. Bollen et al, PRL 96 (2006) 152501
- Fragmentation of 130 MeV/u ^{76}Ge primary beam
  → Fe and Co fragments with an energy of 86 MeV/u



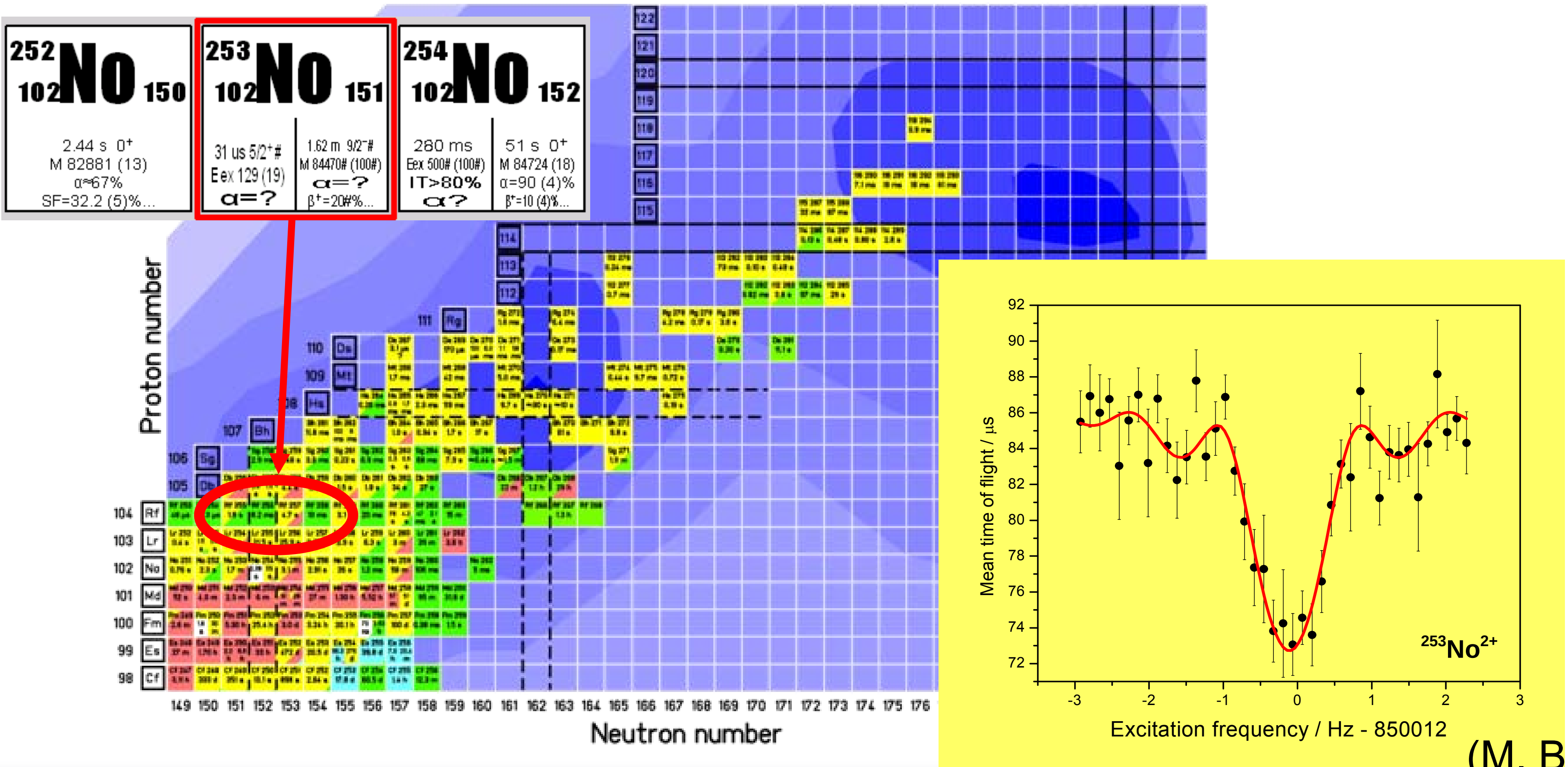




M. Block et al, PRL **100,** 132501 (2008)

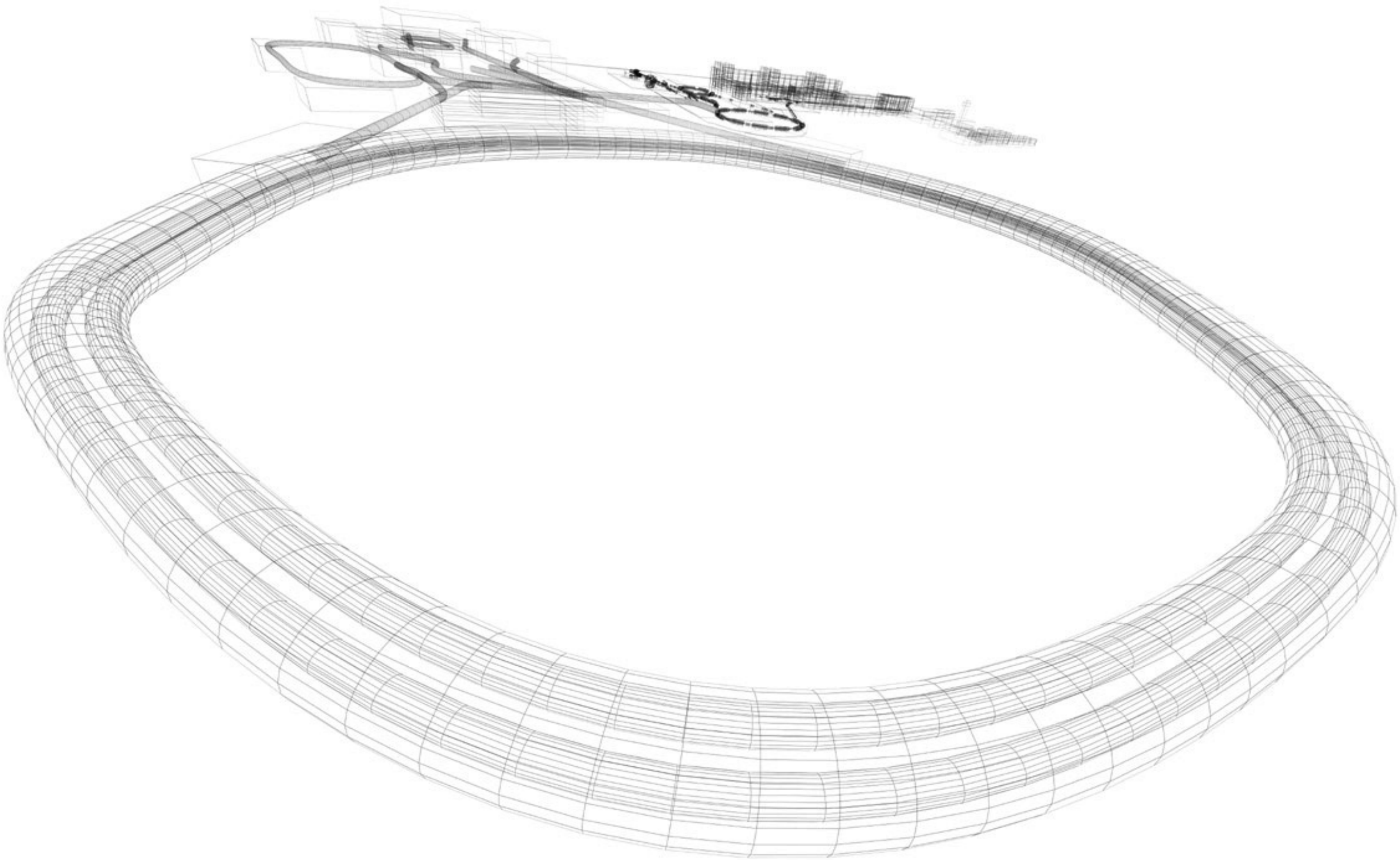
Direct mass measurements above uranium bridge the gap to the island of stability

M. Block[1], D. Ackermann[1], K. Blaum[2], C. Droese[3], M. Dworschak[1], S. Eliseev[2], T. Fleckenstein[4], E. Haettner[4], F. Herfurth[1], F. P. Heßberger[1], S. Hofmann[1], J. Ketelaer[5], J. Ketter[2], H.-J. Kluge[1,6], G. Marx[3], M. Mazzocco[7], Yu. N. Novikov[1,8], W. R. Plaß[1,4], A. Popeko[9], S. Rahaman[10]†, D. Rodríguez[11], C. Scheidenberger[1,4], L. Schweikhard[3], P. G. Thirolf[12], G. K. Vorobyev[1] & C. Weber[10]†

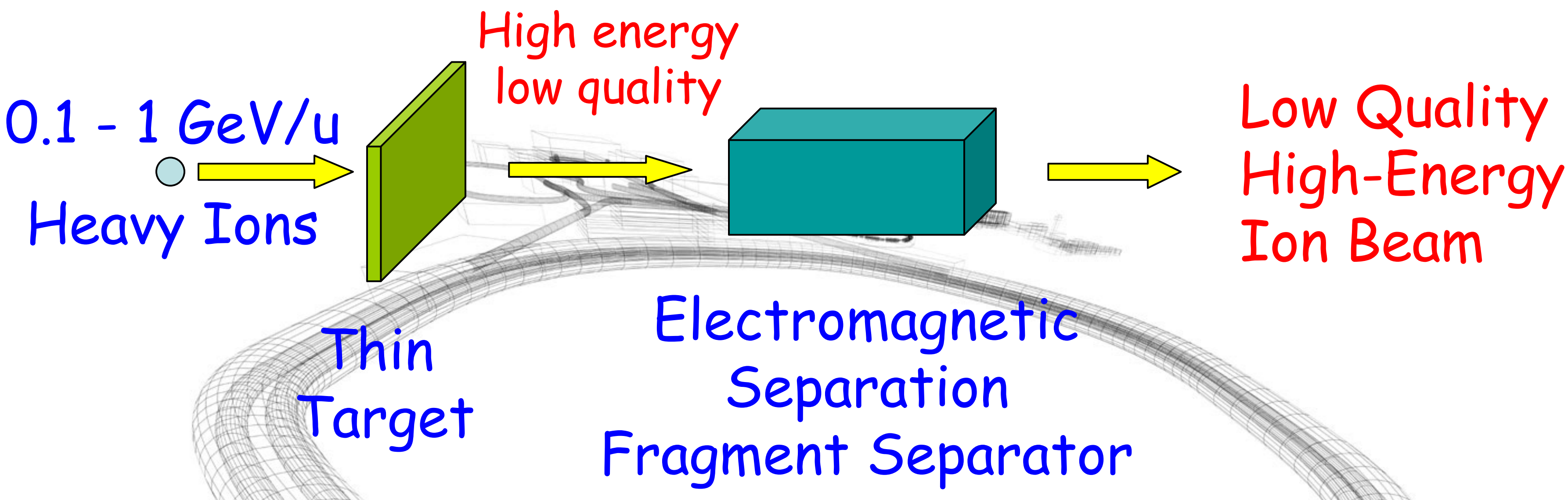


(M. Block)

In-flight fragmentation – towards MATS and LaSpec



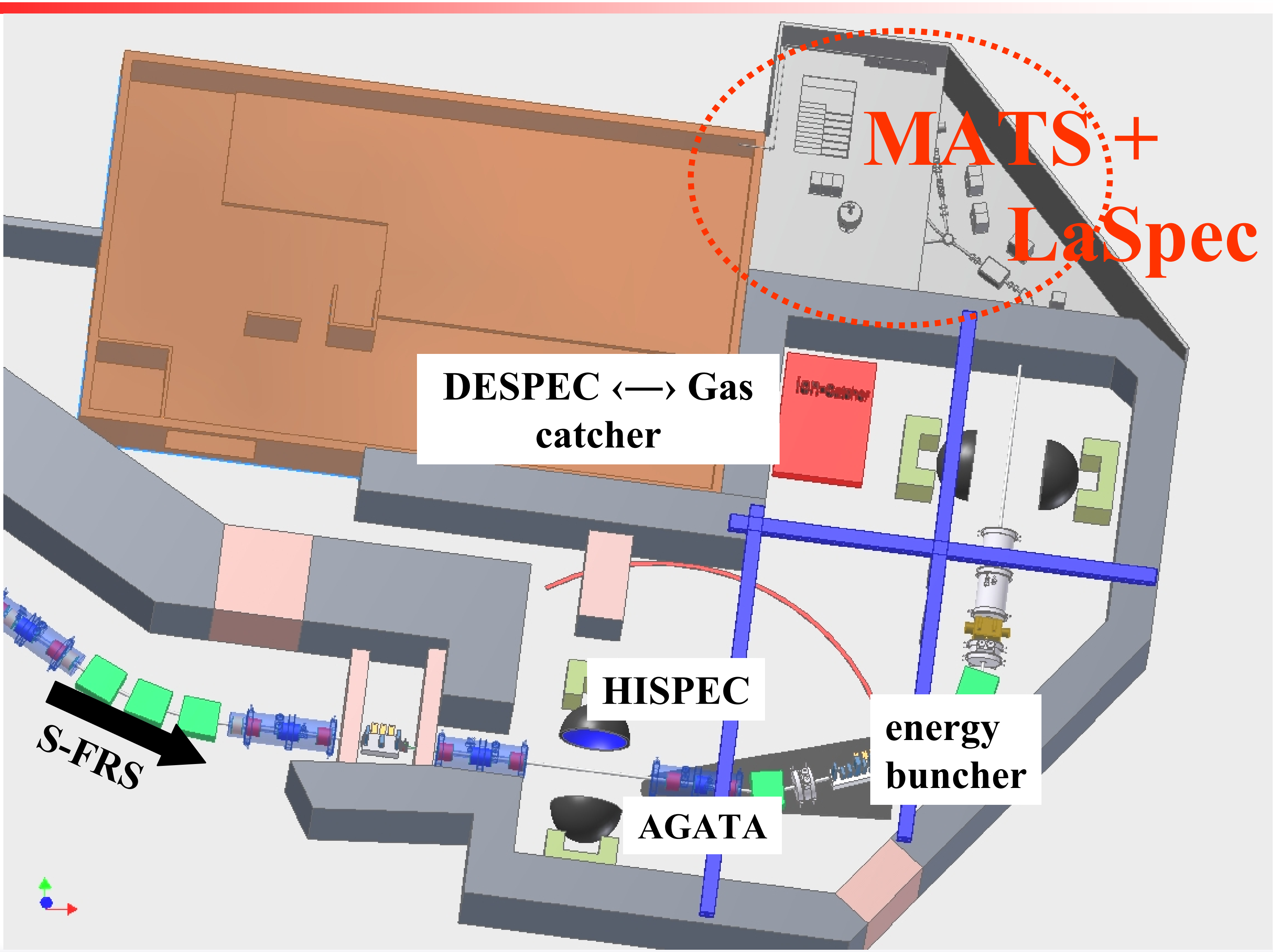
In-flight fragmentation – towards MATS and LaSpec



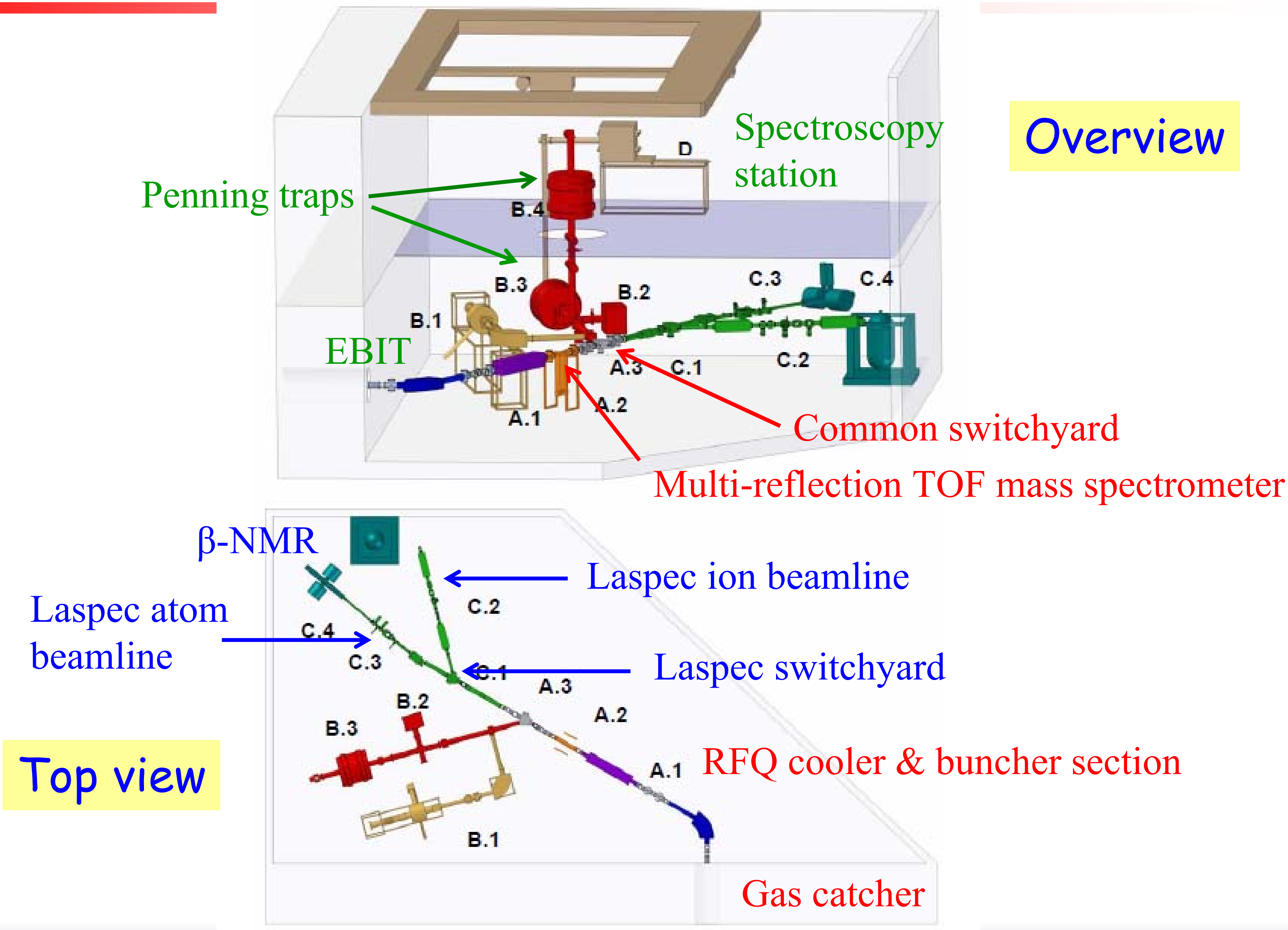
All elements produced chemically non-selective: $T_{1/2}$ ~ 1 μs

Optical and ion trap techniques developed mainly at ISOL facilities have provided nuclear (ground) state properties decades. LaSpec+MATS offers the possibility to make these studies at the limits of stability and lifetime.

Layout at the Low Energy Branch



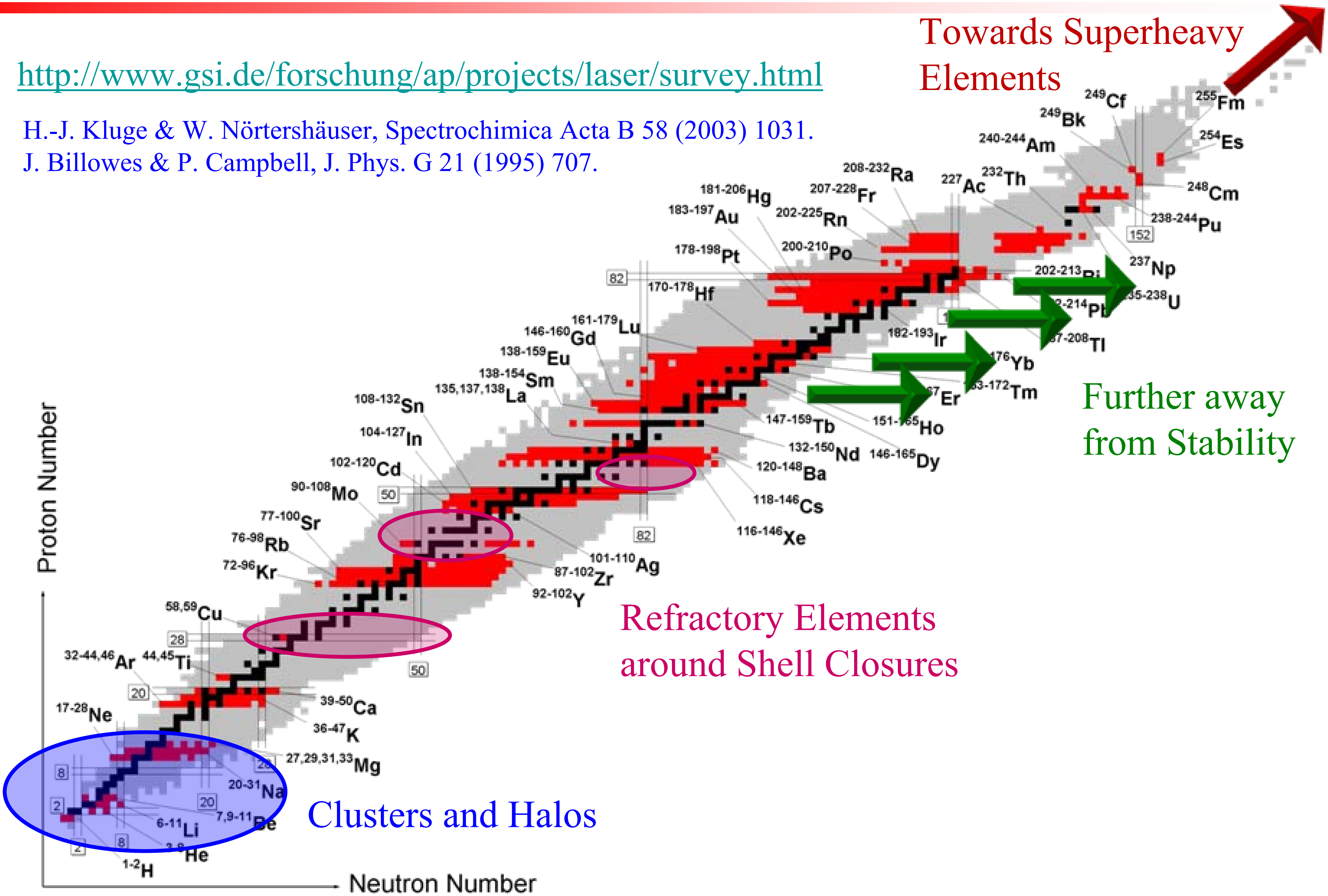
Layout of MATS and LaSpec experiments (TDR)



Present status and LaSpec regions of interest

http://www.gsi.de/forschung/ap/projects/laser/survey.html

H.-J. Kluge & W. Nörtershäuser, Spectrochimica Acta B 58 (2003) 1031.
J. Billowes & P. Campbell, J. Phys. G 21 (1995) 707.



MATS-LaSpec status

- TDR has been submitted (to be published)
- Working collaboration with responsibilities
- LEB hall in module 4, a construction plan and schedule for modules 0-3
- R&D work in progress:
  - Gas cell (KVI, Giessen, JYFL)
  - TRIGA laser and trap setups (Mainz)
  - RFQ, optical manipulation, … (JYFL)
  - Detector trap (LMU)
  - FT-ICR (Heidelberg)

Optical and ion trap techniques developed mainly at ISOL facilities have provided nuclear (ground) state properties decades. LaSpec+MATS offers the possibility to make these studies at the limits of stability and lifetime.

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Collaborators:

J. Billowes, B. Blank, P. Campbell, J. Dobaczewski, J. Hardy, F. Herfurth, J. Kurpeta, Y. Novikov, J. Suhonen, …

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