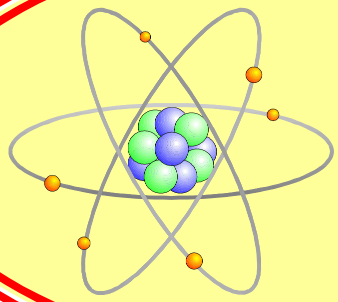
Novel uses of Penning traps in nuclear structure physics

Mass measurements

Thanks to many colleagues at ISOLTRAP, SHIPTRAP and JYFLTRAP



= N · 🟢 + Z · ● + Z · 🟠

\- binding energy

Physics & Chemistry

basic information required

$\delta m/m \approx 1 \cdot 10^{-6}$

Nuclear Physics

nuclear binding energies,
Q-values

$\delta m/m \approx 1 \cdot 10^{-7}$

Nuclear Structure

shell closure, pairing,
deformation, halos

$\delta m/m \leq 1 \cdot 10^{-7}$

Weak Interaction

symmetry tests,
CVC hypothsis

$\delta m/m < 3 \cdot 10^{-8}$

Astro-physics

nuclear synthesis,
r- and rp-process

$\delta m/m < 1 \cdot 10^{-7}$

Fundamental Property

tests of nuclear models
and formulars

$\delta m/m \leq 1 \cdot 10^{-7}$

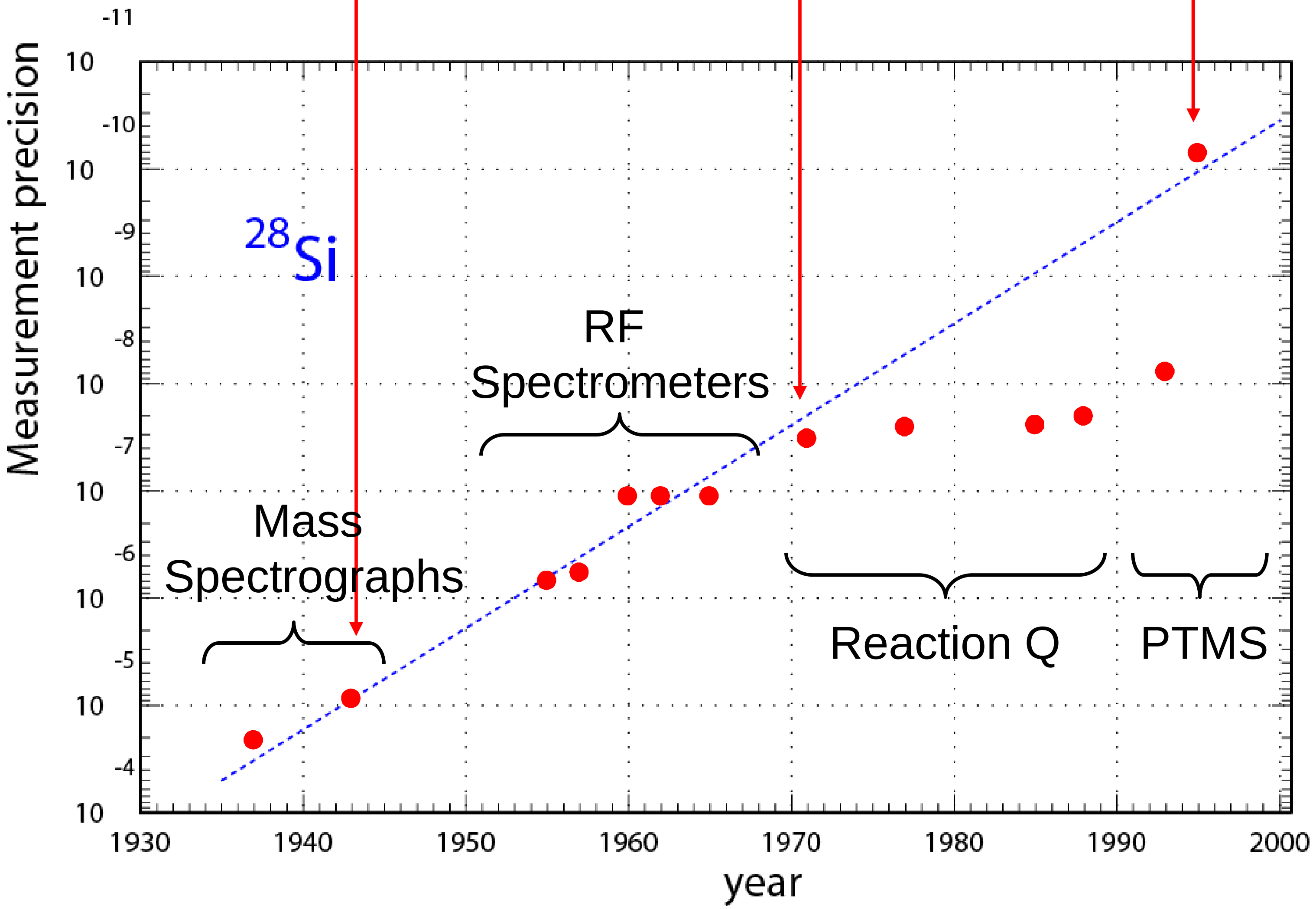
Courtesy: K. Blaum

Gaining Precision: From Past to Present …

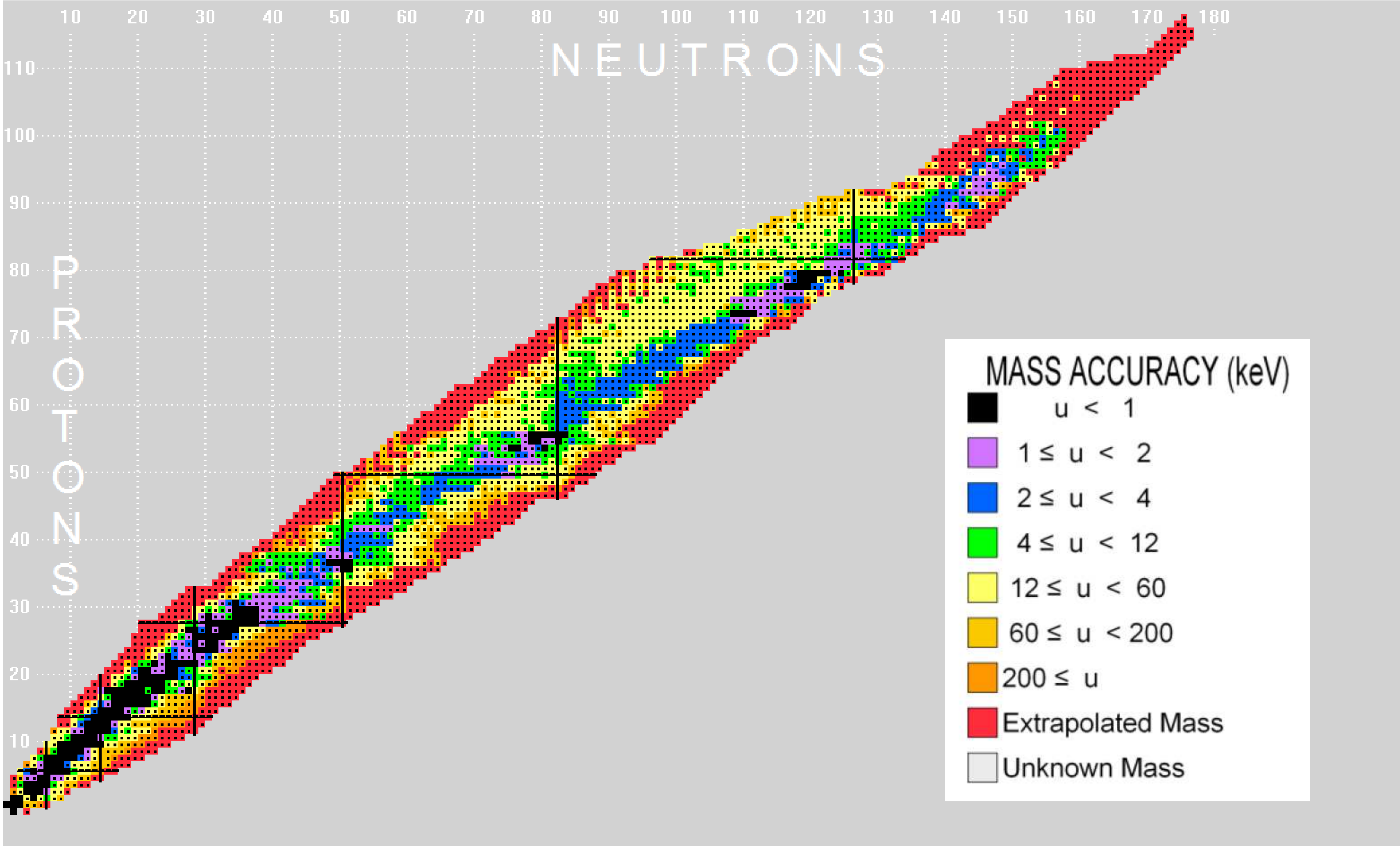
Bulk properties,
liquid drop, shells

Sub-shells,
pairing, halos

Symmetries, fundamental
tests of concepts

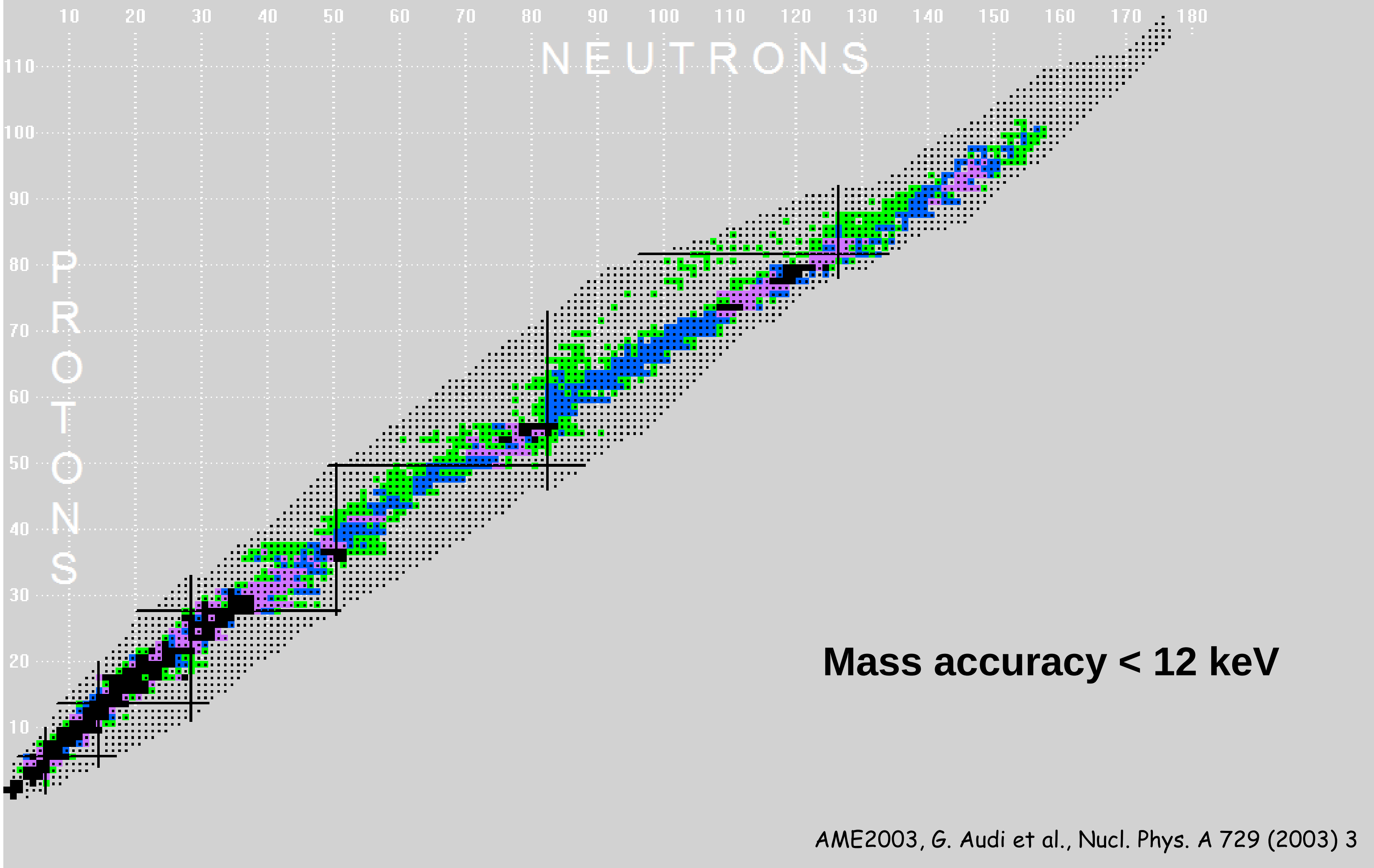


K. Blaum



AME2003, G. Audi et al., Nucl. Phys. A 729 (2003) 3

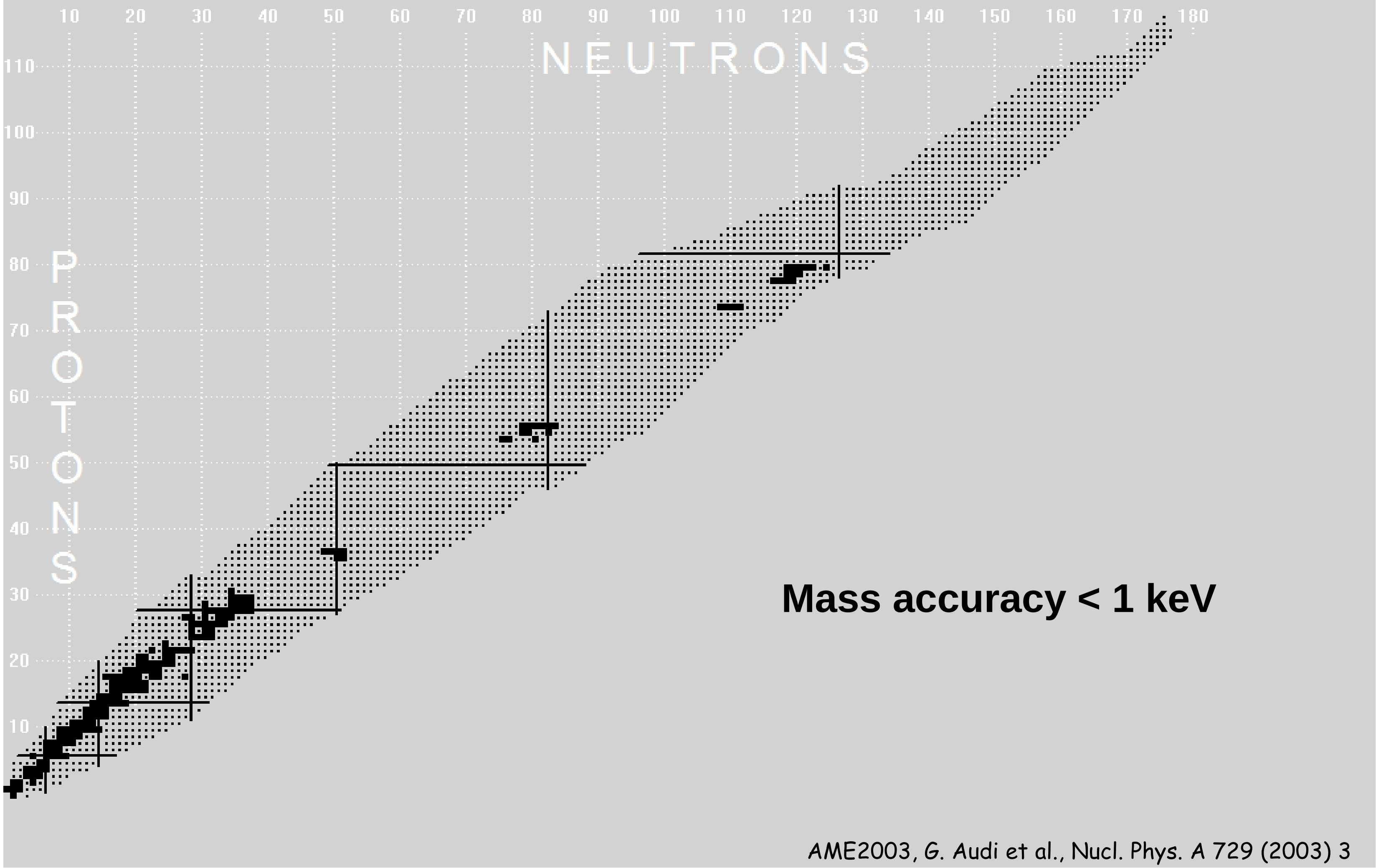
nuclear structure and nuclear astrophysics studies



Mass accuracy < 12 keV

AME2003, G. Audi et al., Nucl. Phys. A 729 (2003) 3

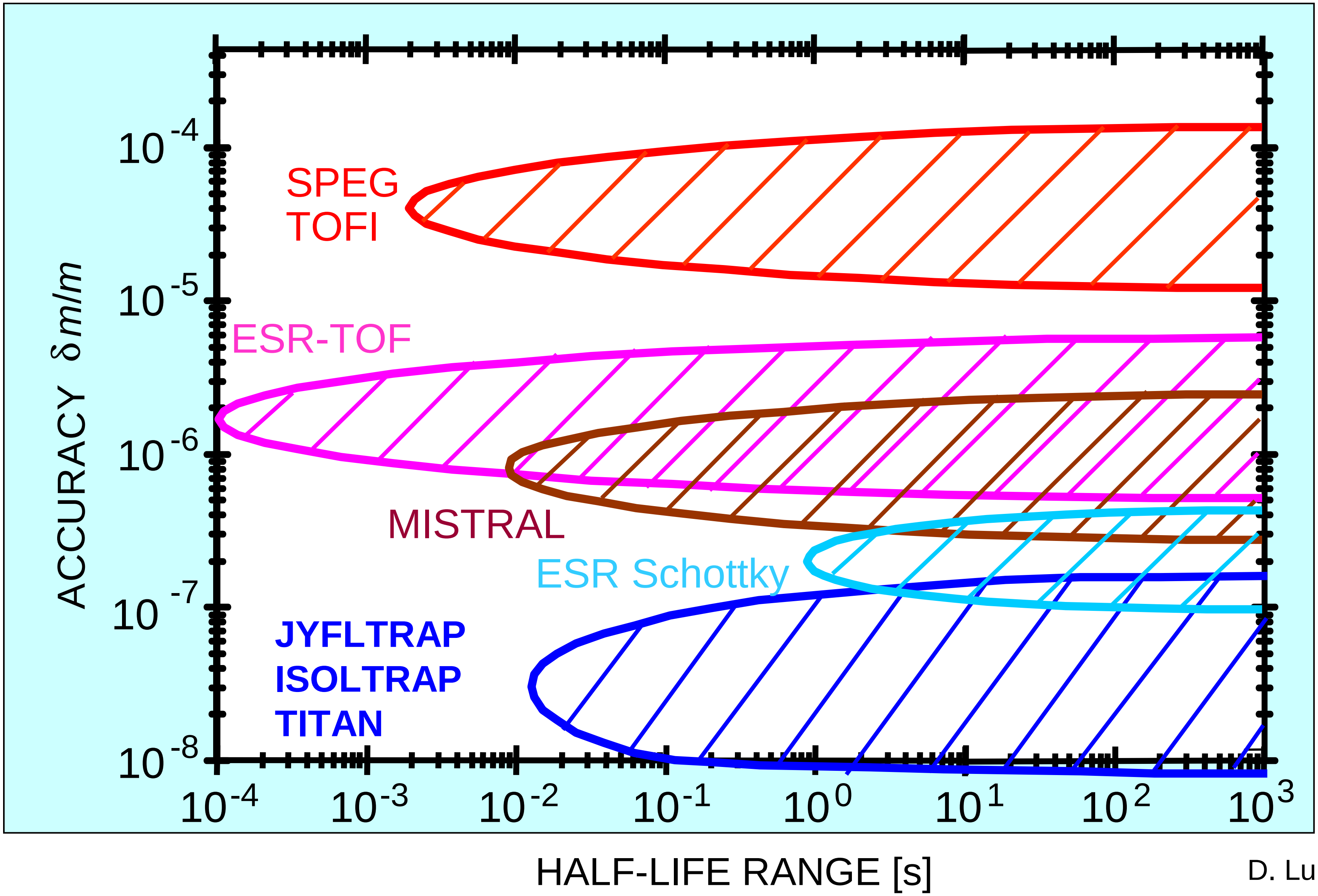
Accuracy required for fundamental physics



Mass accuracy < 1 keV

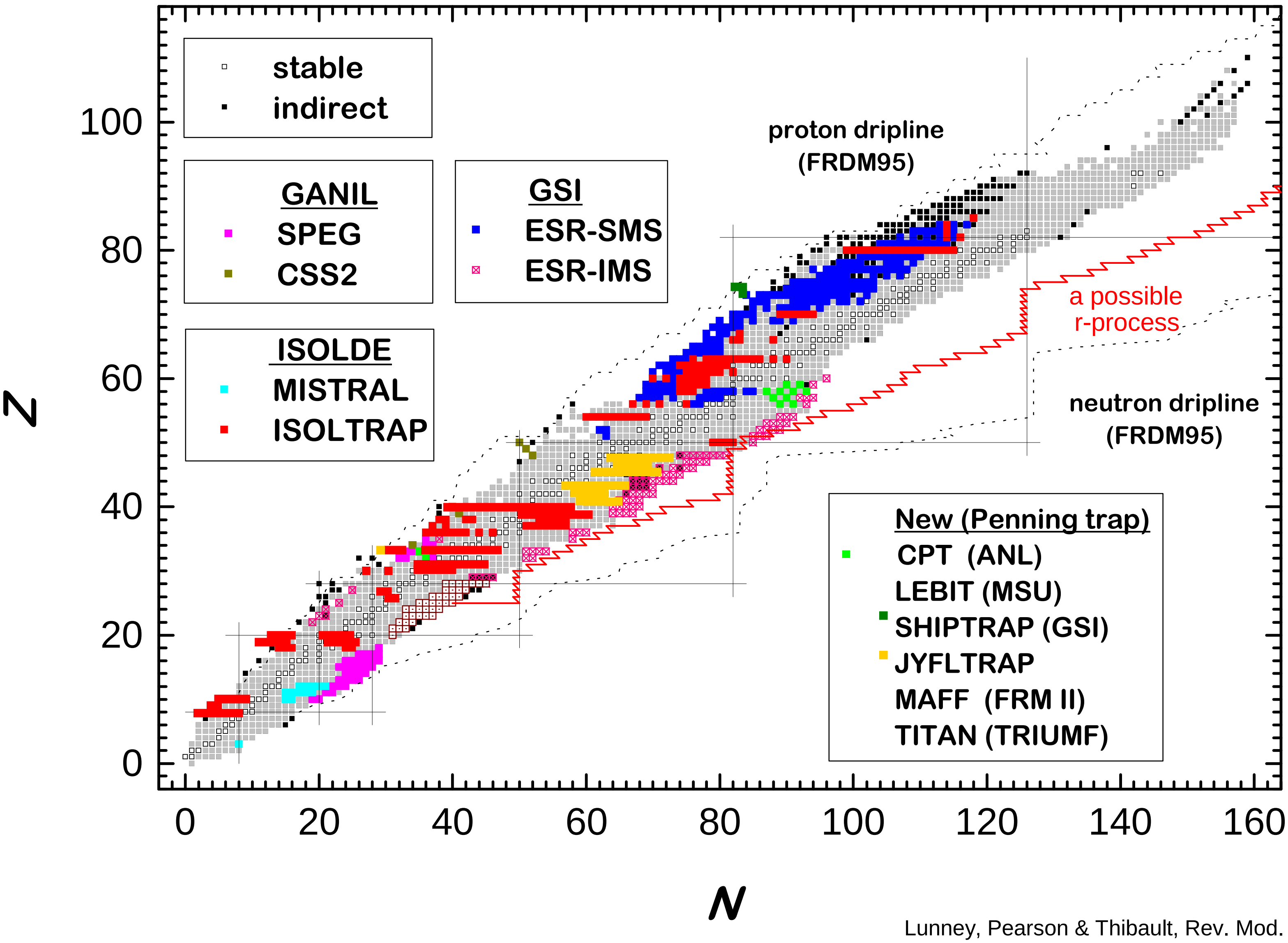
AME2003, G. Audi et al., Nucl. Phys. A 729 (2003) 3

Direct Mass Measurement Techniques in Nuclear Physics



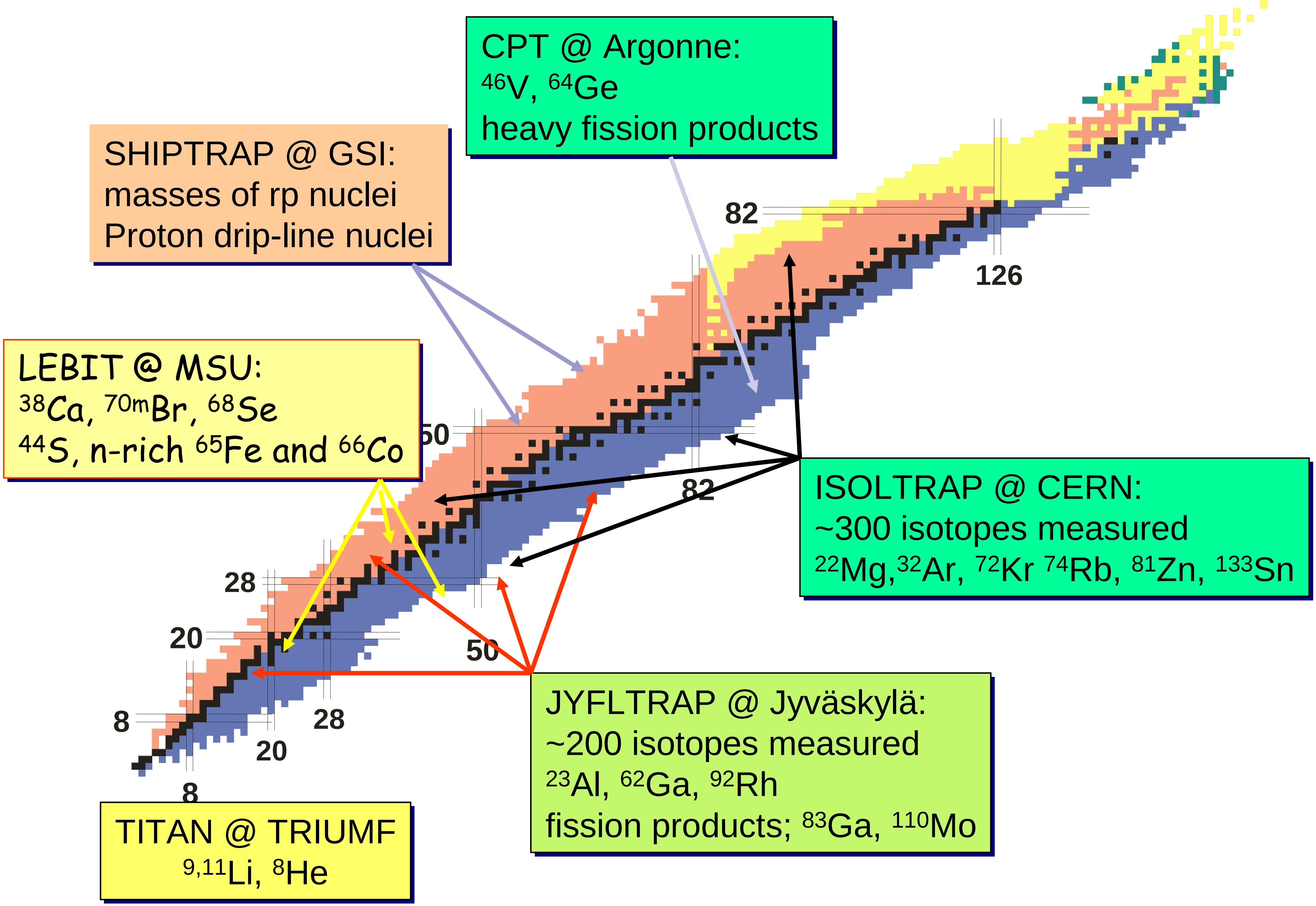
D. Lunney

Mass measurement programs for radionuclides (since 1994)



Lunney, Pearson & Thibault, Rev. Mod. Phys. 75 (2003)

Highlights from TRAP facilities



CPT @ Argonne:
^{46}V, ^{64}Ge
heavy fission products

SHIPTRAP @ GSI:
masses of rp nuclei
Proton drip-line nuclei

LEBIT @ MSU:
^{38}Ca, ^{70m}Br, ^{68}Se
^{44}S, n-rich ^{65}Fe and ^{66}Co

ISOLTRAP @ CERN:
~300 isotopes measured
^{22}Mg,^{32}Ar, ^{72}Kr ^{74}Rb, ^{81}Zn, ^{133}Sn

JYFLTRAP @ Jyväskylä:
~200 isotopes measured
^{23}Al, ^{62}Ga, ^{92}Rh
fission products; ^{83}Ga, ^{110}Mo

TITAN @ TRIUMF
^{9,11}Li, ^{8}He

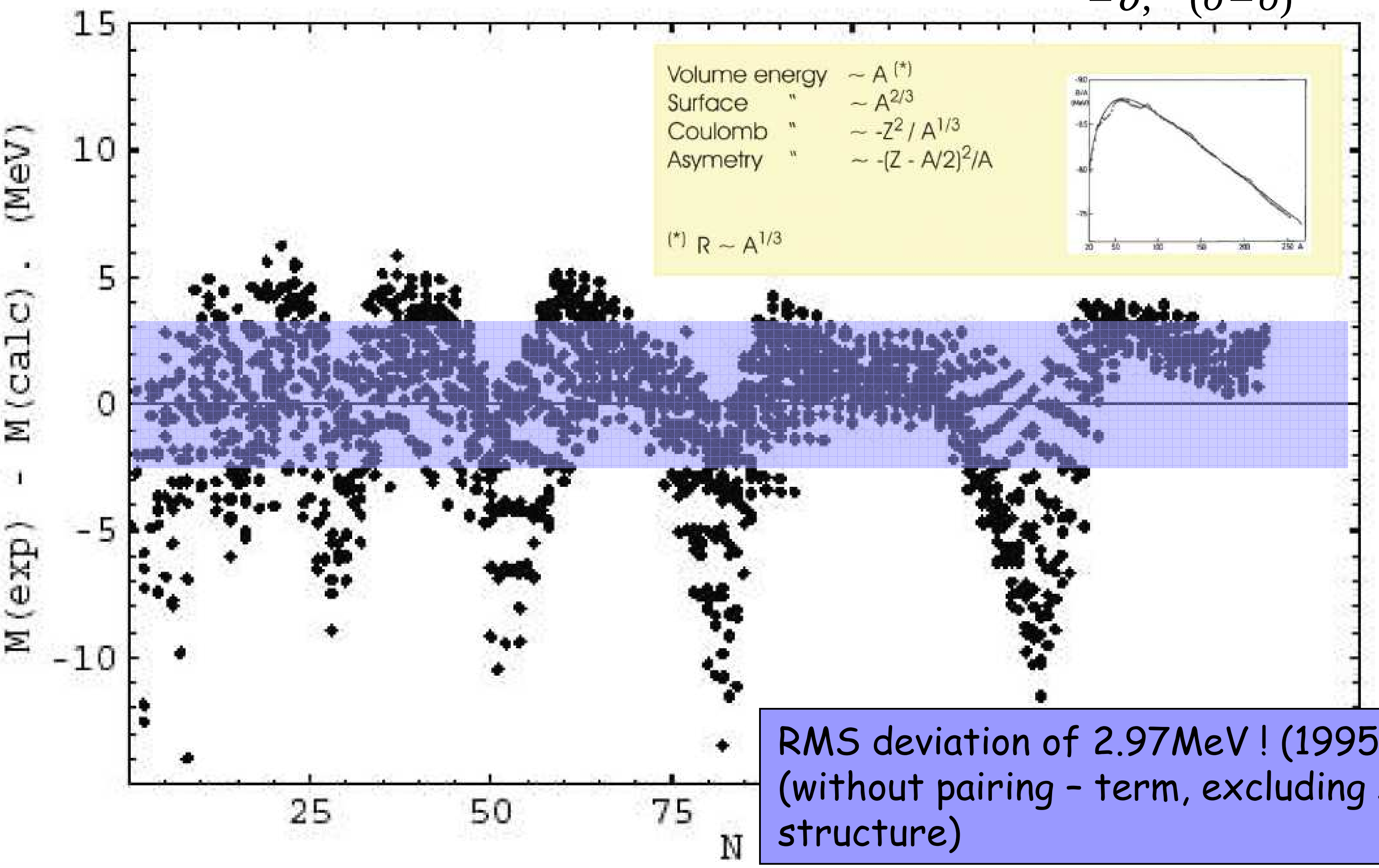
Complementary of Penning trap projects

Type of reaction	ISOL-TRAP	CPT	SHIP-TRAP	JYFL-TRAP	LEBIT	MAFF-TRAP	TITAN	SMILE-TRAP	HI-TRAP	*MATS/ FAIR*
ISOL	x						x			
fusion		x	x							
IGISOL				x						
fragmen-tation					x				x	x
neutron-fission						x				
highly-charged							x	x	x	x
stable				(x)				x	x	
trap ass. spectros.	(x)			x						x

Present facilties are complementary
New facilities are needed

”Macroscopic mass”

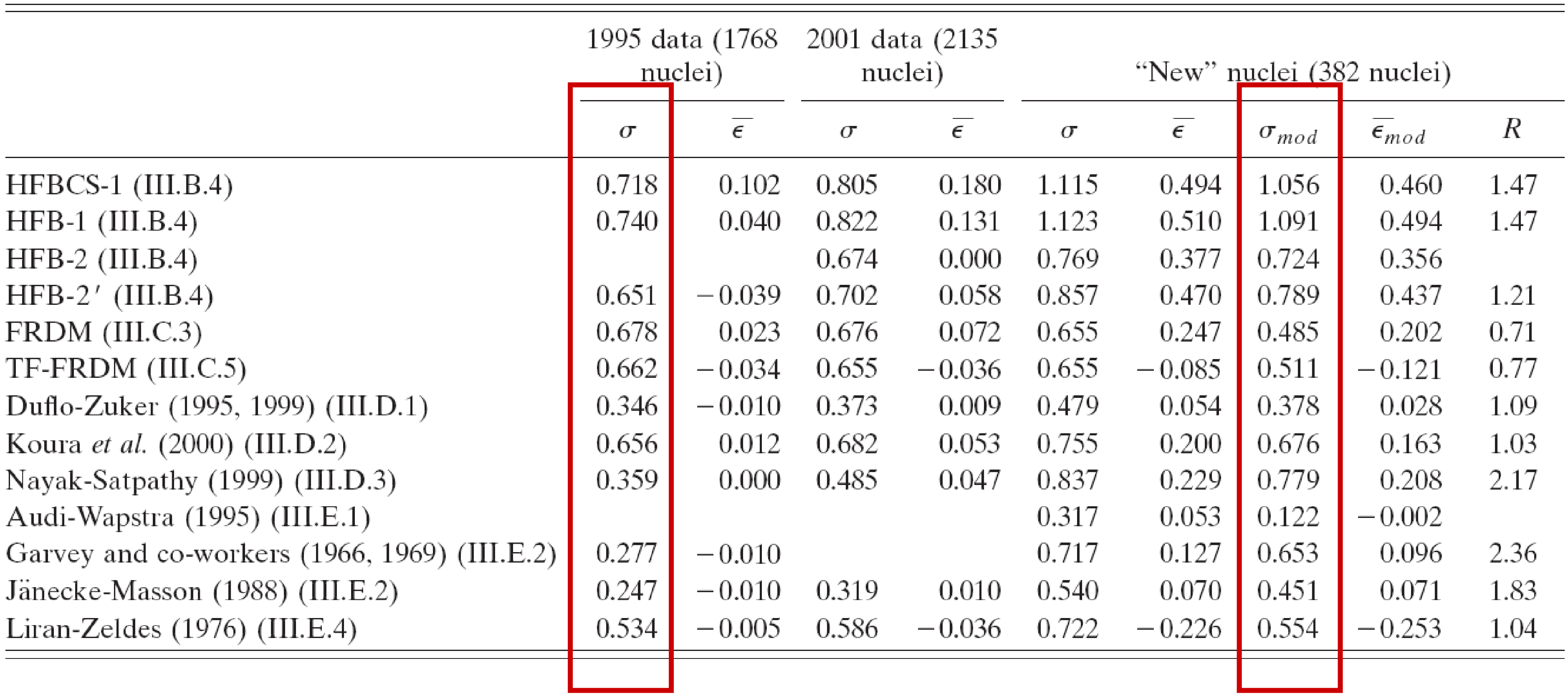
$$B(A,Z)=a_V A-a_s A^{2/3}-a_C Z(Z-1)A^{-1/3}-a_A(A-2Z)^2A^{-1}\begin{array}{ll}+\delta, & (e-e)\\ +0, & (o-e)\\ -\delta, & (o-o)\end{array}$$



RMS deviation of 2.97MeV ! (1995 data) (without pairing – term, excluding shell structure)

C. F. v. Weizsäcker, H.A.Bethe (1935/36)

Predictive power of mass models;



	1995 data (1768 nuclei)		2001 data (2135 nuclei)		"New" nuclei (382 nuclei)				
	σ	$\bar{\epsilon}$	σ	$\bar{\epsilon}$	σ	$\bar{\epsilon}$	σ_{mod}	$\bar{\epsilon}_{mod}$	R
HFBCS-1 (III.B.4)	0.718	0.102	0.805	0.180	1.115	0.494	1.056	0.460	1.47
HFB-1 (III.B.4)	0.740	0.040	0.822	0.131	1.123	0.510	1.091	0.494	1.47
HFB-2 (III.B.4)			0.674	0.000	0.769	0.377	0.724	0.356	
HFB-2′ (III.B.4)	0.651	−0.039	0.702	0.058	0.857	0.470	0.789	0.437	1.21
FRDM (III.C.3)	0.678	0.023	0.676	0.072	0.655	0.247	0.485	0.202	0.71
TF-FRDM (III.C.5)	0.662	−0.034	0.655	−0.036	0.655	−0.085	0.511	−0.121	0.77
Duflo-Zuker (1995, 1999) (III.D.1)	0.346	−0.010	0.373	0.009	0.479	0.054	0.378	0.028	1.09
Koura *et al.* (2000) (III.D.2)	0.656	0.012	0.682	0.053	0.755	0.200	0.676	0.163	1.03
Nayak-Satpathy (1999) (III.D.3)	0.359	0.000	0.485	0.047	0.837	0.229	0.779	0.208	2.17
Audi-Wapstra (1995) (III.E.1)					0.317	0.053	0.122	−0.002	
Garvey and co-workers (1966, 1969) (III.E.2)	0.277	−0.010			0.717	0.127	0.653	0.096	2.36
Jänecke-Masson (1988) (III.E.2)	0.247	−0.010	0.319	0.010	0.540	0.070	0.451	0.071	1.83
Liran-Zeldes (1976) (III.E.4)	0.534	−0.005	0.586	−0.036	0.722	−0.226	0.554	−0.253	1.04

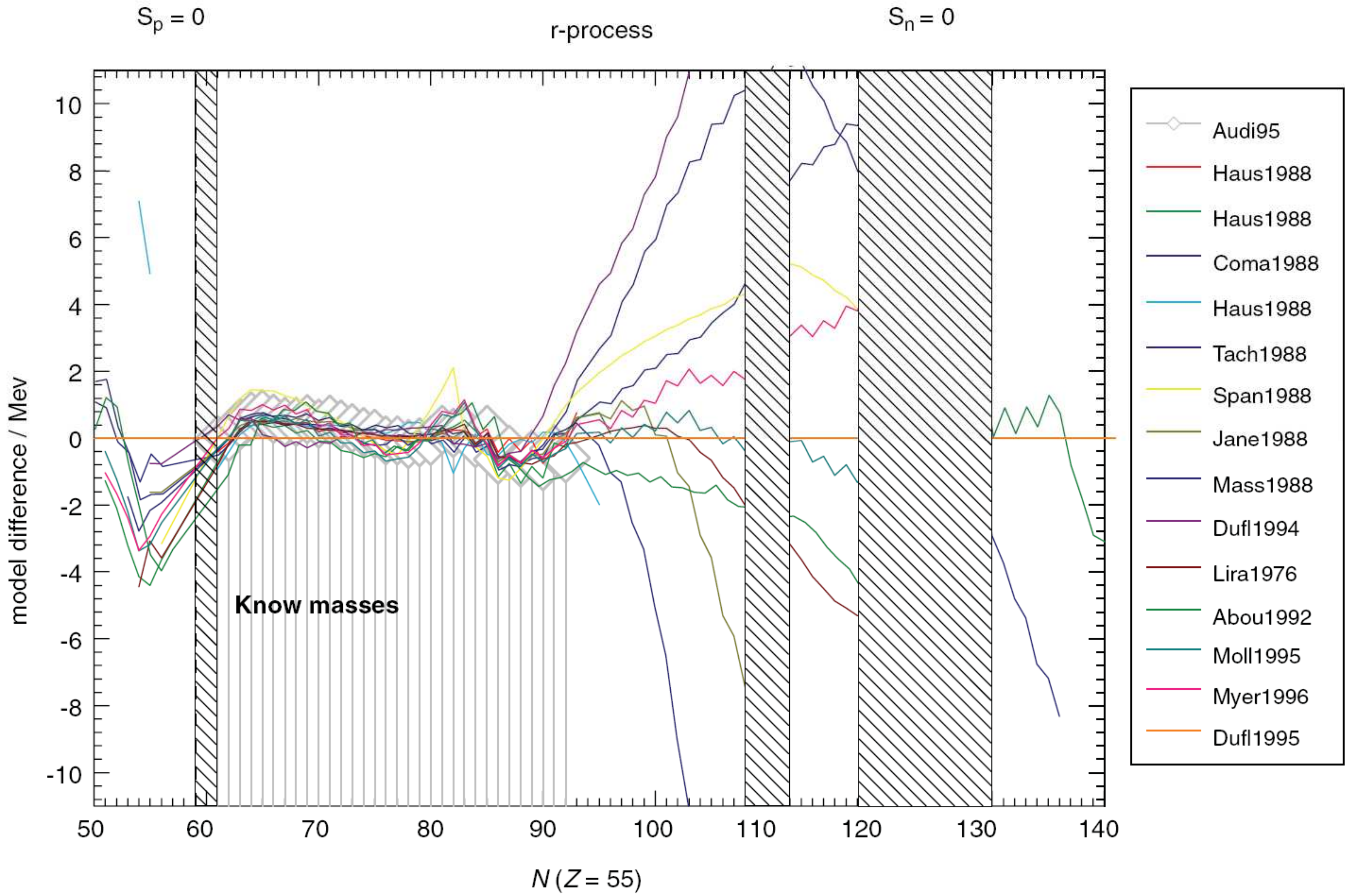
0.25 – 0.74 MeV

0.4 – 1 MeV

D. Lunney et al. Rev. Mod. Phys. 75 (2003) 1021

Differences in mass precictions to Duflo & Zucker

J. Duflo, A.P. Zuker, Phys. Rev. C 52 (1995) R23.



K. Blaum / Physics Reports 425 (2006) 1–78

Do we need precision measurements in nuclear physics at all ?

Absolutely: YES !

Nuclear mass-related observables

Absolute mass --- total binding energy --- Limits of nuclear existence

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)
Shell-gap energy (evolution of magicity)
Energy difference of spin-orbit partner states → $V_{s0}(\mathbf{l}\cdot\mathbf{s})$
Valence proton-neutron interaction energy δV_{pn}

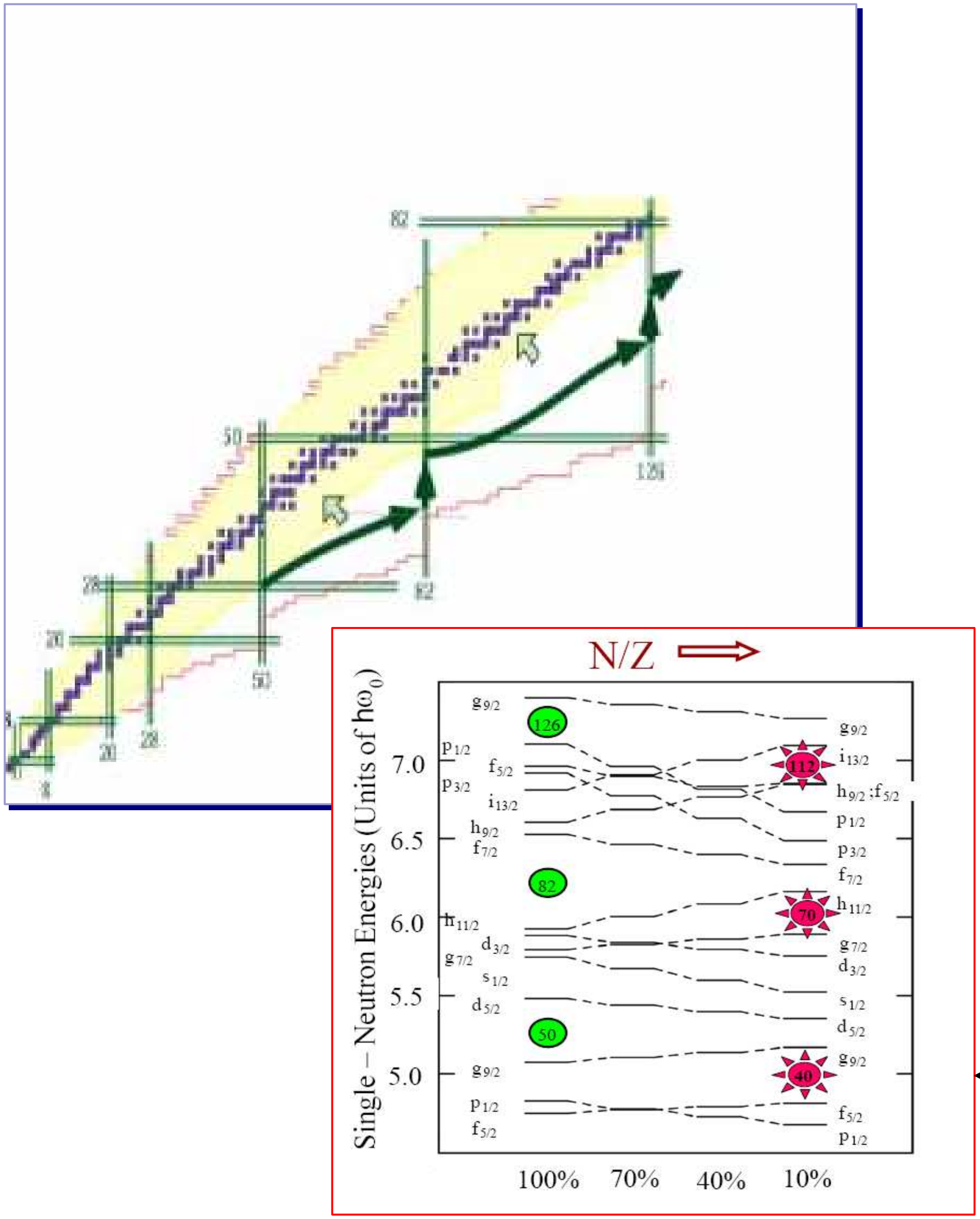
- **Nuclear structure (10-100 keV)**
  - Global correlations (100 keV)
  - Local correlations (10 keV)
    - shell structure, spin-orbit interaction, pairing, collectivity
  - Drip-line phenomena and halos (1 keV)

- **Nuclear astrophysics (1 keV)**

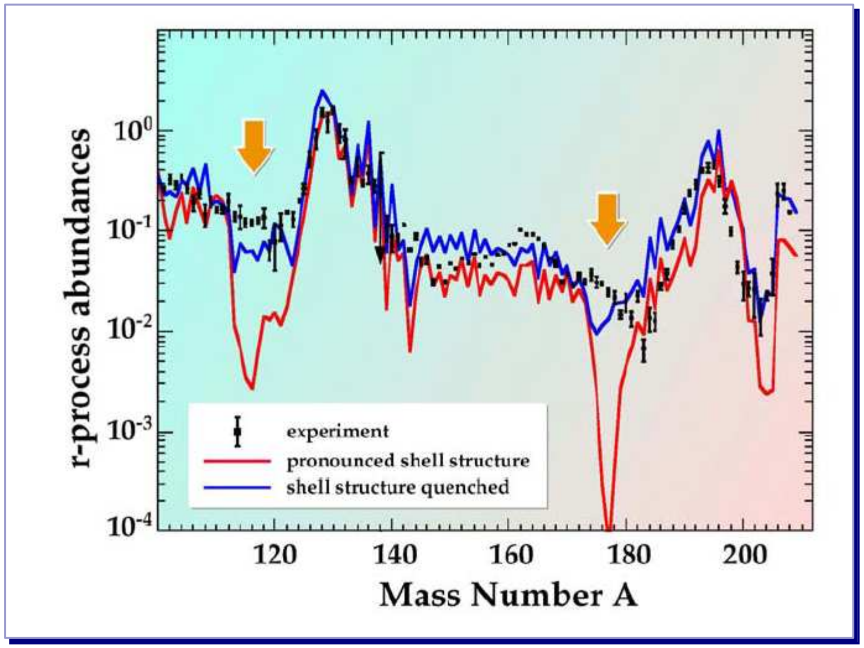
- **Charge symmetry in nuclei (100 eV)**
  - Isospin multiplets
  - Coulomb energy differences

- **Test of Standard Model (< 100 eV)** $\delta m/m \ll 1\cdot 10^{-9}$
  - Nuclear β decay. Electroweak interaction
    - CVC theory and unitarity of CKM matrix
    - Neutrinoless double β decay

Mass measurements for NUCLEAR STRUCTURE

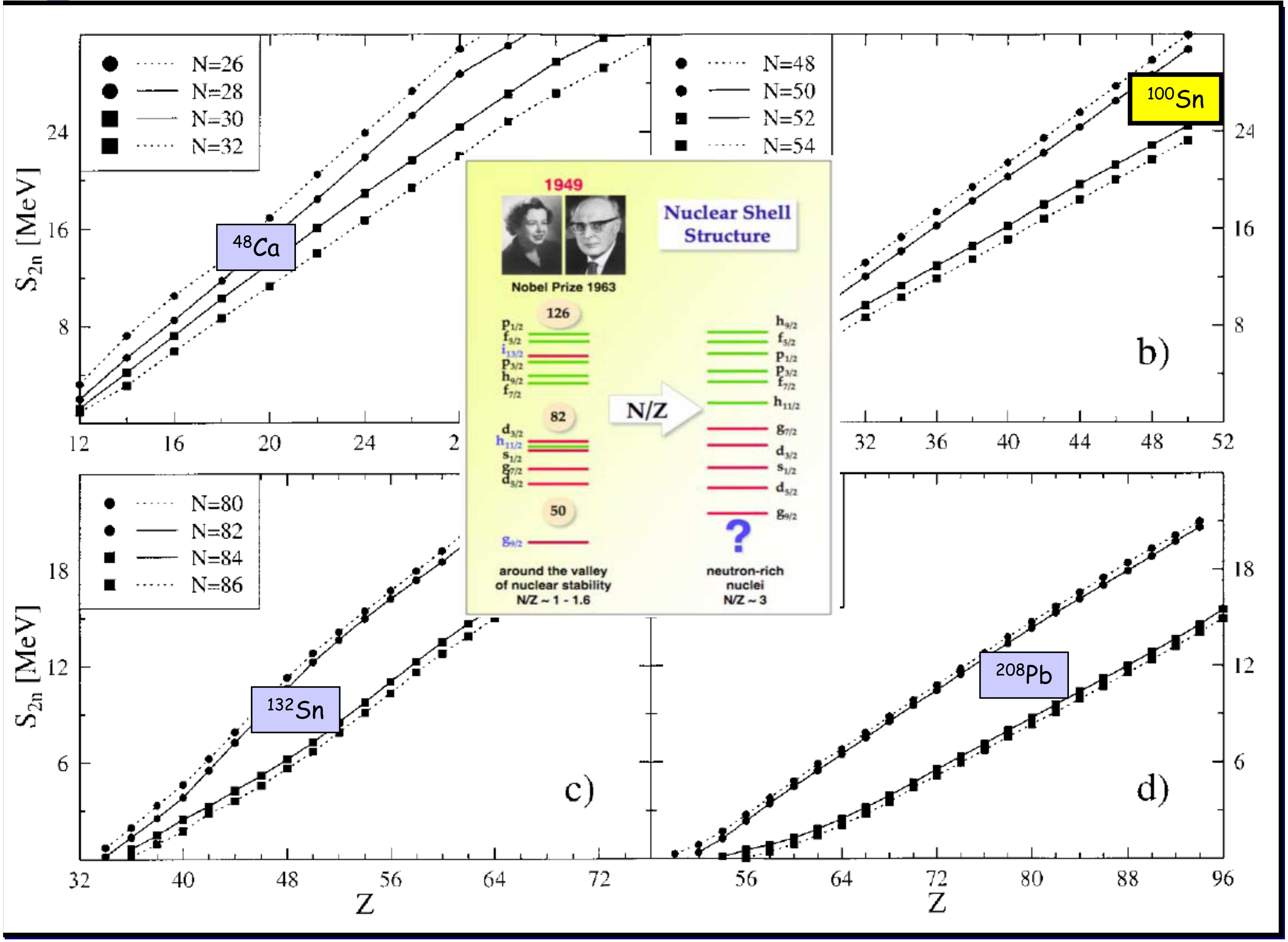


IMPACT ON R-PROCESS ?



Spin-orbit force ?
Pairing interaction ?
Effective force ?
Continuum-coupling?……

Shell gap energy and magicity ?



J.Dobaczewski and W.Nazarewicz
Phil. Trans. R. Soc. Lond. A356, 2007 (1998)

Shell-gap energies – a measure of magicity

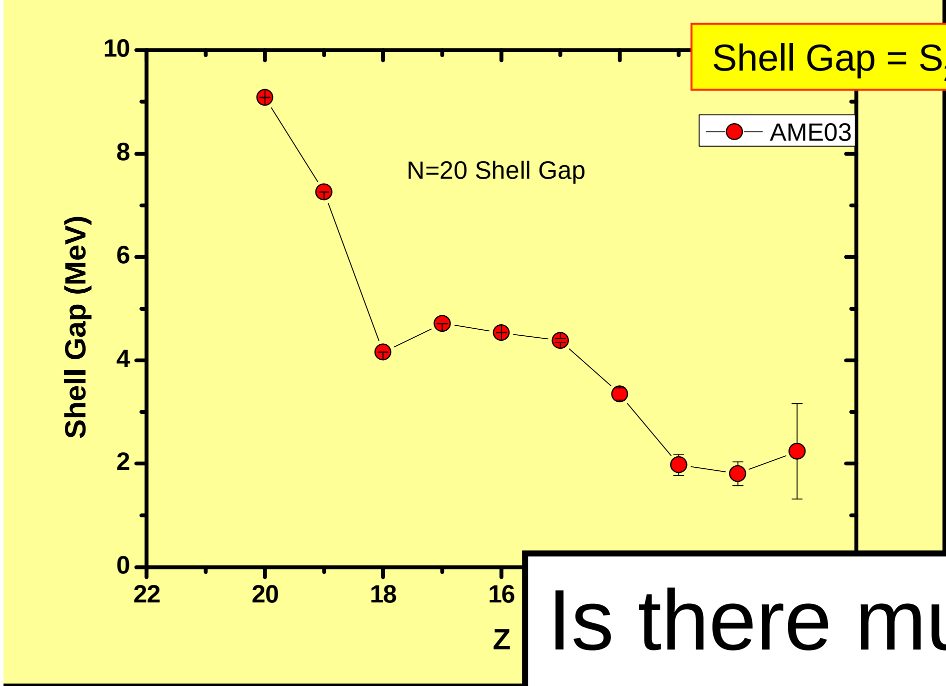
Across the magic proton shell Z_0

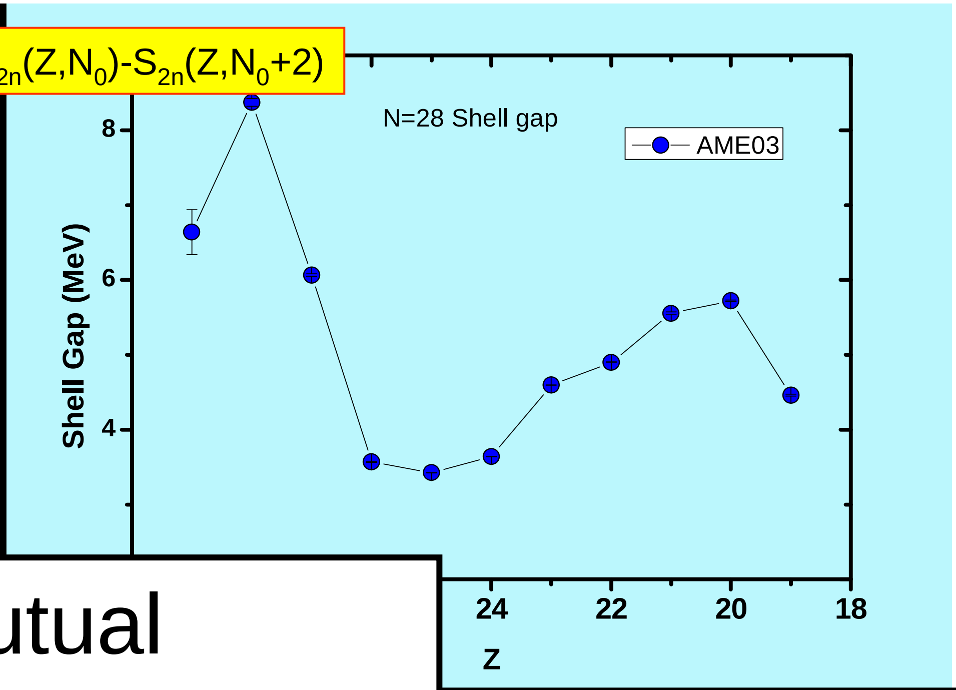
$$\delta_{2p}\,(Z_0,N)= S_{2p}(Z_0,N)-S_{2p}(Z_0+2,N)$$

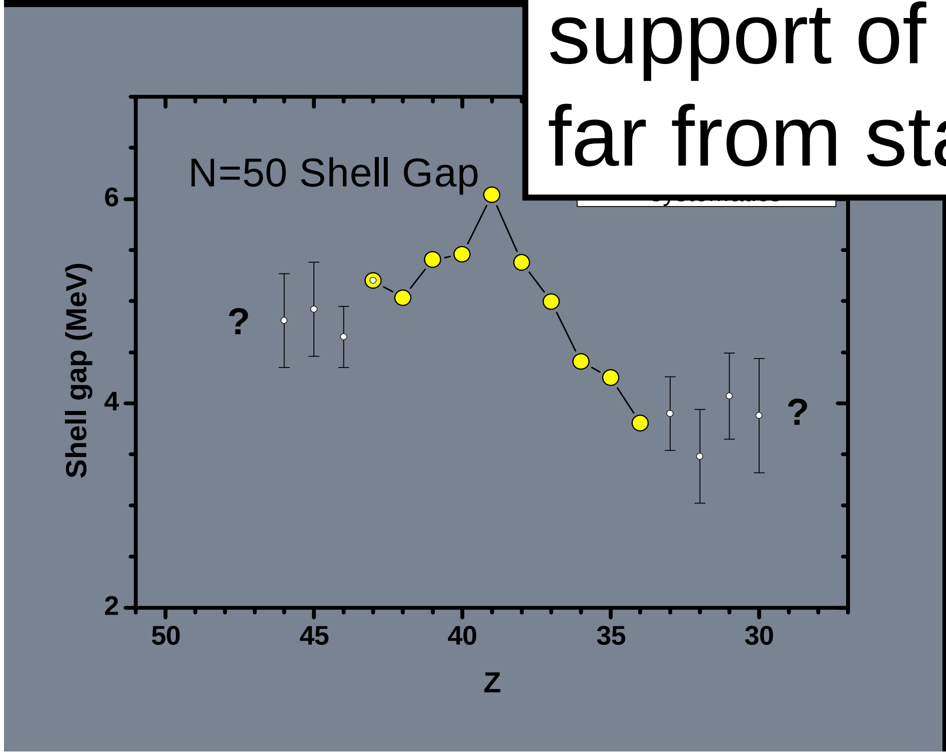
Across the magic neutron shell N_0

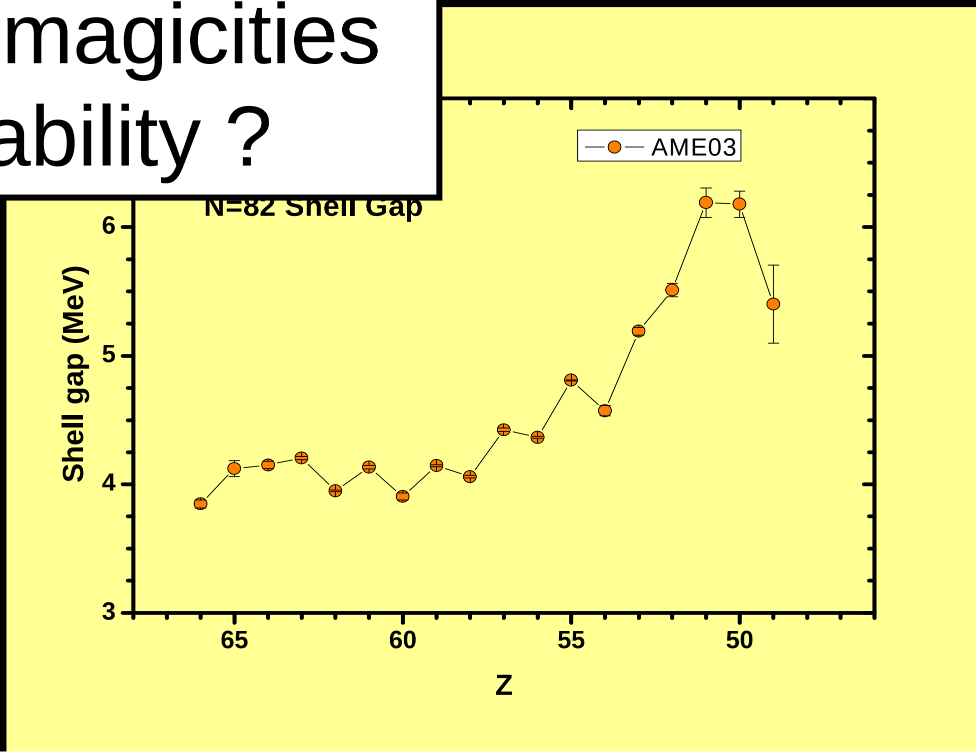
$$\delta_{2n}(Z,N_0)= S_{2n}(Z, N_0)-S_{2n}(Z,N_0+2)$$

Shell Gap = $S_{2n}(Z,N_0)-S_{2n}(Z,N_0+2)$





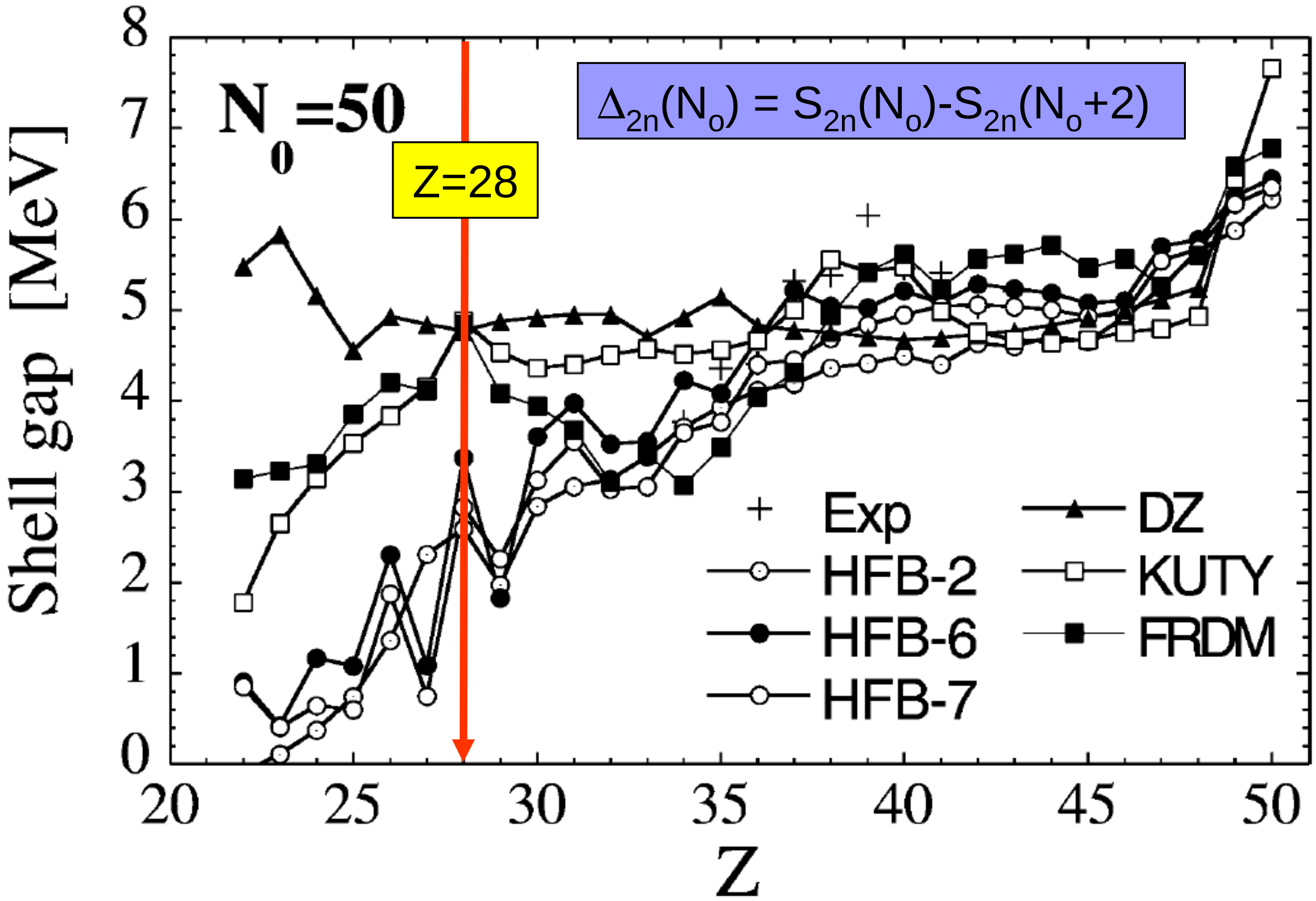




Is there mutual support of magicities far from stability ?

Shell gap energies – theory perspective

J.M. Pearson and S. Goriely, Nucl. Phys. A 777 (2006) 623-644

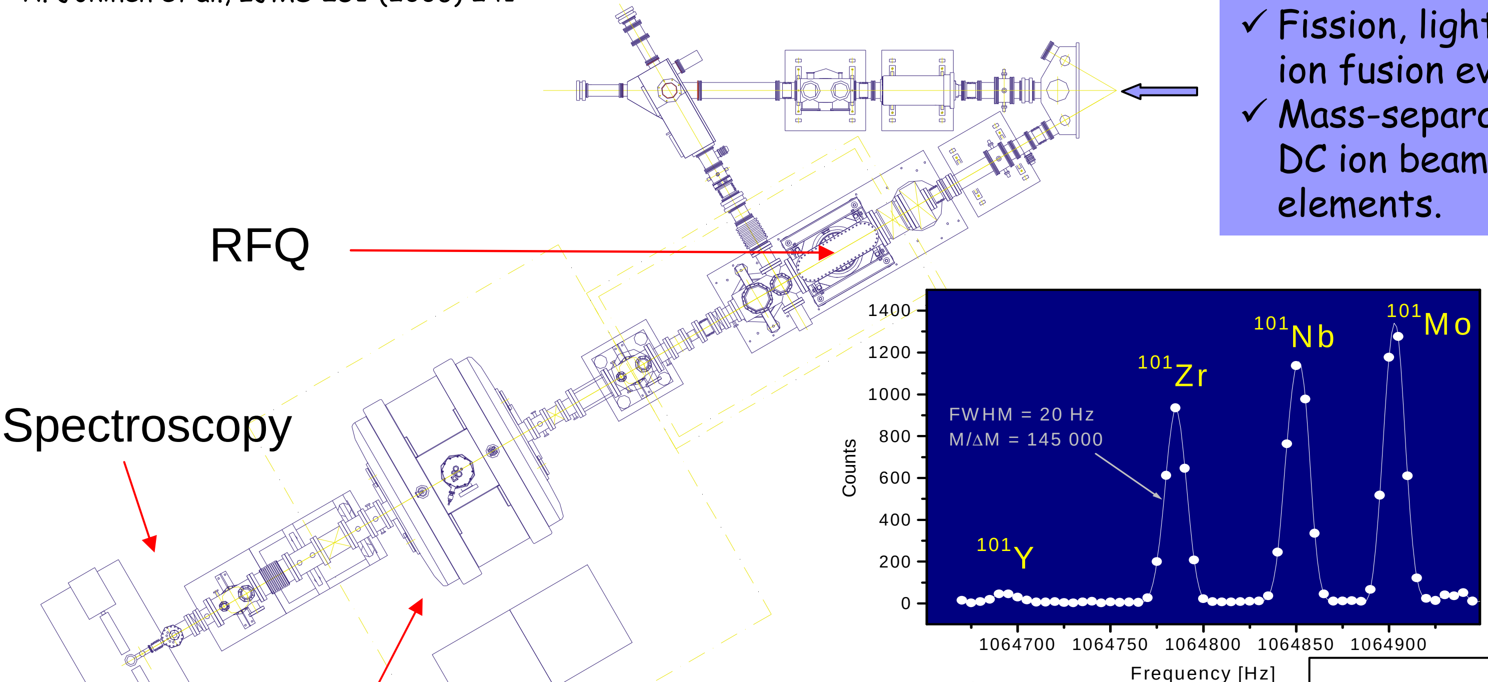


JYFLTRAP

V. Kolhinen et al., NIM A **528** (2004) 776
S. Rinta-Antila et al., PRC **70** (2004) 011301(R)
A. Jokinen et al., IJMS **251** (2006) 241

K130-accelerator + IGISOL:

✓ Fission, light-ion fusion or heavy ion fusion evaporation reactions.
✓ Mass-separated (M/ΔM~300), 1+ DC ion beam at 30 keV of various elements.

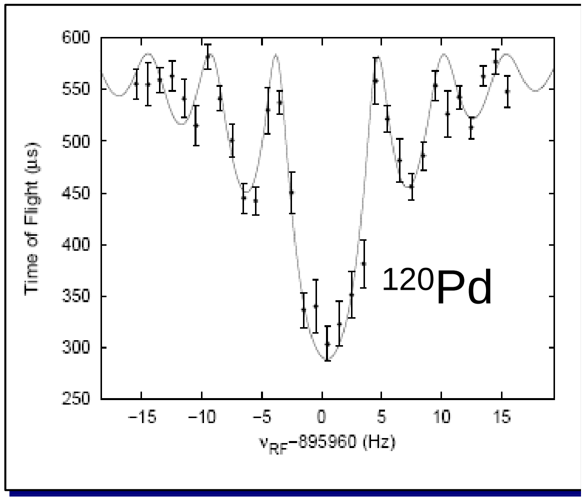


7 T superconducting solenoid @ 30 kV:

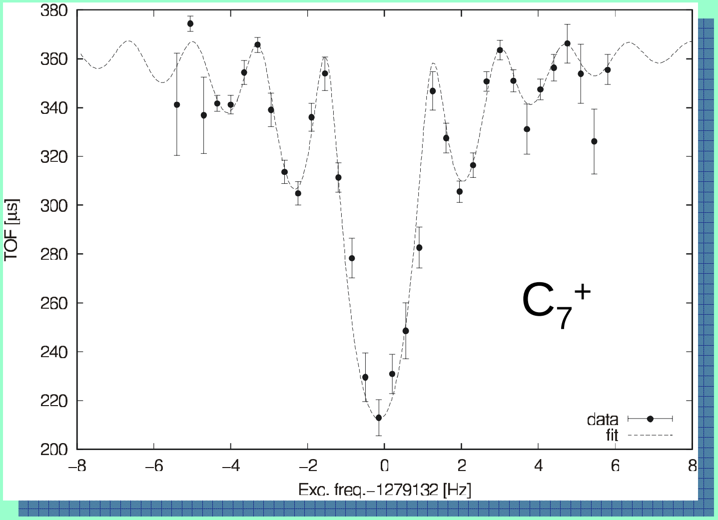
Purification trap (ΔM/M < 10^{-5}):
Cylindrical trap @ 10^{-4} mbar, ΔB/B = 10^{-6} in 1 cm^3
Precision trap (ΔM/M < 10^{-6}):
Cylindrical trap in vacuum, ΔB/B = 10^{-7} in 1 cm^3

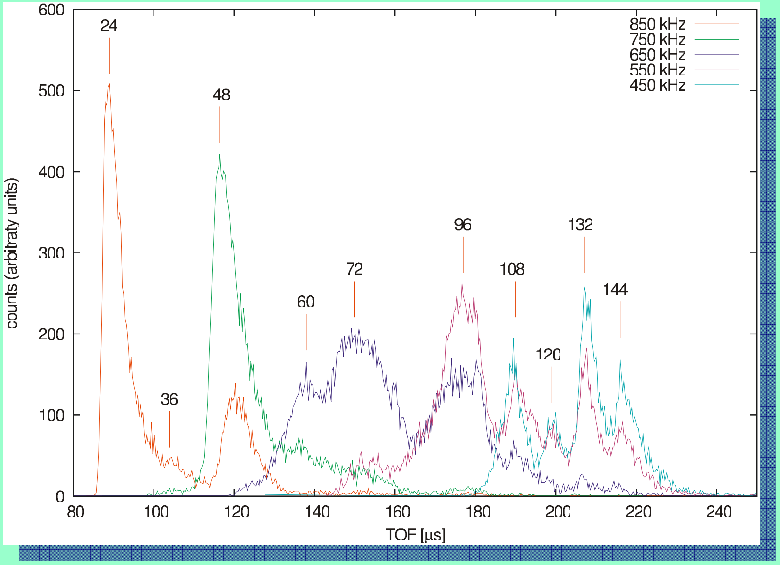
$$f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$$

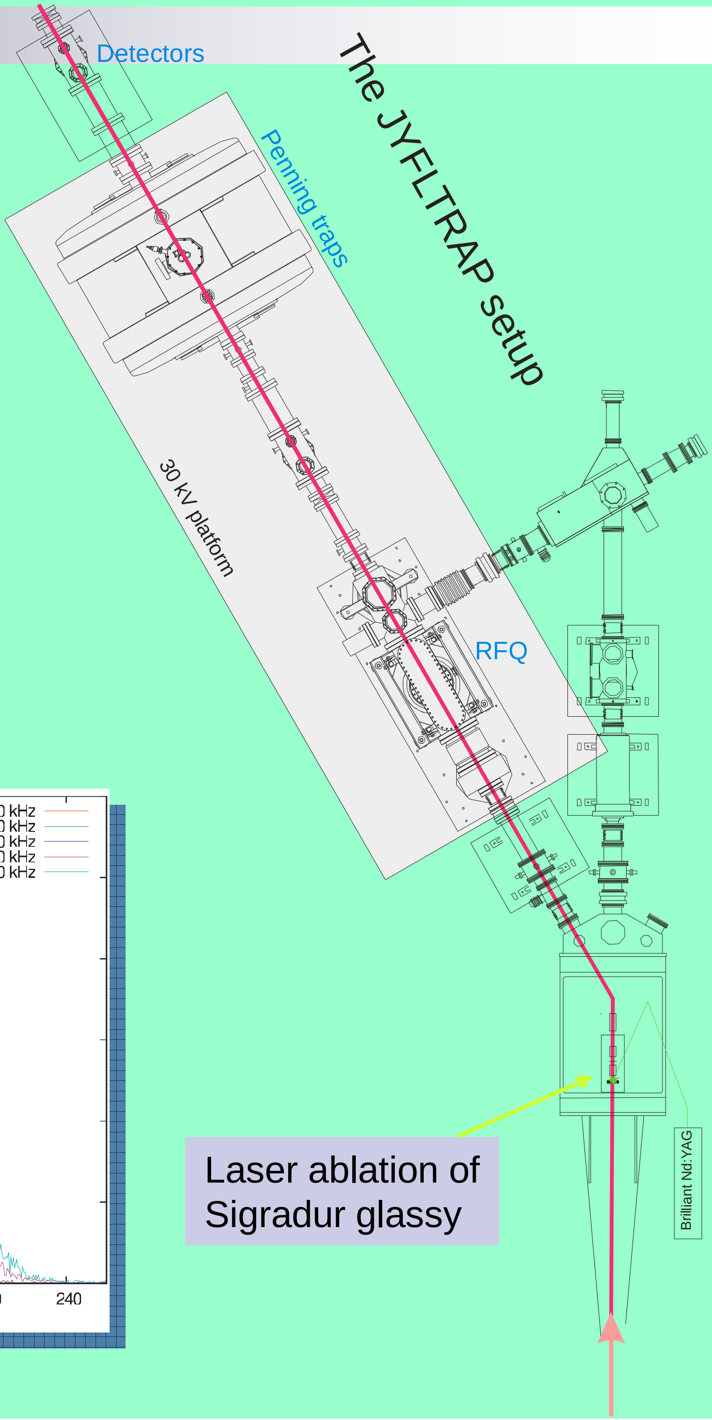
$$\frac{f_{c,ref}}{f_c} = \frac{m - m_e}{m_{ref} - m_e}$$



Calibration with C cluster ions





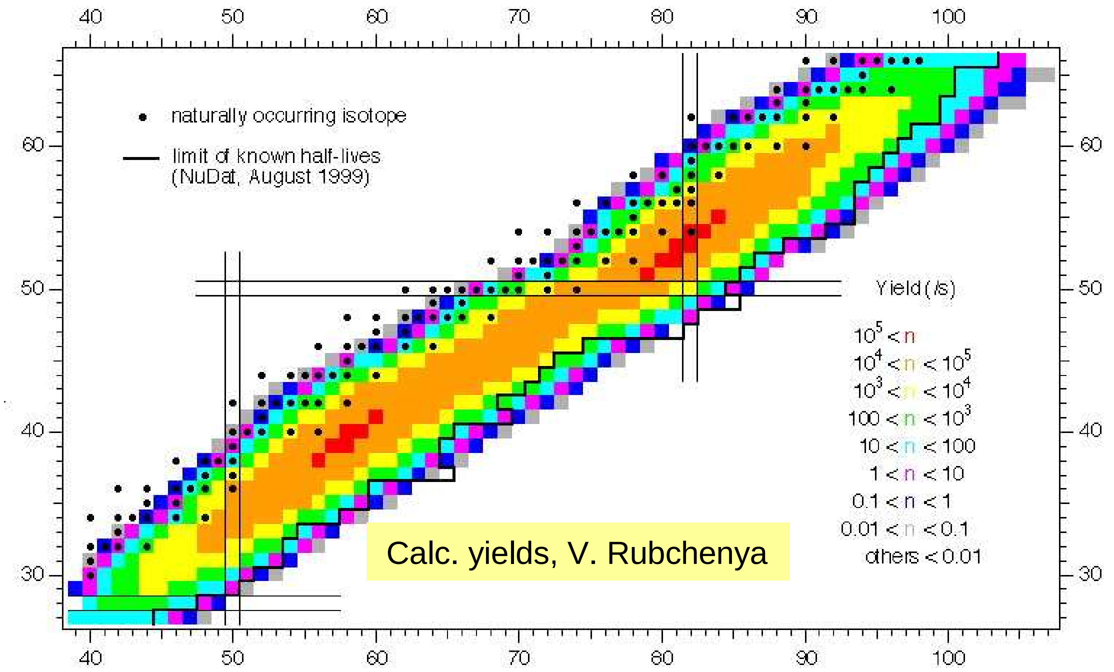


Laser ablation of
Sigradur glassy

V. Elomaa, private communication

Mass measurements of (refractory) neutron-rich nuclei

^{238}U(p,f)-reaction @ 30 MeV and 10-50 μA



Calc. yields, V. Rubchenya

Nuclear structure aspects:

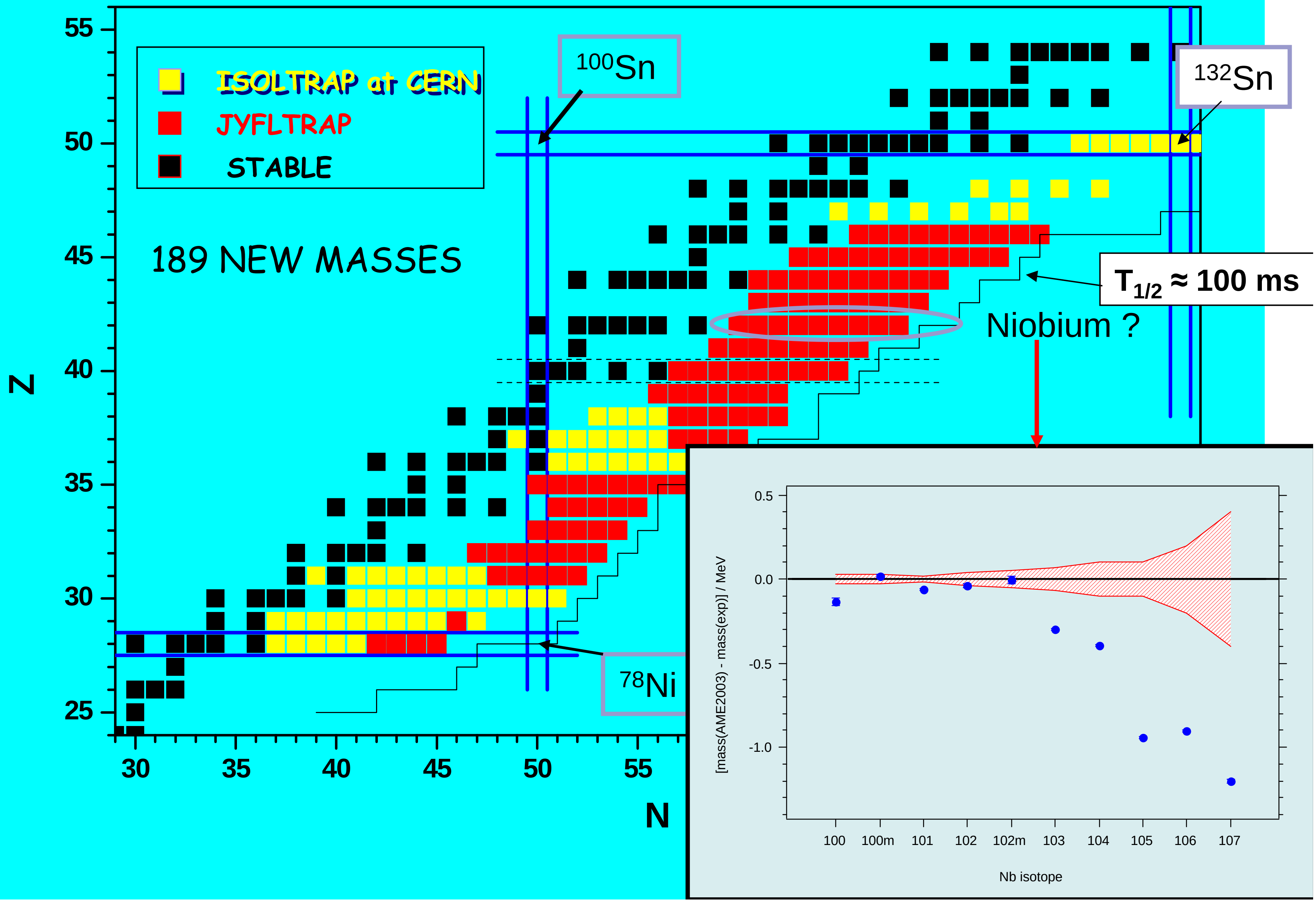
- ✓Shell closure at N=50
- ✓Subshell closure at N=56
- ✓Onset of large deformation at N>58
- ✓Transitional behaviour, Zr→Pd

Astrophysics motivation
Location of r-process path:
(n,γ) – (γ,n) equilibrium.

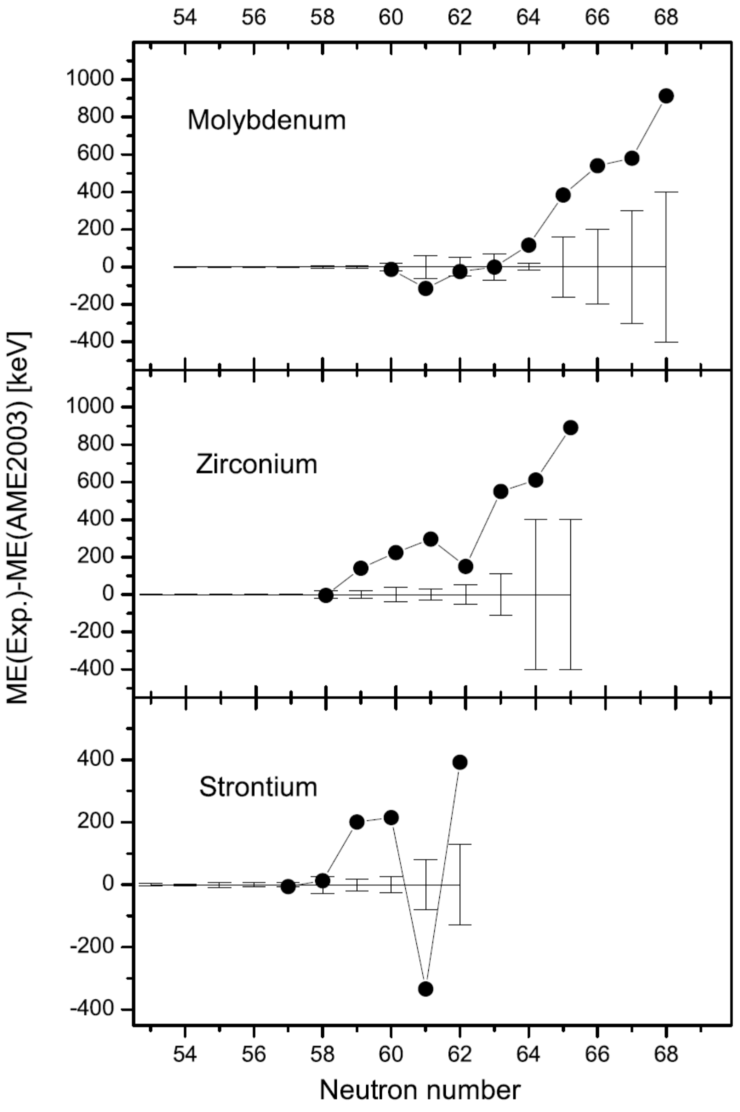
$$\lambda_{\gamma n} \propto \frac{T^{3/2}}{N_n} e^{\left(\frac{S_n}{k_B T}\right)} \lambda_{n\gamma}$$

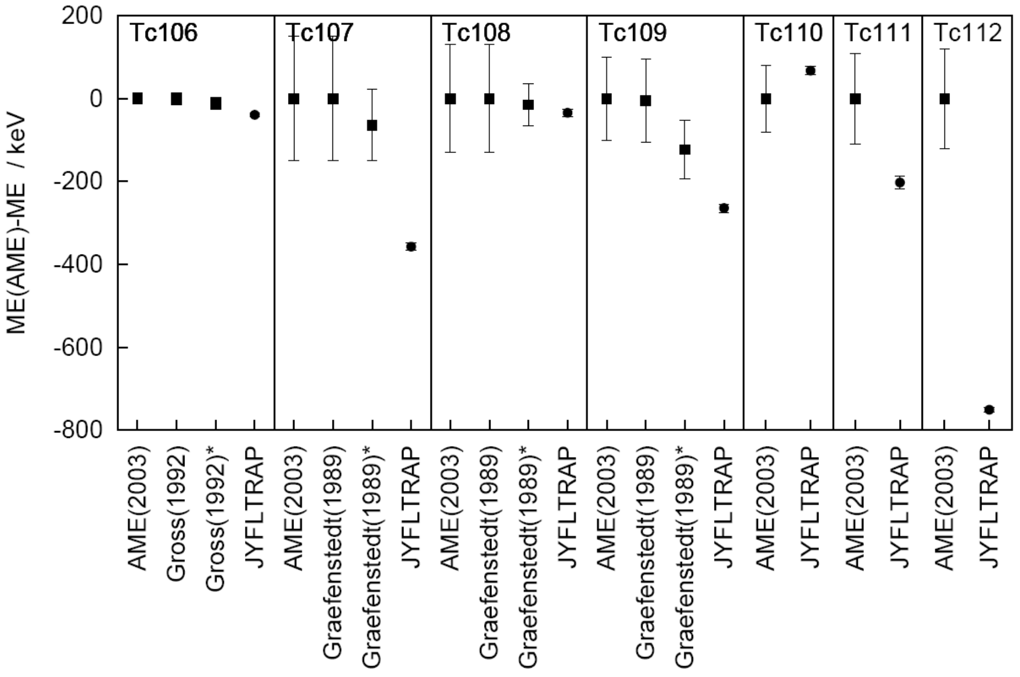
$S_n \leq 3$ MeV

New mass measurements of fission products



More examples





Neutron-rich nuclei are generally **less bound** than estimated in AME03 **!!!**

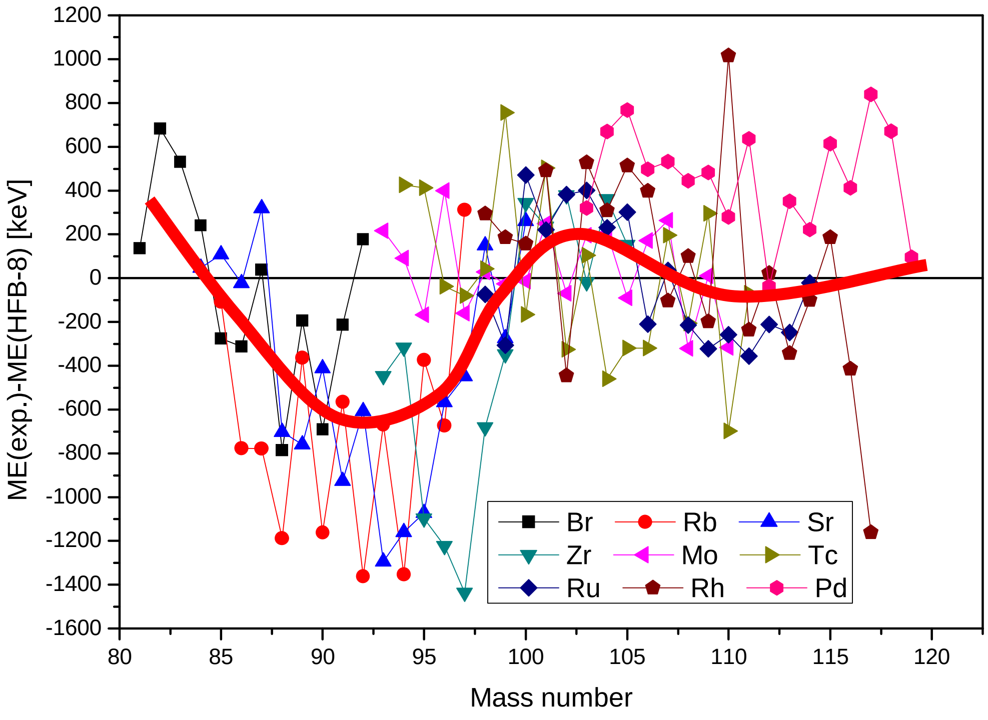
Comparison to mass predictions

(by A. Jokinen)

HFB-8, S. Goriely et al.

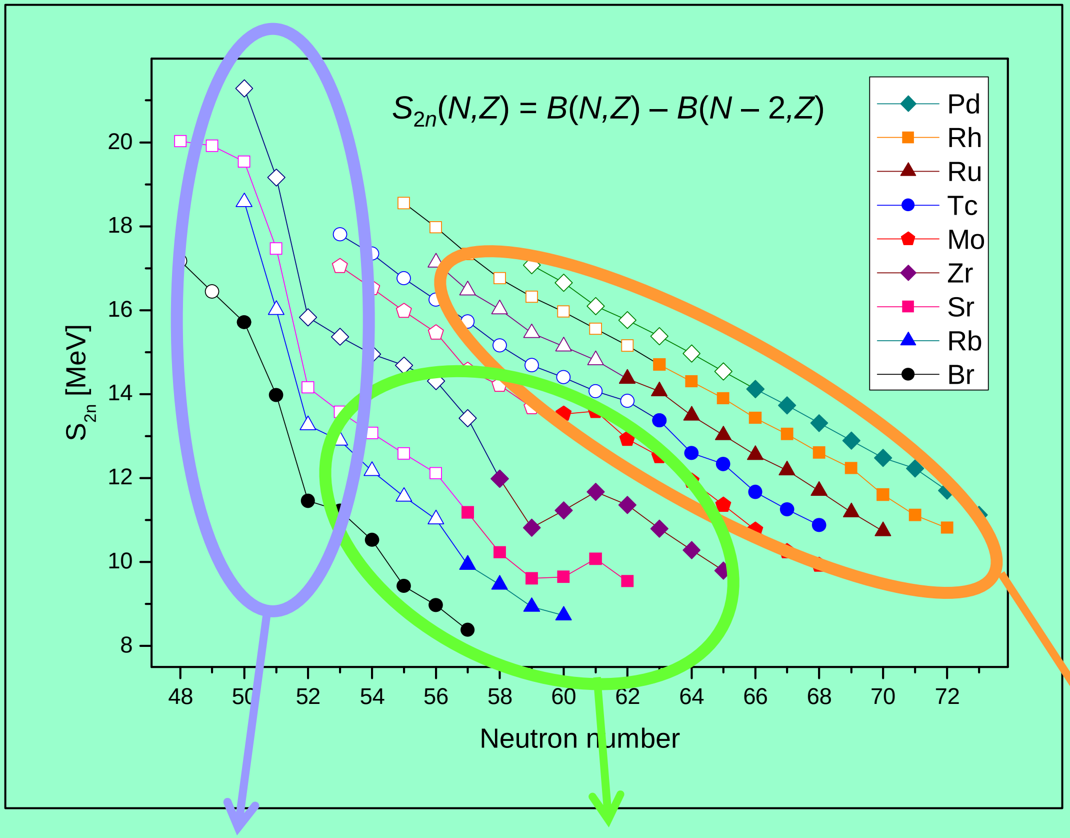
- "The best model in terms of RMS dev. (635 keV)
- Comparison to the new data:
  - ☐ Average deviation -80 keV
  - ☐ RMS deviation 513 keV

- ✓ Binding energies are needed for network calculations
- ✓ R-process path mostly out of reach in the laboratory
- ✓ Mass predictions and extrapolations
- ✓ Plenty of models:
  - ✓HFB-x, S. Goriely et al.
  - ✓FRDM by Möller and Nix
  - ✓Kuty-models, T. Koura et al.,
  - ✓Duflo-Zuker model
- ✓ AME2003 (G. Audi et al.,)
- ✓ New data is needed to benchmark different models and to provide new input

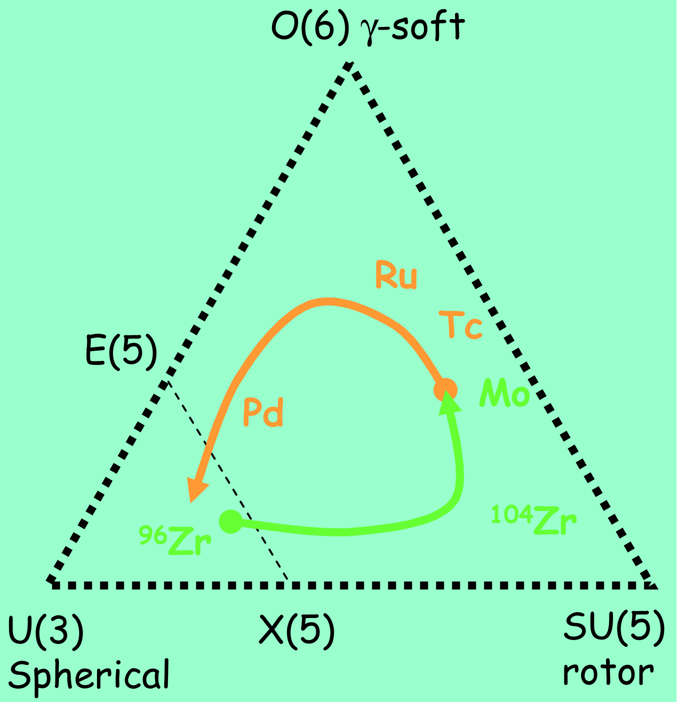


Two-neutron separation energies, S_{2n}

S_{2n} sensitive for structure effects



"Casten triangle"



Sudden drop in S_{2n} due to shell closure at N=50.

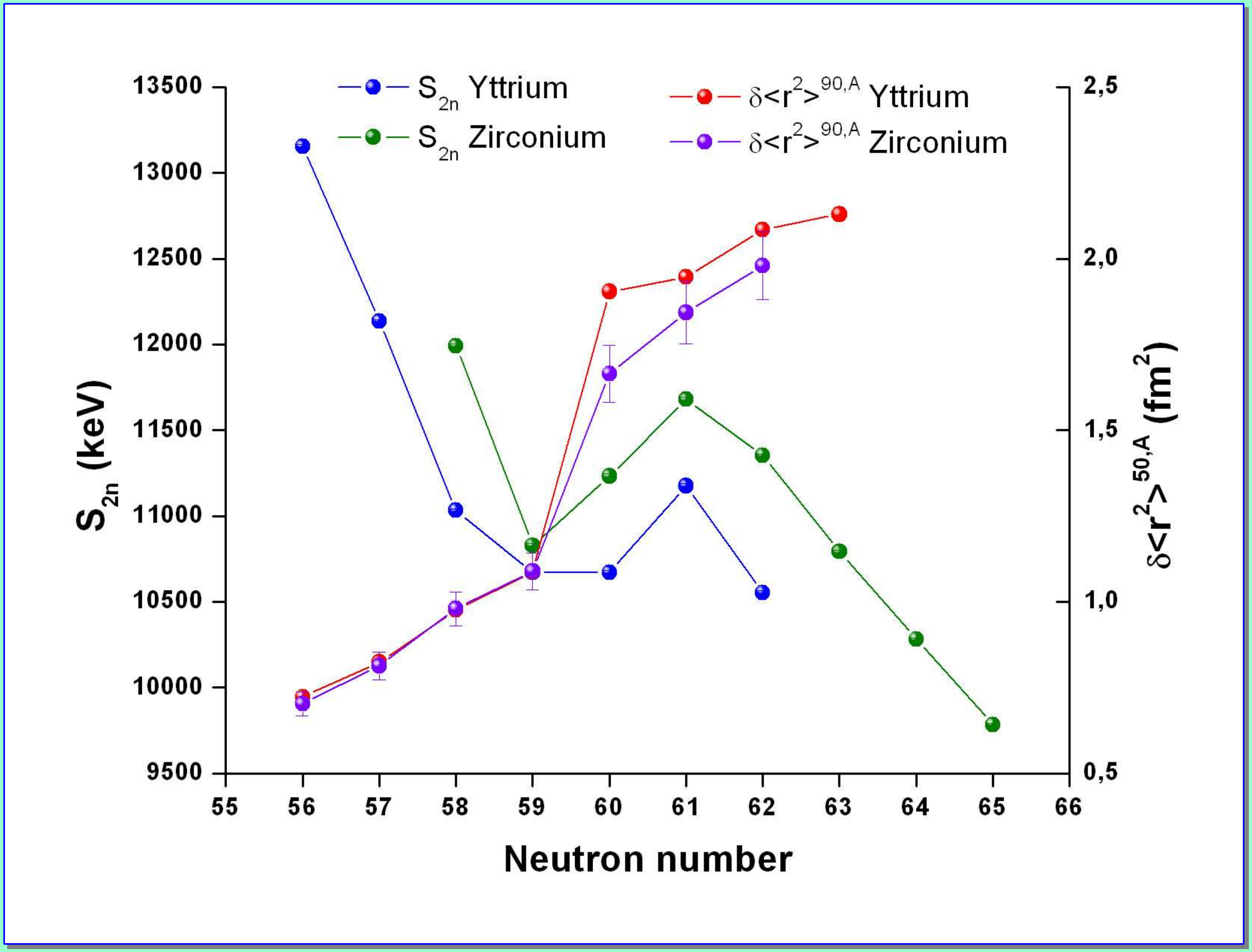
- ✓ Change of deformation
- ✓ Coincides with observed shape changes for Zr and Y isotopes

U. Hager et al, PRL 96(2006)042504
S. Rahaman et al, Eur. Phys. J. A32(2007)87

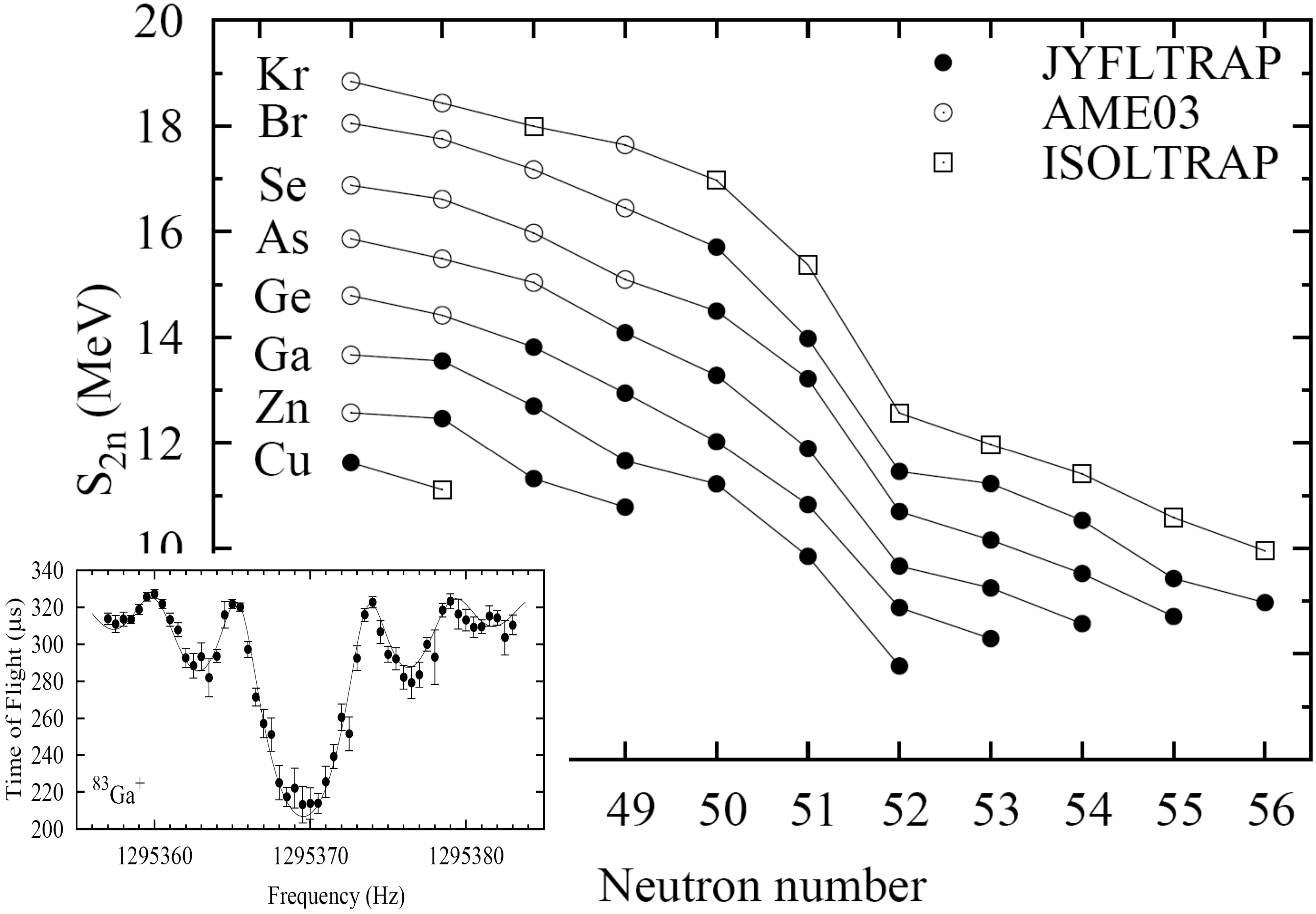
- ✓ Changes from gamma-soft/triaxial nuclei to almost perfect vibrator
- ✓ A smooth trend dominated by the asymmetry term in LD-presentation

U. Hager et al, Phys. Rev. C, in press

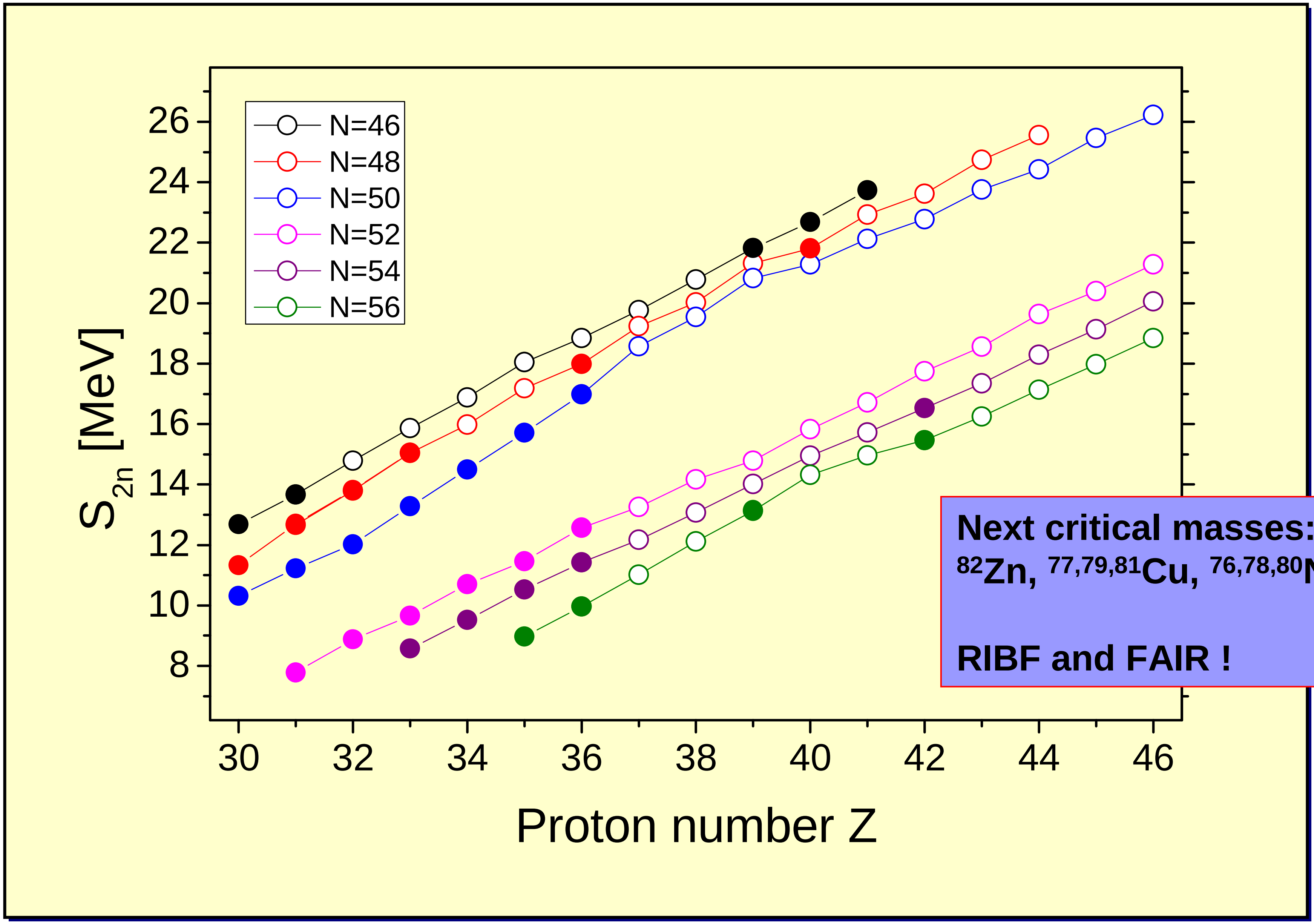
Charge radii and S_{2n}



Two-neutron binding energy across N=50



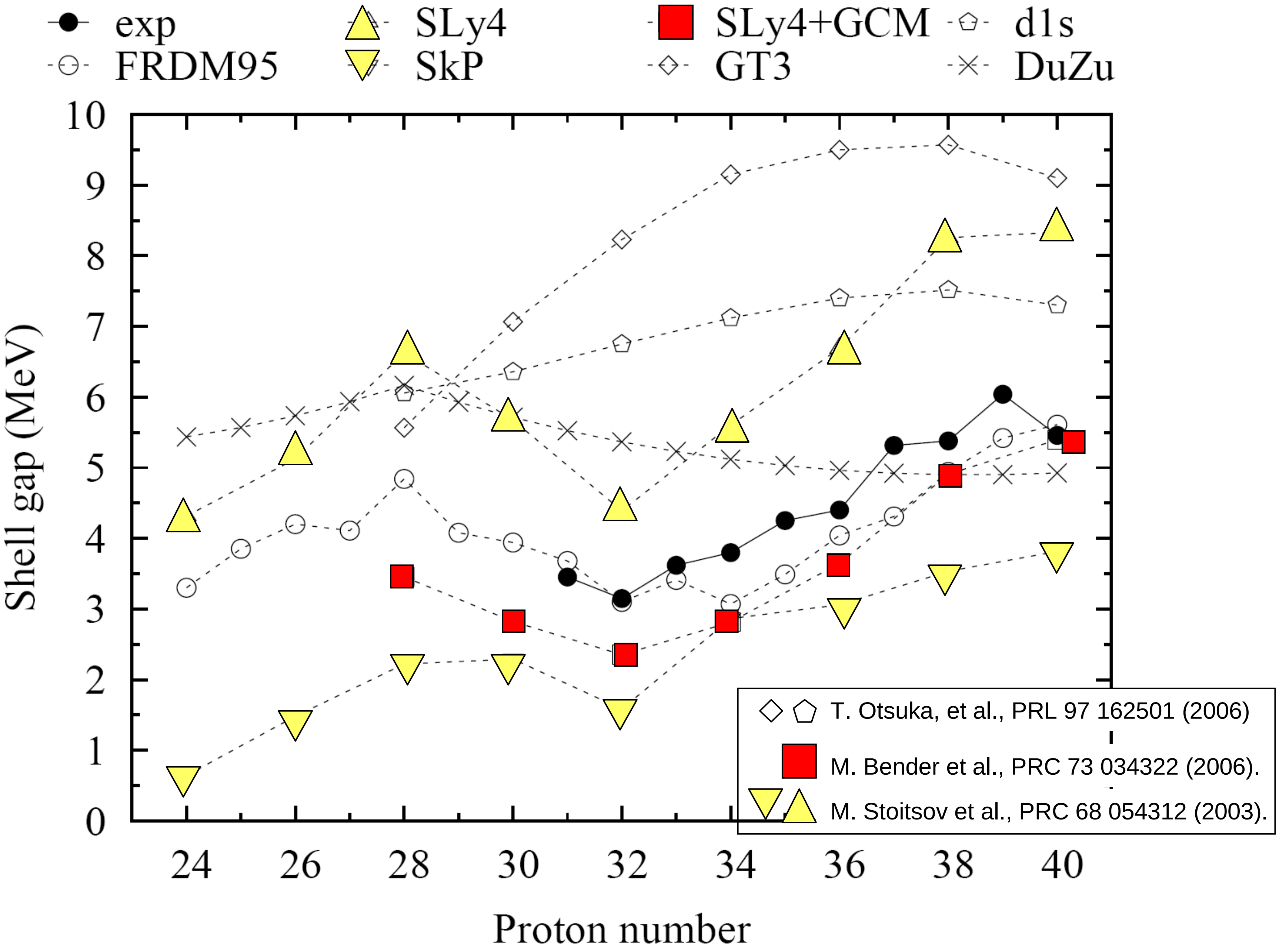
Experimental N=50 shell gap



Next critical masses:
^{82}Zn, ^{77,79,81}Cu, ^{76,78,80}Ni

RIBF and FAIR !

Density functional theories

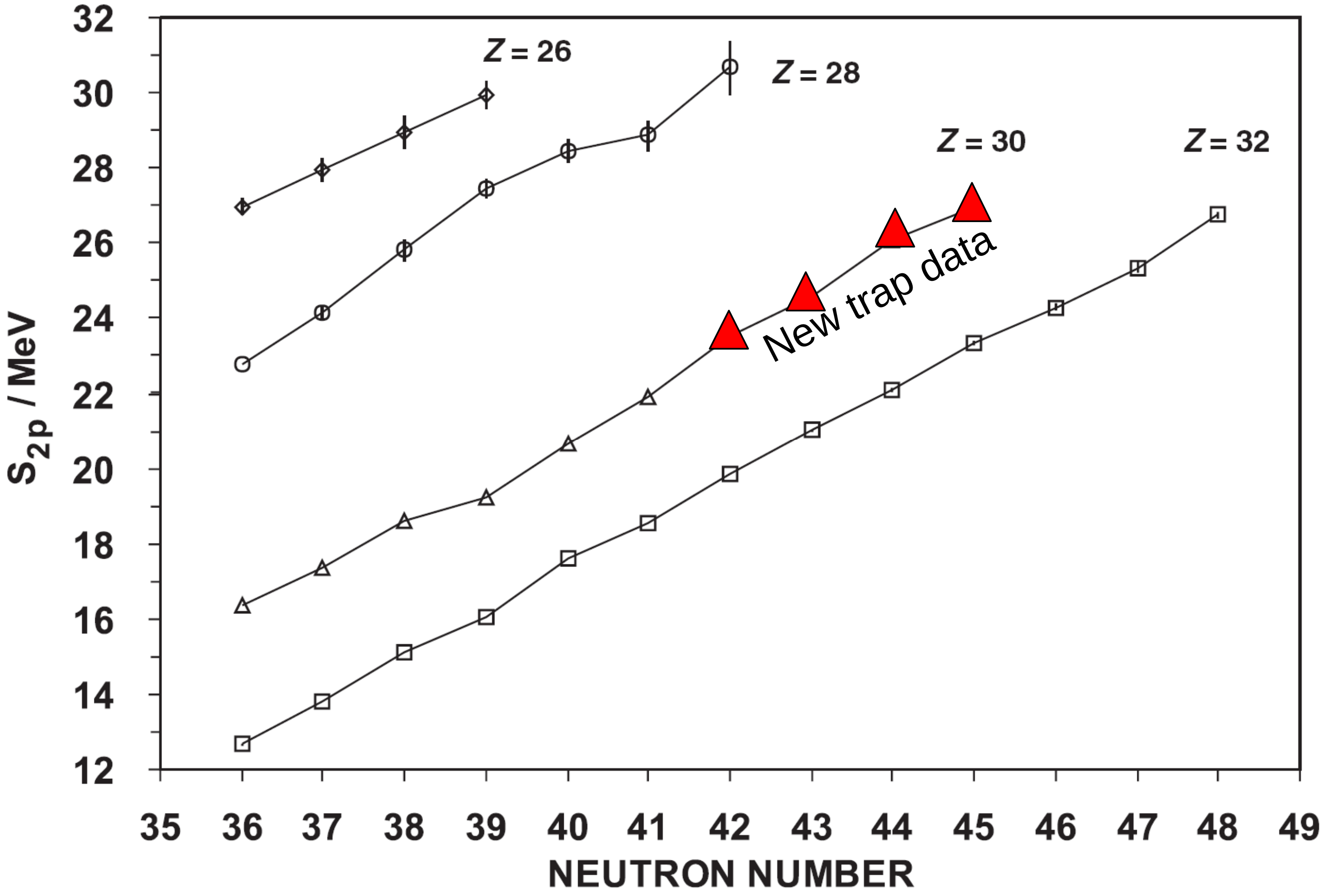


◇ ⬠ T. Otsuka, et al., PRL 97 162501 (2006)

🟥 M. Bender et al., PRC 73 034322 (2006).

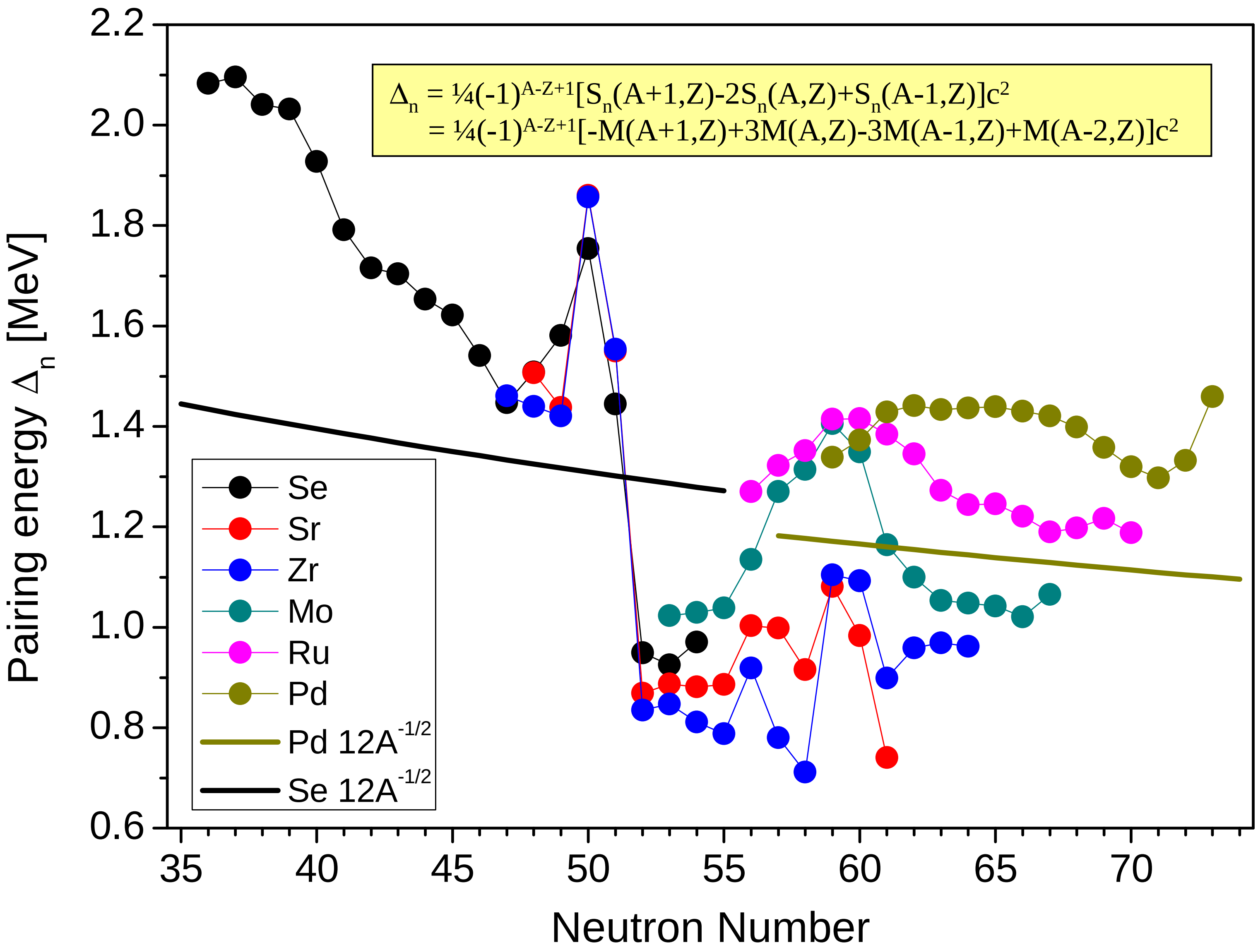
▽ △ M. Stoitsov et al., PRC 68 054312 (2003).

Experimental Z=28 shell gap



S. Rahaman et al., Eur. Phys. J. A 34 (2007) 5

Pairing energies



$$\Delta_n = \tfrac{1}{4}(-1)^{A-Z+1}[S_n(A+1,Z)-2S_n(A,Z)+S_n(A-1,Z)]c^2$$
$$= \tfrac{1}{4}(-1)^{A-Z+1}[-M(A+1,Z)+3M(A,Z)-3M(A-1,Z)+M(A-2,Z)]c^2$$

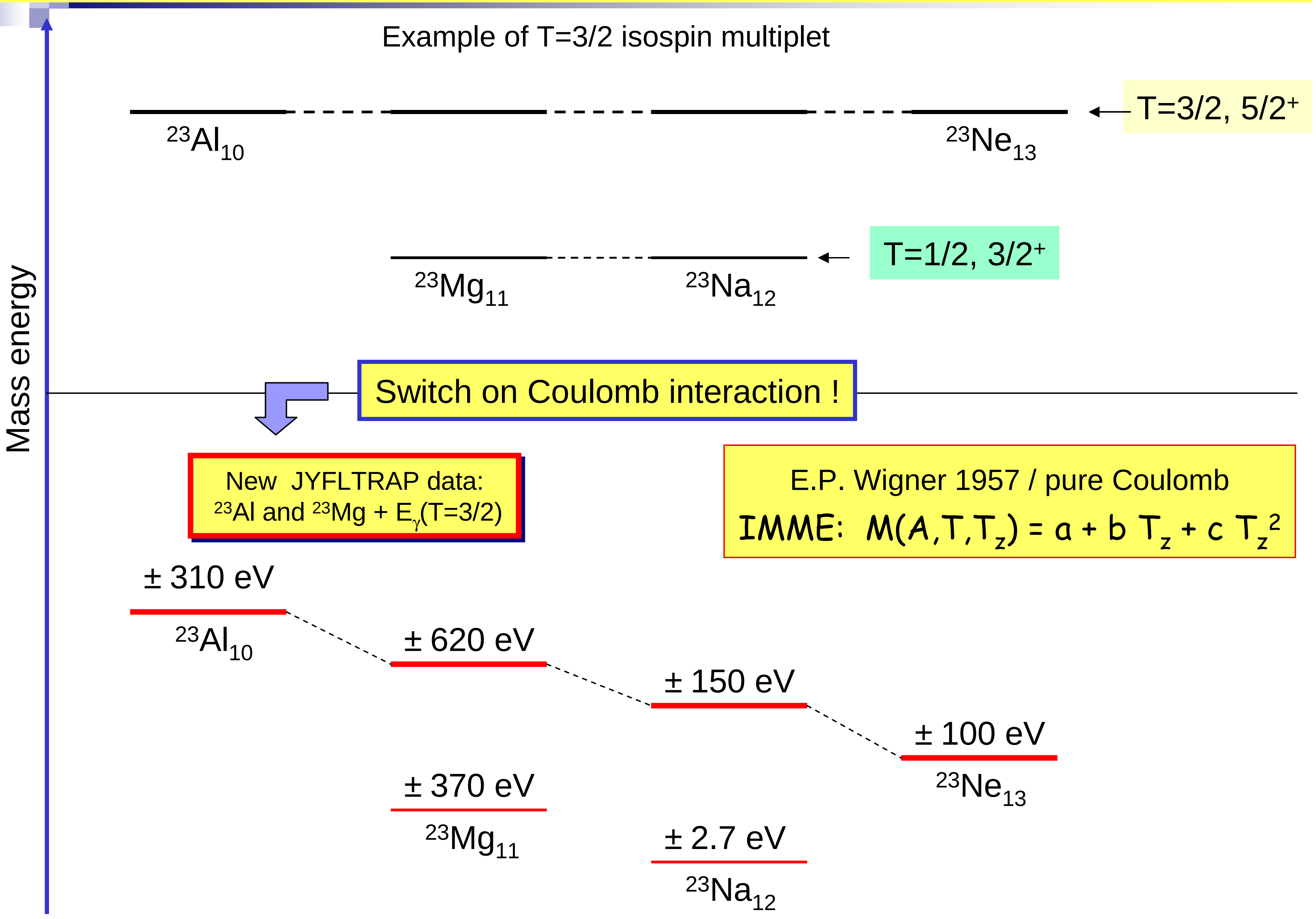
Charge symmetry effects in nuclear structure

Mirror nuclei and states

Isospin multiplets

Test of charge (in)dependence in nuclear interaction

Example of T=3/2 isospin multiplet



Mass energy

$^{23}Al_{10}$ $^{23}Ne_{13}$ ← T=3/2, $5/2^+$

$^{23}Mg_{11}$ $^{23}Na_{12}$ ← T=1/2, $3/2^+$

Switch on Coulomb interaction !

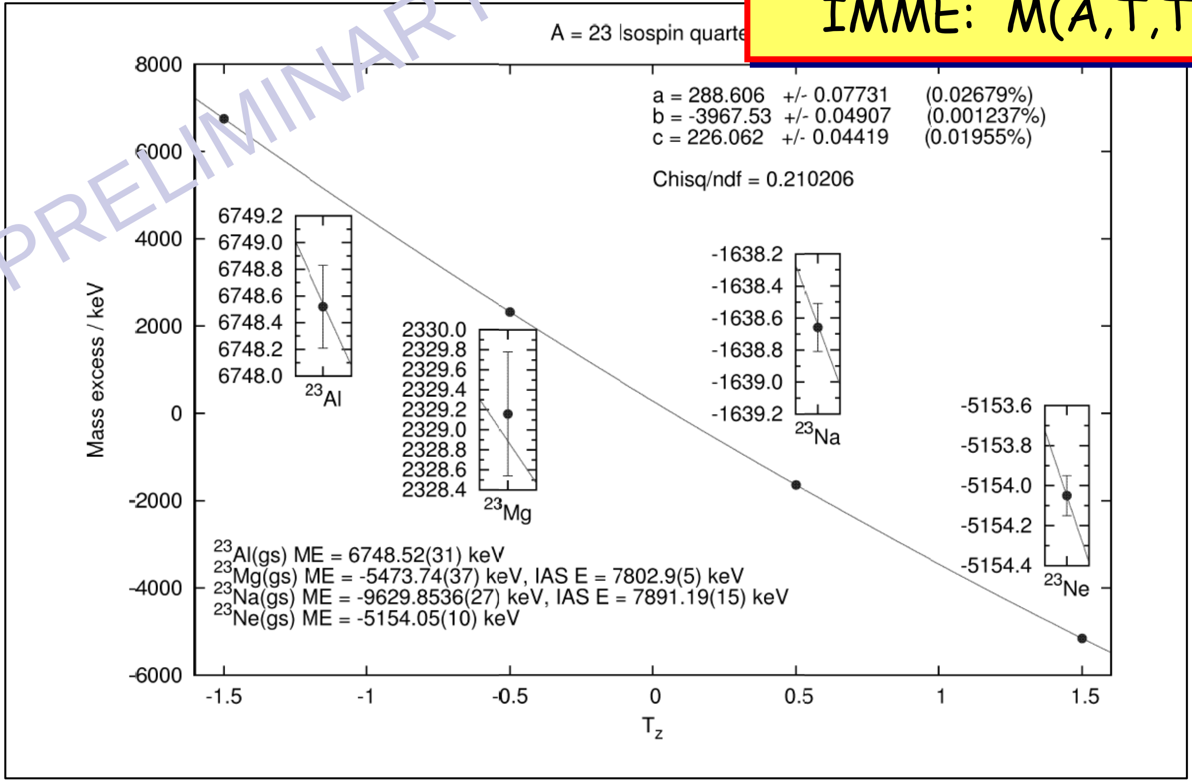
New JYFLTRAP data:
^{23}Al and ^{23}Mg + E_γ(T=3/2)

E.P. Wigner 1957 / pure Coulomb

IMME: $M(A,T,T_z) = a + b\,T_z + c\,T_z^2$

A=23 is the most accurately known isospin multiplet

IMME: $M(A,T,T_z) = a + b\,T_z + c\,T_z^2 + d\,T_z^3$



a = 288.606 +/- 0.07731 (0.02679%)
b = -3967.53 +/- 0.04907 (0.001237%)
c = 226.062 +/- 0.04419 (0.01955%)

Chisq/ndf = 0.210206

^{23}Al(gs) ME = 6748.52(31) keV
^{23}Mg(gs) ME = -5473.74(37) keV, IAS E = 7802.9(5) keV
^{23}Na(gs) ME = -9629.8536(27) keV, IAS E = 7891.19(15) keV
^{23}Ne(gs) ME = -5154.05(10) keV

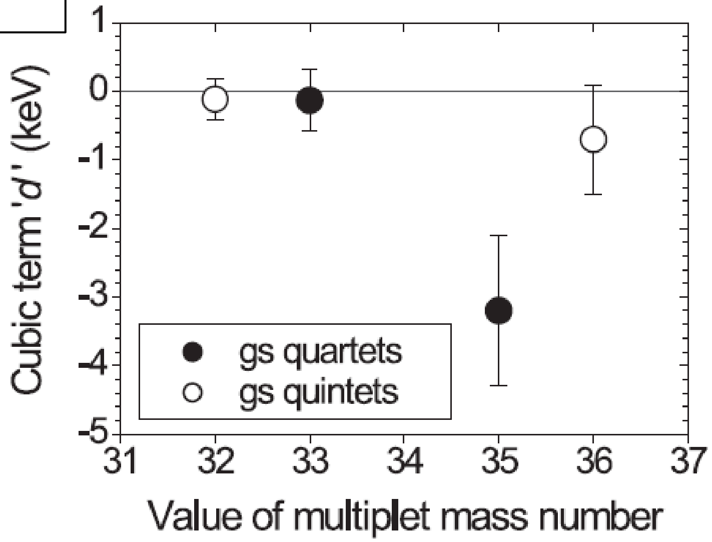
?

A= 23 quartet: d = 0.15 ± 32 keV

perfect quadratic fit !

ISOLTRAP
^{32}Ar,^{33}Ar,^{35}K,^{36}Ca

PHYSICAL REVIEW C **76**, 024308 (2007)

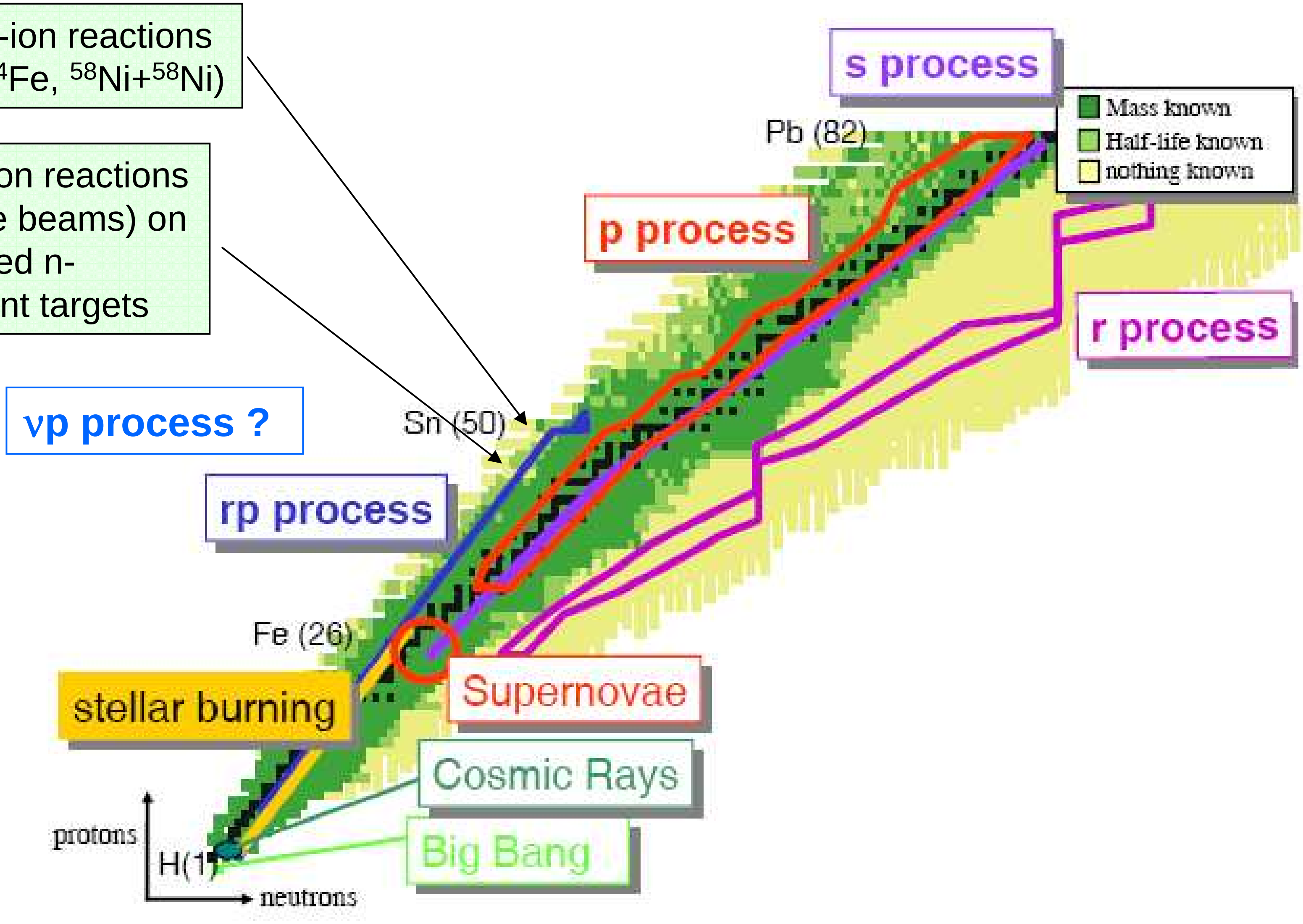


Mass measurements for nuclear astrophysics

Astrophysical processes

Heavy-ion reactions ($^{32}S+^{54}Fe$, $^{58}Ni+^{58}Ni$)

Light-ion reactions (p, ^{3}He beams) on enriched n-deficient targets



Rp-process path for steady-state burning,

H. Schatz et al., Phys. Rev.Lett. 86, 3471 (2001)

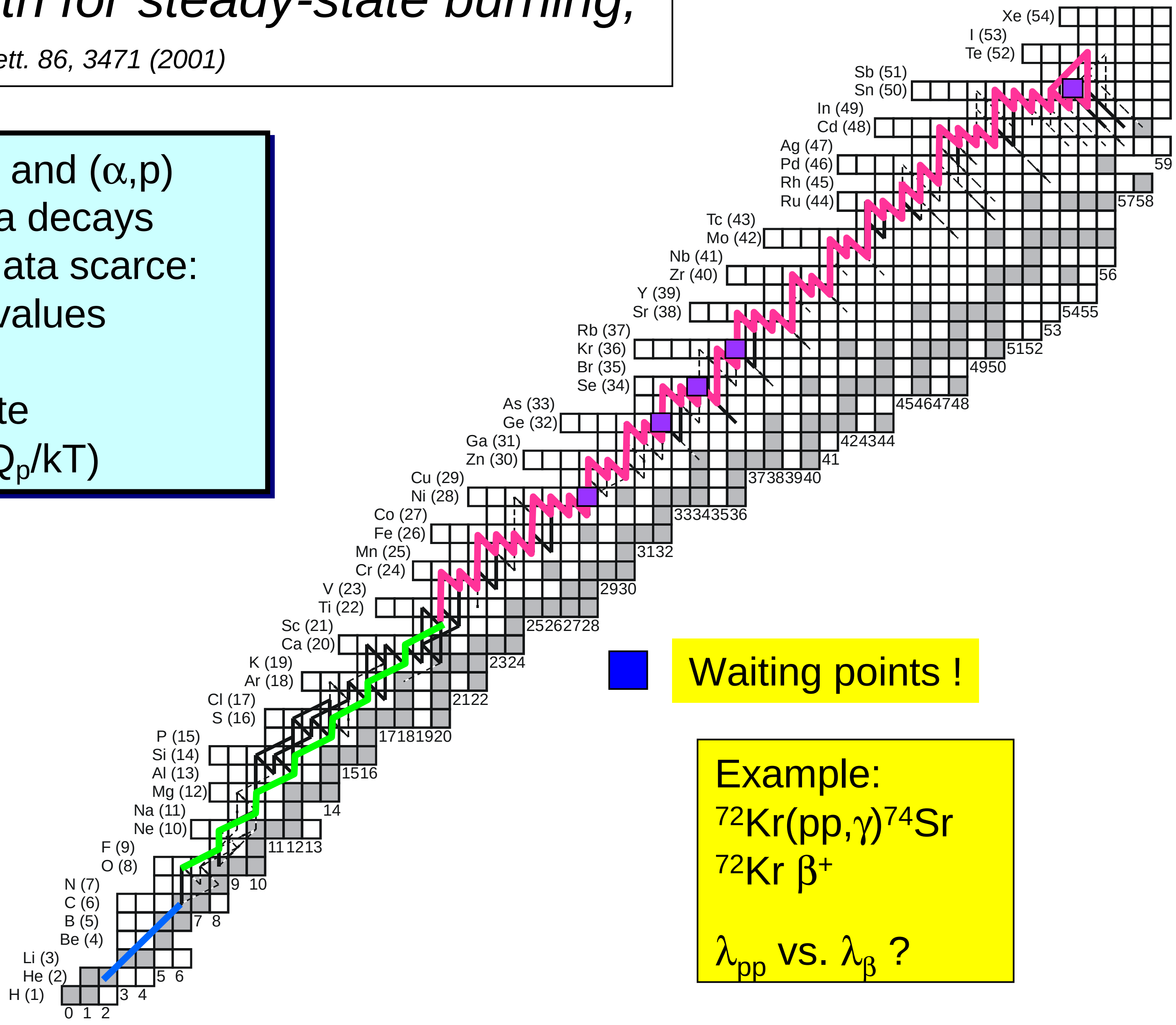
- Sequence of (p,γ) and (α,p) reactions and beta decays
- Nuclear physics data scarce:
- Q-values and S_p-values needed
- Proton capture rate

  $(p,\gamma) \propto \exp(-Q_p/kT)$

JYFLTRAP
SHIPTRAP
LEBIT
CPT

↓

100 new masses of rp-nuclei



■ Waiting points !

Example:
$^{72}Kr(pp,\gamma)^{74}Sr$
$^{72}Kr\ \beta^+$

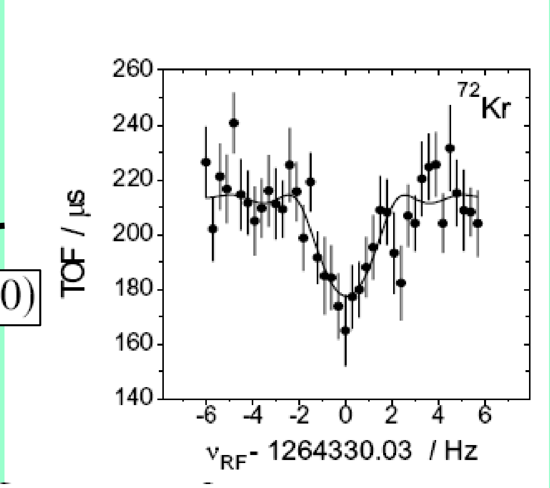
λ_{pp} vs. λ_β ?


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

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

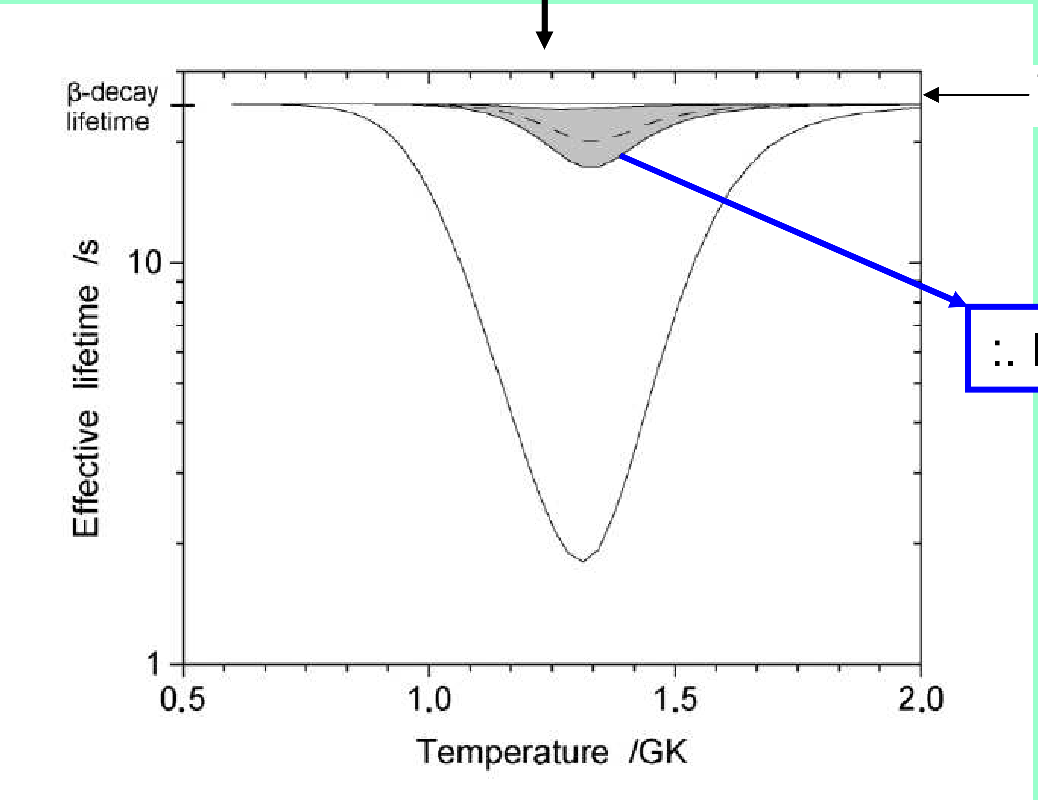
D. Rodríguez,[1,*] V. S. Kolhinen,[2] G. Audi,[3] J. Äystö,[2] D. Beck,[1] K. Blaum,[1,4] G. Bollen,[5] F. Herfurth,[1] A. Jokinen,[2]
A. Kellerbauer,[4] H.-J. Kluge,[1] M. Oinonen,[6] H. Schatz,[5,7] E. Sauvan,[4,†] and S. Schwarz[5]

ISOLTRAP



$-53940.6(8.0)$

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



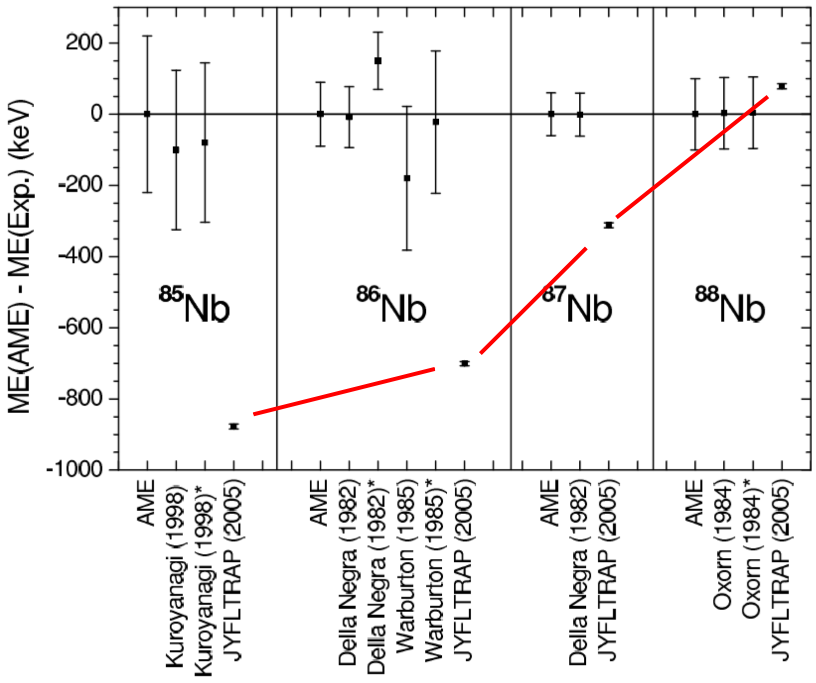
^{72}Kr ($T_{1/2}$ = 17.2 s

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

^{72}Kr strong waiting point

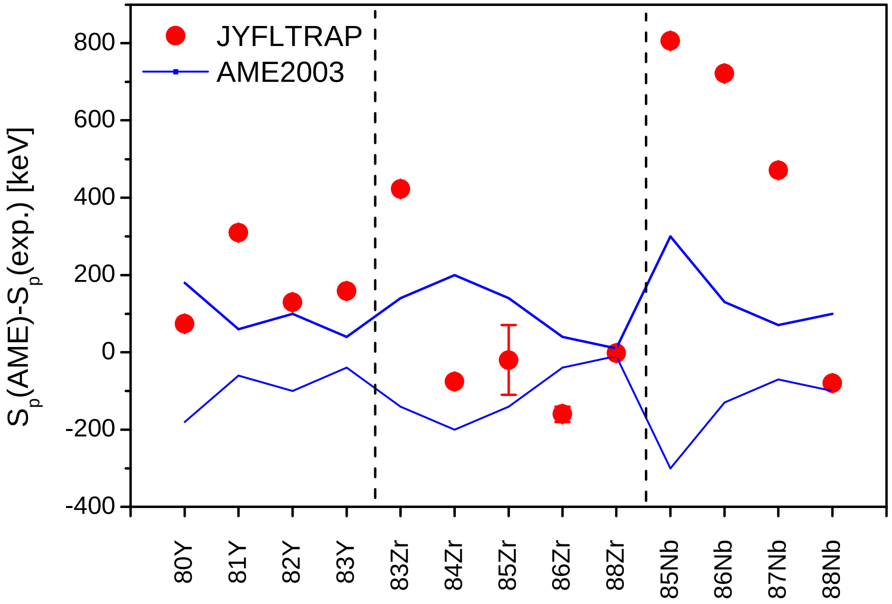
- ✓ ^{32}S beam impinging on ^{54}Fe or ^{nat}Ni target
- ✓ 12 Q_{EC} and S_p values were improved ($^{80-83}$Y, $^{83-86,88}$Zr and $^{85-88}$Nb)
- ✓ Mass of ^{84}Zr for the first time as well S_p-energies of ^{84}Zr and ^{85}Nb.

Mass excesses of Nb-isotopes



Large deviations compared to compiled values [AME2003], which are based on the beta-endpoint measurements.

Proton separation energies

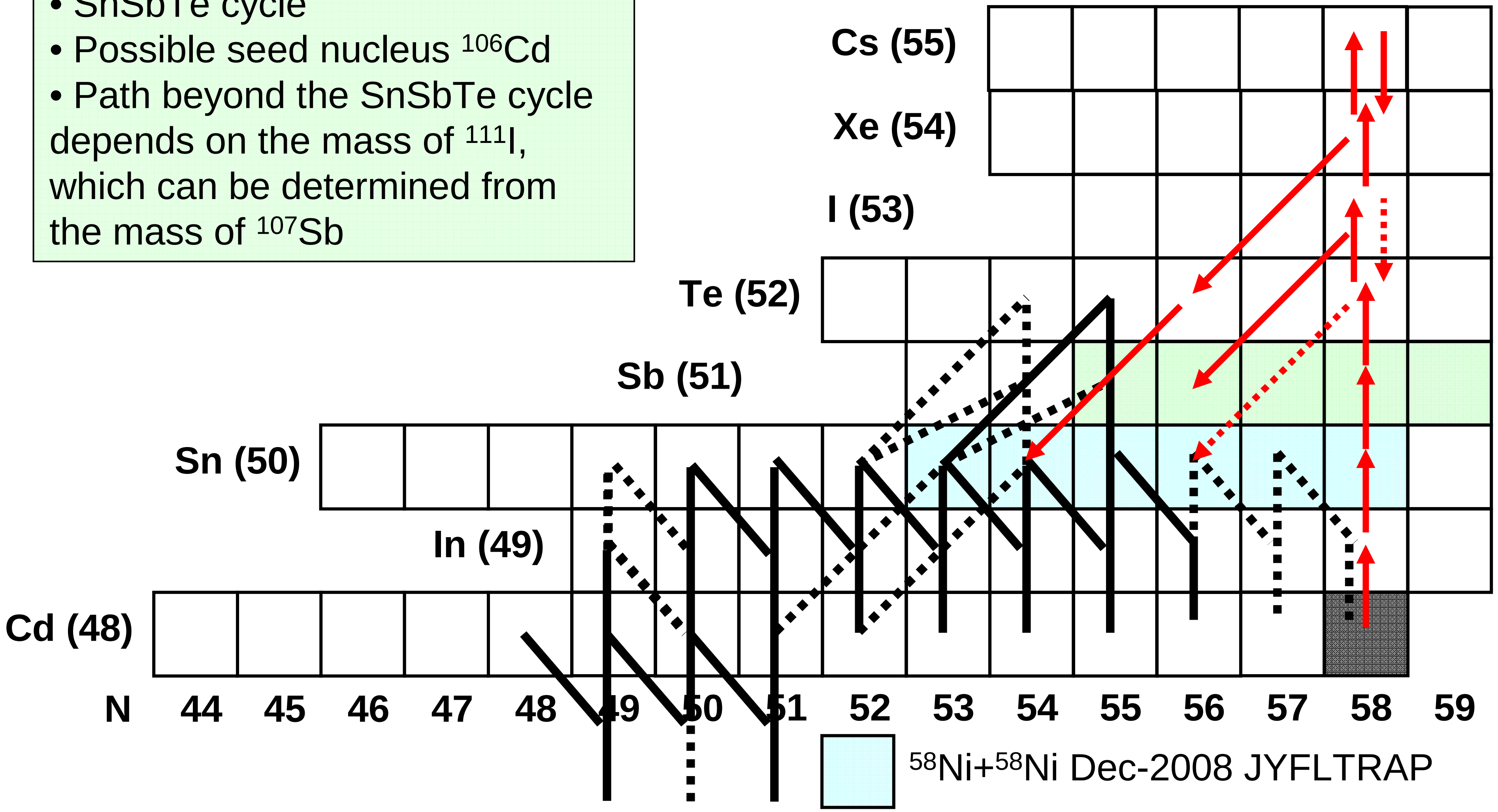


- ✓ Large discrepancies for for Nb-isotopes
- ✓ Need to revise S_p-values, and thus the location of the rp-process path

A. Kankainen, EPJA 29 (2006) 271

Endpoint of the rp-process

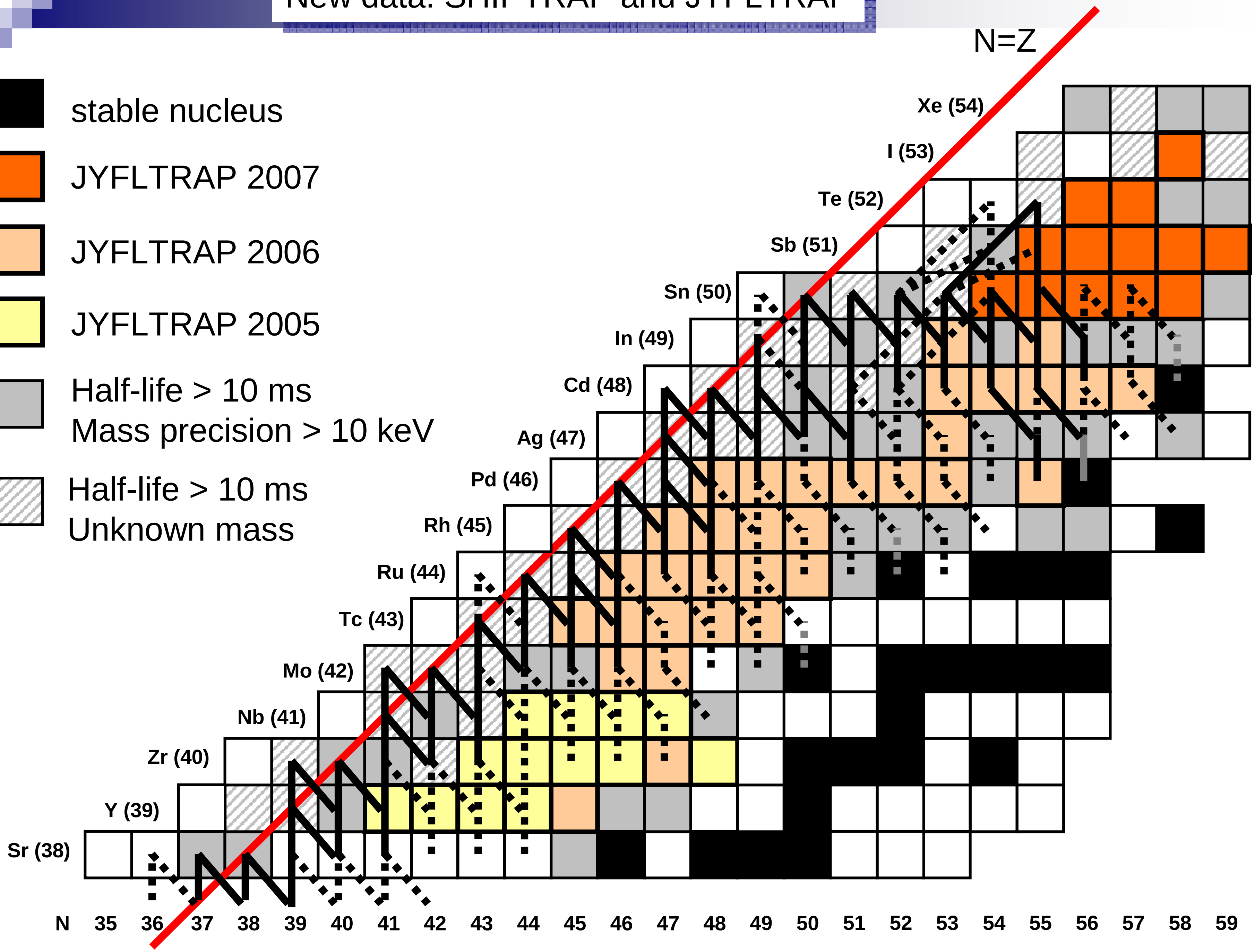
- SnSbTe cycle
- Possible seed nucleus ^{106}Cd
- Path beyond the SnSbTe cycle depends on the mass of ^{111}I, which can be determined from the mass of ^{107}Sb



🟦 ^{58}Ni+^{58}Ni Dec-2008 JYFLTRAP

New data: SHIPTRAP and JYFLTRAP

- ■ stable nucleus
- 🟧 JYFLTRAP 2007
- 🟧 JYFLTRAP 2006
- 🟨 JYFLTRAP 2005
- ⬜ Half-life > 10 ms
  Mass precision > 10 keV
- ▨ Half-life > 10 ms
  Unknown mass

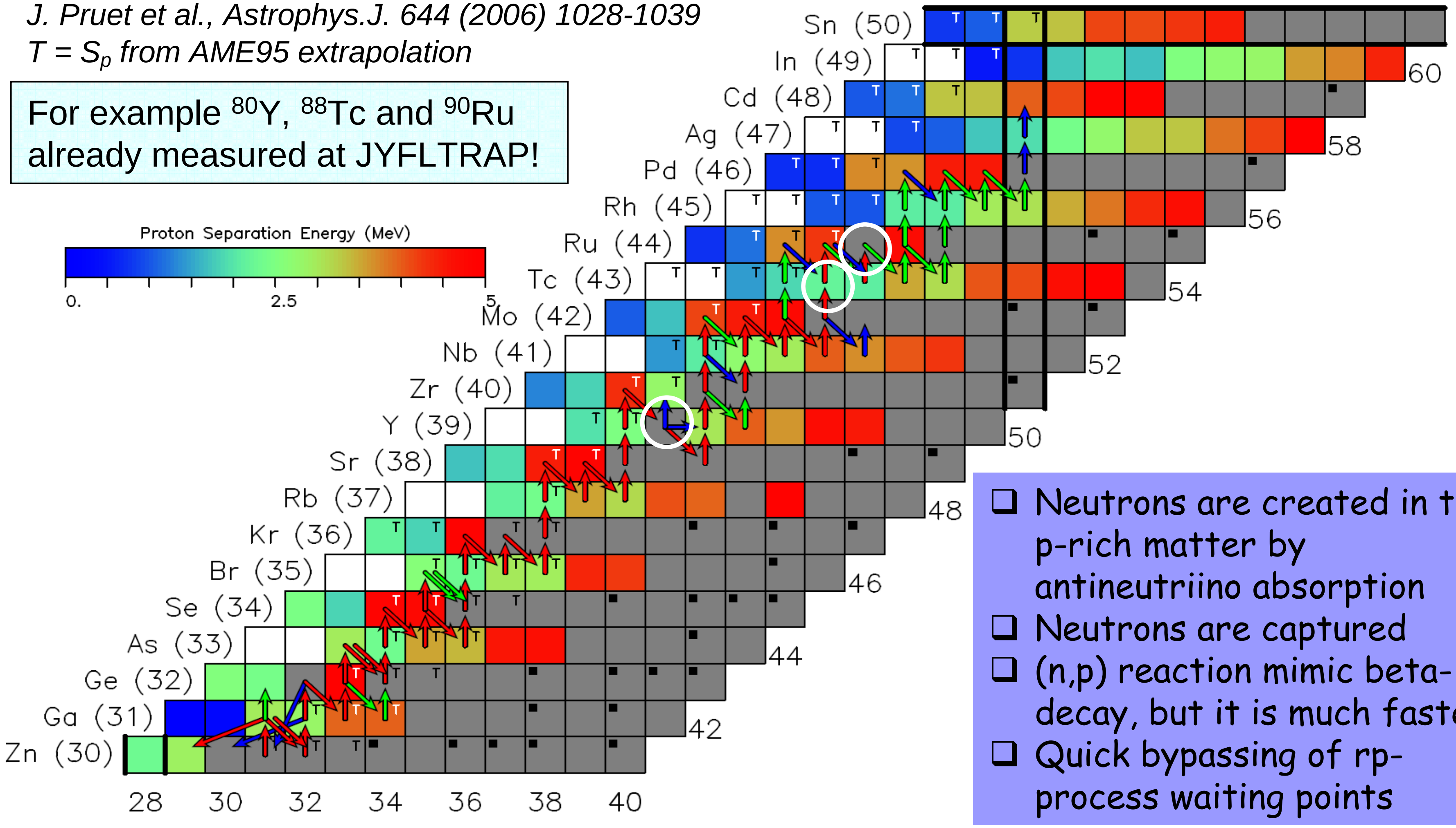


νp-process path

Newly proposed nucleosynthesis process for neutron-deficient nuclei with A>64
C. Fröhlich et al., Phys. Rev. Lett. 96, 142502 (2006)

J. Pruet et al., Astrophys.J. 644 (2006) 1028-1039
T = S_p from AME95 extrapolation

For example ^{80}Y, ^{88}Tc and ^{90}Ru already measured at JYFLTRAP!

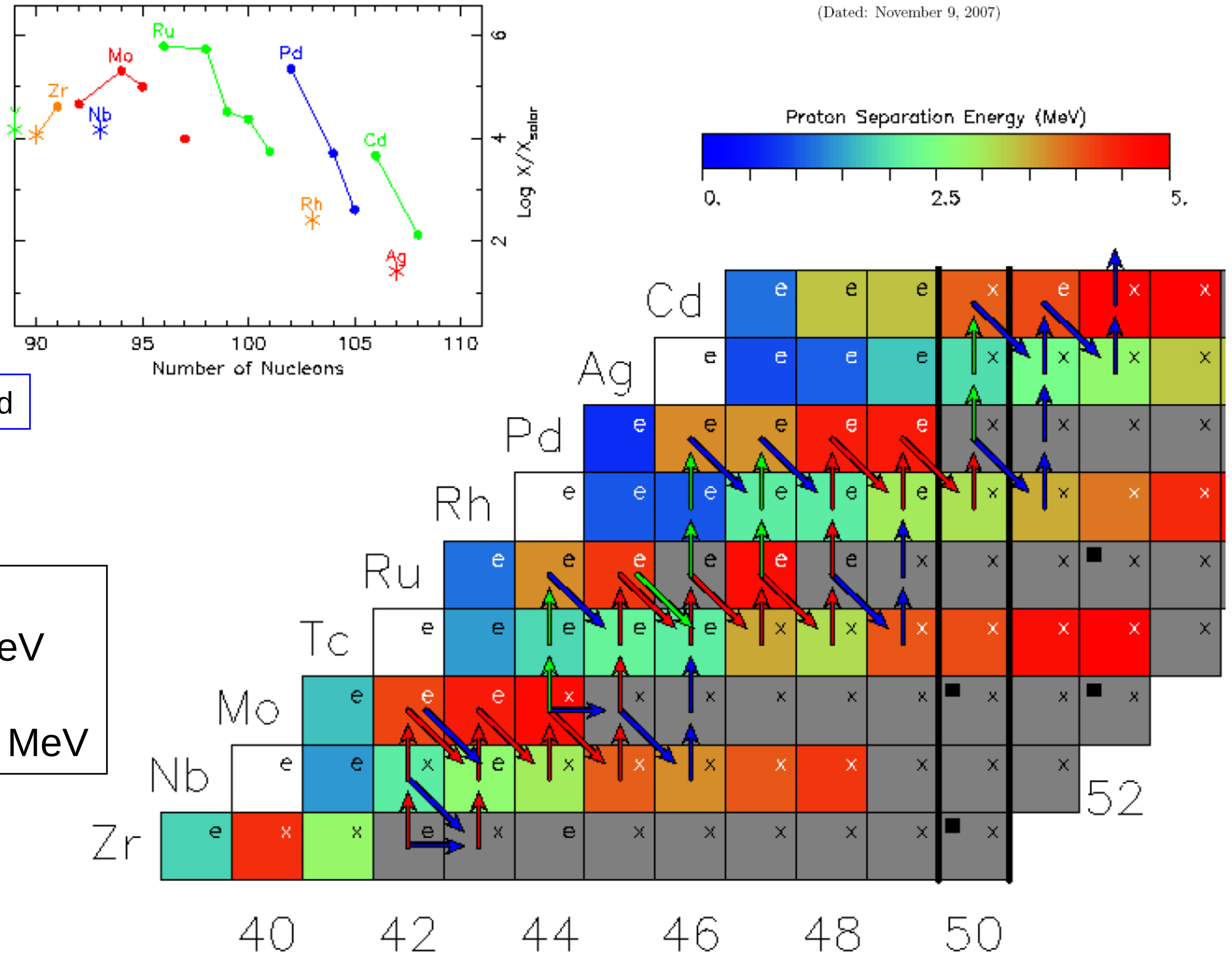


- Neutrons are created in the p-rich matter by antineutriino absorption
- Neutrons are captured
- (n,p) reaction mimic beta-decay, but it is much faster
- Quick bypassing of rp-process waiting points

Predicting the proton separation energy of ^{93}Rh from supernova nucleosynthesis

J. L. Fisker, R. D. Hoffman, J. Pruet
Lawrence Livermore National Laboratory,
7000 East Avenue, Livermore, CA 94550

(Dated: November 9, 2007)

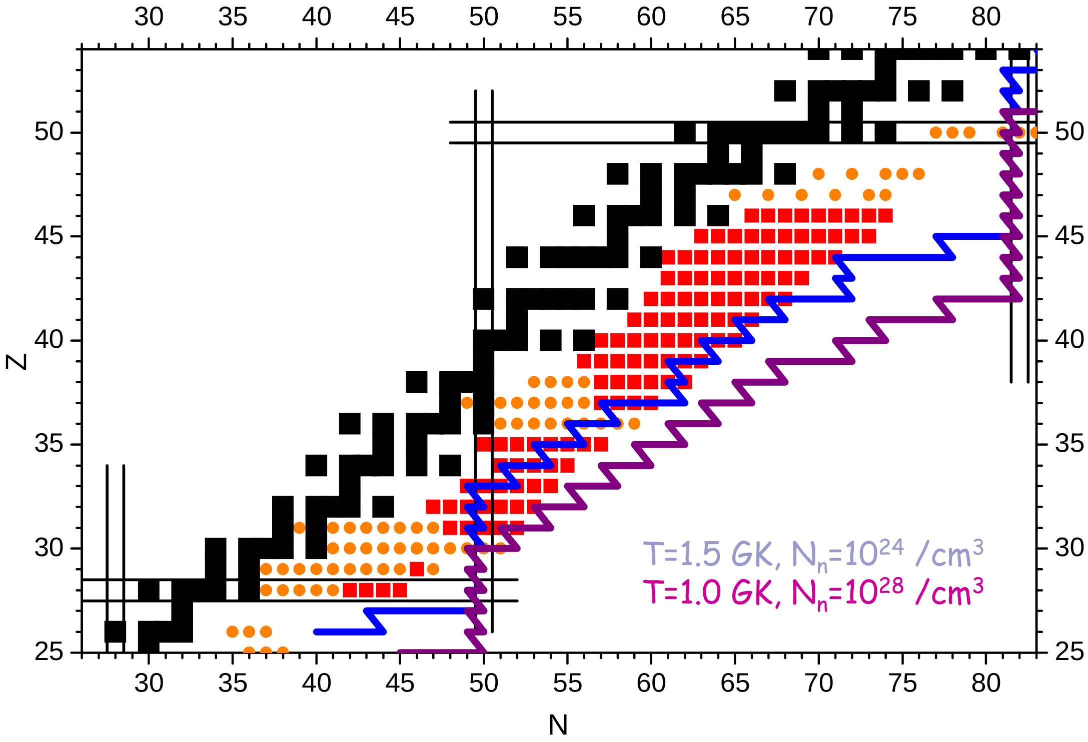


$^{92}\mathrm{Ru}(p,\gamma)^{93}\mathrm{Rh}(p,\gamma)^{94}\mathrm{Pd}$

^{92}Mo ^{94}Mo

Prediction:
S_p = 1.64±0.1 MeV
JYFLTRAP:
S_p=2.001±0.007 MeV

Atomic mass measurements of n-rich radioisotopes



Much more to come !!!

Astrophysics motivation:
Location of r-process path, which in the 1st approximation proceeds along the path where the neutron-capture and photodisintegration are in balance.

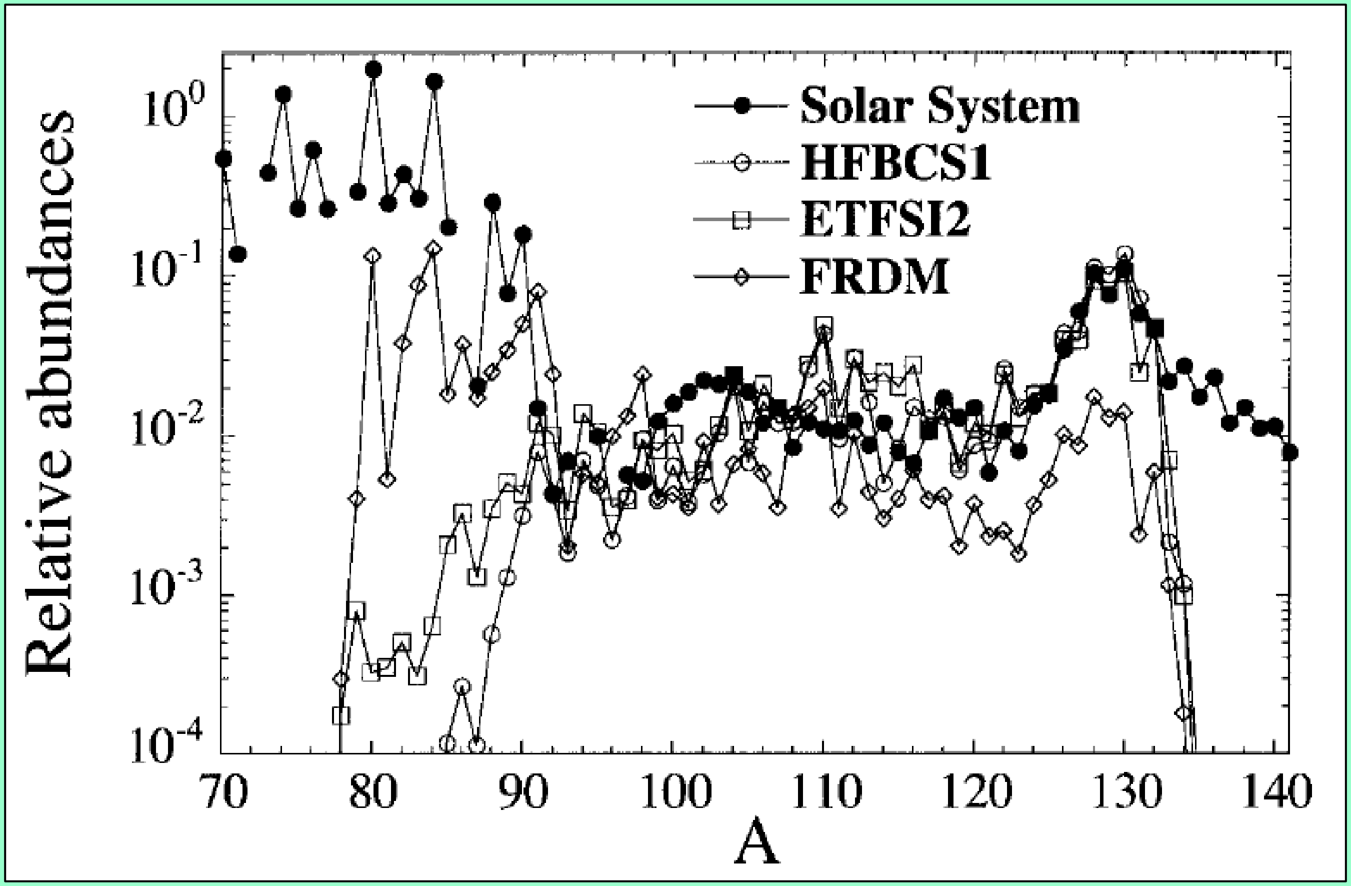
$$\lambda_{\gamma n} \propto \frac{T^{3/2}}{N_n} e^{\left(\frac{S_n}{k_B T}\right)} \lambda_{n\gamma}$$

S_n=2-4 MeV

Mass predictions and r-process abundances

R-process abundances calculated with the HFBCS-1, ETFSI-2 and FRDM mass models in the framework of the canonical model.

The r-process is characterized by $N_n = 10^{21}$ cm^{-3}, $T = 1.2 \times 10^9$ K and $\tau = 2.1$ s.



S.Goriely, Hyperfine interactions 132 (2001) 105