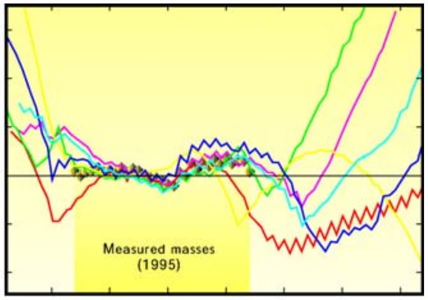
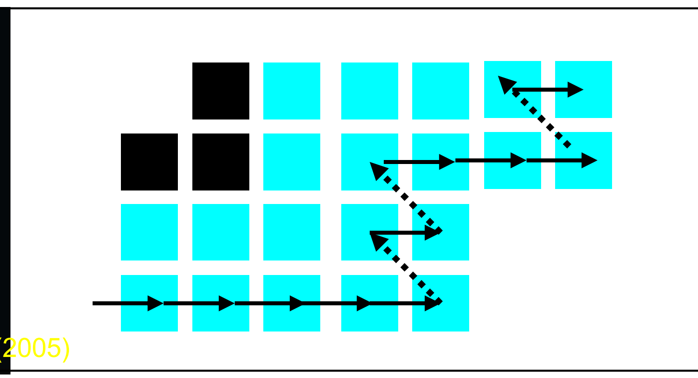
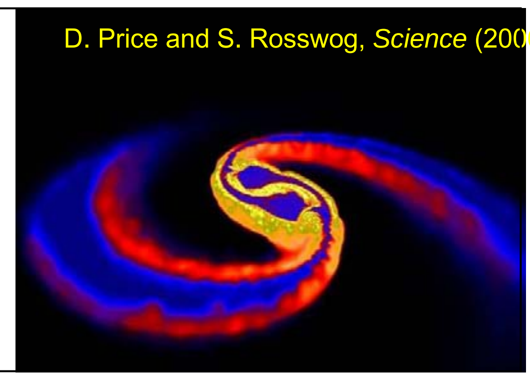


The uroboros of mass measurements and mass models

David Lunney – CSNSM (IN2P3/CNRS) – Université de Paris Sud, Orsay

Woosley & Janka, *Nature Phys.* (2005)





D. Price and S. Rosswog, *Science* (2006)

23-26 April 2013 Heraeus-Seminar:
Nuclear Masses and
(r-process) nucleosynthesis

outline

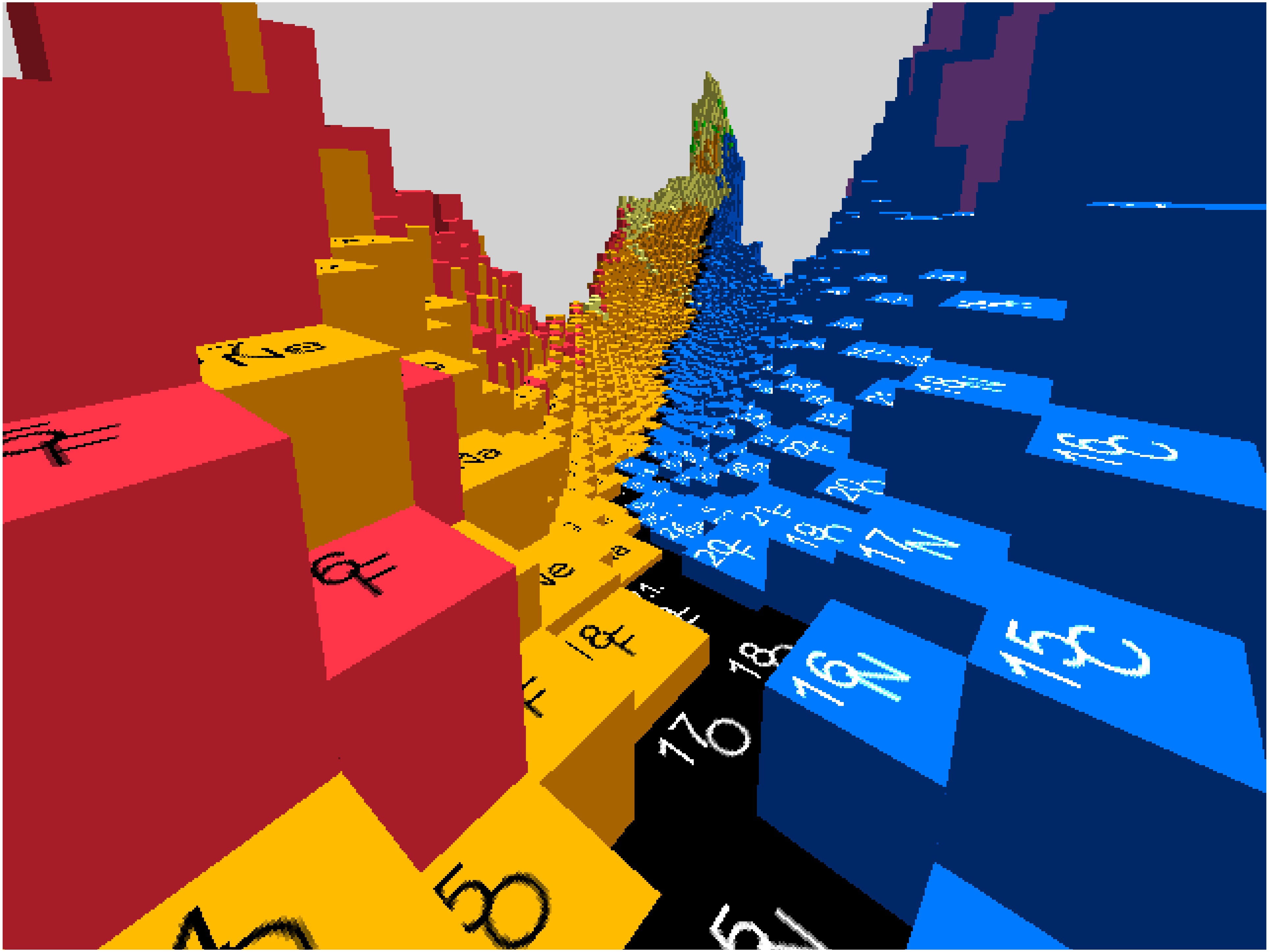
- Quick review of experimental methods
- Some global comparisons and observations
- Mass table (AME2012) and its “DNA”
- Quick review of mass models (classification)
- Some global comparisons and observations
- Conclusions (specific discussion points)

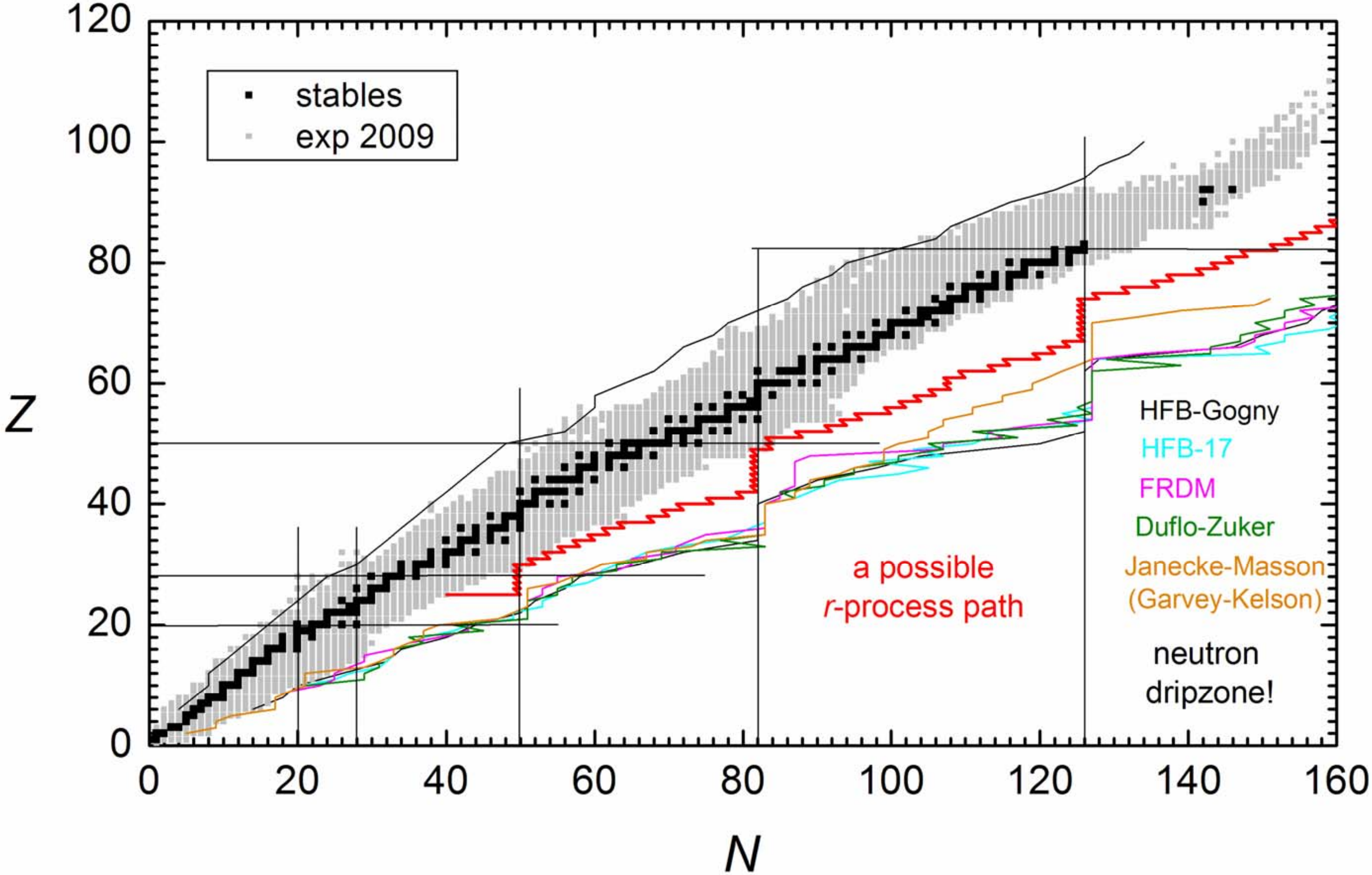
Early alchemical uroboros illustration;
From the work of Cleopatra the
Alchemist (Greco-Roman Egypt).

Drawing by Theodoros Pelecanos;
alchemical tract *Synosius* (1478).

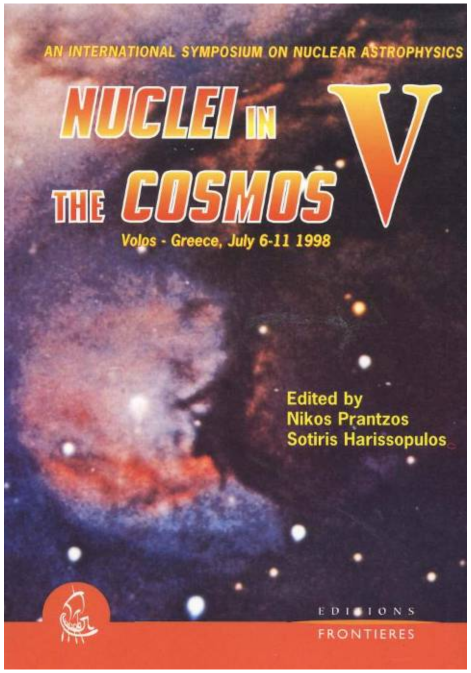
The Alchymist,
In Search of the Philosophers' Stone;
Joseph Wright of Derby, 1771
Source: Wikipedia

The Alchemist, ...and mass spectrometrist!
by Thomas Wijck


16N
15C
17O
17N
18F

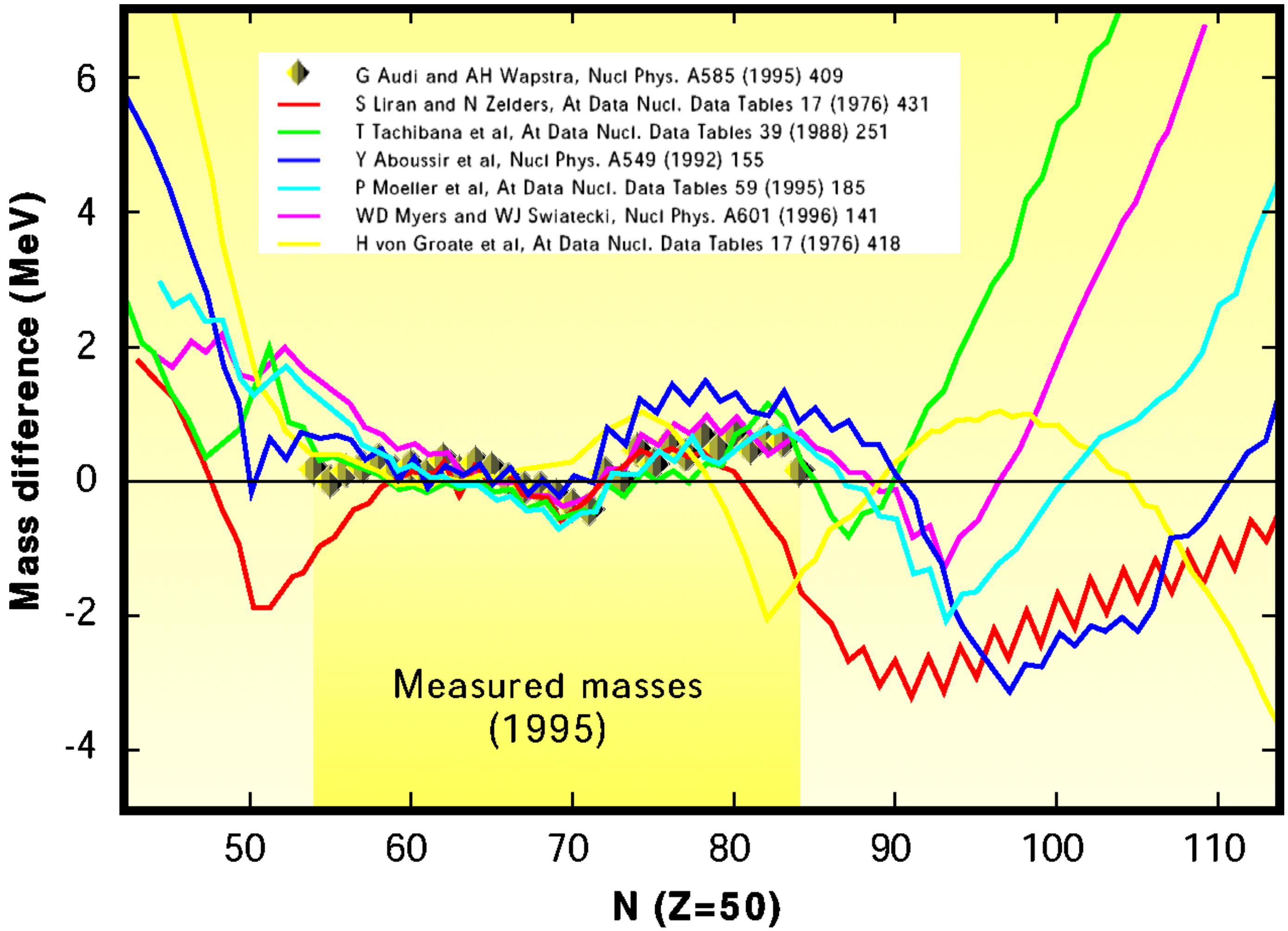


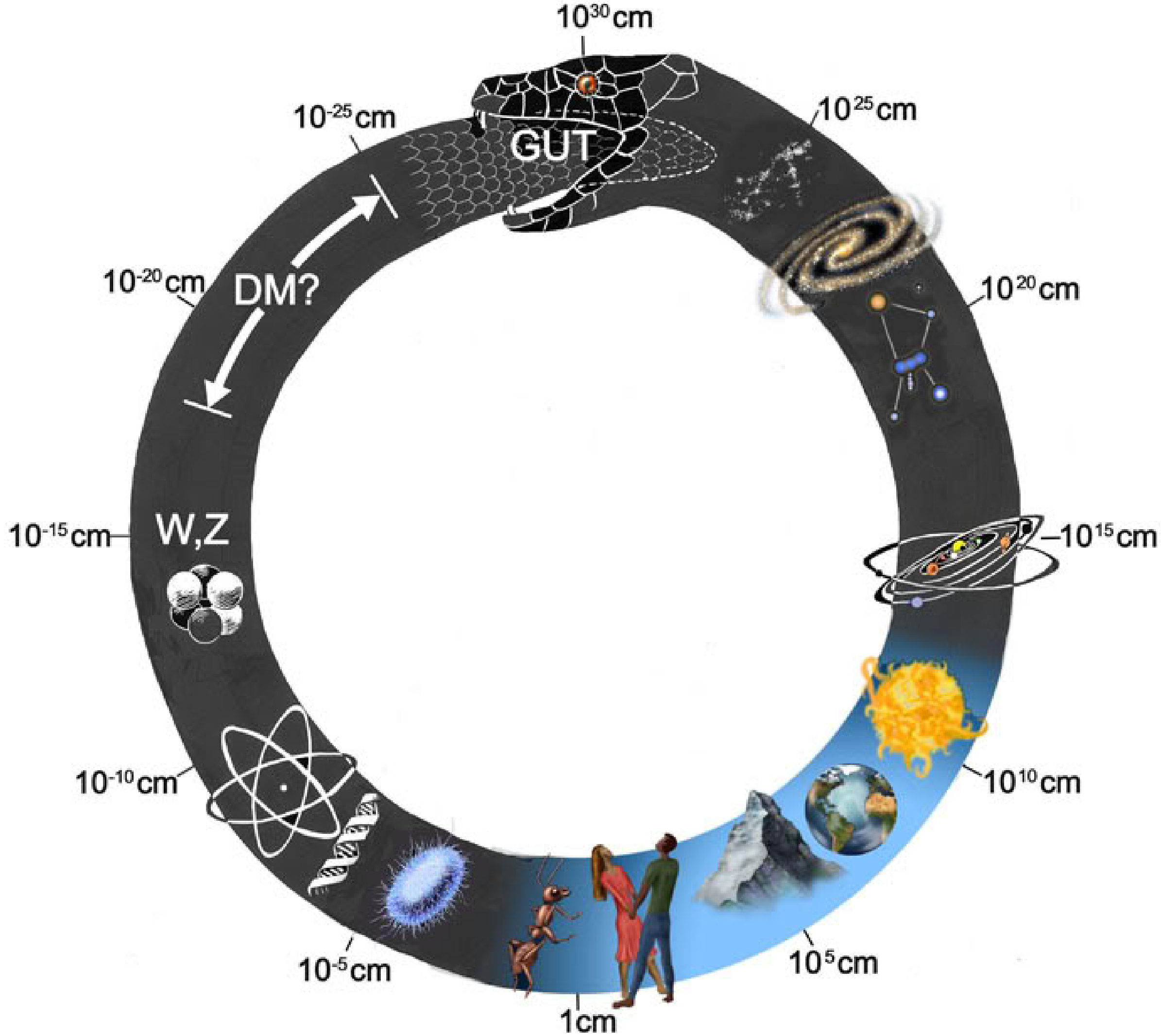
stables
exp 2009
HFB-Gogny
HFB-17
FRDM
Duflo-Zuker
Janecke-Masson
(Garvey-Kelson)
neutron
dripzone!
a possible
r-process path
Z
N
0
20
40
60
80
100
120
140
160



15 years ago

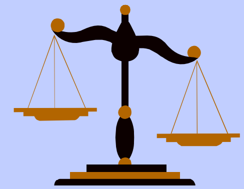
From: D. Lunney, “Nuclear masses:
Experimental programs, theoretical models and astrophysical interest,” p. 296





The Cosmic Uroboros

Techniques



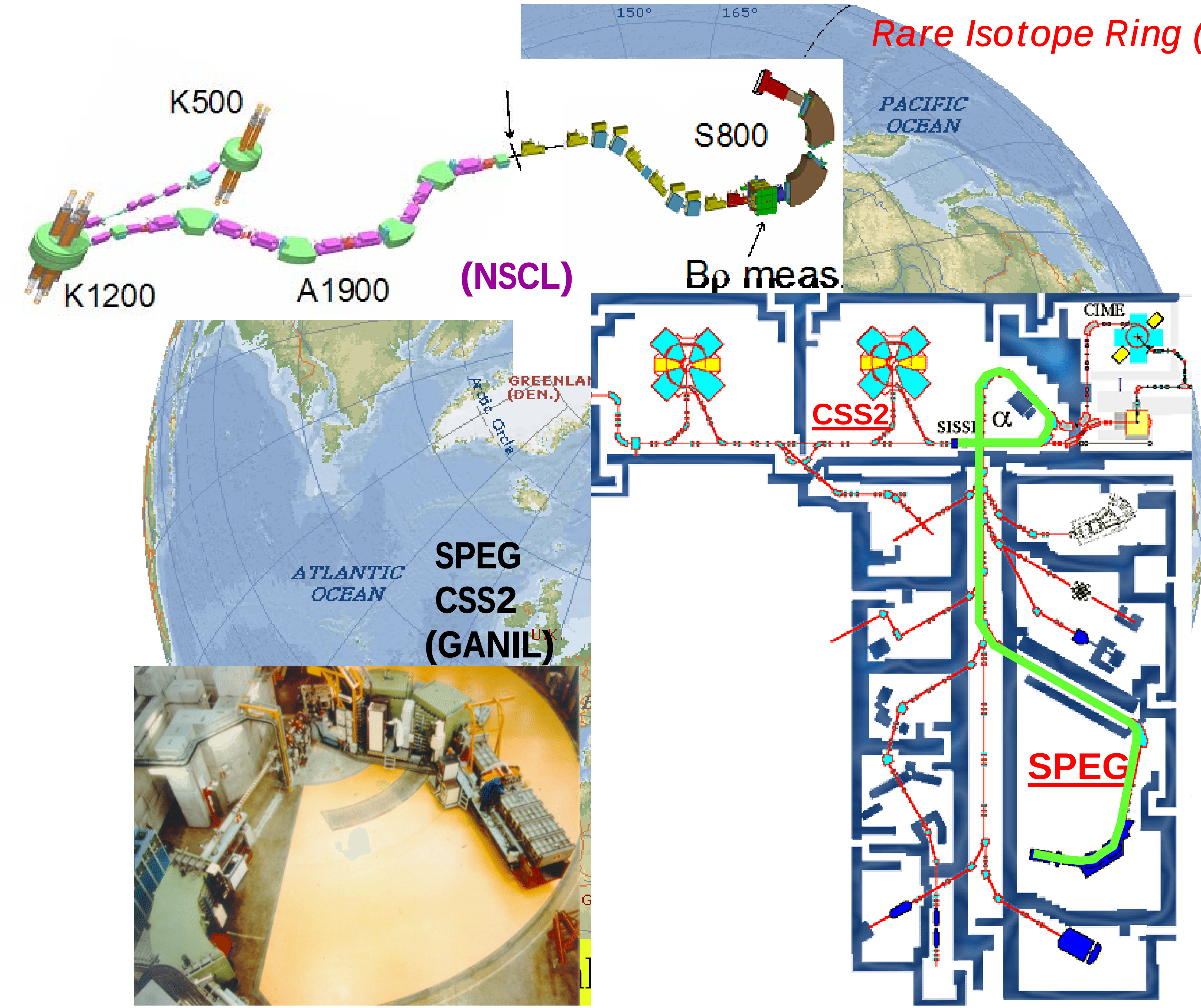
Indirect	*Direct* (*mass spectrometry*)	*PRODUCTION SCHEME*
reactions:	time of flight:	FIFS (MeV)
$A(a,b)B$	*SPEG/CSS2 - GANIL*	gas cell RFQ
$Q = M_A + M_a - M_b - M_B$	*NSCL, ESR - GSI*	ISOL (keV)
decays:	cyclotron frequency:	
$A \rightarrow B + \alpha$	*Penning-trap*	
$Q_\alpha = M_B - M_A$	*Mass spectrometry*	
	ISOLTRAP and…	

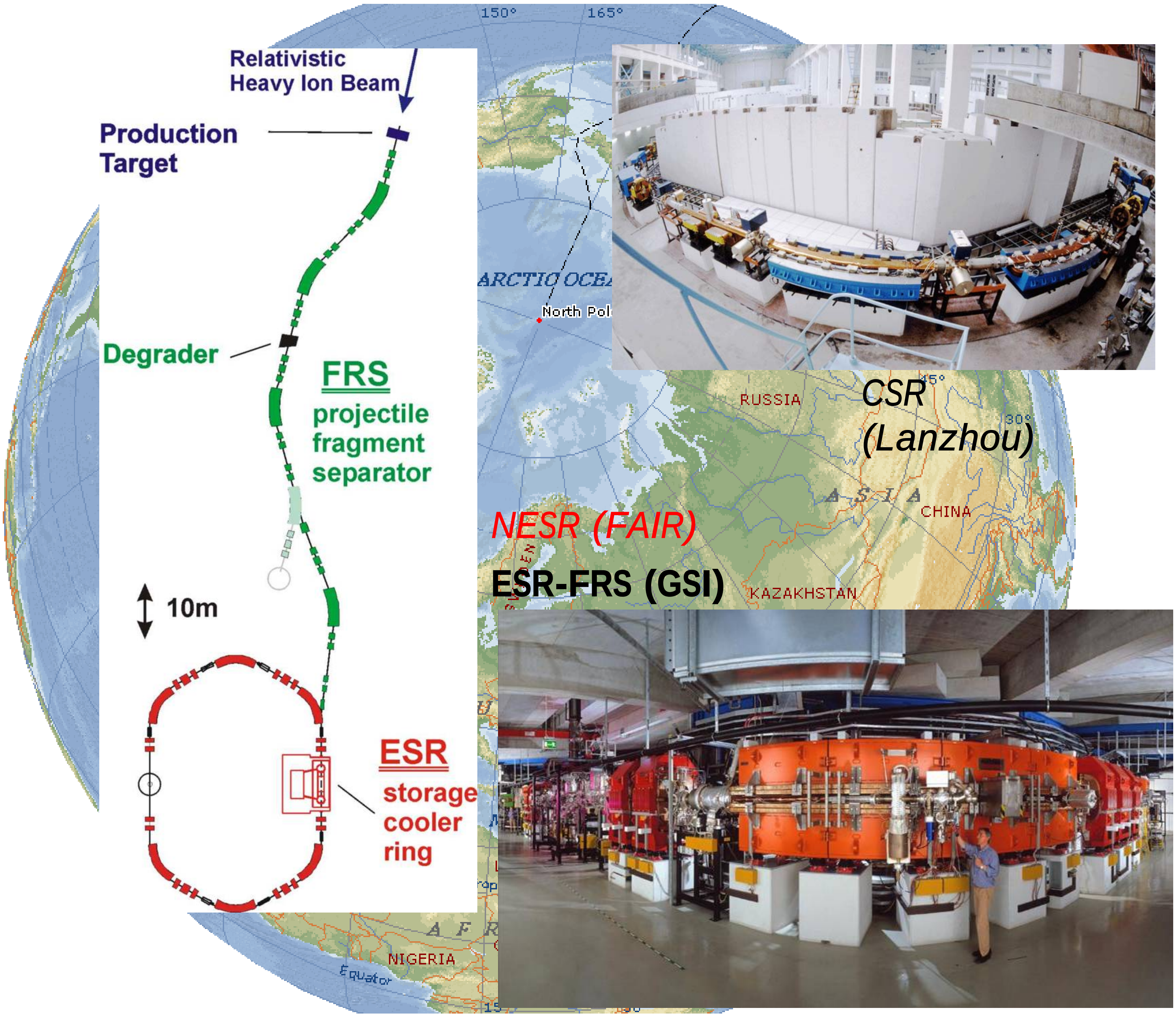
better sensitivity ↑

better precision ↓

Increasing primary beam also increases contamination
→ very fast reflection-type mass separators (R. Wolf)

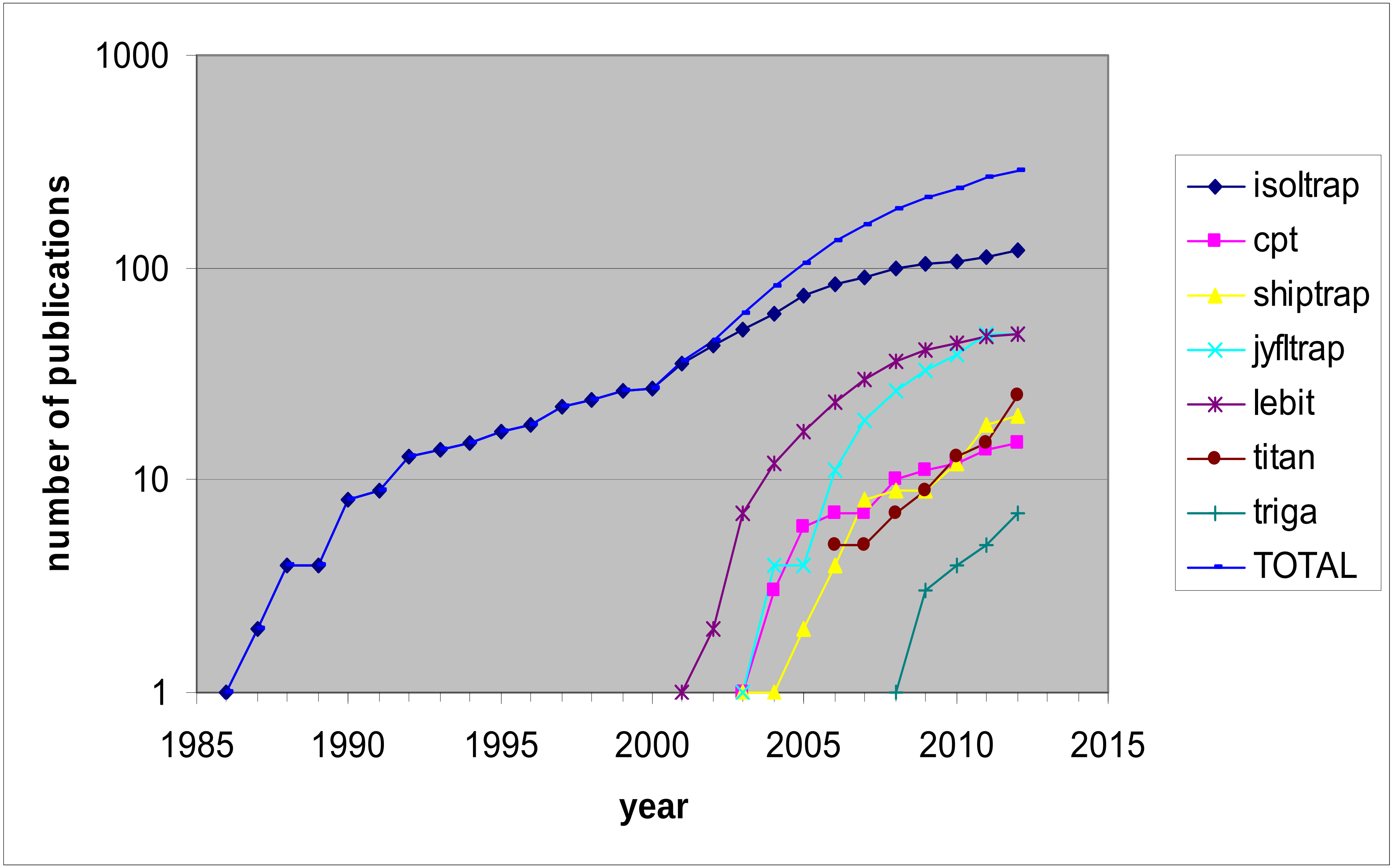
Rare Isotope Ring (RIKEN)




Relativistic
Heavy Ion Beam
Production
Target
Degrader
FRS
projectile
fragment
separator
10m
ESR
storage
cooler
ring
NESR (FAIR)
ESR-FRS (GSI)
CSR
(Lanzhou)
ARCTIC OCEA
North Pol
RUSSIA
A S I A
CHINA
KAZAKHSTAN
NIGERIA
Equator
150°
165°


TITAN (TRIUMF)
LEBIT (NSCL)
CPT (ANL)
NORTH AMERICA
Gas cell
RFQ 1, segmented
RFQ 2
Acceleration optics
From A1900
To buncher
Degrader
Entrance window
Supersonic gas jet
Nozzle
Skimmer
Orifice
JYFLTRAP (IGIS
ISOLTRAP (CERN)
SHIPTRAP (GSI)
MLLTRAP (SPIRAL2)
TRIGATRAP
INDIA
IRAN
SHIPTRAP

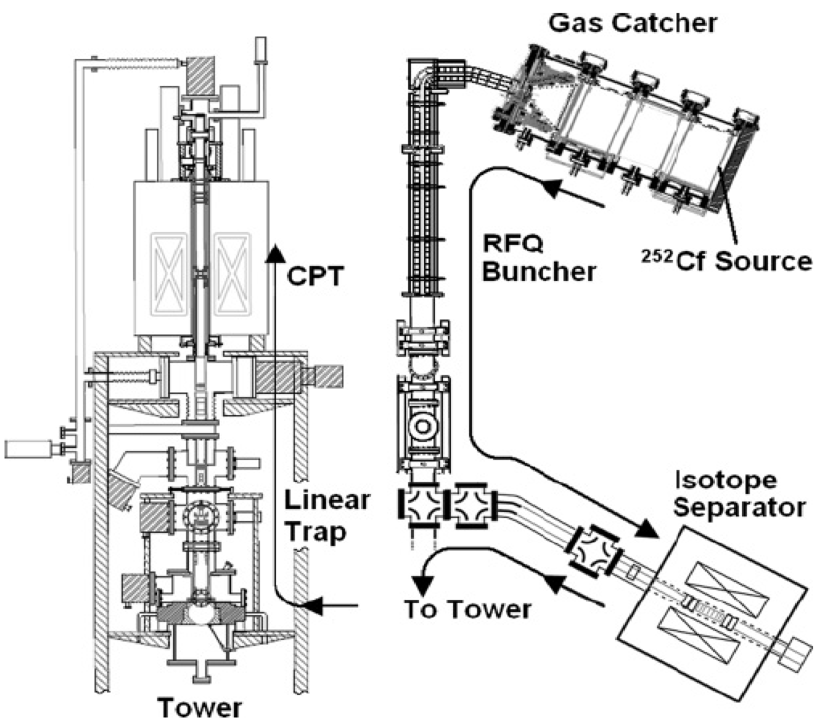
TITAN (TRIUMF)
LEBIT (NSCL)
Bρ-tof (NSCL)
CPT (ANL)
RIR@RIKEN
CSR (HIRFL)
JYFLTRAP (IGISOL)
TRIGATRAP
SHIPTRAP (GSI)
MLL@DESIR
NESR (GSI)
ISOLTRAP (CERN)
NORTH AMERICA
UNITED STATES
CANADA
GREENLAND (DEN.)
ARCTIC OCEAN
North Pole
PACIFIC OCEAN
ATLANTIC OCEAN
RUSSIA
ASIA
CHINA
KAZAKHSTAN
INDIA
Bay of Bengal
EUROPE
U.K.
TURKEY
IRAN
IRAQ
Arabian Sea
INDIAN OCEAN
Mediterranean Sea
EGYPT
SAUDI ARABIA
ALGERIA
LIBYA
Tropic of Cancer
MALI
NIGER
AFRICA
CHAD
SUDAN
ETHIOPIA
NIGERIA
Equator
Arctic Circle
Prime Meridian



1000
100
10
1
1985
1990
1995
2000
2005
2010
2015
number of publications
year
isoltrap
cpt
shiptrap
jyfltrap
lebit
titan
triga
TOTAL

CPT @ Argonne National Lab

year	article	physics	nuclides
2012	J. Van Shelt et al. PRC 85, 045805;	r process	133-134Sb, 134-137Te, 135-139I, 137-141Xe, 141-142Cs
2011	J. Fallis et al. PRC 84, 045807;	rp process	90-92Mo, 90-93Tc, 90-94Ru, 92-95Rh
2008	J. Fallis et al., PRC 78, 022801(R)	rp process	92Ru, 93Rh;
2008	J. Van Schelt et al. POS (NIC X) 150	r process	155Pr, 153-157Nd, 153-159Pm, 157-161Sm, 158-161Eu, 163Gd



PHYSICAL REVIEW C 85, 045805 (2012)

TABLE V. The rms mass-excess difference (σ) and mean mass-excess difference ($\bar{\epsilon}$) of various mass models and the AME03 from the CPT for the measured nuclides presented here.

Model	σ (MeV)	$\bar{\epsilon}$ (MeV)
AME03 [29]	0.171	−0.105
FRDM [73]	0.538	−0.379
HFB2 [74]	0.555	0.281
HFB9 [75]	0.467	−0.175
HFBCS1 [76]	0.546	−0.025
DUZU [77]	0.234	0.062
KTUY05 [78]	0.611	0.438
ETFSI2 [79]	0.396	−0.120

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **78**, 022801(R) (2008)

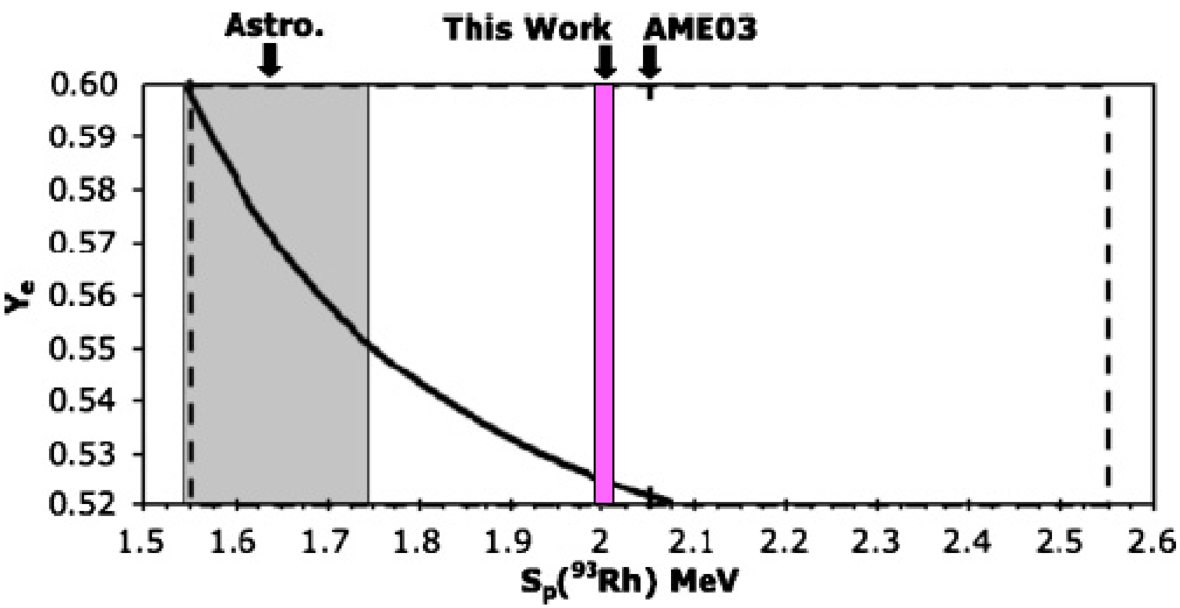
Determination of the proton separation energy of ^{93}Rh from mass measurements

J. Fallis,[1,2] J. A. Clark,[1,2,3] K. S. Sharma,[1] G. Savard,[2,4] F. Buchinger,[5] S. Caldwell,[2,4] J. E. Crawford,[5] C. M. Deibel,[3] J. L. Fisker,[6] S. Gulick,[5] A. A. Hecht,[2,7] D. Lascar,[2,8] J. K. P. Lee,[5] A. F. Levand,[2] G. Li,[2,5] B. F. Lundgren,[2] A. Parikh,[9] S. Russell,[1,2] M. Scholte-van de Vorst,[1,2] N. D. Scielzo,[2,6] R. E. Segel,[8] H. Sharma,[1,2] S. Sinha,[2] M. Sternberg,[2,4] T. Sun,[2] I. Tanihata,[2] J. Van Schelt,[2,4] J. C. Wang,[1,2] Y. Wang,[1,2] C. Wrede,[3] and Z. Zhou[2]

[1]*Department of Physics, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*

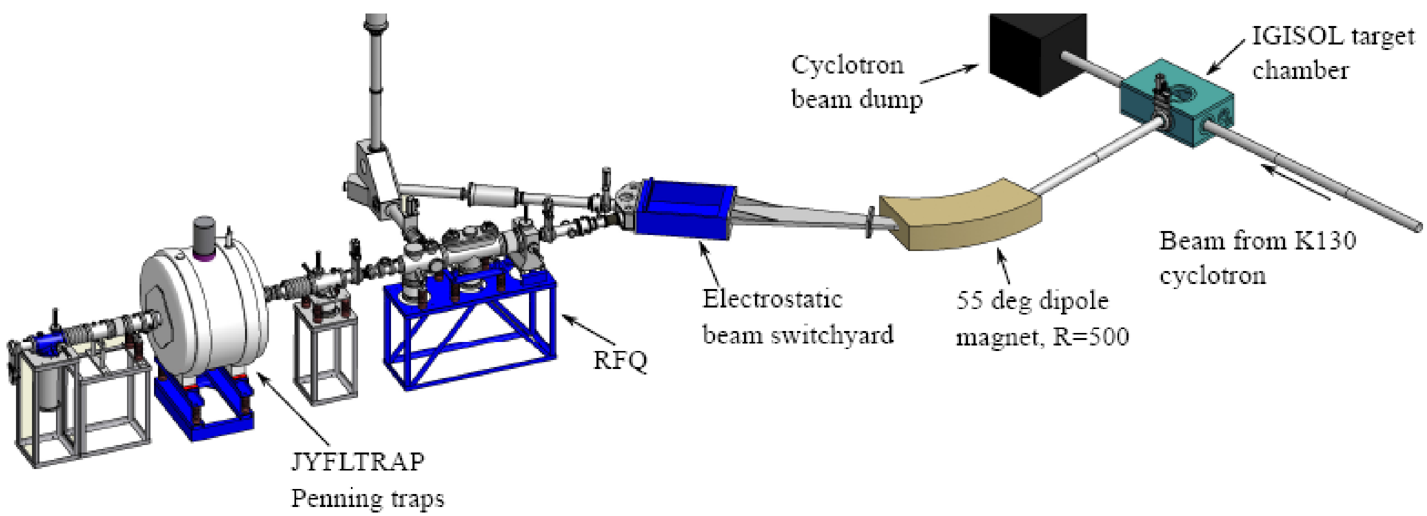
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

Astro.: J. L. Fisker, R. D. Hoffman, and J. Pruet, arXiv:0711.1502v1



JYFLTRAP @ IGISOL-Jyvaskyla

year	article	physics	nuclides
2011	J. Souin et al., Eur. Phys. J. A 47	weak interaction	30S
2011	J. Hakala et al., Eur. Phys. J. A 47	structure	102,103Y, 108Nb, 111Mo, 113,114Tc, 116Ru, 119Rh, 121,122Pd
2012	J. Hakala et al., Phys. Rev. Lett. 109	structure	121-128Cd, 129,131In, 130-135Sn, 131-136Sb, 132-140Te
2013	A. Kankainen et al., Phys. Rev. C 87	isomers	121,123,125Cd, 133Te, 129,131In, 130Sn, 134Sb



From: T. Eronen et al., ACTA PHYSICA POLONICA B 42, 559 (2011)

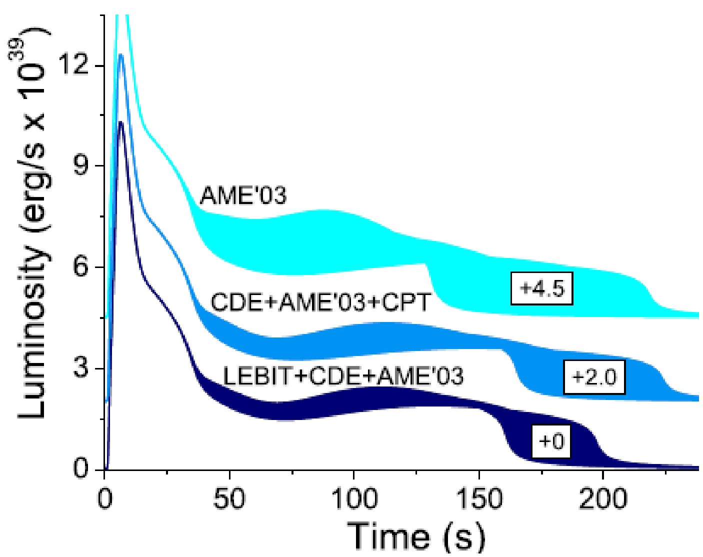
LEBIT @ MSU-East Lansing:

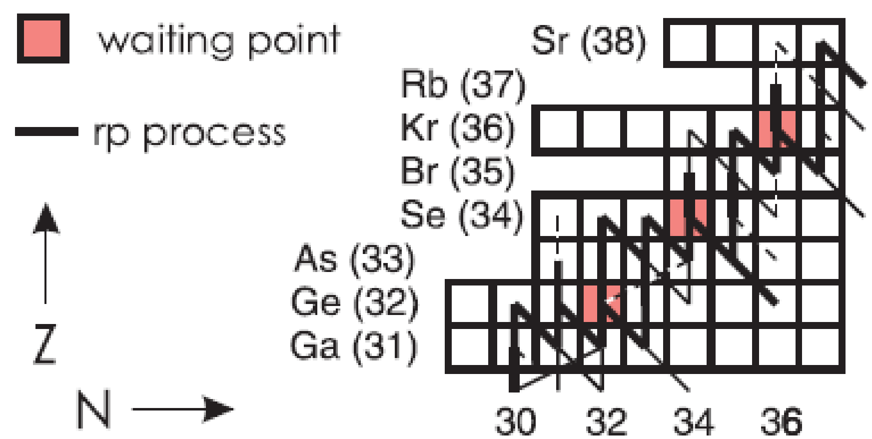
year	article	physics	nuclides
2009	J. Savory et al., PRL 102, 132501	rp process	68,70Se, 70m,71Br
2010	R. Ferrer et al., PRC 81, 044318	structure (N = 40)	63−66Fe; 64−67Co
2012	M. Redshaw et al., Phys. Rev. C 86	neutrino	48Ca
2013	D.L. Lincoln et al., Phys. Rev. Lett. 110	neutrino	82Se

PRL **102,** 132501 (2009) PHYSICAL REVIEW LETTERS week ending 3 APRIL 2009

rp Process and Masses of $N \approx Z \approx 34$ Nuclides

J. Savory,* P. Schury, C. Bachelet, M. Block, G. Bollen, M. Facina, C. M. Folden III, C. Guénaut, E. Kwan, A. A. Kwiatkowski, D. J. Morrissey, G. K. Pang, A. Prinke, R. Ringle, H. Schatz, S. Schwarz, and C. S. Sumithrarachchi
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA



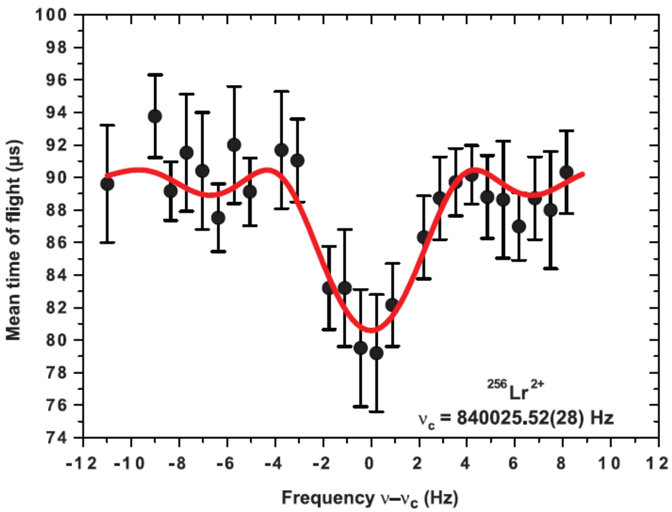


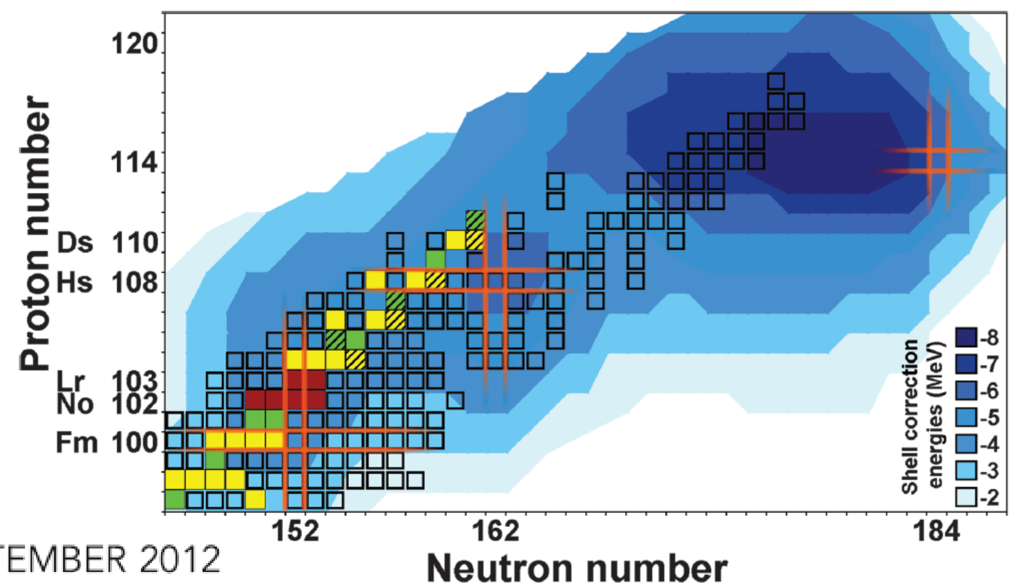
SHIPTRAP @ GSI-Darmstadt:

year	article	physics	nuclides
2011	E. Haettner et al., PRL 106, 122501	rp process	80,84Sr; 85-87Mo
2011	S. Eliseev et al., PRC 83, 038501	neutrino physics	96Ru, 162Er, 168Yb
2011	S. Eliseev et al., PRL 106, 052504	neutrino physics	152Gd
2012	E. Minaya Ramirez et al. Science	structure	252-255No, 255-256Lr

Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

E. Minaya Ramirez,[1,2] D. Ackermann,[2] K. Blaum,[3,4] M. Block,[2*] C. Droese,[5] Ch. E. Düllmann,[6,2,1] M. Dworschak,[2] M. Eibach,[4,6] S. Eliseev,[3] E. Haettner,[2,7] F. Herfurth,[2] F. P. Heßberger,[2,1] S. Hofmann,[2] J. Ketelaer,[3] G. Marx,[5] M. Mazzocco,[8] D. Nesterenko,[9] Yu. N. Novikov,[9] W. R. Plaß,[2,7] D. Rodríguez,[10] C. Scheidenberger,[2,7] L. Schweikhard,[5] P. G. Thirolf,[11] C. Weber[11]



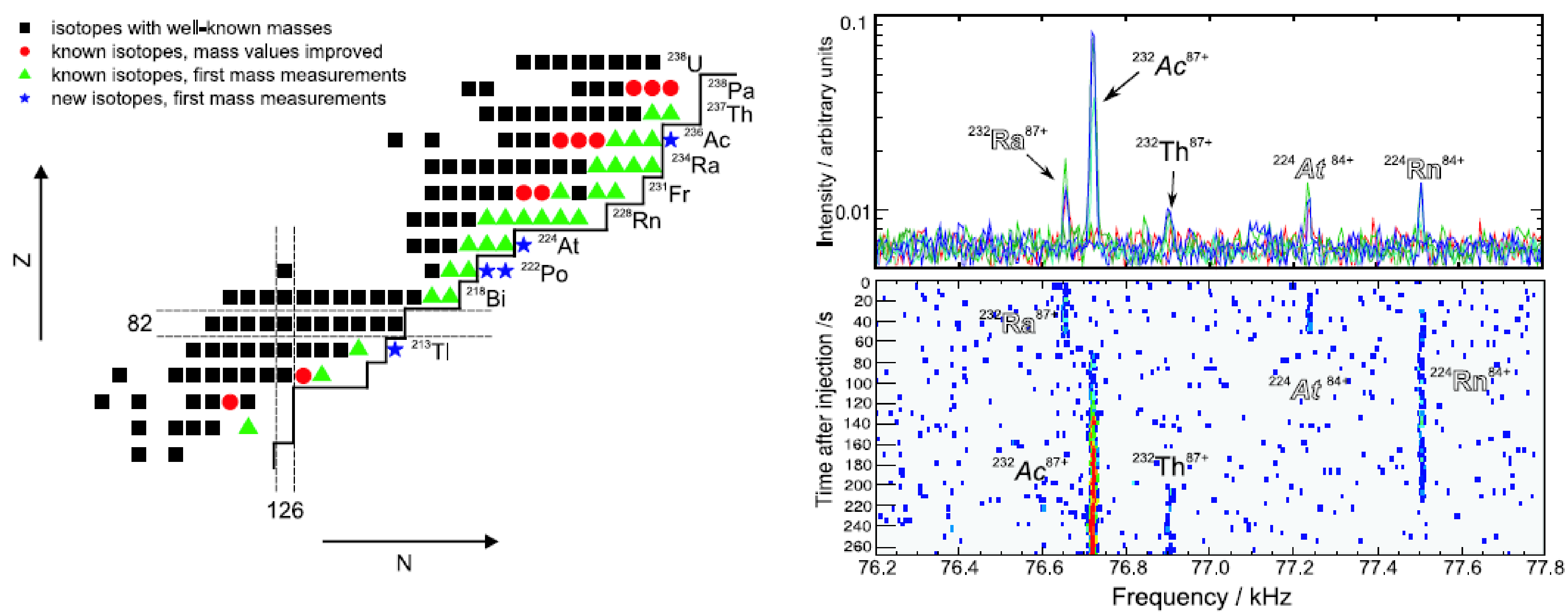


www.sciencemag.org SCIENCE VOL 337 7 SEPTEMBER 2012

ESR @ GSI-Darmstadt:

year	article	physics	nuclides
2010	L. Chen et al., Phys. Lett. B 691	structure	234 236Ac, 224At, 221Po, 222Po, 213Tl
2012	L. Chen et al., Nucl. Physics A 882	structure	n-rich Z = 78 - 91
2013	D. Shubina et al. PRC (submitted)	structure	181,183Lu, 185,186Hf, 187,188Ta, 189,190W, 192,193Re, 195Os

236 *L. Chen et al. / Physics Letters B 691 (2010) 234–237*



CSR @ IMP-Lanzhou:

year	article	physics	nuclides
2011	X.L. Tu et al., Phys. Rev. Lett. 106	*rp* process	63Ge, 65As, 67Se, 71Kr
2012	Y.H. Zhang et al., Phys. Rev. Lett. 109	IMME	41Ti, 45Cr, 49Fe, 53Ni

NUCLEAR ASTROPHYSICS

Star bursts pinned down

One of the main uncertainties in the burn-up of X-ray bursts from neutron stars has been removed with the weighing of a key nucleus, ^{65}As, at a new ion storage ring.

Philip Walker

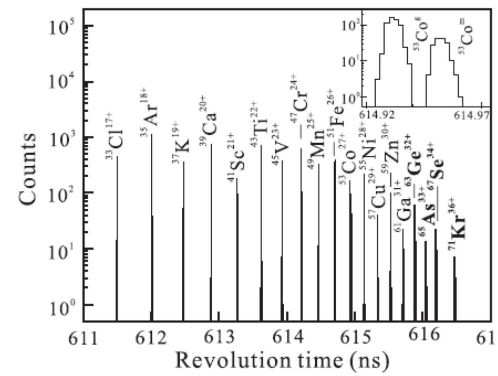
Understanding how the chemical elements formed in stars, and how their formation is related to observable astrophysical phenomena, requires close cooperation between those astrophysicists who study the ways that stars burn and the nuclear physicists who study interactions between atomic nuclei. A fertile area of common interest is the nature of X-ray bursts — flashes of intense radiation that can last from tens to hundreds of seconds. These come from binary star systems, where material falls from the less dense companion star onto the surface of a collapsed neutron star.

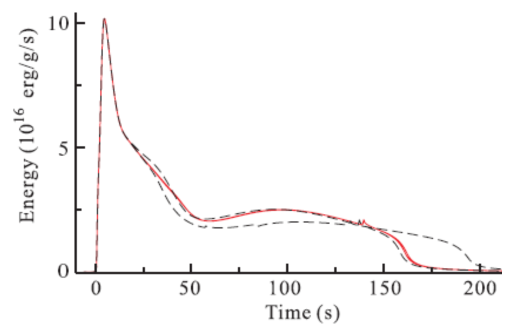
Energy is generated by a rapid succession of proton captures by nuclei, but eventually any given nucleus can hold no more protons, and it must wait to beta-decay — a relatively slow process, because it depends on the weak nuclear interaction. Consequently, these 'waiting point' nuclei assume a key role in determining the time evolution of the radiation burst. Yet, in some cases, it is simply not known whether or not a nucleus can keep hold of another proton. By measuring the mass of the arsenic nucleus ^{65}As — a so-called proton-unbound nucleus, in which a captured proton remains unbound or only loosely bound to the nucleus — Xiaolin Tu and colleagues[1] have now shown that the germanium isotope ^{64}Ge is most likely not, after all, a waiting point in the evolution of X-ray bursts.

There is a long history of laboratory experiments being used to help understand

Figure 1 | A new facility for nuclear physics: the cooler storage ring, now in operation at the Institute of Modern Physics, Lanzhou, in western China.

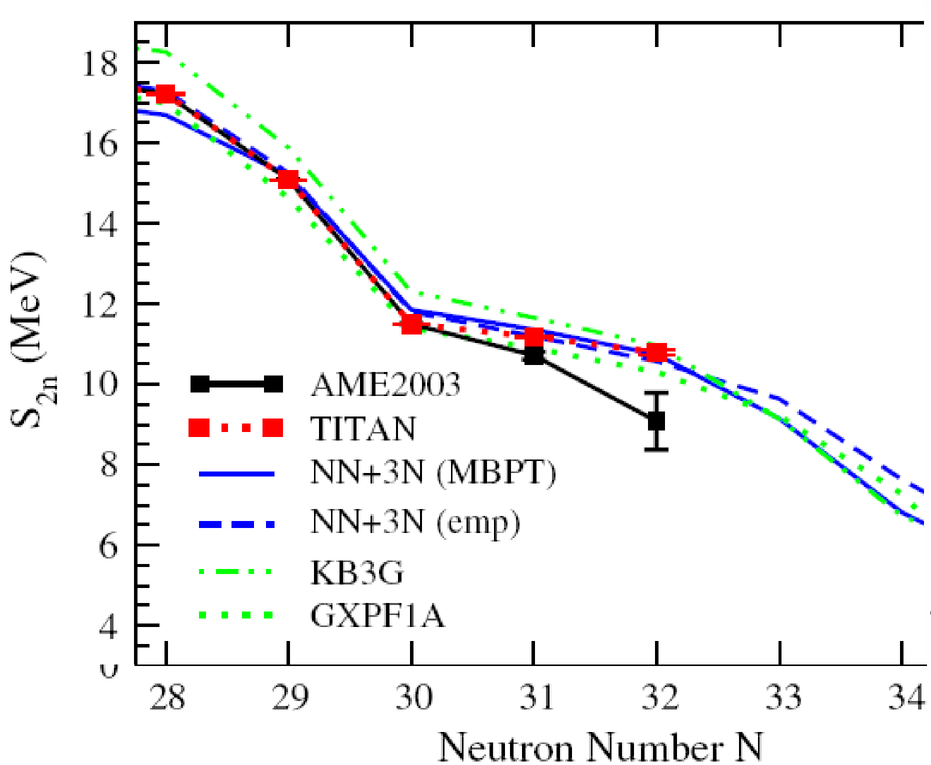
NATURE PHYSICS | VOL 7 | APRIL 2011 | www.nature.com/naturephysics 281

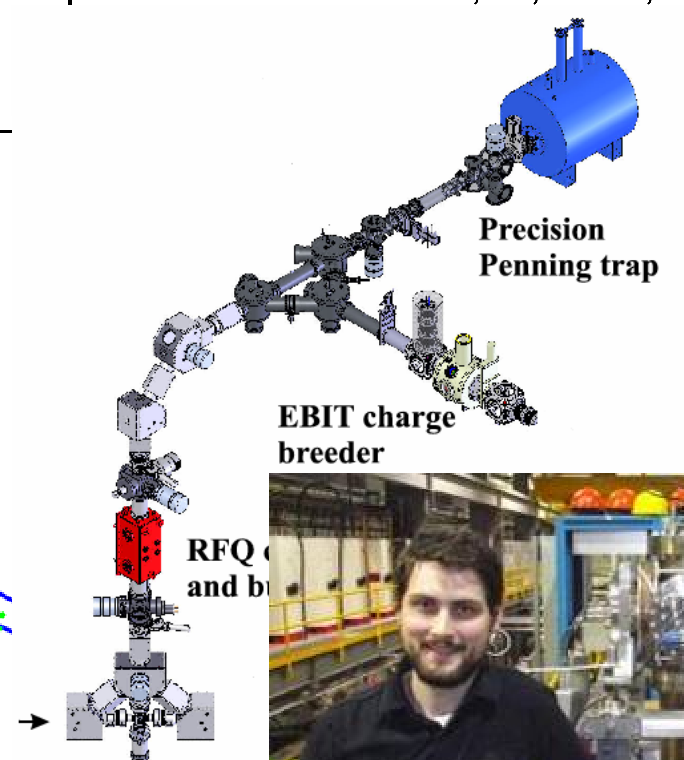


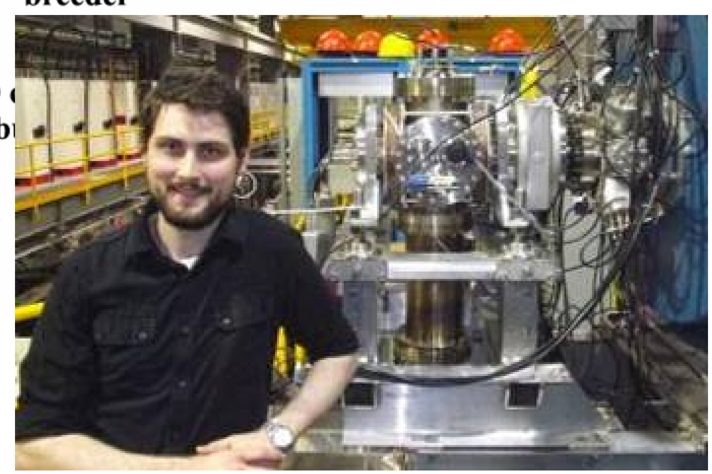


TITAN @ TRIUMF-ISAC:

year	article	physics	nuclides
2011	A. Lapierre et al. PRC	structure (N = 28)	44-50K, 49-50Ca
2012	S. Ettenauer et al. PRL	CVC	74Rb
2012	M. Brodeur et al. PRL	structure	8He
2012	A. Gallant et al. PRL 109	structure (N = 28)	51K, 51-52Ca
2012	V. Simon et al., PRC 85	r process	94,97,98Rb, 94,97-99Sr

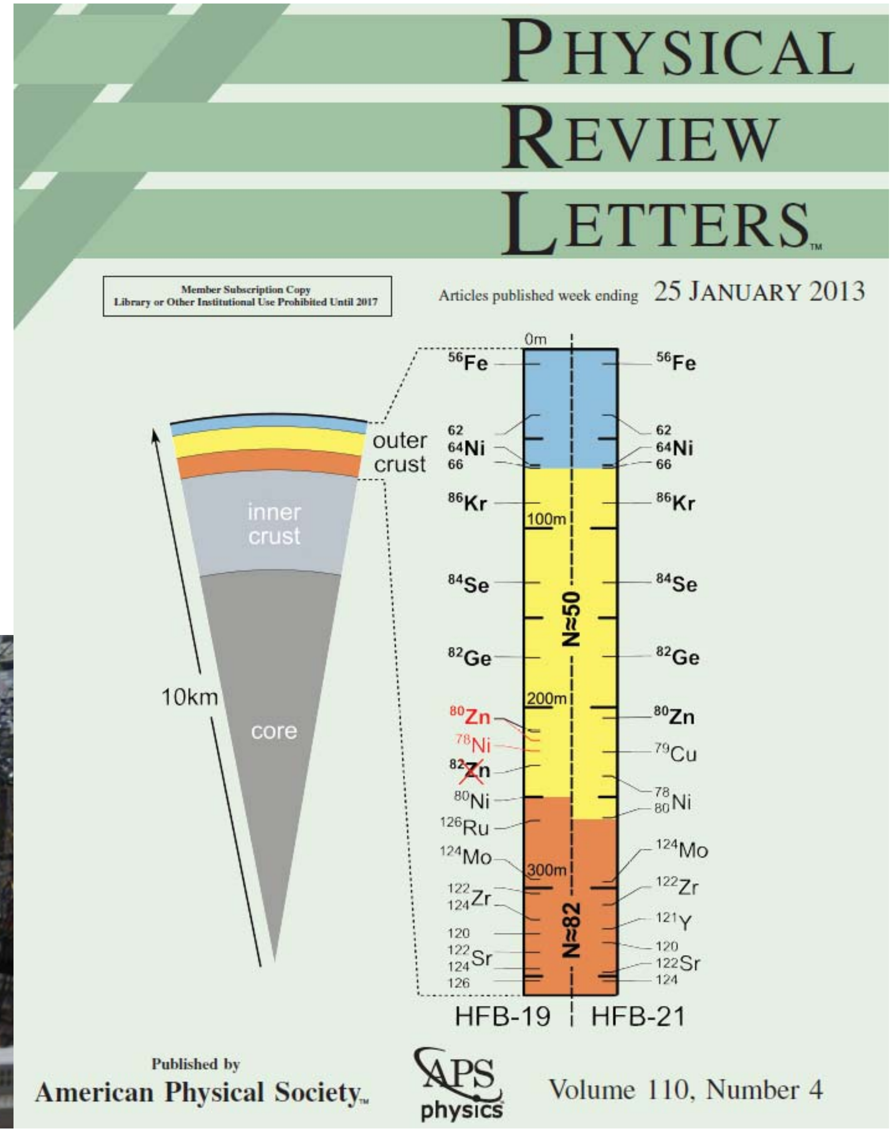






ISOLTRAP @ CERN-ISOLDE

year	article	physics	nuclides
2012	D. Fink et al., Phys. Rev. Lett.		
2012	F. Herfurth et al., EPJA		
2012	S. Naimi et al., PRC 86		
2013	R. Wolf et al. PRL		
2013	F. Wienholtz et al., Nature		

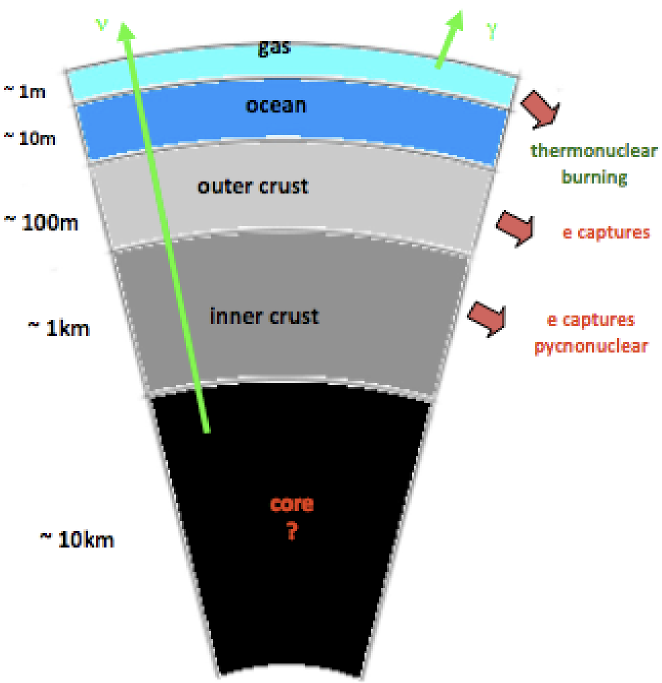


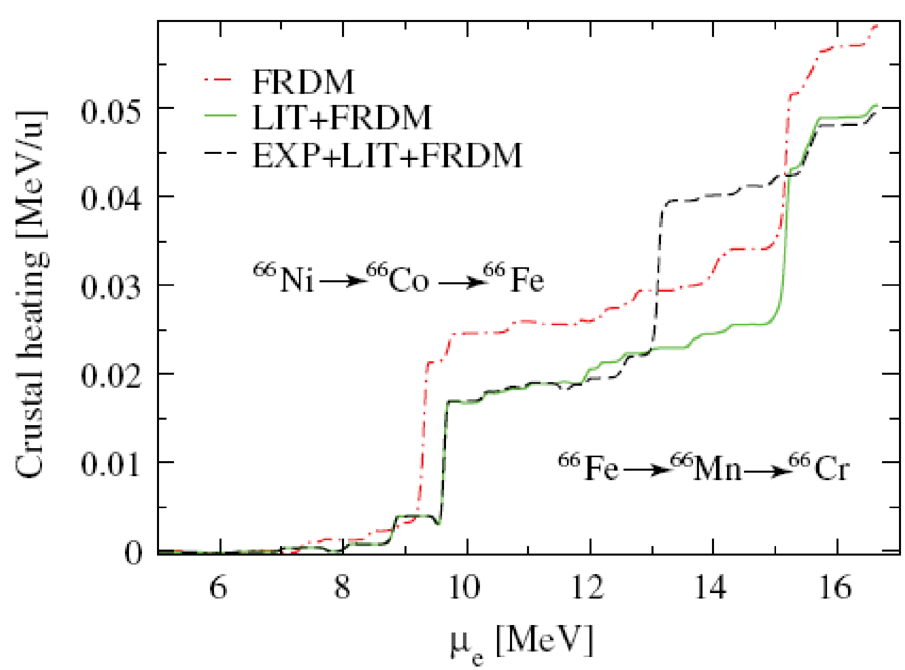
$B\rho$-tof @ NSCL

PRL 107, 172503 (2011) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2011

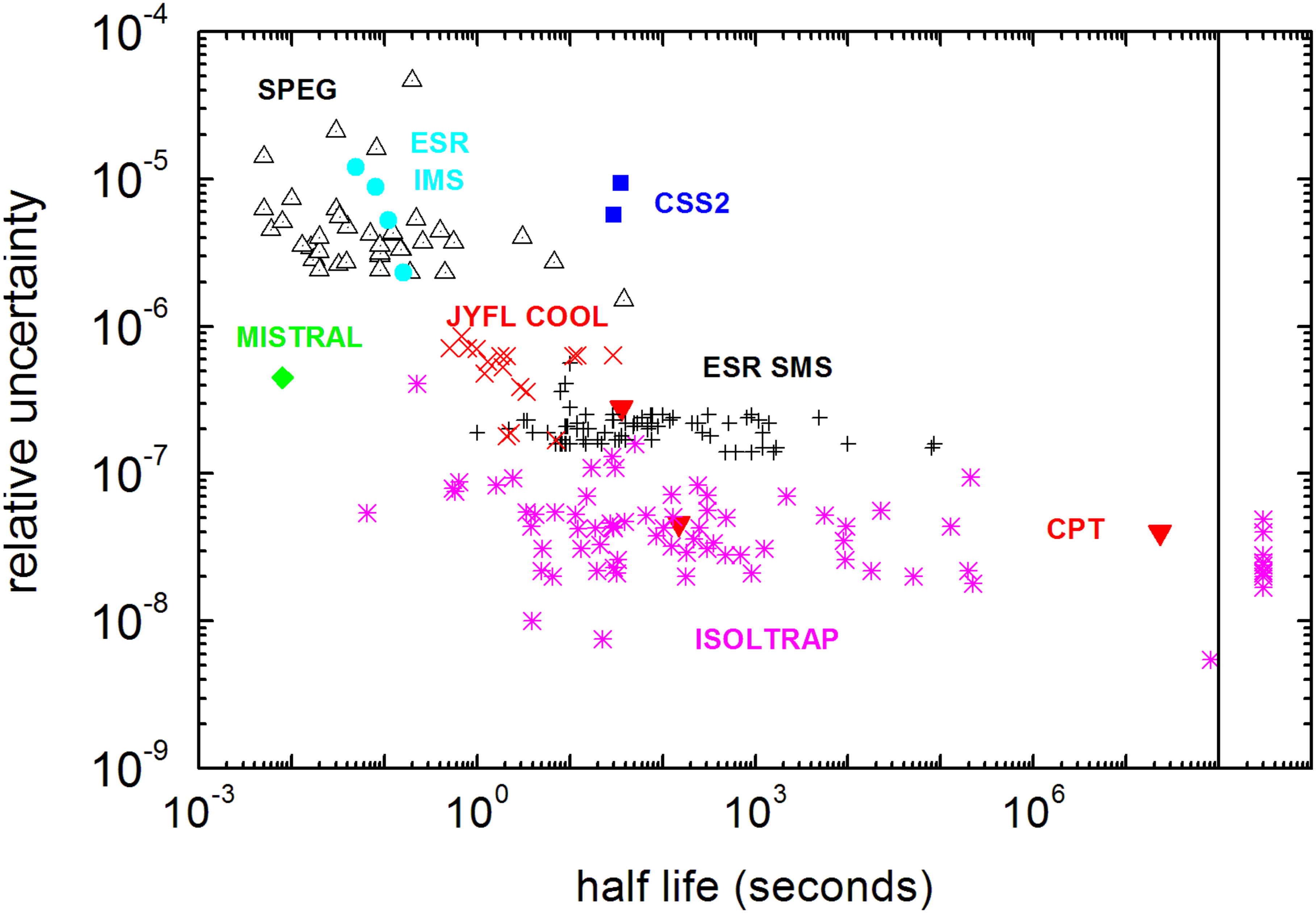
Time-of-Flight Mass Measurements for Nuclear Processes in Neutron Star Crusts

A. Estradé,[1,2,3,*] M. Matoš,[1,3,4] H. Schatz,[1,2,3] A. M. Amthor,[1,2,3] D. Bazin,[1] M. Beard,[5,3] A. Becerril,[1,2,3] E. F. Brown,[1,2,3] R. Cyburt,[1,3] T. Elliot,[1,2,3] A. Gade,[1,2] D. Galaviz,[1,3] S. George,[1,3] S. S. Gupta,[6,3] W. R. Hix,[7] R. Lau,[1,2,3] G. Lorusso,[1,2,3] P. Möller,[8] J. Pereira,[1,3] M. Portillo,[1] A. M. Rogers,[1,2,3] D. Shapira,[7] E. Smith,[9,3] A. Stolz,[1] M. Wallace,[8] and M. Wiescher[5,3]



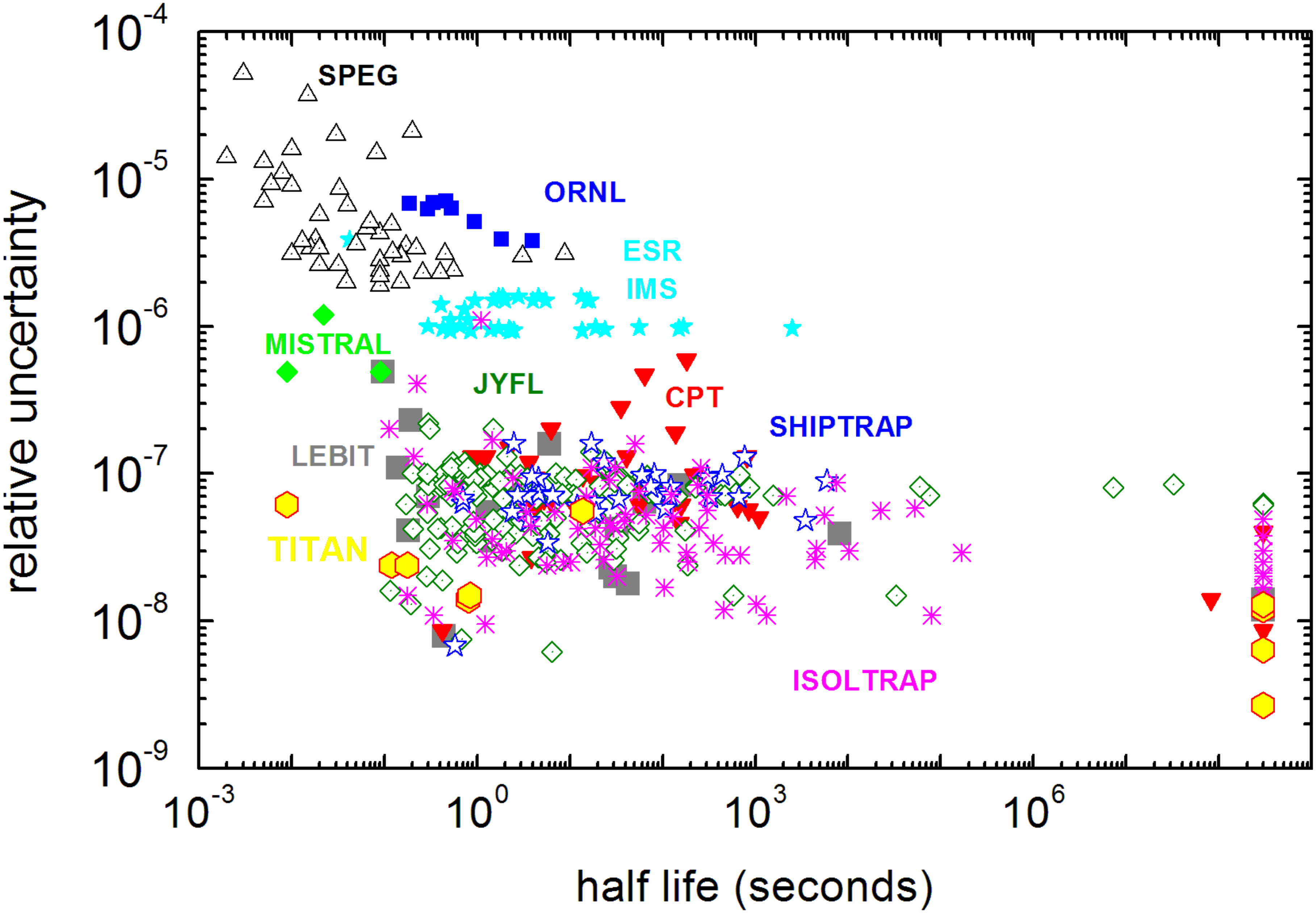


ENAM 2004



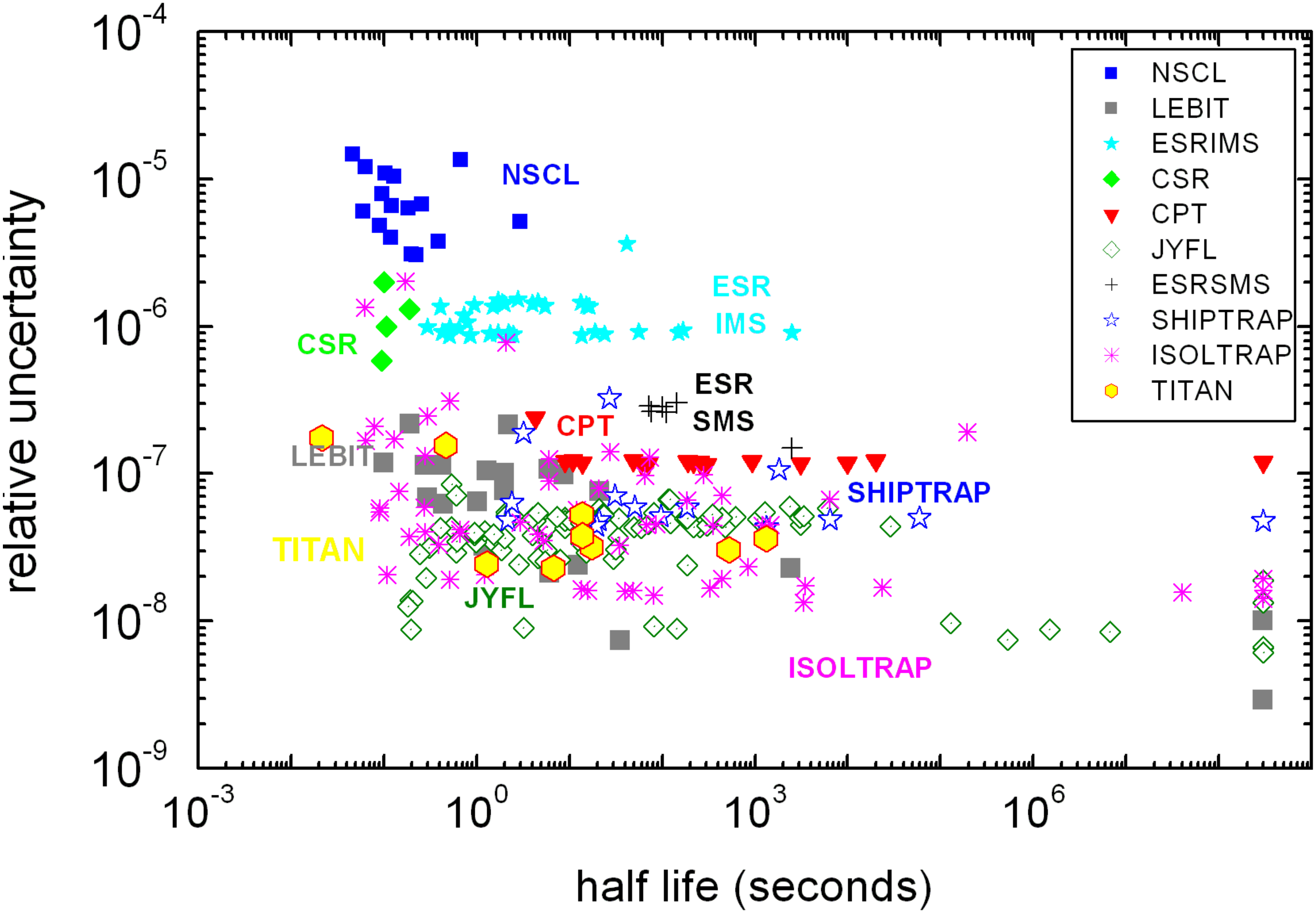
relative uncertainty
half life (seconds)
SPEG
ESR
IMS
CSS2
MISTRAL
JYFL COOL
ESR SMS
CPT
ISOLTRAP
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-3
10^0
10^3
10^6

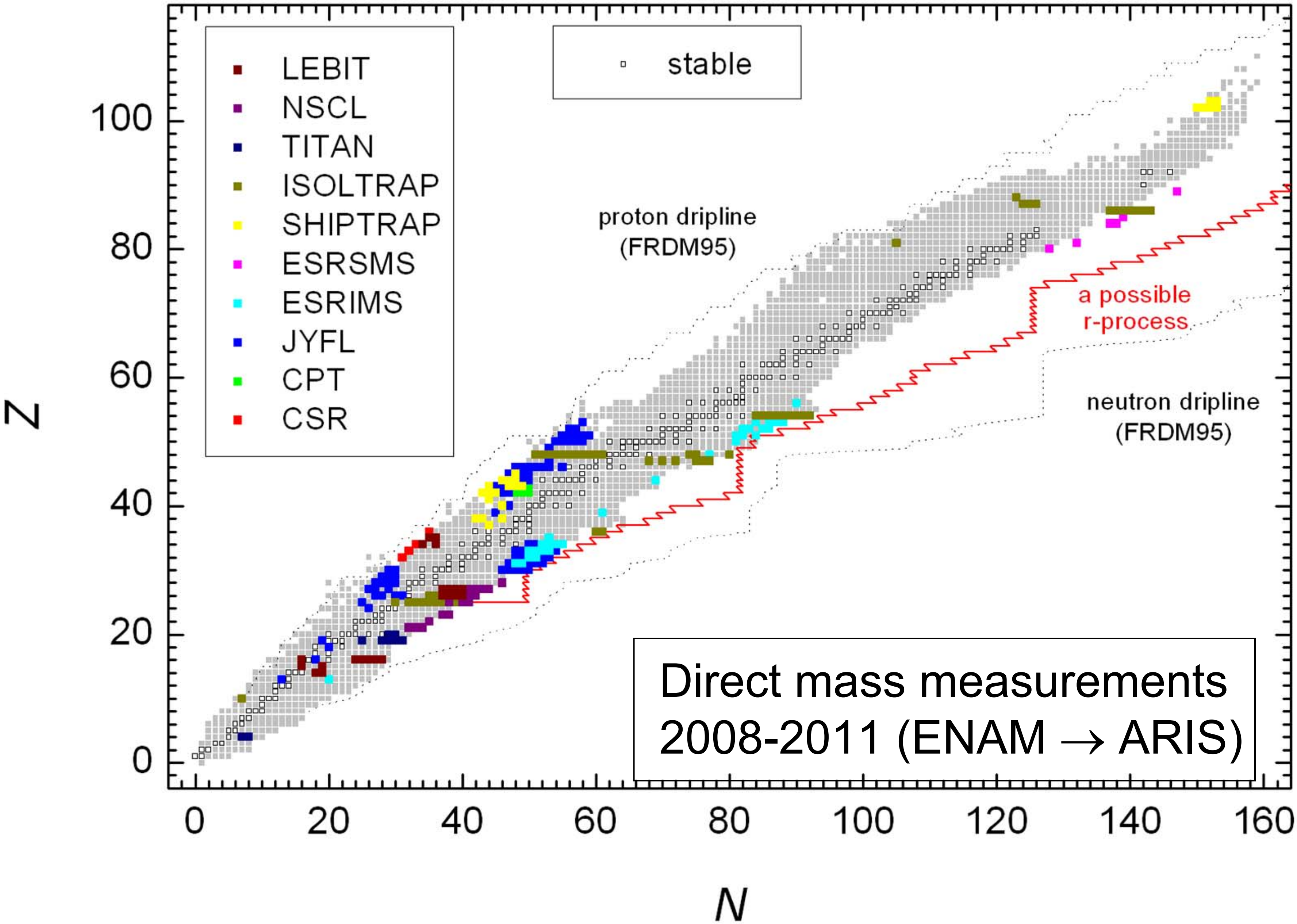
ENAM 2008



relative uncertainty
half life (seconds)
10-4
10-5
10-6
10-7
10-8
10-9
10-3
100
103
106
SPEG
ORNL
ESR
IMS
MISTRAL
JYFL
CPT
SHIPTRAP
LEBIT
TITAN
ISOLTRAP

ARIS 2011


10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
relative uncertainty
10^-3
10^0
10^3
10^6
half life (seconds)
NSCL
ESR
IMS
CSR
ESR
SMS
CPT
LEBIT
SHIPTRAP
TITAN
JYFL
ISOLTRAP
NSCL
LEBIT
ESRIMS
CSR
CPT
JYFL
ESRSMS
SHIPTRAP
ISOLTRAP
TITAN

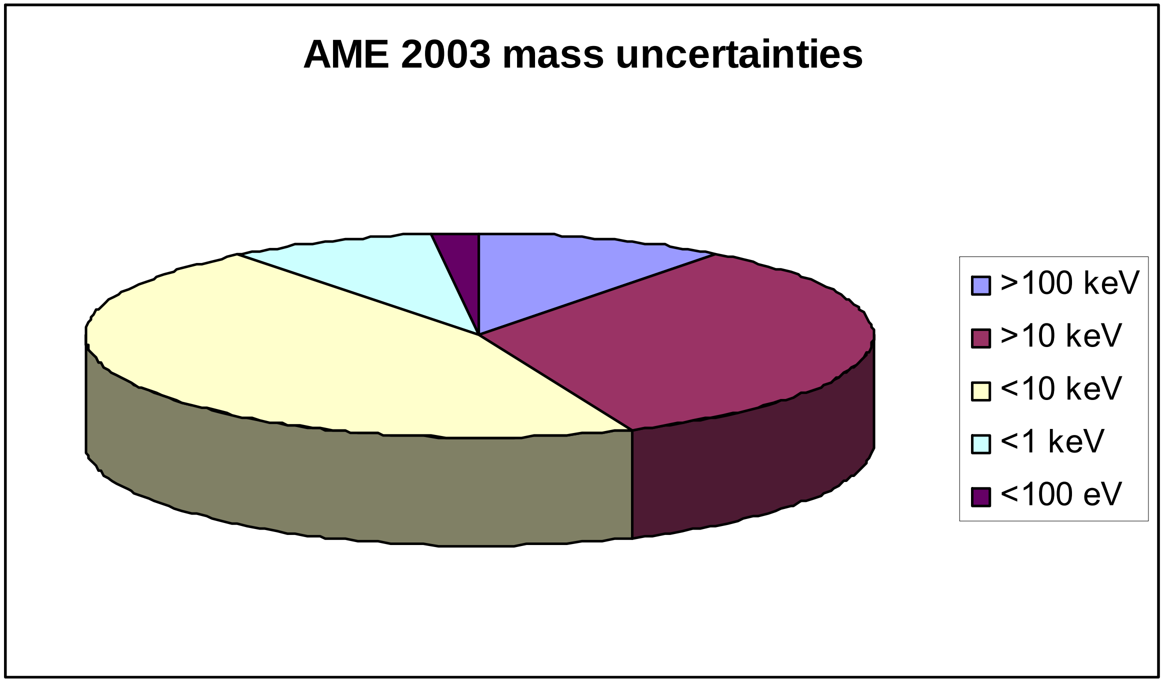


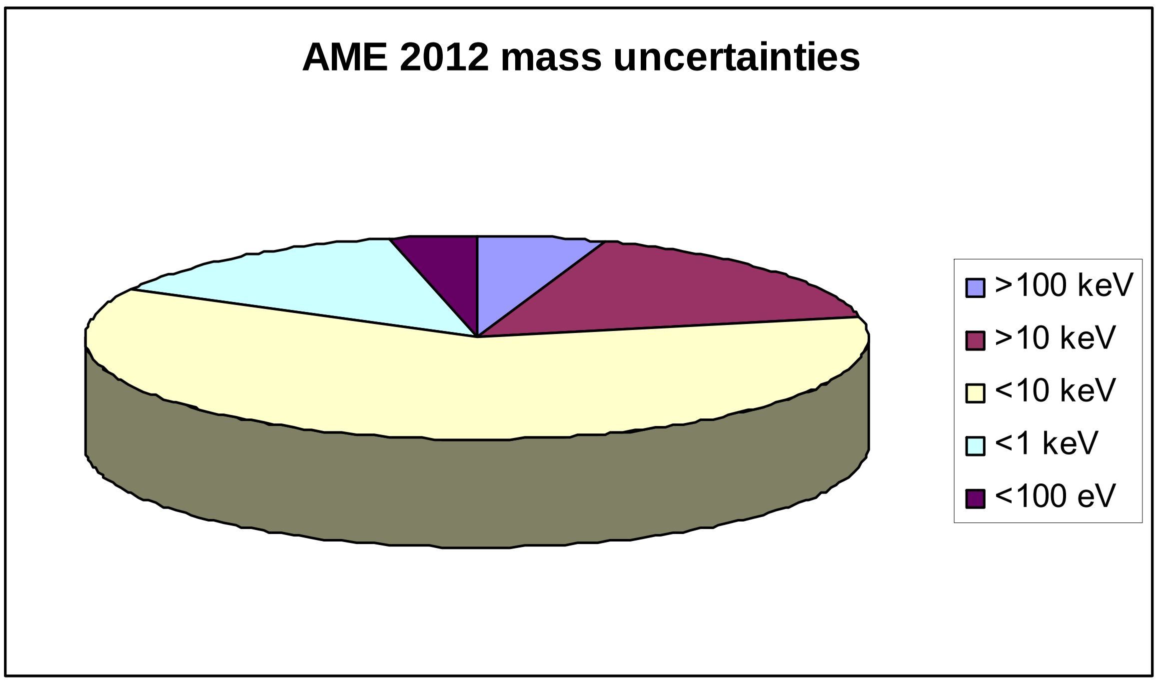
That dripline is far away – will we ever reach it?!

The AME: the stepping stone to theory

	AME2003	AME2012
Total data	7773	12437
Used (–BCDFU)	6169	5556
Equations	1381	1947
Parameters	847	1176
X^2 expected	534	771
X^2 obtained	814	765
gs masses	2228	2438
gs estimations	951	915
isomers	201	336
iso estimations	122	128
Reactions/decays	967	1117
Mass spectrometry	414	830
X–indirect	1.27	1.02
X–direct	1.16	0.96

Data getting better (not going as far...)


AME 2003 mass uncertainties
>100 keV
>10 keV
<10 keV
<1 keV
<100 eV


AME 2012 mass uncertainties
>100 keV
>10 keV
<10 keV
<1 keV
<100 eV

Observations and statistics (from results *published* 2008-2010):

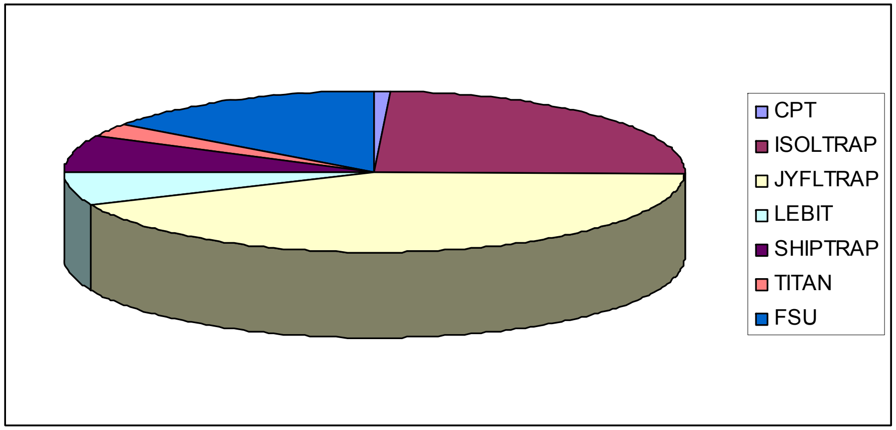
(source: AME2011 update of G. Audi & M. Wang)

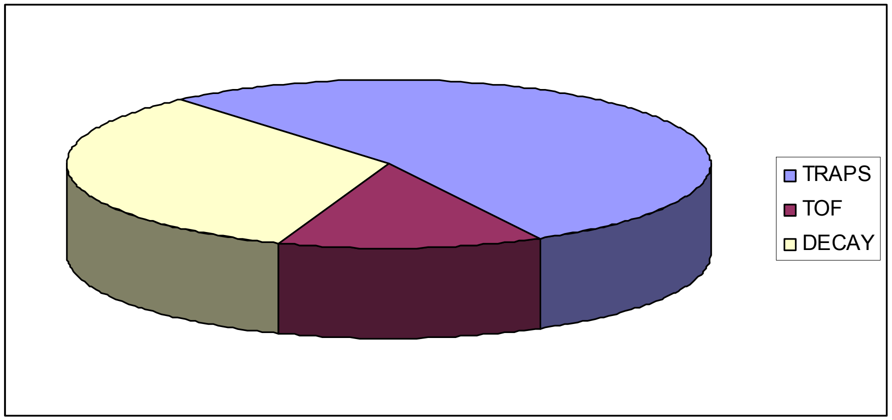
Total of about 200 direct measurements:

TOF: ESR-IMS (35); ESR-SMS (6); NSCL (21);

TRAPS (160):

CPT	(2)
FSU	(42)
ISOLTRAP	(70)
JYFL	(120)
SHIP	(21)
LEBIT	(19)
TITAN	(7)





100 new reaction/decay data from RIKEN, JYFL, GSI, JINR, Kyoto, Berkeley, Andreyev (!)

Observations and statistics (from results *published* 2011-2012):

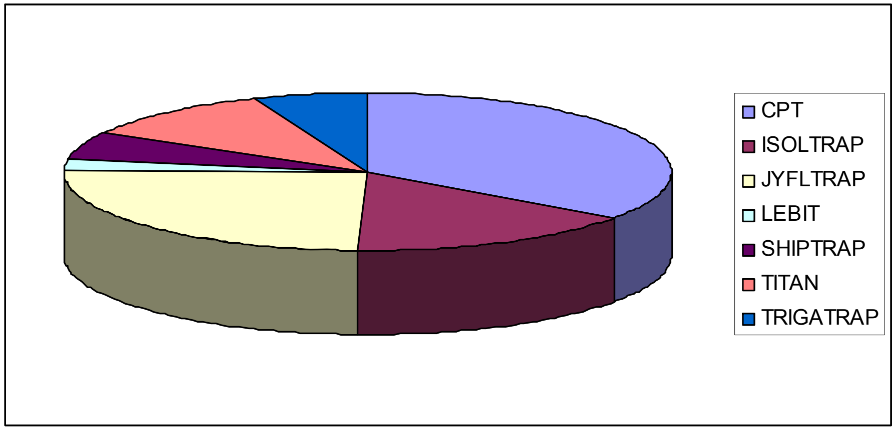
(source: AME2012)

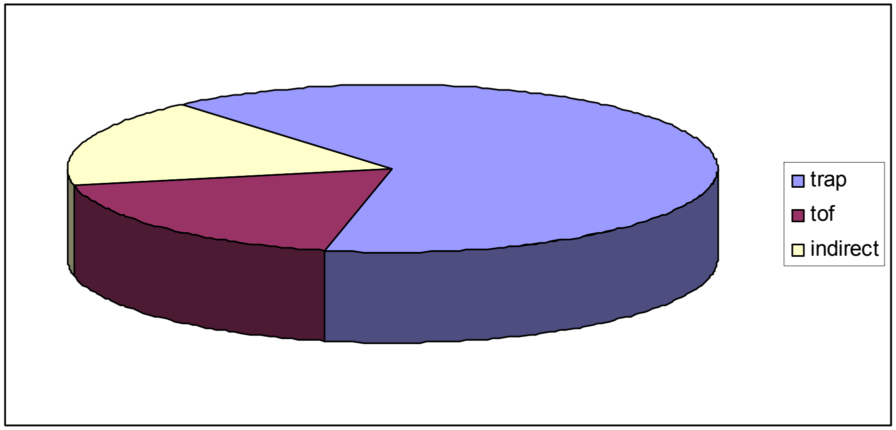
Total of about 447 direct measurements (total data):

TOF (99) : ESR (65); CSR (18); NSCL (16);

TRAPS (348):

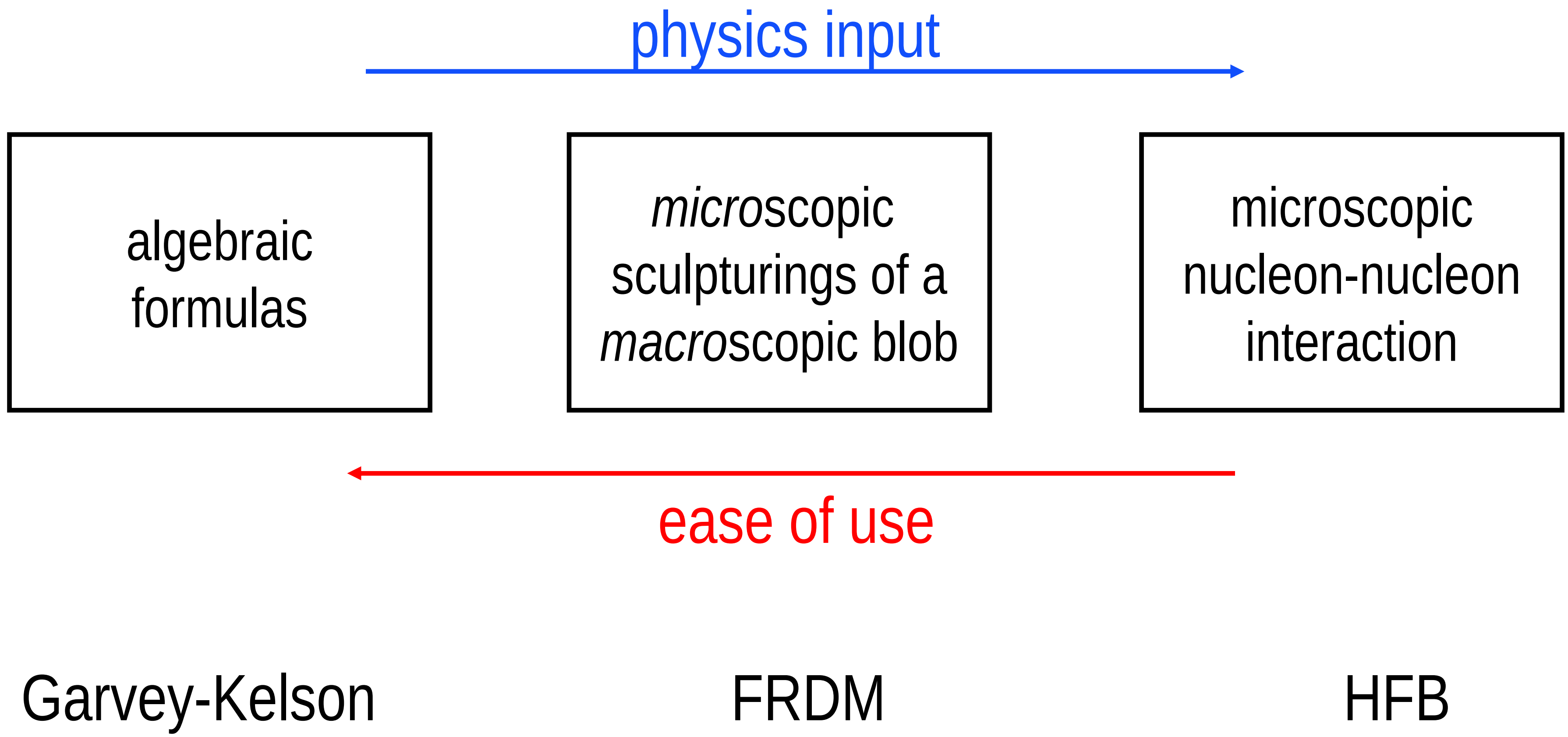
CPT	(122)
ISOLTRAP	(54)
JYFL	(86)
LEBIT	(8)
SHIPTRAP	(20)
TITAN	(37)
TRIGATRAP	(21)





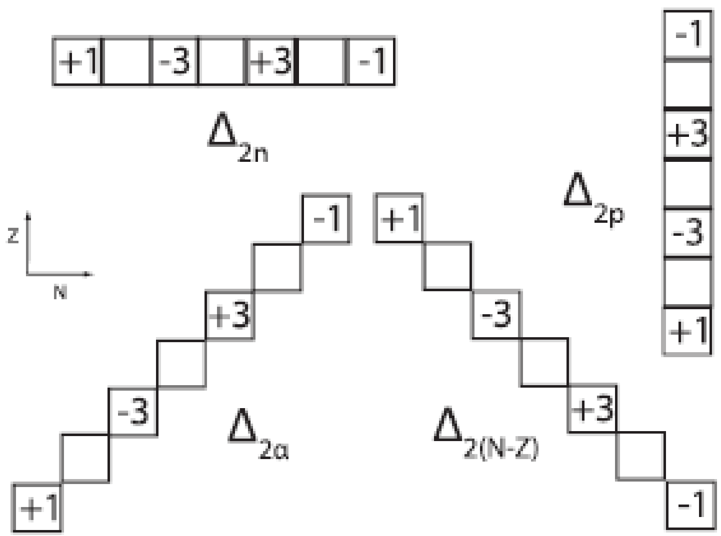
93 new reaction/decay data from:
RIKEN, JYFL, GSI, JINR, et al.

A (very) simplified overview of mass models



PHYSICAL REVIEW C 87, 044313 (2013)
Empirical formulas for nucleon separation energies
M. Bao, Z. He, Y. M. Zhao, and A. Arima

PHYSICAL REVIEW C 87, 024319 (2013)
Extrapolations of nuclear binding energies from new linear mass relations
D. Hove, A. S. Jensen, and K. Riisager



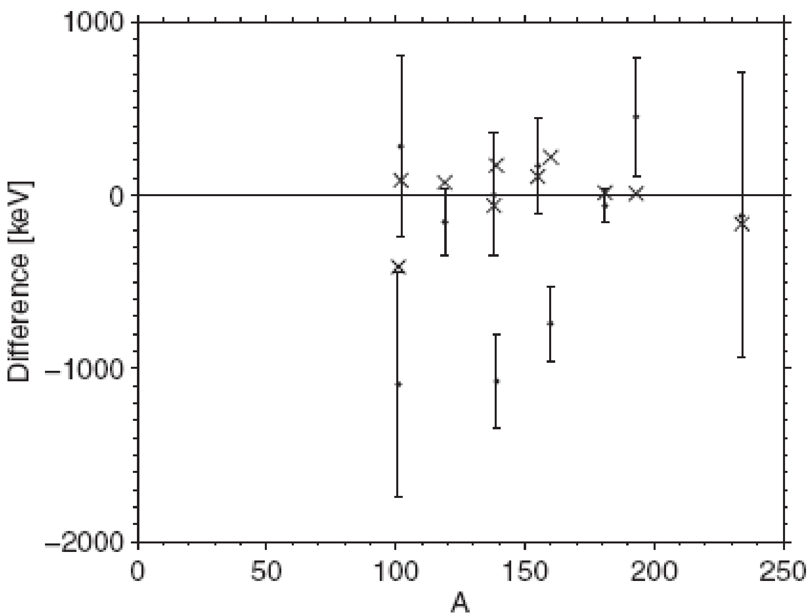


FIG. 5. The differences between our extrapolations and the measured values where the error bars are based solely on the extrapolated uncertainties. The crosses indicate the difference between Audi and Meng's extrapolations and the measurements.

Do we (still) need local formulae?

Theoretical Mass Models: Macroscopic - Microscopic / Liquid Drop

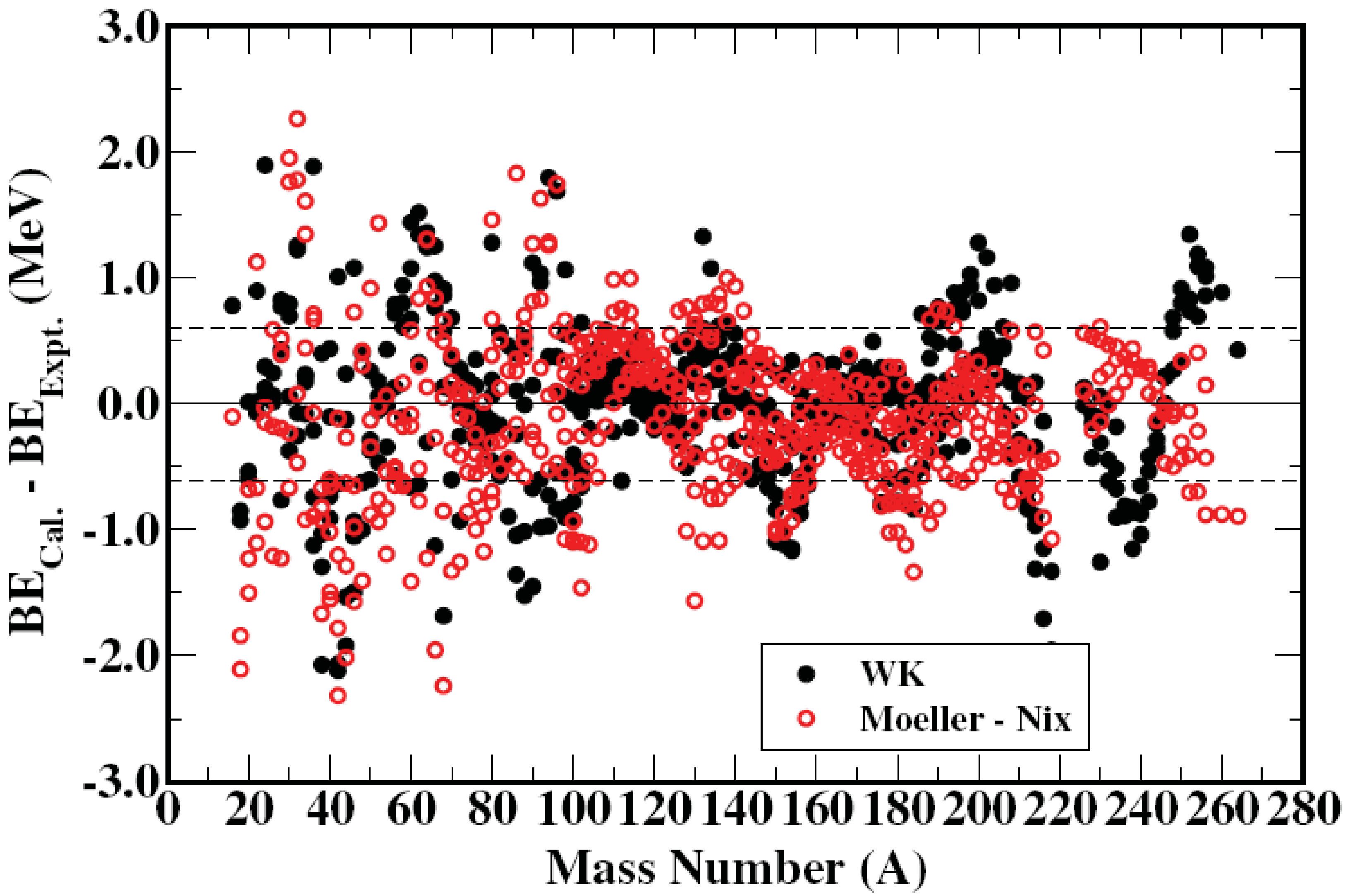
FRDM: Finite Range Droplet Model - New fit to 2011 AME! (2012?)
P. Moller J.R. Nix, W.D. Myers, W.J. Swiatecki,
At. Data Nuc. Data Tables 59 (1995) 185

Kazuhiro Oyamatsu, Kei Iida, Hiroyuki Koura, Phys. Rev. C 82 (2010) 027301
Kazuhiro Oyamatsu, Kei Iida, Phys. Rev. C 81 (2010) 054302

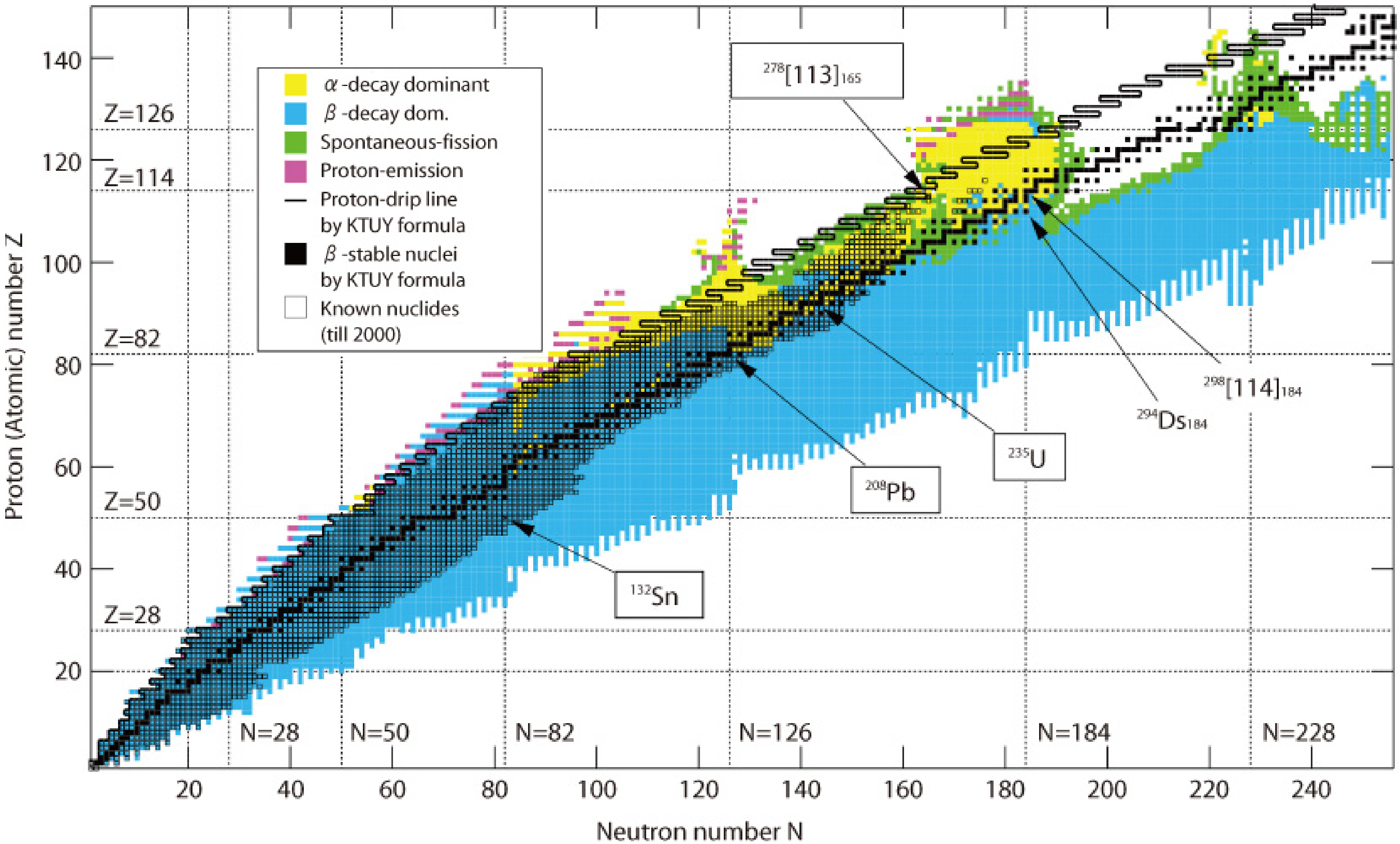
Ning Wang, Zuoying Liang, Min Liu, Xizhen Wu, Phys. Rev. C 82 (2010) 044304
Ning Wang, Min Liu, Xizhen Wu, Phys. Rev. C 81 (2010) 044322

Wigner-Kirkwood (only 10 parameters but even-even cases only!):
A. Bhagwat, X. Vinas, M. Centelles, P. Schuck, R. Wyss, Phys. Rev. C 81 (2010) 044321
A. Bhagwat, X. Vinas, M. Centelles, P. Schuck, R. Wyss, Phys. Rev. C 86 (2012) 044316

Do we (still) need mic-mac models?

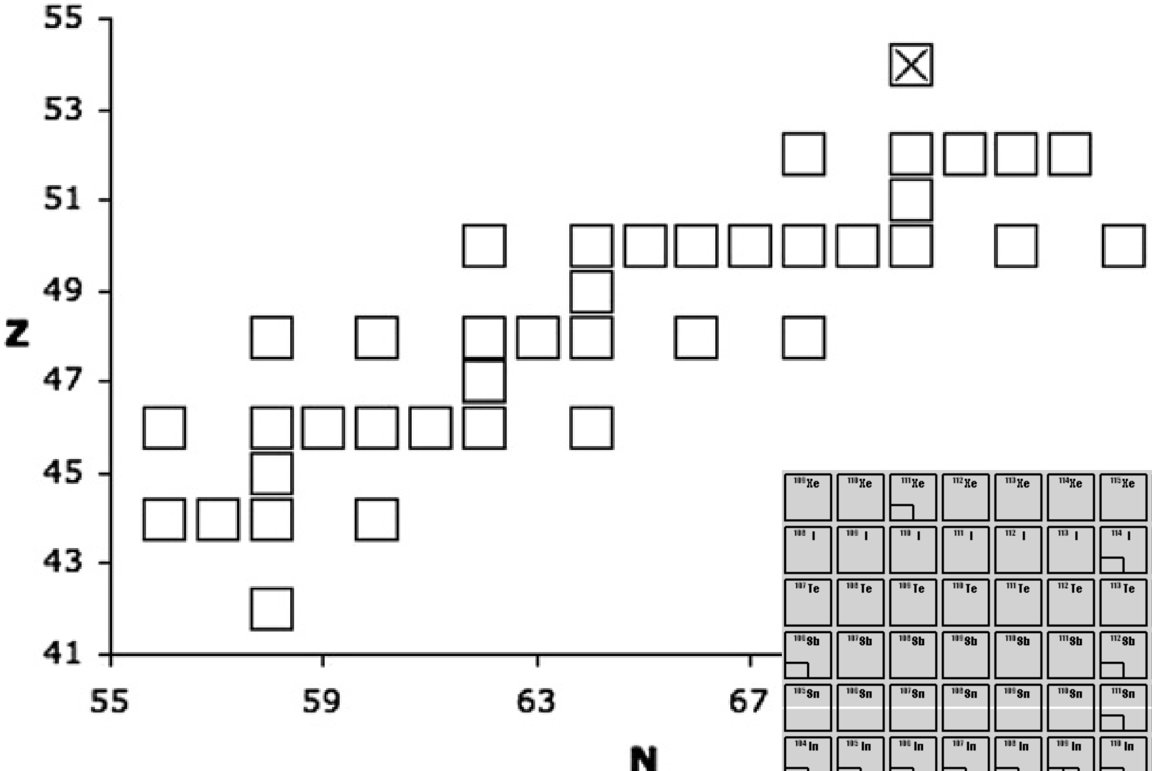


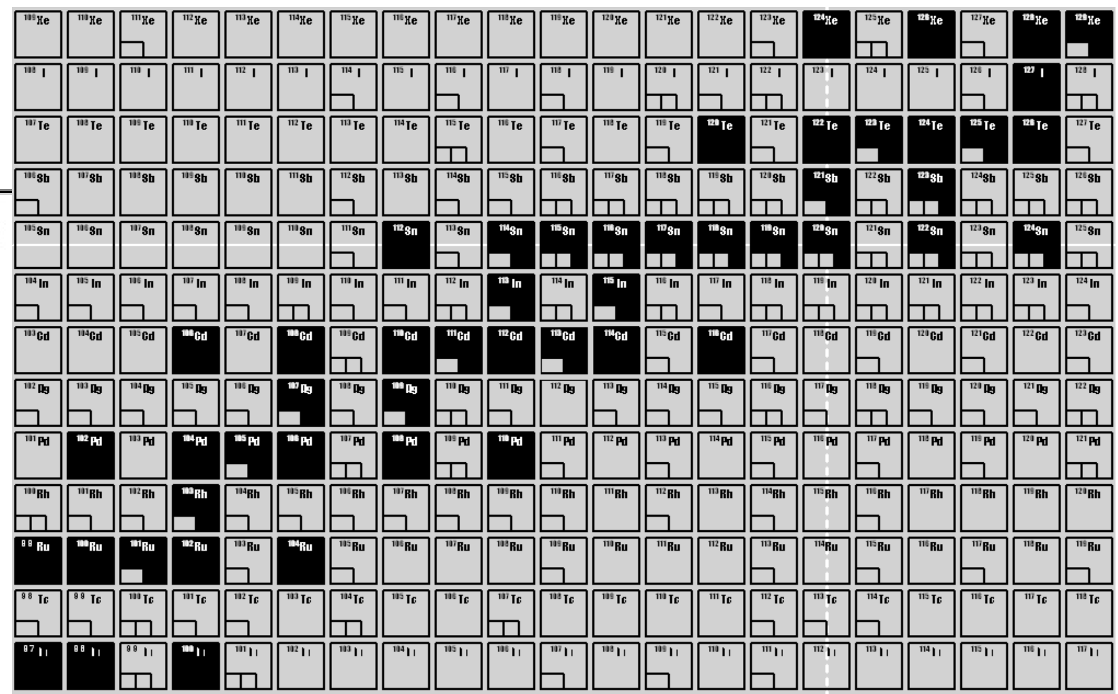
From: A. Bhagwat, et al., Phys. Rev. C86 (2012) 044316


α -decay dominant
β -decay dom.
Spontaneous-fission
Proton-emission
Proton-drip line by KTUY formula
β -stable nuclei by KTUY formula
Known nuclides (till 2000)
278[113]165
298[114]184
294Ds184
235U
208Pb
132Sn
Z=126
Z=114
Z=82
Z=50
Z=28
N=28
N=50
N=82
N=126
N=184
N=228
Proton (Atomic) number Z
Neutron number N
20
40
60
80
100
120
140
160
180
200
220
240

H. Koura

<u>Inverse test: Using exotic masses to predict stable nuclides!</u>



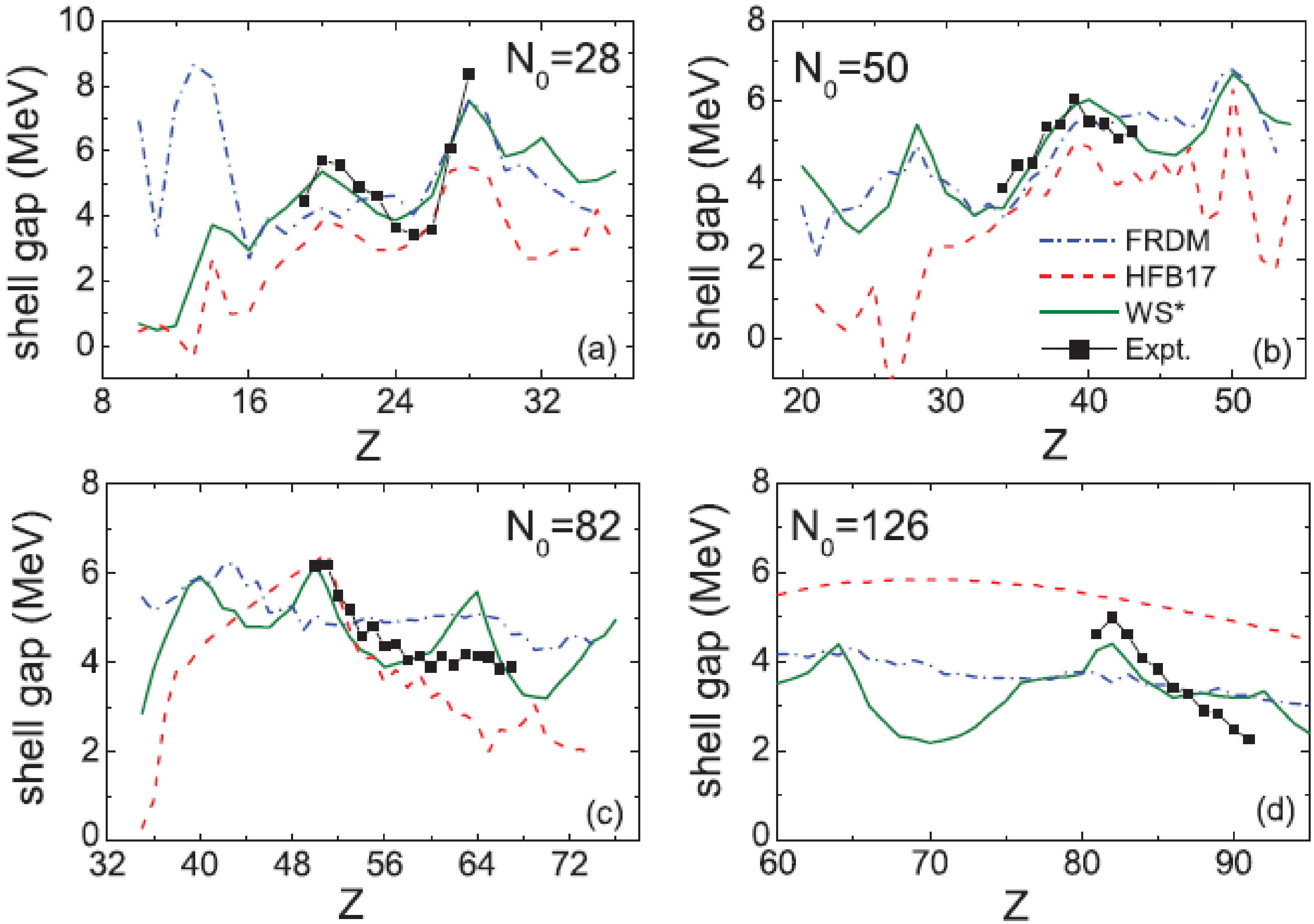


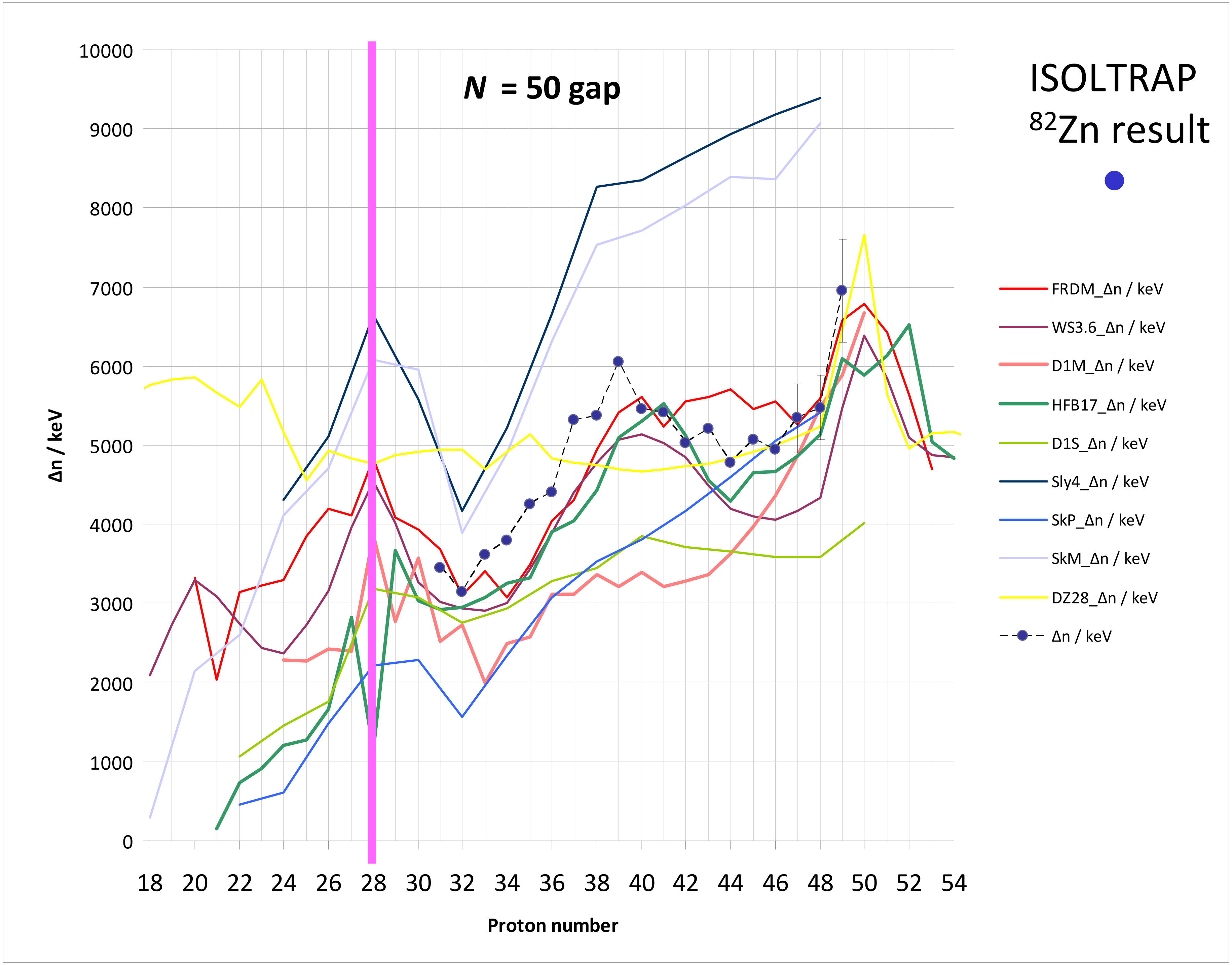
39/50 predicted stable nuclides

An empirical study of the Duflo-Zuker mass formula

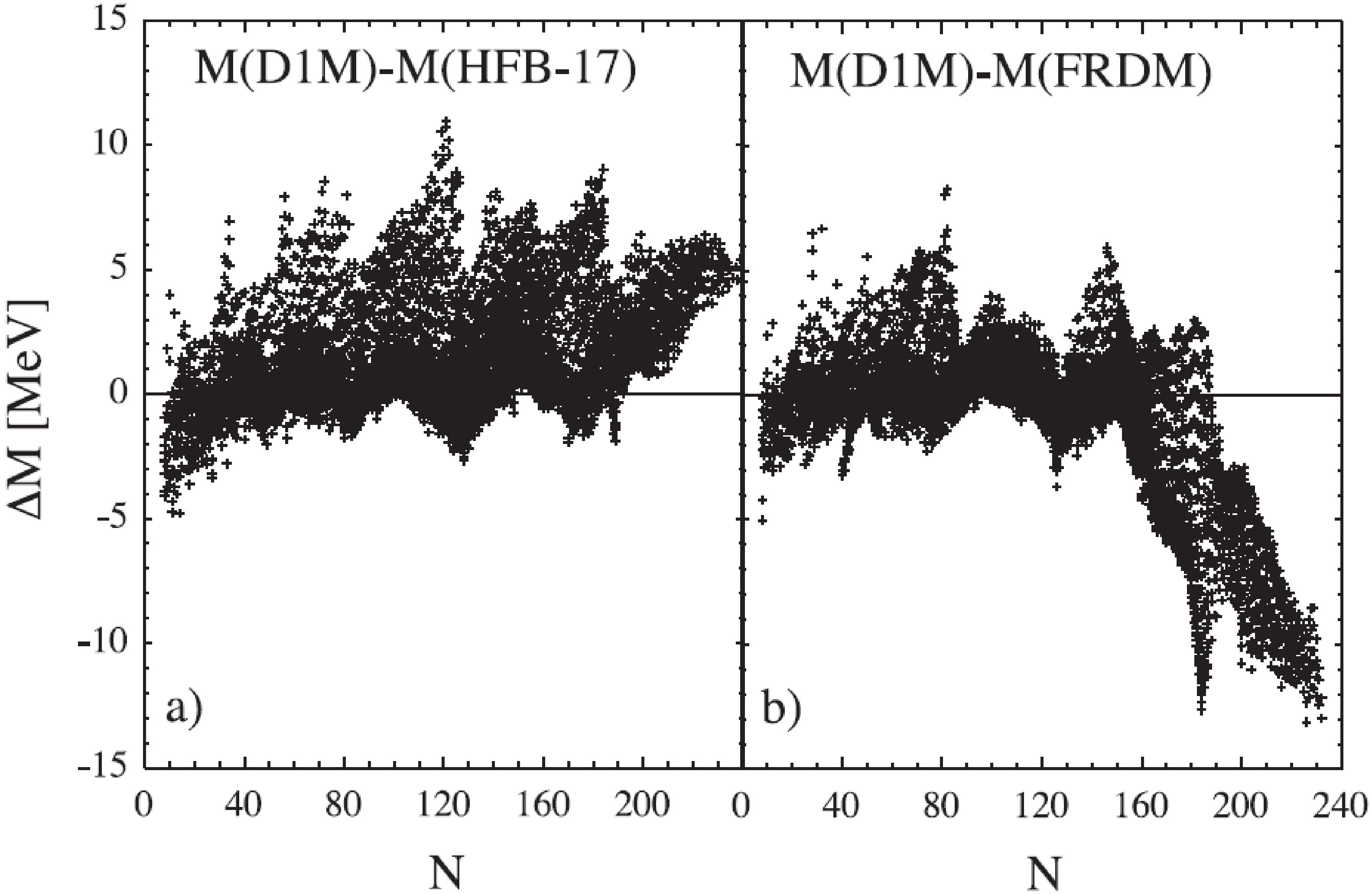
M.W. Kirson, Nuclear Physics A 893 (2012) 27-42

N. Wang et al. PHYSICAL REVIEW C **82**, 044304 (2010)



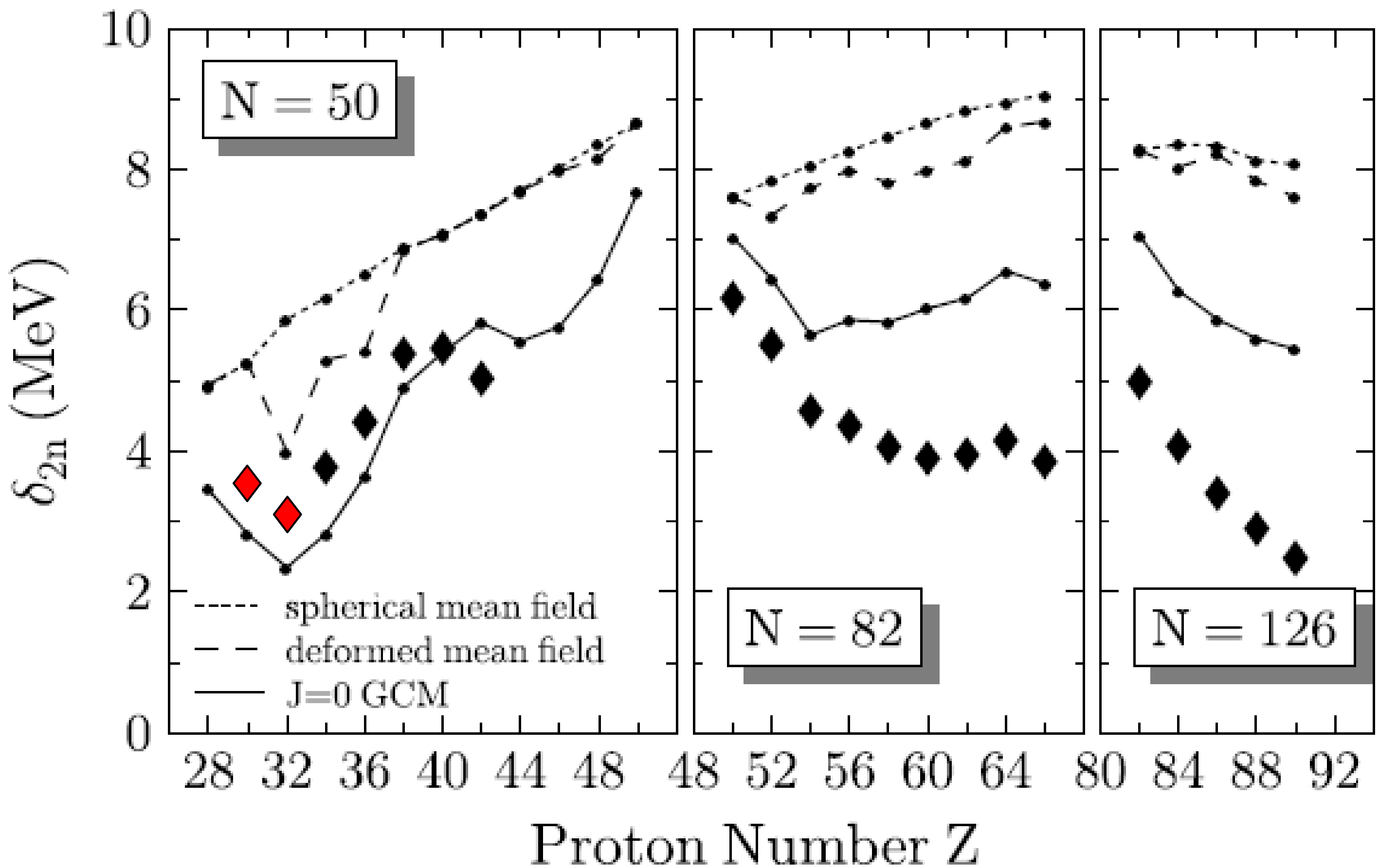

ISOLTRAP
^{82}Zn result
N = 50 gap
Δn / keV
Proton number
FRDM_Δn / keV
WS3.6_Δn / keV
D1M_Δn / keV
HFB17_Δn / keV
D1S_Δn / keV
Sly4_Δn / keV
SkP_Δn / keV
SkM_Δn / keV
DZ28_Δn / keV
Δn / keV

Masses from an interaction (mean field)



Deviation is in the eye of the beholder…

Masses from beyond the mean field

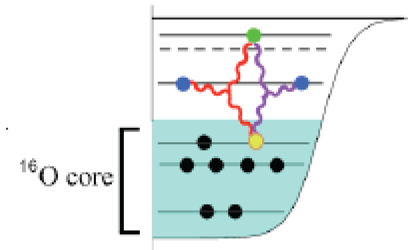


From beyond… to infinity ?

Bender, Bertsch, Heenen, PRC (2006)

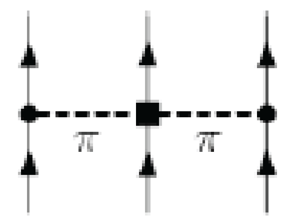
3N forces from chiral effective field theory

Hagen, Hjorth-Jensen, Jansen, Machleidt, Papenbrock
Continuum effects and 3N forces in n-rich O
Phys. Rev. Lett. 108 (2012)



Phys. Rev. Lett. (2012)
New Ca masses across N = 28
A. Gallant and the TITAN Collaboration
A. Schwenk et al., EFT calculations of Ca isotopes

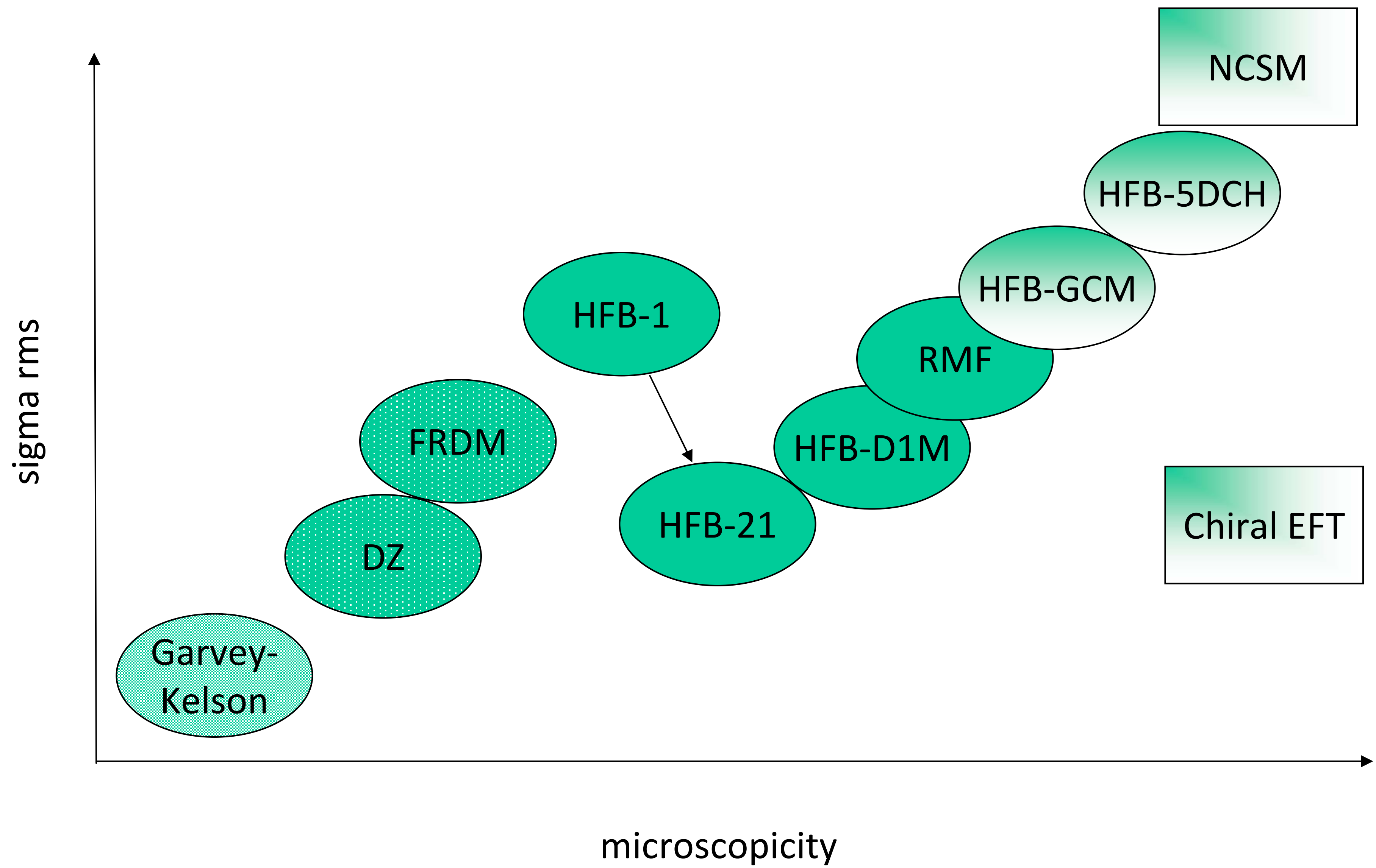
Nature (2013) accepted
N = 32 shell closure in Ca
F. Wienholtz and the ISOLTRAP Collaboration
A. Schwenk et al., EFT calculations of Ca isotopes

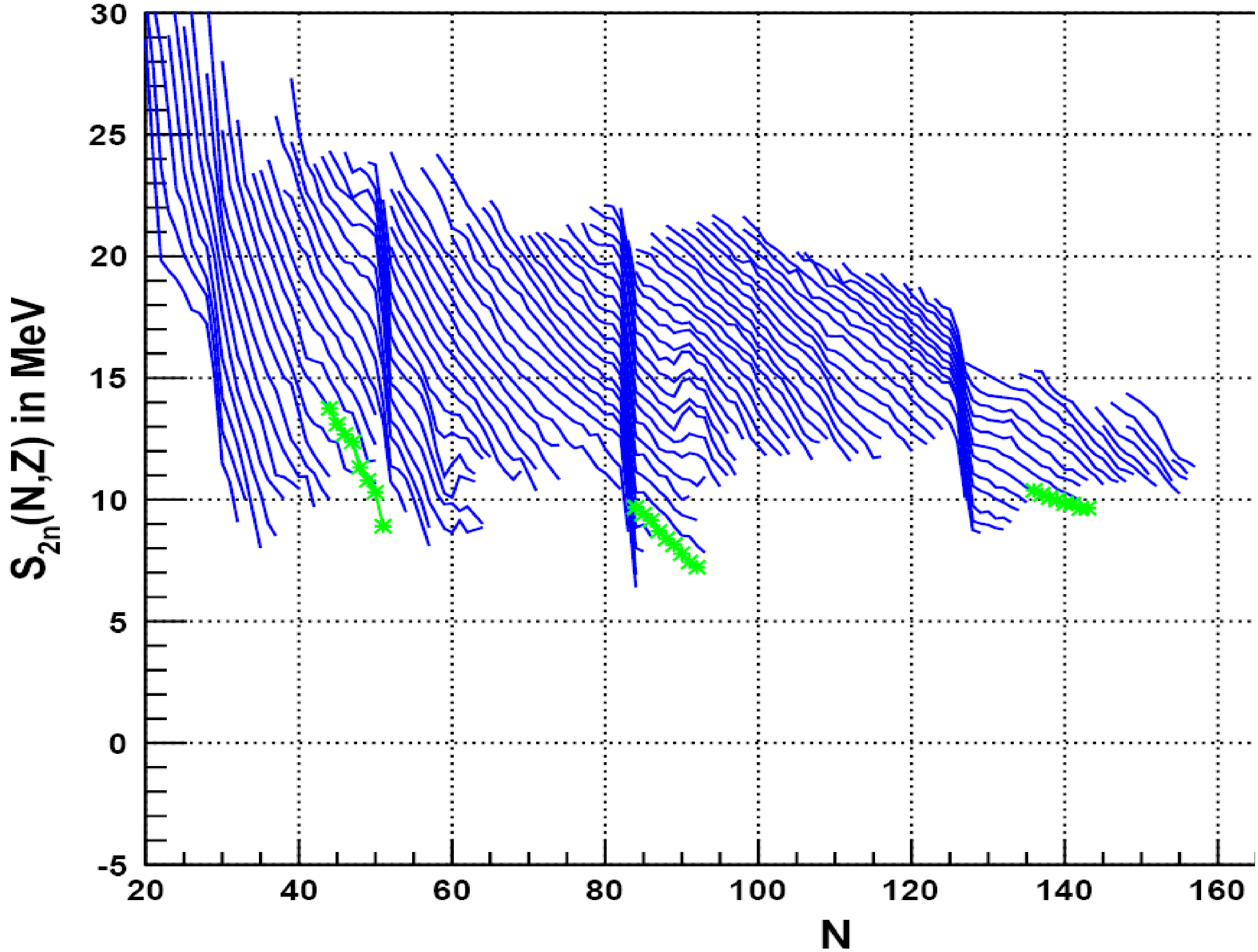


J.D. Holt, J. Menendez, A. Schwenk
Three-body forces and proton-rich nuclei (*N* = 8,20 isotones)
Phys. Rev. Lett. 110 (2013)

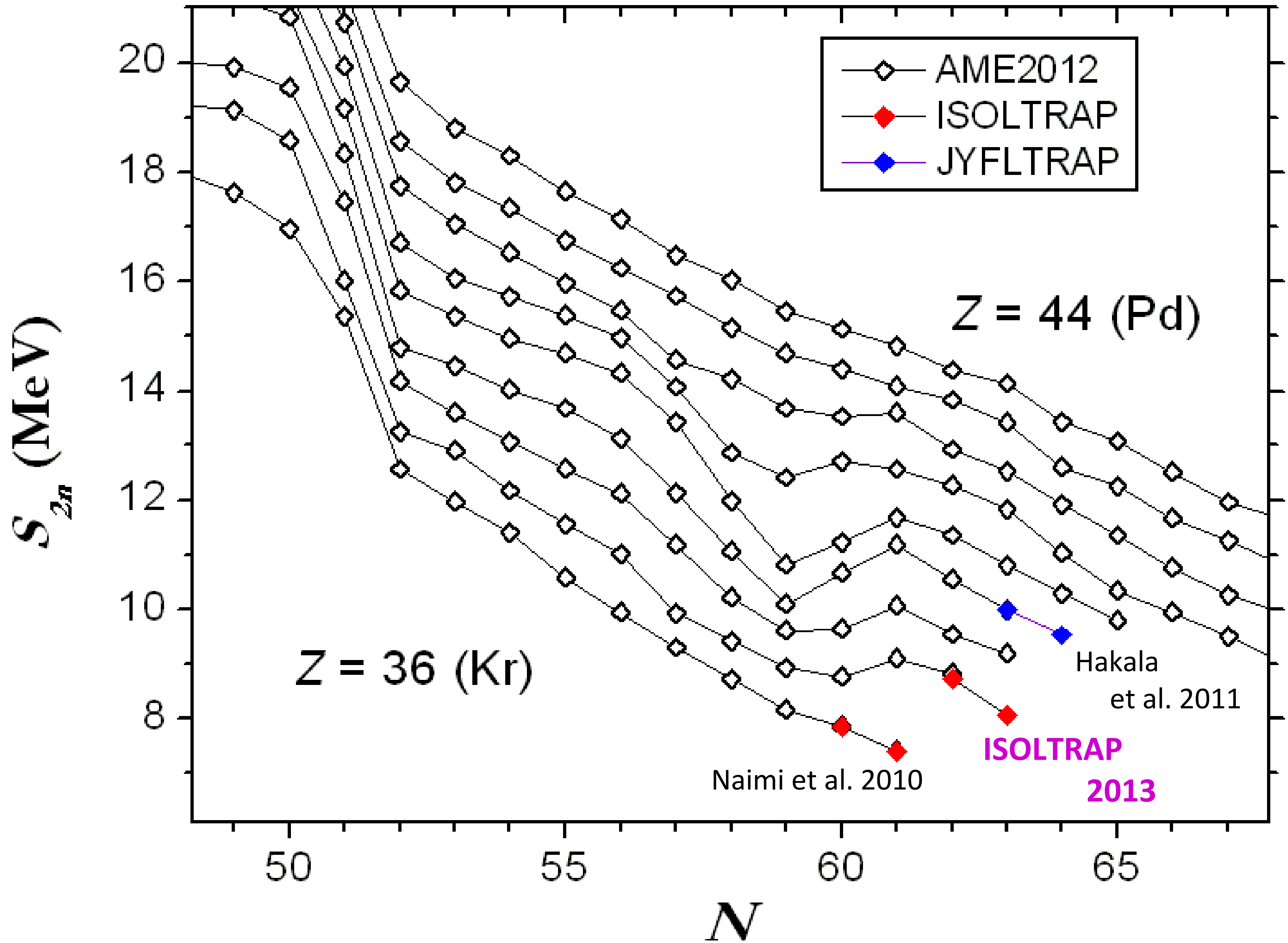
Phys. Rev. C 87, 021303(R) (2013)
Ab initio calculations of medium-mass nuclei with explicit chiral 3N interactions
Sven Binder, Joachim Langhammer, Angelo Calci, Petr Navrátil, and Robert Roth

A (foolhardy?) attempt at classification – for discussion purposes!

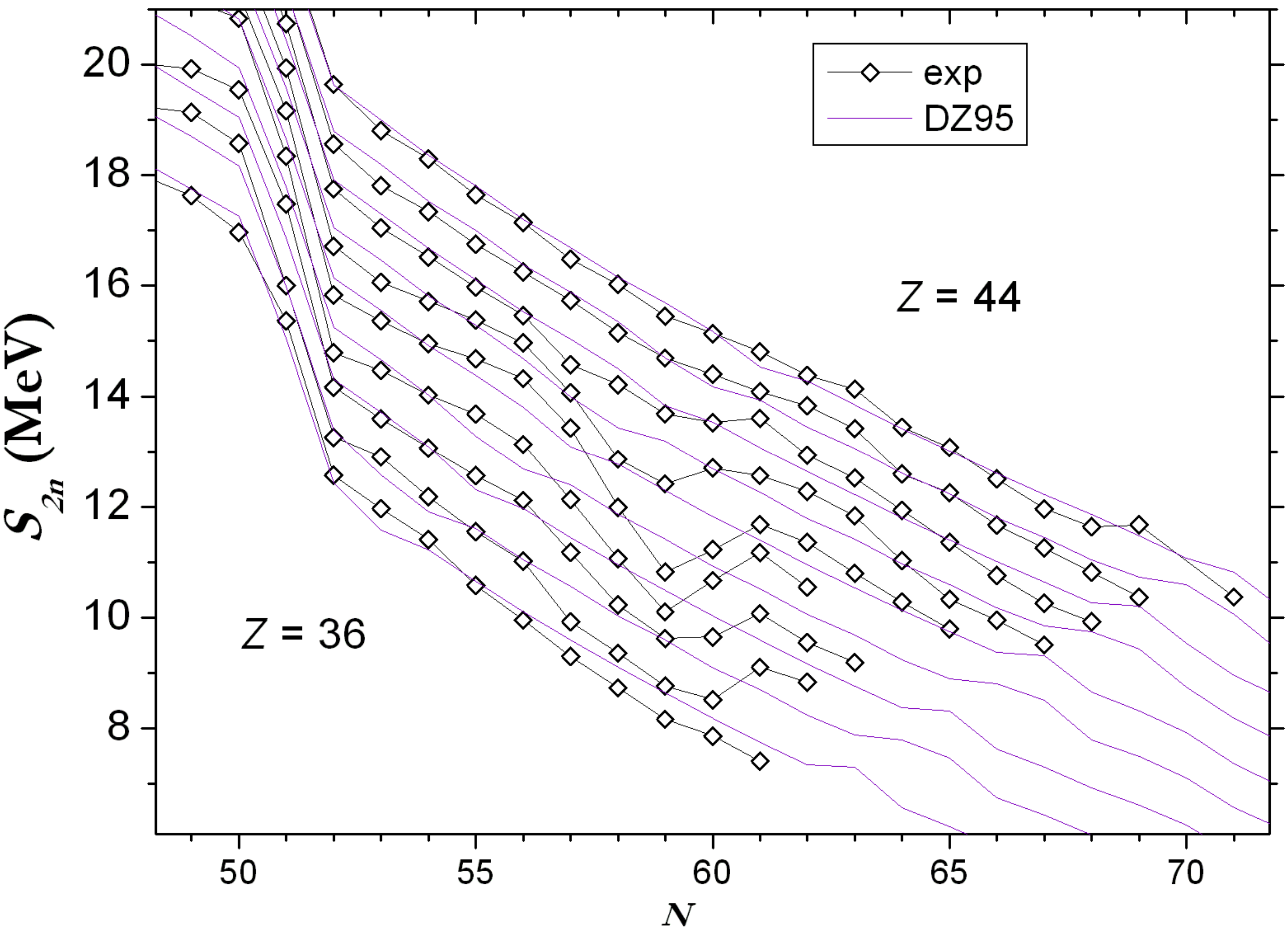


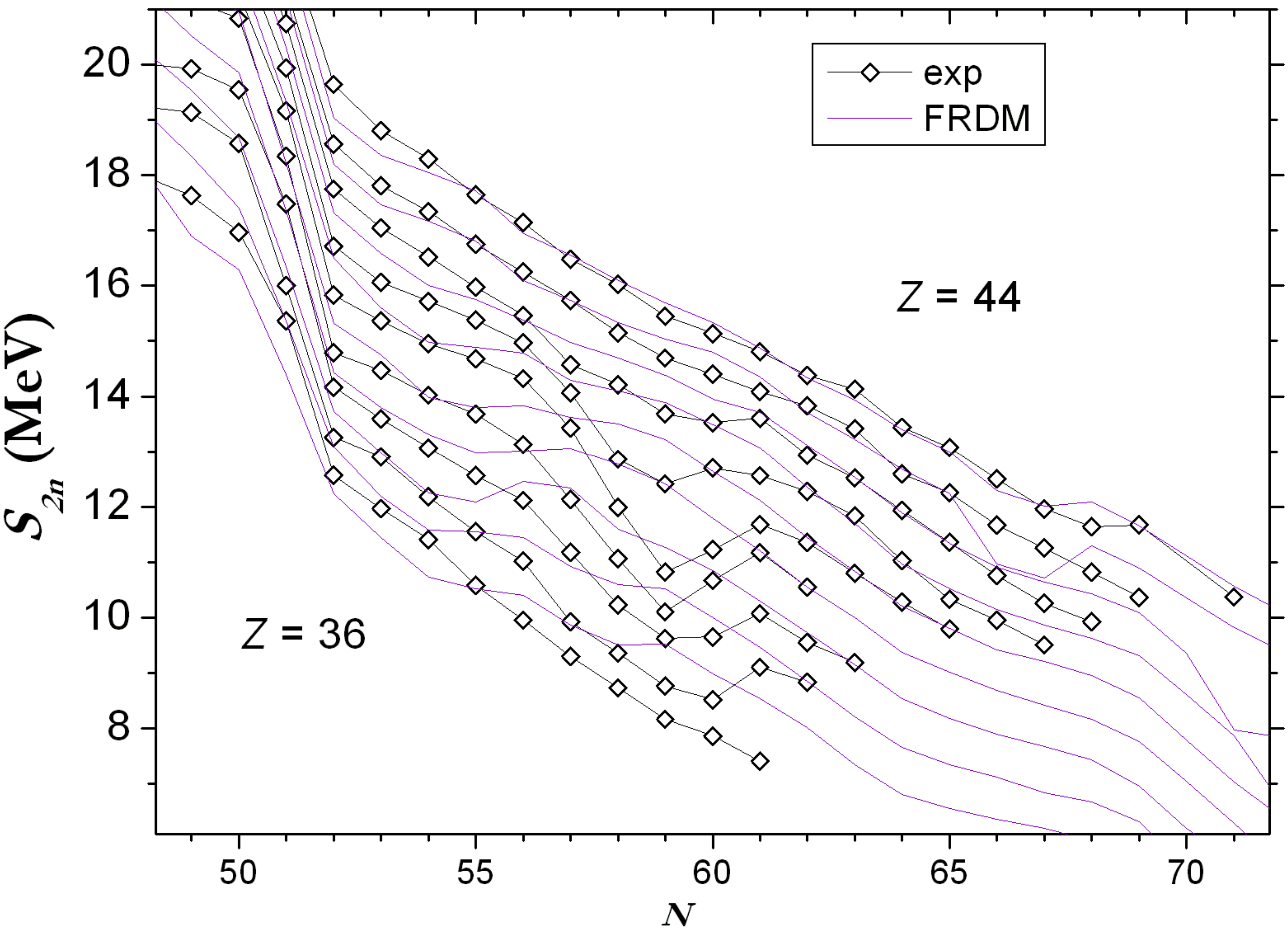


30
25
20
15
10
5
0
-5
20
40
60
80
100
120
140
160
N
S_{2n}(N,Z) in MeV

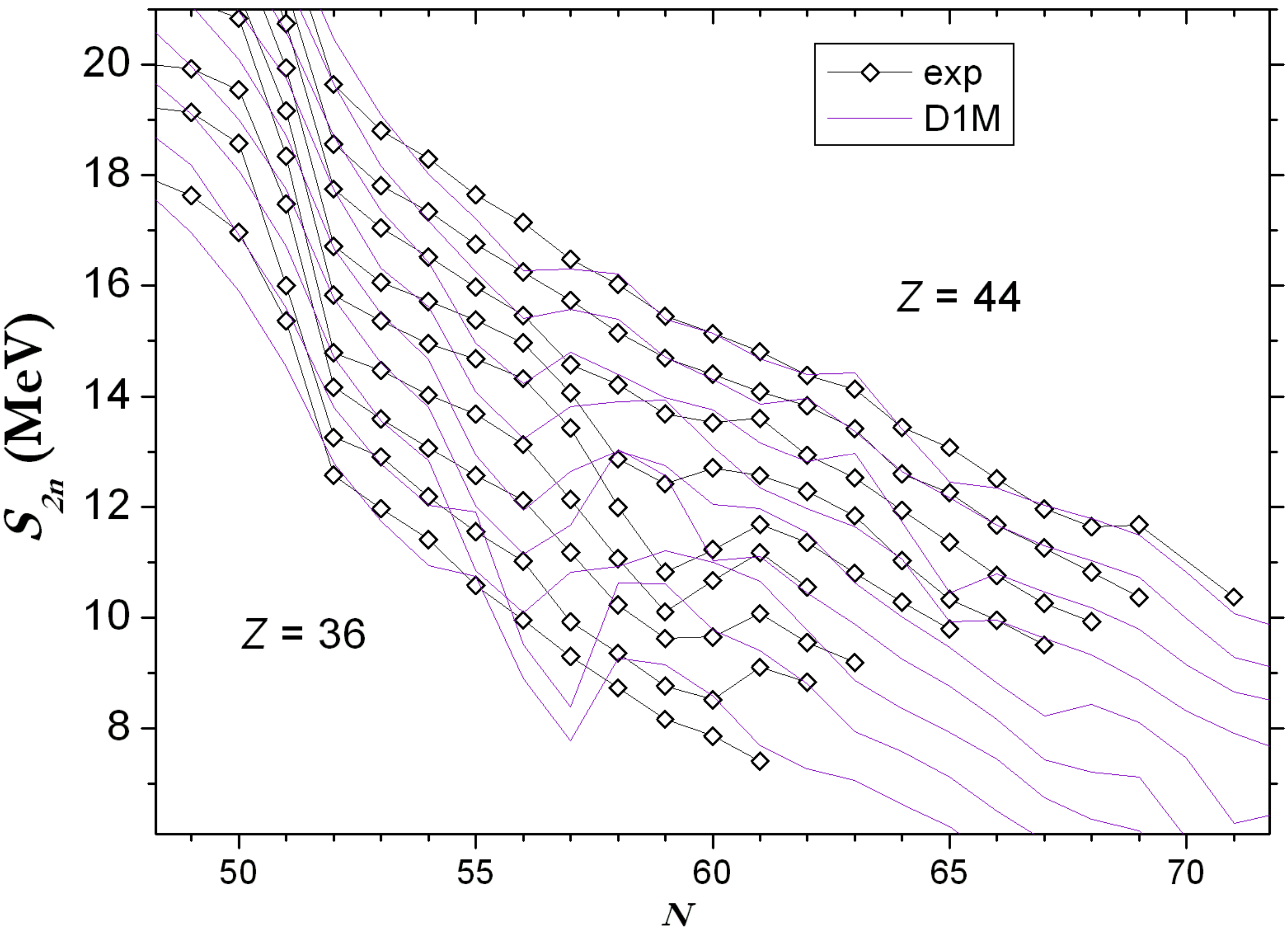


AME2012
ISOLTRAP
JYFLTRAP
Z = 44 (Pd)
Z = 36 (Kr)
Hakala et al. 2011
ISOLTRAP 2013
Naimi et al. 2010
S_{2n} (MeV)
N
20
18
16
14
12
10
8
50
55
60
65


exp
DZ95
Z = 44
Z = 36
S_2n (MeV)
N
20
18
16
14
12
10
8
50
55
60
65
70

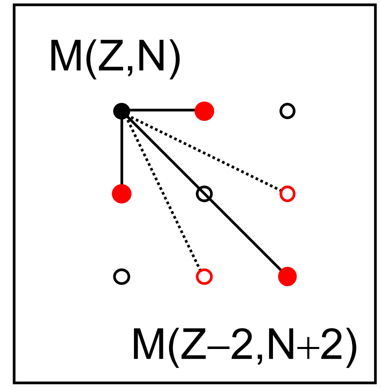


exp
FRDM
Z = 44
Z = 36
S_2n (MeV)
N
20
18
16
14
12
10
8
50
55
60
65
70



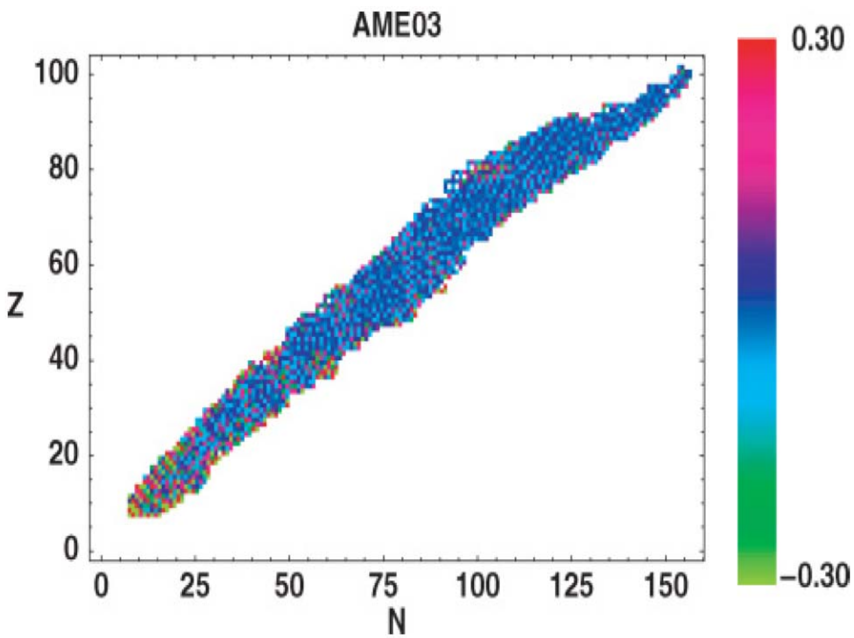
exp
D1M
Z = 44
Z = 36
S_{2n} (MeV)
N
20
18
16
14
12
10
8
50
55
60
65
70

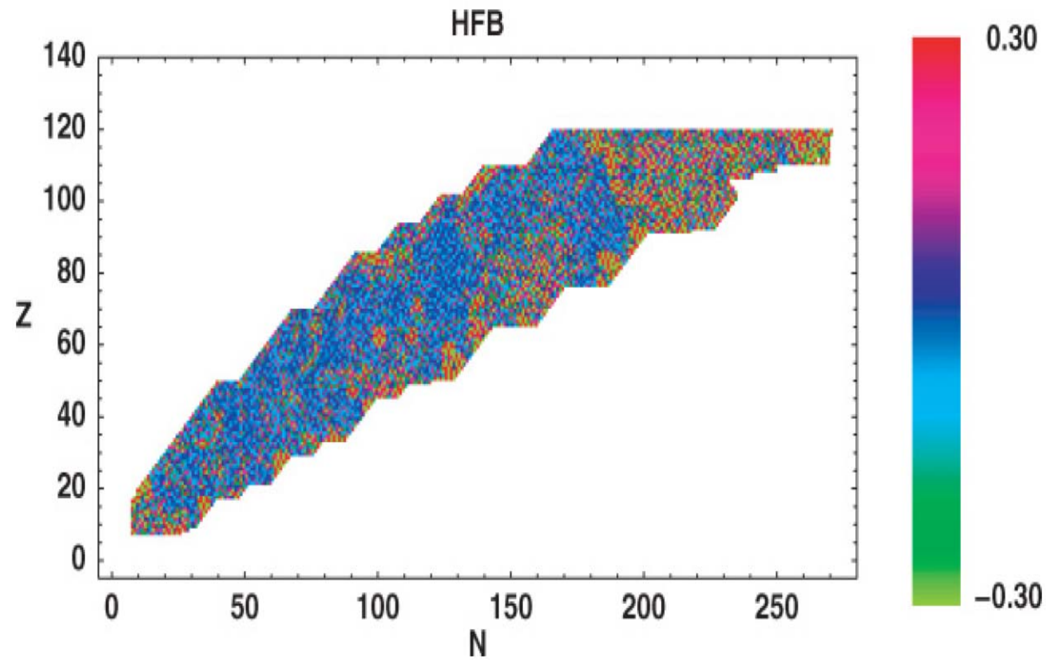
The Garvey-Kelson relations :



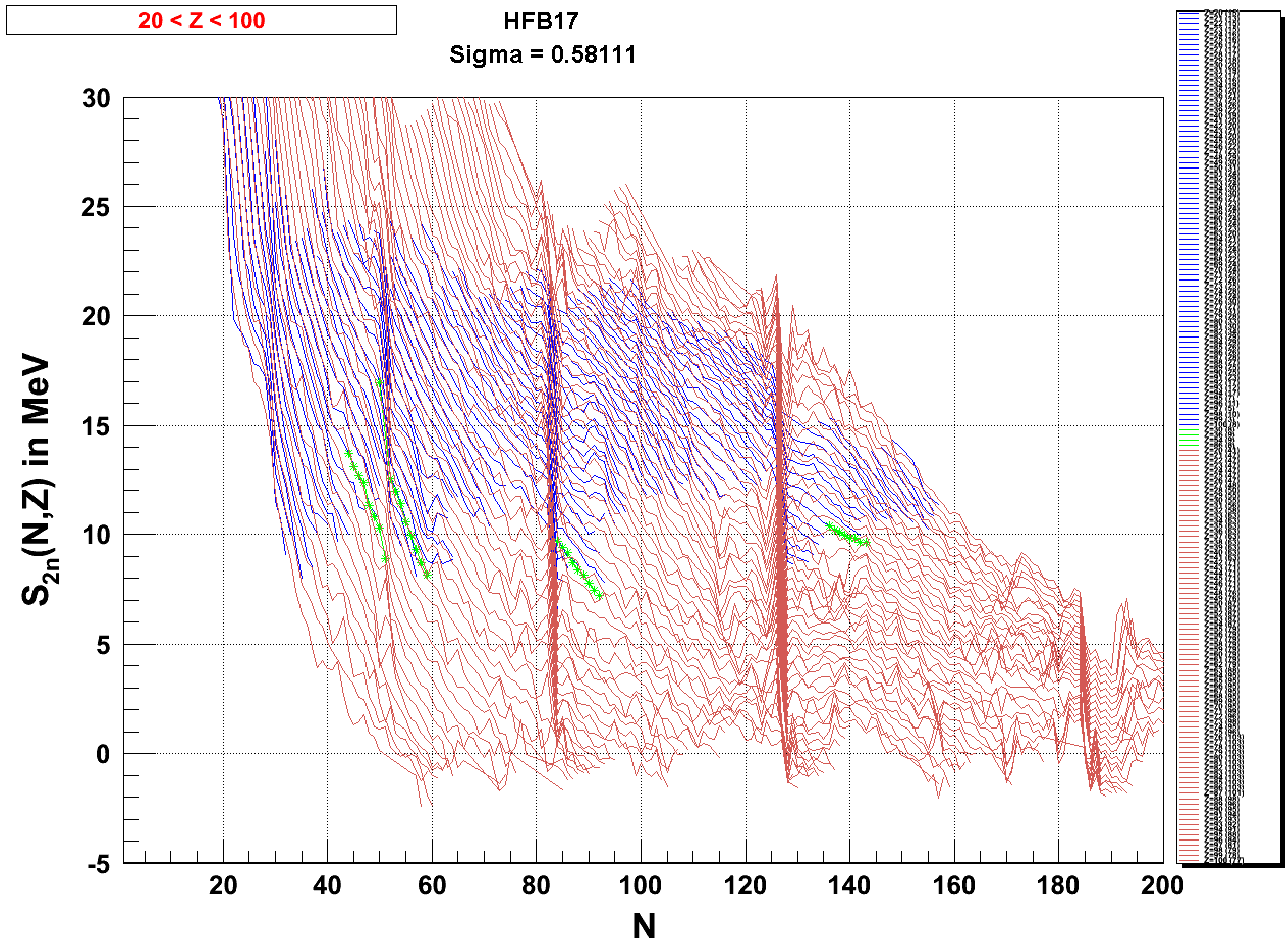
single-particle picture:
1 & 2-body terms cancel;
residual terms uncorrelated

$$M(N+2, Z-2) - M(N, Z) + M(N, Z-1) - M(N+1, Z-2) + M(N+1, Z) - M(N+2, Z-1) = 0$$

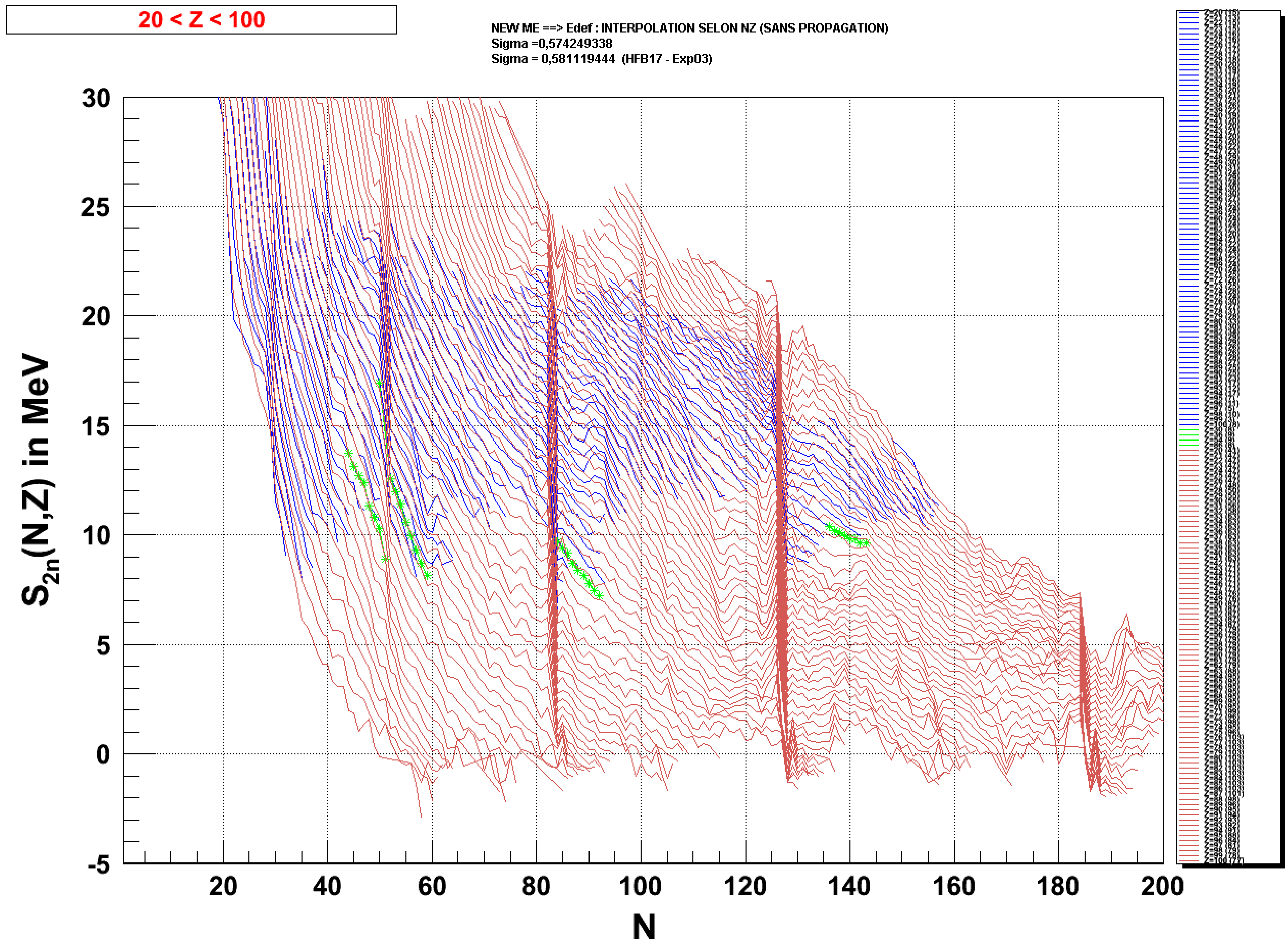


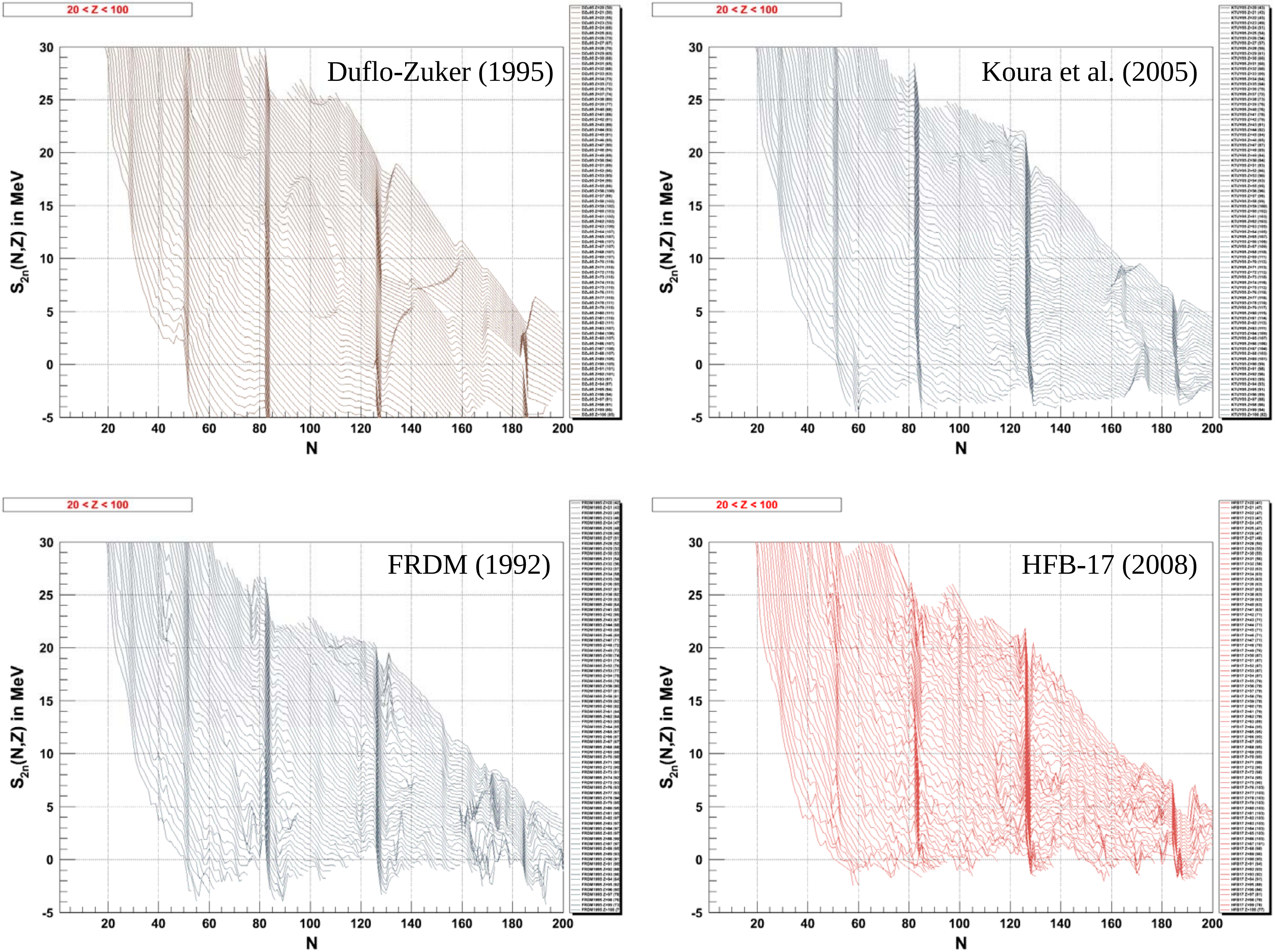


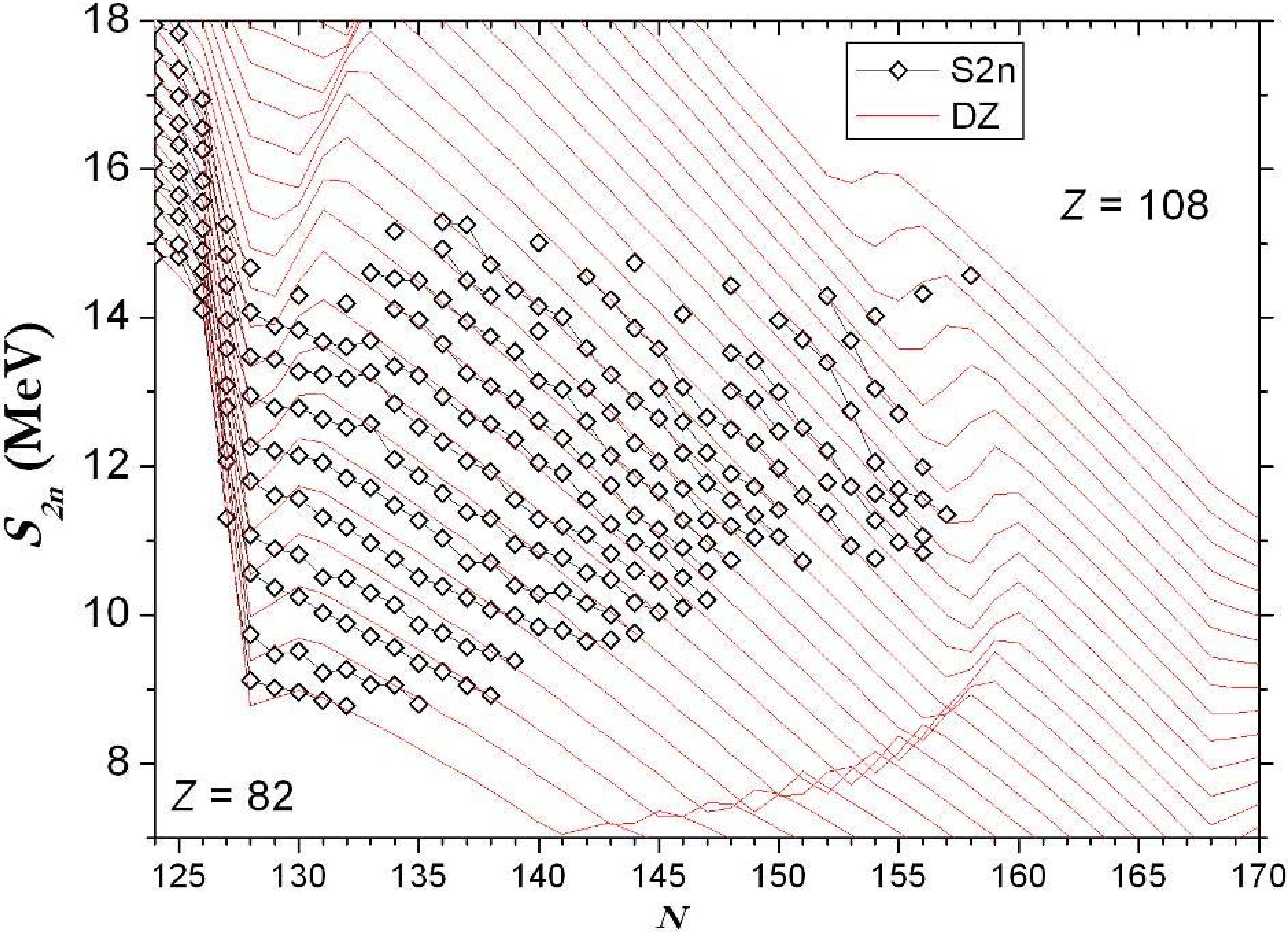
J. Barea, A. Frank, J. G. Hirsch, P. Van Isacker, S. Pittel, and V. Velazquez, PHYS. REV. C **77**, 041304(R) (2008)



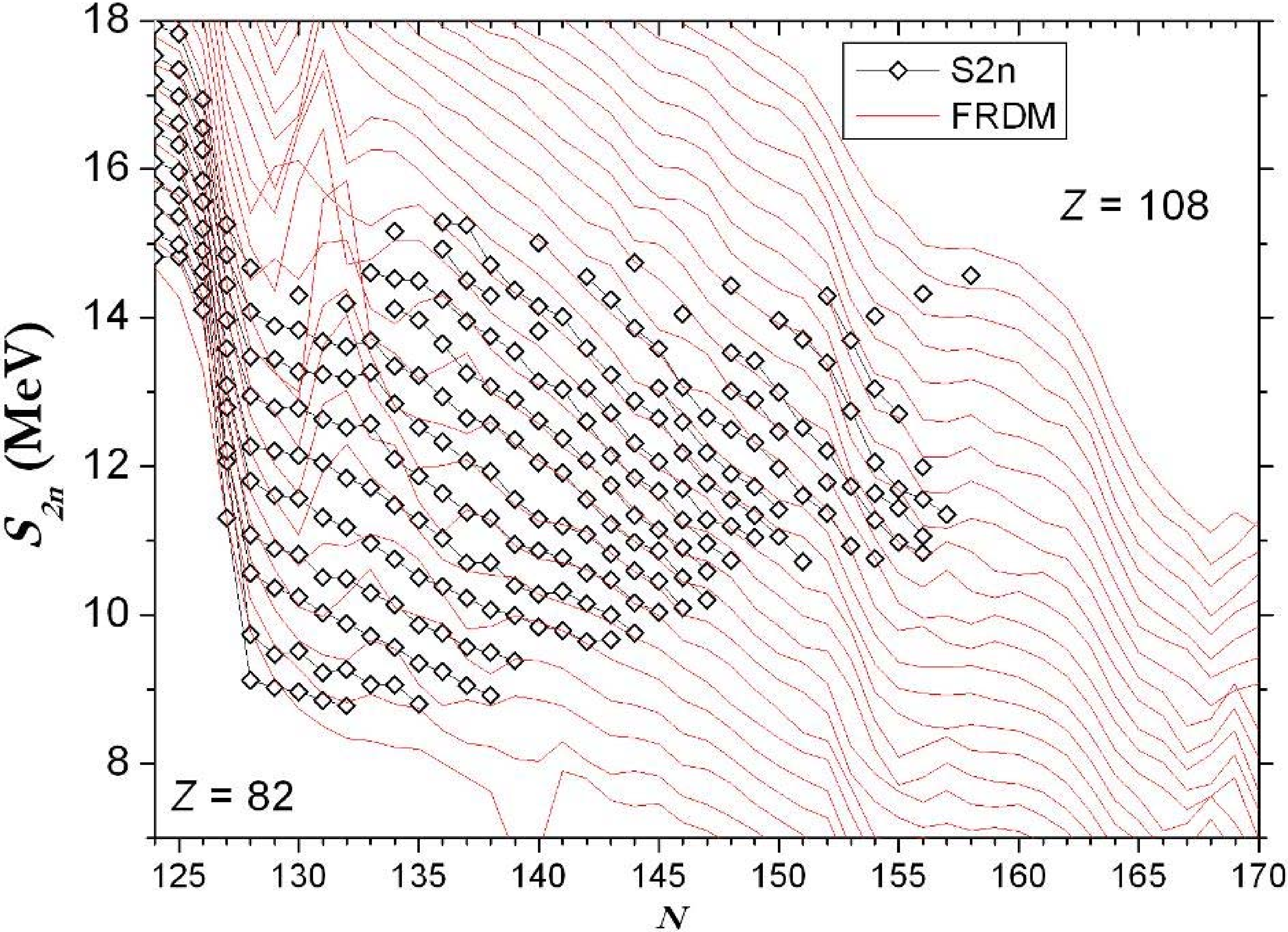
20 < Z < 100
HFB17
Sigma = 0.58111
$S_{2n}(N,Z)$ in MeV
N
30
25
20
15
10
5
0
-5
20
40
60
80
100
120
140
160
180
200


20 < Z < 100
NEW ME ==> Edef : INTERPOLATION SELON NZ (SANS PROPAGATION)
Sigma =0,574249338
Sigma = 0,581119444 (HFB17 - Exp03)
S2n(N,Z) in MeV
30
25
20
15
10
5
0
-5
20
40
60
80
100
120
140
160
180
200
N

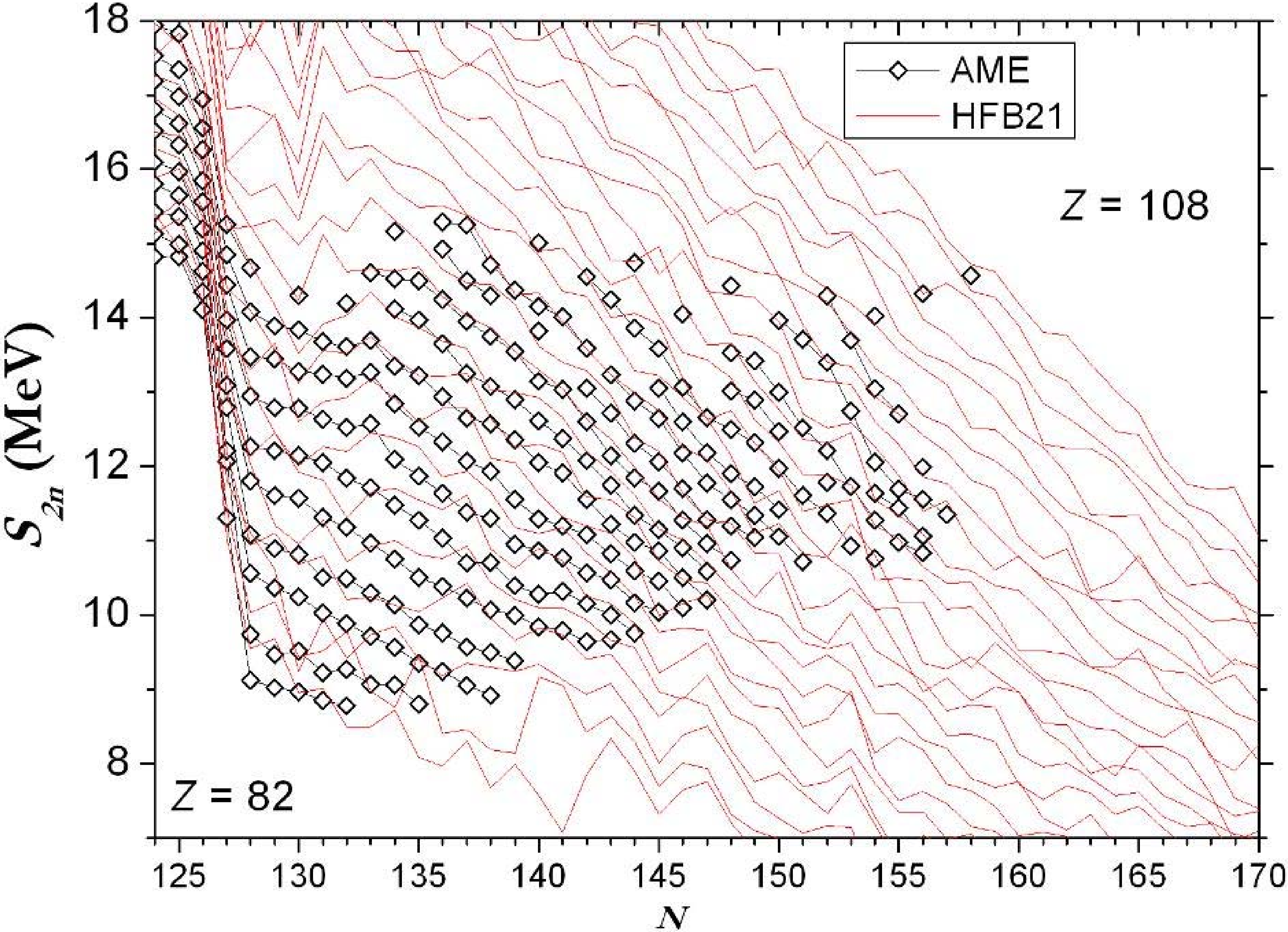

20 < Z < 100
Duflo-Zuker (1995)
S2n(N,Z) in MeV
N
20 < Z < 100
Koura et al. (2005)
S2n(N,Z) in MeV
N
20 < Z < 100
FRDM (1992)
S2n(N,Z) in MeV
N
20 < Z < 100
HFB-17 (2008)
S2n(N,Z) in MeV
N

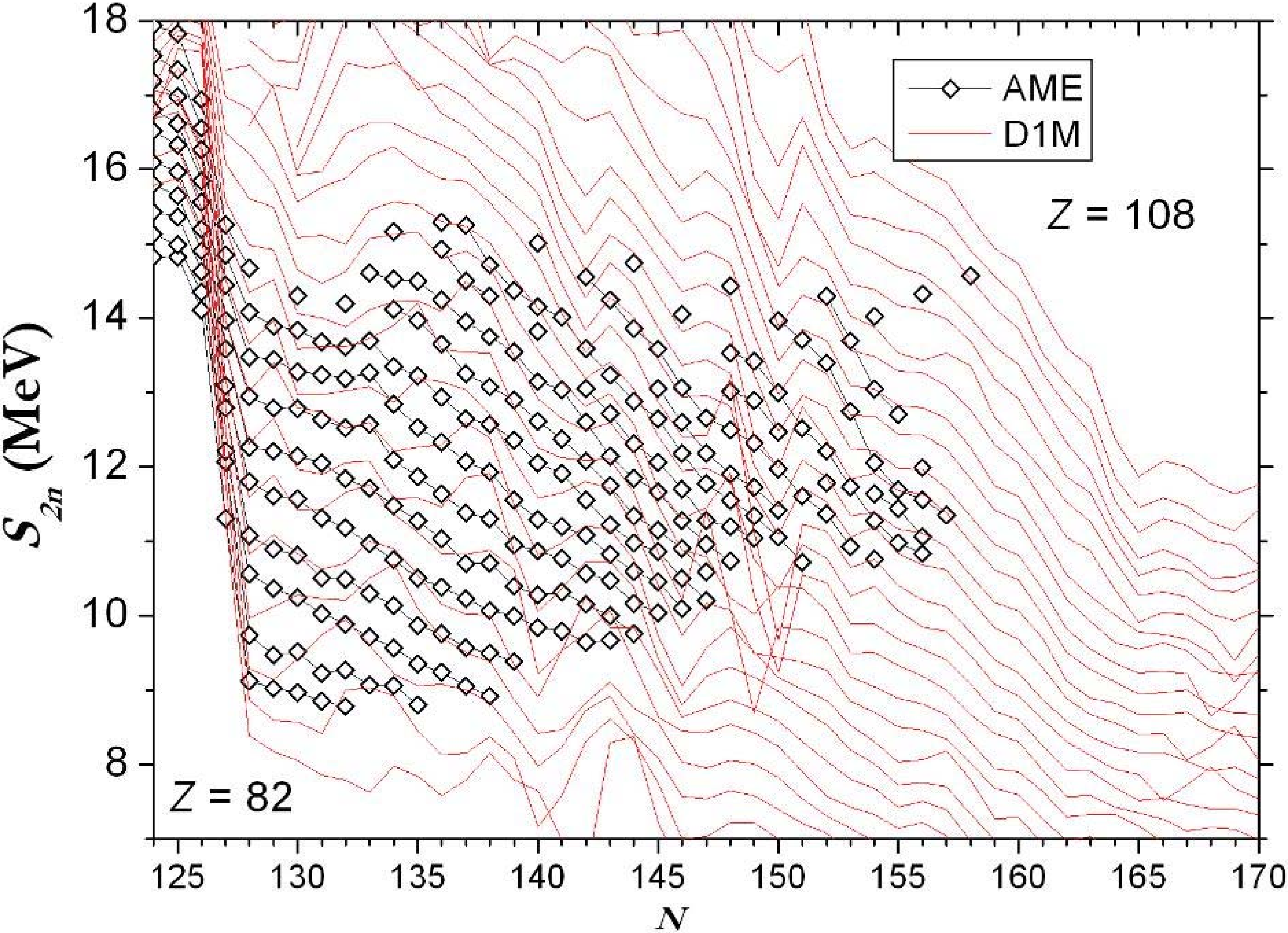


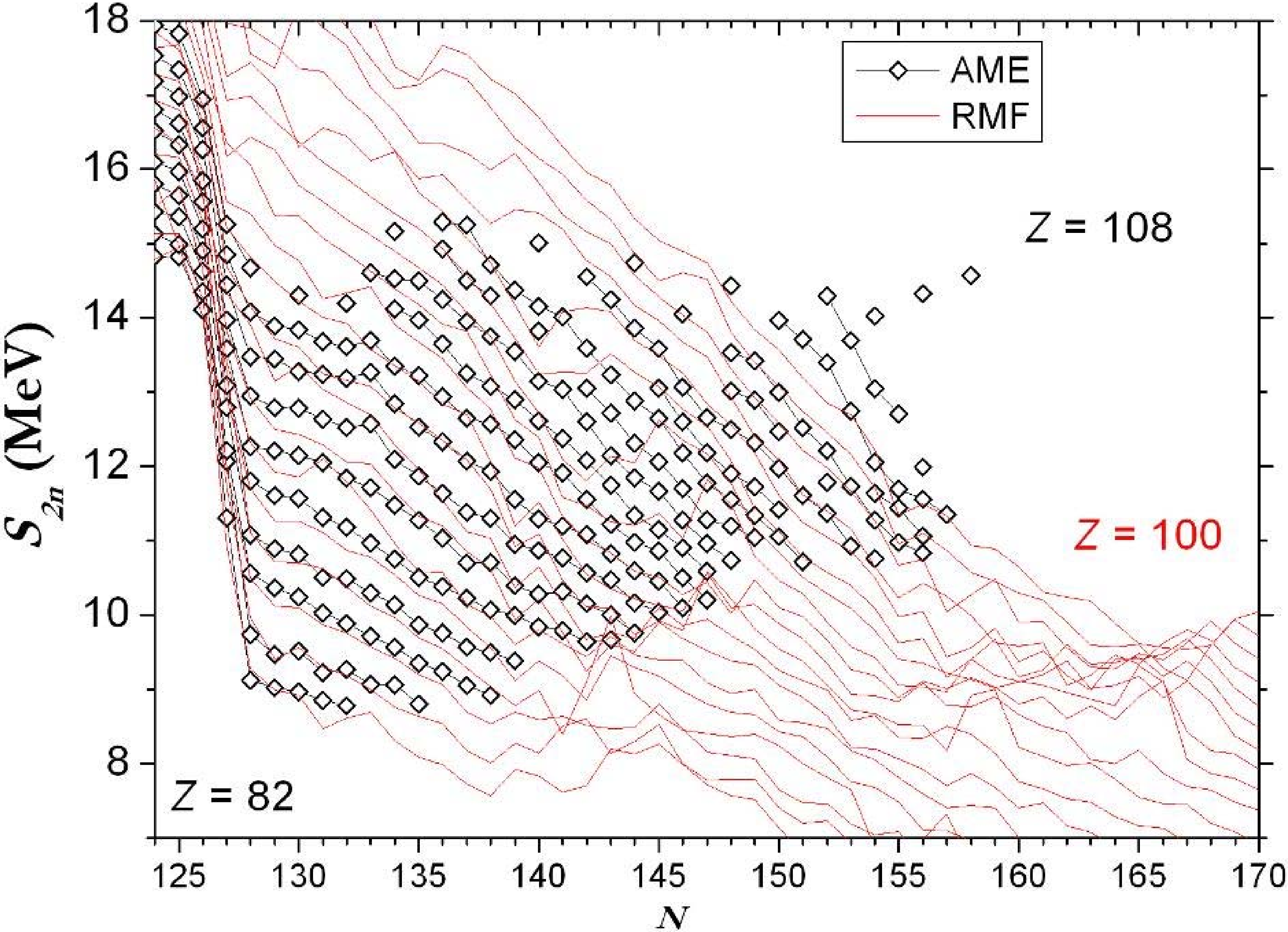
18
16
14
12
10
8
S_{2n} (MeV)
125
130
135
140
145
150
155
160
165
170
N
S2n
DZ
Z = 108
Z = 82



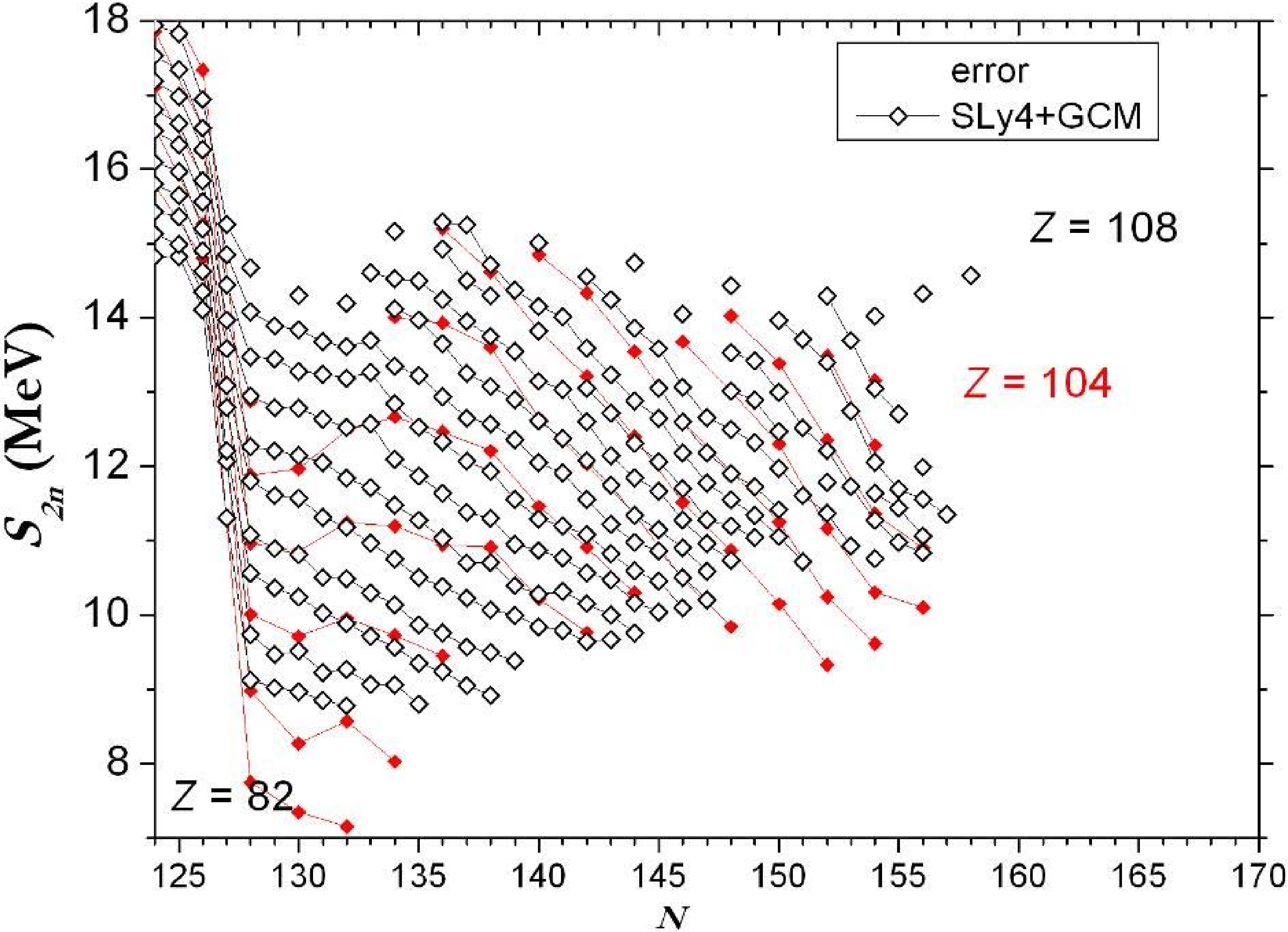
S2n
FRDM
Z = 108
Z = 82
S_{2n} (MeV)
N
18
16
14
12
10
8
125
130
135
140
145
150
155
160
165
170


AME
HFB21
Z = 108
Z = 82
S_2n (MeV)
N
18
16
14
12
10
8
125
130
135
140
145
150
155
160
165
170

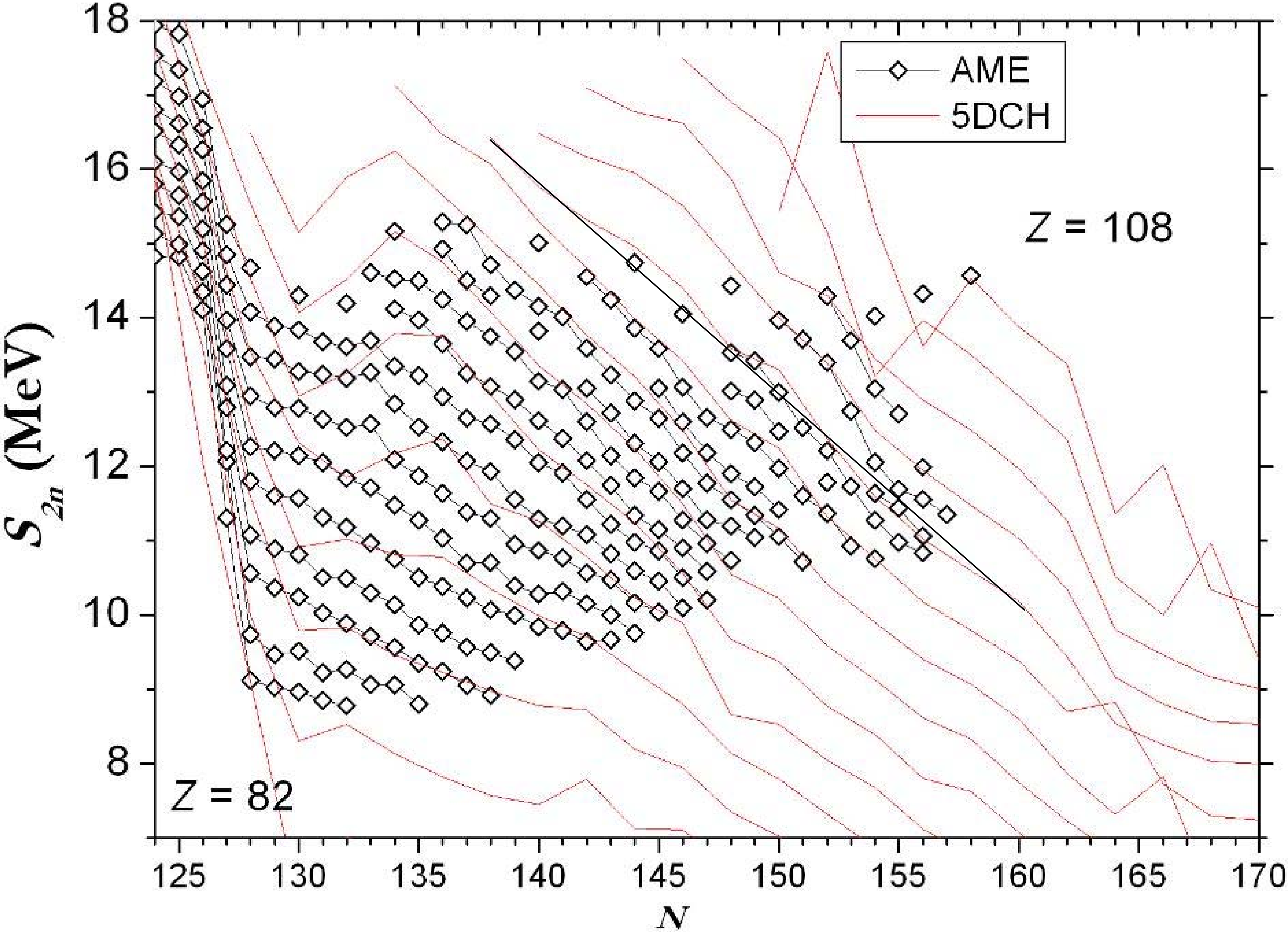

AME
D1M
Z = 108
Z = 82
S2n (MeV)
N
18
16
14
12
10
8
125
130
135
140
145
150
155
160
165
170



AME
RMF
Z = 108
Z = 100
Z = 82
S_{2n} (MeV)
N
18
16
14
12
10
8
125
130
135
140
145
150
155
160
165
170



error
SLy4+GCM
Z = 108
Z = 104
Z = 82
S_{2n} (MeV)
N
18
16
14
12
10
8
125
130
135
140
145
150
155
160
165
170



AME
5DCH
Z = 108
Z = 82
S_{2n} (MeV)
N
18
16
14
12
10
8
125
130
135
140
145
150
155
160
165
170

Nuclear Correlations and the *r* Process

A. Arcones*
Department of Physics, University of Basel, Klingelbergstraße 82, CH-4056, Switzerland
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, D-64291 Darmstadt, Germany

G. F. Bertsch
Department of Physics and Institute for Nuclear Theory, Box 351560, University of Washington, Seattle, Washington 98915, USA
(Received 21 November 2011; published 13 April 2012)

We show that long-range correlations for nuclear masses have a significant effect on the synthesis of heavy elements by the *r* process. As calculated by Delaroche *et al.* [Phys. Rev. C **81**, 014303 (2010)], these correlations suppress magic number effects associated with minor shells. This impacts the calculated abundances before the third *r*-process peak (at mass number $A \approx 195$), where the abundances are low and form a trough. This trough and the position of the third abundance peak are strongly affected by the masses of nuclei in the transition region between deformed and spherical. Based on different astrophysical environments, our results demonstrate that a microscopic theory of nuclear masses including correlations naturally smoothens the separation energies, thus reducing the trough and improving the agreement with observed solar system abundances.

Nuclear Correlations and the *r* Process

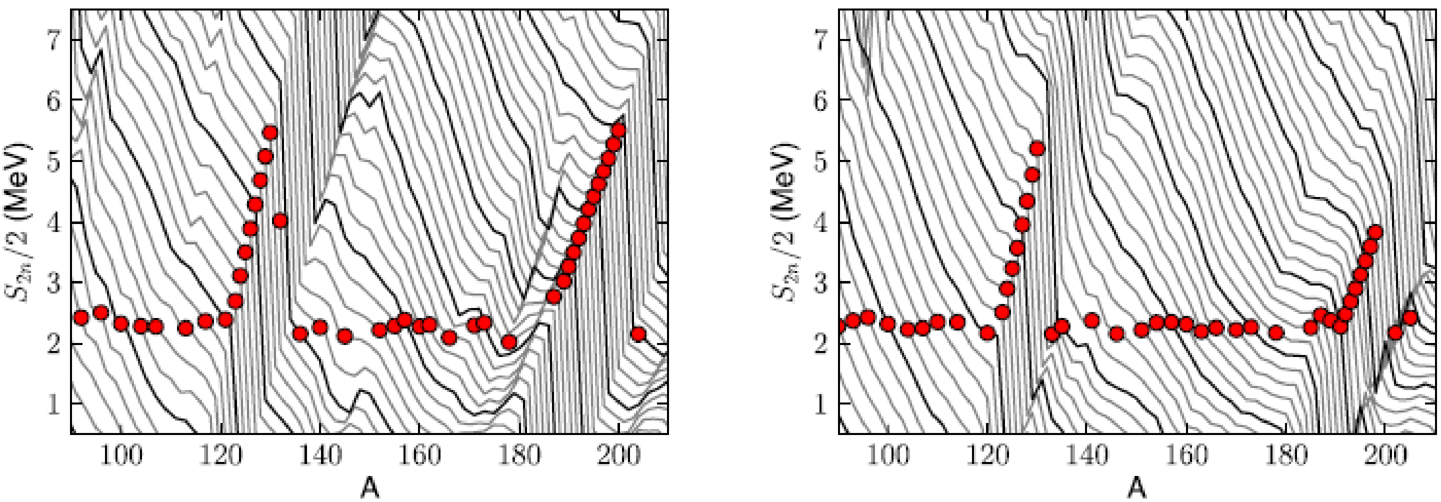
A. Arcones*

Department of Physics, University of Basel, Klingelbergstraße 82, CH-4056, Switzerland
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, D-64291 Darmstadt, Germany

G. F. Bertsch

Department of Physics and Institute for Nuclear Theory, Box 351560, University of Washington, Seattle, Washington 98915, USA

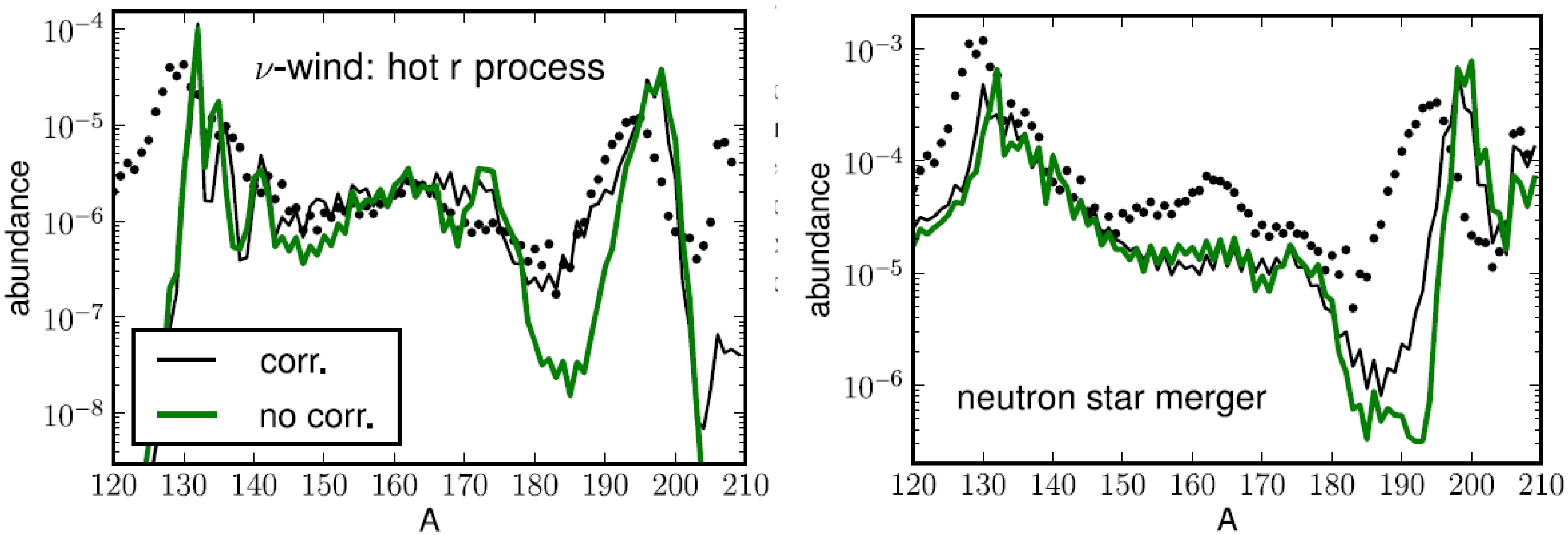
(Received 21 November 2011; published 13 April 2012)



Nuclear Correlations and the *r* Process

A. Arcones*
Department of Physics, University of Basel, Klingelbergstraße 82, CH-4056, Switzerland
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, D-64291 Darmstadt, Germany

G. F. Bertsch
Department of Physics and Institute for Nuclear Theory, Box 351560, University of Washington, Seattle, Washington 98915, USA
(Received 21 November 2011; published 13 April 2012)



Using averages – maybe it's enough after all?

Discussion points

- Experiment: how much farther can we go?
- Are mic-mac models passé?
- Will (Brussels-Montreal) Skyrme HFB continue?
  Should it?!
- Beyond the mean field:
  Will we get odd nuclides?
  Do we need odd nuclides?!
- What is the role of the tensor force?
- Can chiral EFT come to the rescue? When?!
- Is there something better out there…?