Mass measurements for nuclear astrophysics

Lecture 2: the mass evaluation; chaos; the future

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Joint Institute for Nuclear Astrophysics
Special School on Nuclear Mass Models
Argonne National Laboratory
May 8-16, 2007

I. General concepts – binding energy; the mass unit; resolution; precision; accuracy

II. Physics motivation
- a nuclear structure – shells, deformation, pairing, halos (the mass scale)
- b weak interaction – superallowed beta decay and the CKM matrix
- c astrophysics – stellar nucleosynthesis

III. Production of radionuclides – methods of FIFS (fragmentation) et ISOL;
(ion manipulation using traps and gas cells)

IV. Mass measurement techniques
- i. indirect methods – reactions et decays
- ii. direct methods – time of flight (SPEG et CSS2 au GANIL; ESR isochronous mode at GSI); revolution (cyclotron) frequency (ESR Schottky mode; ISOLTRAP and MISTRAL at ISOLDE)

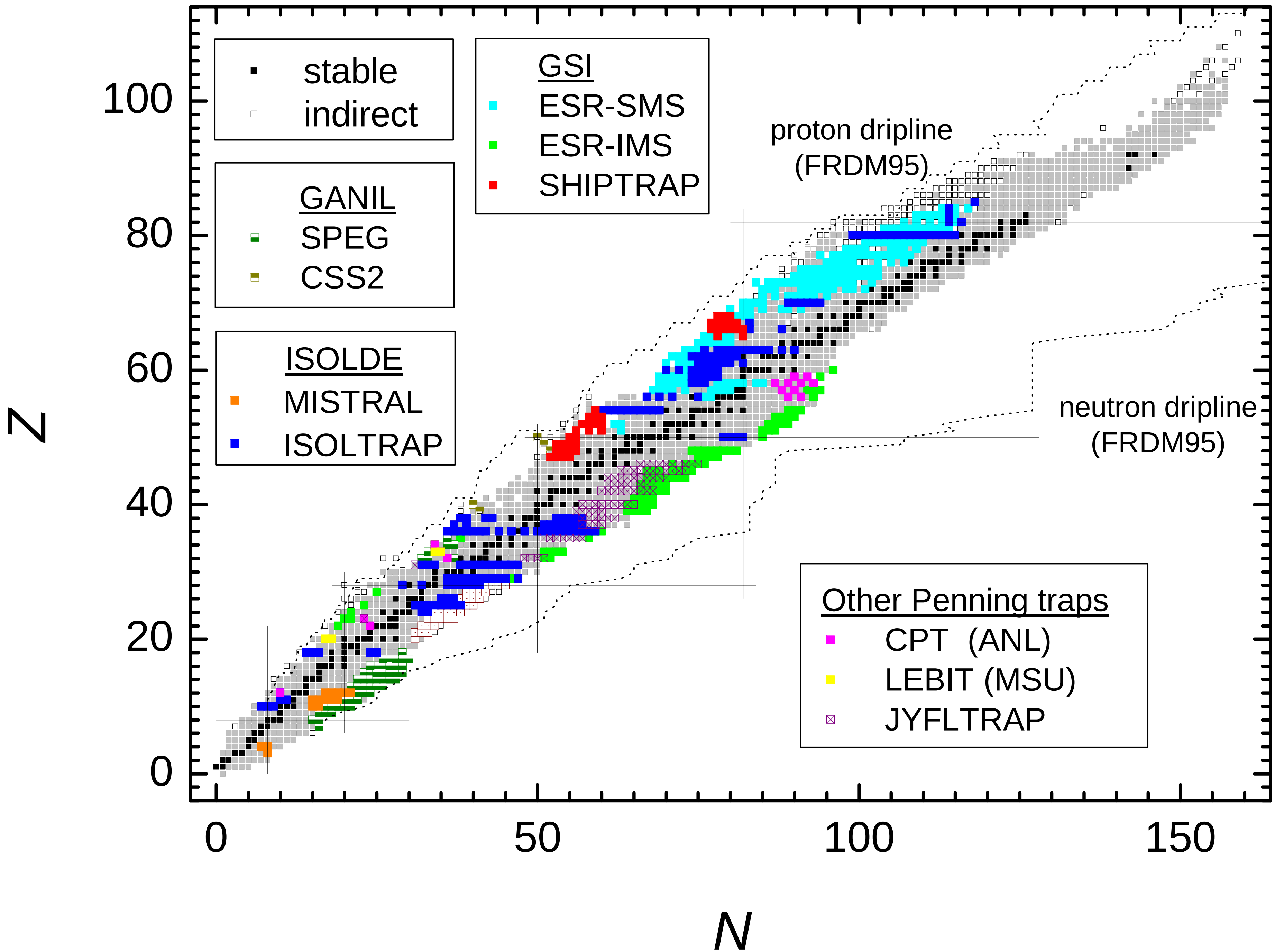
V. Comparisons of the different methods

VI. The atomic mass evaluation (demonstration of the program *NUCLEUS*)

VII. Mass models and comparisons; chaos on the mass surface?

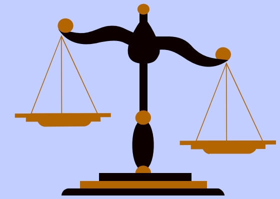
VIII. A look into the future

IX. Conclusions

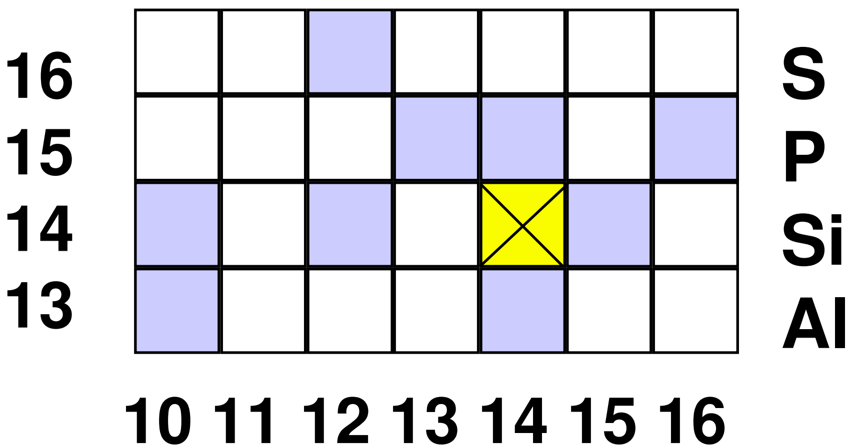


stable
indirect
GANIL
SPEG
CSS2
ISOLDE
MISTRAL
ISOLTRAP
GSI
ESR-SMS
ESR-IMS
SHIPTRAP
proton dripline
(FRDM95)
neutron dripline
(FRDM95)
Other Penning traps
CPT (ANL)
LEBIT (MSU)
JYFLTRAP
Z
N
0
20
40
60
80
100
0
50
100
150

*The atomic mass evaluation**



Not a compilation !



^{27}Al (p,γ) ^{28}Si
^{28}Si (^{3}He,^{8}Li) ^{23}Al
^{28}Si (^{4}He,^{8}He) ^{24}Si
^{28}Si (p,t) ^{26}Si
^{28}Si (p,n) ^{28}P

^{28}Si (d,p) ^{29}Si
^{28}Si (p,γ) ^{29}P
^{28}Si (π^{+},π^{-}) ^{28}S
^{31}P (p,α) ^{28}Si
and ^{28}Si / ^{12}C

* G. Audi and A.H. Wapstra, *Nuclear Physics* A 1988, 1993, 1995, 2003

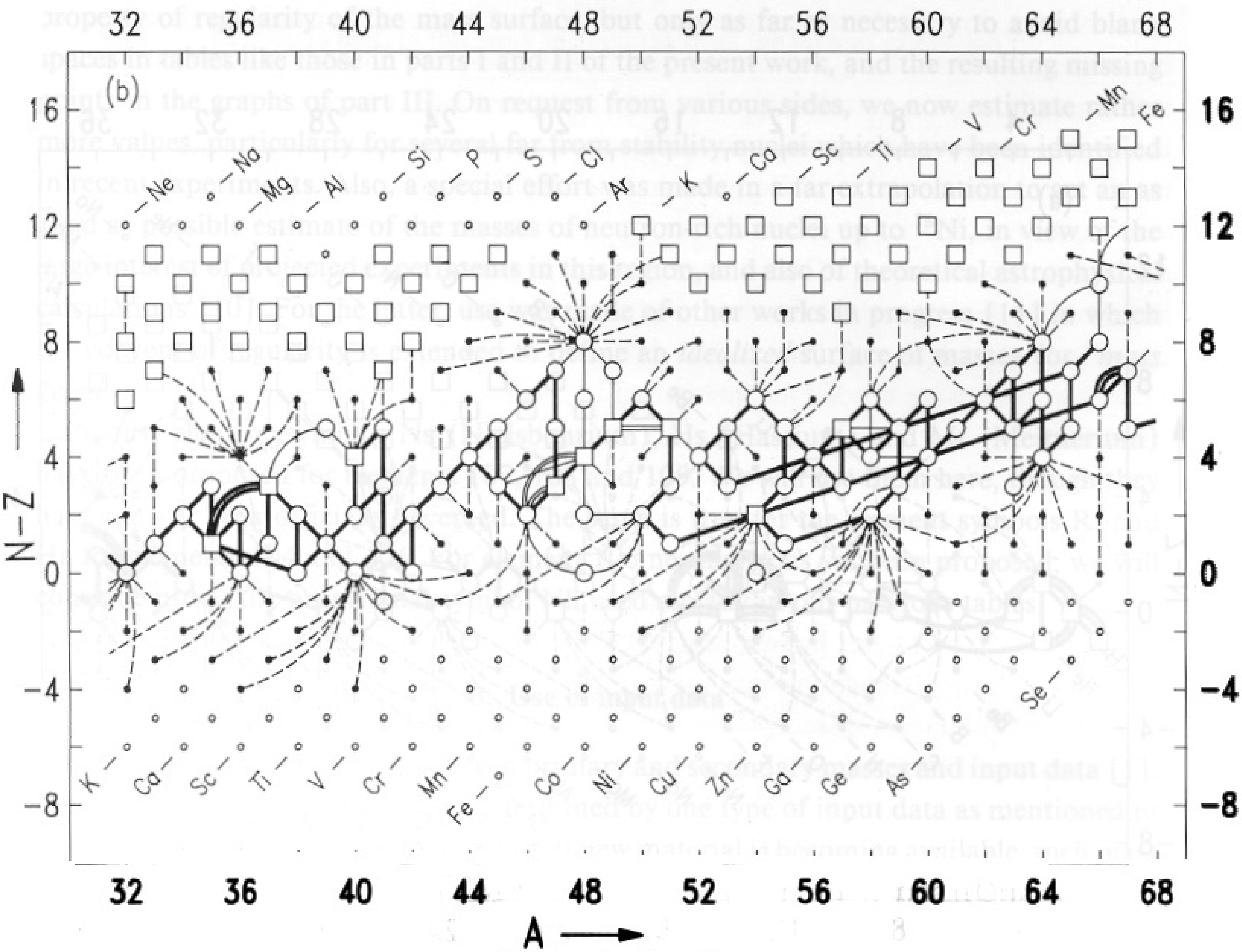
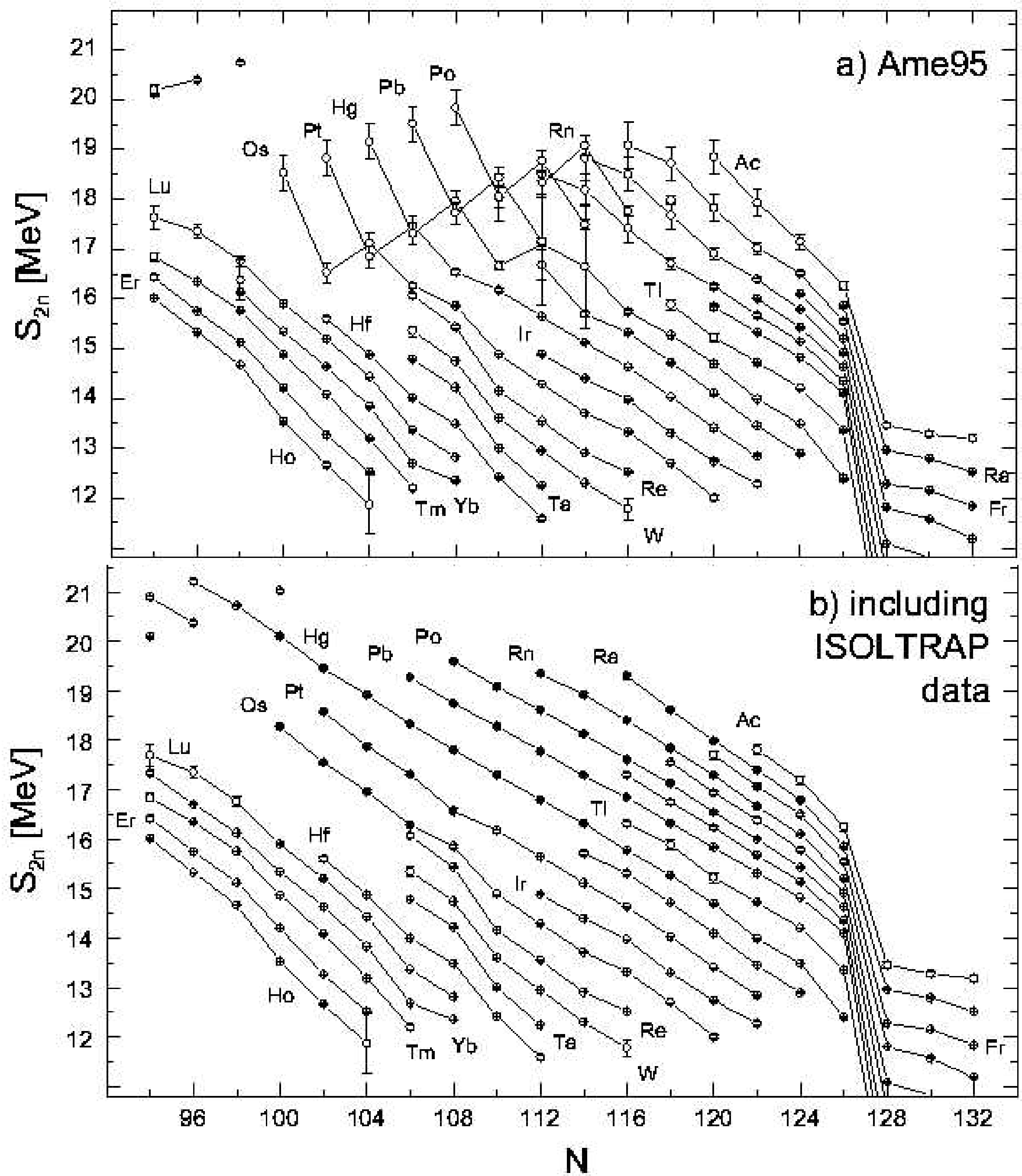


Fig. 1 — continued.



S. Schwarz et al., Nucl. Phys. A 693 (2001)

First determination
of isomeric levels
by mass spectrometry!

The Mass Evaluation

$$\begin{bmatrix} \vdots \\ {}^{28}\mathrm{Si} \\ \vdots \end{bmatrix} = \begin{bmatrix} \ddots & & \\ & 1 & \\ & & \ddots \end{bmatrix} \begin{bmatrix} \cdots & {}^{28}\mathrm{Si} & \cdots \end{bmatrix}$$

<u>least squares mass adjustment (2003)</u>

- 7773 experimental data (374 rejected)
- primary data: 967 energy and 414 inertia
- plus 887 estimated data
- 1381 equations with 847 parameters
- 2228 ground state masses (and 201 isomers)
- plus 951 estimated values (and 122 isomers)

→ Audi-Wapstra mass table

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT

Nuclear Physics A 729 (2003) 337–676

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

The AME2003 atomic mass evaluation *

(II). Tables, graphs and references

G. Audi[a,§], A.H. Wapstra[b] and C. Thibault[a]

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[b] *National Institute of Nuclear Physics and High-Energy Physics, NIKHEF, PO Box 41882, 1009DB Amsterdam, The Netherlands*

N	Z	A	Elt.	Orig.	Mass excess (keV)		Binding energy per nucleon (keV)		Beta-decay energy (keV)			Atomic mass μu	
15	6	21	C	x	45960#	500#	5659#	24#	β^-	20710#	510#	21 049340#	540#
14	7		N	x	25250	100	6608	5	β^-	17190	100	21 027110	100
13	8		O	-3n	8063	12	7389.3	0.6	β^-	8110	12	21 008656	13
12	9		F	-nn	-47.6	1.8	7738.29	0.09	β^-	5684.2	1.8	20 999949.0	1.9
11	10		Ne	-n	-5731.78	0.04	7971.713	0.002		*		20 993846.68	0.04
10	11		Na	-p	-2184.2	0.7	7765.52	0.03	β^+	3547.6	0.7	20 997655.2	0.8
9	12		Mg	+3n	10911	16	7104.7	0.8	β^+	13095	16	21 011713	18
8	13		Al	x	26120#	300#	6343#	14#	β^+	15210#	300#	21 028040#	320#

Atomic Masses Data Center (AMDC): http://www-csnsm.in2p3.fr/

Prof. Dr. Aaldert Hendrik Wapstra (1922–2006): Grand Inquisitor of the Atomic Masses

It is with great sadness that we say "*adieu*" to our colleague Aaldert Wapstra who passed away at home in Amsterdam December 4, 2006.

Wapstra's career in nuclear physics spanned five decades from 1953 when he received his doctorate from the University of Amsterdam and became Professor at Delft Technical University, in 1955. In 1963, he joined the executive board of the IKO, which later became the premier subatomic physics institute of the Netherlands: NIKHEF. Succeeding Van Lieshout in 1971, he was director of NIKHEF until 1982. Although he retired in 1987, his active contribution to the Atomic Mass Evaluation continued through 2005.

The mass of an atom, when measured accurately enough, yields the nuclear binding energy which, in turn, has important implications in a wide range of subatomic physics. Because masses can be determined via the different techniques of decay spectroscopy, reactions or mass spectrometry, the production of a mass table requires a meticulous and rigorous evaluation procedure.

Aaldert Wapstra first provided such an evaluation, at the first international conference dedicated to atomic masses. With F. Everling, L. A. König, and J. H. E. Mattauch, he established the procedure for producing—and testing consistency of—the different results. Since that time, the so-called AME has been updated at regular intervals with the most recently published, 2003 evaluation comprising reliable masses for some 3,000 nuclides. It is the second most cited reference in nuclear physics and forms a unique, common benchmark for nuclear theory.

Aaldert helped formulate the definition of the mass unit, designated as *u*, for "unified" unit, equal to one twelfth the mass of ^{12}C. He liked to joke about its singular name: "Let us be firm in retaining the *u*, let us even make it a double-*u*!" as a reference to has last initial.

The evaluation is a veritable experimental exercise, requiring great fluency in the technical methods of measuring masses. In this regard, Aaldert was extremely interested in various breeds of mass spectrometers, offering such pearls of wisdom as: "My experience, in the course of 55 years in evaluating data, has been that precision measurements with non-focussing instruments should be considered with a healthy distrust."

At the 2004 conference of Exotic Nuclei and Atomic Masses, at Callaway Gardens, near Atlanta—44 years after attending the original conference on masses—Aaldert received the SUNAMCO medal in recognition of his long commitment and numerous achievements in the field. It was fitting that he received an award that he himself had presented others on previous occasions.

In addition to his technical and scientific skills, Aaldert was a great lover of culture. An accomplished pianist, he was particularly fond of music, having a subscription to Amsterdam's famous Concertgebouw. His taste in music was very modern, with the work of Messiaen figuring prominently. He was also a dedicated family man, composing poems for his Grandchildren for the feast of St. Nicolas each year.

Aaldert's fine blend of culture and scientific acumen made it a pleasure to receive him as a visitor in Orsay, where he came regularly for discussions concerning the evaluation. His experience and authority were only less impressive than his profound modesty. It will be difficult to carry on without him.

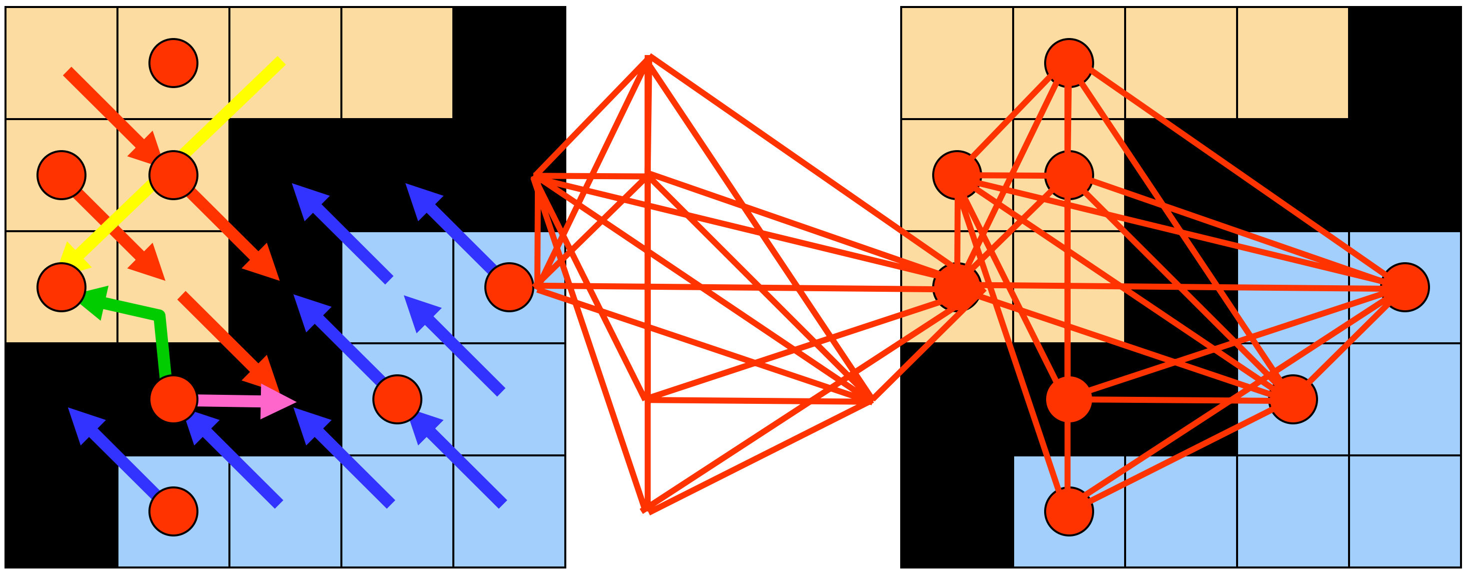
IKO:	Institute of Nuclear Physics Research
NIKHEF:	National Institute for Nuclear Physics and High Energy Physics
SUNAMCO:	Symbols, Units, Nomenclature, Atomic Masses and fundamental Constants; a commission of IUPAP: the International Union of Pure and Applied Physics

For more information see: http://amdc.in2p3.fr/bulletins/Ahw.html

Georges Audi with David Lunney
Csnsm-Orsay

Mass Evaluation

AME **GSI data**



1. Q-values: β-decays (β^+,β^-)
2. Q-values: α-decays
3. Q-values: reactions (p,n), (n,γ), etc.
4. direct measurements (traps, rings)

6169 input data

frequency correlations between all measured ESR data

~$2 \cdot 10^5$ input data

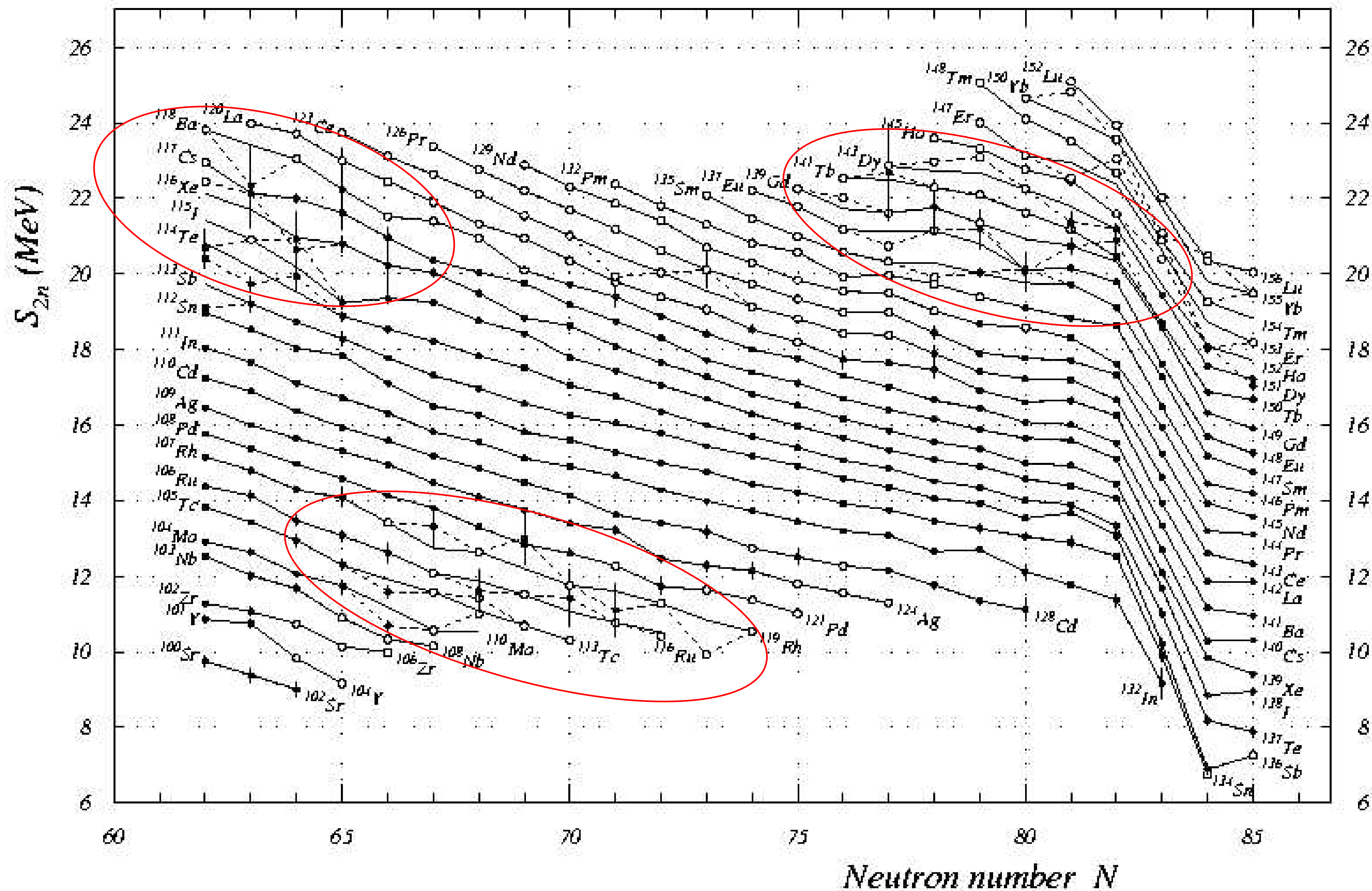
Combined Evaluation

Yu.A. Litvinov, G. Audi et al., ILIMA Technical Proposal

Yu.A. Litvinov et al, NPA756 (2005) 3

A. Wapstra *G. Audi, C. Thibault, NPA729 (2003) 129* discontinuity on the mass surface: new physics? ...or just a mistake?!

AME “systematic” mass values - *geometric* extrapolations



A simplified overview of mass models

physics input →

algebraic formulas (Garvey-Kelson; IMME)	*micro*scopic sculpturings of a *macro*scopic drop (FRDM)	microscopic nucleon-nucleon interaction (RMF / HFB)

← ease of use

Extended Thomas-Fermi Strutinki Integral model

macro: TF Skyrme approximation
micro: Strutinski correction (folded Skyrme)

9 parameters
good mass fit
most nuclear properties

now full HFB

HFBCS:	S. Goriely et al., At. Nuc. Data (2001)
HFB 1:	M. Samyn et al., Nucl. Physics (2002)
HFB 2:	S. Goriely et al., Phys. Rev. C (2002)
HFB 3:	M. Samyn et al., Nucl. Physics (2003)
HFB 4-7:	S. Goriely et al., Phys. Rev. C (2003)
HFB 8:	M. Samyn et al., Phys. Rev. C (2004)
HFB ...	

Other global approaches

Nucleon interaction

Green 's function Monte Carlo
Pieper et al., Phys. Rev. C (2001)
very restricted (*A*< 12)

chiral perturbation theory
Kaiser, Fritsch, Weise, Nucl. Phys. A (2002)
nothing on finite nuclei

Hybrid model

smoothly varying components:
liquid drop, shells, pairing
\+ *fluctuations:* single particle behavior

Koura, Uno, Tachibana, Yamada,
Nucl. Phys. A 674 (2000) 47

no physical transparancy

Other developments

Energy density functional approach
Yu and Bulgac, Phys. Rev. Lett. (2003)
far from a mass table

Mass systematics using neural networks
Clark, Gernoth, Mavrommatis NPA (2004)
σ_{rms} (AME2003) = 1.03 MeV

Shell model inspired

not an interaction but a Hamiltonian:
one- and two-body terms fit

Duflo & Zuker
Phys. Rev. C (1997)

excellent fits to the mass table

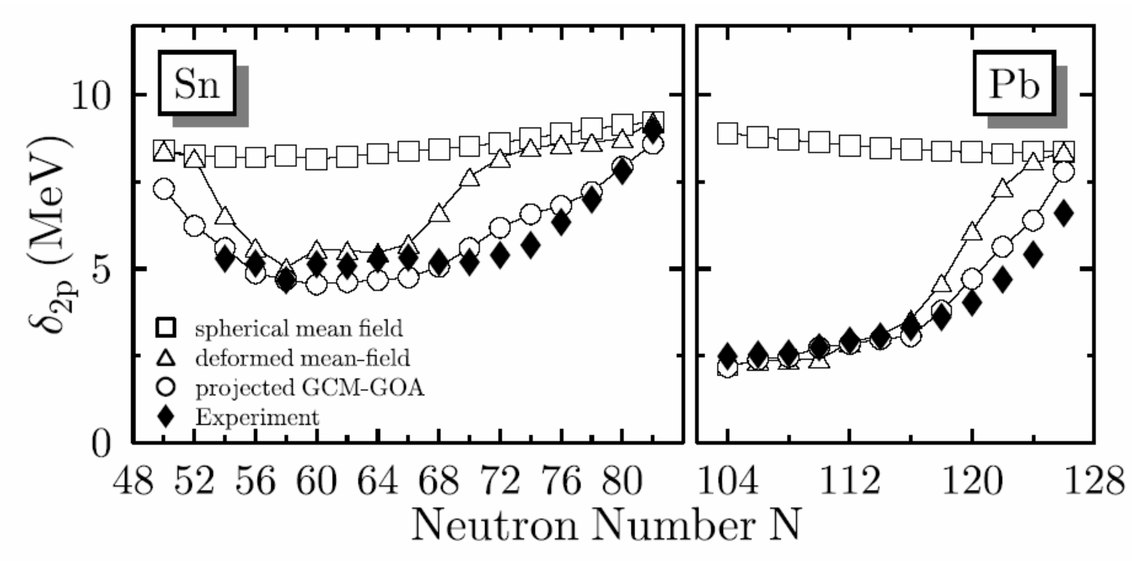
Physical Review Letters 94 (2005)

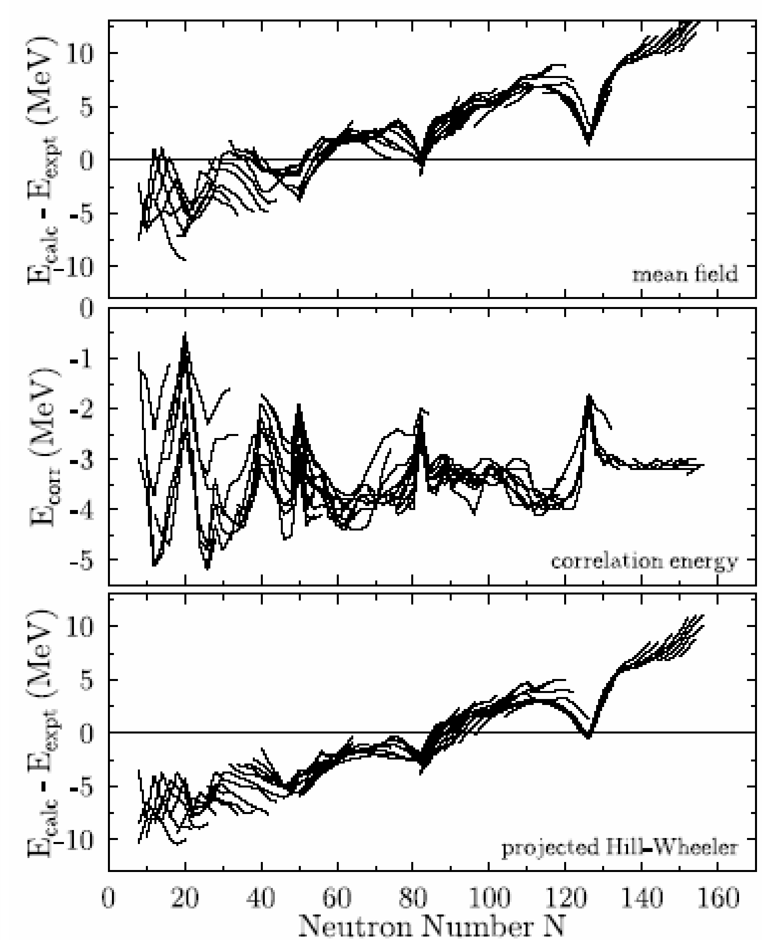
PHYSICAL REVIEW C **73**, 034322 (2006)

Global study of quadrupole correlation effects

M. Bender,[1,2,3] G. F. Bertsch,[1] and P.-H. Heenen[4]

A mean-field mass table!

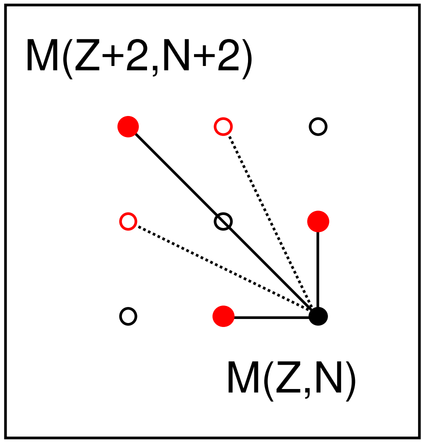




Nuclear Mass Models

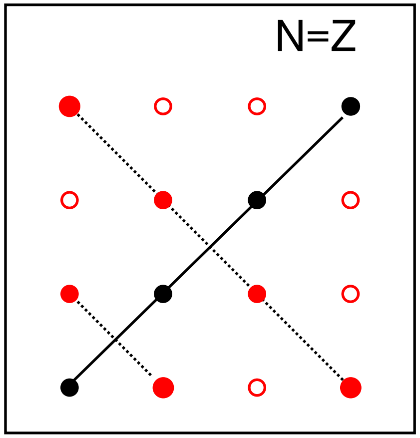
local models (phenomenological) :

Garvey-Kelson relations



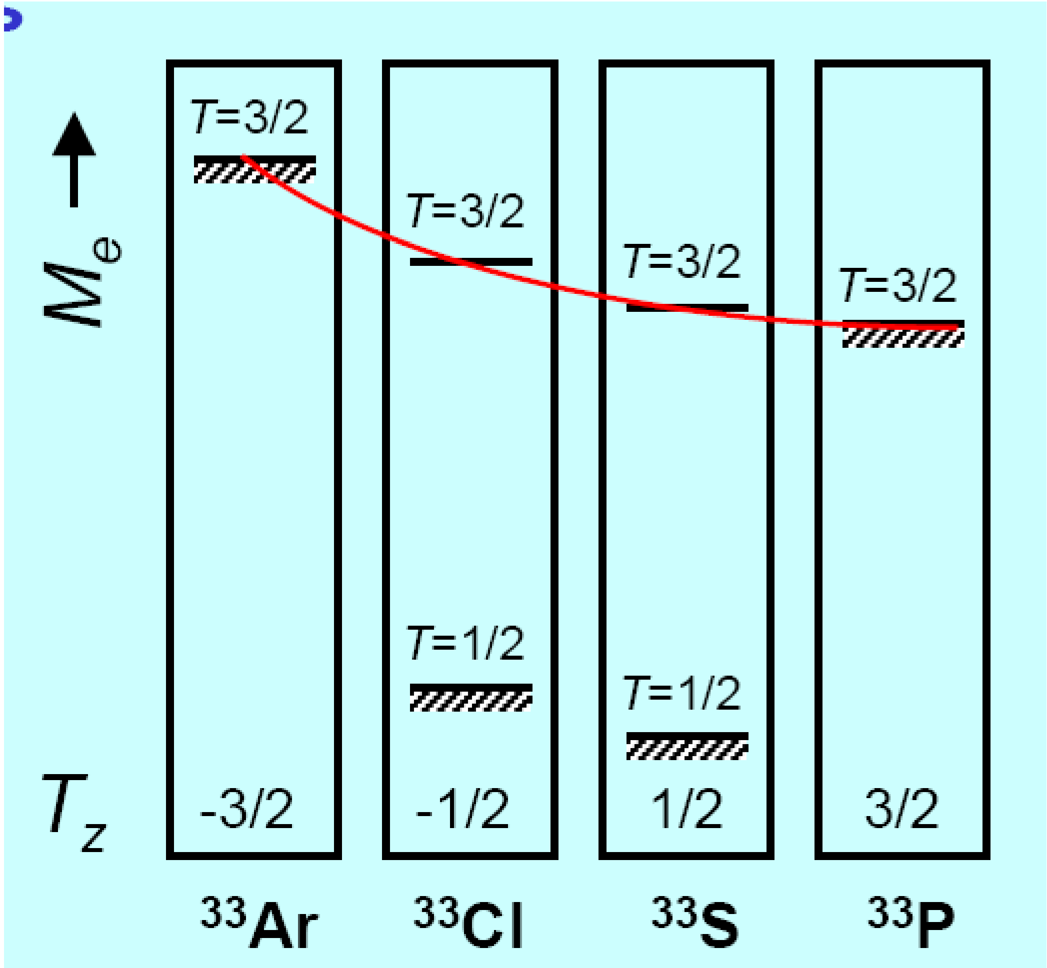
Isobaric Mass Multiplet Equation (IMME):

$M = a + bT_z + c\,T_z^2$



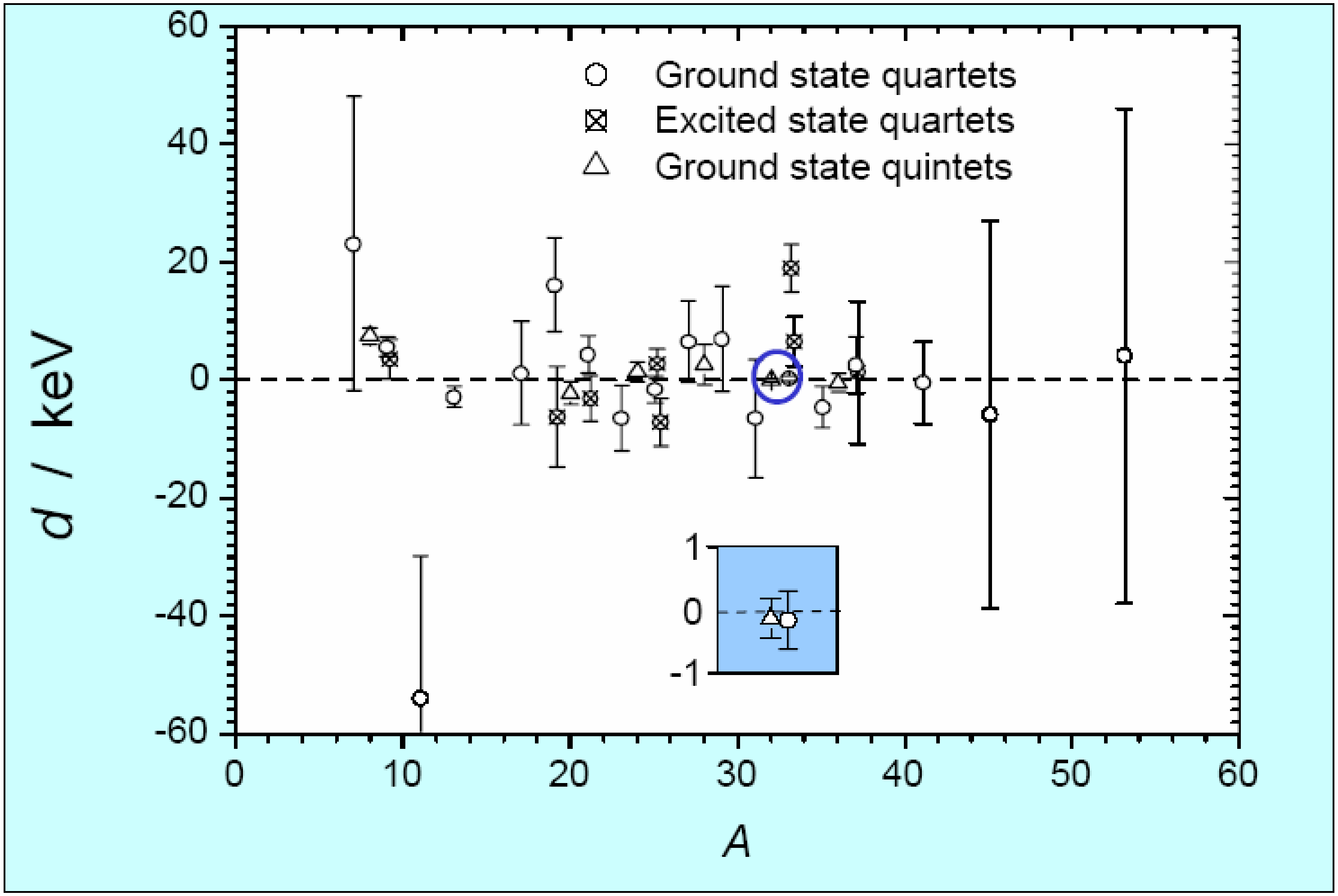
Isobaric Mass Multiplet Equation (IMME):

$$M = a + bT_z + c\,T_z^{\,2}$$



Isobaric Mass Multiplet Equation (IMME):

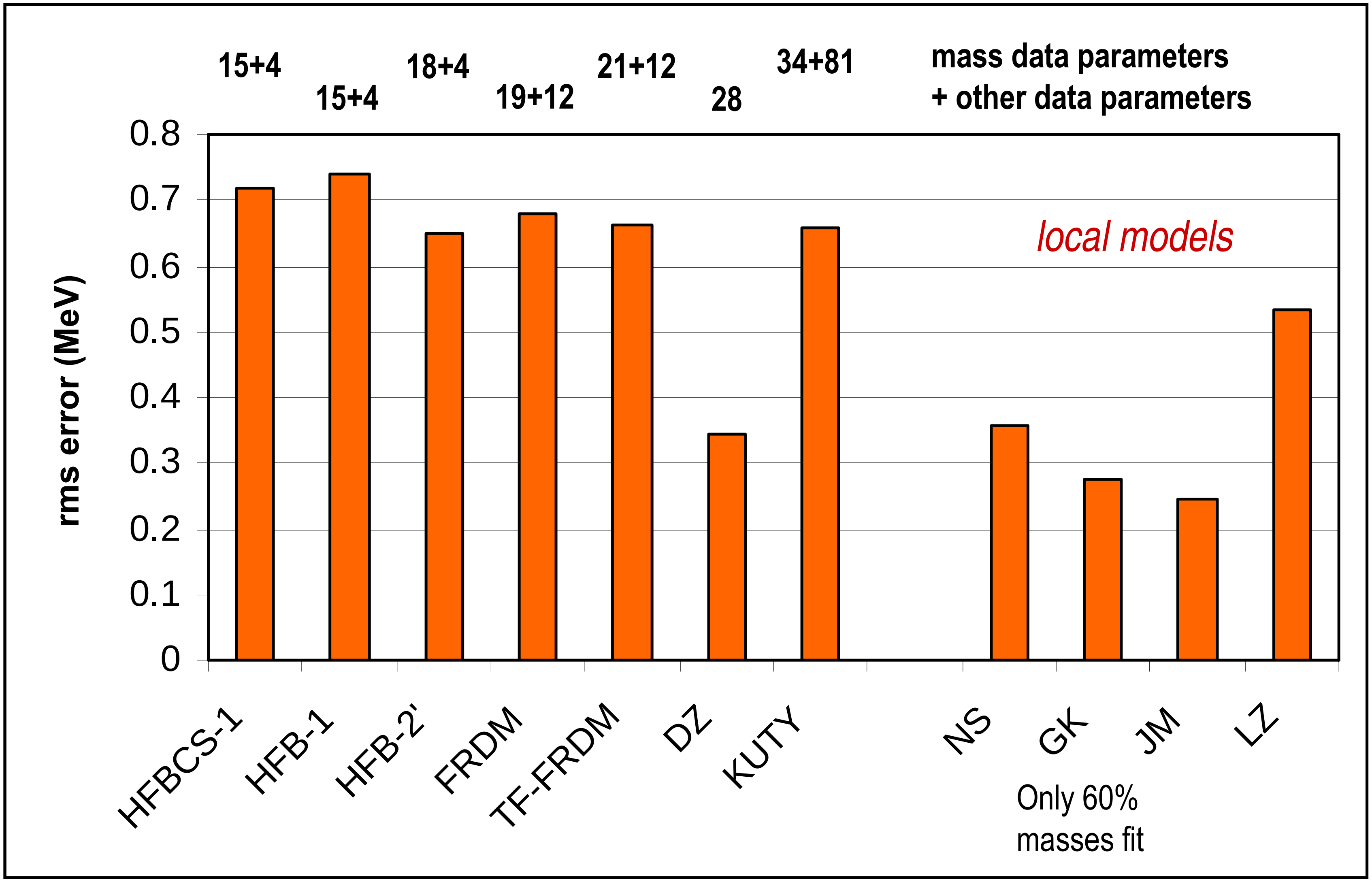
$$M = a + bT_z + c\,T_z^{2} + d\,T_z^{3}\ ?$$



Case of $A = 33$

K. Blaum *et al.*, Phys. Rev. Lett. (2004)

Fit to 1995 AME (1768 masses)



Chaos-limited mass prediction?

VOLUME 88, NUMBER 9 PHYSICAL REVIEW LETTERS 4 MARCH 2002

Nuclear Masses: Evidence of Order-Chaos Coexistence

O. Bohigas and P. Leboeuf

Laboratoire de Physique Théorique et Modèles Statistiques, Bâtiment 100, Université de Paris-Sud, 91405 Orsay Cedex, France

PRL 94, 102501 (2005) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2005

Nuclear Masses Set Bounds on Quantum Chaos

José Barea,* Alejandro Frank,† and Jorge G. Hirsch.‡

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, 04510 México, D.F., México

Piet Van Isacker§

Grand Accélérateur National d'Ions Lourds, BP 55027, F-14076 Caen Cedex 5, France

PRL 96, 042502 (2006) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2006

Correlations in Nuclear Masses

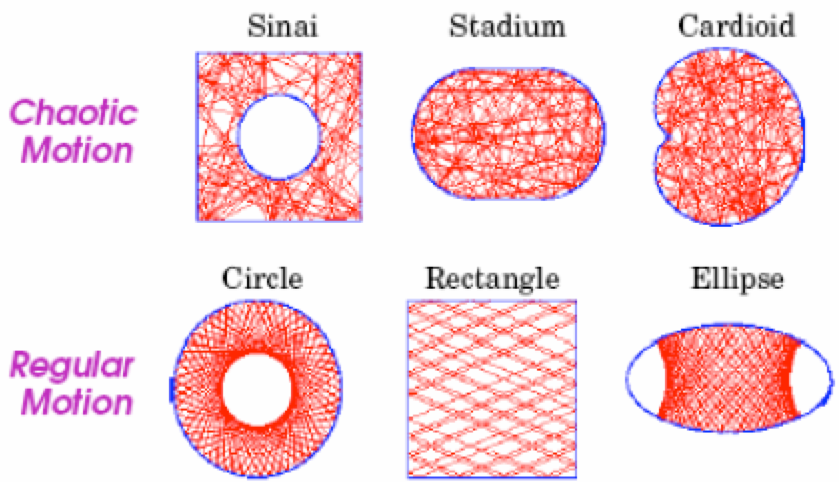
H. Olofsson,[1] S. Åberg,[1] O. Bohigas,[2] and P. Leboeuf[2]

[1]*Division of Mathematical Physics, LTH, Lund University, P.O. Box 118, S-221 00 Lund, Sweden*

[2]*Laboratoire de Physique Théorique et Modèles Statistiques*, Bâtiment 100, Université de Paris-Sud, 91405 Orsay Cedex, France*

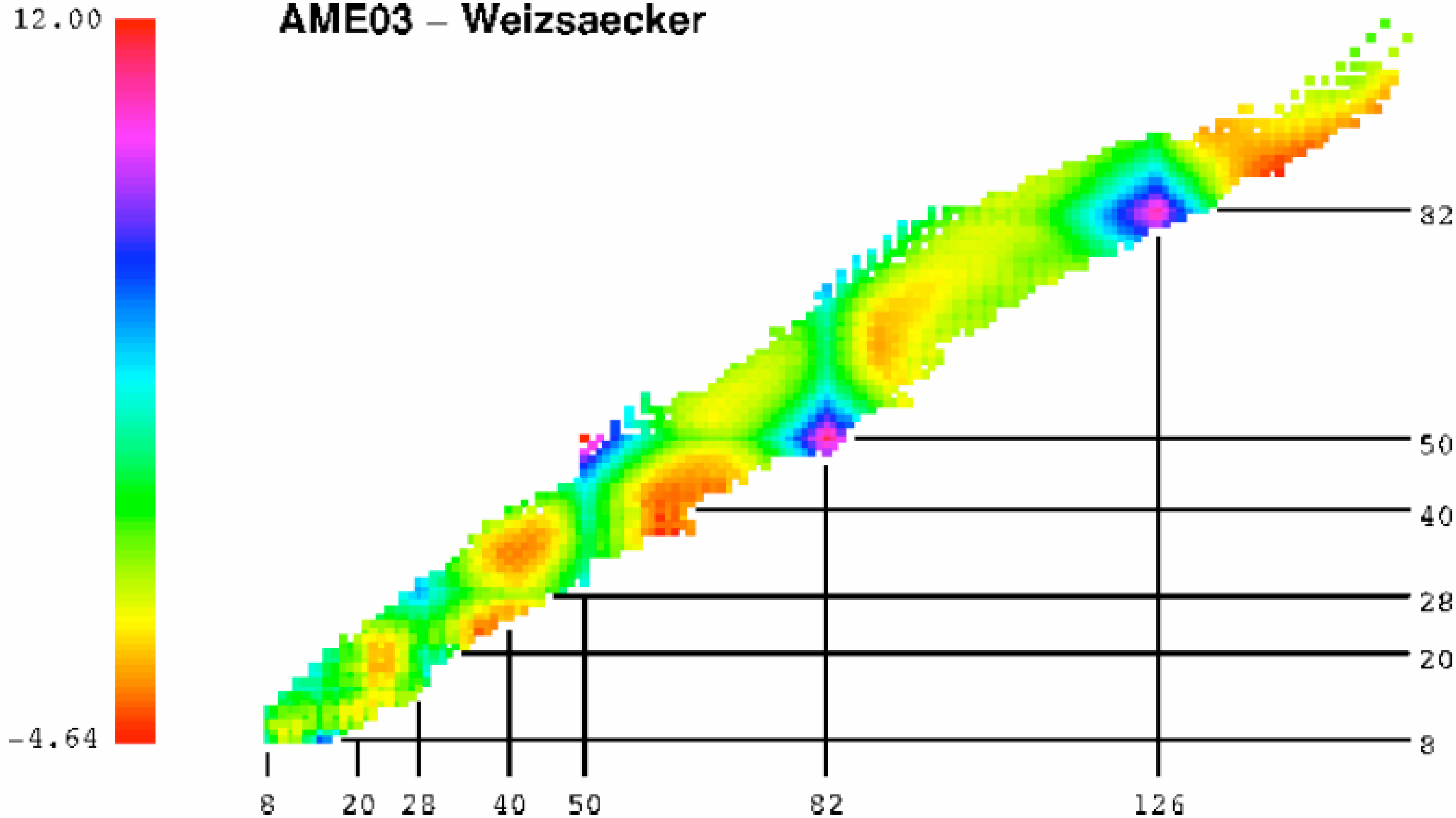
Chaotic and regular systems

- Classically chaotic systems acquire random-matrix statistics in quantum mechanics (BGS conjecture).
- Regular systems are integrable (as many integrals of motion as degrees of freedom).



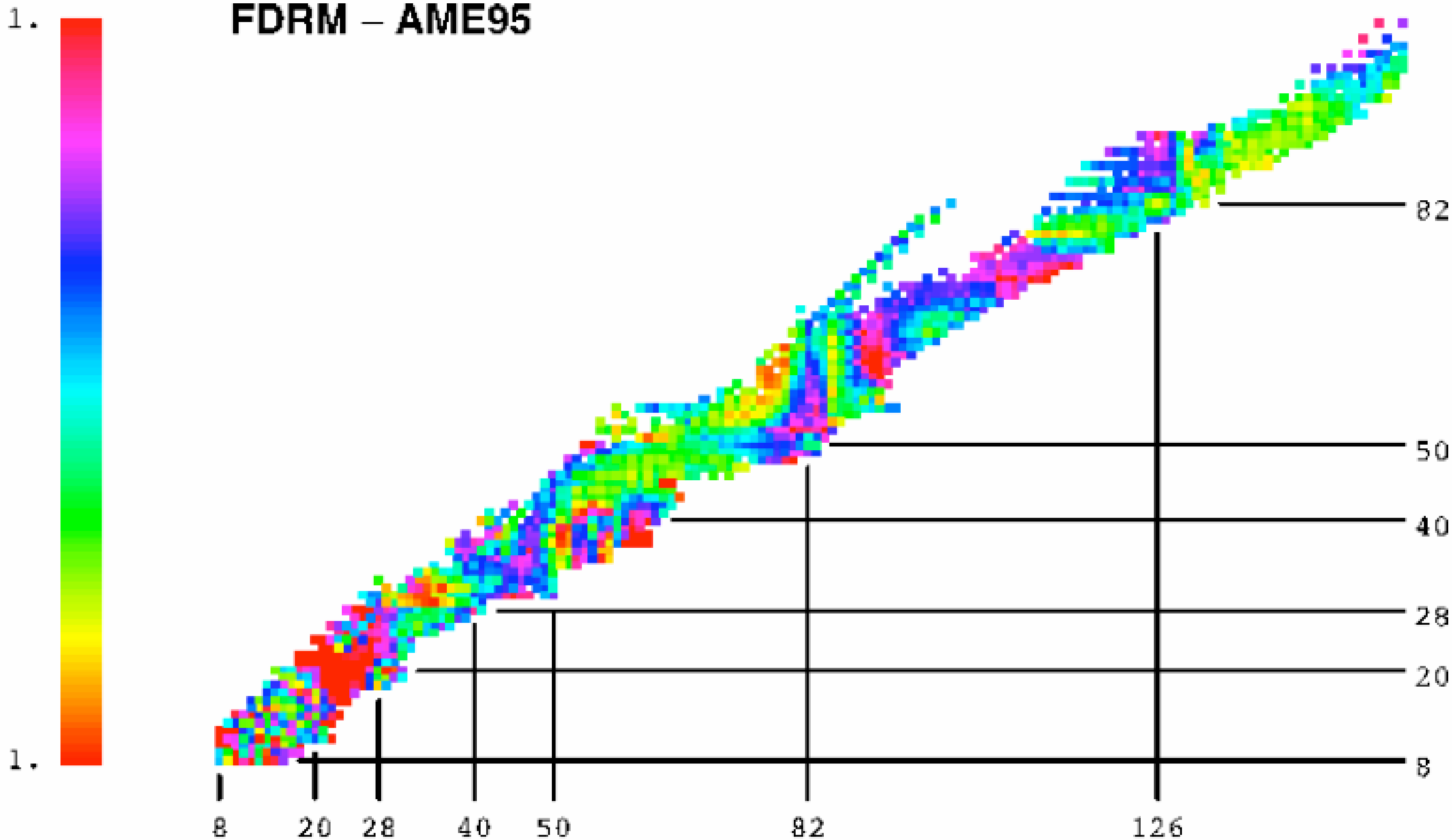
A. Baecker - http://www.physik.tu-dresden.de/~baecker/research.html

Deviations from Weizsäcker



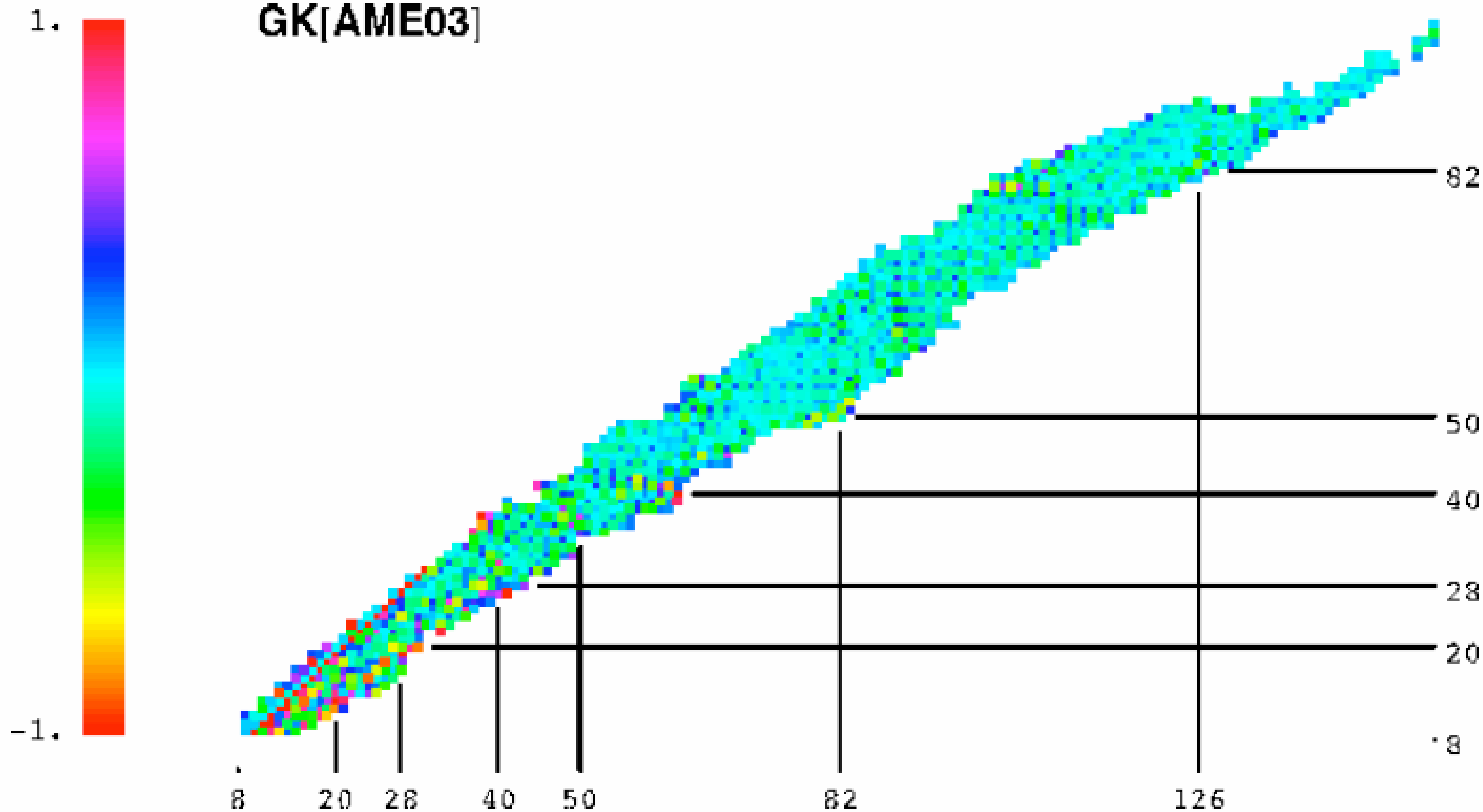
J. Barea, J. Hirsch, A. Frank, UNAM, Mexico
P. Van Isacker, GANIL, France

Deviations from FRDM



J. Barea, J. Hirsch, A. Frank, UNAM, Mexico
P. Van Isacker, GANIL, France

Deviations from GK



J. Barea, J. Hirsch, A. Frank, UNAM, Mexico
P. Van Isacker, GANIL, France

Deviations from GKn

- Definition of σ_{rms}:

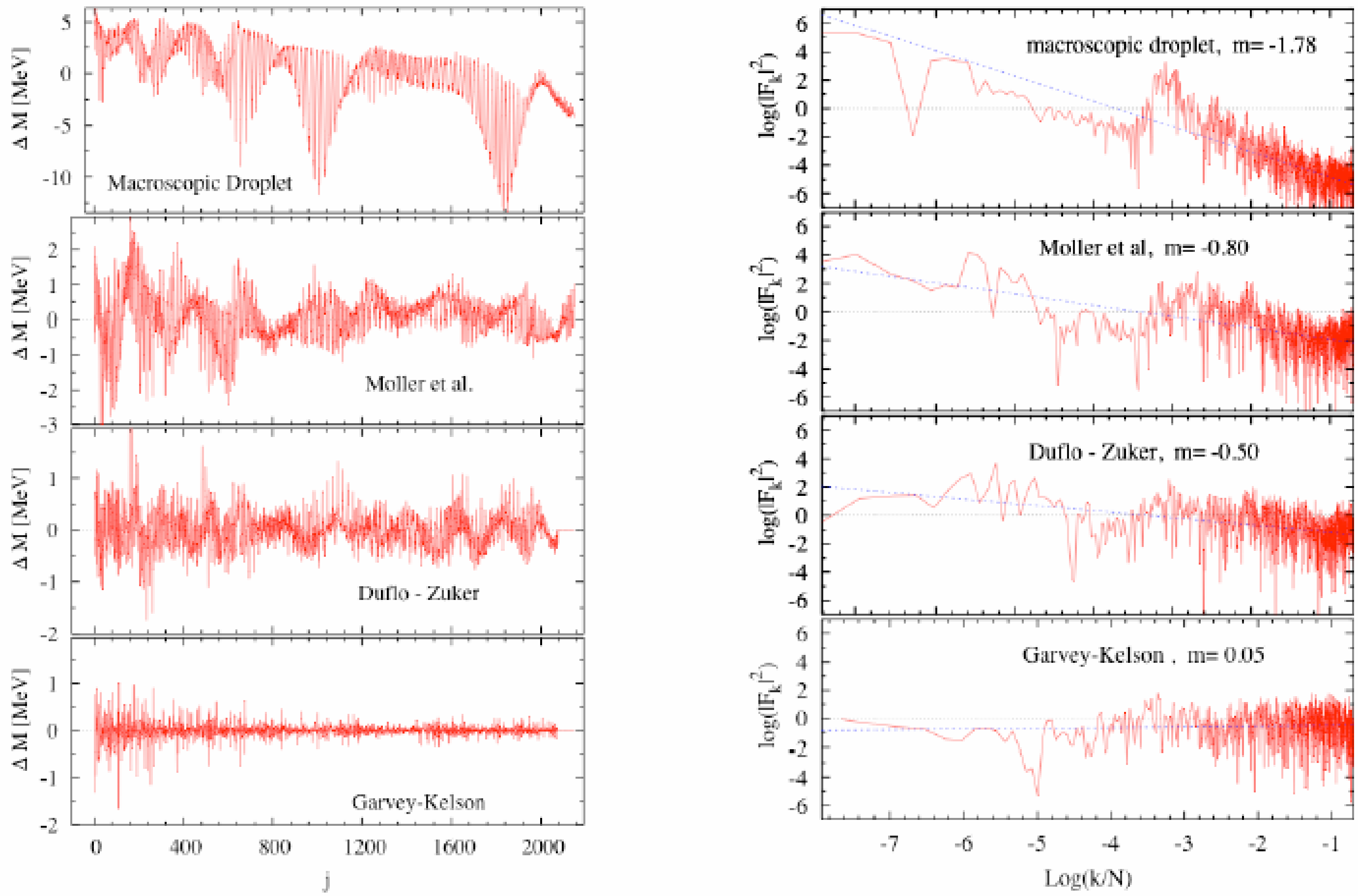
$$\sigma_{\text{rms}} = \sqrt{\frac{1}{M}\sum_{j=1}^{M}\left(B_j^{\text{expt}} - B_j^{\text{theo}}\right)^2}$$

- The deviation (in keV) depends on n:

σ_{rms}	LDM	FRDM	DZ	GK1	GK4	GK7	GK12
M	2154	2154	2154	2085	1841	1571	1008
$A \geq 16$	3211	653	362	163	131	112	87

J. Barea, J. Hirsch, A. Frank, UNAM, Mexico
P. Van Isacker, GANIL, France

LDM, FRDM, DZ, GK fluctuations



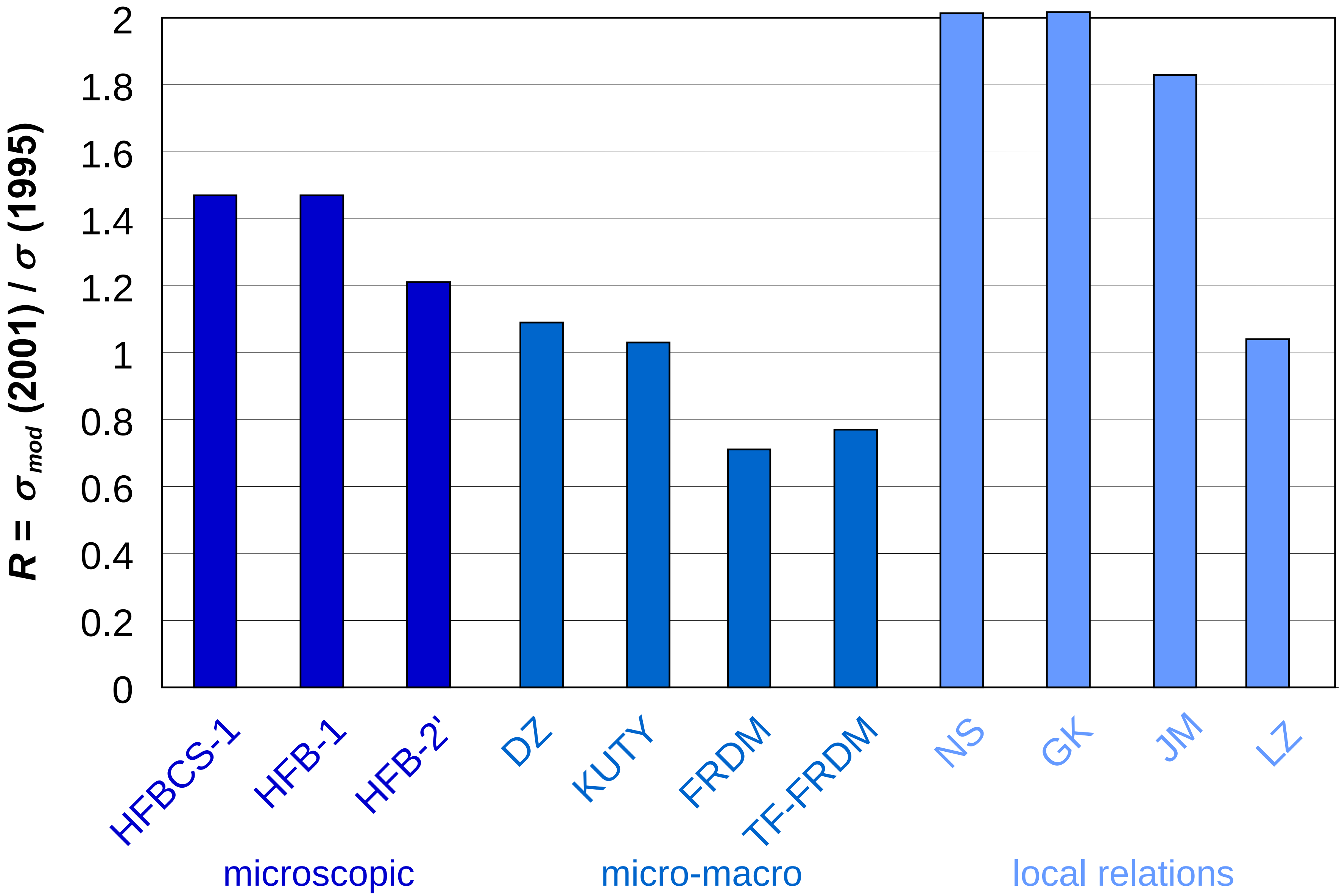
J. Barea, J. Hirsch, A. Frank, UNAM, Mexico

P. Van Isacker, GANIL, France

Conclusions

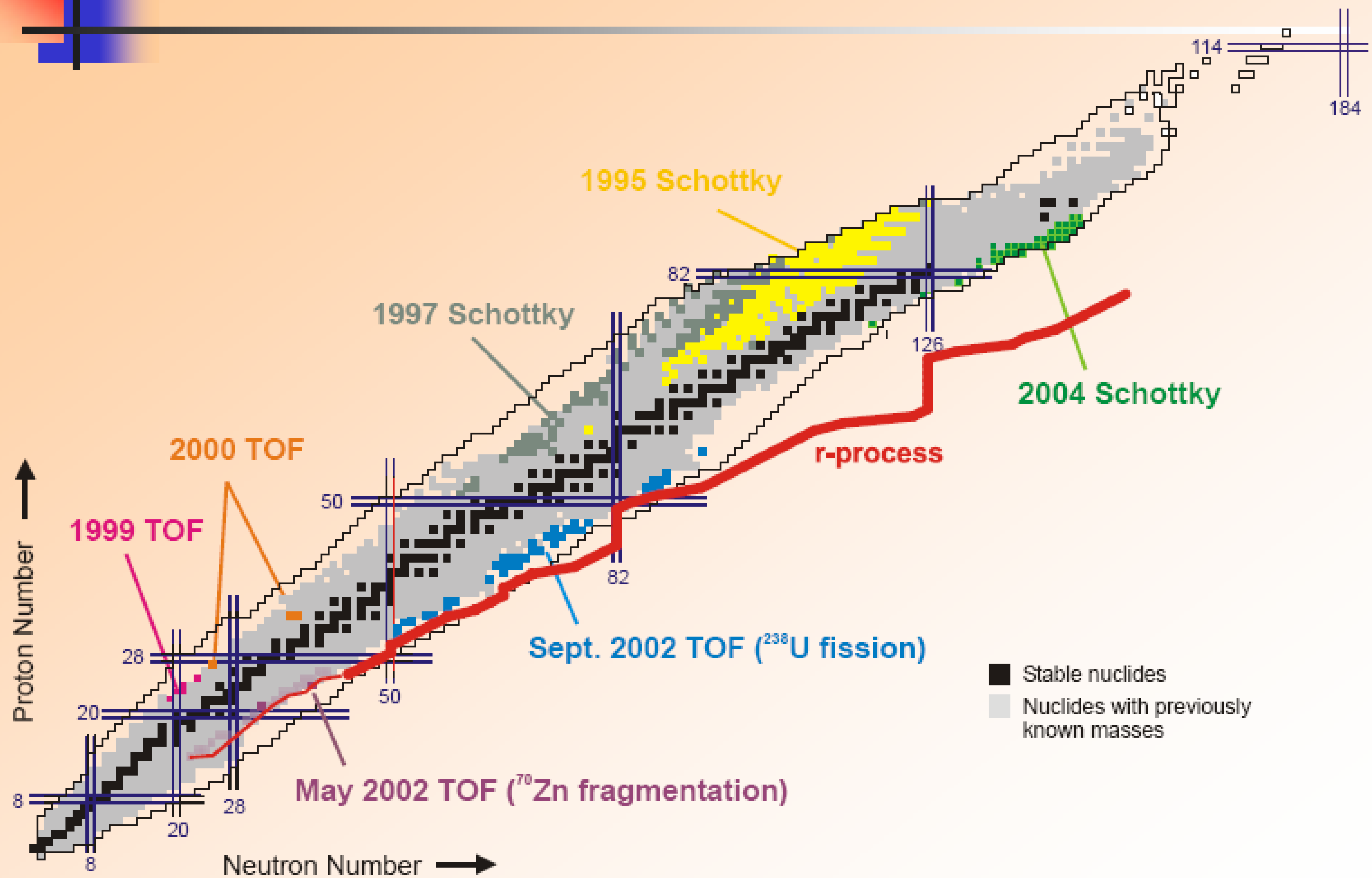
- Chaotic mass component is ***not*** unpredictable and can be (at least partially) calculated!
- Chaotic mass component is *correlated* and the correlation can be tested with GK analysis.
  - Example: A *random* chaotic mass component with $\sigma=2.78\ A^{-1/3}$ leads to rms deviation of 861 keV.
- Can GK relations be used for *predicting* nuclear masses?

testing mass models with new data



See: Lunney, Pearson & Thibault, Rev. Mod. Phys. 75 (2003) 1021

New Masses Measured at the Storage Ring at GSI



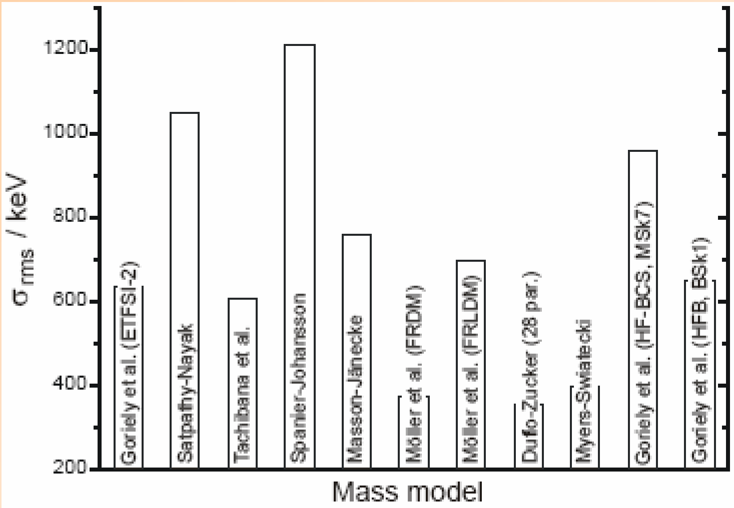
M.Matoš

JINA R-Process Discussion, University of Notre Dame, IN, USA, January 28 - 29, 2005

Predictive Powers of Mass Models

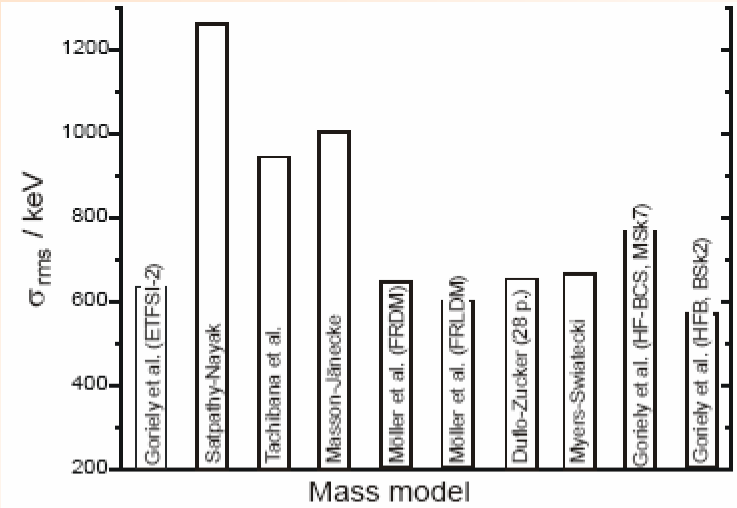
$$\sigma^2_{rms} = \frac{1}{n}\sum_{i=1}^{n}(m_{experiment} - m_{model})^2$$

neutron-deficient nuclides (SMS)



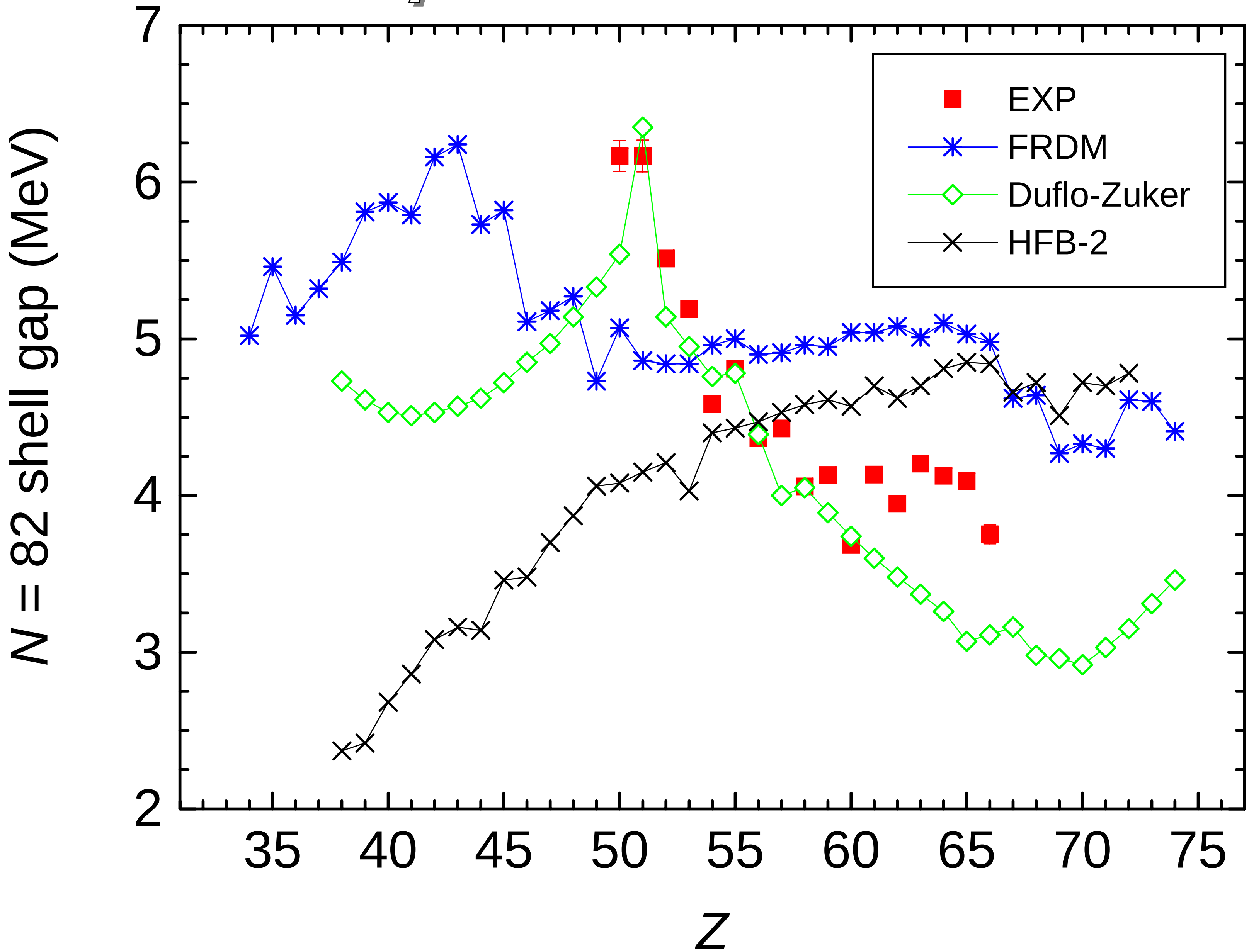
Litvinov, PhD thesis

neutron-rich nuclides (IMS)



M.M., PhD thesis

extrapolation of mass models



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

Restoration of the $N = 82$ shell gap from direct mass measurements of $^{132,134}Sn$

M. Dworschak[1]*, G. Audi[2], K. Blaum[1,3], P. Delahaye[4], S. George[1,3], U. Hager[5], F. Herfurth[1], A. Herlert[4], A. Kellerbauer[6], H.-J. Kluge[1,7], D. Lunney[2], L. Schweikhard[8], and C. Yazidjian[1]
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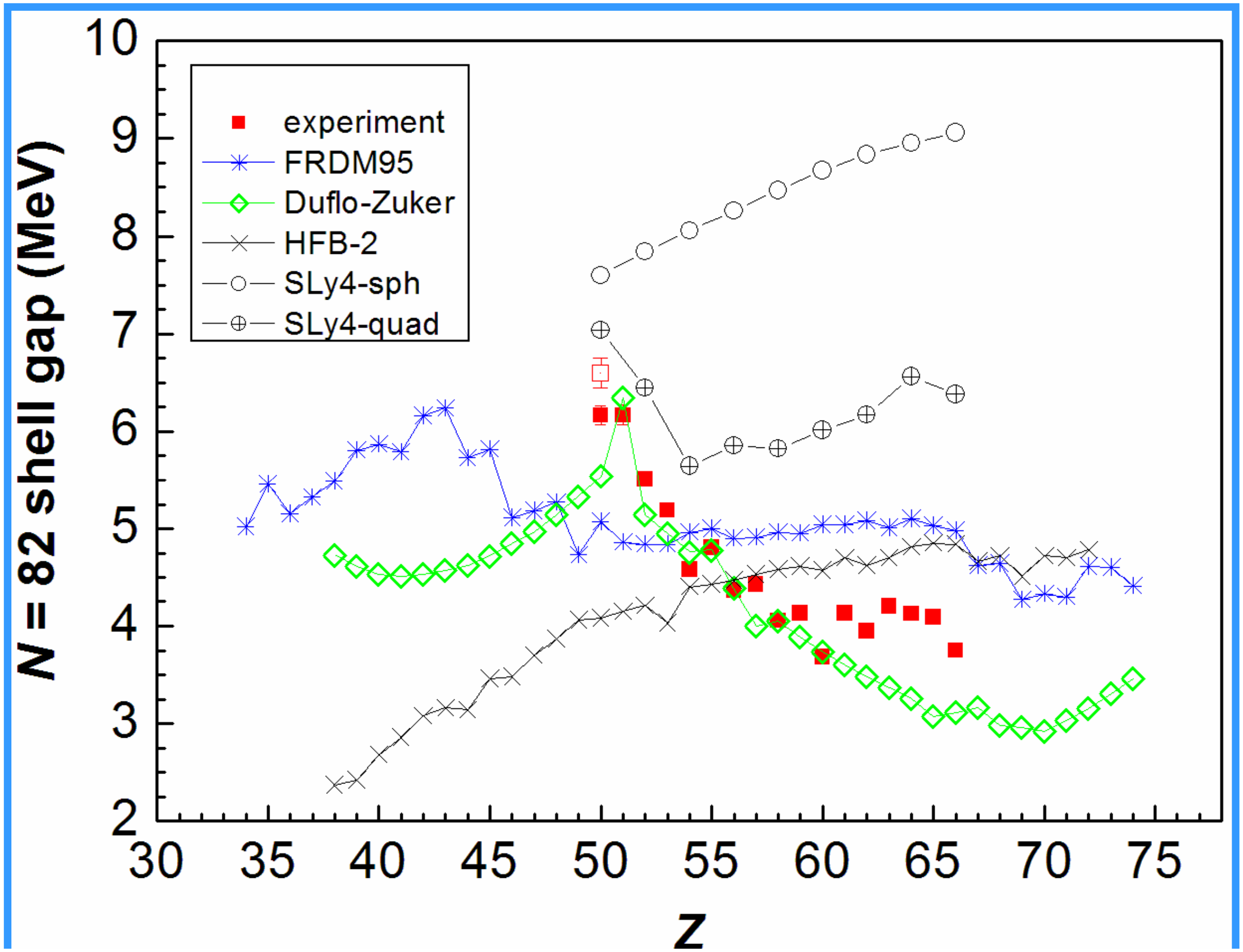
[5]*University of Jyväskylä, Department of Physics, P.O. Box 35 (YFL), 40014 Jyväskylä, Finland*
[6]*Max Planck Institute for Nuclear Physics, P.O. Box 103980, 69029 Heidelberg, Germany*
[7]*Ruprecht-Karls-Universität, Institut für Physik, 69120 Heidelberg, Germany and*
[8]*Ernst-Moritz-Arndt-Universität, Institut für Physik, 17487 Greifswald, Germany*
(Dated: May 8, 2007)



PROCEEDINGS OF SCIENCE

Nucleosynthesis in neutrino heated matter: The νp-process and the r-process

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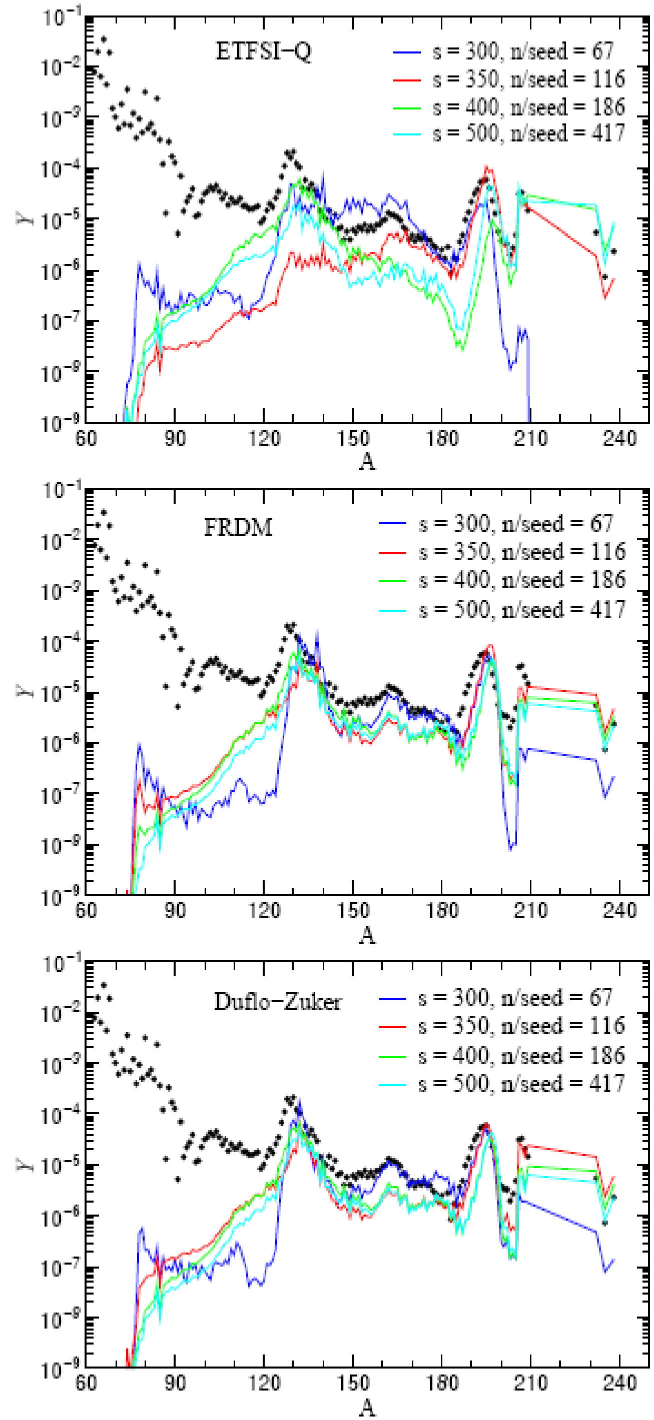
R. Buras and H.-Th. Janka
Max-Planc-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1,
D-85741 Garching, Germany

This manuscript reviews recent progress in our understanding of the nucleosynthesis of medium and heavy elements in supernovae. Recent hydrodynamical models of core-collapse supernovae show that a large amount of proton rich matter is ejected under strong neutrino fluxes. This matter constitutes the site of the νp-process where antineutrino absorption reactions catalyze the nucleosynthesis of nuclei with $A > 64$. Supernovae are also associated with the r-process responsible for the synthesis of the heaviest elements in nature. Fission during the r-process can play a major role in determining the final abundance patter and in explaining the almost universal features seen in metal-poor r-process-rich stars.

International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos - IX
25-30 June 2006
CERN



TITAN (TRIUMF)
RIKEN:
ISO-RING +
Cyclotron
(à la CSS2)
GSI (FAIR):
NESR/CR +
MATS (trap)
MAFFTRAP
SPIRAL2
CSR (HIRBF)
Lanzhou
PACIFIC OCEAN
NORTH AMERICA
UNITED STATES
CANADA
ARCTIC OCEAN
North Pole
GREENLAND (DEN.)
Arctic Circle
RUSSIA
ASIA
CHINA
KAZAKHSTAN
Bay of Bengal
INDIA
ATLANTIC OCEAN
U.K.
UKRAINE
Prime Meridian
TURKEY
IRAN
IRAQ
Arabian Sea
INDIAN OCEAN
Mediterranean Sea
ALGERIA
EGYPT
SAUDI ARABIA
LIBYA
Tropic of Cancer
MALI
NIGER
AFRICA
CHAD
SUDAN
ETHIOPIA
NIGERIA
Equator
150°
165°
75°
60°
45°
30°
15°
30°

MAFF facility at FRM-II

J. Szerypo et al. / Nucl. Instr. and Meth. in Phys. Res. B 204 (2003) 512-

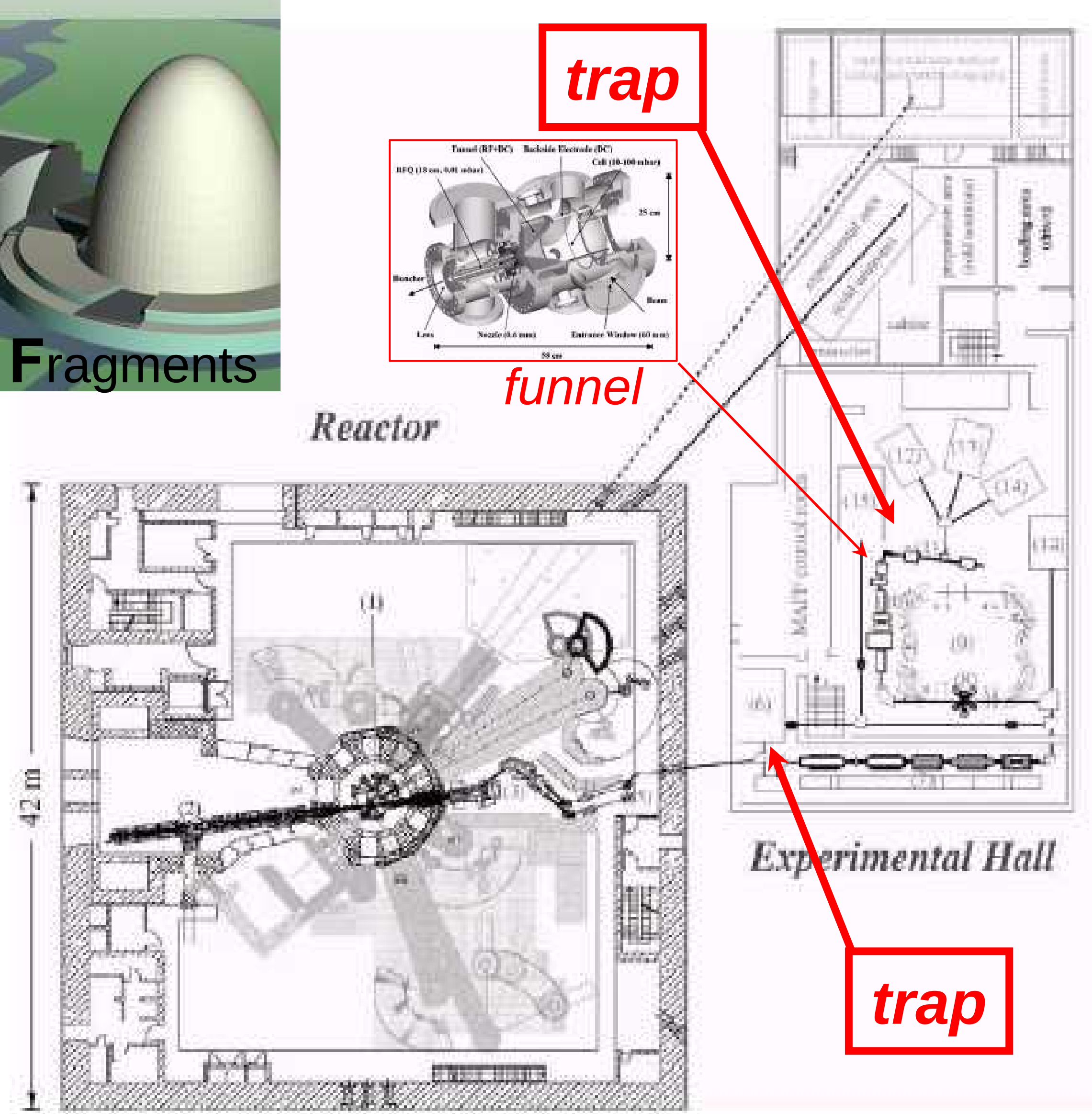
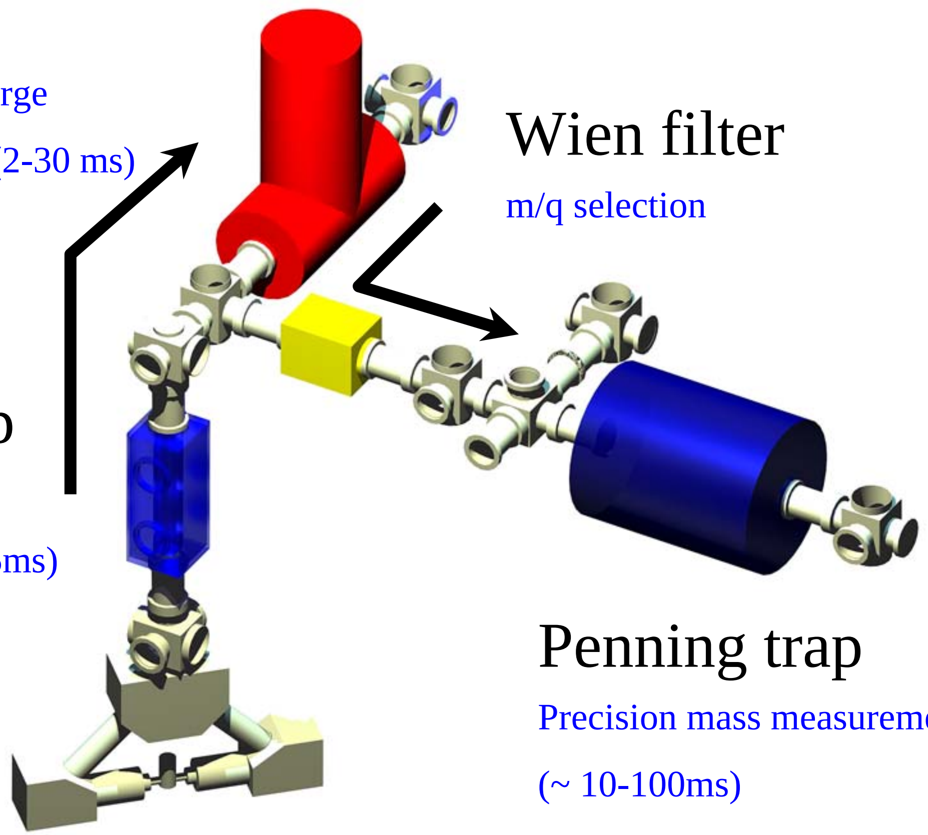


Fig. 1. MAFF layout.

Bavarium

n-rich nuclides

TRIUMF Ion Trap (TITAN) facility



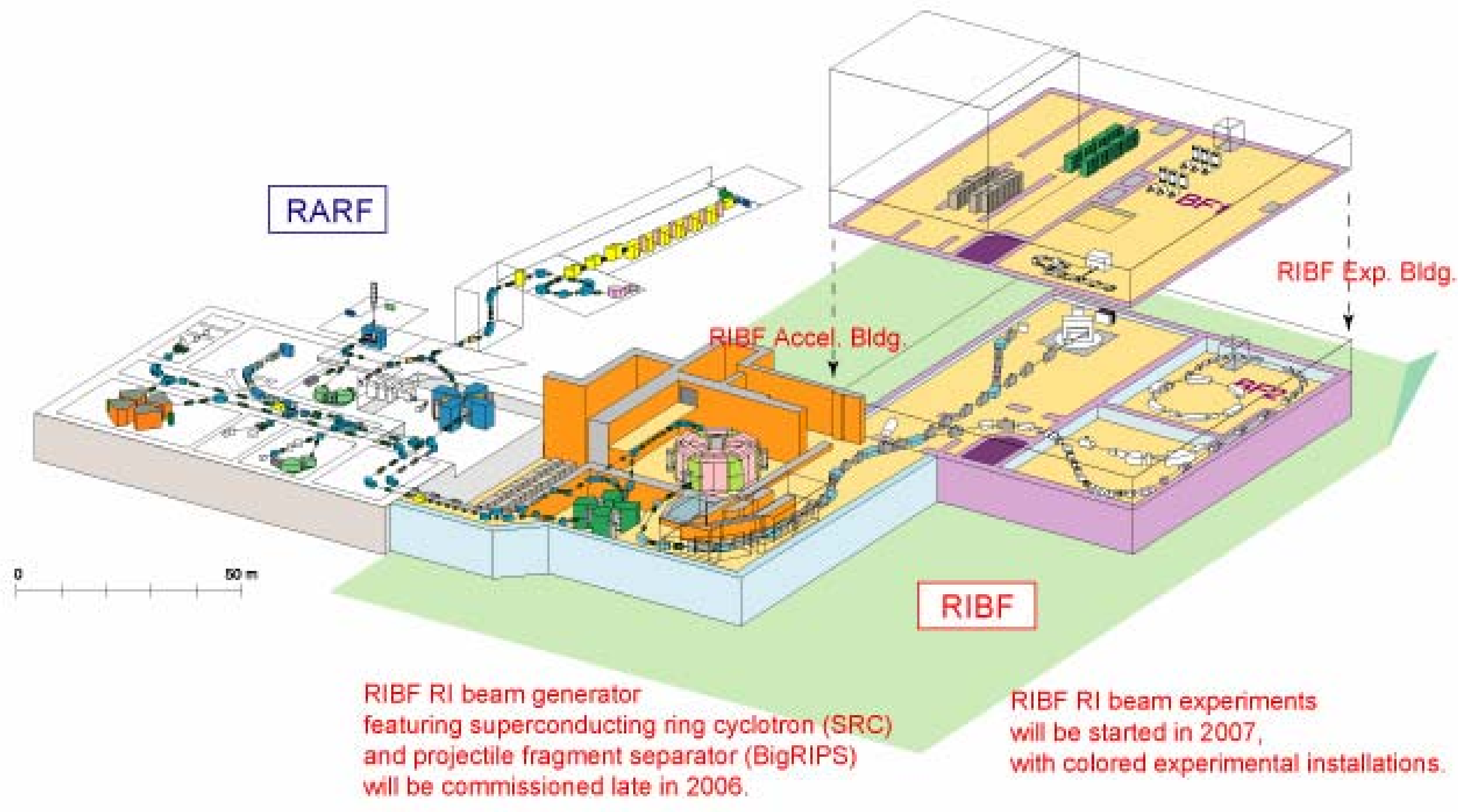
$$f_c = qB/m$$

Mass measurements

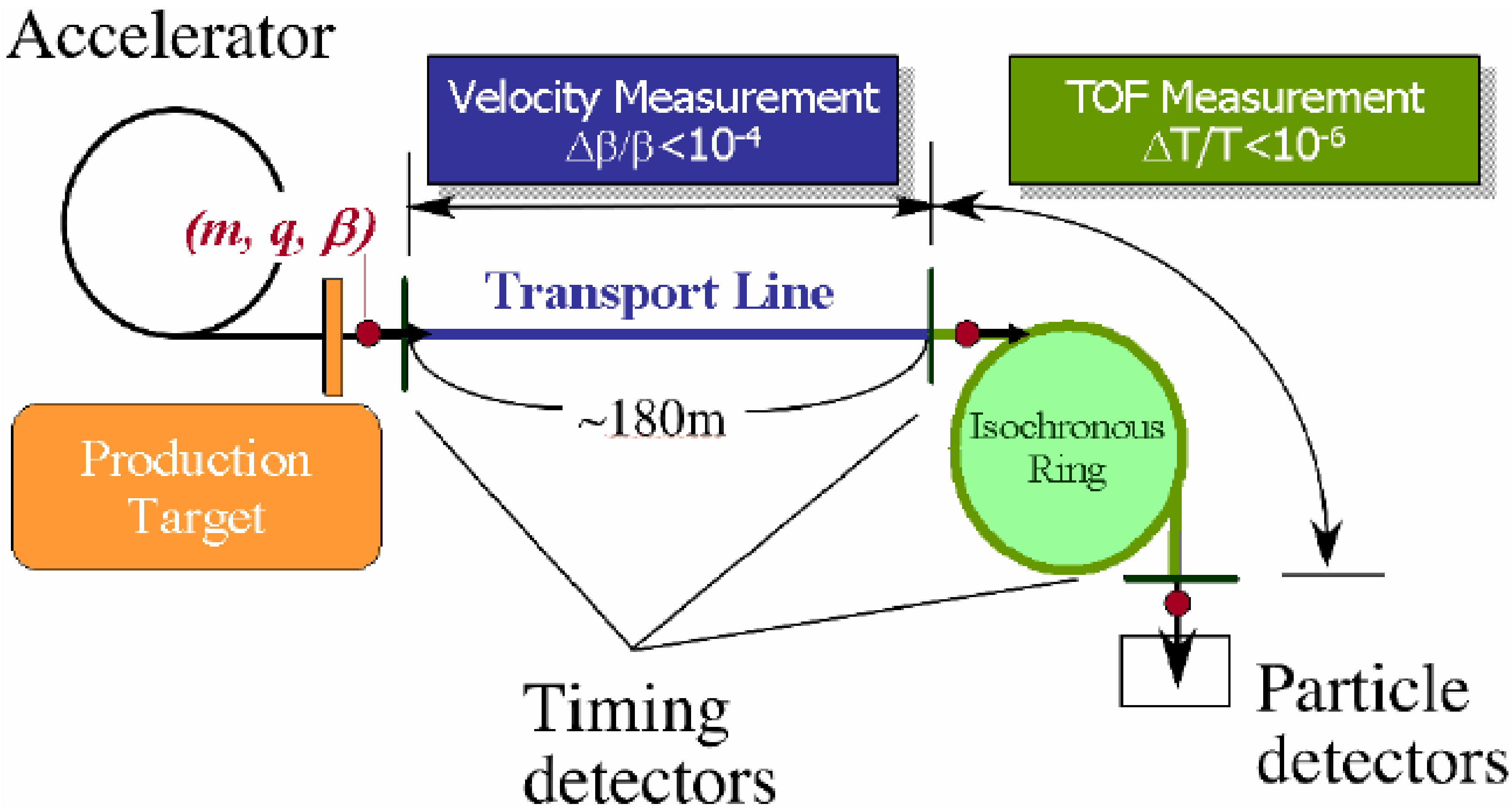
- **$T_{1/2} \approx 10$ ms**
- **$\delta m/m < 1 \cdot 10^{-8}$**
- **Operational 2006**

J. Dilling et al., EMIS 2003

RIKEN (fragmentation) facility

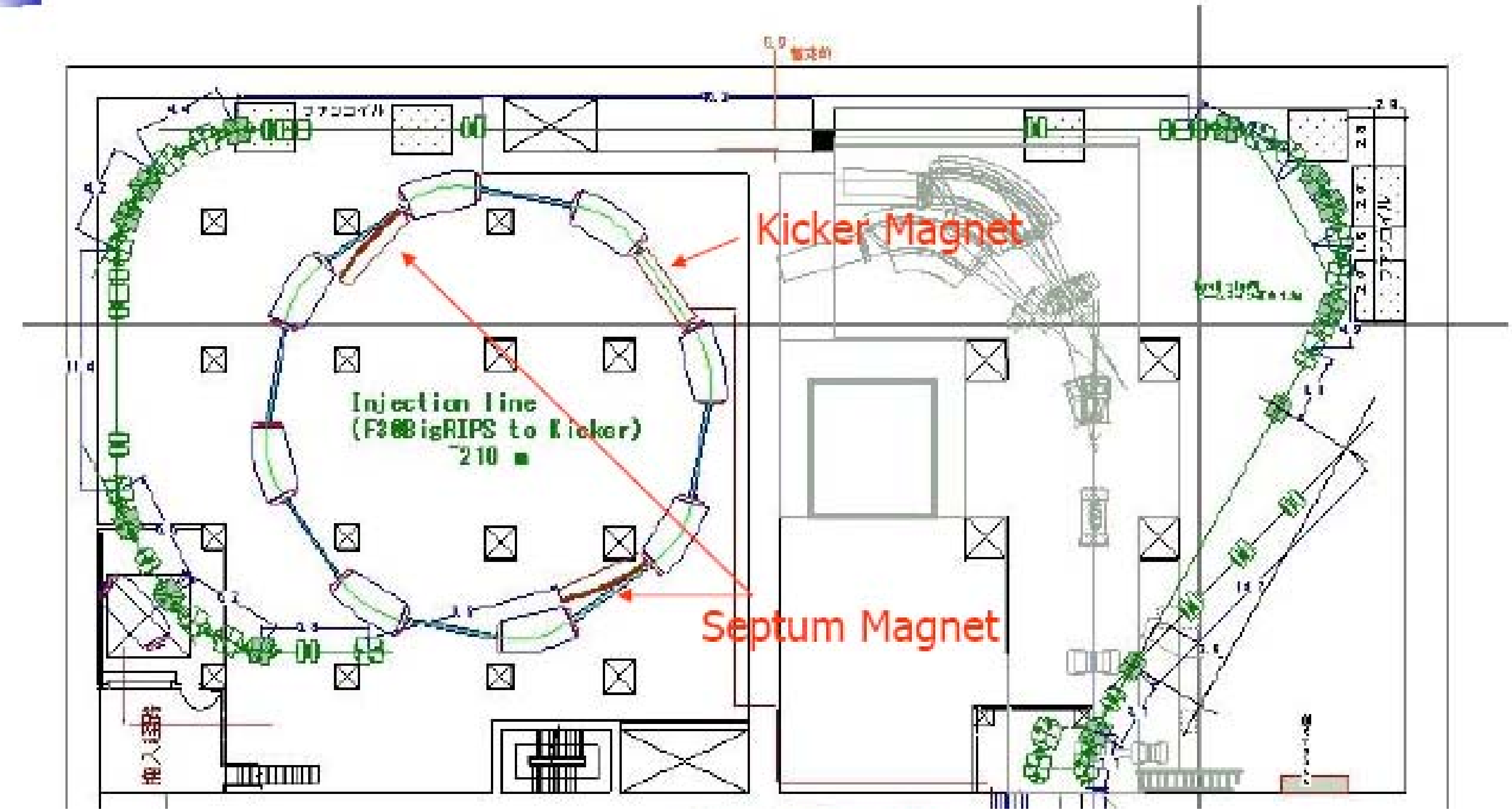


RIKEN RING

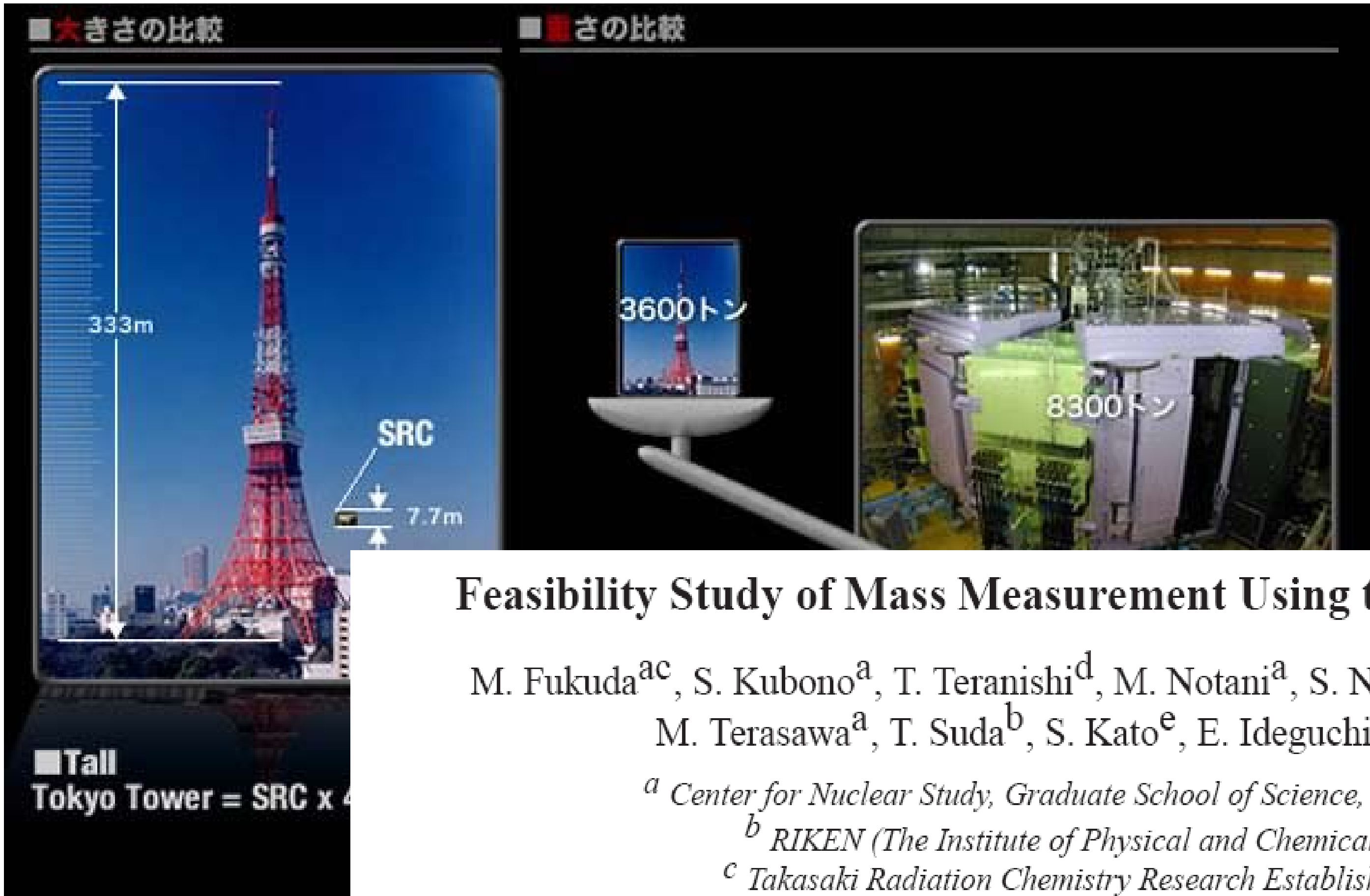


I. Arai, ALMAS Workshop, GSI (2006)

Layout of Experimental Apparatus at RIBF(Plan View)



I. Arai, ALMAS Workshop, GSI (2006)



Feasibility Study of Mass Measurement Using the RIKEN Cyclotrons

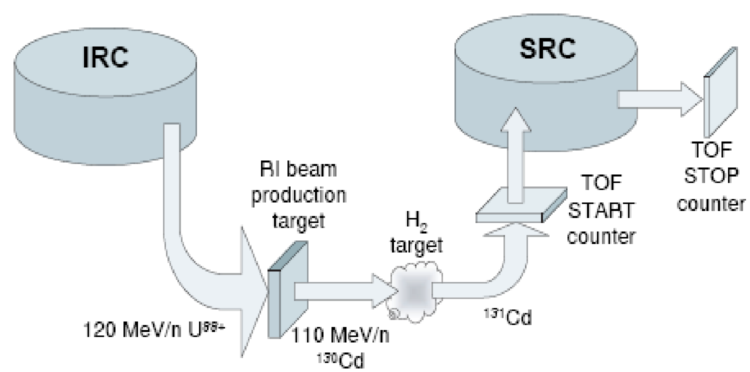
M. Fukuda[ac], S. Kubono[a], T. Teranishi[d], M. Notani[a], S. Nishimura[b], M. Nishimura[b], M. Terasawa[a], T. Suda[b], S. Kato[e], E. Ideguchi[a] and A. Goto[b]

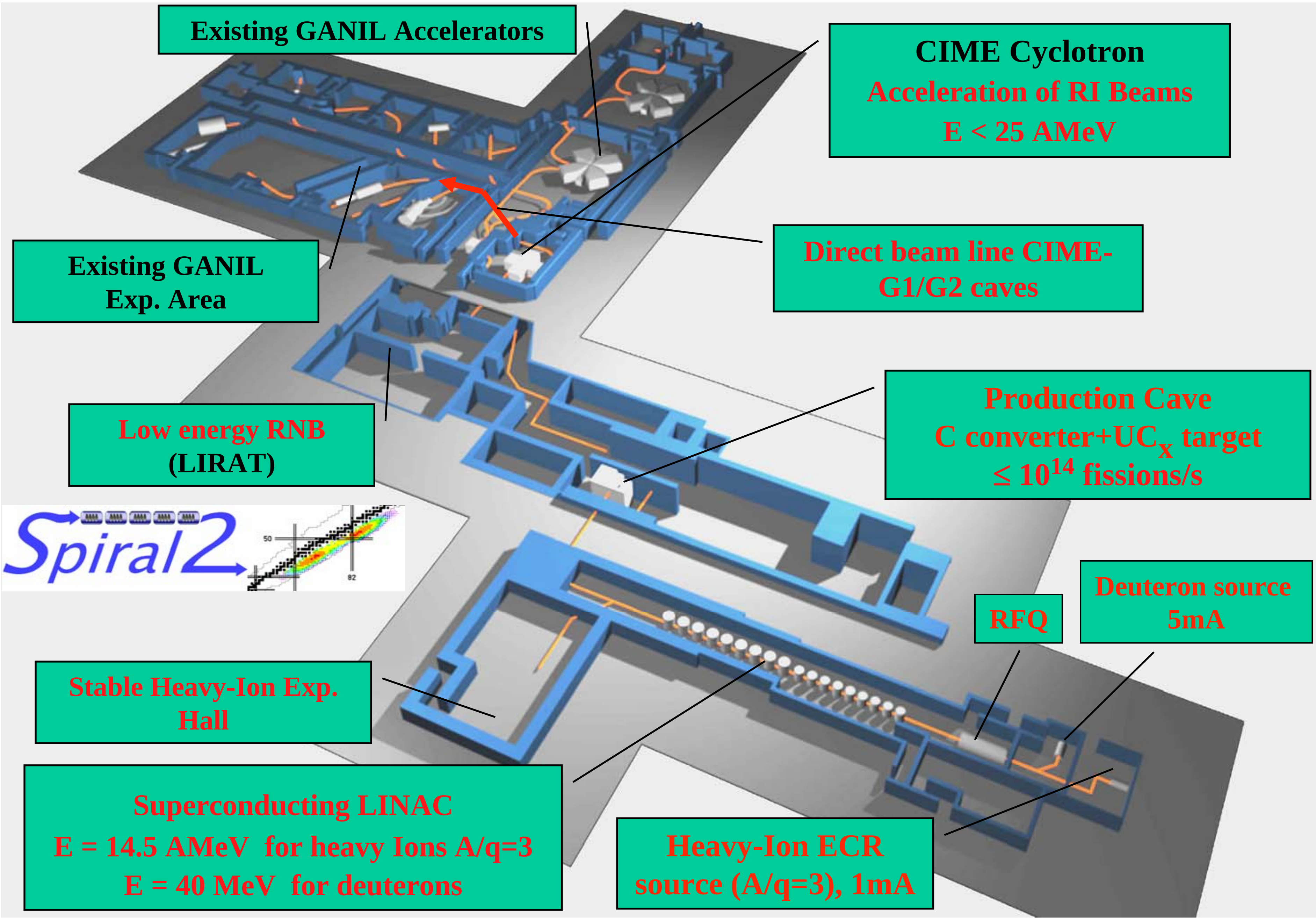
[a] *Center for Nuclear Study, Graduate School of Science, University of Tokyo*
[b] *RIKEN (The Institute of Physical and Chemical Research)*
[c] *Takasaki Radiation Chemistry Research Establishment, JAERI*
[d] *Department of Physics, Kyushu University*
[e] *Department of Physics, Yamagata University*

CNS Annual Report 2003

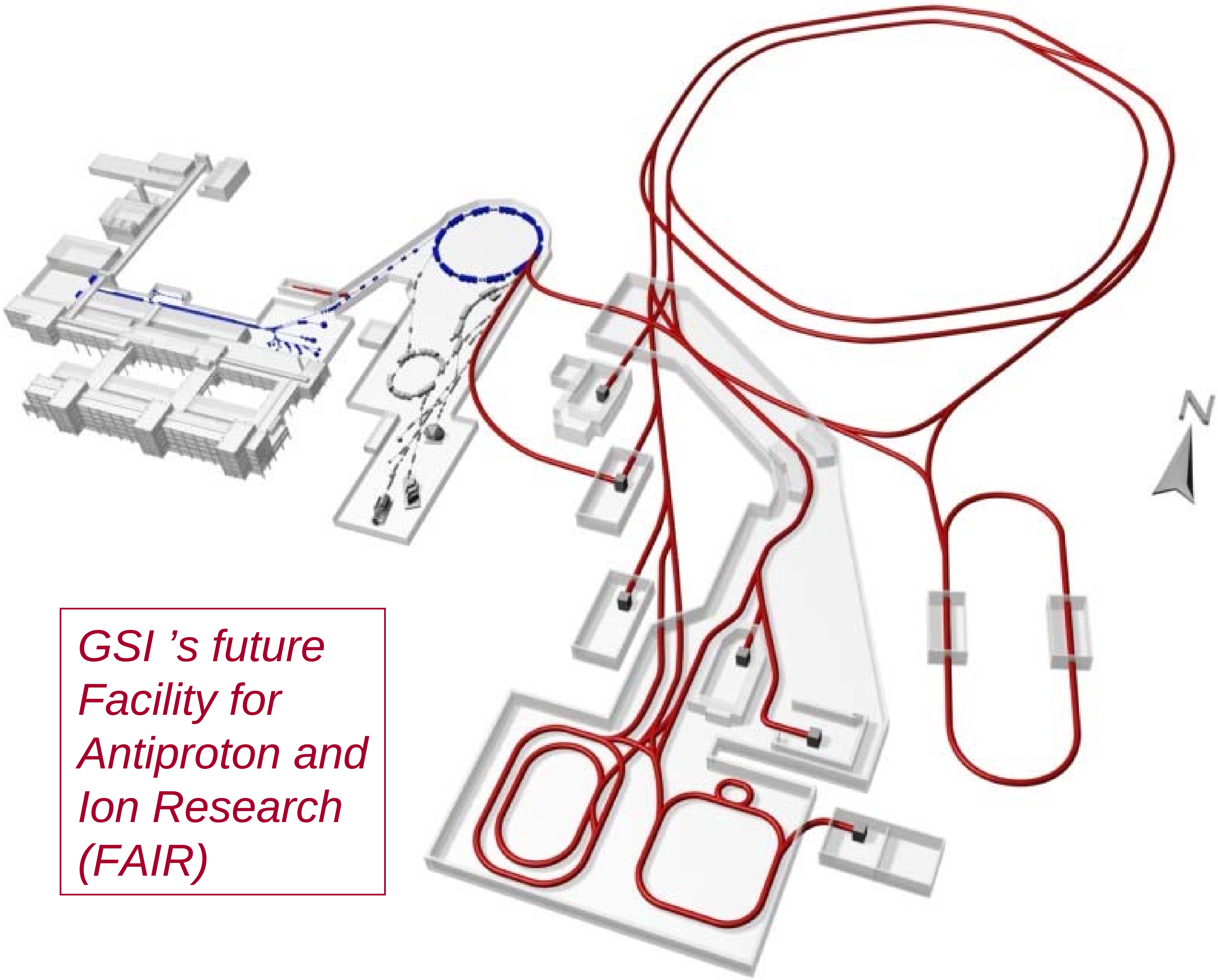
1. Introduction

Investigation of heavy-element nucleosynthesis [1] is required for understanding the mechanism of stellar events and cosmo-chronology. The rapid neutron capture process (r-process) is one of the dominant process for the heavy element nucleosynthesis. The r-process path runs in a very high neutron?density region far away from the stable nuclei. Difficulties lie in experimental simulation of the nucleosynthesis in the r-process using accelerators, since heavy



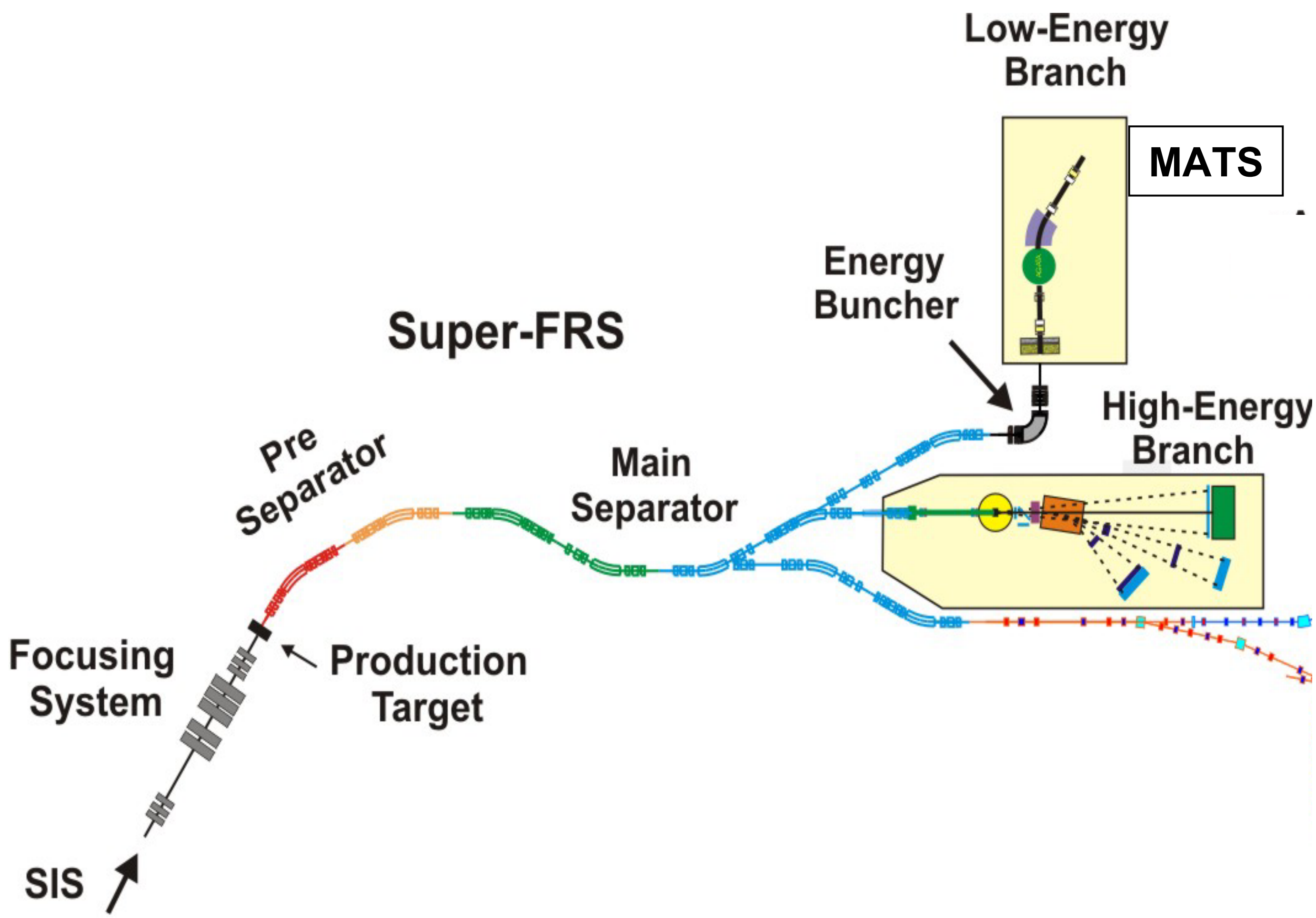

Existing GANIL Accelerators
CIME Cyclotron
Acceleration of RI Beams
E < 25 AMeV
Existing GANIL
Exp. Area
Direct beam line CIME-
G1/G2 caves
Low energy RNB
(LIRAT)
Production Cave
C converter+UC_x target
$\leq 10^{14}$ fissions/s
Spiral2
RFQ
Deuteron source
5mA
Stable Heavy-Ion Exp.
Hall
Superconducting LINAC
E = 14.5 AMeV for heavy Ions A/q=3
E = 40 MeV for deuterons
Heavy-Ion ECR
source (A/q=3), 1mA

Beyond the horizon

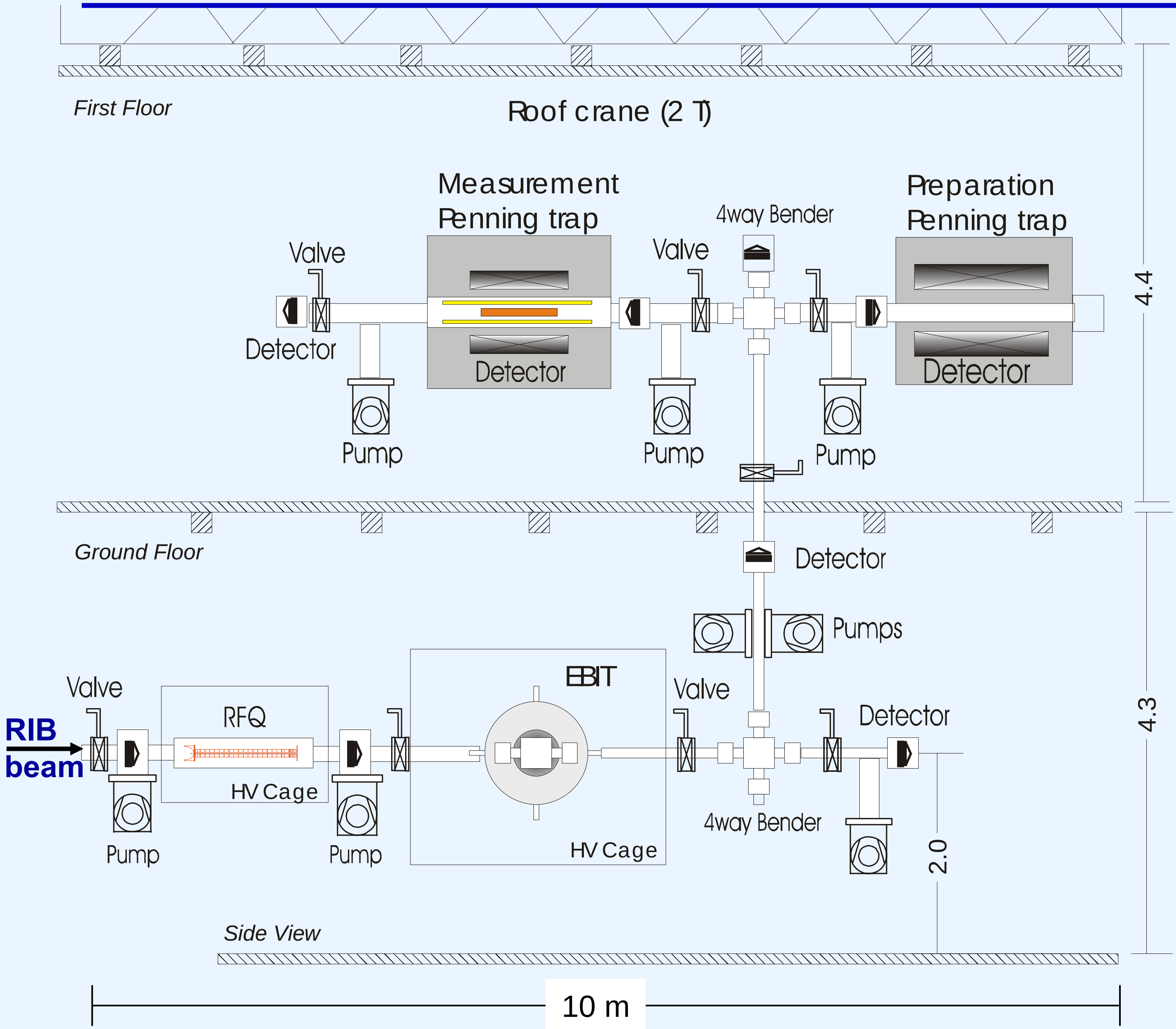


GSI 's future Facility for Antiproton and Ion Research (FAIR)

Mass program at FAIR



MATS Experimental Setup



Detectors:
- FT-ICR
- TOF-ICR
- Si(Li) electron

Precision trap:
measurements

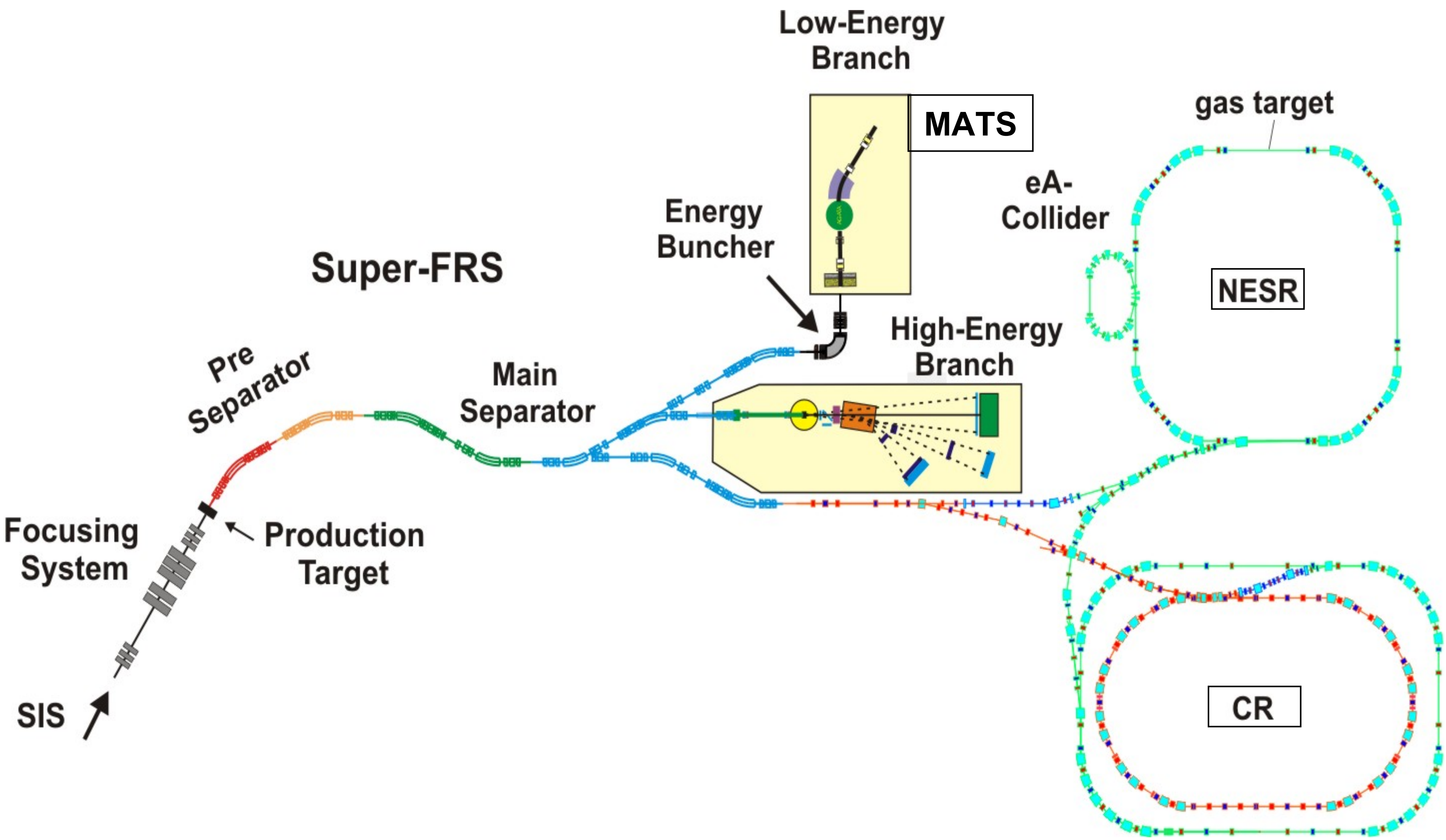
Cooler trap:
beam preparation

q/m selection:
separation

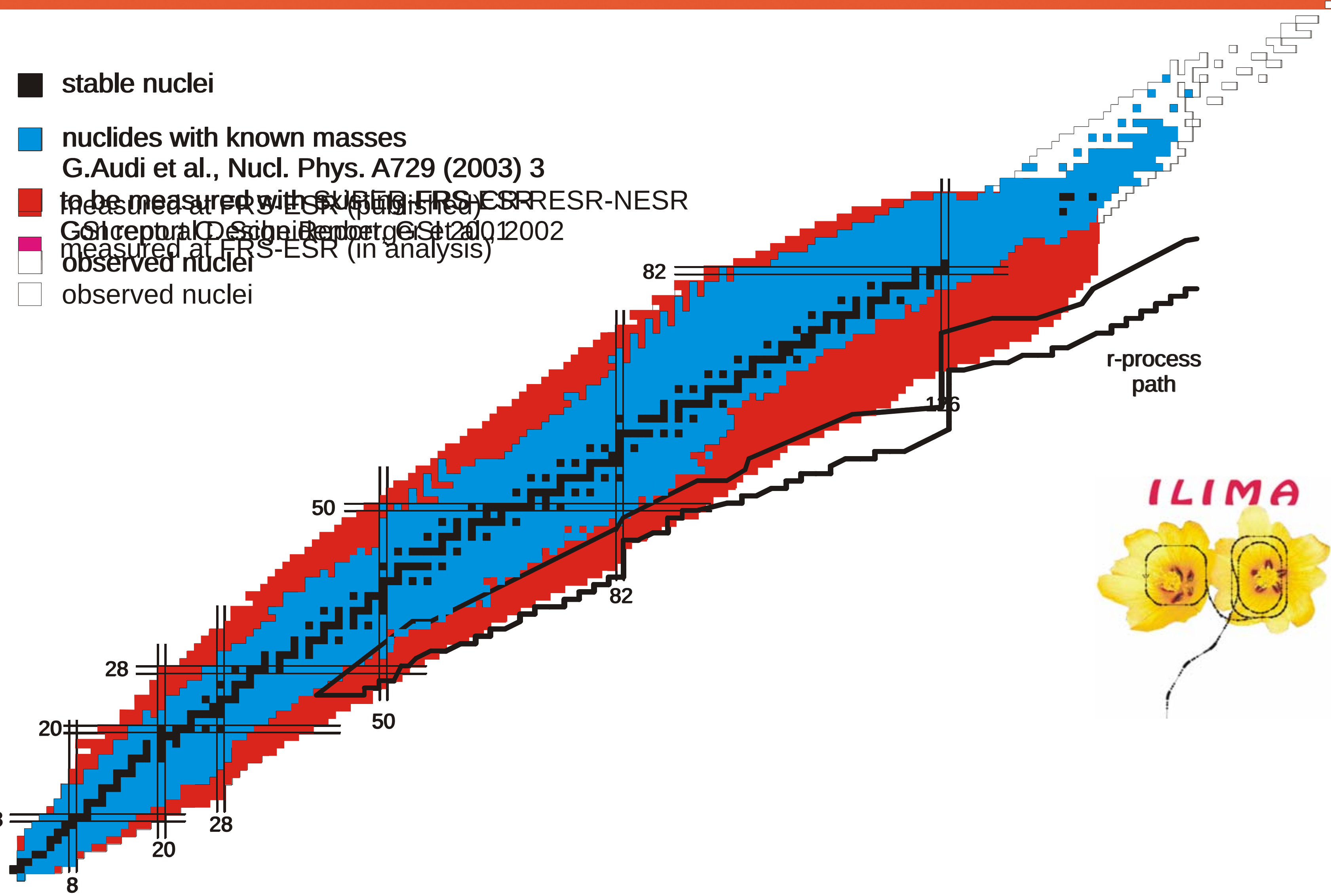
EBIT:
charge breeding

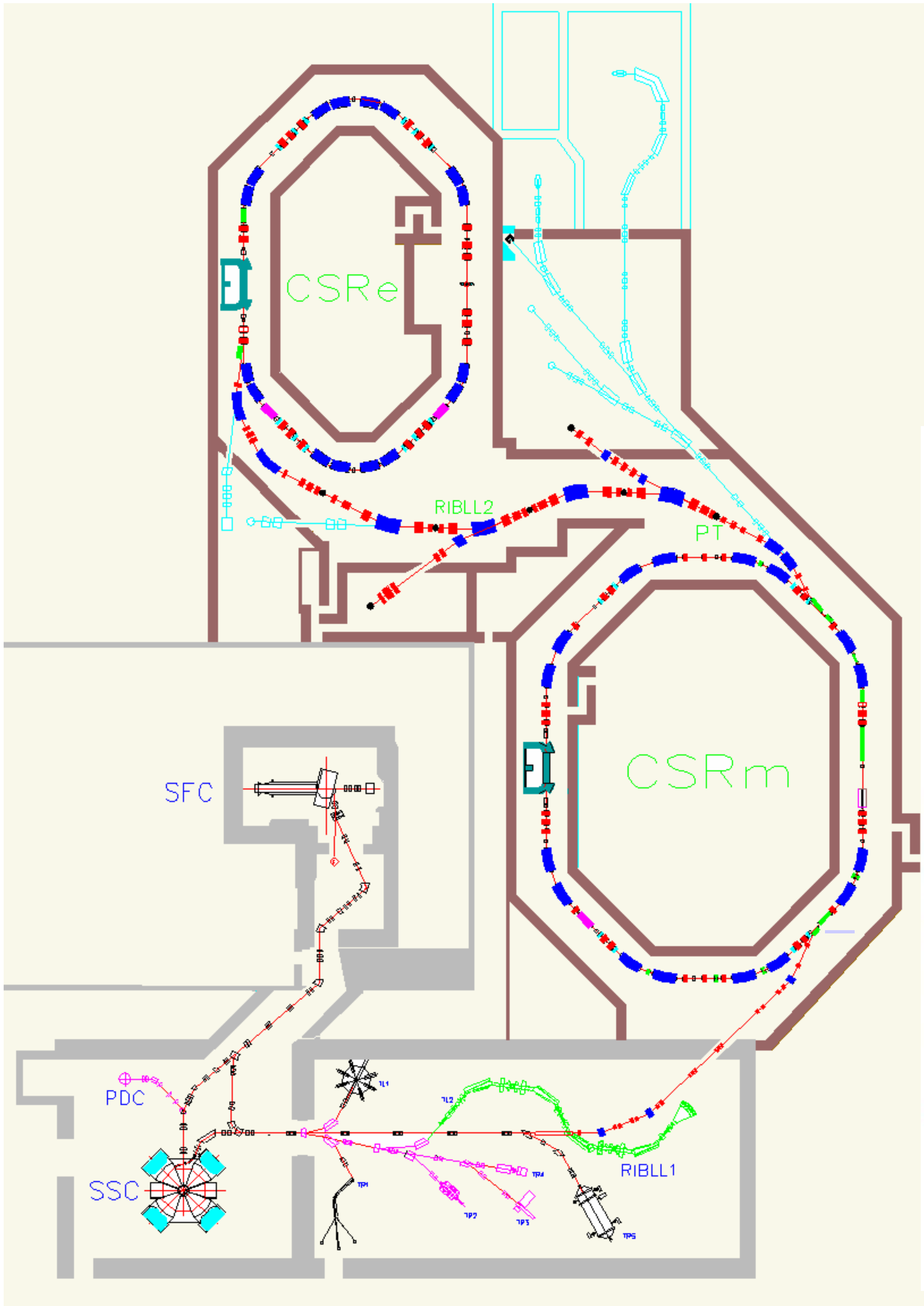
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

Mass program at FAIR



Outlook


stable nuclei
nuclides with known masses
G.Audi et al., Nucl. Phys. A729 (2003) 3
to be measured with SUPER-FRS-CR-RESR-NESR
Conceptual Design Report, GSI 2001
measured at FRS-ESR (published)
C. Scheidenberger et al. 2002
measured at FRS-ESR (in analysis)
observed nuclei
observed nuclei
8
20
28
50
82
8
20
28
50
82
126
r-process
path
ILIMA



HIRFL-CSR News

2004 年第 2 期 (总第 36 期)　3 月 16 日印发　CSR 工程经理办公室主编

完成主环主要设备的安装 完成主环高频累积腔的验收

经过工程建设人员的艰苦奋战，HIRFL-CSR 工程完成了主环主要设备的安装任

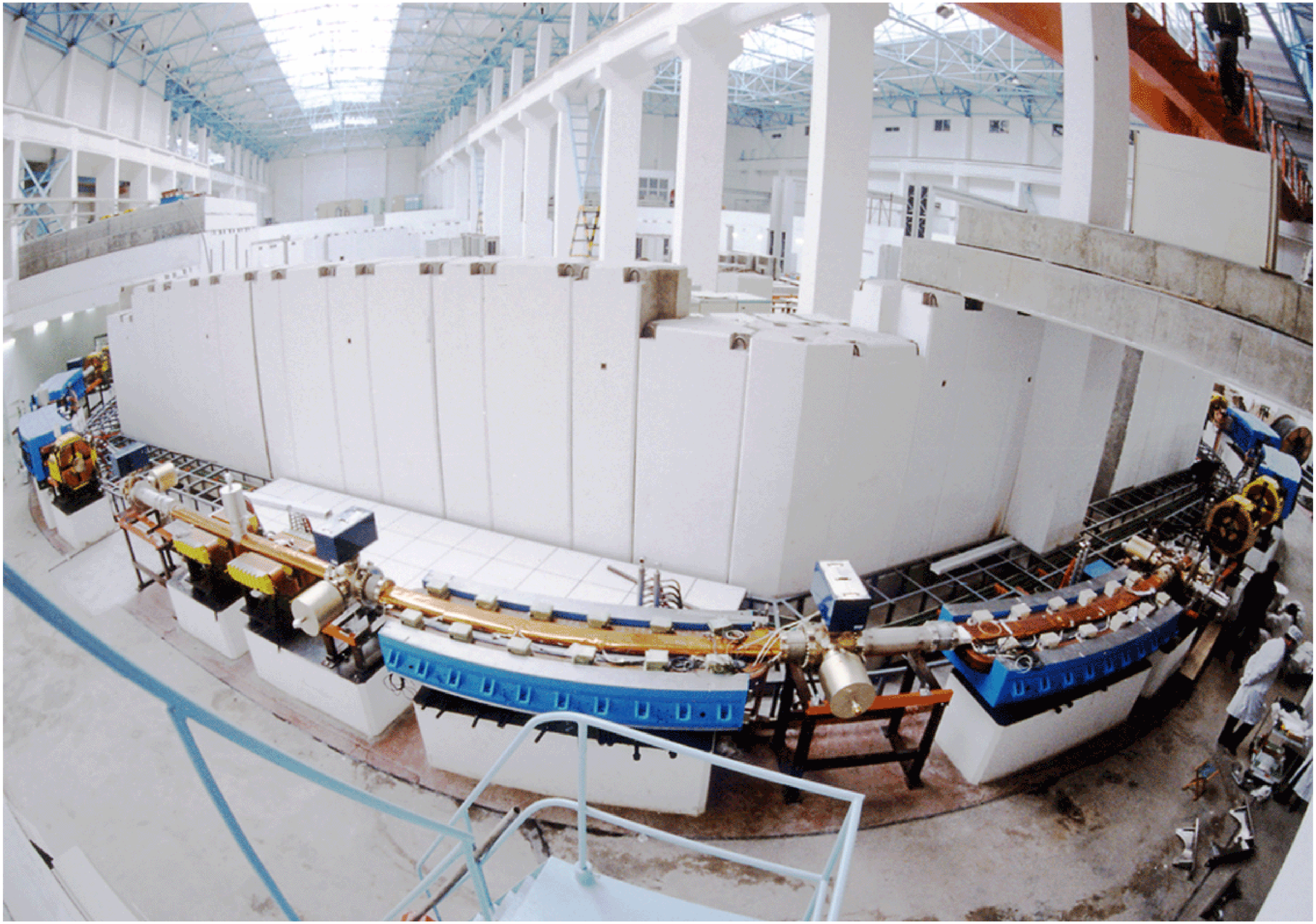
图 1 主环局部图

务（见图 1），主环全线实现闭环。主环 17 块二极磁铁（包括 1 块参考铁）、30 块四极磁铁、8 块六极铁和 38 块校正铁已全部安装就位，并完成了初步准直；完成了 3000A 主环二极铁主达到 10^{-11}mbar 的要求）；主环电子冷却装置、

图 3 主环高频累积腔系统已安装在线

高频加速腔系统和高频累积腔系统已安装就位。

既完成主环电子冷却装置和主环高频加速腔系统之后，今年二月份完成了 25kV 主环高频累积腔系统的安装、调试和验收（见图 3），以 ^{238}U、^{12}C、^{40}Ar 和 ^{84}Kr 四种粒子的加速参数为条件对整个高频系统进行了连续 72 小时的运行达标考验。主要测试结果如下：最大腔体电压为 20kV，频率变化范围为 6~14MHz，失谐引起的



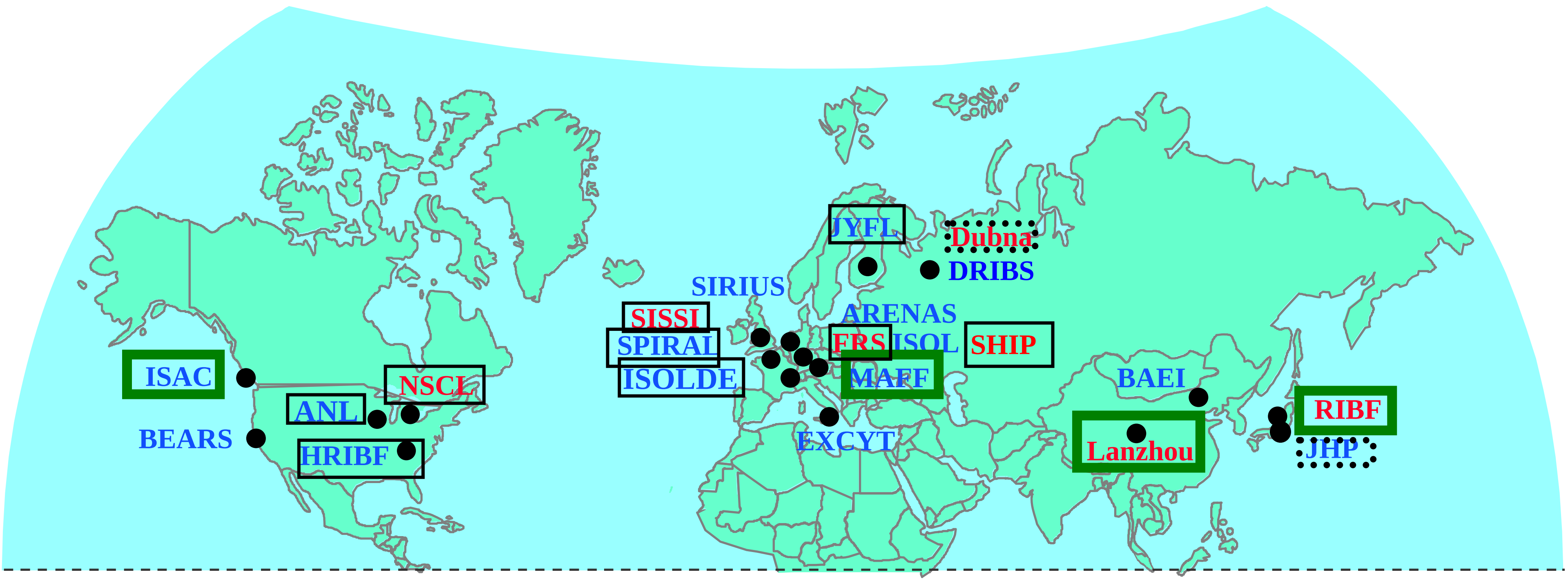
CSR 进展

electron coolers

CSR (Lanzhou)

ESR (Darmstadt)

worldwide radioactive ion beam facilities



ISOL thick-target facilities in-flight separation facilities

MASS MEASUREMENTS (NEAR) FUTURE

I. General concepts – binding energy; the mass unit; resolution; precision; accuracy

II. Physics motivation
   a nuclear structure – shells, deformation, pairing, halos (the mass scale)
   b weak interaction – superallowed beta decay and the CKM matrix
   c astrophysics – stellar nucleosynthesis

III. Production of radionuclides – methods of FIFS (fragmentation) et ISOL;
   (ion manipulation using traps and gas cells)

IV. Mass measurement techniques
   i. indirect methods – reactions et decays
   ii. direct methods – time of flight (SPEG et CSS2 au GANIL;
   ESR isochronous mode at GSI); revolution (cyclotron) frequency
   (ESR Schottky mode; ISOLTRAP and MISTRAL at ISOLDE)

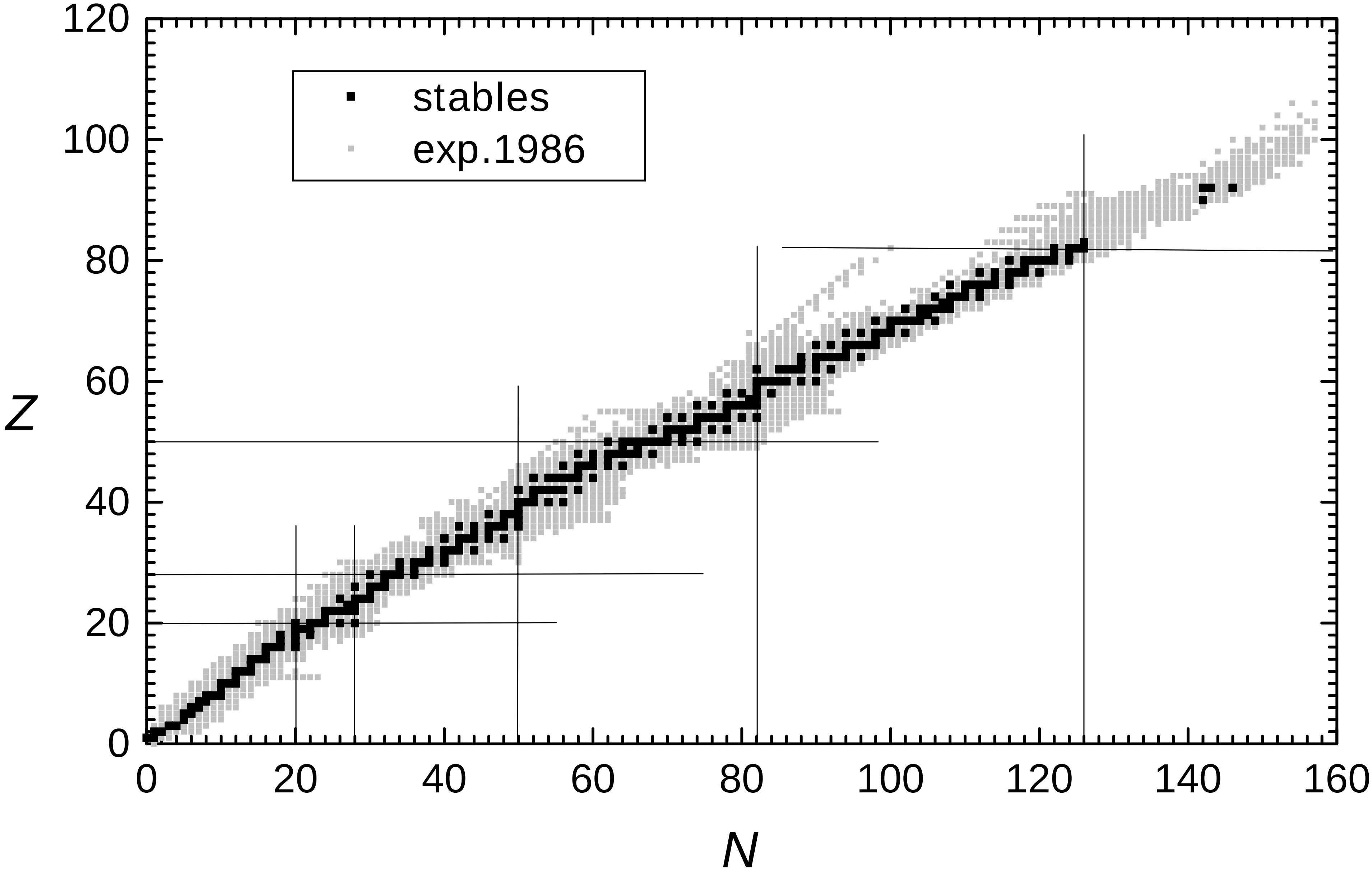
V. Comparisons of the different methods

VI. The atomic mass evaluation (demonstration of the program *NUCLEUS*)

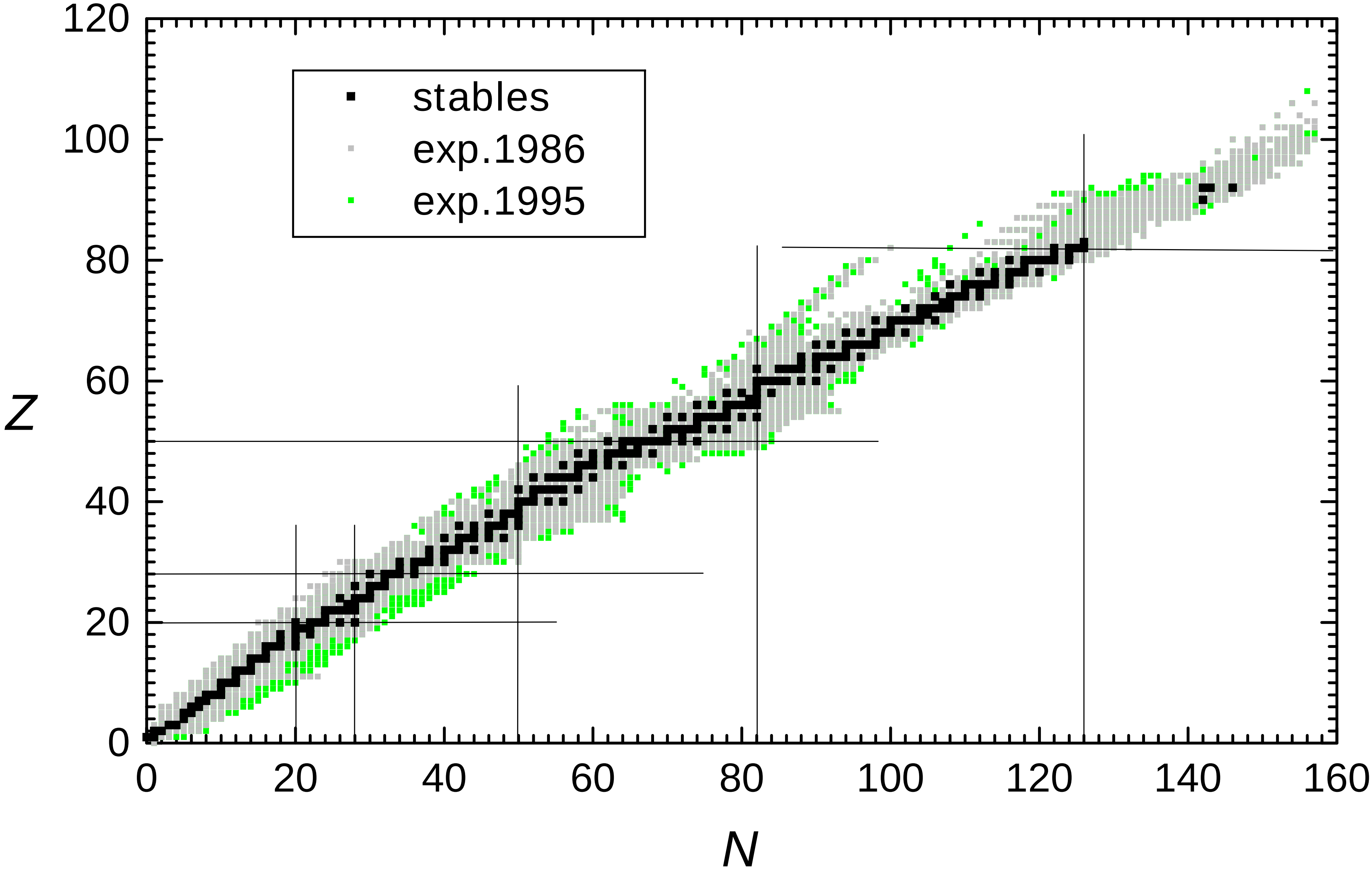
VII. Mass models and comparisons; chaos on the mass surface?

VIII. A look into the future

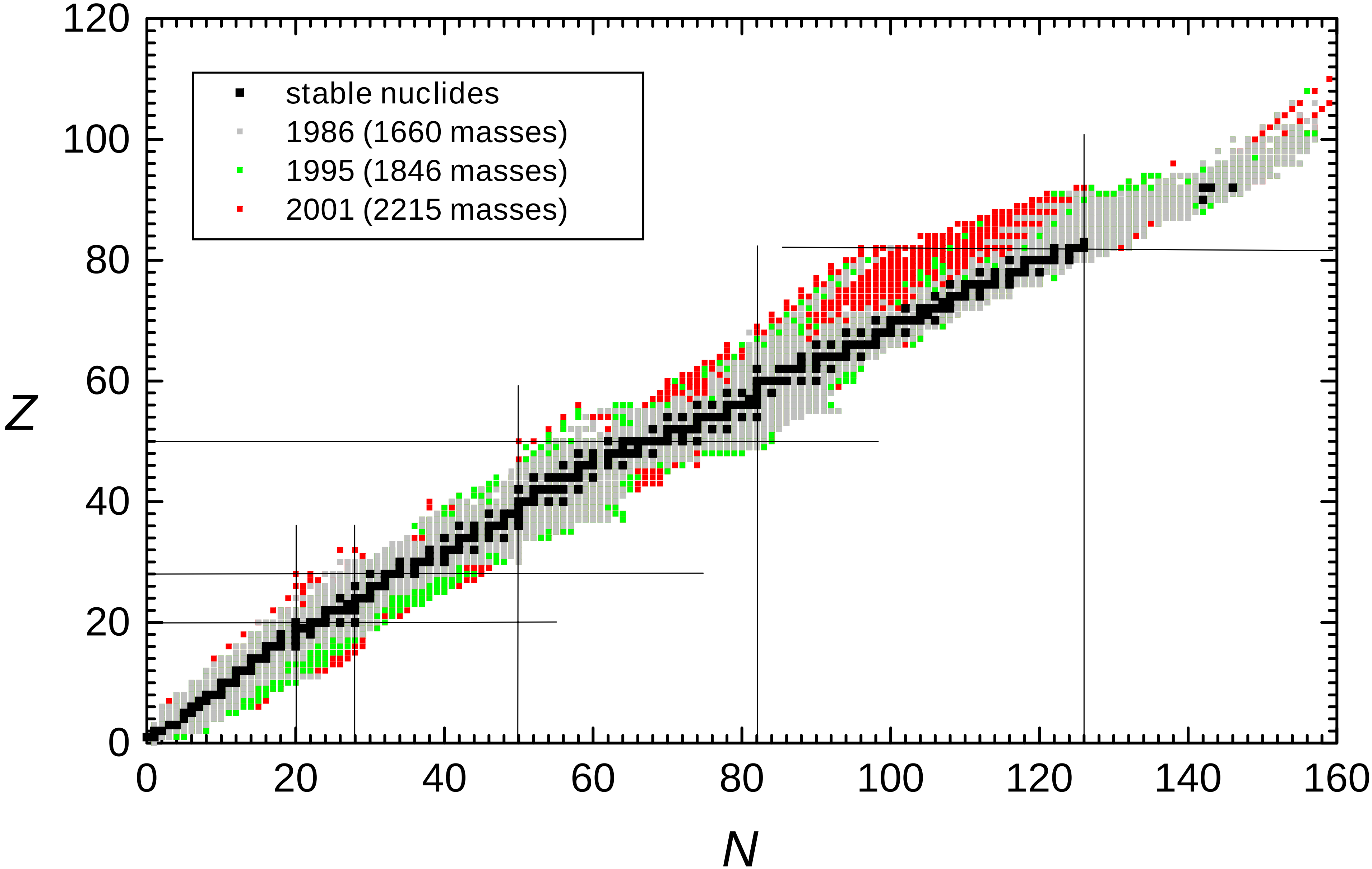
IX. Conclusions



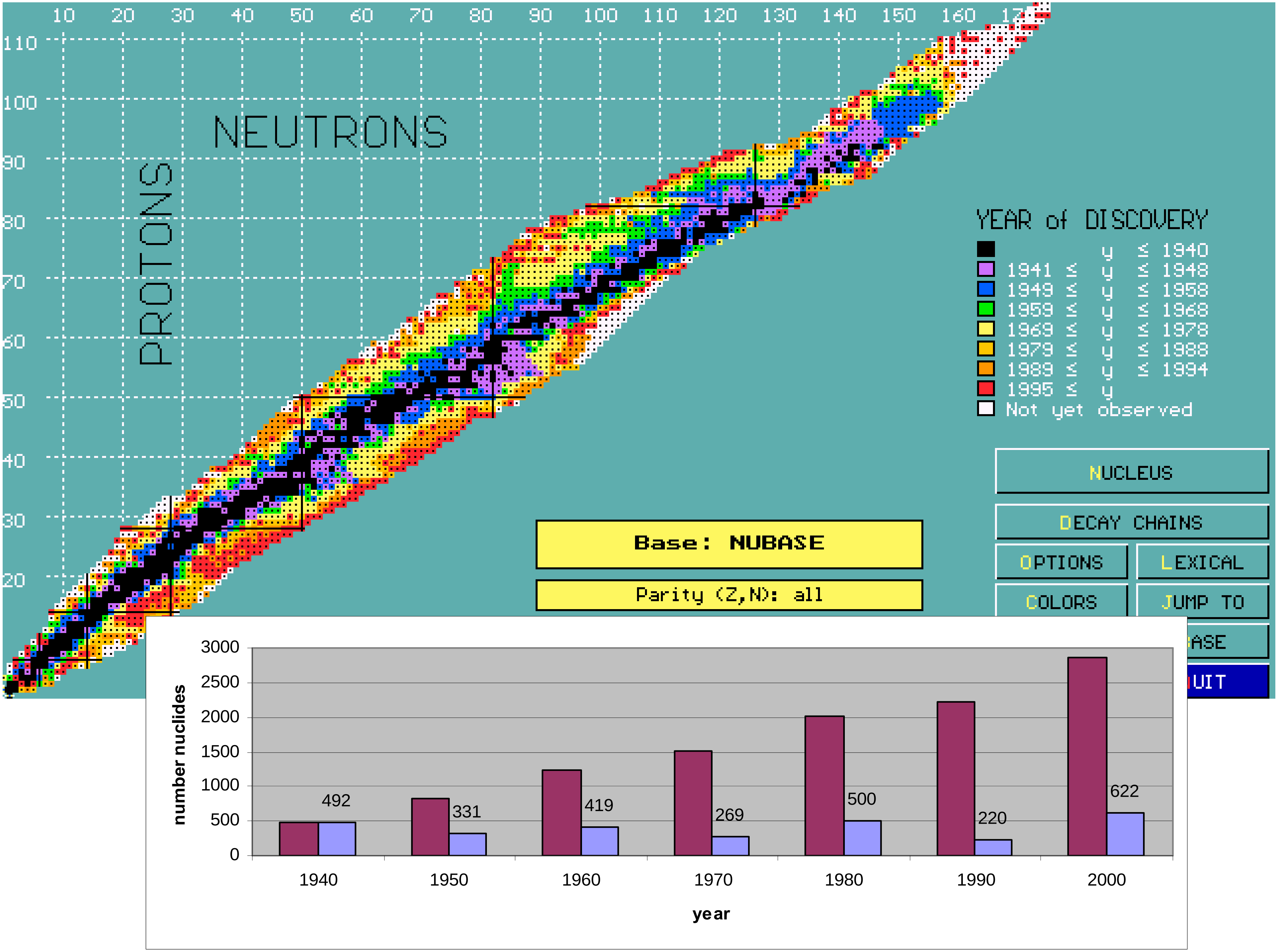
stables
exp.1986
Z
N
0
20
40
60
80
100
120
140
160



stables
exp.1986
exp.1995
Z
N
0
20
40
60
80
100
120
140
160

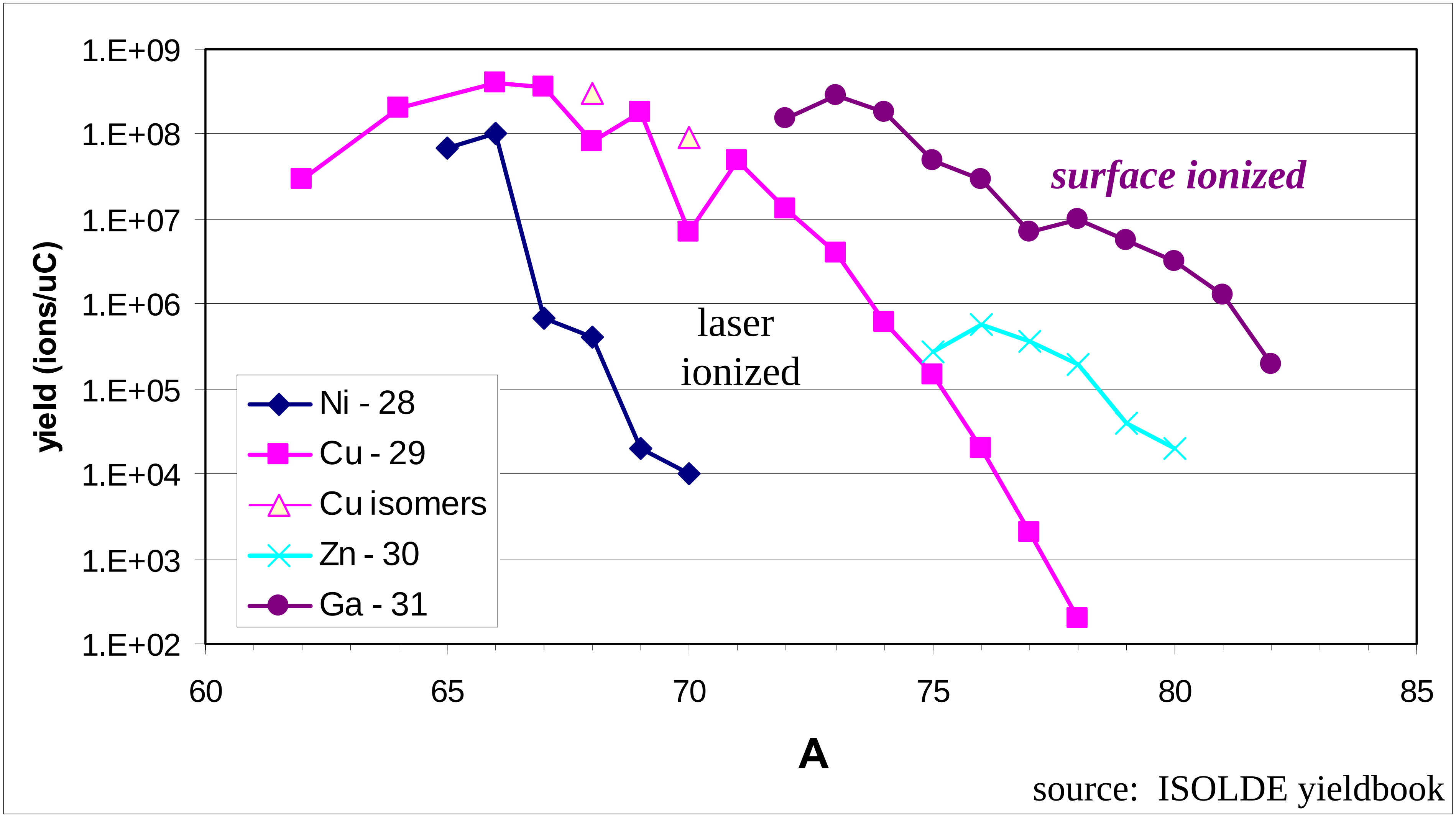


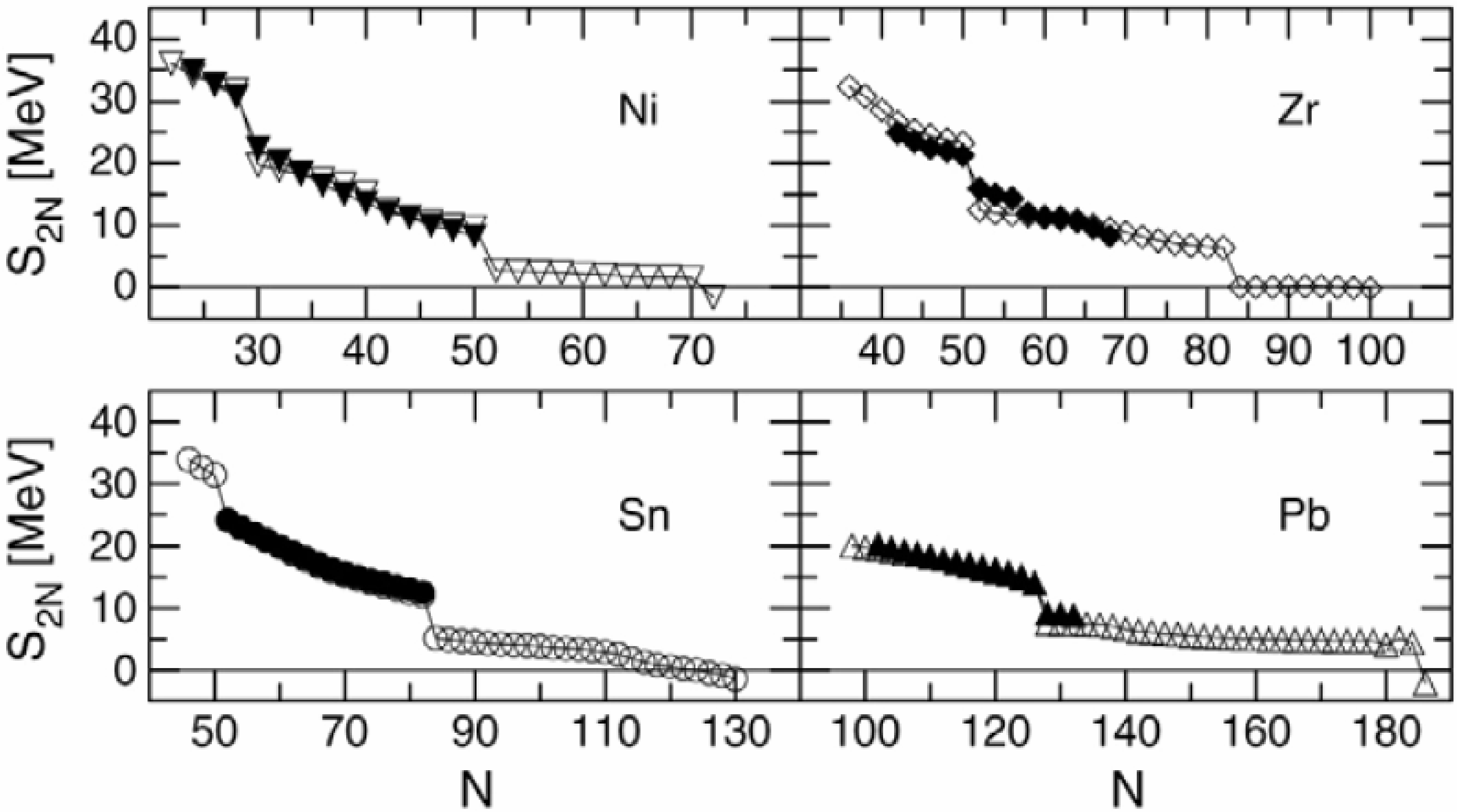
stable nuclides
1986 (1660 masses)
1995 (1846 masses)
2001 (2215 masses)
Z
N
0
20
40
60
80
100
120
140
160



NEUTRONS
PROTONS
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
110 100 90 80 70 60 50 40 30 20
YEAR of DISCOVERY
y ≤ 1940
1941 ≤ y ≤ 1948
1949 ≤ y ≤ 1958
1959 ≤ y ≤ 1968
1969 ≤ y ≤ 1978
1979 ≤ y ≤ 1988
1989 ≤ y ≤ 1994
1995 ≤ y
Not yet observed
NUCLEUS
DECAY CHAINS
OPTIONS
LEXICAL
COLORS
JUMP TO
Base: NUBASE
Parity (Z,N): all
number nuclides
3000
2500
2000
1500
1000
500
0
492
331
419
269
500
220
622
1940
1950
1960
1970
1980
1990
2000
year

Radioactive beam yields: the harsh reality




Ni
Zr
Sn
Pb
S_{2N} [MeV]
S_{2N} [MeV]
N
N
40
30
20
10
0
30
40
50
60
70
40
50
60
70
80
90
100
50
70
90
110
130
100
120
140
160
180

Conclusions

Mass Measurements

higher performance;
programs multiplying
$\Rightarrow$ more data,
better quality

Mass Evaluation

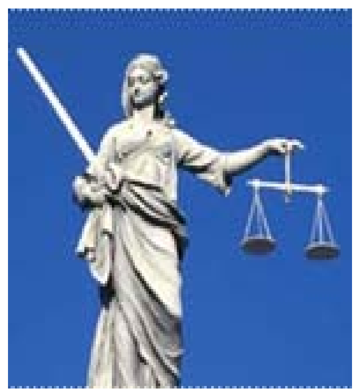
global benchmark

(last judgement)

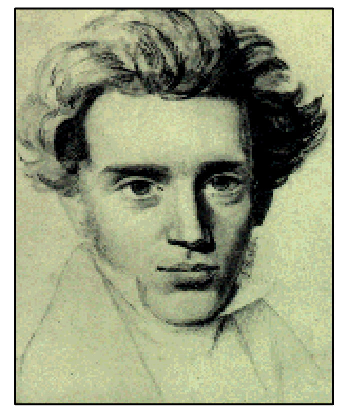
Mass Models

microscopic era;
real need for data
(diagnostic tool)

Lichtenberg:
To find something new,
must build something new.



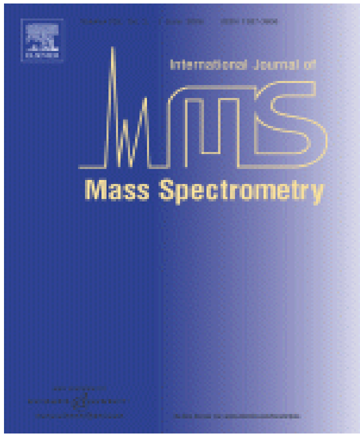
“A false balance is
an abomination to
the Lord:
but a just weight
is his delight.”
— Proverbs 11.1

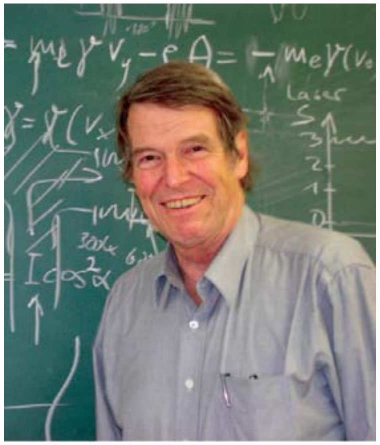


Kierkegaard:
I must find a truth
that is true for me.

Bibliography

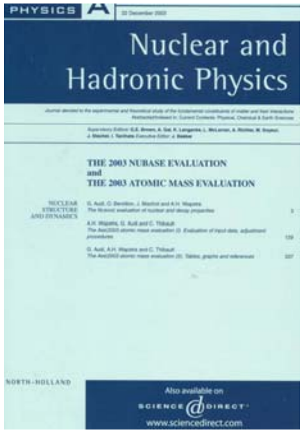
VOL. 251 NOS. 2–3 (2006)
International Journal of
Mass Spectrometry

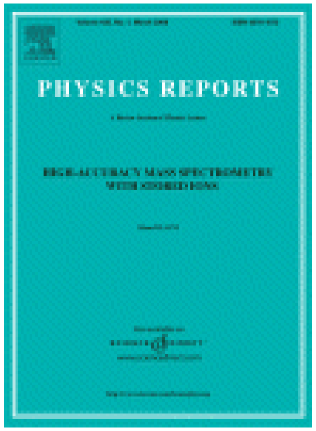




Jürgen Kluge

The 2003 Atomic Mass Evaluation
G. Audi, A.H. Wapstra And C. Thibault
Nuclear Physics A (2003) 337

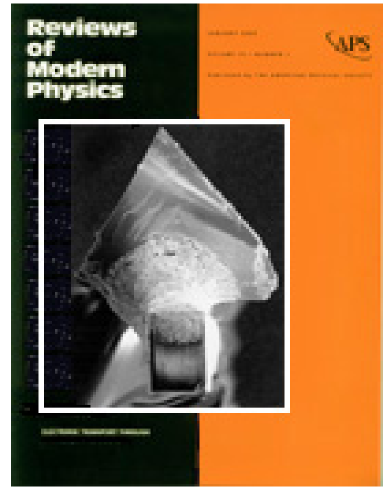




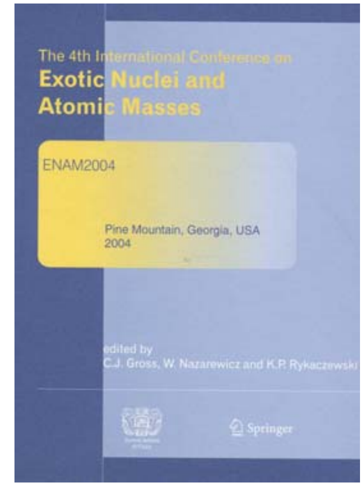
High-accuracy mass spectrometry with stored ions
Klaus Blaum
Physics Reports 425 (2006) 1-78

PRECISION NUCLEAR MEASUREMENTS WITH ION TRAPS
G. Savard, G. Werth
Annual Review of Nuclear and Particle Science 50 (2000) 119-152

Recent trends in the determination of nuclear masses
Reviews of Modern Physics 75, 1021-1066 (2003)
D. Lunney, J.M. Pearson, C. Thibault,

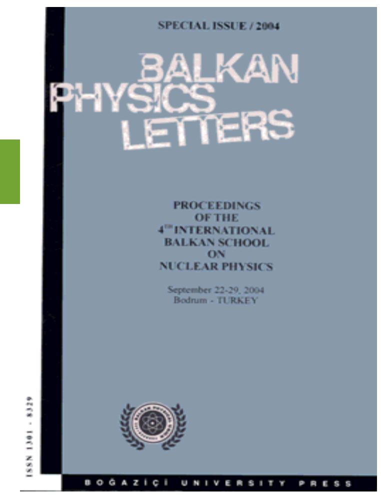


Latest trends from the ever-surprising field of mass measurements
European Physics Journal A 25, s01, 3-8 (2005)
D. Lunney



Mass measurements of exotic nuclei and their importance for stellar nucleosynthesis
Nuclei in the Cosmos IX; POS (NIC – IX) 010
D. Lunney

Mass measurements of exotic nuclei for nuclear structure, fundamental interactions & astrophysics
4th Balkan School of Nuclear Physics (2004) 130-159
D. Lunney



Nuclear Masses: Experimental programs, theoretical models and astrophysical interest
Nuclei in the Cosmos V (1998) 296-302
D. Lunney