The 2016 Atomic Mass Evaluation and the Mass Tables

Georges Audi Csnsm September 2016

the future of the Ame & Nubase evaluations

last published Tables : December 2012 in CPC

now at IMP-Lanzhou : WANG Meng （王猛） new coordinator

next publication planned : December 2016

the Atomic Mass Evaluation (AME)

the experimental data

data evaluation - data treatment - adjusted masses

regularity - estimated unknown masses


AMDC
原子质量评估备忘录签字仪式
Memorandum Signing Ceremony
Atomic Mass Evaluation

The new AME collaboration

Coordinator

Meng Wang[a]

Contributors

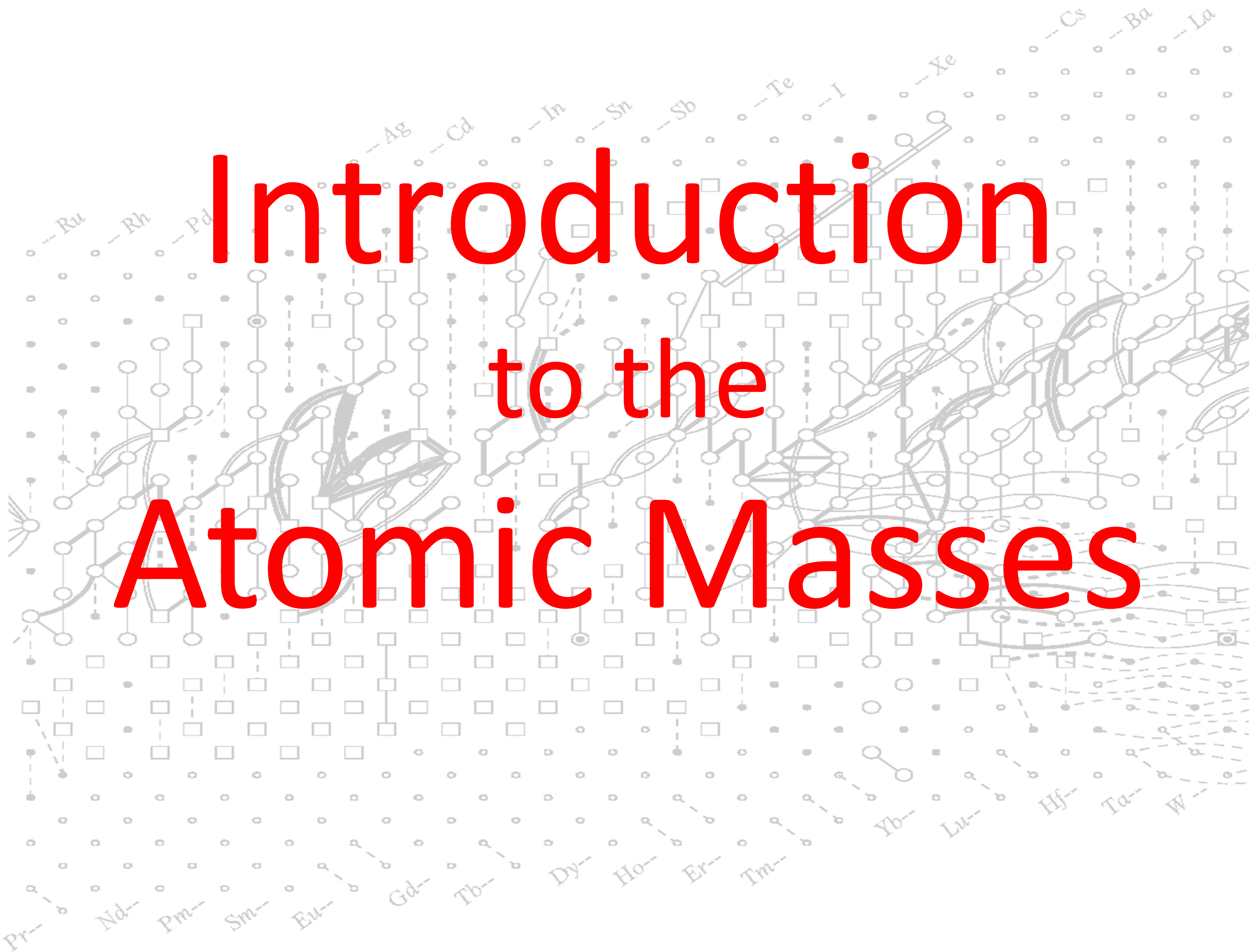
Georges Audi[b], Wenjia Huang[b], Filip Kondev[c], Sarah Naimi[d]

a.*IMP-Lanzhou* b.*CSNSM-Orsay* c.*ANL-Argonne* d.*RIKEN*

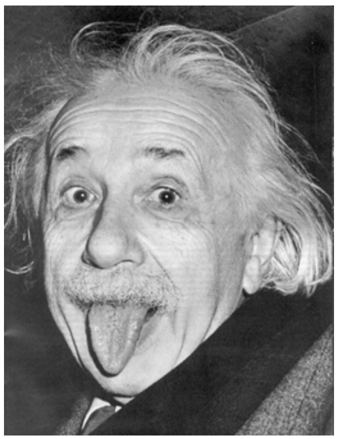
Introduction

to the

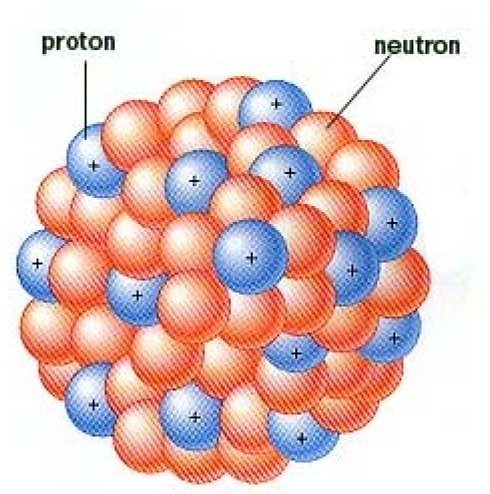
Atomic Masses



Atomic mass



$E = mc^2$

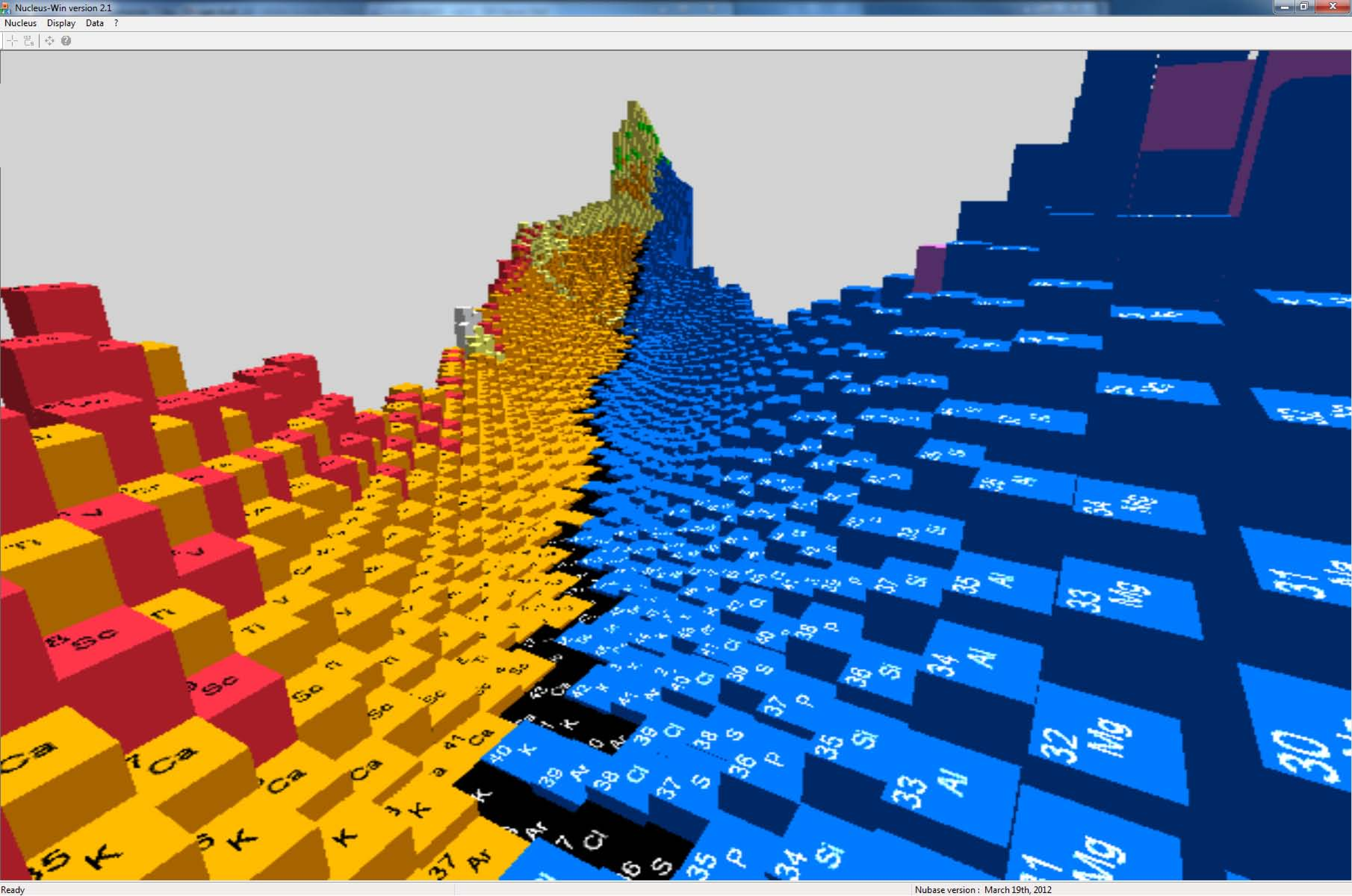


Nuclear physics
Atomic physics
Nuclear astrophysics
Atomic energy
Fundamental symmetries
Metrology
…..

Atomic mass

⇕

Nuclear mass

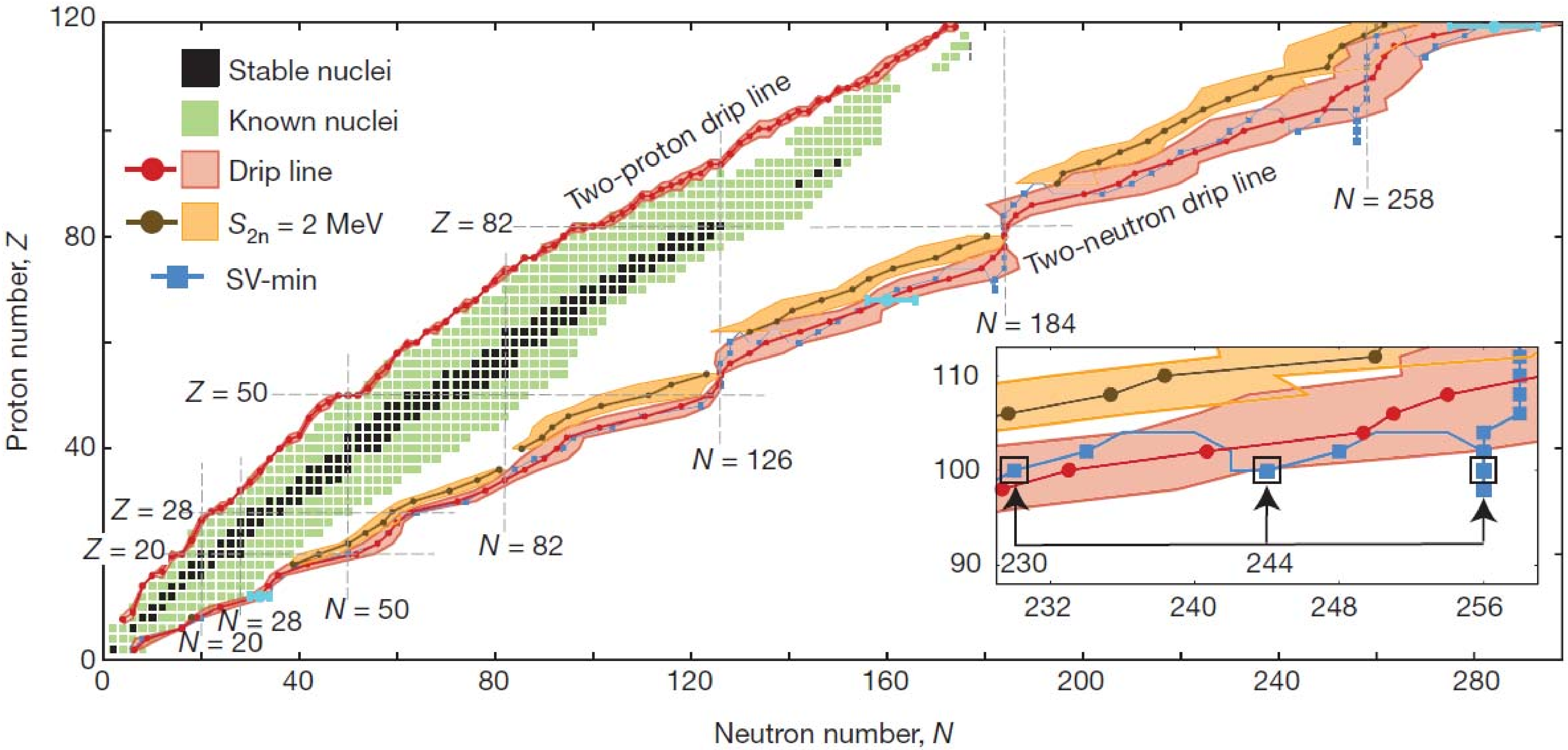

Nucleus-Win version 2.1
Nucleus Display Data ?
33 Mg
35 Al
34 Al
32 Mg
33 Al
38 Si
35 Si
37 P
36 P
39 Cl
38 Cl
37 S
38 S
39 Ar
40 K
35 P
34 Si
Ready
Nubase version : March 19th, 2012

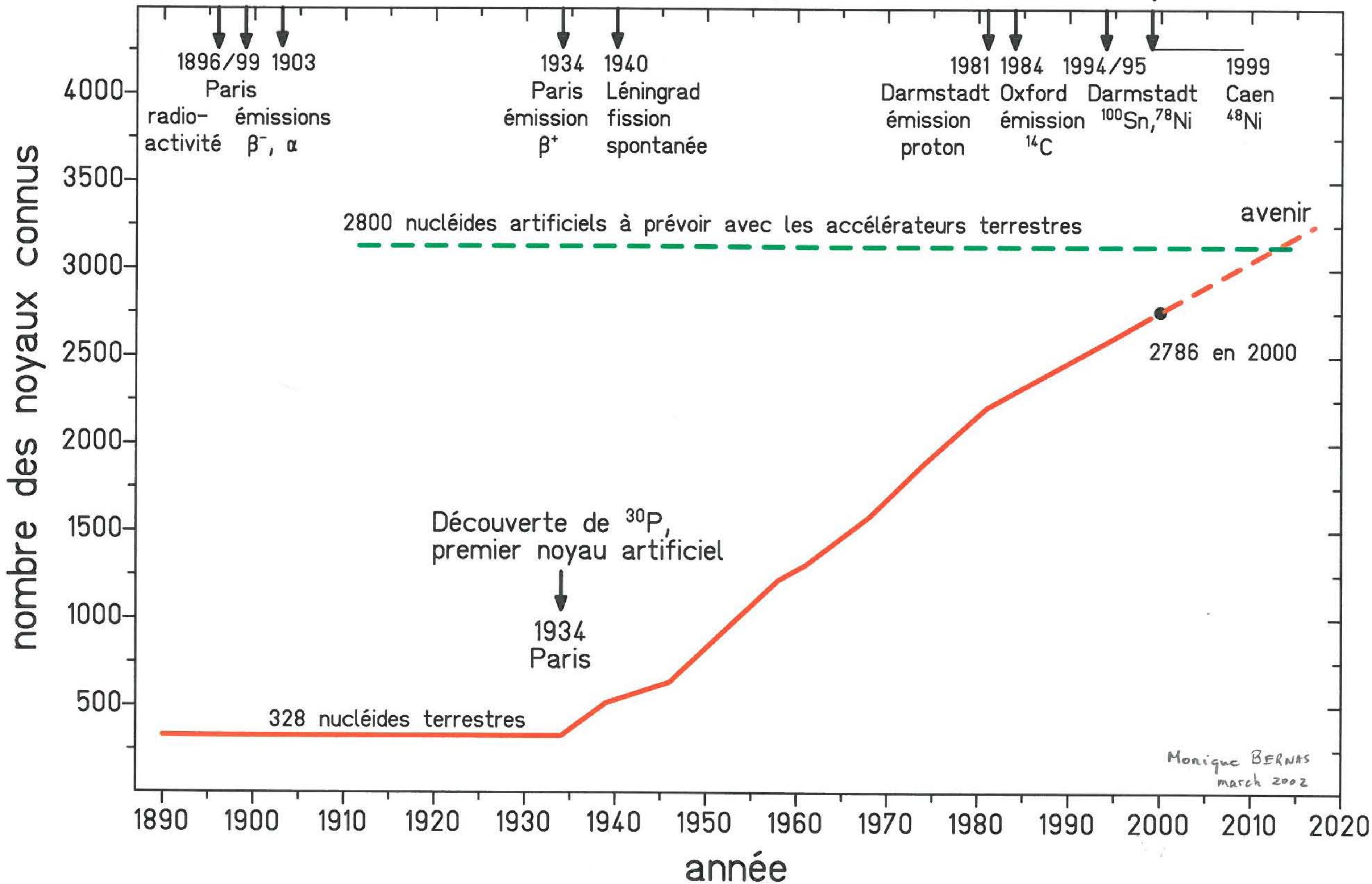
Exotic nuclei

The limits of the nuclear landscape

doi:10.1038/nature11188

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡



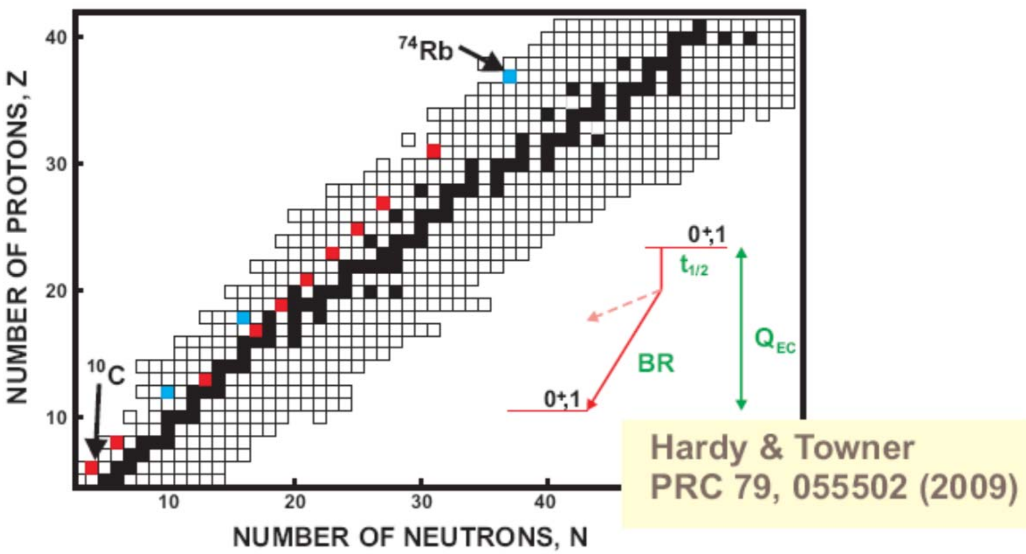


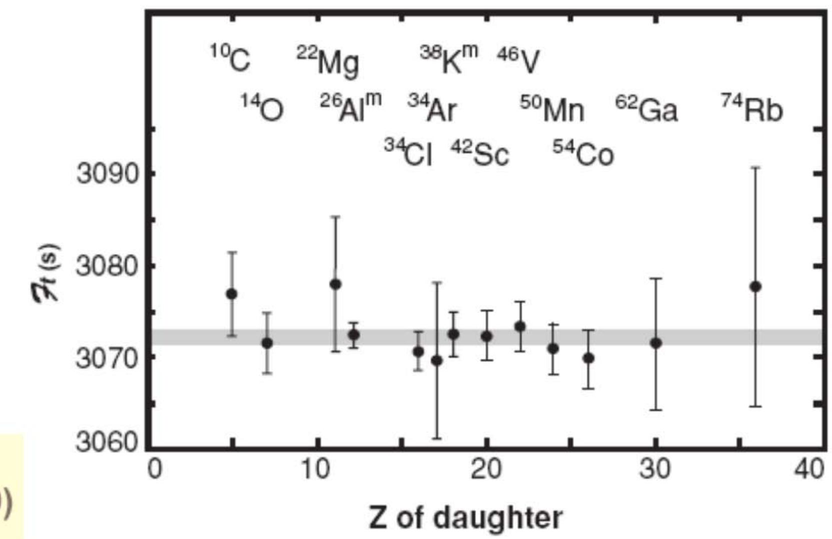
1896/99 Paris radio-activité
1903 émissions β^-, α
1934 Paris émission β^+
1940 Léningrad fission spontanée
1981 Darmstadt émission proton
1984 Oxford émission ^{14}C
1994/95 Darmstadt ^{100}Sn, ^{78}Ni
1999 Caen ^{48}Ni
2800 nucléides artificiels à prévoir avec les accélérateurs terrestres
avenir
2786 en 2000
Découverte de ^{30}P, premier noyau artificiel
1934 Paris
328 nucléides terrestres
nombre des noyaux connus
année
Monique BERNAS march 2002

Motivations

- Nuclear Physics
- Standard Model
- Neutrino Physics
- Astrophysics
- Atomic Physics

Superallowed $0^+ \rightarrow 0^+$ nuclear β decays





$$\mathcal{F}t = \frac{K}{2G_V^2\left(1 + \Delta_R^V\right)}$$

- **Test of**
  the conserved vector current (CVC) hypothesis
- **Test of**
  the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix

1) G_V constant ✔ verified to ± 0.013%

2) $|V_{ud}|=G_V/G_\mu$ = 0.97425 ± 0.00022

3) CKM unitarity established ✔

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99990 \pm 0.00060$$

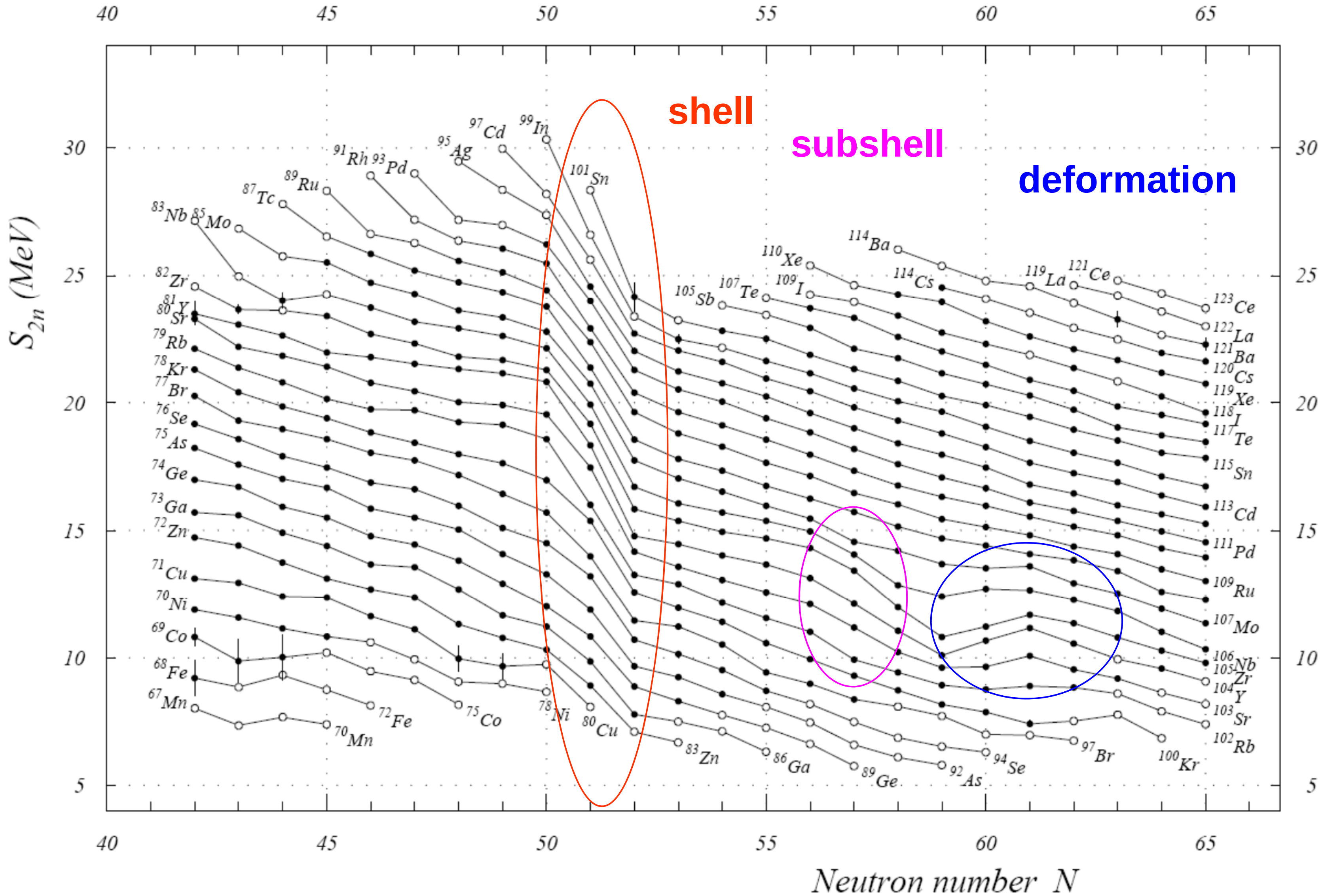
Discoveries

- 1913 : isotopism
- 1919 : age of the Sun
- 1933 : shells
- 1954 : deformed nuclei
- 1974 : magicity may disappear
- 1981 : sub-shells

Discoveries

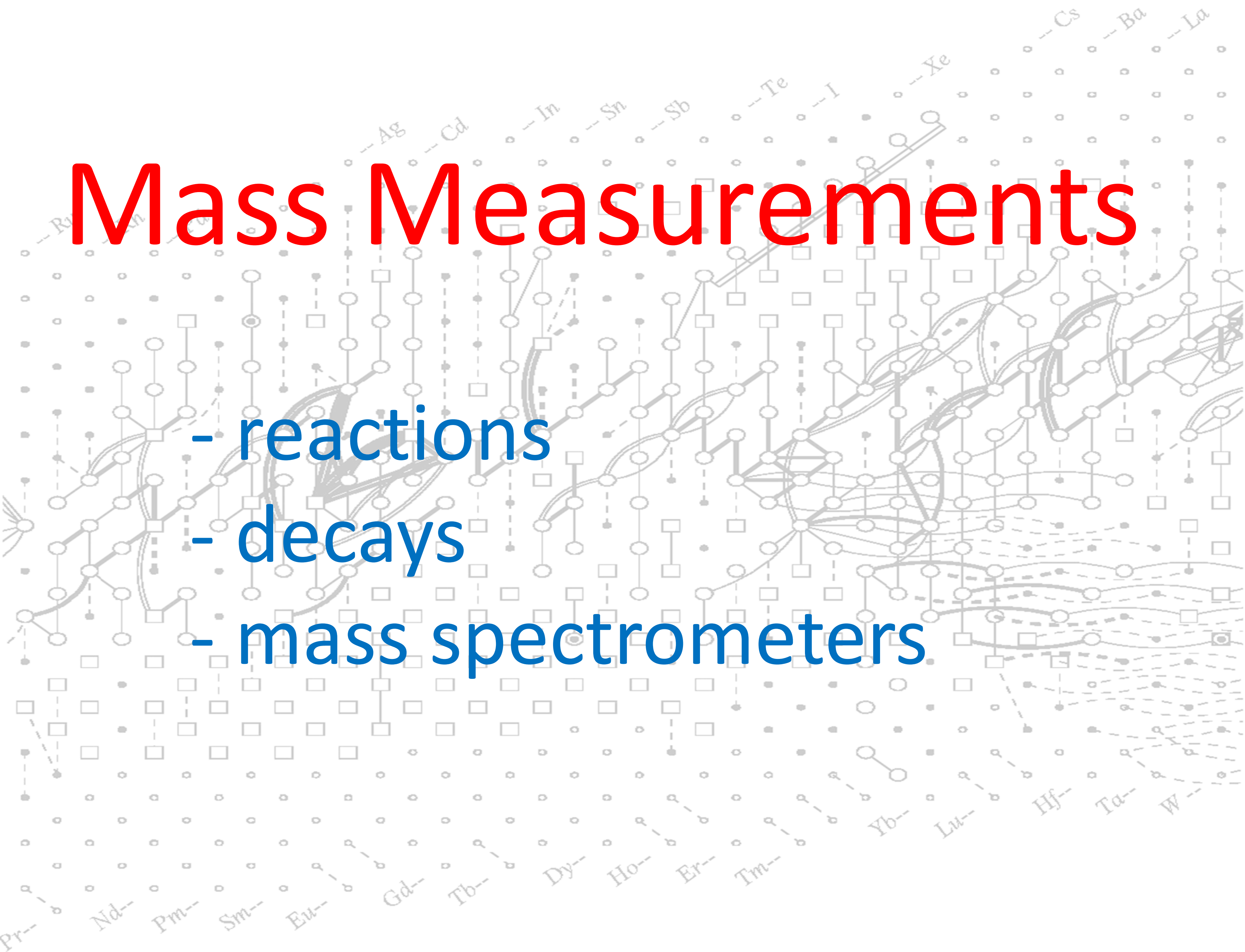
1913	Isotopism 20Ne 22Ne	Thomson
1919	restoring "whole number rule" (e-3)	Aston
1919	H=1.008	Aston
	→ solving the "age of the Sun crisis"	Eddington
1925	"mass defect" breaking (8e-4) full numbers	Aston
1933	closed shells Z=2 Z=8	Elsasser
1934	Z=20 Z=28 Z=50	Elsasser
1934	N=126 with Z=82 (alpha decay systs)	Elsasser
1948	"magic numbers" & shell model	Goeppert-Mayer
1954	deformation N=90	Hogg & Duckworth
1974	magicity disappearance N=20	Klapisch & Thibault
1981	sub-shell closure N=56	Audi
1981	deformation N=60	Audi

Nuclear structure



Mass Measurements

- reactions
- decays
- mass spectrometers



How are atomic masses measured?

Mass measurement:

- inertial mass
- energy

} **Relative** Measurements

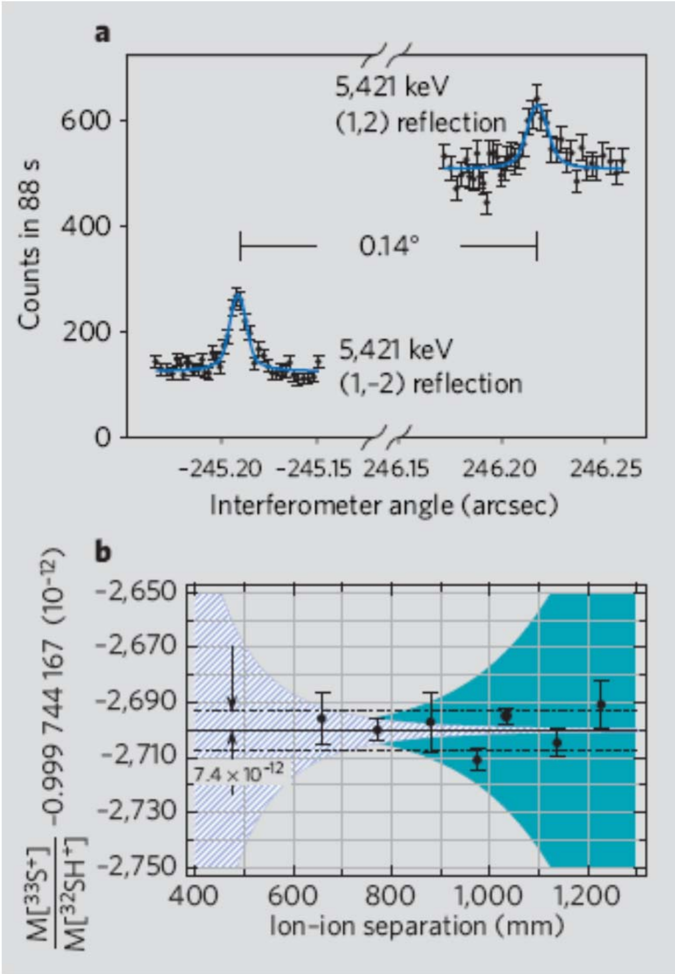
Energy released from neutron capture of ^{32}S ⟹

Mass ratio $M[^{33}S^+]/M[^{32}SH^+]$ ⟹

WORLD YEAR OF PHYSICS

A direct test of $E = mc^2$

NATURE|Vol 438|22/29 December 2005



Experimental Data II

- **Reaction Energies** eV

  A(a,b)B $Q_r = \mathcal{M}_{\mathrm{A}} + \mathcal{M}_{\mathrm{a}} - \mathcal{M}_{\mathrm{b}} - \mathcal{M}_{\mathrm{B}}$

  - close to stability
  - (n,γ) and (p,γ) $\Rightarrow$ backbone
  - self-calibrated A(a,b)B v/s C(a,b)D

- **Desintegration Energies** eV

  A(β^-)B $Q_{\beta^-} = \mathcal{M}_{\mathrm{A}} - \mathcal{M}_{\mathrm{B}}$ ("Atomic")

  A(α)B $Q_\alpha = \mathcal{M}_{\mathrm{A}} - \mathcal{M}_{\mathrm{B}} - \mathcal{M}_\alpha$

  A(p)B $Q_p = \mathcal{M}_{\mathrm{A}} - \mathcal{M}_{\mathrm{B}} - \mathcal{M}_{\mathrm{p}}$

  - far from stability

- **Mass Spectrometry** u (often called "Direct")

  1. Classical Spectrometers
  2. Time-of-Flight Spectrometers ($\mathcal{M}^t$ ($B\rho$) and velocity)
  3. Cyclotron Spectrometers

     a. Radio-Frequency Spectrometer

     b. Penning Trap Spectrometer

     c. Storage Ring Spectrometer

"DIRECT" MASS-MEASUREMENTS
(Mass-Spectrometry)

HISTORY of MASS-SPECTROMETRY

For Stable Species : since the origin of Nuclear Physics

Thompson	1907	isotopism in Ne (1912)
Aston	1919	mass -"defect" (1927)
Mattauch	1936	double focussing R=20.000
A.O. Nier	1951	spectrography → -metry
Barber	1960	deformation in the rare-earth

For Radioactive Species : 1970's

Pioneers : R. Klapisch and C. Thibault

Li Na Rb Cs Fr

TODAY

Measurement of Volts → Measurement of Time (frequencies)

FUTURE

Penning traps - Storage rings

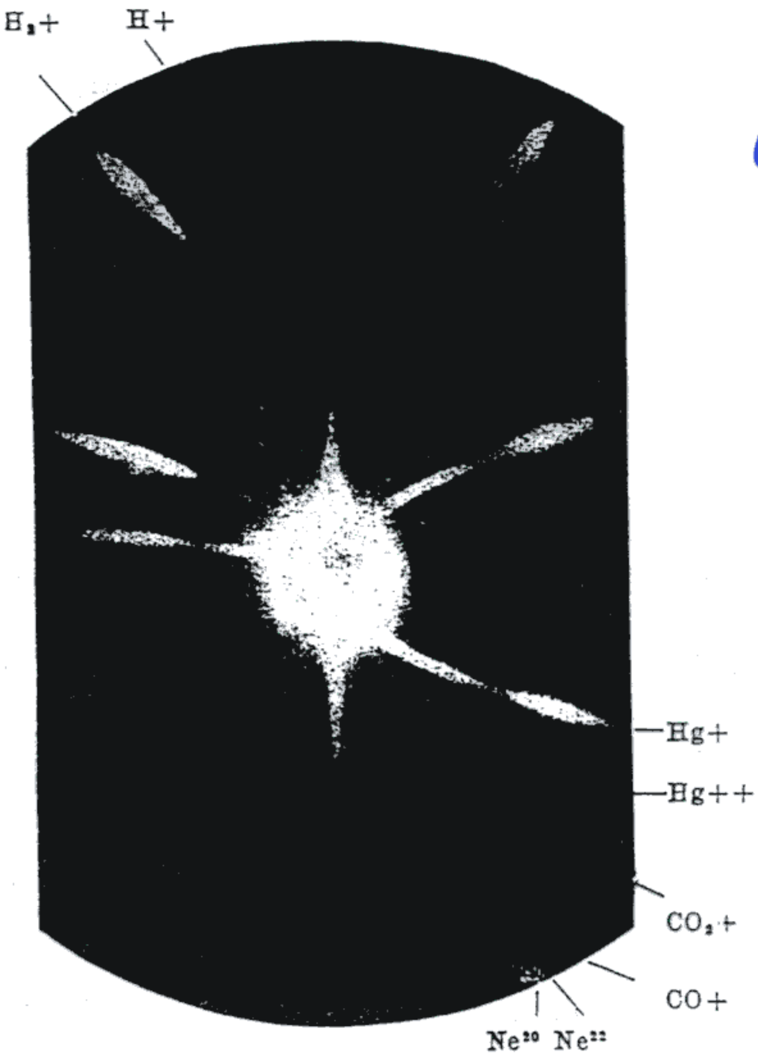


Abb. 82. Kanalstrahlparabeln bei Neonfüllung.
(Aus: F. W. Aston, Isotope. Hirzel, Leipzig.)

THOMPSON 1907

Champs croisés

$\vec{B} \rightarrow x \propto 1/mv^2$

$\vec{E} \rightarrow y \propto 1/mv$

$x = my^2$

1912 découverte de l'isotopisme dans le Ne

"DIRECT" MASS-MEASUREMENTS
(Mass-Spectrometry)

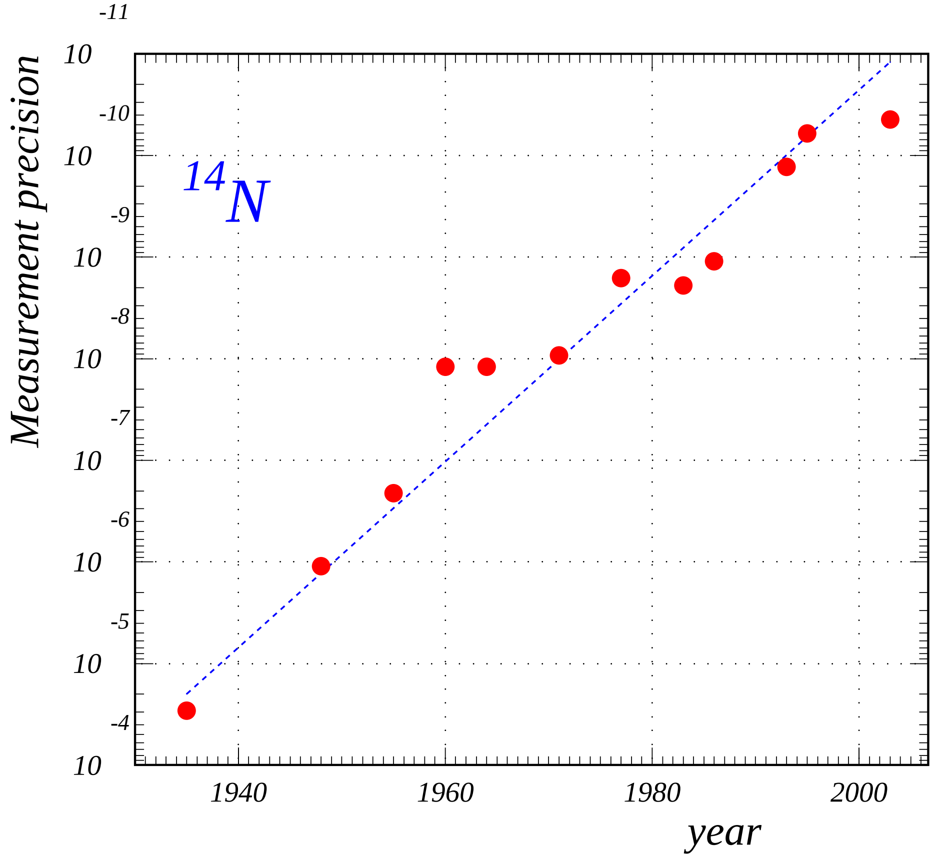
HISTORY of MASS-SPECTROMETRY II

For Stable Species : since the origin of Nuclear Physics

For Radioactive Species : 1970's

1971 Klapisch and C. Thibault
PS at CERN : Na and ^{11}Li
first evidence of vanishing shell $N = 20$
1977 Double-Focussing (G.A.) Isolde-II : Rb Cs Fr
subshell-closure at $N = 56$
deformation at $N = 60$
mapping of heavies - pairing - Wigner - ....
1986 Penning Trap
1986 SPEG & TOFI
1994 MISTRAL
1997 ESR-Schottky
2000 ESR-ToF

Precision for ^{14}N



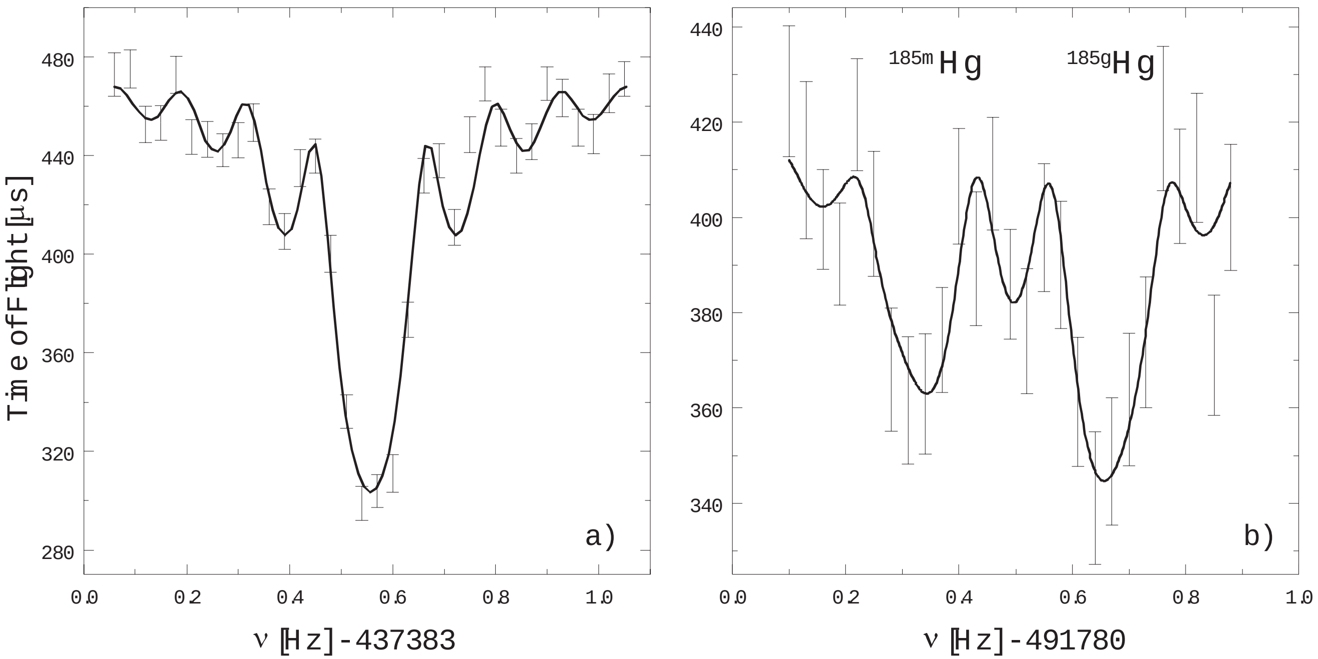
One order of magnitude every 10 years

- 1935: 400 keV
- 1995: 0.9 eV
- 2003: 0.5 eV

2012 : 0.1 eV

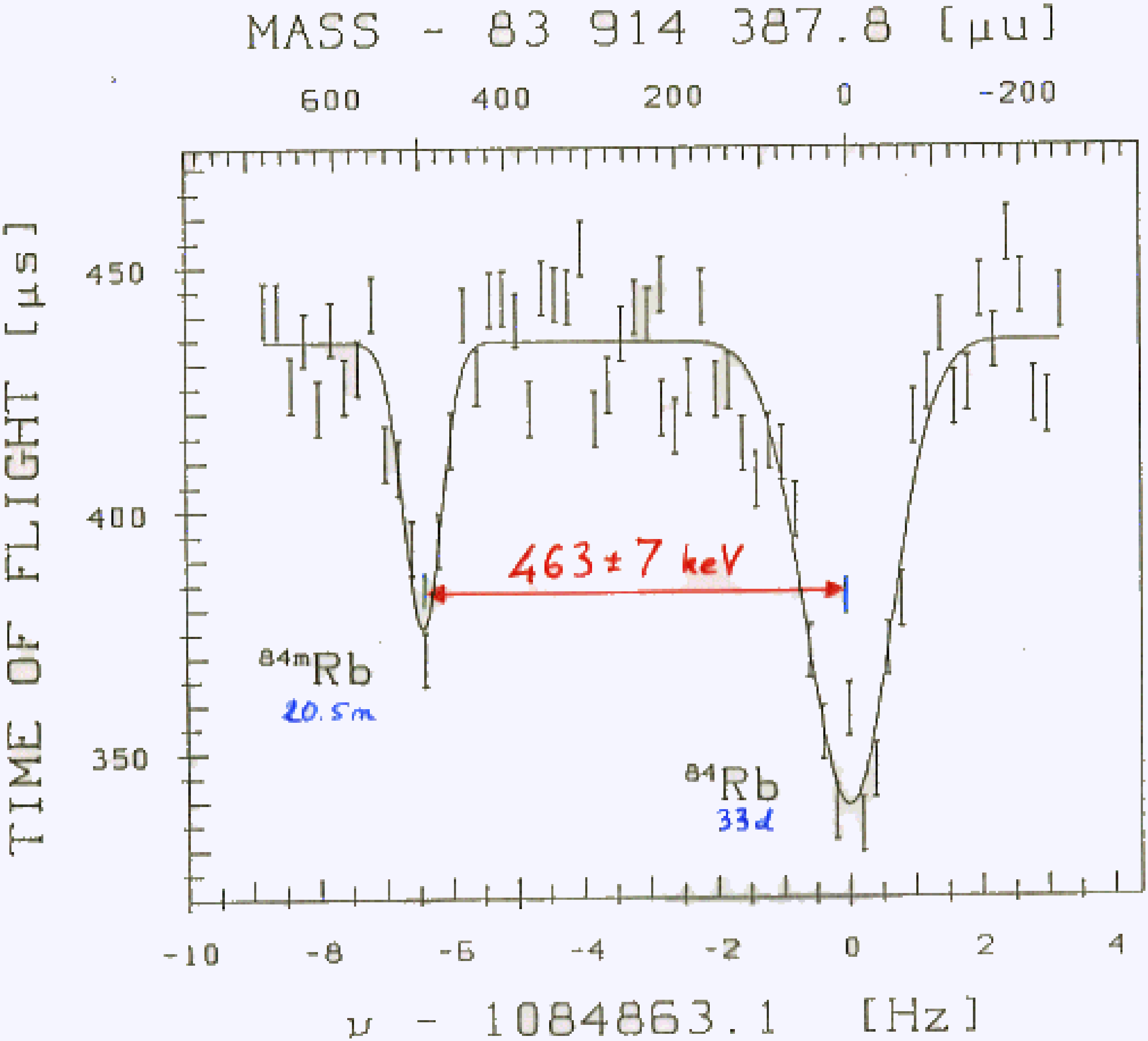
Isomer Separation

- ^{185}Hg - ^{185}Hg^{m}



line width = 50 keV　　Isom. Exc. = 104 keV

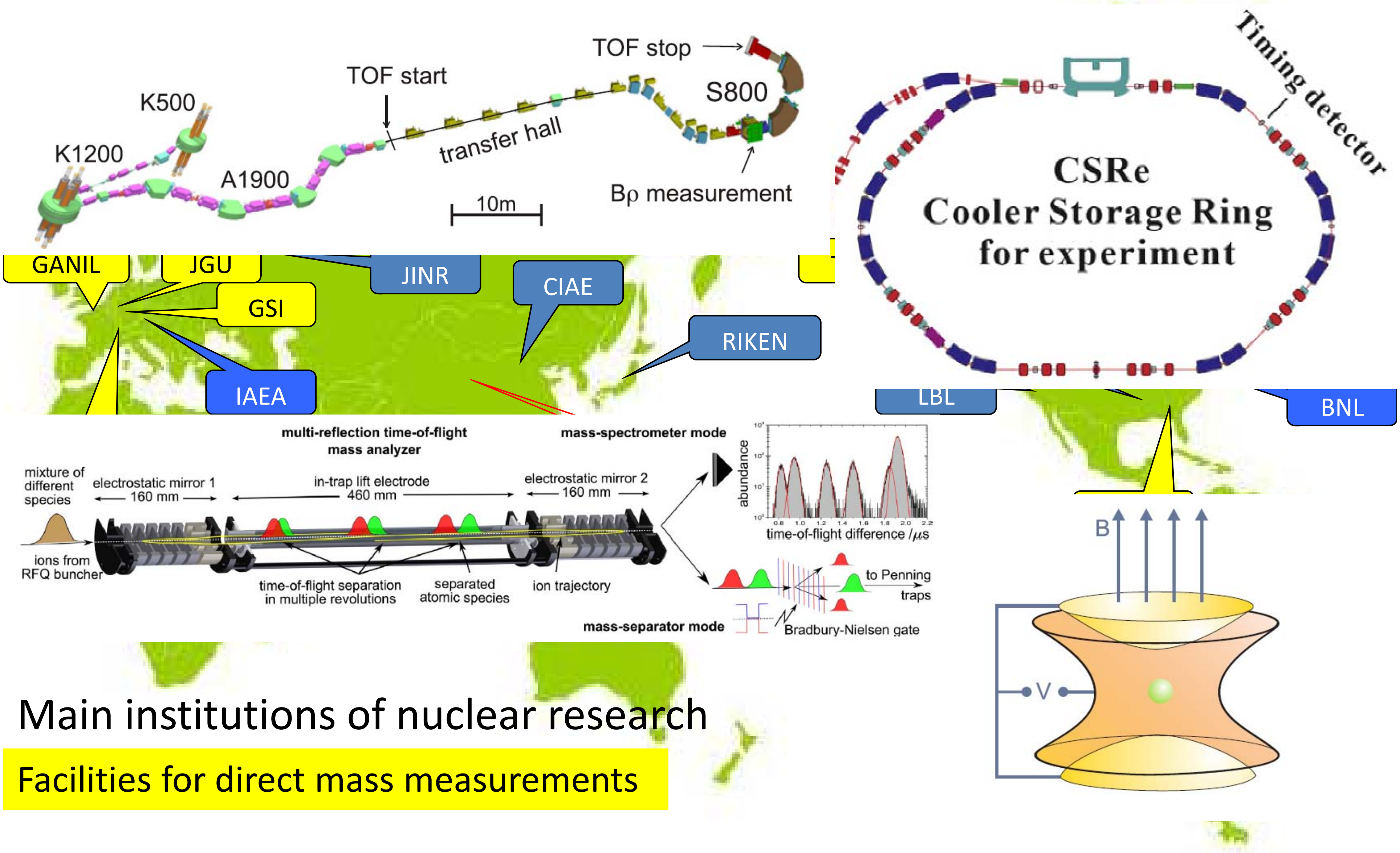
Exc. time = 8 s　　Res. Power = 3.7 millions

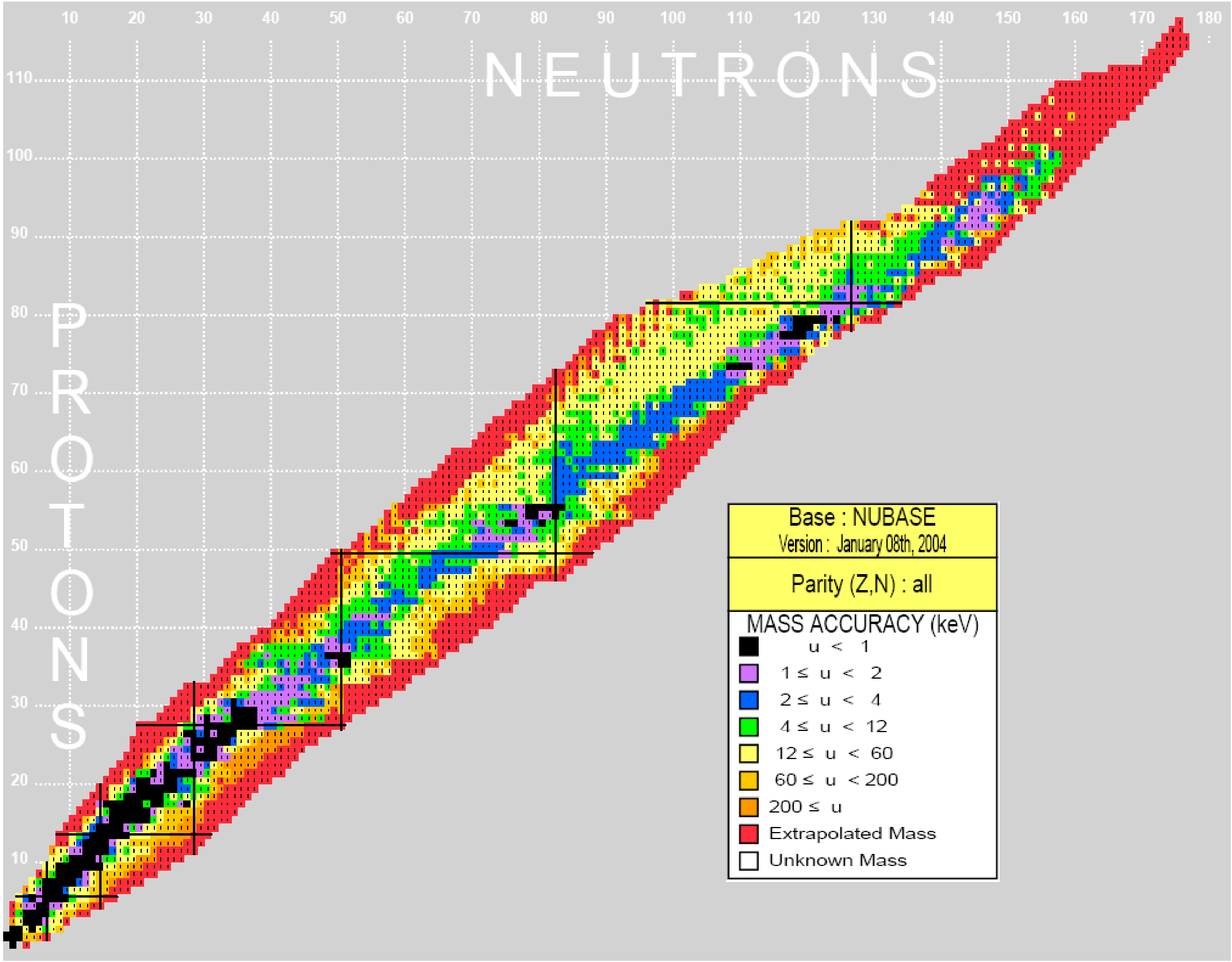


Penning Trap 463 ± 7 keV M. König 1991

Litterature 463.62 ± .09 keV NDS

Mass measurments





NEUTRONS
PROTONS
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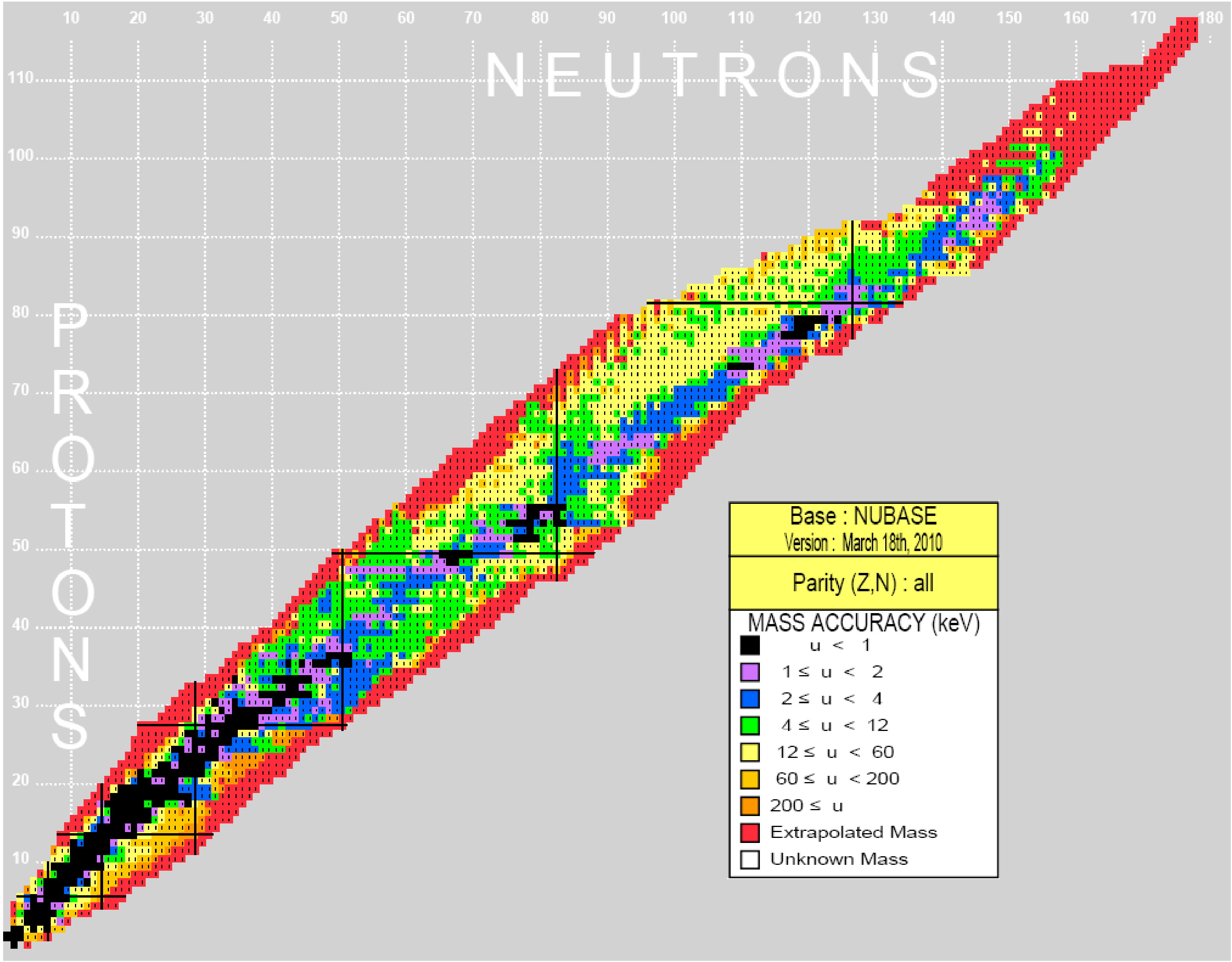
Base : NUBASE
Version : January 08th, 2004
Parity (Z,N) : all
MASS ACCURACY (keV)
u < 1
1 ≤ u < 2
2 ≤ u < 4
4 ≤ u < 12
12 ≤ u < 60
60 ≤ u < 200
200 ≤ u
Extrapolated Mass
Unknown Mass


NEUTRONS
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Base : NUBASE
Version : March 18th, 2010
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MASS ACCURACY (keV)
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12 ≤ u < 60
60 ≤ u < 200
200 ≤ u
Extrapolated Mass
Unknown Mass

Fashions of mass measurements:
Publications in Nature/Science

1. **An Ion Balance for Ultra-High-Precision Atomic Mass Measurements,** S.Rainville, J.K.Thompson, D.E.Pritchard, *Science* 303, 334 (2004)
2. **Cyclotron frequency shifts arising from polarization forces**, J.K.Thompson, S.Rainville, D.E.Pritchard, *Nature(London)* 430, 58 (2004)
3. **A direct test of $E=mc^2$**, S.Rainville, et al., *Nature(London)* 438, 1096 (2005)

4. **Direct mass measurements above uranium bridge the gap to the island of stability,** M.Block et al., *Nature(London)* 463, 785 (2010)
5. **Direct mapping of nuclear shell effects in the heaviest elements,** E. Minaya Ramirez et al., *Science* 337 (6099), 1207-1210 (2012).
6. **Masses of exotic calcium isotopes pin down nuclear forces,** F.Wienholtz et al., *Nature(London)* 498, 346 (2013)

Two frontiers：accuracy, exoticism

Atomic Mass 3H and 3He—Using HD$^+$ as a mass reference

PRL **114,** 013003 (2015) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2015

Atomic Masses of Tritium and Helium-3

E. G. Myers, A. Wagner, H. Kracke, and B. A. Wesson
Department of Physics, Florida State University, Tallahassee, Florida 32306-4350, USA
(Received 11 September 2014; published 7 January 2015)

By measuring the cyclotron frequency ratios of $^3He^+$ to HD^+ and T^+ to HD^+, and using HD^+ as a mass reference, we obtain new atomic masses for ^3He and T. Our results are $M[^3\mathrm{He}] = 3.016\,029\,322\,43(19)$ u and $M[\mathrm{T}] = 3.016\,049\,281\,78(19)$ u, where the uncertainty includes an uncertainty of 0.12 nu in the mass reference. Allowing for cancellation of common systematic errors, we find the Q value for tritium β decay to be $(M[\mathrm{T}] - M[^3\mathrm{He}])c^2 = 18\,592.01(7)$ eV. This allows an improved test of systematics in measurements of tritium β decay that set limits on neutrino mass.

Unc.= 0.2 eV

Detailed calculation for mass HD

Atomic masses and the mass difference between tritium and helium-3.—Using the 2010 CODATA values for the masses of the electron, proton, and deuteron [9] combined with the ground-state energy of HD^+ relative to its separated constituents [25], we predict the atomic mass of the HD^+ ion to be 3.021 378 241 97(12) u, where the uncertainty is due to the uncertainty in the masses of the

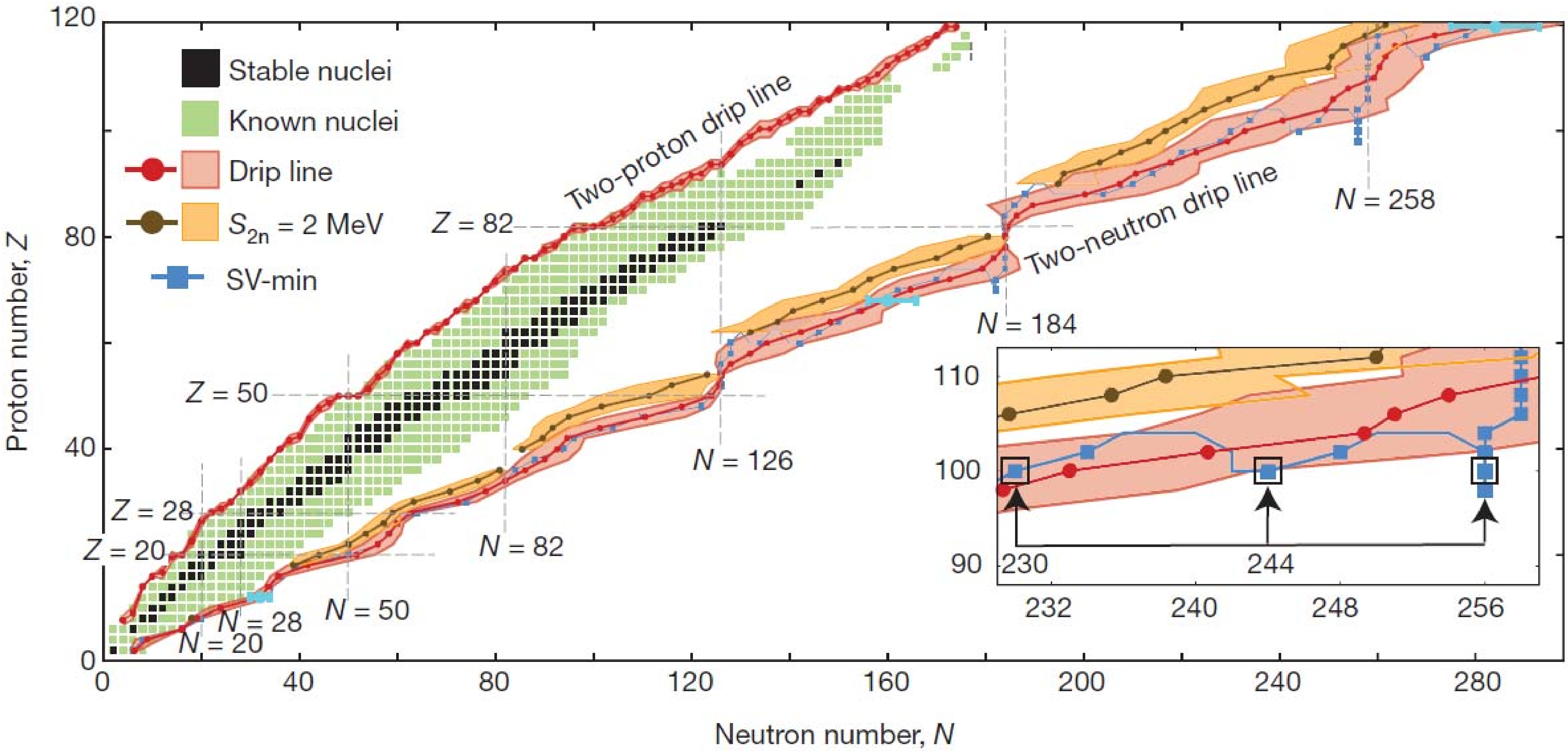
Ame2012	1H	1 007 825 032.23	(09)	(0.093nu)
	2H	2 014 101 778.12	(12)	(0.122nu)
H+D	=	3 021 926 810.35	(14)	(0.136nu)
BEmol	-	4.85		
HD molec.	=	3 021 926 805.50		
me	-	548 579.91		
BEe(+)	+	16.58		
HD+	=	3 021 378 242.17	(14)	
compared to				
2015Myers		3 021 378 241.97	(12)	
The difference is		0.20	(14)	1.4 sigma

Exotic nuclei

The limits of the nuclear landscape

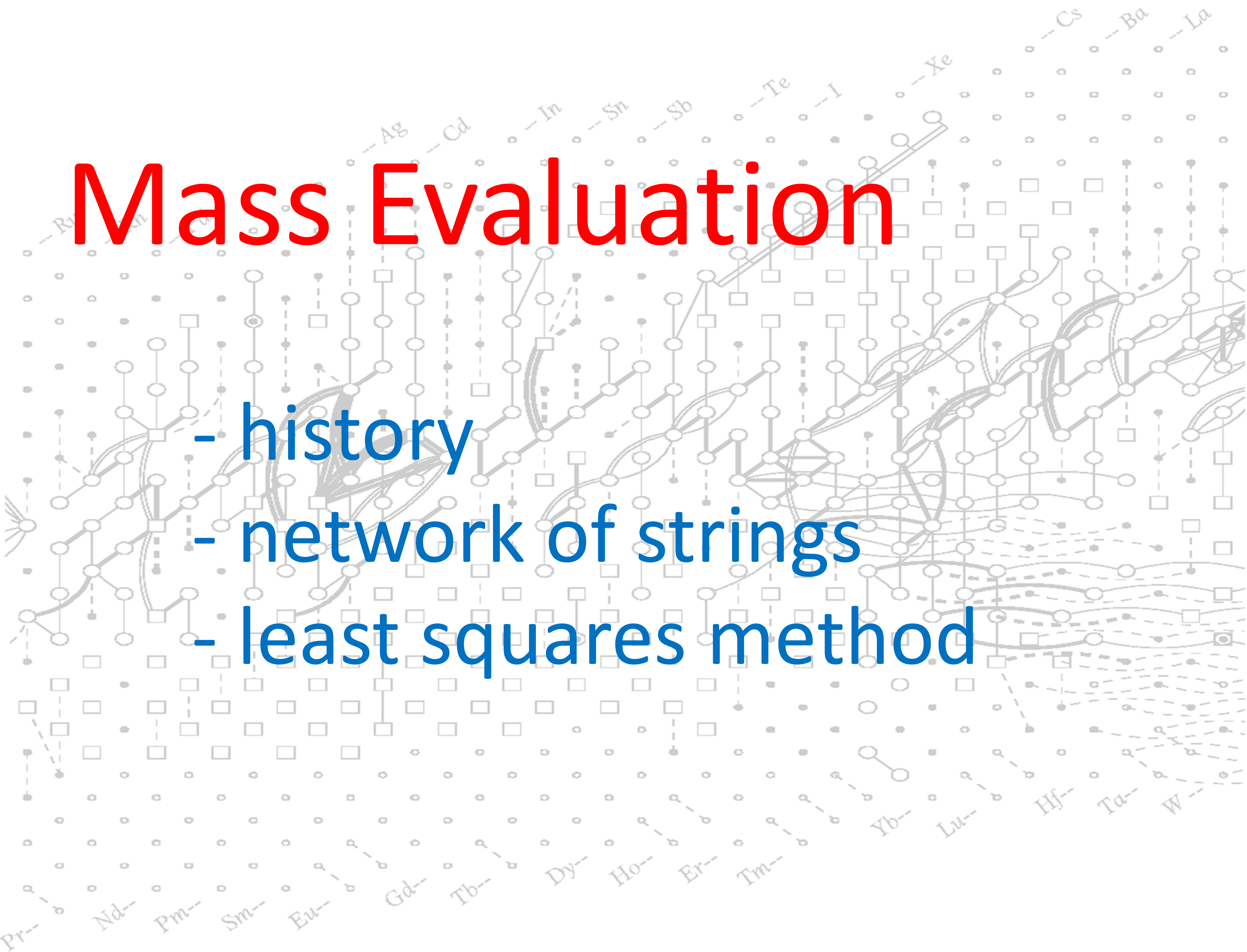
doi:10.1038/nature11188

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡



Mass Evaluation

- history
- network of strings
- least squares method



60 years of mass evaluations

A history of atomic masses can be found in:

Georges Audi

"The history of nuclidic masses and of their evaluation"

International Journal of Mass Spectrometry 251 (2006) 85–94

An early (perhaps the first) attempt for a mass evaluation is

M.S. Livingston, H.A. Bethe, "Nuclear Physics, C. Nuclear dynamics, experimental",
Rev. Mod. Phys. 9 (1937) 245, XVIII. Nuclear masses; p. 366

The authors combined data from mass spectrometry and nuclear reaction and decay data up to 40Ar.

In the early 1950's it was found that the many relations (direct and indirect) overdetermined the mass value of many nuclides.

Aaldert H. Wapstra established a procedure using a least-squares method to solve the problem of overdetermination.

The first table of atomic masses using this method is dated 1955.

60 years of mass evaluation

Ame1955, Ame1961, Ame1964, Ame1971, Ame1977, Ame1983, Ame1993, Ame2003, Ame2012

and now : Ame2016

will appear in CPC in December 2016

(but with no reprints)

to keep closer to experimental life and new results

60 years of mass evaluation

History of Wapstra's type mass tables

A.H. Wapstra, Physica 21 (1955) 367 + 385; J.R. Huizenga, Physica 21 (1955) 410

F. Everling, L.A. König, J.H.E. Mattauch, A.H. Wapstra, Nucl. Phys. 18 (1960) 529
L.A. König, J.H.E. Mattauch, A.H. Wapstra, Nucl. Phys. 31 (1962) 18
J.H.E. Mattauch, W. Thiele, A.H. Wapstra, Nucl. Phys. A67 (1965) 1 + 32 + 73

A.H. Wapstra, K. Bos, At. Data Nucl. Data Tables 19 (1977) 175

A.H. Wapstra, G. Audi, R. Hoekstra, Nucl. Phys. A432 (1985) 185

G. Audi, A.H. Wapstra, Nucl. Phys. A 565 (1993) 66
C. Borcea, G. Audi, A.H. Wapstra, P. Favaron, Nucl. Phys. A 565 (1993) 158
G. Audi, A.H. Wapstra, M. Dedieu, Nucl. Phys. A 565 (1993) 193

G. Audi & A.H. Wapstra, Nucl. Phys. A 595 (1995) 409 ; an update

A.H. Wapstra, G. Audi, C. Thibault, Nucl. Phys. A 729 (2003) 129
G. Audi, A.H. Wapstra, C. Thibault, Nucl. Phys. A 729 (2003) 337

G. Audi, M. Wang, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer,
Chinese Physics C 36 (2012) 1287
M. Wang, G. Audi, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer,
Chinese Physics C 36 (2012) 1603

AME2012

December 2012 issue of Chinese Physics **C** (IOP Science)

Volume 36 Number 12 December 2012

1157 **The NUBASE2012 evaluation of nuclear properties**
G. Audi, F.G. Kondev, M. Wang, B. Pfeiffer , X. Sun, J. Blachot, M. MacCormick

1287 **The AME2012 atomic mass evaluation (I). Evaluation of input data, adjustment procedures**
G. Audi, M. Wang, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer

1603 **The AME2012 atomic mass evaluation (II). Tables, graphs and references**
M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer

IMP 中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences

GSI

CSNSM

Argonne NATIONAL LABORATORY

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Evaluation of Nuclear Data

- **Theoretical evaluation** (= theoretical predictions)

  predict values for large sets of nuclei

  make effective calculations for : r-process - reactors - . . .

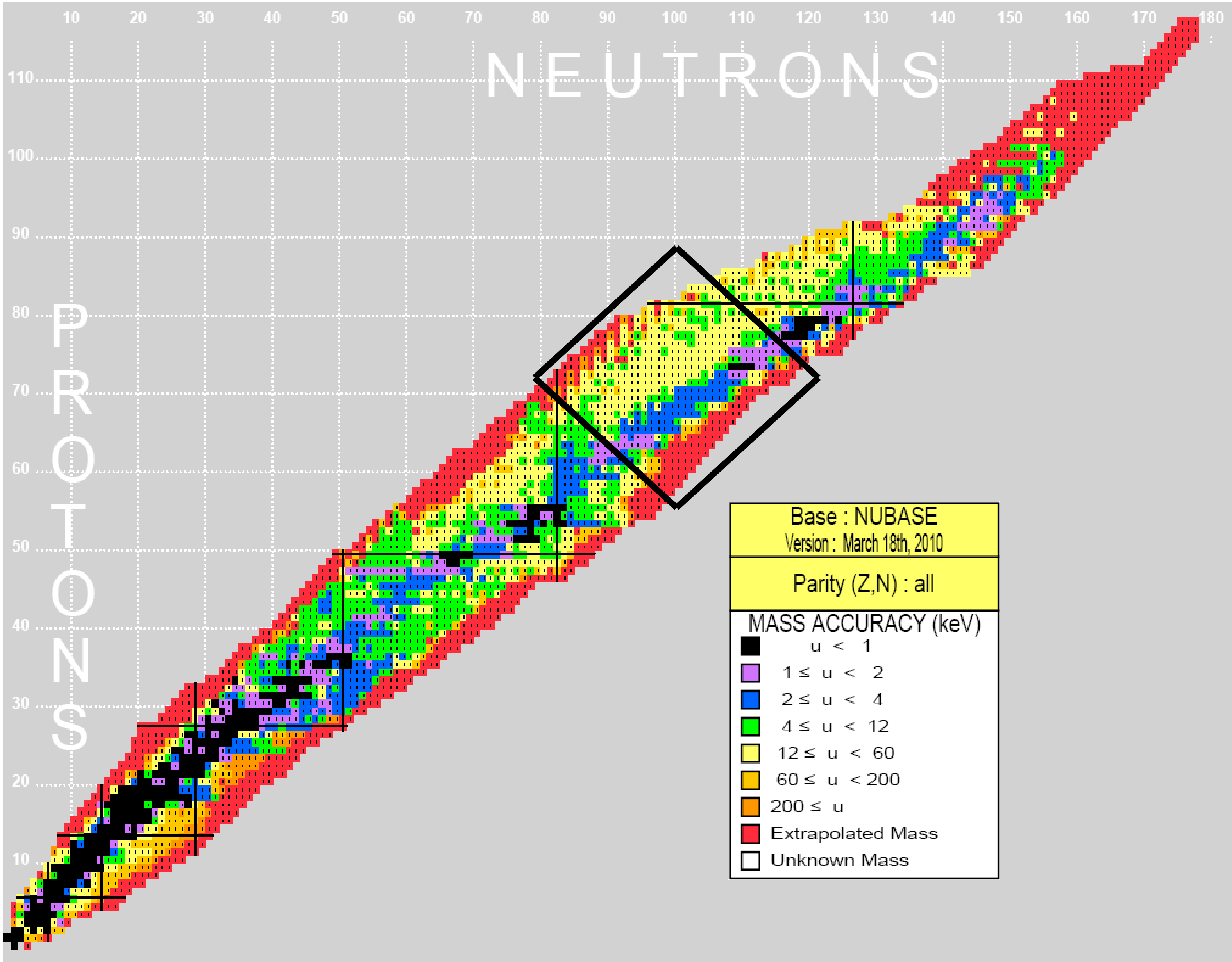
  uncertainties : just starting   security $<=>$ feasibility

- **Evaluation of experimental data**

  basic blocks : results from experiments

  if available : prefered to theoretical predictions

  allows also to test theoretical “evaluations”



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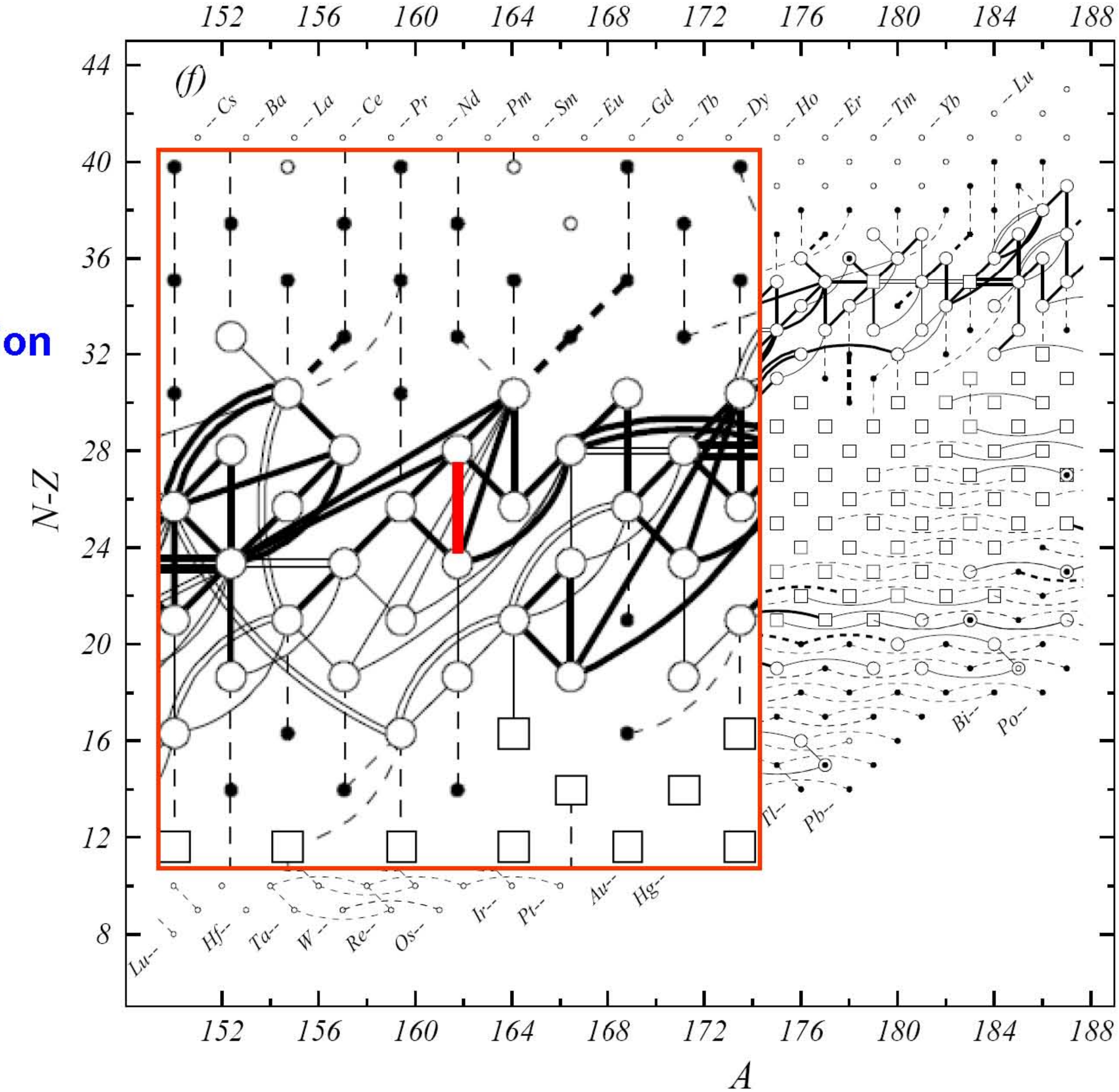
Extrapolated Mass
Unknown Mass

Atomic Mass Evaluation

Evaluation ≠ Compilation

Atomic masses are extracted from the complex network of string tensions.



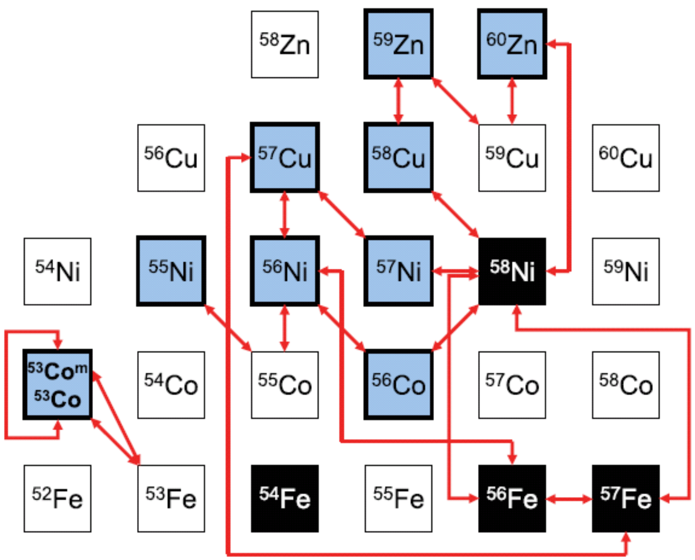
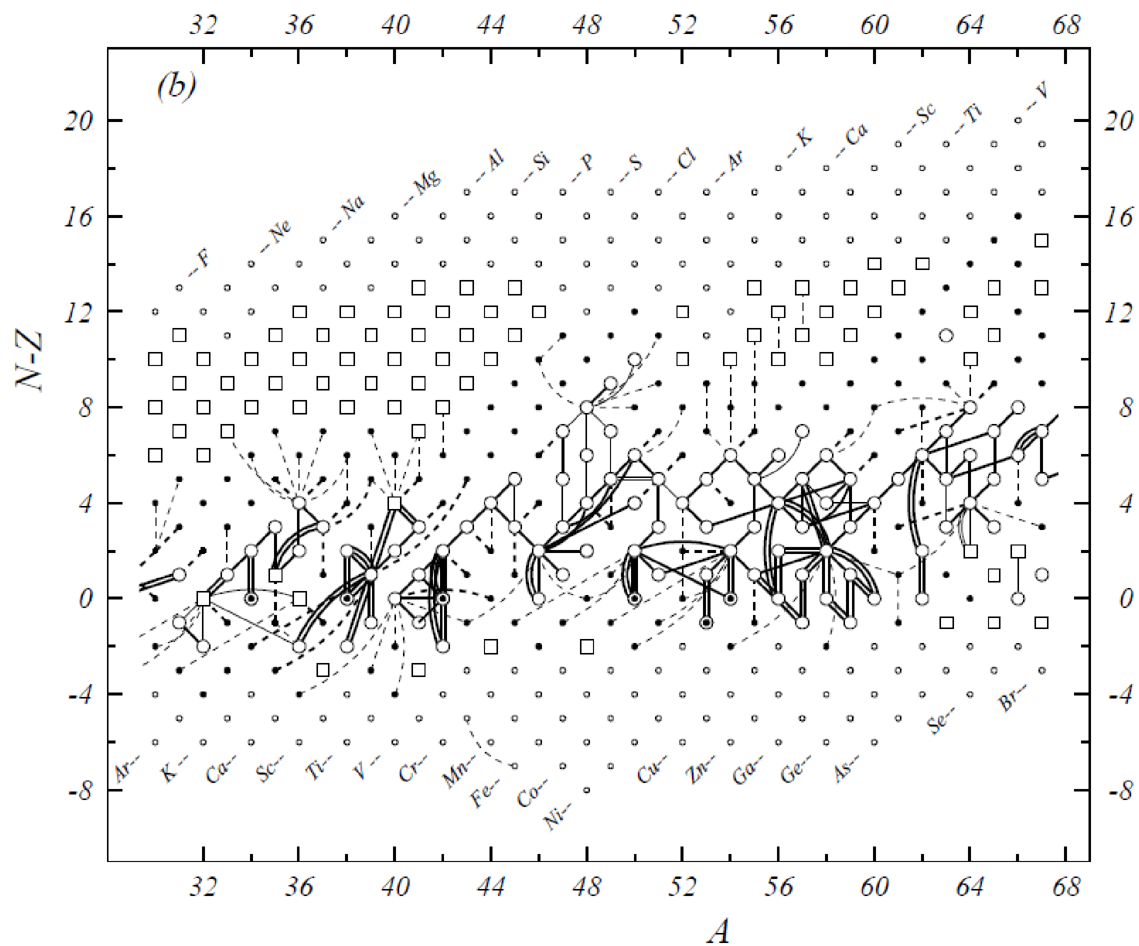
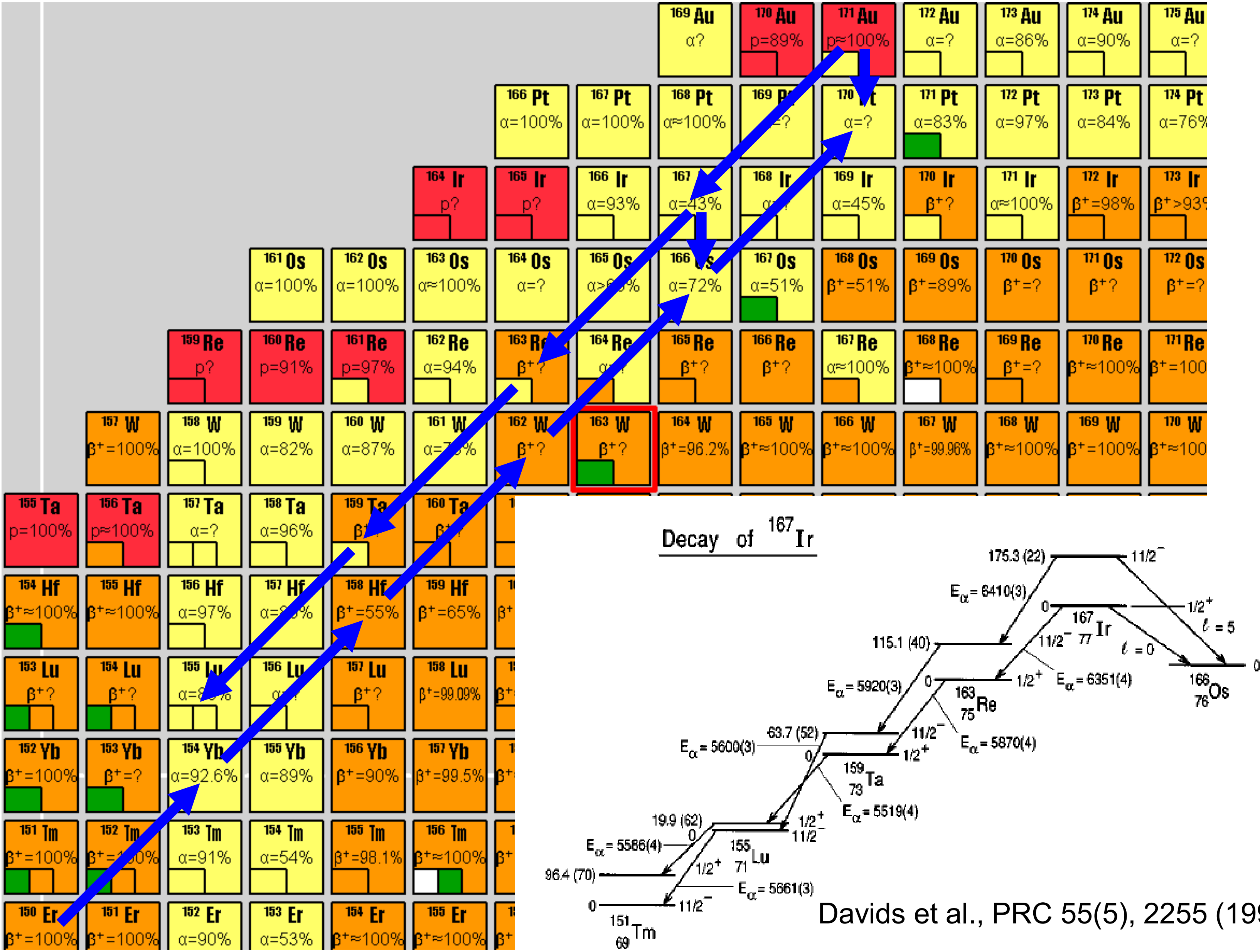


FIG. 2. (Color online) The highlighted nuclides were measured in this work. The red arrows show the measured frequency ratio pairs.

A.Kankainen et al.,
Phys.Rev. C 82, 034311 (2010)





Davids et al., PRC 55(5), 2255 (1997)

FIG. 14. Decay scheme of correlated alphas from ^{167}Ir.

Experimental Data

- **Energy Relation**

  expressed in eV or keV

  keV*: *standard* volt

  adopt a value for $2e/h$ in Josephson

  keV: *international* volt

  from evaluation of fundamental constants

- **Inertial mass in EM field**

  expressed in u or μu, the

  "unified mass unit"

  $1\text{u} = \mathcal{M}(^{12}\text{C})/12$ since 1960

Conversion factor:

$$1\text{u} = 931\,494.009\,0 \pm 0.007\,1 \quad \text{keV}^*$$
$$1\text{u} = 931\,494.013 \pm 0.037 \quad \text{keV}$$

Treatment of Data - LSM - 1

Q data $q_i \pm dq_i$

M unknown quantities m_μ with $Q > M$

Q equations to M parameters overdetermined

$$\sum_{\mu=1}^{M} k_i^\mu m_\mu = q_i \pm dq_i \quad \Rightarrow \quad \boxed{\mathbf{K}|m\rangle = |q\rangle}$$

and the diagonal weight matrix $\mathbf{W}$: $w_i^i = 1/(dq_i dq_i)$

Very simple construction

$$^{\mathbf{t}}\mathbf{KWK}|m\rangle = {}^{\mathbf{t}}\mathbf{KW}|q\rangle$$

$$\mathbf{A}|m\rangle = {}^{\mathbf{t}}\mathbf{KW}|q\rangle$$

$\mathbf{A}$ normal matrix square, positive, symmetric and regular

$\Rightarrow$ invertible : $\mathbf{A}^{-1}$

$$|\overline{m}\rangle = \mathbf{A}^{-1}\ {}^{\mathbf{t}}\mathbf{KW}|q\rangle \quad \Rightarrow \quad \boxed{|\overline{m}\rangle = \mathbf{R}|q\rangle}$$

"Flow-of-information" matrix : $\Rightarrow$ $\boxed{\mathbf{F} = {}^{\mathbf{t}}\mathbf{R} \otimes \mathbf{K}}$

NIM 249 (1986) 443

Treatment of Data -

adj. value of exp. data $\Rightarrow$ $|\overline{q}\rangle = \mathbf{KR}|q\rangle$

Consistency of data

$v_i = (\overline{q}_i - q_i)/dq_i \quad \Rightarrow \quad \chi^2 = \sum_{i=1}^{Q} v_i^2$

expected $\chi_{expect} = Q - M \pm \sqrt{2(Q-M)}$

normalized χ_n = consistency factor = Birge ratio

$\chi_n = \sqrt{\chi^2/(Q-M)} \quad \chi_{n-expected} = 1 \pm 1/\sqrt{2(Q-M)}$

Partial consistency factor, χ_n^p, for a group of p data:

$$\chi_n^p = \sqrt{\frac{Q}{Q-M}\;\frac{1}{p}\;\sum_{i=1}^{p} v_i^2}.$$

Present status

Statistics

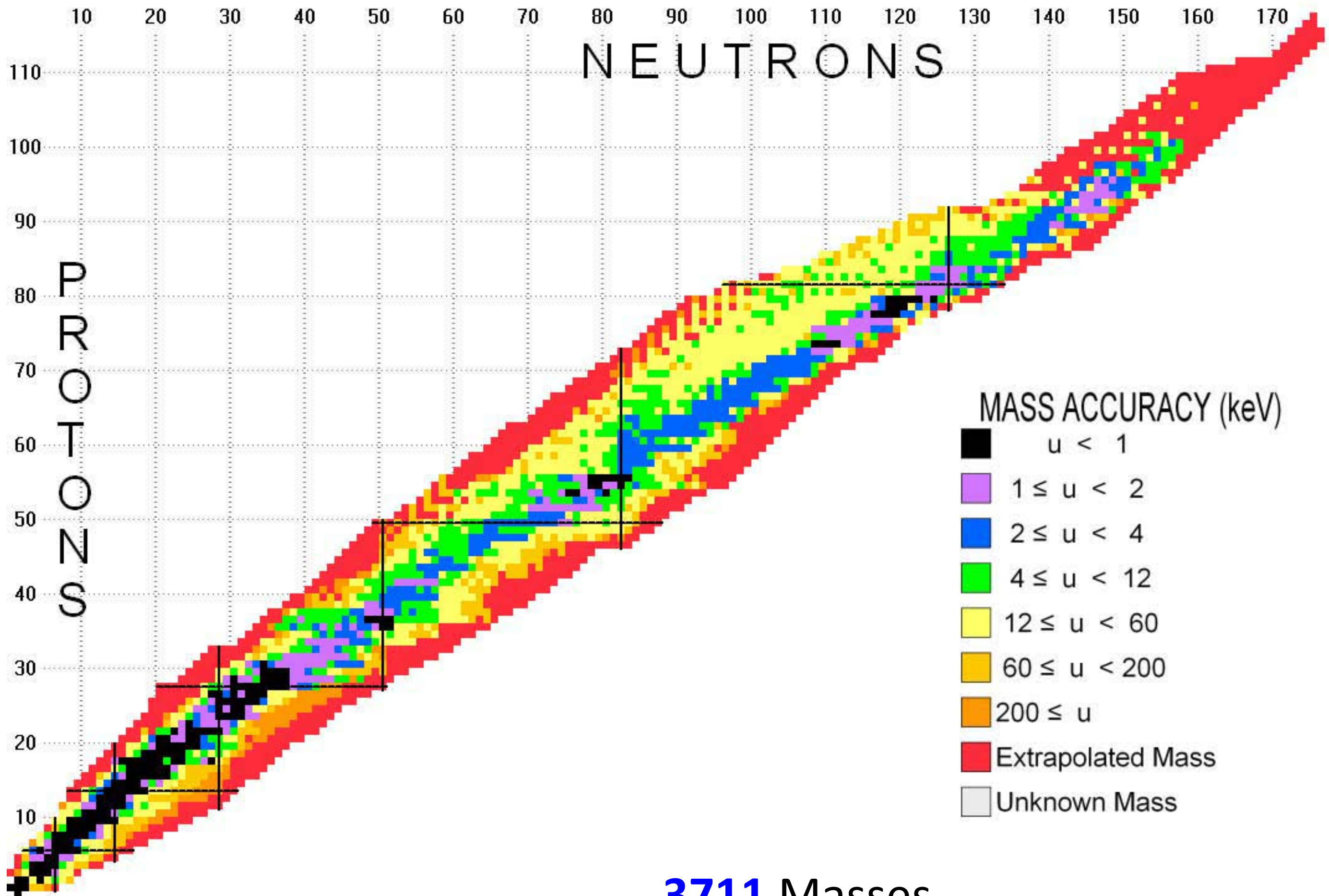
Input data

13809 input equations
5275 mass spectrometry
8534 reactions

3711 **Masses**

2416 known ground state
232 known isomers
1063 estimated

Accuracy of mass values



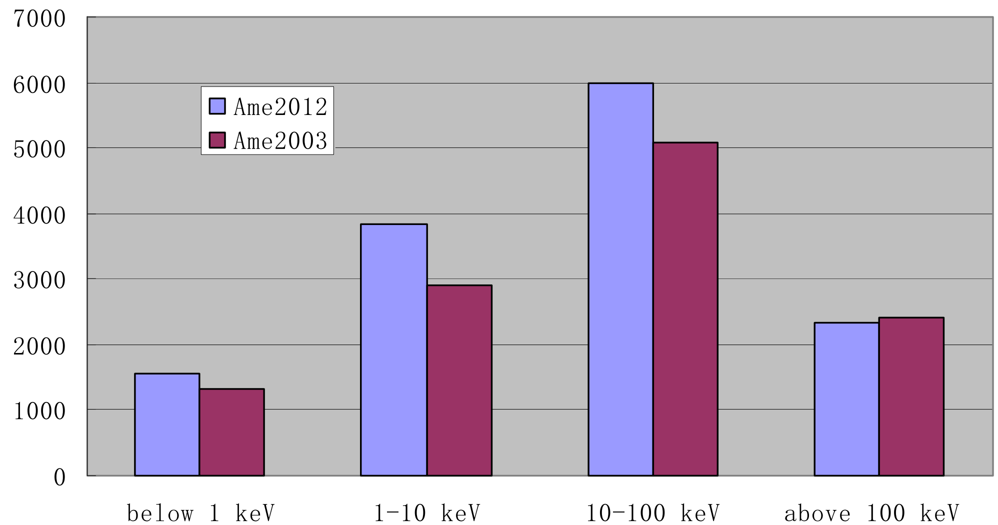
13809 input equations in **AME12**

- **5275** mass spectrometry
- **8534** reactions & decays

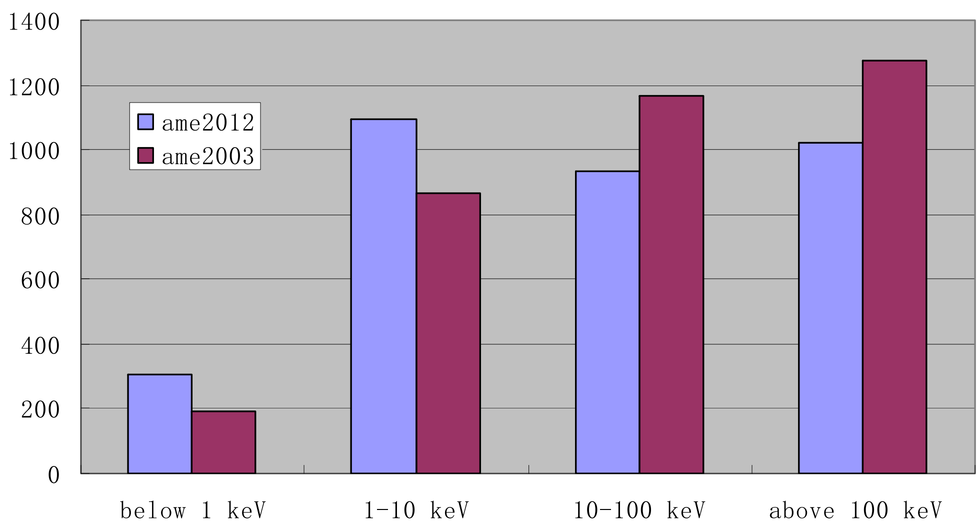
3711 Masses

- **2416** known ground state
- **232** known isomers
- **1063** extrapolated

Precisions in Ame2003 v/s Ame2012

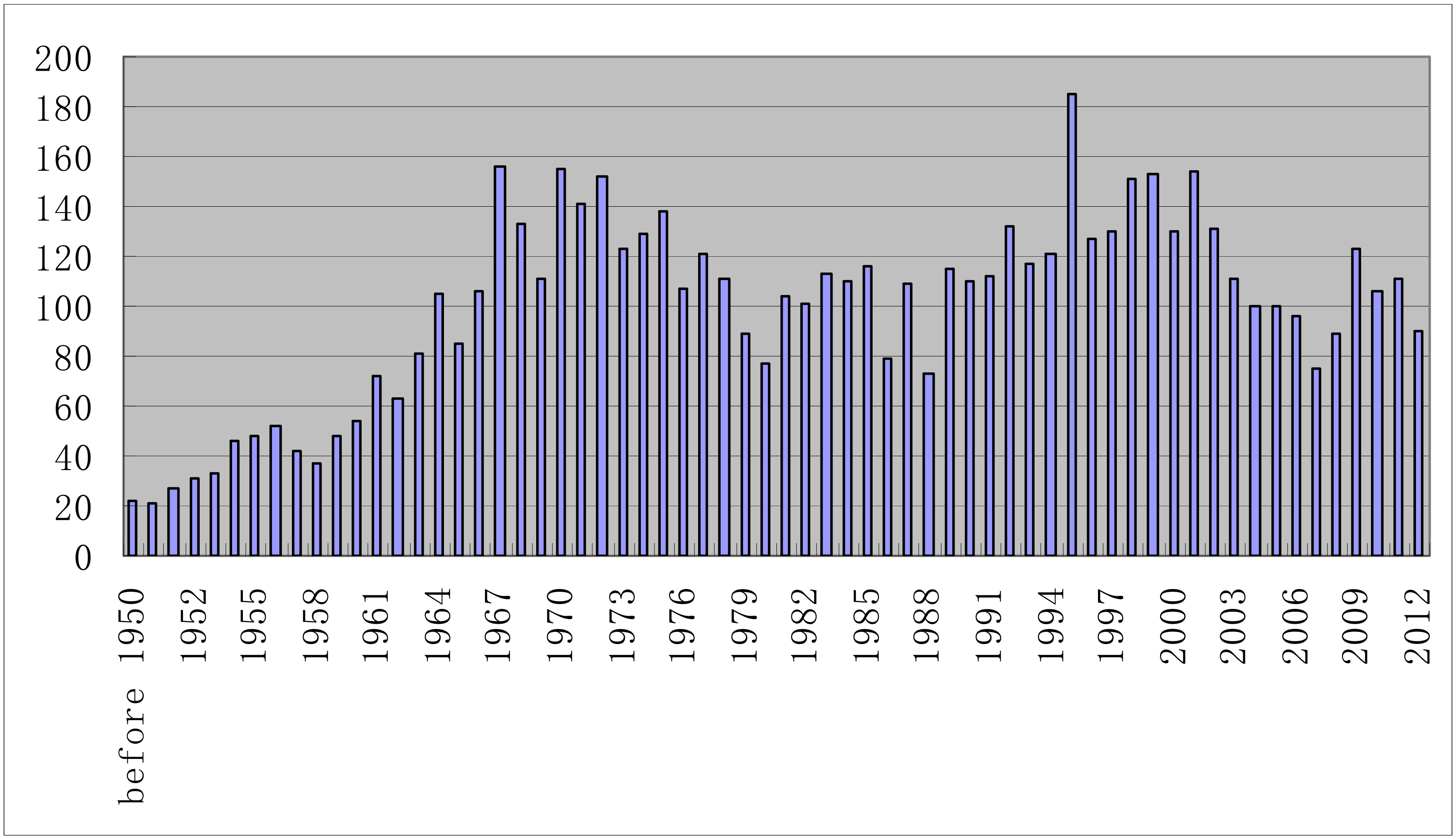


Input data



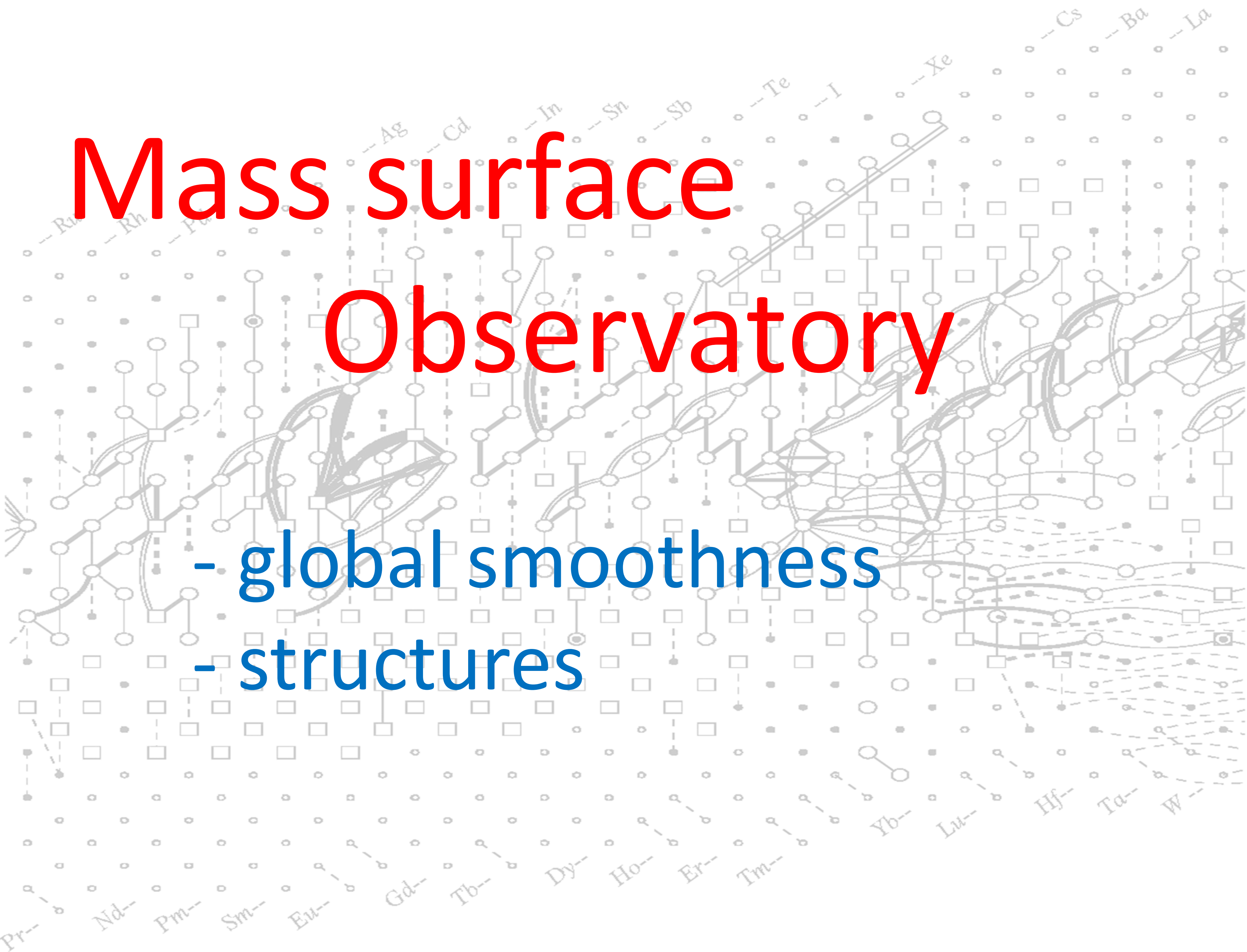
masses

Amount of work: reference per year



Mass surface Observatory

- global smoothness
- structures



The Ame ("Atomic Mass Evaluation")

- Regularity of the mass-surface

  Smoothness and structures

  Surface in 3D space

  Structures on the Surface: Shells - Deformations - Wigner

  Regularity is a basic property of the surface of masses

  Consequences :

  New Physics

  Outliers

  Conflict among Data

  Estimate unknown masses

Regularity of the Mass Surface II

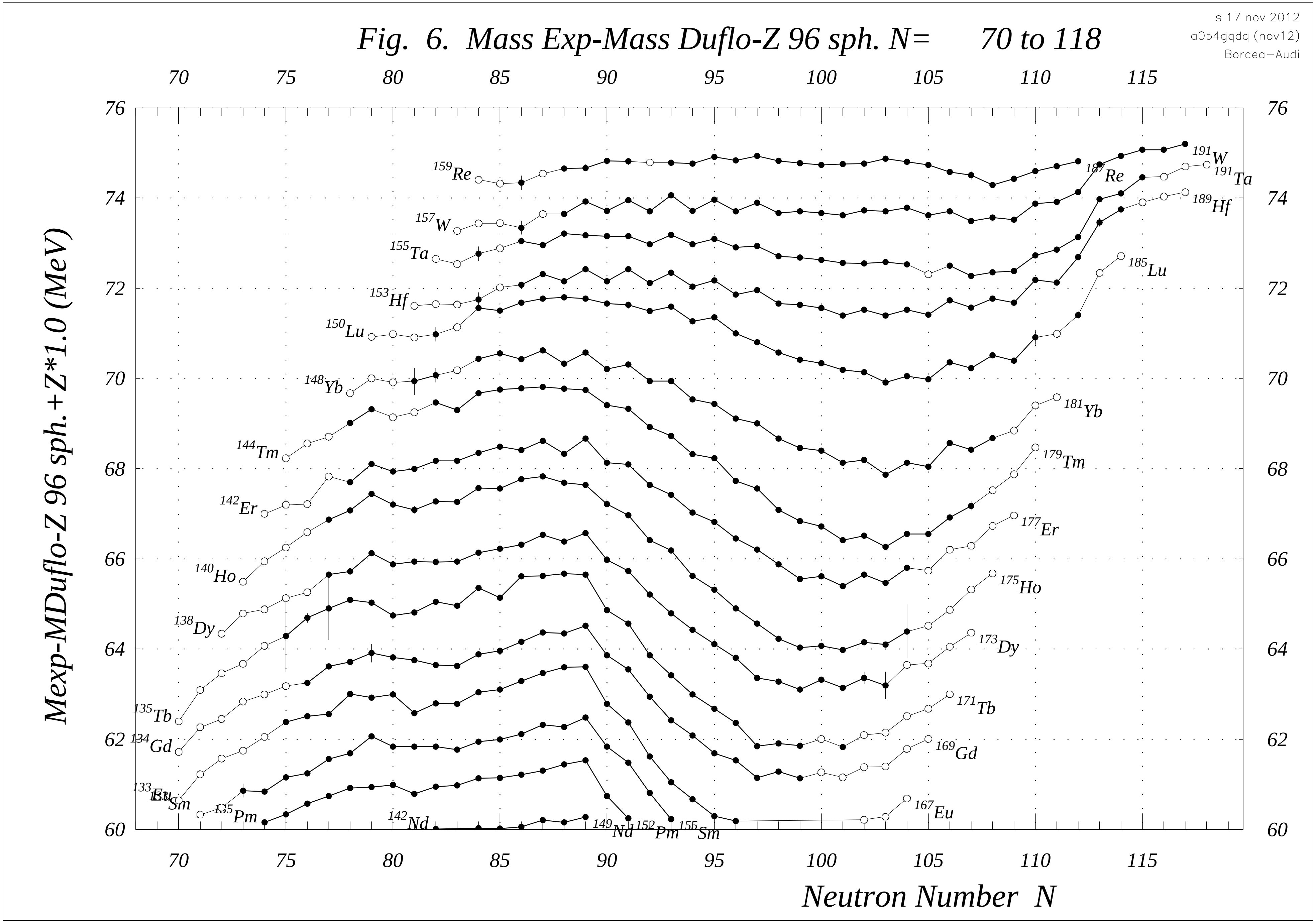
- New Physics
  - Coherent deviations in (N, Z)
    - $\Rightarrow$ new physical property (e.g. $^{23}N_{15}$ $N = 108 - 115$ Cs_{63-112})
- Outliers
  - One single 'Irregularity'
    - $\Rightarrow$ question correctness of datum

      re-measure same and/or measure neighbors

      strongly deviating 1-experiment (chaotic surf.):

      $\Rightarrow$ replace by estimated 'recommended' value
- Conflict among Data
  - $\Rightarrow$ which one agrees with estimate?
- Unknown Masses
  - $\Rightarrow$ Estimates : Interpolate - Extrapolate

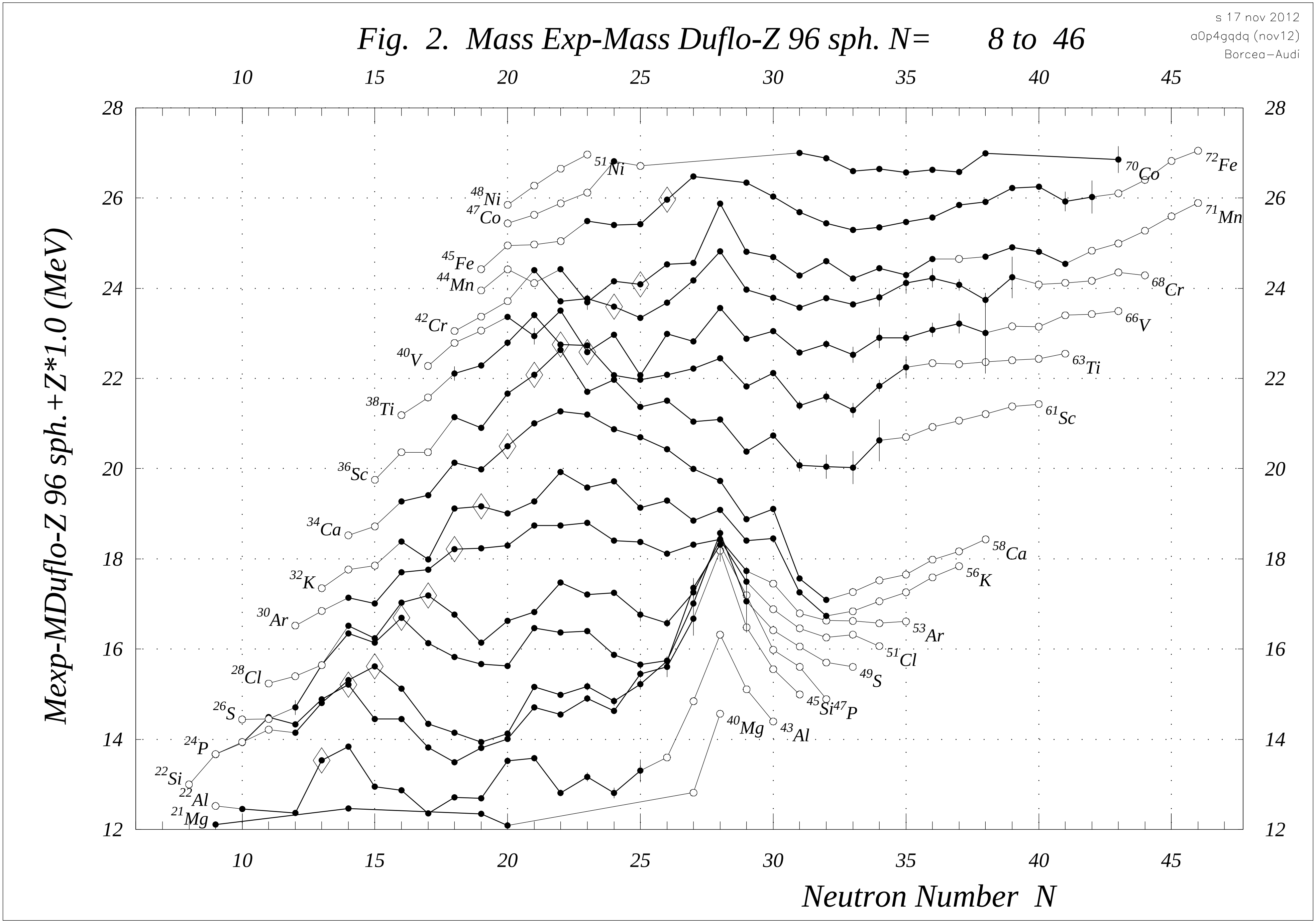
Fig. 6. Mass Exp-Mass Duflo-Z 96 sph. N= 70 to 118



Recent observations of the mass surface

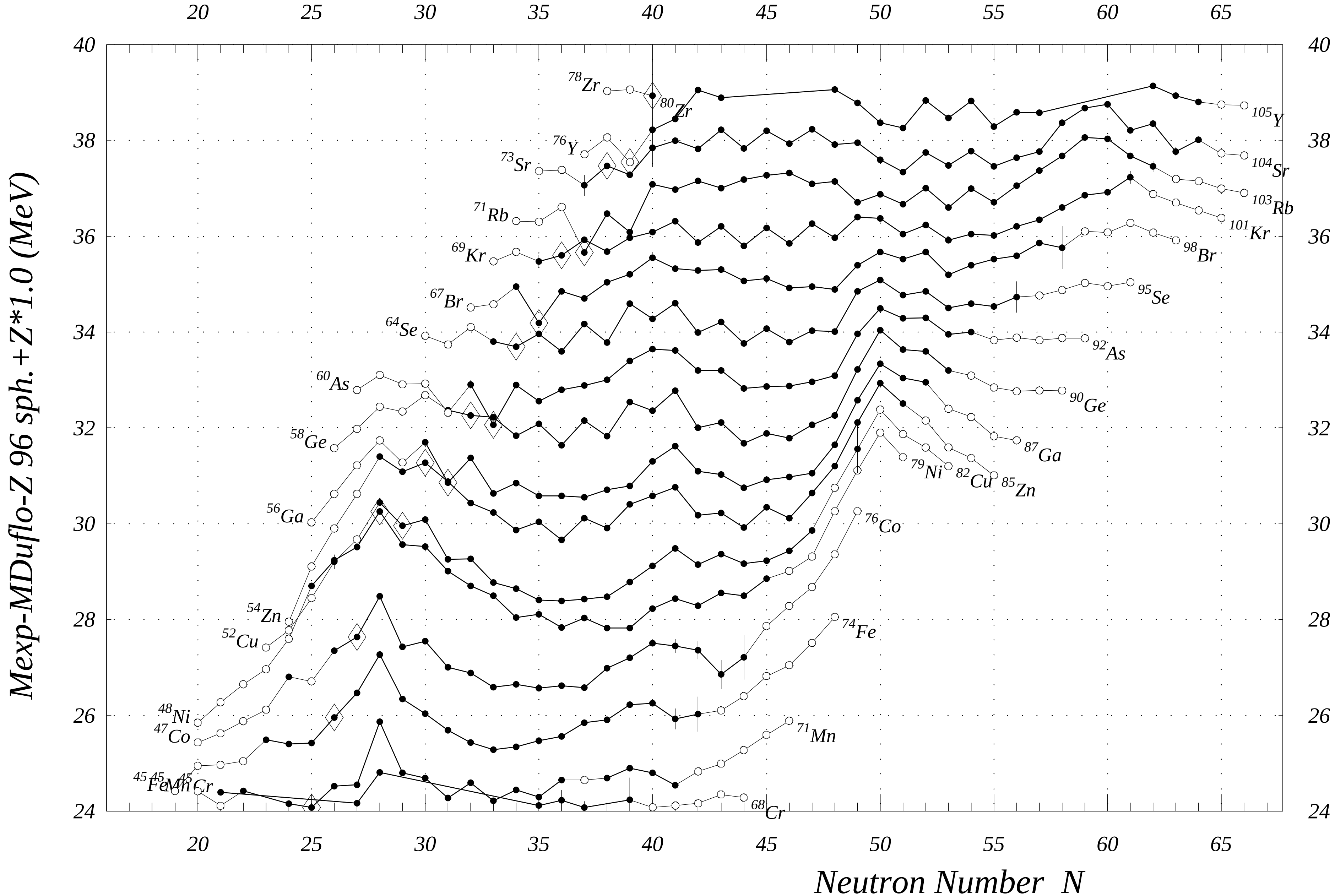
- Magic numbers vanishing (quenching)
  when going far from stability
  earlier : $N = 20$, $N = 28$
  now also (since Ame2003) : $N = 50$, $N = 82$

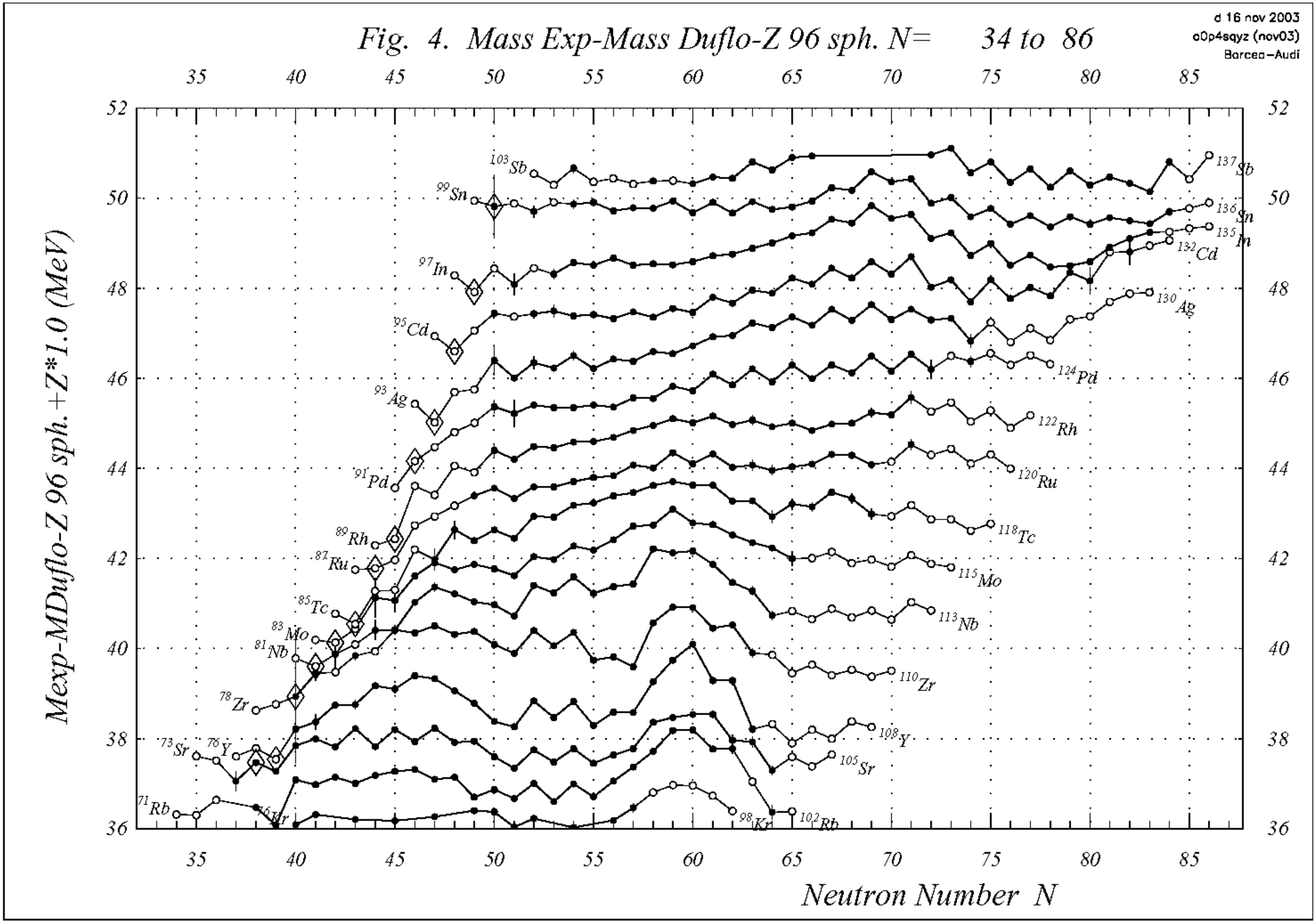
- Rising of the wings
  Q_β's often underestimated
  r-process paths less far from stability
  expected influence on reactors and on waste calculations


s 17 nov 2012
a0p4gqdq (nov12)
Borcea–Audi
Fig. 2. Mass Exp-Mass Duflo-Z 96 sph. N= 8 to 46
Mexp-MDuflo-Z 96 sph.+Z*1.0 (MeV)
Neutron Number N
21Mg
22Al
22Si
24P
26S
28Cl
30Ar
32K
34Ca
36Sc
38Ti
40V
42Cr
44Mn
45Fe
47Co
48Ni
51Ni
70Co
72Fe
71Mn
68Cr
66V
63Ti
61Sc
58Ca
56K
53Ar
51Cl
49S
45Si
47P
43Al
40Mg

s 17 nov 2012
a0p4gqdq (nov12)
Borcea–Audi

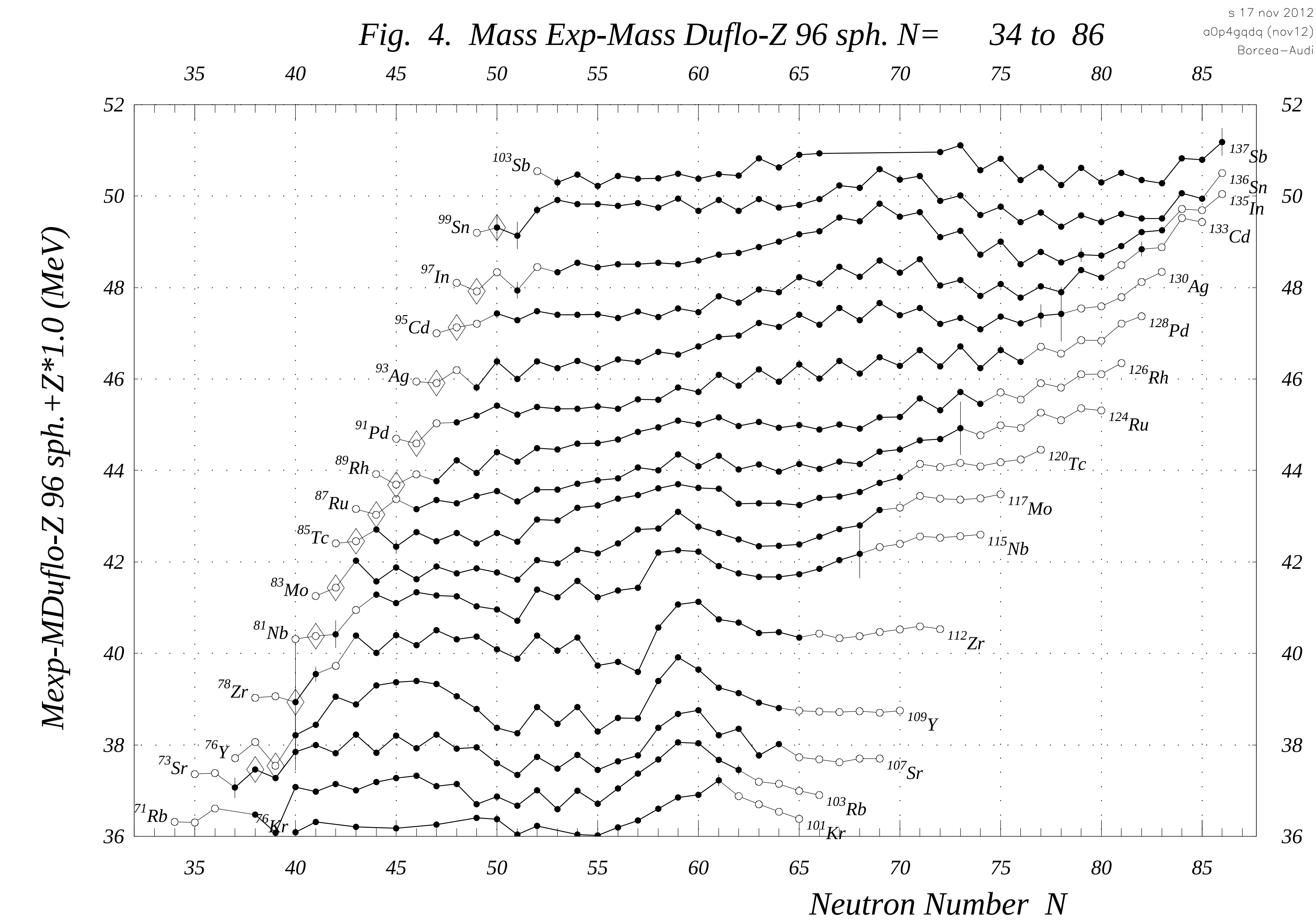
Fig. 3. Mass Exp-Mass Duflo-Z 96 sph. N= 18 to 66





d 16 nov 2003
a0p4sqyz (nov03)
Barcea–Audi
Fig. 4. Mass Exp-Mass Duflo-Z 96 sph. N= 34 to 86
Mexp-MDuflo-Z 96 sph.+Z*1.0 (MeV)
Neutron Number N
103Sb
137Sb
99Sn
136Sn
135In
97In
132Cd
95Cd
130Ag
93Ag
124Pd
122Rh
91Pd
120Ru
89Rh
118Tc
87Ru
115Mo
85Tc
113Nb
83Mo
81Nb
110Zr
78Zr
108Y
73Sr
76Y
105Sr
71Rb
98Kr
102Rb

Fig. 4. Mass Exp-Mass Duflo-Z 96 sph. N= 34 to 86



s 17 nov 2012
a0p4gqdq (nov12)
Borcea–Audi

Fig. 24. α-decay energies N = 122 to 145

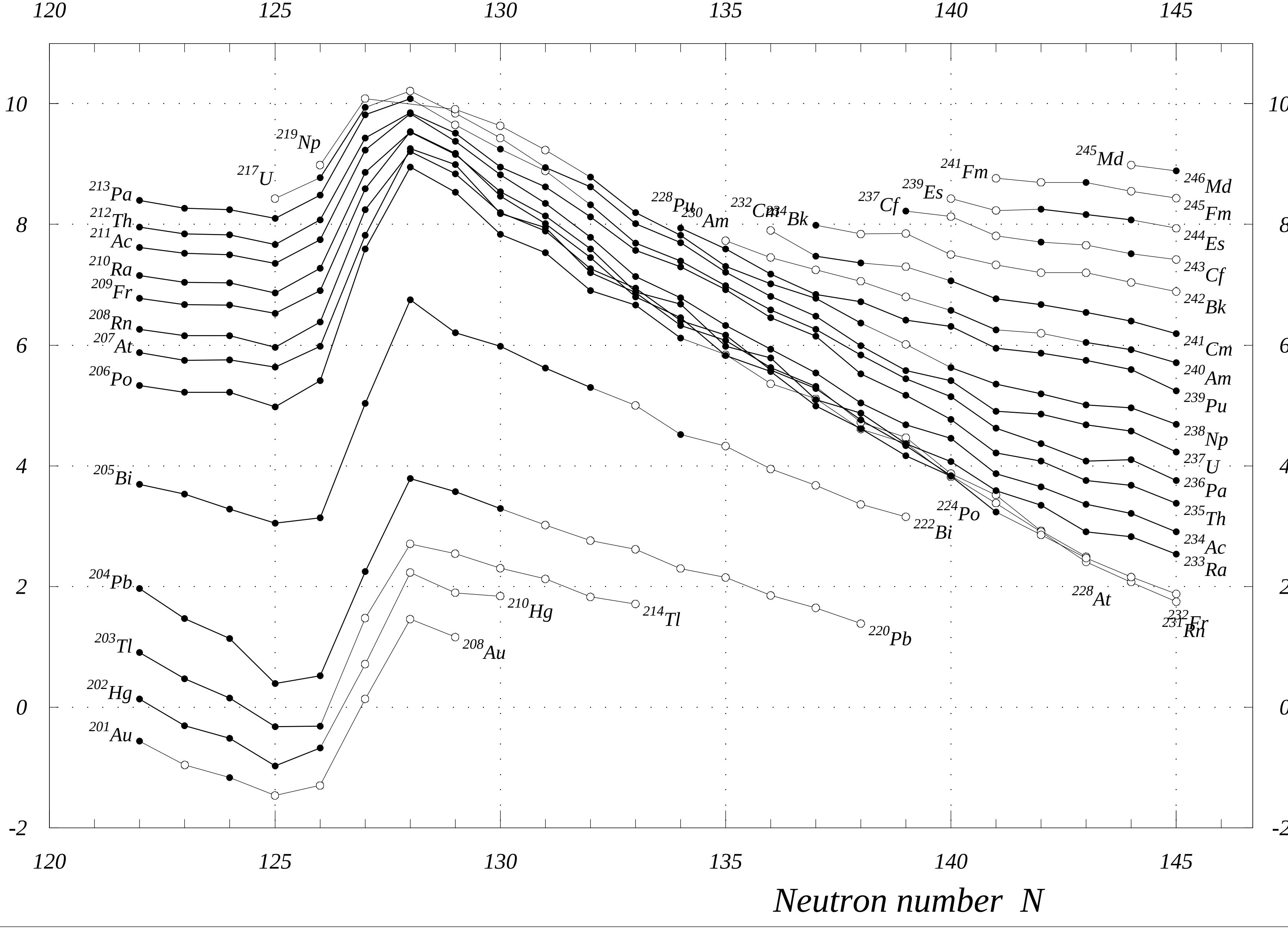
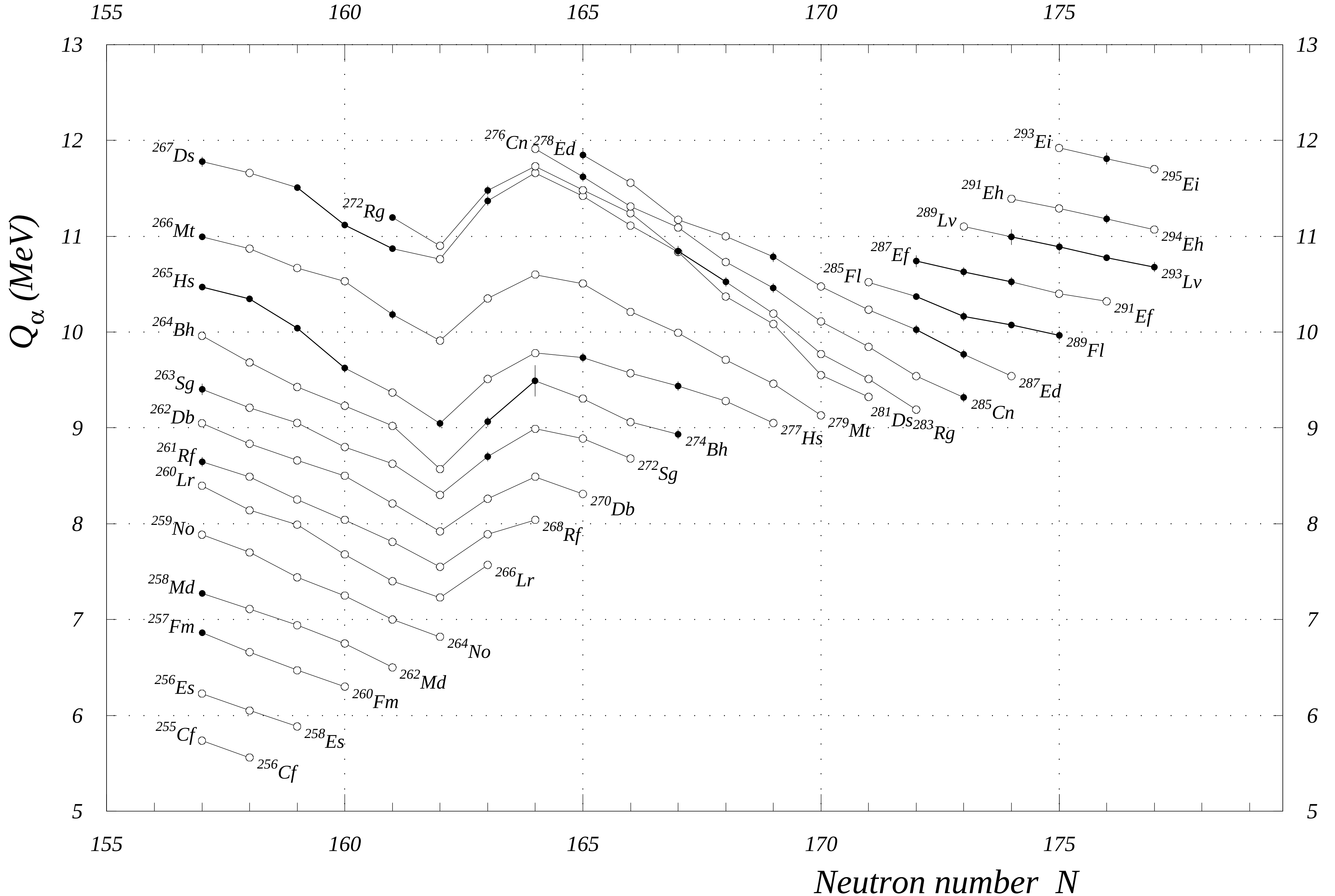


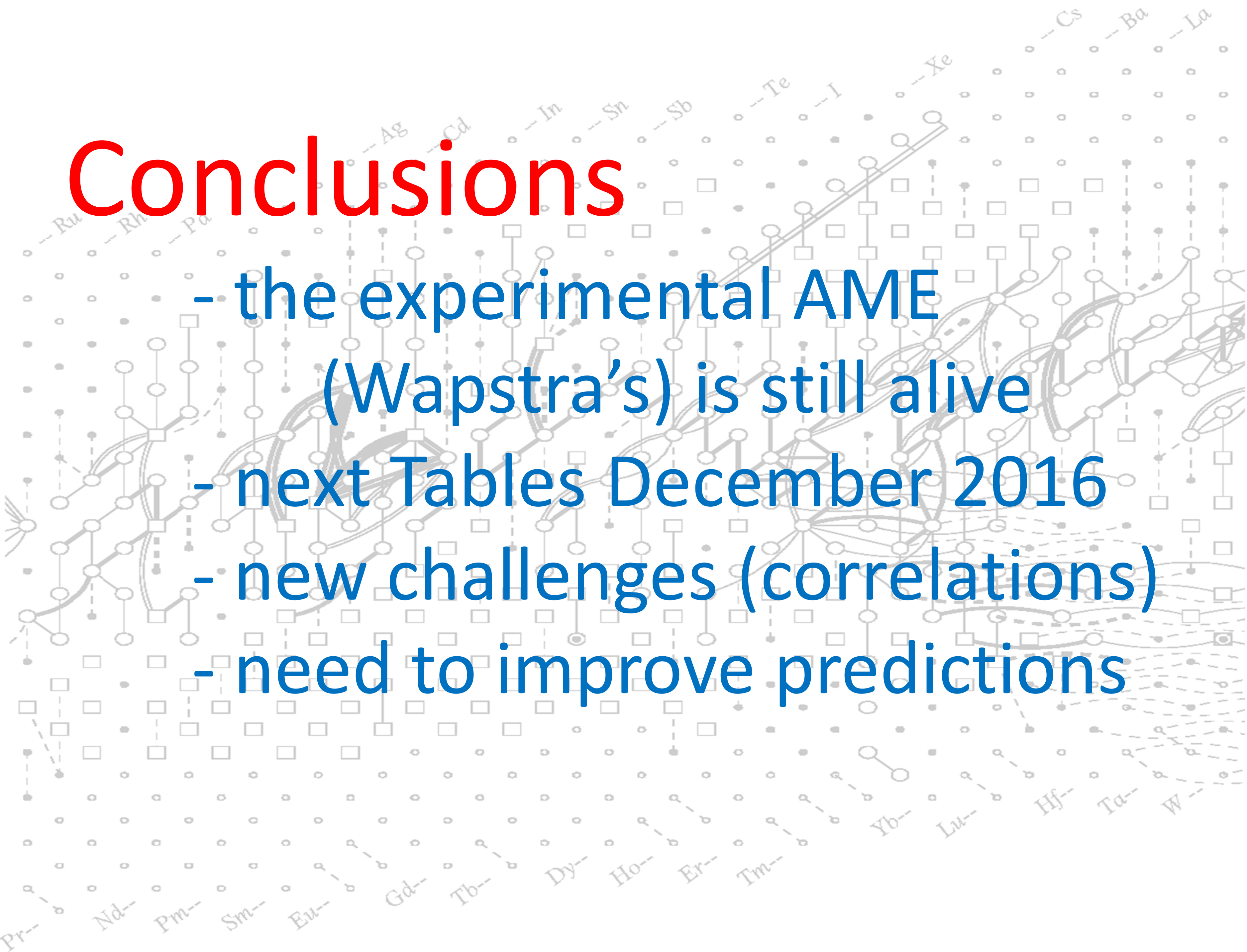
Fig. 26. α-decay energies   N = 157 to 178

s 17 nov 2012
a0p4gqdq (nov12)
Borcea–Audi



Conclusions

- the experimental AME (Wapstra's) is still alive
- next Tables December 2016
- new challenges (correlations)
- need to improve predictions



Thank you for your attention!

AME collaboration:

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