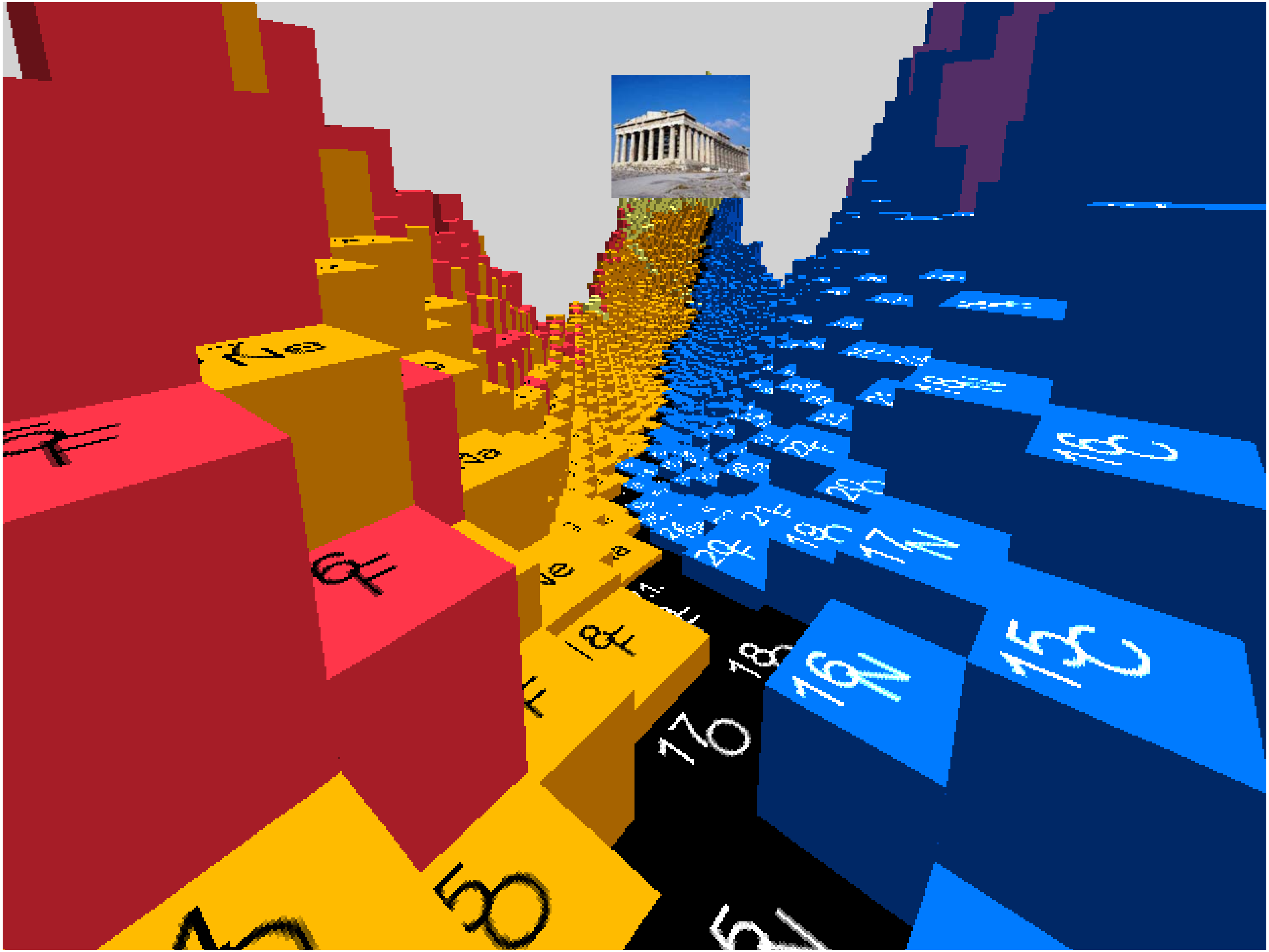
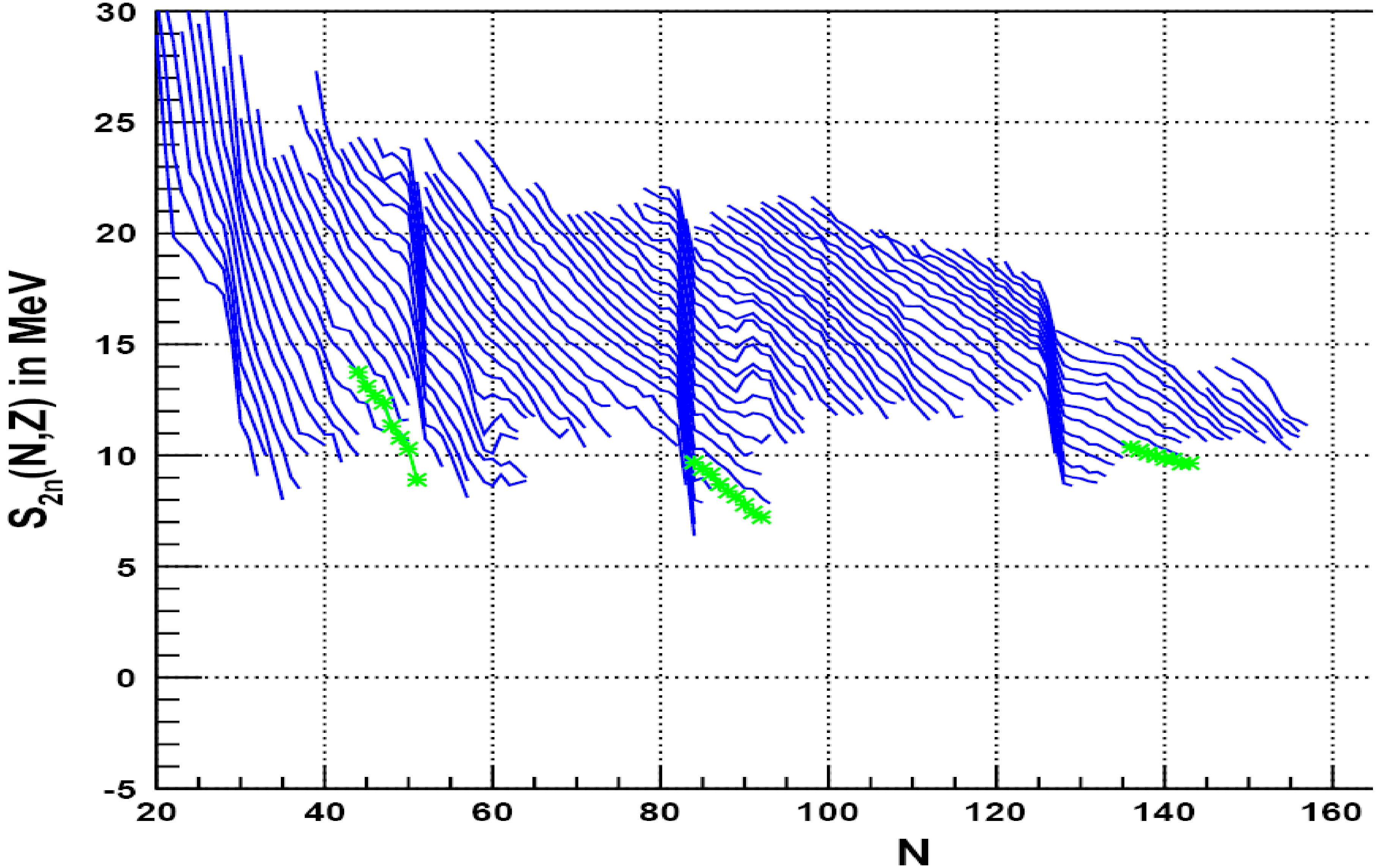
Acropolistic view of the mass surface and the columns of nucleosynthesis

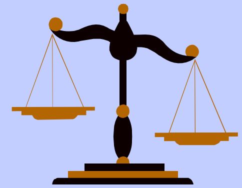
David Lunney – CSNSM (IN2P3/CNRS) – Université de Paris Sud, Orsay



16N
15C
17N
17O
16C



Big question of nuclear physics: are magic numbers *really* magic?

Techniques 

Indirect

<u>reactions:</u>

A(a,b)B

$Q = M_A + M_a - M_b - M_B$

<u>decays:</u>

$A \rightarrow B + \alpha$

$Q_\alpha = M_B - M_A$

Direct

(mass spectrometry)

<u>time of flight</u>:

SPEG/CSS2 - GANIL

NSCL, ESR - GSI

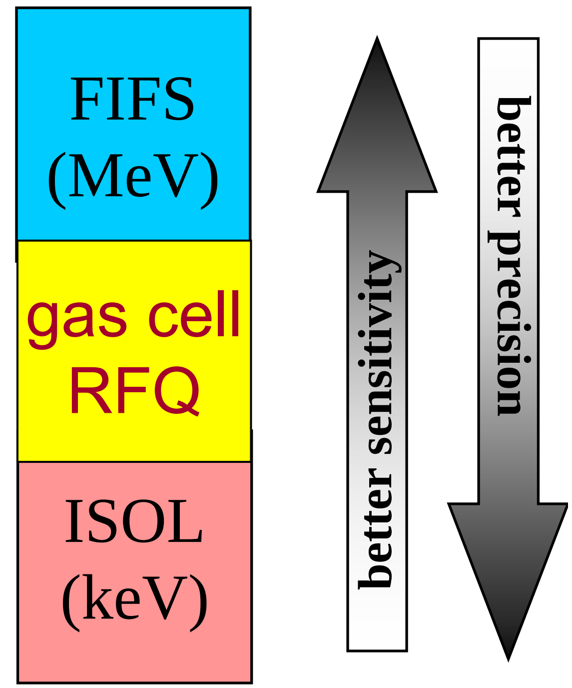
<u>cyclotron frequency:</u>

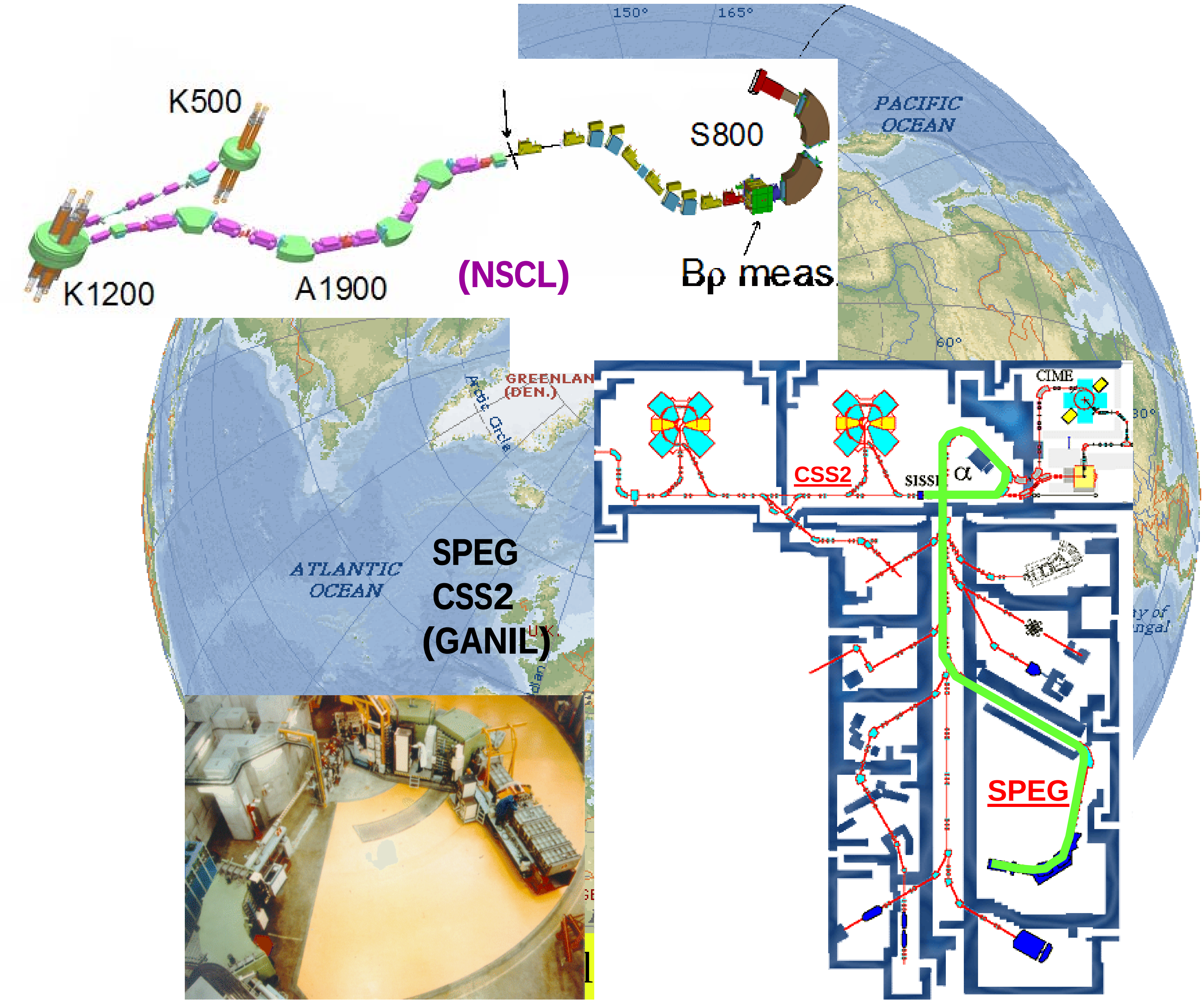
Penning-trap

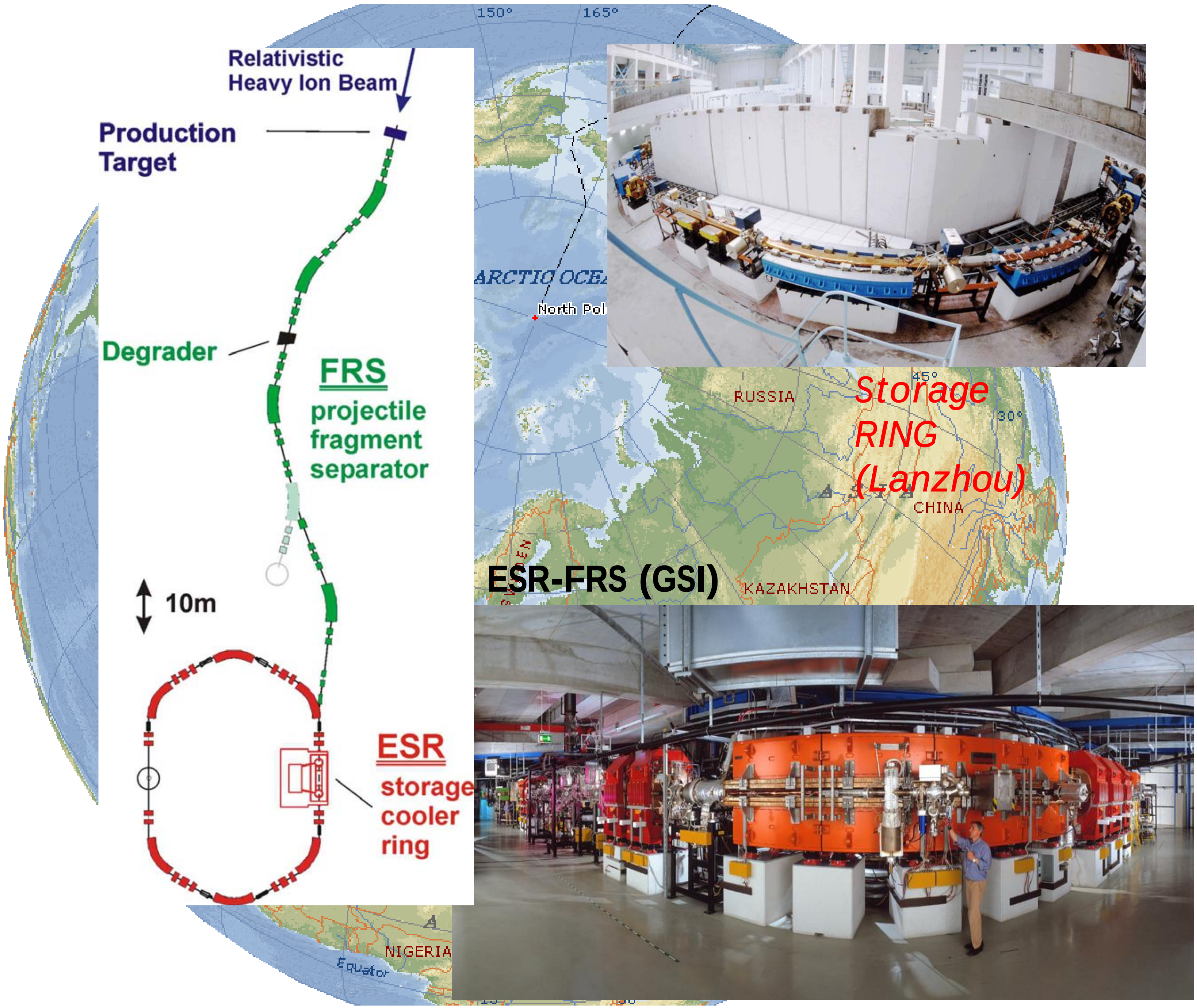
Mass spectrometry

ISOLTRAP and…

PRODUCTION SCHEME




K500
K1200
A1900
S800
(NSCL)
Bρ meas.
PACIFIC OCEAN
ATLANTIC OCEAN
SPEG
CSS2
(GANIL)
CIME
CSS2
SISSI
α
SPEG


150°
165°
Relativistic
Heavy Ion Beam
Production
Target
Degrader
FRS
projectile
fragment
separator
10m
ESR
storage
cooler
ring
ARCTIC OCEA
North Pol
RUSSIA
45°
30°
Storage
RING
(Lanzhou)
CHINA
ESR-FRS (GSI)
KAZAKHSTAN
NIGERIA
Equator


TITAN (TRIUMF)
LEBIT (NSCL)
CPT (ANL)
ISOLTRAP (CERN)
SHIPTRAP (GSI)
JYFLTRAP (IGISO
MLLTRAP (SPIRAL2)
TRIGATRAP
NORTH AMERICA
UNITED STATES
ATLANTIC OCEAN
U.K.
INDIA
IRAN
SHIPTRAP

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

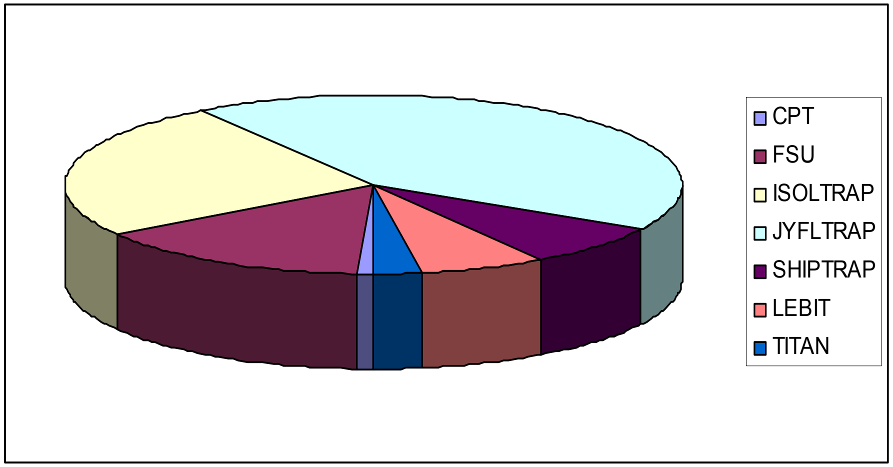
(source: AME2011 update of G. Audi & M. Wang)

Total of about 200 direct measurements:

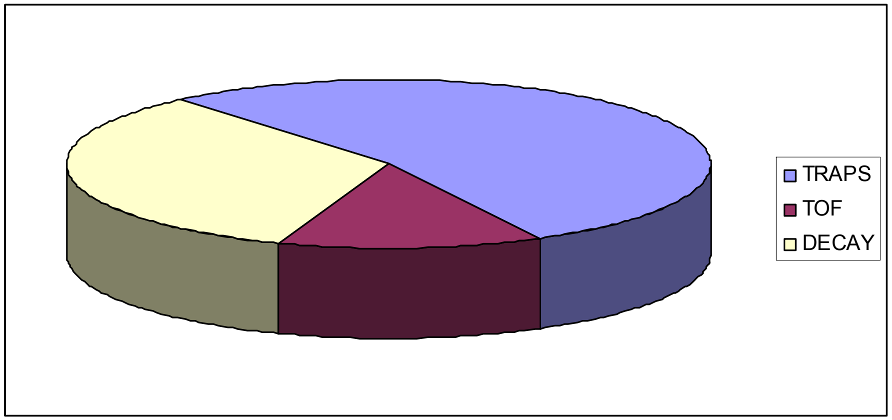
ESR-IMS (35); ESR-SMS (6); NSCL (21);

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 (!)



Eur. Phys. J. A (2011) **47**: 75
DOI 10.1140/epja/i2011-11075-6

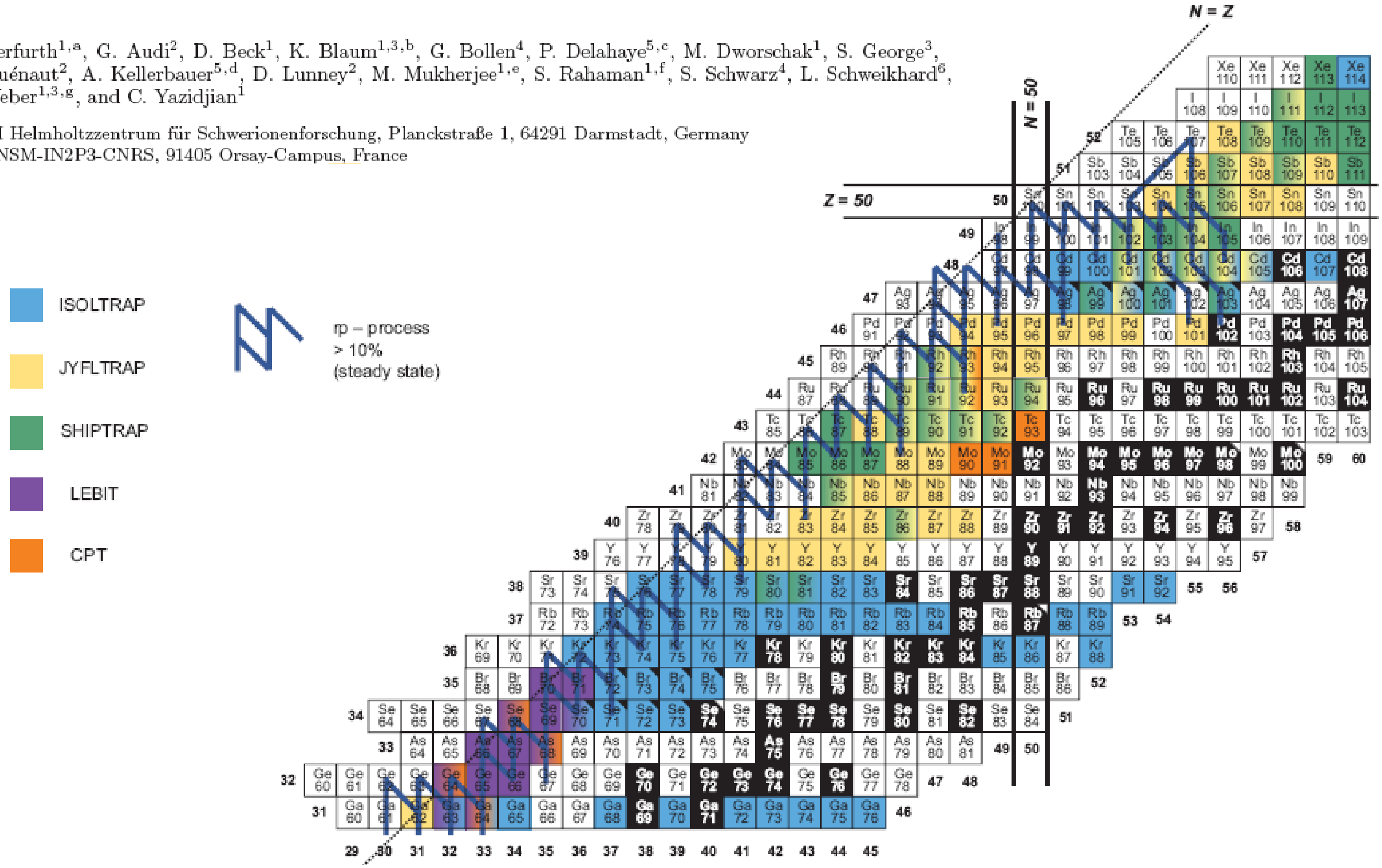
THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article – Experimental Physics

New mass data for the rp-process above Z = 32

F. Herfurth[1,a], G. Audi[2], D. Beck[1], K. Blaum[1,3,b], G. Bollen[4], P. Delahaye[5,c], M. Dworschak[1], S. George[3], C. Guénaut[2], A. Kellerbauer[5,d], D. Lunney[2], M. Mukherjee[1,e], S. Rahaman[1,f], S. Schwarz[4], L. Schweikhard[6], C. Weber[1,3,g], and C. Yazidjian[1]

[1] GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
[2] CSNSM-IN2P3-CNRS, 91405 Orsay-Campus, France



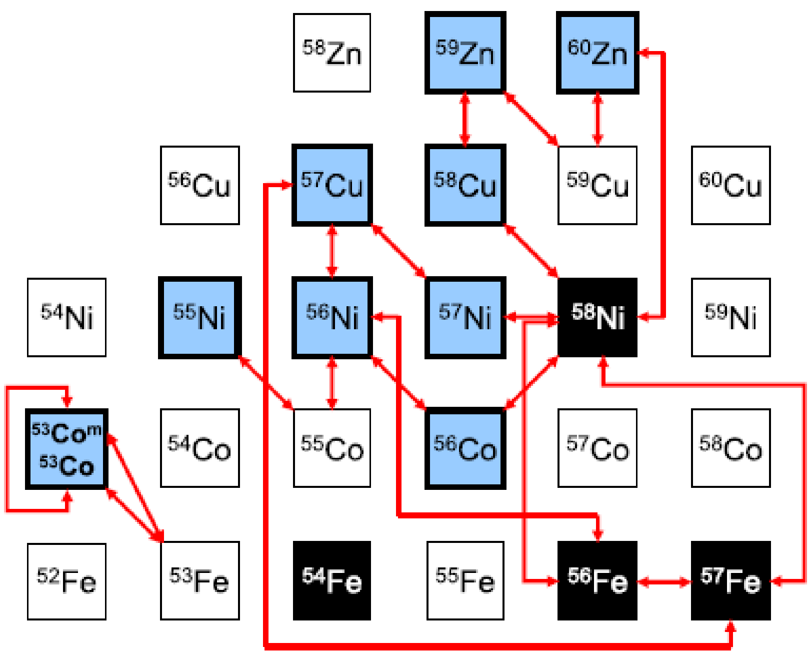
JYFLTRAP @ IGISOL - Jyväskylä

CU10170

Mass measurements in the vicinity of the doubly-magic waiting point ^{56}Ni

A. Kankainen,* V.-V. Elomaa,† T. Eronen, D. Gorelov, J. Hakala, A. Jokinen, T. Kessler, V.S. Kolhinen, I.D. Moore, S. Rahaman,‡ M. Reponen, J. Rissanen, A. Saastamoinen, C. Weber,§ and J. Äystö
Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland

Masses of ^{56,57}Fe, ^{53}Co^m, ^{53,56}Co, ^{55,56,57}Ni, ^{57,58}Cu, and ^{59,60}Zn have been determined with the JYFLTRAP Penning trap mass spectrometer at IGISOL with a precision of $\delta m/m \leq 3 \times 10^{-8}$.



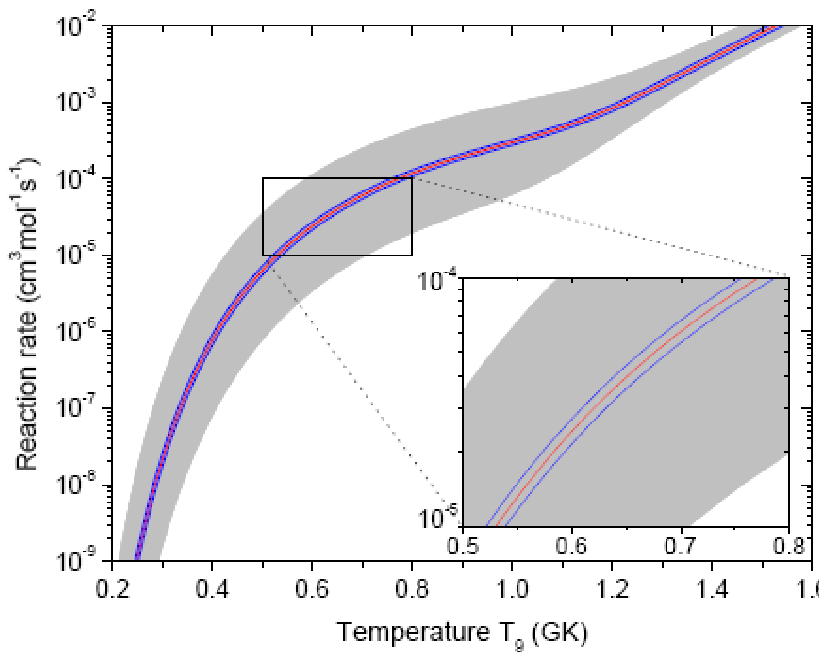


FIG. 13: (Color online) Total reaction rate for ^{56}Ni(p,γ)^{57}Cu.

CPT @ ANL - Argonne

RAPID COMMUNICATIONS

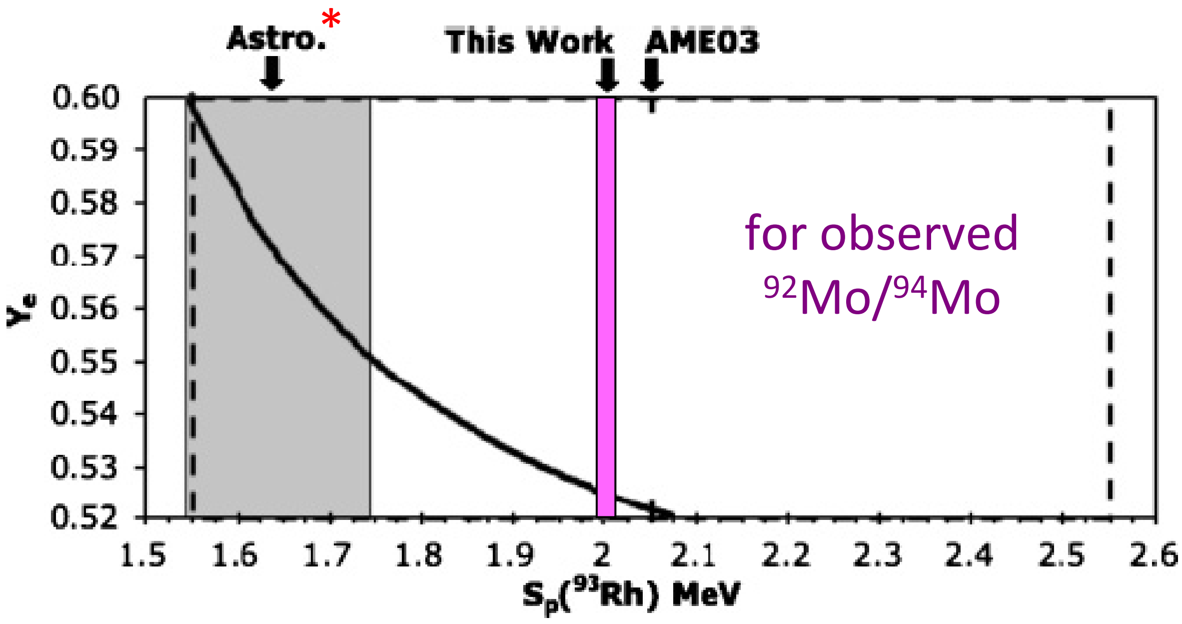
PHYSICAL REVIEW C **78**, 022801(R) (2008)

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*



* J. L. Fisker, R. D. Hoffman, and J. Pruet, arXiv (2007)

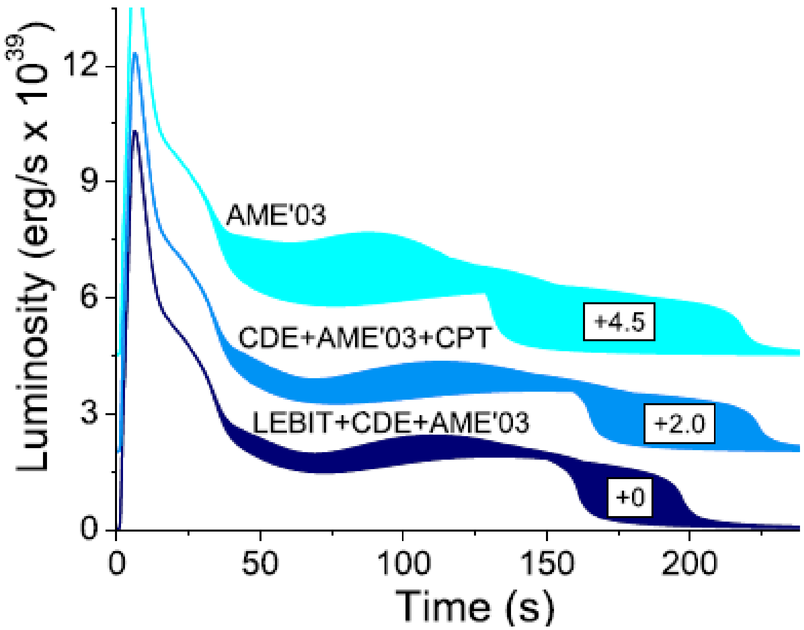
LEBIT @ MSU-East Lansing

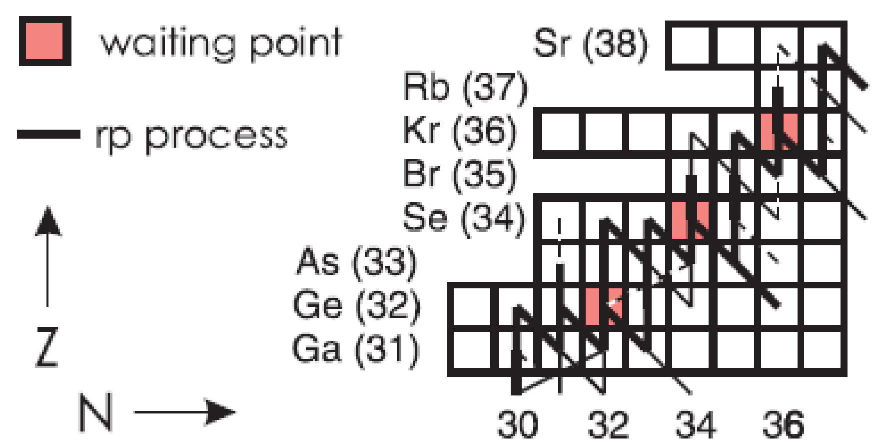
PRL 102, 132501 (2009) PHYSICAL REVIEW LETTERS week ending 3 APRIL 2009

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





PRL **106,** 112501 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

Direct Mass Measurements of Short-Lived $A = 2Z - 1$ Nuclides ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr and Their Impact on Nucleosynthesis in the *rp* Process

X. L. Tu,[1,2] H. S. Xu,[1,*] M. Wang,[1] Y. H. Zhang,[1] Yu. A. Litvinov,[3,4,1] Y. Sun,[5,1] H. Schatz,[6] X. H. Zhou,[1] Y. J. Yuan,[1] J. W. Xia,[1] G. Audi,[7] K. Blaum,[3] C. M. Du,[1,2] P. Geng,[1,2] Z. G. Hu,[1] W. X. Huang,[1] S. L. Jin,[1,2] L. X. Liu,[1,2] Y. Liu,[1] X. Ma,[1] R. S. Mao,[1] B. Mei,[1] P. Shuai,[8] Z. Y. Sun,[1] H. Suzuki,[9] S. W. Tang,[1,2] J. S. Wang,[1] S. T. Wang,[1,2] G. Q. Xiao,[1] X. Xu,[1,2] T. Yamaguchi,[10] Y. Yamaguchi,[11] X. L. Yan,[1,2] J. C. Yang,[1] R. P. Ye,[1,2] Y. D. Zang,[1,2] H. W. Zhao,[1] T. C. Zhao,[1] X. Y. Zhang,[1] and W. L. Zhan[1]

[1]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*

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.

CSR @ HIRFL Lanzhou

^{64}Ge *not* an rp waiting point

SHIPTRAP @ GSI - Darmstadt

Selected for a Viewpoint in *Physics*

PRL **106**, 122501 (2011) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2011

Mass Measurements of Very Neutron-Deficient Mo and Tc Isotopes and Their Impact on *rp* Process Nucleosynthesis

E. Haettner,[1,2,*] D. Ackermann,[2] G. Audi,[3] K. Blaum,[4] M. Block,[2] S. Eliseev,[2,†] T. Fleckenstein,[1] F. Herfurth,[2] F. P. Heßberger,[2] S. Hofmann,[2] J. Ketelaer,[5,†] J. Ketter,[4] H.-J. Kluge,[2] G. Marx,[6] M. Mazzocco,[7] Yu. N. Novikov,[2,8] W. R. Plaß,[1,2] S. Rahaman,[9,‡] T. Rauscher,[10] D. Rodríguez,[11] H. Schatz,[12] C. Scheidenberger,[1,2] L. Schweikhard,[6] B. Sun,[1,13] P. G. Thirolf,[14] G. Vorobjev,[2,8] M. Wang,[15] and C. Weber[9,§]

Physics

Physics **4**, 24 (2011)

Viewpoint

Putting rare isotopes on the scale

Jens Dilling
TRIUMF and University of British Columbia, 4004 Wesbrook Mall, Van
Canada

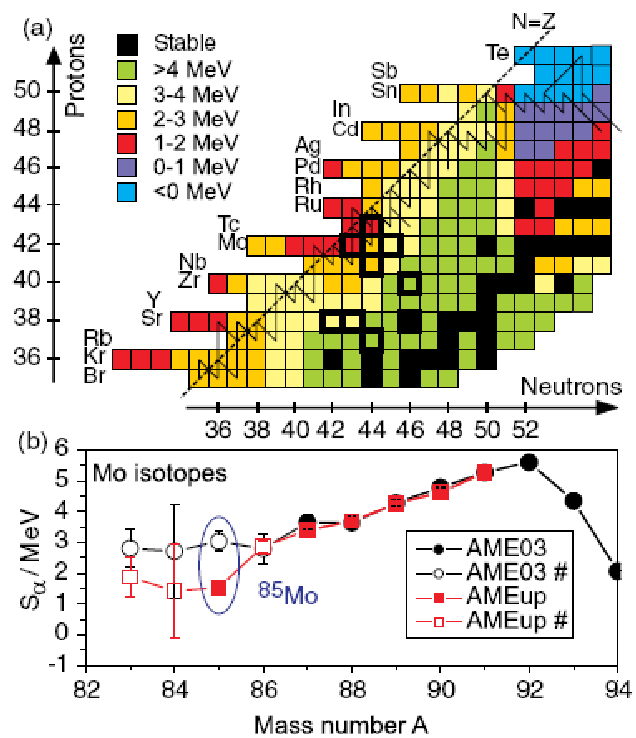
Chris Ruiz
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Ca

Published March 21, 2011

New mass measurements of proton-rich nuclei will allow scientists to more accurately simulate the nucleosynthesis that occurs on the surface of neutron stars.

Subject Areas: **Astrophysics, Nuclear Physics**

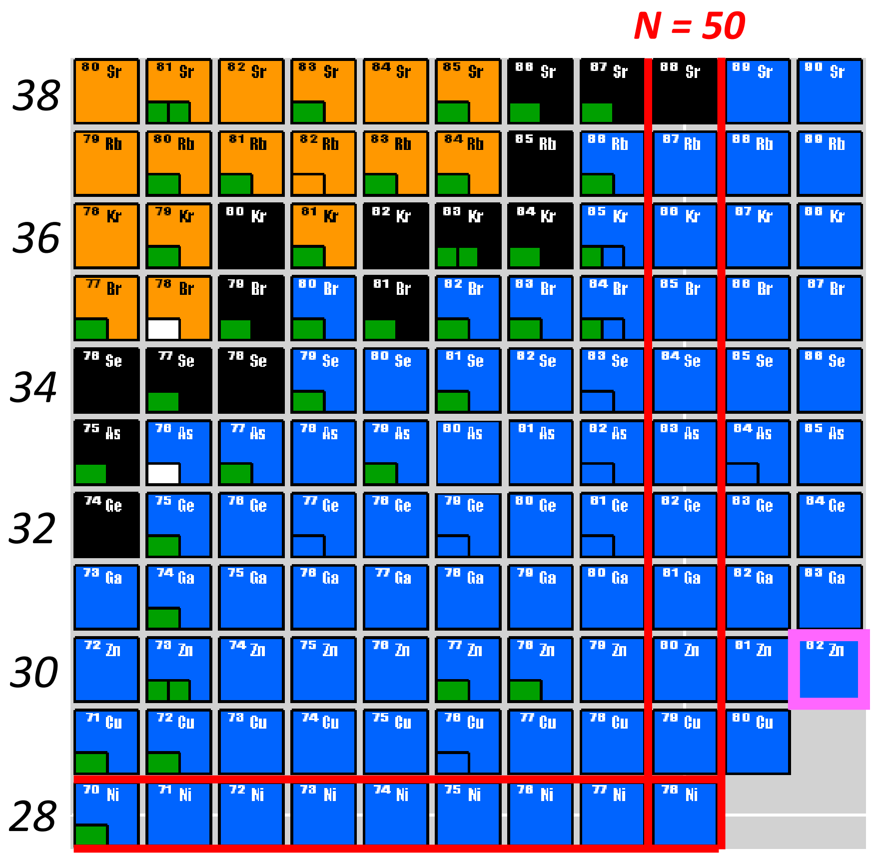
A Viewpoint on:
Mass Measurements of Very Neutron-Deficient Mo and Tc Isotopes and Their Impact on rp Process Nucleosynthesis
E. Haettner et al.
Phys. Rev. Lett. **106**, 122501 (2011) – Published March 21, 2011

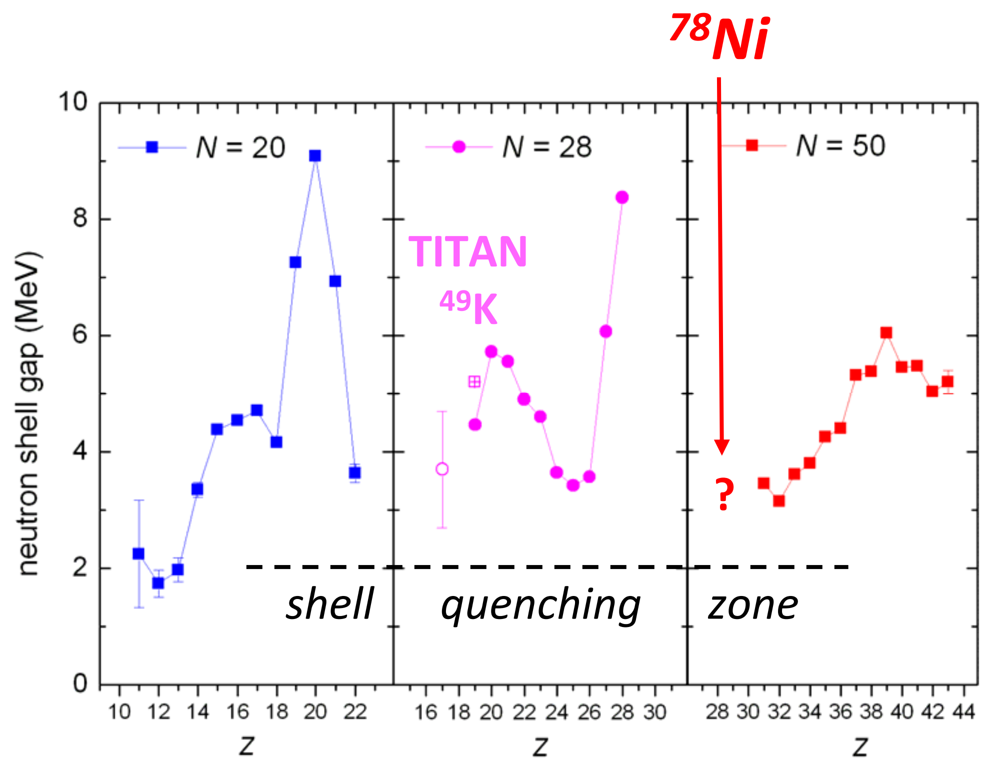


ISOLTRAP @ CERN-ISOLDE

year	article	physics	nuclides
2008	W. Geithner et al., PRL	structure (halo)	17Ne
2009	D. Neidherr et al., PRL 102, 112501	structure	223-229Rn
2009	M. Breitenfeldt et al., PRC 80, 035805	rp process	99-109Cd
2009	D. Neidherr et al., PRC 80, 044323	structure	136-146Xe
2010	M. Breitenfeldt et al., PRC 81, 034313	structure	112−124Ag; 114-128Cd
2010	S. Naimi et al., PRL 105, 032502	structure (shape)	96,97Kr
2011	S. Naimi et al., PRC submitted	structure (N = 40)	58-66Mn

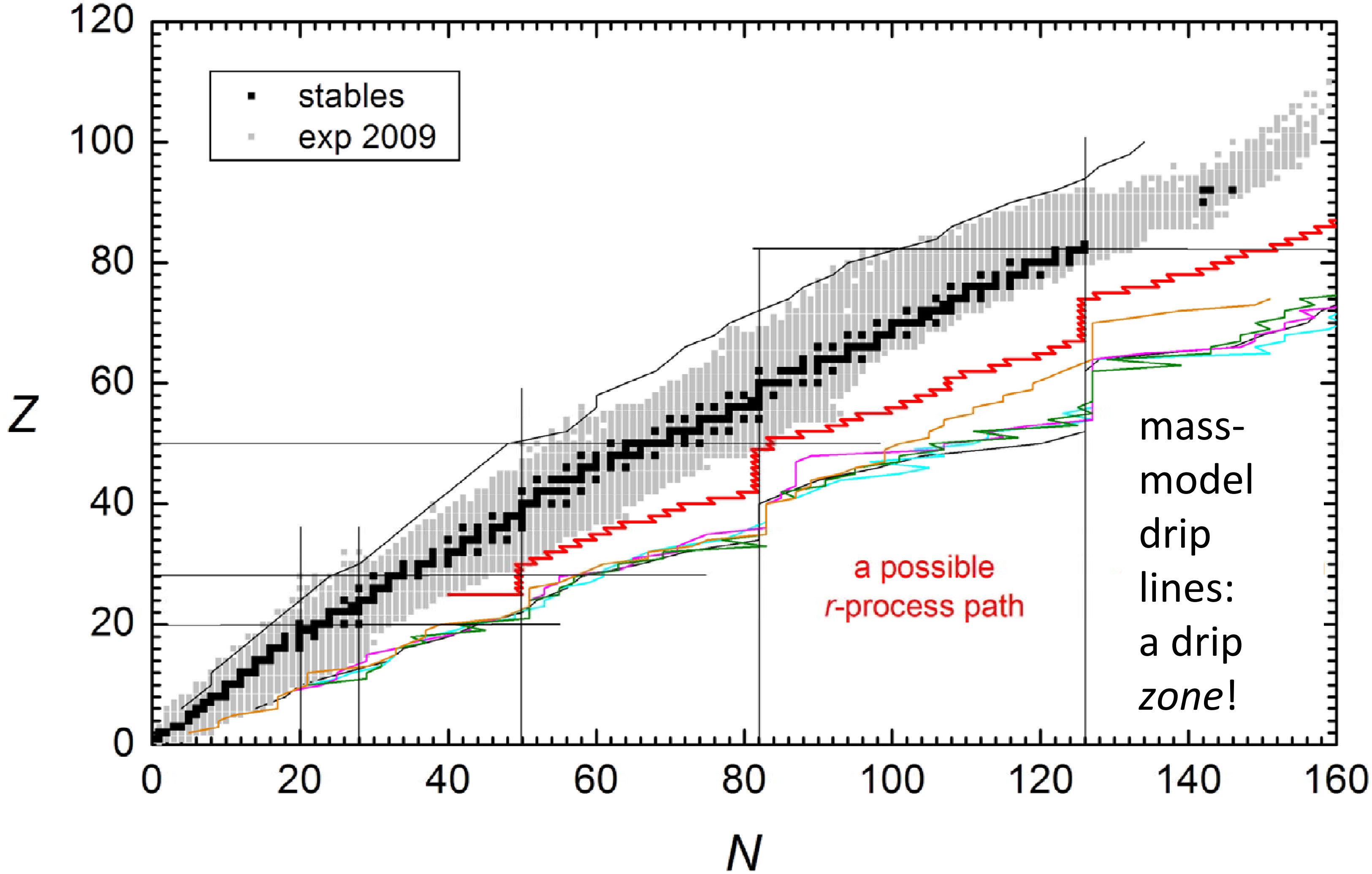
Oct. 2011 ISOLTRAP measurement of ^{82}Zn mass
→ most exotic test yet of the N = 50 gap

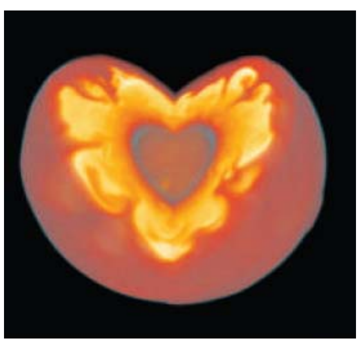




Using ISOLDE UCx target plus extras:

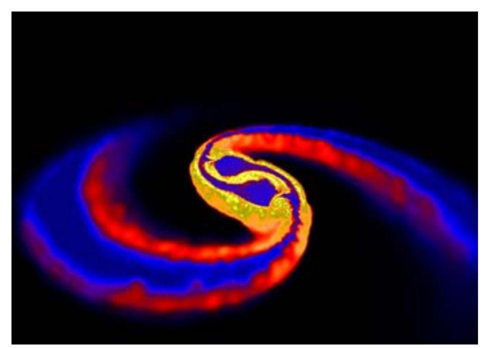
neutron converter
laser ionization
quartz transfer line
isobaric mass purification



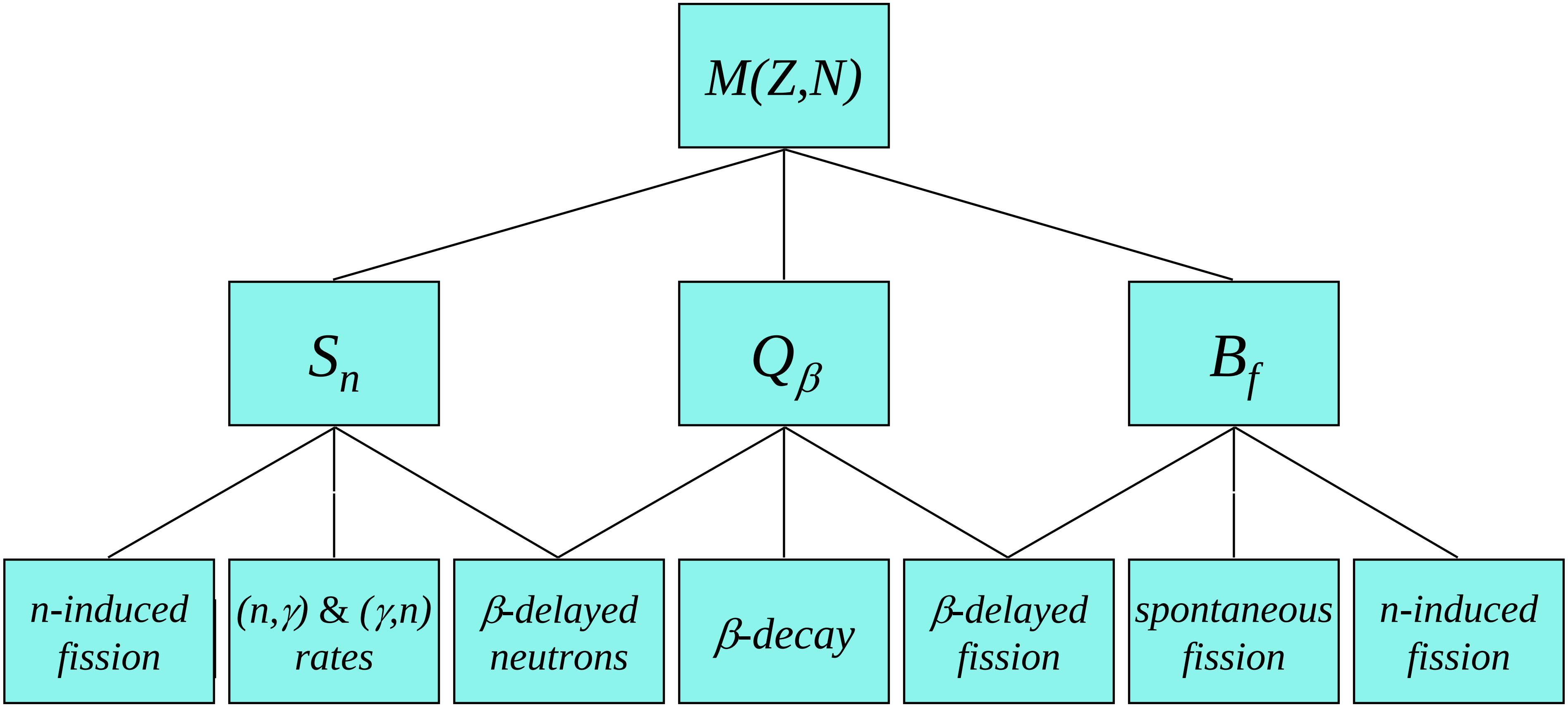


S. Woosley
and T. Janka,
Nature Physics
(2005)

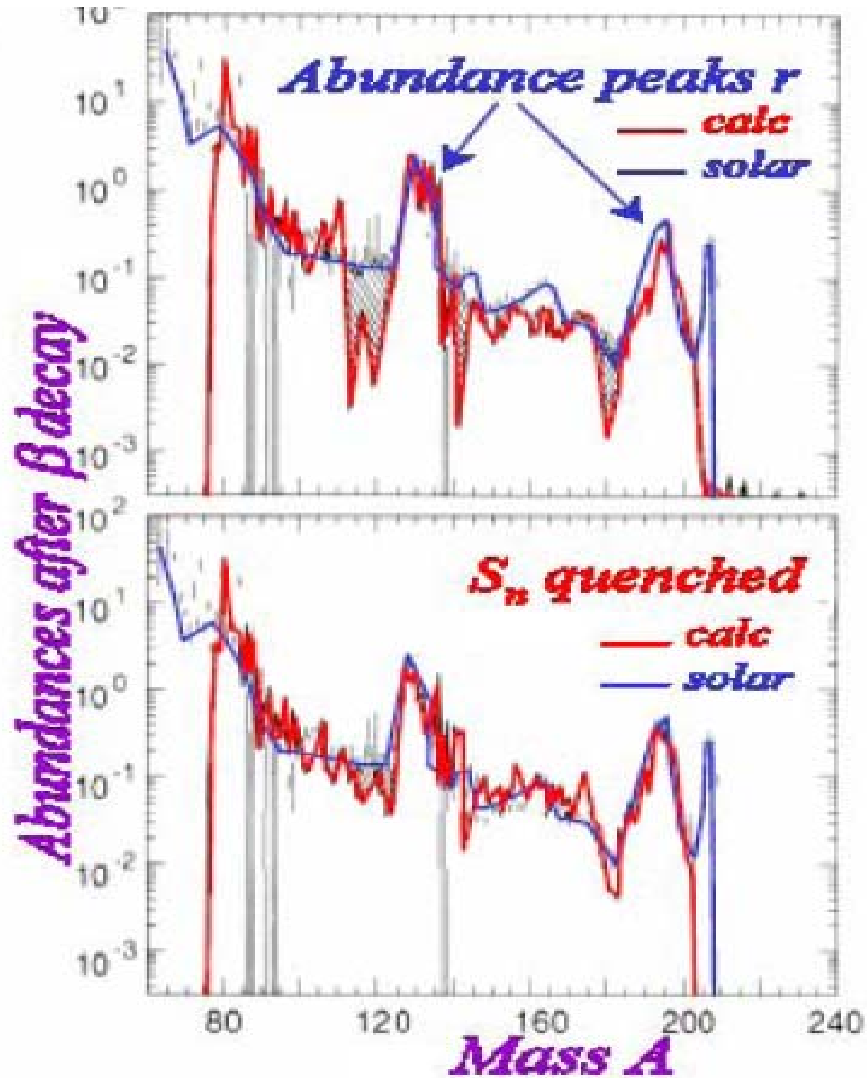
D. Price and
S. Rosswog,
Science (2006)



implication of the mass for *r* process input



Would like a microscopic model (based on an interaction) to calculate…everything!
(Gospel of St. Marcel: *microscopicism*)



ETFSI-*Q*

Big question of nuclear physics: are magic numbers *really* magic?

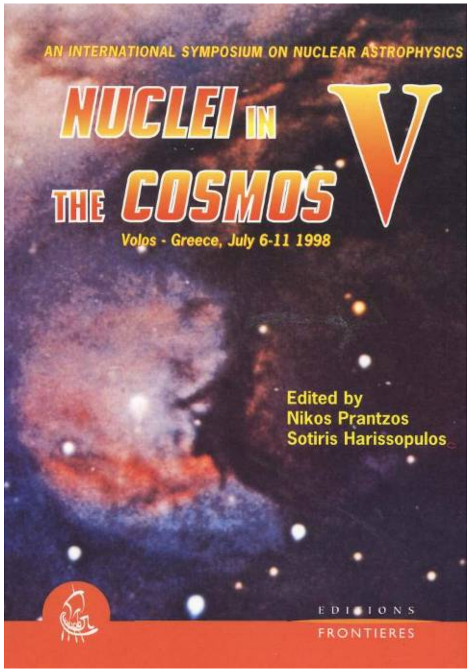
A (very) simplified overview of mass models

physics input →

algebraic formulas	*micro*scopic sculpturings of a *macro*scopic blob	microscopic nucleon-nucleon interaction

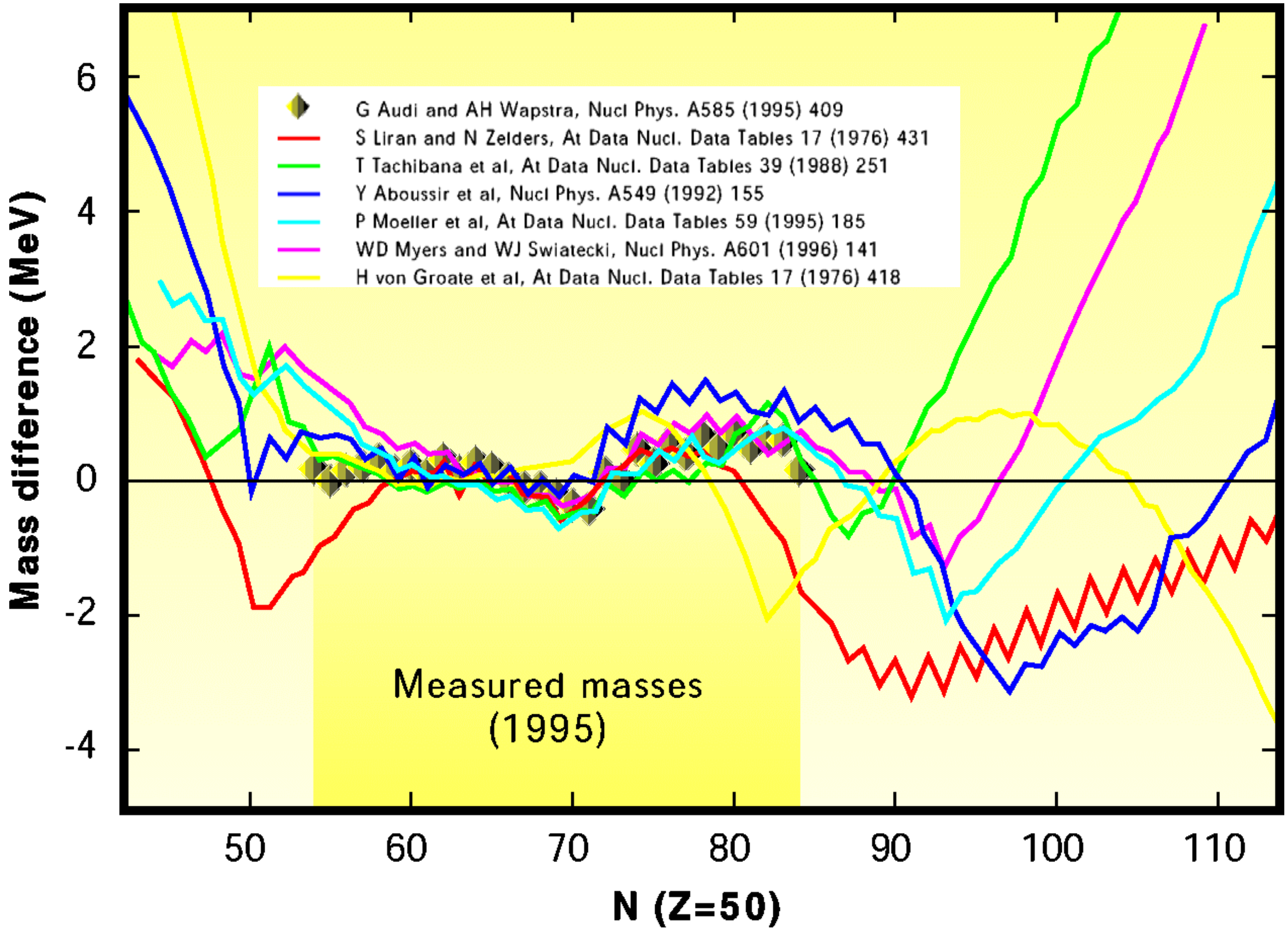
← ease of use

Garvey-Kelson	FRDM	HFB



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

13 years ago
(in Greece!)



Models diverge – but not as bad as $^{12}C(\alpha,\gamma)^{16}O$!

A brief history of HFB mass tables

HFB mass tables		**Explorations**
HFBCS:	S. Goriely et al., At. Nuc. Data (2001)	
HFB 1:	M. Samyn et al., Nucl. Phys. A (2002)	
HFB 2:	S. Goriely et al., Phys. Rev. C (2002)	
HFB 3:	M. Samyn et al., Nucl. Phys. A (2003)	I: pairing density dependence
HFB 4-7:	S. Goriely et al., Phys. Rev. C (2003)	II: effective mass
HFB 8:	M. Samyn et al., Phys. Rev. C (2004)	III: particle number projection
HFB 8:	M. Samyn et al., Phys. Rev. C (2005)	V. extension to fission barriers
HFB 9:	S. Goriely et al., Nucl. Phys. A (2005)	IV: neutron-matter constraint
HFB 10-13:	S. Goriely et al., Nucl. Phys. A (2006)	VI: weakened pairing
HFB 14:	S. Goriely et al., Phys. Rev. C (2007)	VII: simultaneous barrier fits
HFB 15:	S. Goriely & J.M. Pearson, Phys. Rev. C (2008)	VIII: role of Coulomb exchange
HFB 16:	N. Chamel et al., Nucl. Phys. A (2008)	IX: constraint to neutron pairing gap
HFB 17:	S. Goriely et al., Phys. Rev. Lett. (2009)	X: microscopic pairing (σ_{rms} < 0.6 MeV)
HFB 18:	N. Chamel et al., Phys. Rev. C (2009)	XI. stabilizing n-stars against collapse
HFB D1M:	S. Goriely + CEA, Phys. Rev. Lett. (2009)	First HFB-Gogny table
HFB 19-21:	S. Goriely et al., Phys. Rev. C (2010)	XII. stability of neutron-star matter
?		

S. Goriely, N. Chamel, *Université Libre de Bruxelles*;
J.M. Pearson, *Université de Montréal*

Other "recent" work: macroscopic - microscopic / liquid drop

Kazuhiro Oyamatsu, Kei Iida, Hiroyuki Koura, Phys. Rev. C82 (2010) 027301
Kazuhiro Oyamatsu, Kei Iida, Phys. Rev. C81 (2010) 054302

Wigner-Kirkwood:
A. Bhagwat, X. Vinas, M. Centelles, P. Schuck, R. Wyss, Phys. Rev. C81 (2010) 044321

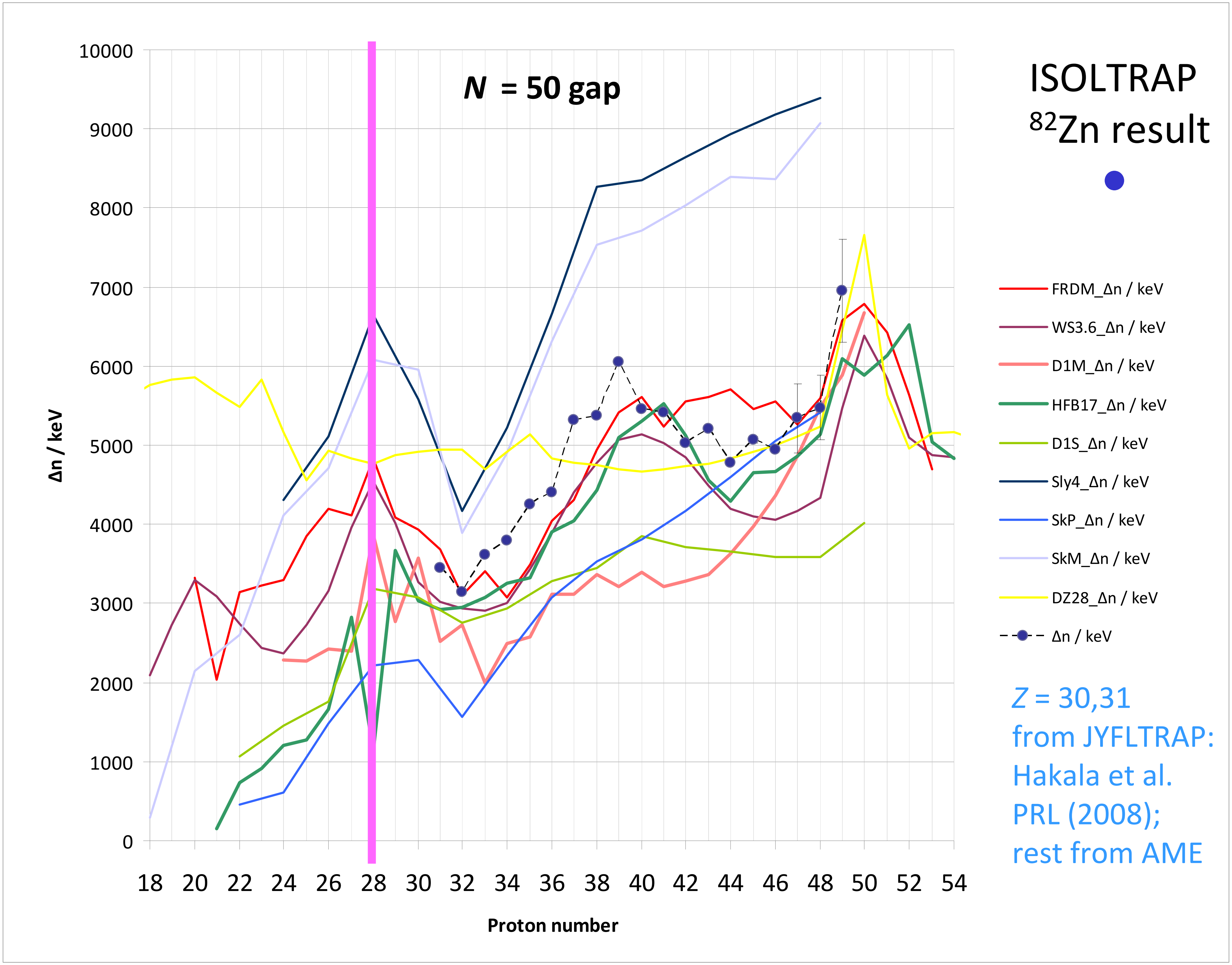
Ning Wang, Zuoying Liang, Min Liu, Xizhen Wu, Phys. Rev. C82 (2010) 044304
Ning Wang, Min Liu, Xizhen Wu, Phys. Rev. C81 (2010) 044322

FRDM: Finite Range Droplet Model - New fit to 2011 AME!
P. Moller et al., At. Data Nuc. Data Tables 59 (1995) 185

Other microscopic "fundamentalist" models

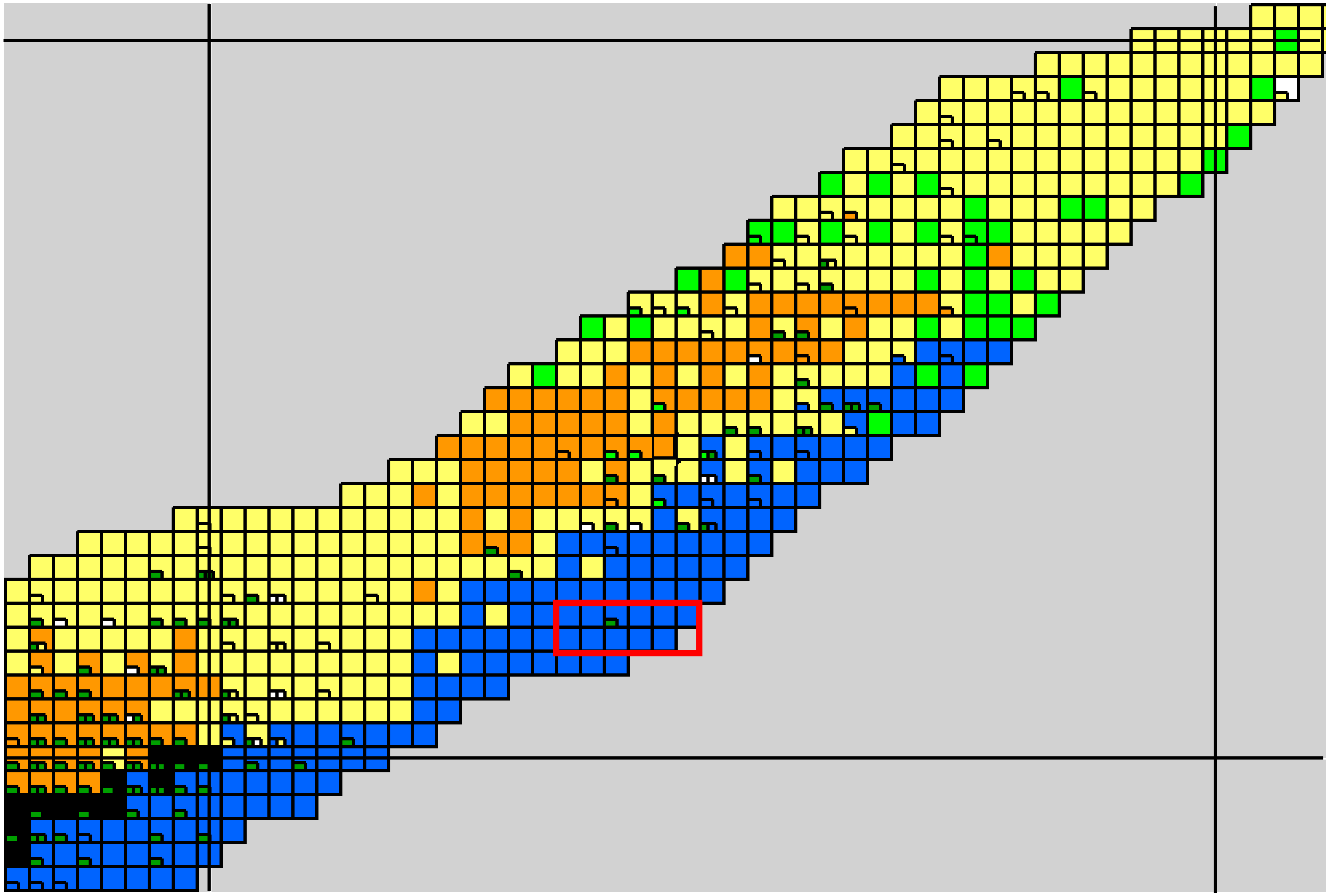
Delaroche et al. PRC (2010) D1S-5DCH (Gogny force)
Bender, Bertsch, Heenen, PRC (2006) SLy4-GCM (Skyrme force)

only even-even nuclides!

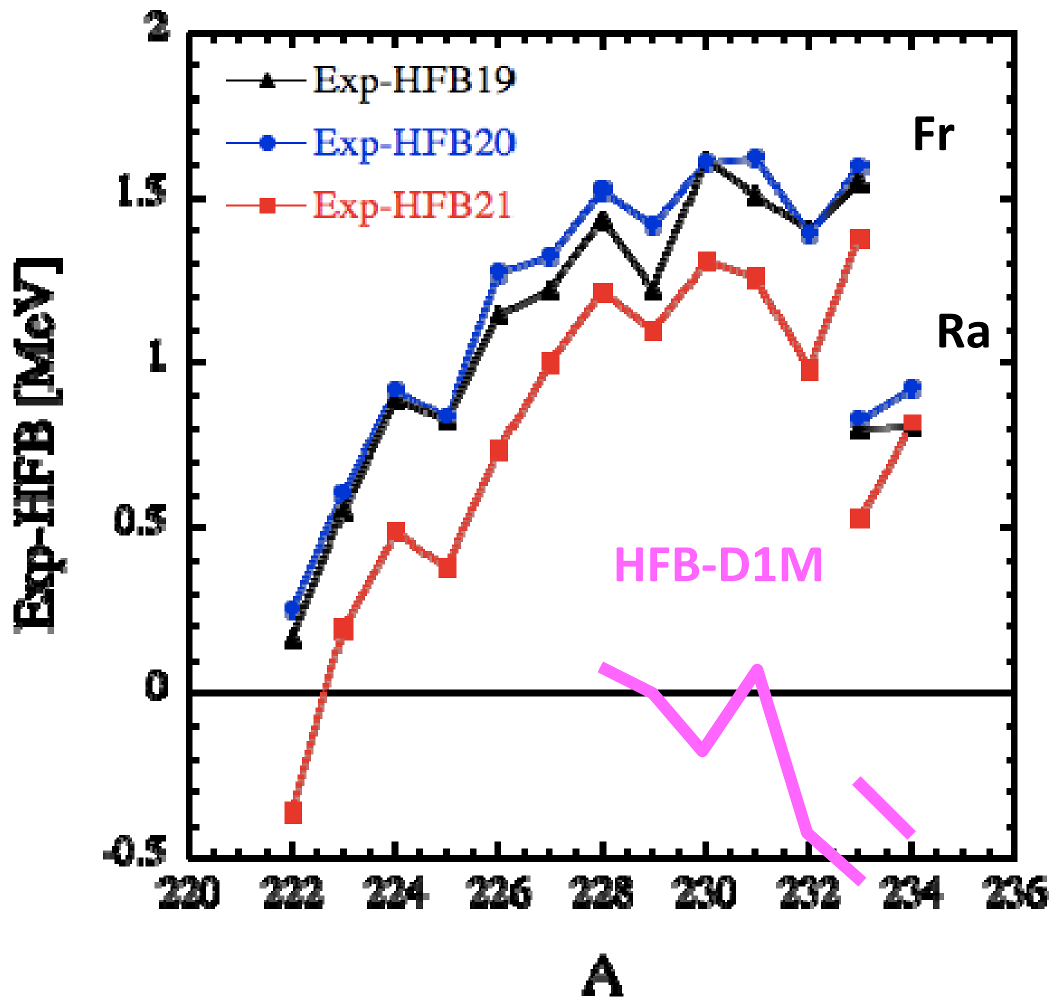


N = 50 gap
ISOLTRAP
82Zn result
FRDM_Δn / keV
WS3.6_Δn / keV
D1M_Δn / keV
HFB17_Δn / keV
D1S_Δn / keV
Sly4_Δn / keV
SkP_Δn / keV
SkM_Δn / keV
DZ28_Δn / keV
Δn / keV
Z = 30,31 from JYFLTRAP: Hakala et al. PRL (2008); rest from AME
Δn / keV
Proton number

New (August 2011) ISOLTRAP measurements

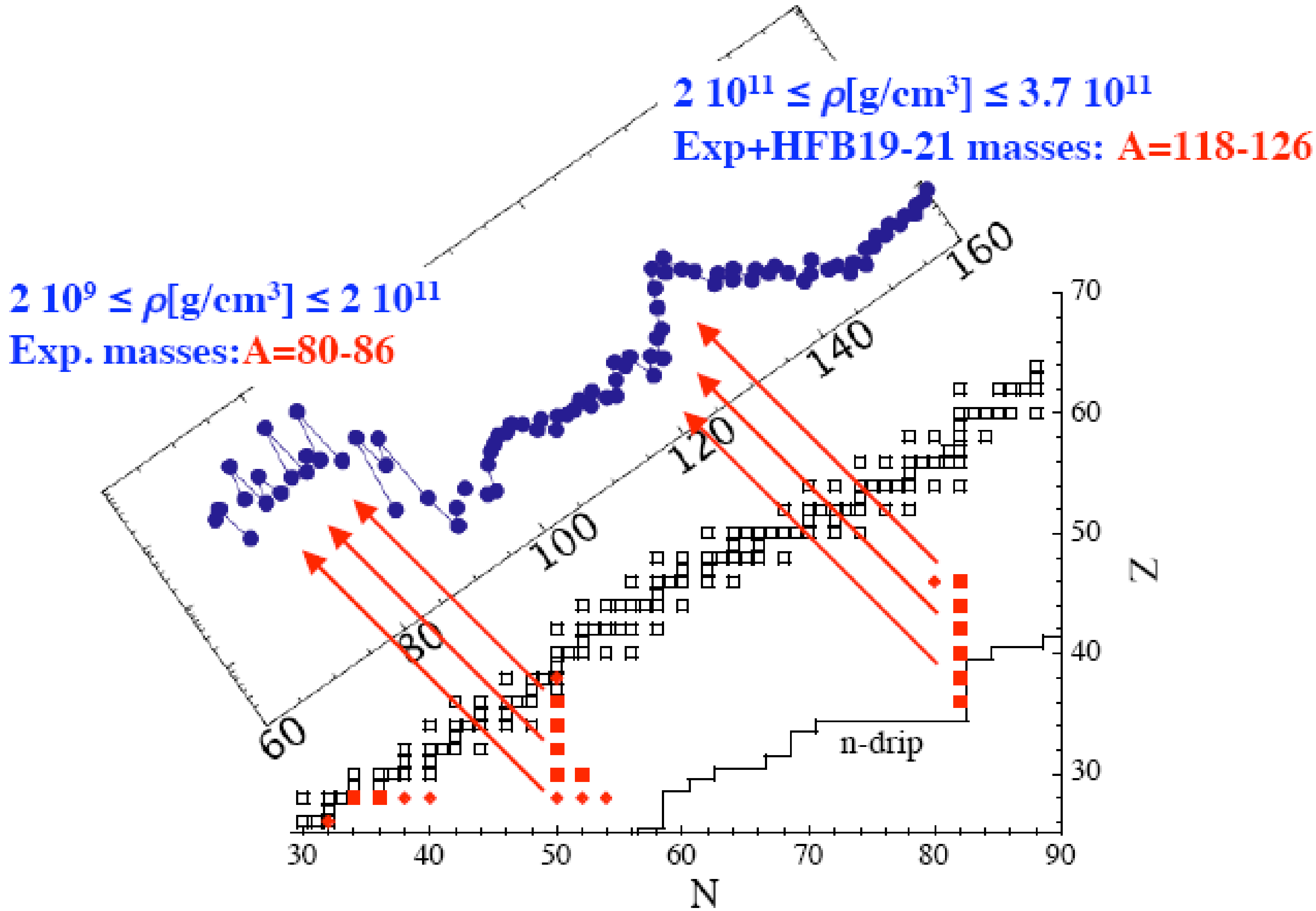


Comparison with new (August 2011) ISOLTRAP measurements



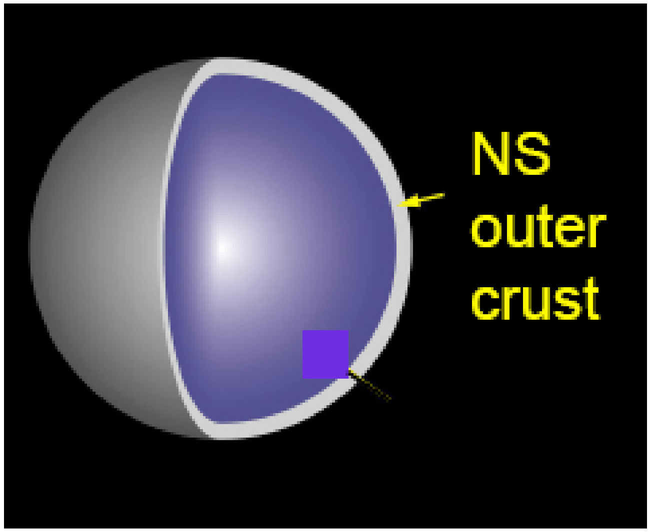
Delaroche et al. (D1S-5DCH): no Fr (Z odd) and only ^{234}Ra (-11.9 MeV…)
Bender-Bertsch-Heenen (SLy4+GCM): no predicted masses…

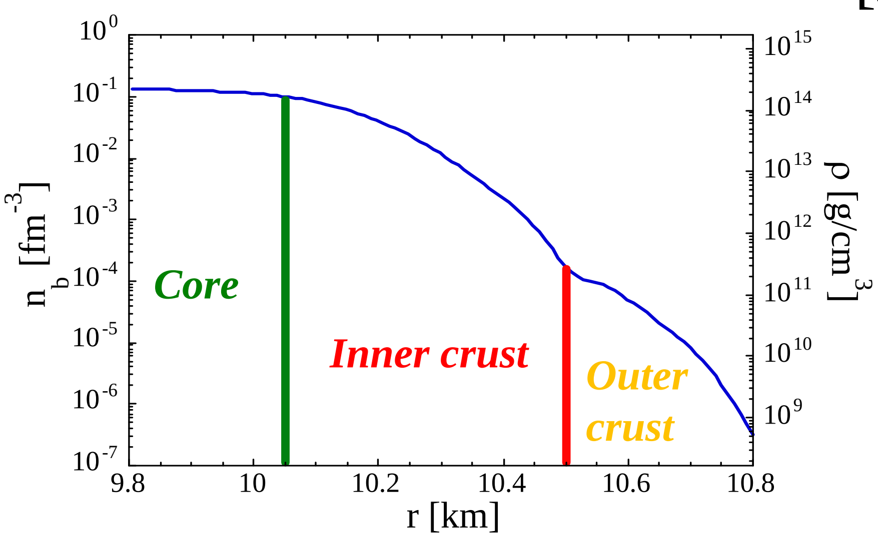
Composition of the cold outer crust

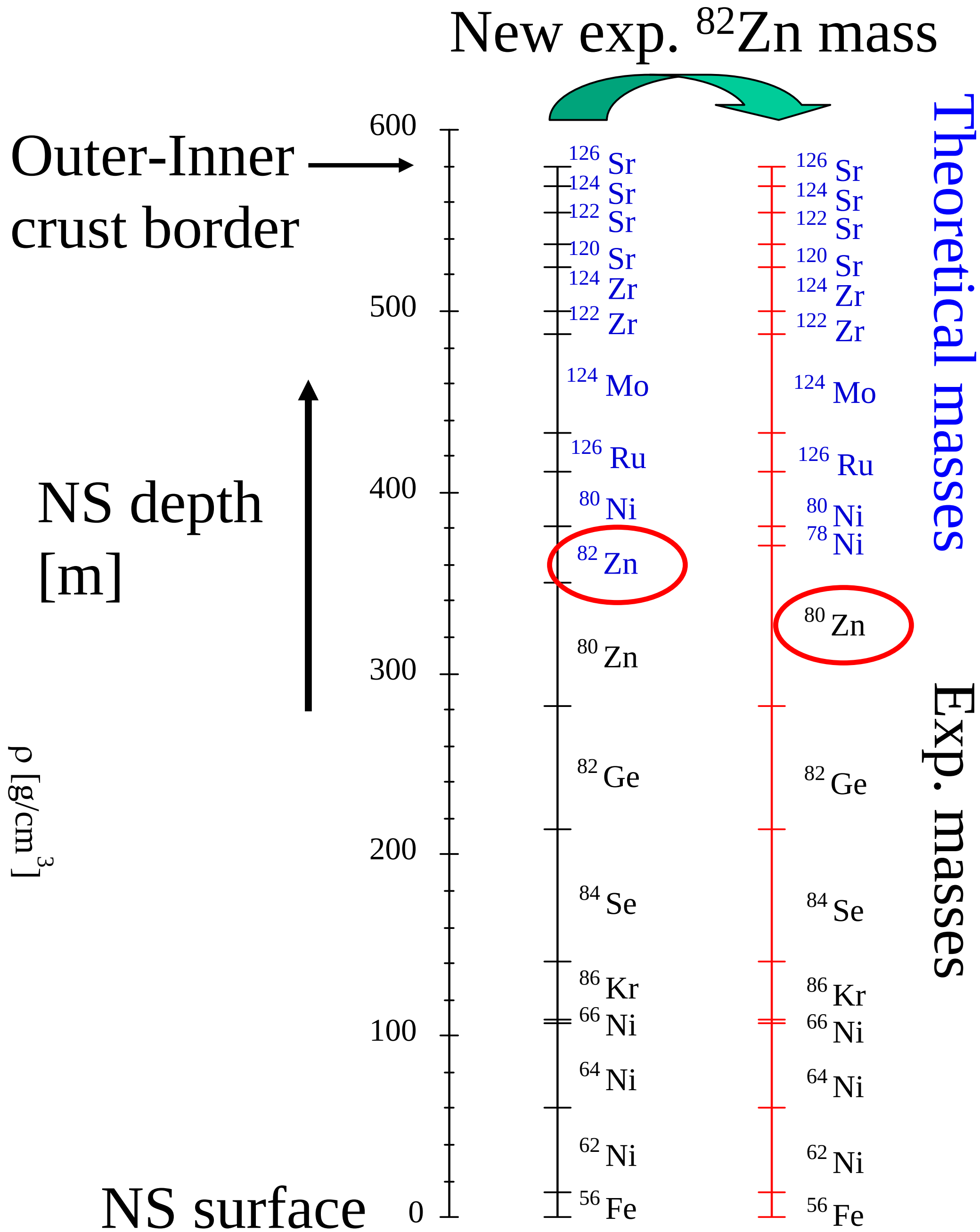


Ejection of the outer crust material: enrichment of nuclei up to A~130 !

S. Goriely, N. Chamel, H.-T. Janka, J.M. Pearson, A&A (2011)







J.M. Pearson, S. Goriely and N. Chamel, PRC 83 (2011)

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

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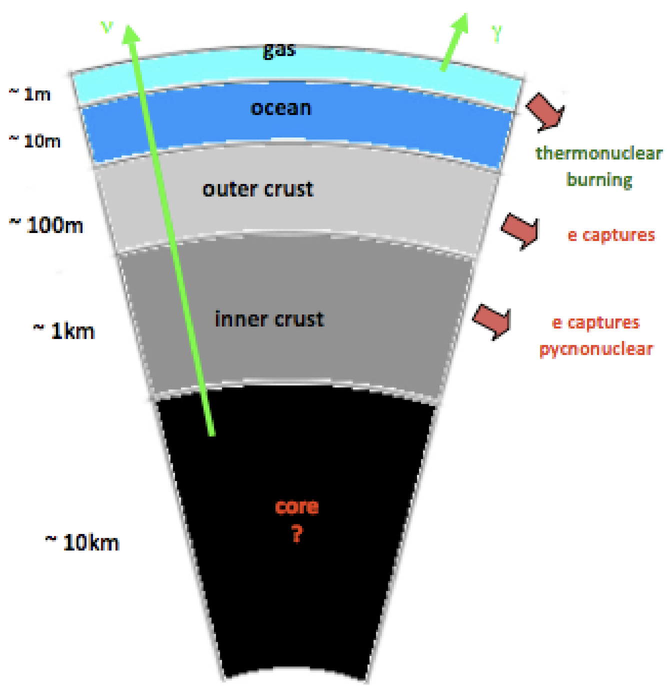

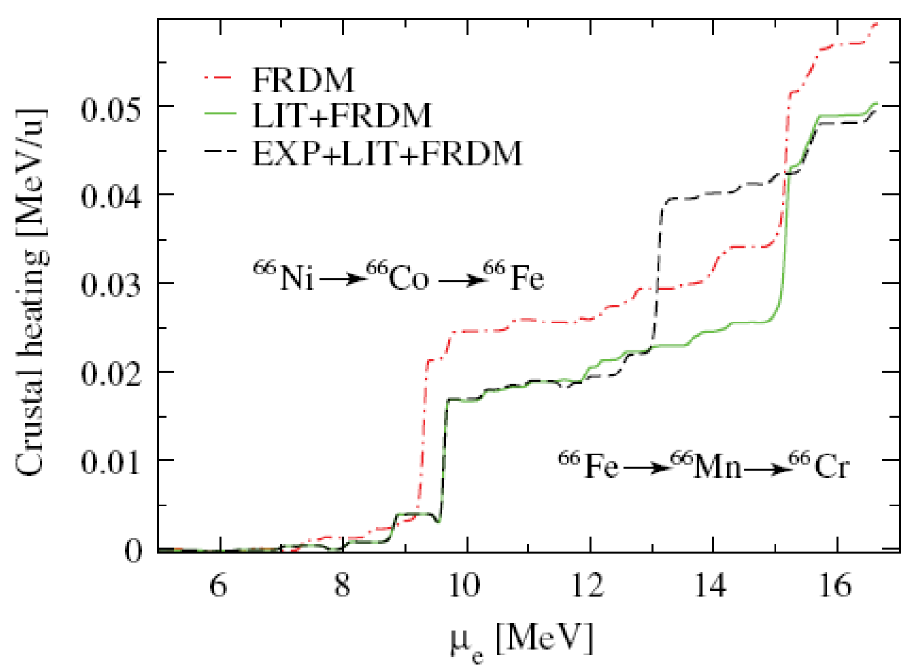

Workshop on
Thermonuclear Reaction Rates for Astrophysics Applications
24-25 November 2011, Athens, Greece

Acropolistic view of the mass surface
and the columns of nucleosynthesis

More mass data of better quality

N=50 shell for Z=30 + heavy Fr/Ra

Microscopic models with good predictions

Shell quenching phenomenon quenched ?

Neutron stars a promising *r*-process site ?

Are *x*-ray bursts a viable observable ?

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