Mass measurements for nuclear astrophysics

Lecture 1: introductory physics and methods

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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)

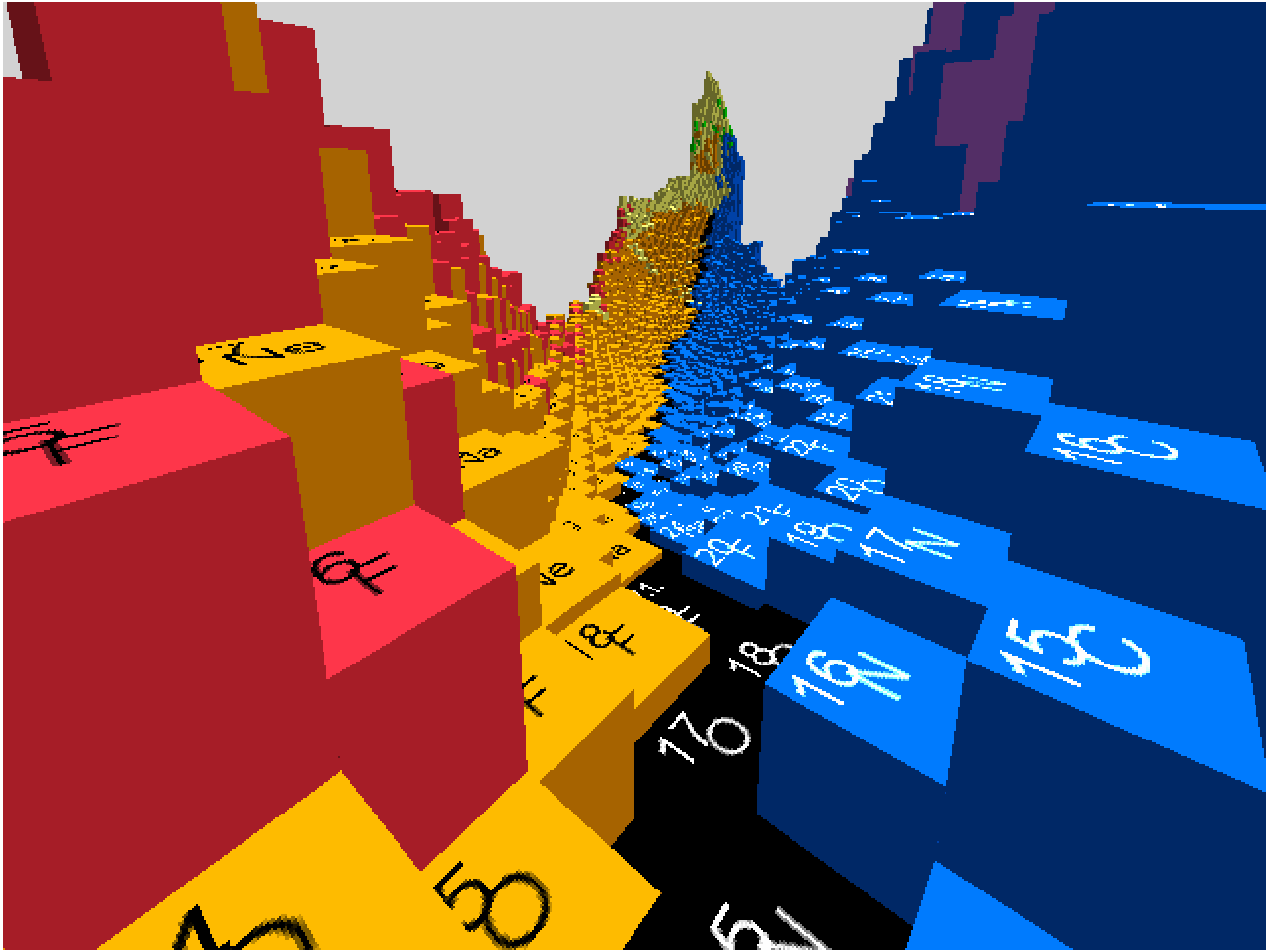
V. Comparisons of the different methods

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

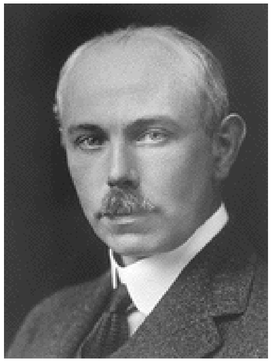


16N
15C
17N
17O
16C

Some introductory remarks on history

High resolution mass spectrographs

F.W.Aston (~1920's): 212 isotopes discovered
Packing fraction



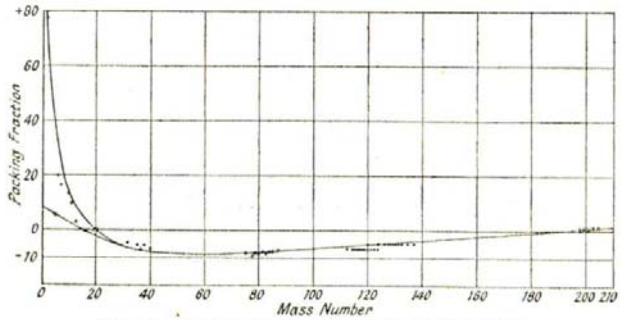
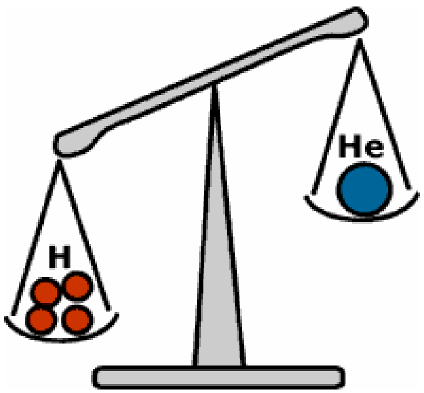


Fig. 20.—Aston's Original Packing Fraction Curve (1927).

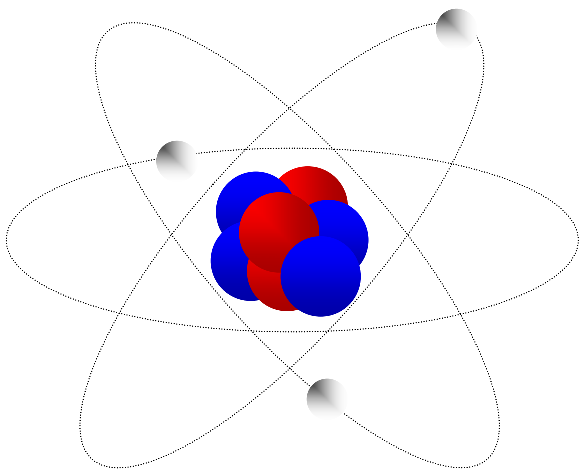
A. Eddington (~1920)
Stellar combustion



$$E = mc^2$$

How the sun shines,"
J. Bahcall
http://nobelprize.org/physics/

the atomic mass



$$Z \cdot m_p + N \cdot m_n$$

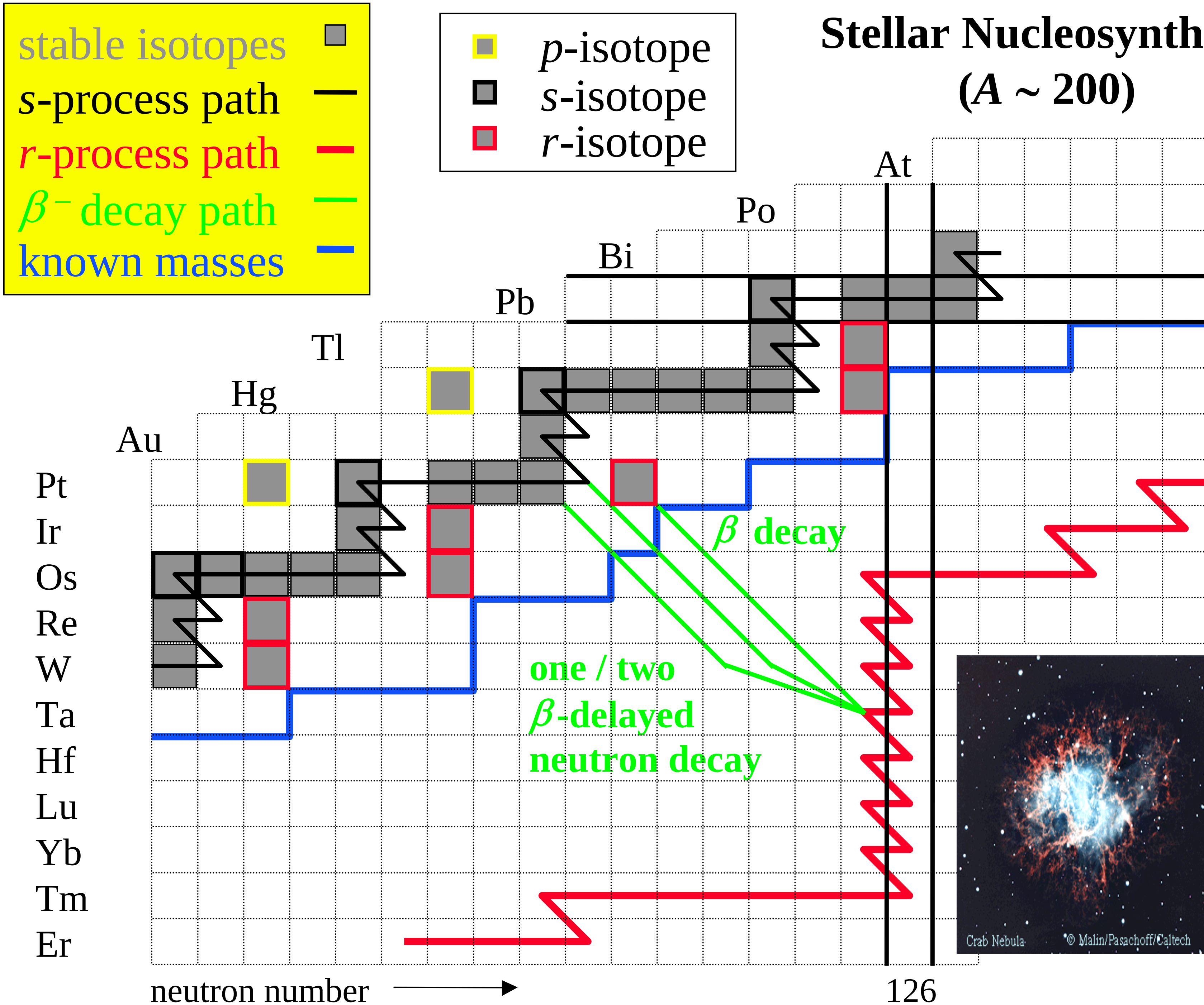
$$(+ Z \cdot m_e)$$

– BINDING ENERGY

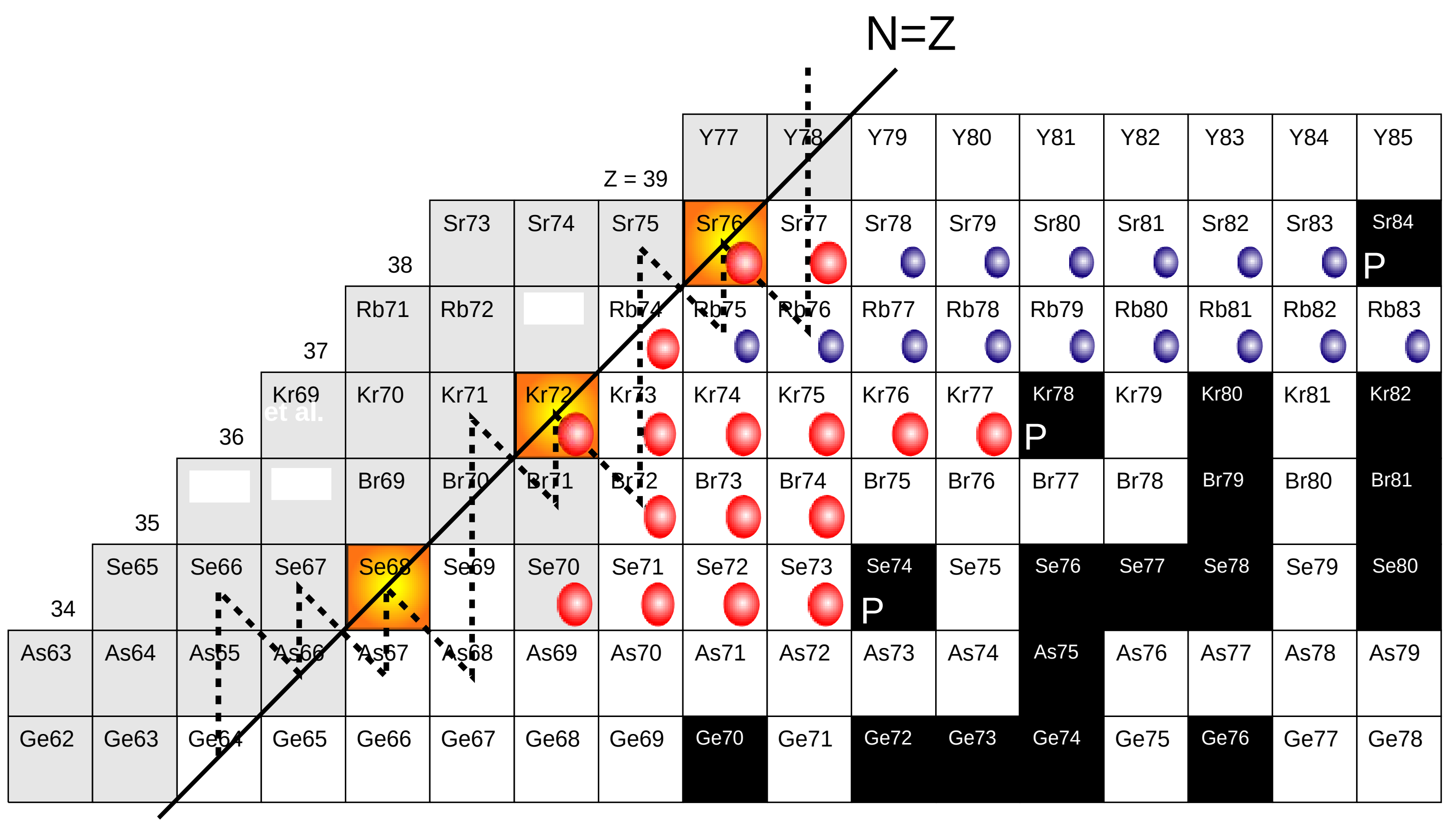
nuclear structure
(shells, shapes, halos)

nuclear astrophysics
(decay mode, reaction)

Stellar Nucleosynthesis
($A \sim 200$)



rapid proton-capture (rp) process



----- possible rp - process main path

(H. Schatz et al. Phys. Rep. 294 (1998) 167)

possible waiting points

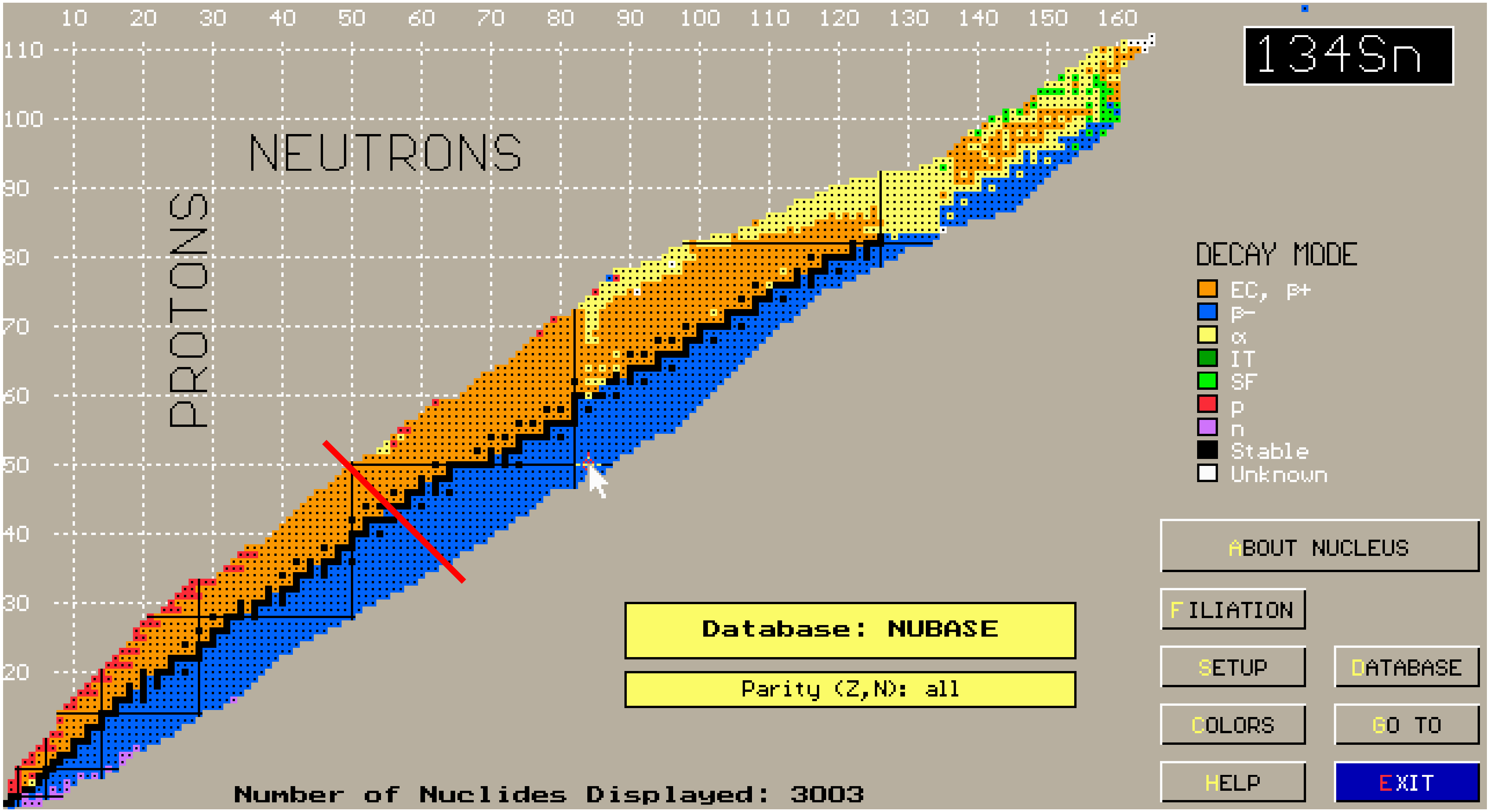
mass excess not yet measured

(AME95)

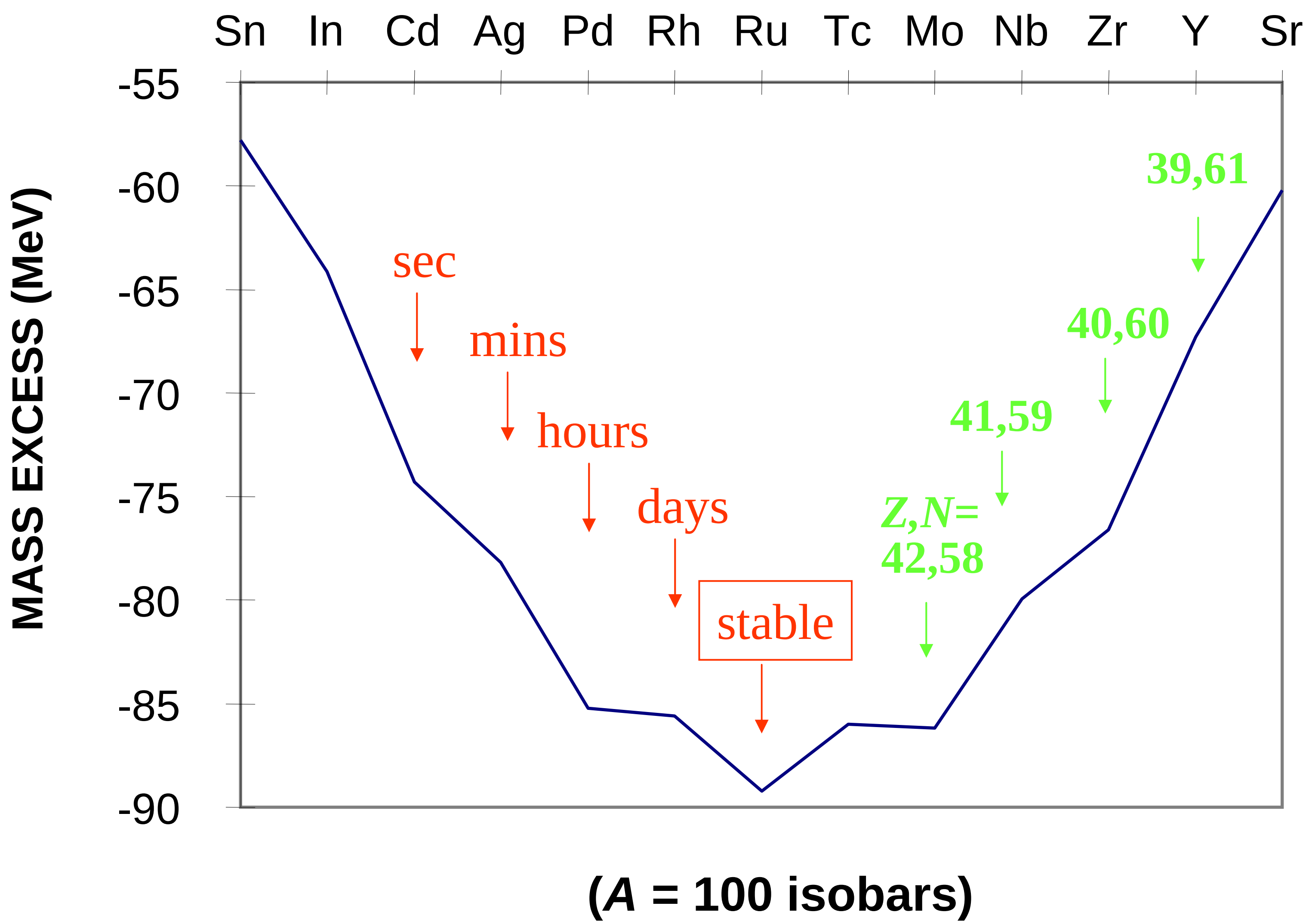
ISOLTRAP measurements

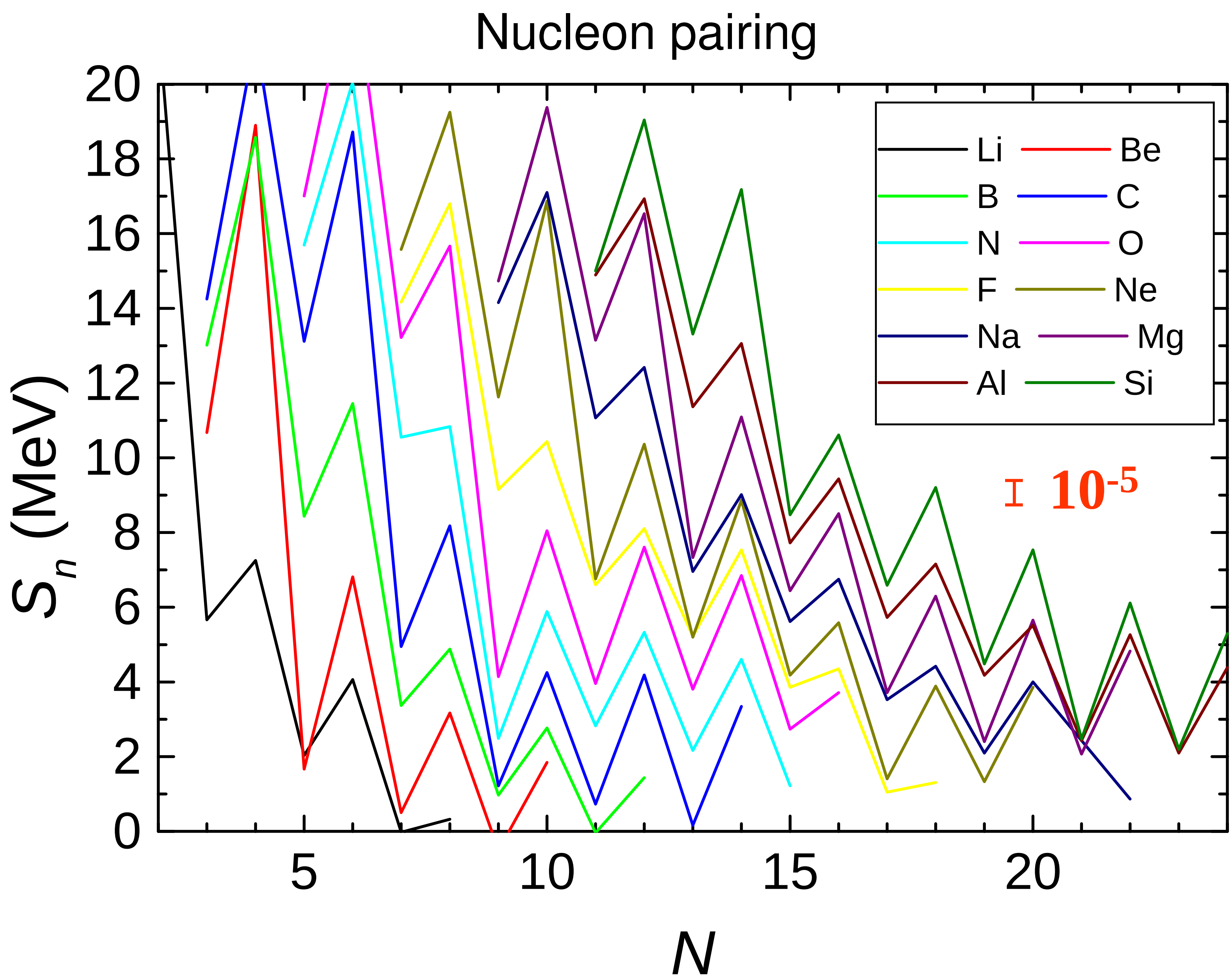
2000 - 2002

before 2000



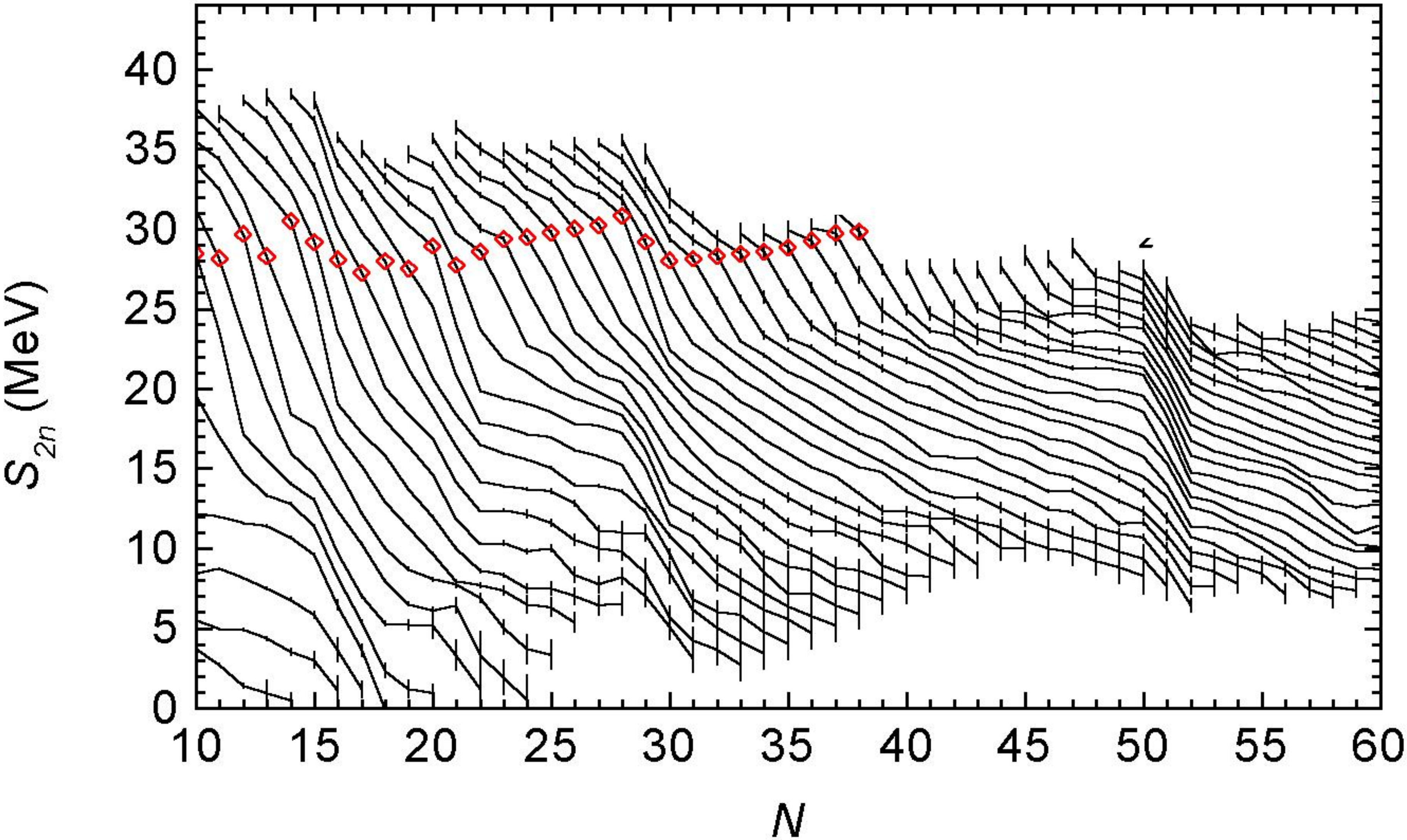
NEUTRONS
PROTONS
134Sn
DECAY MODE
EC, β+
β-
α
IT
SF
p
n
Stable
Unknown
ABOUT NUCLEUS
FILIATION
SETUP
DATABASE
COLORS
GO TO
HELP
EXIT
Database: NUBASE
Parity (Z,N): all
Number of Nuclides Displayed: 3003


Sn
In
Cd
Ag
Pd
Rh
Ru
Tc
Mo
Nb
Zr
Y
Sr
-55
-60
-65
-70
-75
-80
-85
-90
MASS EXCESS (MeV)
sec
mins
hours
days
stable
39,61
40,60
41,59
Z,N=
42,58
(A = 100 isobars)



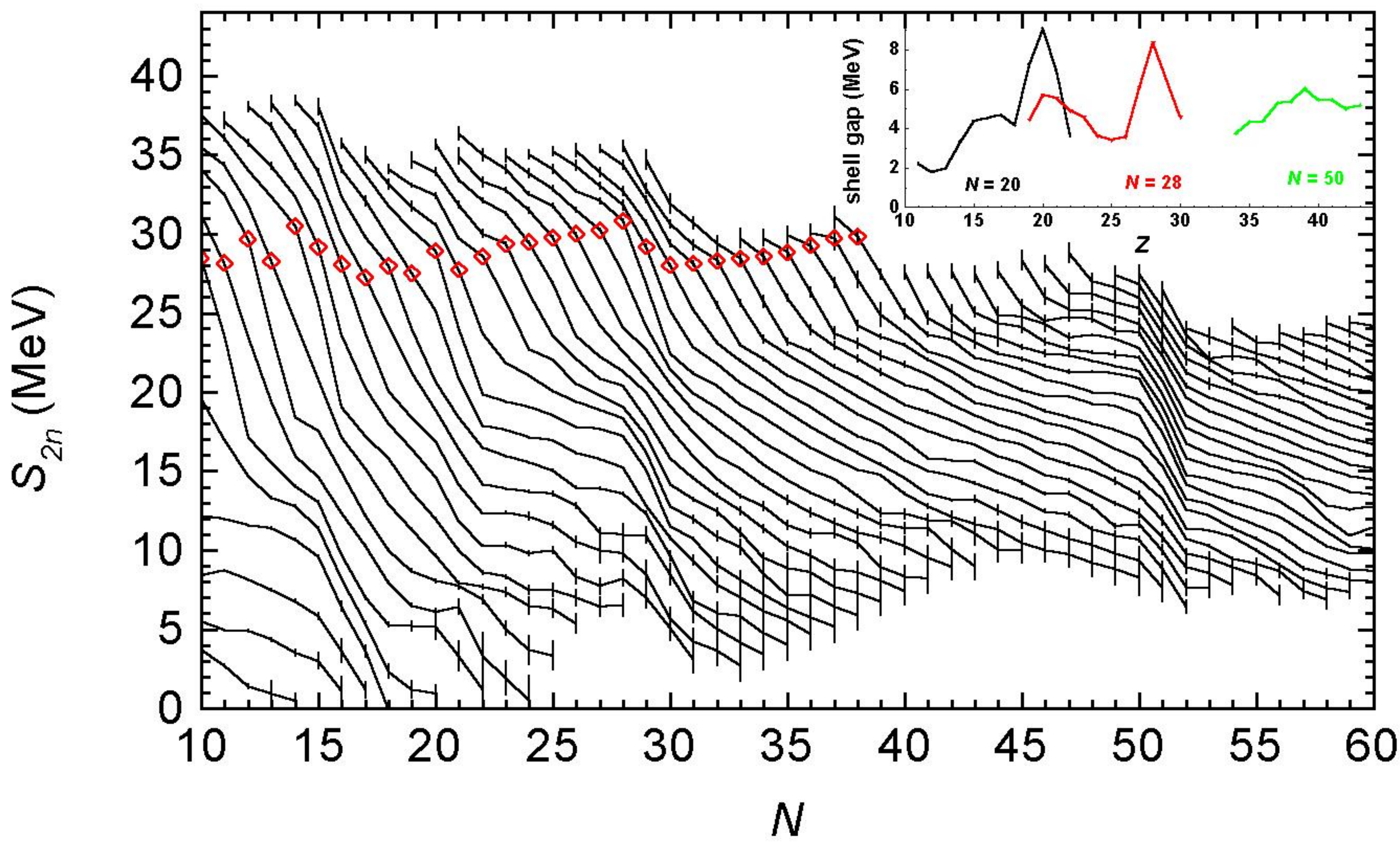
Nucleon pairing
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
S_n (MeV)
N
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
10^{-5}

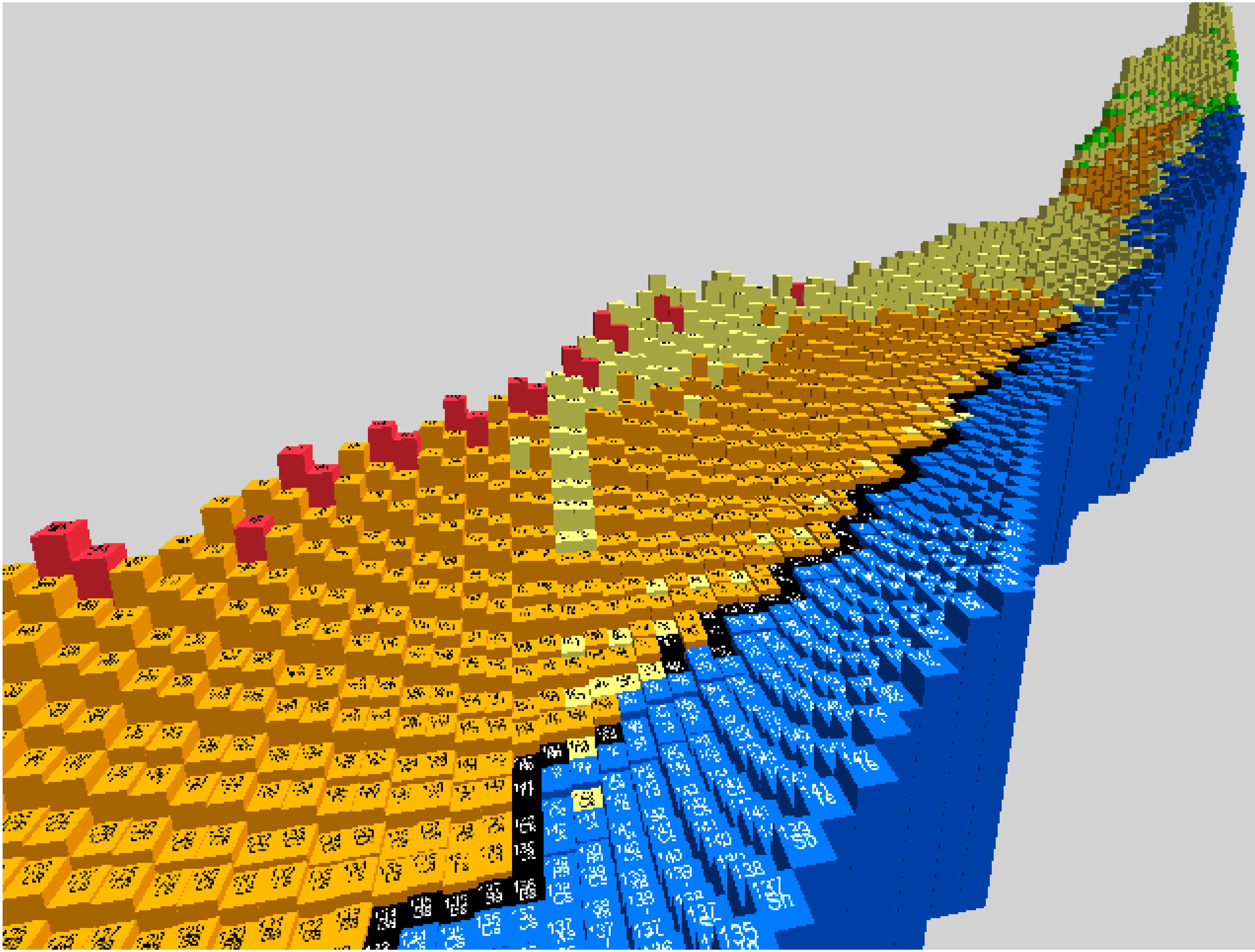
nuclear structure from the mass surface

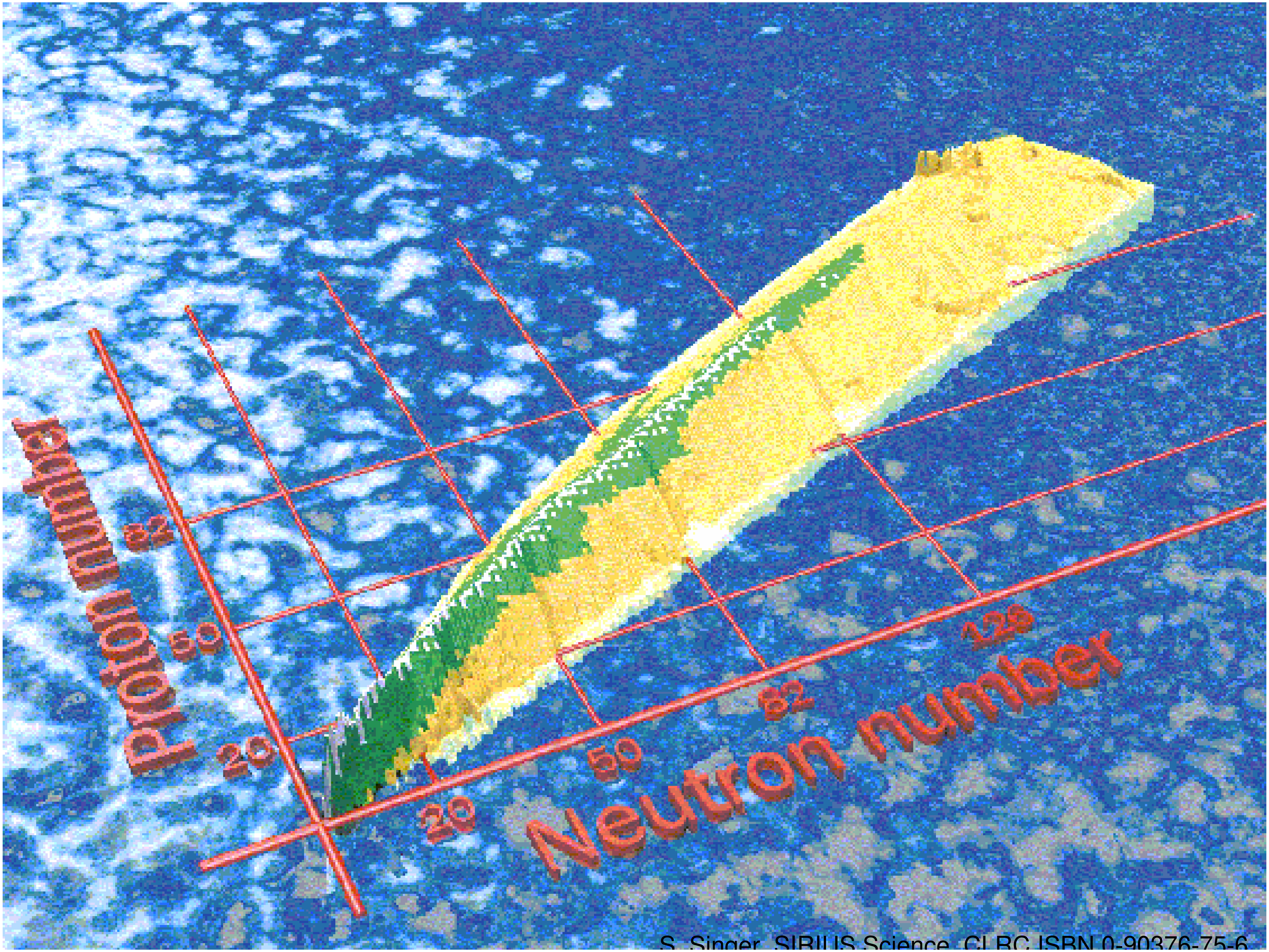


nuclear structure from the mass surface

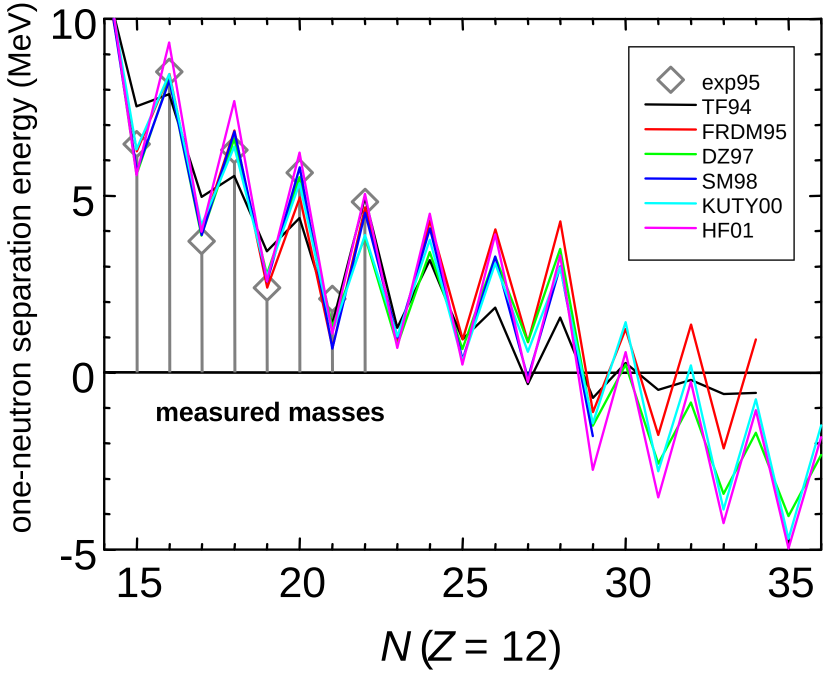
shell opening and magic number migration





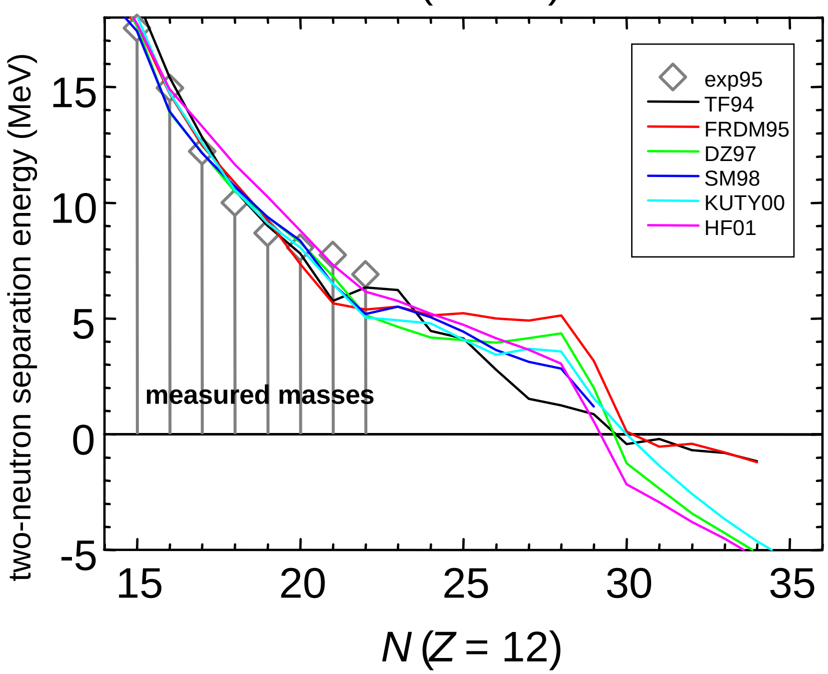


S. Singer, SIRIUS Science, CLRC ISBN 0-90376-75-6



one-neutron separation energy (MeV)
10
5
0
-5
15
20
25
30
35
N (Z = 12)
exp95
TF94
FRDM95
DZ97
SM98
KUTY00
HF01
measured masses

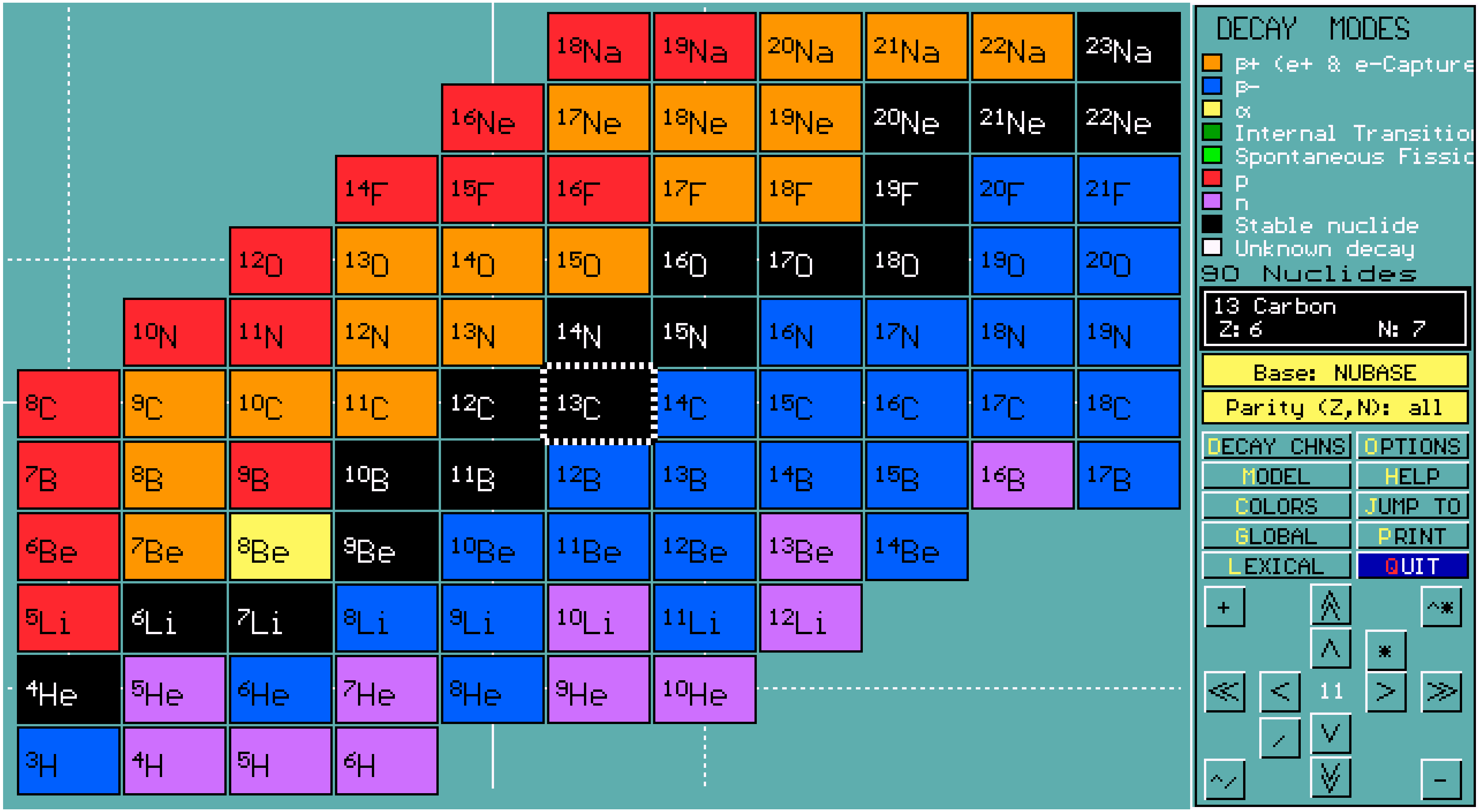
S_n



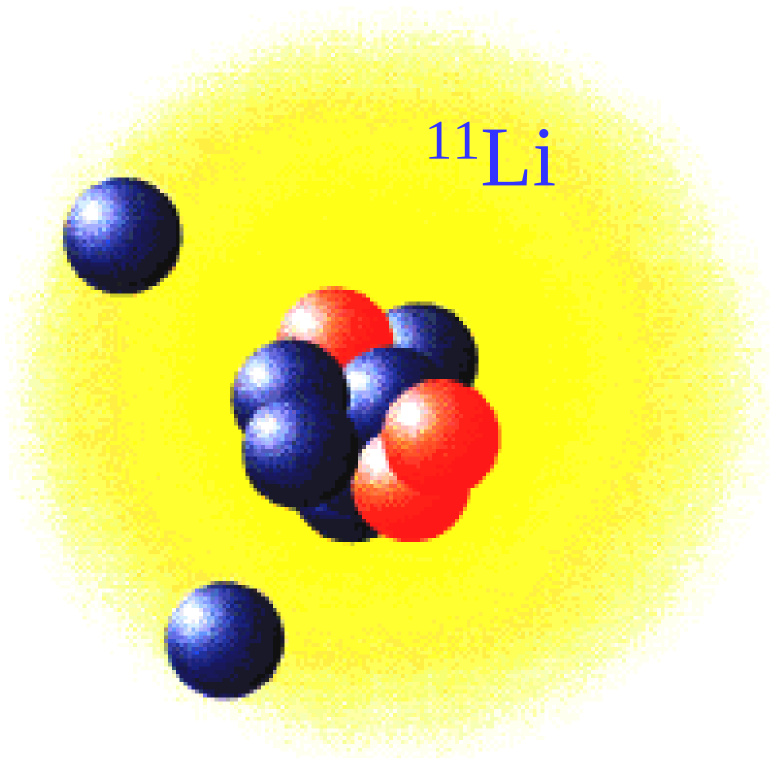
two-neutron separation energy (MeV)
15
10
5
0
-5
15
20
25
30
35
N (Z = 12)
exp95
TF94
FRDM95
DZ97
SM98
KUTY00
HF01
measured masses

S_{2n}

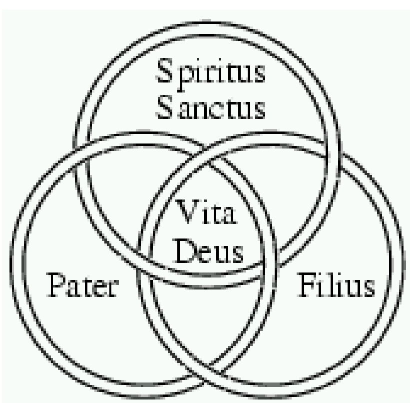
drip line phenomena - small binding energies



Superlarge nuclides



two-neutron halo



Borromean system

Simple, illustrative approach
(Hansen and Jonson, 1987)

$$\rho = \hbar/(2\mu S_{2n})^{1/2}$$

For 3-body models:
S_{2n} is ***input*** parameter

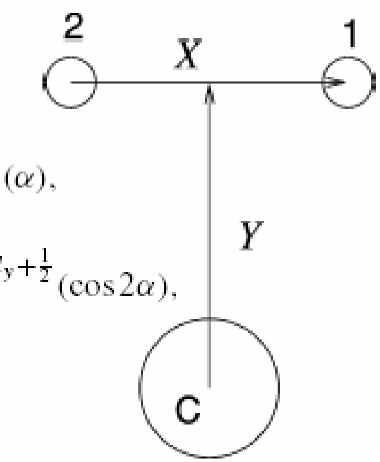


Fig. 1. The **T**-set of Jacobi coordinates.

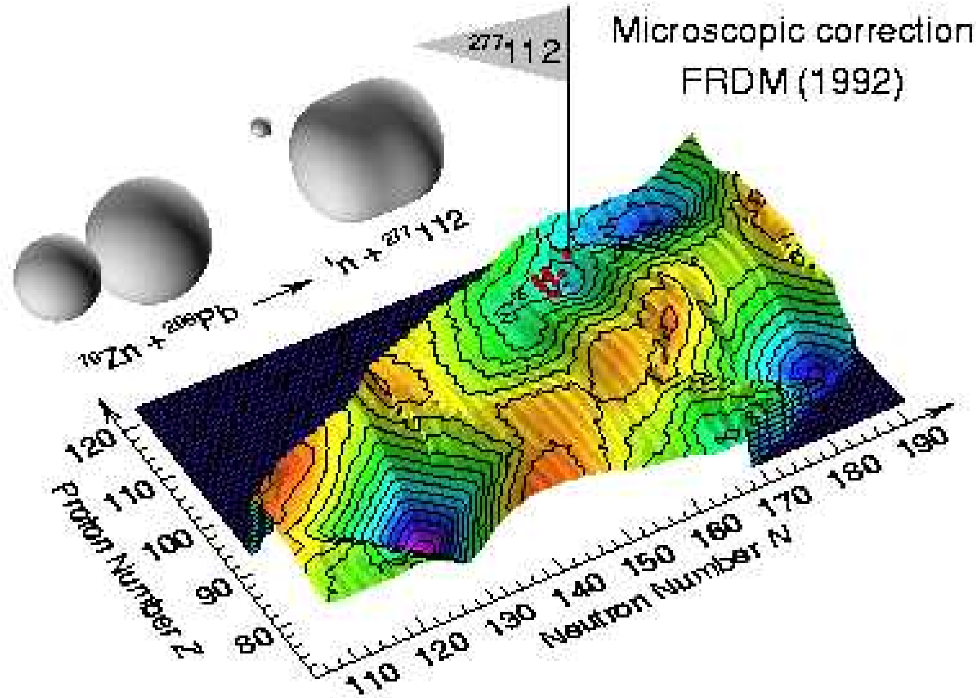
$$\psi_{l_x,l_y}^{LSjIJ}(x,y) = \rho^{-\frac{5}{2}} \sum_K \chi_{Kl_xl_y}^{LSjIJ}(\rho)\phi_K^{l_xl_y}(\alpha),$$

$$\phi_K^{l_xl_y}(\alpha) = N_K^{l_xl_y}(\sin\alpha)^{l_x}(\cos\alpha)^{l_y} P_n^{l_x+\frac{1}{2},l_y+\frac{1}{2}}(\cos 2\alpha),$$

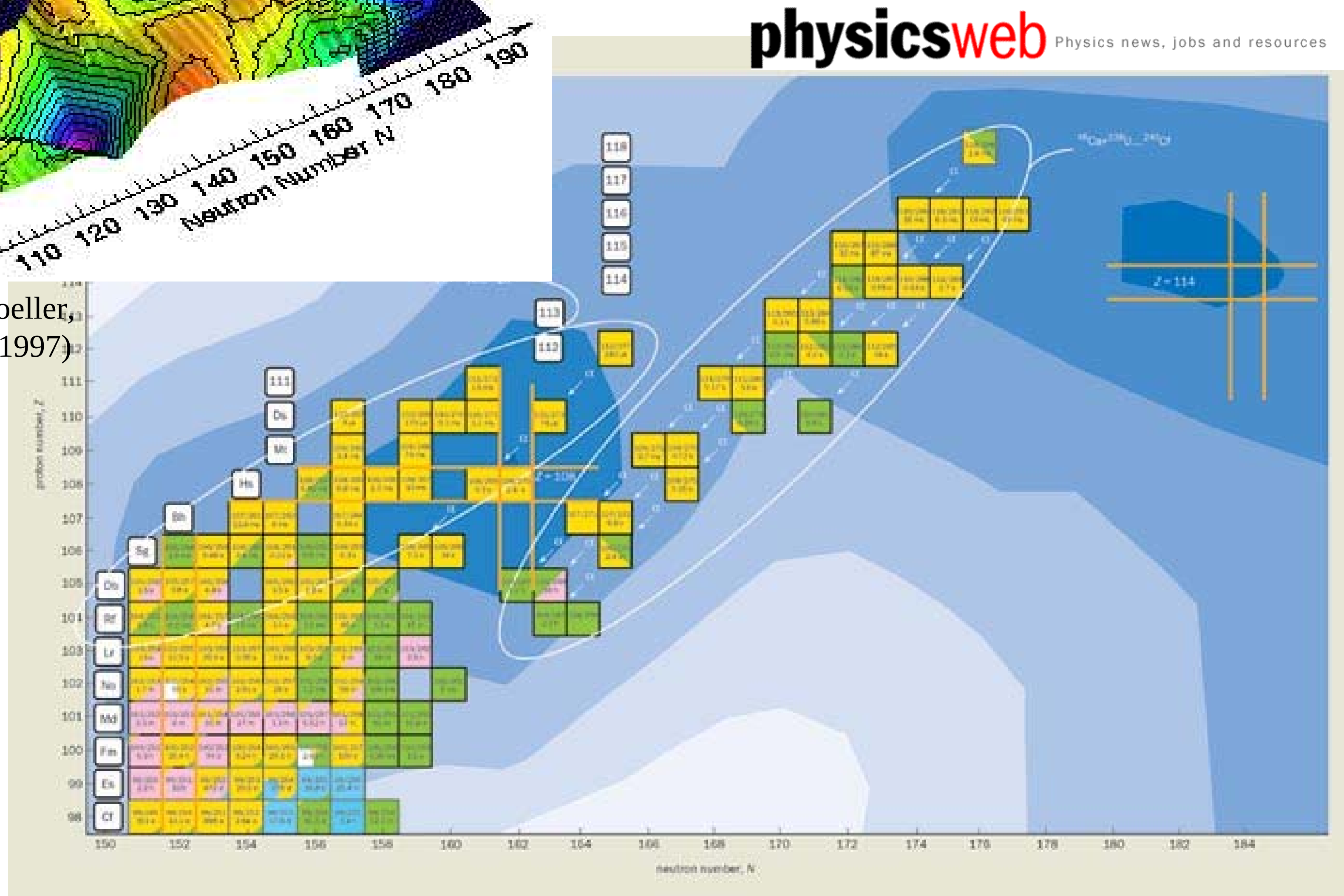
$$V_{nc}(r,\theta',\phi') = \frac{V_0}{1+e^{\frac{r-R(\theta',\phi')}{a}}} - 2\left(\frac{\hbar^2}{m_\pi c}\right)^2 \frac{V_{ls}}{r}\frac{d}{dr}\frac{1}{1+e^{\frac{r-R_{ws}}{a_{ws}}}}\mathbf{l}\cdot\mathbf{s}.$$

T. Tarutina et al. / Nuclear Physics A 733 (2004) 53–66

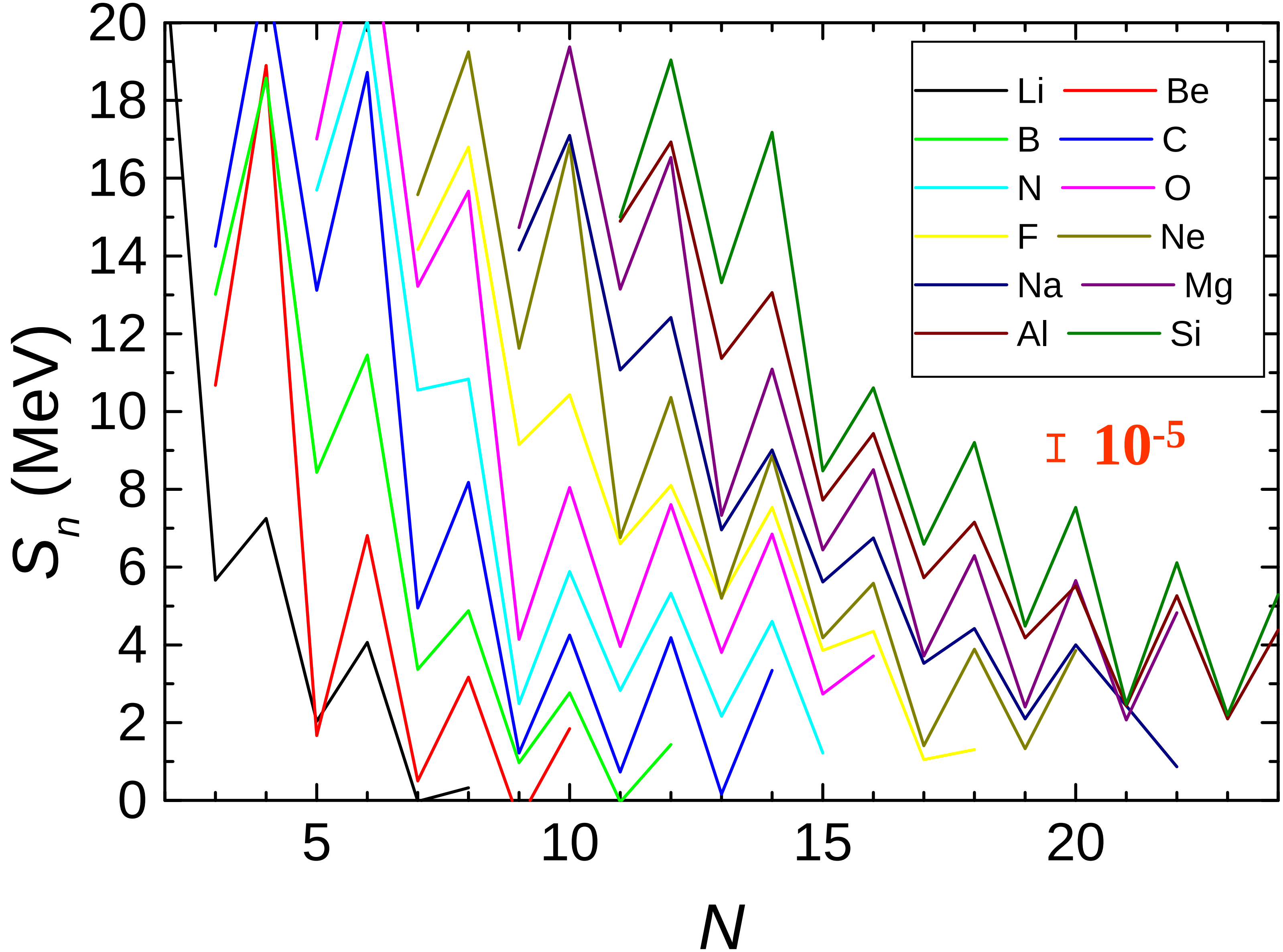
Superheavy Elements



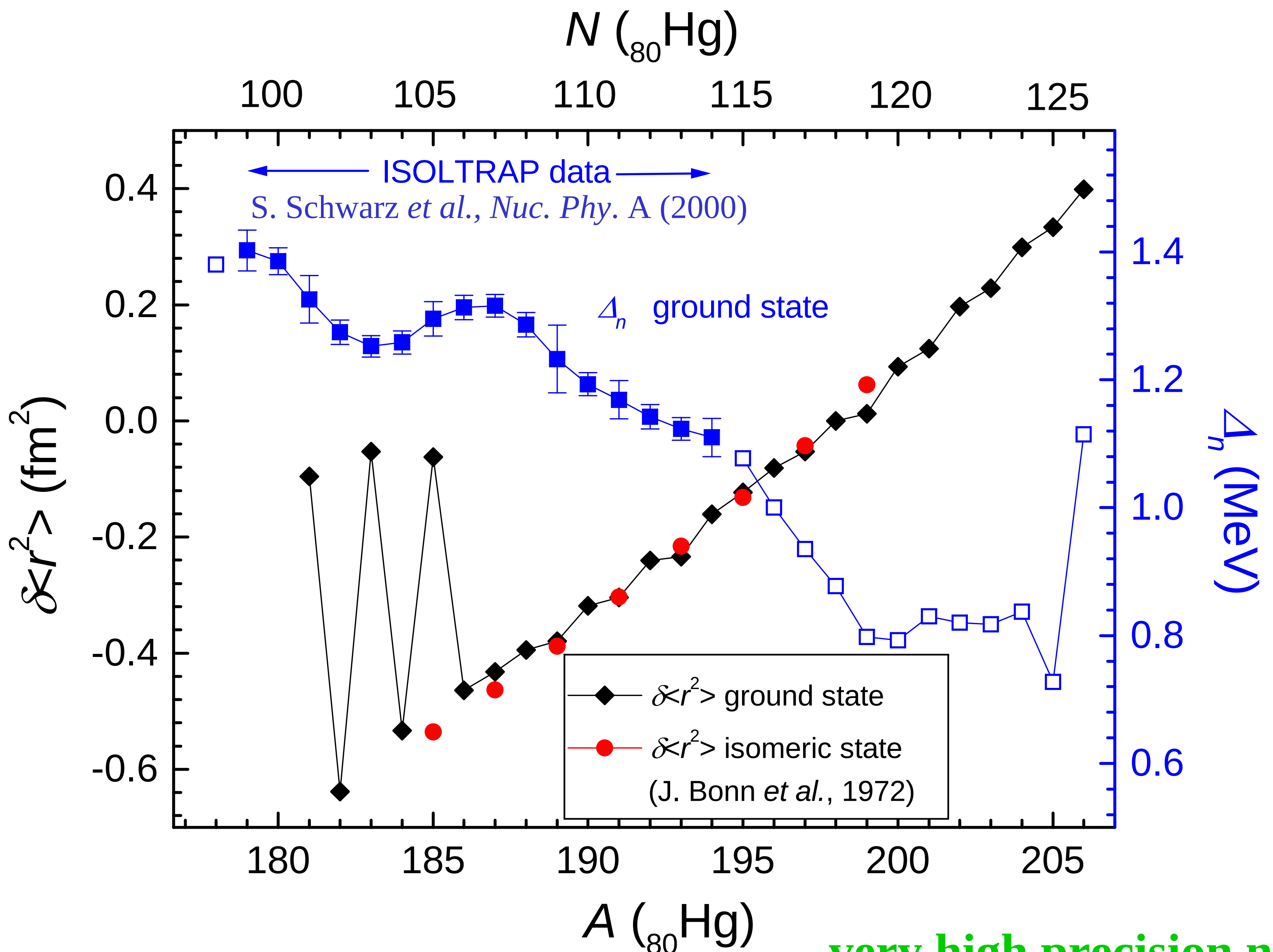
J.R. Nix and P. Moeller,
LA-UR-97-4220 (1997)



Nucleon pairing



pairing energy... $\Delta^{(3)}(N) = \frac{(-1)^N}{2}\left[B(N-1) + B(N+1) - 2B(N)\right]$

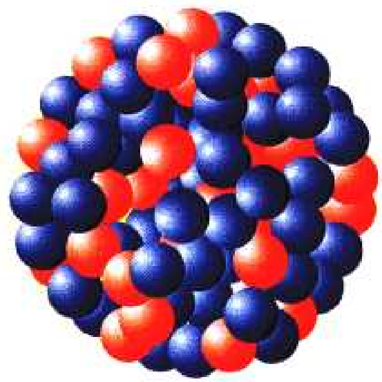


...very high precision needed

Hancock bldg
(344 m high)

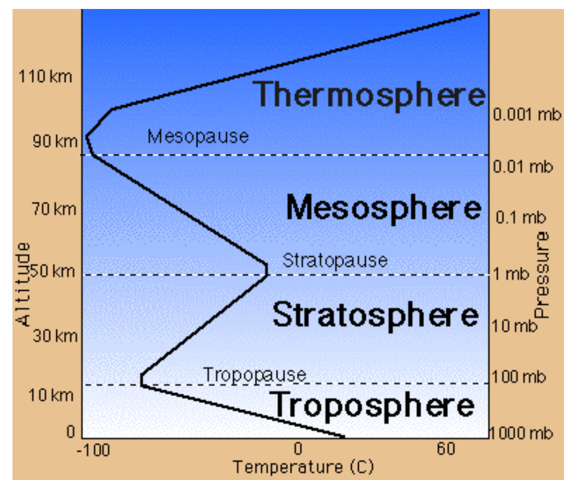
Earth's radius: 6000 km

Shell gap of
^{132}Sn ~ 6 MeV

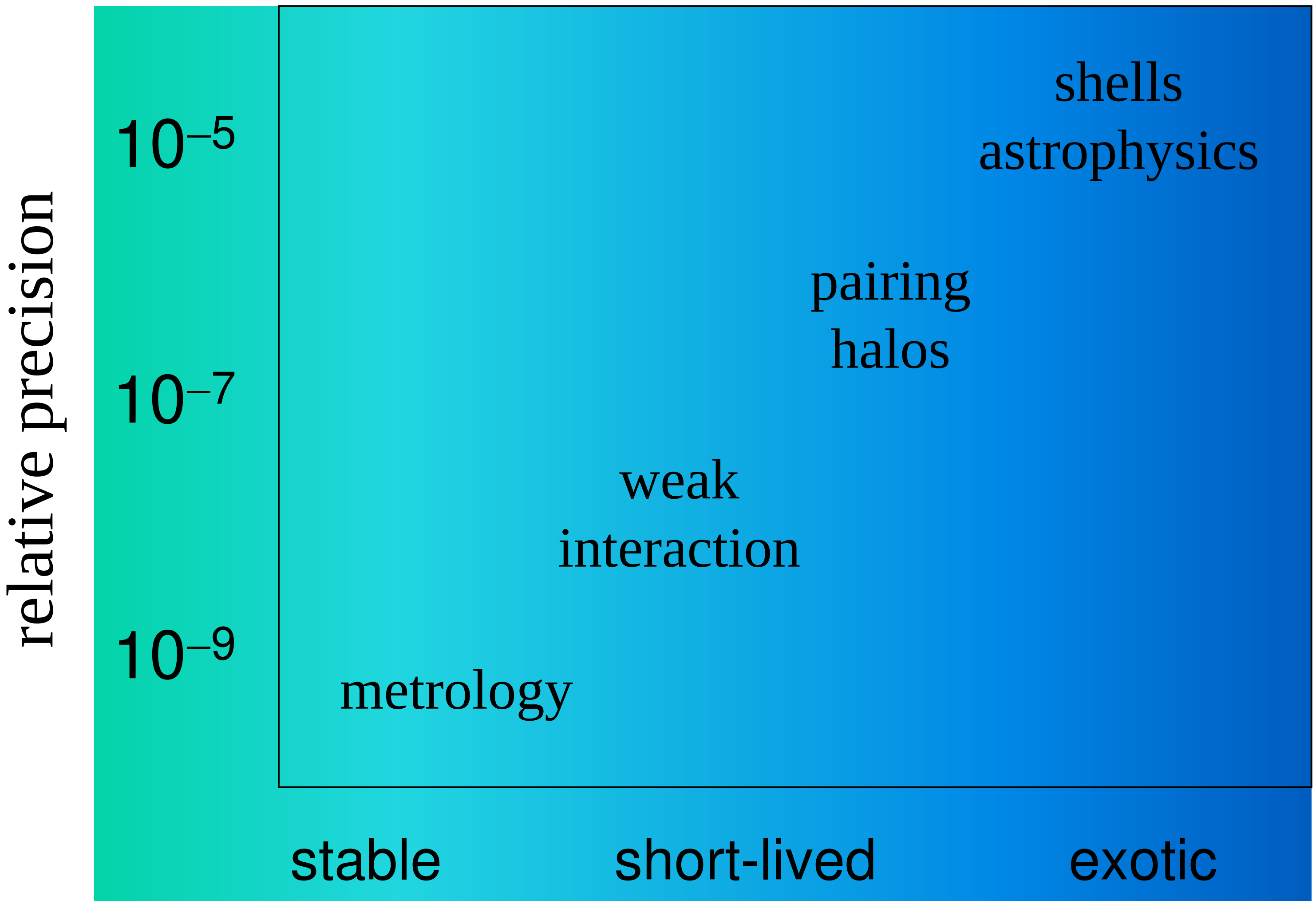


Binding Energy
of ^{132}Sn ~ 1 GeV

Pairing gap: 1 MeV



mass measurements:
what you want - what you need



NATURE|Vol 438|22/29 December 2005

WORLD YEAR OF PHYSICS

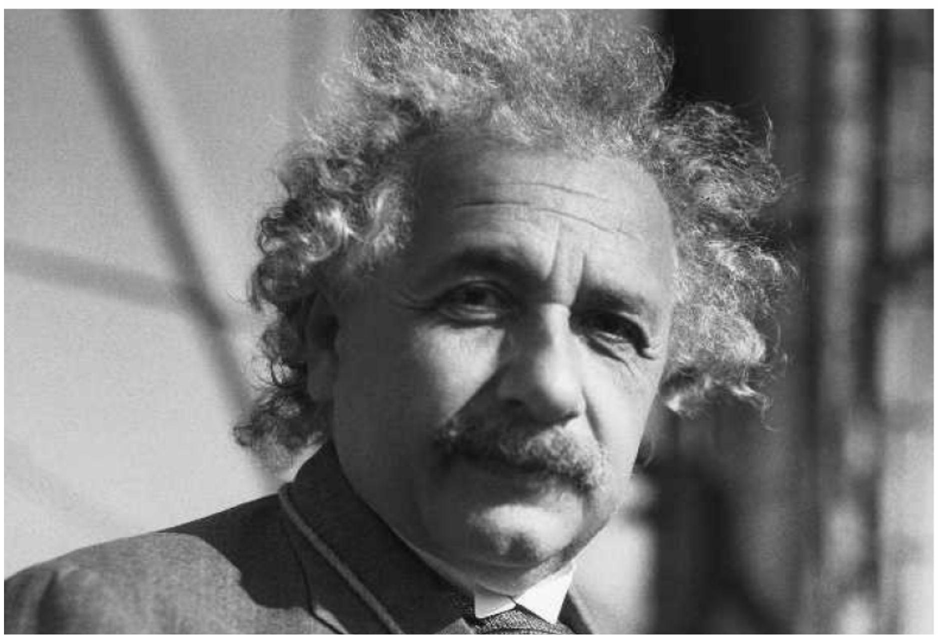
A direct test of $E = mc^2$

One of the most striking predictions of Einstein's special theory of relativity is also perhaps the best known formula in all of science: $E = mc^2$. If this equation were found to be even slightly incorrect, the impact would be enormous — given the degree to which special relativity is woven into the theoretical fabric of modern physics and into everyday applications such as global positioning systems. Here we test this mass–energy relationship directly by combining very accurate measurements of atomic-mass difference, Δm, and of γ-ray wavelengths to determine E, the nuclear binding energy, for isotopes of silicon and sulphur. Einstein's relationship is separately confirmed in two tests, which yield a combined result of $1 - \Delta mc^2/E = (-1.4 \pm 4.4) \times 10^{-7}$, indicating that it holds to a level of at least 0.00004%. To our knowledge, this is the most precise direct test of the famous equation yet described.

Our direct test is based on the prediction that when a nucleus captures a neutron and emits a γ-ray, the mass difference Δm between the initial (including unbound neutron) and final nuclear states, multiplied by c^2 (where c is the speed of light), should equal the energy of the emitted γ-ray(s), as determined from Planck's relation $E = hf$ (where h is Planck's constant and f is frequency).

The total energy of the γ-rays emitted as
the daug
decays t
state wa
by sumn
vidual γ
These w
by wave
suremen
Bragg s
The ma
Δm is r
simultan
isons of
frequenc
proporti
mass) o
initial a
topes co
period c
Penning trap.

BETTMANN/CORBIS



Simon Rainville[*†], James K. Thompson[*], Edmund G. Myers[‡], John M. Brown[§], Maynard S. Dewey[||], Ernest G. Kessler Jr[||], Richard D. Deslattes[||], Hans G. Börner[¶], Michael Jentschel[¶], Paolo Mutti[¶], David E. Pritchard[*]

[*]Research Laboratory of Electronics, MIT-Harvard Center for Ultracold Atoms, and
[||]National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
[¶]Institut Laue-Langevin, 38042 Grenoble Cedex,

undergoing this nuclear reaction, the comparison is expressed in terms of measured quantities as

$$\Delta Mc^2 = (M[^{A}X] - M[^{A+1}X] + M[D] - M[H])c^2 = 10^3 N_A h (f_{A+1} - f_D) \text{ mol AMU kg}^{-1} \quad (1)$$

where the Avogadro constant N_A relates the measured mass $M[X]$ in unified atomic mass units (AMU) to its mass in kilograms $m[X]$. We made comparisons for $^{A+1}X = {}^{29}Si$ and $^{A+1}X = {}^{33}S$. The mass of the neutron $M[n]$ is determined from the masses[1] of hydrogen $M[H]$ and deuterium $M[D]$ combined with f_D, the frequency of the γ-ray corresponding to the deuteron binding energy[2]. The molar Planck constant is $N_A h = 3.990312716(27) \times 10^{-10}$ J s mol^{-1}; numbers in parentheses indicate uncertainty on the last digits. This figure has been independently confirmed at about the 5×10^{-8}

Because the diffraction angle for a 5-MeV

Motivation from "fundamental" physics

metrology:

the kilogram: ^{28}Si atomic mass standard
and other fundamental constants
(what if they vary with time?!)

NATURE 2589—26/5/2004—VBICKNELL—104661

A precision measurement of the mass of the top quark

DØ Collaboration*

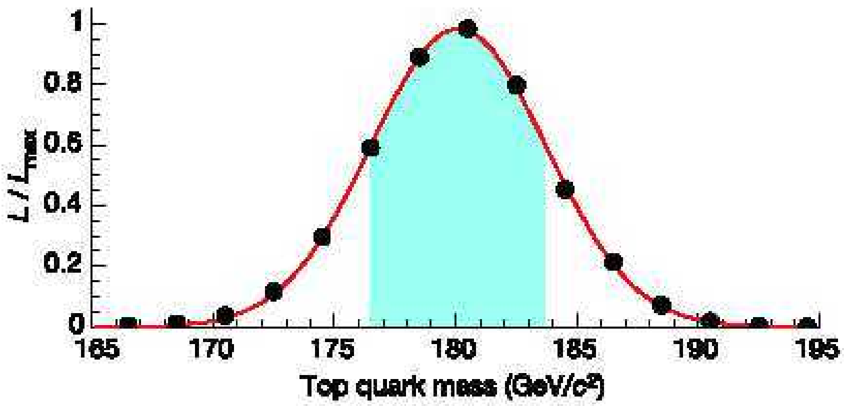


Figure 4 Determination of the mass of the top quark using the maximum-likelihood
corresponds to a mass of 180.1 GeV/c^2, which is the new DØ measurement of M_t
$\pm$3.6 GeV/c^2 statistical uncertainty of the fit.

NATURE | doi:10.1038/nature02589 | www.nature.com/nature

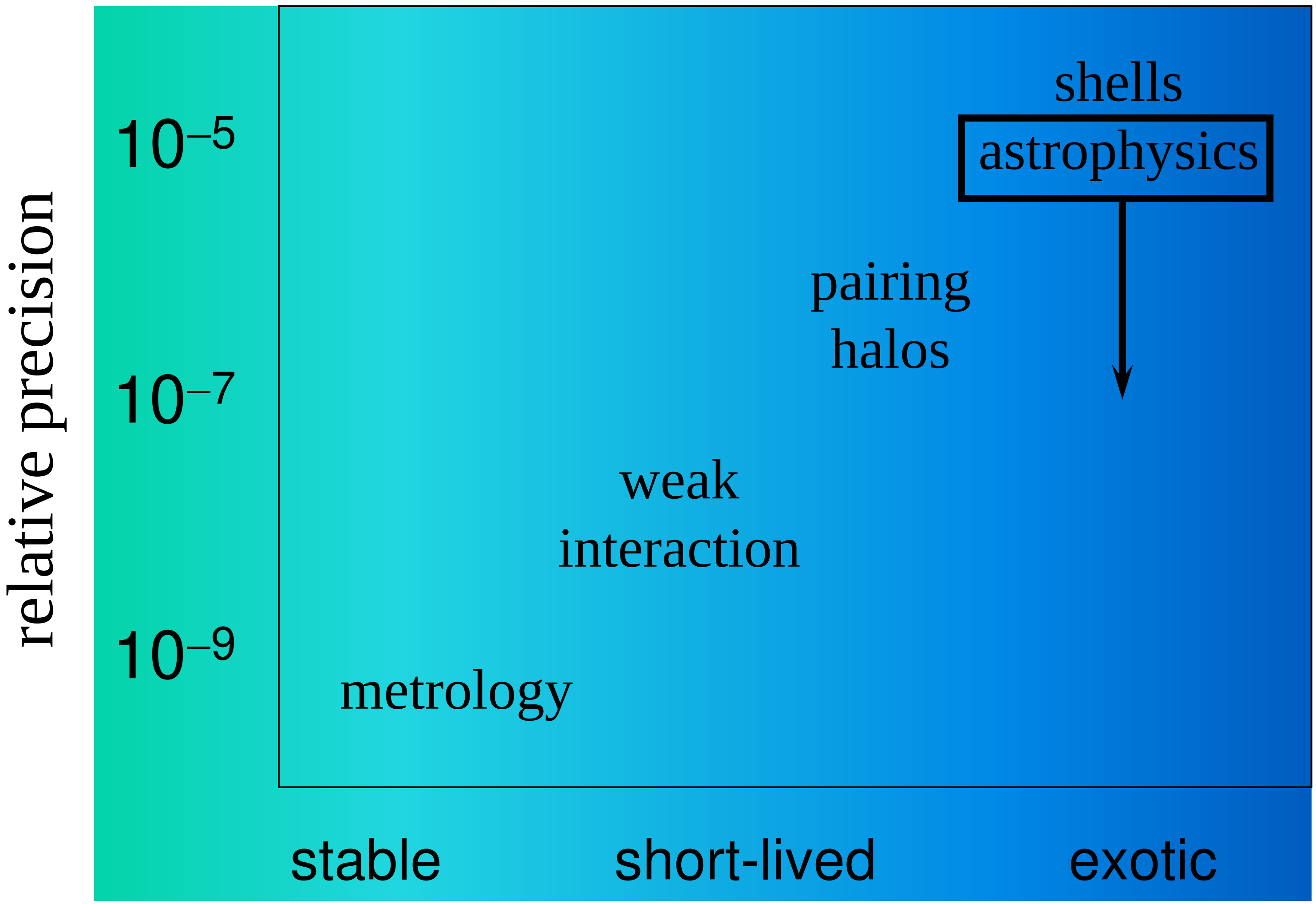
What does a relative uncertainty of 10^{-8} mean?

weight (empty): 164000 kg

contact lenses?

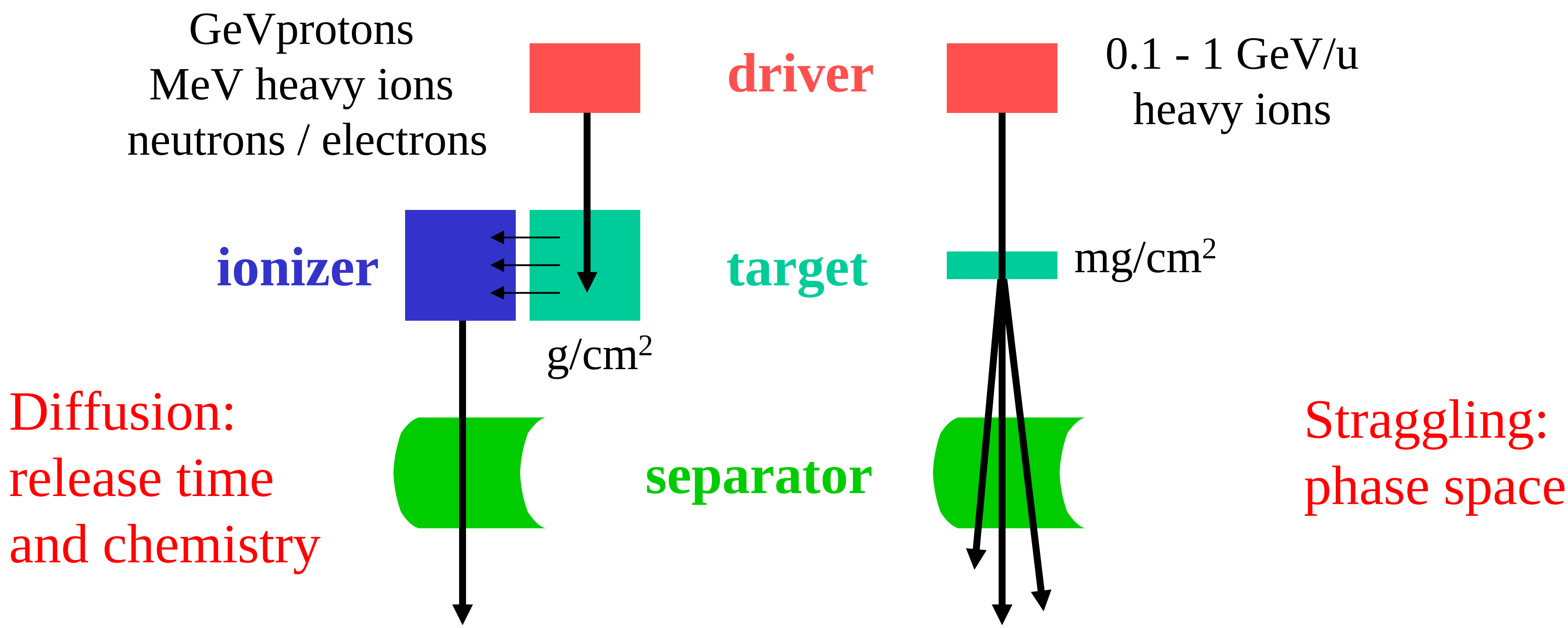
mass measurements:

what you want - what you need



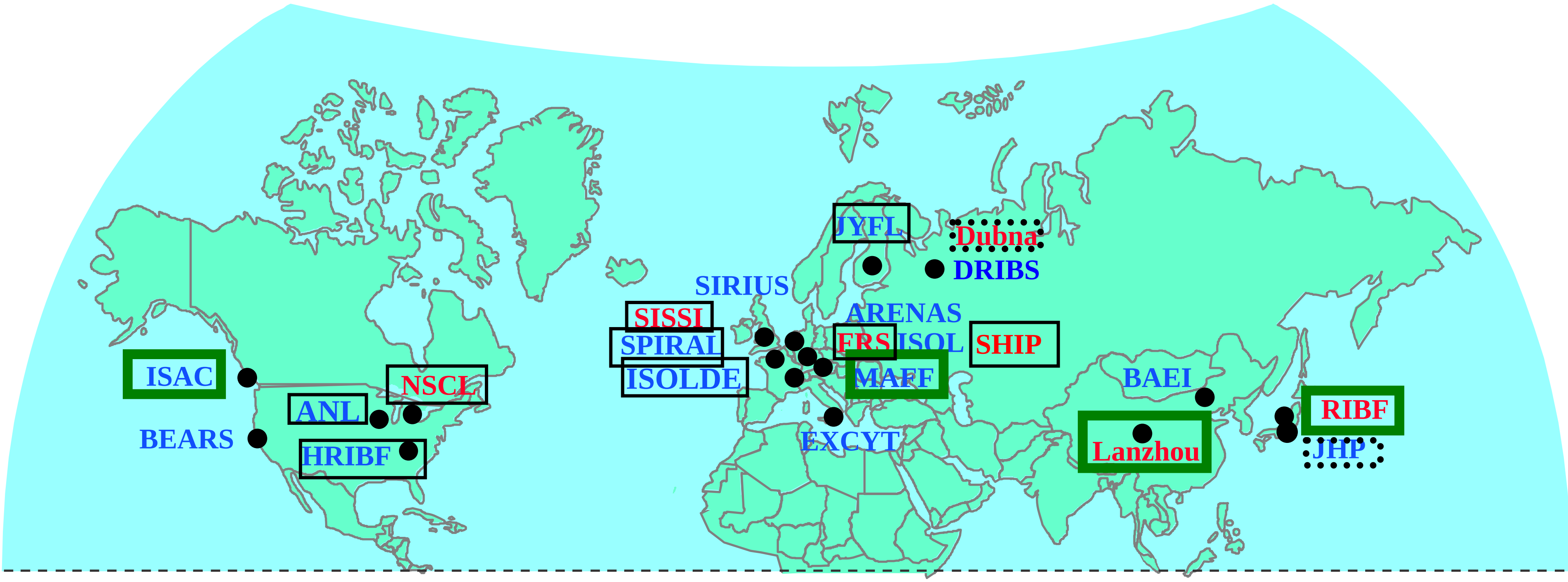
Production (and separation) techniques for exotic nuclides

Isotope Separation On-Line (ISOL)	Fragmentation In-Flight Separation (FIFS)



10-100 keV	0.1-1 GeV
good beam quality	short lived / unbound
(charge-breeding) post-acceleration	deceleration or stopping

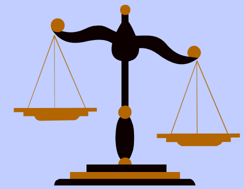
worldwide radioactive ion beam facilities



ISOL thick-target facilities in-flight separation facilities

MASS MEASUREMENTS (NEAR) FUTURE

Techniques

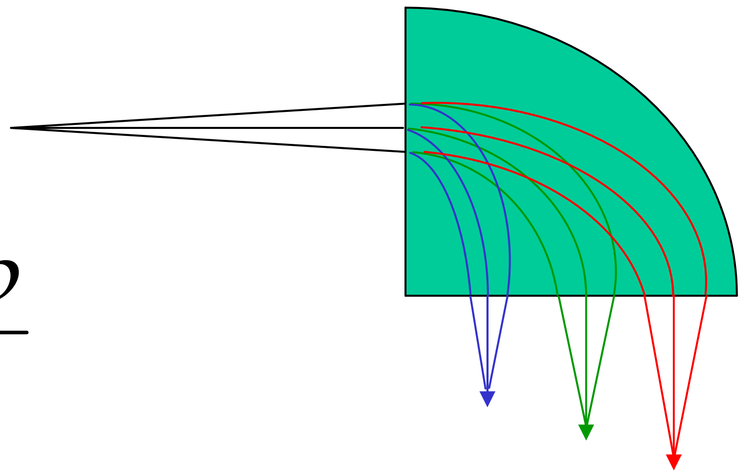


Indirect *(energy)*	*Direct* *(mass spectrometry)*	*PRODUCTION SCHEME*
reactions: $A(a,b)B$ $Q = M_A + M_a - M_b - M_B$	time of flight: $TOF = (m/q)\ (L/B\rho)$	FIFS (MeV)
decays: $A \rightarrow B + \alpha$ $Q_\alpha = M_B - M_A$	cyclotron frequency: $f_c = qB/m$	ISOL (keV)

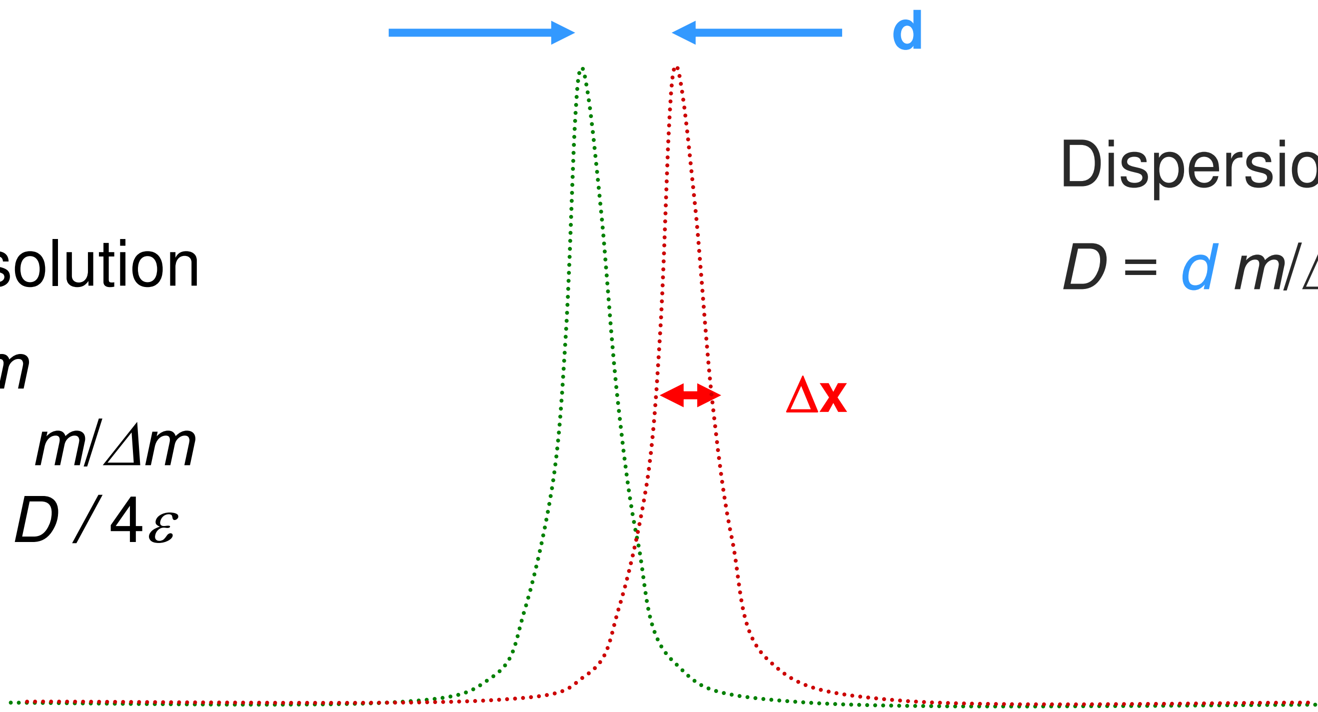
better sensitivity ↑

better precision ↓

$$\frac{m}{q} = \frac{B\rho}{v}$$



Mass separator
-spectroscope
-spectrograph
-spectrometer



Dispersion

$D = d\ m/\Delta m$

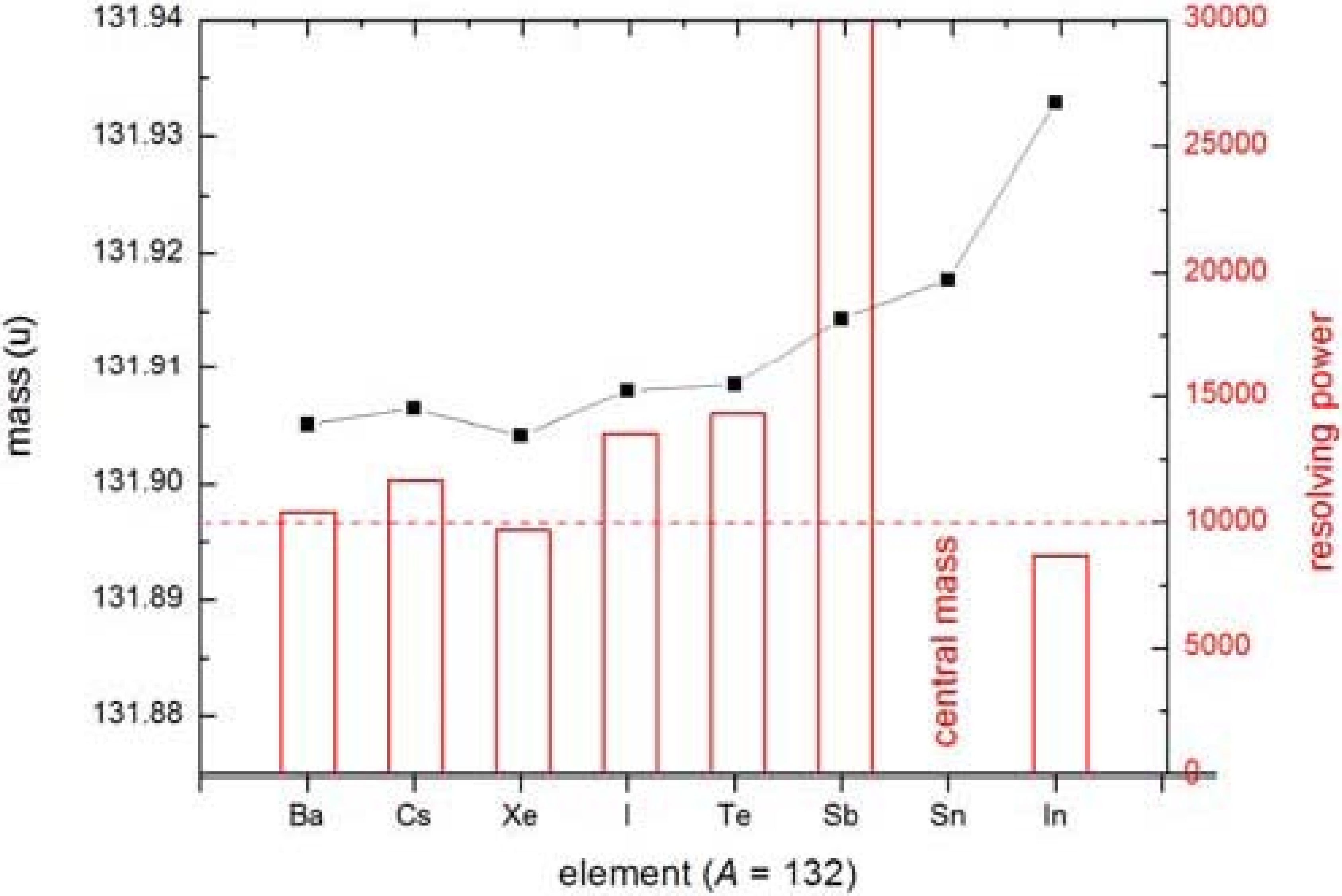
Mass Resolution

$R = m/\Delta m$

$= d/\Delta x \ \ m/\Delta m$

$= \pi\,\Delta a\, D\,/\,4\varepsilon$

high resolution *necessary but not sufficient* for high precision

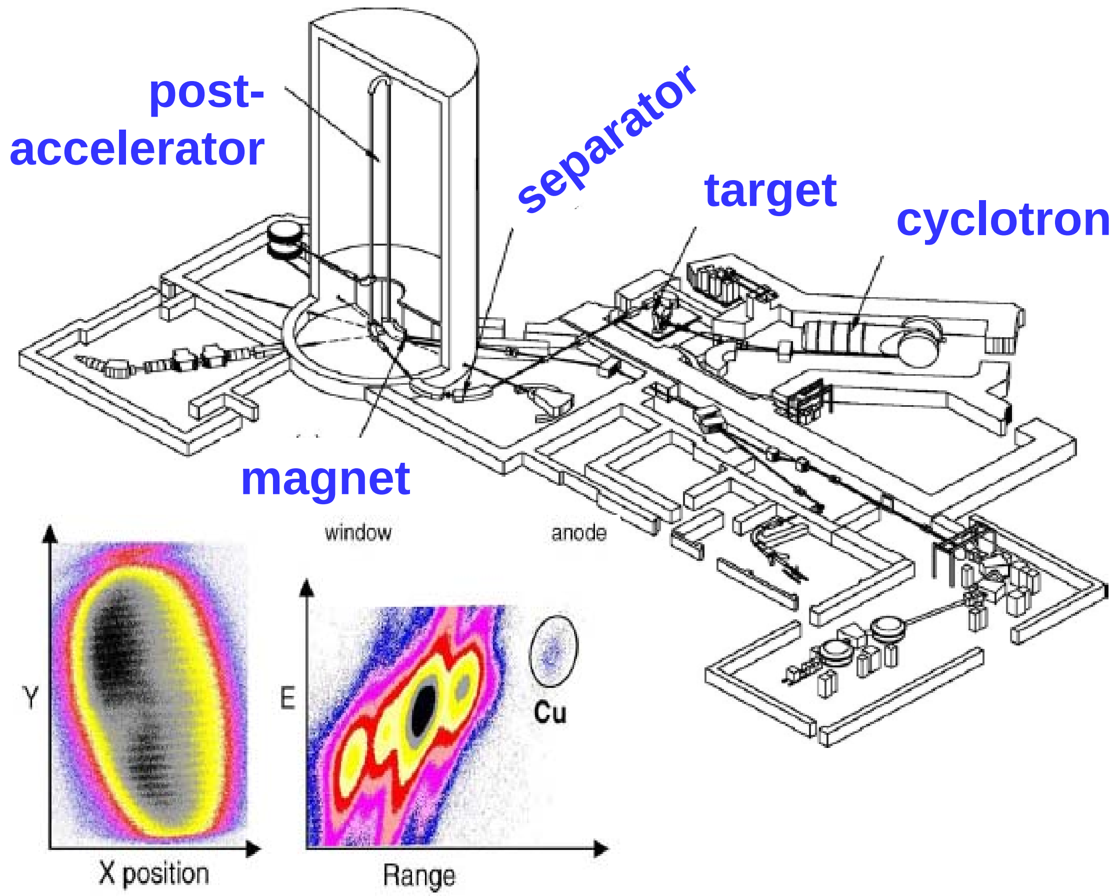


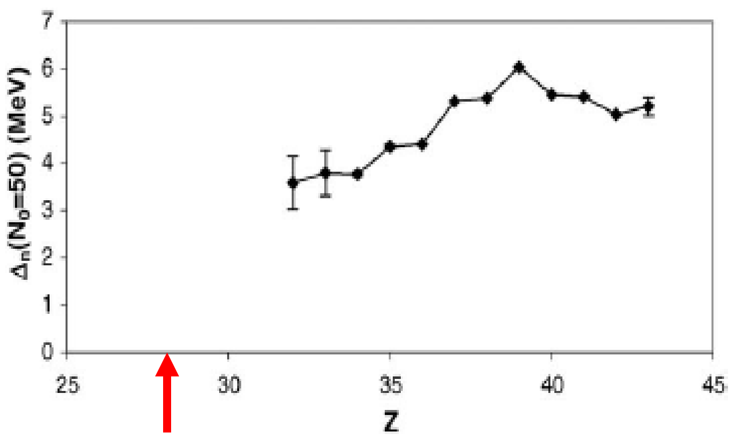
131.94
131.93
131.92
131.91
131.90
131.89
131.88
mass (u)
30000
25000
20000
15000
10000
5000
0
resolving power
central mass
Ba
Cs
Xe
I
Te
Sb
Sn
In
element (A = 132)

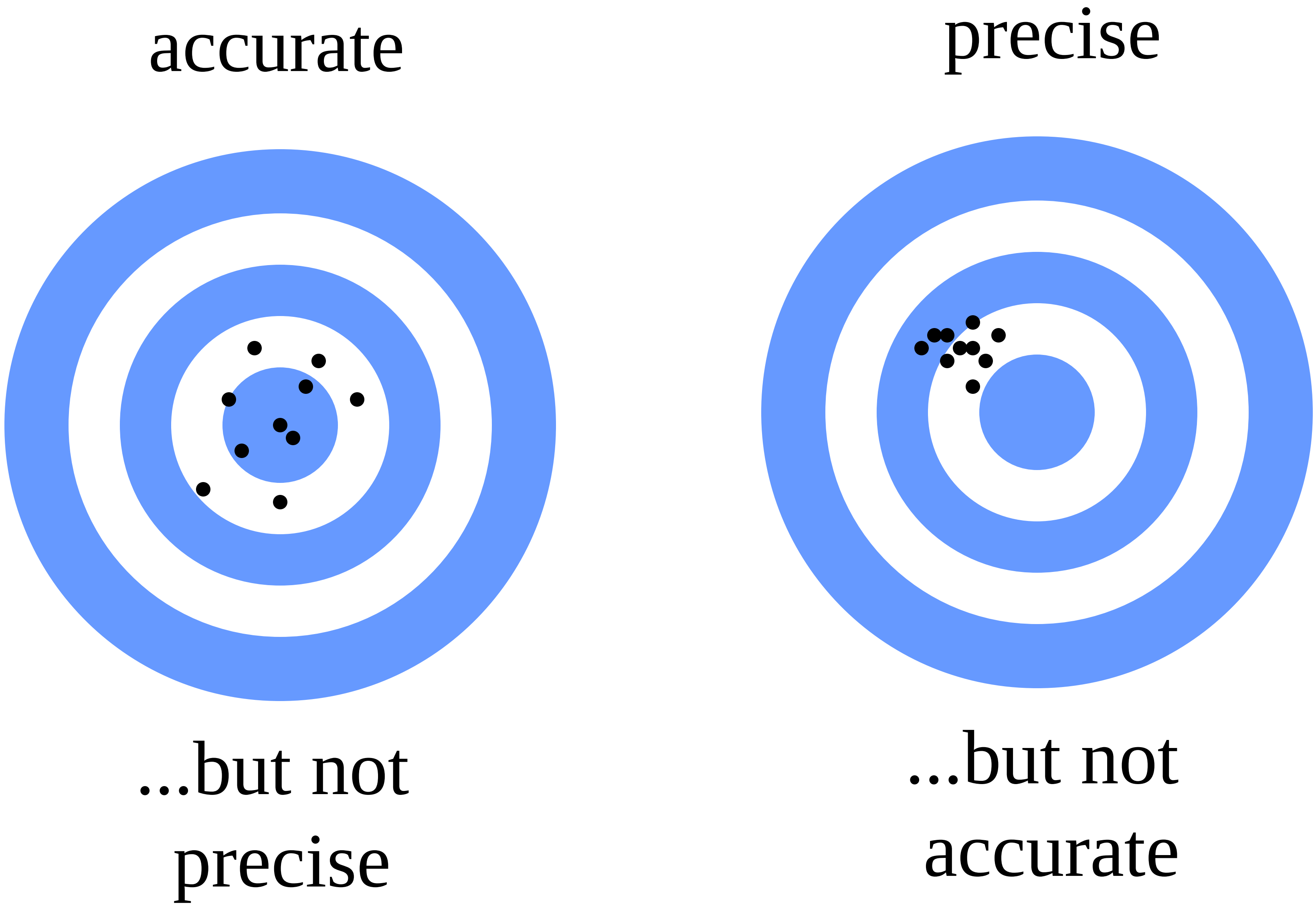
Available online at www.sciencedirect.com
SCIENCE DIRECT
International Journal of Mass Spectrometry 251 (2006) 119–124
International Journal of Mass Spectrometry
www.elsevier.com/locate/ijms

Opportunistic mass measurements at the Holifield Radioactive Ion Beam Facility

P.A. Hausladen[a,*], J.R. Beene[a], A. Galindo-Uribarri[a], Y. Larochelle[b], J.F. Liang[a], P.E. Mueller[a], D. Shapira[a], D.W. Stracener[a], J. Thomas[c], R.L. Varner[a], H. Wollnik[a]

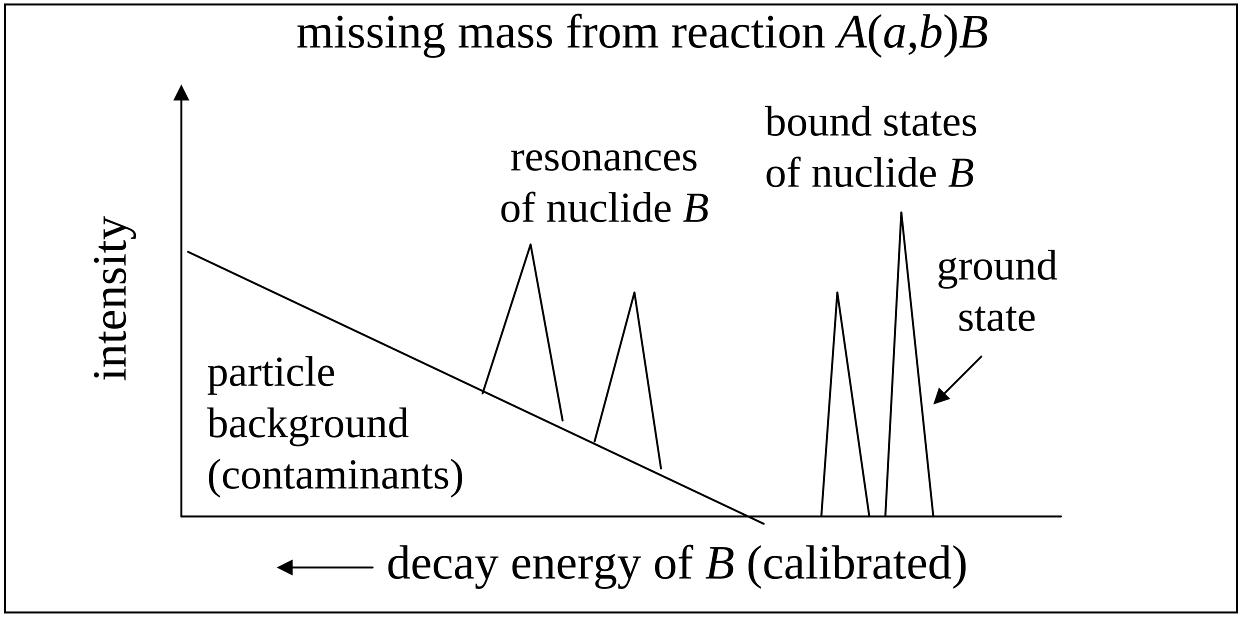




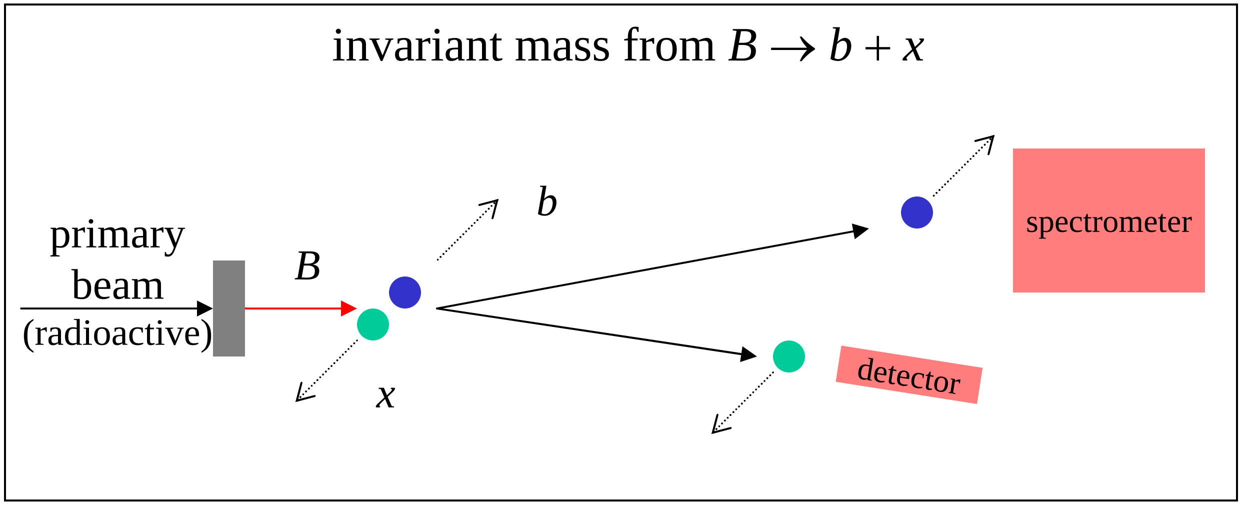


high precision *necessary but not sufficient* for high accuracy

Mass measurements by reactions



$$M_B = M_A + M_a - M_b - Q$$

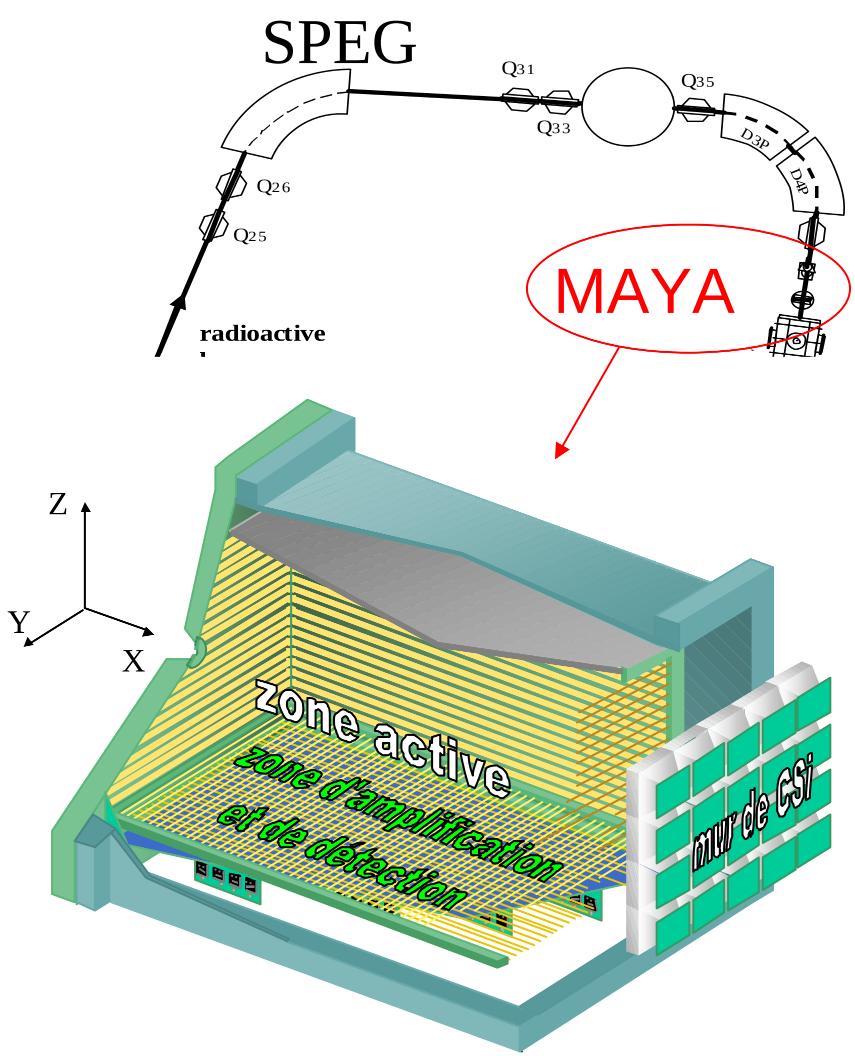


$$M_B = \{ M_x^2 + M_b^2 + 2E_x^{lab}E_b^{lab} - 2P_x^{lab}P_b^{lab} \}^{1/2}$$

^{10}Li, ^{13}Be, ^{18}Na

Somewhat limited but imperative for unbound

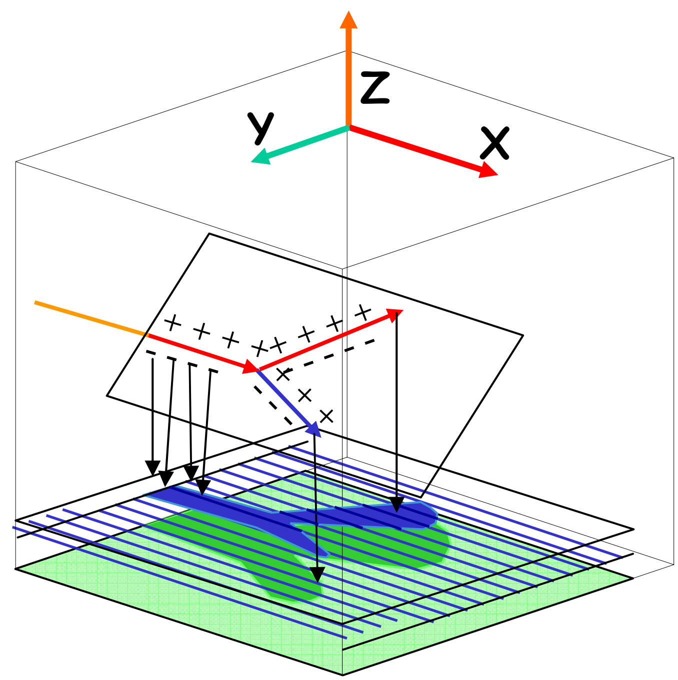
masses of unbound nuclides using MAYA at GANIL



C.-E. Demonchy Ph.D. (2003)

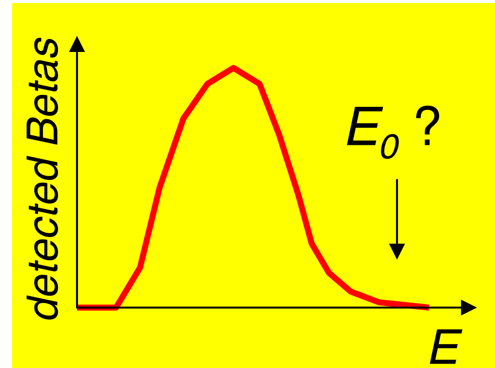
^{26}F (d,^{3}He) ^{25}O reaction

^{20}Ne	^{21}Ne	^{22}Ne	^{23}Ne	^{24}Ne	^{25}Ne	^{26}Ne	^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne
^{19}F	^{20}F	^{21}F	^{22}F	^{23}F	^{24}F	^{25}F	^{26}F	^{27}F	^{28}F	^{29}F
^{18}O	^{19}O	^{20}O	^{21}O	^{22}O	^{23}O	^{24}O	^{25}O	^{26}O	^{27}O	^{28}O
^{17}N	^{18}N	^{19}N	^{20}N	^{21}N	^{22}N	^{23}N	^{24}N	^{25}N		

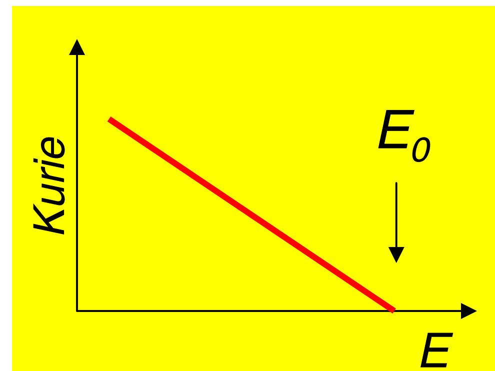


Mass measurements by Beta decay: $Q_\beta = M_{parent} - M_{daughter}$

$$P(p)\,dp = \frac{G^2\,|M_{if}|^2}{2\pi^3\hbar^7c^3}\,p^2(E_0-E)^2\,F(Z,E)$$

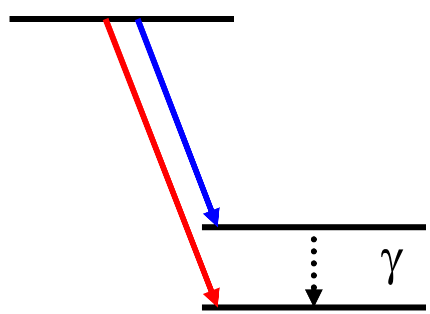


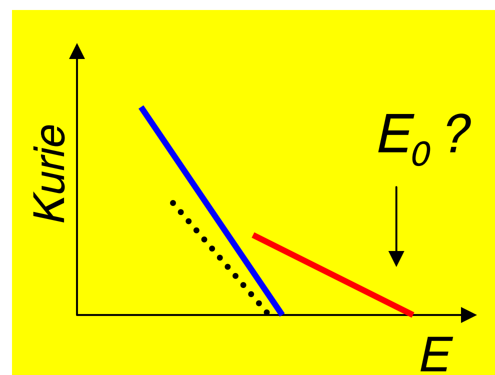
Kurie Plot: $[P(p)\,/\,p^2\,F(Z,E)]^{1/2}$ vs. E



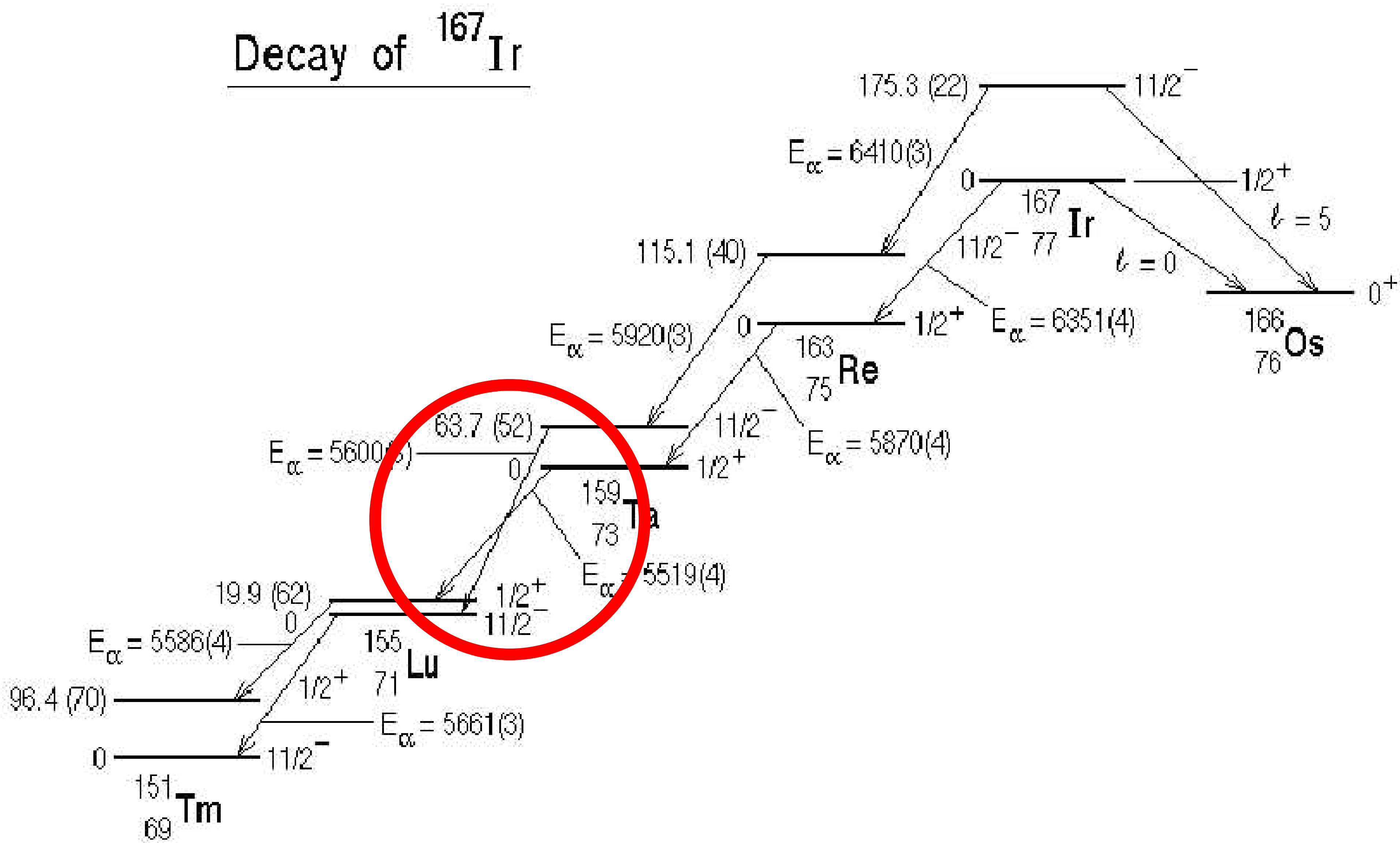
Instrumentation effects (response function)

Decay Branching (detailed spectroscopy)



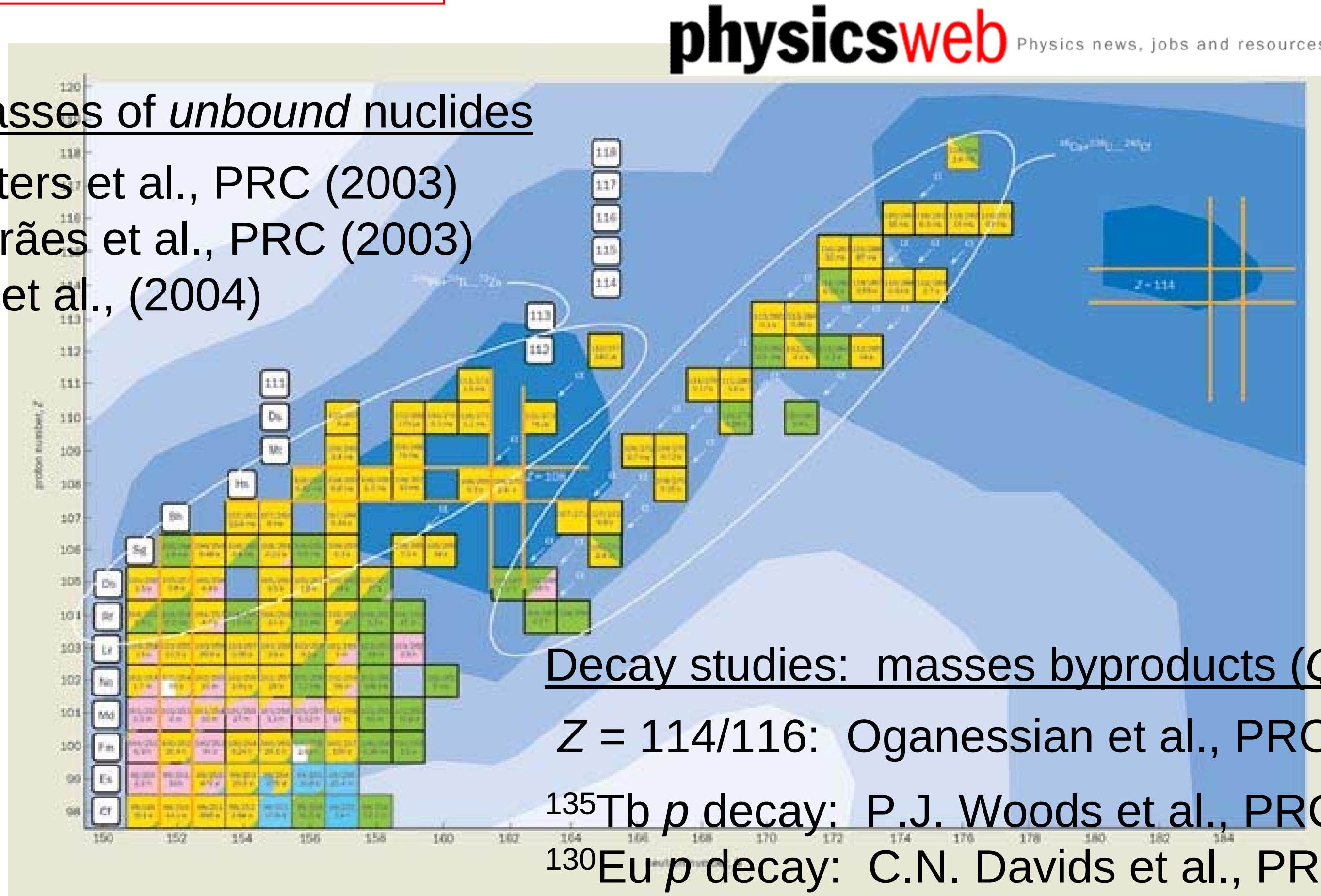


Mass measurements by alpha and proton decay



C.N. Davids et al., Hyp. Int. 132 (2001) 133 *reactions and decays*

(so-called 'indirect' techniques)



Reactions: masses of *unbound* nuclides

^{15}F: W. A. Peters et al., PRC (2003)

^{11}N: V. Guimarães et al., PRC (2003)

^{25}O: W. Mittig et al., (2004)

Decay studies: masses byproducts (*Q*-values)

Z = 114/116: Oganessian et al., PRC (2004)

^{135}Tb *p* decay: P.J. Woods et al., PRC (2004)

^{130}Eu *p* decay: C.N. Davids et al., PRC (2004)

^{233}Am α decay: M. Sakama et al., PRC (2004)

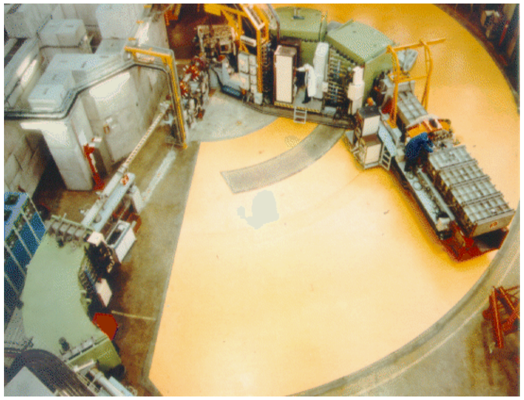
^{265}Bh α decay: Z.G. Gan et al., EPJA (2004)

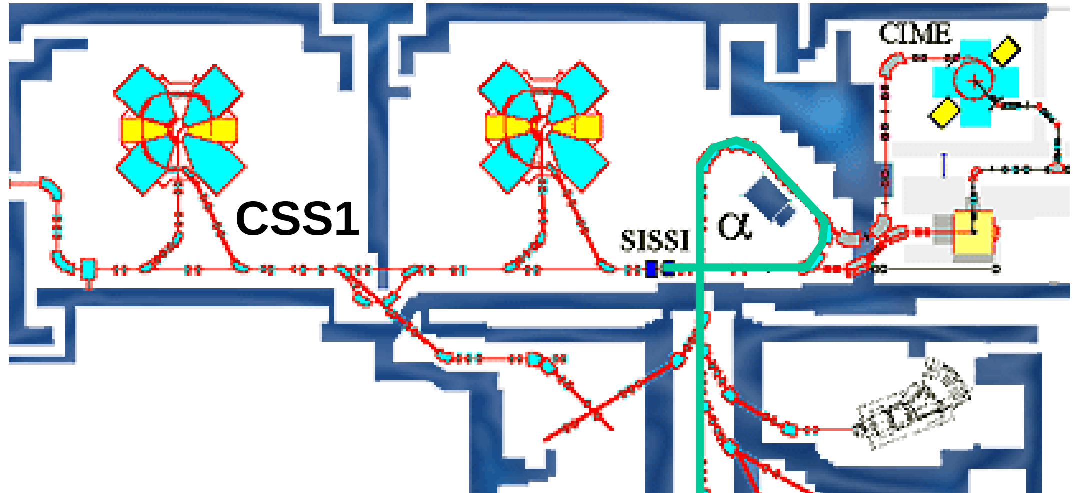
^{130}Cd β decay: I. Dillmann et al., PRL (2003)

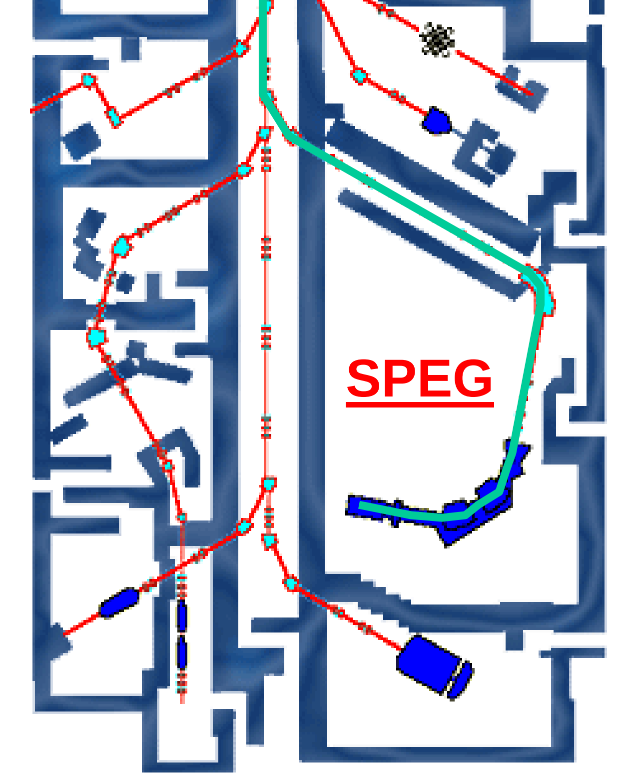
Mass values for the most exotic species


UW-PTMS
FSU-TRAP (MIT)
SMILE-TRAP (MSI)
SPEG
CSS2
(GANIL)
ESR-FRS (GSI)
ISOLTRAP (CERN)
MISTRAL (CERN)
NORTH AMERICA
PACIFIC OCEAN
ARCTIC OCEAN
North Pole
CANADA
GREENLAND (DEN.)
UNITED STATES
RUSSIA
ASIA
CHINA
KAZAKHSTAN
ATLANTIC OCEAN
SWEDEN
U.K.
UKRAINE
EUROPE
INDIA
Bay of Bengal
TURKEY
IRAN
IRAQ
Arabian Sea
INDIAN OCEAN
ALGERIA
Mediterranean Sea
EGYPT
SAUDI ARABIA
LIBYA
Tropic of Cancer
MALI
NIGER
AFRICA
CHAD
SUDAN
ETHIOPIA
NIGERIA
Equator
Arctic Circle

mass measurement programs at *GANIL*







SPEG

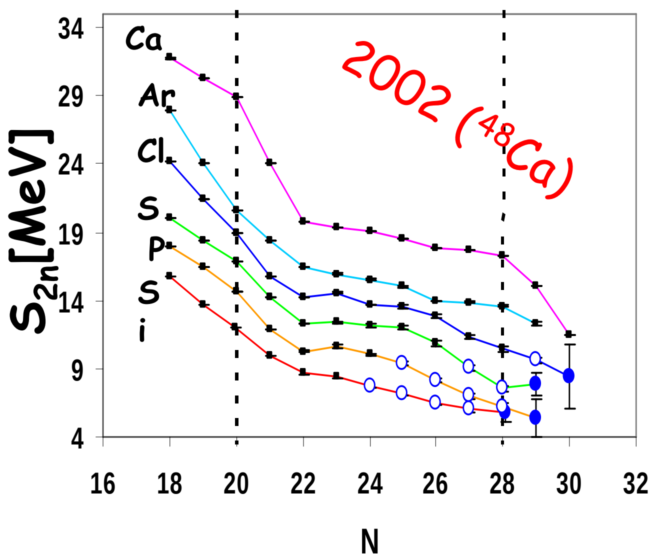
time-of-flight

+ magnetic rigidity

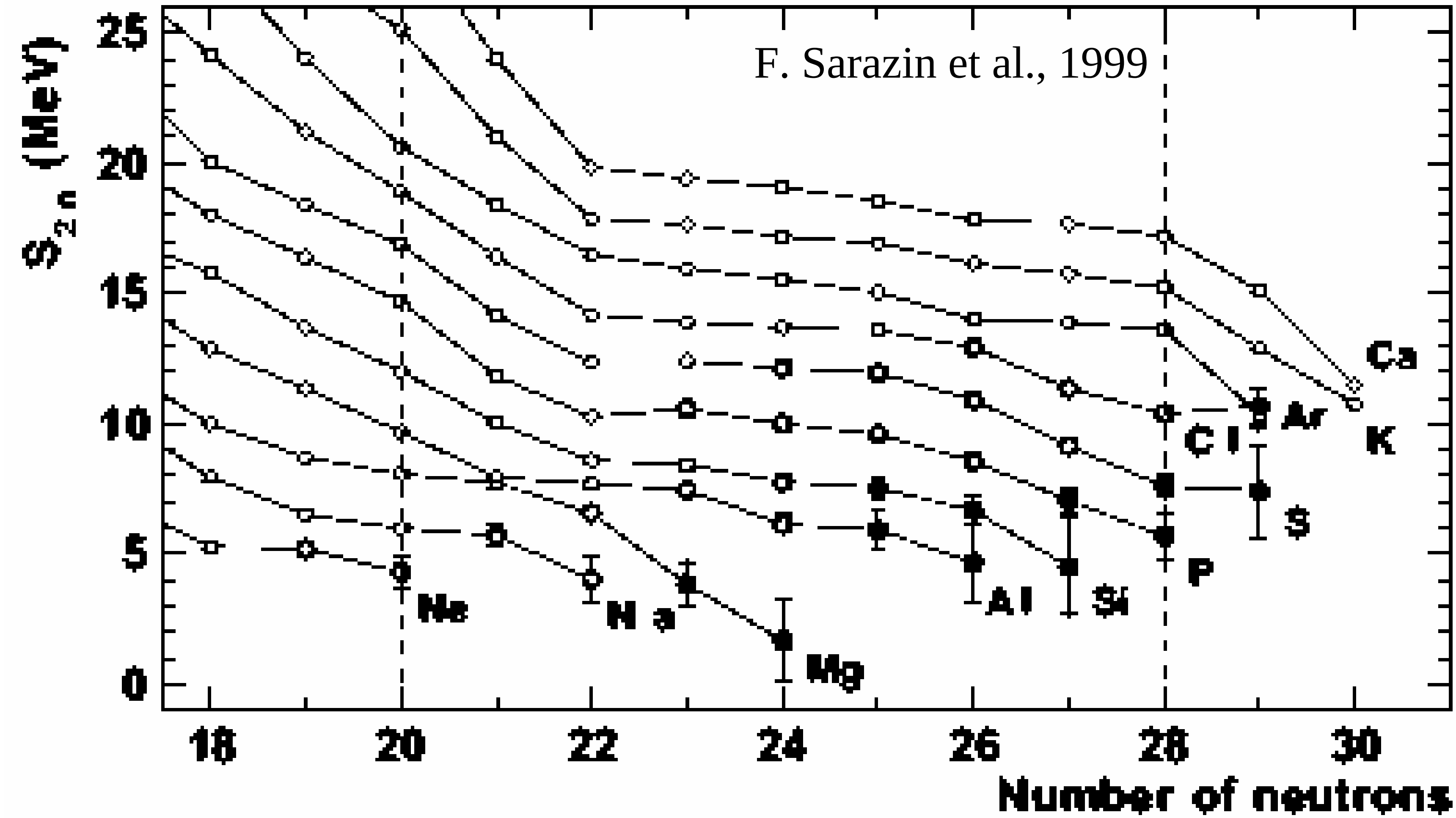
$m = q\,B\rho\,T\,/\,L$

Resolving power: 10^4

***extremely* sensitive**

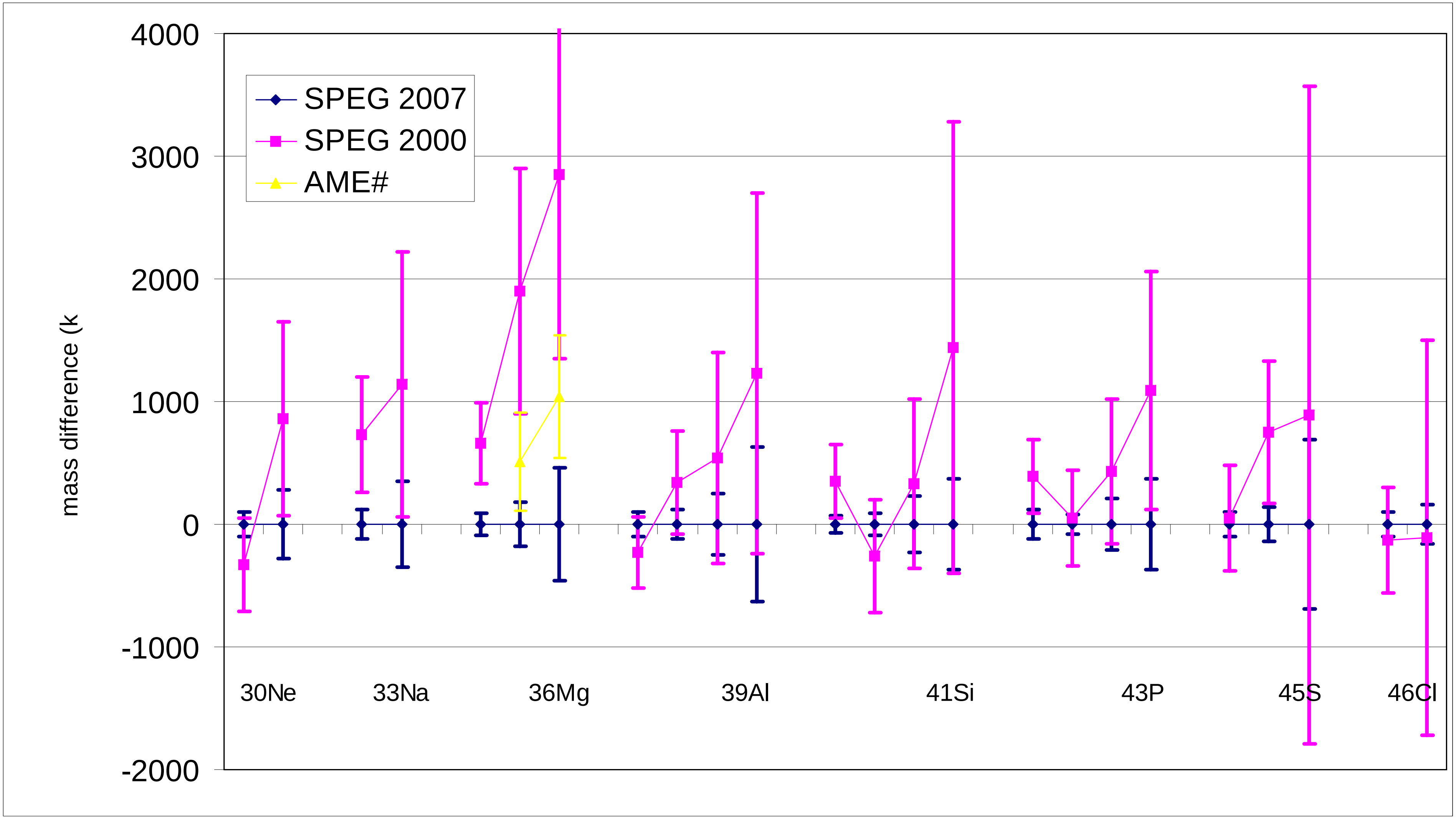


B. Jurado, H. Savajols *et al*., PLB (2007)

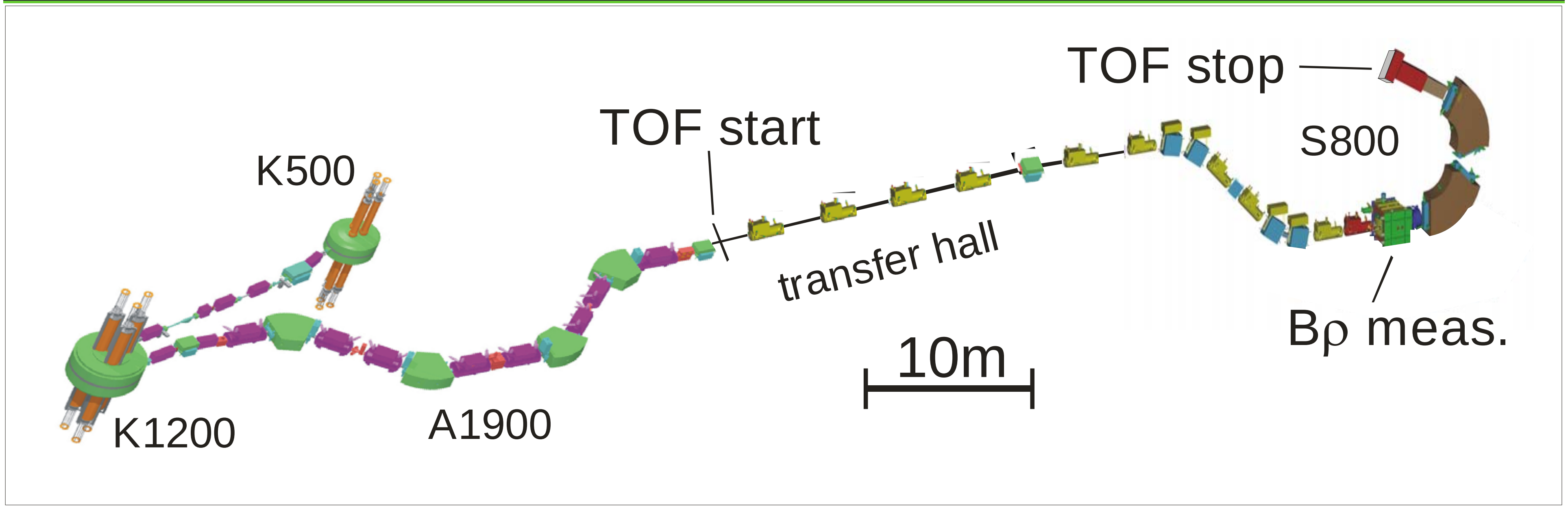


SPEG

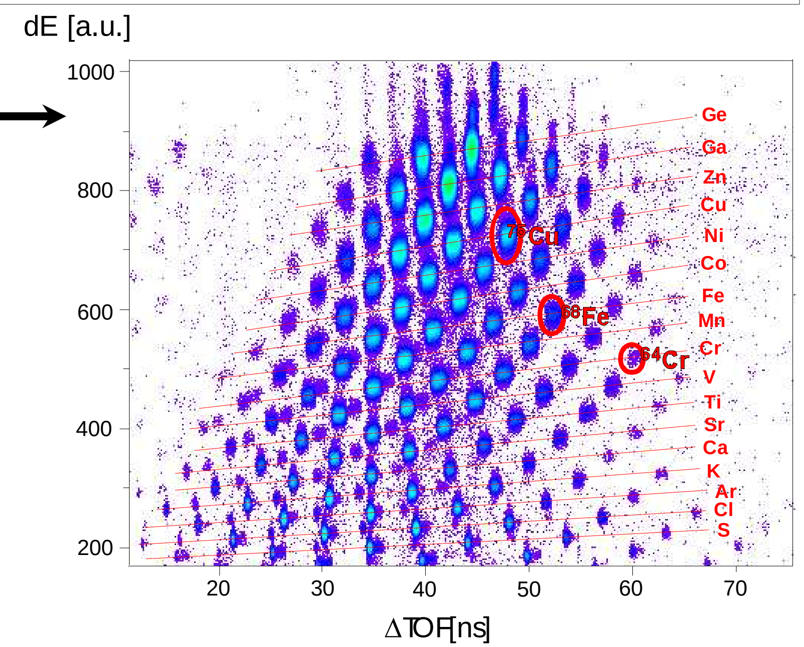
resolving ~ 5000
sensitivity ~ 0.01 /s



4000
3000
2000
1000
0
-1000
-2000
mass difference (k
SPEG 2007
SPEG 2000
AME#
30Ne
33Na
36Mg
39Al
41Si
43P
45S
46Cl



^{86}Kr primary beam →

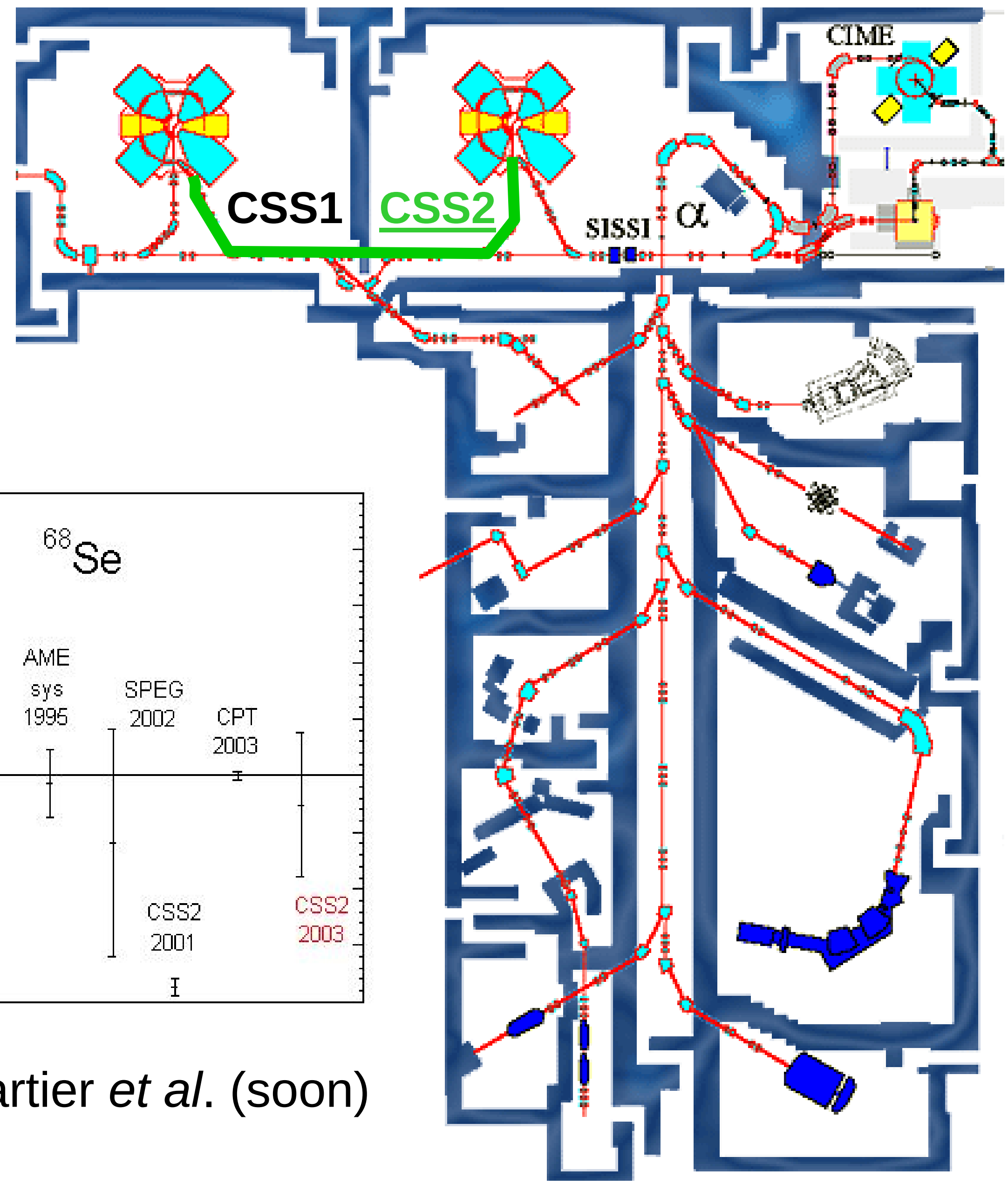


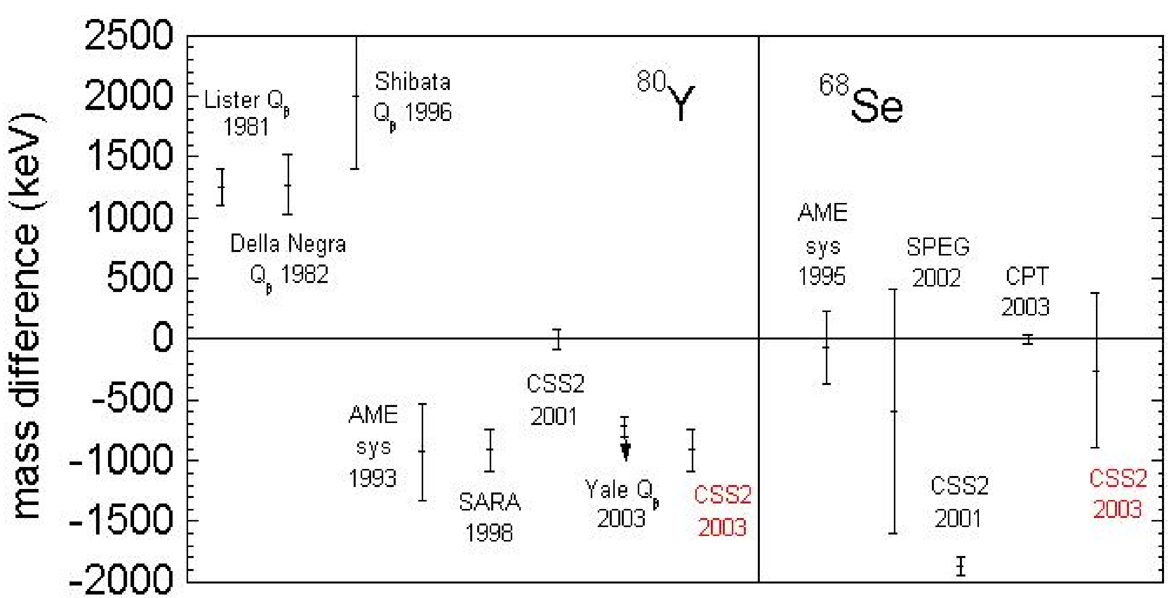
M. Matoš (CGS-12, Notre Dame)
AIP Conf. Proc. 819 (2006) 164

A. Estrade (NiC-IX, CERN)
Proceedings of Science (2006)

mass measurement programs at *GANIL*

CSS2
time-of-flight:
phase difference
with acceleration
(longer flight path)



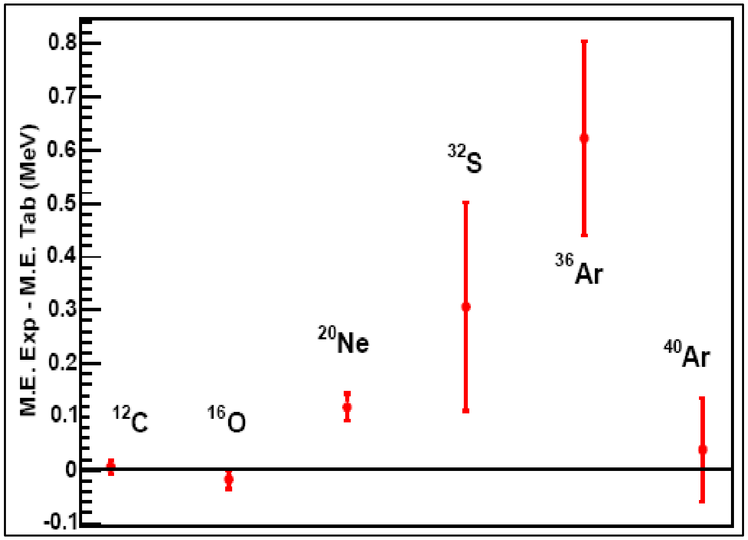


M.B. Gomez Hornillos, M. Chartier *et al*. (soon)

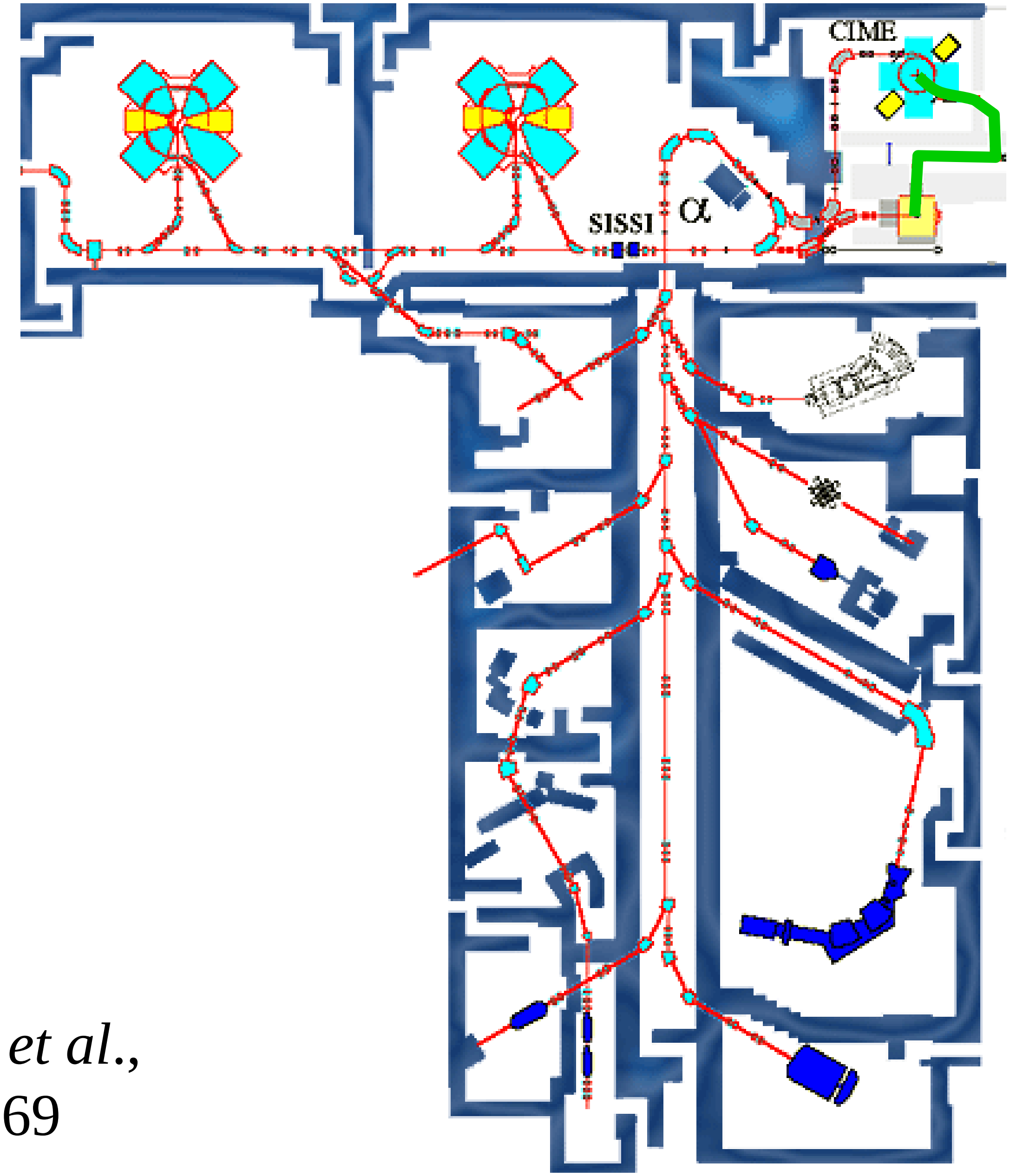
mass measurement programs at *GANIL*

CIME (SPIRAL)

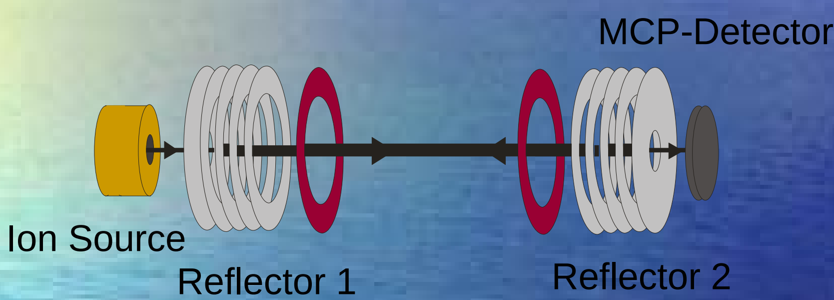
time-of-flight:
variable RF
acceleration

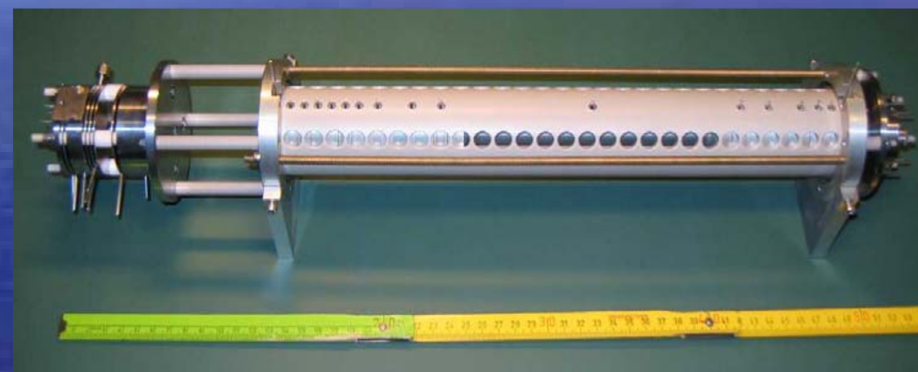


M.-B. Gomes Hornillos *et al.*,
J. Phy. G 31 (2005) S1869



Multiple-Reflection TOF-MS





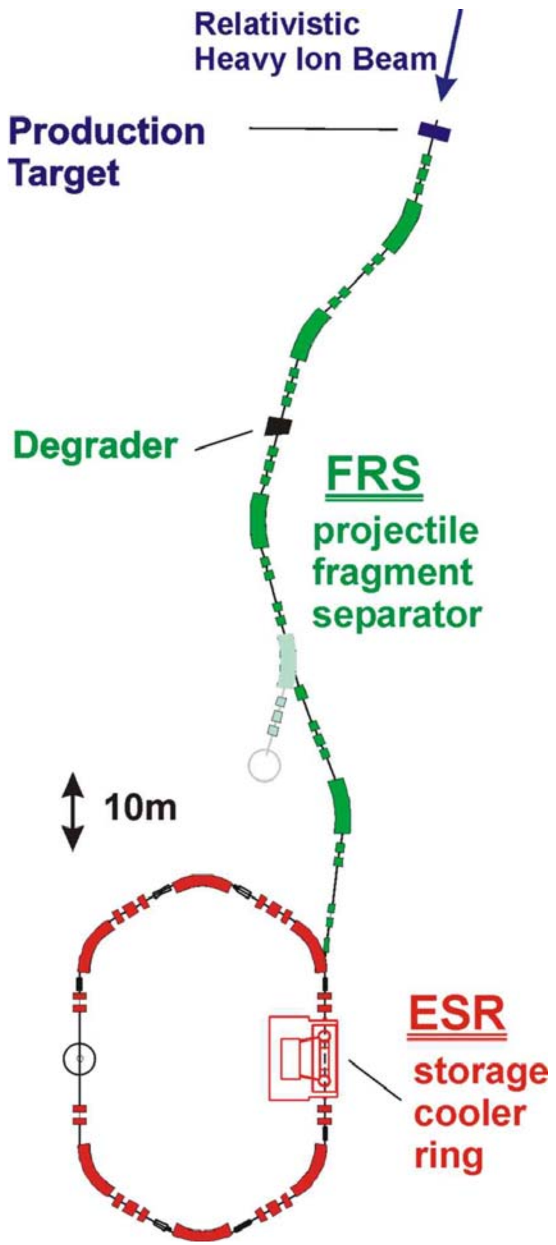
mass measurement accuracy (~ ppm)
short measurement durations (< 1 ms)

Eigenschaften und Struktur kurzlebiger Kerne
IONAS

Casares, Geissel, Plass, Scheidenberger, Wollnik *et al*.

(*Proc. 48th ASMS Conf. Mass Spectrom. Allied Topics*, Long Beach, CA, 2000)

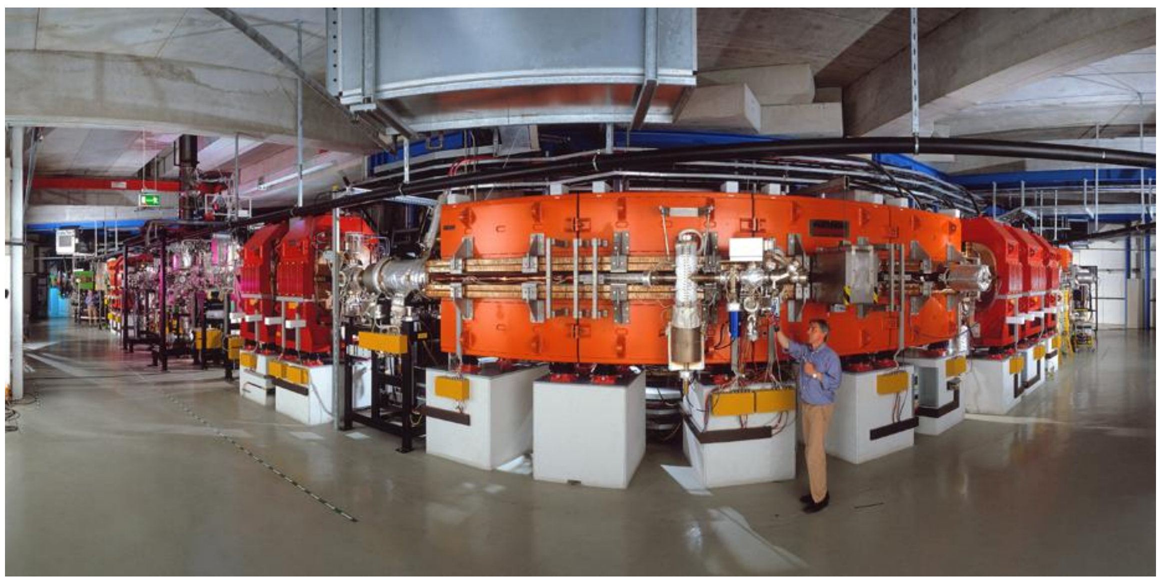
mass measurement programs at *GSI*



Experimental Storage Ring:

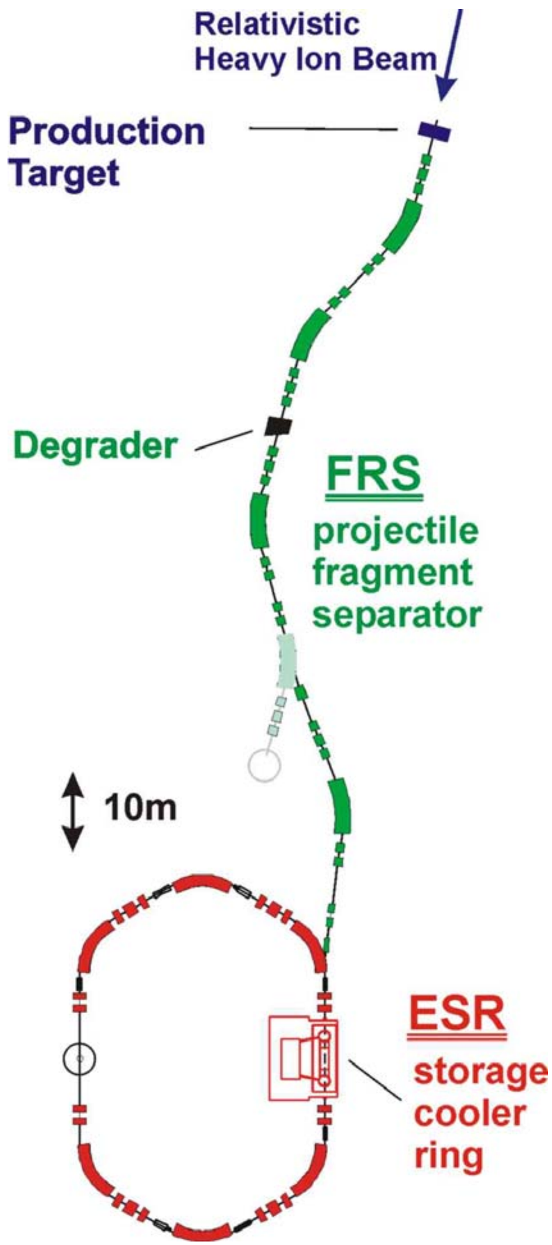
$\Delta m/m = \gamma_t^2 \, \Delta f/f + (\gamma_t^2 - \gamma^2) \, \Delta v/v$

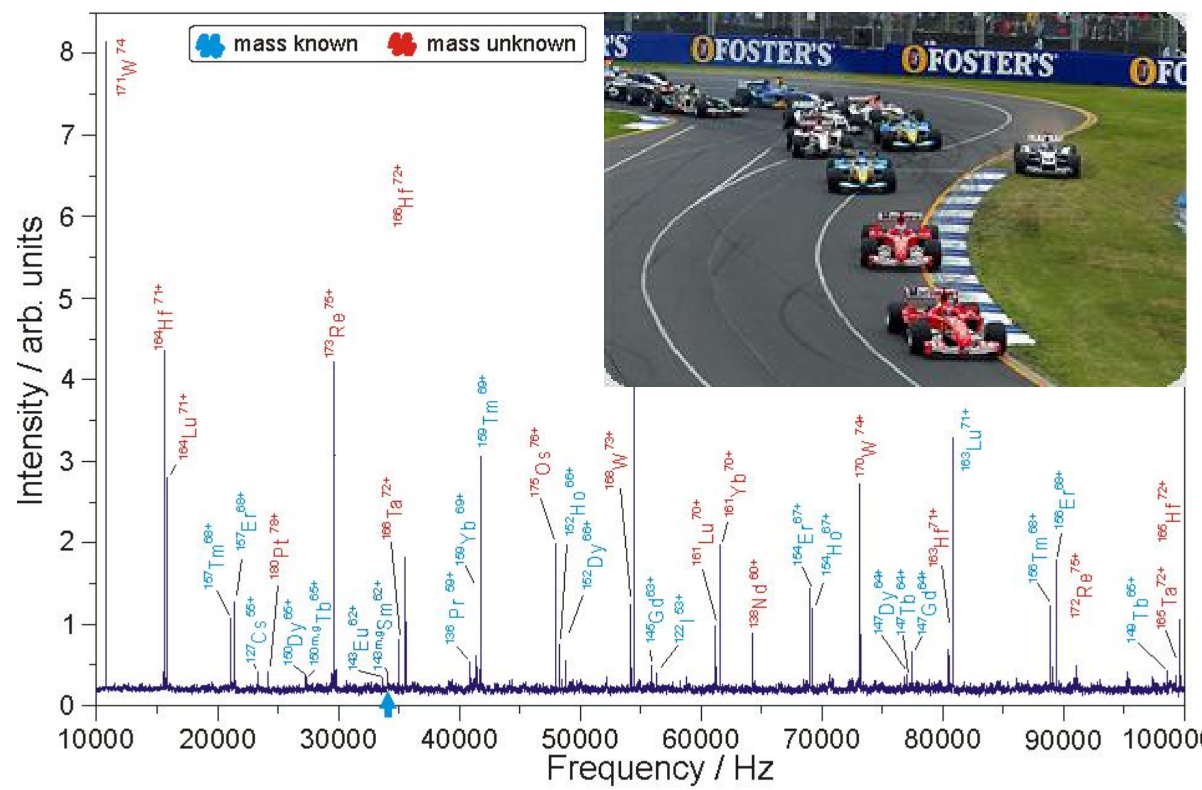
Schottky Mode	**Isochronous Mode**
very precise but cooling slow	very fast but not so precise



mass measurement programs at *GSI*

Experimental Storage Ring:
stripped, H- and He-like ions





Nuclear Physics in Storage Rings

Mass Measurements and Decay Studies in the ESR

Reaction studies in the ESR

Yuri A. Litvinov

Arbeitstreffen Kernphysik, Schleching

22 February 2007

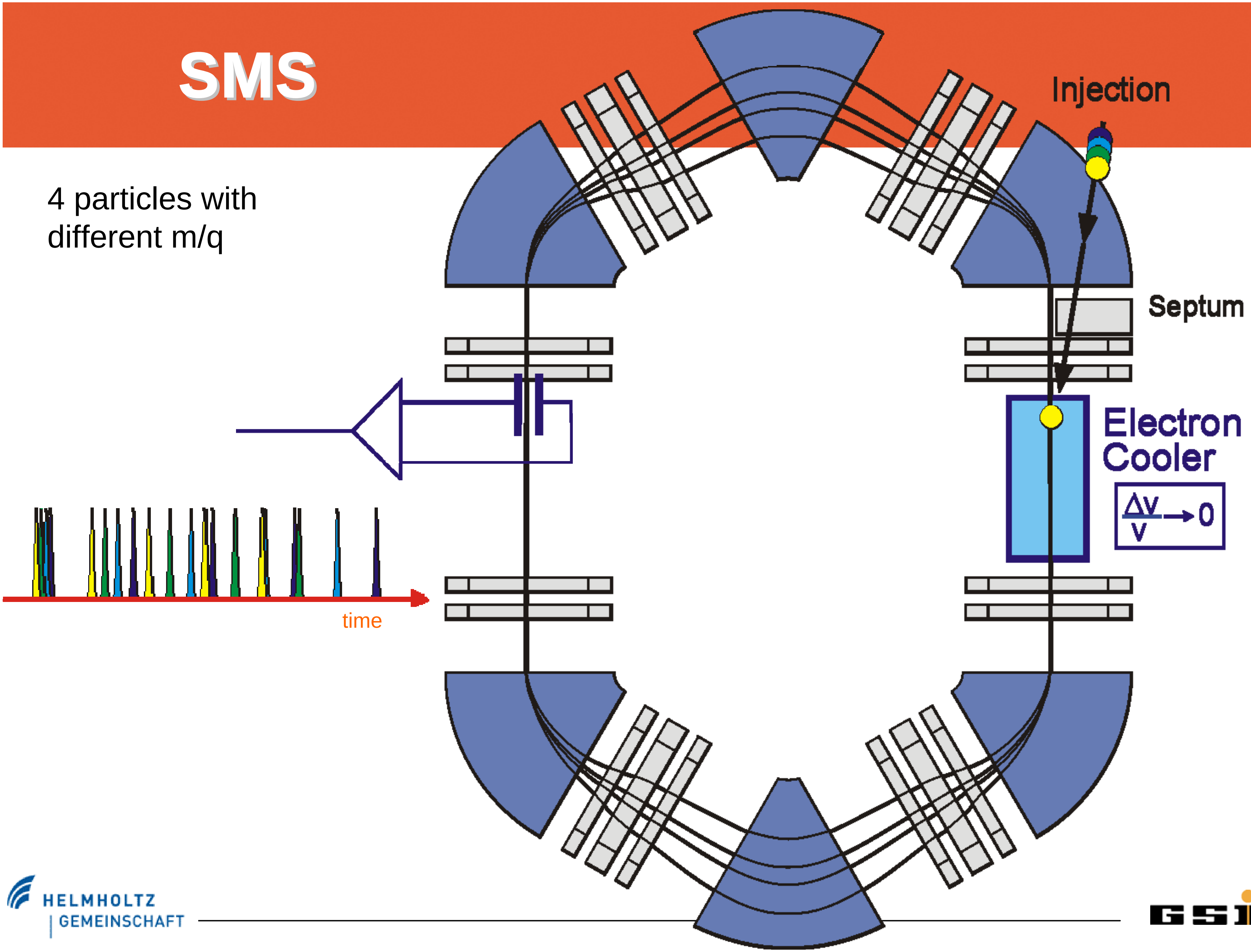
Mass matters !

HELMHOLTZ GEMEINSCHAFT

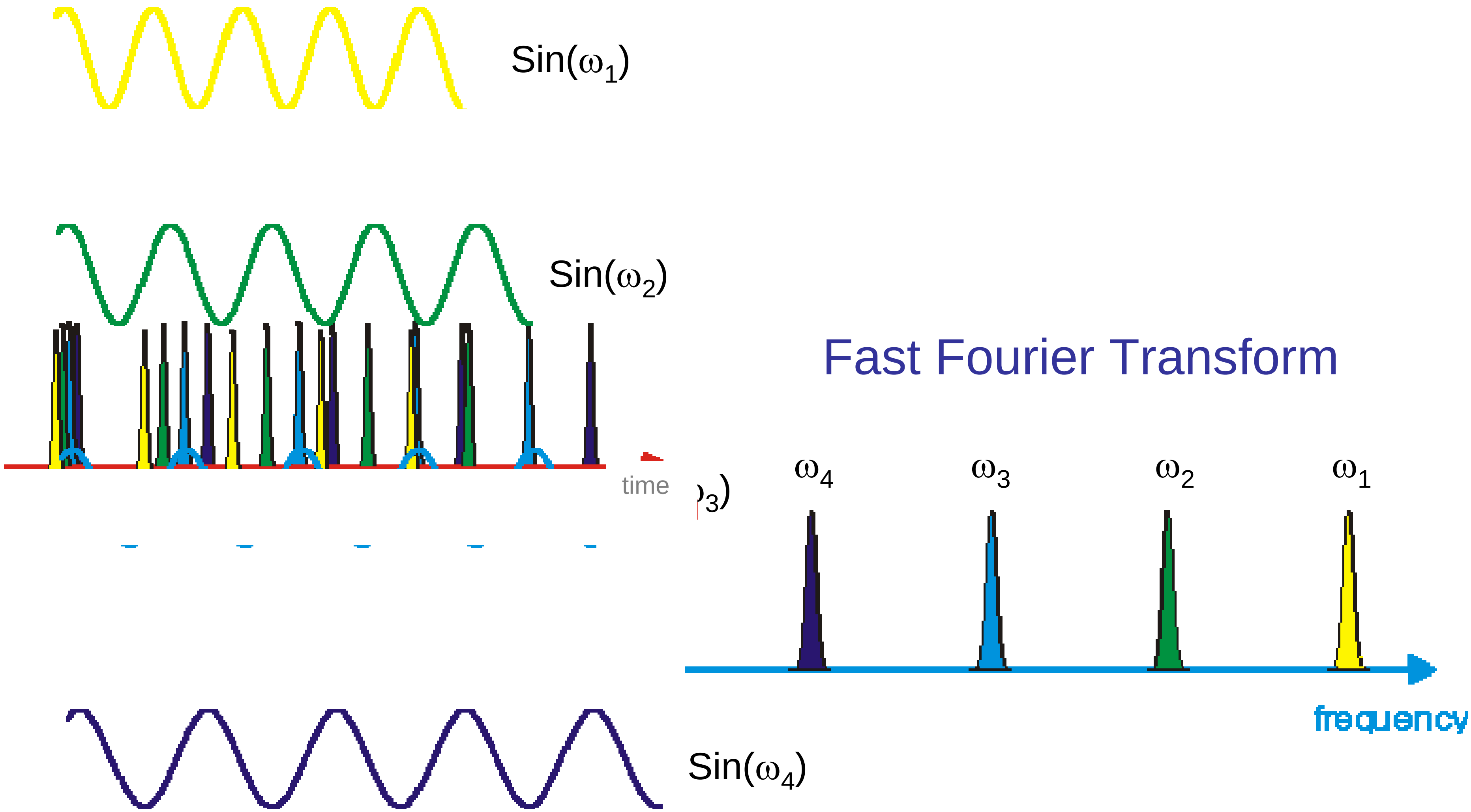
GSI

SMS

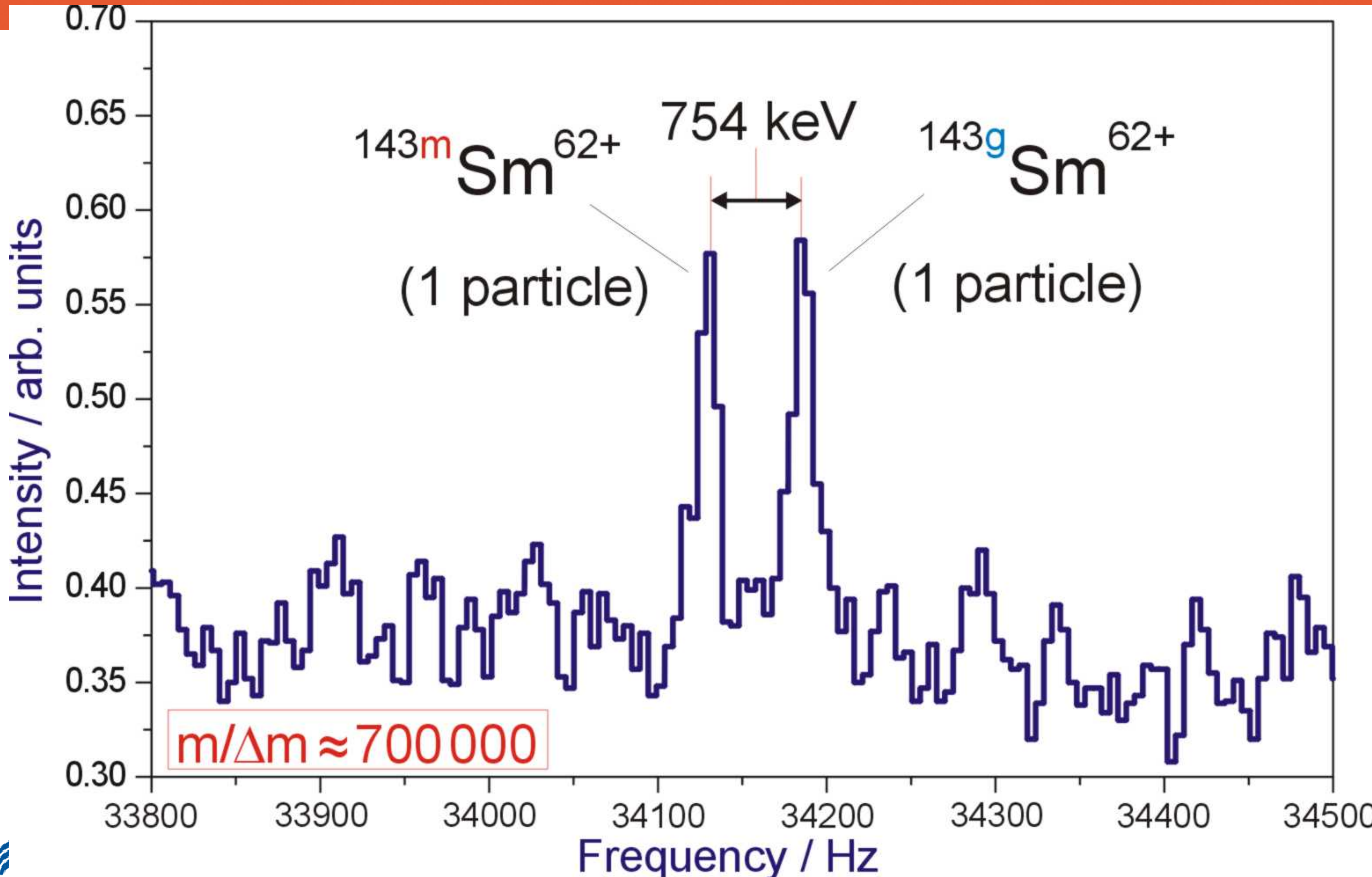
4 particles with
different m/q

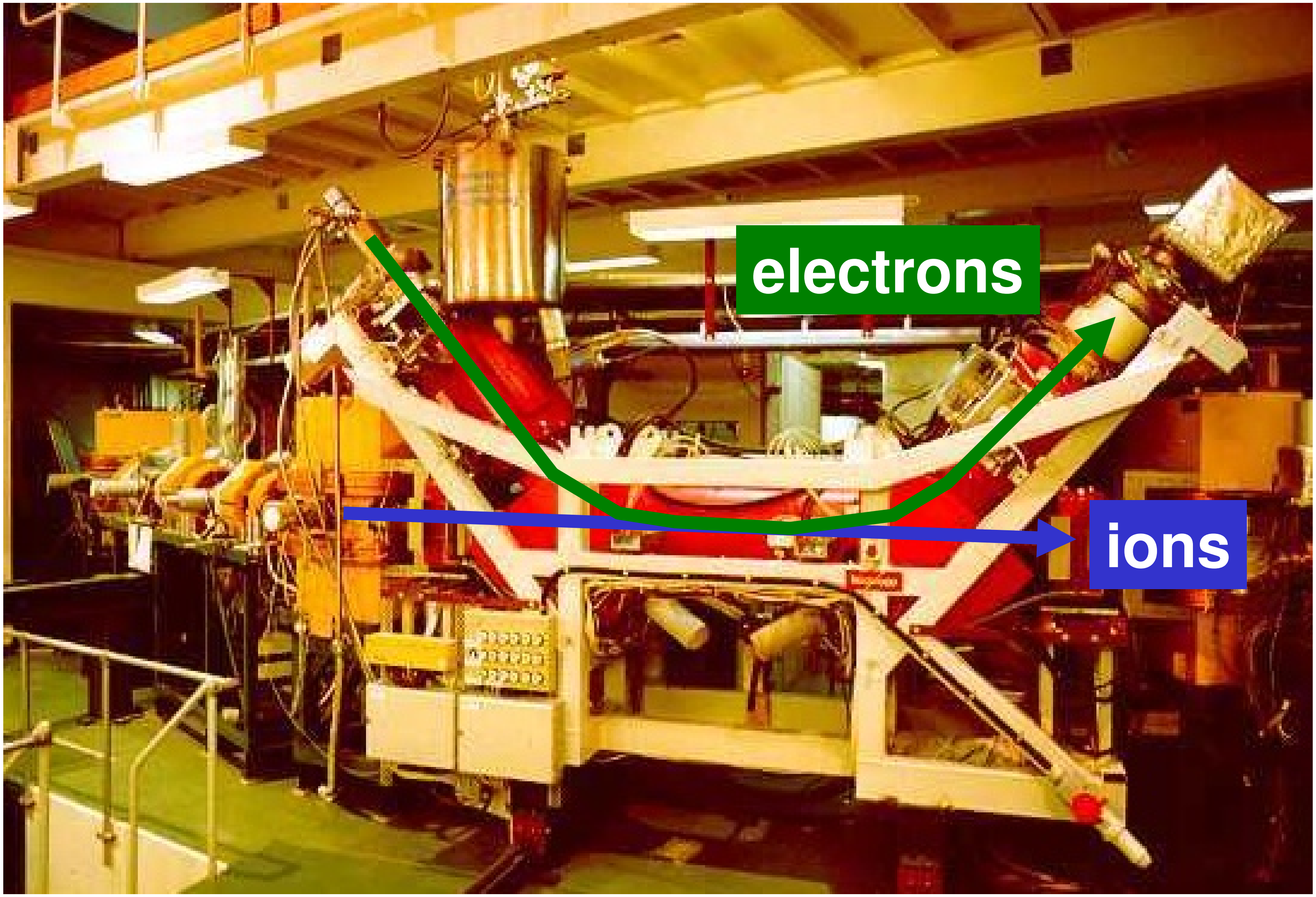


SMS


Sin(ω1)
Sin(ω2)
time
Fast Fourier Transform
ω4
ω3
ω2
ω1
frequency
Sin(ω4)

Broad-band Schottky Frequency Spectra



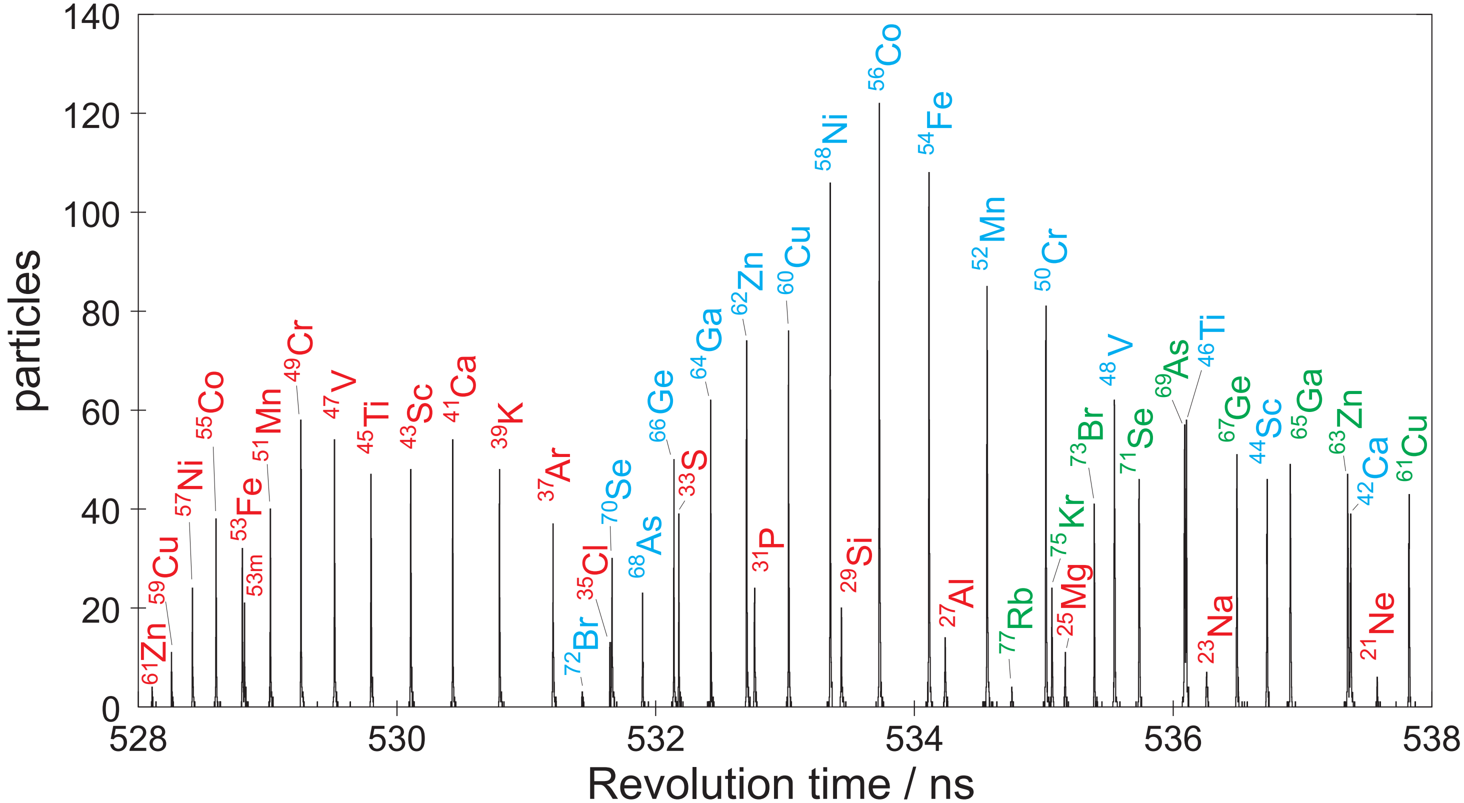


Electron cooling of fast ion beams (CRYRING at MSI, Stockholm)

IMS: Time-of-Flight Spectra

Nuclei with half-lives as short as 20 microseconds are accessible

About 13% in mass-over-charge range



M. Hausmann et al., Hyperfine Interactions 132 (2001) 291

Measured Mass Surface

Masses of more than 1100 Nuclides were measured

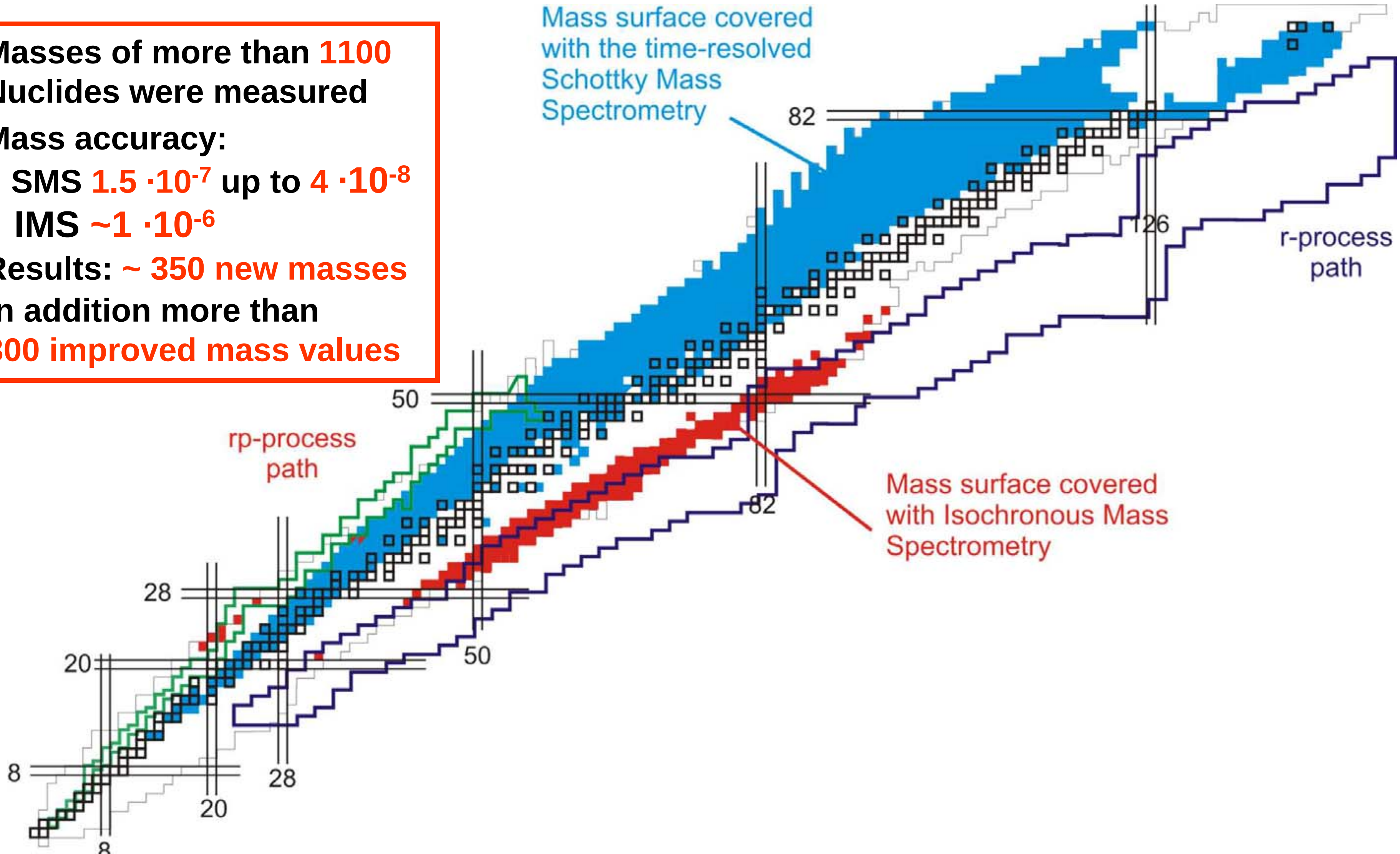
Mass accuracy:

SMS $1.5 \cdot 10^{-7}$ up to $4 \cdot 10^{-8}$

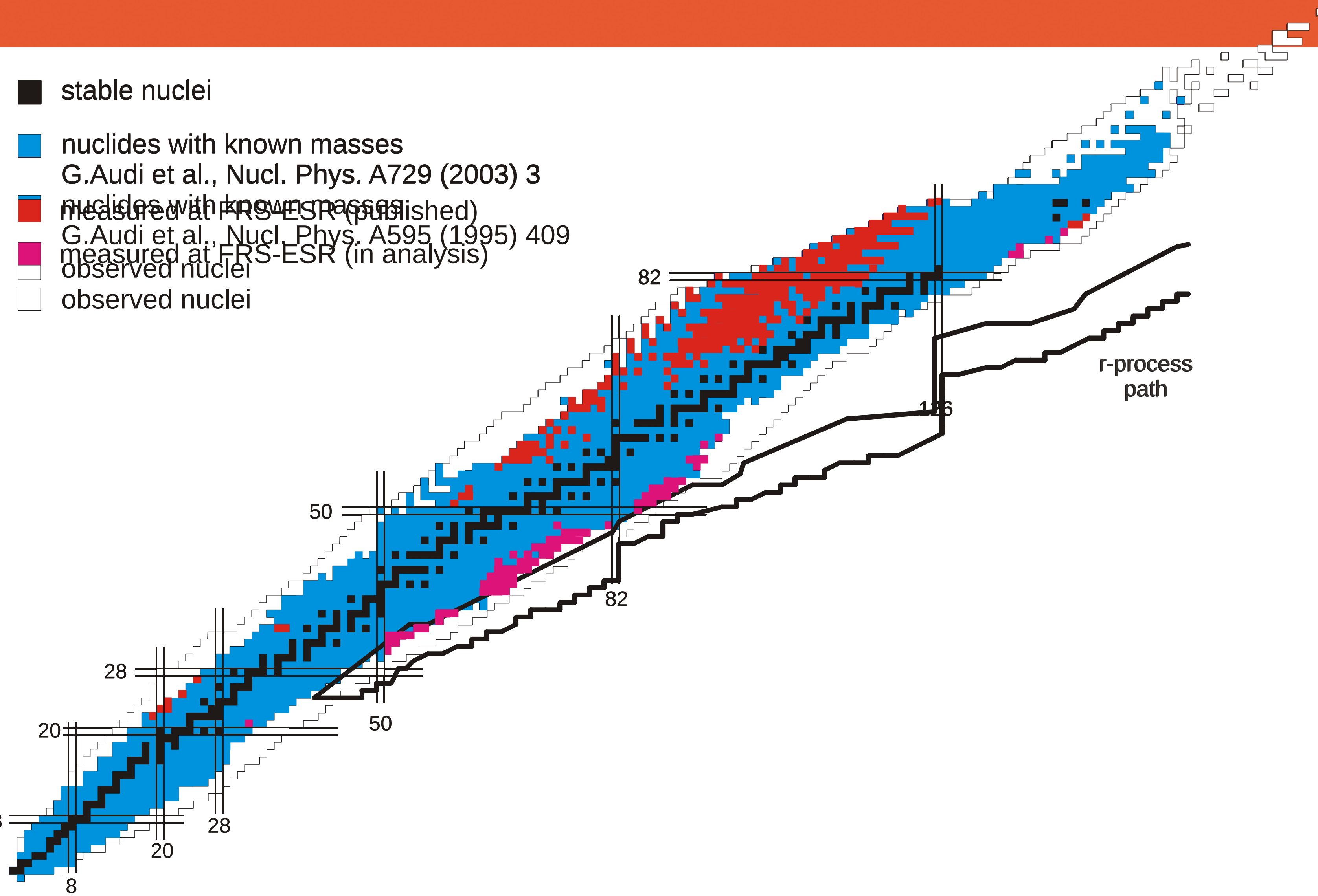
IMS $\sim 1 \cdot 10^{-6}$

Results: ~ 350 new masses

In addition more than 300 improved mass values



Present Knowledge of Atomic Masses



<u>Yu. Litvinov, *Ph.D.* (2003):</u>

~ 600 species in the ring

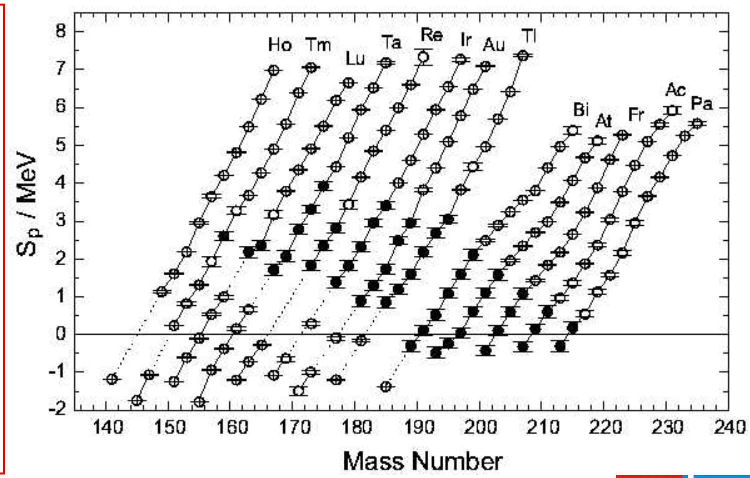
466 masses measured

(117 calibration masses)

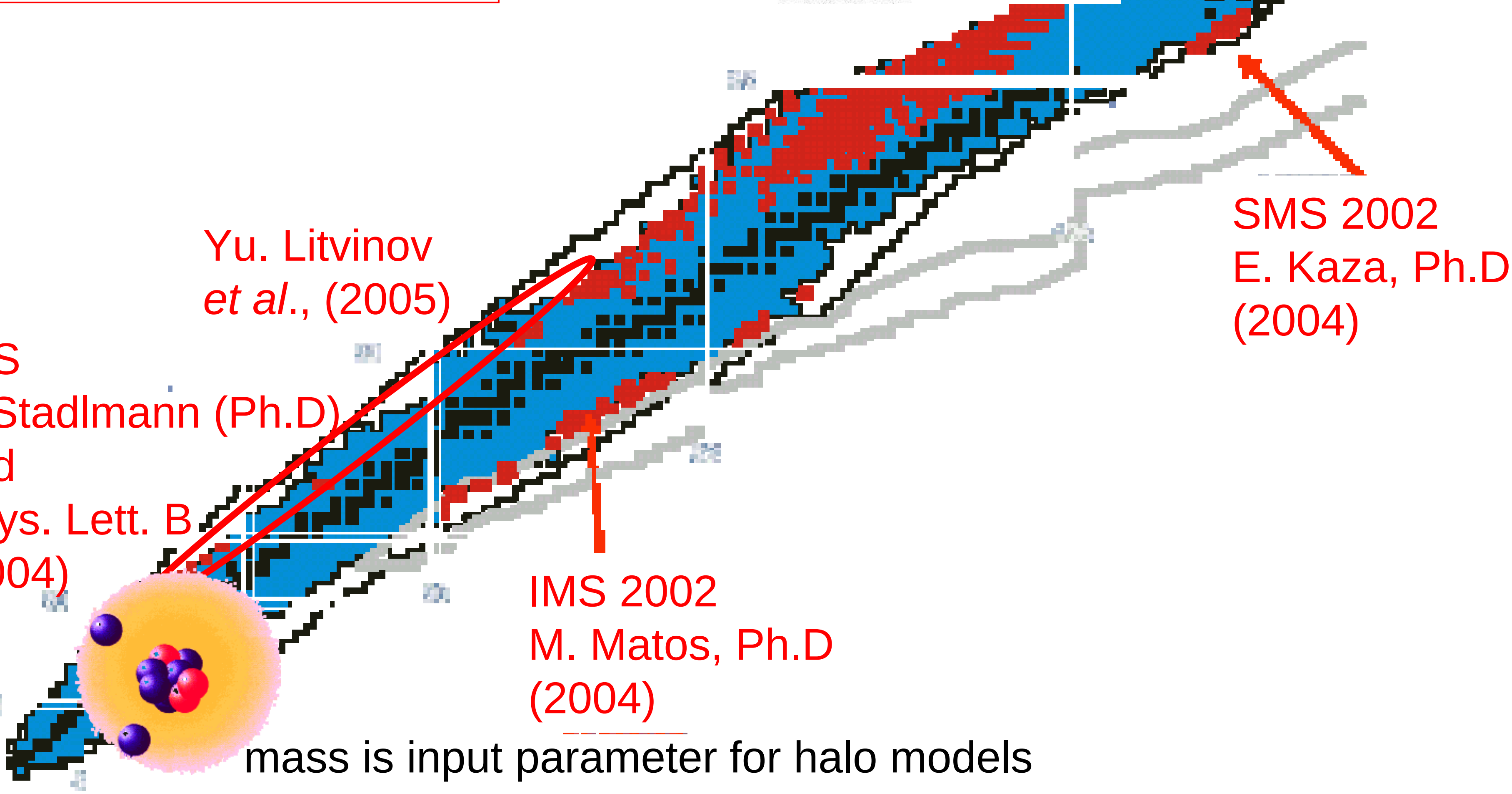
139 masses from links

200 improved masses

75 new mass values



Yu. Novikov *et al.*, Nucl Phys A (2002)



Yu. Litvinov *et al.*, (2005)

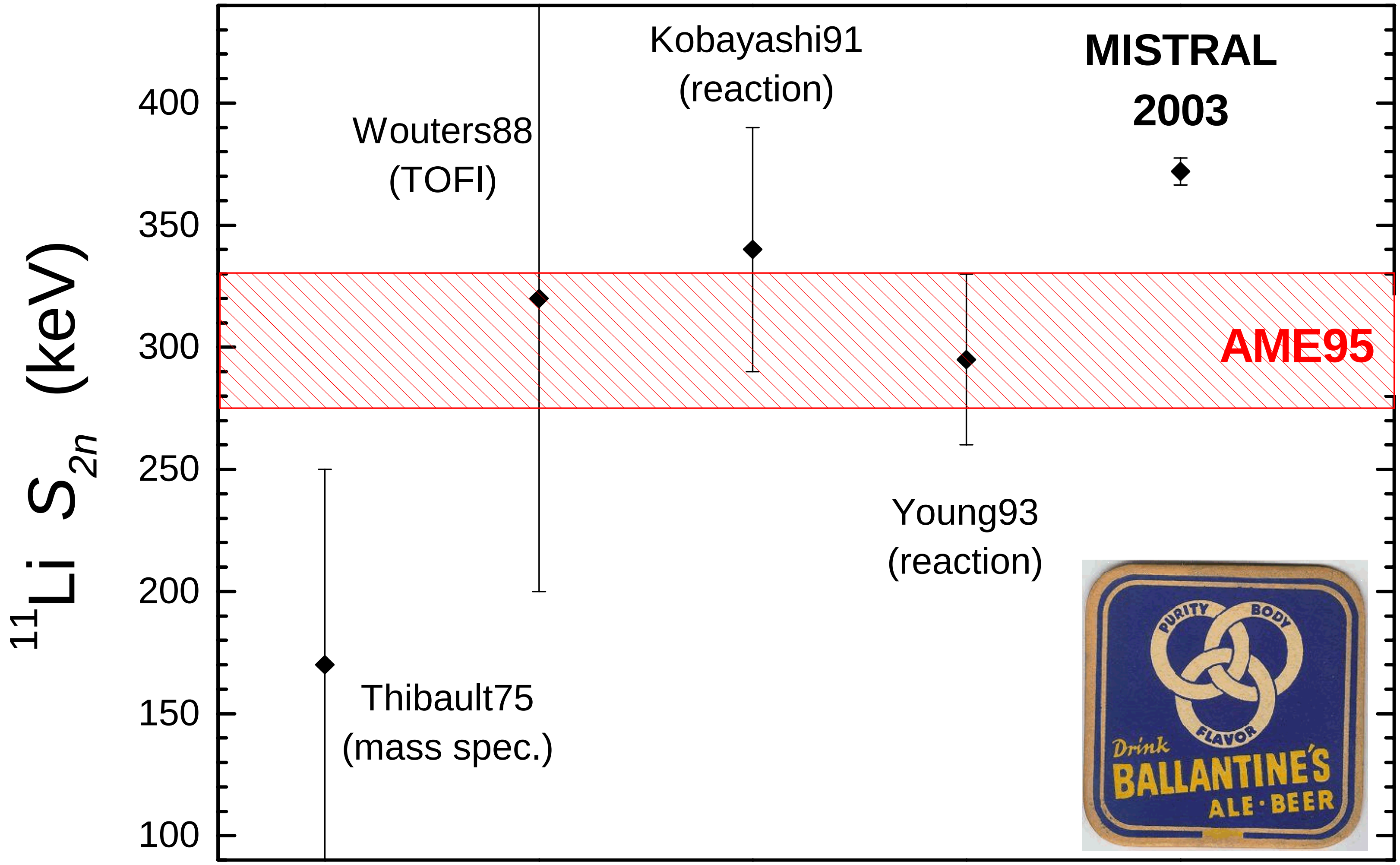
IMS
J. Stadlmann (Ph.D) and
Phys. Lett. B (2004)

SMS 2002
E. Kaza, Ph.D (2004)

IMS 2002
M. Matos, Ph.D (2004)

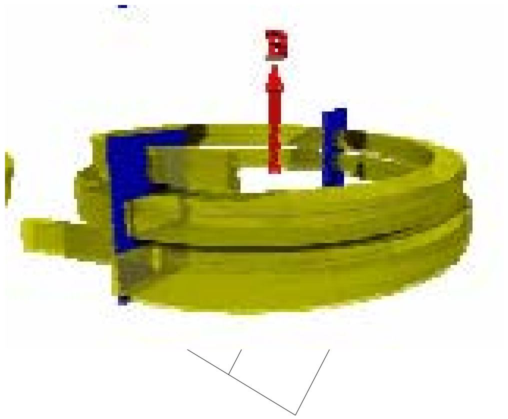
mass is input parameter for halo models

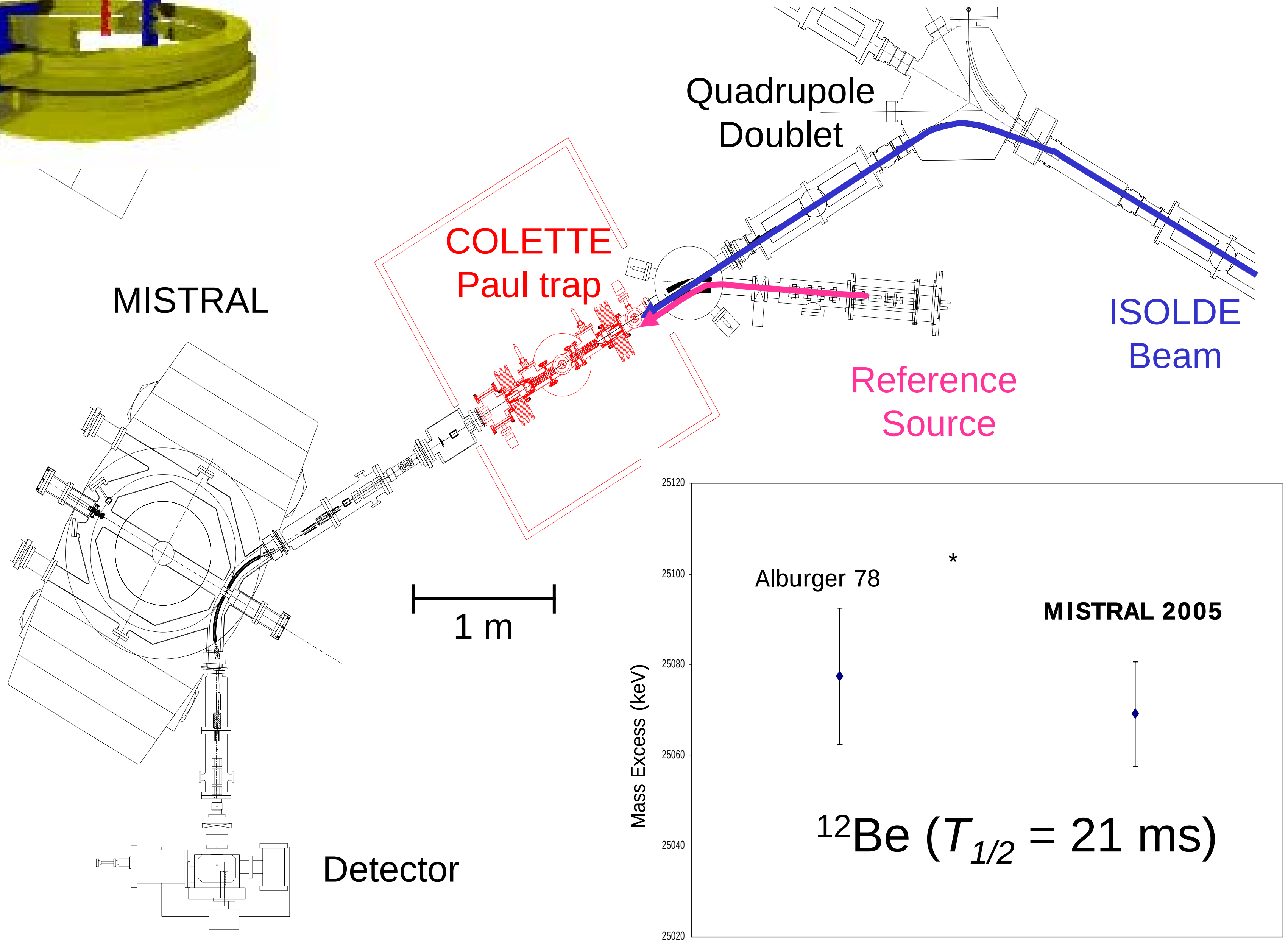
A new binding energy for the ^{11}Li halo



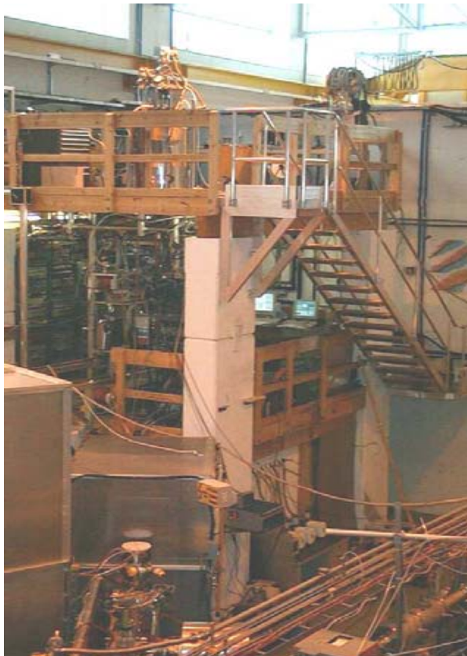
23% higher than currently used to adjust models...

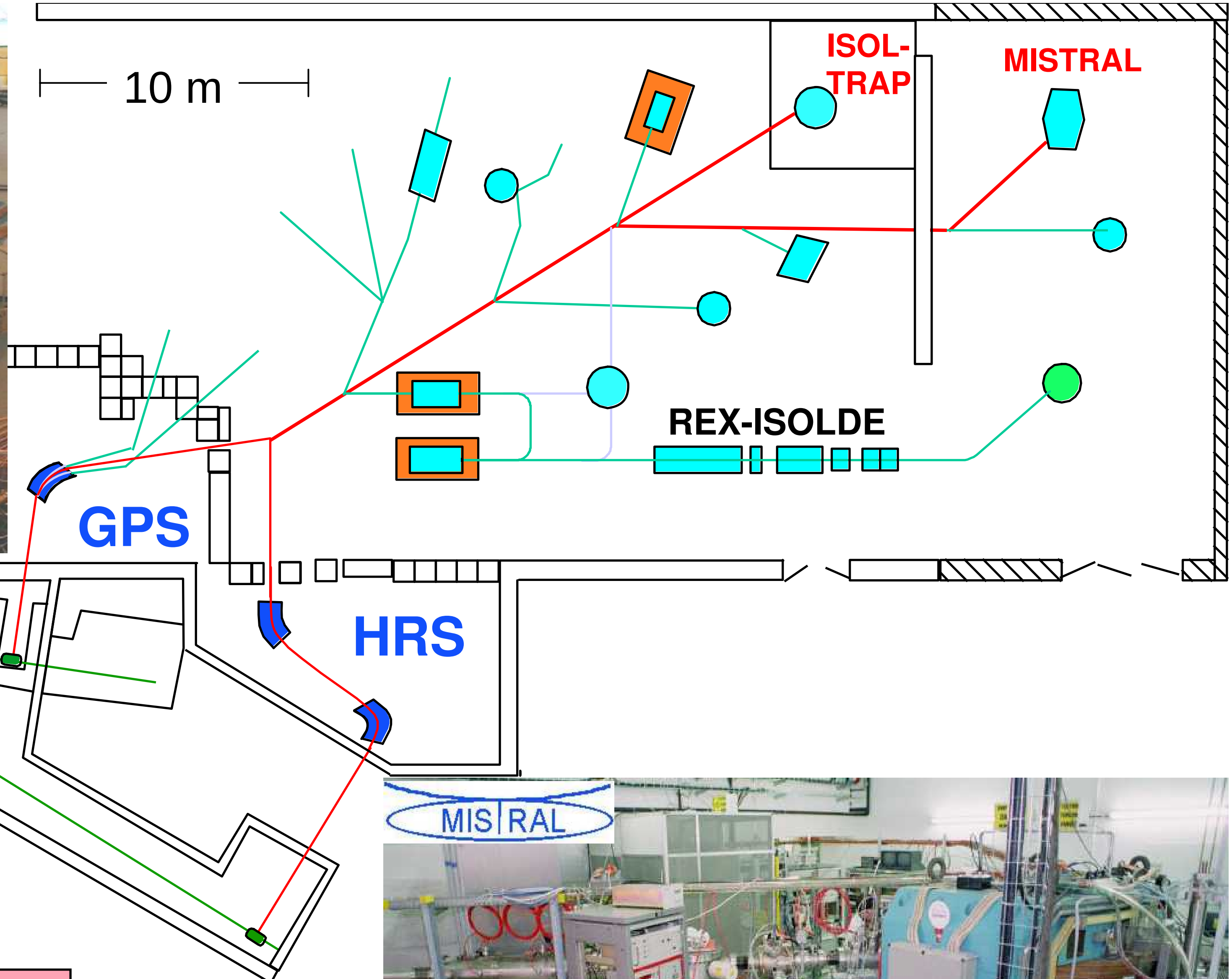
C. Bachelet, Ph.D. thesis (2004)





* D.E. Alburger et al. Phys. Rev. C 18, 2727 (1978)

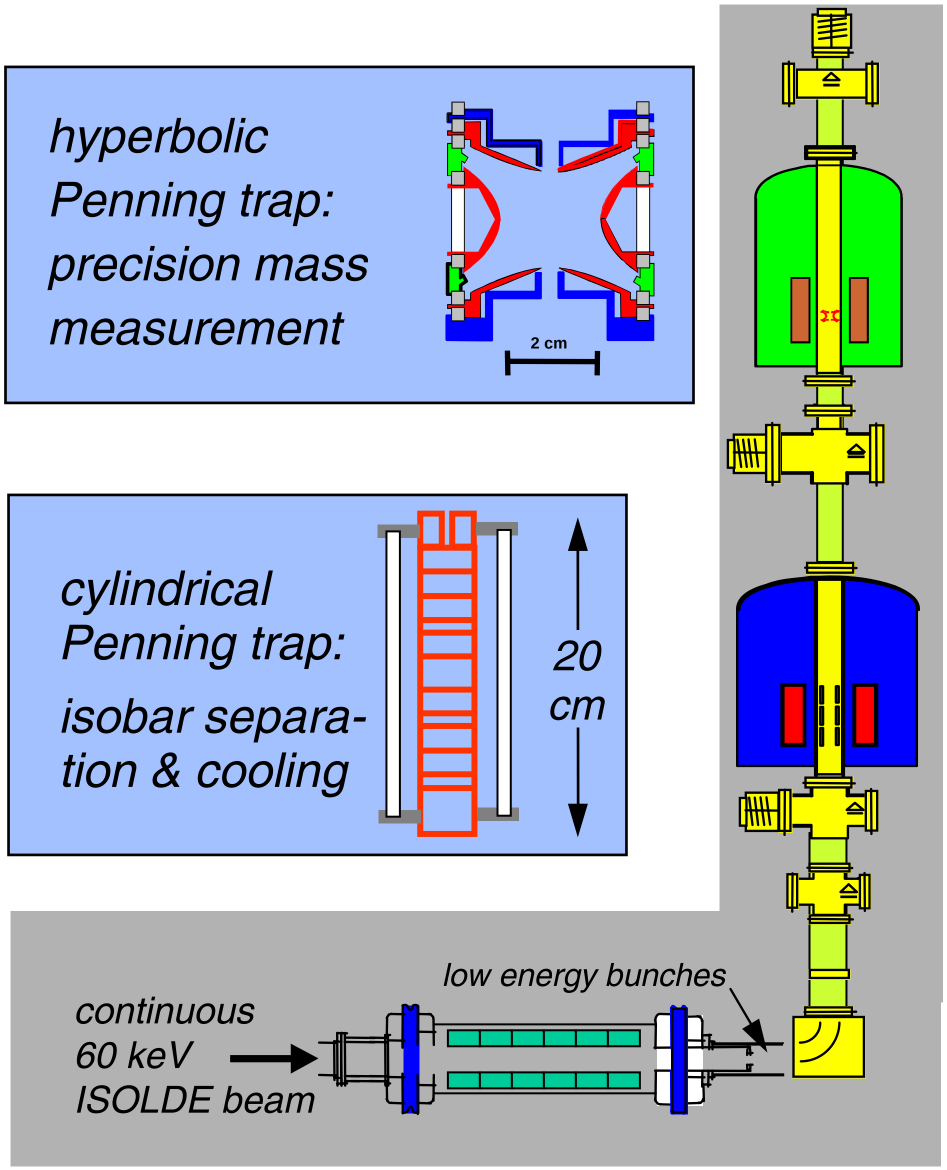


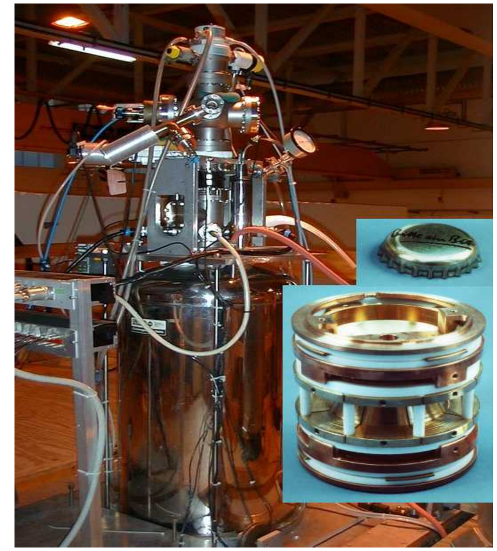


ISOLDE

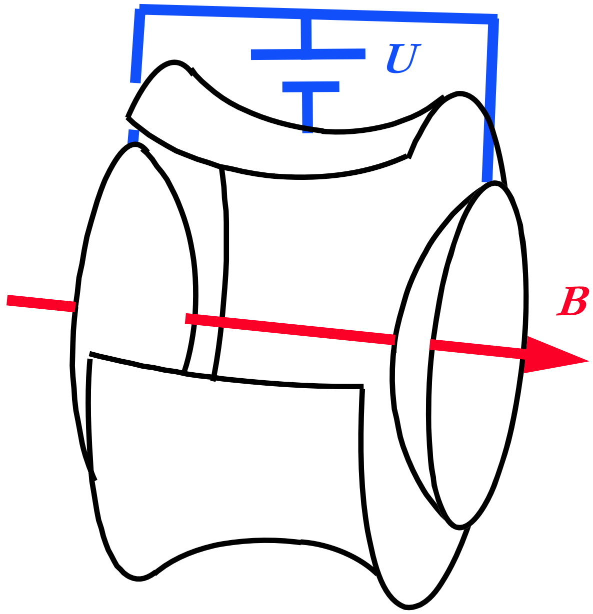
CERN, Geneva

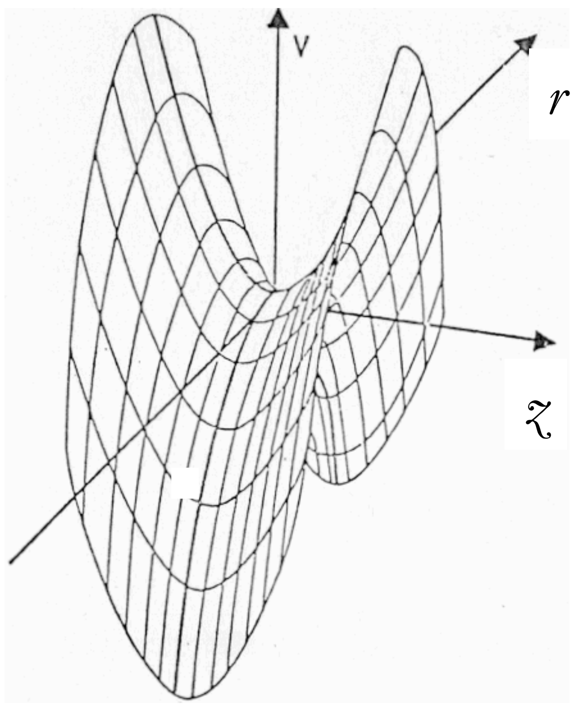
*The mass spectrometer **ISOLTRAP***

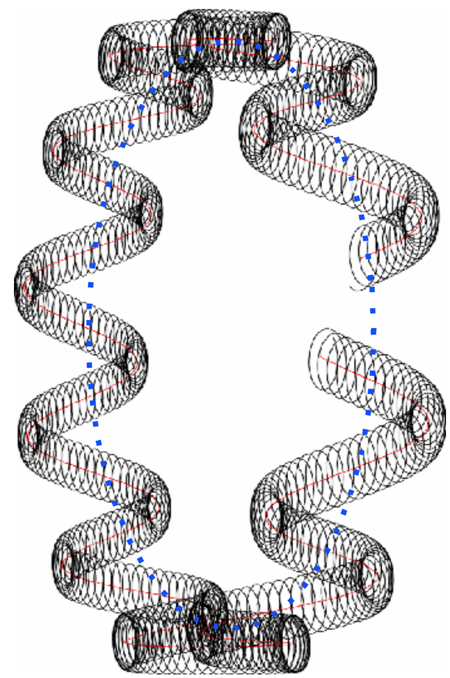




Penning Trap







$\omega_c = qB/2\pi m$

ω_z SHM

mass independent

$\omega_c = \omega_+ + \omega_-$

in a quadrupole field

PROCEEDINGS OF SCIENCE

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

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D. Mocelj, C. Fröhlich, F.-K. Thielemann, I. Panov, T. Rauscher, M. Liebendörfer
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B. Pfeiffer
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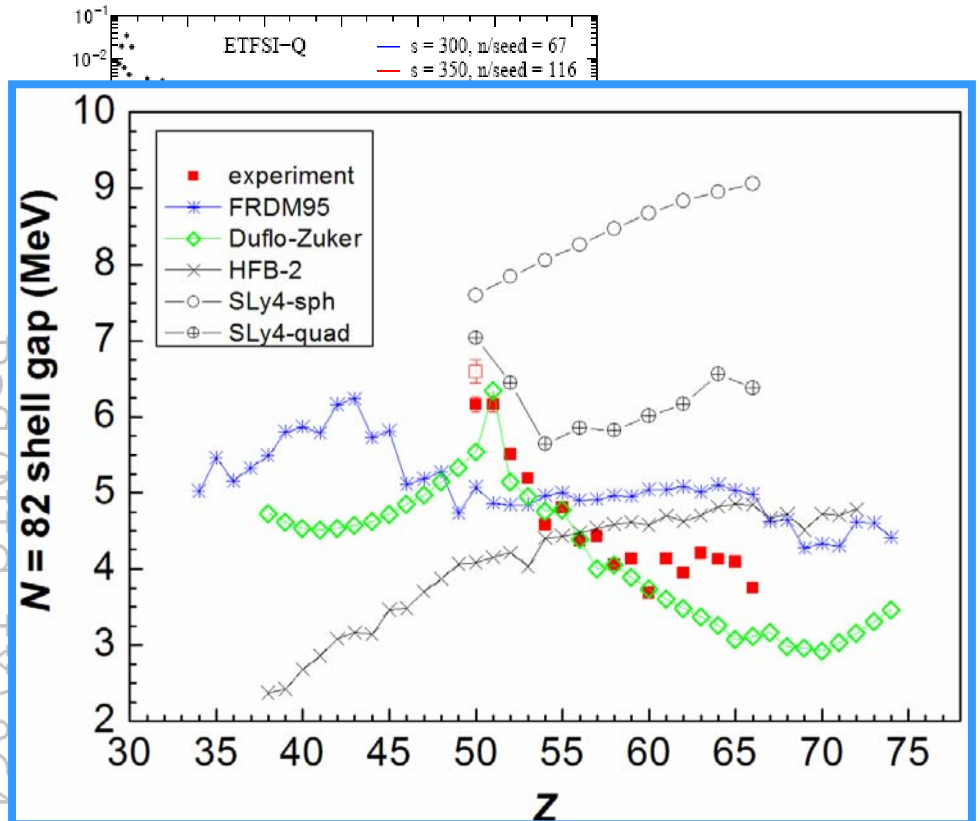
R. Buras and H.-Th. Janka
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1,
D-85741 Garching, Germany

This manuscript reviews recent progress in our understanding of the r
and heavy elements in supernovae. Recent hydrodynamical models o
show that a large amount of proton rich matter is ejected under str
matter constitutes the site of the νp-process where antineutrino ab
the nucleosynthesis of nuclei with $A > 64$. Supernovae are also ass
responsible for the synthesis of the heaviest elements in nature. Fissic
play a major role in determining the final abundance patter and in expl
features seen in metal-poor r-process-rich stars.

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

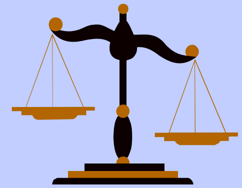


APS/123-QED

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]
[1]*GSI, Planckstraße 1, 64291 Darmstadt, Germany*
[2]*CSNSM–IN2P3–CNRS, Université de Paris Sud, 91405 Orsay, France*
[3]*Johannes Gutenberg-Universität, Institut für Physik, 55099 Mainz, Germany*
[4]*CERN, Physics Department, 1211 Geneva 23, Switzerland*
[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)

Techniques



Indirect

reactions:

$A(a,b)B$

$Q = M_A + M_a - M_b - M_B$

decays:

$A \rightarrow B + \alpha$

$Q_\alpha = M_B - M_A$

Direct

(mass spectrometry)

time of flight:

SPEG/CSS2, GANIL

ESR, GSI

cyclotron frequency:

ISOLTRAP, ISOLDE

MISTRAL, ISOLDE

PRODUCTION SCHEME

FIFS (MeV)

gas cell RFQ

ISOL (keV)

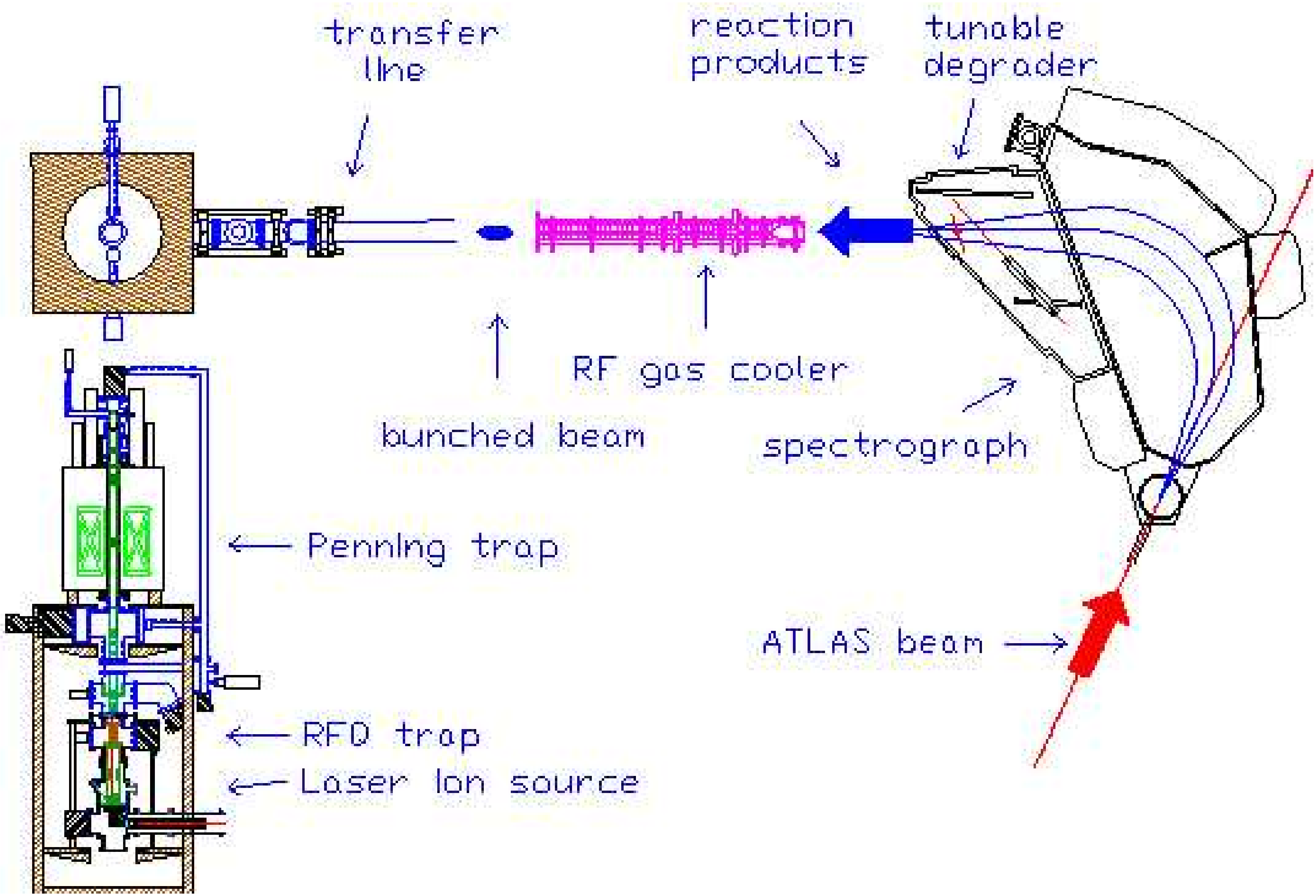
better sensitivity

better precision

'the best of both worlds'

→ *CPT* at *ANL*

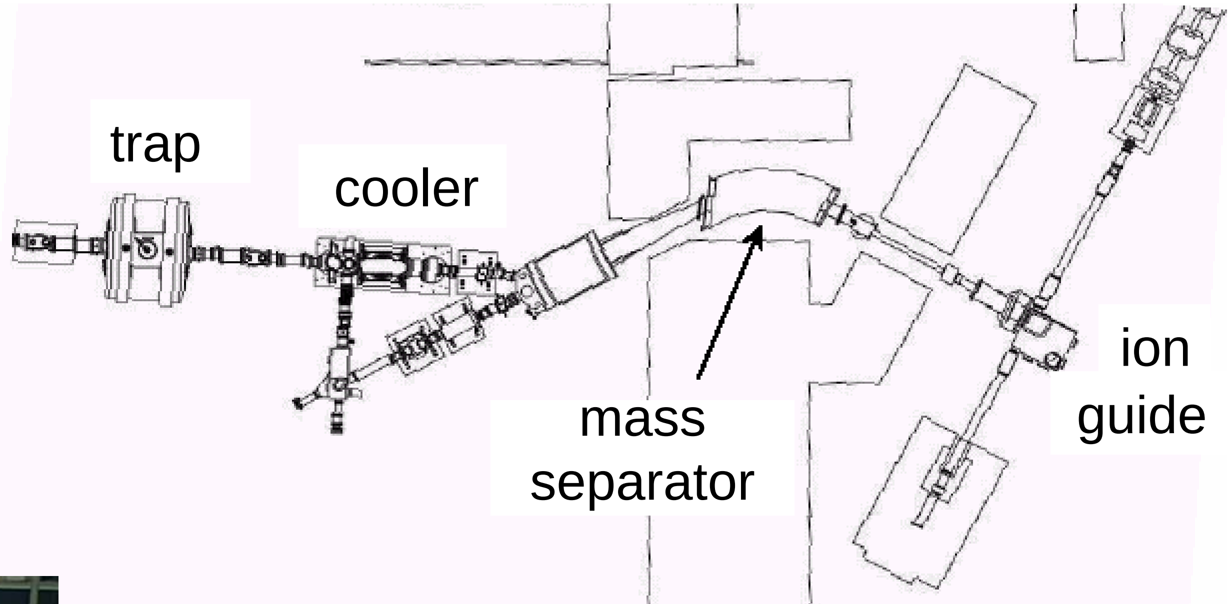
Canadian Penning Trap (CPT) facility at ANL




TITAN (TRIUMF)
(RIKENRING)
CPT (ANL)
LEBIT (NSCL)
JYFLTRAP
SMILETRAP (MSI)
ISOLTRAP (CERN)
SHIPTRAP (GSI)
MATS (FAIR)
MAFFTRAP
150°
165°
PACIFIC OCEAN
NORTH AMERICA
UNITED STATES
CANADA
ARCTIC OCEAN
North Pole
75°
60°
45°
30°
GREENLAND (DEN.)
Arctic Circle
RUSSIA
ASIA
CHINA
ATLANTIC OCEAN
SWEDEN
KAZAKHSTAN
Bay of Bengal
U.K.
INDIA
IRAN
IRAQ
Arabian Sea
ALGERIA
Mediterranean Sea
EGYPT
SAUDI ARABIA
LIBYA
Tropic of Cancer

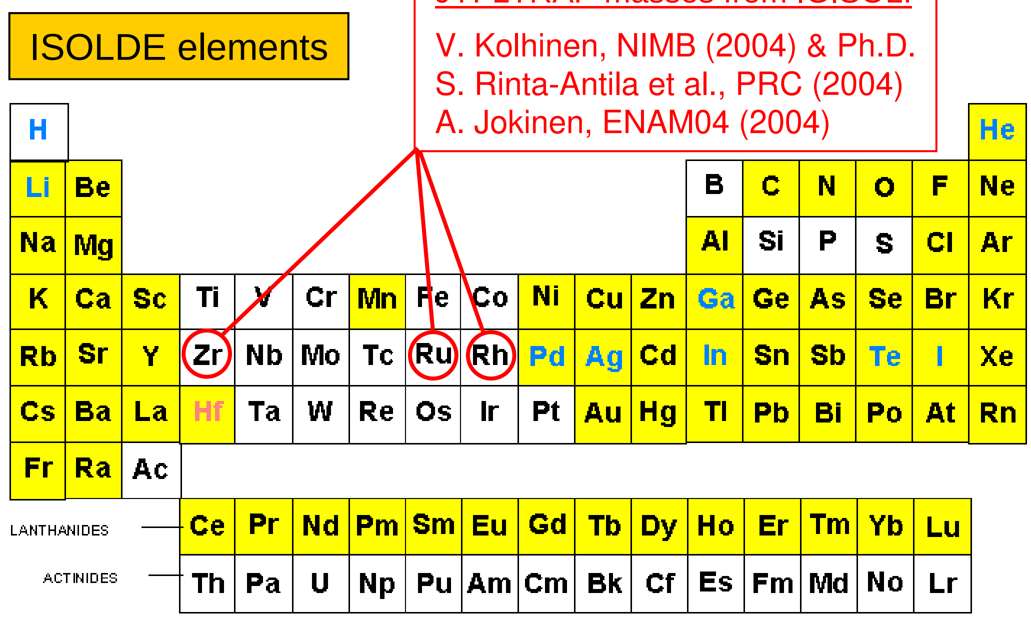

Before there were Backstreet Boys...
Before the other guys got 'N Sync...
Danny, Jordan, Johnny, Donnie and Joey changed the rules...
NEW KIDS ON THE BLOCK
or "what ISOLTRAP hath wrought"

JYFLTRAP at the IGISOL facility in Jyväskylä



JYFLTRAP masses from IGISOL:

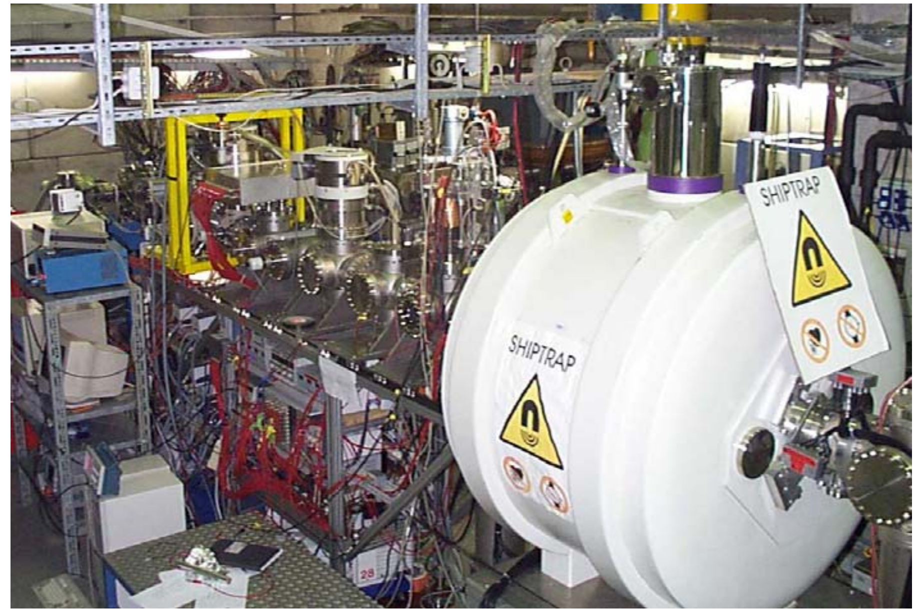
V. Kolhinen, NIMB (2004) & Ph.D.
S. Rinta-Antila et al., PRC (2004)
A. Jokinen, ENAM04 (2004)

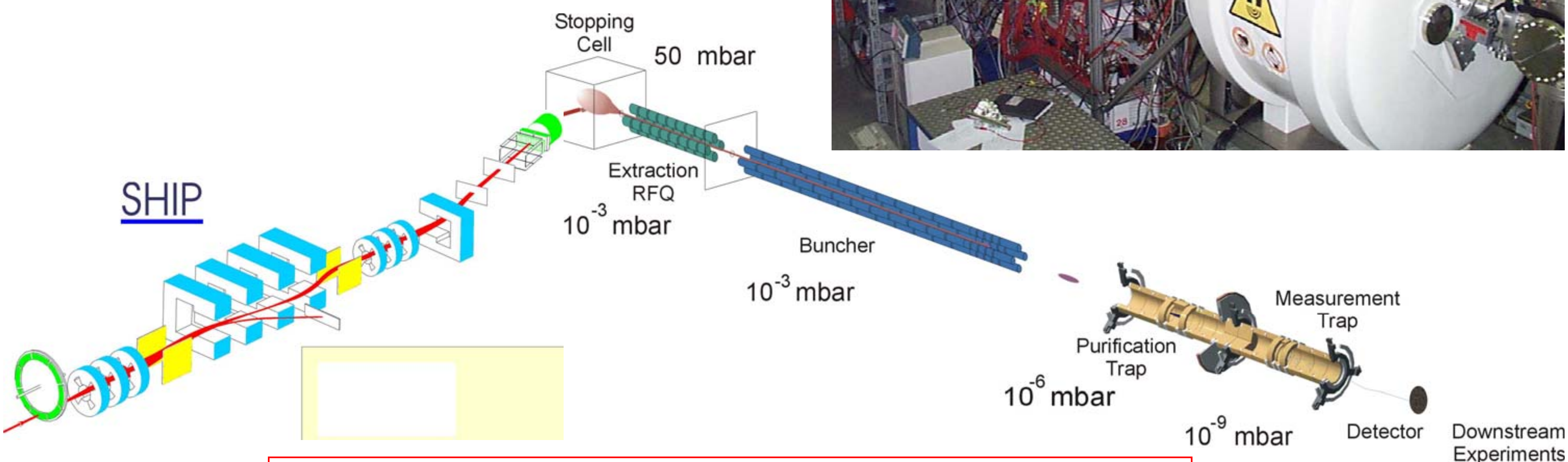


SHIPTRAP facility at GSI

ISOL facility for transuranium nuclides

for
- Nuclear Physics
- Chemistry
- Atomic Physics
- Mass Measurements



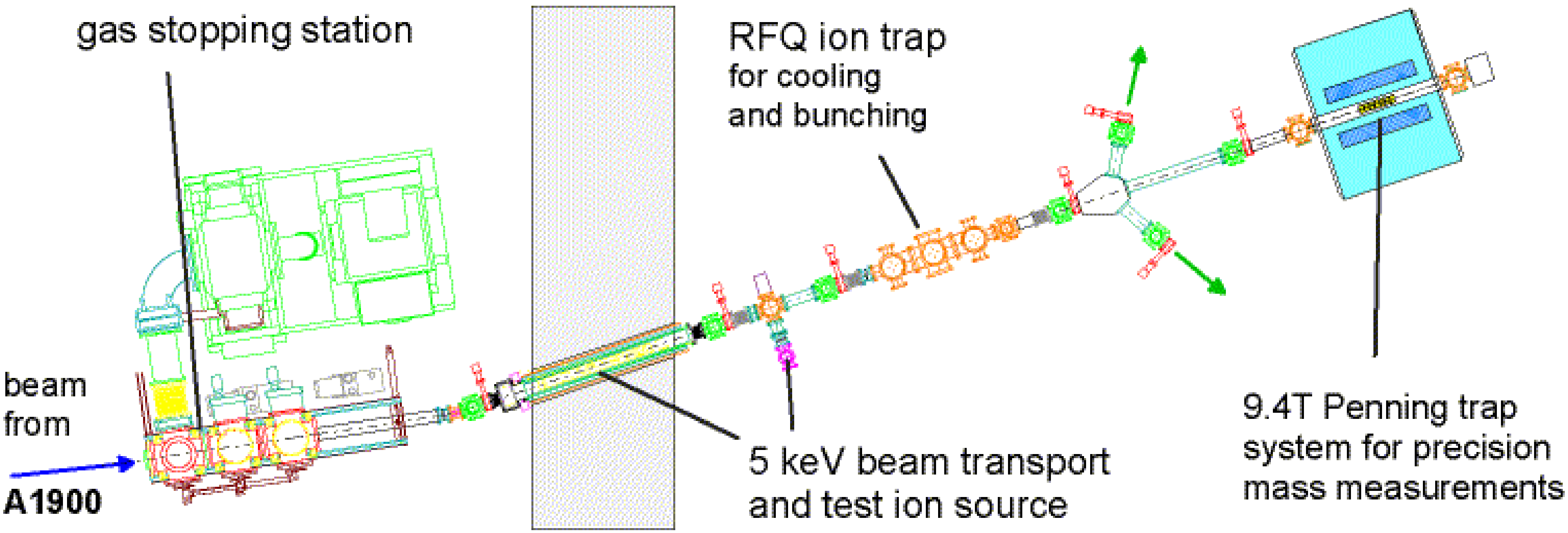


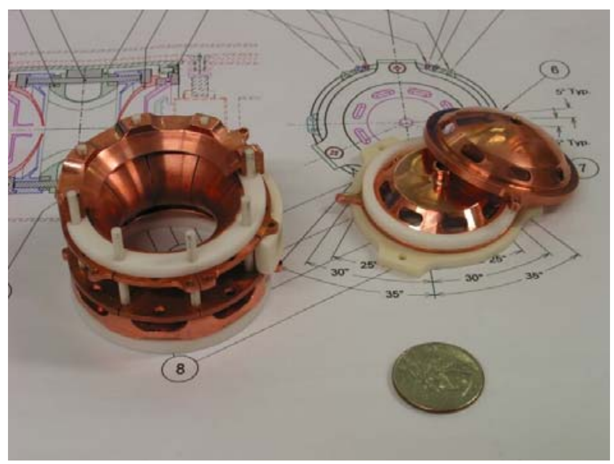
^{92}Mo (^{58}Ni,*xpyn*) ^{147}Ho

→ new masses for ^{147}Ho, ^{147,148}Er (~10^{-6})

(M. Bloch *et al*., ENAM04) → Ana Martin!

Low Energy Beam & Ion Trap (LEBIT) facility at NSCL/MSU





G. Bollen EMIS/ENAM proceedings

Let’s pause and catch our breath…

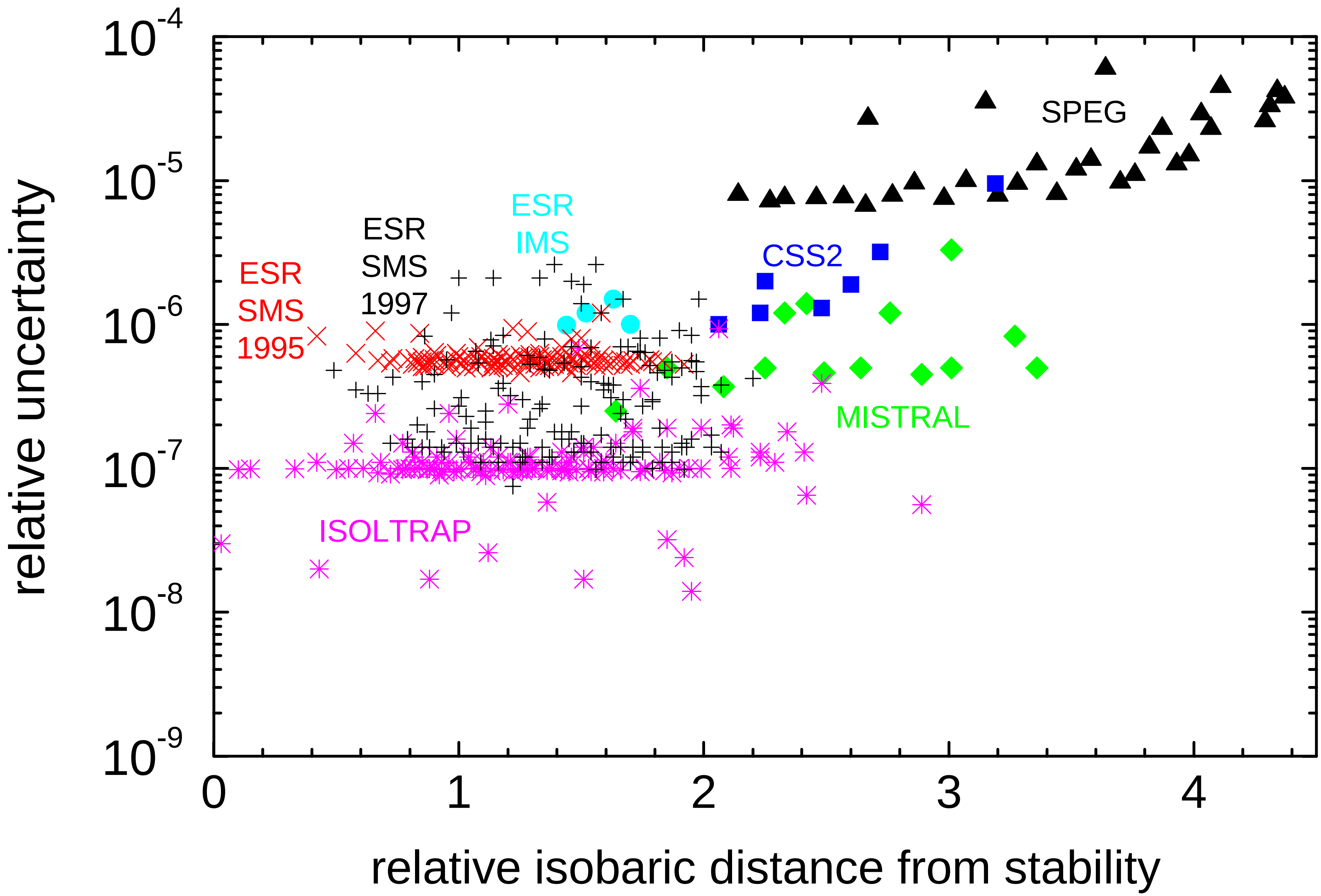
How do all these (different?) programs compare?

Are they really different?
Are they complementary?

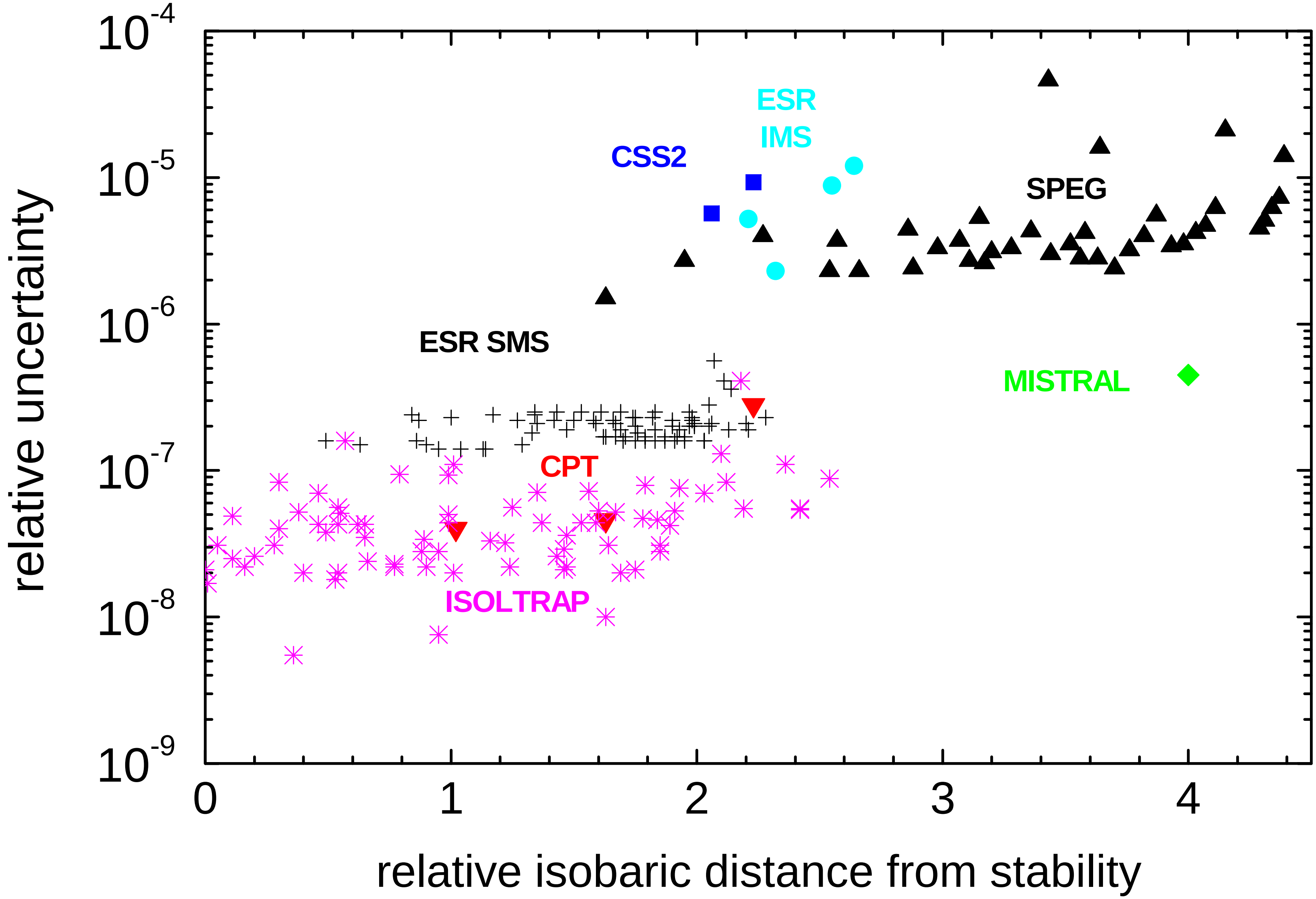
(no one facility has enough beam time…
…or students to analyze the data!)

comparison of current (direct) mass measurement programs

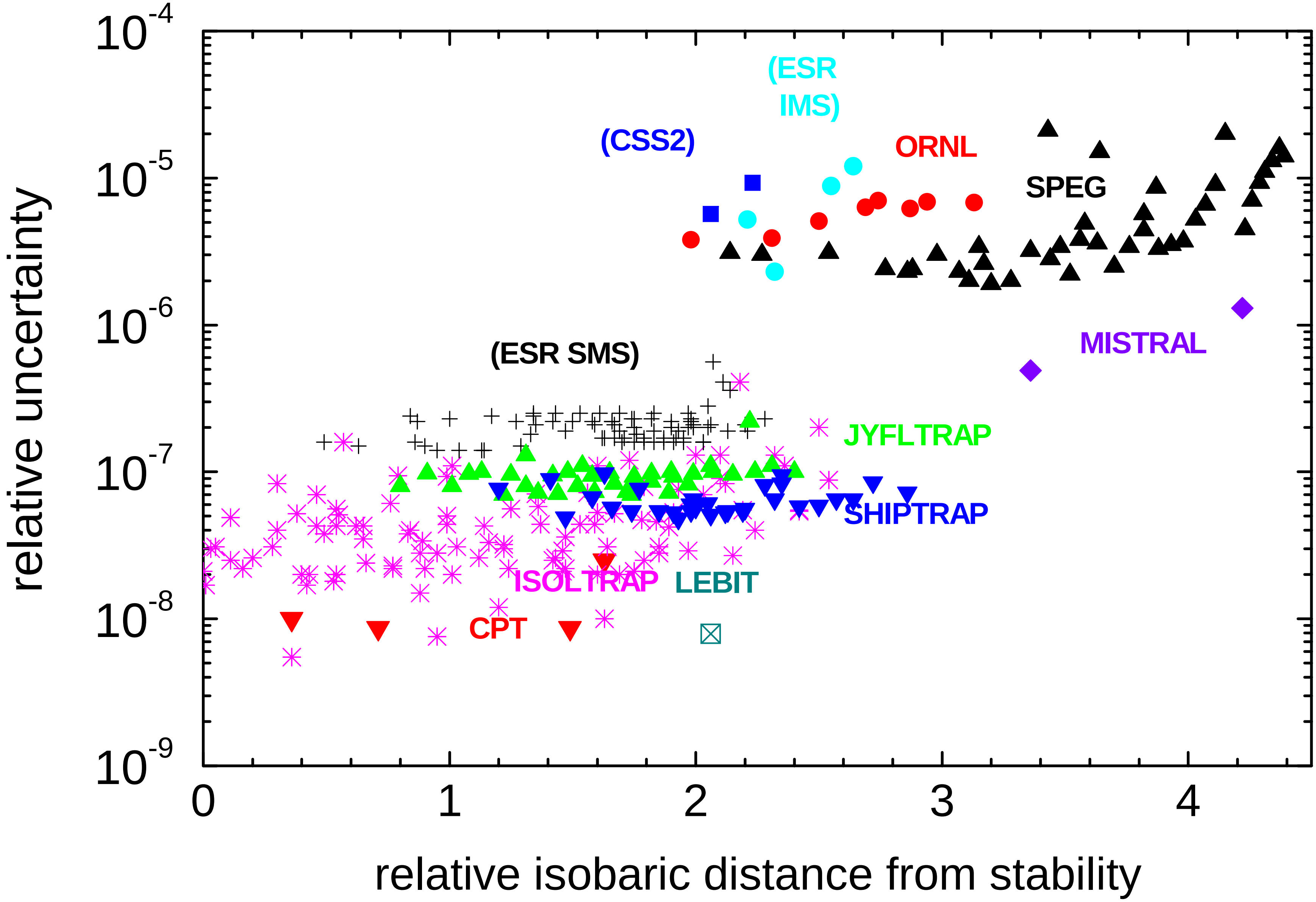
	SPEG	ESR	MISTRAL	ISOLTRAP
resolution	10^4	10^6	10^5	10^7
precision	10^{-5} - 10^{-6}	$1\text{-}5 \times 10^{-7}$	$3\text{-}6 \times 10^{-7}$	$1\text{-}5 \times 10^{-8}$
sensitivity	10^{-1}/s	1	10^3/s	10^2/s
half-life	1 μs	10 s	1 ms	50 ms
applicability	A < 70	universal	universal (ISOLDE)	universal (ISOLDE)
forte	exotic species	life-times	short $T_{½}$ & accuracy	highest accuracy
Achilles heel	μs-isomers	calibration	sys. error	meas. time
future	better timing CIME	isochronous mode $\rightarrow$ μs	cooler	ICR detection



Reviews of Modern Physics, 75 (2003) 1021

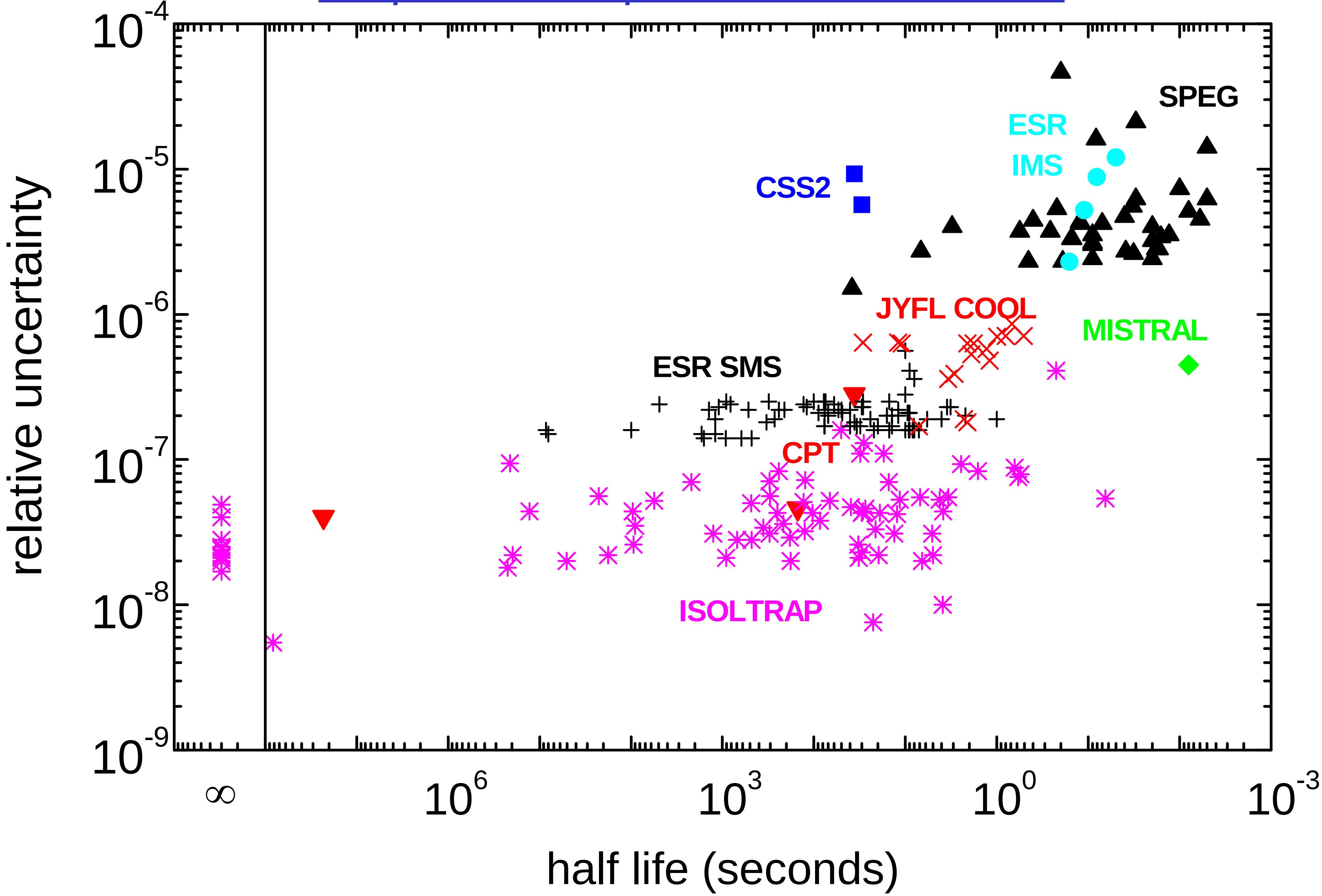


ENAM04 Proc., Eur. Phys. J. A, 25 (2005) 3

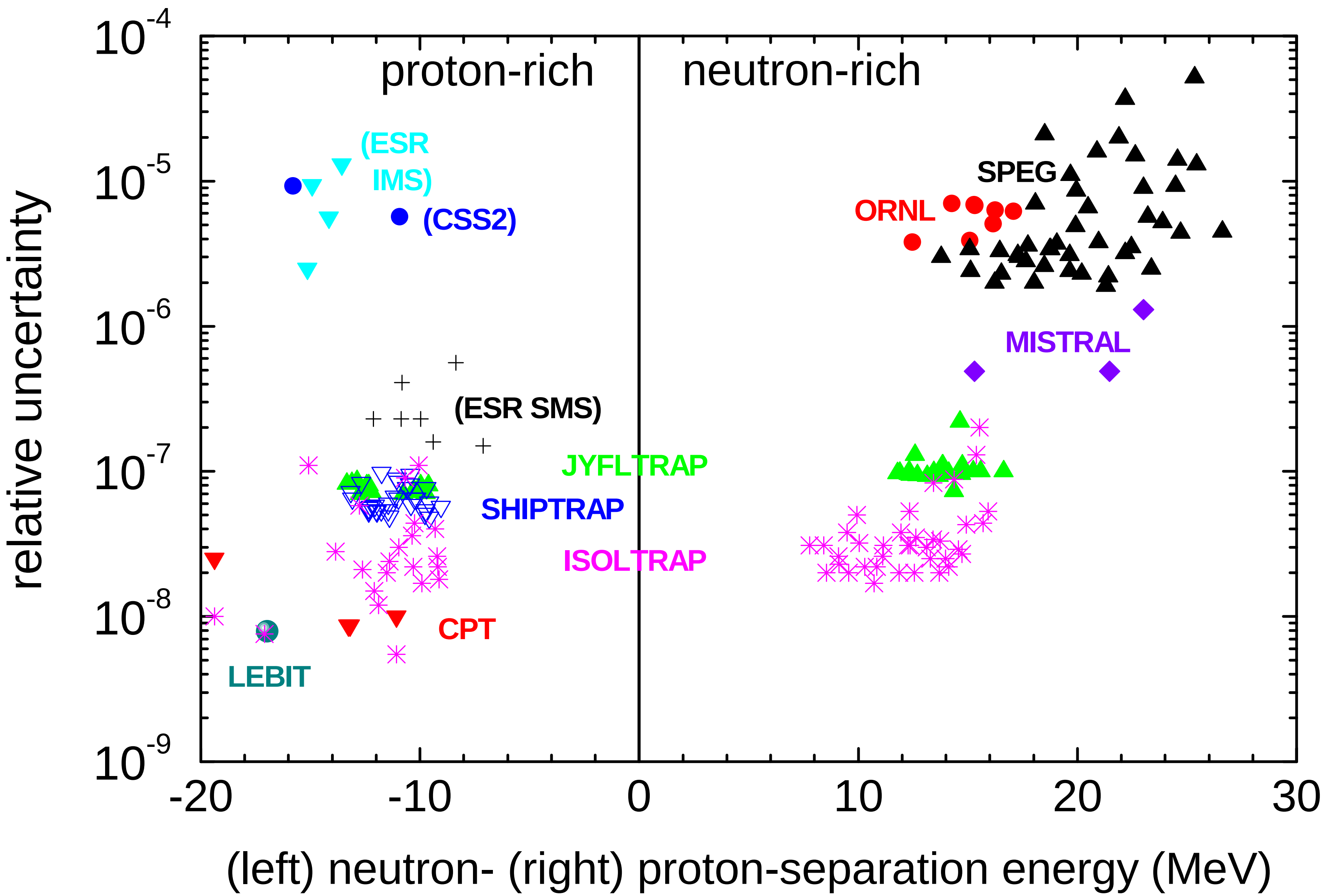


Proc. Nuclei in the Cosmos IX, PoS (2006) ?

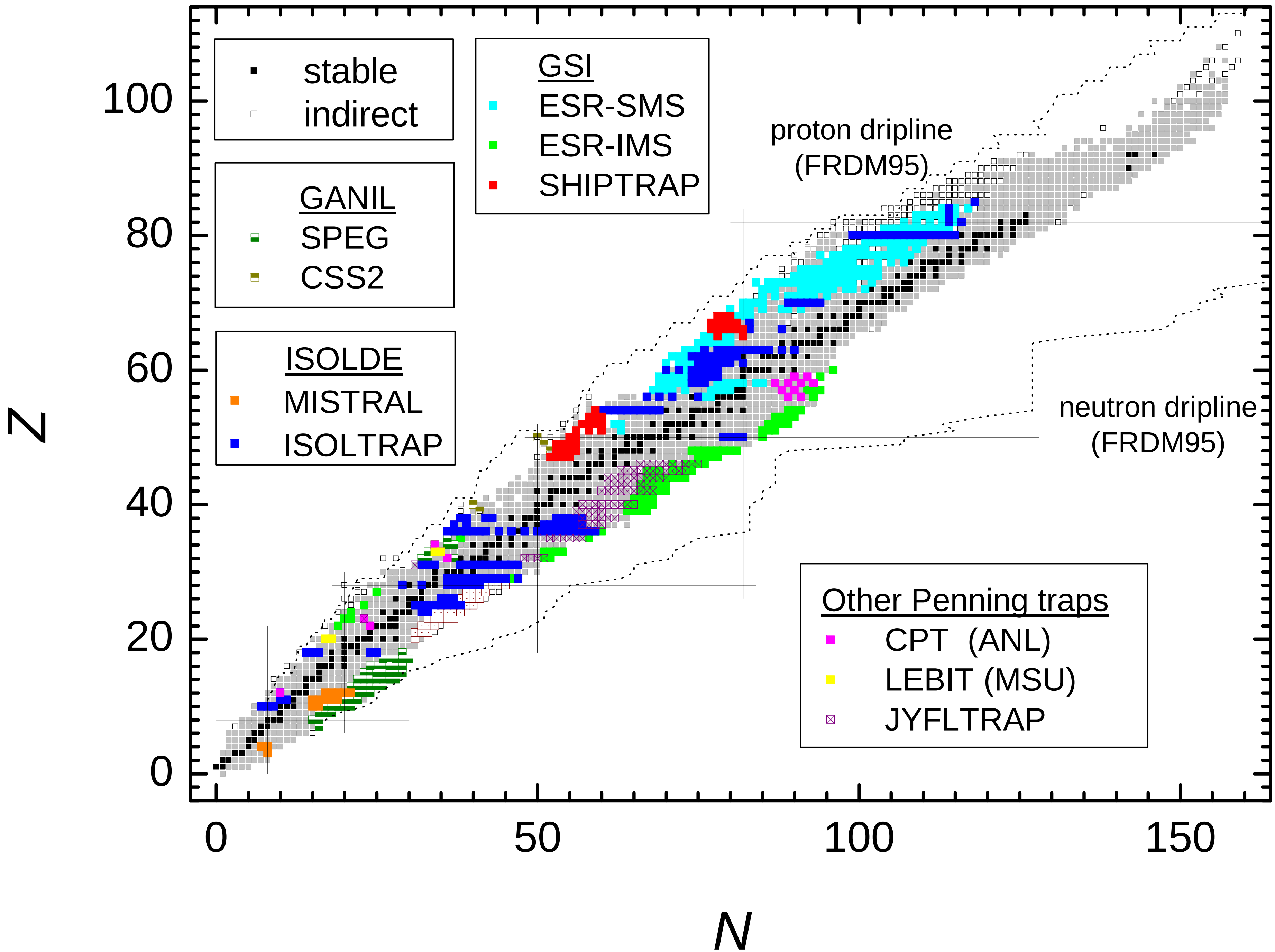
Performance of the various methods



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



proton-rich
neutron-rich
(ESR
IMS)
(CSS2)
SPEG
ORNL
MISTRAL
(ESR SMS)
JYFLTRAP
SHIPTRAP
ISOLTRAP
CPT
LEBIT
relative uncertainty
(left) neutron- (right) proton-separation energy (MeV)
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
-20
-10
0
10
20
30



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

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