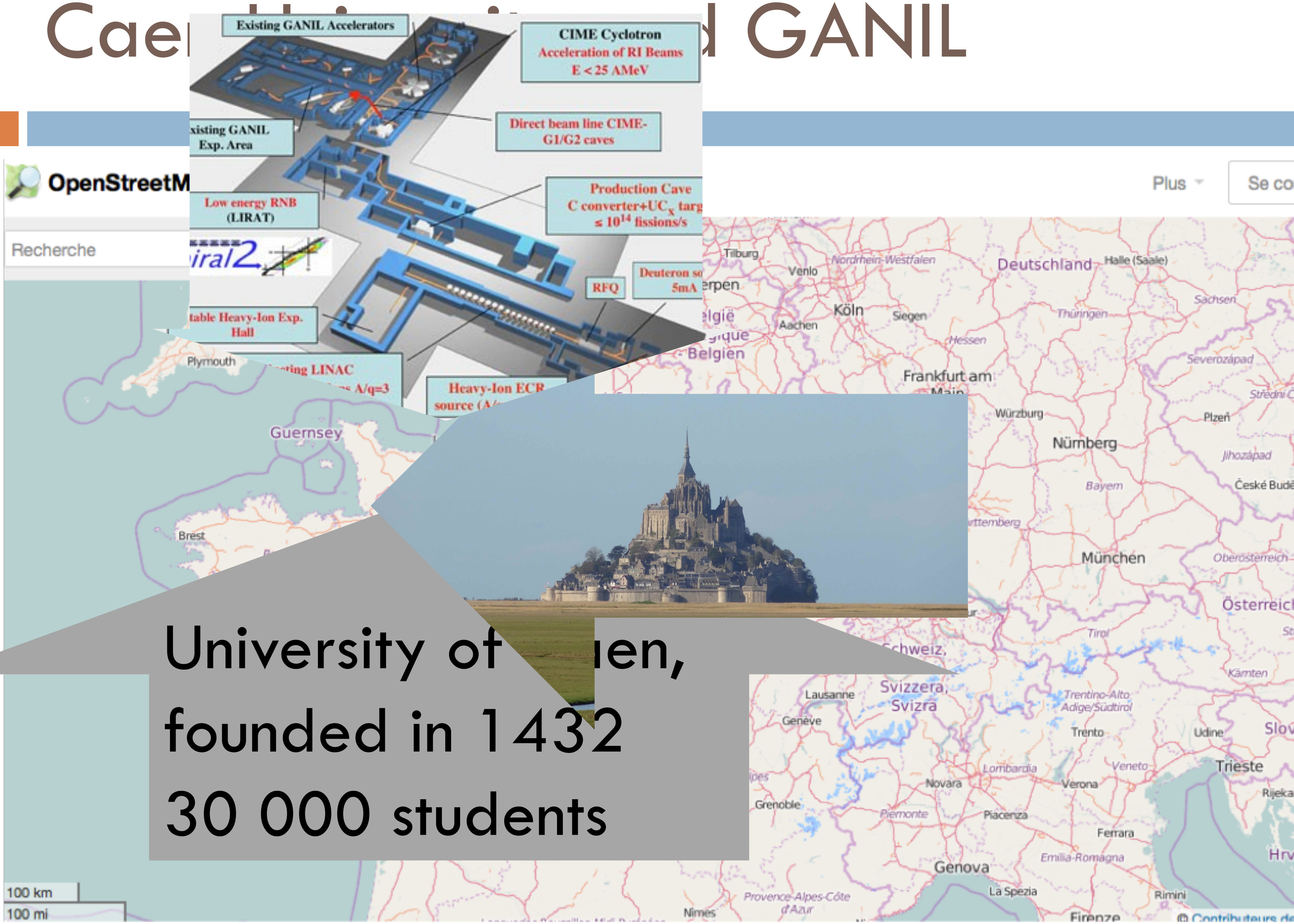
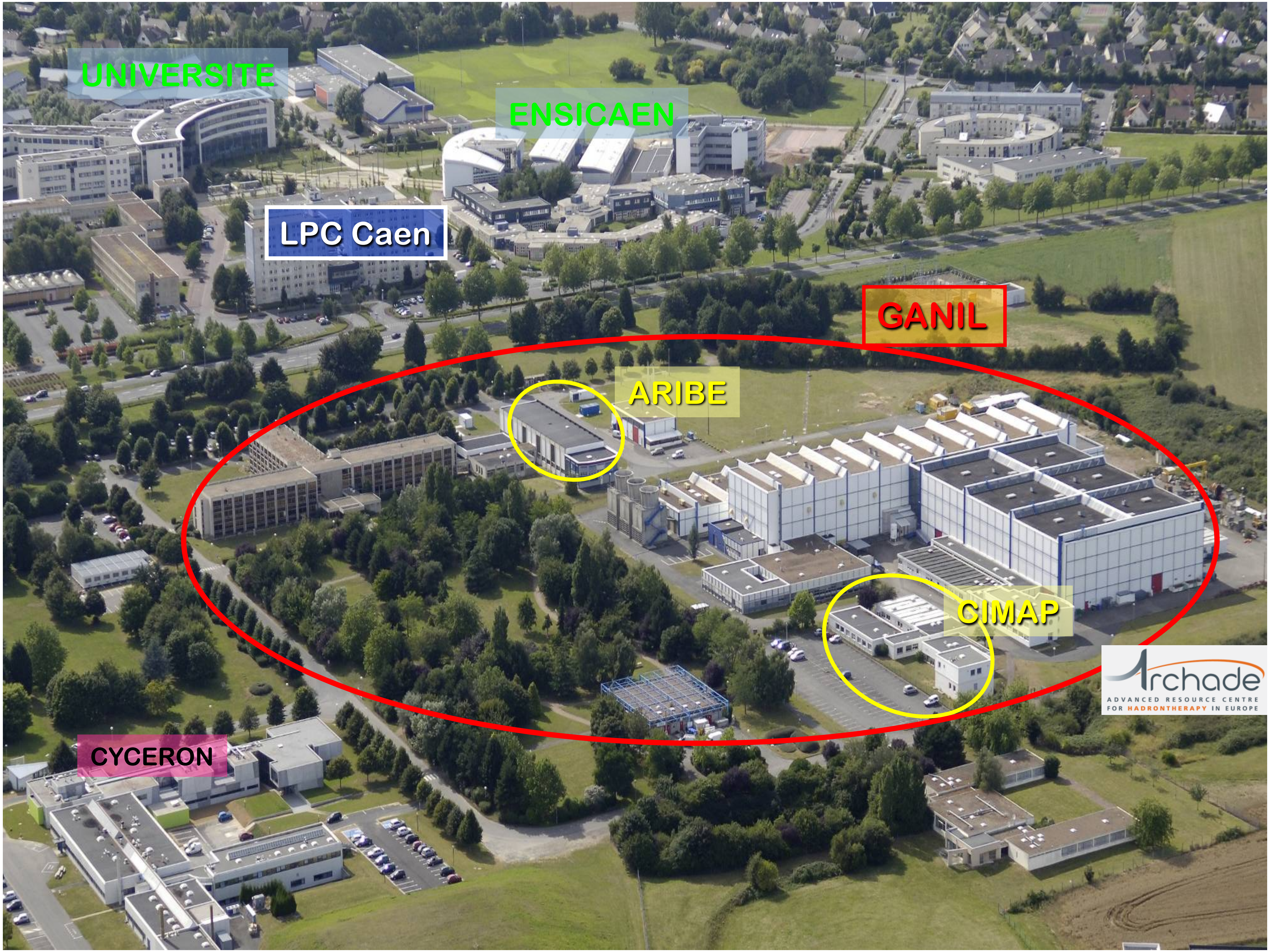
SYNTHESIS OF SUPER-HEAVY ELEMENTS, WHAT CAN WE PREDICT?

David Boilley
GANIL and Normandie Université

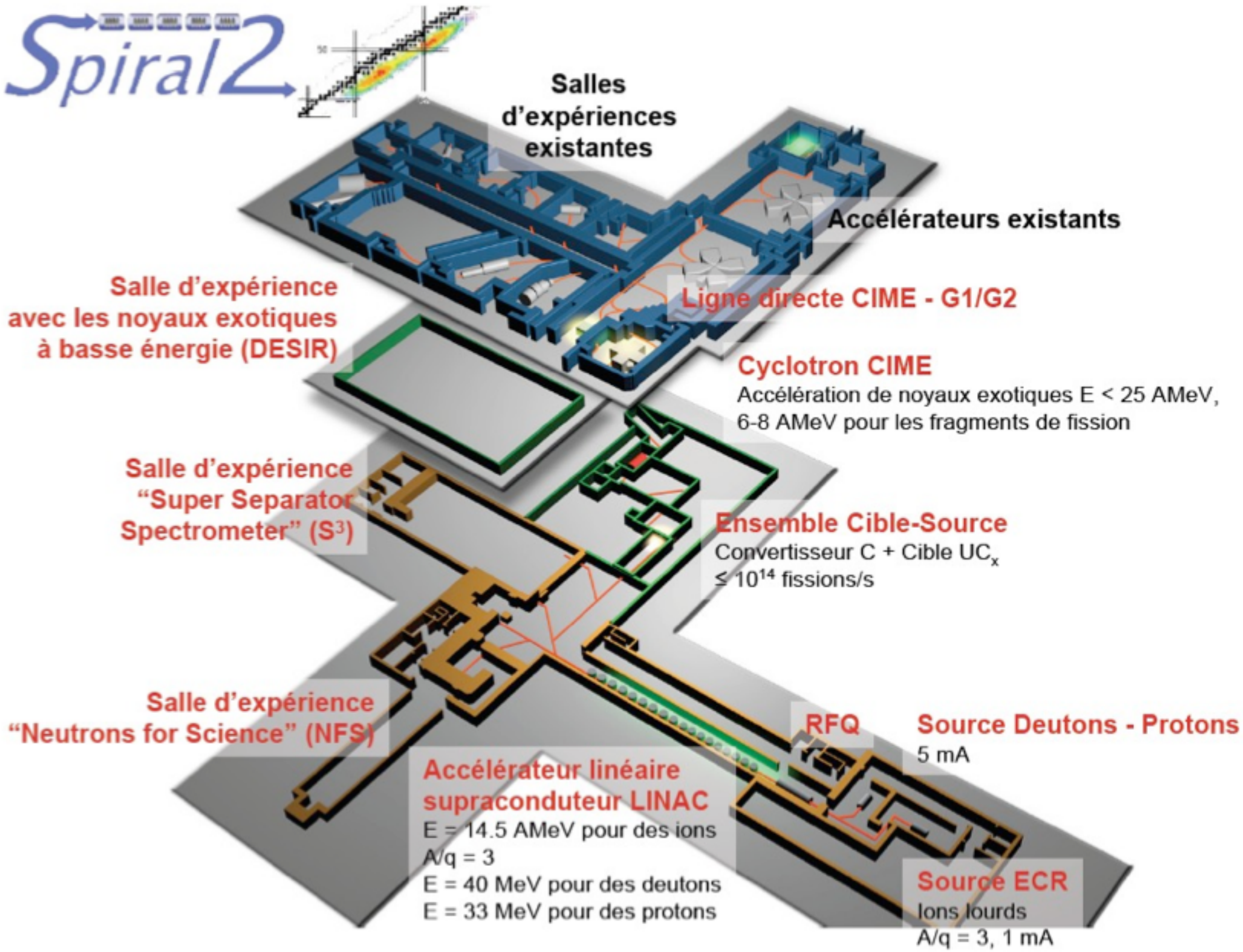
Cae… d GANIL

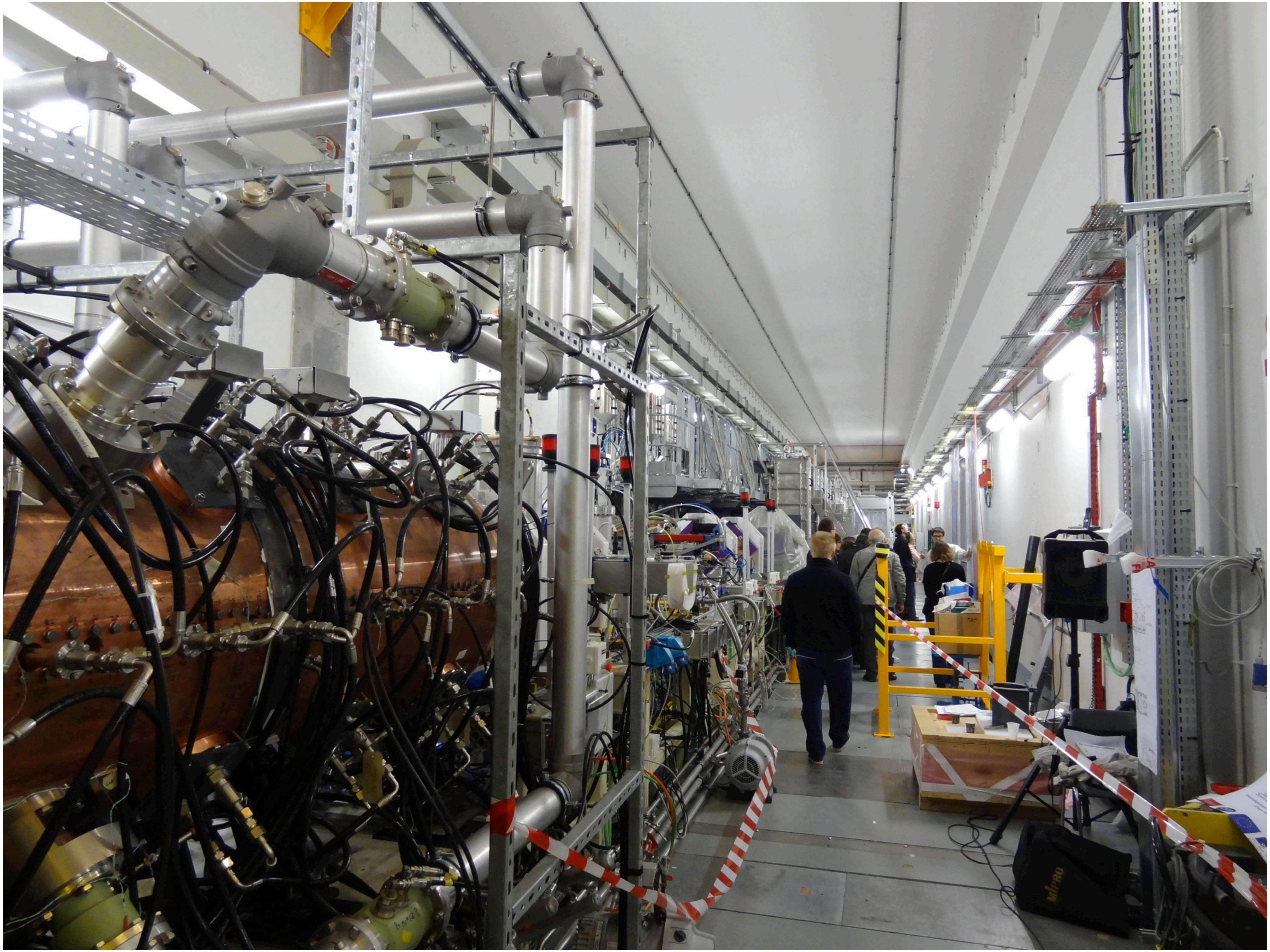


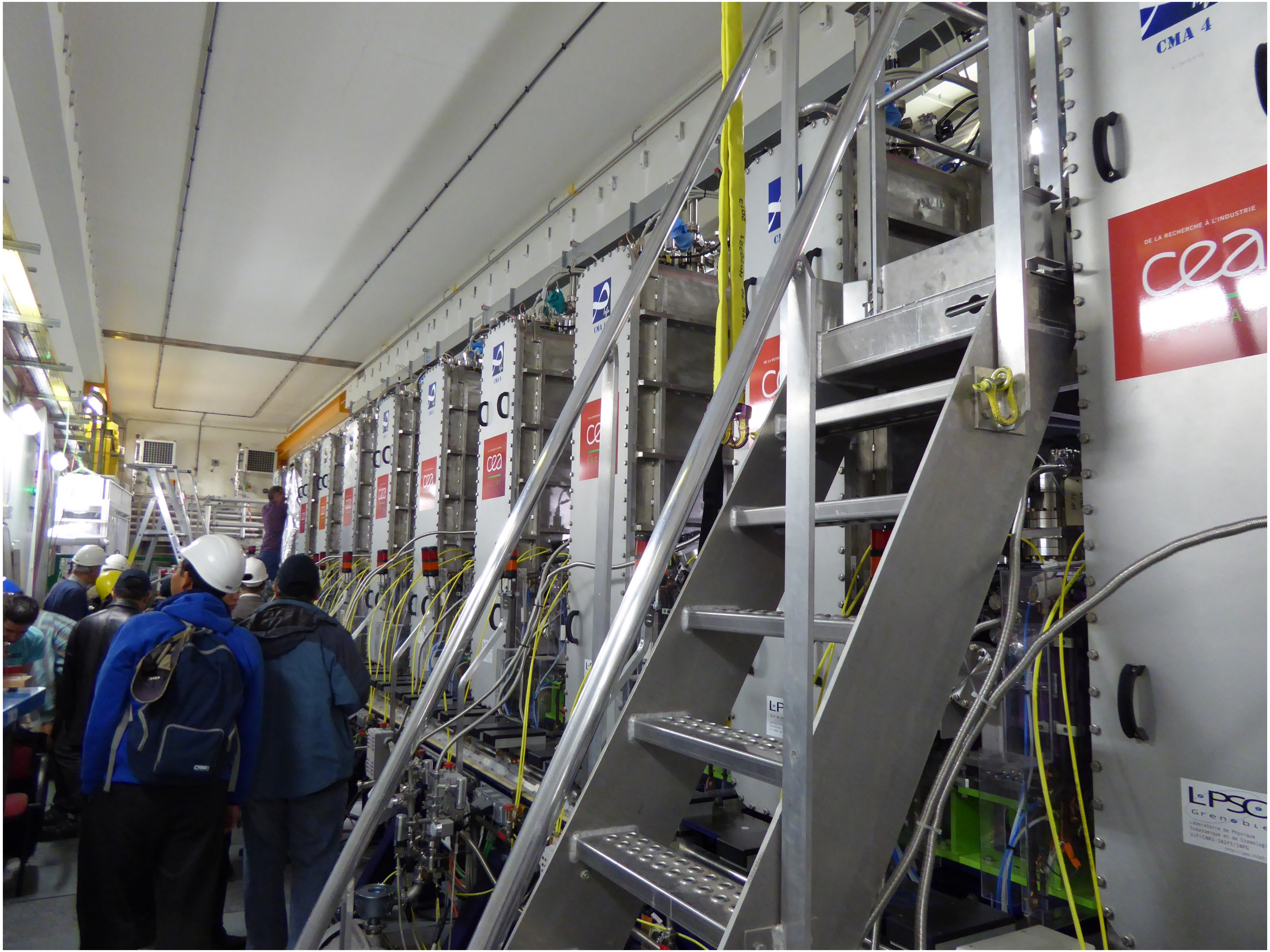
University of …en,
founded in 1432
30 000 students

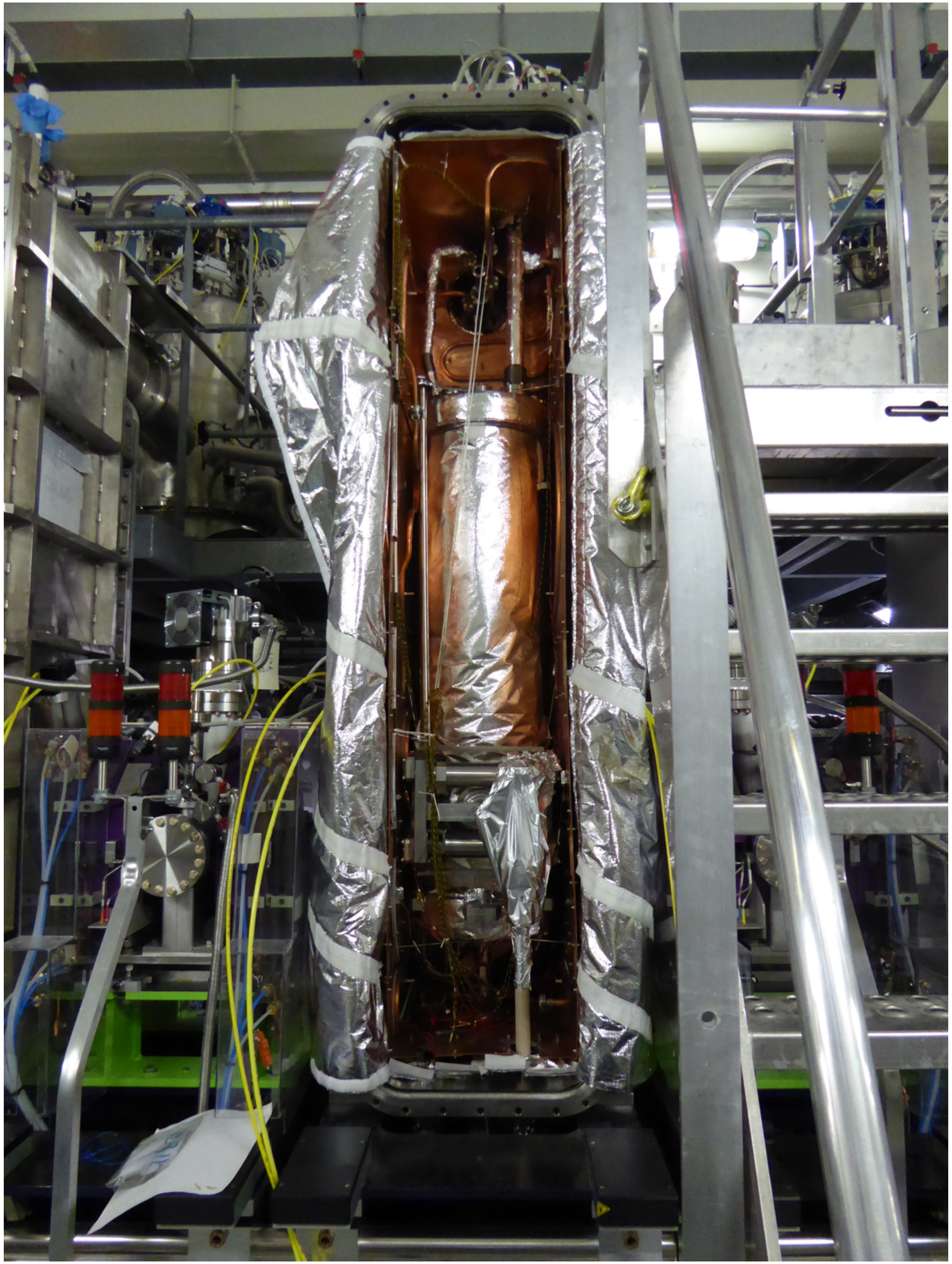

UNIVERSITE
ENSICAEN
LPC Caen
GANIL
ARIBE
CIMAP
CYCERON
Archade
ADVANCED RESOURCE CENTRE FOR HADRONTHERAPY IN EUROPE

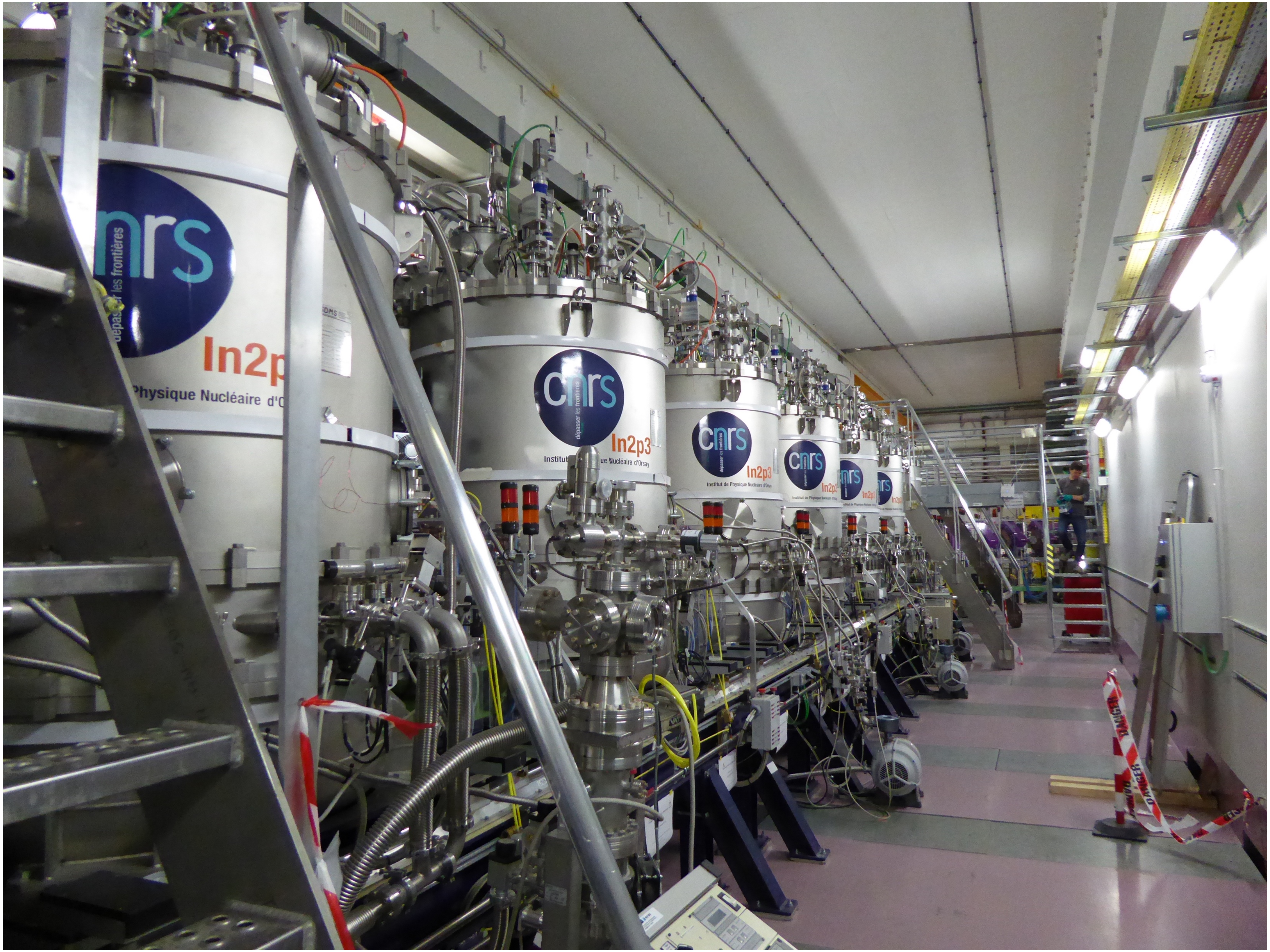
GANIL-SPIRAL2



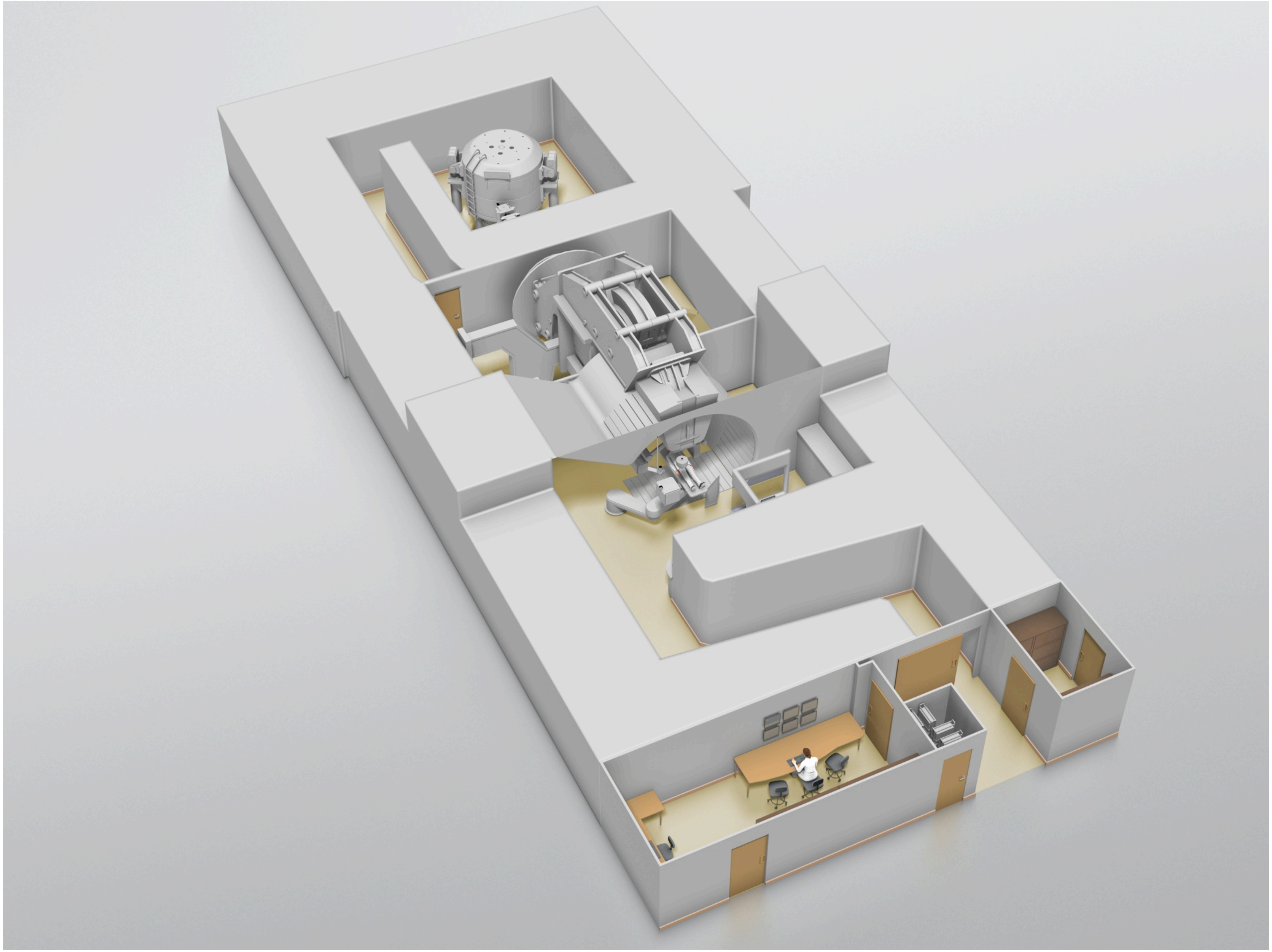



CMA 4
DE LA RECHERCHE À L'INDUSTRIE
cea




cnrs
dépasser les frontières
In2p3
DANGER

Applications



Synthesis of super-heavy-elements: what can we predict?

David BOILLEY,

Hongliang LÜ (吕宏亮) and Bartholomé CAUCHOIS

GANIL and Normandie Université/Unicaen

Yasuhisa ABE (阿部恭久)
RCNP, Osaka
(大阪大学核物理研究センター)

Caiwan SHEN (沈彩万)
Huzhou University
(湖州师范学院)

Anthony MARCHIX
CEA/DRF/IRFU Saclay

Michał Kowal
NCBJ (Warsaw)

Guy Royer
Subatech and Univ. de Nantes

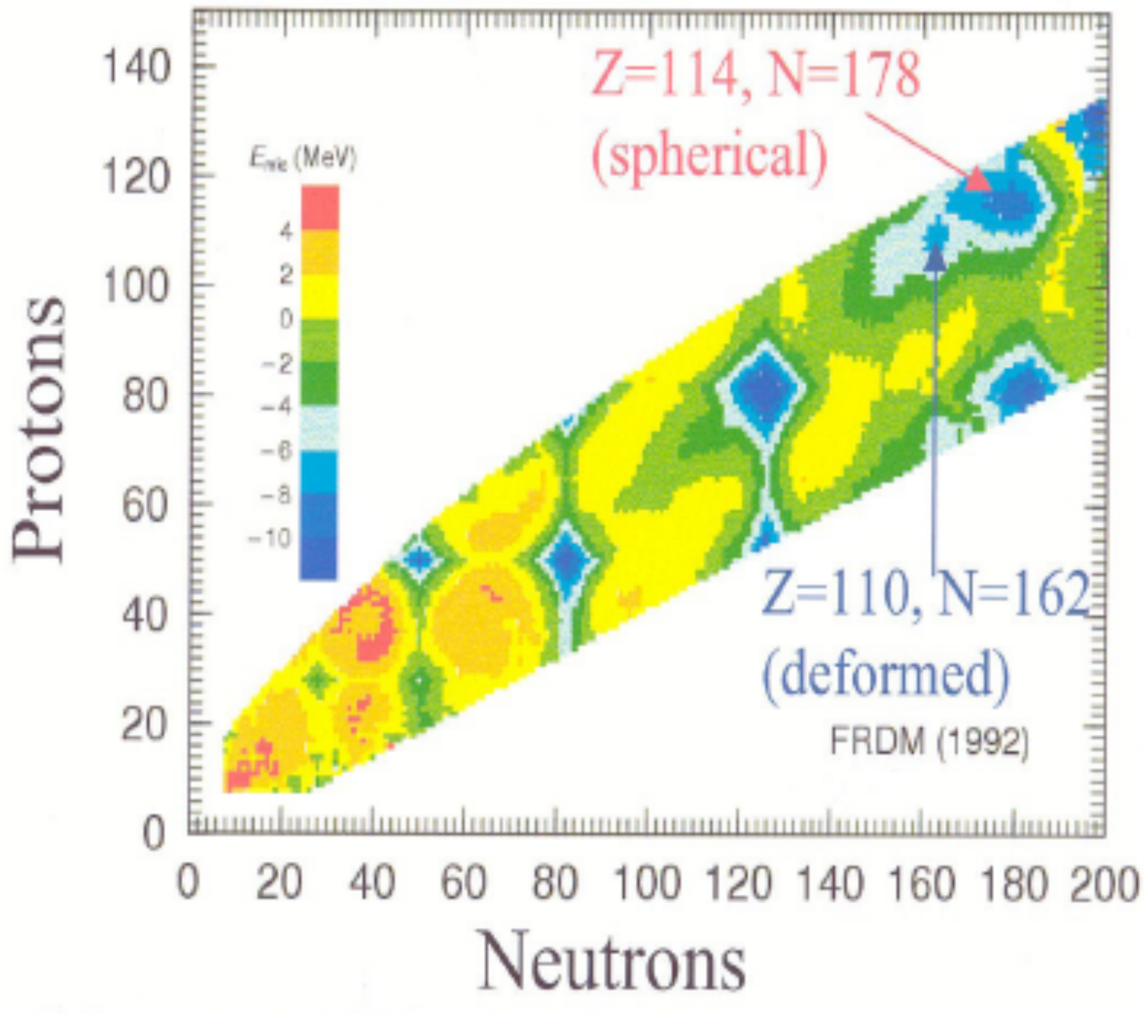
What is the heaviest element?

- Size of atoms is limited. Why?
- Chemistry: Zmax=172
- Nucleus: Zmax=?

- Liquid Drop Model: no fission barrier
- Extra stability from the shell closure

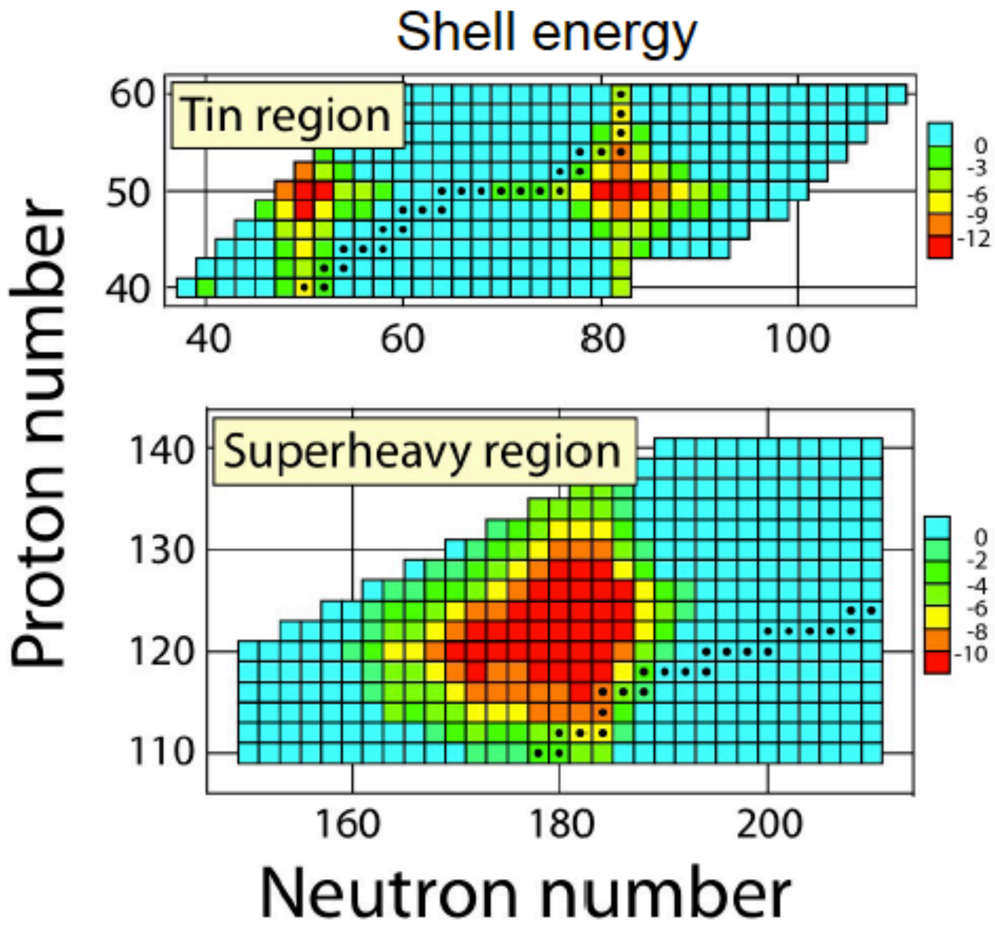
Shell energy correction

	Z	N
W. S.	114	184
F.R.D.M.	114	178
H.F.B.	126	184
R.M.F.	120	172



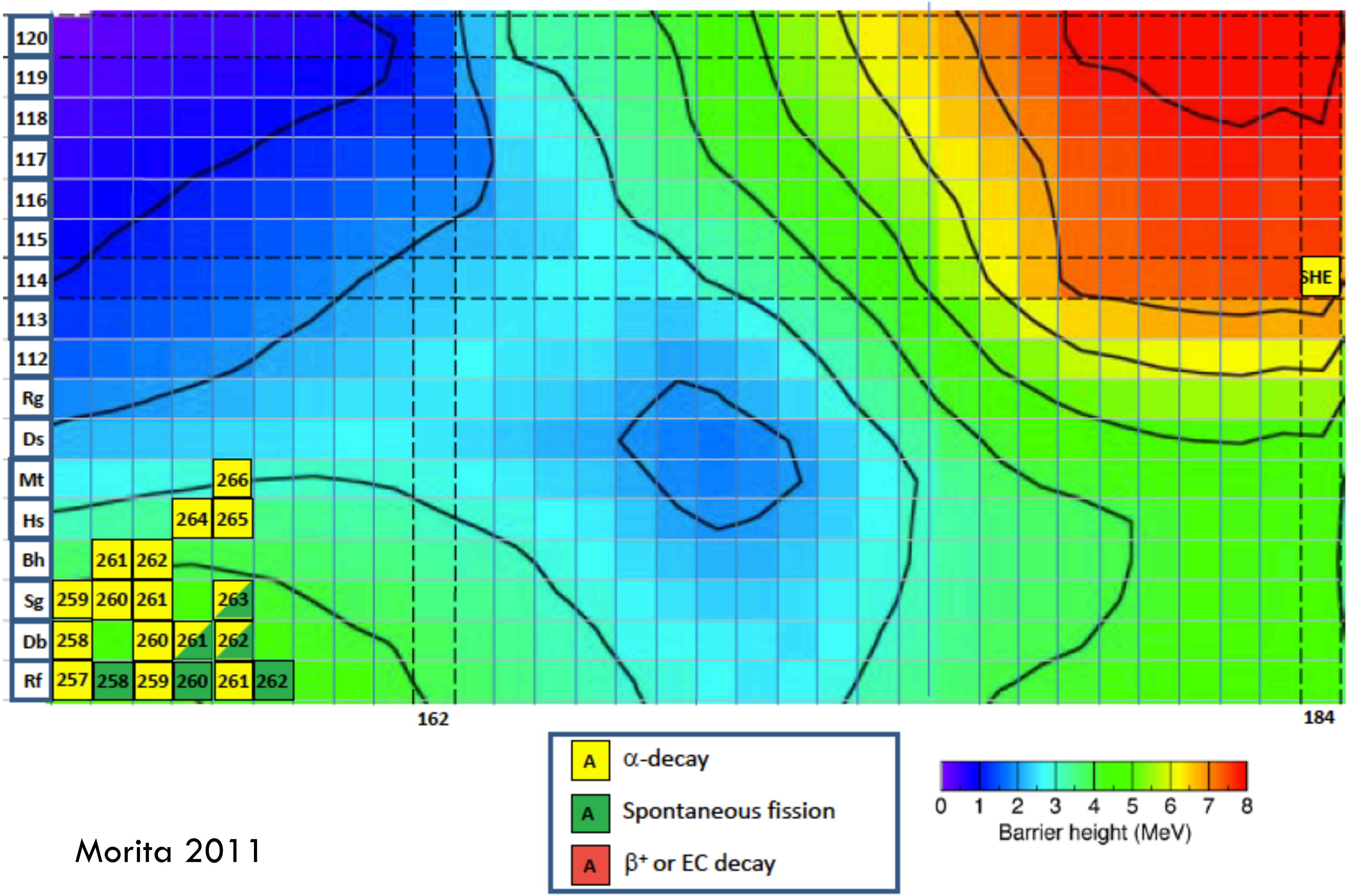
P. Möller et al

Shell correction energy



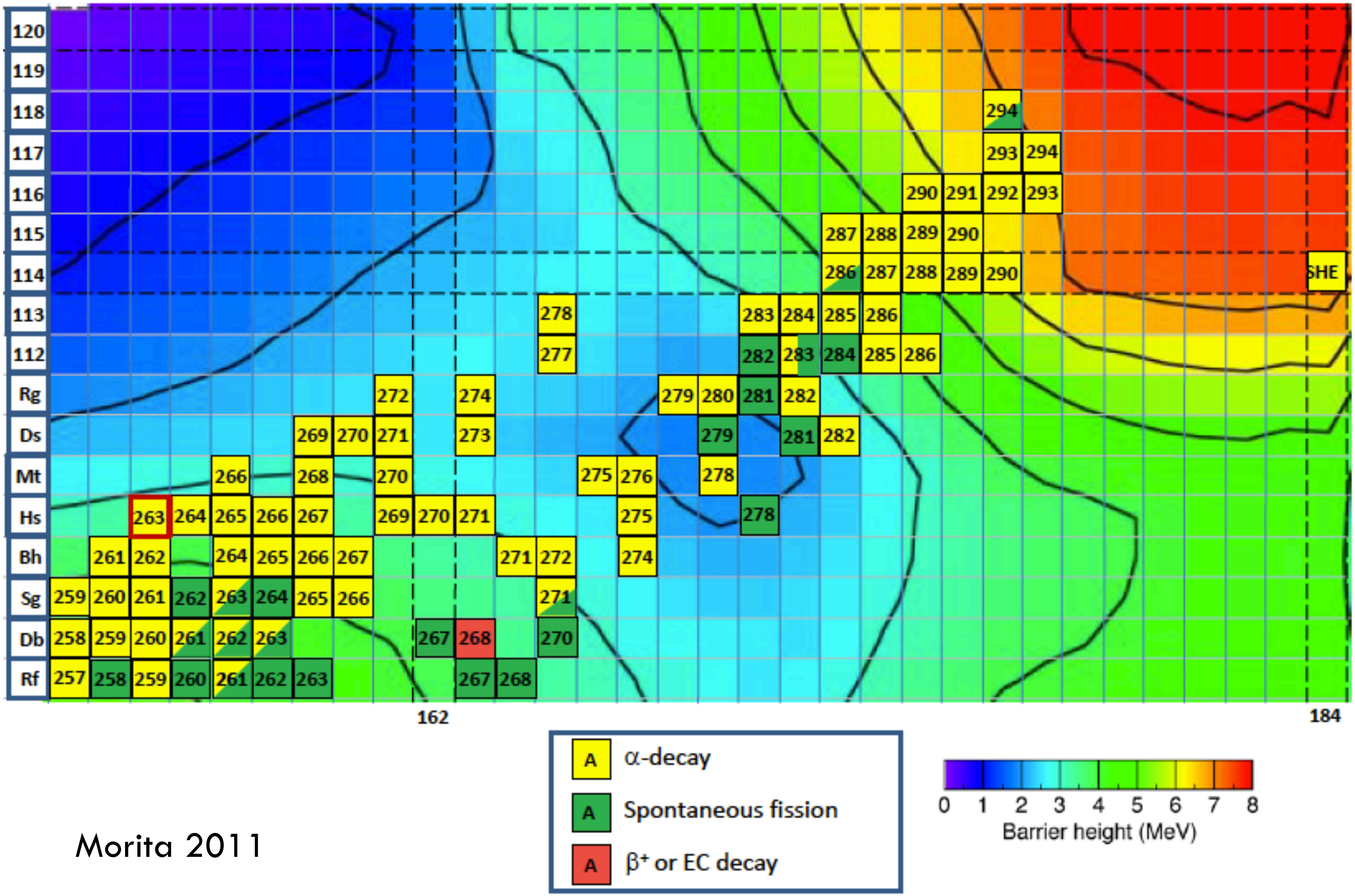
M. Bender et al. Phys. Lett. B 515, 42–48 (2001)

one end of nuclear chart '84—'94



Morita 2011

one end of nuclear chart 2010



Morita 2011

Latest periodic table

IUPAC Periodic Table of the Elements

Key:

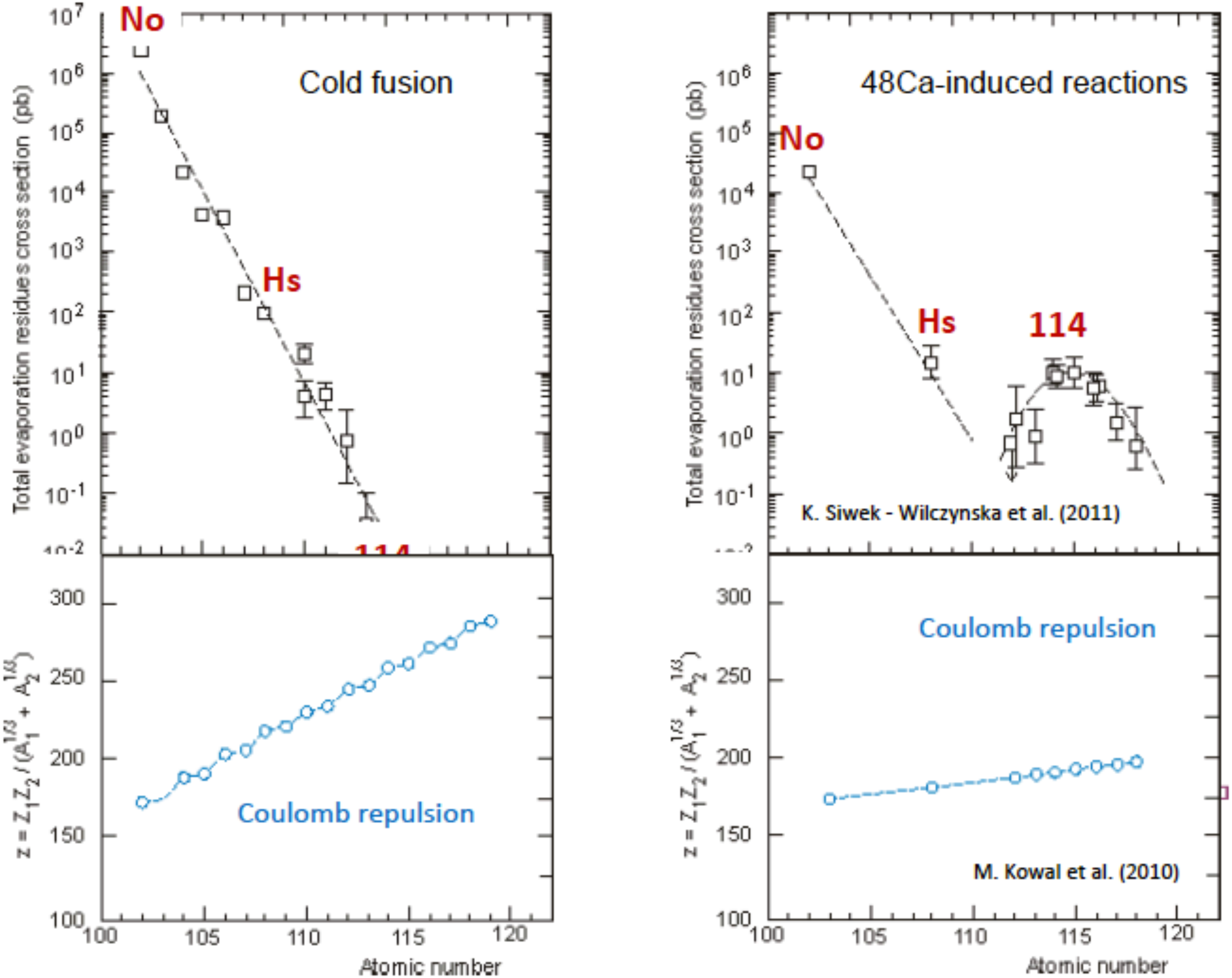
atomic number **Symbol** name conventional atomic weight standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.008 [1.0078, 1.0082]																	2 **He** helium 4.0026
3 **Li** lithium 6.94 [6.938, 6.997]	4 **Be** beryllium 9.0122											5 **B** boron 10.81 [10.806, 10.821]	6 **C** carbon 12.011 [12.009, 12.012]	7 **N** nitrogen 14.007 [14.006, 14.008]	8 **O** oxygen 15.999 [15.999, 16.000]	9 **F** fluorine 18.998	10 **Ne** neon 20.180
11 **Na** sodium 22.990	12 **Mg** magnesium 24.305 [24.304, 24.307]											13 **Al** aluminium 26.982	14 **Si** silicon 28.085 [28.084, 28.086]	15 **P** phosphorus 30.974	16 **S** sulfur 32.06 [32.059, 32.076]	17 **Cl** chlorine 35.45 [35.446, 35.457]	18 **Ar** argon 39.948
19 **K** potassium 39.098	20 **Ca** calcium 40.078(4)	21 **Sc** scandium 44.956	22 **Ti** titanium 47.867	23 **V** vanadium 50.942	24 **Cr** chromium 51.996	25 **Mn** manganese 54.938	26 **Fe** iron 55.845(2)	27 **Co** cobalt 58.933	28 **Ni** nickel 58.693	29 **Cu** copper 63.546(3)	30 **Zn** zinc 65.38(2)	31 **Ga** gallium 69.723	32 **Ge** germanium 72.630(8)	33 **As** arsenic 74.922	34 **Se** selenium 78.971(8)	35 **Br** bromine 79.904 [79.901, 79.907]	36 **Kr** krypton 83.798(2)
37 **Rb** rubidium 85.468	38 **Sr** strontium 87.62	39 **Y** yttrium 88.906	40 **Zr** zirconium 91.224(2)	41 **Nb** niobium 92.906	42 **Mo** molybdenum 95.95	43 **Tc** technetium	44 **Ru** ruthenium 101.07(2)	45 **Rh** rhodium 102.91	46 **Pd** palladium 106.42	47 **Ag** silver 107.87	48 **Cd** cadmium 112.41	49 **In** indium 114.82	50 **Sn** tin 118.71	51 **Sb** antimony 121.76	52 **Te** tellurium 127.60(3)	53 **I** iodine 126.90	54 **Xe** xenon 131.29
55 **Cs** caesium 132.91	56 **Ba** barium 137.33	57-71 lanthanoids	72 **Hf** hafnium 178.49(2)	73 **Ta** tantalum 180.95	74 **W** tungsten 183.84	75 **Re** rhenium 186.21	76 **Os** osmium 190.23(3)	77 **Ir** iridium 192.22	78 **Pt** platinum 195.08	79 **Au** gold 196.97	80 **Hg** mercury 200.59	81 **Tl** thallium 204.38 [204.38, 204.39]	82 **Pb** lead 207.2	83 **Bi** bismuth 208.98	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
87 **Fr** francium	88 **Ra** radium	89-103 actinoids	104 **Rf** rutherfordium	105 **Db** dubnium	106 **Sg** seaborgium	107 **Bh** bohrium	108 **Hs** hassium	109 **Mt** meitnerium	110 **Ds** darmstadtium	111 **Rg** roentgenium	112 **Cn** copernicium	113 **Nh** nihonium	114 **Fl** flerovium	115 **Mc** moscovium	116 **Lv** livermorium	117 **Ts** tennessine	118 **Og** oganesson

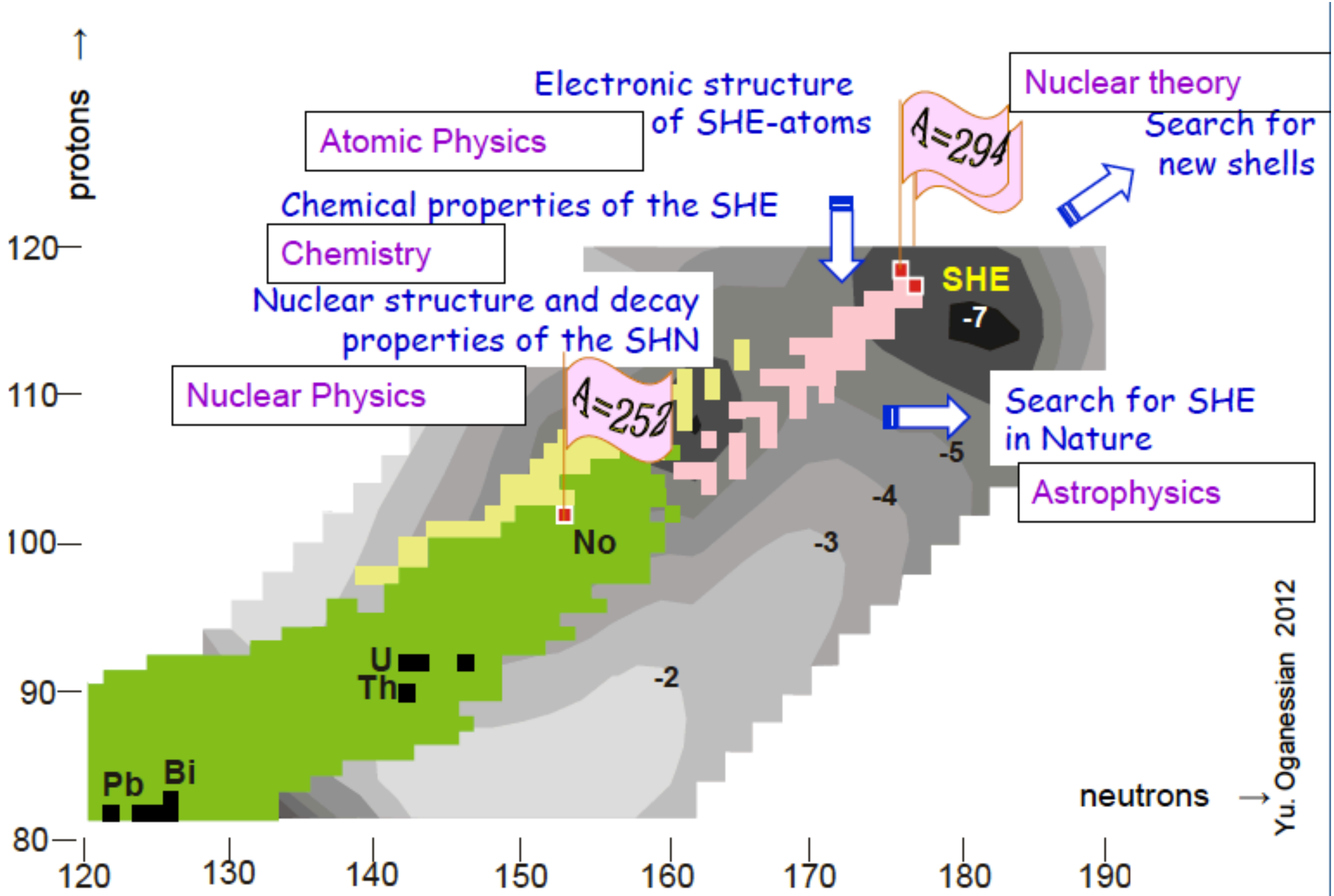
57 **La** lanthanum 138.91	58 **Ce** cerium 140.12	59 **Pr** praseodymium 140.91	60 **Nd** neodymium 144.24	61 **Pm** promethium	62 **Sm** samarium 150.36(2)	63 **Eu** europium 151.96	64 **Gd** gadolinium 157.25(3)	65 **Tb** terbium 158.93	66 **Dy** dysprosium 162.50	67 **Ho** holmium 164.93	68 **Er** erbium 167.26	69 **Tm** thulium 168.93	70 **Yb** ytterbium 173.05	71 **Lu** lutetium 174.97
89 **Ac** actinium	90 **Th** thorium 232.04	91 **Pa** protactinium 231.04	92 **U** uranium 238.03	93 **Np** neptunium	94 **Pu** plutonium	95 **Am** americium	96 **Cm** curium	97 **Bk** berkelium	98 **Cf** californium	99 **Es** einsteinium	100 **Fm** fermium	101 **Md** mendelevium	102 **No** nobelium	103 **Lr** lawrencium

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 28 November 2016.



Cold fusion
No
Hs
114
Total evaporation residues cross section (pb)
$z = Z_1Z_2/(A_1^{1/3} + A_2^{1/3})$
Coulomb repulsion
Atomic number
48Ca-induced reactions
No
Hs
114
K. Siwek - Wilczynska et al. (2011)
Coulomb repulsion
M. Kowal et al. (2010)
Atomic number



Yuri Oganessian. "Synthesis of SH-nuclei" FUSHE 2012, May14, 2012, Weilrod, Germany

Questions for theoreticians

- Can we guide the experiments?

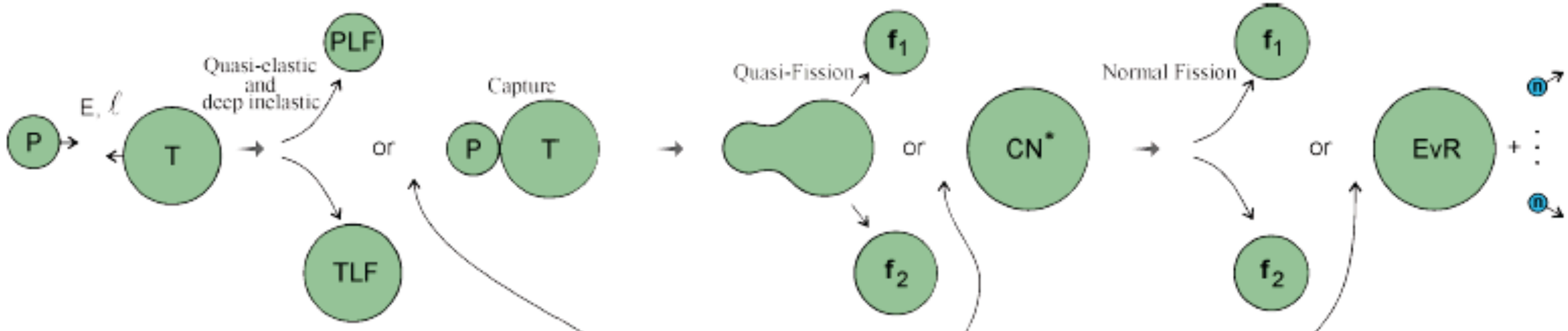
Difficulties

- Models cannot be extrapolated from lighter systems
  - Fusion hindrance
- Extremely low cross sections
  - Few data with few information

Residue cross sections

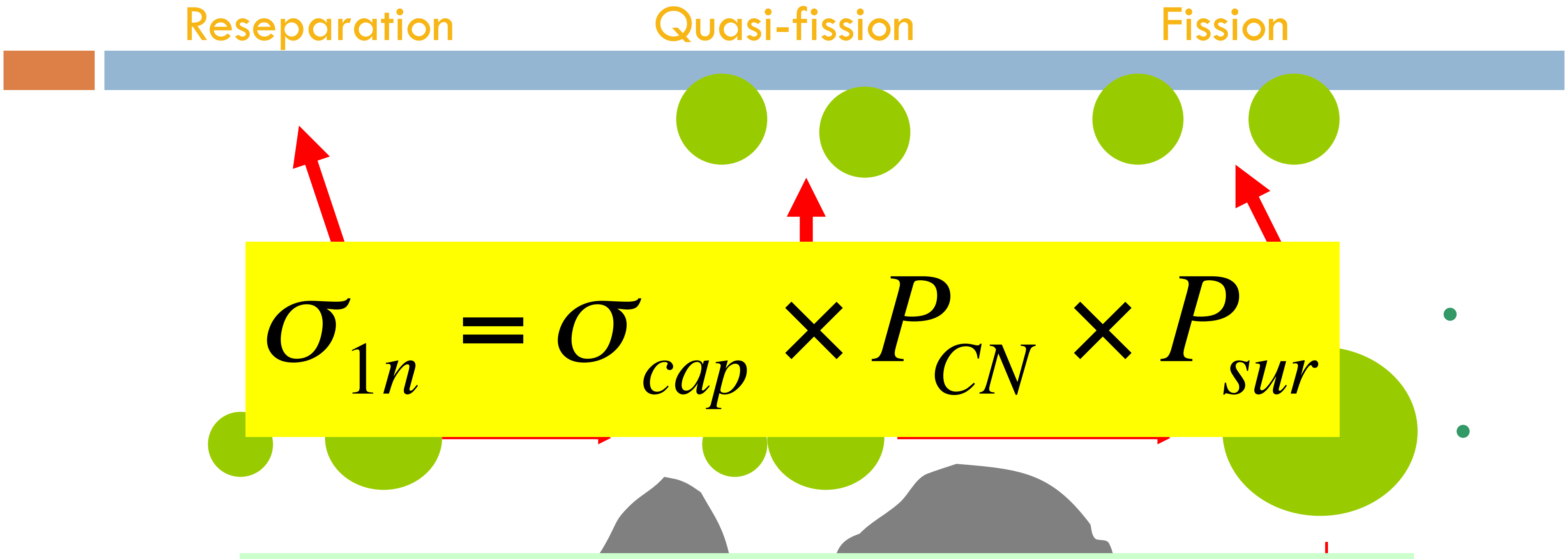
Reaction to form SHE

Synthesis of SHE in fusion reactions (conventional view)



$$\sigma_{ER}^{xn}(E) = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)\cdot P_{cont}(\ell,E)\cdot P_{CN}(\ell,E^*)\cdot P_{xn}(\ell,E^*)$$

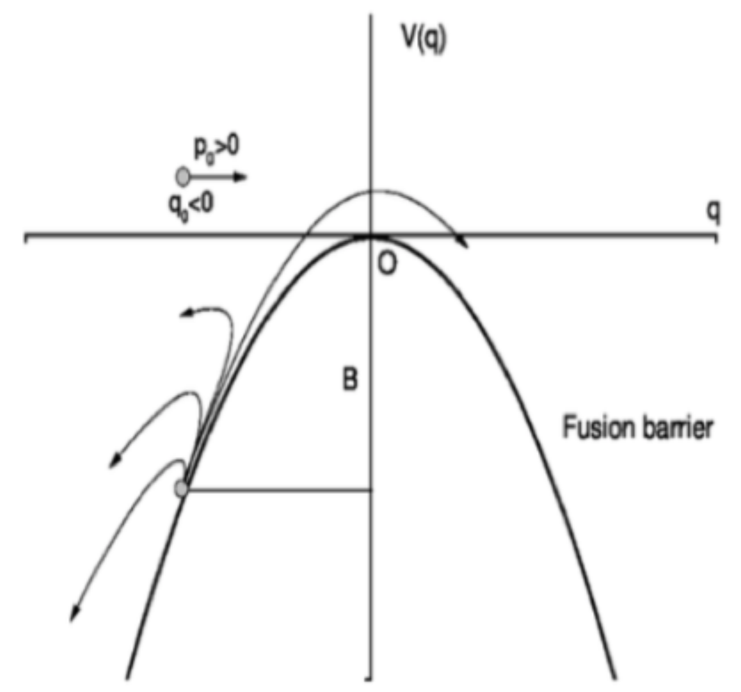
Reaction



$$\sigma_{1n} = \sigma_{cap} \times P_{CN} \times P_{sur}$$

- What is the size of the inner barrier?
- How large is the dissipation?
- Correct dynamical description?
- ...
- *No reliable data*

Fusion by diffusion

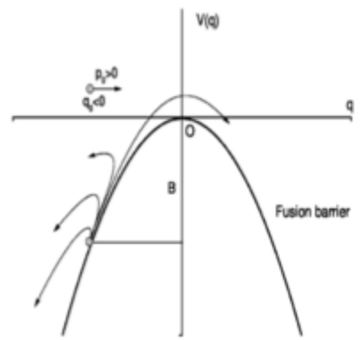


- What is the initial condition?
- N-dimension problem
- Fast variables are eliminated after a short time τ
- Slow variables start at τ with a slipped initial condition

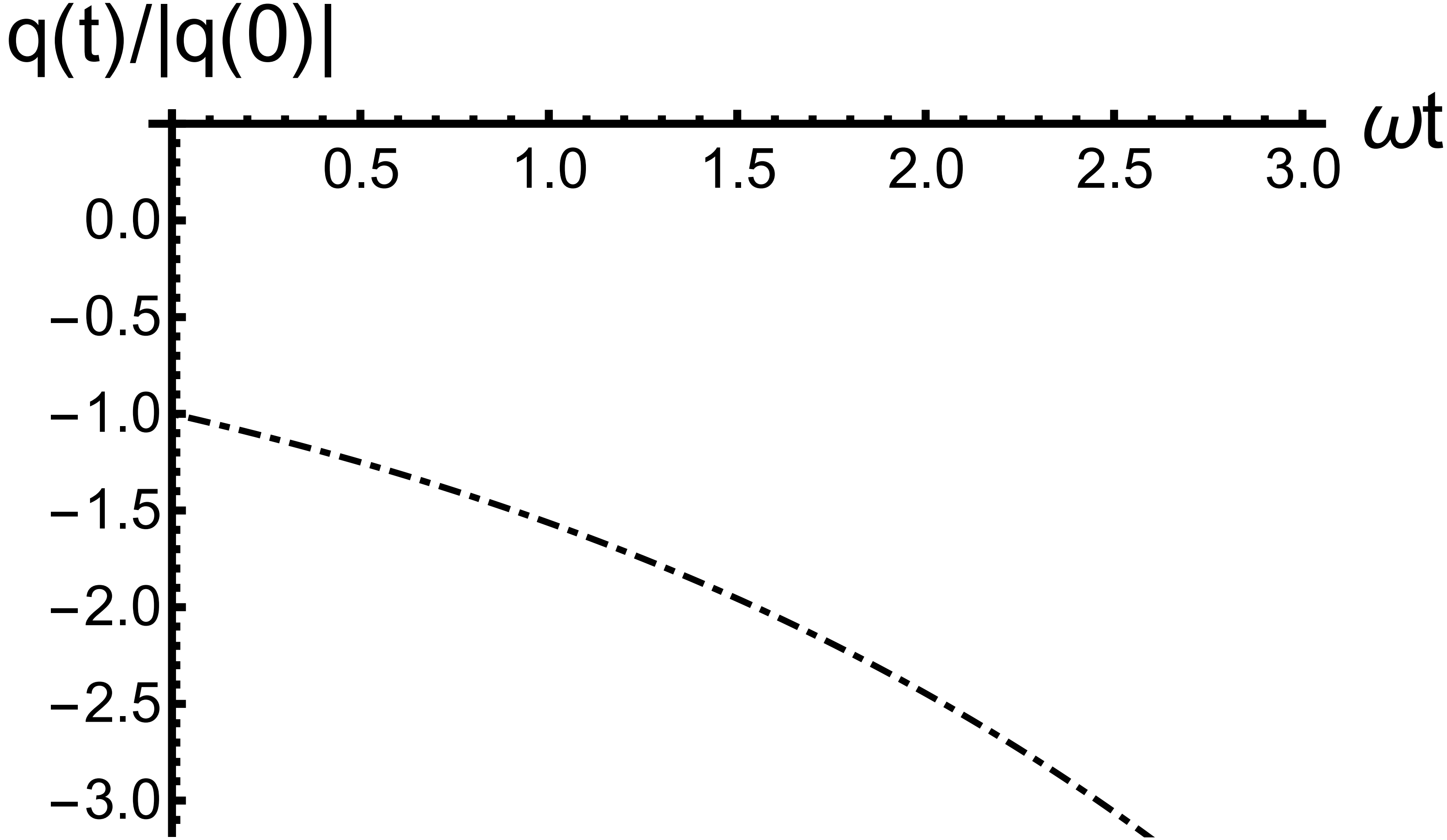
Y. Abe, D. B., B.G. Giraud and T. Wada, Phys. Rev. E61, 1125 (2000)
D. B., Y. Abe and JD Bao, Eur. Phys. J. A18, 627 (2003)

Example

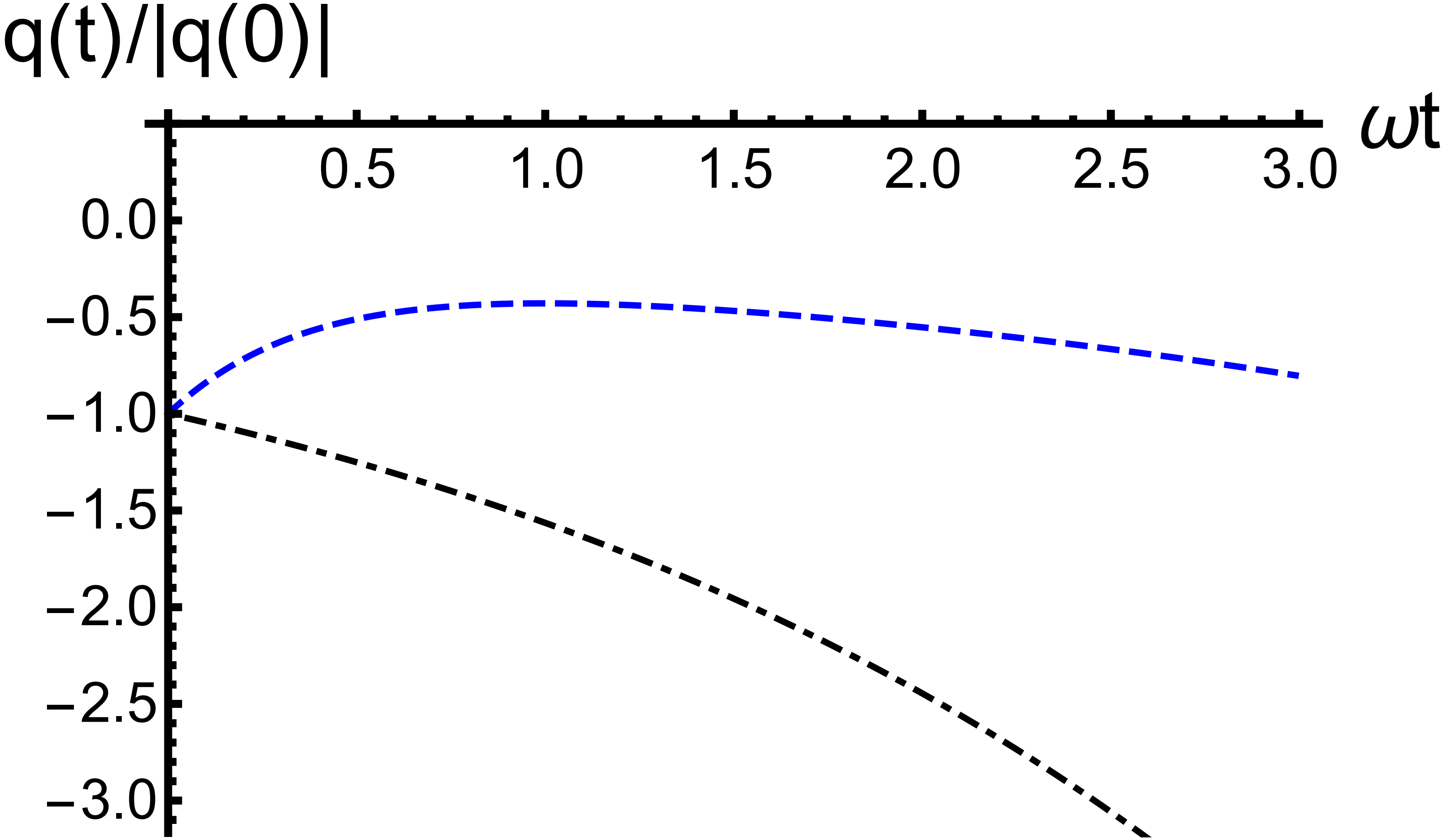
- Langevin: $\ddot{q} + \beta\dot{q} - \omega^2 q = r(t)$
- Smoluchowski: $\beta\dot{q} - \omega^2 q = r(t)$ $\beta \gg \omega$
- Fluctuation-dissipation: $\langle r(t)r(t')\rangle = \frac{2T\beta}{m}\delta(t-t')$
- Elimination of fast variable => $q(\tau) = q_0 + \frac{\dot{q}_0}{\beta}$



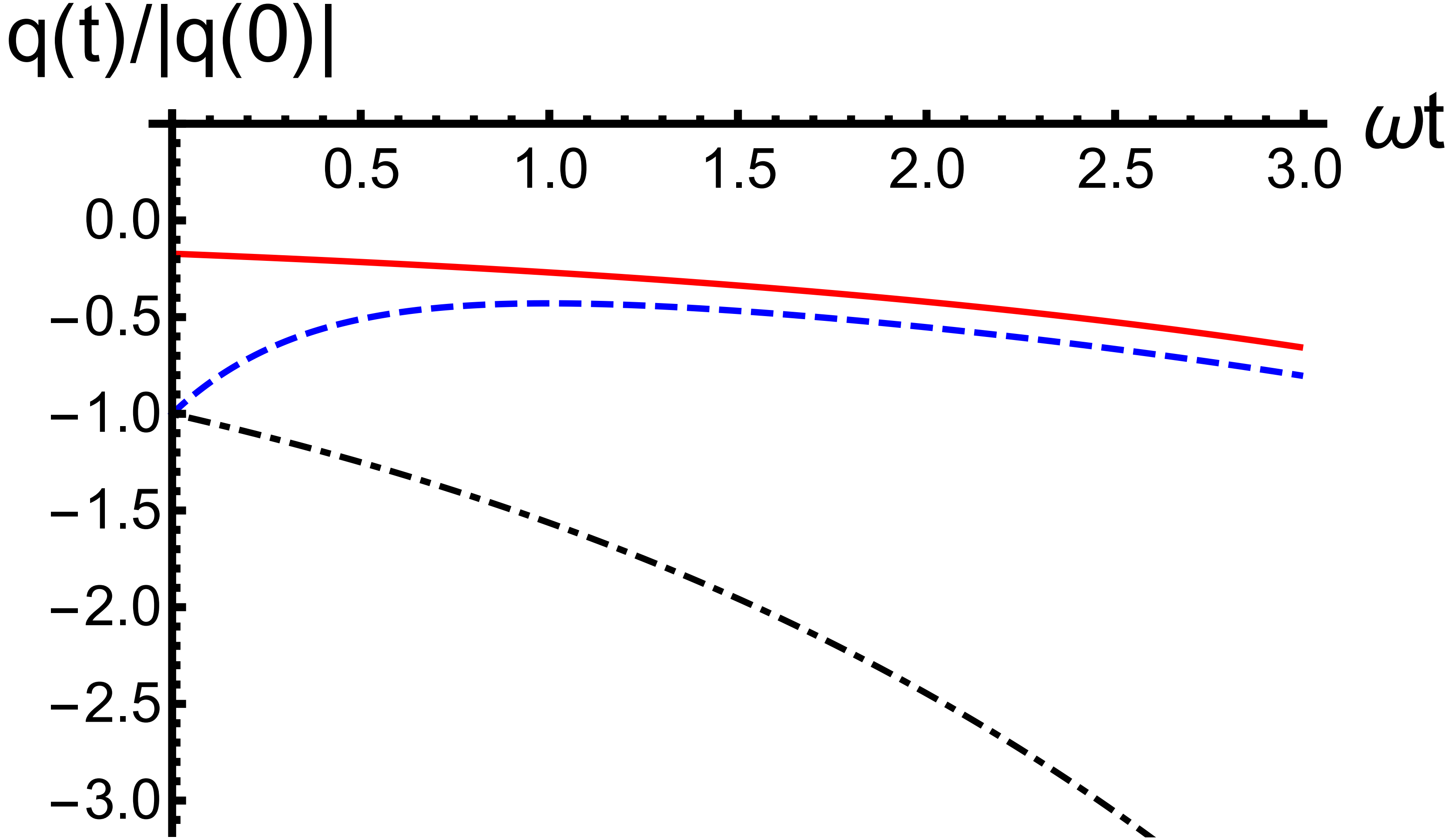
Test



Test

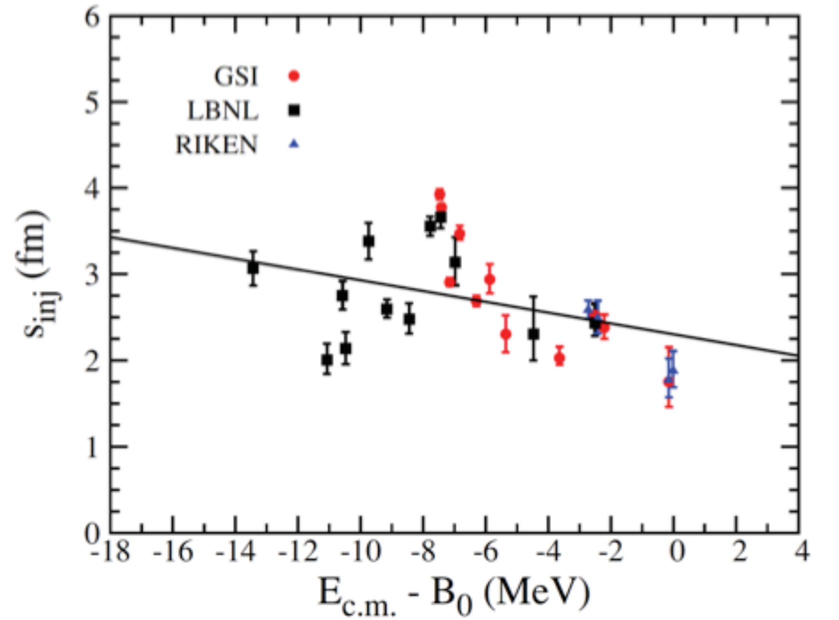


Test

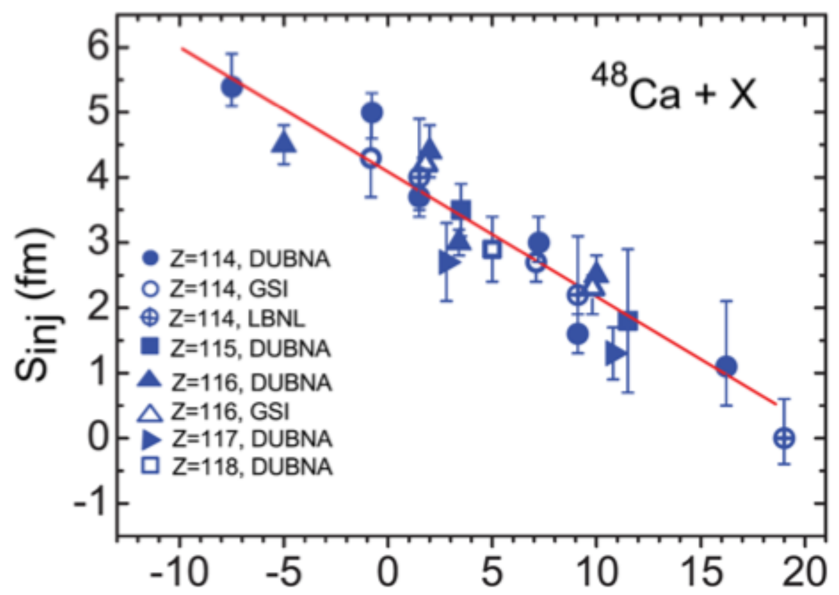


Phenomelogical shift

Cold fusion (PRC.83. 054602)

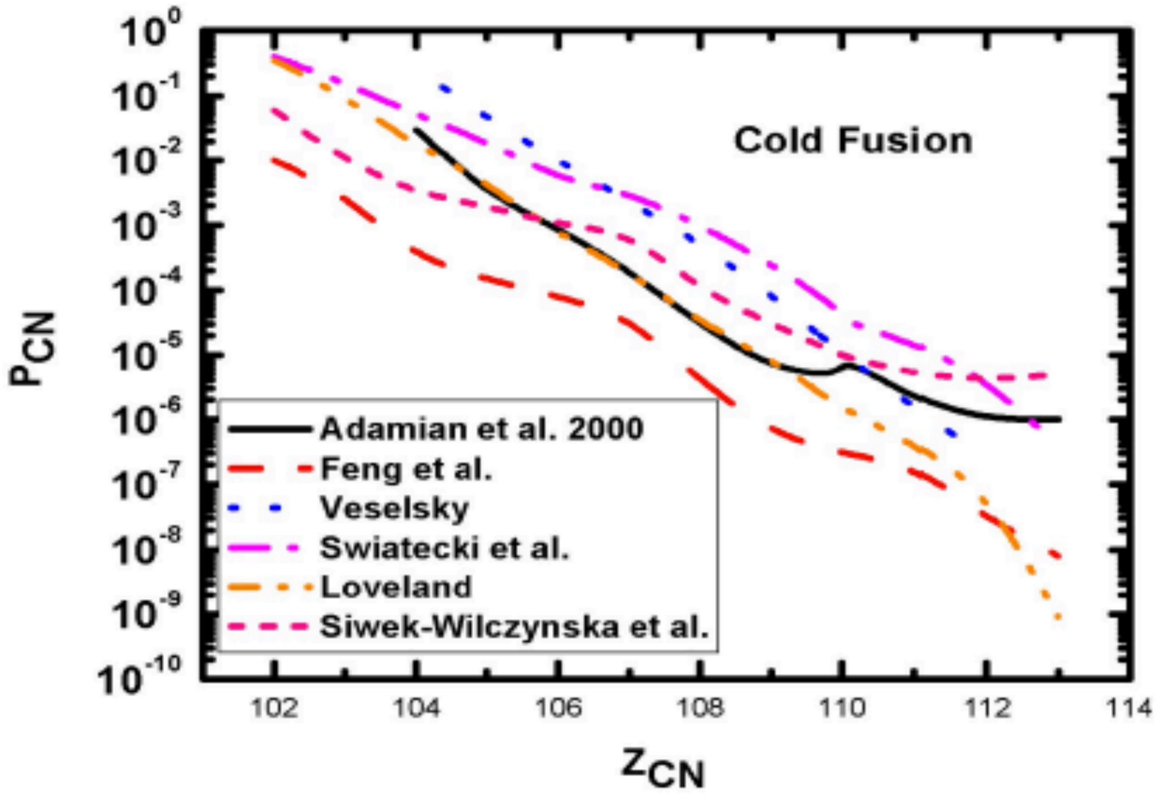


Hot fusion (PRC.86. 014611)



Can we assess hindrance?

Despite correctly predicting σ_{EVR} correctly, the values of P_{CN} (and W_{sur})differ significantly

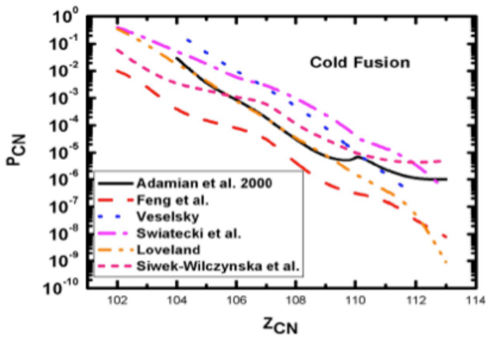


One – two orders of magnitude!

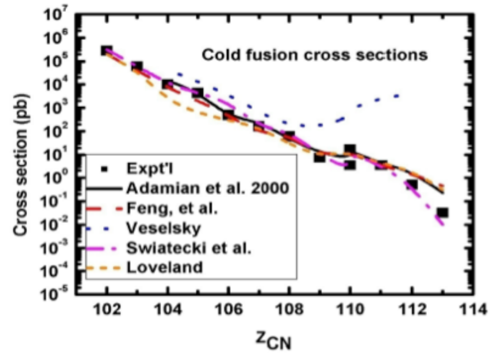
Naik, Loveland et al, Phys. Rev. C **76**, 054604

What's the problem?

σ_{cap} x



x P_{sur}=



The best known part has the same discrepancies as the less known part!

Uncertainty analysis

Stretegy

- The best known part has the same discrepancies as the less known part!
- Is it due to uncertainties?

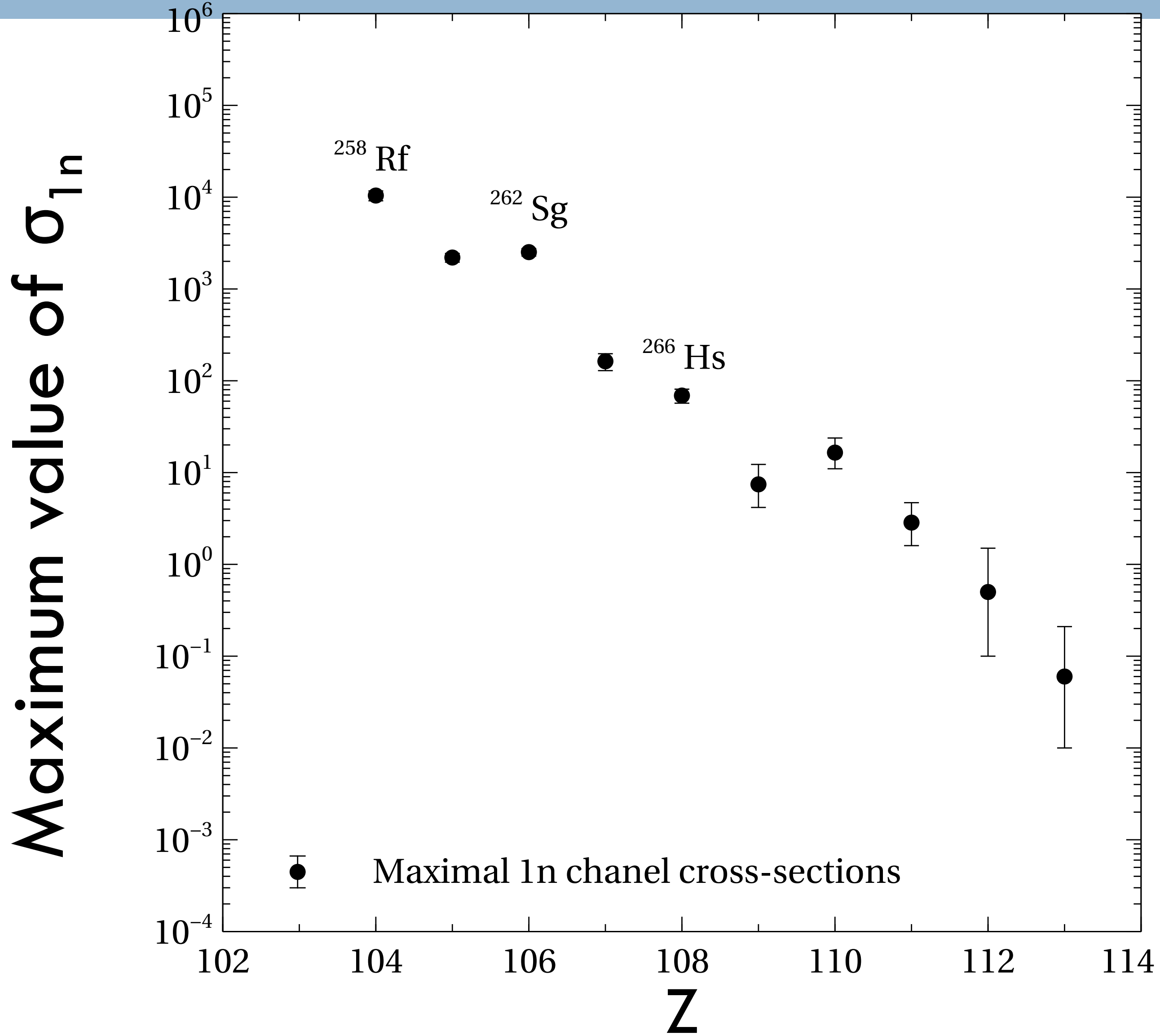
$$\sigma_{1n} = \sigma_{cap} \times P_{CN} \times P_{sur}$$

$$P_{CN} = \frac{\sigma_{1n}}{\sigma_{cap} \times P_{sur}}$$

Experiments

Models

Experimental uncertainties



Survival probability

$$P_{sur} = \frac{\Gamma_n}{\Gamma_n + \Gamma_f}$$

- **B_f < B_n => Fission dominates:**
  - Parameters entering the fission width have a great influence
  - Fission barrier is most sensitive parameter
  - Nuisance parameters:
    - Damping energy: $11 < Ed < 19\ \mathrm{MeV}$
    - Friction coefficient: $1 < \beta < 5\ \mathrm{zs}^{-1}$

Computer Physics Communications 200 (2016) 381–399

Contents lists available at ScienceDirect

Computer Physics Communications

journal homepage: www.elsevier.com/locate/cpc

KEWPIE2: A cascade code for the study of dynamical decay of excited nuclei☆

Ho

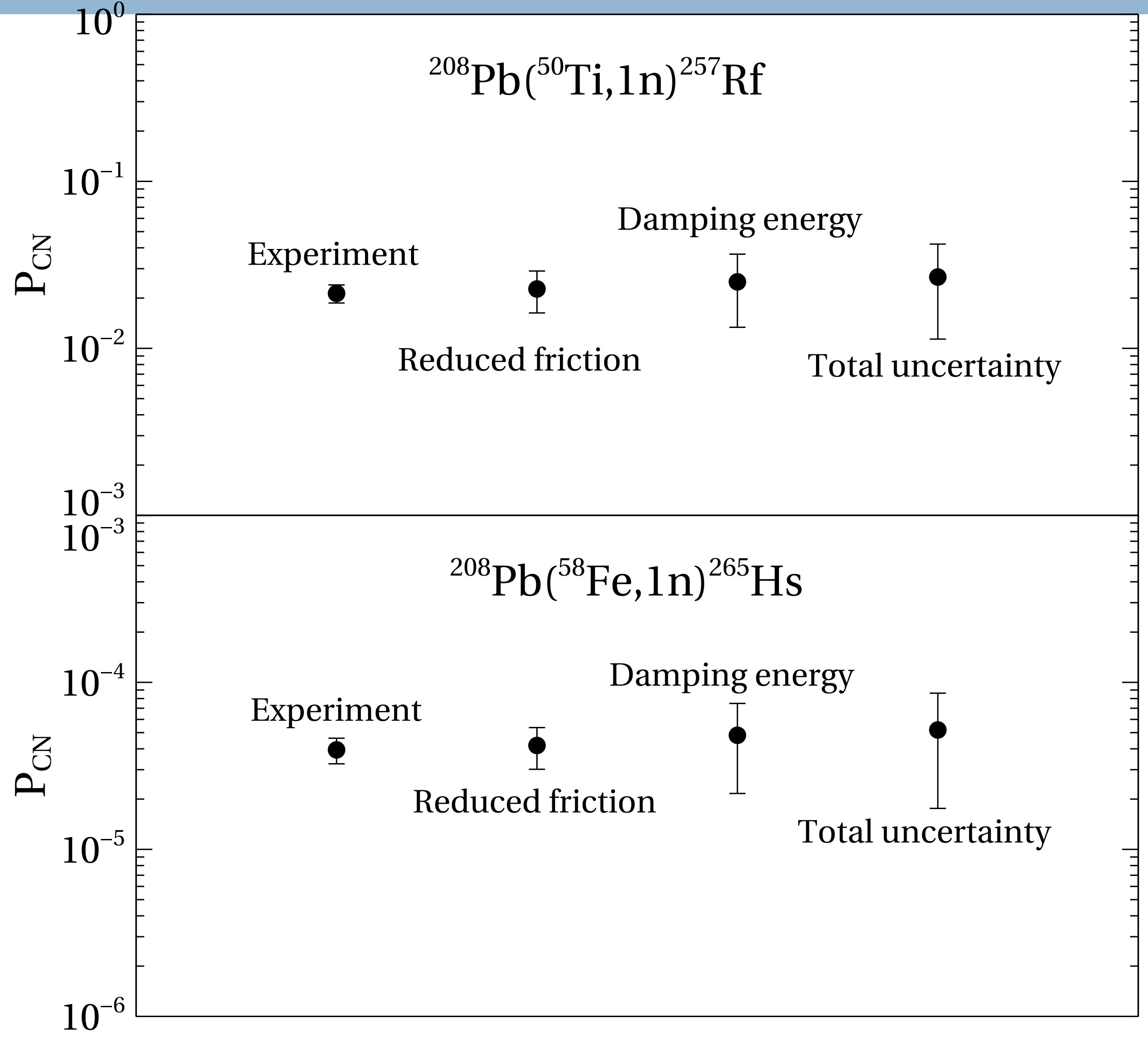
JCGM 100:2008

GUM 1995 with minor corrections

Evaluation of measurement data — Guide to the expression of uncertainty in measurement

Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure

Nuisance parameters



Fission barriers

- In the past:

$$Bf \approx B_{LDM} - \Delta E_{shell}$$

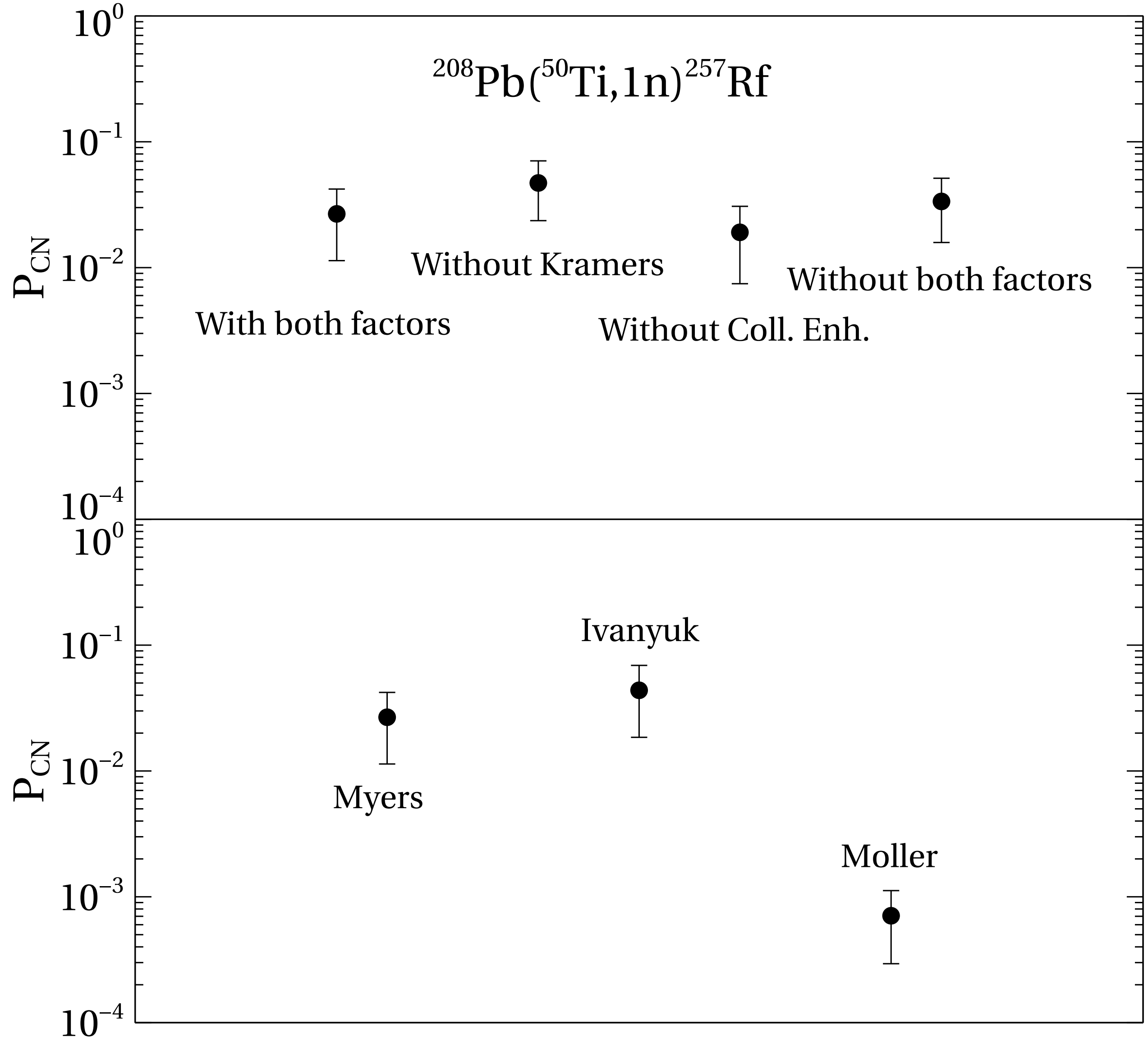
- Nowadays:
  - Tables: Moller et al, M. Kowal et al… : differ by few MeV's

Fission barriers (MeV)

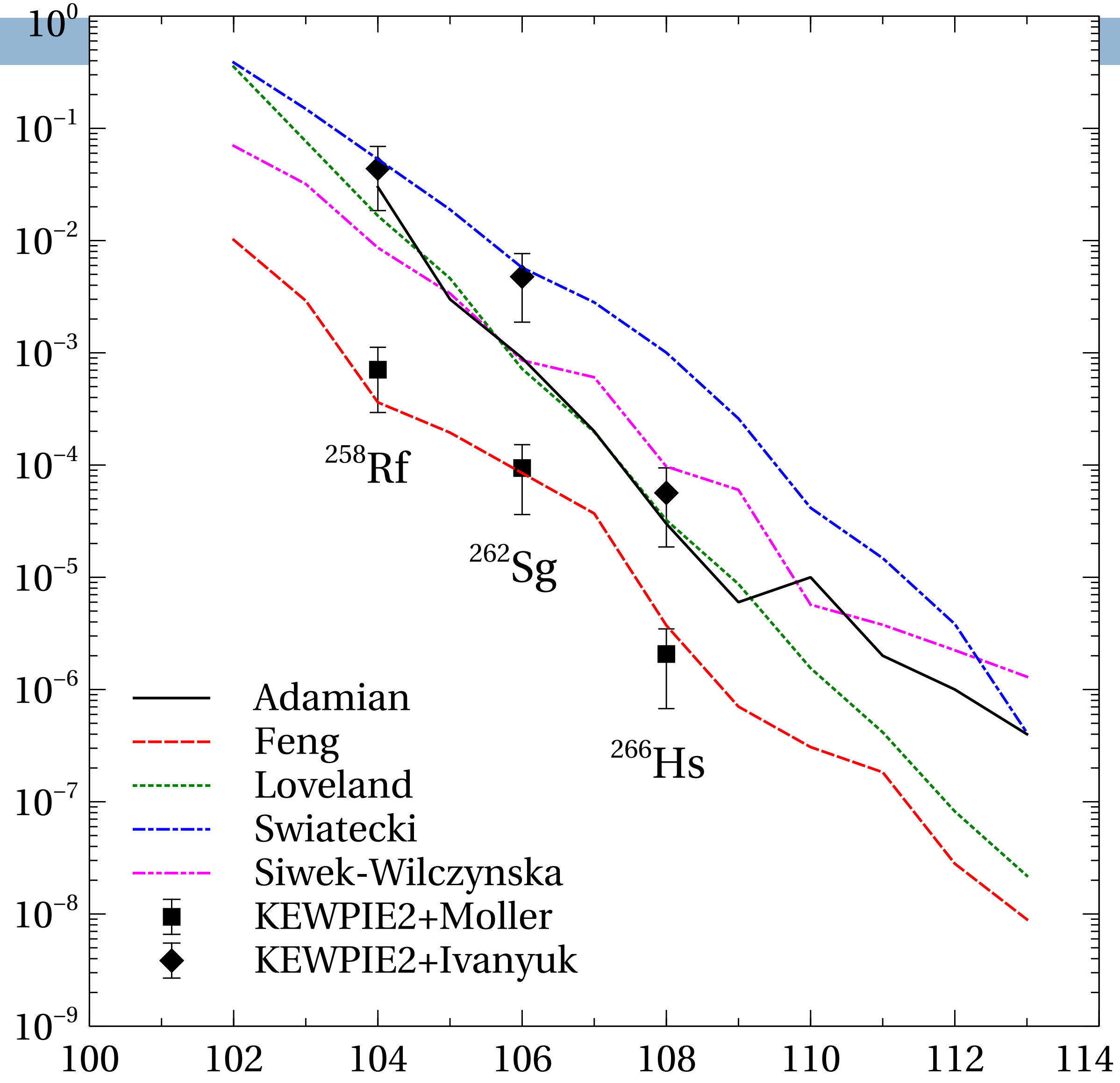
Same shell correction energy

Reaction	Möller	Ivanyuk
208Pb(50Ti,**1**n)257Rf	5.65	4.47
208Pb(54Cr,**1**n)261Sg	5.91	4.57
208Pb(58Fe,**1**n)265Hs	6.26	5.22

Various models



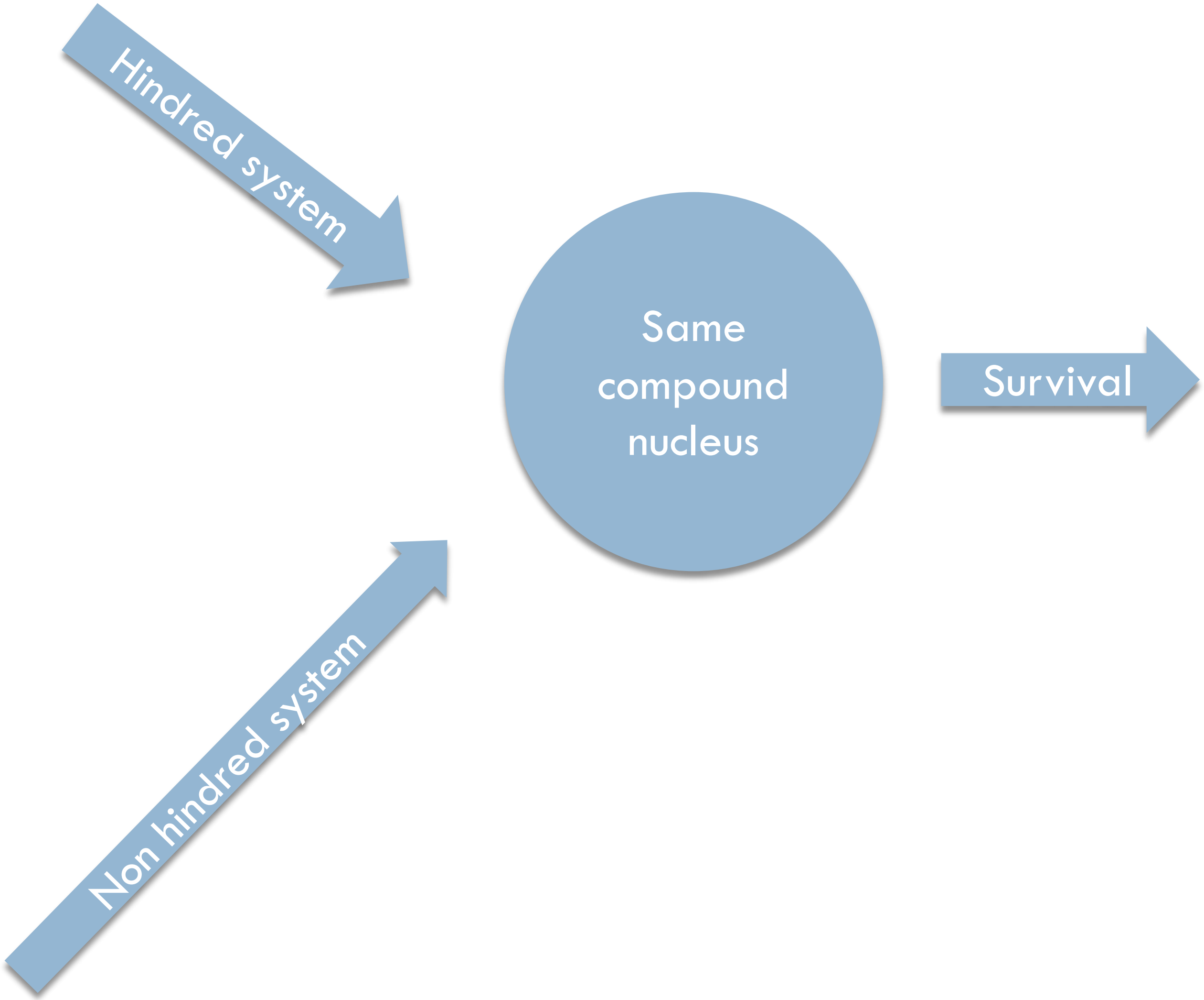
Summary



10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
100
102
104
106
108
110
112
114
^{258}Rf
^{262}Sg
^{266}Hs
Adamian
Feng
Loveland
Swiatecki
Siwek-Wilczynska
KEWPIE2+Moller
KEWPIE2+Ivanyuk

Partial conclusions

- Fusion hindrance and fission barriers are both unknown



How accurate can be the predictions?

Fusion-by-diffusion model

Survival probability

- Cold fusion (1n)

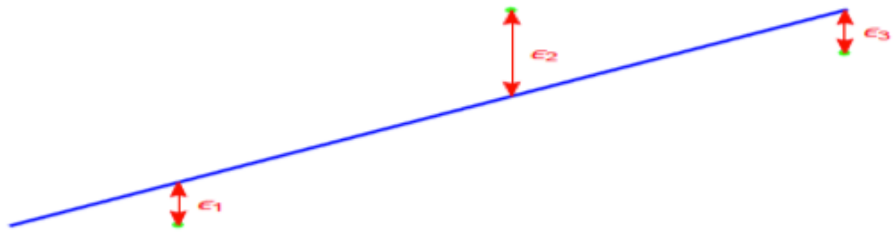
$$P_{sur} = \frac{\Gamma_n}{\Gamma_n + \Gamma_f}$$

- Γ_n depends on S_n
- Γ_f depends on B_f

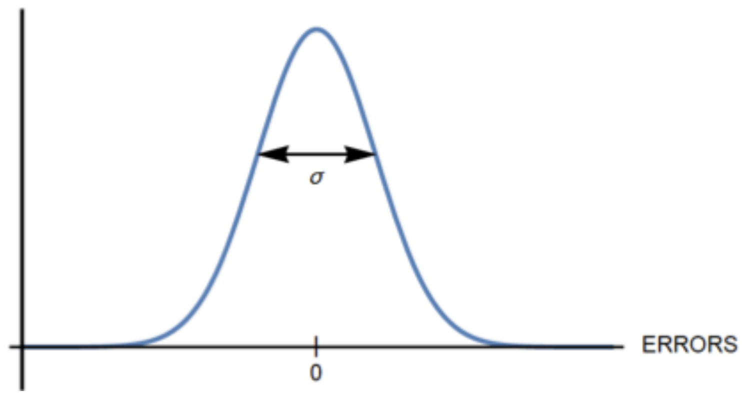
=> We shall start our study with masses

Regression analysis

- Experimental data = theory + errors



- Homoscedastic assumption:
  - Gaussian distribution
  - Mean value = 0
  - Variance = σ^2



- Estimator: $$\sigma^2 = \frac{1}{N_n - N_p} \sum \varepsilon_i^2$$

Model

- : AME2016 with Z,N>8 and u<150 keV

- SCE + Pairing: Thomas Fermi – no uncertainties
  - Myers and Swiatecki 1994

- LDM: linear equation
  - G. Royer (NPA917, 1 (2013))

Least squares

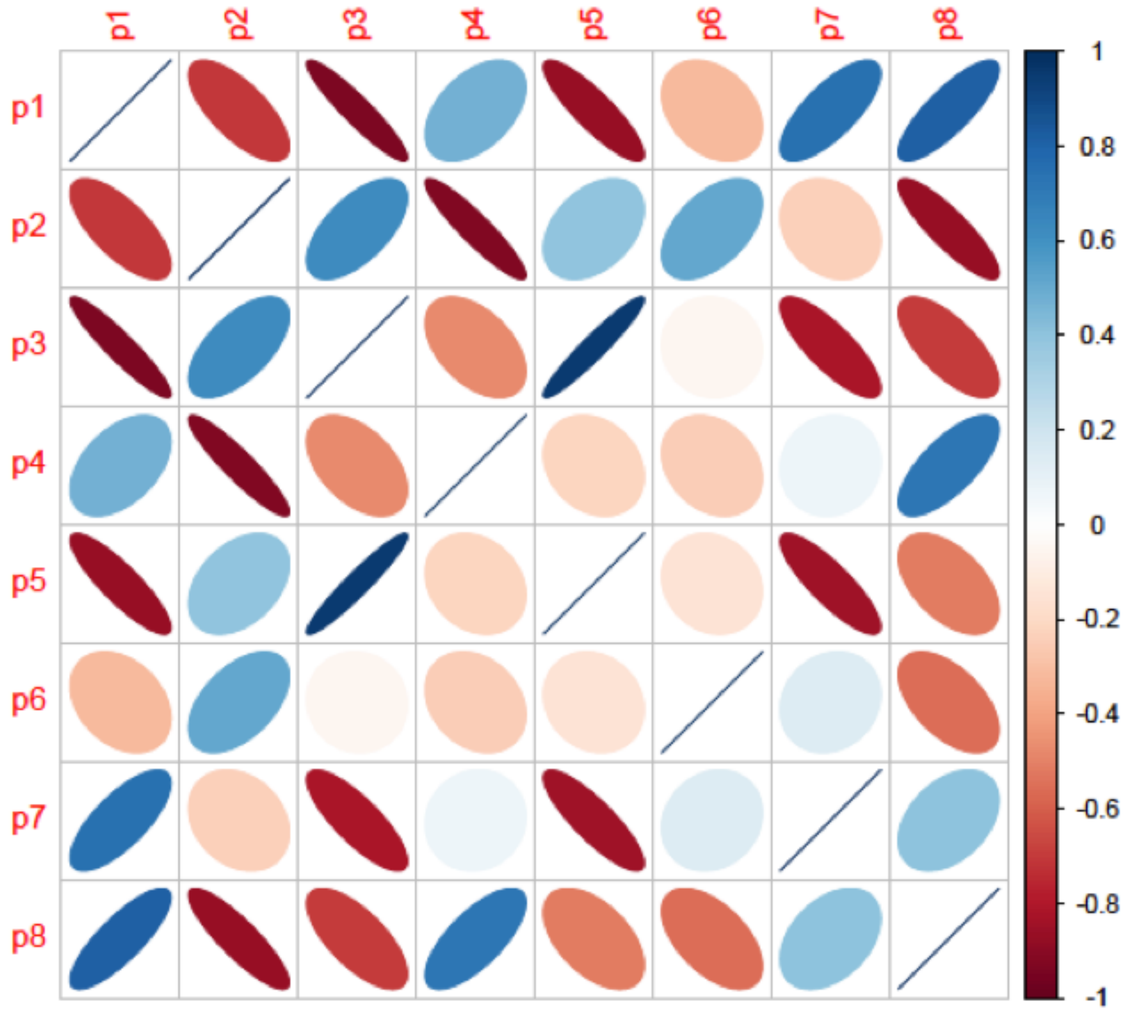
LDM: results

$$B'_{Th,i} = \left(p_1 + p_2 I_i^2\right) A_i + \left(p_3 + p_4 I_i^2\right) A_i^{\frac{2}{3}} + p_5 \frac{Z_i^2}{A_i^{\frac{1}{3}}} + p_6 \frac{Z_i^2}{A_i} + p_7 \left|N_i - Z_i\right| e^{-\left(\frac{A_i}{50}\right)^2} + p_8 e^{-80 I_i^2}$$

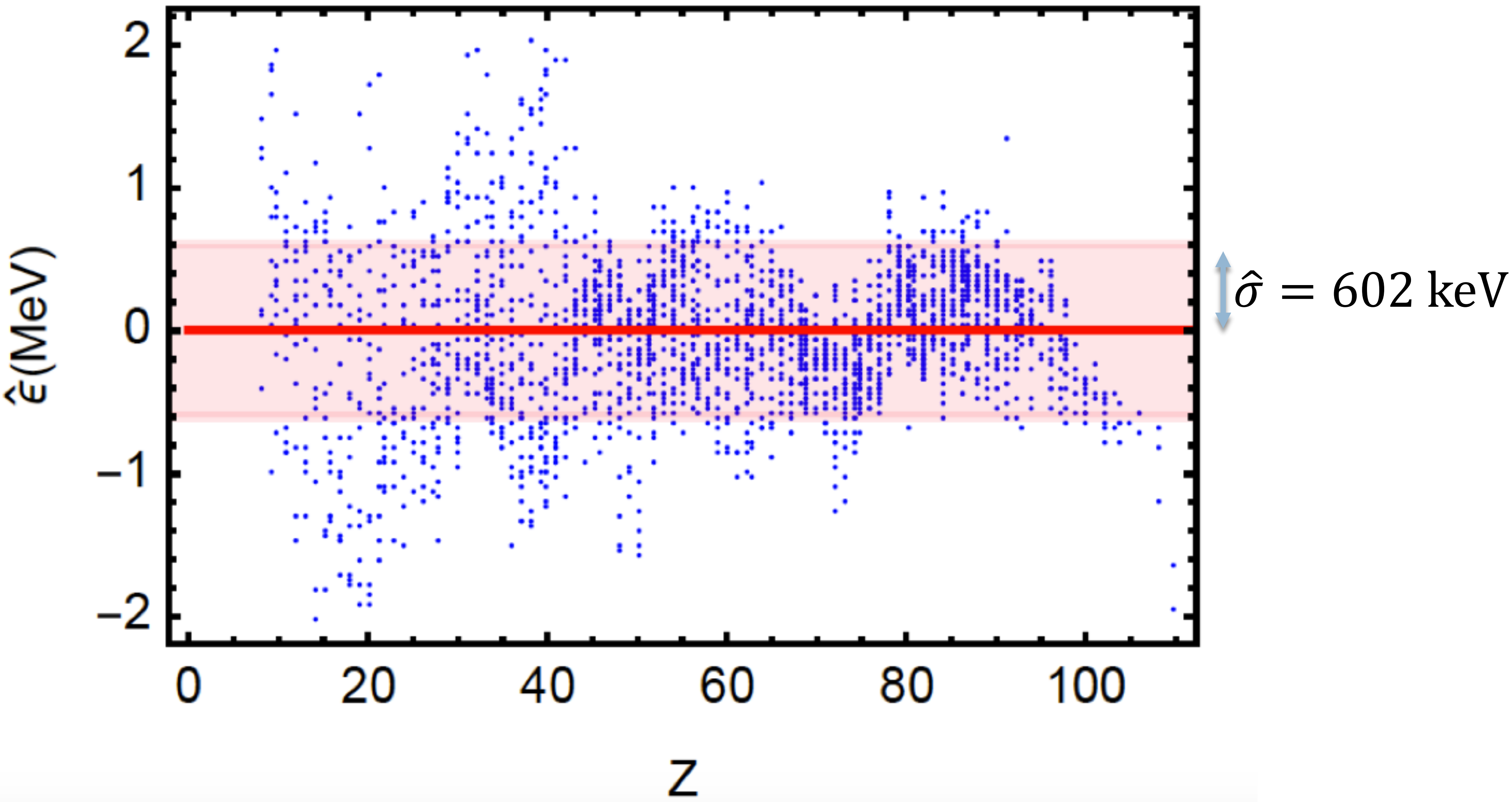
	$\hat{p}$ [MeV]	$\hat{u}(\hat{p})$[MeV]	$\lvert\hat{u}(\hat{p})/\hat{p}\rvert$ [%]
$\hat{p}_1$	15.4829	0.0145	0.1
$\hat{p}_2$	-27.8219	0.0843	0.3
$\hat{p}_3$	-17.5783	0.0505	0.3
$\hat{p}_4$	31.1447	0.3797	1.2
$\hat{p}_5$	-0.7058	0.0008	0.1
$\hat{p}_6$	0.9251	0.0288	3.1
$\hat{p}_7$	-0.2942	0.0293	10.0
$\hat{p}_8$	2.7265	0.1693	6.2

$$u(\hat{p}) \propto \hat{\sigma}$$

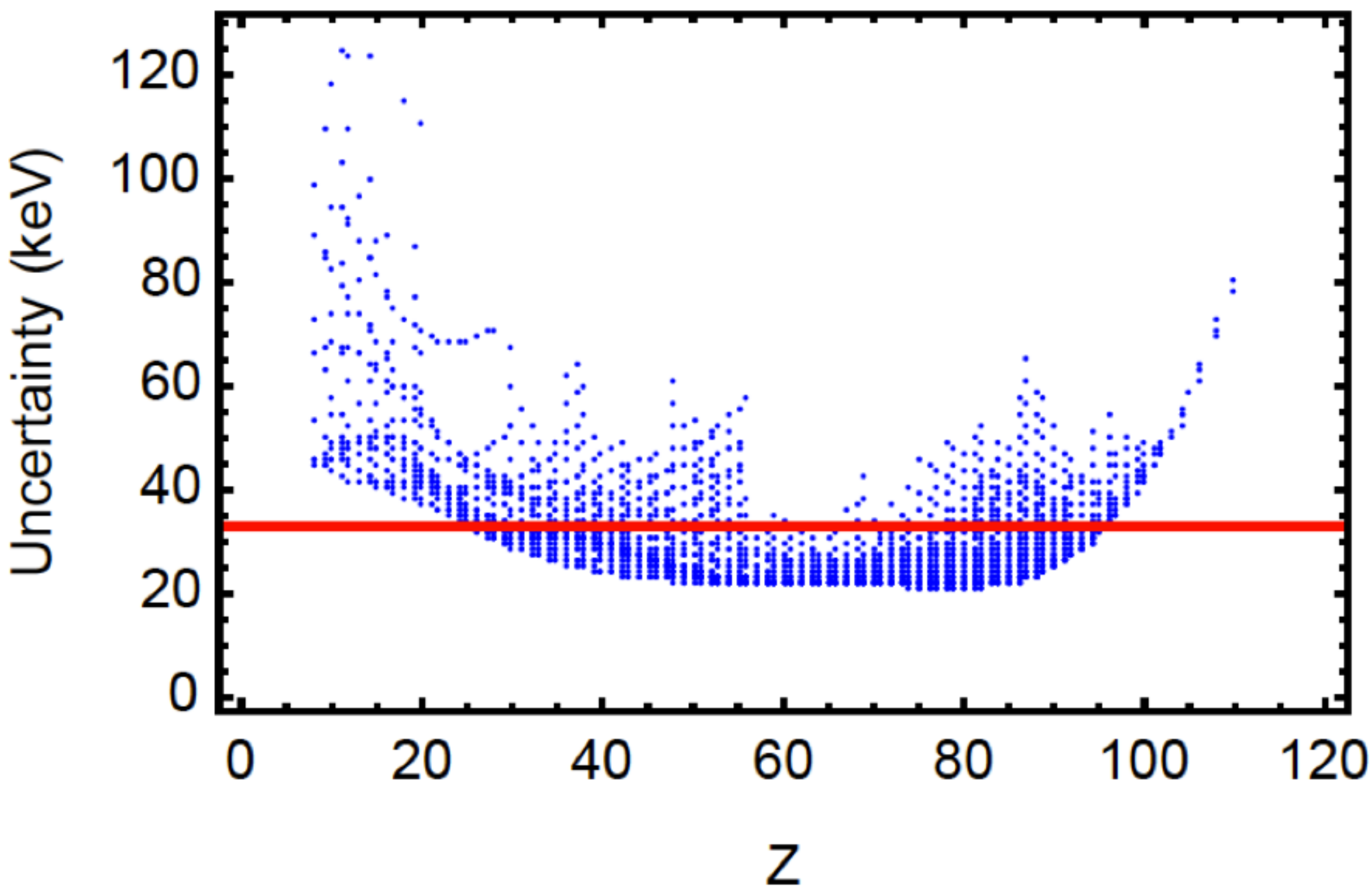
Correlation matrix



Errors or residuals



Estimated binding energies



Finally…

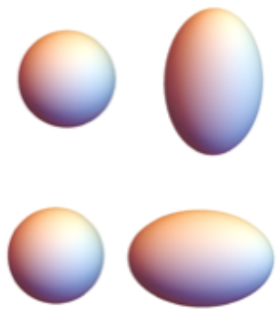
- $u(B_f) = 0.5$ MeV; $u(\beta)$; $u(Ed)$…

- At best, we can hope an accuracy of one order of magnitude in the survival probability.

Capture

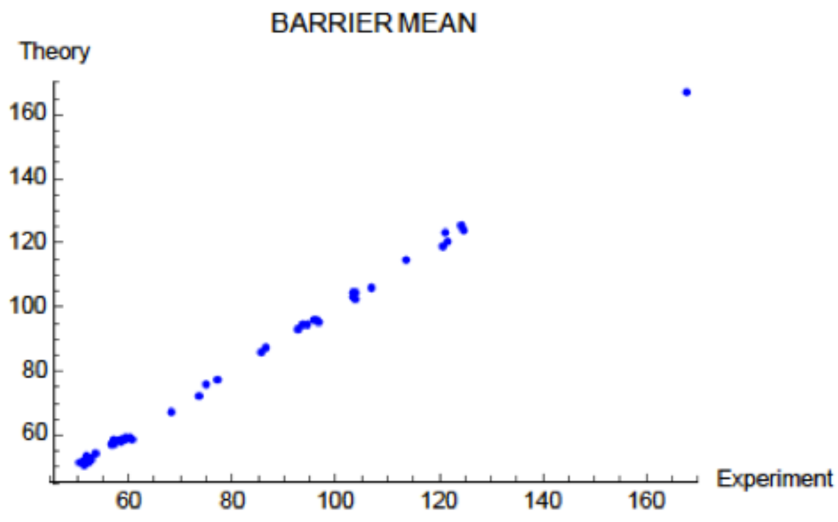
Capture model

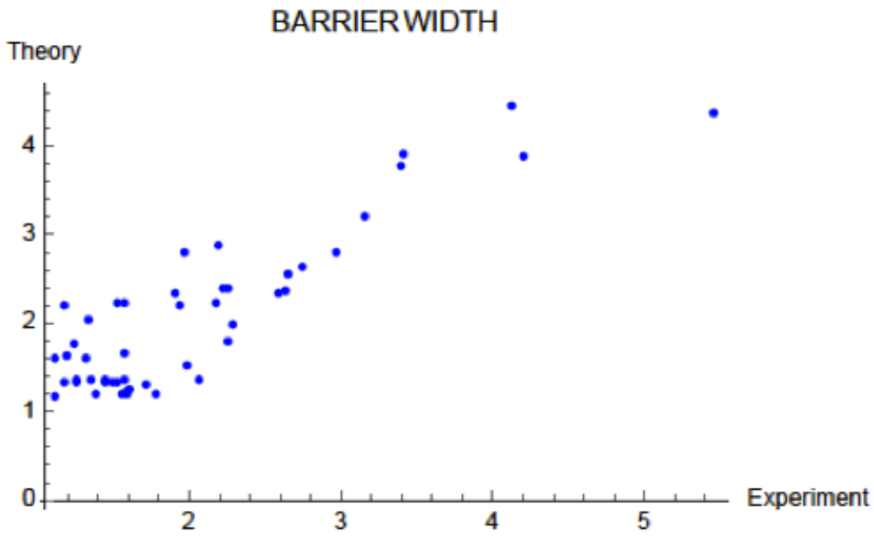
- $\sigma_{cap} = \pi R^2 \left(1 - \frac{B_C}{E_{cm}}\right)$ with Gaussian barrier distribution
- Adjusted parameters:
  - Coulomb barrier
  - Radius
  - Width of the barrier distribution
- 48 reactions used in the fit



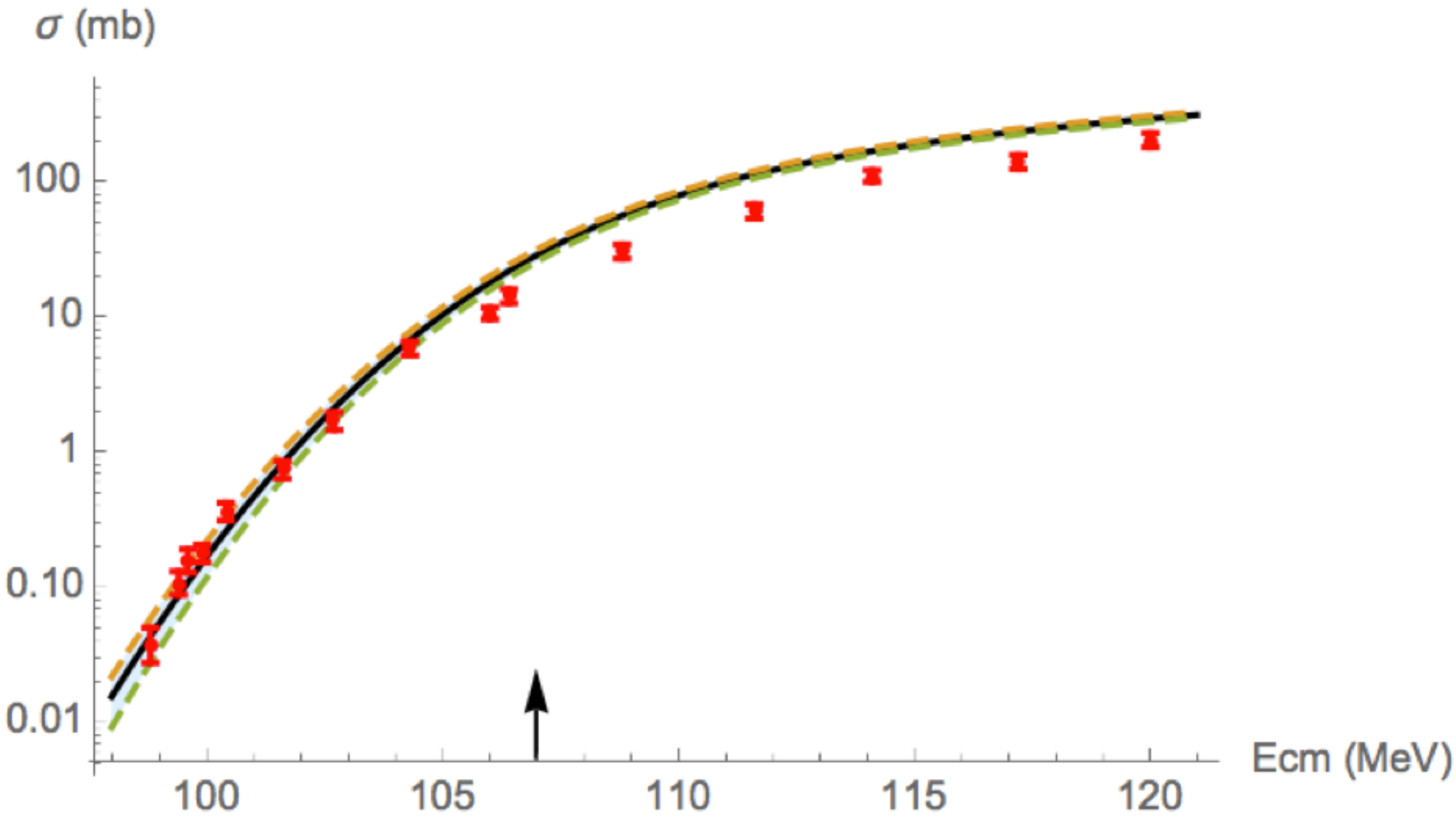
K. Siwek-Wilczynska et al., Acta Phys. Pol. B 33, 451 (2002).

Parameters of the barrier distribution





Uncertainties in capture



(a) $^{58}Ni+^{74}Ge \rightarrow ^{132}Nd^{*}$

Wrap-up

$^{208}Pb + ^{50}Ti \rightarrow ^{257}Rf + 1n$ @ $E_{cm} = 185$ MeV

- $\sigma_{exp} = (10.419 \pm 1.3)$ nb
- $\sigma_{cap} = (0.43 \pm 0.11)$ mb
- $P_{sur} = 0.089 \pm 0.072$
- P_{CN} few orders of magnitude

No hope to get better than 1 order of magnitude accuracy

Conclusions and perspectives

- How to assess models? Especially fusion hindrance?
- The fission-barrier height plays an important role in fusion-evaporation reaction calculations.
- Further effort will concentrate on a more consistent description of the whole process including uncertainties
- New strategies to constrain fusion hindrance
- No hope to get better accuracy than an order of magnitude

Thank you for your attention !