Production of heavy and superheavy neutron rich nuclei

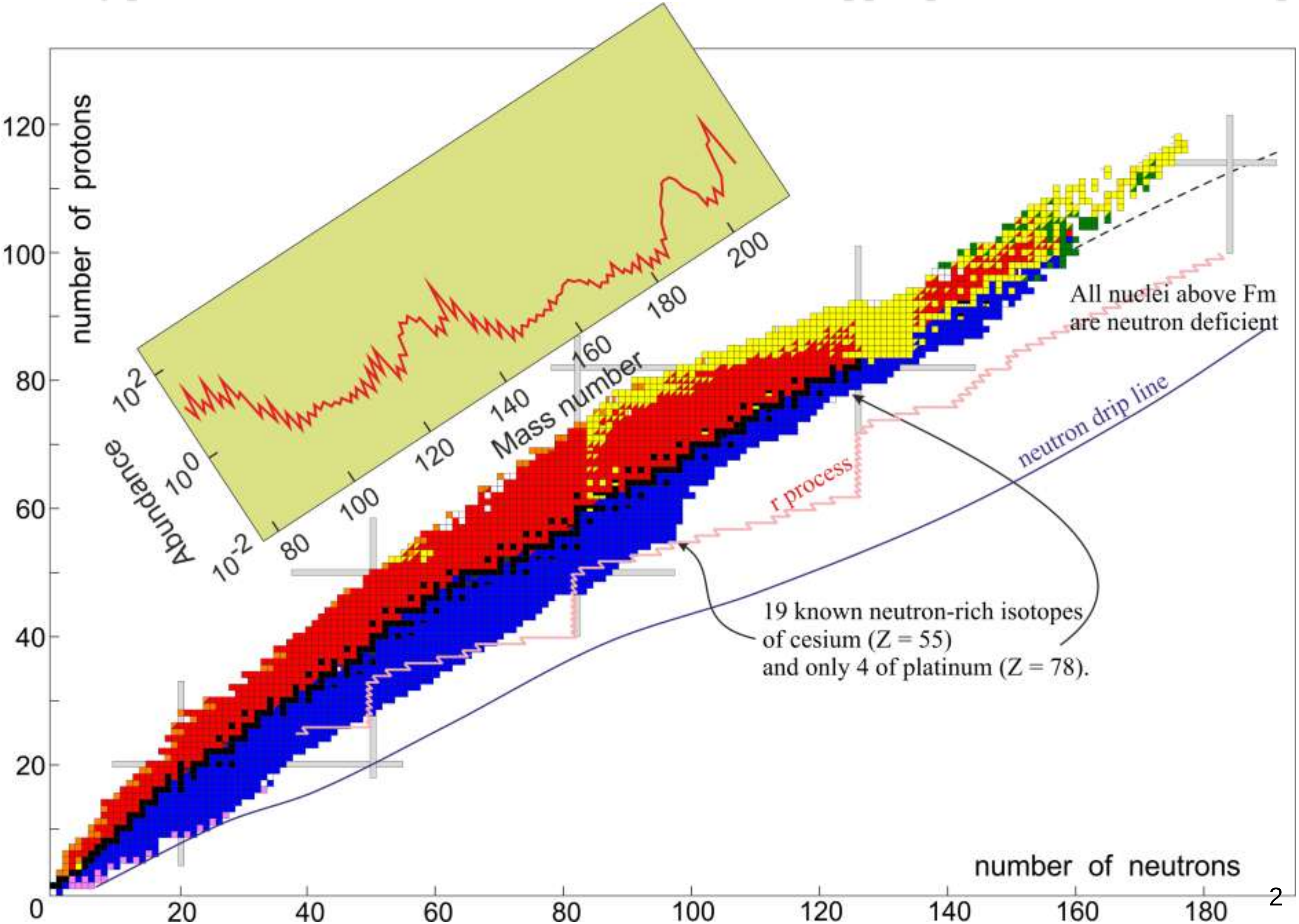
- **Unexplored north-east area of the Nuclear Map**
- **Our predictions and proposals:**
  - **Elements 119 and 120 are on the way. What’s the next?**
  - **Filling the gap of not-yet-synthesized isotopes of SH elements (Z=106 - 116)**
  - **Narrow (hypothetical) pathway to the Island of Stability**
  - **Production of new neutron enriched SH nuclei in transfer reactions**
  - **Shell effects in damped collisions of heavy ions ?**
  - **Production of trans-target nuclei (inverse quasi-fission process)**
  - **Production of neutron rich nuclei located along the neutron closed shell N=126**
- **New facilities are needed. They are coming**

Valeriy Zagrebaev

JINR *(Dubna)*

EURISOL meeting, July 1, 2013, Krakow, Poland

Mostly proton-rich nuclei were studied so far in the upper part of the nuclear map



All nuclei above Fm are neutron deficient

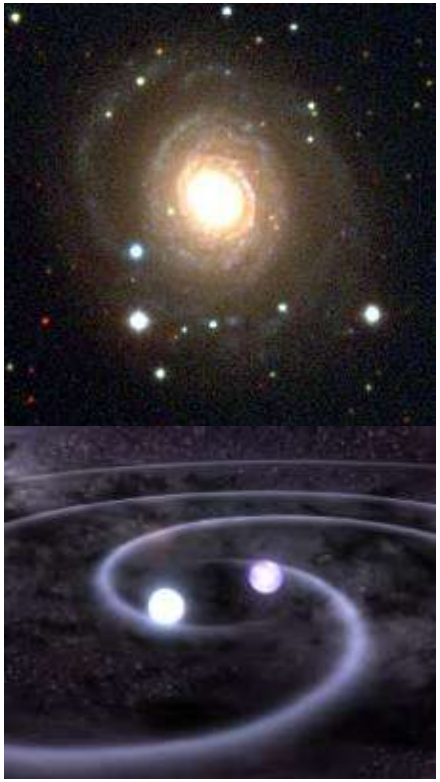
19 known neutron-rich isotopes of cesium (Z = 55) and only 4 of platinum (Z = 78).

Abundance of the elements in the Universe

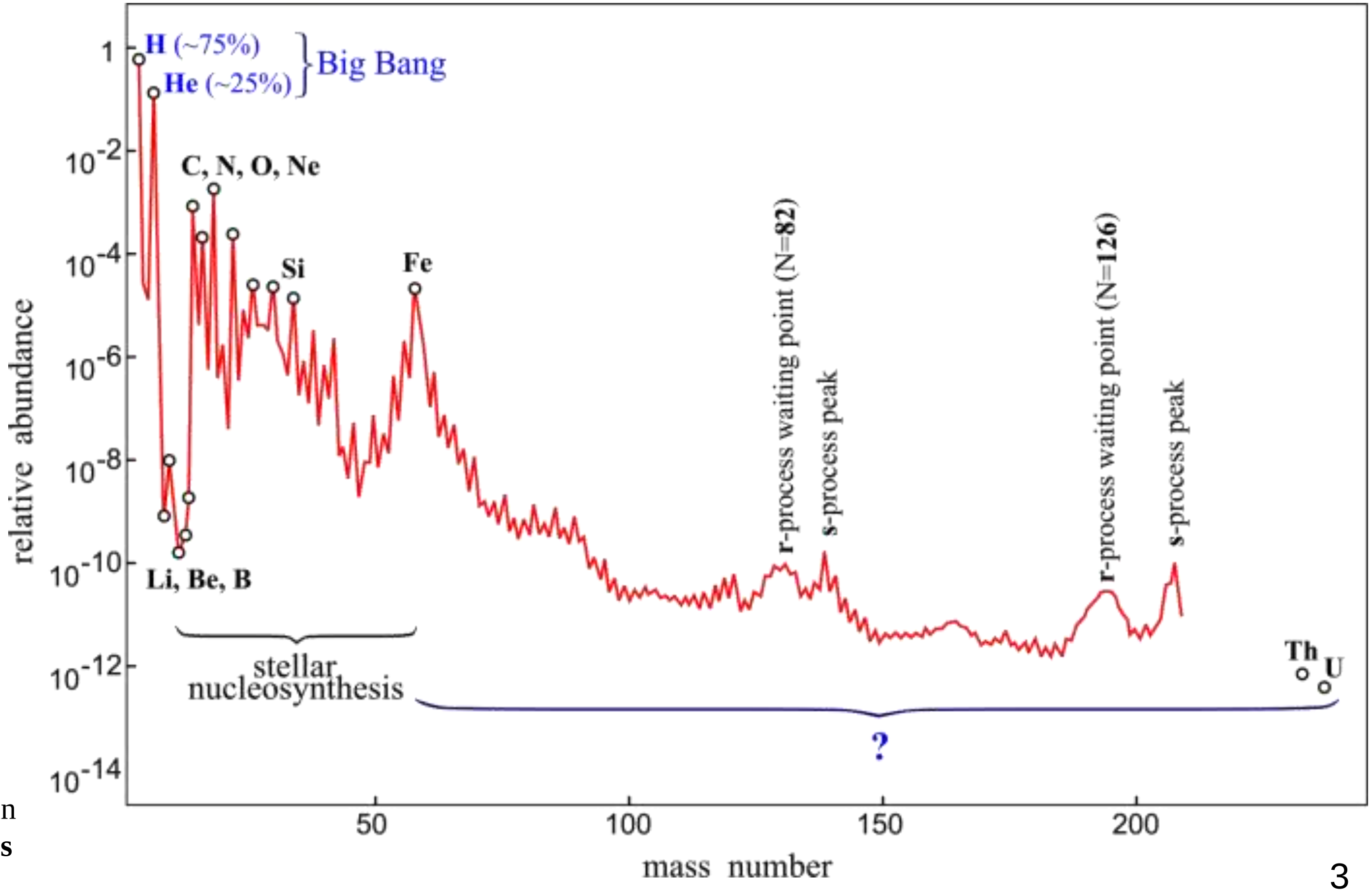
The 11 Greatest Unanswered Questions of Physics
(National Research Council, NAS, USA, 2002):

1. **What is dark matter?**
2. **What is dark energy?**
3. **How were the heavy elements from iron to uranium made?**
4. **Do neutrinos have mass?**

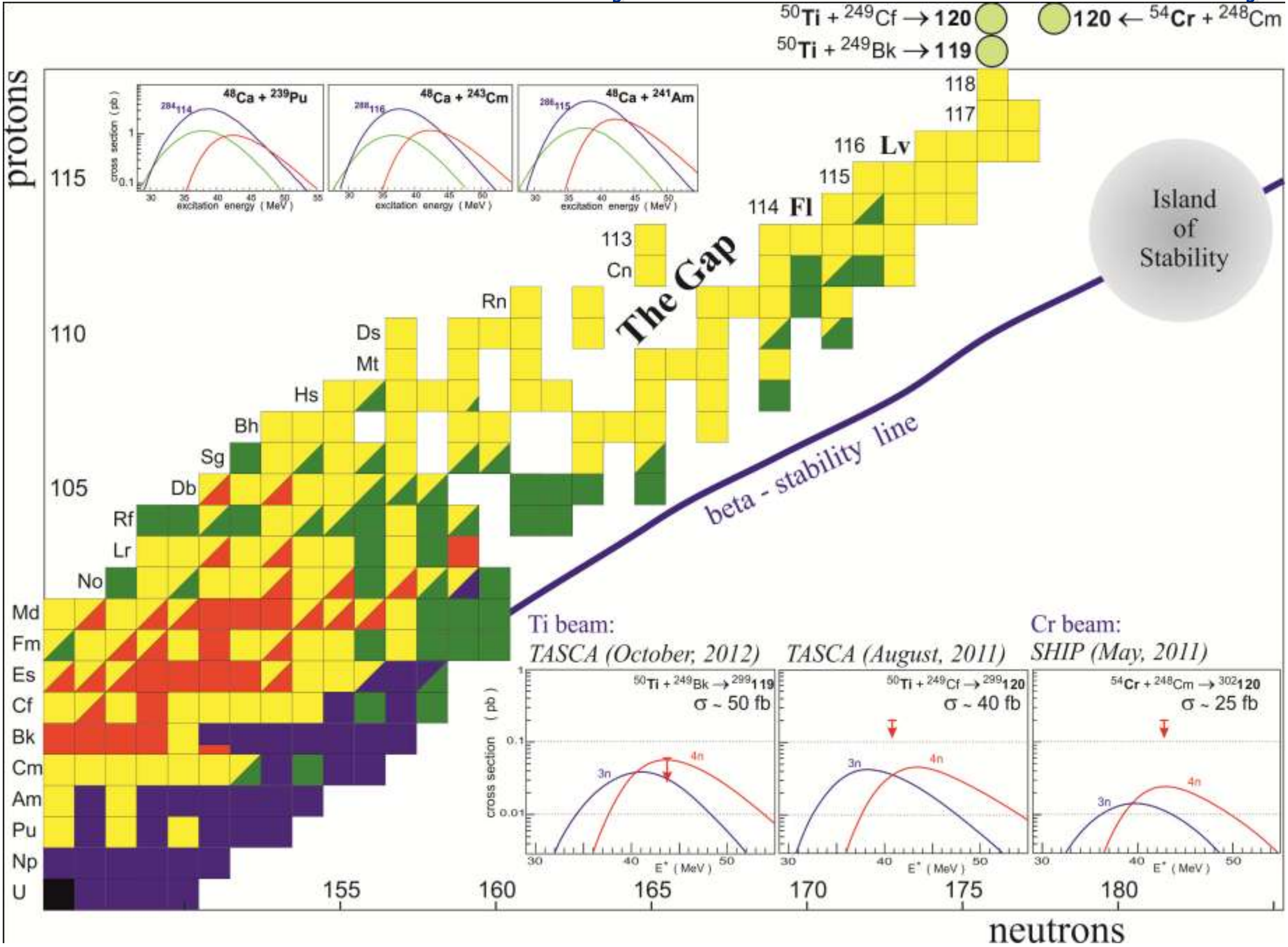
…



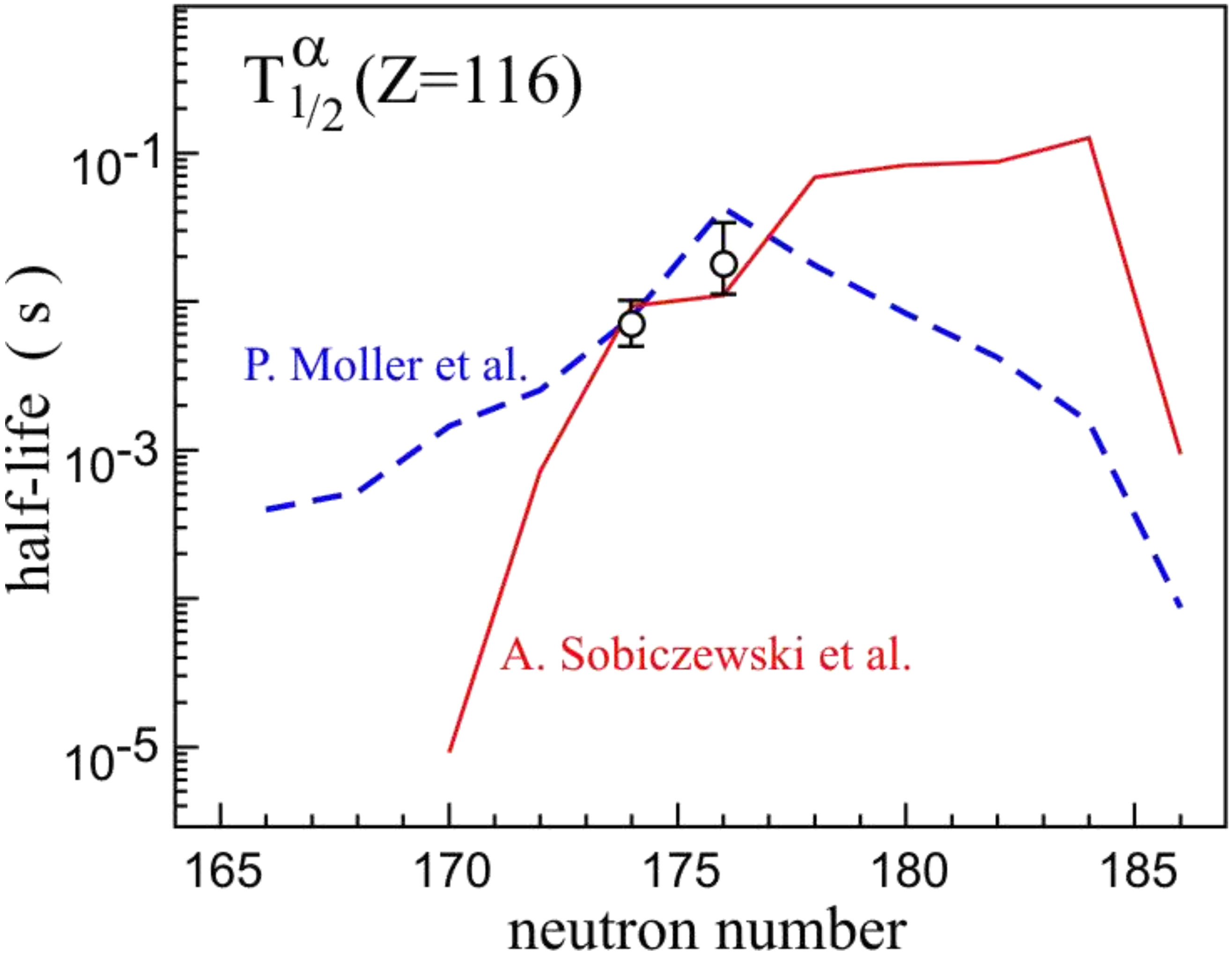
Strong neutron fluxes are expected in **core-collapse supernova explosions** or in the **mergers of neutron stars.**



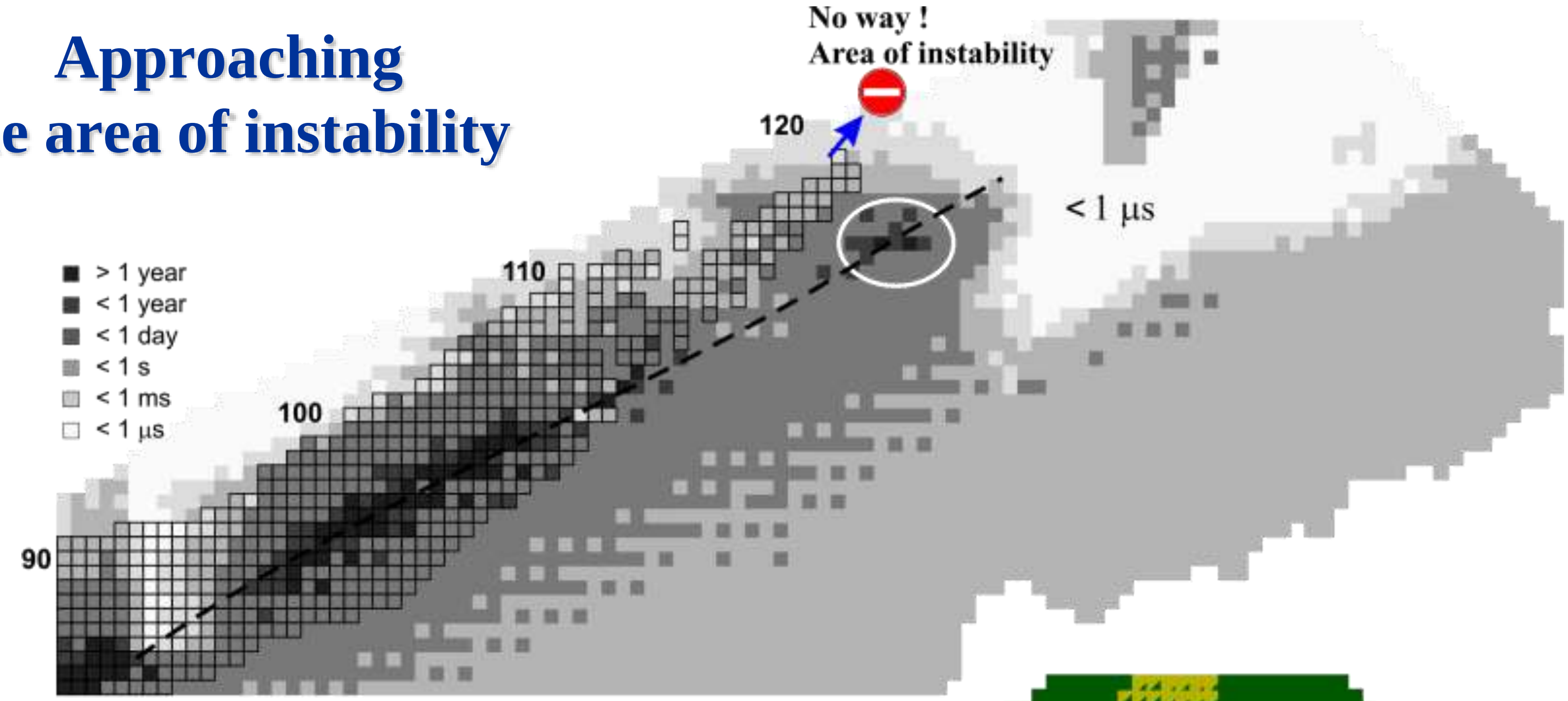
SHE: we are far from the stability line and from the Island of Stability

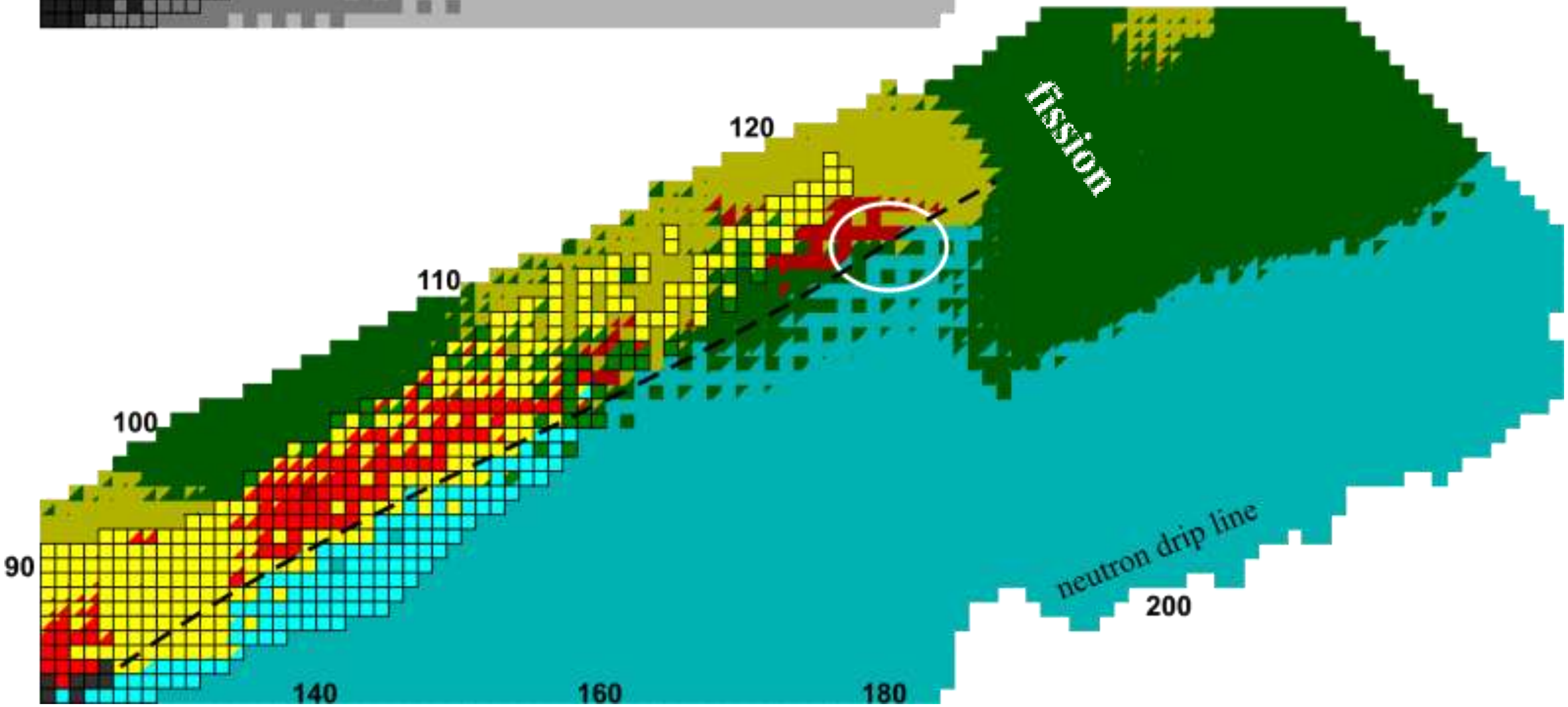


Our ability of predictions in superheavy mass area



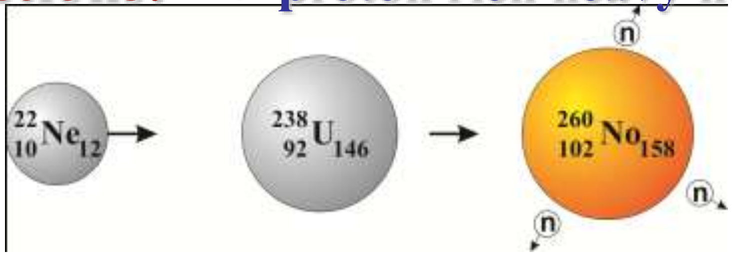
Approaching the area of instability





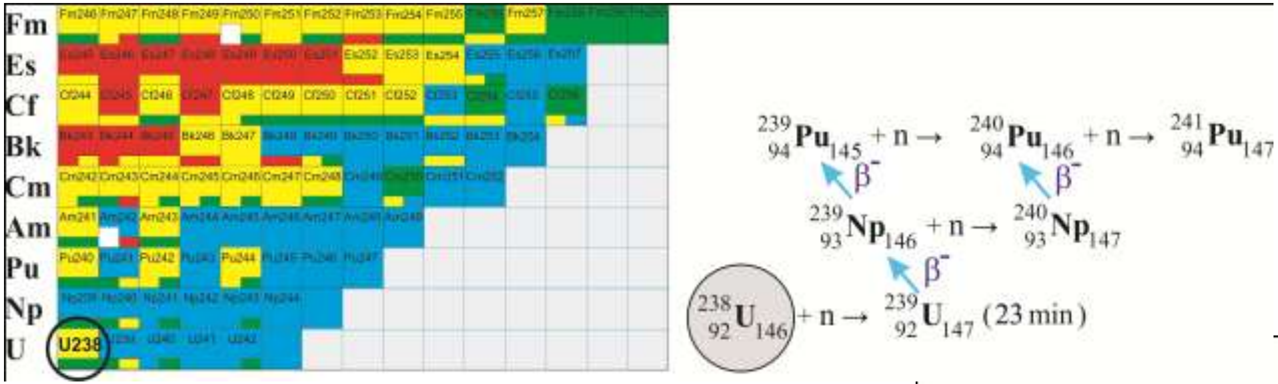
There are only 3 methods for synthesis of heavy nuclei

1. Fusion reactions: → proton rich heavy nuclei

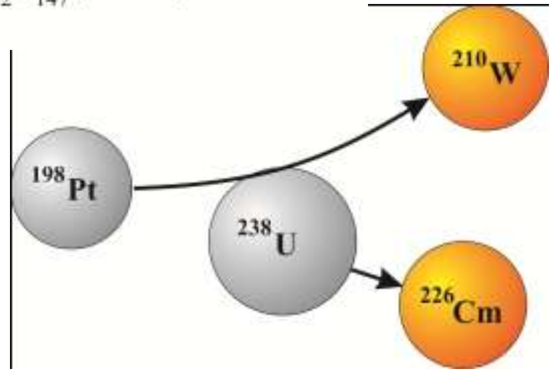


2. Sequence of neutron capture and beta(-) decay processes:

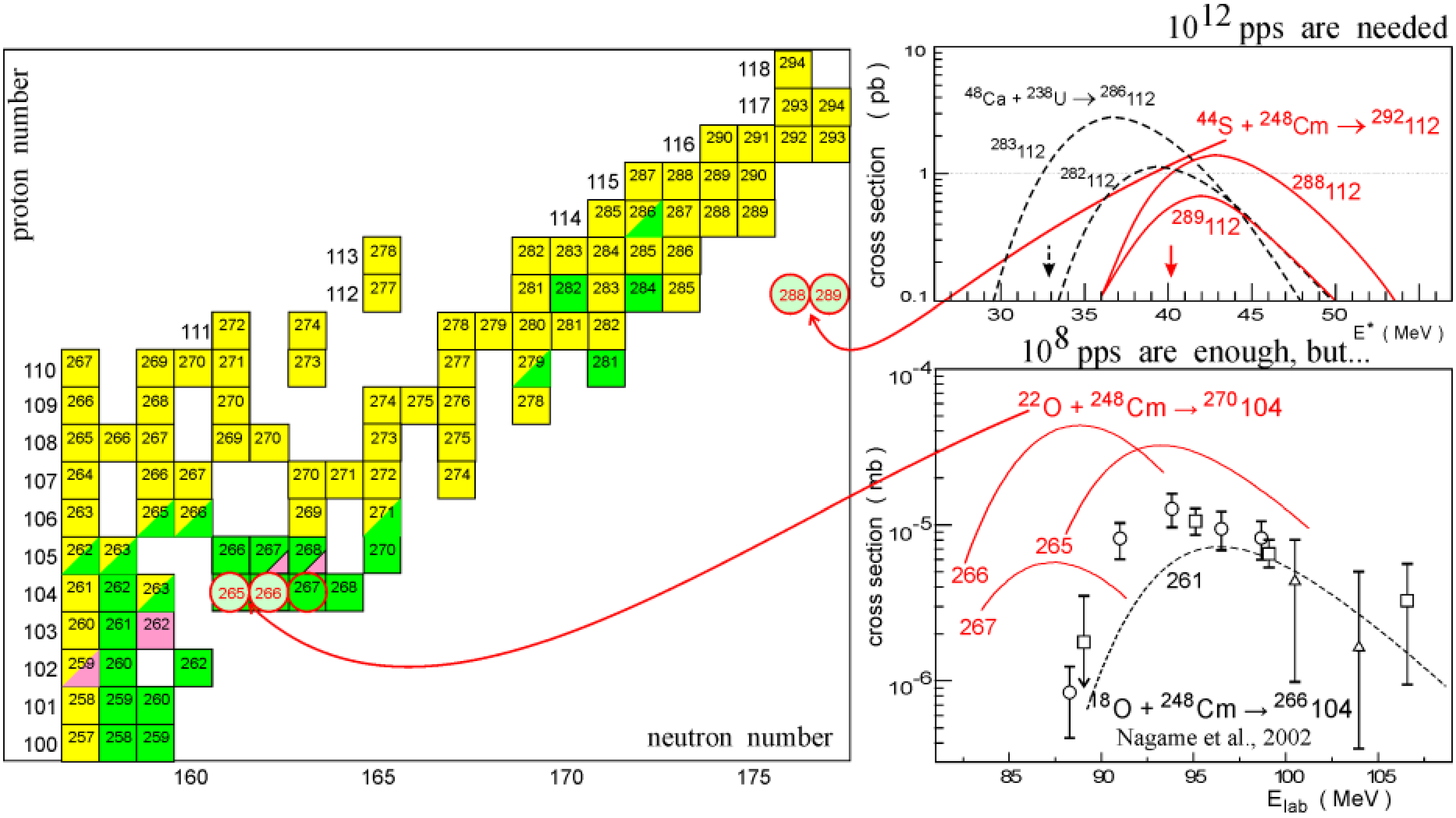
neutron fluxes in reactors are too low, nuclear explosions are forbidden



3. Multi-nucleon transfer reactions



The use of low-energy Radioactive Ion Beams for the production of neutron rich superheavy nuclei ?

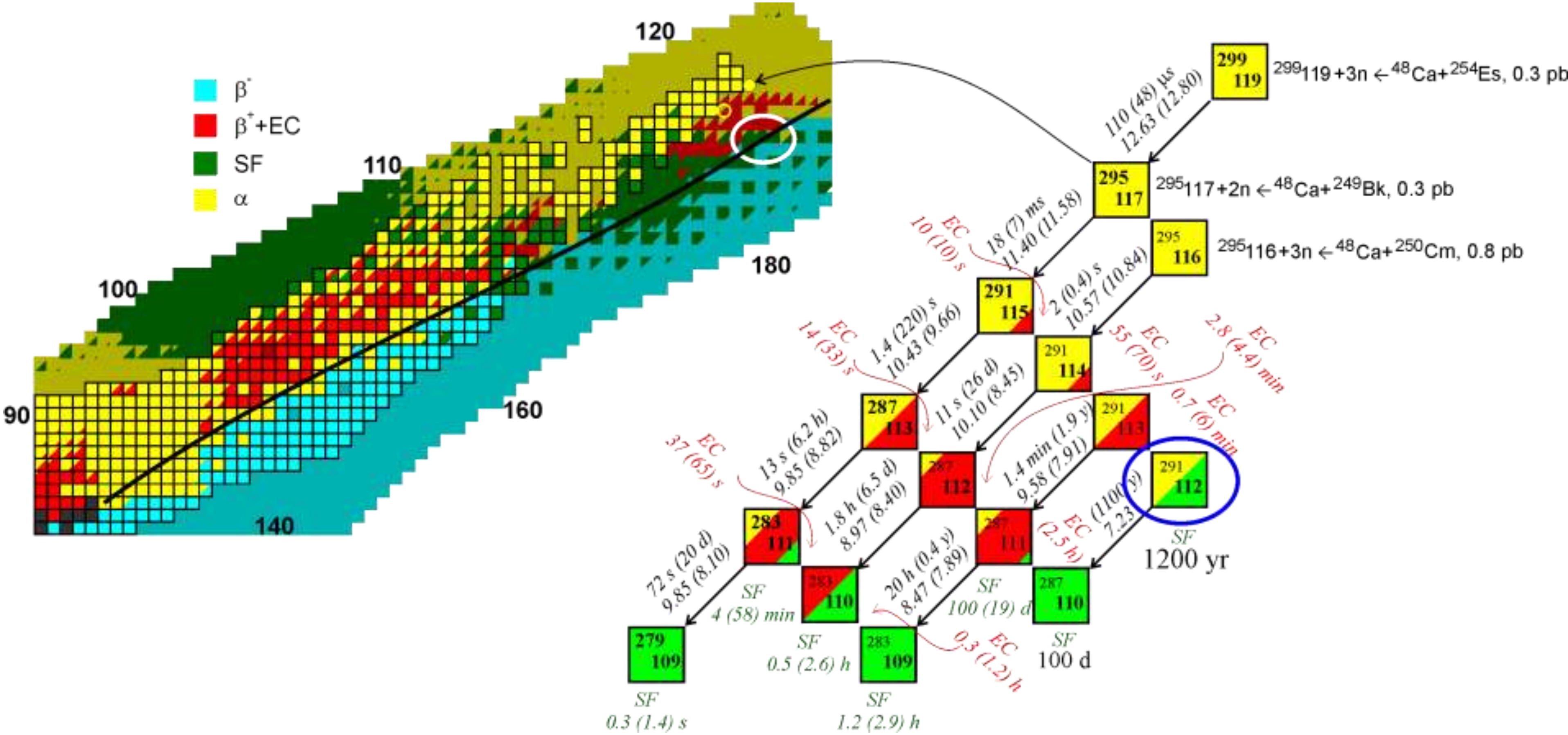


10^{12} pps are needed

10^{8} pps are enough, but…

No chances today. But in the nearest future …

Narrow (hypothetical) pathway to the Island of Stability still exists probably !



Nucleosynthesis by neutron capture

n_0 is the neutron flux

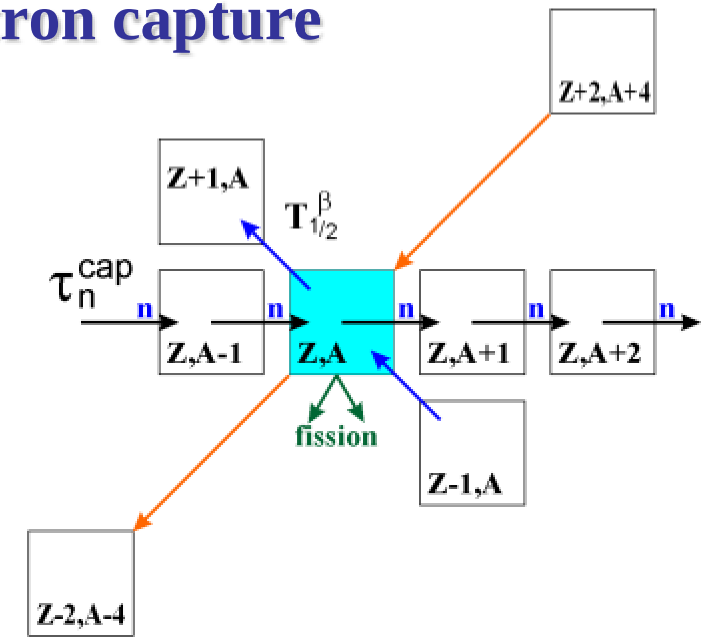
time of neutron capture

$$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$$

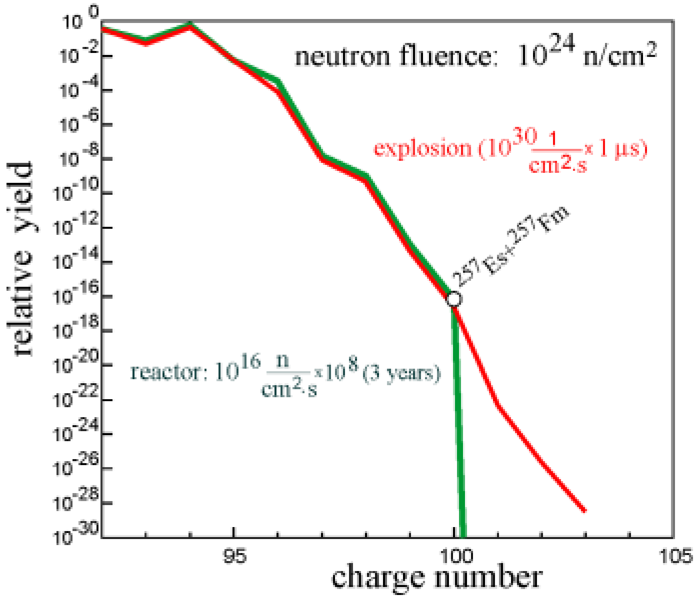
$$(Z,A) \rightarrow (Z,A+1) \quad \text{if} \quad T_{1/2} > \tau_n^{cap}$$

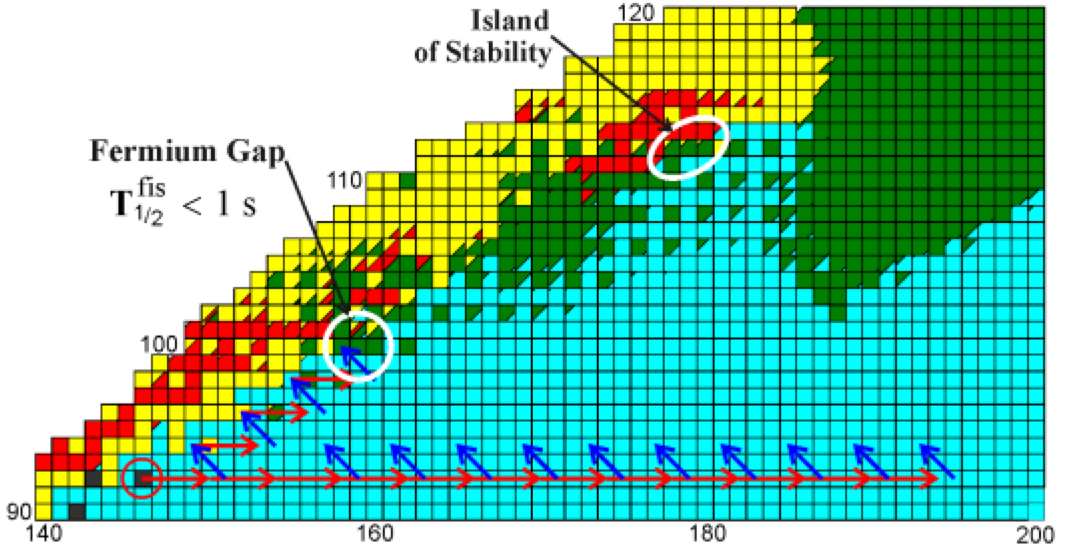
nuclear reactor: $\tau_n^{cap} \sim 1$ year

nuclear explosion: $\tau_n^{cap} \sim 1\ \mu s$



$$\frac{dN_{ZA}}{dt} = N_{ZA-1}\, n_0\, \sigma^{n\gamma}_{ZA-1} - N_{ZA}\, n_0\, \sigma^{n\gamma}_{ZA} - N_{ZA}\frac{\ln 2}{T^{\beta}_{ZA}} - N_{ZA}\frac{\ln 2}{T^{\alpha}_{ZA}} - N_{ZA}\frac{\ln 2}{T^{fis}_{ZA}} + N_{Z-1A}\frac{\ln 2}{T^{\beta}_{Z-1A}} + N_{Z+2A+4}\frac{\ln 2}{T^{\alpha}_{Z+2A+4}}$$





Theoretical models of transfer reactions

Multi-nucleon transfers in damped collisions

Master equation

L.G. Moretto and J.S. Sventek, Phys. Lett. B **58**, 26 (1975)

Fokker-Plank equation

W. Norenberg, Phys. Lett. B **52**, 289 (1974)

Langevin equations

P. Frobrich and S.Y. Xu, Nucl. Phys. **A477**, 143 (1988)

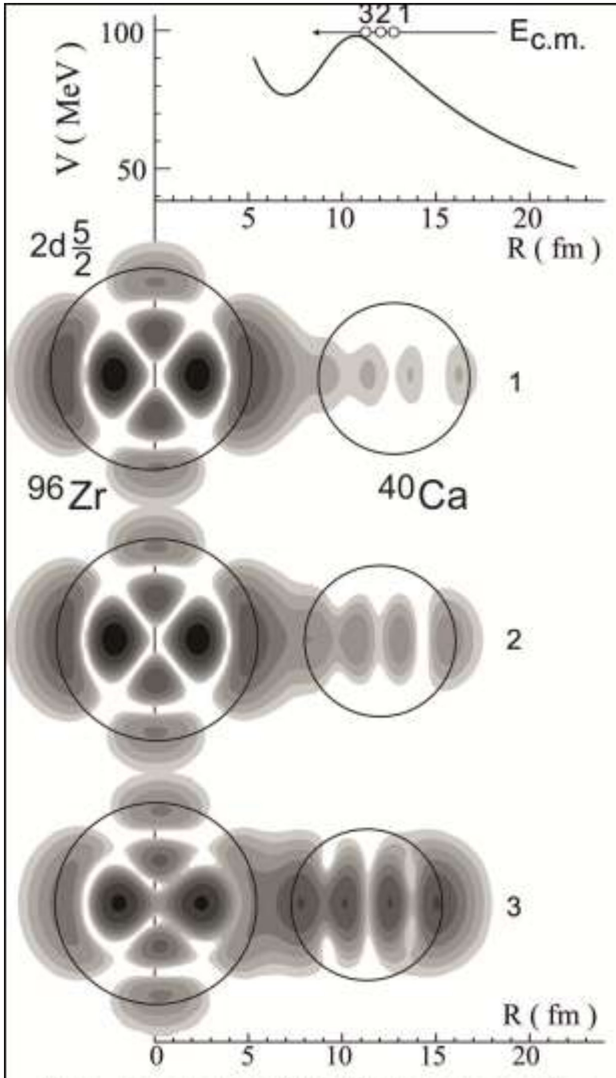
Semi-classical approaches

E. Vigezzi and A. Winther, Ann. Phys. (N.Y.) **192**, 432 (1989).
V.I. Zagrebaev, Ann. Phys. (N.Y.) **197**, 33 (1990).

Few-nucleon transfers (GRAZING)

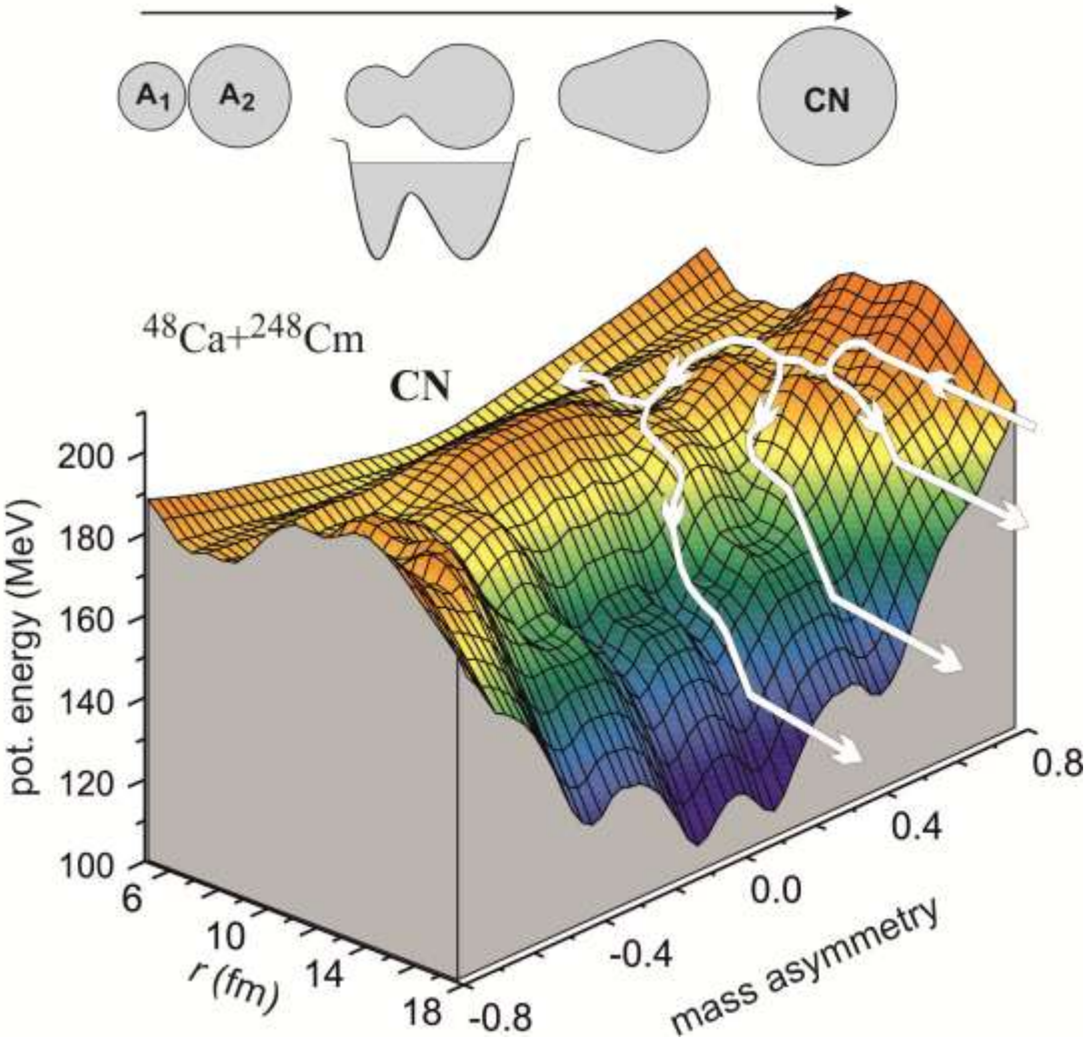
A. Winther, Nucl. Phys. **A594**, 203 (1995)
http://personalpages.to.infn.it/nanni/grazing

Adiabatic dynamics of low-energy heavy ion collisions and nucleon transfers



time-dependent Schrödinger equation
for single particle wave functions
(Zagrebav, Samarin, Greiner, 2007);

- overlapped mean fields
- two-center shell model
- adiabatic potential energy



System of coupled Langevin type Equations of Motion

Variables: $\{R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta_Z, \eta_N\}$

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ^0_Z, λ^0_N - nucleon transfer rate

$$\frac{dR}{dt} = \frac{p_R}{\mu_R}$$

$$\frac{d\vartheta}{dt} = \frac{\ell}{\mu_R R^2}$$

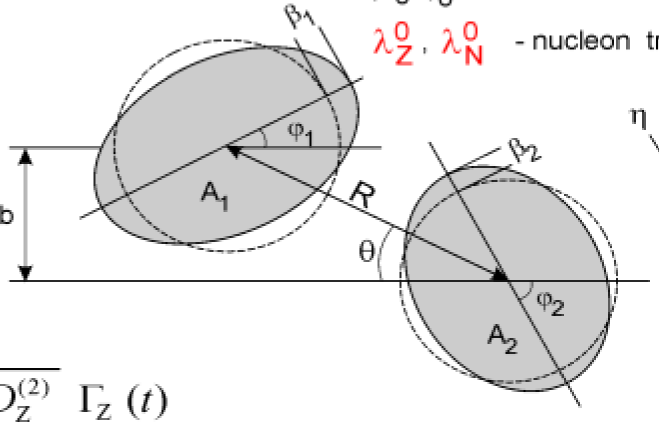
$$\frac{d\varphi_1}{dt} = \frac{L_1}{\Im_1}, \quad \frac{d\varphi_2}{dt} = \frac{L_2}{\Im_2}$$

$$\frac{d\beta_1}{dt} = \frac{p_{\beta 1}}{\mu_{\beta 1}}$$

$$\frac{d\beta_2}{dt} = \frac{p_{\beta 2}}{\mu_{\beta 2}}$$

$$\frac{d\eta_Z}{dt} = \frac{2}{Z_{CN}} D^{(1)}_Z + \frac{2}{Z_{CN}} \sqrt{D^{(2)}_Z}\ \Gamma_Z(t)$$

$$\frac{d\eta_N}{dt} = \frac{2}{N_{CN}} D^{(1)}_N + \frac{2}{N_{CN}} \sqrt{D^{(2)}_N}\ \Gamma_N(t)$$



$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$

$$\eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

$$\eta_N = \frac{N_1 - N_2}{N_1 + N_2}$$

$$\lambda^0_Z = \lambda^0_N = \frac{\lambda^0}{2}$$

$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + \frac{\ell^2}{\mu_R R^3} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial R} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial R} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial R} - \gamma_R \frac{p_R}{\mu_R} + \sqrt{\gamma_R T}\,\Gamma_R(t)$$

$$\frac{d\ell}{dt} = -\frac{\partial V}{\partial \vartheta} - \gamma_{\rm tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) R + \sqrt{\gamma_{\rm tang}\, T}\,\Gamma_{\rm tang}(t)$$

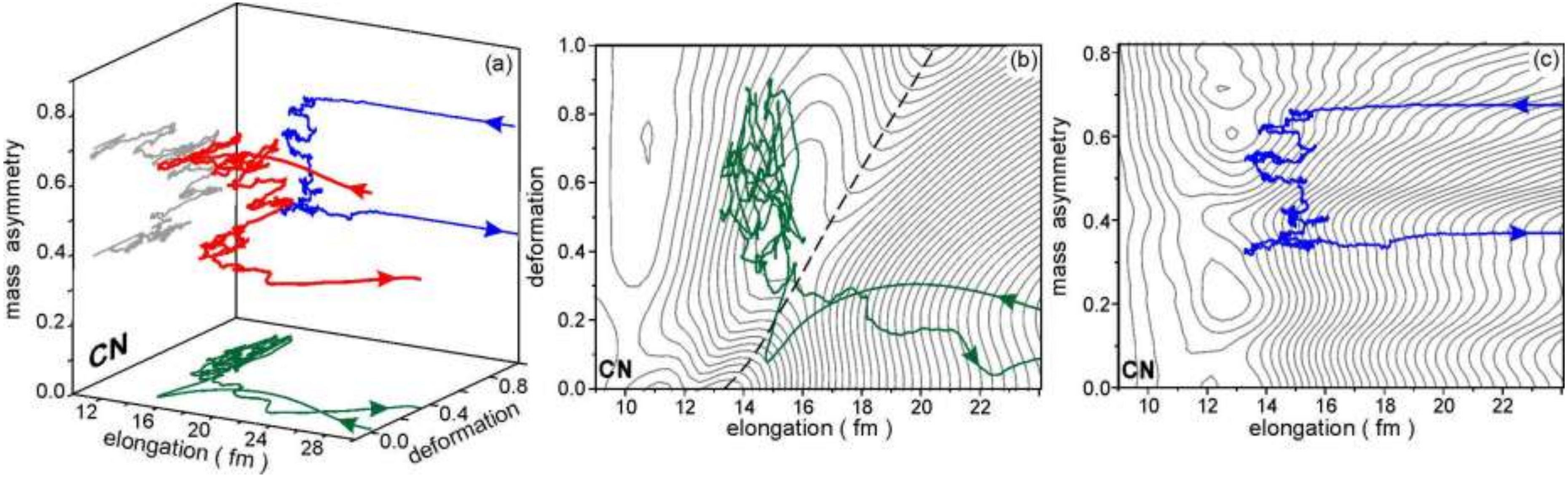
$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{\rm tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_1 - \frac{a_1}{R}\sqrt{\gamma_{\rm tang}\, T}\,\Gamma_{\rm tang}(t)$$

$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{\rm tan}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{\rm tang}\, T}\,\Gamma_{\rm tang}(t)$$

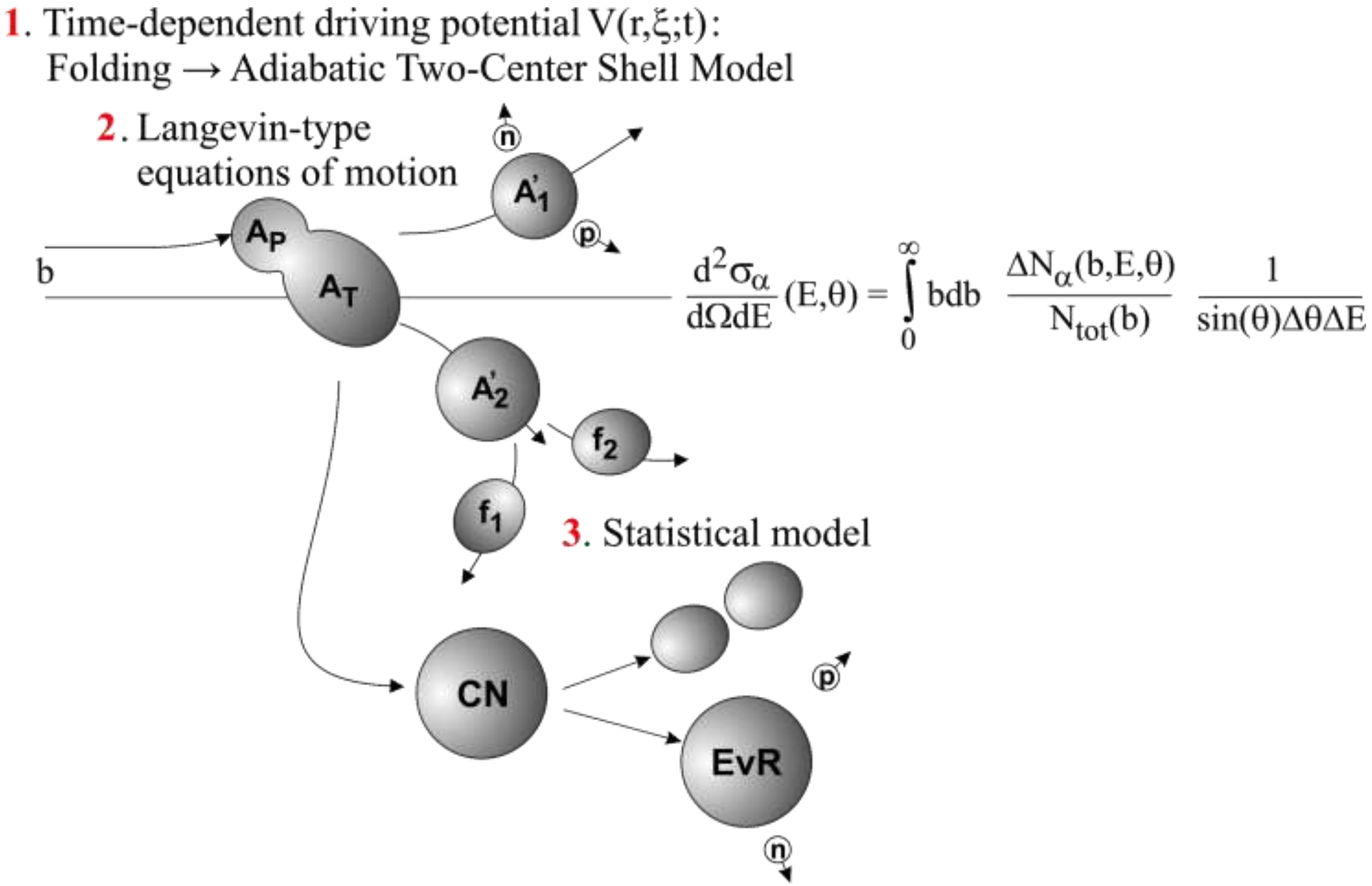
$$\frac{dp_{\beta 1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_1} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_1} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_1} - \gamma_\beta \frac{p_{\beta 1}}{\mu_{\beta 1}} + \sqrt{\gamma_{\beta 1} T}\,\Gamma_{\beta 1}(t)$$

$$\frac{dp_{\beta 2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_2} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_2} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_2} - \gamma_\beta \frac{p_{\beta 2}}{\mu_{\beta 2}} + \sqrt{\gamma_{\beta 2} T}\,\Gamma_{\beta 2}(t)$$

Typical trajectory in the “distance-deformation-mass asymmetry” space (48Ca + 248Cm, E=210 MeV)



Simulation of experiment. Cross sections



1. Time-dependent driving potential $V(r,\xi;t)$:
Folding → Adiabatic Two-Center Shell Model

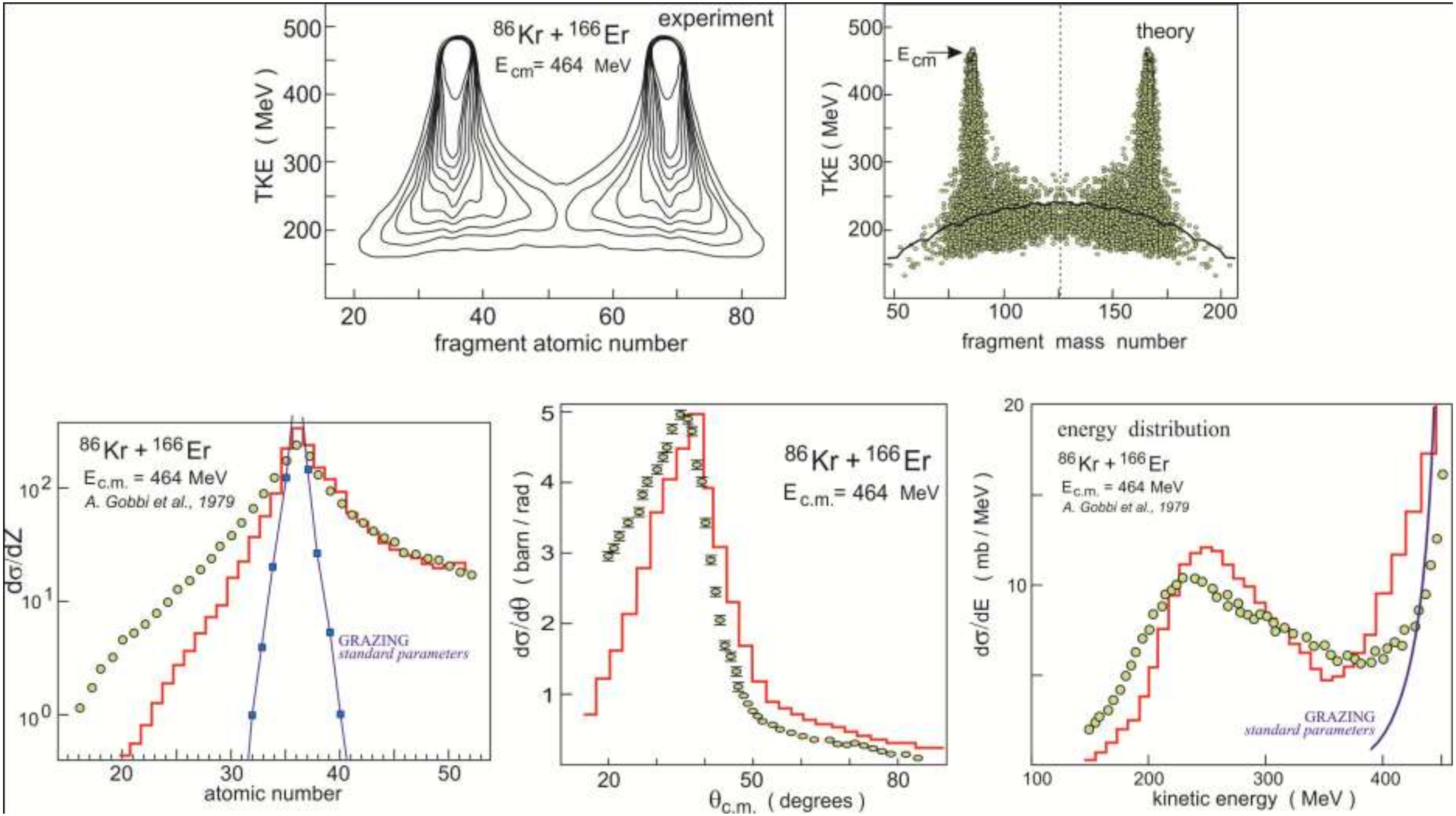
2. Langevin-type equations of motion

3. Statistical model

$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty bdb \; \frac{\Delta N_\alpha(b,E,\theta)}{N_{tot}(b)} \; \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$

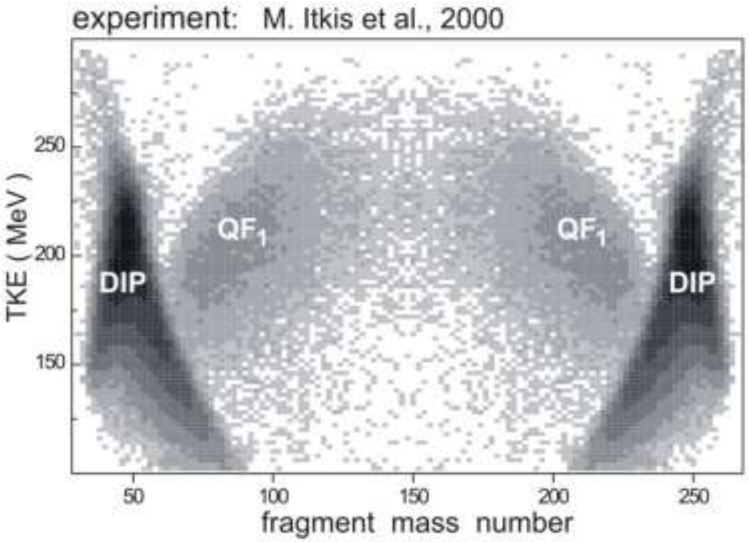
Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

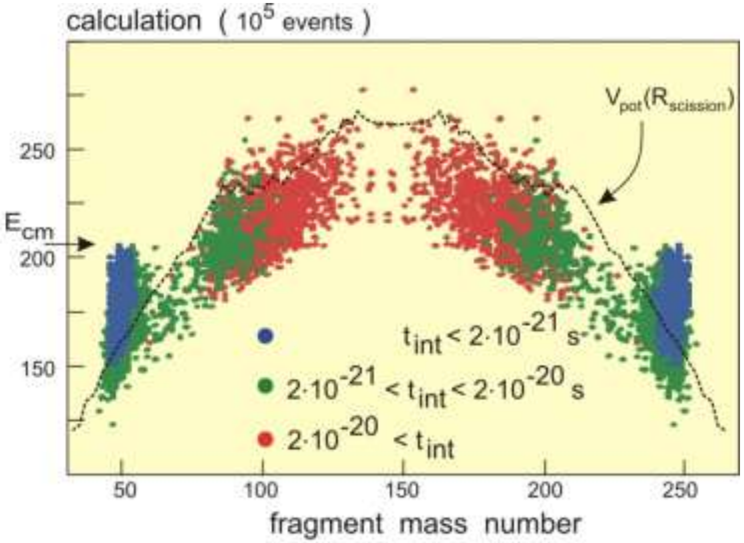
Quite satisfactory agreement with experiments on DI scattering

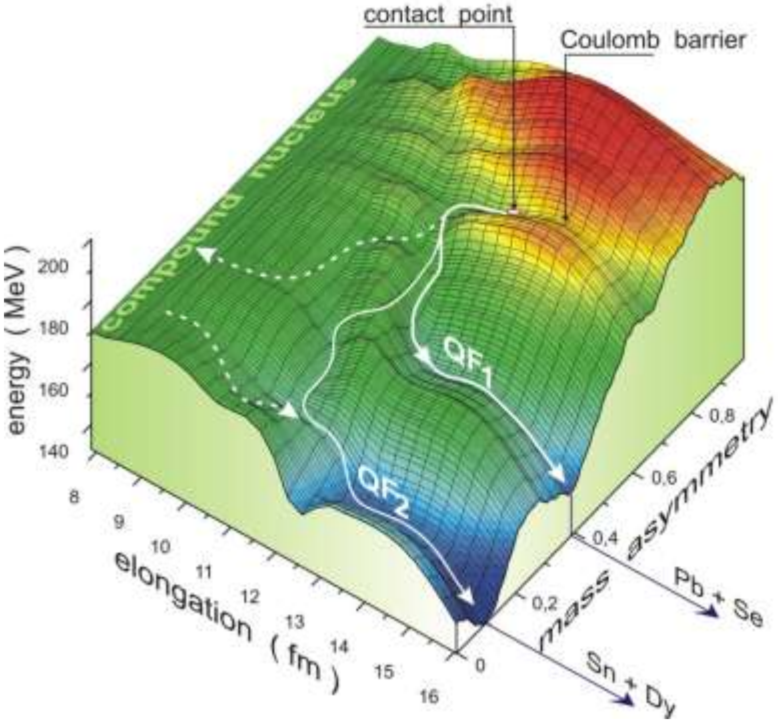


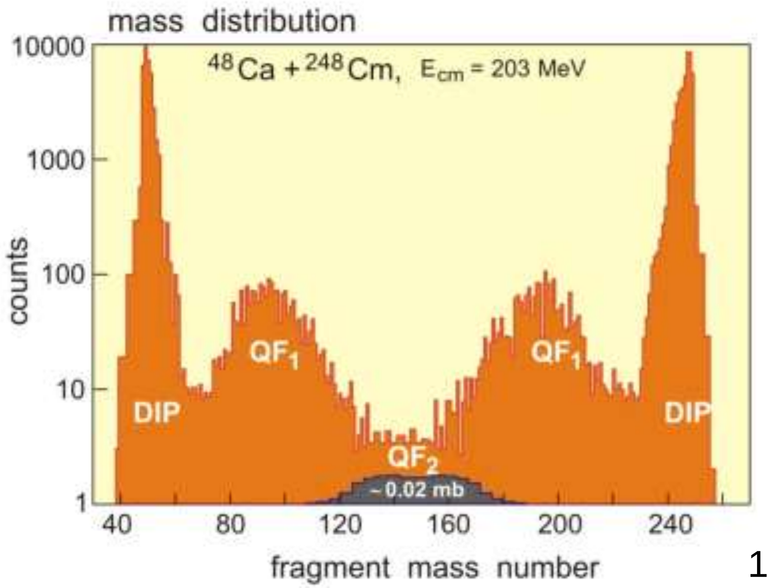
Quasi-Fission process is understood quite well

(example: ^{48}Ca + ^{248}Cm)

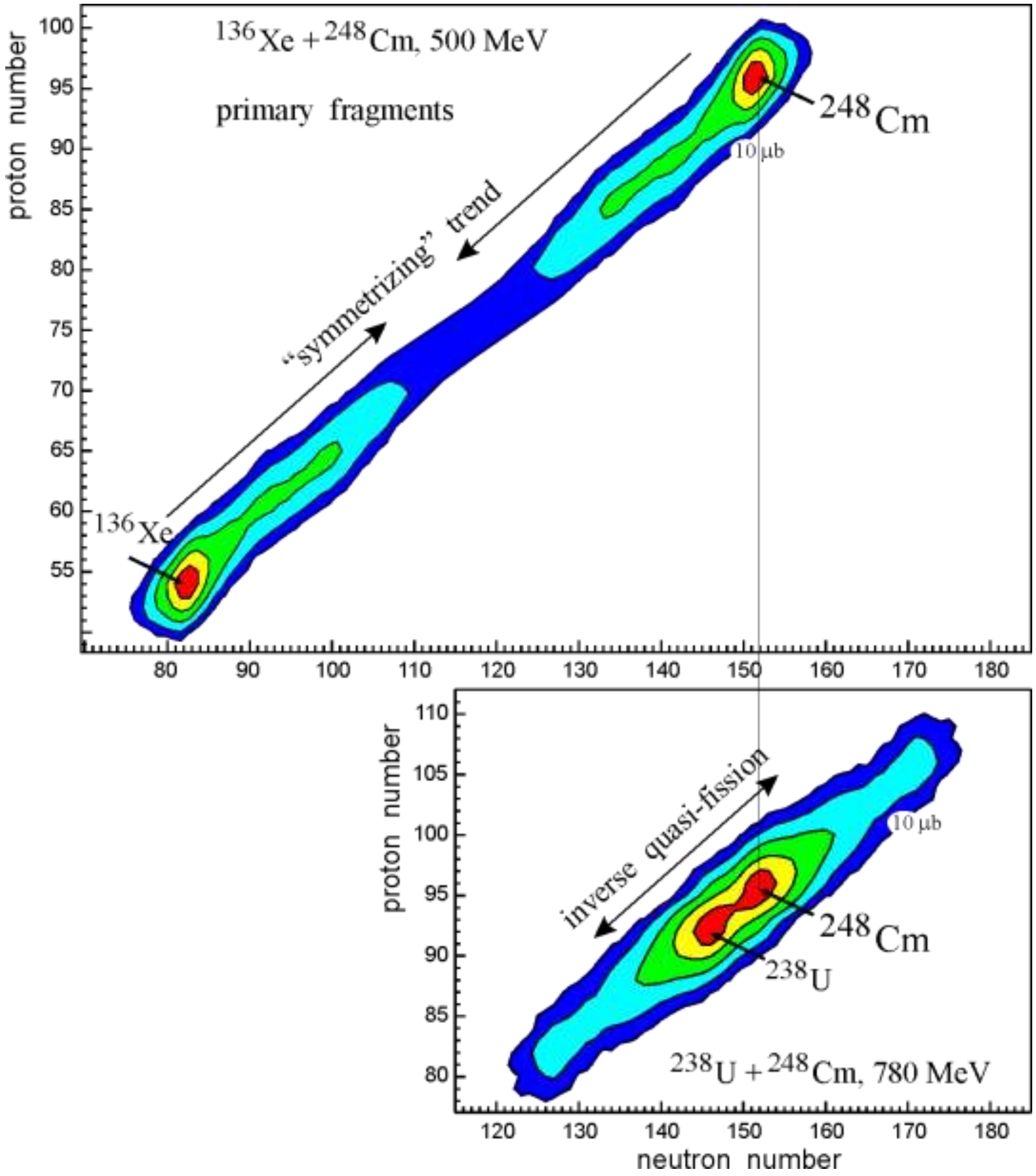




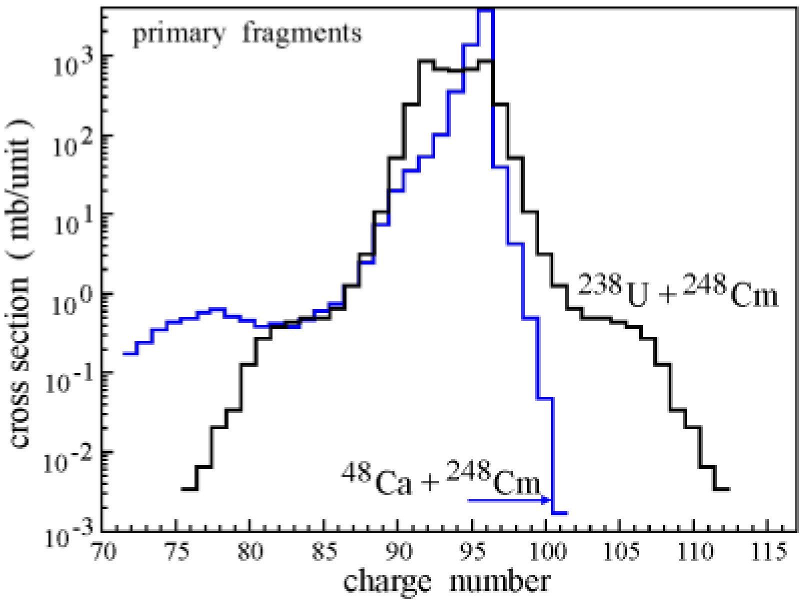


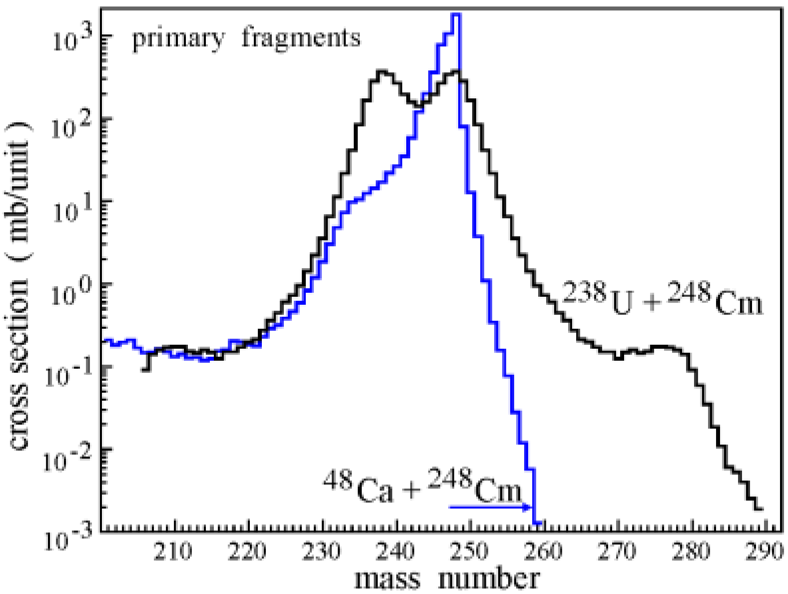


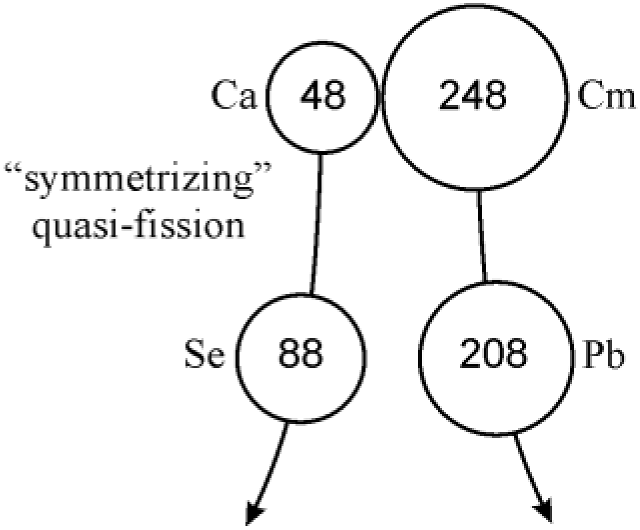
Multi-nucleon transfers for production of Super-Heavy Elements
(choice of reaction is very important)

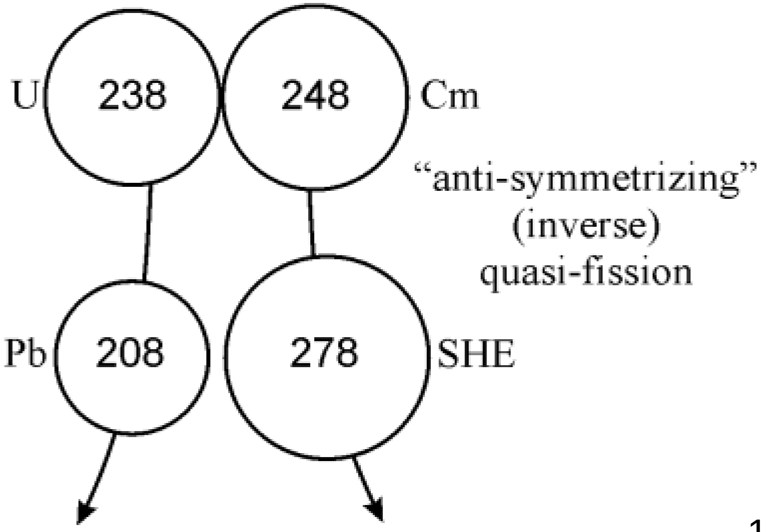


“Inverse quasi-fission” reactions

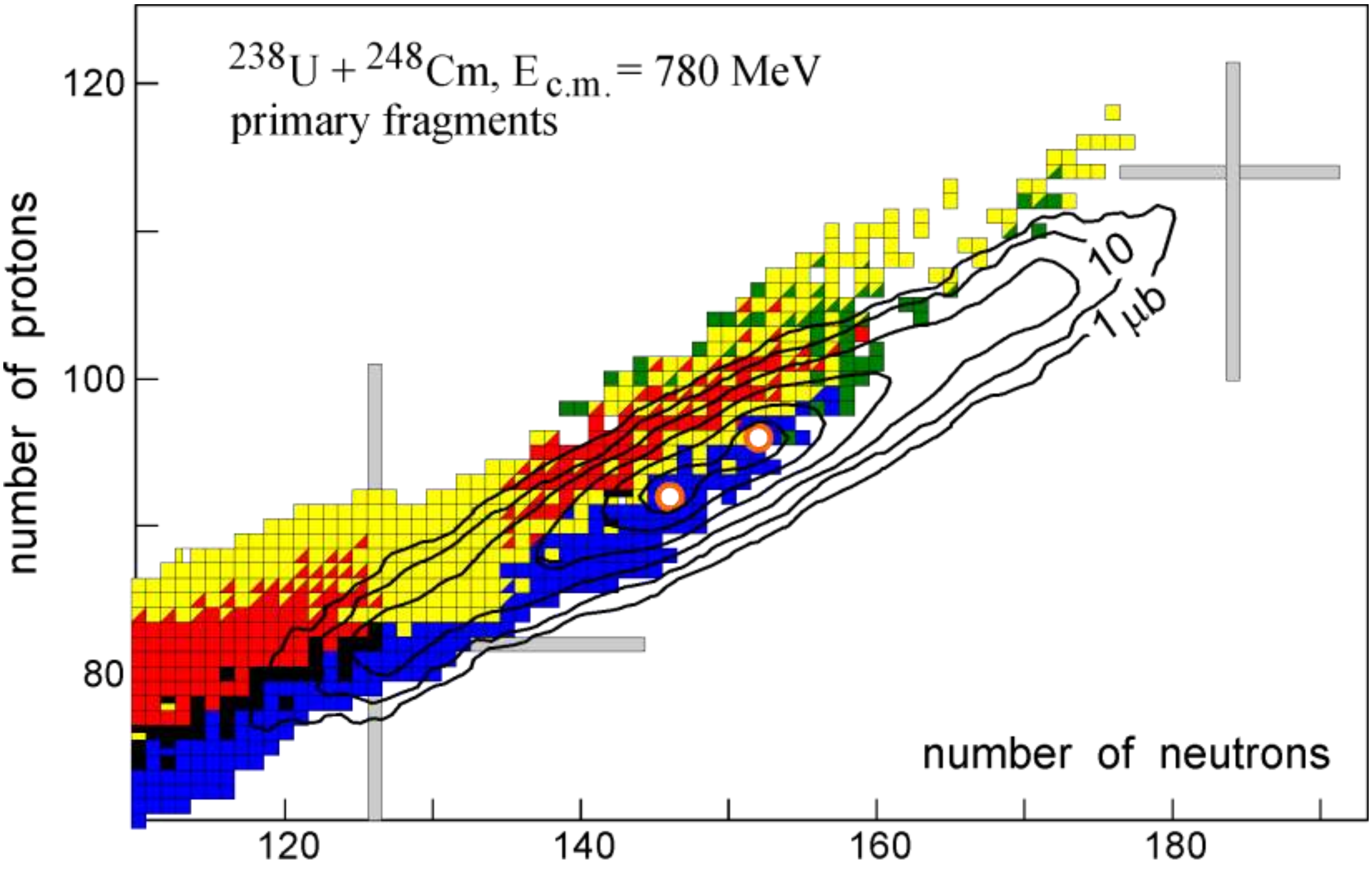




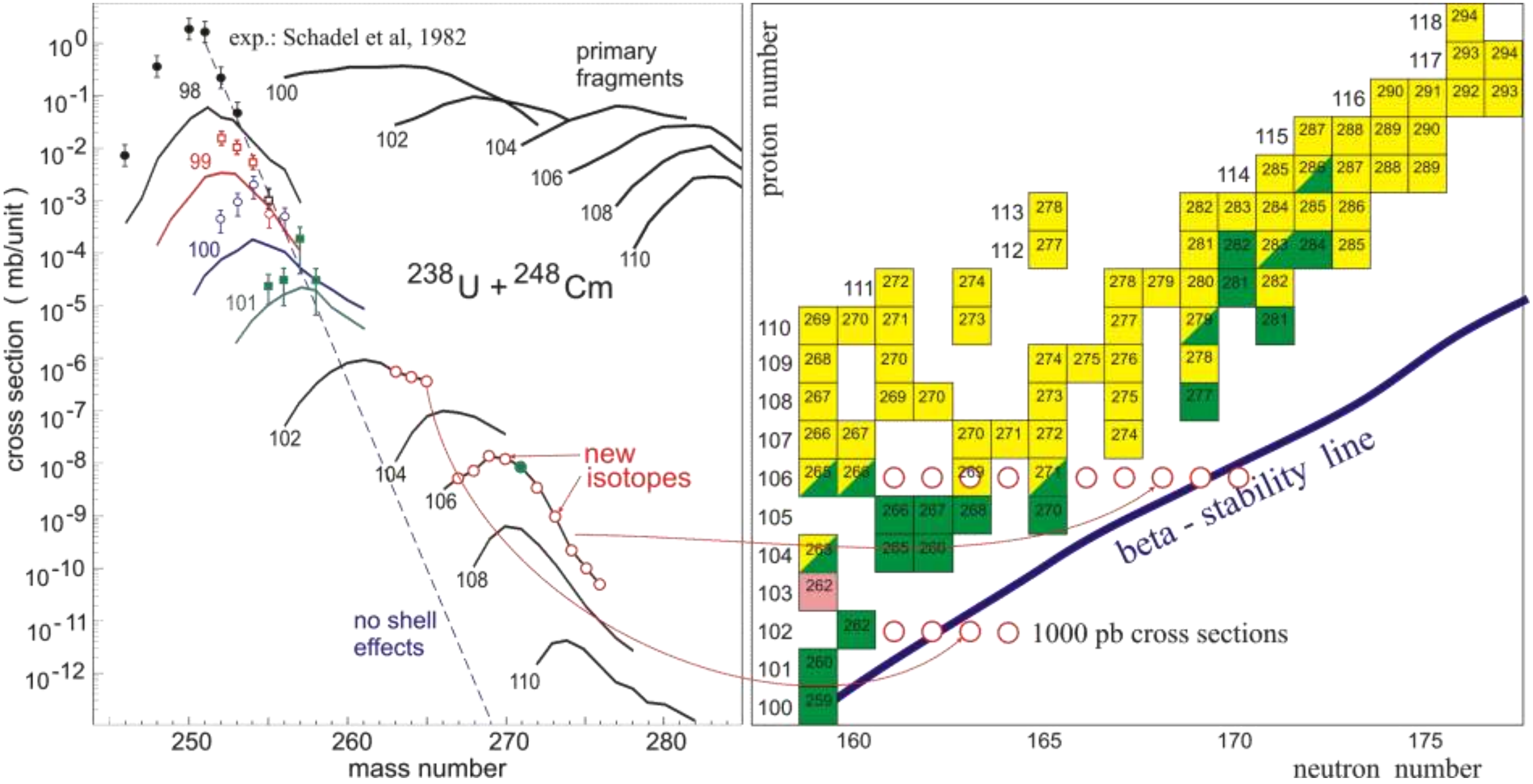




238U + 248Cm. Primary fragments

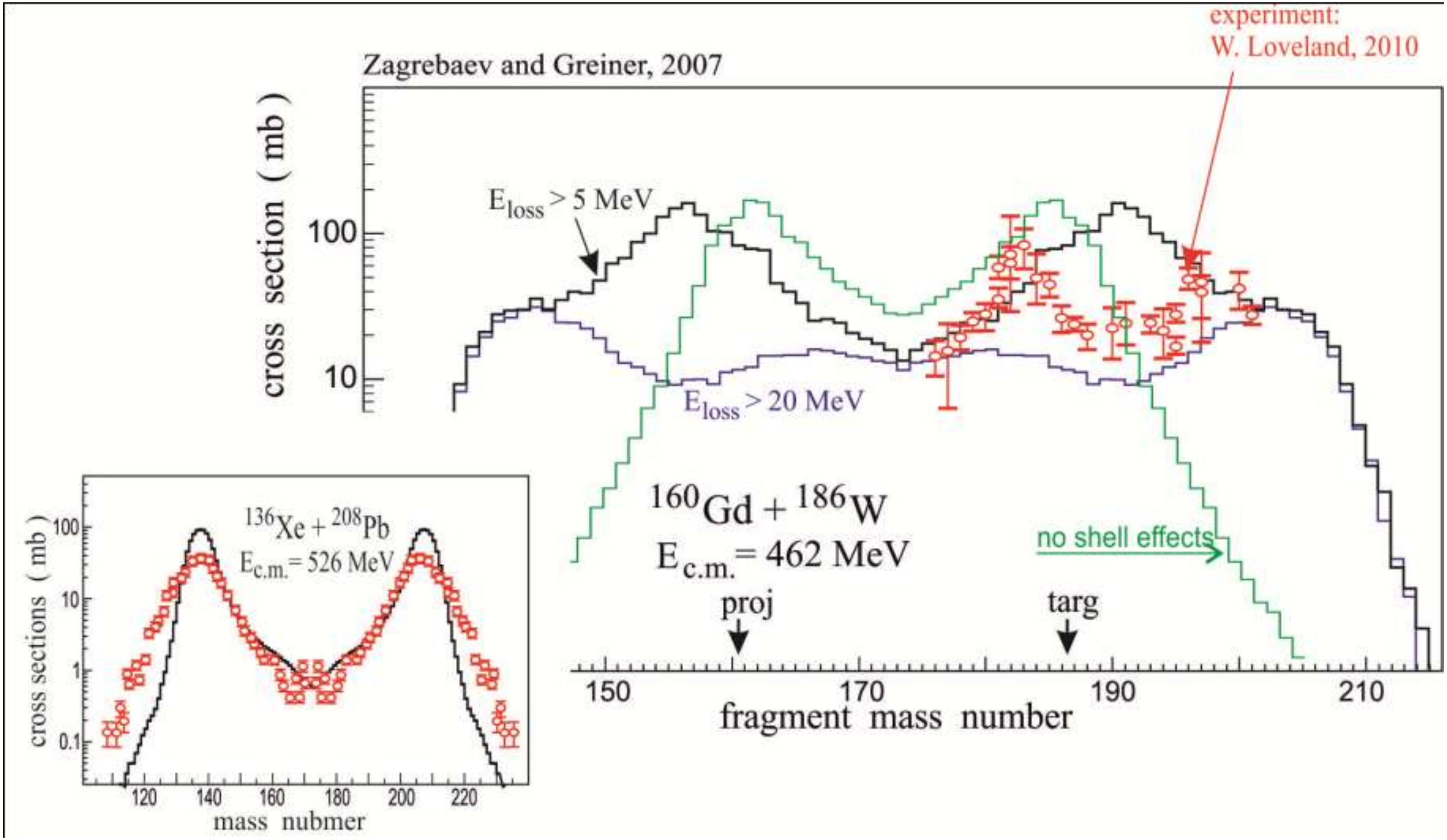


Production of transfermium nuclei along the line of stability looks quite possible owing to shell effects



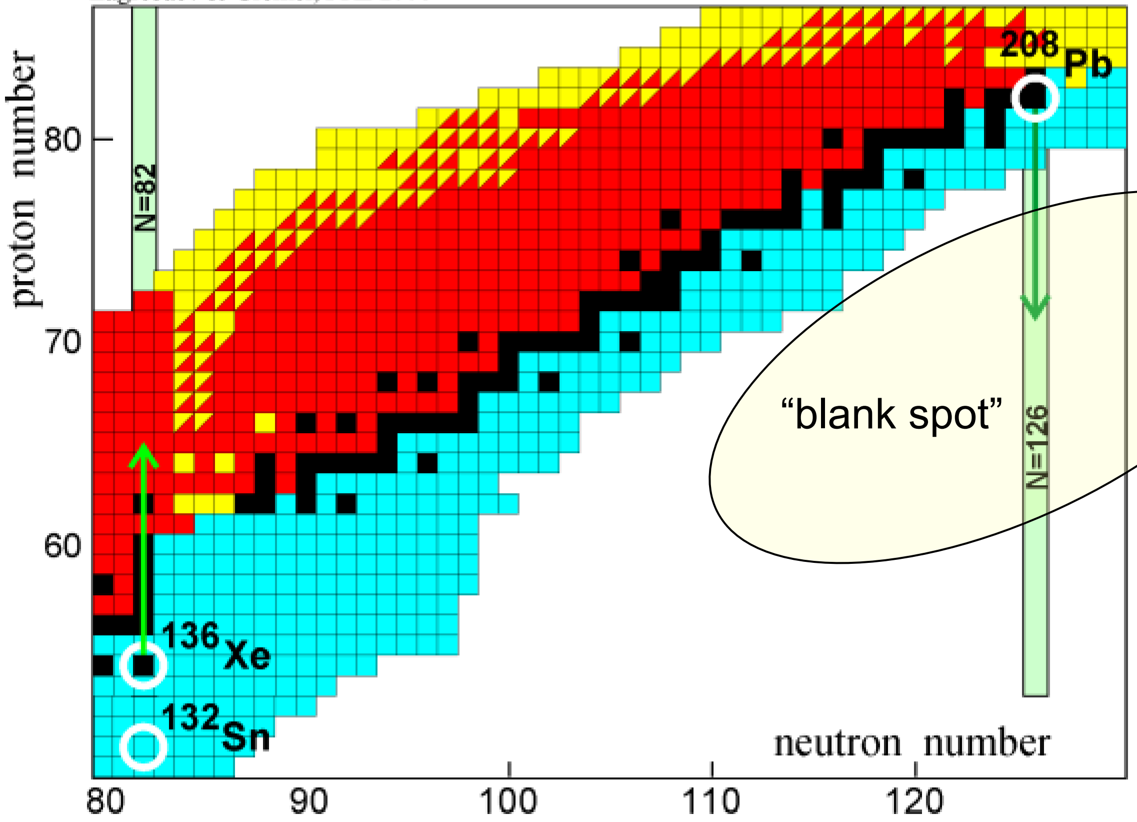
Rather wide angular distribution of reaction fragments:
a new kind of separator is needed

Shell effects in low-energy multi-nucleon transfer reactions is not studied yet !



Production of new heavy nuclei in the region of N=126

Zagrebaev & Greiner, PRL 2008

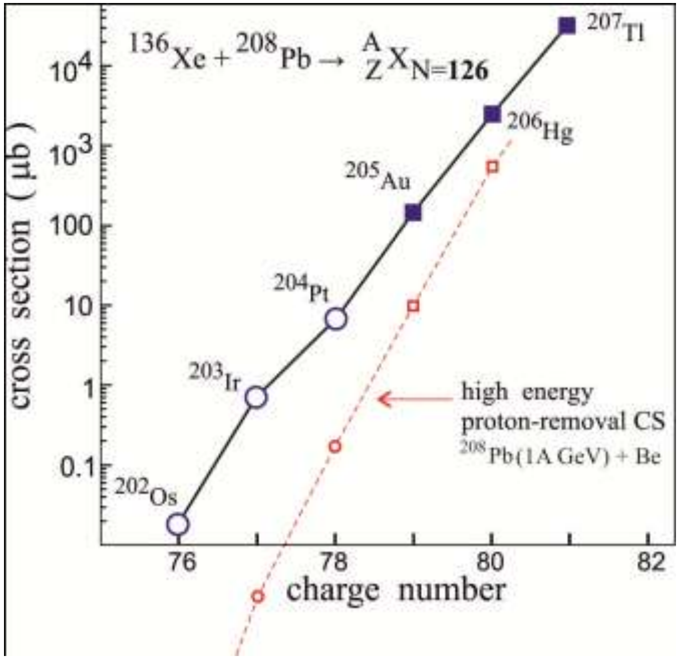


proton transfer along the neutron closed shells:

$^{136}\mathrm{Xe}_{N=82} + {}^{208}\mathrm{Pb}_{N=126} \rightarrow {}^{136+\Delta Z}\mathrm{X}_{N=82} + {}^{208-\Delta Z}\mathrm{Y}_{N=126} + Q \approx 0$

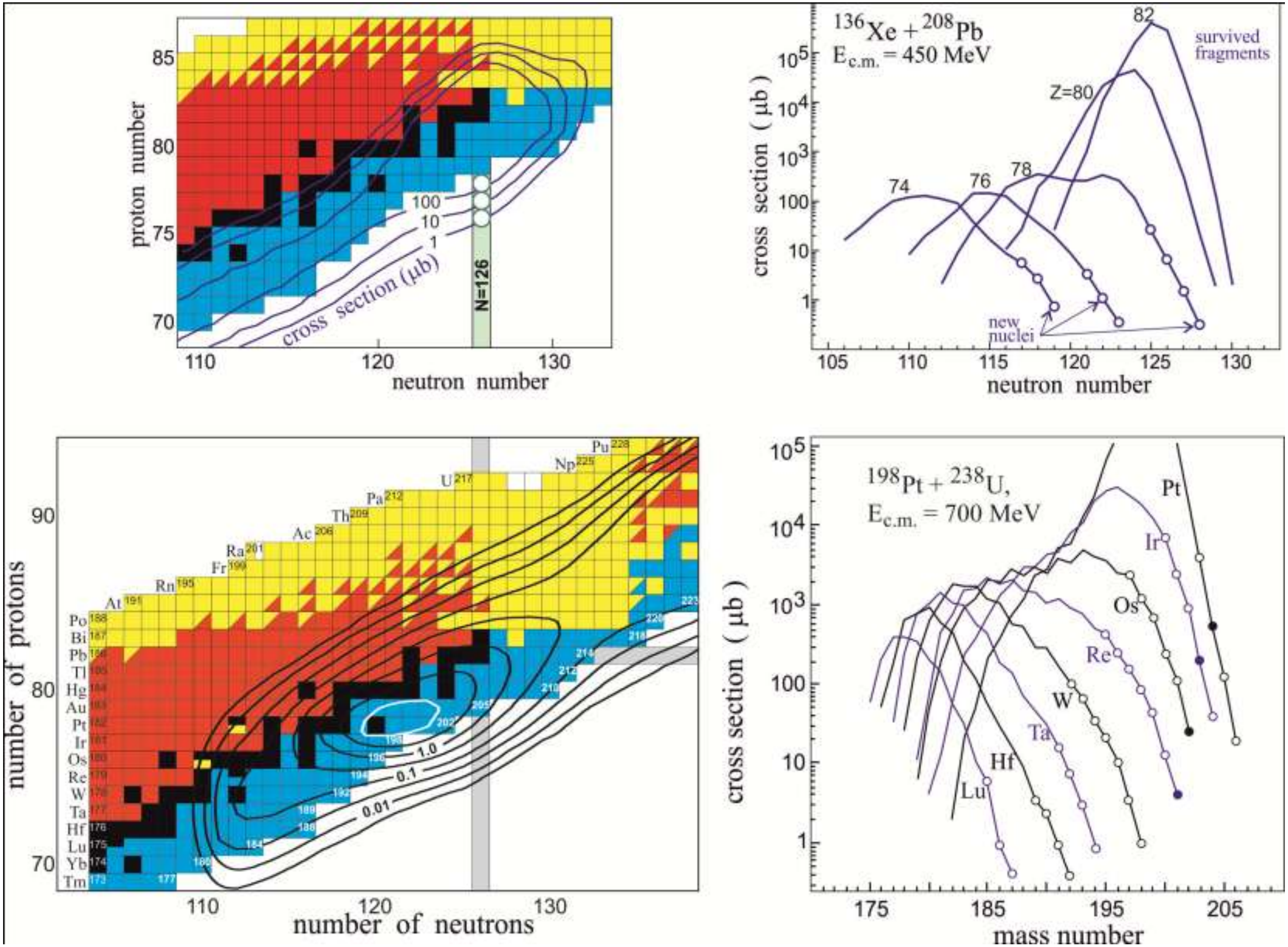
Reactions with $Q \approx 0$ are very favorable for proton transfer

The use of ^{132}Sn is even better !

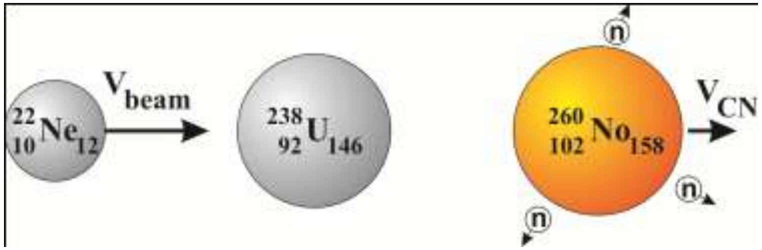


Isotope production with radioactive beams(54Ca, 154Xe),
Dasso, Pollarolo, Winther, PRL 1994

Production of neutron rich heavy nuclei located in the region of the last "waiting point" of astrophysical nucleosynthesis

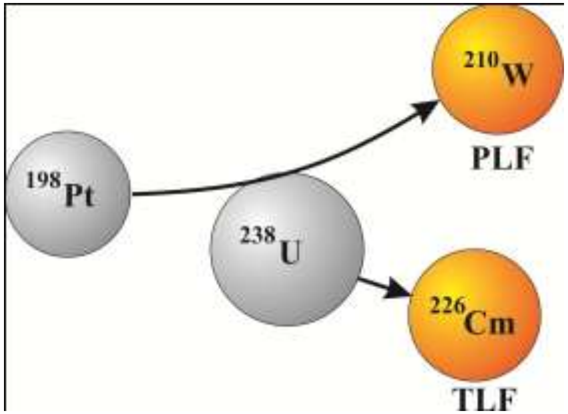


Fusion reactions



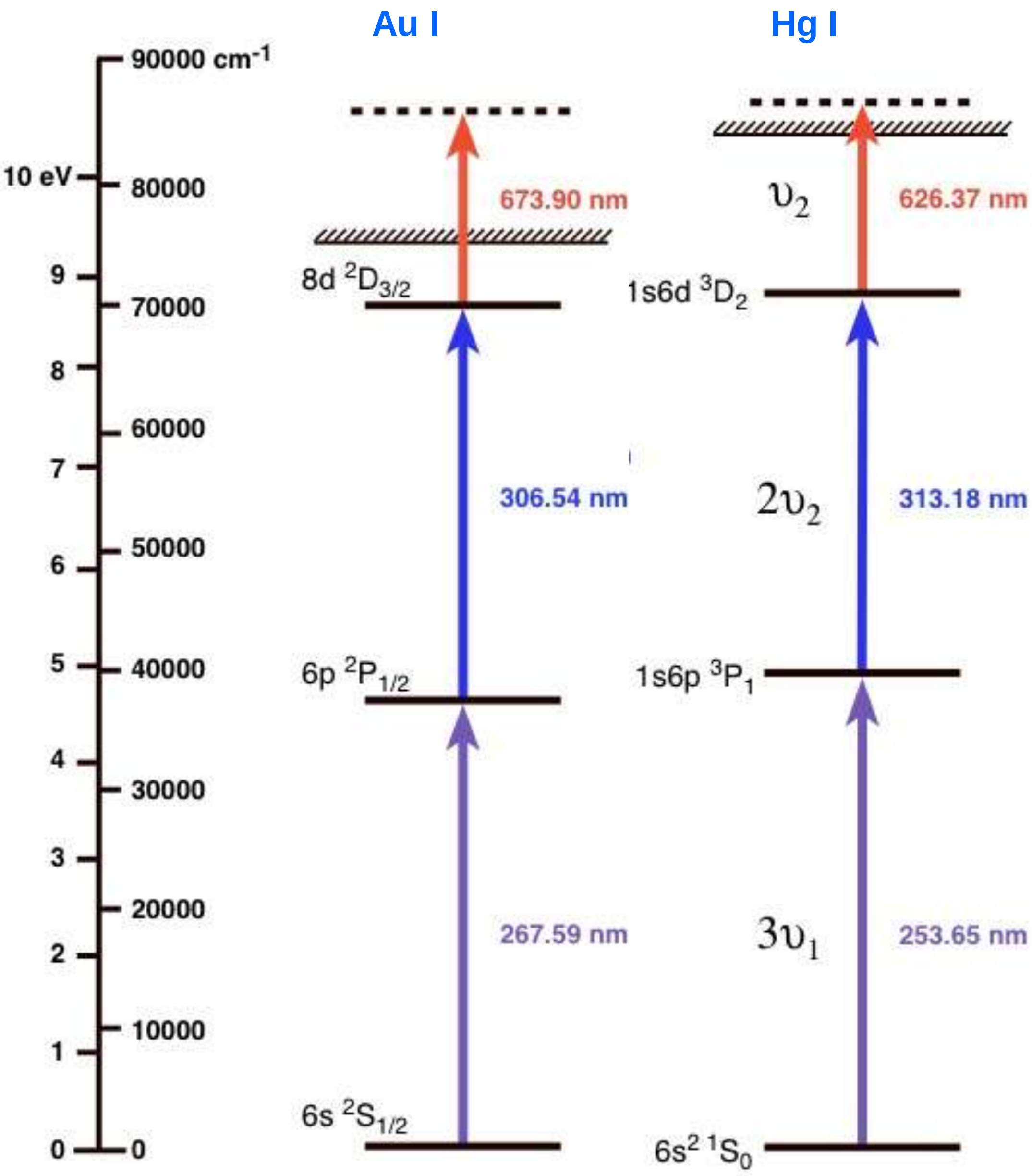
How to separate a given nucleus from all the other transfer reaction products ?

Transfer reactions



Available separators are not applicable !

Selective laser ionization ! (Au & Hg as an example)



Ionization Schemes

Au I

Level	Energy, cm^{-1}	Configuration	Wavelength, nm	
E_0	0	$6s\ ^2S_{1/2}$	λ_1	267.6
E_1	37358.99	$6p\ ^2P_{1/2}$	λ_2	306.5
E_2	69971.42	$8d\ ^2D_{3/2}$	λ_3	673.9

Chemical series	Transition metals
Group, Period, Block	11, 6, *d*
Atomic mass	196.96655(2) g/mol
Electron configuration	[Xe] $4f^{14}\ 5d^{10}\ 6s$
Ionization potential	74408.88 cm^{-1} (9.22553 eV)

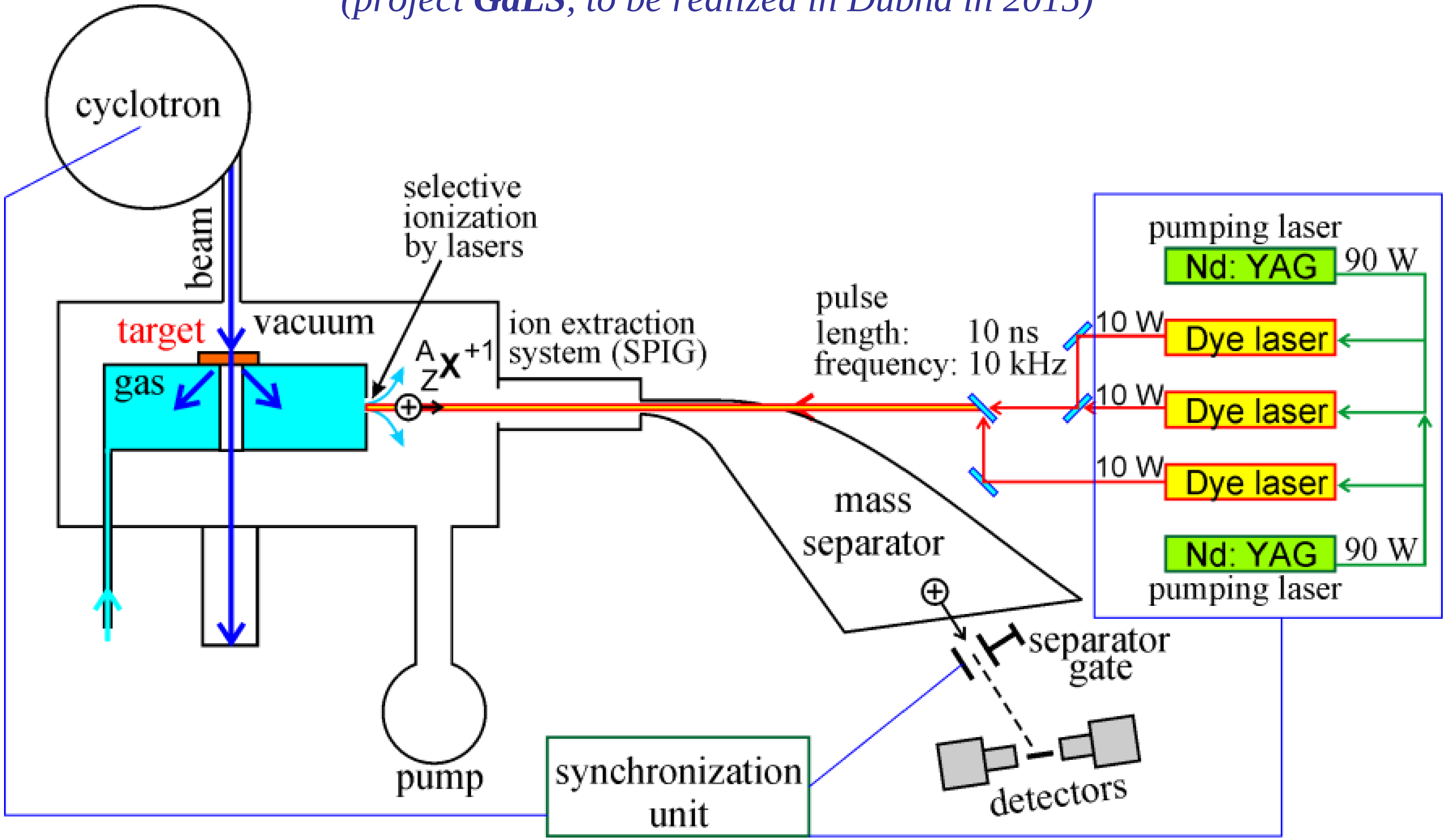
Hg I

Level	Energy, cm^{-1}	Configuration	Wavelength, nm	
E_0	0	$6s^2\ ^1S_0$	λ_1	253.65
E_1	39412.30	$6s\ 6p\ ^3P_1$	λ_2	313.18
E_2	71396.22	$6s\ 6d\ ^3D_2$	λ_3	626.37

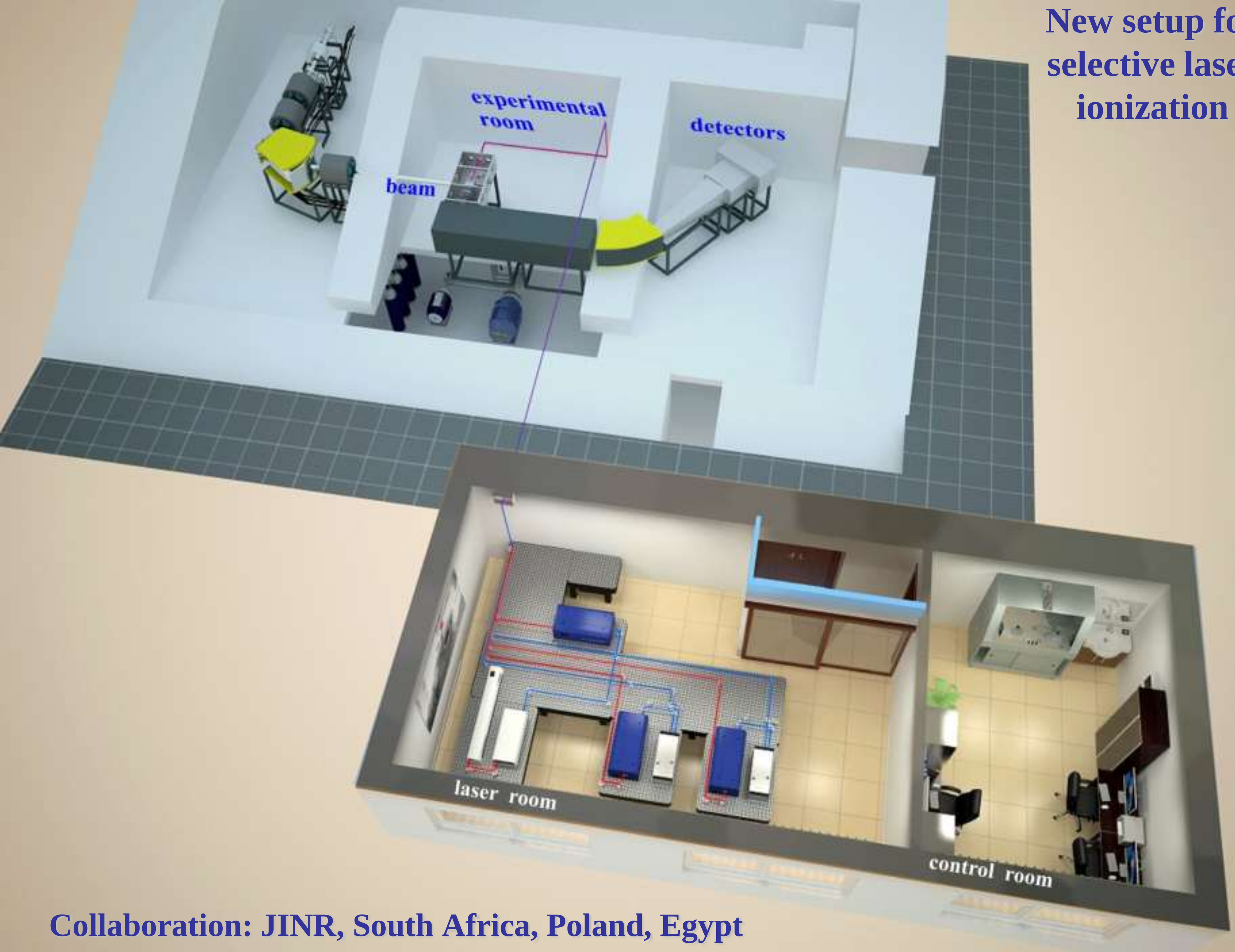
Chemical series	
Group, Period, Block	12, 6, *d*
Atomic mass	200.59(2) g/mol
Electron configuration	[Xe] $4f^{14}\ 5d^{10}\ 6s^2$
Ionization potential	84184.1 cm^{-1} (10.4375 eV)

New setup for selective laser ionization of multi-nucleon transfer reaction products stopped in gas

*(project **GaLS**, to be realized in Dubna in 2015)*



New setup for selective laser ionization



Collaboration: JINR, South Africa, Poland, Egypt

Summary

- **North-east part of the nuclear map is still "terra incognita". Heavy neutron rich nuclei are not synthesized and studied yet. It's time to develop these new lands.**
- **Multi-nucleon transfer reactions can be used for synthesis of new neutron enriched transfermium nuclei located along the beta-stability line. U-like beams are needed as well as a new kind of separators!**
- **Multi-nucleon transfer reactions can be also used for synthesis of new neutron rich nuclei located along the closed neutron shell N=126 having the largest impact on the astrophysical r-process. Cross sections are higher than 1 μb.**
- **Shell effects and dynamics of the "inverse quasi-fission processes" in heavy ion damped collisions should be studied much better.**
- **Selective laser separation of reaction products is a very promising tool.**

JINR *(Dubna)*

Valeriy Zagrebaev (FLNR, Dubna)
Walter Greiner (FIAS, Frankfurt)
Sergey Zemlyanoy (FLNR, Dubna)

FIAS *(Frankfurt)*