Superheavies: Theoretical incitements and predictions

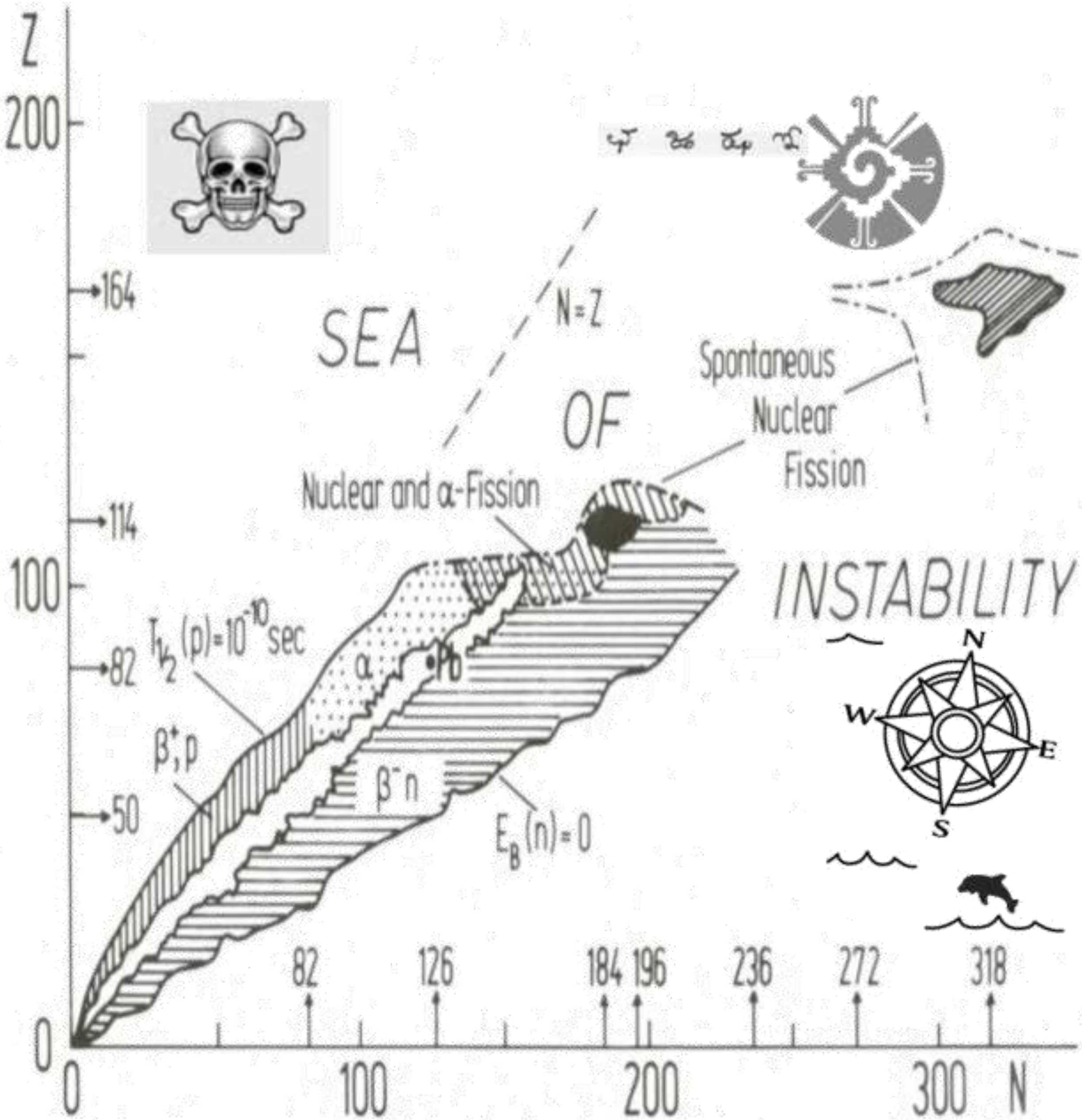
- **Superheavy dreams of Walter Greiner**
- **Exotic properties of superheavy nuclei**
- **Fusion reactions**
- **Multi-nucleon transfer reactions**
- **Non-accelerative SHE production**
- **Summary**

Valery Zagrebaev and Walter Greiner

for Advances in Nuclear Physics in Our Time, *November 29, 2010*, Goa

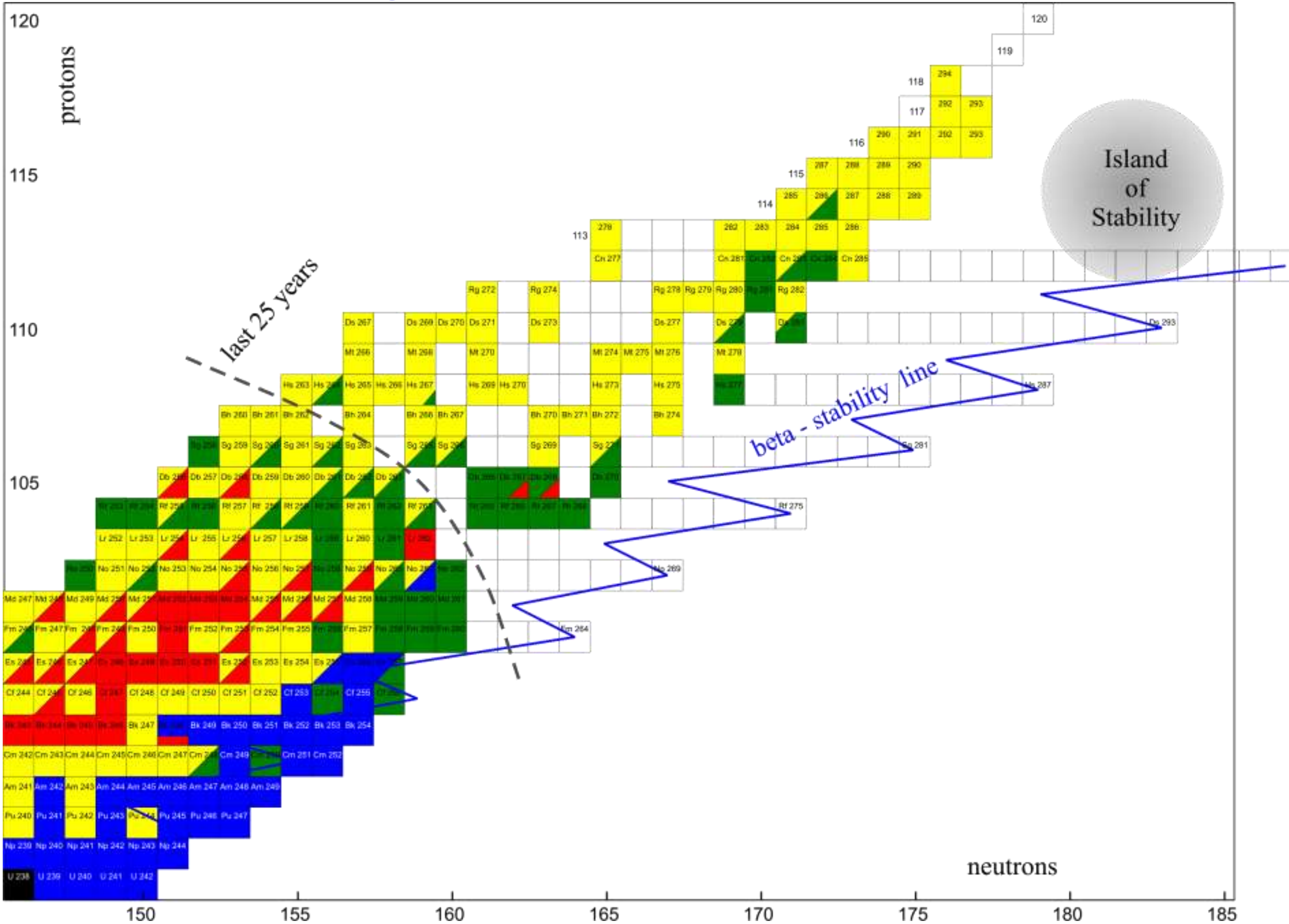
JINR *(Dubna)*

FIAS *(Frankfurt)*

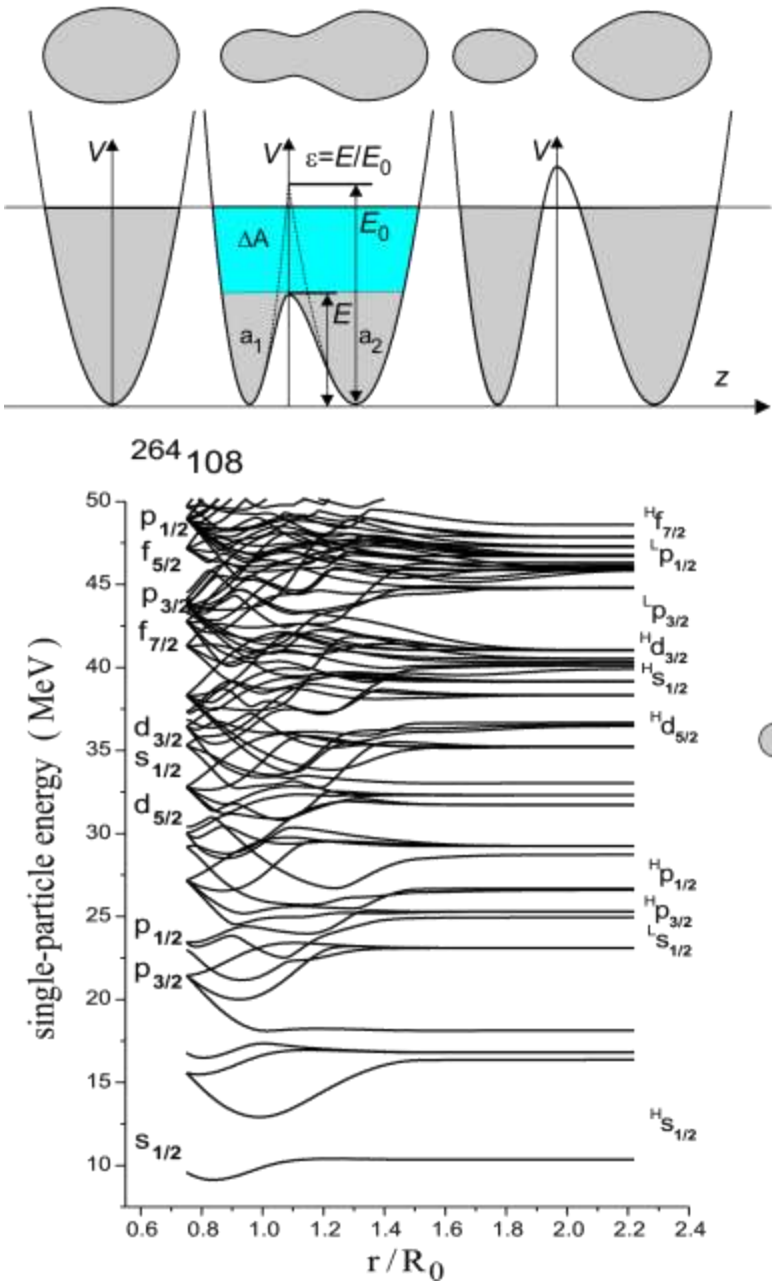


Ancient Nuclear Map and dreams of Walter Greiner

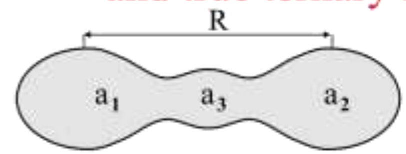
Great progress in synthesis of superheavy nuclei



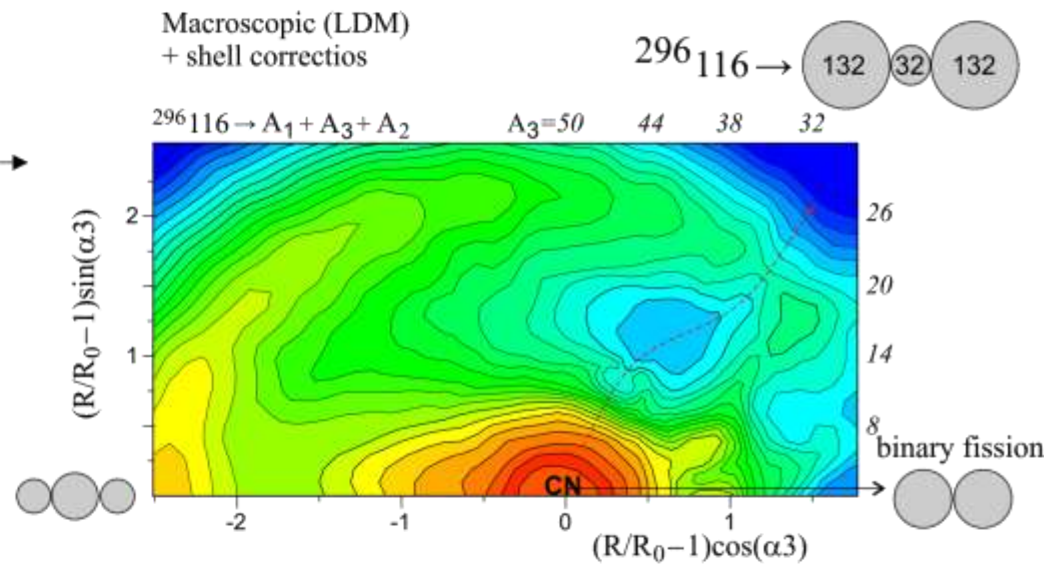
Two - Center Shell Model

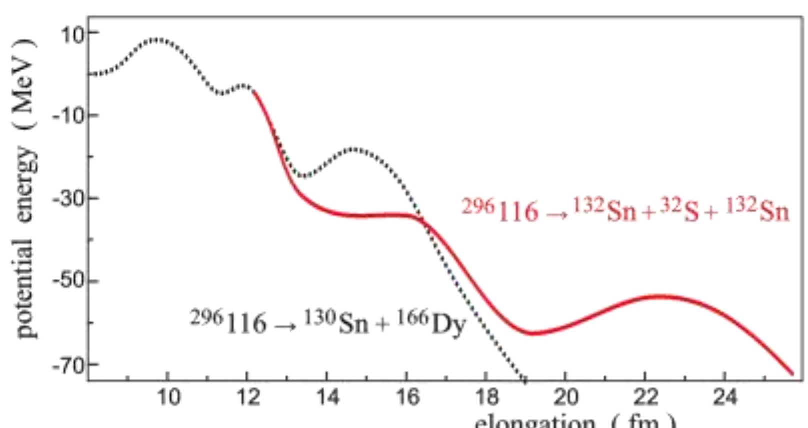


Three - Center Shell Model and true ternary fission of SH nuclei

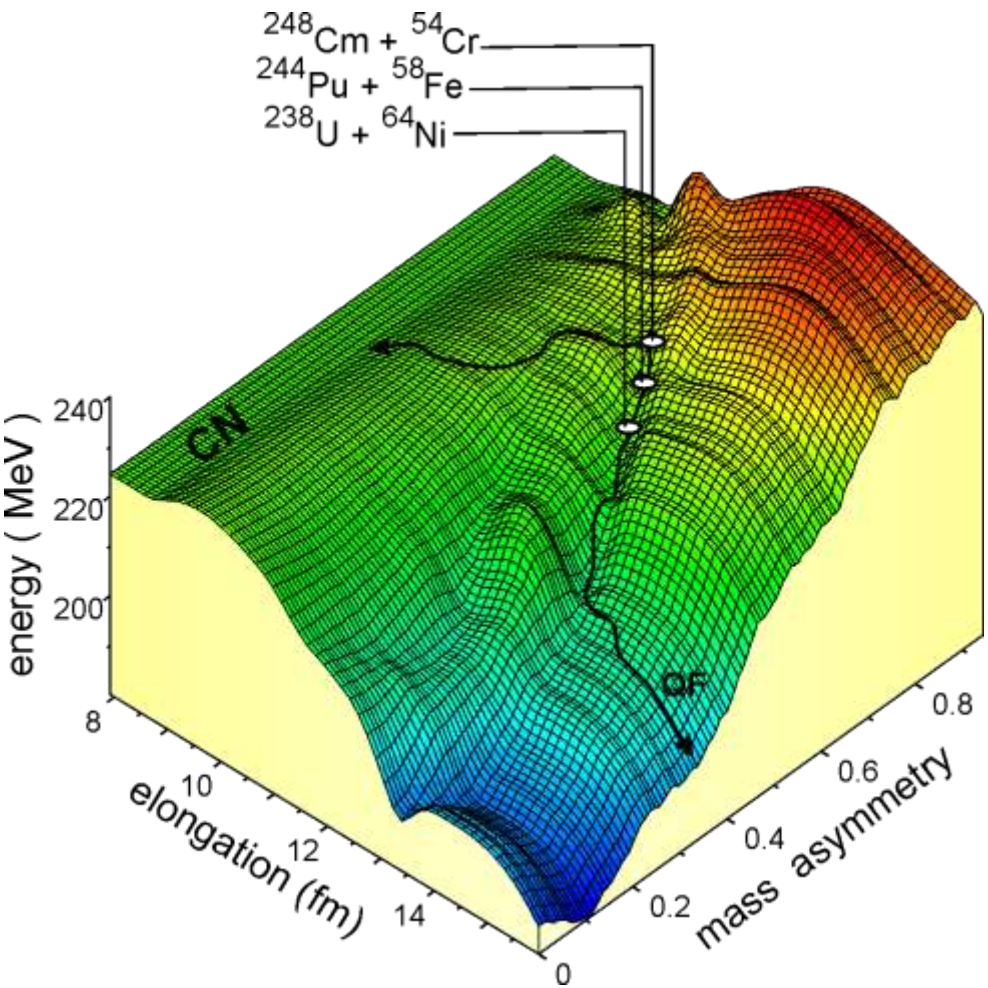


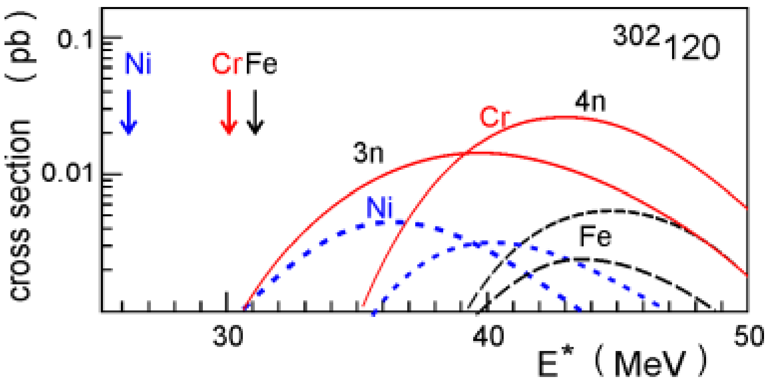
$$V(R,A_3,\delta) \quad \alpha_3 = \pi \frac{A_3}{100}$$

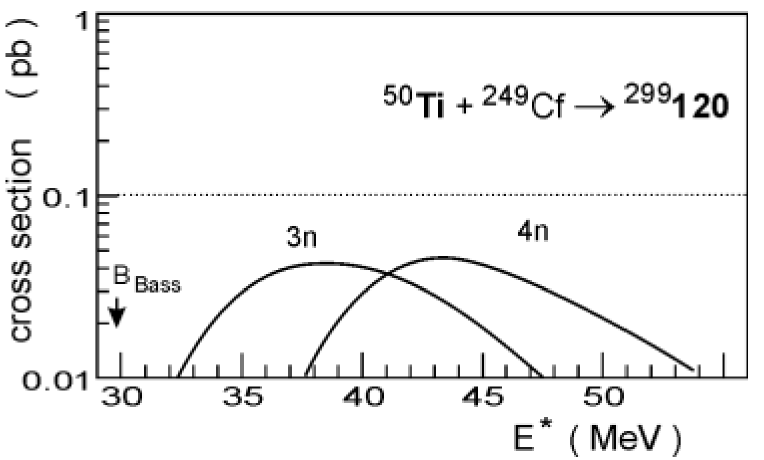




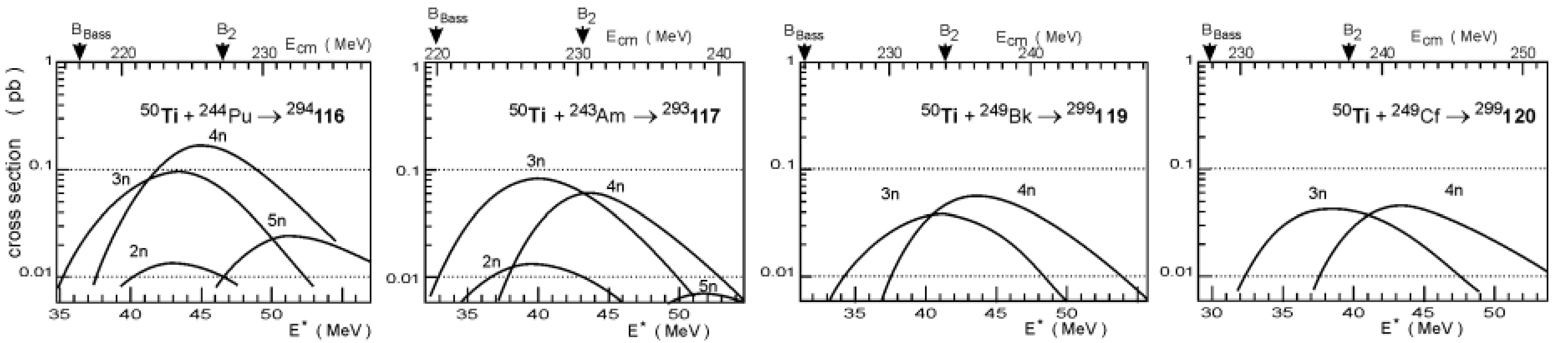
Beyond ^{48}Ca: Synthesis of 120



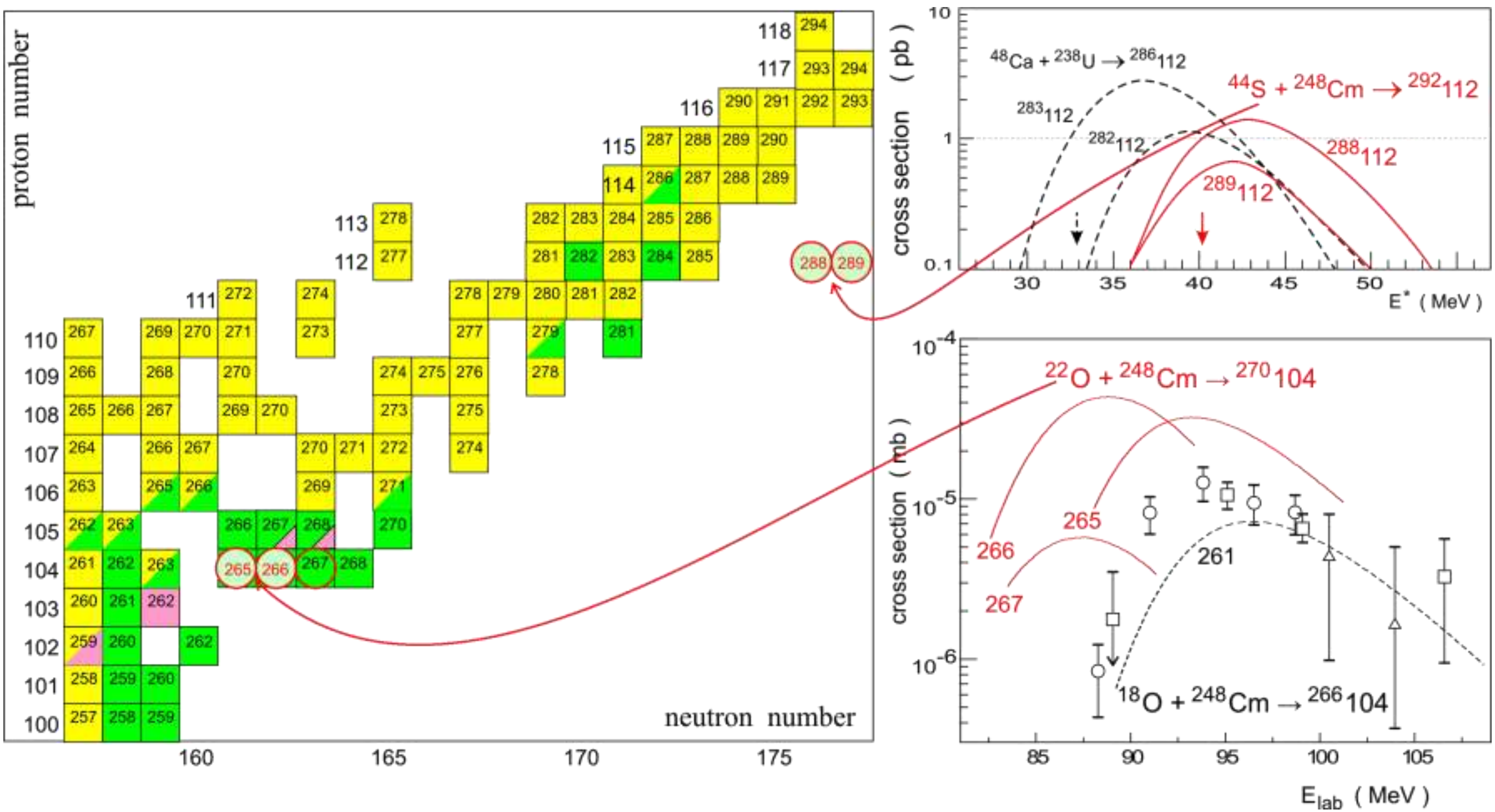




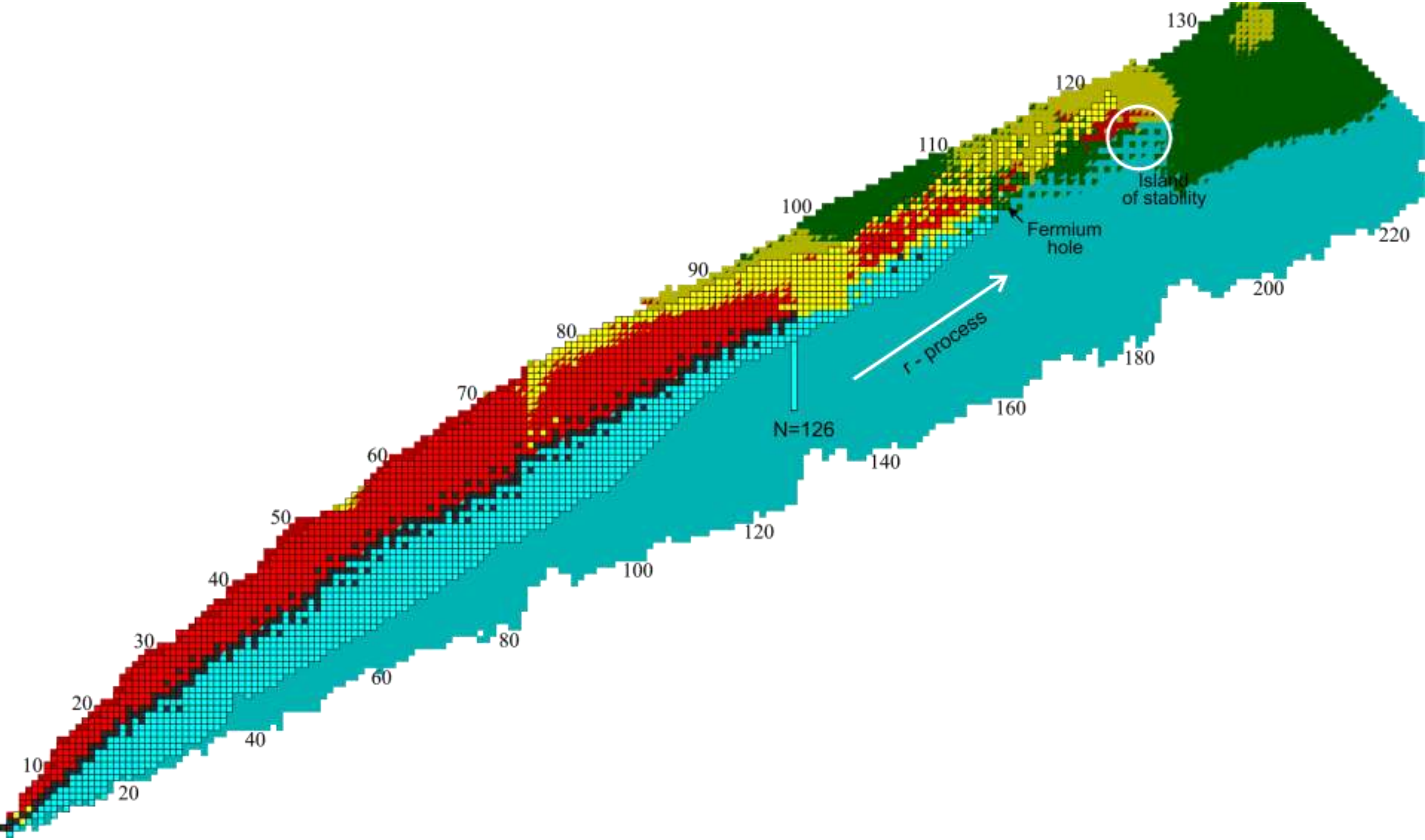
^{50}Ti - induced fusion reactions



Radioactive Ion Beams for production of neutron rich superheavy nuclei ?

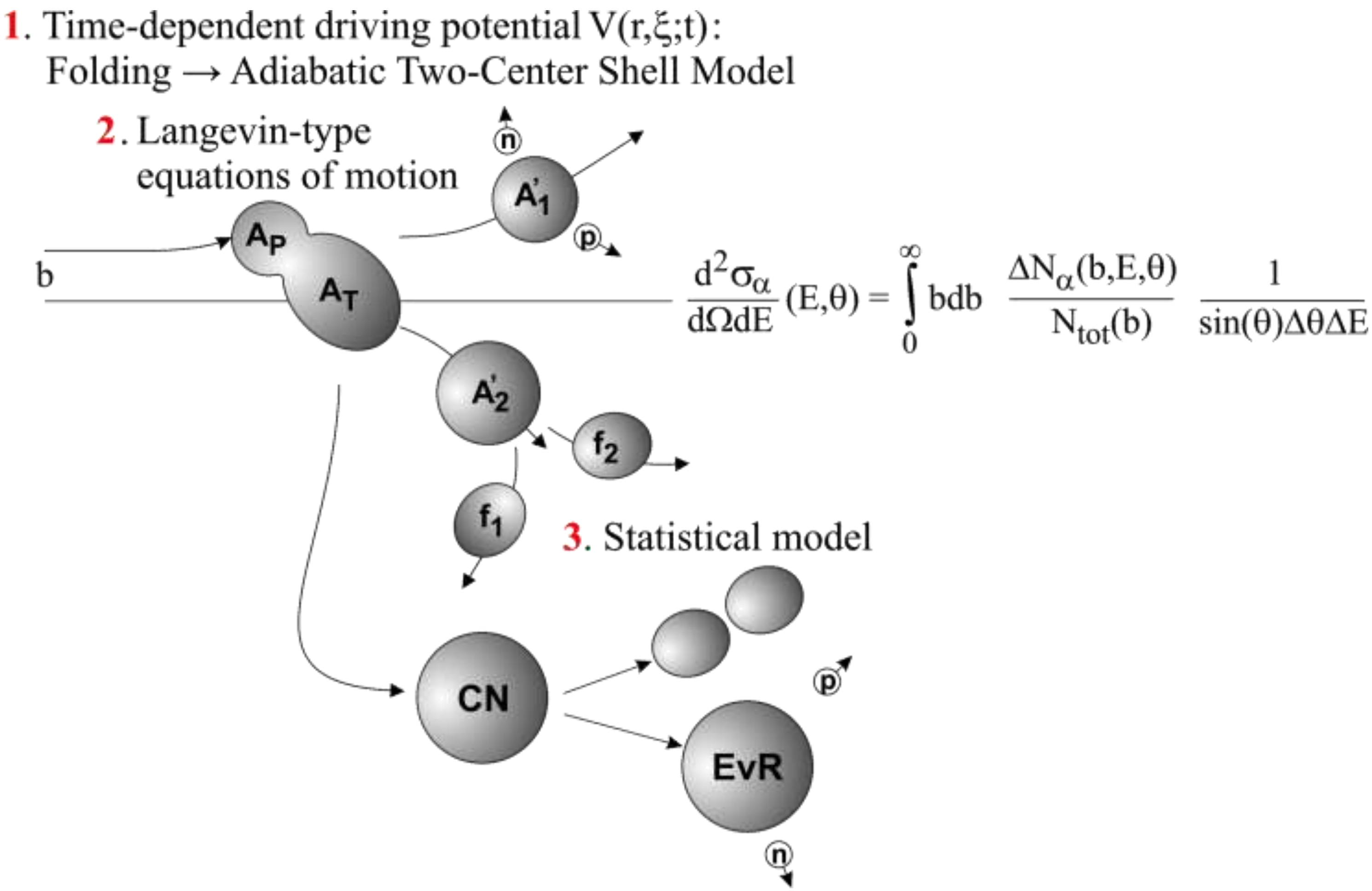


Big map and big problems



Multi-nucleon transfer reactions in low-energy heavy ion collisions

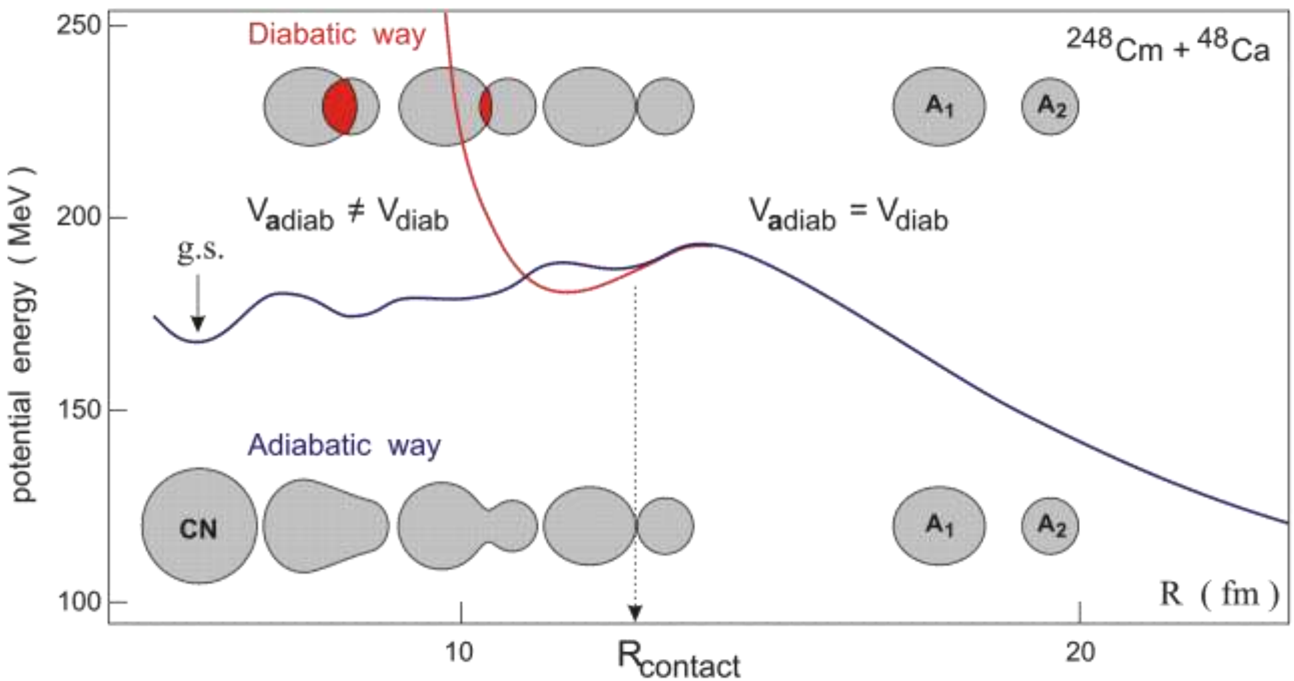
Simulation of experiment and cross sections



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

Time-dependent Driving Potential

$$V_{diabat}(R,\beta_1,\beta_2,\alpha,...) = V_{12}^{folding}(Z_1,N_1,Z_2,N_2;R,\beta_1,\beta_2,...) + M(A_1) + M(A_2) - M(Proj) - M(Targ)$$



$$V_{adiabat}(R,\beta_1,\beta_2,\eta,...) = M_{TCSM}(R,\beta_1,\beta_2,\eta,...) - M(Proj) - M(Targ)$$

Time-dependent driving potential has to be used

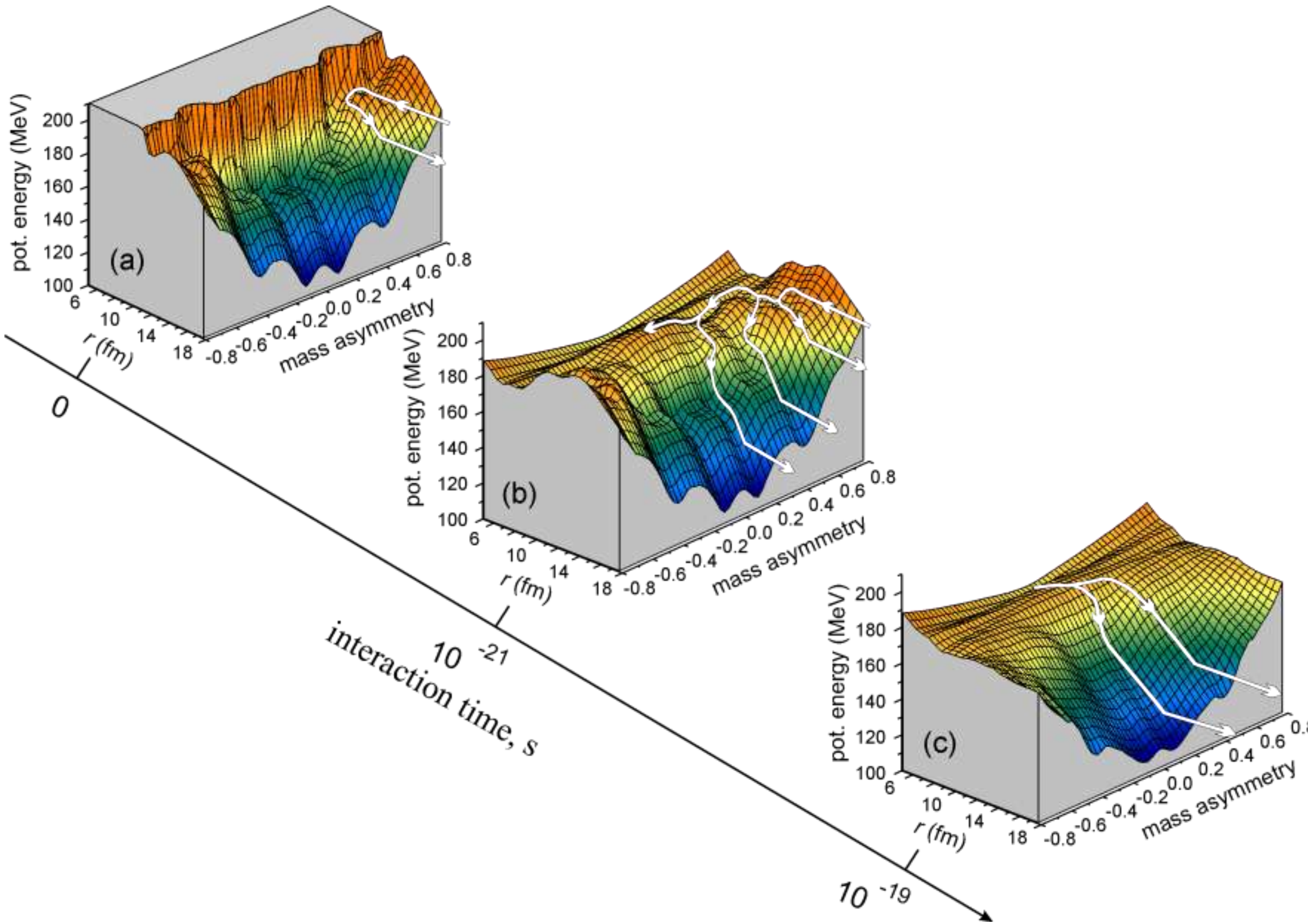
$$V(t) = V_{diab}(\xi)\cdot\exp(-\frac{t_{int}}{\tau_{relax}}) + V_{adiab}(\xi)\cdot[1-\exp(-\frac{t_{int}}{\tau_{relax}})]$$

$\tau_{relax} \sim 10^{-21}$ s

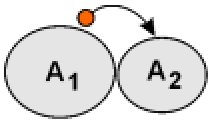
the same degrees of freedom ($\xi = R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta_Z, \eta_N$) *!*

All forces, $F_i(t) = -\partial V/\partial \xi_i$, *are quite smooth*

Time-dependent Driving Potential



Nucleon Exchange



$A_1 \to A_1 - 1$
$A_2 \to A_2 + 1$

(L. Moretto, 1974)

Distribution function $\varphi(A_1,t)$ → Master equation $\dfrac{\partial\varphi}{\partial t} = \sum\limits_{A_1'=A_1\pm1} \lambda(A_1' \to A_1)\cdot\varphi(A_1') - \lambda(A_1 \to A_1')\cdot\varphi(A_1)$

$$\frac{\partial\varphi}{\partial t} = -\frac{\partial}{\partial A_1}\left(D^{(1)}\varphi\right) + \frac{\partial^2}{\partial A_1^2}\left(D^{(2)}\varphi\right)$$

Fokker - Planck
(W. Nörenberg, 1974)

$$\frac{dA_1}{dt} = D^{(1)} + \sqrt{D^{(2)}}\,\Gamma(t)$$

Langevin type eq.

$$\eta = \frac{A_1 - A_2}{A_{CN}} = \frac{A_1 - (A_{CN} - A_1)}{A_{CN}} = \frac{2A_1 - A_{CN}}{A_{CN}}$$

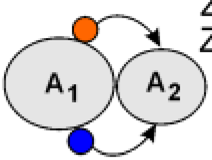
$$\frac{d\eta}{dt} = \frac{2}{A_{CN}} D_A^{(1)} + \frac{2}{A_{CN}}\sqrt{D_A^{(2)}}\,\Gamma(t)$$

at $A' = A \pm 1$

$$D^{(1)} = \lambda(A_1 \to A_1 + 1) - \lambda(A_1 \to A_1 - 1)$$

$$D^{(2)} = \frac{1}{2}[\lambda(A_1 \to A_1 + 1) + \lambda(A_1 \to A_1 - 1)]$$

transition probability $\lambda^{(\pm)} = \lambda_0 \sqrt{\dfrac{\rho(A\pm1)}{\rho(A)}} P_{tr}(R; A \to A\pm1)$, $\rho \sim exp(2\sqrt{aE^*})$, $E^* = E_{c.m.} - V(R,\beta_1,\beta_2,\eta)$



$Z_1 \to Z_1 - 1$
$Z_2 \to Z_2 + 1$

$N_1 \to N_1 - 1$
$N_2 \to N_2 + 1$

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

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

$$D_{N,Z}^{(1)} = \lambda_{N,Z}(A \to A+1) - \lambda_{N,Z}(A \to A-1)$$

$$D_{N,Z}^{(2)} = \frac{1}{2}[\lambda_{N,Z}(A \to A+1) + \lambda_{N,Z}(A \to A-1)]$$

$$\lambda_{N,Z}^{(\pm)} = \lambda_{N,Z}^{0}\sqrt{\frac{\rho(A\pm1)}{\rho(A)}} P_{tr}(R; A \to A\pm1)$$

System of coupled Langevin type Equations of Motion

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

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

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

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

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

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

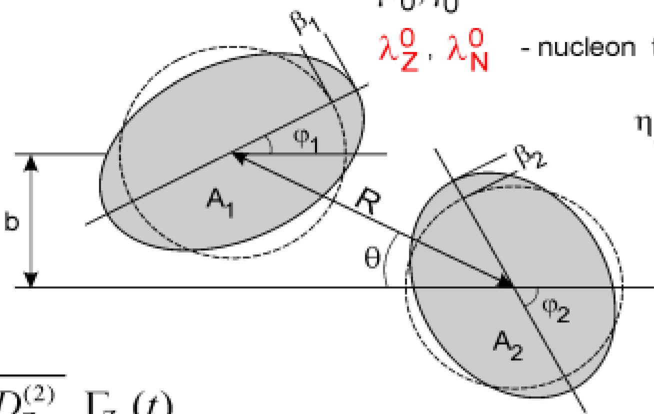
$$\frac{d\eta_Z}{dt} = \frac{2}{Z_{CN}} D_Z^{(1)} + \frac{2}{Z_{CN}} \sqrt{D_Z^{(2)}}\; \Gamma_Z(t)$$

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

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_Z^0, λ_N^0 - nucleon transfer rate



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

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

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

$$\lambda_Z^0 = \lambda_N^0 = \frac{\lambda^0}{2}$$

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

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

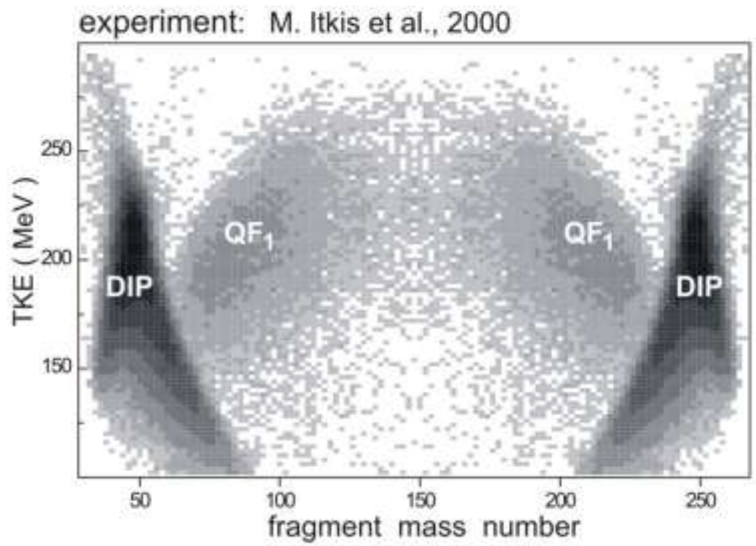
$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_1 - \frac{a_1}{R}\sqrt{\gamma_{tang} T}\,\Gamma_{tang}(t)$$

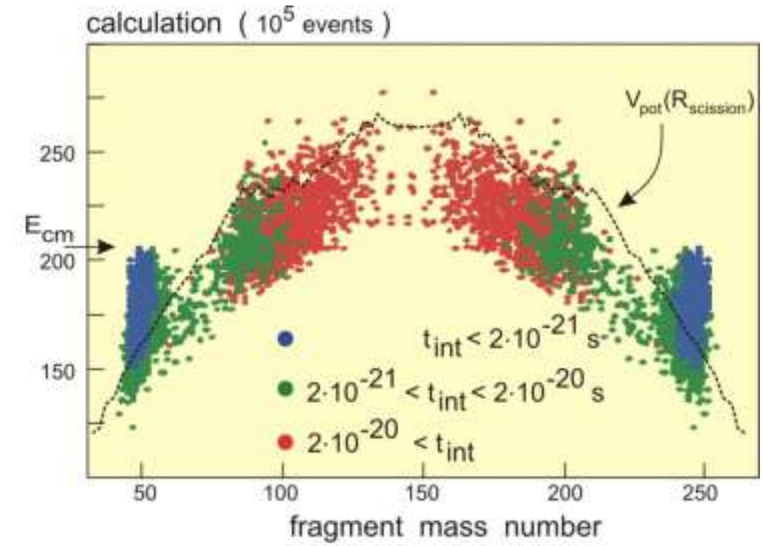
$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{tan}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{tang} T}\,\Gamma_{tang}(t)$$

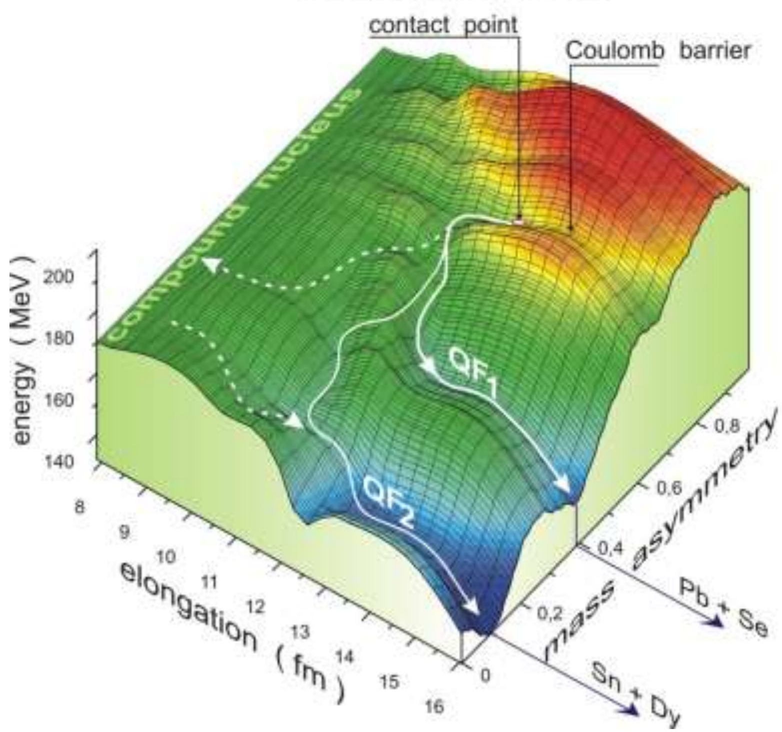
$$\frac{dp_{\beta 1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_1} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_1} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial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

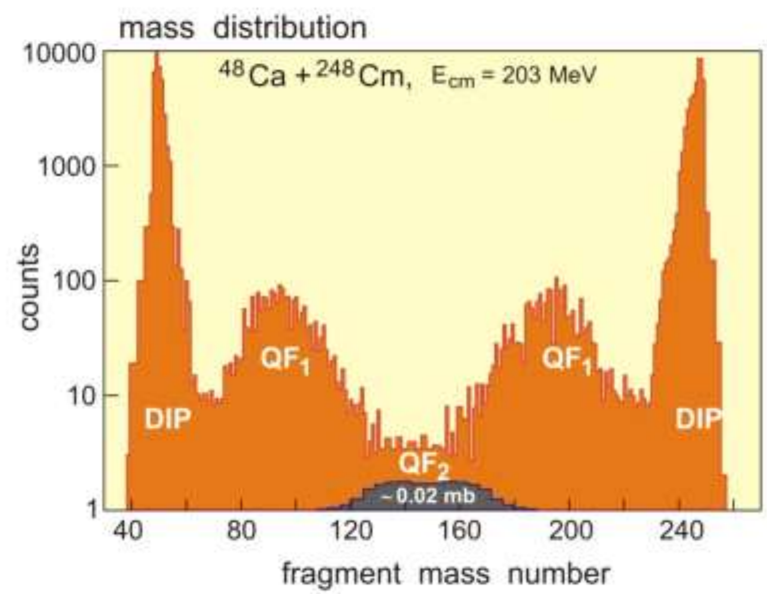
$$\frac{dp_{\beta 2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_2} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_2} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial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

Good agreement with experiment: e.g. $^{48}Ca + ^{248}Cm$

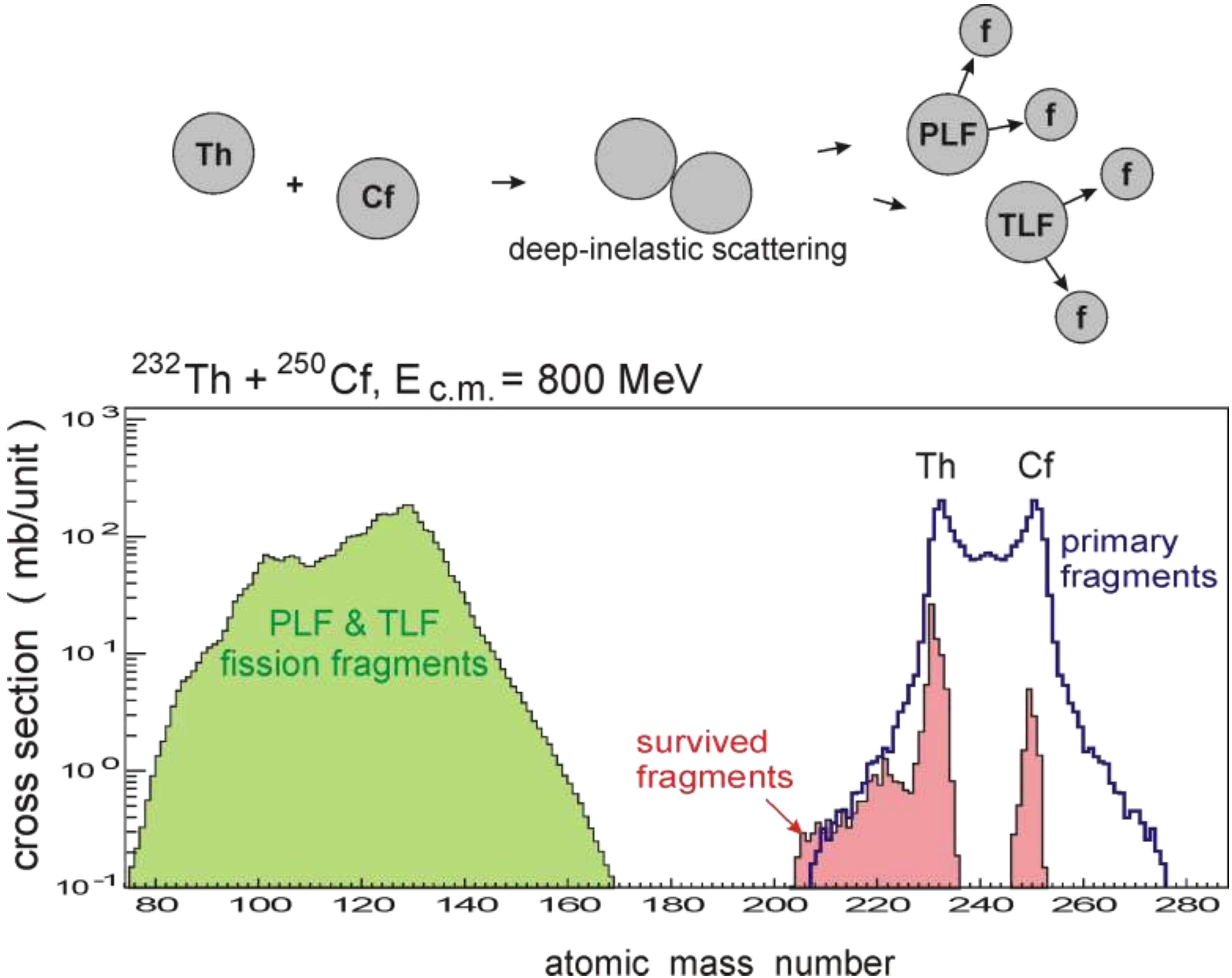




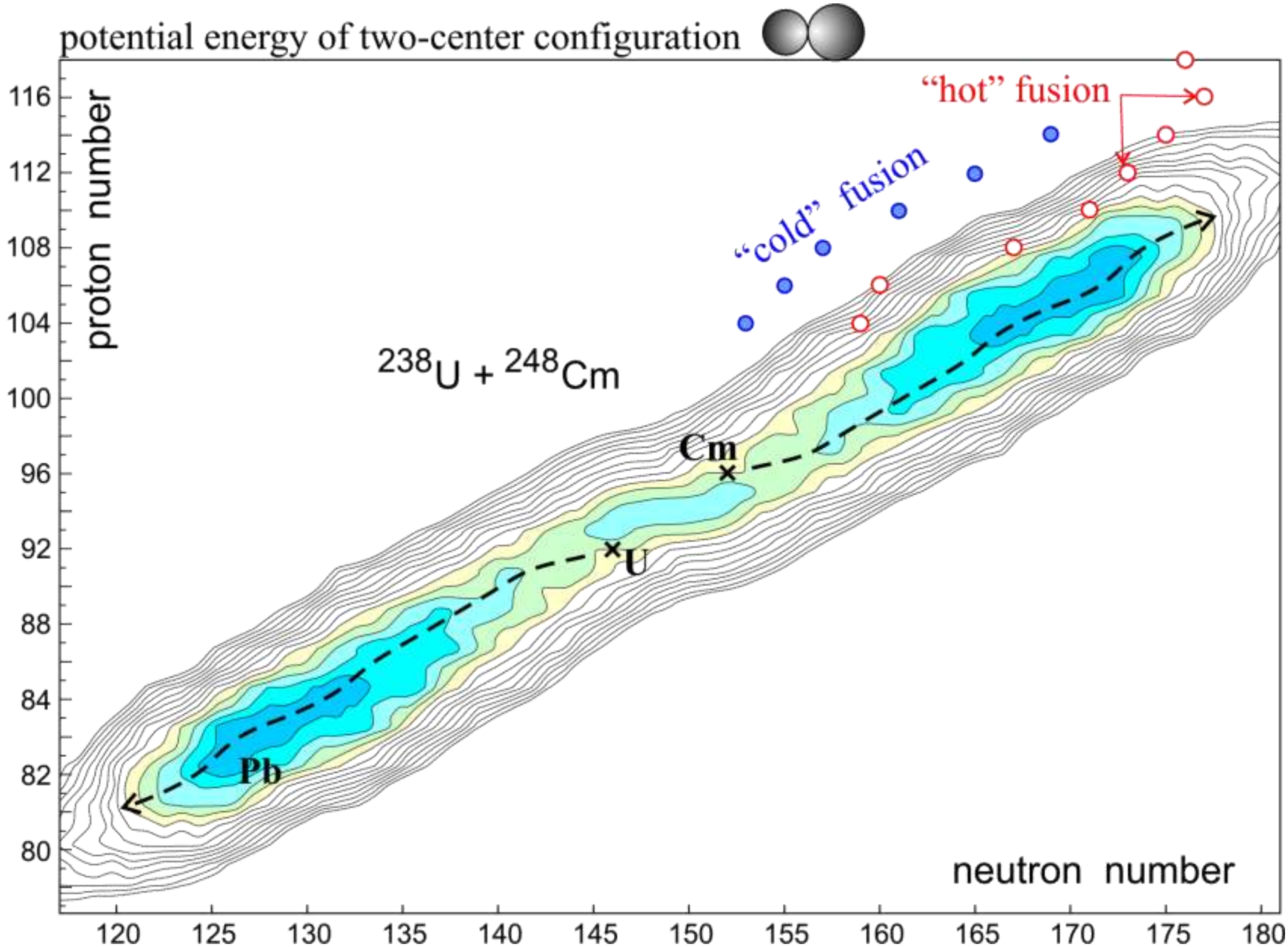




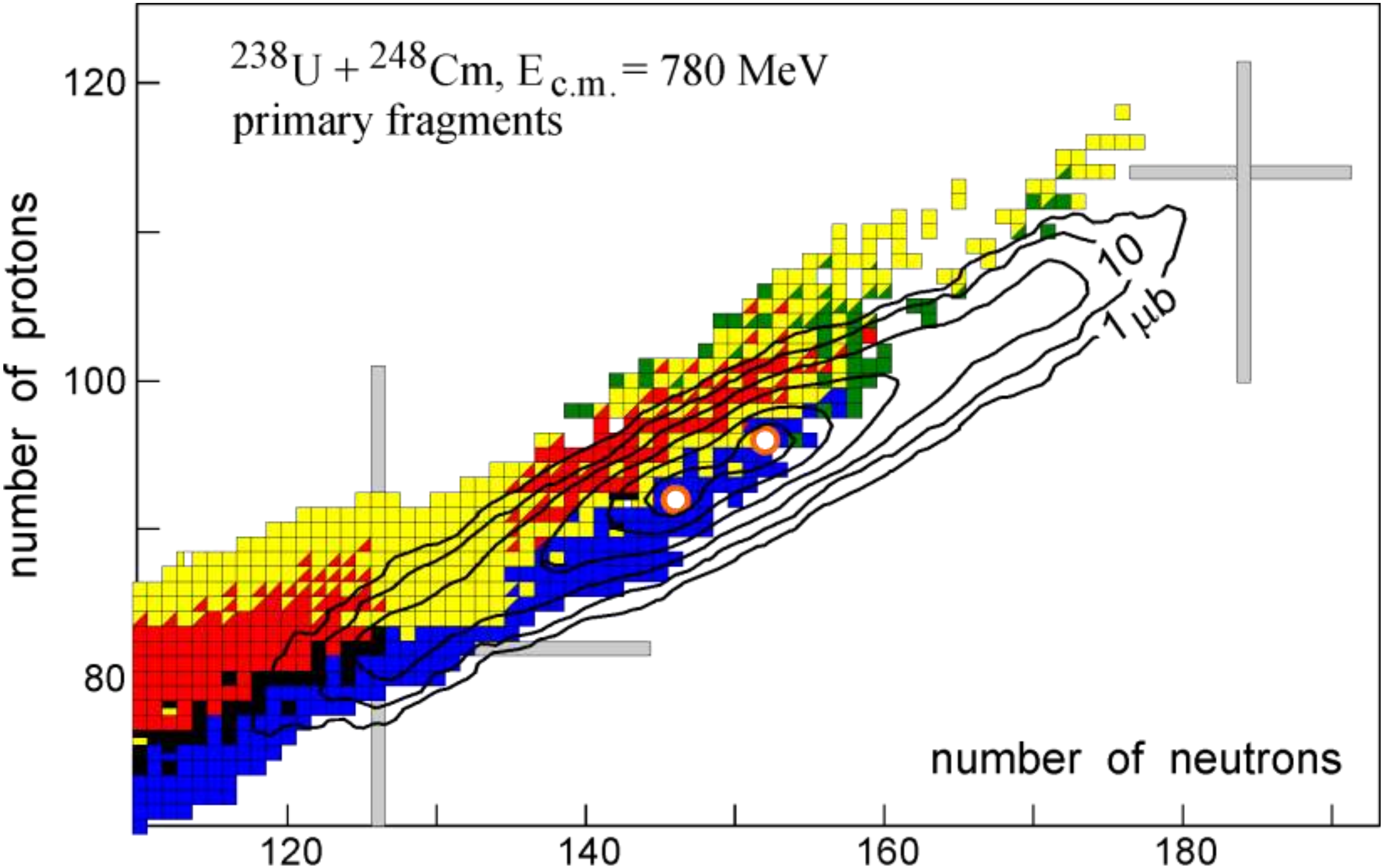
Transfer reactions in damped collision of very heavy nuclei ?



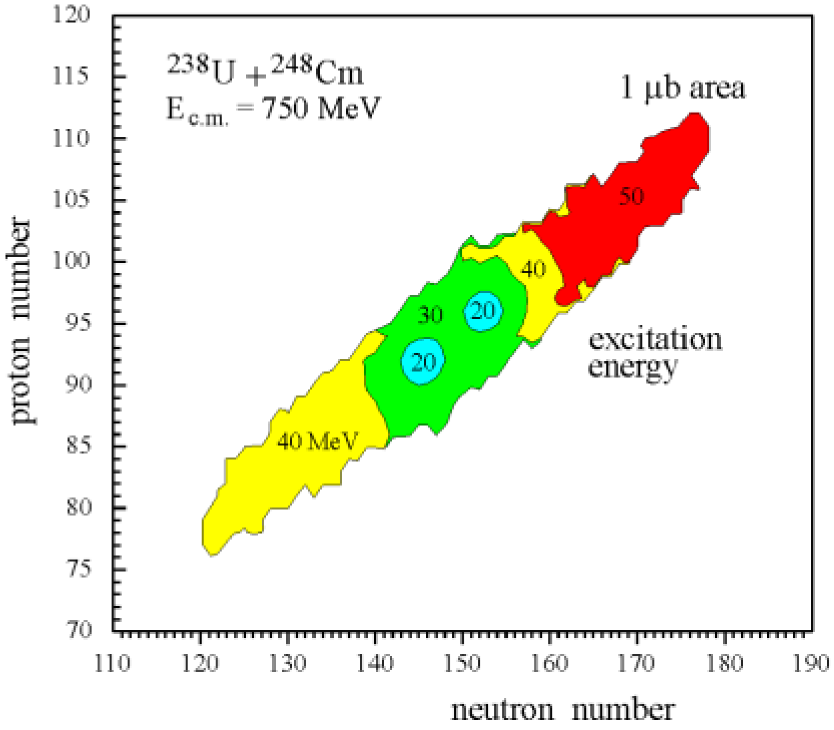
Most probable way of evolution of the giant nuclear system

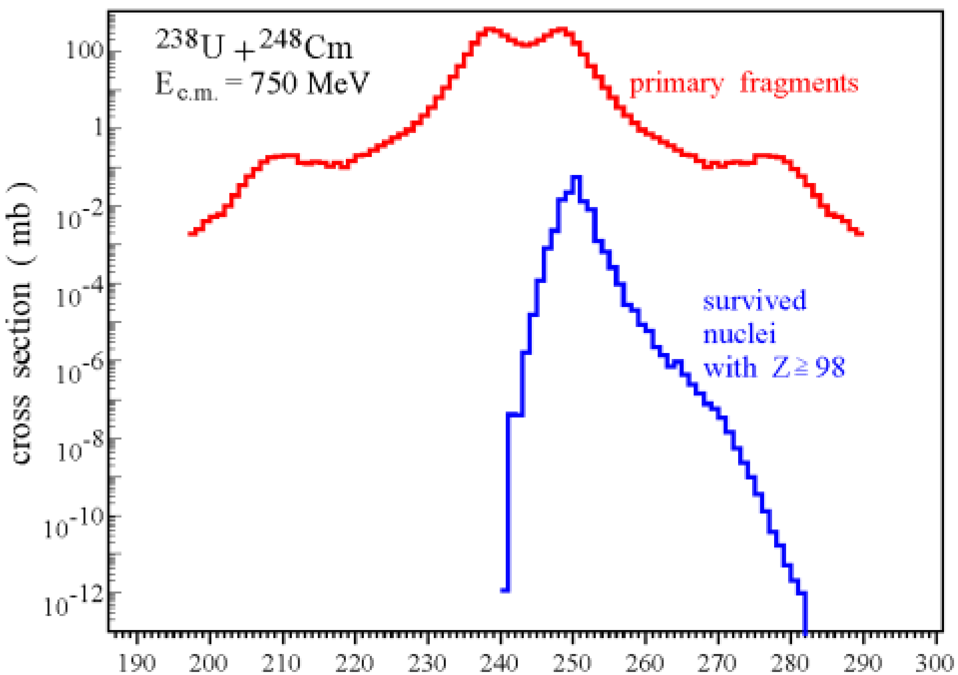


238U + 248Cm. Primary fragments

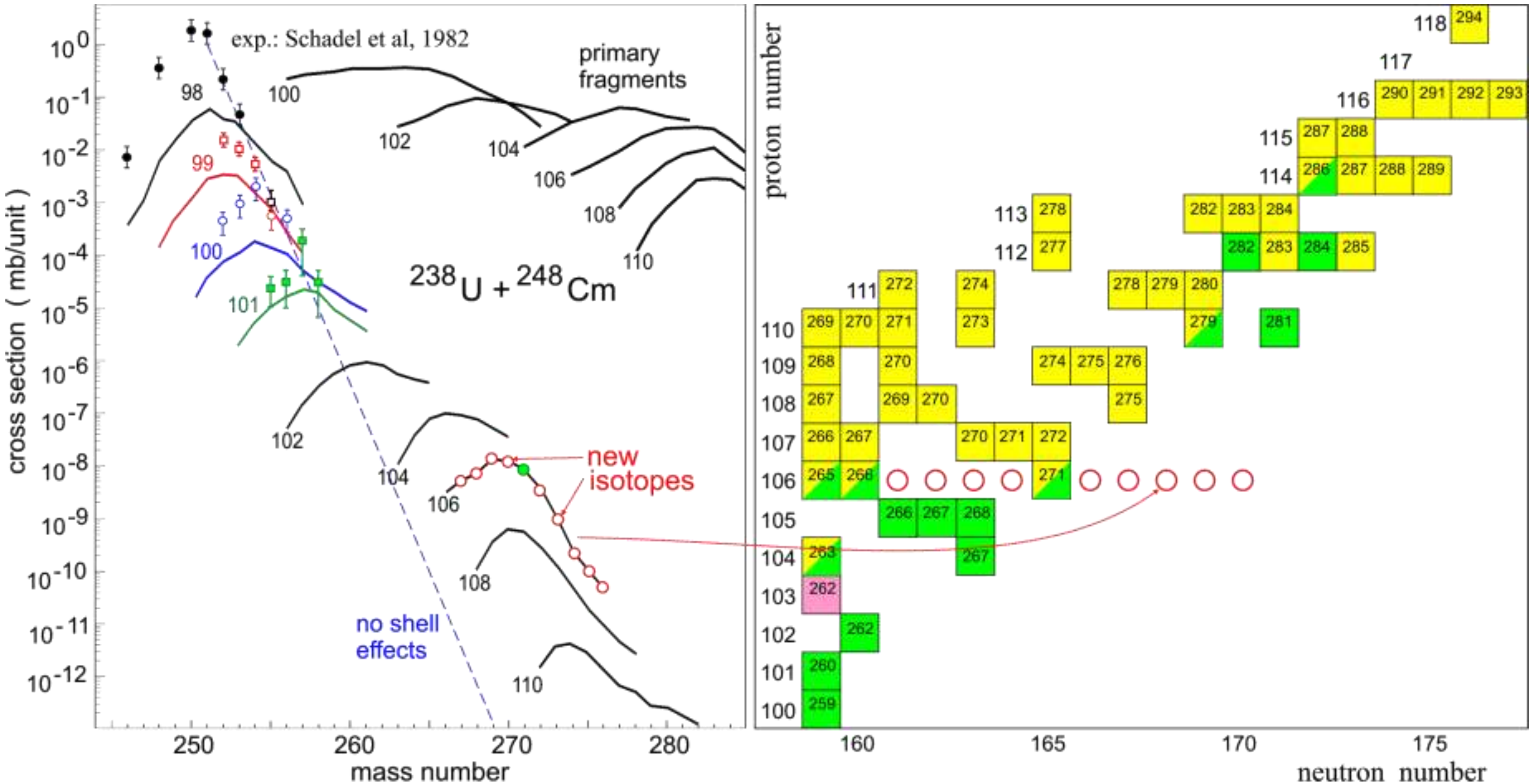


238U + 248Cm. Excitation energies and survival probability





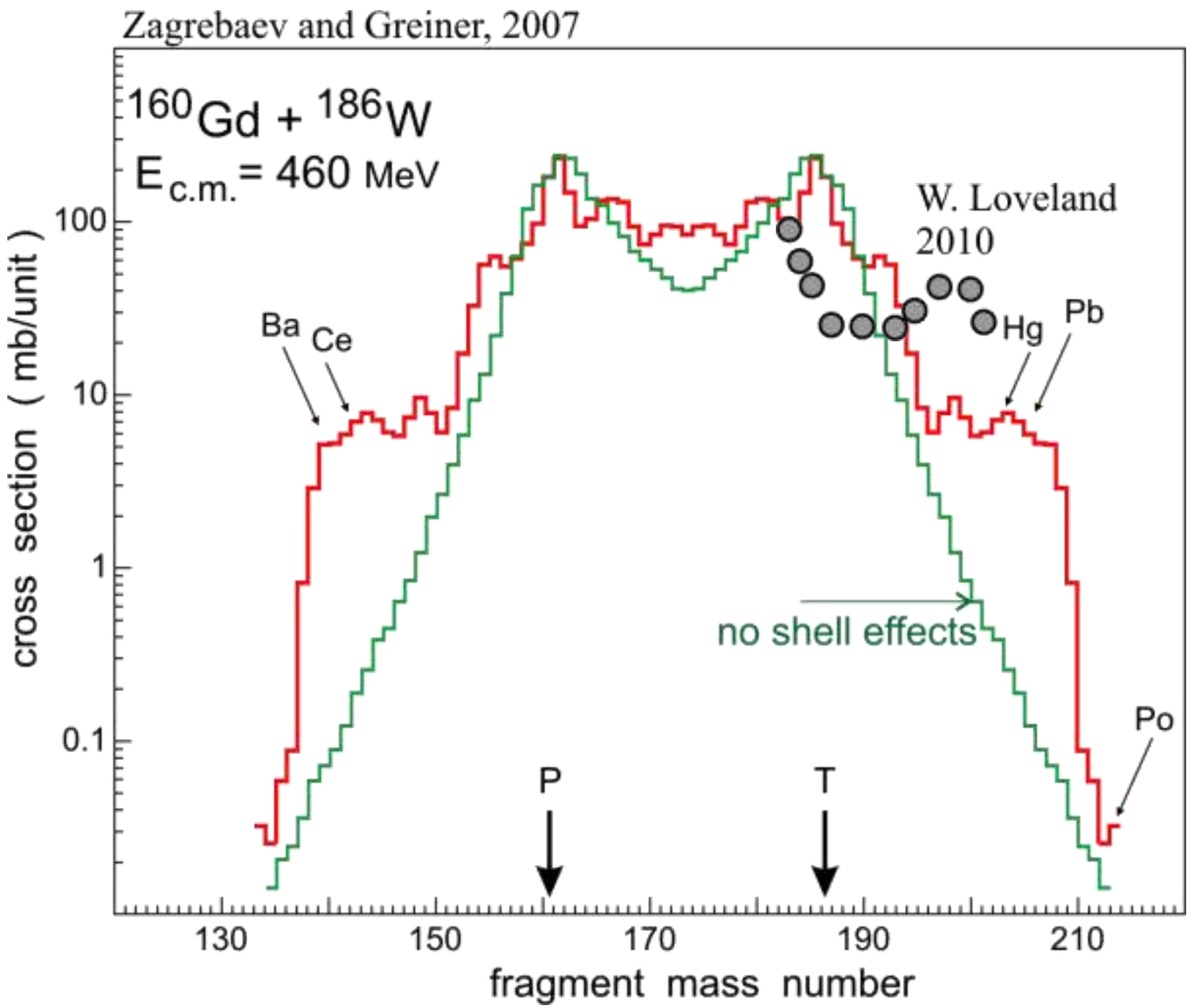
Isotopic yield of SHE in collisions of heavy actinide nuclei



How much is a role of the shell effects in damped collisions ?

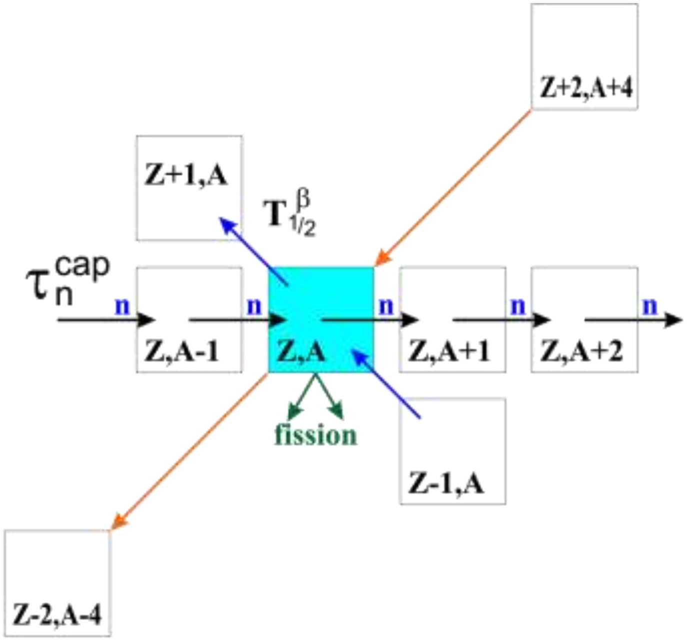
$^{160}Gd + ^{186}W$

(proposal for a new experiment)



Non-accelerative production of superheavy nuclei

Nucleogenesis under the influence of neutron flux



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

time of neutron capture

$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$ n_0 is the neutron flux ($\frac{1}{cm^2 \cdot sec}$),

$\sigma(n,\gamma)$ is the n-capture cross section (~ 1 barn = 10^{-24} cm^2, E_n= 0.5 MeV)

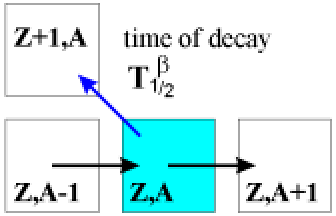
the shift to the right stops

when $\mathbf{T}_{1/2}(\mathbf{Z},\mathbf{A}) < \tau_n^{cap}$

n_0 (reactor) < $10^{19}\frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} > 10^5$ sec (1 day)

n_0 (explosion) ~ $10^{30}\frac{1}{cm^2 \cdot sec}$, τ_n^{cap} ~ 1 μs

Nucleogenesis in reactors and in nuclear explosion



$T^{\beta}_{1/2}$

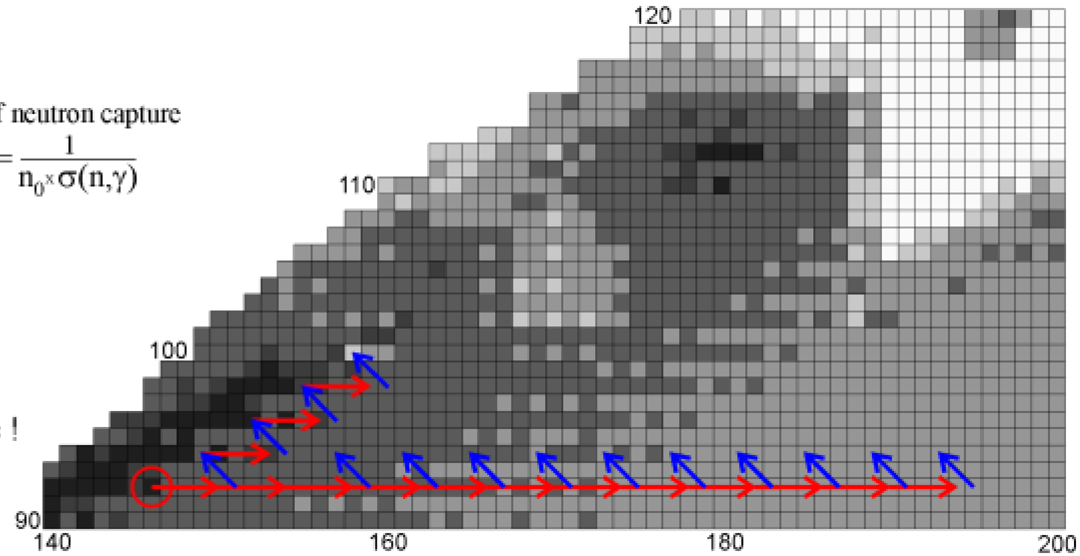
time of neutron capture $\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$

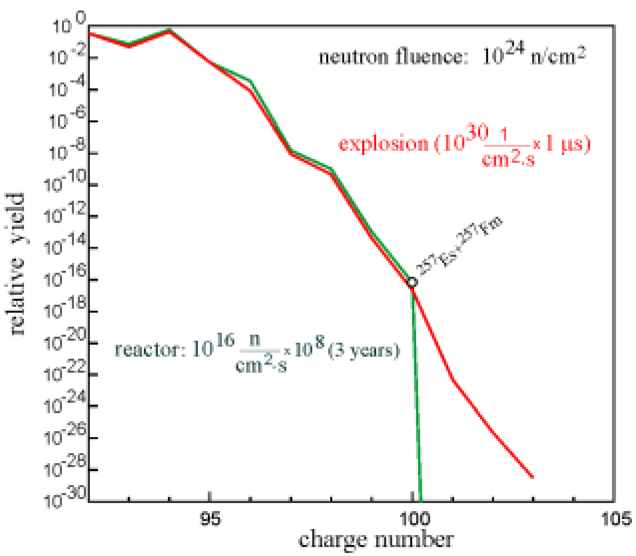
neutron capture stops when $T^{\beta}_{1/2}(Z,A) < \tau_n^{cap}$

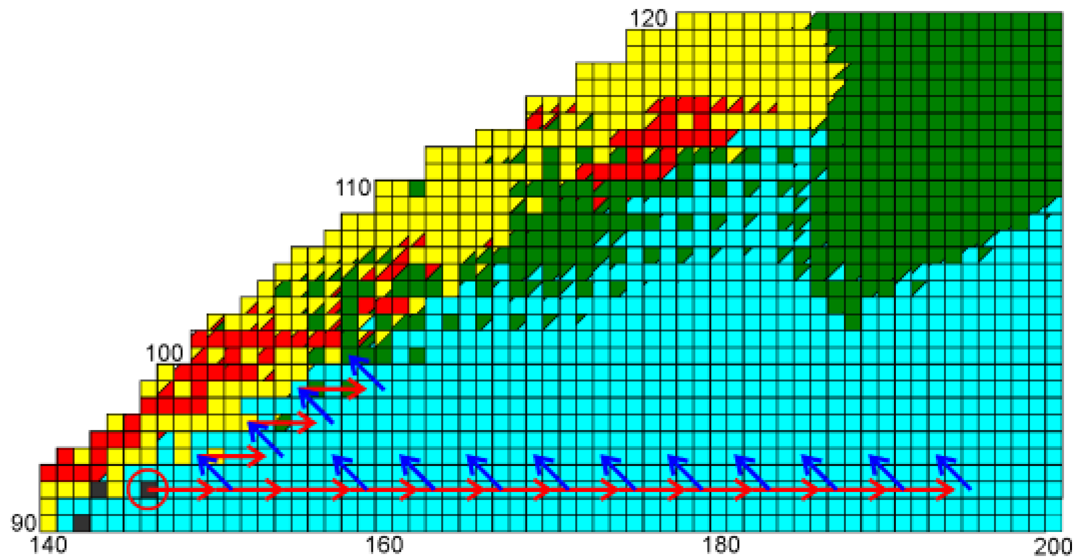
n_0 (reactor) $< 10^{19} \frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} > 10^5$ sec (1 day),

but $T^{fis}_{1/2}$ ($^{258\text{-}260}$Fm) <= 1 sec !

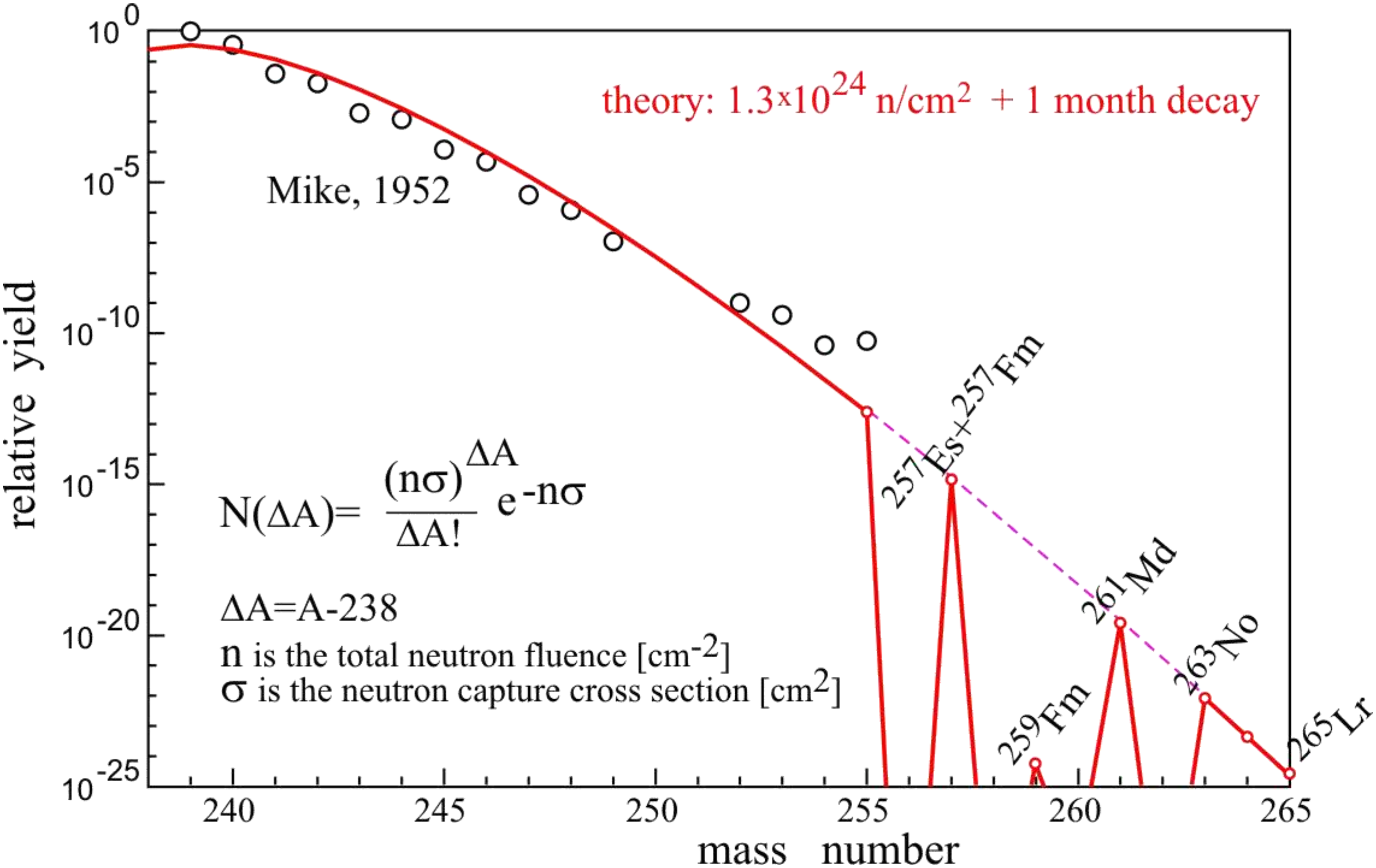
n_0 (explosion) $\sim 10^{30} \frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} \sim 1\ \mu s$



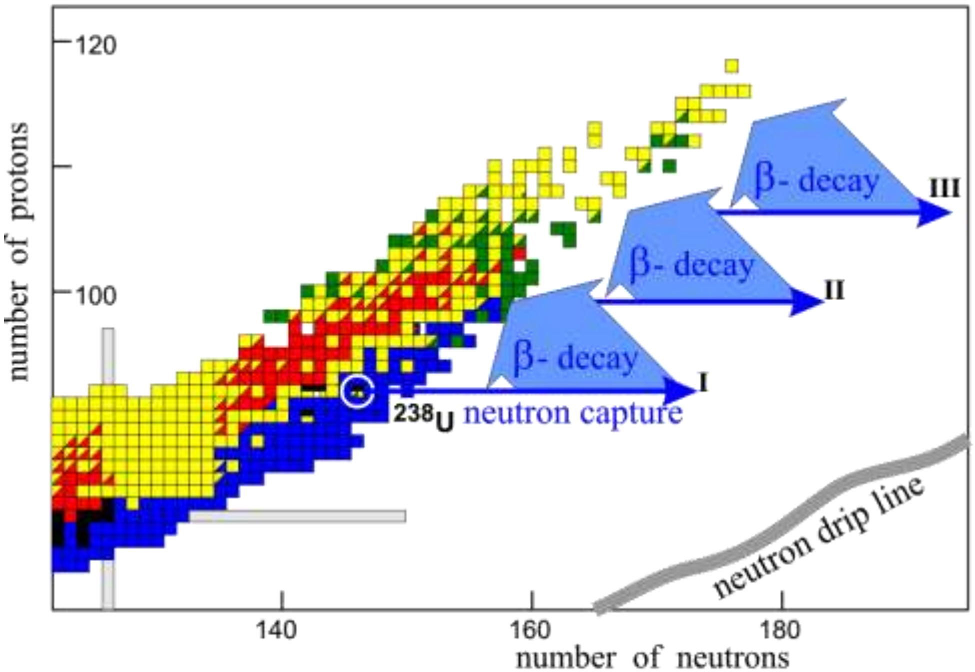


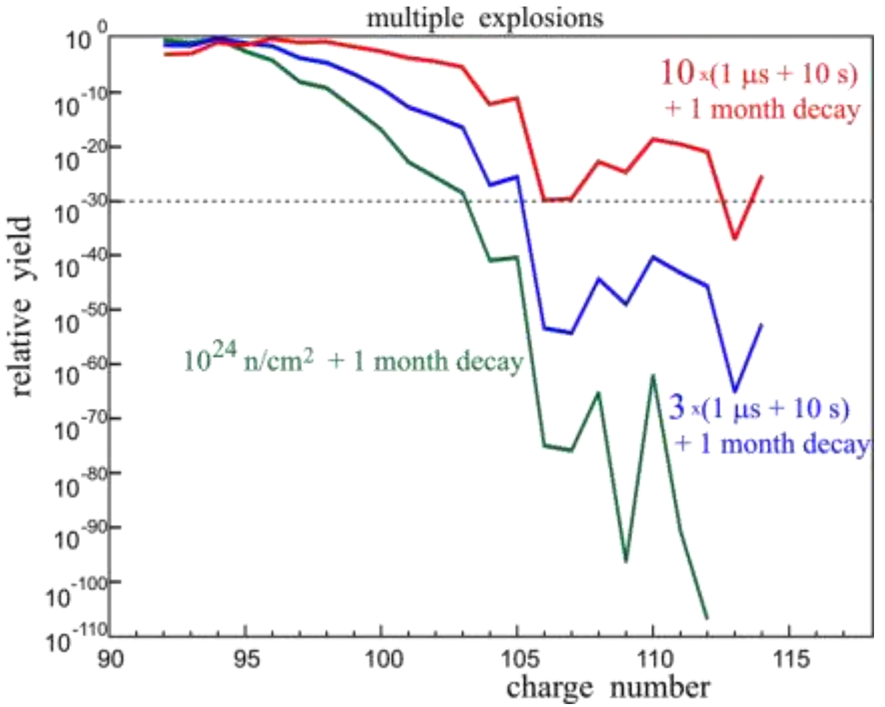


Rapid neutron capture in nuclear explosion



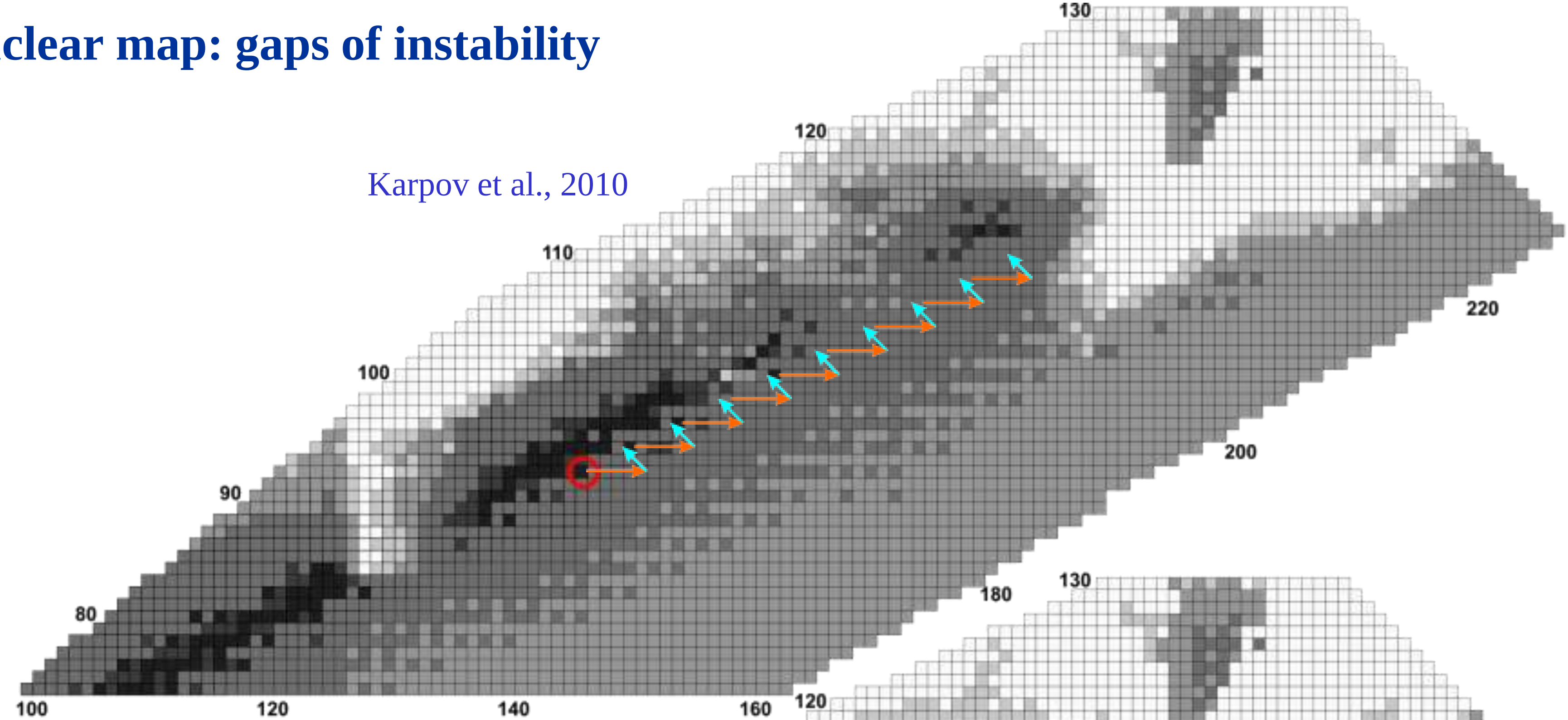
Multiple nuclear explosions



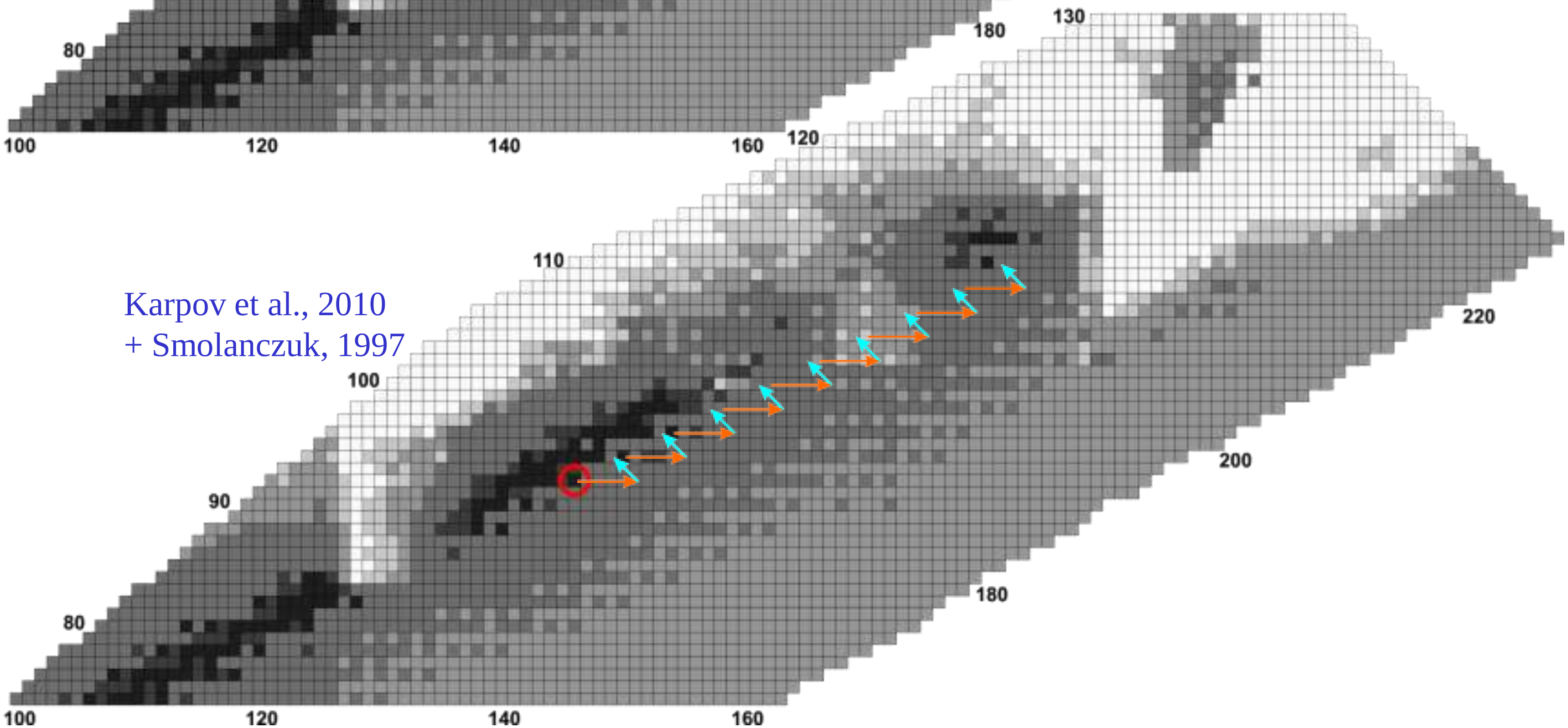


Nuclear map: gaps of instability

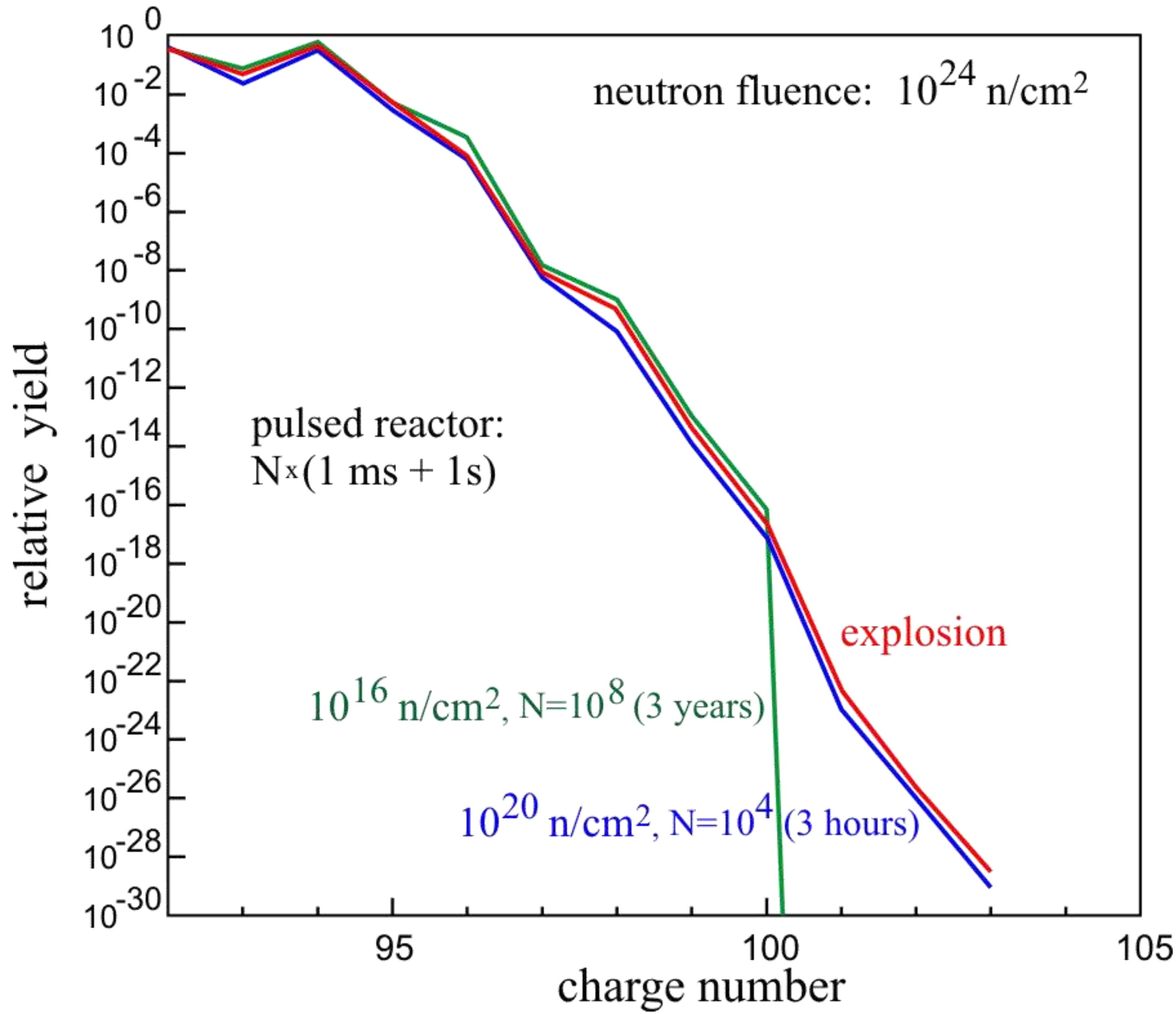
Karpov et al., 2010



Karpov et al., 2010
+ Smolanczuk, 1997

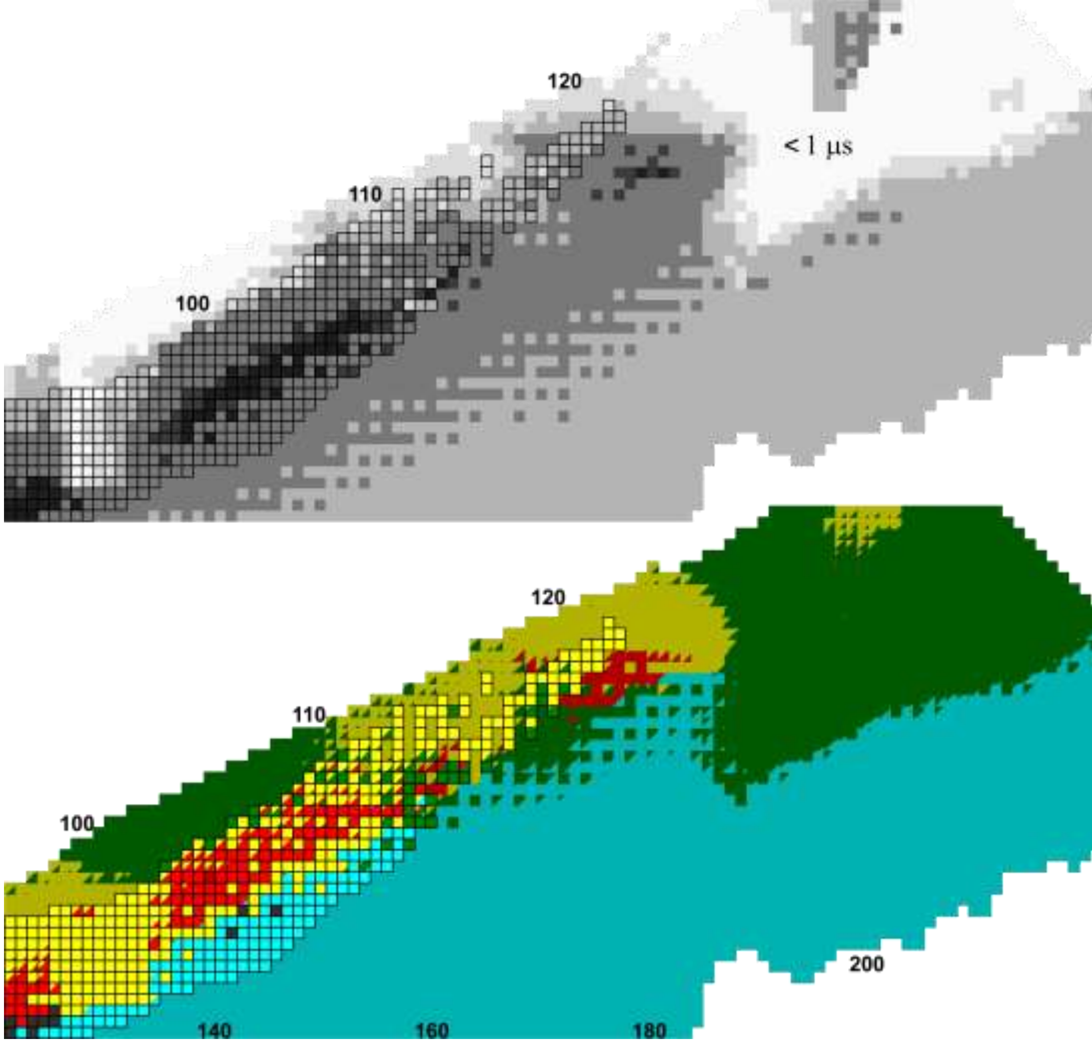


Pulsed reactors ?



Problems

- Where are the islands of stability ?
- What is the most stable SH element to find it in Nature ?
- How much is the shell-effect enhancement in transfer reactions?
- Is it possible to overcome the Fm hole ? What is the nearest “blue” (beta-decayed) Fm isotope ?
- How deep (short-living) is the gap in the region of Z~108, A~270 ?
- Is it possible to construct desired pulsed reactor? Or soft multiple explosions are still cheaper?



What is the next idea
of this smoking gentleman ?