Production and Study of New Neutron Rich Heavy Nuclei in Multinucleon Transfer Reactions

- **State of the art: neutron rich heavy nuclei are not synthesized yet**
- **Outline of the model (2 slides only)**
- **Our predictions and proposals:**
  - **Shell effects in damped collisions of heavy ions ?**
  - **Production of trans-target nuclei (inverse quasi-fission process)**
  - **Synthesis of neutron enriched transfermium nuclei**
  - **Production of neutron rich nuclei located along the neutron closed shell N=126**
- **New setup for selective laser separation of heavy neutron rich nuclei**
- **Summary**

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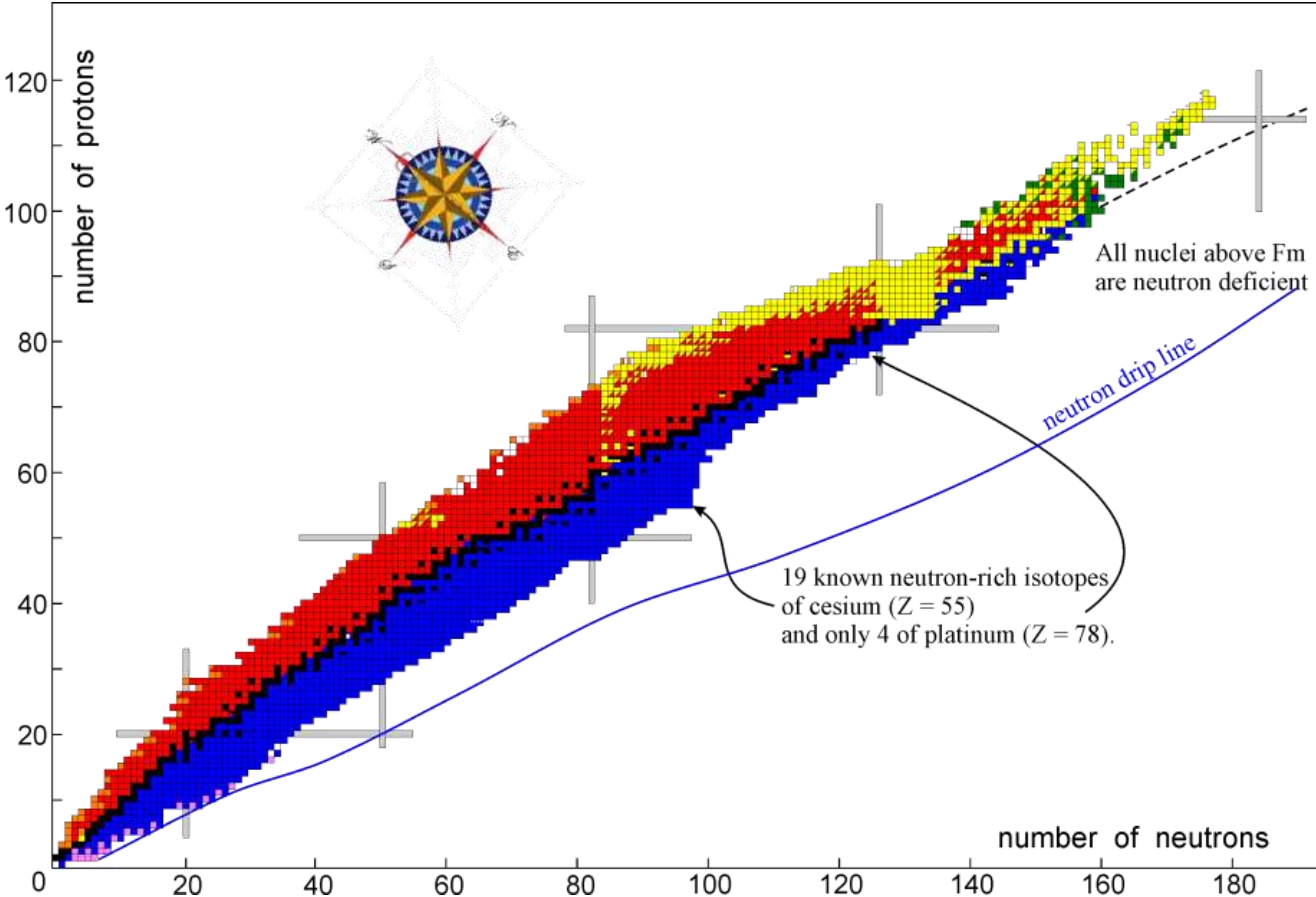
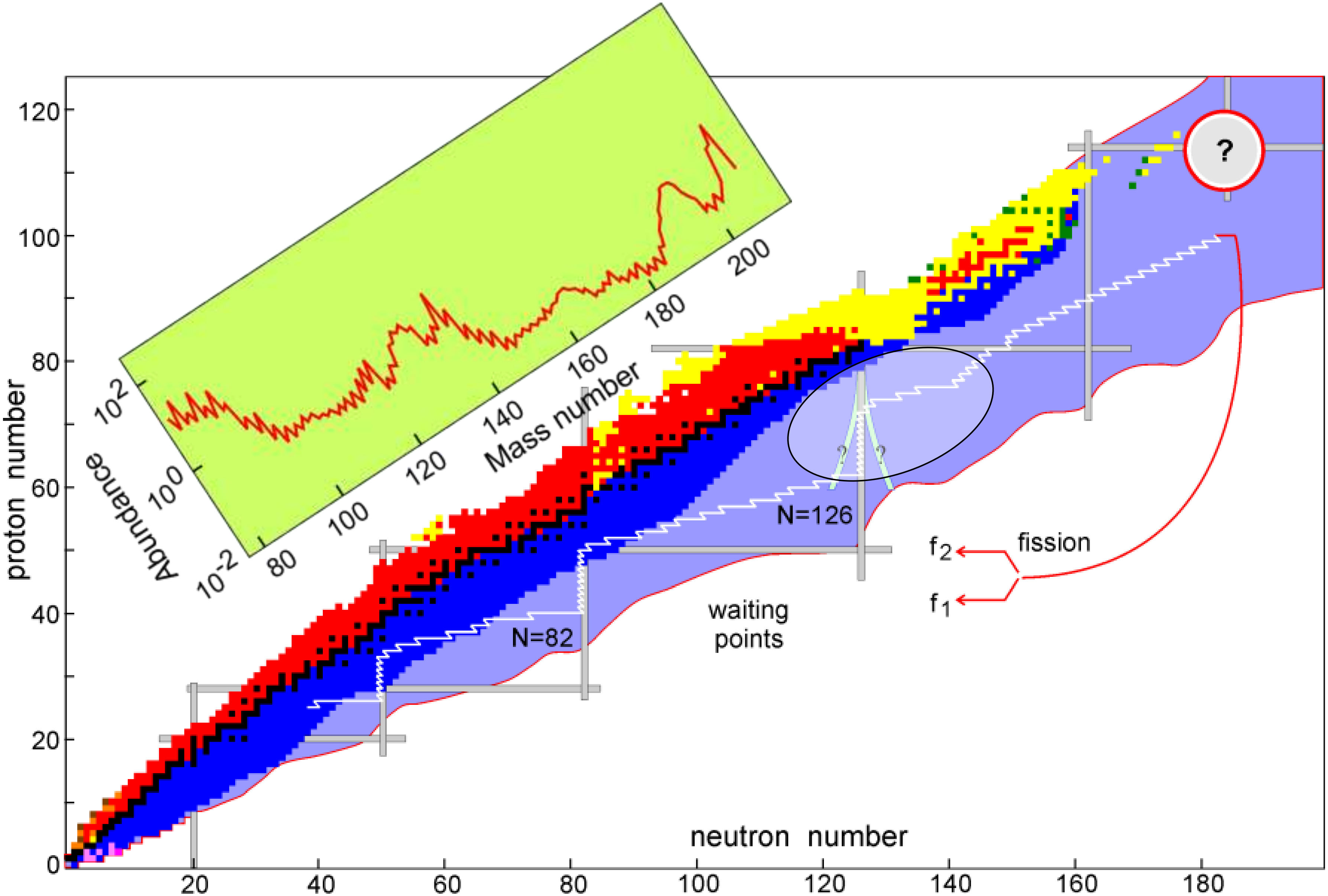
for "HIAS-2013", April 11, 2013, Canberra, Australia

At the present time there are no neutron rich heavy and superheavy nuclei



r-process of nucleosynthesis
and the neutron closed shell in the region of N=126

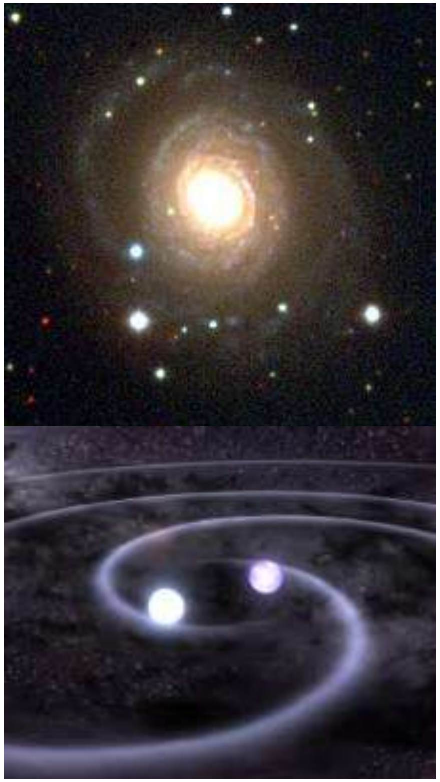


Abundance of the elements in the Universe

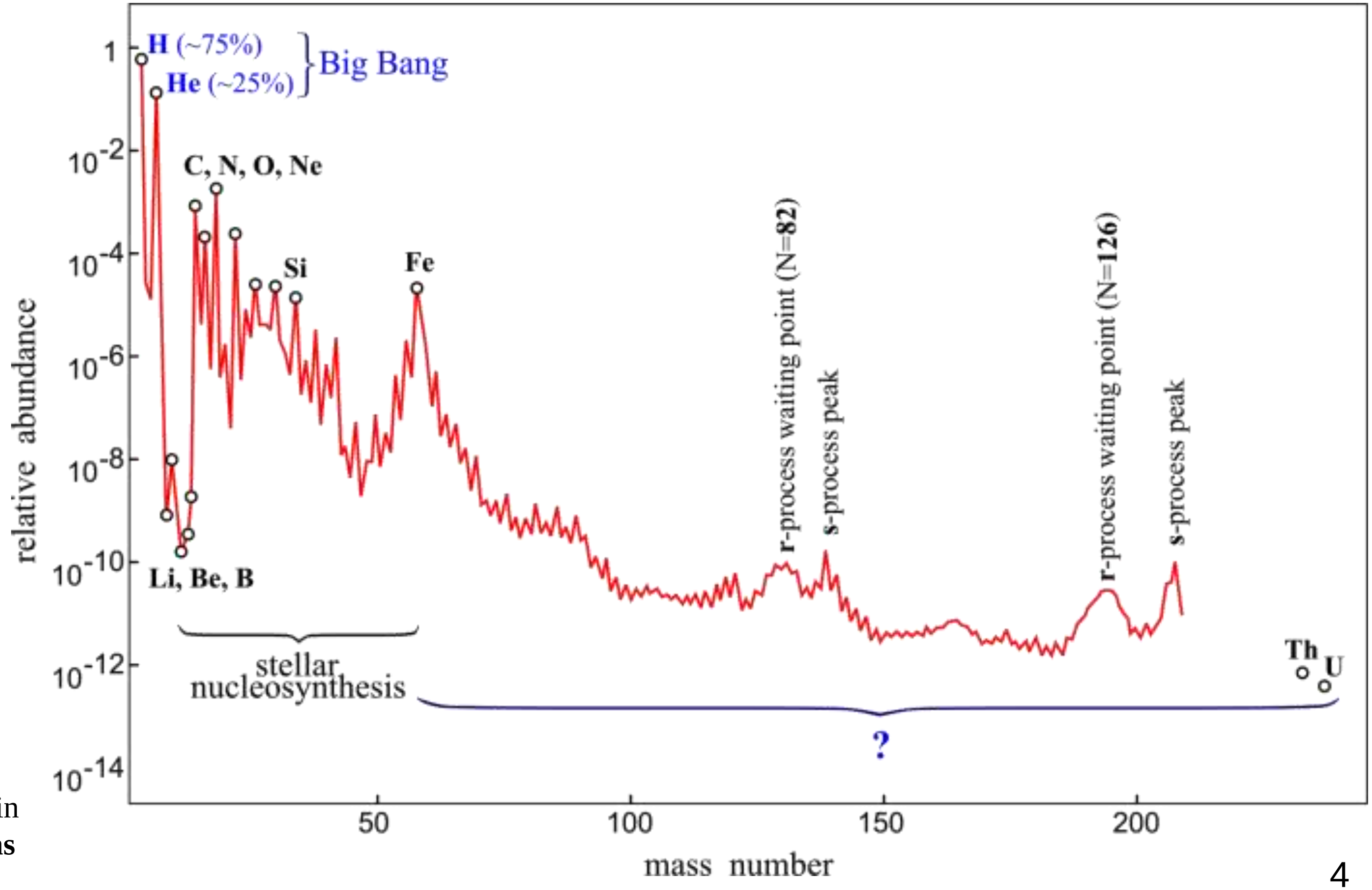
The 11 Greatest Unanswered Questions of Physics
(National Research Council, NAS, USA, 2002):

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?**

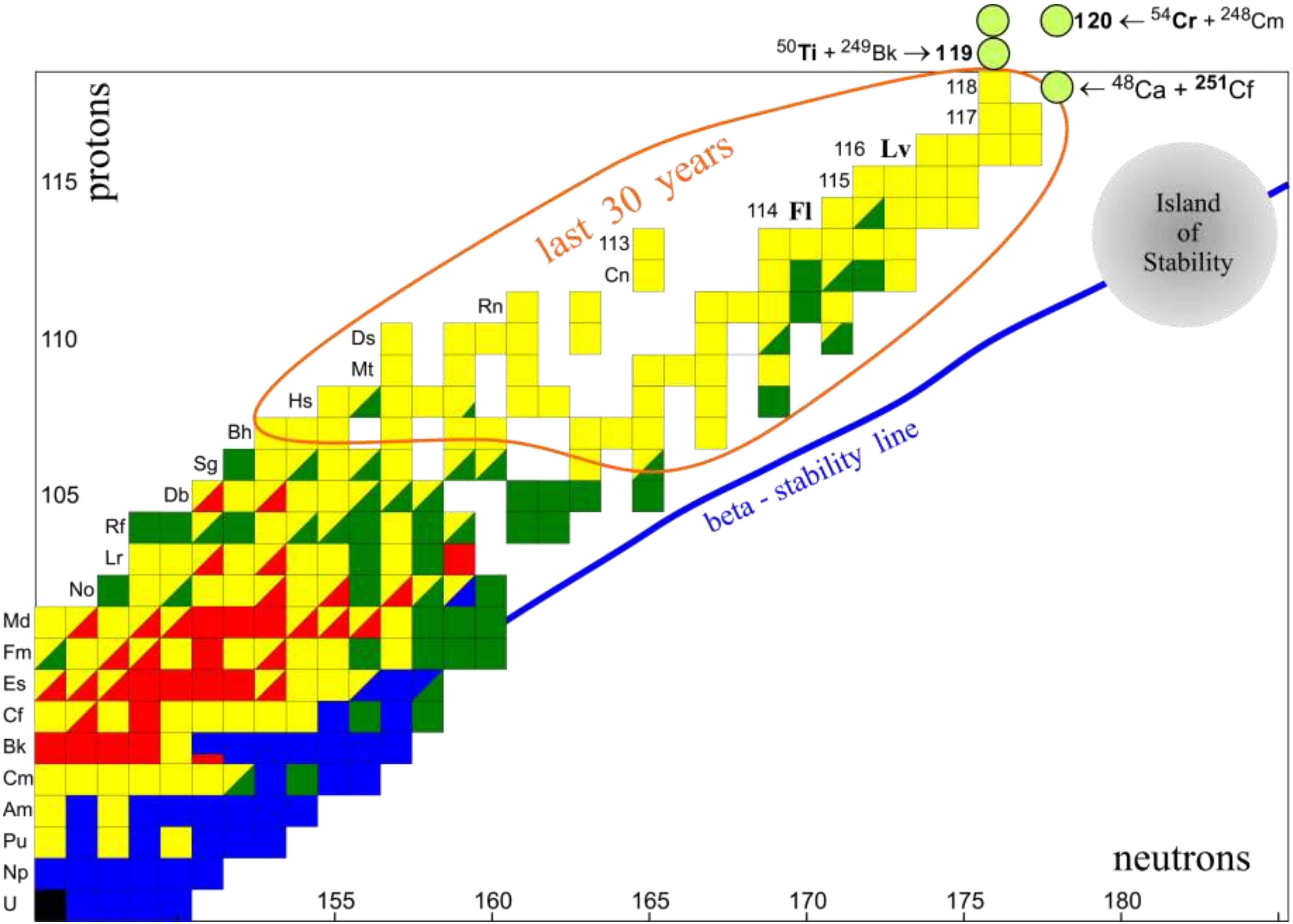
…



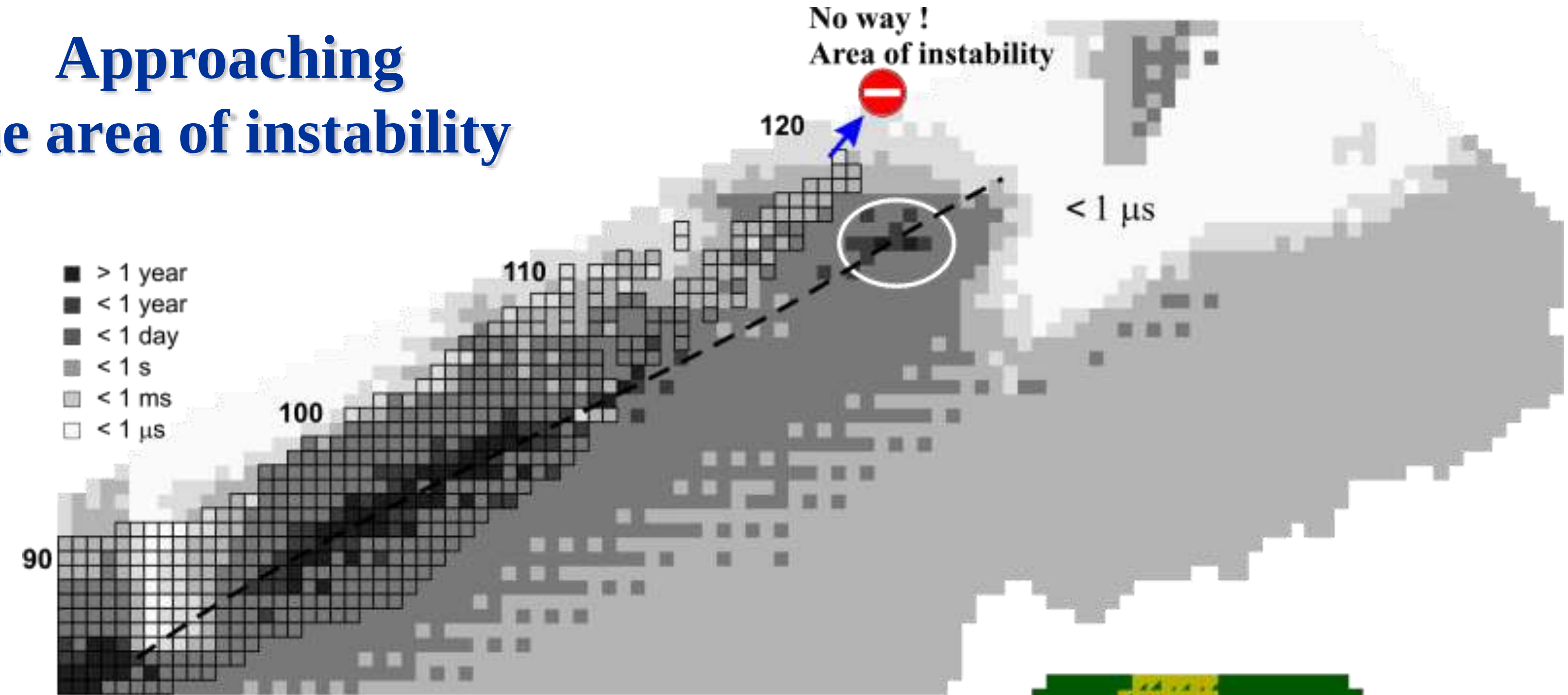
Strong neutron fluxes are expected in **core-collapse supernova explosions** or in the **mergers of neutron stars.**

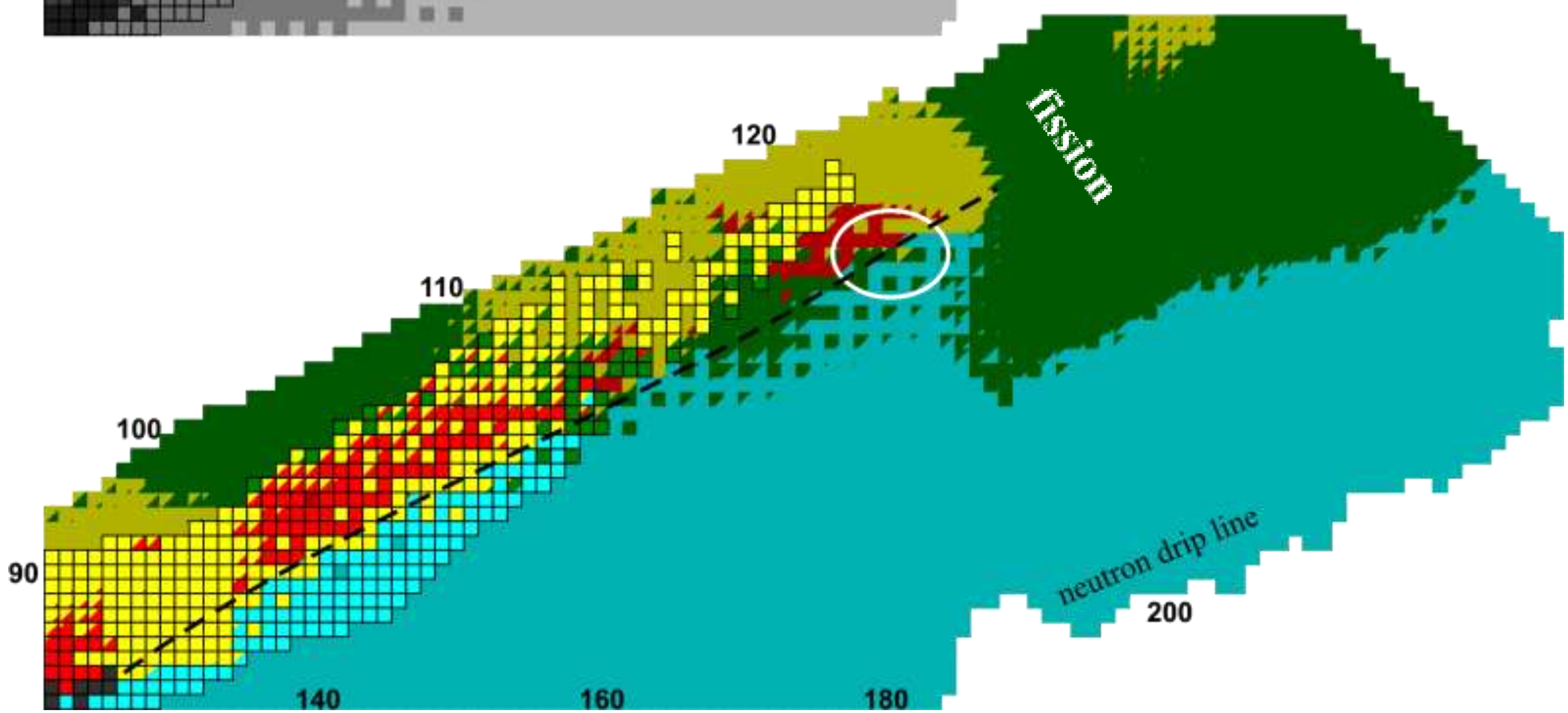


SHE: we are far from the stability line and from the Island of Stability



Approaching the area of instability





There are only 3 methods for synthesis of heavy nuclei

1. Fusion reactions: beams of stable nuclei ($\rightarrow$ proton rich),
radioactive ion beams (no chances)

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

Synthesis of heavy and SH nuclei in **transfer reactions**

[1] E. K. Hulet *et al.*, Phys. Rev. Lett. **39**, 385 (**1977**).
[2] M. Schaedel *et al.*, Phys. Rev. Lett. **41**, 469 (**1978**).
[3] H. Essel, K. Hartel, W. Henning, P. Kienle, H. J. Koerner, K. E. Rehm, P. Sperr,W.Wagner, and H. Spieler, Z. Phys. A **289**, 265 (**1979**).
[4] H. Freiesleben, K. D. Hildenbrand, F. P¨uhlhofer, W. F. W. Scneider, R. Bock, D. V. Harrach, and H. J. Specht, Z. Phys. A **292**, 171 (**1979**).
[5] H. Gaeggeler *et al.*, Phys. Rev. Lett. **45**, 1824 (**1980**).
[6] M. Schaedel *et al.*, Phys. Rev. Lett. **48**, 852 (**1982**).
[7] K. J. Moody, D. Lee, R. B. Welch, K. E. Gregorich, G. T. Seaborg, R. W. Lougheed, and E. K. Hulet, Phys. Rev. C **33**, 1315 (**1986**).
[8] R. B. Welch, K. J. Moody, K. E. Gregorich, D. Lee, and G. T. Seaborg, Phys. Rev. C **35**, 204 (**1987**).
…

… a long history. New isotopes of Fm and Md were synthesized 30 years ago.

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)

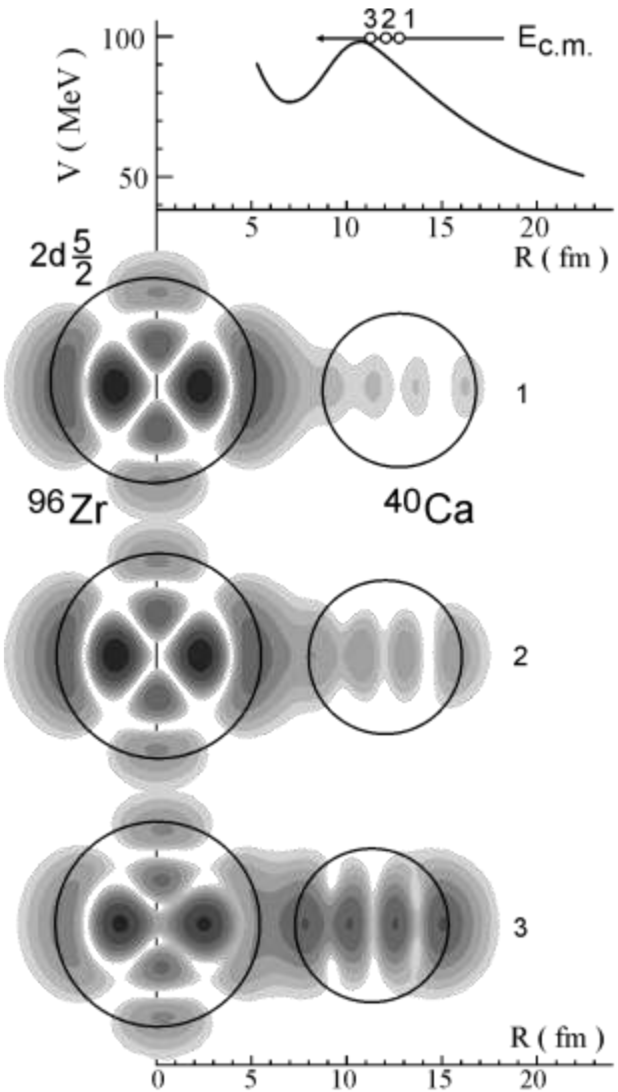
Semi-classical approaches

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)

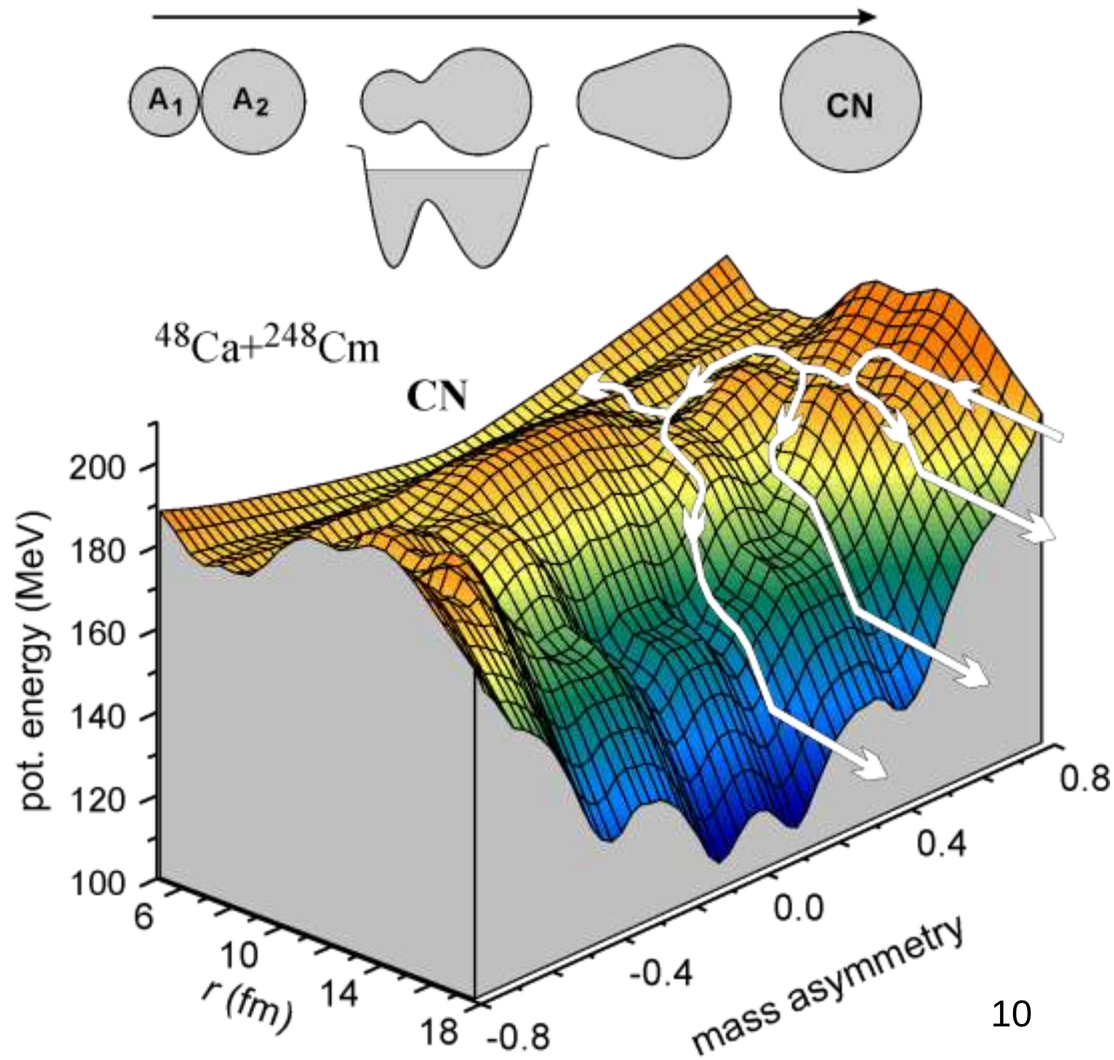
A. Winther, Nucl. Phys. **A594**, 203 (1995)
http://personalpages.to.infn.it/nanni/grazing

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



time-tependent 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

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

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

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

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

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

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

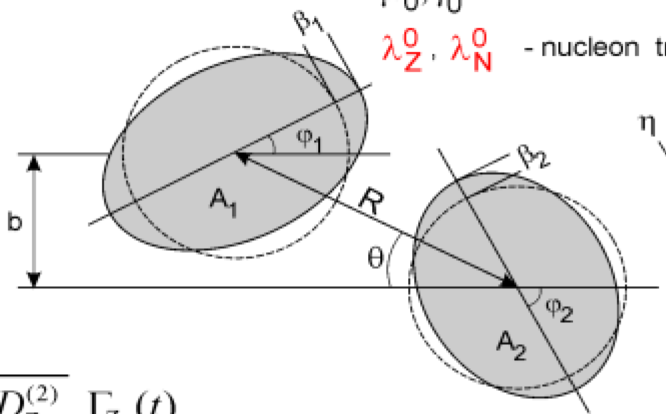
$$\frac{d\eta_Z}{dt}=\frac{2}{Z_{CN}}D_Z^{(1)}+\frac{2}{Z_{CN}}\sqrt{D_Z^{(2)}}\;\Gamma_Z(t)$$

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

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_Z^0, λ_N^0 - nucleon transfer rate



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

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

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

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

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

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

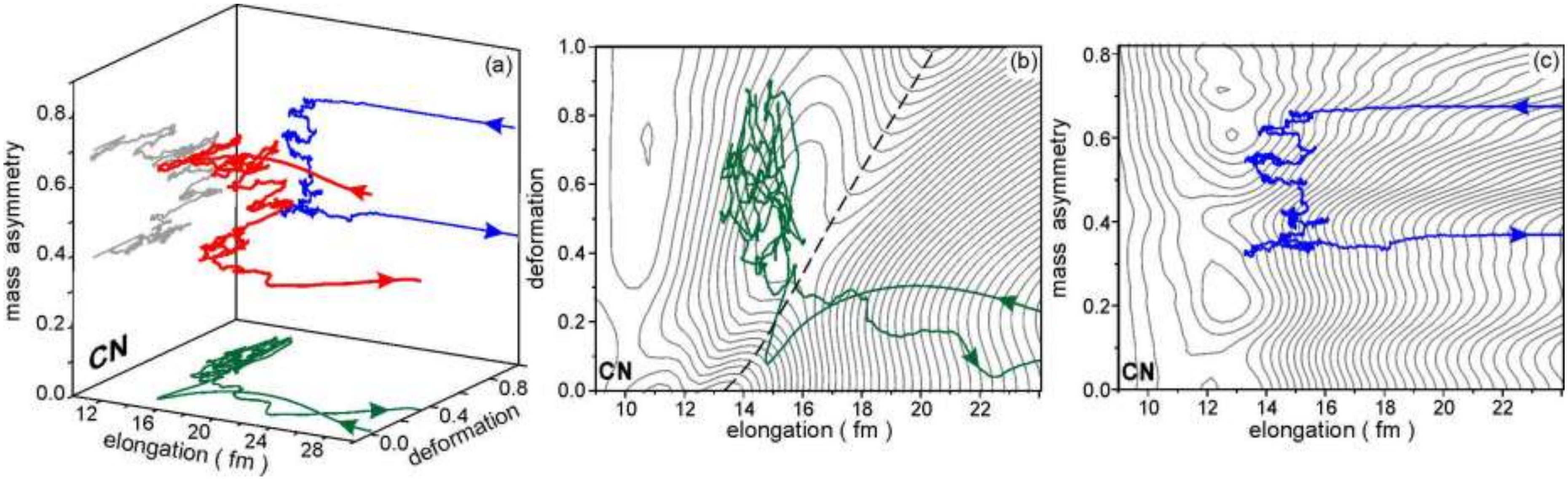
$$\frac{dL_1}{dt}=-\frac{\partial V}{\partial\varphi_1}+\gamma_{tang}\left(\frac{\ell}{\mu_R R}-\frac{L_1}{\Im_1}a_1-\frac{L_2}{\Im_2}a_2\right)a_1-\frac{a_1}{R}\sqrt{\gamma_{tang}T}\,\Gamma_{tang}(t)$$

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

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

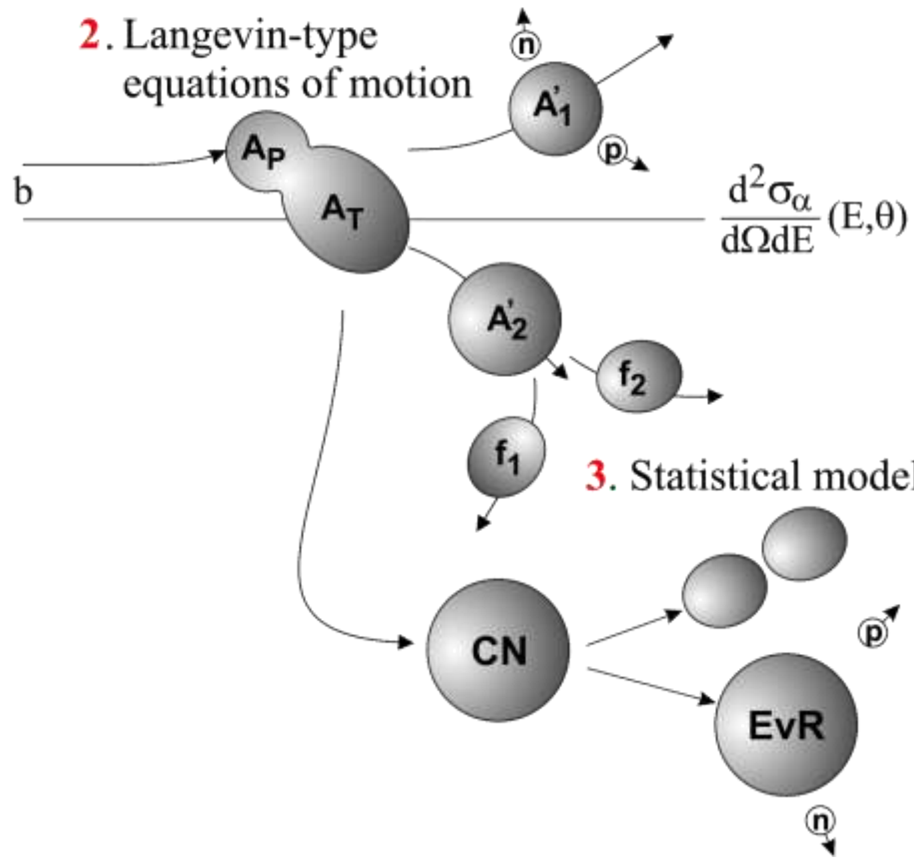
$$\frac{dp_{\beta 2}}{dt}=-\frac{\partial V}{\partial\beta_2}+\frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial\mu_{\beta 1}}{\partial\beta_2}+\frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial\mu_{\beta 2}}{\partial\beta_2}+\left(\frac{\ell^2}{2\mu_R^2 R^2}+\frac{p_R^2}{2\mu_R^2}\right)\frac{\partial\mu_R}{\partial\beta_2}-\gamma_\beta\frac{p_{\beta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

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



Simulation of experiment and cross sections

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

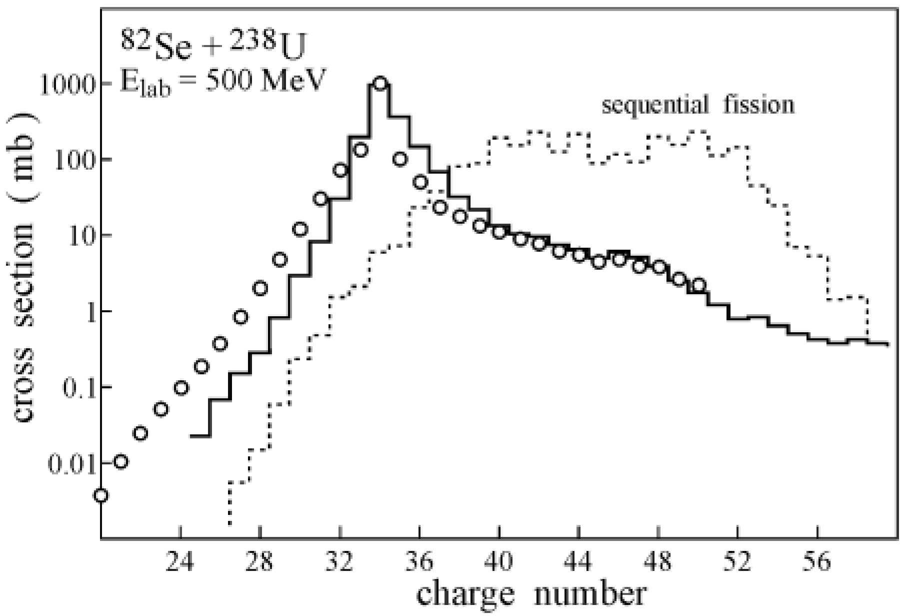


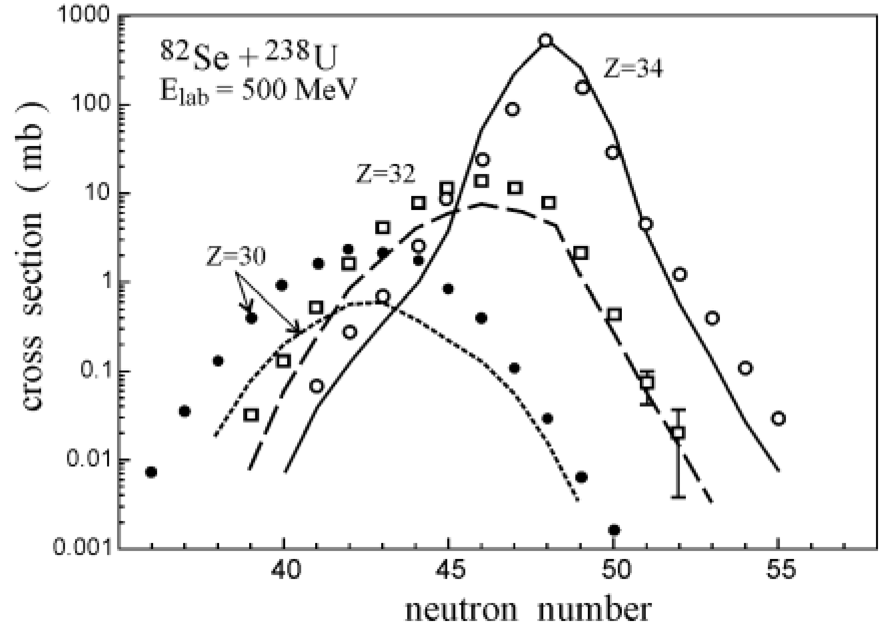
$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty b\,db\ \frac{\Delta N_\alpha(b,E,\theta)}{N_{tot}(b)}\ \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$

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

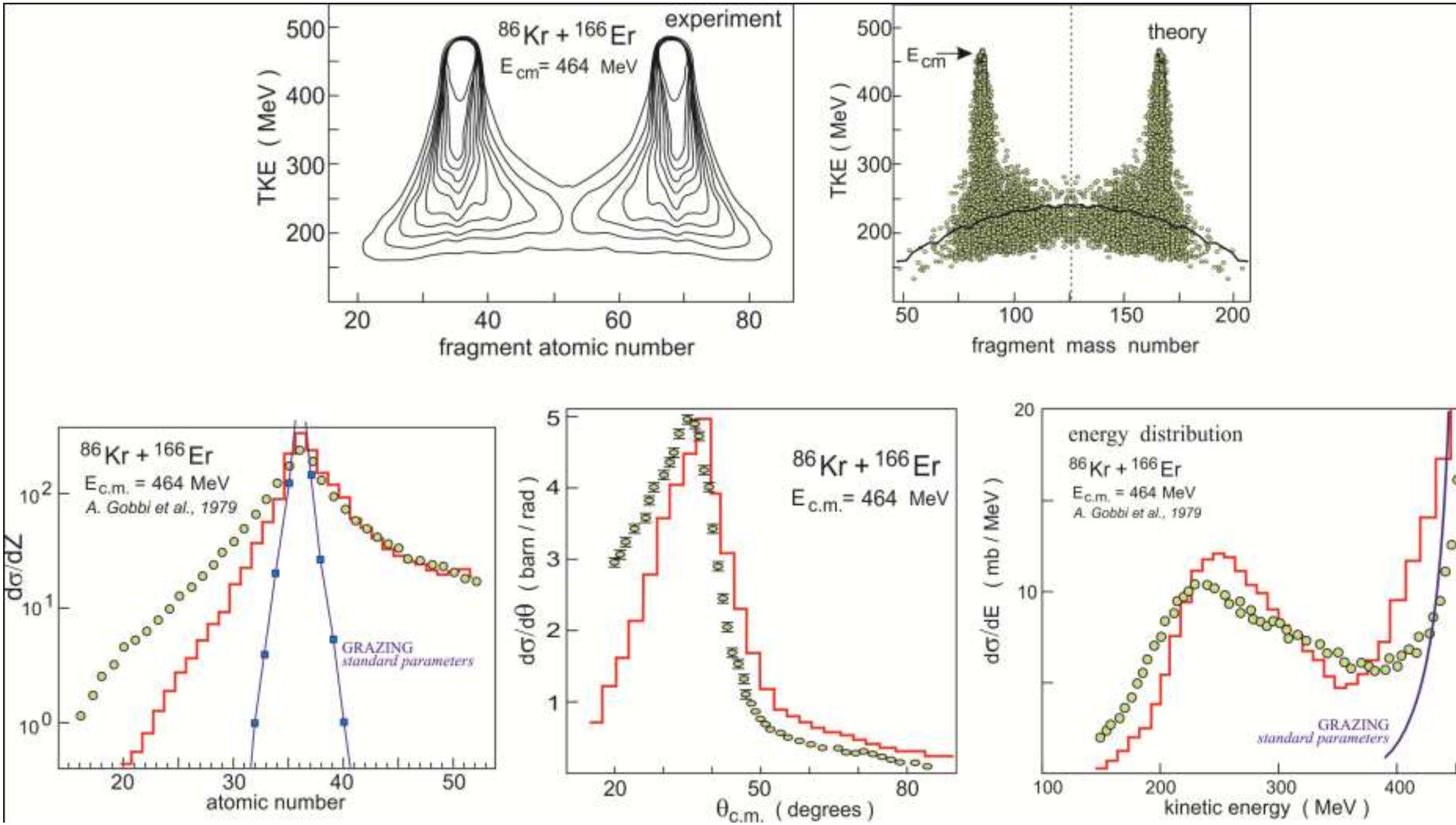
Comparison with experiment on multi-nucleon transfer

Experiment: L. Corradi et al., 2006

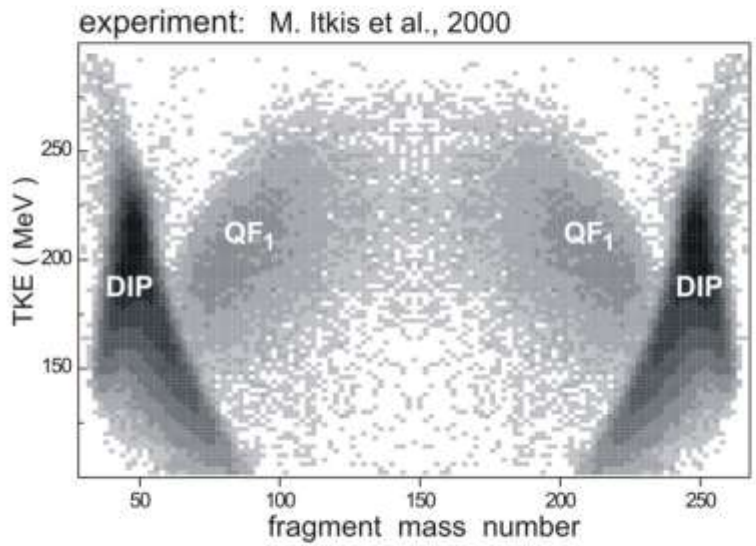


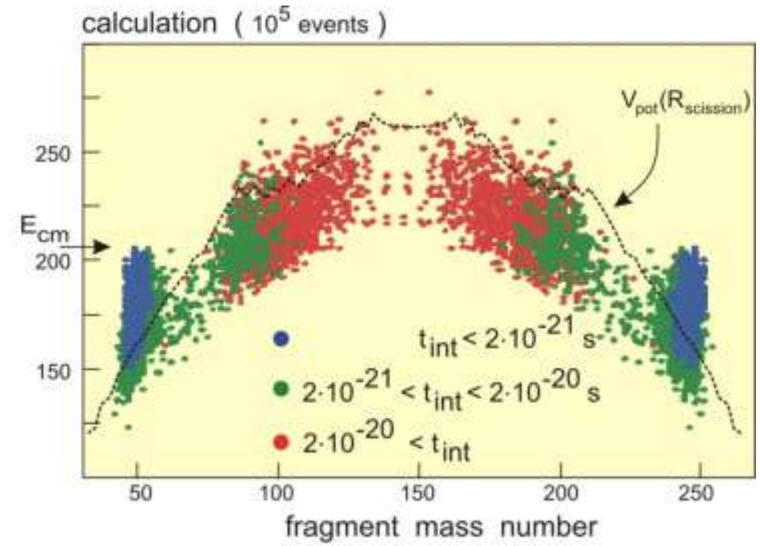


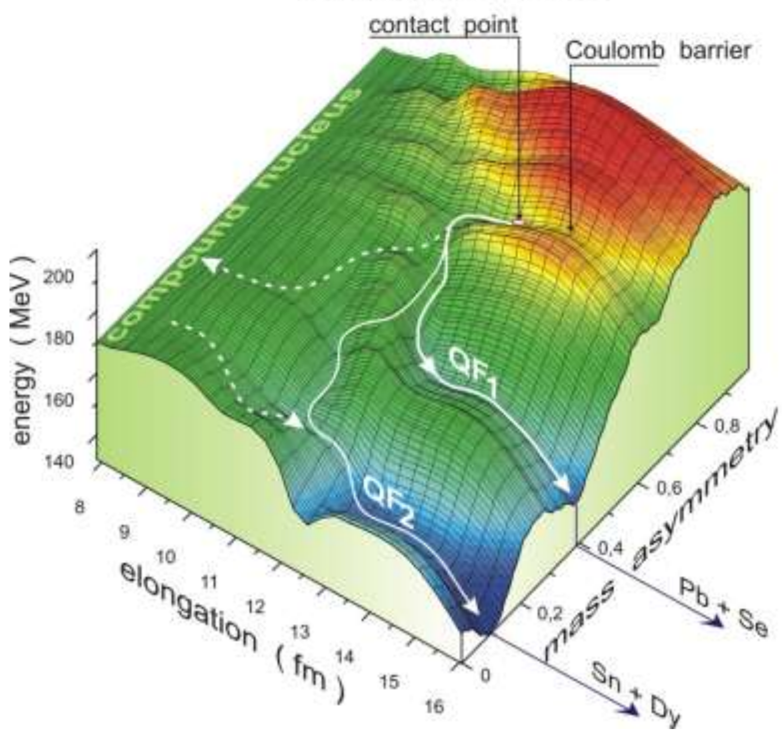
Quite satisfactory agreement with experiments on DI scattering

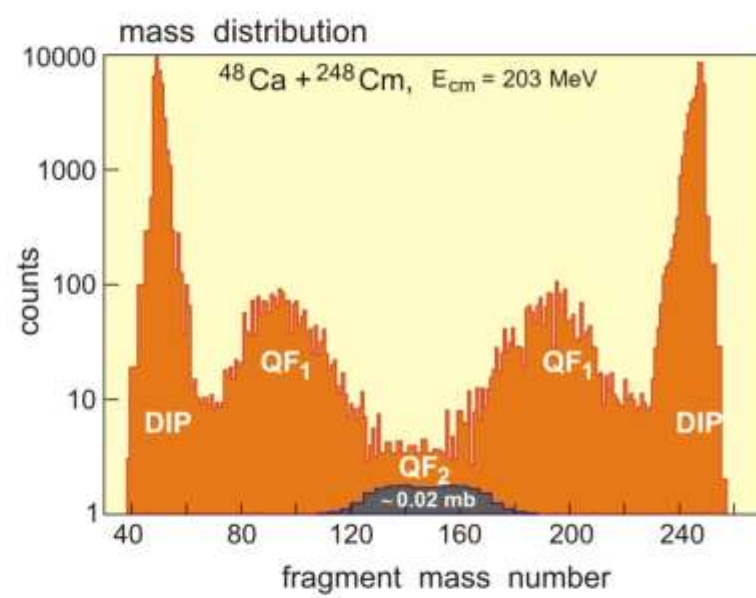


Quasi-Fission process: $^{48}Ca + ^{248}Cm$

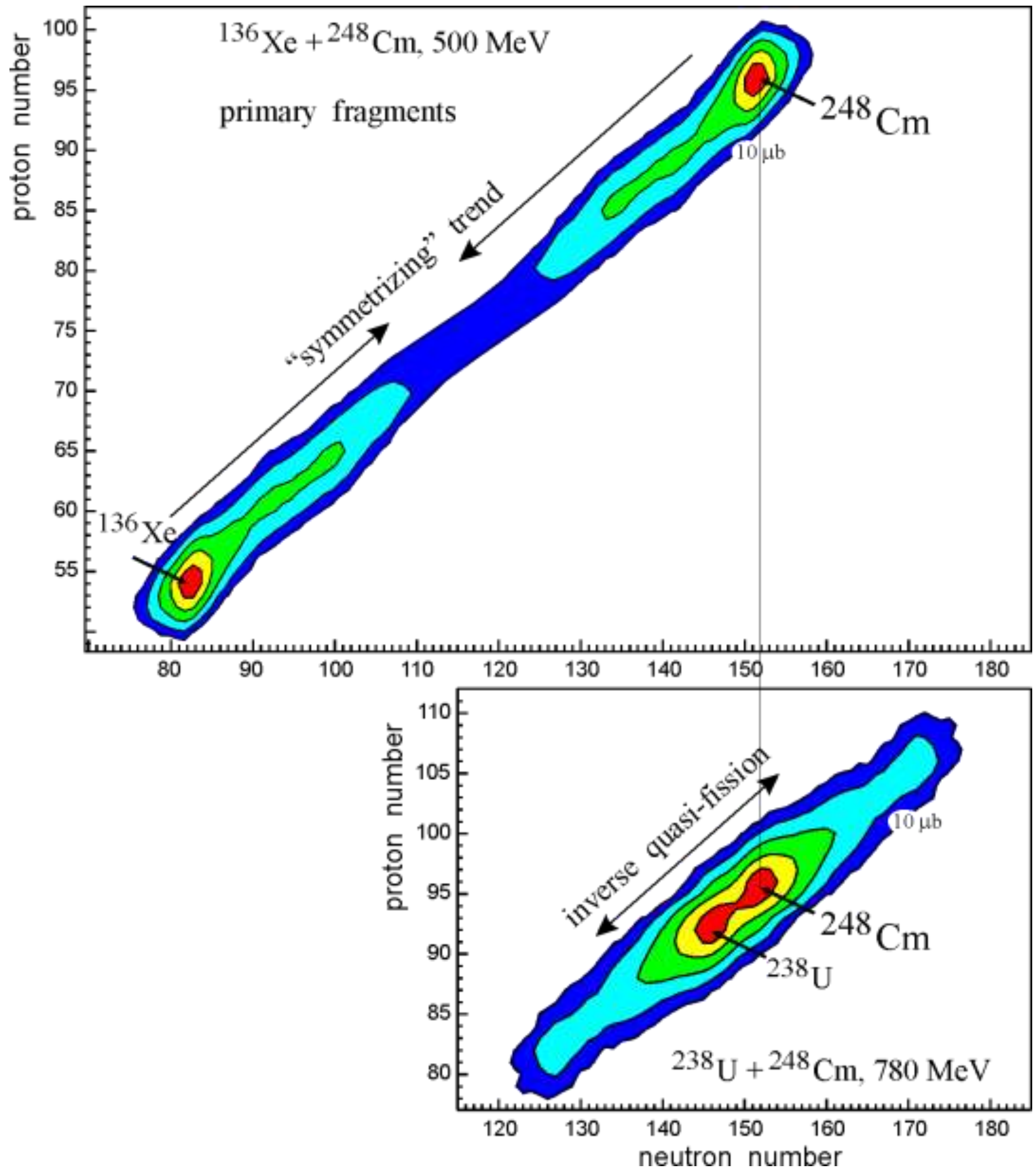




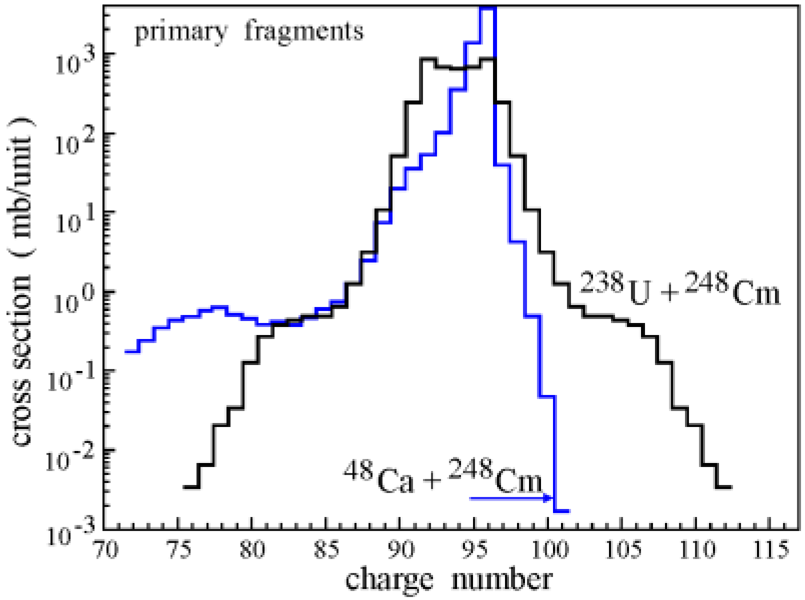


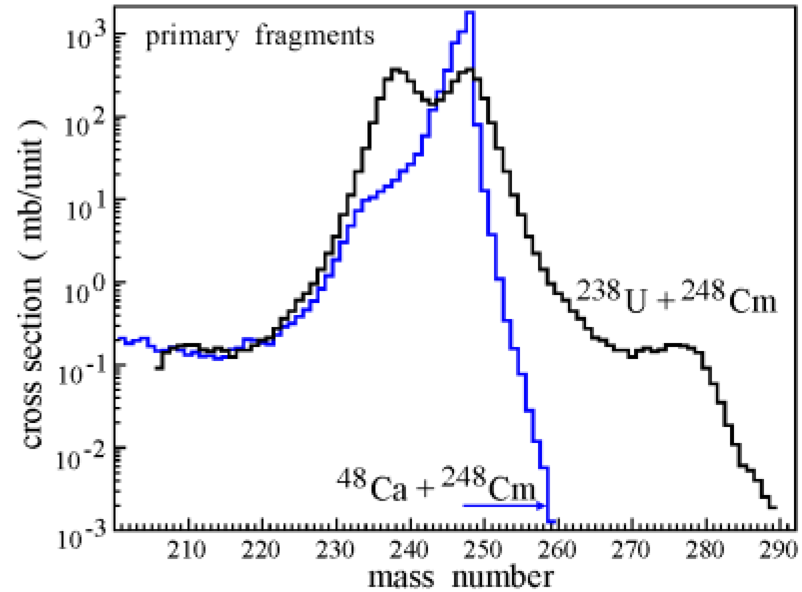


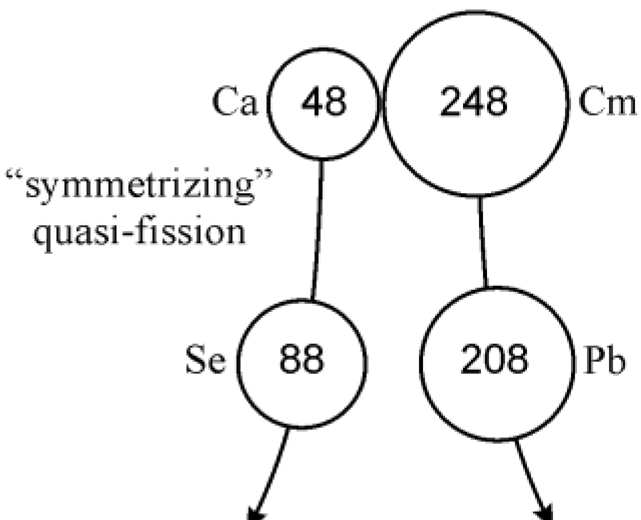
Multi-nucleon transfers for production of Super-Heavy Elements
(choice of reaction is very important)

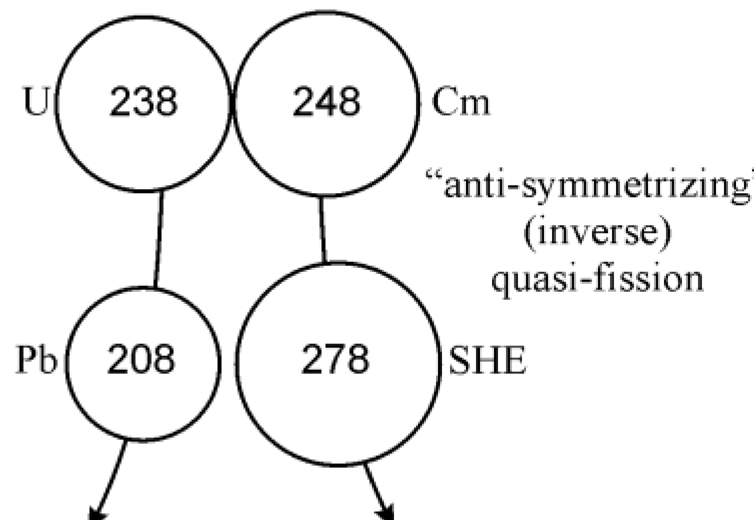


“Inverse quasi-fission” reactions

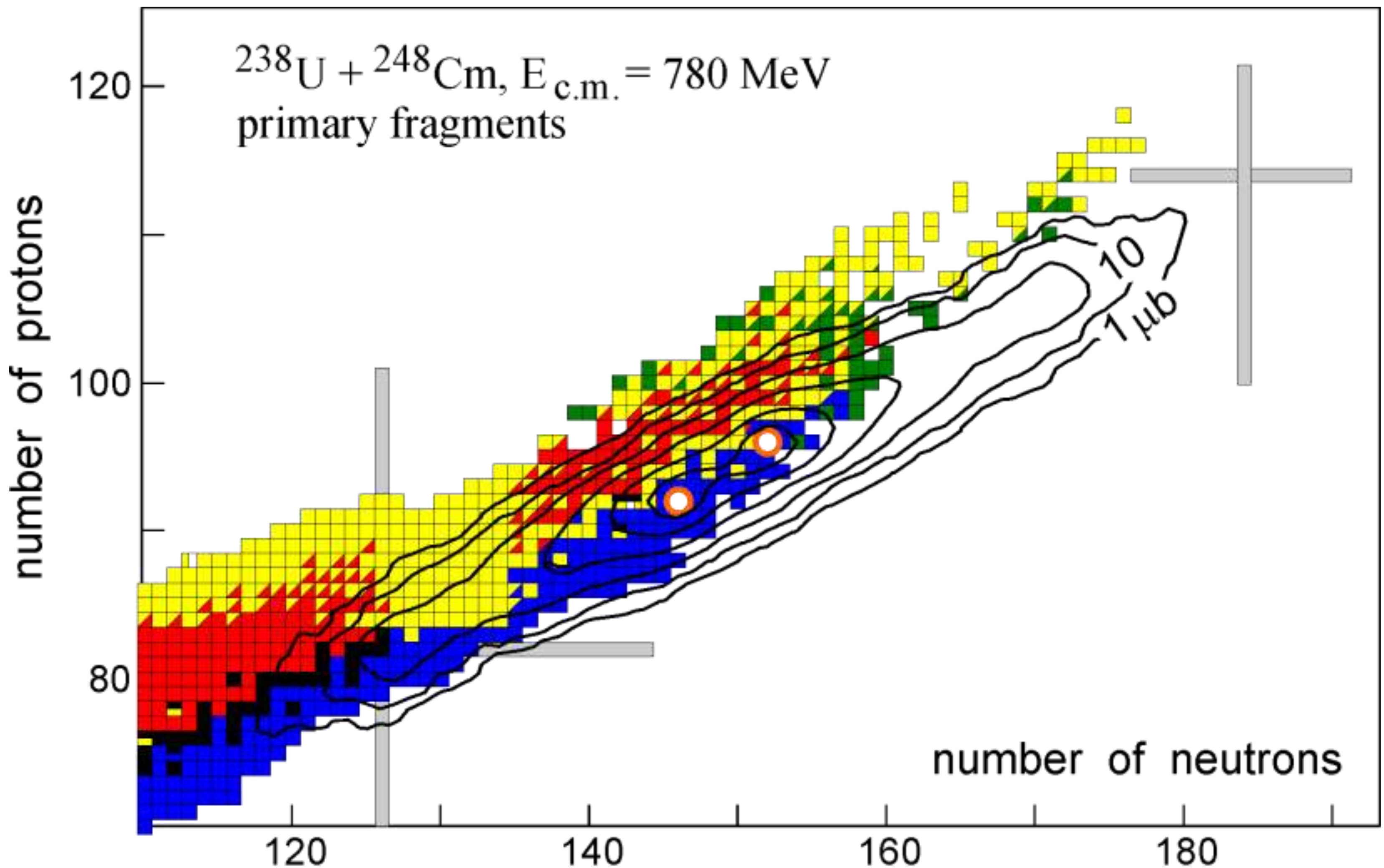




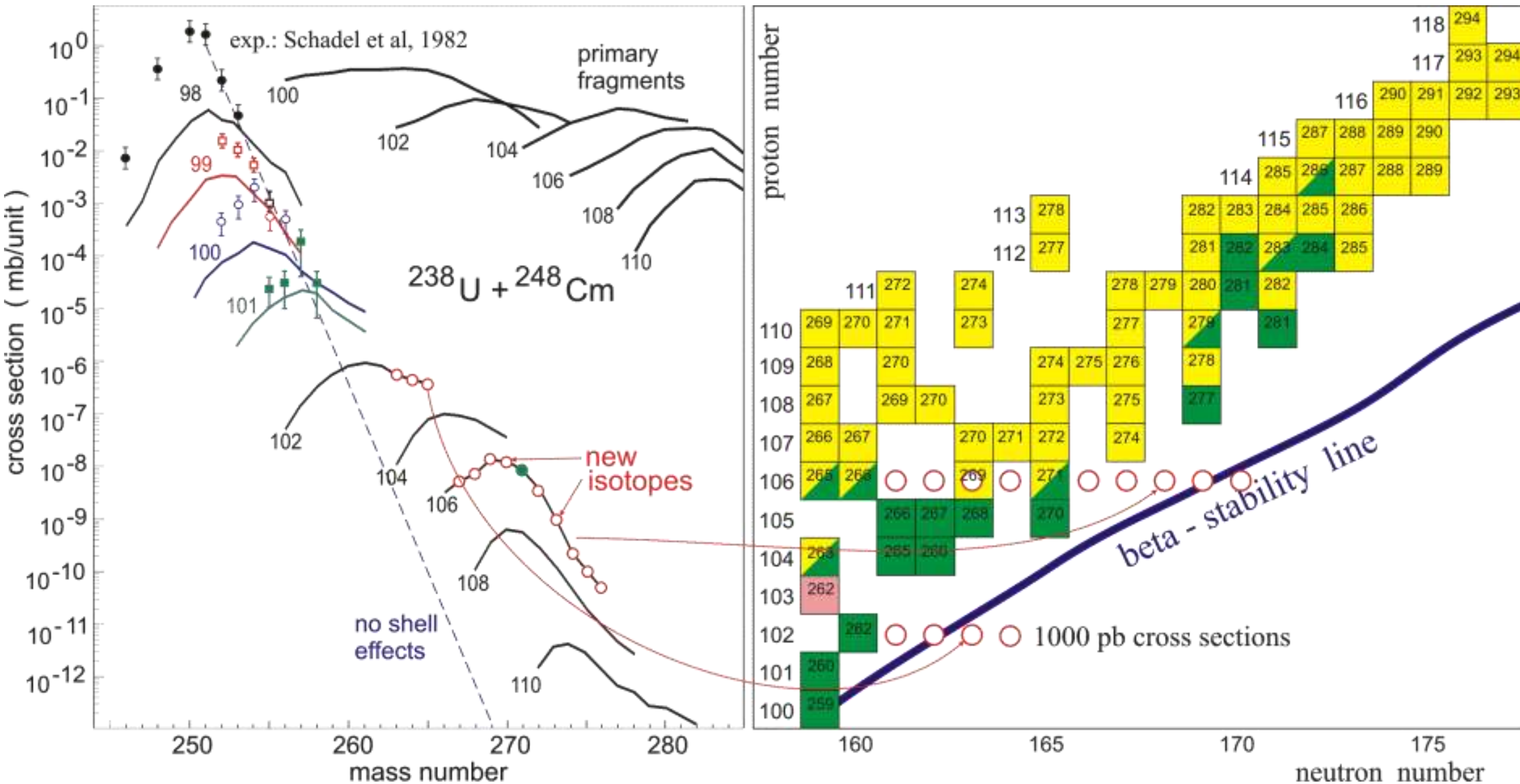




238U + 248Cm. Primary fragments

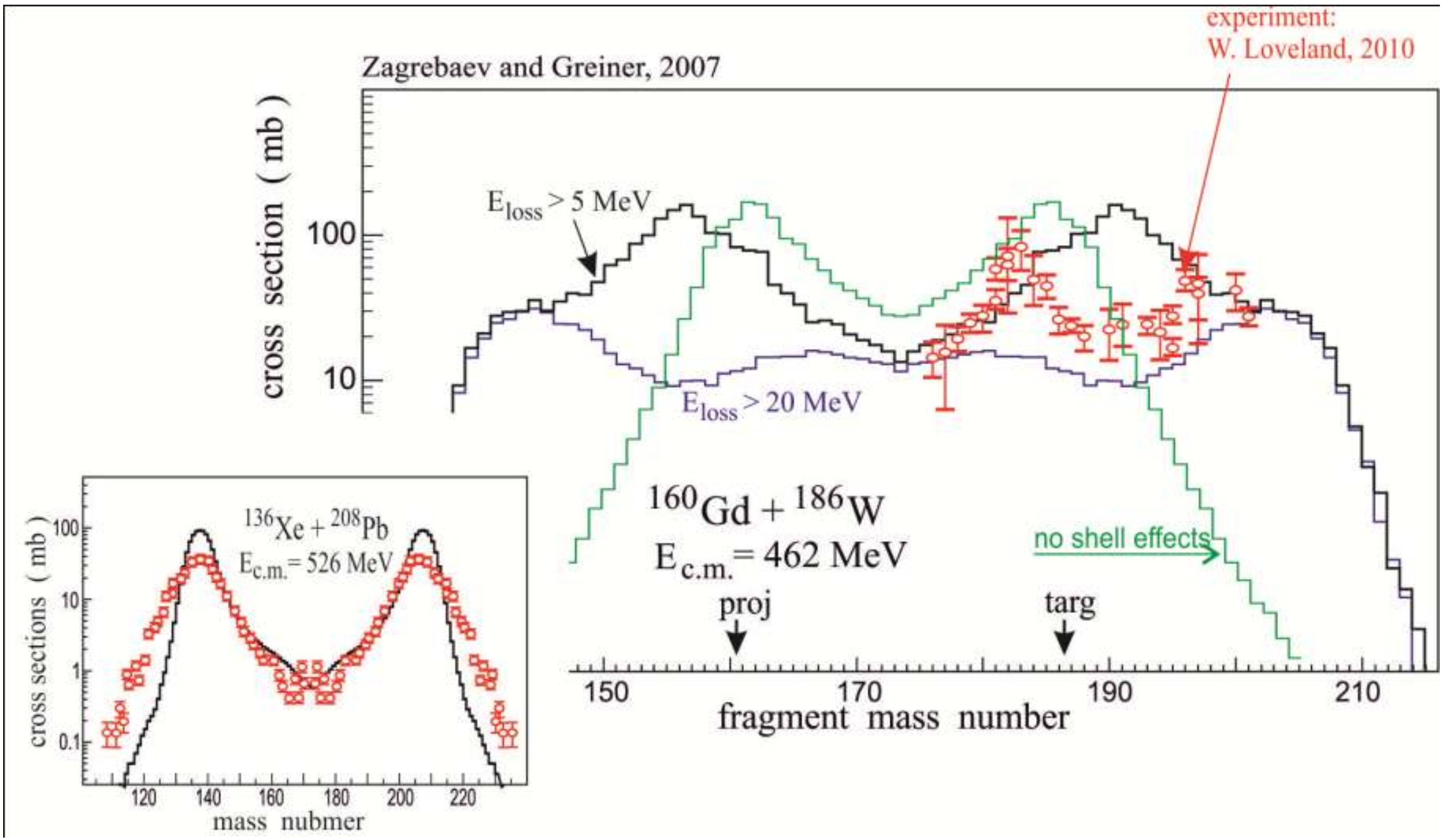


Production of transfermium nuclei along the line of stability looks quite possible owing to shell effects

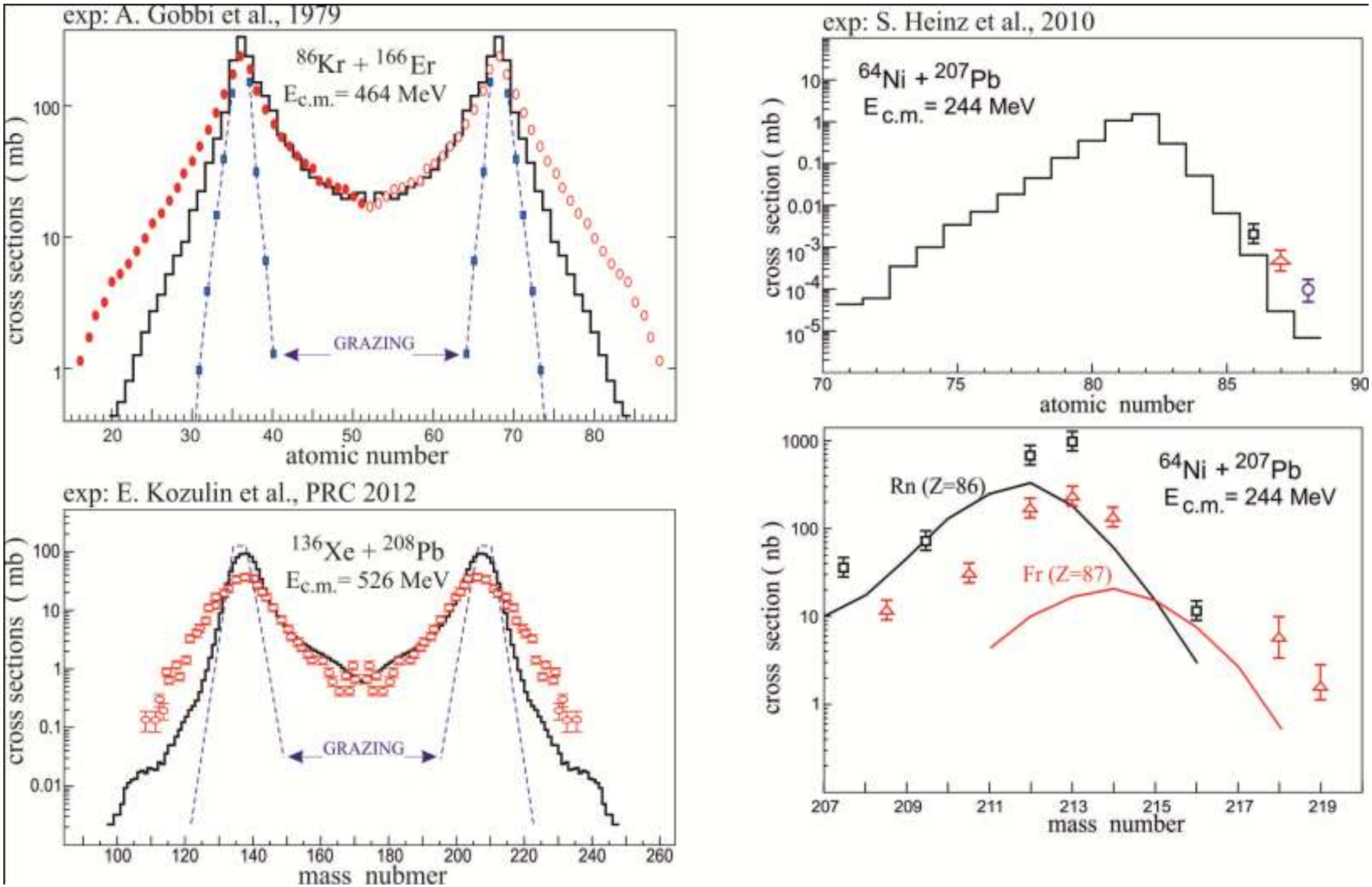


Rather wide angular distribution of reaction fragments:
a new kind of separator is needed

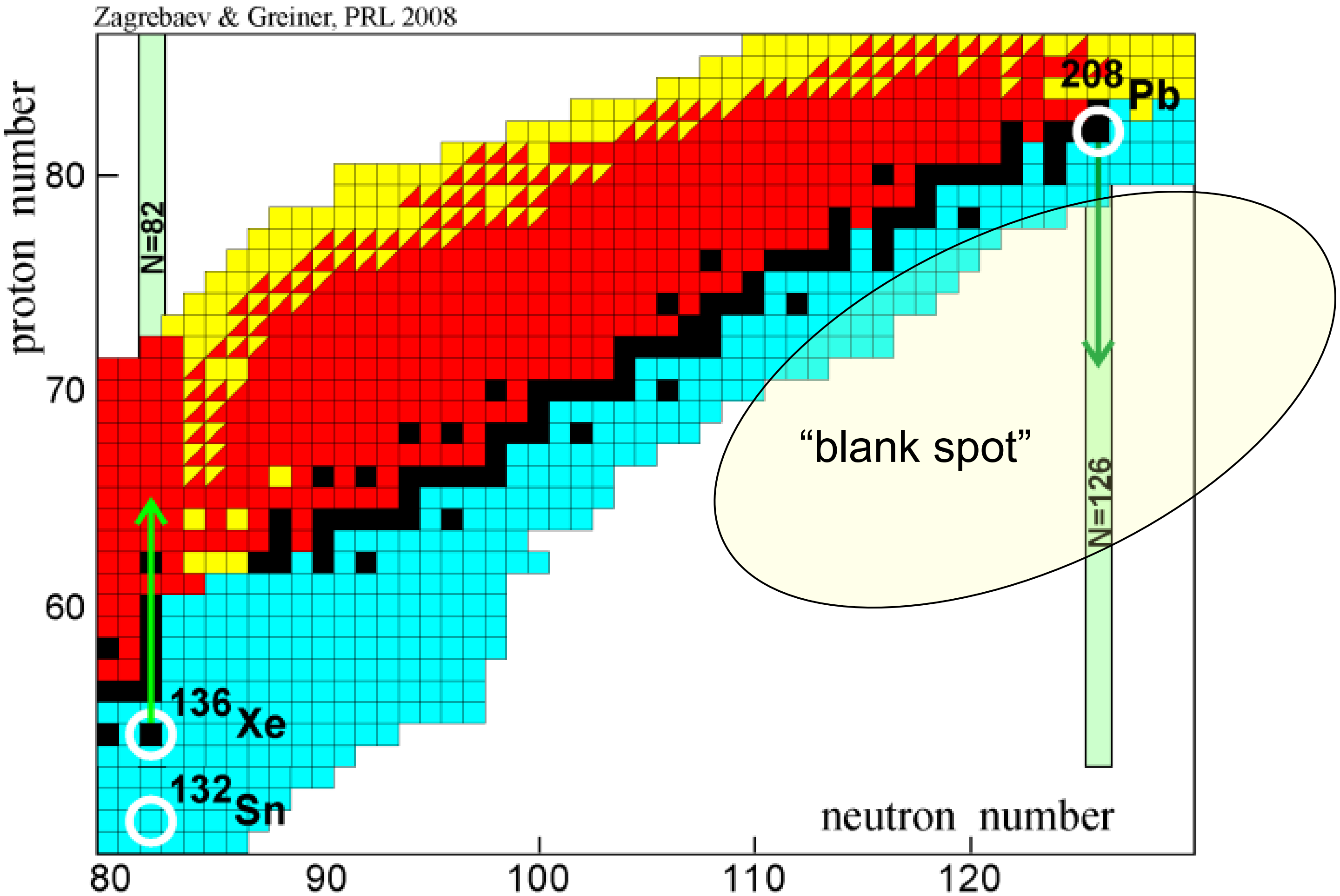
Shell effects in low-energy multi-nucleon transfer reactions ?



Underestimation of the yield of trans-target nuclei ?



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



proton transfer along the neutron closed shells:

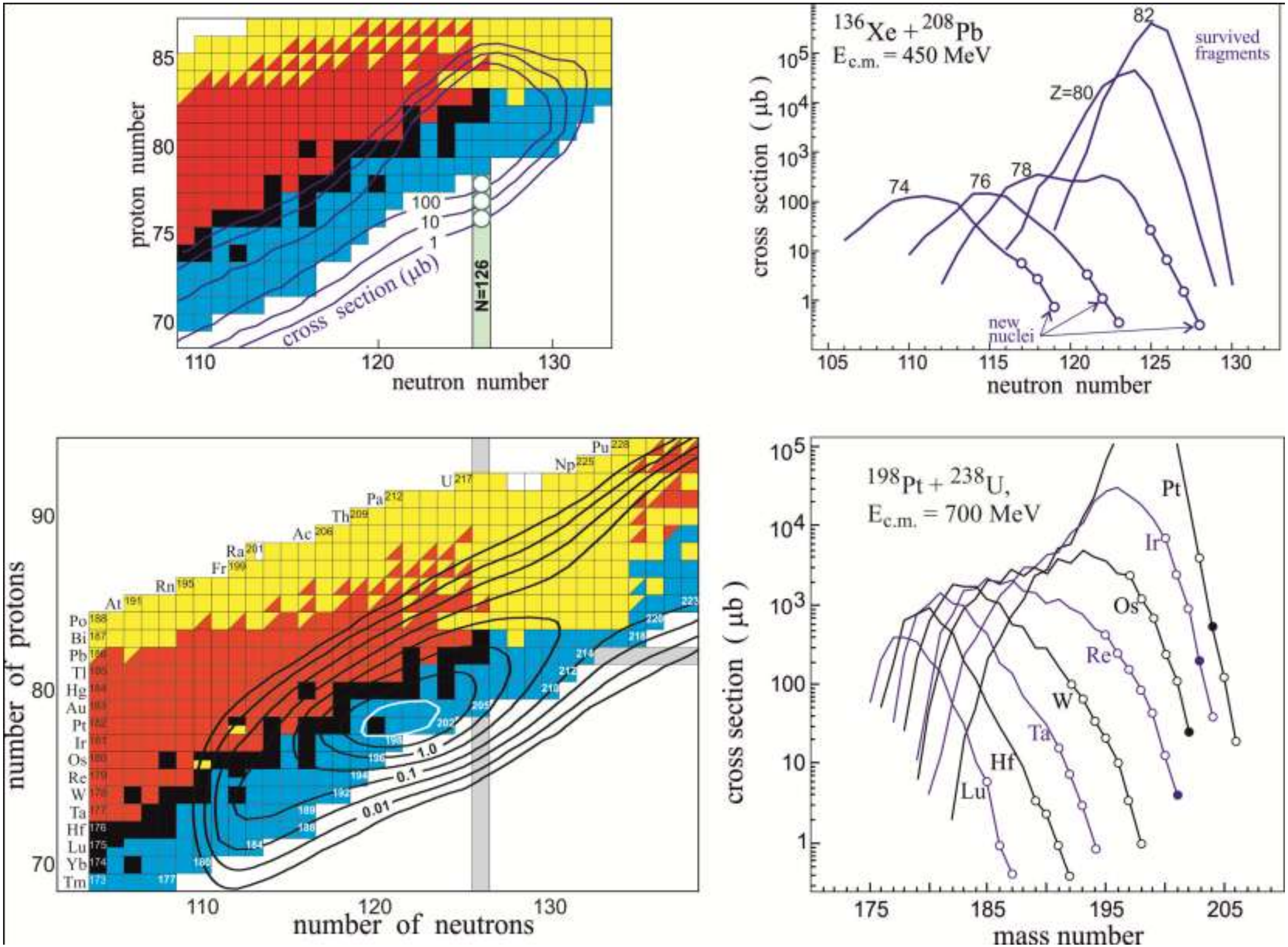
$^{136}Xe_{N=82} + {}^{208}Pb_{N=126} \rightarrow {}^{136+\Delta Z}X_{N=82} + {}^{208-\Delta Z}Y_{N=126} + Q \approx 0$

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

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

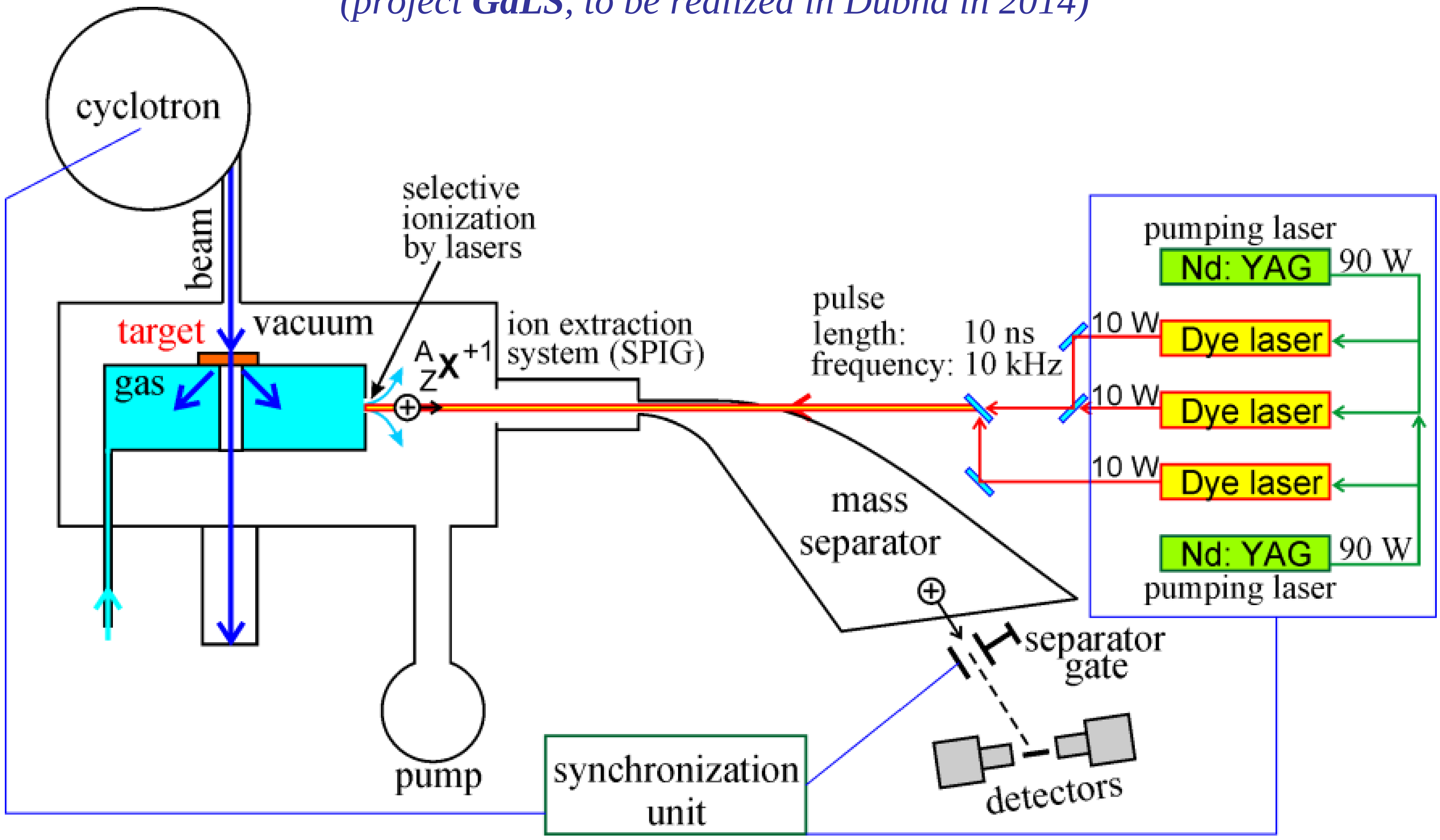
Isotope production with radioactive beams, Dasso, Pollarolo, Winther, PRL 1994

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

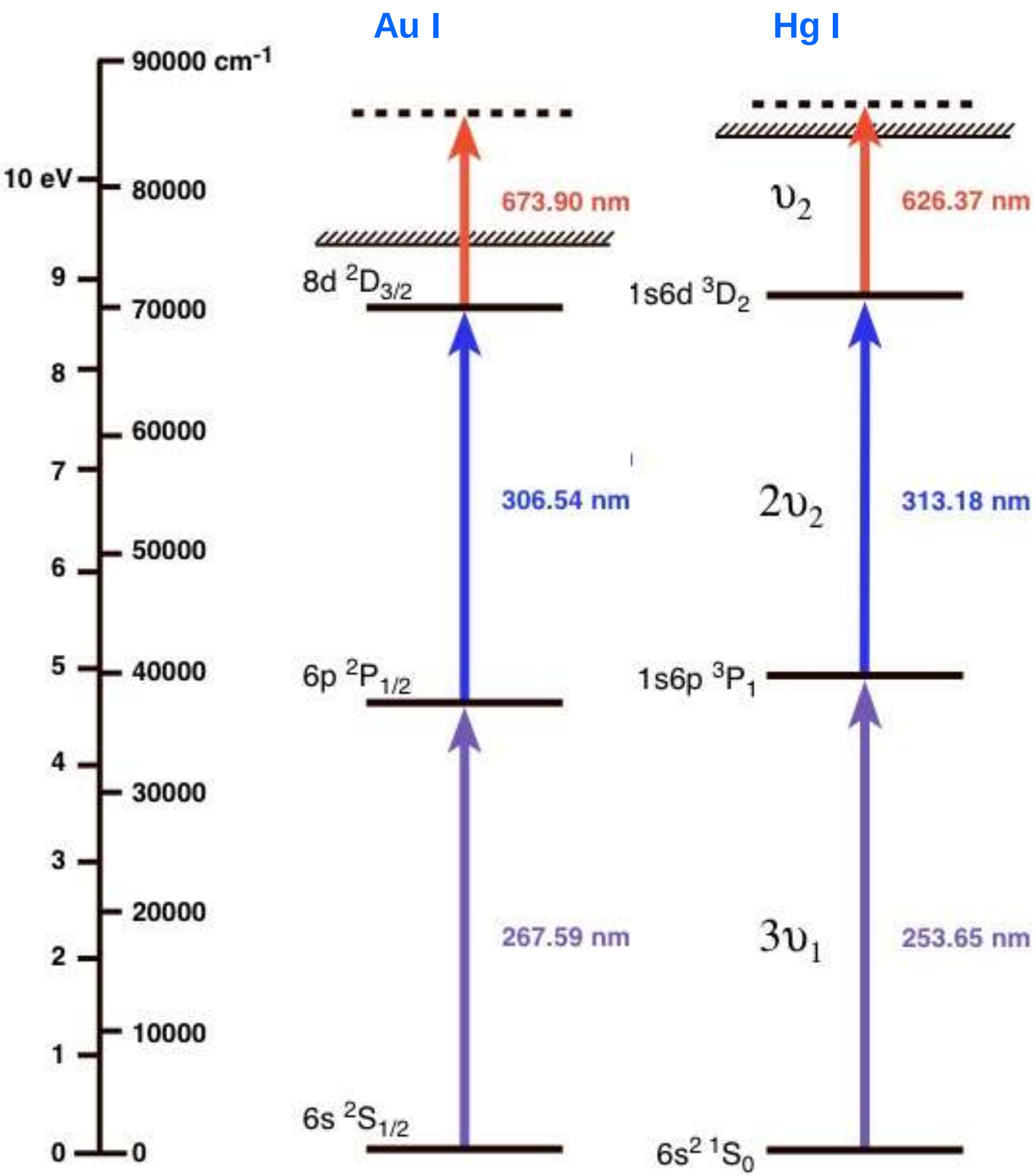


New setup for selective laser ionization of multi-nucleon transfer reaction products stopped in gas

*(project **GaLS**, to be realized in Dubna in 2014)*



Selective laser ionization of Au & Hg atoms



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

Summary

- **North-east part of the nuclear map is still "terra incognita".**
  Heavy neutron rich nuclei are not synthesized and studied yet.

- **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 separator!**

- **Multi-nucleon transfer reactions can be used also 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 HI damped collisions should be studied much better. There are several quite promising experiments to be perform just now.**

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