Synthesis of neutron enriched superheavy nuclei

- **Neutron rich heavy nuclei are not synthesized yet !**
- **How to synthesize neutron rich heavy nuclei ?**
  - **Fusion reactions ? No.**
  - **Neutron capture ? Maybe.**
  - **Transfer reactions ? Quite possible.**
- **How to separate neutron rich heavy nucleus if it would be produced ?**

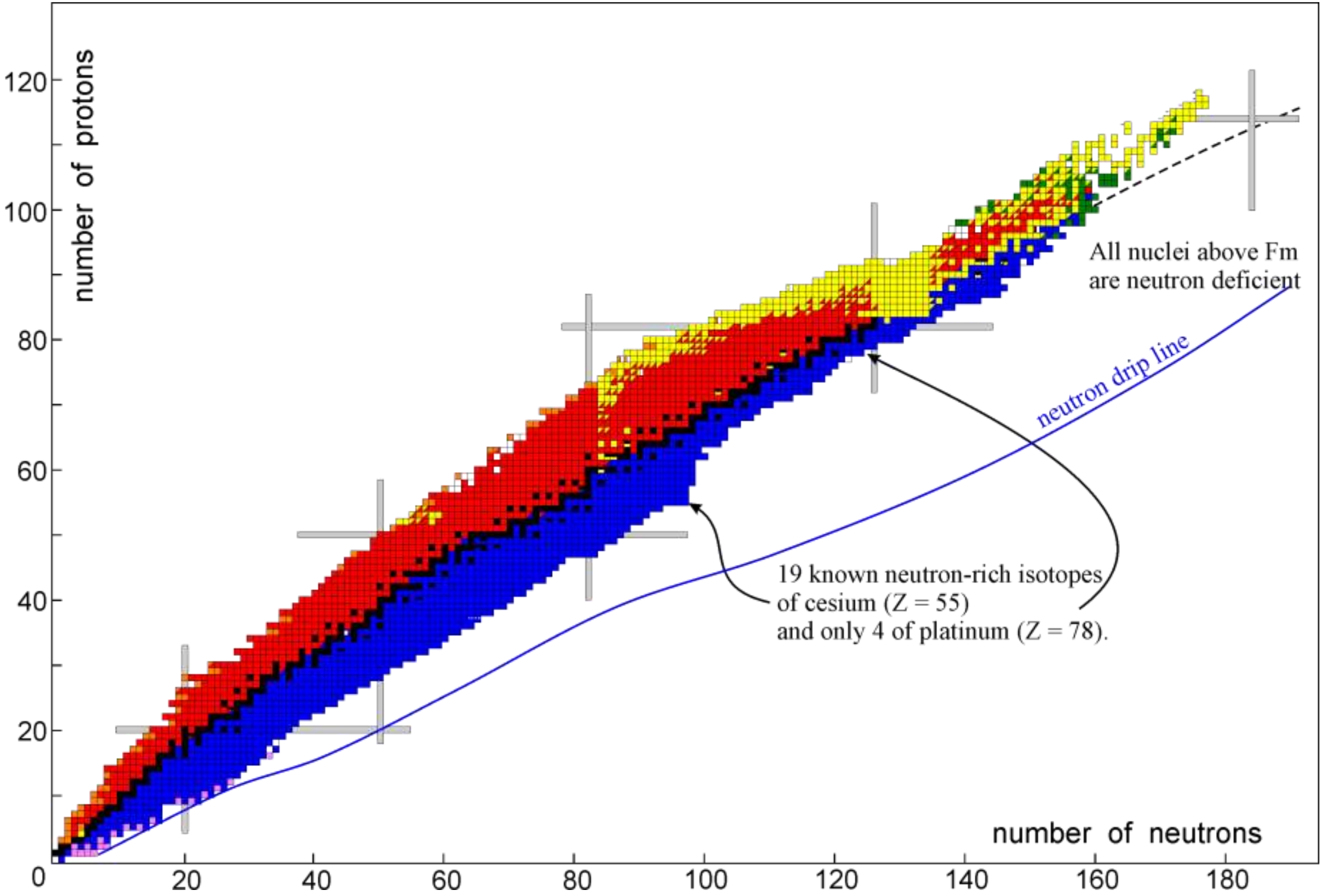
Valeriy Zagrebaev and Walter Greiner

JINR *(Dubna)*

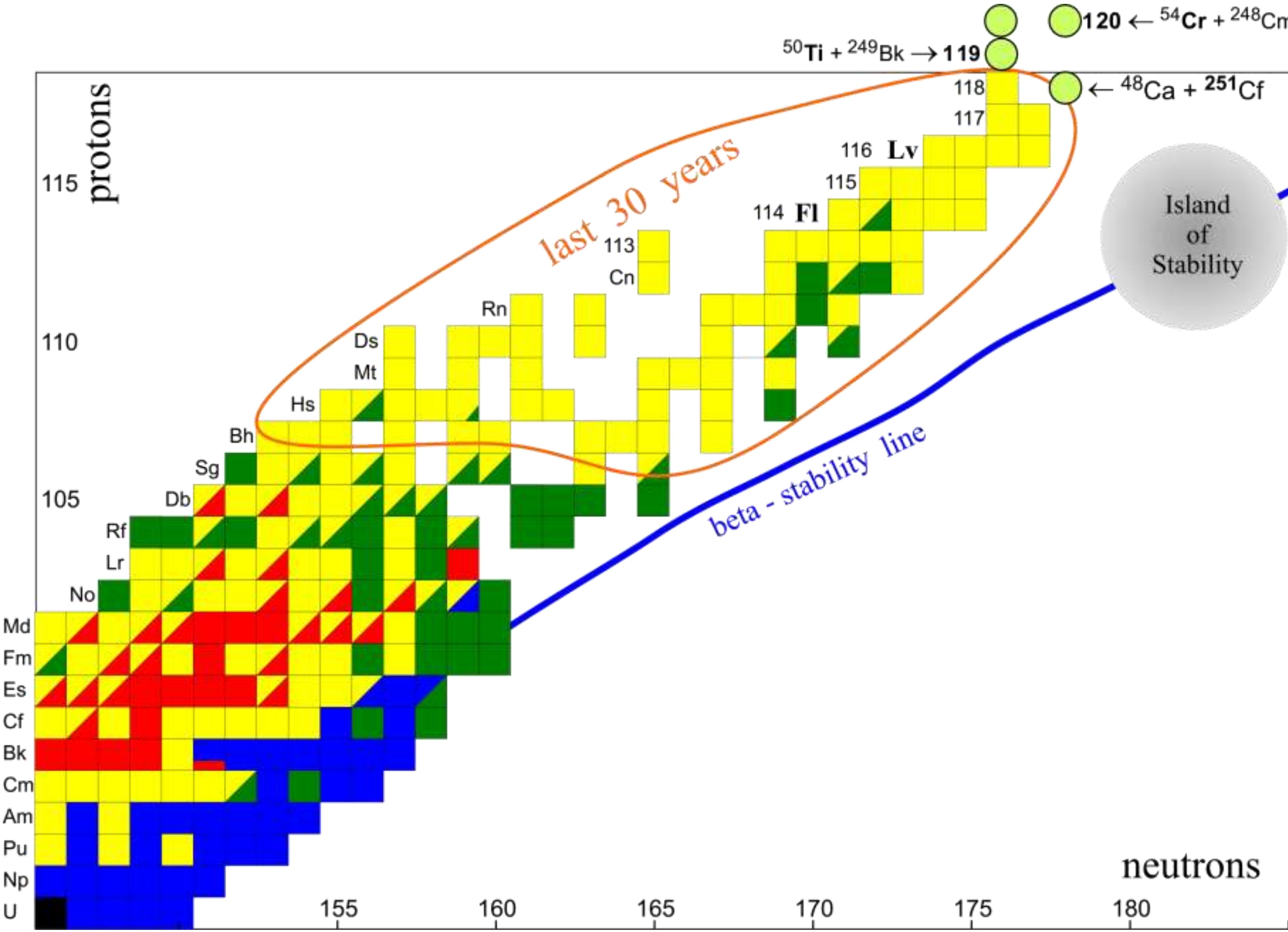
FIAS *(Frankfurt)*

for ICNF5, *November 7, 2012*, Sanibel Island, Florida

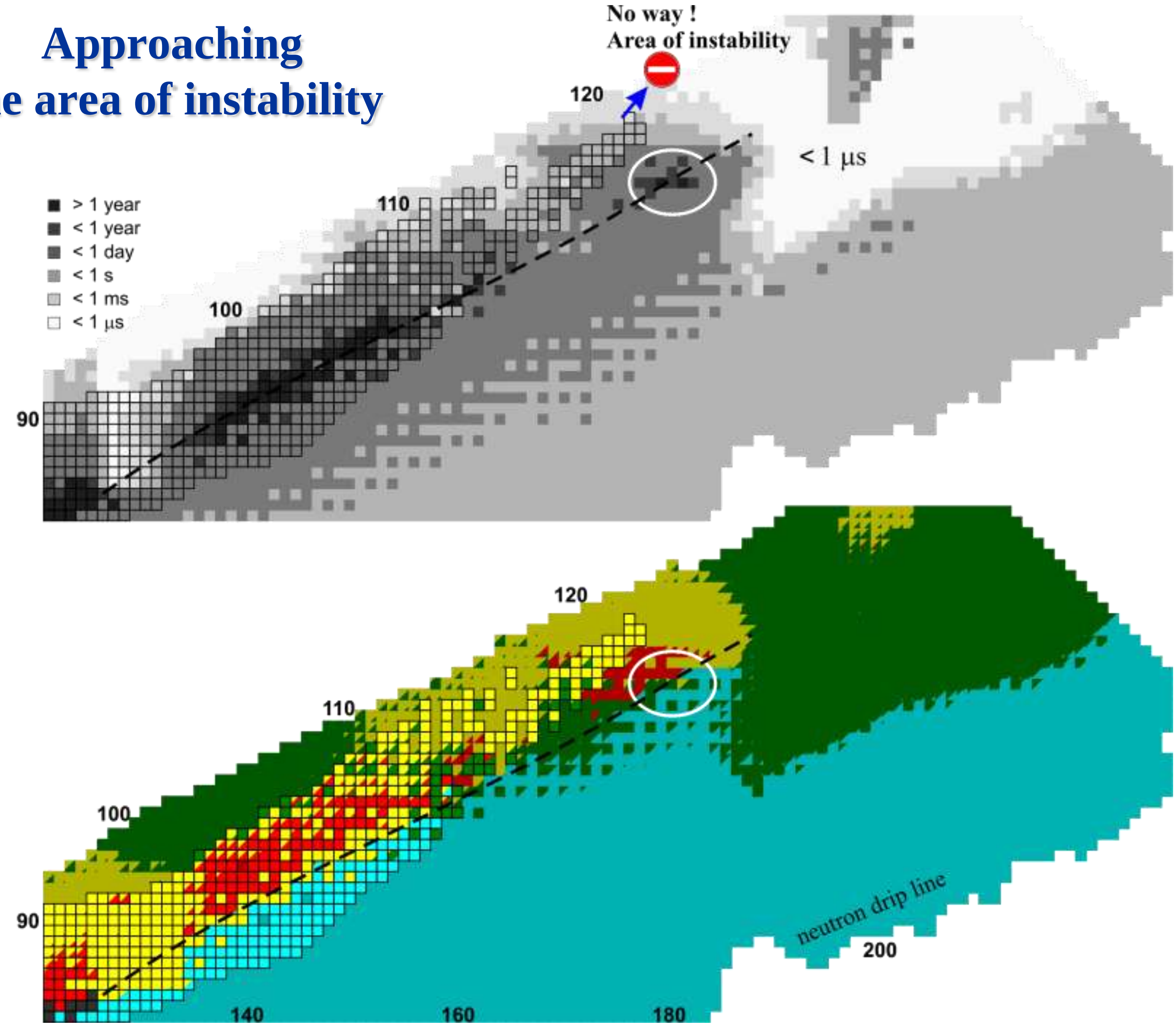
There are no neutron rich heavy and superheavy nuclei



We are still far from the Island of Stability



Approaching the area of instability



How can we synthesize neutron rich heavy nuclei ?

1. Fusion reactions: beams of stable nuclei,
   radioactive ion beams

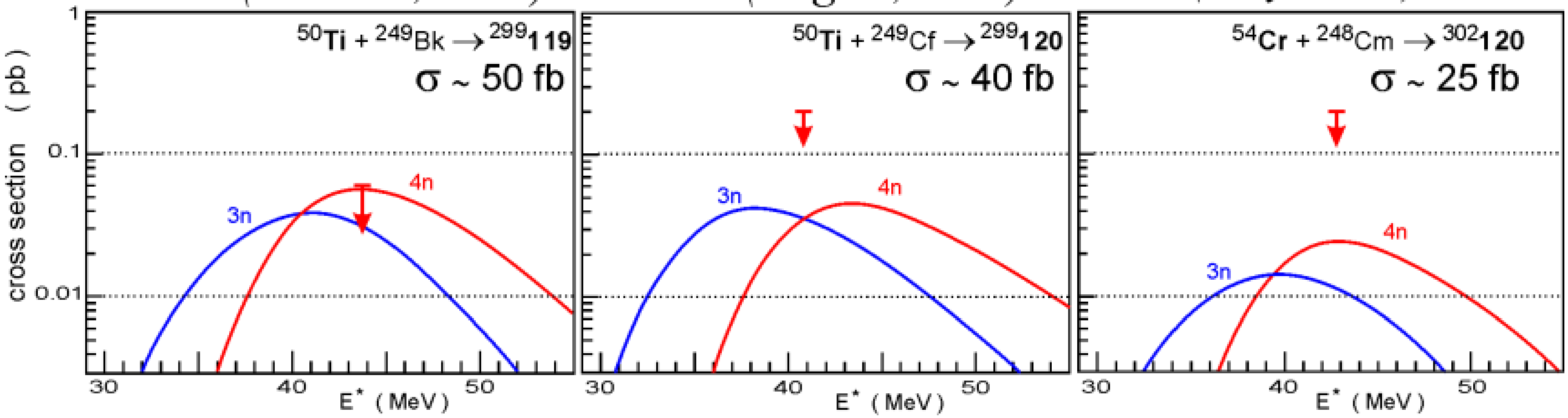
2. Neutron capture processes

3. Multi-nucleon transfer reactions

New elements 119 and 120 are coming !

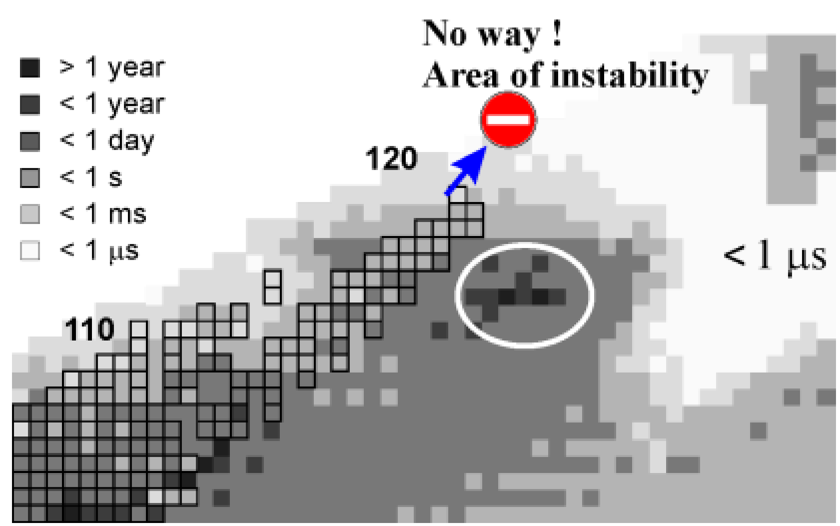
Ti beam: *TASCA (October, 2012)* *TASCA (August, 2011)*

Cr beam: *SHIP (May, 2011)*



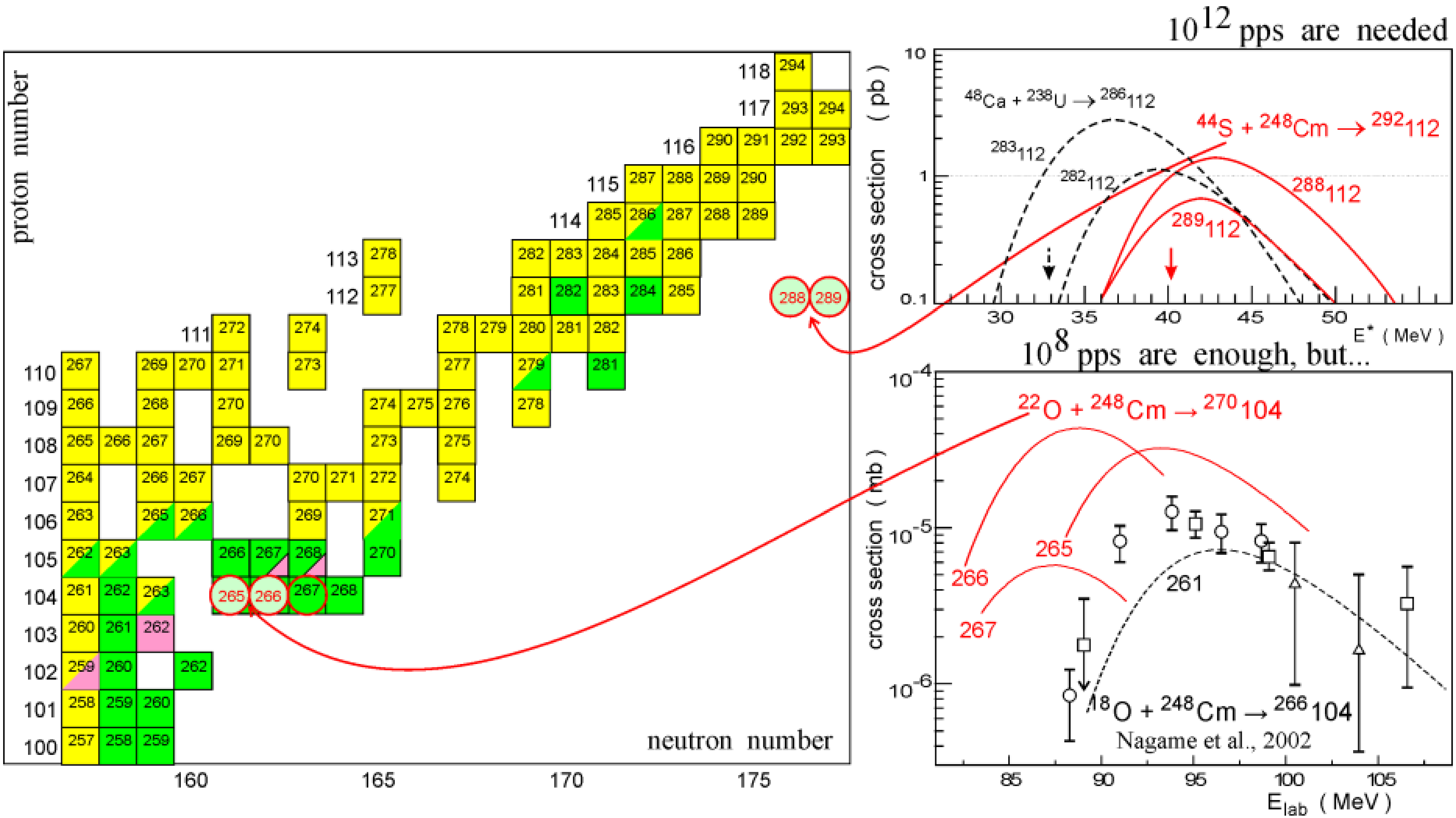
predictions: Zagrebaev & Greiner, PRC 2008

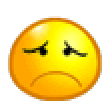
factor $\frac{1}{20}$ as compared to ^{48}Ca



Probably, these elements are the last ones which will be synthesized in the nearest future

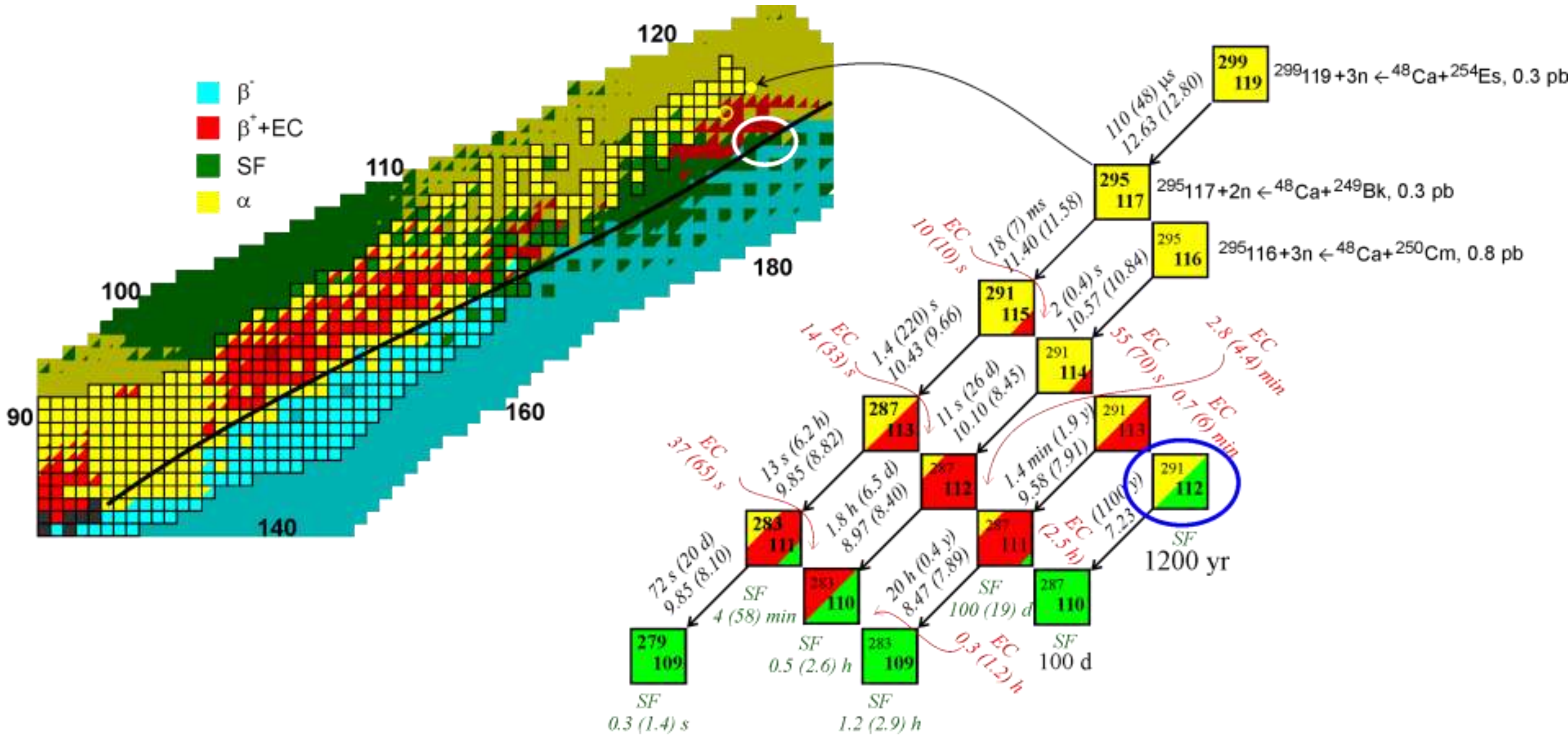
Use of low-energy Radioactive Ion Beams for the production of neutron rich superheavy nuclei ?





No chances today and in the nearest future

Narrow pathway to the Island of Stability is found at last !



Nucleosynthesis by neutron capture

n_0 is the neutron flux

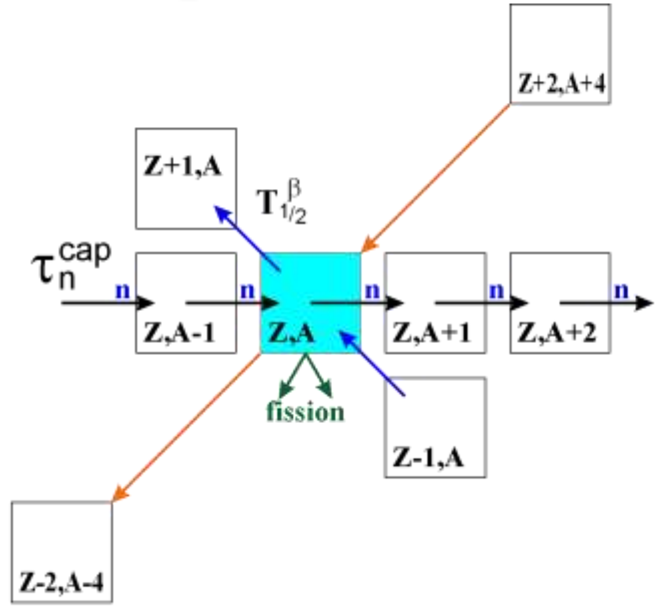
time of neutron capture

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

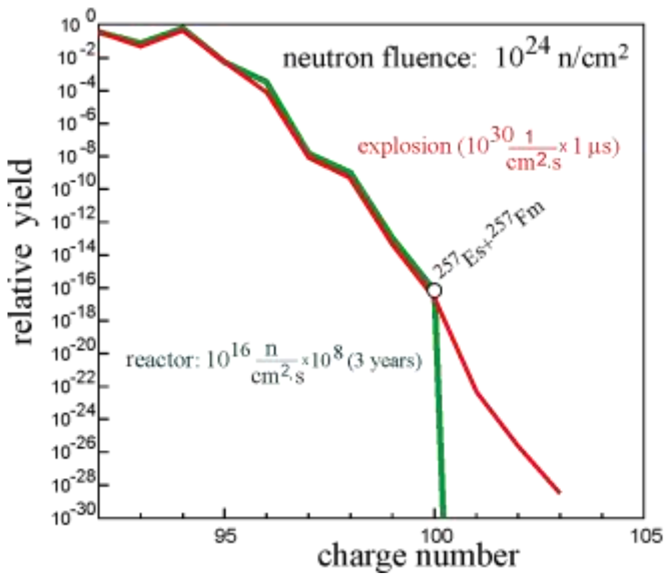
$(Z,A) \rightarrow (Z,A+1)$ if $T_{1/2} > \tau_n^{cap}$

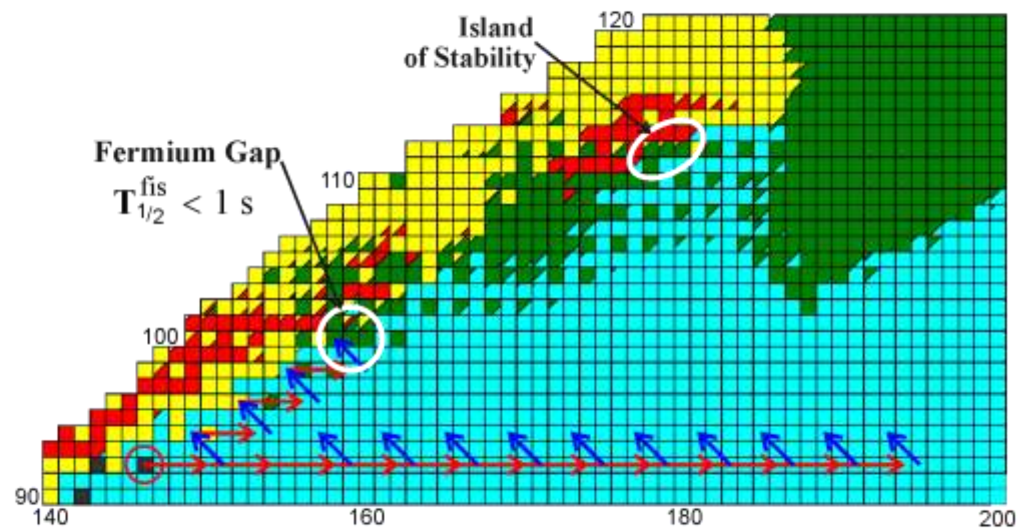
nuclear reactor: $\tau_n^{cap} \sim 1$ year

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

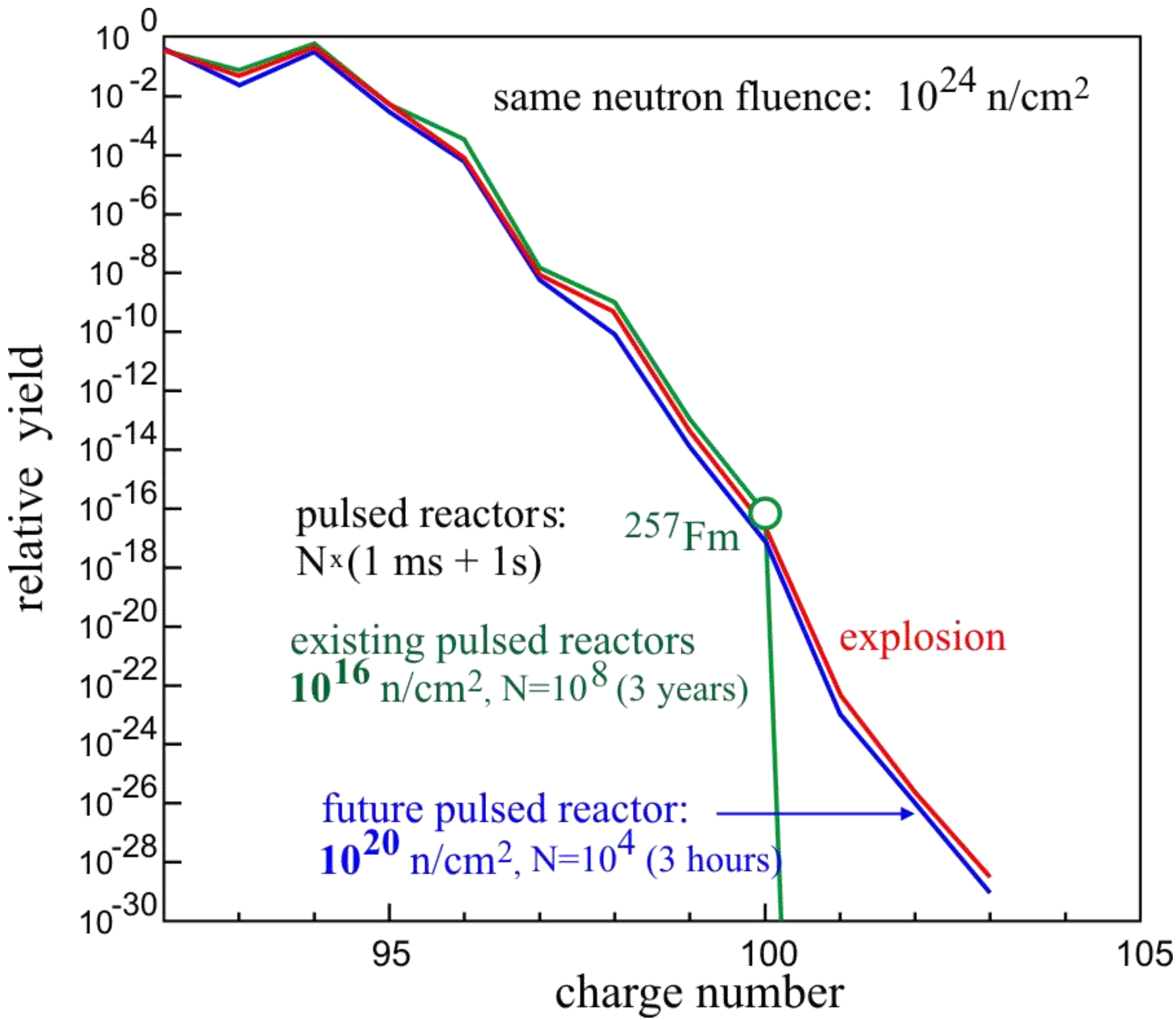


$$\frac{dN_{ZA}}{dt} = N_{ZA-1}\, n_0\, \sigma_{ZA-1}^{n\gamma} - N_{ZA}\, n_0\, \sigma_{ZA}^{n\gamma} - N_{ZA} \frac{\ln 2}{T_{ZA}^{\beta}} - N_{ZA} \frac{\ln 2}{T_{ZA}^{\alpha}} - N_{ZA} \frac{\ln 2}{T_{ZA}^{fis}} + N_{Z-1A} \frac{\ln 2}{T_{Z-1A}^{\beta}} + N_{Z+2A+4} \frac{\ln 2}{T_{Z+2A+4}^{\alpha}}$$





Next generation of pulsed reactors: We need factor 1000 only !

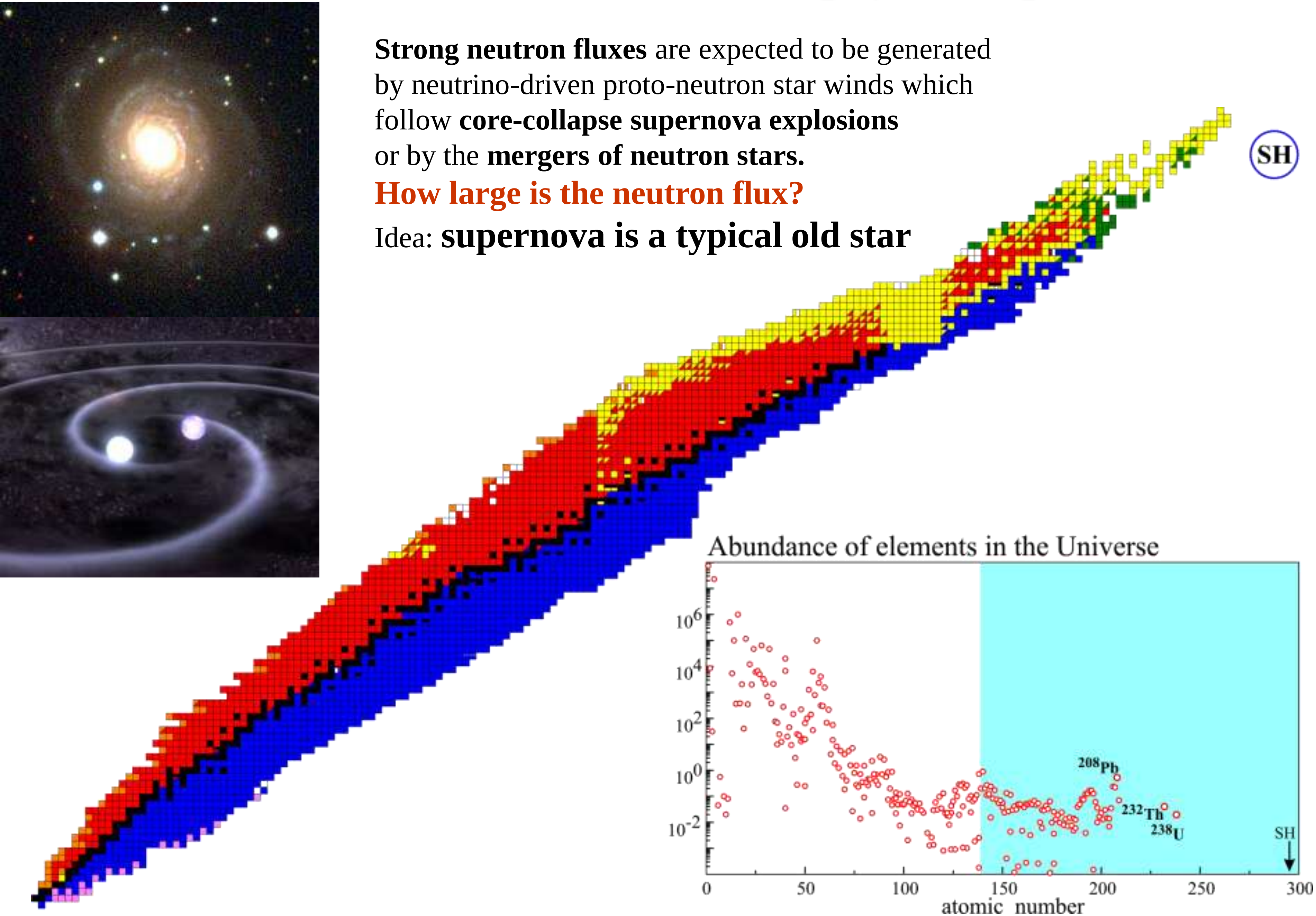


Formation of SH elements in astrophysical r-process

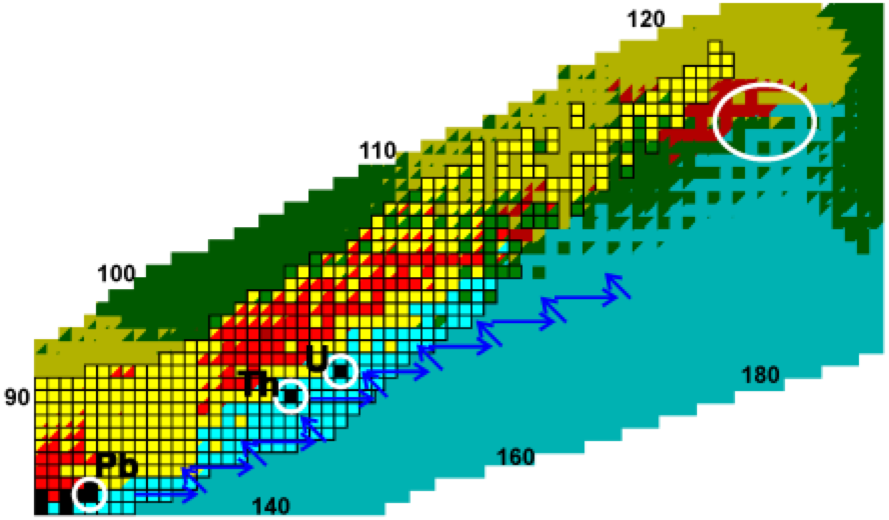
Strong neutron fluxes are expected to be generated by neutrino-driven proto-neutron star winds which follow **core-collapse supernova explosions** or by the **mergers of neutron stars.**

How large is the neutron flux?

Idea: **supernova is a typical old star**

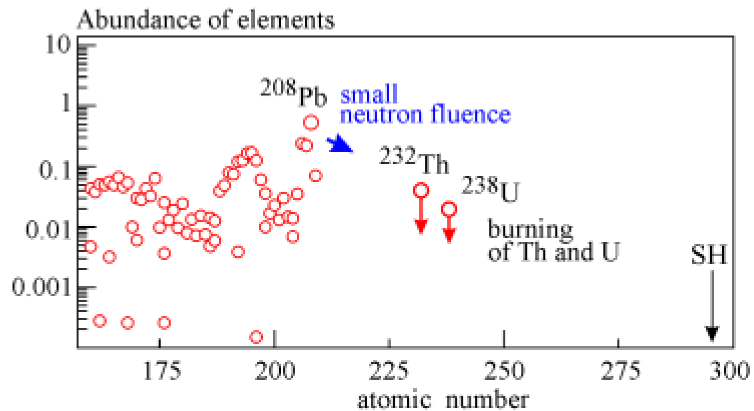


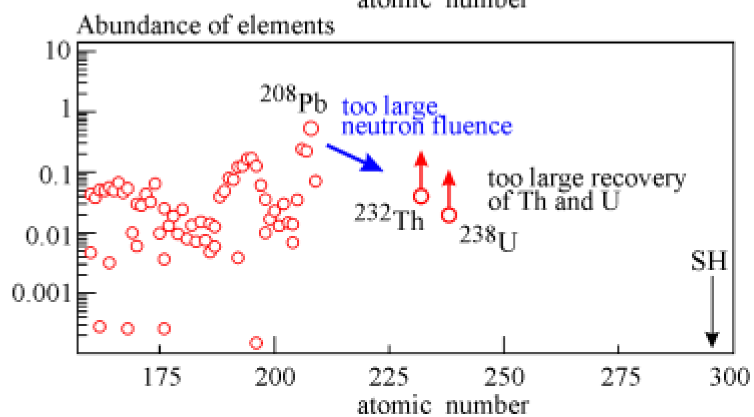
Formation of SH elements in astrophysical r-process

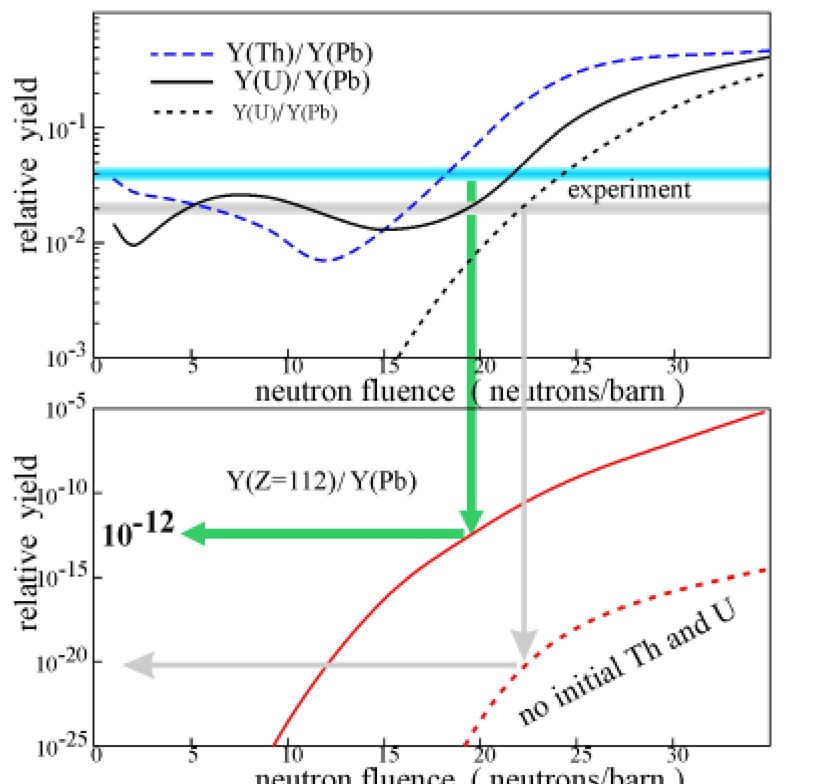


In the course of neutron irradiation initial Th and U material are depleted transforming to heavier elements and going to fission, while more abundant Pb and lighter stable elements enrich Th and U.

Unknown total neutron fluence is adjusted in such a way that the ratios **Th/Pb and U/Pb keep their experimental values.**







Search for SHE in cosmic rays

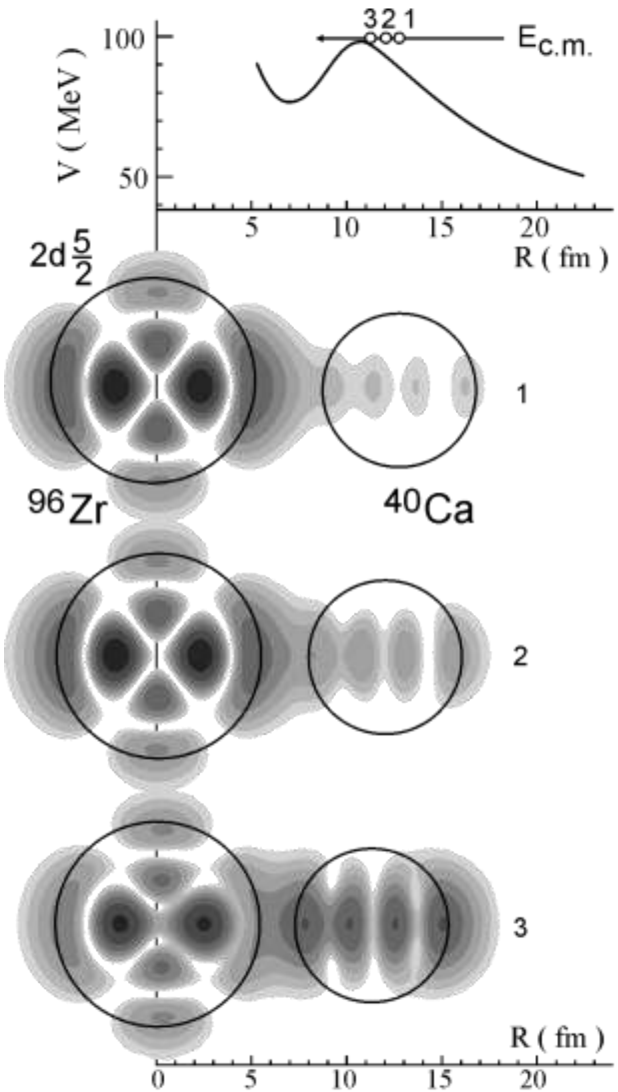
1971, Dubna, P. Fowler: Tracks of SHE!?

Synthesis of 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**).
…

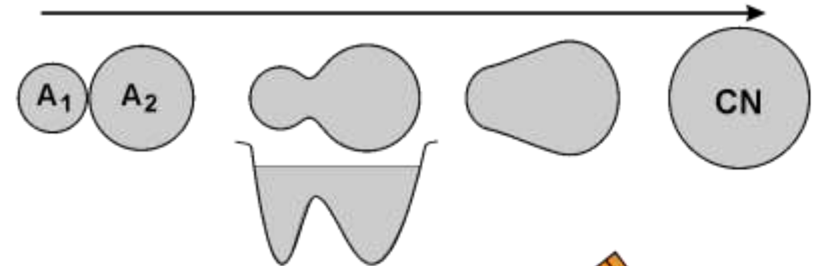
… a long history. Isotopes of Fm and Md were synthesized 30 years ago.

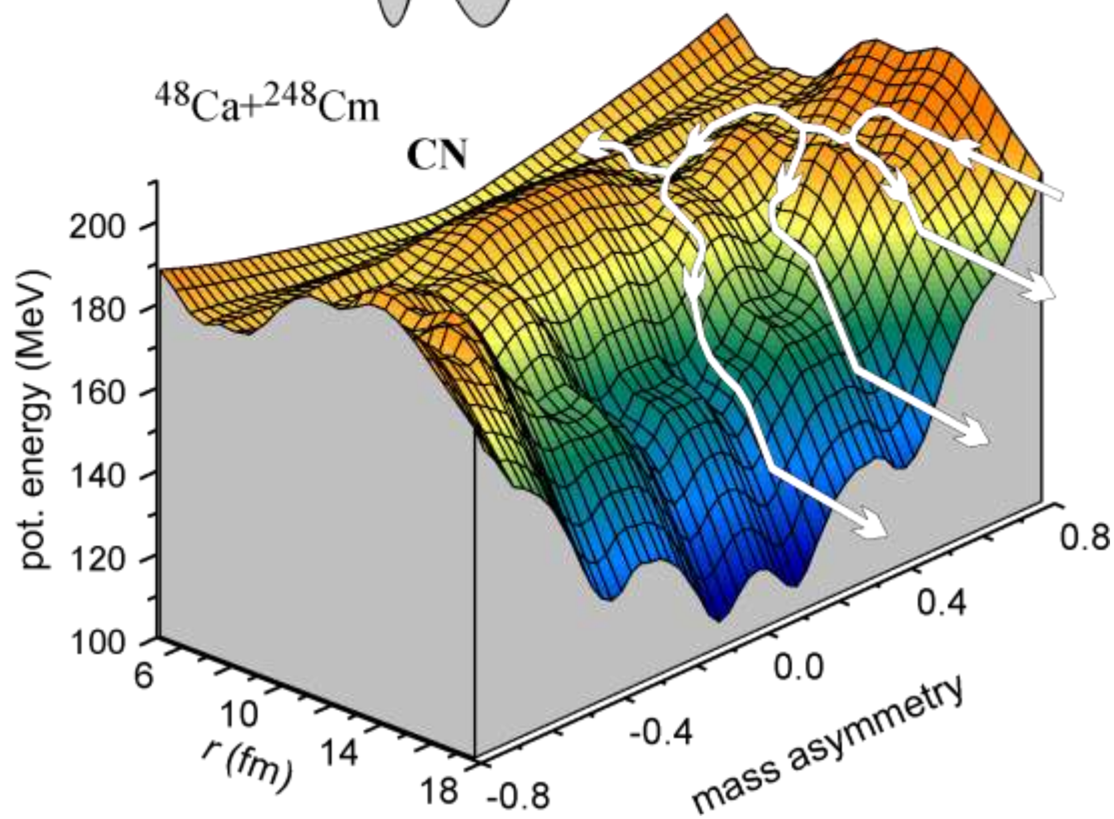
Adiabatic formation of compound nucleus in competition with quasi-fission



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

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

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

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

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

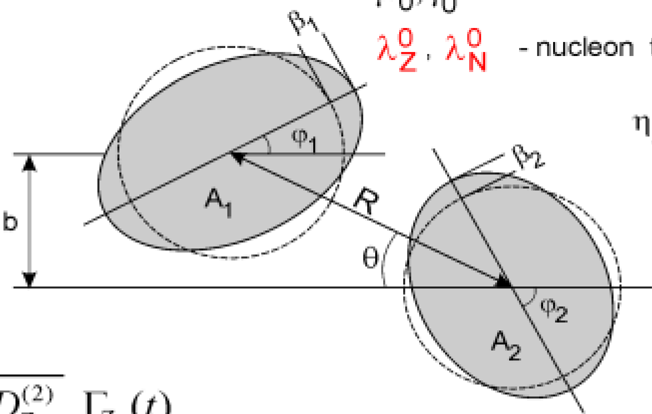
$$\frac{d\eta_Z}{dt}=\frac{2}{Z_{CN}}D_Z^{(1)}+\frac{2}{Z_{CN}}\sqrt{D_Z^{(2)}}\;\Gamma_Z(t)$$

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

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_Z^0, λ_N^0 - nucleon transfer rate



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

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

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

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

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

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

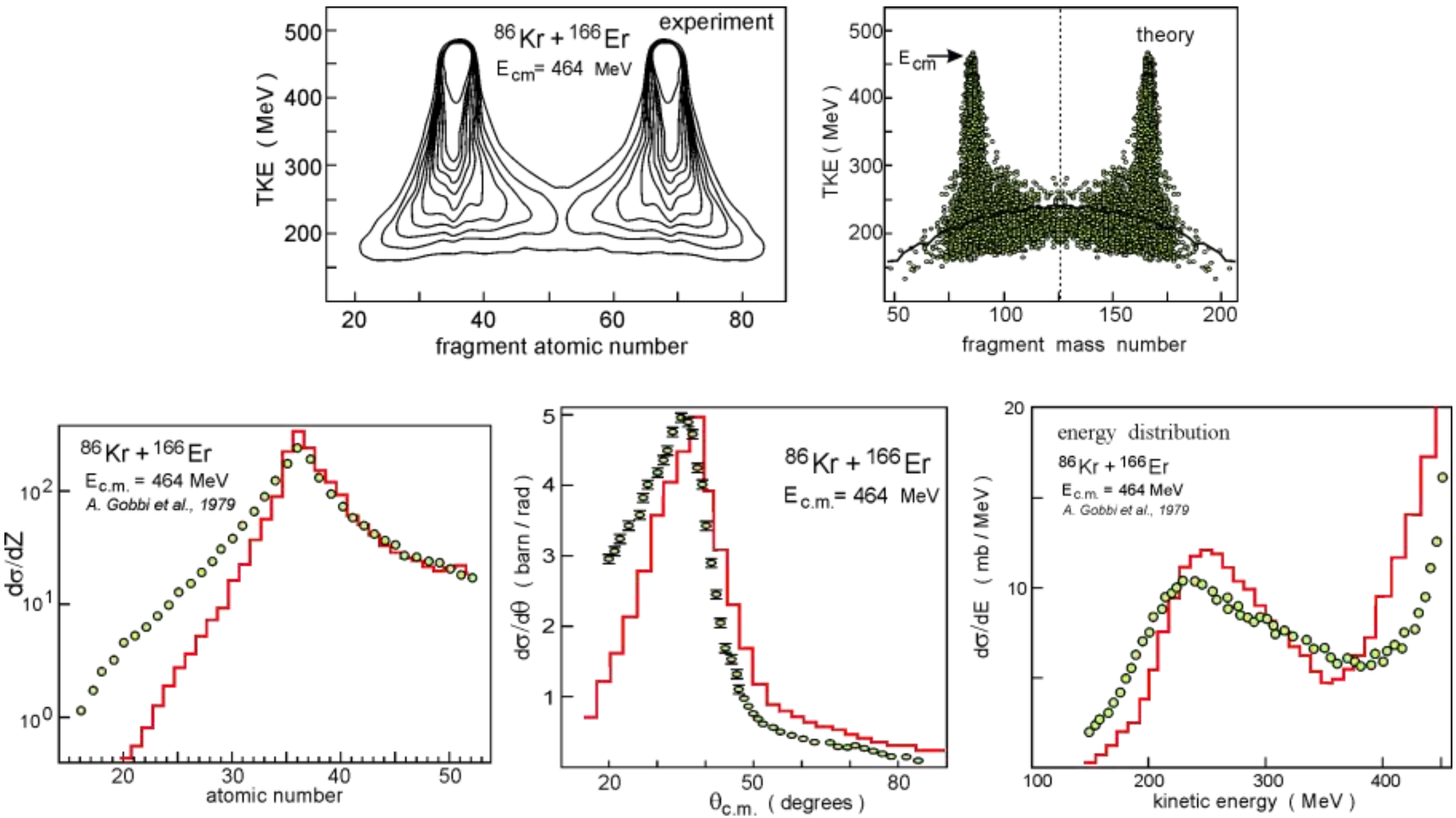
$$\frac{dL_1}{dt}=-\frac{\partial V}{\partial \varphi_1}+\gamma_{\rm tang}\left(\frac{\ell}{\mu_R R}-\frac{L_1}{\Im_1}a_1-\frac{L_2}{\Im_2}a_2\right)a_1-\frac{a_1}{R}\sqrt{\gamma_{\rm tang}T}\,\Gamma_{\rm tang}(t)$$

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

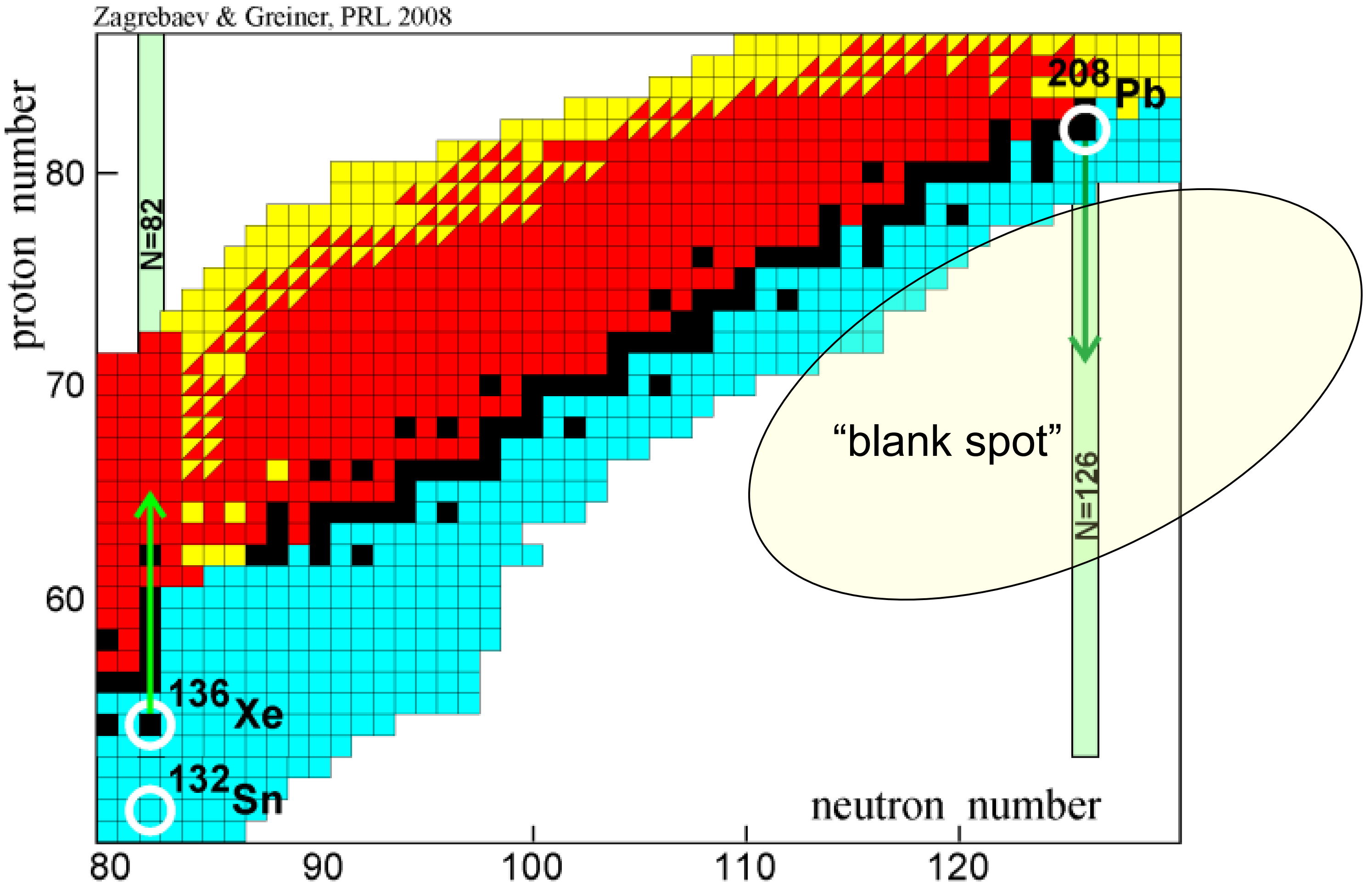
$$\frac{dp_{\beta 1}}{dt}=-\frac{\partial V}{\partial \beta_1}+\frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_1}+\frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_1}+\left(\frac{\ell^2}{2\mu_R^2 R^2}+\frac{p_R^2}{2\mu_R^2}\right)\frac{\partial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

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

Quite satisfactory agreement with experiments on DI scattering



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



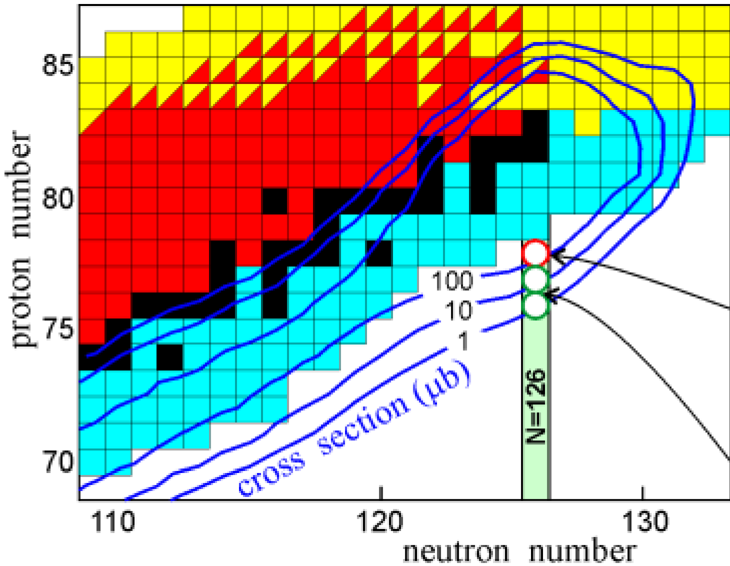
proton transfer along the neutron closed shells:

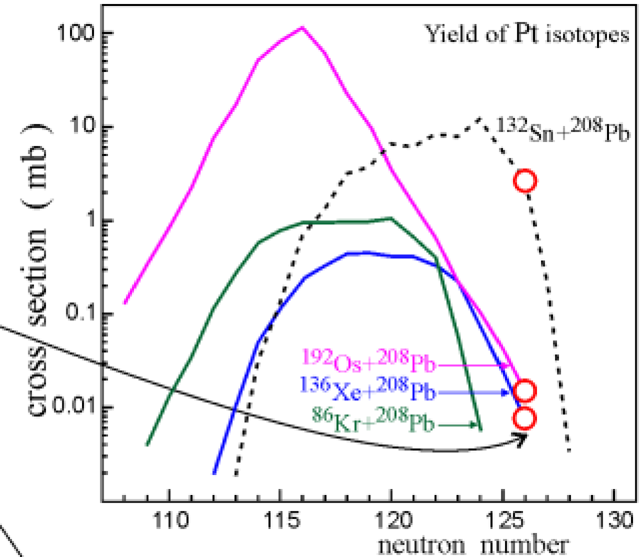
$$^{136}Xe_{N=82} + {}^{208}Pb_{N=126} \rightarrow {}^{136+\Delta Z}X_{N=82} + {}^{208-\Delta Z}Y_{N=126} + Q \approx 0$$

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

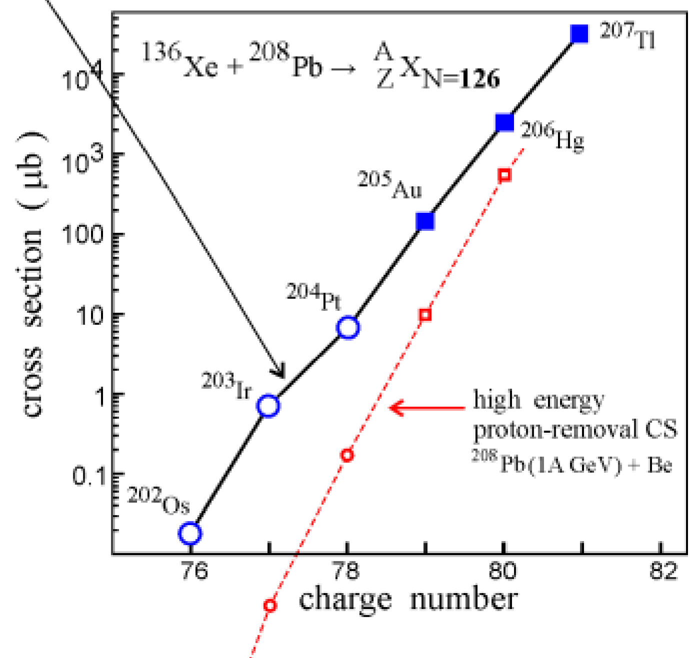
The use of ^{132}Sn is even better !

Production on new heavy nuclei in the Xe + Pb collisions

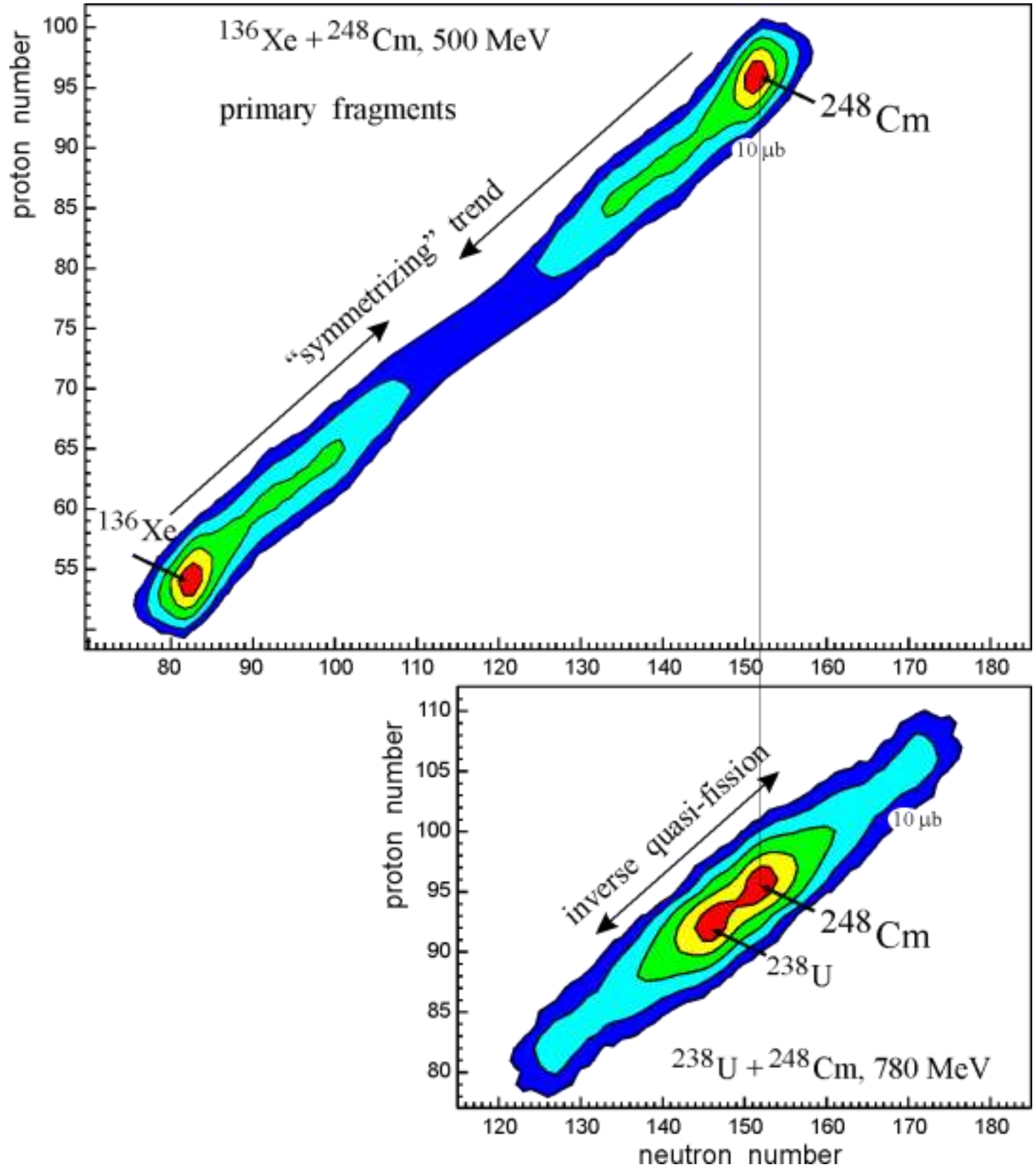




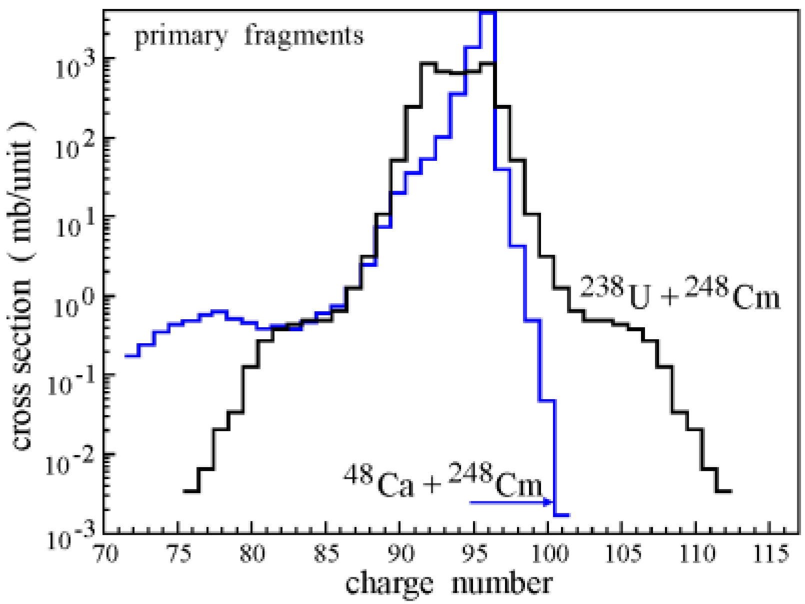
Several tens of new neutron-rich nuclides can be produced with cross section higher than one microbarn in the near-barrier collision of 136Xe with 208Pb

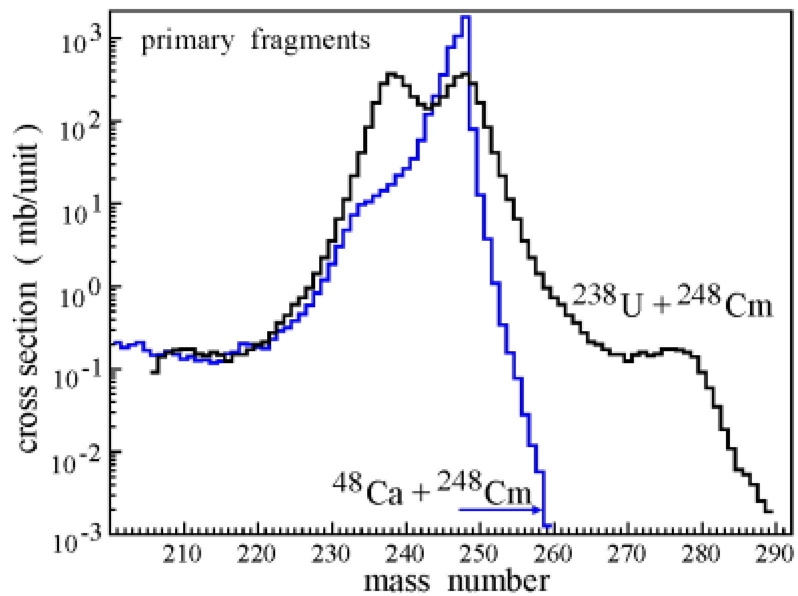


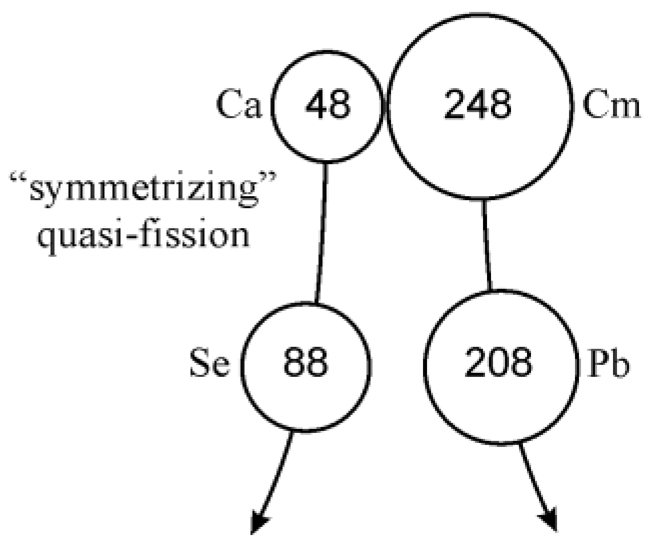
Multi-nucleon transfer for production of superheavies
(choice of reaction is very important)

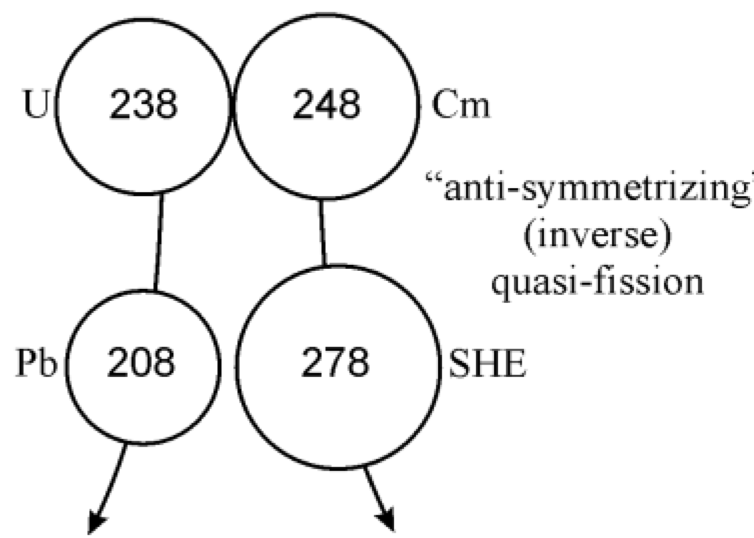


U-like beams give us more chances to produce neutron rich SH nuclei in “inverse quasi-fission” reactions

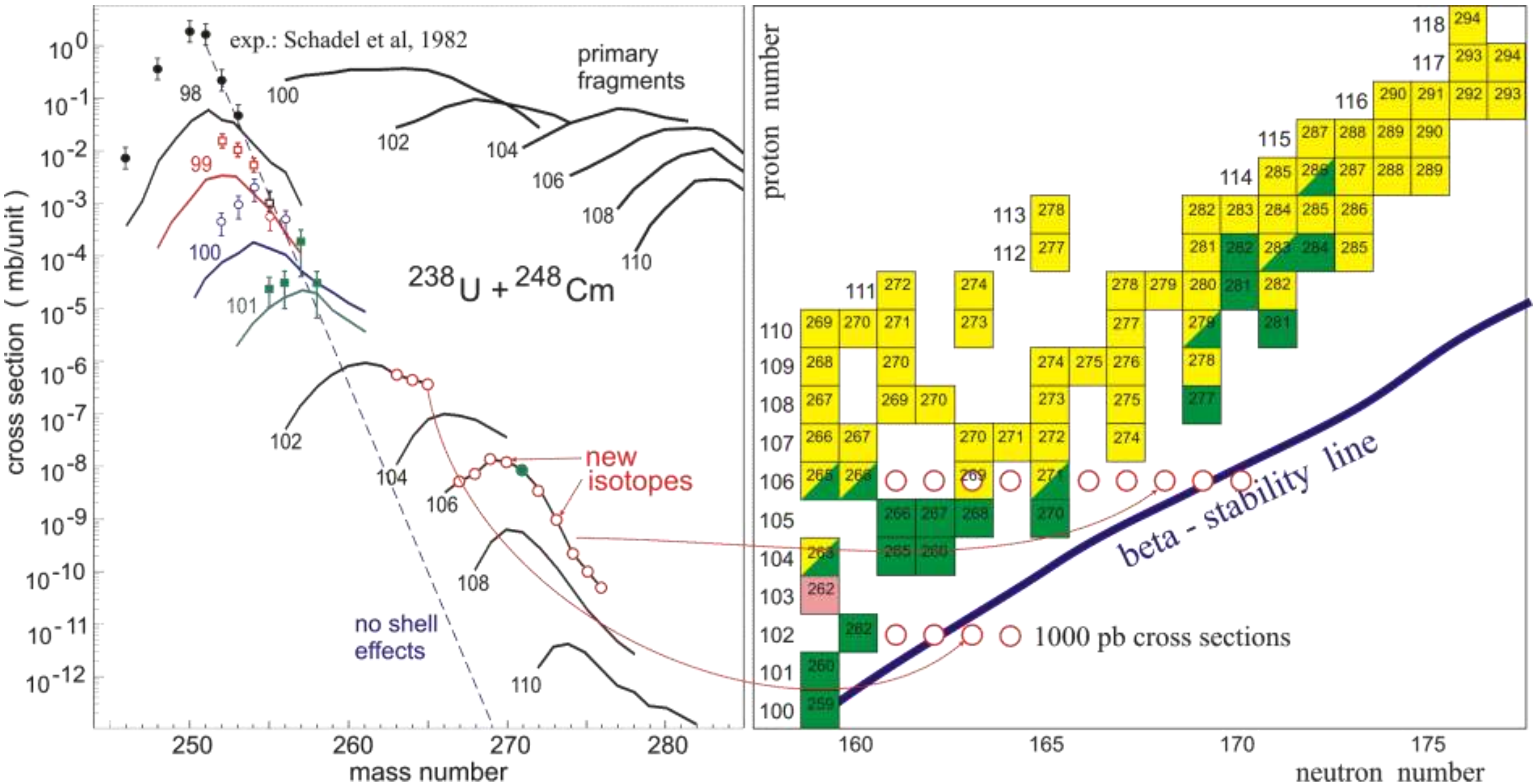






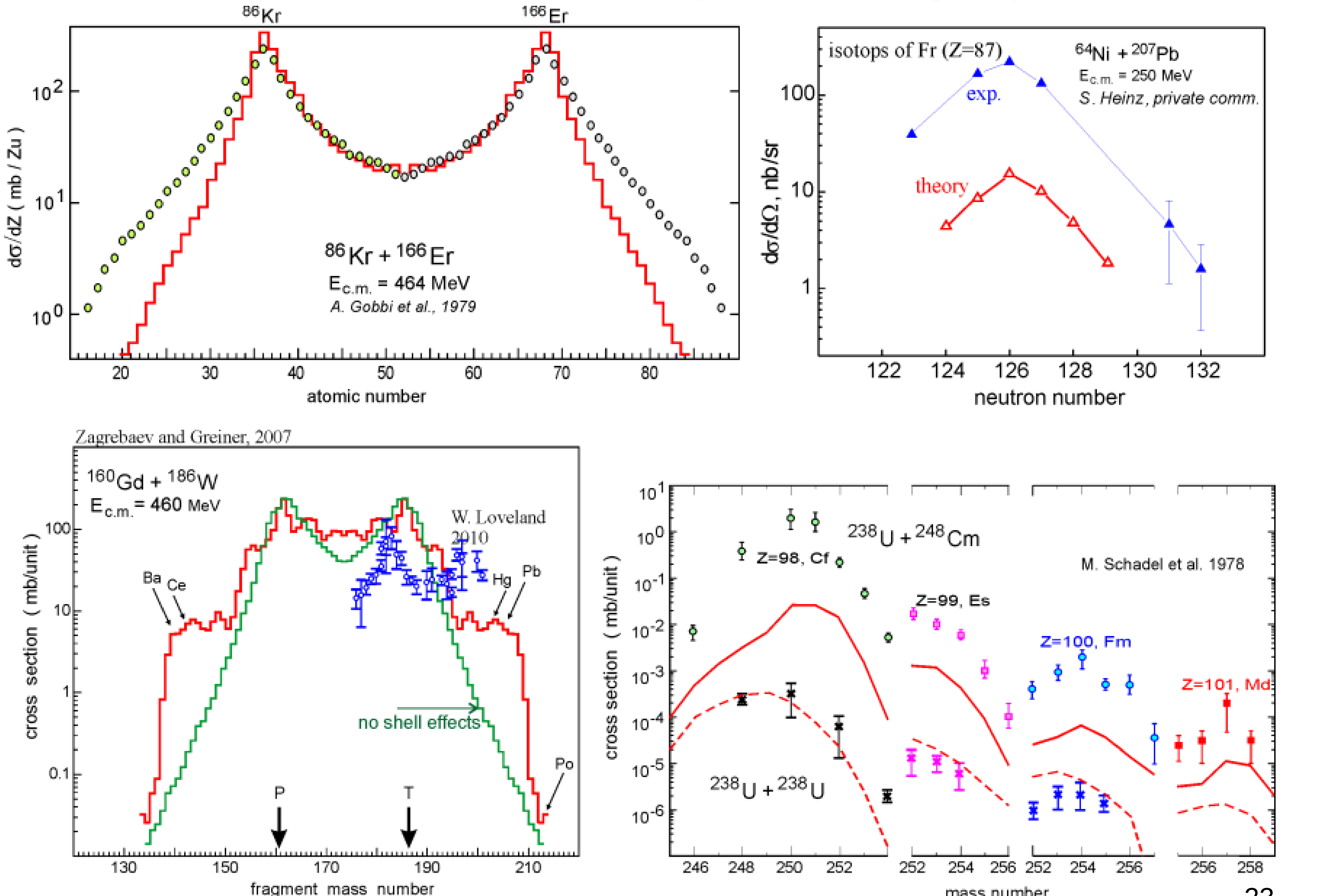


Production of transfermium nuclei along the line of stability looks quite possible



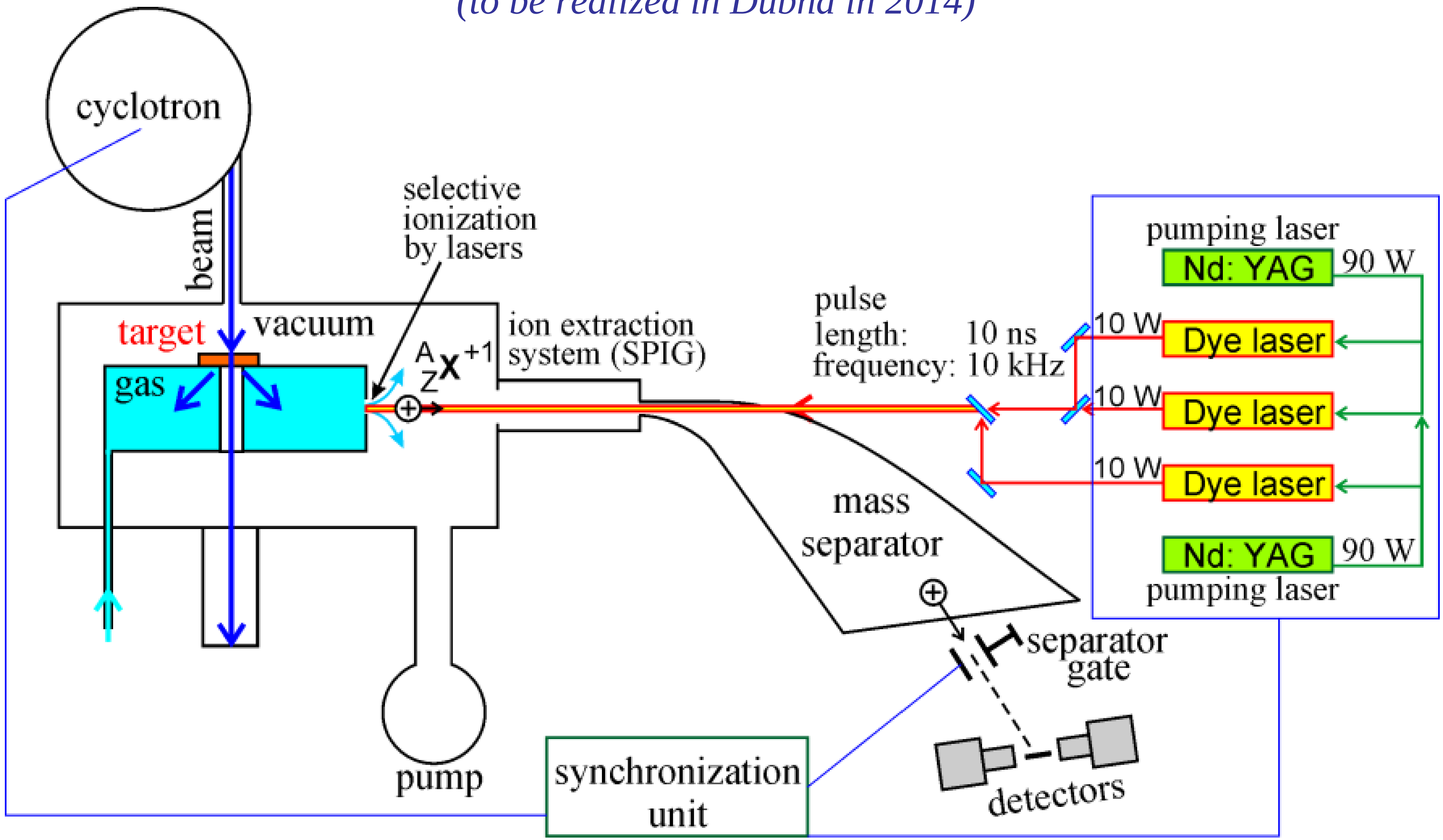
Wide angular distribution of reaction fragments:
separators of a new kind are needed

Underestimation of "anti-symmetrizing" dynamics



Schematic view of setup for resonance laser ionization of nuclear reaction products stopped in gas

(to be realized in Dubna in 2014)



Summary

- **Fusion reactions lead to formation of neutron deficient nuclei.**
  Beams of radioactive medium mass nuclei (like ^{44}S) may help us to produce isotopes of SH elements located close to the stability line if their intensity would be 10^{12} pps.
  Fusion of accelerated fission fragments does not give us any hopes.

- **The narrow pathway to the island of stability still exists by means of fusion reactions accompanied by electron capture (e.g., ^{48}Ca+^{250}Cm).**

- **A macroscopic amount of the long-living SH nuclei located at the island of stability may be produced with the use of pulsed nuclear reactors of the next generation (factor 1000 is needed).**

- **Multi-nucleon transfer reactions can be really used for synthesis of neutron enriched long-living SH nuclei located along the beta-stability line. U-like beams are needed as well as new separators!**

- **Production of long-living SH nuclei in the astrophysical r-process looks not so much pessimistic: relative yield of SH / Pb may be about 10^{-12}.**

Valeriy Zagrebaev and Walter Greiner

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for ICNF5, *November 7, 2012*, Sanibel Island, Florida