Future of superheavy element research: Which nuclei could be synthesized within the next few years?

- **State of the art**
- **Outline of the model** **(4 slides only)**
- **Our predictions and proposals:**
  - **Elements 119 and 120 are coming**
  - **Filling the Gap of not-yet-synthesized isotopes of SH elements (Z=106-116)**
  - **Narrow pathway to the Island of Stability**
  - **Production of new neutron rich SH nuclei in transfer reactions**
  - **Synthesis of SH nuclei by neutron capture (SHE in nature)**
- **Summary**

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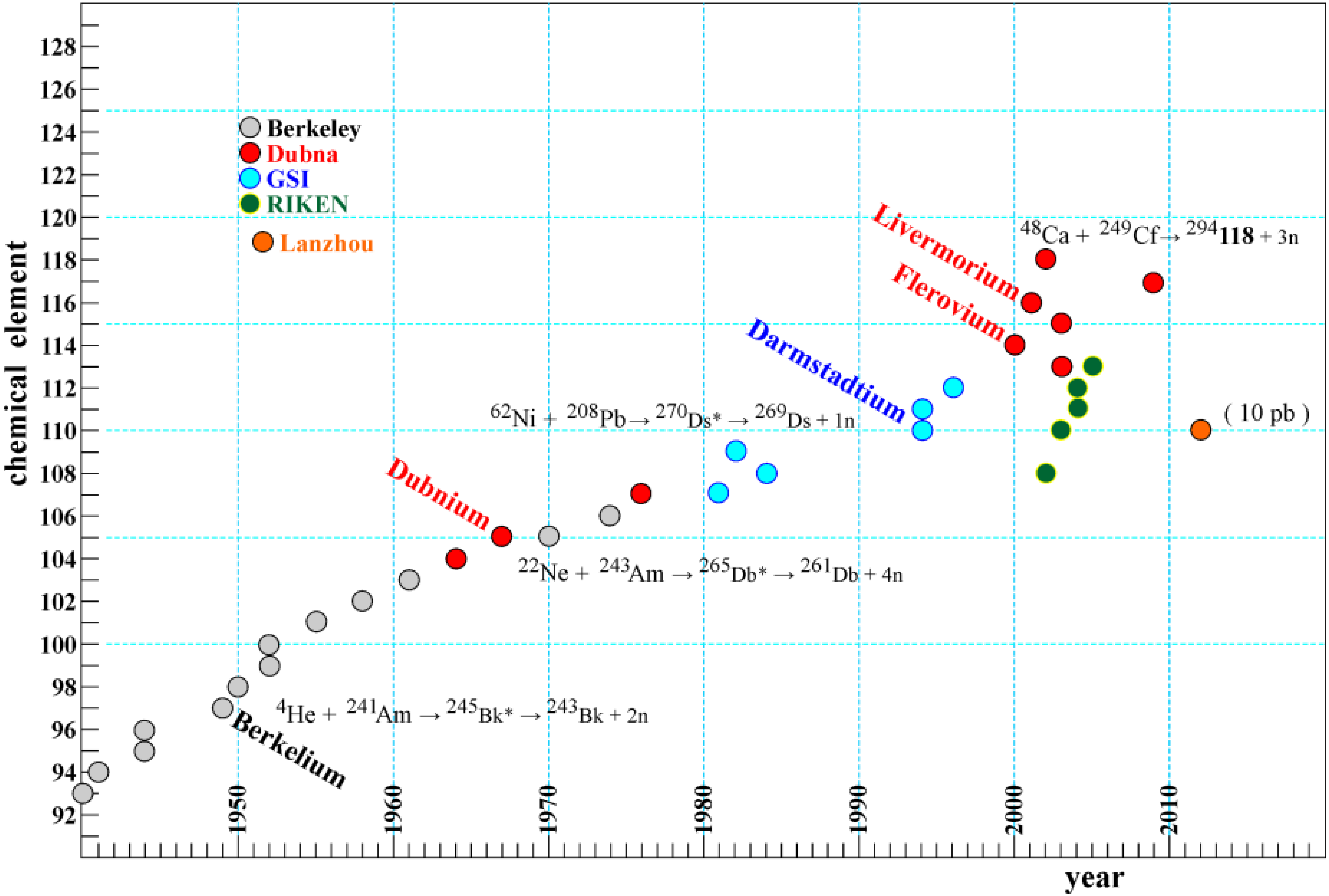
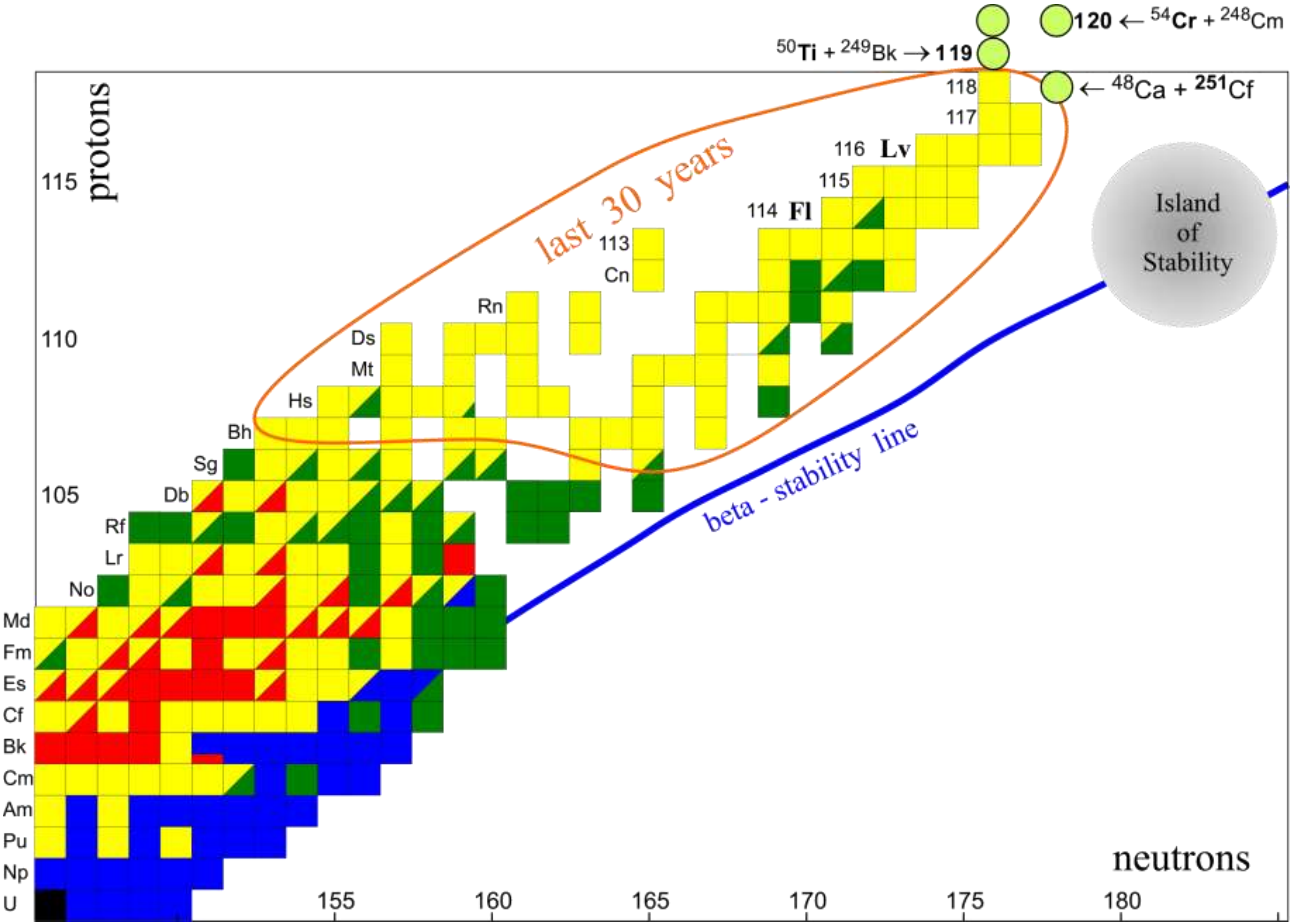
for "NN 2012", *May 28, 2012*, San Antonio, USA

Hand-made elements (history)

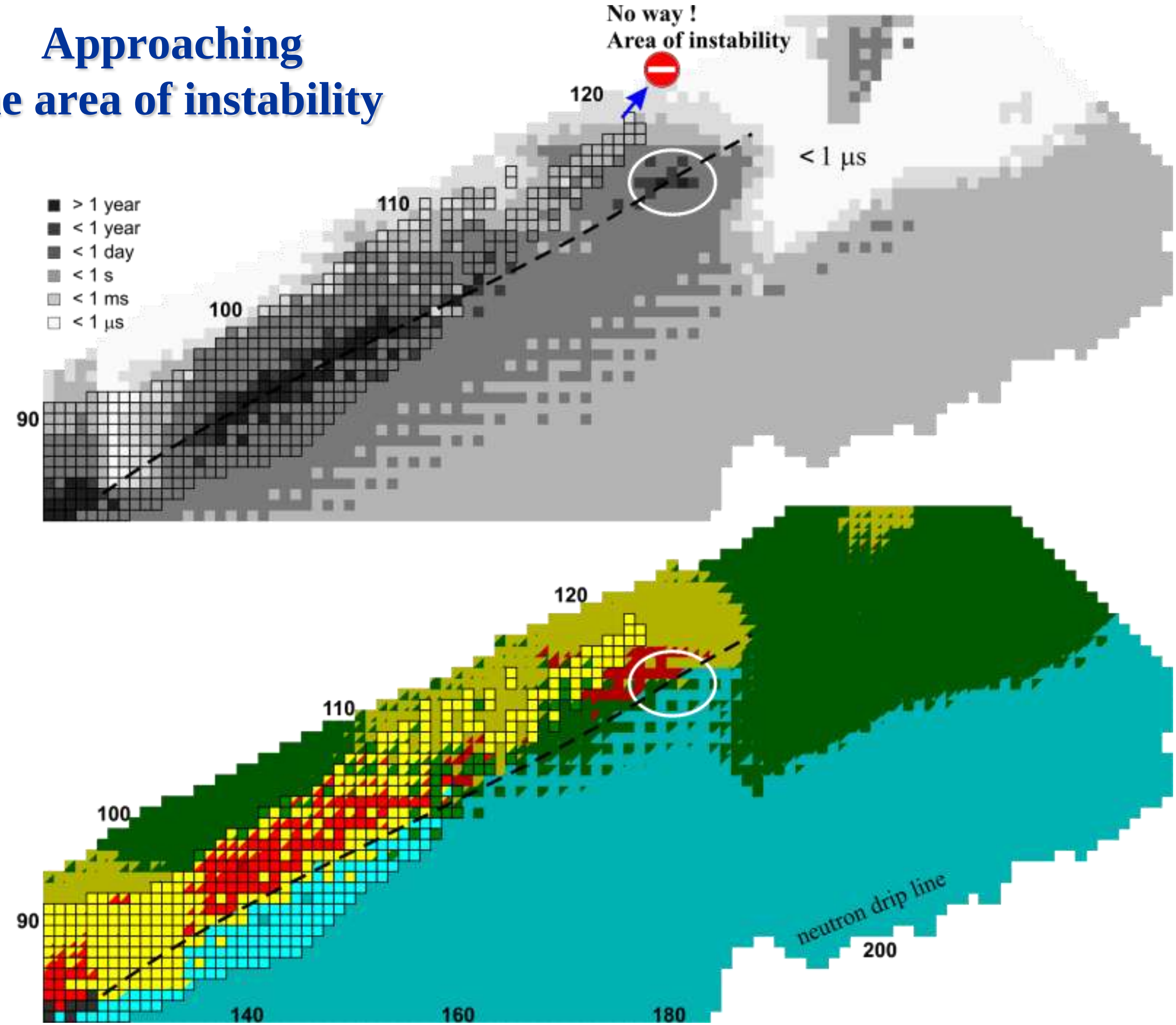


A new player in the field: see the talk of *Xiaohong Zhou* (IMP/Lanzhou), Tuesday, May 29

We are still far from the Island of Stability



Approaching the area of instability



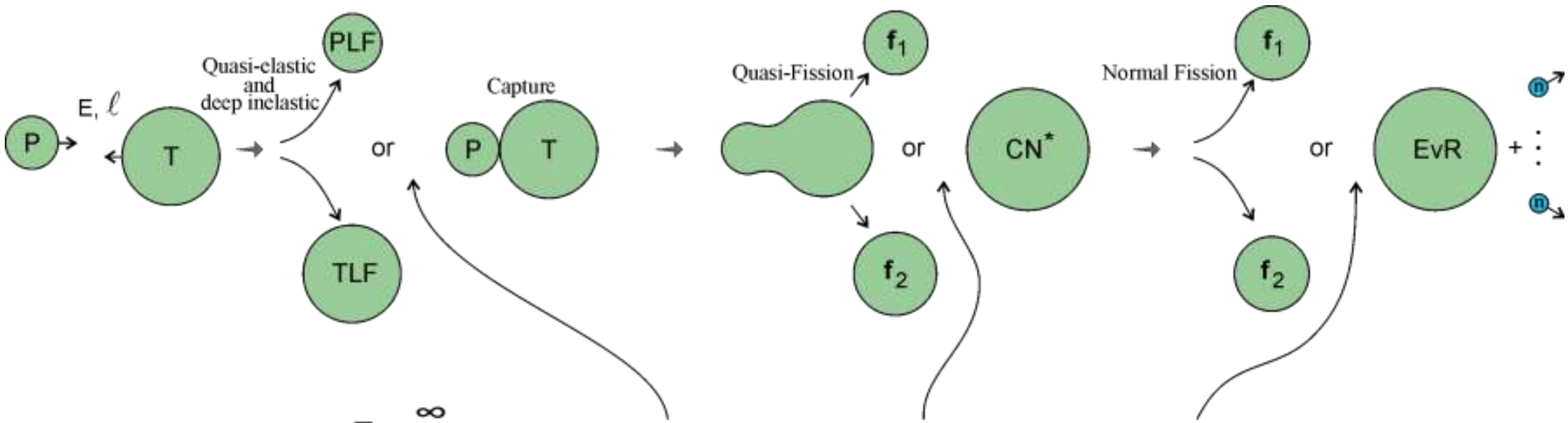
How can we synthesize superheavy nuclei ?

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

2. Multi-nucleon transfer reactions

3. Neutron capture [+ subsequent beta(-) decay] **processes**

Synthesis of SHE in fusion reactions (conventional view)



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

$$\sigma_{capture}(E) \overset{exp}{=} \sum (f_{1,2}^{all} + EvR), \quad \text{if} \quad f_1 f_2 \neq PLF, TLF$$

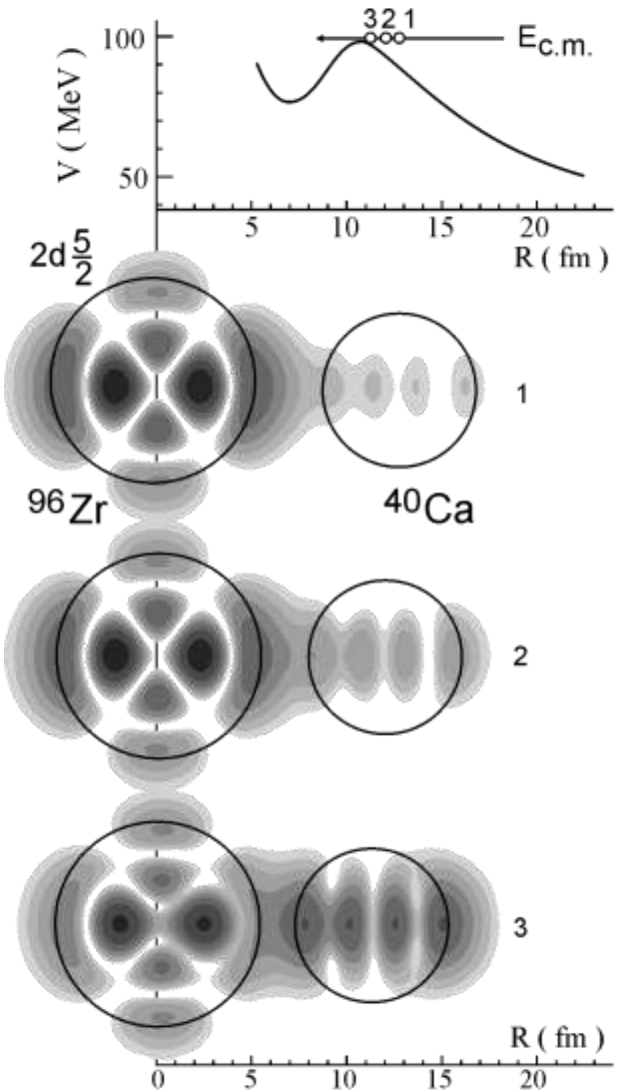
$$\sigma_{CN} \equiv \sigma_{fusion}(E) \overset{exp}{=} \sum (f_{1,2}^{NF} + EvR), \quad \text{if} \quad f_{1,2}^{NF} \neq f_{1,2}^{QF}$$

P_{cont} : Penetration probability of the multi-dimensional Coulomb barrier $V_C^B(r, \beta_1, \beta_2, \varphi_1, \varphi_2)$ - ?

P_{CN} : Probability of CN formation (evolution in the space of shape parameters)

P_{xn} : Survival probability of excited CN (Statistical Model: Γ_n, Γ_f, E_n^{sep}, B_{fis})

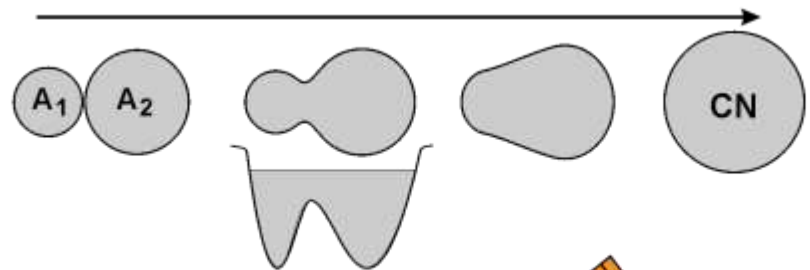
Adiabatic formation of compound nucleus in competition with quasi-fission

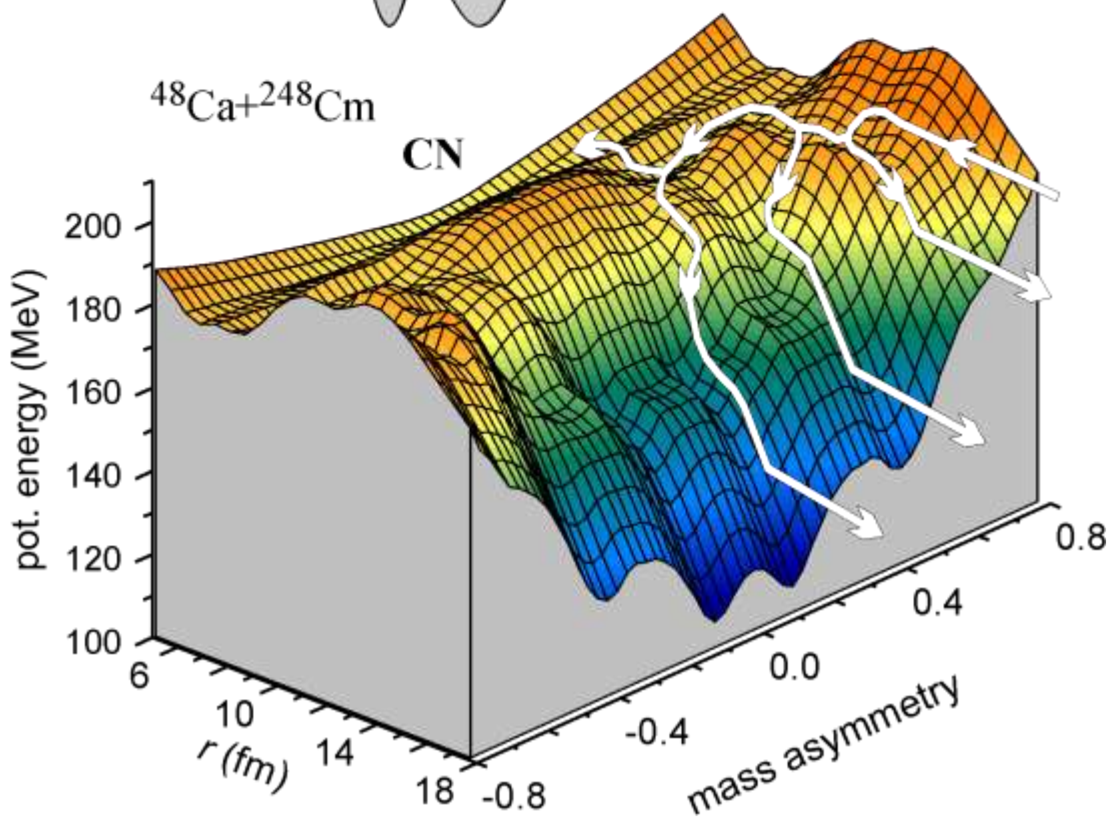


time-tependent Schrödinger equation for single particle wave functions

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

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

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

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

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

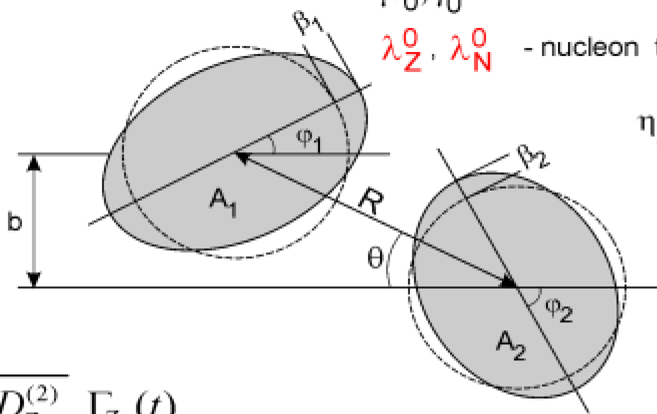
$$\frac{d\eta_Z}{dt}=\frac{2}{Z_{CN}}D_Z^{(1)}+\frac{2}{Z_{CN}}\sqrt{D_Z^{(2)}}\;\Gamma_Z(t)$$

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

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_Z^0, λ_N^0 - nucleon transfer rate



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

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

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

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

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

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

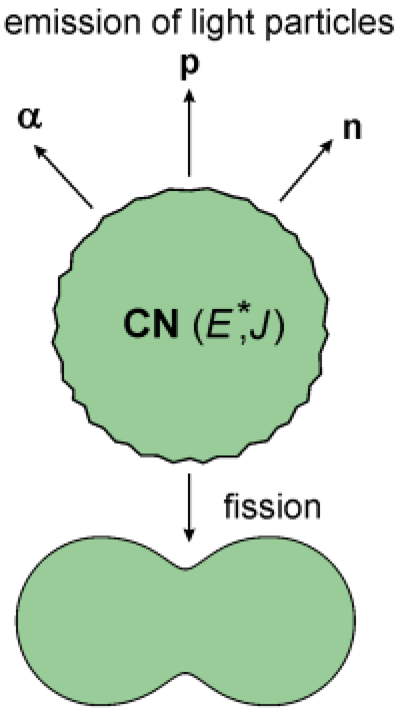
$$\frac{dL_1}{dt}=-\frac{\partial V}{\partial\varphi_1}+\gamma_{tang}\left(\frac{\ell}{\mu_R R}-\frac{L_1}{\Im_1}a_1-\frac{L_2}{\Im_2}a_2\right)a_1-\frac{a_1}{R}\sqrt{\gamma_{tang}T}\,\Gamma_{tang}(t)$$

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

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

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

Cooling (survival) of excited compound nucleus (Statistical Model)



$$\Gamma_{A\to B+a}(E^*,J) = \frac{1}{2\pi\rho_A(E^*,J)} \int_0^{E^*-E_a^{sep}} \sum_{l,j} T_{lj}(e_a) \cdot \sum_{I=|J-j|}^{I=J+j} \rho_B(E^* - E_a^{sep} - e_a, I; \beta_{g.s.})\, de_a$$

$$\Gamma_{fission}(E^*,J) = \frac{K_{Kramers}(\eta,T)}{2\pi\rho_A(E^*,J)} \int_0^{E^*} T_{fis}(e) \cdot \rho_A(E^* - e, J; \beta_2^{saddle})\, de$$

$$\Gamma_\gamma^L(E^*,J) = \frac{1}{2\pi\rho_A(E^*,J)} \int_0^{E} \sum_{I=|J-L|}^{I=J+L} f_L(e_\gamma) \cdot e_\gamma^{2L+1} \cdot \rho_A(E^* - e_\gamma, I)\, de_\gamma$$

Survival probability: **CN** $(E_0^*, J_0) \to$ **EvR**(g.s.) + xn + Nγ

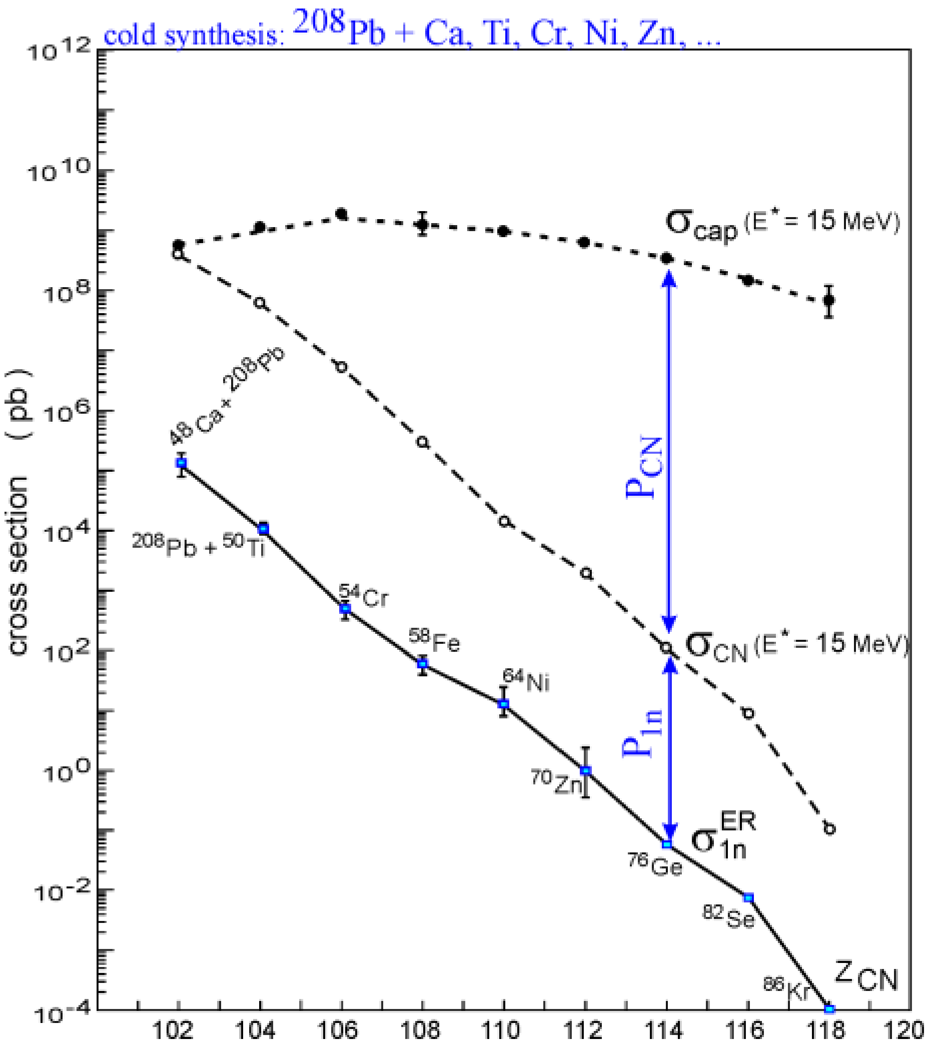
$$P_{xn} = \int_0^{E_0^*-E_n^{sep}(1)} \frac{\Gamma_n}{\Gamma_{tot}}(E_0^*,J_0)\, P_n(E_0^*,e_1)\, de_1 \int_0^{E_1^*-E_n^{sep}(2)} \frac{\Gamma_n}{\Gamma_{tot}}(E_1^*,J_1)\, P_n(E_1^*,e_2)\, de_2 \cdots \int_0^{E_1^*-E_n^{sep}(x)} \frac{\Gamma_n}{\Gamma_{tot}}(E_{x-1}^*,J_{x-1})\, P_n(E_{x-1}^*,e_x)\, G_{N\gamma}(E_x^*,J_x \to g.s.)\, de_x$$

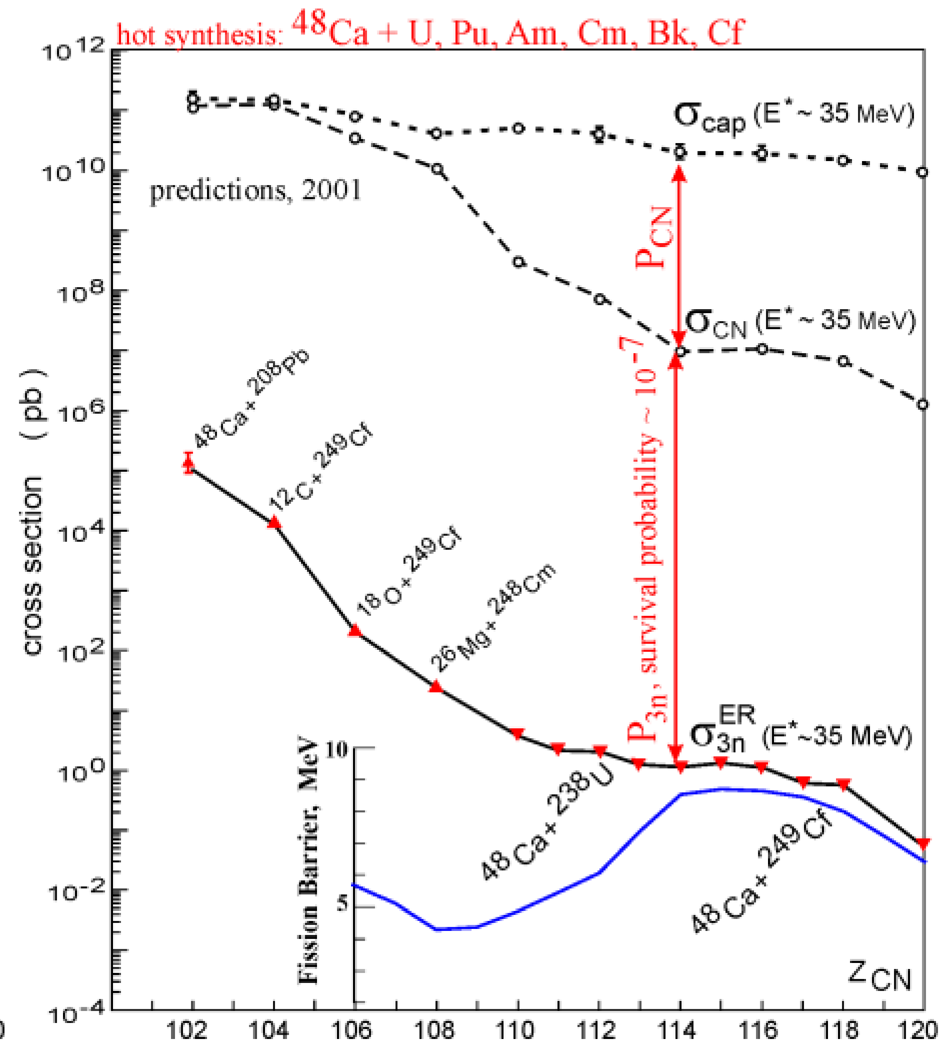
Cross section for formation of evaporation residues:

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

http://nrv.jinr.ru/nrv/Statistical Model

Cross sections of the “cold” and “hot” synthesis of SHE

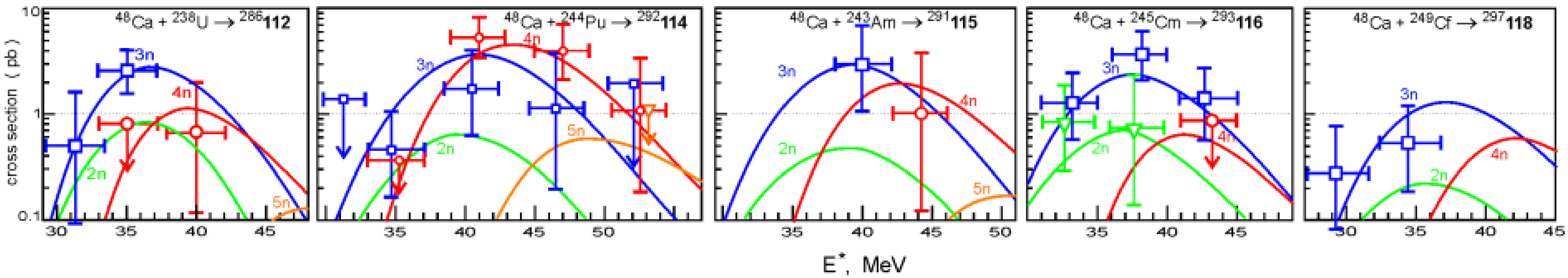




Cross sections for formation of SHE with Z=112-118 have been predicted to be nearly constant owing to increasing values of the fission barriers of formed CN

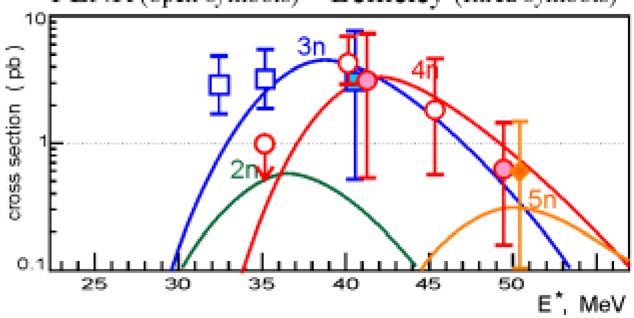
Predictive power of the theory for the hot fusion reactions

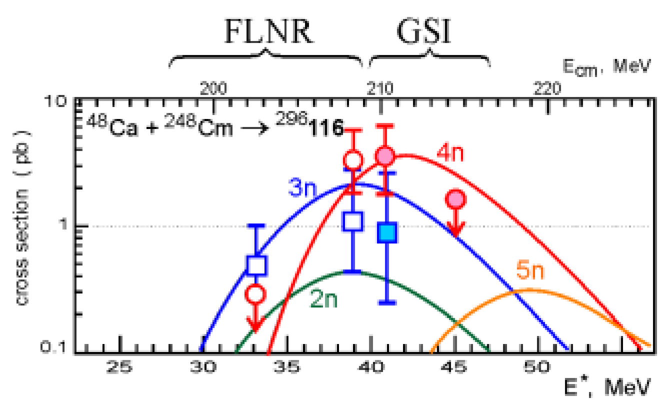
predictions of 2002



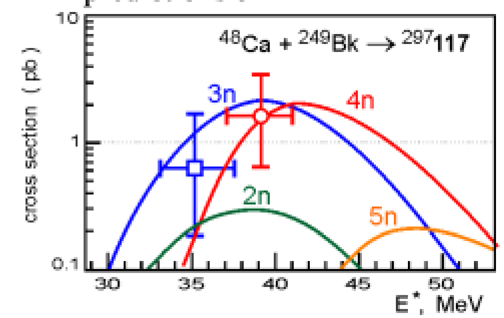
^{48}Ca + ^{242}Pu → ^{290}114

FLNR (open symbols) Berkeley (filled symbols)





predictions of 2008



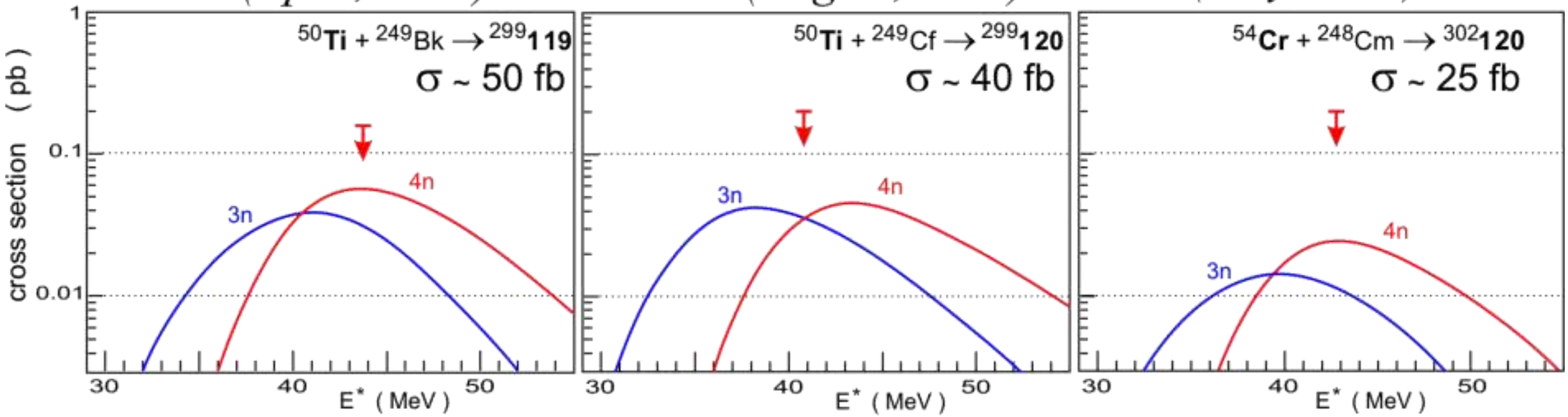
New elements 119 and 120 are coming !

Ti beam:

TASCA (April, 2012) *TASCA (August, 2011)*

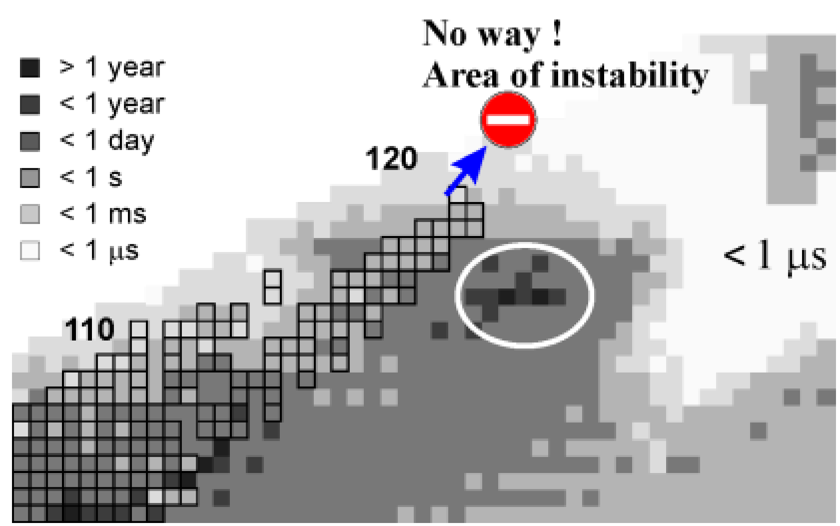
Cr beam:

SHIP (May, 2011)



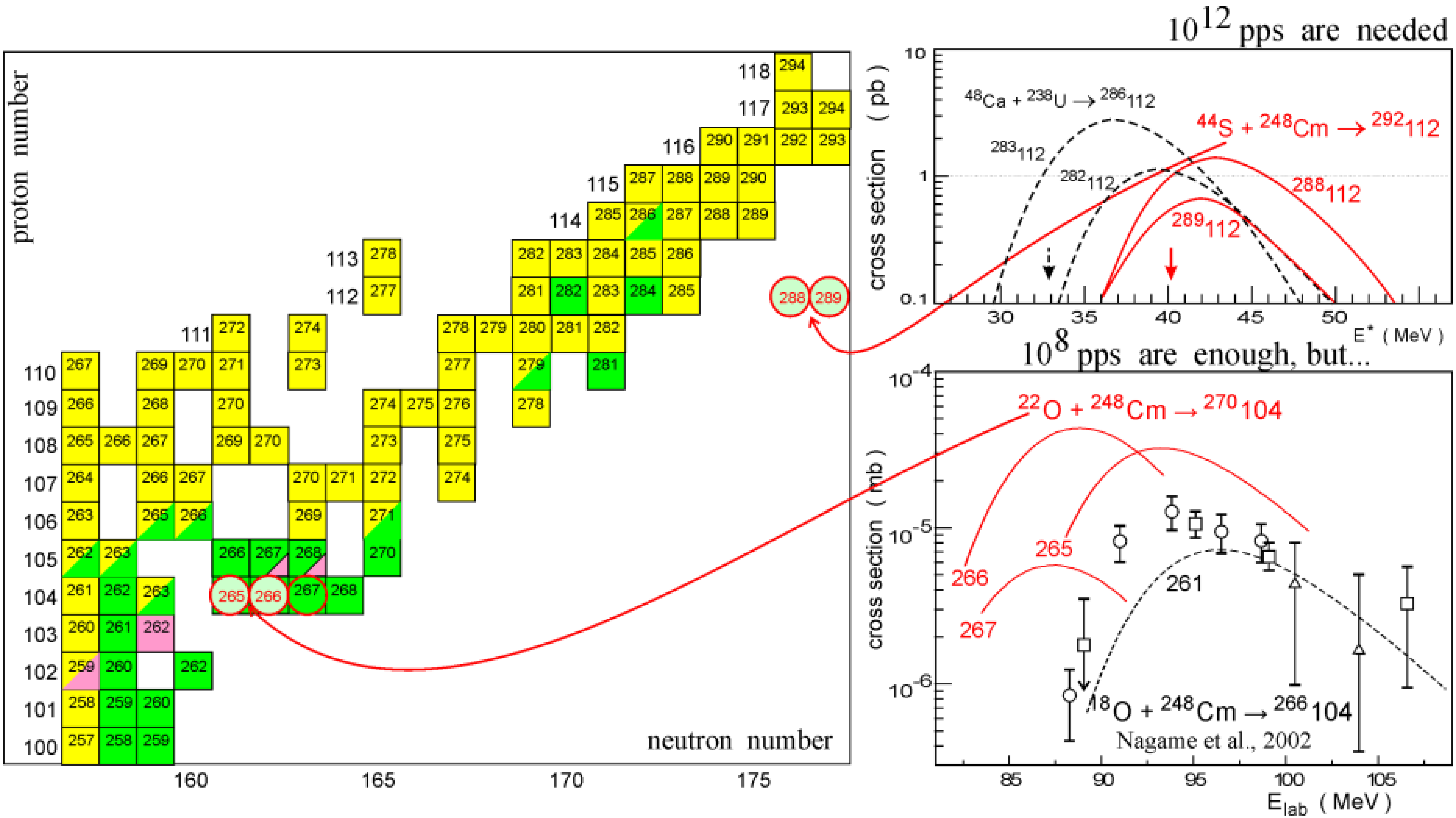
predictions: Zagrebaev & Greiner, PRC 2008

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



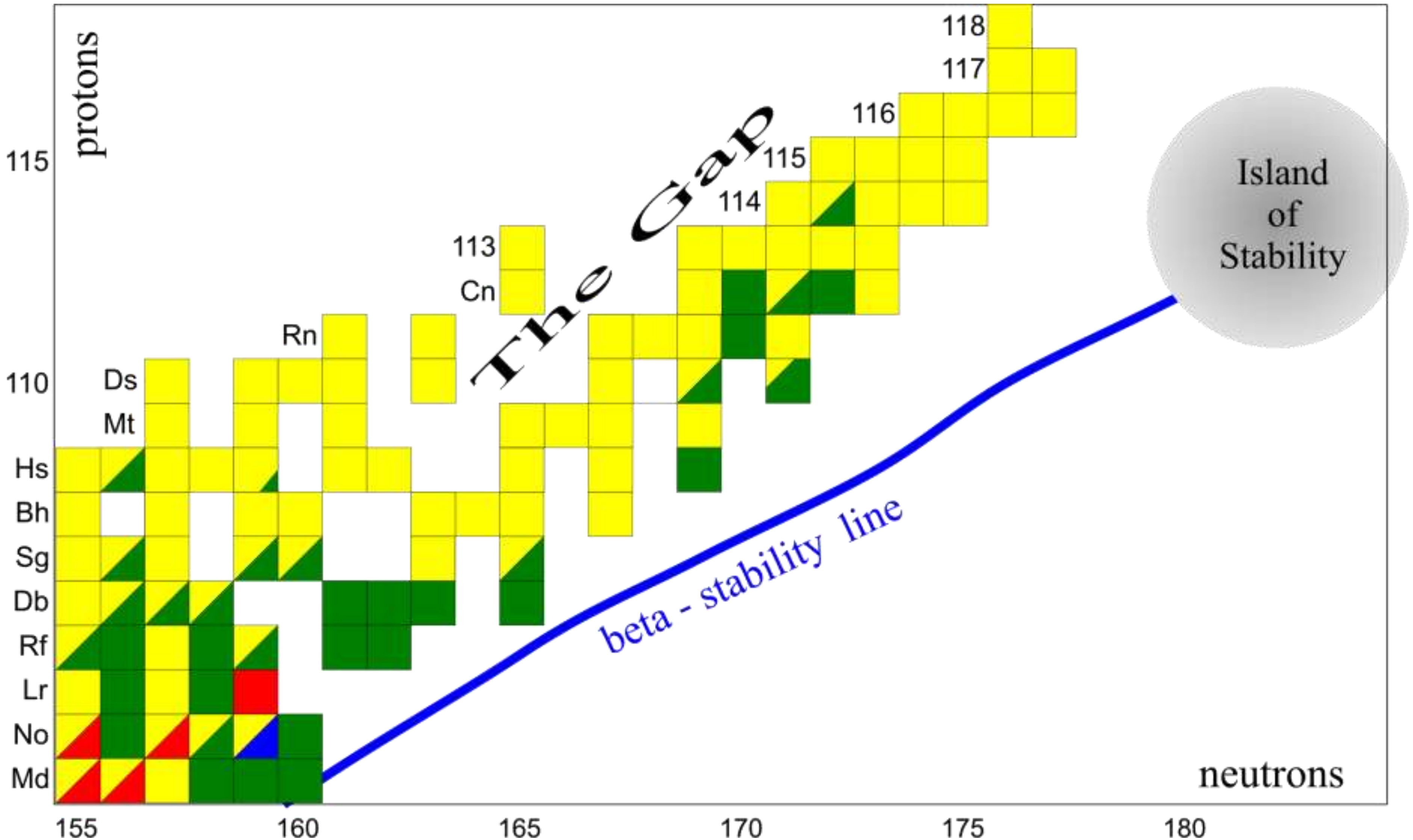
Probably, these elements are the last ones which will be synthesized in the nearest future

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

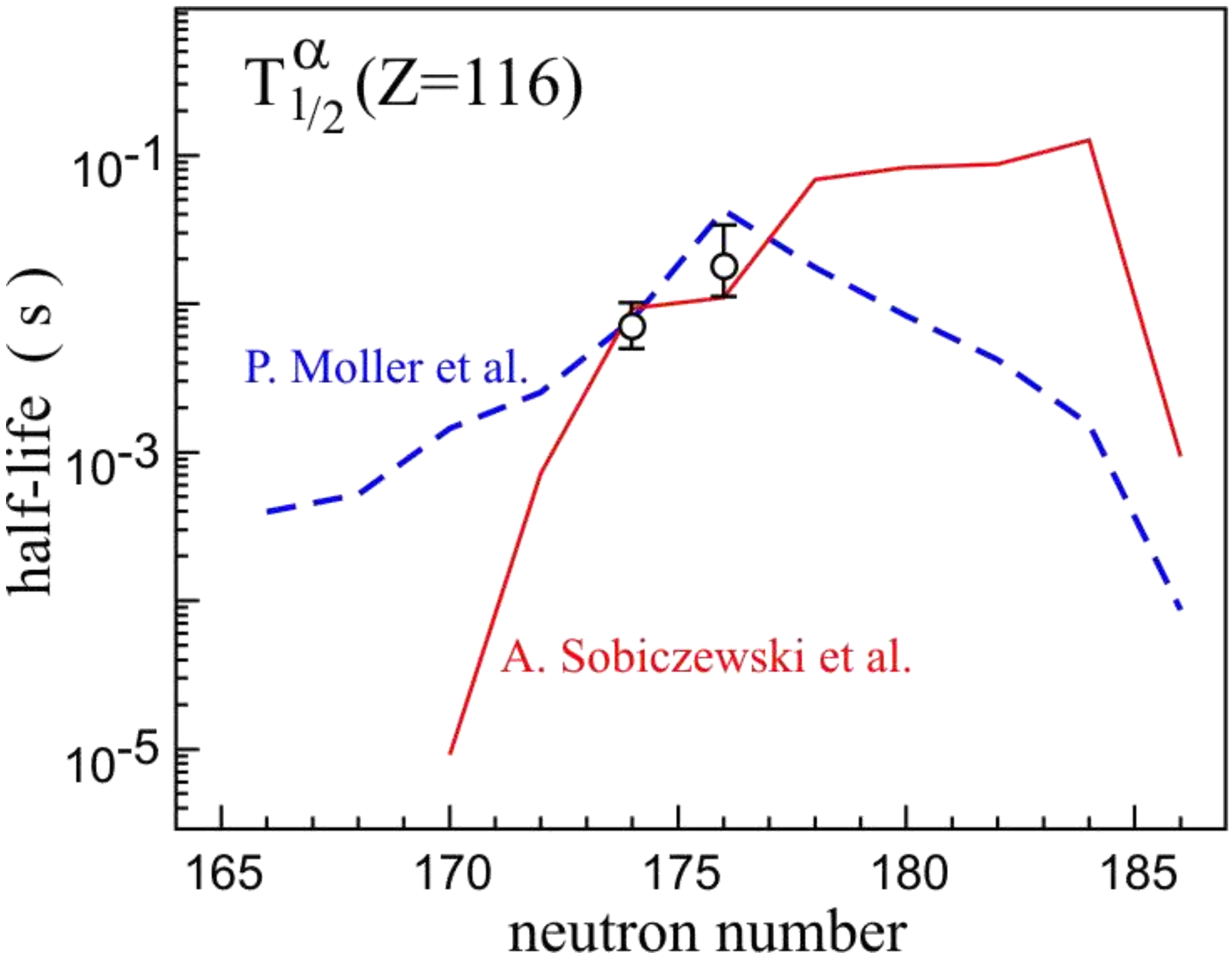


No chances today and in the nearest future

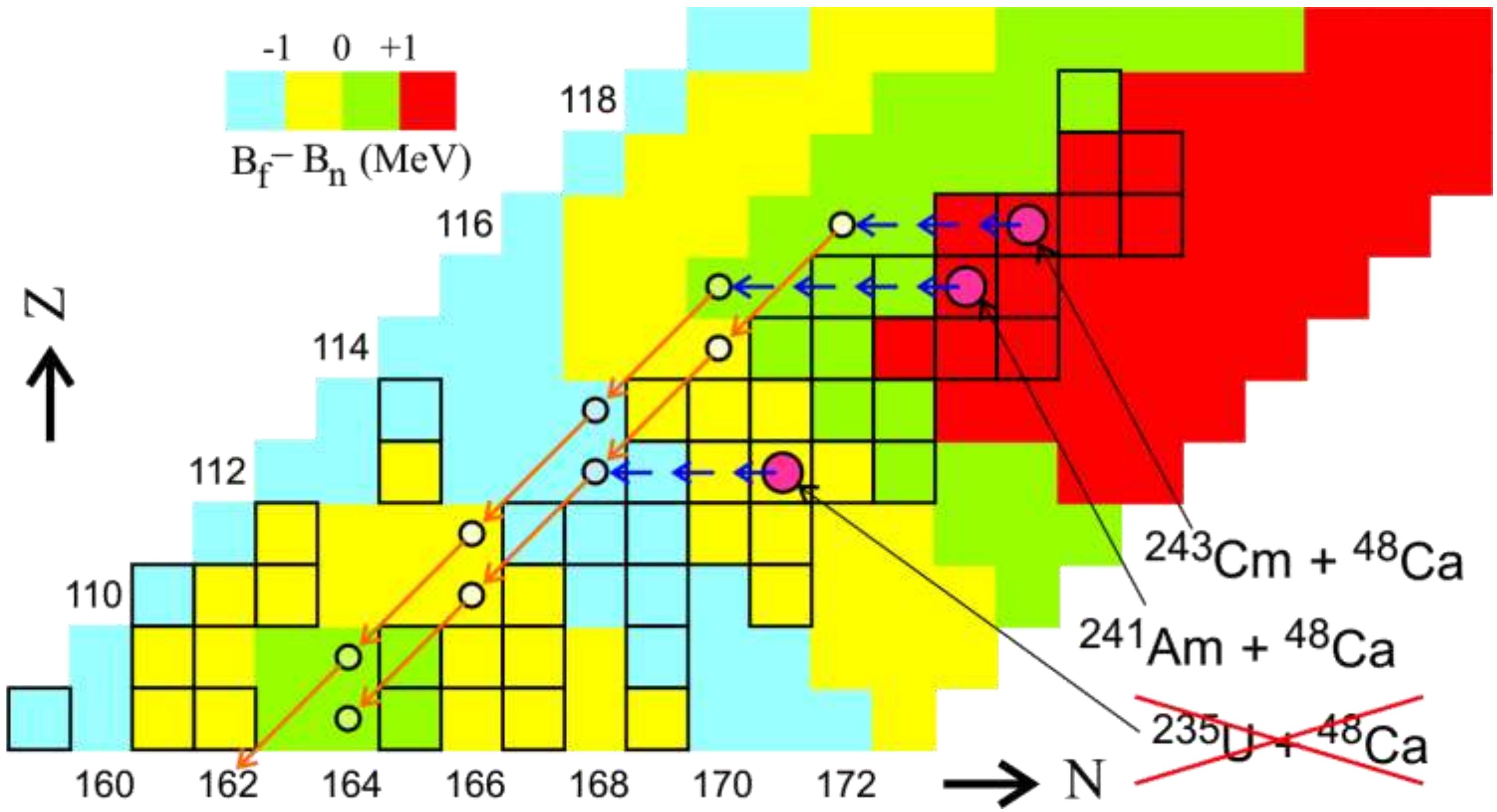
It is important to fill the Gap in superheavy mass area



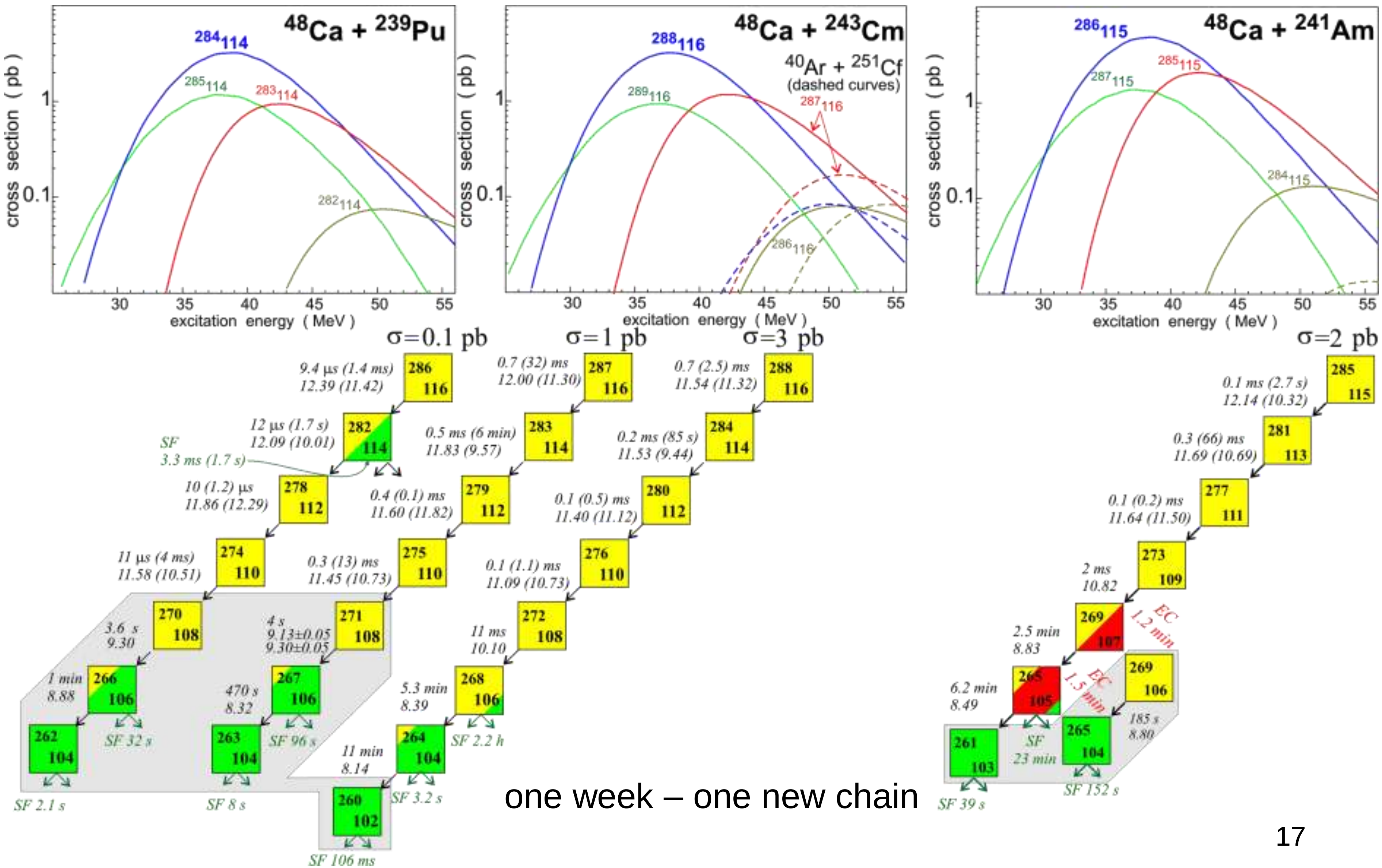
Our ability of predictions in superheavy mass area



It is easier to fill the Gap from above using available actinide targets ^{241}Am, ^{239}Pu, ^{243}Cm…

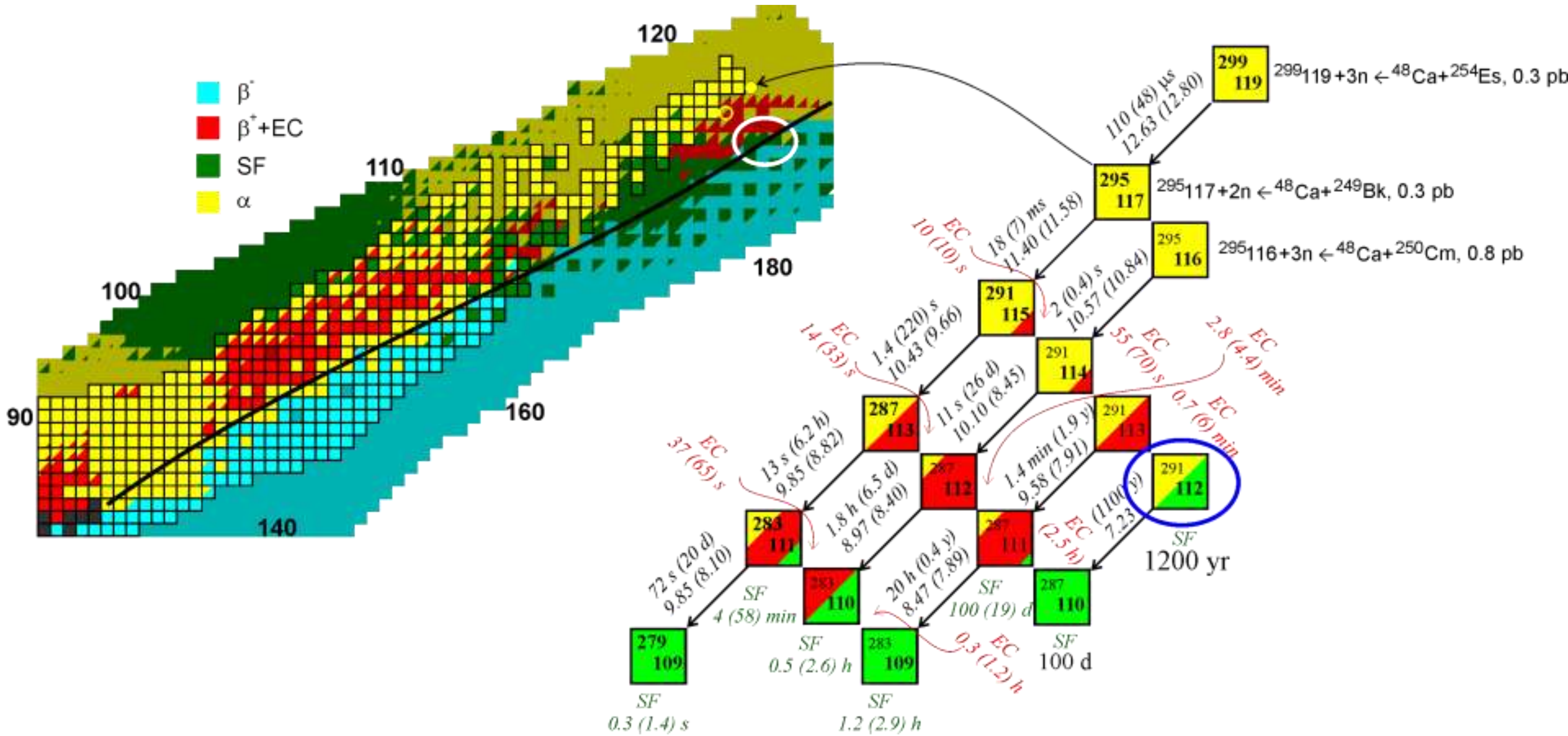


Predicted cross sections are high enough to perform experiments at available facilities just now



one week – one new chain

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

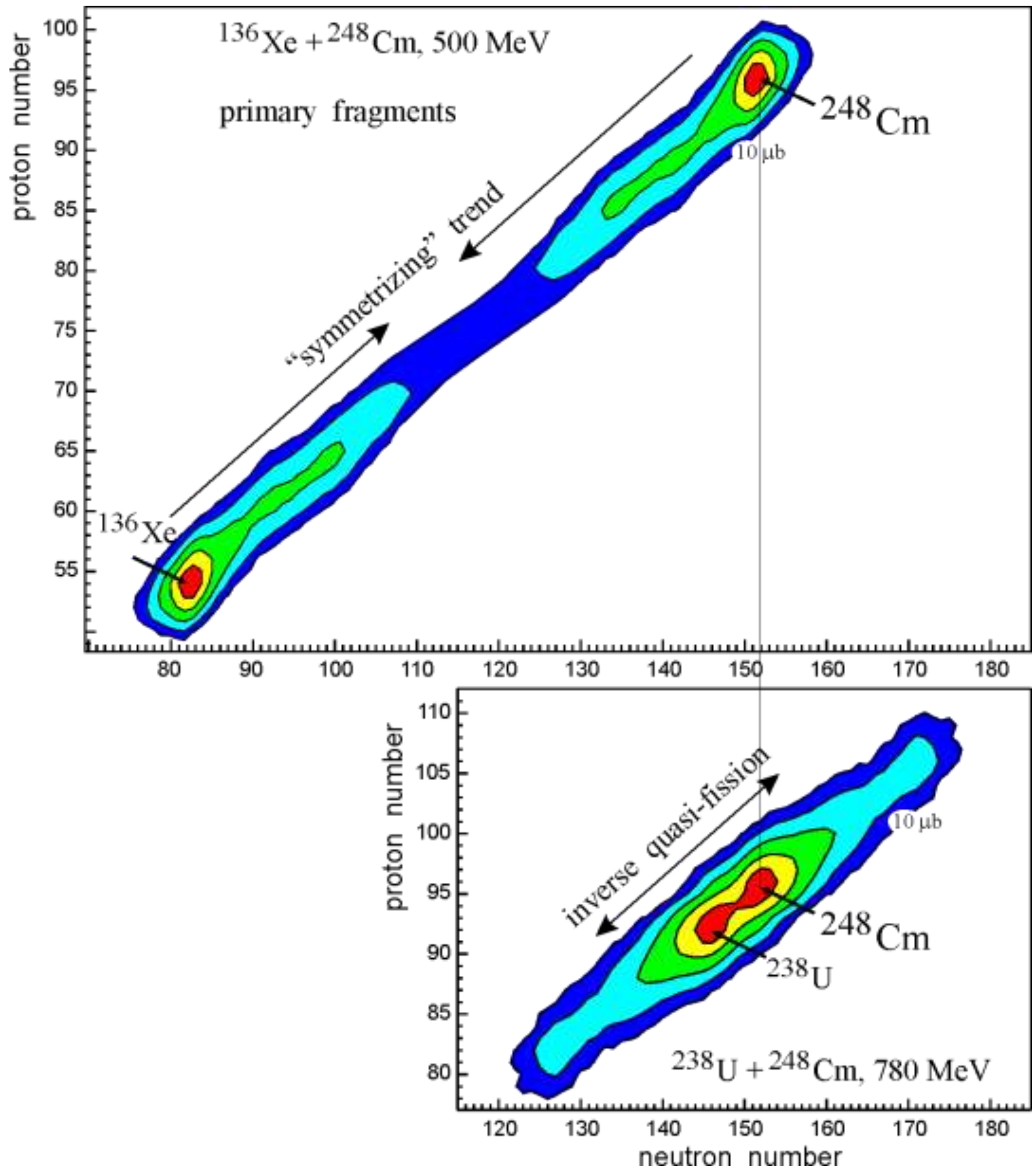


Synthesis of SH nuclei in **transfer reactions**

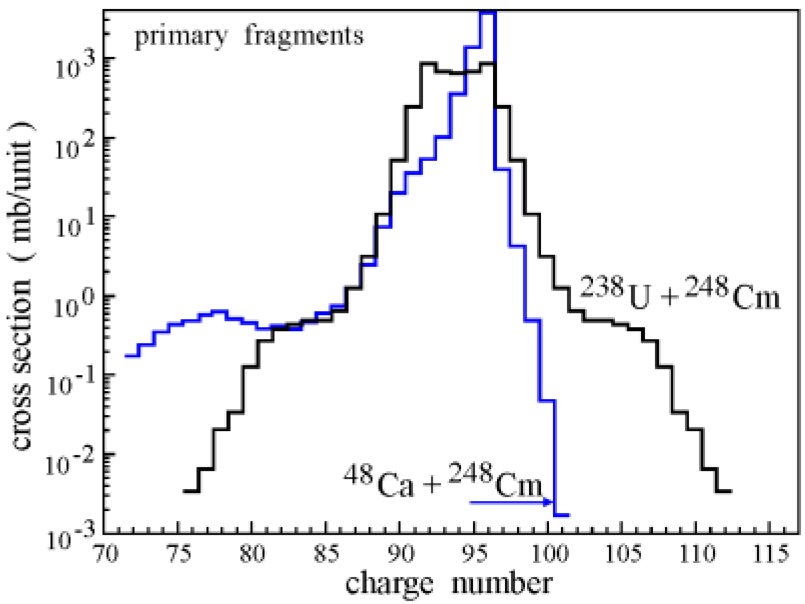
[1] E. K. Hulet *et al.*, Phys. Rev. Lett. **39**, 385 (**1977**).
[2] M. Schaedel *et al.*, Phys. Rev. Lett. **41**, 469 (**1978**).
[3] H. Essel, K. Hartel, W. Henning, P. Kienle, H. J. Koerner, K. E. Rehm, P. Sperr,W.Wagner, and H. Spieler, Z. Phys. A **289**, 265 (**1979**).
[4] H. Freiesleben, K. 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**).
…

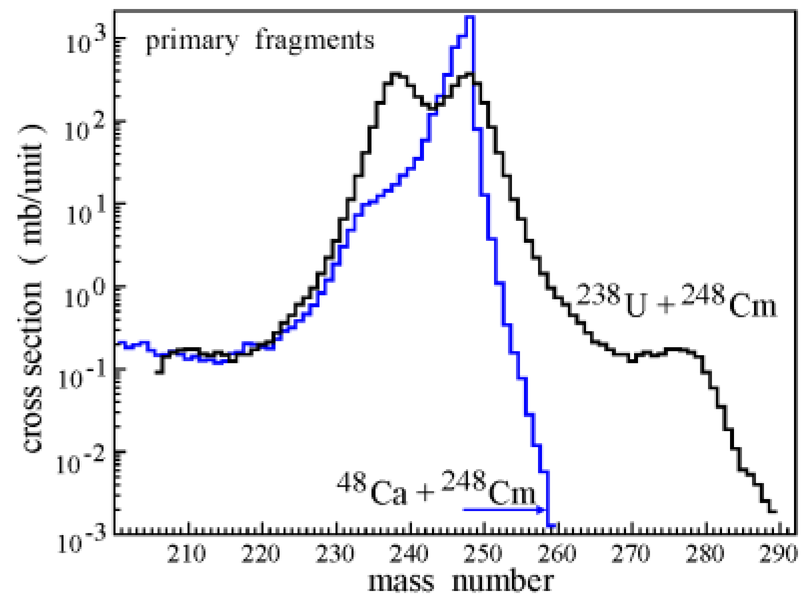
… a long history. Isotopes of Fm and Md were synthesized 30 years ago.

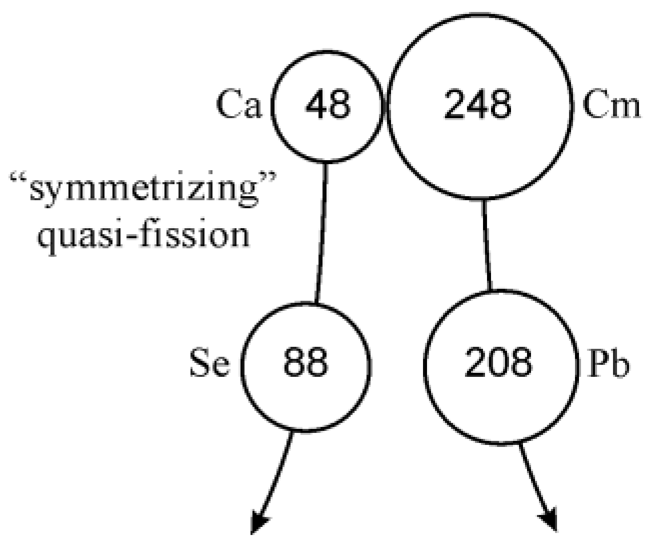
Multi-nucleon transfer for production of superheavies
(choice of reaction is very important)

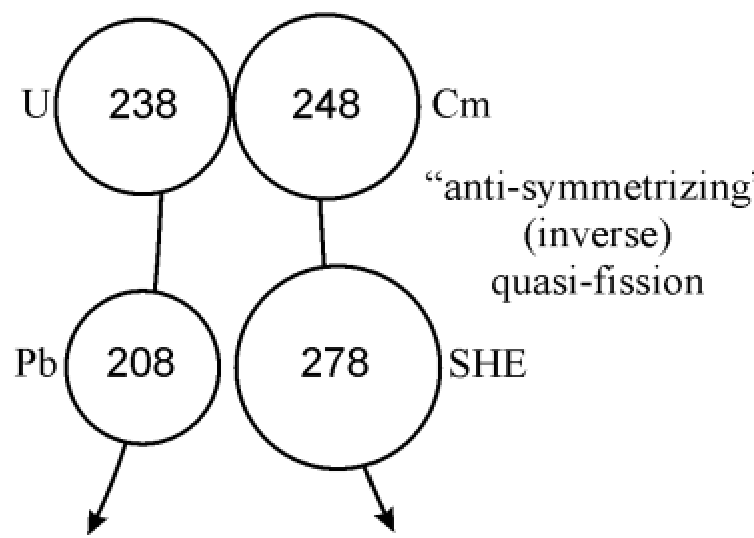


U-like beams give us more chances to produce neutron rich SH nuclei in "inverse quasi-fission" reactions

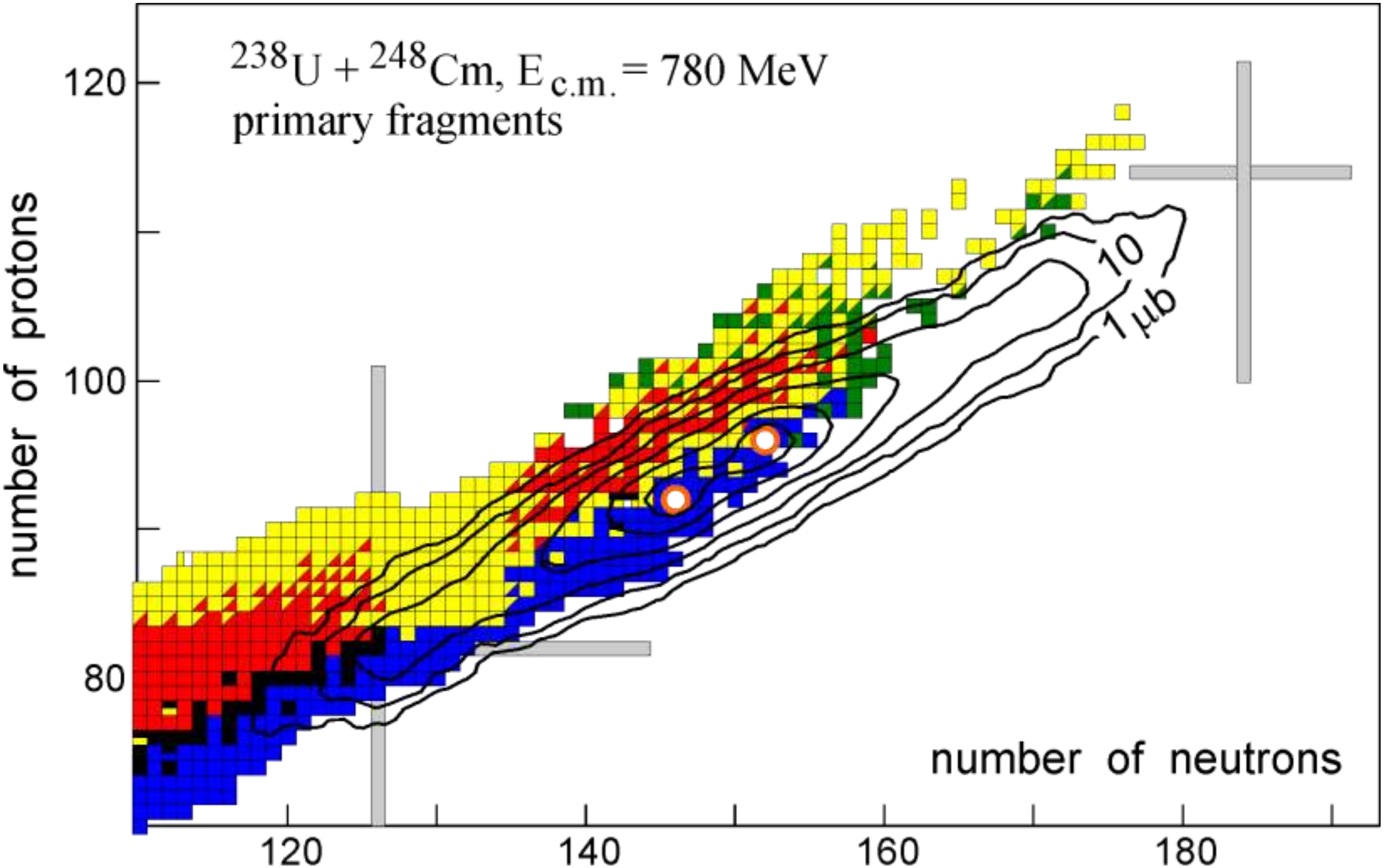




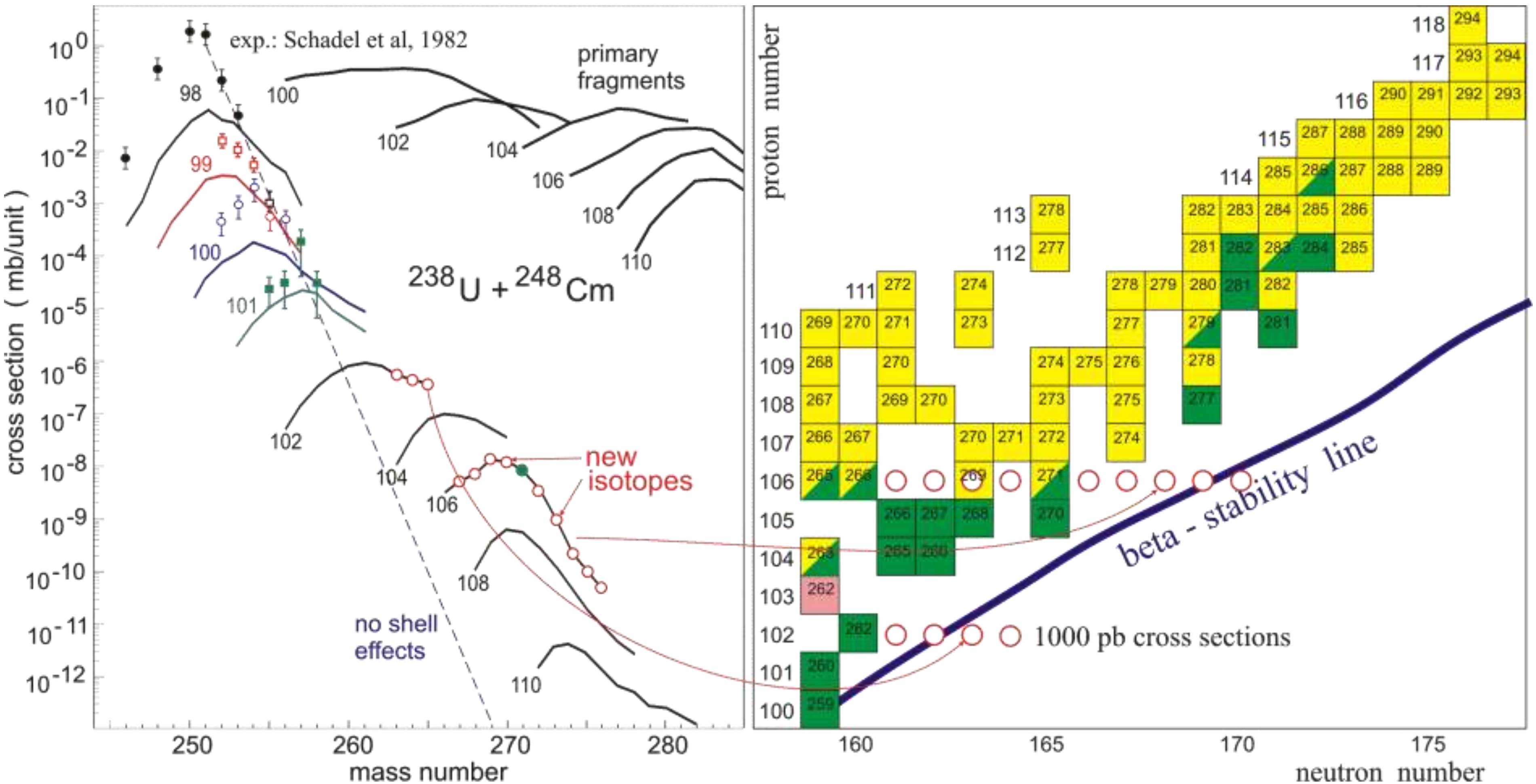




238U + 248Cm. Primary fragments



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



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

Nucleosynthesis by neutron capture

n_0 is the neutron flux

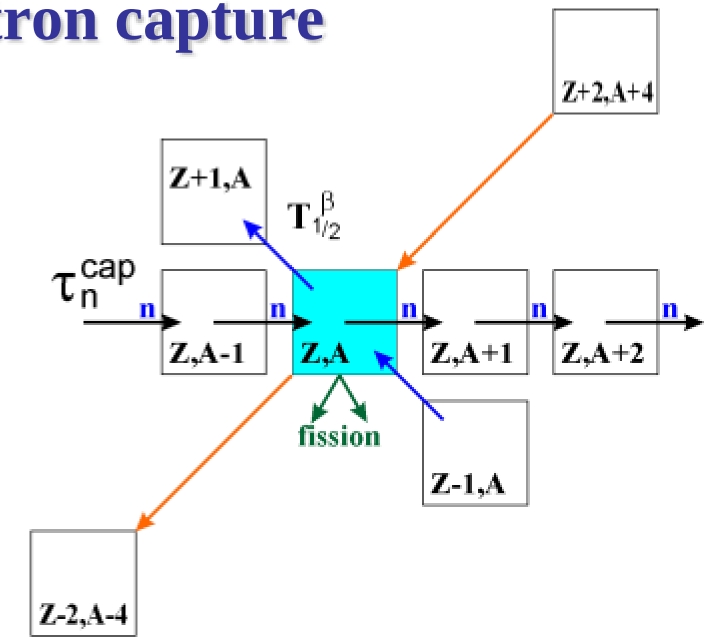
time of neutron capture

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

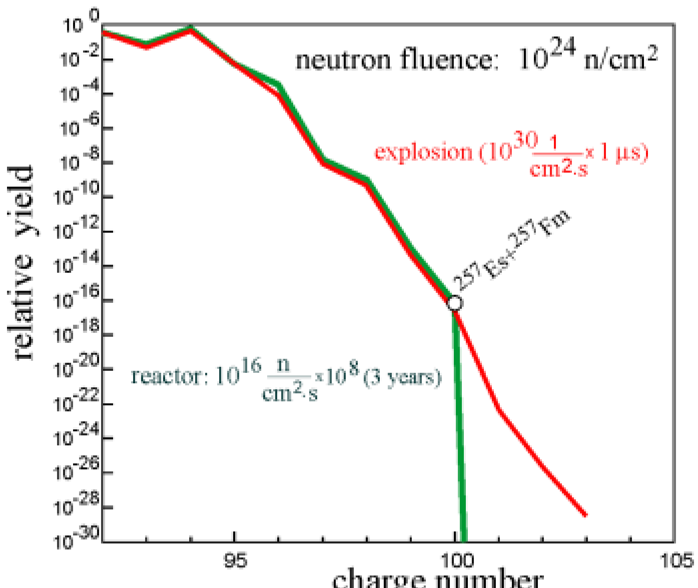
$$(Z,A) \rightarrow (Z,A+1) \text{ if } T_{1/2} > \tau_n^{cap}$$

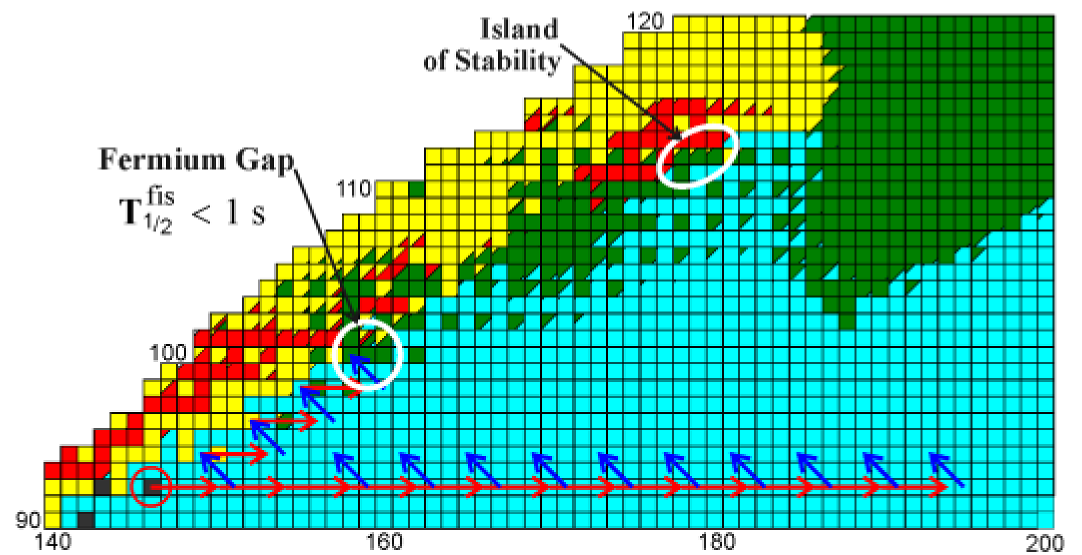
nuclear reactor: $\tau_n^{cap} \sim 1$ year

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



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

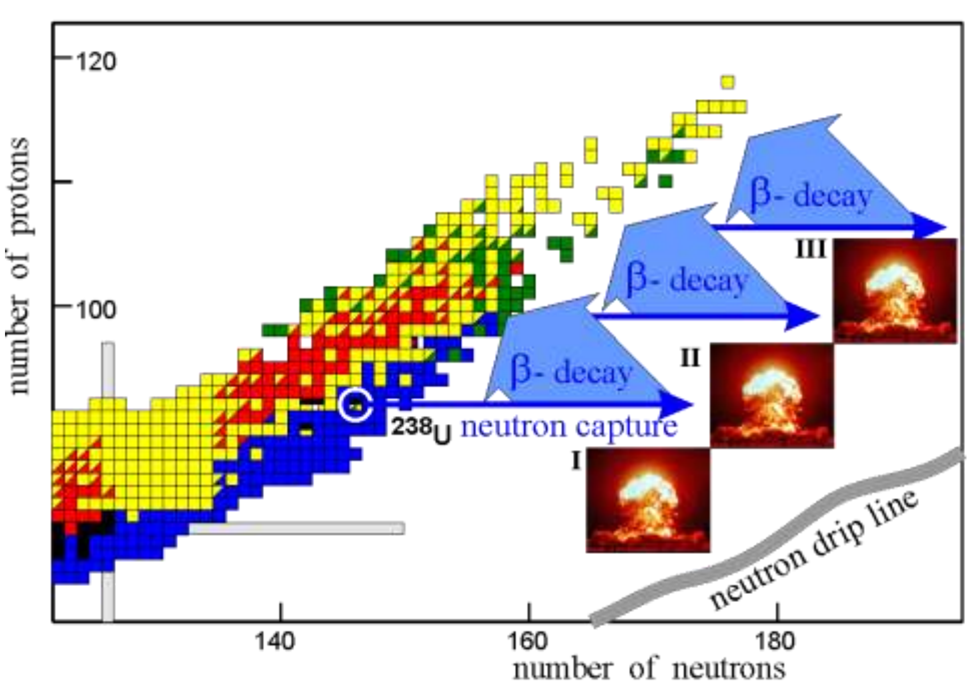


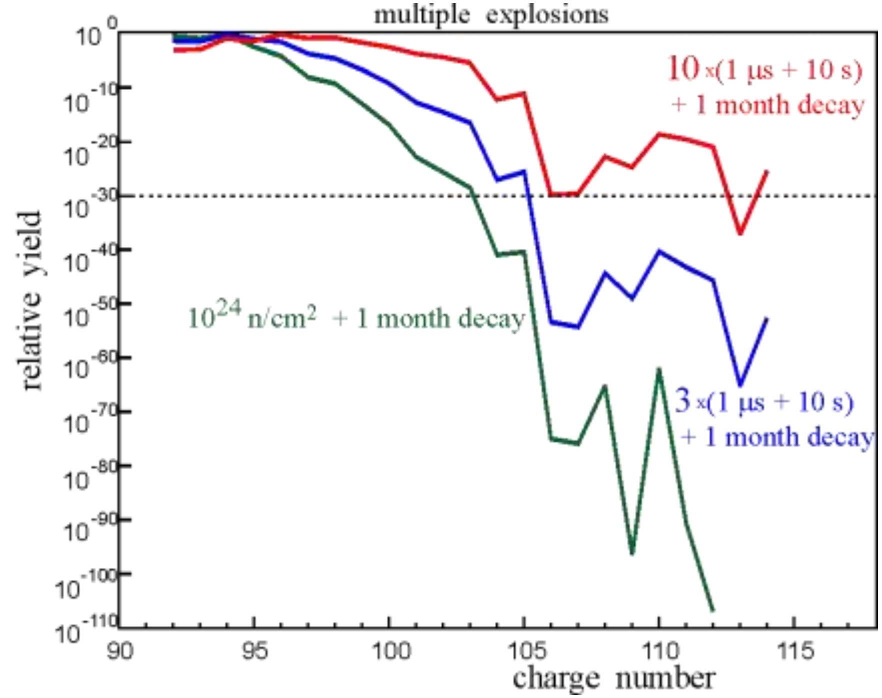


Multiple nuclear explosions

(proposed first by H.W. Meldner, PRL 28,1972)

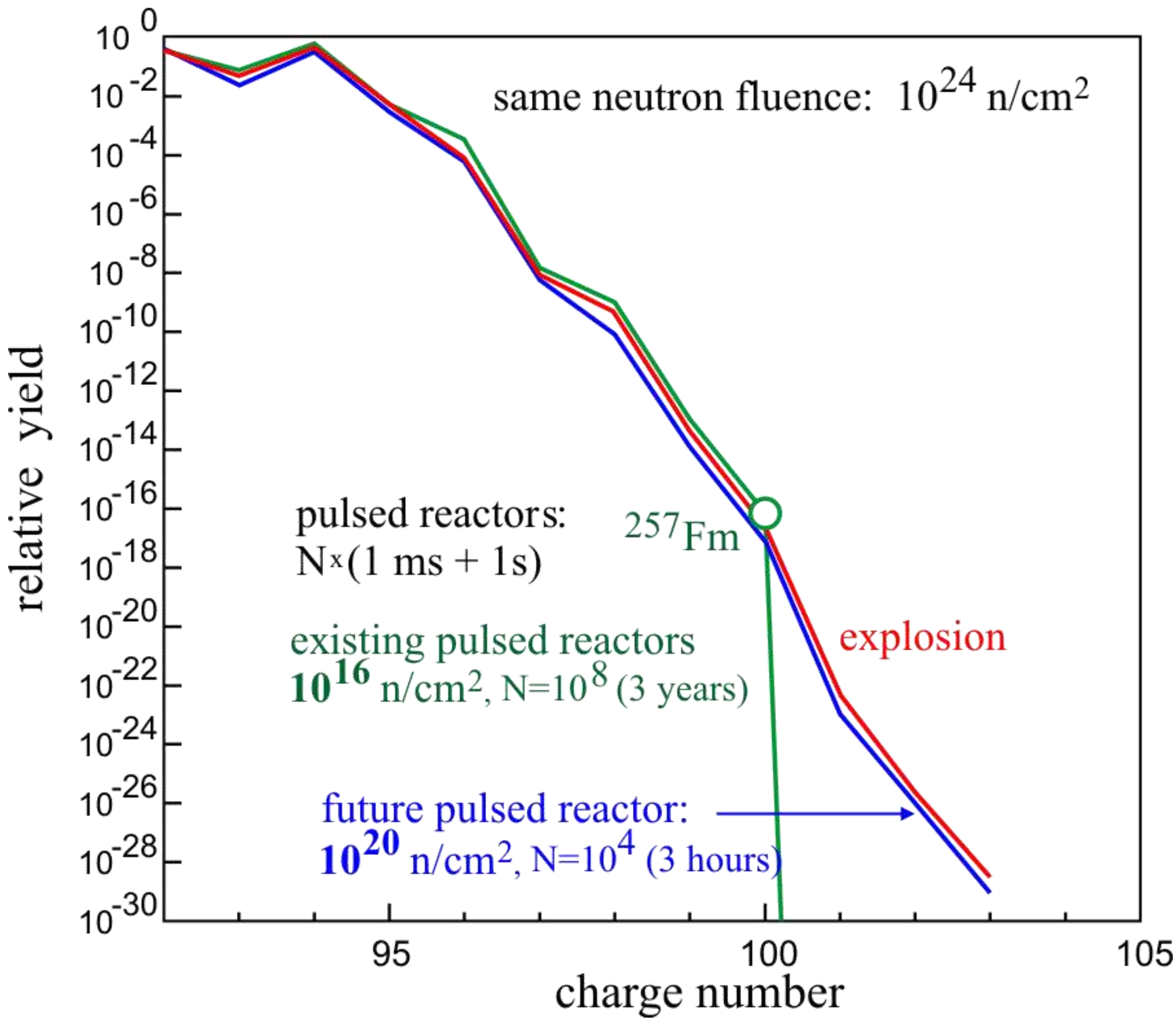
Edward Teller: Technically it is quite possible





Probability for formation of element 112 increases by **90 orders** of magnitude **!**

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

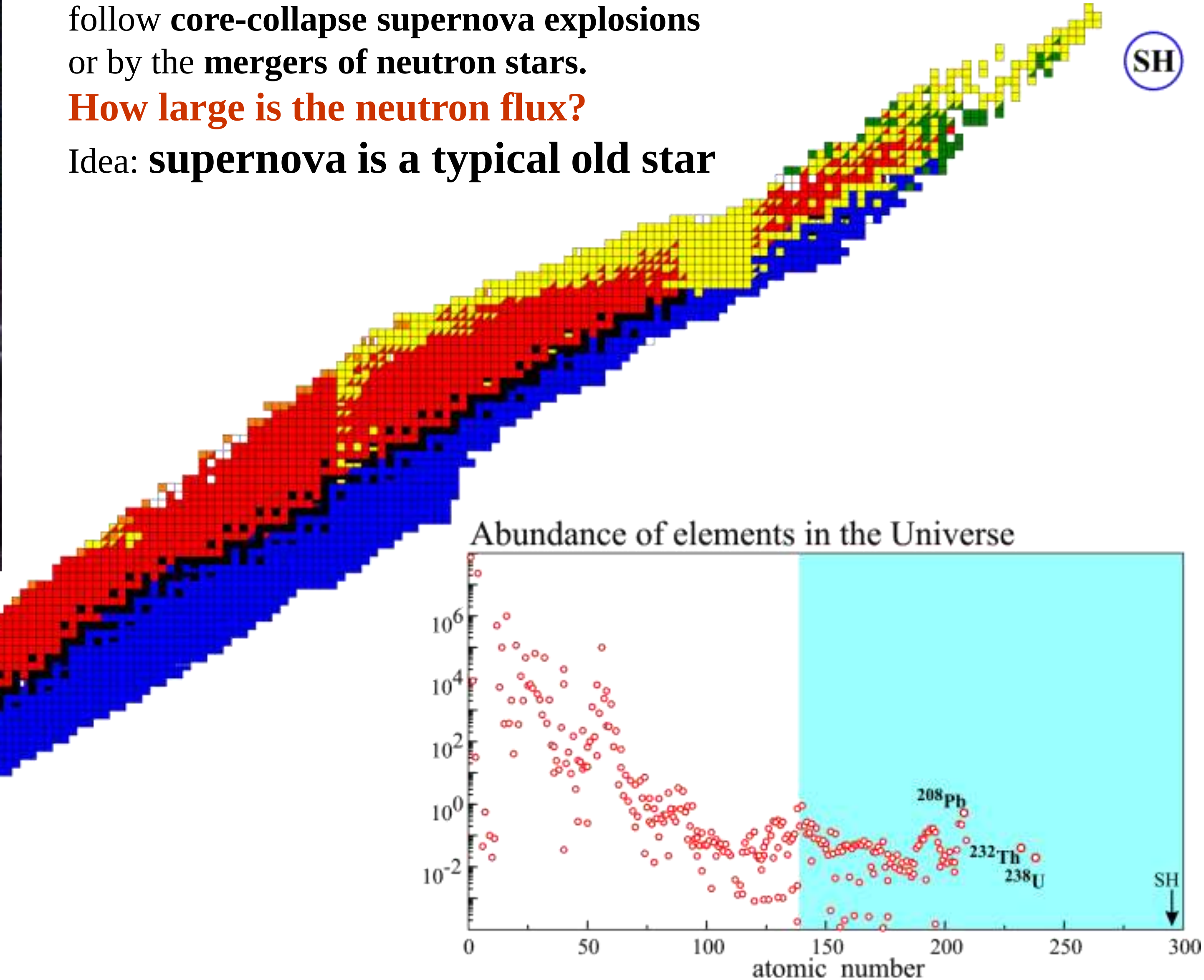


Formation of SH elements in astrophysical r-process

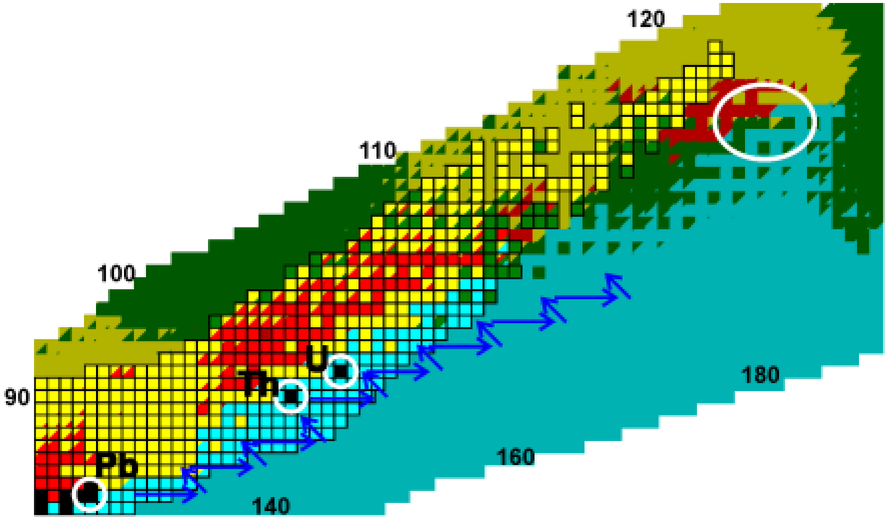
Strong neutron fluxes are expected to be generated by neutrino-driven proto-neutron star winds which follow **core-collapse supernova explosions** or by the **mergers of neutron stars.**

How large is the neutron flux?

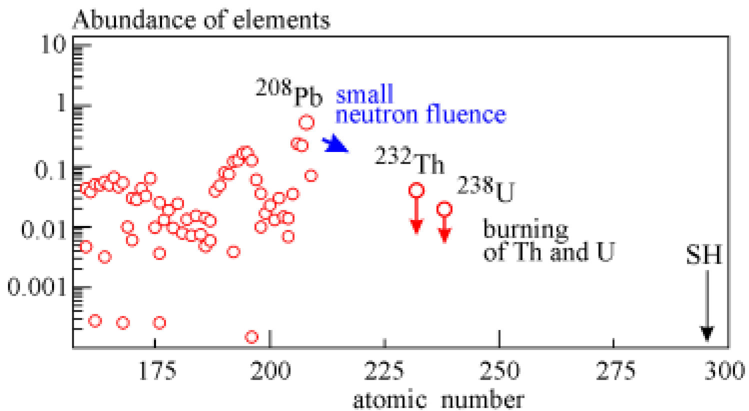
Idea: **supernova is a typical old star**

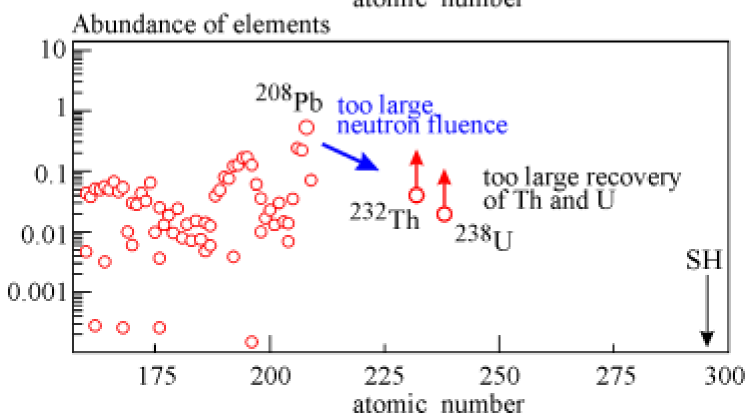


Formation of SH elements in astrophysical r-process

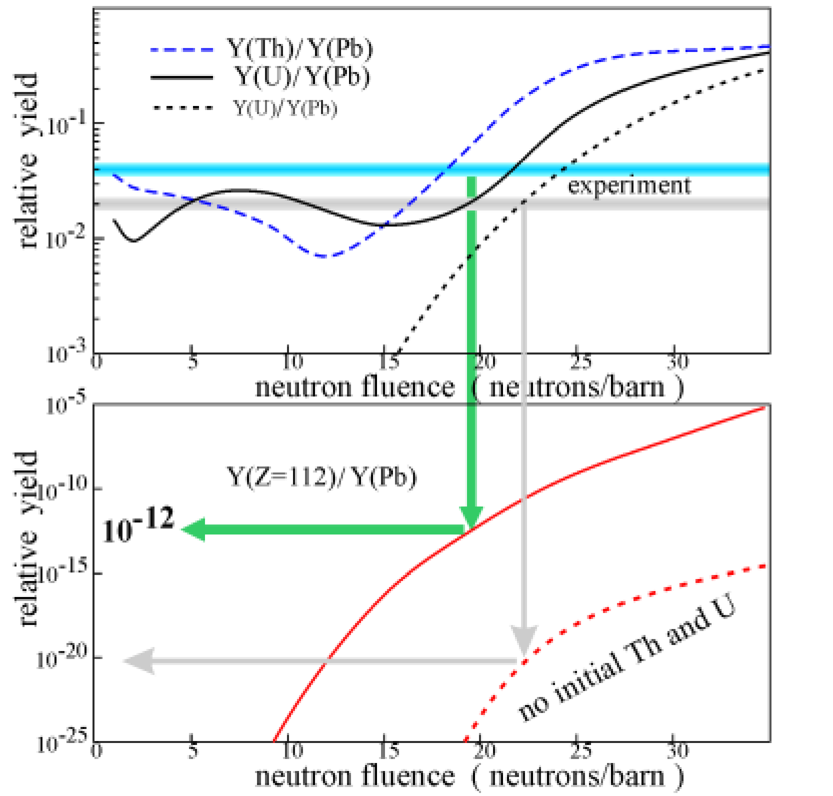


In the course of neutron irradiation initial Th and U material are depleted transforming to heavier elements and going to fission, while more abundant Pb and lighter stable elements enrich Th and U.





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



Summary

- **Elements 119 and 120 can be really synthesized in the Ti and/or Cr fusion reactions with cross sections of about 0.05 - 0.02 pb.**
  It may be that they are the heaviest SH elements with $T_{1/2} > 1$ μs ?
- **The gap in SH mass area (Z=106-116) can be easily filled in fusion reactions of 48Ca with lighter isotopes of actinides (239Pu, 241Am, 243Cm, …).**
- **The narrow pathway to the island of stability is found at last !**
- **Multi-nucleon transfer reactions can be 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!
- **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).**
- **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}.

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