Production of Heavy and Superheavy Neutron Rich Nuclei

- Few words about fission of superhevies
- Upper part of the nuclear map: Pessimistic view
- Fusion reactions: What else can they give us?
- Transfer reactions: How far can we go?
- n-capture processes: Back to old methods?
- Summary

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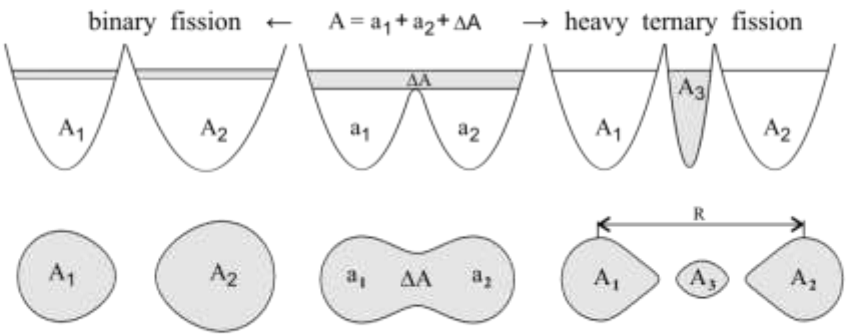
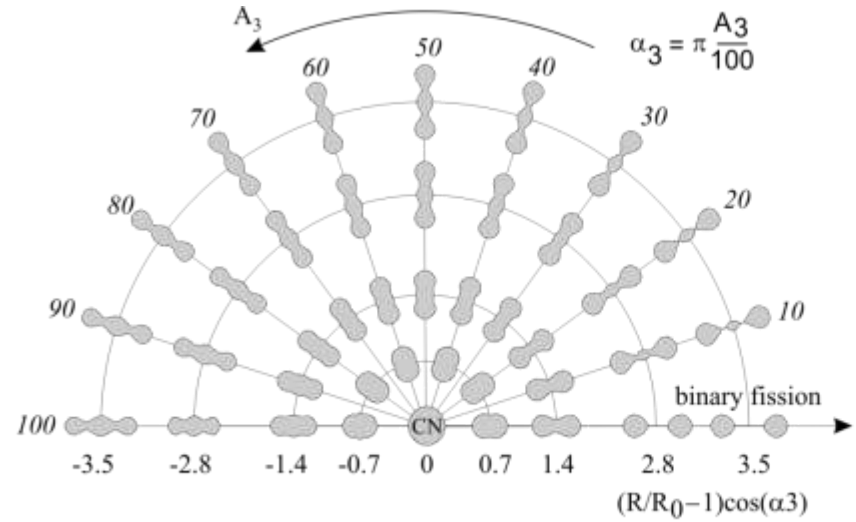
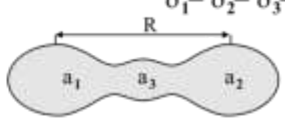
for DANF-2011, October 17, 2011, Smolenice

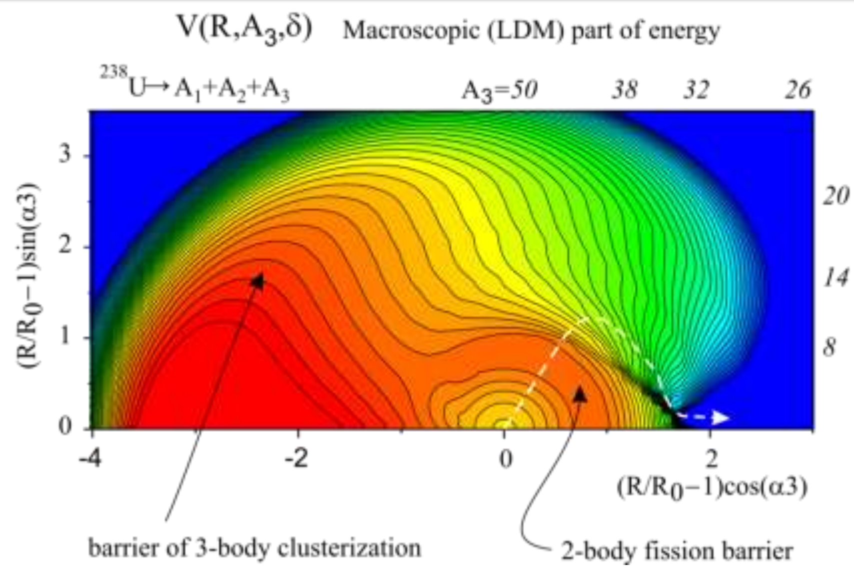
Three-center shell model





Restrictions: $a_1 = a_2$ and, thus, $A_1 = A_2$
$\delta_1 = \delta_2 = \delta_3 = \delta$





Unusual properties of superheavy nuclei: true ternary fission is very probable

(Zagrebaev, Karpov and Greiner, PRC, 2010)

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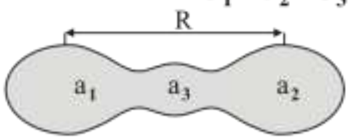
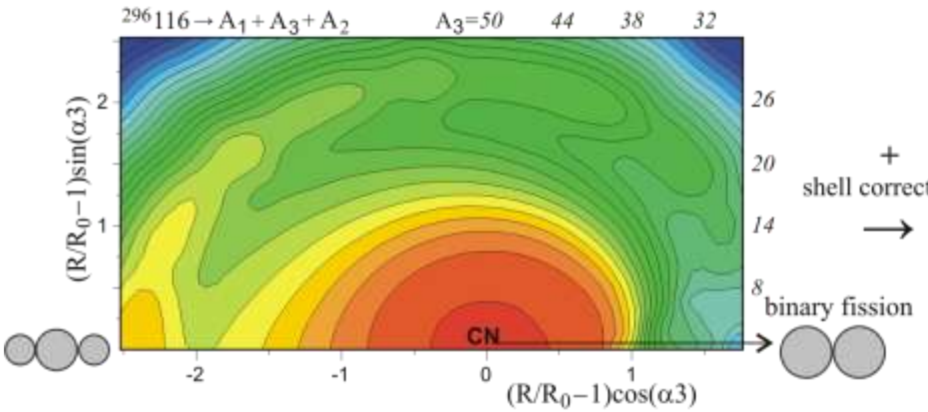


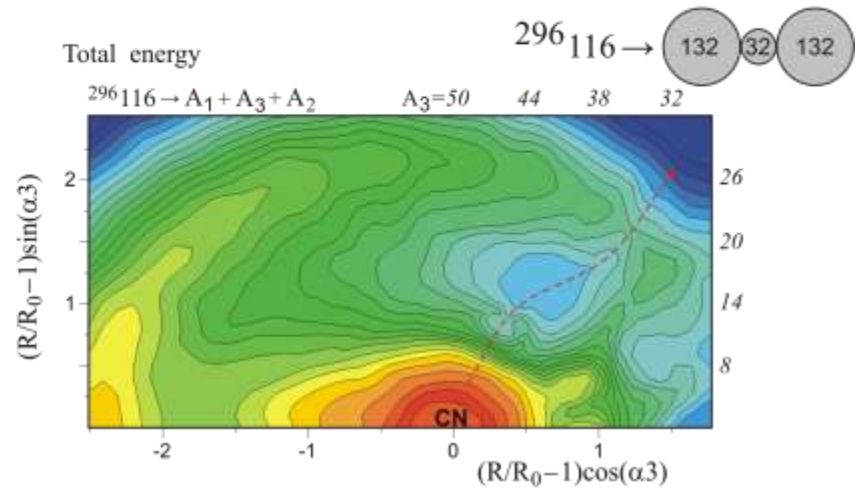
$V(R, A_3, \delta)$ $\alpha_3 = \pi \frac{A_3}{100}$

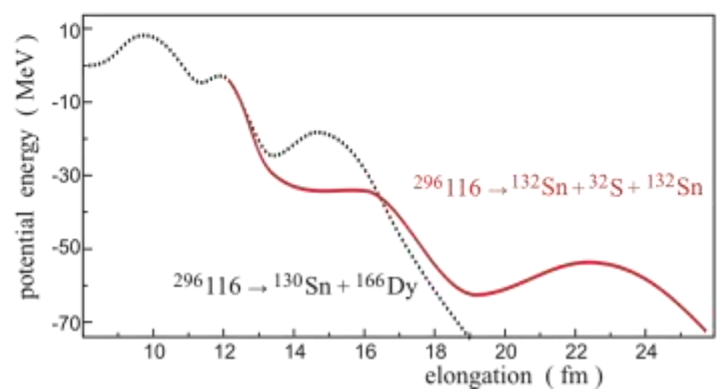
Macroscopic (LDM) part of energy



\+ shell corrections →

Total energy

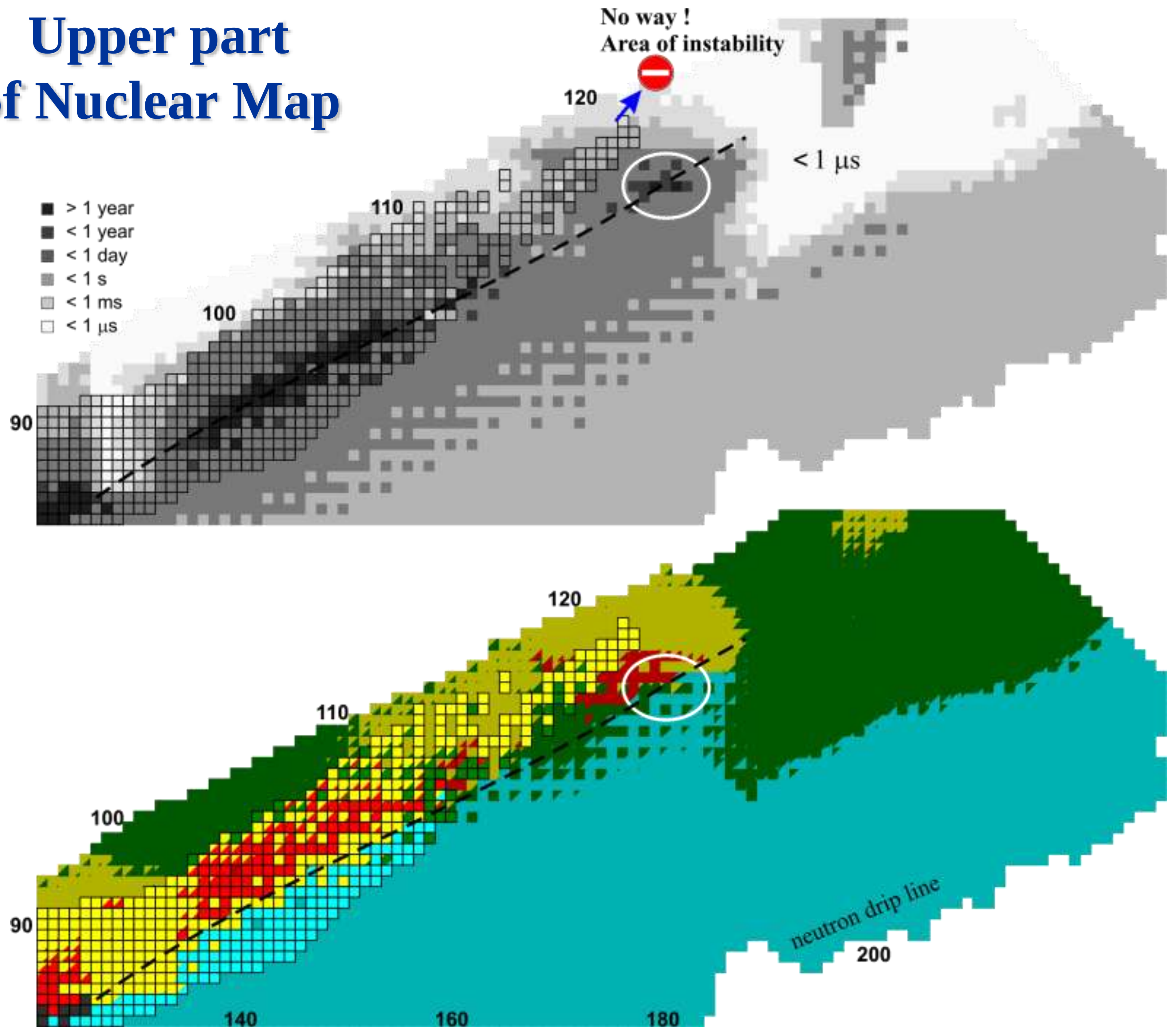




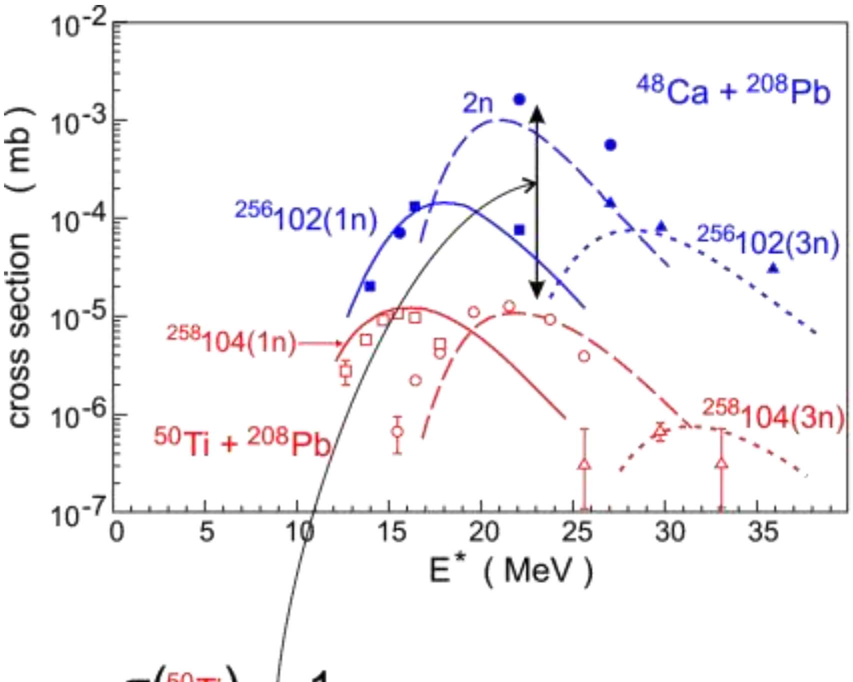
Larger effect is expected for:

$^{64}Ni + ^{238}U \rightarrow ^{130}Sn + ^{42}Ca + ^{130}Sn$

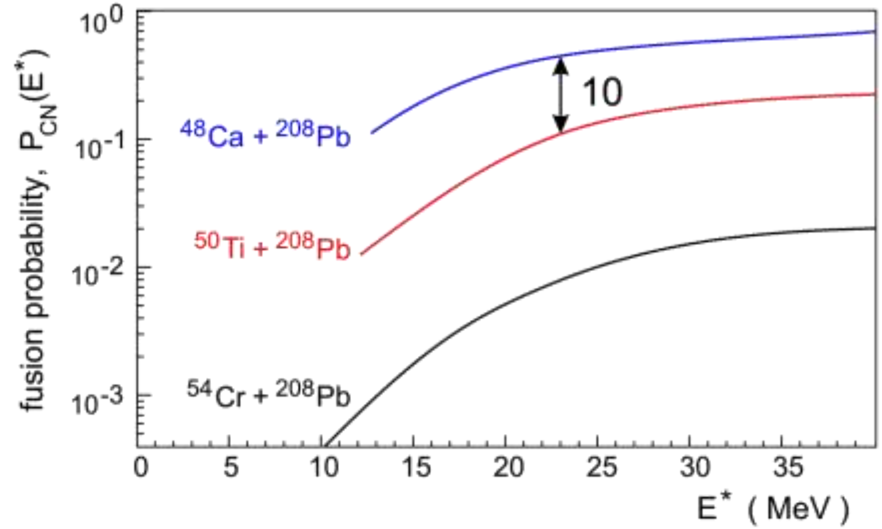
Upper part of Nuclear Map

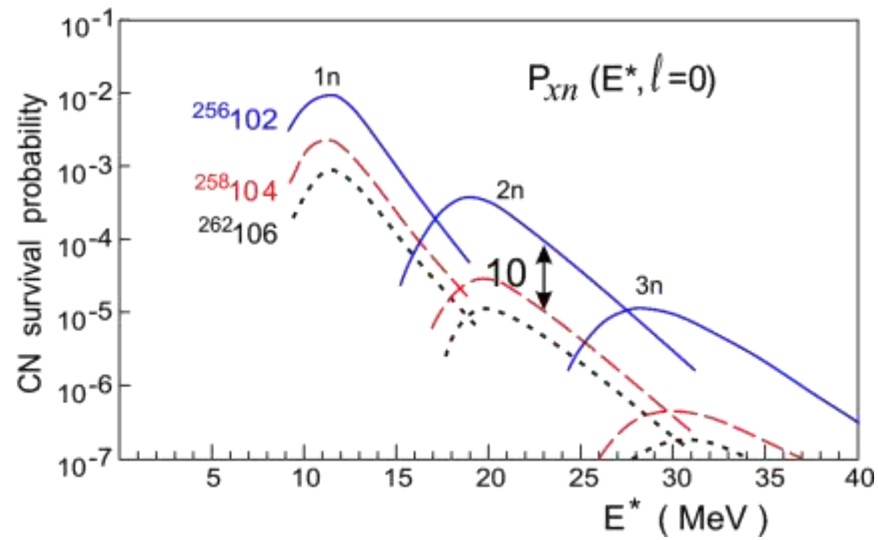


Epoch of ^{48}Ca is almost over. How much is ^{50}Ti worse?



$$\frac{\sigma(^{50}\mathrm{Ti})}{\sigma(^{48}\mathrm{Ca})} = \frac{1}{100}$$



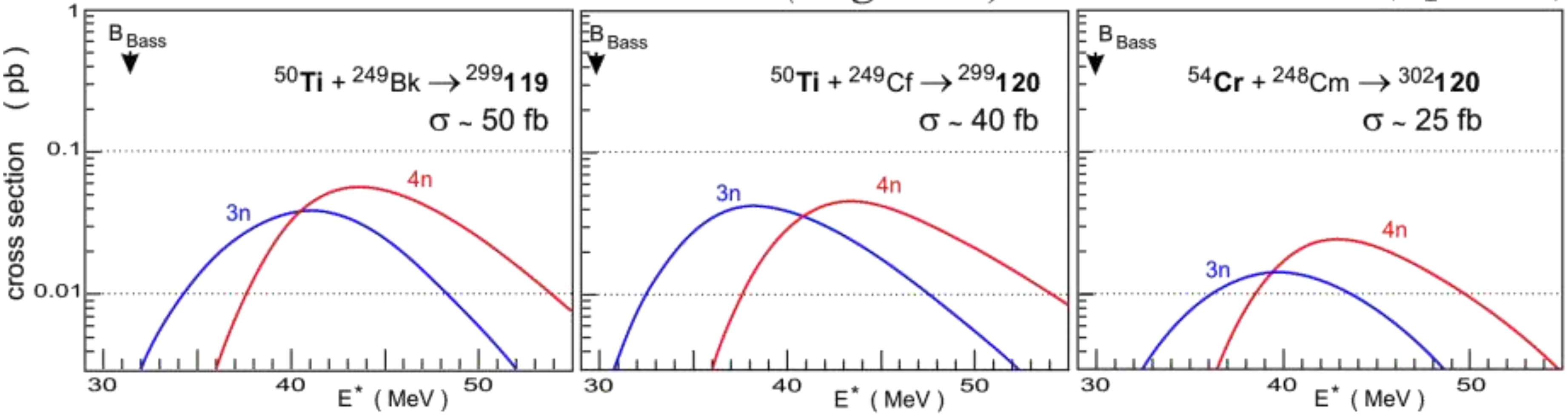


	B_{LD}	δW	B_f	E_n
^{256}102	1.26	4.48	**5.7**	**7.1**
^{258}104	0.77	4.49	**5.3**	**7.6**

Beyond ^{48}Ca: ^{50}Ti and ^{54}Cr induced fusion reactions

Ti beam: started at TASCA (August 19)

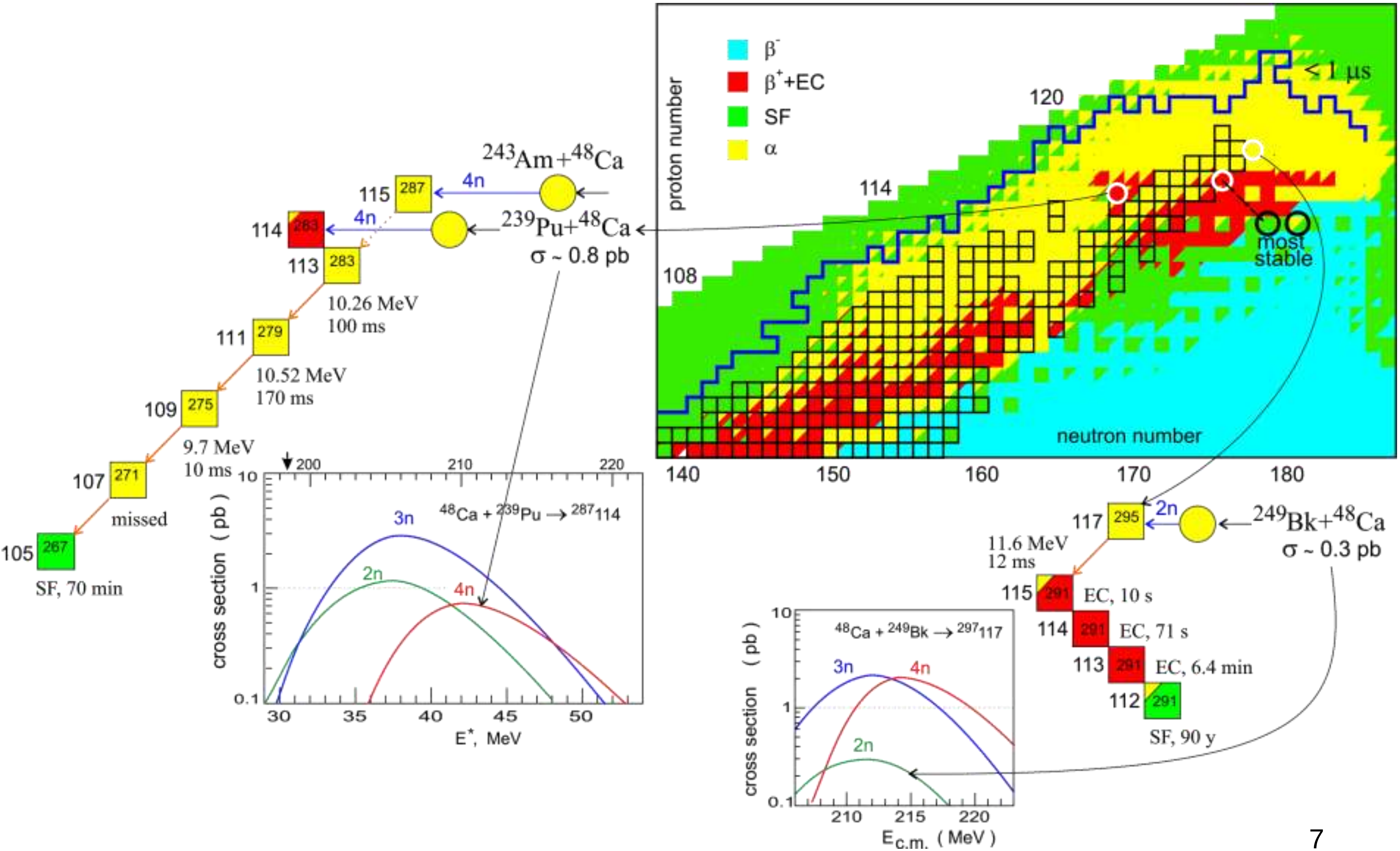
Cr beam: started at SHIP (April 23)



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

Perhaps, these elements are the last ones which will be synthesized in nearest future !?

Narrow pathway to the island of stability



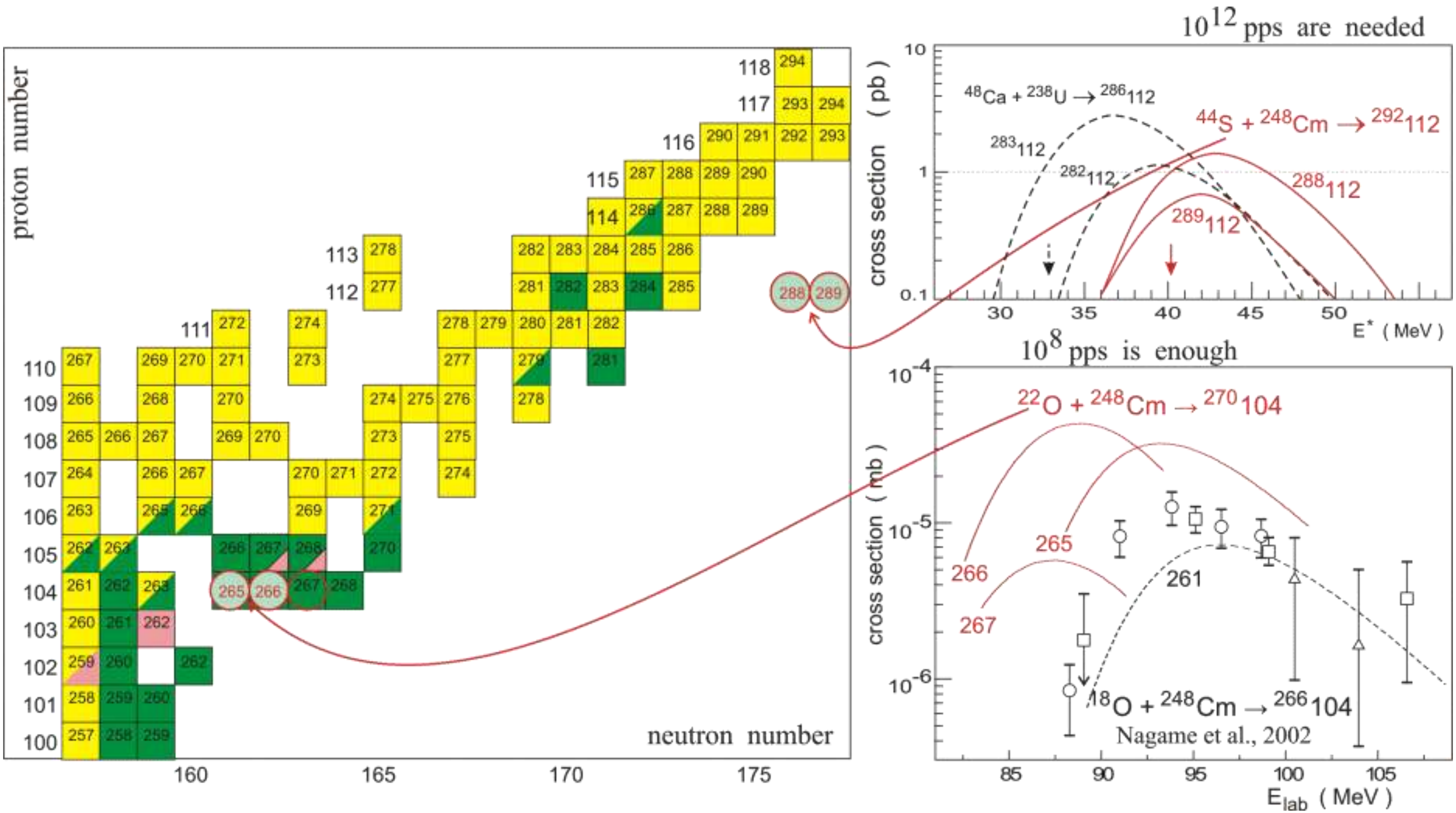
How can we synthesize heavy neutron rich nuclei ?

1. Fusion reactions with radioactive beams
   (e.g., $^{22}O+^{248}Cm$, …)

2. Multi-nucleon transfer reactions

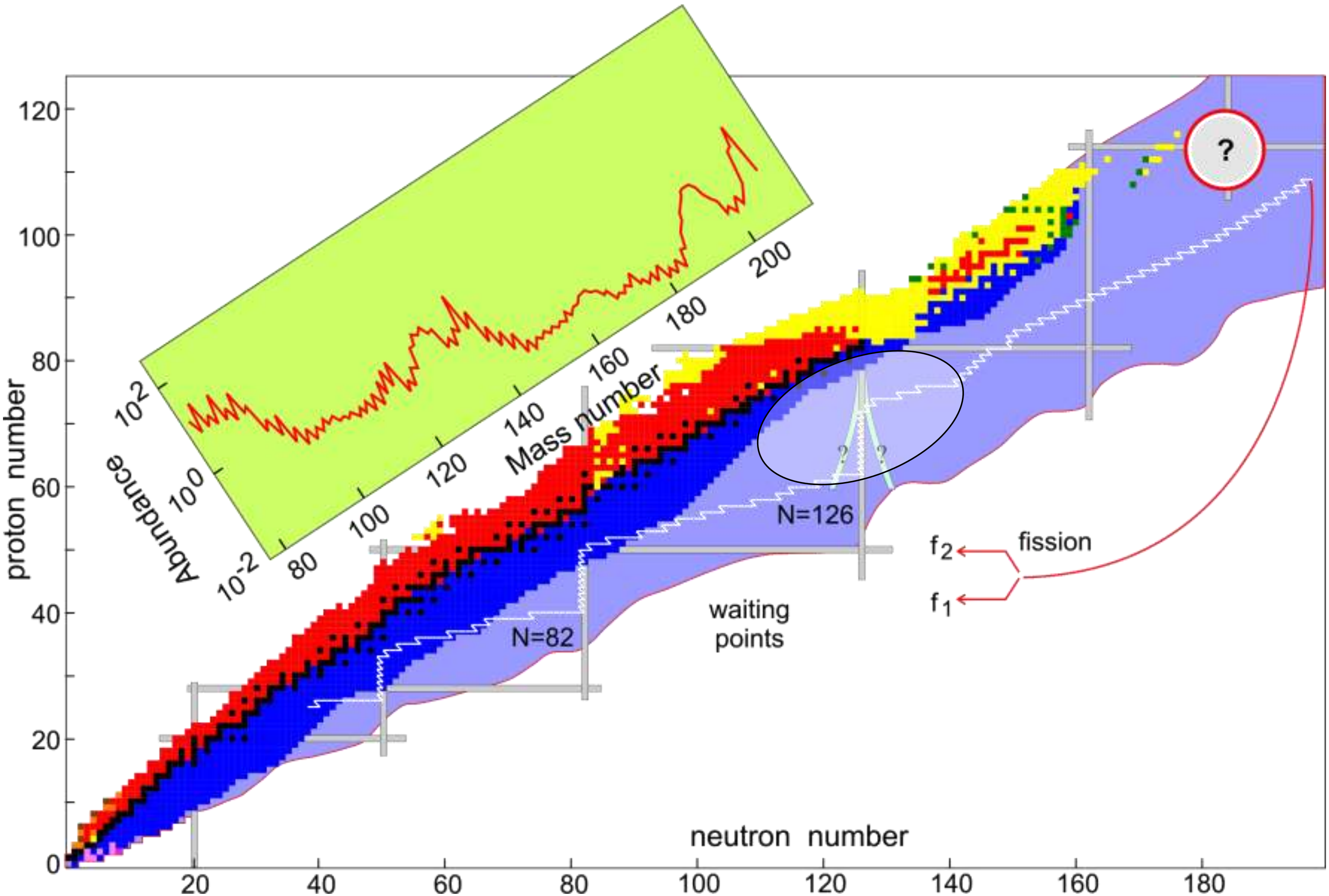
3. Neutron capture processes

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



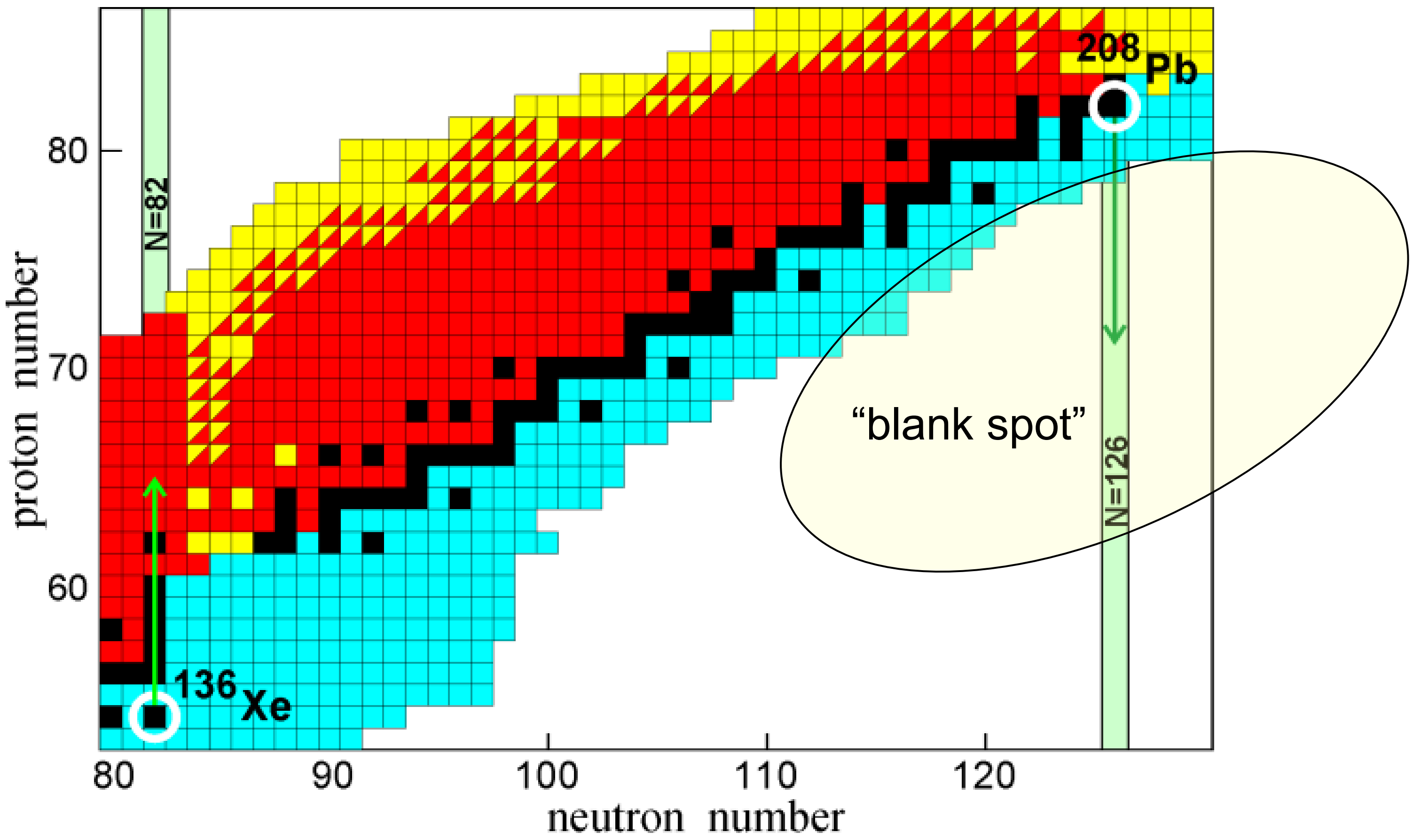
No chances today. But in future ?

Astrophysical r-process and heavy neutron rich nuclei



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

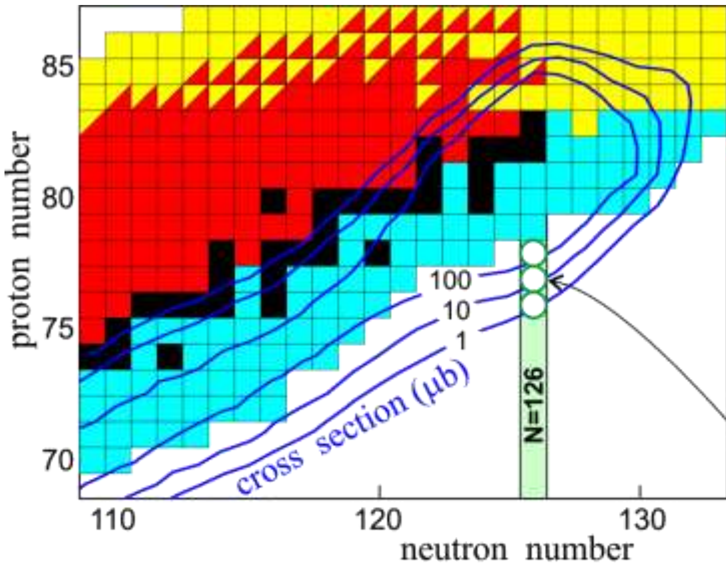
(Zagrebaev and Greiner, Phys. Rev. Lett., 2008)

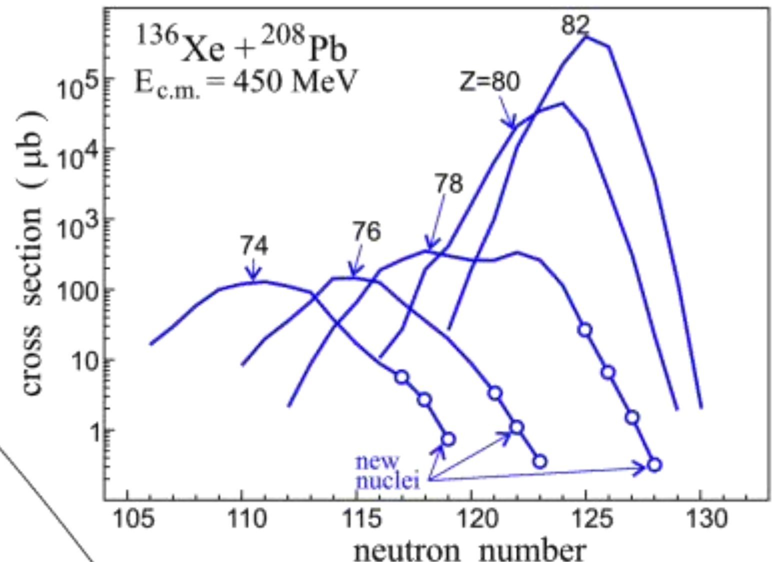


proton transfer along the neutron closed shells:

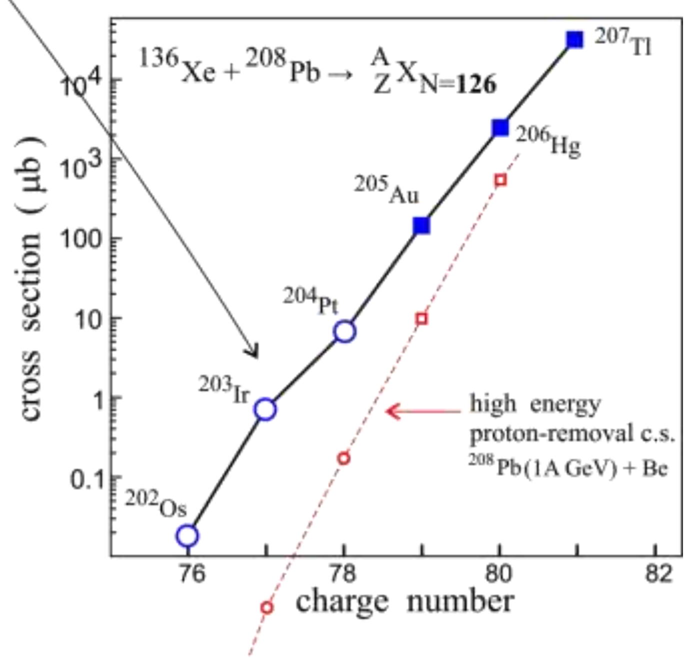
$$^{136}Xe_{N=50} + {}^{208}Pb_{N=\mathbf{126}} \rightarrow {}^{136+\Delta Z}X_{N=50} + {}^{208-\Delta Z}Y_{N=\mathbf{126}} + Q \approx 0$$

Production of new heavy nuclei in the Xe + Pb collisions

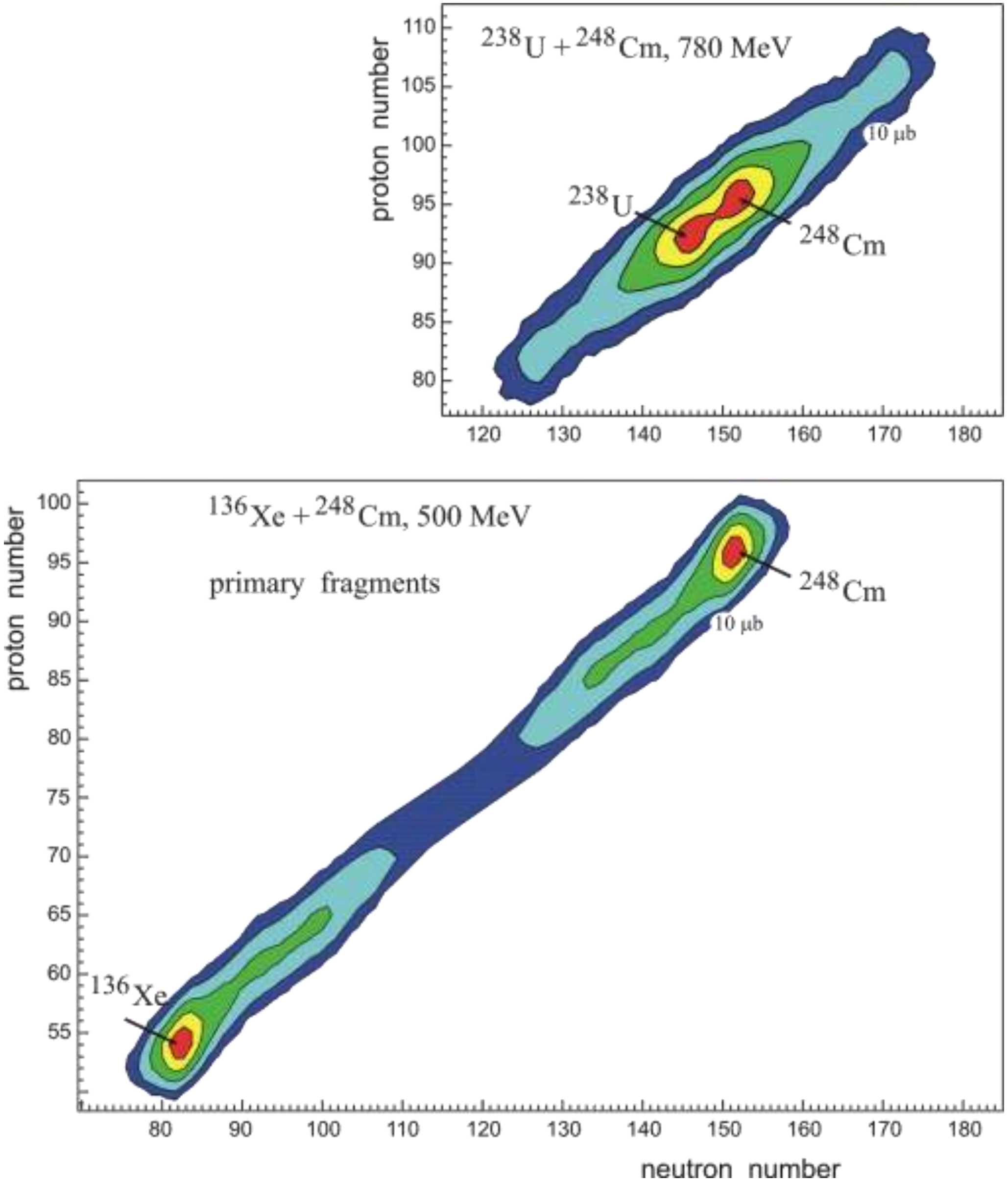




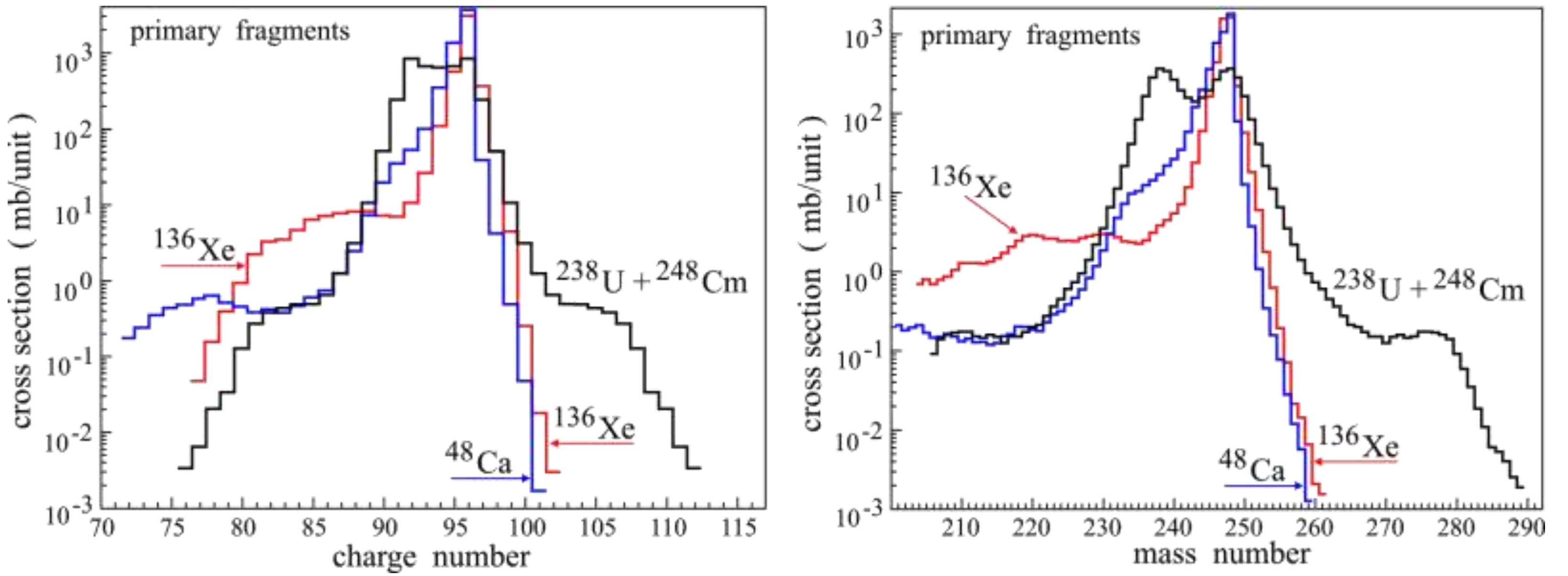
Several tens of new neutron-rich nuclides can be produced with cross section higher than one microbarn in the near-barrier collision of 136Xe with 208Pb



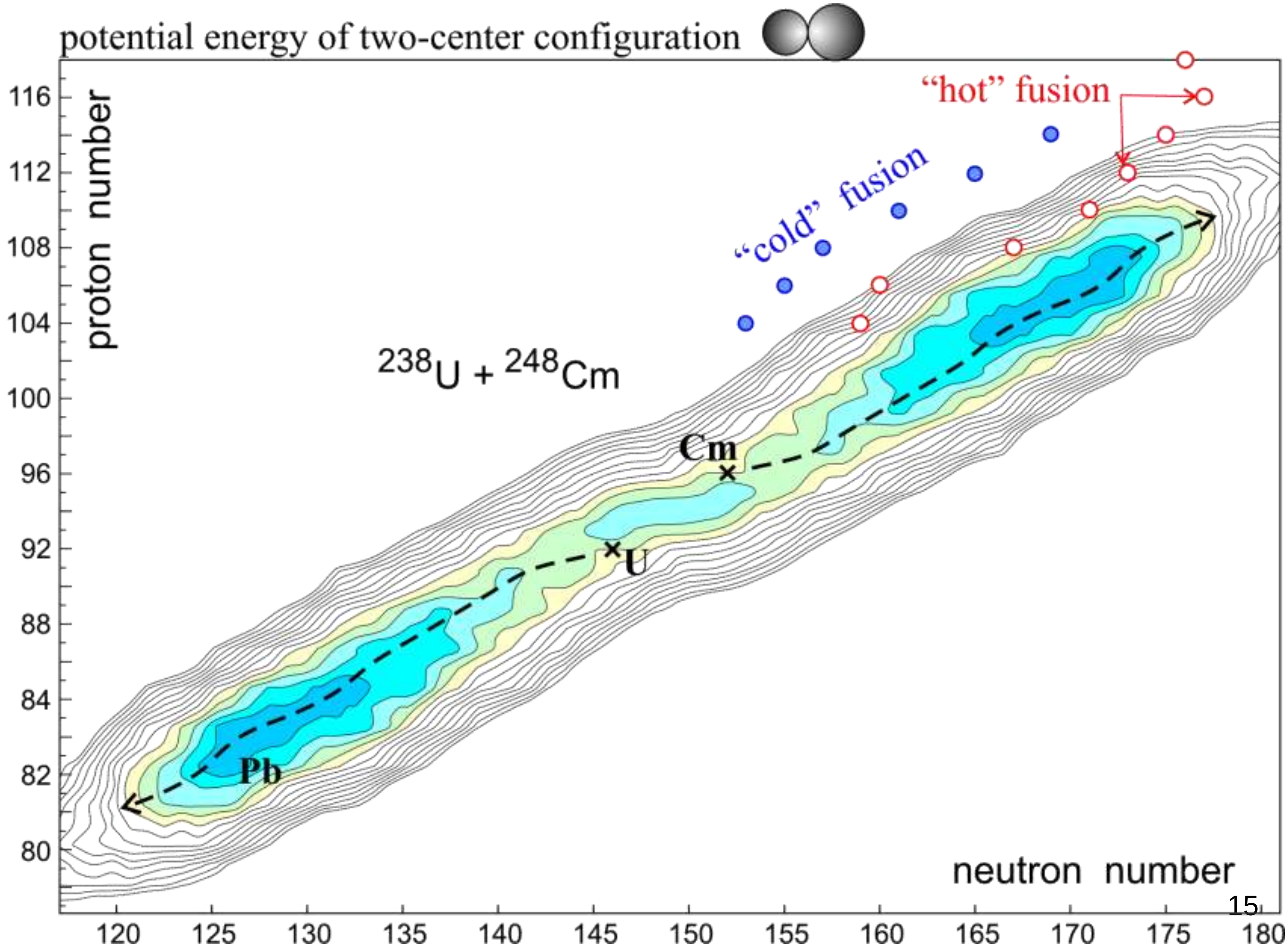
Multi-nucleon transfer for production of superheavies
(choice of reaction is very important)



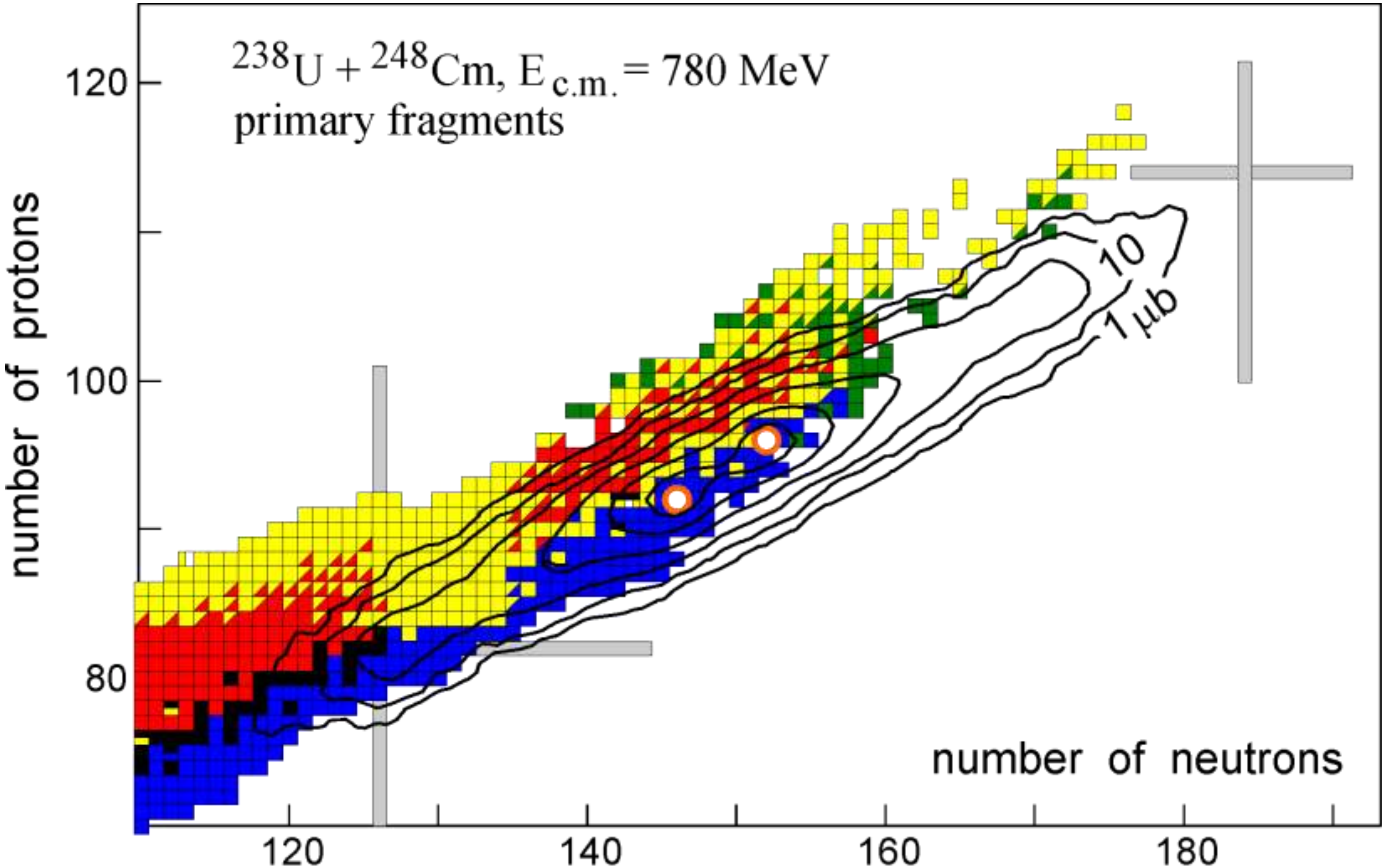
Only U-like beams give us a chance to produce neutron rich SH nuclei in transfer reactions



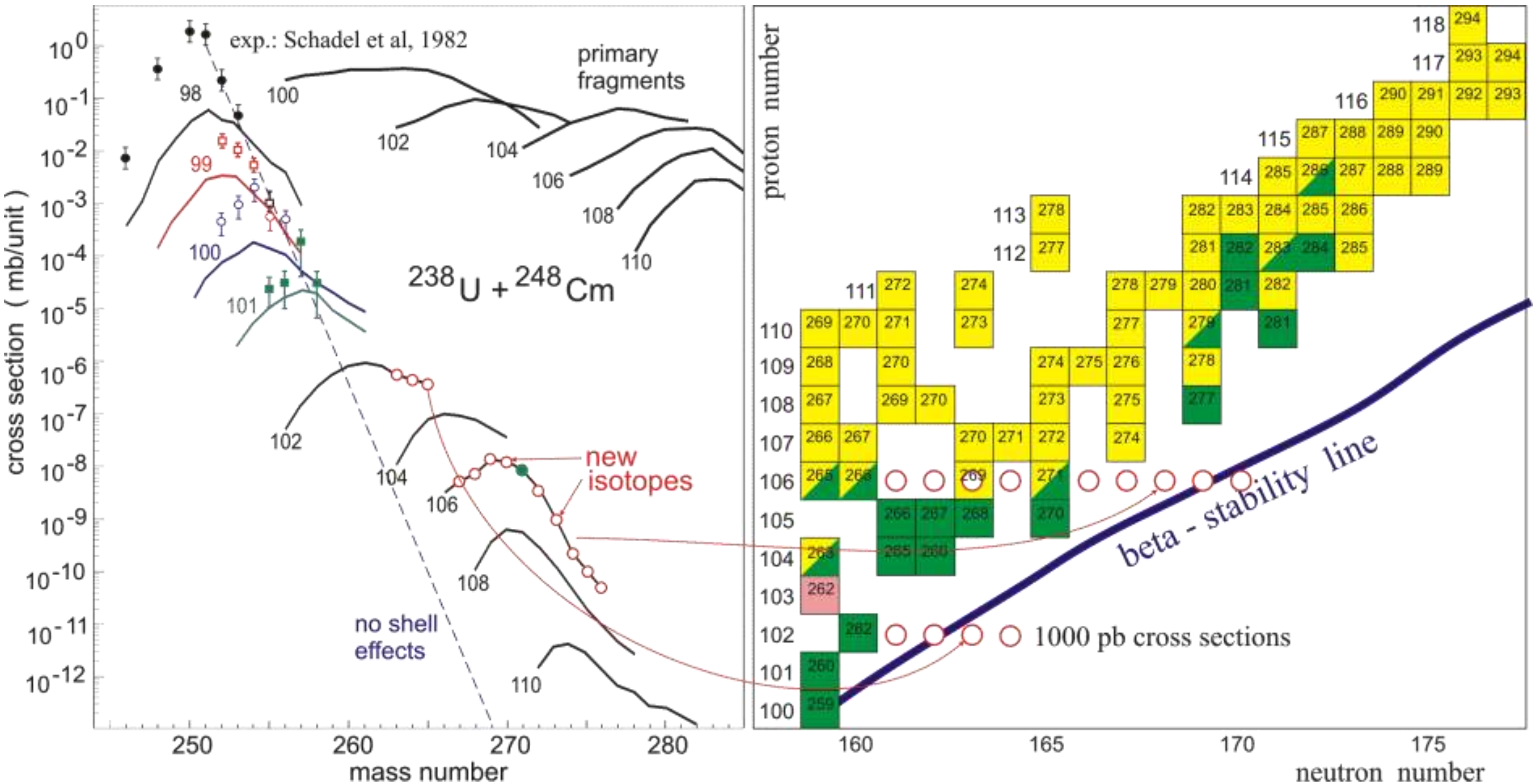
Anti-symmetrising driving potential of the giant nuclear system



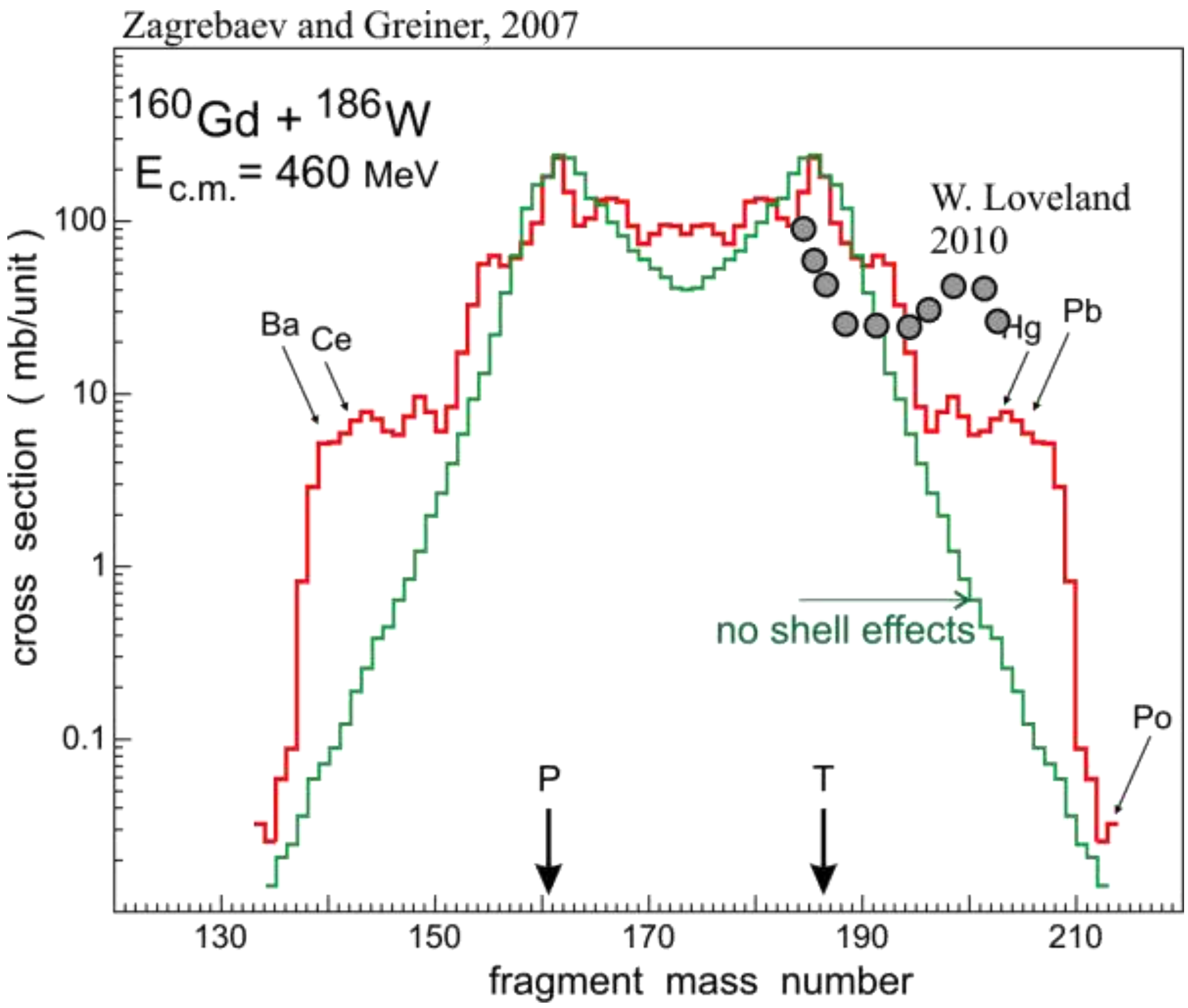
238U + 248Cm. Primary fragments



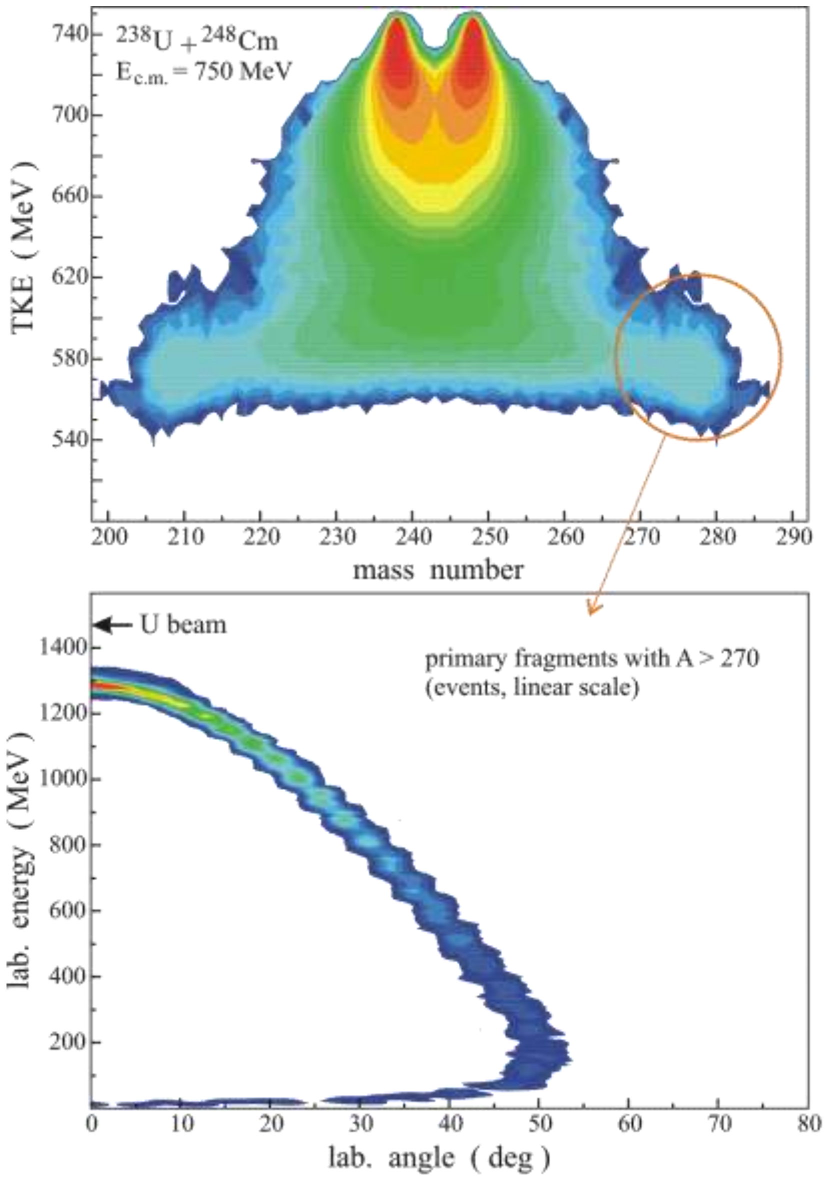
Study of transfermium nuclei along the line of stability becomes possible at last



How much is a role of the shell effects in damped collisions ? Test reaction: $^{160}Gd + ^{186}W$

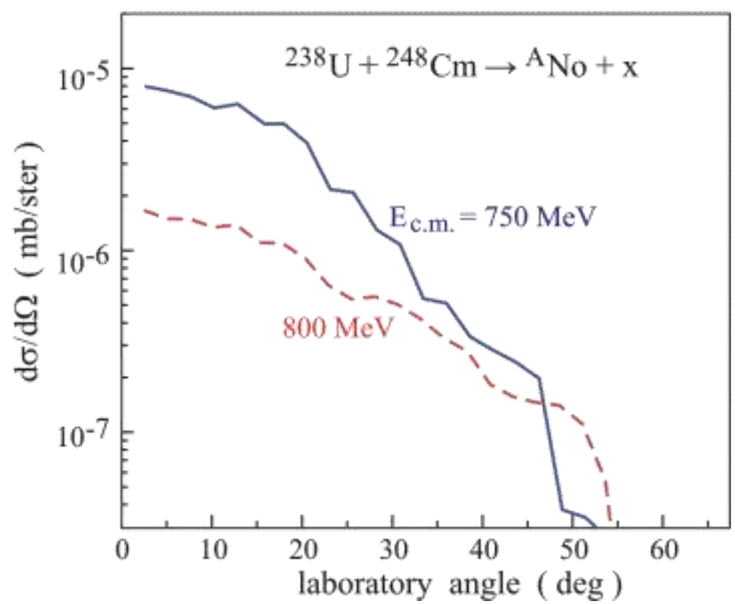


Angular and energy distributions of transfer reaction products

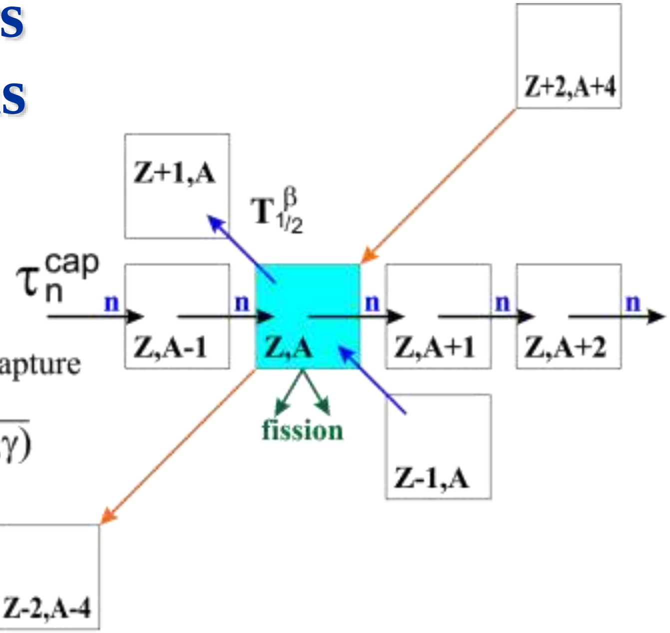


(1) No any “grazing” features

(2) Separators of new kind are needed



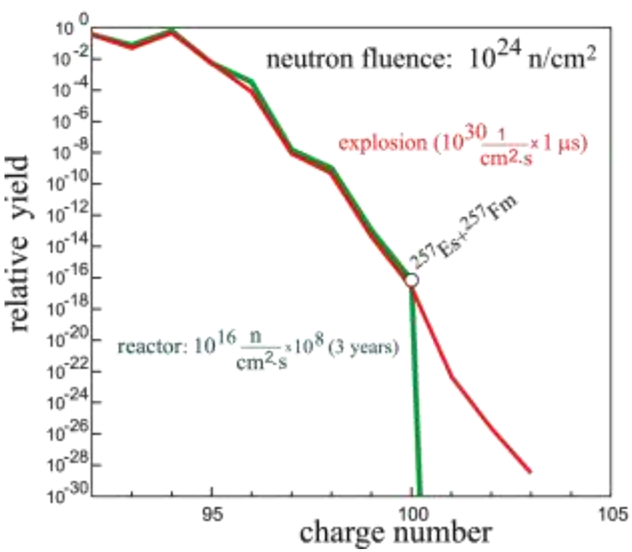
Nucleogenesis in reactors and in nuclear explosions

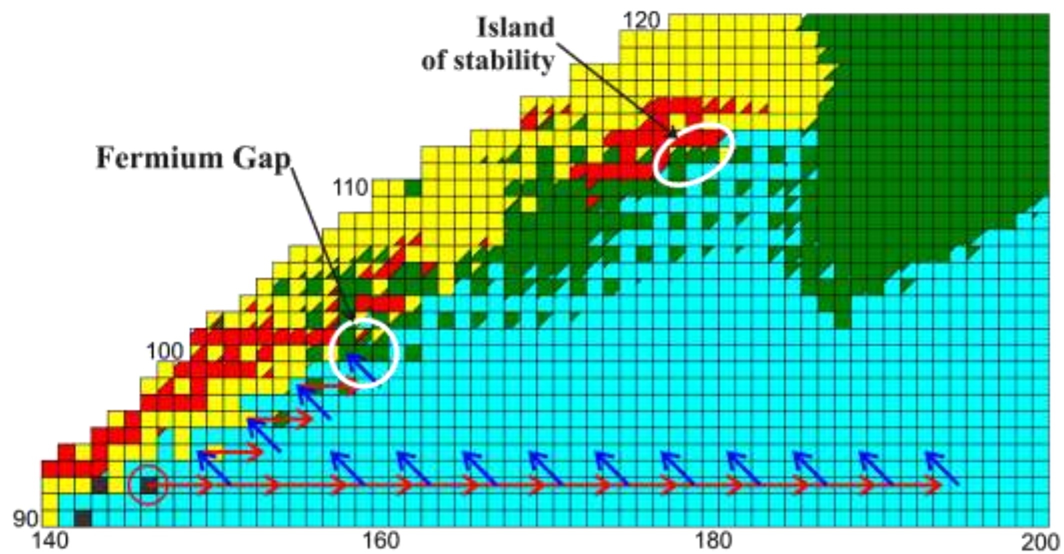


time of neutron capture

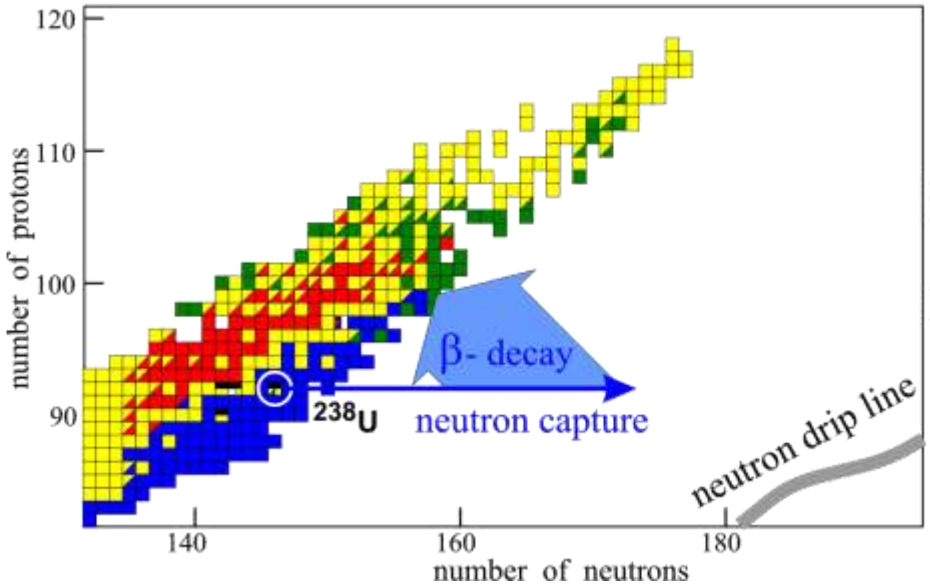
$$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$$

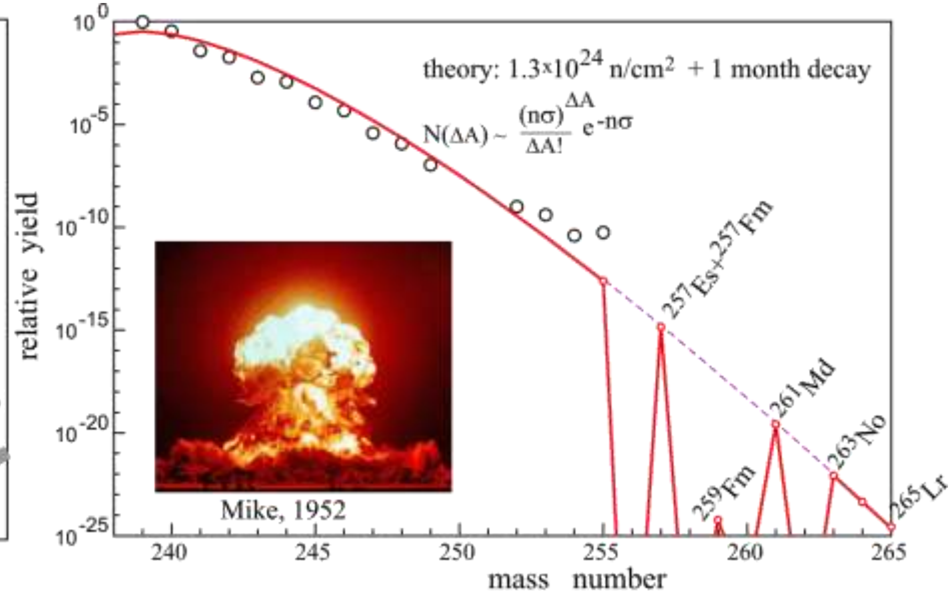
$$\frac{dN_{ZA}}{dt} = N_{ZA-1}\, n_0\, \sigma^{n\gamma}_{ZA-1} - N_{ZA}\, n_0\, \sigma^{n\gamma}_{ZA} - N_{ZA} \frac{\ln 2}{T^{\beta}_{ZA}} - N_{ZA} \frac{\ln 2}{T^{\alpha}_{ZA}} - N_{ZA} \frac{\ln 2}{T^{fis}_{ZA}} + N_{Z-1A} \frac{\ln 2}{T^{\beta}_{Z-1A}} + N_{Z+2A+4} \frac{\ln 2}{T^{\alpha}_{Z+2A+4}}$$





Rapid neutron capture in nuclear explosions



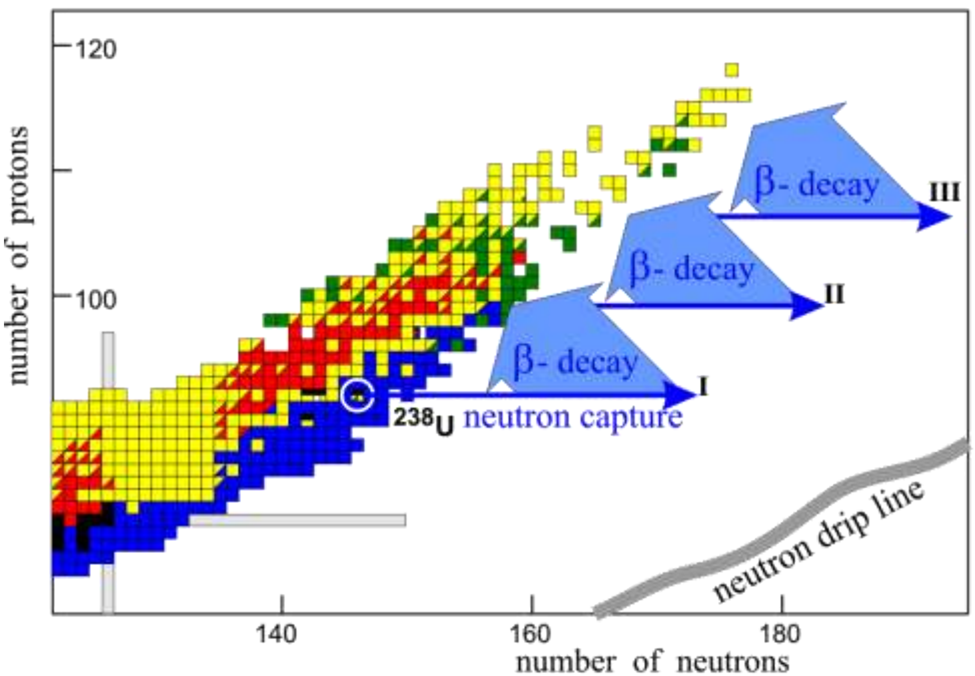


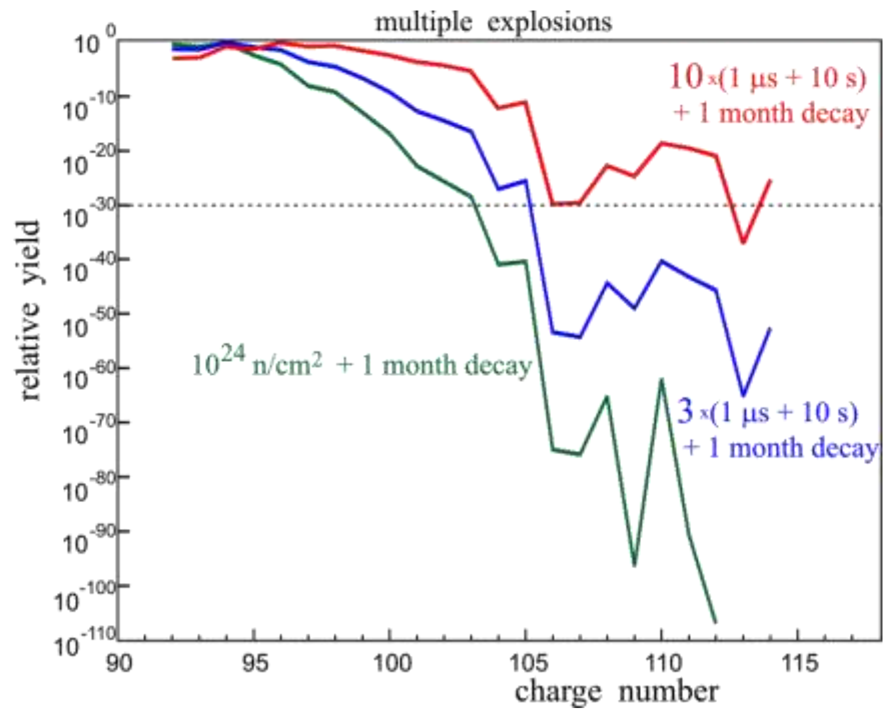
How much could be enhancement in the yield of superheavies in multiple (one by one) nuclear explosions **?**

(the idea was already discussed by Edward Teller and his colleagues 40 years ago)

Multiple nuclear explosions

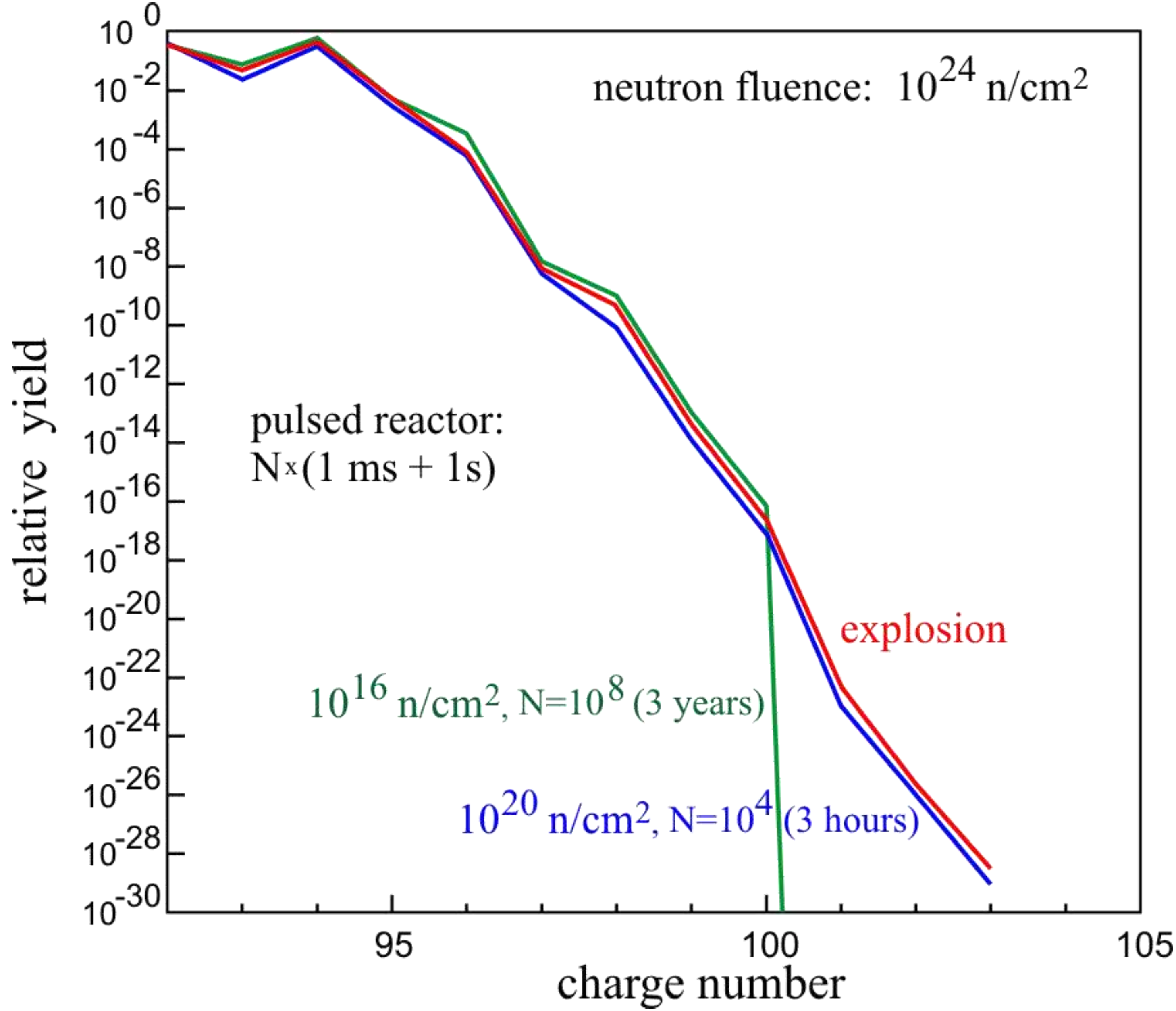
(Edward Teller: Technically it is quite possible)





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

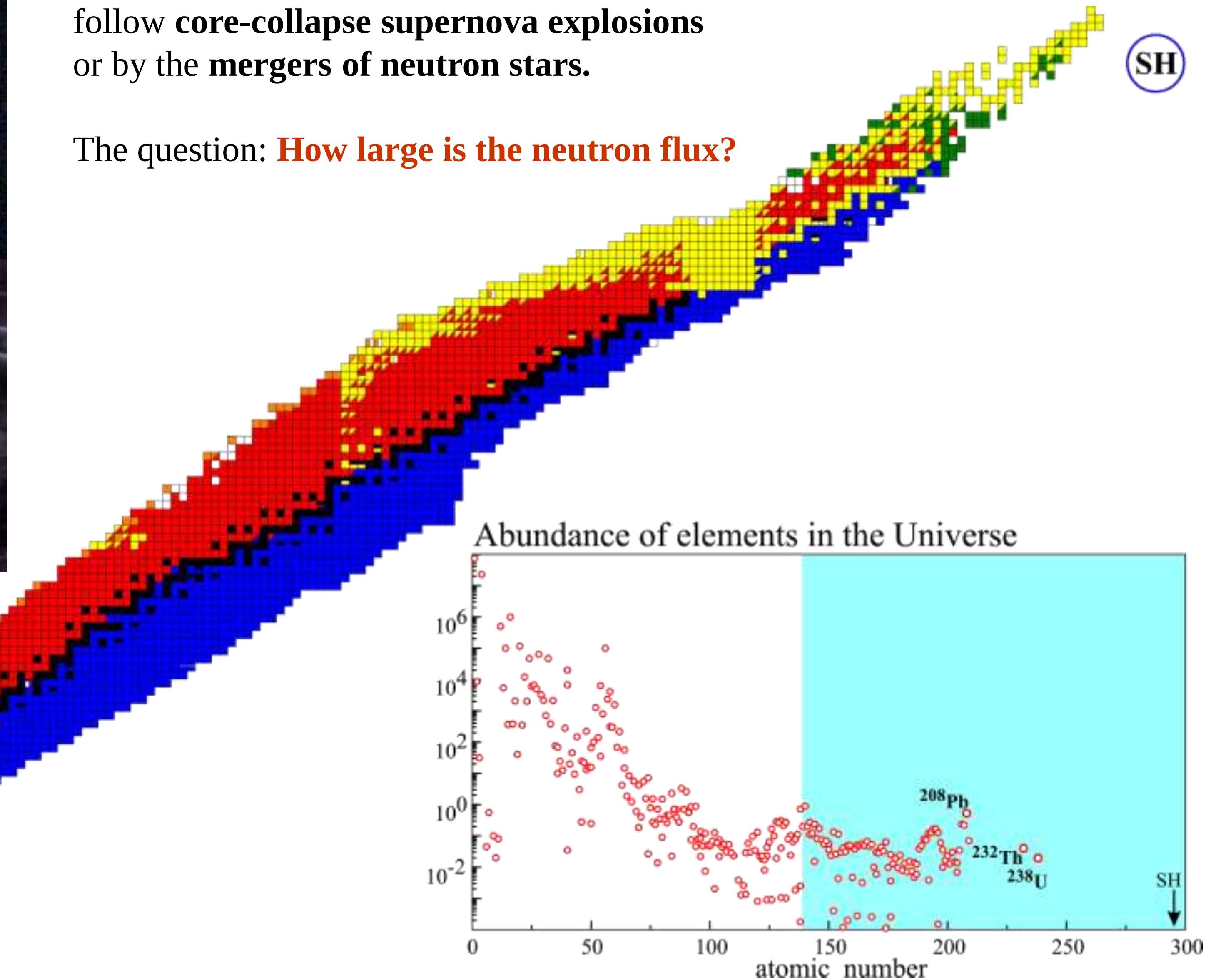
Next generation of Pulsed Reactors: We need factor 10^3 only !



Formation of SH elements in astrophysical r-process

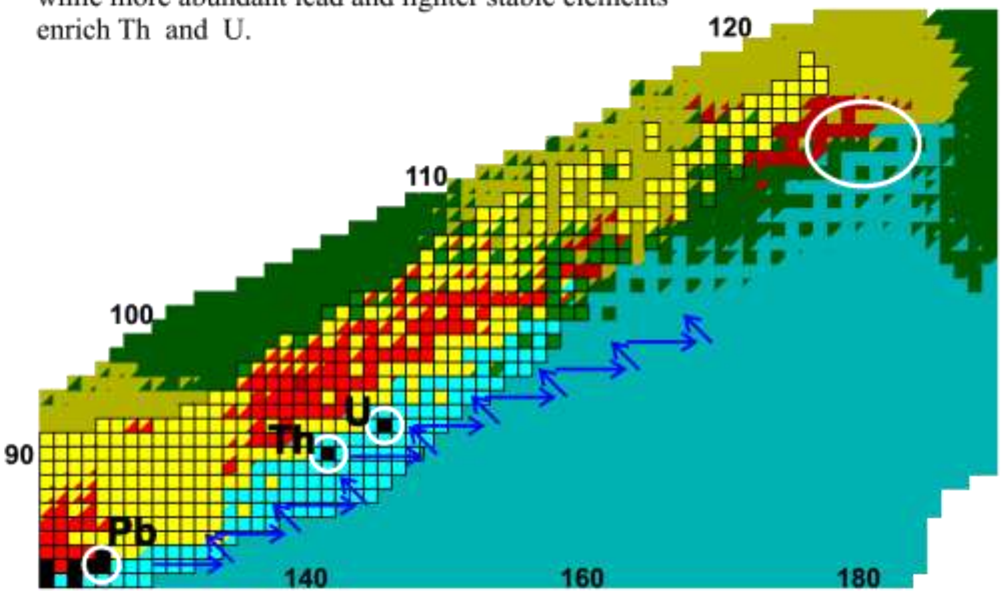
Strong neutron fluxes are expected to be generated by neutrino-driven proto-neutron star winds which follow **core-collapse supernova explosions** or by the **mergers of neutron stars.**

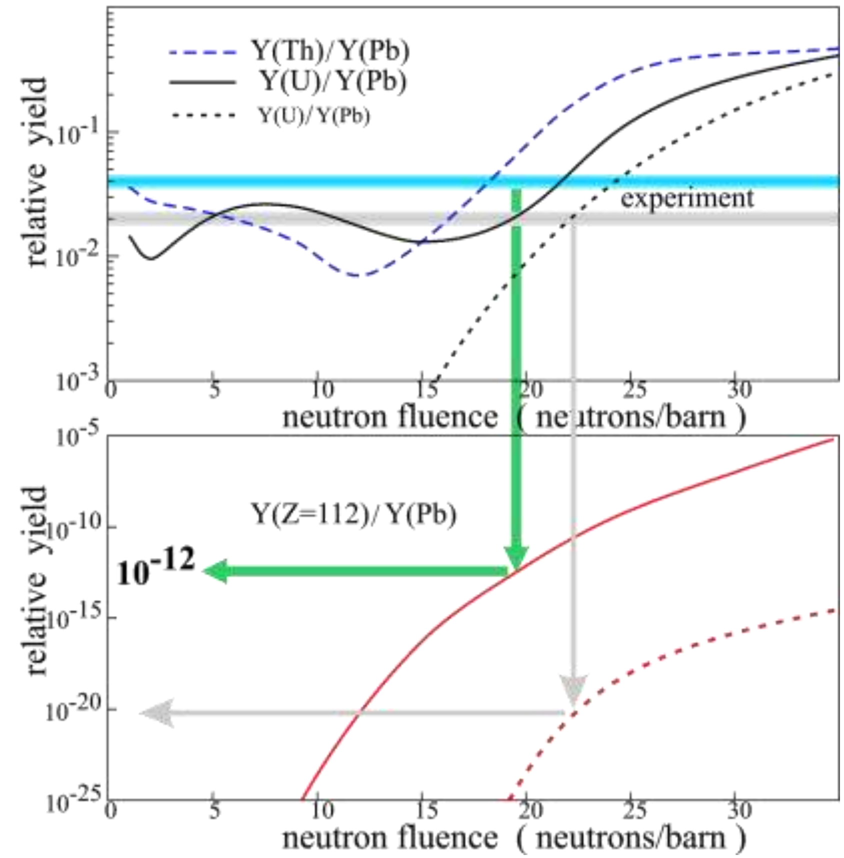
The question: **How large is the neutron flux?**



Formation of SH elements in astrophysical r-process

During intensive neutron irradiation initial Th and U material are depleted transforming to heavier elements and going to fission, while more abundant lead 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 its experimental values.

For a given neutron fluence one gets the relative yield of SH elements, SH/Pb.

Summary

- **Elements 119 and 120 may be synthesized in the Ti and/or Cr fusion reactions with cross sections of about 0.02 - 0.04 pb.**
  Perhaps they are the last SH elements with $T_{1/2} > 1$ μs ?
- **Multi-nucleon transfer reactions are to be used for synthesis of neutron enriched long-living SH nuclei close to beta-stability line.**
  48Ca and 136Xe beams are insufficient. Uranium-like beam is needed !
- **A macroscopic amount of the long-living SH nuclei located at the island of stability may be really produced in the multiple (rather "soft") nuclear explosions. This goal could be also reached by the use of pulsed nuclear reactors of 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 is about 10^{-12}.**

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