Synthesis of superheavy nuclei: nearest and distant opportunities

- **Fusion reactions**
  - **Elements 119 and 120 are on the way. What's the next?**
  - **Filling the gap of not-yet-synthesized isotopes of SH elements (Z=106 - 116)**
  - **Narrow (hypothetical) pathway to the Island of Stability**
  - **Radioactive ion beams**
- **Neutron capture process**
  - **Pulsed nuclear reactors of the next generation**
  - **Astrophysical nucleosynthesis and SHE in nature**
- **Transfer reactions**
  - **Shell effects in damped collisions of heavy ions ?**
  - **Production of new neutron rich SH nuclei in transfer reactions**

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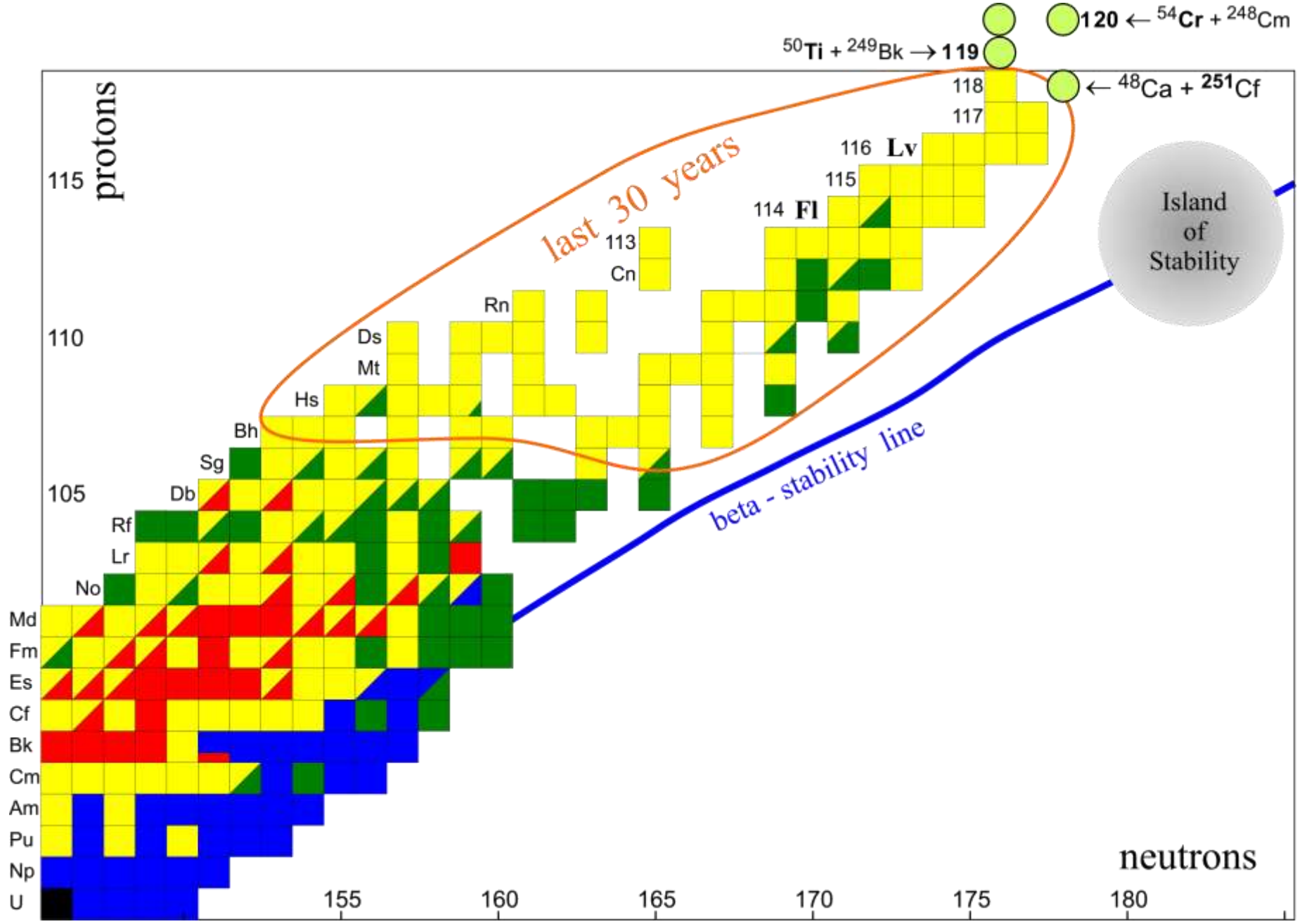
Mazurian Lakes Conference on Physics, Poland, 2013

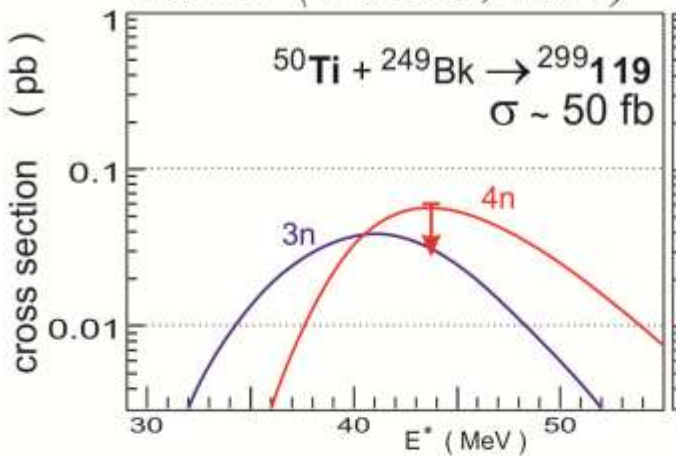
We are still far from the Island of Stability



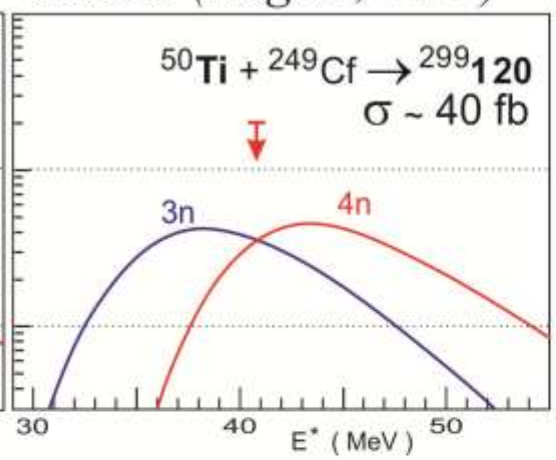
New elements 119 and 120 are coming !

Ti beam:

TASCA (October, 2012)

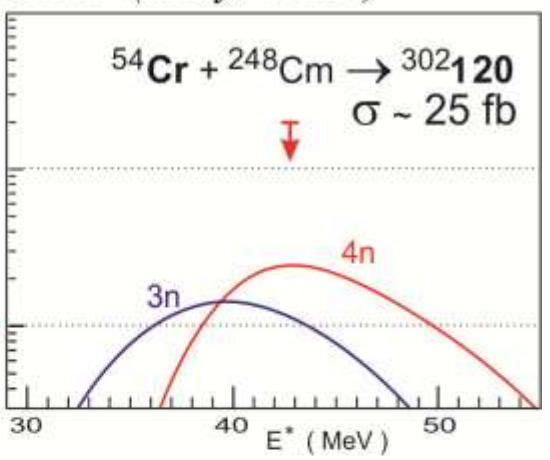


TASCA (August, 2011)



Cr beam:

SHIP (May, 2011)

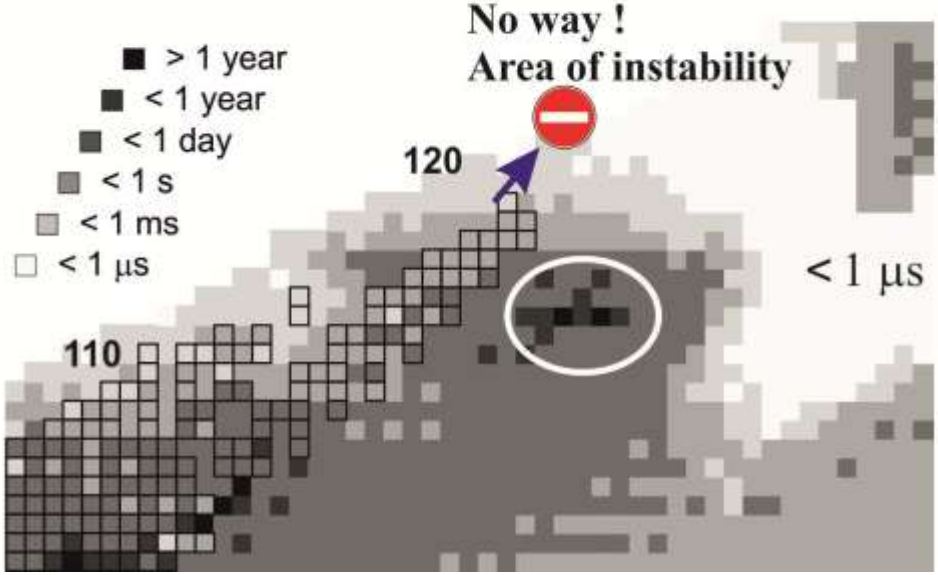


our predictions (PRC 2008):

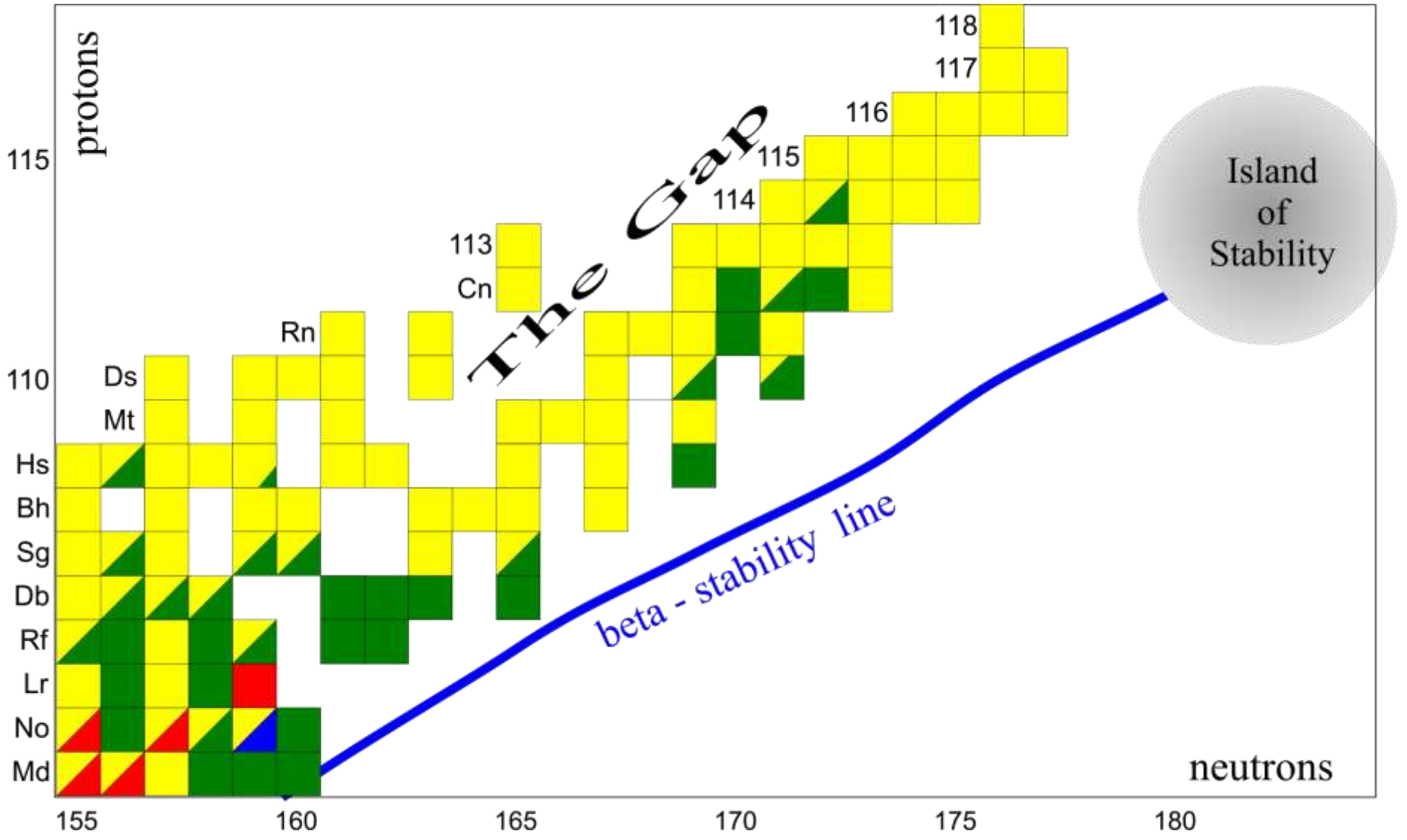
factor $\frac{1}{20}$ as compared to ^{48}Ca

Approaching the area of instability:

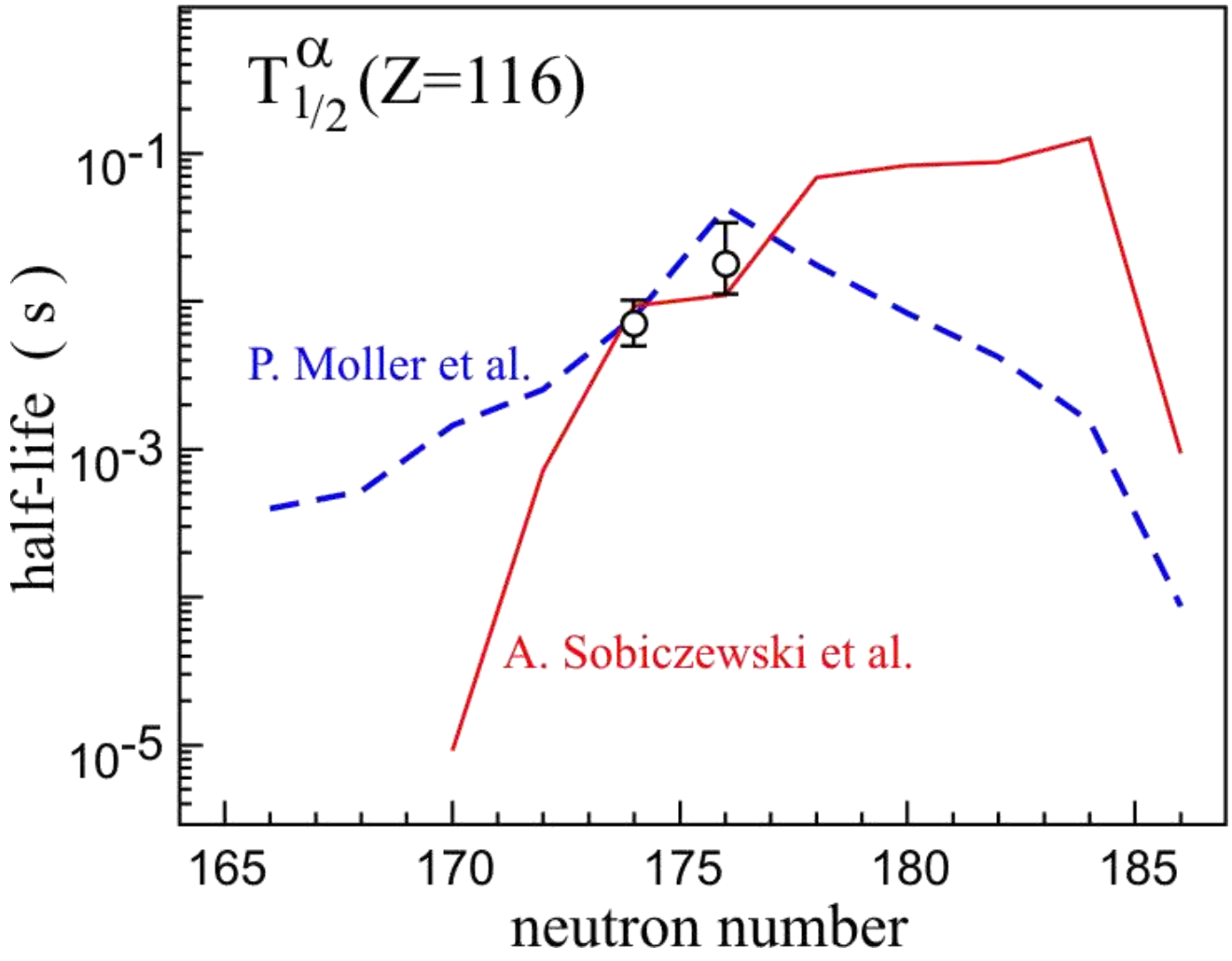
Probably, these elements are the last ones which will be synthesized in the nearest future



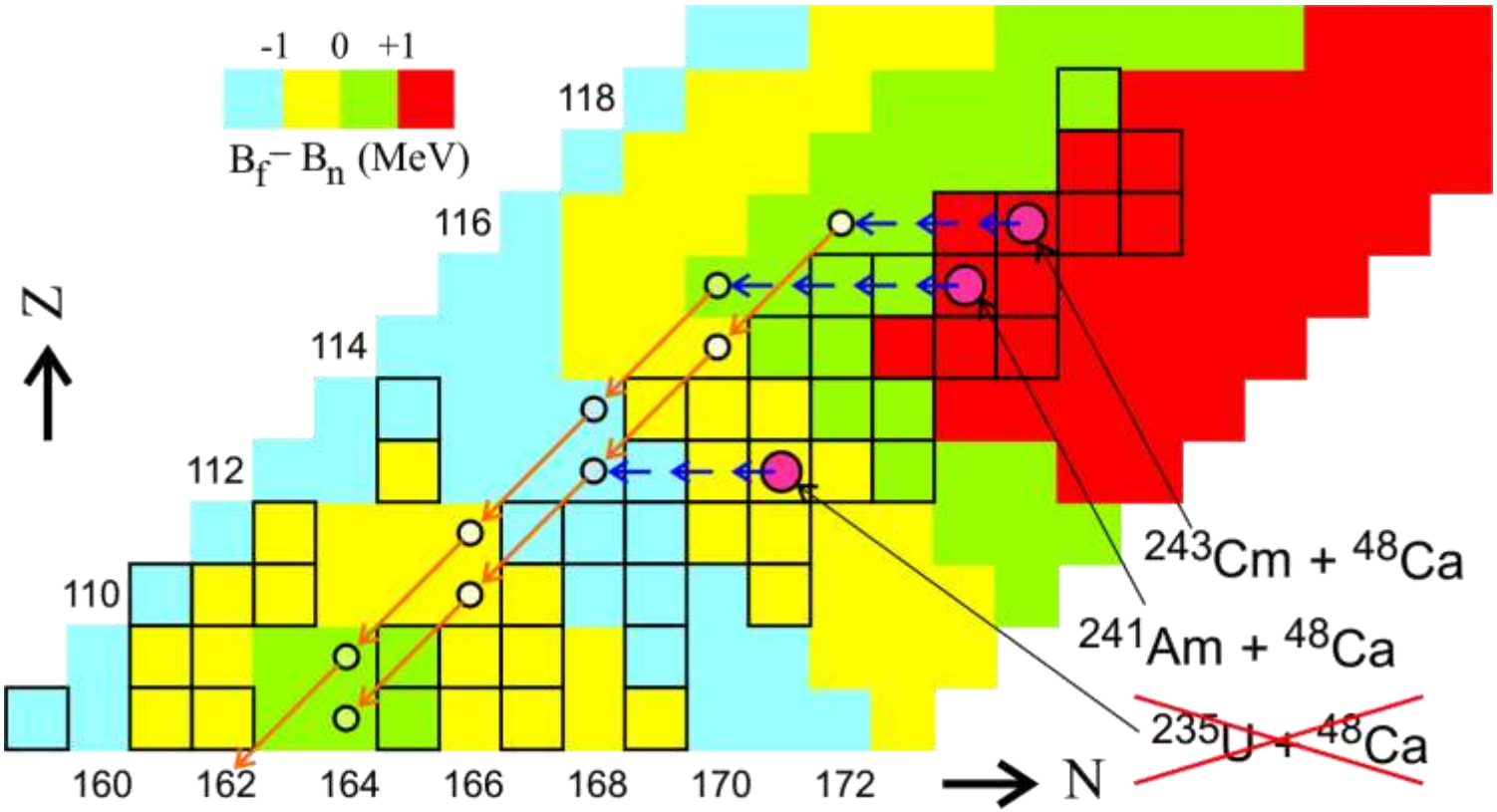
It is important to fill the Gap in superheavy mass area



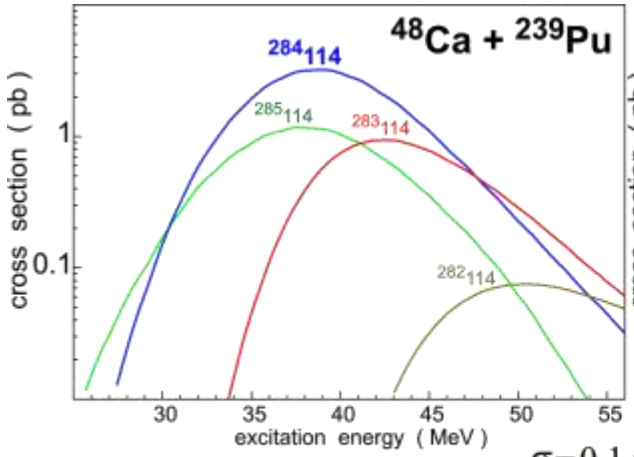
Our ability of predictions in superheavy mass area

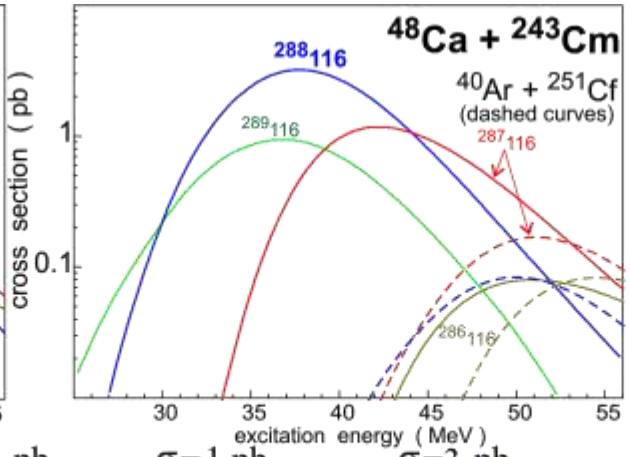


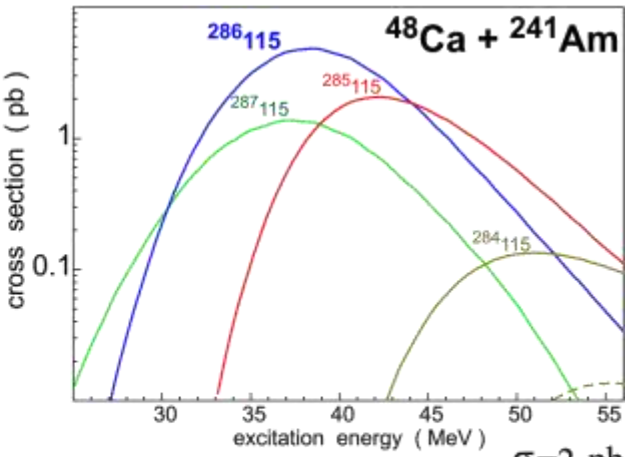
It is easier to fill the Gap from above using available actinide targets ^{241}Am, ^{239}Pu, ^{243}Cm…

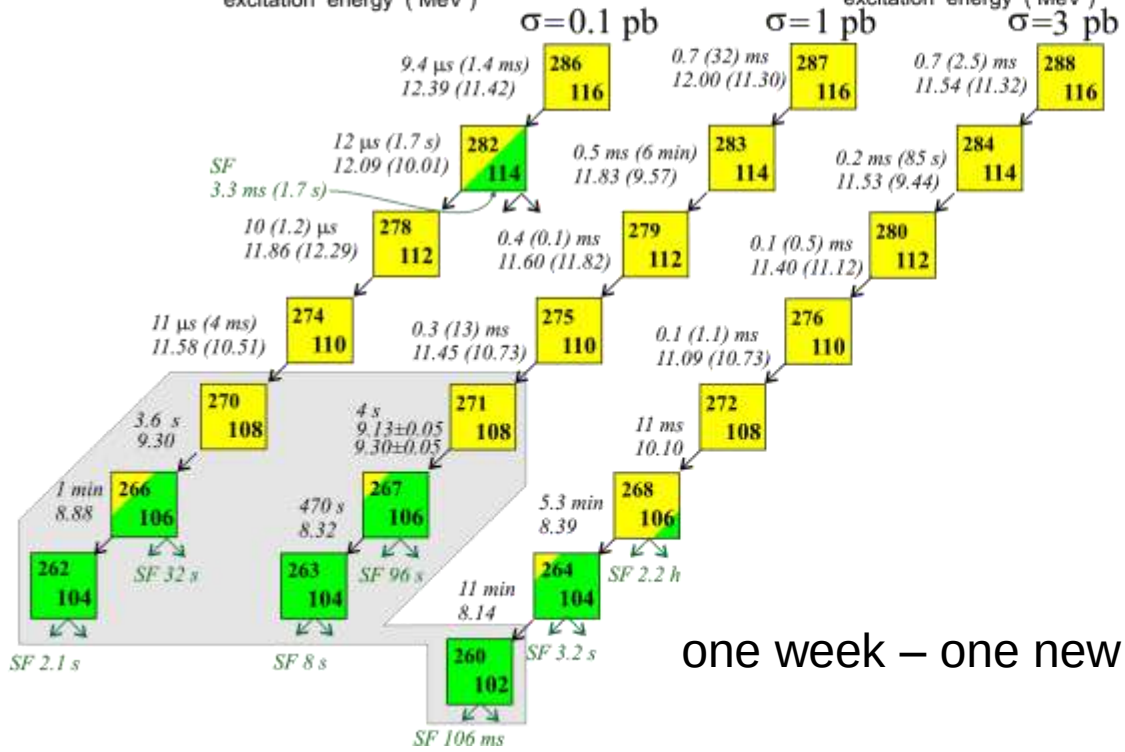


Predicted cross sections are high enough to perform experiments at available facilities just now



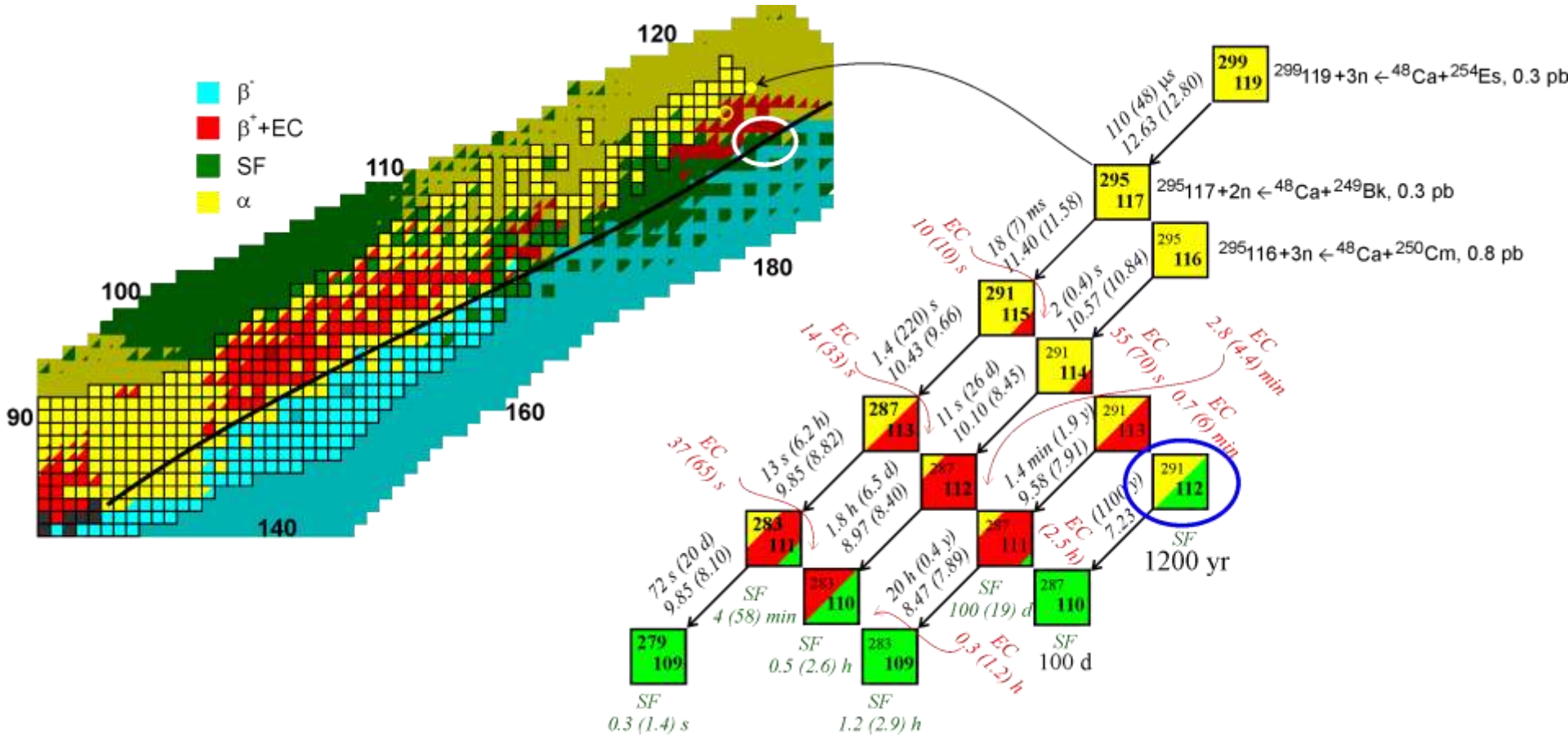




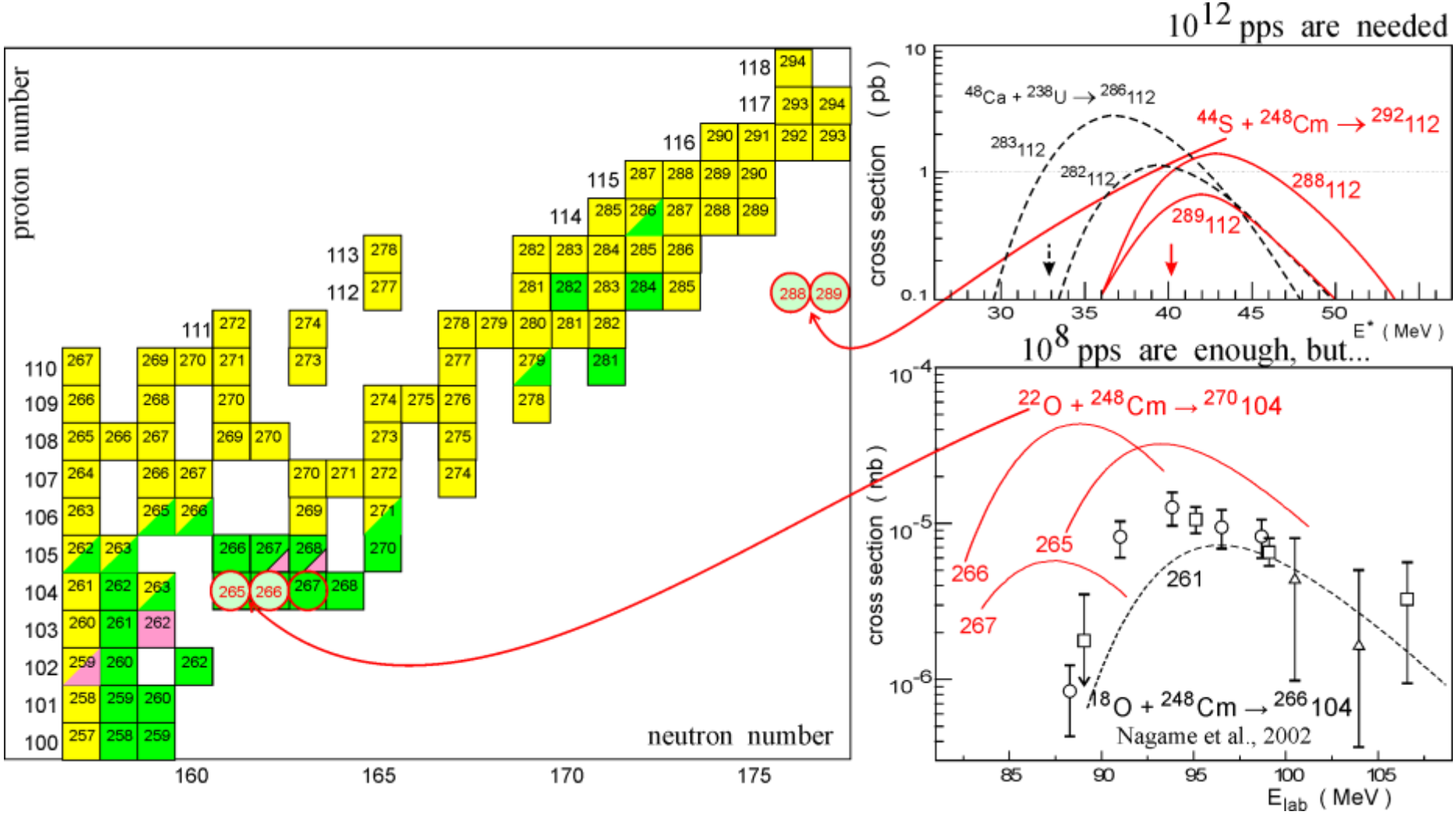


one week – one new chain

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



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



No chances today and in the nearest future

Nucleosynthesis by neutron capture

n_0 is the neutron flux

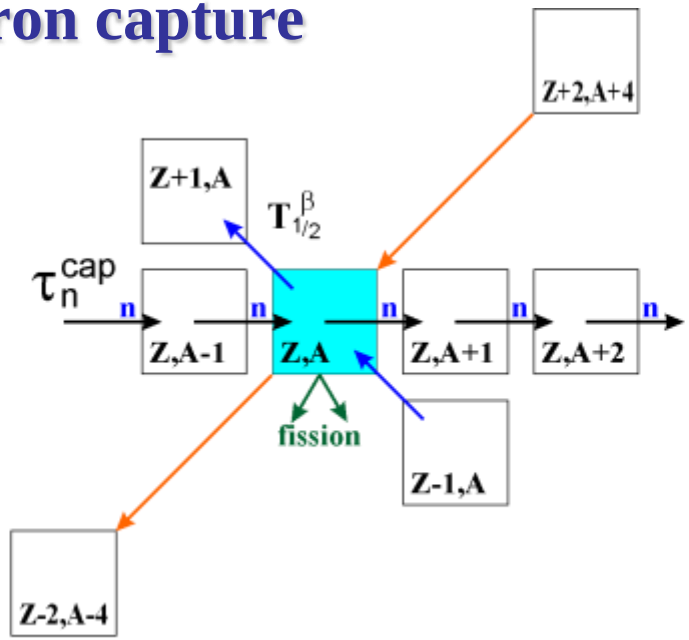
time of neutron capture

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

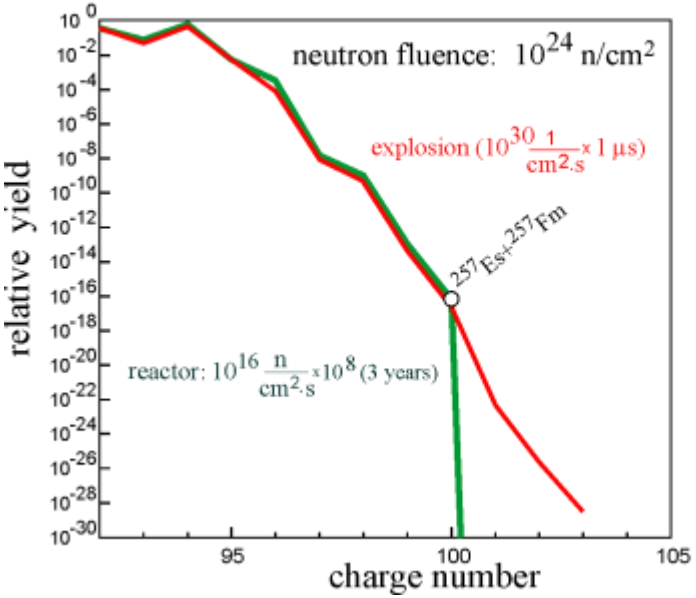
$(Z,A) \rightarrow (Z,A+1)$ if $T_{1/2} > \tau_n^{cap}$

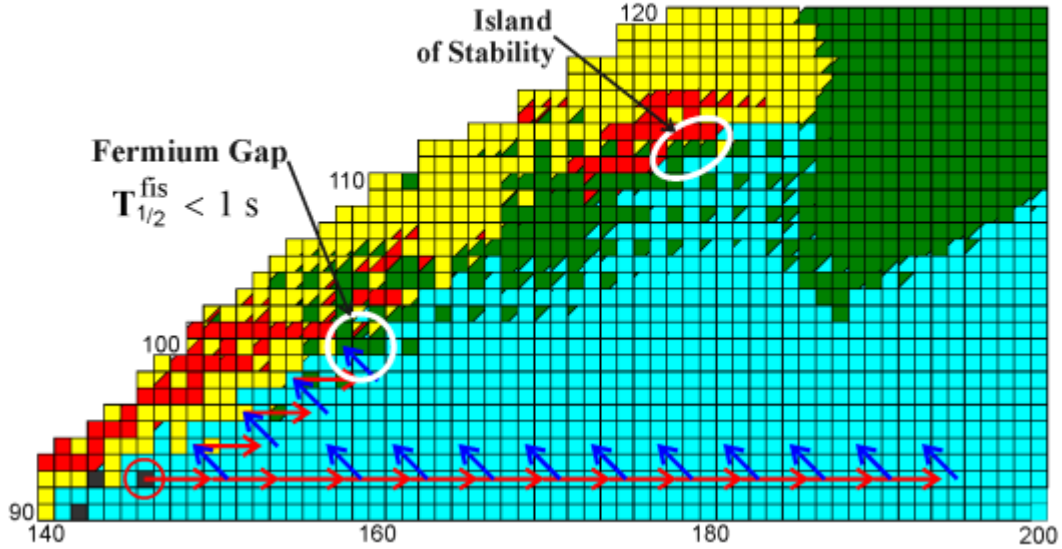
nuclear reactor: $\tau_n^{cap} \sim 1$ year

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



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

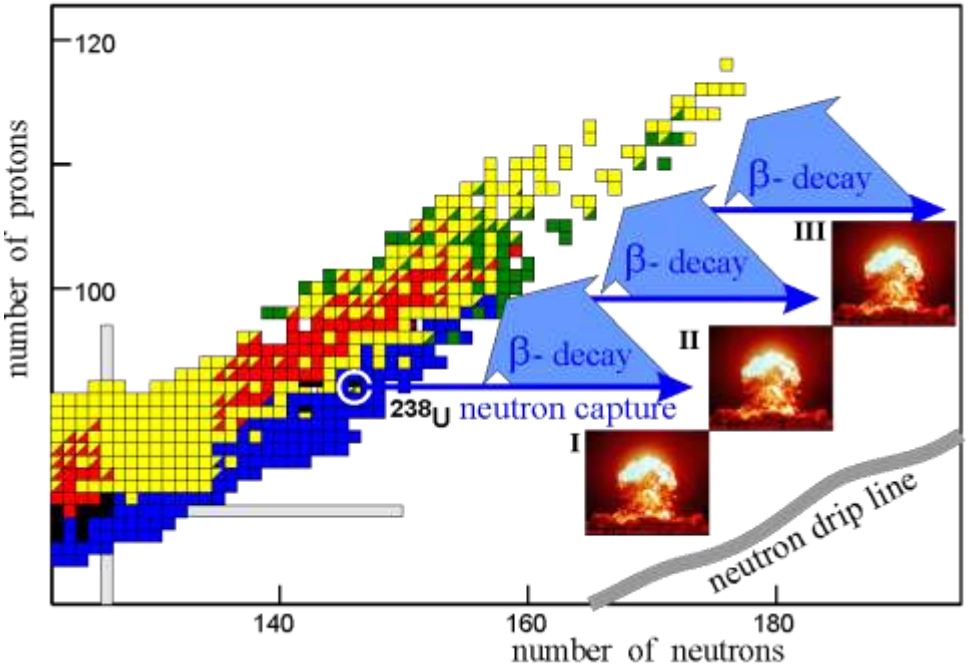


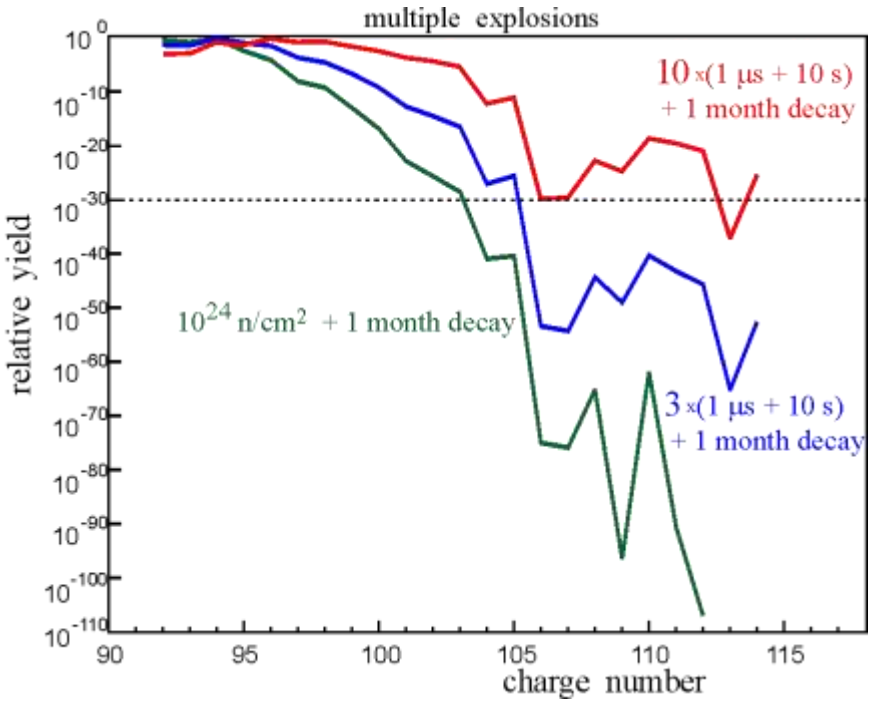


Multiple nuclear explosions

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

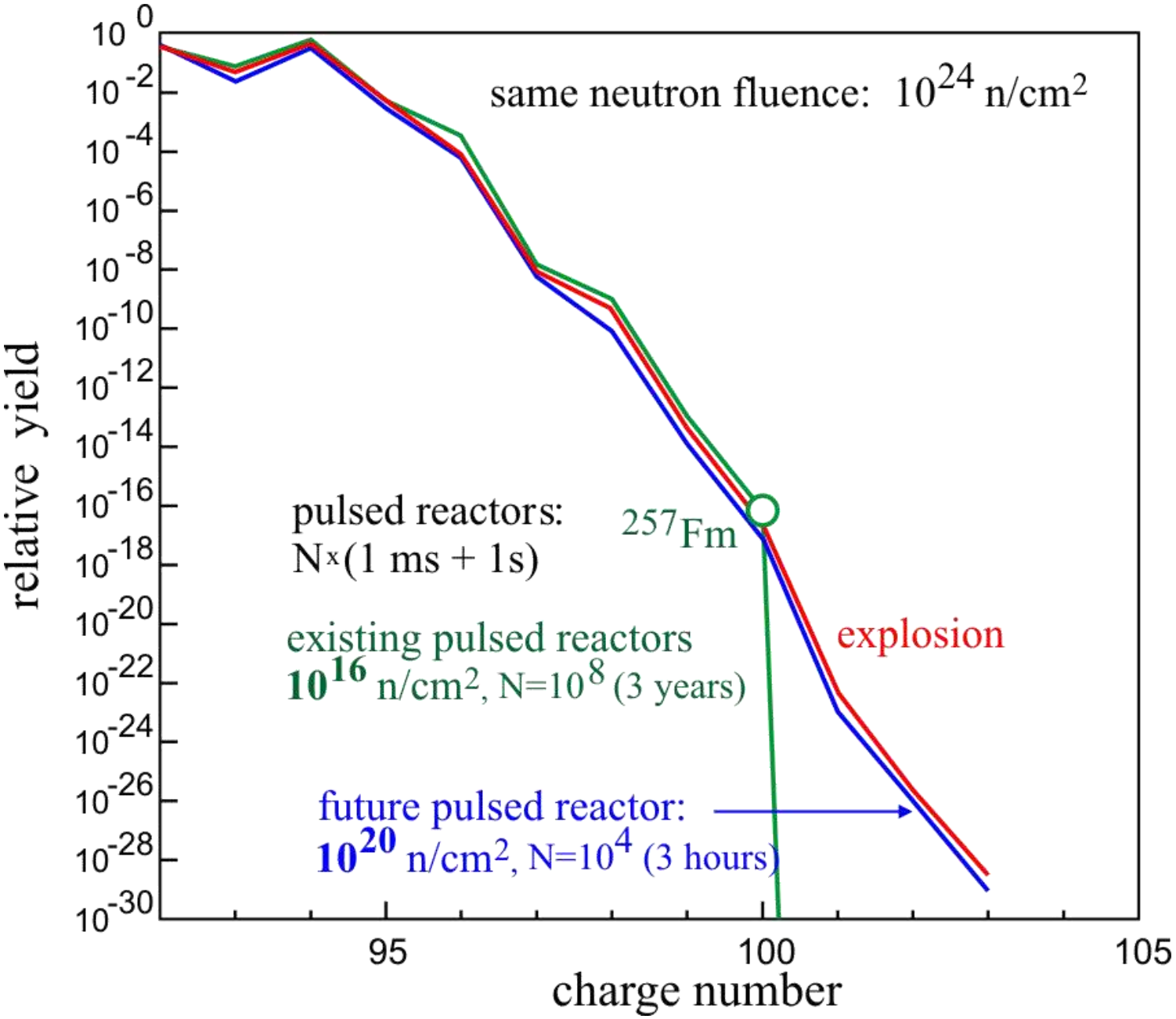
Edward Teller: “Technically it is quite possible”





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

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



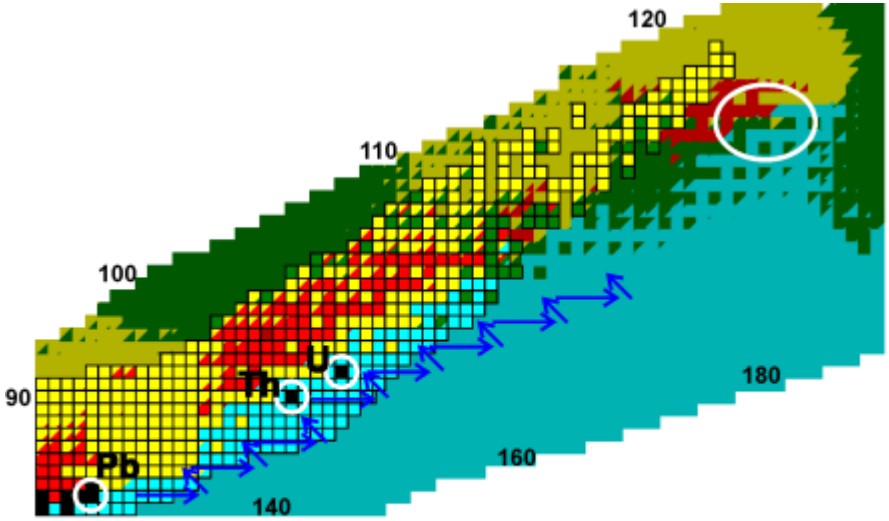
Formation of SH elements in astrophysical r-process

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?

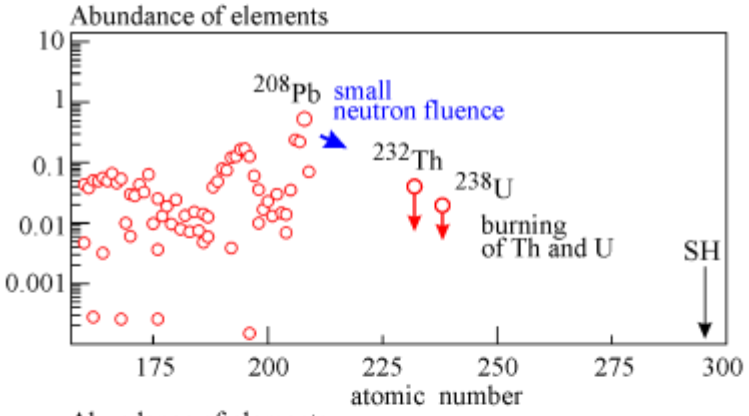
Idea: **supernova is a typical old star**

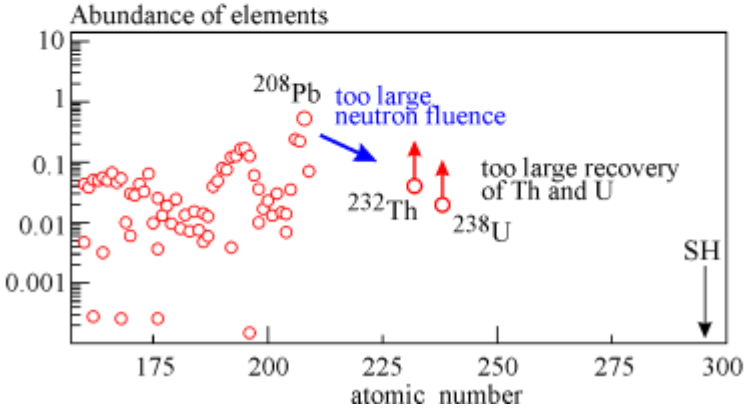
Formation of SH elements in astrophysical r-process

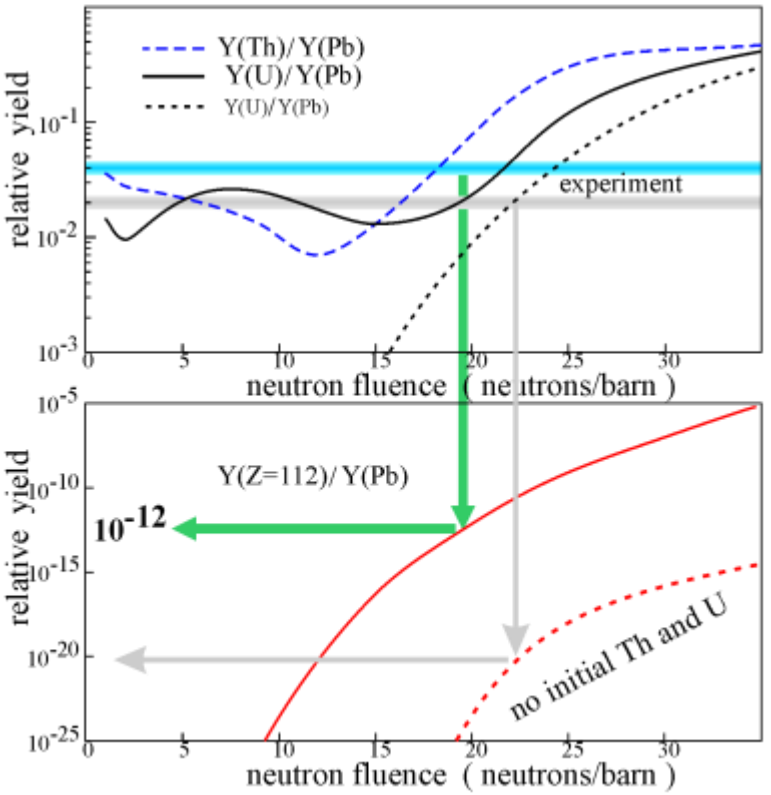


In the course of neutron irradiation initial Th and U material are depleted transforming to heavier elements and going to fission, while more abundant Pb and lighter stable elements enrich Th and U.

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





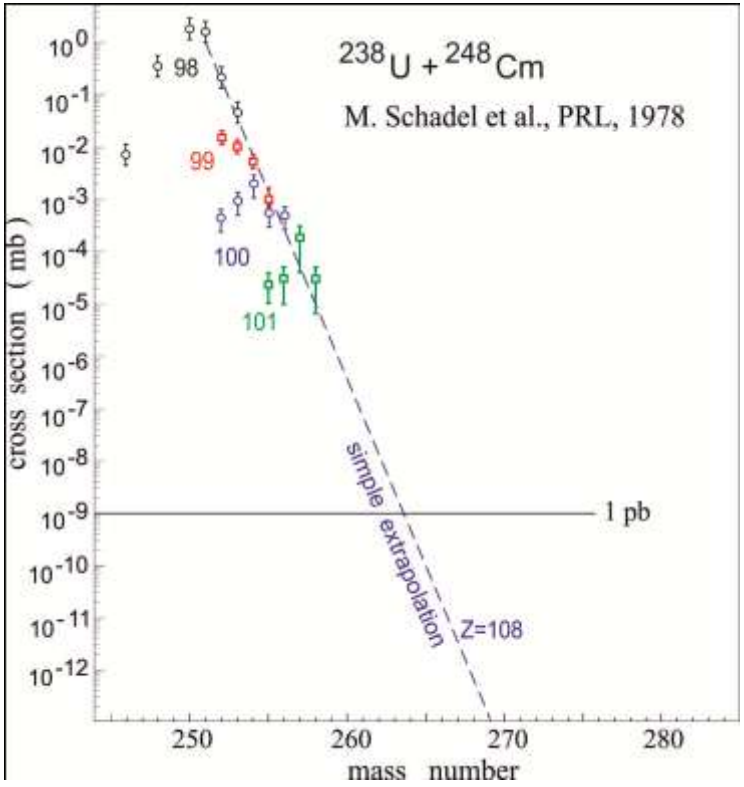


Synthesis of SH nuclei in **transfer reactions**

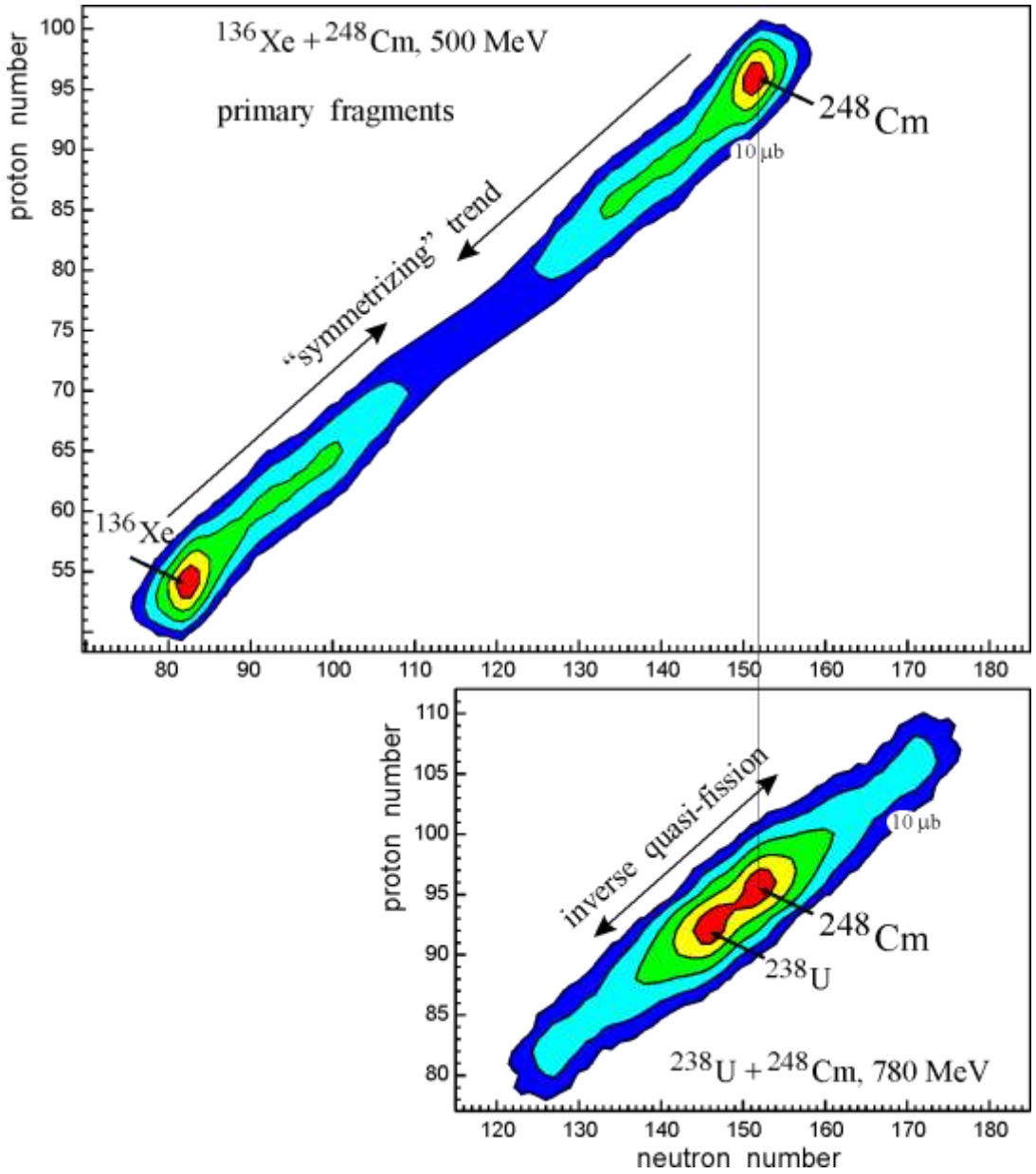
[1] E. K. Hulet *et al.*, Phys. Rev. Lett. **39**, 385 (**1977**).
[2] M. Schaedel *et al.*, Phys. Rev. Lett. **41**, 469 (**1978**).
[3] H. Essel, K. Hartel, W. Henning, P. Kienle, H. J. Koerner, K. E. Rehm, P. Sperr,W.Wagner, and H. Spieler, Z. Phys. A **289**, 265 (**1979**).
[4] H. Freiesleben, K.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

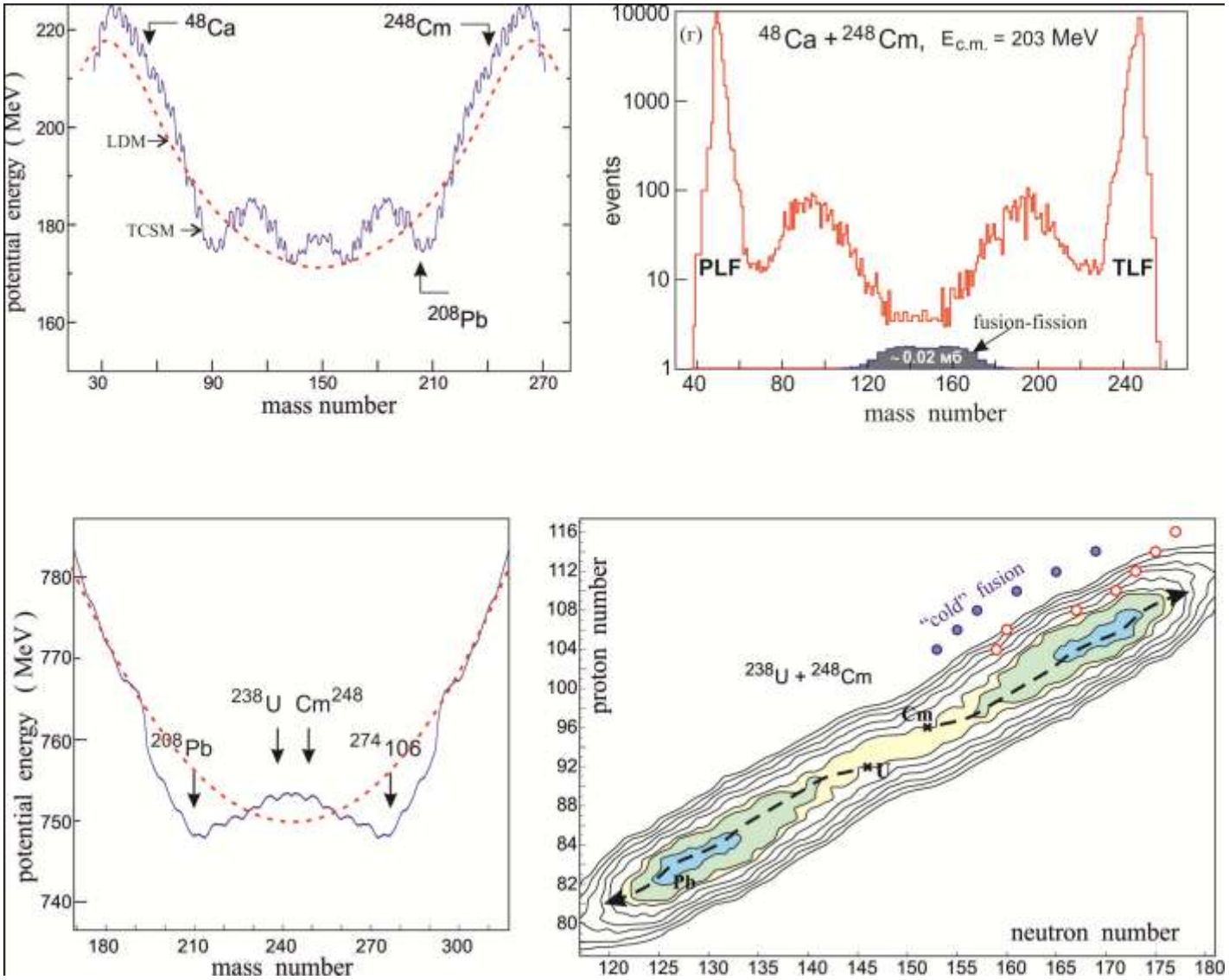


Production of superheavies in multi-nucleon transfers (choice of reaction is very important)

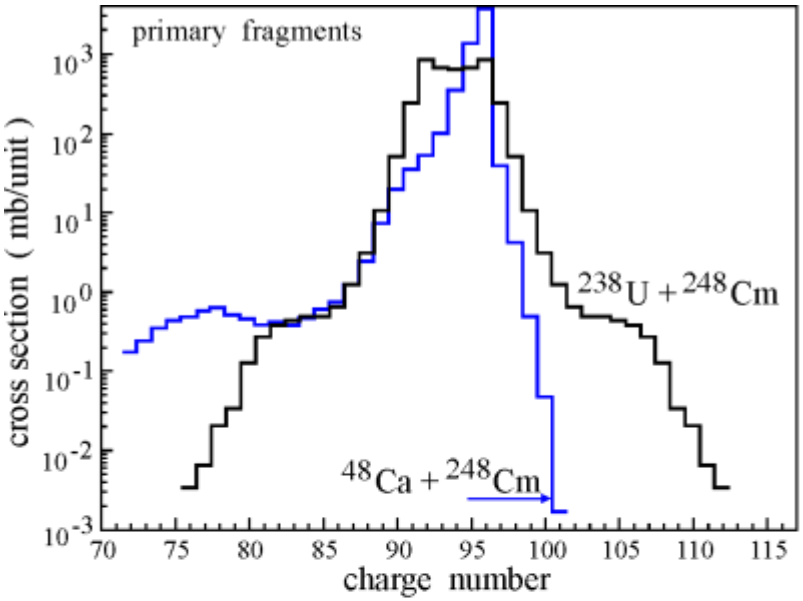


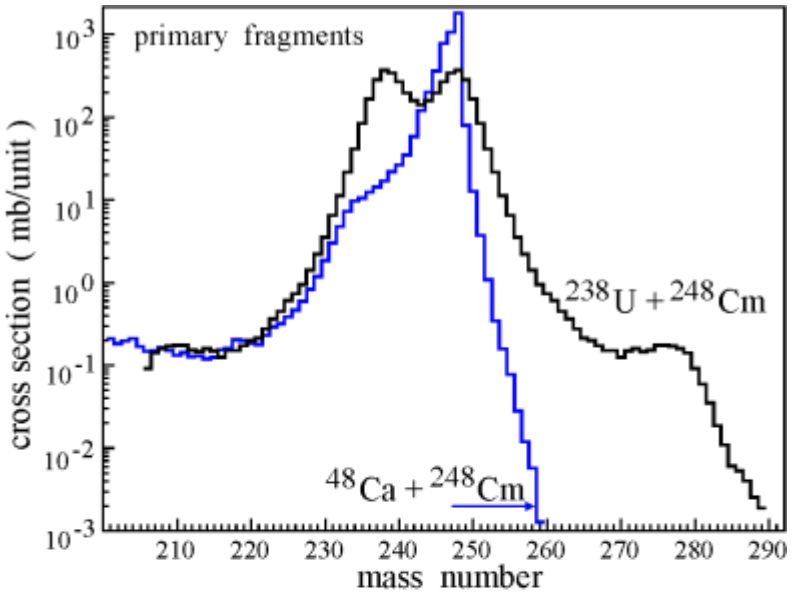
Shell effects: lead valley

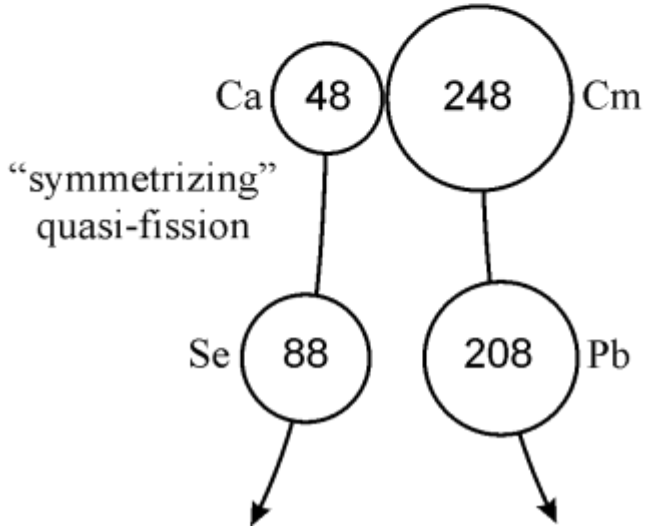
normal (symmetrizing) and inverse (anti-symmetrizing) quasi-fission

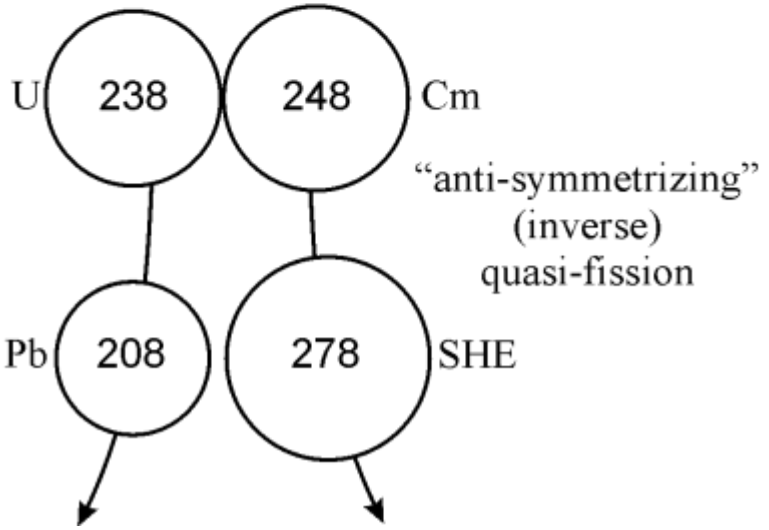


U-like beams give us more chances to produce neutron rich SH nuclei in “inverse quasi-fission” reactions

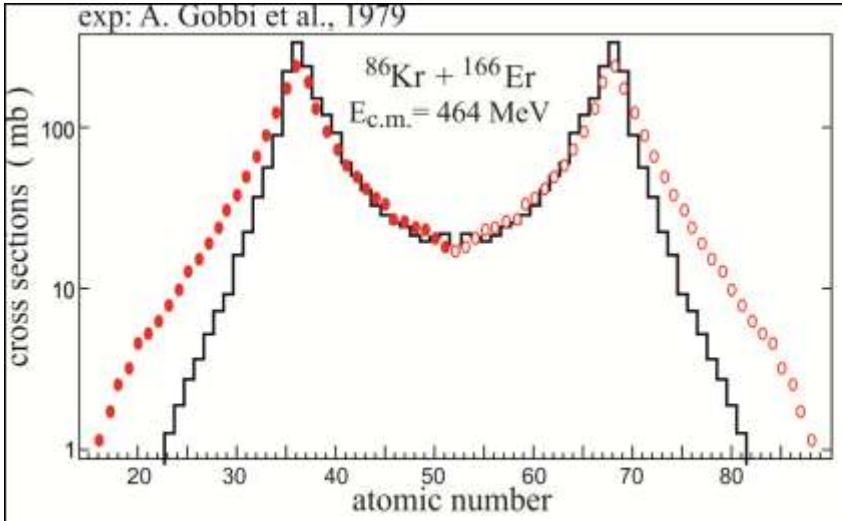


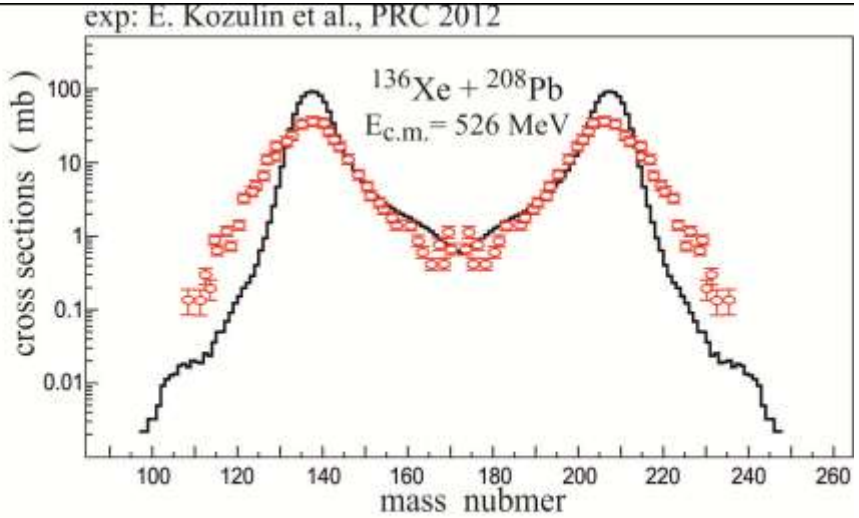


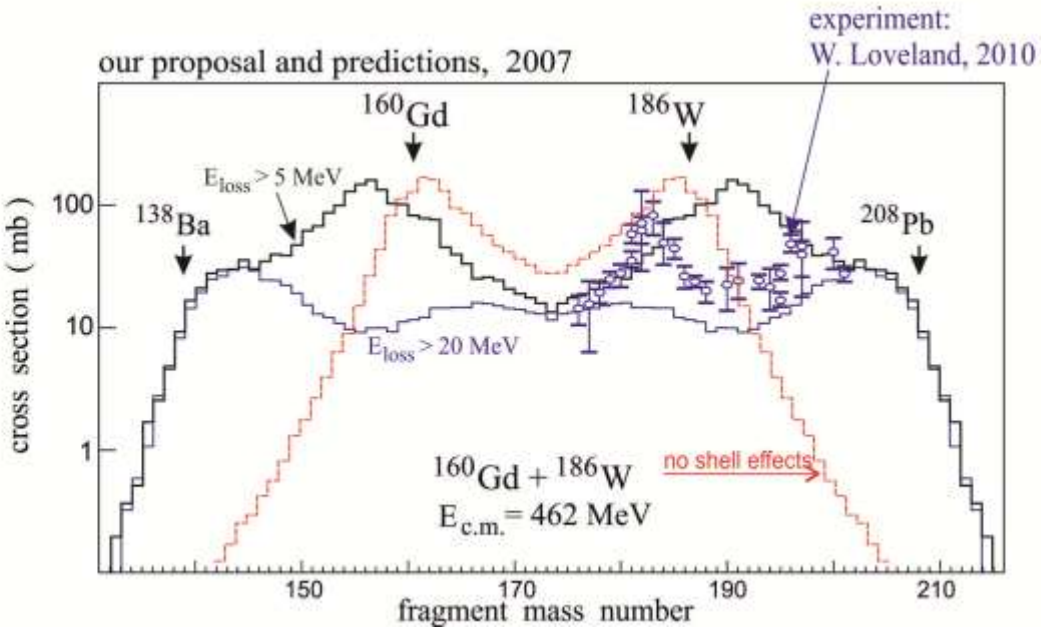




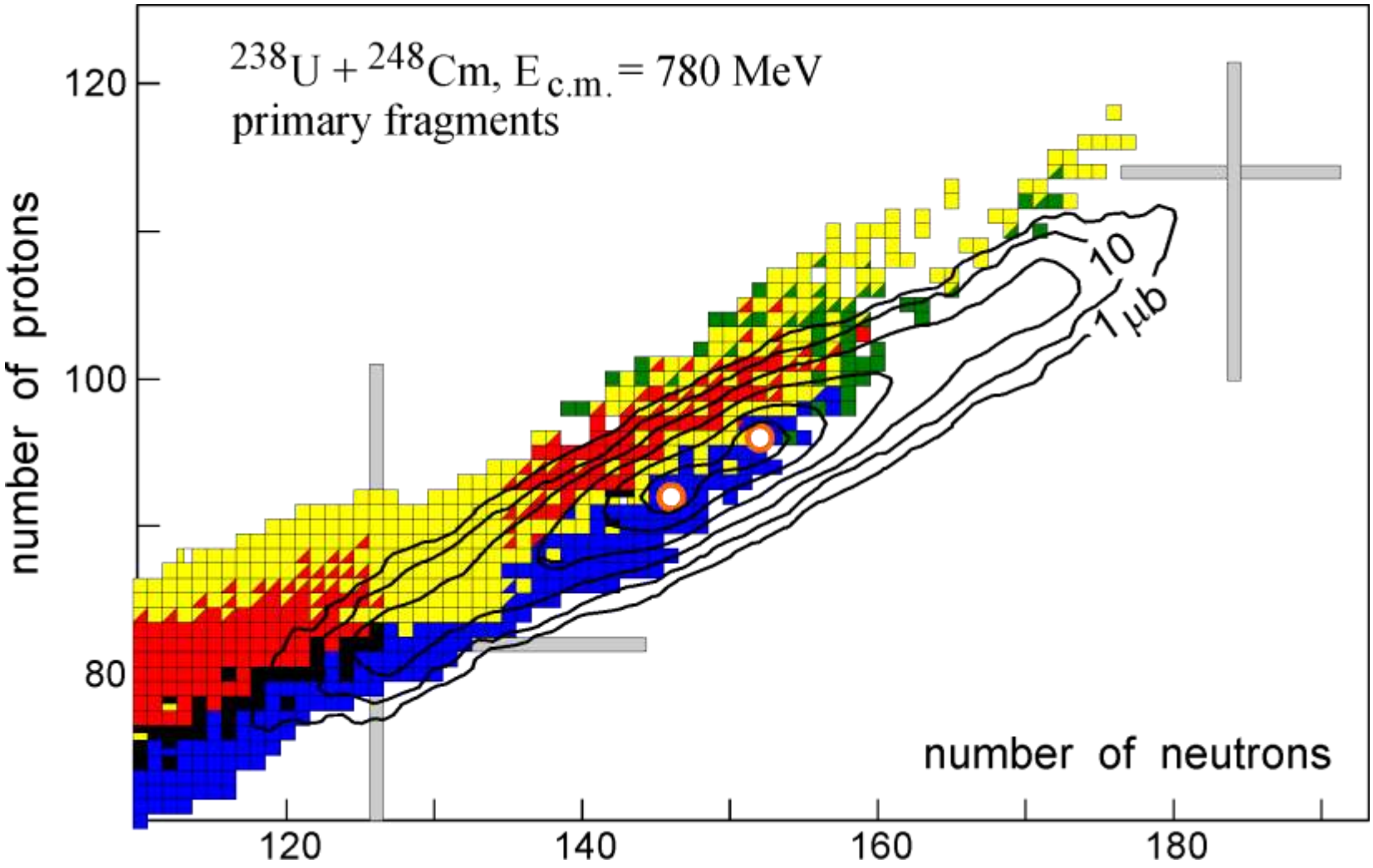
Experimental evidences on “inverse” quasi-fission ?



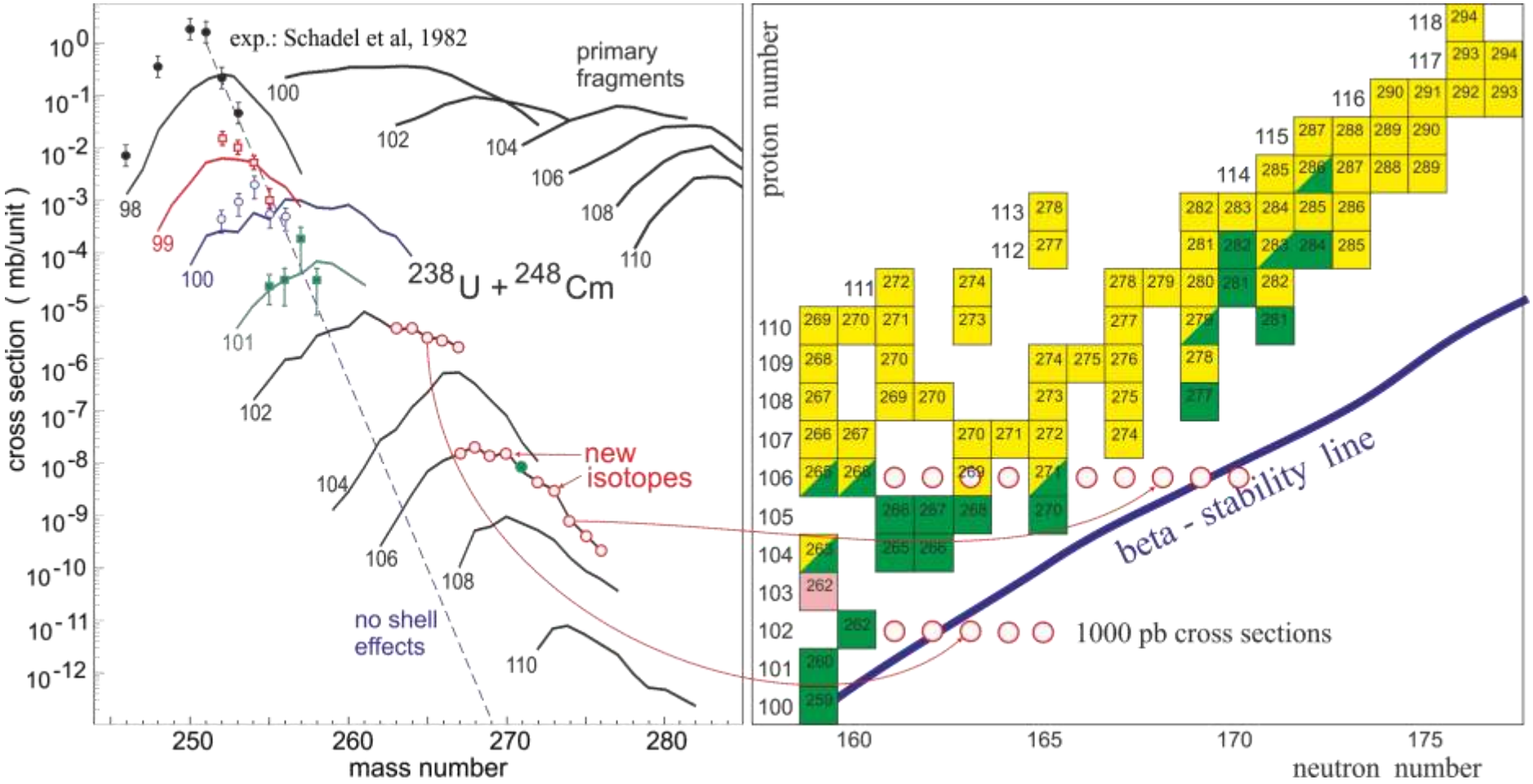




238U + 248Cm. Primary fragments



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

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.**
  Perhaps 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 probably exists !**
- **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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