Symposium in: YIPQS long-term workshop (MCD2022)
"Developments of Physics of Unstable Nuclei (YKIS2022b)"

Recent Developments in Microscopic Theories for Low-Energy Heavy-Ion Reactions: Towards Superheavy Element (SHE) synthesis

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Photo: "the japan times" https://www.japantimes.co.jp/culture/2020/11/21/books/kyoto-literary-guide/

Voyage towards the limit of existence

The continent of stability has been well explored..

The Great Wall of China by Stacy Funderburke @shutterstock

Now we are sailing towards the edge of the nuclear landscape..

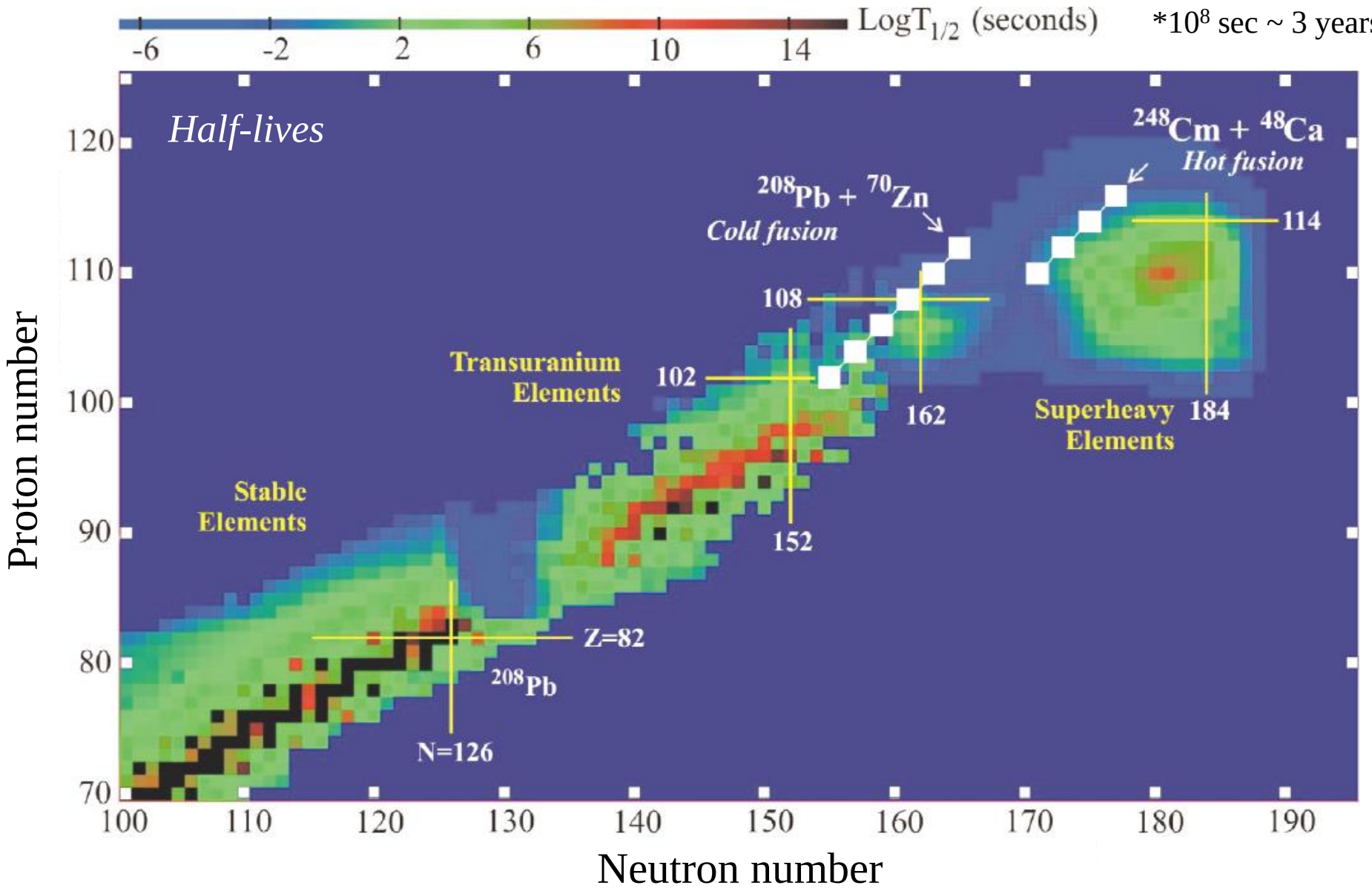
Stable nuclei: 288
Experiment: ~3200
Theory: ~7000

- drip lines
- shell structure
- deformation
- skin, halo
- nuclear matter properties
- nucleosynthesis
- ...

"Flat Earth" by iStock; "Fanciful view of ship sailing over edge of Earth" by Georgia Studies Images

What is the heaviest element?

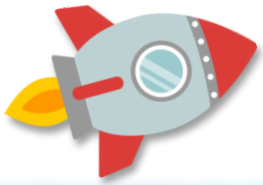
The north-east part of the nuclear map



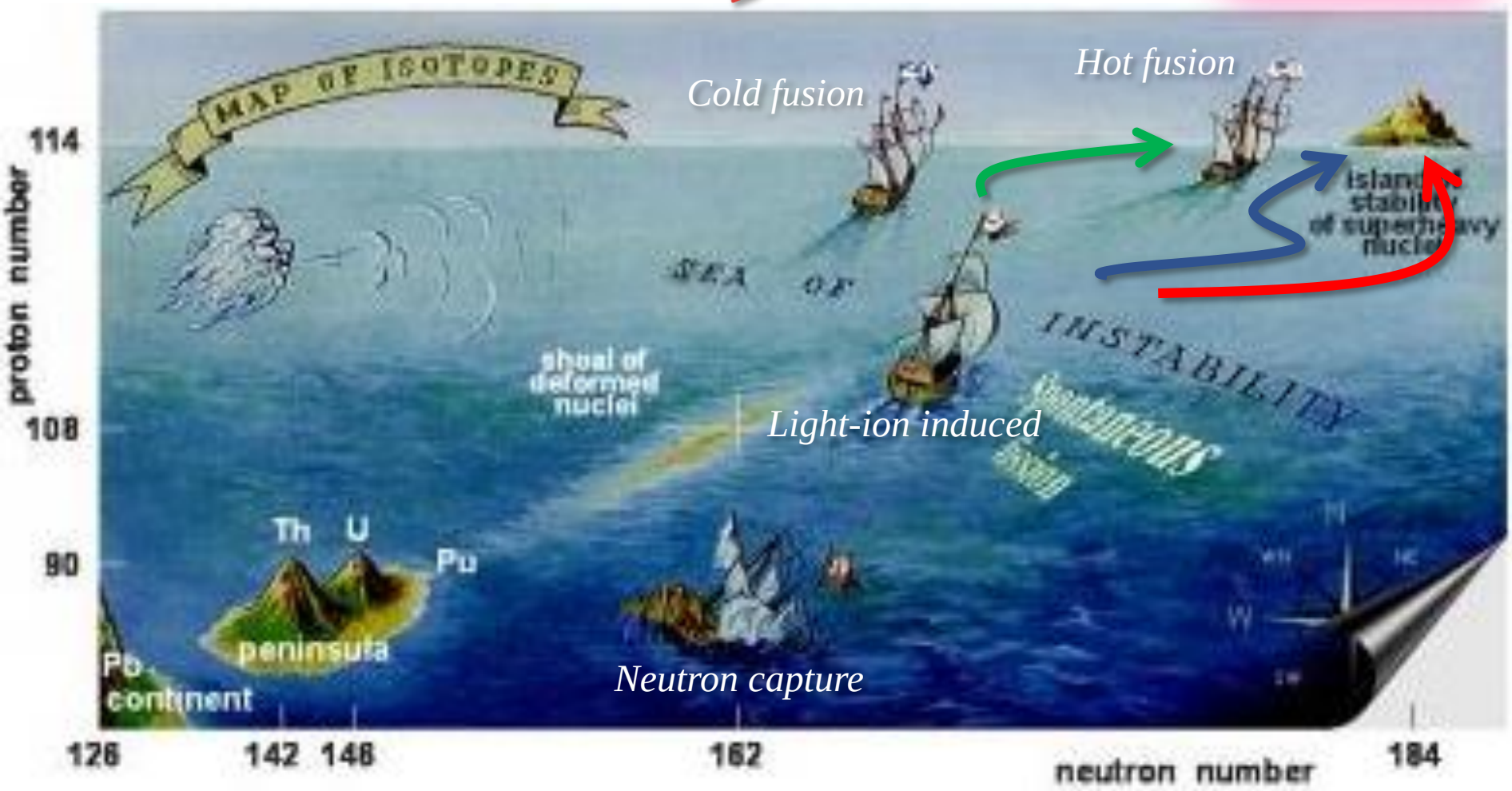
Yuri Oganessian, Pure Appl. Chem. **78**, 889 (2006)

The north-east part of the nuclear map

We do need theoretical predictions!



Z = 119, 120, ...



a few words about the theory..

✓ There is no adjustable parameter on reaction dynamics

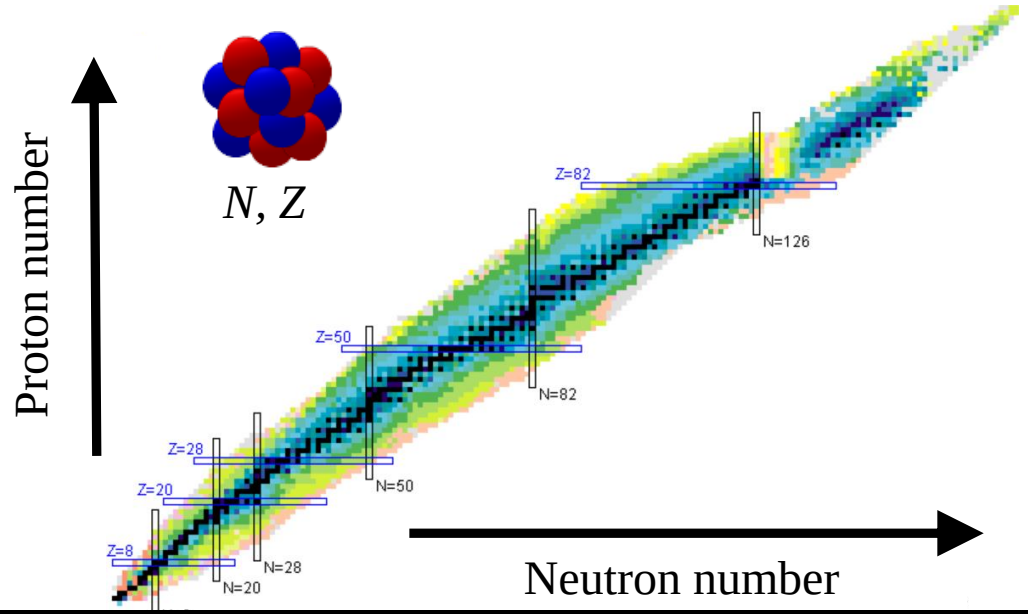
$$S = \int_{t_0}^{t_1} dt \left(i\hbar \sum_i \langle \phi_i(t) | \frac{\partial}{\partial t} | \phi_i(t) \rangle - E[\rho(t)] \right)$$

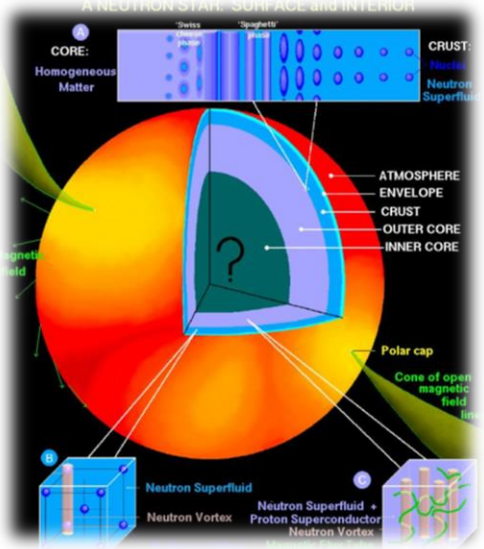
$$i\hbar \frac{\partial \phi_i(\boldsymbol{r}\sigma q, t)}{\partial t} = \hat{h}[\rho(t)]\phi_i(\boldsymbol{r}\sigma q, t) \quad : \text{TDHF eq.}$$

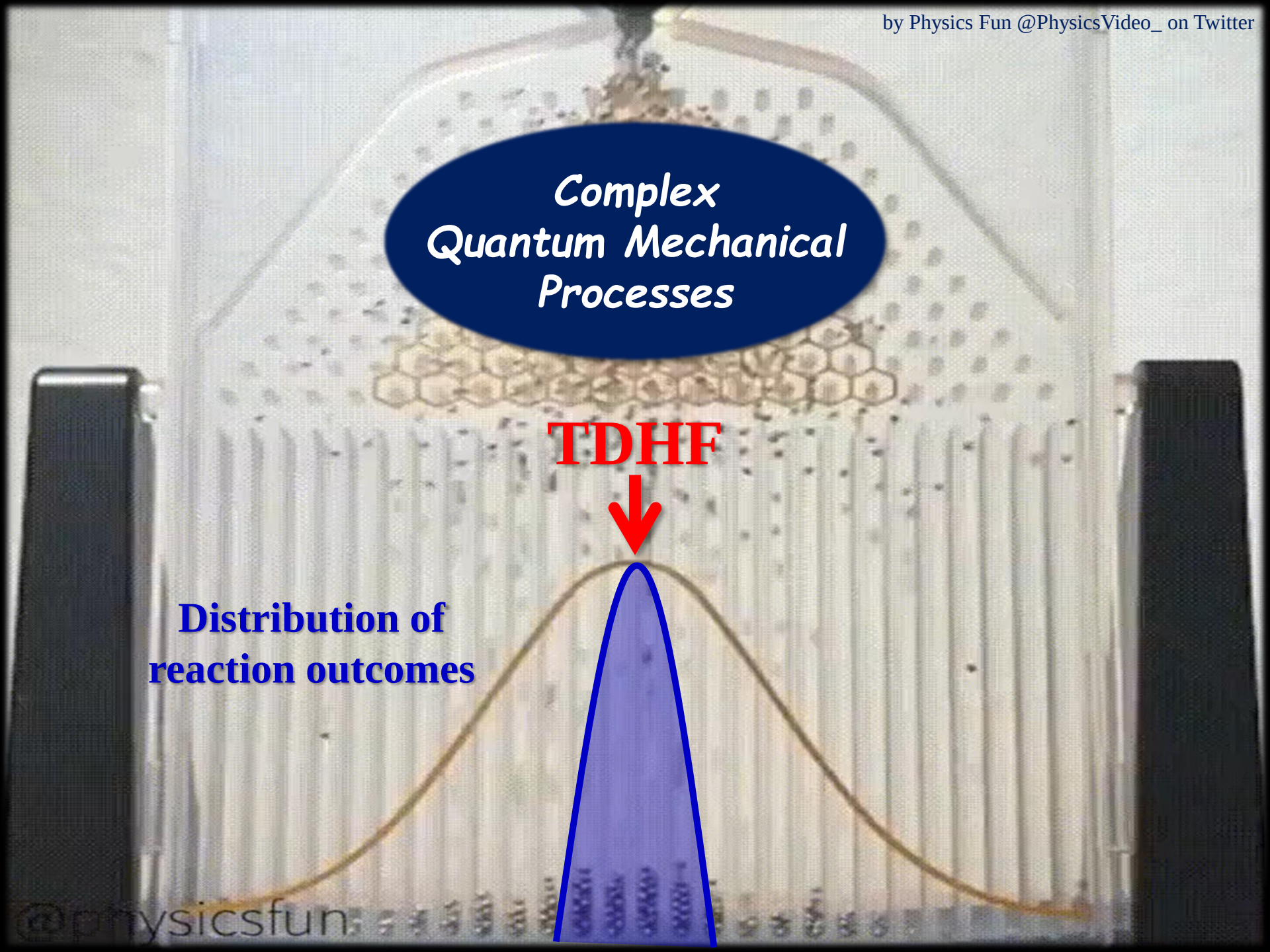
Effective interaction

$$E[\rho] = \langle \Phi | \hat{H} | \Phi \rangle$$

Energy Density Functional (EDF)



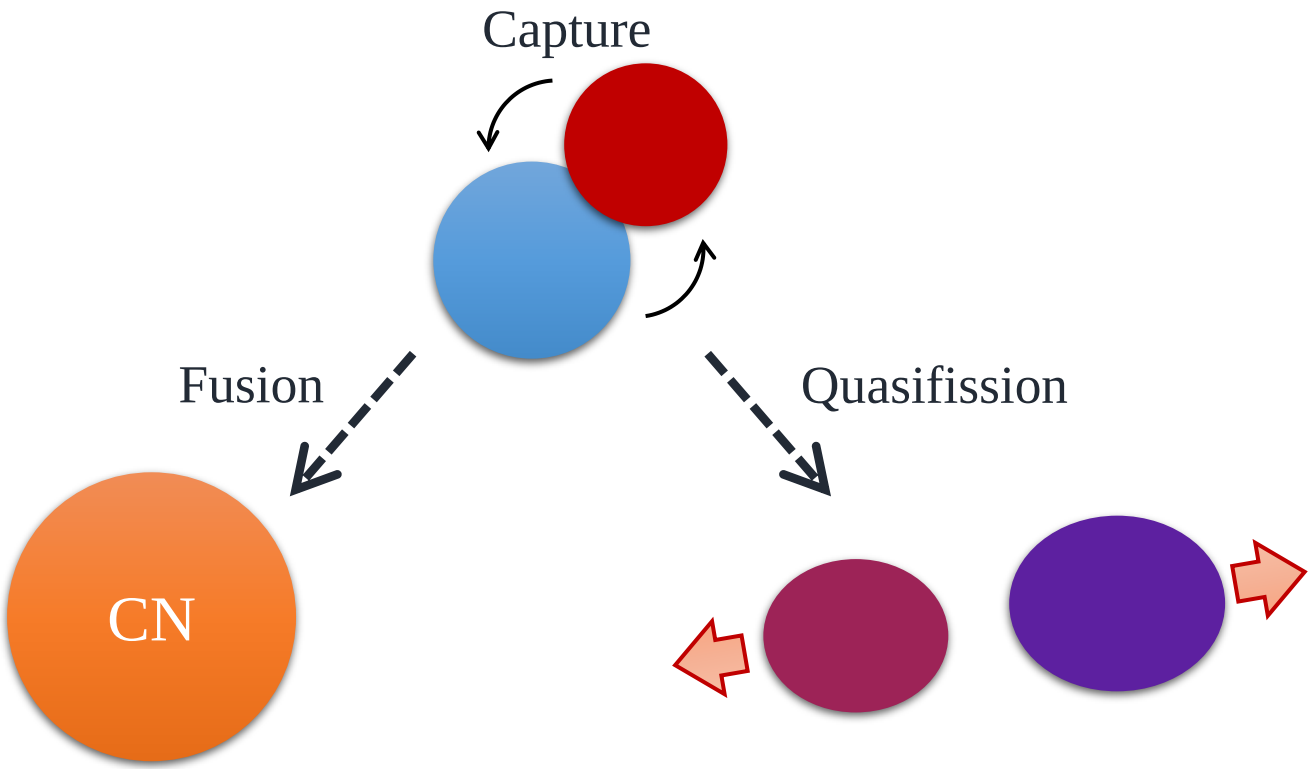




Let’s see how it works

Quasifission process

A fast (~10^{-21}-10^{-20} sec) fission process before compound nucleus formation (fusion)



$$\sigma_{\mathrm{ER}} \sim W_{\mathrm{surv}} * \sigma_{\mathrm{cap}} * P_{\mathrm{CN}}$$

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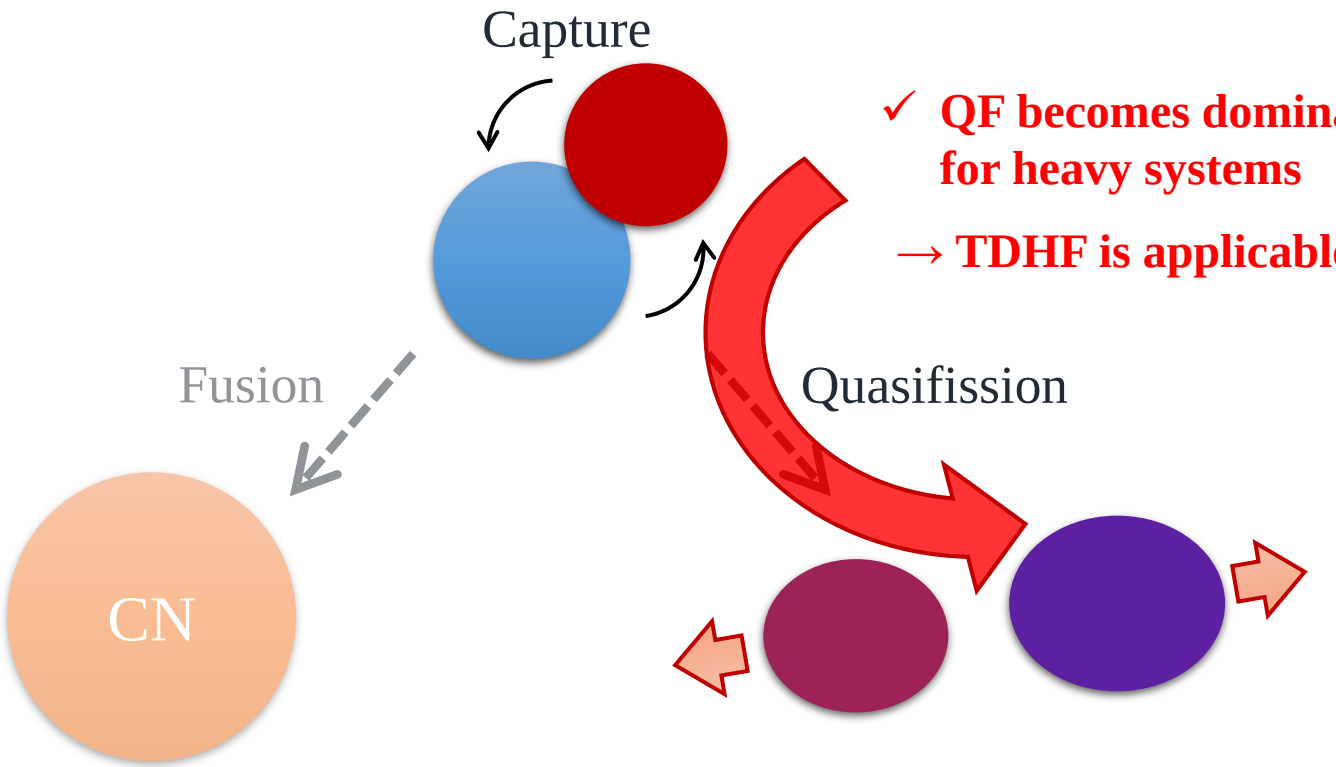


✓ **QF becomes dominant for heavy systems**

→ TDHF is applicable!

$$\sigma_{\mathrm{ER}} \sim W_{\mathrm{surv}} * \sigma_{\mathrm{cap}} * P_{\mathrm{CN}}$$

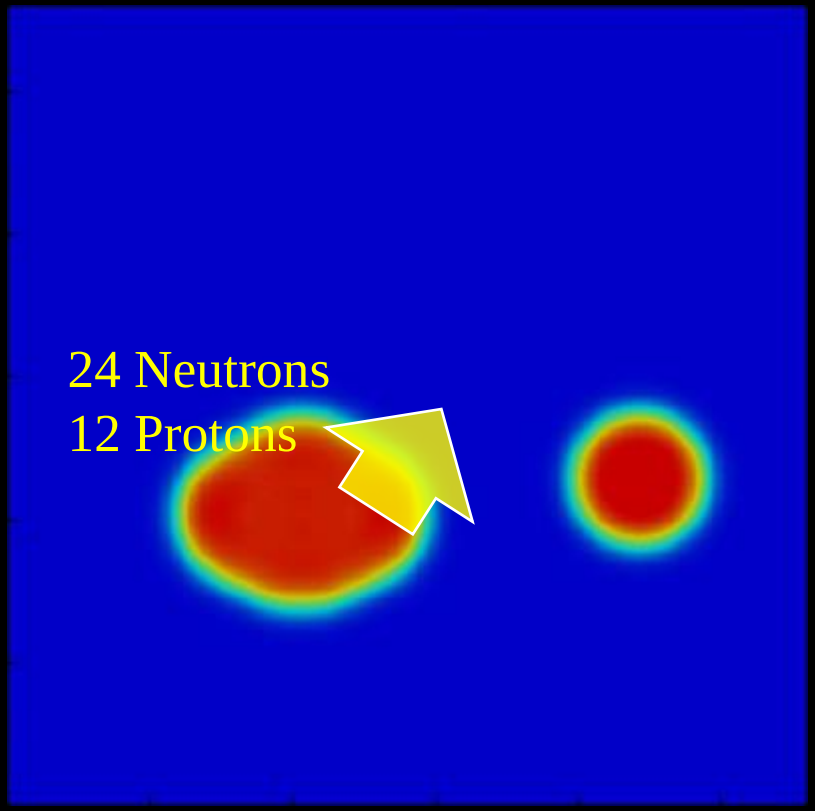
^{64}Ni+^{238}U at E_{lab}=390 MeV

K. Sekizawa and K. Yabana, PRC**93**(2016)054616

Quasifission dynamics in TDHF

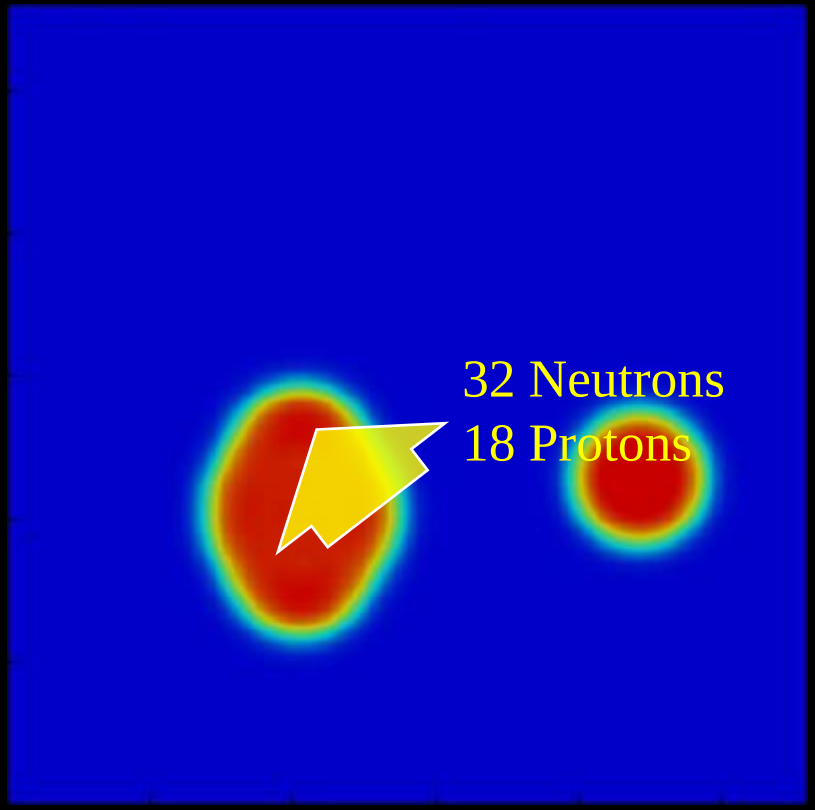
Tip collision

Shell effects of ^{208}Pb



Side collision

More mass-symmetric

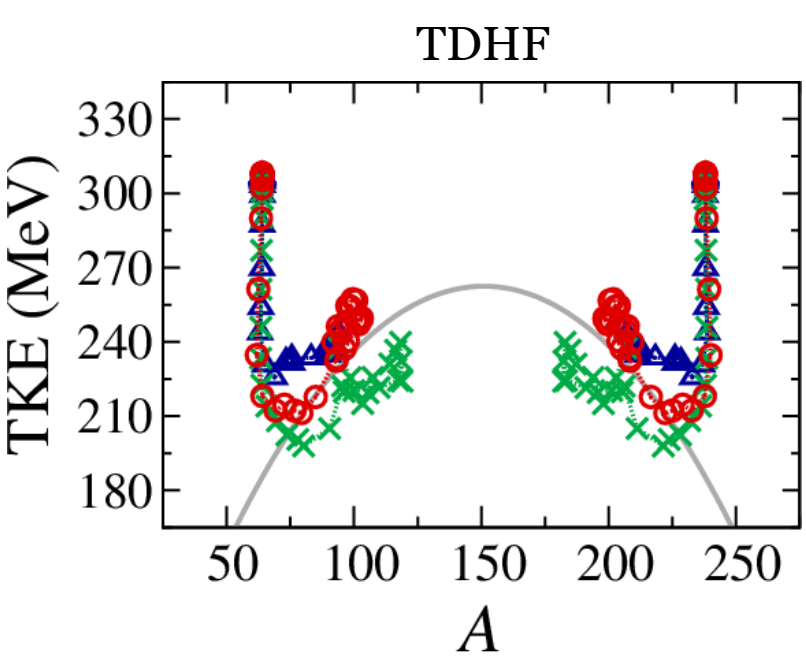


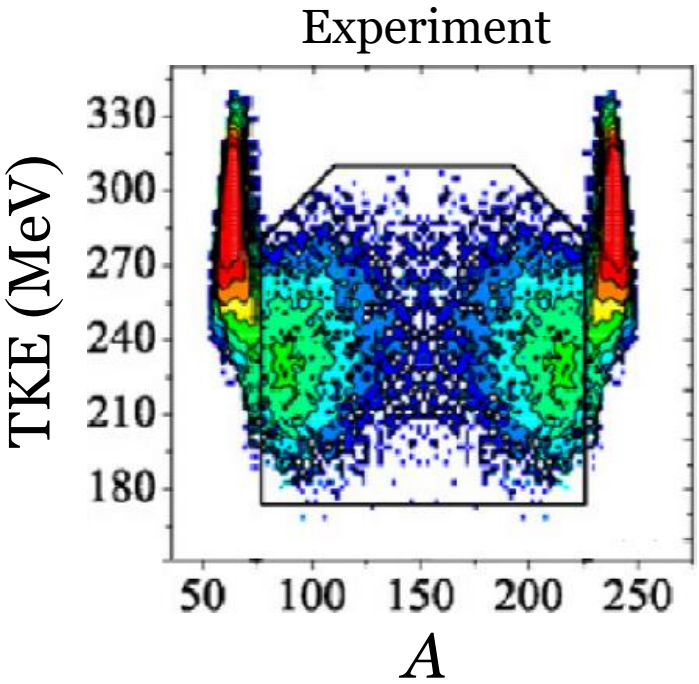
^{64}Ni+^{238}U at E_{lab}=390 MeV

K. Sekizawa and K. Yabana, PRC**93**(2016)054616

TDHF provides quantitative description of quasifission dynamics

TKE-*A* distribution: Comparison with experimental data





Expt.: E.M. Kozulin *et al.*, PLB**686**(2010)227

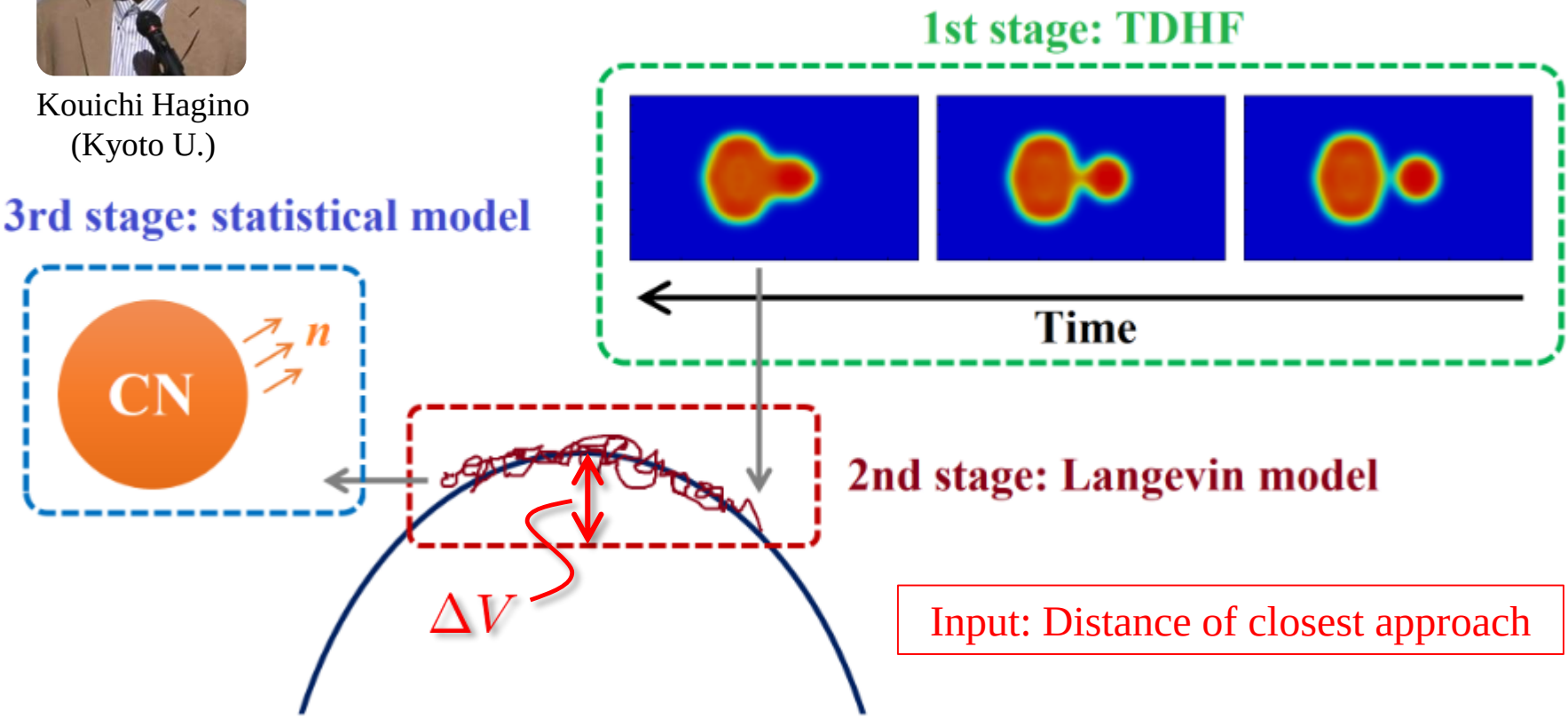
However, TDHF can not describe the process of the compound-nucleus formation

To study fusion reactions for SHE synthesis, we have proposed a “TDHF+Langevin” approach

Kouichi Hagino
(Kyoto U.)

K. Sekizawa and K. Hagino, PRC**99**(2019)051602(R)
Rapid Comm. with Editors' Suggestion

TDHF + Langevin approach: Idea



Input: Distance of closest approach

We use fusion-by-diffusion model to describe the "up-hill diffusion" over the inner barrier

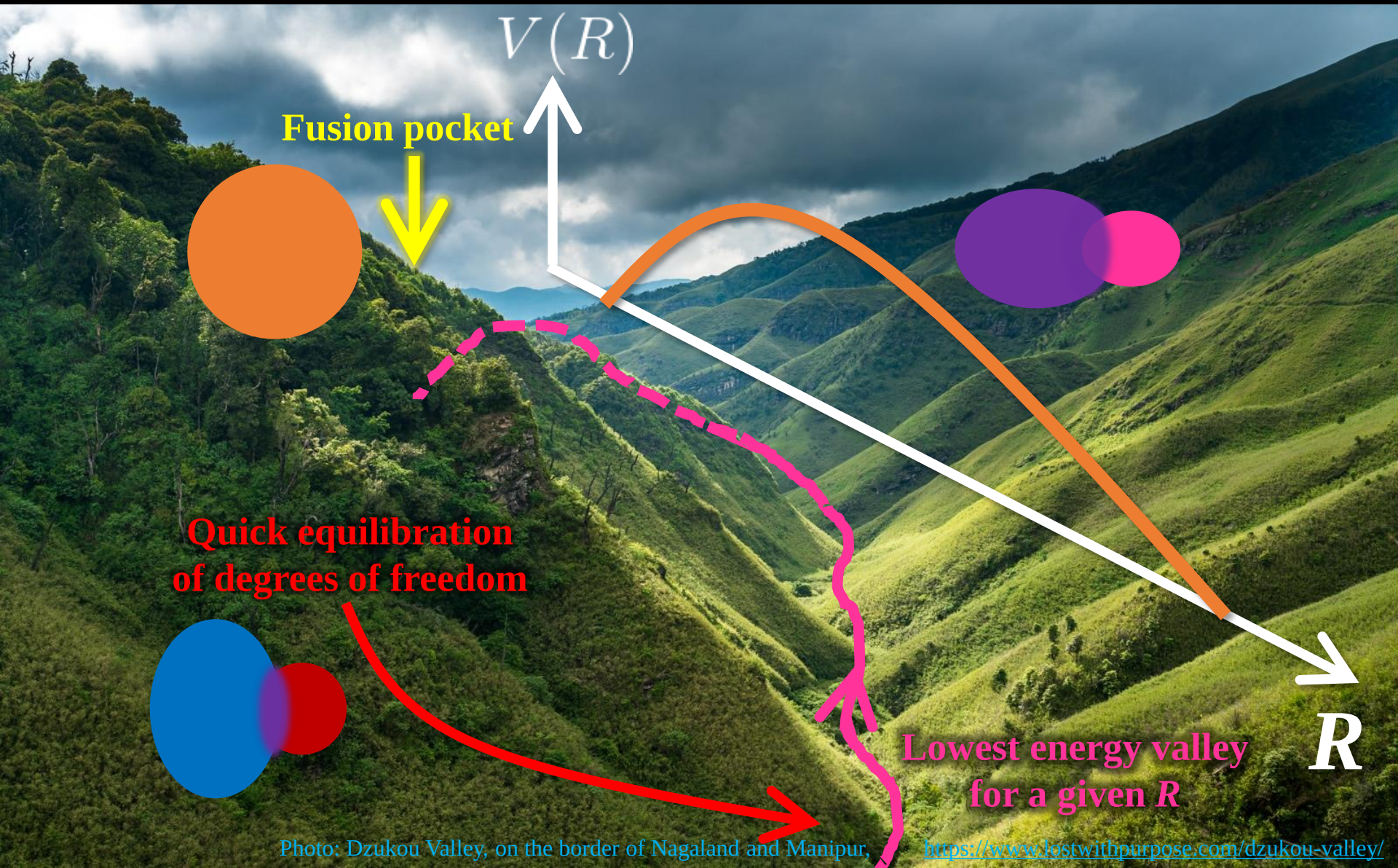
➢ **Analytical formula can be derived:**

$$P_{\rm CN} = \frac{1}{2}\left[1 - {\rm erf}\left(\frac{\Delta V}{T}\right)\right]$$

Fusion-by-diffusion model:
W.J. Świątecki, K. Siwek-Wilczyńska, and J. Wilczyński, Acta Phys. Pol. B **34**(2003)2049; PRC**71**(2005)014602
K. Hagino, PRC**98**(2018)014607

The essence of the fusion-by-diffusion model:

"Quick" equilibration of DoF and "slow" diffusion through a valley over a barrier



K. Sekizawa and K. Hagino, PRC**99**(2019)051602(R)

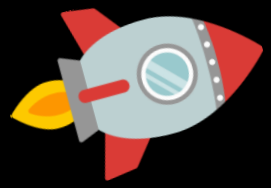
Magicity of ^{48}Ca affects the survival probability via the lower excitation energy

System	CN	E^* (MeV)	$R_{\rm min}$ (fm)	$P_{\rm CN}$ ($\times 10^4$)	$W_{\rm sur}$ ($\times 10^9$)	$P_{\rm CN}\,W_{\rm sur}$ ($\times 10^{13}$)
			TDHF	FBD		
^{48}Ca+^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr+^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V+^{249}Bk	^{300}120	37.0	12.94	3.95	0.117	0.461
^{48}Ca+^{257}Fm	^{305}120	30.5	12.94	2.49	0.729	1.82

Very similar for all systems

Thus, $P_{\rm CN}$ is also similar (higher E^*, larger $P_{\rm CN}$)

Note:
Survival probability also depends on the fission barrier height!

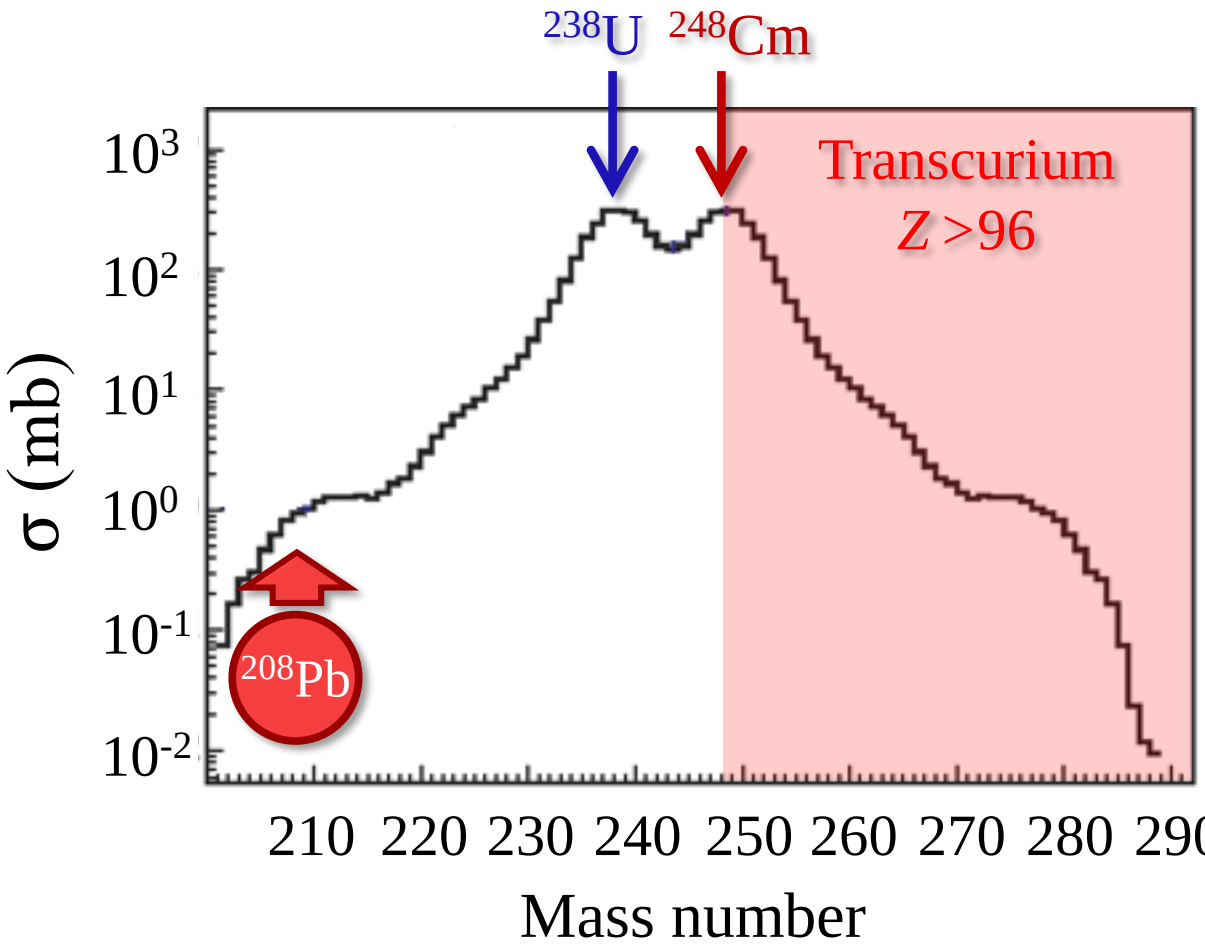


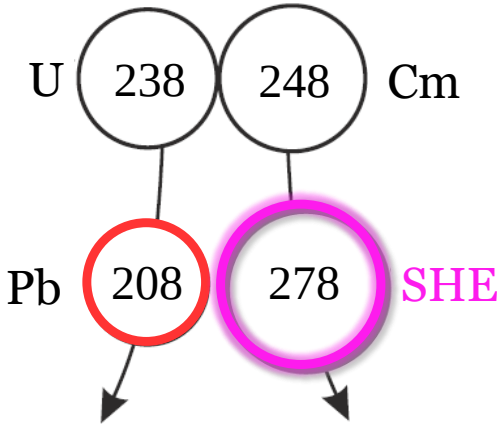
Exploring novel reaction dynamics:

“Inverse” quasifission

Prediction by Langevin-model calculations

Production cross section for primary products in $^{238}U+^{248}Cm$

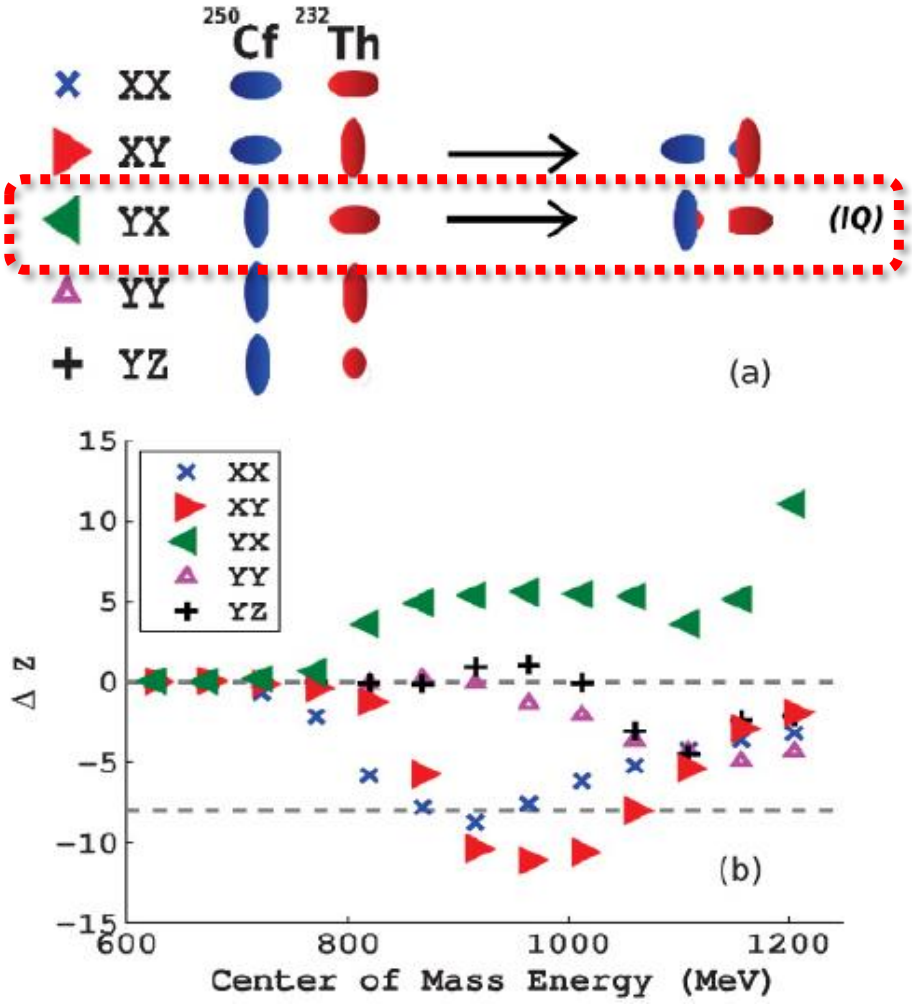




V.I. Zagrebaev and W. Greiner, PRC**87**(2013)034608

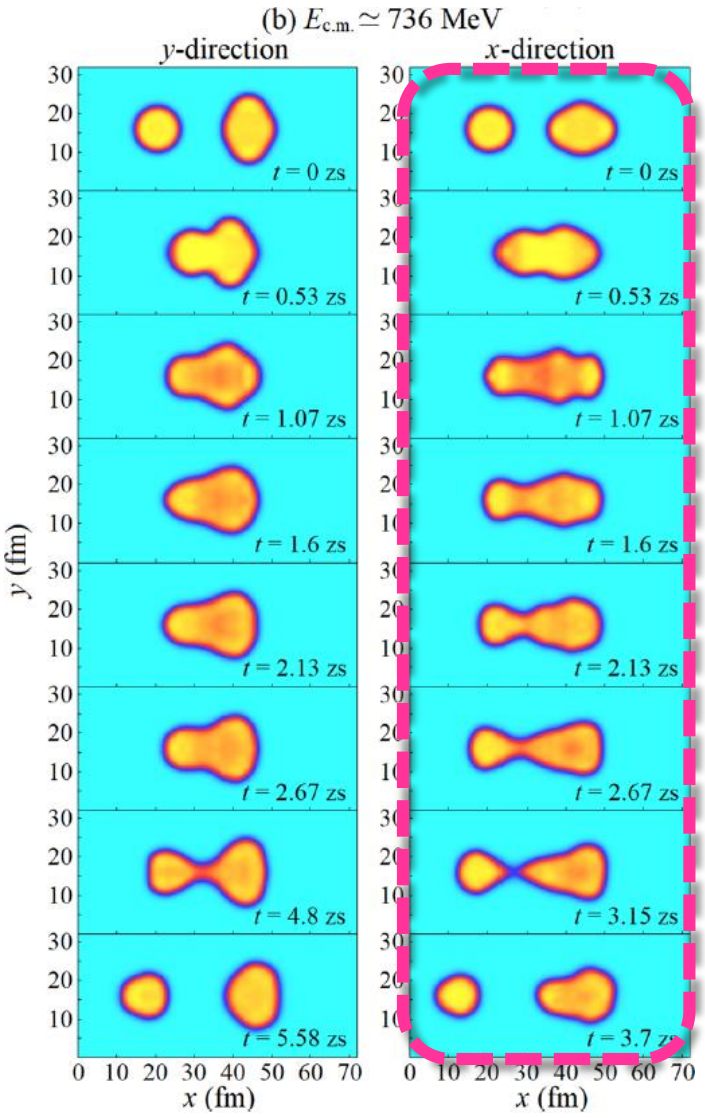
Inverse quasifission (IQF) mechanisms in TDHF

Orientation-induced IQF



D.J. Kedziora and C. Simenel, PRC**81**(2010)044613

Surface-vibration-induced IQF



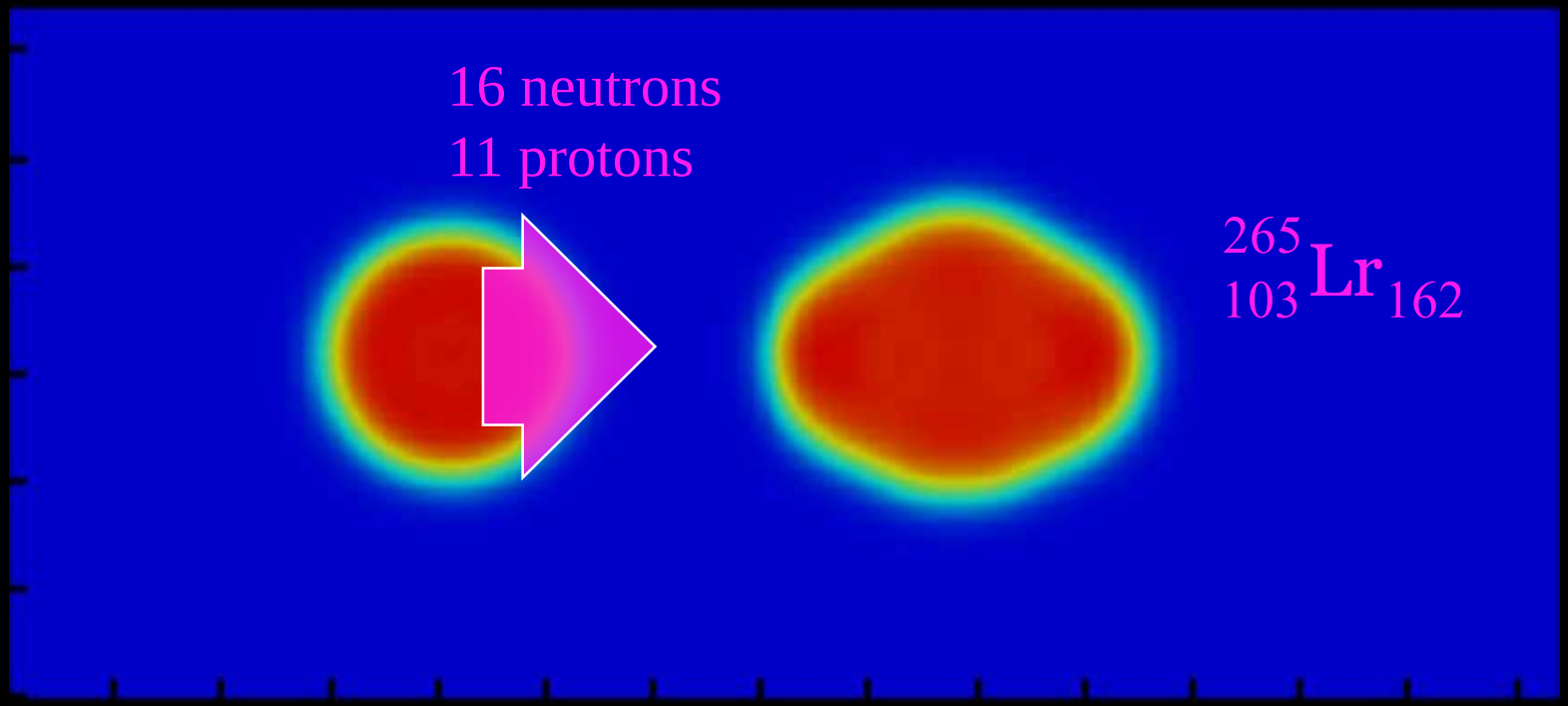
K. Sekizawa, PRC**96**(2017)041601(R)

K. Sekizawa, PRC**96**(2017)041601(R)

Complex dynamics allows for developing a neck increasing mass asymmetry

- **Dynamics of neck evolution** may be a key to produce exotic isotopes

^{238}U+^{124}Sn at $E_{\rm lab}$=9 MeV/A



What we have learned?

✓ QF dynamics depend strongly on shell effects and orientation

Naive question:

"Can we reach Island of Stability by Inverse QF?"

e.g.

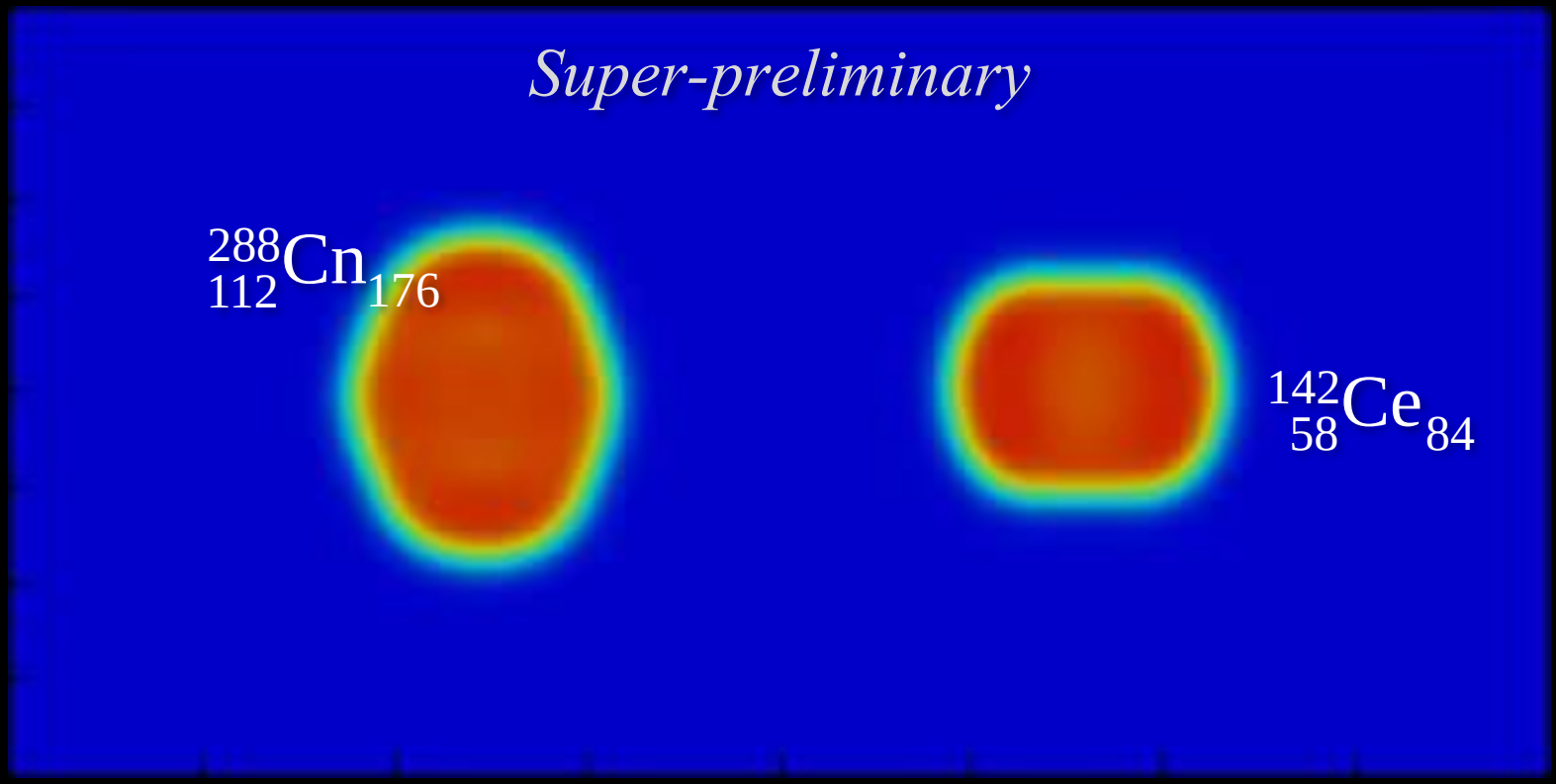
$$^{186}_{74}W_{112} + ^{248}_{96}Cm_{152} \rightarrow \underbrace{^{136}_{56}Ba_{80}}_{Z \sim 50,\ N \sim 82} + \underbrace{^{298}_{114}Fl_{184}}_{\text{IOS}}$$

Super-preliminary

Inverse quasifission occurs forming a SHE with a peculiar shape

although reaction products are too much excited..

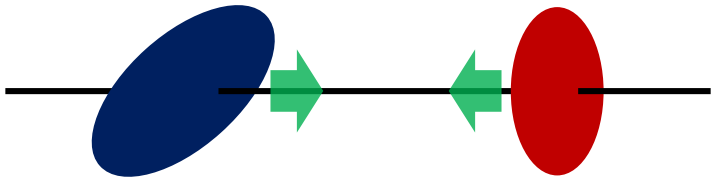
^{186}W+^{248}Cm, b = 0.5 fm, E-V_B ~ 500 MeV



Let me show what happened in the simulations:

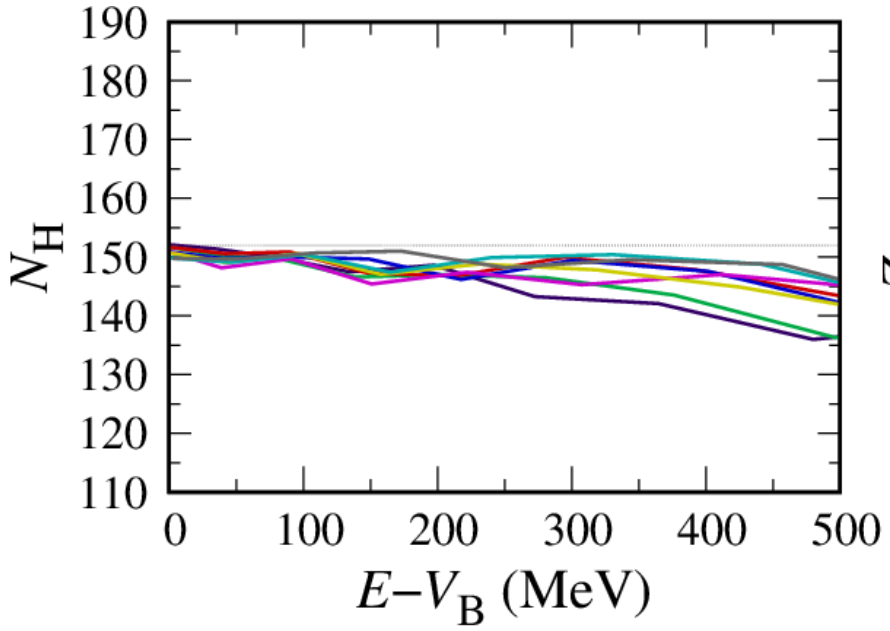
Super-preliminary

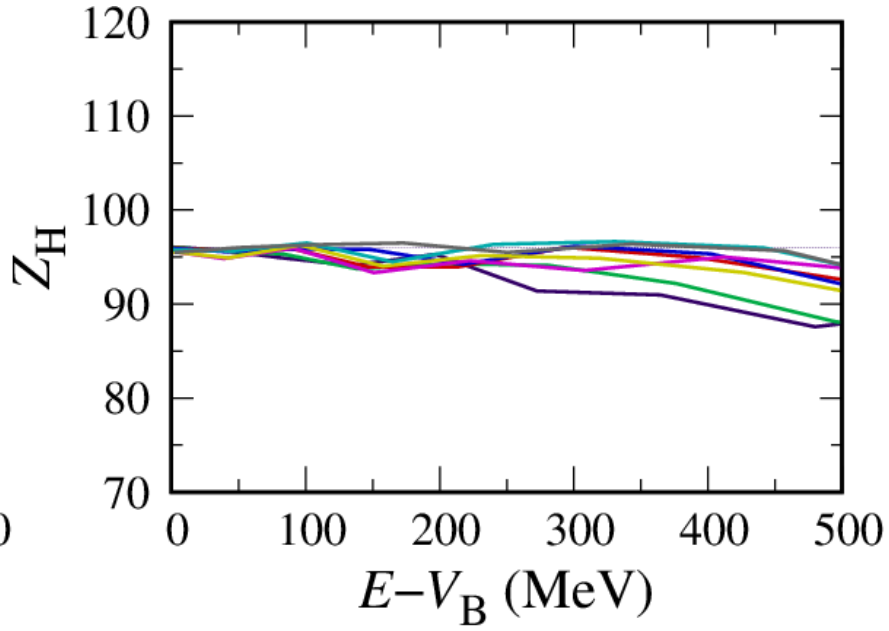
■ ‘Side-on-side’ (hugging) configuration



^{186}W+^{248}Cm
^{180}Hf+^{248}Cm
^{176}Yb+^{248}Cm
^{170}Er+^{248}Cm
^{164}Dy+^{248}Cm
^{160}Gd+^{248}Cm
^{154}Sm+^{248}Cm
^{150}Nd+^{248}Cm

Average number of neutrons (left) and protons (right) in the heavier fragment

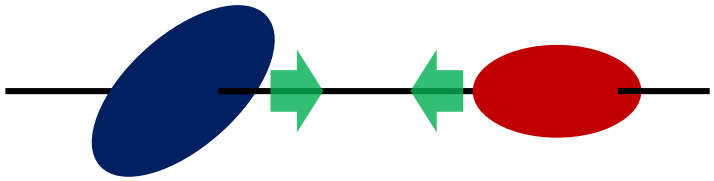




Let me show what happened in the simulations:

Super-preliminary

■ 'Tip-on-side' configuration



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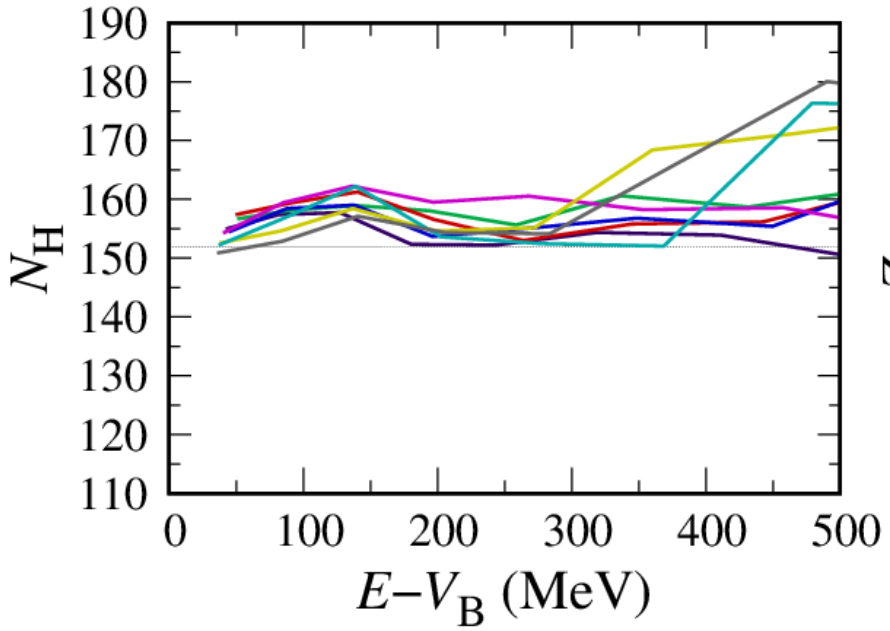
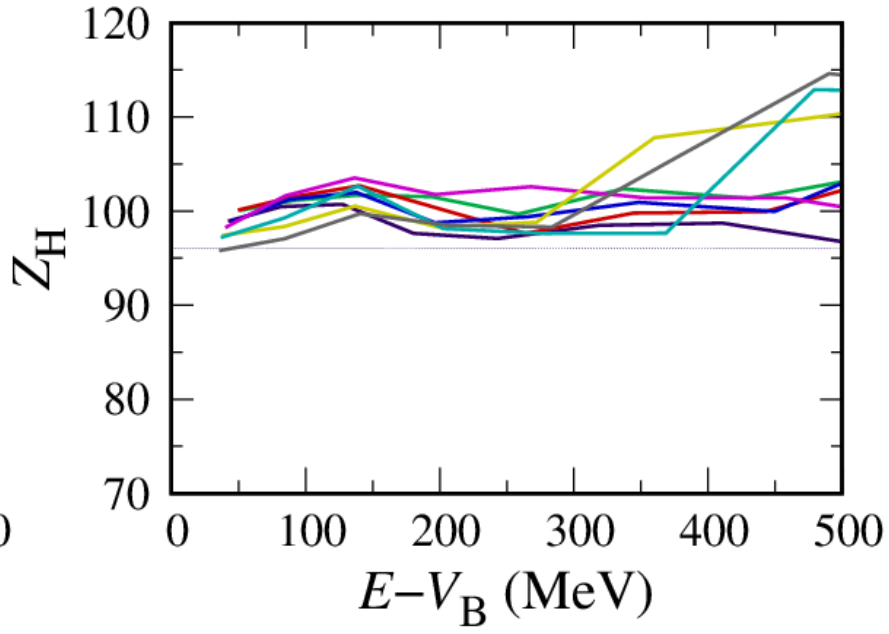
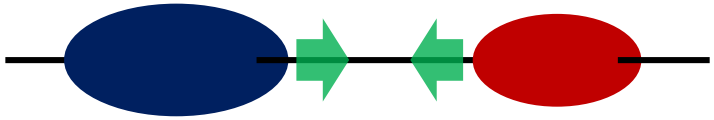




Let me show what happened in the simulations:

Super-preliminary

■ 'Tip-on-tip' configuration



$^{186}W+^{248}Cm$
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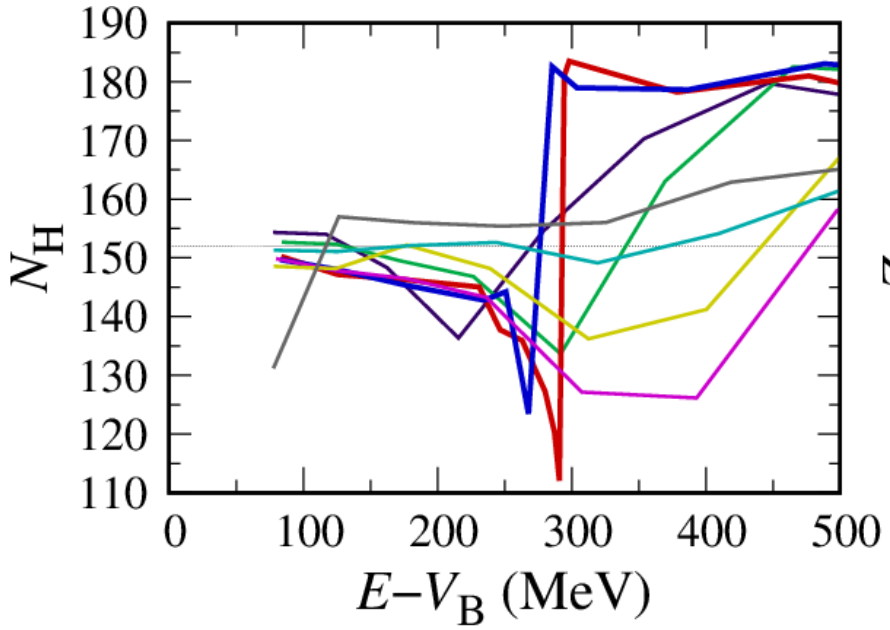
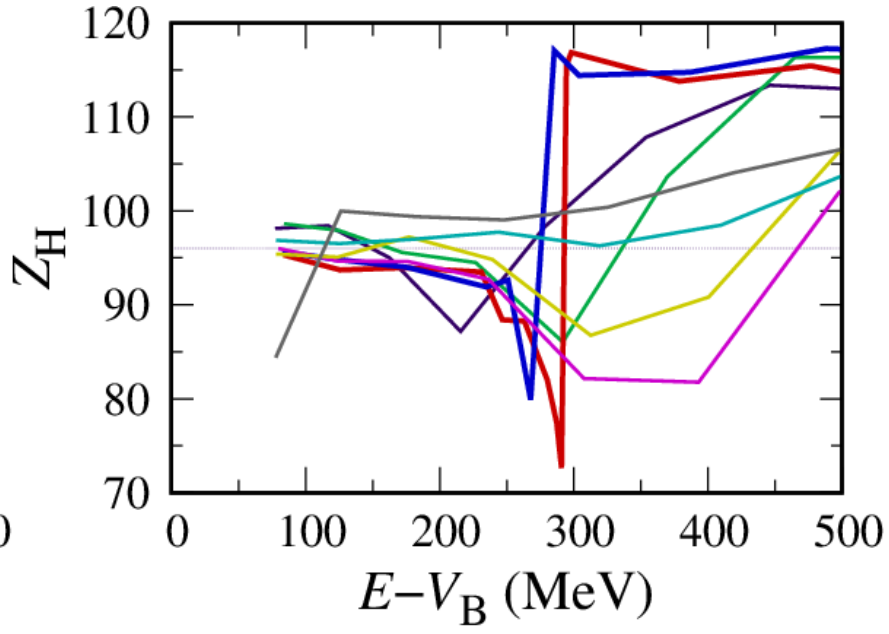
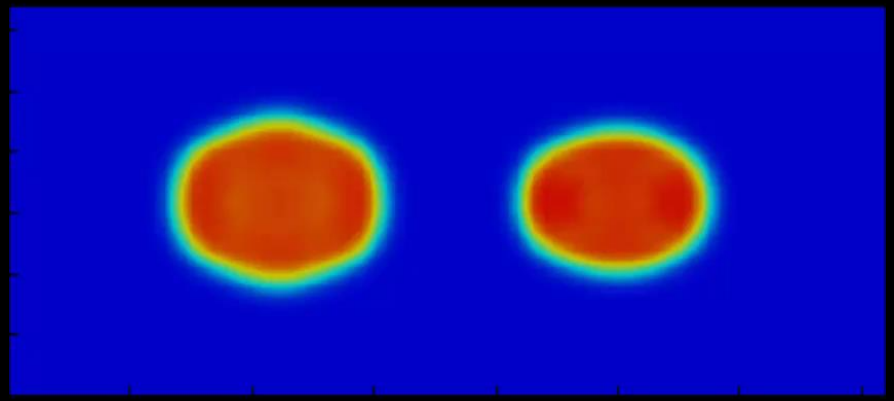




Super-preliminary

Tip-on-tip collisions of ^{160}Gd+^{248}Cm

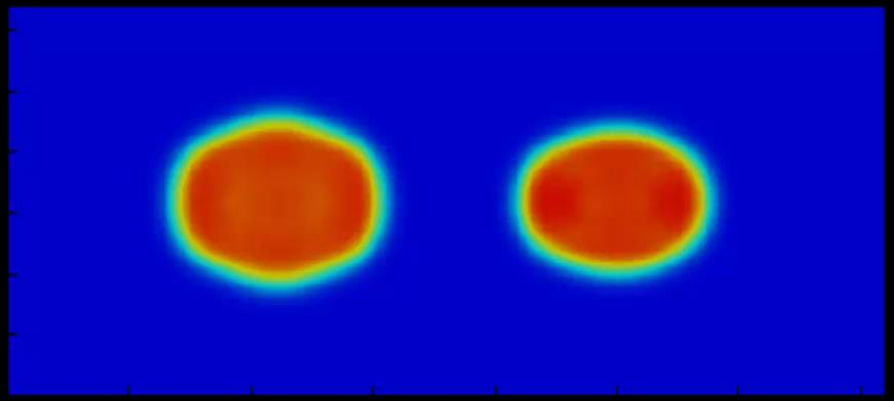
E-V_B ~ 291 MeV



(E~797 MeV, E/V_B~1.57)

TKEL ~ 372 MeV

E-V_B ~ 295 MeV



(E~801 MeV, E/V_B~1.58)

TKEL ~ 507 MeV

Summary

TDHF+Langevin

TDRPA

SMF

TDHFB

SuperHeavy Element

SHE

Extensions

ME: Microscopic thEory

TDHF

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