HPCI Strategic Programs for Innovative Research (SPIRE)
Field 5 “The origin of matter and the universe”

# Fission Dynamics of Superheavy Compound Nuclei

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based on TDDFT calculations
(Time-dependent density functional calculations)

Collaborations:
T. Otsuka (U. Tokyo)
S. Heinz (GSI)
Y. Aritomo (Tokyo Tech.)

# Today's topic

Show fission dynamics related with the superheavy synthesis reaction:

$$^{248}\mathrm{Cm} + {}^{48}\mathrm{Ca} \longrightarrow ({}^{296}\mathrm{Lv})^{*} = \mathbf{({}^{296}116)^{*}} \longrightarrow$$

based on 3-dimensional Time-dependent density functional calculations (TDDFT)

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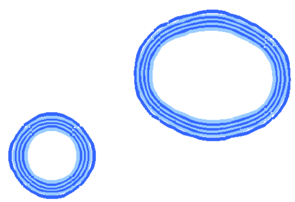

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TDDFT with SkM*

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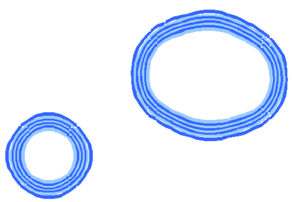

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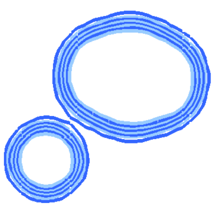

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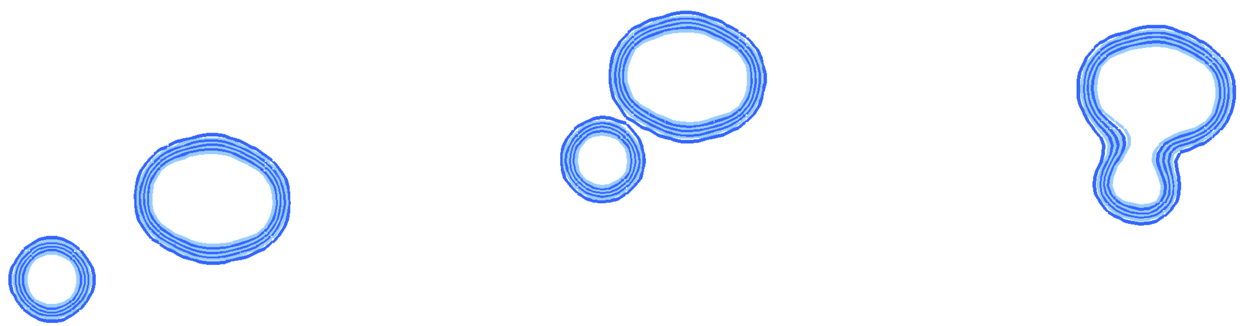

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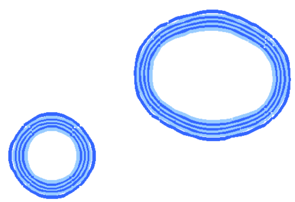

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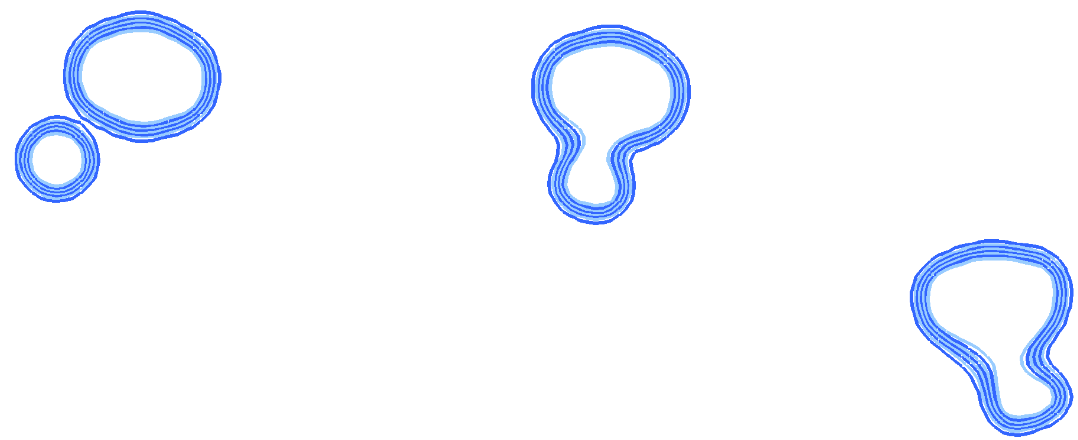

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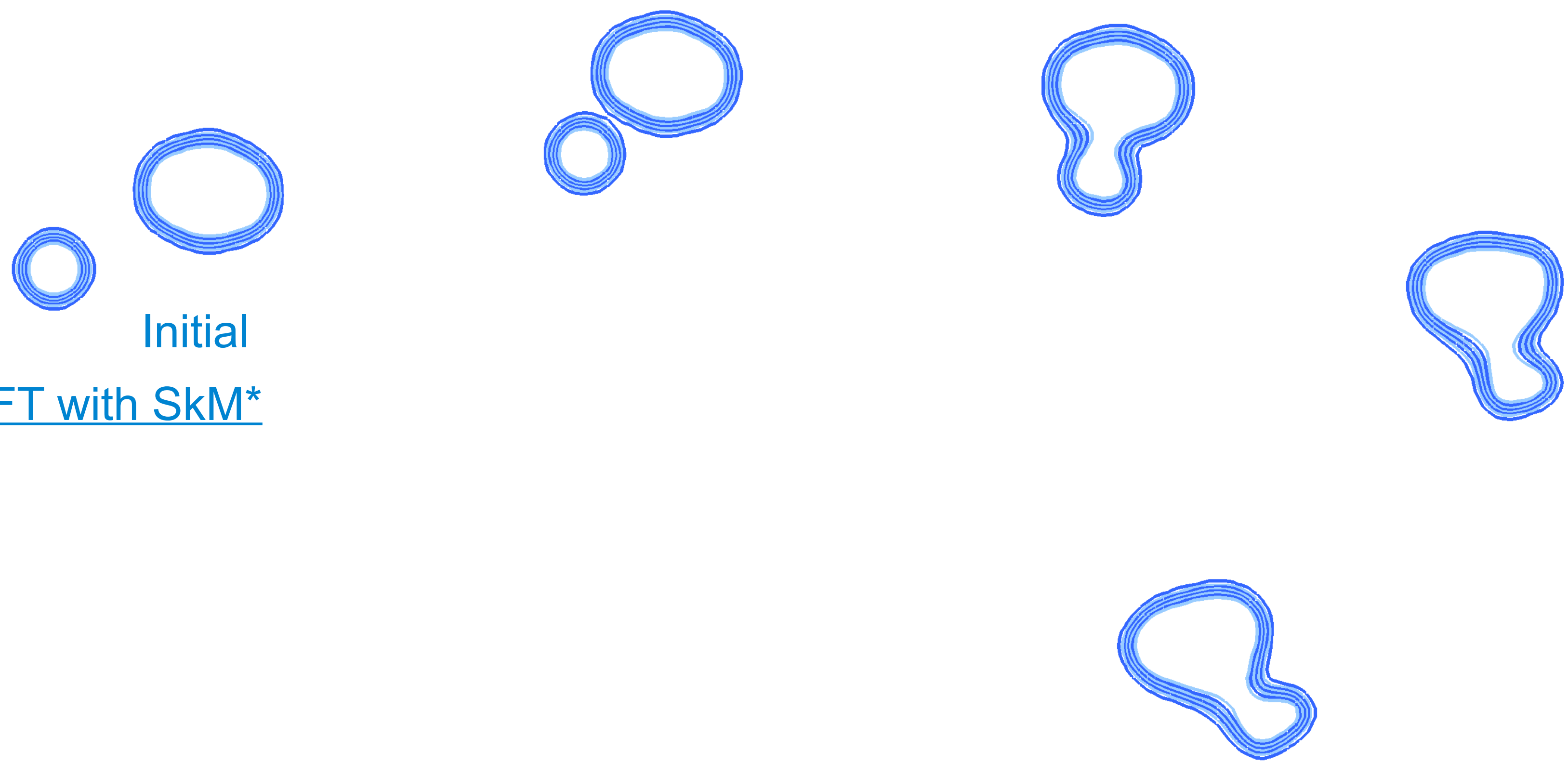

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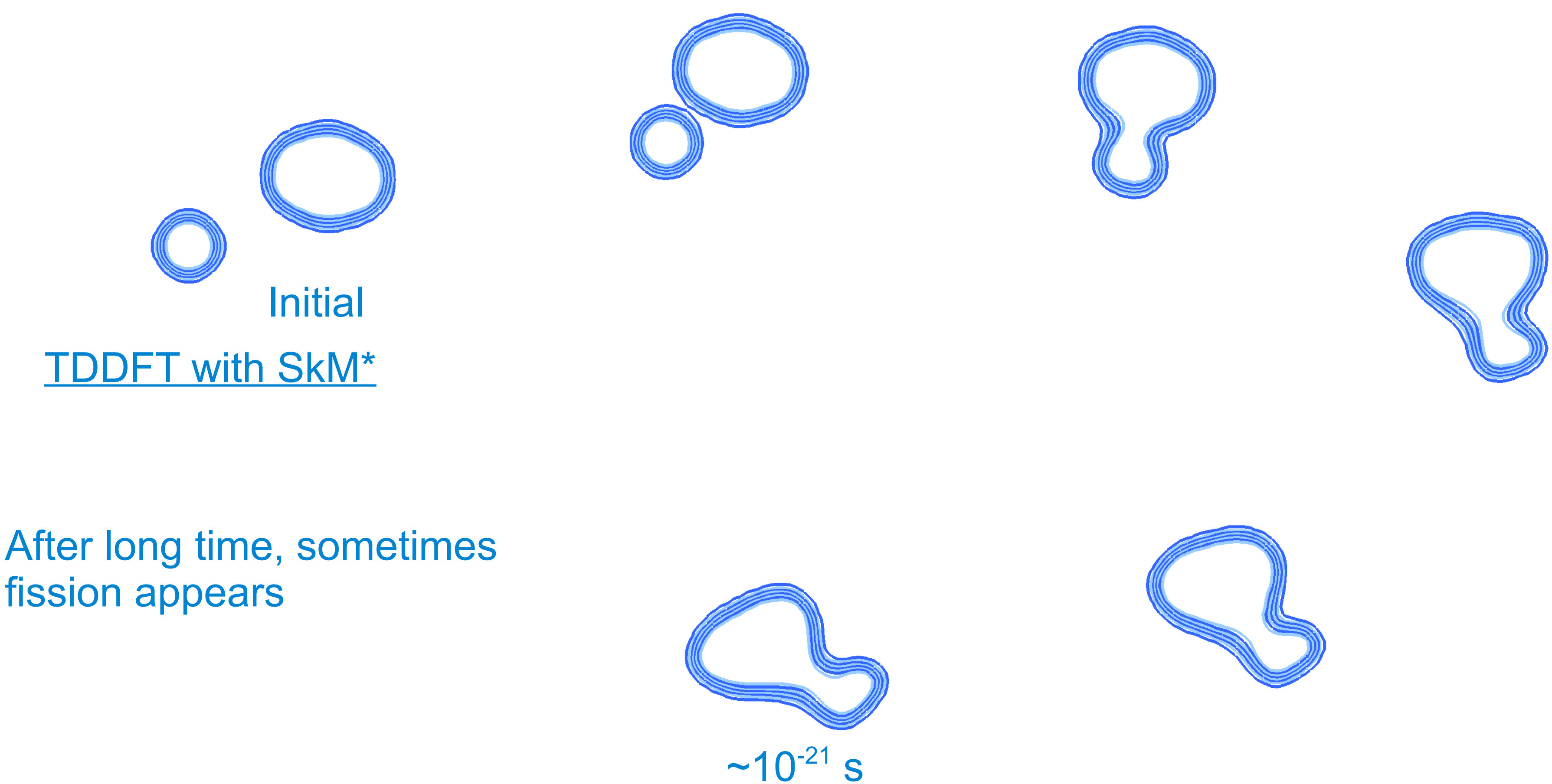

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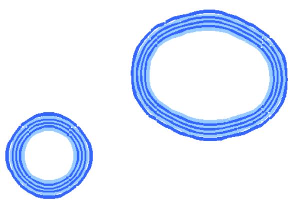

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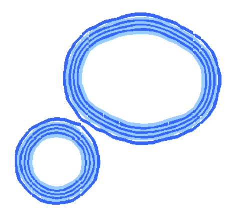
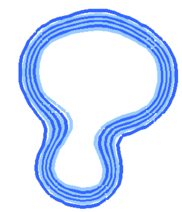
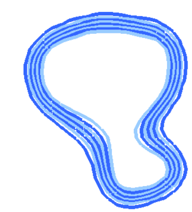


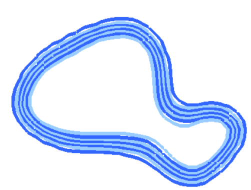
Fusion
(Quasi-fission)
Fusion-fission
Emission of particle

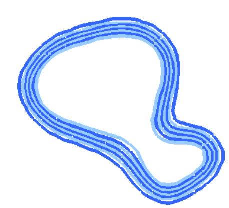




(1) Capture or not ?
(2) Compound formation or not ?
(3) Survive or not (Decay) ?

After long time, sometimes fission appears





~$10^{-21}$ s

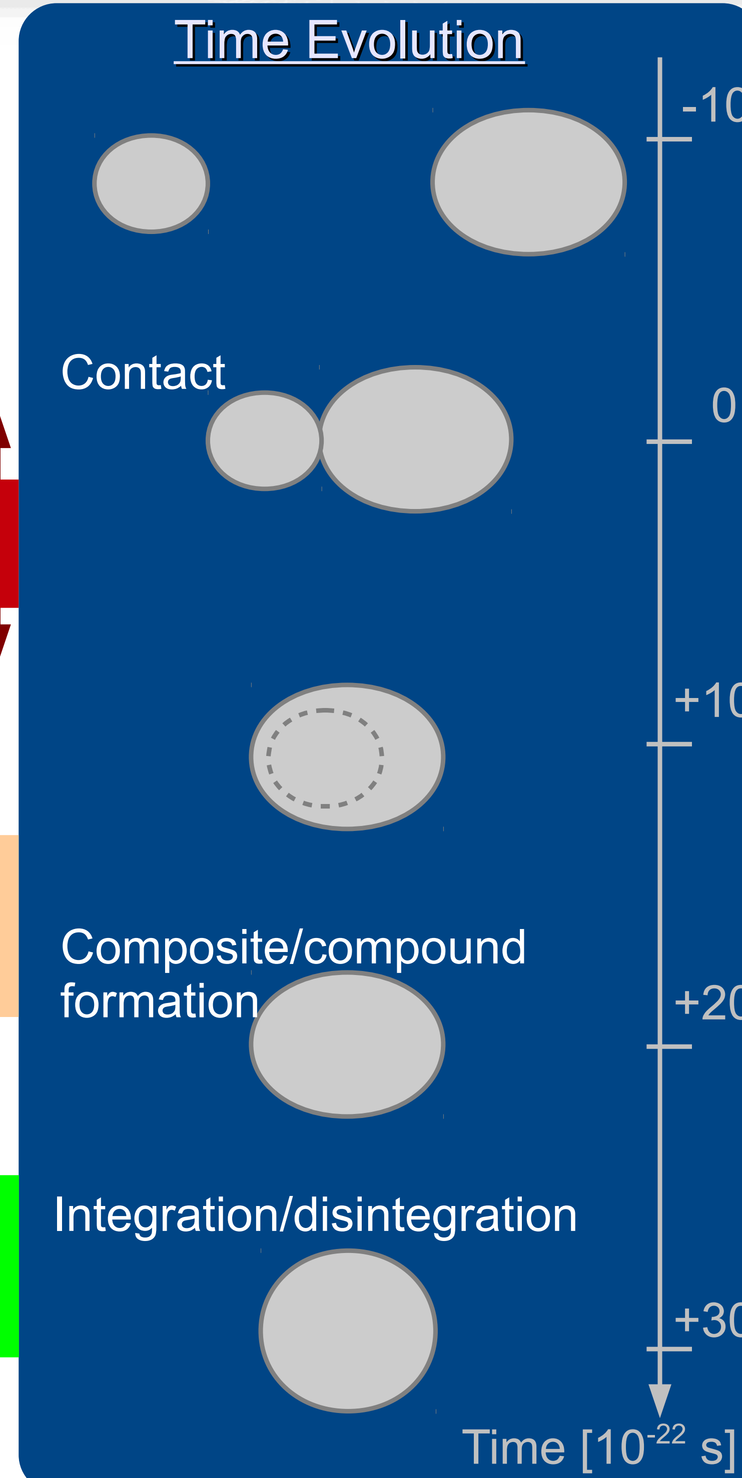
# Several time scales in low-energy heavy-ion reactions

low-energy heavy-ion collision treats integration/fusion and disintegration/fission of quantum system

The typical time-scale of charge equilibration is the order of a few [$10^{-22}$s]; Iwata-Otsuka-Maruhn-Itagaki PRL (2010)

Relatively longer time (~1 [$10^{-21}$s]) is necessary for the composite formation; suggested by **several** TDDFT calculations

[Measured] The typical time-scale of low-energy heavy-ion collision is 1000 [fm/c] ~ 3 [$10^{-21}$s]; suggested by **many** TDDFT calculations



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The typical time-scale of charge equilibration is the order of a few [$10^{-22}$s]; Iwata-Otsuka-Maruhn-Itagaki PRL (2010)

We would ask “ Why ? ”

Relatively longer time (~1 [$10^{-21}$s]) is necessary for the composite formation; suggested by several TDDFT calculations

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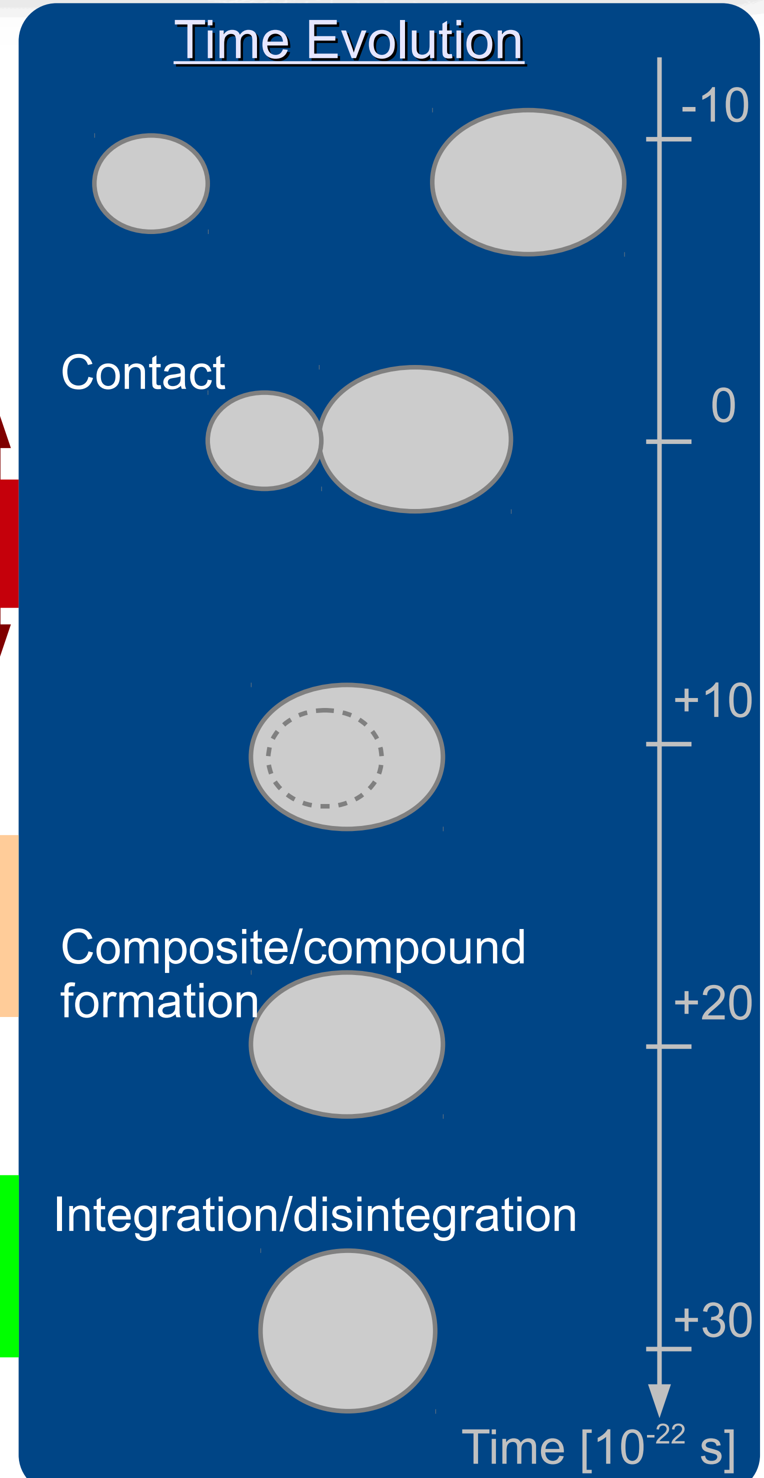
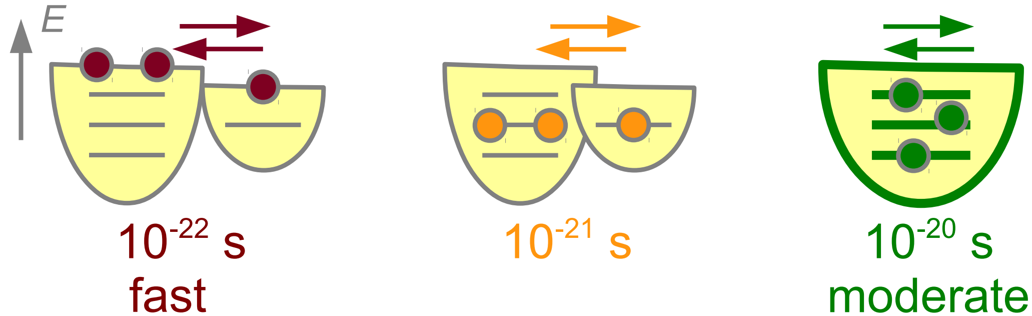


# It's all about the motion of particles

$10^{-22}$ s … Fermi momentum of nucleon
(Fermionic system)

$10^{-21}$ s … Collective oscillation of nuclear system
(larger influence of nuclear force)

$10^{-20}$ s … Momentum equilibration

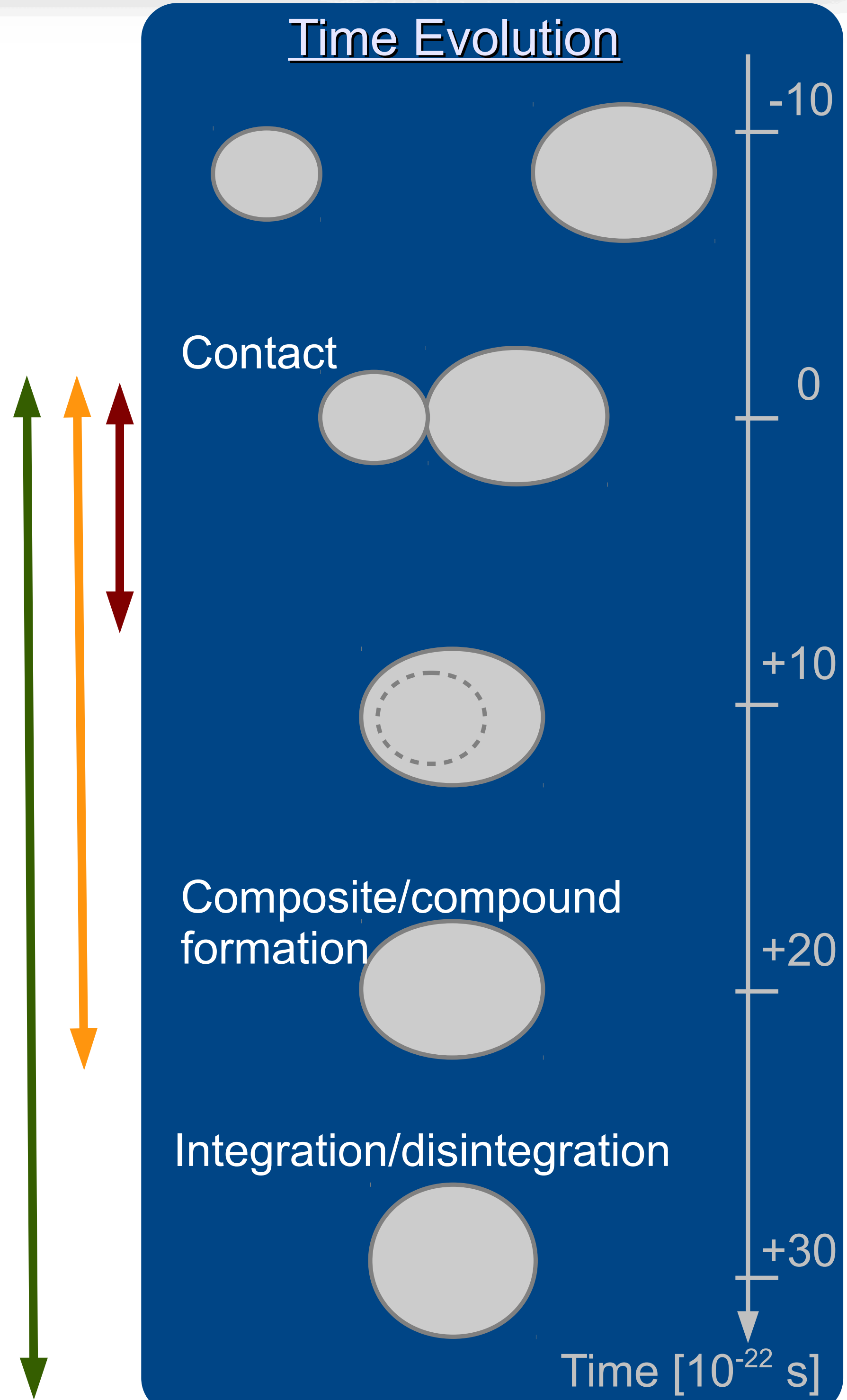



In addition,

$10^{-15}$ s … Thermal equilibration (~Wiener process)
(slow) fission, (slow) decays

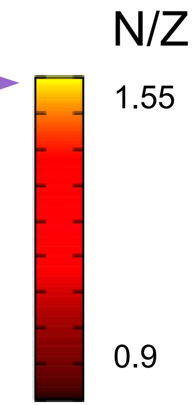
TDDFT can investigates events < $10^{-20}$s

For more explanation, see Iwata JPCS to appear; arXiv1303.0498

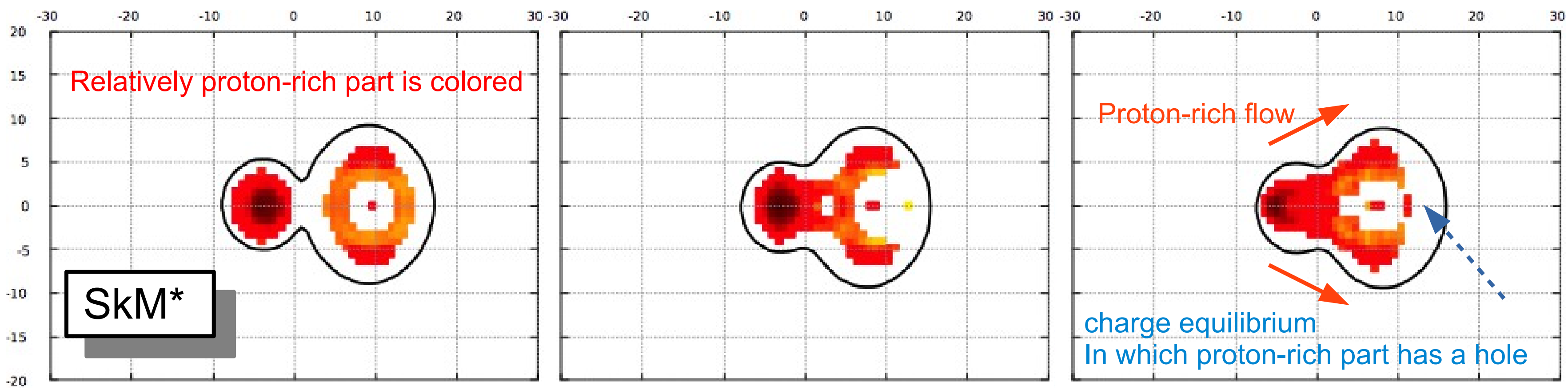


$^{248}\mathrm{Cm} + {}^{48}\mathrm{Ca} \rightarrow ({}^{296}116)^*$

| | N/Z |
|---|---|
| $^{248}$Cm | 1.583... |
| $^{296}$116 | 1.551... |
| $^{48}$Ca | 1.4 |




## Charge equilibration




Contour: 0.015 fm$^{-3}$

Time

Total duration time = 3.0 [$10^{-22}$s]

It gives a fundamental information about the symmetry energy …
(the symmetry energy is a unique driving force of charge equilibration)

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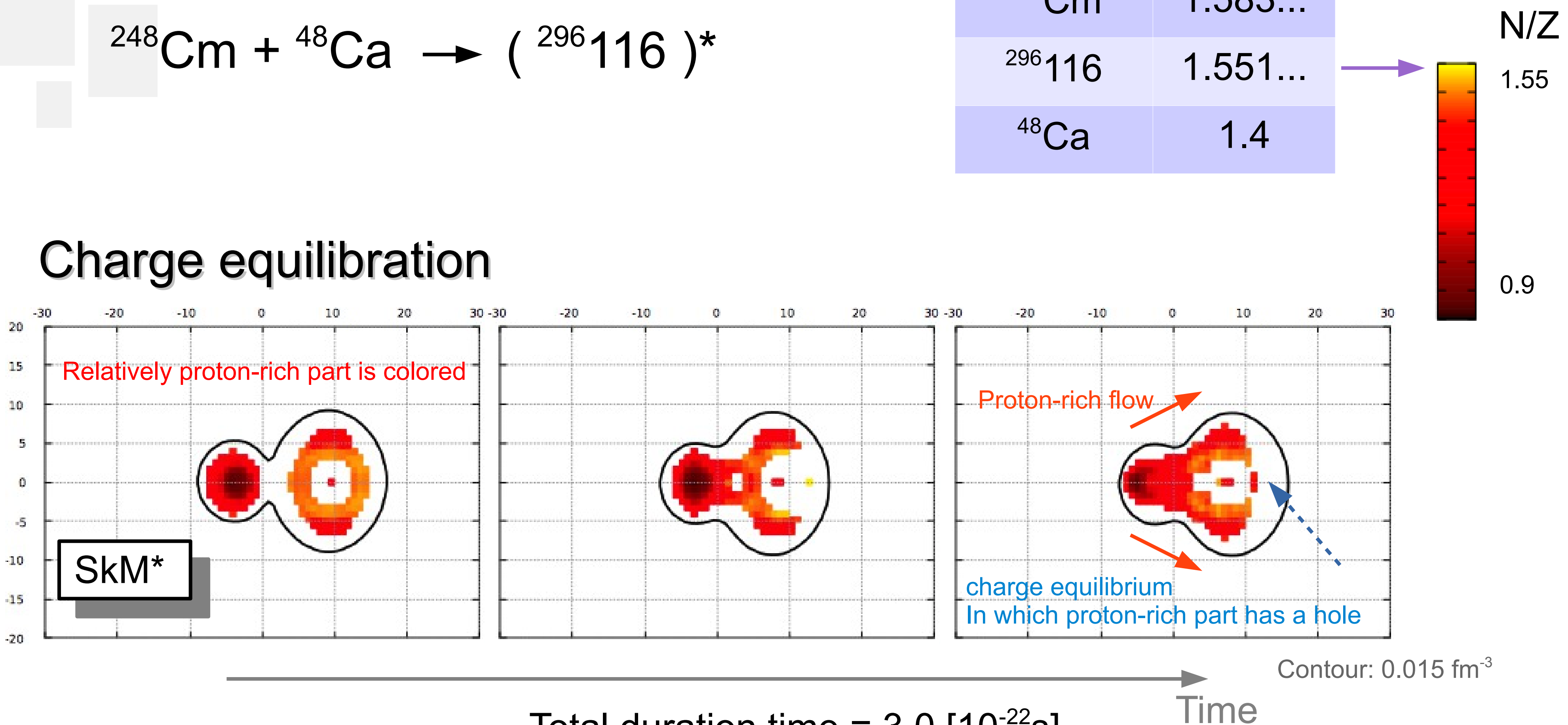


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It gives a fundamental information about the symmetry energy …
(the symmetry energy is a unique driving force of charge equilibration)

Charge equilibration has common propagation speed (~ Fermi velocity) mostly independent of energy and impact parameter

# Fast charge equilibration in superheavy synthesis

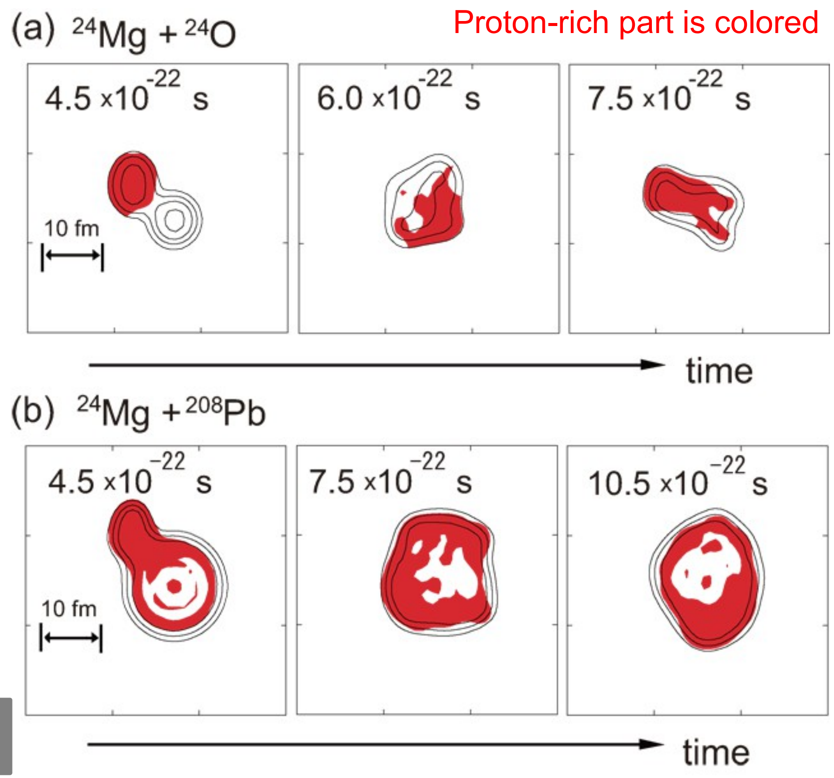
Iwata-Otsuka-Maruhn-Itagaki PRL (2010)

There are two types of charge equilibration dynamics ...

Type 1

Type 2

SkM*




Reaction between **light** nuclei
… motion similar to GDR oscillation

Reaction including **heavy** nuclei
… motion different from GDR oscillation
It can be distinguished whether GDR oscillation curve is regular/smooth or not.

[hole] due to the large Coulomb force

In case of superheavy synthesis we have “Type 2” charge equilibration
In which a hole of proton-rich part is formed.

Our recent project to clarify the symmetry energy
- Localization (N/Z pattern formation)
- Transition between type1 and type2

# Shape evolution of merging nucleus

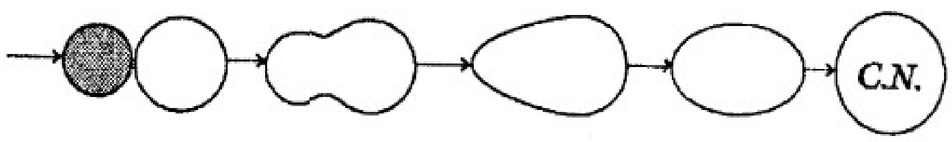
Shape evolution is one of the most fundamental properties,
but we do not know what kind of common/general property exists in that;

*e.g.*, in the necking, there are two different kinds of assumption on the neck formation in presently-used two different theoretical models

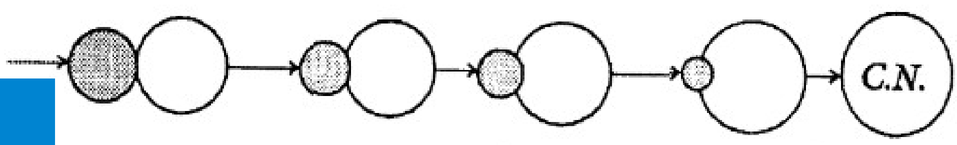
It has not been clear for a long time

Neck is point-like or not

The macroscopic dynamical model
Fusion of two nuclear liquid drops




The dinuclear system concept
Conservation of nuclear individuality




These models need to assume the evolution of shapes.

**Simple and essential problem**

This kind of question should be answered by microscopic method such as TDDFT.

Aritomo-Iwata, in preparation

# Shape evolution of merging nucleus

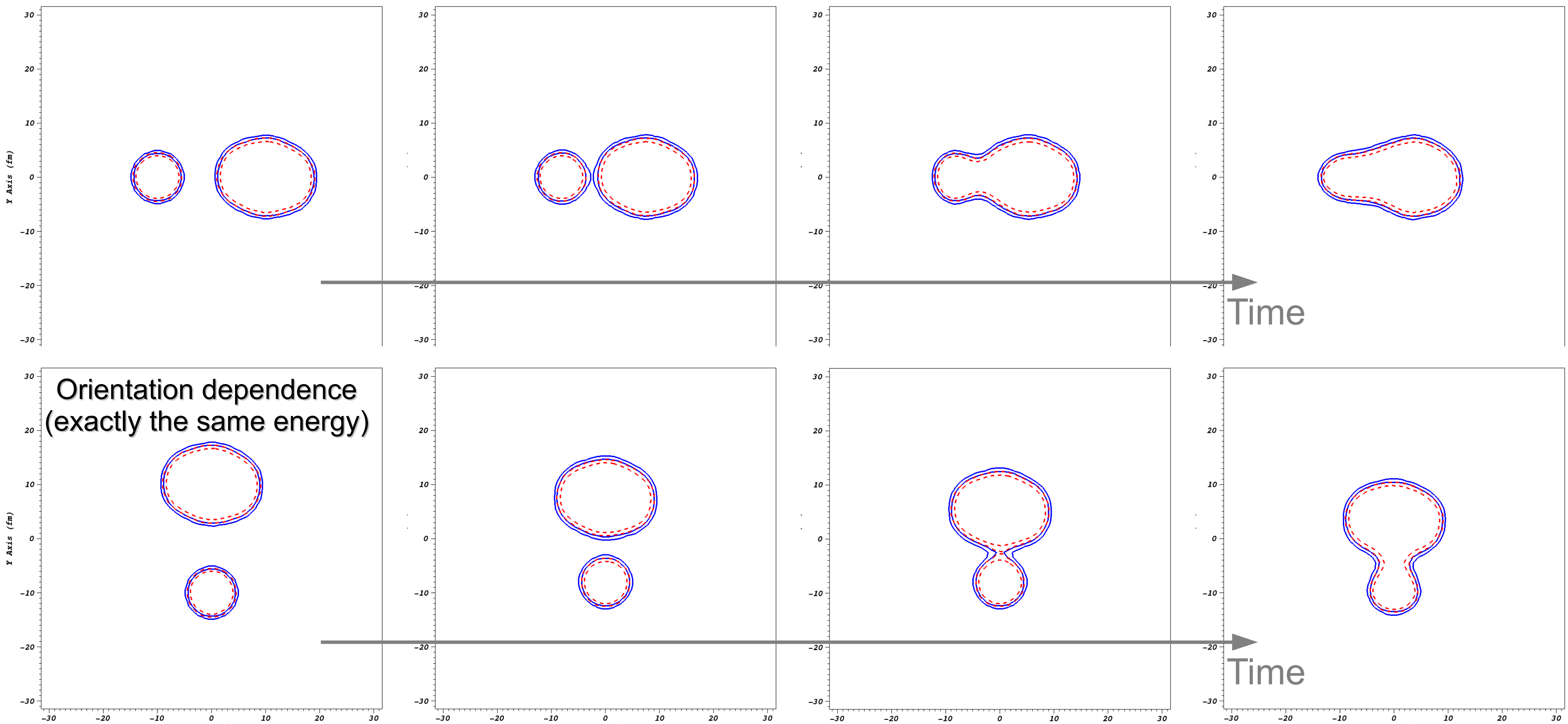
SkM*

$^{248}Cm + ^{48}Ca \rightarrow (^{296}116)^*$

neutron

proton

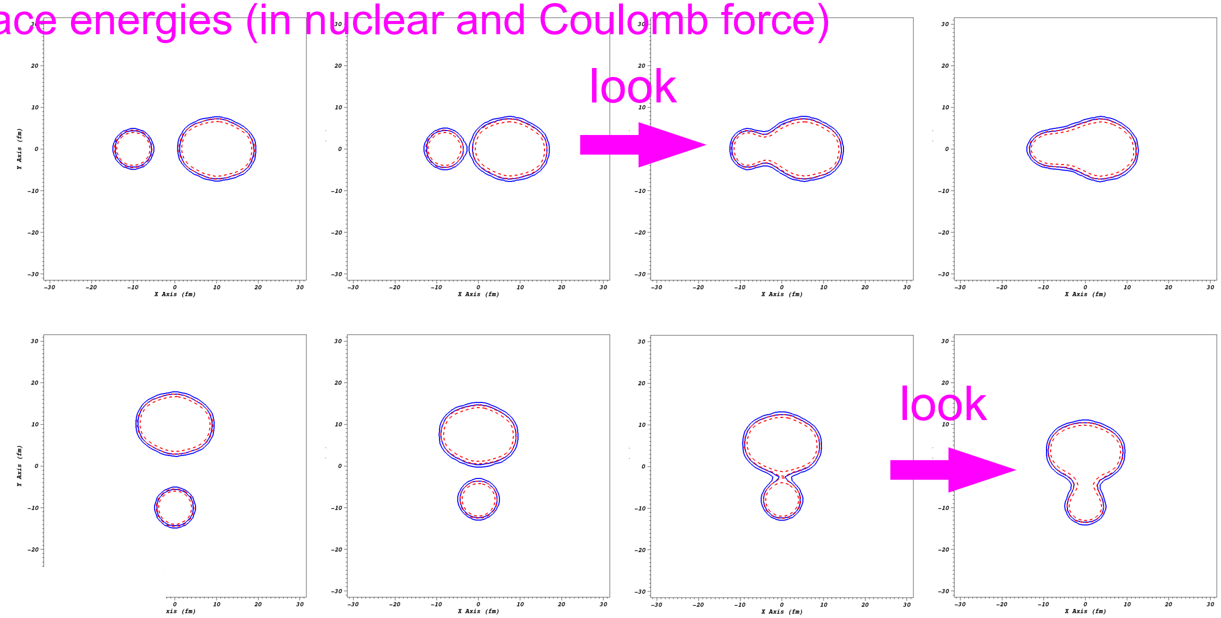
Contour: 0.015 fm$^{-3}$ and 0.030 fm$^{-3}$



Aritomo-Iwata, in preparation

# Shape evolution of merging nucleus

Competition between volume and surface energies (in nuclear and Coulomb force)




Again, it is worth comparing

The macroscopic dynamical model
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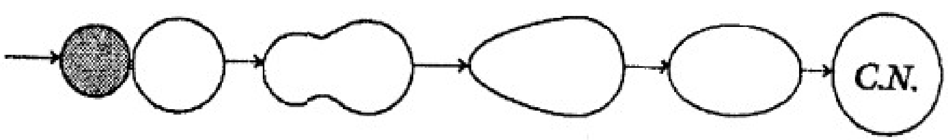


Changing surface

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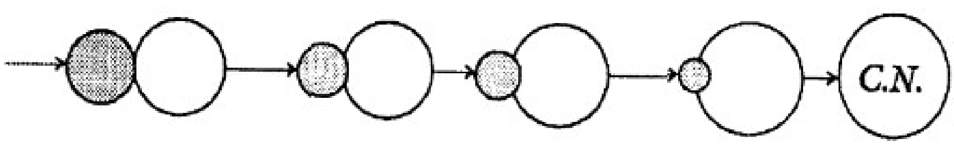


Changing volume

Aritomo-Iwata, in preparation

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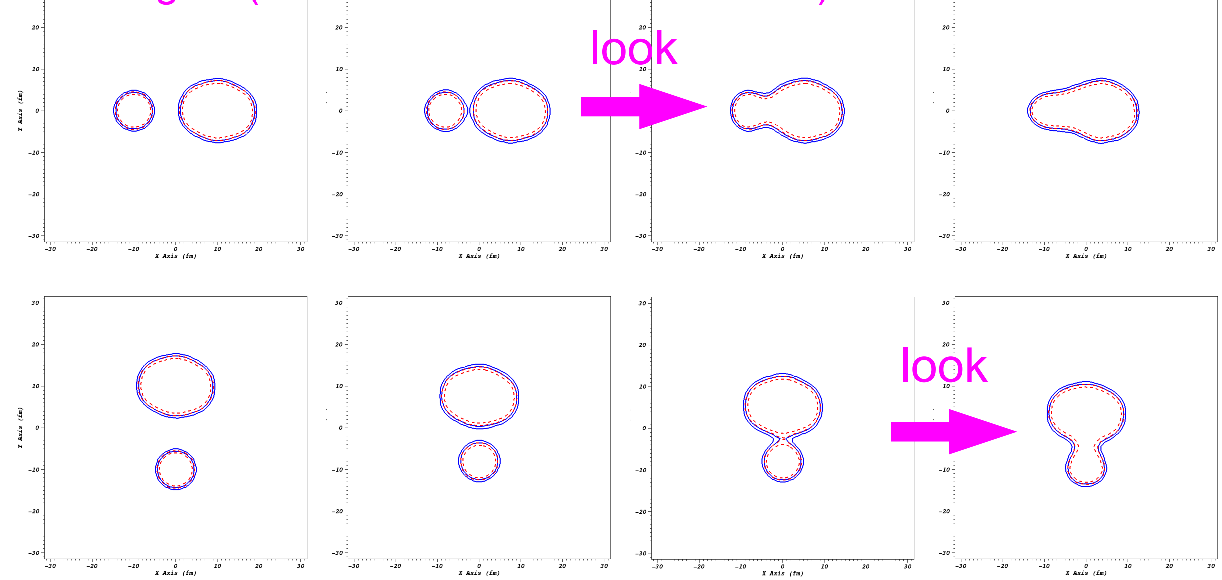


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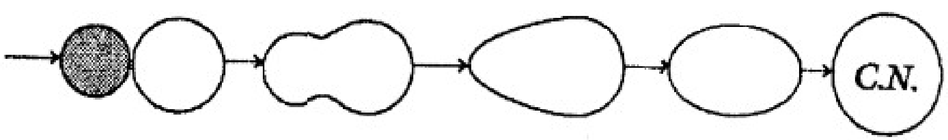


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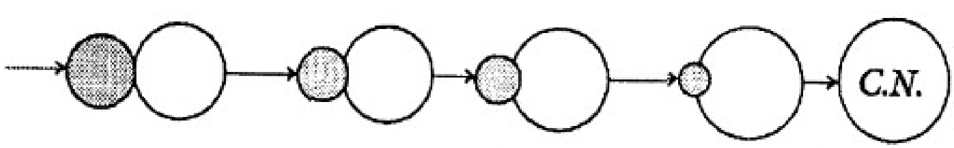



Changing volume

A remark on “neck formation” …

Most of time, large neck is formed, and point-like neck formation is quite rare.

[Reasonable]

Easier to change

Volume energy >> Surface energy
(0.99 A ) (0.02 $A^{2/3}$) in WB formula

# TDDFT final products

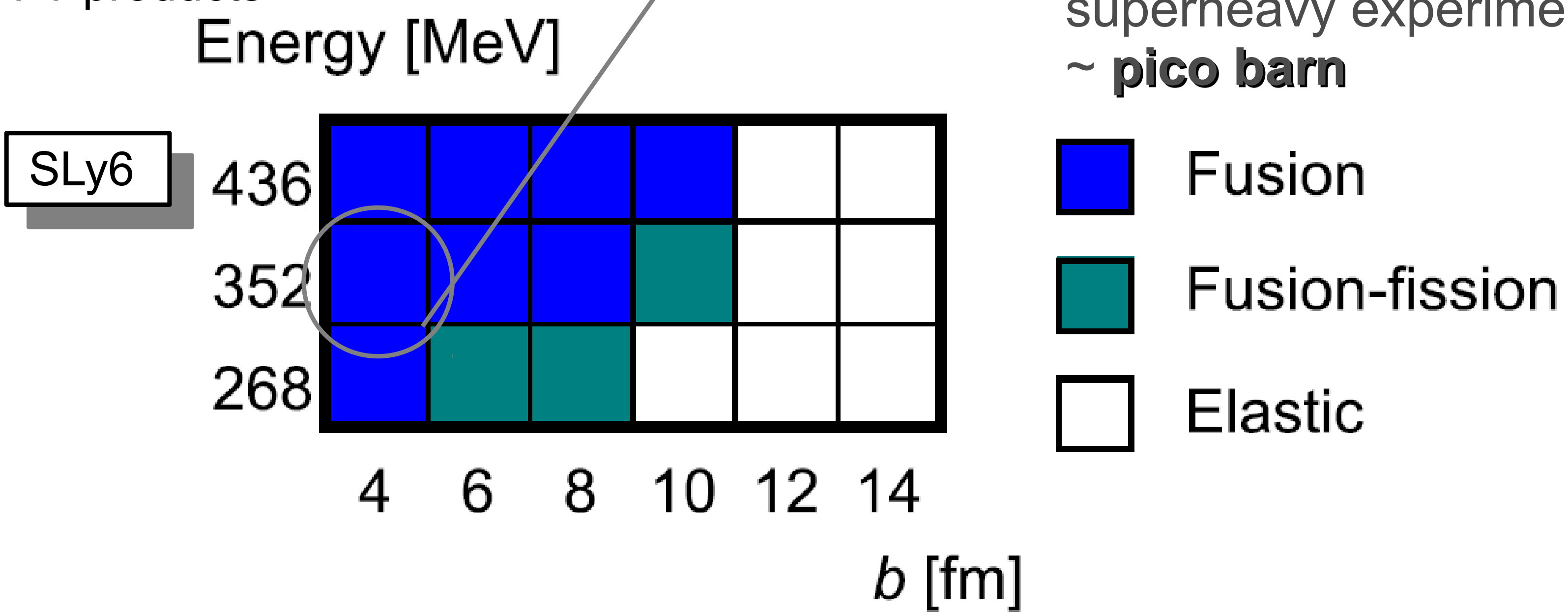
Iwata-Heinz, JPCS (2012)

$^{248}Cm + {}^{48}Ca \rightarrow ({}^{296}116)^*$

Here is a systematic result of the TDDFT products

Geometric cross section for this event:
$5^2$ Pi - $3^2$ Pi [fm$^2$] ~ 50 [fm$^2$] = 500 [mb]

superheavy experiments
~ **pico barn**




1) Quite different from the experiments;
**Fusion is over estimated to a very large extent.**
→ These TDDFT final states are only states after around $10^{-20}$s.

2) Fission appears only for states with higher angular momentum
→ Fission mechanism of a specific kind is included in the TDDFT

# TDDFT final products

$^{248}Cm + ^{48}Ca \rightarrow (\, ^{296}116 \,)^*$

Indeed,

Fusion cross section

= Capture cross section * Compound formation prob. * Survival prob.

~1 only for light or medium mass collisions

Due to the lack of slow processes in the TDDFT

There are many publications/presentations in these 10 years saying ...

"TDDFT can describe fusion cross section very well"

Caution

of collisions between light or medium mass nuclei

a correct statement

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**Abandon to connect the early and typical duration-time stages to the late stage,** and conduct new calculation for fission events.

# Fission (long history, but still only at the beginning)

Competition between (short-range) nuclear force and (long-range) Coulomb force, such a competition is common to nuclear pasta formation.

- Its mechanism is complicated;

☆ collective effect

Surface and Coulomb competition … fully included in the TDDFT

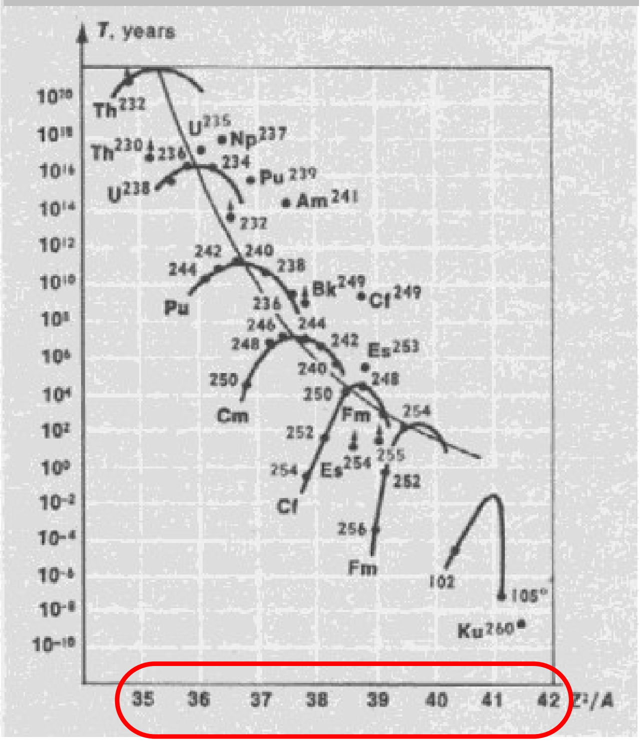
☆ pairing effect

☆ single particle degrees of freedom (non-collective effect)

☆ thermal effect (non-adiabatic effect)

☆ tunneling effect

Experimental value
for half life( spontaneous fission)




- 1930's Bohr and Wheeler; liquid drop model

→ $(Z^2/A) = 49.2$ empirical threshold value

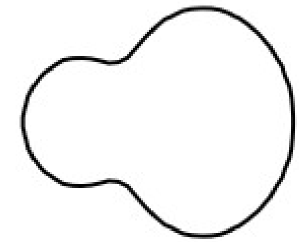
Competition between Surface and Coulomb Energies

# The most important thing is to prepare good initial states

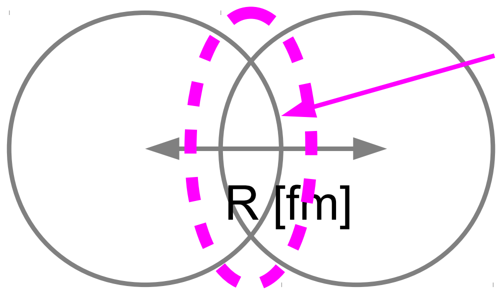
$(^{296}116)^*$ ⟶ $(Z^2/A) \sim 59.7 > 49.2$

Large enough

Example of initial state



We prepare many many initial state
by changing $A_1$, $A_2$, $Z_1$, $Z_2$, $R$.




1) Prepare two nuclei using static Hartree-Fock calculations.

$Z_1 + Z_2 = 116$

$A_1 + A_2 = 296$

Any possible numbers are examined to obtain the energy dependent mass distribution
… (now under calculations ...)

2) Two nuclei is put in a distance R[fm] without giving any velocities to the center-of-mass

Several $R$[fm] is examined

# Shape evolution of fissioning nucleus

SkM*

( $^{296}116$ )* → $(Z^2/A) \sim 59.7 > 49.2$

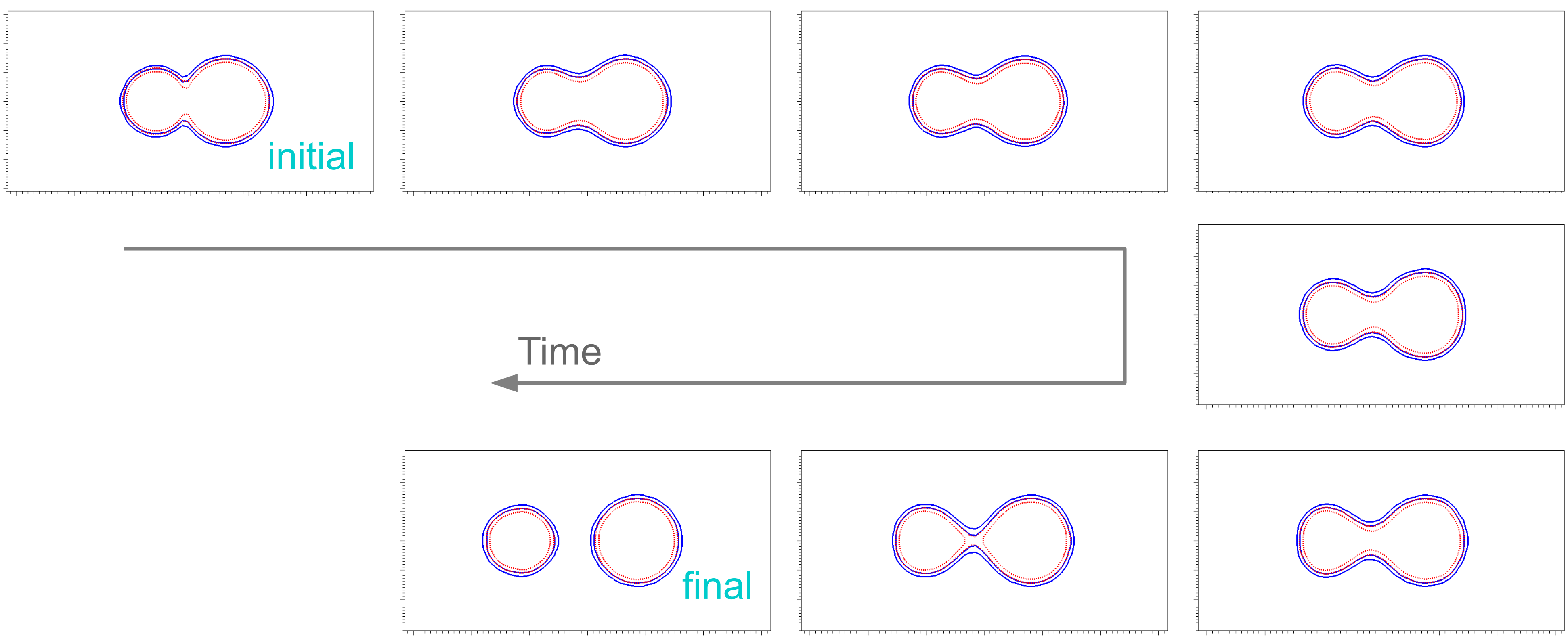
Large enough

$^{296}116^* \rightarrow {}^{208}Pb + {}^{88}Se$

Contour: 0.015 fm$^{-3}$ and 0.030 fm$^{-3}$

neutron (solid line)

proton (dashed line)



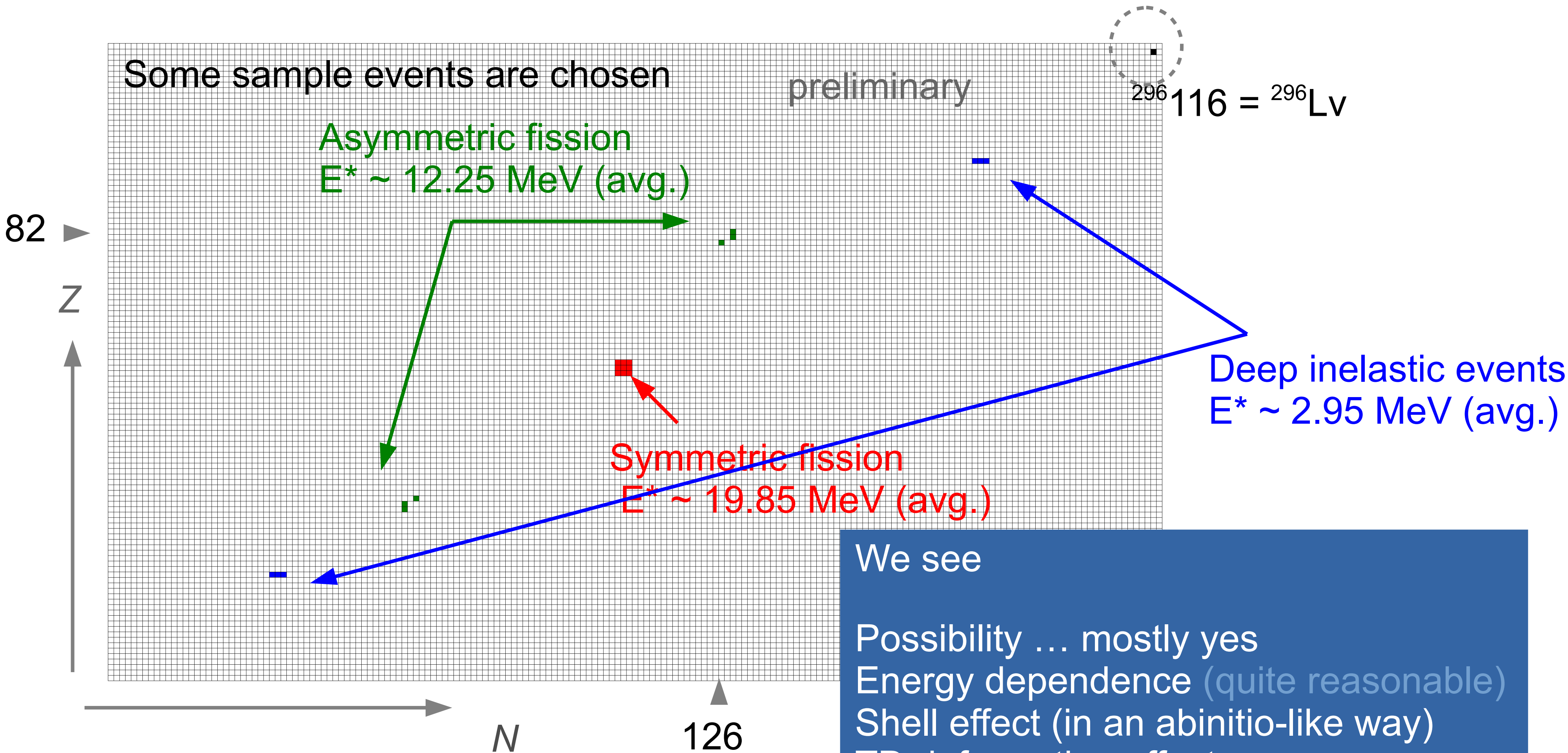

$\sim 10^{-21}$s

Iwata-Heinz-Otsuka, in preparation

$^{248}\mathrm{Cm} + ^{48}\mathrm{Ca} \rightarrow (^{296}116)^* \rightarrow (Z^2/A) \sim 59.7 > 49.2$

Large enough

Results (on going); products are shown in color (RGB)




We see

Possibility … mostly yes
Energy dependence (quite reasonable)
Shell effect (in an abinitio-like way)
TD deformation effect
Pauli effect (in dynamics)

# Summary

- The TDDFT is developing in order to clarify the reaction mechanism throughout the process.
- [Very early moment] the appearance of charge equilibration is sufficiently clarified using the TDDFT.
- [Early stage] shape evolution will be quantitatively discussed using microscopic TDDFT soon (Aritomo-Iwata, in preparation).
- For heavy reactions, even fusion cross section is not correct, which is due to the lack of slow processes in TDDFT.

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- [Late stage] Mainly due to the competition between the Coulomb and surface energies, the possibility of fission …(Iwata-Heinz-Otsuka, in preparation)

Now TDDFT research opens a door to investigate processes with different time scales …