Perspectives on nuclear reaction theory and superheavy elements

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1. Nuclear Reactions: overview
2. Coupled-channels approach with a beyond-mean-field method
3. Time-dependent GCM for many-body tunneling
4. Fusion for superheavy elements and TDHF
5. Summary

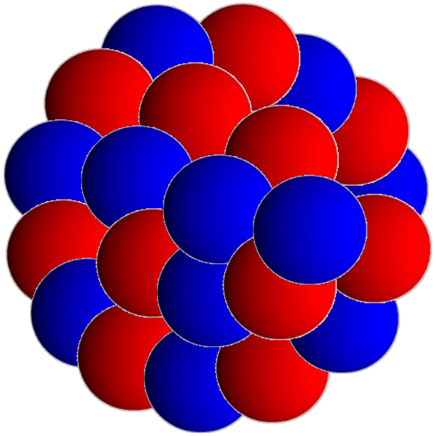
Mini-Workshop on nuclear physics and nuclear astrophysics, 2020.1.15, Soongsil University

Introduction: low-energy nuclear physics

- behaviors of atomic nuclei as a quantum many-body systems

  ⟵ understanding based on strong interaction

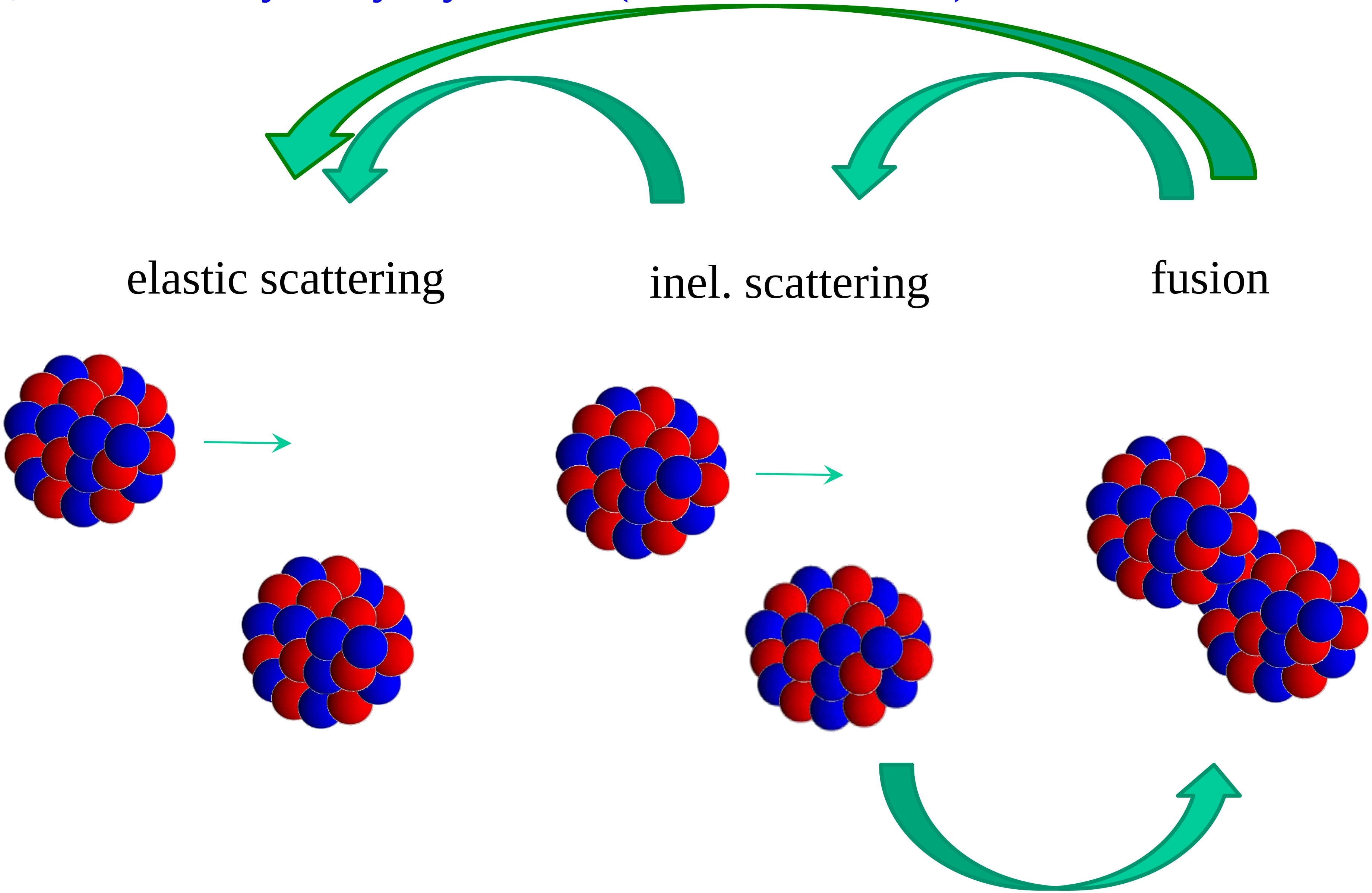
- static properties: nuclear structure
  - ✓ ground state properties (mass, size, shape,….)
  - ✓ excitations
  - ✓ nuclear matter
  - ✓ decays



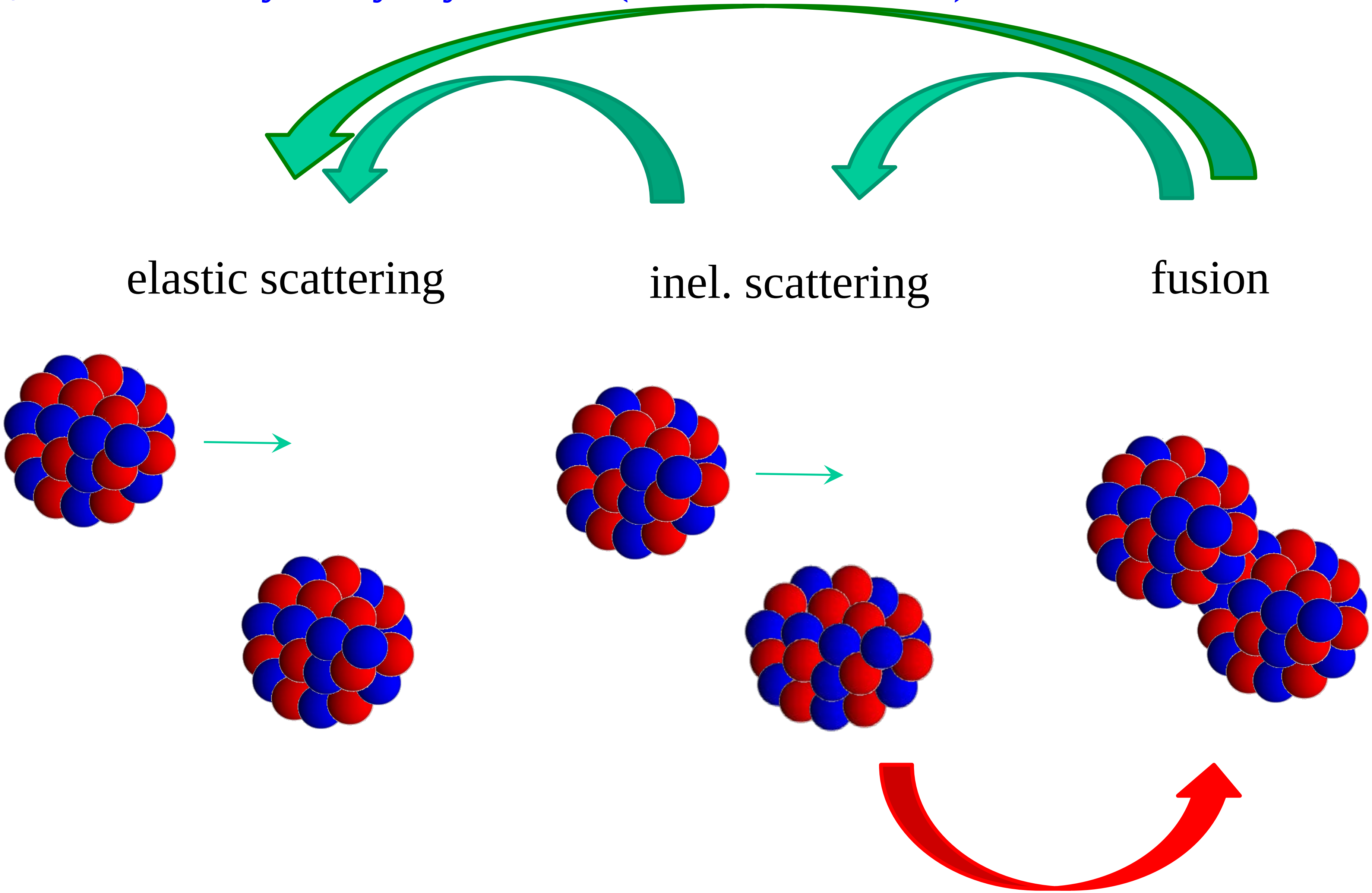
- dynamics: nuclear reactions

an interplay between nuclear structure and nuclear reaction

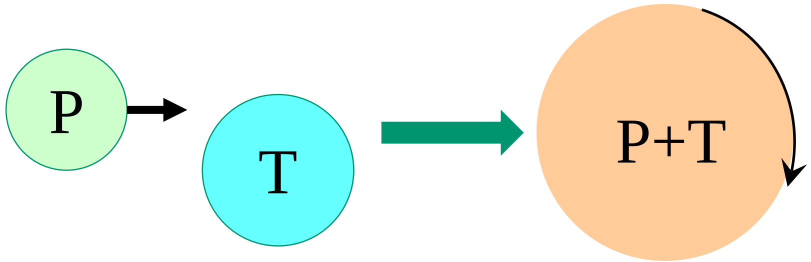
Quantum Many-body Dynamics (nuclear reactions)



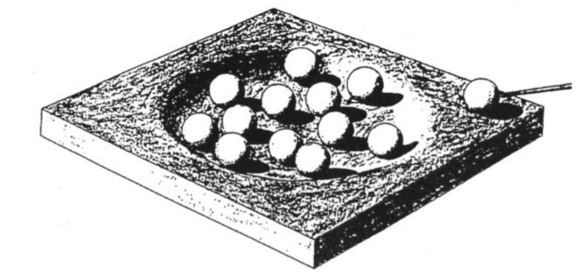
Quantum Many-body Dynamics (nuclear reactions)



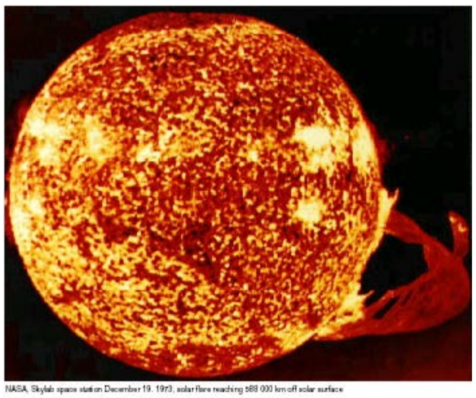
Fusion reactions: compound nucleus formation



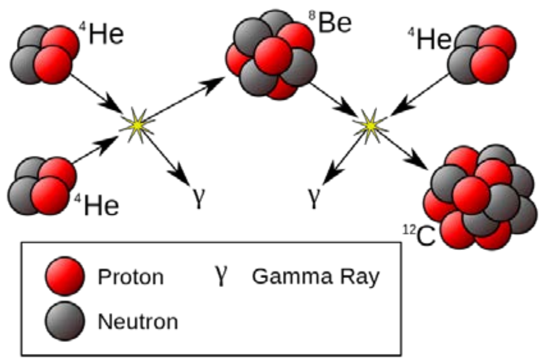
compound
nucleus



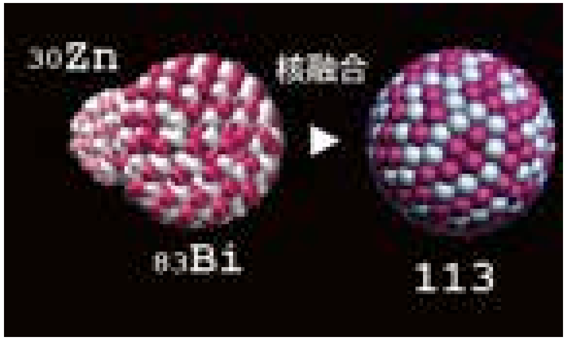
cf. Bohr '36



energy production
in stars (Bethe '39)



nucleosynthesis



superheavy elements

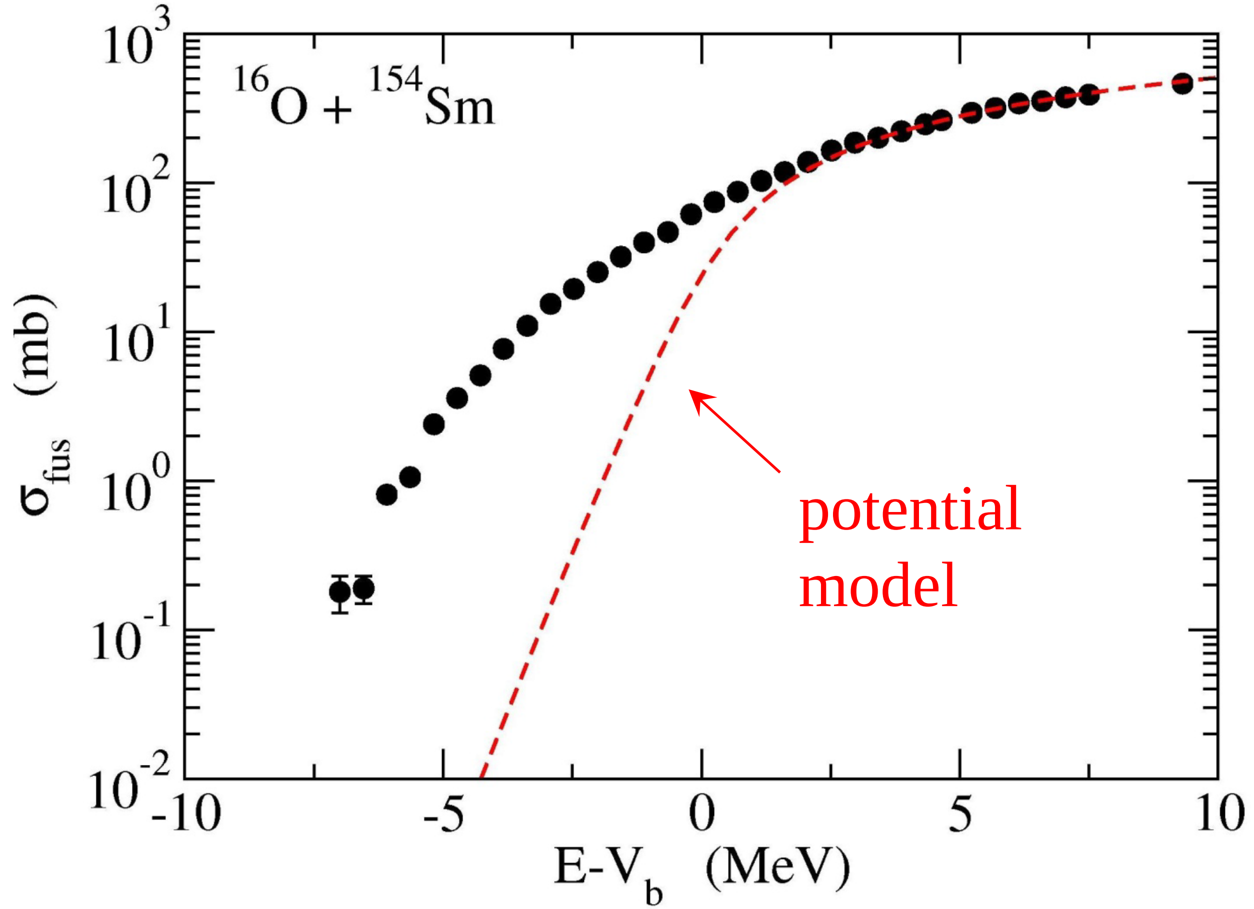
Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

⟵ microscopic understanding: an ultimate goal of nuclear physics

Discovery of large sub-barrier enhancement of σ_{fus} (~80's)

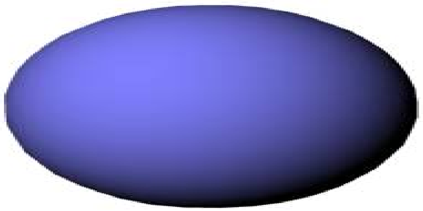
potential model: inert nuclei (no structure)

$$\sigma_{\rm fus} = \frac{\pi}{k^2}\sum_l (2l+1)(1-|S_l|^2)$$

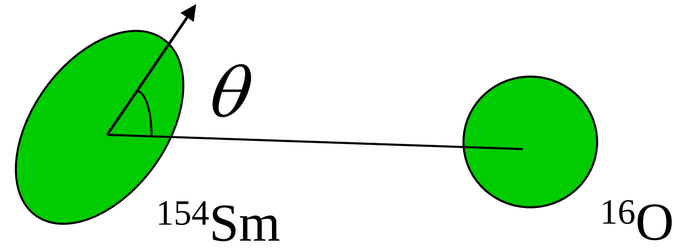


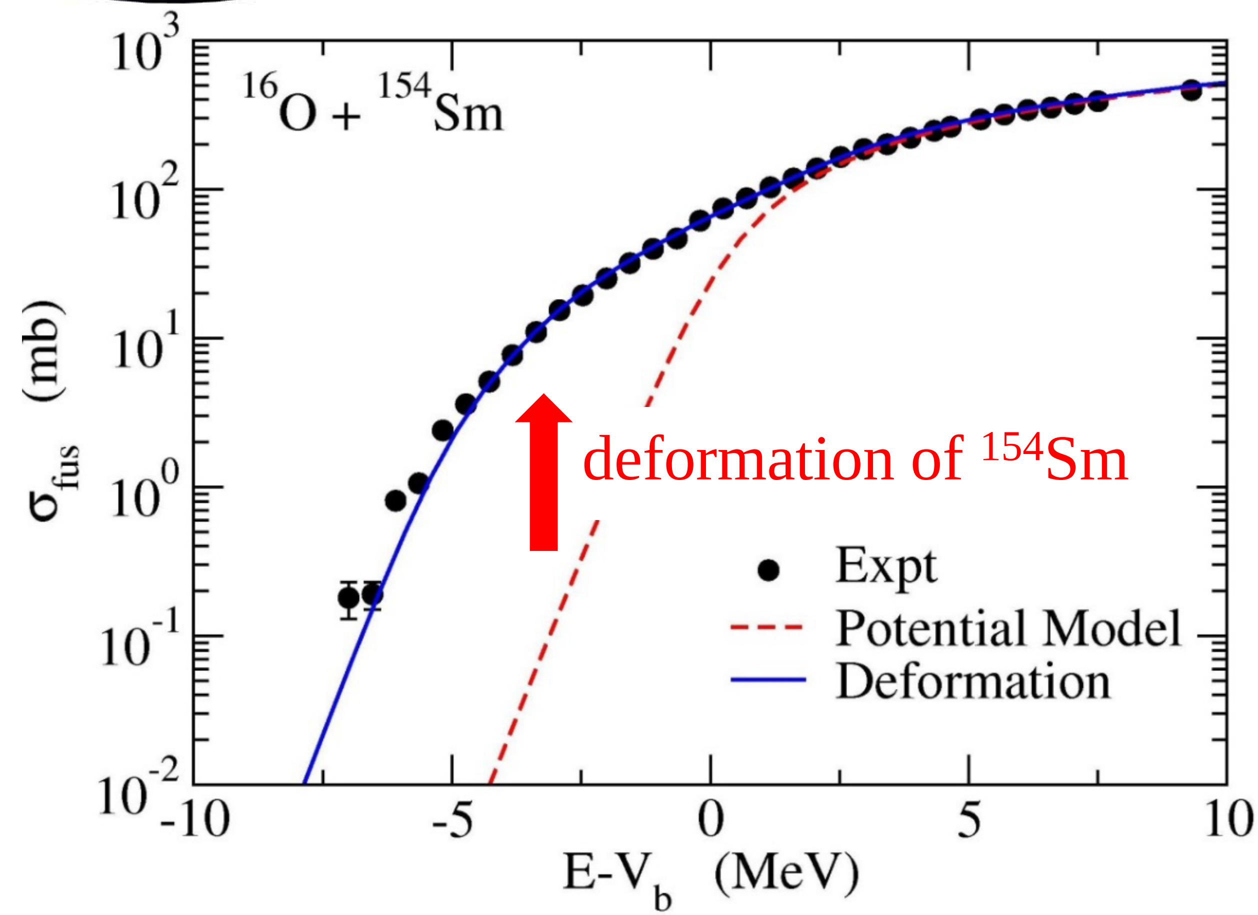
Discovery of large sub-barrier enhancement of σ_{fus} (~80's)

^{154}Sm : a typical deformed nucleus

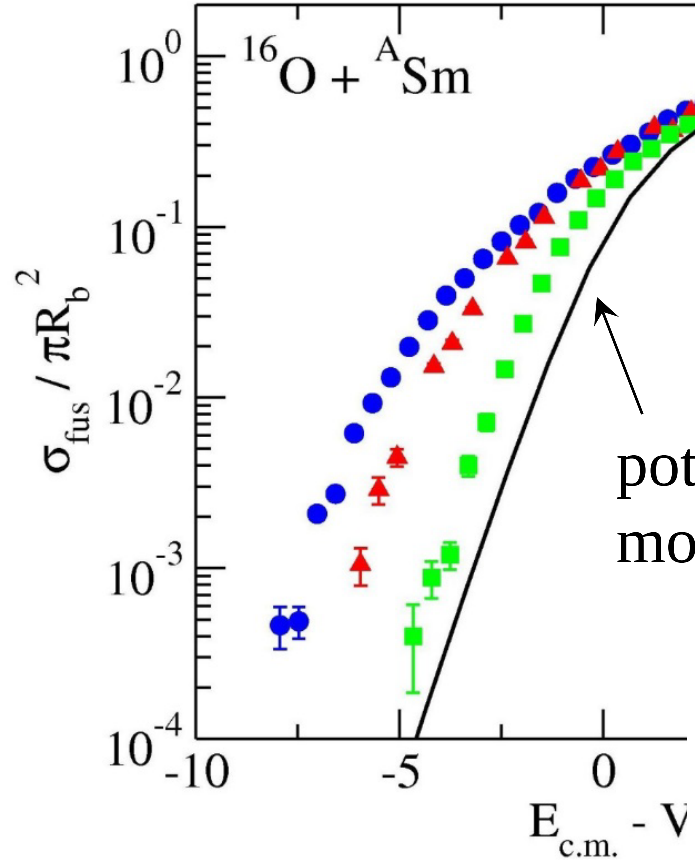


^{154}Sm



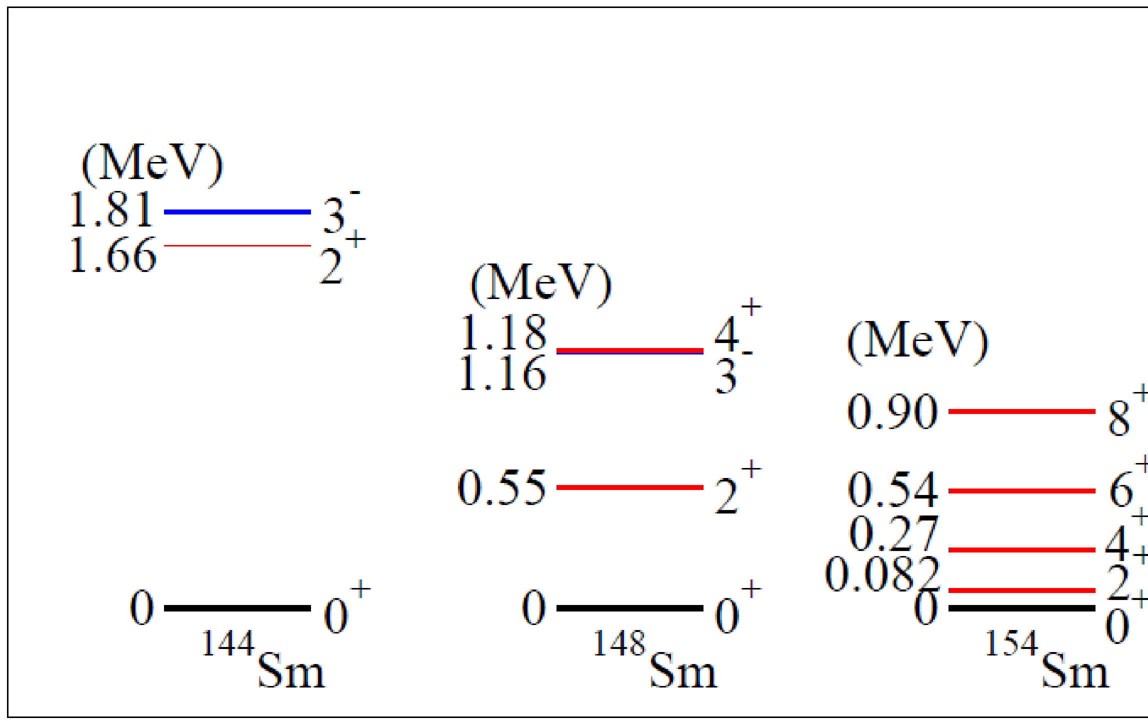


K. H. and N. Takigawa, Prog. Theo. Phys.128 ('12)1061.



enhancement of fusion cross sections

: a general phenomenon

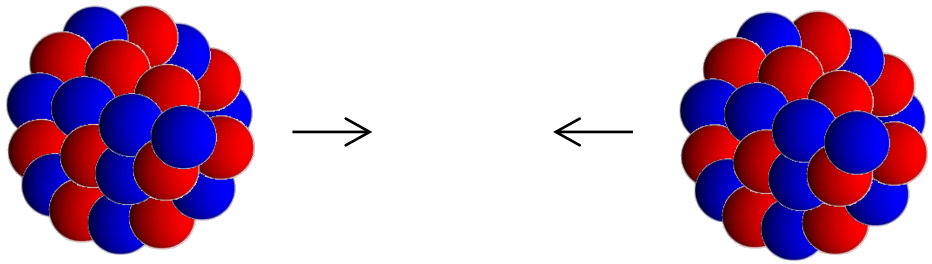


strong correlation with nuclear spectrum

→ coupling assisted tunneling

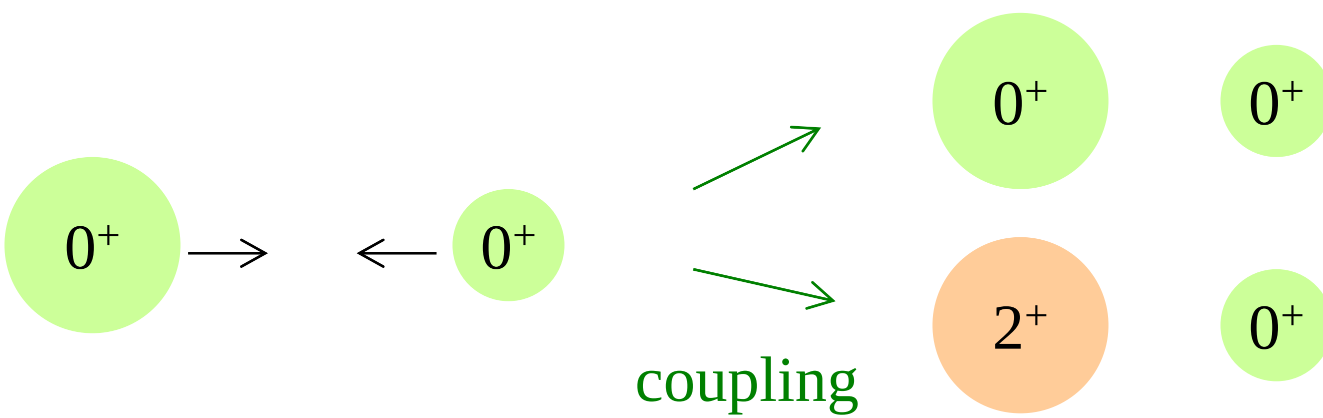
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



still very challenging

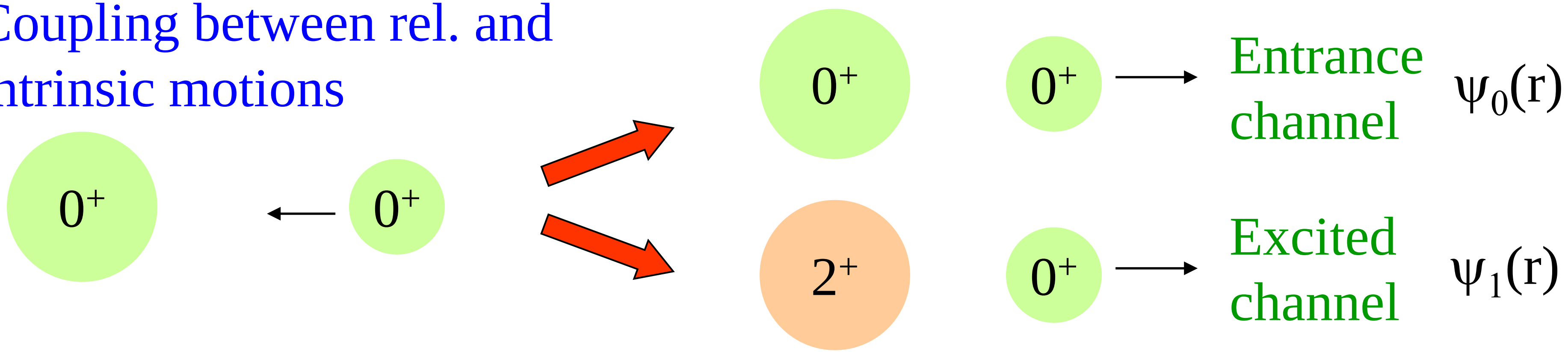
→ two-body problem, but with excitations
(coupled-channels approach)

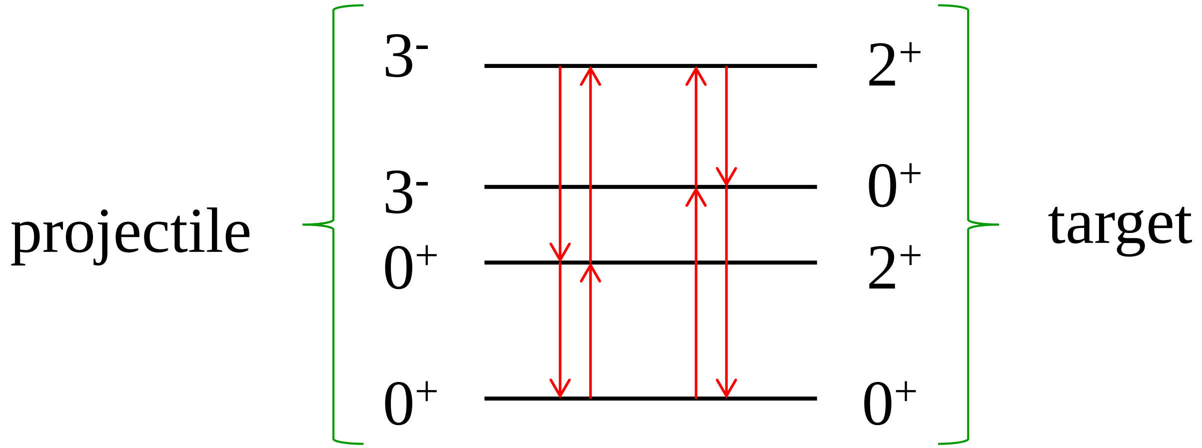


scattering theory with excitations

Coupled-channels method: a quantal scattering theory with excitations

Coupling between rel. and intrinsic motions





$$\Psi(\boldsymbol{r},\xi)=\sum_k \psi_k(\boldsymbol{r})\phi_k(\xi)$$

coupled Schroedinger equations for $\psi_k(r)$

Inputs for C.C. calculations

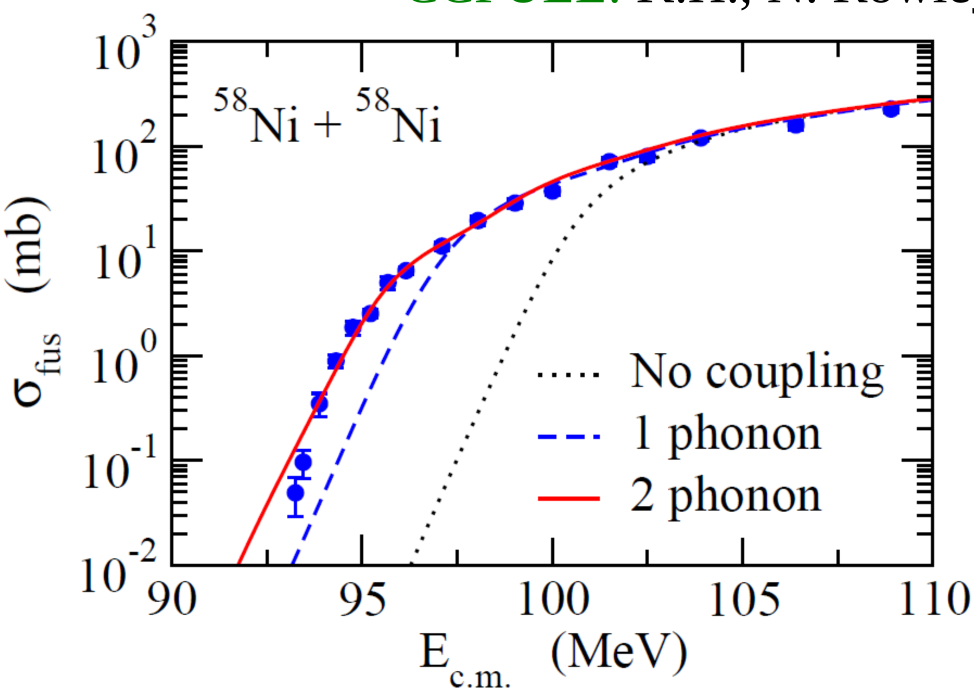
i) Inter-nuclear potential

✓ a fit to experimental data at above barrier energies

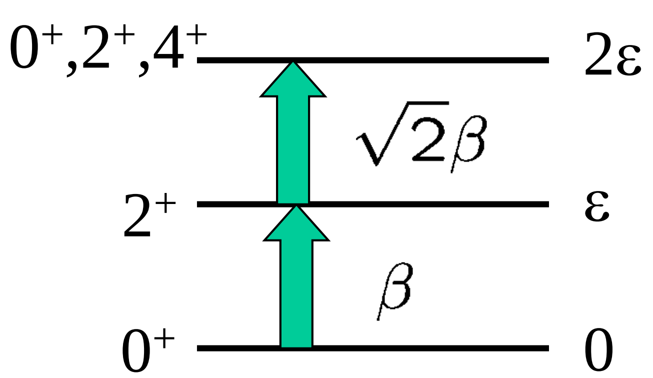
ii) Intrinsic degrees of freedom

✓ types of collective motions (rotation / vibration) a/o transfer
✓ coupling strengths and excitation energies
✓ how many states

CCFULL: K.H., N. Rowley, A.T. Kruppa, CPC123 ('99) 143



simple harmonic oscillator



Semi-microscopic modeling of sub-barrier fusion

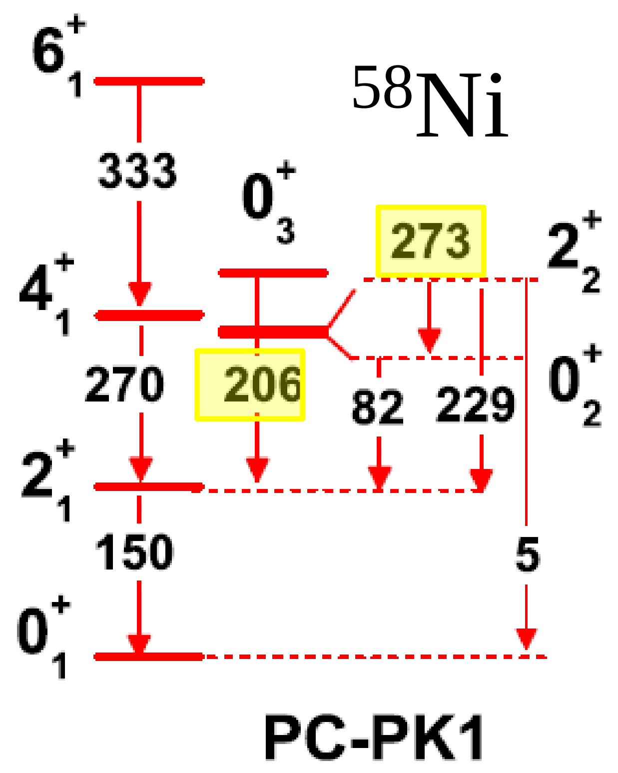
K.H. and J.M. Yao, PRC91('15) 064606

Beyond-mean-field method

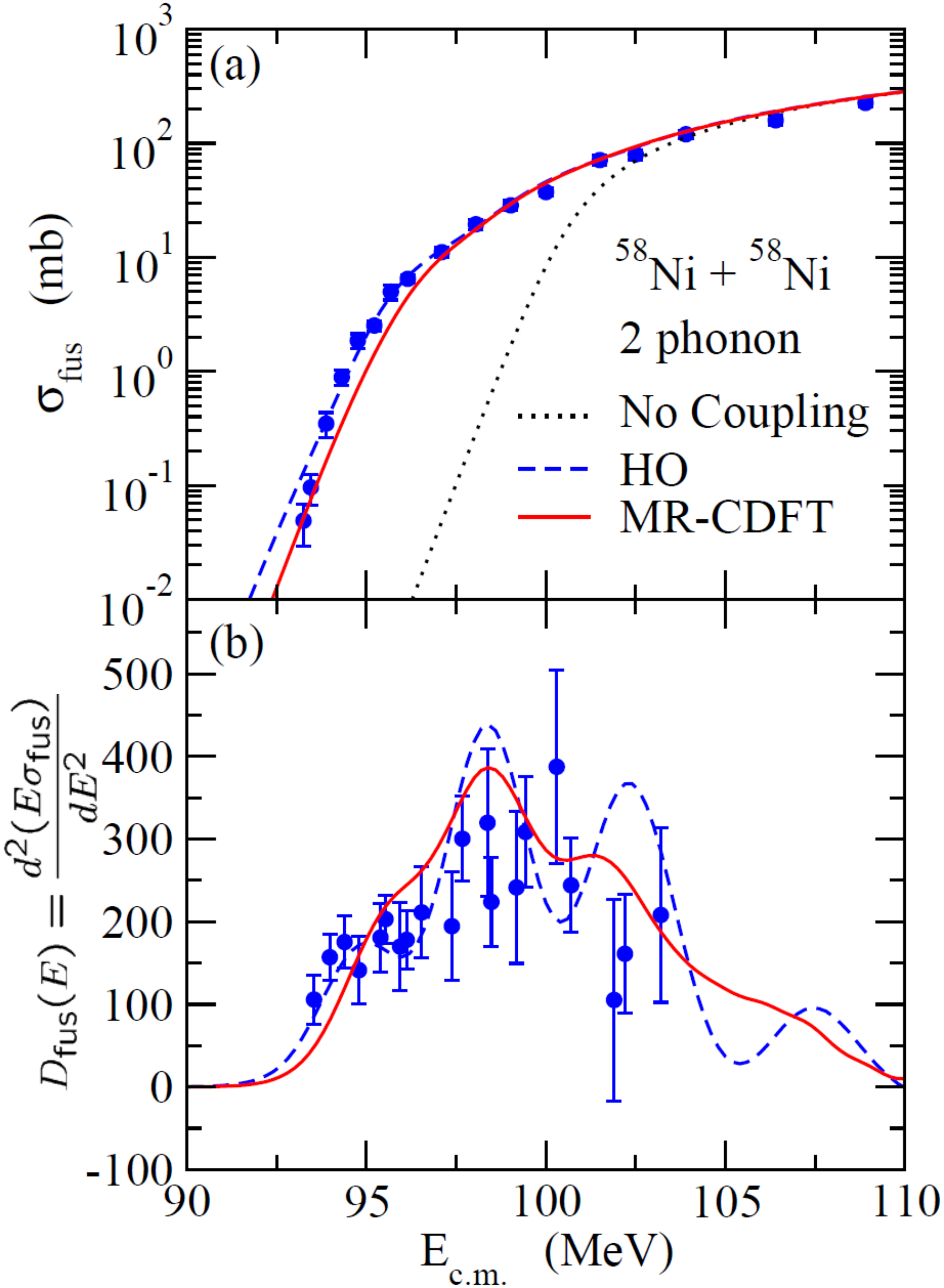
$$|JM\rangle = \int d\beta\, f_J(\beta)\hat{P}^J_{M0}|\Phi(\beta)\rangle$$

✓ MF + ang. mom. projection
+ particle number projection
+ generator coordinate method (GCM)

M. Bender, P.H. Heenen, P.-G. Reinhard, Rev. Mod. Phys. 75 ('03) 121
J.M. Yao et al., PRC89 ('14) 054306



→ C.C. calculations

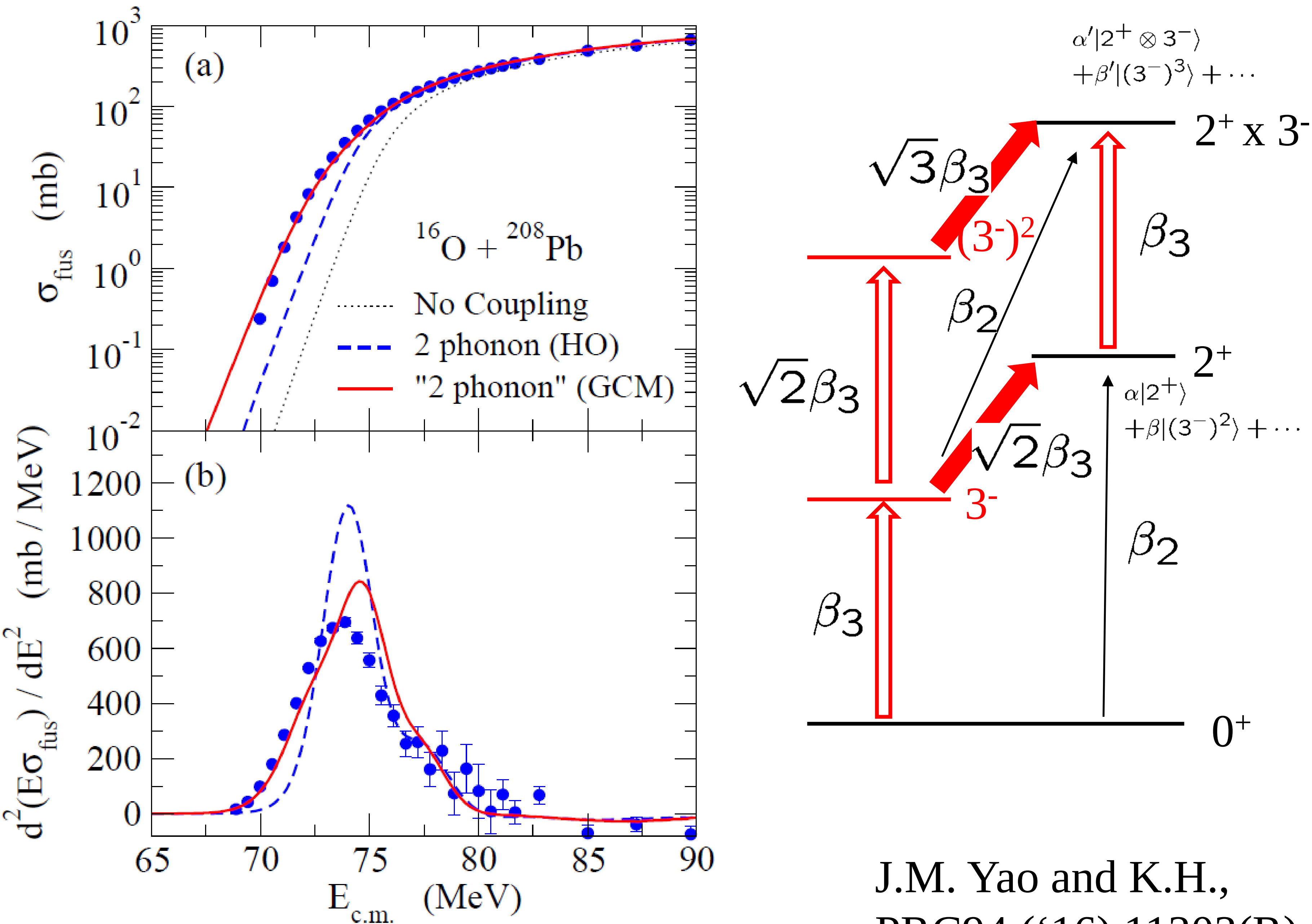


^{58}Ni+^{58}Ni

anharmonicity of 2^+ phonon
→ only a minor improvement

Next, more non-trivial case with 2^+ - 3^- coupling:
anharmonicity of oct. vib. in ^{208}Pb

K.H. and J.M. Yao, PRC91 (‘15) 064606



J.M. Yao and K.H.,
PRC94 ('16) 11303(R)

From phenomenological approach to microscopic approach

Macroscopic (phenomenological)

C.C. with collective model

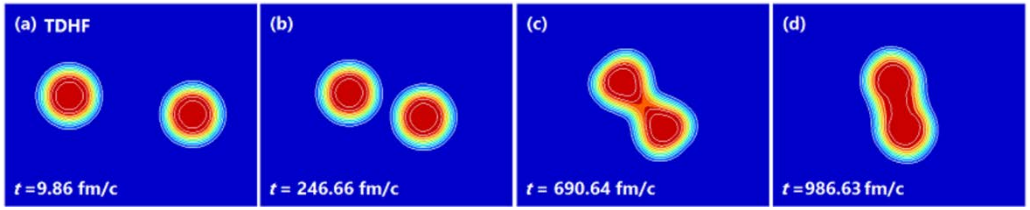
C.C. with inputs from microscopic nuclear structure calculations

C.C. with inputs based on TDHF

TDHF simulations

Microscopic

TDHF = Time Dependent Hartree-Fock



S. Ebata, T. Nakatsukasa, JPC Conf. Proc. 6 ('15)

ab initio, but no tunneling

Time-dependent GCM for many-body tunneling

N. Hasegawa, K.H., and Y. Tanimura, in preparation

TDHF simulations

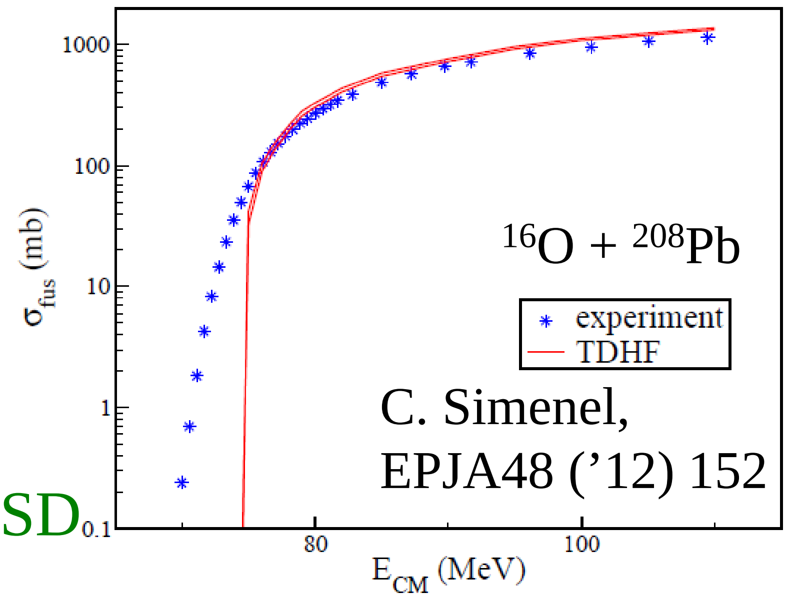
ab initio, but no tunneling

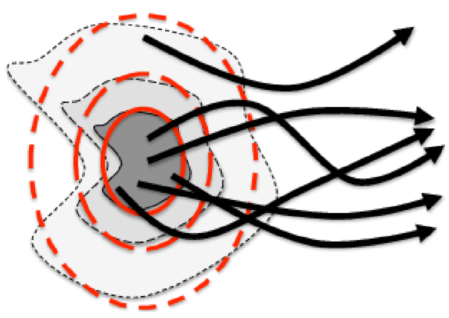
need to go Beyond the mean-field app.

✓ Time-dependent GCM

a single Slater determinant (SD) to multi-SD

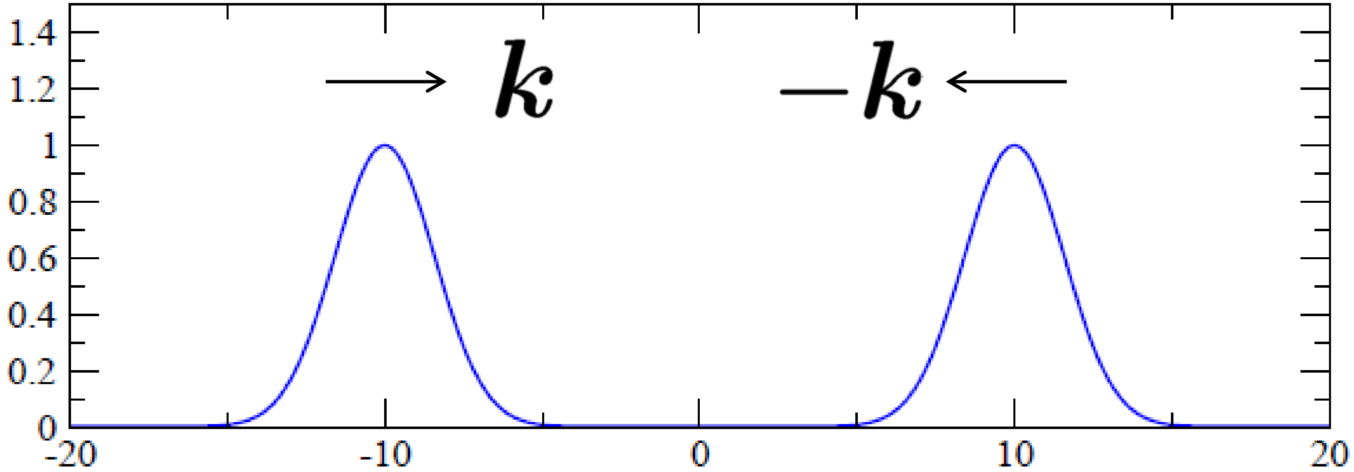
$$|\Psi(t)\rangle = \int dq\, f(q,t)|\Phi_q(t)\rangle$$





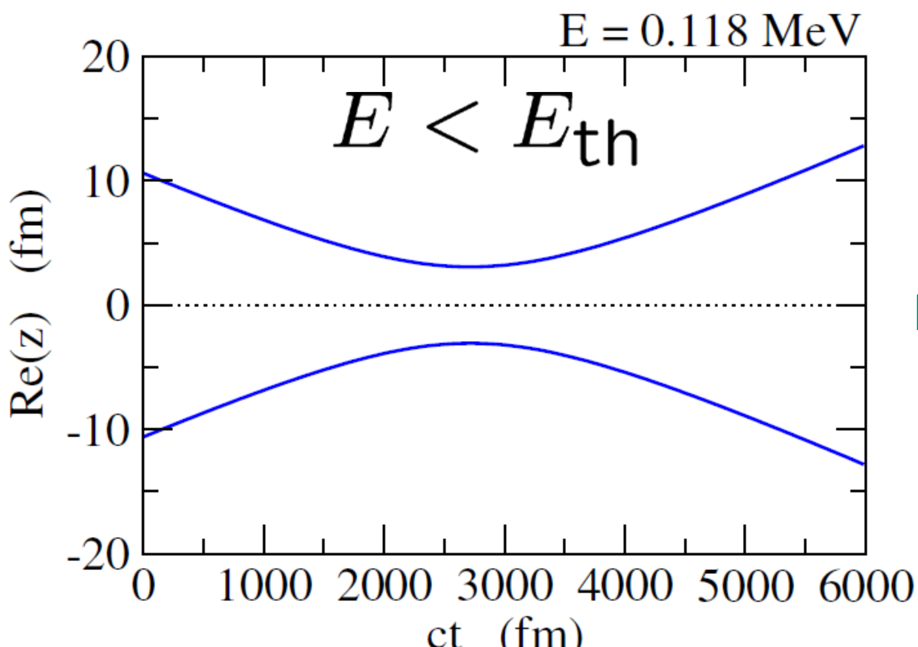
TDHF

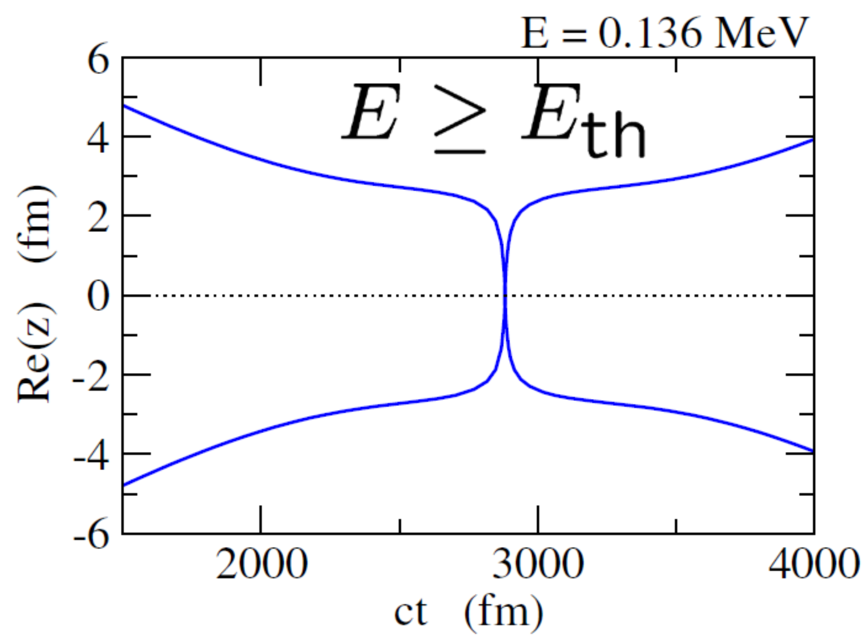
$$\Psi(t) = \Phi_{\mathsf{SD}}(t)$$



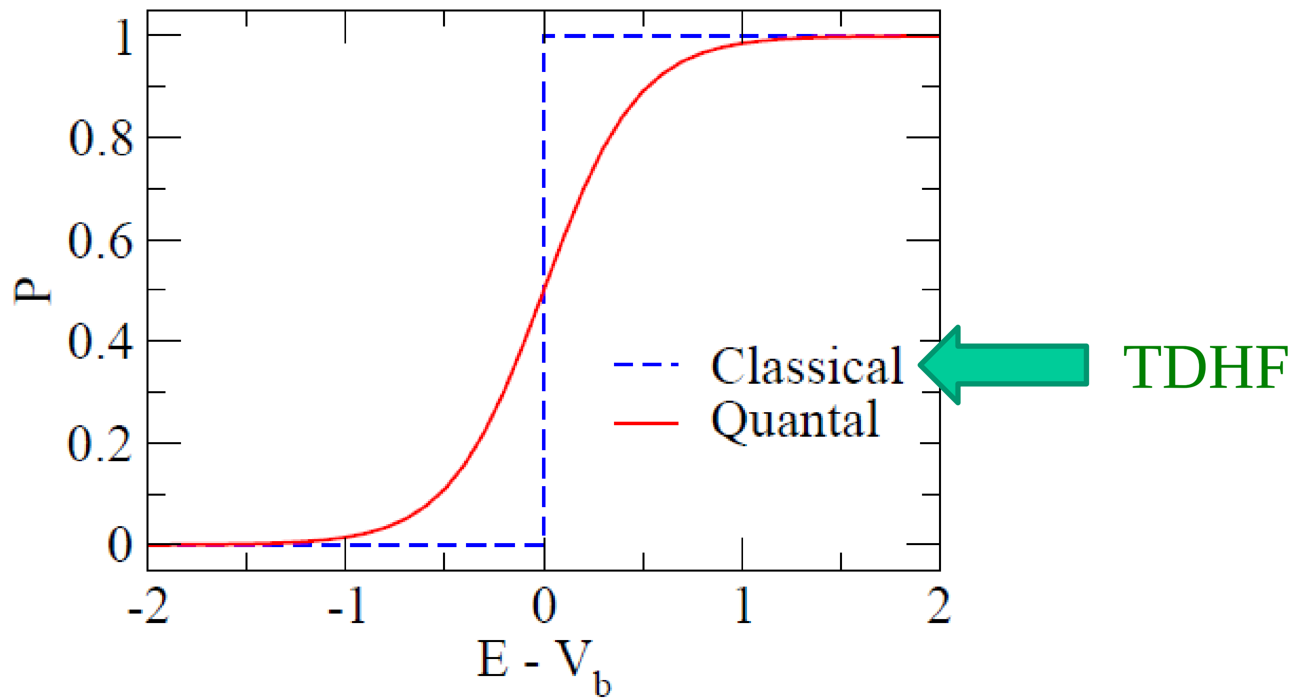
$$e^{ikx}\varphi_i(x+x_0) \qquad e^{-ikx}\varphi_i(x-x_0)$$

α+α in 1D



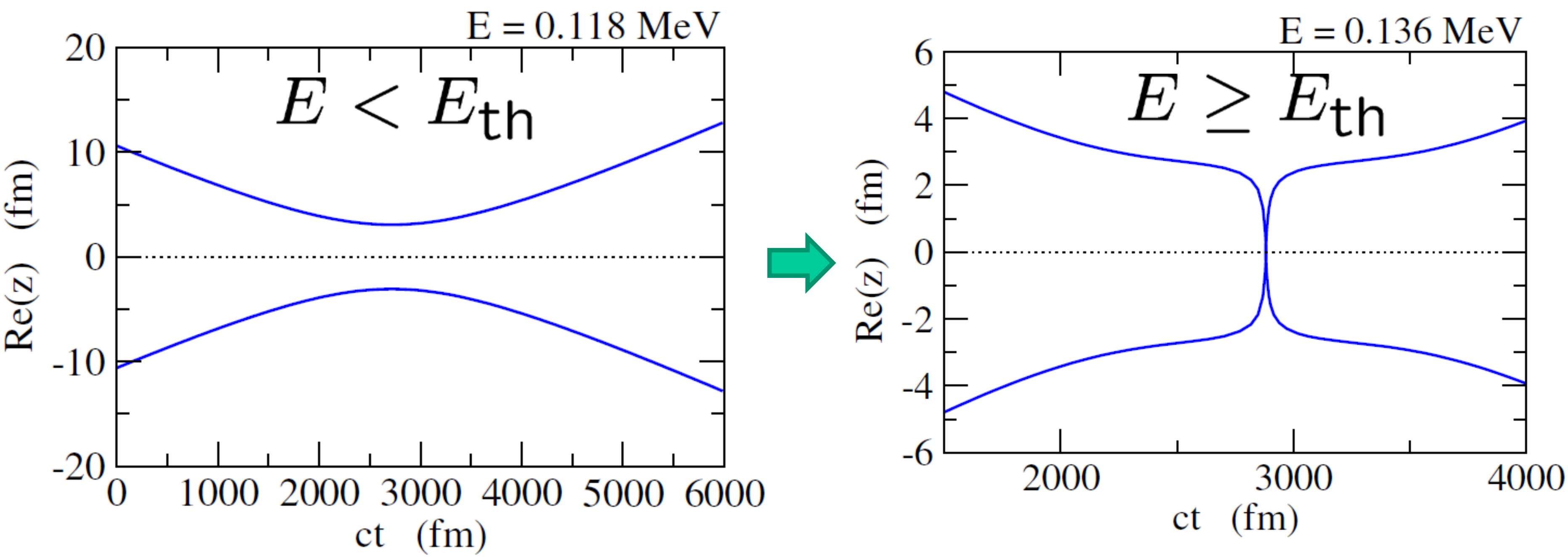


TDHF



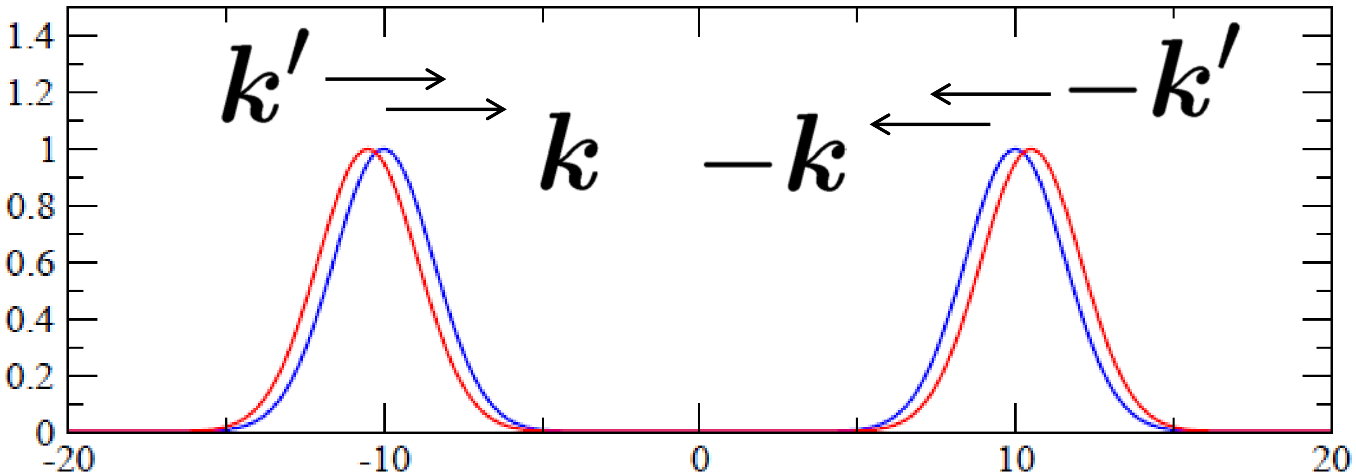
1
0.8
0.6
0.4
0.2
0
P
-2
-1
0
1
2
E - V_b
Classical
Quantal
TDHF

α+α in 1D



E = 0.118 MeV
$E < E_{th}$
20
10
0
-10
-20
Re(z) (fm)
0
1000
2000
3000
4000
5000
6000
ct (fm)
E = 0.136 MeV
$E \geq E_{th}$
6
4
2
0
-2
-4
-6
Re(z) (fm)
2000
3000
4000
ct (fm)

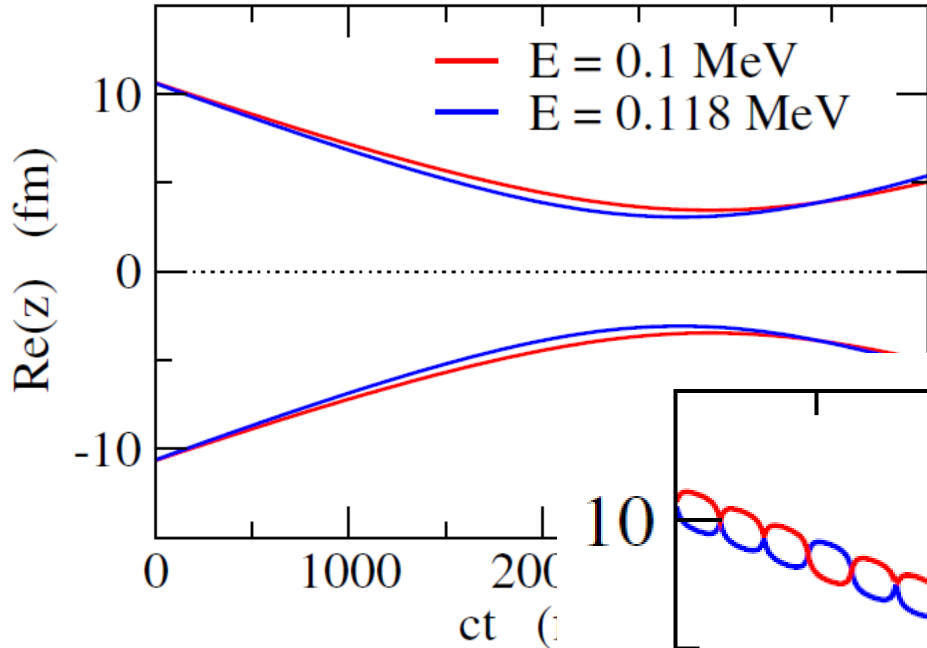
TDGCM



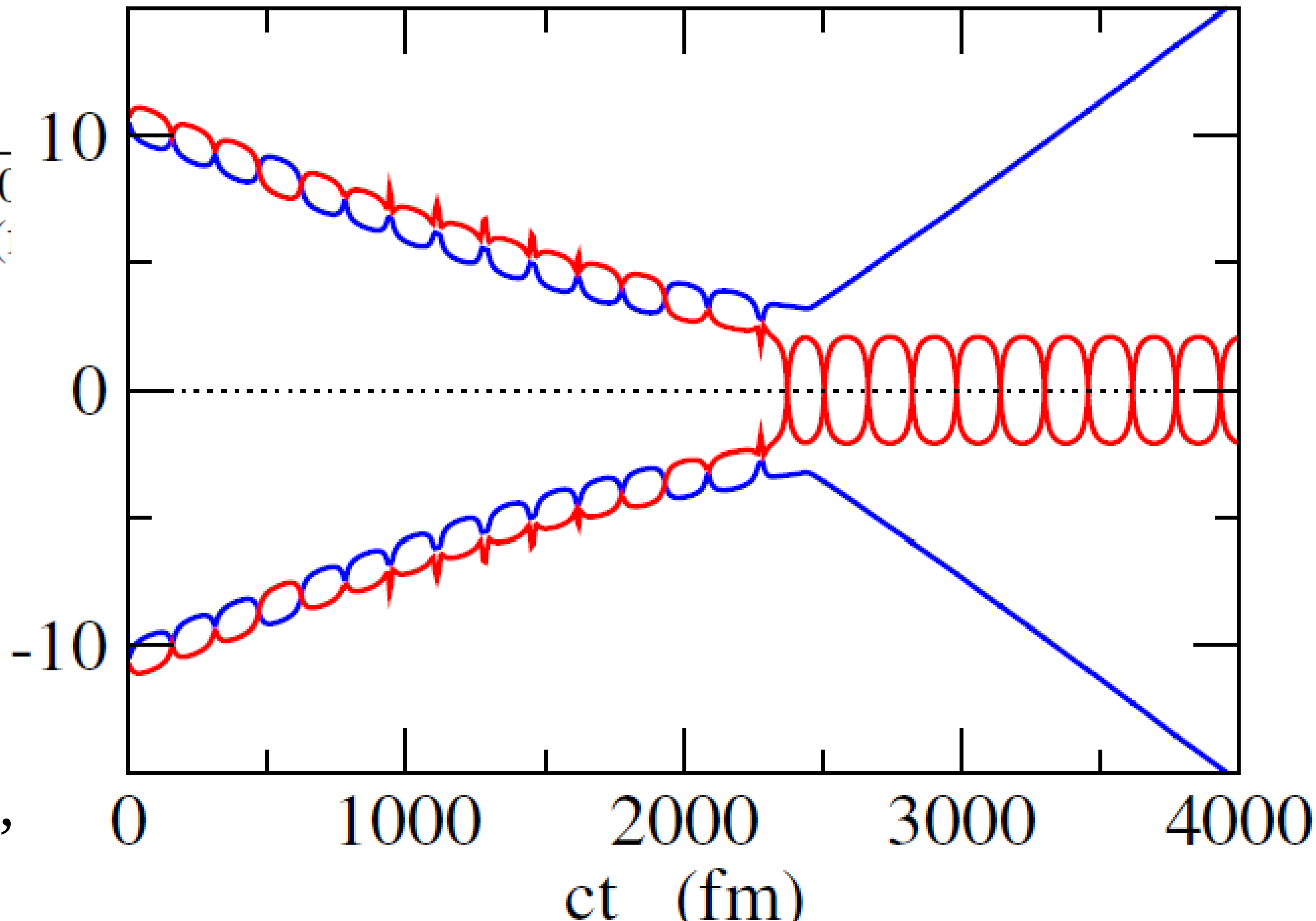
$$\Psi(t) = \sum_k \underline{f_k(t)}\,\underline{\Phi_{\mathrm{SD},k}(t)}$$

time-dep. variational principle

$$\delta \int dt \frac{\langle \Psi(t) | i\hbar\partial_t - H | \Psi(t)\rangle}{\langle \Psi(t) | \Psi(t)\rangle} = 0$$



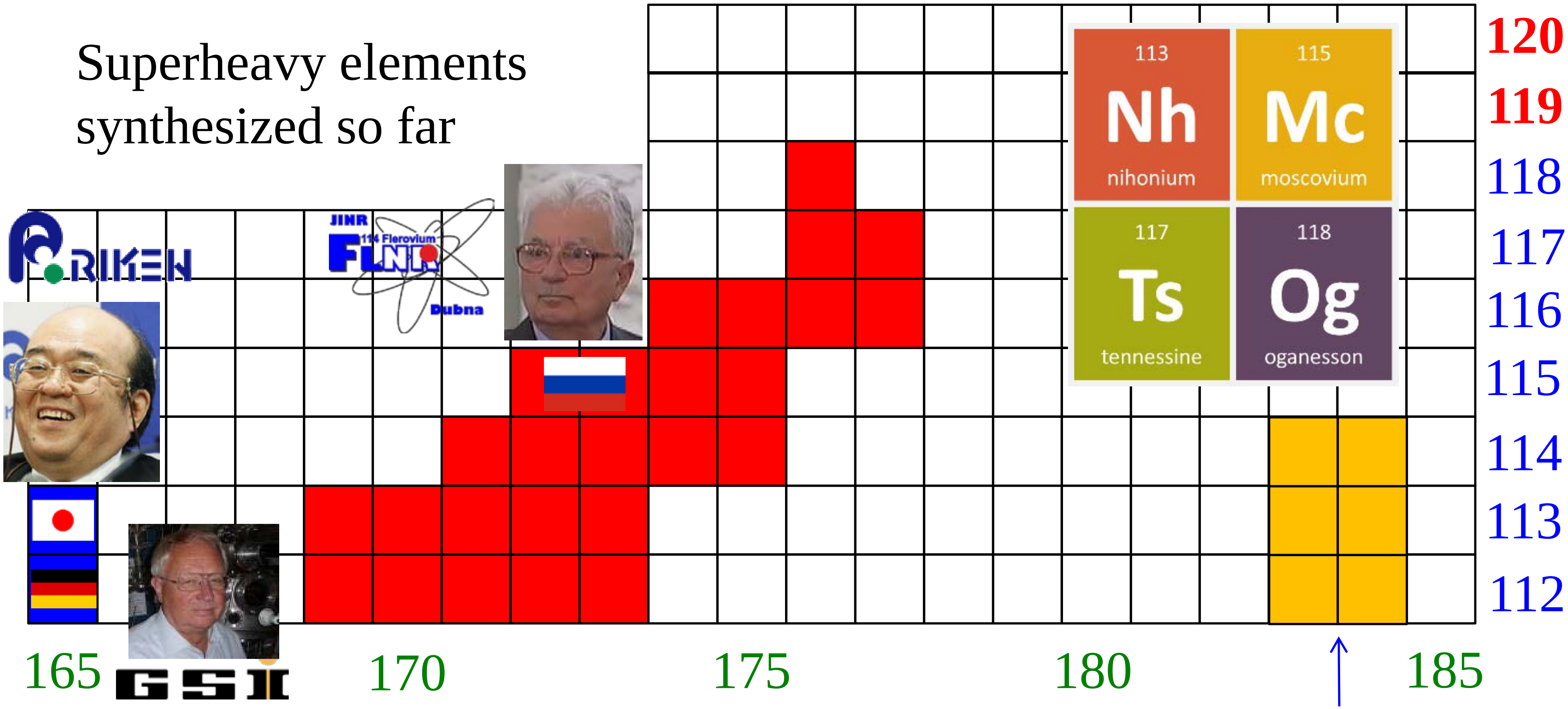
TDGCM
(a superposition of two SD)



N. Hasegawa, K.H., and Y. Tanimura, in preparation

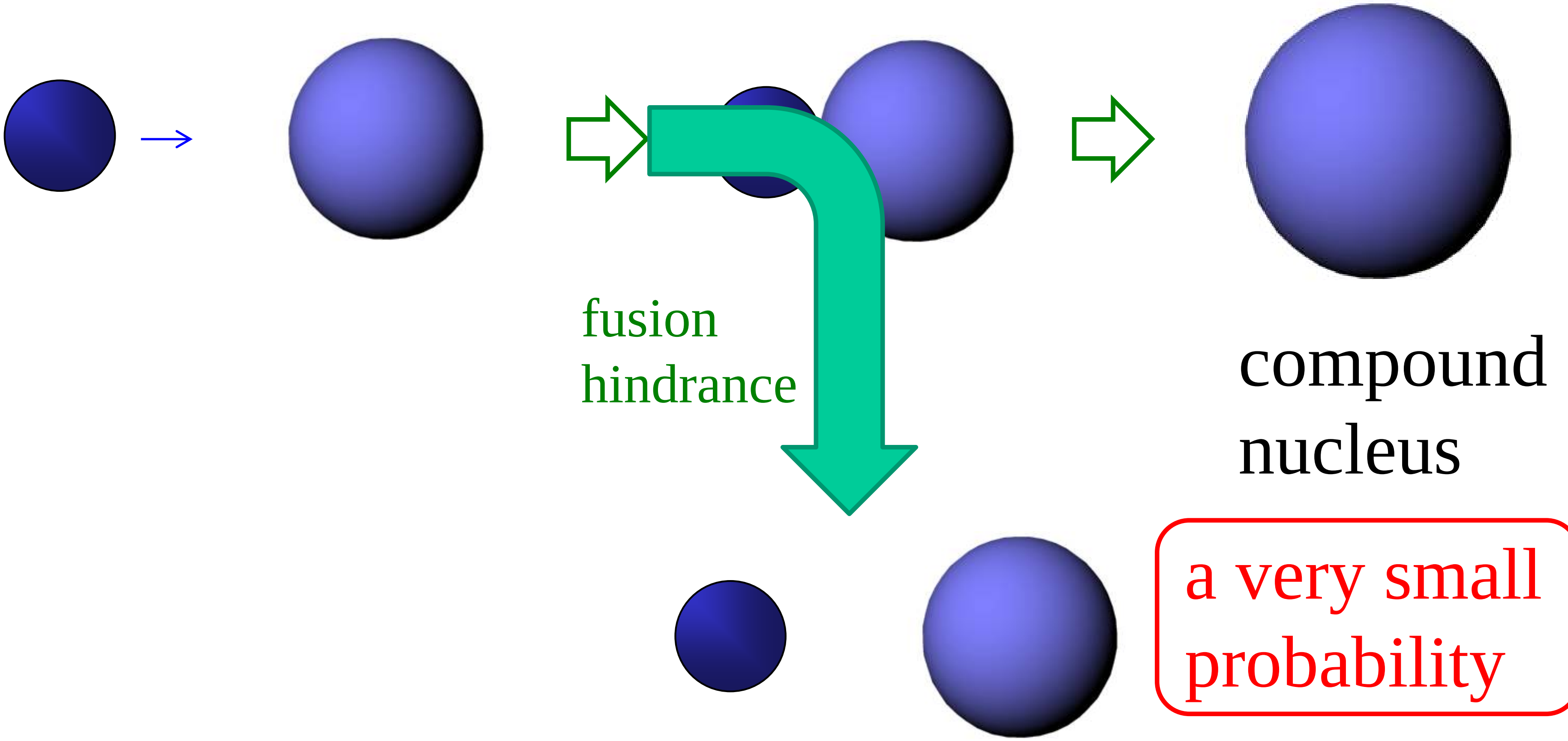
Fusion for superheavy elements

Superheavy elements synthesized so far



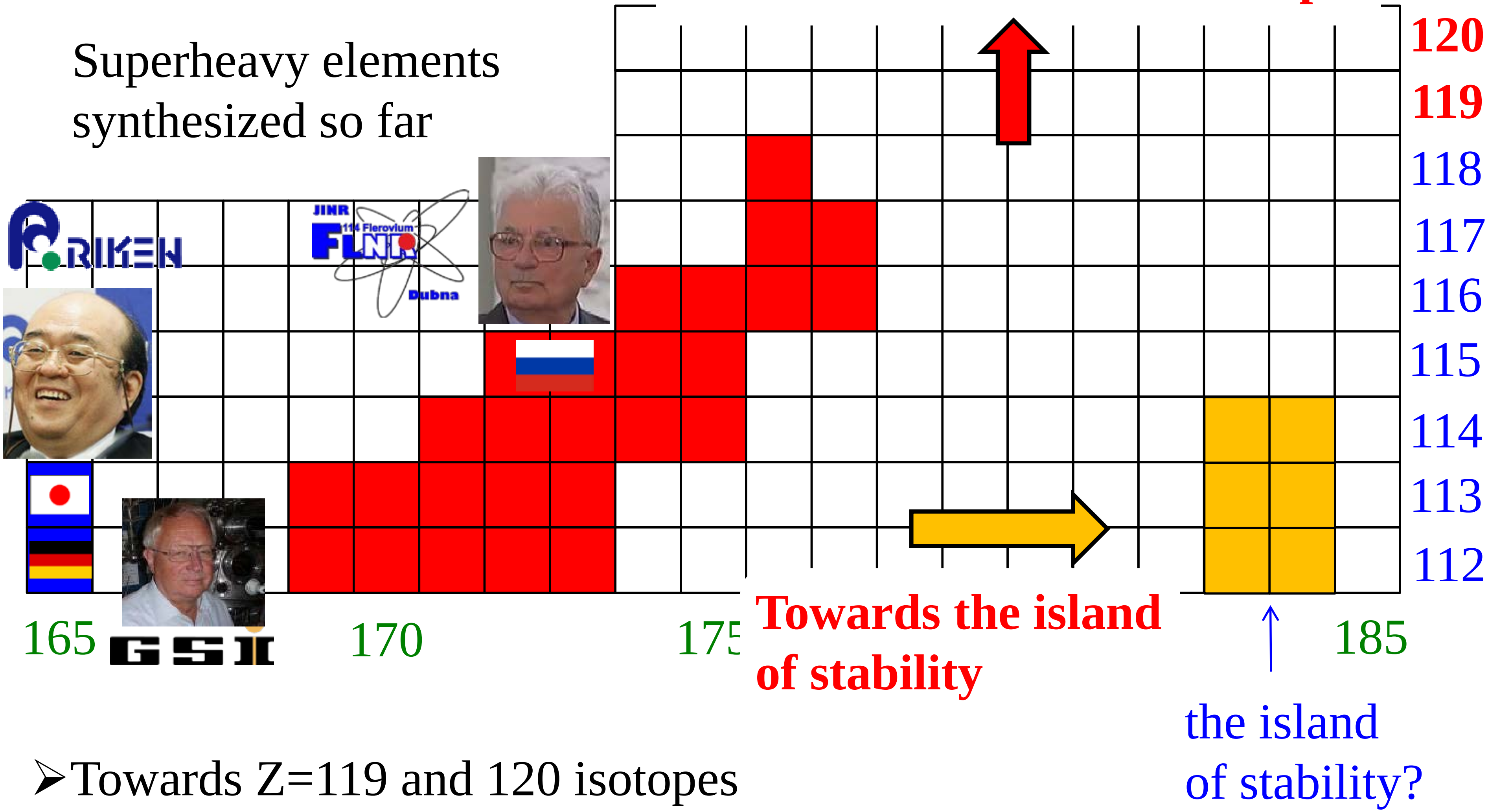
the island of stability?
(Swiatecki et al., 1966)

Fusion for SHE: fusion hindrance



strong Coulomb repulsion
→ re-separation

Future directions of SHE



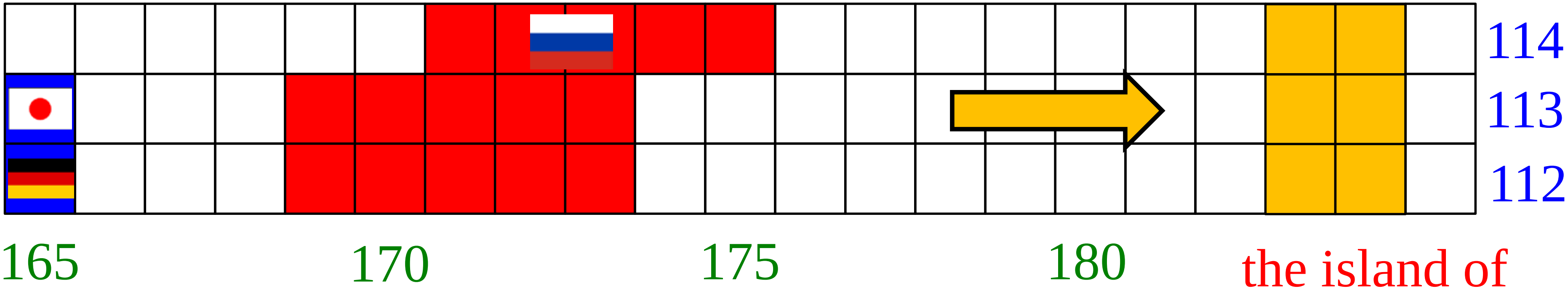
- ➢ Towards Z=119 and 120 isotopes

  Hot fusion reactions with ^{48}Ca, $^{50}_{22}$Ti, $^{51}_{23}$V, $^{54}_{24}$Cr etc.

- ➢ Towards the island of stability

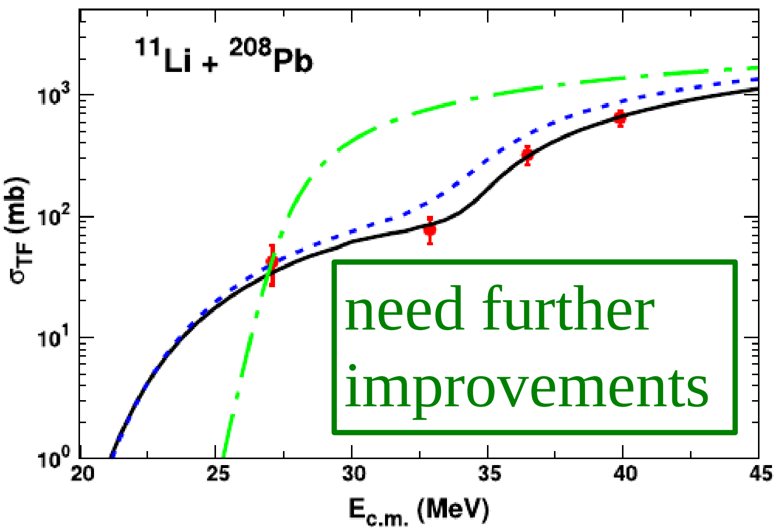
  neutron-rich beams: indispensable → reaction dynamics?

Towards the island of stability: Fusion of unstable nuclei

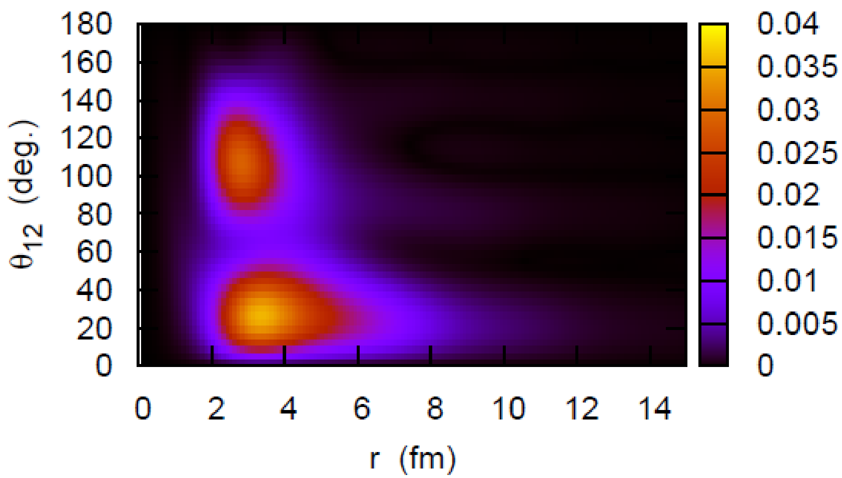


the island of stability

neutron-rich beams: indispensable→reaction dynamics?

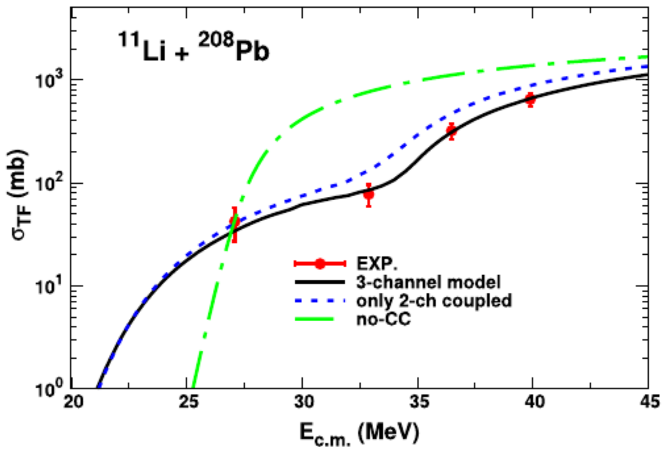


K.-S. Choi, K. Hagino et al., Phys. Lett. B780 ('18) 455



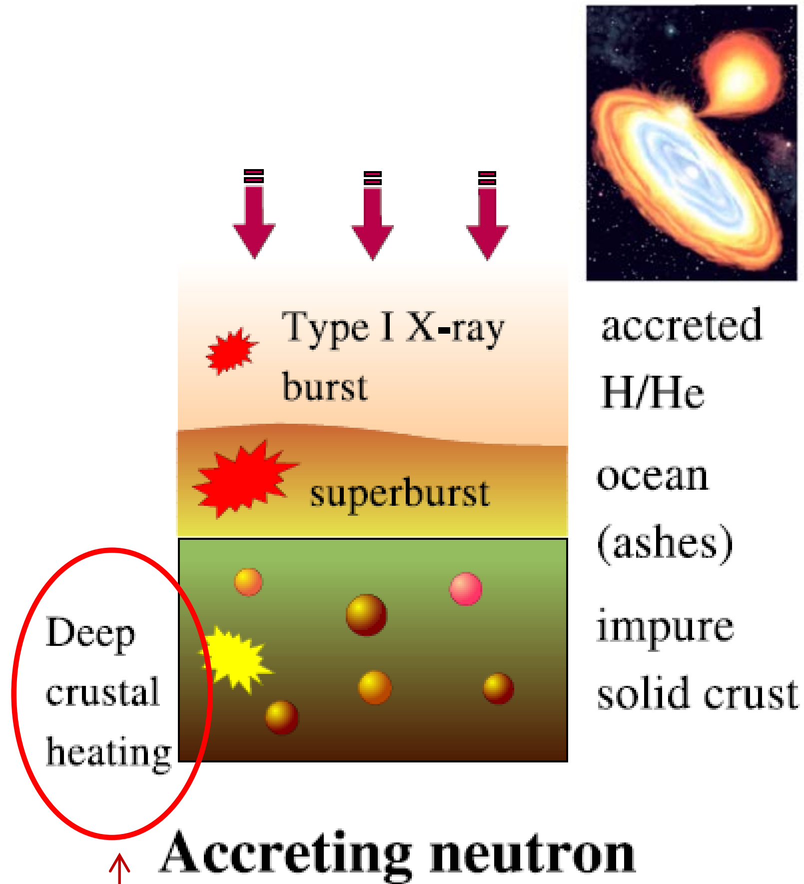
K.H. and H. Sagawa, PRC72('05)044321

good understandings of the structure of neutron-rich nuclei is also important reactions of neutron-rich nuclei



✓ fusion
✓ transfer

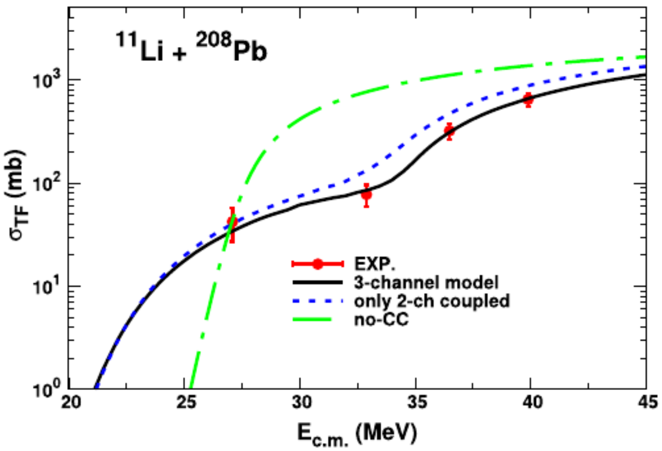
➢ development of microscopic nuclear reaction theory
➢ nuclear ractions in neutron stars



fusion of neutron-rich nuclei

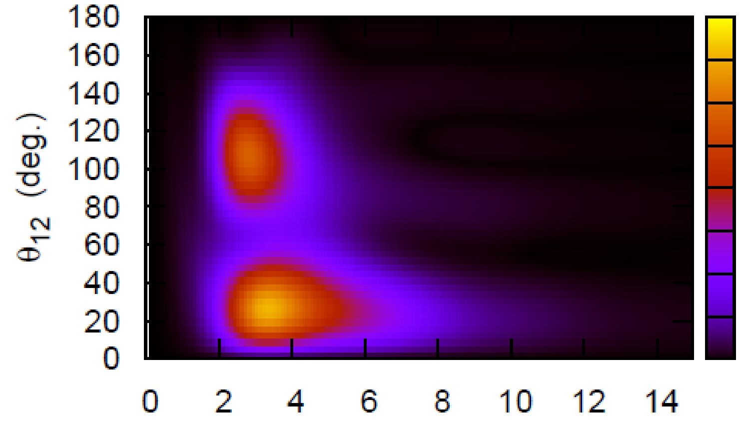
$^{24}O + ^{24}O$, $^{28}Ne + ^{28}Ne$ etc.

reactions of neutron-rich nuclei



- ✓ fusion
- ✓ transfer

structure of neutron-rich nuclei



- ✓ nucleon correlations
- ✓ collective motions
- ✓ fission

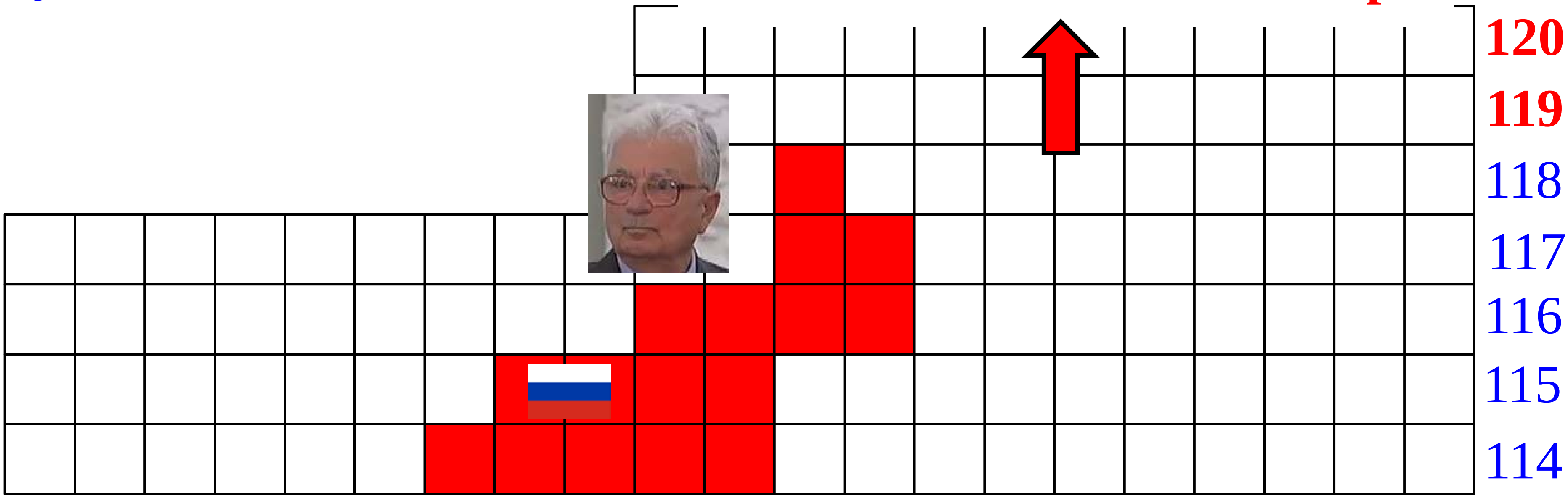
- ➢ development of microscopic nuclear reaction theory
- ➢ nuclear ractions in neutron stars

from few-body to many-body

Physics of SHE with n-rich nuclei as important ingredient

Synthesis of Z=119 and 120

Towards Z=119 and 120 isotopes



hot fusion reactions with ^{48}Ca:

$^{48}_{20}Ca + {}_{99}Es \rightarrow 119$

$^{48}_{20}Ca + {}_{100}Fm \rightarrow 120$

short lived → not available with sufficient amounts

$^{48}Ca \rightarrow {}^{50}_{22}Ti$, ${}^{51}_{23}V$, ${}^{54}_{24}Cr$ projectiles

closed shell → open shells

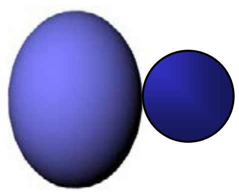
how much will cross sections be affected?

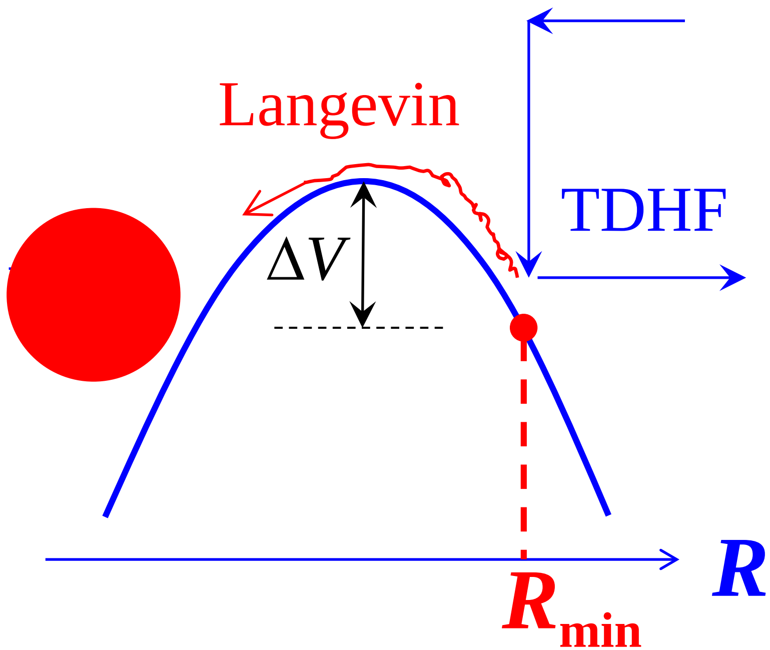
TDHF + Langevin approach

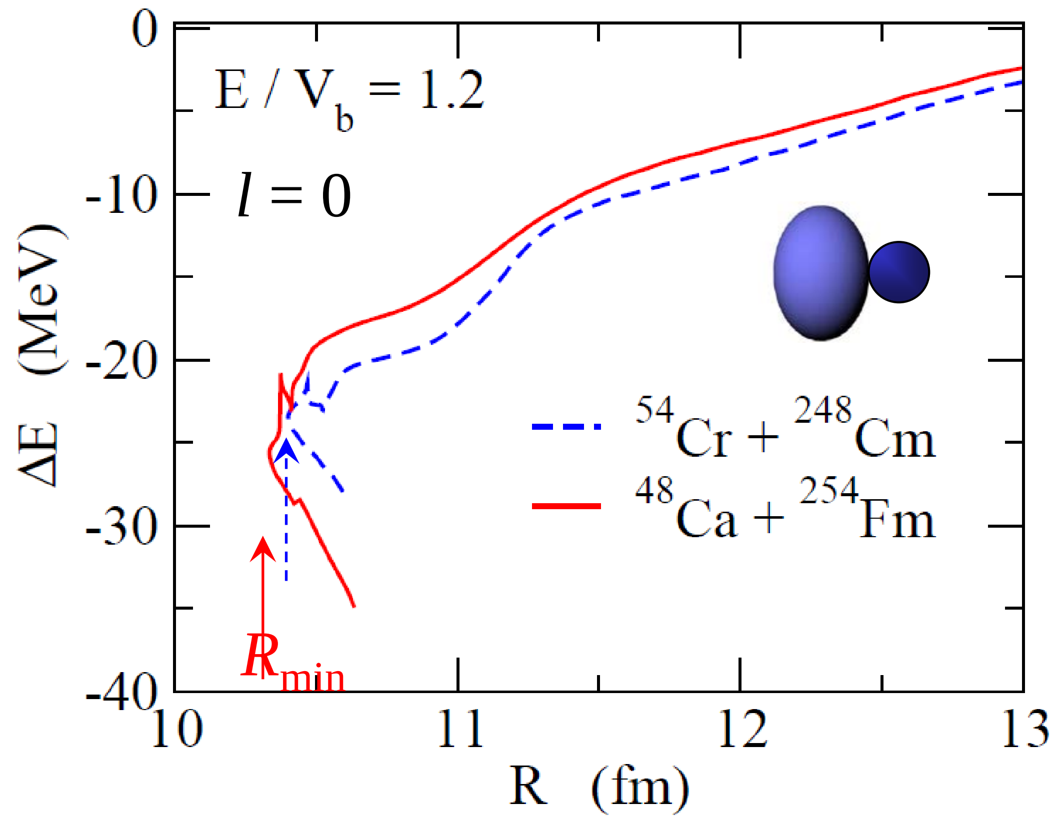
K. Sekizawa and K. H.,
PRC99 (2019) 051602(R)

$^{54}Cr + ^{248}Cm \rightarrow\ ^{302}120$
$^{48}Ca + ^{254}Fm \rightarrow\ ^{302}120$

side
collision







→ Langevin caluclation

New model for fusion for SHE: TDHF + Langevin approach

K. Sekizawa and K.H., PRC99 (2019) 051602(R)

how special is ^{48}Ca ?

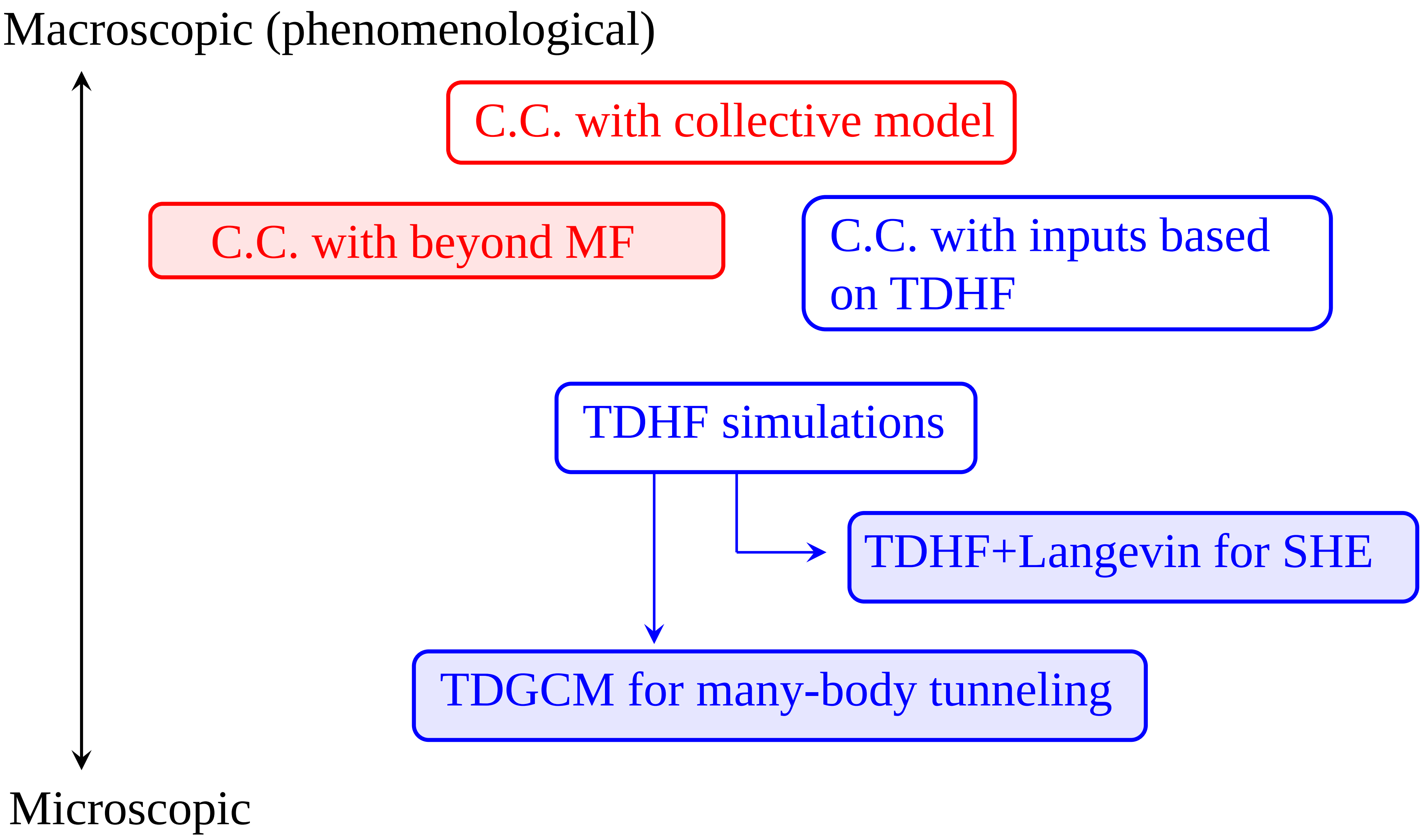
System	CN	E^* (MeV)	R_{min} (fm)	P_{CN} ($\times 10^4$)	W_{sur} ($\times 10^9$)	$P_{CN} W_{sur}$ ($\times 10^{13}$)
^{48}Ca + ^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr + ^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V + ^{249}Bk	^{300}120	37.0	12.94	3.95	0.117	0.461
^{48}Ca + ^{257}Fm	^{305}120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

similar P_{CN}

no special role of ^{48}Ca in the entrance channel

Summary

From phenomenological to microscopic nuclear reaction theories



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한국항공대학교 KOREA AEROSPACE UNIVERSITY 1952

KYOTO UNIVERSITY KYOTO JAPAN FOUNDED 1897

a picture from Sep., 2018

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