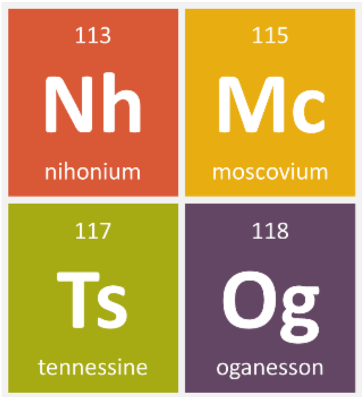
Open issues in physics of SHE
: nuclear reaction perspectives



Kouichi Hagino
Kyoto University

1. Introduction: fusion for superheavy elements
2. Theoretical issues in the Langevin approach
3. Towards a microscopic description
4. Summary

Kyoto-Soongsil Nuclear Physics Joint Workshop, June 7-8, 2024, Soongsil University

Kyoto-Soongsil Nuclear Physics Joint Workshop (75th OMEG SSANP workshop)

Jun 7 – 8, 2024
Soongsil University
Asia/Seoul timezone

Enter your search term

Why Kyoto-Soongsil?

Nuclear many-body seminar @ Kyoto University

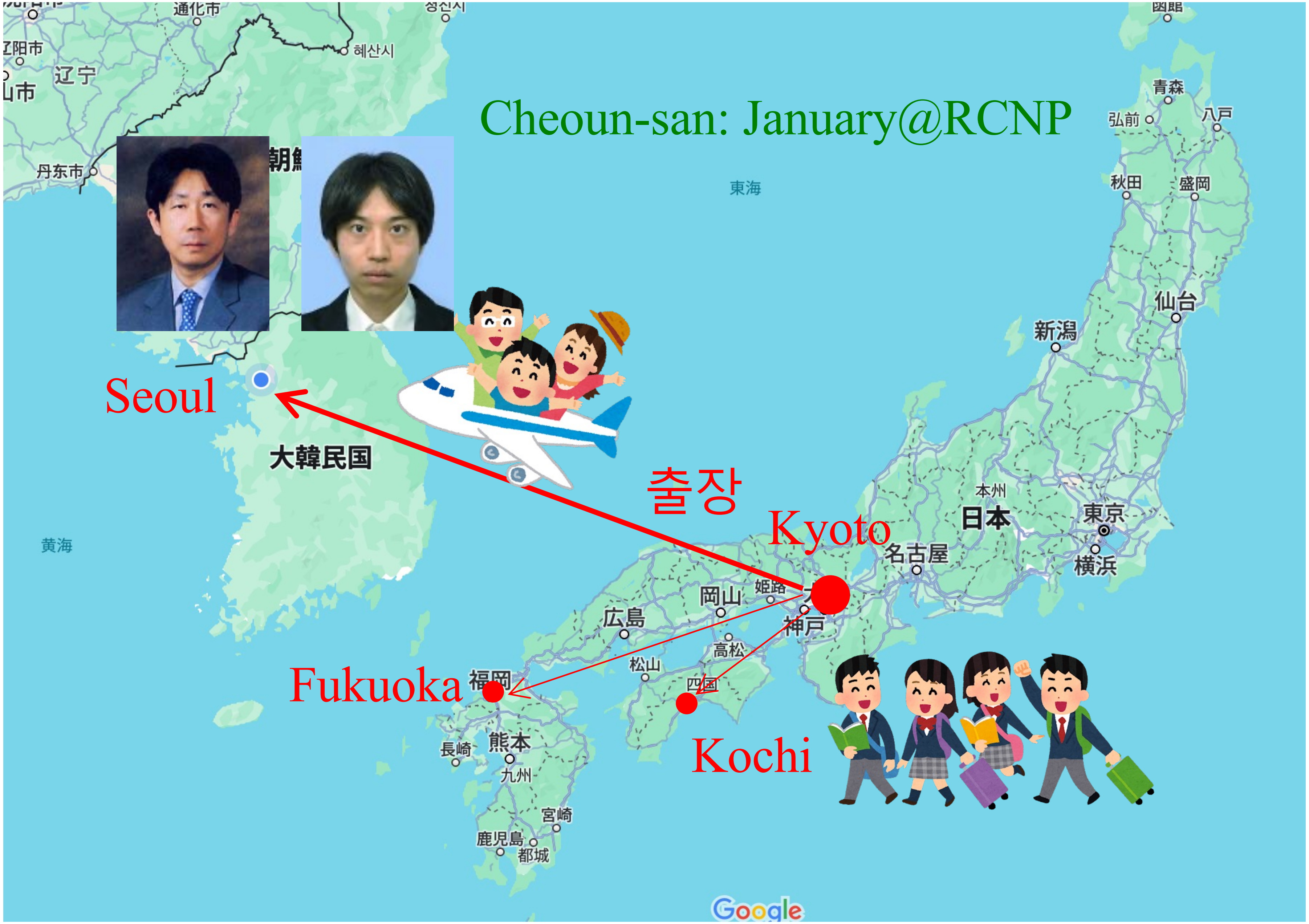
every Friday, 10:30 - 12:30

Nuclear many-body seminar @ Kyoto University

every Friday, 10:30 - 12:30

Nuclear many-body seminar @ Kyoto University

every Friday, 10:30 - 12:30



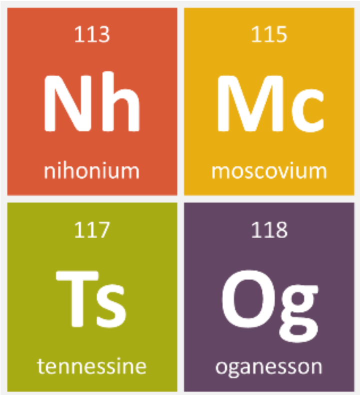
Nuclear many-body seminar @ Kyoto University

every Friday, 10:30 - 12:30

Nuclear many-body seminar @ Kyoto University

every Friday, 10:30 - 12:30

Open issues in physics of SHE
: nuclear reaction perspectives

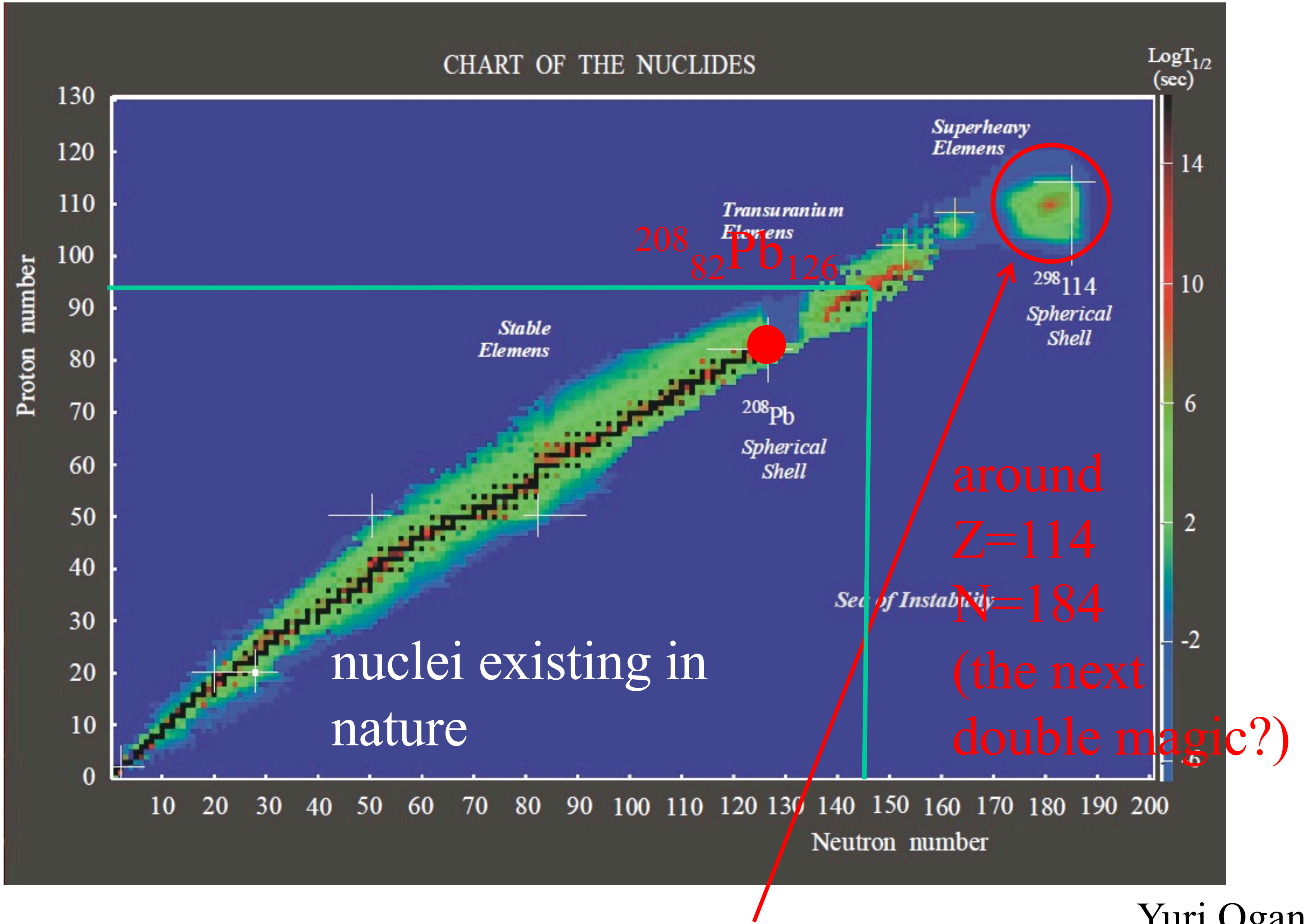


Kouichi Hagino
Kyoto University

1. Introduction: fusion for superheavy elements
2. Theoretical issues in the Langevin approach
3. Towards a microscopic description
4. Summary

Kyoto-Soongsil Nuclear Physics Joint Workshop, June 7-8, 2024, Soongsil University

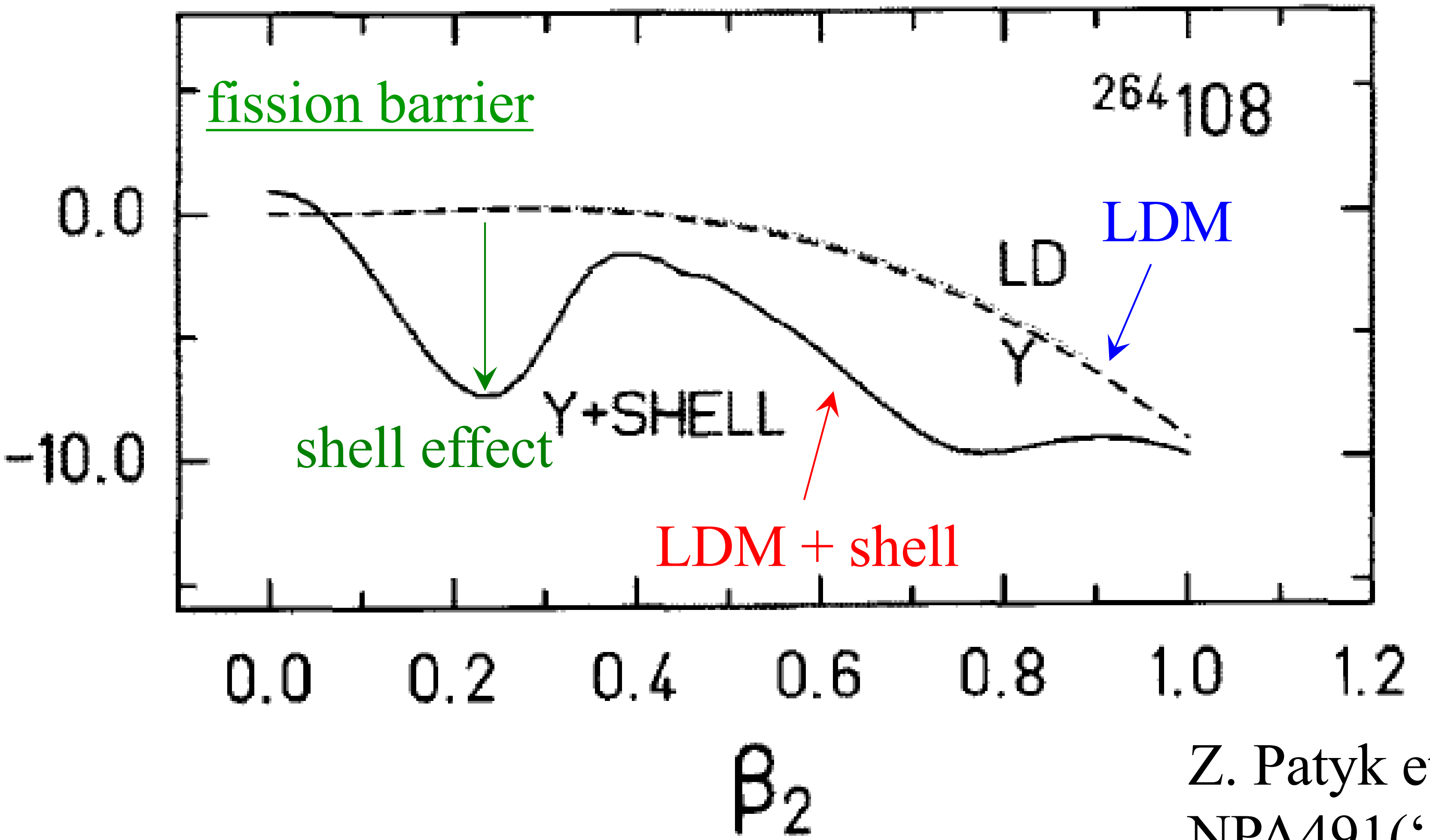
Superheavy elements (the island of stability)



Yuri Oganessian

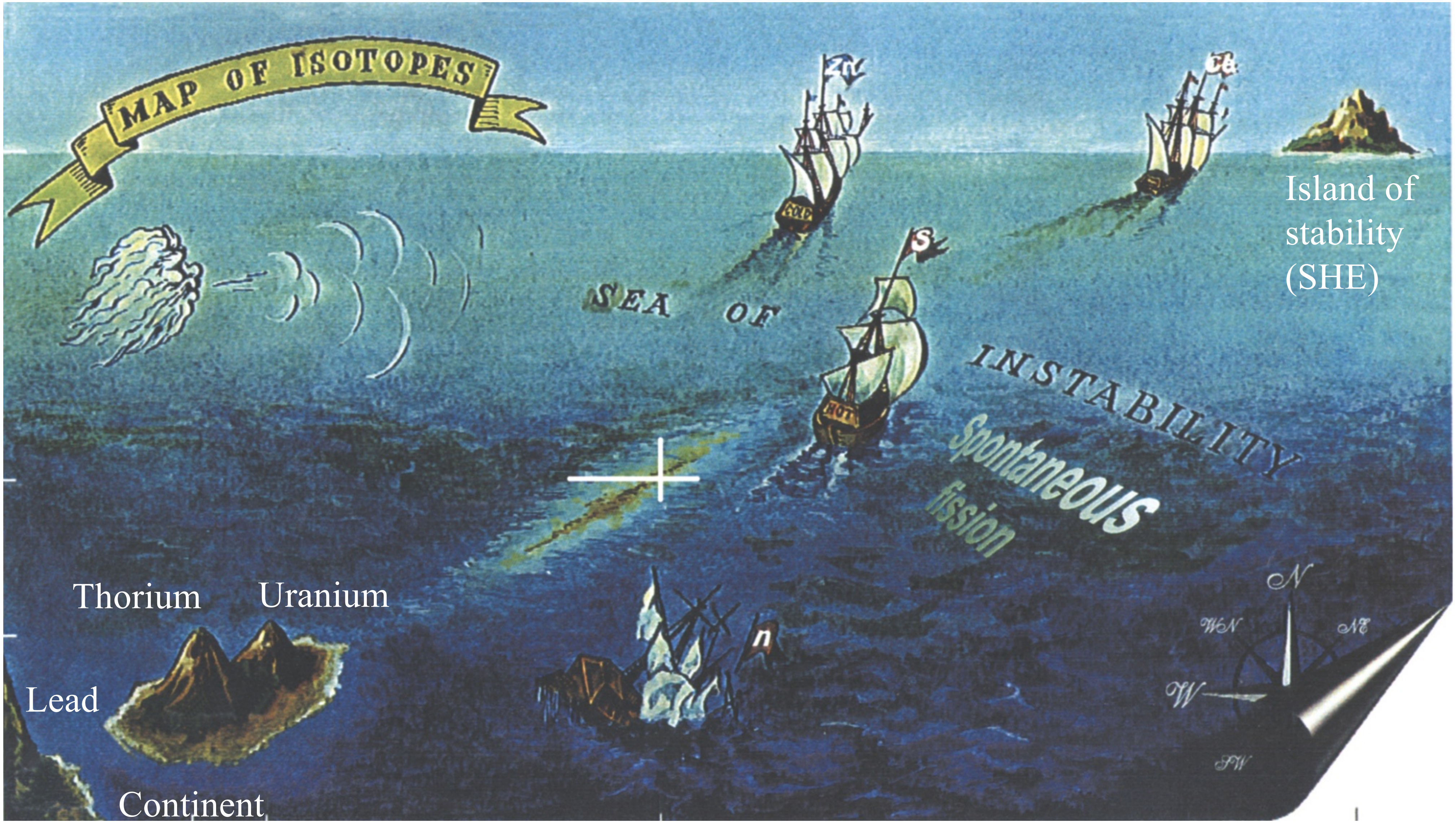
long-lived with $10^{3\text{-}5}$ years

stabilization due to the shell effect



Z. Patyk et al., NPA491('89) 267

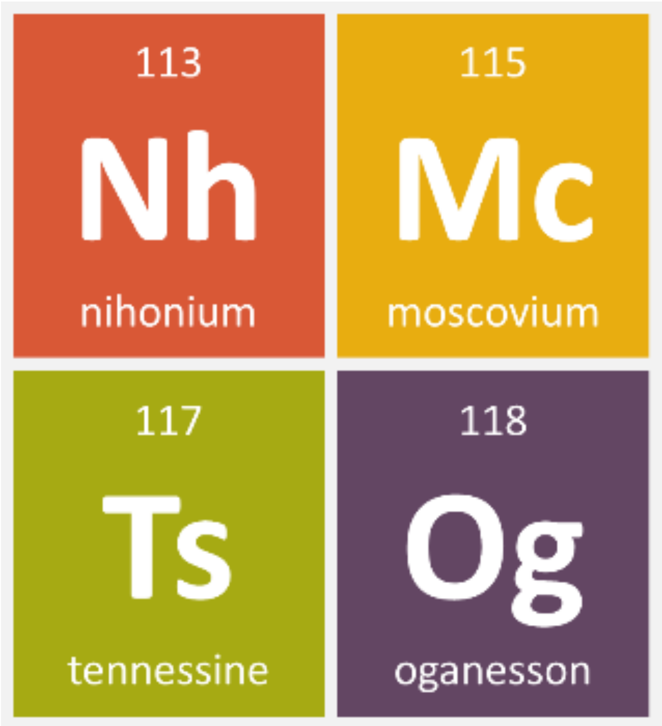
QM shell effect (magic numbers) increases B_{fiss} and stabilizes a nucleus



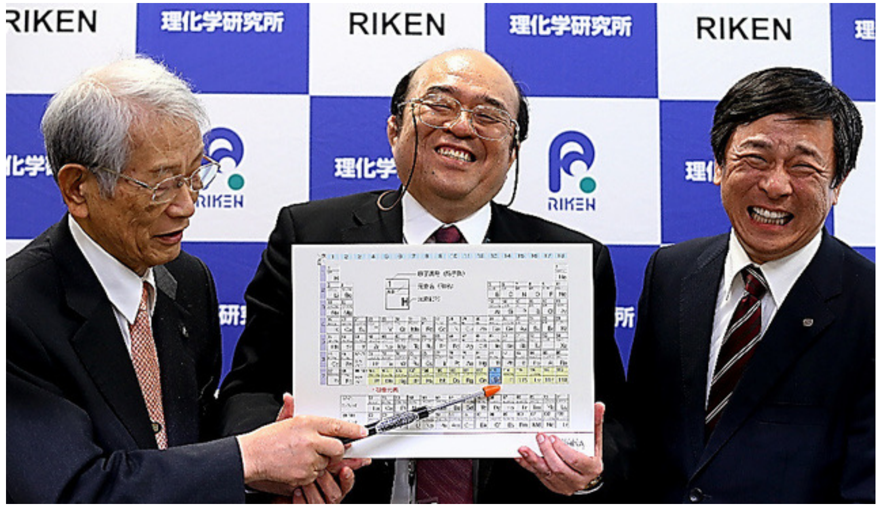
Yuri Oganessian

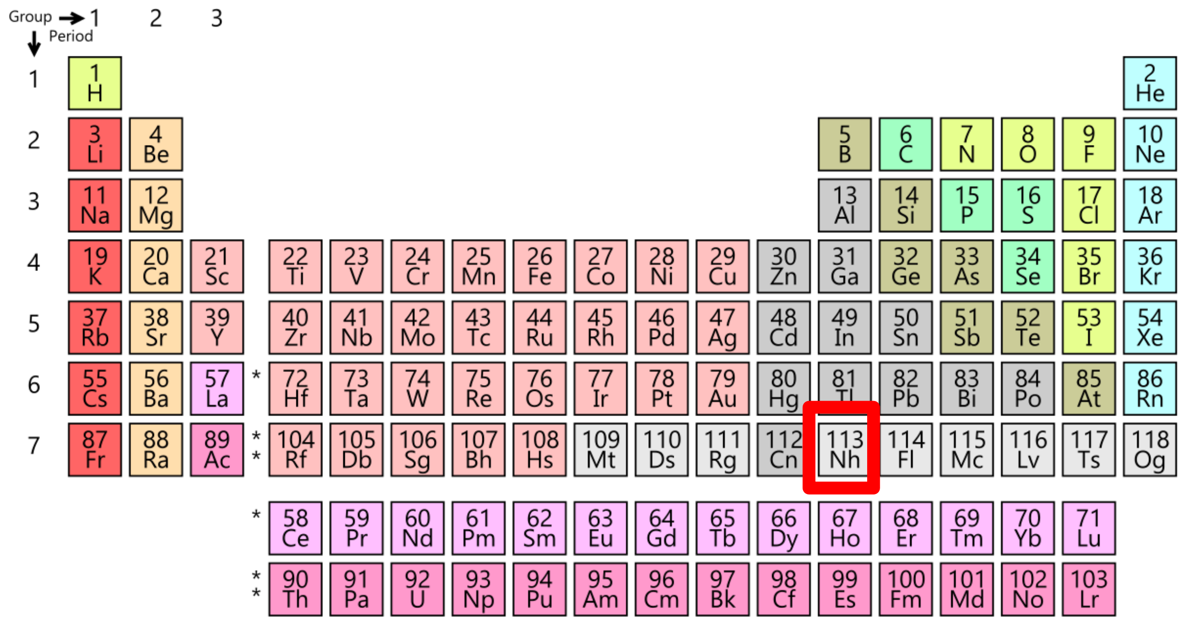
Fusion reactions for SHE

the element 113: Nh



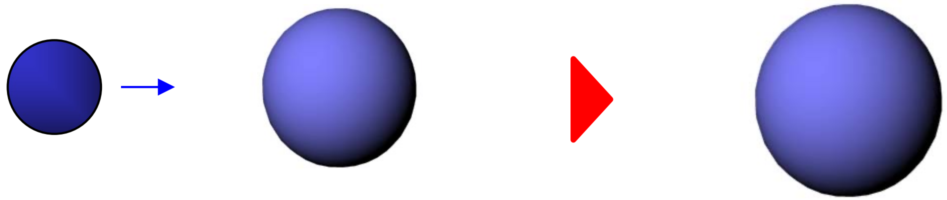
November, 2016





Wikipedia

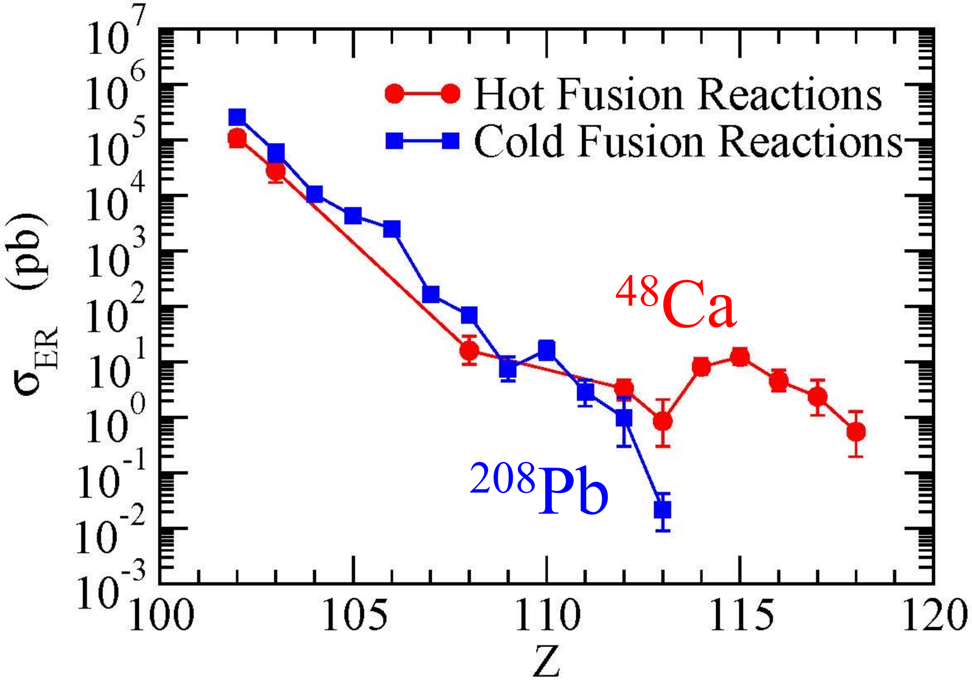
$^{70}_{30}Zn$ $^{209}_{83}Bi$ $^{279}_{113}Nh^*$

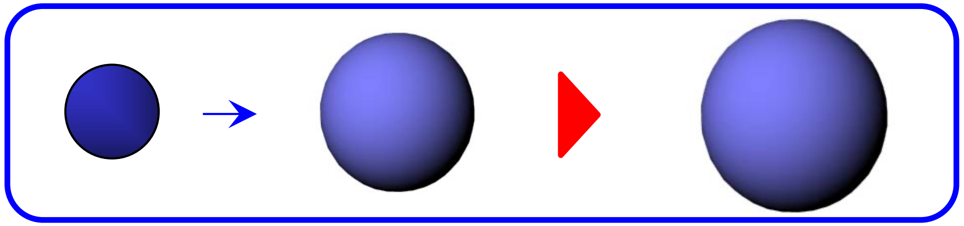


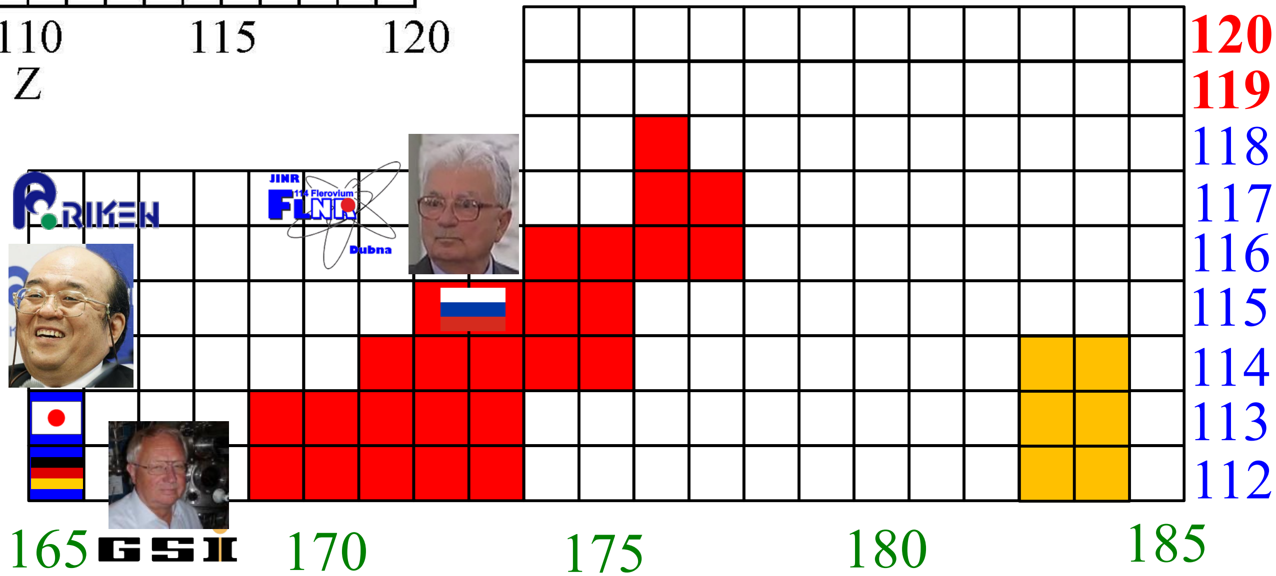
Heavy-ion fusion reaction

Fusion for superheavy elements

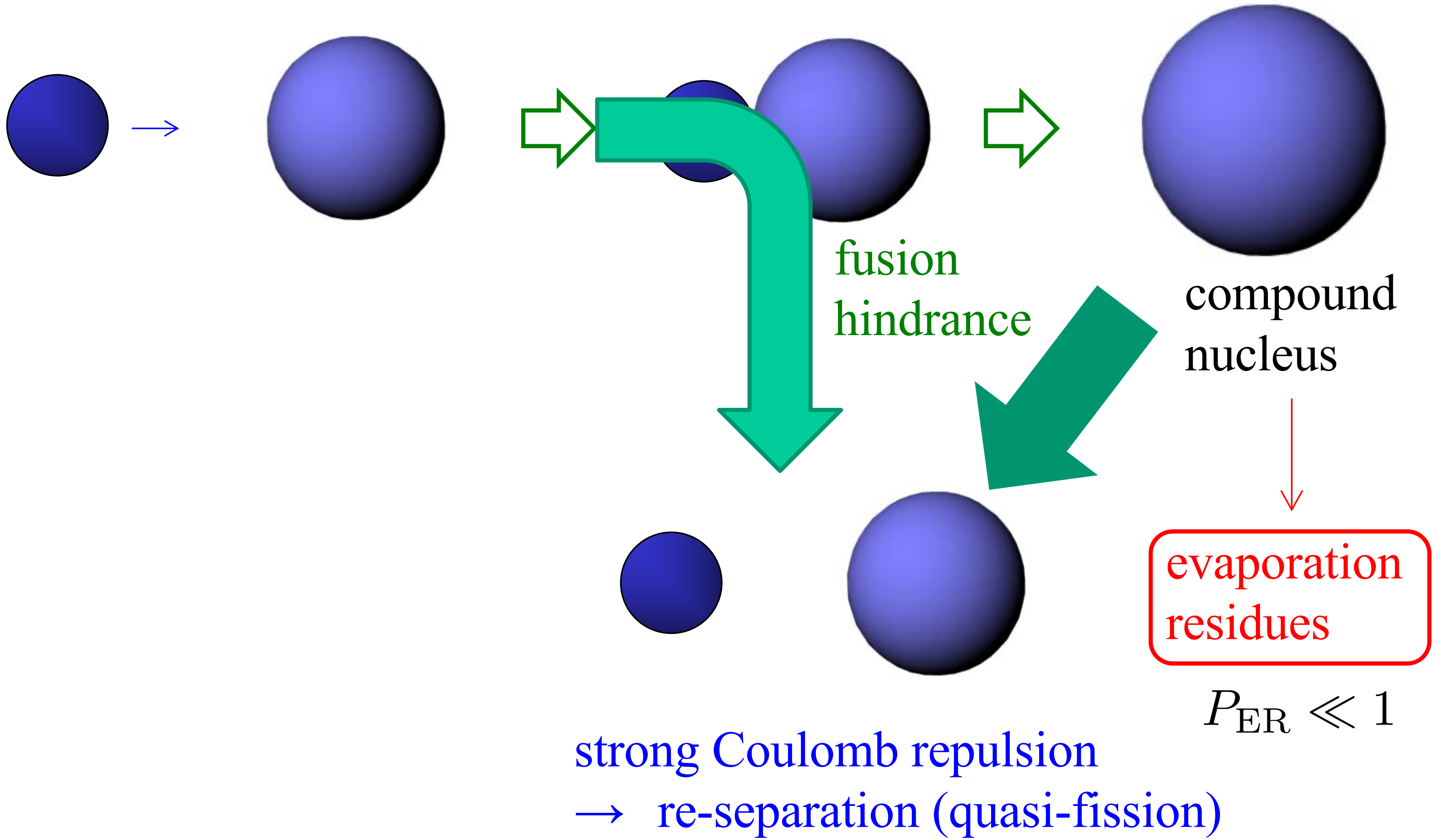
Heavy-ion fusion reactions



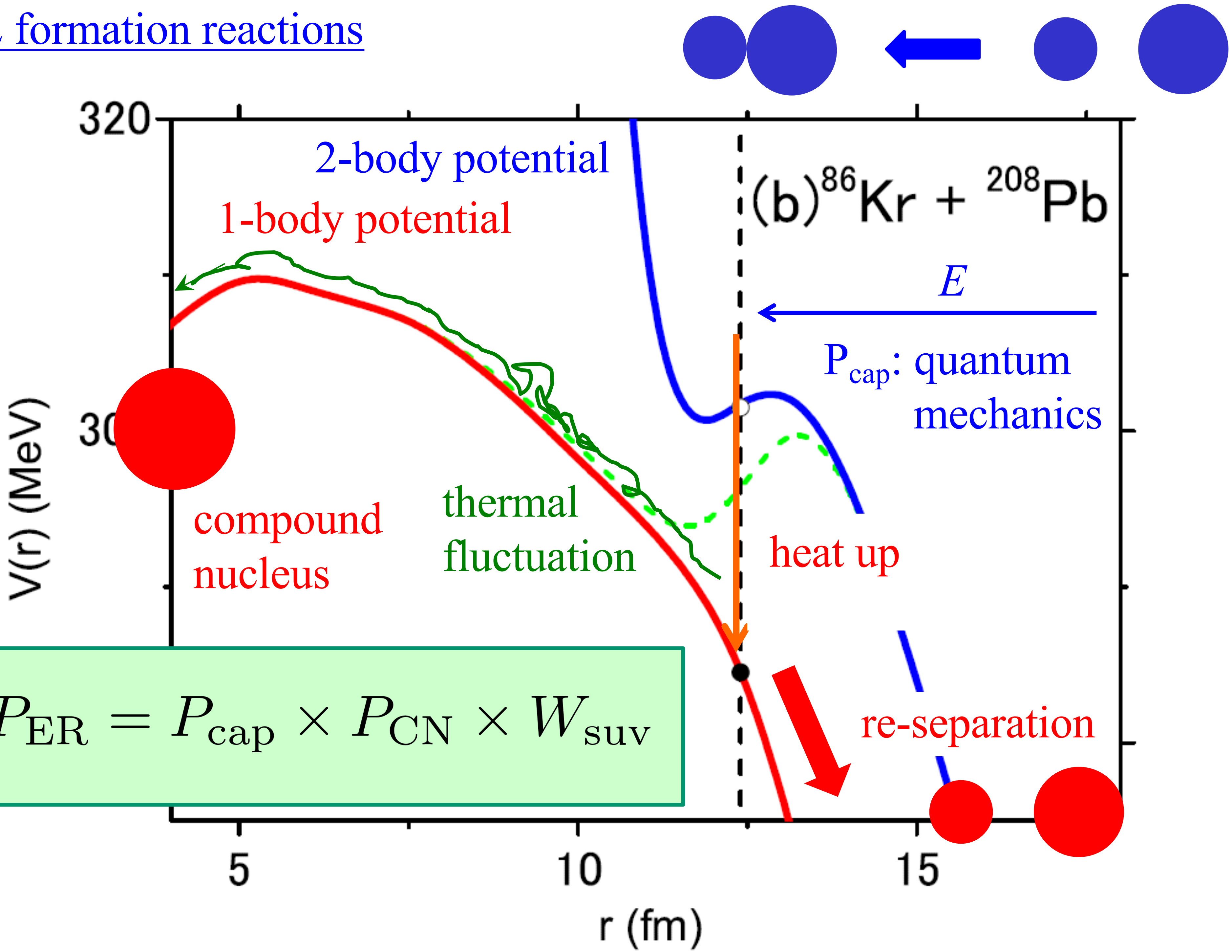




Fusion for SHE: fusion hindrance

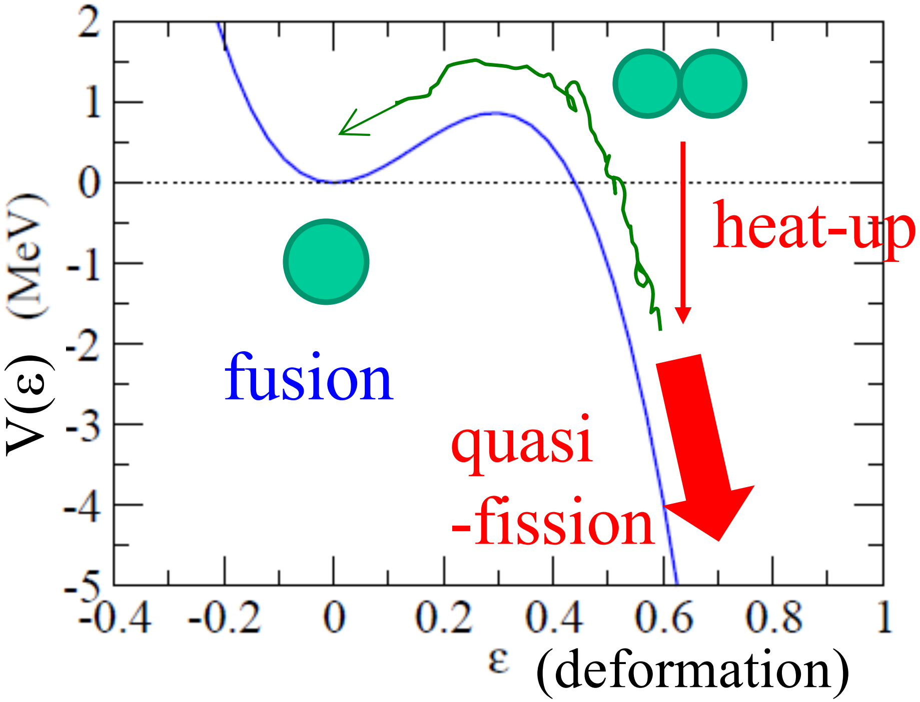


SHE formation reactions



$$P_{\mathrm{ER}} = P_{\mathrm{cap}} \times P_{\mathrm{CN}} \times W_{\mathrm{suv}}$$

Langevin approach

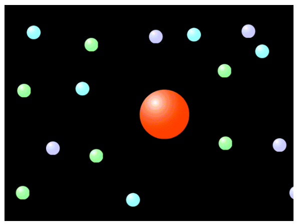


thermal fluctuation

⟶ Langevin method

$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

Browninan motion



classical Langevin equation

$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

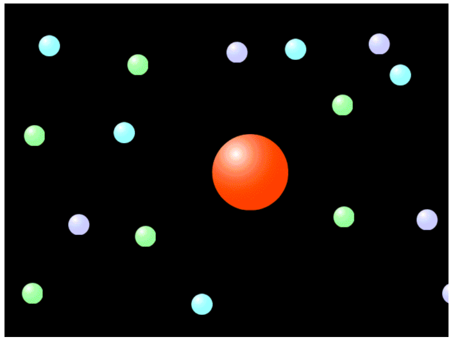
friction random interaction $\longrightarrow \langle R(t)\rangle = 0$

classical: $\langle R(t)R(t')\rangle = 2D\,\delta(t-t')$

$D = \gamma T$ (Einstein relation)

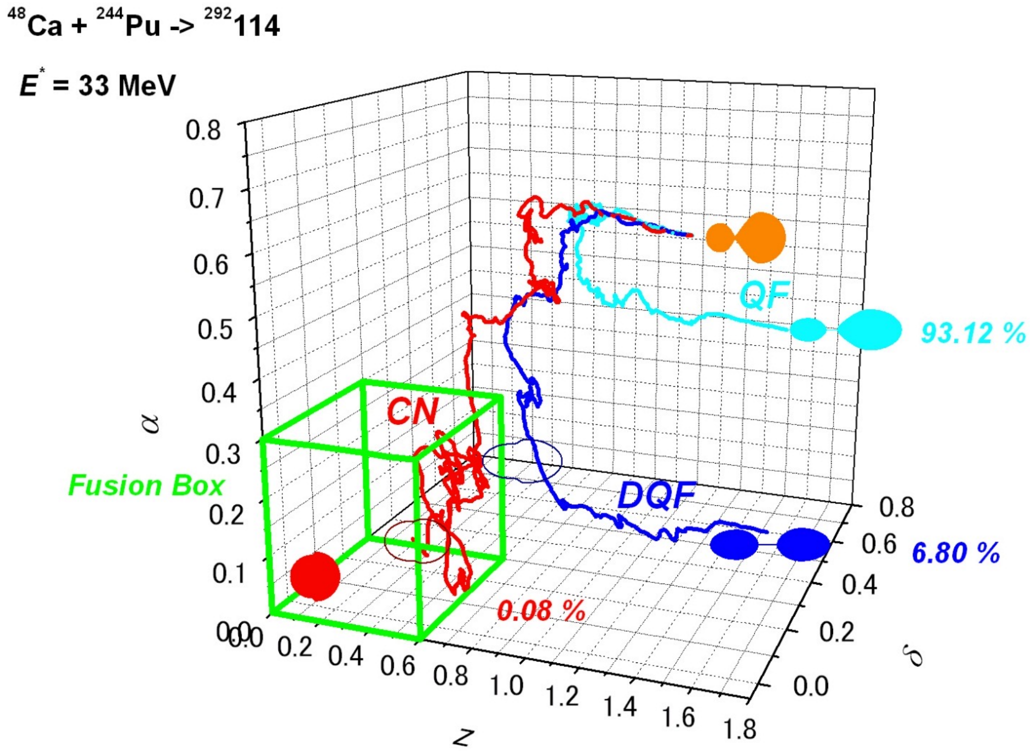
(white noise; no memory)

Brownian motion



interaction of a Brownian particle with atoms

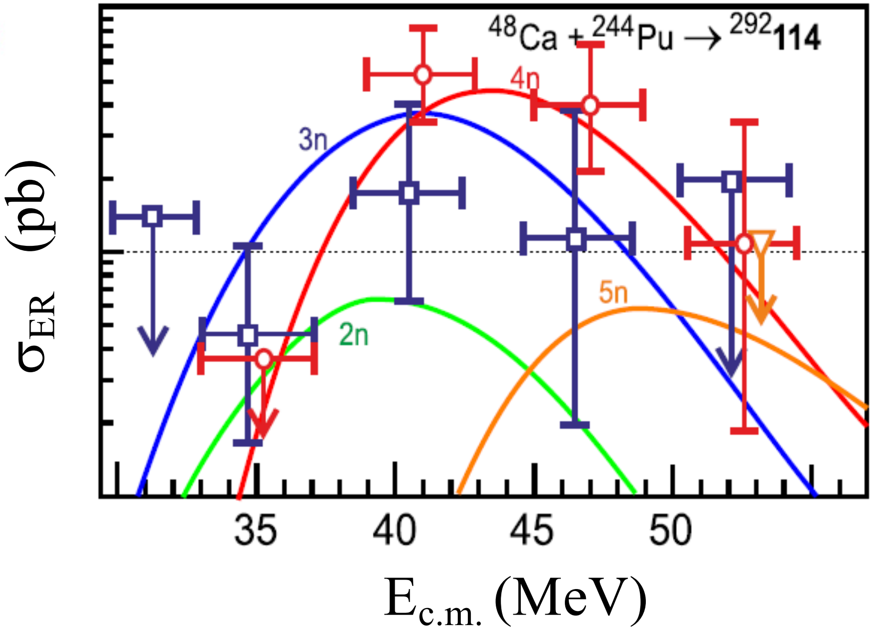
Langevin approach



Y. Aritomo (Kindai)

multi-dimensional extension:

q:
- internuclear separation,
- deformation,
- asymmetry of the two fragments

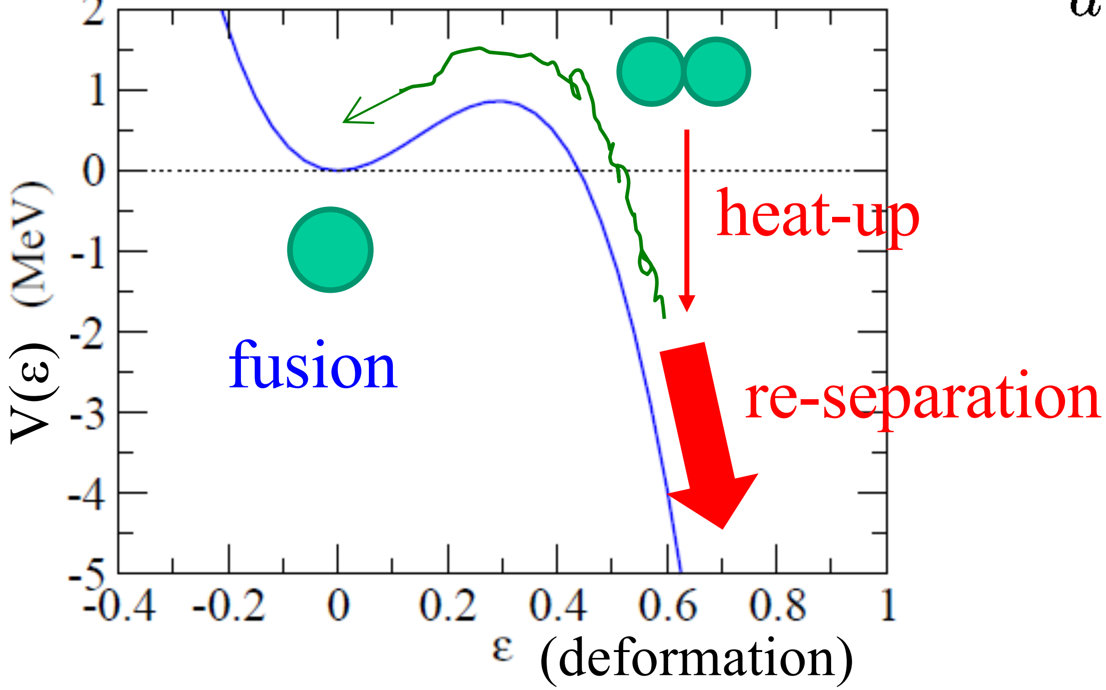


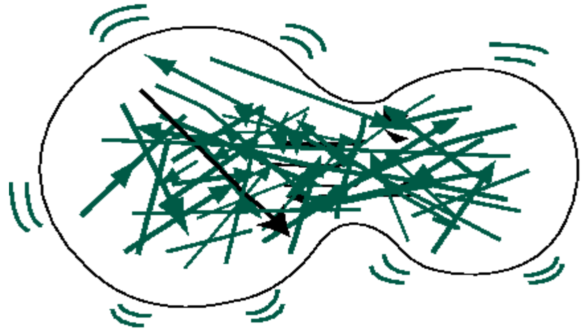
V.I. Zagrebaev and W. Greiner (2015)

successful,
at least phenomenologically

Langevin approach

$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$





nuclear intrinsic d.o.f.
: internal environment

→ open quantum systems

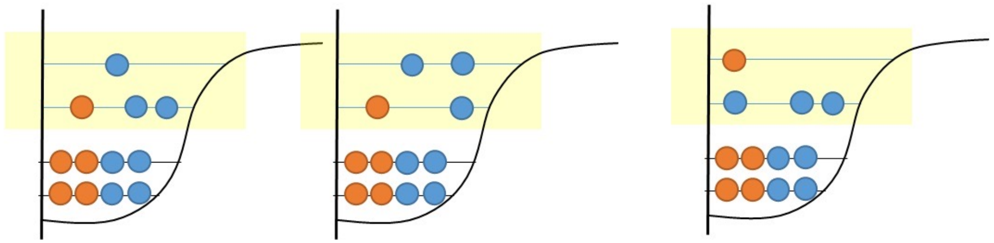
Theoretical issues

✓how to thermaize? mechanisms?
✓is thermal equilibrium OK?
✓Is Markovian approximation OK?
✓quantum effects?

▪a quantal theory for friction
▪a microscopic approach

Shell model approach?

Shell model

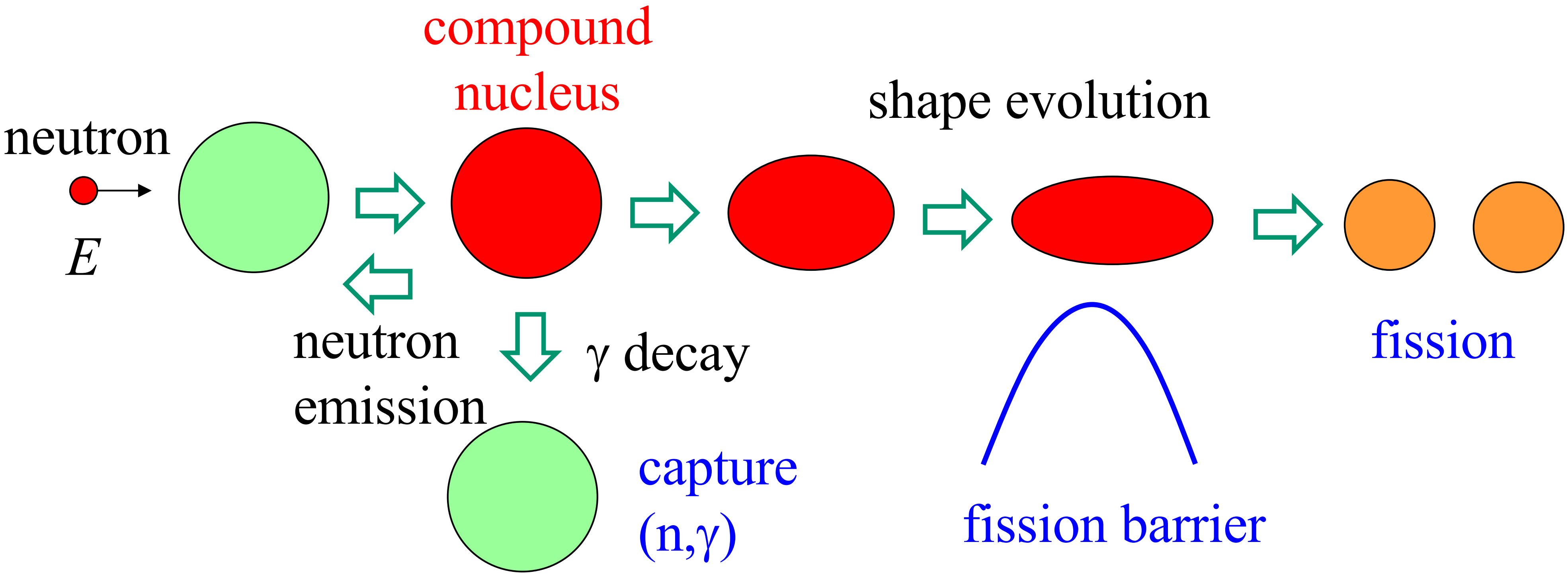


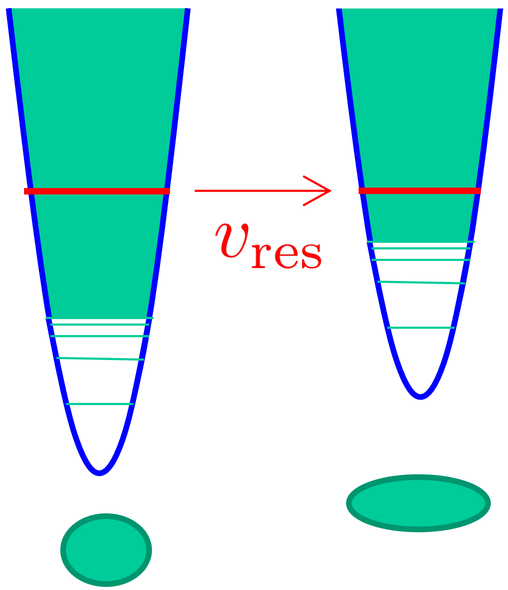
$$|\Psi\rangle = v_1|m_1\rangle + v_2|m_2\rangle + v_3|m_3\rangle + \cdots$$

Figure: Noritaka Shimizu (Tsukuba)

many-particle many-hole configurations
in a mean-field potential
→mixing by <u>residual interactions</u>

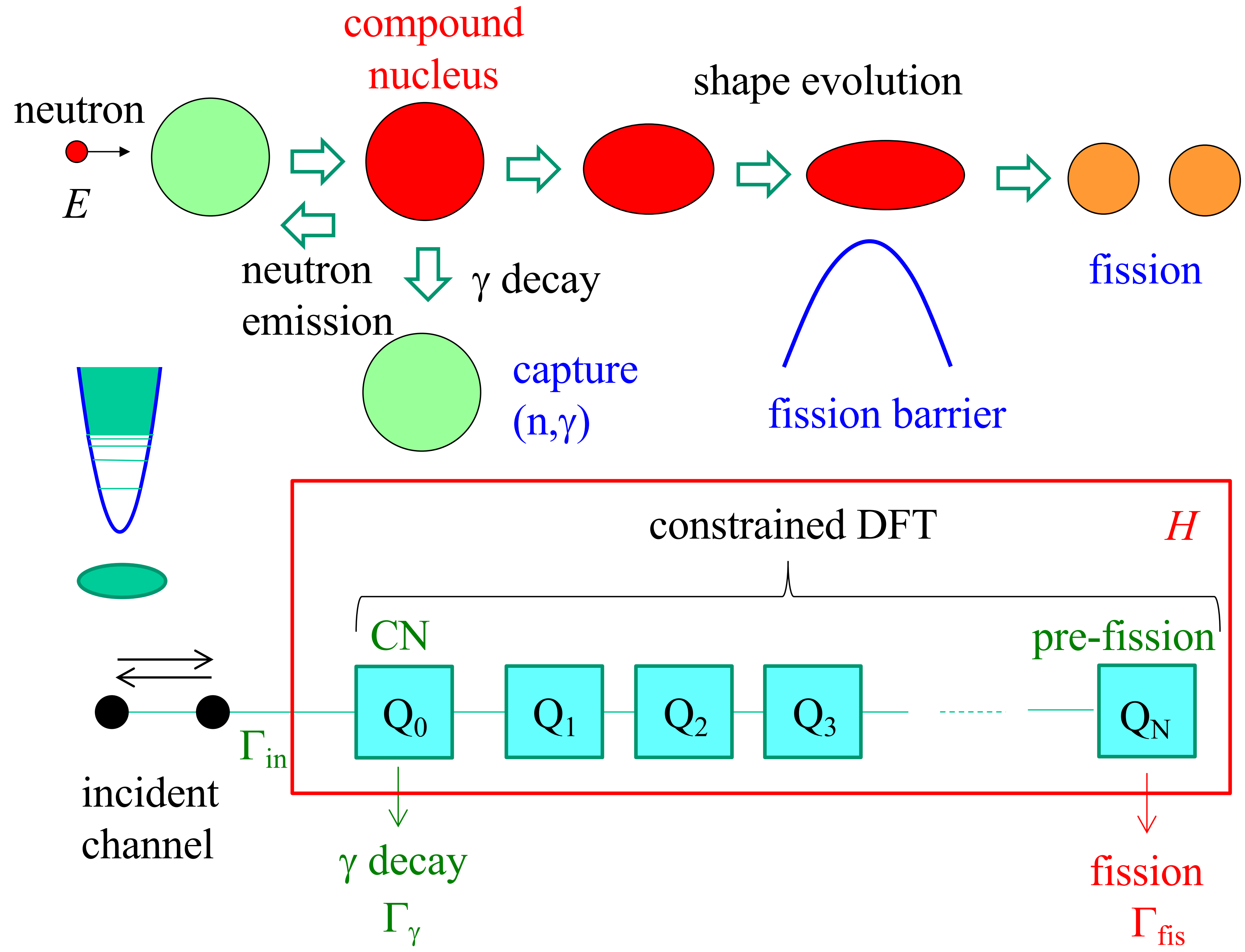
fission problem





- Many-body configurations in a MF pot. for each shape
- hopping due to res. int.

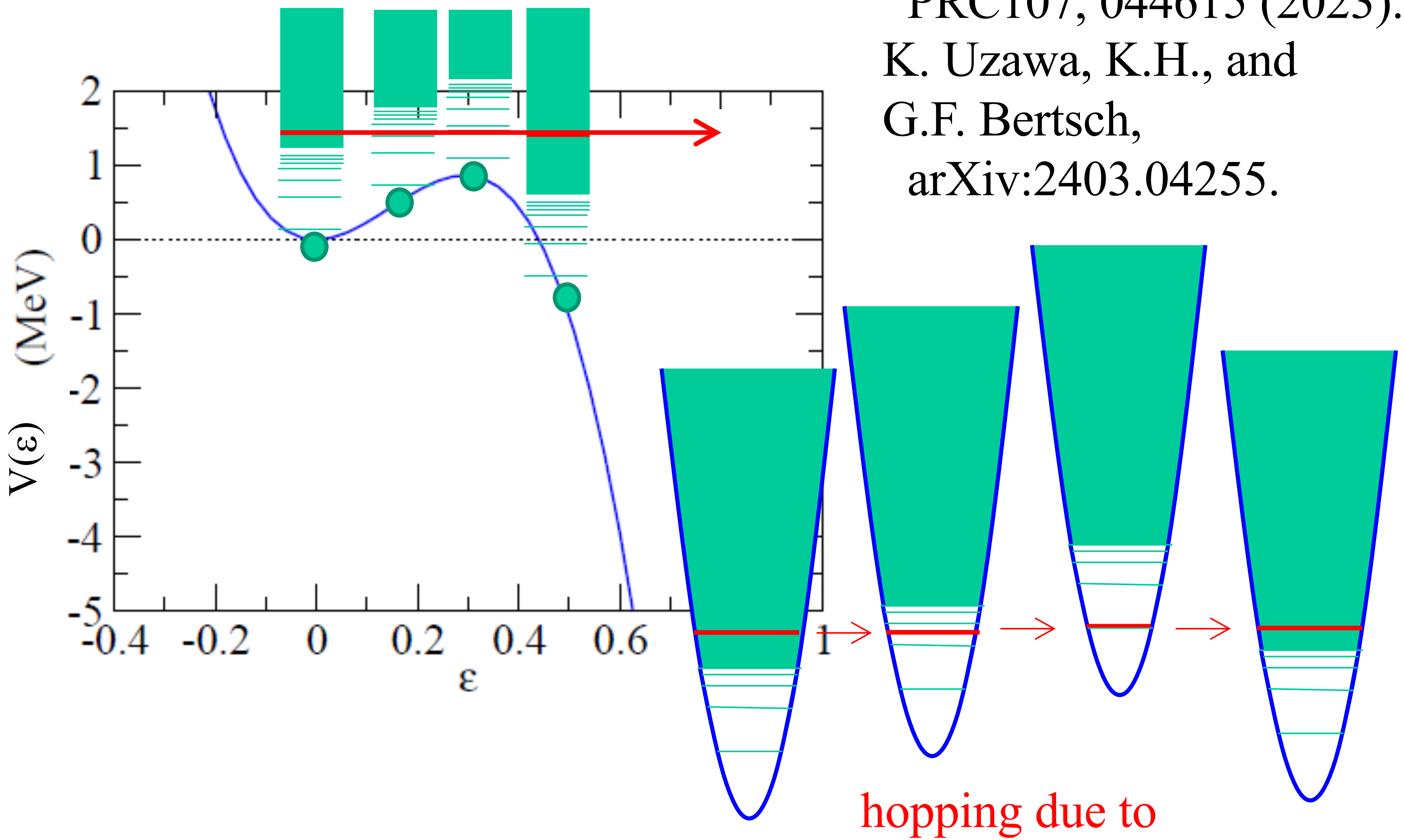
→ shape evolution



compound
nucleus
neutron
E
shape evolution
neutron
emission
γ decay
fission
capture
(n,γ)
fission barrier
constrained DFT
H
CN
pre-fission
Q_0
Q_1
Q_2
Q_3
Q_N
Γ_{in}
incident
channel
γ decay
Γ_γ
fission
Γ_{fis}

Towards a microscopic description for induced fission

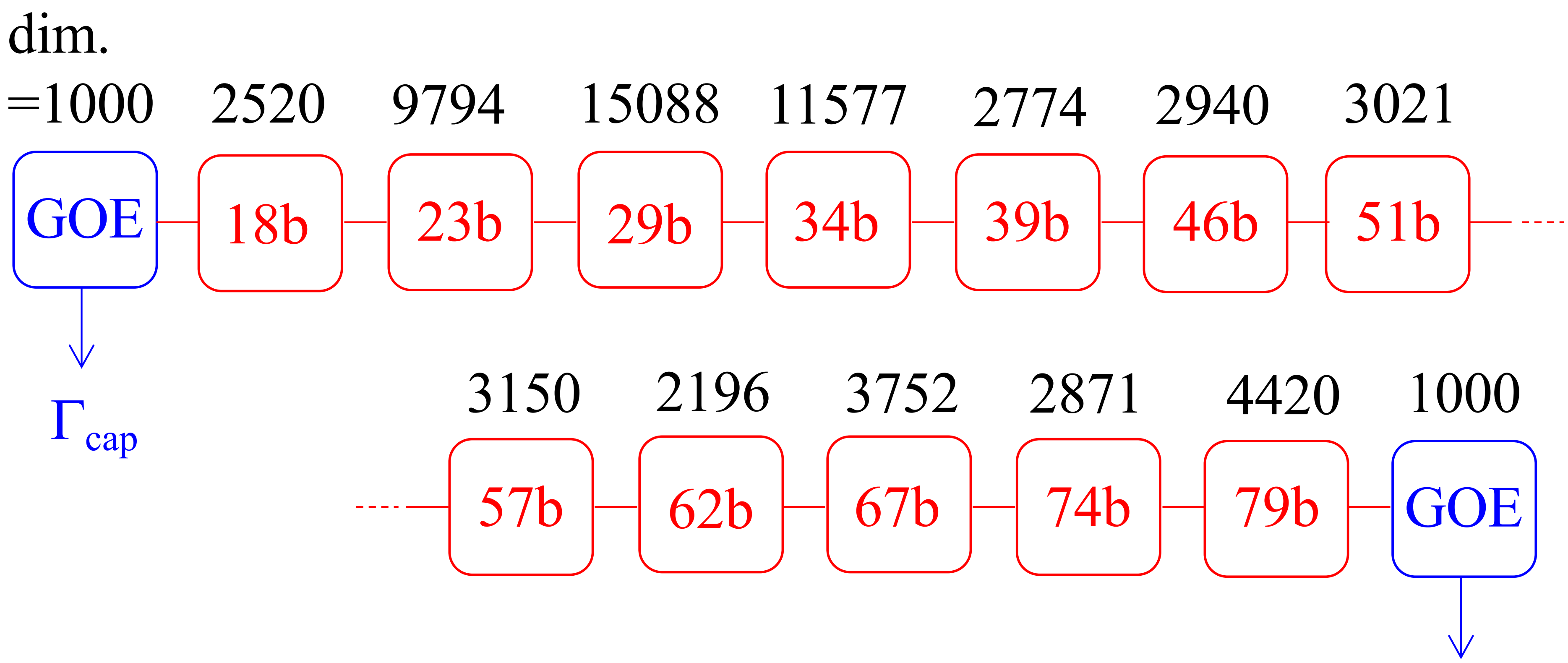
G.F. Bertsch and K.Hagino,
PRC107, 044615 (2023).
K. Uzawa, K.H., and
G.F. Bertsch,
arXiv:2403.04255.



hopping due to
residual interactions

Application to low-energy fission of ^{236}U

G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).
K. Uzawa, K.H., and G.F. Bertsch, arXiv:2403.04255.



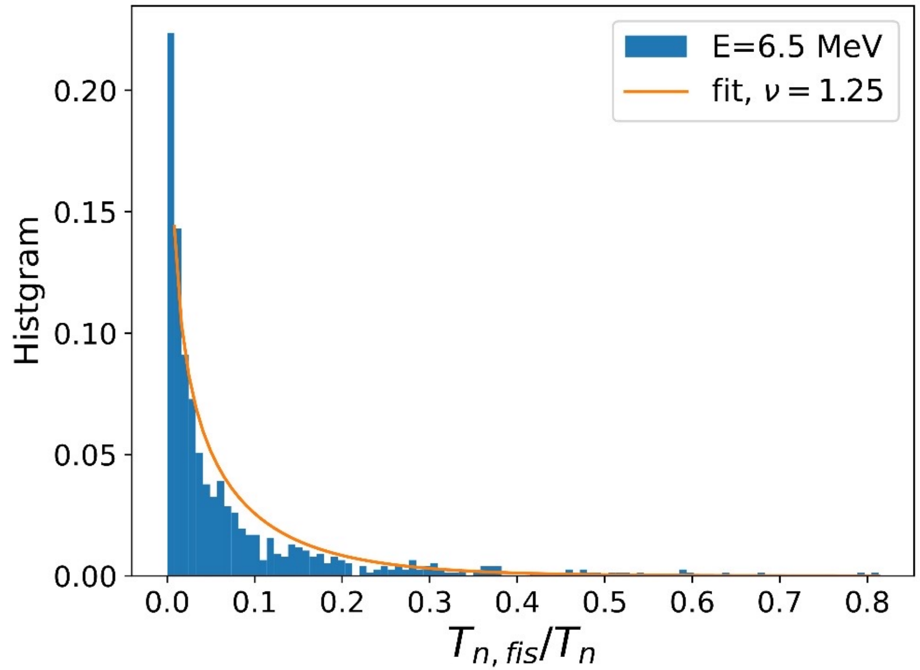
Skyrme UNEDF1, seniority zero config. up to 5 MeV
$\longrightarrow$ 66,103 x 66,103 dim. Hamiltonian

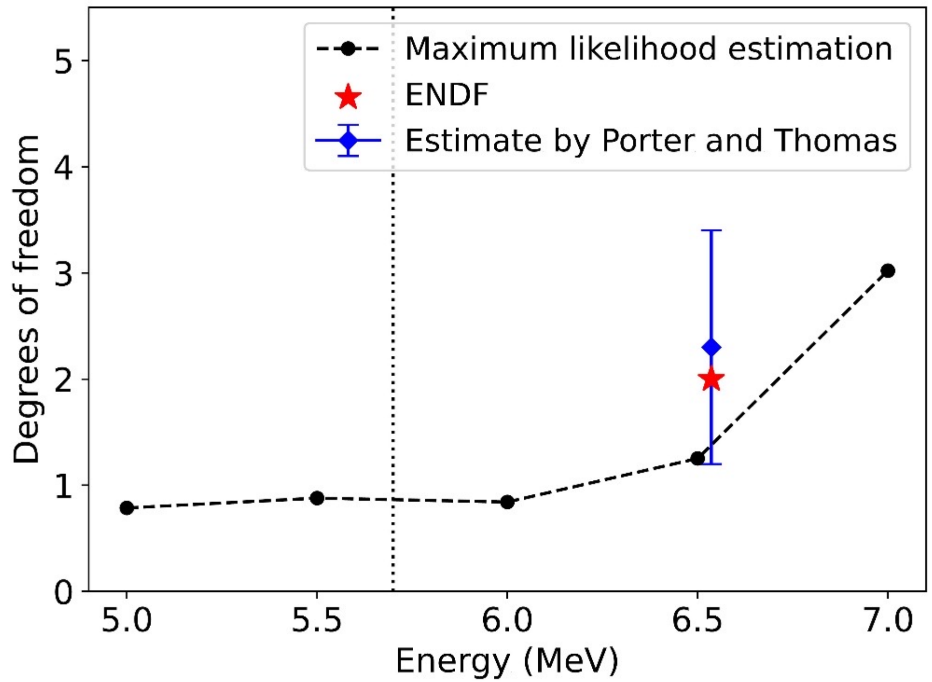
$$T_{CN\to{\rm fis}} = {\rm Tr}[\Gamma_n G \Gamma_{\rm fis} G^\dagger]; \quad G = (H - NE)^{-1}$$

Application to low-energy fission of ^{236}U

G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).
K. Uzawa, K.H., and G.F. Bertsch, arXiv:2403.04255.

$$P_\nu(x) = \frac{\nu}{2\Gamma(\nu/2)}\left(\frac{\nu x}{2}\right)^{\nu/2-1} e^{-\nu x/2}$$

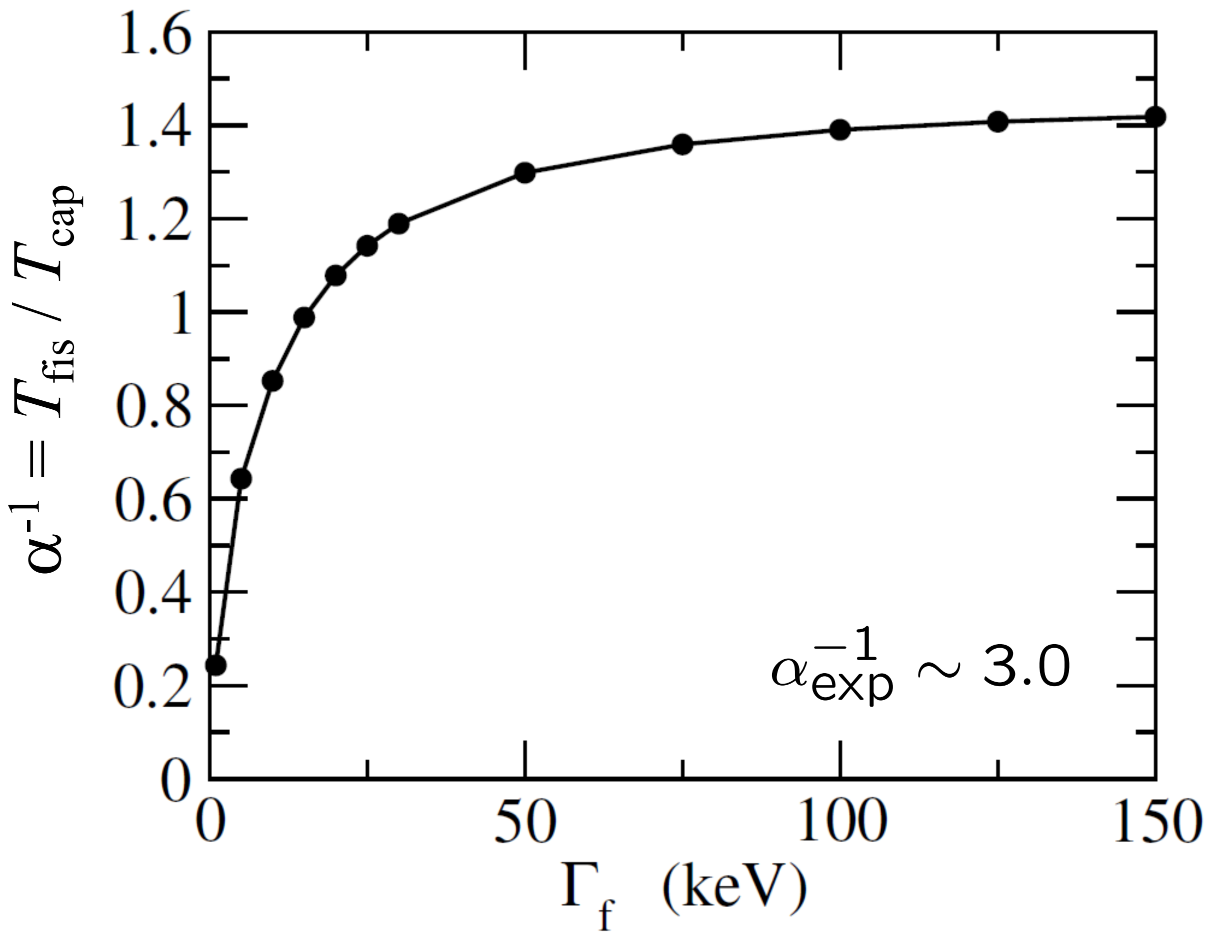




Only a small number of freedom participate in induced fission

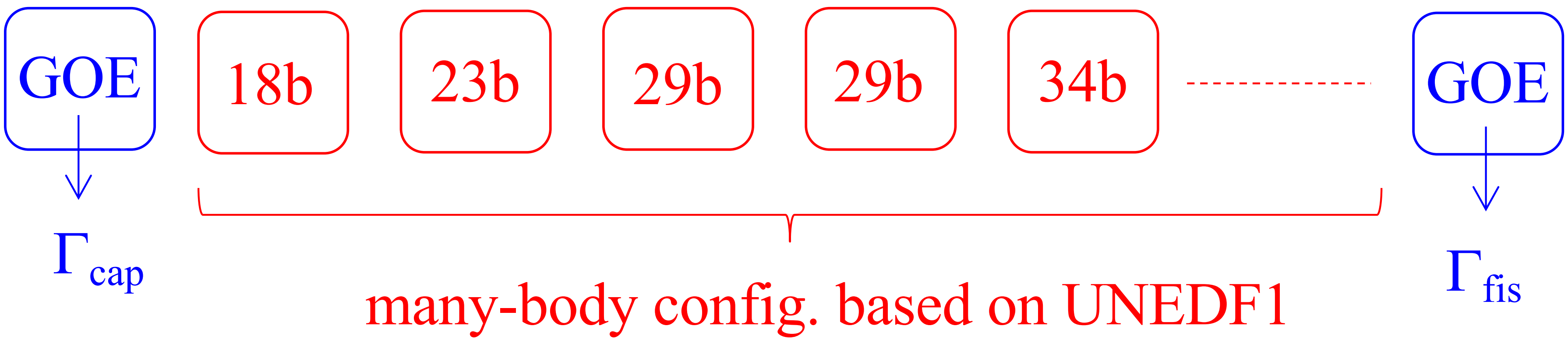
← the transition state theory

insensitivity property



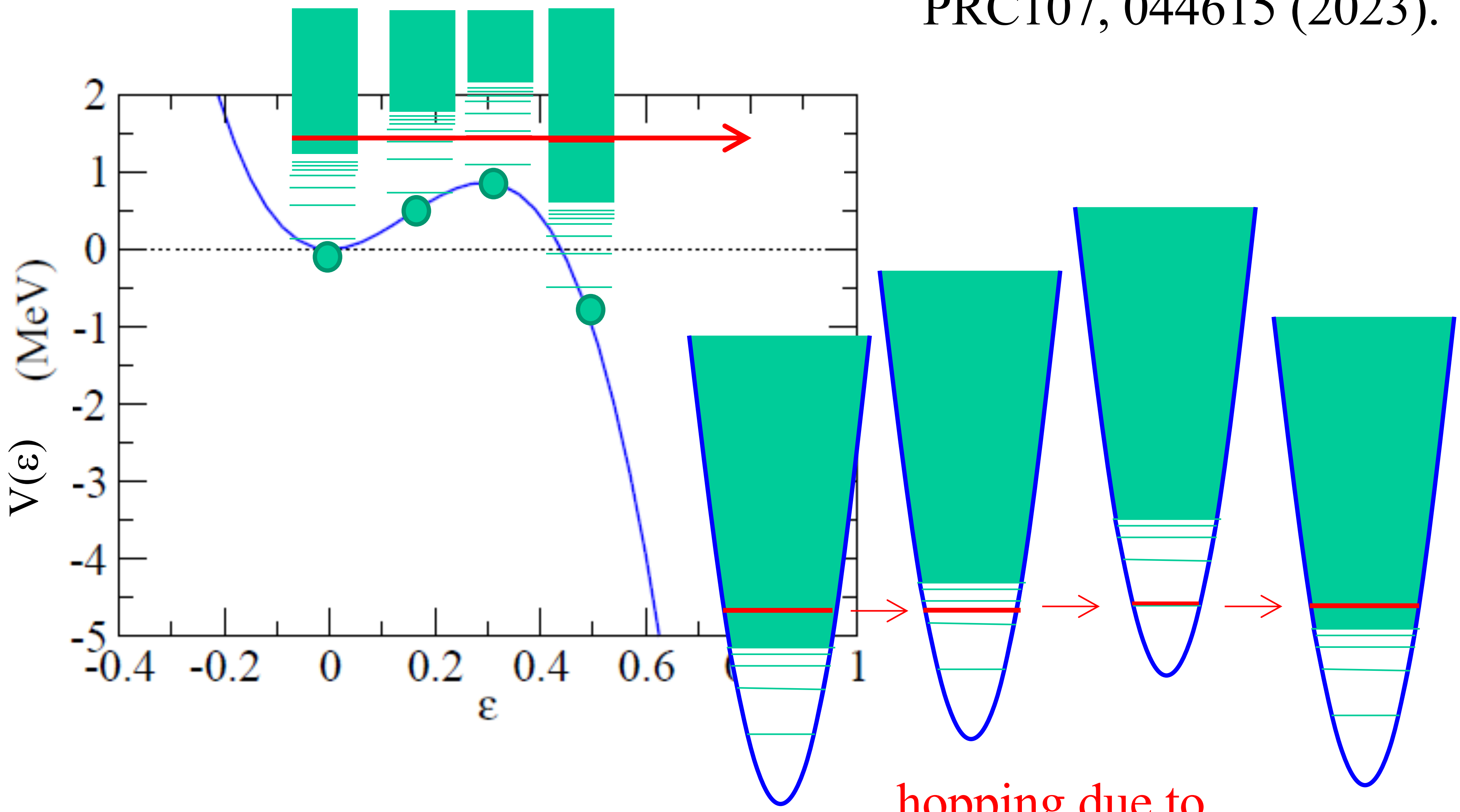
insensitive to Γ_f
(post-barrier dynamics)
→the main assumption of the transition state theory (TST)

K.H. and G.F. Bertsch, JPSJ 93, 064003 (2024).



Towards a microscopic description for induced fission

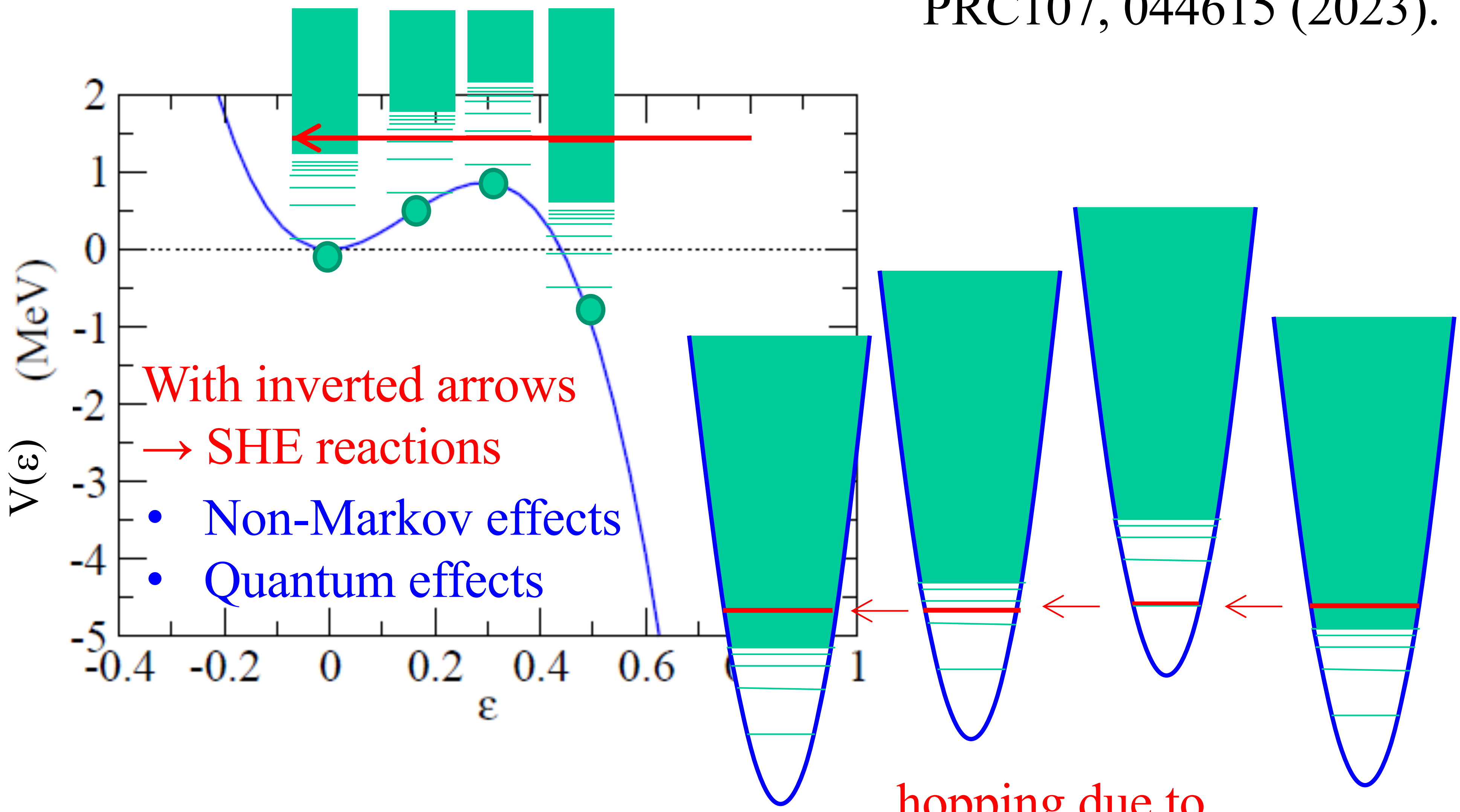
G.F. Bertsch and K.Hagino, PRC107, 044615 (2023).



hopping due to
residual interactions

Towards a microscopic description for induced fission

G.F. Bertsch and K.Hagino,
PRC107, 044615 (2023).

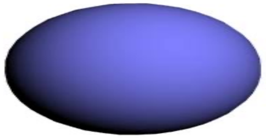


With inverted arrows
→ SHE reactions

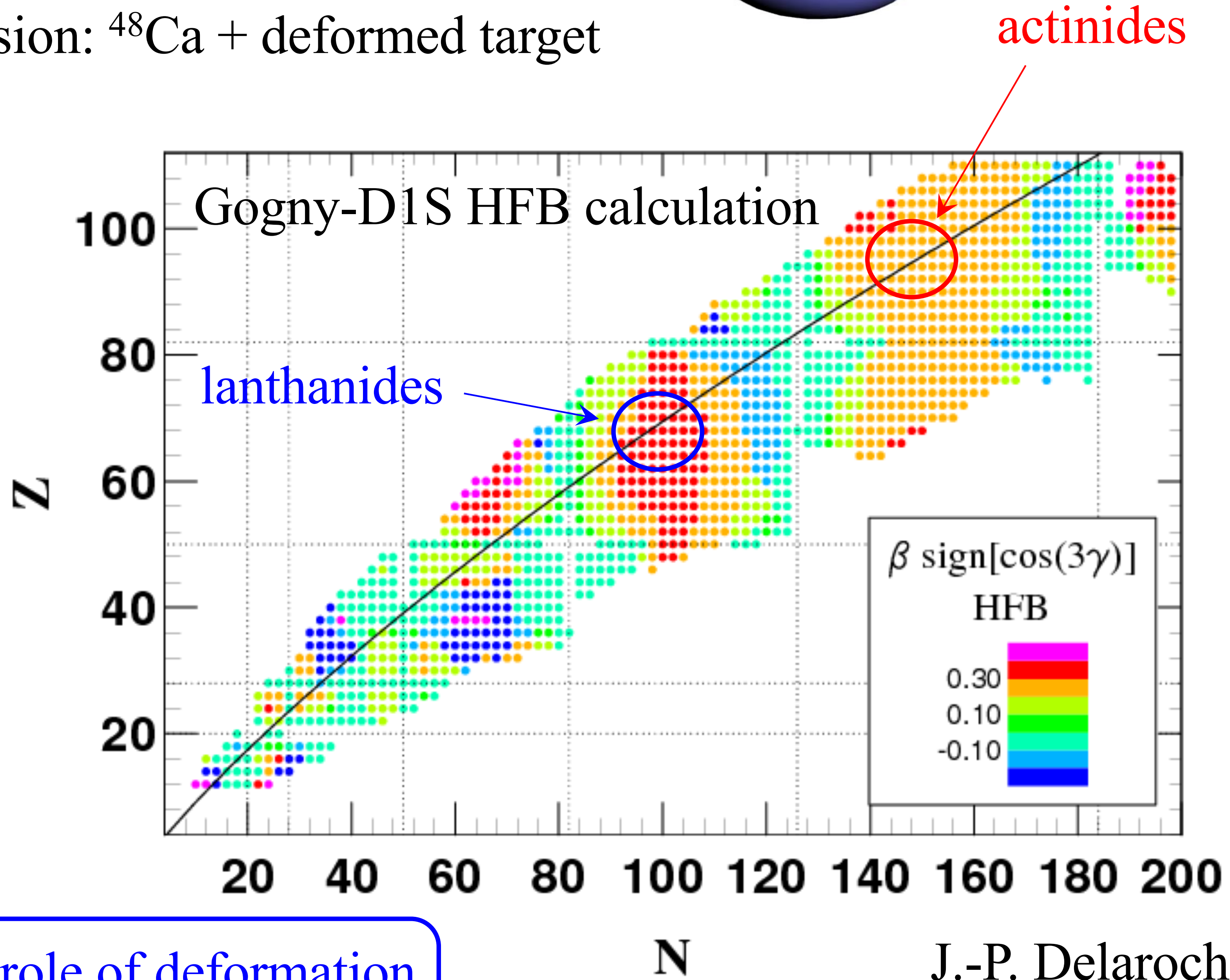
- Non-Markov effects
- Quantum effects

hopping due to
residual interactions

Another issue: Nuclear Deformation



hot fusion: ^{48}Ca + deformed target

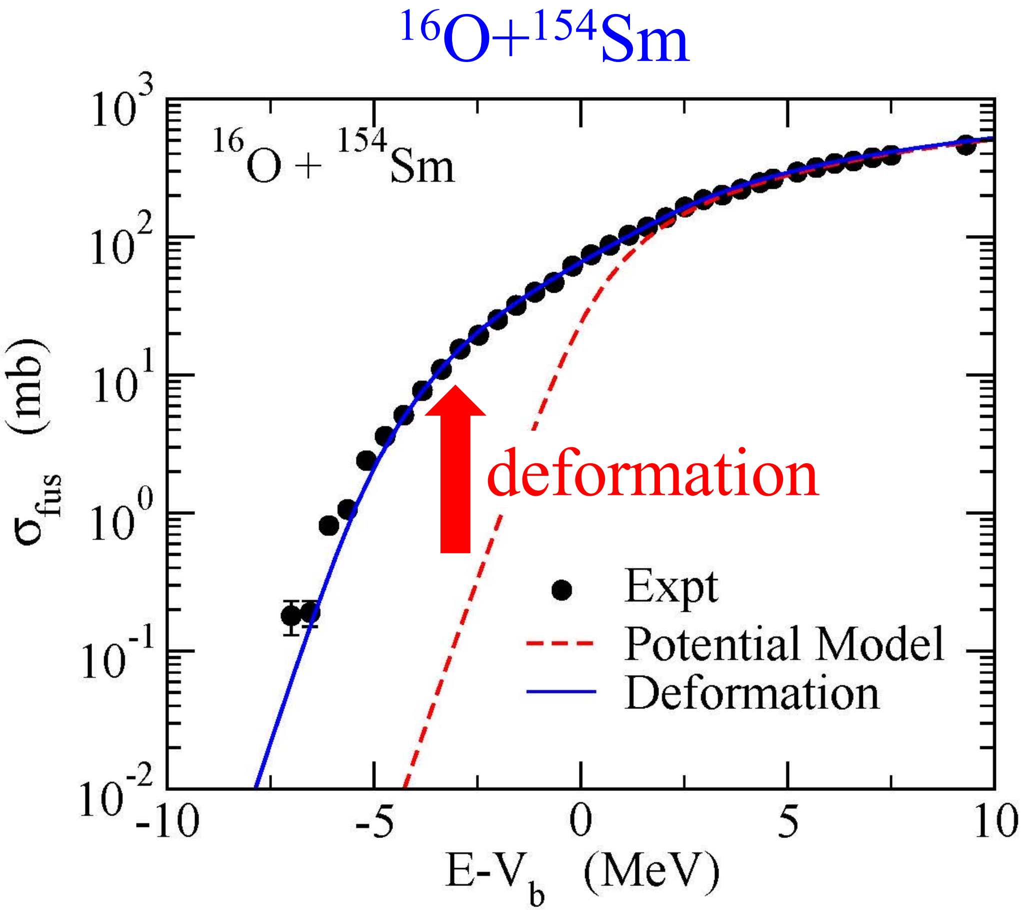


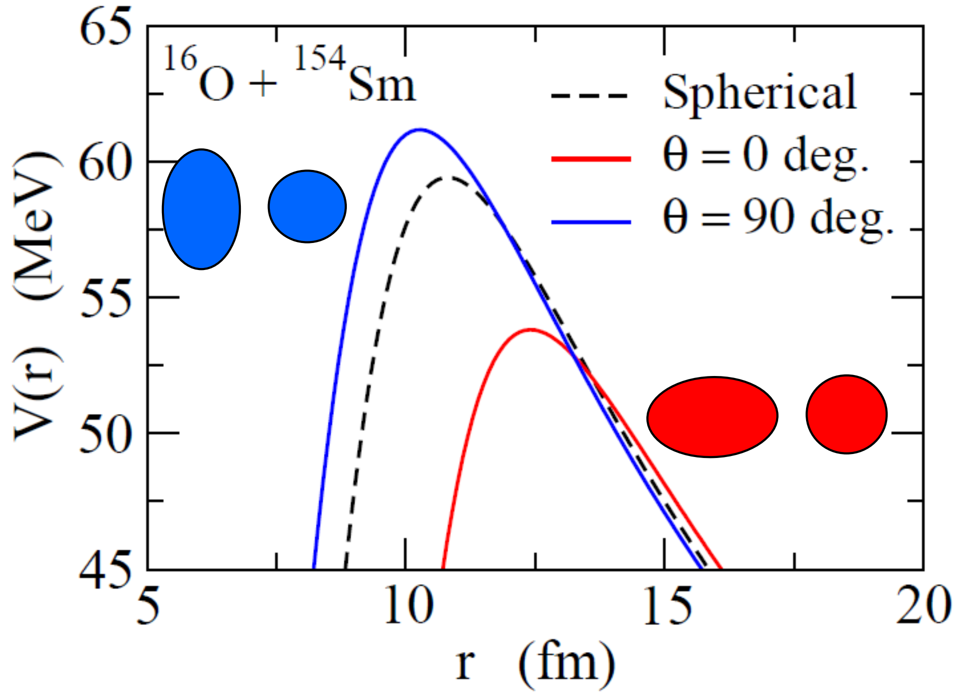
the role of deformation in heavy-ion reactions?

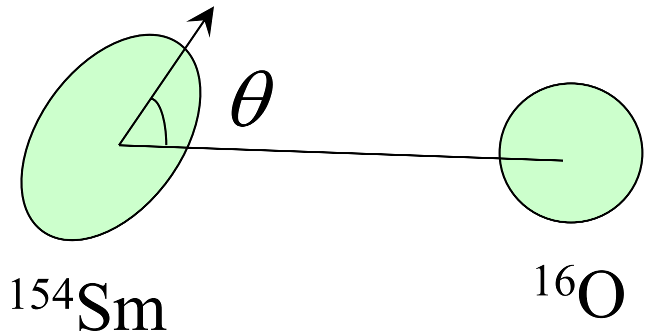
J.-P. Delaroche et al., PRC81 ('10) 014303

Nuclear deformation and barrier distribution

Nuclear deformation → a large sub-barrier enhancement of fusion cross sections



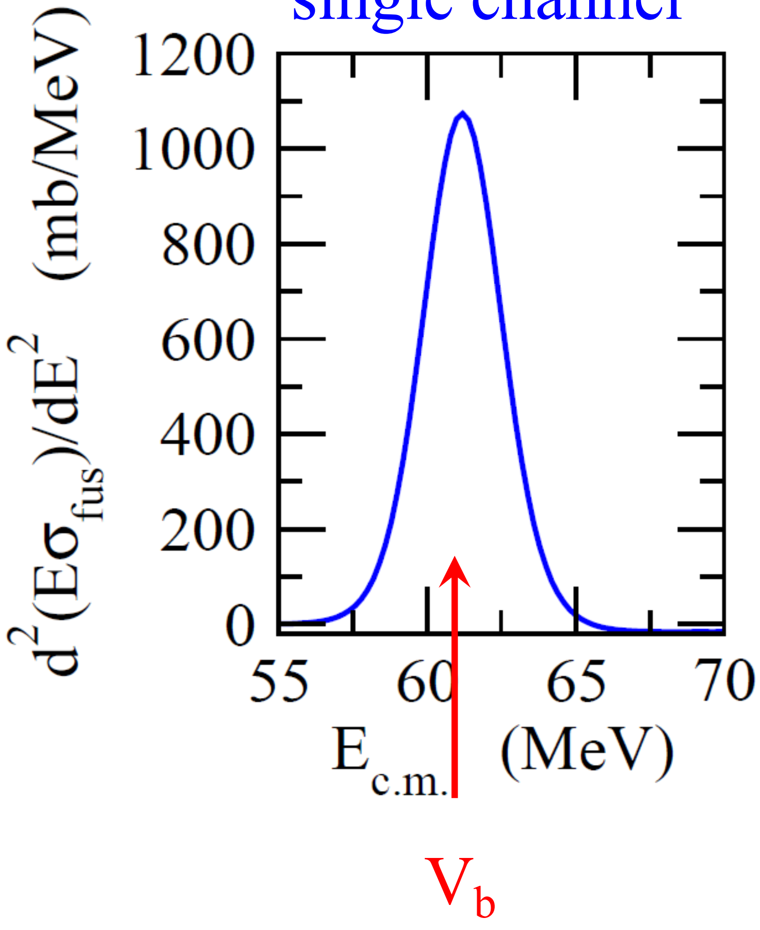




Fusion barrier distribution [Rowley, Satchler, Stelson, PLB254('91)]

$$D_{\rm fus}(E) = \frac{d^2(E\sigma_{\rm fus})}{dE^2} \propto \frac{dP_{l=0}}{dE}$$

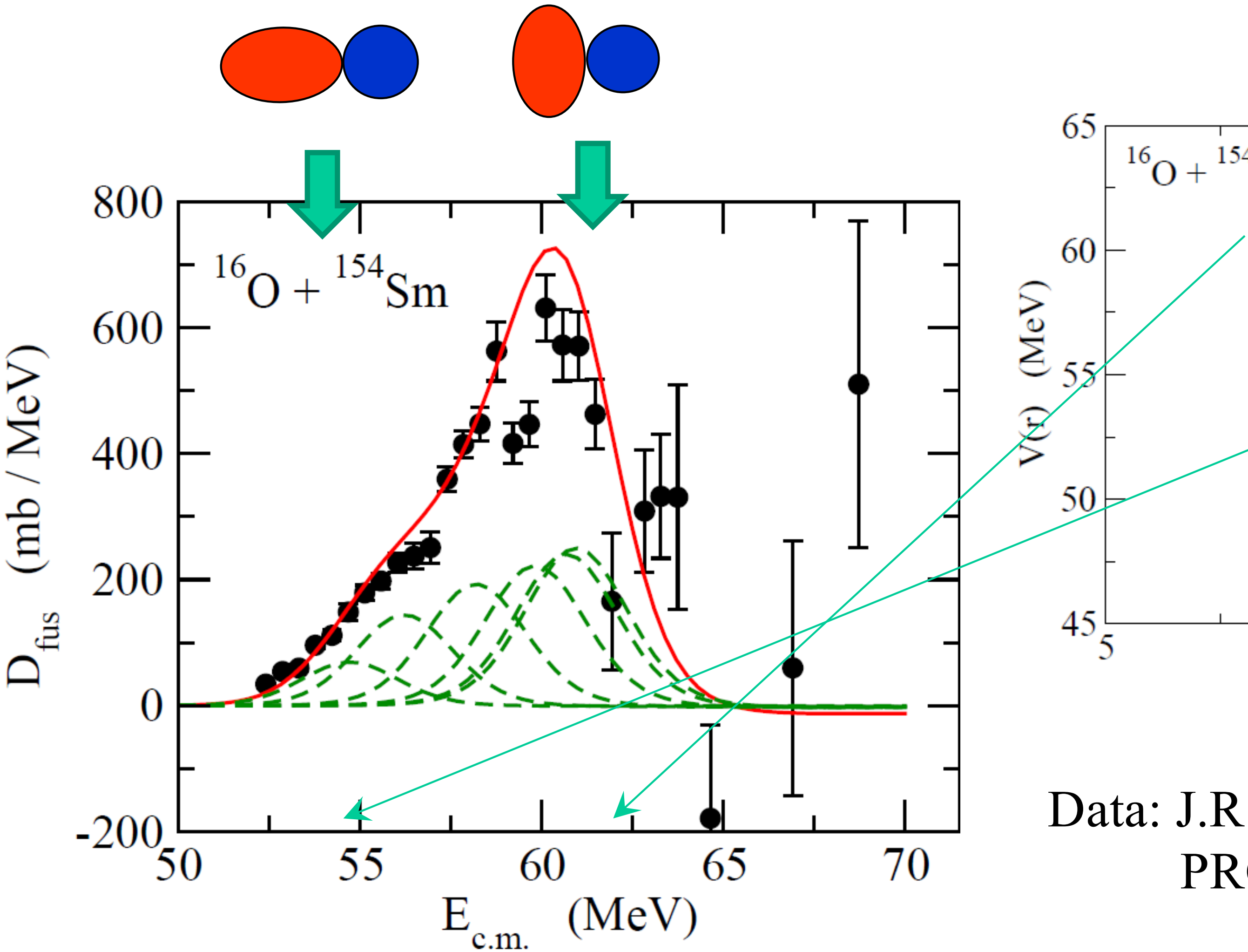
single channel

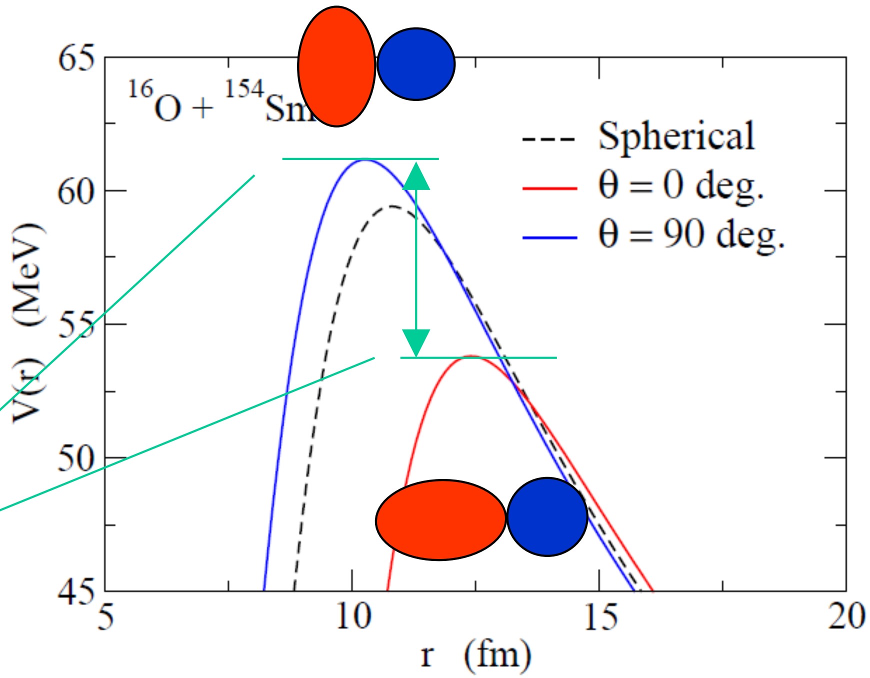


K.H., N. Takigawa, PTP128 ('12) 1061

✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254('91))

$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$



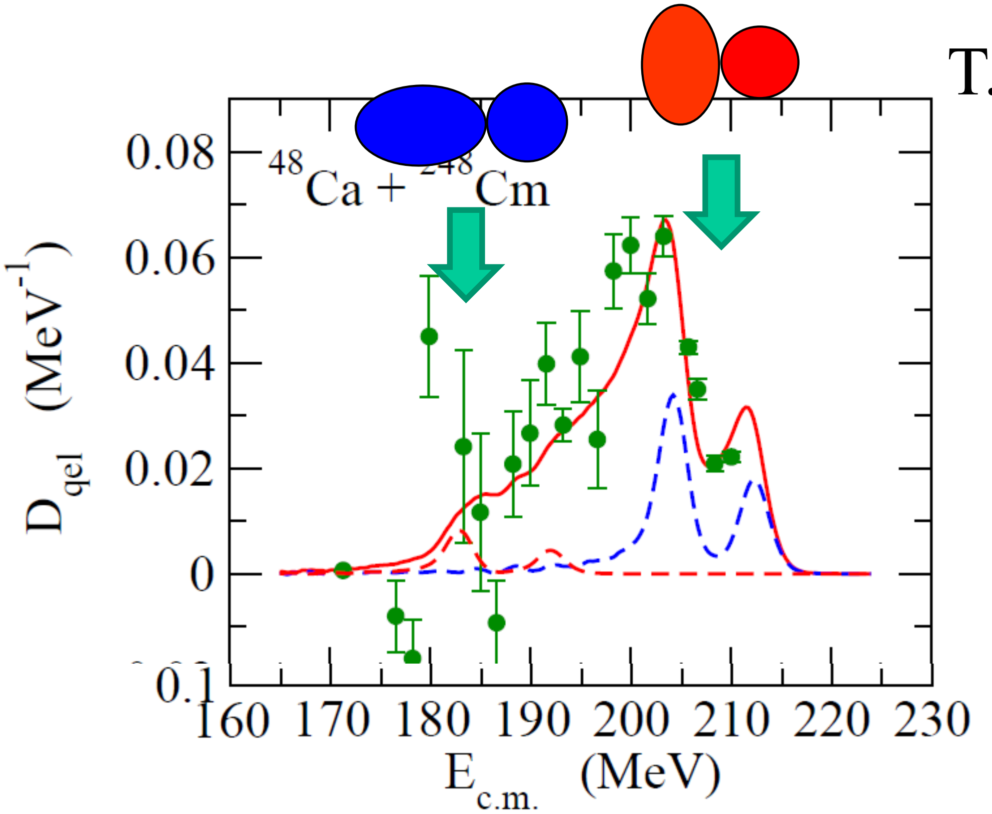


Data: J.R. Leigh et al., PRC52 ('95) 3151

can be used to identify the side/tip collisions

Application to hot fusion reactions

$^{48}Ca + ^{248}Cm \rightarrow ^{296}{}_{116}Lv^*$



T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

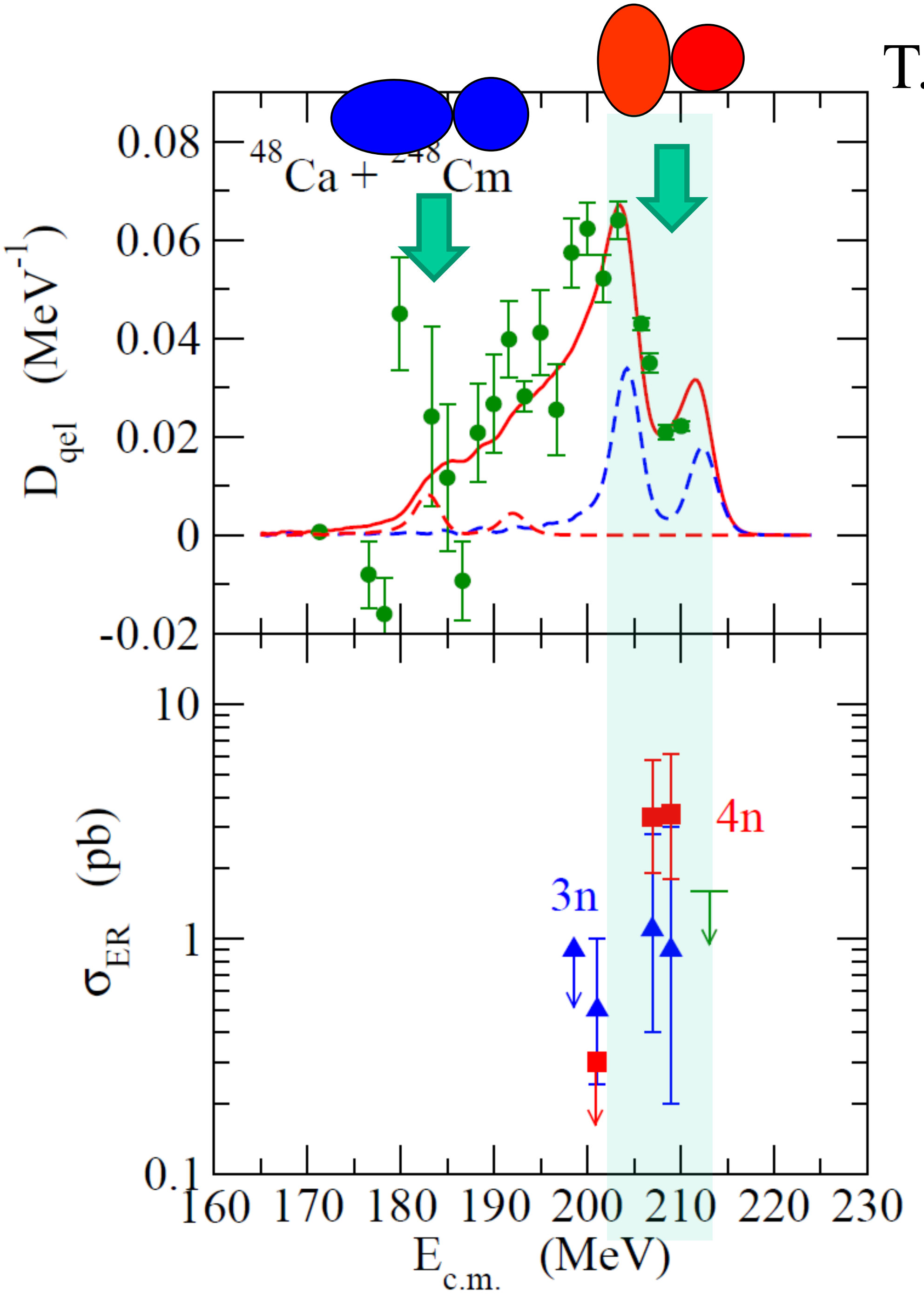
capture barrier distribution

$^{51}V+^{248}Cm \rightarrow ^{299}119^*$

M. Tanaka et al.,
JPSJ91, 084201 (2022)

Application to hot fusion reactions

$^{48}Ca + ^{248}Cm \rightarrow ^{296}{}_{116}Lv^*$

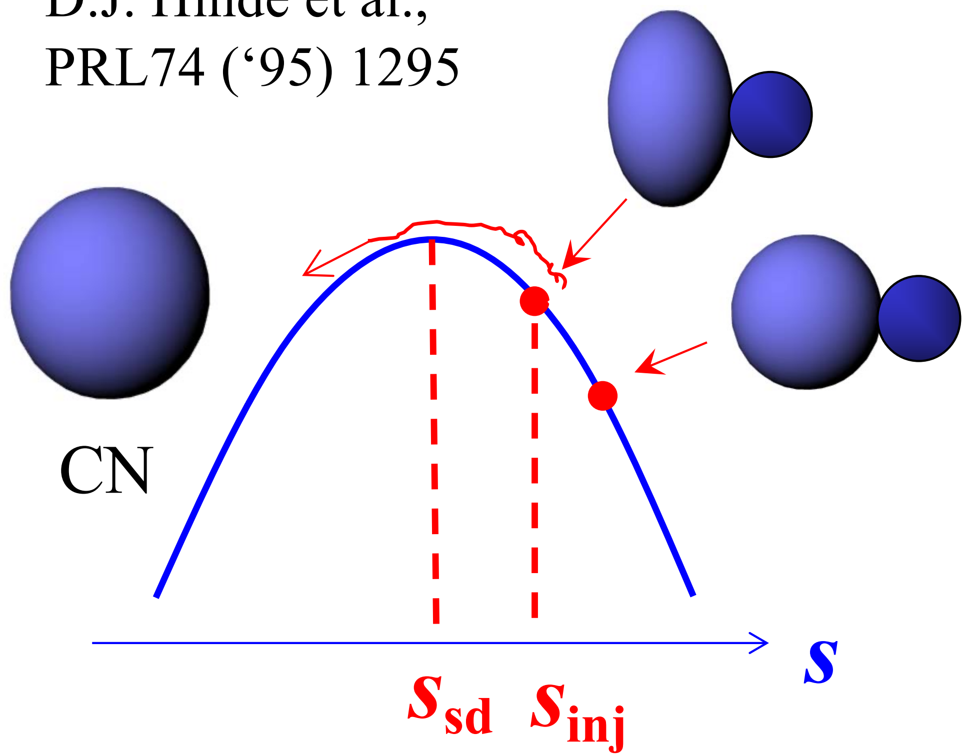


T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

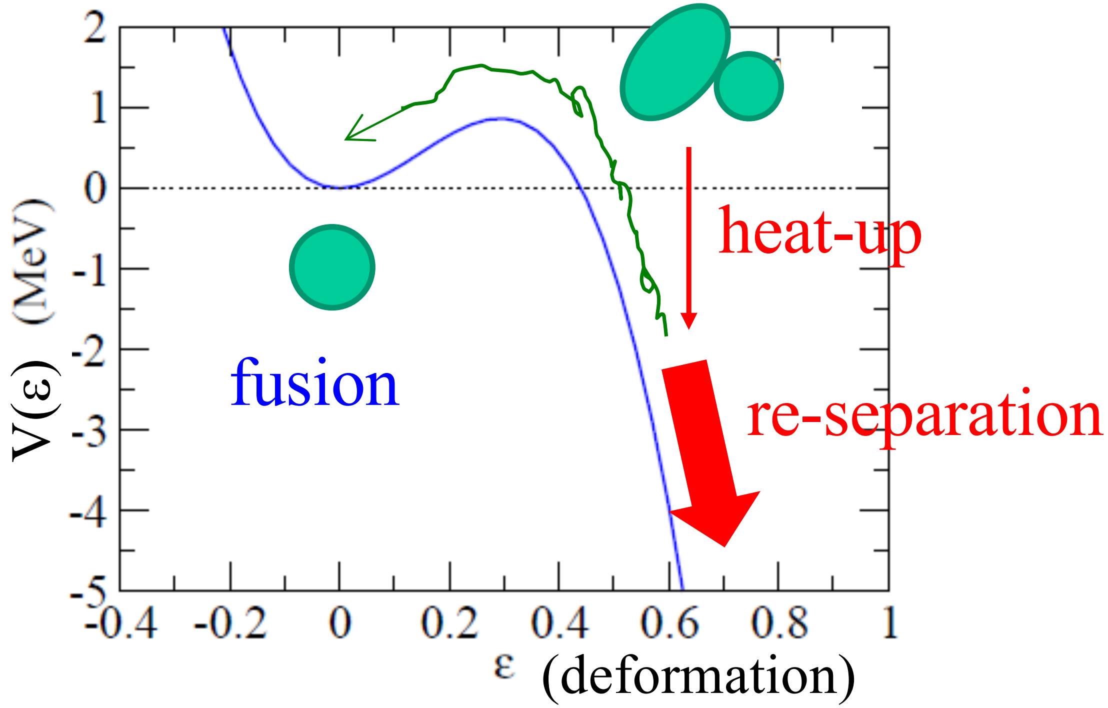
capture barrier distribution

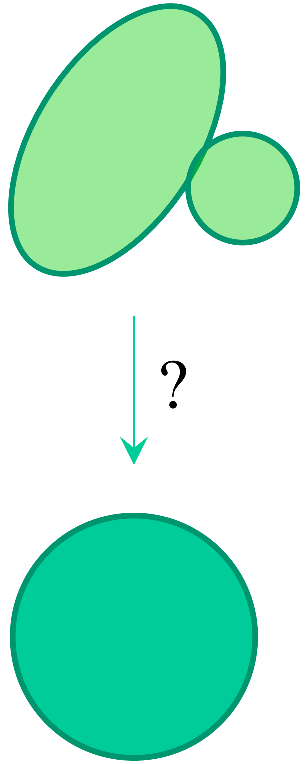
cf. notion of compactness:

D.J. Hinde et al.,
PRL74 ('95) 1295



open problems



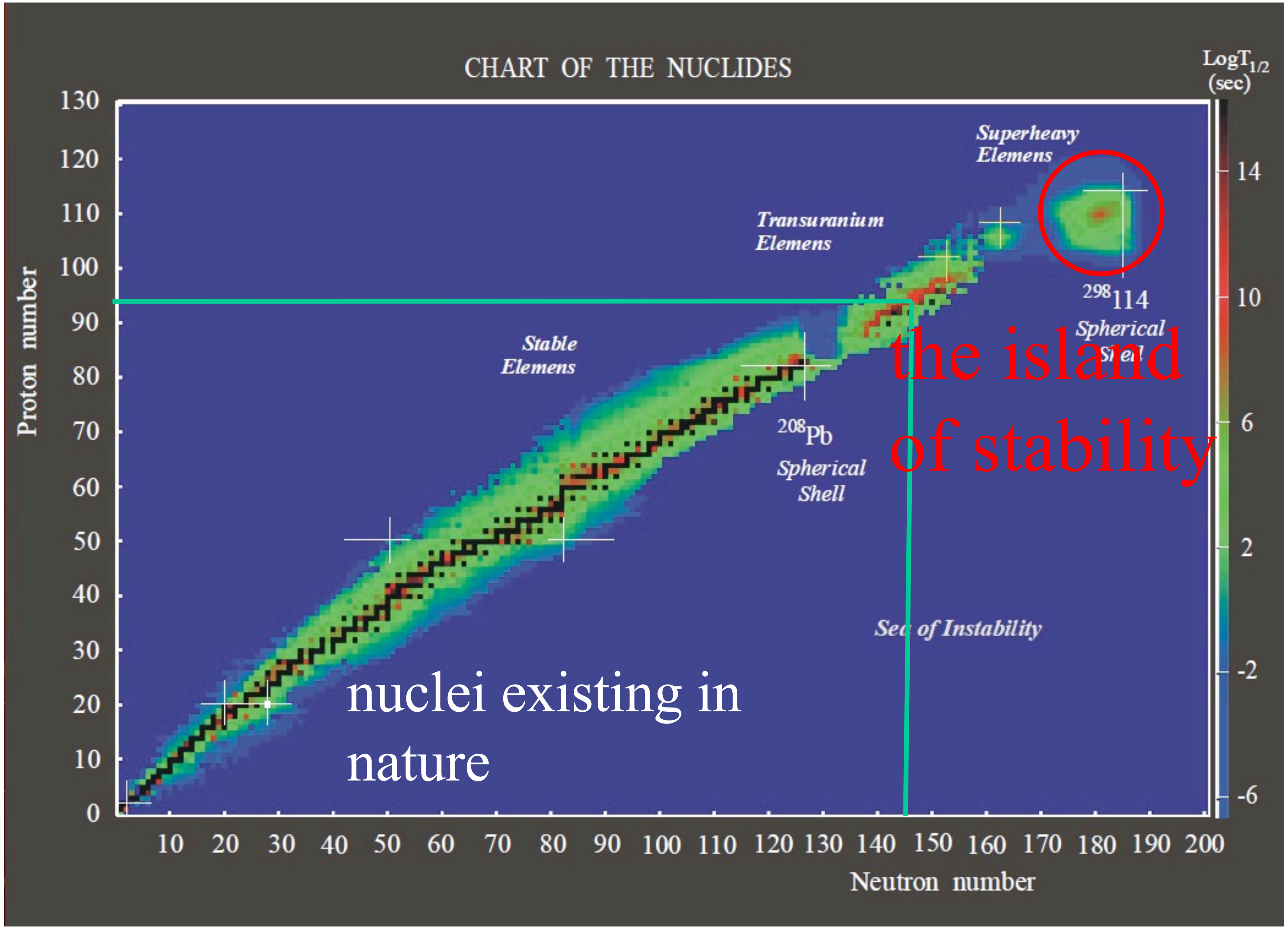


- how is the shape evolved to a compound nucleus?
- Deformation: a quantum effect
  how does the deformation disappear during heat-up?

quantum friction/open quantum systems

cf. M. Tokieda and K.H., Ann. of Phys. 412 ('20) 168005.
Coupled-channels approach to the Caldeira-Leggett model

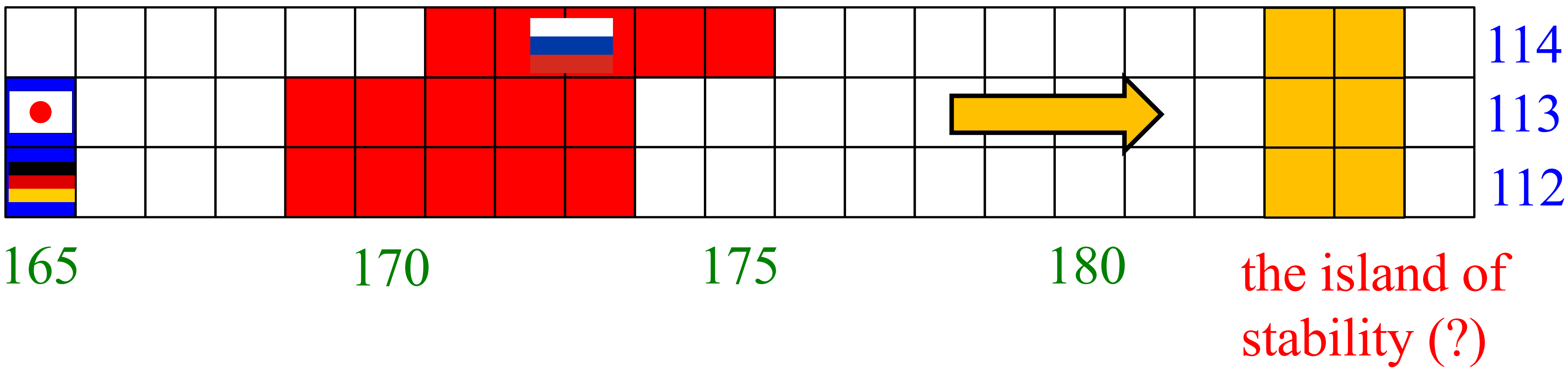
Another important issue: physics of neutron-rich nuclei



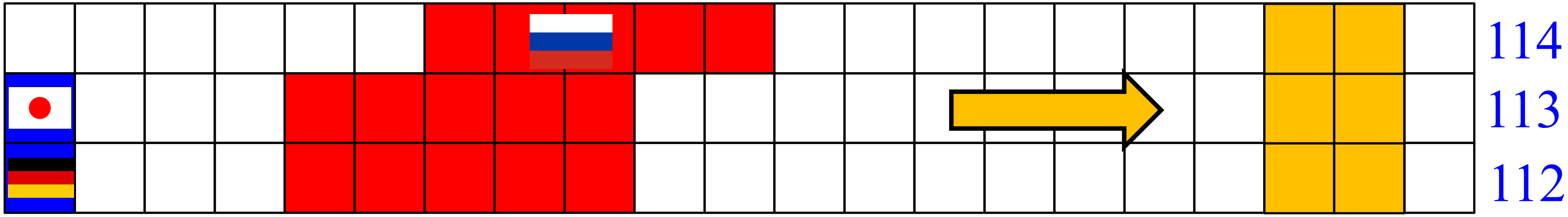
Yuri Oganessian

how to reach the island of stability?

Fusion of unstable nuclei

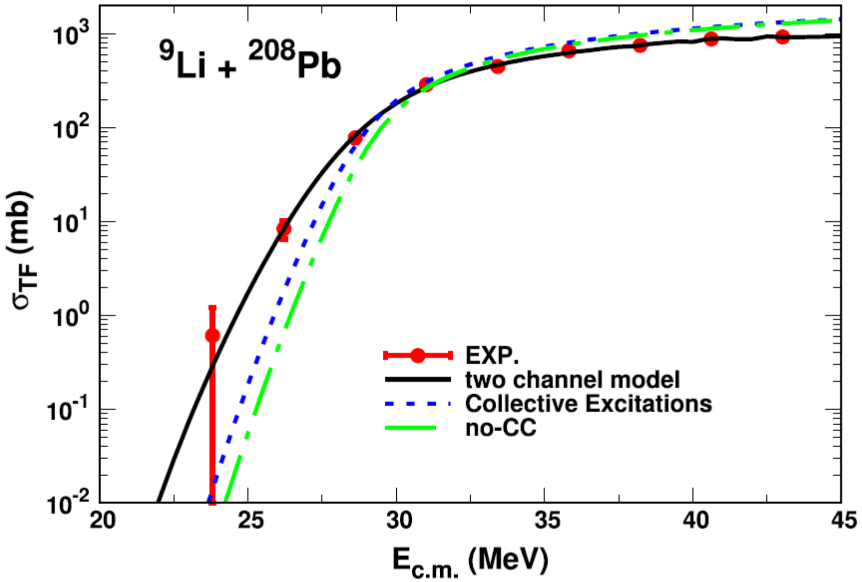


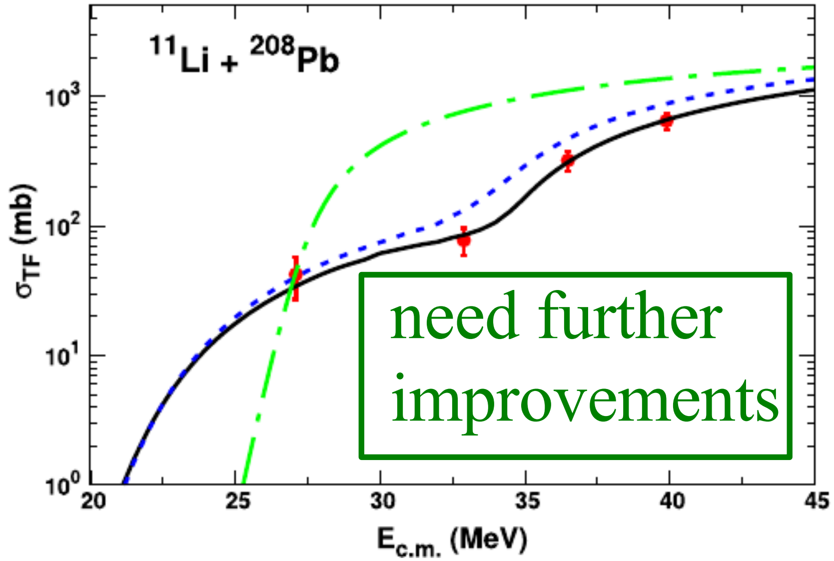
Fusion of unstable nuclei



neutron-rich beams: indispensable
→reaction dynamics?

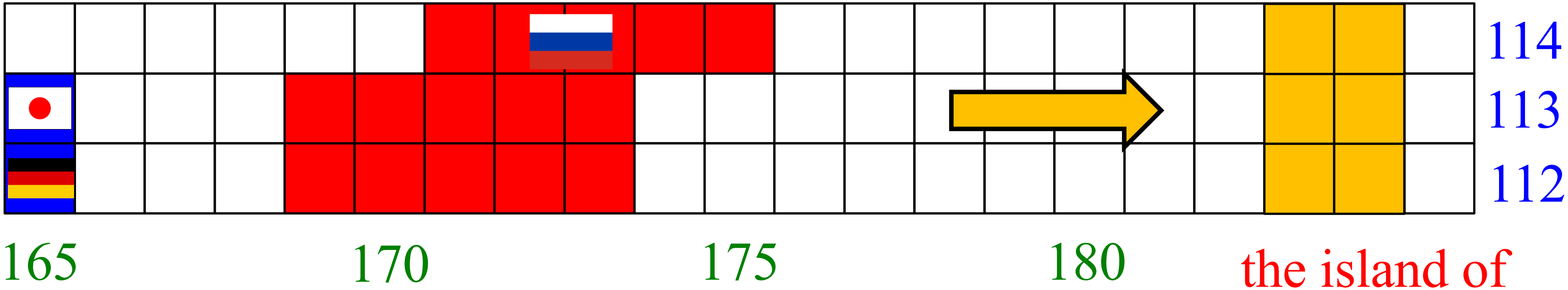
K.-S. Choi, K. Hagino et al.,
Phys. Lett. B780 ('18) 455





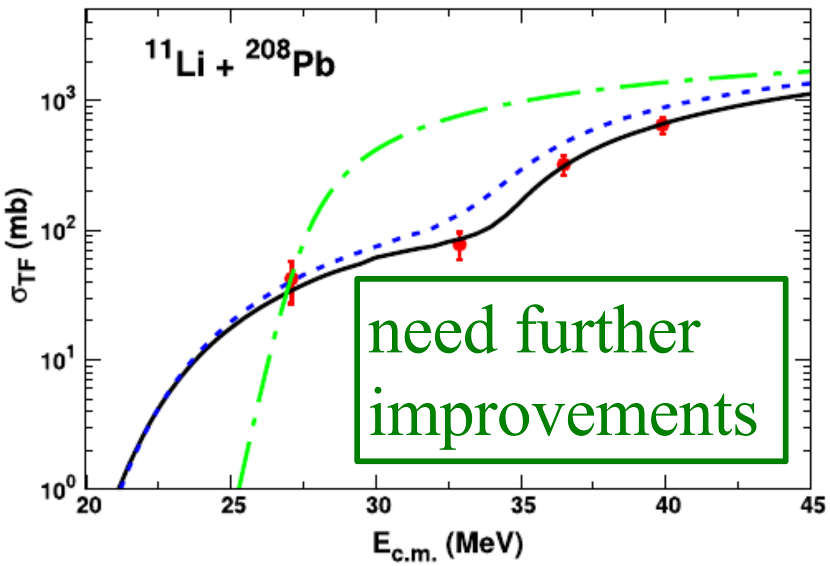
simultaneous explanation for ^{9}Li+^{208}Pb and ^{11}Li+^{208}Pb with:
^{11}Li+^{208}Pb ⟵⟶ ^{9}Li+^{210}Pb ⟵⟶ ^{7}Li+^{212}Pb transfer couplings

Fusion of unstable nuclei

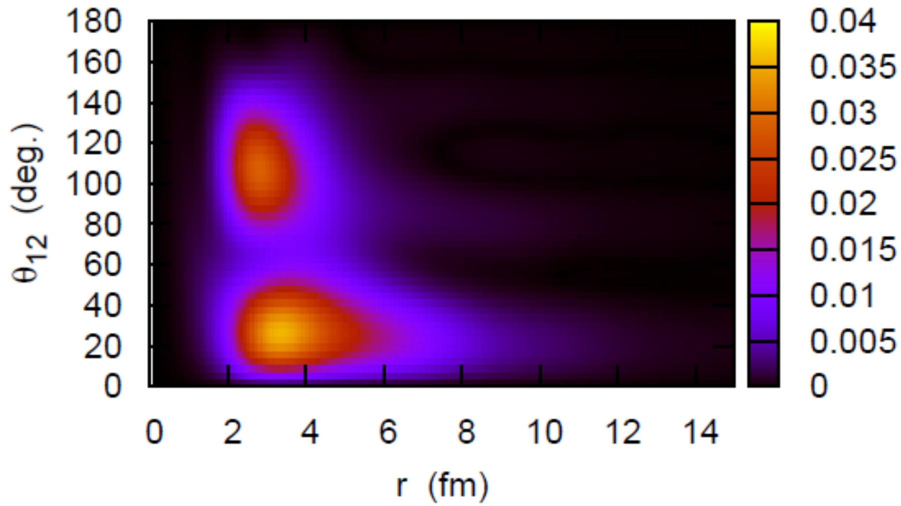


the island of stability

neutron-rich beams: indispensable→reaction dynamics?



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

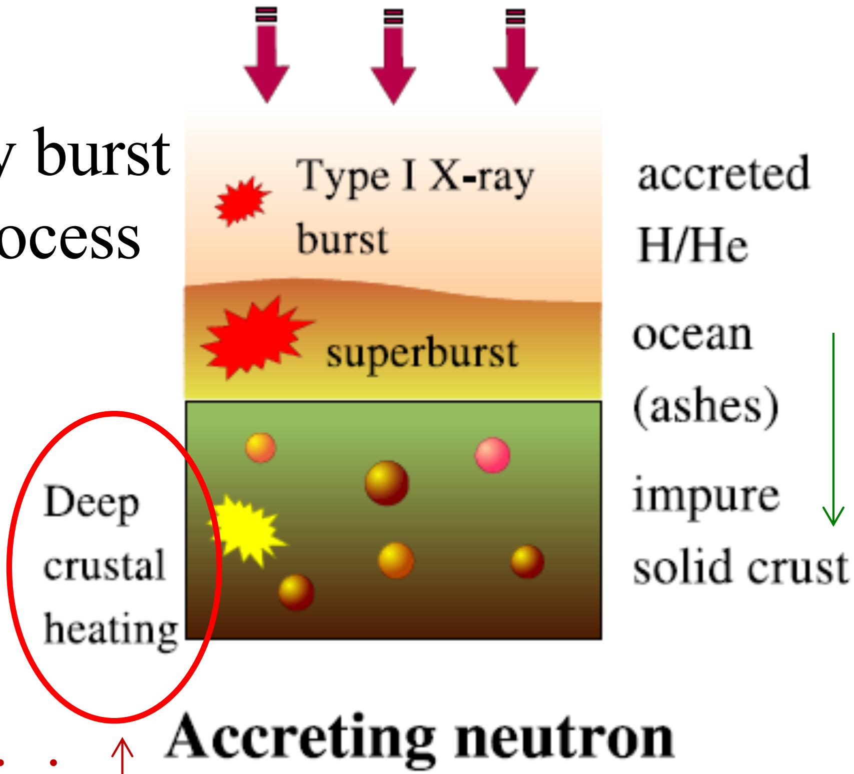


K.H. and H. Sagawa, PRC72('05)044321

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

fusion of neutron-rich nuclei
in accreting（質量降着）neutron stars

X-ray burst
rp-process



origin ↑

fusion of neutron-rich nuclei
when Z becomes small enough

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

electron capture

$(A,Z) + e^- \rightarrow (A,Z-1) + \nu_e$

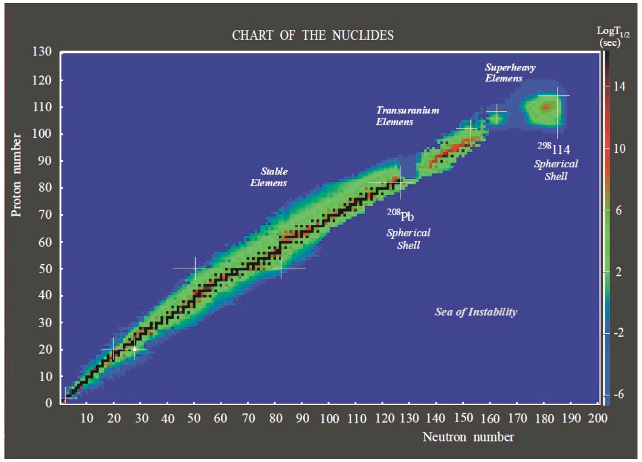
towards neutron-rich nuclei

N. Chamel and P. Haensel,
Living Rev. Relativity, 11 (‘08) 10.

Summary

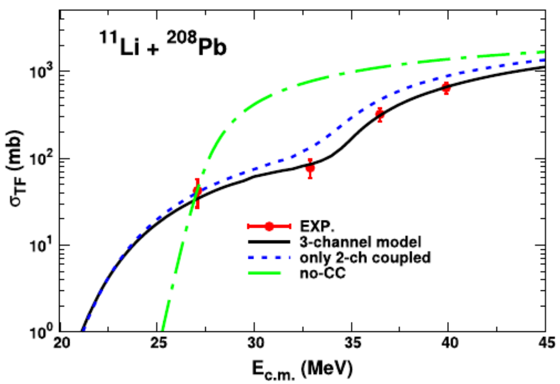
Physics of SHE

- SHE
- the island of stability

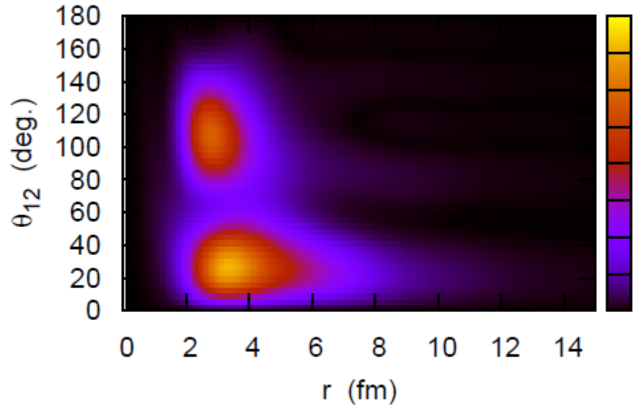


open quantum systems (OQS)

Reactions of n-rich nucl.



Structure of n-rich nucl.



SHE + neutron-rich nuclei + OQS → new direction