Towards a microscopic dynamical description of fission process with TDGCM

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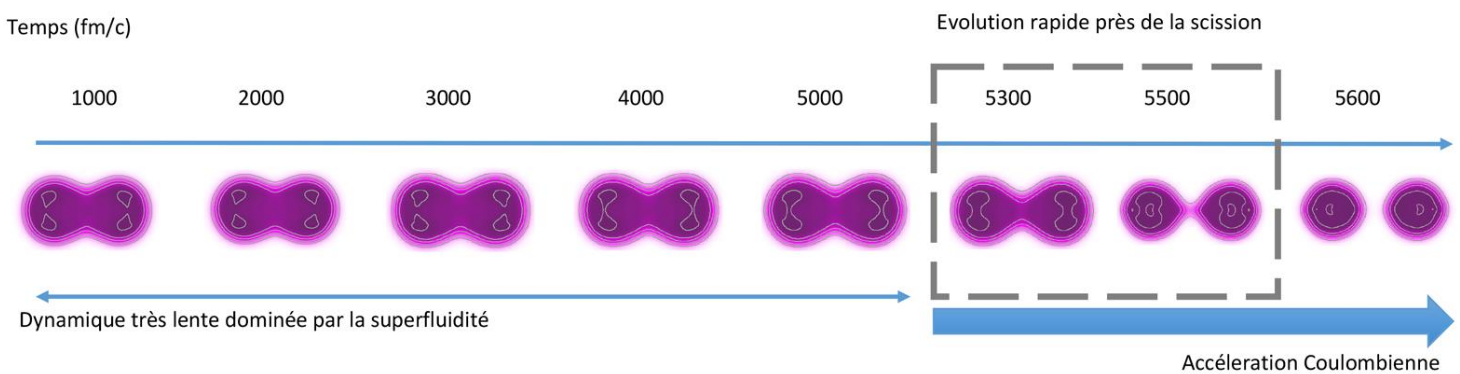
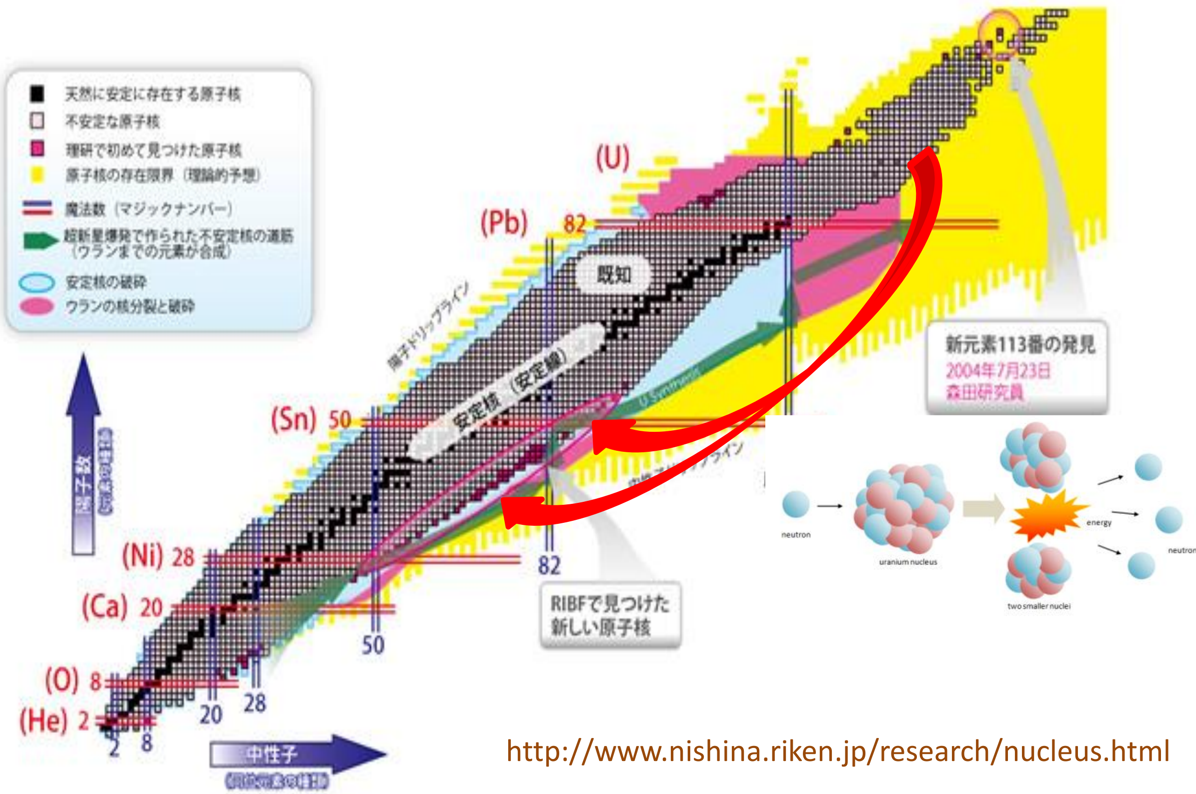


Nuclear Fission Dynamics, YITP, Oct. 28 - Nov. 8, 2019

Nuclear fission

- **Importance**
  - Astrophysical process
  - Stability/instability of super-heavy elements
  - Production of radioactive isotopes
  - Energy production



http://www.nishina.riken.jp/research/nucleus.html

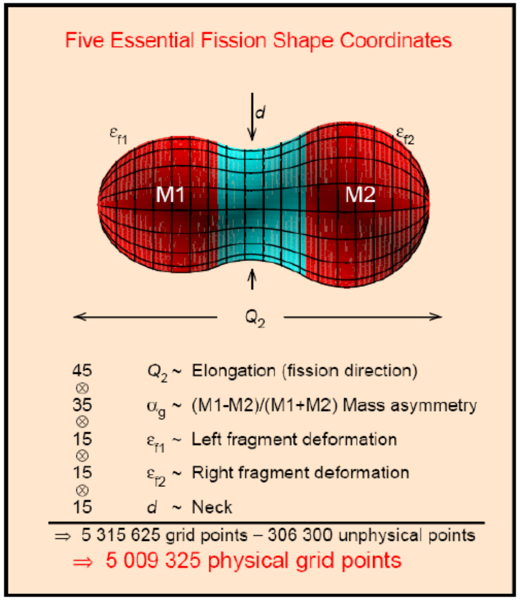
- **Theoretical challenges**
  - Quantum tunneling of many-body system
  - Coupling between collective and internal degrees of freedom

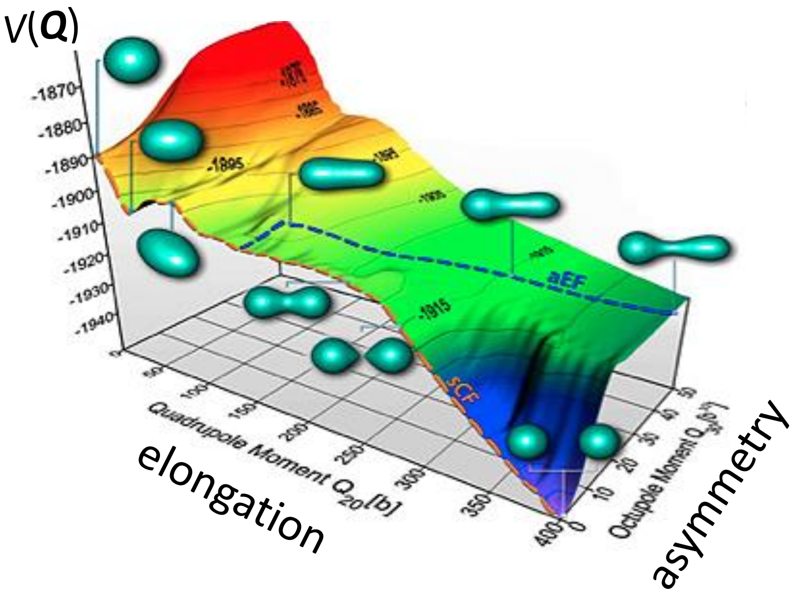
Theories of fission

- **Conventional strategy**

Dynamics of *A* particles → a few effective degrees of freedom

1. Select a set of relevant collective degrees of freedom (DOF) $\boldsymbol{Q}$
   elongation, mass asymmetry, etc.
2. Construct a collective Hamiltonian $H = P^2/2M(Q) + V_{coll}(\boldsymbol{Q}) + \ldots$
3. Solve the equations of motion of $\boldsymbol{Q}$ to get fission observables
   lifetime, fragment mass/charge distribution, etc.





Microscopic theories

Two categories:

1. **Collective model** based on microscopic methods
2. **Time-dependent mean field**

Microscopic theories

1. **Collective model** based on microscopic methods

Collective Hamiltonian constructed with constrained HF(B) calculation

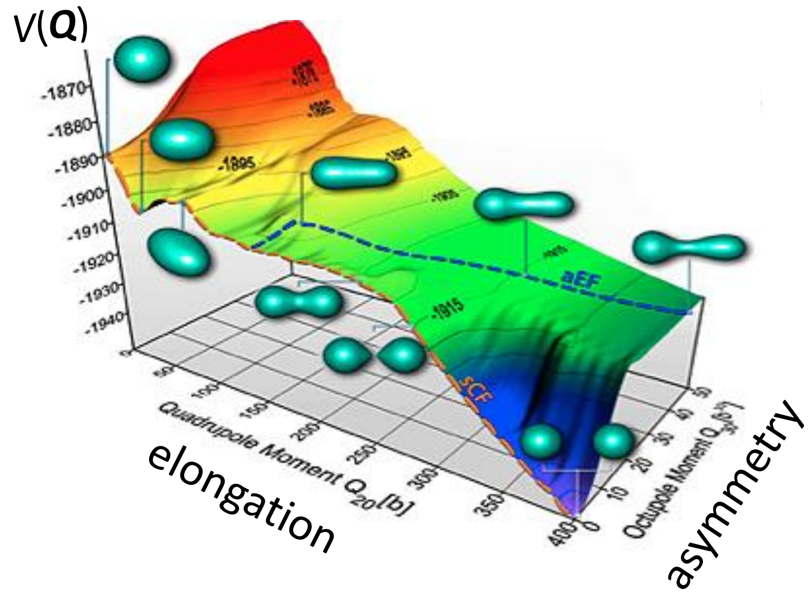
$$|\Psi(t)\rangle = \int d\boldsymbol{Q}\; f(\boldsymbol{Q},t)|\Phi(\boldsymbol{Q})\rangle$$

– **Schrödinger (Hill-Wheeler-Griffin) eq.**

H. Goutte *et al.*, PRC**71**, 024316 ('05); D. Regnier *et al.*, PRC**93**, 054611 ('16); Tao *et al.*, PRC**96**, 024319 ('17)

– **Langevin eq.** for dynamic with dissipation/fluctuation

Sadhukhan *et al.*, PRC**93**, 011304(R) ('16)



Microscopic theories

2. Time-dependent mean-field

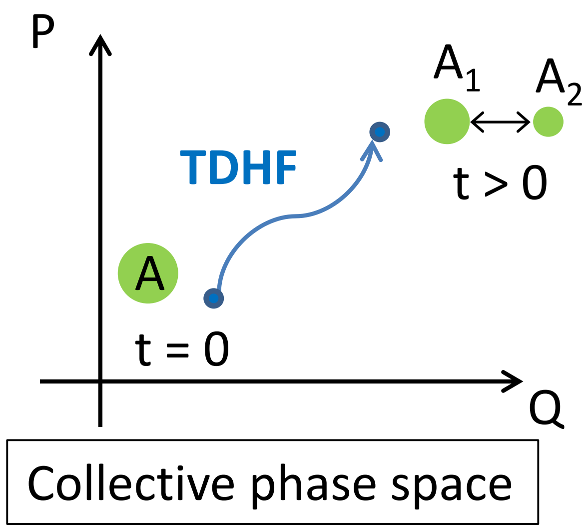
– **Time-dependent Hartree-Fock(-Bogoliubov)** (TDHF(B))

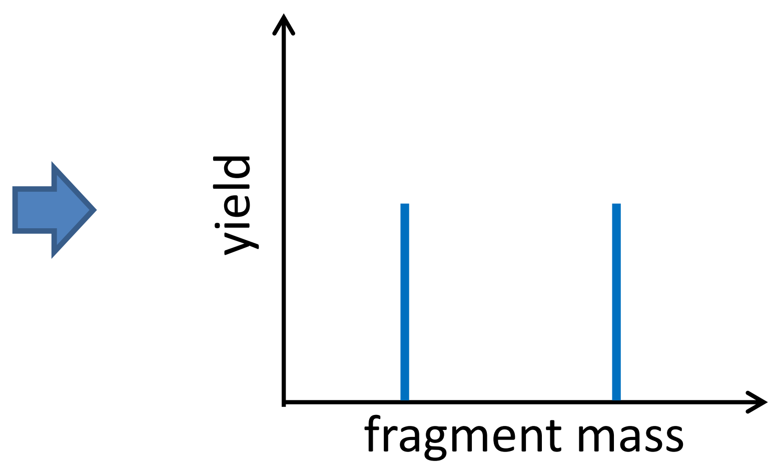
C. Simenel and S. Umar, PRC**89**, 031601(R) ('14); G. Scamps, C. Simenel, and D. Lacroix, PRC**92**, 011602 ('15); YT, D. Lacroix, and G. Scamps, PRC**92**, 034601 ('15); A. Bulgac et al, PRL**116**, 122504 ('16)

✓ no need to select collective DOFs *a priori*

✓ coupling between collective and internal DOFs

✓ collective motion is classical (**deterministic, no tunneling**)





Microscopic theories

2. Time-dependent mean-field

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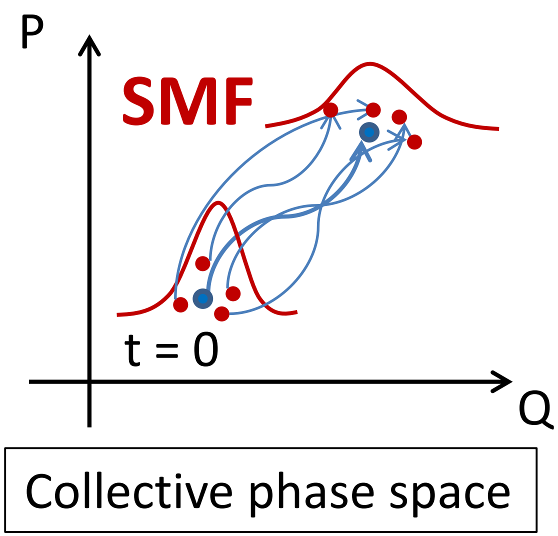
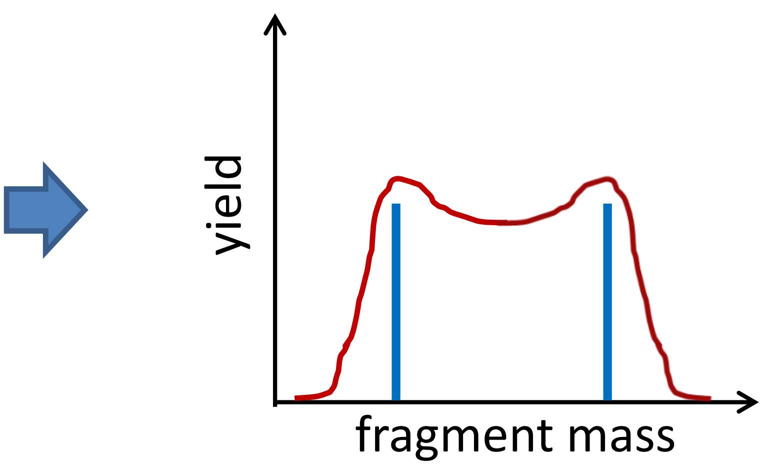
- **Stochastic mean field** (SMF)
  YT, D. Lacroix, and S. Ayik, PRL**118**, 152501 (2017).

  ✓ fluctuation by initial-state sampling

  ✓ **no tunneling**





Microscopic theories

Two categories:

1. **Collective model** based on microscopic methods
   - ✓ Selection of relevant DOFs
   - ✓ Construction of H_{coll} (potential, inertia, friction,…)
2. **TDHF(B), SMF**
   - ✓ No need to select collective DOFs *a priori*
   - ✓ coupling between collective and internal DOFs
   - ✓ **No quantum tunneling**

Microscopic theories

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1. **Collective model** based on microscopic methods
   - ✓ Selection of relevant DOF's
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A new challenge:

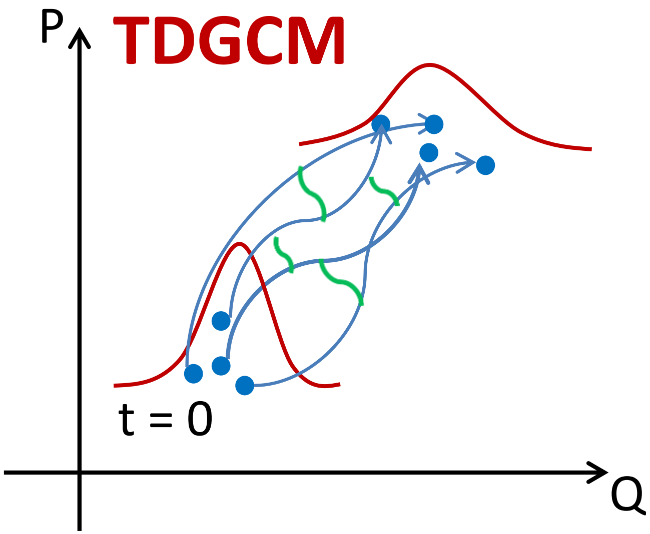
- ☐ **Time-dependent generator coordinate method (TDGCM)**

Microscopic theories

☐ Time-dependent generator coordinate method (TDGCM)

Ansatz:

$$|\Psi(t)\rangle = \int d\boldsymbol{Q}\ f(\boldsymbol{Q},t)|\Phi(\boldsymbol{Q},t)\rangle$$



✓ Unified dynamical description **from tunneling to scission**

✓ Collective space is not restricted

TDGCM with AMD basis (3D)

Trial state: superposition of AMD states

$$|\Psi(t)\rangle = \sum_a |\Phi_a(t)\rangle$$

AMD (FMD) parametrization of Slater determinant

$$\langle x_1, x_2, \ldots, x_A|\Phi\rangle = \frac{1}{\sqrt{A!}} \sum_\sigma \mathrm{sgn}(\sigma) \prod_{i=1}^{A} \langle x_{\sigma(i)}|\phi_i\rangle$$

-- Single-particle wave function

$$|\phi_i\rangle = |b_i, \boldsymbol{Z}_i\rangle \otimes |\chi_i^\uparrow, \chi_i^\downarrow\rangle \otimes |\tau_i\rangle$$

$$\langle \boldsymbol{r}|b_i, \boldsymbol{Z}_i\rangle = e^{-\frac{1}{2b_i}(\boldsymbol{r}-\boldsymbol{Z}_i)^2}$$

$$|\chi_i^\uparrow, \chi_i^\downarrow\rangle = \chi_i^\uparrow|\uparrow\rangle + \chi_i^\downarrow|\downarrow\rangle$$

$$|\tau\rangle = |n\rangle \text{ or } |p\rangle$$

$\{X\} \equiv \{\boldsymbol{Z}, b, \chi^\uparrow, \chi^\downarrow\}$ are complex variational parameters

TDGCM with AMD basis

Time-dependent variational principle
→ Equations of motion

P. Kramer and M. Saraceno, Lecture Notes in Physics 140 (Springer, 1981)

$$i\hbar \sum_{\beta} \frac{\partial^2 (\log\langle\Psi|\Psi\rangle)}{\partial X_\alpha^* \partial X_\beta} \dot{X}_\beta = \frac{\partial}{\partial X_\alpha^*} \frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle}$$

α = {a,i,p} (Slater determinant, nucleon, and Gaussian variable)

plan

- ^{8}Be → α + α
  - relative motion restricted in 1D
  - (angular momentum projection for rotation?)
- Heavier (not too much) systems
  - fictitious system with e^2 increased
  - analysis of collective paths, neck dynamics and excitation of fragments, nucleon emissions, …
- … Heavy systems including SHEs