Calculations in Cluster Physics

1. Introduction: recent cluster physics
2. Formulation of AMD
3. Present status of structure studies with AMD
4. Future strategy

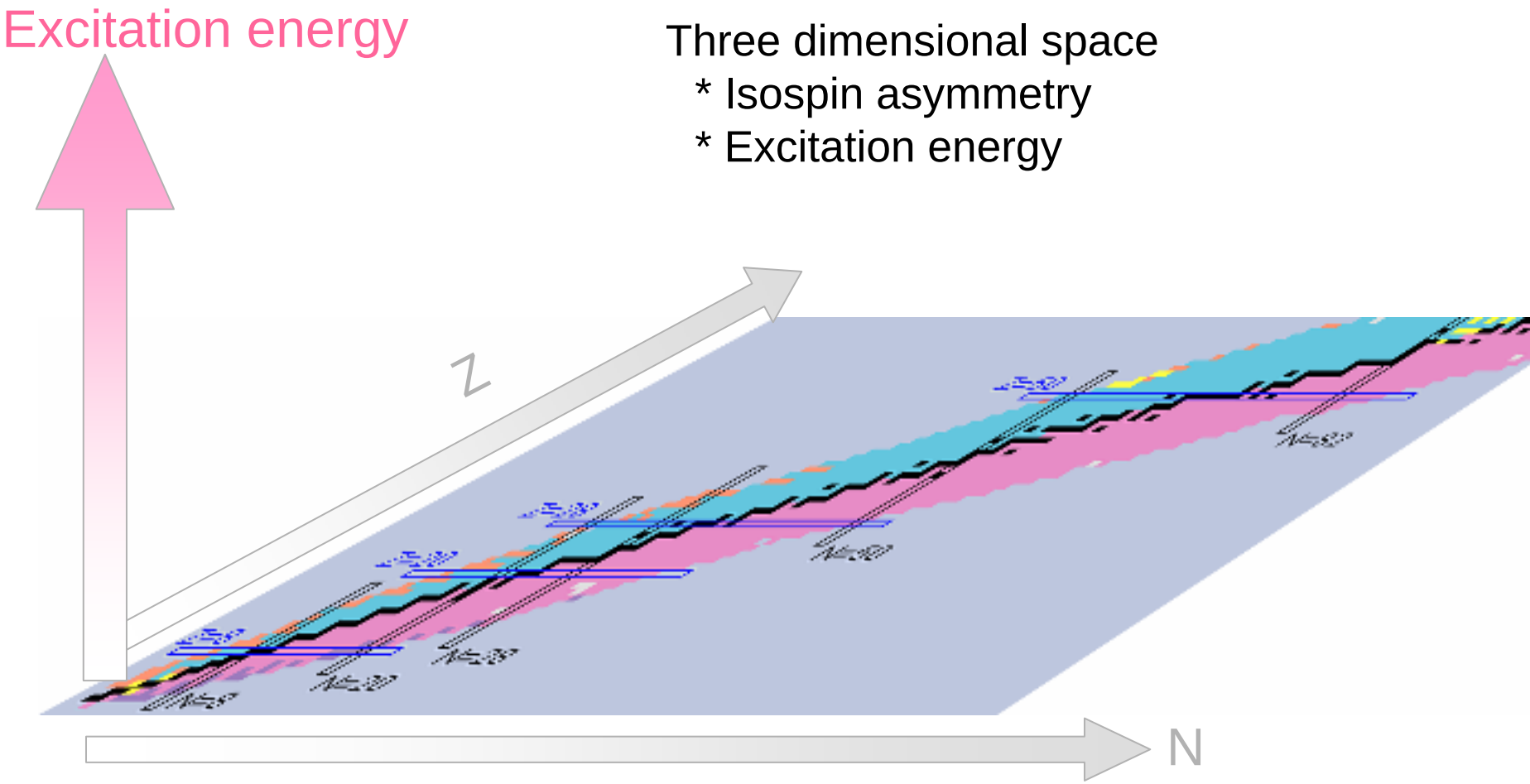
Y. Kanada-En'yo (YITP, Kyoto Univ.)

1.Introduction

Target

In nuclear structure studies, research target is rapidly expanding on the nuclear chart. We should also stress an axis “excitation energy” on the nuclear chart, because variety of phenomena appears in ground and excited states in each of nucleus, as functions of isospin asymmetry and excitation energy.

Three dimensional space
* Isospin asymmetry
* Excitation energy



Our focus: spatial correlation of multi nucleons

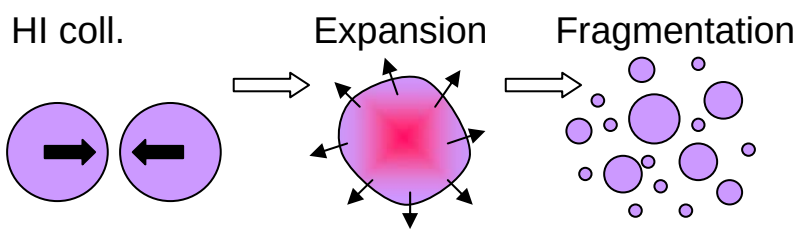
Dynamics of nuclear many-body system

In nuclear many-body system,

spatial correlation is one of essential features

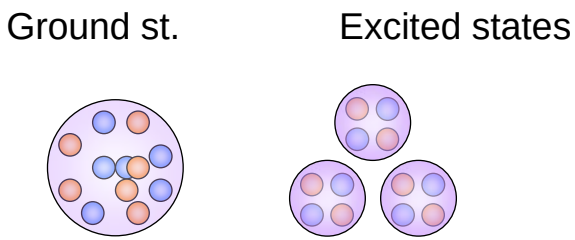
because of the saturation properties of energy and density

Multi fragmentation in HI coll.



Talk given by Ono

Cluster structure in excited states

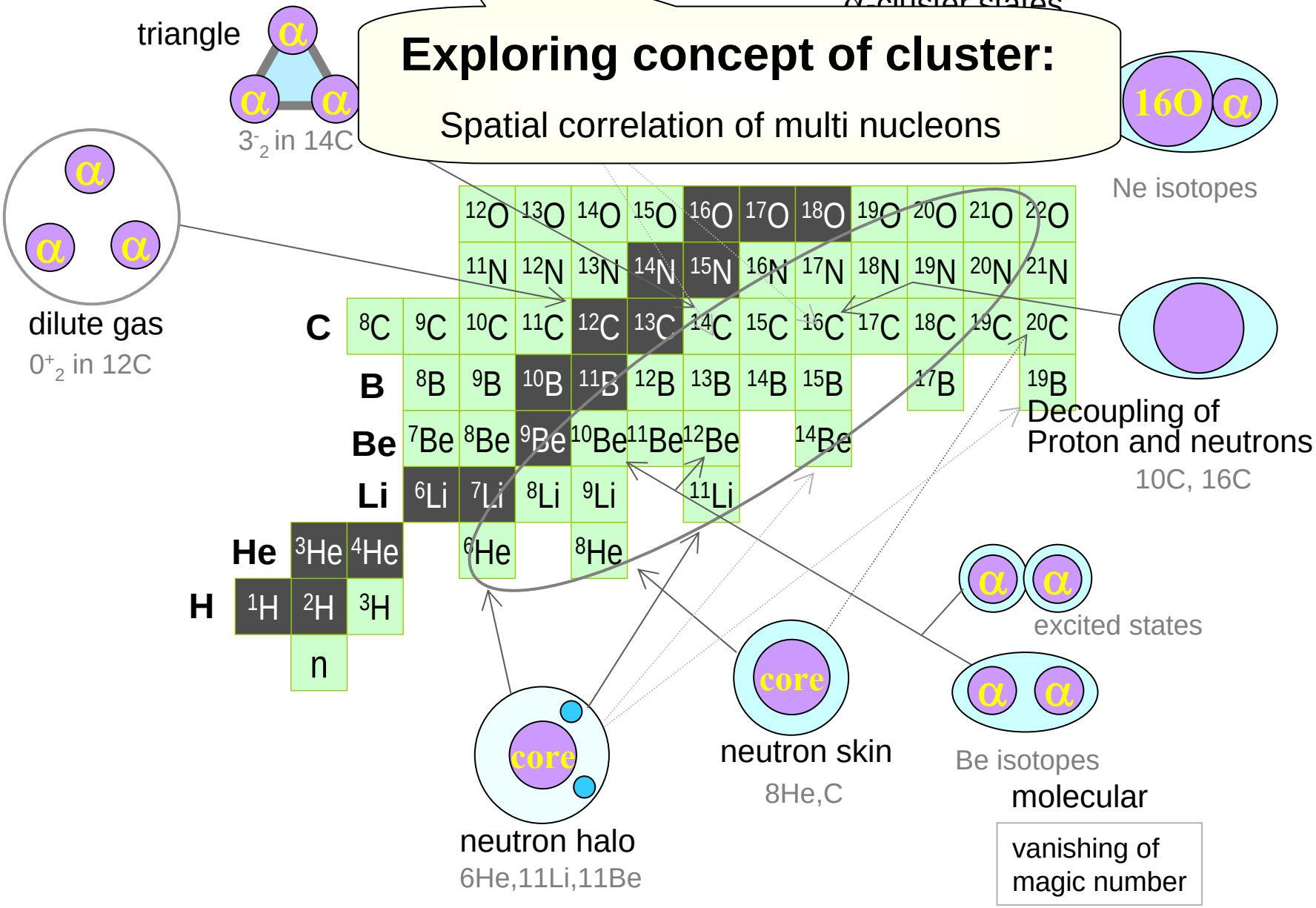


remarkable progress in development of physics unstable nuclei

Exotic structure in light nuclei

Exploring concept of cluster:

Spatial correlation of multi nucleons

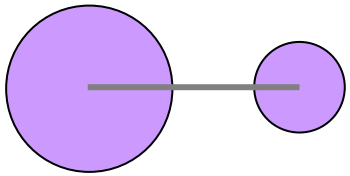


Conventional cluster structure

Weak coupling picture:

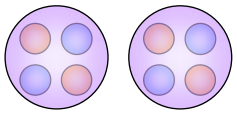
Clusters are formed by tightly bound nucleons.

Weakly coupled inter-cluster motion is considered.



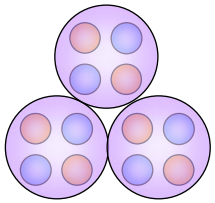
Typical clustering in stable nuclei

^{8}Be



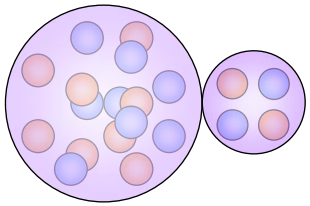
$\alpha + \alpha$

^{12}C



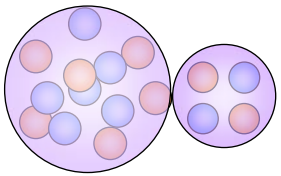
$3\ \alpha$

^{20}Ne



$^{16}O + \alpha$

^{16}O*



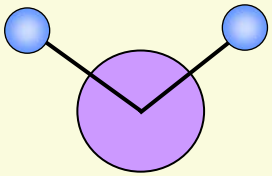
$^{12}C + \alpha$

Exploring concept of clustering (1)

halo nuclei: ^{6}He, ^{11}Li

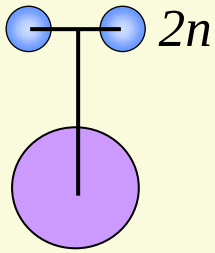
Esbensen et al.,
Zhukov et al.
Descouvemont et al.
A.Tosaka et al.,
S. Aoyama et al.
K.Varga et al.,

V-type



core-n

T-type

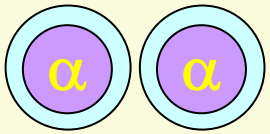


di-neutron
correlation

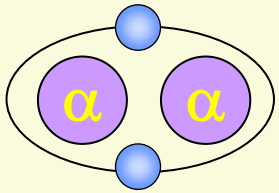
A variety of structure appears due to valence neutron degree of freedom
For example, halo nuclei & MO in Be and Ne isotopes.

Molecular structures

neutron-rich Be isotopes



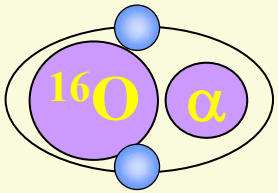
^{6}He+^{6}He
in ^{12}Be



2α-core
neutron orbit

Seya, Von Oerzten,
Descouvemont et al.,
Itagaki et al.,
K-E et al.
M. Ito et al.

Ne, O isotopes



Kimura et al.,
Yoshida et al.,
Furutachi et al.

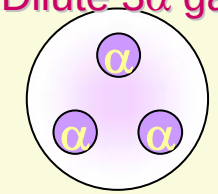
Breaking magic number
N=8, 20 with clustering

Exploring concept of clustering (2)

α-cluster gas

Dilute 3α gas

$^{12}C(0_2^+)$

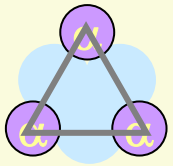


$^{16}O^*$

Tohsaki et al., Yamada et al.,
Funaki et al. Wakasa et al.,

cluster crystalization

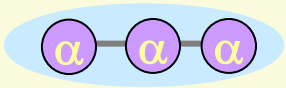
$^{14}C^*(3^-_2)$



triangle

Itagaki et al.,
Von Oertzen et al.

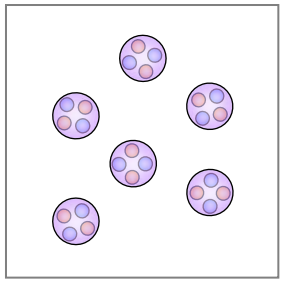
Price et al.



$^{12,14,15,16}C^*$ linear chain

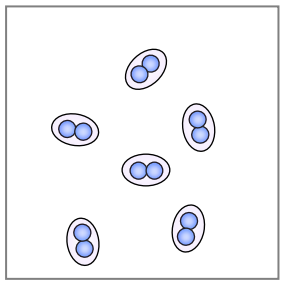
Nuclear matter

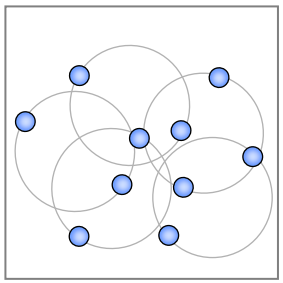
α-condensation



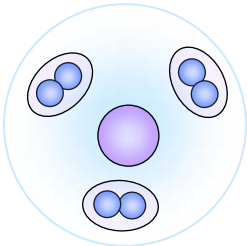
Roepche et al.

dineutron-cond.





BEC-BCS matsuo et al.



Exploring concept of clustering (3)

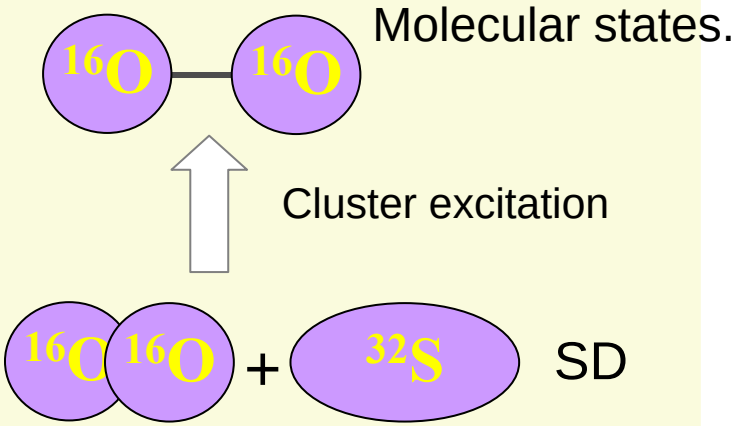
Cluster phenomena are found also in heavier mass region like sd shell region.

For example, largely deformed states like superdeformations in 32S and 40Ca have significant cluster component, and molecular resonances are built on the superdeformed bands..

Coexistence of cluster & mean-field

- Low-lying states
- Heavier nuclear region

Superdeformation & cluster

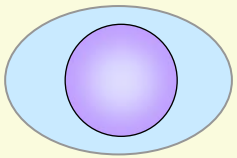


Z=N nuclei: ^{32}S, ^{40}Ca

Kimura et al., Y. K-E. et al.,Taniguchi et al.

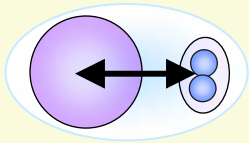
Decoupling of protons and neutrons

^{16}C, ^{10}Be



Elekes et al.,
Y. K-E,
Takashina et al.

^{16}C, ^{11}Li



Core+2n

Soft dipole mode

cluster aspects

"Cluster" is one of the essential features in nuclear many-body system:
Surprisingly, cluster aspects appear in wide region of nuclei.

- in unstable nuclei as well as stable nuclei.
- in low-lying states as well as highly excited states.
- heavier mass nuclei as well as light nuclei.

Systematic study focusing on cluster phenomena

Today's talk

Developments of theoretical Methods:

◆ less assumption,	**MO, GCM, COSM, AMD,SVM,FMD**
◆ ab-initio type calculation (semi ab-initio)	**FMD+UCOM,AMD+Brueckner**
◆effective nuclear force in structure models	**Effect of tensor force**
◆ resonances & continuum	**CSM, R-matrix, ACCC**

Coexistence of cluster phenomena and mean-field features
in low-lying states and in heavier mass region.

Microscopic models

Cluster phenomena

Multi fragmentation

Molecular Dynamics

Cluster structure
Molecular reso.

Clustesr models

Molecular approach

Mean-field aspect

Mean-field effe

TDHF

Fermionic behavior
in Nuclear reactions

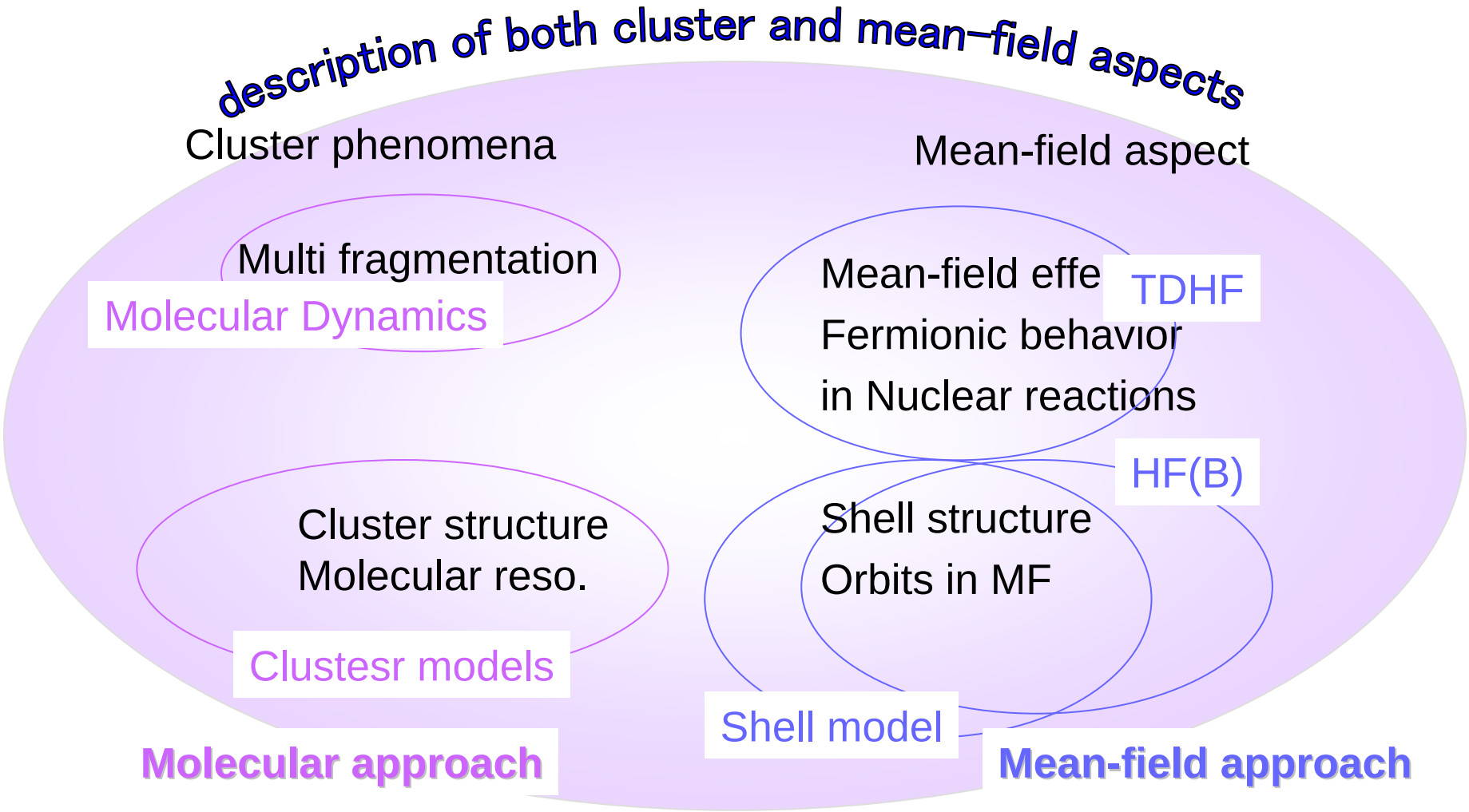
HF(B)

Shell structure
Orbits in MF
pairing

Shell model

Mean-field approach

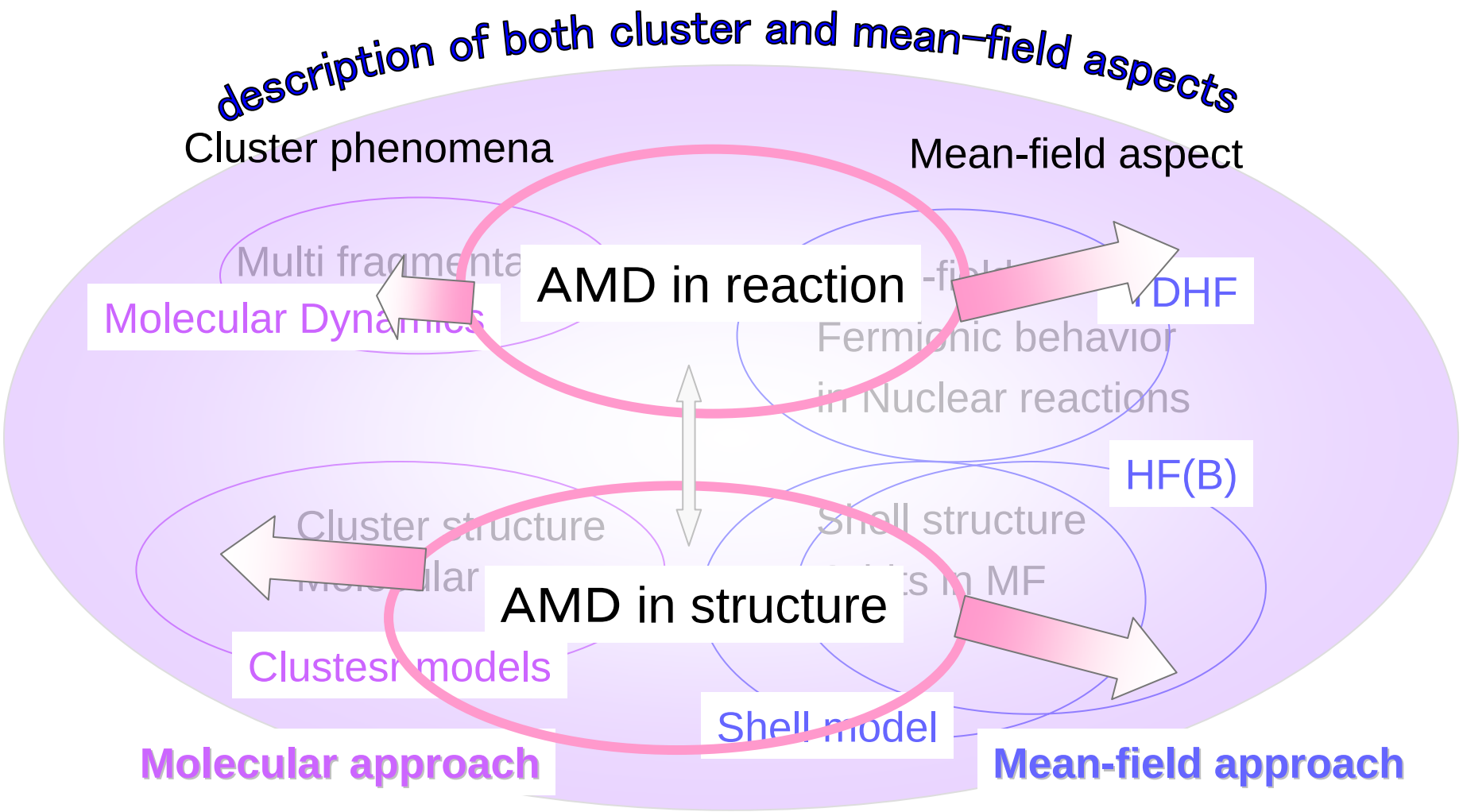
Microscopic models



AMD in 1990's

Antisymmetrized molecular dynamics

Microscopic models



AMD in 1990's

Antisymmetrized molecular dynamics

2. Formulation of AMD

Structure study with AMD

Variational method

$$\delta \frac{\langle \Phi | H | \Phi \rangle}{\langle \Phi | \Phi \rangle} = 0$$

Model wave fn.: Φ proper model space and handy wave fn.

Effective force
(phenomenological effective nuclear force)

$$H^{\mathrm{eff}} = \sum_{i=1} t_i + \sum_{i<j} v_{ij}^{\mathrm{eff}} + \sum_{i<j<k} v'^{\mathrm{eff}}_{ijk}$$

AMD wave function

$$\Phi = c\Phi_{\mathrm{AMD}} + c'\Phi'_{\mathrm{AMD}} + c''\Phi''_{\mathrm{AMD}} + \cdots$$

Slater determinant

$$\Phi_{\mathrm{AMD}} = \det\{\varphi_1, \varphi_2, \cdots, \varphi_A\}$$

Gauss packet

spatial

$$\varphi_{\mathbf{i}} = \phi_{\mathbf{Z_i}} \chi_{\mathbf{i}} \begin{cases} \phi_{\mathbf{Z_i}}(\mathbf{r_j}) \propto \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z_i}}{\sqrt{\nu}}\right)^2\right] \\ \chi_{\mathbf{i}} = \begin{pmatrix} \frac{1}{2} + \xi_{\mathbf{i}} \\ \frac{1}{2} - \xi_{\mathbf{i}} \end{pmatrix} \times \quad p \text{ or } n \end{cases}$$

Intrinsic spin

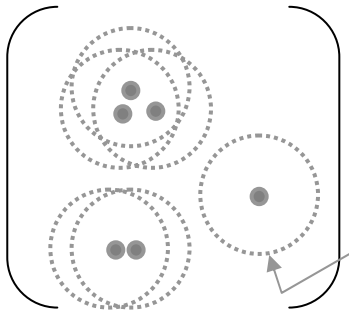
isospin

$$\Phi_{\mathrm{AMD}}(\mathbf{Z})$$

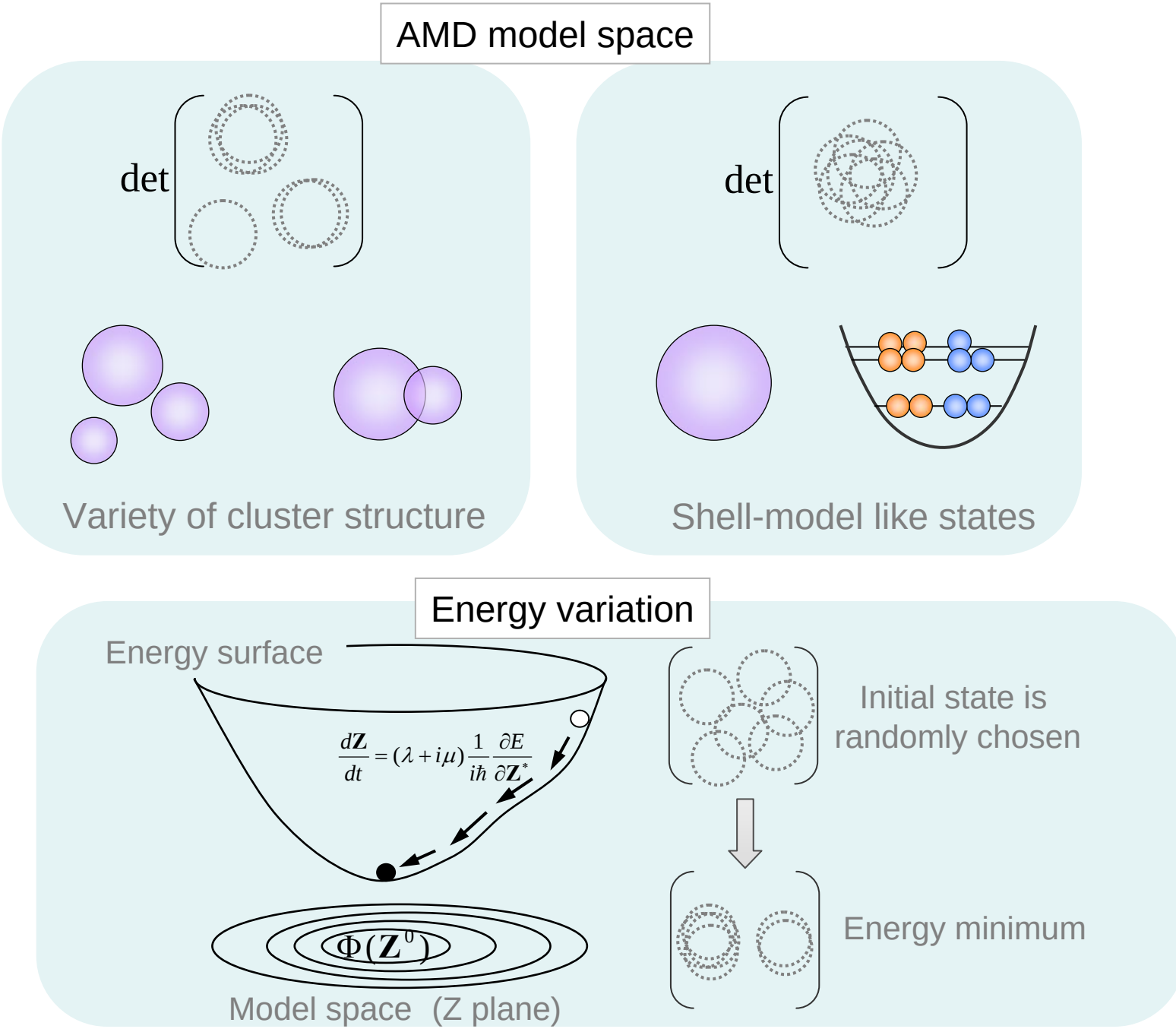
$$\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \cdots, \mathbf{Z}_A, \xi_1, \cdots, \xi_A\}$$

Variational parameter:
position of Gaussians &
spin orientation

det



Gauss packet


AMD model space
det
det
Variety of cluster structure
Shell-model like states
Energy variation
Energy surface
$\frac{d\mathbf{Z}}{dt} = (\lambda + i\mu)\frac{1}{i\hbar}\frac{\partial E}{\partial \mathbf{Z}^*}$
$\Phi(\mathbf{Z}^0)$
Model space (Z plane)
Initial state is randomly chosen
Energy minimum

Versions of AMD and their computational costs

1 T.U.=1Tflops × 1000 hour

$$\Phi = c\Phi_{\mathrm{AMD}} + c'\Phi'_{\mathrm{AMD}} + c''\Phi''_{\mathrm{AMD}} + \cdots$$

Computational cost: Mass number (A)^4～6,
Superposition: base number^2

Simple AMD — Parity projection

$$P^{\pm}\Phi = \Phi(\mathbf{Z}) \pm \Phi(-\mathbf{Z})$$

Excited states beyond mean-field

VAP — Spin-parity projection — ×2000～10000

$$\Phi(\mathbf{Z}) = P^{J}_{MK} P^{\pm} \Phi_{\mathrm{AMD}}(\mathbf{Z})$$

A～20 — K-E. et al.

Superposition of base fn. — Independent AMD wave function

～100-1000 base	× 10^4～10^6	A<10	Itagaki et al.
～50 base	×1000	A～44	Kimura, Taniguchi et al.

Largest computation

Improvement of single-particle wave fn. — A<10

deformed Gauss, superposition of Gaussians

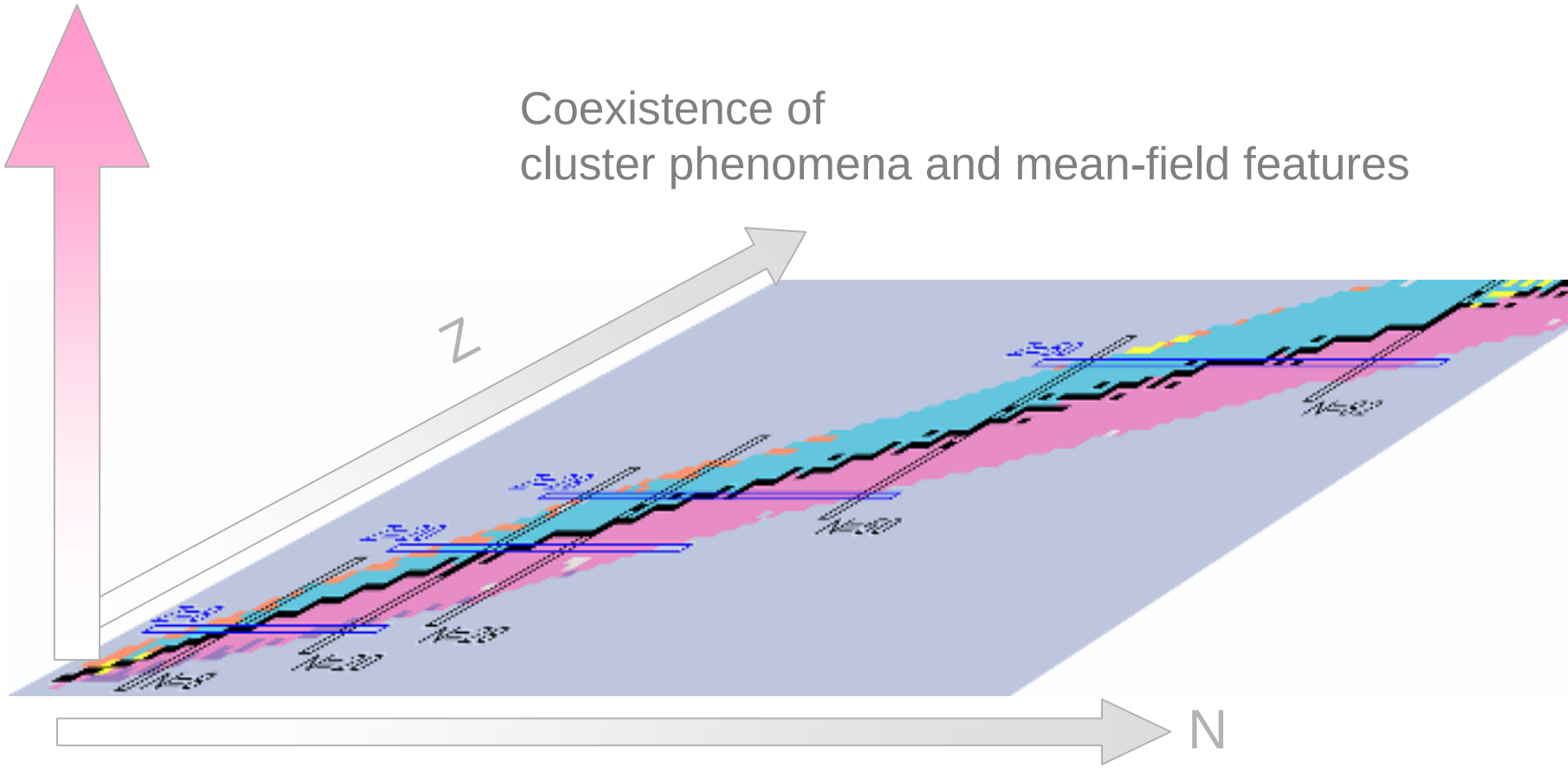
3. Present status of AMD study

Three dimensional space

* Isospin asymmetry
* Excitation energy

Excitation energy

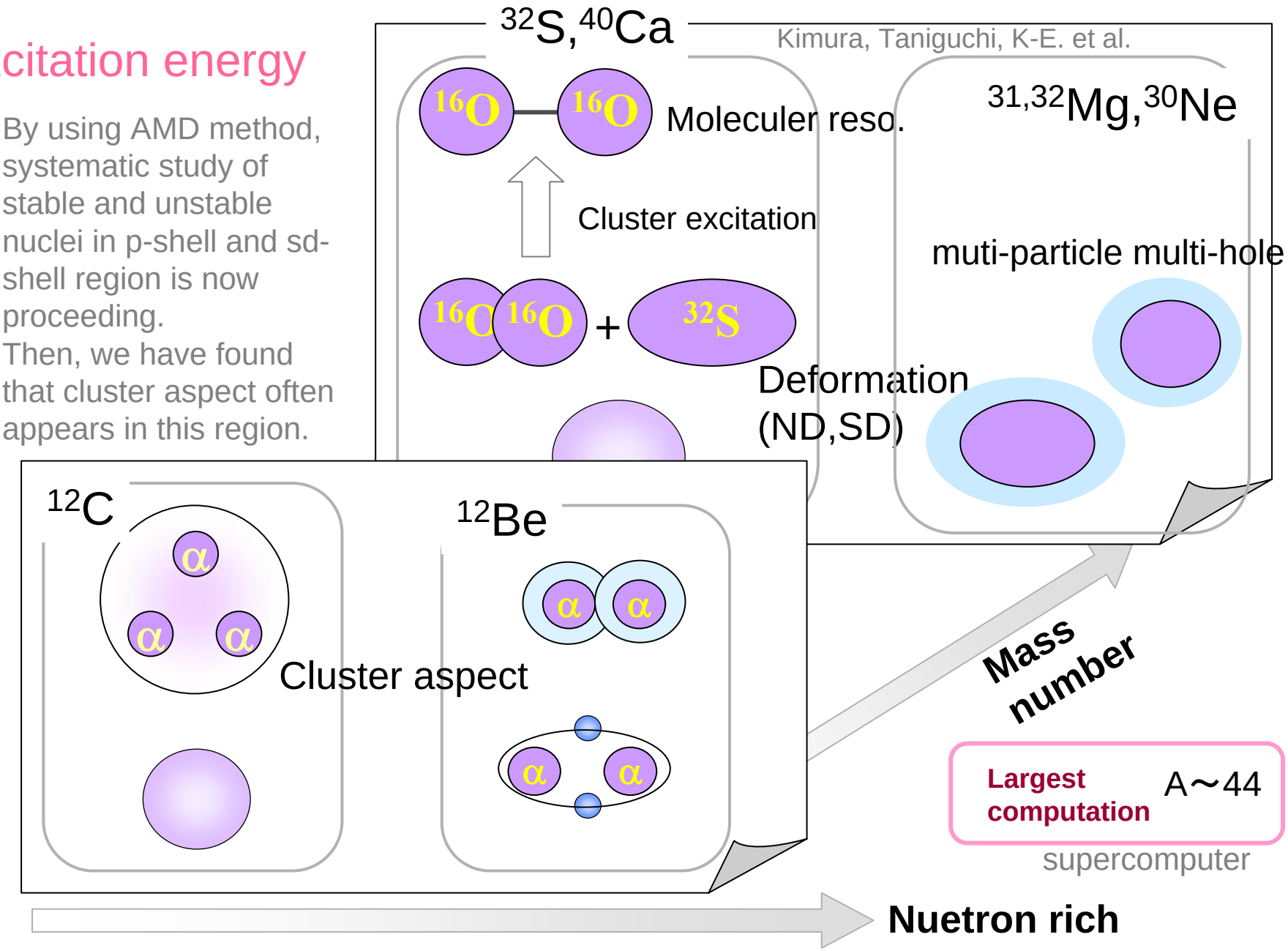
Coexistence of
cluster phenomena and mean-field features



Cluster aspects even in heavier mass and neutron-rich regions

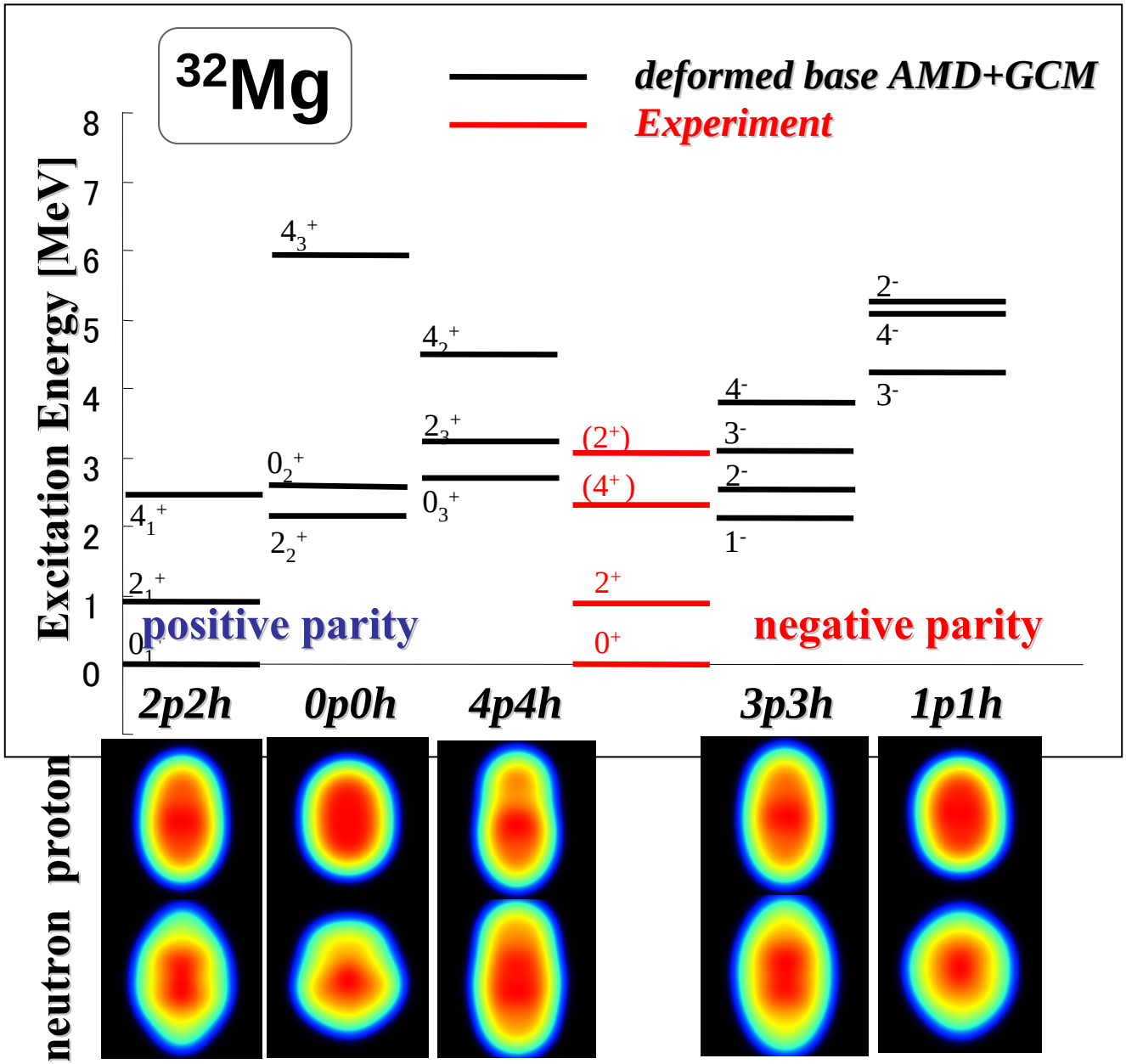
Excitation energy

By using AMD method, systematic study of stable and unstable nuclei in p-shell and sd-shell region is now proceeding.
Then, we have found that cluster aspect often appears in this region.



Many-particle many-hole states in low-energy region

Deformed AMD calc. with Gogny D1S by M. Kimura



In Mg32, the AMD results suggested that Many-particle many – hole states exist in low-energy region.

4. Present status and future strategy

In a point of view of computational research

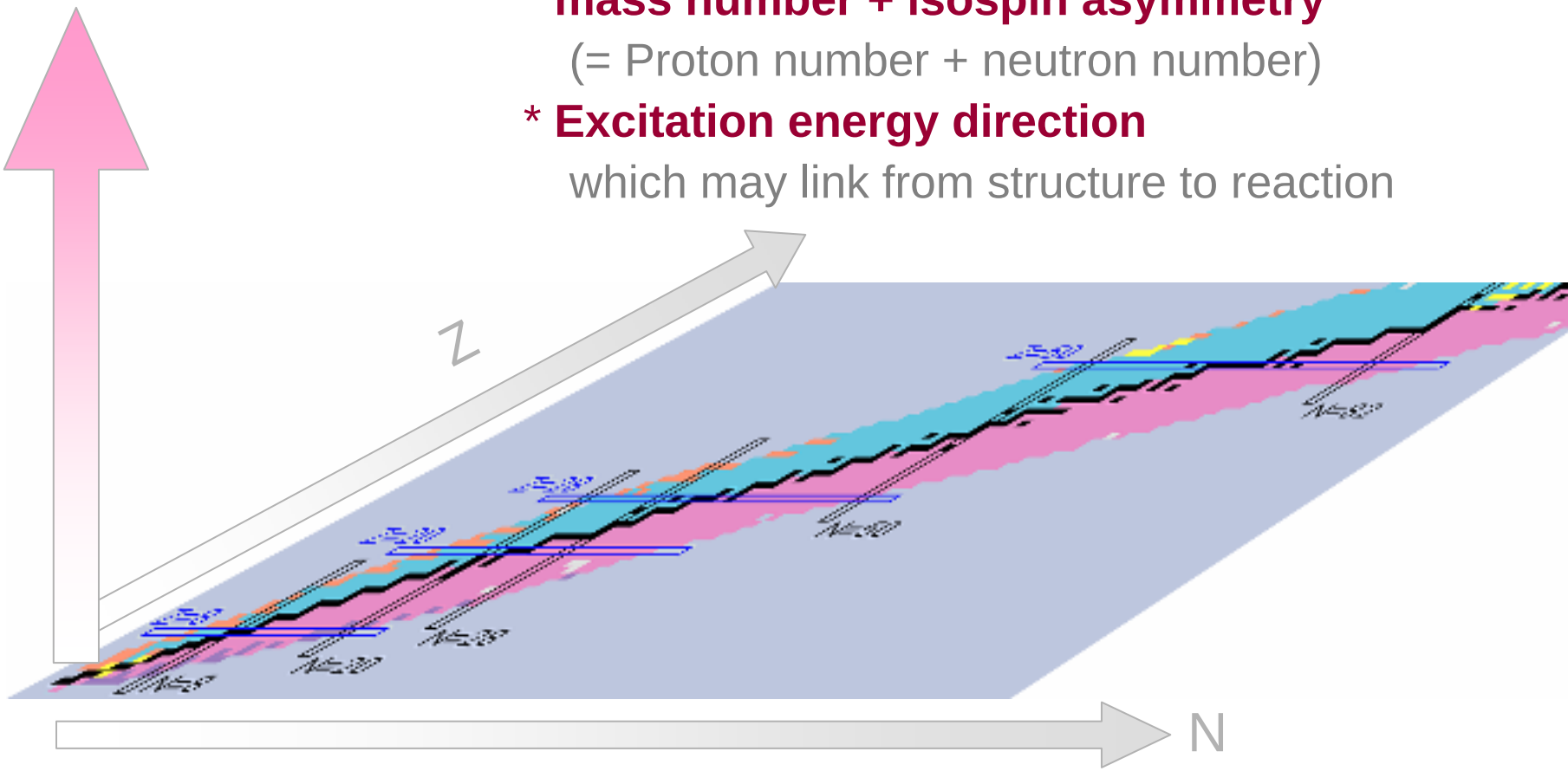
Future direction of nuclear structure study

In general, one of the future directions of nuclear structure study is to extend the three dimensional space. Namely, systematic study of ground and excited states in wide mass number region.

Excitation energy

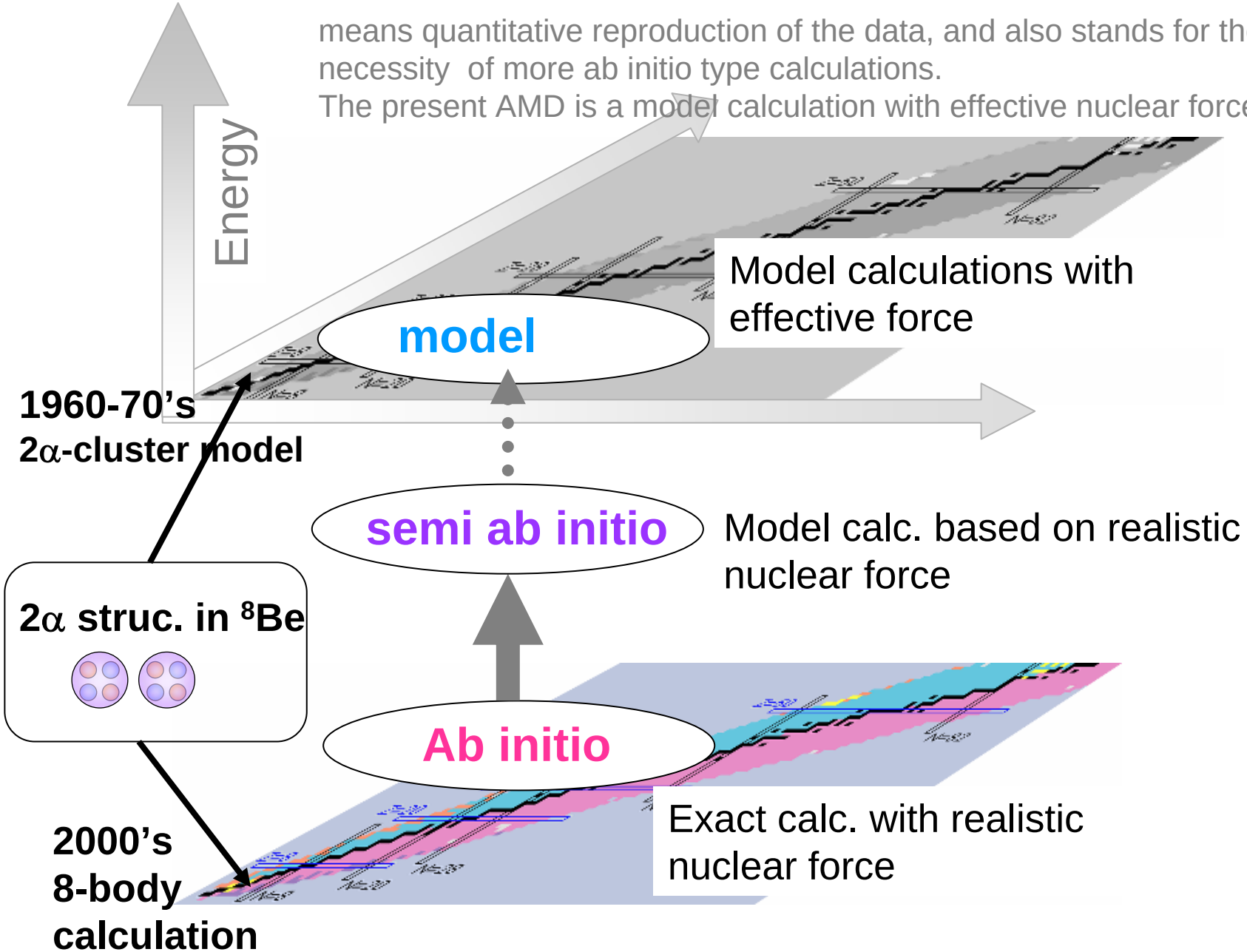
Three dimensional

* **mass number + isospin asymmetry**
  (= Proton number + neutron number)
* **Excitation energy direction**
  which may link from structure to reaction



Another direction “foundamental”, ”precise” or “ab initio”

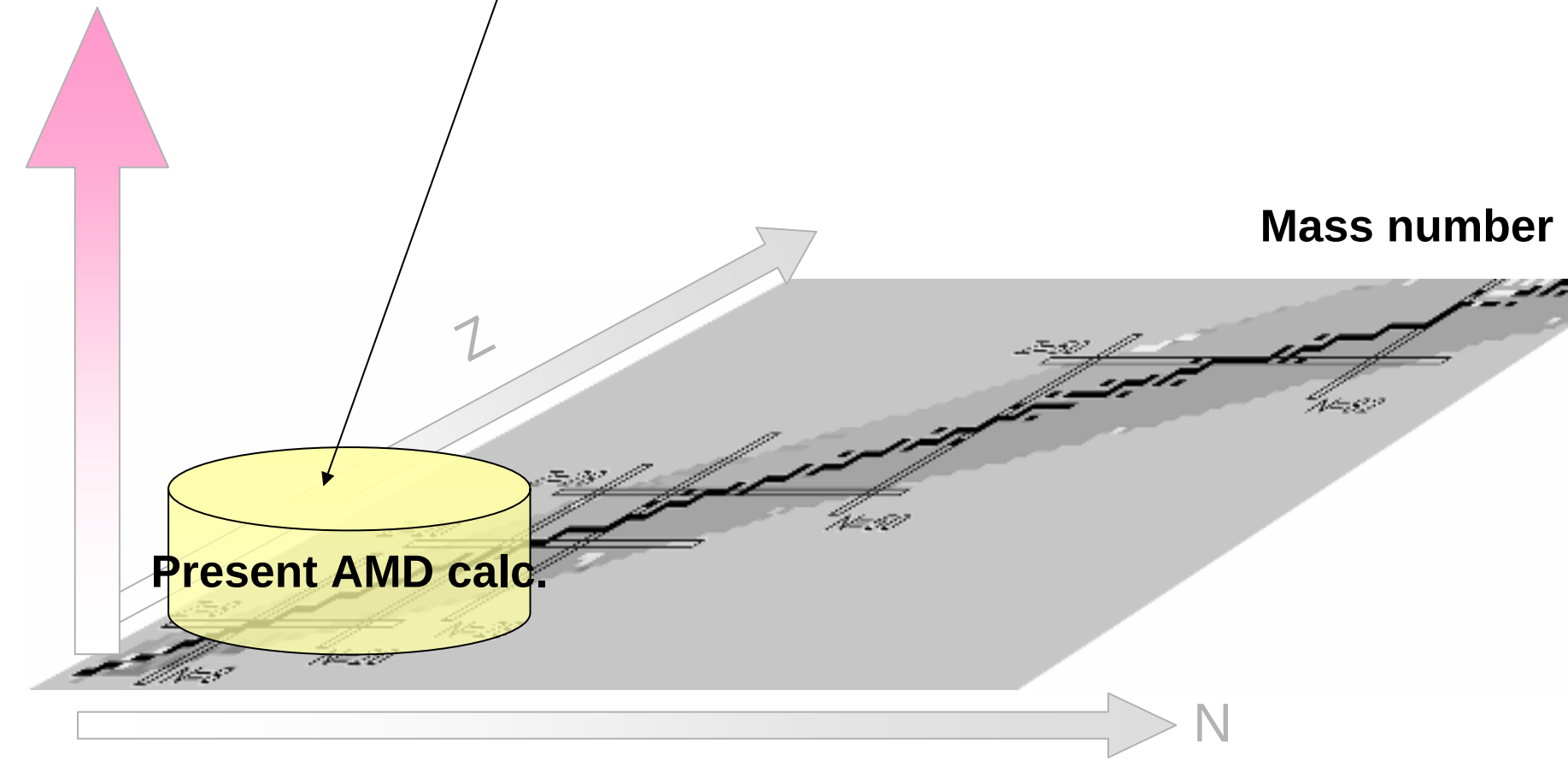
means quantitative reproduction of the data, and also stands for the necessity of more ab initio type calculations.
The present AMD is a model calculation with effective nuclear forces.



Present status of AMD calculation (scale, facility)

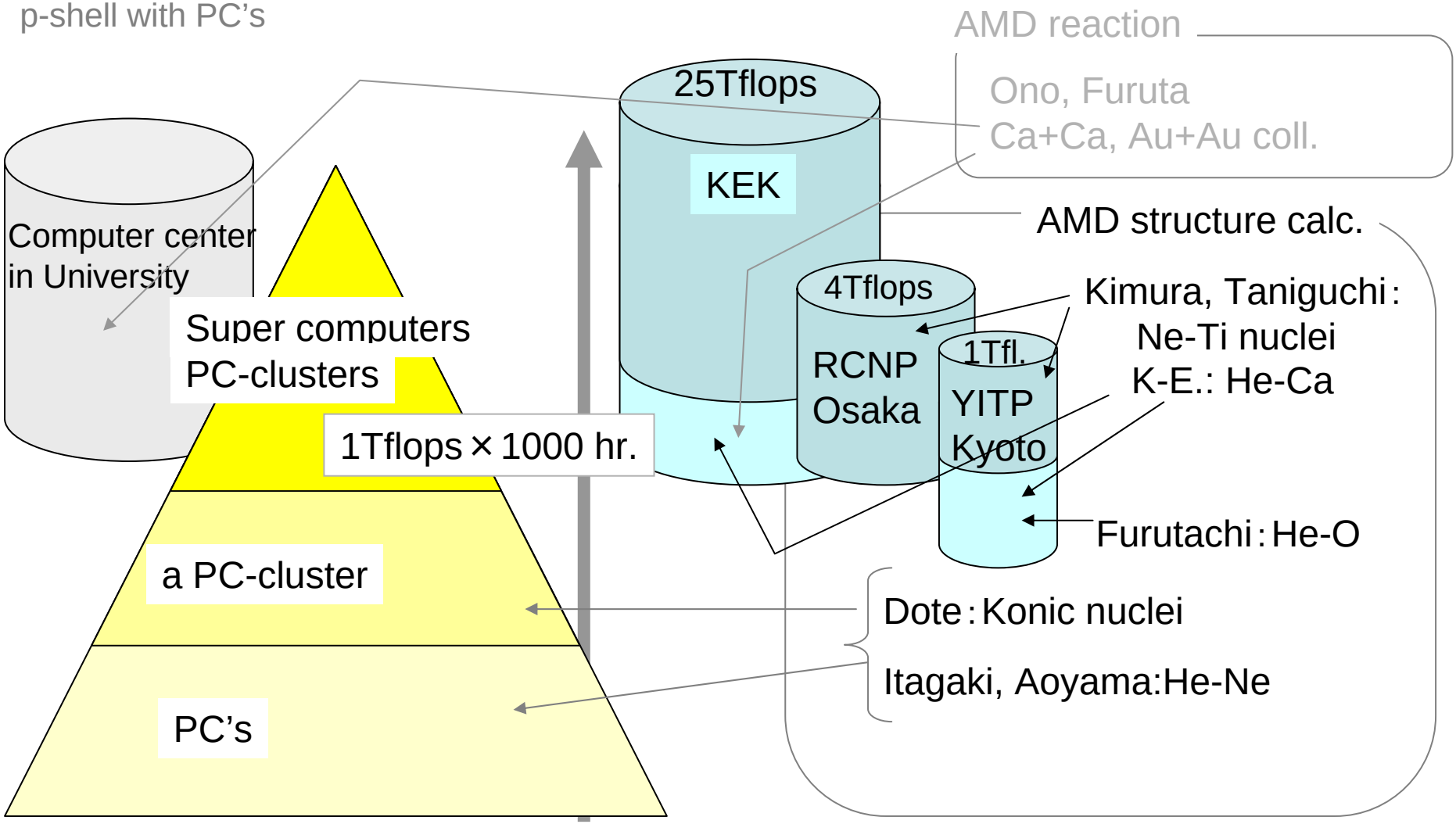
tera flops computers:

Systematic study of ground and excited states in p-shell and sd-shell nuclei is proceeding now.

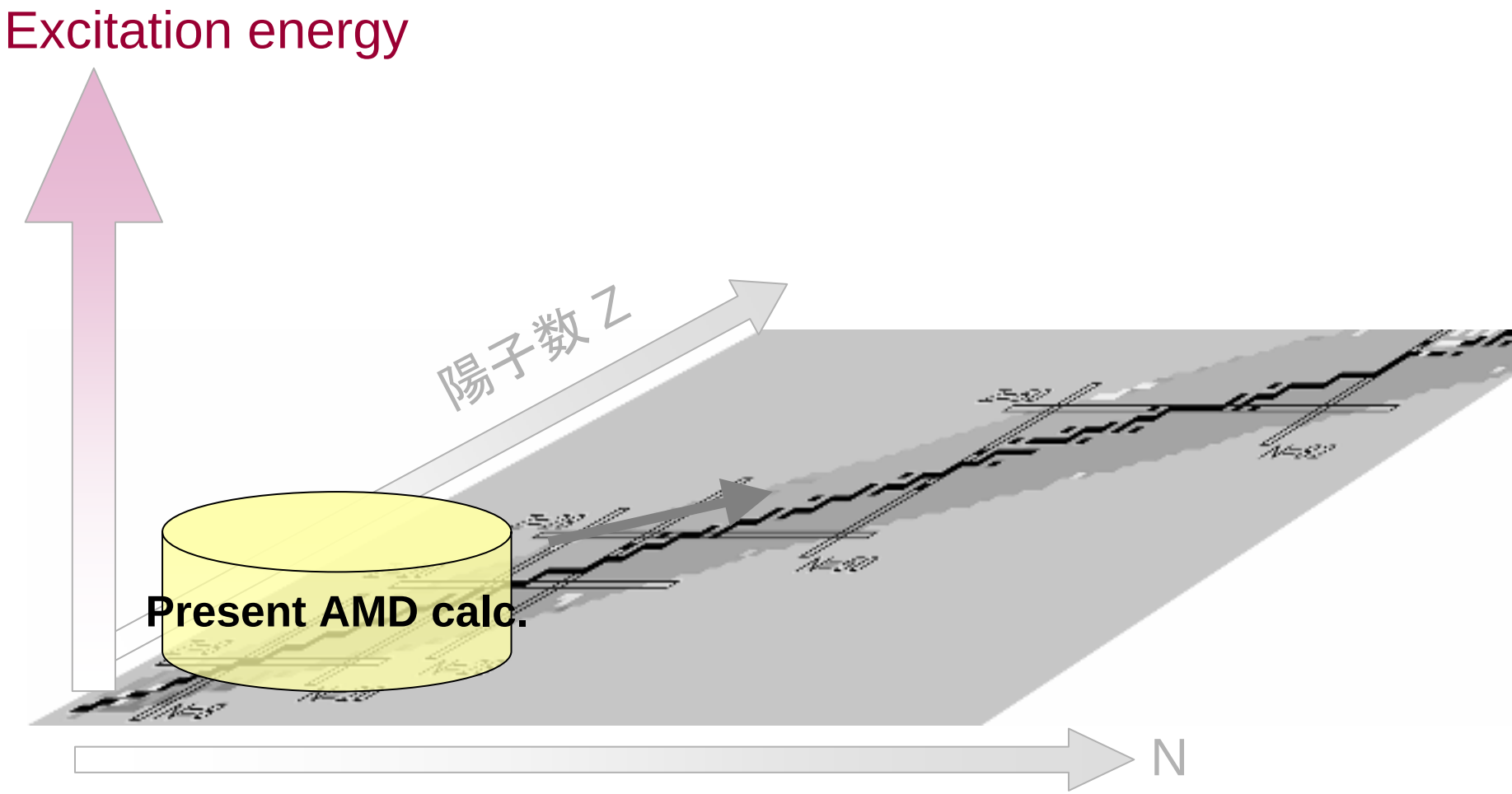


Present status of AMD calculation (scale, facility)

The numerical calculations of AMD are performed by many groups by using computer facilities in Japan. AMD calc. of sd-shell nuclei with super comupters (1Tflops x 500-1000 hr.), p-shell with PC's

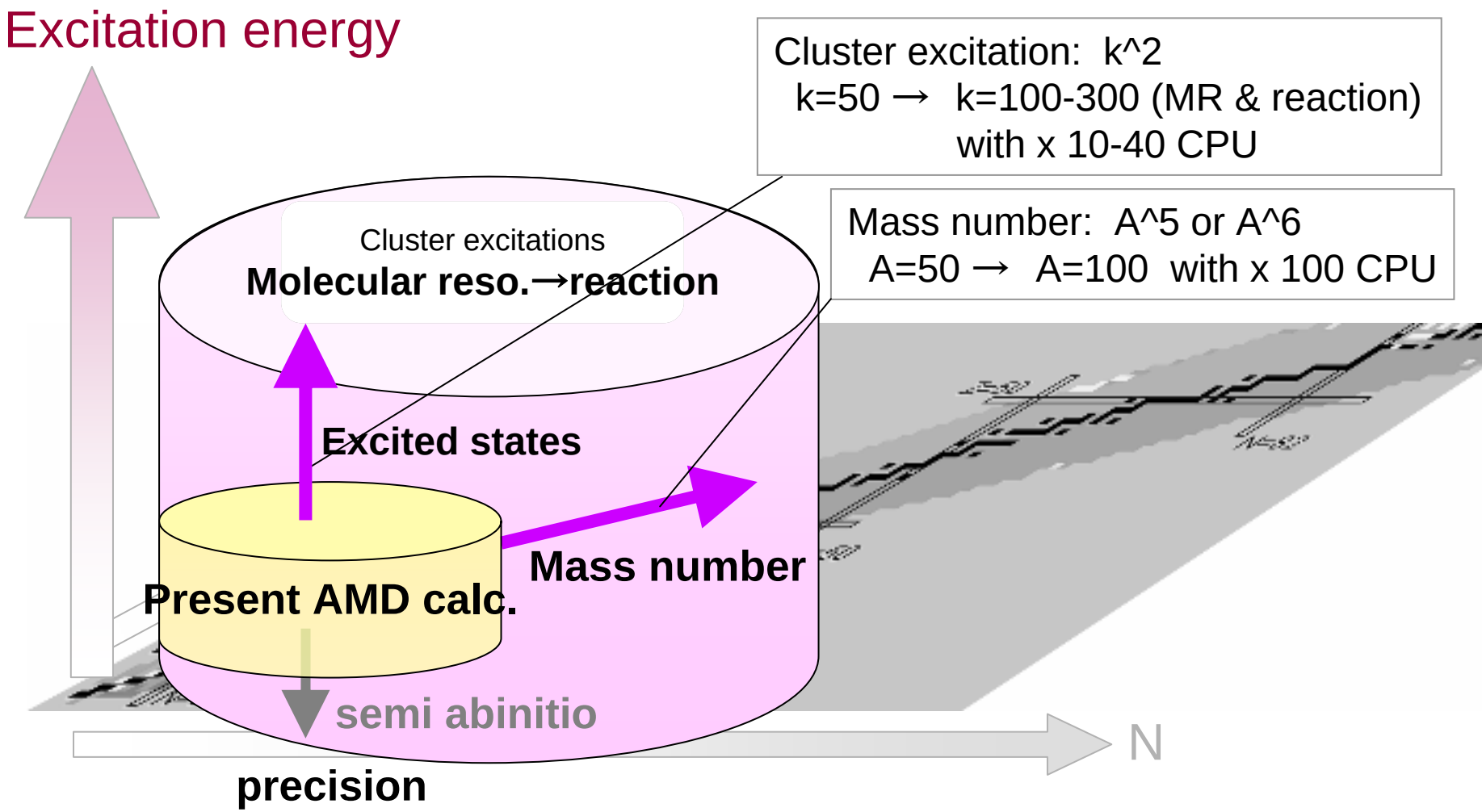


If we have more computational power, what can we do ?

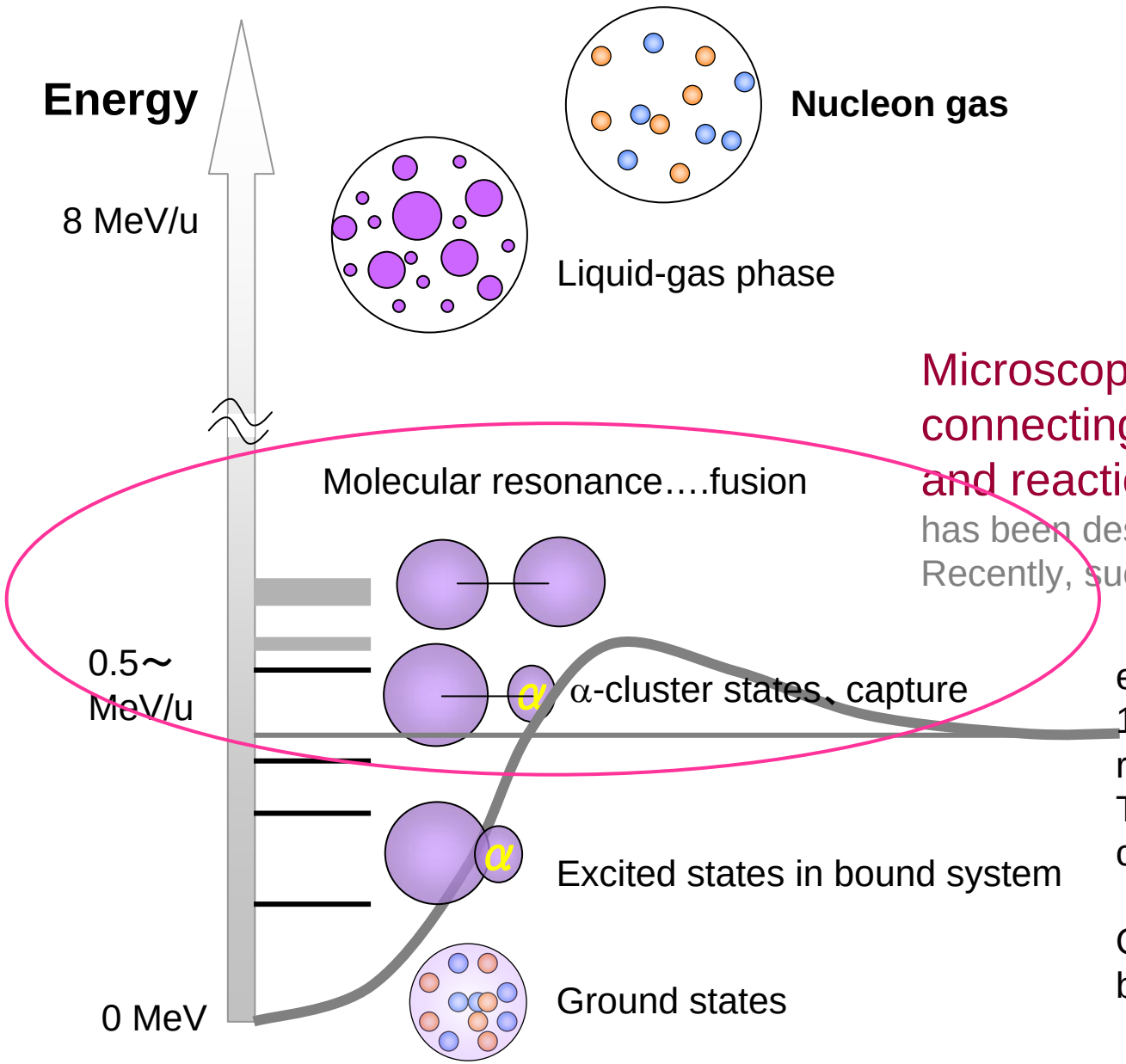


If we have more computational power, what can we do ?

Mass number: systematic study can be performed in A<100 region
with 100 times larger computational power.
Excitation: we should focus on the cluster excitation, and develop the structure study to low-energy reactions with 40 times larger computational power.



Microscopic calculations of low-energy reaction



Microscopic calculations connecting structure and reaction

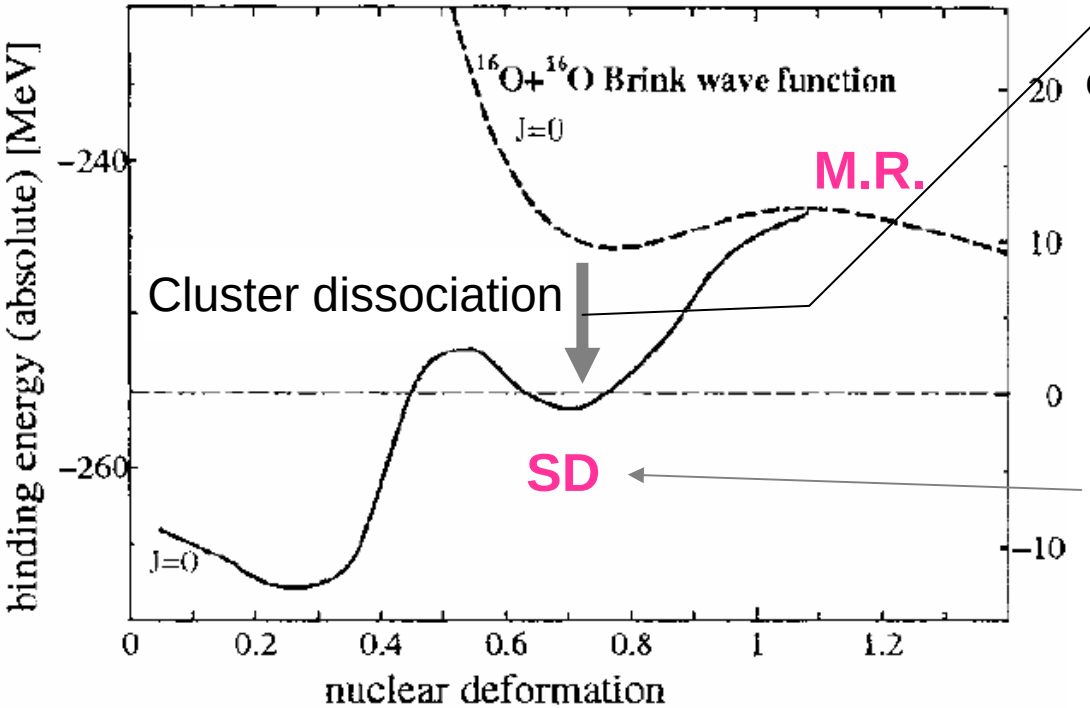
has been desired for a long time.
Recently, such studies started actually.

example.
12Be structure & He+He reaction
Talk by Ito was cancelled unfortunately.

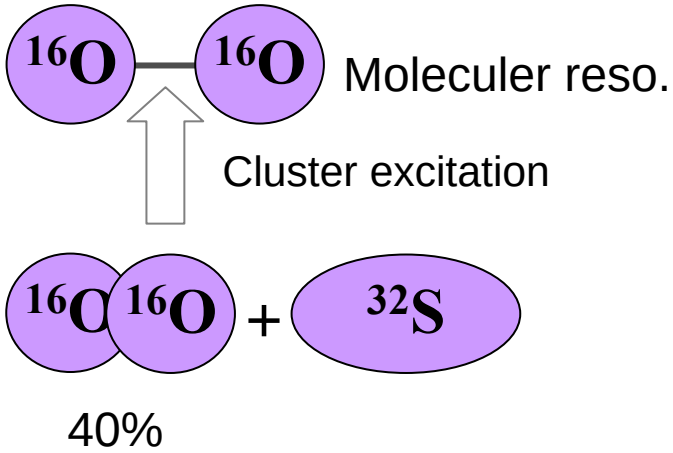
Other activities by FMD groups

AMD calc. for ^{32}S and ^{16}O-^{16}O

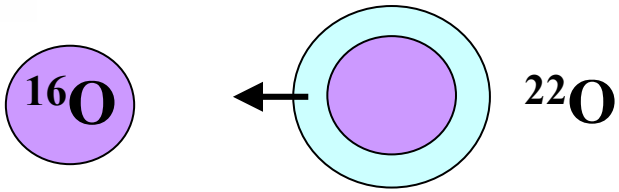
^{32}S:^{16}O+^{16}O By Kimura et al., PRC(2004)



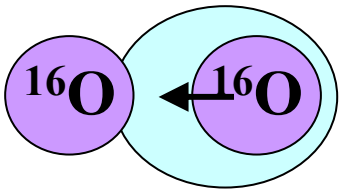
- Connect the M.R. with the low-lying deformed states.
- extra attraction due to dissociation of clusters inside of the barrier.



^{16}O+^{22}O Near future



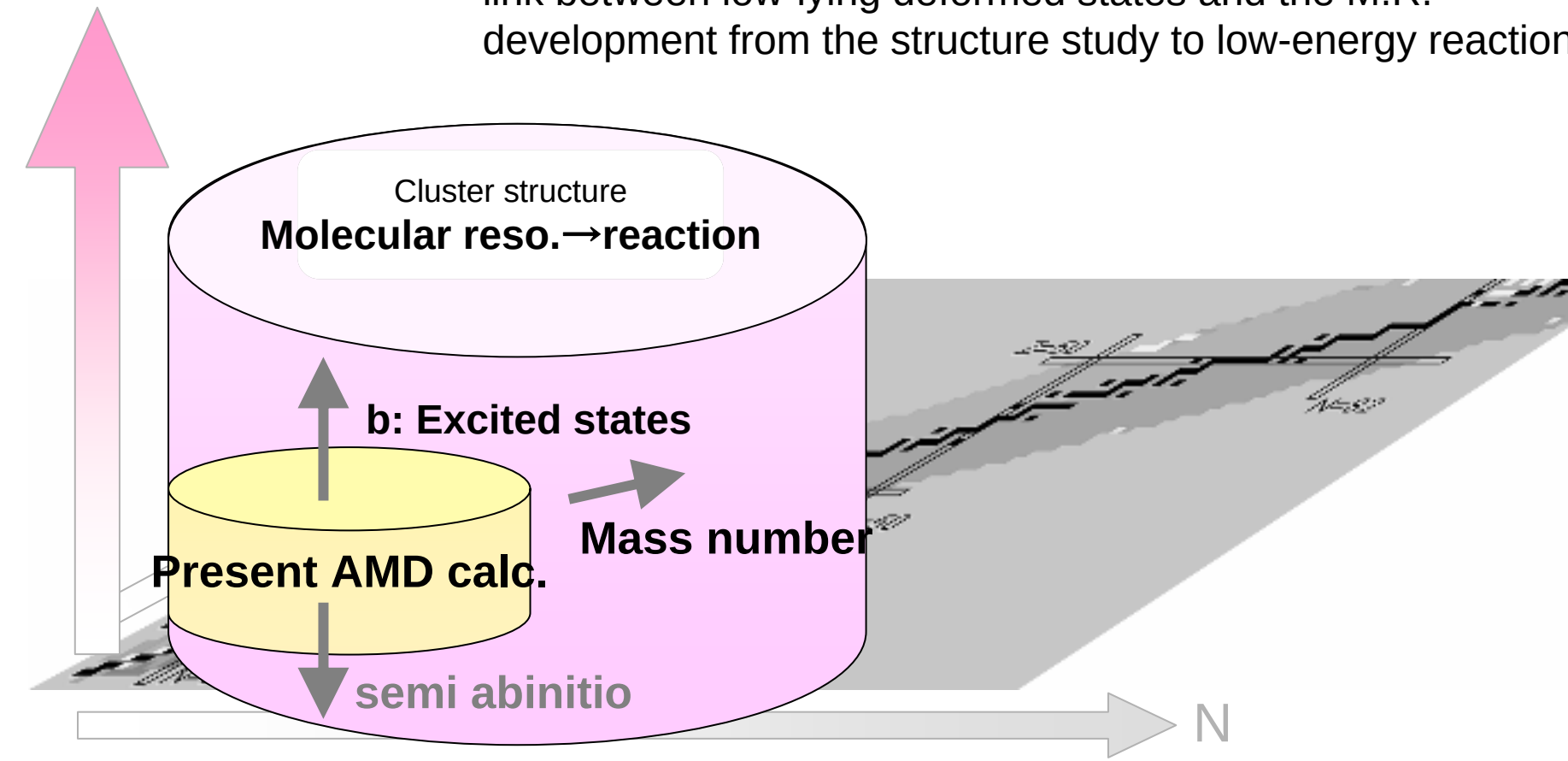
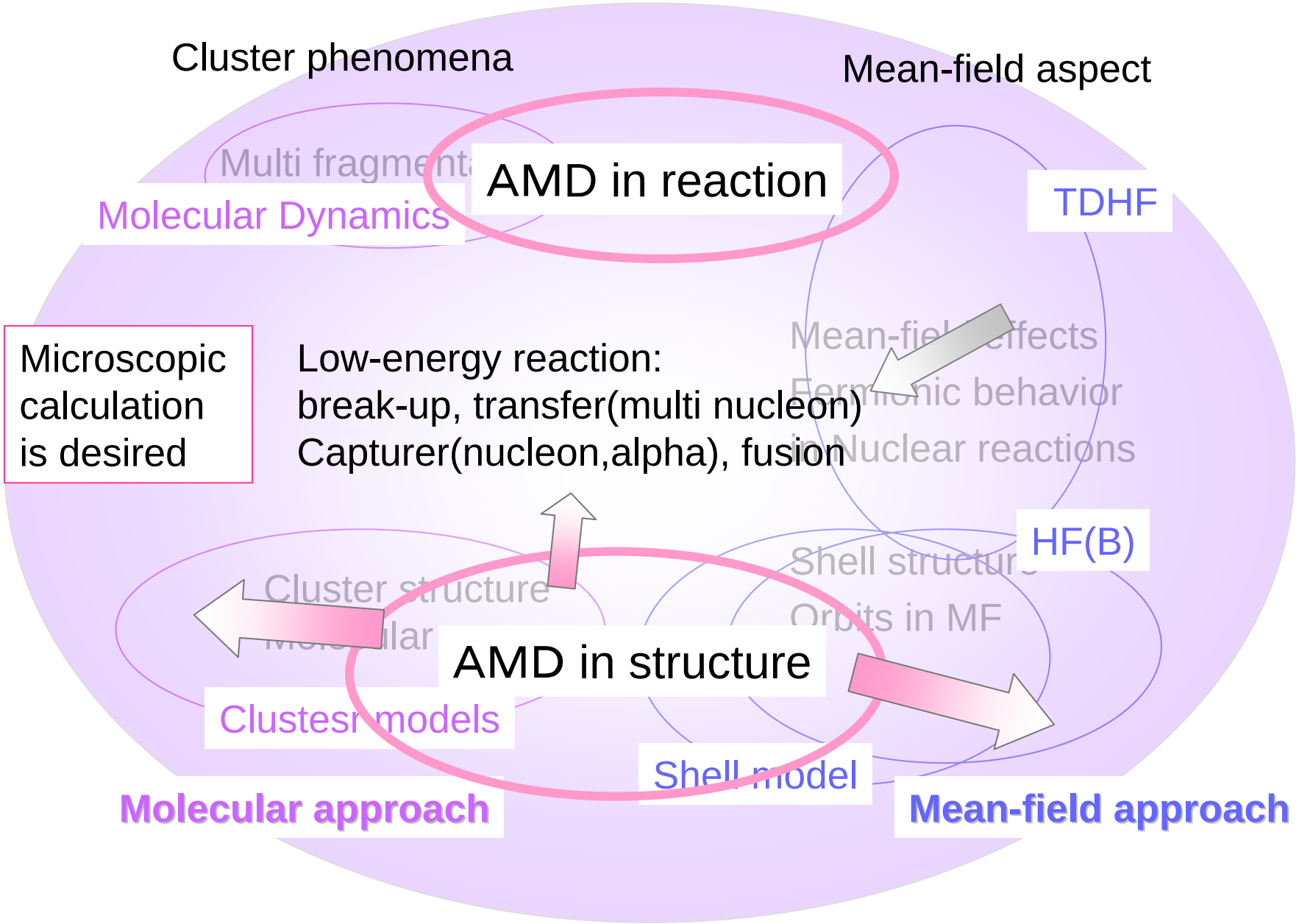
Preliminary results by Taniguchi
Adiabatic energy surface with AMD



If we have 1 peta flops in future,

We should achieve systematic study
with respect to cluster aspects in excited states

Special attention to
cluster excitation such as α-cluster states & M.R.
link between low-lying deformed states and the M.R.
development from the structure study to low-energy reaction



Microscopic models