2nd International Symposium on

Clustering as a window on the hierarchical structure of quantum systems (CLUSHIQ2022, EMMI workshop)

Clusters & Hierarchies

Oct.31-Nov.3, 2022, @Sendai Int. Center

Welcome address & Introduction

Takashi Nakamura

Tokyo Institute of Technology

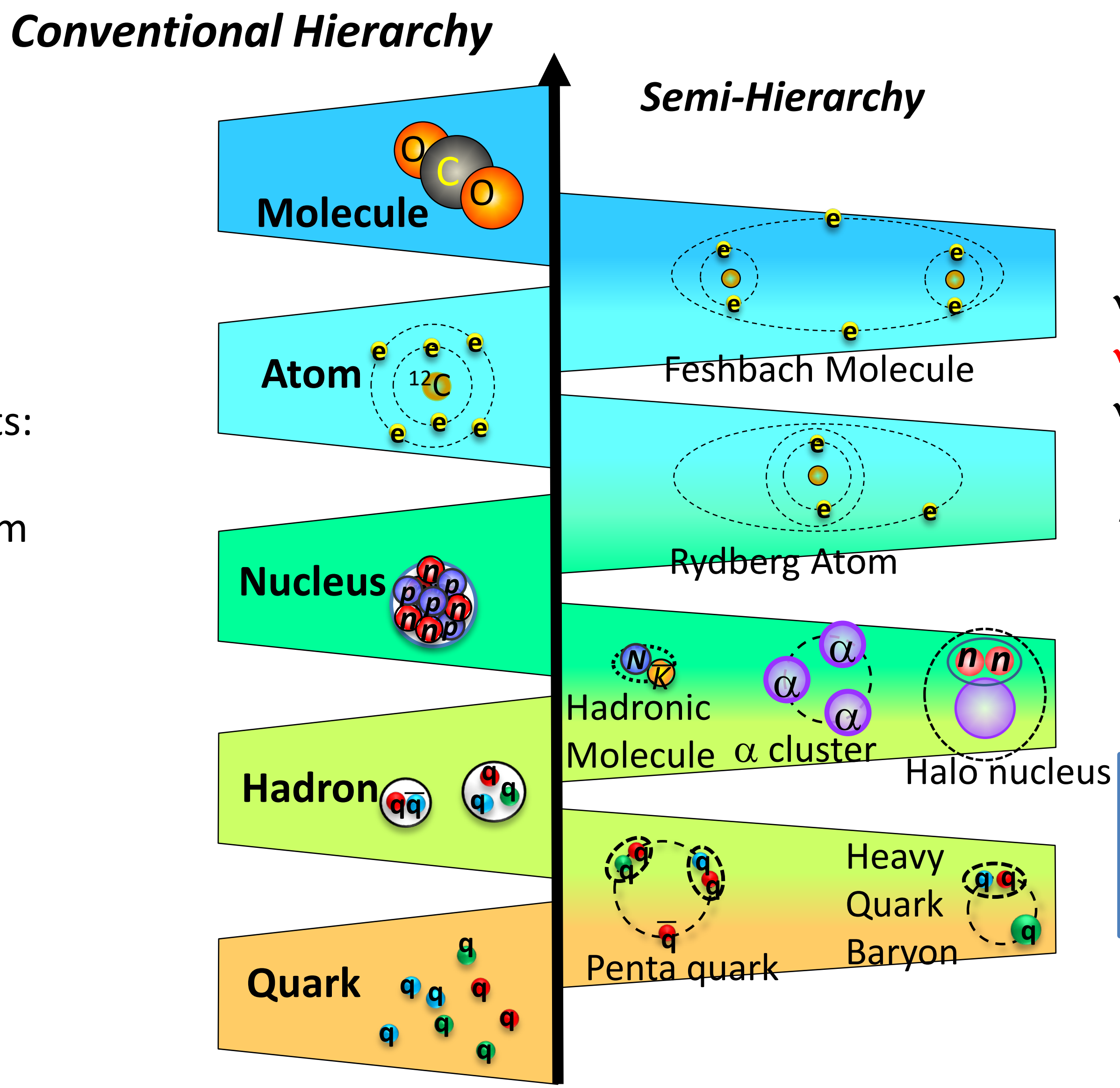
EMMI 東北大学 RIKEN ANPhA Asian Nuclear Physics Association 文部科学省 MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

"Clustering as a window on the hierarchical structure of quantum matter"(2018-2022)

Grant-in-Aid for Science Research on Innovative Areas（新学術領域 MEXT Kakenhi 18H05400)

Clusters and Semi-Hierarchy

- ✓ Big Gap between Hierarchies
- ✓ **Strongly Bound**
- ✓ Simple constituents: Nucleus= "nucleonic" system



- ✓ Smaller Gap between Hierarchies
- ✓ **Weakly Bound (Unbound)**
- ✓ Mixed constituents: Halo Nucleus
  =*"nucleonic"+"dineutron" system*

Semi-Hierarchy:
Key Aspects to understand the hierarchical structure of matter

Bridging Hierarchies

"Clustering as a window on the hierarchical structure of quantum matter"(2018-2022)

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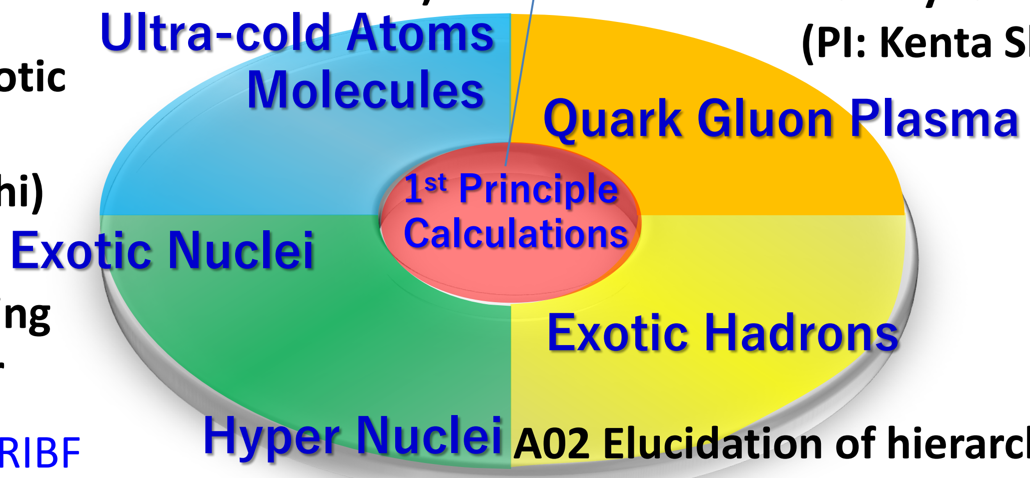
C02 Universal physics of quantum matter at the change of the hierarchy and the state (PI: Munekazu Horikoshi)

D01 Emergence mechanism of hierarchical structure of matter studied by ab-initio calculations (PI: Emiko Hiyama)

C01 Ultracold atom study of exotic phenomena bridging different hierarchies(PI: Yoshiro Takahashi)



A01 Dynamics to bridge quark and hadron hierarchies (PI: Kenta Shigaki) CERN LHC-ALICE

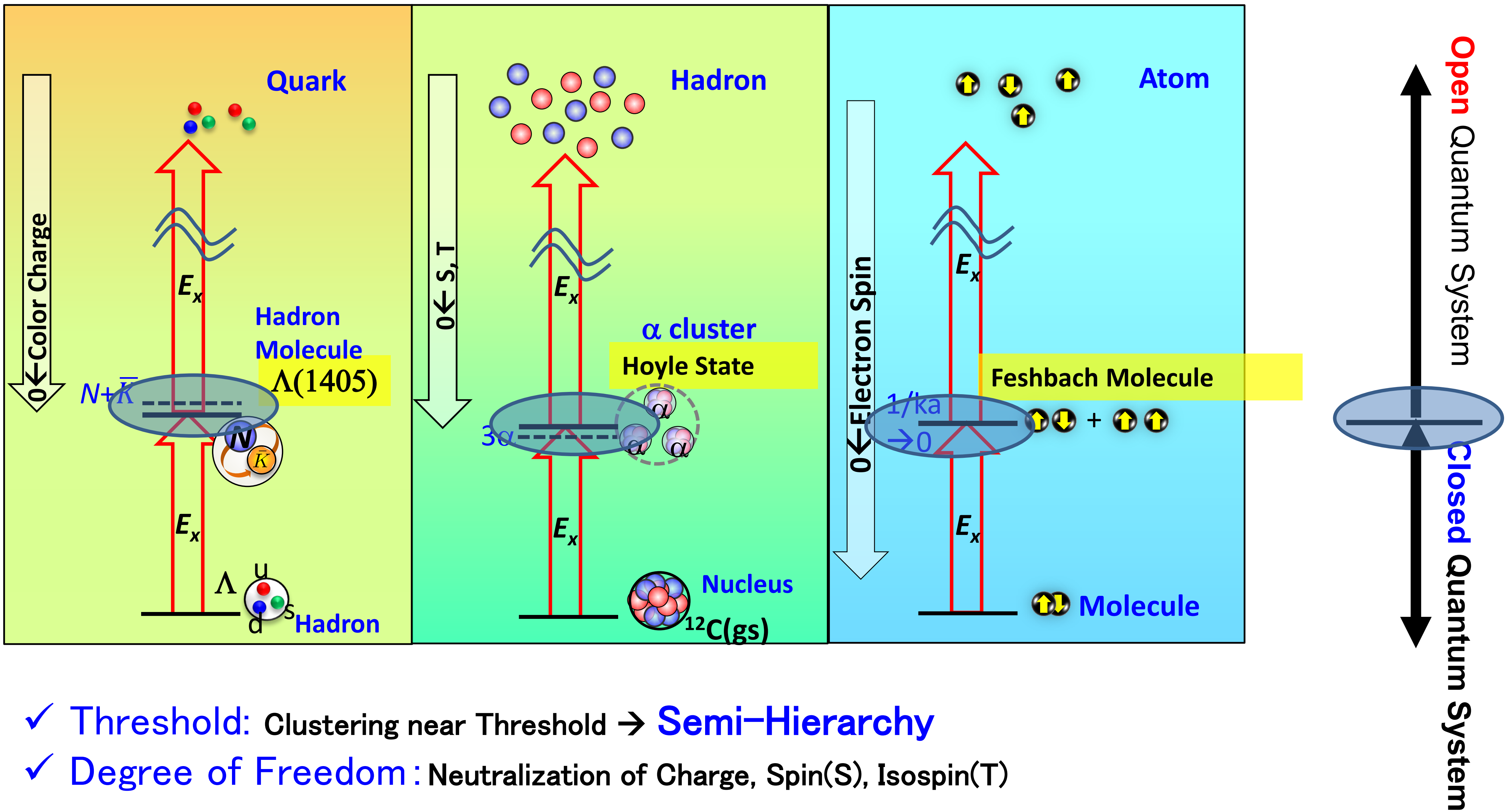
B02 Exotic nuclei for investigating hierarchical structure of matter (PI. Takashi Nakamura) RIKEN-RIBF

A02 Elucidation of hierarchical structure between quark and hadron phases by means of quark clusters (PI: Hiroaki Ohnishi)

J-PARC, SPring8

B01 Clusters of strange hadrons for investigating hierarchical structure of matter (PI: Hirokazu Tamura) J-PARC

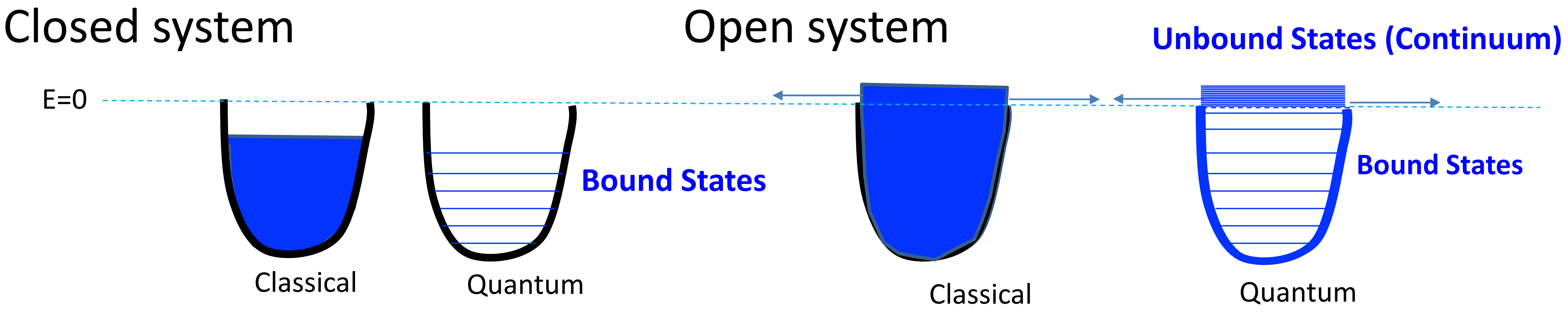
Semi-Hierarchy: Clustering and Hierarchy of Matter



✓ Threshold: Clustering near Threshold → Semi–Hierarchy

✓ Degree of Freedom : Neutralization of Charge, Spin(S), Isospin(T)

Closed or Open?



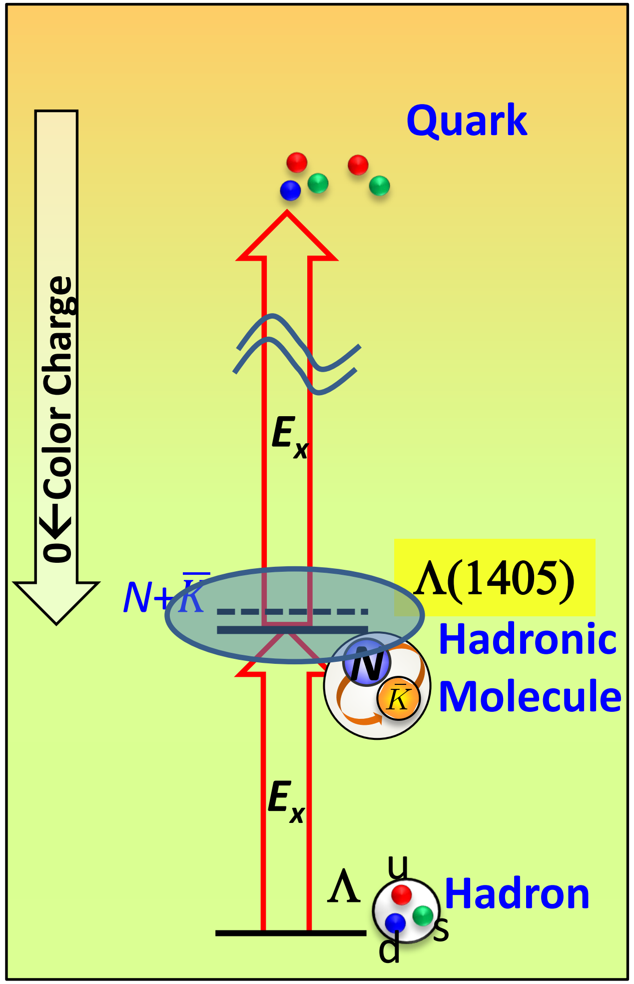
- Normal particles: Bound and Isolated system→ Closed quantum system
- Particles at the edge: Highly excited states → (Near) Open quantum system

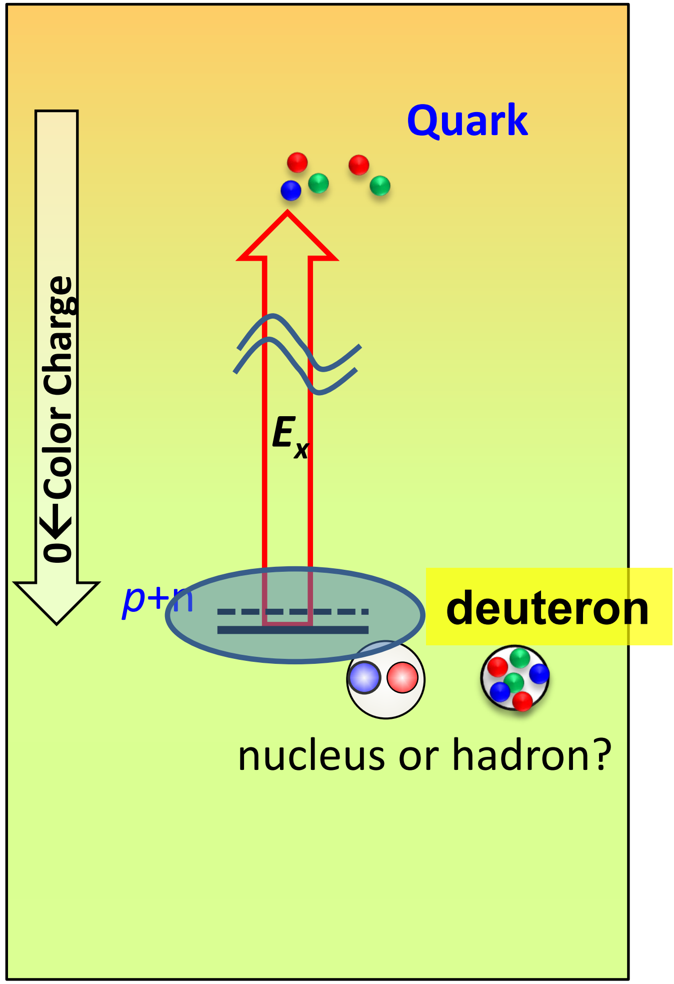
Boundary of Open–Closed regions: → Exotic phenomena?

Key Questions

- What is the Role of "Threshold" in the formation of clusters and semi-hierarchy?
- How the cluster in a specific hierarchy is mixed with more fundamental hierarchy?
- Can we understand the cluster from more fundamental hierarchy and interactions?
- What is the fundamental law behind the seemingly common phenomena among different hierarchies?
- What is common and what is different in phenomena/particles/interactions in a wide range of hierarchies?

What is the Role of "Threshold" in the formation of clusters and semi-hierarchy?





deuteron :

a nucleus (two-nucleon system, cluster)

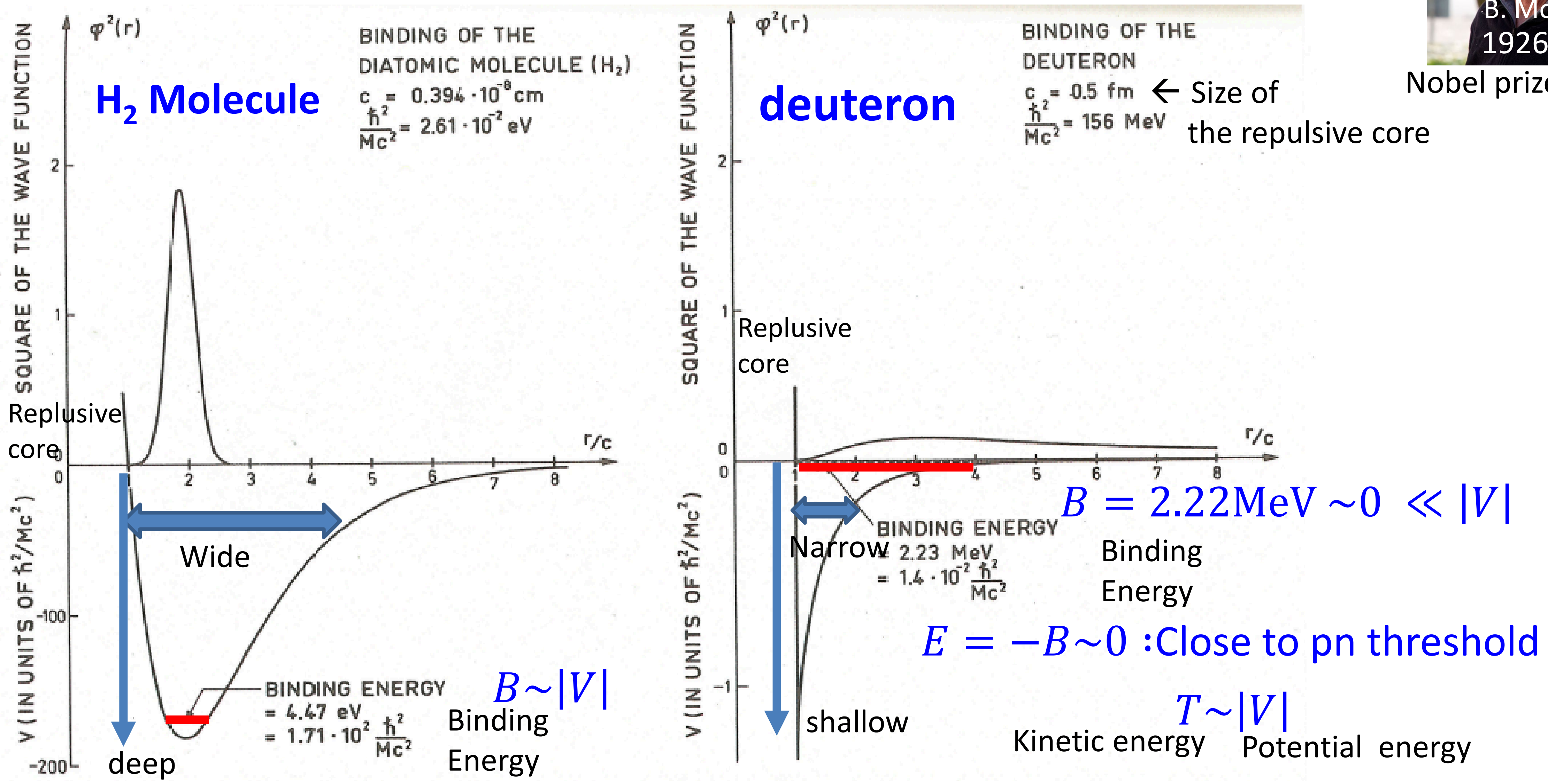
or

a hadron (6q system)?

Deuteron in the text book

Nuclear Structure, Bohr & Mottelson p269, Vol.1

Nobel prize 1975

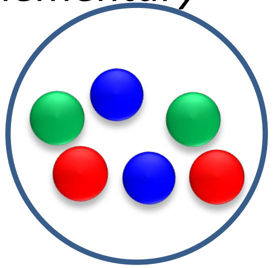


deuteron : a nucleus (two-nucleon system, cluster) or a hadron (6q system)?

S. Weinberg, PR 137, 672 (1965)
T. Hyodo, IJMPA 28, 1330045 (2013)

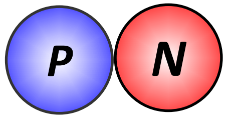
Compositeness : Z

deuteron (hadron)
: *elementary*



Z~1

Deuteron (nucleus)
: *composite (cluster)*



Z~0

$$|bound\ state\rangle = \sqrt{Z}|elementary\rangle + \sqrt{1-Z}|composite\rangle$$

S-wave scattering length $a = \frac{2(1-Z)}{2-Z}R + \mathcal{O}(m_\pi^{-1})$

Effective range $r_e = -\frac{Z}{1-Z}R + \mathcal{O}(m_\pi^{-1})$

Deuteron: Weakly bound:
(B=2.22 MeV, $a = 5.42$fm, $r_e = 1.74$fm)

⇒ **Z~0**

Cluster formation (2-body)
is dictated by **scattering length**
or equivalently **closeness to threshold**

Note: Weak bound limit:

Binding energy $B = \frac{\hbar}{ma^2}$ $\sqrt{\langle R^2\rangle} = \frac{\hbar}{\sqrt{2\mu B}} = 4.31\ fm$ $a \sim R$

Threshold effect in two-body system: → Universality

S-wave 2-body system: $a_s \sim \lambda\!\!\bar{}$ $\lambda\!\!\bar{} = \lambda/2\pi$

Atom/Molecule (a pair of Fermions)

Slide: Y. Ohashi
School Mar.2019

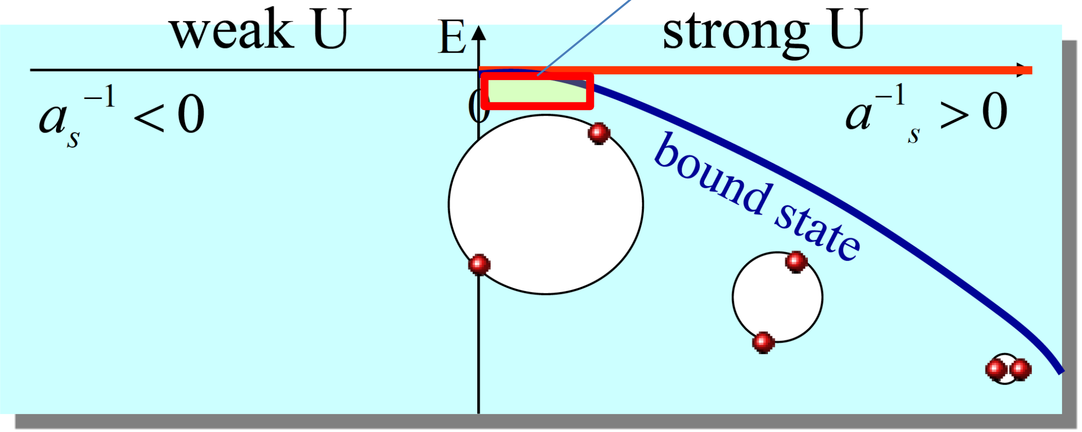
Bound state solution : $a_s > 0$

$$E = -\frac{1}{m a_s^2}$$

$$\Psi(\mathbf{R} = \mathbf{r}_1 - \mathbf{r}_2) = \frac{1}{\sqrt{2\pi a_s}} \frac{e^{-R/a_s}}{R}$$

Molecular size∼ a_s

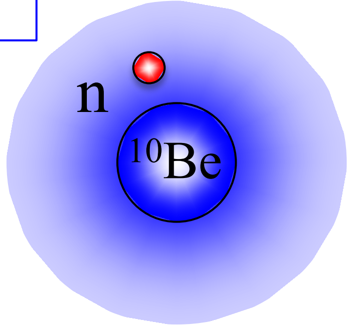
1n halo nucleus



$$E = -\frac{1}{m a_s^2}$$

S-wave 1n-halo nucleus

^{11}Be



^{10}Be+n

S_n=0.502 MeV≪ 8MeV

^{11}Be

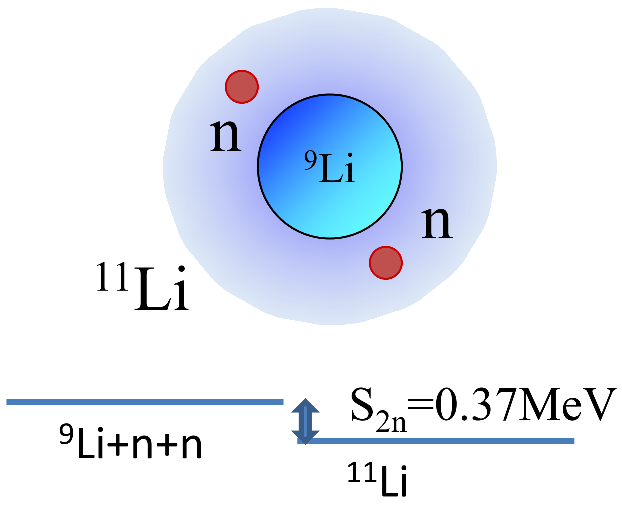
$$E = -S_n = -\frac{\hbar}{2\mu \lambda\!\!\bar{}^2}$$

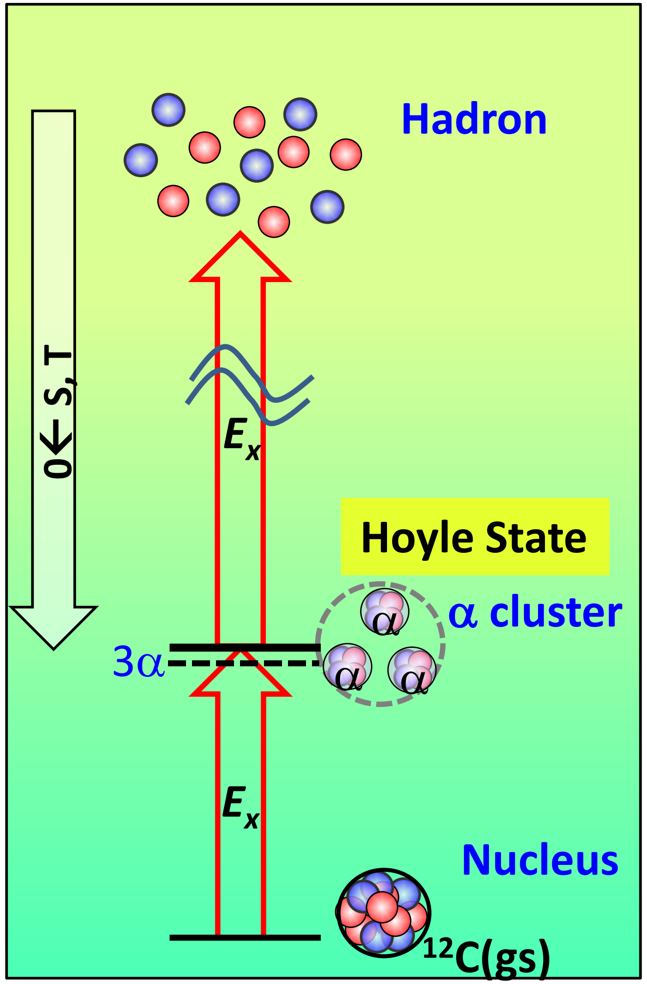
$$\psi(r) = C\frac{e^{-r/\lambda\!\!\bar{}}}{r} \qquad \lambda\!\!\bar{} = a_s$$

S_n=0.502 MeV → a_s = 6.77 fm

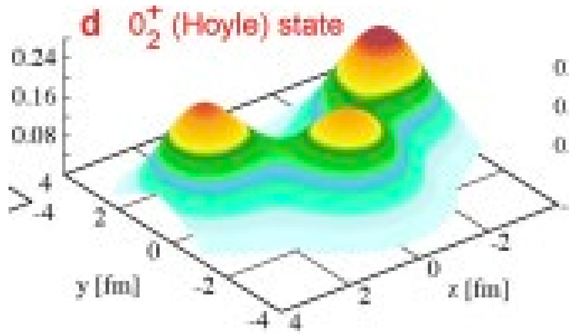
c.f. exp. $\sqrt{\langle r^2 \rangle}$ = 5.77(16) fm

Two-body cluster → Three-body Cluster?





Hoyle State: 3 α cluster



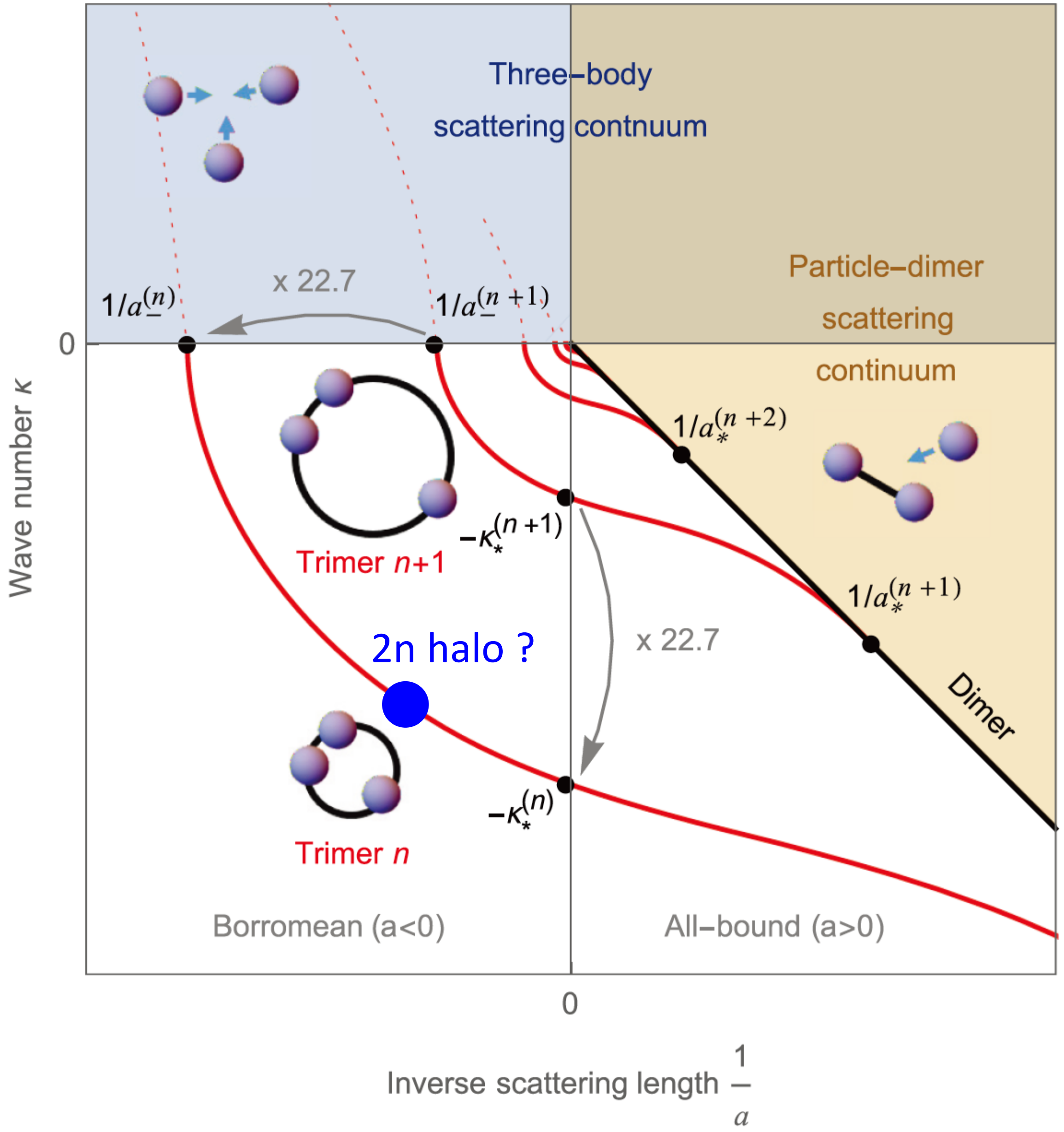
3α: ~66%

Ab-initio calculations: 3α-cluster state without requiring the threshold effect

T.Otsuka et al., Nature com. 2234 (2022).

Any universality for three-body systems over a wide range of hierarchies?

Universality in three-body cluster?



Efimov States

P.Naidon, S. Endo, Rep. Prog. Phys. 80, 056001

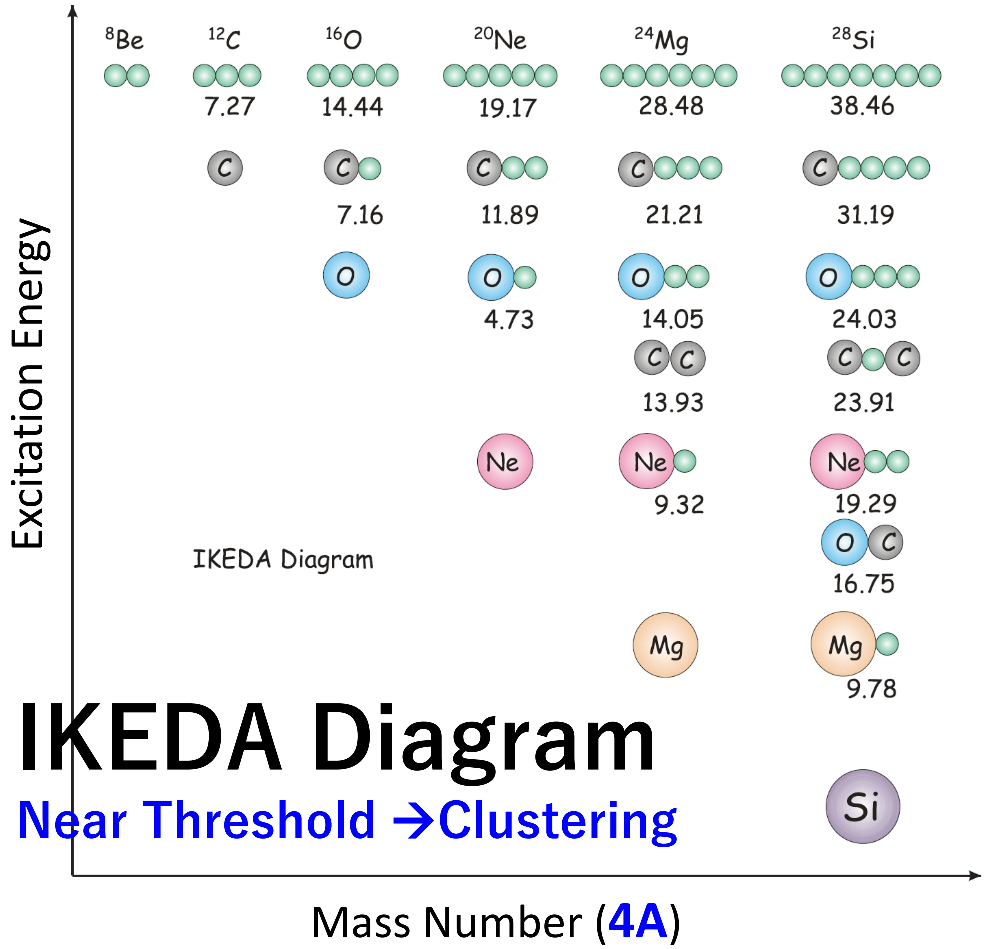
2n Halo Nuclei: Efimov States?

Likely Efimov Ground State,

But no Efimov resonances

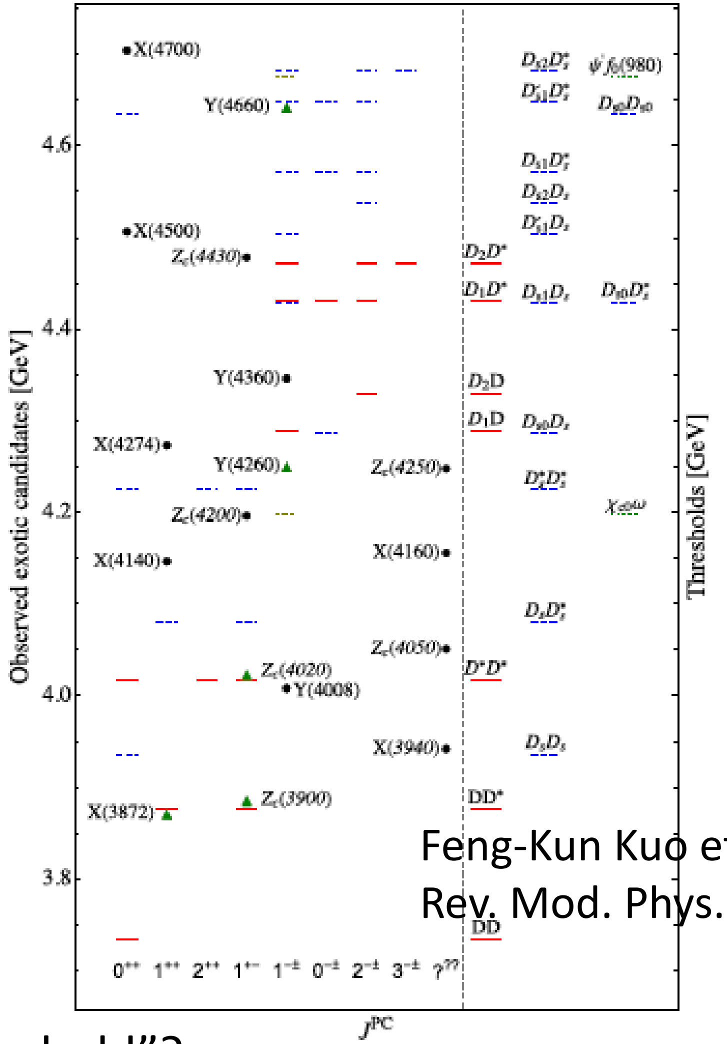
How about unbound resonance?

More “Thresholds”



IKEDA Diagram

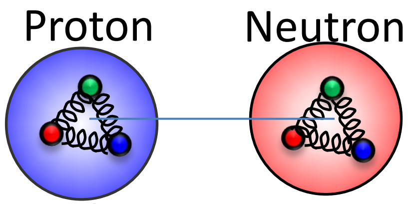
Near Threshold →Clustering



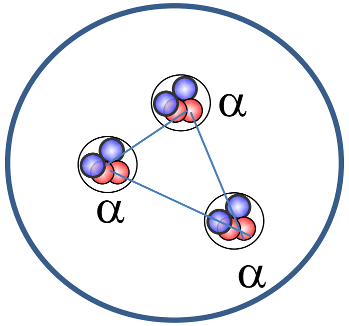
Feng-Kun Kuo et al.,
Rev. Mod. Phys. 90, 015004 (2018)

- N-body Cluster can be understood in terms of “Threshold”?
- Can we understand Cluster in the continuum (Resonance) in terms of “Threshold”?
- Effect of Mixture of other configurations: How is it relevant to “Threshold”?
- Relation of Cluster Formation to the many-body effect (Pauli Principle), density, and interactions?

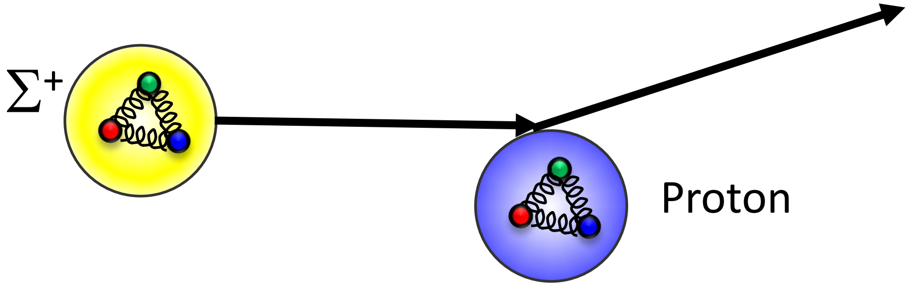
Interactions between cluster particles



deuteron



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



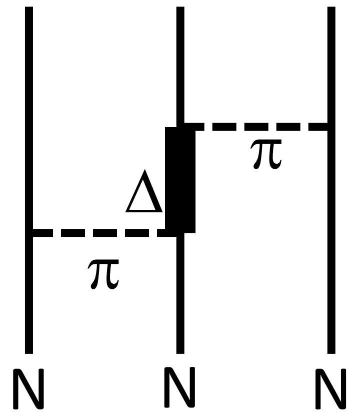
Elastic Scattering of hyperon on proton at J-PARC

T. Nanamura et al., PTEP 2022, 093D01 (2022).

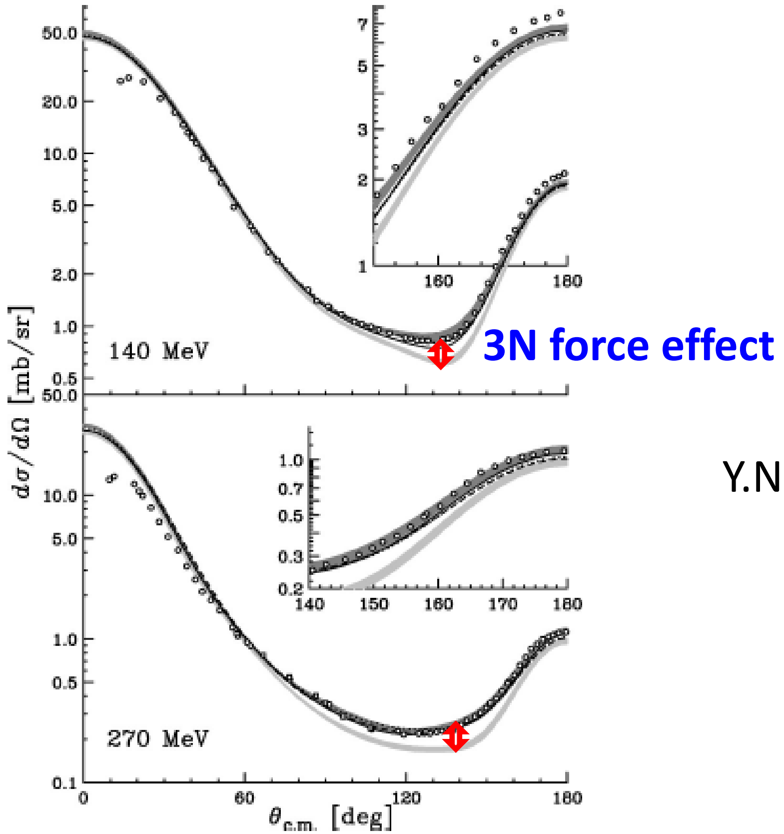
K. Miwa et al., PRC104, 045204 (2021)., K. Miwa et al., PRL128, 072501 (2022).

- Interactions:
  →Strong Inside, Weak Outside
- Can we build and understand the cluster-cluster interaction from more fundamental interactions?

3-body force



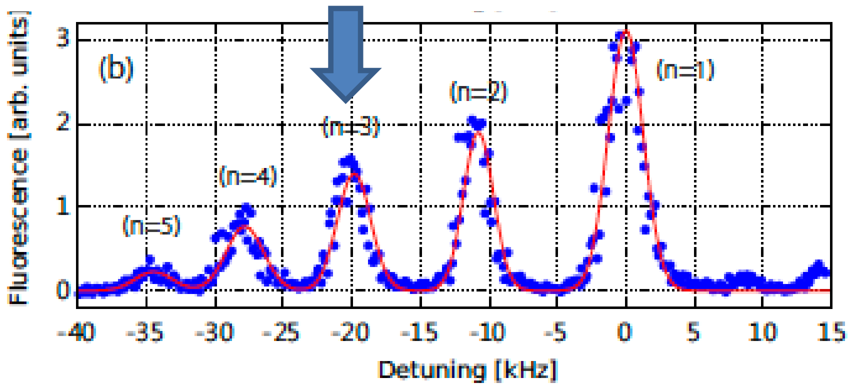
Fujita Miyazawa-type 3N force
Prog.Theor.Phys. **17**, 360 (1957).



d+p elastic scattering

K. Sekiguchi et al., PRC65, 034003 (2002).

Site-occupancy resolved Spectra in Optical Lattice



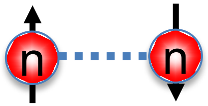
Y.Nakamura, Y.Takahashi et al., PRA**99**, 033609 (2019).

Fujita-Miyazawa type three-body force may explain **three-atomic states** in optical lattice.

c.f.
^{3}He+p: A.Watanabe et al. PRC103, 044001(2021).
Chiral Effective Field Theory: E.Epelbaum, EPJ A 92, 56 (2020).

dineutron : universality in fermion pair?

Pairing correlation in Nuclei

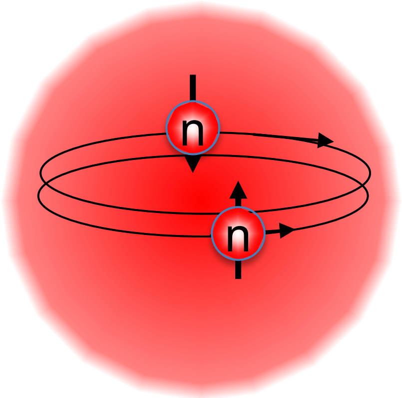


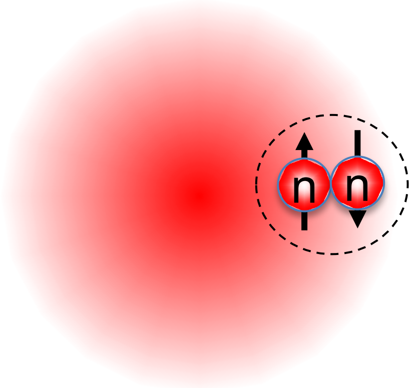
2n in Free space: S-wave Scattering Length: $a_s = -18.9(4) fm$

A.Gårdestig, J.Phys. G, Nucl. Part Phys. 36, 053001 (2009).

$|a_s| \gg r_e = 2.80(11) fm$

PRC36, 691 (1987)





A.B.Migdal, Sov.J.Nucl.Phys.**238**(1973).

→ Strong-correlated dineutron (quasi-bound two neutrons)

BCS-like Pairing Correlation

(long range, weak coupling)

Known for (normal) nuclei for 60 years

*Bohr, Mottelson, Pines, Phys.Rev.**110**, 936(1958).*

Dineutron correlation

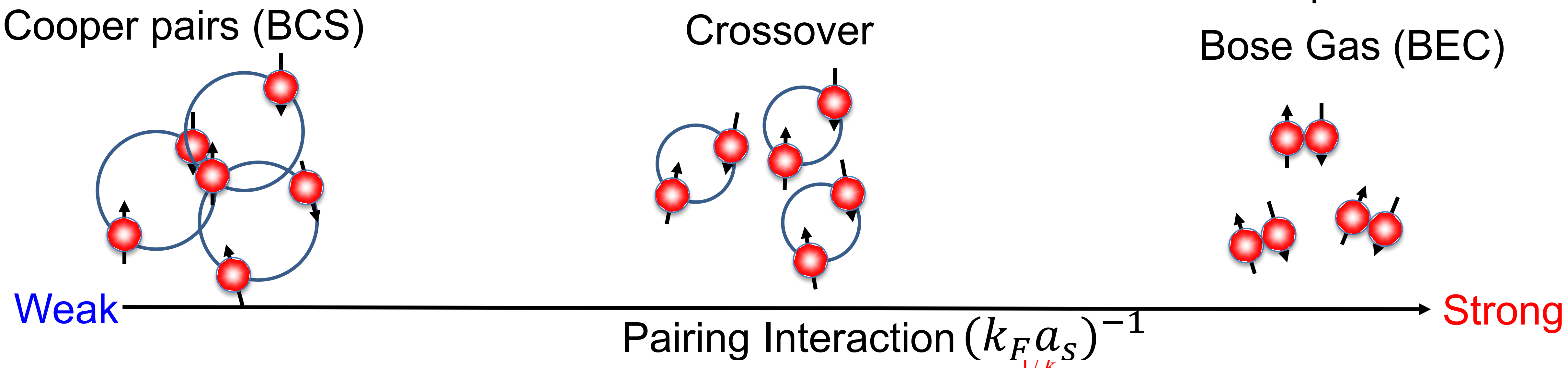
(short-range, strong coupling)

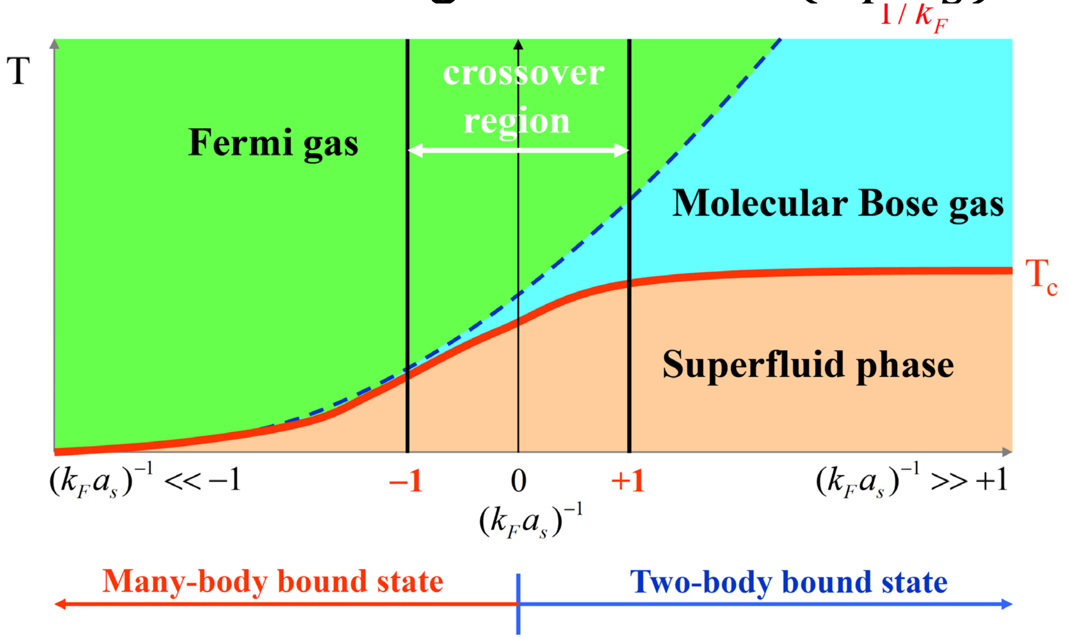
Not yet established

(A Few examples suggested in Halo Nuclei)

Analogy in atomic systems

Ultra-cold atom experiments

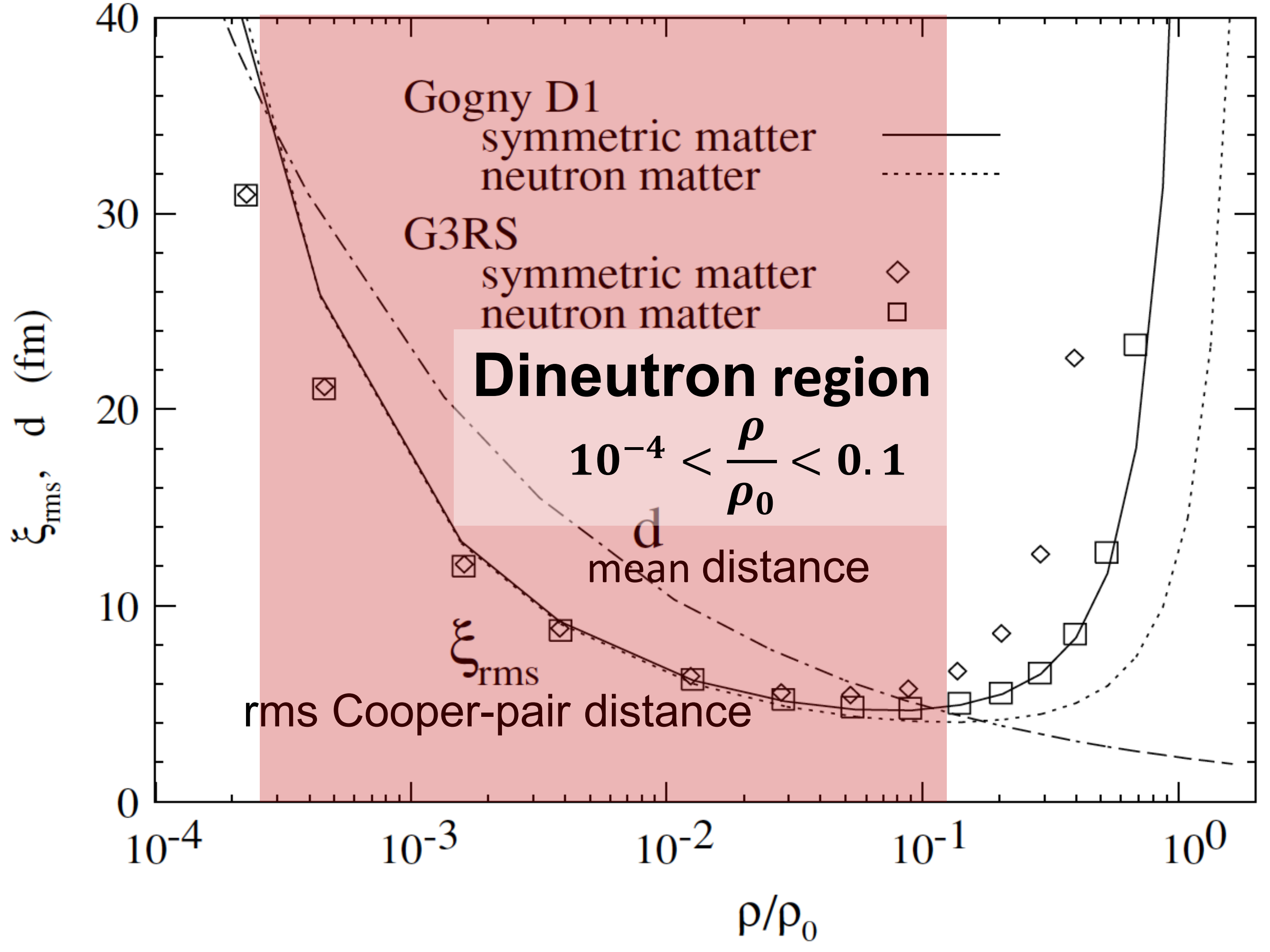




←Slide: Y. Ohashi School Mar.2019

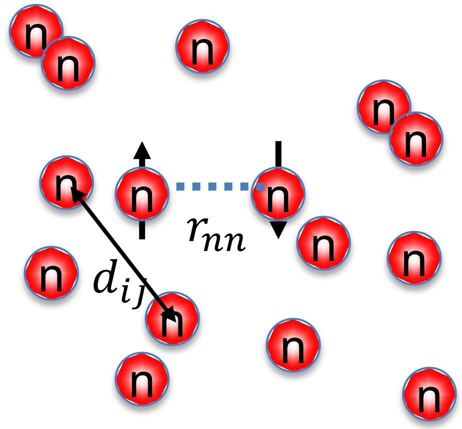
Density dependence of nn correlation

Mean field theory for nuclear matter M.Matsuo Phys. Rev. C73, 044309 (2006).



$$\xi_{rms} = \sqrt{\langle r_{nn}{}^2 \rangle} = \int d\vec{r}\, r^2 |\psi_{pair}(r)|^2$$

rms distance of the cooper pair



Neutron matter

Dineutron in ^{11}Li (2n-halo nucleus)

TN et al., PRL96, 252502(2006).

Y. Kubota et al., PRL125, 252501 (2020)

"dineutron localized near the surface of the core"

Dineutron in ^{19}B (2n-halo nucleus)

K.J. Cook, TN et al., PRL 124, 212503 (2020).

Dineutron in ^{6}He (2n-halo nucleus)

Y.L. Sun, TN et al., PLB814, 136072 (2021).

Further Questions on dineutron

- Dineutron: Crossover or BEC? (Most likely crossover, M. Matsuo PRC 2006)
- Multi-Dineutron?
  - ^{4}n (tetra-neutron) observed as a resonance in the RIKEN experiment.

    M.Duer et al., Nature 606, 678 (2022). ^{2}n-^{2}n?
  - ^{28}O=^{24}O+^{2}n+^{2}n? Y.Kondo et al.
  - Our group will investigate 6n states in ^{10}He
- What is common and what is different between dineutron and atomic fermion pair?
- What is common and what is different between dineutron and diquark?

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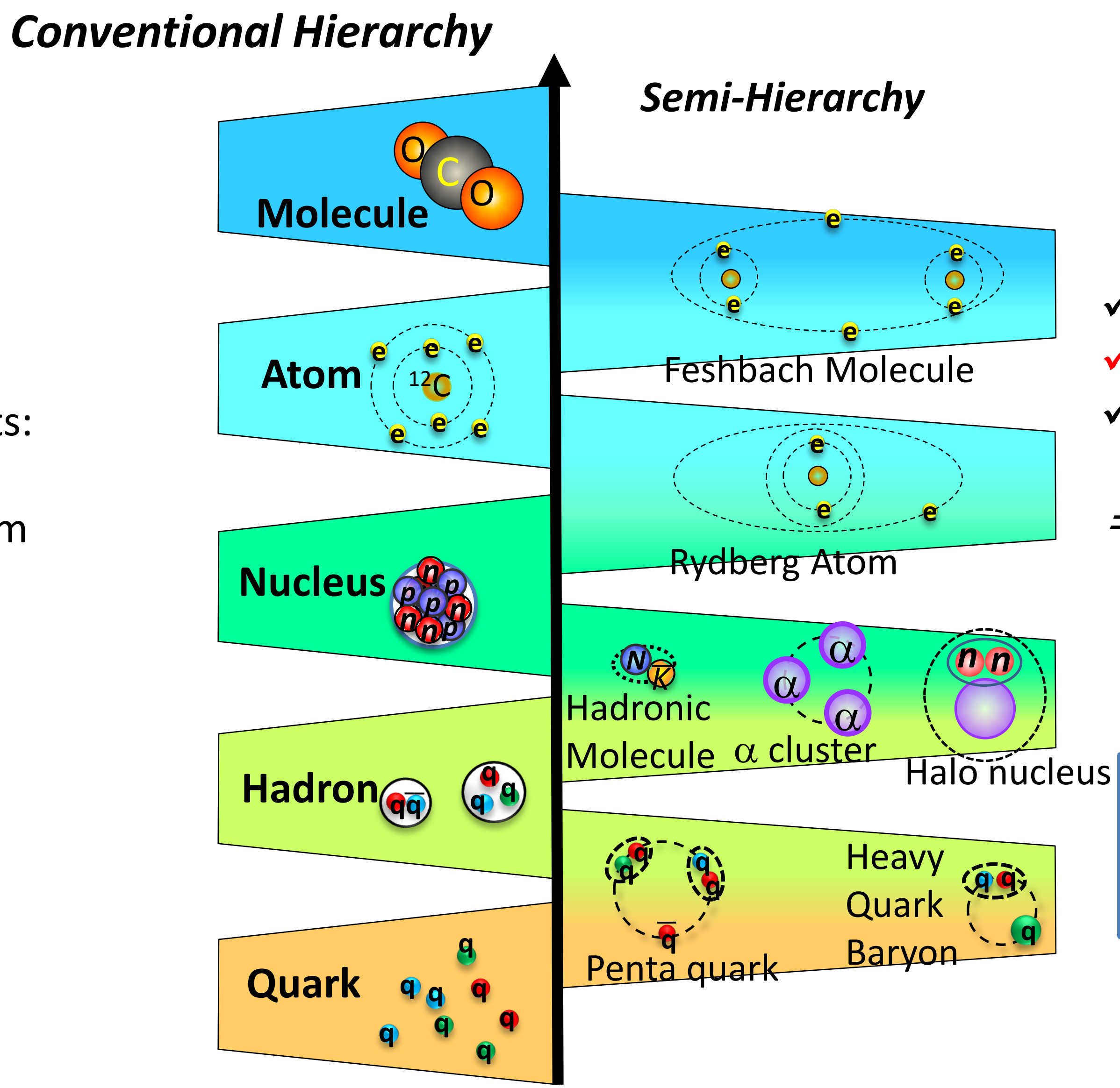

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Key Aspects to understand the hierarchical structure of matter

What is common and what is different?

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Best three poster presenters will be awarded ANPhA prizes

Enjoy CLUSHIQ2022 Symposium !

All the sciences, and not just the sciences but all the efforts of intellectual kinds, are an endeavor to see the connections of the hierarchies. *Richard P. Feynman, The Character of Physical Law*

Kaisen-don (Sashimi-Rice-bowl)

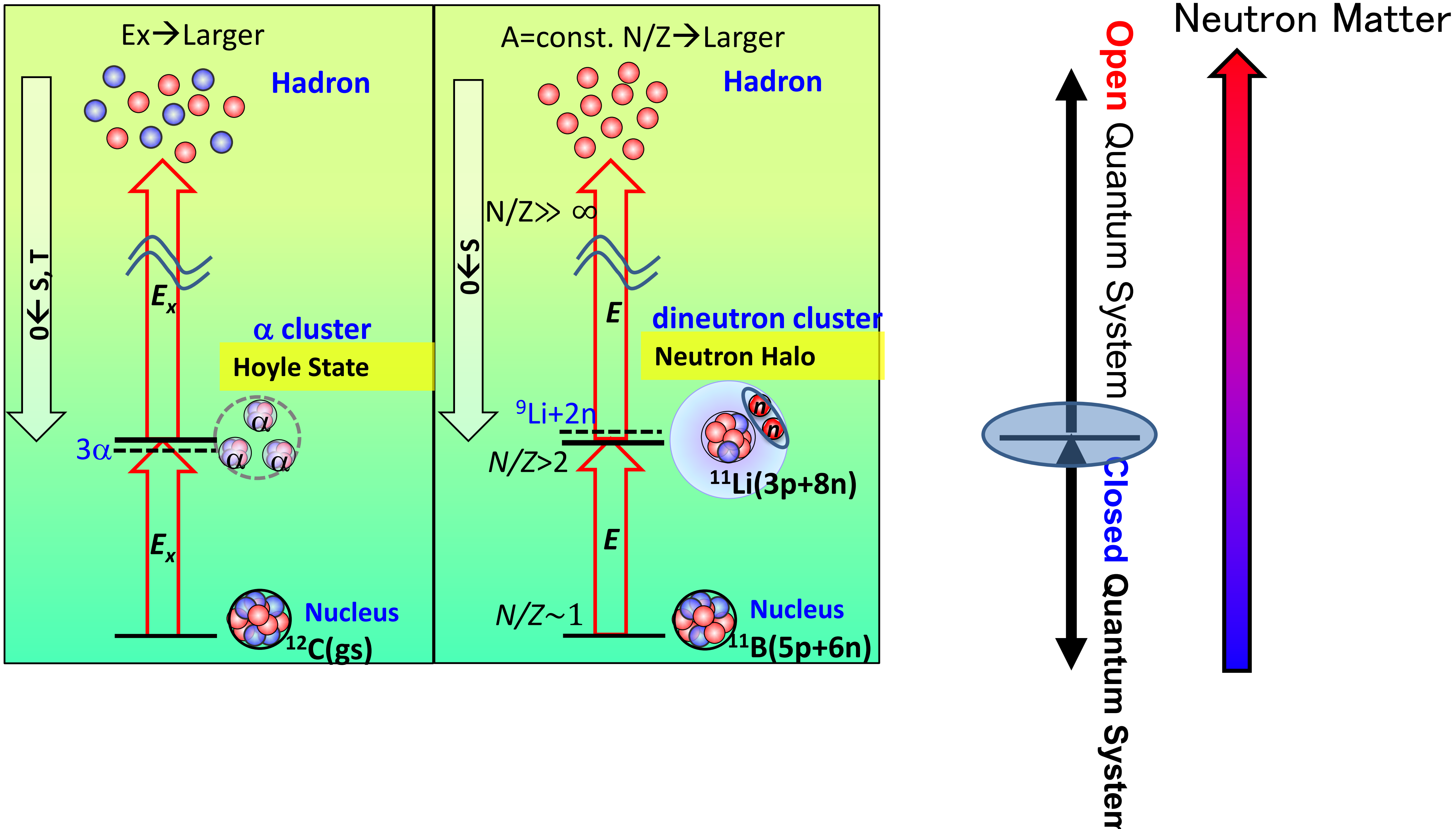
Gyutan (Beaf-tongue)

Statue of Lord DATE-MASAMUNE

Zuiganji-temple in Matsushima

Backup

Semi-Hierarchy in neutron-rich limit



Compositeness of bound states

Compositeness approach for a bound state |B>

S. Weinberg, Phys. Rev. 137, B672 (1965); T. Hyodo, IJMPA 28, 1330045 (2013)

$$H = H_0 + V \qquad H|B\rangle = -B|B\rangle, \quad \langle B|B\rangle = 1$$

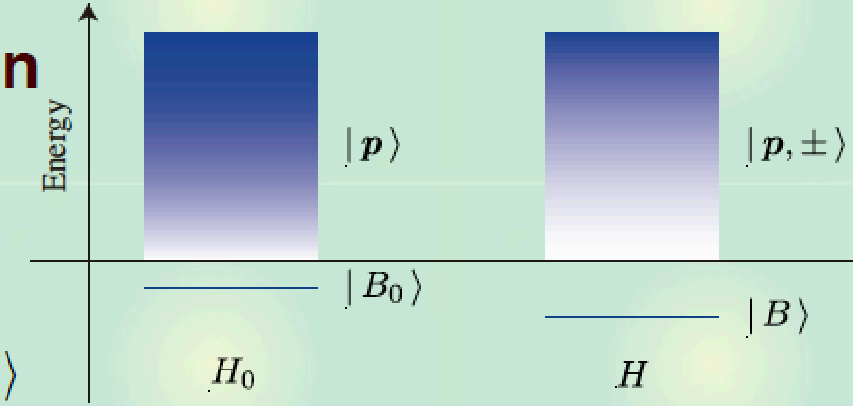
Decompose H into free part + interaction

Complete set for free Hamiltonian : bare |B₀ > + continuum

$$1 = |B_0\rangle\langle B_0| + \int d\boldsymbol{p}|\boldsymbol{p}\rangle\langle\boldsymbol{p}|$$

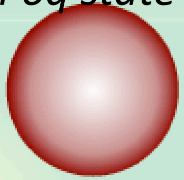
6q state(discrete) *p-n continuum*

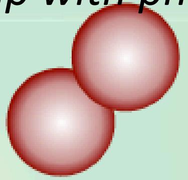
$$1 = \underbrace{\langle B|B_0\rangle\langle B_0|B\rangle}_{Z} + \int \underbrace{d\boldsymbol{p}\langle B|\boldsymbol{p}\rangle\langle\boldsymbol{p}|B\rangle}_{X}$$



Z : **elementary** X : **composite**

Overlap with 6q state (discrete) *Overlap with pn continuum*





In QCD,

H₀ : **free hadrons**

V : **hadron interaction**

Z, X : **real and nonnegative --> probabilistic interpretation**

$$\Rightarrow 0 \le Z \le 1, \quad 0 \le X \le 1$$

Itlic texts by T.Nakamura

Slide by T. Hyodo

Weak binding limit

In general, Z depends on the choice of the potential V.

- Z : model-(scheme-)dependent quantity

$$1 - Z = \int dp \frac{|\langle p|V|B\rangle|^2}{(E_p + B)^2}$$ ← **V-dependent**

At the weak binding (R ≫ R_{typ}), Z is related to observables.

S. Weinberg, Phys. Rev. 137, B672 (1965); T. Hyodo, IJMPA 28, 1330045 (2013)

$$a = \frac{2(1-Z)}{2-Z} R + \mathcal{O}(R_{\text{typ}}), \quad r_e = \frac{-Z}{1-Z} R + \mathcal{O}(R_{\text{typ}}),$$

a **: scattering length,** r_e **: effective range**

$R = (2\mu B)^{-1/2}$ **: radius (binding energy)**

R_{typ} **: typical length scale of the interaction**

Criterion for the structure:

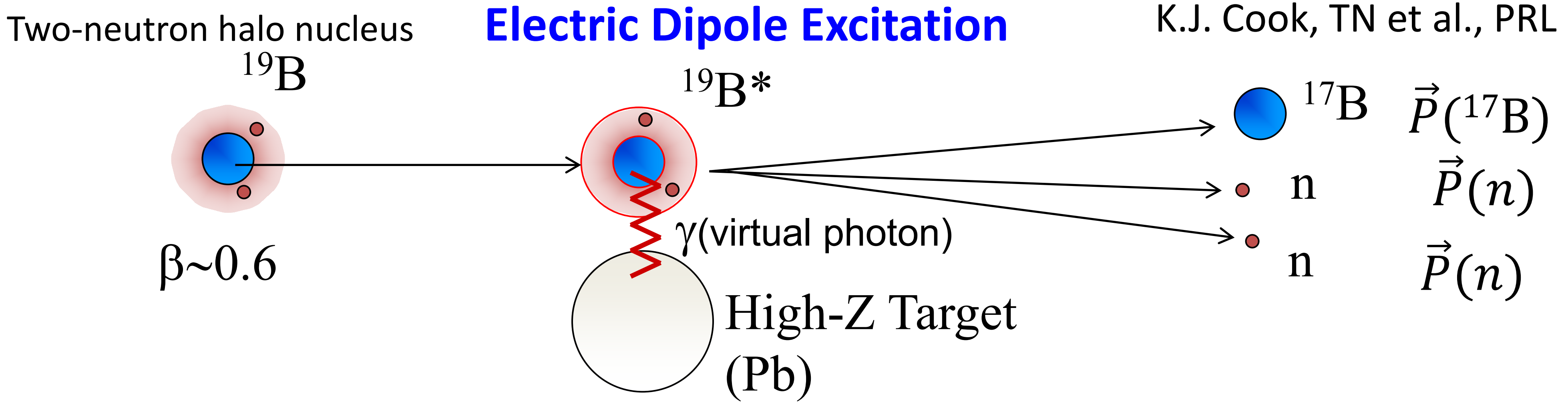
$$\begin{cases} a \sim R_{\text{typ}} \ll -r_e & \text{(elementary dominance)}, \quad Z \sim 1 \\ a \sim R \gg r_e \sim R_{\text{typ}} & \text{(composite dominance)}. \quad Z \sim 0 \text{ (deuteron)} \end{cases}$$

Slide by T. Hyodo

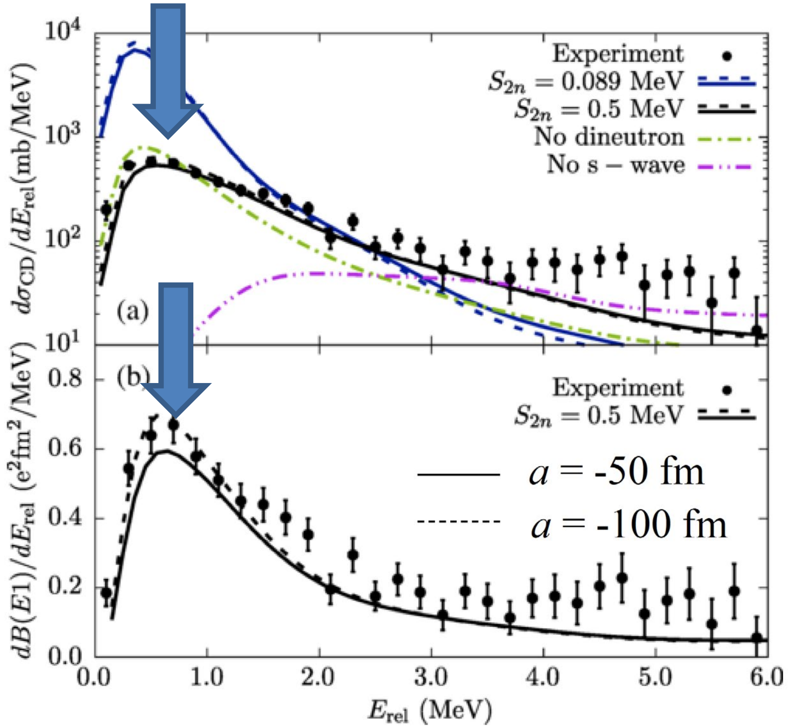
Coulomb Breakup of ^{19}B @RIKEN RIBF

Electric Dipole Excitation

K.J. Cook, TN et al., PRL 124, 212503 (2020).



Strong Electric Dipole Transitions (Soft E1 Excitation)



B(E1) = 1.64 ± 0.06 (stat) ± 0.12 (sys) e^{2}fm^2

Soft E1 Excitation: Signature of Halo!