2nd IBS Conference on
Exotic Nuclei
Daejeon, 22–24, July 2026

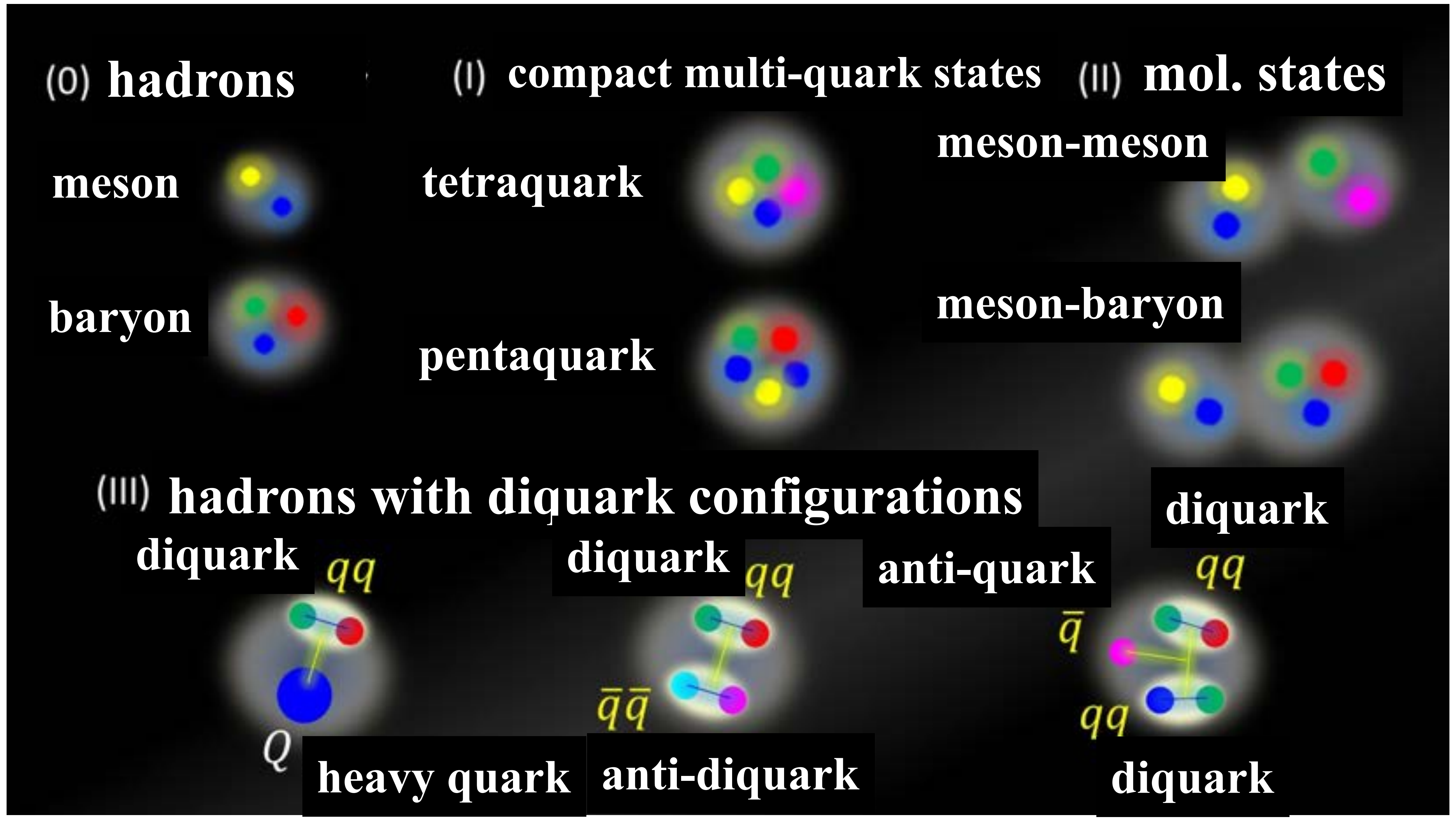
Knockout reaction studies of few-nucleon correlations in nuclei

Tomohiro Uesaka (RIKEN)
on behalf of the SAMURAI and ONOKORO Collaborations

Order in physical systems through formation of subsystems

Crossroad between few-body and many-body physics
Crossroad between low-energy and high-energy physics

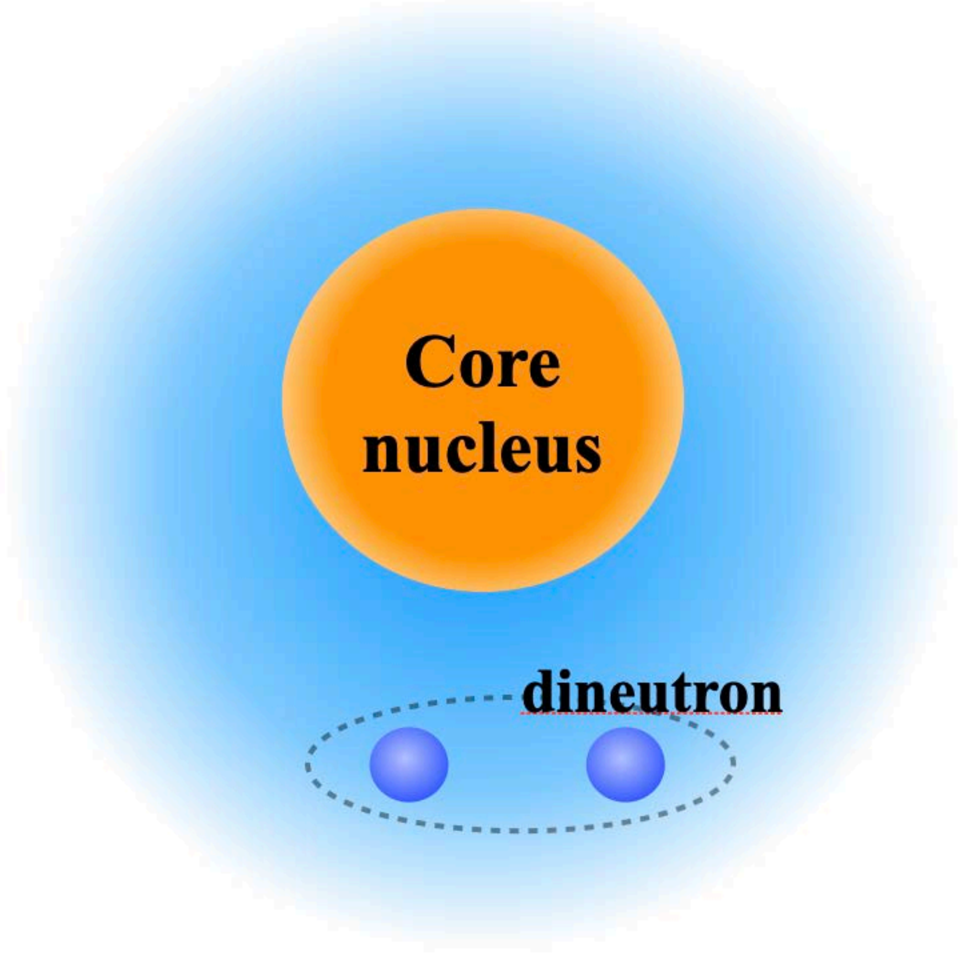
di- / multi-quark correlation in hadrons

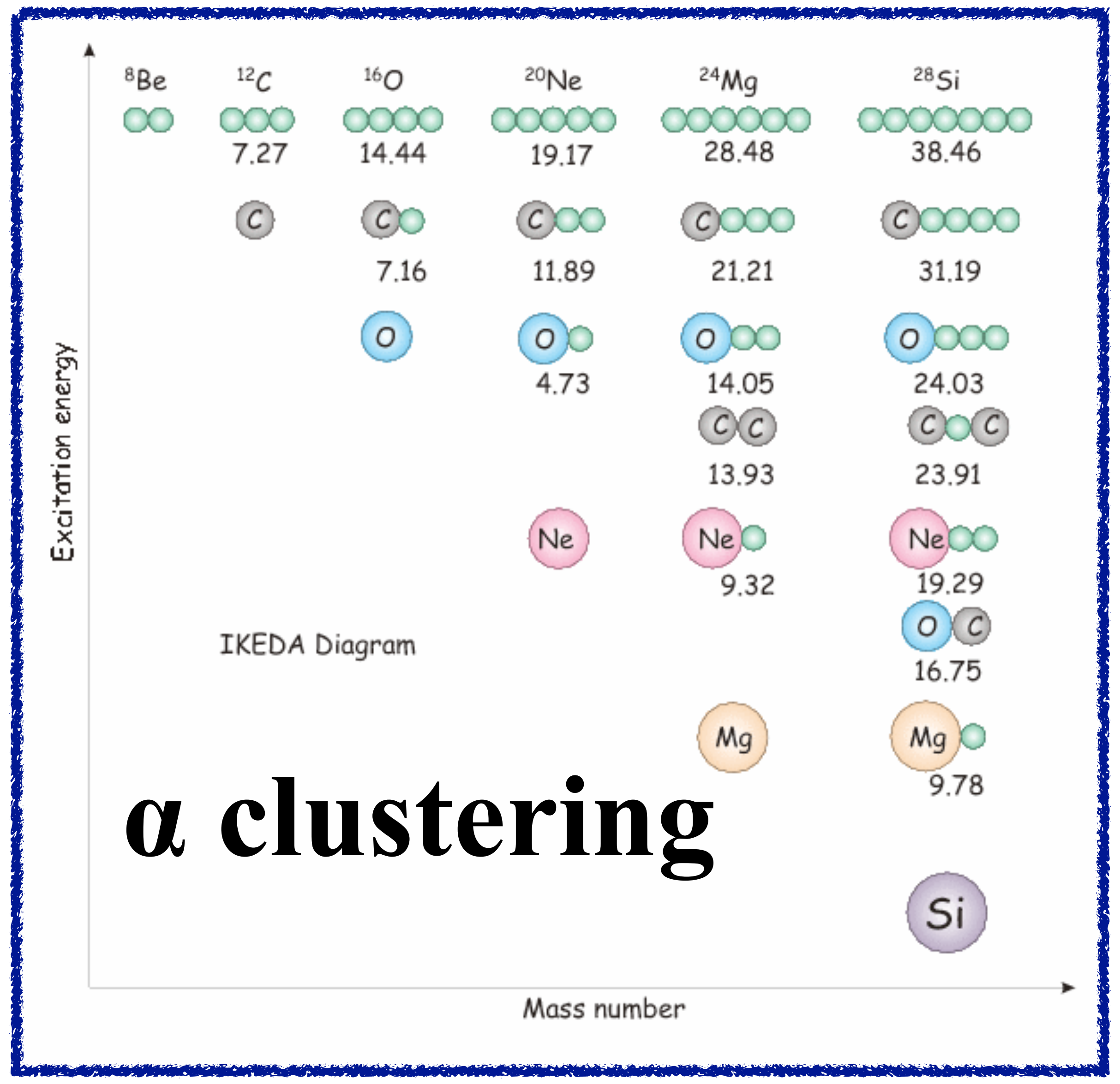


http://kakudan.rcnp.osaka-u.ac.jp/jp/overview/world/Flavor.html
(in Japanese)

hadron production

multi-nucleon correlation in neutron drip-line nuclei

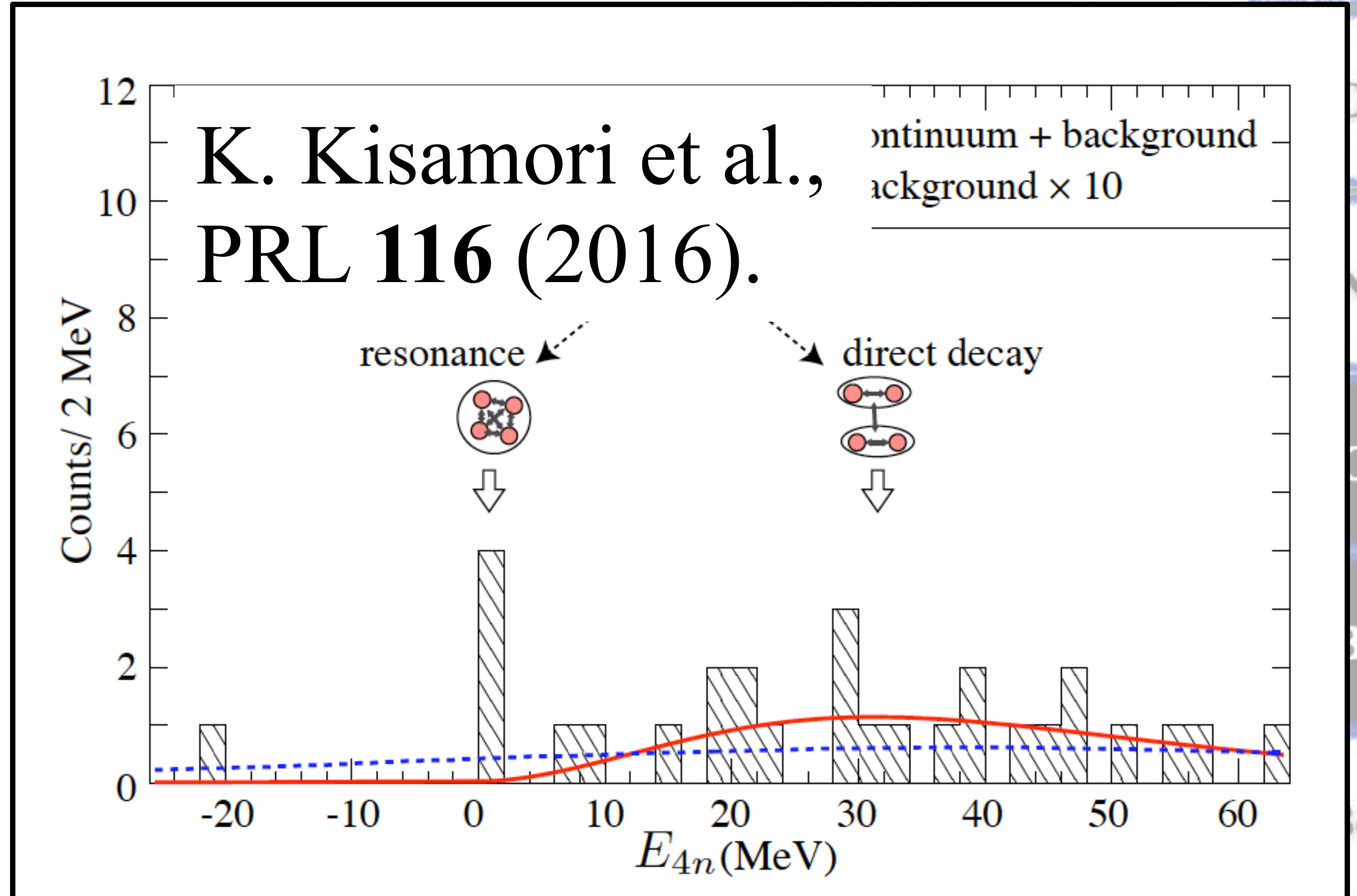


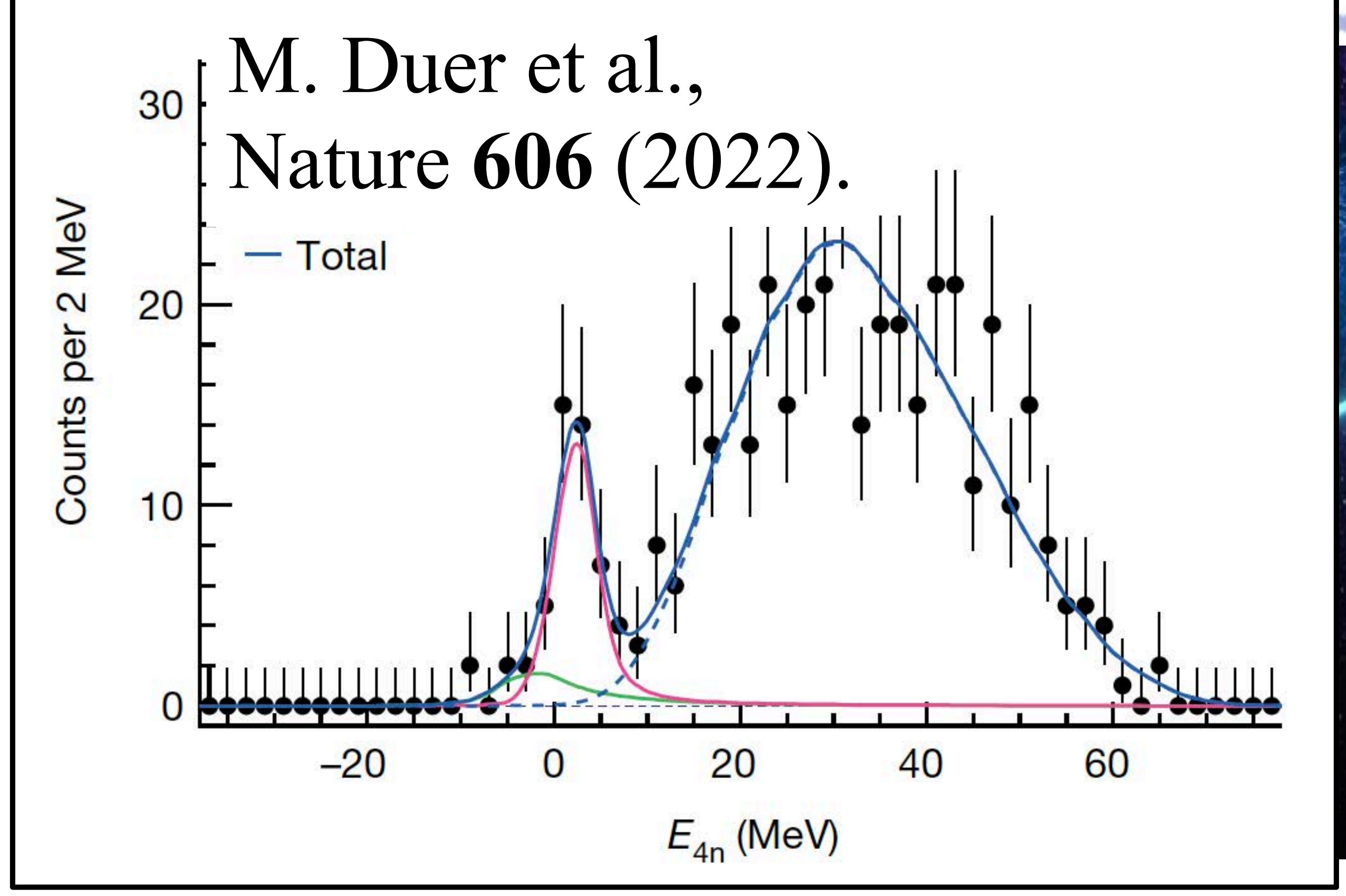


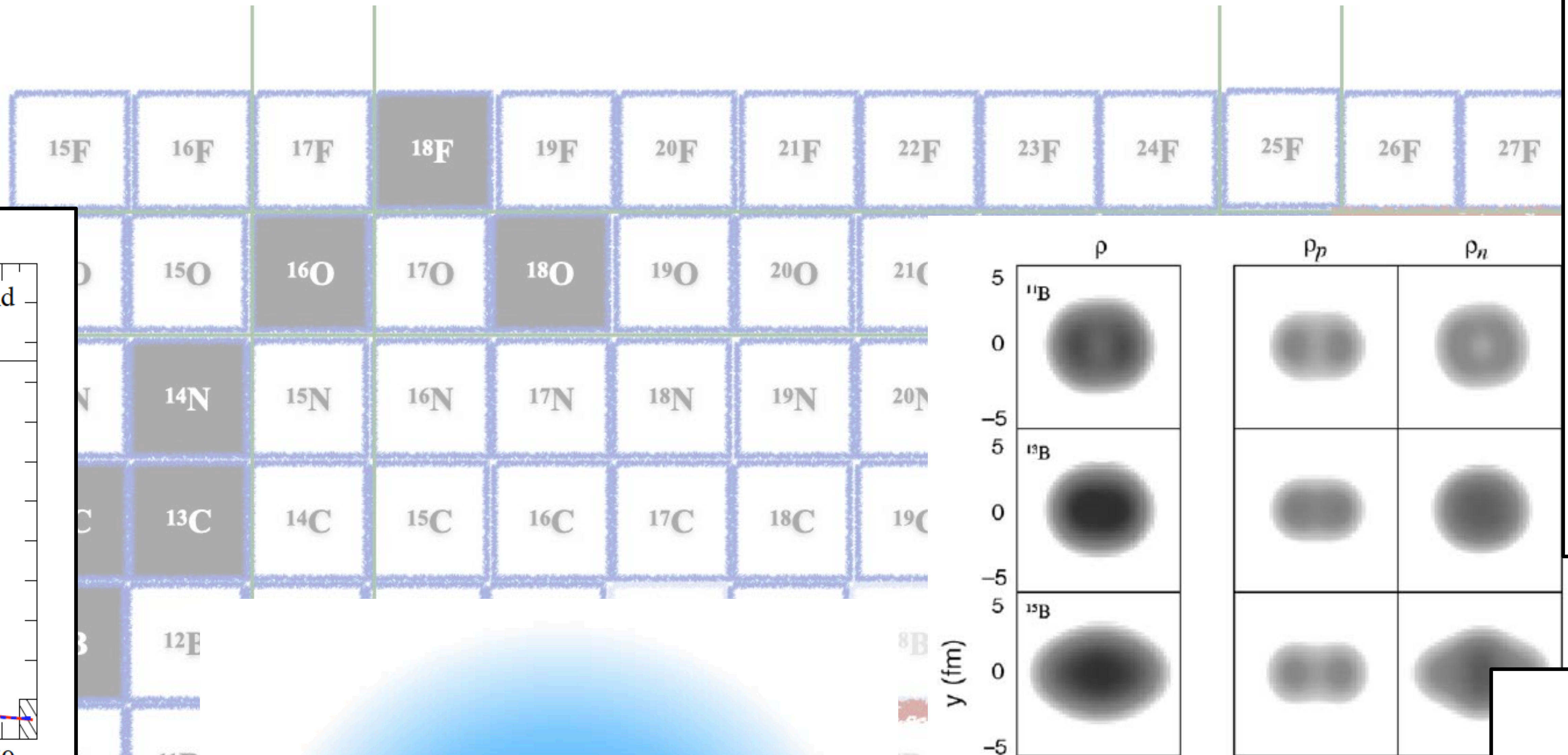
α-particle emission in heavy-ion reactions

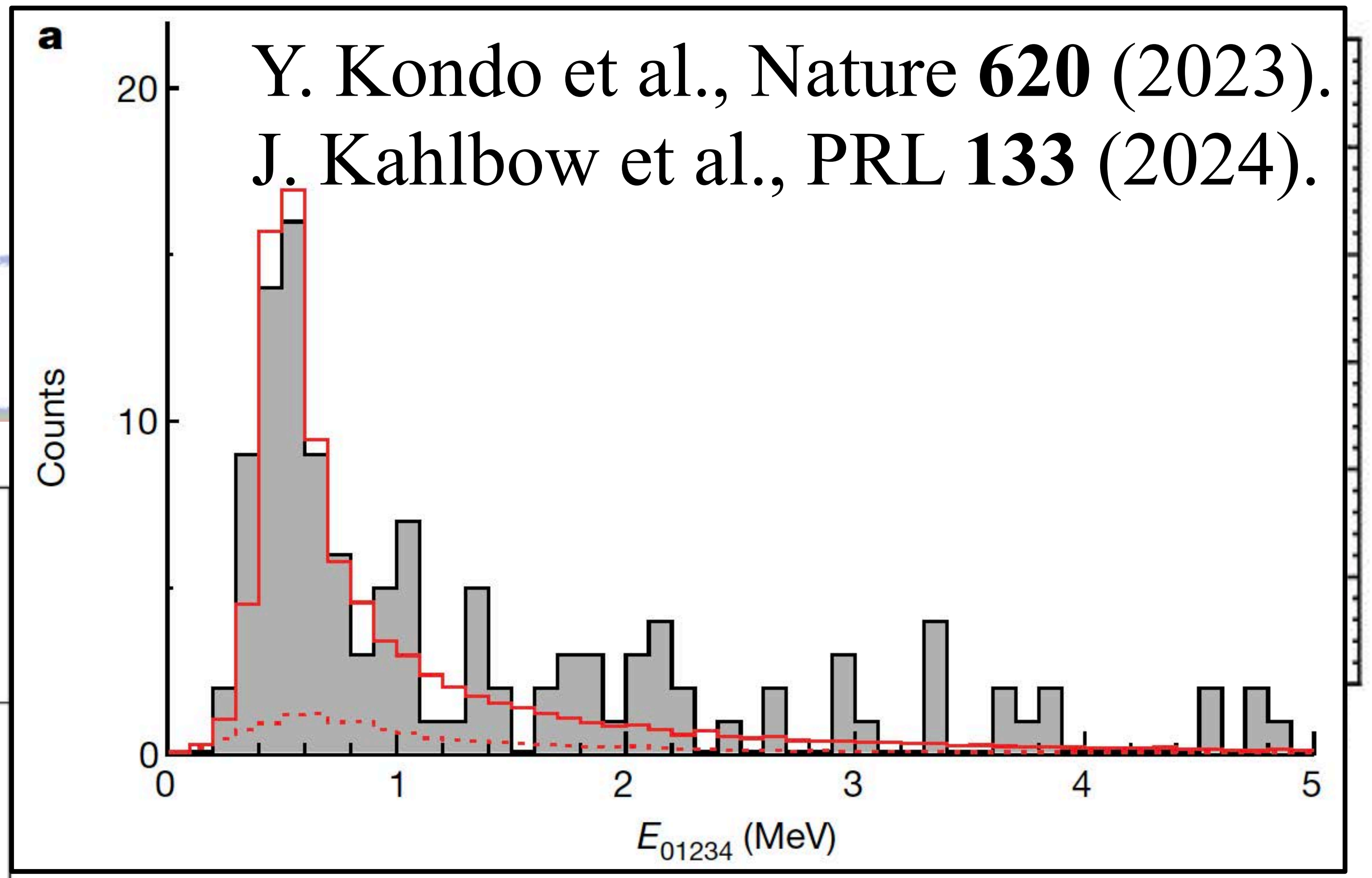
Few-nucleon correlations near the drip-line

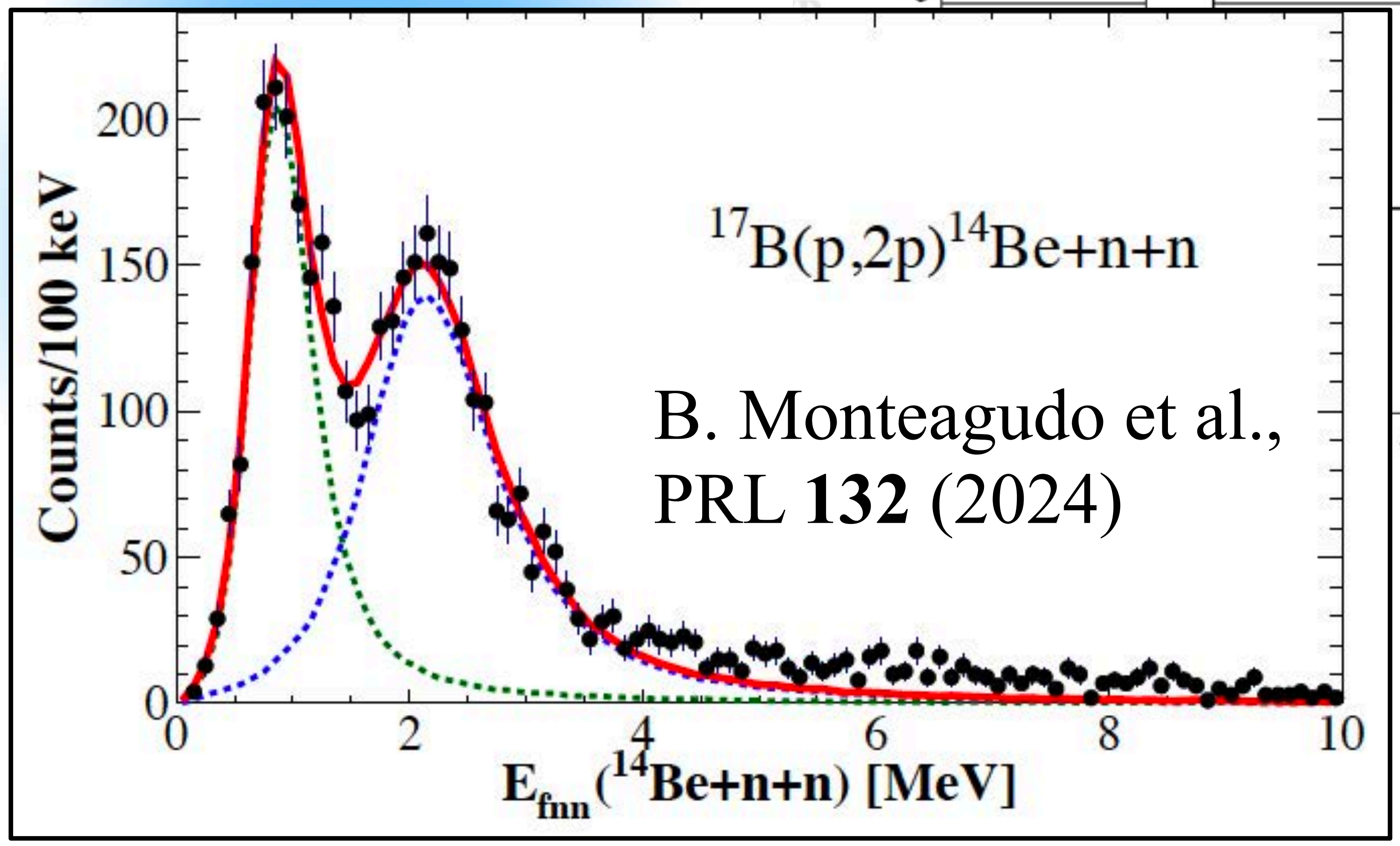
At the limit of nuclear binding, mean-field effects are less manifested, and thus the few-nucleon correlations become more prominent.

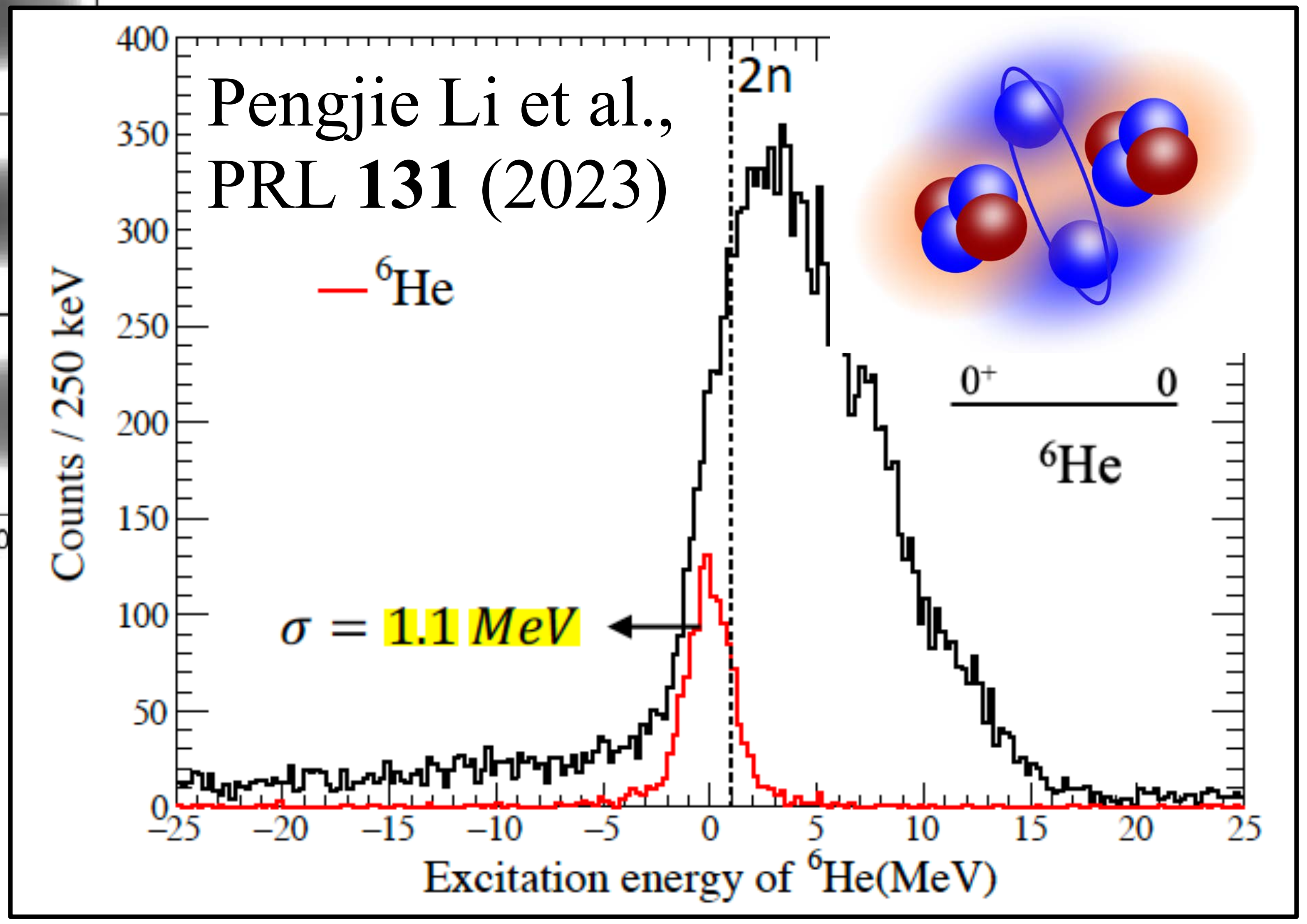






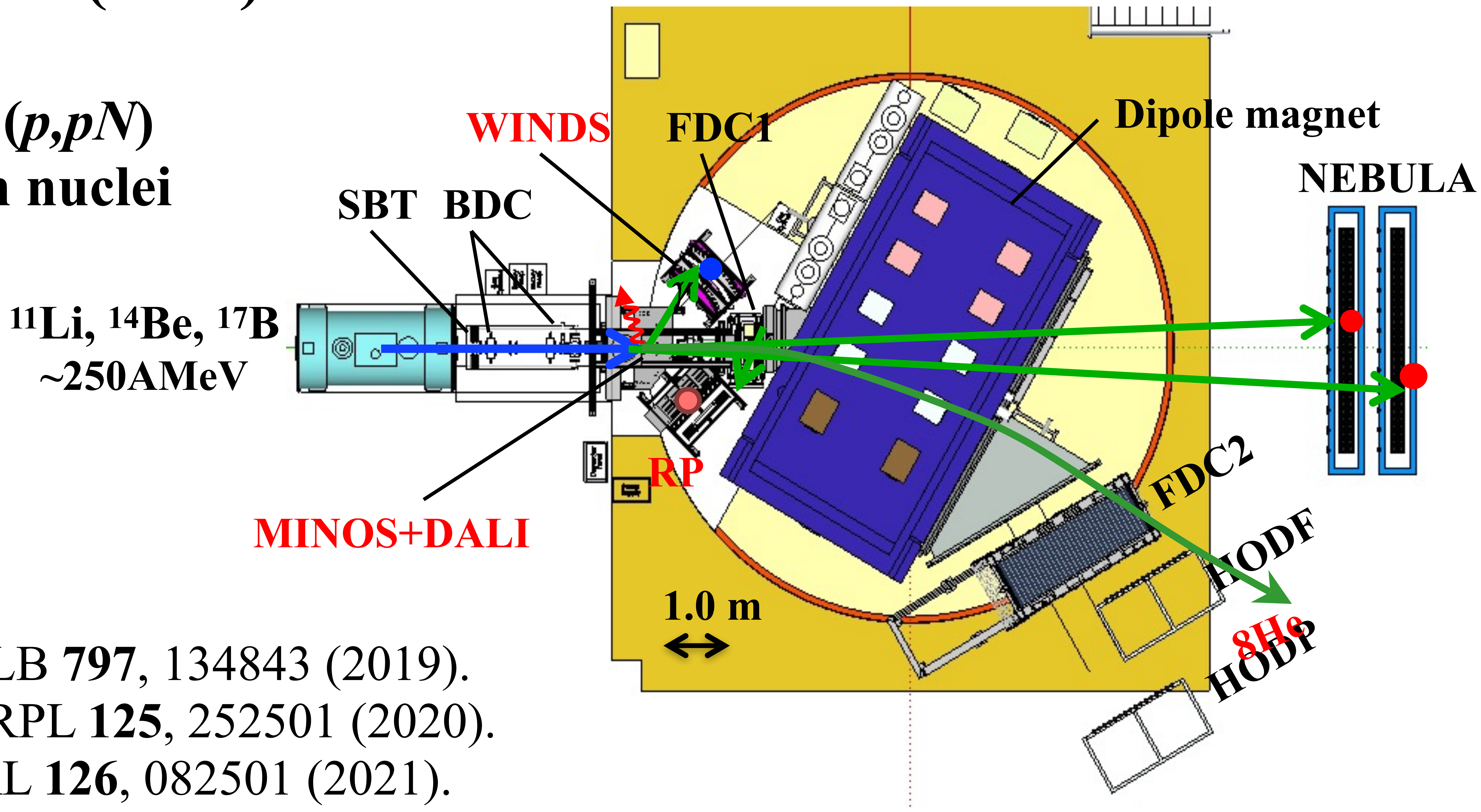






SAMURAI18 at RIKEN (2014)

Neutron/proton knockout (*p,pN*) reactions from Borromean nuclei

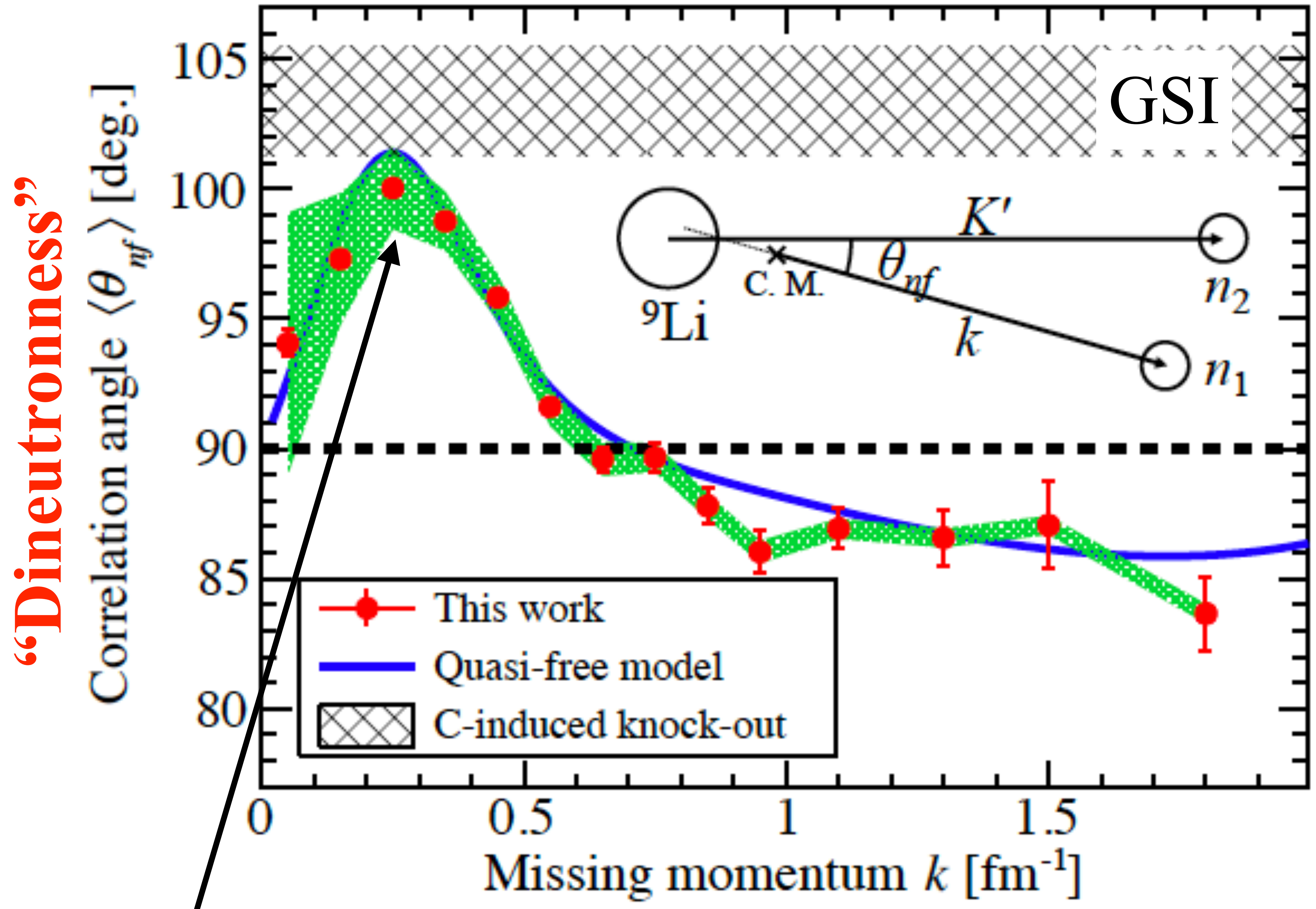


^{14}Be(p,pn)^{13}Be : A. Corsi et al., PLB **797**, 134843 (2019).
^{11}Li(p, pn)^{10}Li : Y. Kubota et al., RPL **125**, 252501 (2020).
^{17}B(p,pn)^{16}B : Z. Yang et al., PRL **126**, 082501 (2021).
^{17}B(p,2p)^{16}Be : B. Monteagudo et al., PRL **132**, 082501 (2024).
^{14}Be(p,2p)^{13}Li : P. André et al. PLB **857**, 138977 (2024).
^{11}Li(p,2p)^{10}He: Y.L. Sun et al., Nat. Comm. 17, 4674 (2026).

Universality of dineutron: A. Corsi, Y. Kubota, Z.H. Yang et al., PLB **840,** 137875 (2023).

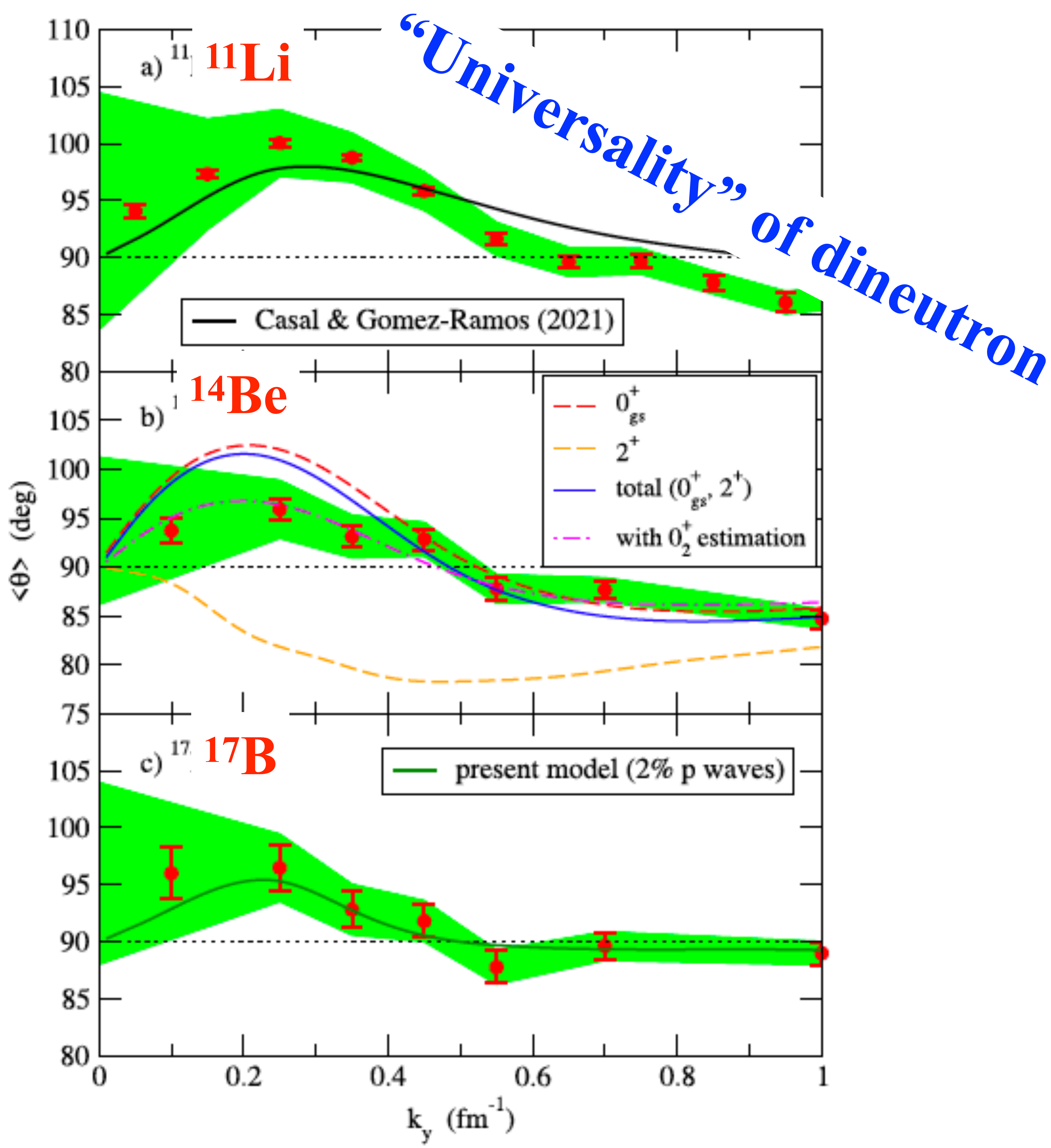
Surface localization of the dineutron in ^{11}Li and its universality

Y. Kubota, A. Corsi et al., PRL **125**, 252501 (2020).



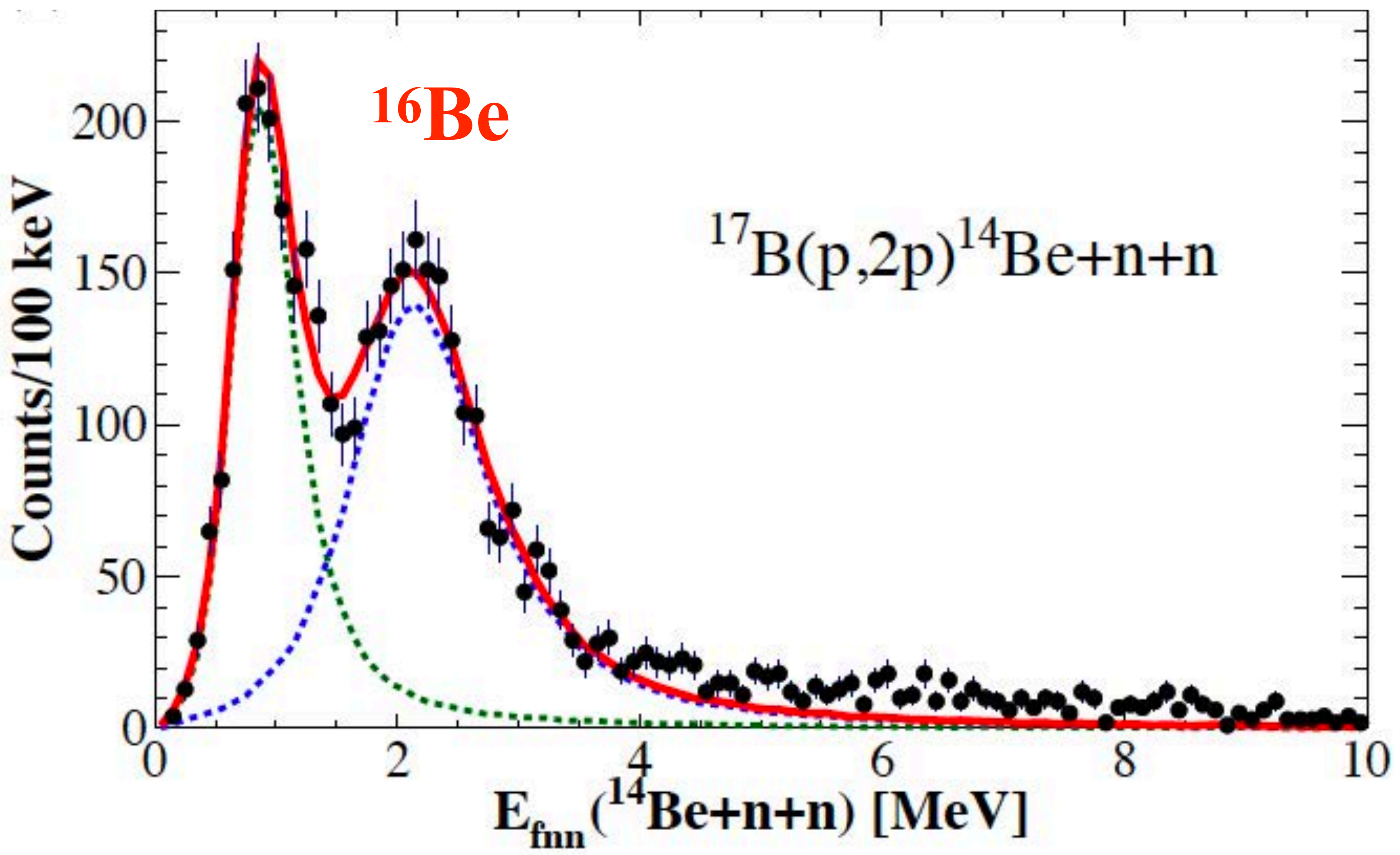
Dineutron is localized in
a limited region around
r~3.6fm (surface of the ^{9}Li core)
↔ Hagino et al., PRL99 (2007)

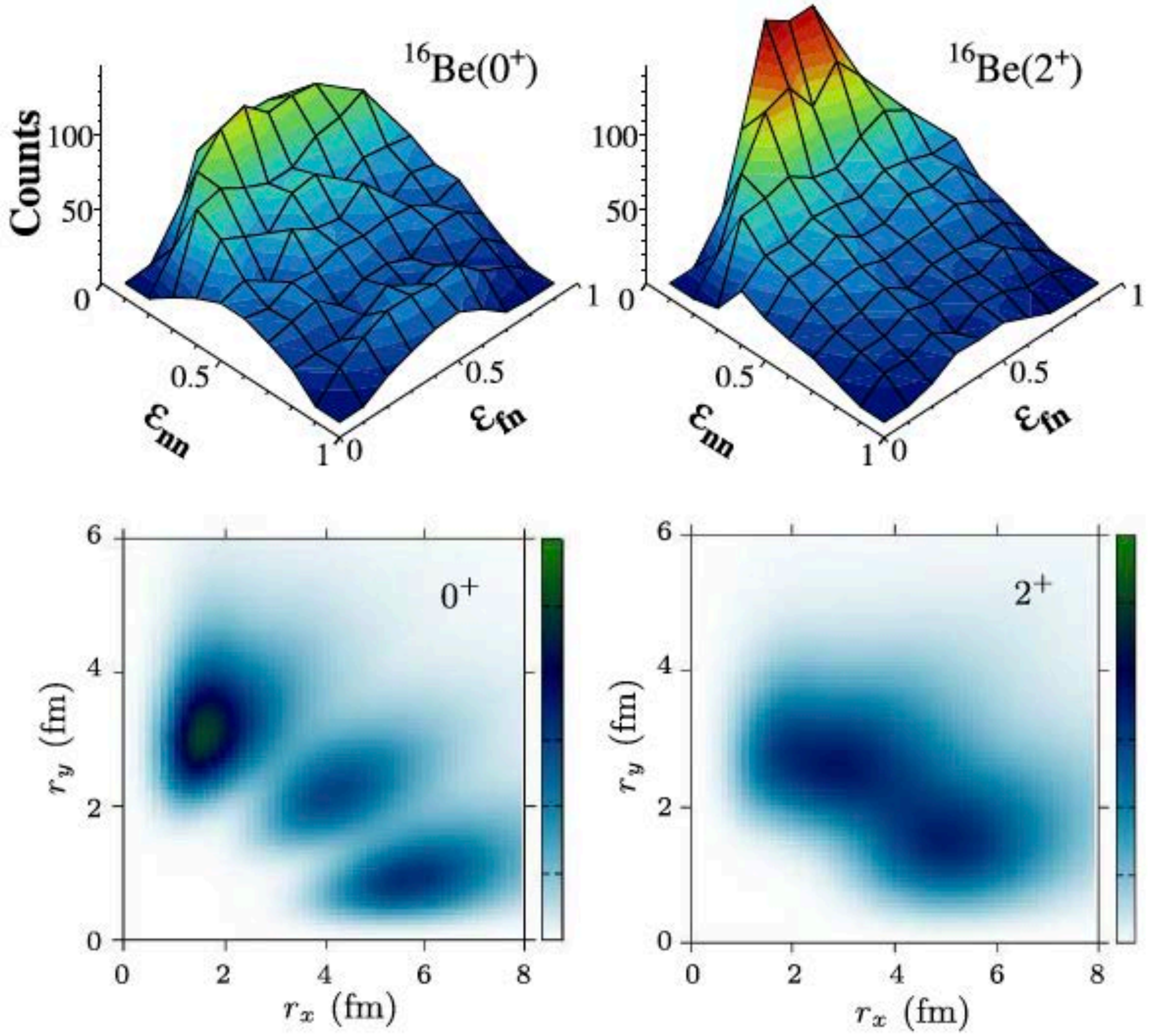
A. Corsi Y. Kubota, Z.H. Yang et al.,
PLB **840**, 137875 (2023)



New results on $^{17}B(p,2p)^{16}Be$

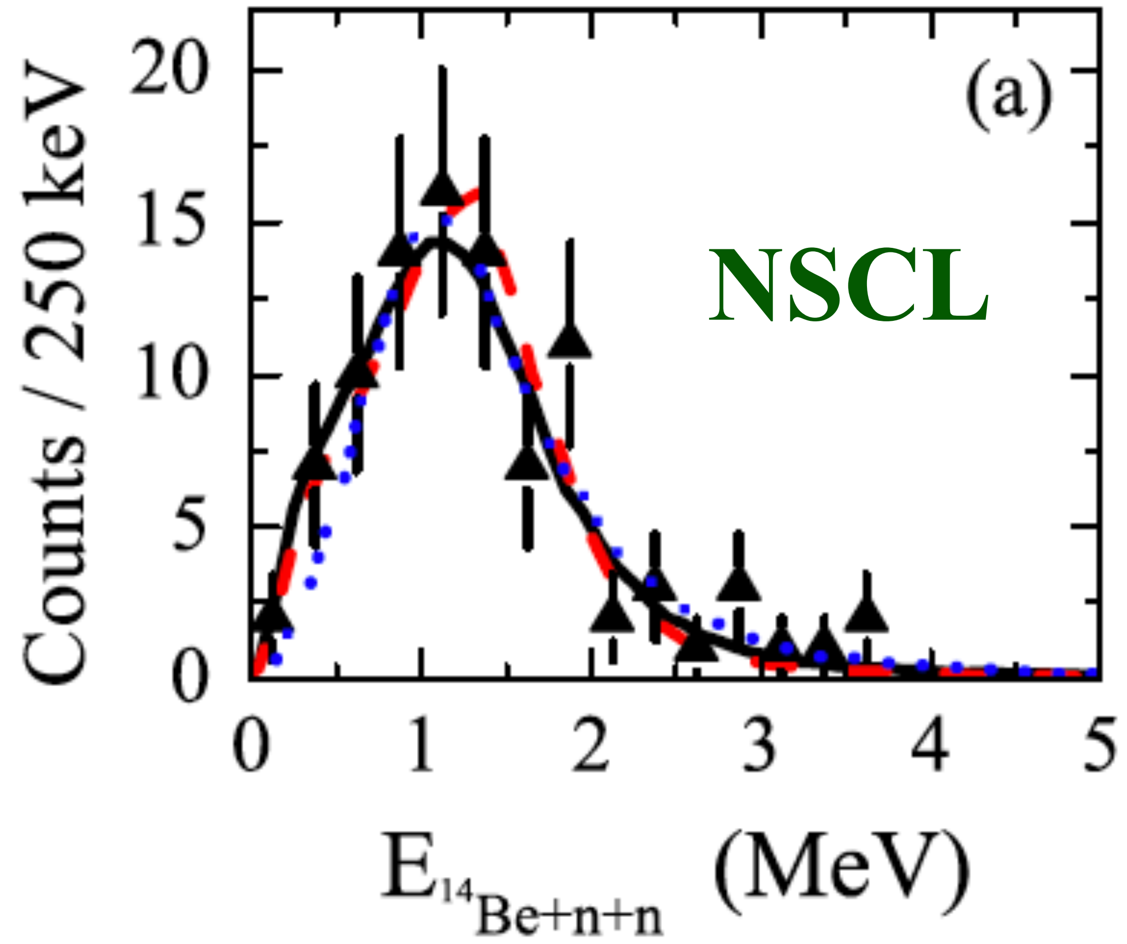
B. Monteagudo, M. Marques et al., PRL **132**, 082501 (2024)





^{16}Be: two-neutron decay nucleus

A. Spyrou et al., PRL 108 (2012).

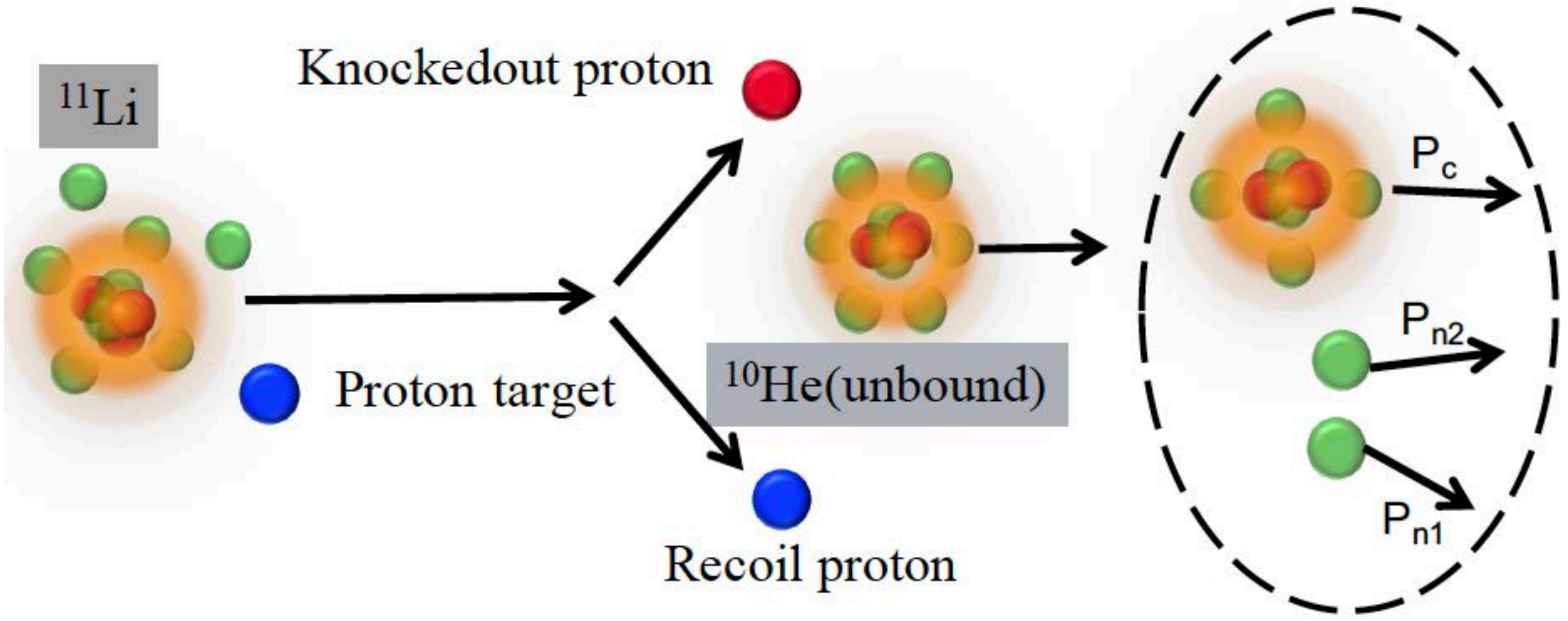


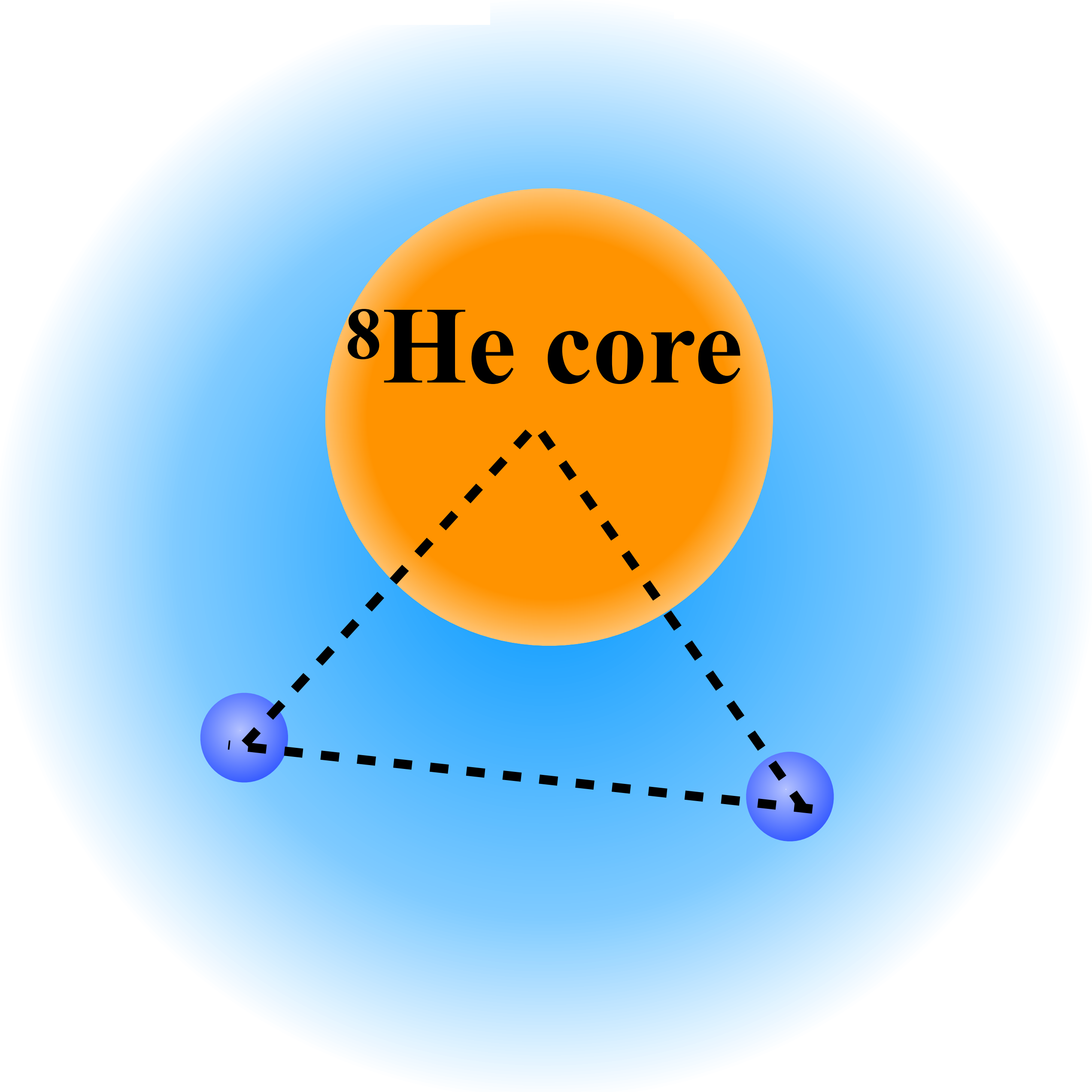
Ground state: decay by emission of a "spatially compact" dineutron

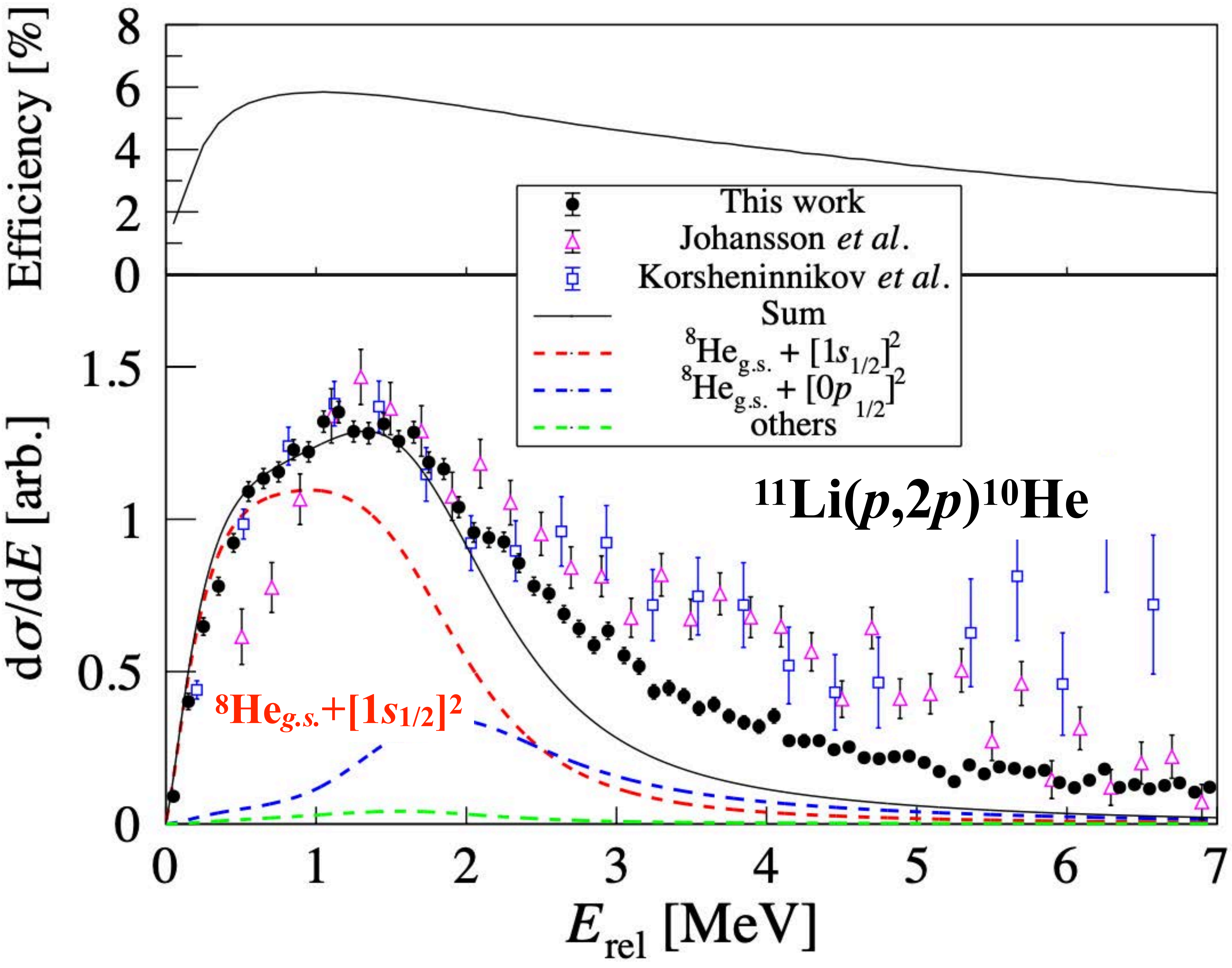
2^+ ex. state: decay by a two-neutron pair with small relative momentum

^{10}He: New result from SAMURAI

Yelei Sun et al., Nat. Comm. 17, 4674 (2026)







From nuclei to universalities in physics systems

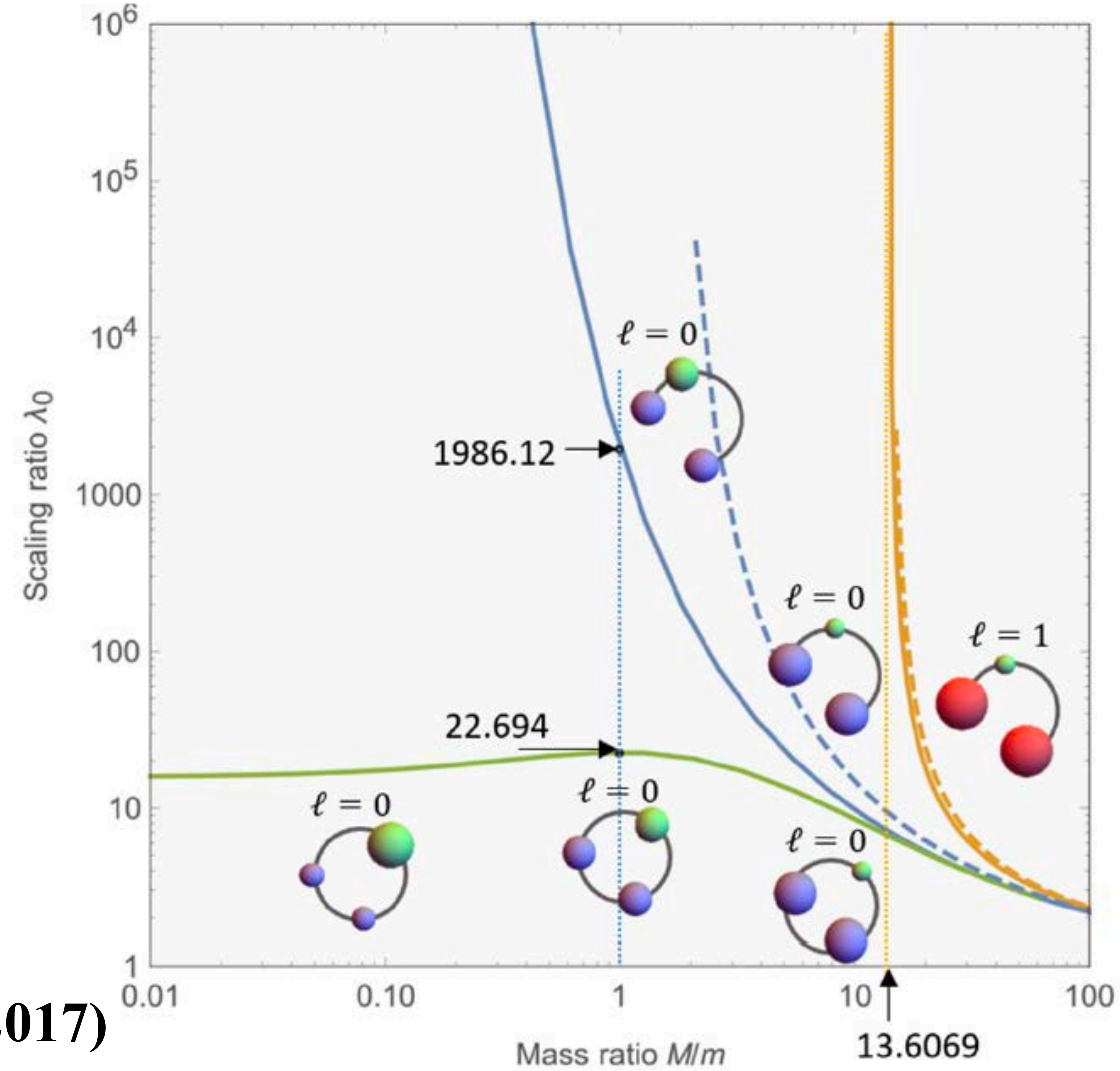
When the interaction satisfies some conditions (e.g., scattering lengths $|a| \to \infty$ or 0), universality emerges.

The famous example is the Efimov states for $|a| \to \infty$ in all the subsystems.

Search for the Efimov states in nuclear systems is still ongoing.

^{19}B observed in the SAMURAI DayOne experiment could be a good candidate.

J. Carbonell1, E. Hiyama, R. Lazauskas, F. M. Marques, Journal of Physics Conference Series 1643, 012120 (2020).



P. Naidon and S. Endo, Rep. Prog. Phys. 80, 056001 (2017)

A new universal halo state predicted

Hongo and Son proposed a new family of universal halo states:

M. Hongo and D.T. Son, "Universal properties of weakly bound two-nucleon halo nuclei", Physical Review Letters 128, 212501 (2022).

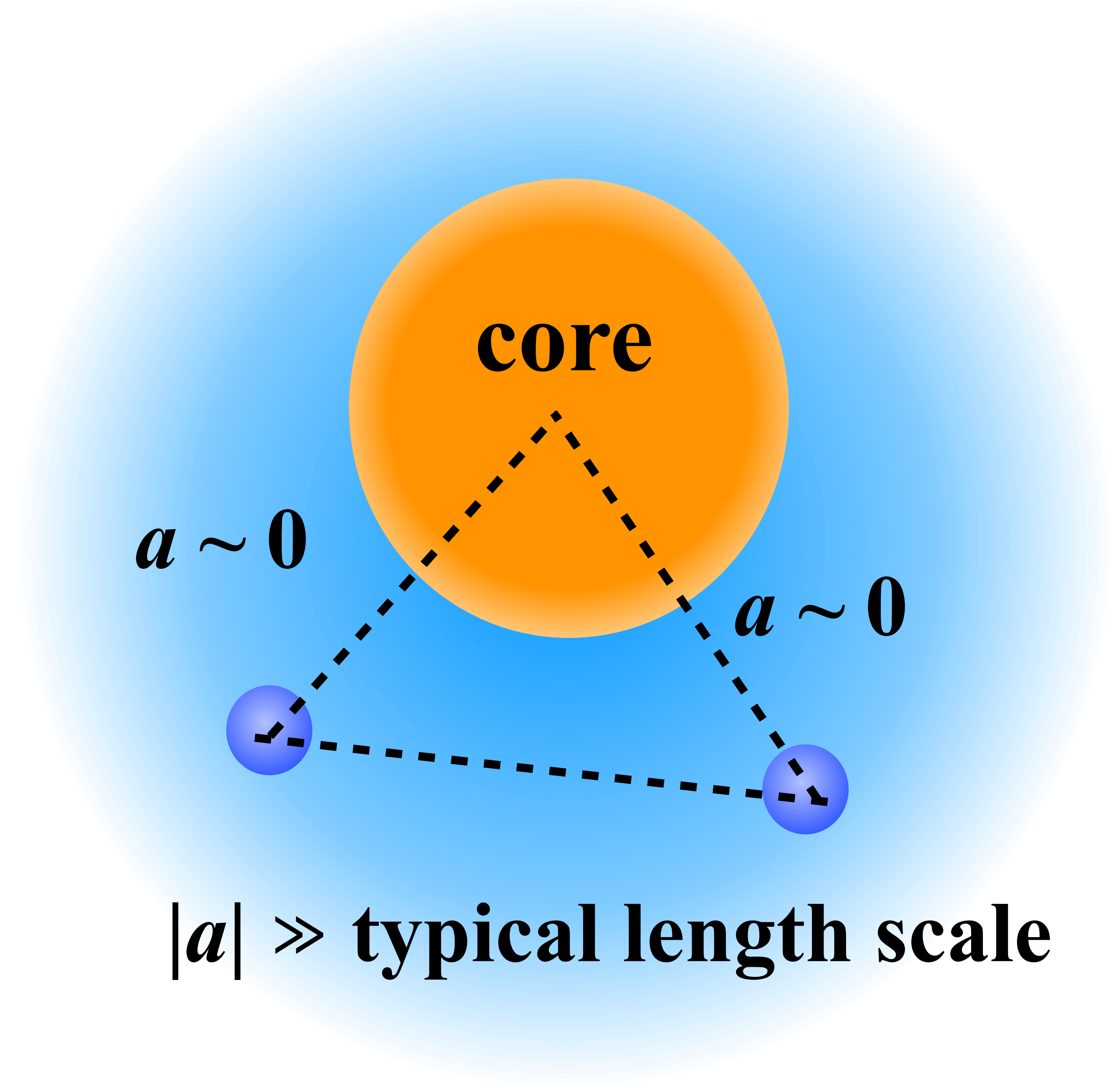
Scattering length $|a|$ is large ($\gg$ typical length scale of the system) for one subsystem, and $a \sim 0$ for other subsystems

Universality in radii is predicted

$$\frac{\langle r_m^2 \rangle}{\langle r_c^2 \rangle} = \begin{cases} \frac{2}{3}A, & B \gg \epsilon_n, \\ A, & B \ll \epsilon_n, \end{cases} \tag{21}$$

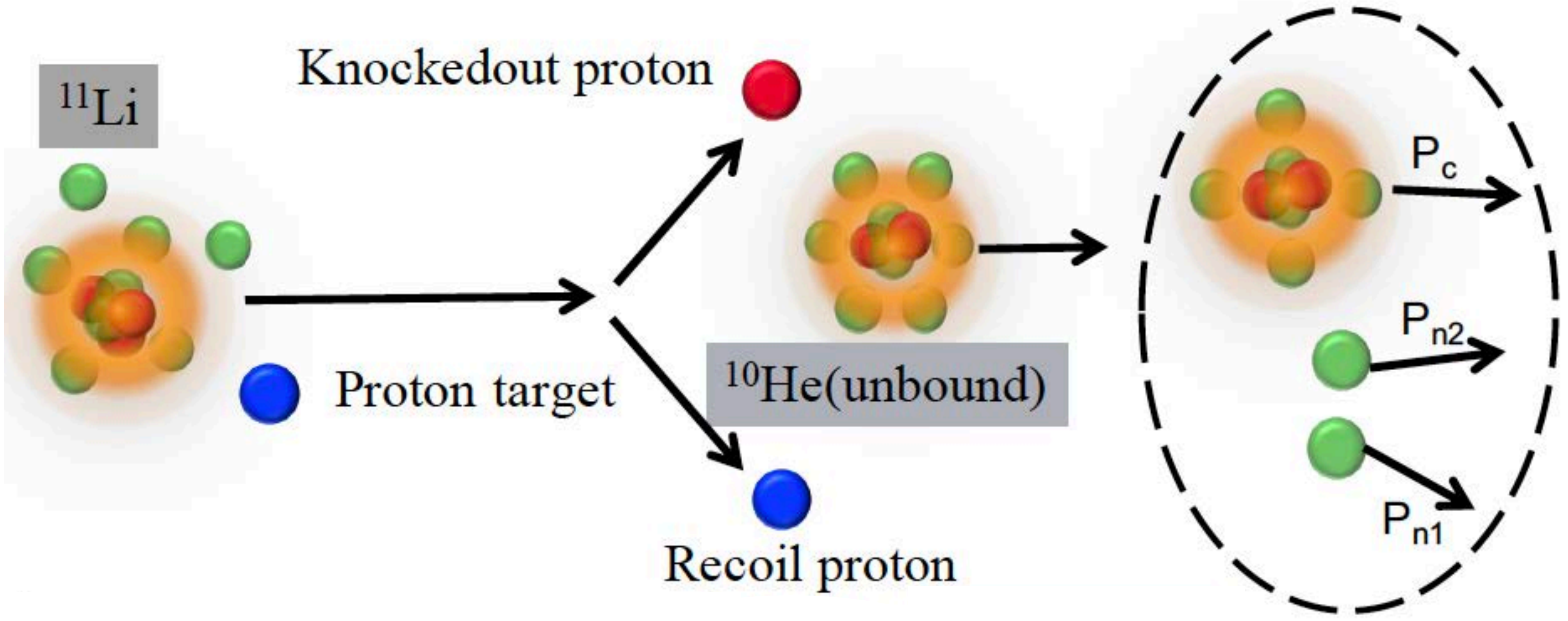
$$\frac{\langle r_{cn}^2 \rangle}{\langle r_{nn}^2 \rangle} = \begin{cases} 1 + \frac{3}{2A}, & B \gg \epsilon_n, \\ \frac{A+1}{2A}, & B \ll \epsilon_n. \end{cases} \tag{22}$$

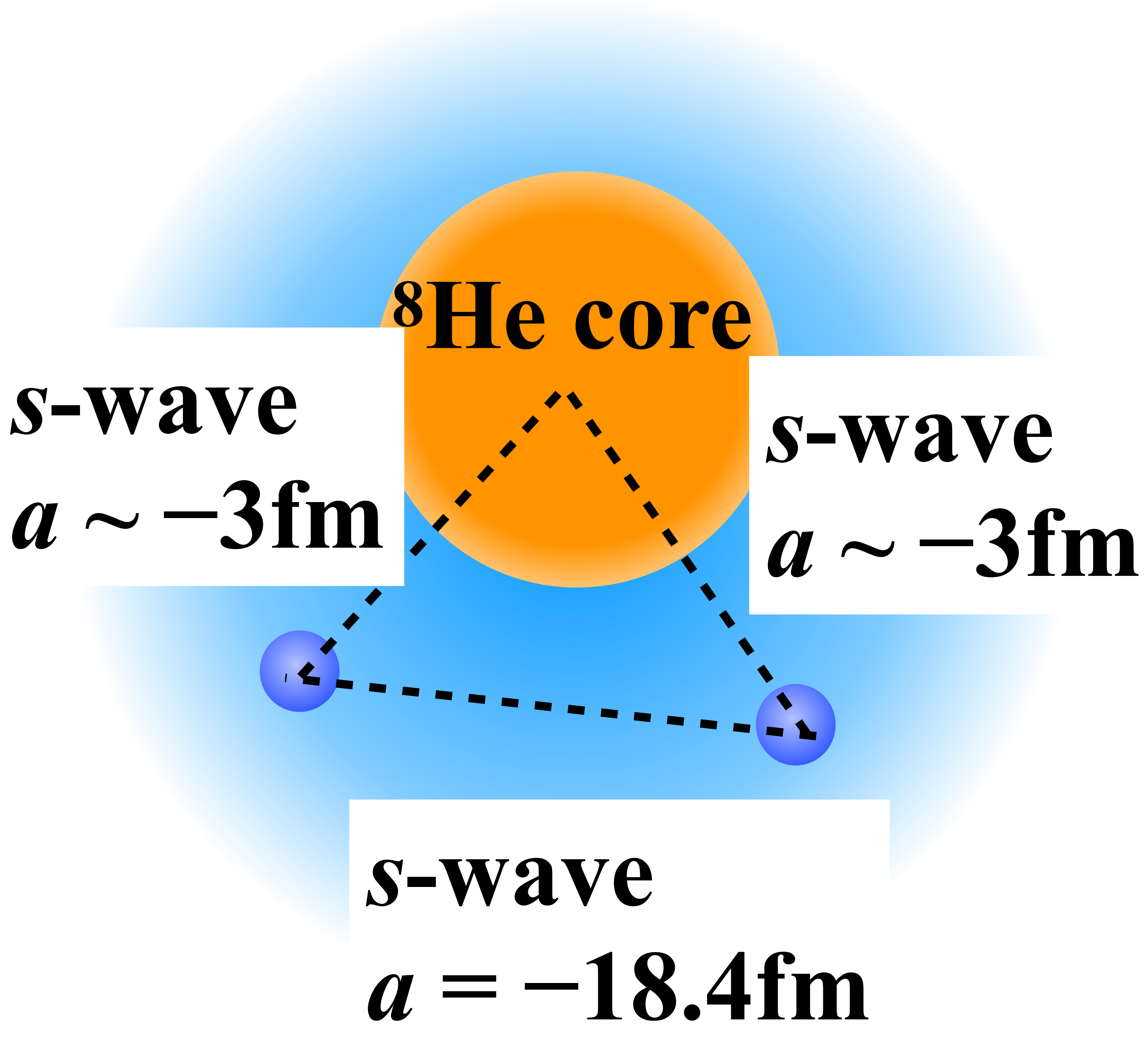
No experimental observation

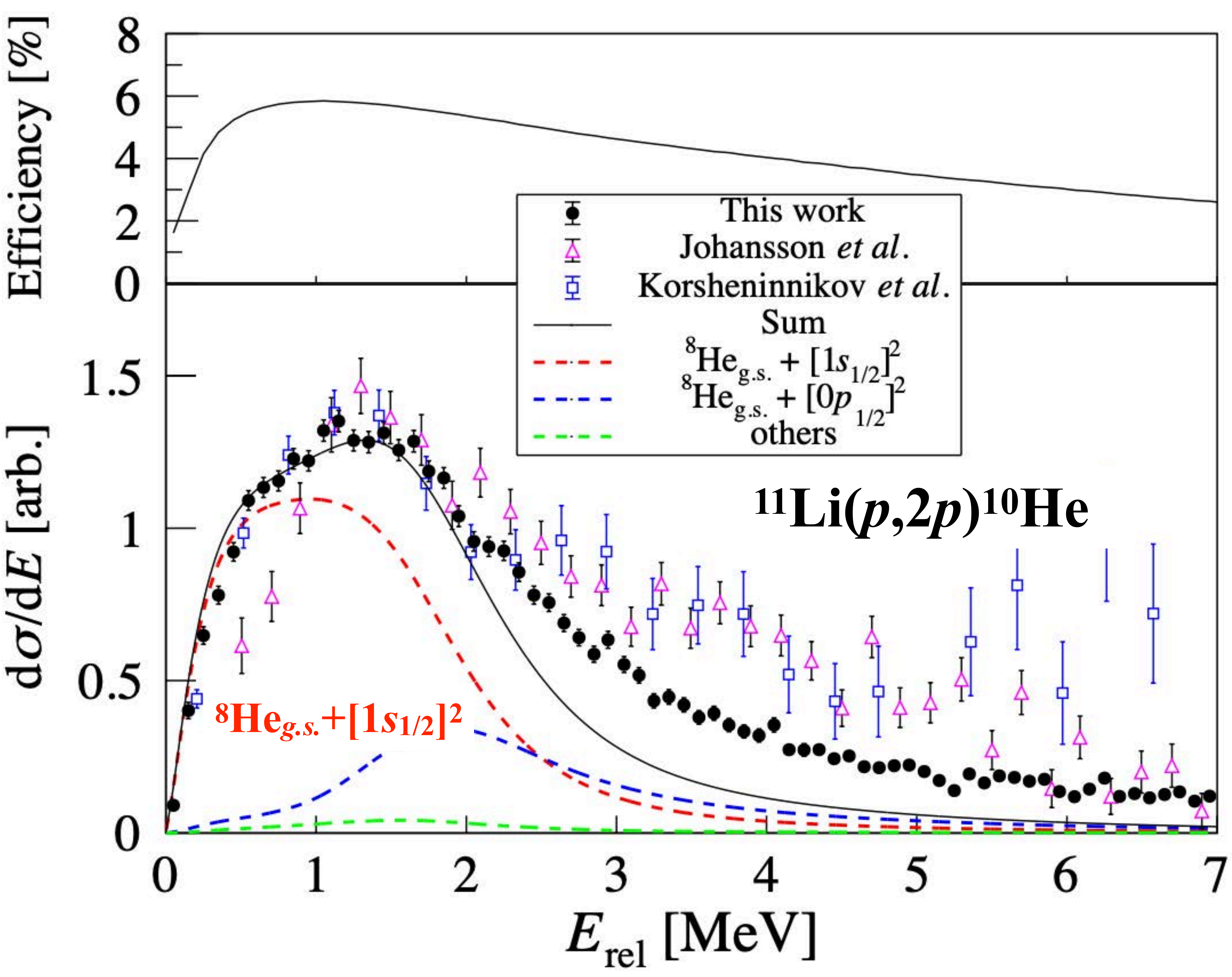


^{10}He: New result from SAMURAI

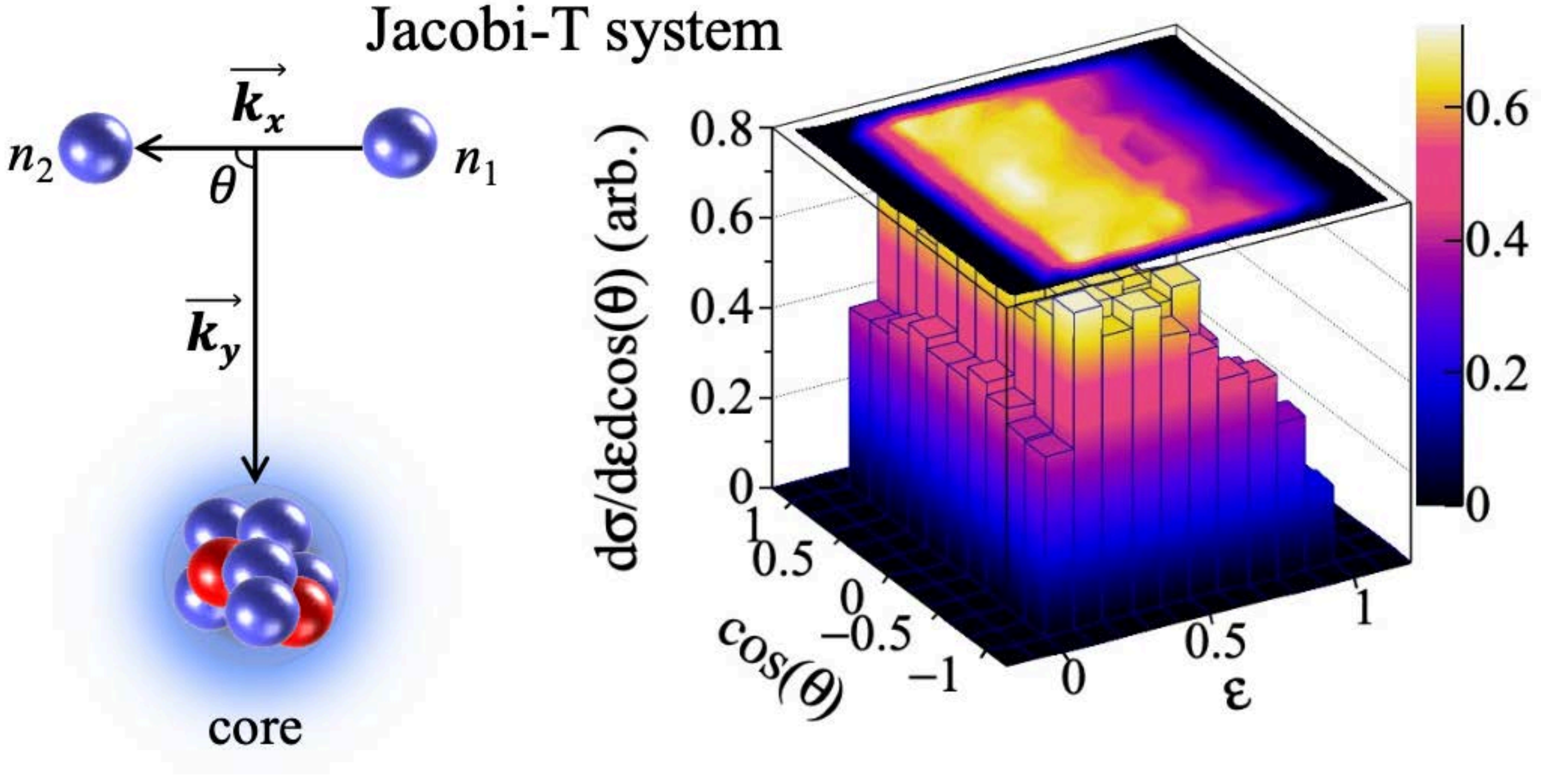
Yelei Sun et al., Nat. Comm. 17, 4674 (2026)

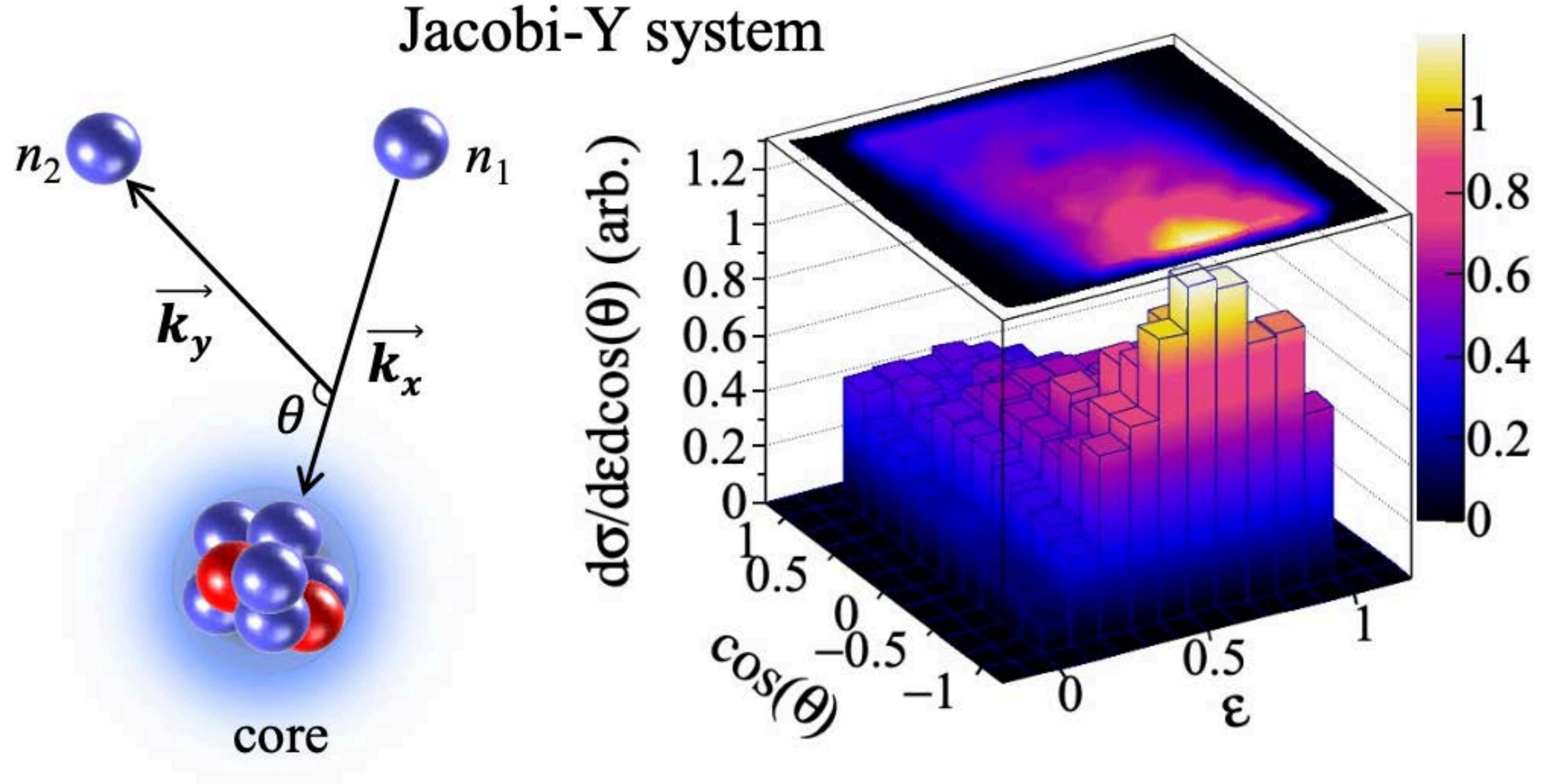


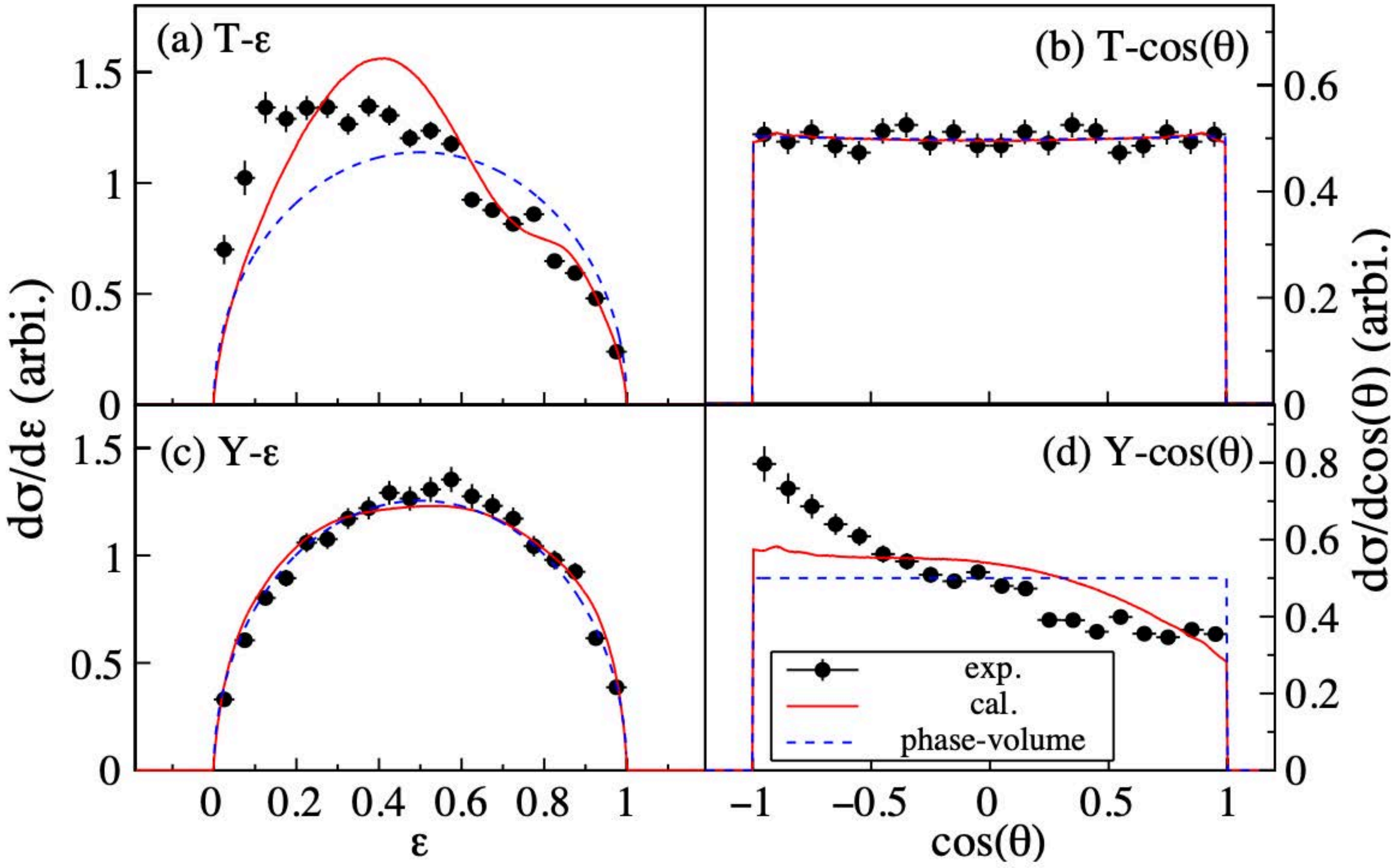




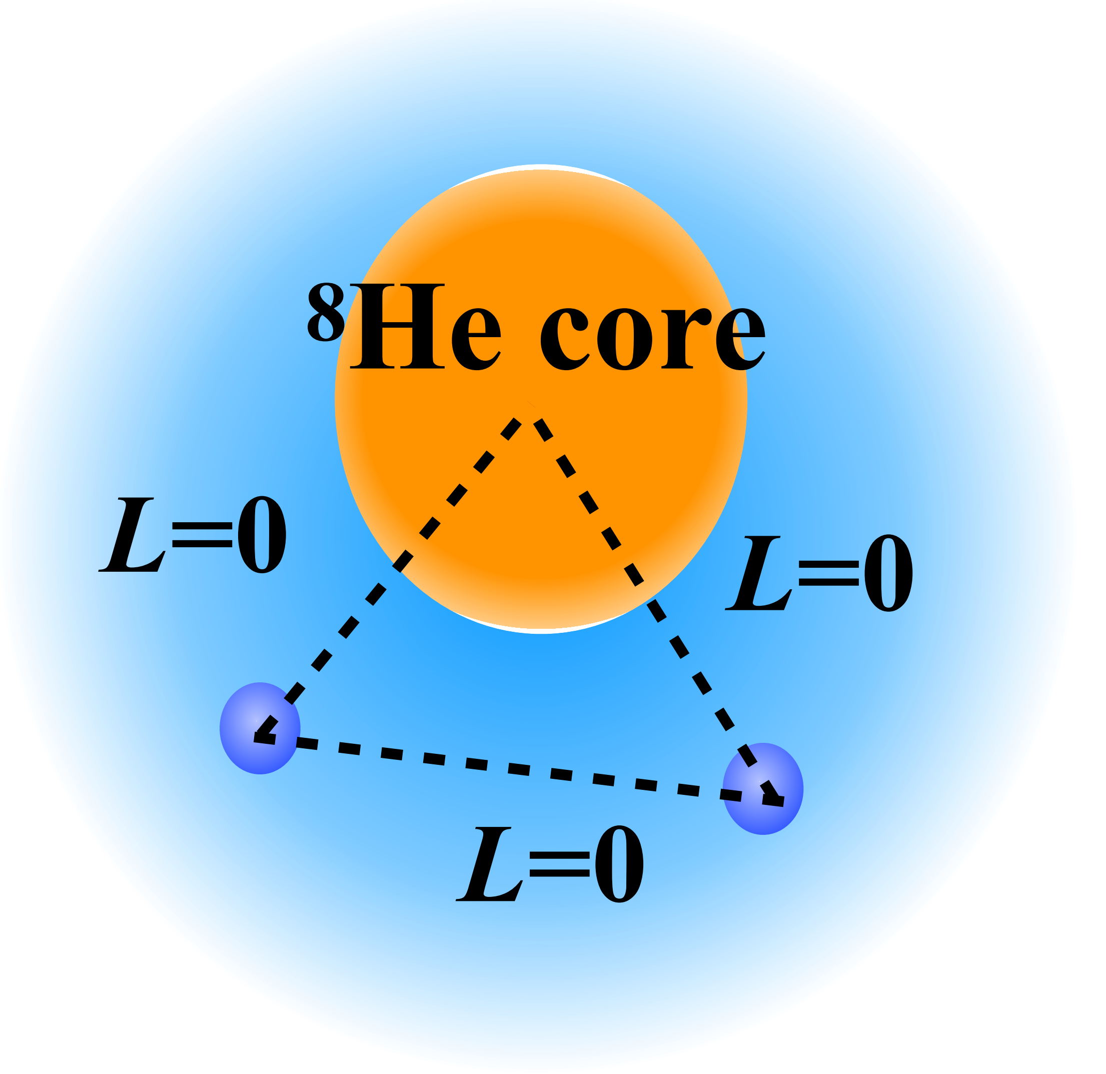
Three-body correlations of the 0_1^+ state







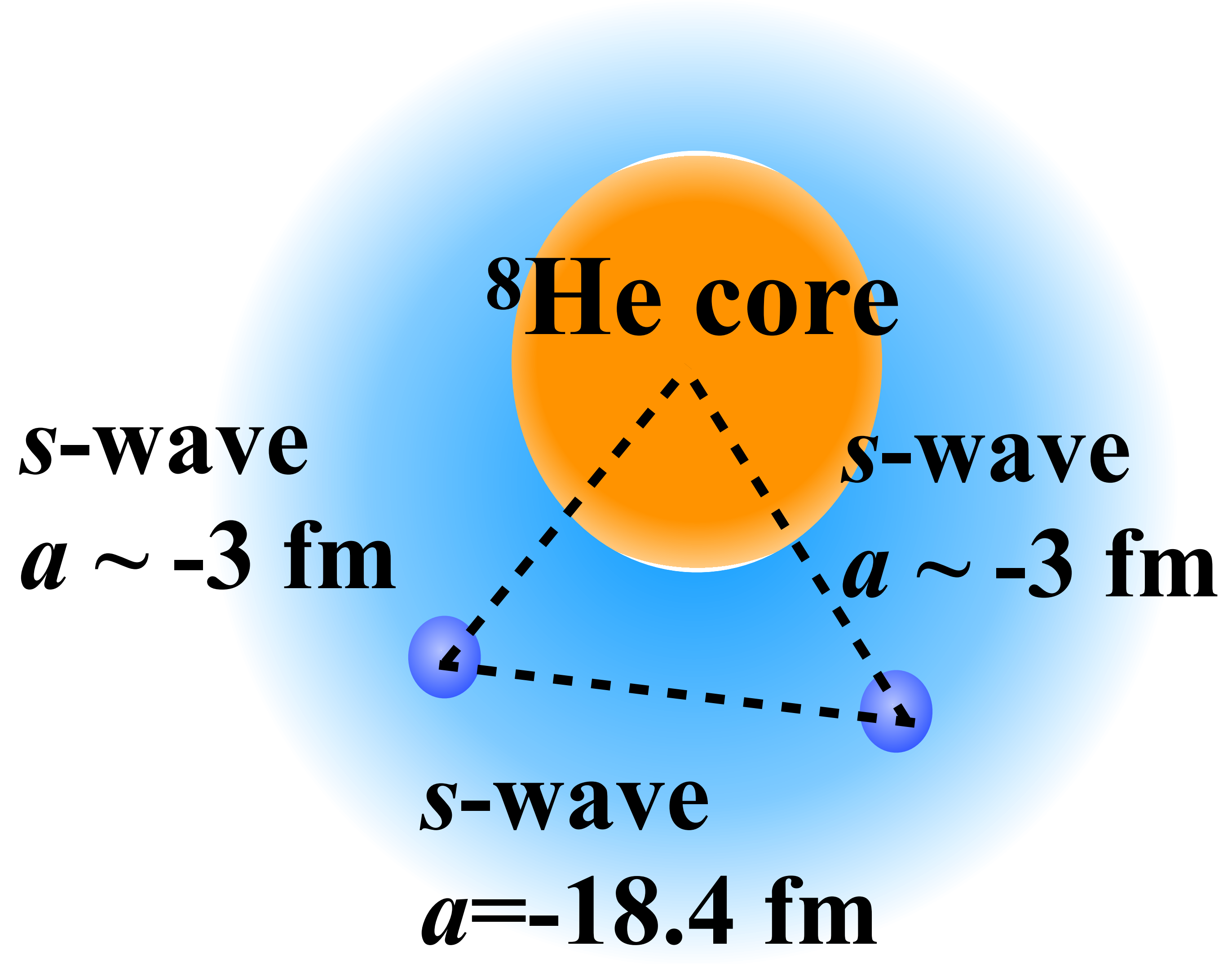
→Support L=0 nature of all the subsystems.



Yelei Sun et al.

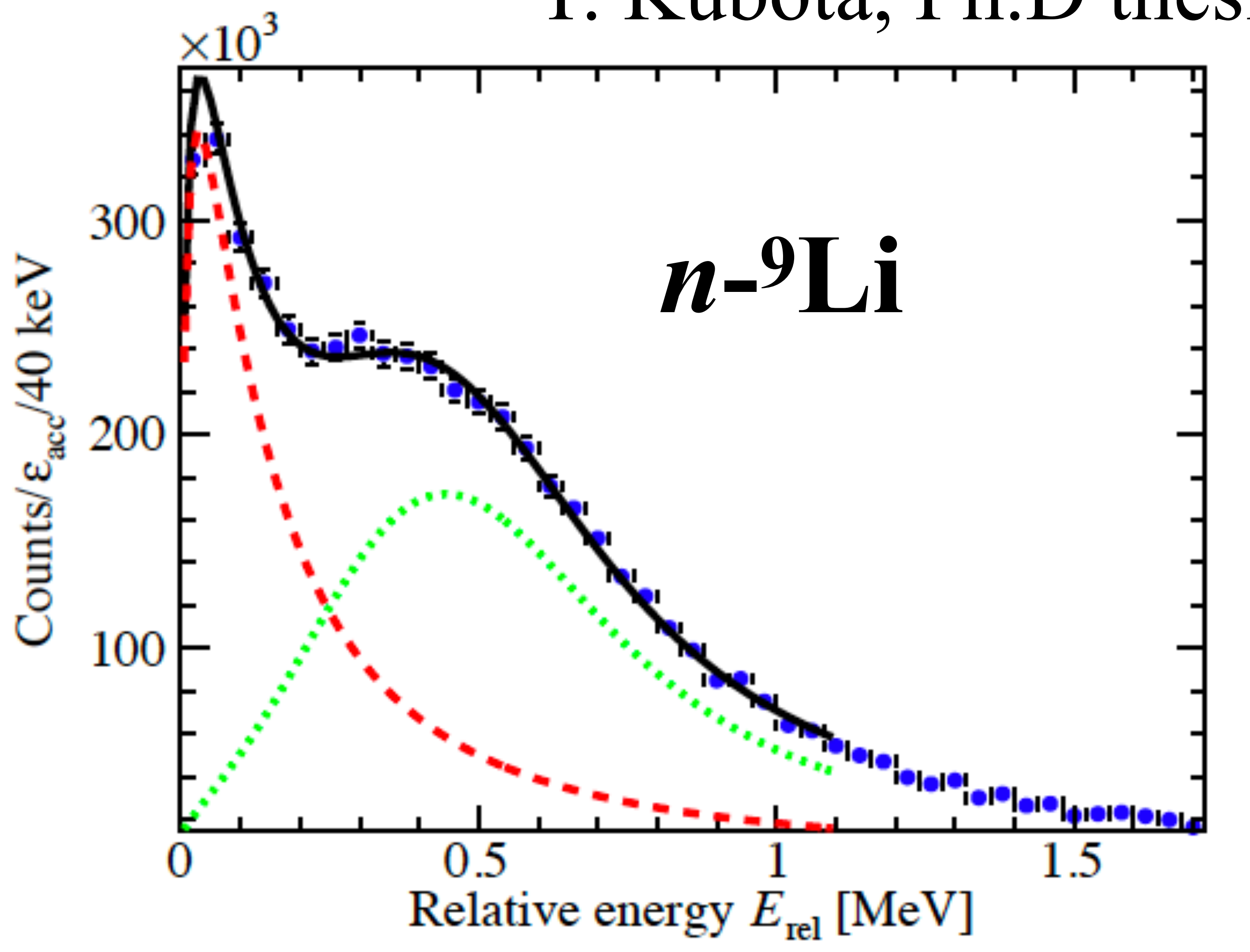
^{10}He ground state: 3-body s-wave resonance

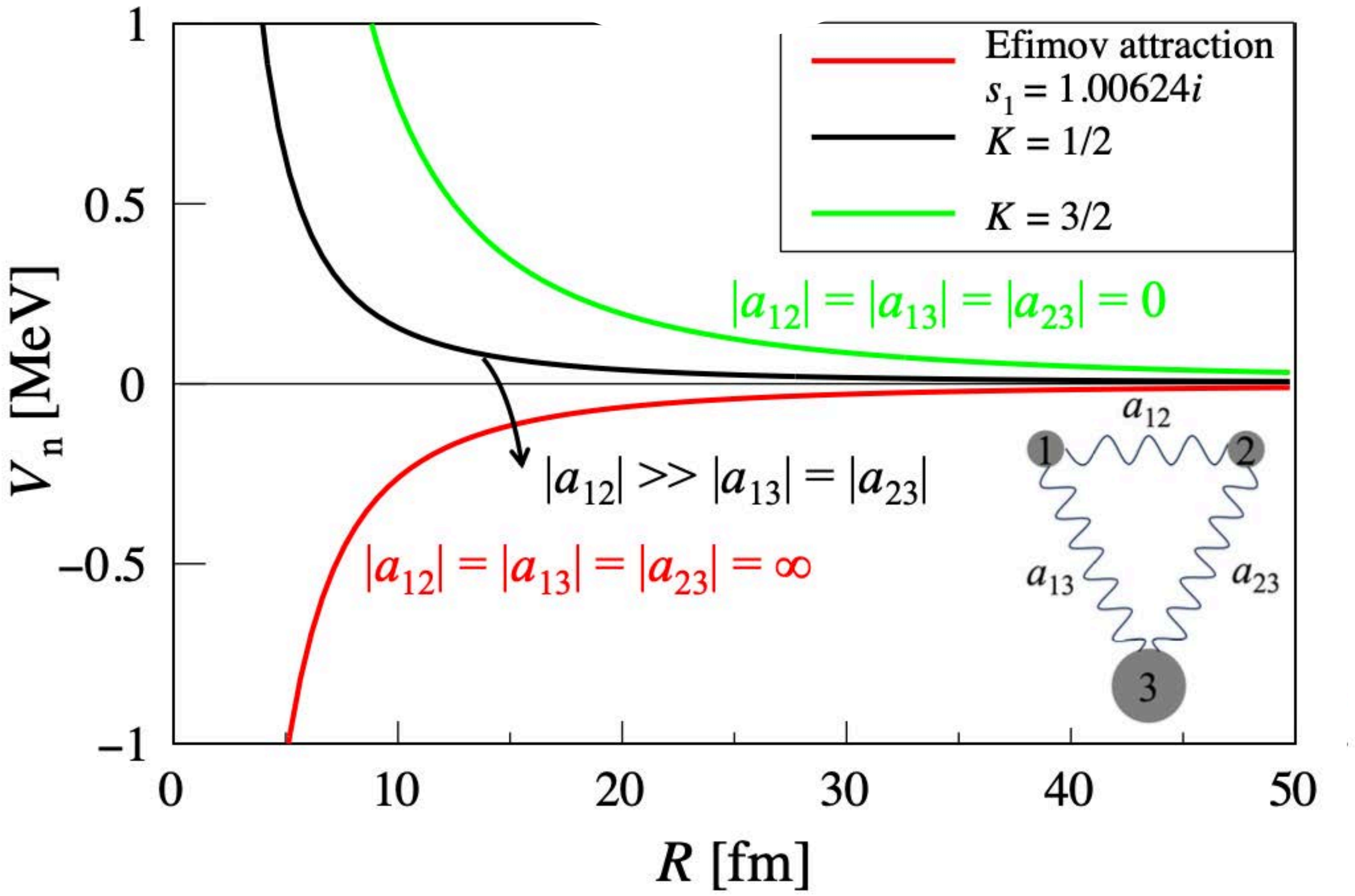
Yelei Sun et al.,
Nat. Comm. 17, 4674 (2026)



2-body s-wave systems w/o Coulomb interaction cannot be resonances.
→ virtual states

Y. Kubota, Ph.D thesis





Why can the 3-body s-wave state be a resonance?
→ due to the universal repulsive long-range force unique in 3-body states with $a_{nn} \gg a_{nc}$.

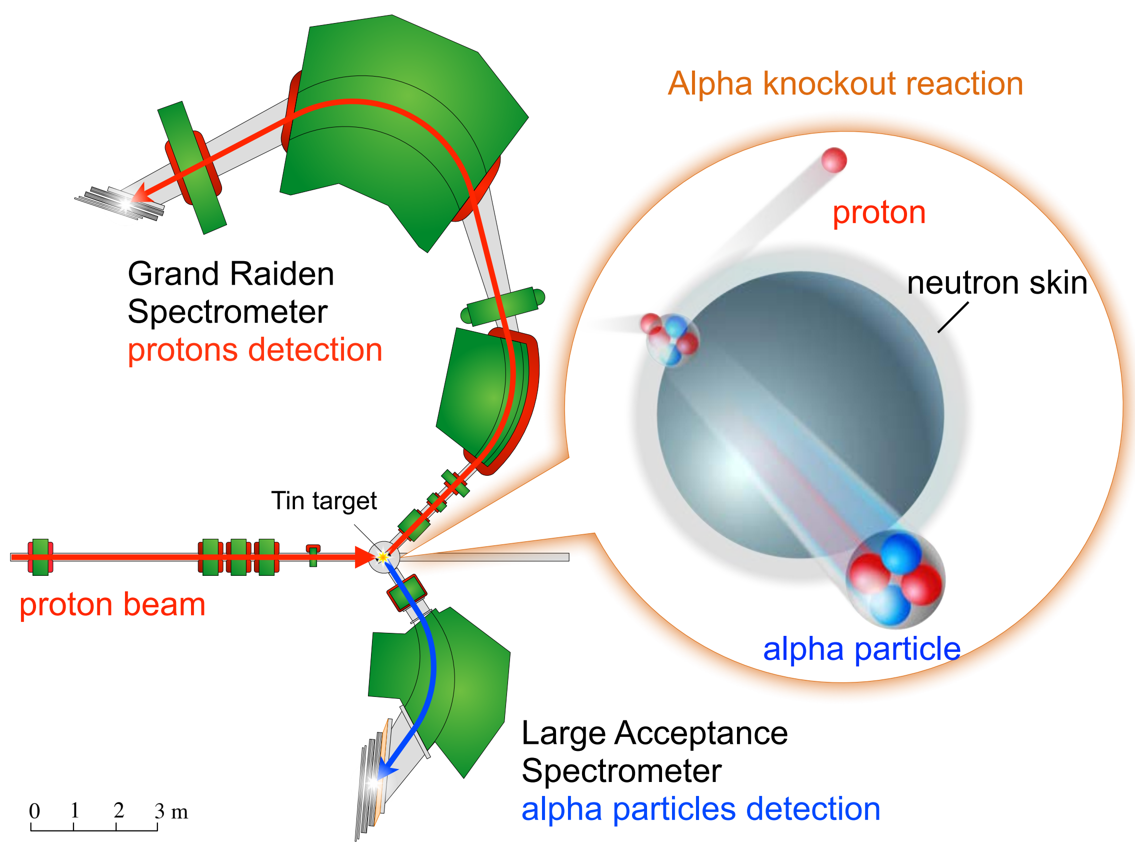
The ^{10}He ground state is the first observed case of the Hongo-Son's universal s-wave state.
Studies with other systems, e.g. cold atoms, and theoretical studies will follow.

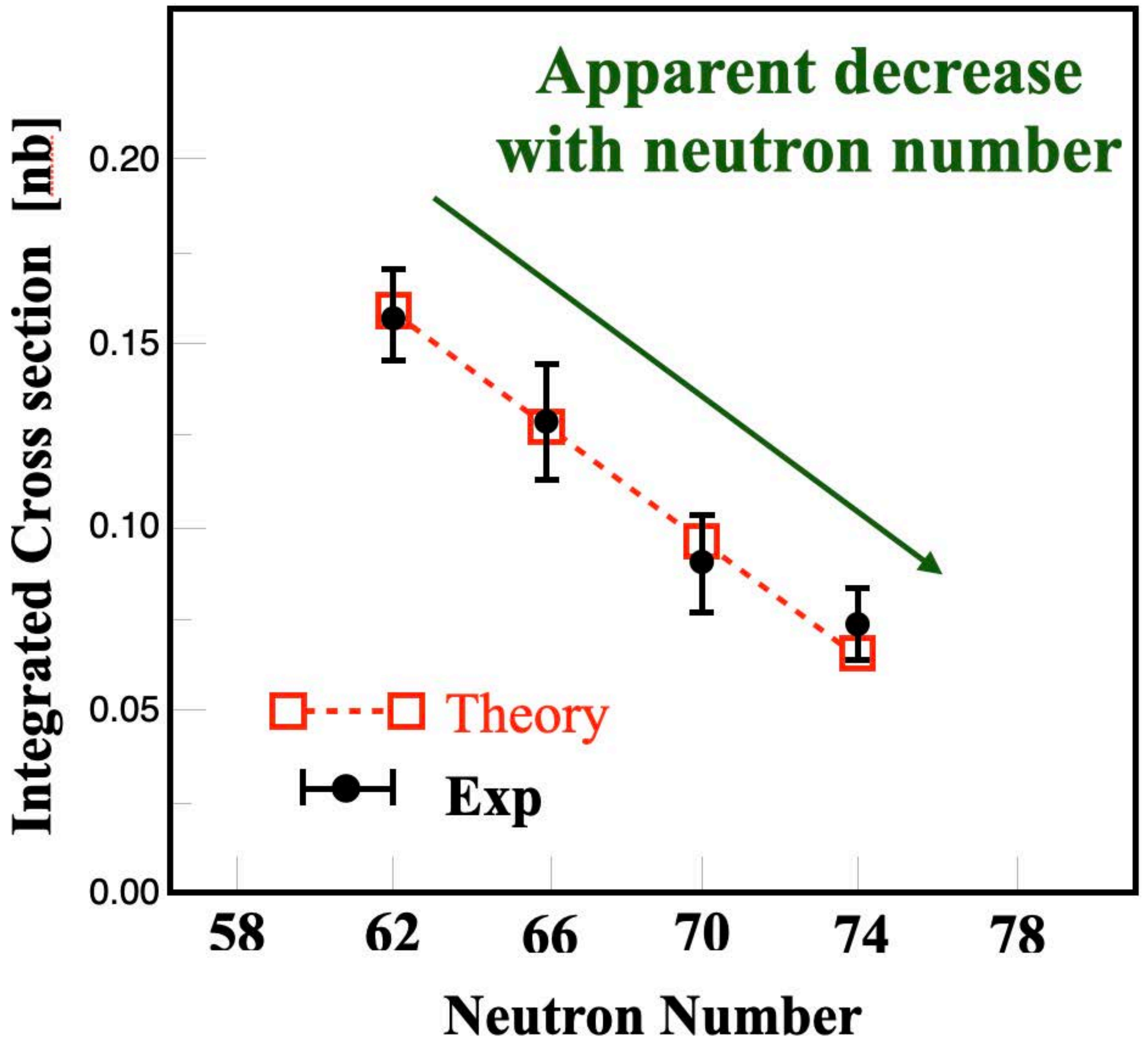
Knockout reaction studies of nuclear clustering

Quasi-free cluster knockout (*p,pα*) reactions

J. Tanaka, Z.H. Yang et al., Science 371, 260 (2021).

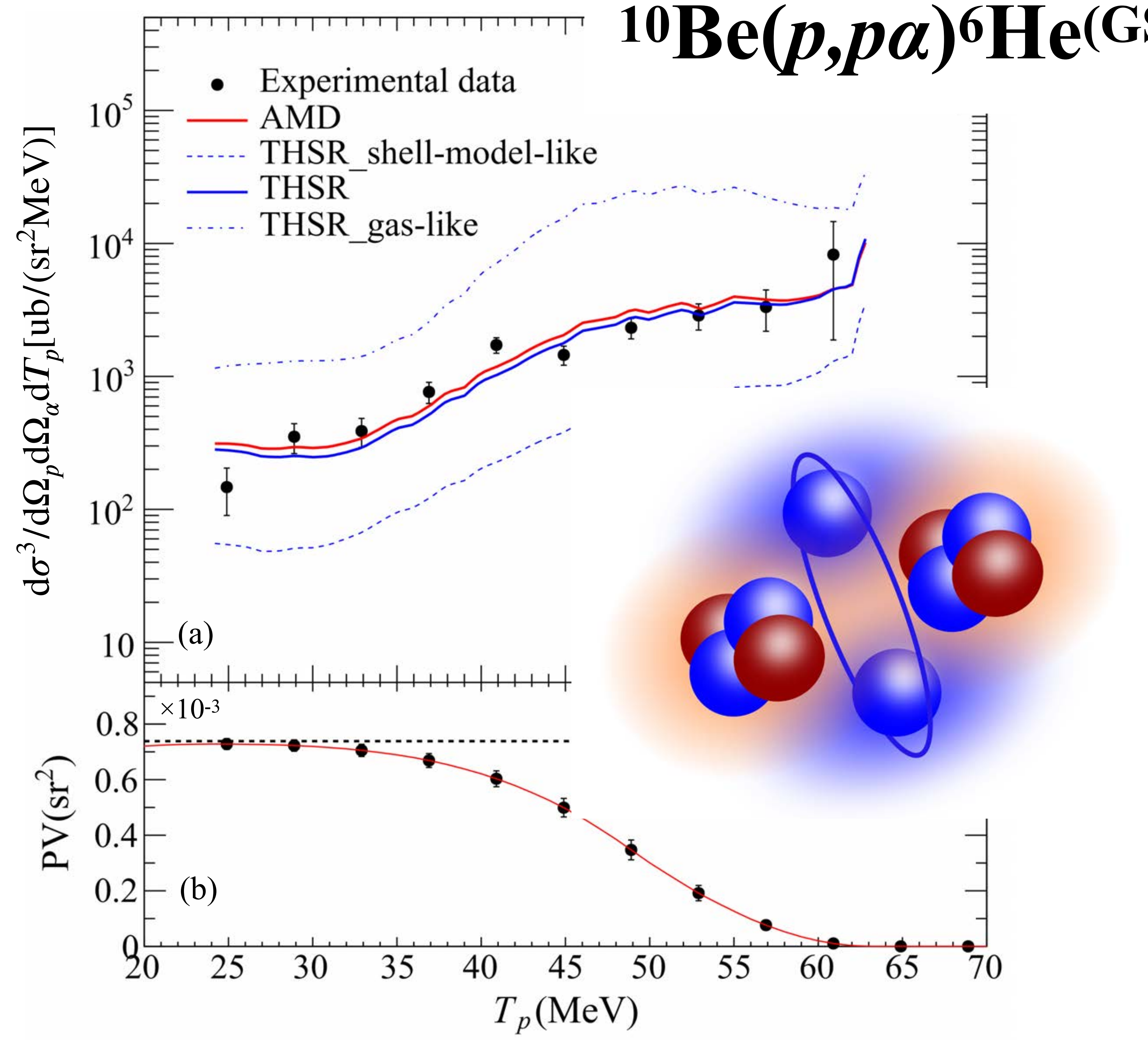
Formation of α in Sn isotopes



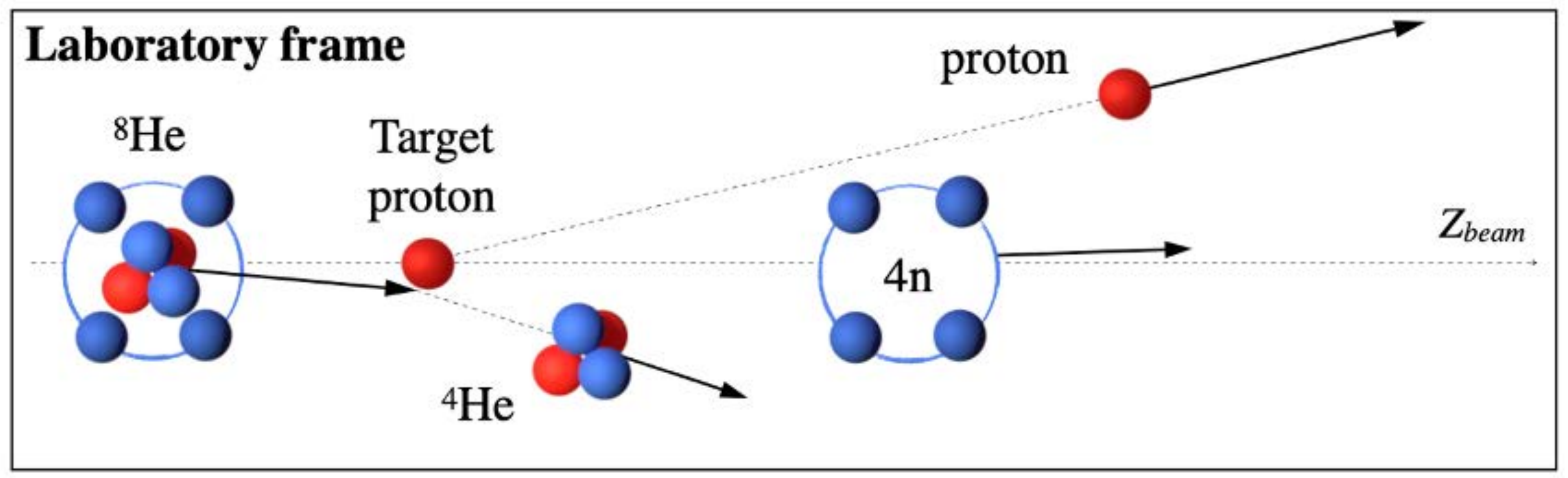


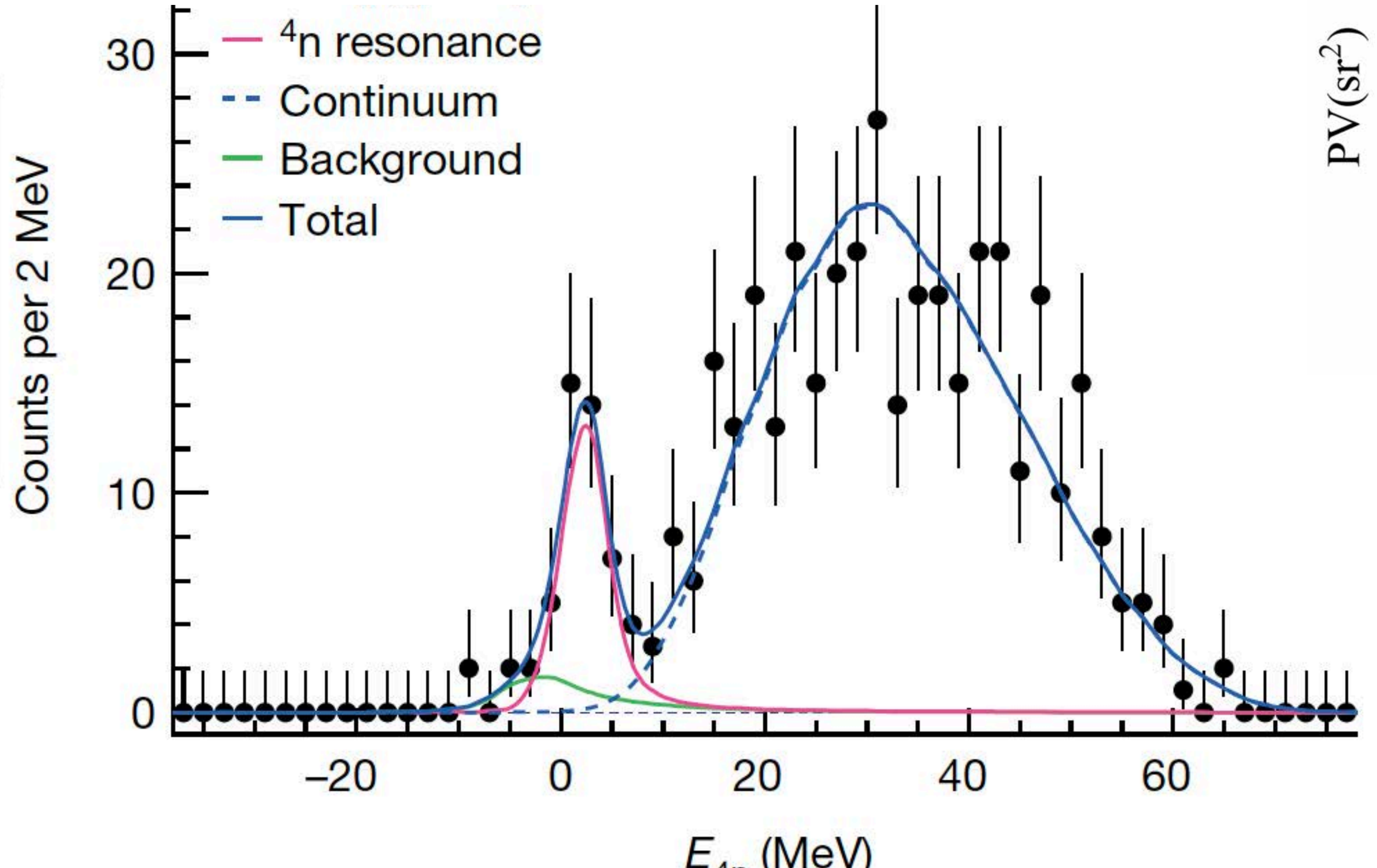
Pengjie Li, D. Beuamel et al., PRL 131, 212501 (2023).

^{10}Be(*p,pα*)^{6}He$^{(GS)}$



M. Duer et al., Nature 606 (2022).





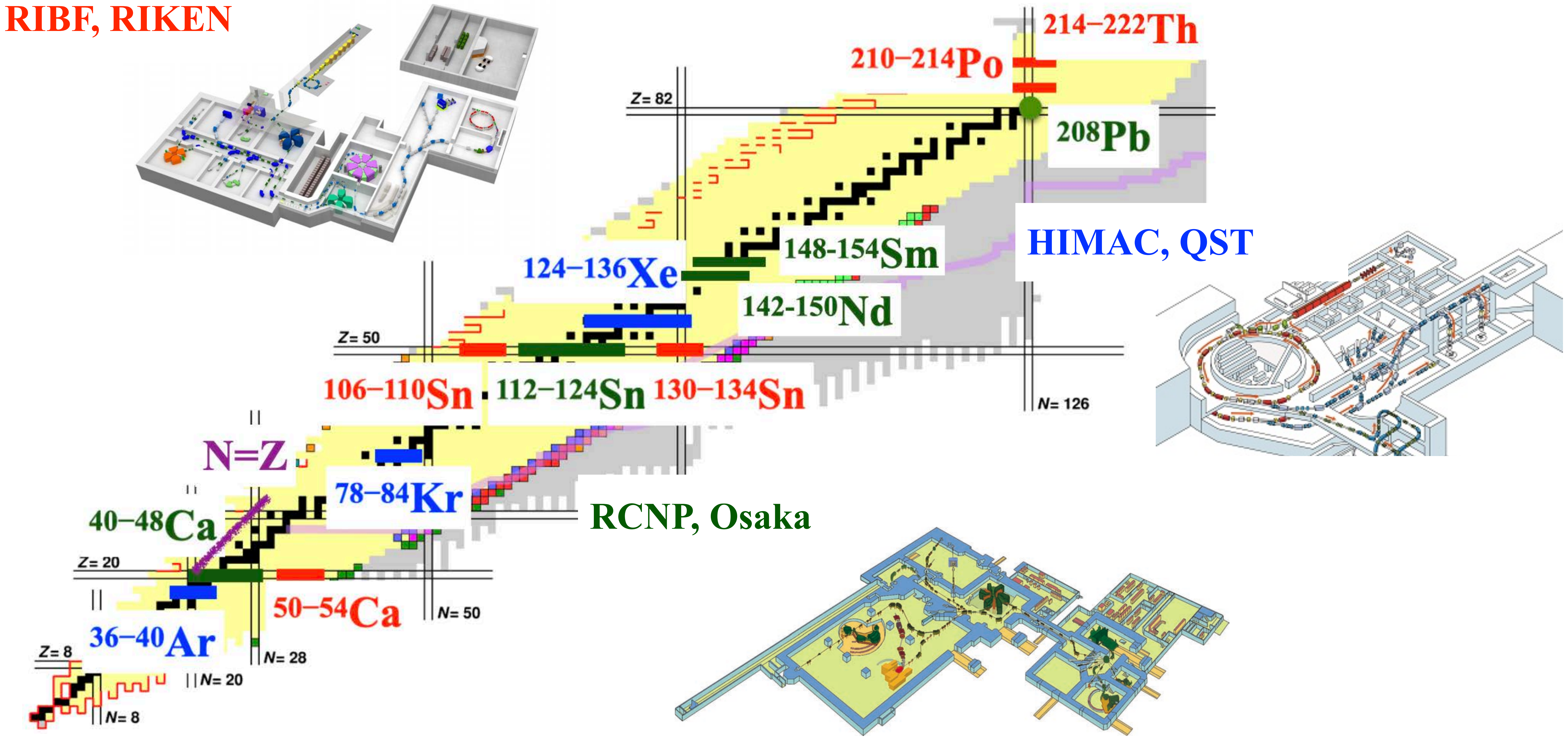
^{8}He(*p,pα*)^{4}*n*

@ θ_{CM}=180deg

ONOKORO Project

Looking for *d*, *α*, *t*, and ^{3}He in stable & unstable isotopes using (*p*,*pX*) knockout reactions at 200−300 MeV/u

- **Relevance of deuteron clusters to short-range correlation**
- **α cluster formation and and understanding of α-decay**
- **Their coexistence with *independent* nucleons**
- **Possible peculiarity around low-density surface?**



2023−2024 1st experiment for stable nuclei @RCNP
June 2025 : 1st experiment for unstable nuclei @RIBF

^{12}C(p,pd)^{10}B(0^+, T=1) @E_p=226 MeV

<u>C.S. Lee,</u> Y. Kubota, TU et al., Prog. Theo. Exp. Phys. **2026**, 053D01.

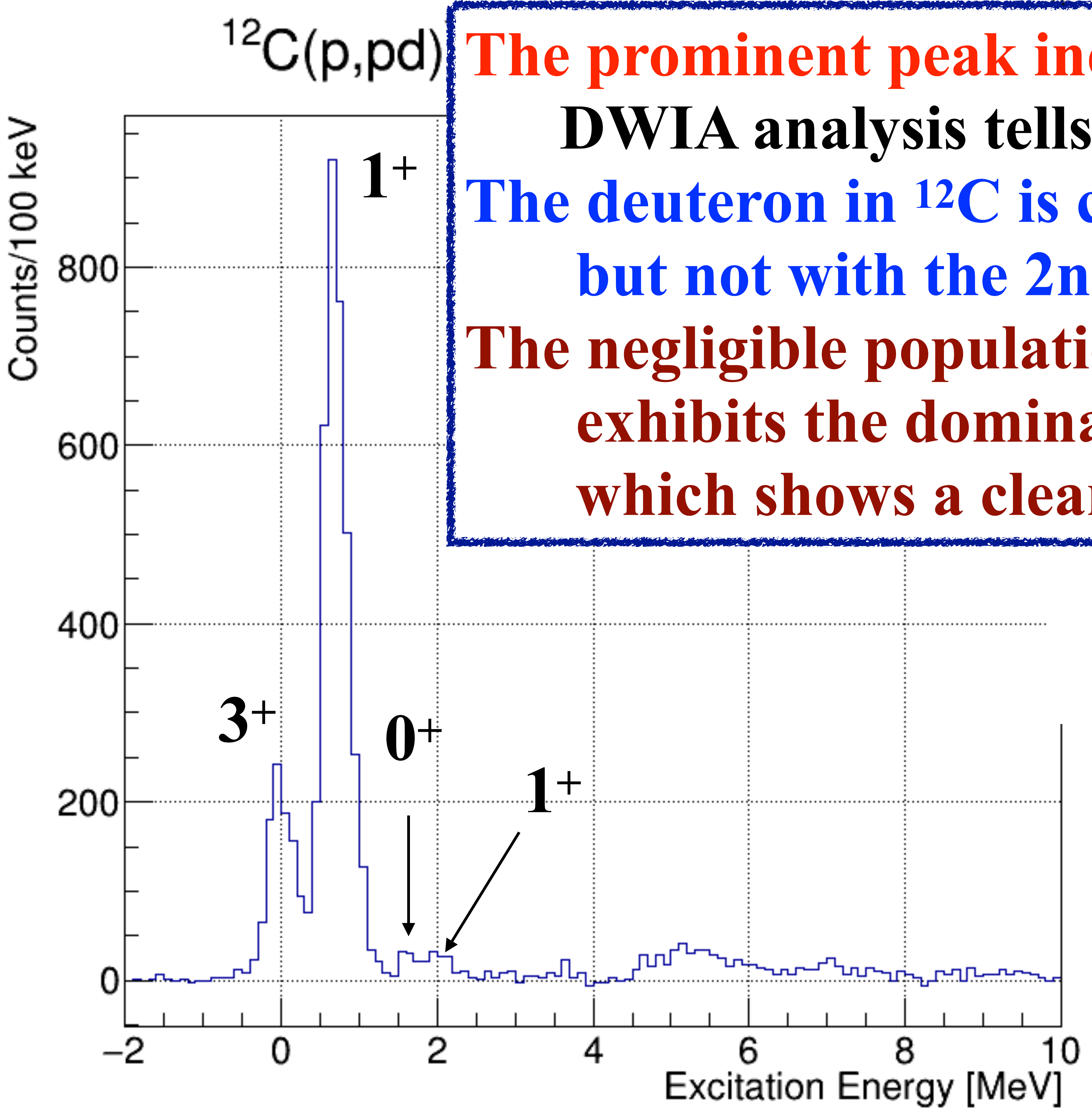
Recoilless (p_d~0) condition

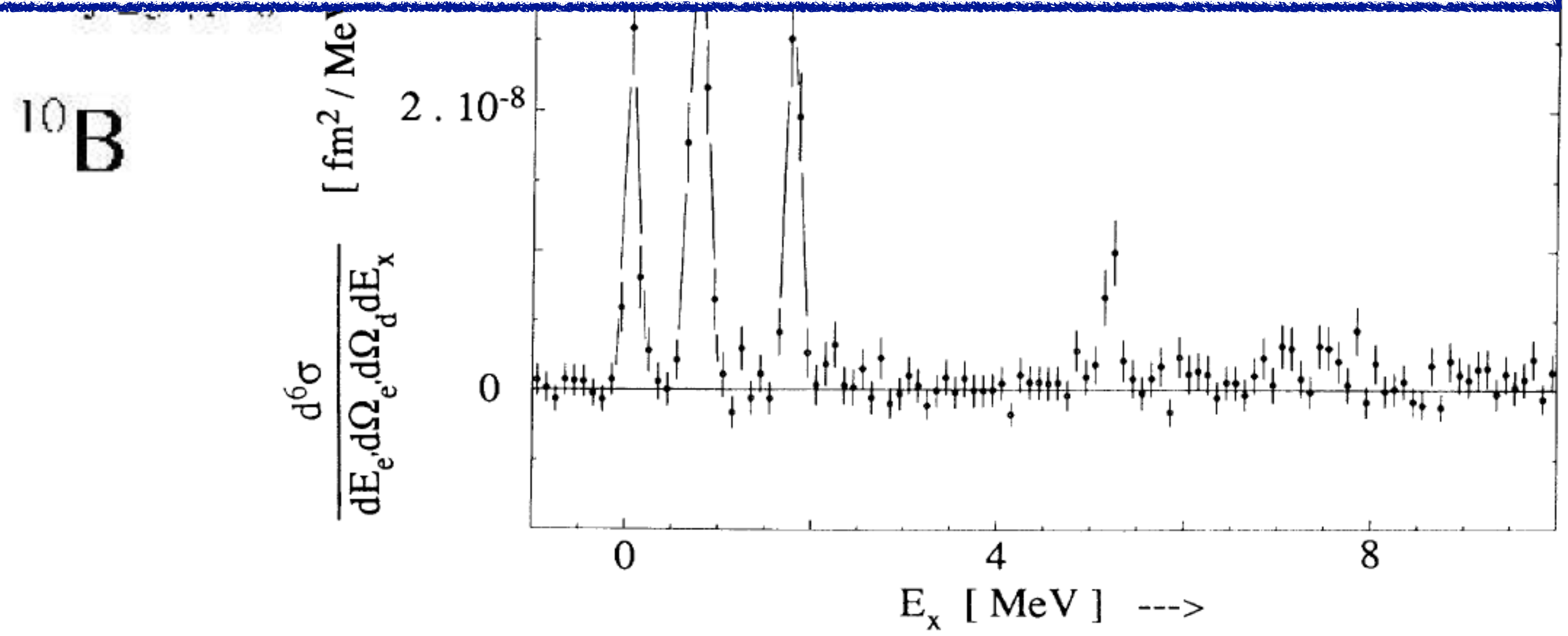
The prominent peak indicates the existence of "deuterons" in ^{12}C.

DWIA analysis tells us that the number of S-wave deuterons in ^{12}C is ~1.6.

The deuteron in ^{12}C is coupled with the 1st 1^+ state (0.718 MeV), but not with the 2nd 1^+ state (2.154 MeV).

The negligible population of the 0^+ state (T=1) at 1.740 MeV exhibits the dominance of the direct deuteron knockout process, which shows a clear contrast to the (e,$e'd$) case.

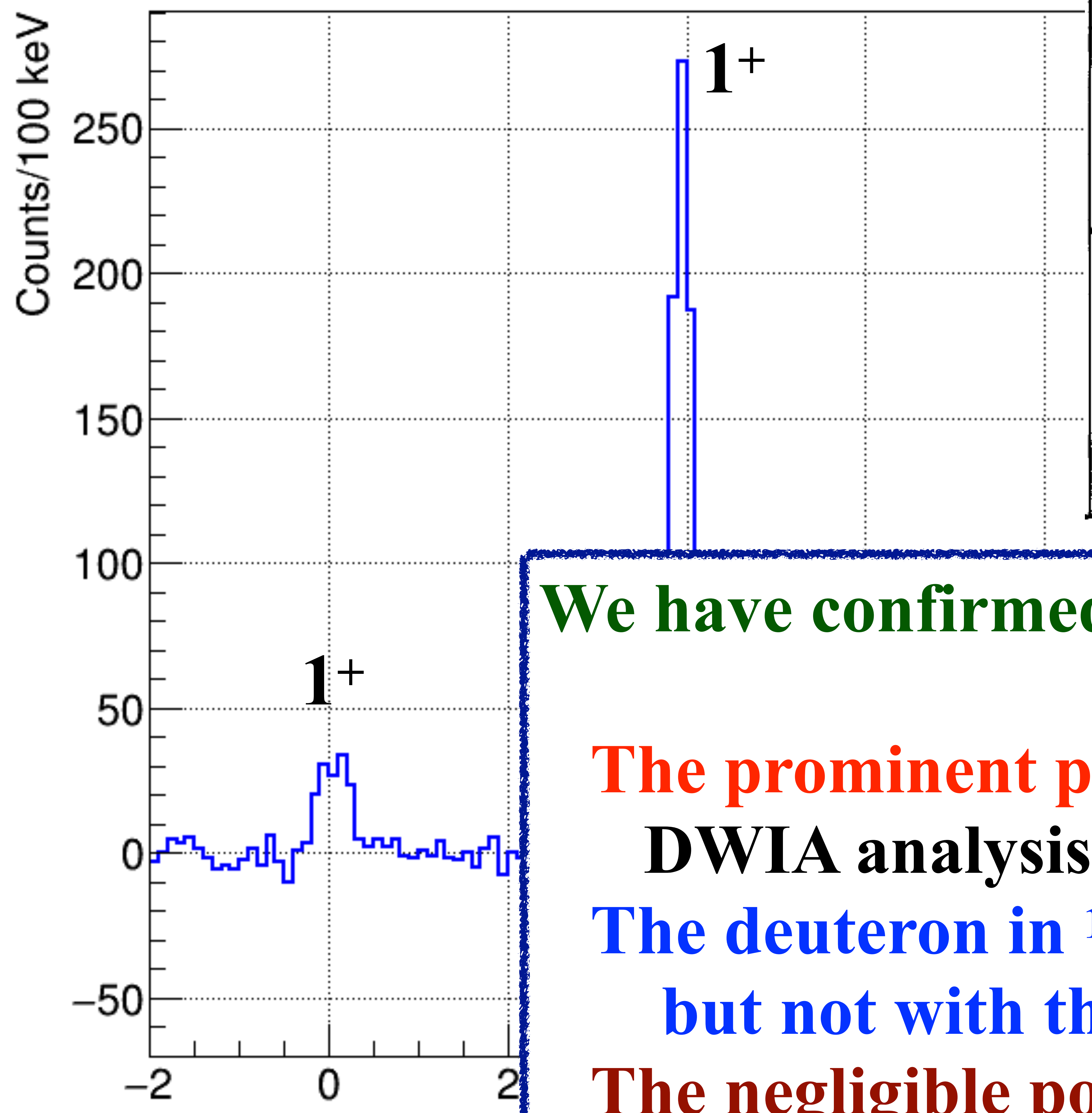


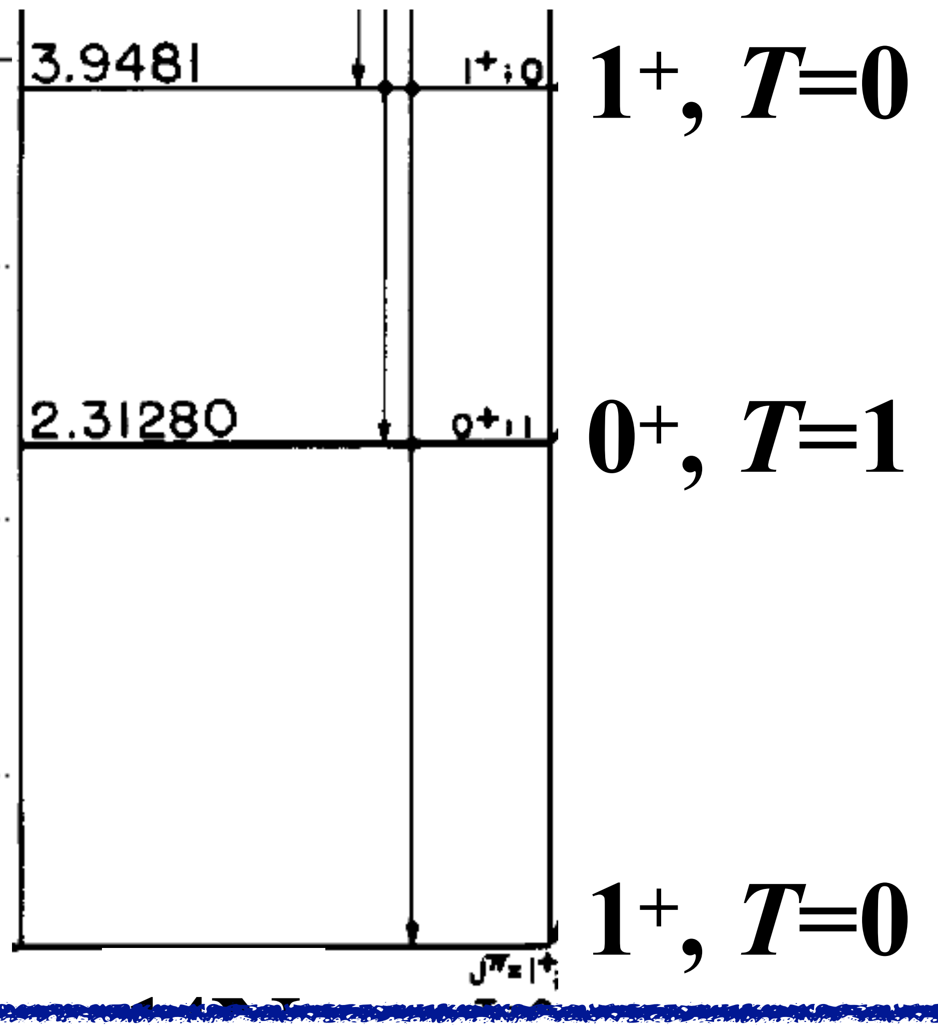


$^{16}O(p,pd)^{14}N(0^+, T=1)$ @E_p=226 MeV

Recoilless (p_d~0) condition

C.S. Lee, Y. Kubota, TU et al., Prog. Theo. Exp. Phys. **2026**, 053D01.





We have confirmed our conclusions for ^{12}C can also be applied to ^{16}O:

The prominent peak indicates the existence of "deuteron" in ^{16}O.

DWIA analysis tells us that the number of S-wave deuterons in ^{16}O is ~1.9.

The deuteron in ^{12}C is coupled with the 2nd 1^+ state (3.948 MeV), but not with the gnd 1^+ state (0 MeV).

The negligible population of the 0^+ state (T=1) at 2.313MeV exhibits the dominance of the direct deuteron knockout process.

ONOKORO @ RIBF

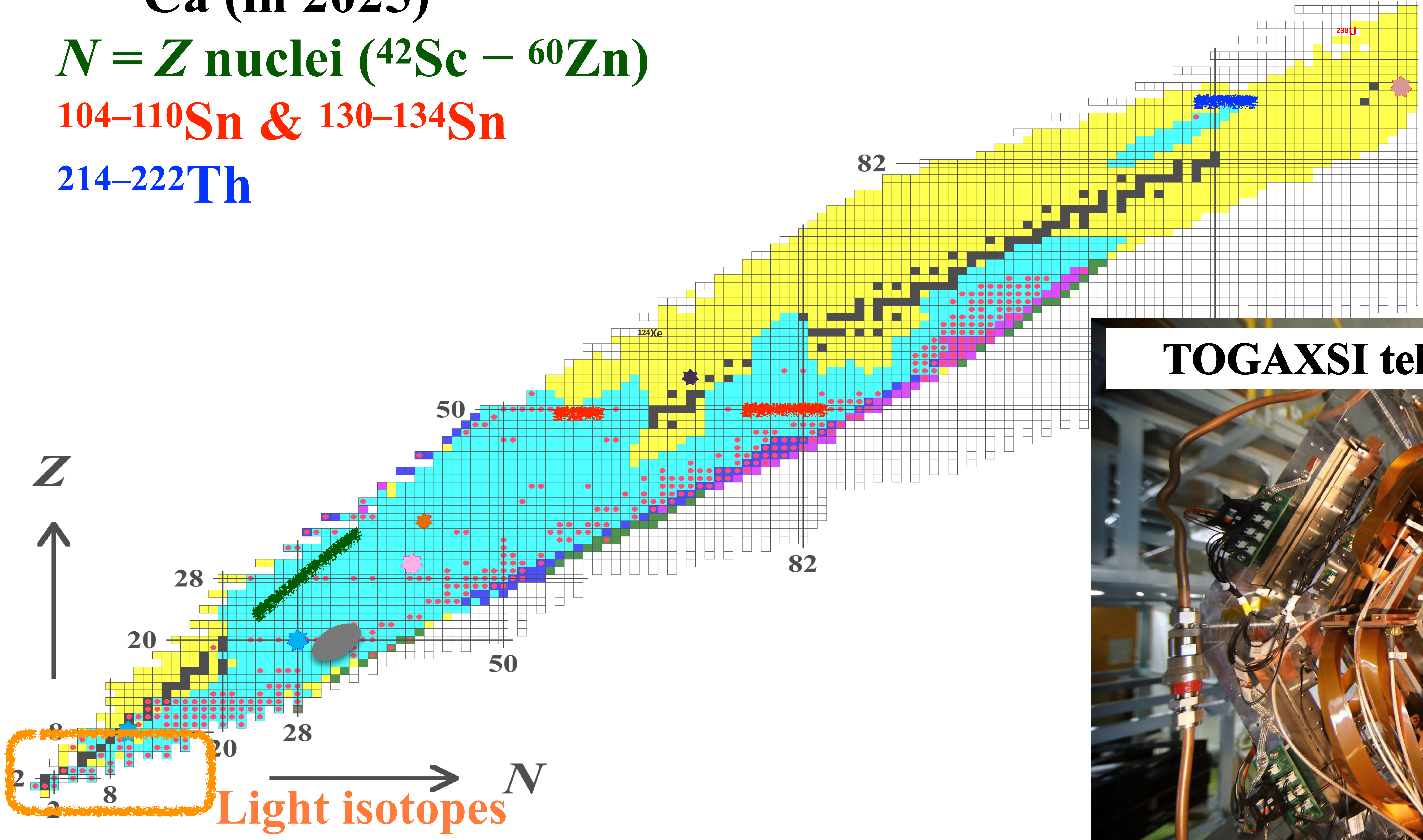
Yuki Kubota

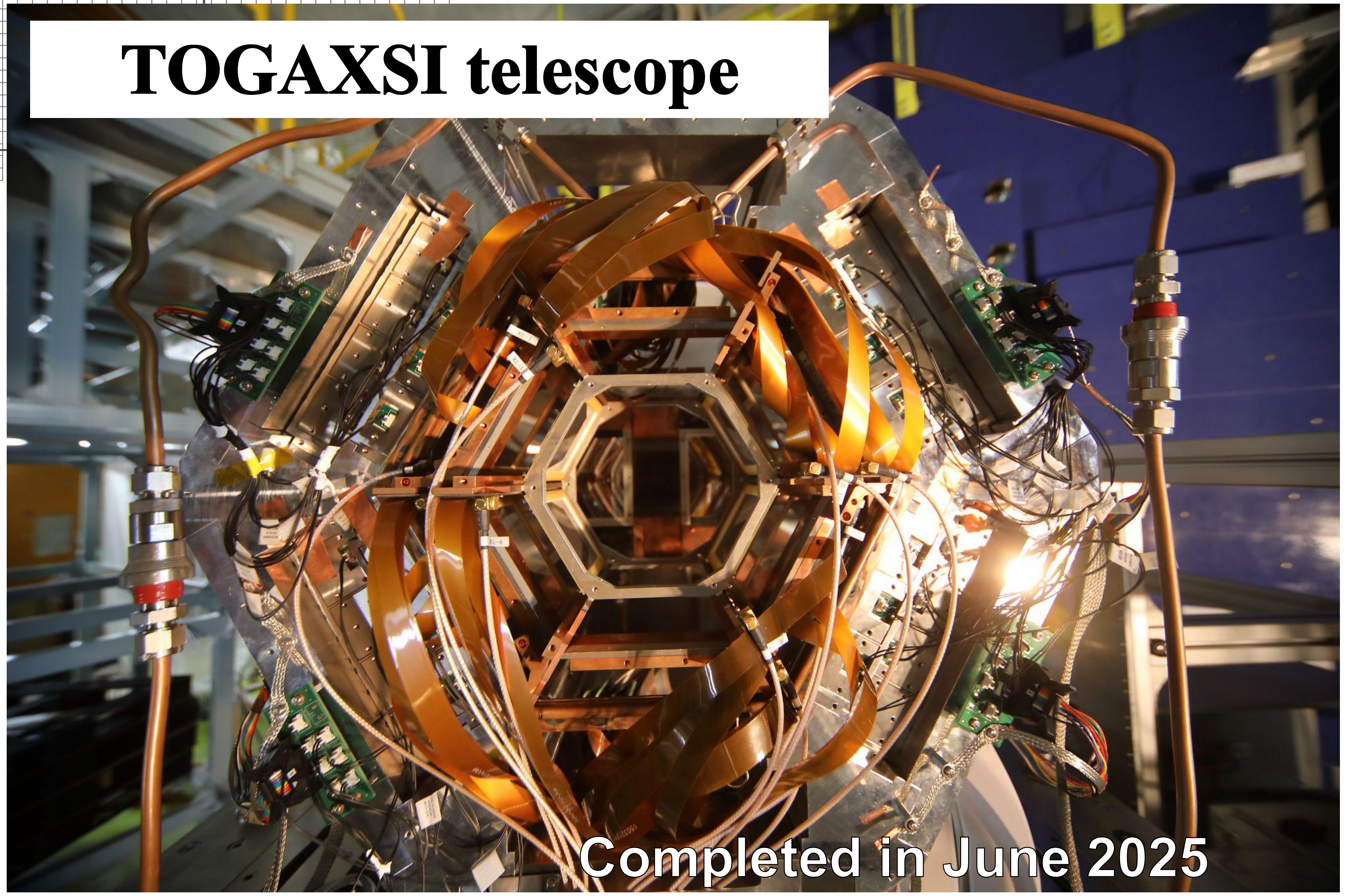
$^{50\text{-}52}$Ca (in 2025)

$N = Z$ nuclei (^{42}Sc – ^{60}Zn)

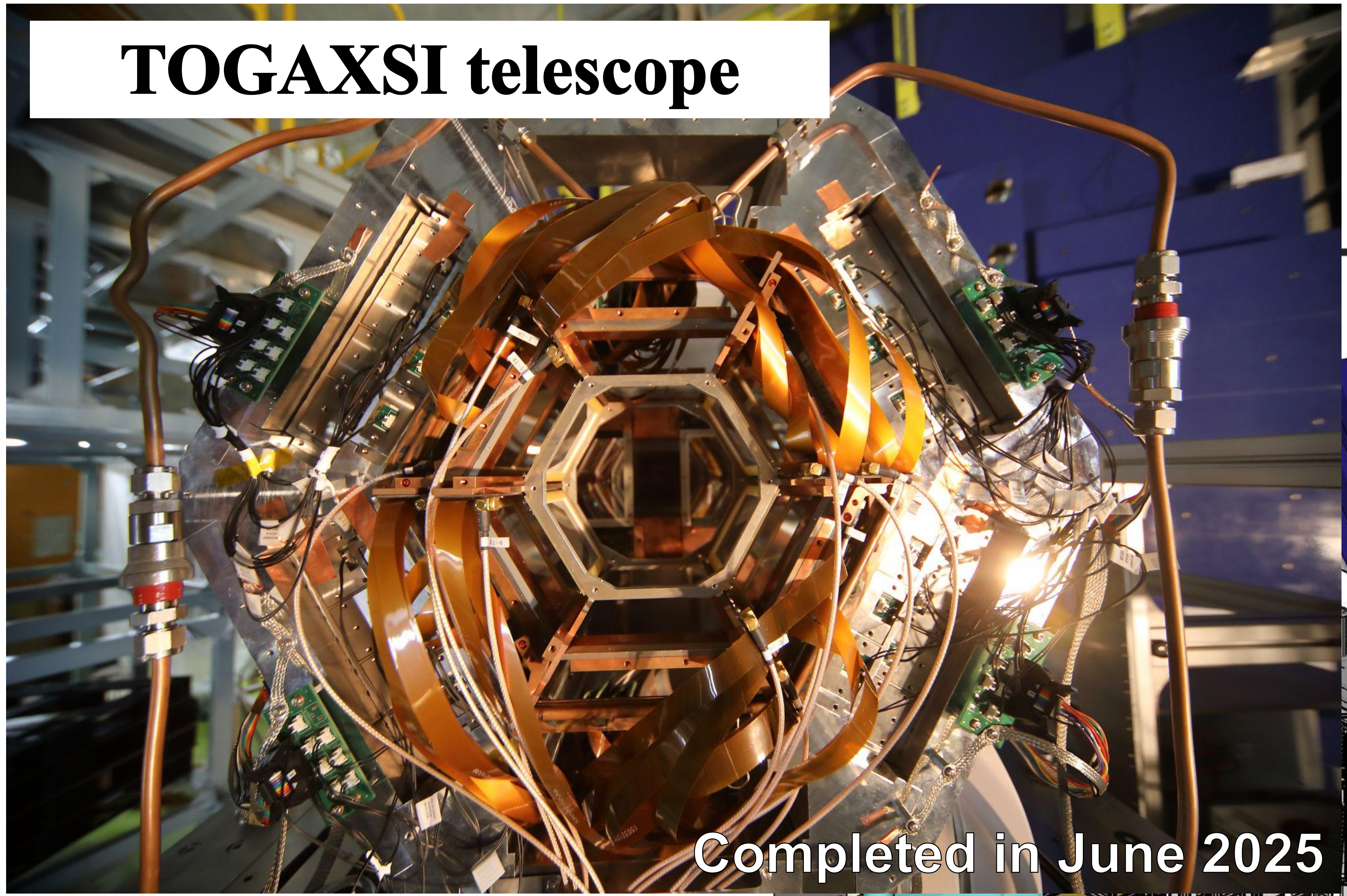
$^{104–110}$Sn & $^{130–134}$Sn

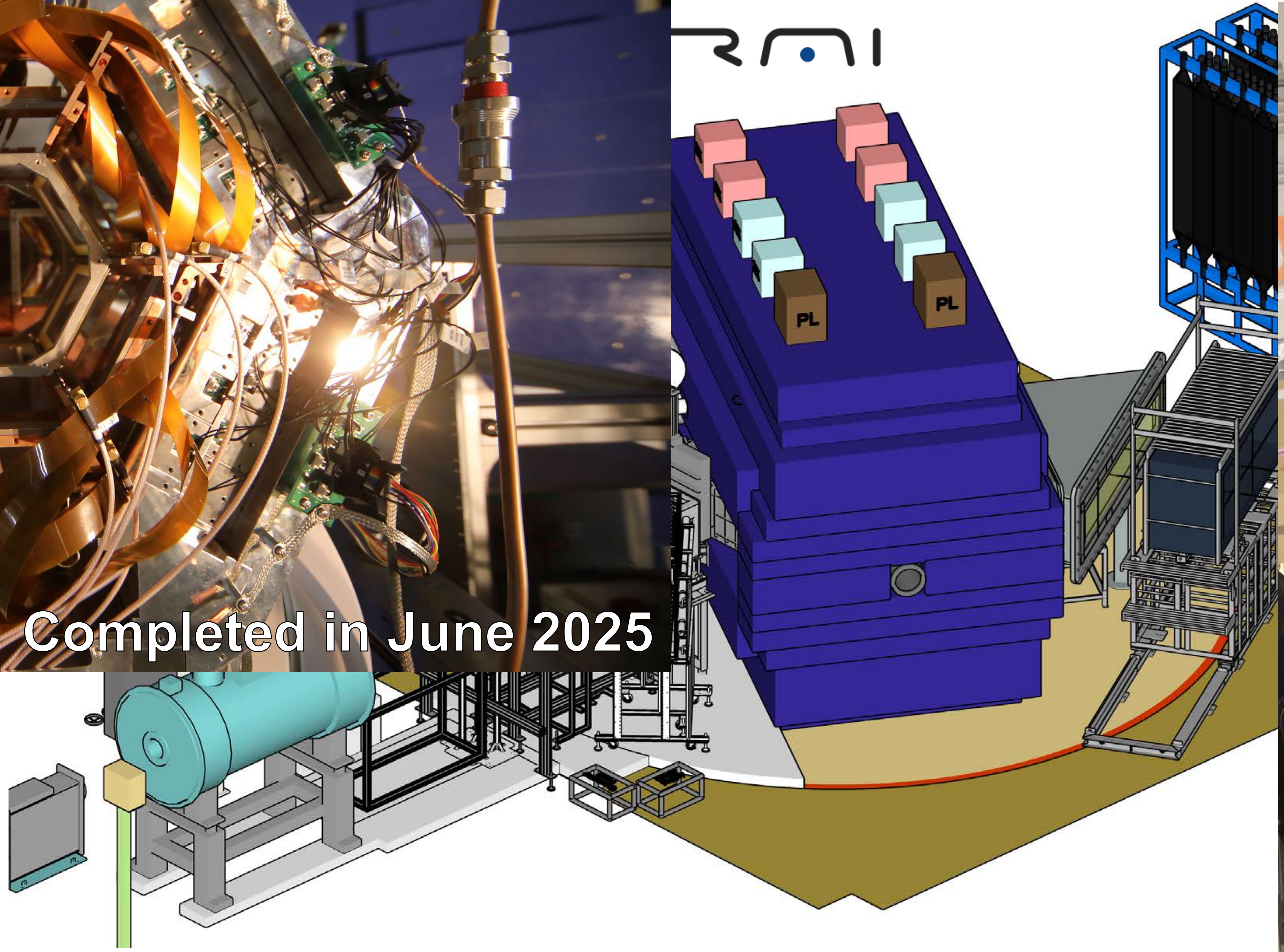
$^{214–222}$Th

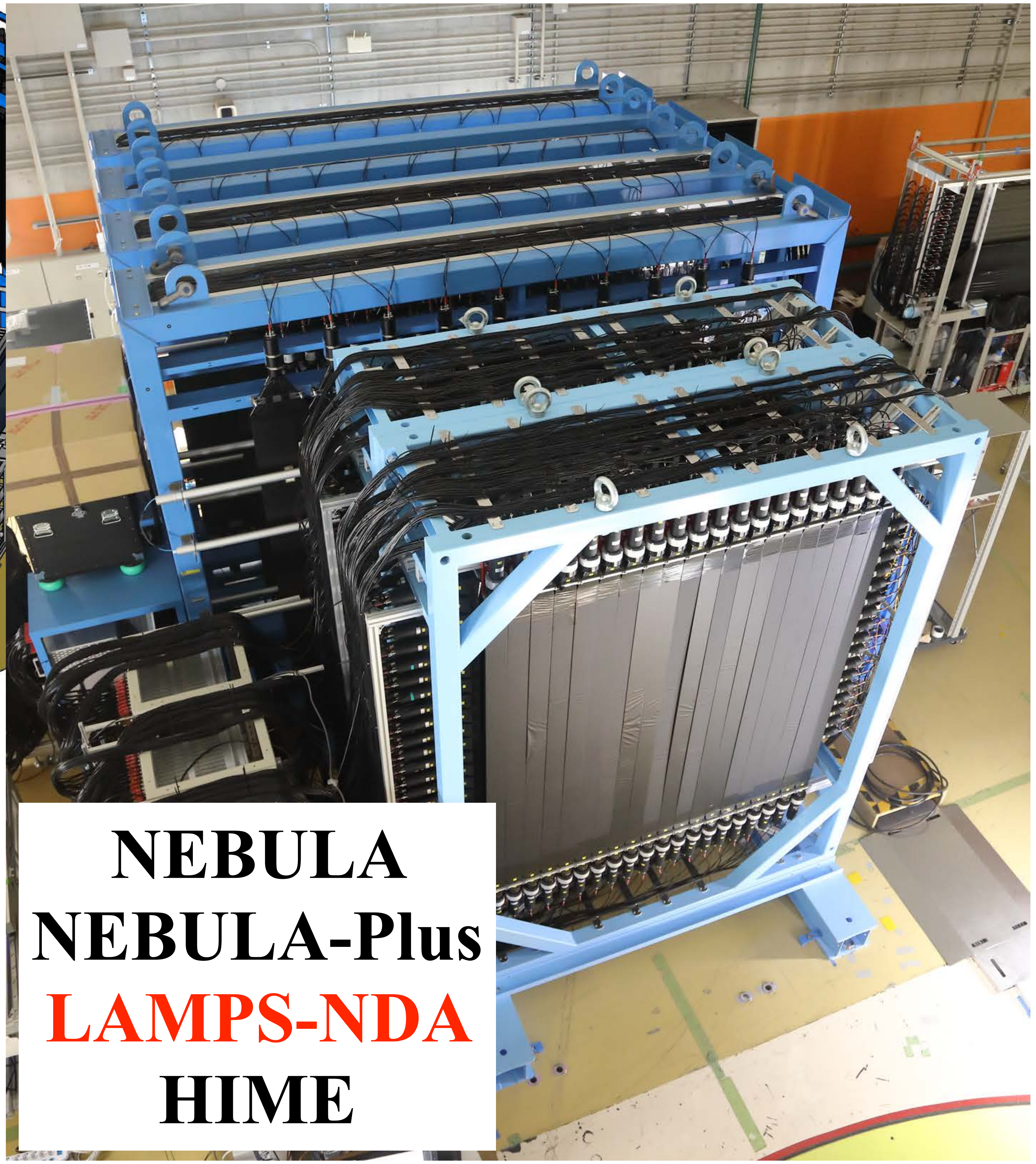




New detector setups at SAMURAI







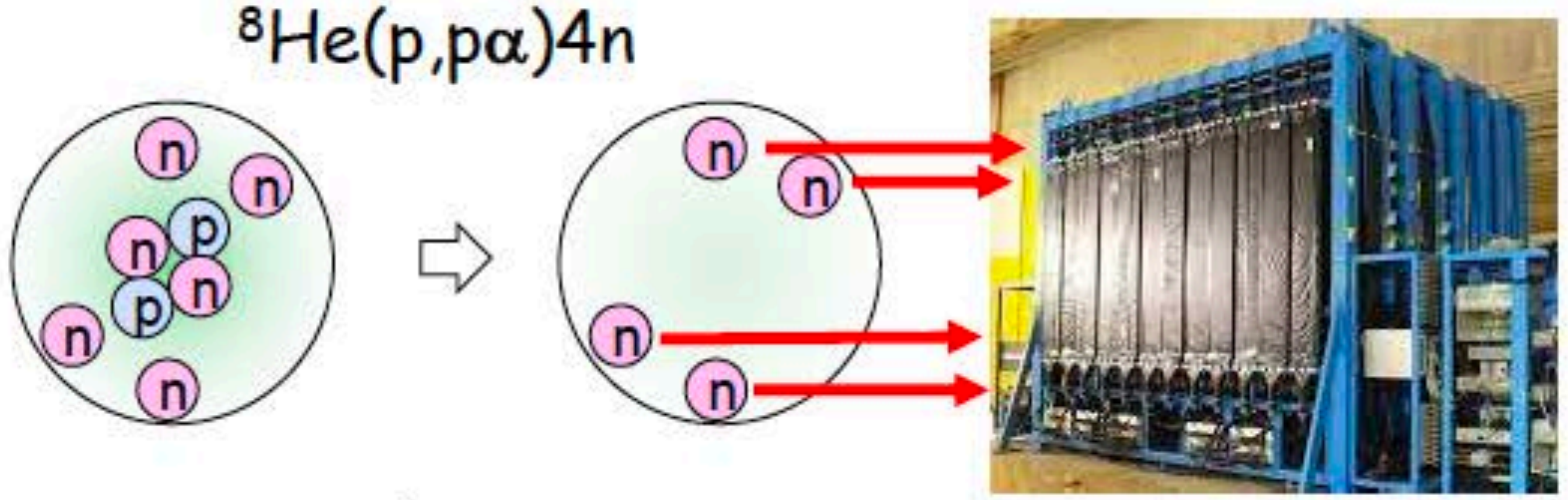
New experiment to explore multineutron states

Miki, Duer et al.

^{6,8}He(p,pα)/(p,3p) conducted in May 2026

- Neutron correlations in **final state**

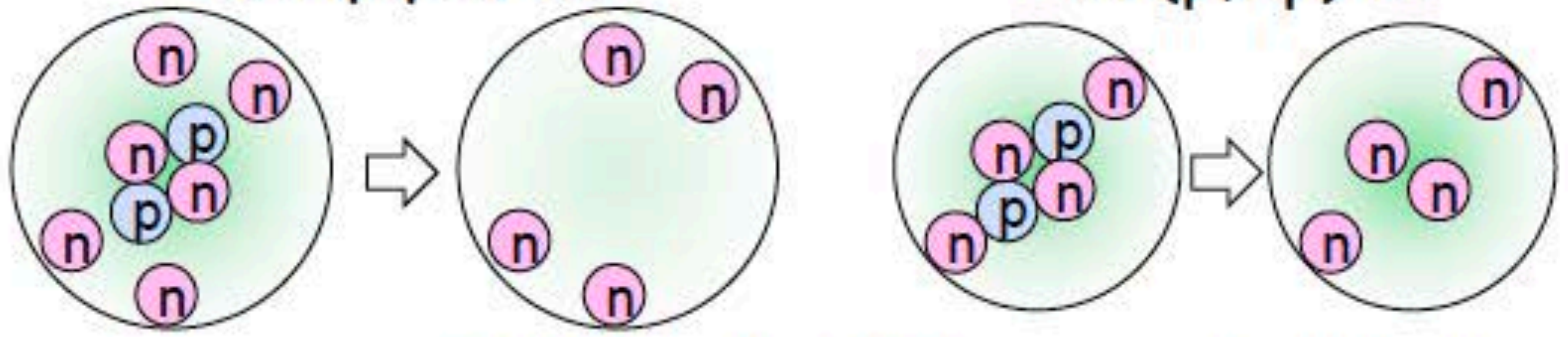
^{8}He(p,pα)4n



See if any enhancement in 2n -2n configuration

- Neutron correlations in **initial state**

^{8}He(p,pα)4n ^{6}He(p,3p)4n

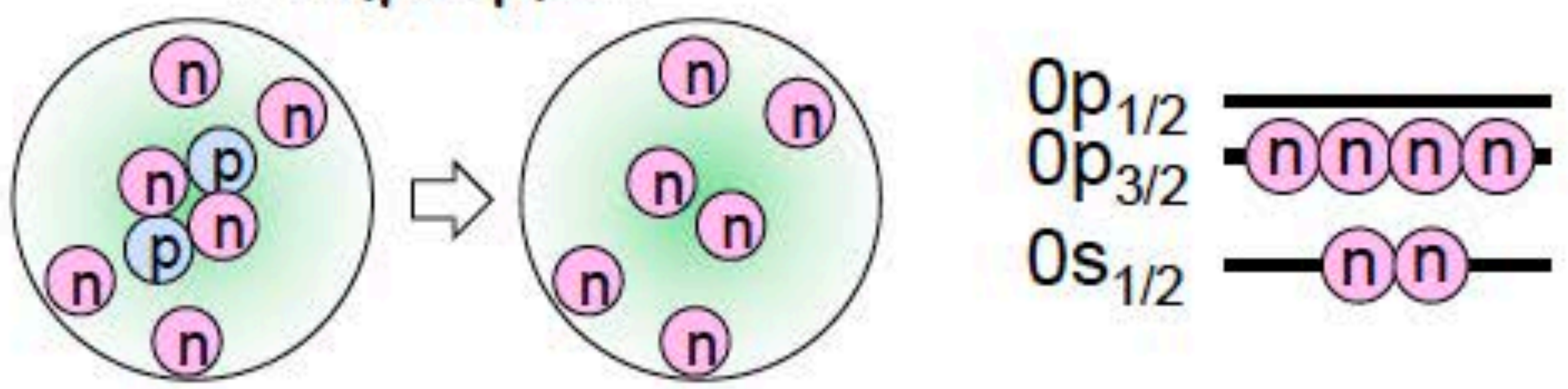


Different initial neutron distributions

See if any change in
- Missing/invariant mass
- 4n distribution

- Neutron correlations in **further neutron-rich** system

^{8}He(p,3p)6n



See if multi-neutron peak persistently appear.
See if any shell-like stability at N=6

We realize all of them at once by using versatile setup of **SAMURAI+TOGAXSI**.


LAMPS
NDA

Summary

Few-nucleon correlation is a key for the understanding the order formation of nuclear nuclei.

At the limit of nuclear binding, mean-field effects are less manifest, and thus the few-nucleon correlations are expected to become more prominent.

Two-neutron correlation in Borromean nuclei : ^{11}Li, ^{14}Be, ^{17}B(*p*,*pN*)

Cluster knockout reactions under ONOKORO project:
from stable nuclei to unstable nuclei

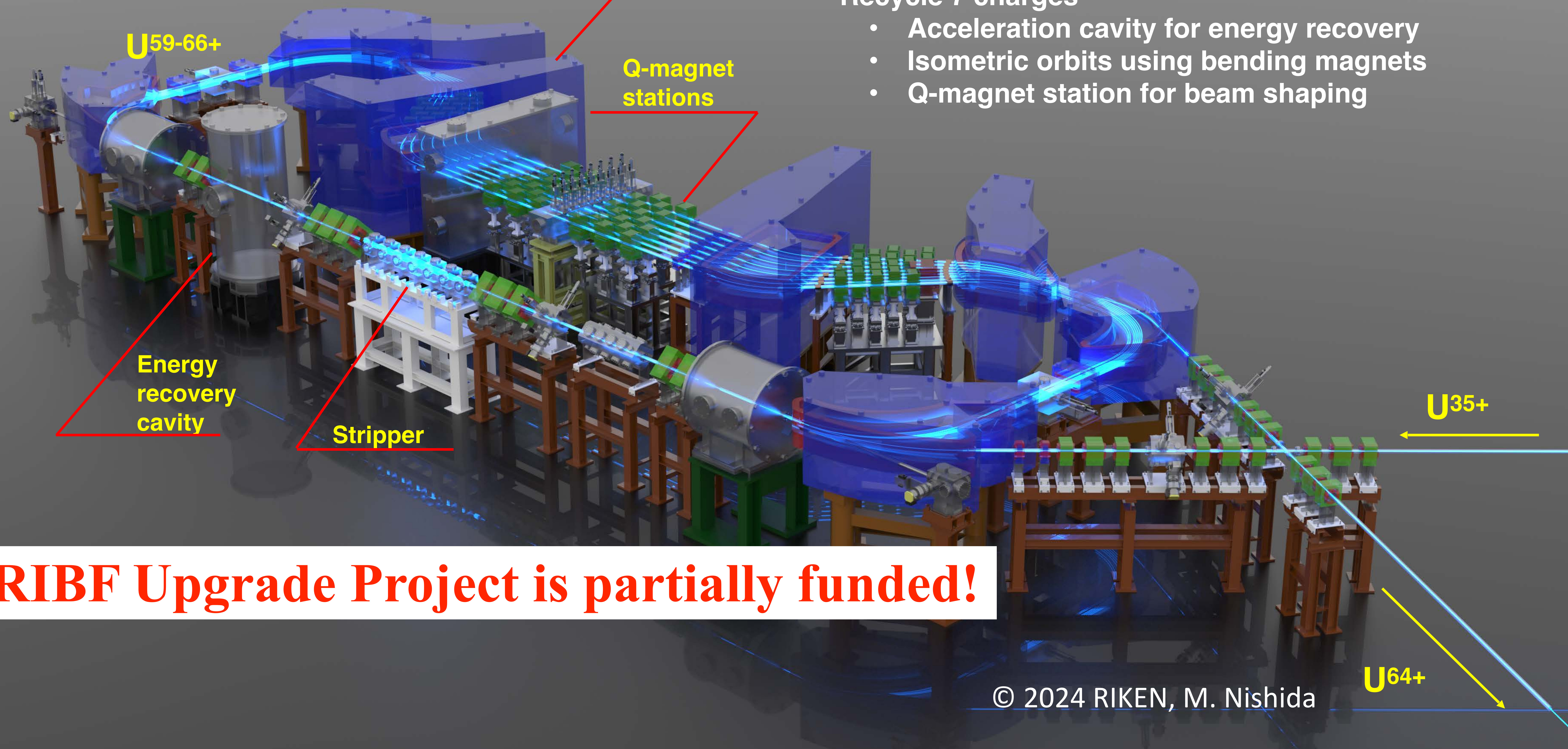
TOGAXSI and LAMPS-NDA @SAMURAI
→ fully exploited in the experiment to search for multi-neutron systems

Courtesy of H.Imao

Charge Stripper Ring (CSR)

Recycle 7 charges

- Acceleration cavity for energy recovery
- Isometric orbits using bending magnets
- Q-magnet station for beam shaping



RIBF Upgrade Project is partially funded!

H. Imao, JINST, **15**, P12036 (2020)

Stable beam oscillations for 8 charges