QNP2024, 8–12 July, 2024

Manifestations of non-uniformity in nuclei — challeges with knockout reactions —

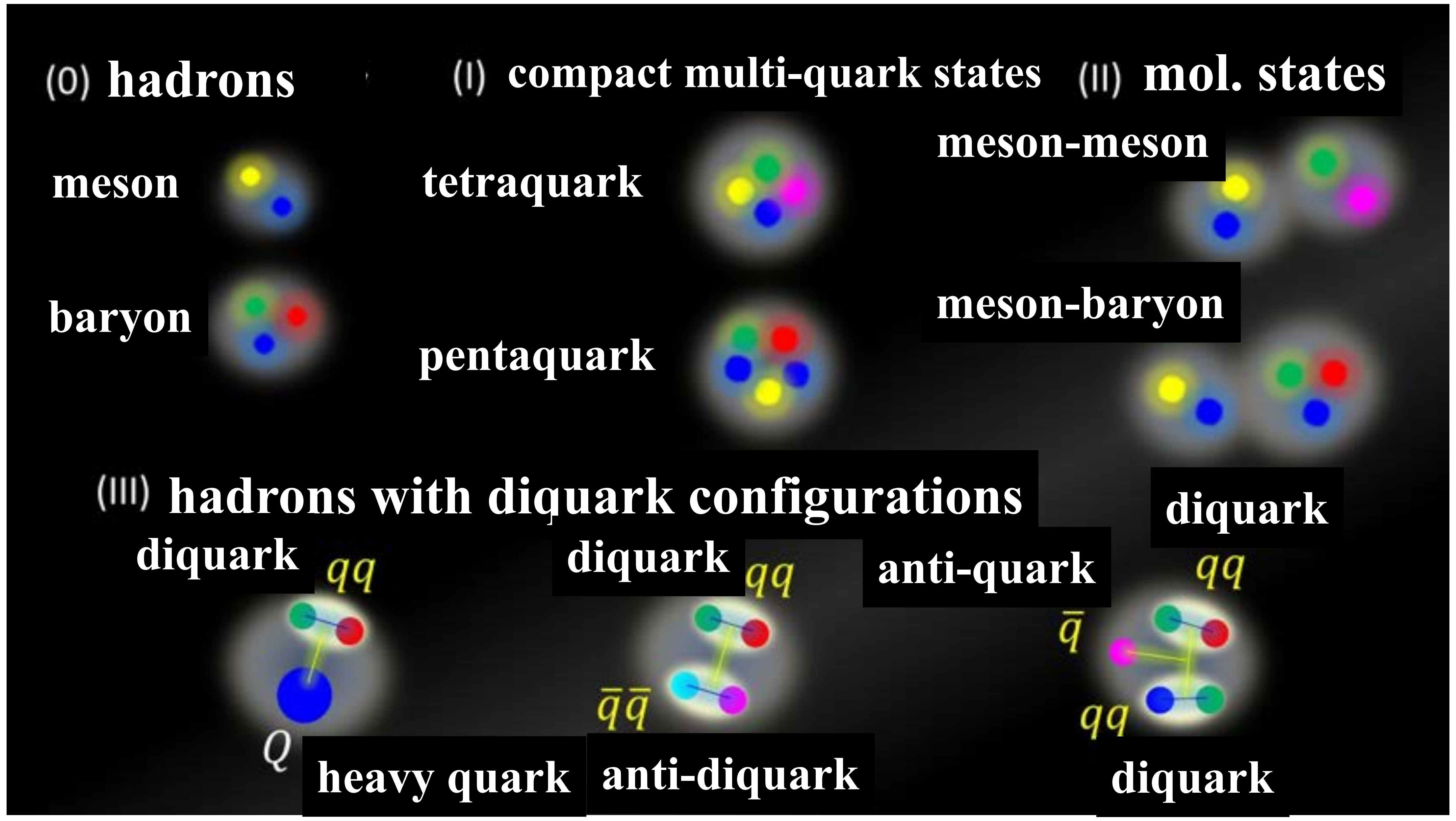
Tomohiro Uesaka (RIKEN)

on behalf of

ONOKORO collaboration

Order in physical systems through formation of subsystems
→ non-uniformity

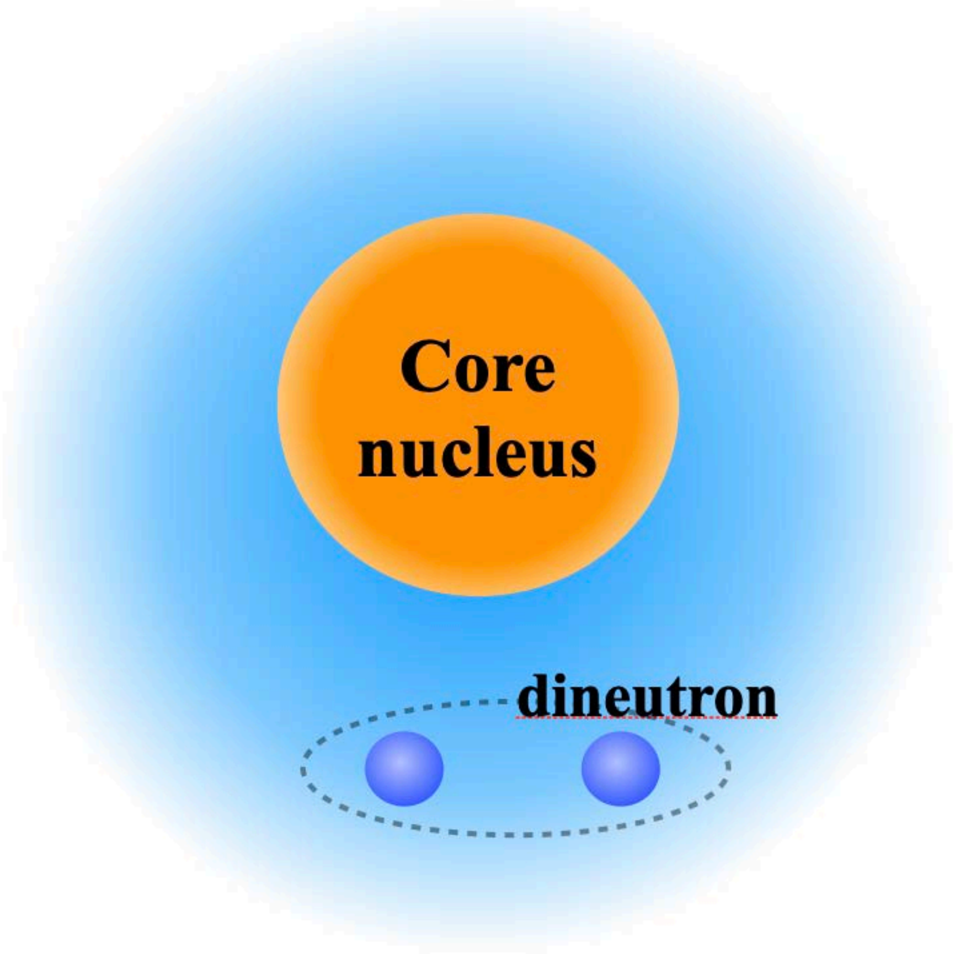
di- / multi-quark correlation in hadrons

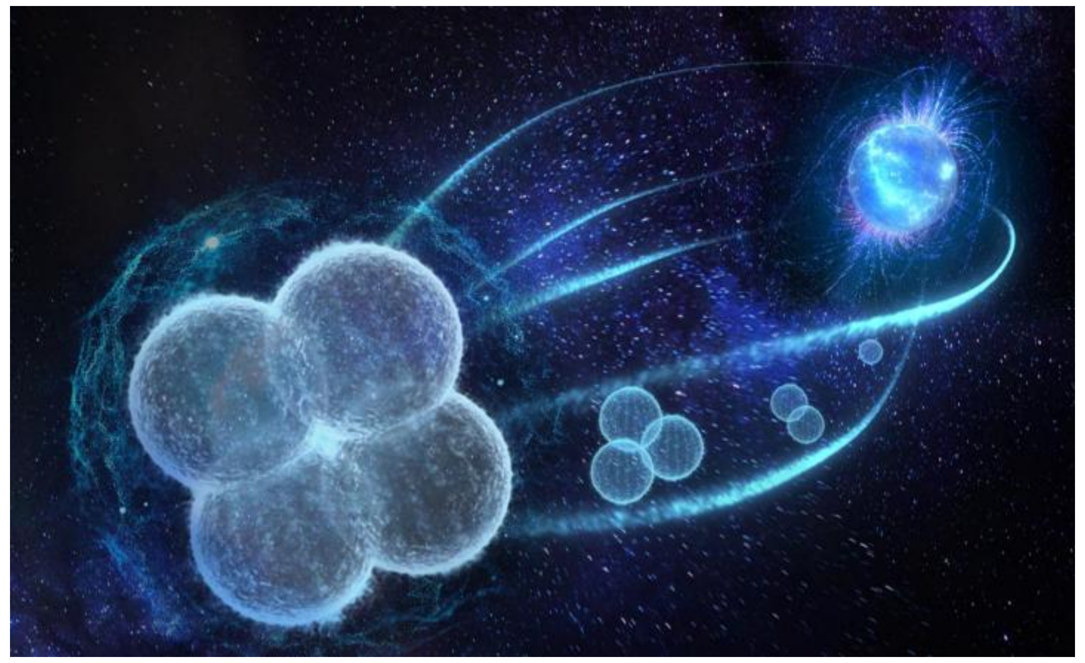


http://kakudan.rcnp.osaka-u.ac.jp/jp/overview/world/Flavor.html
(in Japanese)

hadron production

di/tetraneutron correlation in neutron drip-line nuclei





Kisamori, Shimoura et al., PRL 116, 052501 (2016).
M. Duer et al., Nature 606, 678 (2022).

α-particle emission in heavy-ion reactions

Nuclei are made of α-particle?

Success of Gamow's model of α-decay (Gamow 1928)
in terms of quantum-mechanical tunneling
→ People thought nuclei are made of α particles!

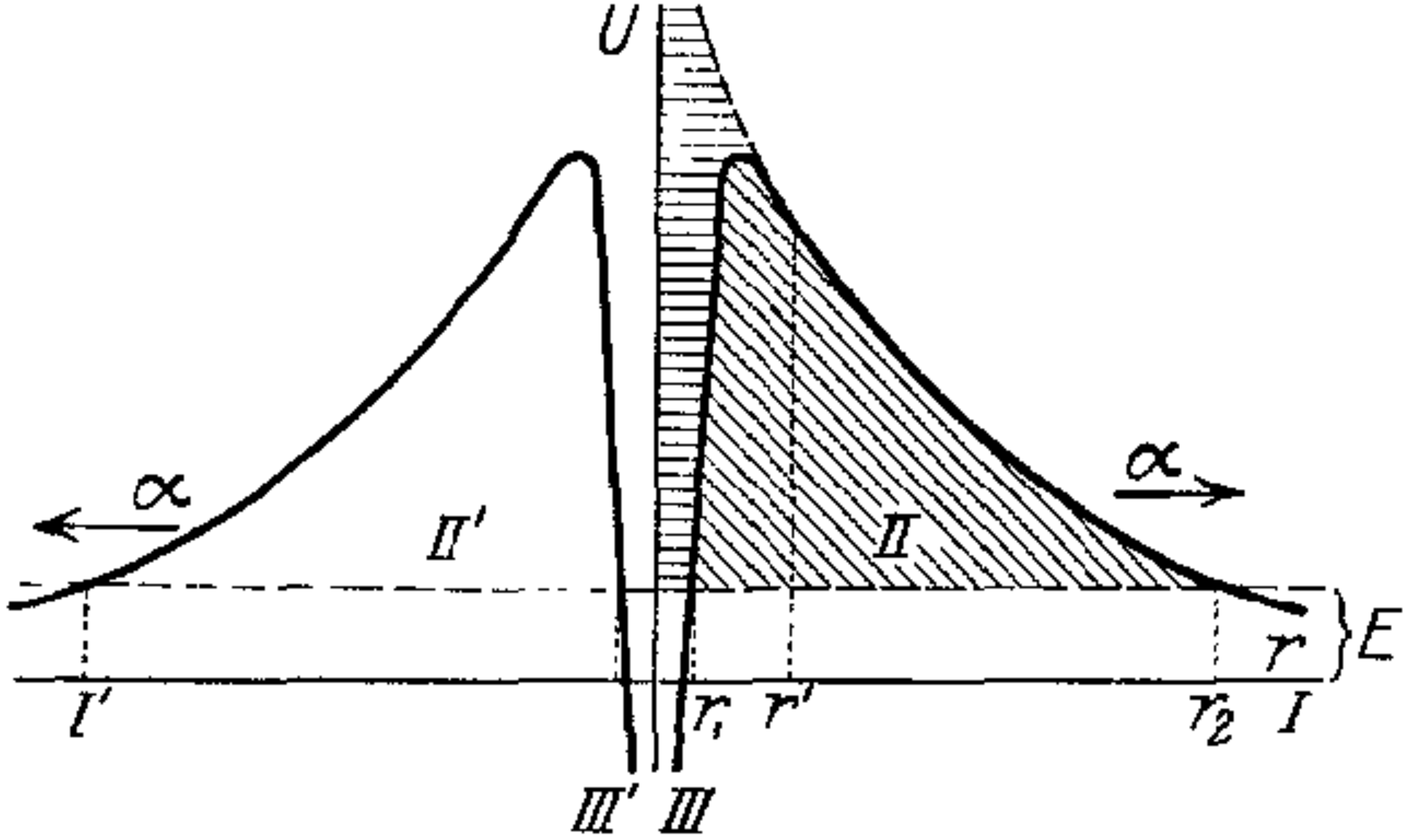
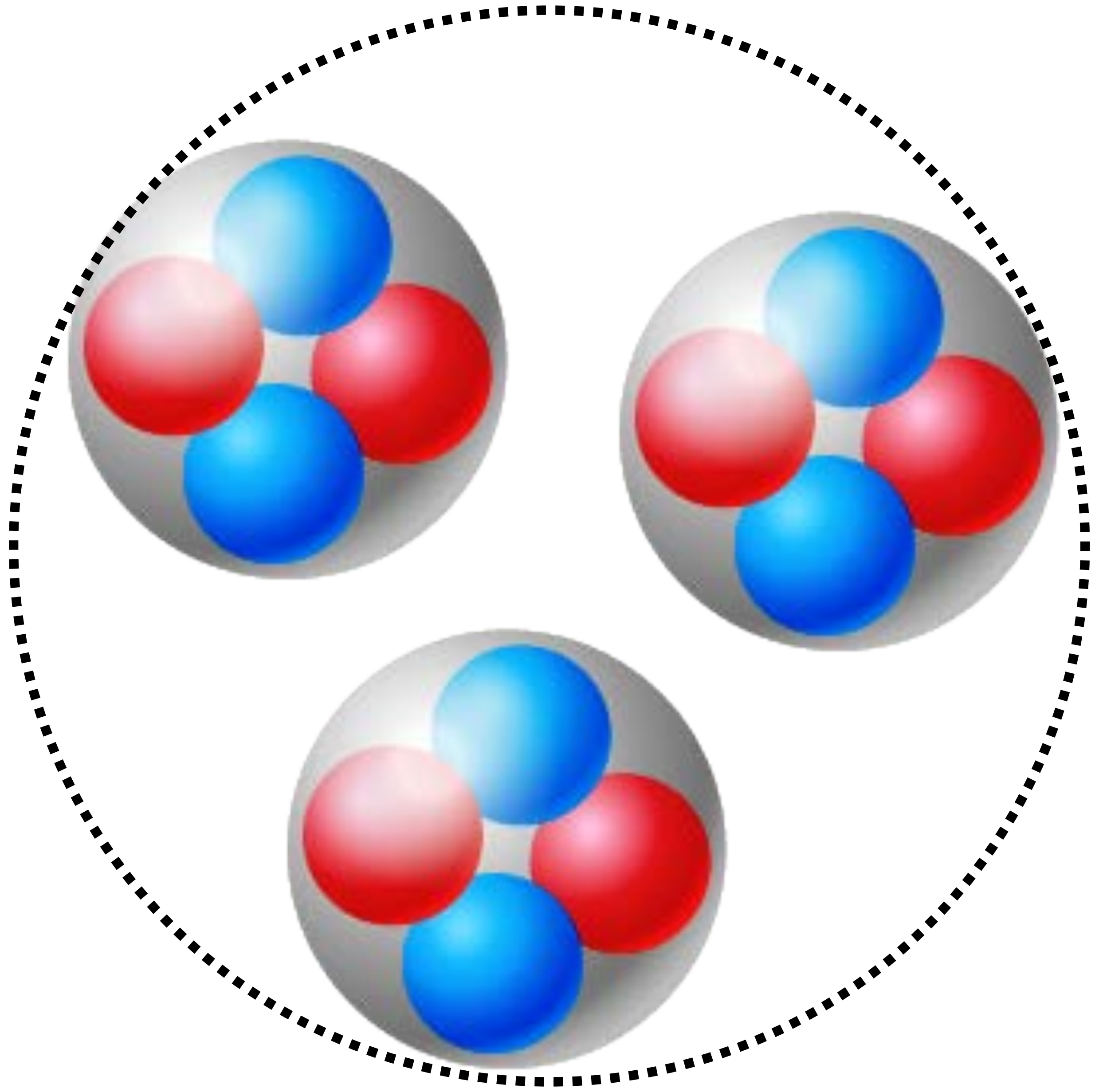
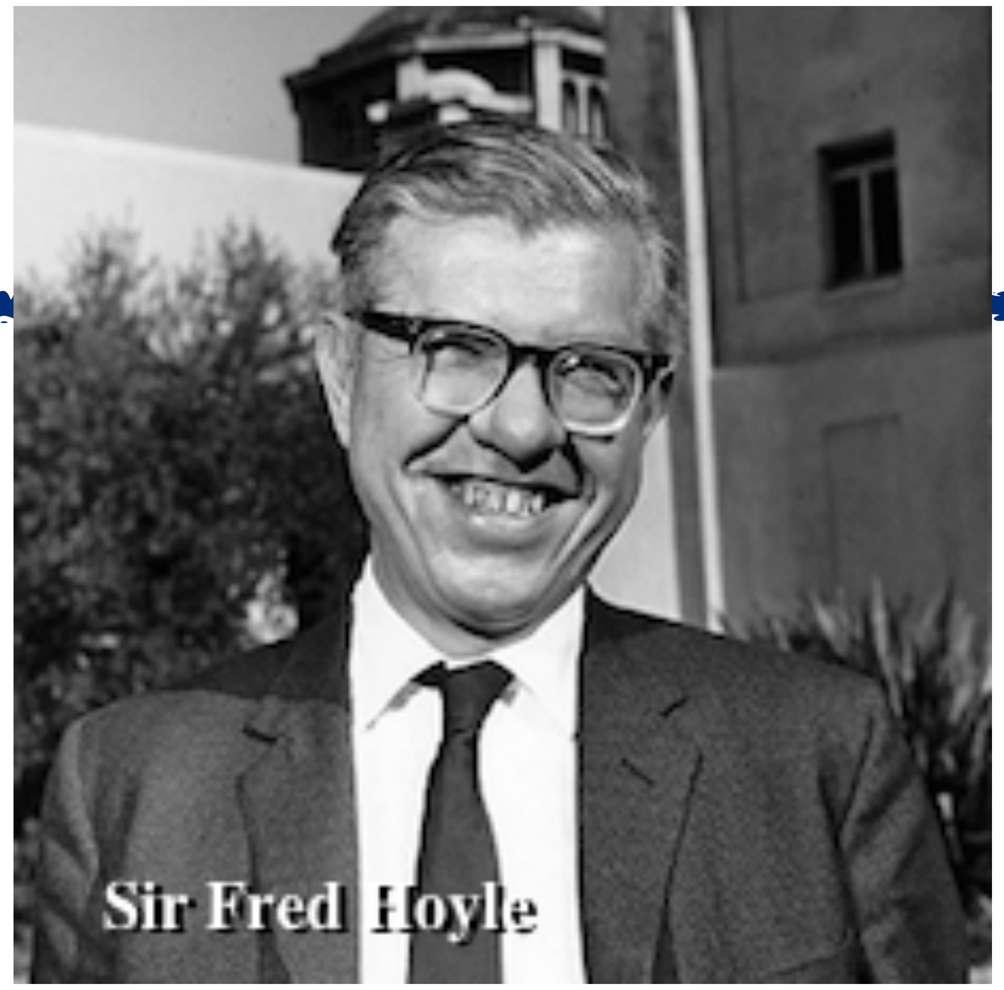
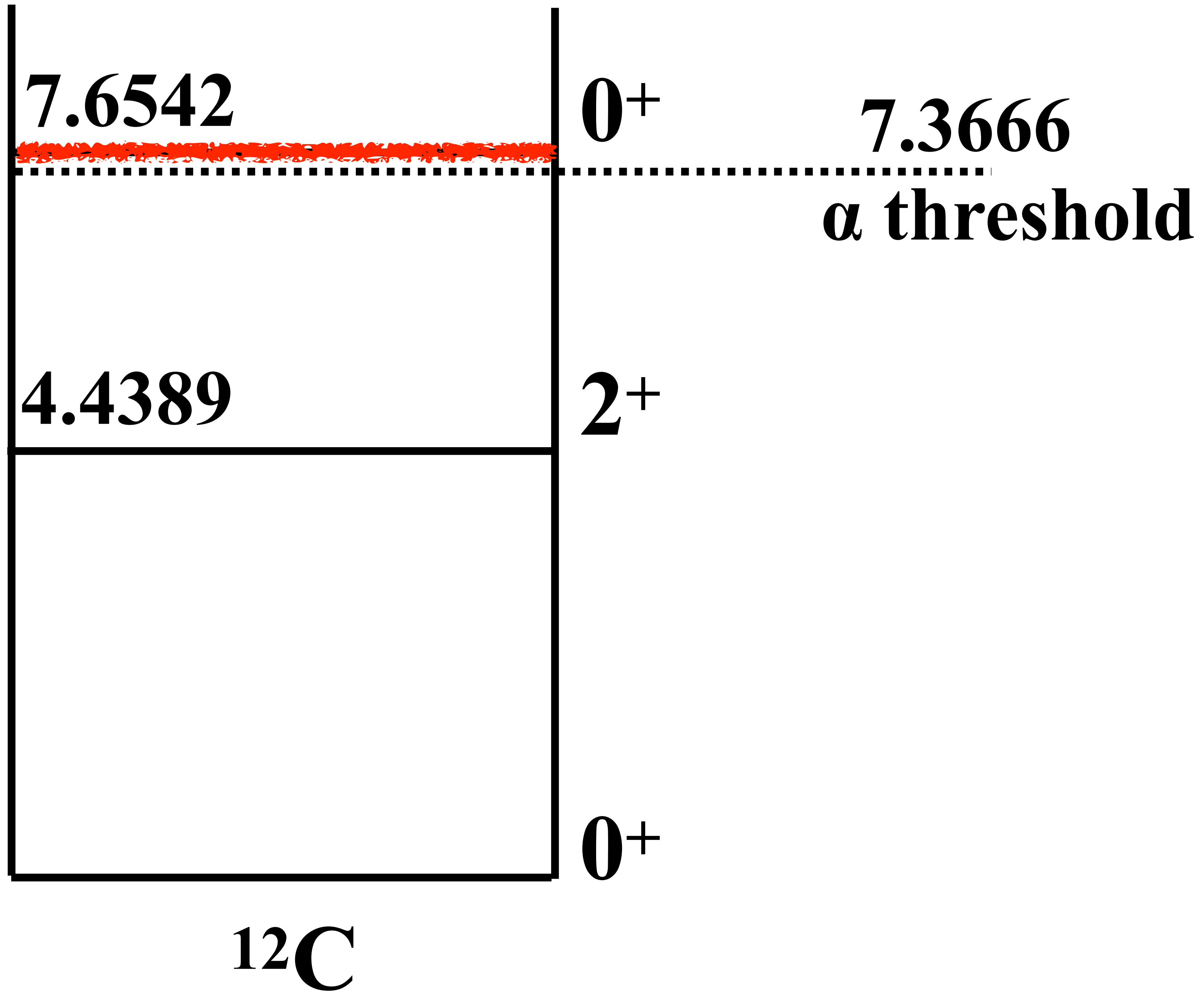


Fig. 4.

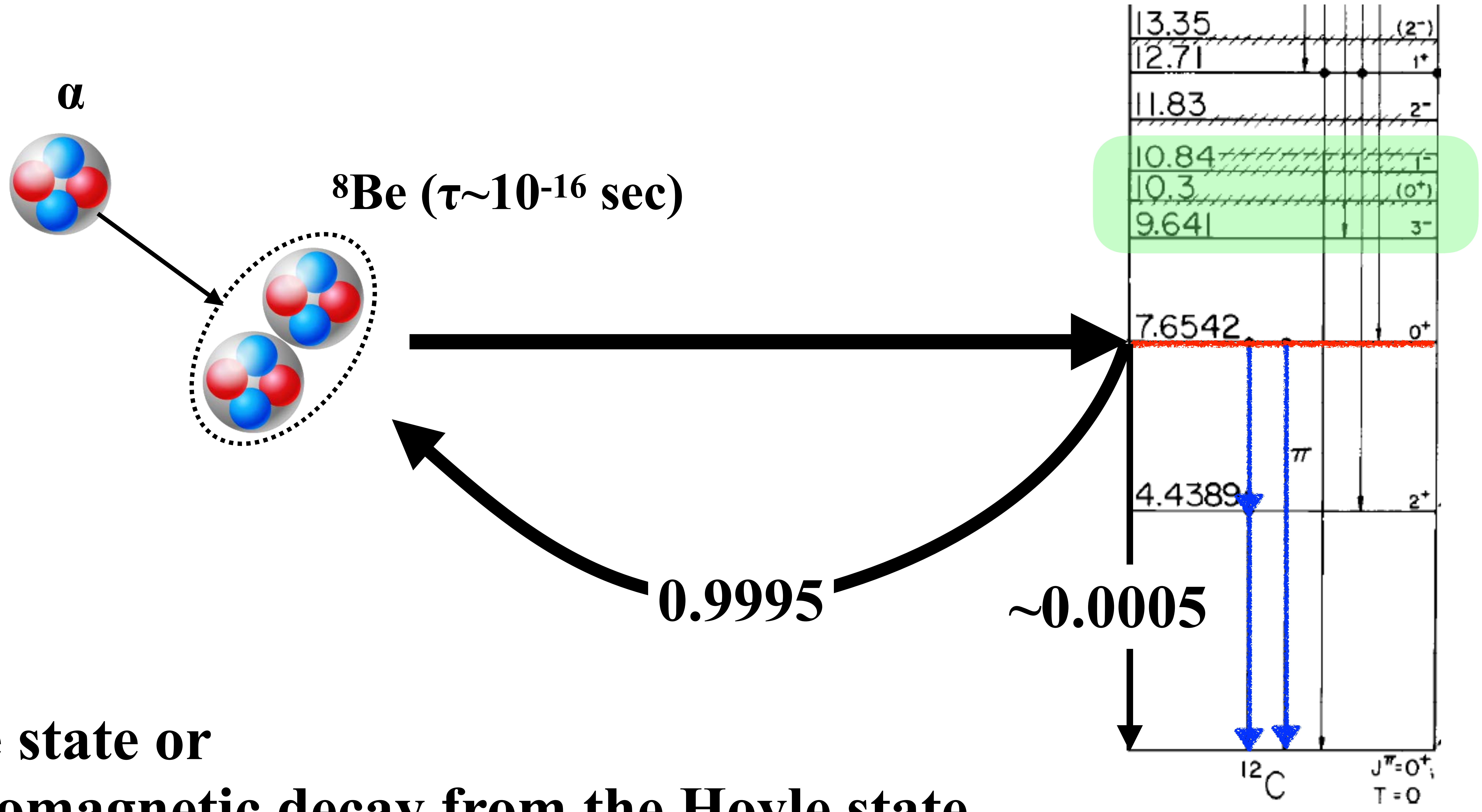
Hoyle state





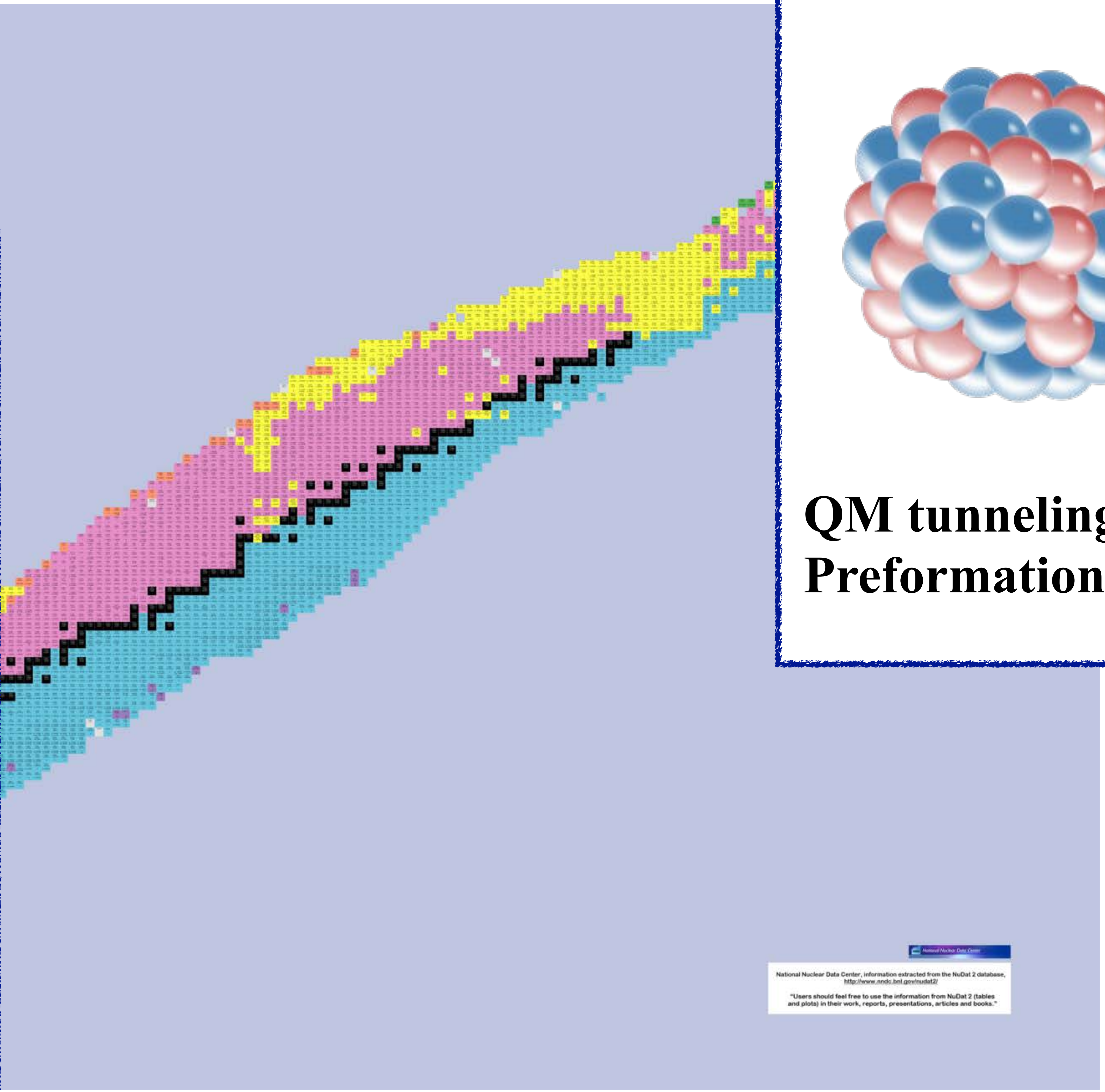


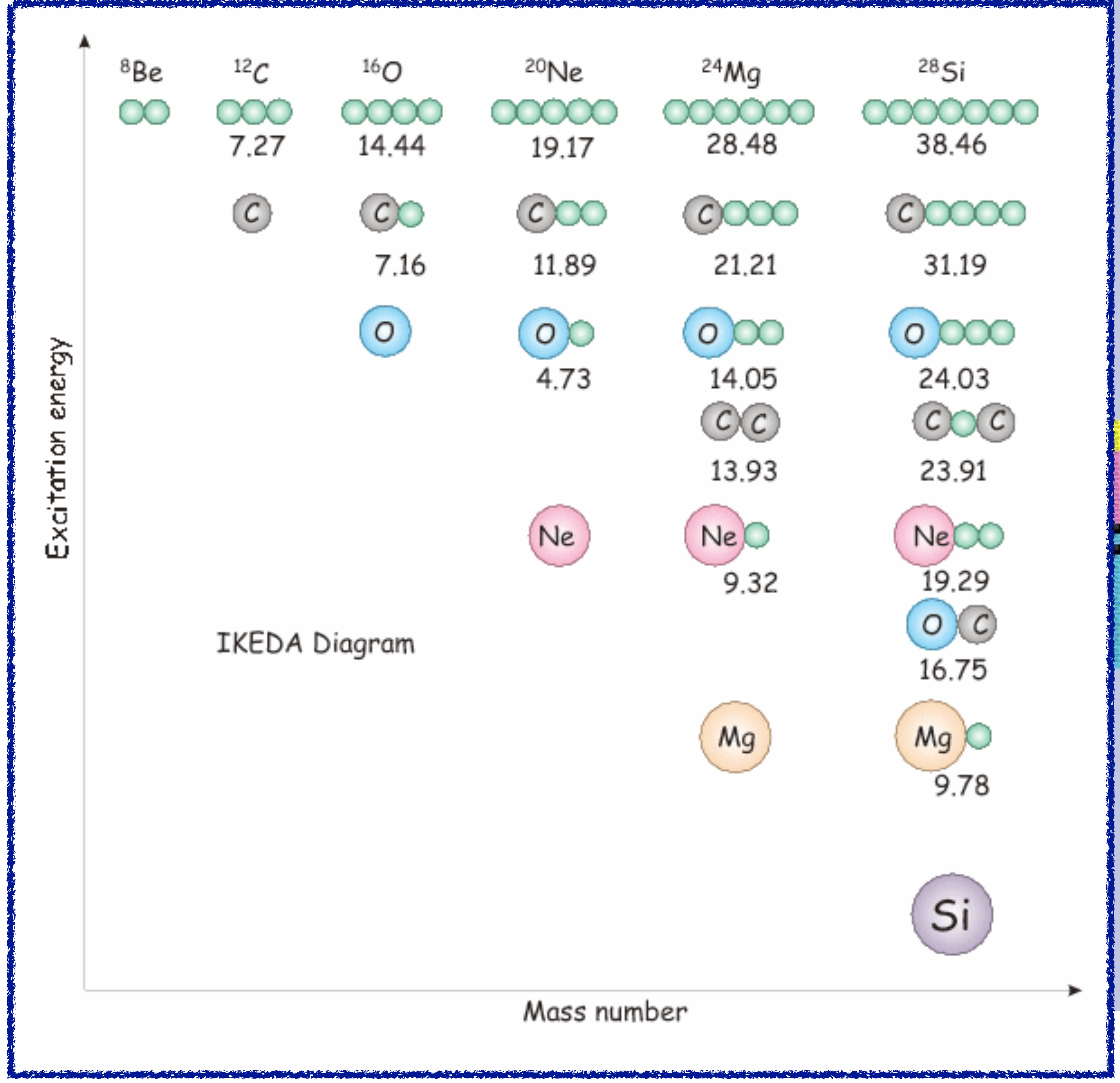
Helium burning, origin of Carbon

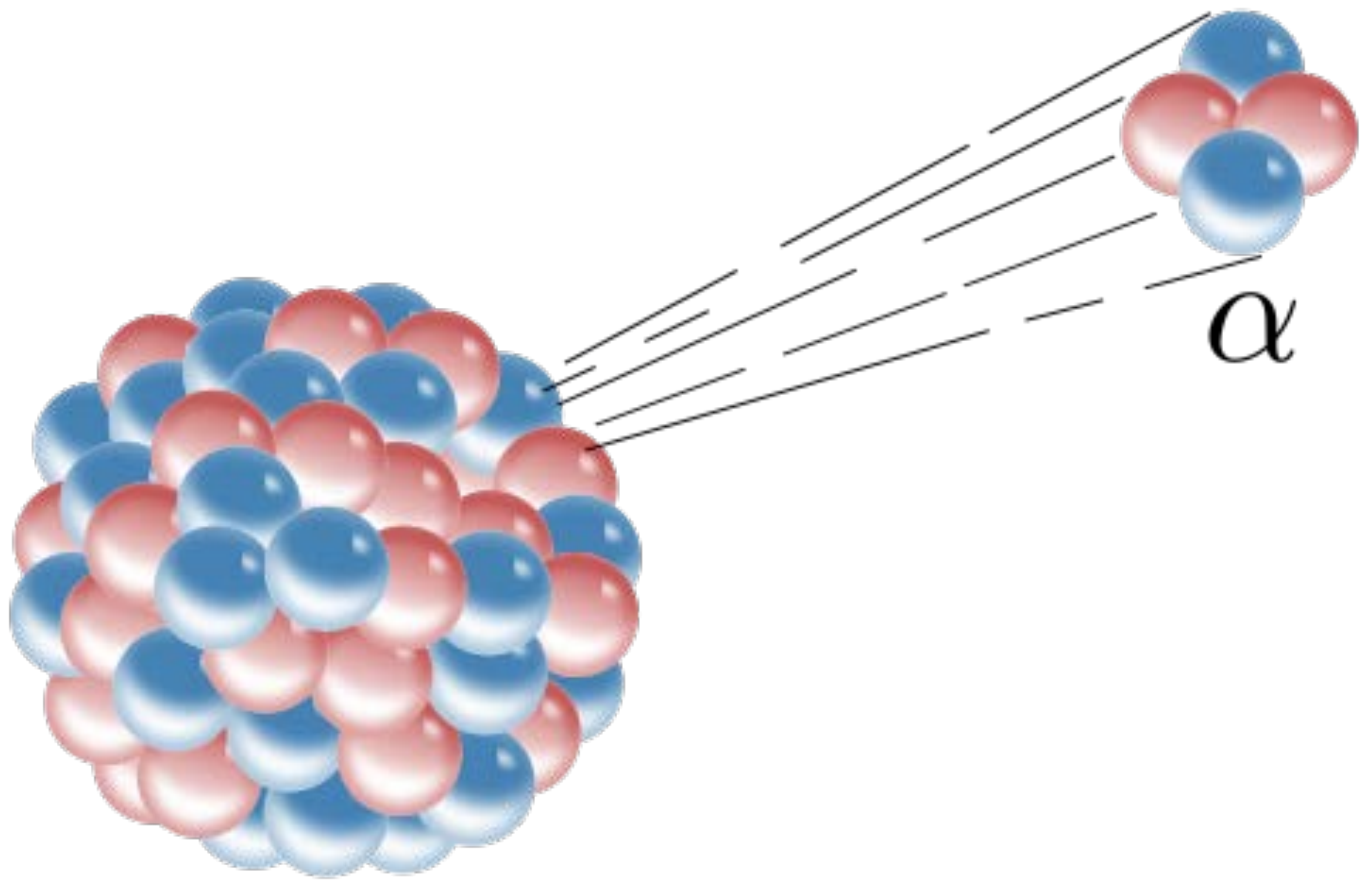


No Hoyle state or
No electromagnetic decay from the Hoyle state
→ no (or much less) carbon and no life.

Clusters are known to exist in light and heavy nuclei







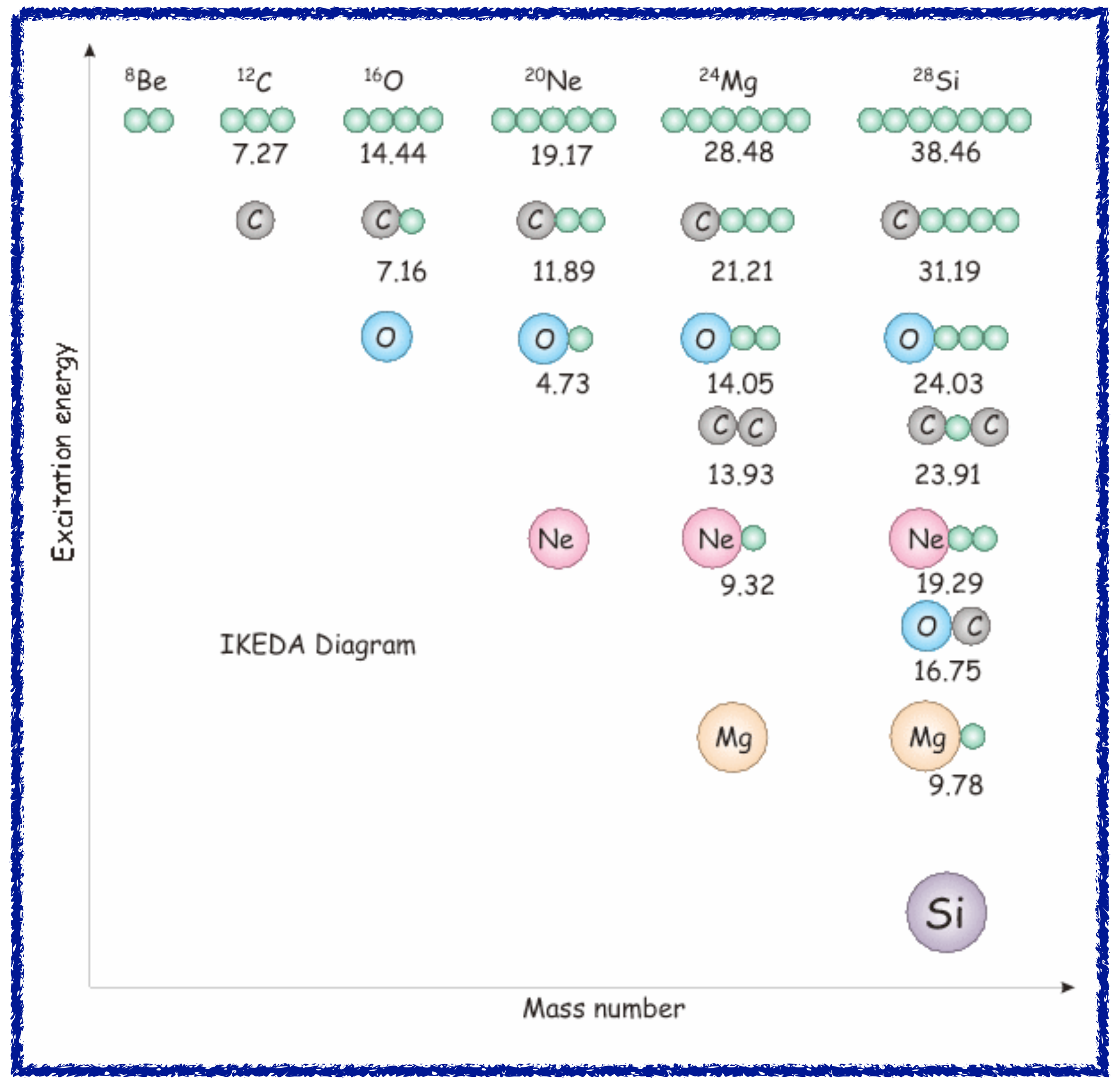
QM tunneling
Preformation mechanism?

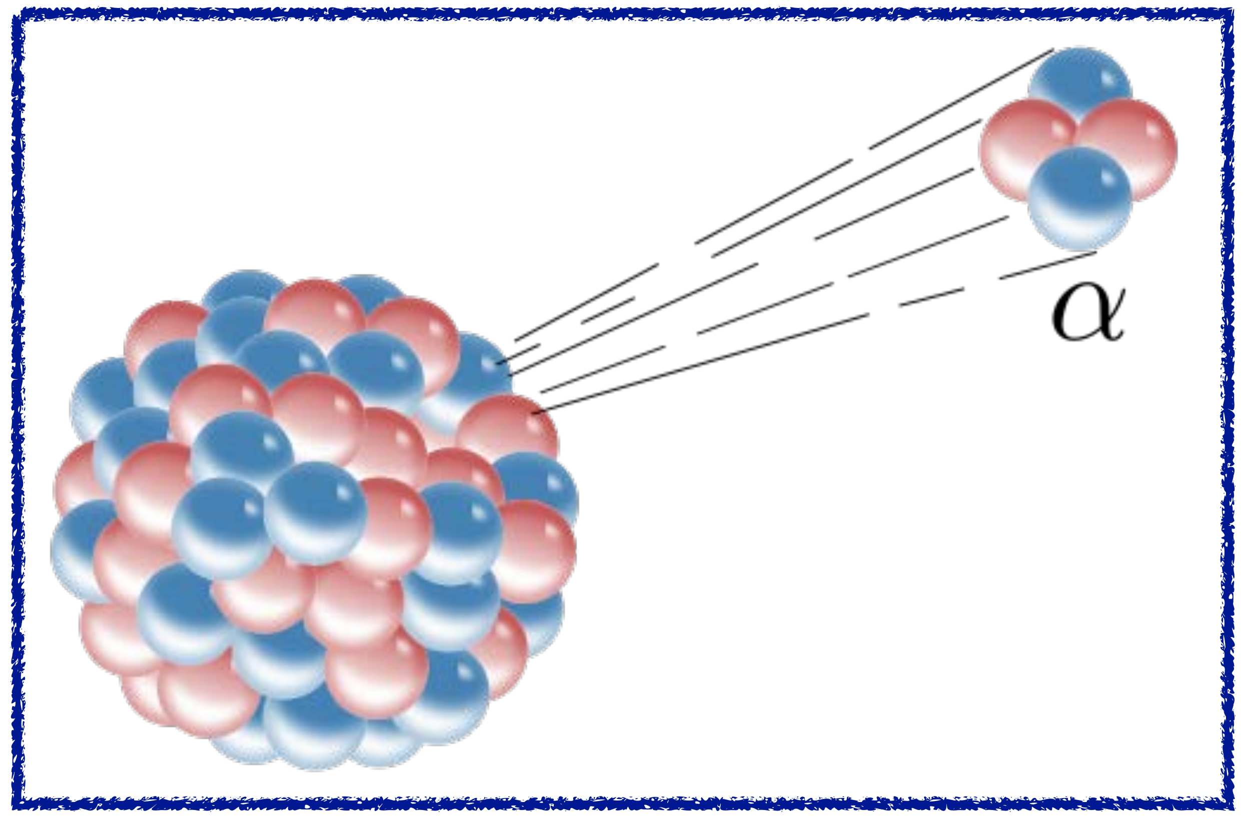
Long history of α-cluster studies

α decay

Hoyle state

Ikeda diagram





We should turn our eyes on new aspects of clustering in nuclei

"Generalized" clusters

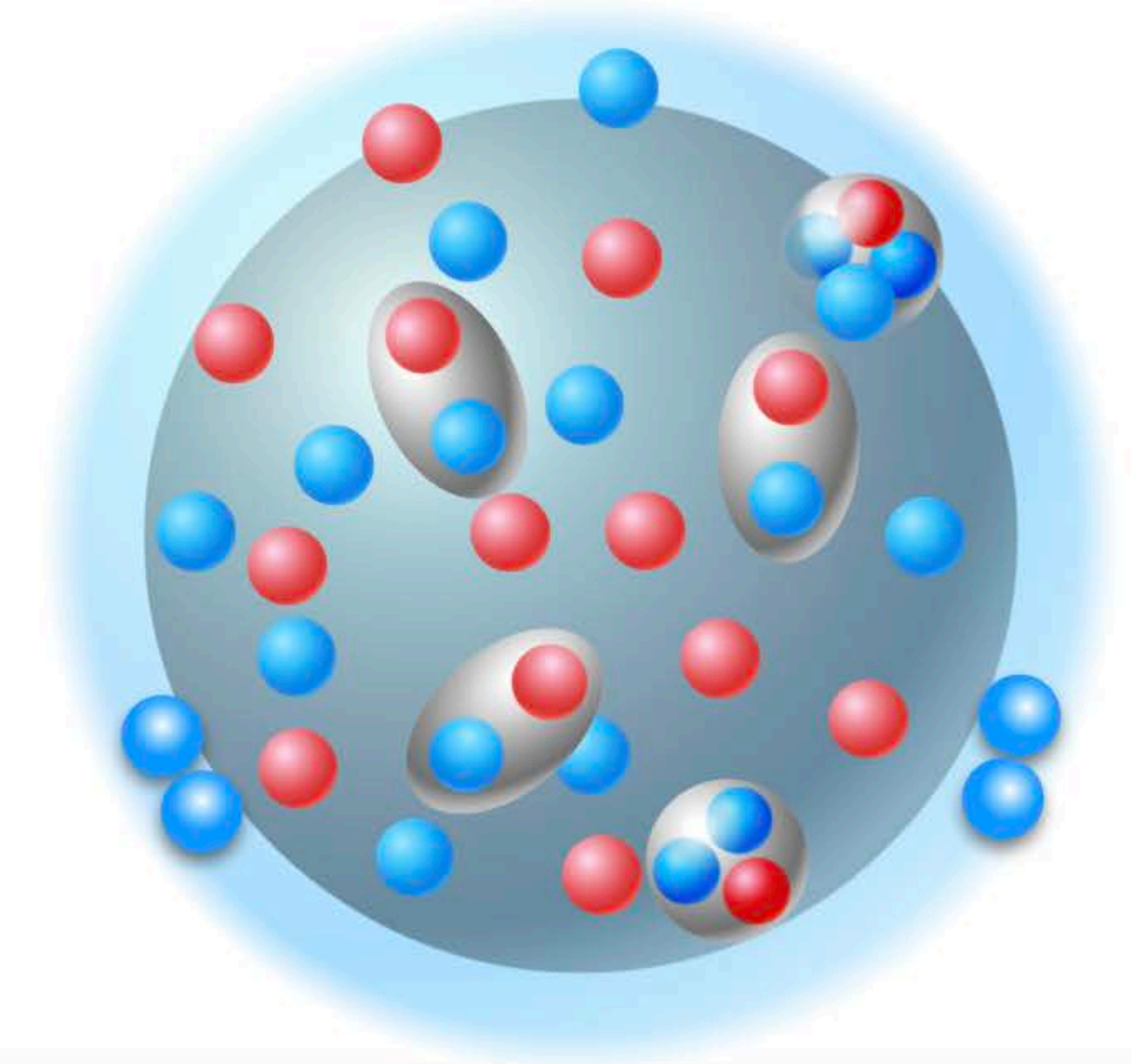
more weakly bound than α particle

such as *d*, *t*, ^{3}He, ^{2}n, ^{4}n etc.

Cluster "ubiquitousness"

occurrence of clustering

in *any* nuclei



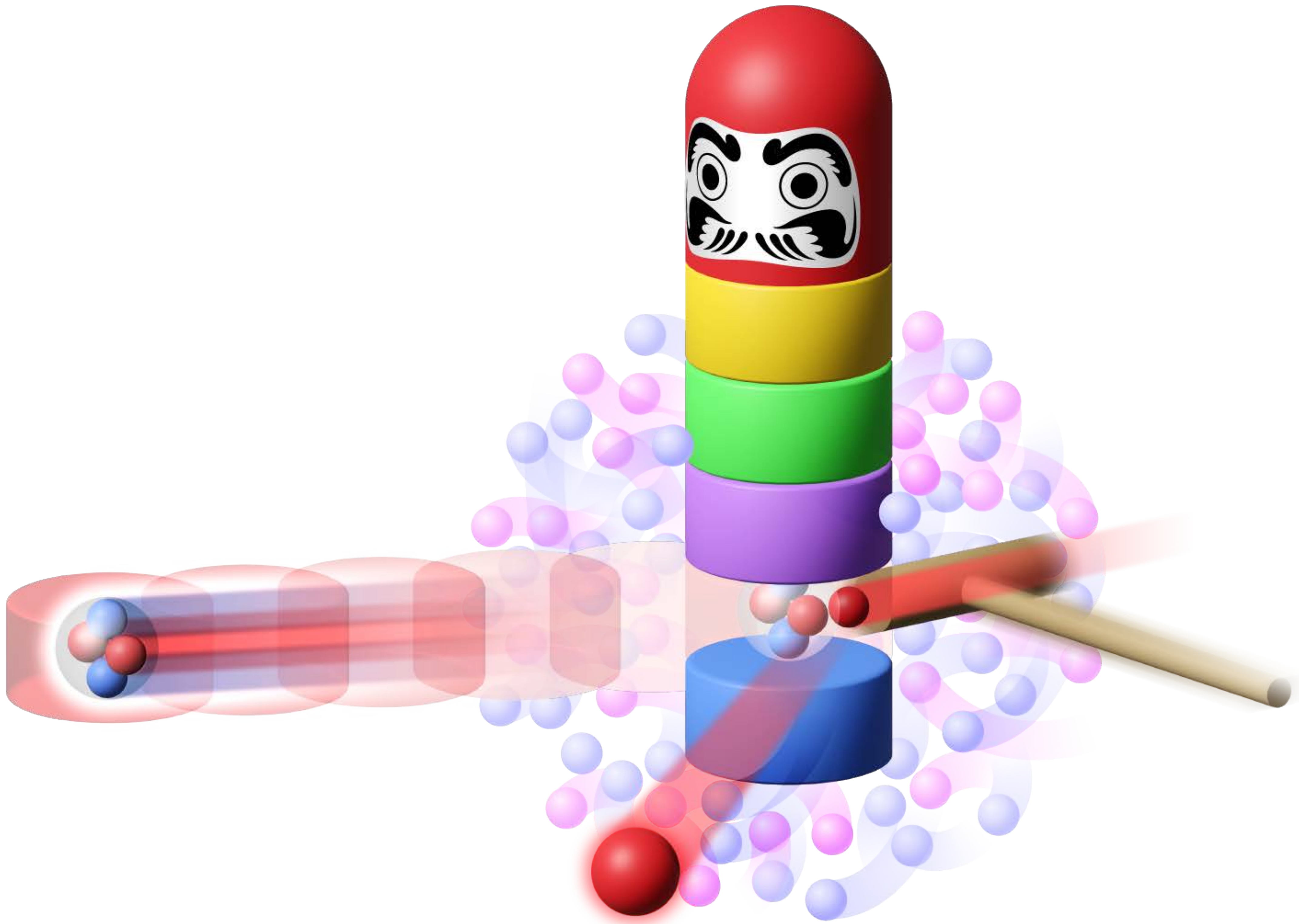
TU & N. Itagaki, Phil. Trans. R. Soc. A **382**:20230123 (2024).

Cluster knockout reaction

Quantum-mechanical “Daruma otoshi”

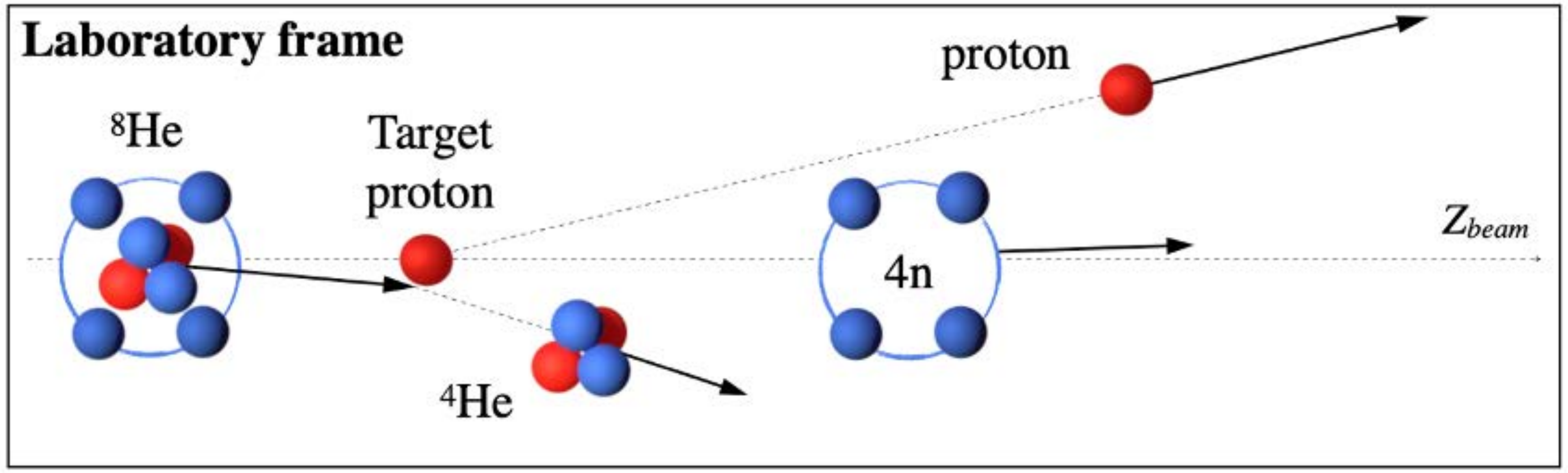
Knocking out a piece (⇔nucleon/cluster)
by a hammer (⇔high-energy proton)
with a large impact
(⇔large momentum transfer)

→ The other pieces (⇔the residual nucleus)
don’t realize that the piece is removed
(⇔initial-state information is kept).



c.f. (p,pα) experiments @ 100 MeV.
T.A. Carey et al., PRC 29, 1273 (1984).

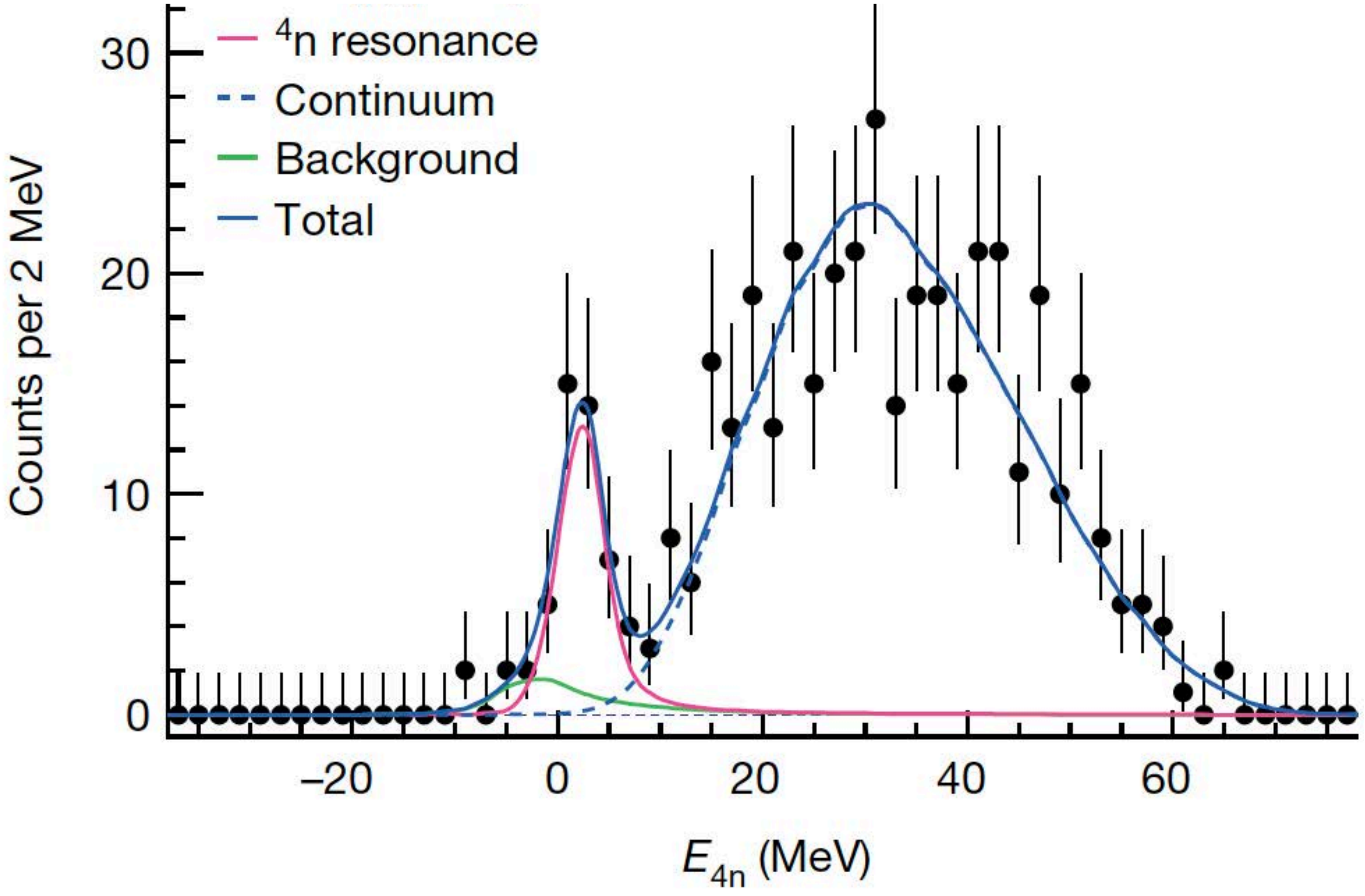
Cluster knockout reaction studies @RIBF



Production of tetraneutron

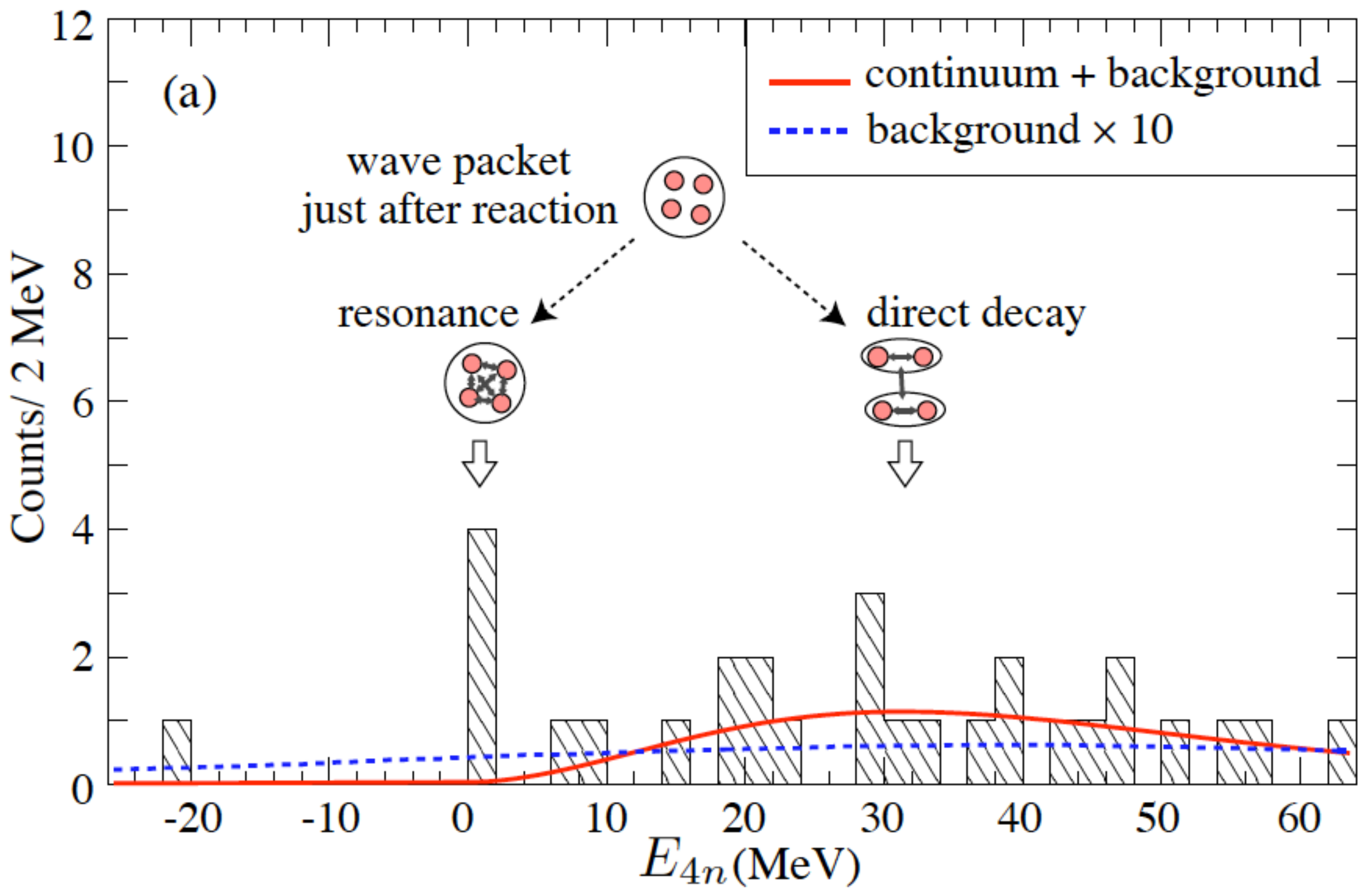
M. Duer et al., Nature 606 (2022).

$^8He(p,p\alpha)^4n$ @ θ_{CM}=180deg



E= 2.37 ±0.38(stat.)±0.44(sys.) MeV
Γ = 1.75 ±0.22(stat.)±0.30(sys.) MeV

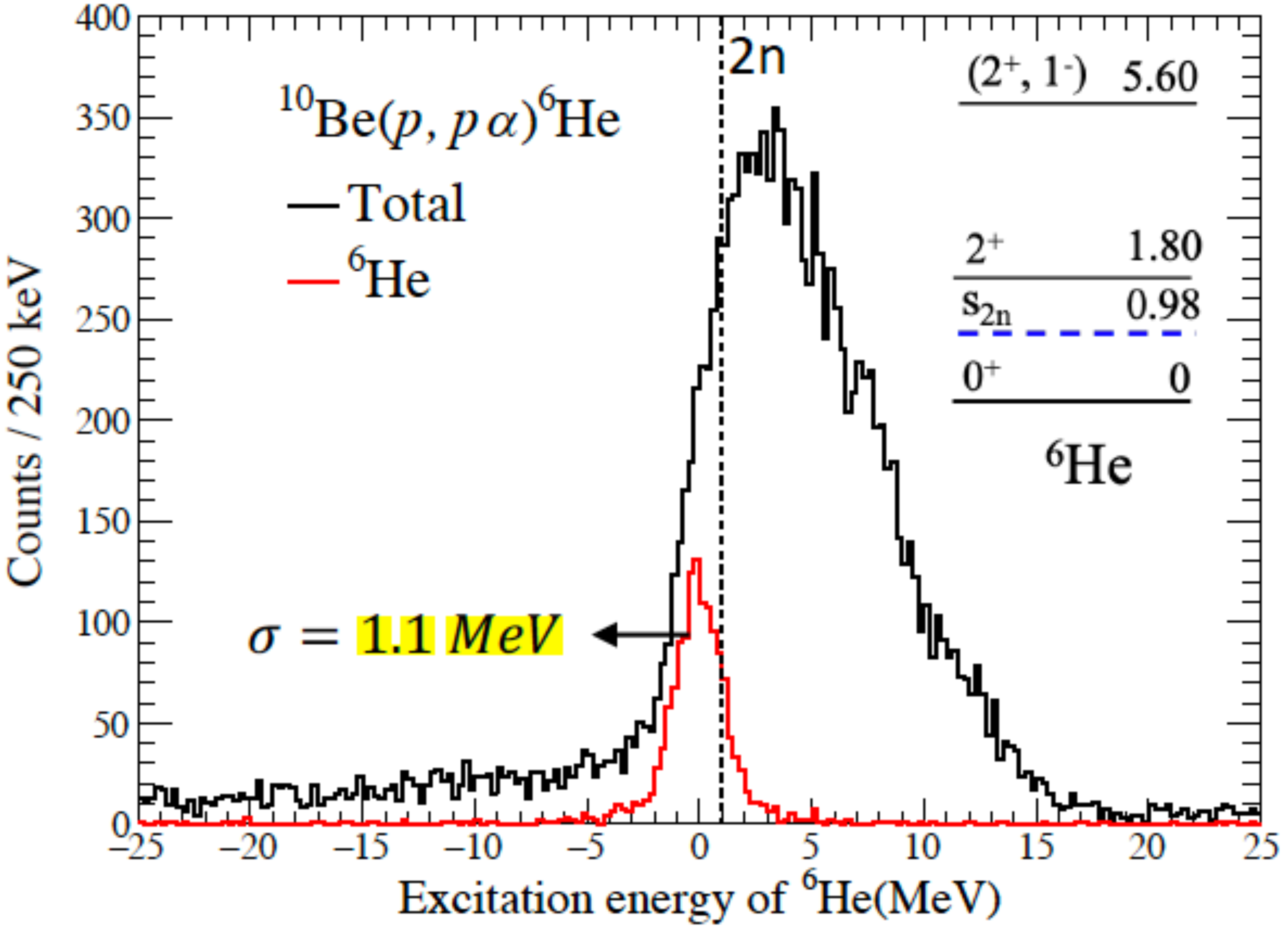
K. Kisamori, et al., PRL 116 (2016).
$^4He(^8He,^8Be)^4n$
@SHARAQ

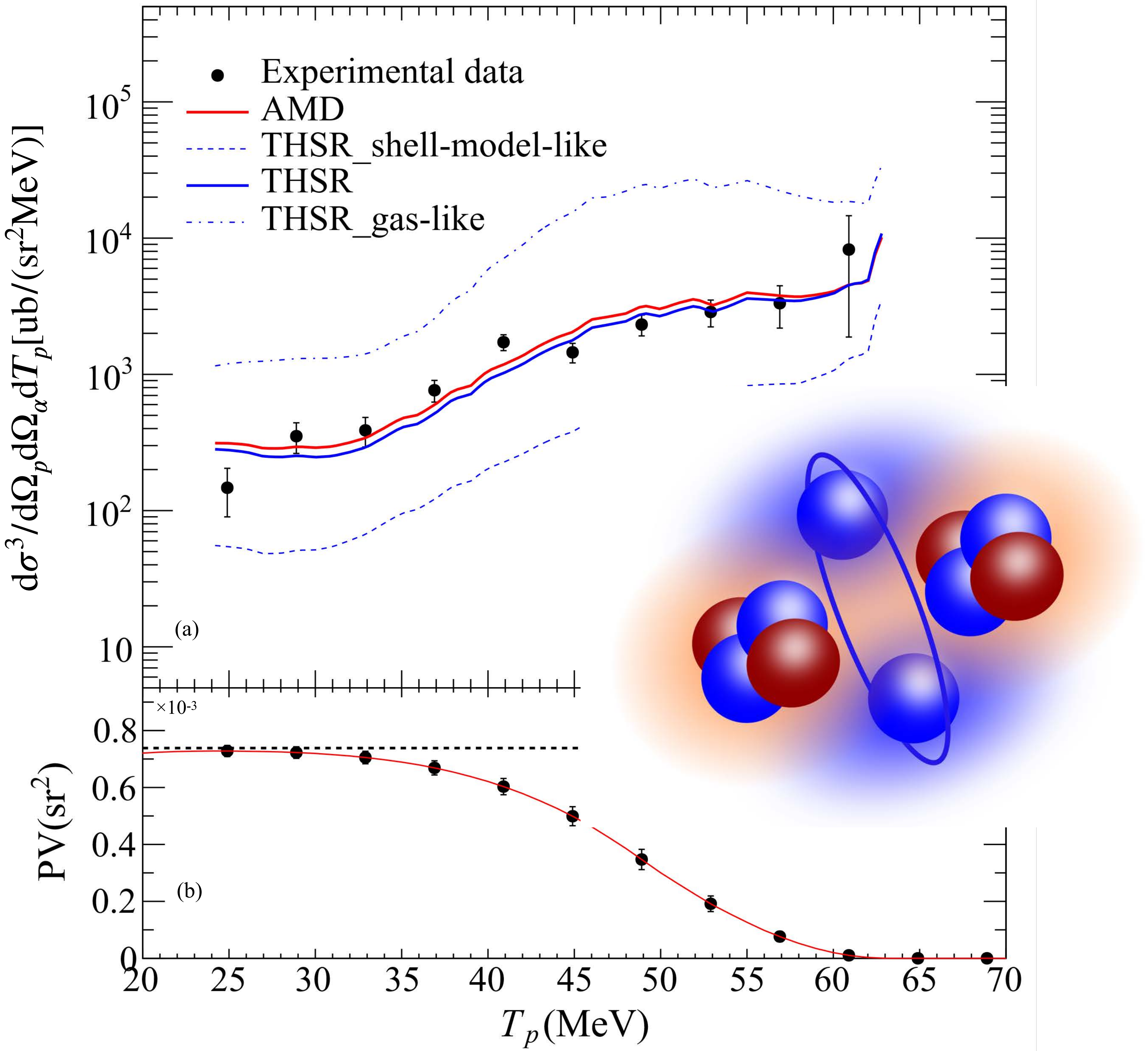


E_{4n} = 0.83 ± 0.65 (stat.) ± 1.25 (syst.) MeV

Molecular sructure of ^{10}Be (α-α-2n)

^{10}Be(*p*,*pα*)





Pengjie Li, D. Beaumel et al.,
Physial Review Letters 131, 212501 (2023).

α clusters in tin isotopes

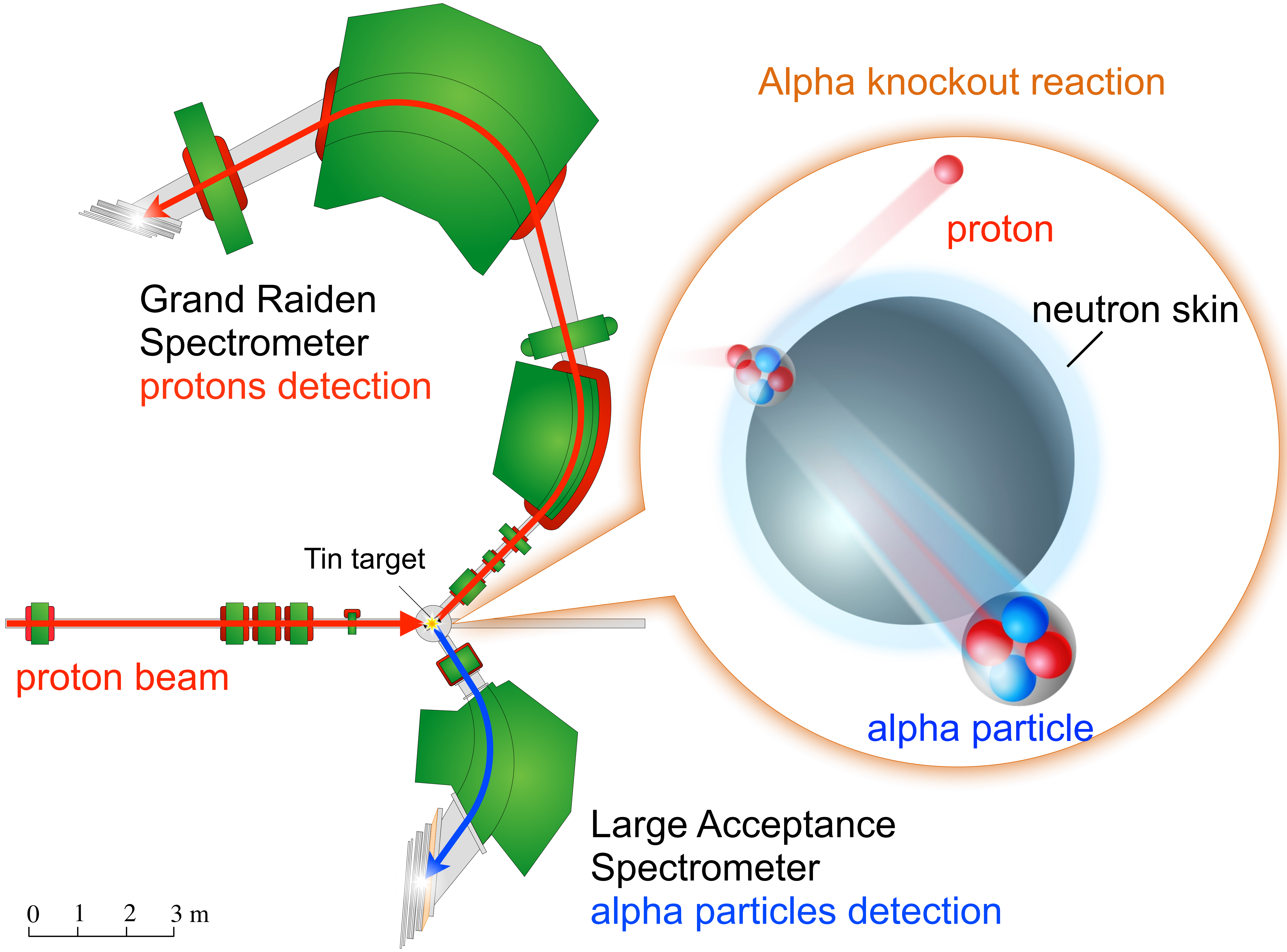
REPORT

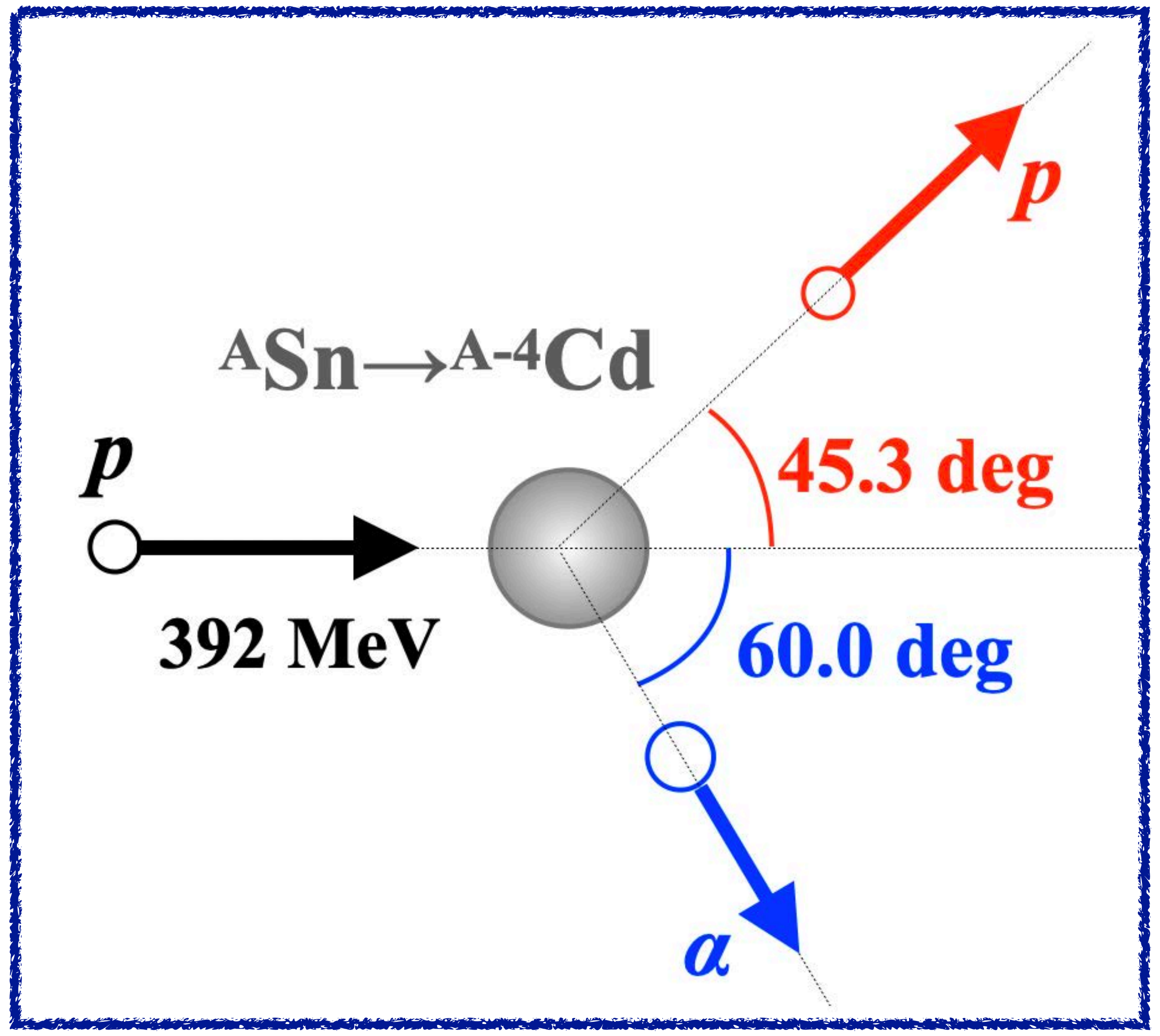
NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

$^{112,116,120,124}Sn(p,p\alpha)$
@ E_p=392 MeV

J. Tanaka, Z.H. Yang,
S. Typel, TU, T. Aumann et al.,
Science 371, 260–264 (2021)



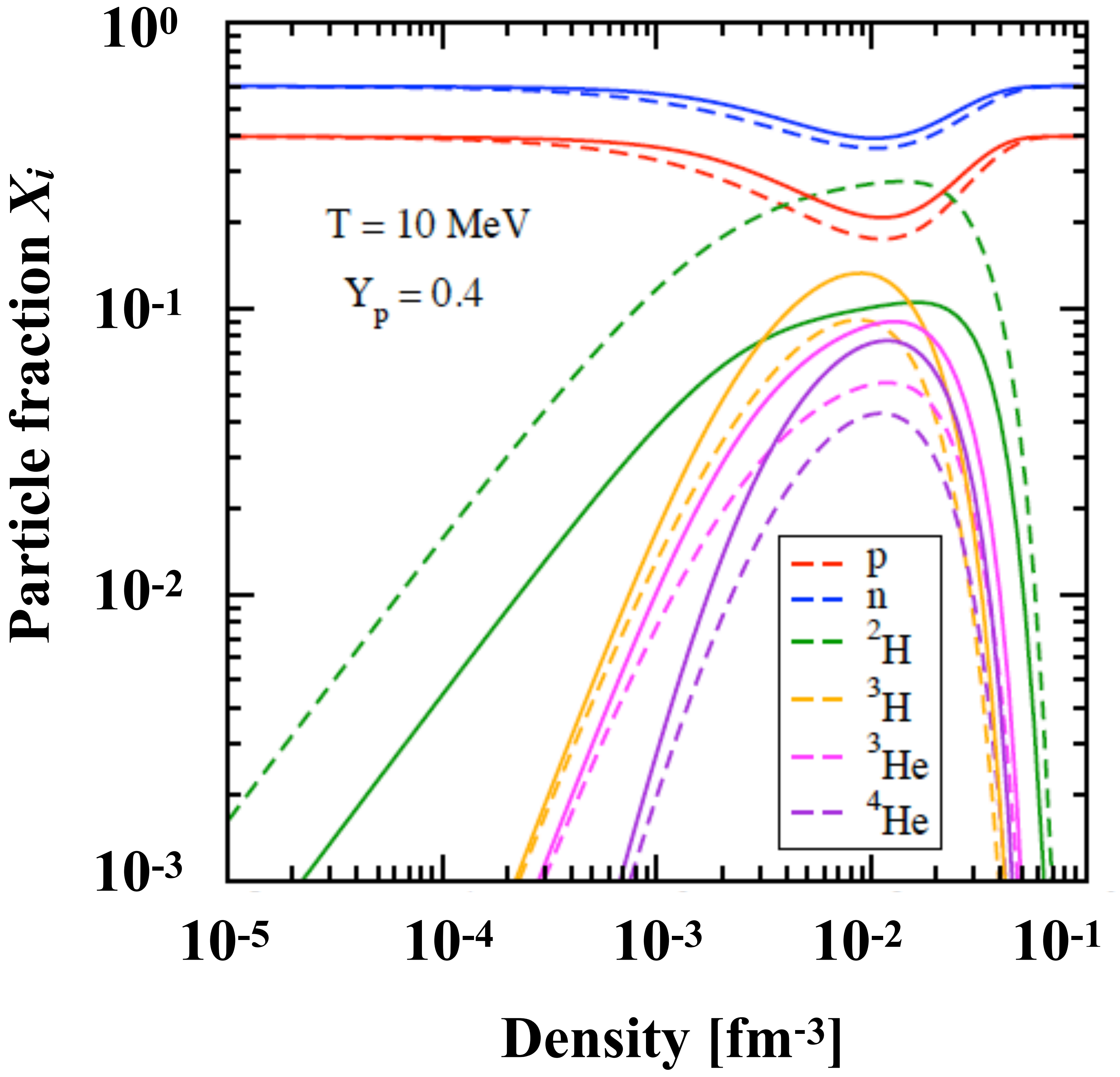


Clustering in dilute nuclear matter

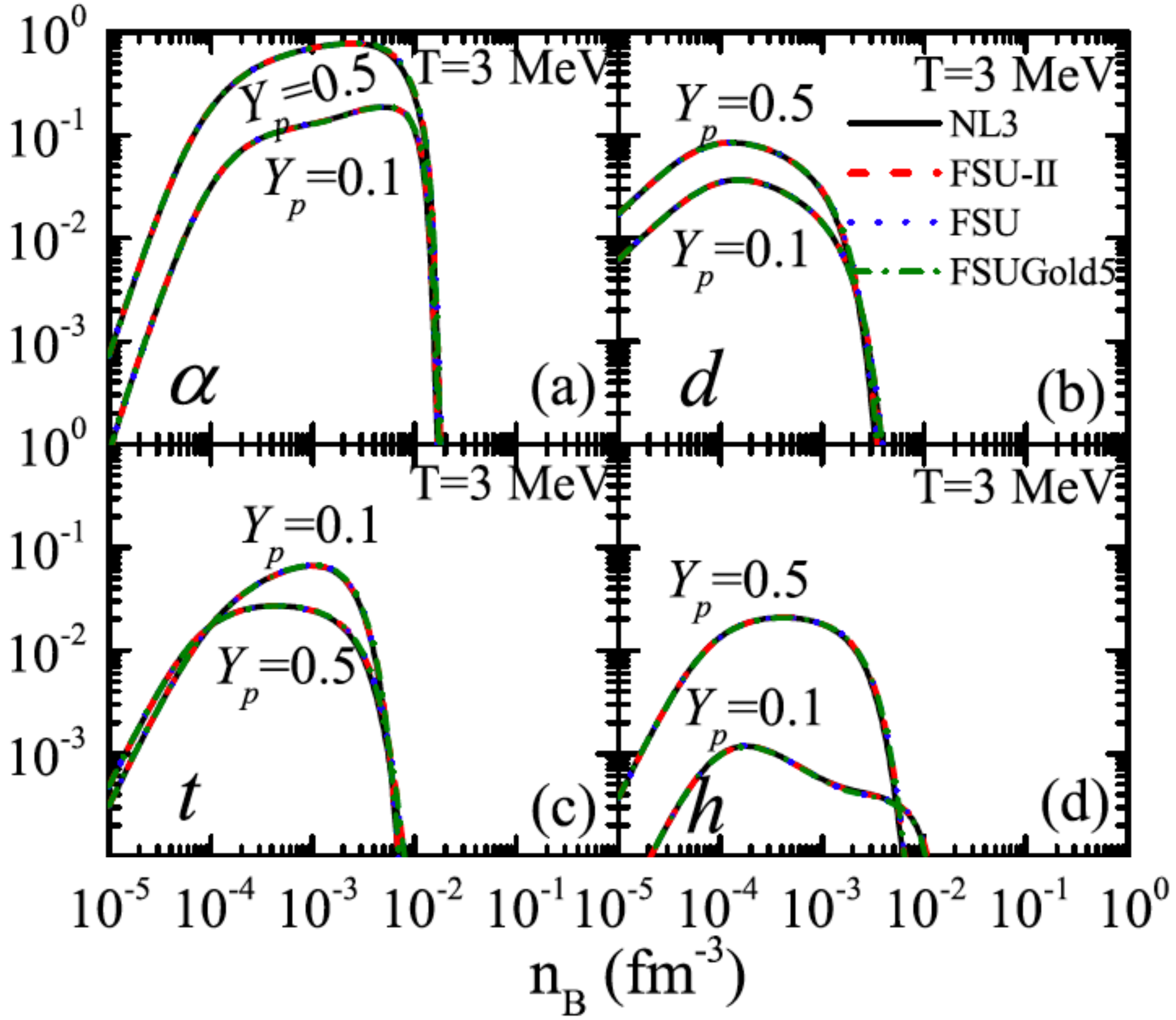
An important aspect of the supernova EOS is the formation of light nuclei and their properties in the hot and dense medium. Note that the two classic supernova EOS include only alpha particles of all possible light nuclei, which are implemented with excluded volume effects.

M. Hempel et al., Astrophys. J. 748 (2012)

S. Typel,
J. Phys. Conf. Ser. 420, 012078 (2013)



Z.W. Zhang and L.W. Chen
Physical Review C 95, 064330 (2017)

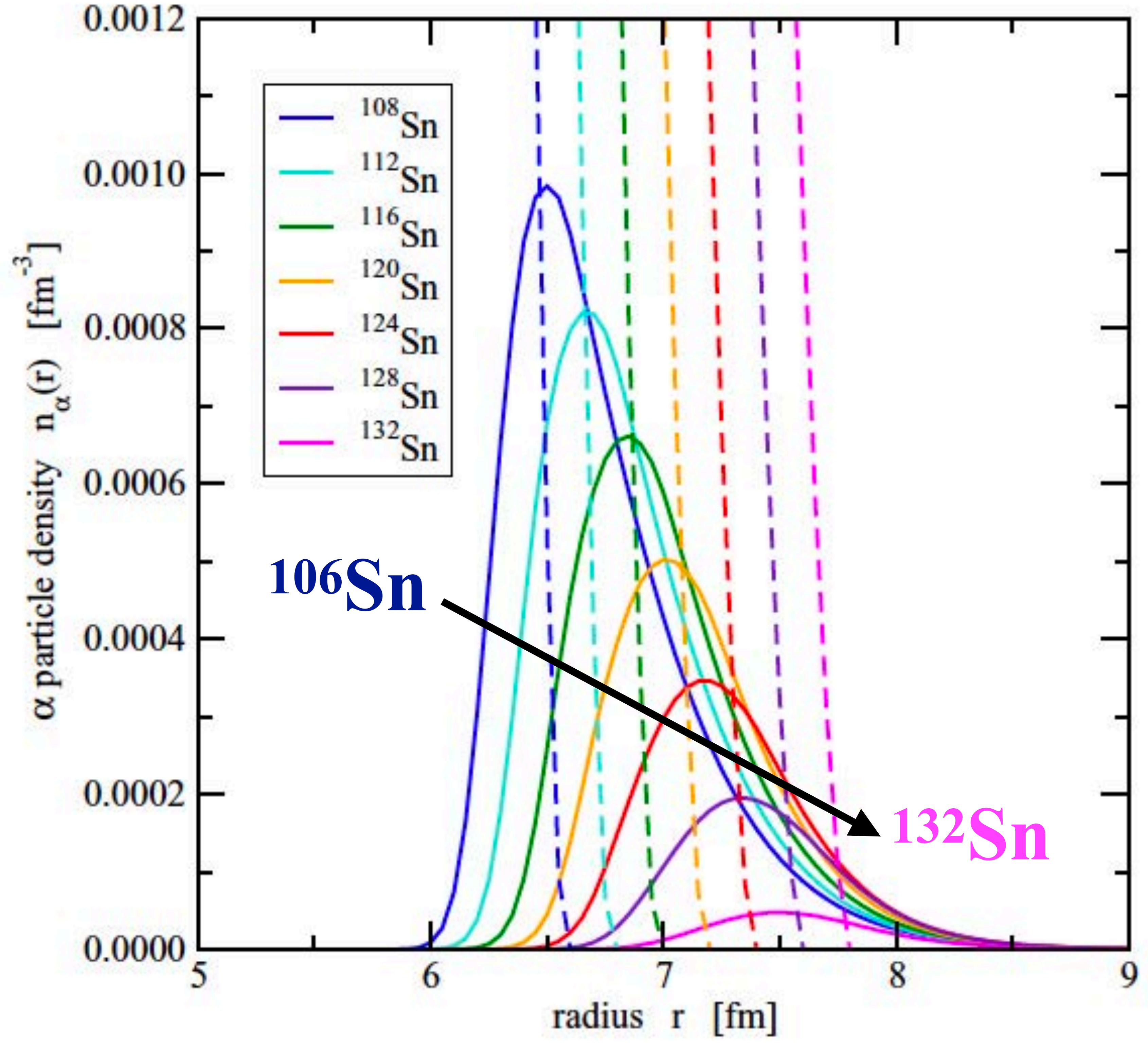


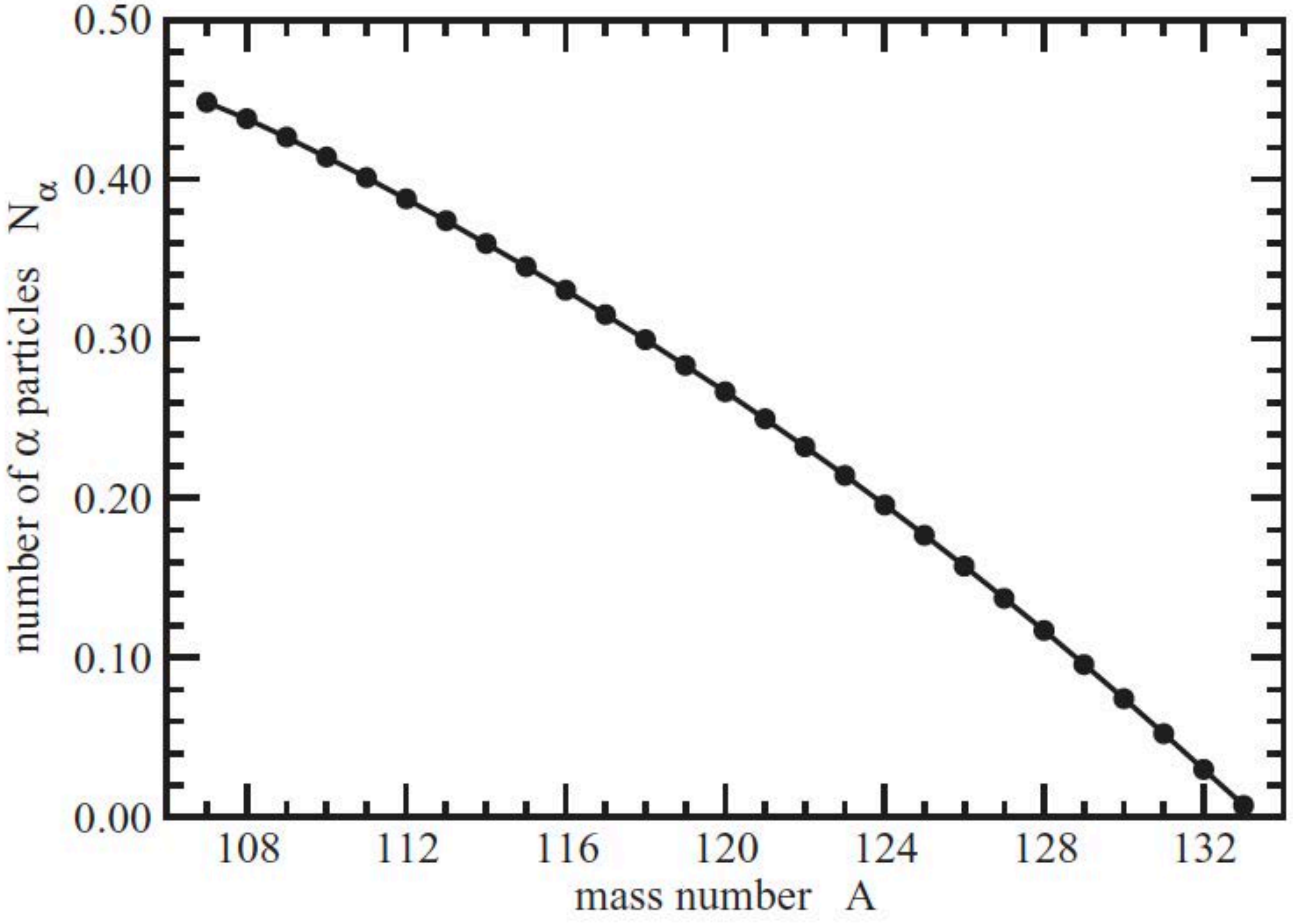
Clusters grow at < 0.1 ρ_{sat}. Occurrence of clusters depends on isospin asymmetry.

Where is the sign of clustering in nuclear matter?

On the dilute (=non-saturated) surface of heavy nuclei, clusters develop.

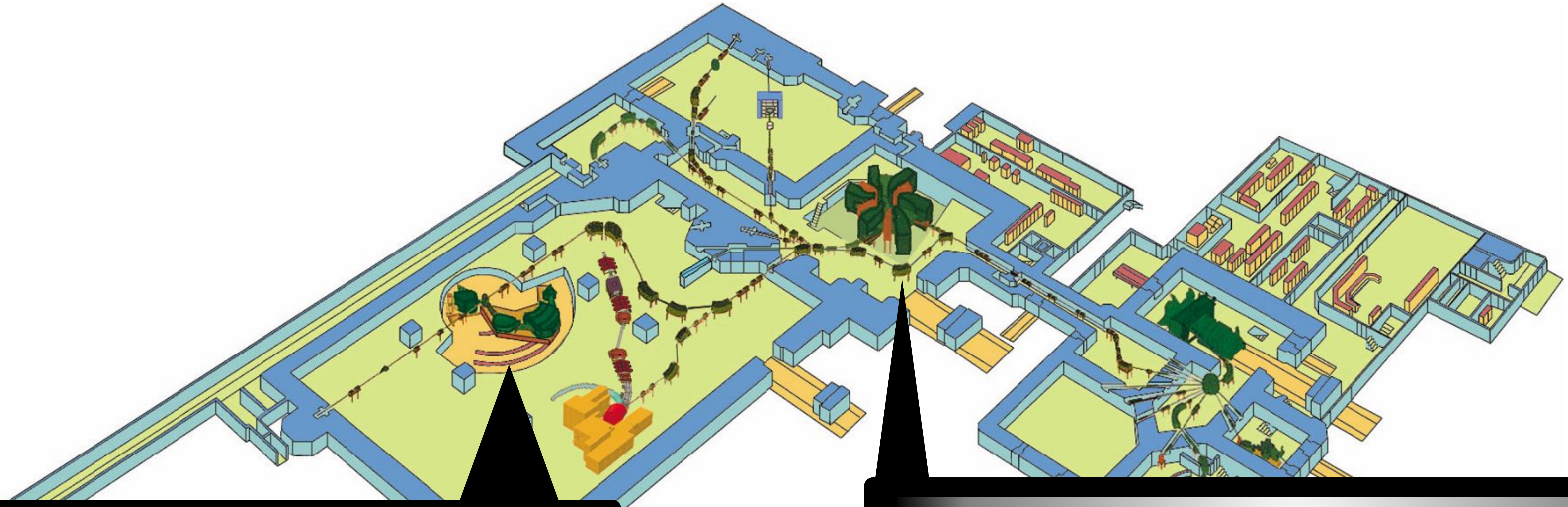
S. Typel, PRC **89**, 064321 (2014).



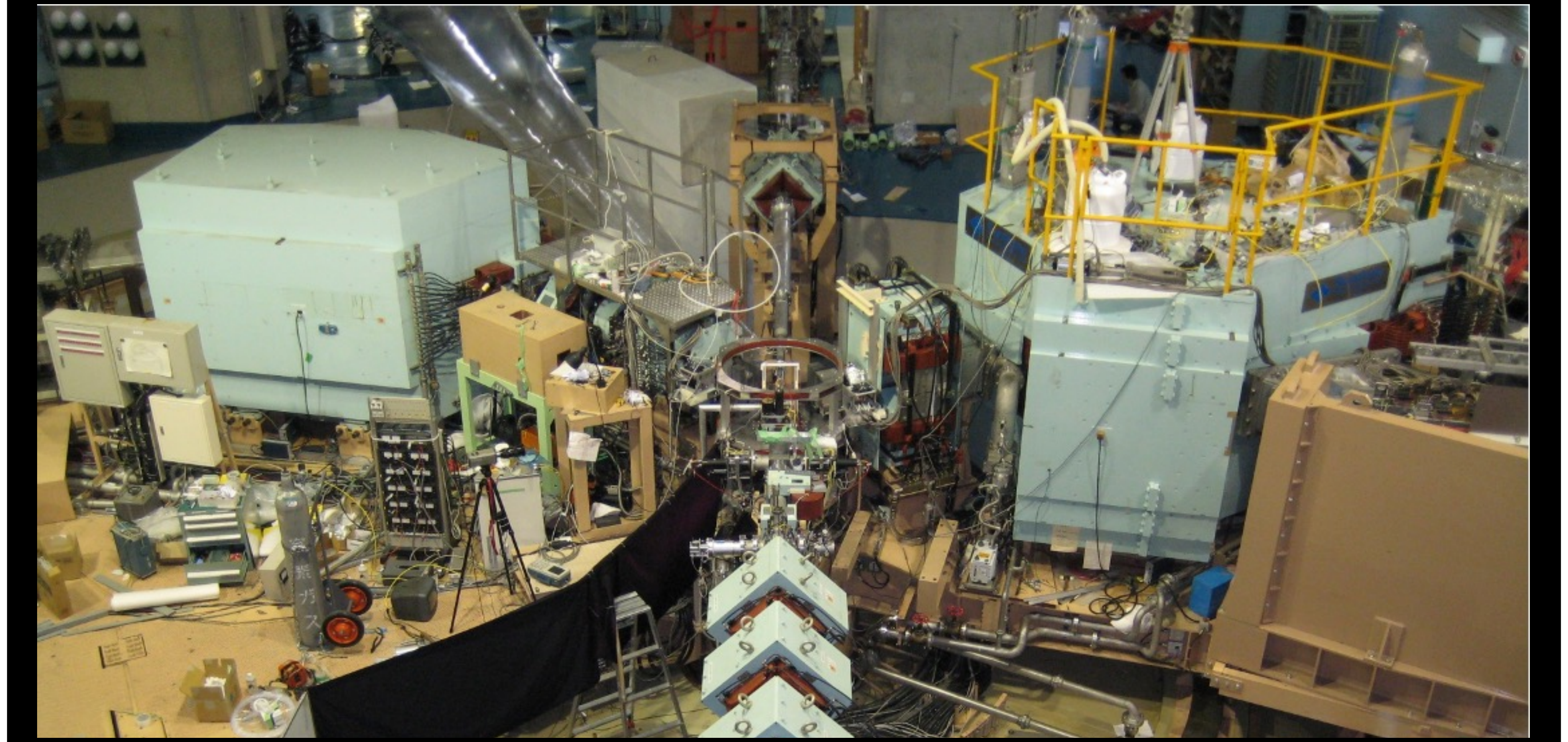


"The surface α" decreases as a function of excess neutron

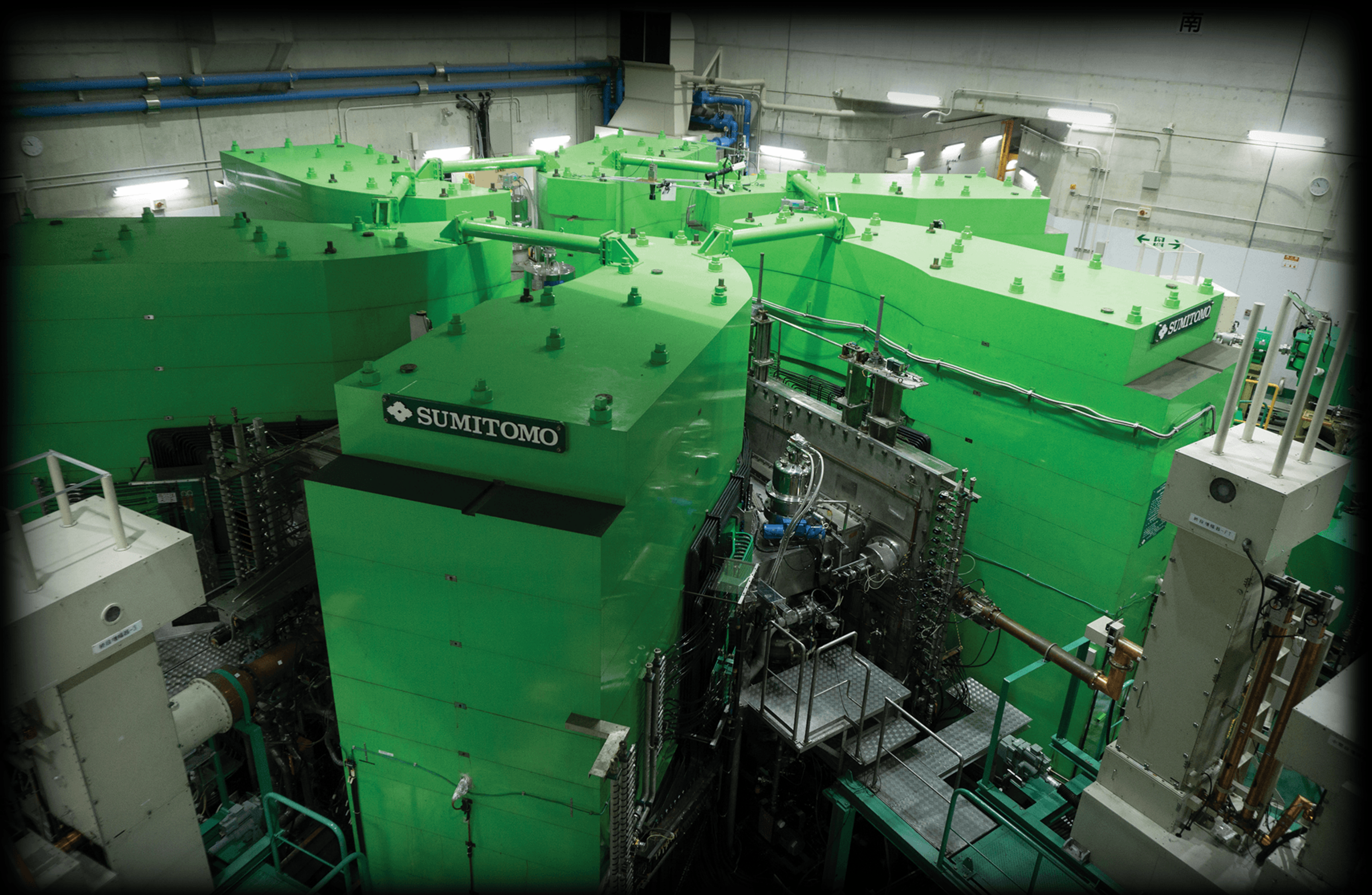
Experiment at RCNP Osaka University



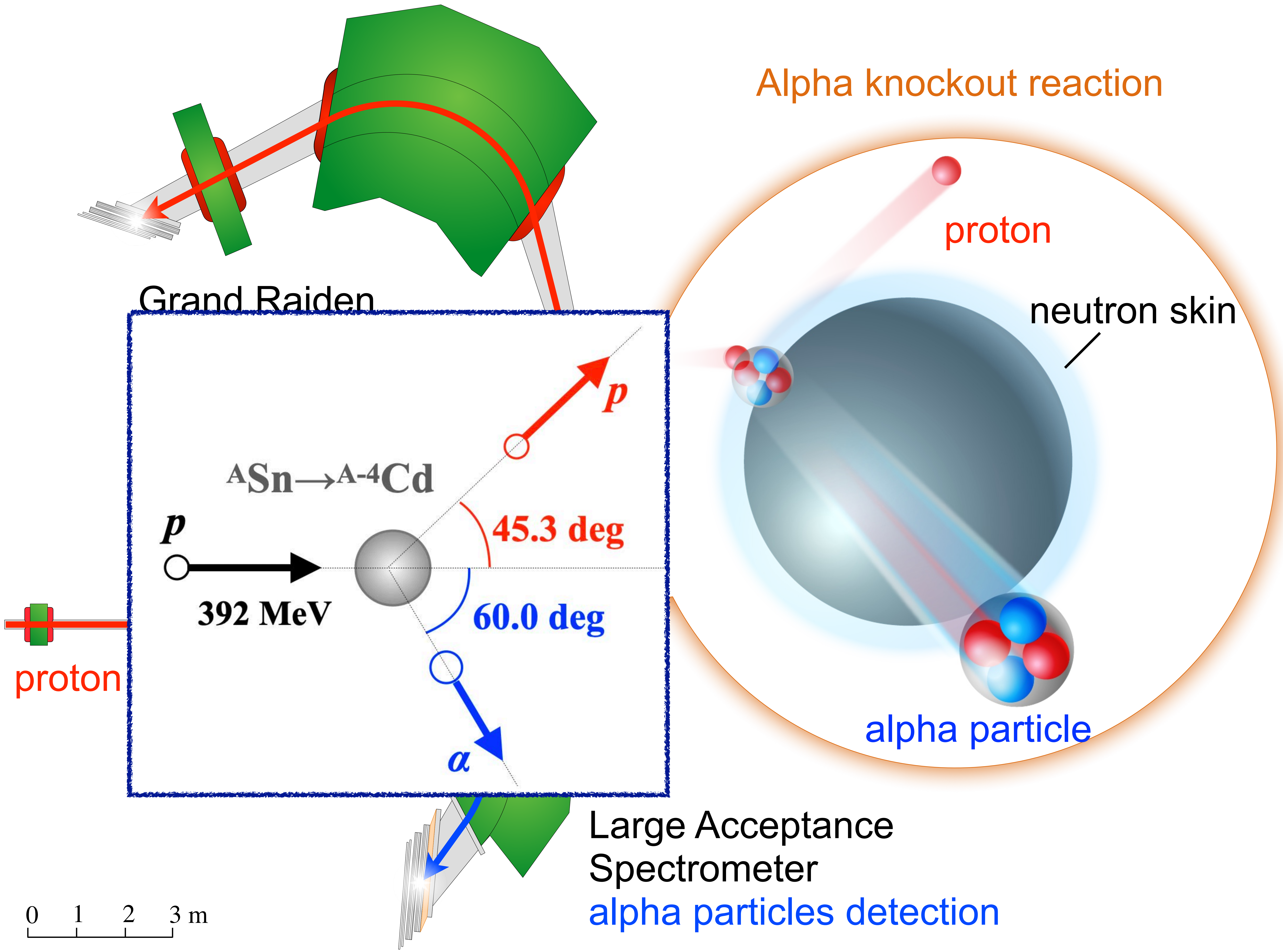
Grand Raiden and LAS spectrometers



Ring Cyclotron



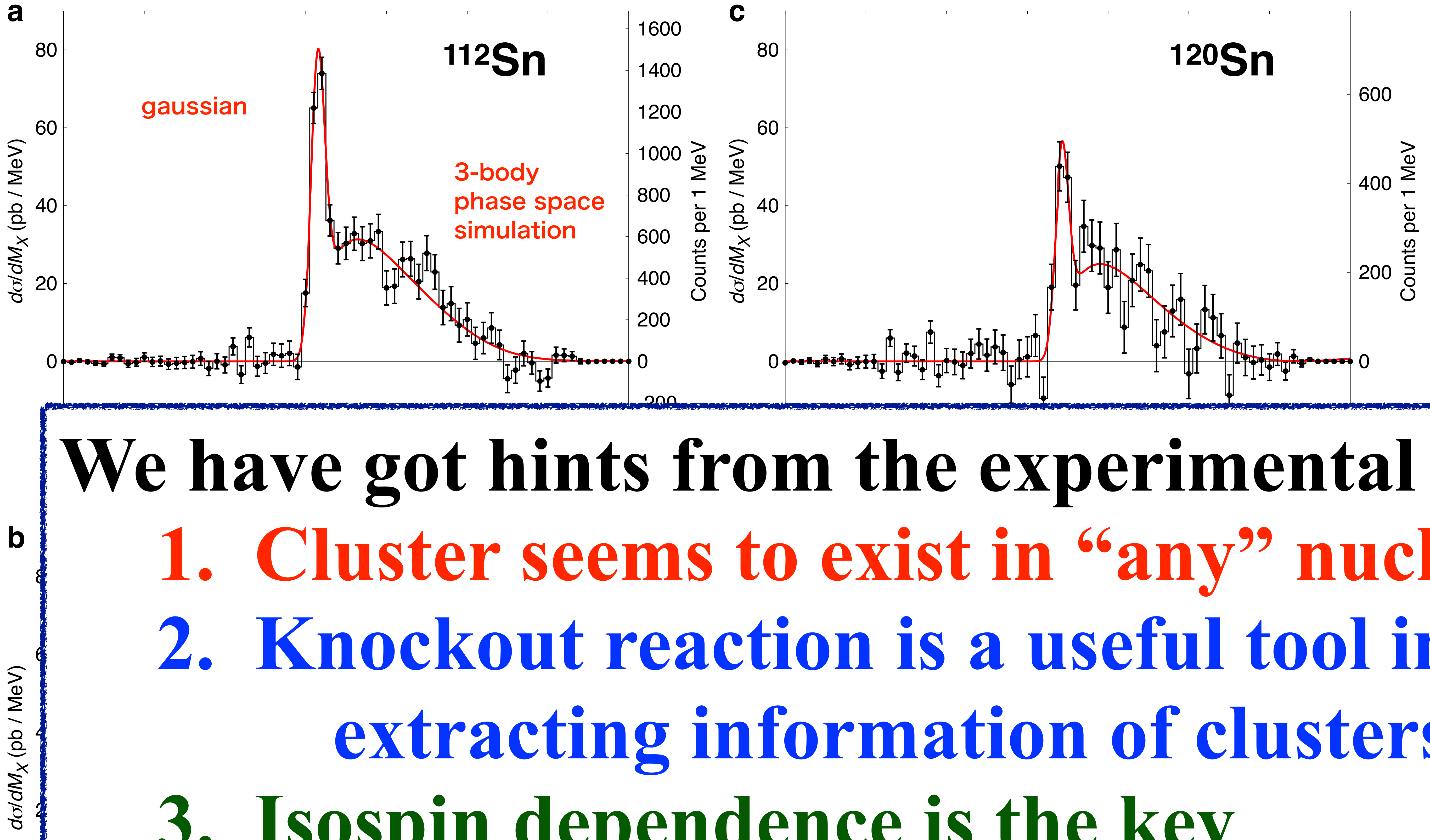
$^{112,116,120,124}Sn(p,p\alpha)$ @ E_p=392 MeV

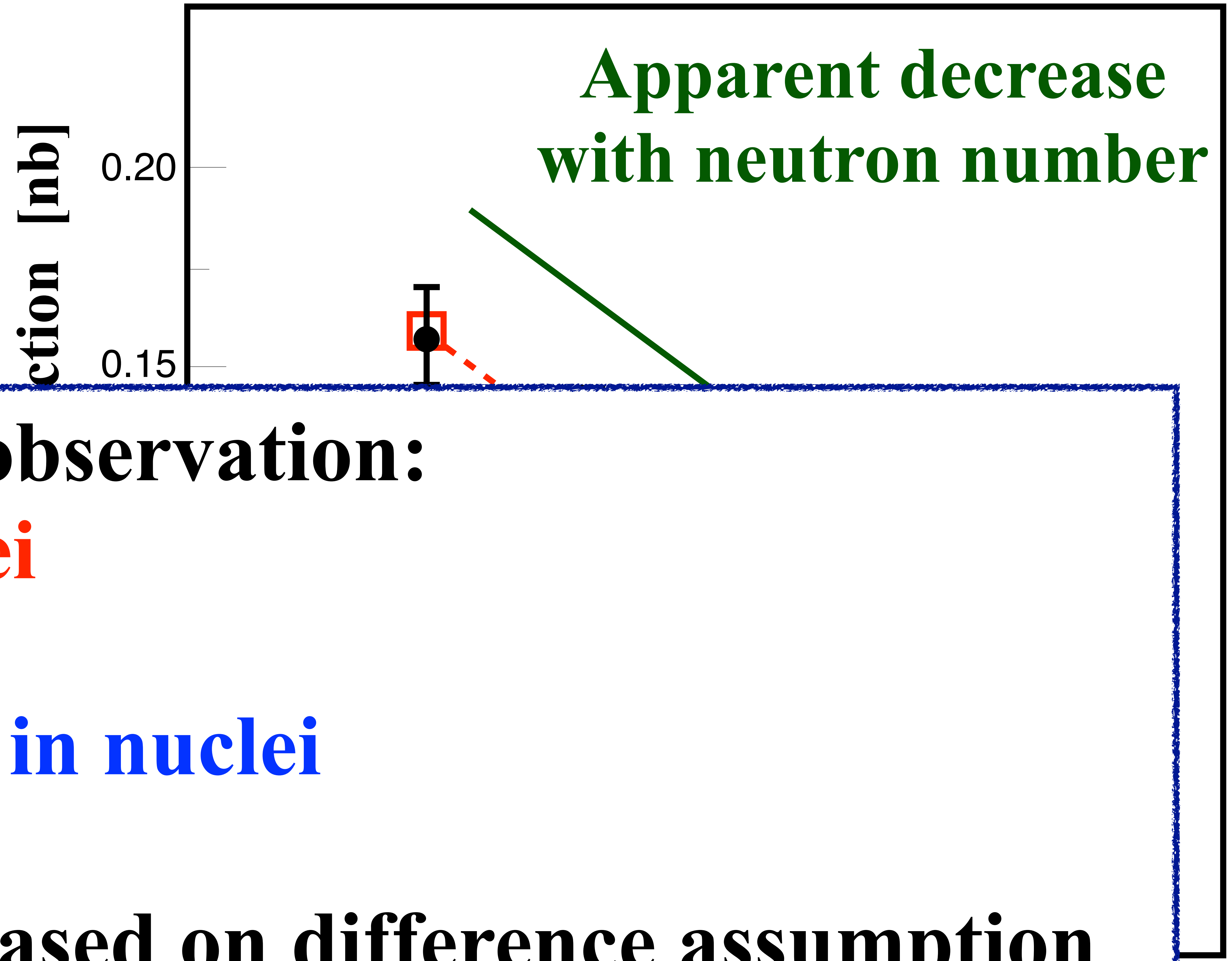


What we observed

The tendency is consistent with theoretical prediction based on a surface-α hypothesis!

^{A}Sn(p,$p\alpha$)$^{A-4}$Cd missing mass spectrum





We have got hints from the experimental observation:

1. **Cluster seems to exist in "any" nuclei**
2. **Knockout reaction is a useful tool in extracting information of clusters in nuclei**
3. **Isospin dependence is the key**

c.f. new theoretical calculations based on difference assumption

Nakatsukasa & Hinohara, PRC 108, 014318 (2023).

Excitation energy in Cd [MeV]

"Generalized" clusters

Looking for all the clusters in stable and unstable isotopes

Cluster "ubiquitousness"

ONOKORO Project

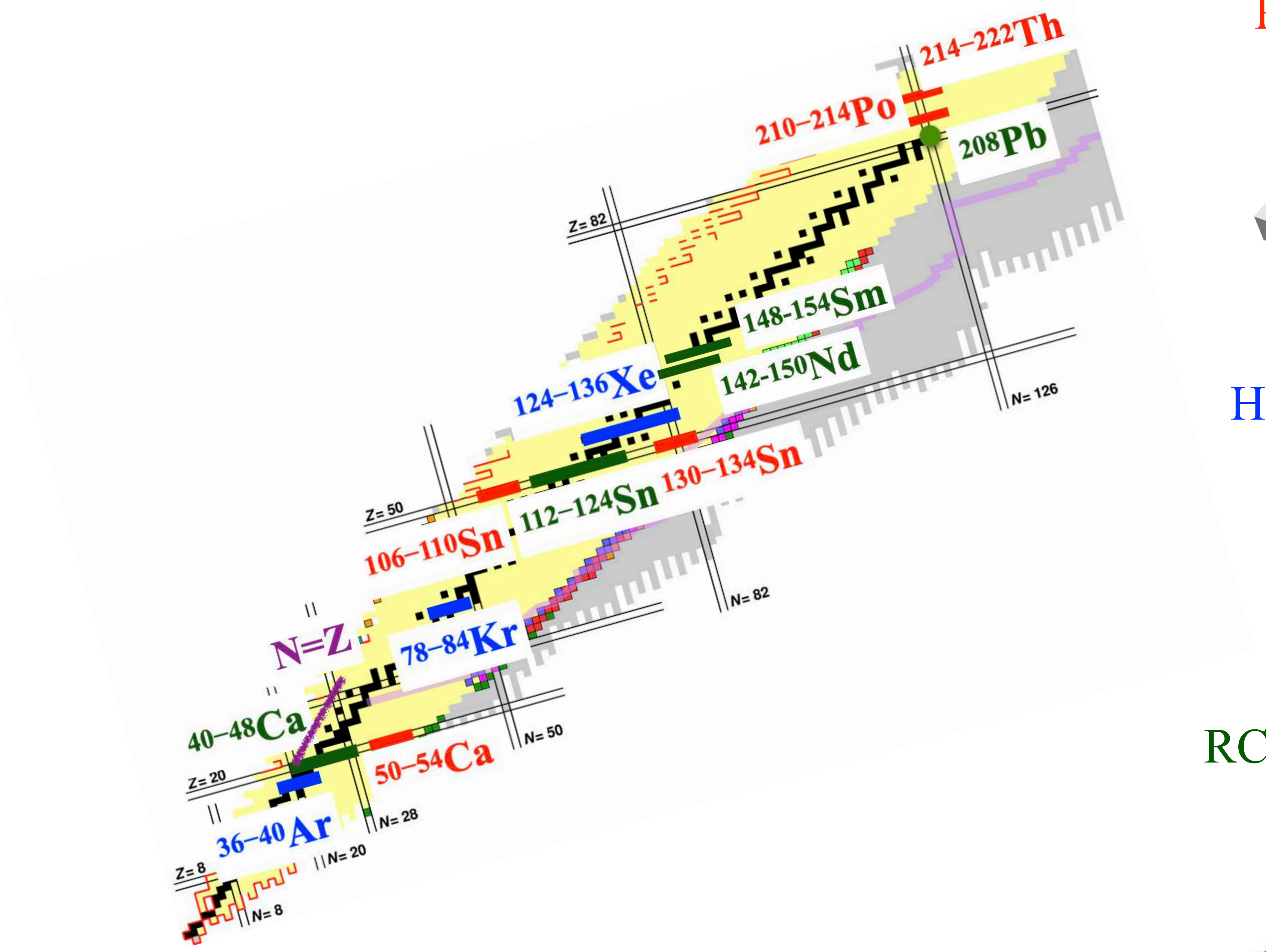
ONOKORO

Clustering in medium-heavy nuclei via knockout

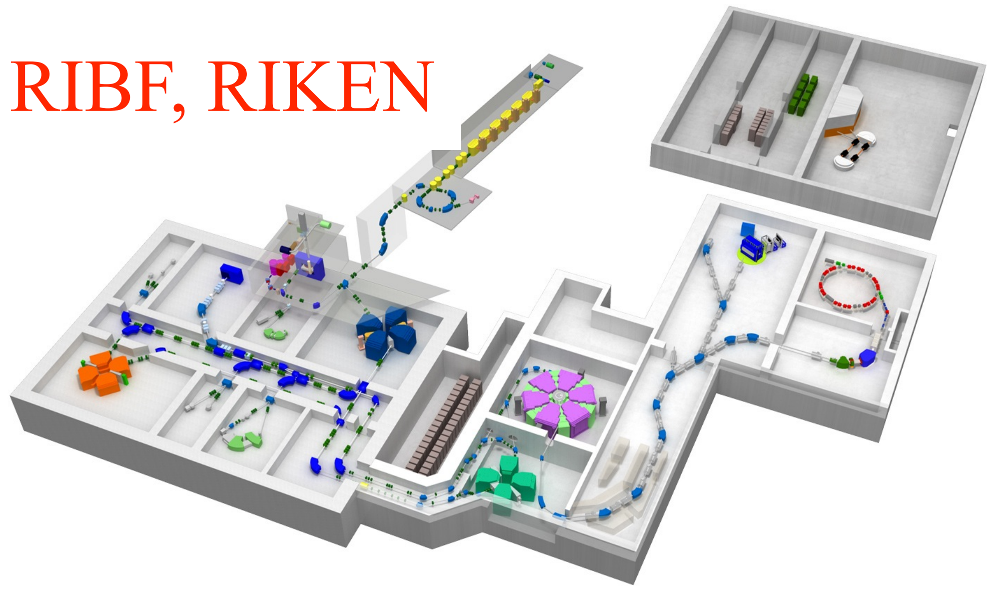
(*p*,*p*<u>*X*</u>) cluster knocout reactions @ E/A = 200—300 MeV

X: *d*, *t*, ^{3}He, α

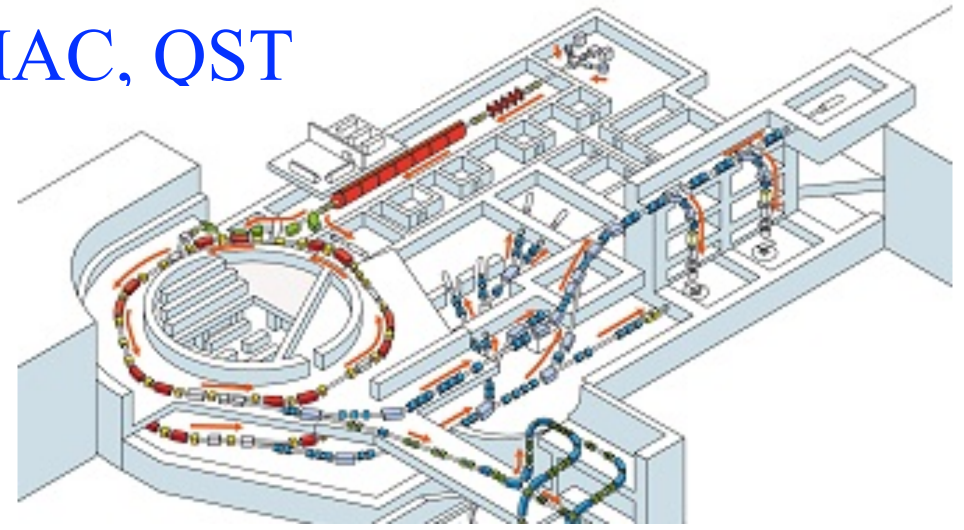
Wide mass region A=40−220	×	Stable and unstable nuclei	×	All the light clusters d, t, ^{3}He, α …



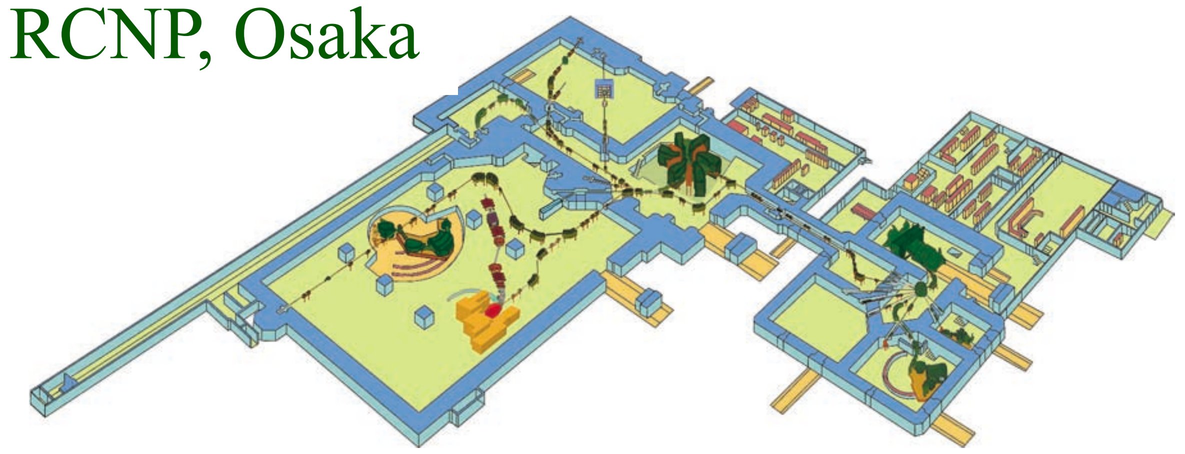
RIBF, RIKEN

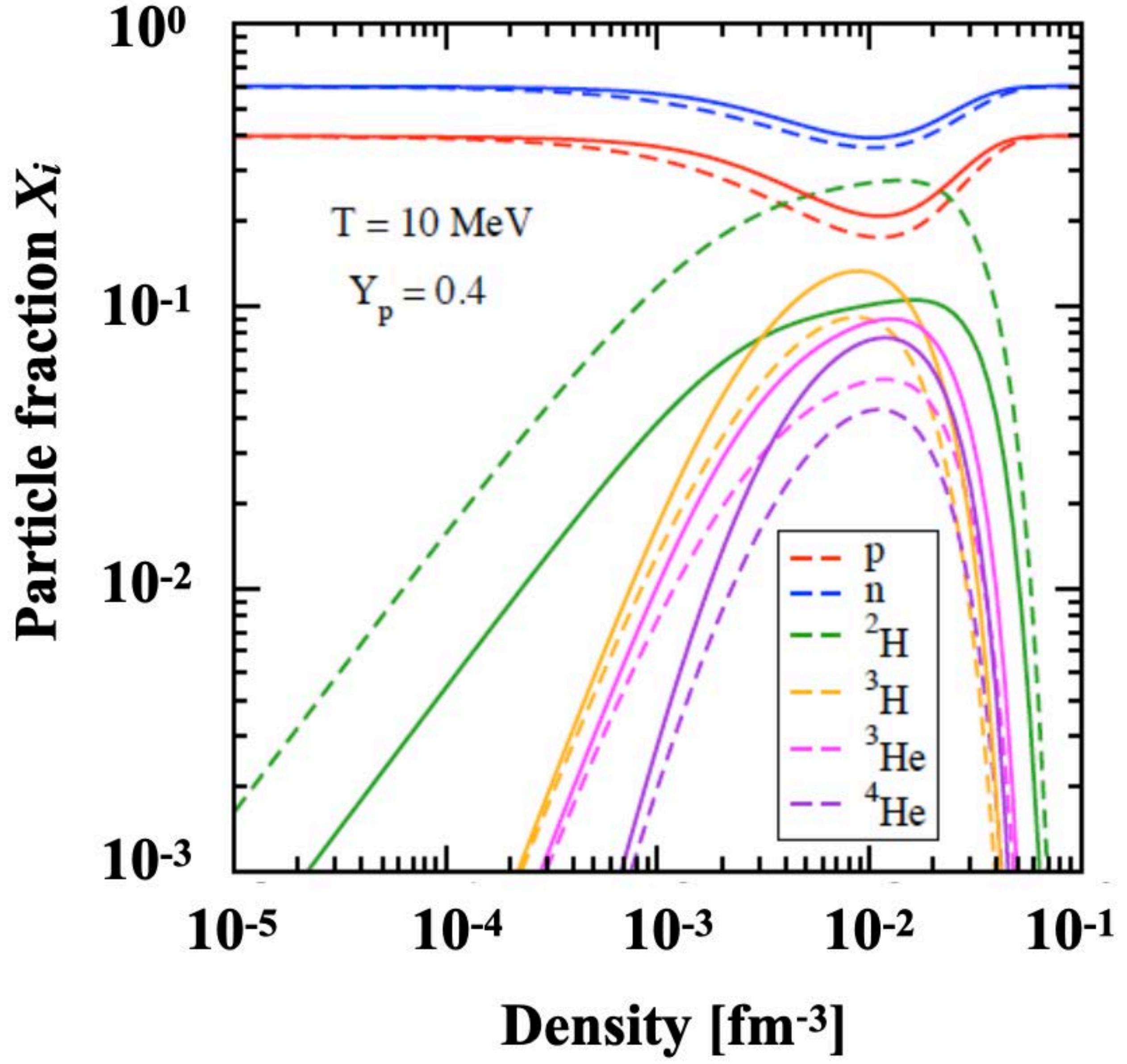


HIMAC, QST



RCNP, Osaka





Clustering in medium to heavy nuclei

- Nature of clustering in medium to heavy nuclei

  Quite little is known.

- Questions to be answered

  How can the mean-field picture be compatible with that with clusters?

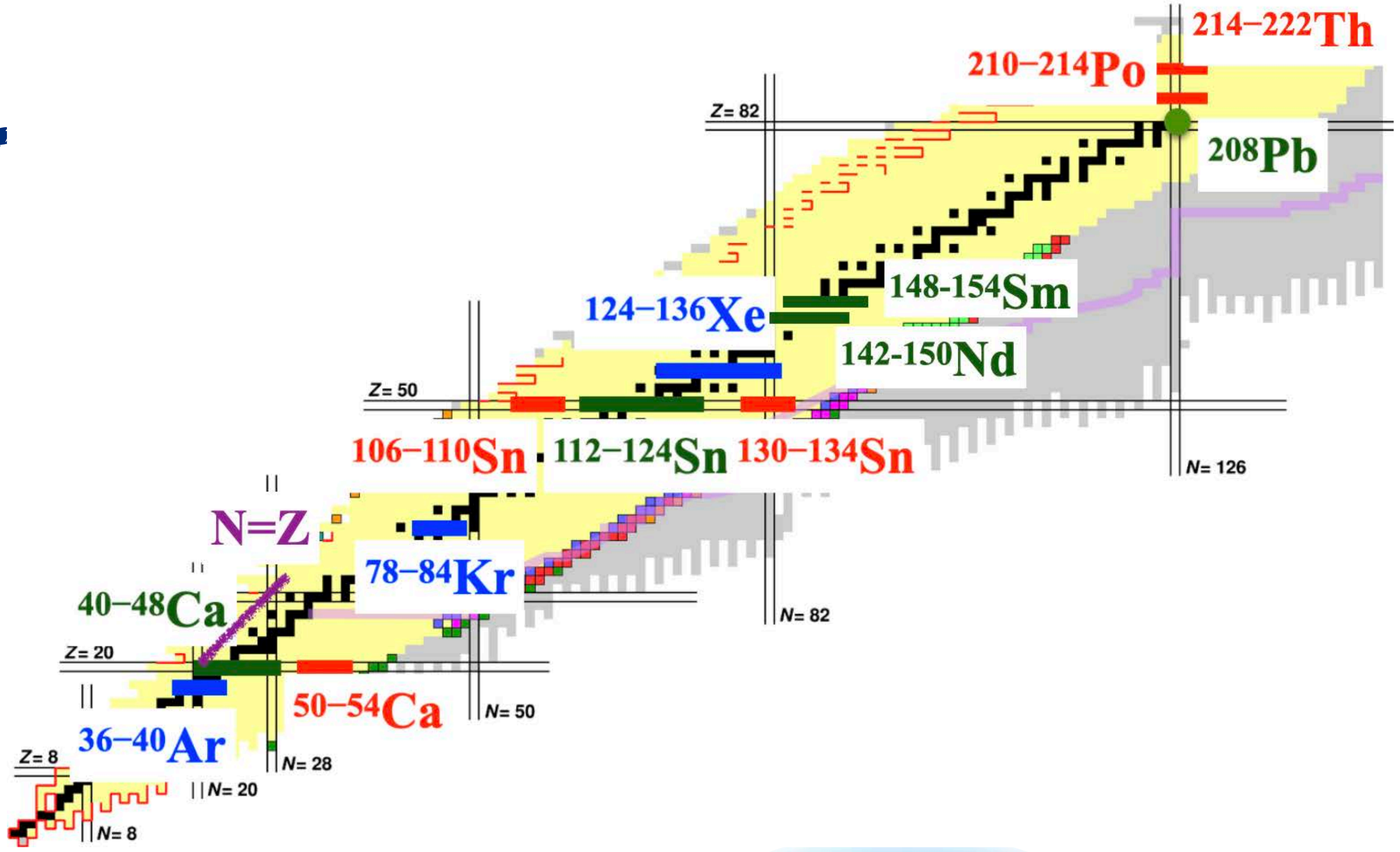
  The peculiarity of low-density surface?

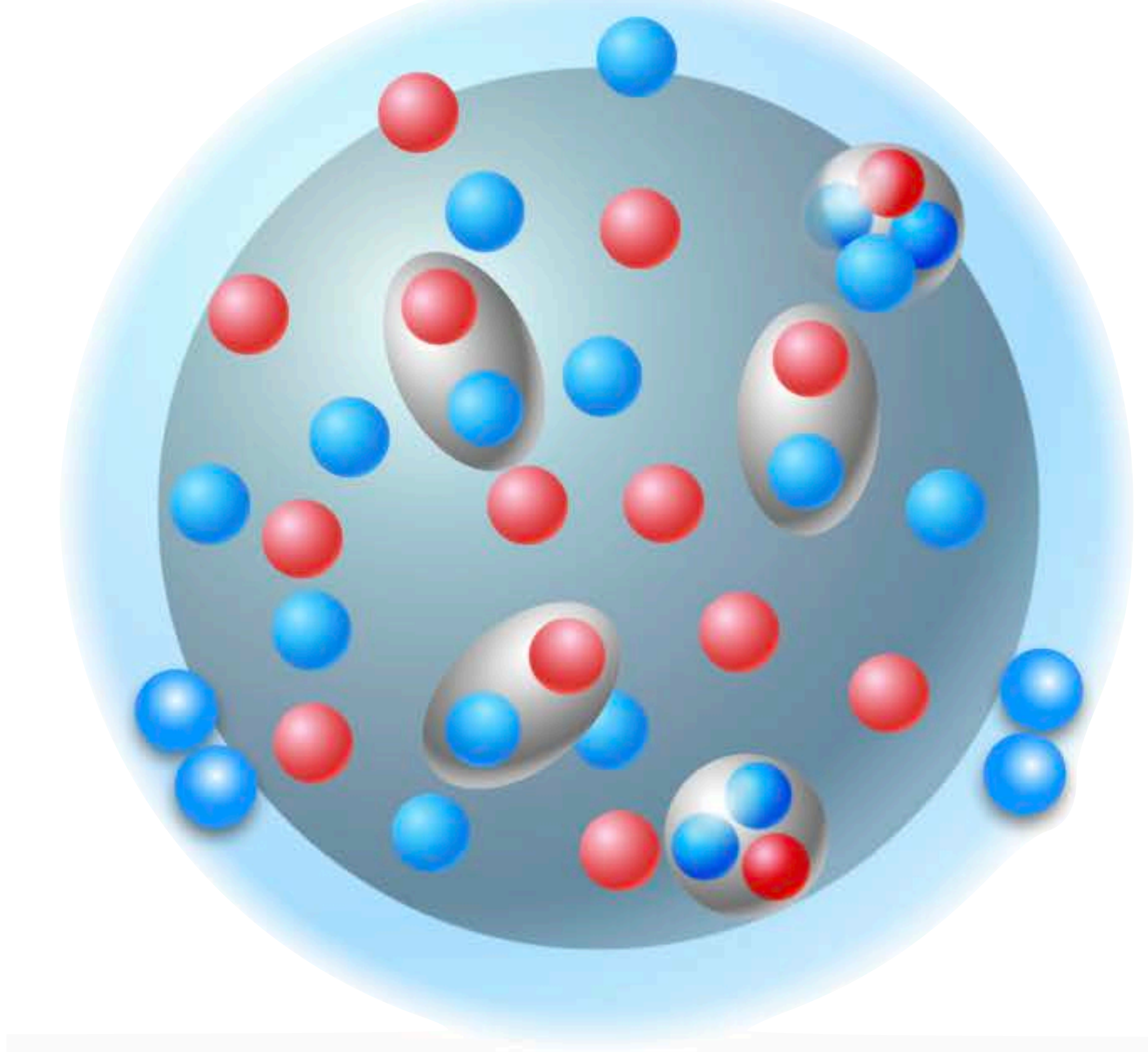
- Possible access to α preformed in α-decay nuclei

- Relevance of deuteron clusters

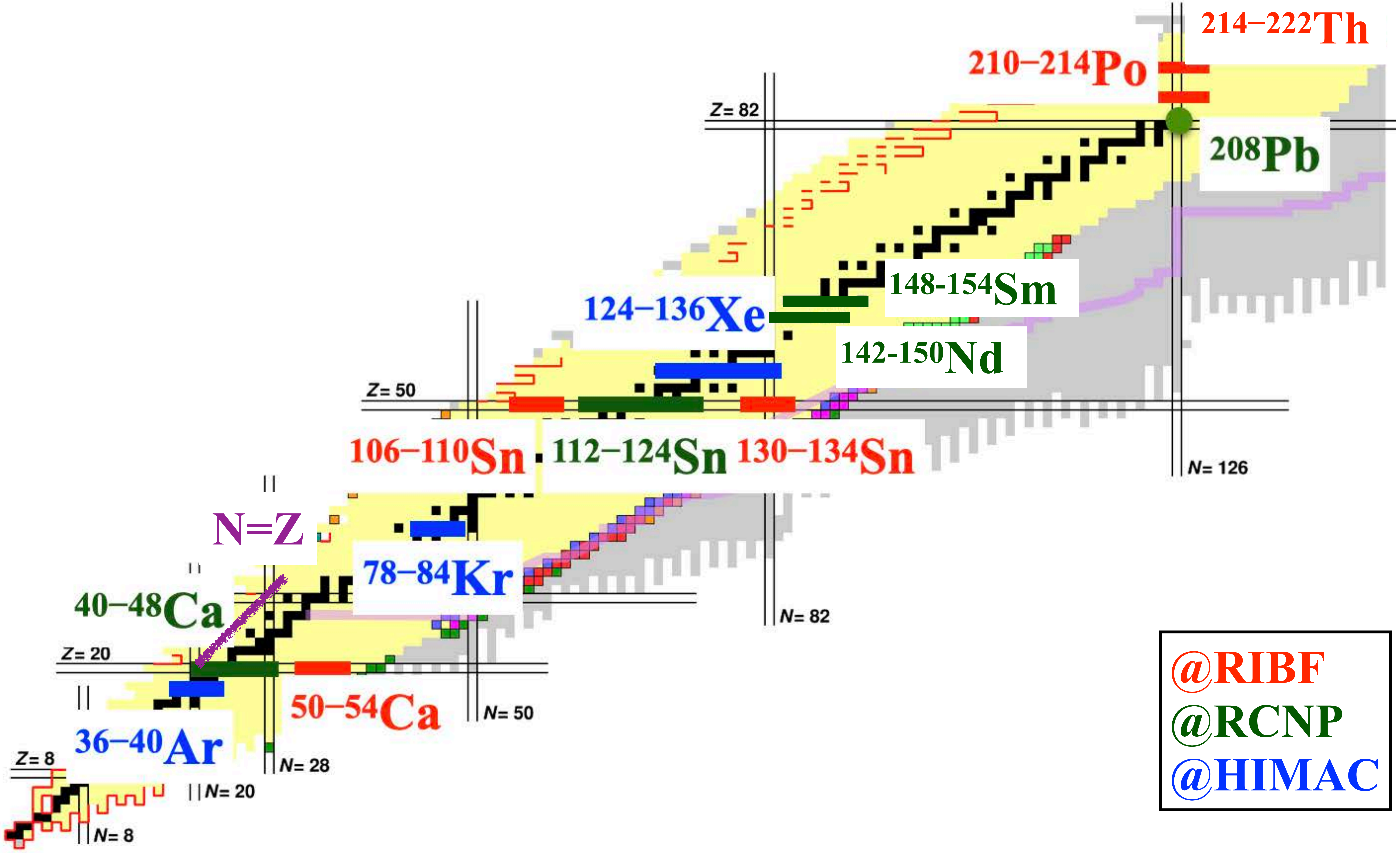
  to short-range correlation

- First determination of t/^{3}He mirror ratio and its evolution with isospin asymmetry





Planned experiments under the ONOKORO project



First experiments at RCNP (July 2023 & April 2024)

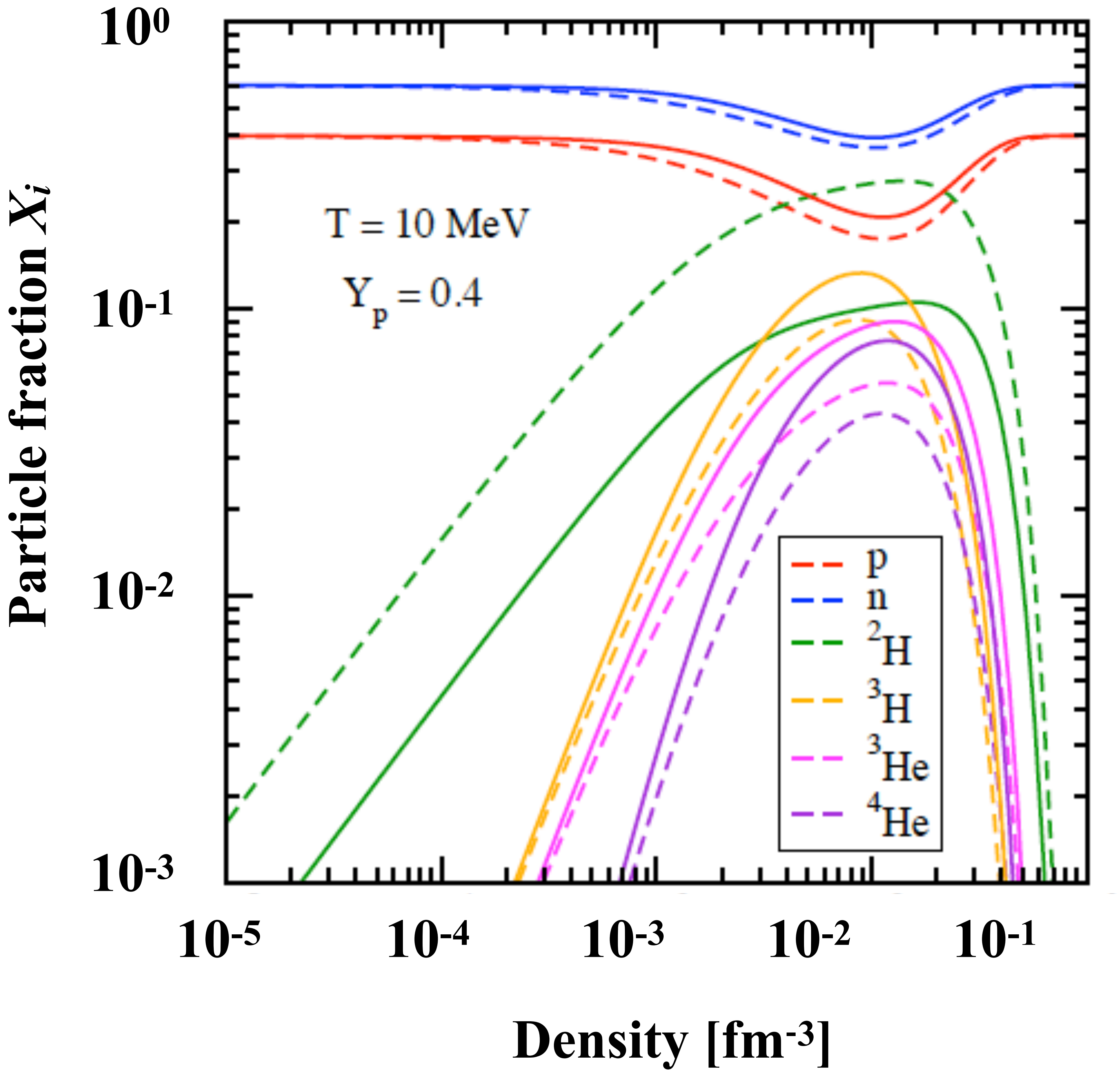
$^{40-48}$Ca(p,pd), (p,pt), (p,p^3He), (p,$p\alpha$) at 230 MeV, together with ^{6,7}Li, ^{12}C, ^{16}O data

Collaboration

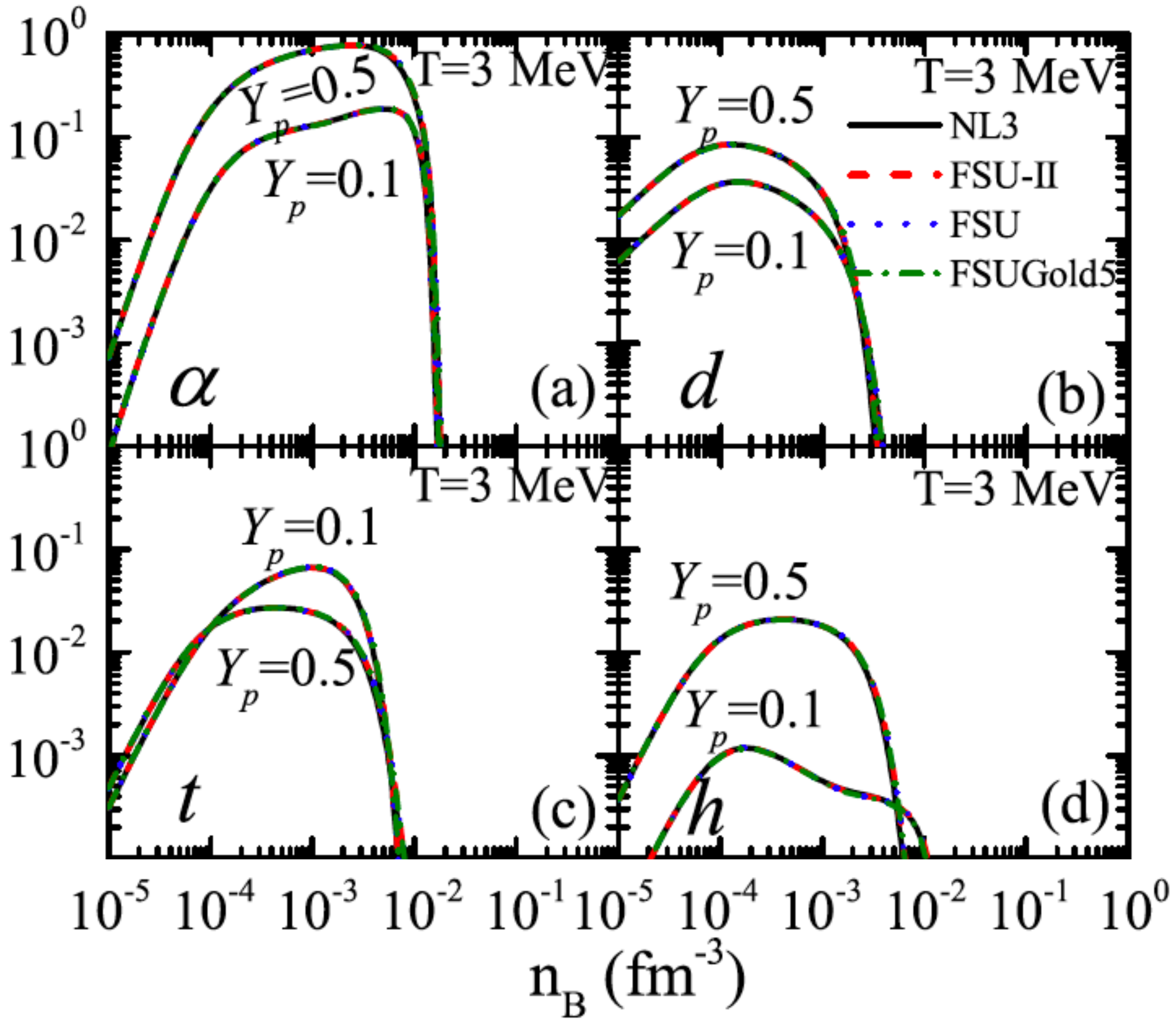
RIKEN, Kyoto, RCNP, Kyushu, Osaka, Konan, Miyazaki, Peking, CENS IBS, IJCLab

Predictions of nuclear matter theories, revisited

S. Typel,
J. Phys. Conf. Ser. 420, 012078 (2013)



Z.W. Zhang and L.W. Chen
Physical Review C 95, 064330 (2017)



Clusters grow at < 0.1 ρ_{sat}.
Occurrence of clusters depends on isospin asymmetry.

Deuteron in nuclei

Deuteron

is the only bound state of two nucleons

embodies tensor force effects

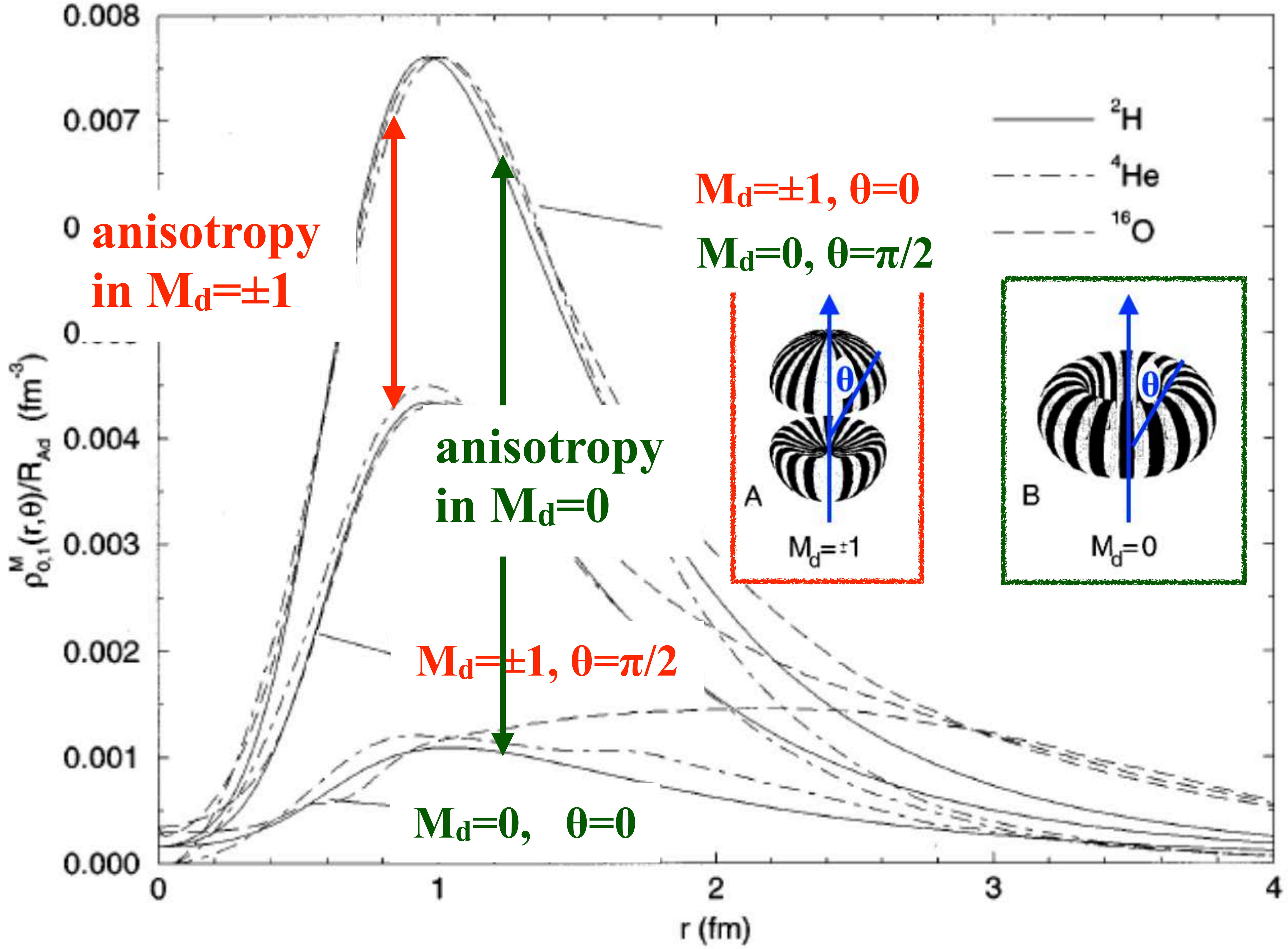
However, in the long history of nuclear physic scientist's eyes did not focus on deuteron clustering in nuclei.

(probably due to weak binding of deuteron)

"Femtometer toroidal structure in nuclei"

Forest et al., Phys. Rev. C 54, 646 (1996)

Density distribution for T=0, S=1 pairs in ^2H, ^4He, ^{16}O

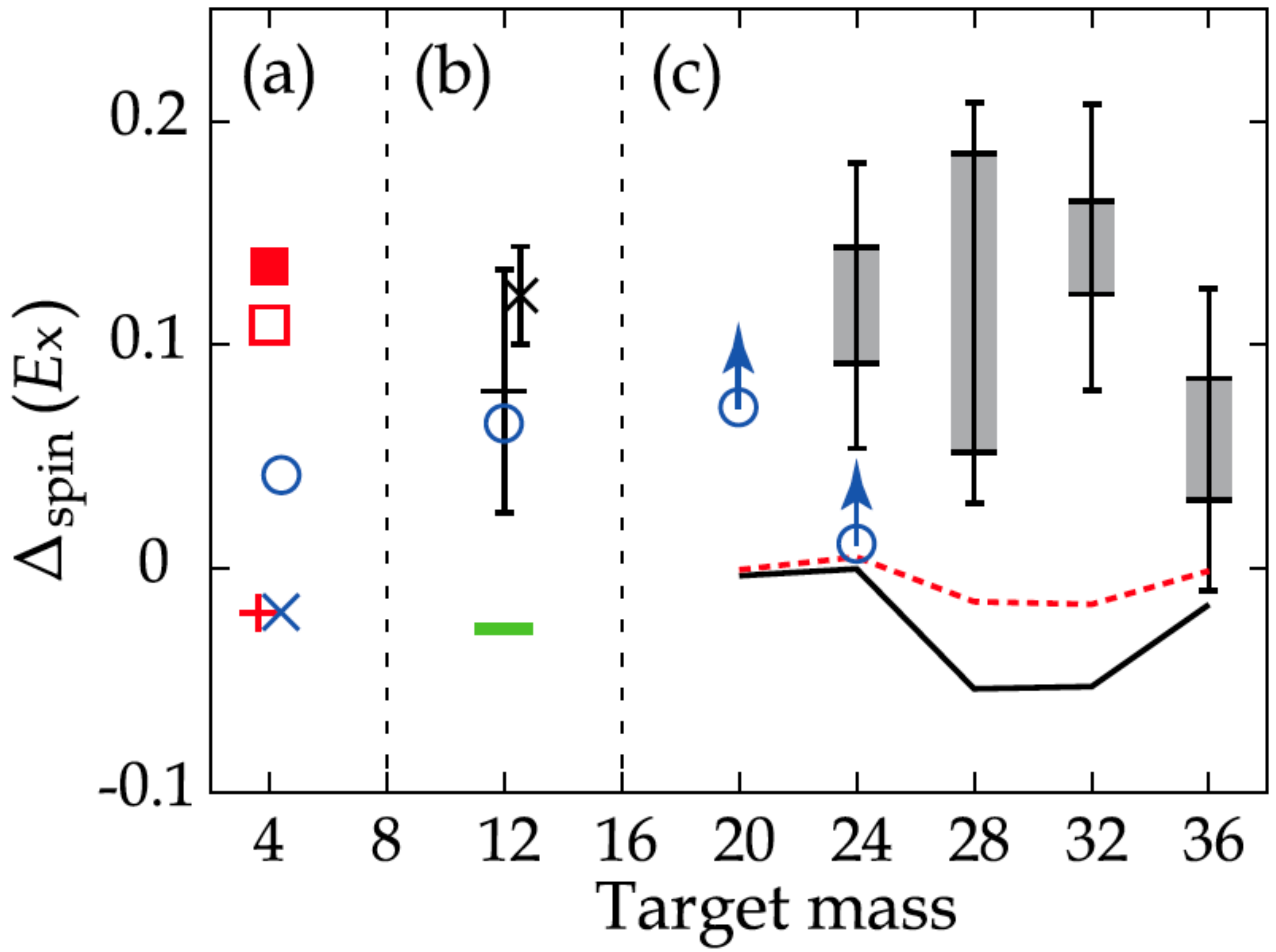


"Deuteron-like" spin-dependent anisotropy is persistent in nuclei

Experimental signatures of deuteron in nuclei

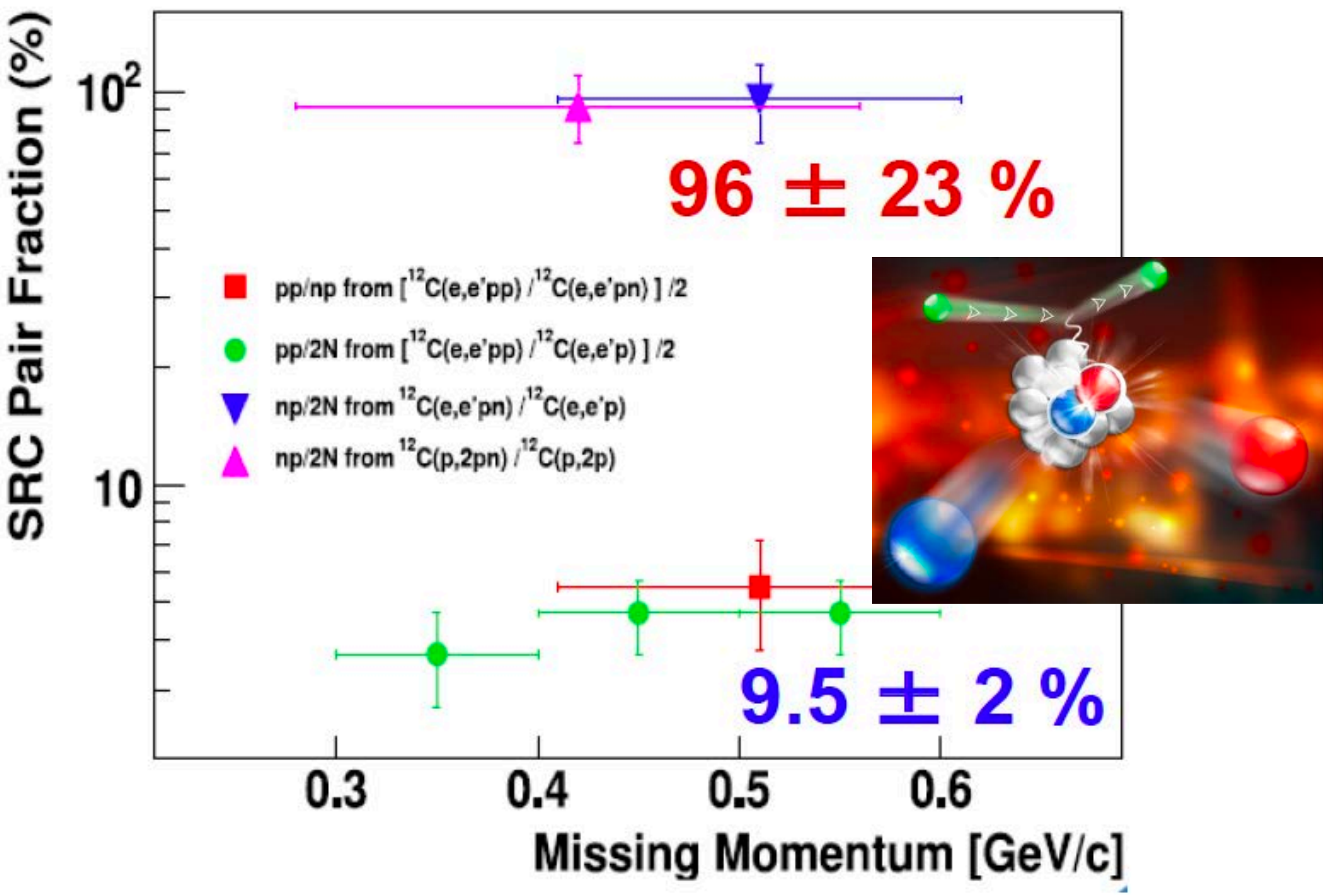
Finite spin expectation values in N=Z nuclei

Matsubara et al., Phys. Rev. Lett. 115

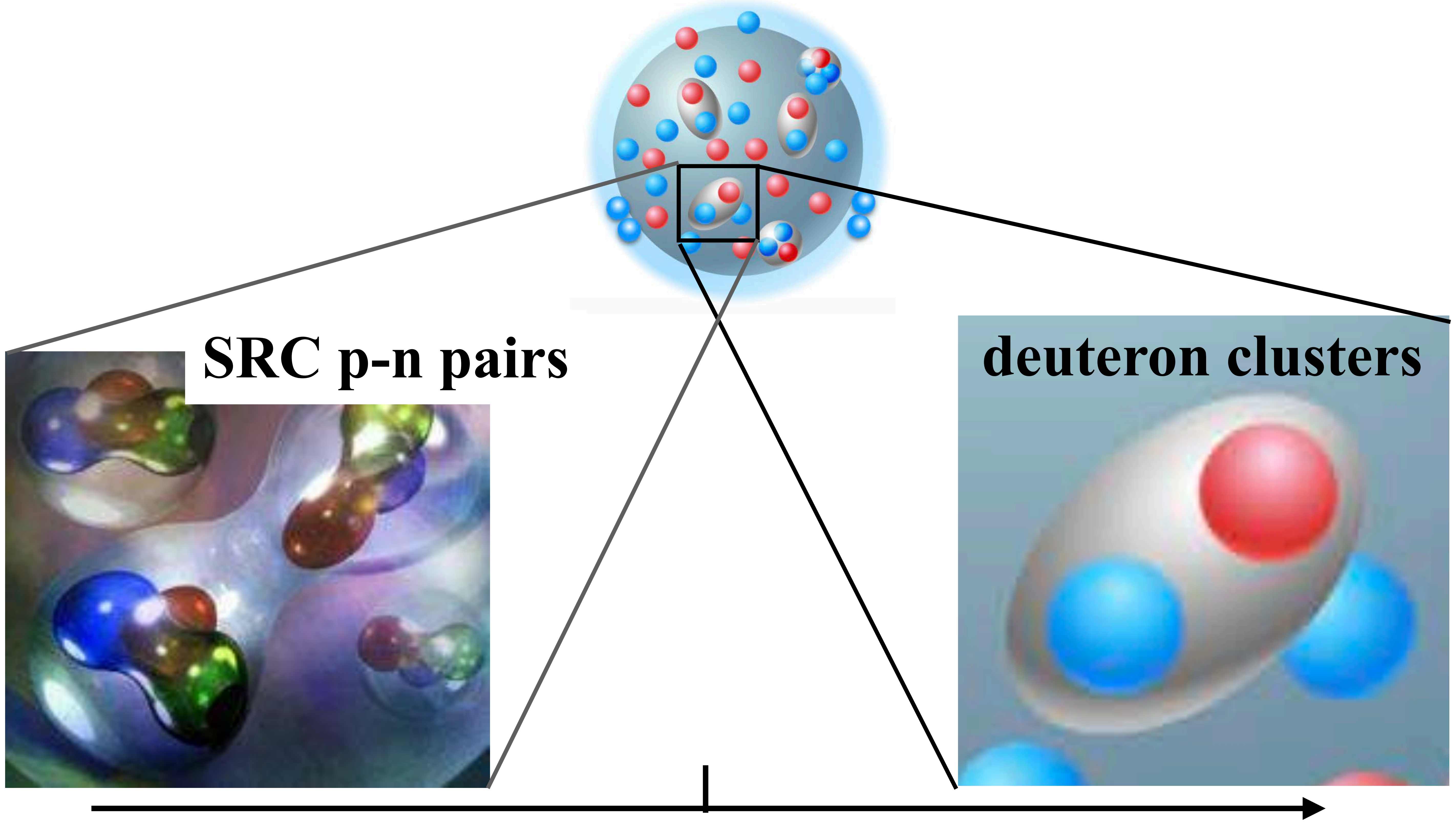


***p-n* dominance in short-range correlation**

R. Subedi et al., Science 320, 1476 (2008)



Look at deuterons in nuclei by knocking them out



small p-n distance

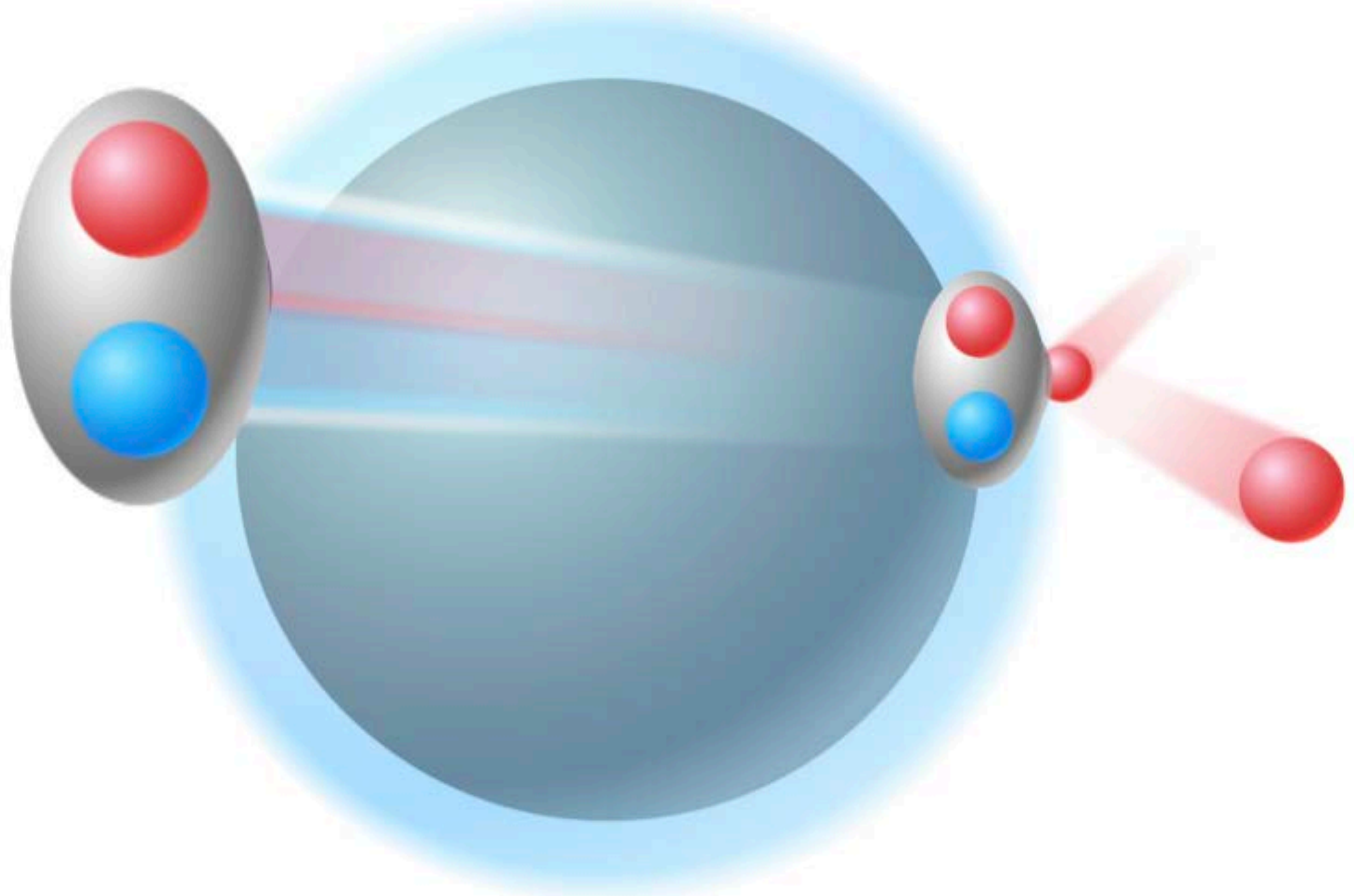
Proton radius

large p-n distance

quark-gluon dynamics

nucleon-meson dynamics

Just knock them out!



$^{40-48}$Ca(*p*,*pd*) @ 226 MeV

ONOKORO

Indication of decreasing trends with the excess neutron in the deuteron formation probability.

unpublished data removed

Reaction analyses (DWIA) to extract the deuteron formation probability are ongoing.

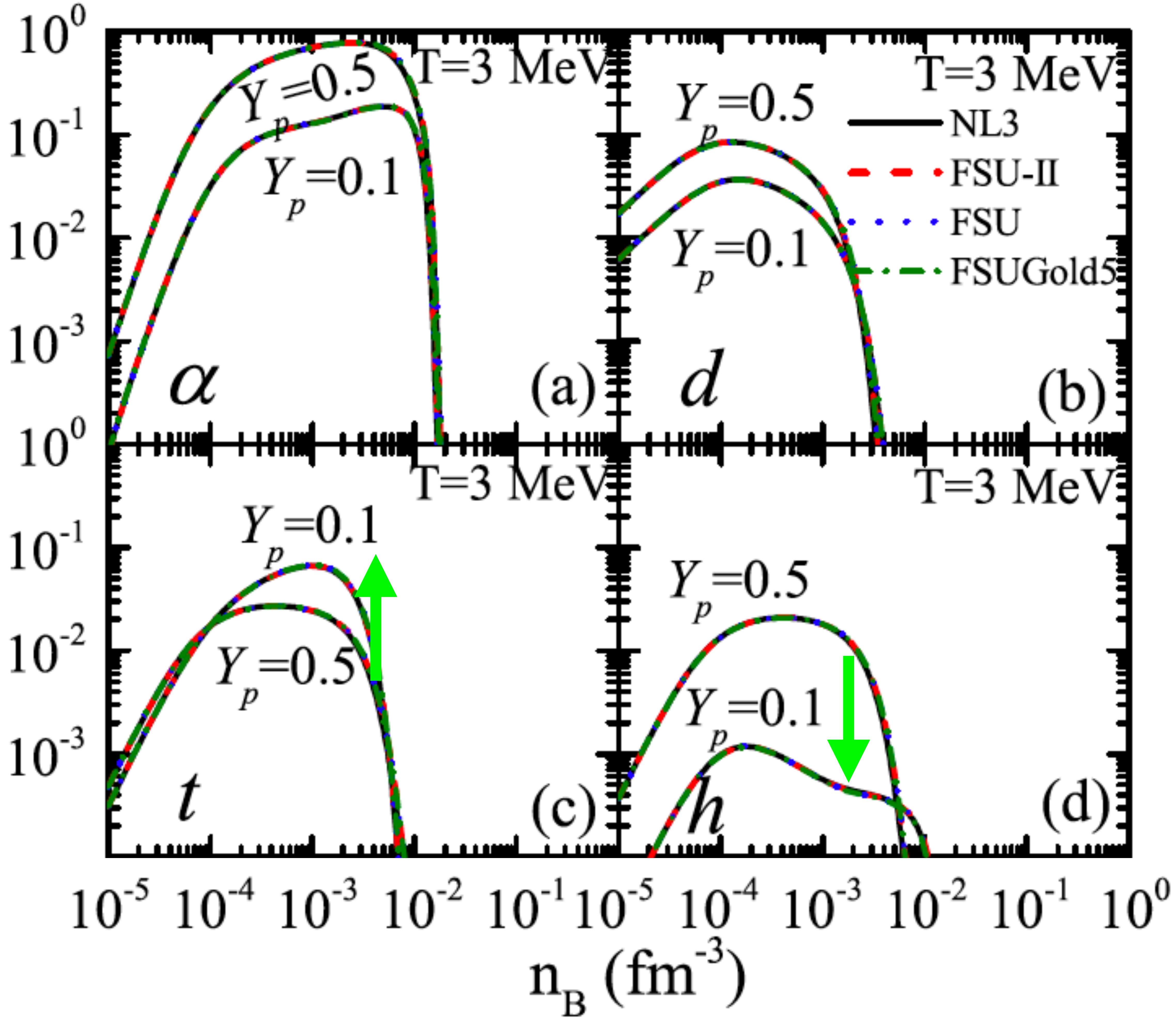
Triton and ^{3}He clusters

Interesting to see the t/^{3}He mirror ratio which is expected to depend strongly on the isospin asymmetry.

Basically, little is known with t and ^{3}He clusters in nuclei

no data at all, except for p-shell nuclei (e.g. ^{7}Li, ^{7}Be)

quite few (p,pt)/(p,p^{3}He) data

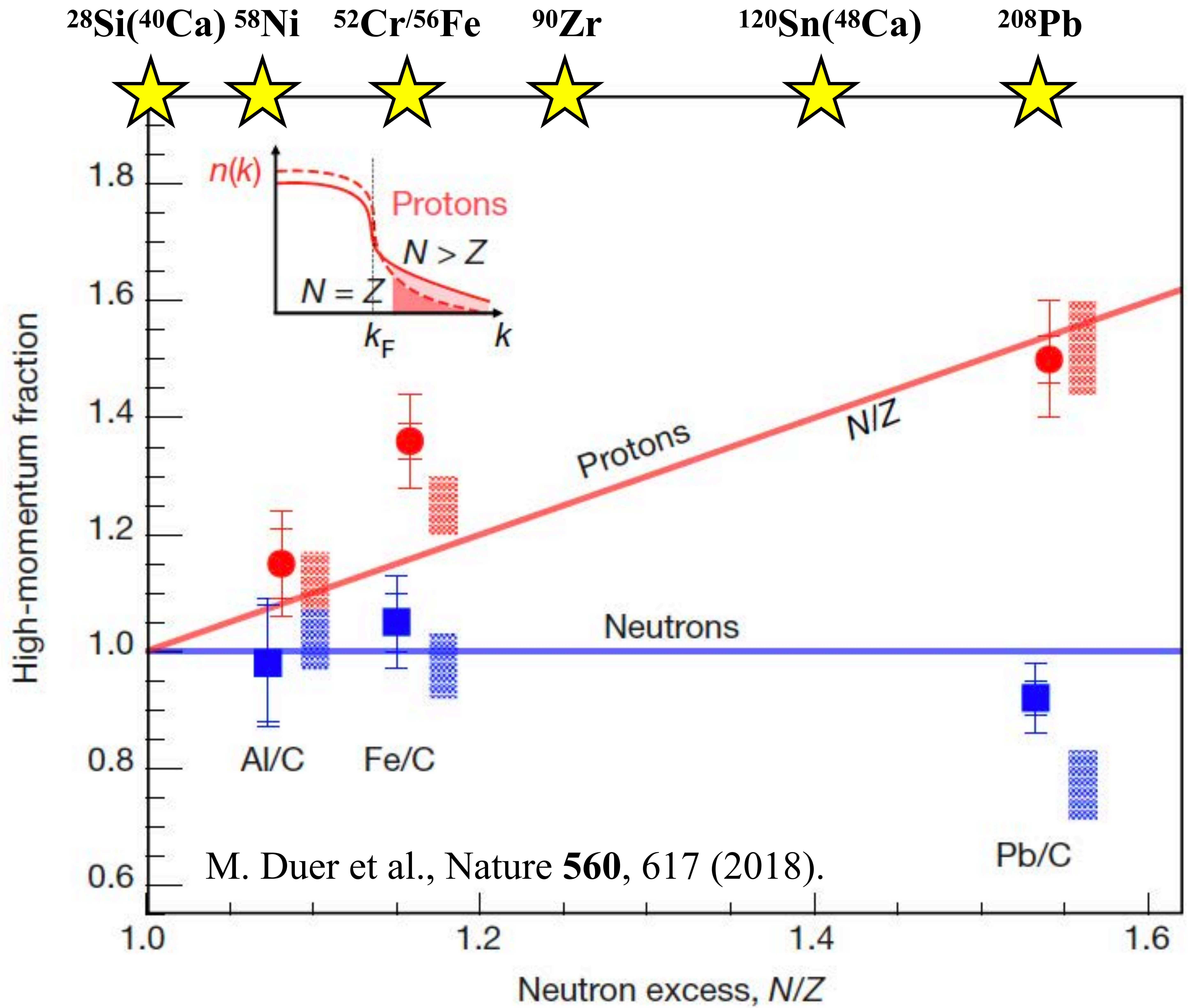


Comparison between (*p*,*pt*) and (*p*,*p*^{3}He)

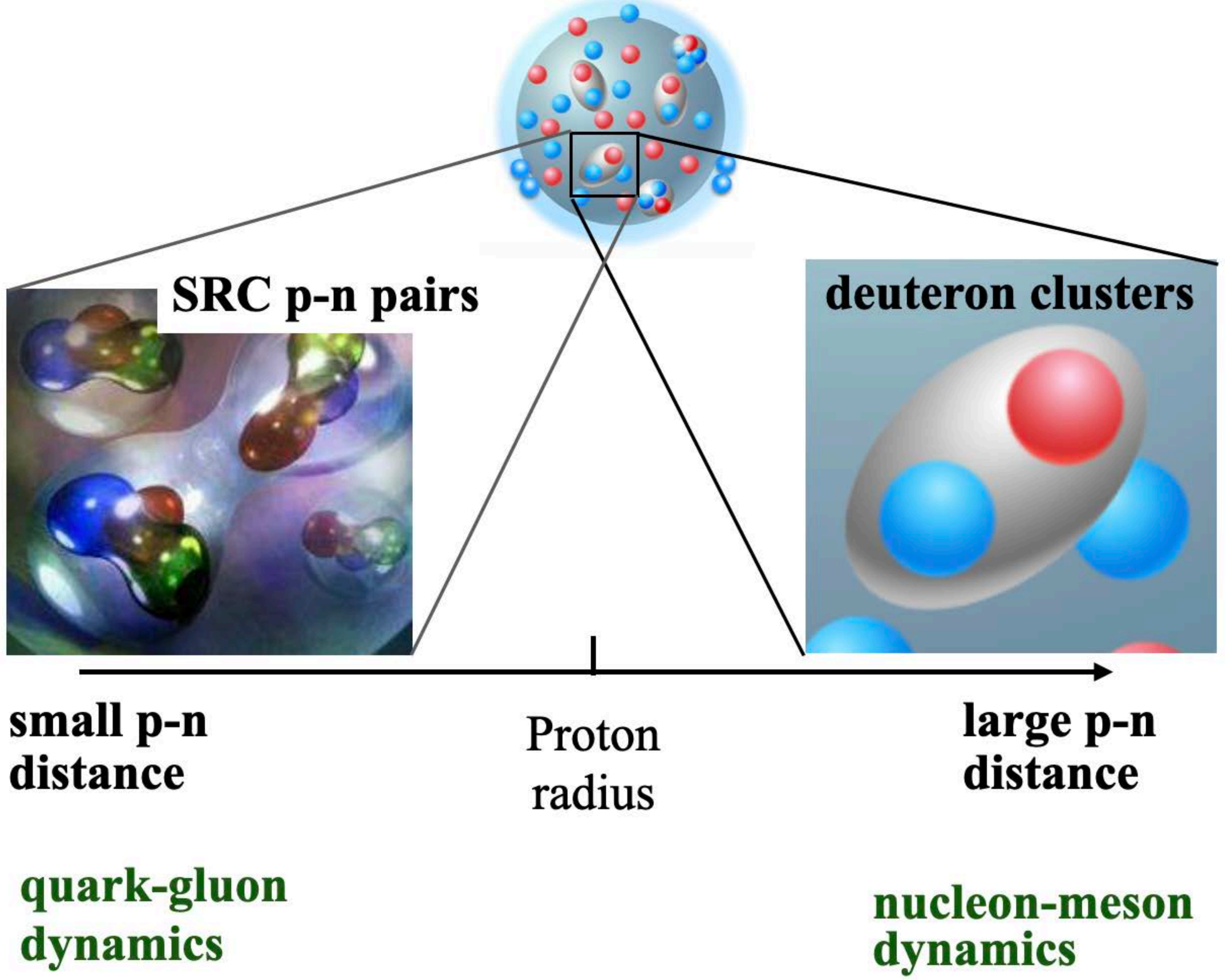
unpublished data
removed

(Near) Future Experiments

Comparison of the (*p,pd*) data with SRC data from JLab



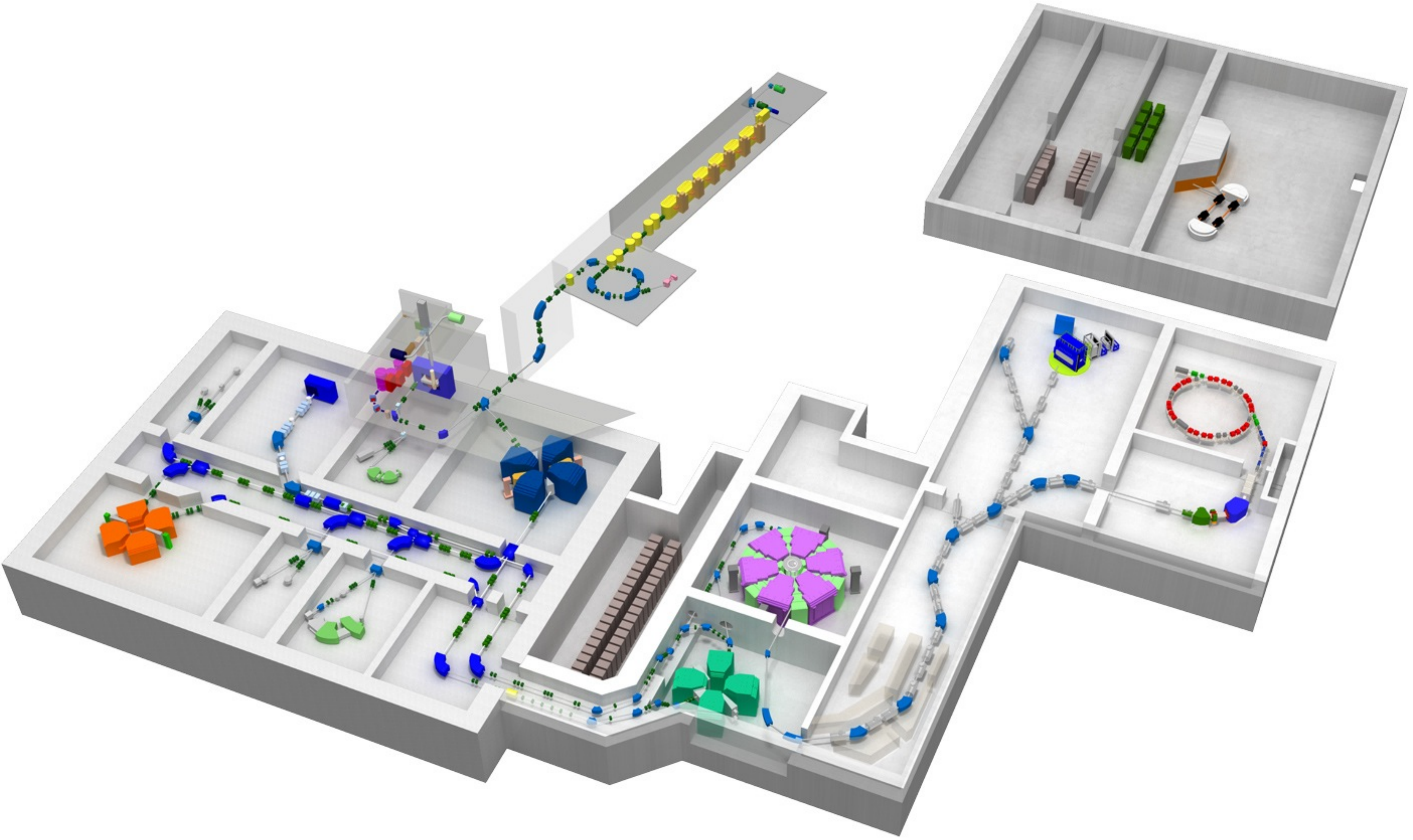
M. Duer et al., Nature **560**, 617 (2018).



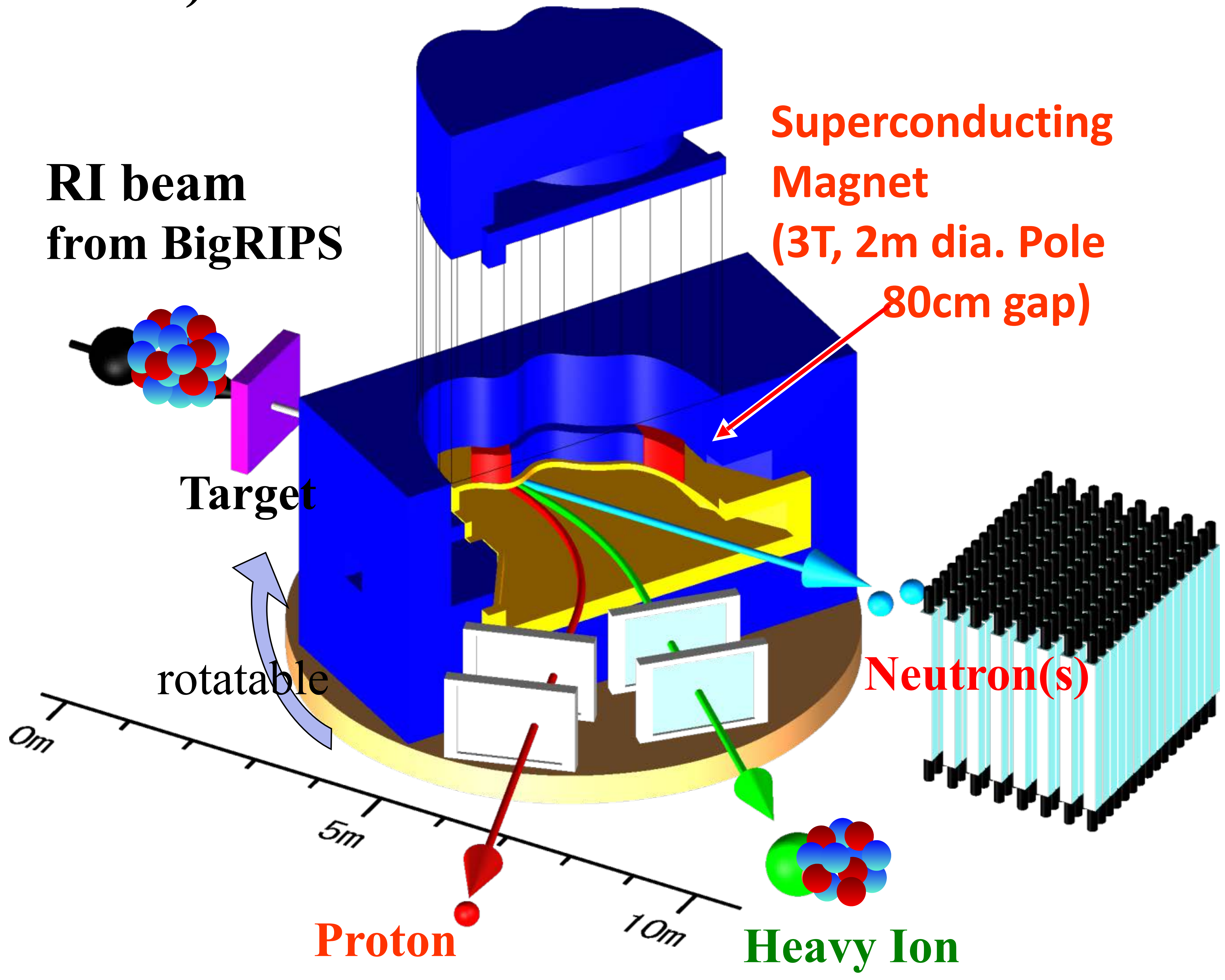
RI Beam Factory

Availability of high-intensity RI beam in a wide energy range

Primary beam:	345 MeV/u
Fast RI beam:	100—300 MeV/u
Energy degraded beam:	20— MeV/u (and even lower)

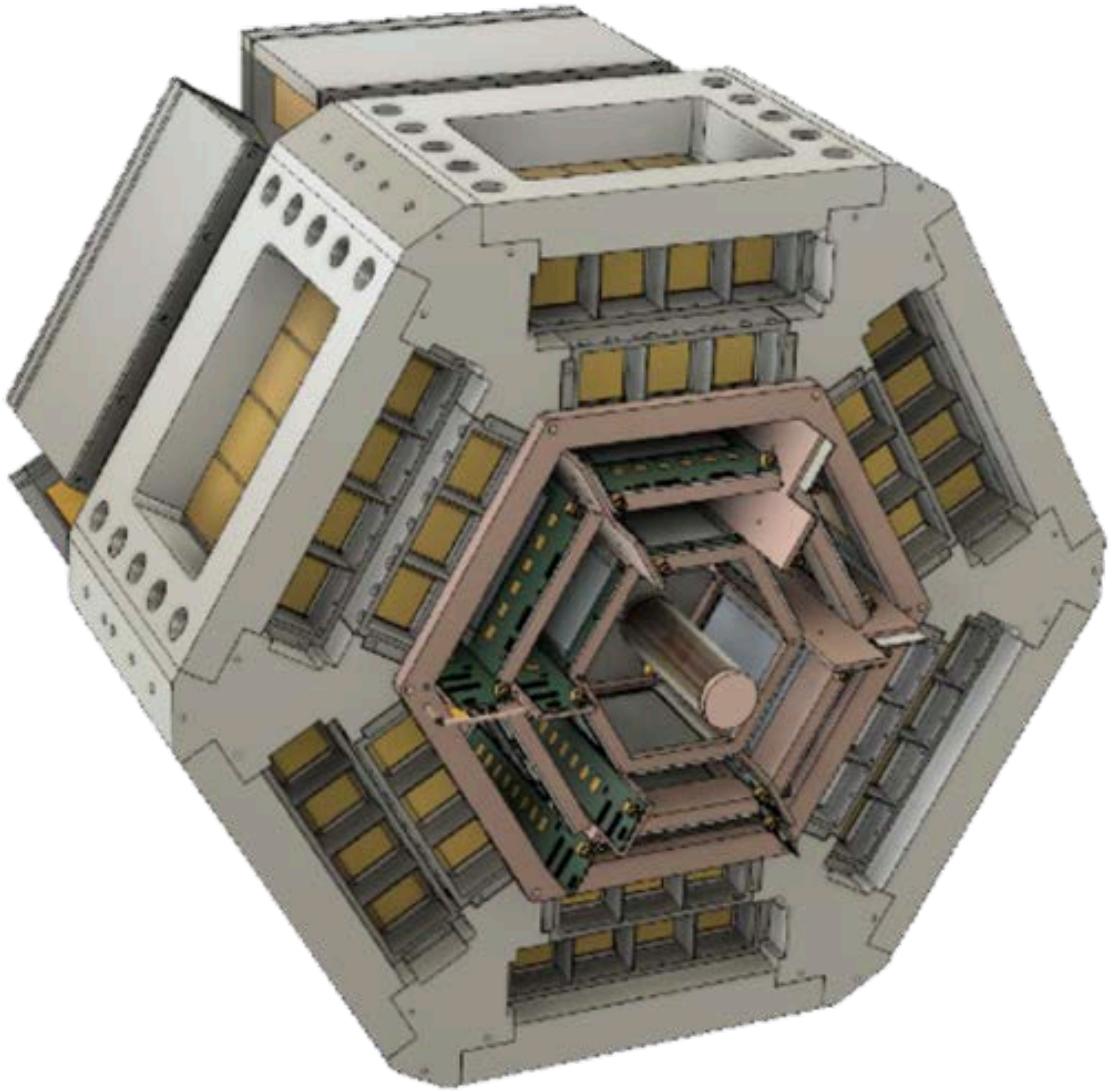


SAMURAI



TOGAXSI (戸隠) telescope

A new detector array for *inverse-kinematics* cluster and nucleon knock-out reaction experiments under construction.



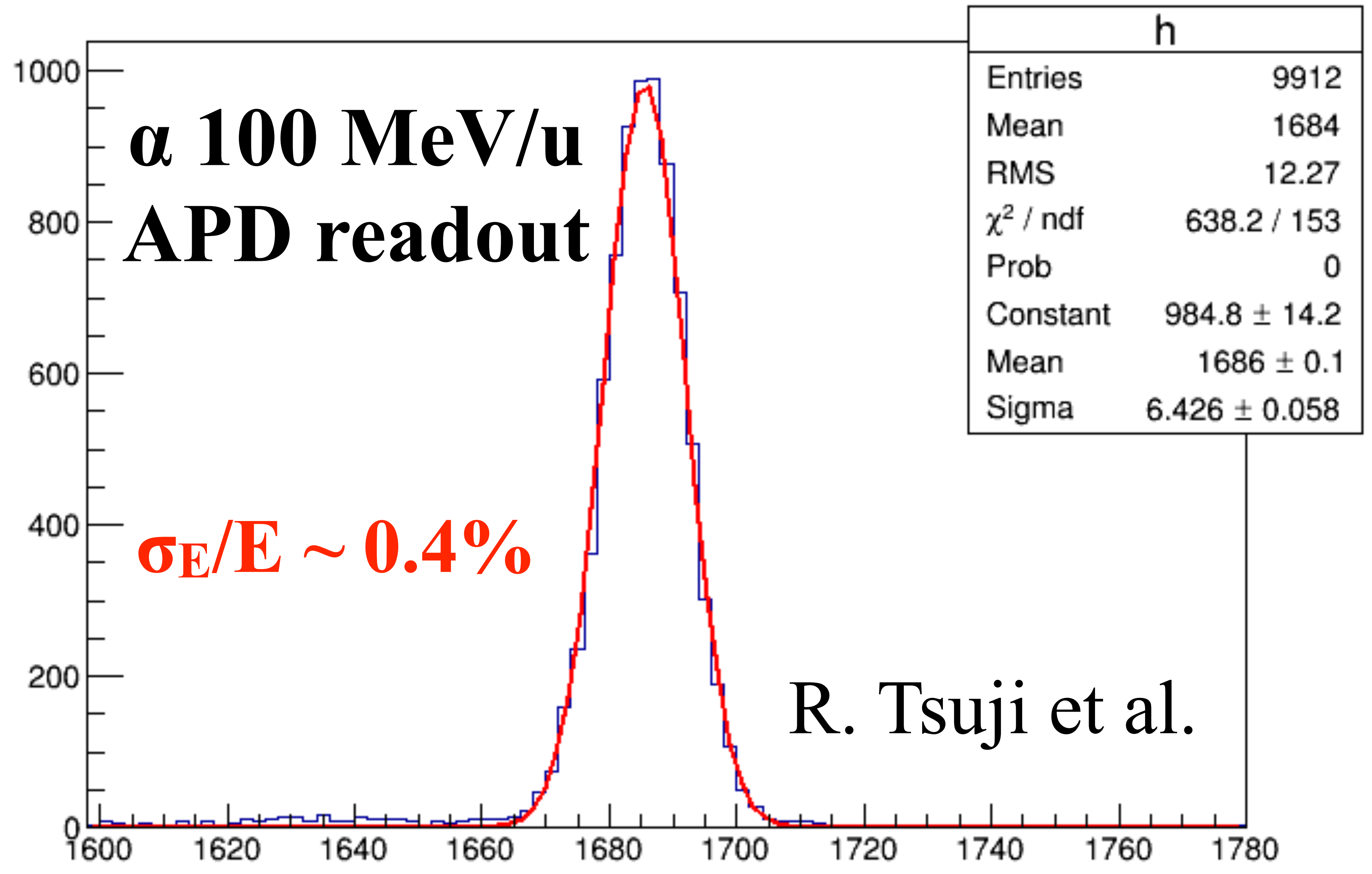
~ 500 mm

~100 GAGG:Ce

$\rho = 6.63$ g/cm^2

$\tau_{decay} = 92$ ns

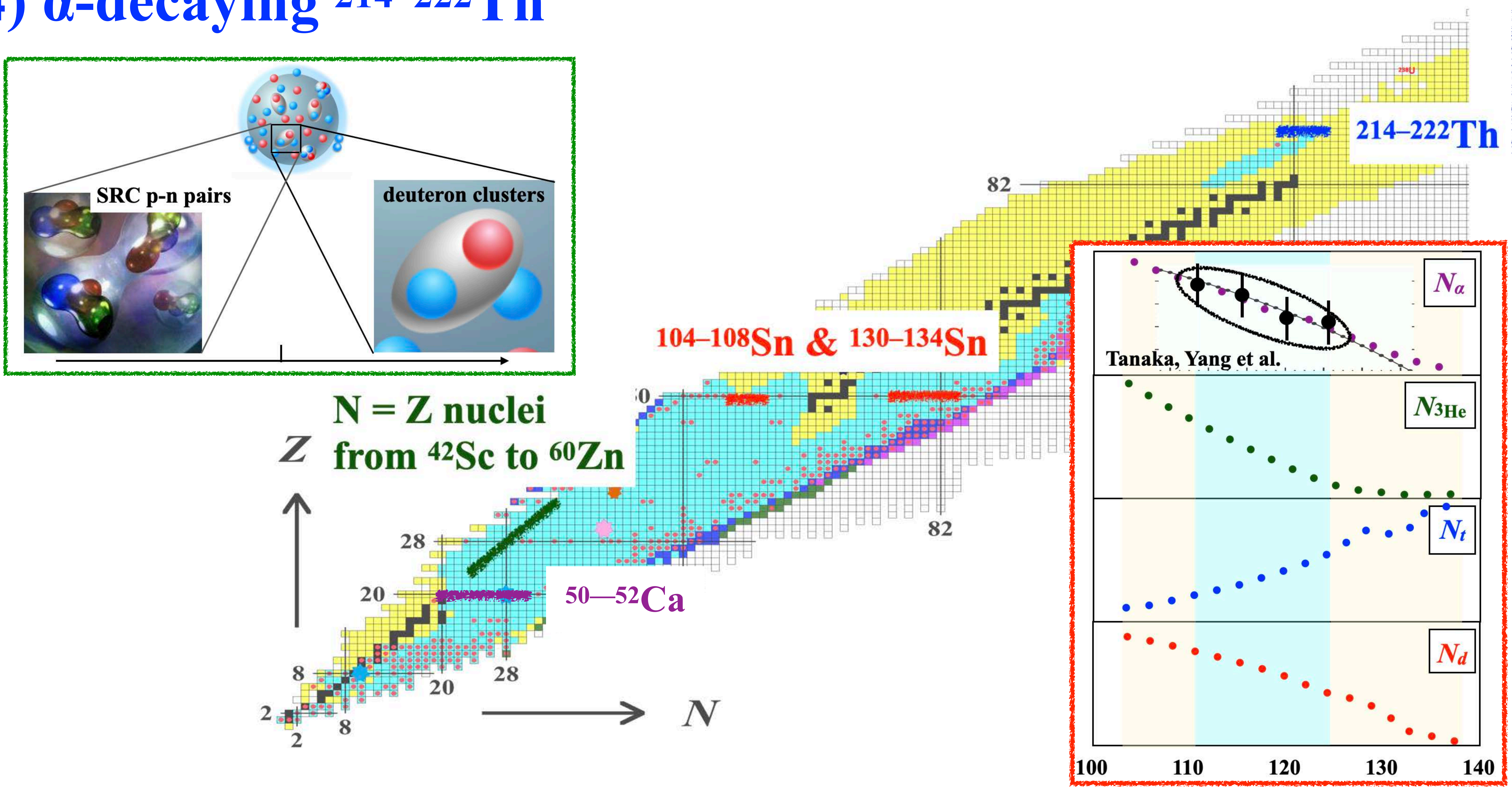
no hygroscopic nature

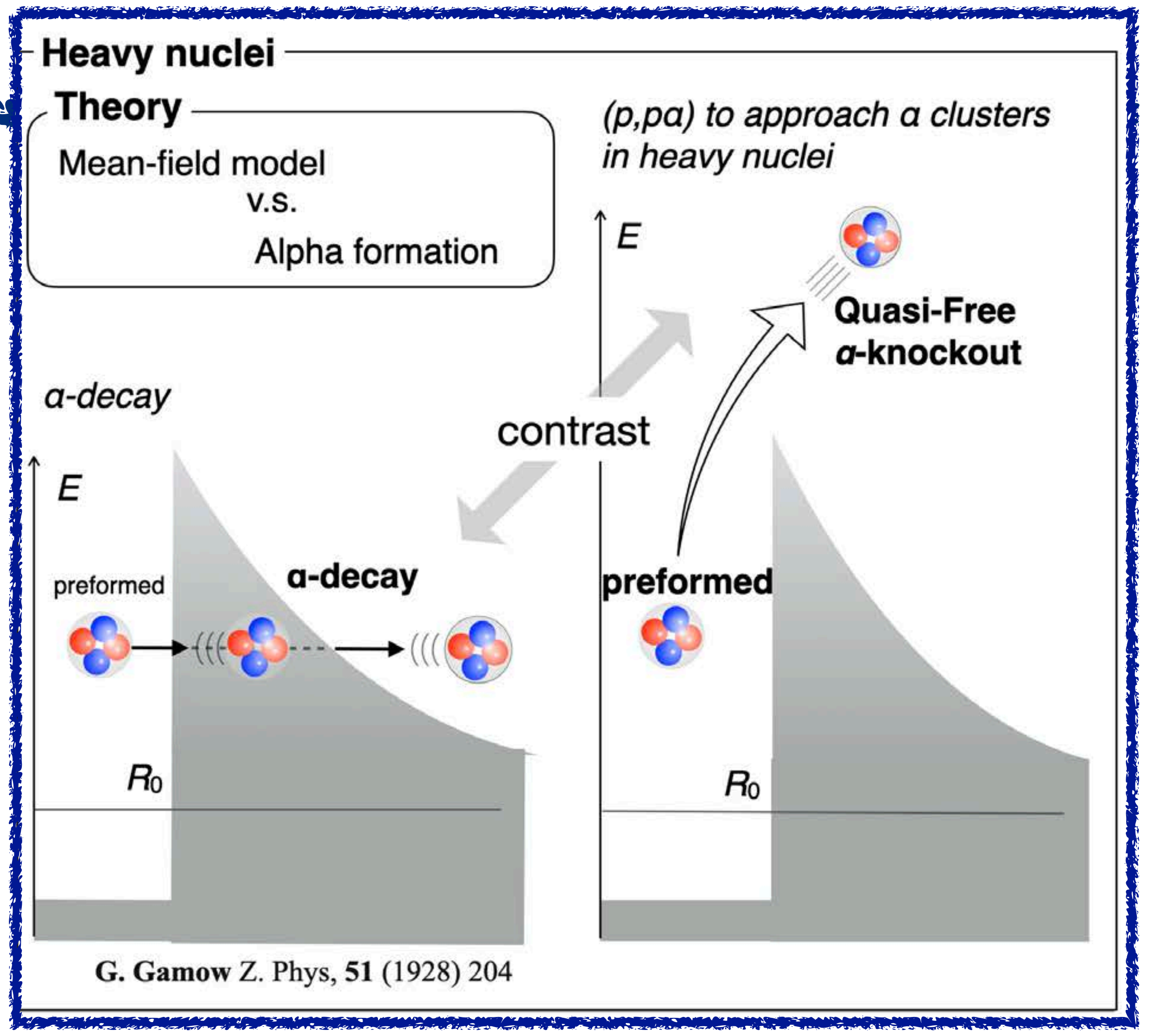


J. Tanaka, R. Tsuji, K. Higuchi et al., NIMB 542, 4 (2023)

Future plan at RIBF

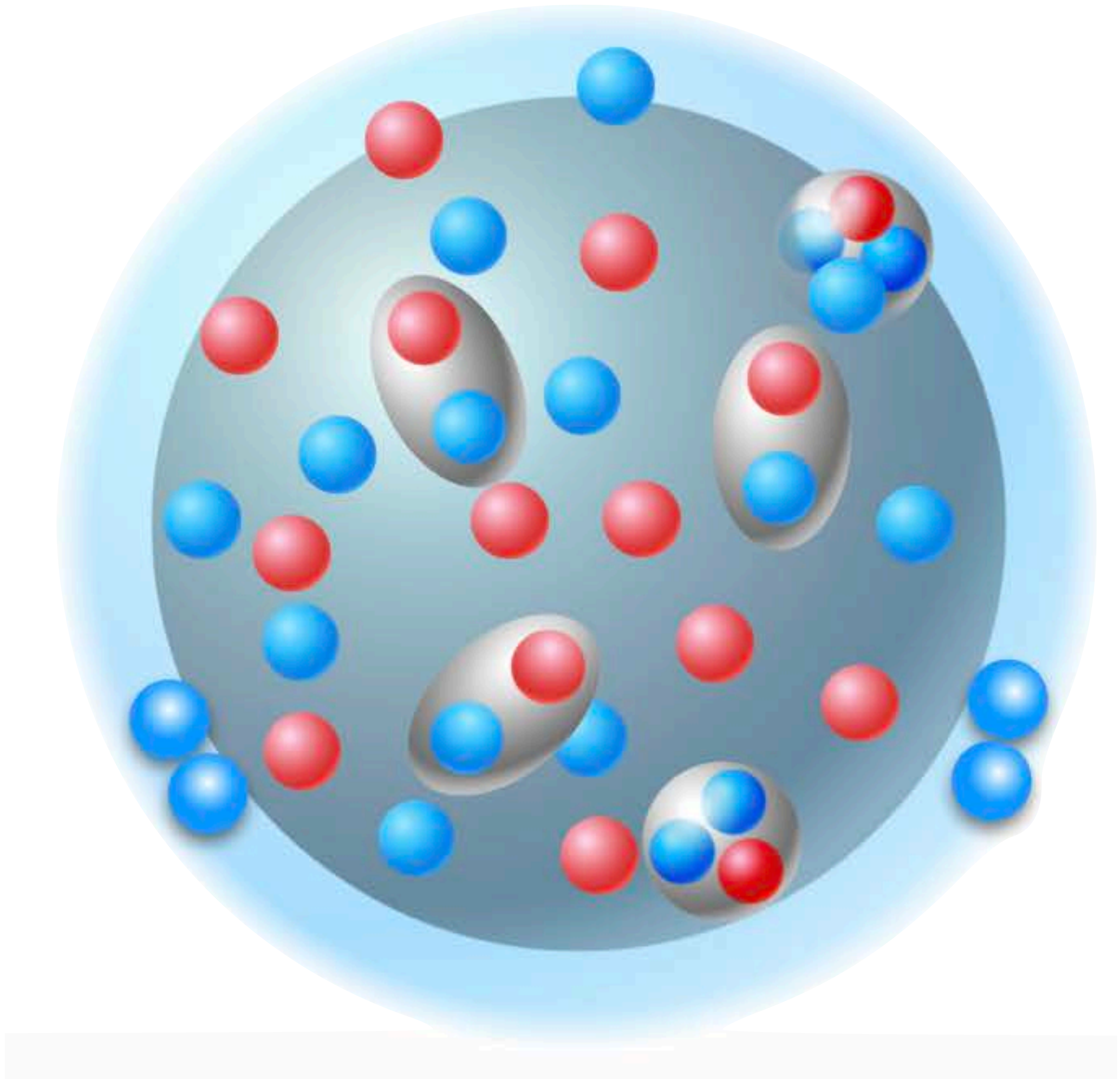
1) $^{50\text{-}52}$Ca : extension of the Ca isotope chain
2) $^{104–108}$Sn & $^{130–134}$Sn
3) $N = Z$ nuclei (^{42}Sc—^{60}Zn, including ^{56}Ni)
4) α-decaying $^{214–222}$Th





surface α formation
v.s.
bulk α formation

Order in nucleon many-body systems through formation of subsystems (clusters)



We are challenging using knockout reactions.

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