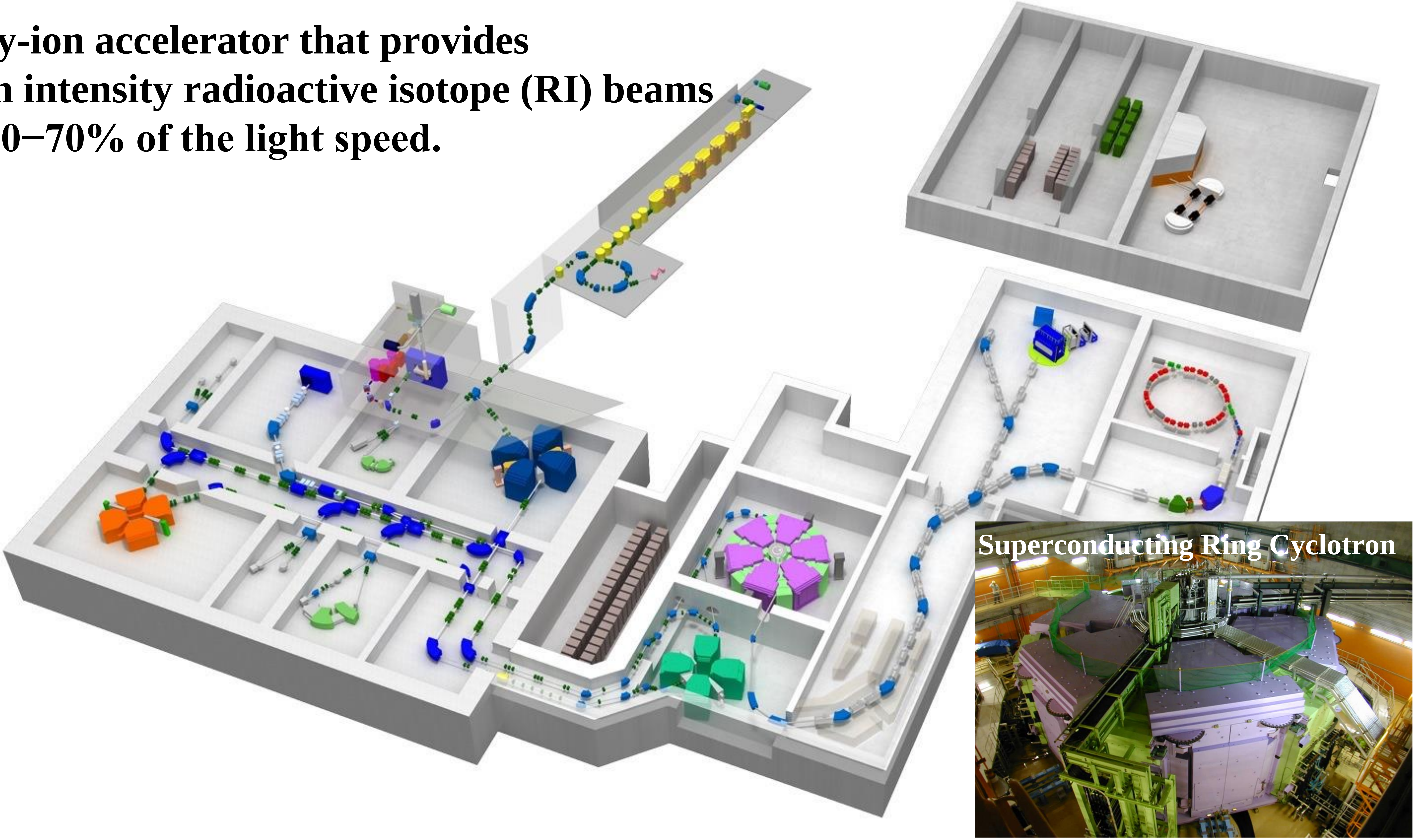
ANPhA Symposium
15–16, November 2024

Correlation and dynamics near and beyond the neutron dripline — Challenges at SAMURAI —

Tomohiro Uesaka (RIKEN)
on behalf of the SAMURAI Collaboration

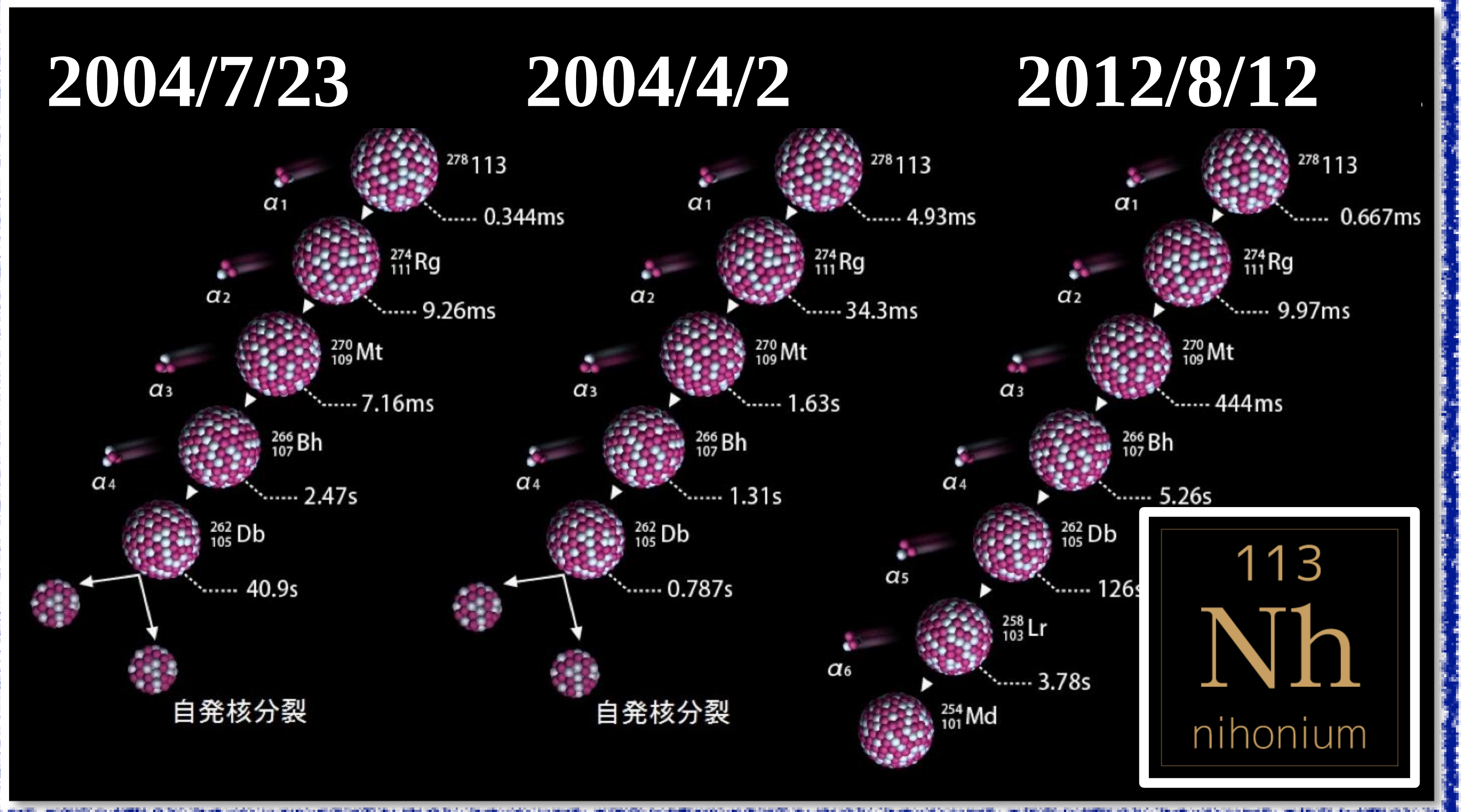
RI Beam Factory at RIKEN

Heavy-ion accelerator that provides
high intensity radioactive isotope (RI) beams
at 60−70% of the light speed.

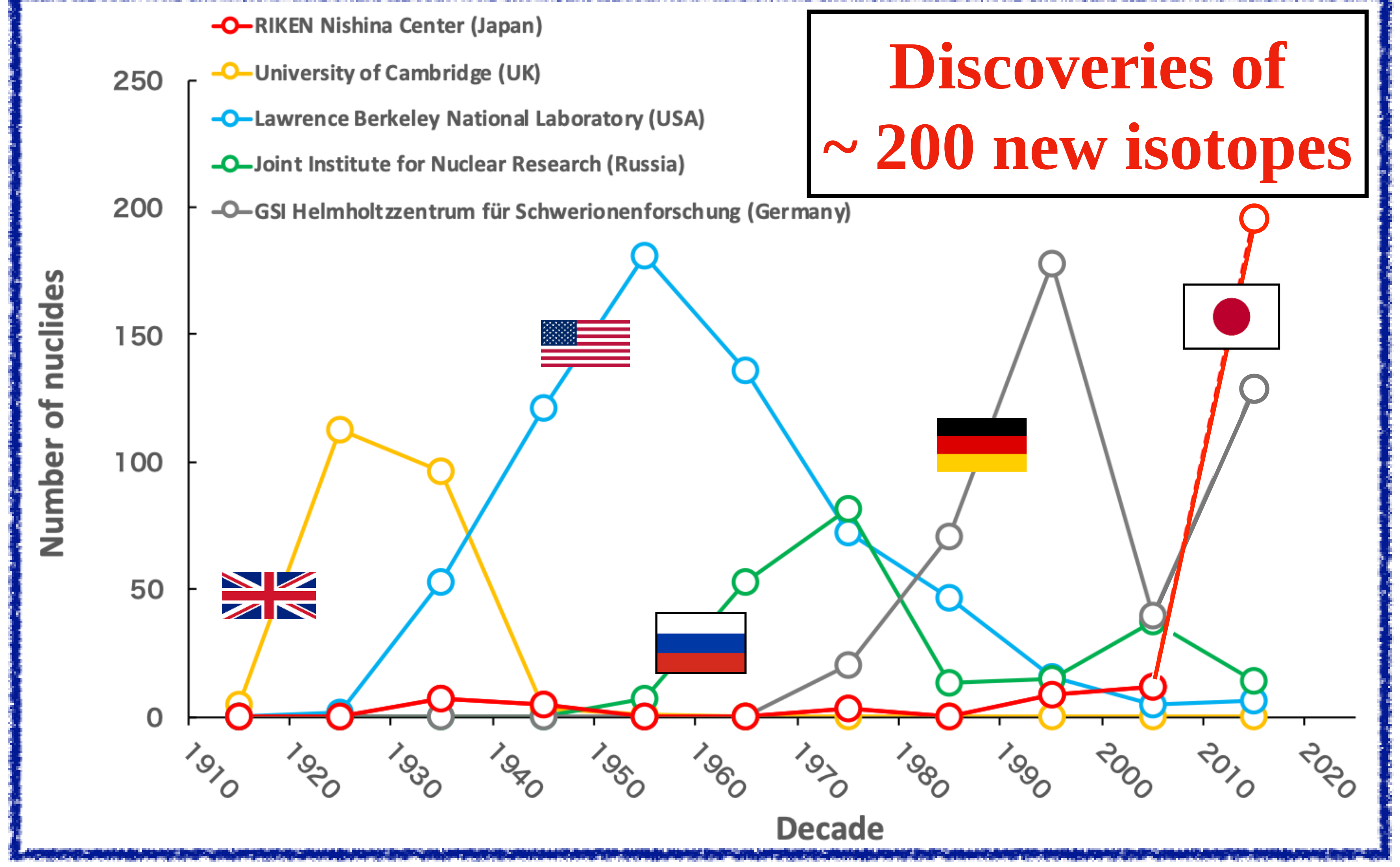


Selected Achievements at RIBF

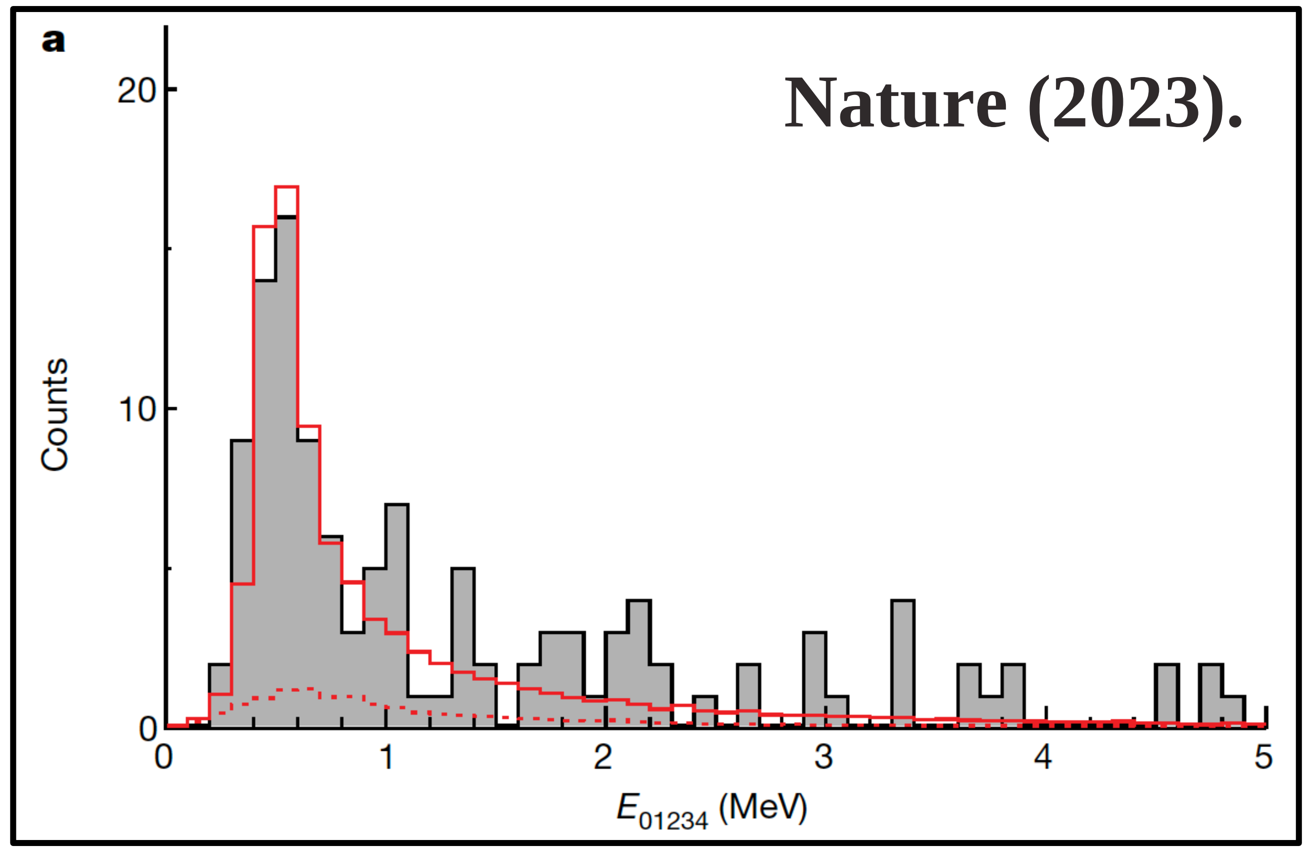
Discovery of Nihonium (Z=113)



Discoveries of ~ 200 new isotopes

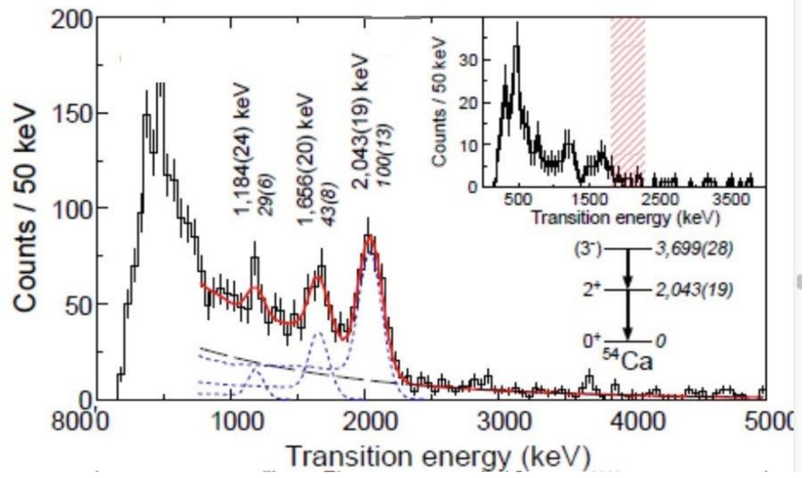


Discoveries of ^{28}O

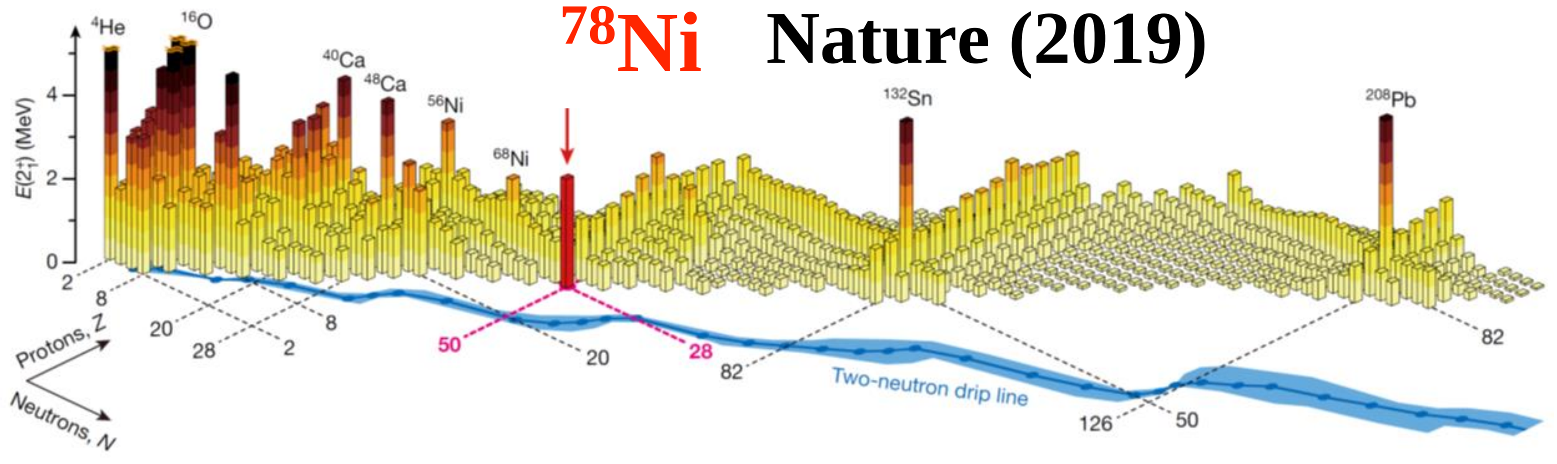


Evolution of nuclear magicity far from the stability line

N=34, Nature (2013)

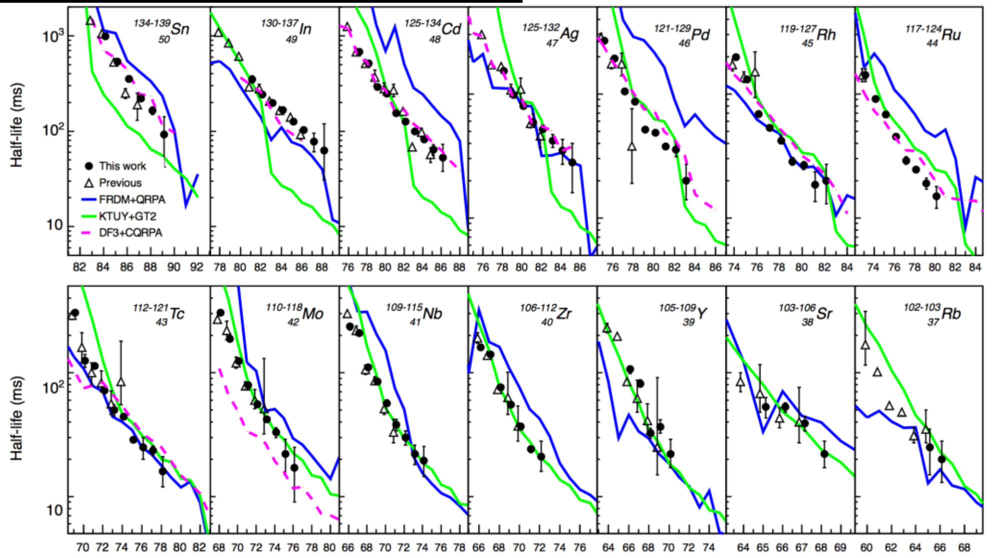


^{78}Ni Nature (2019)



Data crucial for understanding the origin of heavy elements

EURICA

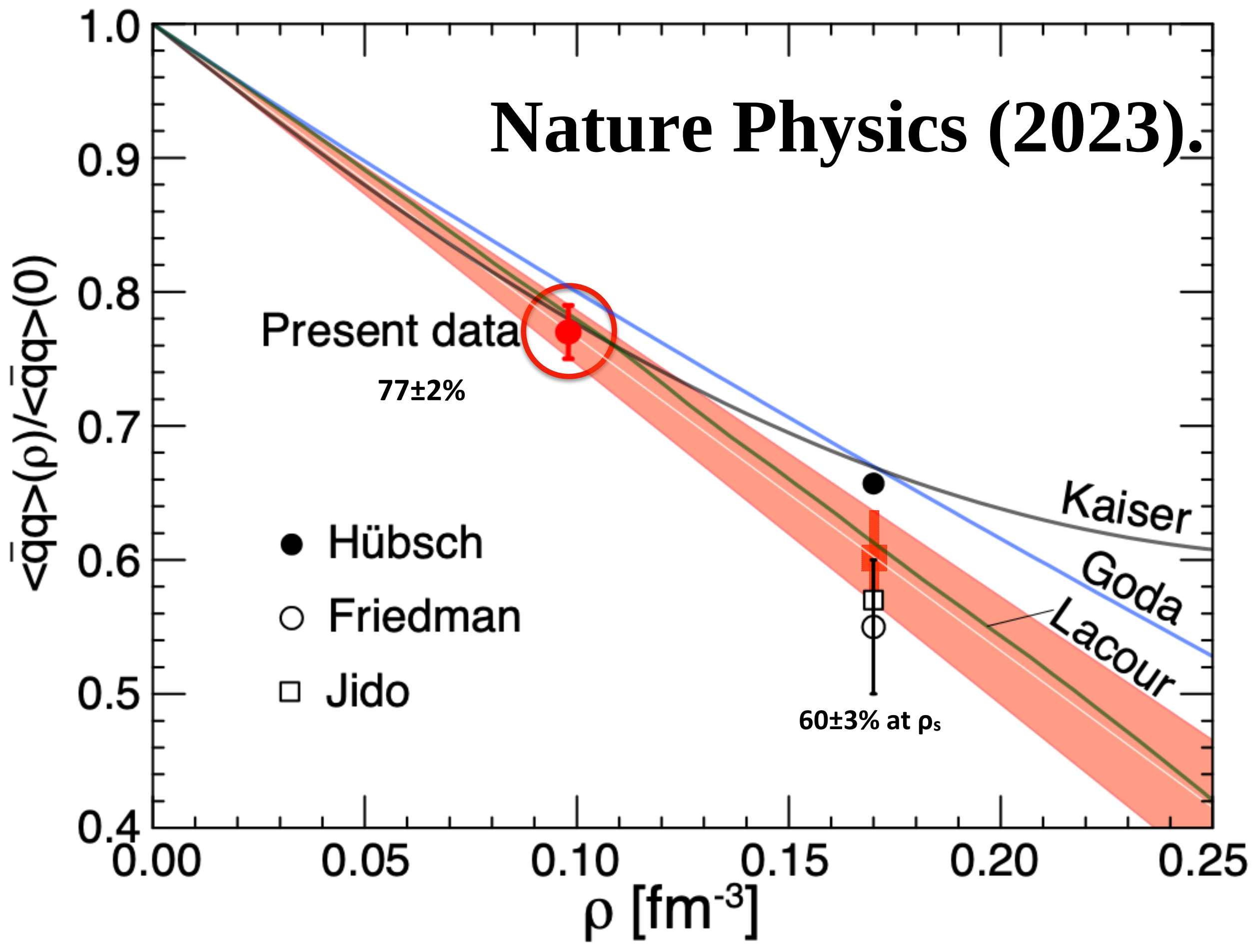


Lifetime
PRL (2015) etc.

Mass
PRL (2023) etc.

P_{xn}, PRL (2022)

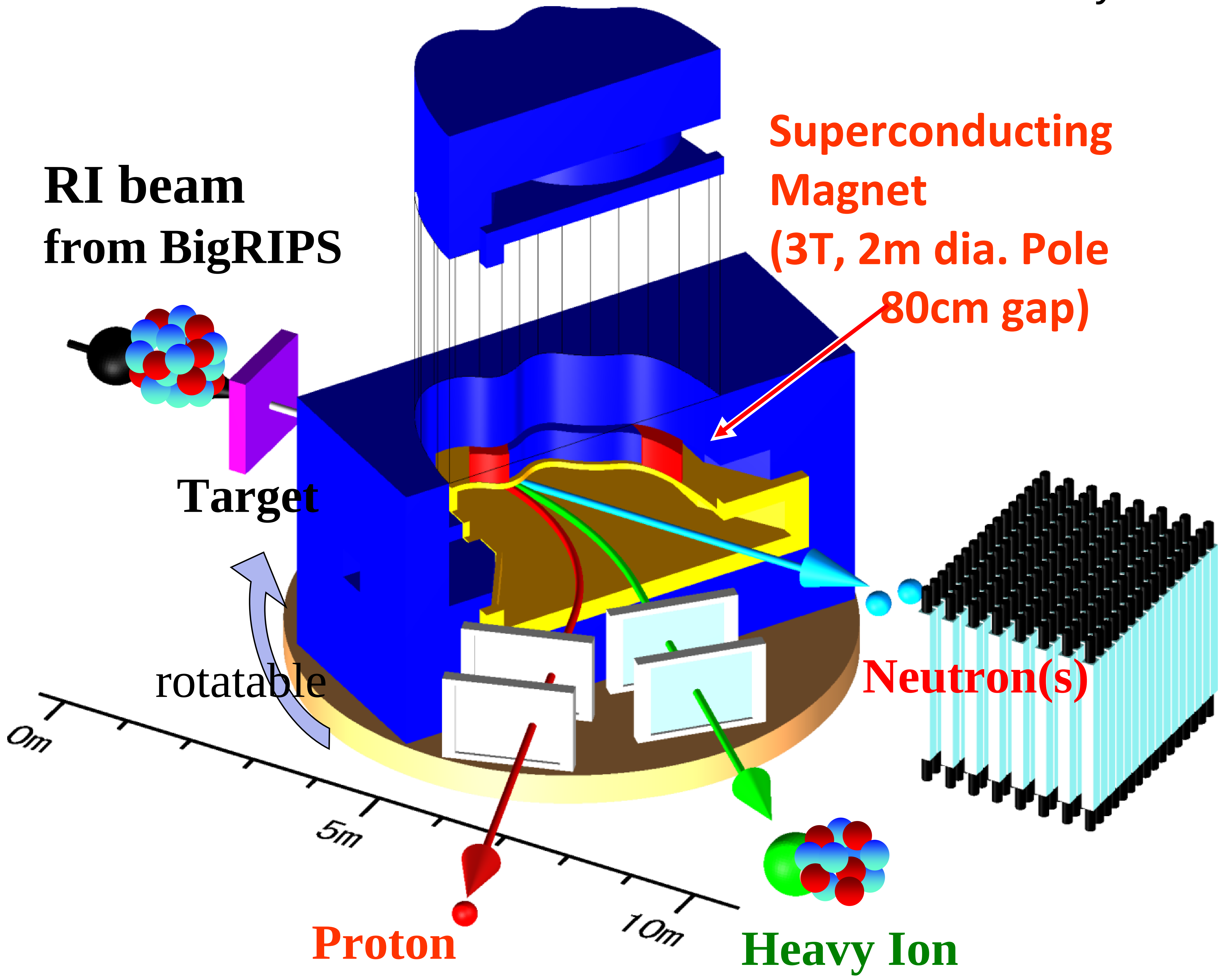
Partial restoration of chiral symmetry observed in pionic atoms



Superconducting Analyzer for MUlti-particle from RAdio Isotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence

T.Kobayashi et al., NIM B 317, 294 (2013).



Large momentum acceptance

$B\rho_{max} / B\rho_{min} \sim 2 - 3$

Good Momentum Resolution

$\Delta p/p \sim 1/700$ (designed value)

(5σ separation for A=100)

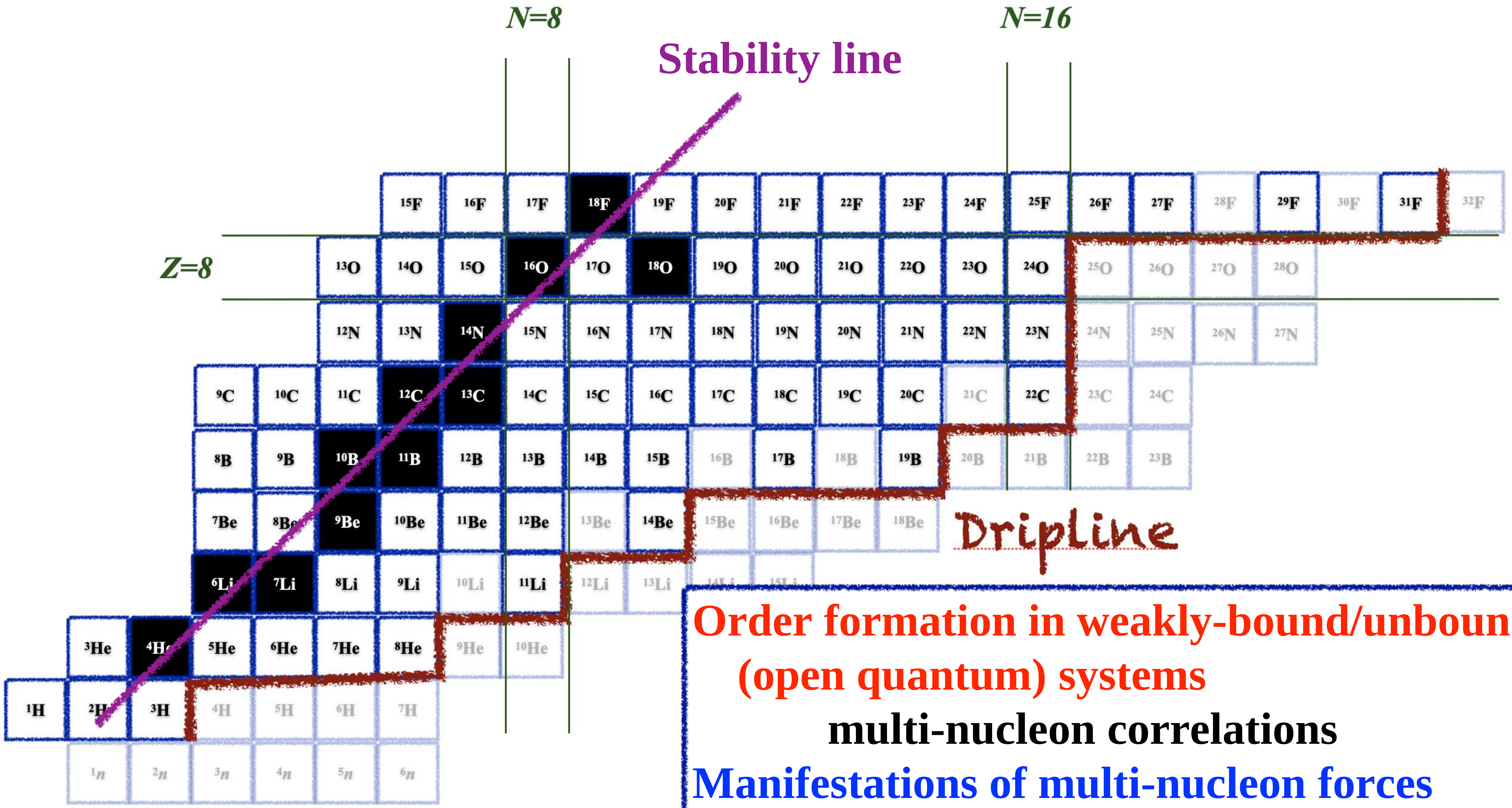
Large angular acceptance for *n*

20 deg (H) x 10 deg(V)

(~100% coverage < E_{rel} ~ 2MeV,

~ 30% coverage at E_{rel} ~ 10 MeV)

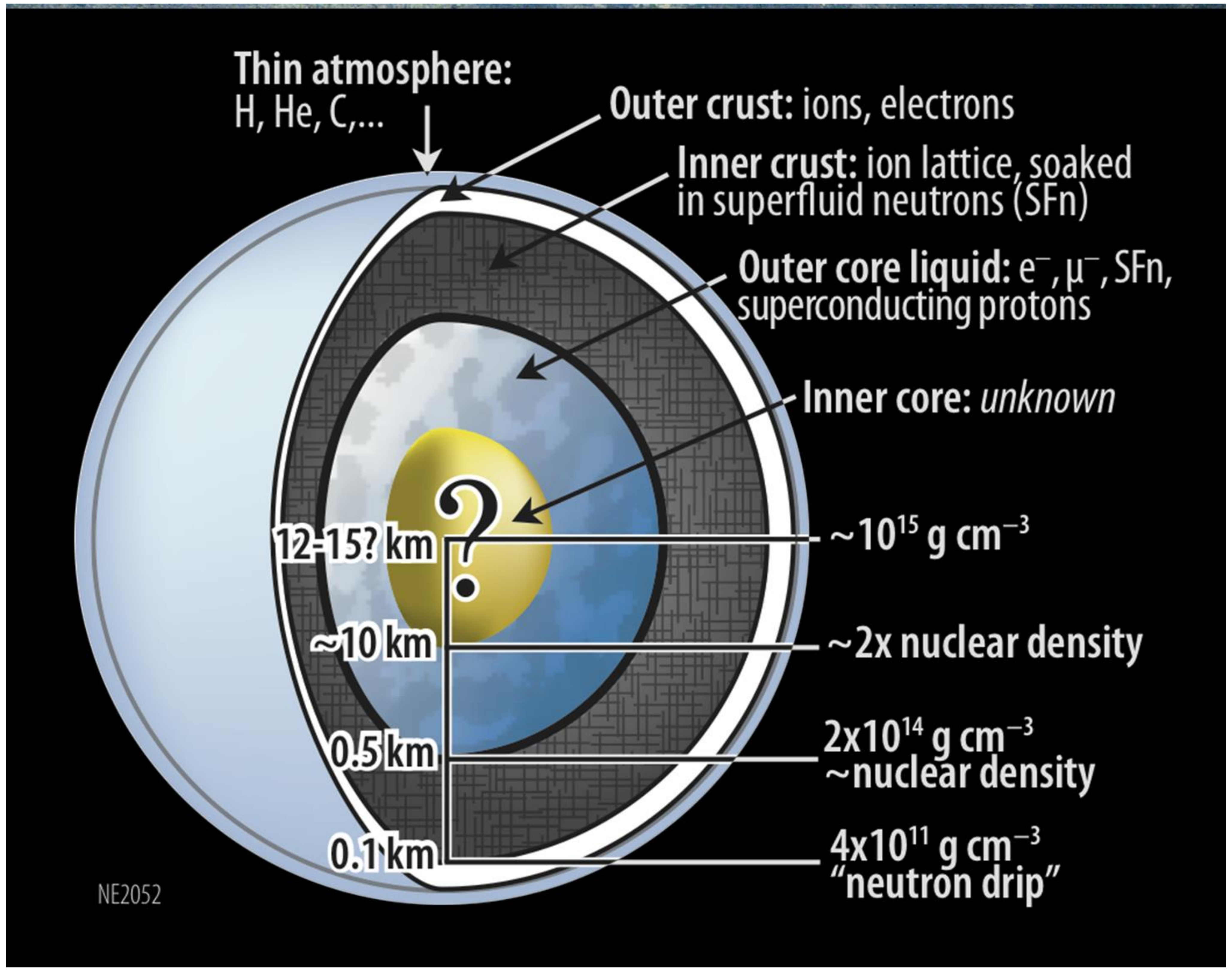
Towards and beyond the limit of nuclear stability

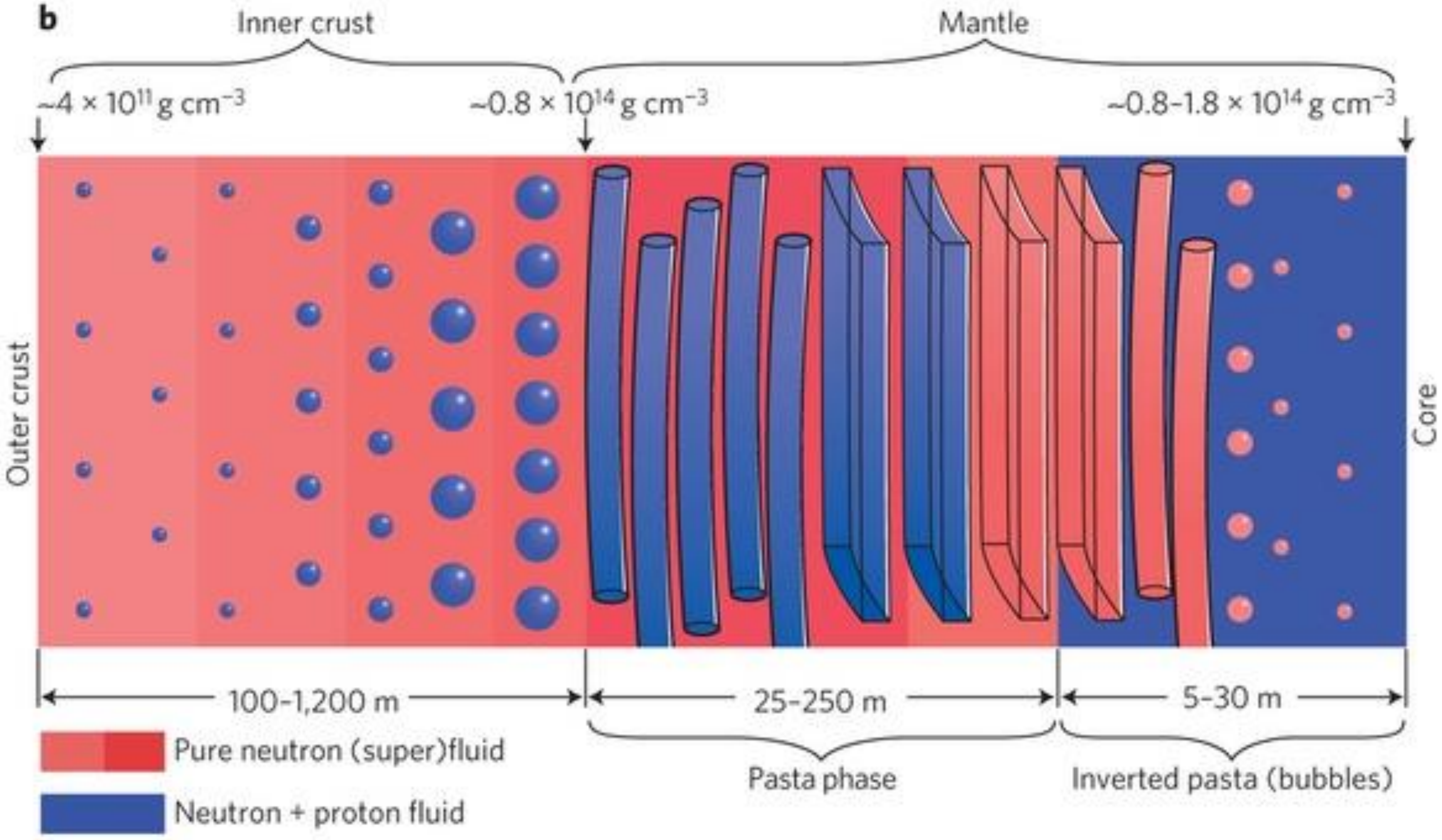


Order formation in weakly-bound/unbound
(open quantum) systems
multi-nucleon correlations
Manifestations of multi-nucleon forces
Implications to structure and dynamics of neutron stars

Neutron star : mysterious compact object in the universe

Mass ~ Solar mass
Radius ~ 10 km
Density ~ tons/cm^3 (big nucleus)
95% neutrons





Quantum mechanical correlations impact thermodynamical properties of neutron-rich matter.

The Astrophysical Journal, 748:70 (27pp), 2012 March 20 doi:10.1088/0004-637X/748/1/70

NEW EQUATIONS OF STATE IN SIMULATIONS OF CORE-COLLAPSE SUPERNOVAE

M. Hempel[1], T. Fischer[2,3], J. Schaffner-Bielich[4], and M. Liebendörfer[1]
[1] Departement Physik, Universität Basel, Klingelbergstr. 82, 4056 Basel, Switzerland
[2] GSI, Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany
[3] Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 9, 64289 Darmstadt, Germany
[4] Institut für Theoretische Physik, Ruprecht-Karls-Universität, Philosophenweg 16, 69120 Heidelberg, Germany
Received 2011 August 3; accepted 2012 January 17; published 2012 March 6

An important aspect of the supernova EOS is the formation of light nuclei and their properties in the hot and dense medium.

Thermodynamic variables, like, e.g., the symmetry energy, are modified due to the appearance of light nuclei.

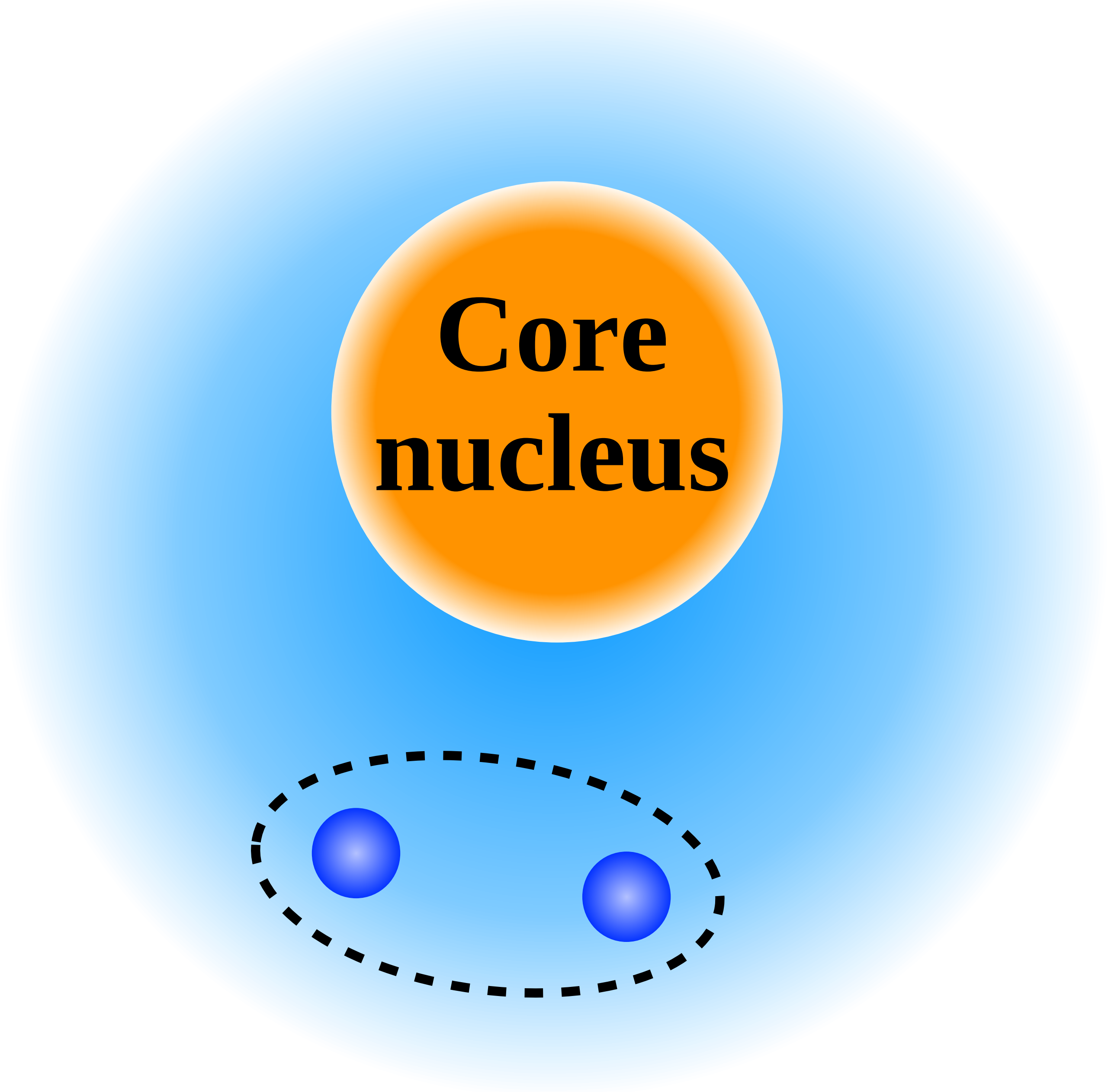
In the supernova environment light nuclei can possibly influence the neutrino transport and consequently the supernova neutrino signal and dynamics.

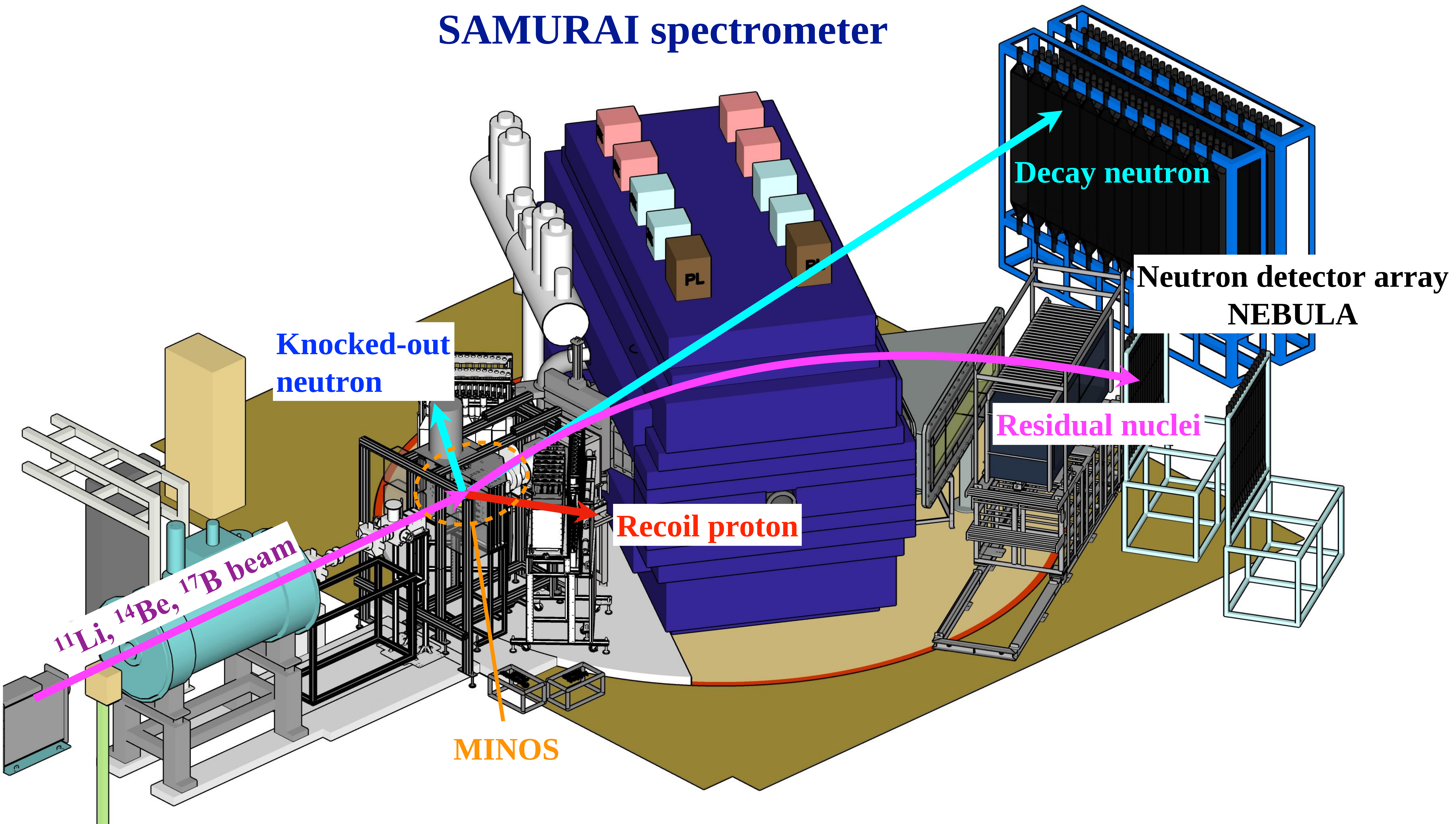
Dineutron correlation

In 1973, A.B. Migdal hypothesized existence of
a "bound" 2*n* system in a finite nucleus (in a potential).

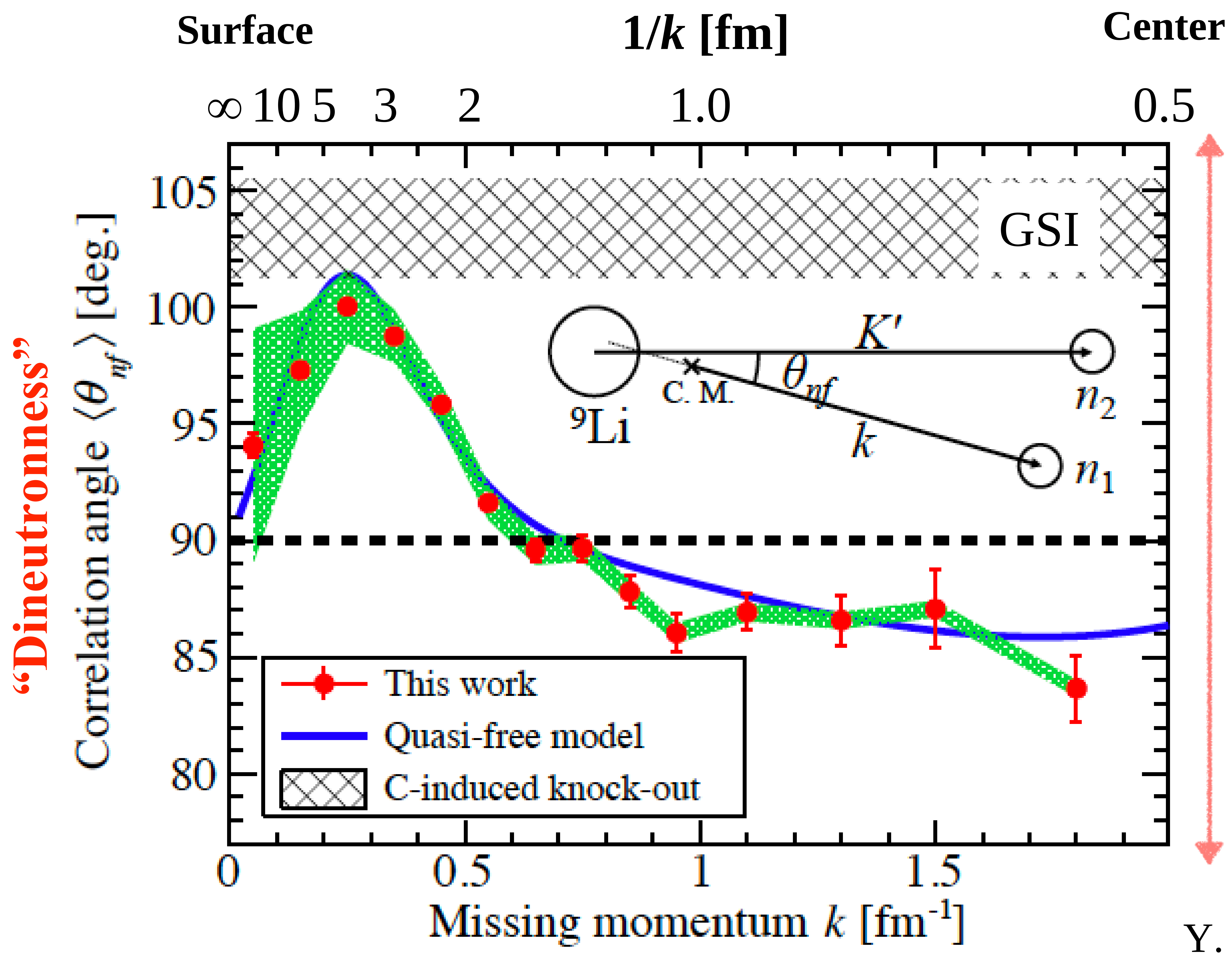
Discovery of a halo in ^{11}Li (1985) triggered extensive studies of
a dineutron as a spatially-compact $^1S_0$ neutron pair.
experimental studies at RIKEN, GSI, NSCL, GANIL, TRIUMF . . .

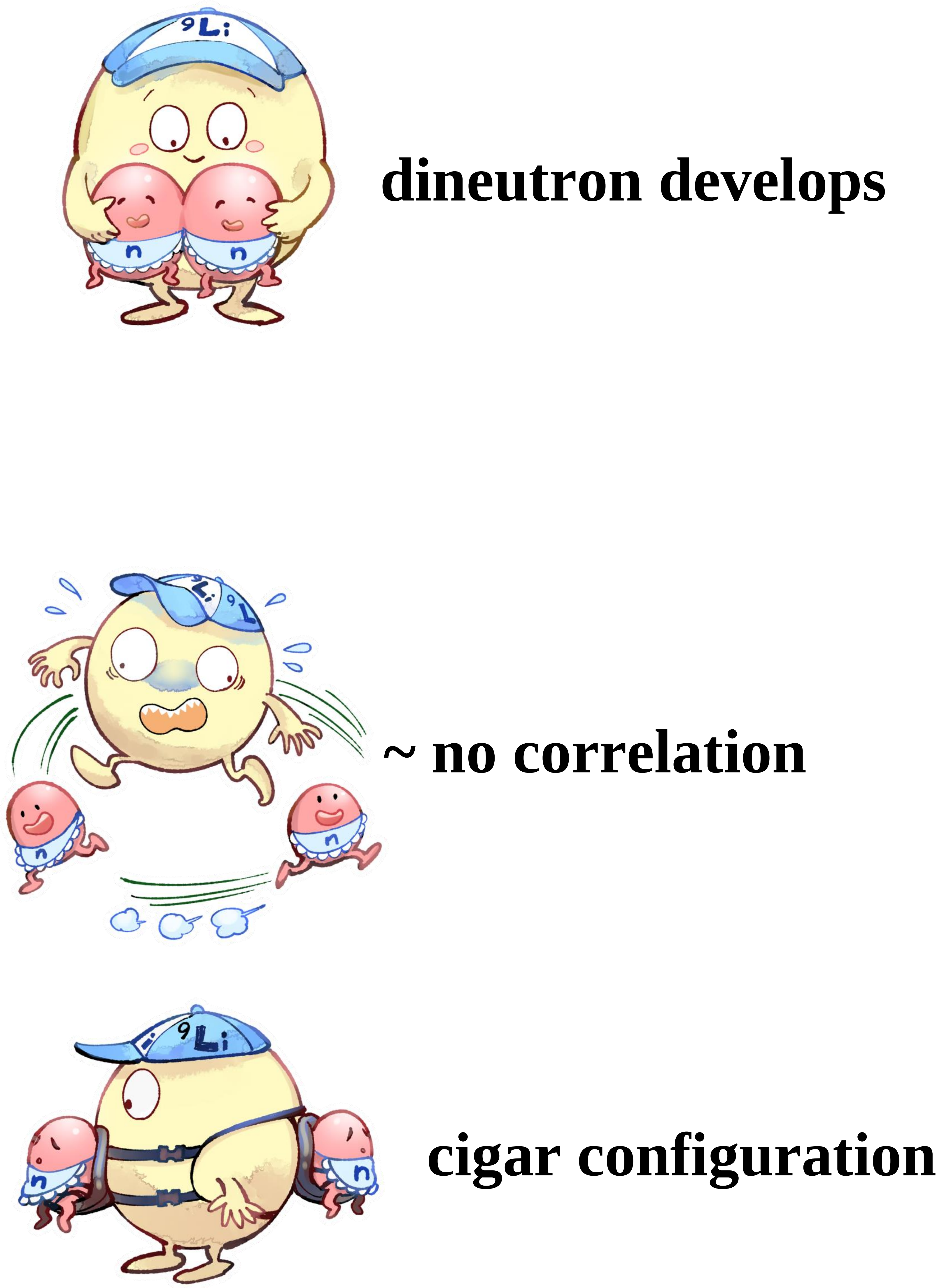
From the previous studies, we learned that
Dineutron correlation exists in ^{11}Li,
but there are many open questions
Magnitude of the dineutron correlation,
Spatial distribution,
Effects of the excited core,
etc etc.




SAMURAI spectrometer
Decay neutron
Neutron detector array
NEBULA
Knocked-out
neutron
Residual nuclei
Recoil proton
11Li, 14Be, 17B beam
MINOS
PL

Spatial distribution of dineutron revealed

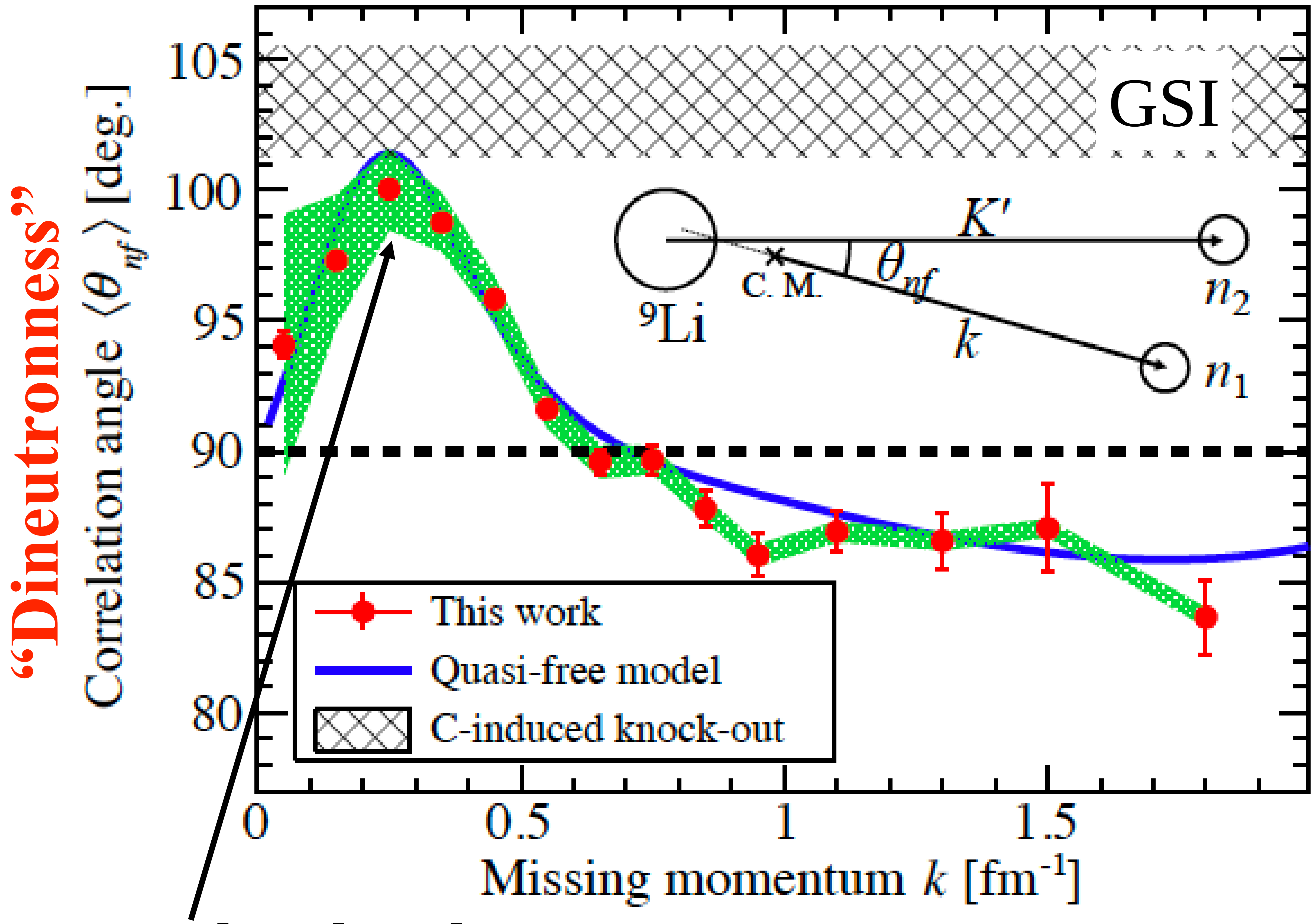




Y. Kubota, et al., PRL **125**, 252501 (2020).

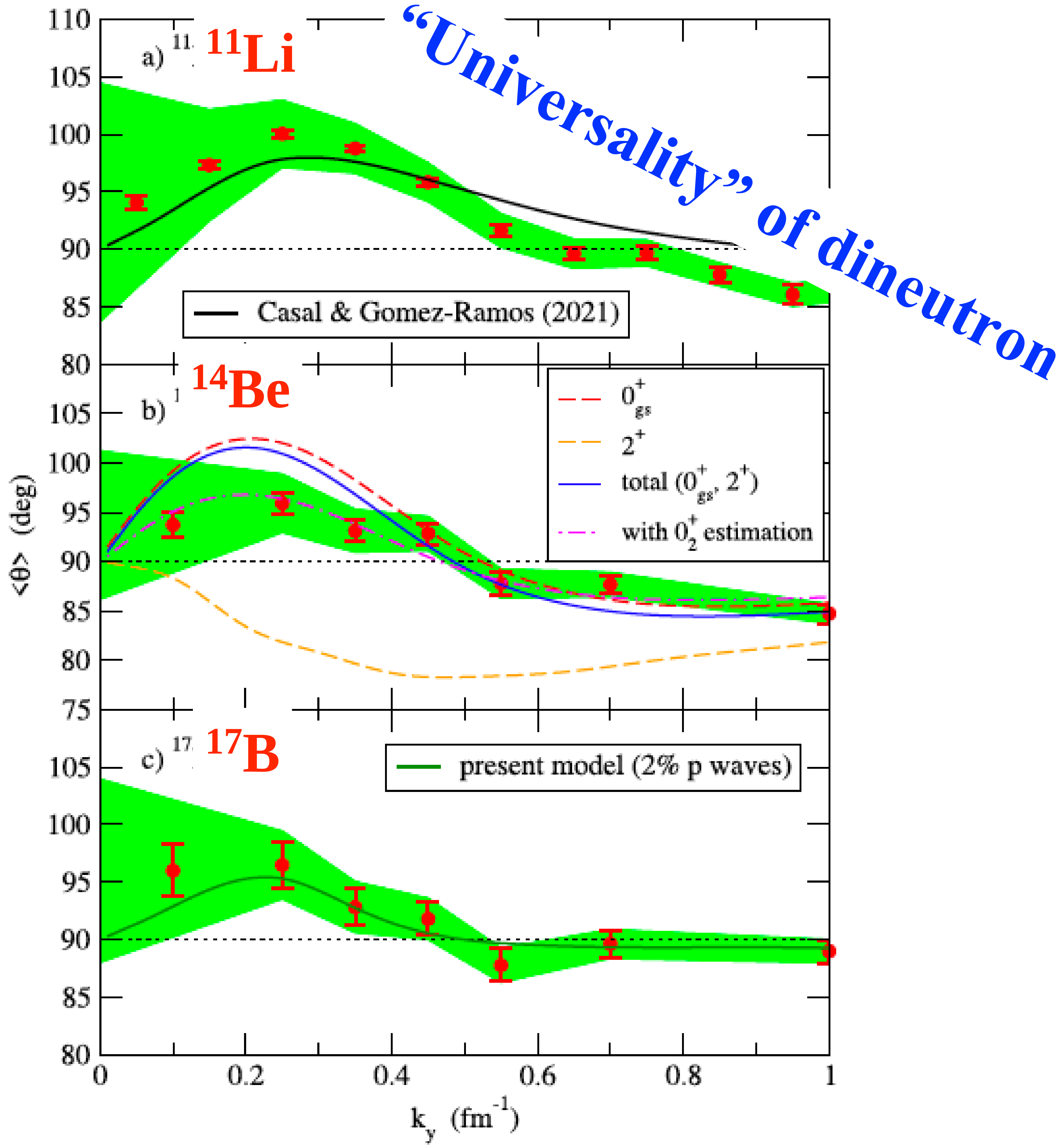
Surface localization of the dineutron in ^{11}Li and its universality

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



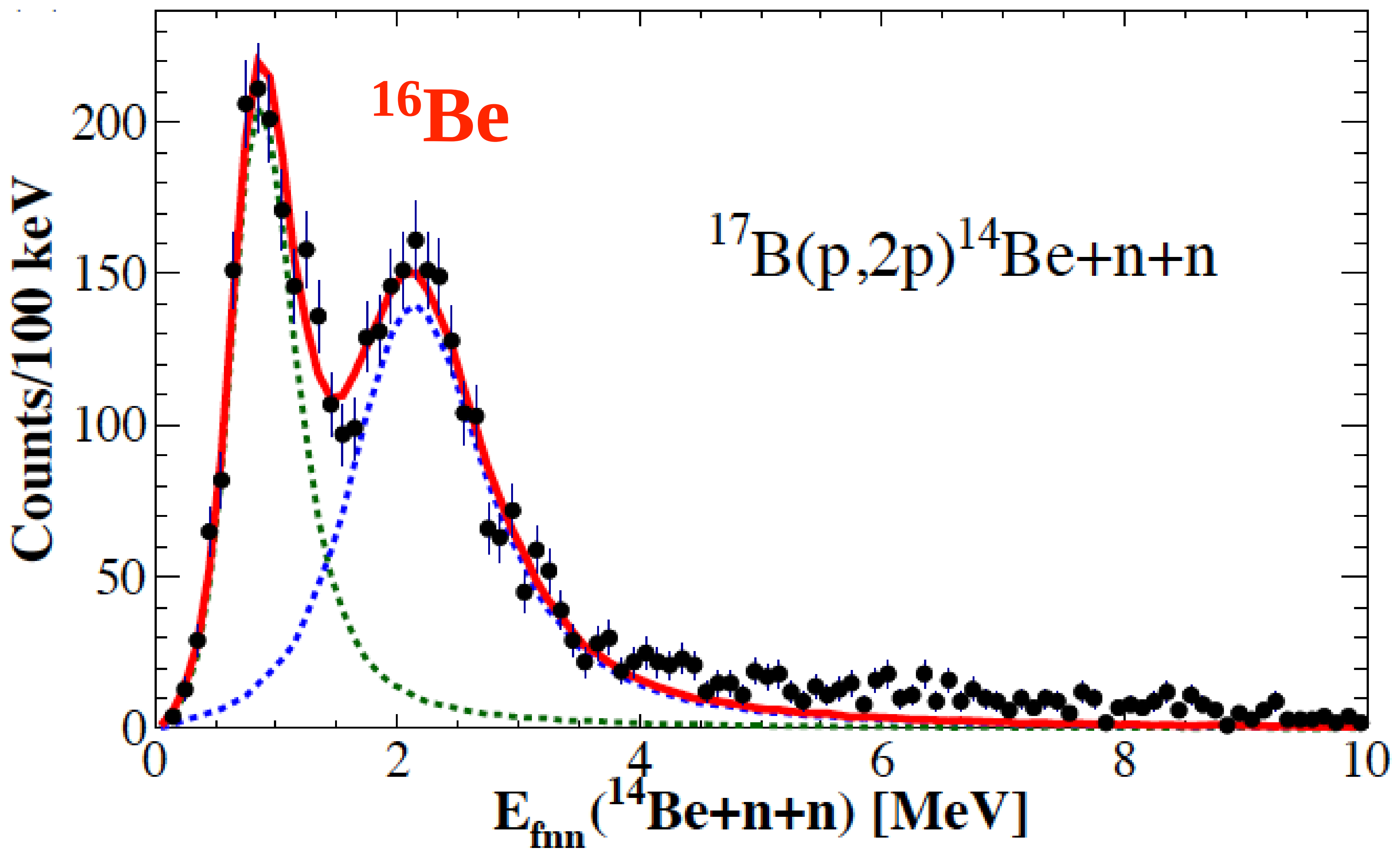
Dineutron is localized in
a limited region around
r~3.6fm (surface of the ^{9}Li core)
   ↔ Hagino et al., PRL99 (2007)

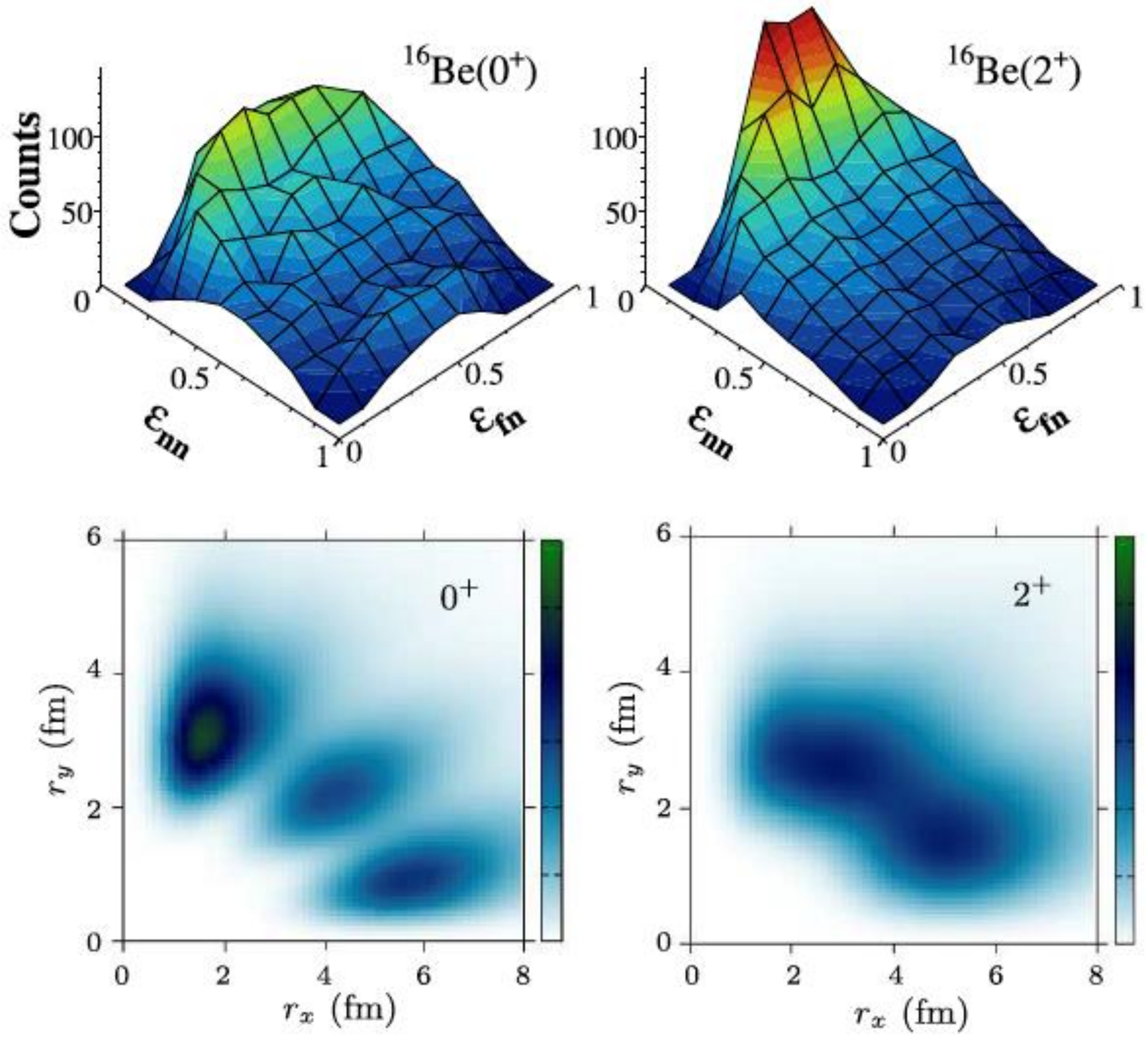
A. Corsi Y. Kubota, Z.H. Yang et al.,
PLB **840**, 137875 (2023)



New results on ^{16}Be

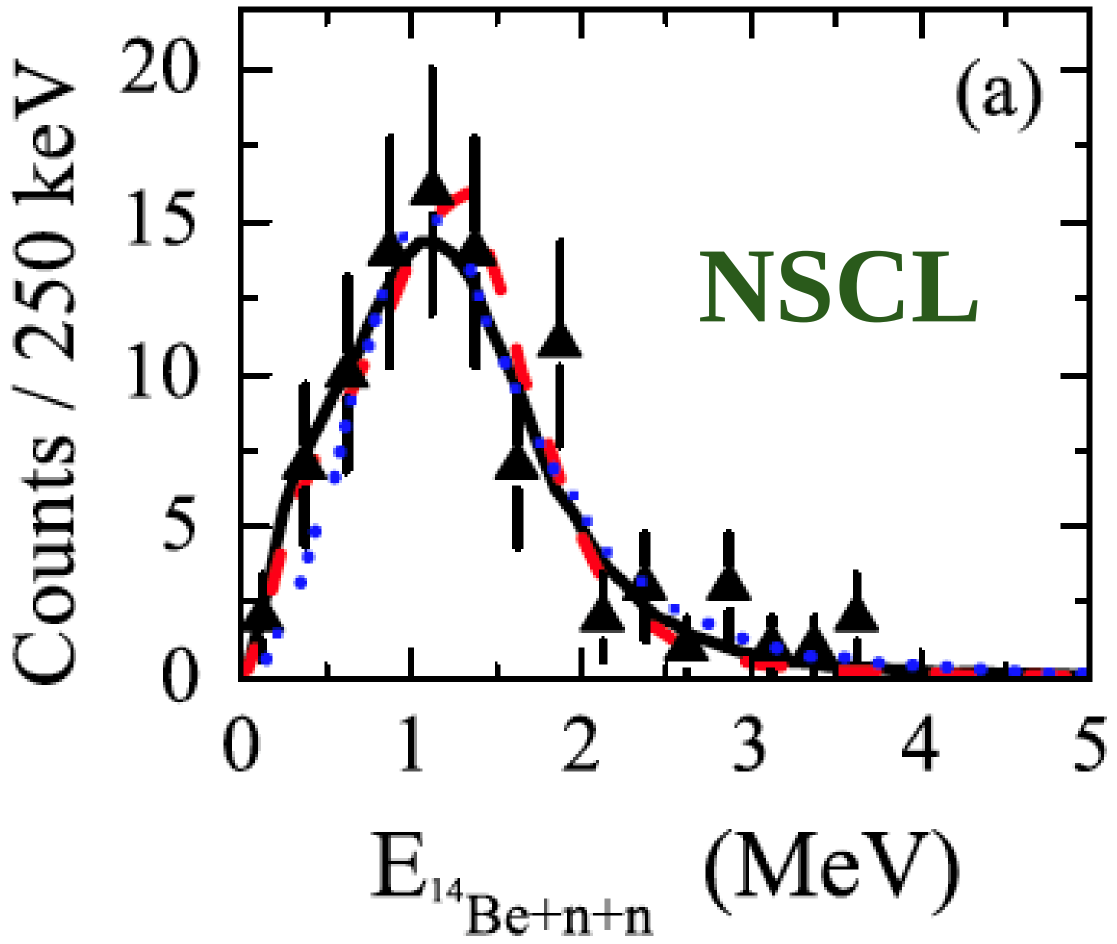
B. Monteagudo, M. Marques et al., PRL **132**, 082501 (2024)





^{16}Be: two-neutron decay nucleus

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



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

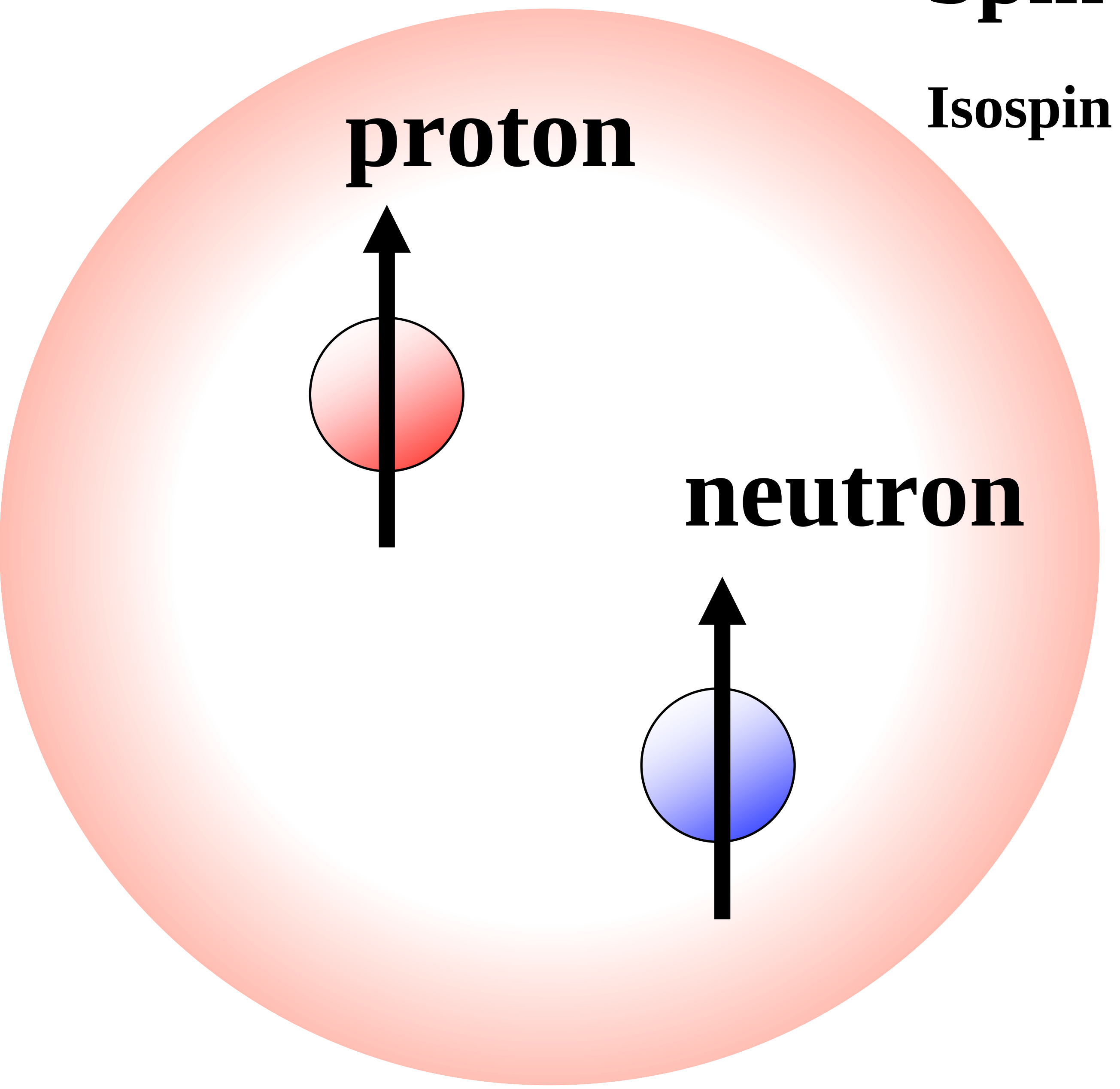
2^+ ex. state: decay by a two-neutron pair with small relative momentum

Deuteron clustering as a manifestation of S=1 correlations in nuclei?

Deuteron is the only bound state of two nucleons.

70% of its binding energy originates from the tensor force driven by pion exchange.

Binding energy	**2.225 MeV**
RMS radius	**1.9 fm**
Spin-parity	**1^+**
Isospin	**0**



PHYSICAL REVIEW C VOLUME 54, NUMBER 2 AUGUST 1996

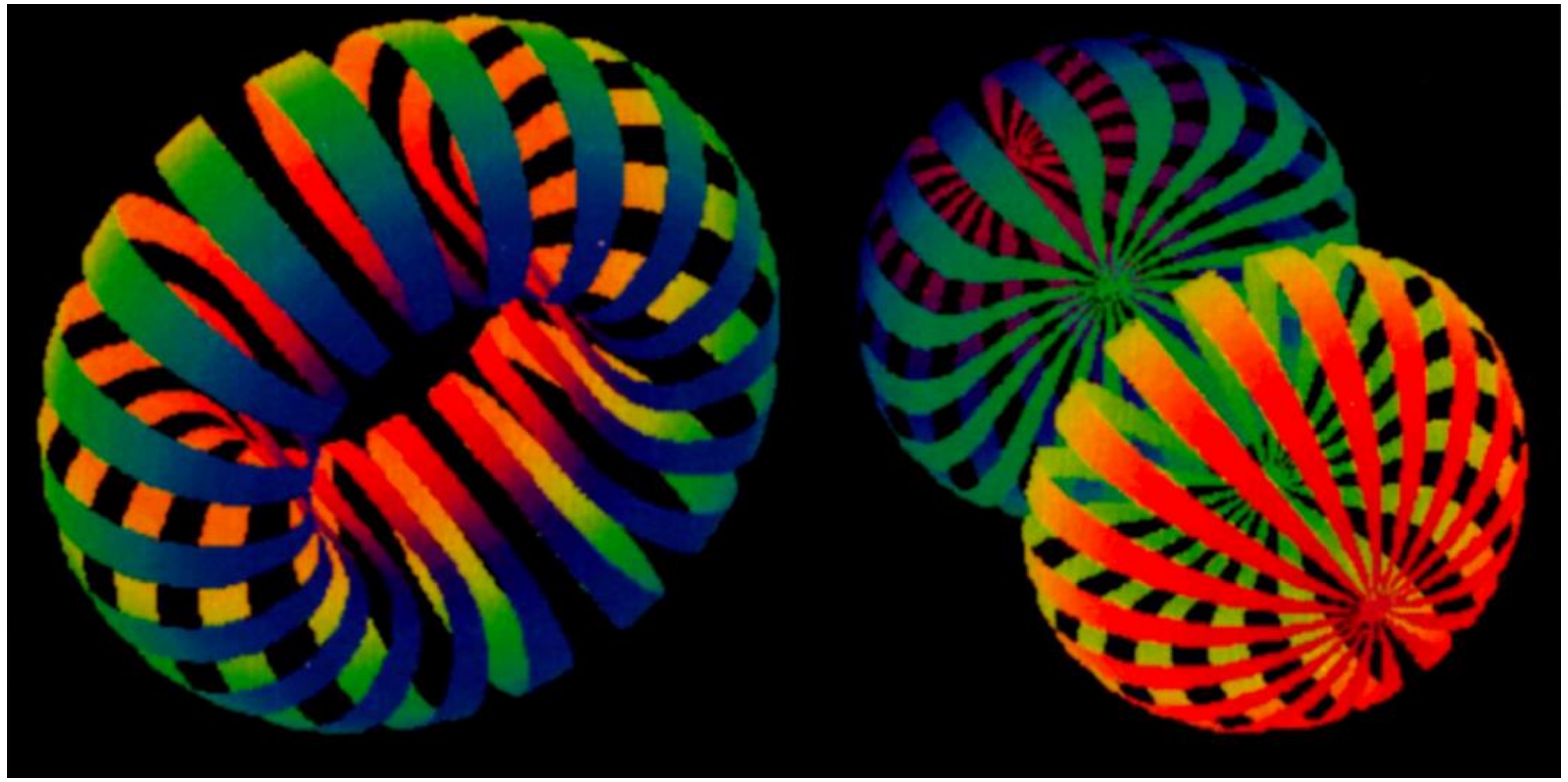
Femtometer toroidal structures in nuclei

J. L. Forest[*] and V. R. Pandharipande[†]
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

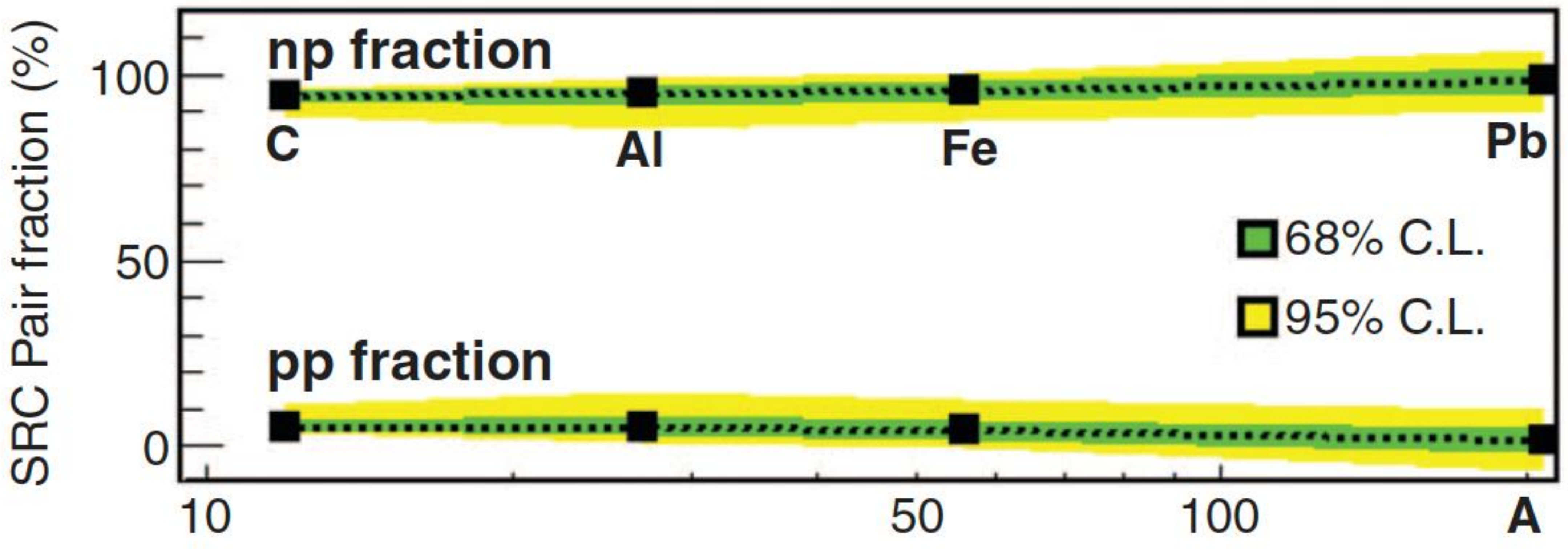
Steven C. Pieper[‡] and R. B. Wiringa[§]
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

R. Schiavilla[‖]
CEBAF Theory Group, Newport News, Virginia 23606,
and Department of Physics, Old Dominion University, Norfolk, Virginia 23529

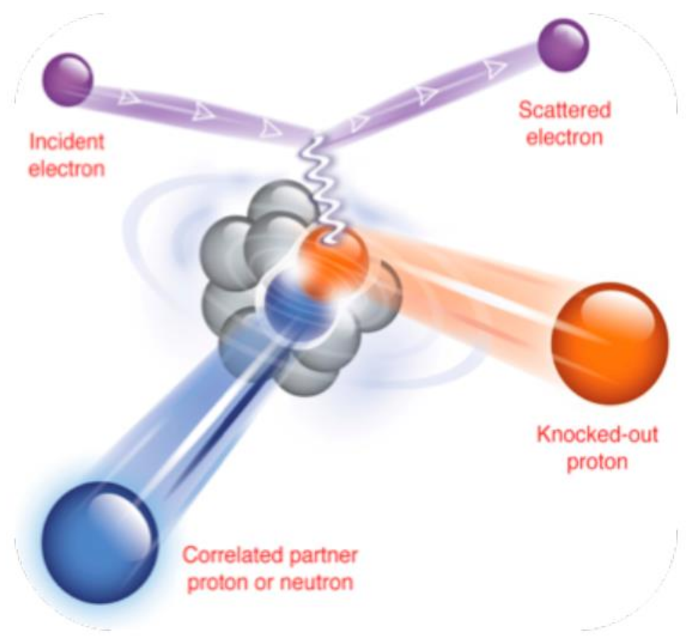
A. Arriaga[¶]
Centro de Fisica Nuclear da Universidade de Lisboa, Avenida Gama Pinto 2, 1699 Lisboa, Portugal
(Received 19 March 1996)

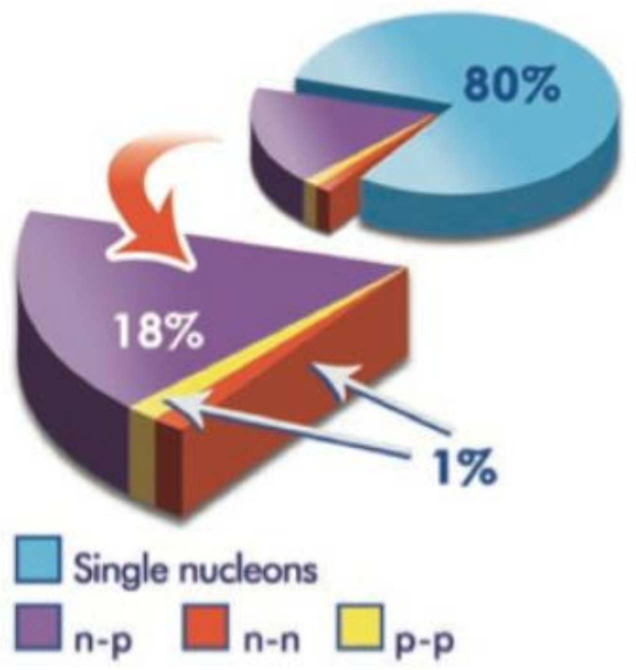


Experimental signatures of deuteron in nuclei



O. Hen et al., Science 364, 614 (2014).

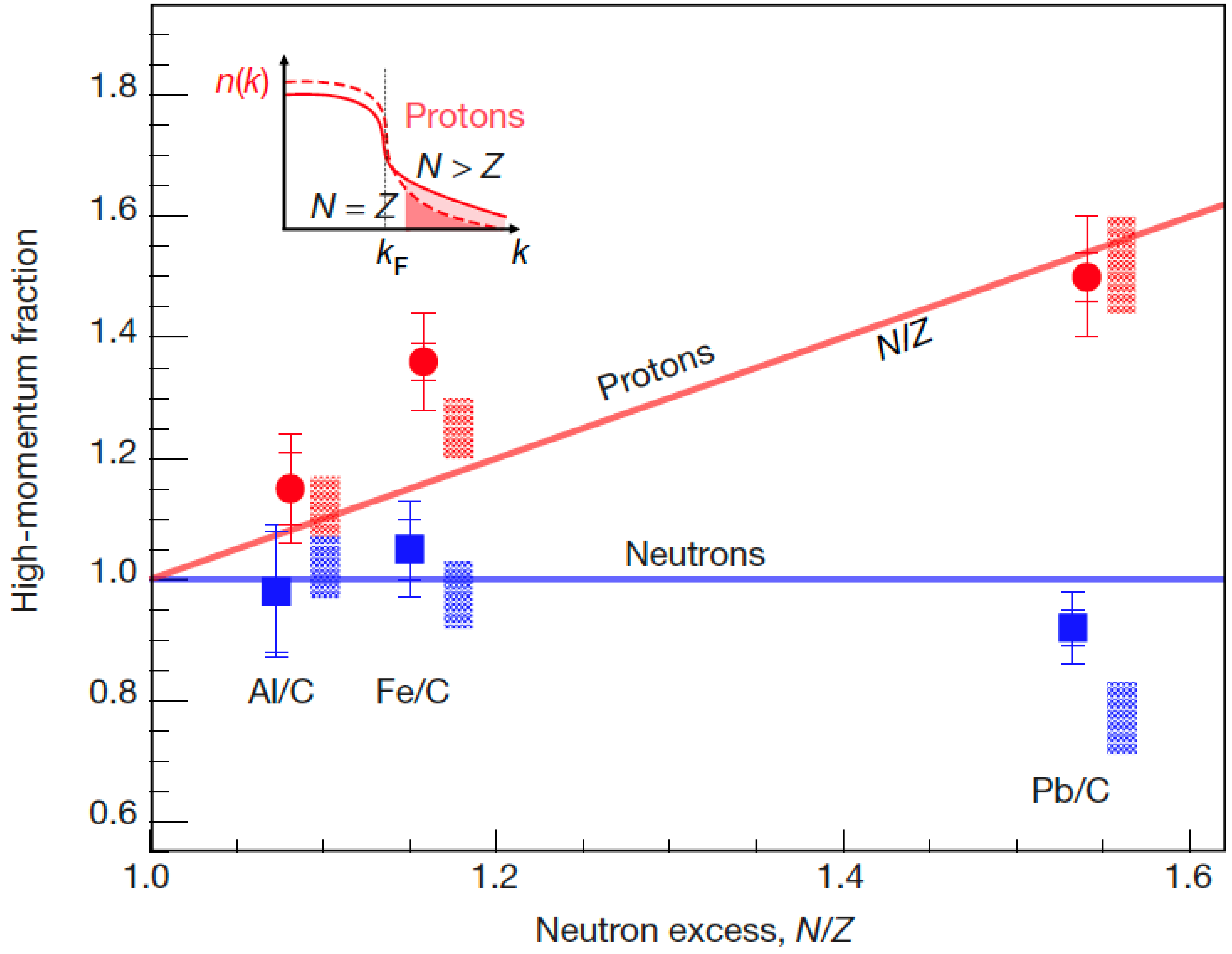




<u>N-N pairs at k_{rel} = 2 fm^{-1} (inter-nucleon distance of 0.5 fm) are >90 % likely to be proton-neutron pairs.</u>

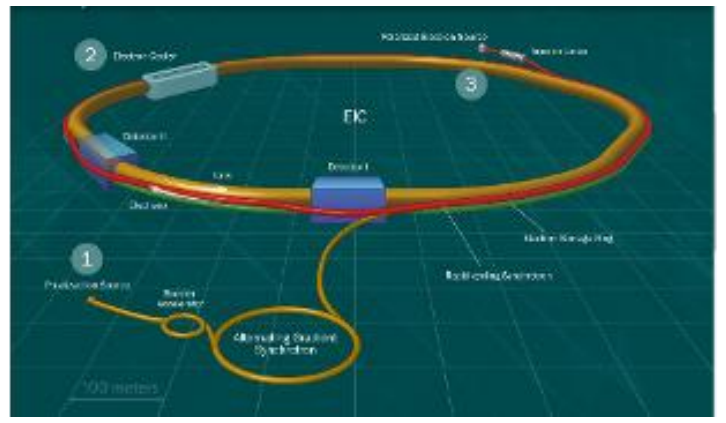
Short-range correlation (SRC)

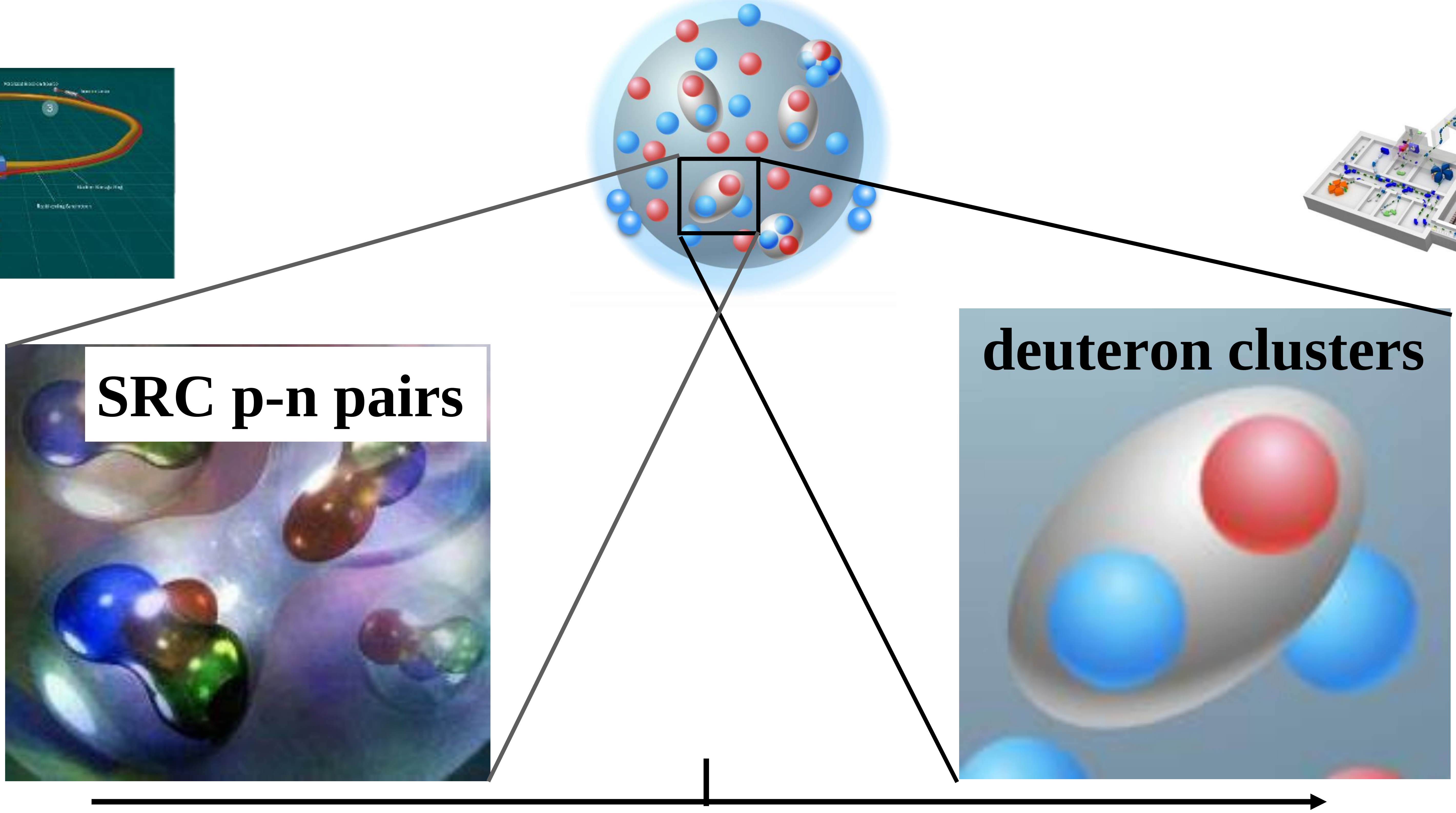
M. Duer et al., Nature 560, 617 (2018).



Indication of stronger SRC for proton in neutron-abundant environment.

Looking at *p-n* correlation in different resolutions





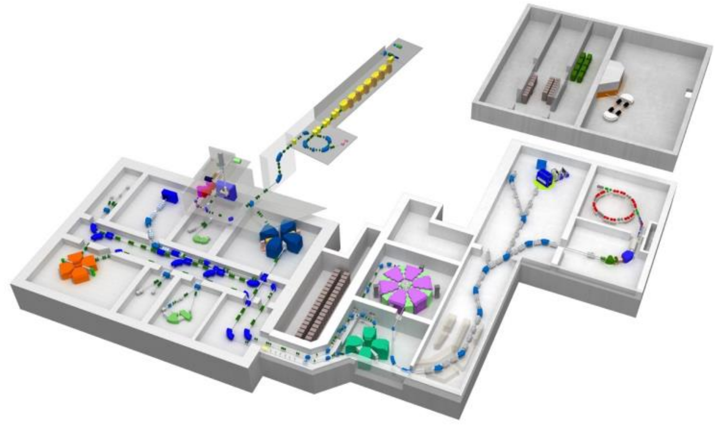
small p-n distance

Proton radius (~0.8 fm)

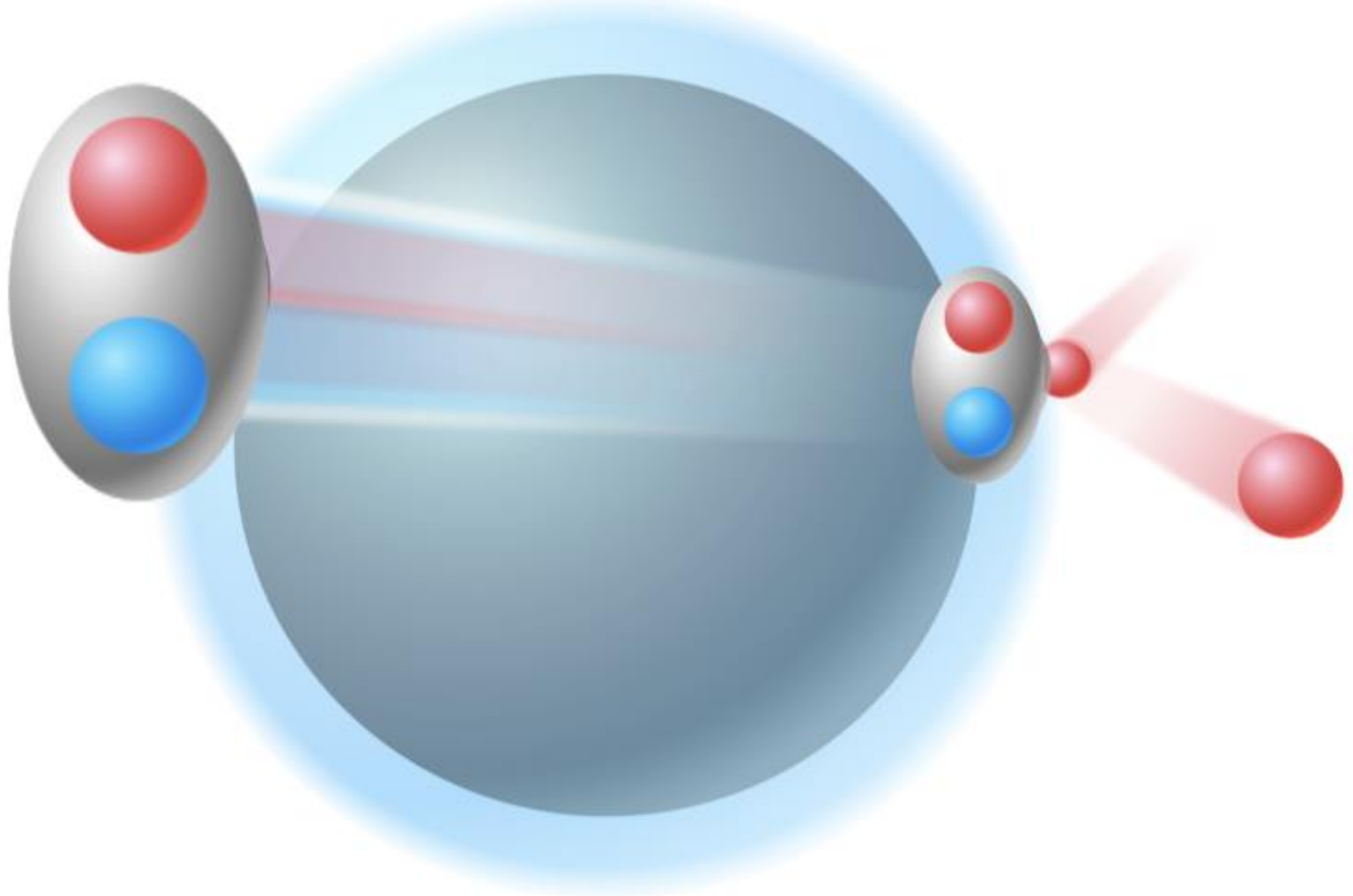
large p-n distance

quark-gluon dynamics

nucleon-meson dynamics



Just knock them out!

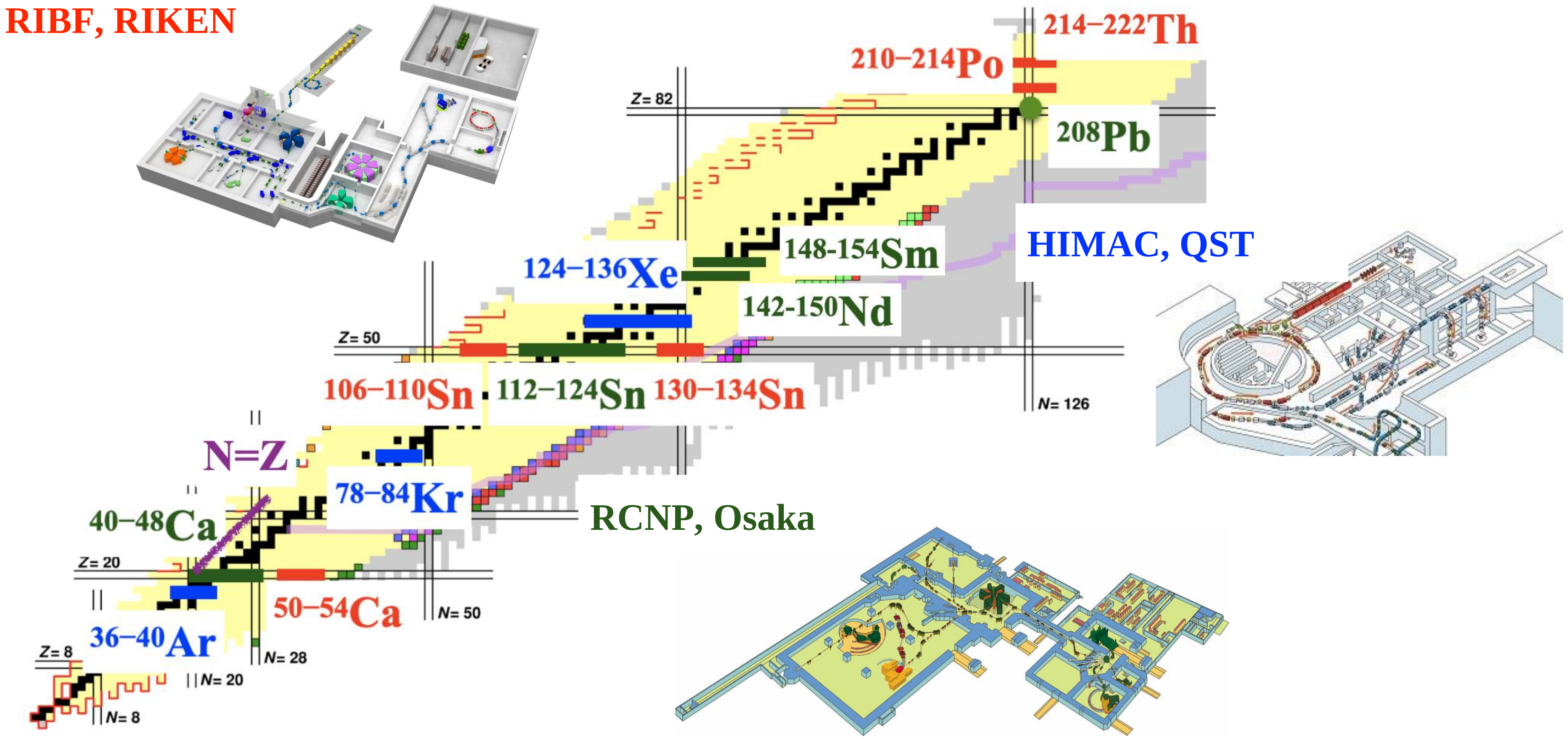


RIBF-EIC under RIKEN initiative is about to start.

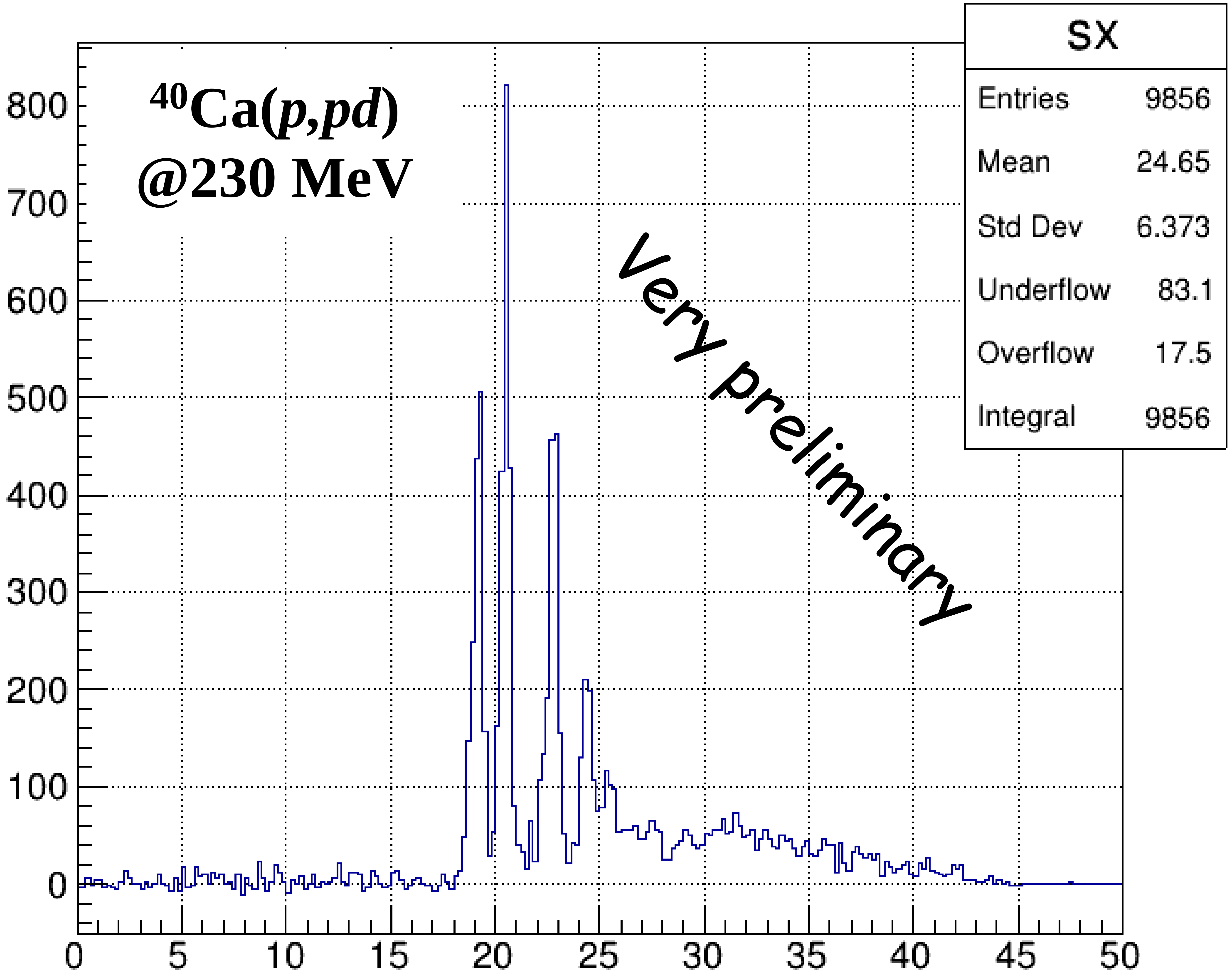
ONOKORO Project

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?



Our preparatory experiment indicates existence of deuterons

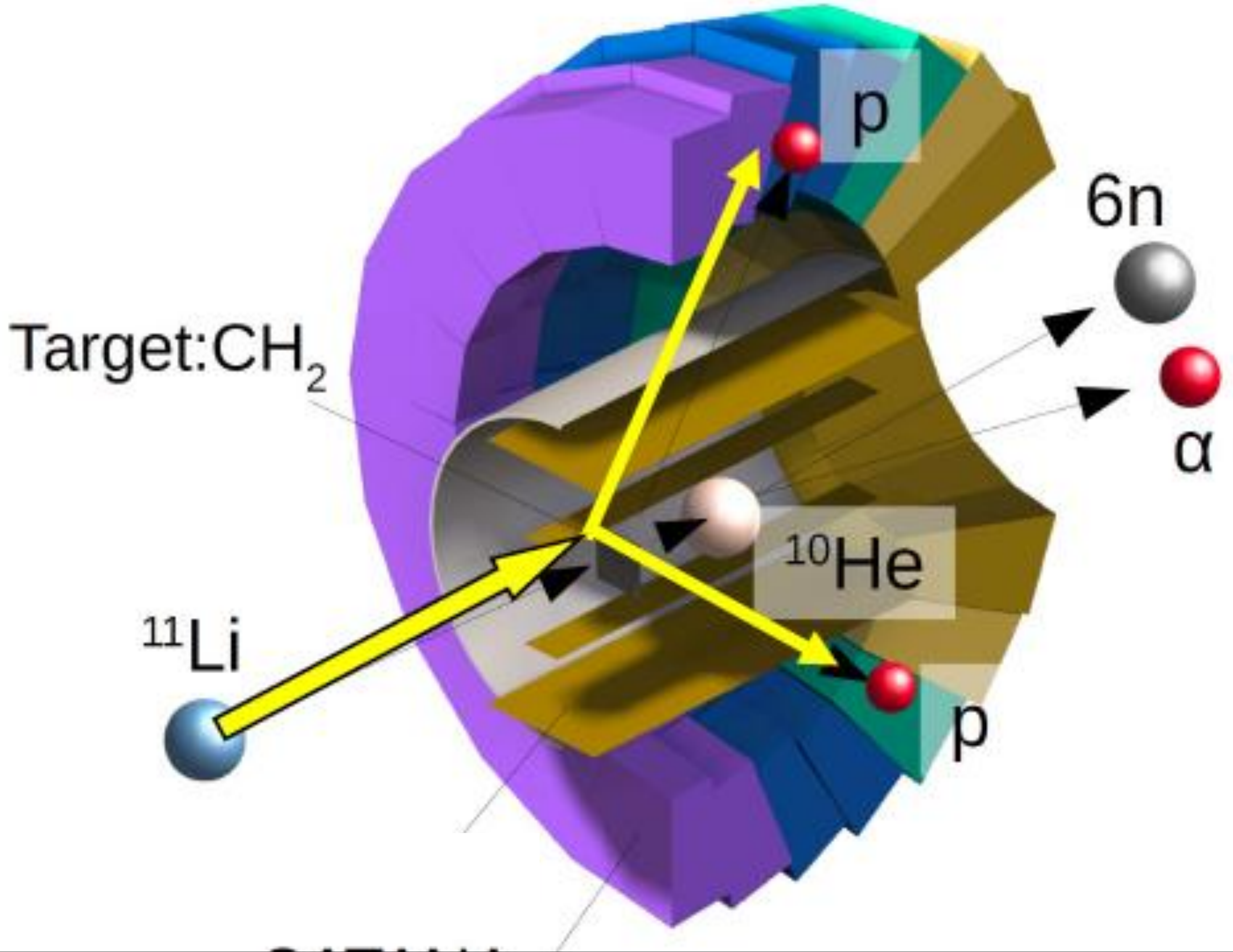


Deuteron separation energy [MeV]

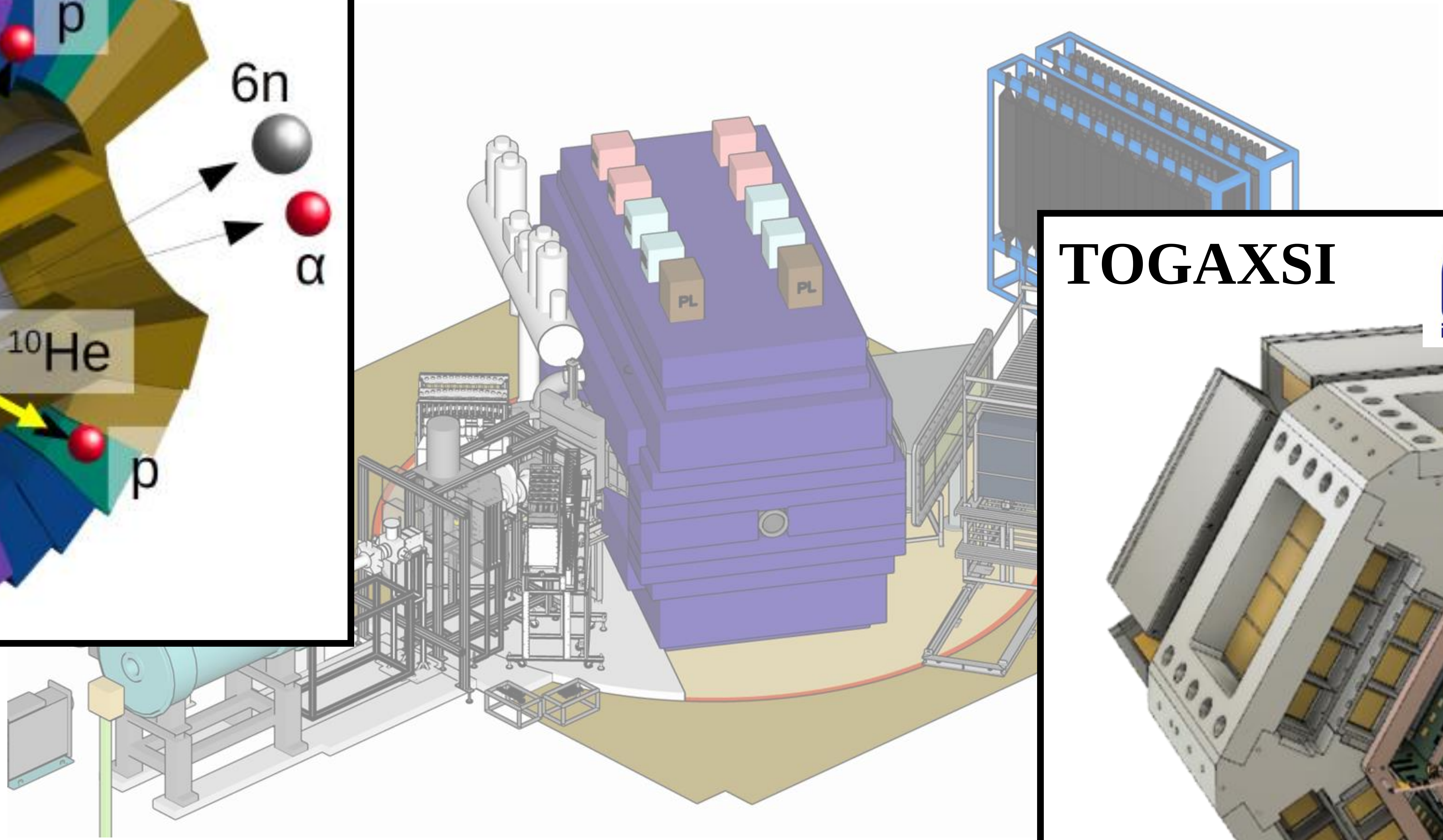
R. Tsuji et al.

SAMURAI, a growing facility : Introduction of missing mass devices

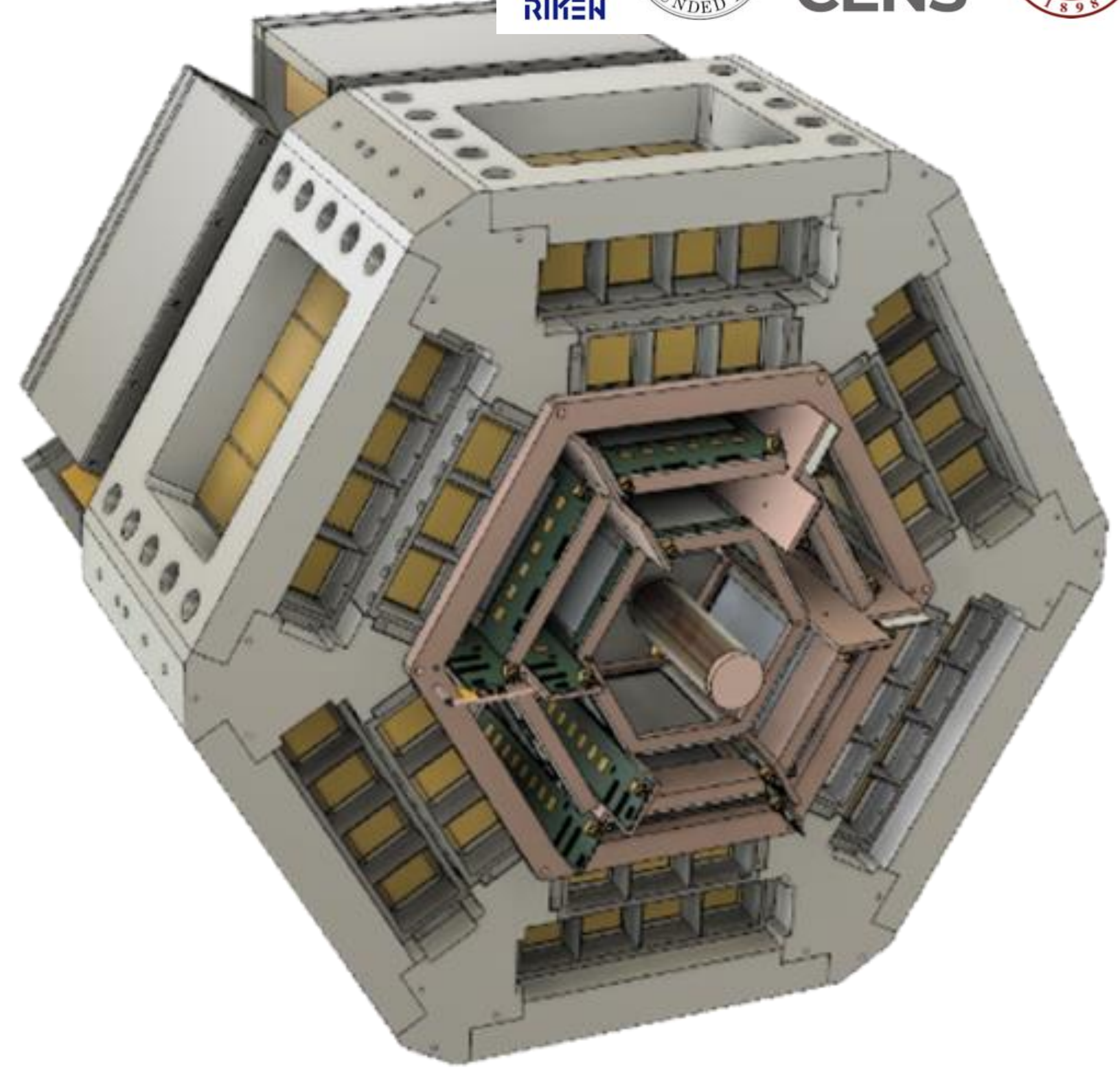
STRASSE-CATANA+



Hongna Liu, TU Darmstadt, Science Tokyo



TOGAXSI

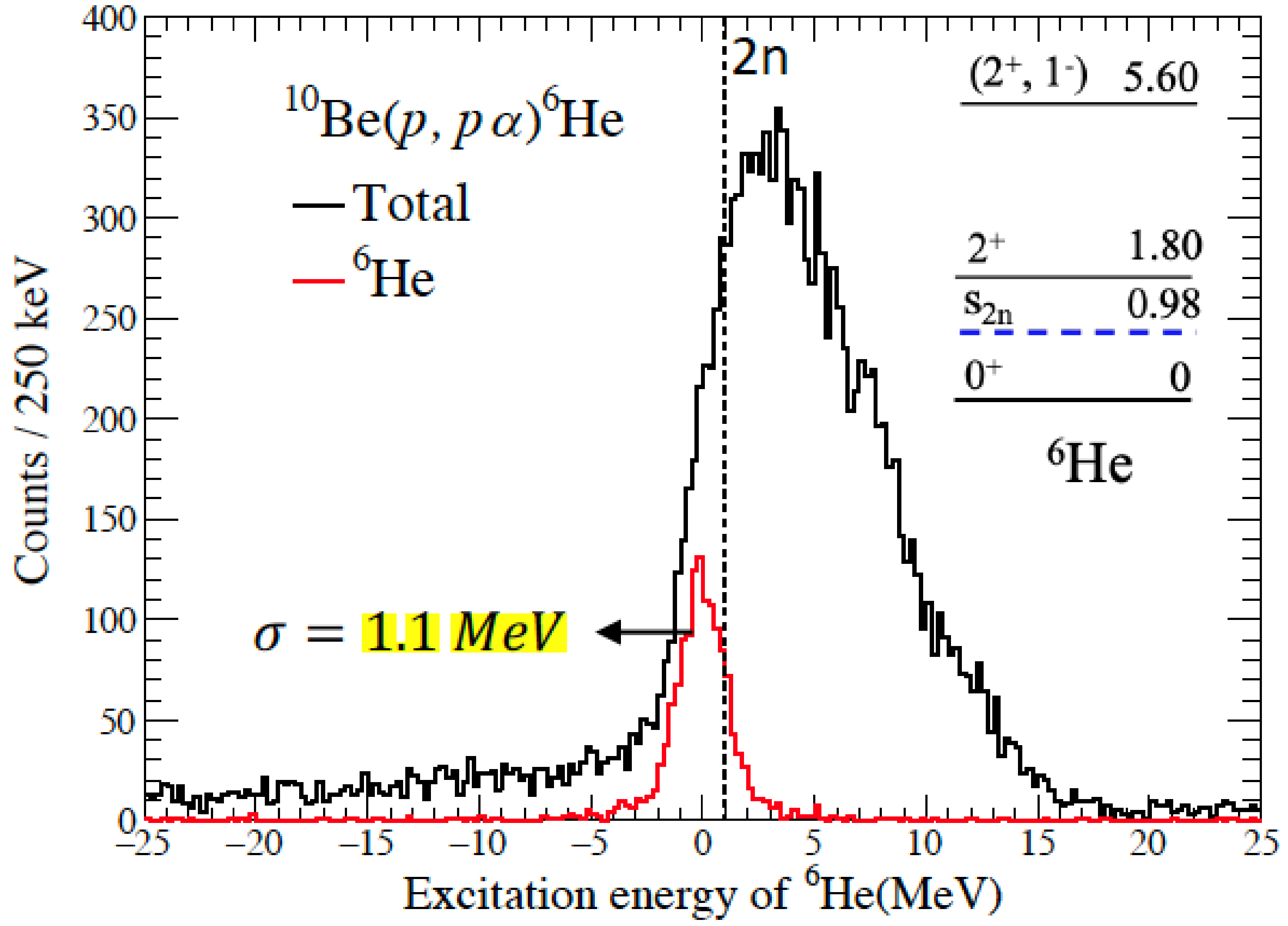


RIKEN, Kyoto, IBS-CENS, PKU

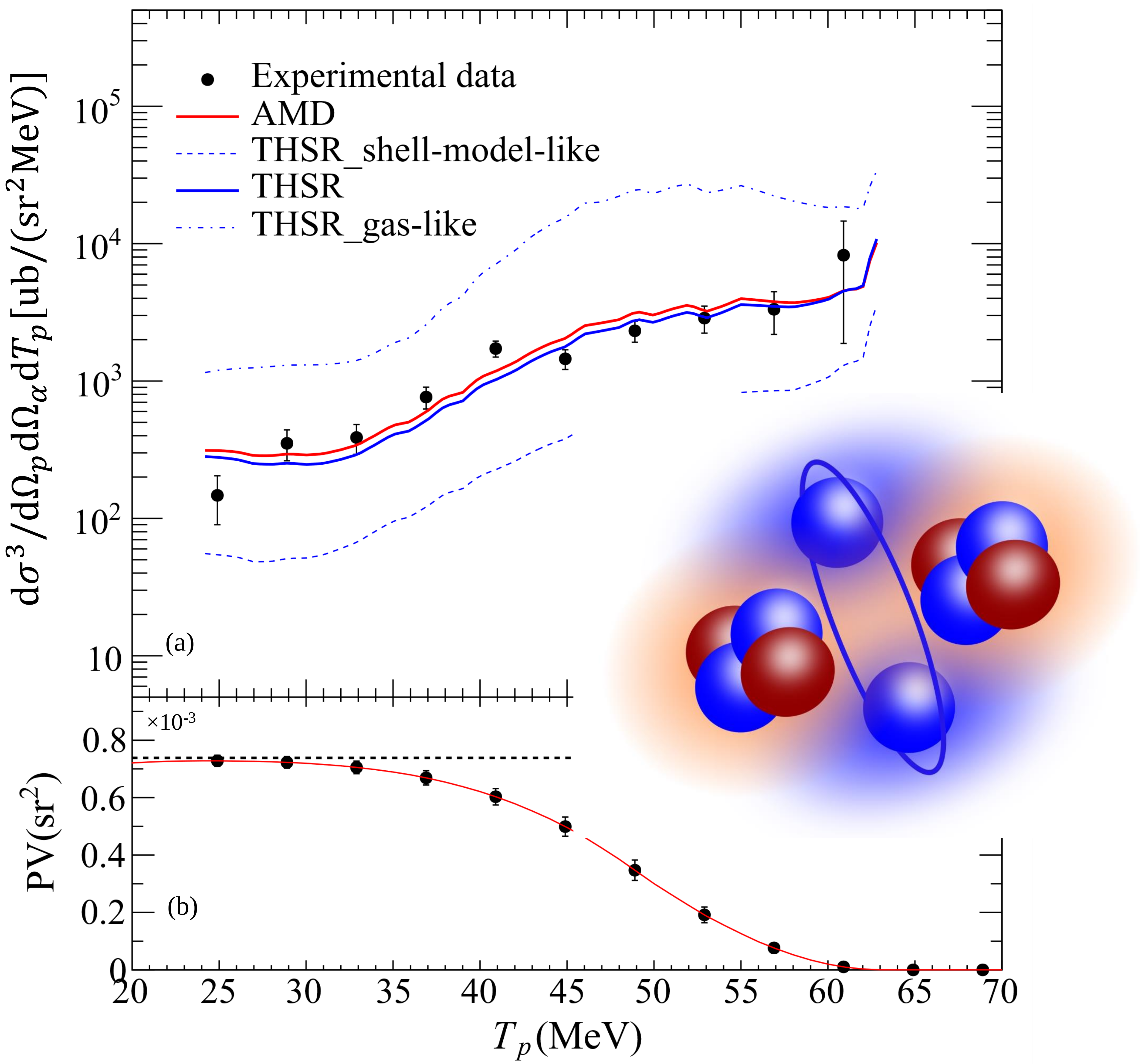
Molecular structure in Be isotopes

Pengjie Li, D. Beuamel et al.,
PRL 131, 212501

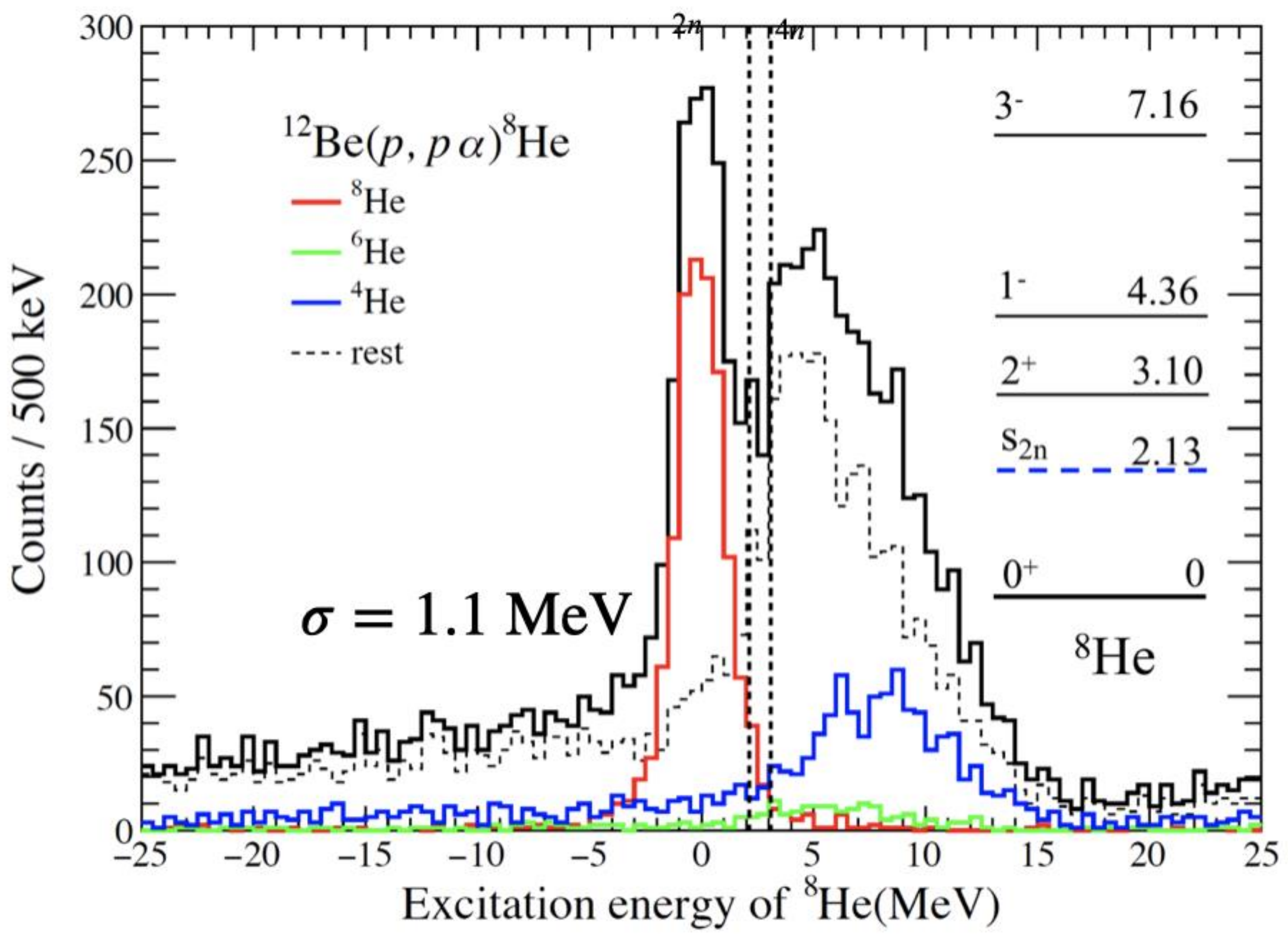
Use of (*p,pα*) knockout reaction under the inverse-kinematics



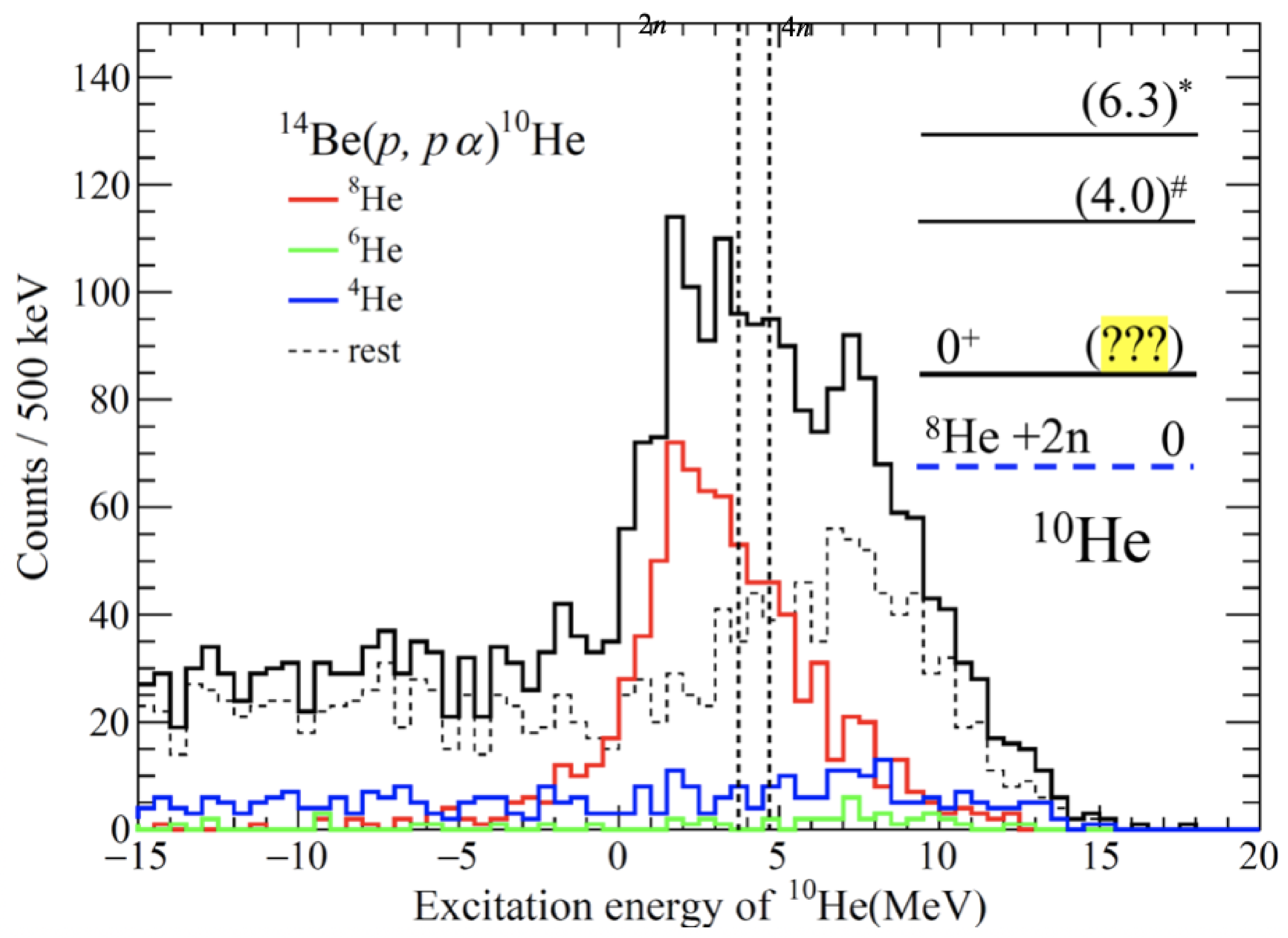
^{10}Be(*p,pα*)^{6}He$^{(GS)}$



^{12}Be(*p,pα*)^{8}He



^{14}Be(*p,pα*)^{10}He

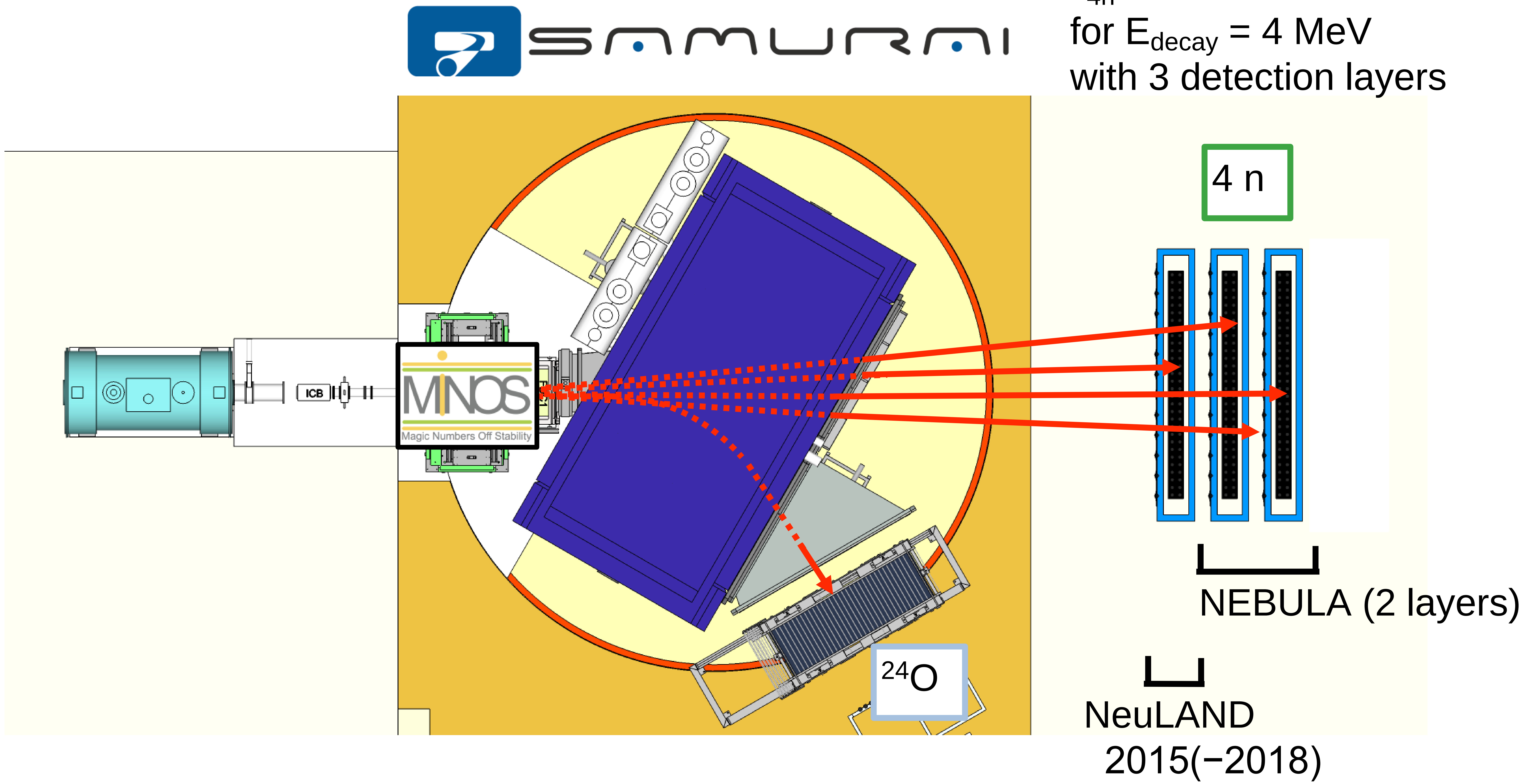


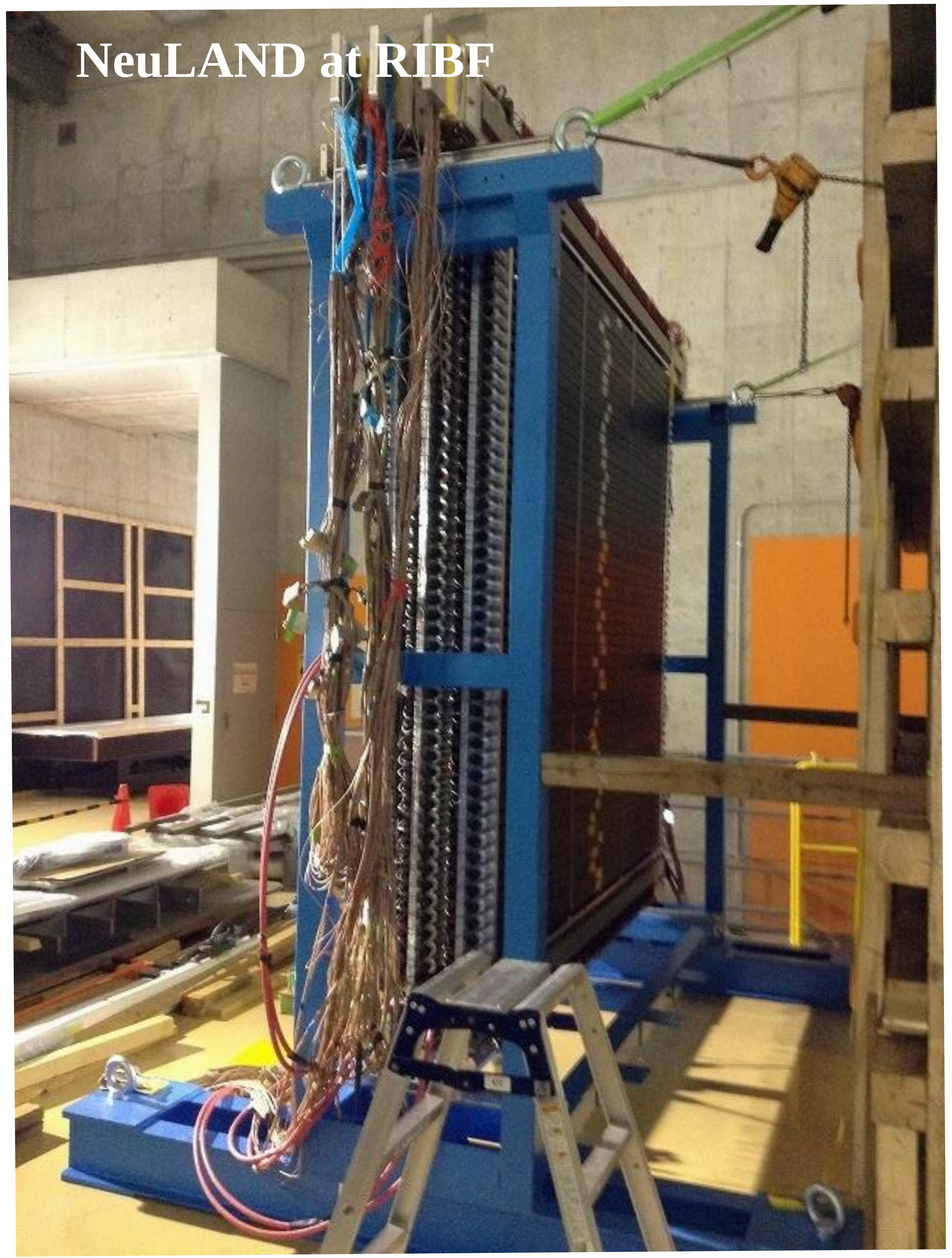
Particle decays following the (*p,pα*) reaction

Multi-neutron detection capability is the KEY

SAMURAI + MINOS (2014−) + NeuLAND (2015−2018)

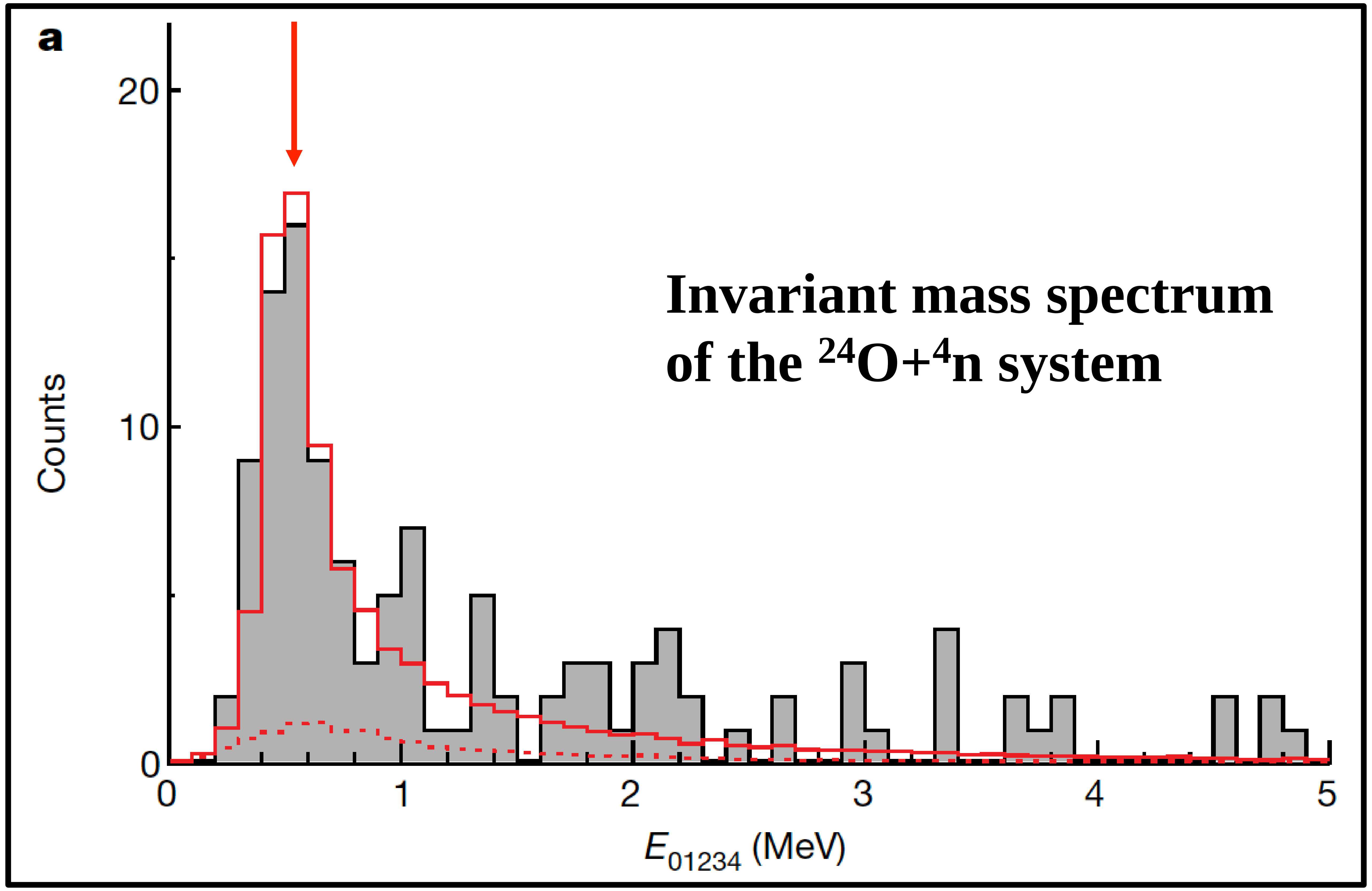
ε_{4n} = 0.8%
for E_{decay} = 4 MeV
with 3 detection layers

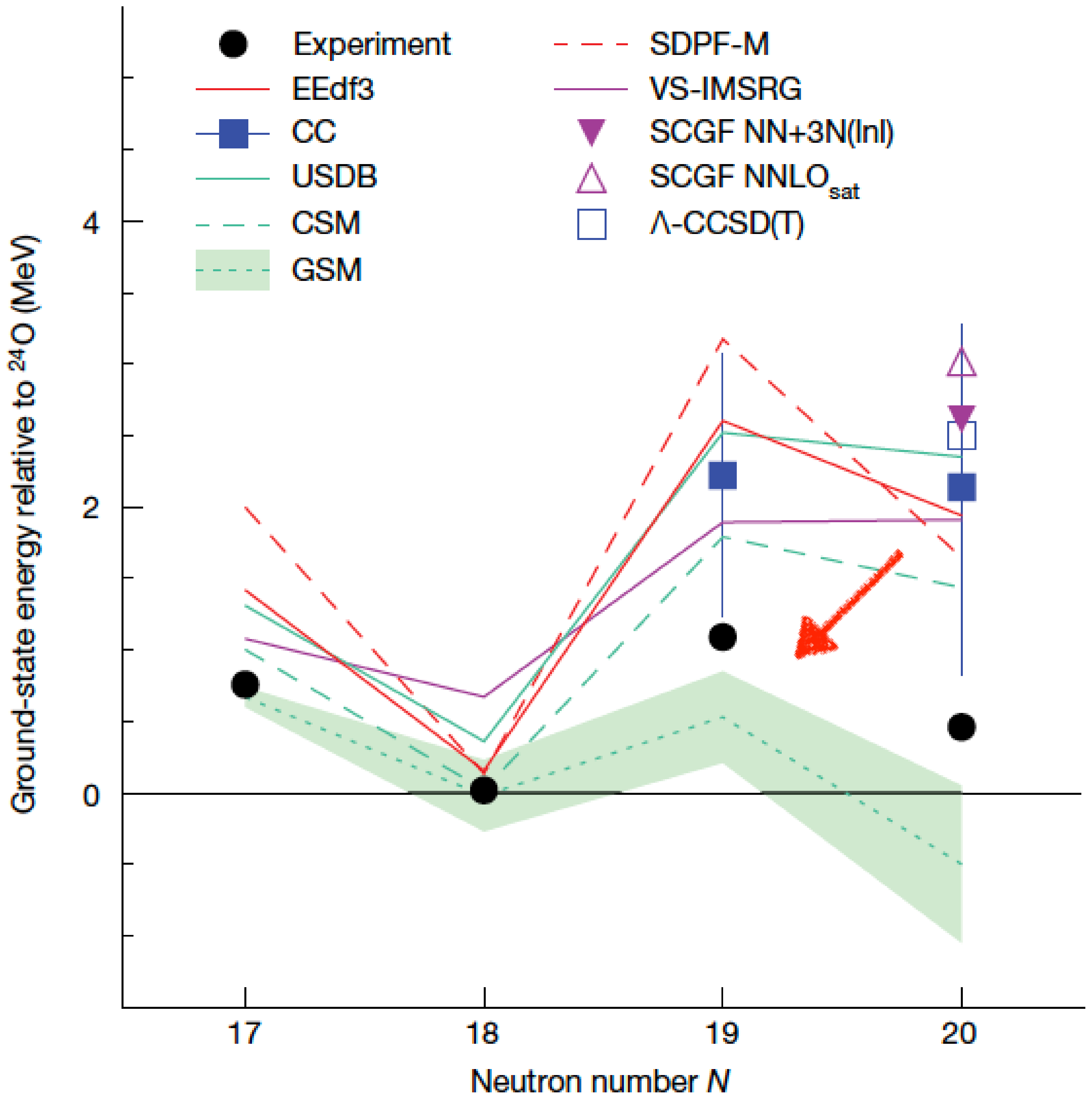




First observation of ^{28}O using $^{29}F(p,2p)$

Y. Kondo et al., Nature 620, 965 (2023).

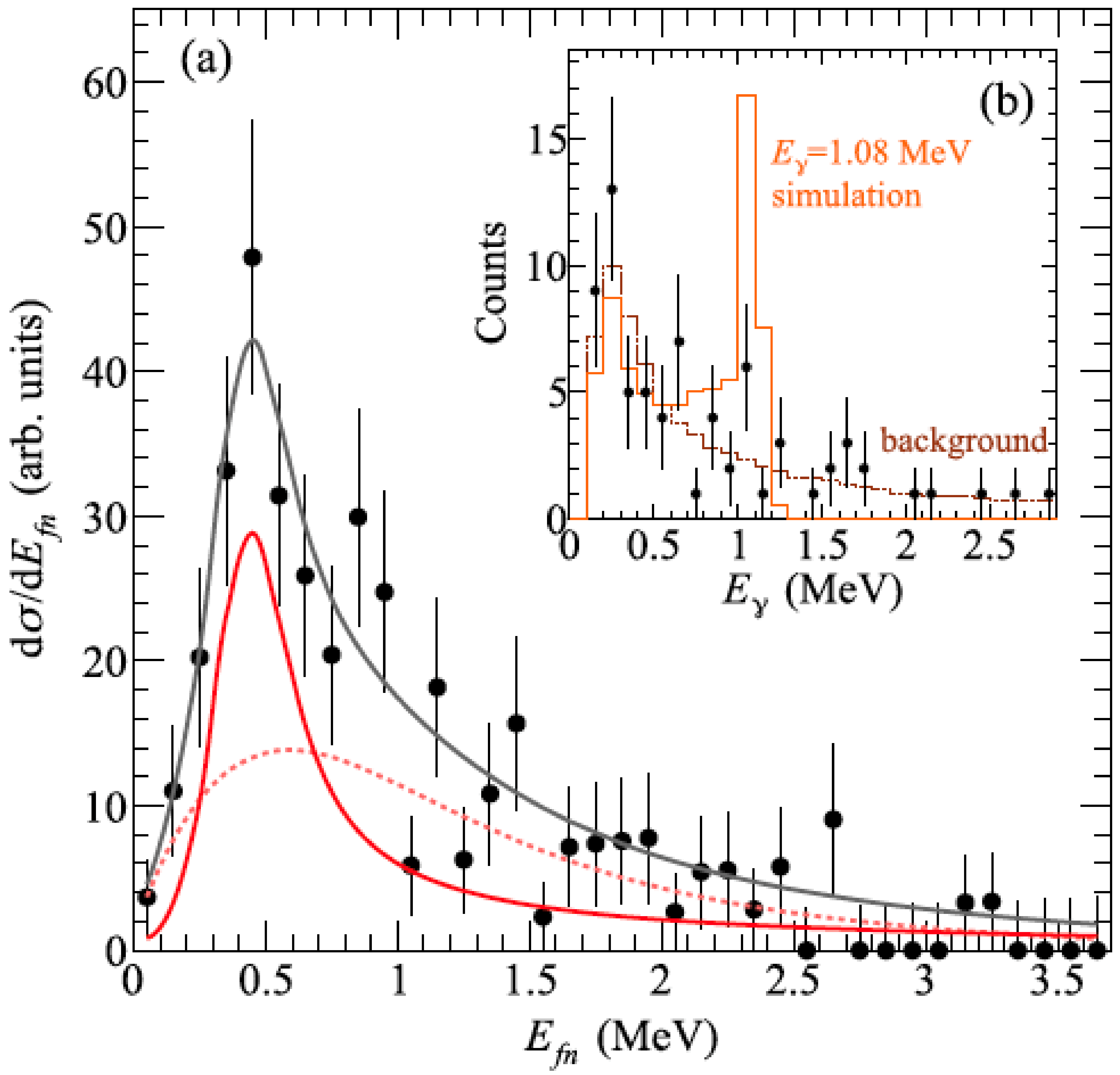


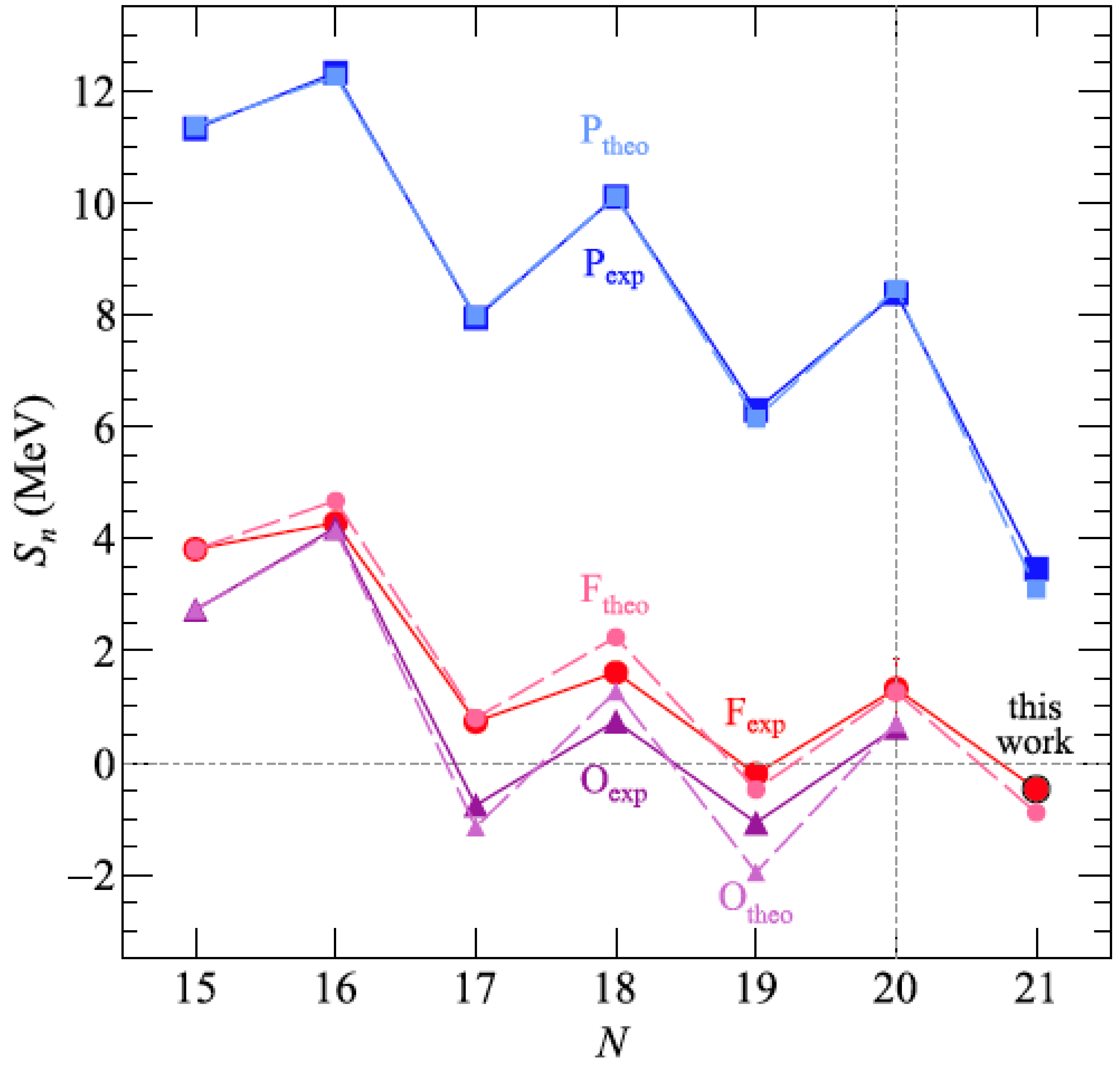


^{28}O is NOT a doubly magic nucleus.
The island of inversion extends south to Z=8.

New results on ^{30}F

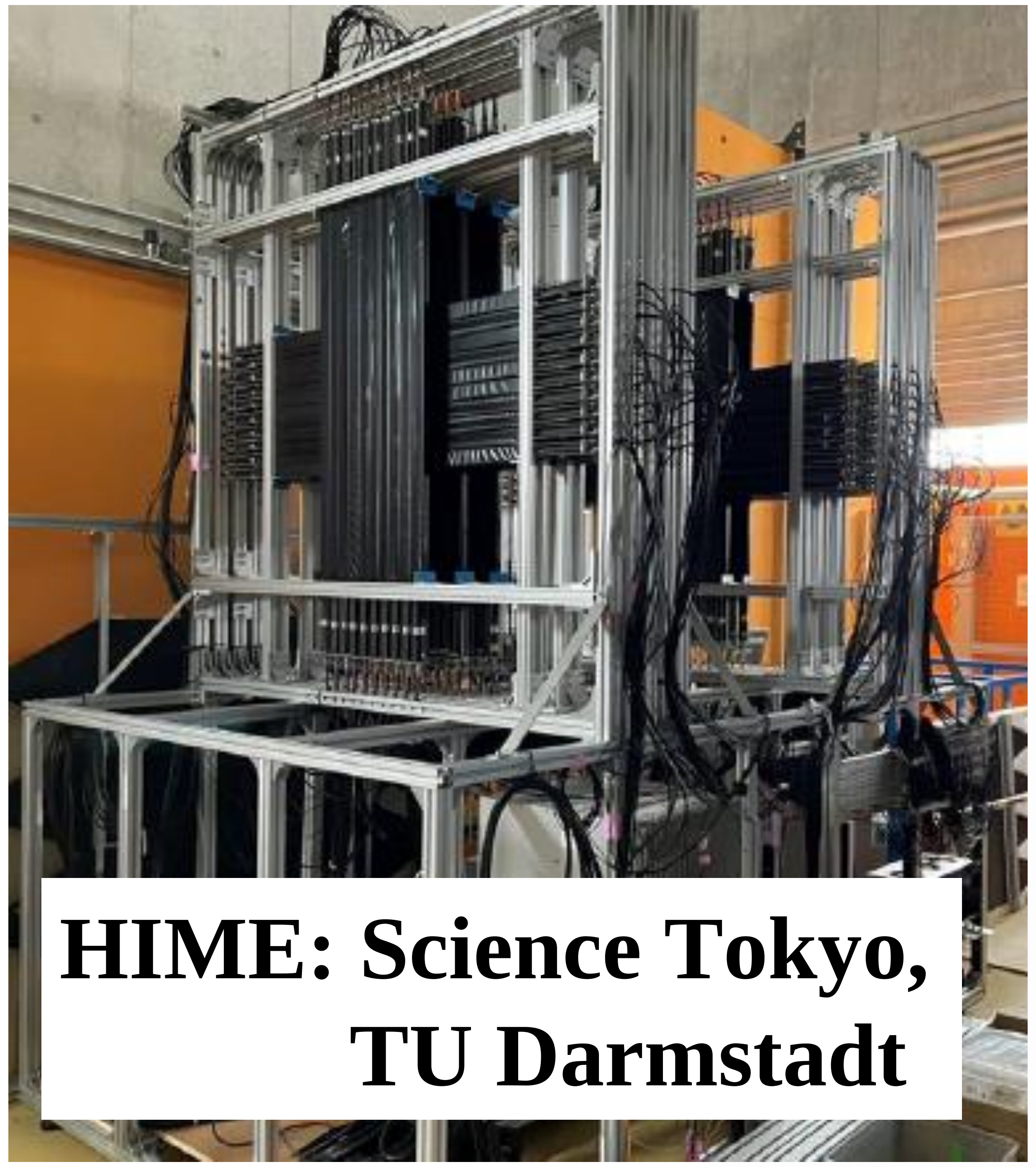
J. Kahlbow, T. Aumann et al., PRL 133, 082501 (2024),
Magicity versus Superfluidity around ^{28}O
viewed from the Study of ^{30}F





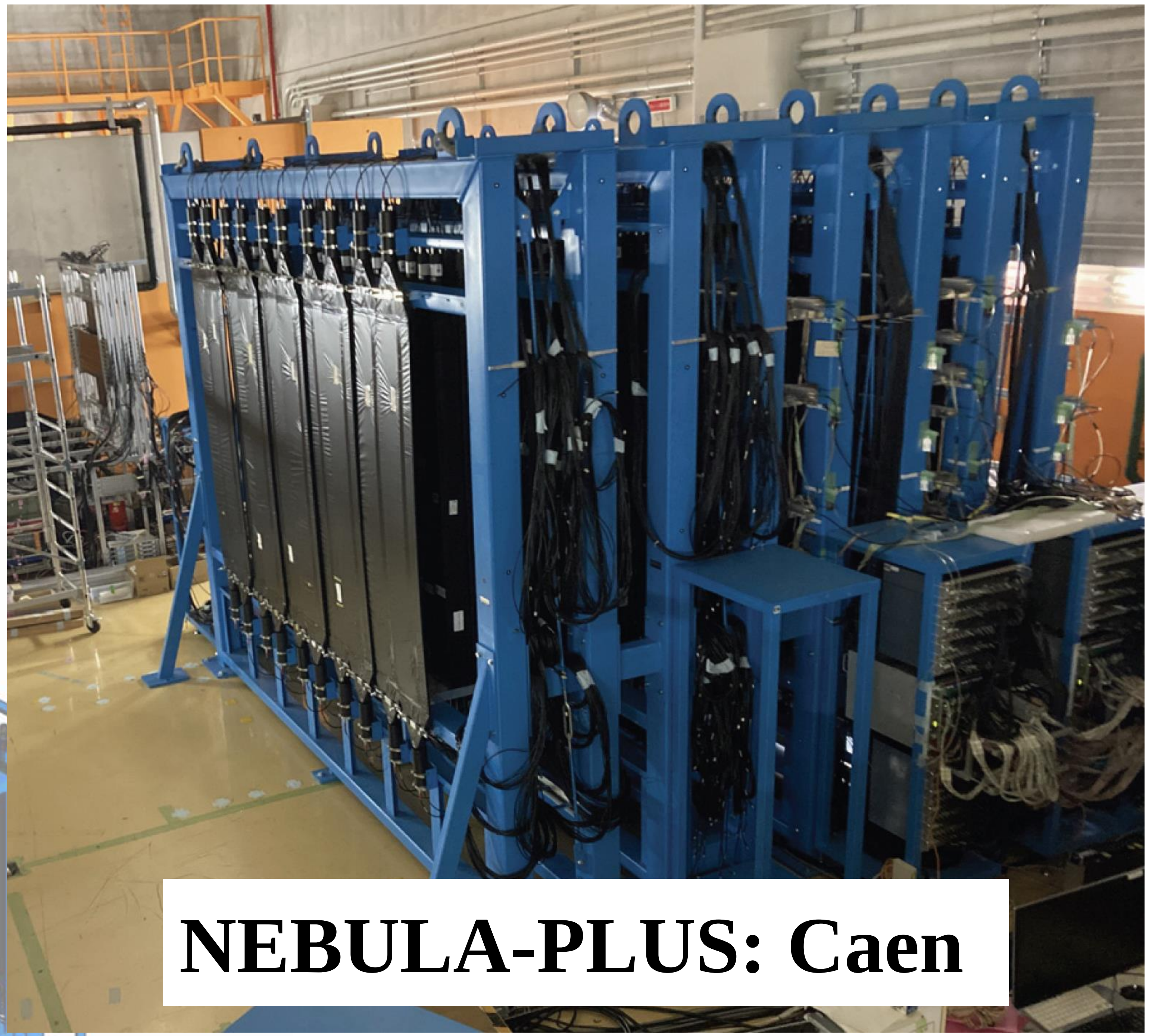
Disappearance of N=20 magicity confirmed
Indication of superfluidity in the region

SAMURAI, a growing facility : Multi-neutron detection capability

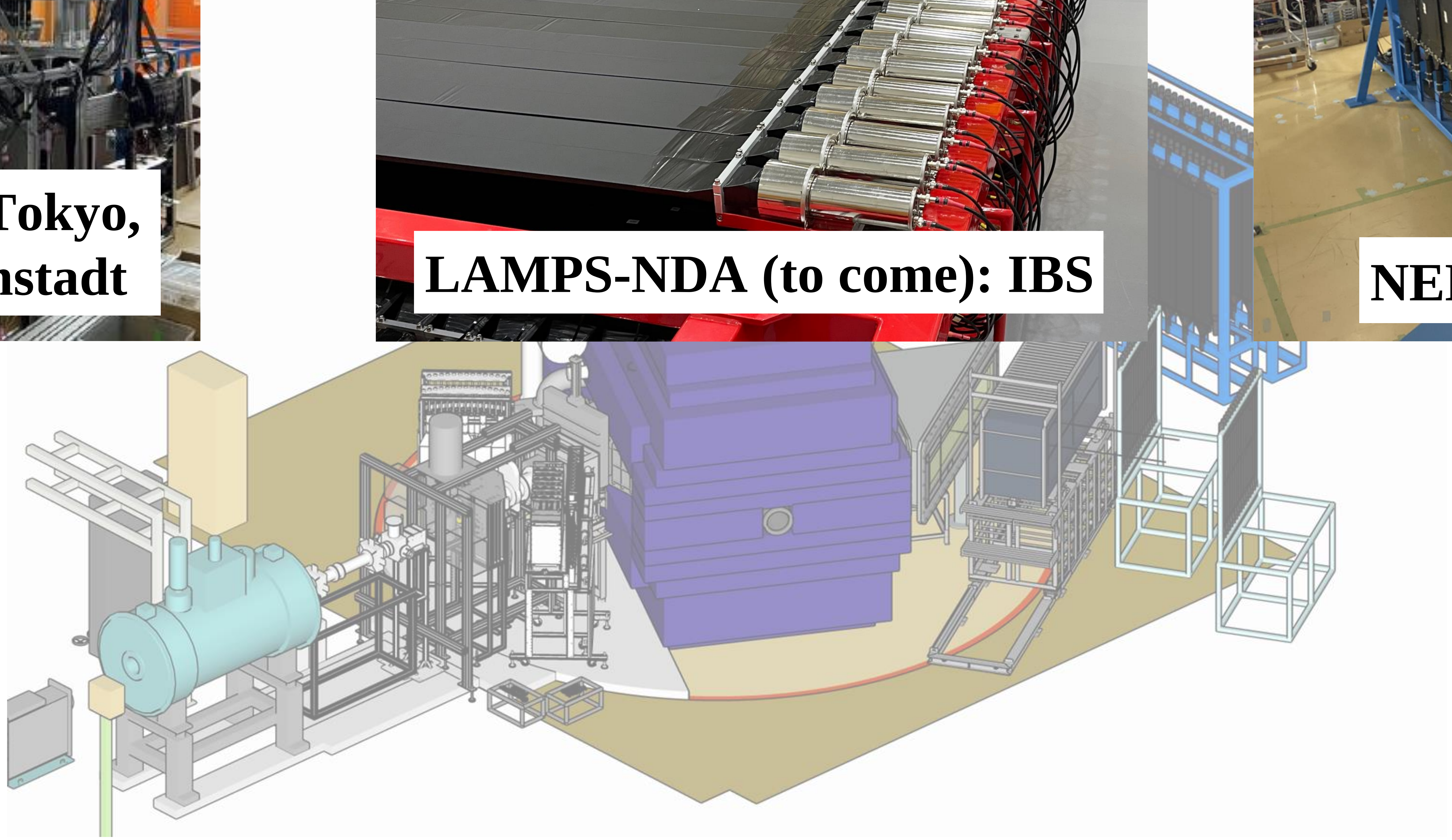


HIME: Science Tokyo, TU Darmstadt

LAMPS-NDA (to come): IBS

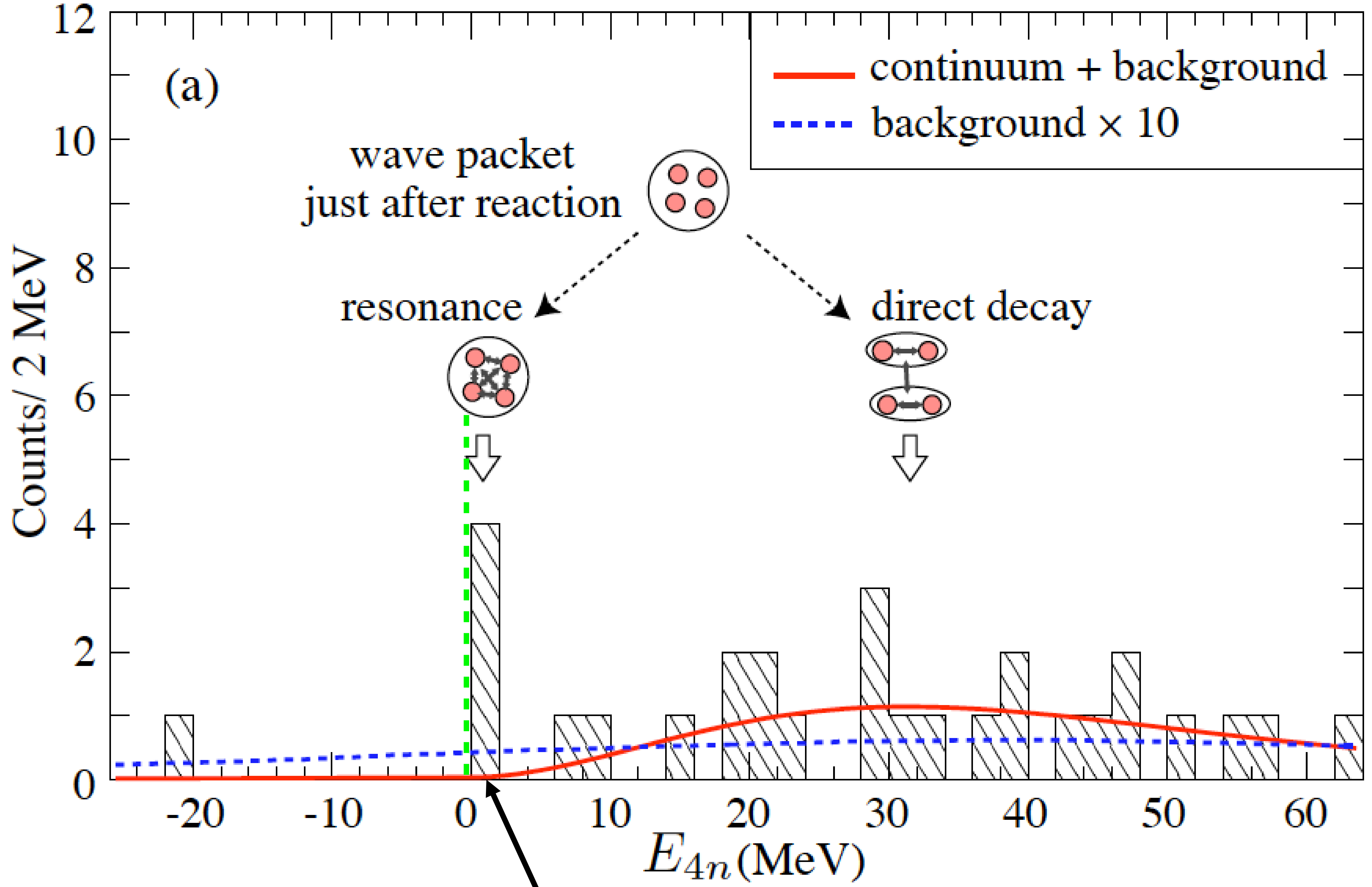


NEBULA-PLUS: Caen

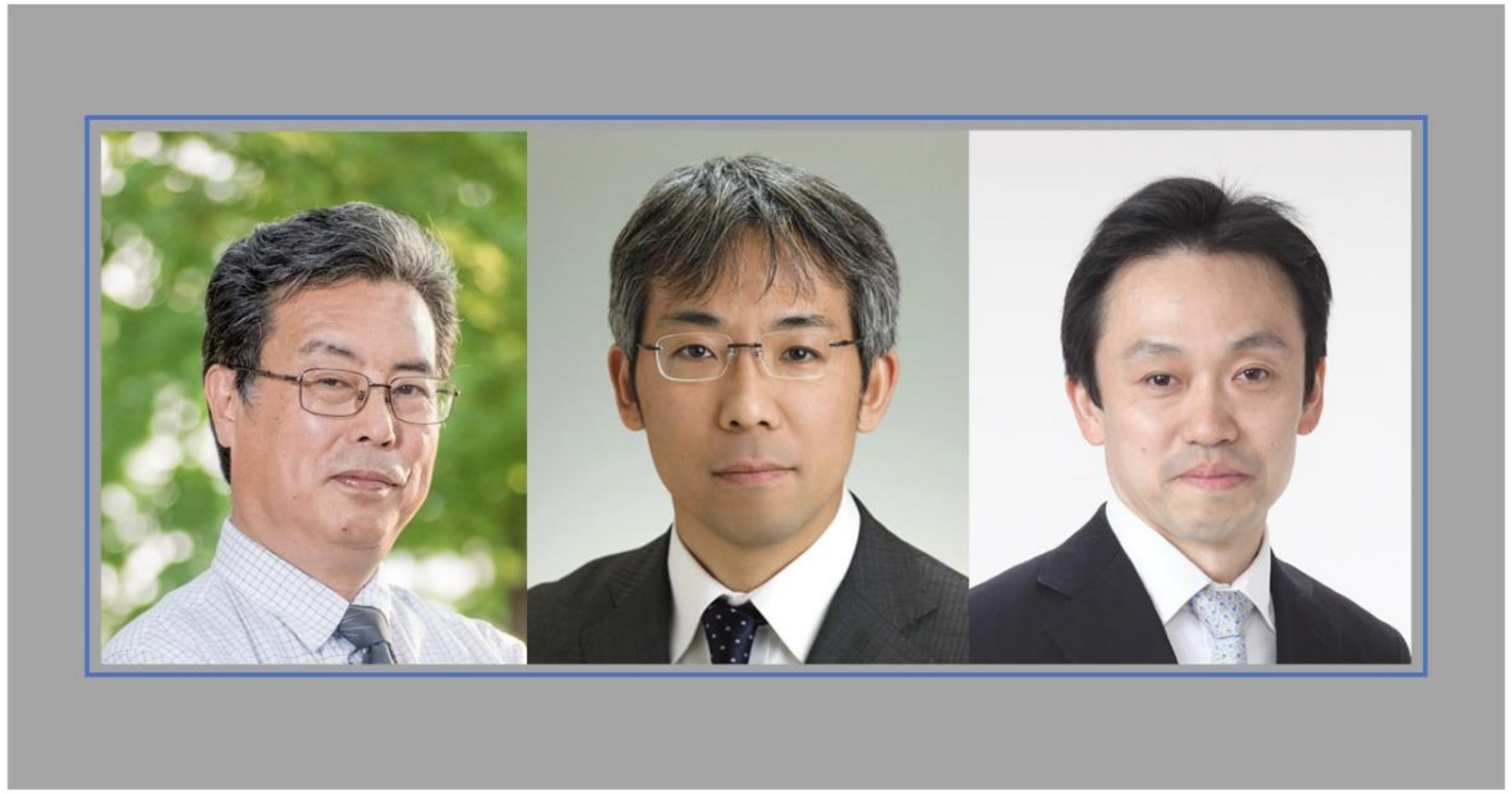


Observation of a Tetraneutron system: “Element Number Zero”

Kisamori, Shimoura et al., PRL 116, 052501 (2016)



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



2024年度 (第70回) 仁科記念賞受賞者を発表

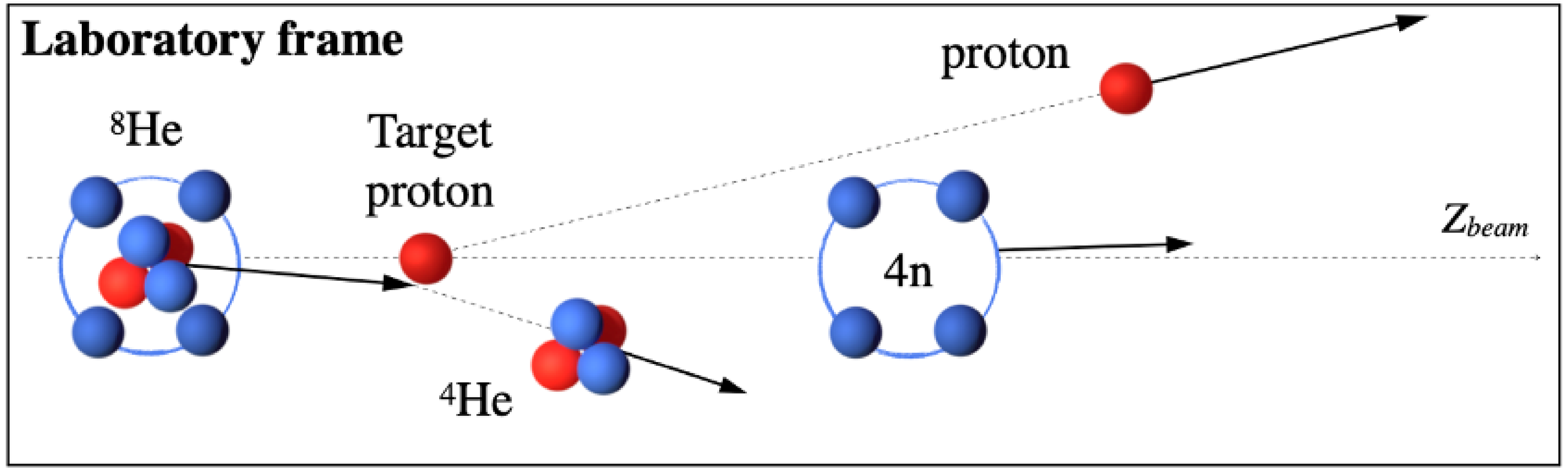
2024年度仁科記念賞受賞者は、下浦 享　理化学研究所開拓研究本部研究員: 東京大学名誉教授 （写真左）、青木 大 東北大学金属材料研究所 教授 （写真中）および　村上修一 東京科学大学理学院物理学系 教授（写真右）の3件、3氏に決定し、2024年11月7日に(公社)日本ア

The Nishina memorial prize in 2024 is awarded to Shimoura-san!

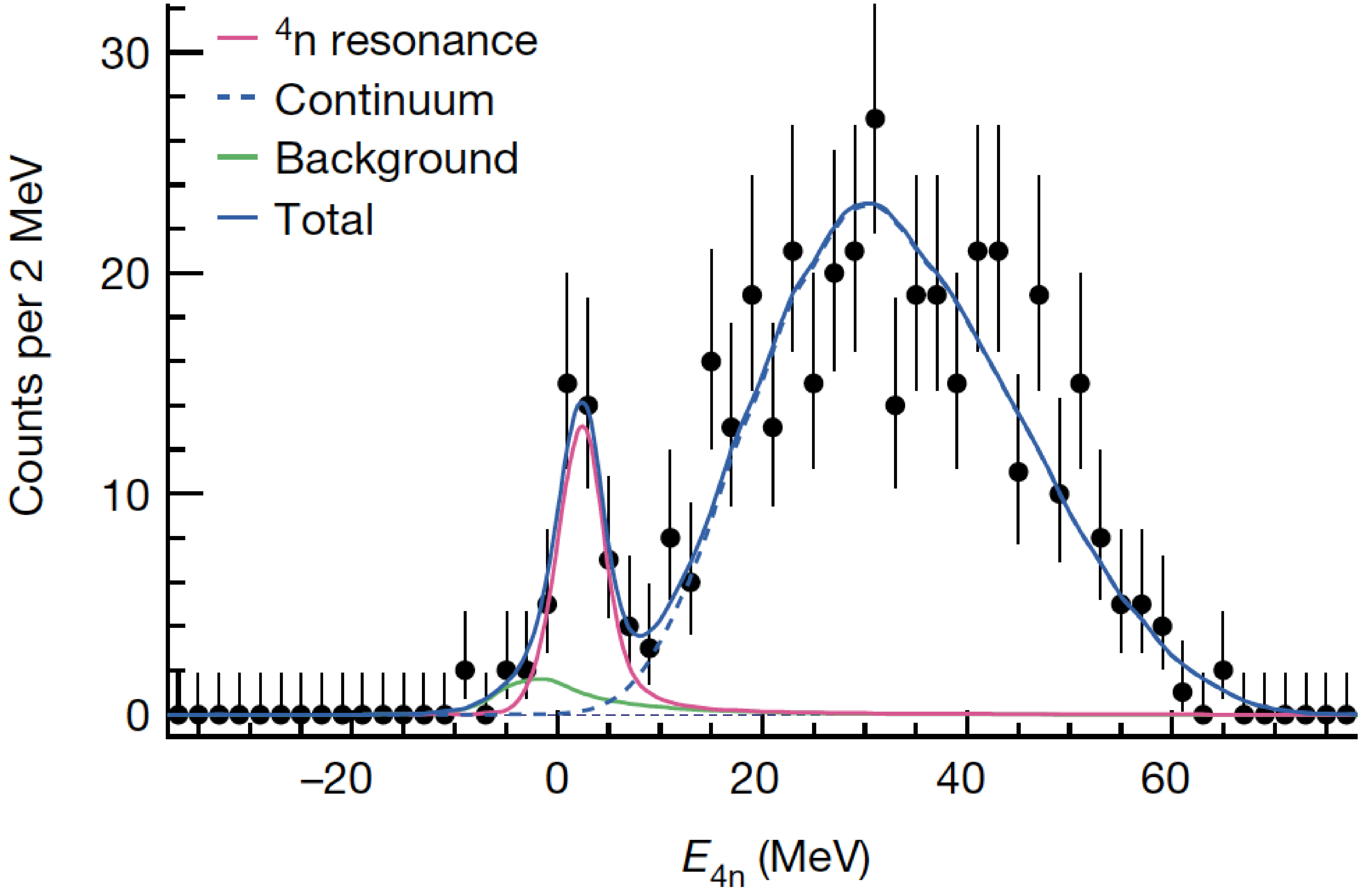
Tetraneutron production by the different method

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

Tetraneutron is produced through α-removal from a ^{8}He nucleus



^{8}He(p,$p\alpha$)^4n @ θ_{CM}=180deg



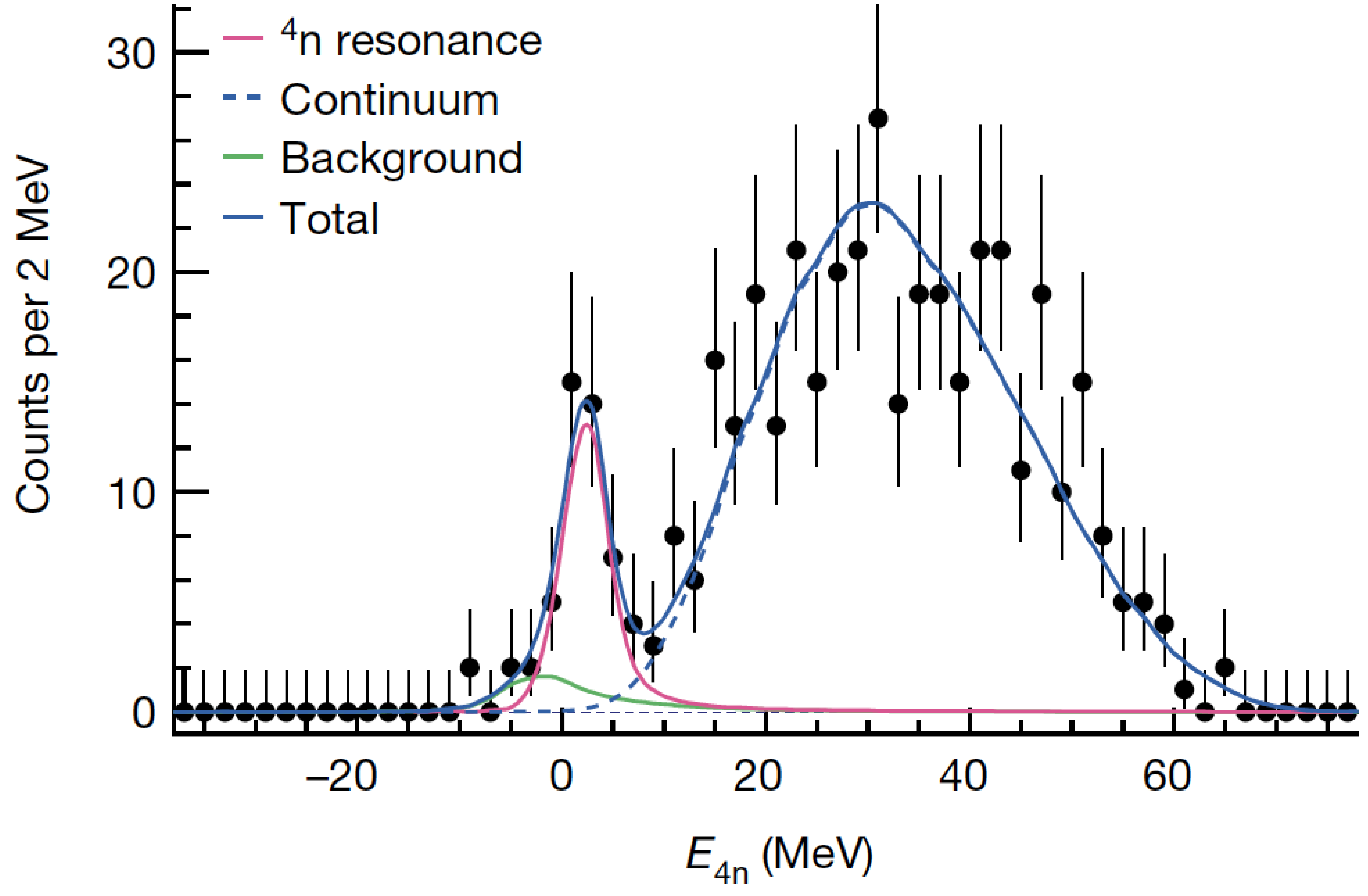
E= 2.37 ±0.38(stat.)±0.44(sys.) MeV

Γ = 1.75 ±0.22(stat.)±0.30(sys.) MeV

Nature of Tetraneutron?

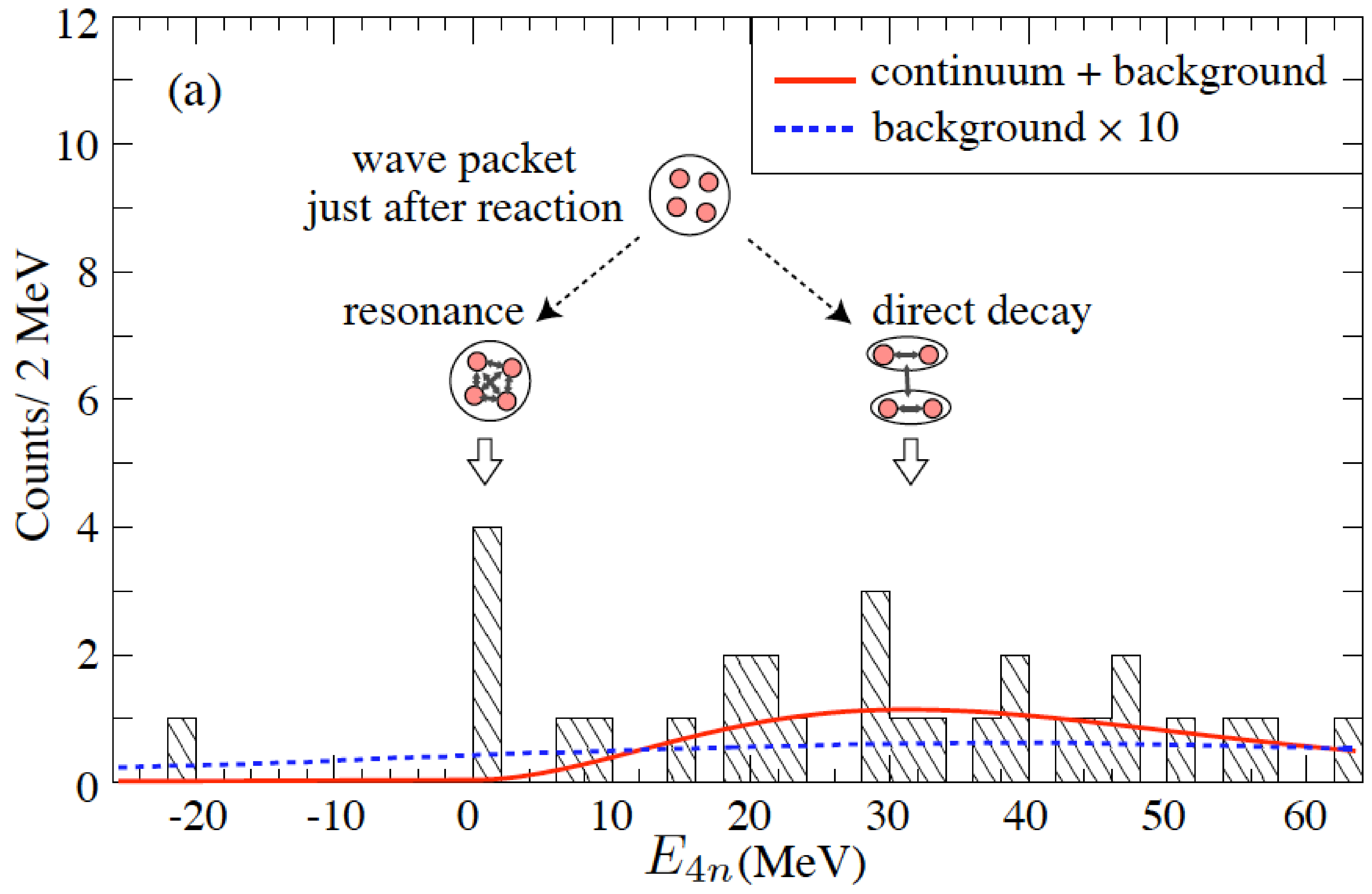
M. Duer et al., Nature 606 (2022)

^{8}He(p,$p\alpha$)^{4}n @ θ_{CM}=180deg



Kisamori, Shimoura et al., PRL 116 (2016)

^{4}He(^{8}He,^{8}Be)^{4}n @SHARAQ



Big debates on its nature:

Resonance or not?

Mechanism to stabilize it. Correlations among neutrons?

Initial state (the way it is produced) effect

Near future experiments to explore multineutron states

Miki, Duer et al.

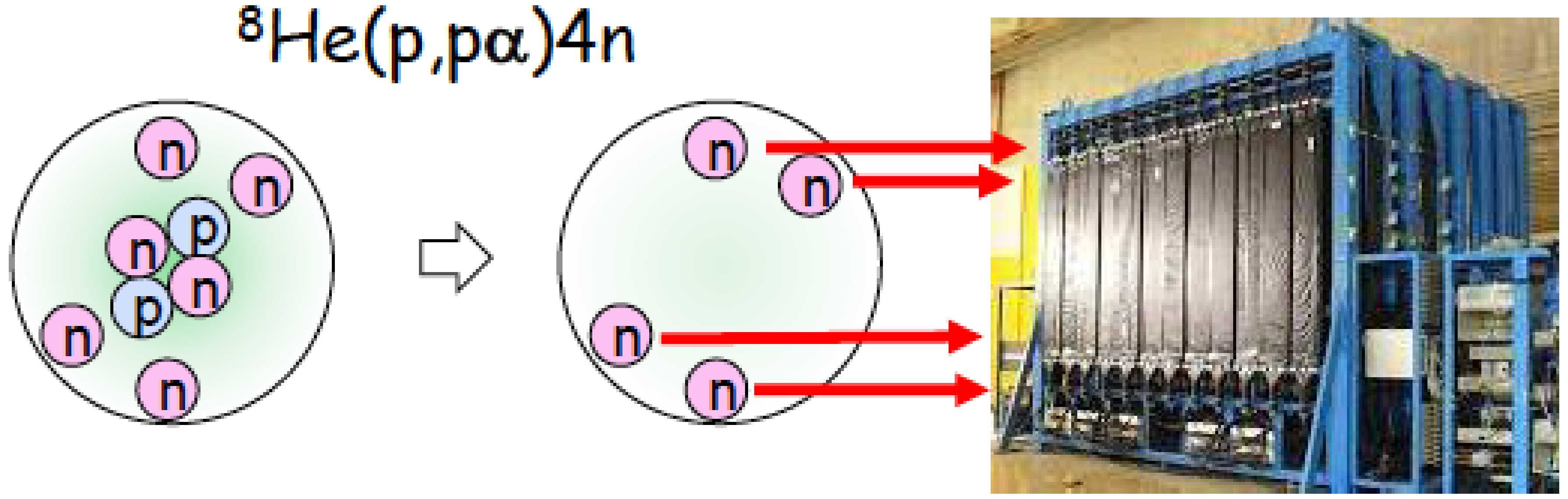
^{6,8}He(p,pα)/(p,3p)

multi-*n* detection capability

large acceptance telescope array for missing mass

- Neutron correlations in **final state**

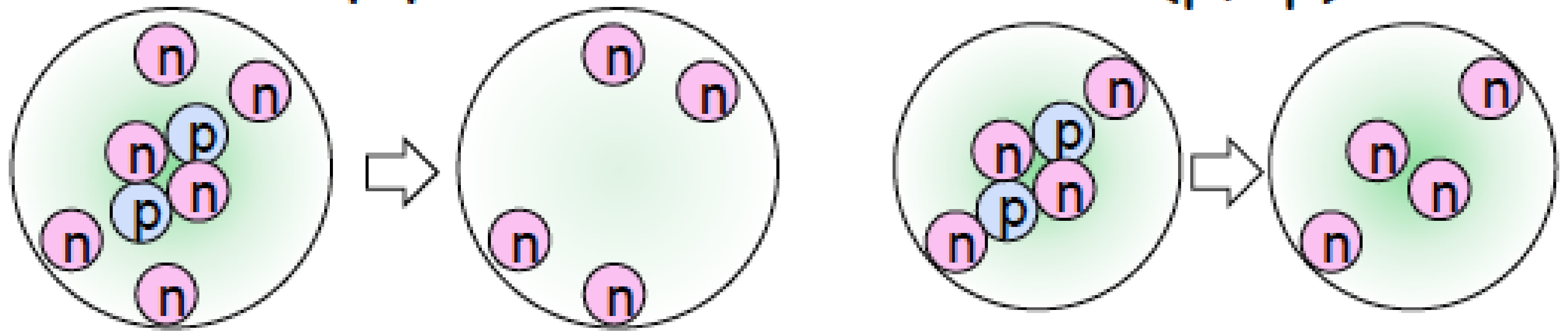
^{8}He(p,pα)4n



See if any enhancement in 2n -2n configuration

- Neutron correlations in **initial state**

^{8}He(p,pα)4n ^{6}He(p,3p)4n

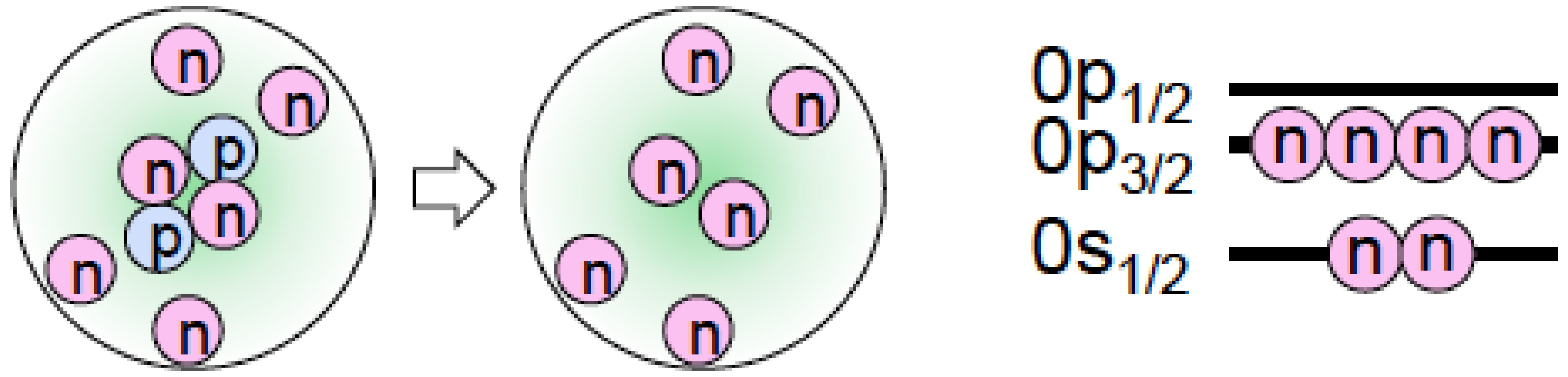


Different initial neutron distributions

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

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

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



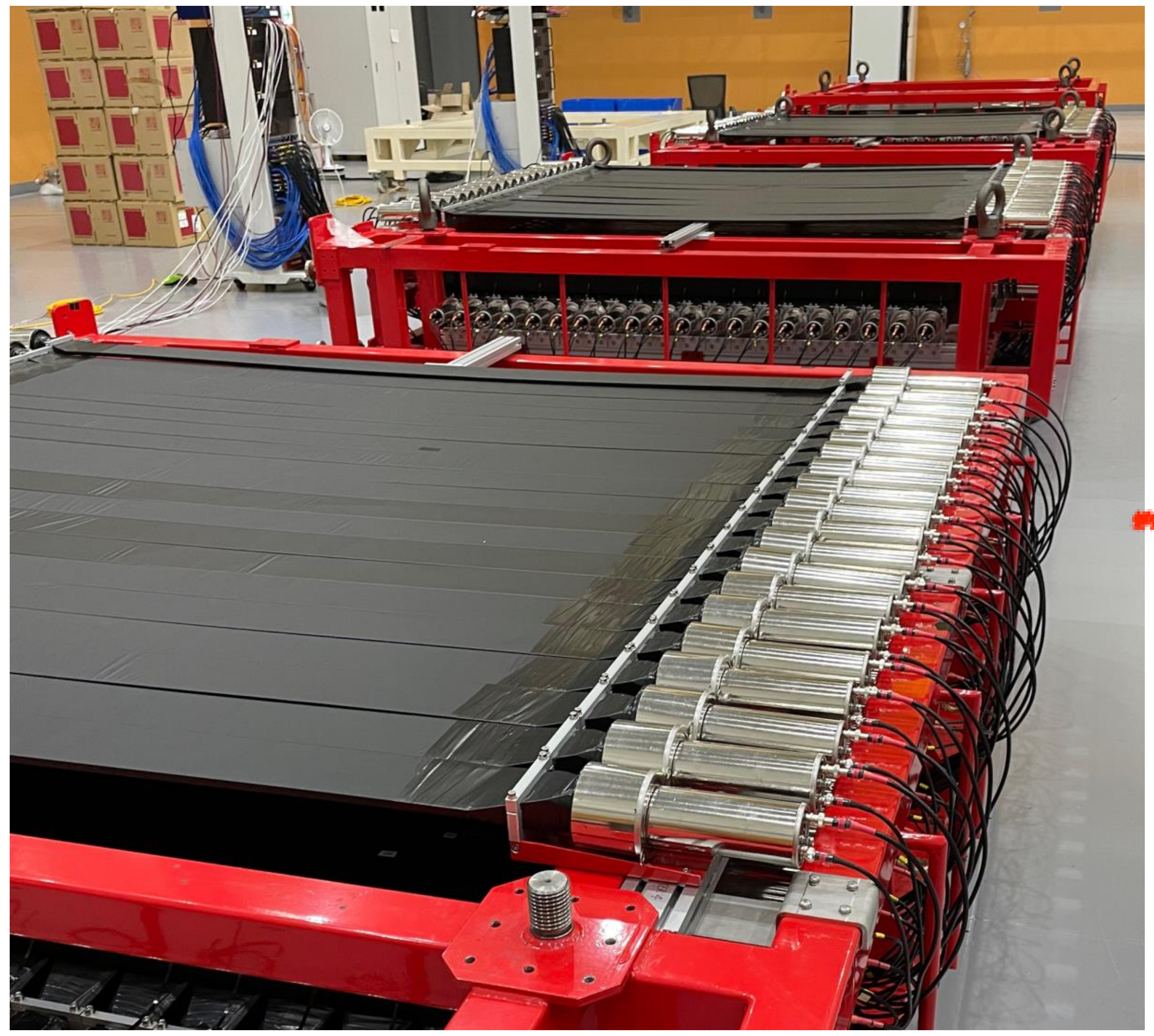
See if multi-neutron peak persistently appear.
See if any shell-like stability at N=6

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

Introduction of TOGAXSI&LAMPS-NDA to SAMURAI

LAMPS-NDA

"10×10×200 cm^3" × 160 bars

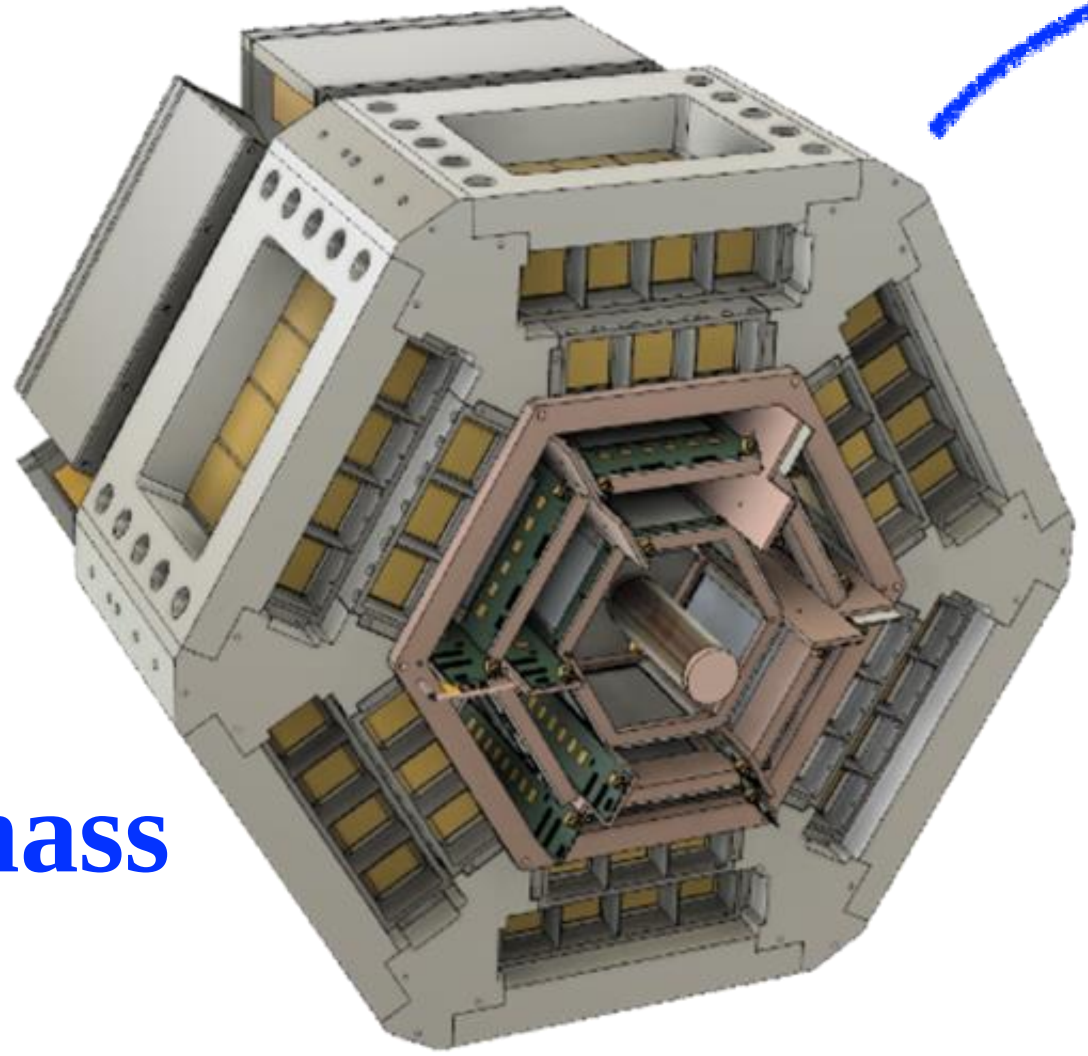


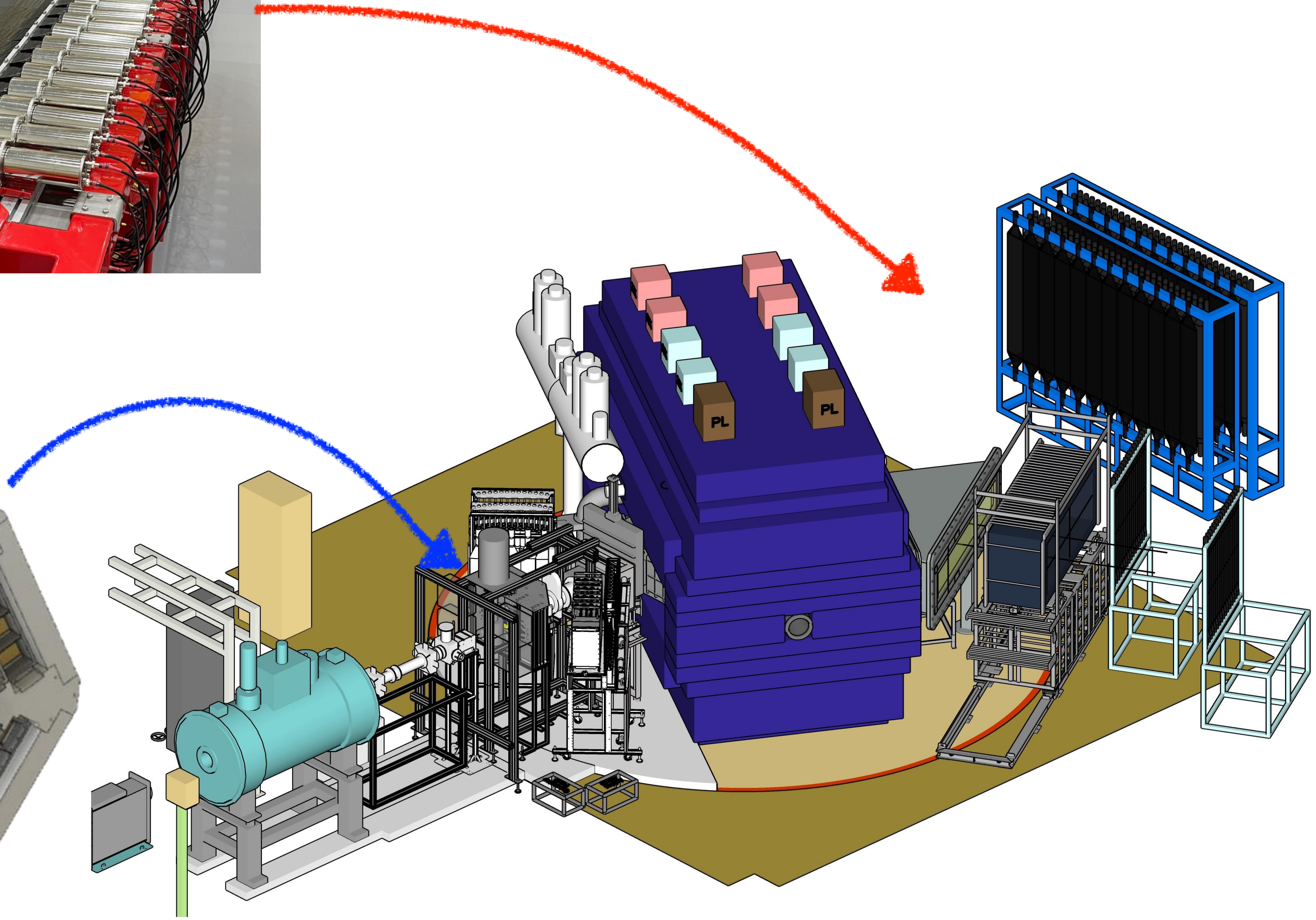
Reinforcement of multi-neutron detection capabilities

TOGAXSI

missing-mass array for (p,pX) reactions

X: d, t, ^{3}He, α, p, 2p





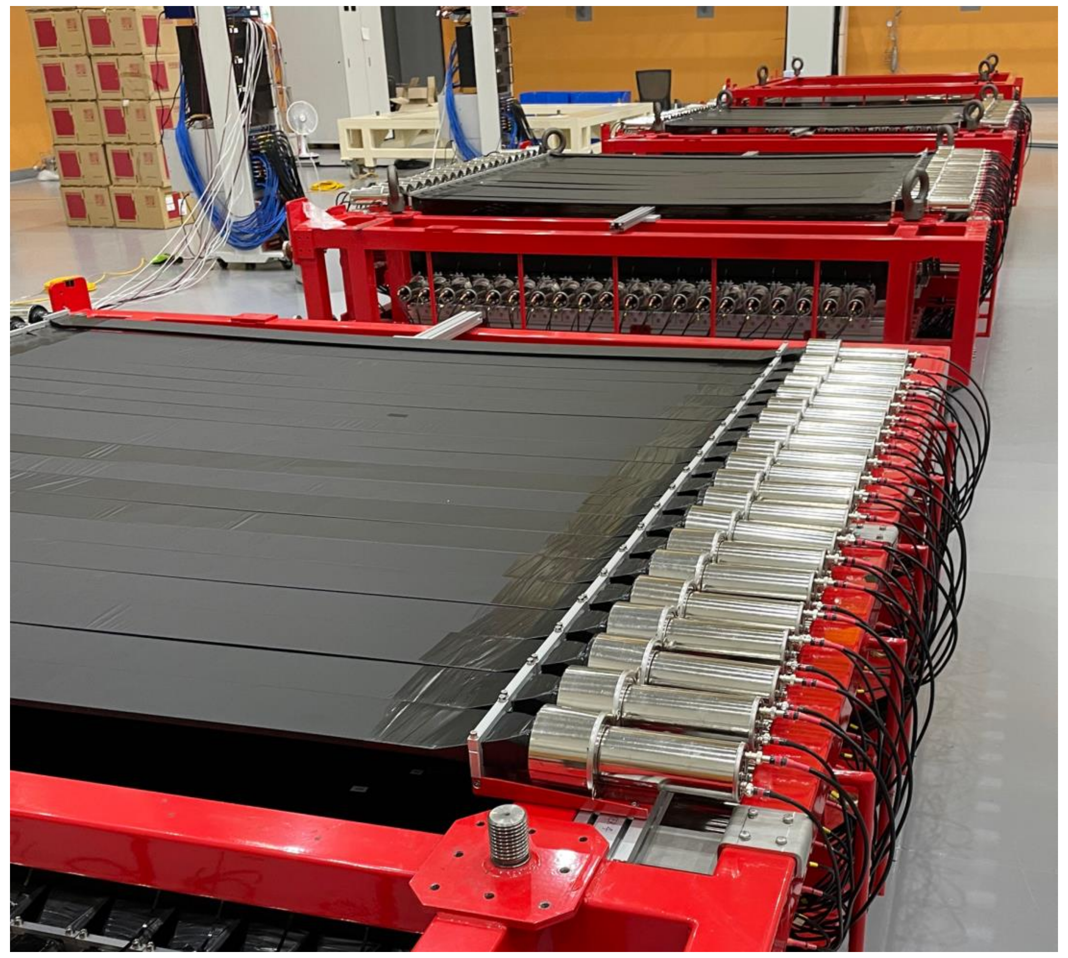
Reinforcement of missing-mass detection capabilities

IBS-RIKEN Collaboration opens new research opportunities

LAMPS-NDA

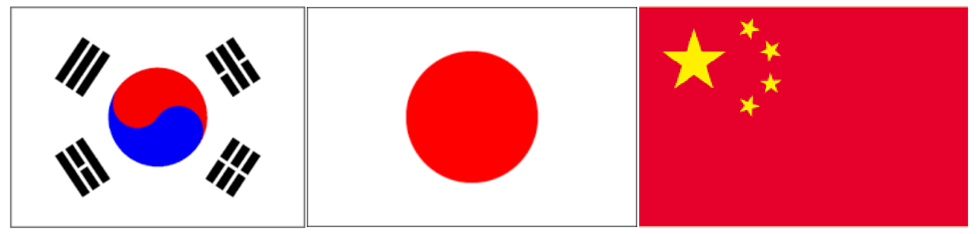
“10×10×200 cm^3”

× 160 bars



Simulation by Siwei Huang (PKU)

w/ K. Miki and Y. Kondo

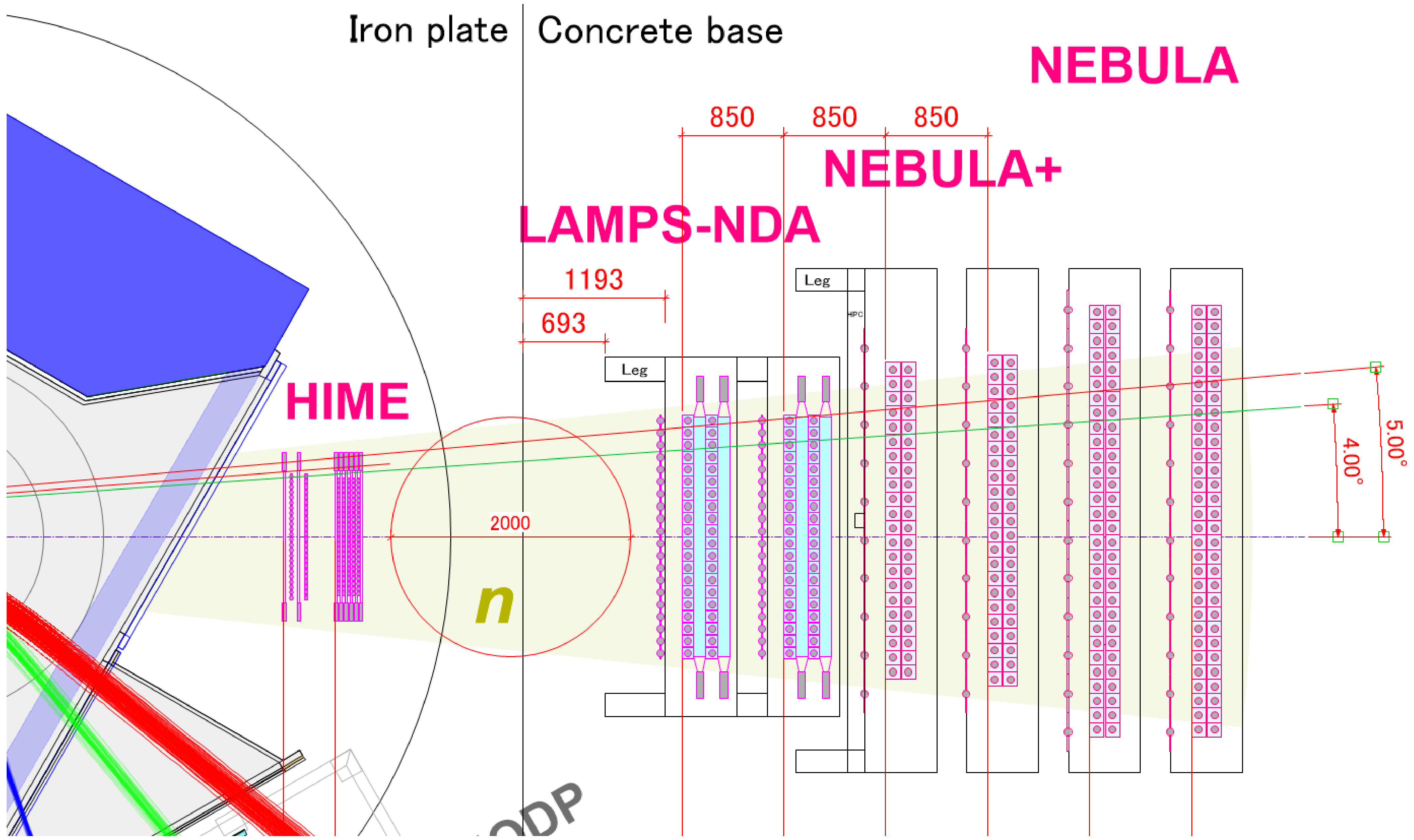


4n

E_{rel} [MeV]	Efficiency [%]	Gated eff. [%]	Resolution (FWHM) [MeV]	Crosstalk [%]
HIME + NEBULA				
1	2.1	2.1	0.24	13
2	1.7	1.7	0.34	15
3	1.2	1.2	0.43	17
5	0.65	0.65	0.60	22
HIME + NDA(4 dp) + NEBULA				
1	4.2	3.9	0.27	12
2	3.5	3.1	0.37	14
3	2.7	2.3	0.47	17
5	1.4	1.2	0.63	24

6n

E_{rel} [MeV]	Efficiency [%]	Gated eff. [%]	Resolution (FWHM) [MeV]	Crosstalk [%]
HIME + NEBULA				
1	0.15	0.15	0.29	30
2	0.16	0.16	0.38	31
3	0.14	0.14	0.45	31
5	0.08	0.08	0.76	34
HIME + NDA(4 dp) + NEBULA				
1	0.40	0.35	0.31	28
2	0.44	0.38	0.44	28
3	0.39	0.33	0.57	30
5	0.24	0.20	0.77	36



with LAMPS-NDA, we can challenge the world-first 6-neutron detection experiments

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

^{11}Li(p,3p)^{9}H→6n + t

Summary

Correlation and dynamics will characterize stability and order-formation near and beyond the drip-line.

Newly-introduced detectors open access to nuclei previously unreachable and enlarge research opportunities.

ASIAN COLLABORATION IS THE CORE.

ONOKORO Collaboration

New Uzbekistan University A. Sanetullaev

Y. Kubota, K. Higuchi, T. Sugiyama, T. Pohl, S. Koyama, S. Shimoura, H. Baba, S. Takeshige, Y. Chazono, T. Uesaka, H. Otsu, M. Sasano, K. Yoneda, Y. Li, R. Matsumura, H. Sato, M. Nishimura, P. Doornenbal

B. Hong

J. Zenihiro, Y. Hijikata, R. Tsuji, S. Ogio, T. Yano, T. Nakada, R. Yoshida, M. Dozono,

K. Miki, S. Kurosawa, R. Urayama

Y.L.Sun, B.H. Sun

K. Ogata, S. Ogawa, S. Kawase, T. Wakasa

RCNP J. Tanaka, A. Tamii, S. Ota, N. Kobayashi

Y. Maeda

H.Liu

K. Yoshida

Y. Matsuda H. Akimune

T. Kawabata, T. Furuno

S. Paschalis M. Petri

S. Kim, D. Ahn, I.K. Hahn, J. Hwang L. Stuhl, Z. Korkuu, D. Kim

Z.H. Yang, S. Huang

M. Itoh S. Adachi

T. Nakamura, Y. Kondo K. Sekiguchi, A. Watanabe

M. Takano

A. Corsi

A. Obertelli, H. Liu, Y. Sun, T. Aumann, H. Scheit, D. Rossi, D. Symochko, A. Jedele, M. Duer, S. Typel

D. Beaumel, V. Alcindor, M. Assie, S. Franchoo

N.A. Orr, F.M. Marques, J. Gibelin, A. Matta, F. Flavigny, F. Delaunay, N.L.Achouri

R. Gernhaeser, M. Boehmer

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