Exotic Hadron Spectroscopy 2023
Durham

UNIVERSITY of York

# On the long-standing quest for the tetra-neutron: a recent observation of four-neutron correlations

Stefanos Paschalis

"Observation of a correlated free four-neutron system"
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

RIKEN

SAMURAI

DFG Deutsche Forschungsgemeinschaft

TECHNISCHE UNIVERSITÄT DARMSTADT

Bundesministerium für Bildung und Forschung

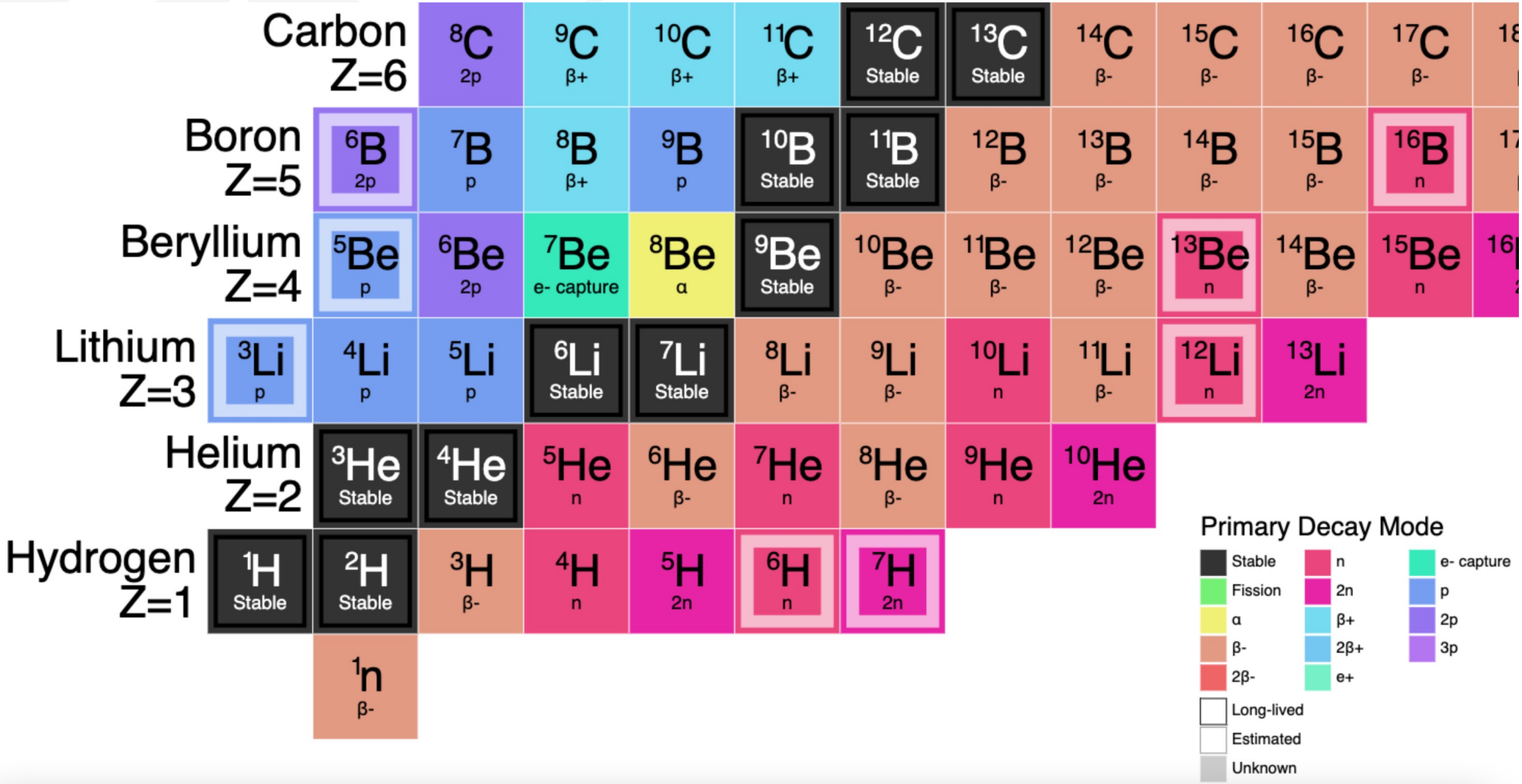
SFB 1245

HIC for FAIR Helmholtz International Center

UKRI Science and Technology Facilities Council

# Nuclear landscape

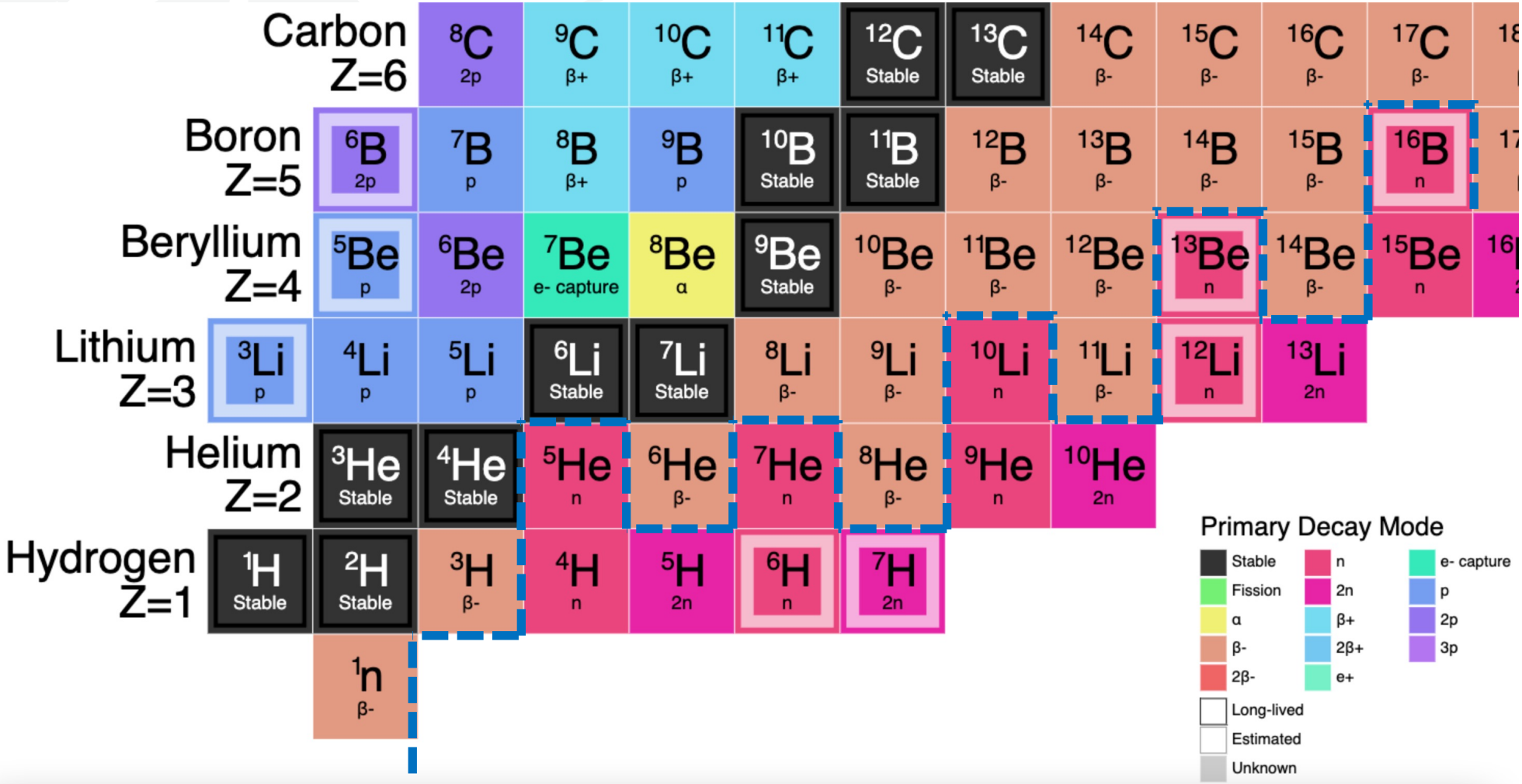
## Light nuclei




https://people.physics.anu.edu.au/~ecs103/chart/

# Nuclear landscape

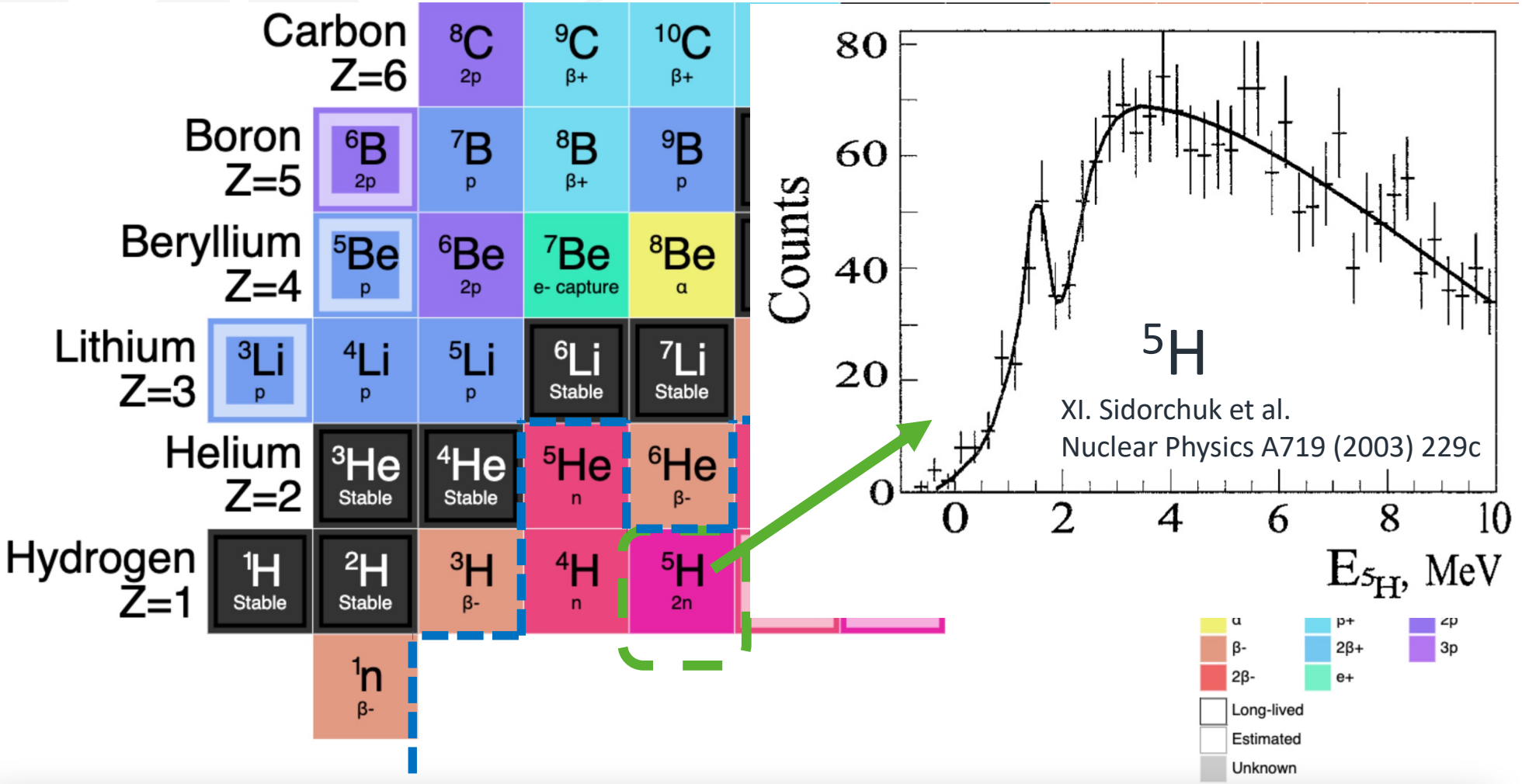
## Light nuclei




https://people.physics.anu.edu.au/~ecs103/chart/

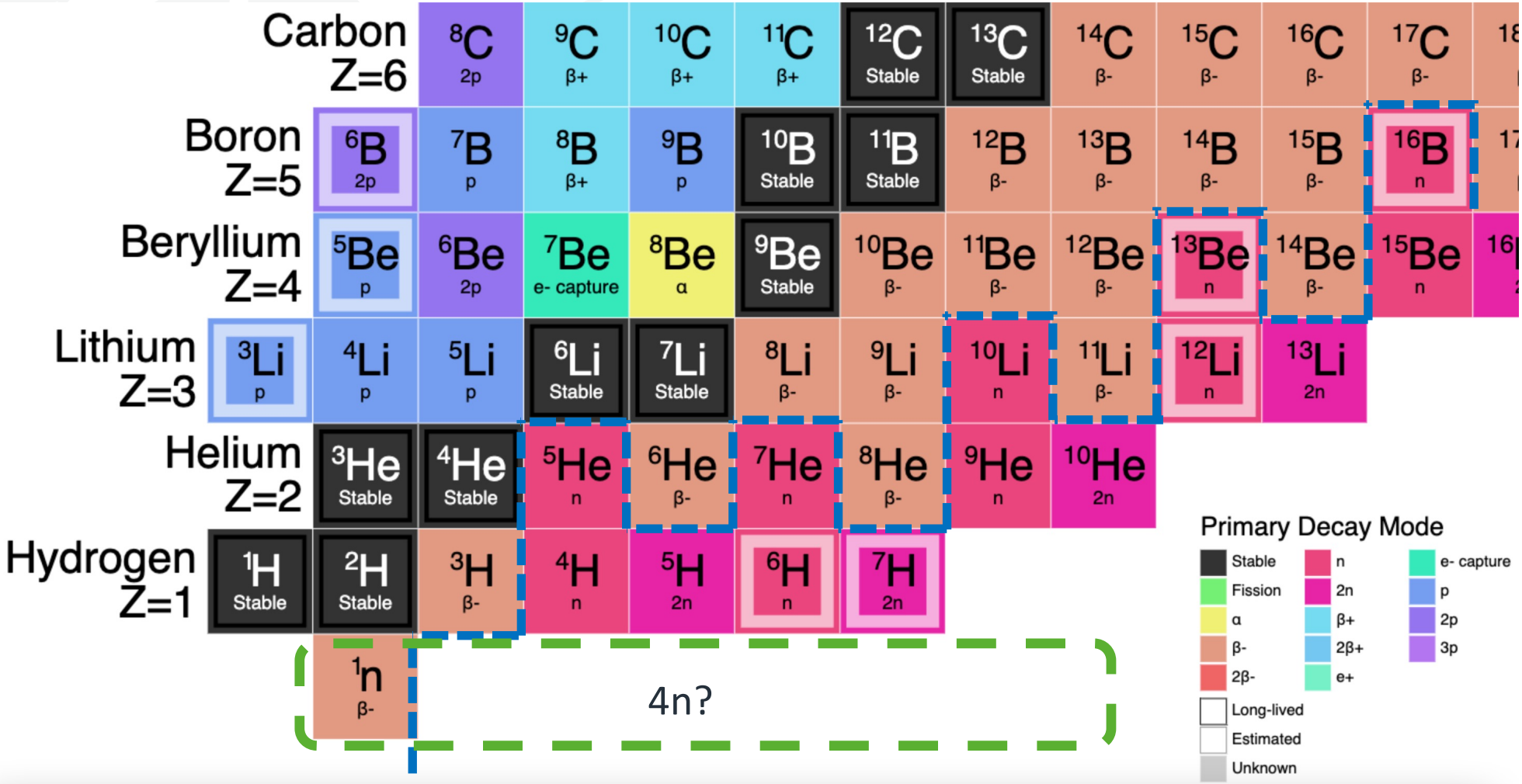
# Nuclear landscape

## Light nuclei



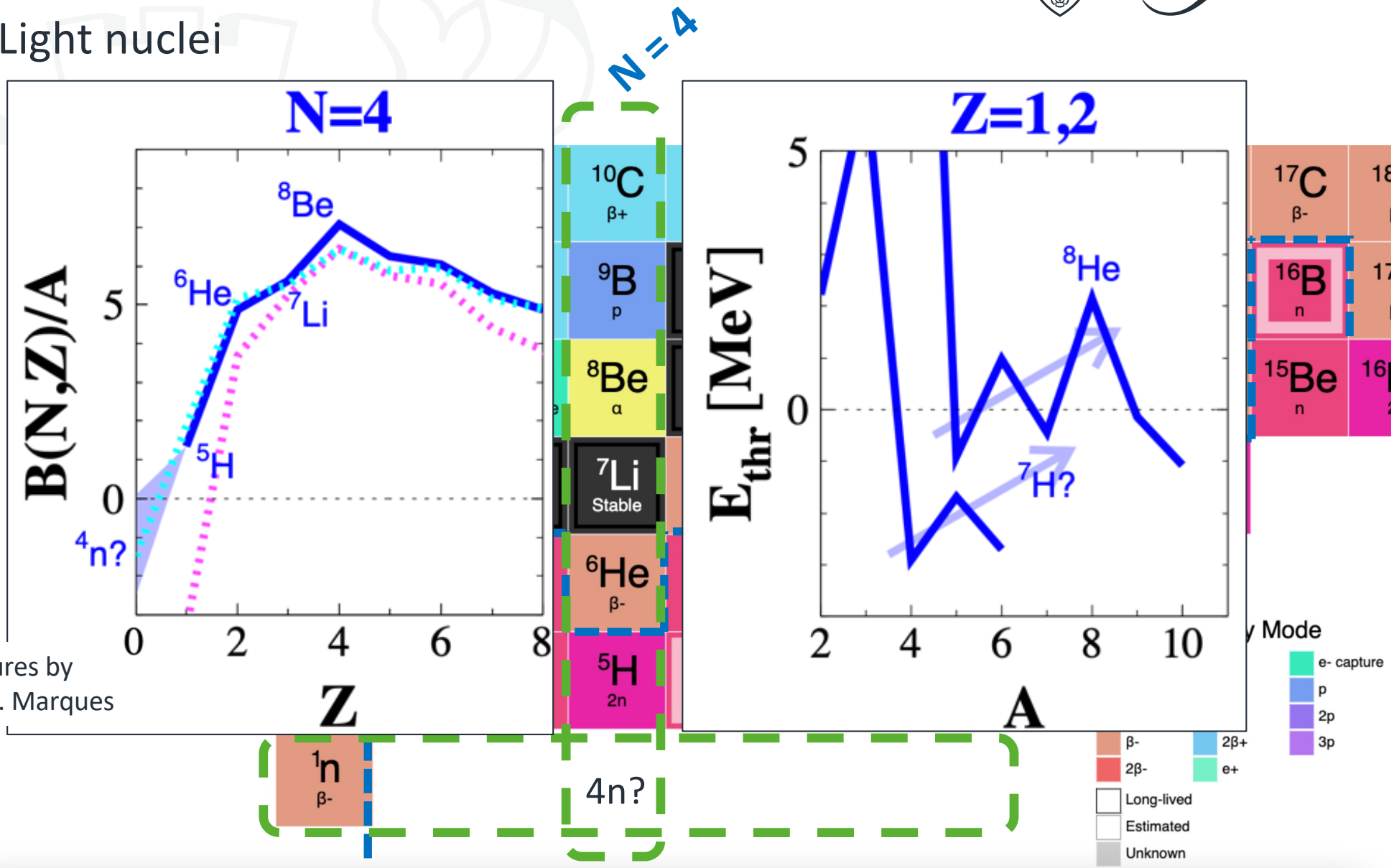
# Nuclear landscape

## Light nuclei



# Nuclear landscape

Light nuclei

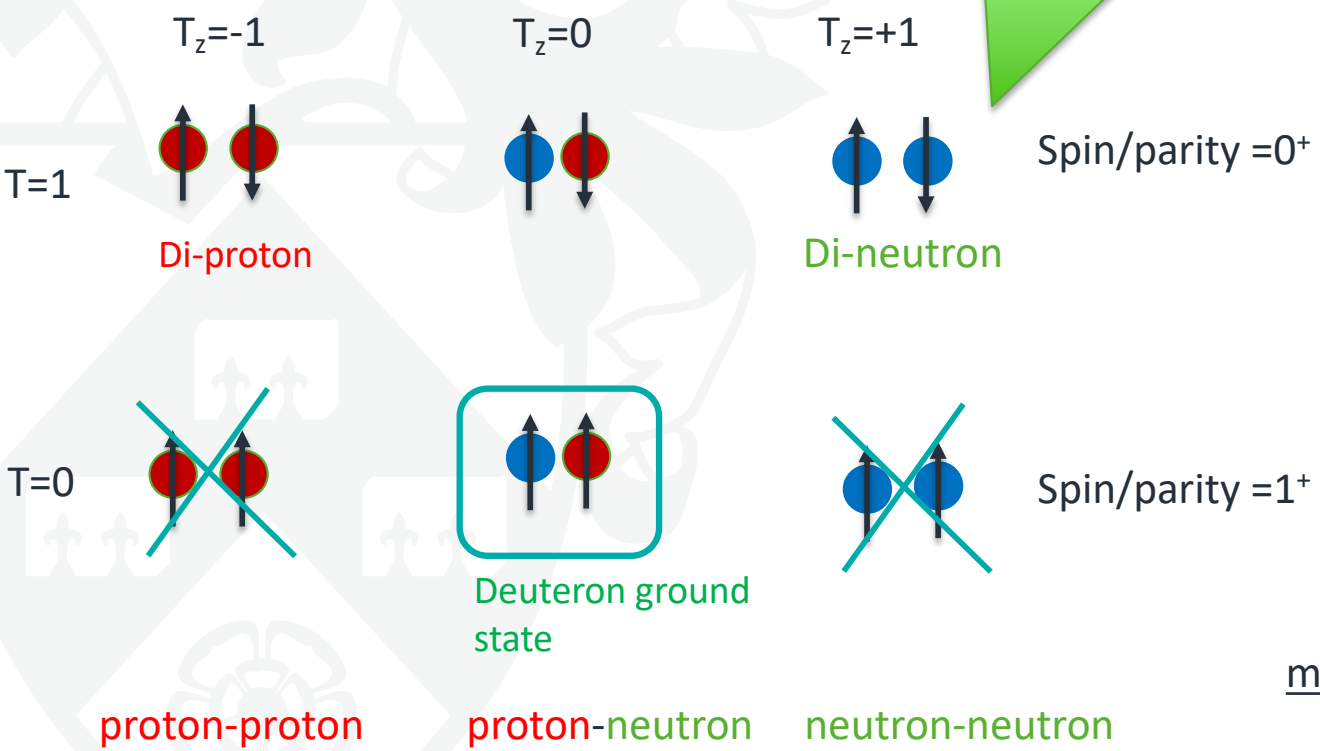



Figures by
F.M. Marques

# Nuclear Forces

is known to be unbound by only about 100 keV.

Two-nucleon Systems:




multi-nucleon Systems sensitive to:

- Small change in NN interactions
- poorly known multi-nucleon forces
- coupling to the continuum

# Motivation

Probing multi-neutron systems:

- Enables studies of unique few-body fermionic systems, where the interplay of various components of the nuclear interaction – T = 3/2 component of three-nucleon forces – and QM effects such as coupling to the continuum can have a drastic effect
  - Provides fundamental and stringent test for ab-initio type of nuclear theory predictions with different interactions

- Has implications for neutron rich matter – neutron stars

# Motivation

but how do we access it?
and how do we measure it?

Probing multi-neutron systems:

- Enables studies of unique few-body fermionic systems, where the interplay of various components of the nuclear interaction – T = 3/2 component of three-nucleon forces – and QM effects such as coupling to the continuum can have a drastic effect
  - Provides fundamental and stringent test for ab-initio type of nuclear theory predictions with different interactions

- Has implications for neutron rich matter – neutron stars

# A 60-year quest…

# experimental work

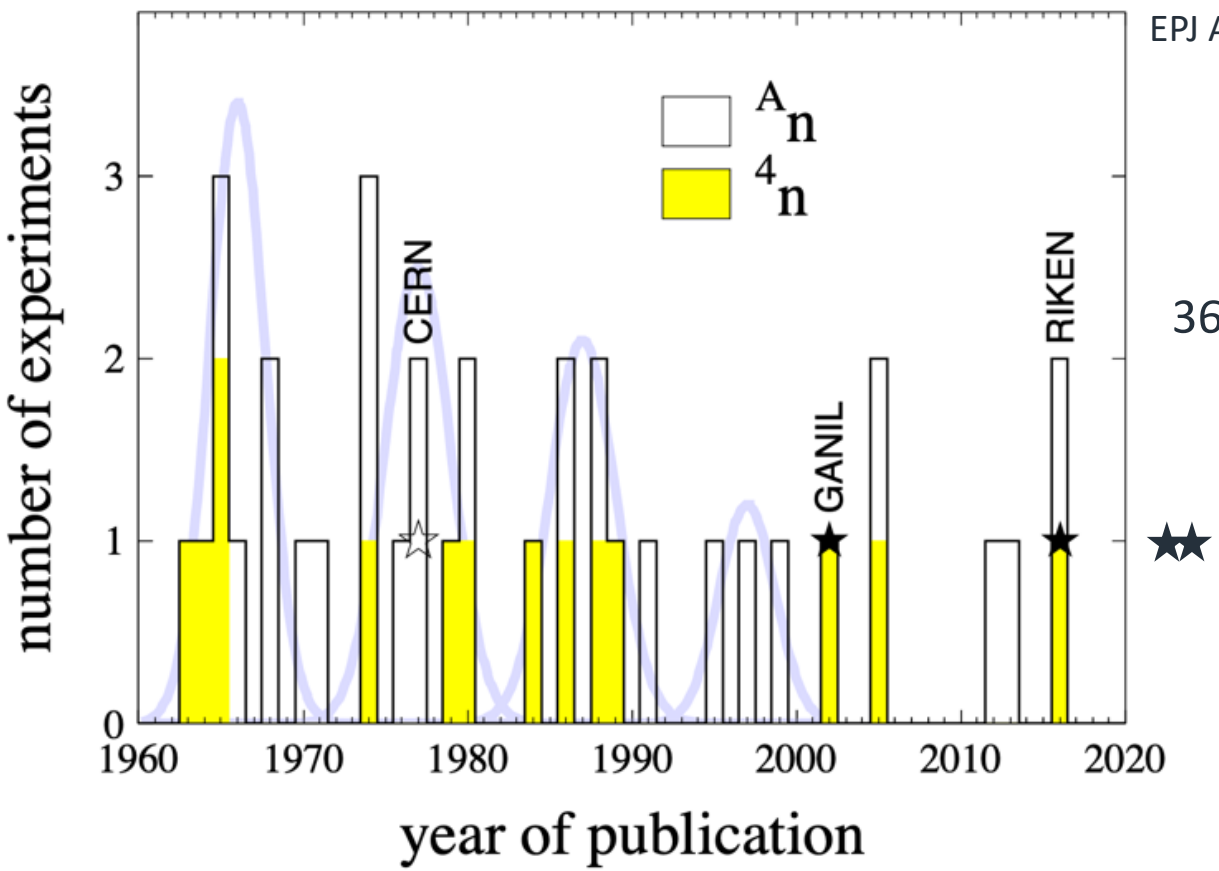
# A 60-year quest

## Experimental work – throughout the decades

For a recent, comprehensive review see: **The quest for light multineutron systems**

F. Miguel Marqués[1] and Jaume Carbonell[2]

EPJ A 57, 105 (2021)



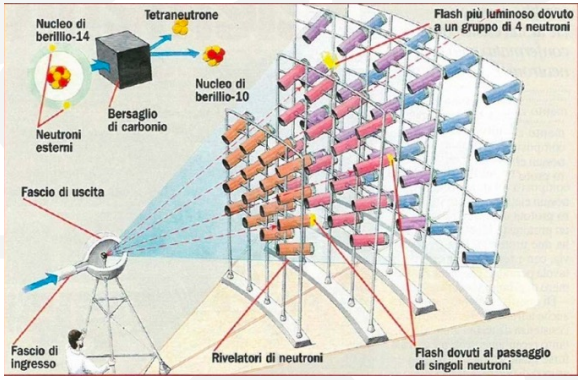

36+ experiments searching for multi-neutrons!!

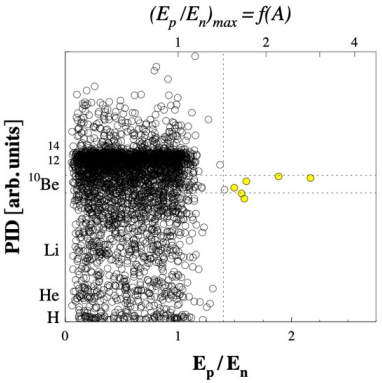
# A 60-year quest

## Experimental work

GANIL – 2002

C ($^{14}$Be, $^{10}$Be) 4n




- 6 events consistent with bound 4n or a low-energy resonance (E(4n) < 2 MeV)

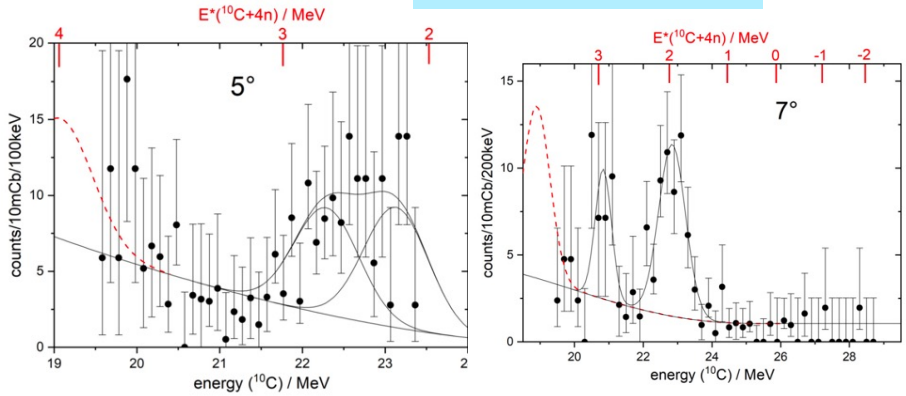
F.M. Marques et al., PRC 65, 044006 (2002) and arXiv:nucl-ex/0504009

Thomas Faestermann et al., PLB 824 (2022) 136799

TUM – 2022

Multi-nucleon transfer

$^{7}$Li($^{7}$Li,$^{10}$C) $^{4}$n




- 4n resonance E(4n) = 2.93 MeV, Γ < 0.24 MeV

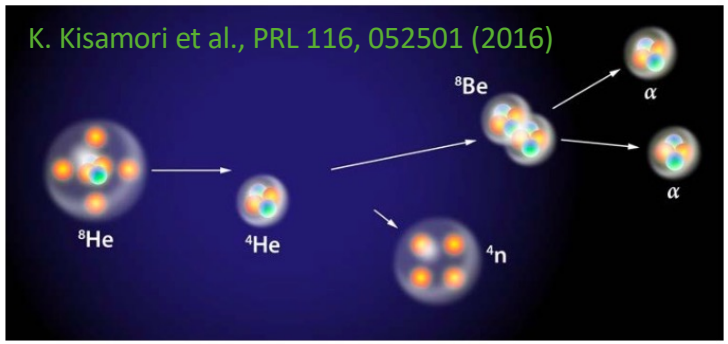
  or

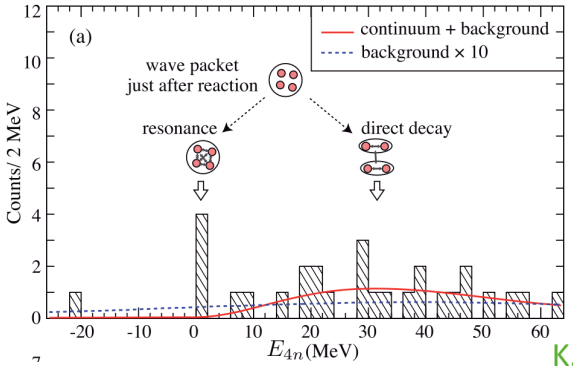
- 4n bound by 0.42(16) MeV & $^{10}$C in 1$^{st}$ excited state

RIKEN – SHARAQ/RIBF – 2016

$^{4}$He ($^{8}$He, $^{8}$Be) $^{4}$n

Double charge exchange reaction




- 4 events consistent with 4n resonance:

  E(4n) = 0.8 ± 1.3 MeV, Γ < 2.6 MeV

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

A 60-year quest…

theoretical work

# A 60-year quest

## Theoretical calculations

**Binding Energy of a Neutron Gas**

K. A. Brueckner
*University of California, La Jolla, California*

John L. Gammel
*Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

and

Joseph T. Kubis
*Princeton University, Princeton, New Jersey*
(Received December 28, 1959)

*We conclude that a neutron gas is not bound at any density….*

NONEXISTENCE OF THE TETRANEUTRON*

Y. C. Tang and B. F. Bayman

School of Physics, University of Minnesota, Minneapolis, Minnesota
(Received 17 June 1965)

*Here again, we find that there is neither a bound nor a resonant 4n system.*

# A 60-year quest

## Theoretical calculations

VOLUME 90, NUMBER 25 PHYSICAL REVIEW LETTERS week ending 27 JUNE 2003

**Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?**

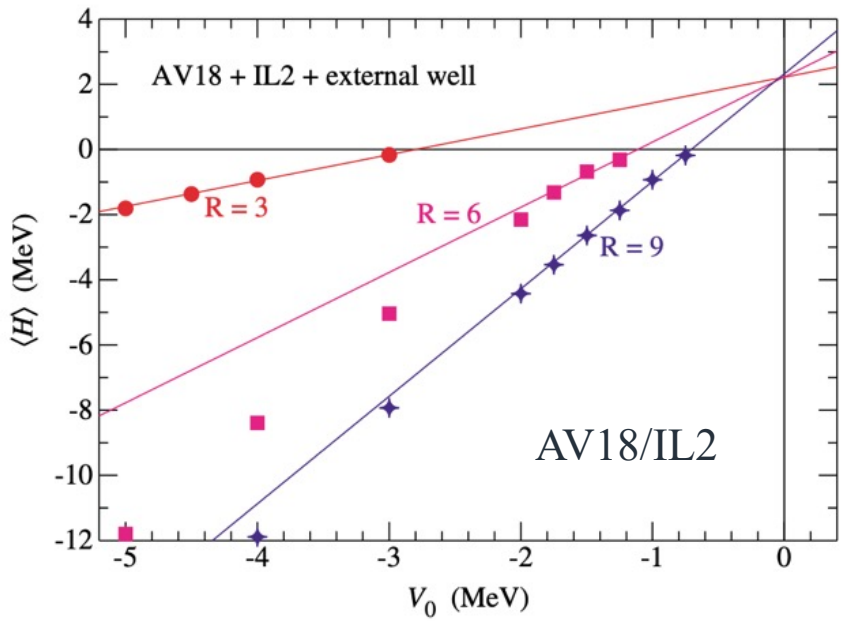



FIG. 1 (color online). Energies of $^4n$ in external wells versus the well-depth parameter $V_0$.

Steven C. Pieper*

**Regarding a bound $^4$n:**
"… our current very successful understanding of nuclear forces would have to be severely modified in ways that, at least to me, are not at all obvious."

**Regarding a $^4$n resonance state:**
"This suggests that there might be a $^4$n resonance near 2 MeV, but since the GFMC calculation with no external well shows no indication of stabilizing at that energy, the resonance, if it exists at all, must be very broad. In any case, the AV18/IL2 model does not produce a bound $^4$n."

# A 60-year quest

## Theoretical calculations, resonance or not?

(3n) Lazauskas, PRC 71 (2005) 044004 : 3NF
(4n) Lazauskas, PRC 72 (2005) 034003 : 4NF
(3,4n) Hiyama, PRC 93 (2016) 044004 : 3NF(T =3/2)

No, 3n/4n

Shirokov, PRL 117 (2016) 182502
Gandolfi, PRL 118 (2017) 232501
Fossez, PRL 119 (2017) 032501
Li, PRC 100 (2019) 054313

Yes, 3n/4n

Deltuva, PRL 123 (2019) 069201
Deltuva, PRC 100 (2019) 044002
Ishikawa, PRC 102 (2020) 034002

No, 3n/4n

Deltuva, PLB 782 (2018) 238
Higgins, PRL 125 (2020) 052501

non-resonant low-energy enhancement of the density of states in the four-neutron spectrum.

Lazauskas, PRL 130 (2022) 102501

non-resonant dineutron-dineutron correlations

# Latest Experimental work

SAMURAI at RIBF/RIKEN

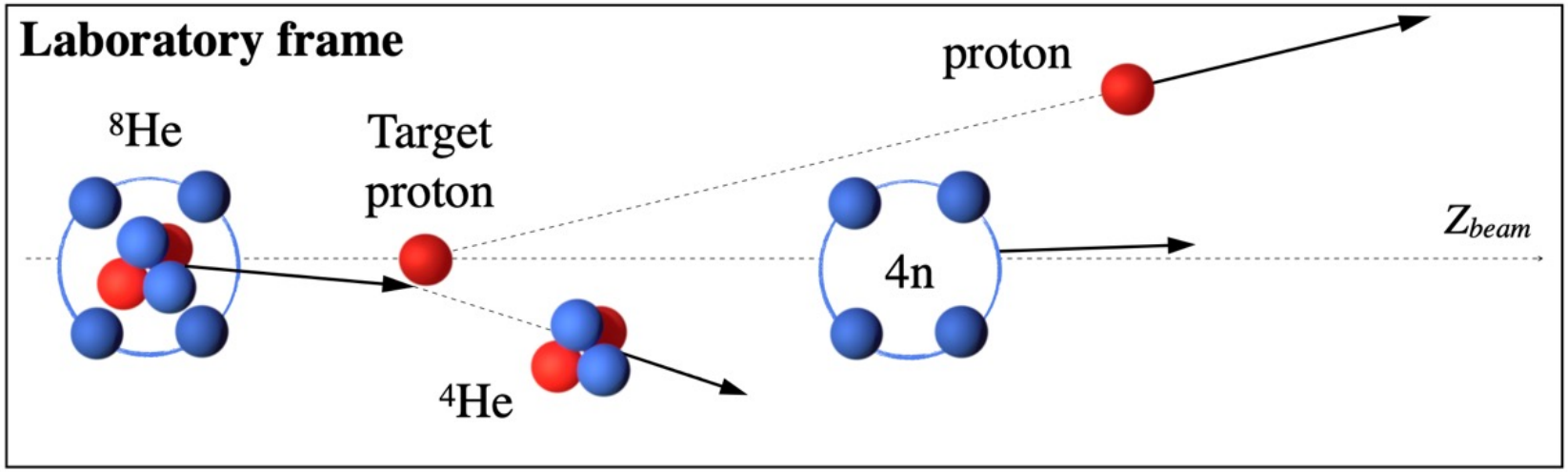
"Observation of a correlated free four-neutron system"
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

# Method

**$^{8}$He(p,pα)$^{4}$n** Quasi-Elastic knockout reaction at large momentum transfer

Reconstruct the energy of the **missing mass** of the $^{4}$n system through the precise measurement of the charge particles involved in the reaction (p, α).

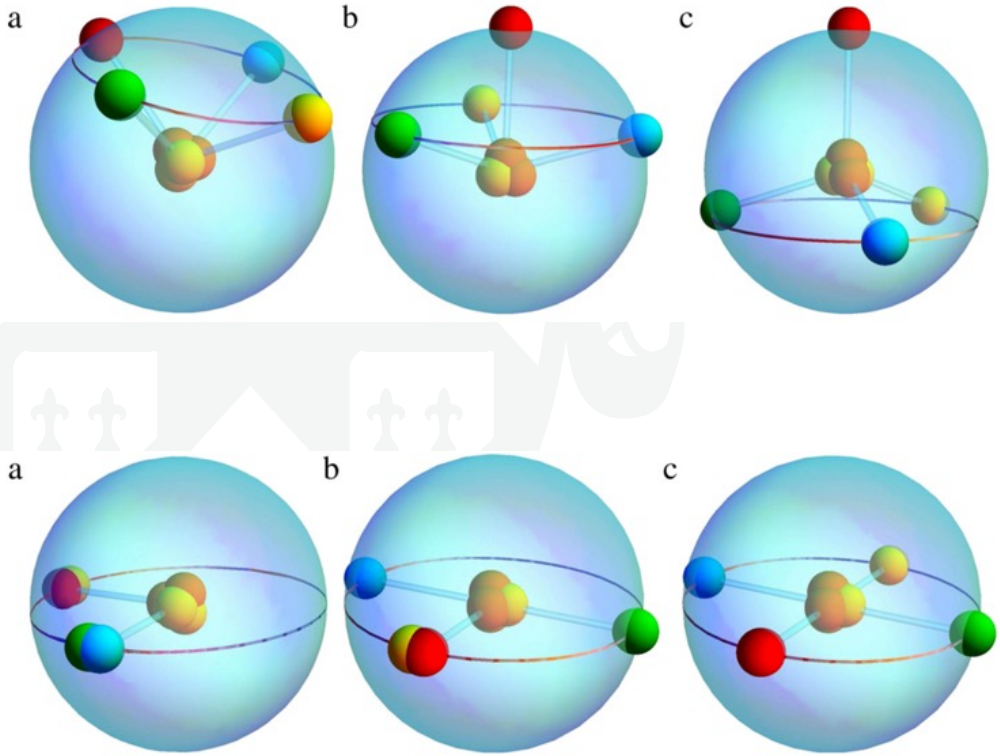
**Quasi-elastic scattering of α in $^{8}$He**



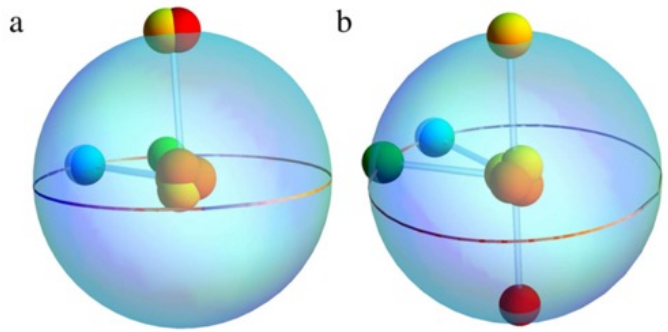
# Method

**$^{8}$He(p,pα)$^{4}$n** Quasi-Elastic knockout reaction at large momentum transfer

- $^{8}$He a good starting point to populate a 4n system. Highest possible A/Z=4. Well-formed α cluster. Large overlap < $^{8}$He | α ⊗ 4n >




**Tetrahedral configurations**




**Great circle configurations**

P. Mei, P. Van Isacker , Annals of Physics 327 (2012) 1182–1201

# Method

## $^{8}$He(p,pα)$^{4}$n Quasi-Elastic knockout reaction at large momentum transfer

- $^{8}$He a good starting point to populate a 4n system. Highest possible A/Z=4.
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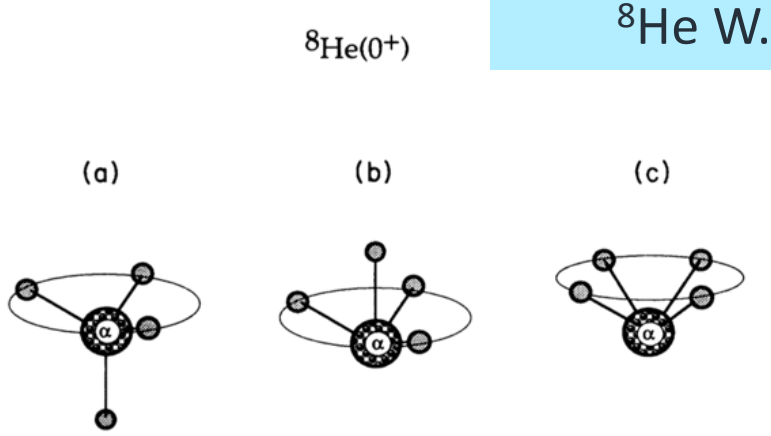
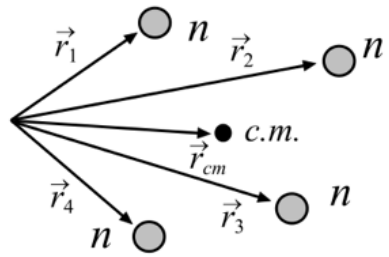
$^{8}$He W.F. in the COSMA model




I. initial structure
II. reaction mechanism, and
III. final-state interaction (FSI)

$^{4}n$




Two of the three most probable configurations found in $^{8}$He can be associated with a $^{4}$n system. The probability for each of them is approx. 30%.
M.V. Zhukov, PRC 50, R1 (1994)

"Sudden removal of the α-particle from $^{8}$He"
The exact case of interest is studied within the COSMA model.
L.V. Grigorenko et al., EPJA 19, 187 (2004)

# Method

**$^8$He(p,pα)$^4$n** Quasi-Elastic knockout reaction at large momentum transfer

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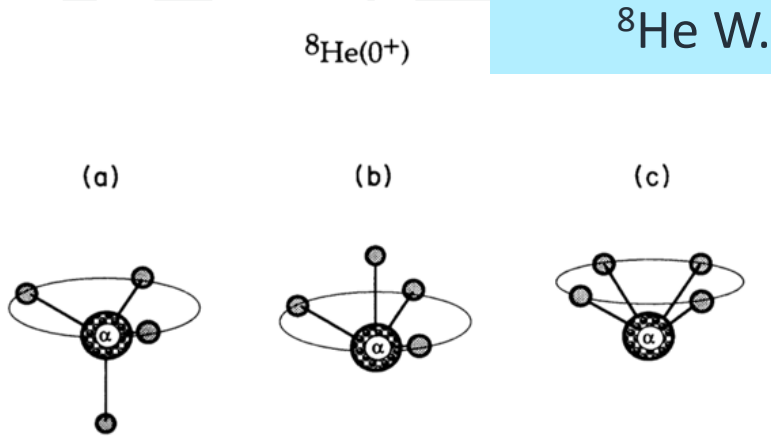


$^8$He W.F. in the COSMA

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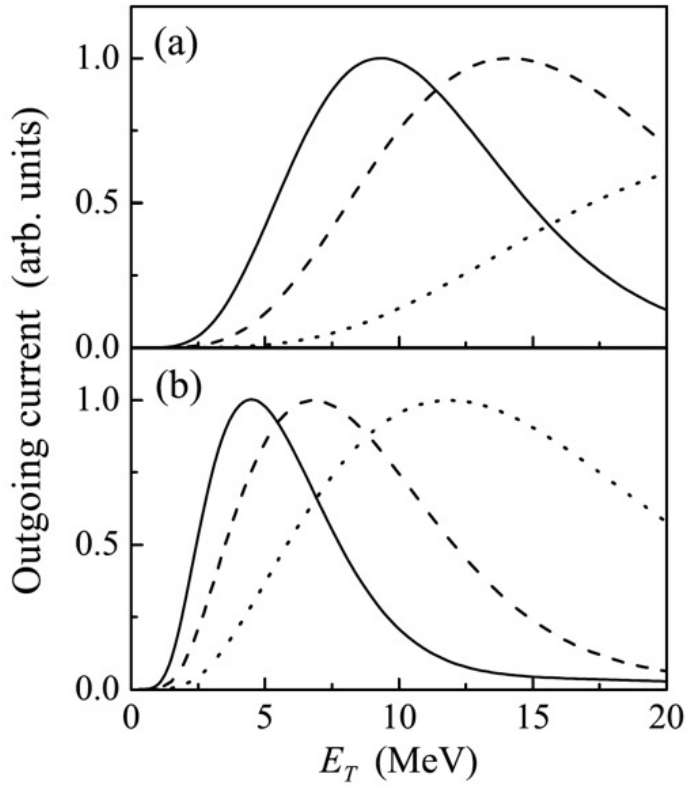
L.V. Grig

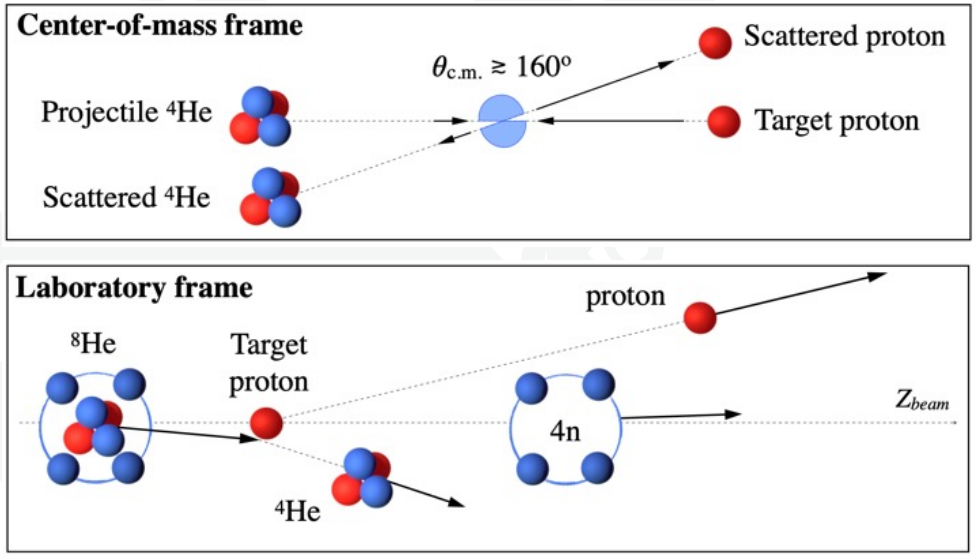


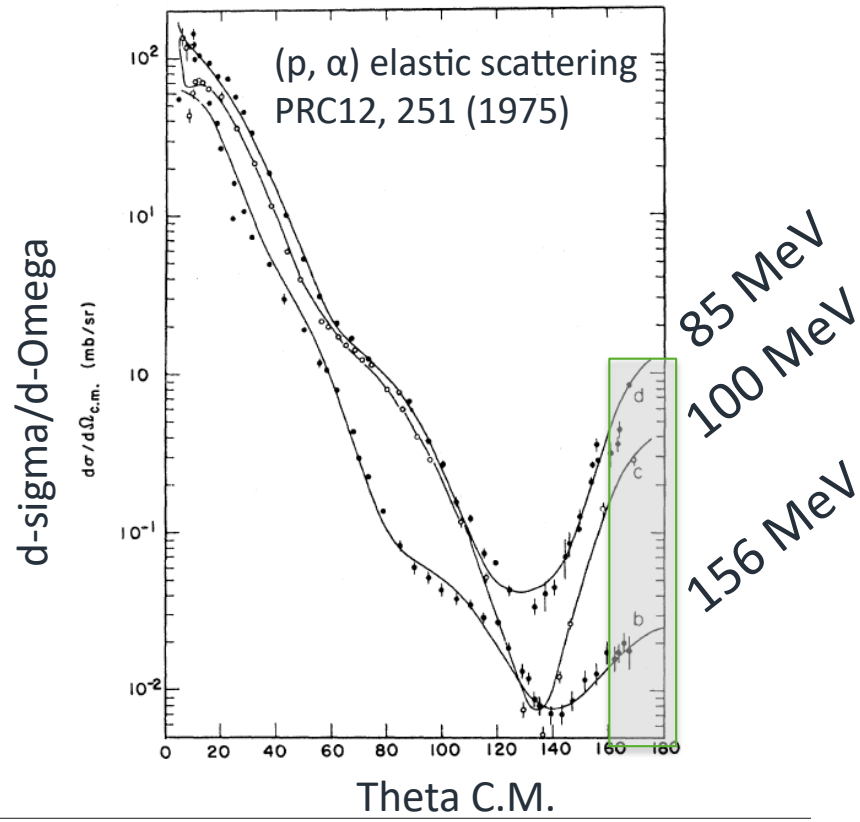
# Method

**$^{8}$He(p,pα)$^{4}$n** Quasi-Elastic knockout reaction at large momentum transfer

- (p, α) elastic scattering data is well known.

**Quasi-elastic scattering of α in $^{8}$He**

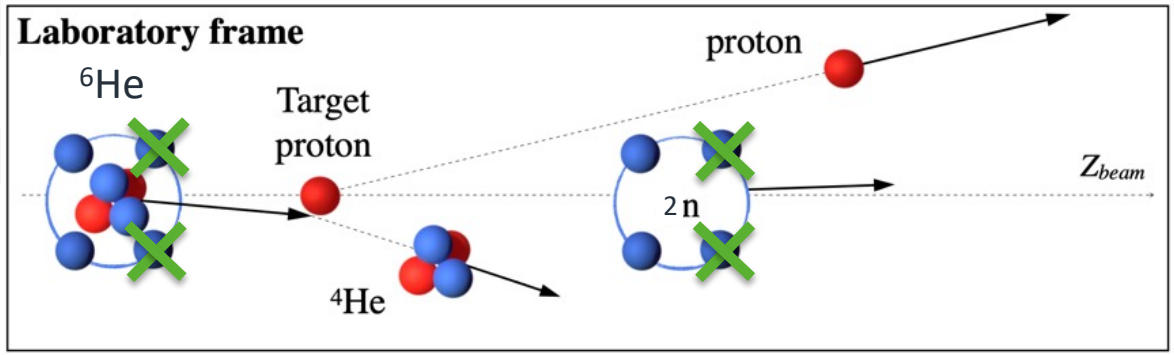


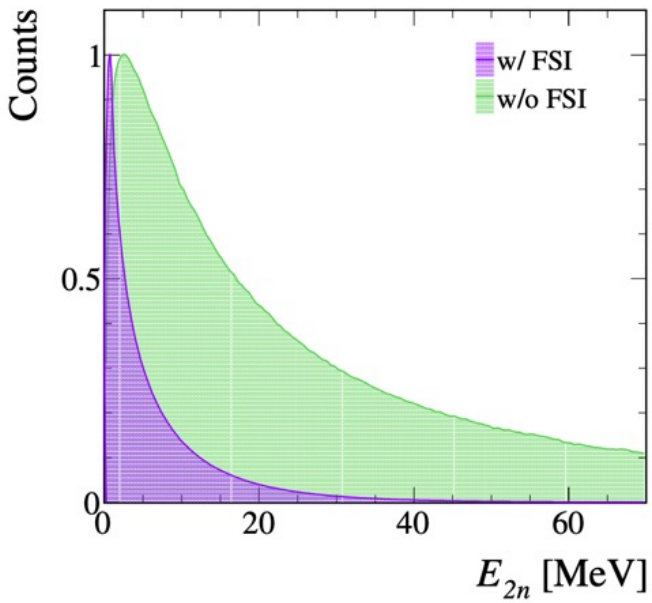



# Method

**$^{8}$He(p,pα)$^{4}$n** Quasi-Elastic knockout reaction at large momentum transfer

- Helium beams allow for a "control case" to be employed **$^{6}$He(p,pα)$^{2}$n** !!

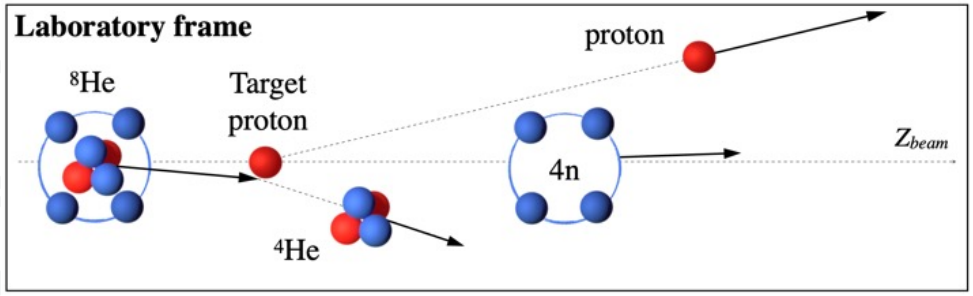


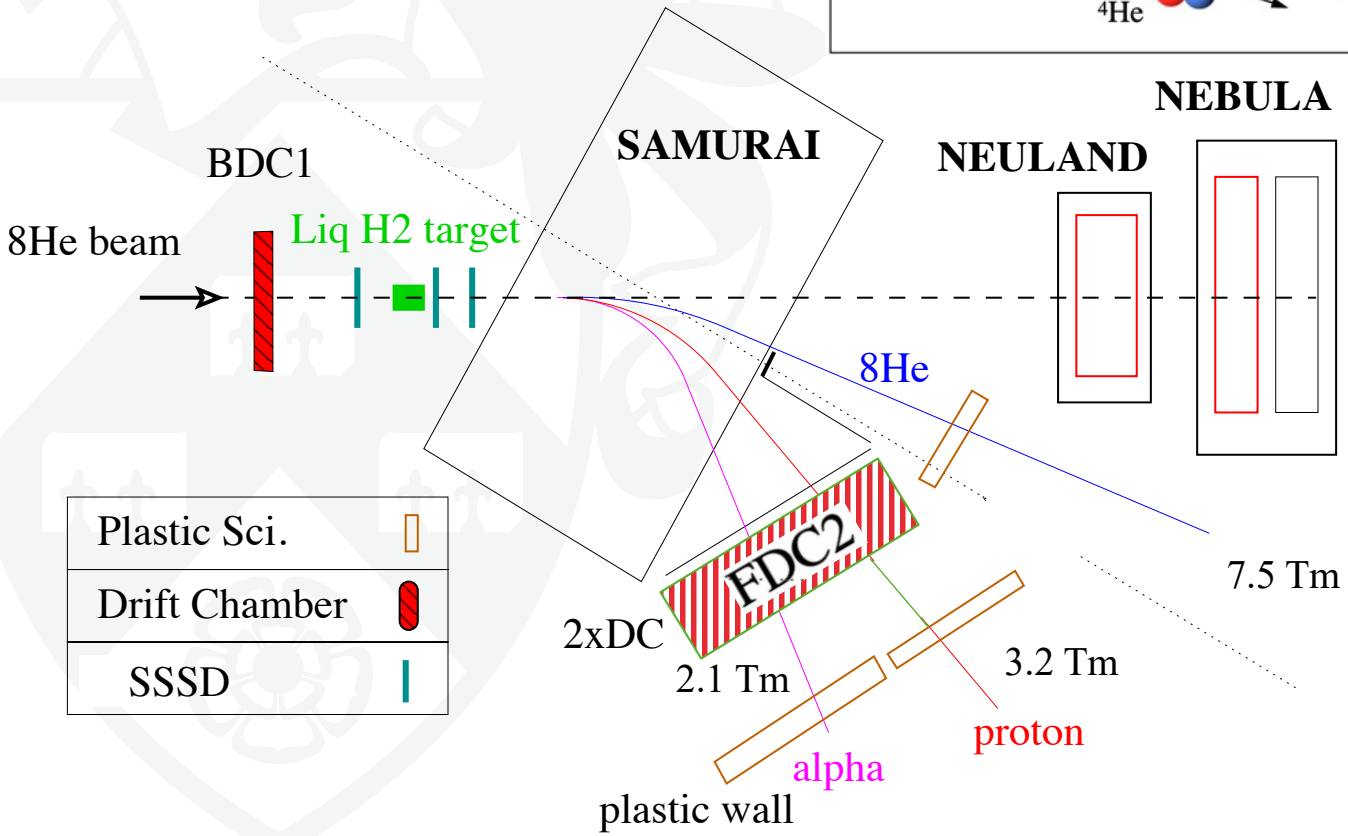



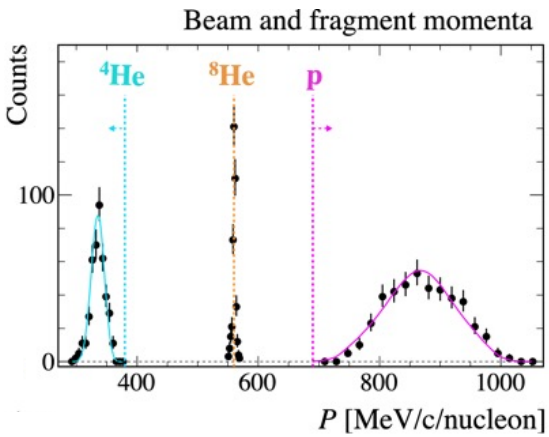

Theory:
Göbel, M. et al., "Neutron-neutron scattering length from the $^{6}$He(p, pα)nn reaction"
PRC 104, 024001 (2021).

# Experimental setup

## SAMURAI at RIBF/RIKEN



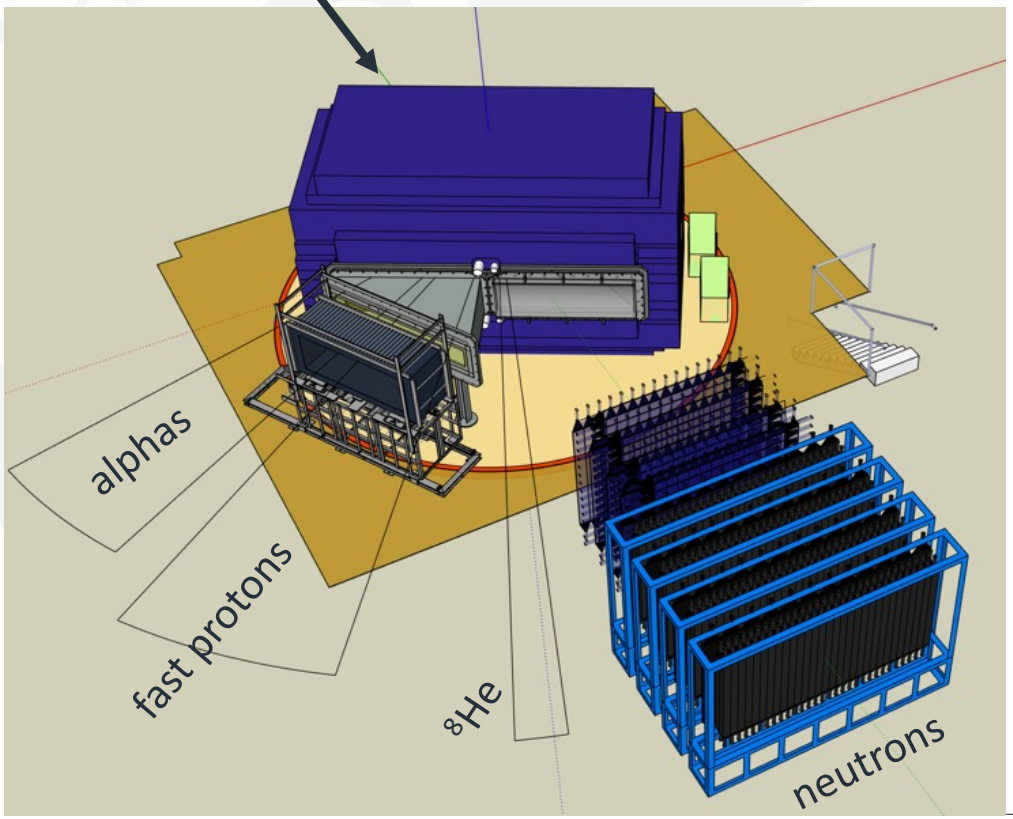



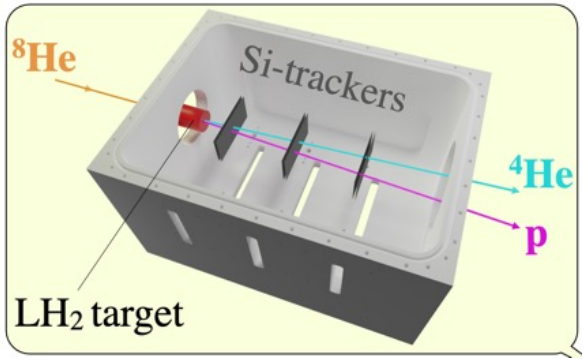
# Experimental setup

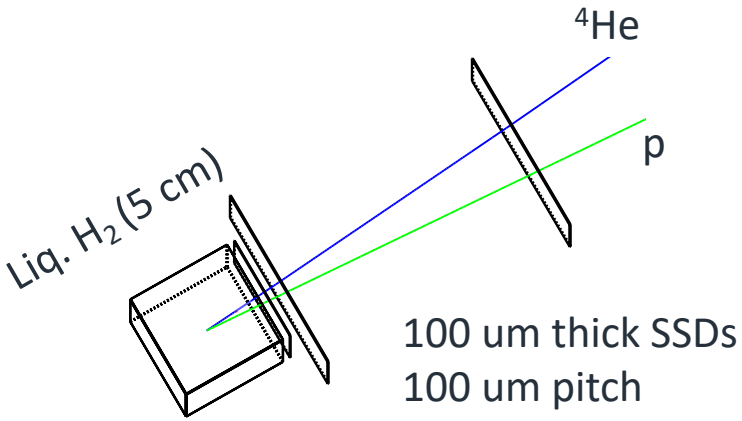
SAMURAI at RIBF/RIKEN

incoming $^{8}$He beam from BigRIPS




Precise vertex reconstruction

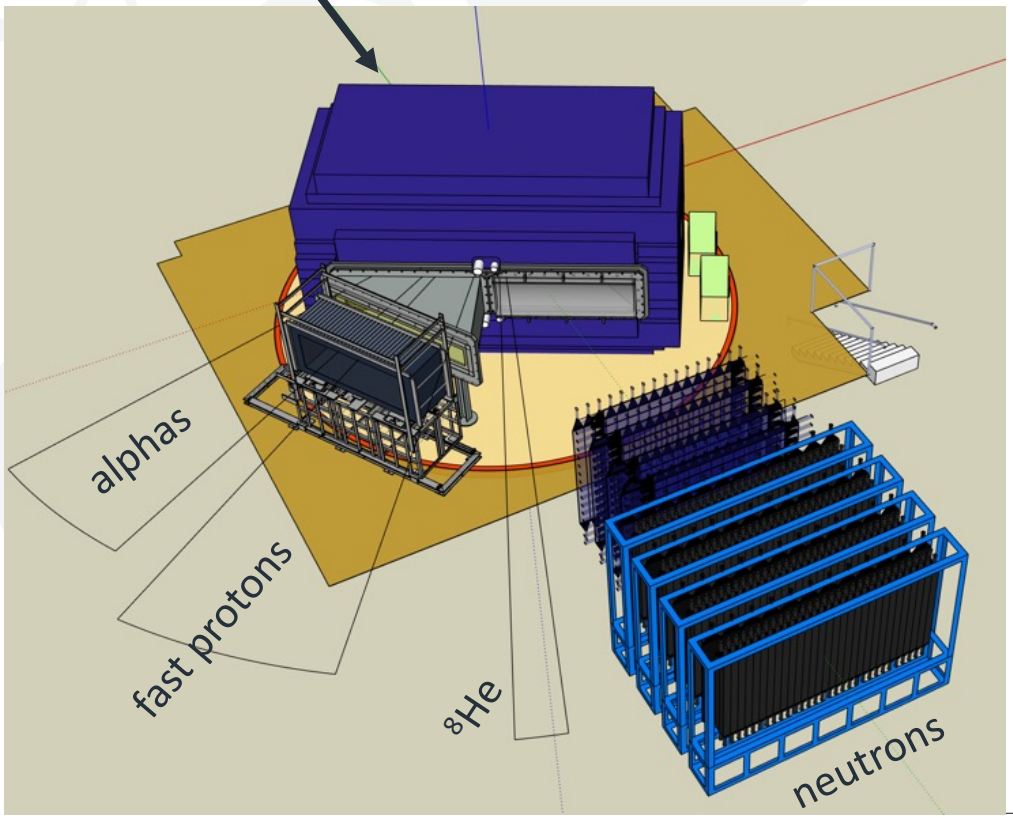


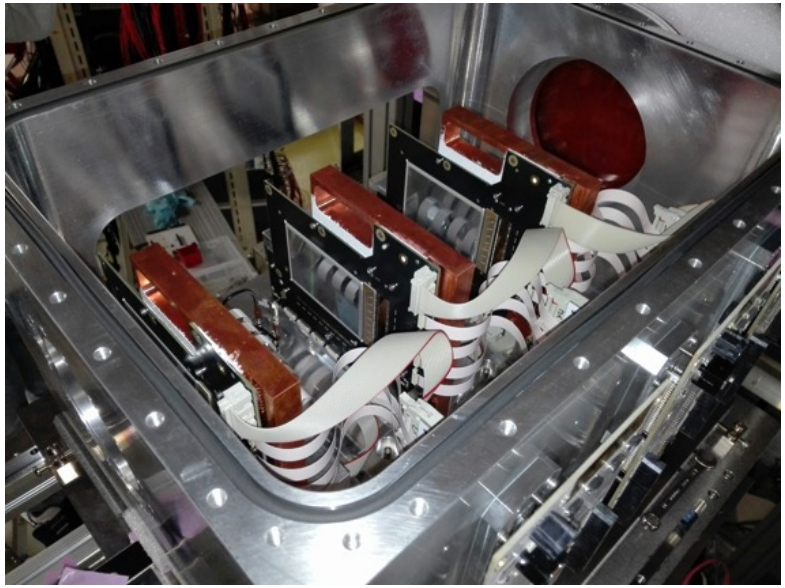



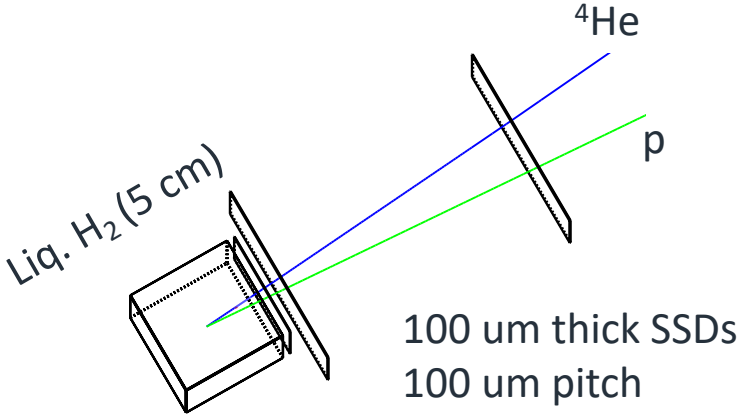
# Experimental setup

SAMURAI at RIBF/RIKEN

incoming $^{8}$He beam from BigRIPS





# Experimental setup

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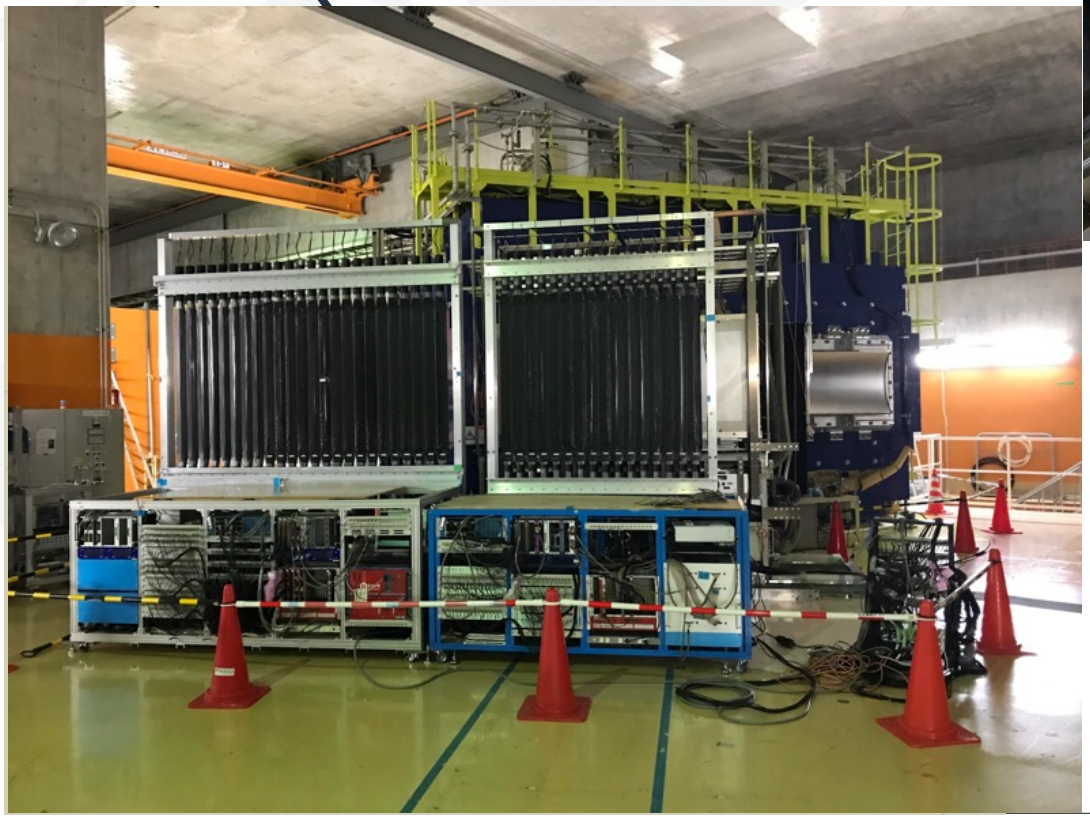
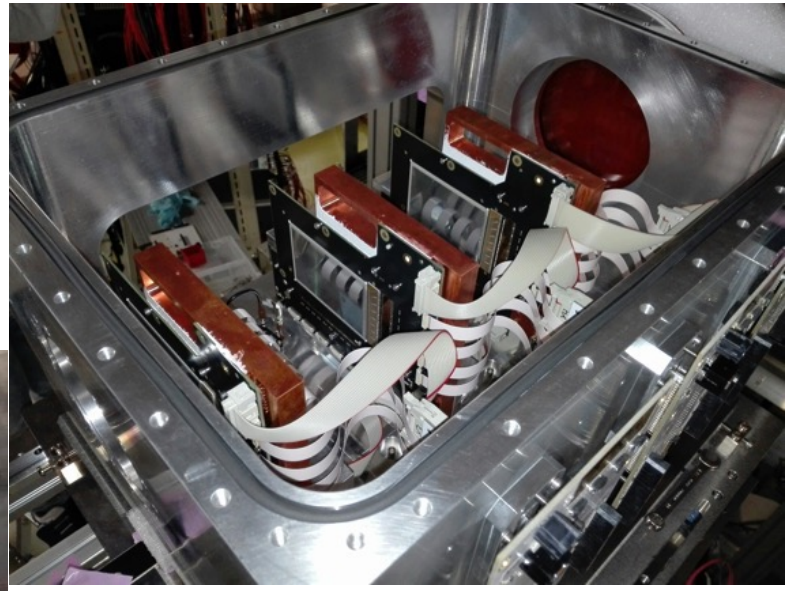
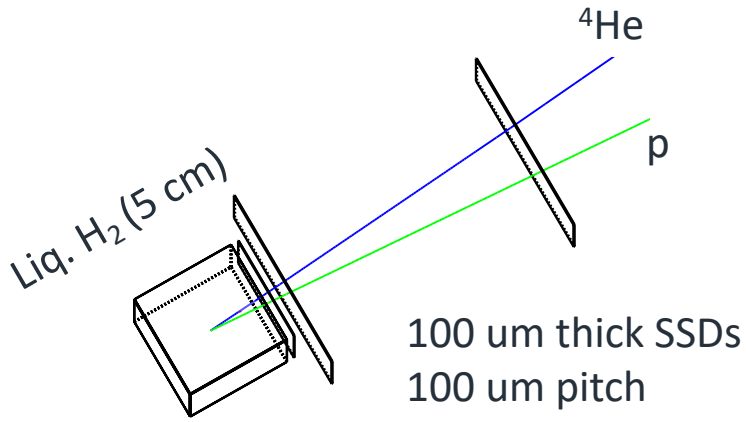
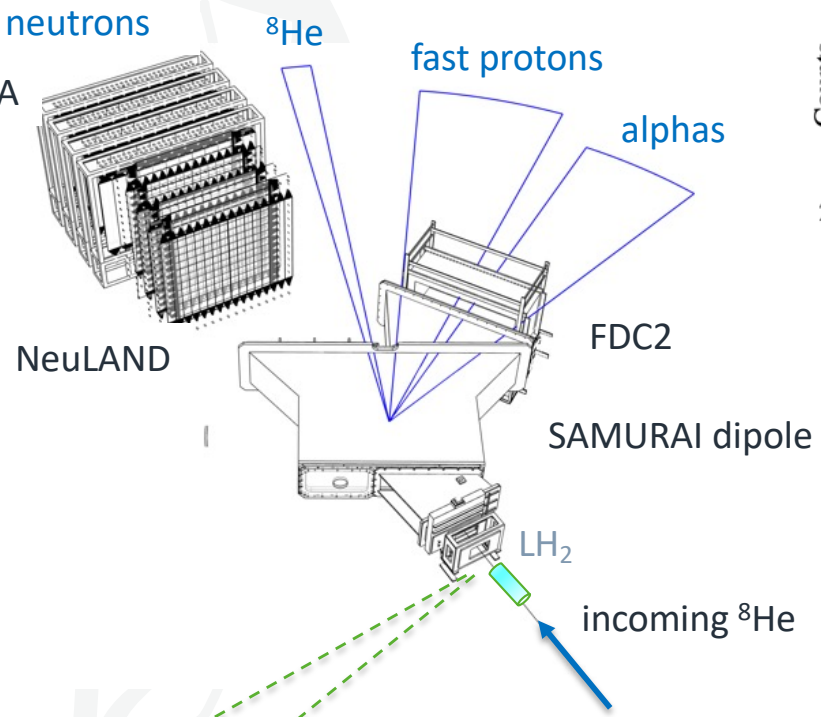


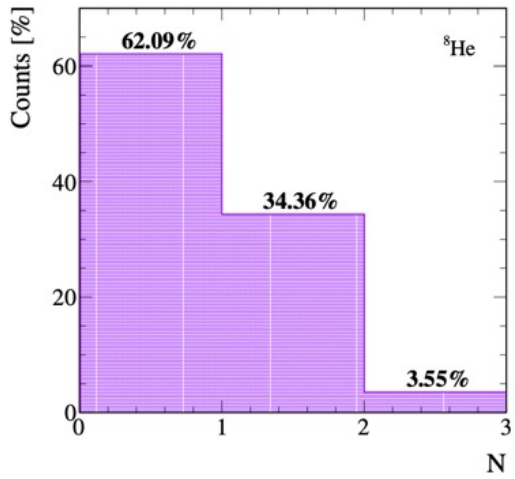


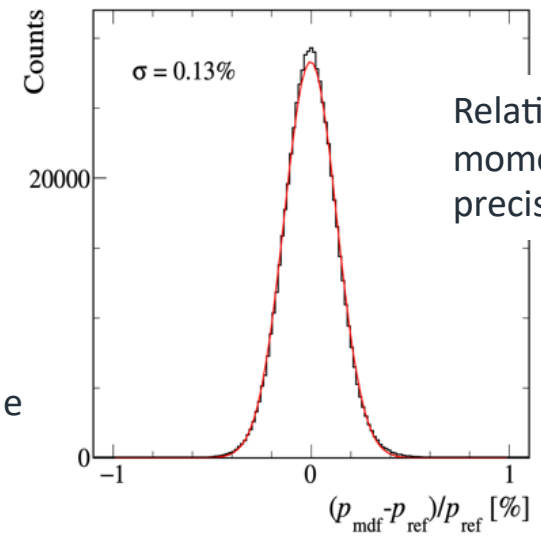


# Experimental challenges

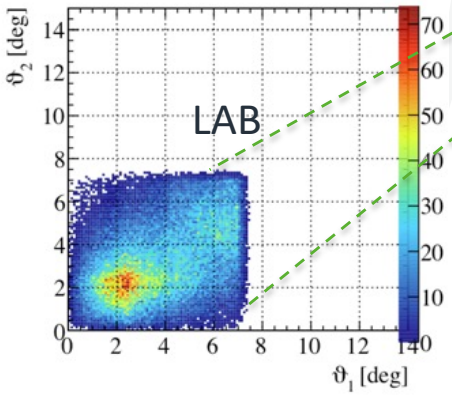



Multi-neutron detection

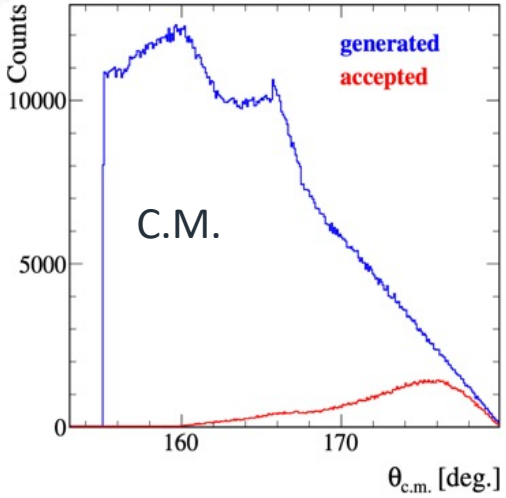


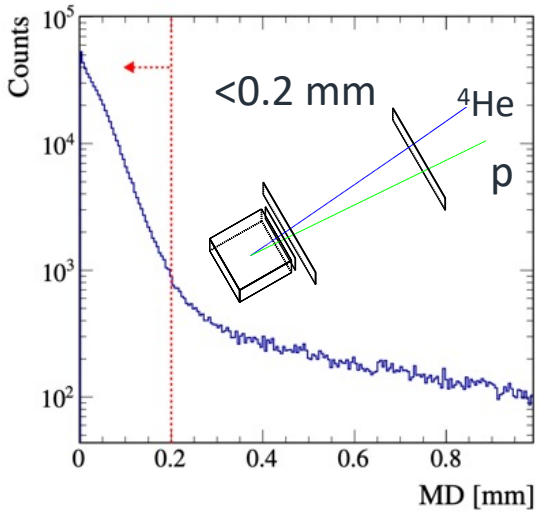

Relative momentum precision




Acceptance of p and alpha through the dipole magnet



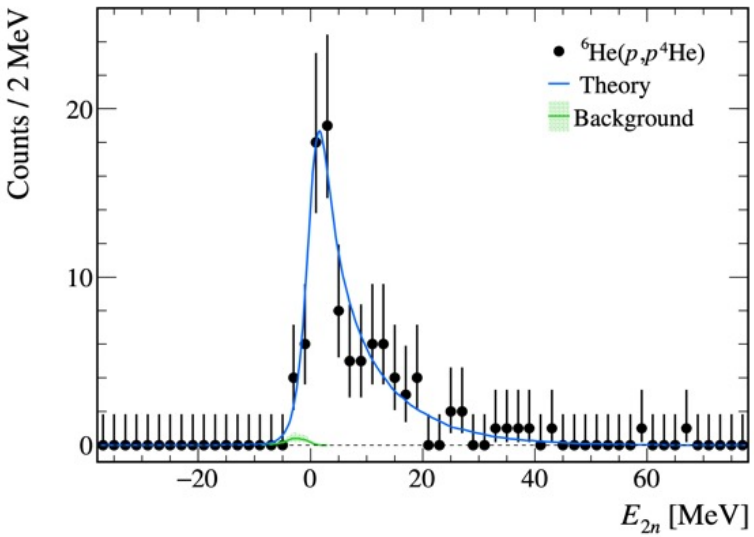

Reaction vertex reconstruction



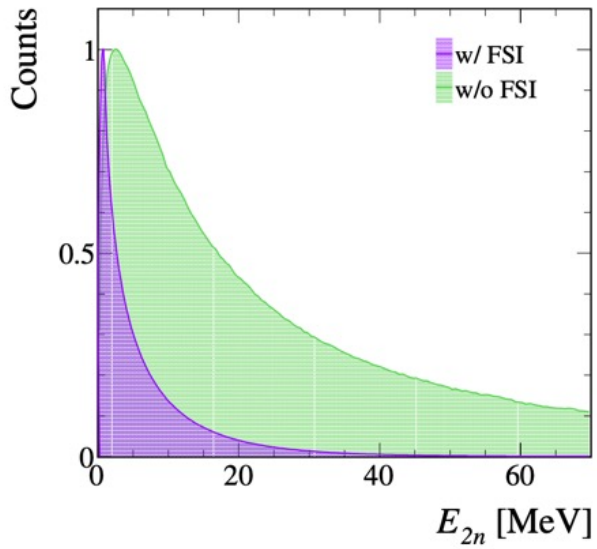
# Results:
# Missing-mass spectra

Control reaction - **$^6$He(p,pα)$^2$n**

two-neutron system




Theory:
Göbel, M. et al., "Neutron-neutron scattering length from the $^6$He(p, pα)nn reaction"
PRC 104, 024001 (2021).



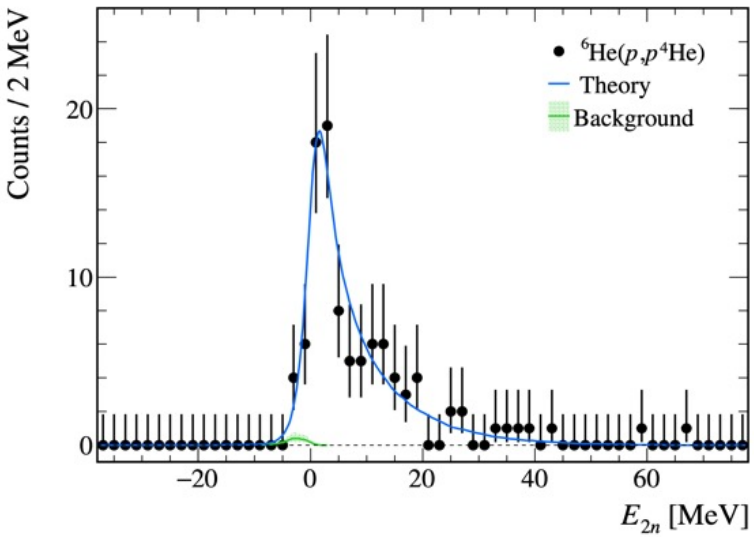

Confirming the expected low-energy peak of di-neutron of about 100 keV relative-energy

"Observation of a correlated free four-neutron system"
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

# Results:
# Missing-mass spectra

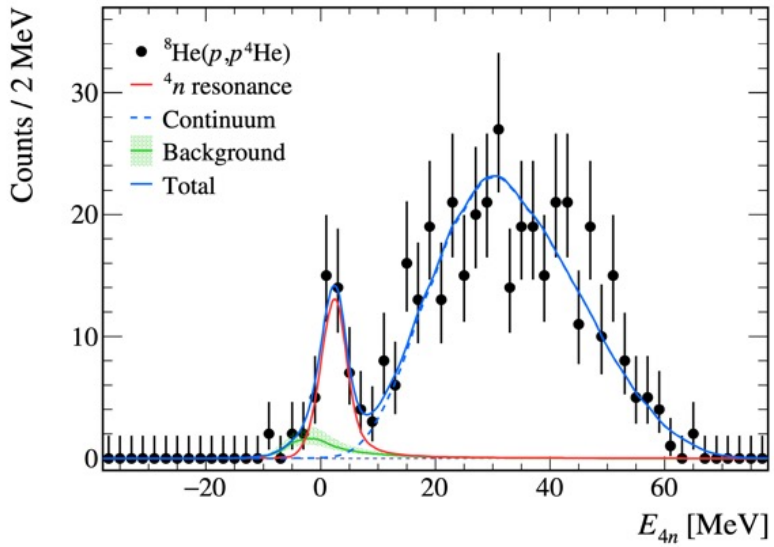
Control reaction - **$^{6}$He(p,pα)$^{2}$n**

two-neutron system




**$^{8}$He(p,pα)$^{4}$n**

four-neutron system




Confirming the expected low-energy peak of di-neutron of about 100 keV relative-energy

A near-threshold resonance-like structure:
$E_r$ = 2.37 ± 0.38(stat.) ± 0.44(sys.) MeV

Γ = 1.75 ± 0.22(stat.) ± 0.30(sys.) MeV

"Observation of a correlated free four-neutron system"
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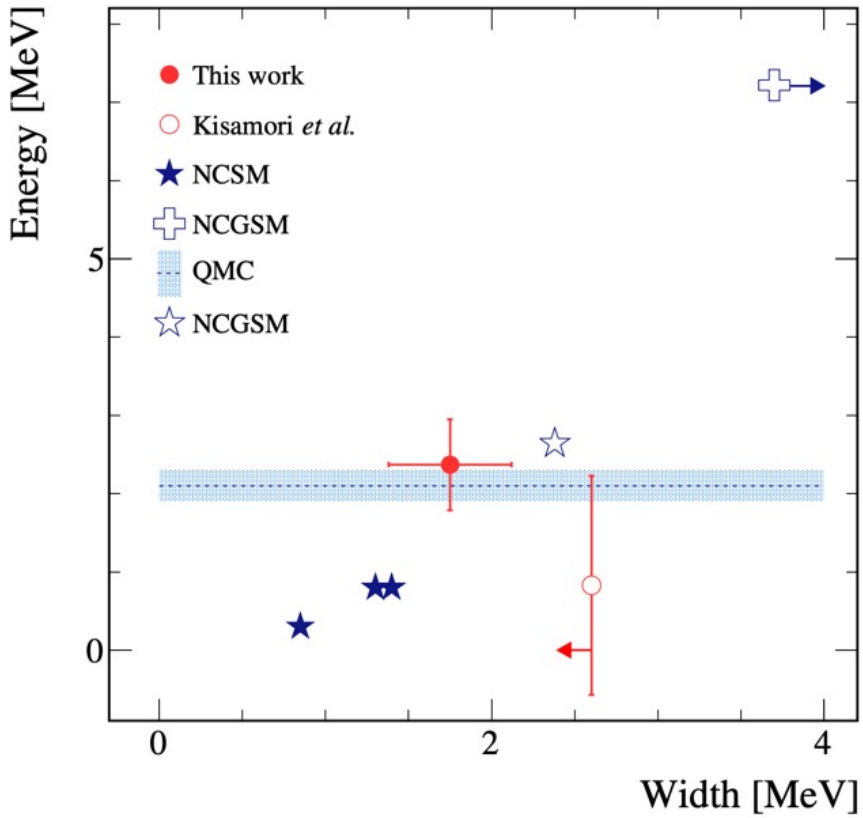
# Comparison of experimental results with theory predictions




- No-Core Shell Model (NCSM)
  PRL 117, 182502 (2016)
- No-Core Gamow Shell Model (NCGSM)
  PRC 100, 054313 (2019)
  PRL 119, 032501 (2017)
  (where the blue arrow indicates that the width is predicted to be larger than 3.7 MeV)
- Quantum Monte Carlo (QMC)
  PRL 118, 232501 (2017)

$E_r$ = 2.37 ± 0.38(stat.) ± 0.44(sys.) MeV

Γ = 1.75 ± 0.22(stat.) ± 0.30(sys.) MeV

"Observation of a correlated free four-neutron system"
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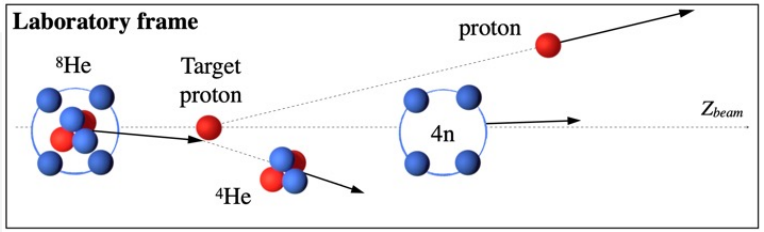
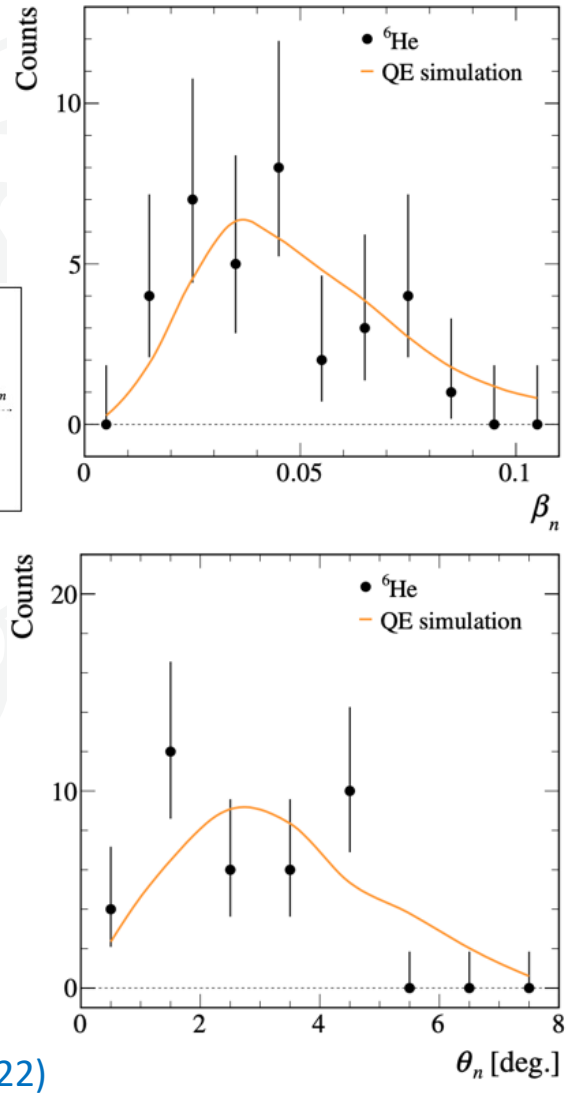
# Neutron detection

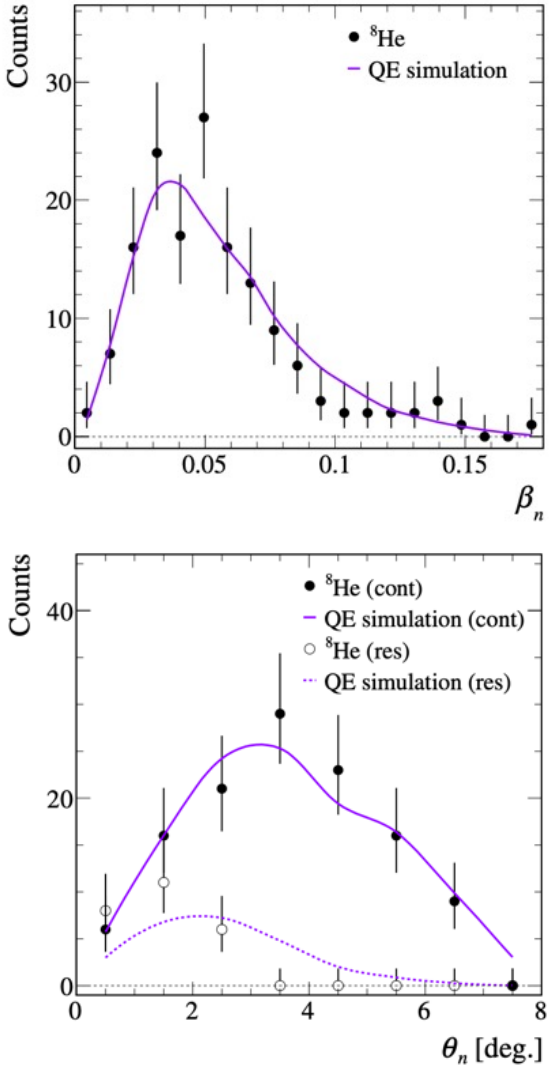
Events with one detected neutron are consistent with expected distributions




$^6$He(p,pα)$^2$n




$^8$He(p,pα)$^4$n




Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

# Now what?
# Future perspectives

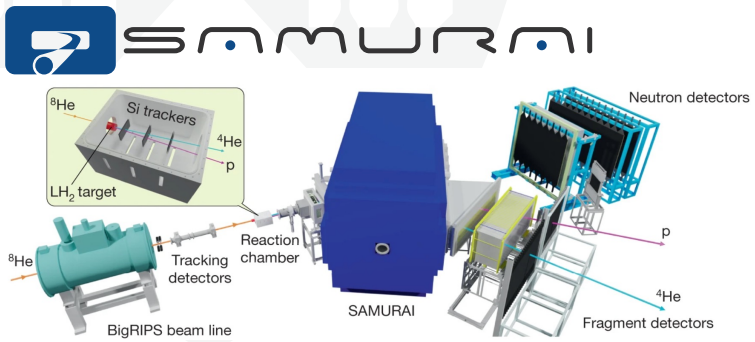
## Experimentally

Our goal is now to measure the correlations between these decaying four neutrons

Approved!!
highest priority

**New exper. proposal:**

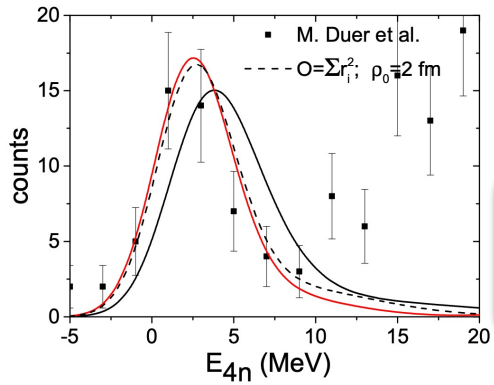
**Correlations in multi-neutron systems** December 28, 2022
**e.g. $^6$He(p,3p) and $^8$He(p,pα) at smaller CM angle**




## Theory

Can the experimental signal be reproduce by ab-initio theories?

"Low energy structures in nuclear reactions with 4n in the final state"
Lazauskas, PRL 130 (2022) 102501




? Dependency on:
how we produce it &
how we measure it

strong sensitivity of the response function to the neutrons' initial distribution inside $^8$He

# Summary and Conclusions

- We have presented the experimental observation of a resonance-like structure consistent with a tetraneutron resonant state near threshold.

- $^{8}$He beam and a quasi-elastic (p,pa) reaction at large momentum transfer in inverse kinematics enabled access to the $^{4}$n system in a recoil-less way.

- The finely tuned experimental apparatus (SAMURAI setup) and the high intensity radioactive beams provided by RIBF enabled a high-resolution measurement yielding a low-energy peak with a statistical significance well beyond the 5σ level.

- Next generation experiments - where four neutron systems are accessed in different ways and where all four neutrons are detected.

- Further, elaborate ab initio nuclear theories accounting fully for the effect of the continuum are needed in order to understand the observed low-energy peak and its origin.

# Observation of a correlated free four-neutron system

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Thank you!!