# RECENT RESULT ON THE 4N SYSTEM FROM SAMURAI@RIKEN

Meytal Duer, TU Darmstadt

NUSTAR Annual Meeting 2023
March 1st, 2023

# AT AND BEYOND THE NEUTRON DRIP-LINE

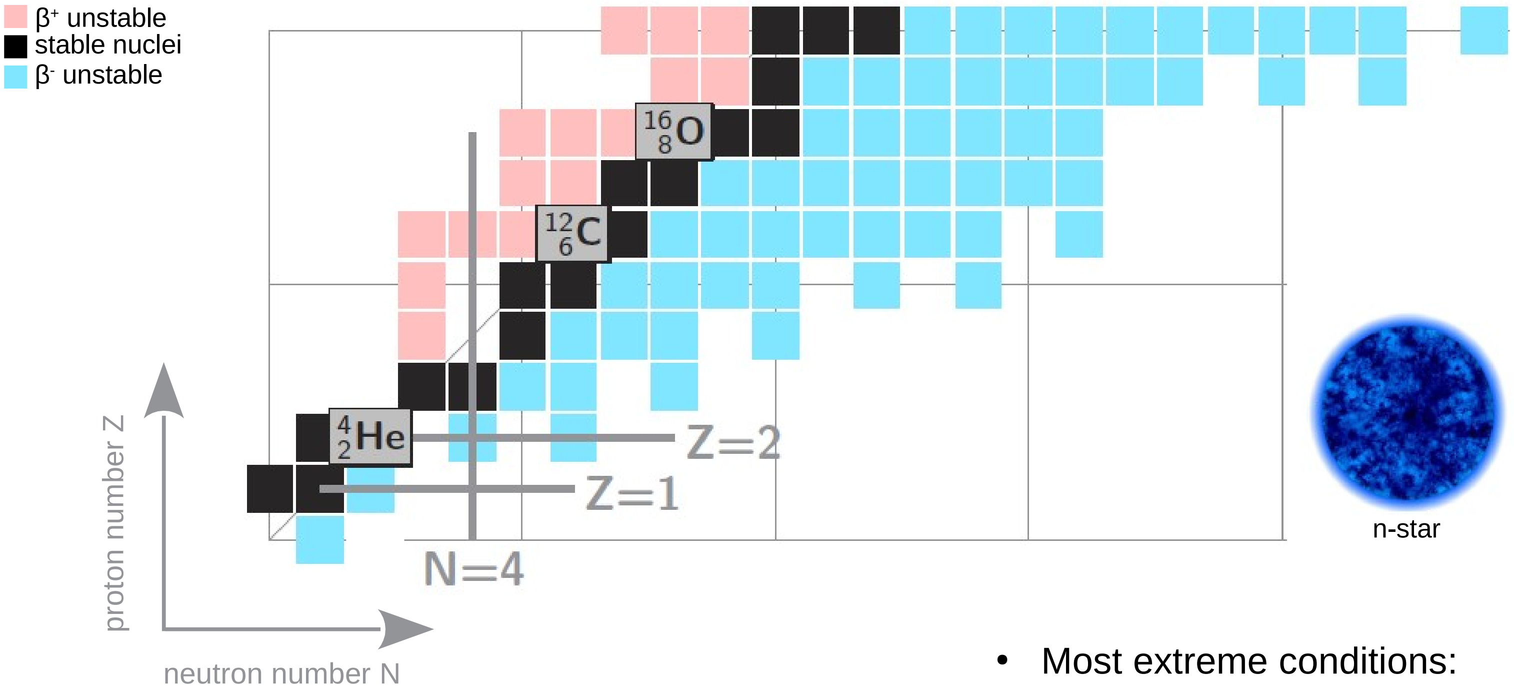


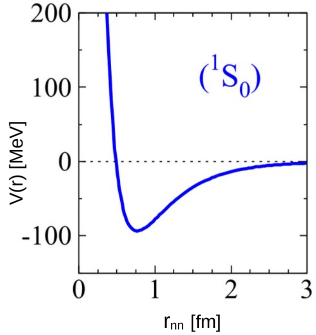

Figure from Marqués, EPJP 136 (2021)

- Most extreme conditions:
  large N/Z asymmetry and low-density
- Neutron halo/skin
- **Correlations: di-neutron, neutron droplets**
- Neutron matter, and more..

# DI-NEUTRON CORRELATIONS

Low-denisty nuclear matter

- neutron-neutron interactions dominated by attractive *S*-wave
  - di-neutron unbound by ~100 keV
  - large scattering length: $a_{nn}$=-18.9(4) fm
  - **strong correlations even at very low-density**



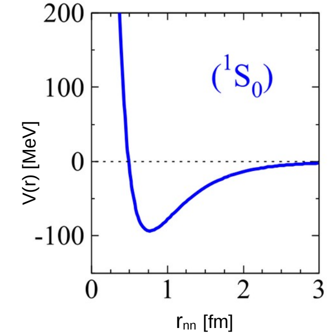

Marqués, EPJP 136 (2021)

# DI-NEUTRON CORRELATIONS

TECHNISCHE UNIVERSITÄT DARMSTADT

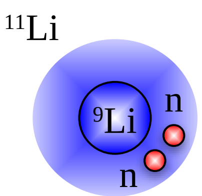
Low-denisty nuclear matter

- neutron-neutron interactions dominated by attractive *S*-wave
  - di-neutron unbound by ~100 keV
  - large scattering length: $a_{nn}$=-18.9(4) fm
  - **strong correlations even at very low-density**

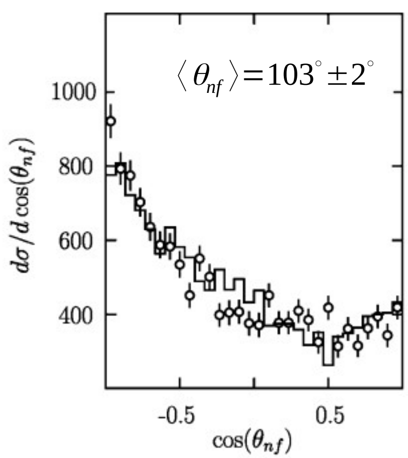



Marqués, EPJP 136 (2021)

## Di-neutron correlations in $^{11}$Li

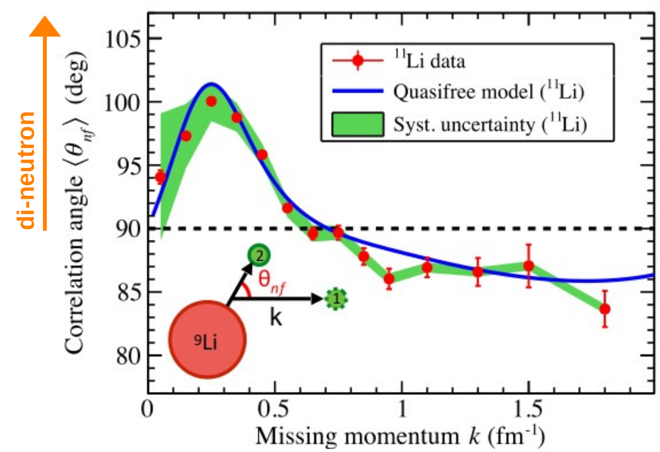



ALDAIN@GSI
C induced n-knockout




Simon *et al.*, PRL 83 (1999)

SAMURAI@RIKEN
p induced n-knockout




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

# MULTI-NEUTRON SYSTEMS

TECHNISCHE UNIVERSITÄT DARMSTADT

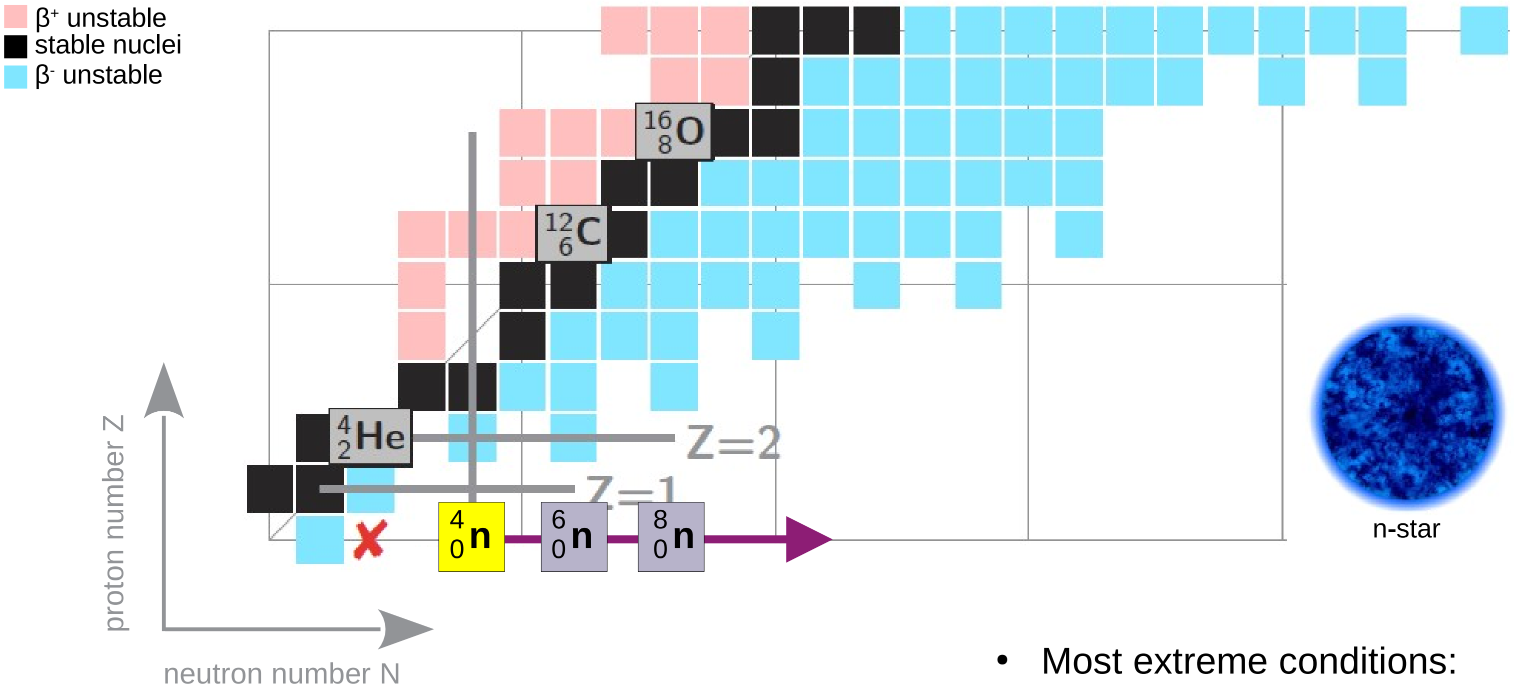



Figure from Marqués, EPJP 136 (2021)

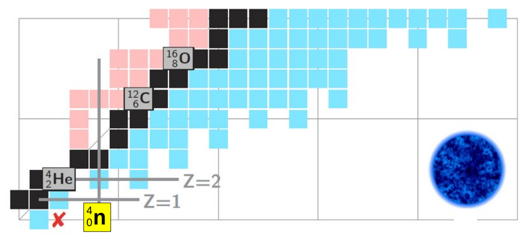
- Most extreme conditions:
  large N/Z asymmetry and low-density
- Neutron halo/skin
- **Correlations: di-neutron, neutron droplets**
- Neutron matter, and more..

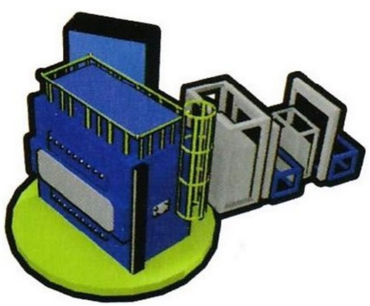
# OUTLINE

TECHNISCHE UNIVERSITÄT DARMSTADT

❶ **The tetra-neutron context**

- experimental quest
- theoretical predictions



❷ **The 4n experiment at SAMURAI: quasi-free α-knockout reaction**

- experimental method
- results and discussion

❸ **Future perspectives**

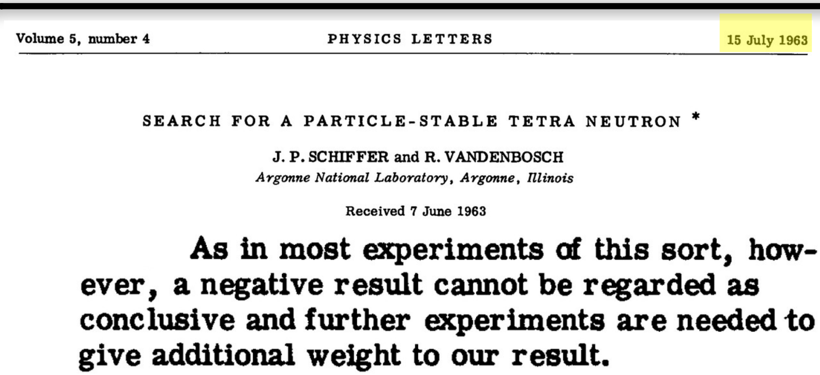
next-generation experiments

# A 60-YEAR QUEST

TECHNISCHE UNIVERSITÄT DARMSTADT

## XX century:

- fission of uranium
  e.g. Schiffer & Vandenbosch, Phys. Lett. 5 (1963)



Volume 5, number 4 PHYSICS LETTERS 15 July 1963

SEARCH FOR A PARTICLE-STABLE TETRA NEUTRON *

J. P. SCHIFFER and R. VANDENBOSCH
*Argonne National Laboratory, Argonne, Illinois*

Received 7 June 1963

**As in most experiments of this sort, however, a negative result cannot be regarded as conclusive and further experiments are needed to give additional weight to our result.**

- transfer reactions
  e.g. Cerny et al., Phys. Lett. 53B (1974)
- double-charge-exchange $^{4}He(\pi^{-},\pi^{+})$ reaction
  e.g. Ungar et al., Phys. Lett. B 144 (1984)

➢ No indication for a tetra-neutron

## XXI century:

radioactive-ion beams

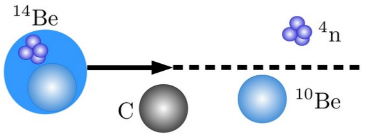
➢ first positive signals

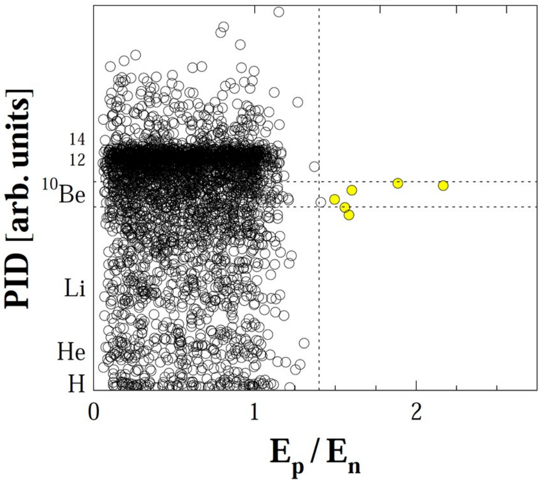
# THE ELUSIVE TETRA-NEUTRON

TECHNISCHE UNIVERSITÄT DARMSTADT

GANIL 2002

breakup reaction:




6 candidates: bound $^{4}$n or low-energy resonance ($E_r$<2 MeV)

Marqués *et al.*, PRC 65 (2002)

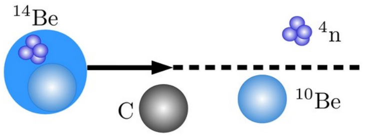
Marqués *et al.*, arXiv:nucl-ex/0504009 (2005)

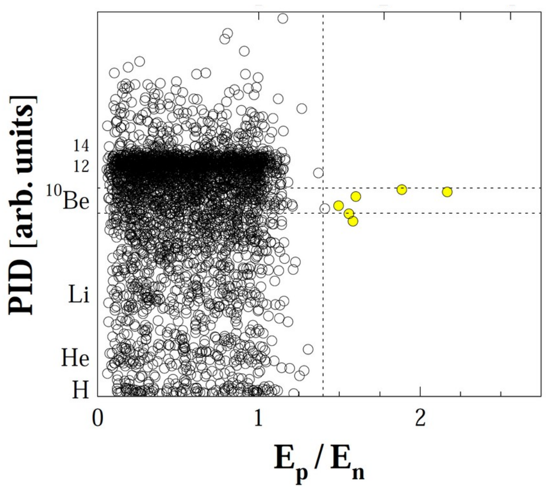
# THE ELUSIVE TETRA-NEUTRON

TECHNISCHE UNIVERSITÄT DARMSTADT

## GANIL 2002

breakup reaction:



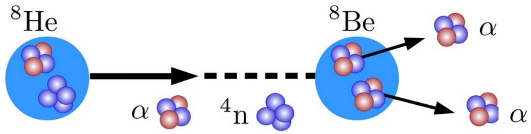

6 candidates: bound $^4$n or low-energy resonance ($E_r$<2 MeV)

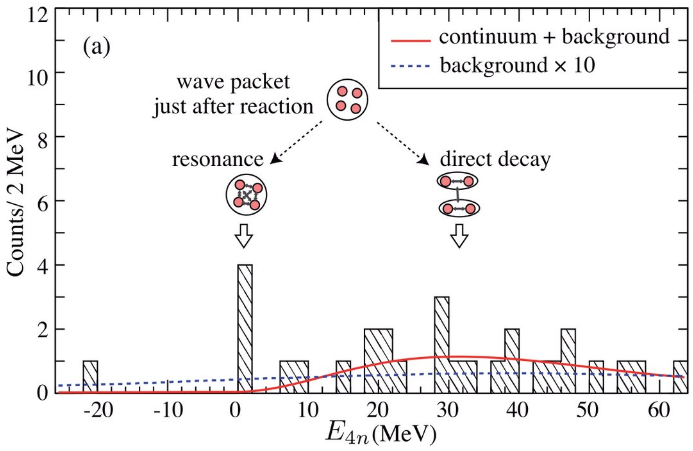
Marqués *et al.*, PRC 65 (2002)

Marqués *et al.*, arXiv:nucl-ex/0504009 (2005)

## RIKEN 2016

double-charge-exchange:




4 candidates for $^4$n resonance: $E_r$=0.8±1.4 MeV, Γ<2.6 MeV

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

# TETRA-NEUTRON RESONANCE?

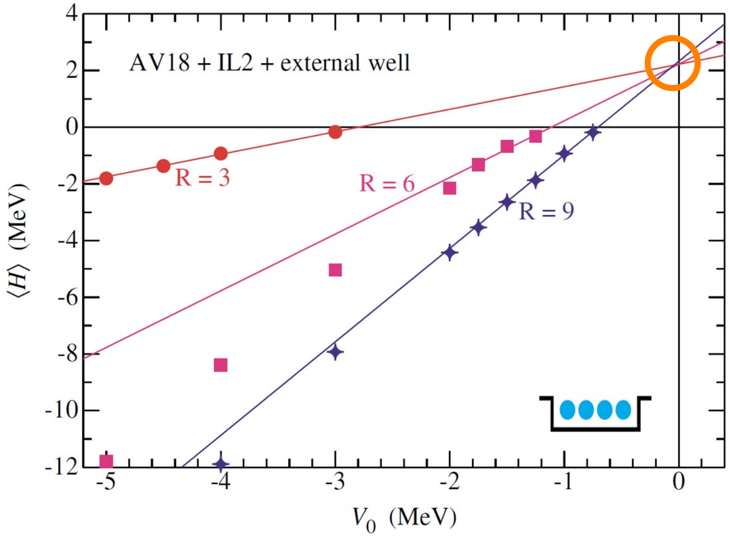
TECHNISCHE UNIVERSITÄT DARMSTADT

Historical consensus: **no bound tetra-neutron**

Pieper PRL 90, 2003:

$$H=\sum_{i=1}^{A} T_i+\sum_{i<j=1}^{A} V_{ij}+\sum_{i<j<k=1}^{A} V_{ijk}+\sum_{i=1}^{A} V_{WS}(r_i)$$

- neutrons trapped in Woods-Saxon potential with radius R and depth $V_0$
- resonance energy by extrapolation to $V_0 \to 0$
- **possible resonance around 2 MeV**



# TETRA-NEUTRON RESONANCE?

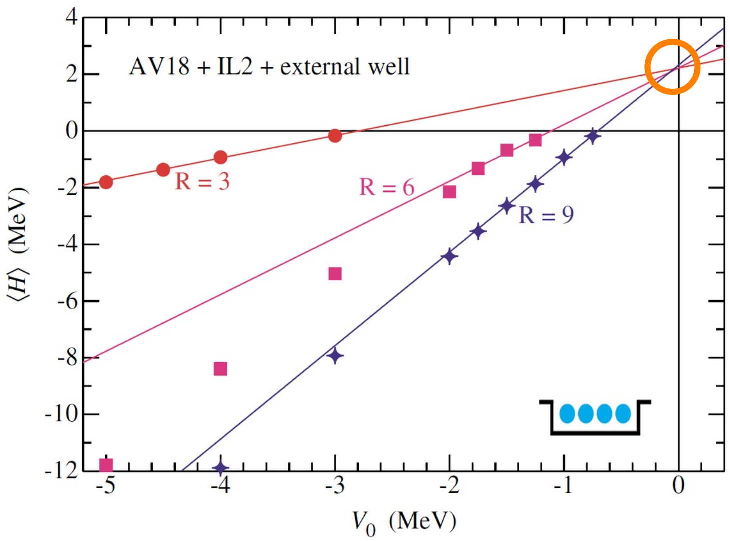
TECHNISCHE UNIVERSITÄT DARMSTADT

Historical consensus: **no bound tetra-neutron**

<u>Pieper PRL 90, 2003:</u>

$$H=\sum_{i=1}^{A} T_i + \sum_{i<j=1}^{A} V_{ij} + \sum_{i<j<k=1}^{A} V_{ijk} + \sum_{i=1}^{A} V_{WS}(r_i)$$

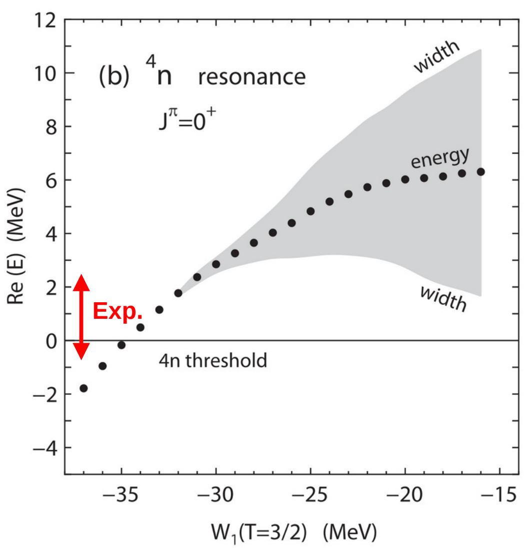
- neutrons trapped in Woods-Saxon potential with radius R and depth $V_0$
- resonance energy by extrapolation to $V_0 \to 0$
- **possible resonance around 2 MeV**




<u>Hiyama *et al.*, PRC 93, 2016:</u>

Full treatment of continuum

- no 4n resonance
- resonance behaviour only for **unrealistic attractive T=3/2 3N force**
  - 15 times larger than T=1/2
  - inconsistent with known light nuclei



# TETRA-NEUTRON RESONANCE?

TECHNISCHE UNIVERSITÄT DARMSTADT

All studies agree on:

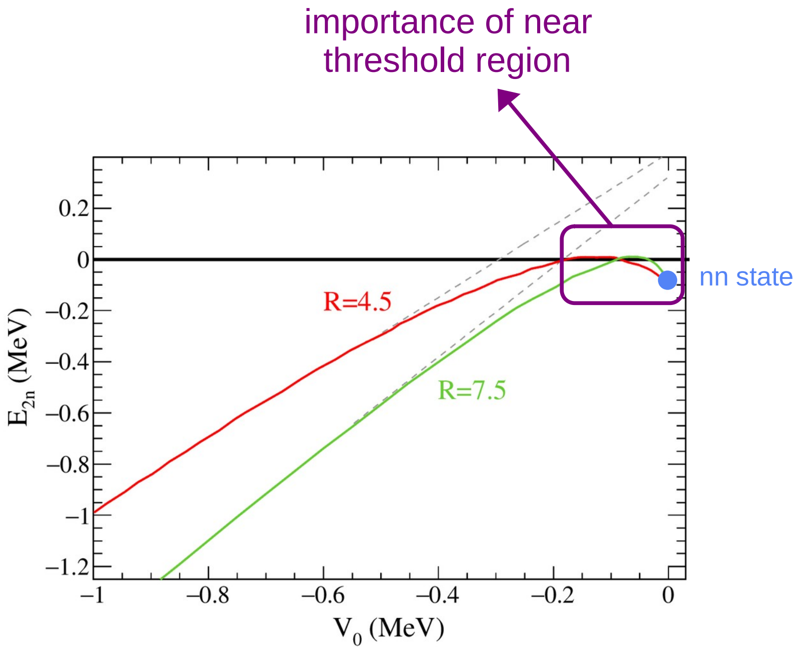
- dominance of $V_{nn}$ ($^1S_0$)
- negligible contribution of 3N force

Contradictory results:

- do not origin from different interactions
- methods to solve the few-neutron problem
  and/or
  **treatment of the continuum**

From bound state to the continuum

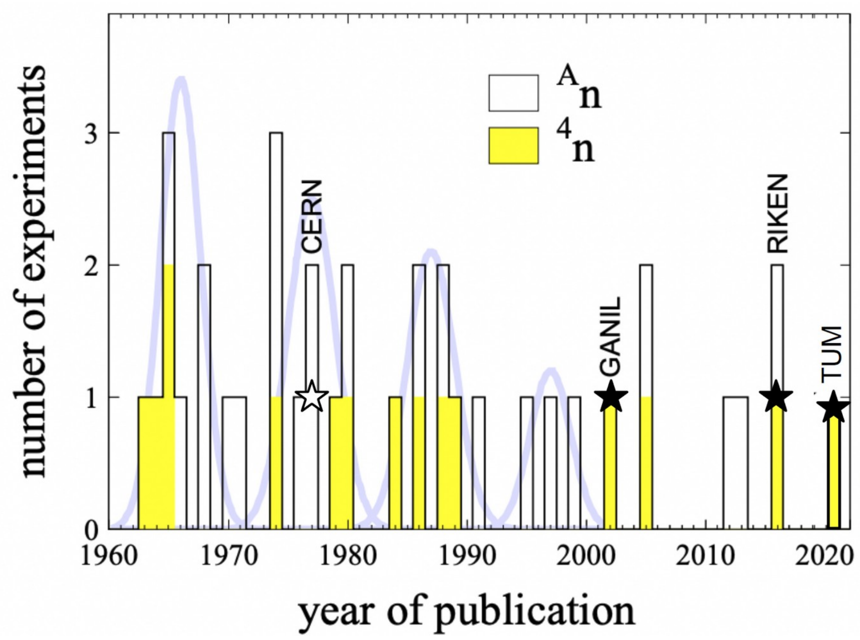
example: 2n ($^1S_0$) confined in a trap




Modified from Deltuva & Lazauskas, PRL 123 (2019)

# A 60-YEAR QUEST

TECHNISCHE UNIVERSITÄT DARMSTADT




Modified from Marqués & Carbonell, EPJA 57 (2021)

Experiment:

- so far, three (weak) positive signals:
  ★ GANIL 2002, RIKEN 2016, TUM 2022
  indications for bound / unbound

Theory:

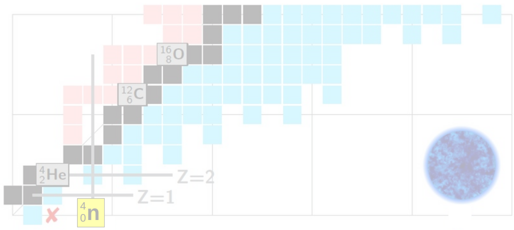
- no bound 4n
- no consensus about a resonant state

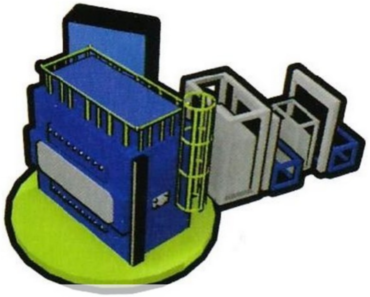
# OUTLINE

TECHNISCHE UNIVERSITÄT DARMSTADT

❶ **The tetra-neutron context**

- experimental quest
- theoretical predictions



❷ **The 4n experiment at SAMURAI: quasi-free α-knockout reaction**

- experimental method
- results and discussion

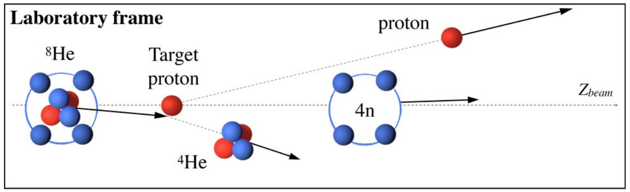
❸ **Future perspectives**

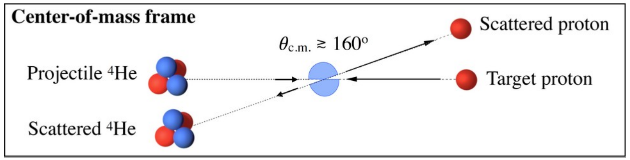
next-generation experiments

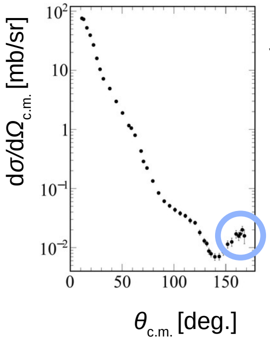
# PRESENT EXPERIMENTAL WORK

## Quasi-free knockout $^{8}He(p,p^{4}He)$ at 156 AMeV

- Large momentum transfer
  - sudden removal of an α-particle from $^{8}He$
  - 4n as spectators




elastic p-$^{4}$He @ 156 MeV
V. Comparat *et al.*, PRC (1975)

this experiment

# PRESENT EXPERIMENTAL WORK

TECHNISCHE UNIVERSITÄT DARMSTADT

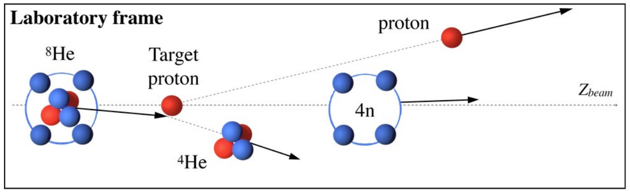
## Quasi-free knockout $^8$He(p,p$^4$He) at 156 AMeV

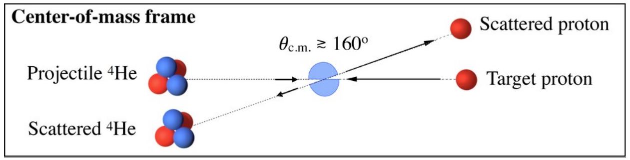
- Large momentum transfer
  - sudden removal of an α-particle from $^8$He
  - 4n as spectators

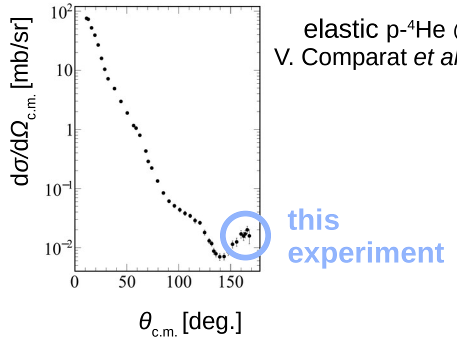
- 4n energy spectrum via **missing-mass**
  - precise measurement of charged particles

$$P_{miss} = P_{^8He} + P_{p(tgt)} - P_{^4He} - P_p$$

$$E_{4n} = \sqrt{E_{miss}^2 - \boldsymbol{P}_{miss}^2} - 4\,m_n$$



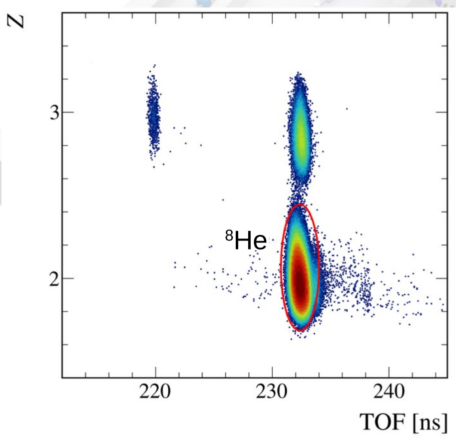



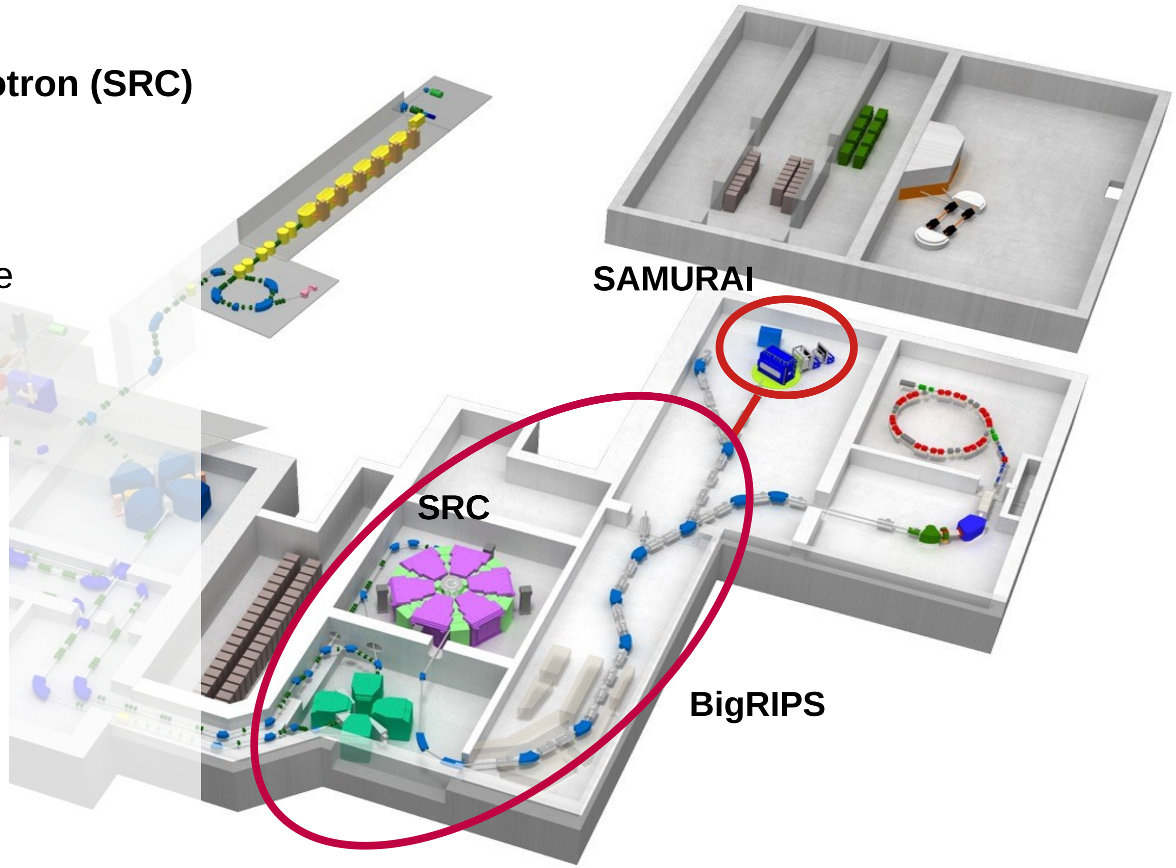

elastic p-$^4$He @ 156 MeV
V. Comparat *et al.*, PRC (1975)

# THE RADIOACTIVE ION BEAM FACTORY (RIBF)

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Superconducting Ring Cyclotron (SRC)**
  primary $^{18}O$ beam
- **BigRIPS fragment separator**
  production and selection of $^{8}He$
- **SAMURAI setup**

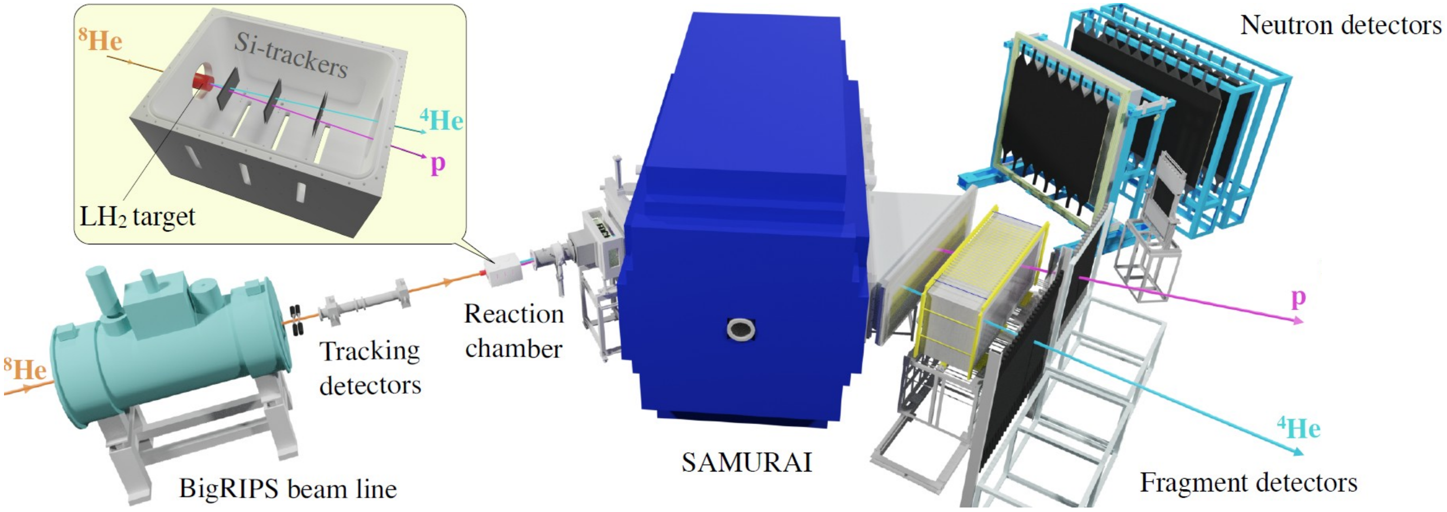


# SAMURAI SETUP AT RIBF

TECHNISCHE UNIVERSITÄT DARMSTADT

**SAMURAI dipole magent:** 1.25 T (up to 3 T)
Tracking & PID of **$^{8}$He beam**
Tracking & PID of **fragments (p, $^{4}$He)**
**Neutrons** (not possible in this experiment)



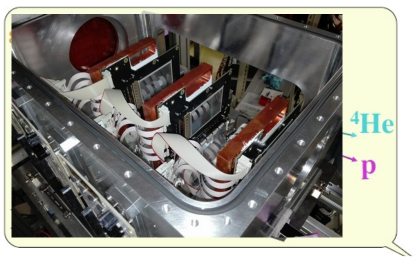
# SAMURAI SETUP AT RIBF

**SAMURAI dipole magent:** 1.25 T (up to 3 T)

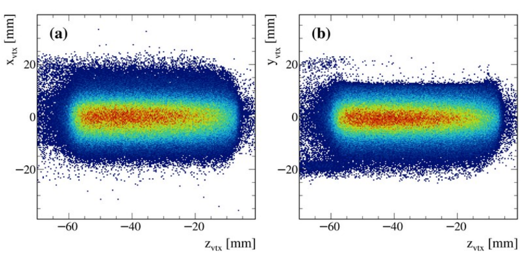
Tracking & PID of **$^{8}$He beam**

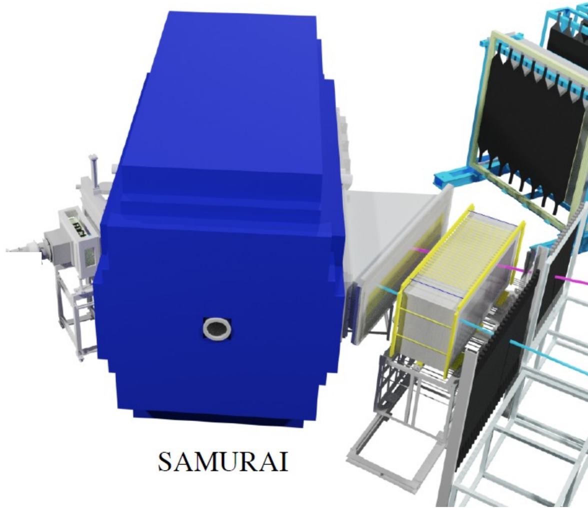
Tracking & PID of **fragments (p, $^{4}$He)**

**Neutrons** (not possible in this experiment)

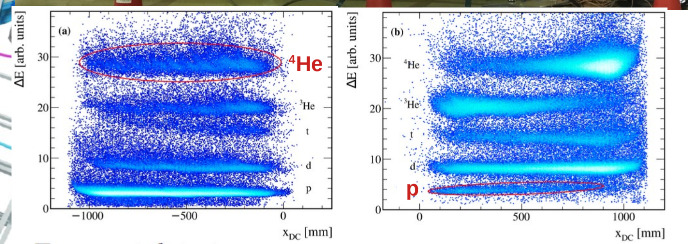



reaction vertex reconstruction at target



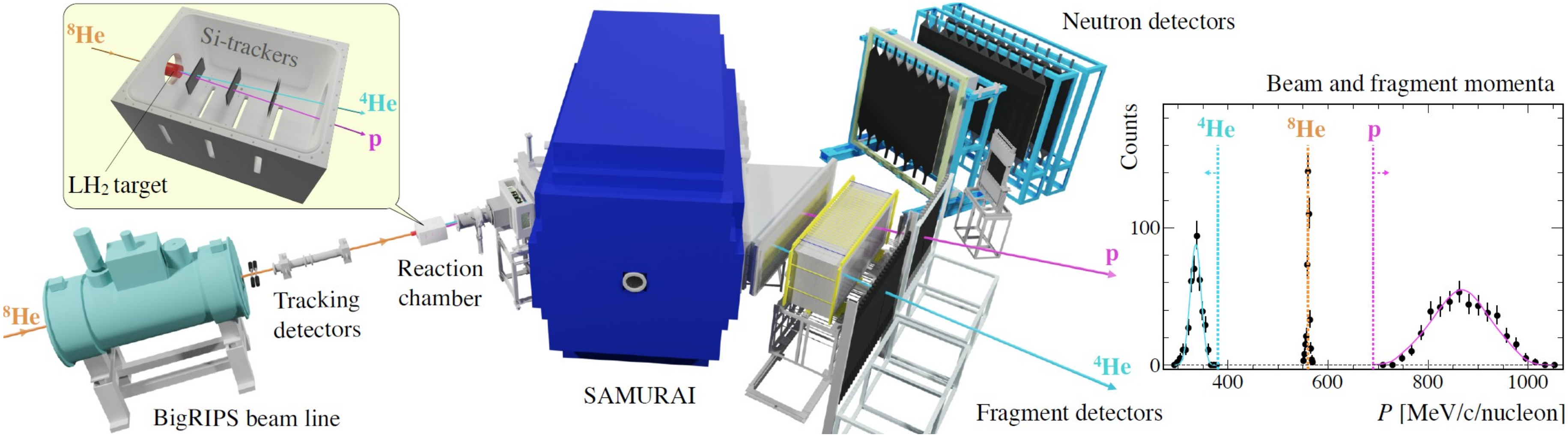
SAMURAI




Fragment detectors

# SAMURAI SETUP AT RIBF

**SAMURAI dipole magent:** 1.25 T (up to 3 T)
Tracking & PID of $^{8}$**He beam**
Tracking & PID of **fragments (p, $^{4}$He)**
**Neutrons** (not possible in this experiment)



# SAMURAI SETUP AT RIBF

**SAMURAI dipole magent:** 1.25 T (up to 3 T)

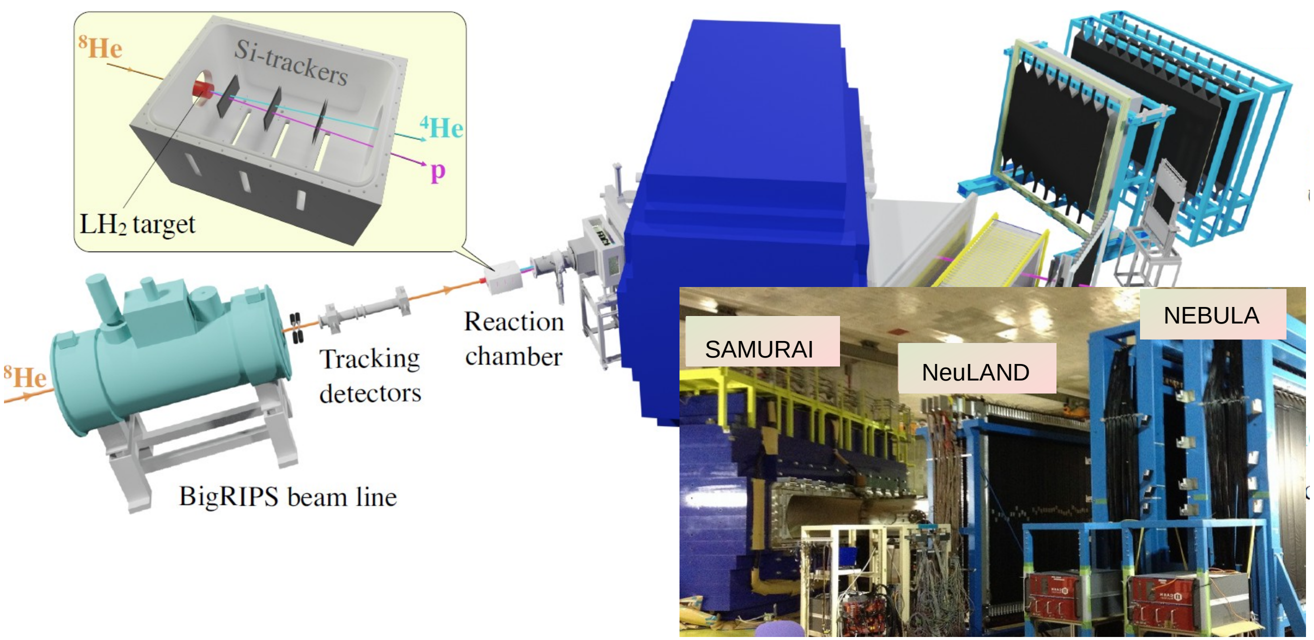
Tracking & PID of **$^{8}$He beam**

Tracking & PID of **fragments (p, $^{4}$He)**

**Neutrons** (not possible in this experiment)

## NeuLAND demonstrator (R$^{3}$B) + NEBULA

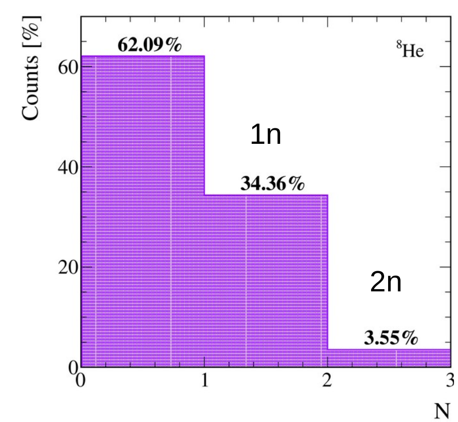
successful experimental campaign (2015-2017)




### In this measurement:

small p-$^{4}$He cross section ~1 μb

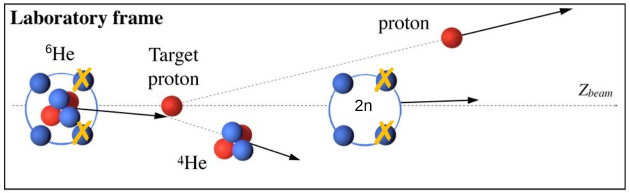
- relatively low statistics $^{8}$He(p,p$^{4}$He)
- 4n detection impossible



# RESULTS: MISSING-MASS SPECTRA

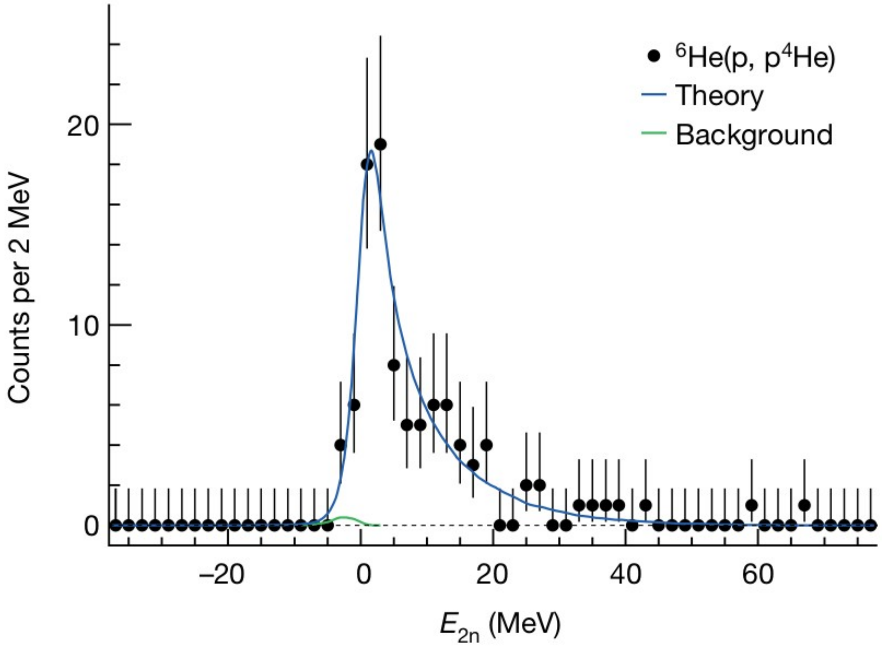
## Benchmark measurement:

- quasi-free knockout $^6He(p,p^4He)$




- 2n relative-energy spectrum is expected to be well described by theory
- theoretical input M. Göbel *et al*., PRC 104 (2021)
  - 3-body ($^4He$+2n) cluster model
  - nn final-state interaction

## $^6He(p,p^4He)2n$

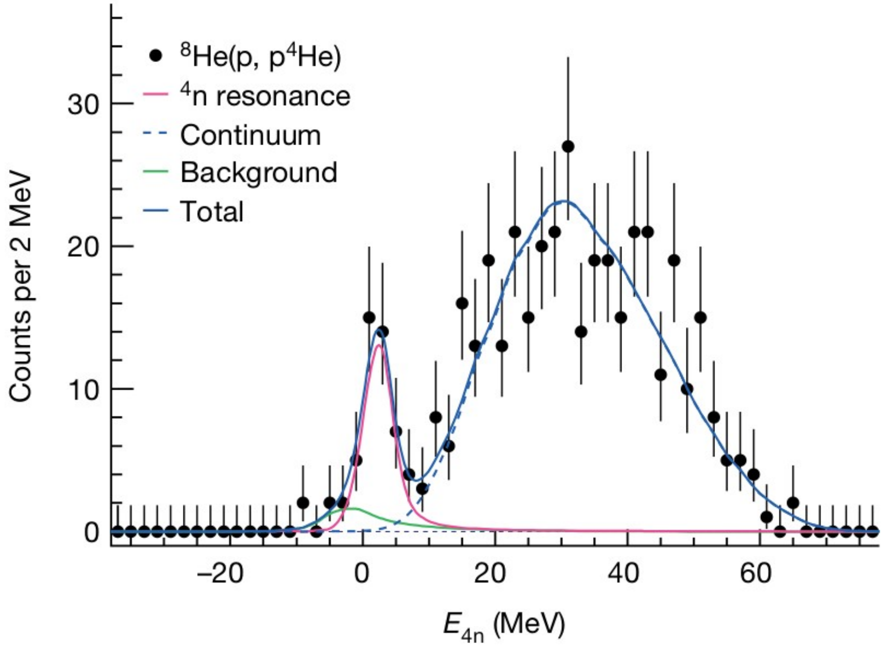



**confirms the expected di-neutron low-energy peak ~100 keV**

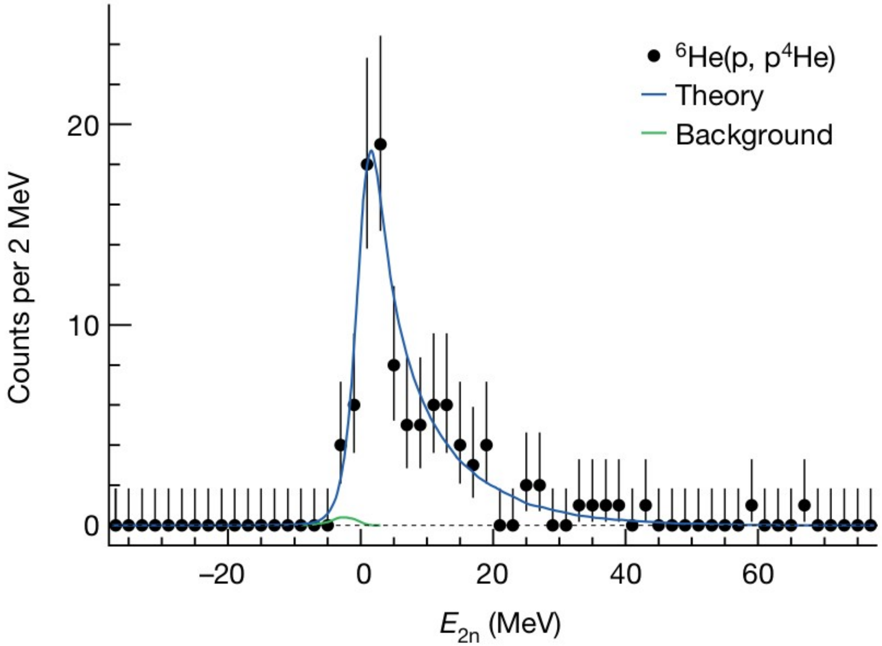
# RESULTS: MISSING-MASS SPECTRA

TECHNISCHE UNIVERSITÄT DARMSTADT

## $^{8}He(p,p^{4}He)4n$




## $^{6}He(p,p^{4}He)2n$



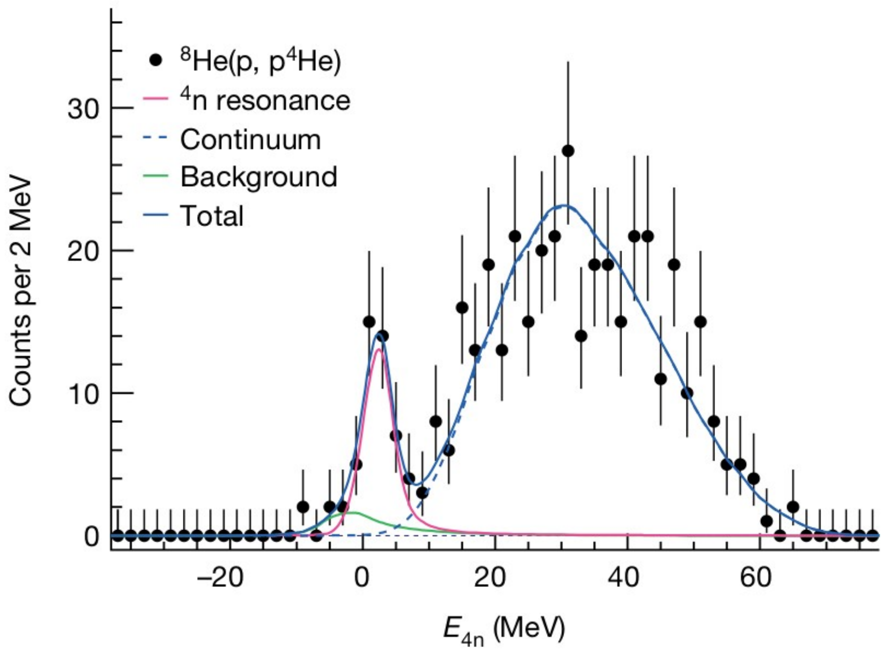

**confirms the expected di-neutron low-energy peak ~100 keV**

MD *et al.*, Nature 606, 678 (2022)

# RESULTS: MISSING-MASS SPECTRA

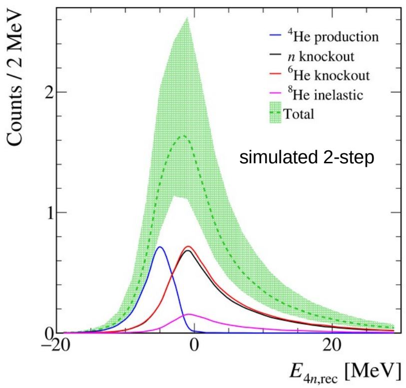
TECHNISCHE UNIVERSITÄT DARMSTADT

### $^{8}He(p,p^{4}He)4n$




MD *et al.*, Nature 606, 678 (2022)

- Continuum component:
  five-body ($^{4}He+4n$) COSMA model
  Zhukov *et al.*, PRC (1994); Grigorenko *et al.*, EPJA (2004)
- Background estimate: two-step reactions (~3%)

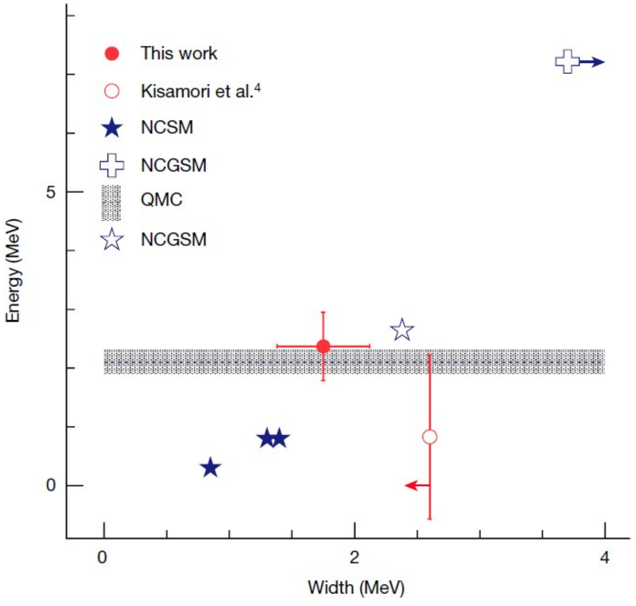



- **Resonance like-structure:**
  **$E_r$ = 2.37±0.38(stat.)±0.44(sys.) MeV**
  **Γ = 1.75±0.22(stat.)±0.30(sys.) MeV**

# A TETRA-NEUTRON CORRELATION?

TECHNISCHE UNIVERSITÄT DARMSTADT

***Predictions for a tetra-neutron***

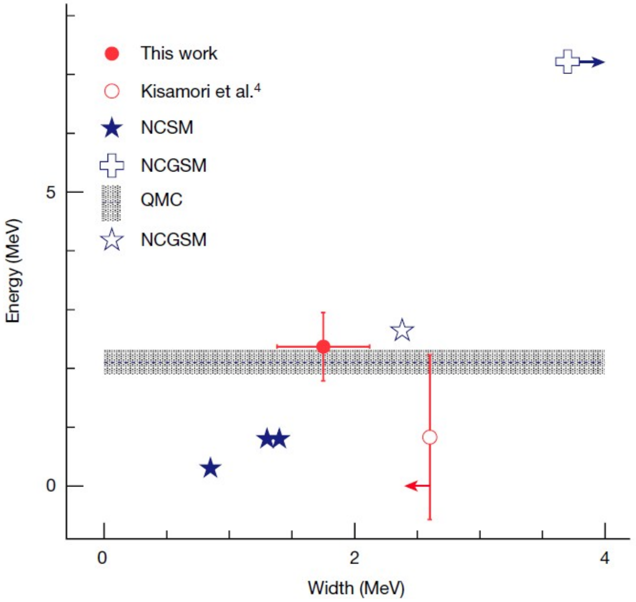



Shirokov PRL 117 (2016); Gandolfi PRL 118 (2017);
Fossez PRL 119 (2017); Li PRC 100 (2019);

# A TETRA-NEUTRON CORRELATION?

TECHNISCHE UNIVERSITÄT DARMSTADT

***Predictions for a tetra-neutron***



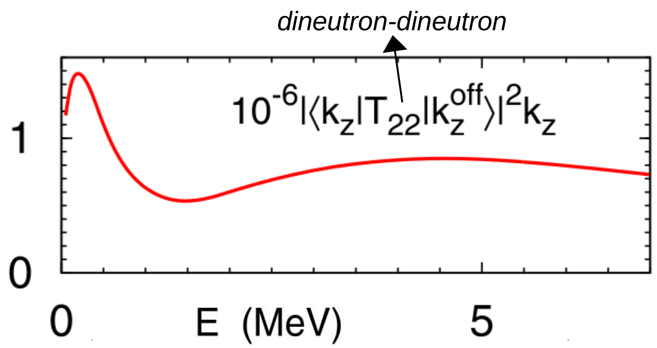

★ Shirokov PRL 117 (2016); Gandolfi PRL 118 (2017);
Fossez PRL 119 (2017); ☆ Li PRC 100 (2019);

*Full treatment of continuum* → ***No tetra-neutron***

A recent erview: Marqués & Carbonell, EPJA 57 (2021)

***Low-energy structures***

*"the four-neutron system is studied using exact continuum equations for transition operators... This indicates the absence of an observable 4n resonance, in contrast to a number of earlier works.* ***Even without an observable resonance the transition operators exhibit pronounced low-energy peaks****"*

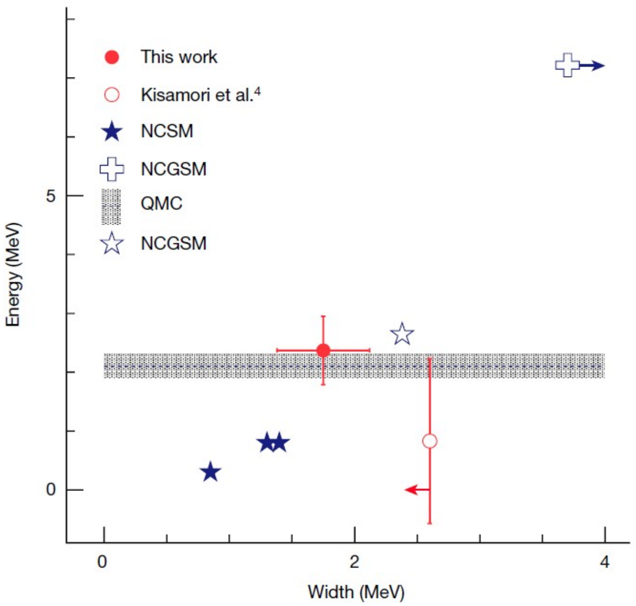



Deltuva, PLB 782 (2018)

# A TETRA-NEUTRON CORRELATION?

TECHNISCHE UNIVERSITÄT DARMSTADT

***Predictions for a tetra-neutron***



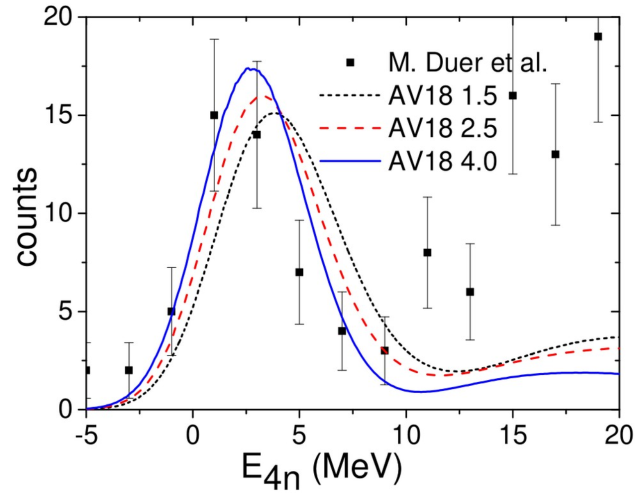

★ Shirokov PRL 117 (2016); ▒ Gandolfi PRL 118 (2017);
✚ Fossez PRL 119 (2017); ☆ Li PRC 100 (2019);

*Full treatment of continuum* → ***No tetra-neutron***

A recent erview: Marqués & Carbonell, EPJA 57 (2021)

***Low-energy structures***

***Dineutron-dineutron correlations?***




Laszauskas, Hiyama, Carbonell, arXiv:2207.07575v2 [nucl-th] (2022) accepted in PRL (Feb. 2023)

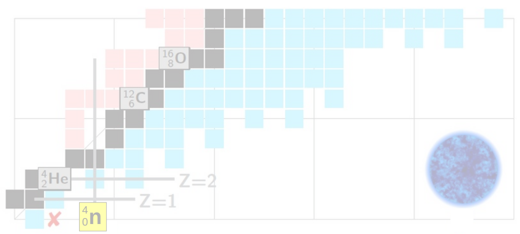
*"we propose a natural explanation for the low energy structure: it emerges as* ***a consequence of final state interaction among the 4n and the -important- presence of four neutrons in the periphery of the $^{8}$He projectile****"*

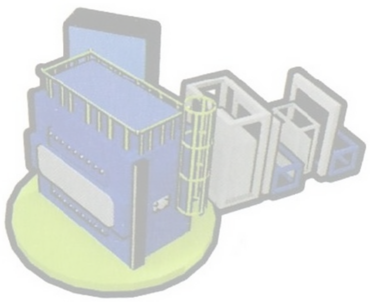
# OUTLINE

TECHNISCHE UNIVERSITÄT DARMSTADT

## ➊ The tetra-neutron context

- experimental quest
- theoretical predictions



## ➋ The 4n experiment at SAMURAI: quasi-free α-knockout reaction

- experimental method
- results and discussion

## ❸ Future perspectives

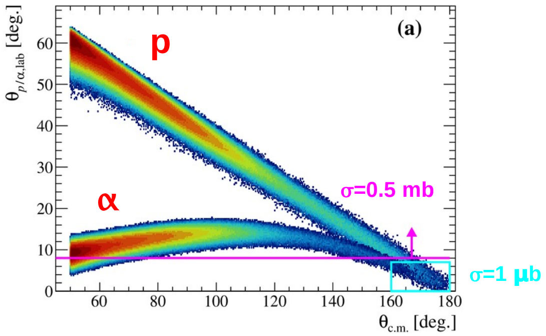
next-generation experiments

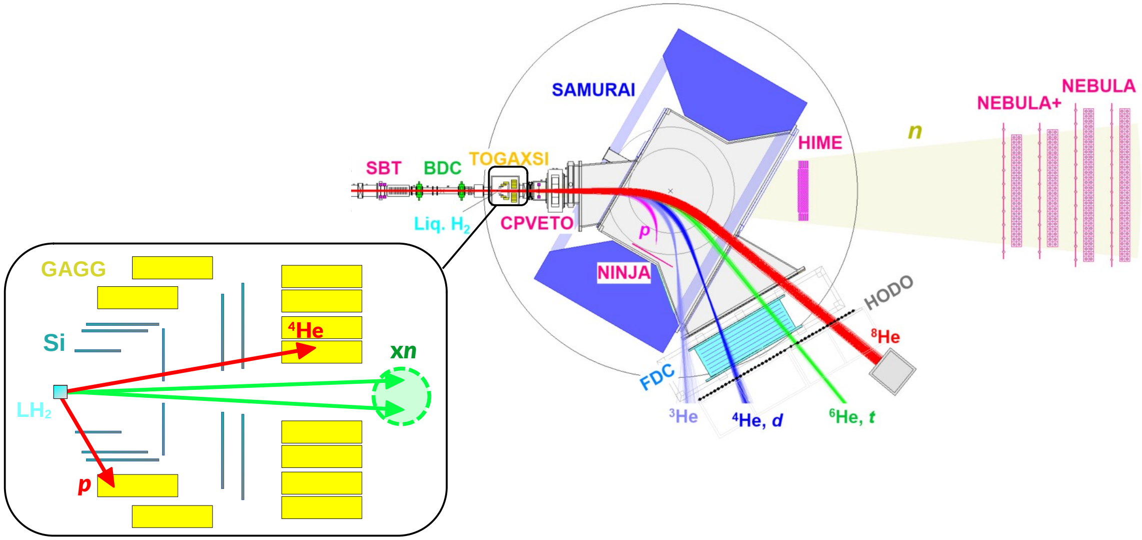
# FUTURE PERSPECTIVES

TECHNISCHE UNIVERSITÄT DARMSTADT

**1. Correlations in multi-neutron systems** Accepted proposal 2022 (SAMURAI74), K. Miki, MD, T. Uesaka *et al.*

- **Neutron detection: exclusive $^{8}$He(p,pα)4n**
  all four neutrons in coincidence



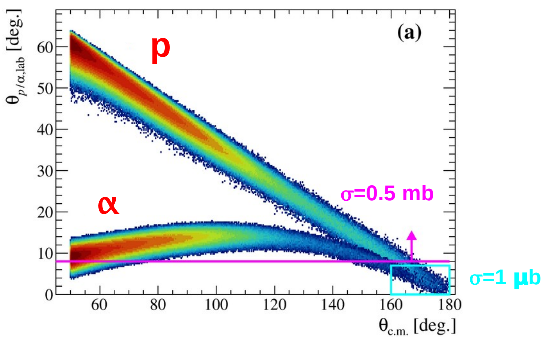



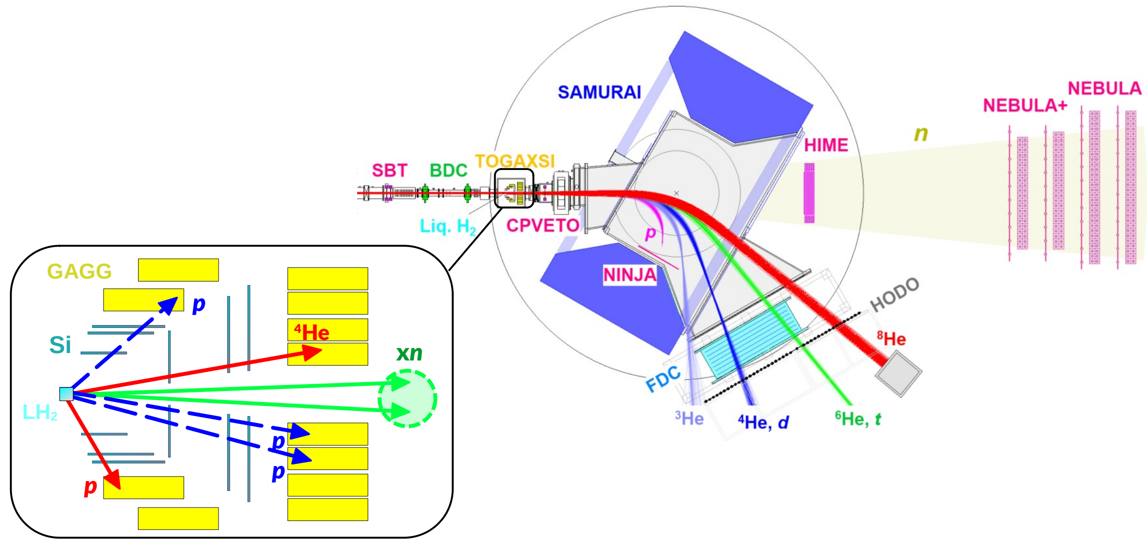
# FUTURE PERSPECTIVES

TECHNISCHE
UNIVERSITÄT
DARMSTADT

**1. Correlations in multi-neutron systems** Accepted proposal 2022 (SAMURAI74), K. Miki, MD, T. Uesaka *et al.*

- **Neutron detection: exclusive $^{8}$He(p,pα)4n**
  all four neutrons in coincidence



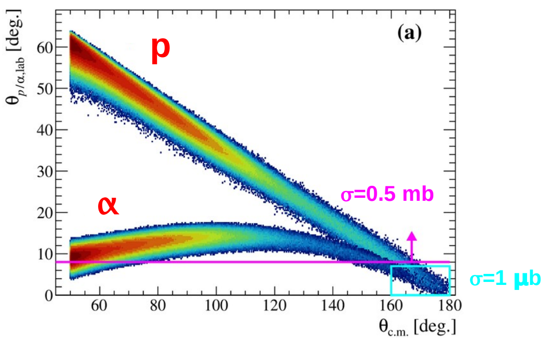

- **Reaction mechanism: $^{6}$He(p,3p)4n knockout**
  investigate 6n via $^{8}$He(p,3p) knockout (missing-mass)

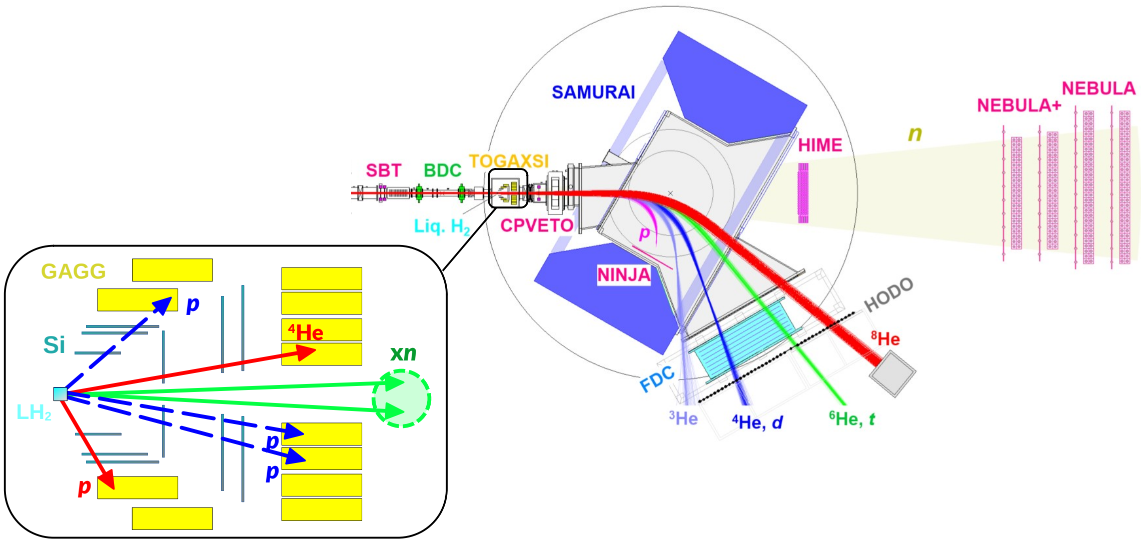
# FUTURE PERSPECTIVES

TECHNISCHE UNIVERSITÄT DARMSTADT

## 1. Correlations in multi-neutron systems
Accepted proposal 2022 (SAMURAI74), K. Miki, MD, T. Uesaka *et al.*

- **Neutron detection: exclusive $^{8}$He(p,pα)4n**
  all four neutrons in coincidence

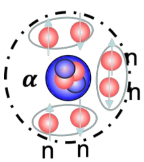



- **Reaction mechanism: $^{6}$He(p,3p)4n knockout**
  investigate 6n via $^{8}$He(p,3p) knockout (missing-mass)

## 2. nn correlations from $^{10}$He decay
T. Nakamura *et al.* (SAMURAI47), 2023

- $^{11}$Li(p,2p) knockout: $^{10}$He → $^{8}$He + 2n / $^{6}$He + 4n / $^{4}$He + 6n
  - mainly missing-mass: (p,2p) + fragment
  - 2n in coincidence



# *Thank you!*

**SAMURAI19 experiment:** M. Duer, T. Aumann, R. Gernhäuser, V. Panin, S. Paschalis, D. M. Rossi, N. L. Achouri, D. Ahn, H. Baba, C. A. Bertulani, M. Böhmer, K. Boretzky, C. Caesar, N. Chiga, A. Corsi, D. Cortina-Gil, C. A. Douma, F. Dufter, Z. Elekes, J. Feng, B. Fernández-Domínguez, U. Forsberg, N. Fukuda, I. Gasparic, Z. Ge, J. M. Gheller, J. Gibelin, A. Gillibert, K. I. Hahn, Z. Halász, M. N. Harakeh, A. Hirayama, M. Holl, N. Inabe, T. Isobe, J. Kahlbow, N. Kalantar-Nayestanaki, D. Kim, S. Kim, T. Kobayashi, Y. Kondo, D. Körper, P. Koseoglou, Y. Kubota, I. Kuti, P. J. Li, C. Lehr, S. Lindberg, Y. Liu, F. M. Marqués, S. Masuoka, M. Matsumoto, J. Mayer, K. Miki, B. Monteagudo, T. Nakamura, T. Nilsson, A. Obertelli, N. A. Orr, H. Otsu, S. Y. Park, M. Parlog, P. M. Potlog, S. Reichert, A. Revel, A. T. Saito, M. Sasano, H. Scheit, F. Schindler, S. Shimoura, H. Simon, L. Stuhl, H. Suzuki, D. Symochko, H. Takeda, J. Tanaka, Y. Togano, T. Tomai, H. T. Törnqvist, J. Tscheuschner, T. Uesaka, V. Wagner, H. Yamada, B. Yang, L. Yang, Z. H. Yang, M. Yasuda, K. Yoneda, L. Zanetti, J. Zenihiro, and M. V. Zhukov.