Part 4
From single-particle spectroscopy to correlation studies

Physics cases with (*p*,*pX*) reaction in RI beam experiments

Single-particle spectroscopy of nucleons and clusters

- Quenching of single particle strengths
- Spin-orbit coupling } w/ a polarized target
- Medium effects on the NN scattering } w/ a polarized target
- Cluster physics

Study of neutron structure (change) using (*p*,2*p*) reaction:

Neutron-neutron correlation via combined analysis of (*p*,*pN*) reaction and decay

Why can we relate it to change of neutron structure

DWIA T-matrix

$$T = \langle \Psi_R \chi^{(-)}(k_{\rm out}) \chi^{(-)}(k_{ko}) \,|\, t_{pp} \,|\, \chi^{(+)}(k_{\rm in}) \Psi_A \rangle$$

Nuclear structure contribution comes from the overlap function $\langle \Psi_R | \Psi_A \rangle$.

$$\langle \Psi_R | \Psi_A \rangle = \langle \psi_R^n \phi_R^p | \psi_A^n \phi_A^p \rangle = \langle \psi_R^n | \psi_A^n \rangle \langle \phi_R^p | \phi_A^p \rangle$$

$$= \langle \psi_R^n | \psi_A^n \rangle \langle \psi_R^p | \{ \sum_i a_j \phi_{njl}^p \psi_R^p \} \rangle$$

When it can be safely assumed that the neutron structure doesn't change by a proton removal/addition, and thus $\langle \psi_R^n | \psi_A^n \rangle \sim 1$ and the "spectroscopic factor" a_j can be determined using the experimental data.

However, a proton is undoubtedly removed from some specific shell, the cross section is maily determined by the $\langle \psi_R^n | \psi_A^n \rangle$ term.

Can (p,2p) reaction be used to investigate neutron (shell) structure?

As you have learned, the (p,2p) reaction is a probe to proton single particle states.
Is it ridiculous to think about applying it to the study of neutron structure?

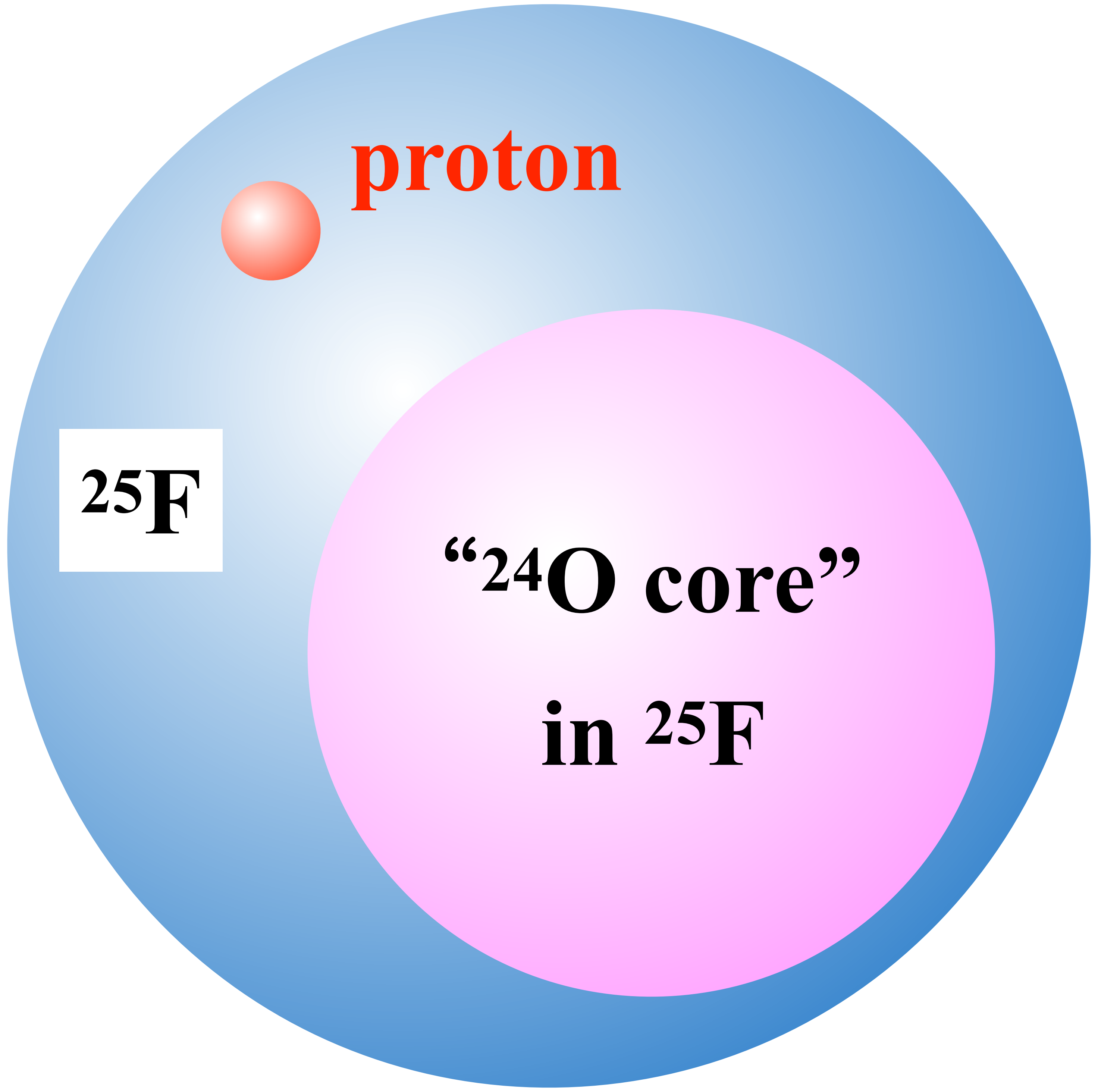
Case of a proton removal from ^{25}F

T.L. Tang et al., PRL 124, 212502 (2020).

T.L. Tang

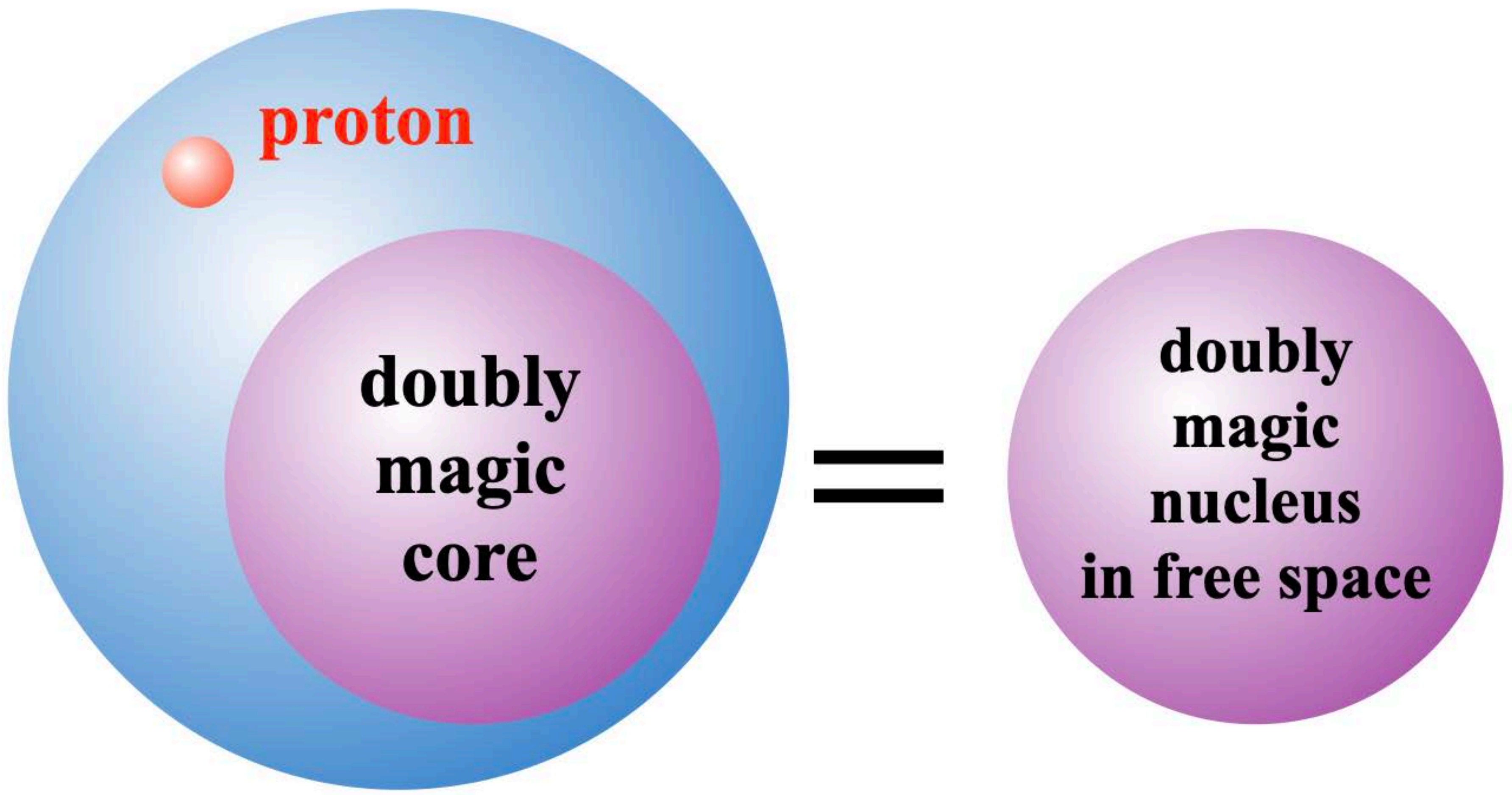
What happens if we remove a proton from ^{25}F?
Does the ground state of ^{24}O remain?

→ ^{25}F(p,2p) reaction @ RIBF

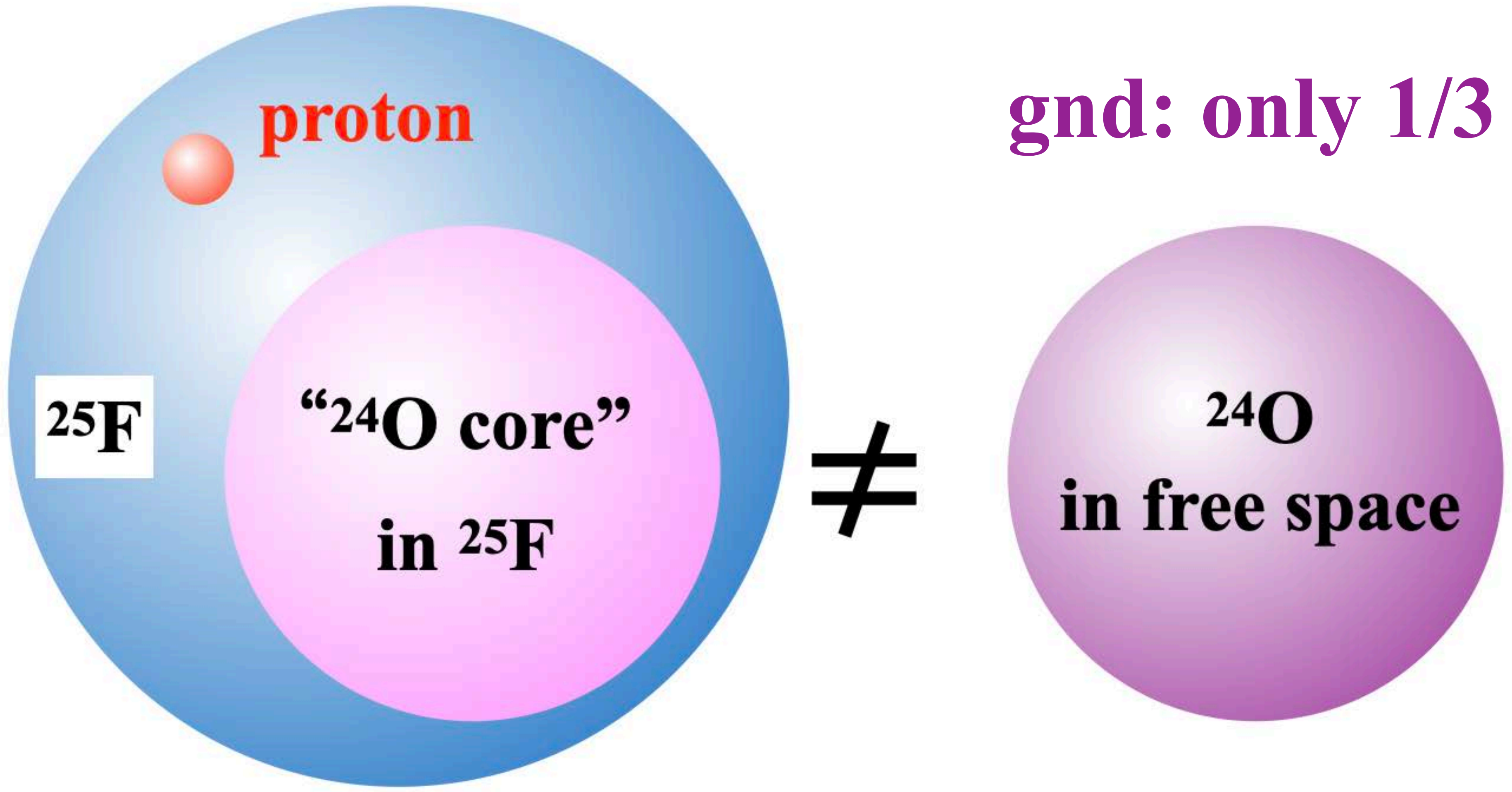


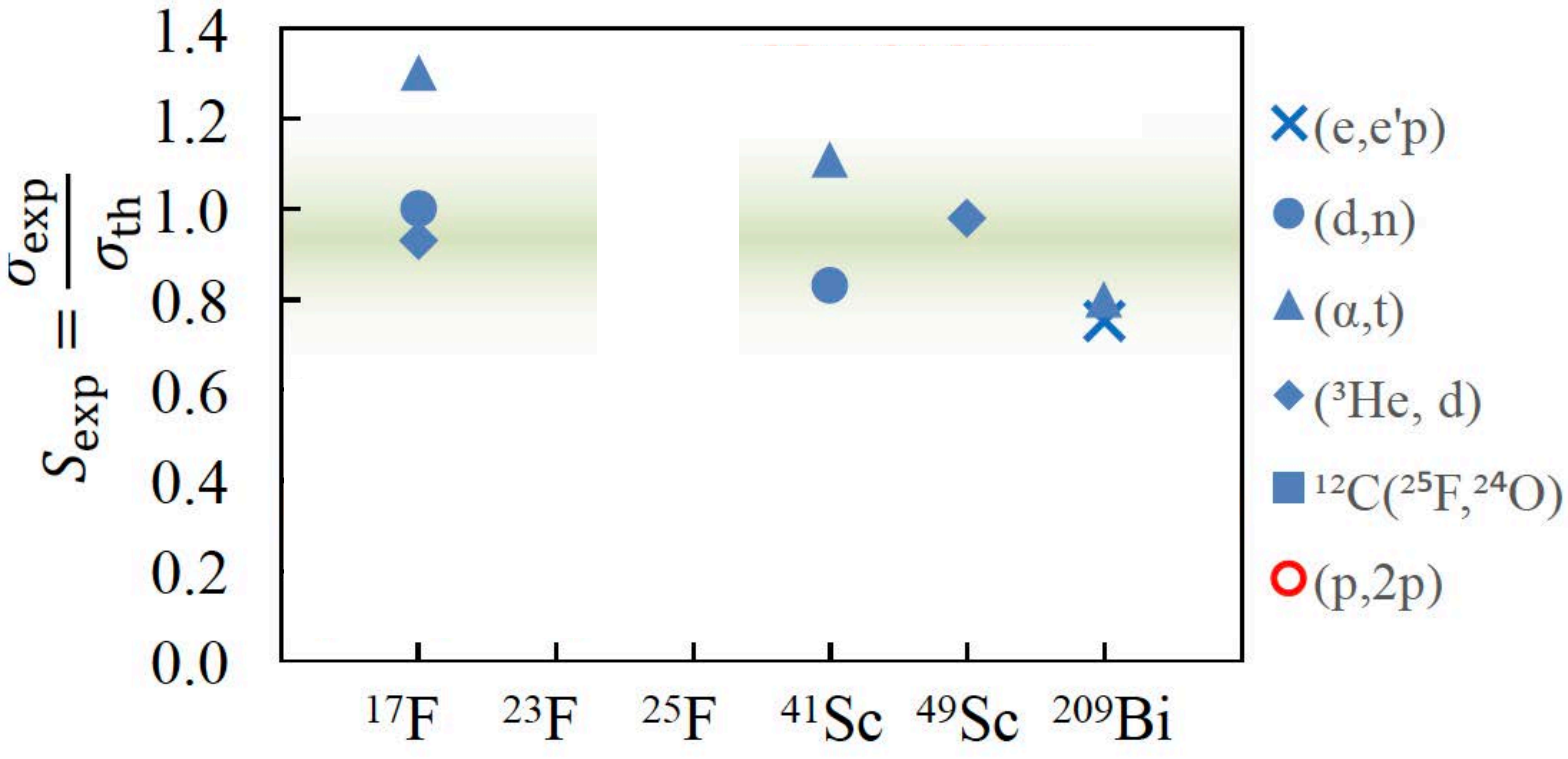
What remains after a proton removal?

Naive expectation



Results for $^{25}F(p,2p)^{24}O$

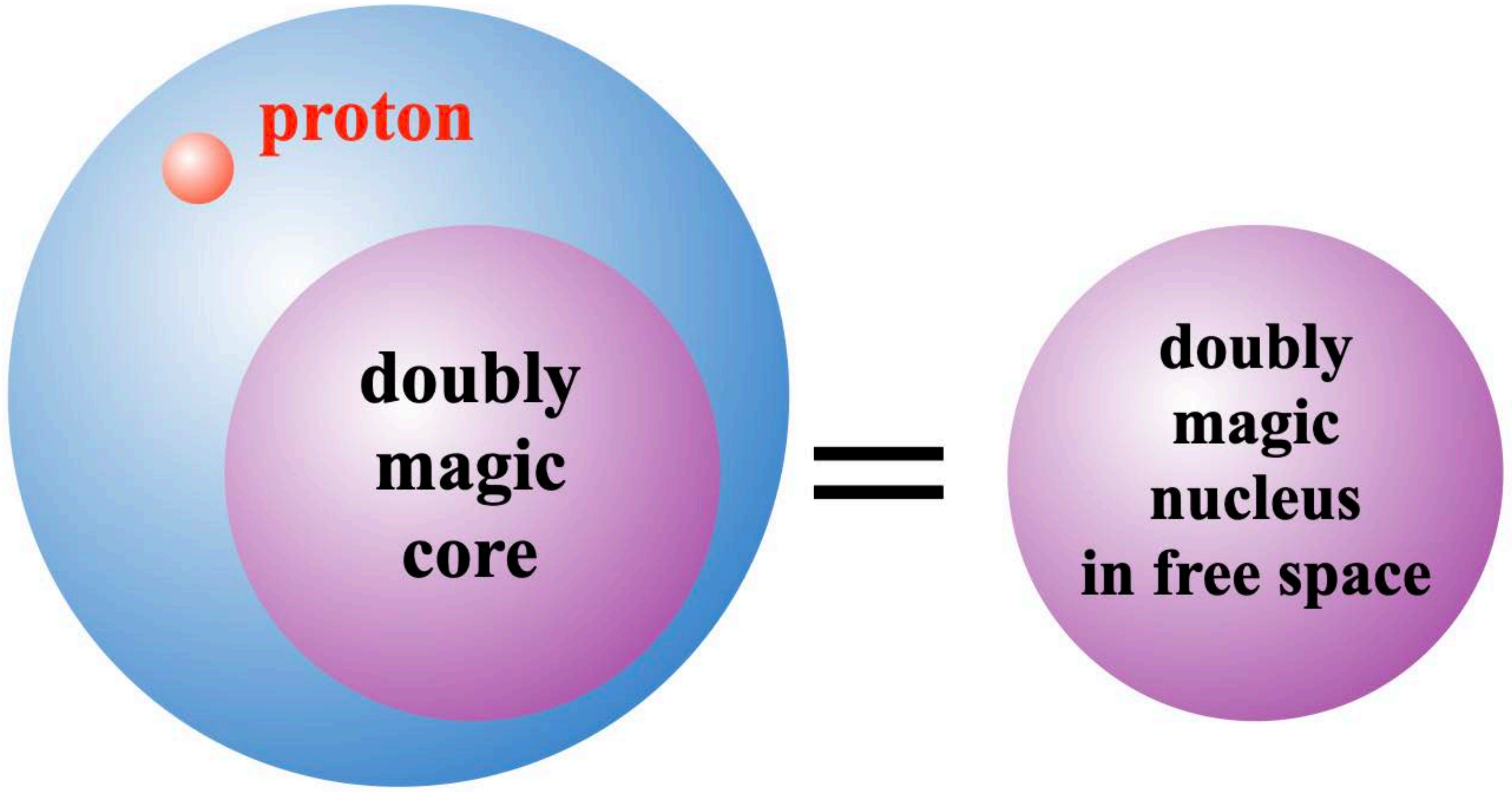




A single proton removal can make a heck of difference on the neutron structure.

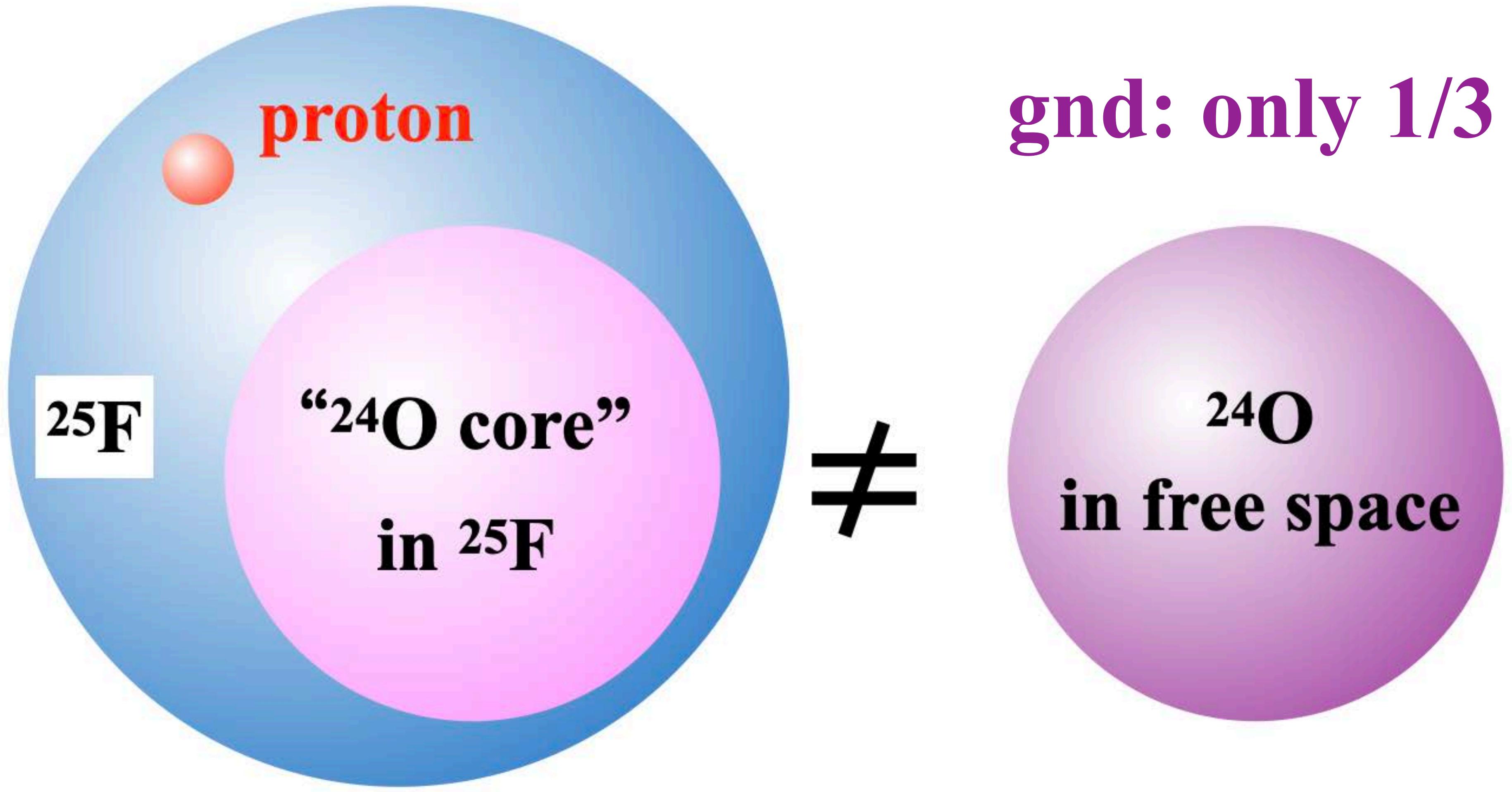
What remains after a proton removal?

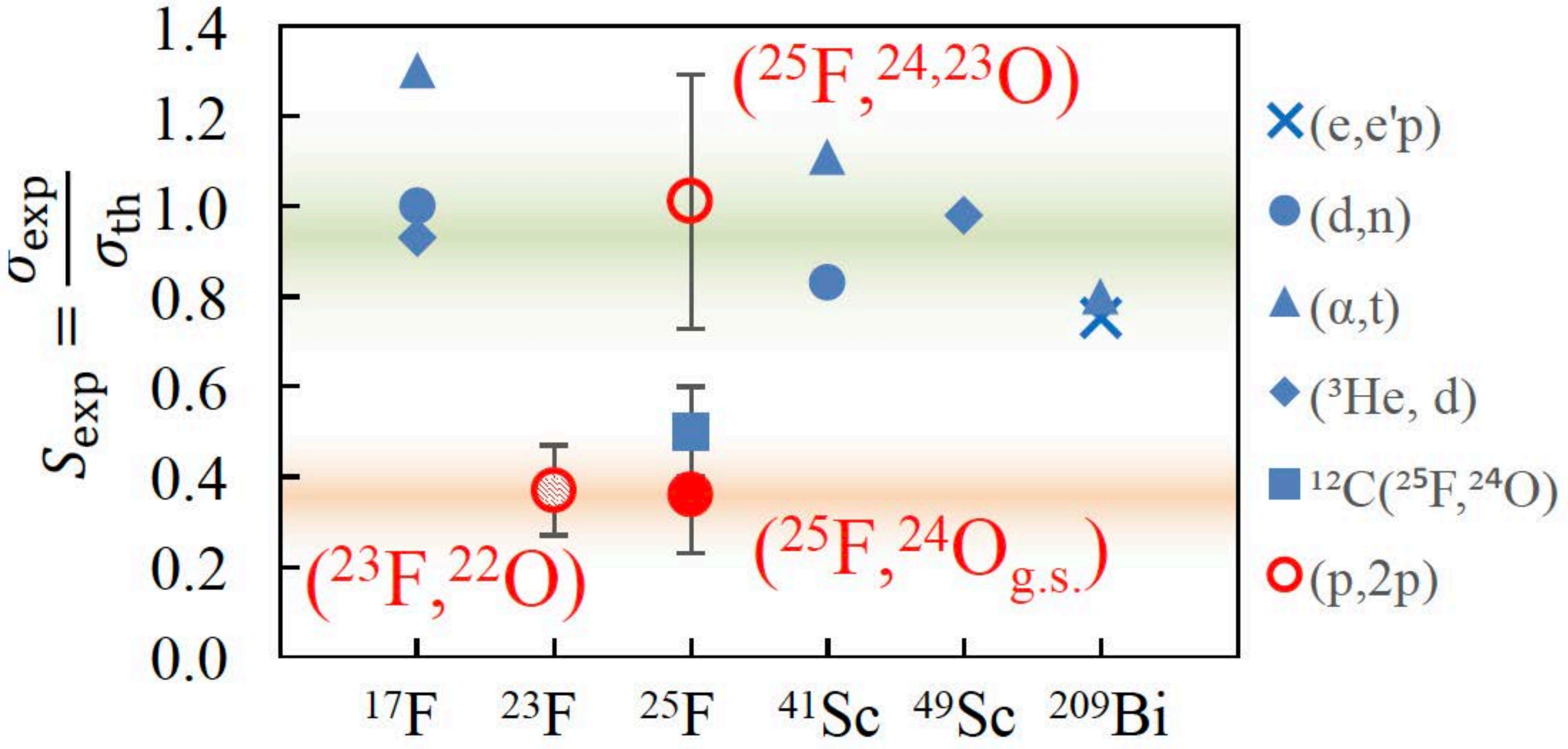
Naive expectation



Results for $^{25}F(p,2p)^{24}O$

gnd: only 1/3



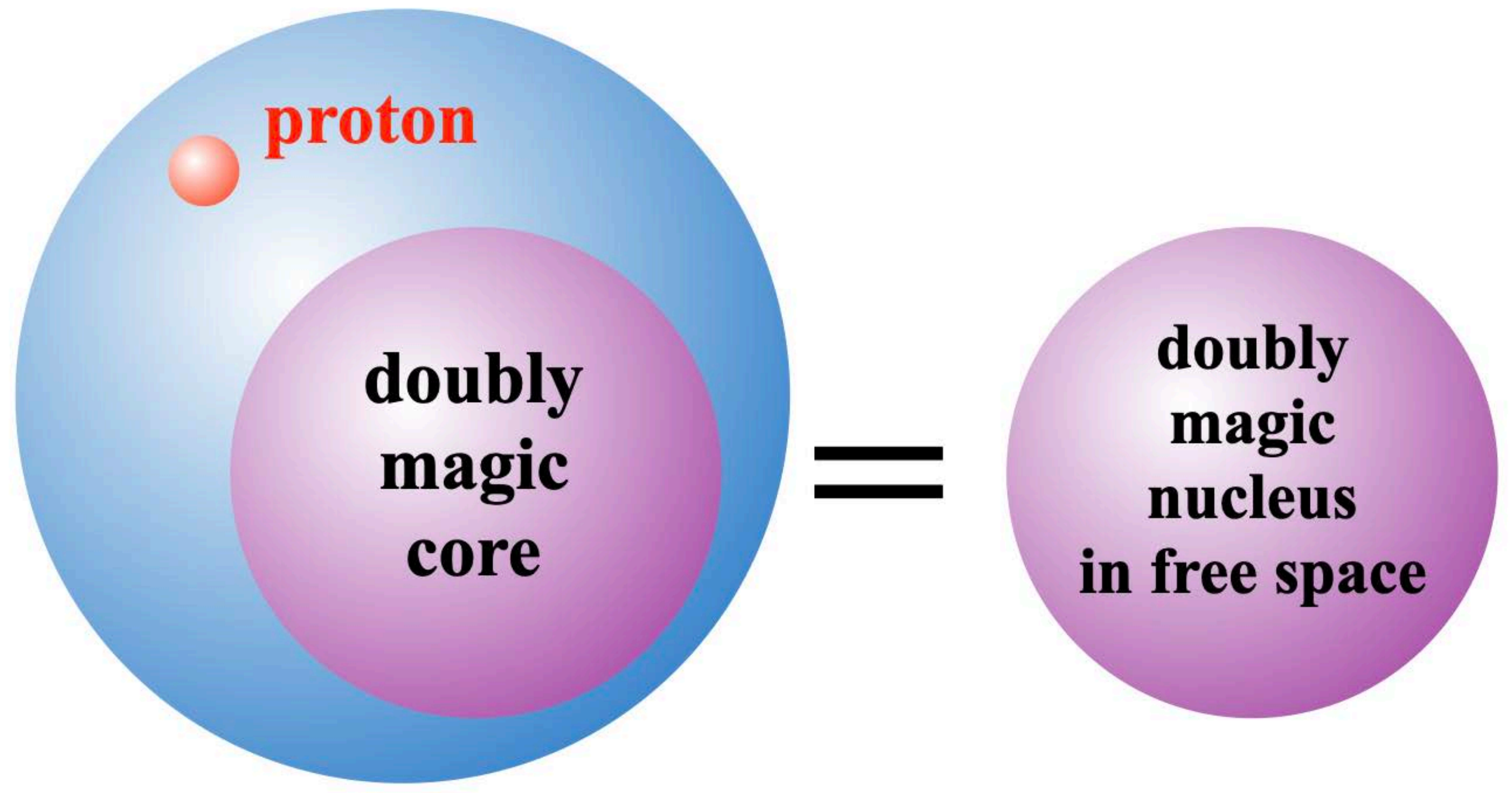


A single proton removal can make a heck of difference on the neutron structure.

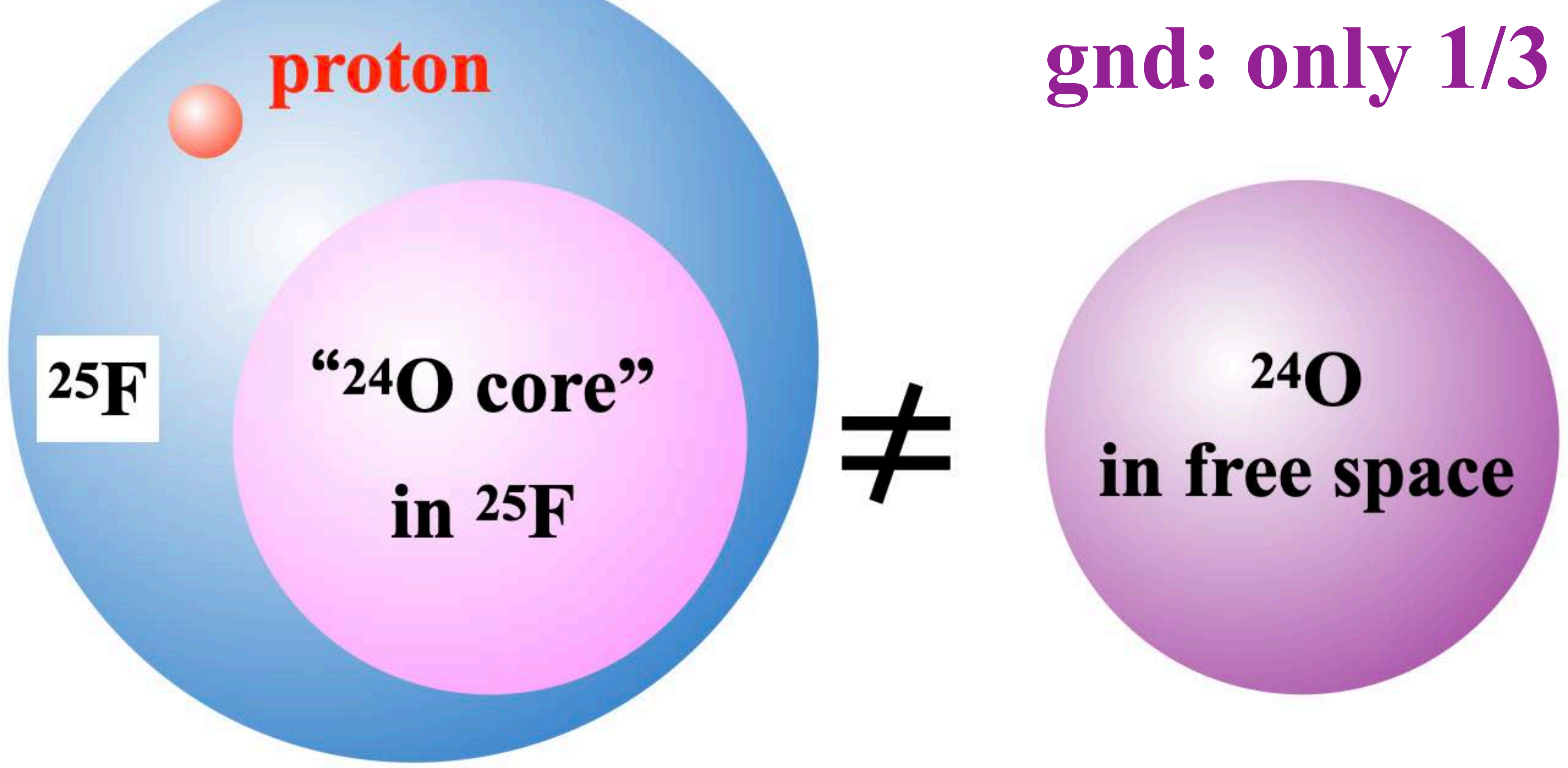
What remains after a proton removal?

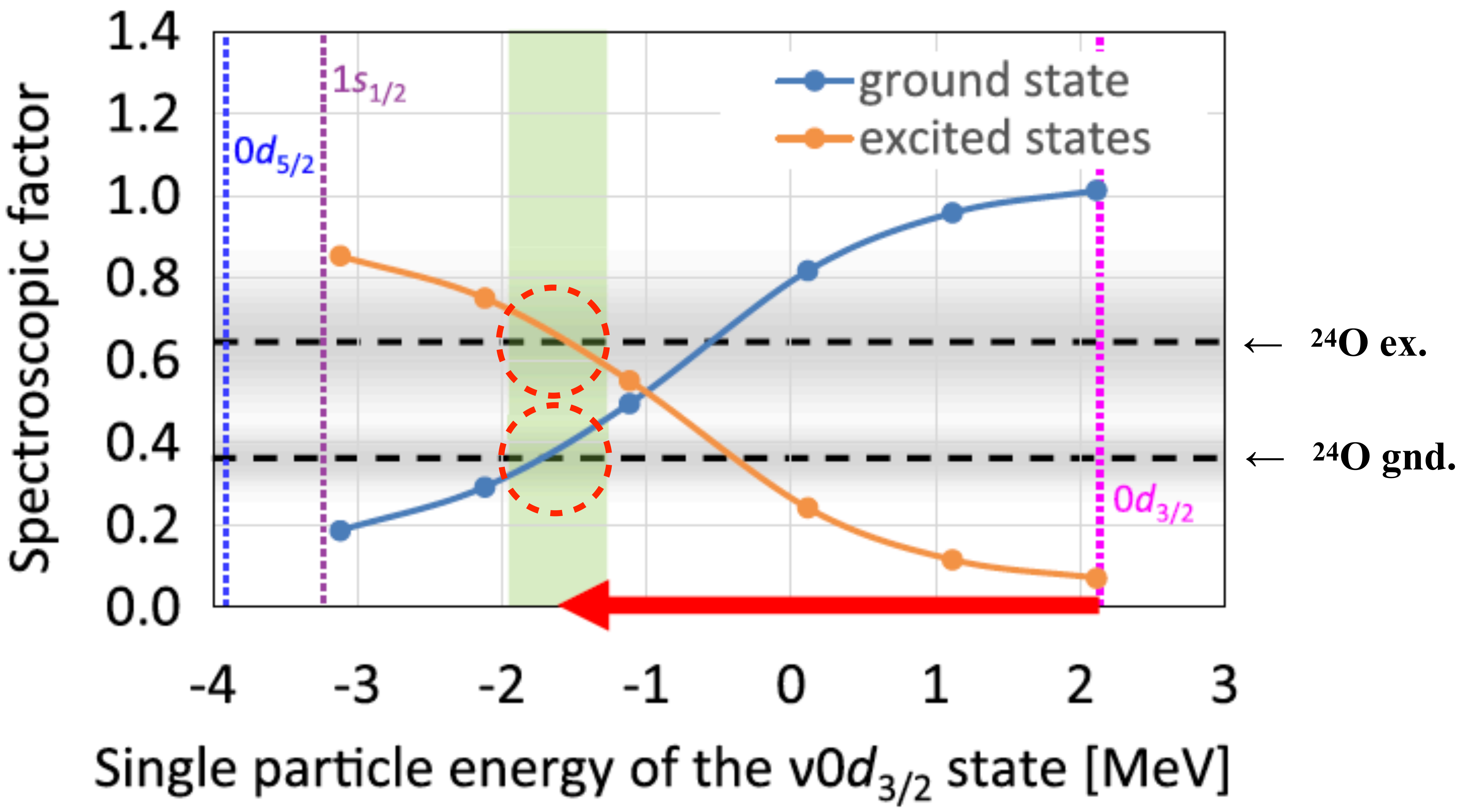
T.L. Tang et al., PRL 124, 212502 (2020).

Naive expectation



Results for ^{25}F(p,2p)^{24}O



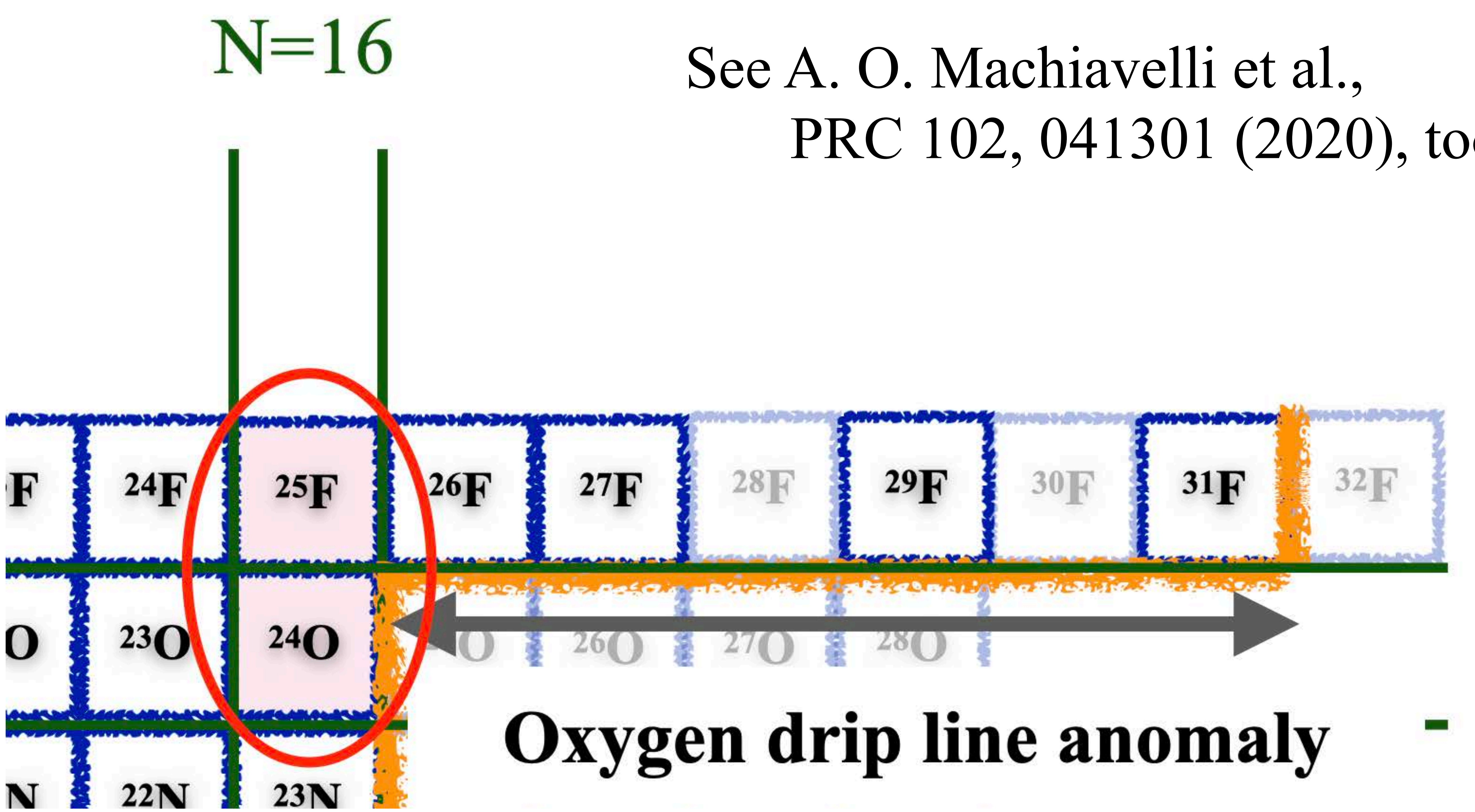


A single proton can make a heck of difference on the neutron structure.

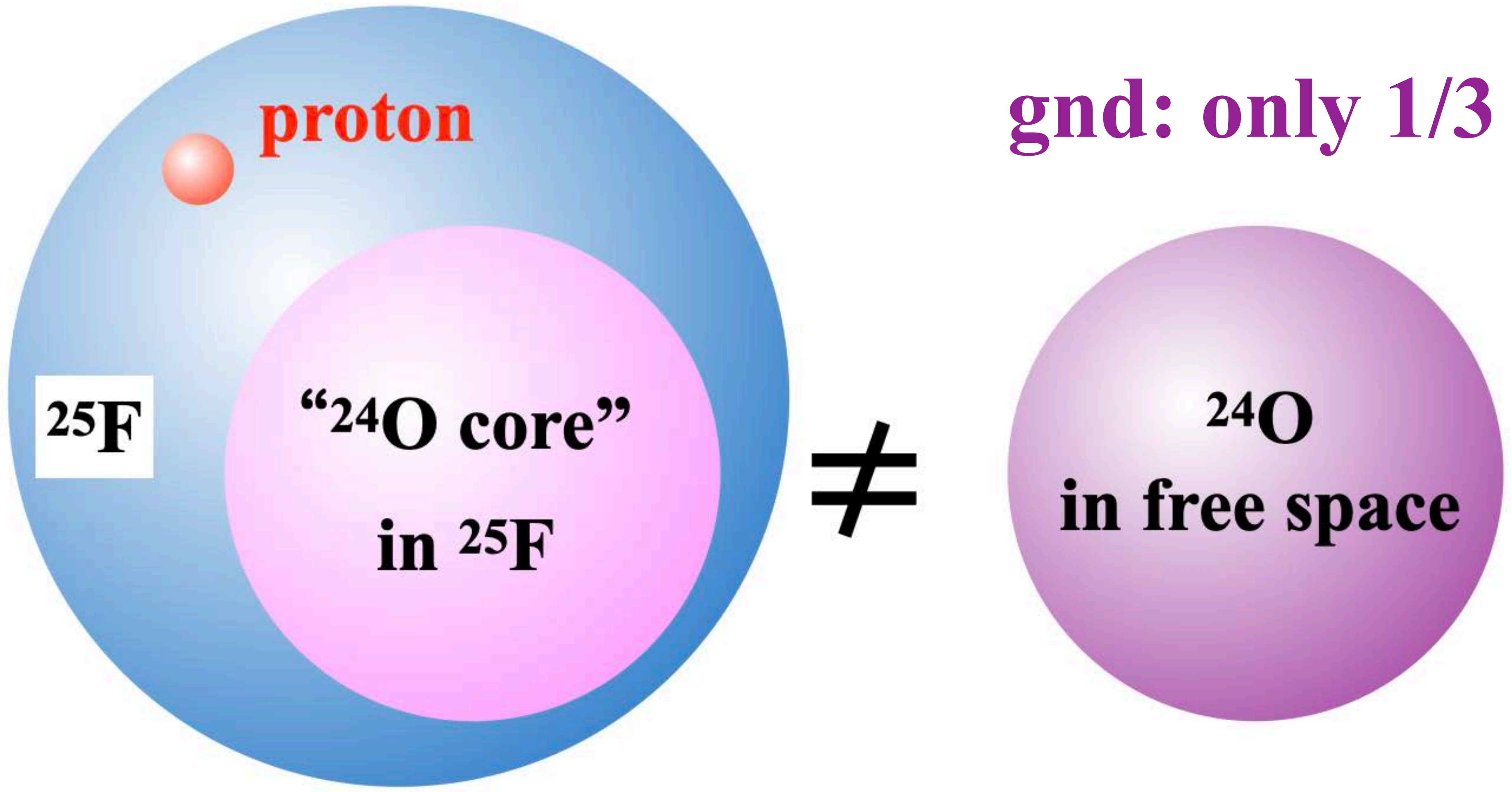
→ Possibility of unexpectedly strong proton-neutron interaction in the *sd* shell.

Hint to understand the mechanism underlying the dripline anomaly

See A. O. Machiavelli et al., PRC 102, 041301 (2020), too.



Results for ^{25}F(p,2p)^{24}O



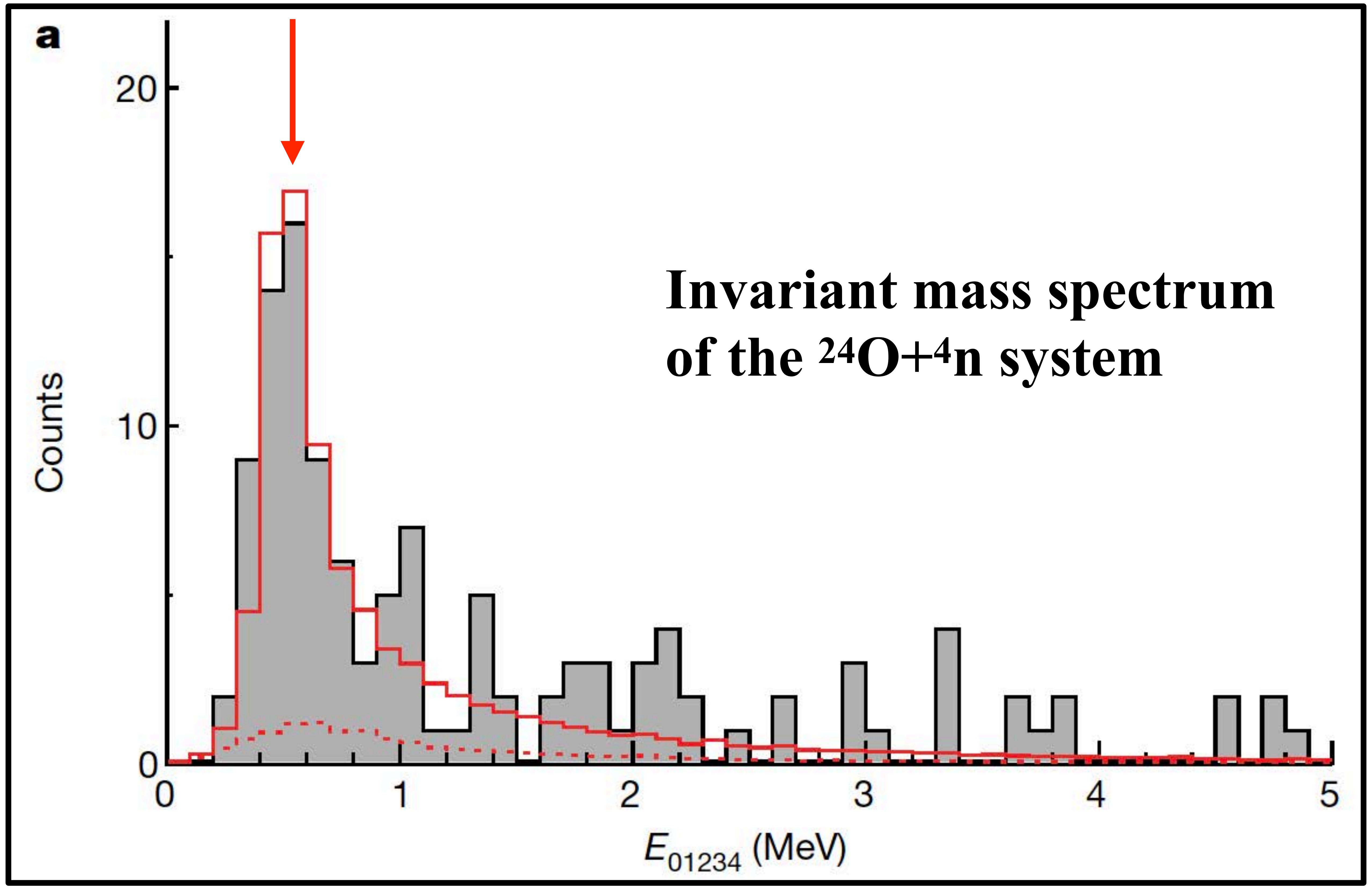
A single proton can make a heck of difference on the neutron structure.

→ **Possibility of unexpectedly strong proton-neutron interaction in the *sd* shell.**

→ **may hint at the mechanism of the oxygen dripline anomaly.**

The similar logic was used in the discussion of magicity in ^{28}O

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



$d_{5/2}$ proton removal via ^{29}F(p,2p)^{28}O

DWIA analysis tells the $d_{5/2}$ S-factor is

$C^2S = 0.48\,^{+0.05}_{-0.06}$ (stat) ±0.05 (syst)

The value is comparable to a shell model prediction of C^2S_{theo} = 0.68 ×0.65 = 0.44.

The neutron structure in ^{28}O has a large overlap with that of ^{29}F where the N=20 magicity is known to be significantly broken.

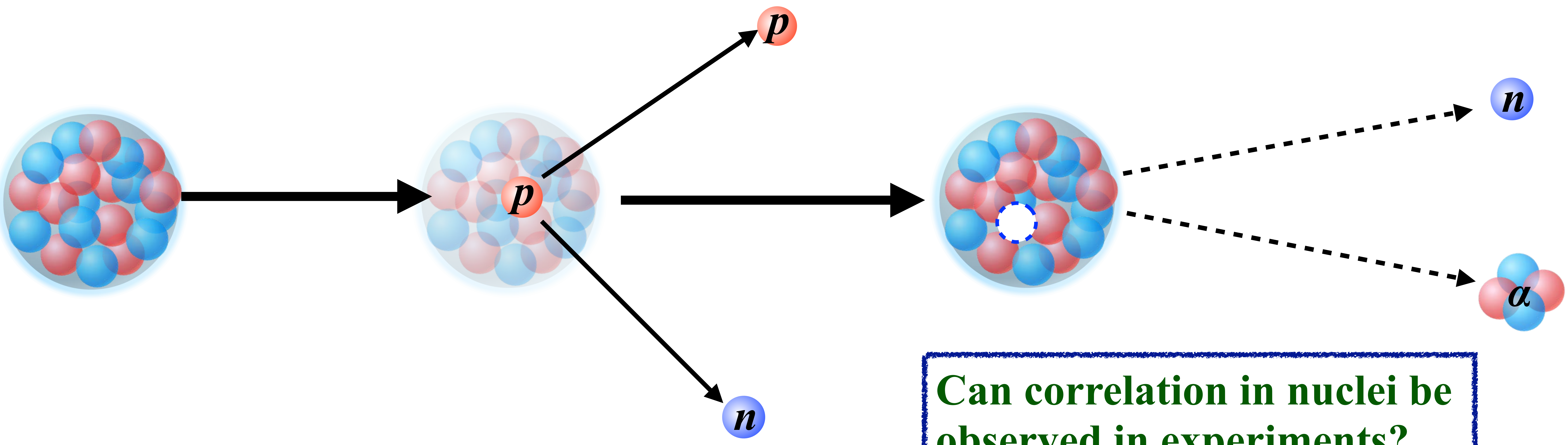
P. Doornenbal, et al. PRC **95**, 041301(R) (2017).

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

New opportunities in inverse kinematics

Combined analyses of knockout and decay processes

In inverse kinematics, the center-of-momentum system is moving with a large velocity.
→ Detections of decay particles are relatively easy.

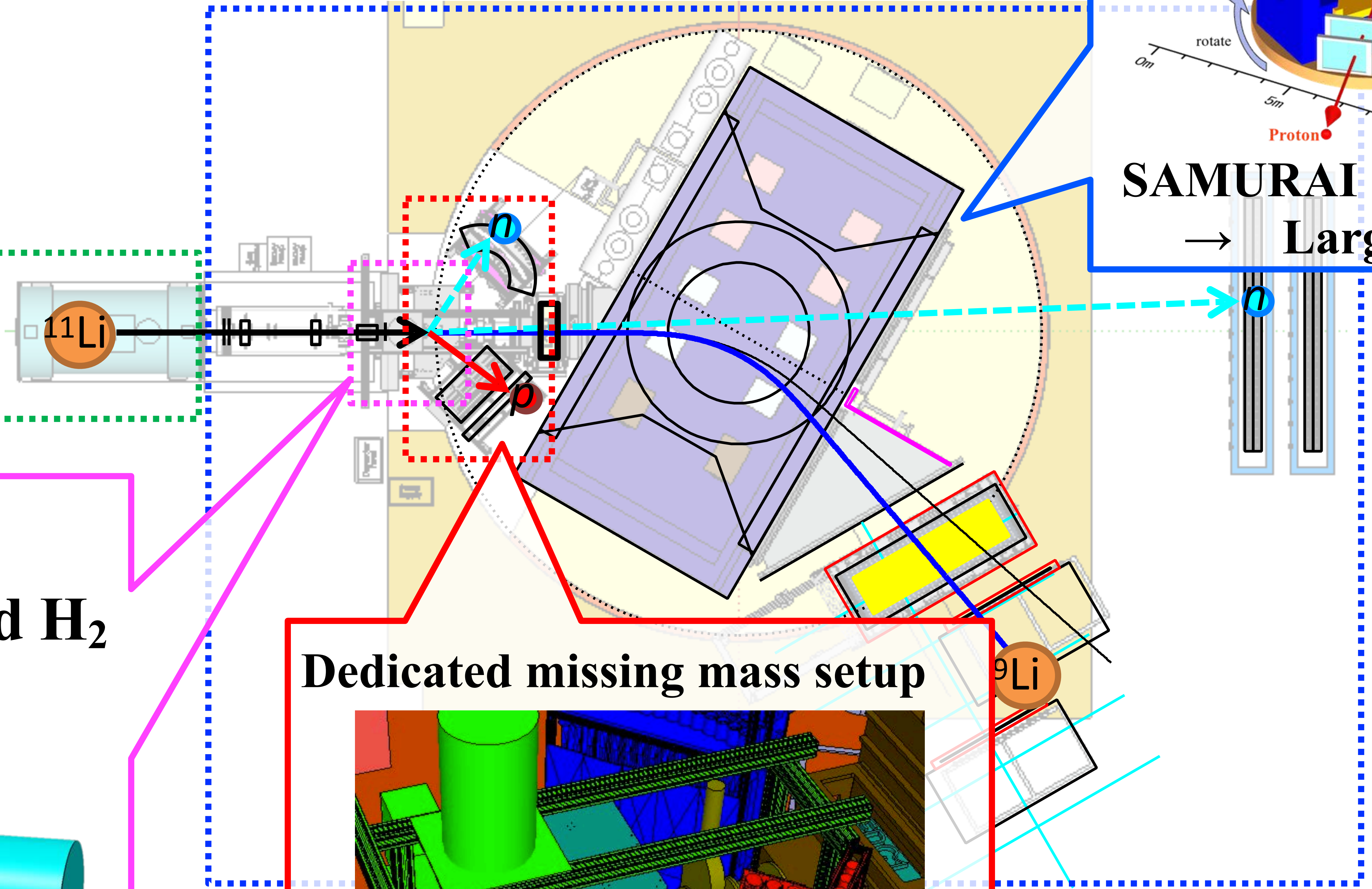


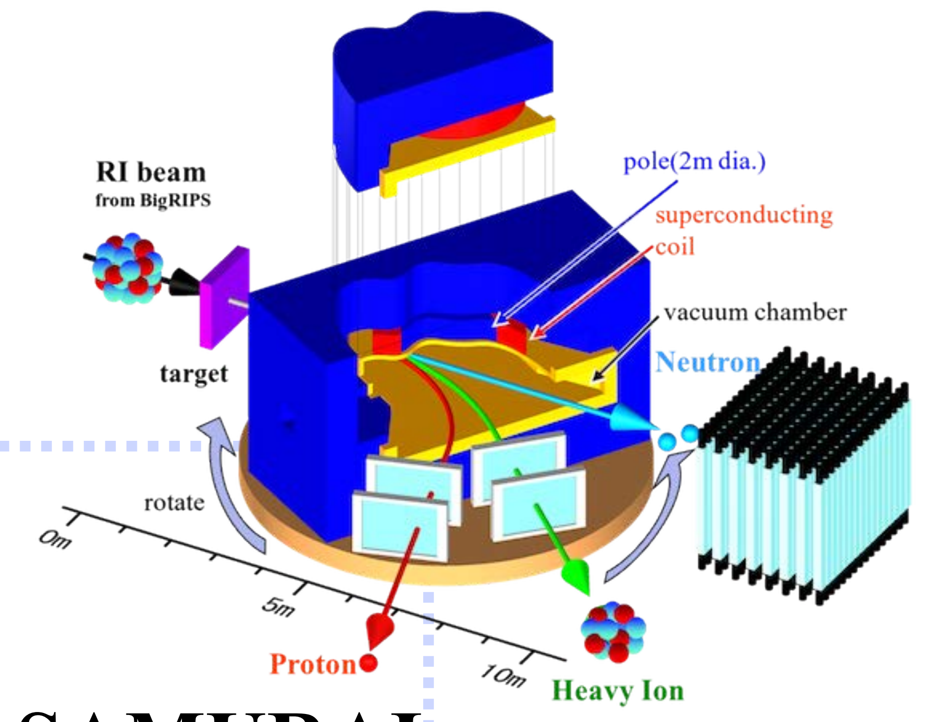
Can correlation in nuclei be observed in experiments?
Yes!

SAMURAI18 at RIKEN (2014)

Cocktail beam:
^{11}Li (180 kpps)
^{14}Be (25 kpps)
^{17}B (18 kpps)
^{19}B (0.1 kpps)

Experimental setup

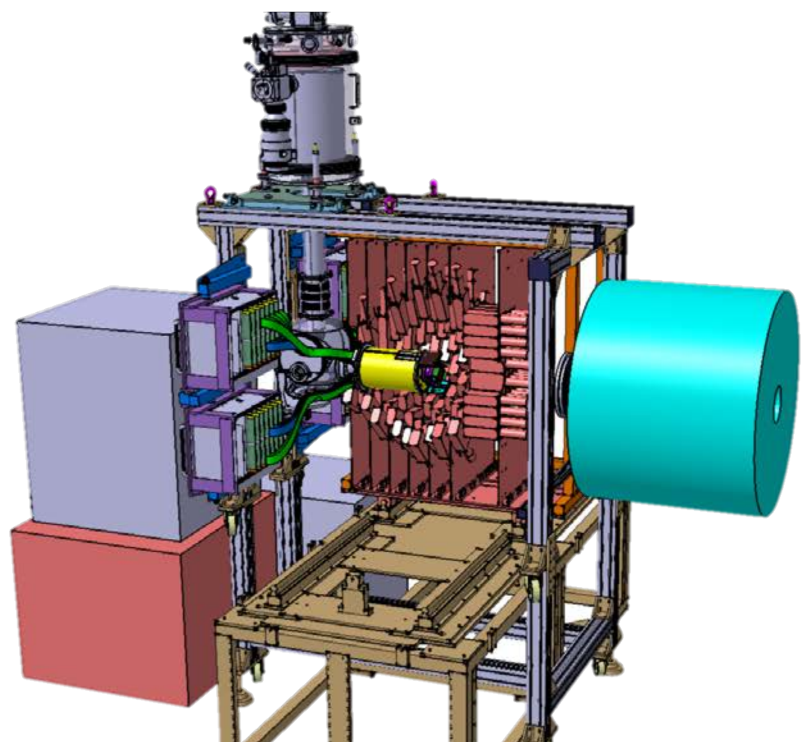




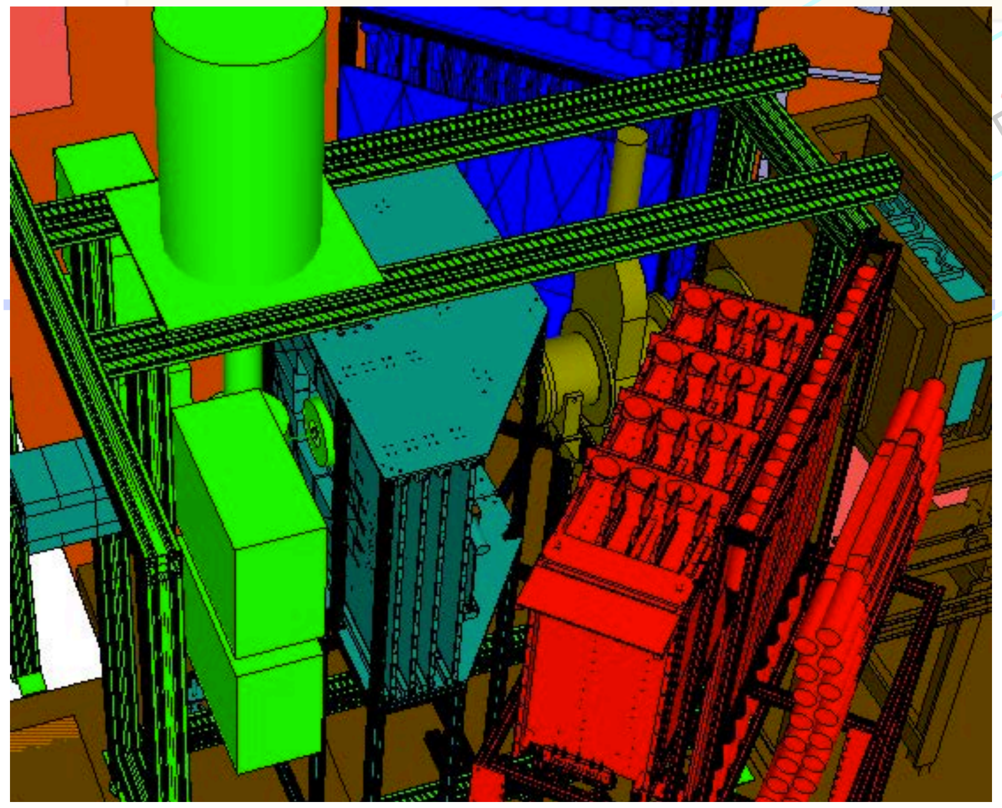
SAMURAI
→ Large acceptance

MINOS

15-cm-thick Liquid H_2



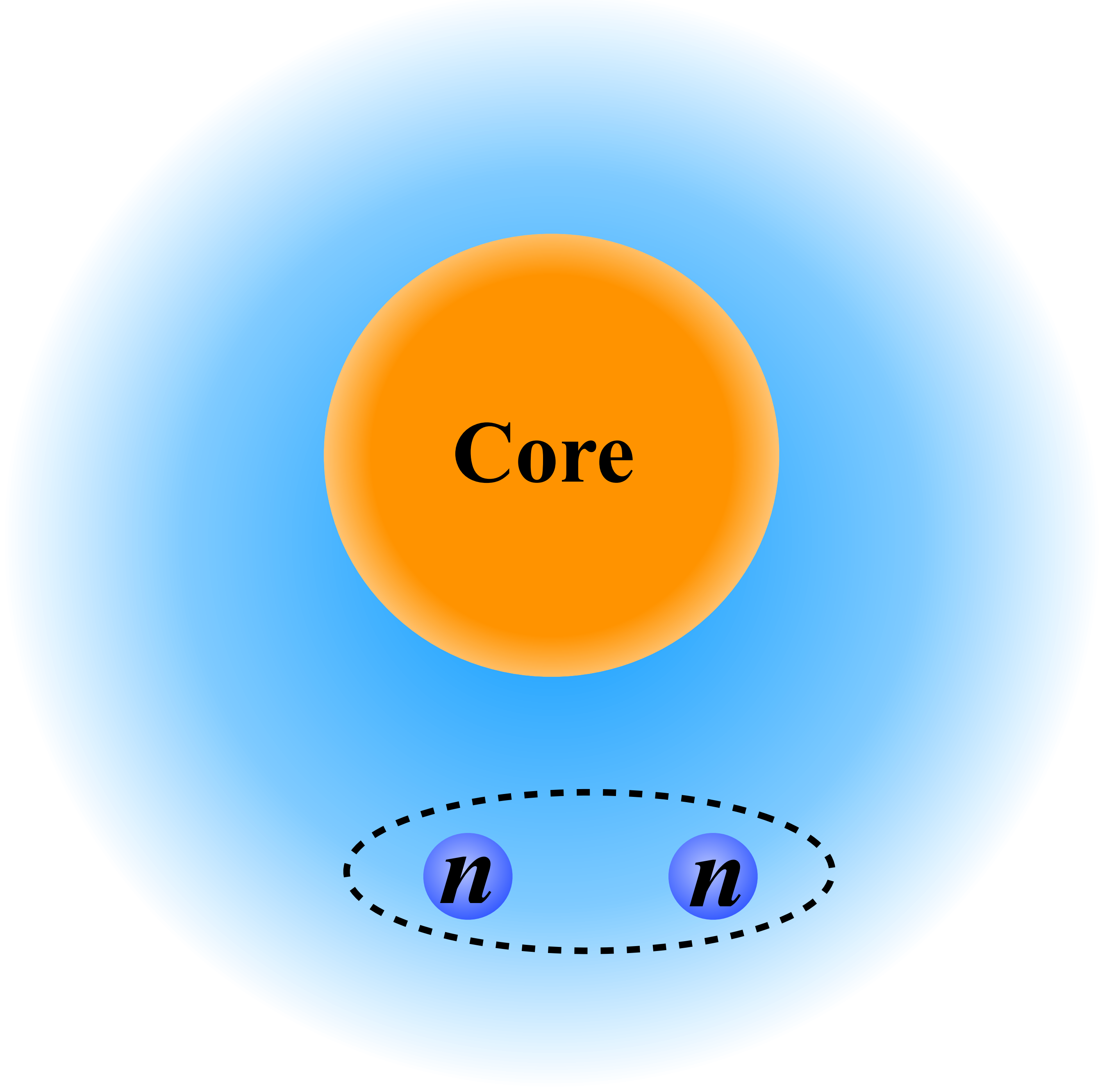
Dedicated missing mass setup



^{14}Be(p,pn)^{13}Be : A. Corsi et al., PLB **797**
^{11}Li(p, pn)^{10}Li : Y. Kubota et al., RPL **125**
^{17}B(p,pn)^{16}B : Z. Yang et al., PRL **126**
^{17}B(p,2p)^{16}Be : B. Monteagudo et al., PRL **132**
^{14}Be(p,2p)^{13}Li : P. André et al. PLB **857**
^{11}Li(p,2p)^{10}He: Y.L. Sun et al., Nat. Comm. **17**
Universality of dineutron:
A. Corsi, Y. Kubota et al.., PLB **840**.

The first fully exclusive experiment with RI beams.

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 triggered extensive studies of dineutron correlation.

experimental studies at RIKEN, GSI, NSCL, GANIL, TRIUMF

From the previous studies, we learned that

Dineutron correlation exists in ^{11}Li,

but we still don’t know

Magnitude of the dineutron correlation (θ_{opening}),

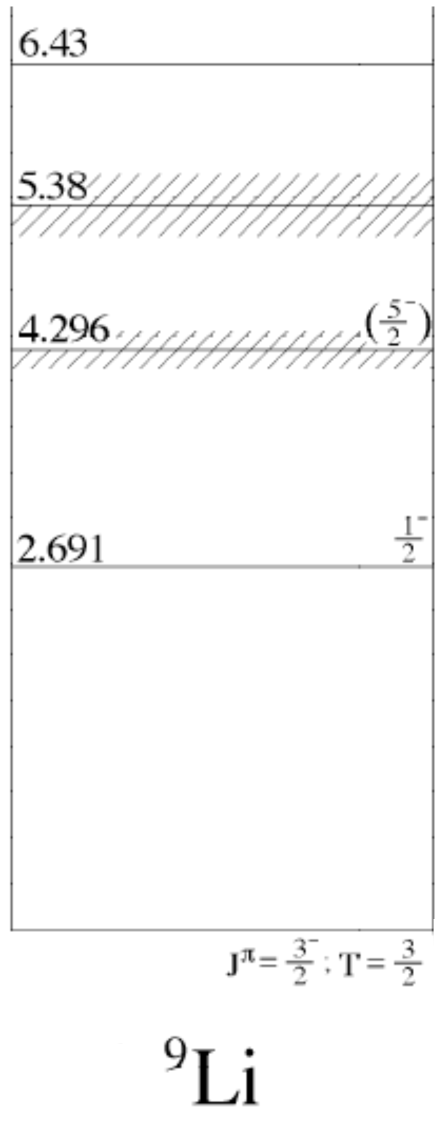
Density dependence of the magnitude,

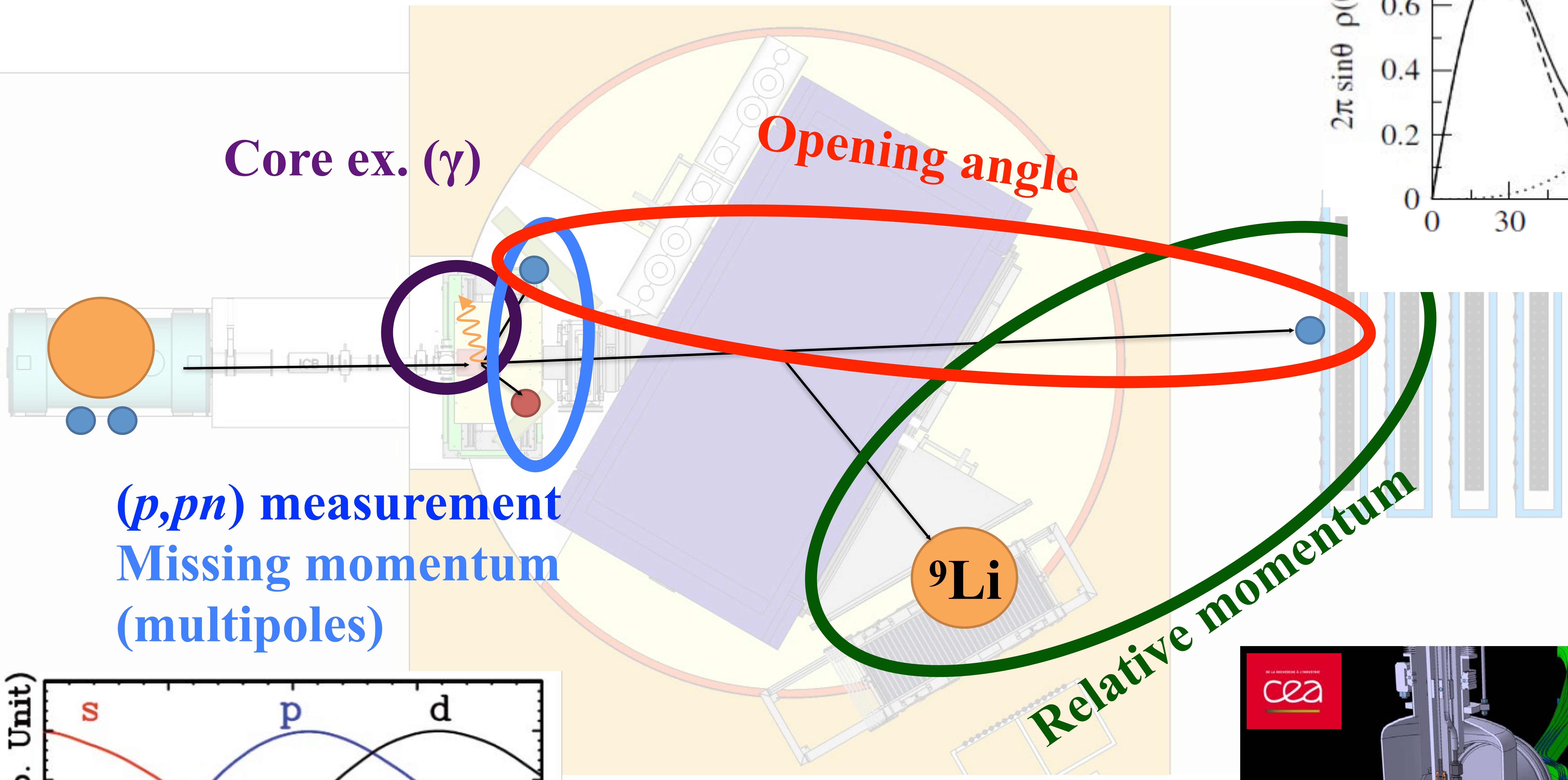
Effects of the excited core,

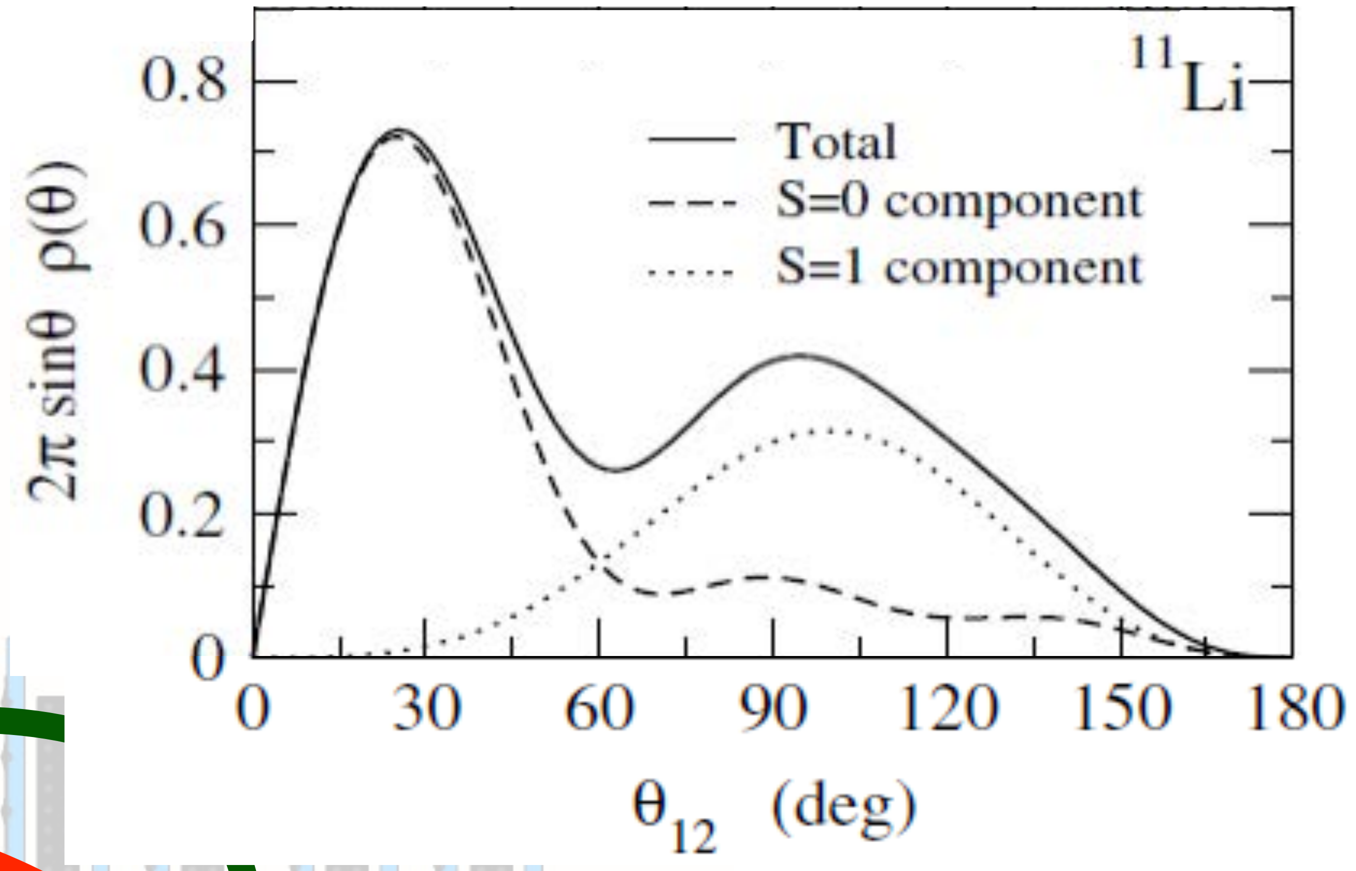
etc etc.

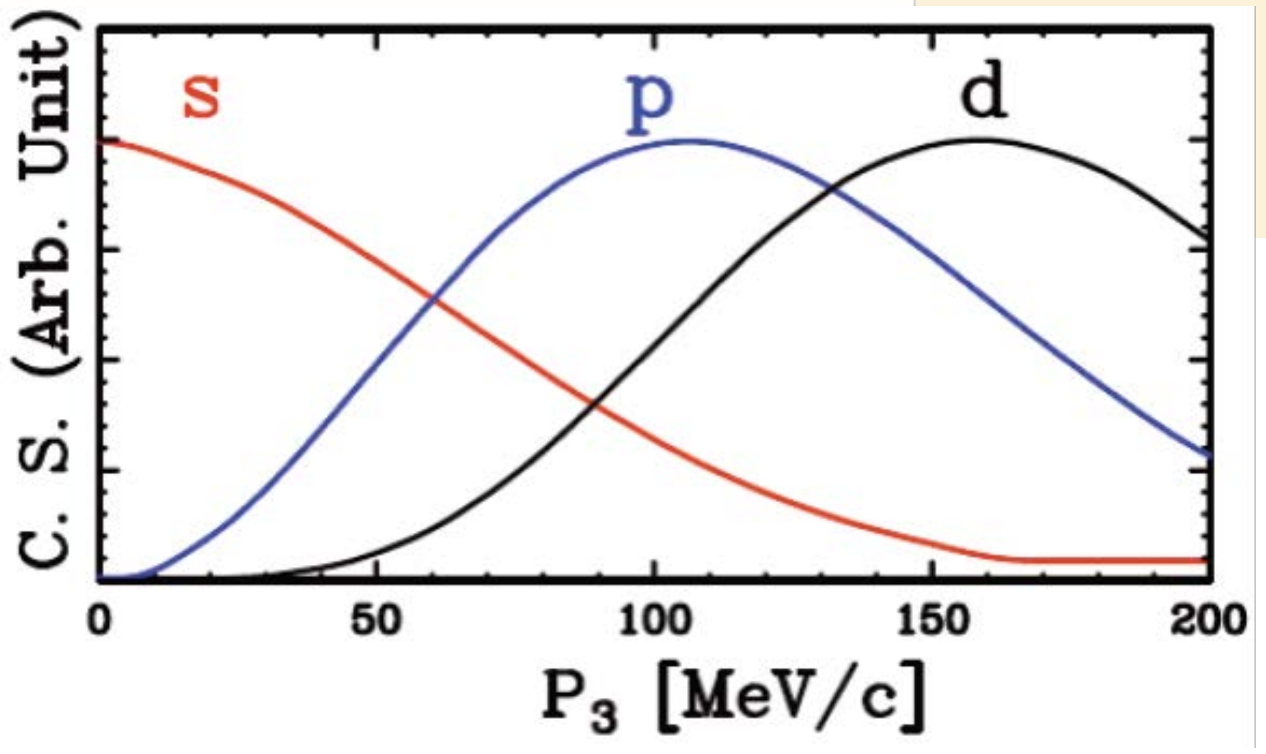
Dineutron from correlation analyses of (*p,pn*) delayed neutron emission

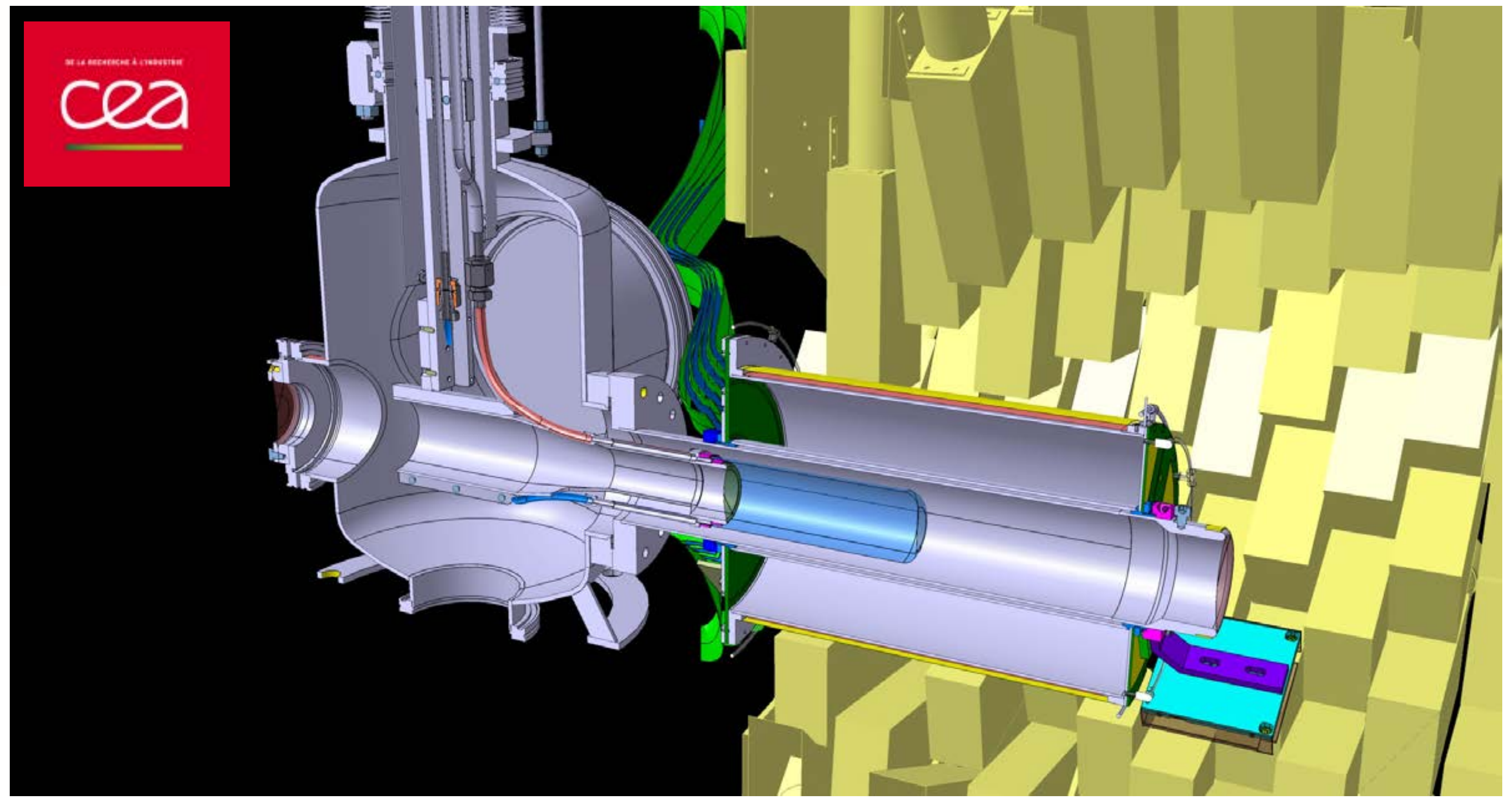
$^{11}Li(p,pn)^{10}Li \rightarrow n + ^{9}Li$ @ 250MeV





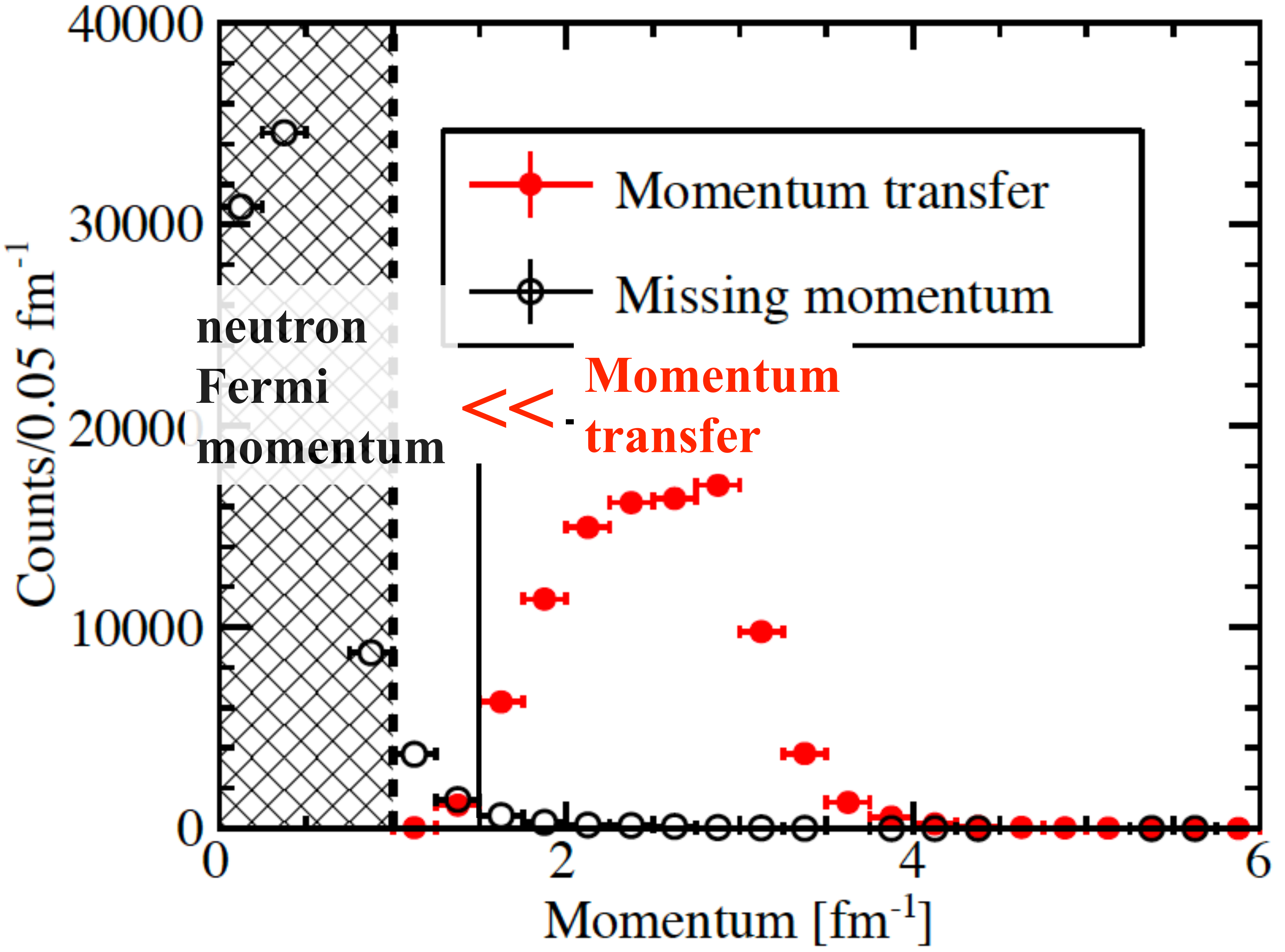




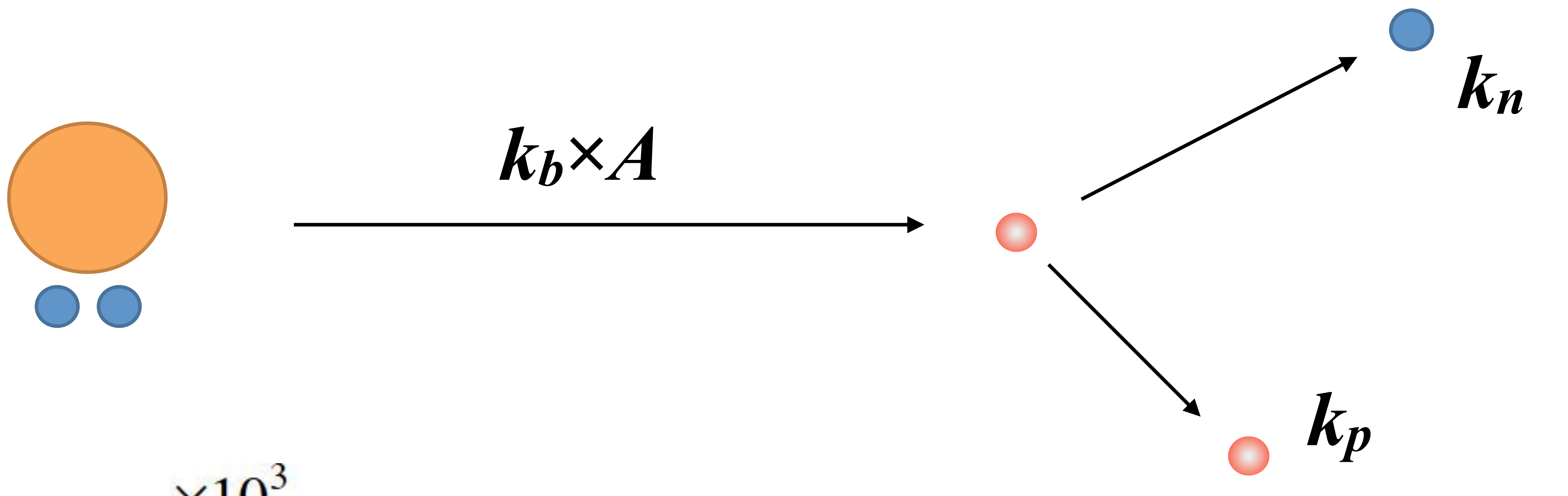


Quasi-free condition

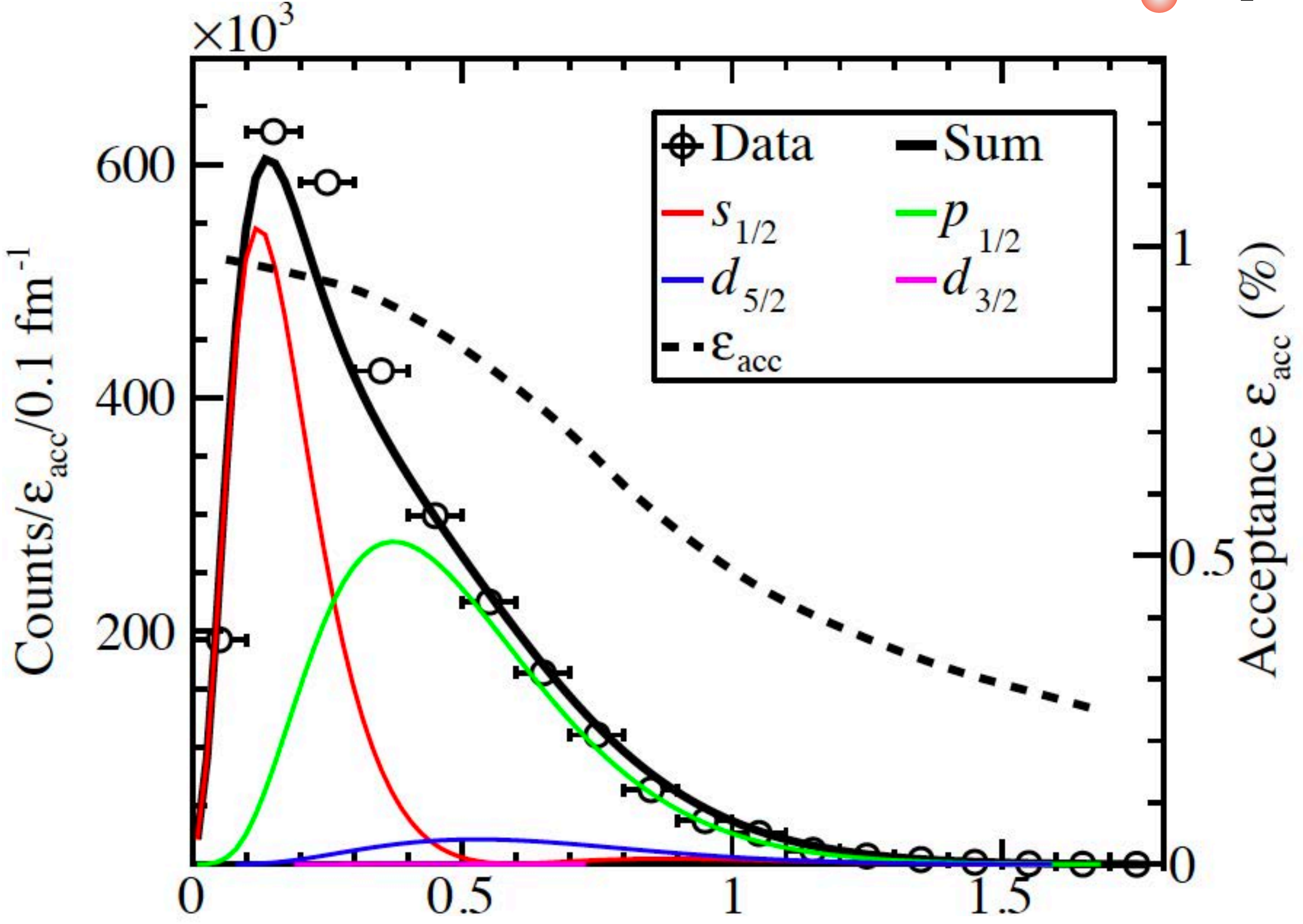
Clean quasi-free knockout condition
Suppression of 3-body FSI



Fermi momentum of knocked-out neutron in ^{11}Li



$$\vec{k}_{\text{miss}} = \vec{k}_n + \vec{k}_p - \vec{k}_b$$

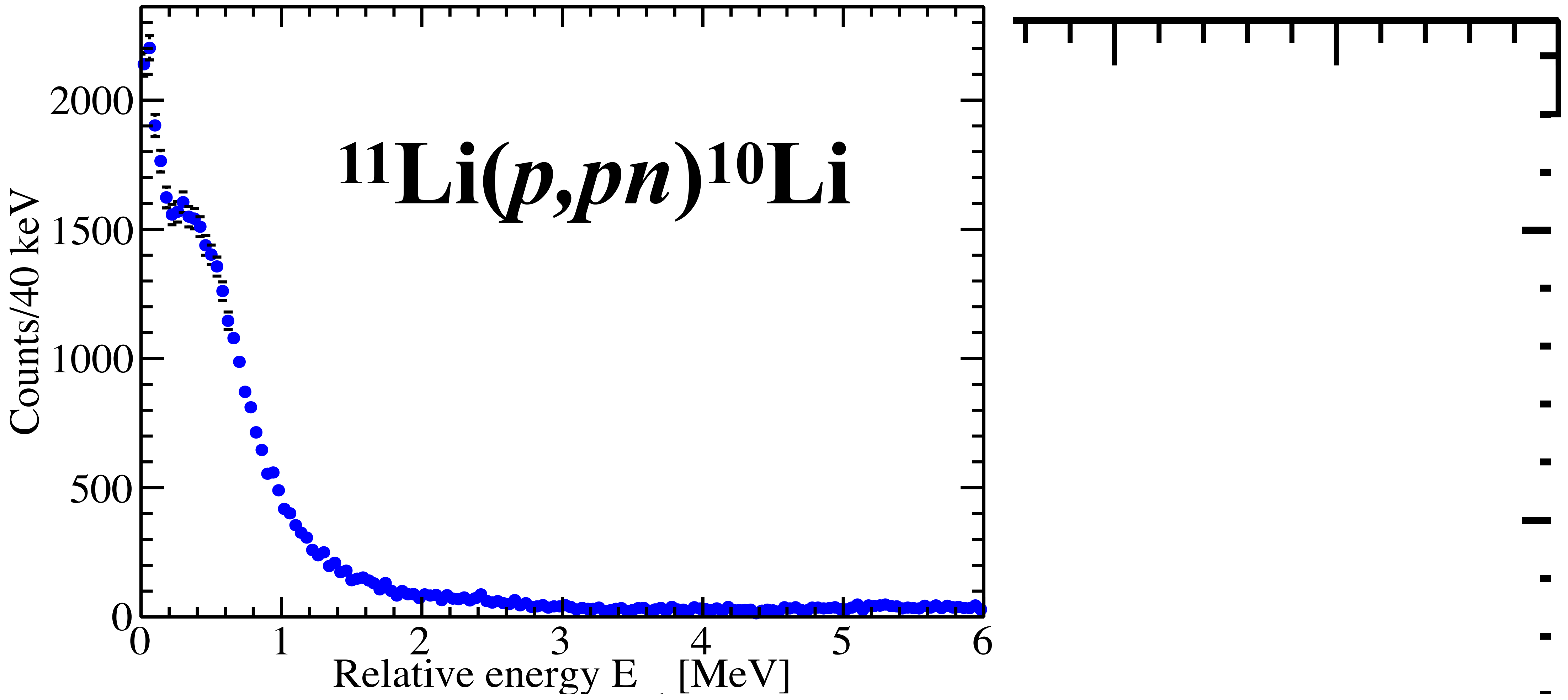


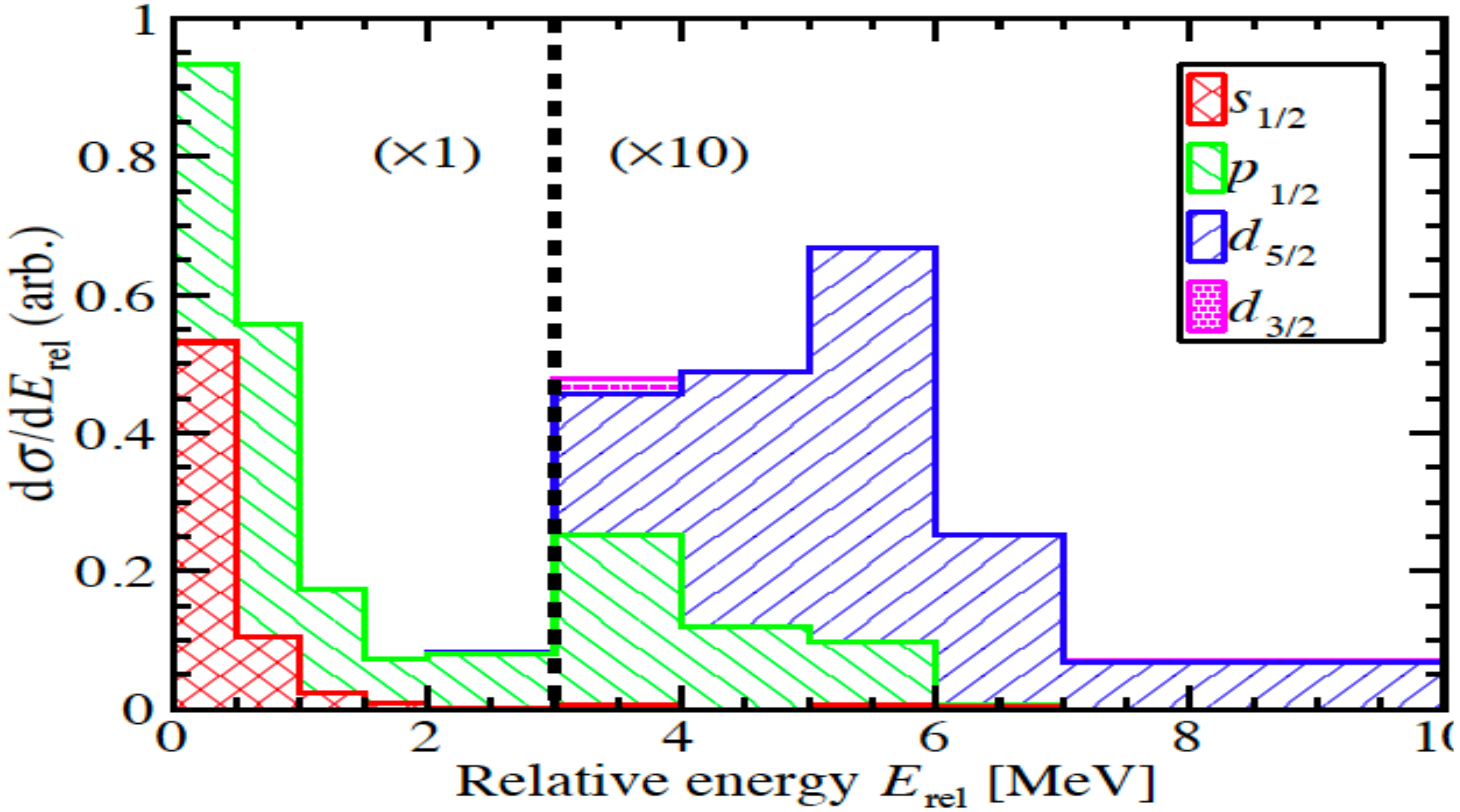
The momentum distribution is a Fourier transform of the density distributions of valence neutrons in ^{11}Li.

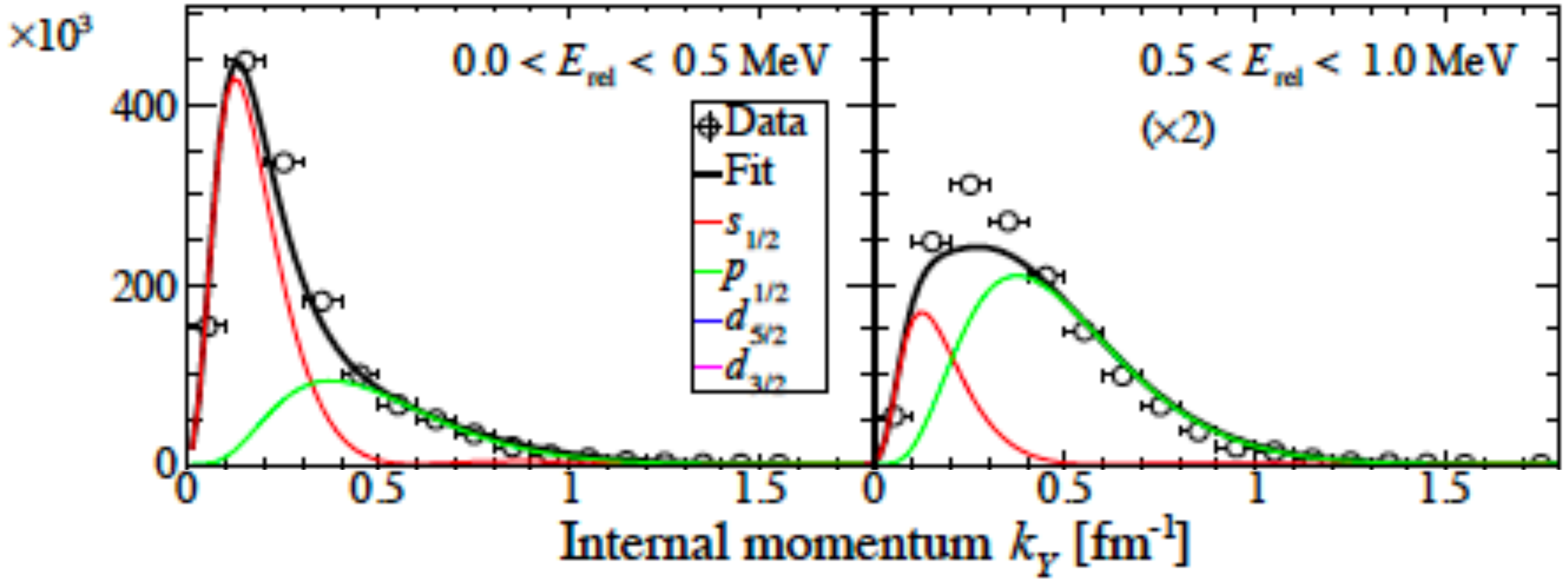
Mixture of $1s_{1/2}$ and $0p_{1/2}$
→ dineutron correlation

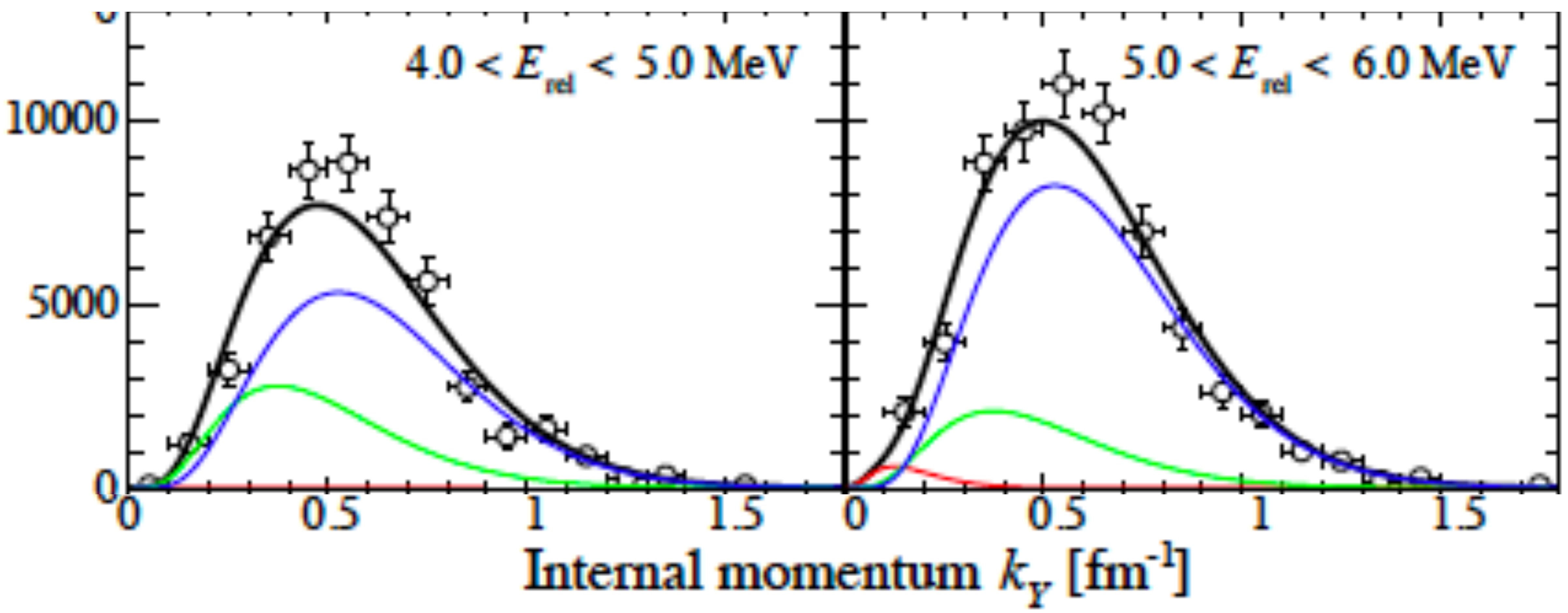
neutron position in ^{11}Li ↔ Missing momentum [fm^{-1}]

Decomposition of the multipole components

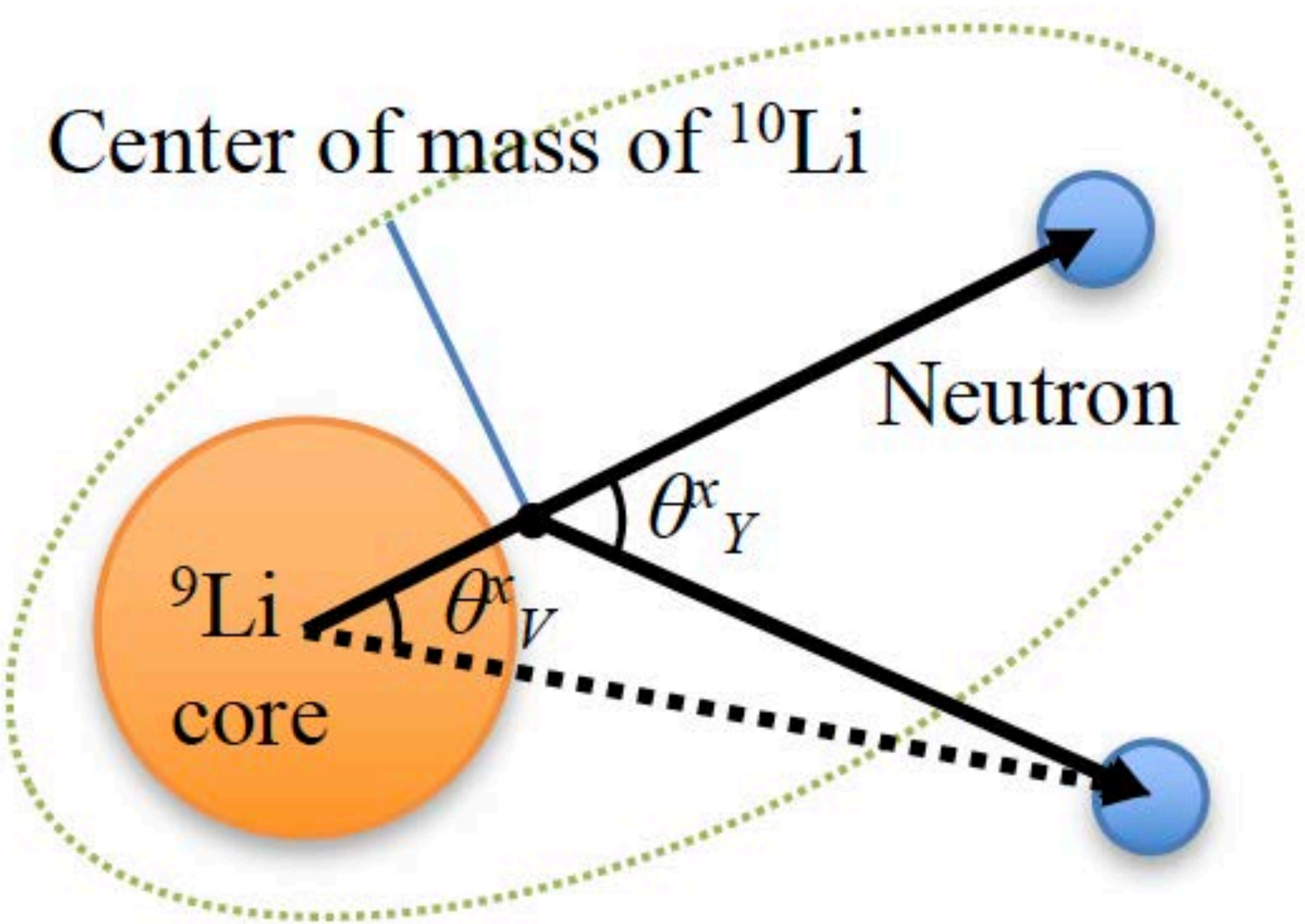




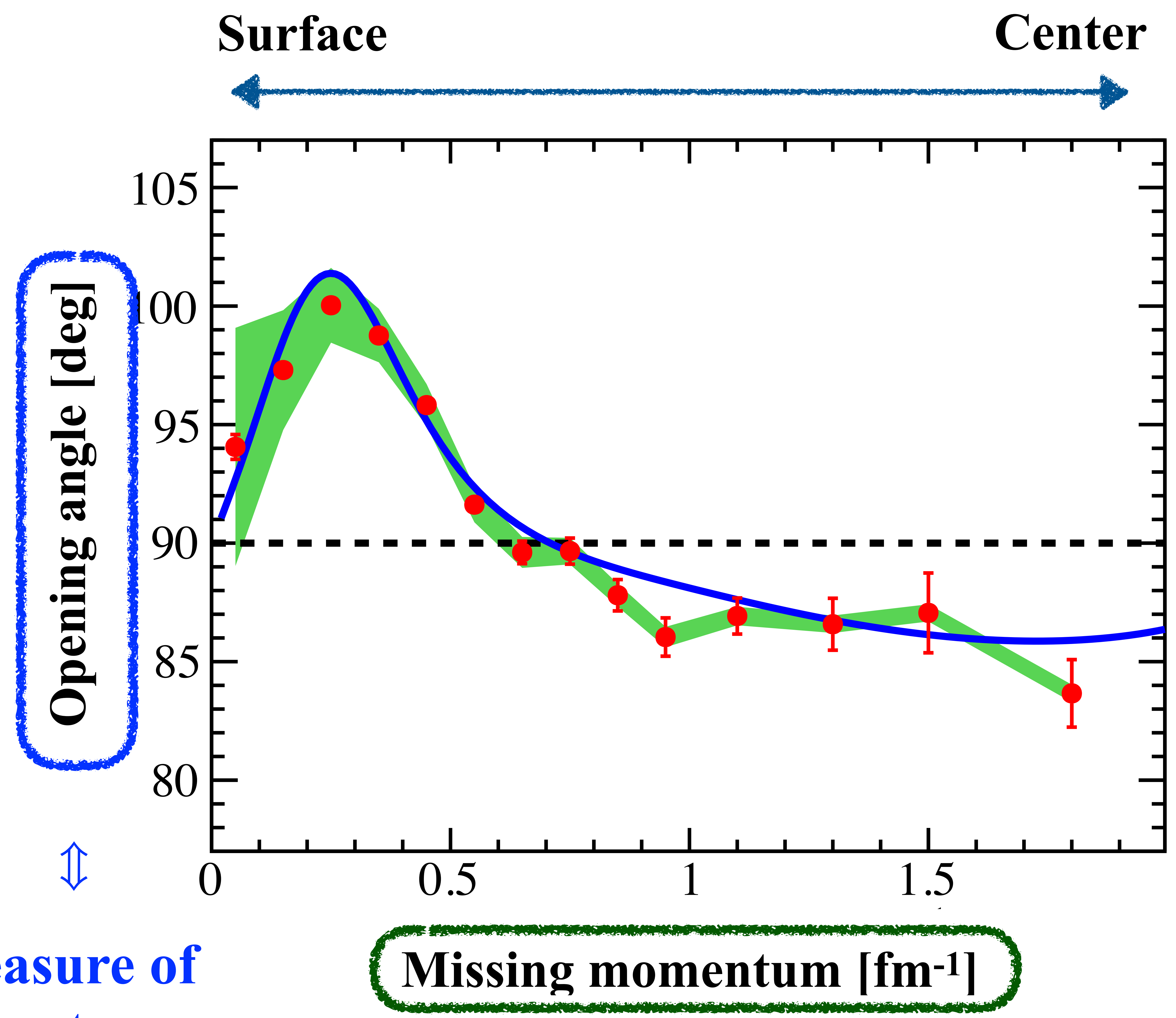




Opening angle: measure of dineutron correlation



Momentum dependence of the opening angle



⇕

measure of dineutron correlation

⇔ **core - n distance**

dineuton develops

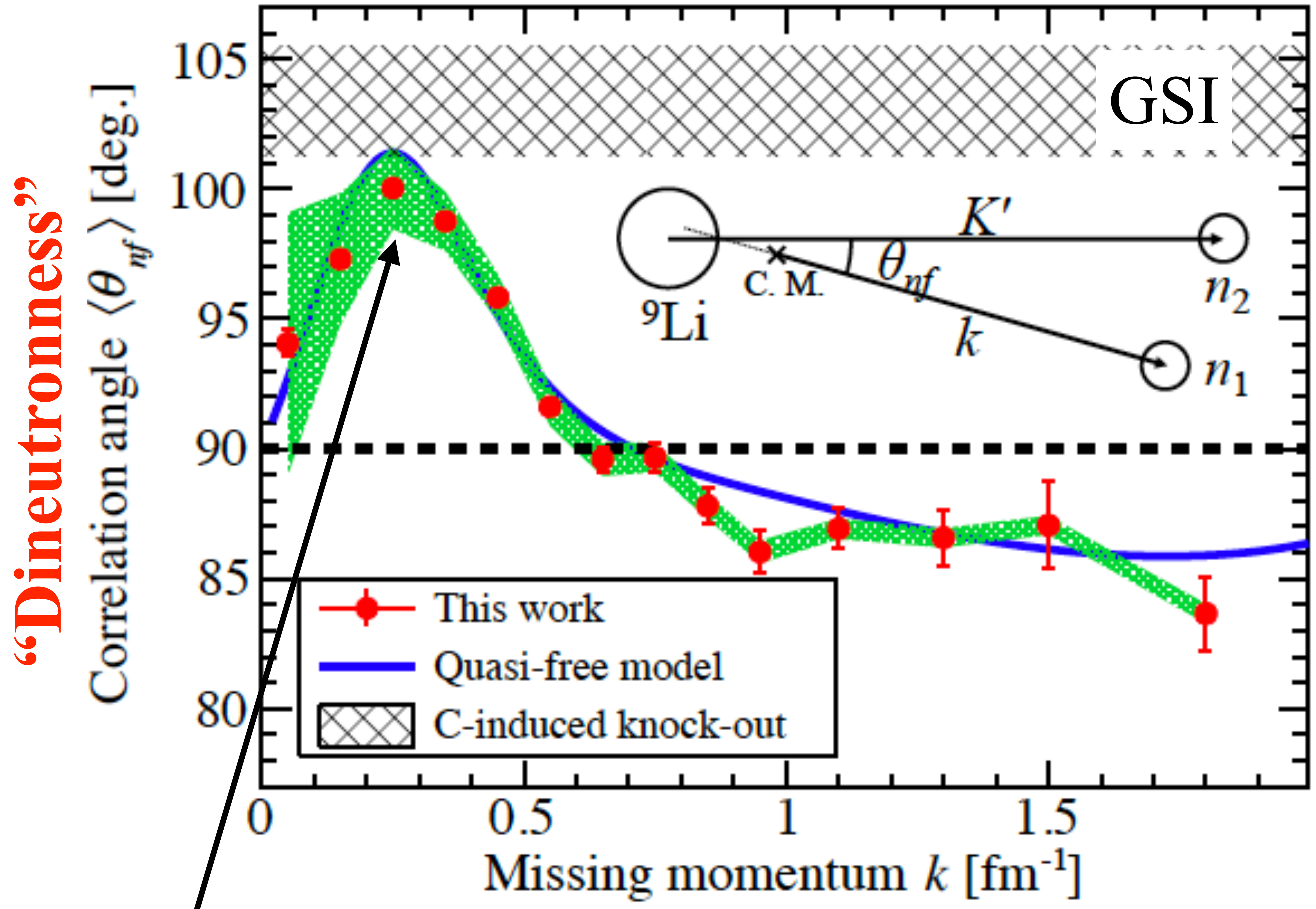
~ no cor-relation

cigar config.

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

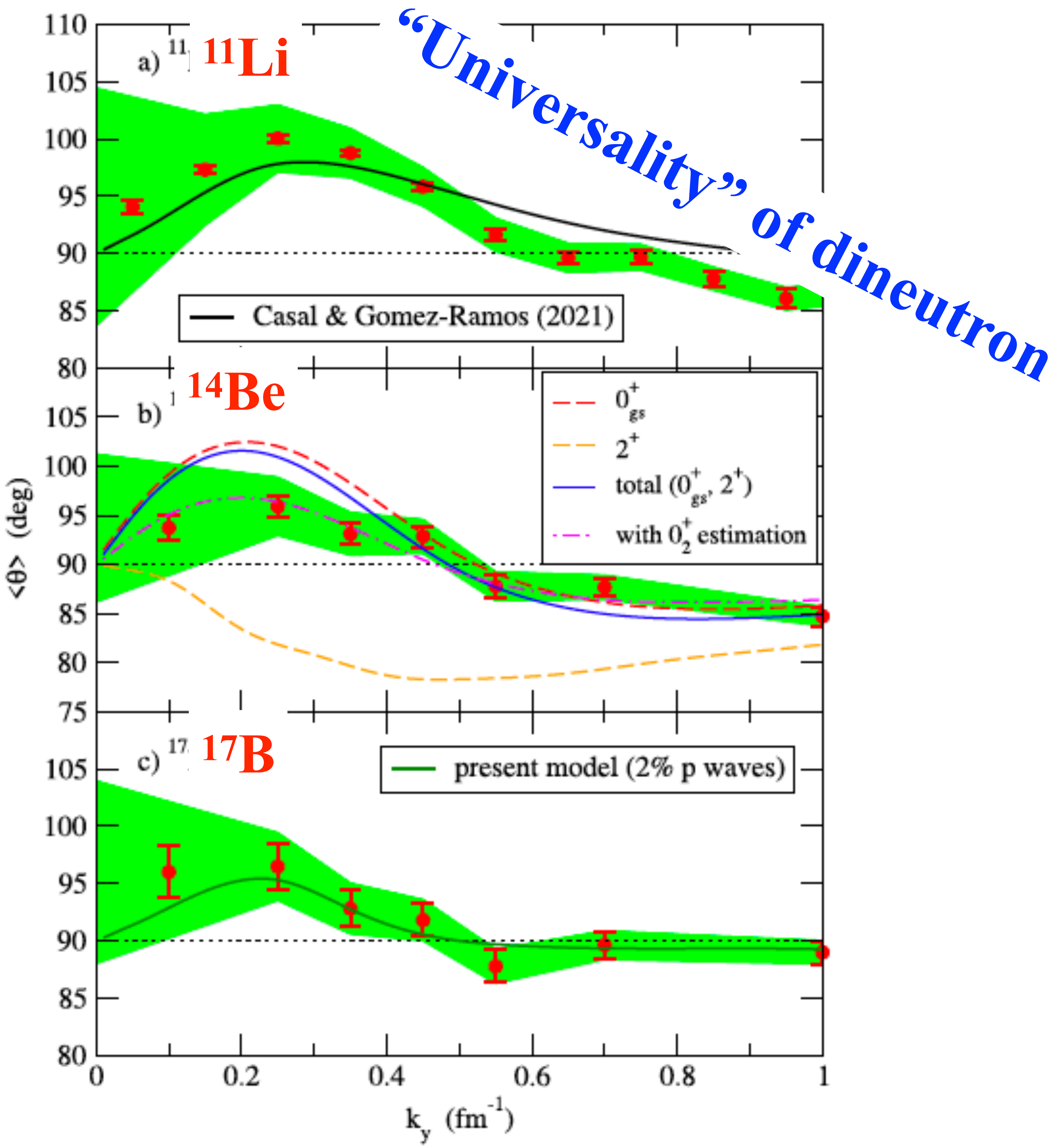
Surface localization of the dineutron in ^{11}Li and its universality

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



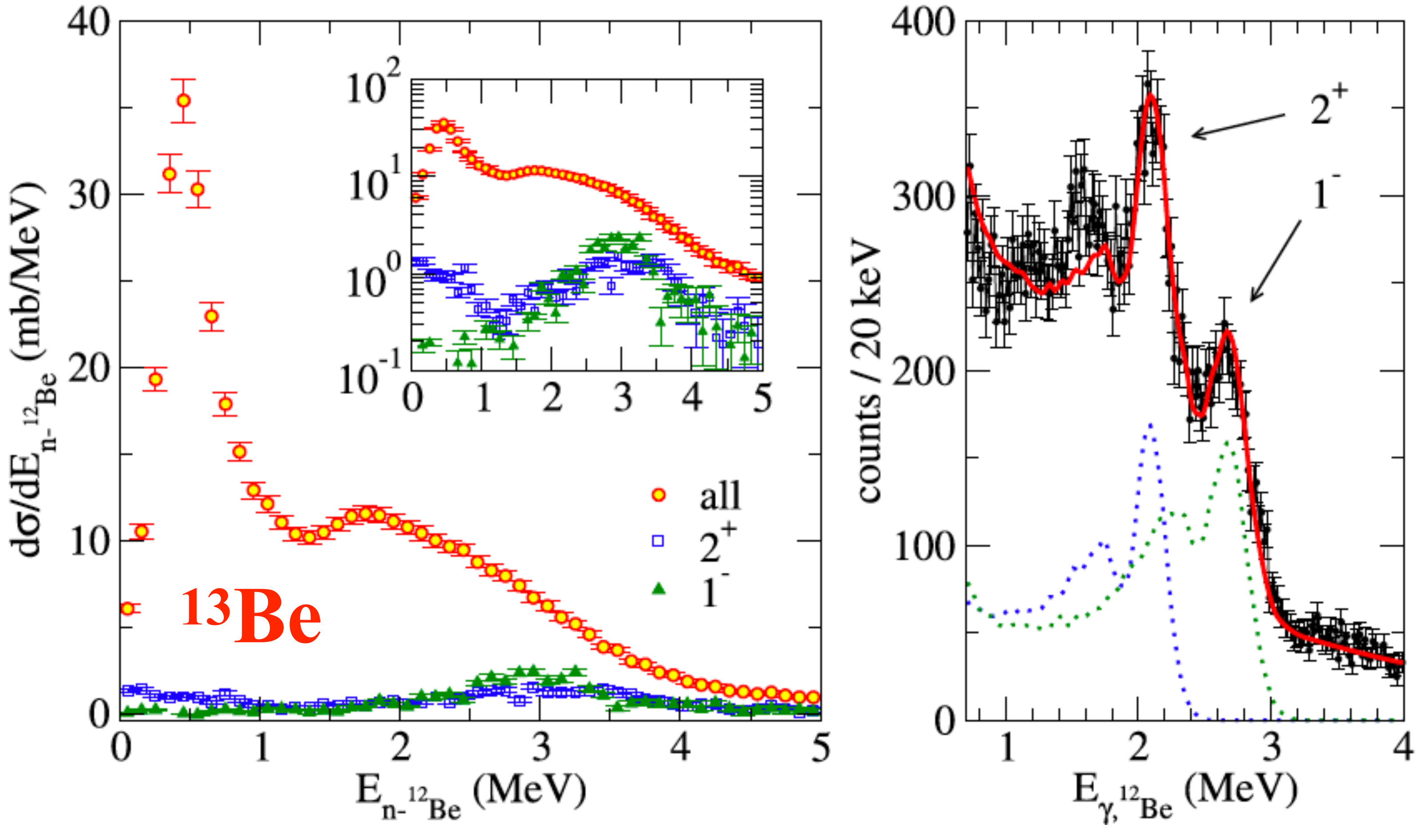
Dineutron is localized in
a limited region around
r~3.6fm (surface of the ^{9}Li core)
↔ Hagino et al., PRL99 (2007)

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

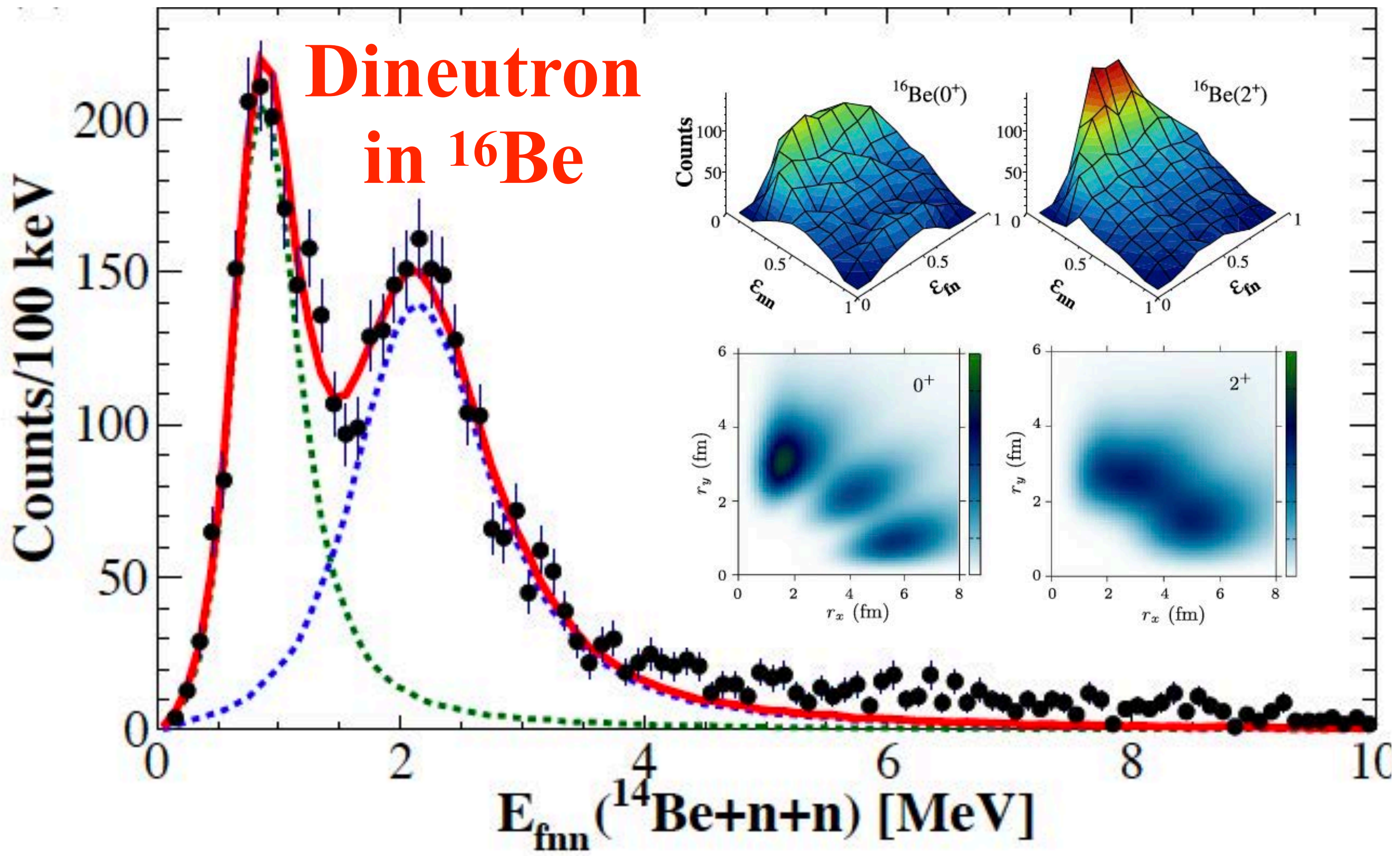


Results from SAMURAI18 experiment

A. Corsi et al., PLB **797**, 134843 (2019)

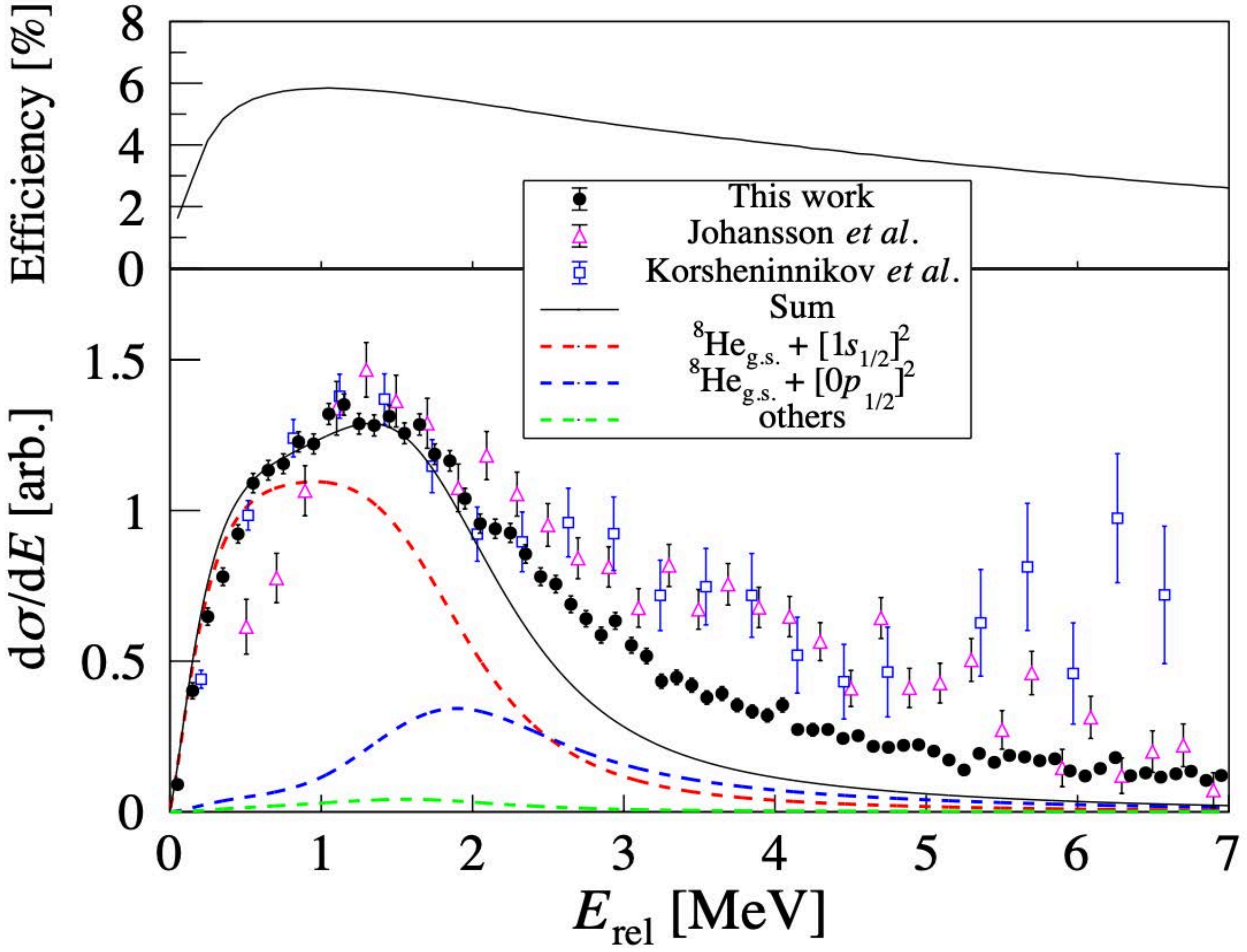


B. Monteagudo et al., PRL **132**, 082501 (2024)

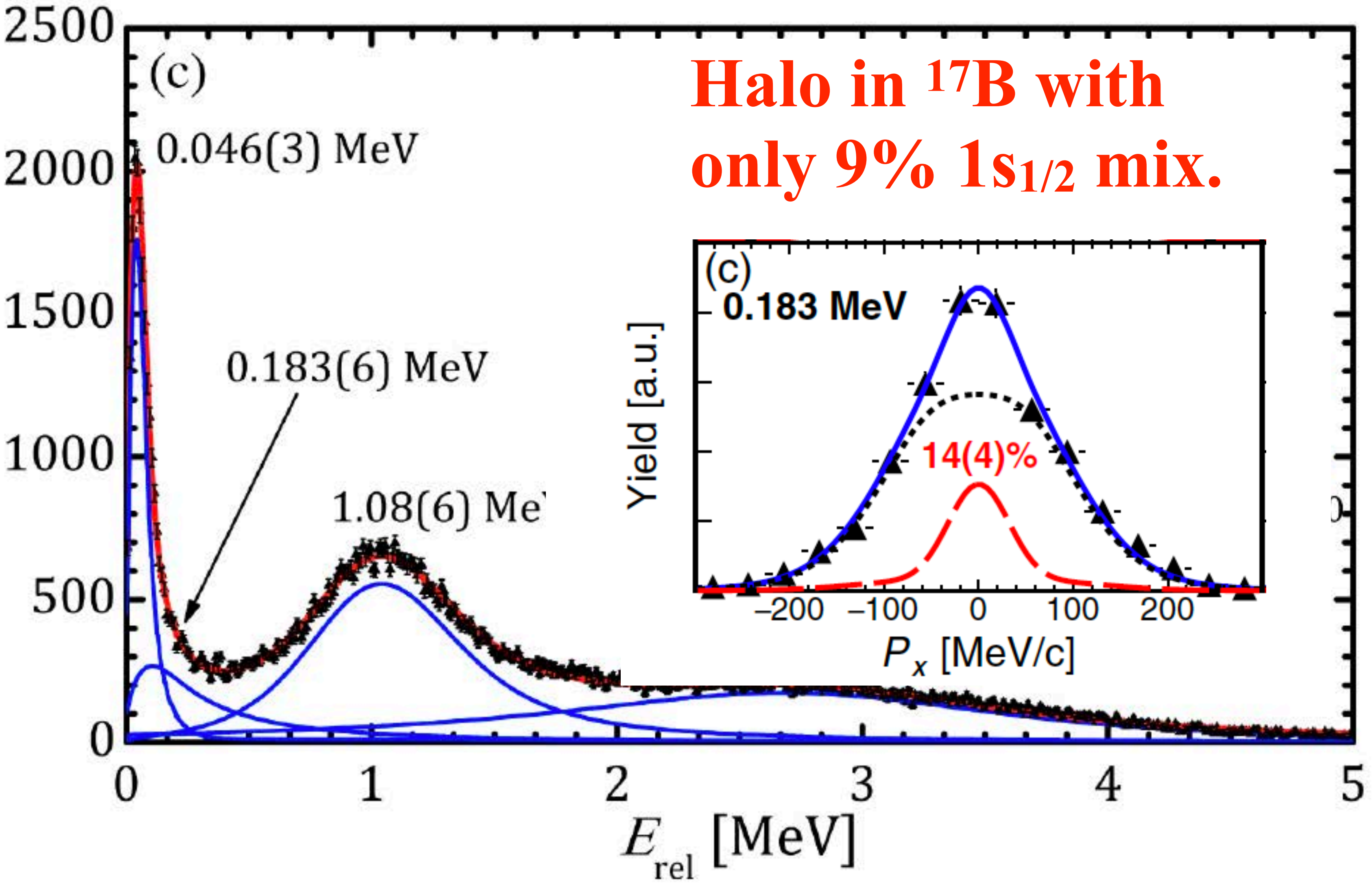


Y.L. Sun et al.,
Nature Comm. **17**:4674 (2026).

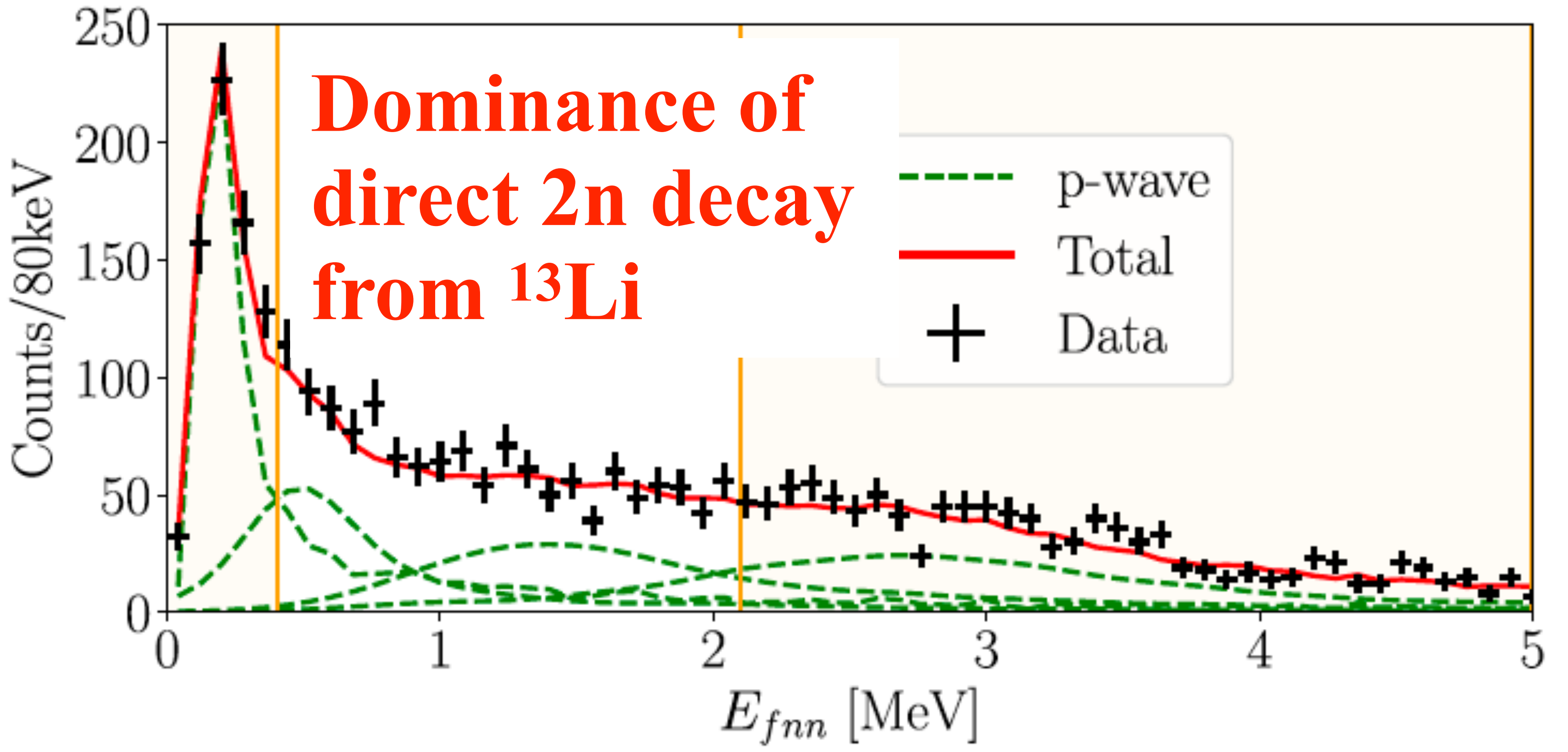
Discovery of a universal 3-body s-wave resonance in ^{10}He



Z.H. Yang et al., PRL **126**, 082501 (2021)

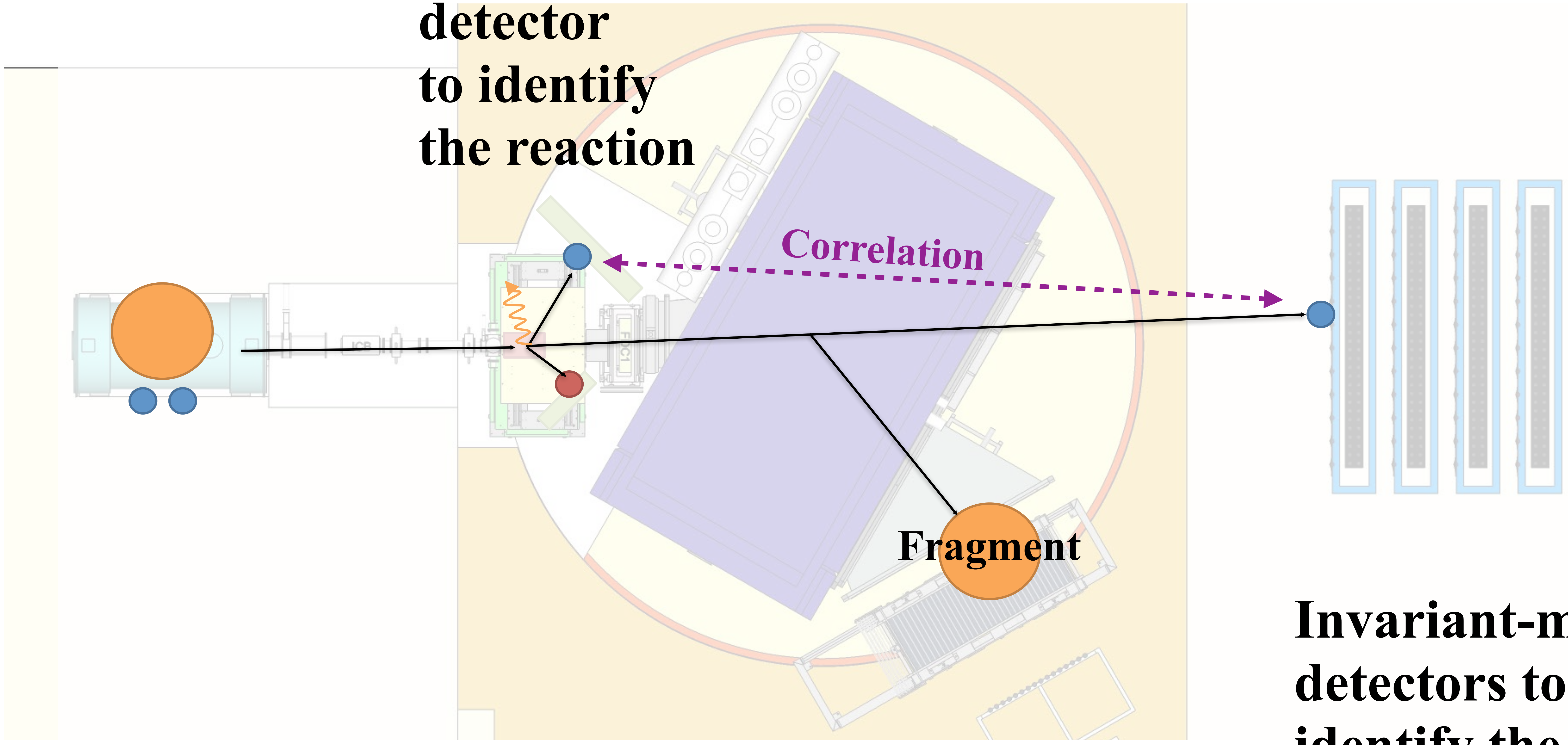


P. Andre et al., PLB **857**, 138977 (2024).



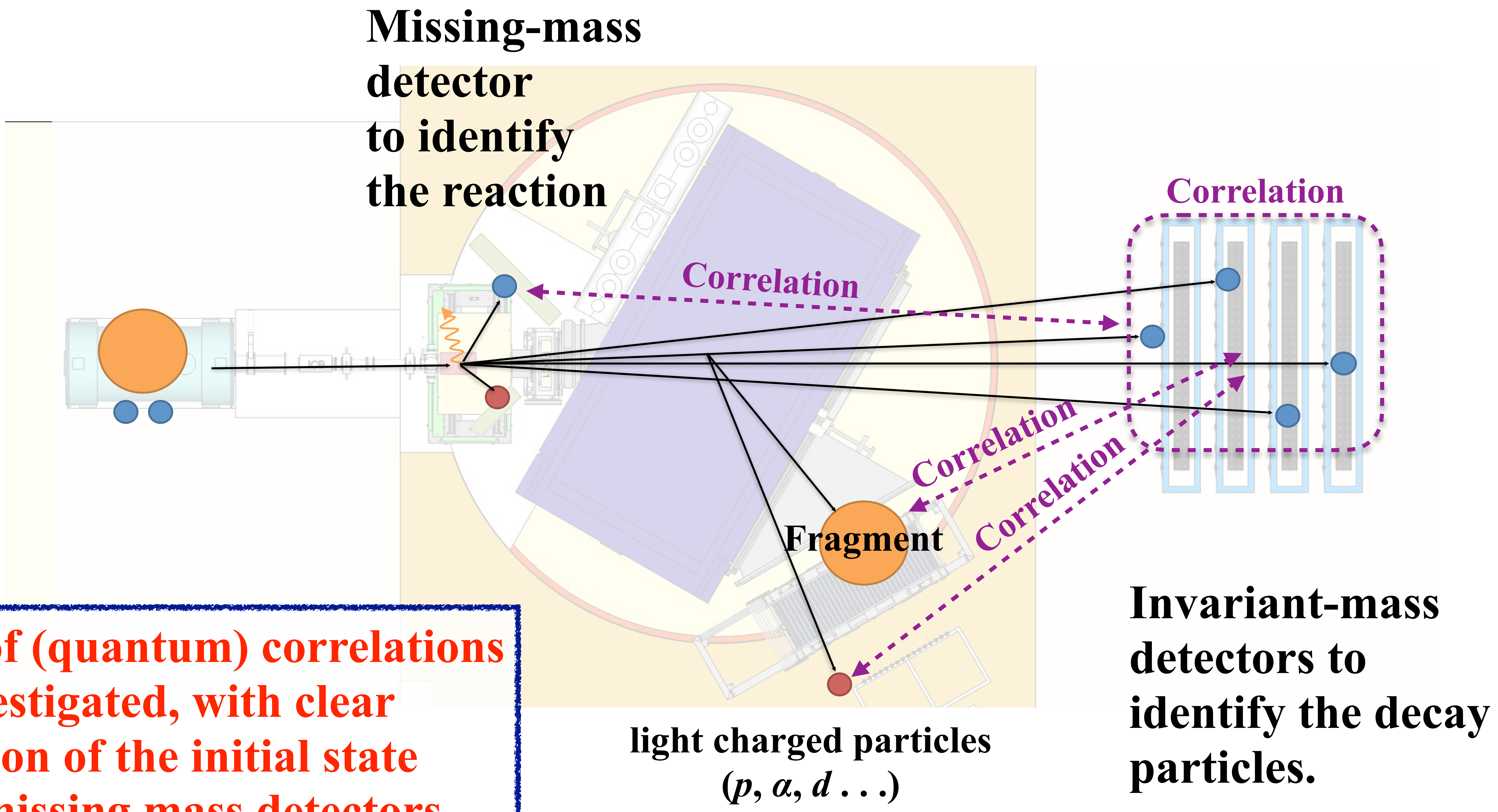
A new standard in RI-beam experiments

Missing-mass detector to identify the reaction



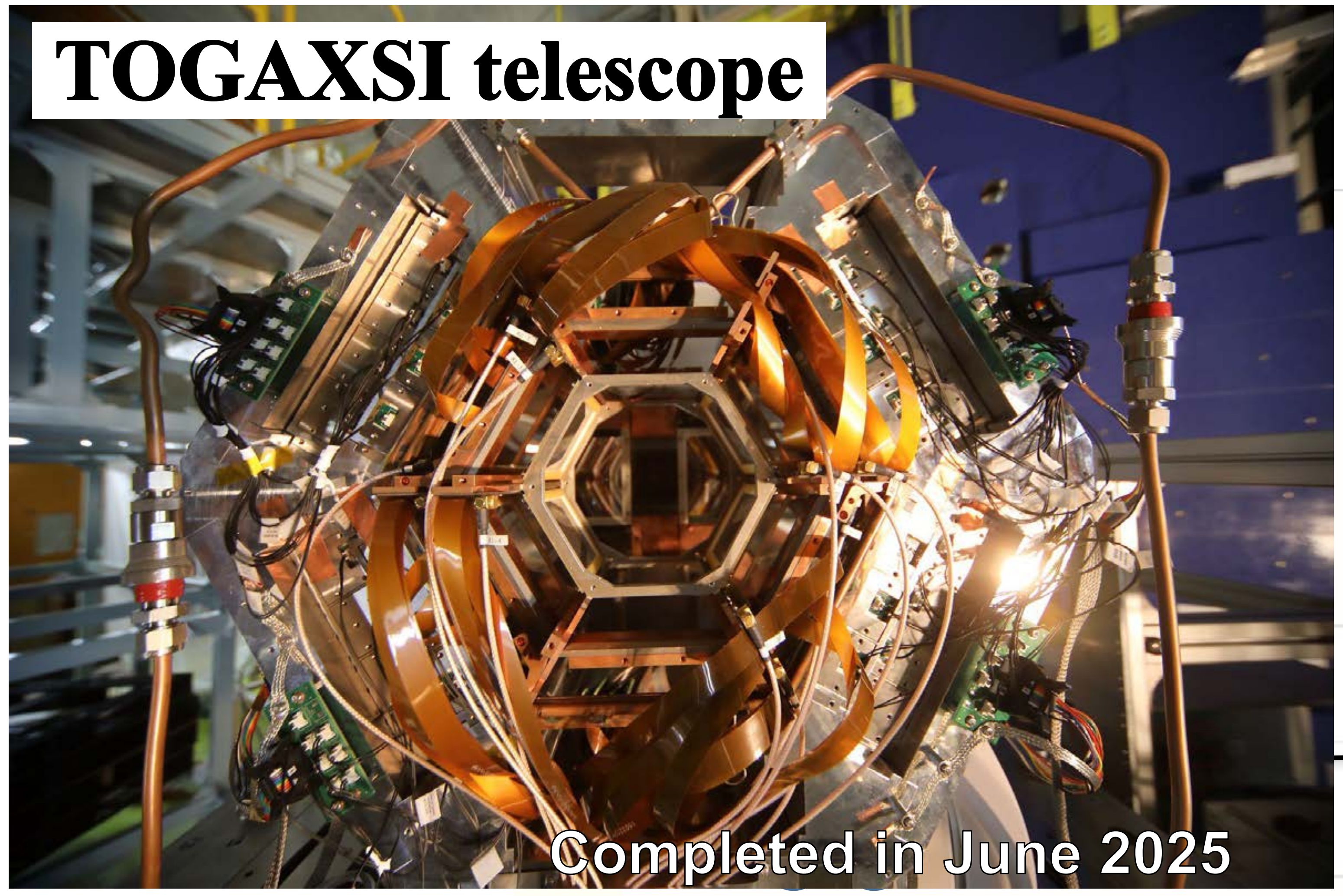
Invariant-mass detectors to identify the decay particles.

A new standard in RI-beam experiments

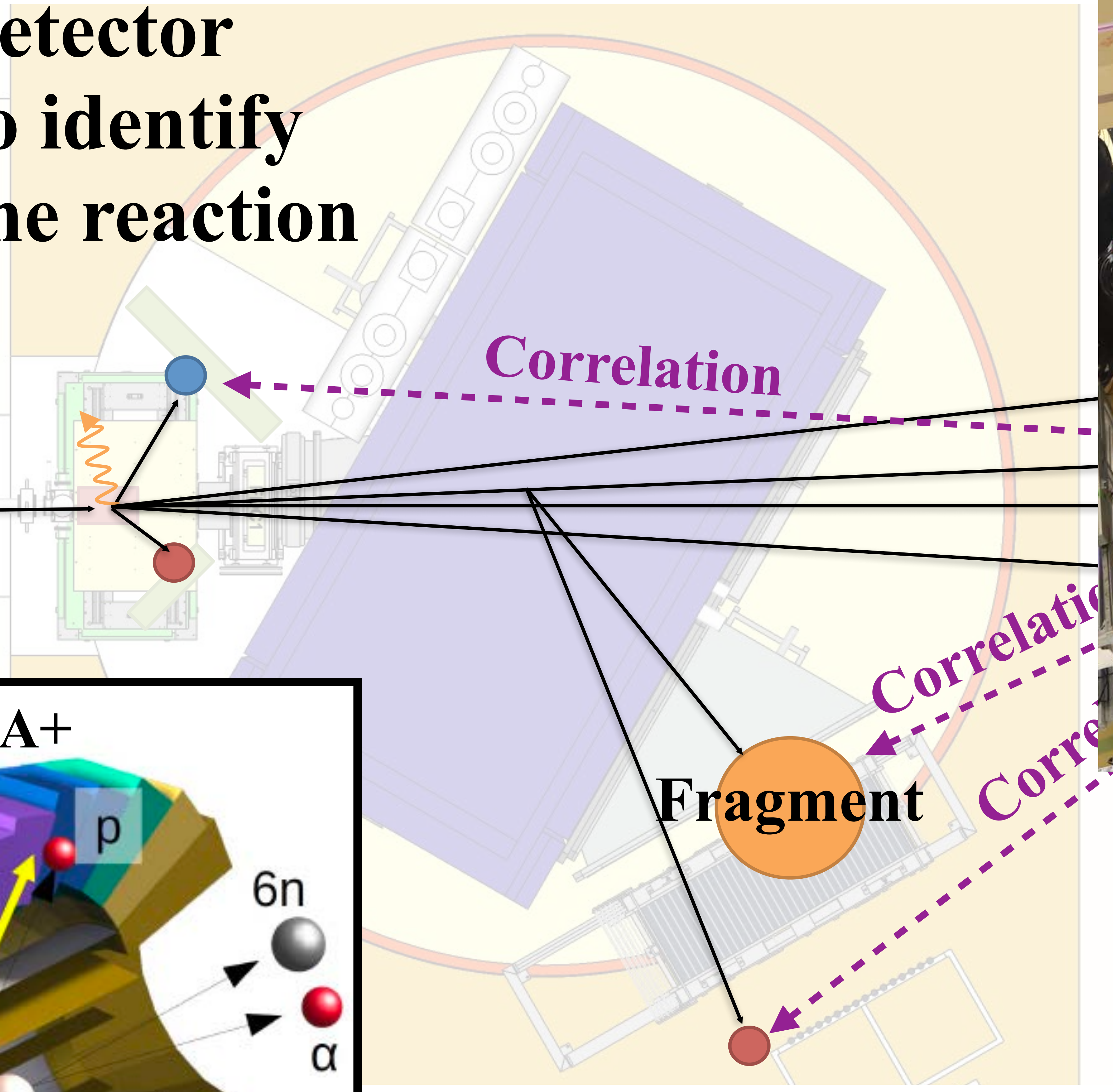


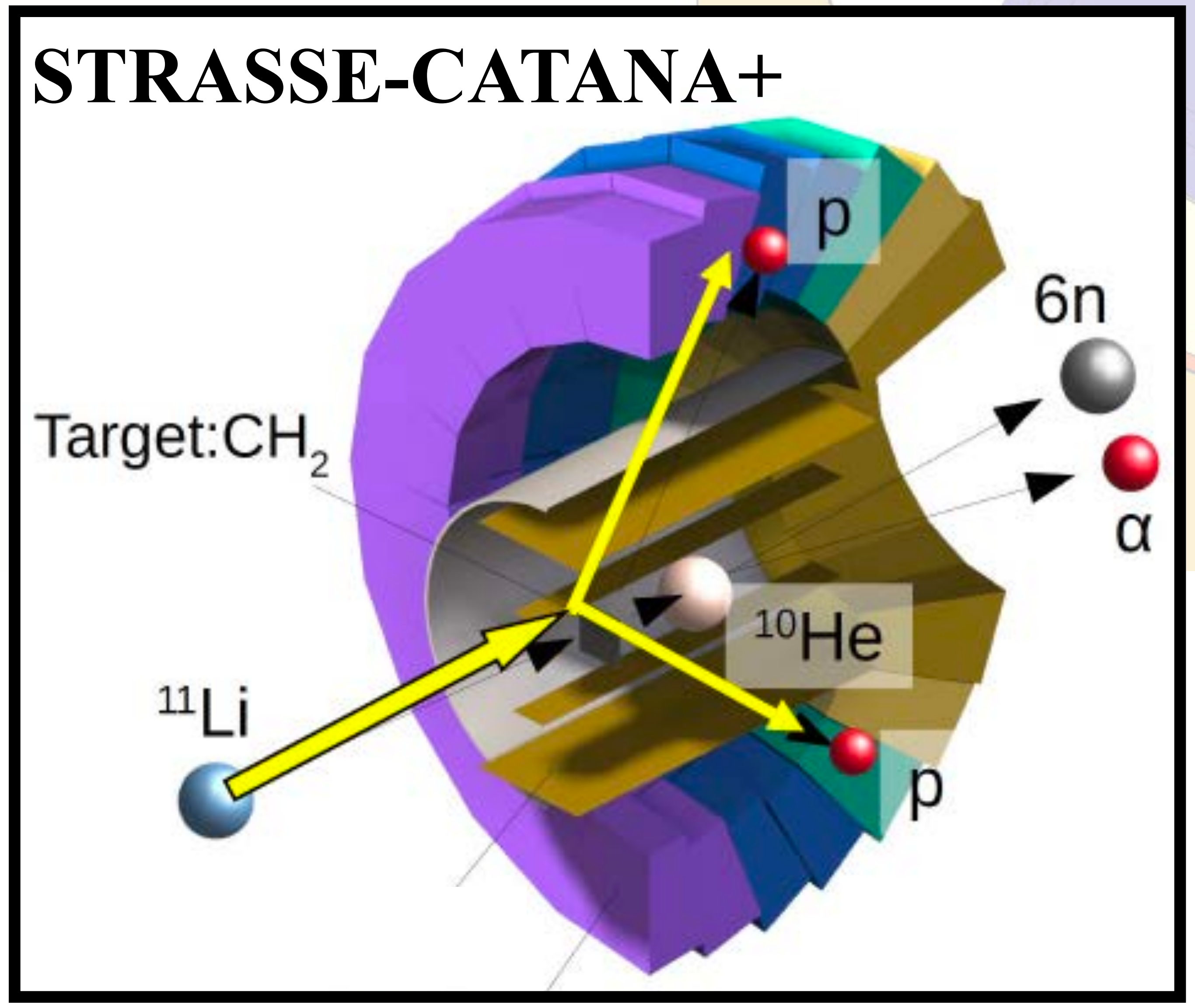
A variety of (quantum) correlations can be investigated, with clear identification of the initial state using the missing mass detectors.

A new standard in RI-beam experiments

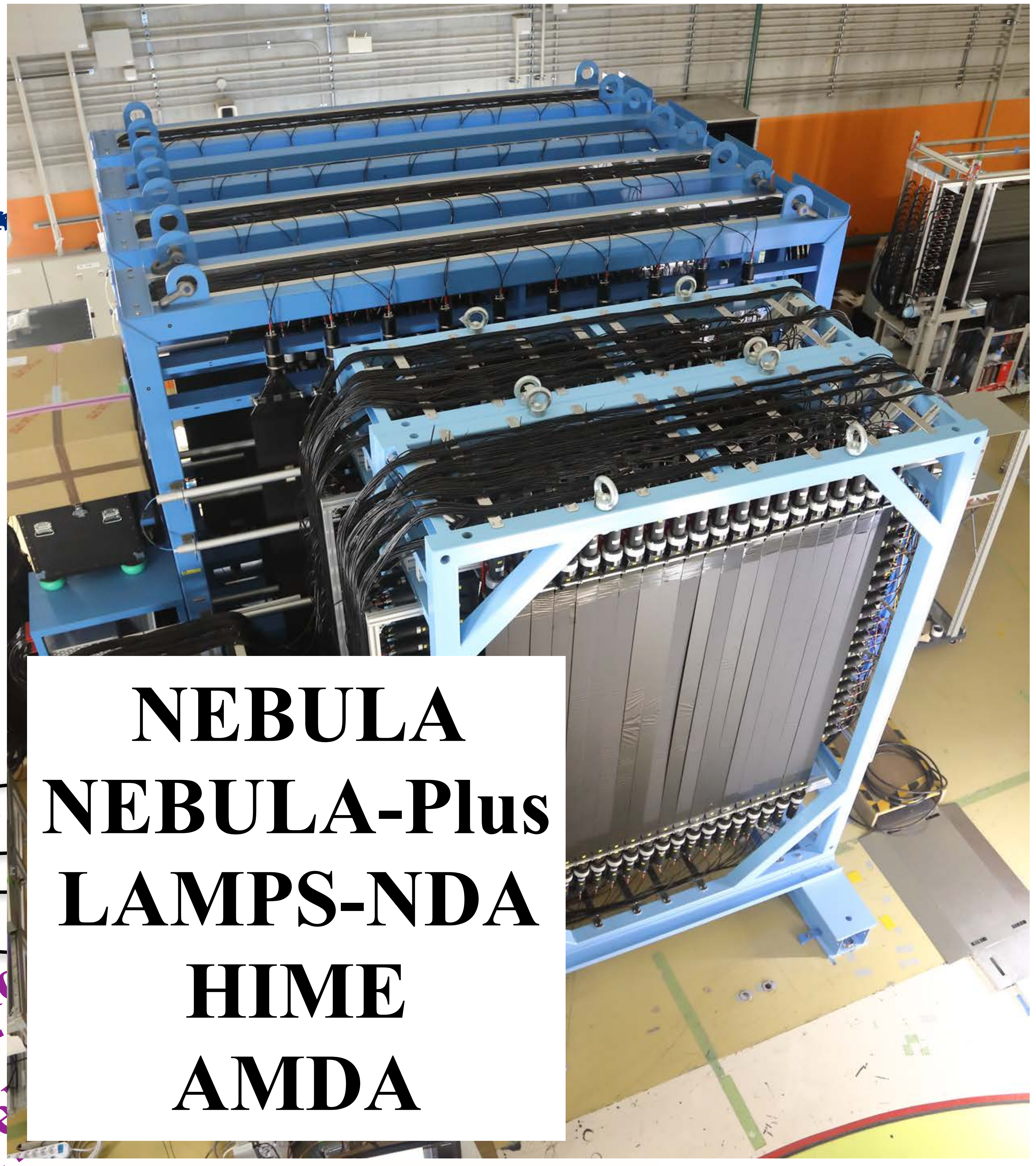


Missing-mass detector to identify the reaction



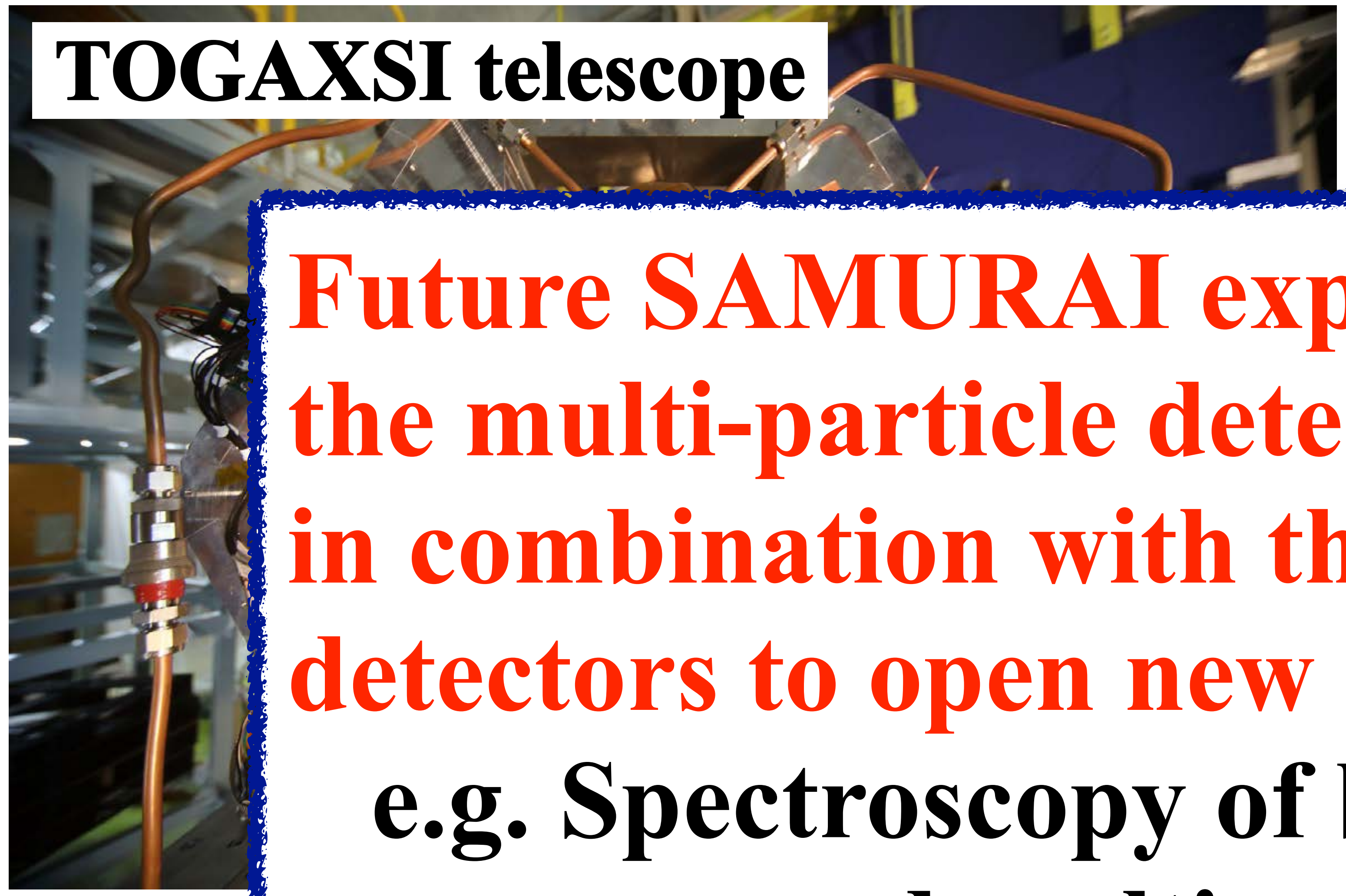


light charged particles
(p, α, d . . .)



Invariant-mass detectors to identify the decay particles.

A new standard in RI-beam experiments

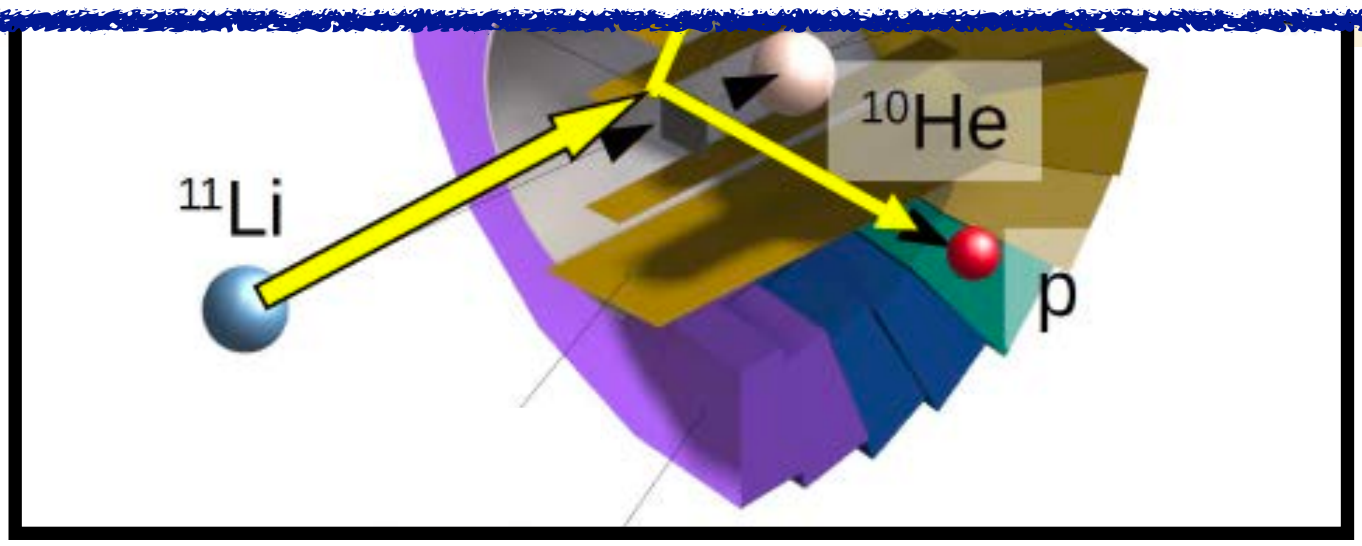


Missing-mass detector

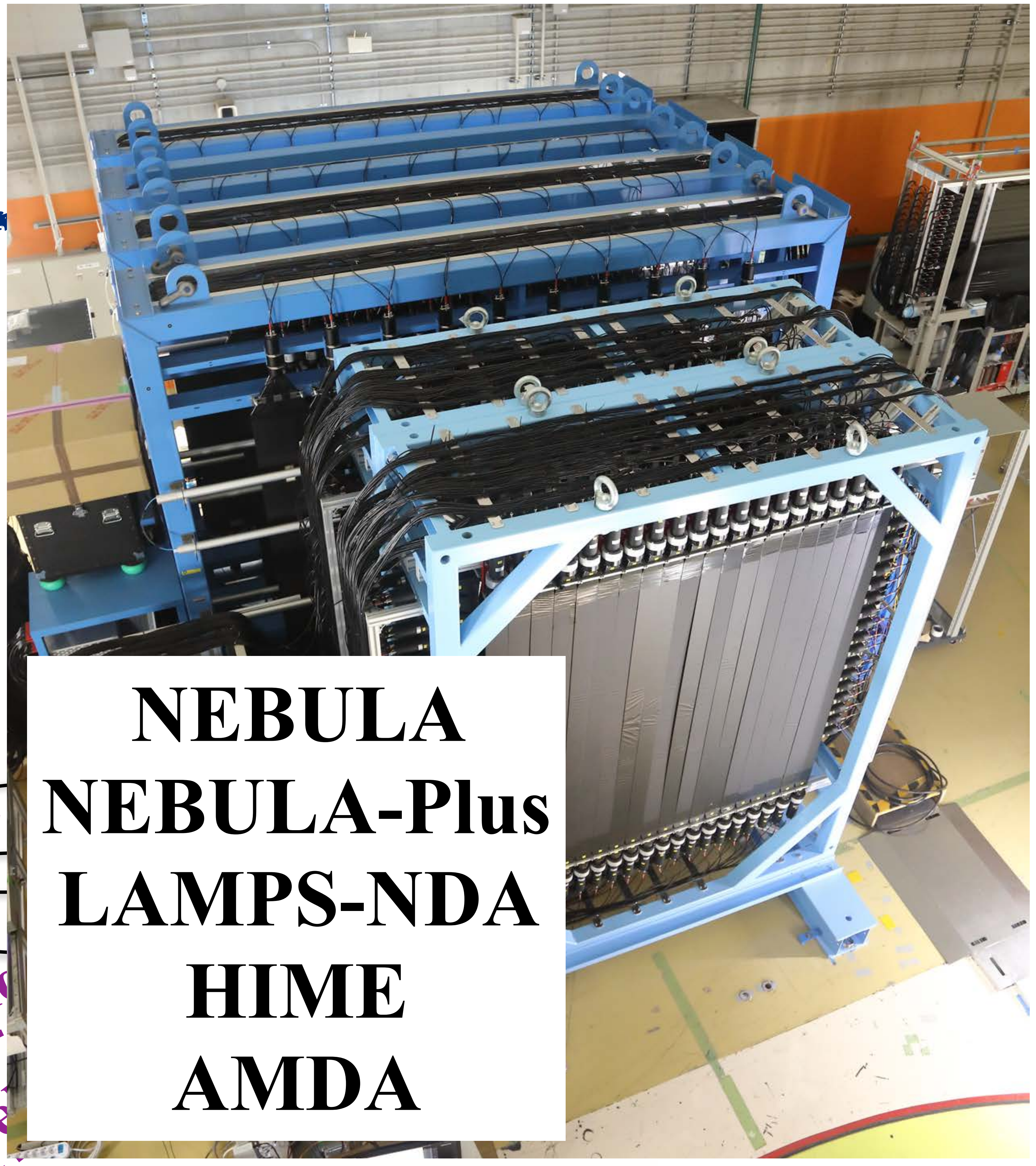
Future SAMURAI experiments will exploit the multi-particle detection capability in combination with the new missing mass detectors to open new scientific opportunities.

e.g. Spectroscopy of beyond-the-dripline nuclei and multi-neutron correlation in them
Clustering in ground and (highly) excited states
Fission studies using the (*p*,2*p*) reaction

Your ideas!



light charged particles (*p*, *α*, *d* . . .)



NEBULA
NEBULA-Plus
LAMPS-NDA
HIME
AMDA

Invariant-mass detectors to identify the decay particles.

Summary of the part 4

The (p,pX) reaction as an experimental tool beyond a single-particle spectroscopy is discussed.

When a proton single-particle structure is well understood, the (p,2p) reaction can be used to probe neutron structures.

Case of ^{25}F(p,2p)^{24}O and ^{29}F(p,2p)^{28}O

→ hint of proton-neutron interaction in neutron-rich nuclei

Combination of the (p,pX) reactions and decay particle detection opens broad opportunities:

SAMURAI18 experiment: dineutron correlation

The first fully exclusive measurement with RI-beams

Extension with reinforced detectors (TOGAXSI, CATANA-STRASSE, LAMPS-NDA...)

→ Studies of a variety of (quantum) correlations in nuclei.