# Exotic nuclei
# for investigating hierarchical structure of matter

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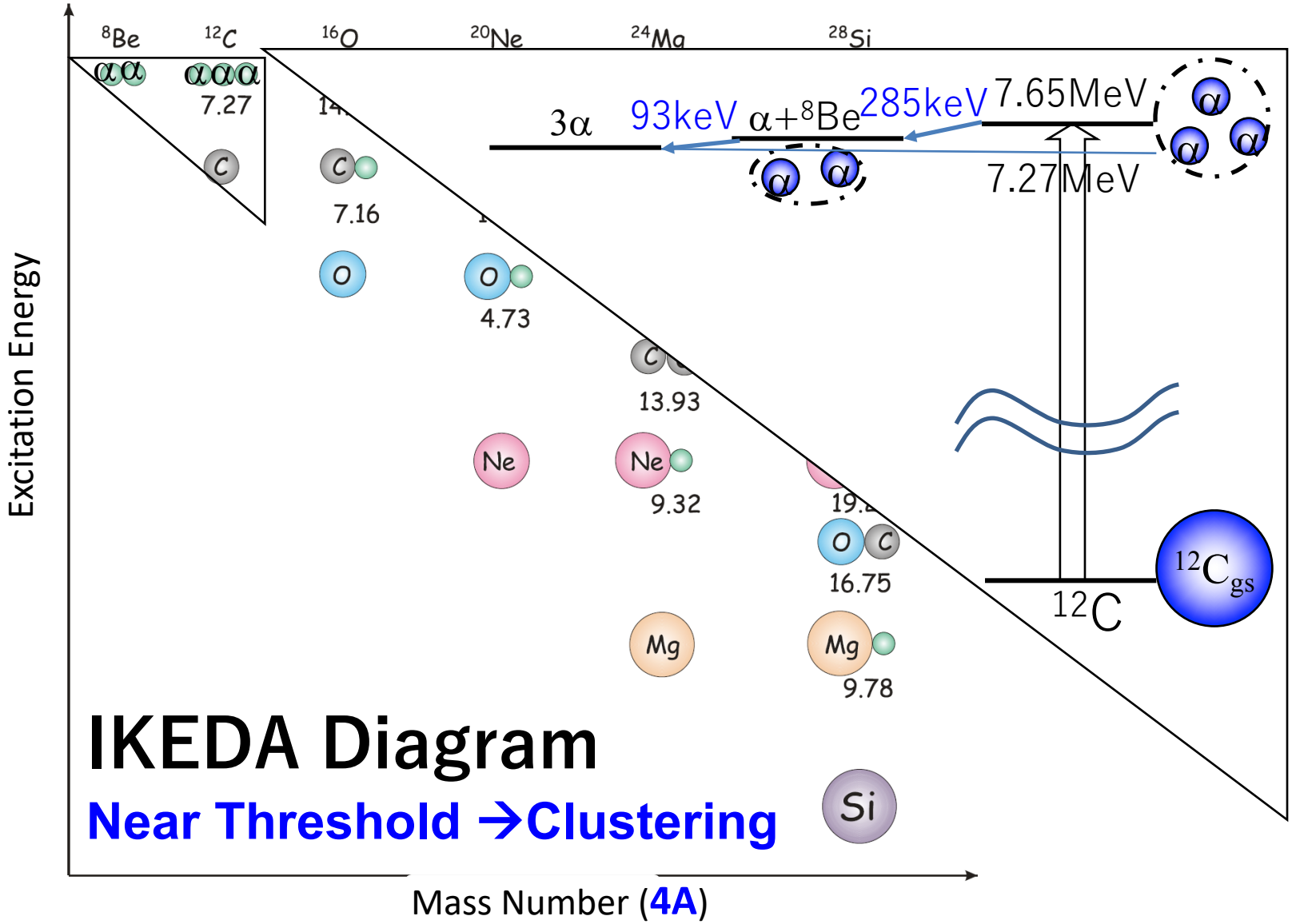
# Contents

- Multi-neutron clusters
- Recent Experiments on barely unbound 2n/3n/4n emitters --- $^{26}O$,$^{27}O$,$^{28}O$
- Near-future experiment on multi-neutron cluster--- $^{10}He$
- Summary

# α-Cluster

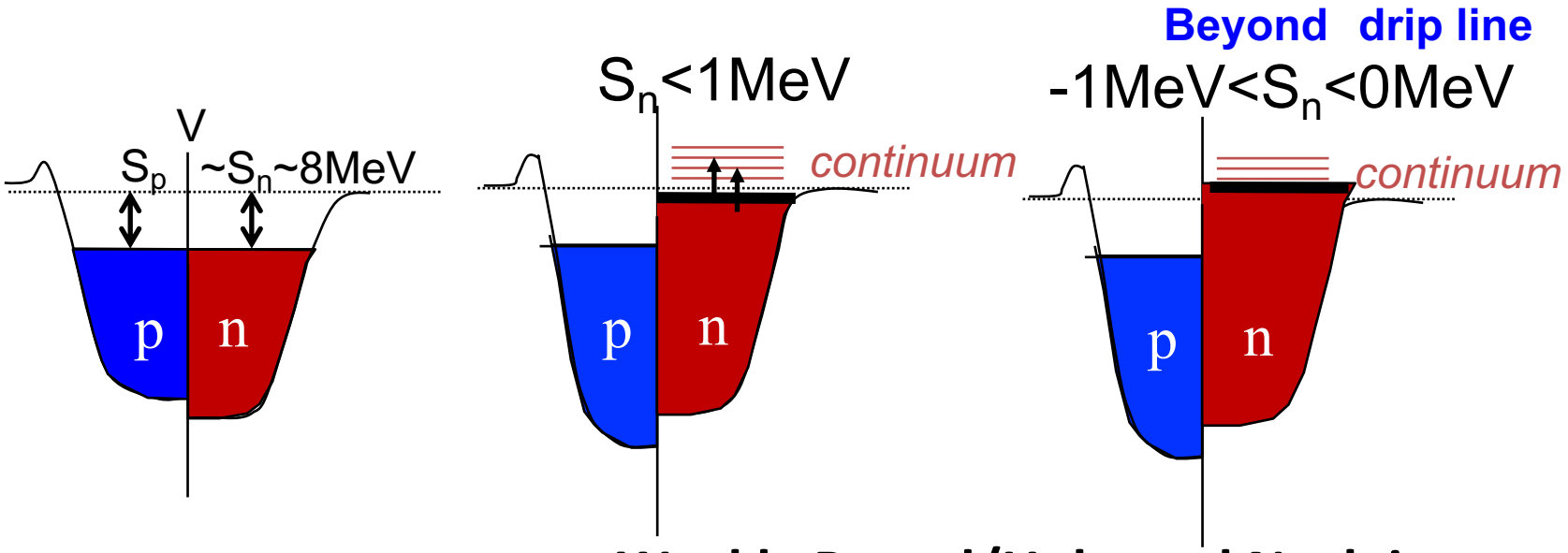
K.Ikeda, N.Takigawa, H.Horiuchi,Prog.Theo.Phys.Suppl.464.(1968).
M.Freer, Rep. Prog. Phys. 70, 2149 (2007).



# Multi-neutron cluster near drip line?

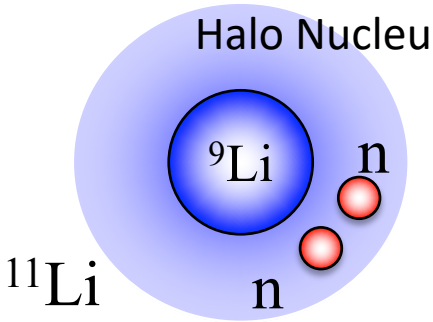
Stable Nuclei

Neutron-rich Nuclei

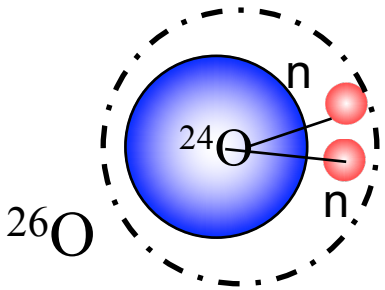



**Weakly Bound/Unbound Nuclei**

**Threshold → Clustering**




$S_{2n}$=0.37MeV

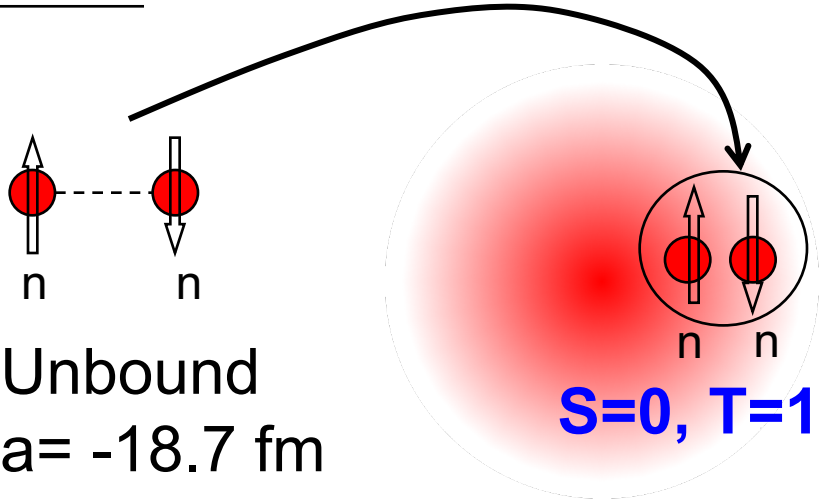



$S_{2n}$= –0.018(5) MeV

Kondo, TN et al., PRL116,102503(2016).

# Dineutron?

***What happens if "two neutrons" are on the surface of a nucleus?***



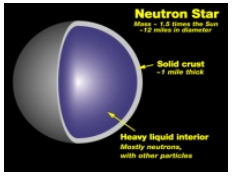

Unbound
a= -18.7 fm

s-wave scattering length

A.B.Migdal
Strongly correlated "dineutron"
Sov.J.Nucl.Phys.238(1973).

**Dineutron:**
@ **Low-dense** Neutron skin/halo?
/Inner crust of Neutron star?

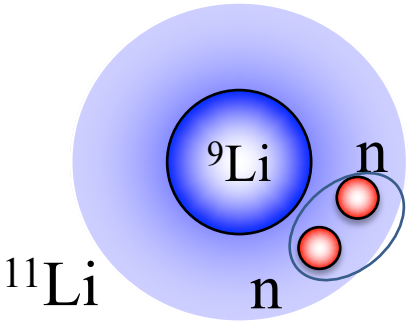
M.Matsuo
PRC73,044309(2006).
A.Gezerlis, J.Carlson,
PRC81,025803(2010)




neutron-star

## Possible dineutron site

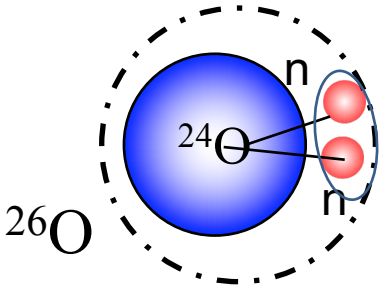
### 2n Halo Nuclei?




$S_{2n}$=0.37MeV

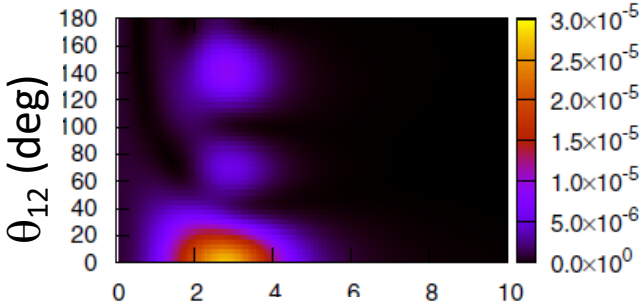
T.Nakamura PRL96, 252502 (2006).

### 2n weakly-unbound nuclei?



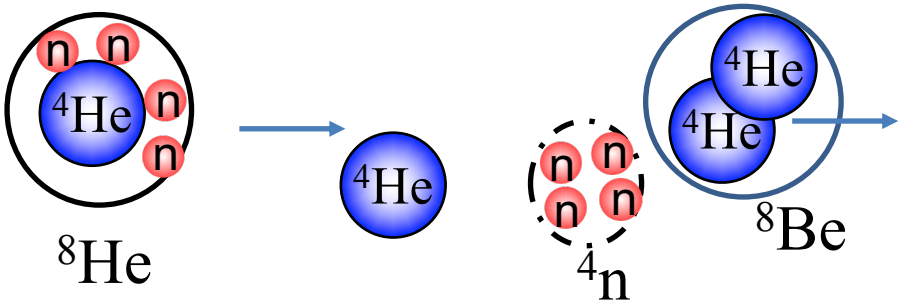

$S_{2n}$= –0.018(5) MeV

Kondo, TN et al., PRL116,102503(2016).

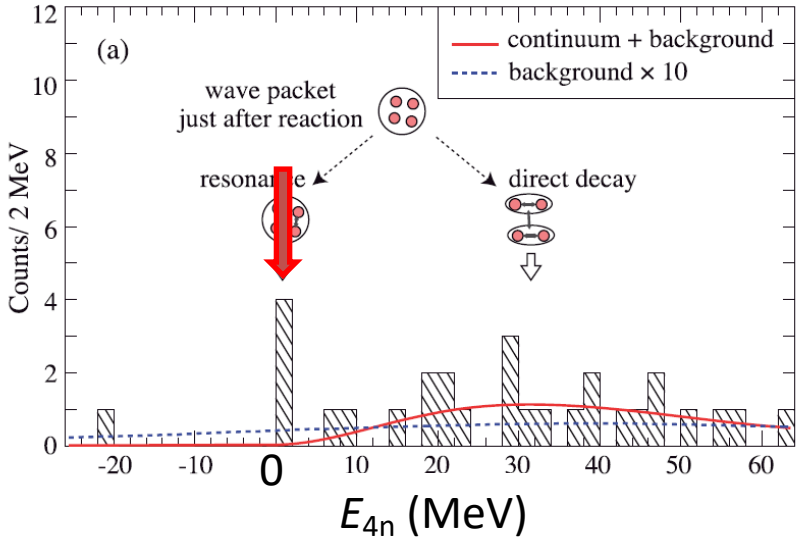



Hagino, Sagawa,
PRC93,034330(2016)

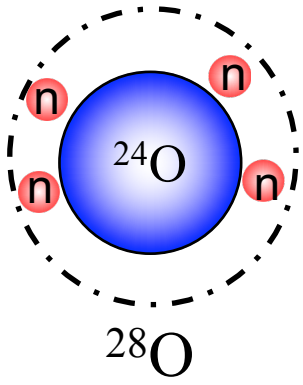
# Tetra-neutron?



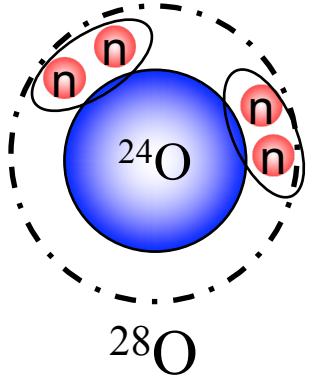

K.Kisamori et al., PRL116, 052501 (2016).



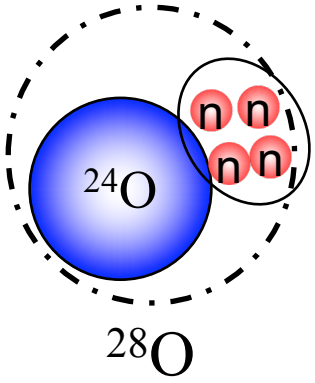

***What happens if "four neutrons" are on the surface of a nucleus?***




Non-correlated?




Double-dineutrons?




Tetra-neutron droplet?

***What happens if "N neutrons" are on the surface of a nucleus?***

***Multi-neutron cluster inside a nucleus?***

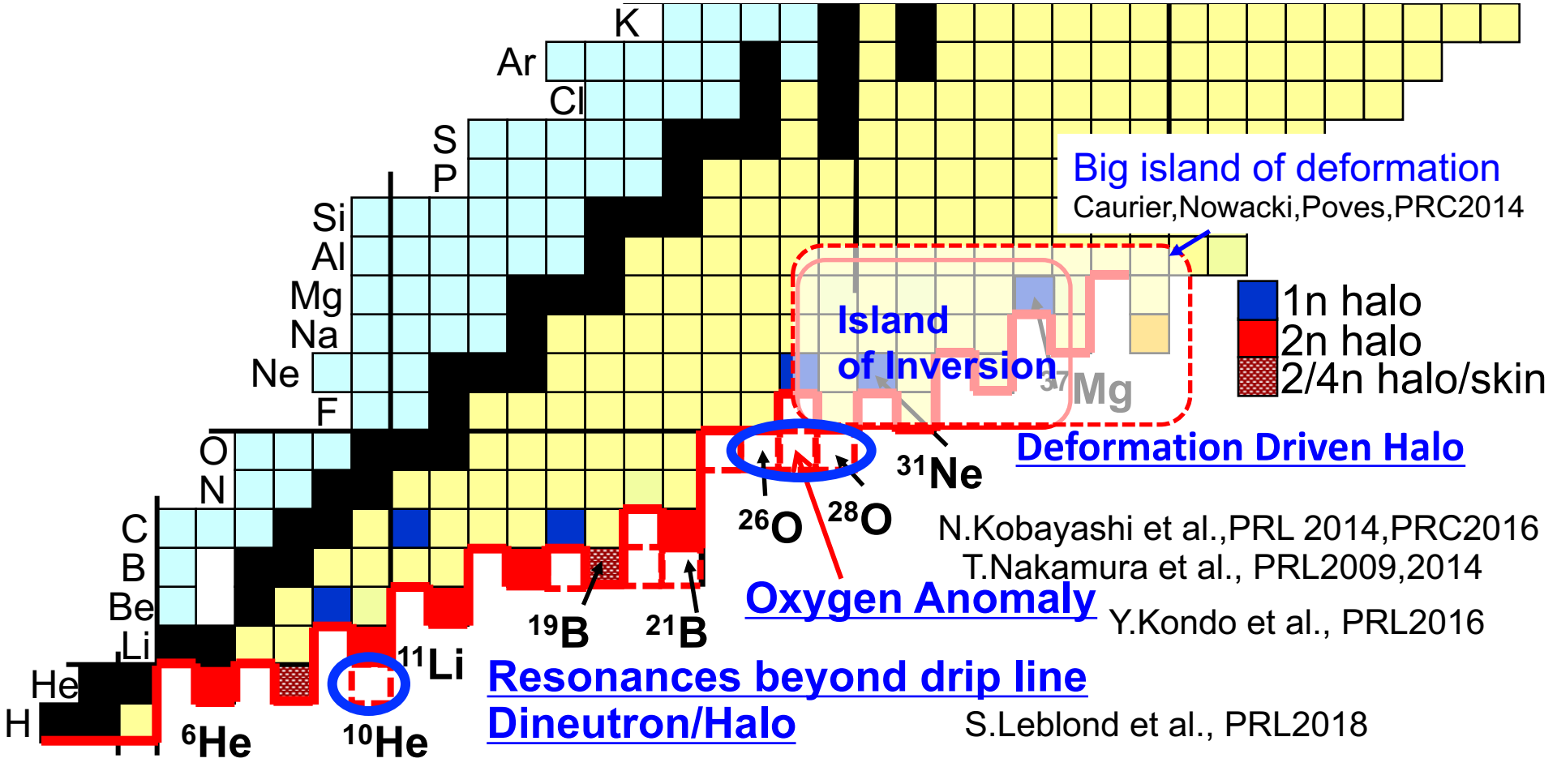
# Evolution Towards the Stability Limit

**Drip Line** (***Weakly Bound, -Unbound Nuclei, halo, dineutron, cluster***)

⇕

**Shell Evolution** (***New/Lost Magic Number, Deformation, Shape Coexistence***)

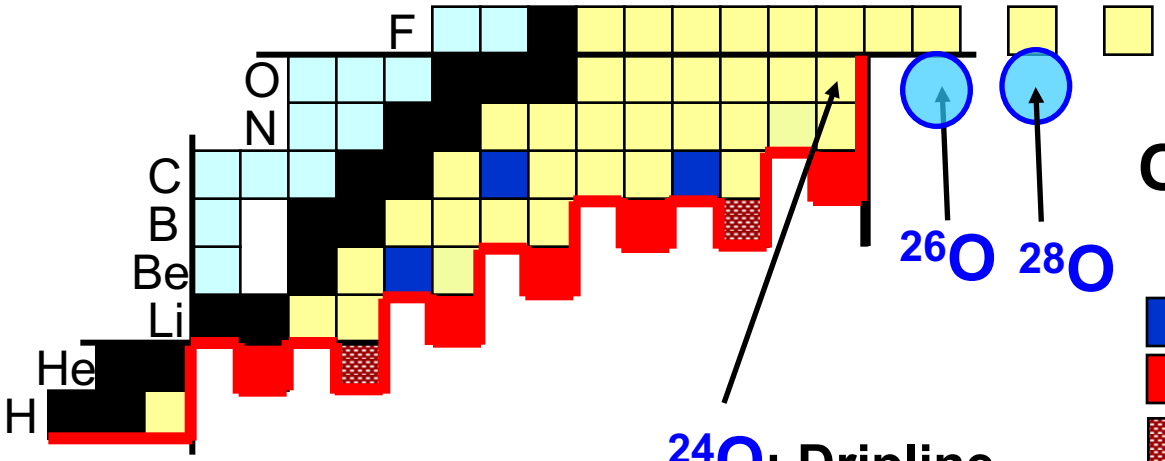
**Cluster Formation**



# Recent Experiments on barely unbound 2n/3n/4n emitters --- $^{26}$O,$^{27}$O,$^{28}$O

**Yosuke Kondo, TN & SAMURAI Collaboration**

**Y. Kondo, TN et al., Phys. Rev. Lett. 116, 102503, (2016).**



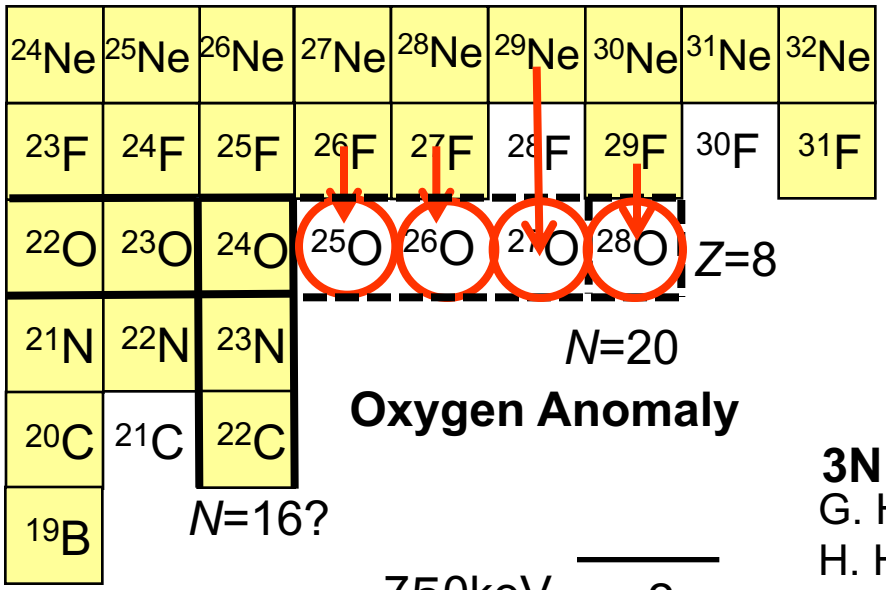

**Oxygen Anomaly**

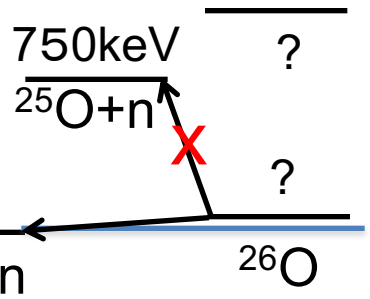
1n halo known
2n halo known
4n halo/skin candidates

# Spectroscopy of $^{25\text{-}28}$O—beyond the neutron drip line

**Spokesperson Yosuke Kondo**

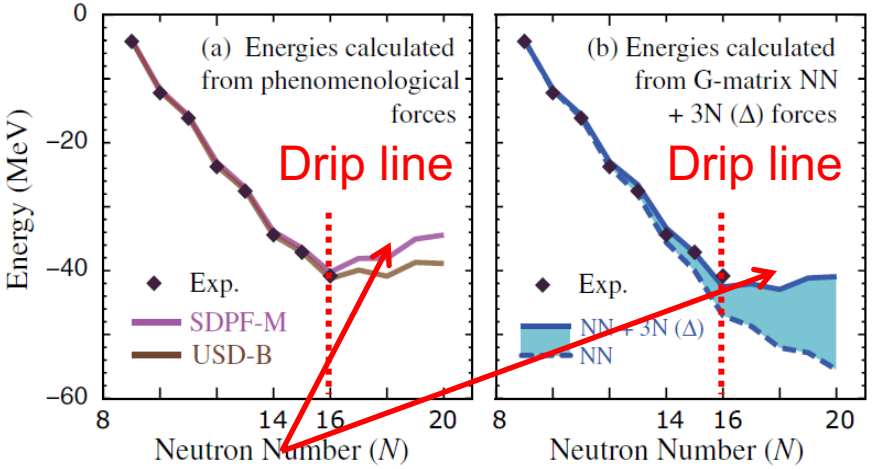
Experimental study of *unbound* oxygen isotopes towards the possible *double magic nucleus* $^{28}$O




E. Lunderberg et al.PRL108, 142503 (2012)
C. Caesar et al.PRC88, 034313 (2013).

T. Otsuka et al., PRL105, 032501 (2010).

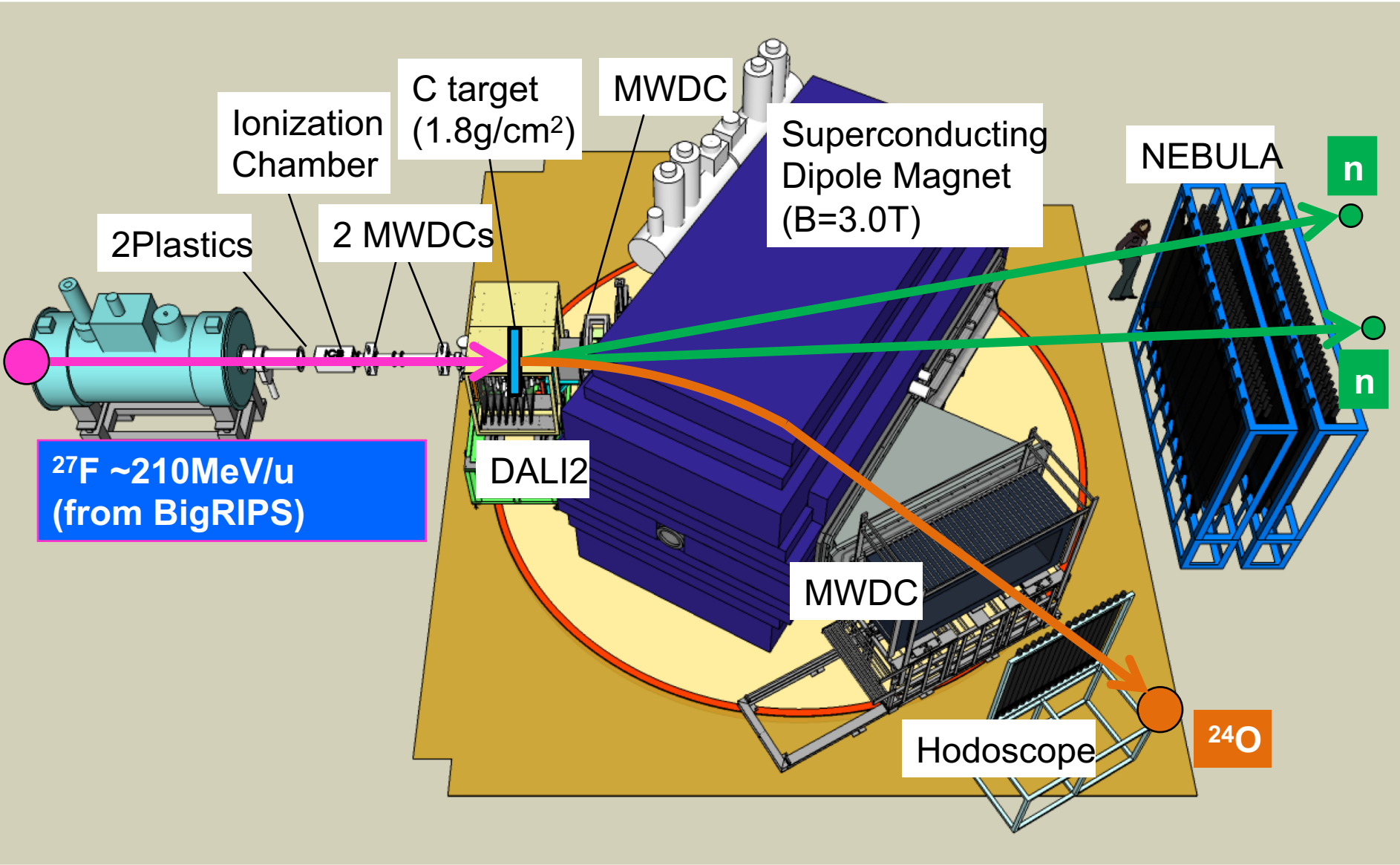



**3N force:** significant at N>16
G. Hagen et al., PRL108, 242501(2012).
H. Hergert et al., PRL110, 242501(2013).
S.K.Bogner et al., PRL113, 142501(2014).

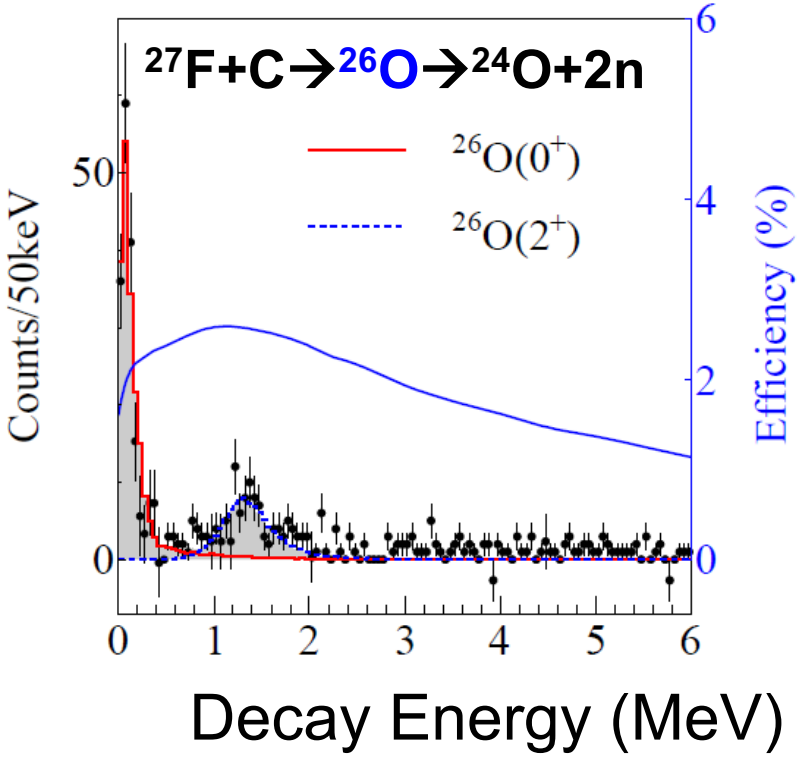
**Continuum Effect:**
A.Volya, V.Zelevinski, PRL94,052501(2005).
K. Tsukyiyama, T. Otsuka, PTEP2015, 093D01 (2015).

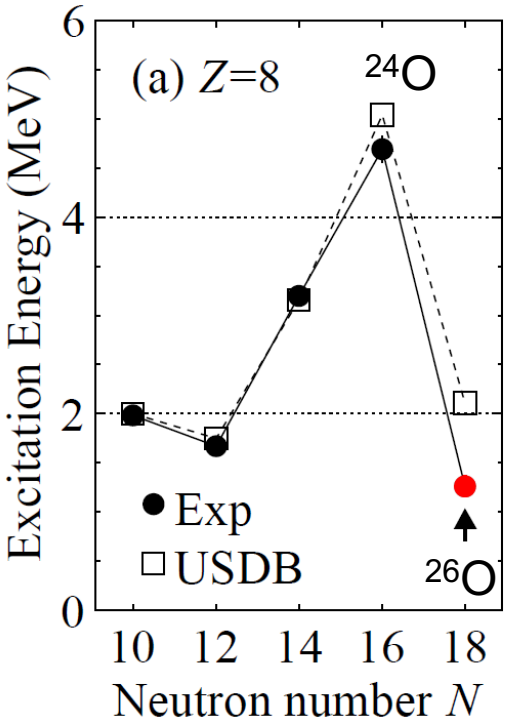
**nn correlations:**
L.V. Grigorenko et al., PRL111,042501(2013).
K. Hagino, H. Sagawa PRC89,014331(2014).

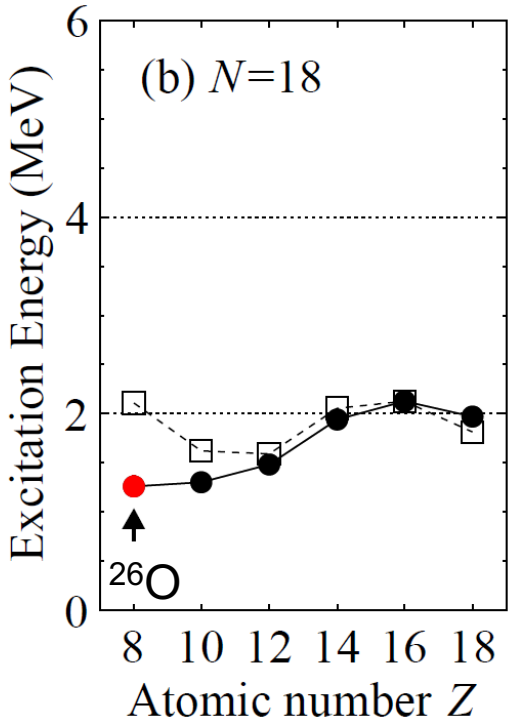
# Experimental Setup at SAMURAI at RIBF



# Results of $^{26}$O




**Ground state (0$^+$)**

5 times higher statistics than previous study

**18±3(stat)±4(syst)keV**

Finite value is determined for the first time

**1$^{st}$ excited state (2$^+$)**

Observed for the first time

**$1.28^{+0.11}_{-0.08}$MeV**

**N=16 shell closure ($^{24}$O)** is confirmed

USDB cannot describe 2$^+$ energy at $^{26}$O

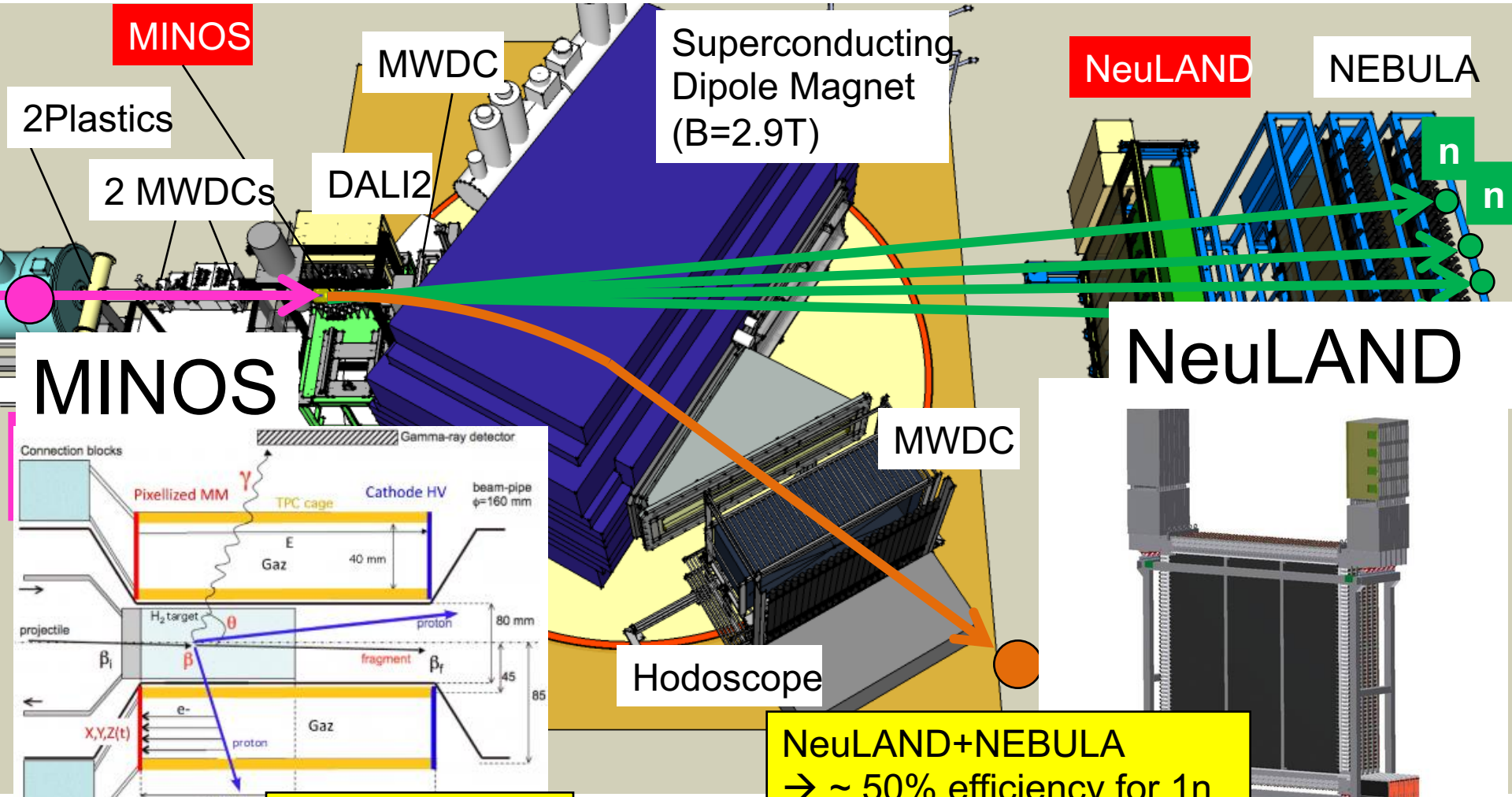
→effects of

**pf shell?, continuum?**

**2n Correlations?, 3N force?**

**Y. Kondo et al., Phys. Rev. Lett. 116, 102503, (2016)**

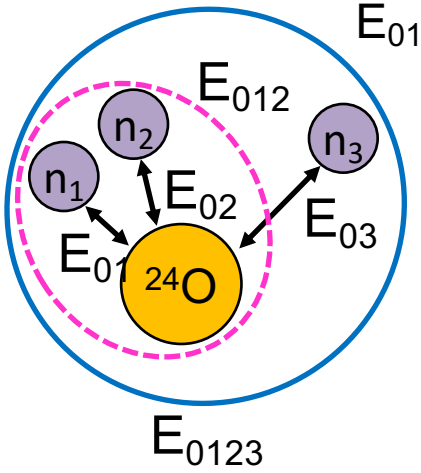
# $^{28}O$ measurement @ RIBF-SAMURAI

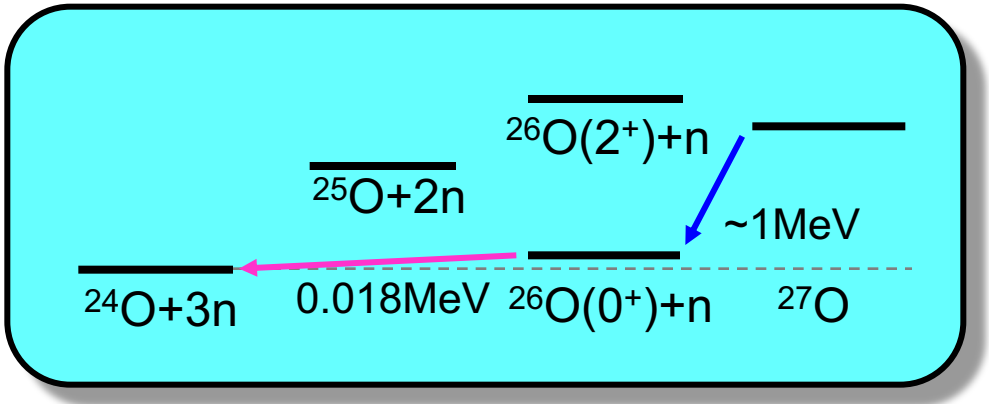



Y.Kondo, TN, T.Tomai, NIMB 463, 173 (2020).

# Decay energy spectrum($^{24}$O+3n coincidence)

$^{29}F+^{1}H \rightarrow {}^{24}O+3n+X$



# Theoretical predictions towards $^{28}$O

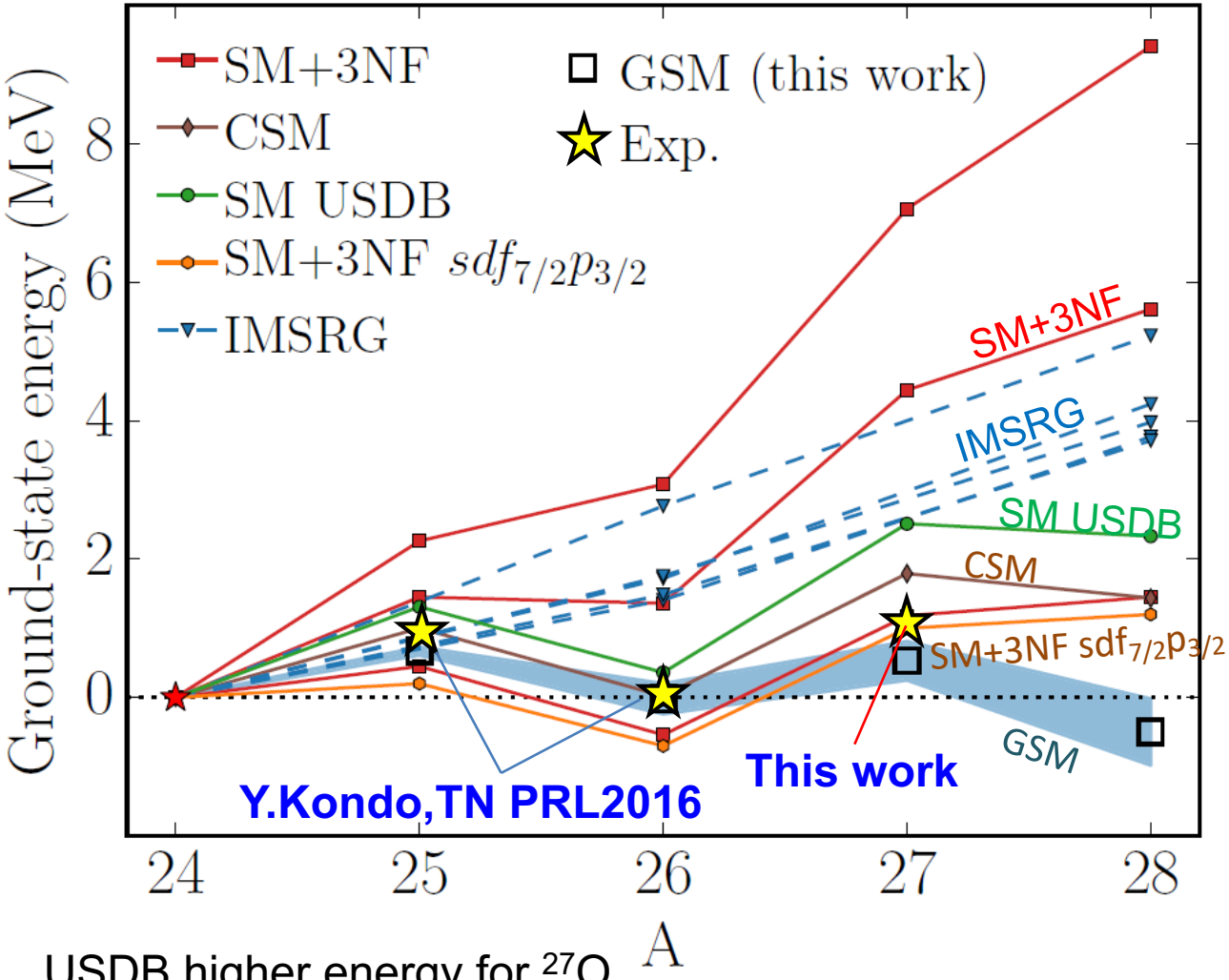



*Fig. from K. Fossez et al., PRC 96, 024308 (2017)*

SM USDB: B. A. Brown, Int. J. Mod. Phys. E26, 1740003 (2017)

SM+3NF: T. Otsuka et al., PRL105, 032501 (2010)

SM+3NF $sdf_{7/2}p_{3/2}$:

CSM: A. Volya et al., PRL94, 052501 (2005), A. Volya et al., PRC74, 064314, (2006)

IMSRG: V. Lapoux et al., PRL117, 052501, (2016), H. Hergert

USDB higher energy for $^{27}$O
→There are missing effects

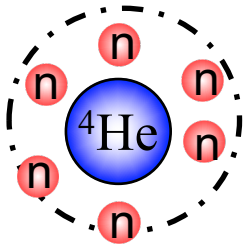
# Multi-neutron cluster experiment in the near future

– 6n cluster in $^{10}$He?

# *Hexa-neutron?*

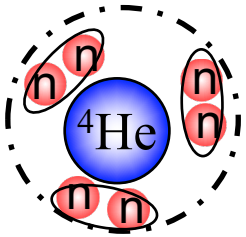
**$^6$n** is more stable than **$^4$n** ?


***What happens if "six neutrons" are on the surface of a nucleus?***



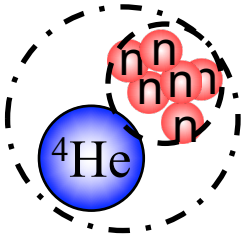

$^{10}$He

Non-correlated?



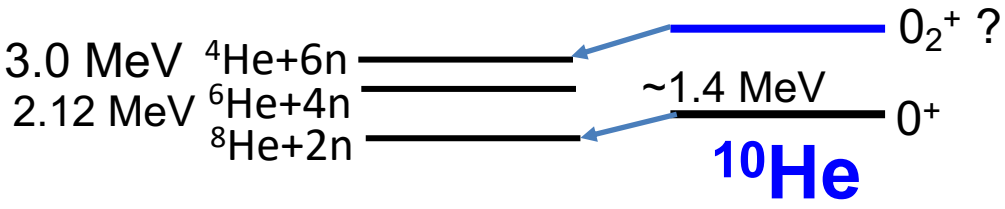

$^{10}$He

Triple-dineutrons?




$^{10}$He

Hexa-neutron droplet?

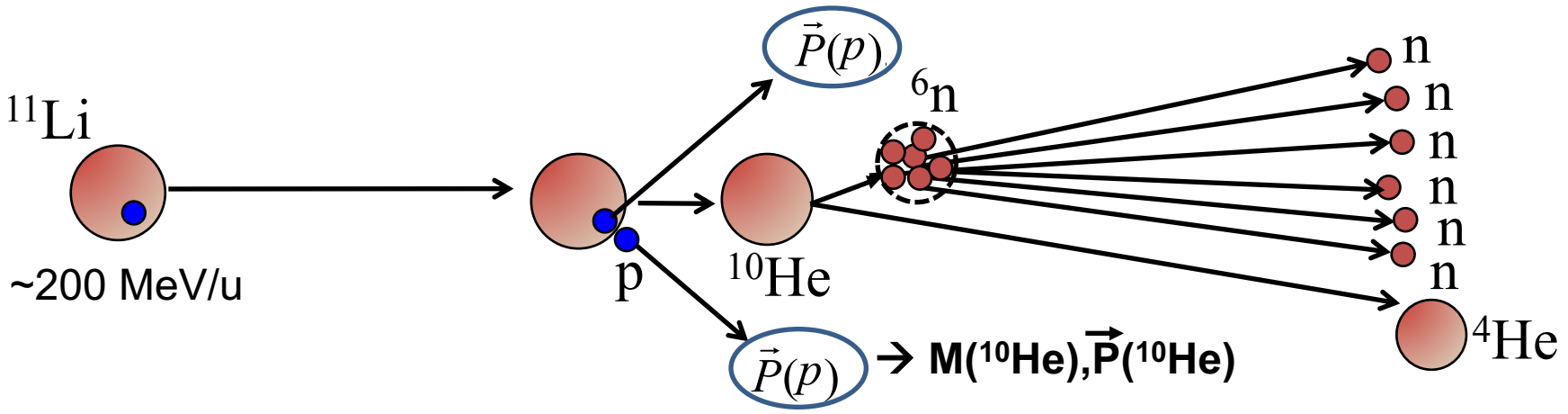


# Experimental Method : (p,2p) missing mass method

$^{11}$Li(p,2p)$^{10}$He*

$^{10}$He*→$^{8}$He+2n, $^{6}$He+4n, $^{4}$He+6n

+ tagging $^{4}$He,$^{6}$He,$^{8}$He, and nn at forward detectors




**Missing Mass Method:**

**+ Need to measure "only" projectile and two recoil protons**

**+ Absolute Excitation Energy (Ex) directly obtained**

**(Wide Ex range, Flat acceptance curve for Ex, No need of γ, n coin.)**

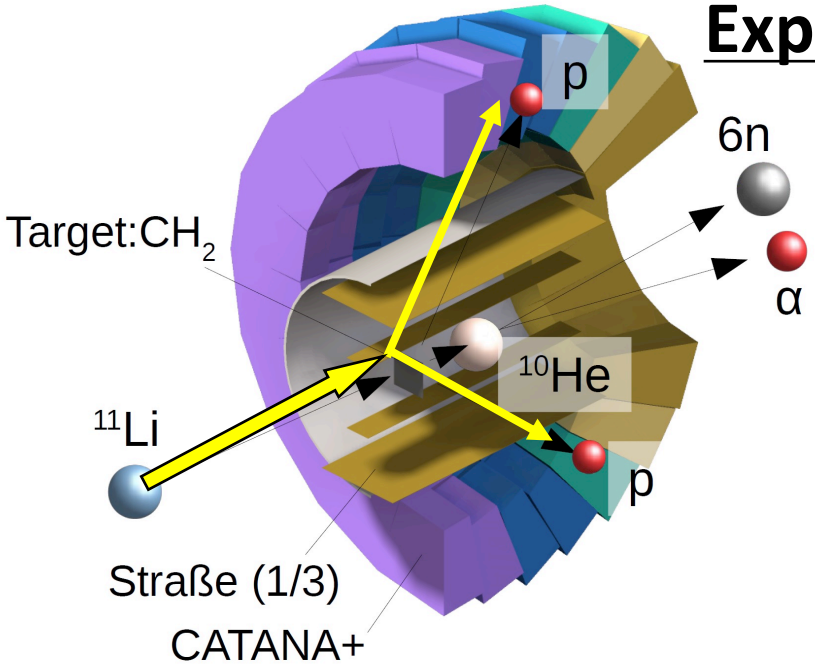
**+ States with high-neutron multiplicities (eg. 6n emitter) accessible**

**- Worse energy resolution (1-2MeV) for a given target thickness**

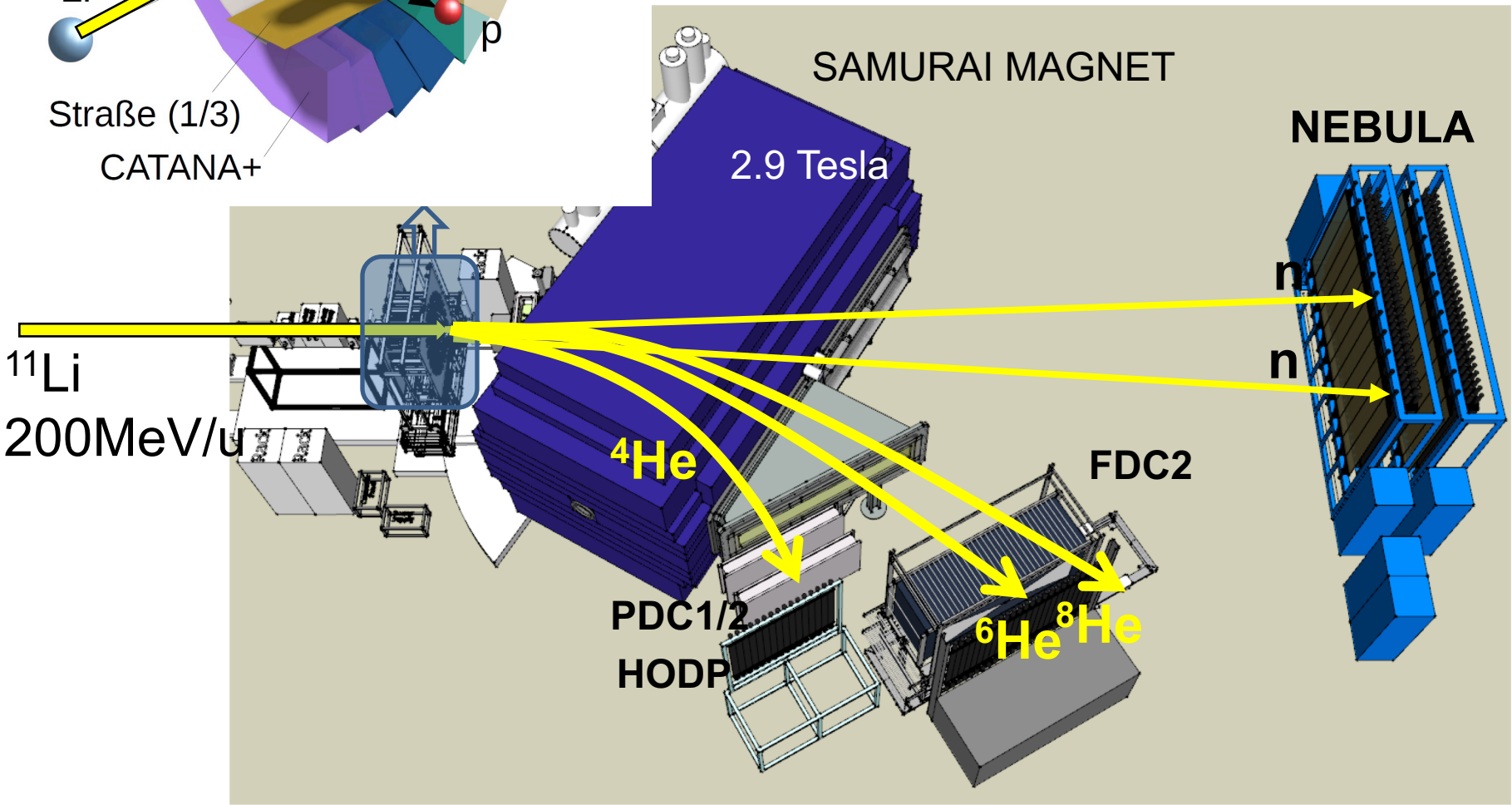
**Compared to Invariant mass spectroscopy**

T.Nakamura, H.Sakurai, H.Watanabe, Prog. Part. Nucl. Phys. **97**, 53 (2017).

# Experimental Setup




Collaboration with TUD (A. Obertelli et al.)



# Summary and Outlook

✓ **Key Questions**

– Multi-neutron clusters on the surface of weakly bound/unbound nuclei?

✓ **Spectroscoy of Super-heavy Oxygen →Barely Unbound 2n emitter $^{26}$O**

***Y. Kondo, TN et al., PRL 116, 102503 (2016).***

→**$^{26}$O($0^+_{gs}$): Very weakly unbound 2n states → Correlation? Continuum?**

**$^{26}$O($2^+$): Found for the first time at $E_{rel}$=1.28(11) MeV → Shell Evolution?**

→ **$^{27,28}$O : Experiment Successfully Done: Preliminary Results**

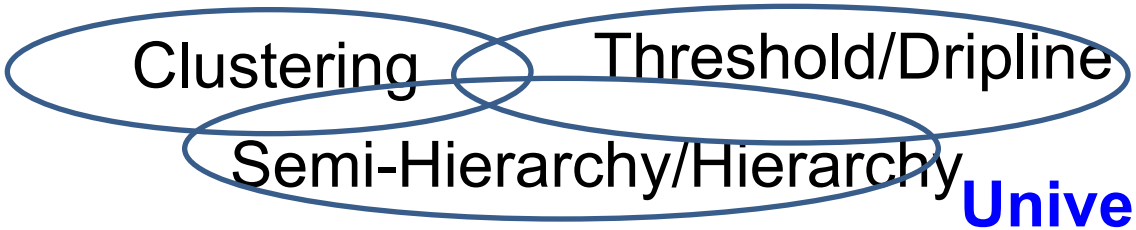
**$^{27}$O: E($^{24}$O+3n)~1.1 MeV, Sequential decay through $^{26}$O(gs,$0^+$)**

**$^{28}$O: Observed: To be shown soon**

## Near Future: Variety of spectroscopies along n-drip line

**4n, 6n… states? → $^{4}$n,$^{6}$n… cluster?**

$^{11}$Li(p,2p)$^{10}$He exp.
Approved at RIBF




**Universality?**

# Day-one(S02,S03,S04) Collaboration—
# $^{19}$B,$^{20,21}$B,$^{21}$C,$^{22}$C,$^{25,26}$O,...


Tokyo Institute of Technology: **Y.Kondo, T.Nakamura**, N.Kobayashi, R.Tanaka, R.Minakata, S.Ogoshi, S.Nishi, D.Kanno, T.Nakashima, J. Tsubota, A. Saito,

**K.J.Cook, A.Kurihara,Y.Yoshitome, H.Miki**

LPC CAEN: **N.A.Orr**, **J.G.Gibelin**, F.Delaunay, F.M.Marques, N.L.Achouri, S.Leblond, Q. Deshayes

Tohoku University : T.Koabayshi, K.Takahashi, K.Muto

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Seoul National University: Y.Satou, S.Kim, J.W.Hwang

Kyoto University : T.Murakami, N.Nakatsuka

GSI : Y.Togano

Univ. of York: A.G.Tuff

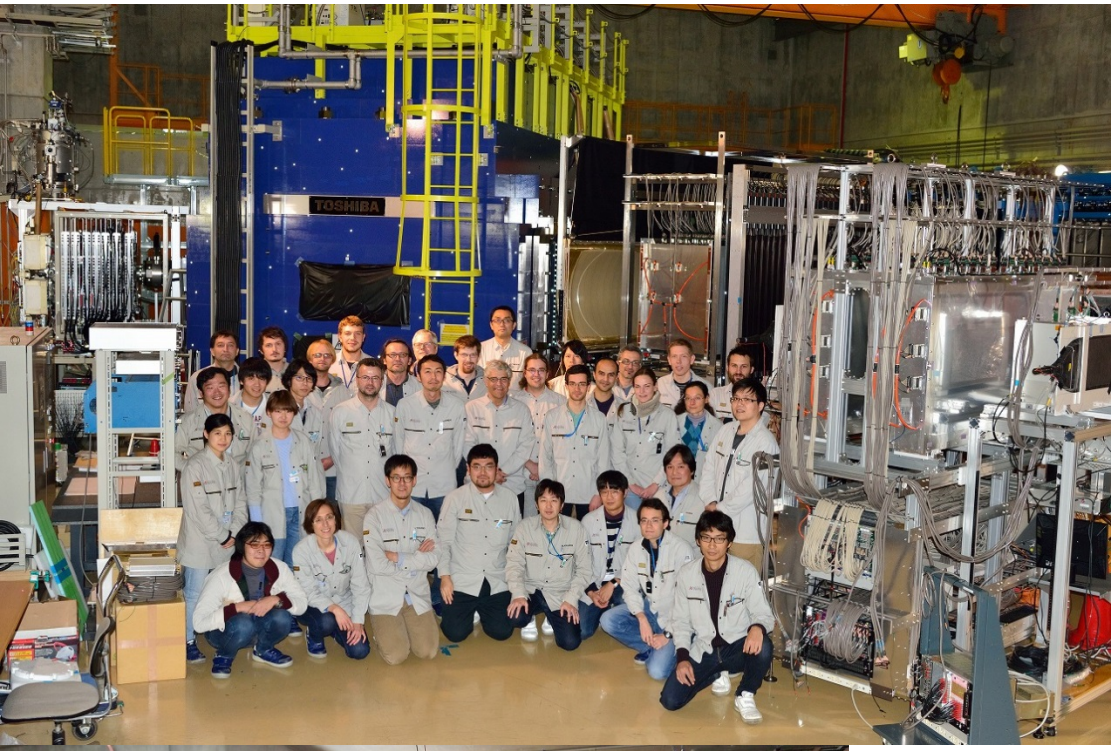
GANIL: A.Navin

Technische Universit¨at Darmstadt: T.Aumann

Rikkyo Univeristy: D.Murai

Universit´e Paris-Sud, IN2P3-CNRS: M.Vandebrouck

# SAMURAI21 collaboration—$^{27,28}$O




**Y.Kondo**, **T.Nakamura**, N.L.Achouri, H.Al Falou, L.Atar, T.Aumann, H.Baba, K.Boretzky, C.Caesar, D.Calvet, H.Chae, N.Chiga, A.Corsi, H.L.Crawford, F.Delaunay, A.Delbart, Q.Deshayes, Zs.Dombrádi, C.Douma, Z.Elekes, P.Fallon, I.Gašparić, J.-M.Gheller, J.Gibelin, A.Gillibert, M.N.Harakeh, A.Hirayama, C.R.Hoffman, M.Holl, A.Horvat, Á.Horváth, J.W.Hwang, T.Isobe, **J.Kahlbow**, N.Kalantar-Nayestanaki, S.Kawase, S.Kim, K.Kisamori, T.Kobayashi, D.Körper, S.Koyama, I.Kuti, V.Lapoux, S.Lindberg, F.M.Marqués, S.Masuoka, J.Mayer, K.Miki, T.Murakami, M.A.Najafi, K.Nakano, N.Nakatsuka, T.Nilsson, A.Obertelli, F.de Oliveira Santos, N.A.Orr, H.Otsu, T.Ozaki, V.Panin, S.Paschalis, **A.Revel**, D.Rossi, A.T.Saito, T.Saito, M.Sasano, H.Sato, Y.Satou, H.Scheit, F.Schindler, P.Schrock, M.Shikata, Y.Shimizu, H.Simon, D.Sohler, O.Sorlin, L.Stuhl, S.Takeuchi, M.Tanaka, M.Thoennessen, H.Törnqvist, Y.Togano, T.Tomai, J.Tscheuschner, J.Tsubota, T.Uesaka, H.Wang, **M.Yasuda**, Z.Yang, K.Yoneda

Tokyo Tech, Argonne, ATOMKI, CEA Saclay, Chalmers, CNS, Cologne, Eotvos, GANIL, GSI, IBS, KVI-CART, Kyoto Univ., Kyushu Univ., LBNL, Lebanese-French University of Technology and Applied Science, LPC-CAEN, MSU, Osaka Univ., RIKEN, Ruđer Bošković Institute, SNU, Tohoku Univ., TU Darmstadt, Univ. of Tokyo

88 Participants (+few analysis)

25 Institutes