Exploring the most neutron-rich nuclei and beyond

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Contents

- Introduction
  - Why we exist?
  - Why hierarchical structure exists in quantum world?
  - Clustering is key to this?
- Exotic Nuclei in a nutshell (不安定核の物理）
- Dineutron cluster in neutron-rich nuclei
  - Coulomb breakup of 2n halo nuclei
  - Spectroscopy of Super-heavy oxygen isotopes
- Summary and Outlook

Introduction of Introduction

Existence of human being depends on a subtle balance of Nature

人間の存在は自然の絶妙なバランスで決まっている

There are no particle-stable A="5" and "8" nuclei in nature

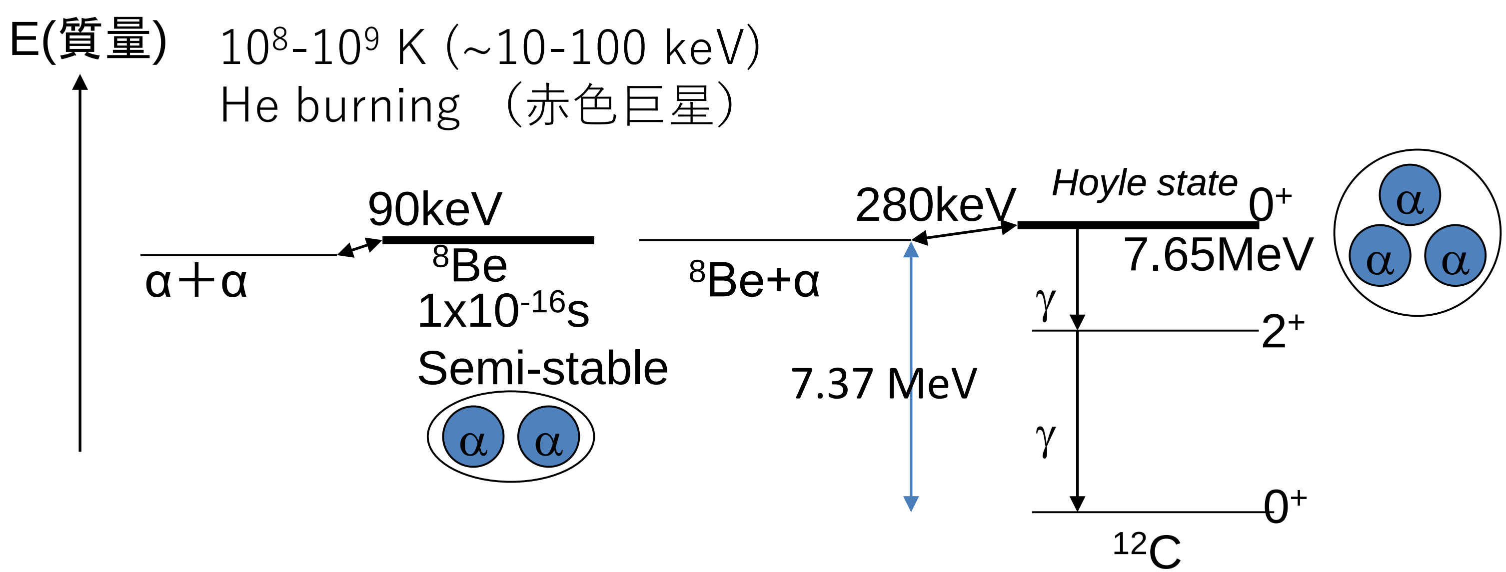
^{1}H,^{2}D, ^{3}He,^{4}He,(5), ^{6}Li, ^{7}Li,(8),^{9}Be,^{10}B,…,^{209}Bi

Big Bang: Mostly H and ^{4}He (Heavier than ^{7}Li were not produced)

→ How are heavier elements synthesized?

Triple alpha Reaction

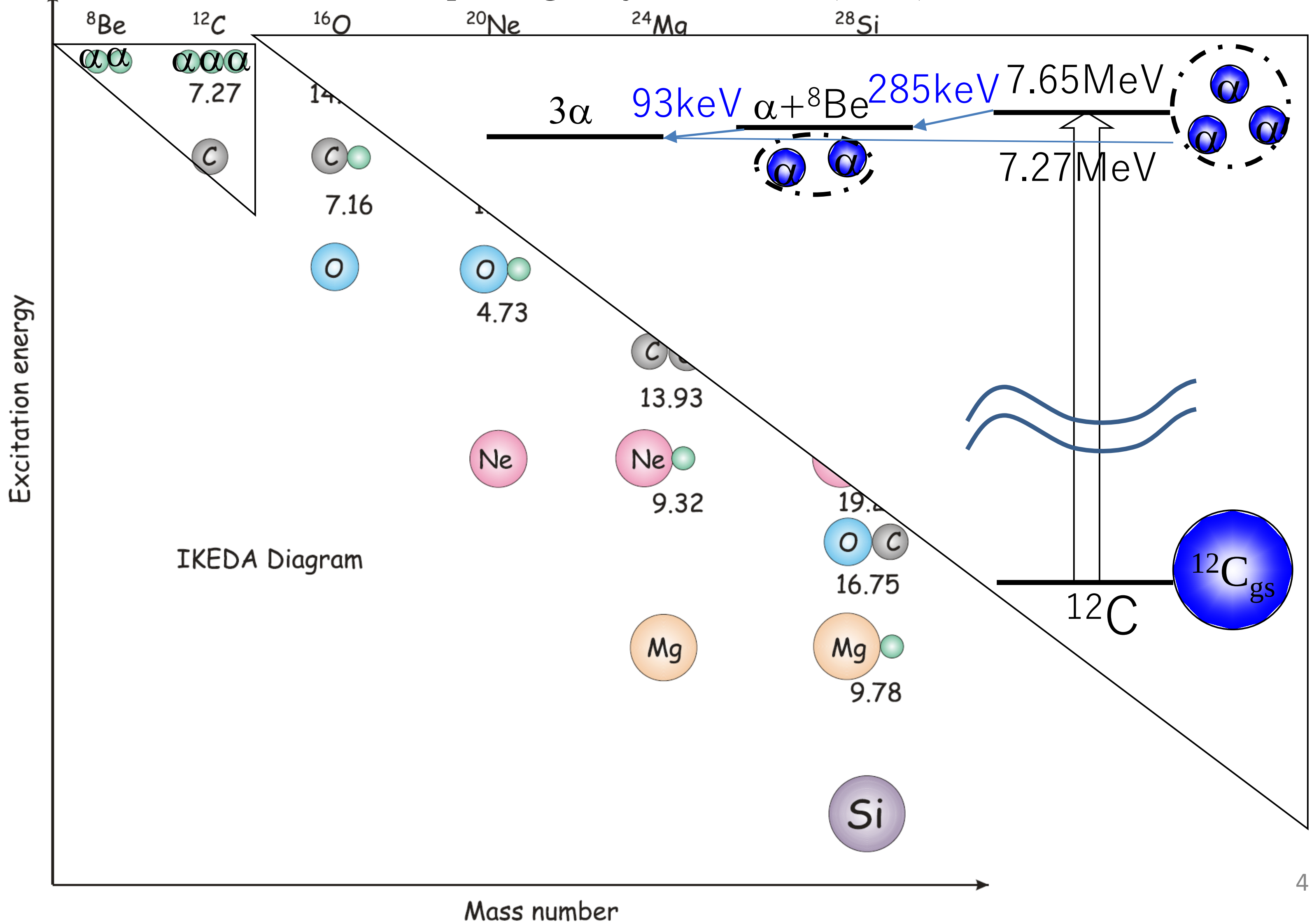
Triple-α: Detour for the synthesis of elements ^{12}C→Heavier elements



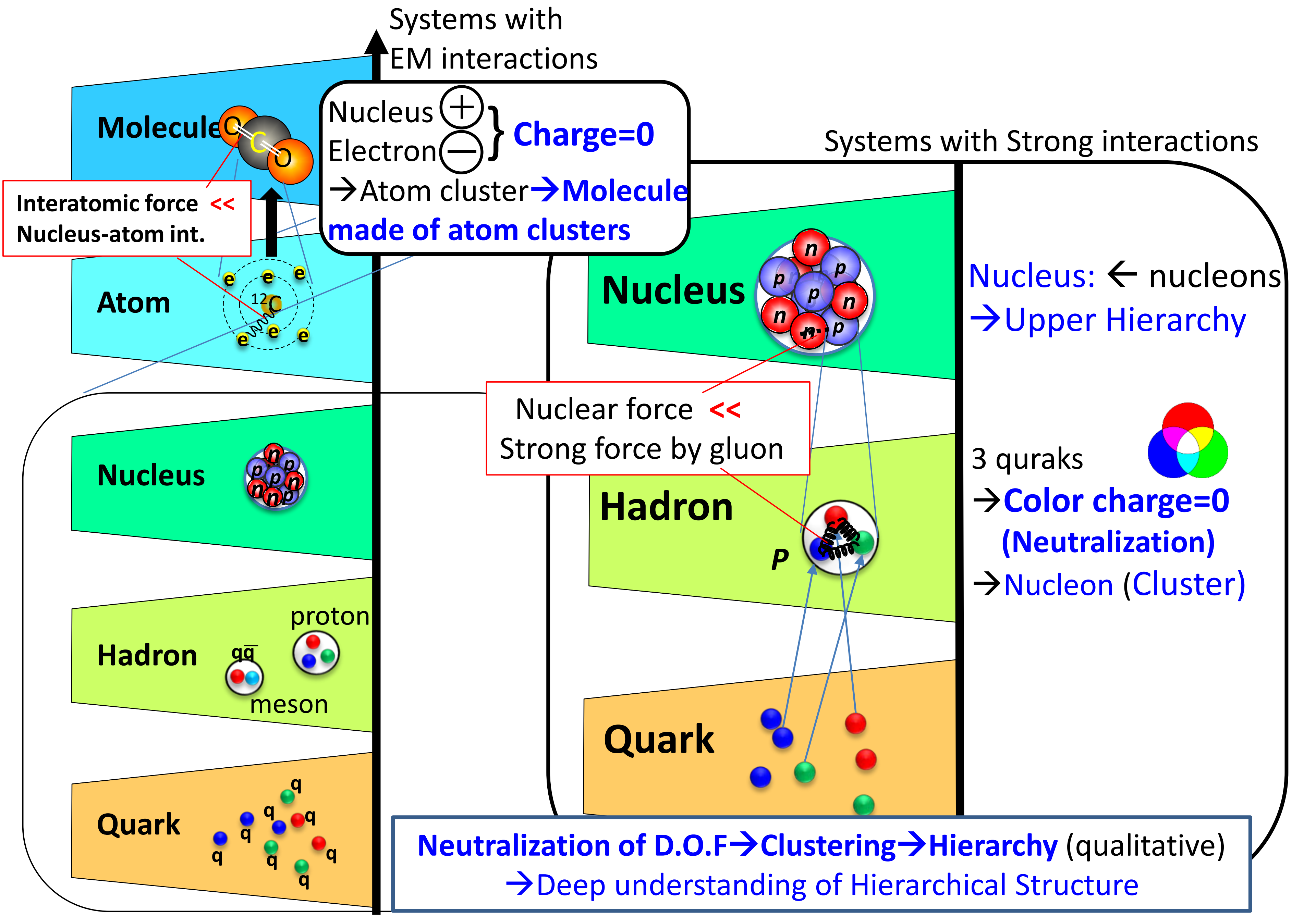
α-Cluster

IKEDA Diagram

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

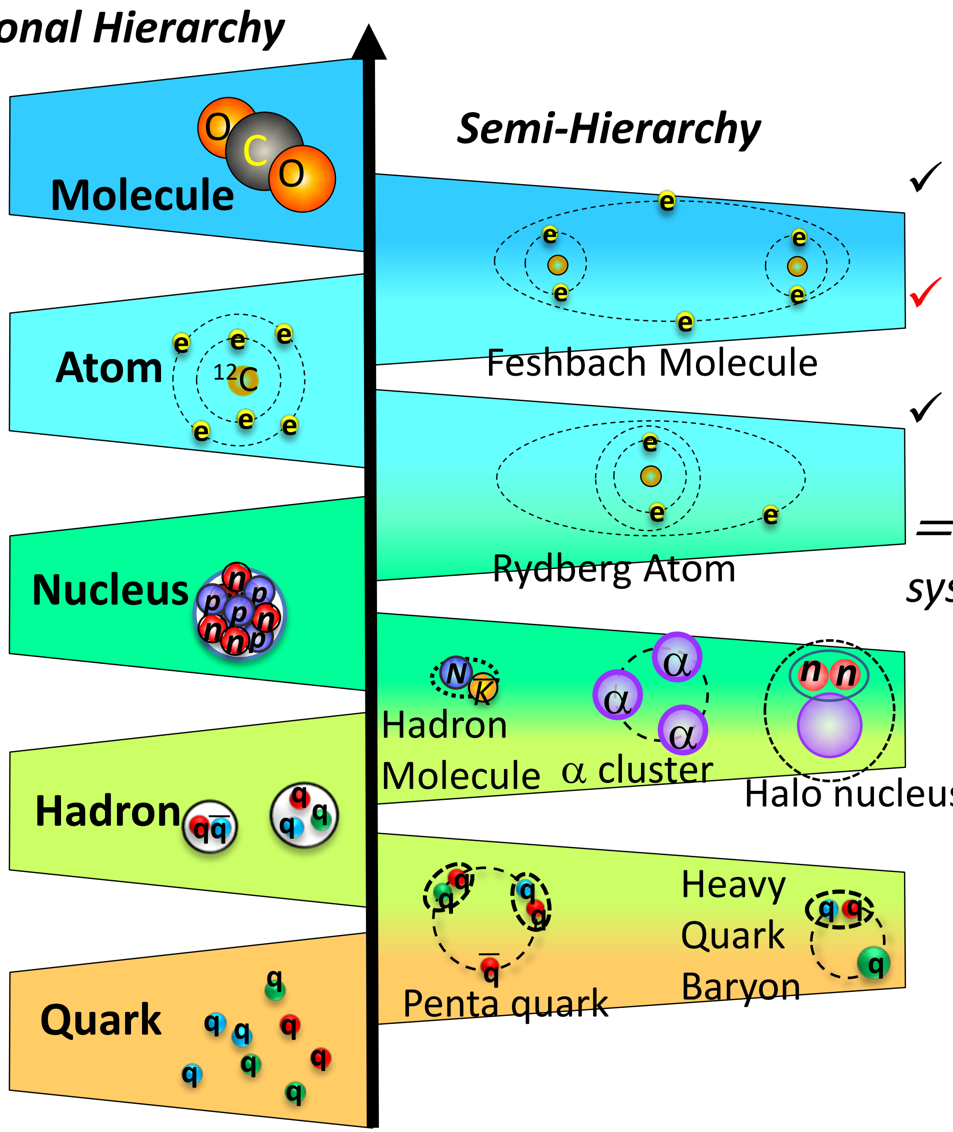


Clustering: Key to understand **hierarchy** in quantum world?



Clusters and Semi-Hierarchy

- ✓ Big Gap between Hierarchies
- ✓ **Strongly Bound**
- ✓ Simple constituents: Nucleus= "nucleonic" system

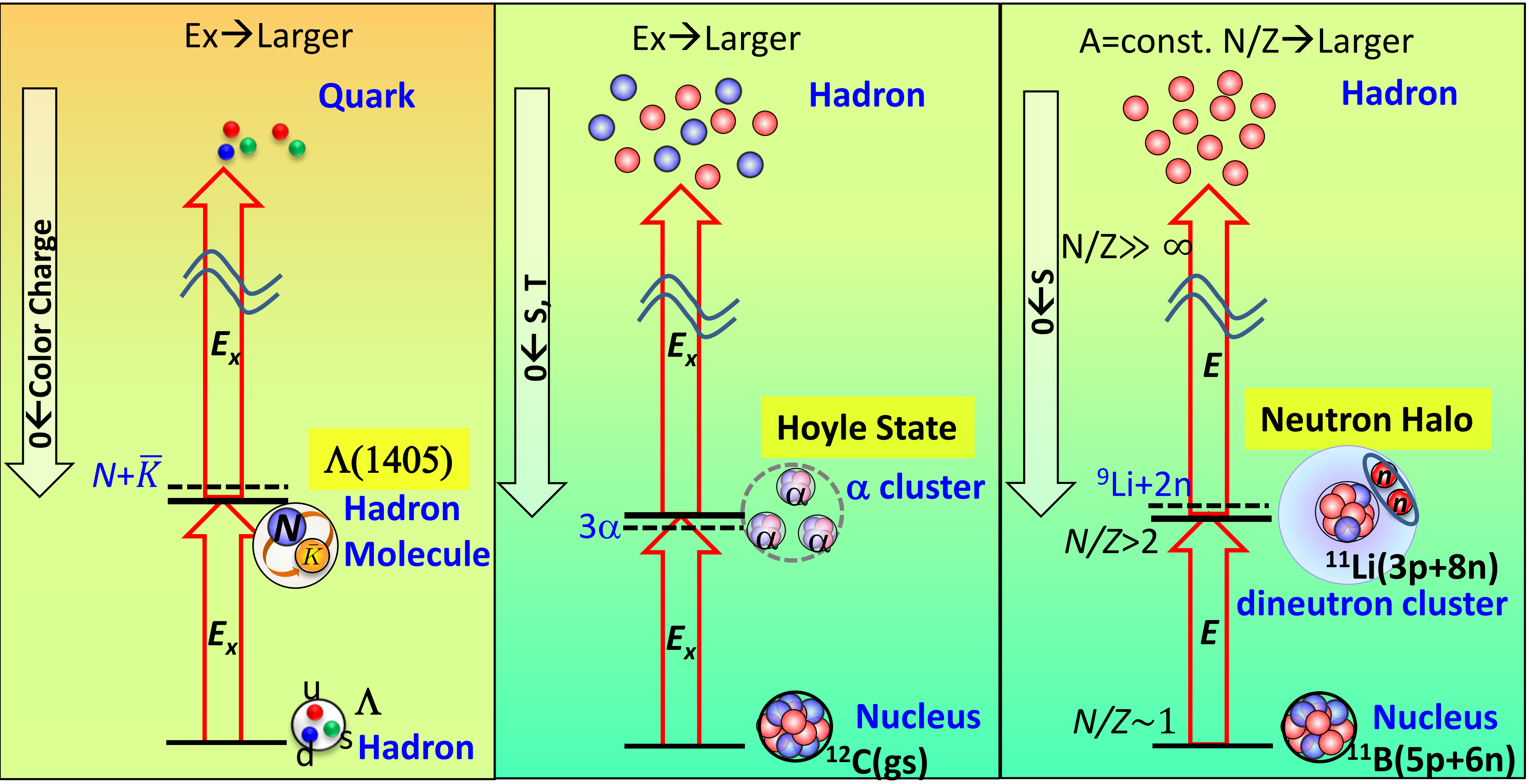


- ✓ Smaller Gap between Hierarchies
- ✓ **Weakly Bound (Unbound)**
- ✓ Mixed constituents: Halo Nucleus *="nucleonic"+"dineutron" system*

Semi-Hierarchy: Key Aspects to understand the hierarchical structure of matter

Key factors for clustering and hierarchy formation

- ✓ Degree of Freedom : **Neutralization of Charge, Spin(S), Isospin(T)**
- ✓ Threshold: **Clustering near Threshold → Semi-Hierarchy**
- ✓ Degree of Separation: **Compositeness, Spectroscopic factor**

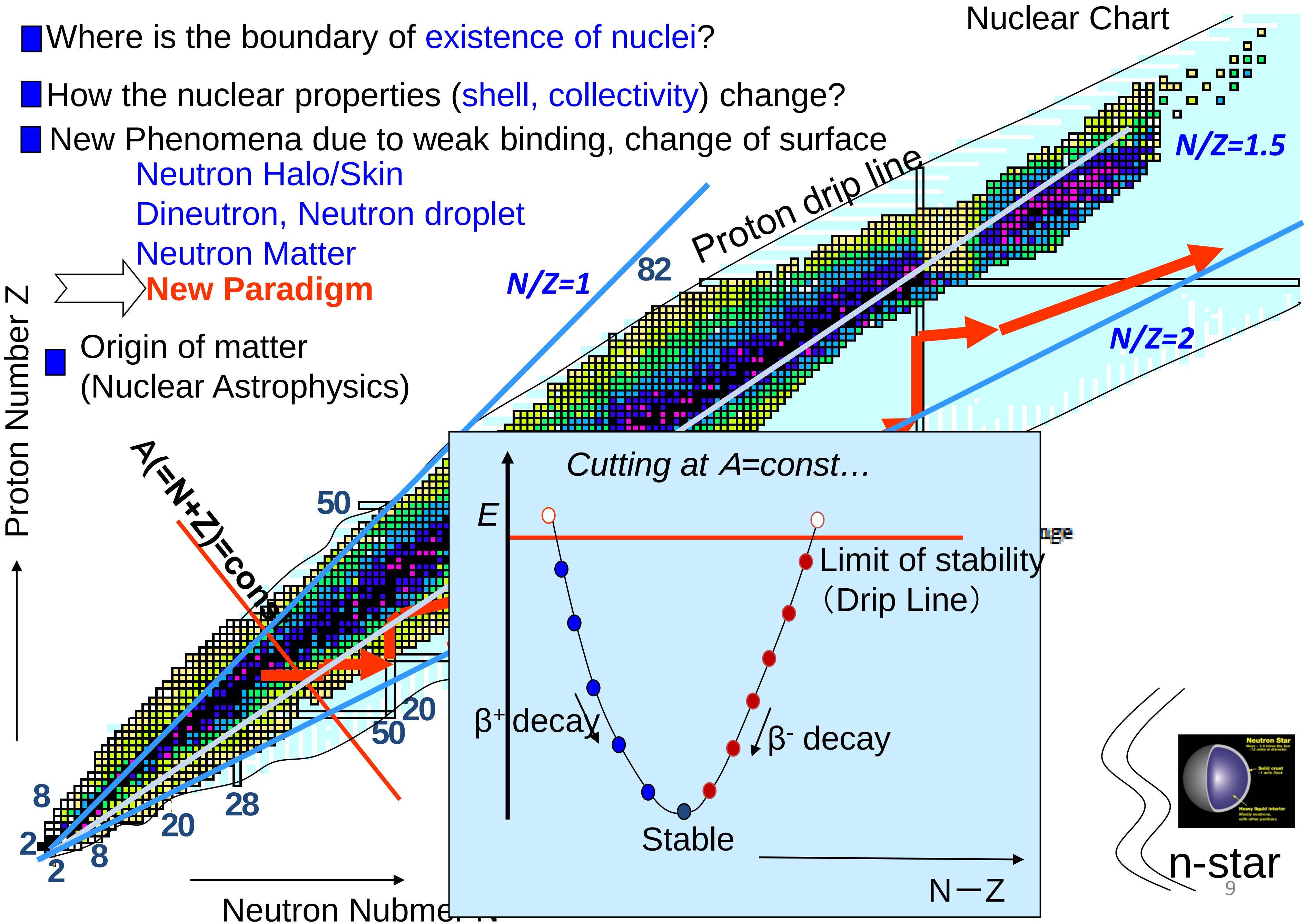


Physics of Rare Isotopes (Exotic Nuclei) in a nutshell

不安定核の物理

Towards the neutron-rich limit

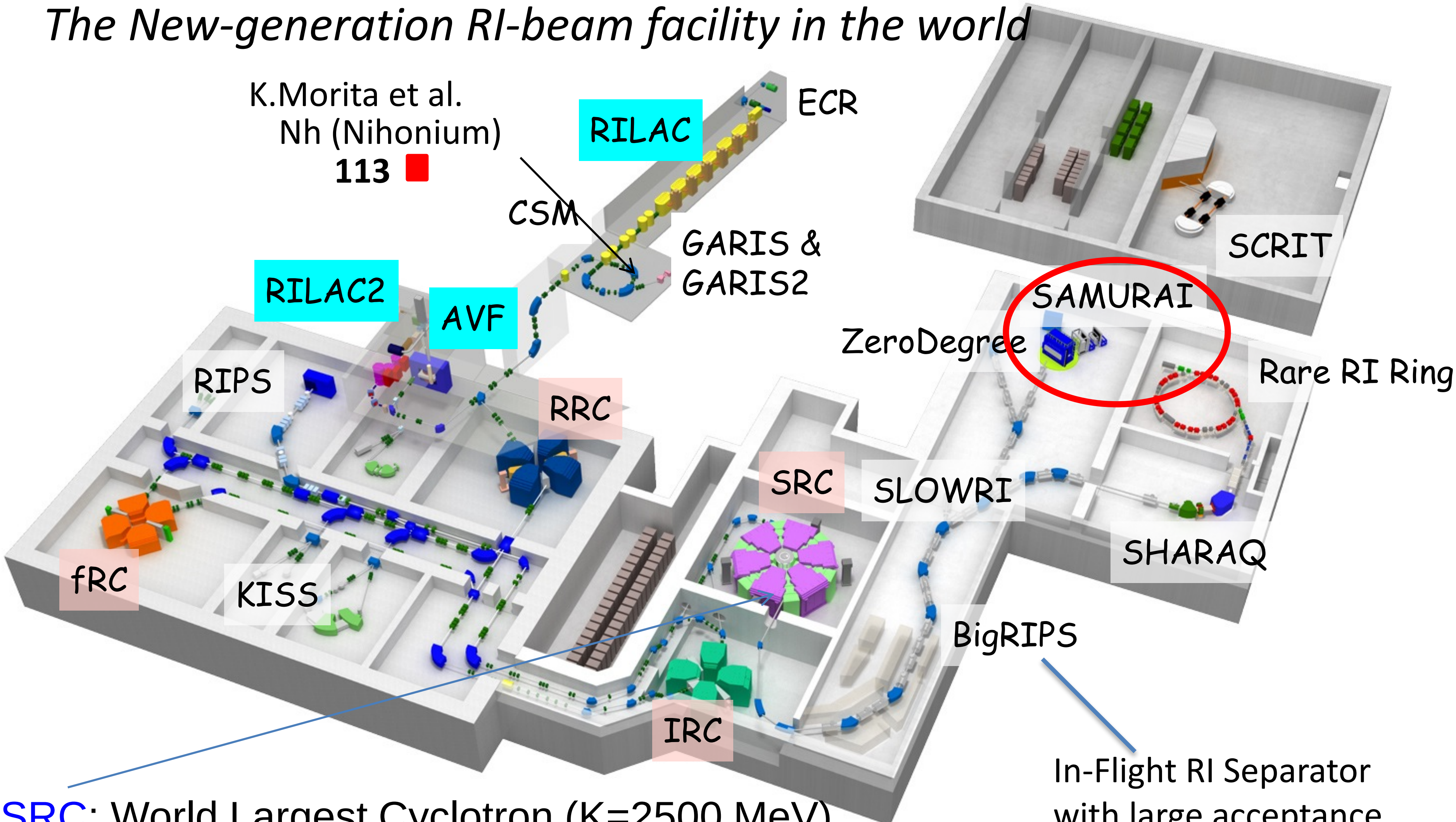
- Where is the boundary of existence of nuclei?
- How the nuclear properties (shell, collectivity) change?
- New Phenomena due to weak binding, change of surface
  - Neutron Halo/Skin
  - Dineutron, Neutron droplet
  - Neutron Matter
  - ⇨ **New Paradigm**
- Origin of matter (Nuclear Astrophysics)



RI Beam Factory (RIBF) at RIKEN

2007~

The New-generation RI-beam facility in the world



In-Flight RI Separator with large acceptance

SRC: World Largest Cyclotron (K=2500 MeV)

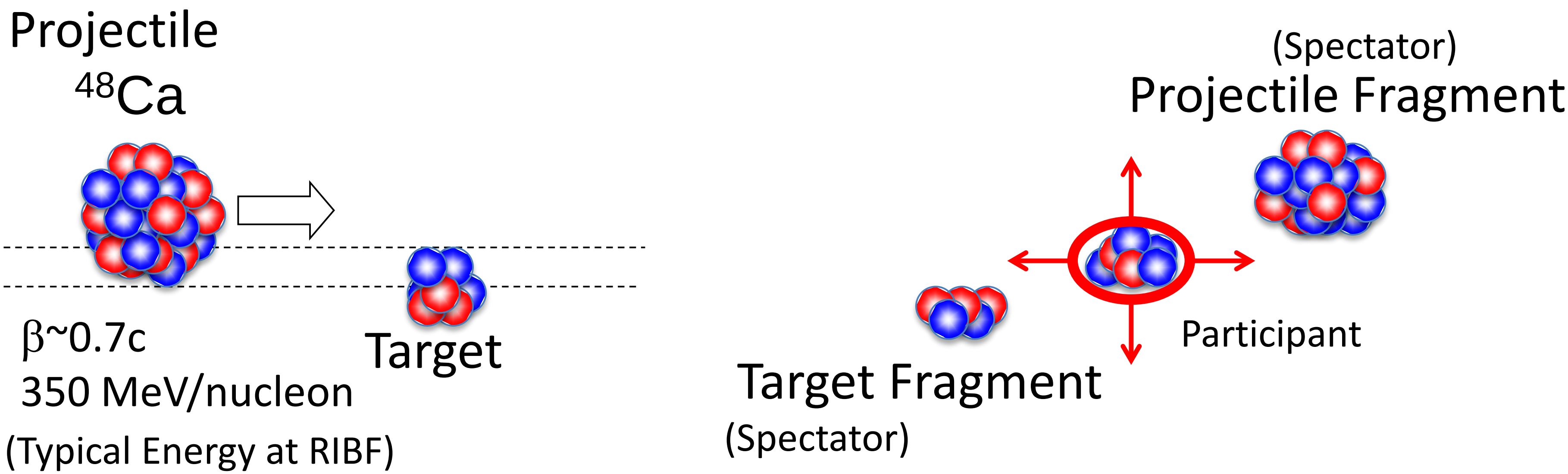
Heavy Ion Beams up to ^{238}U at 345MeV/u

eg. ^{48}Ca: ~700pnA (~4x10^{12}pps) *~10 times compared to 2008*

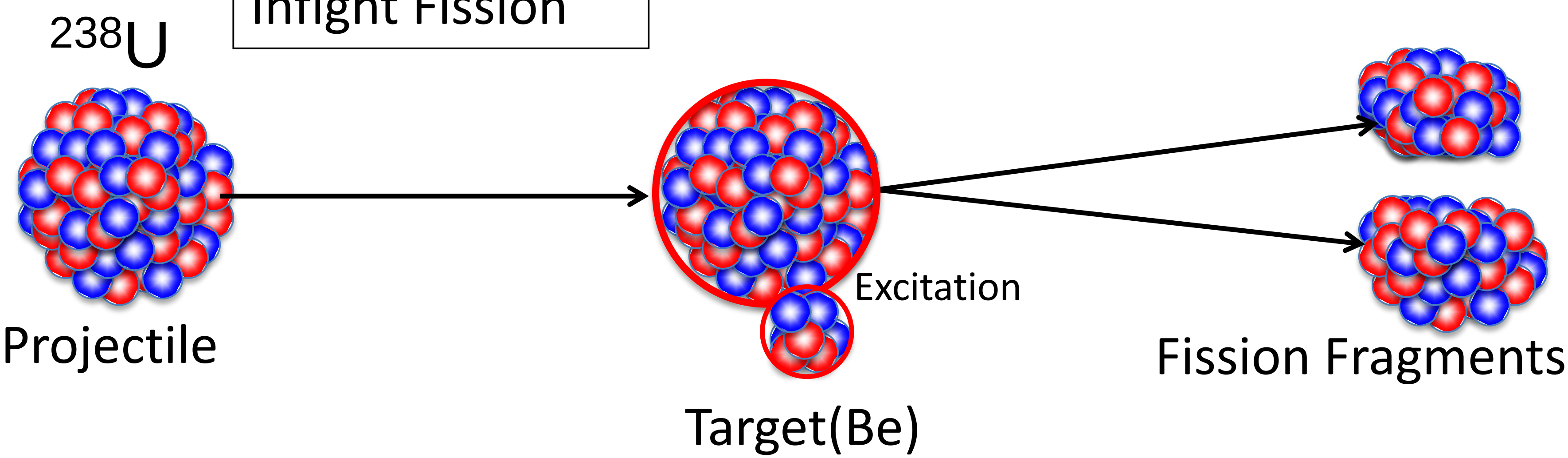
^{238}U: ~70pnA (~4x10^{11} pps) *~10^{3} times compared to 2007*

How To Produce RI Beam (In-flight RI Production)

Projectile Fragmentation)

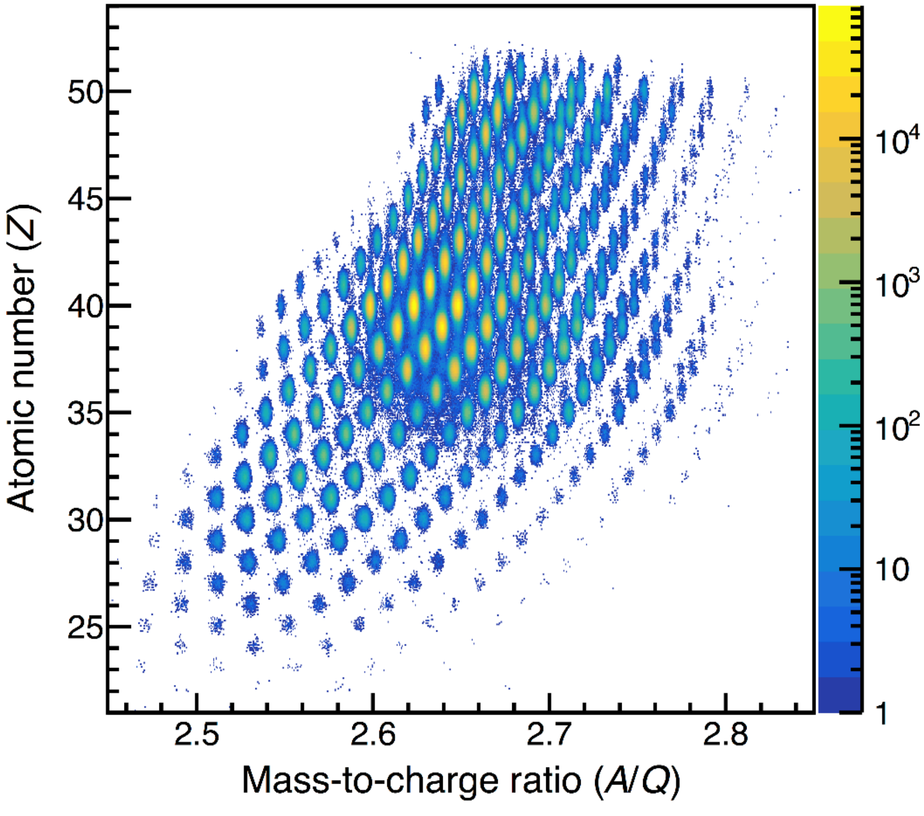


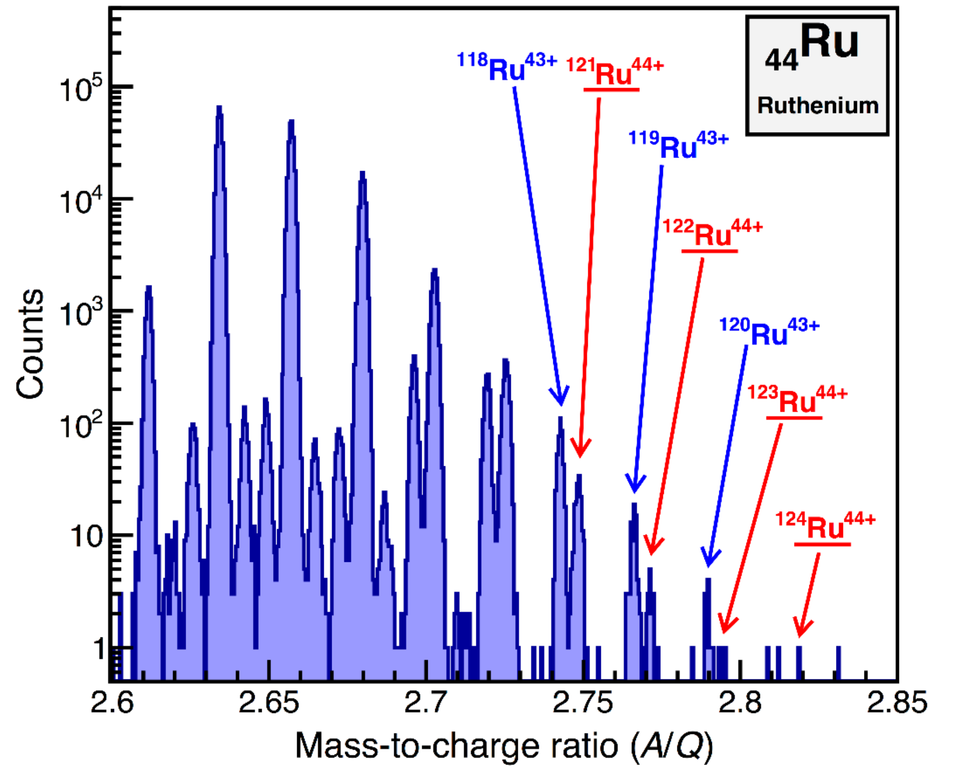
Infight Fission



Particle Identification:

^{238}U (345 MeV/u) + Be (2.9 mm), Bρ = 7.990 Tm



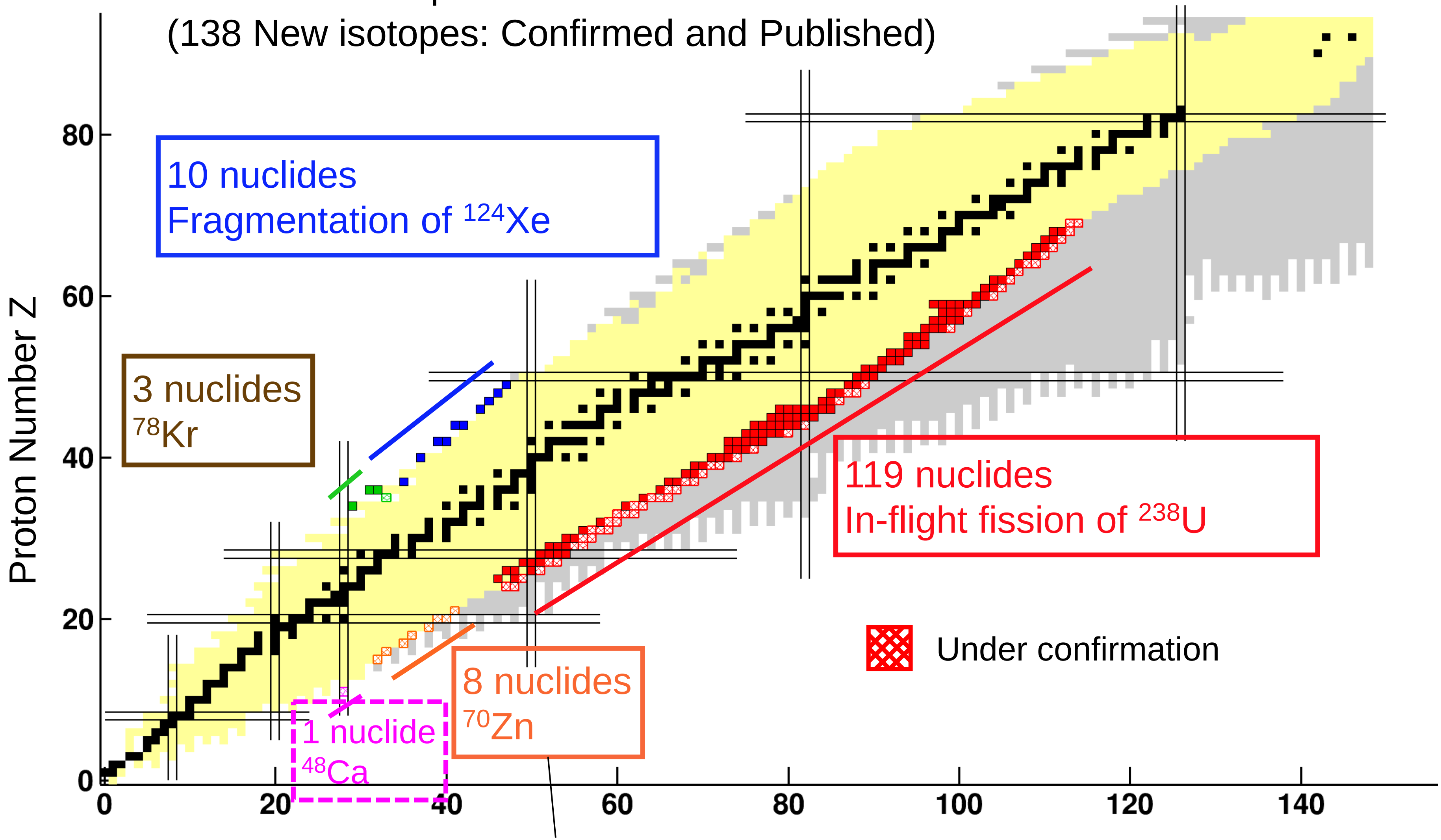


N.Fukuda et al., Nucl. Instr. Meth. B **317**, 323 (2013).

Slide: Courtesy of N.Fukuda

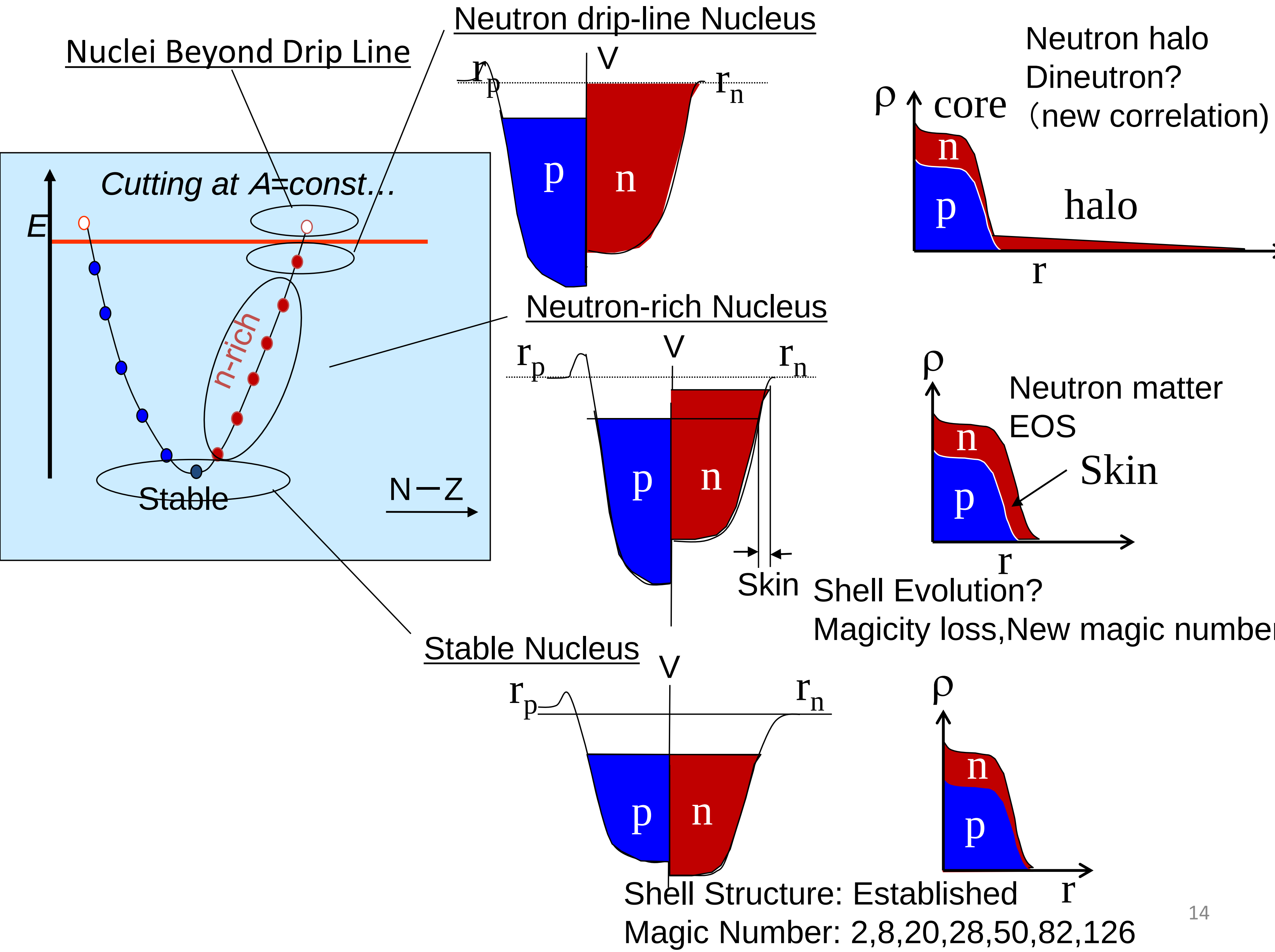
New Isotopes observed at RIBF (2007-2018)

194 New isotopes: Observed
(138 New isotopes: Confirmed and Published)

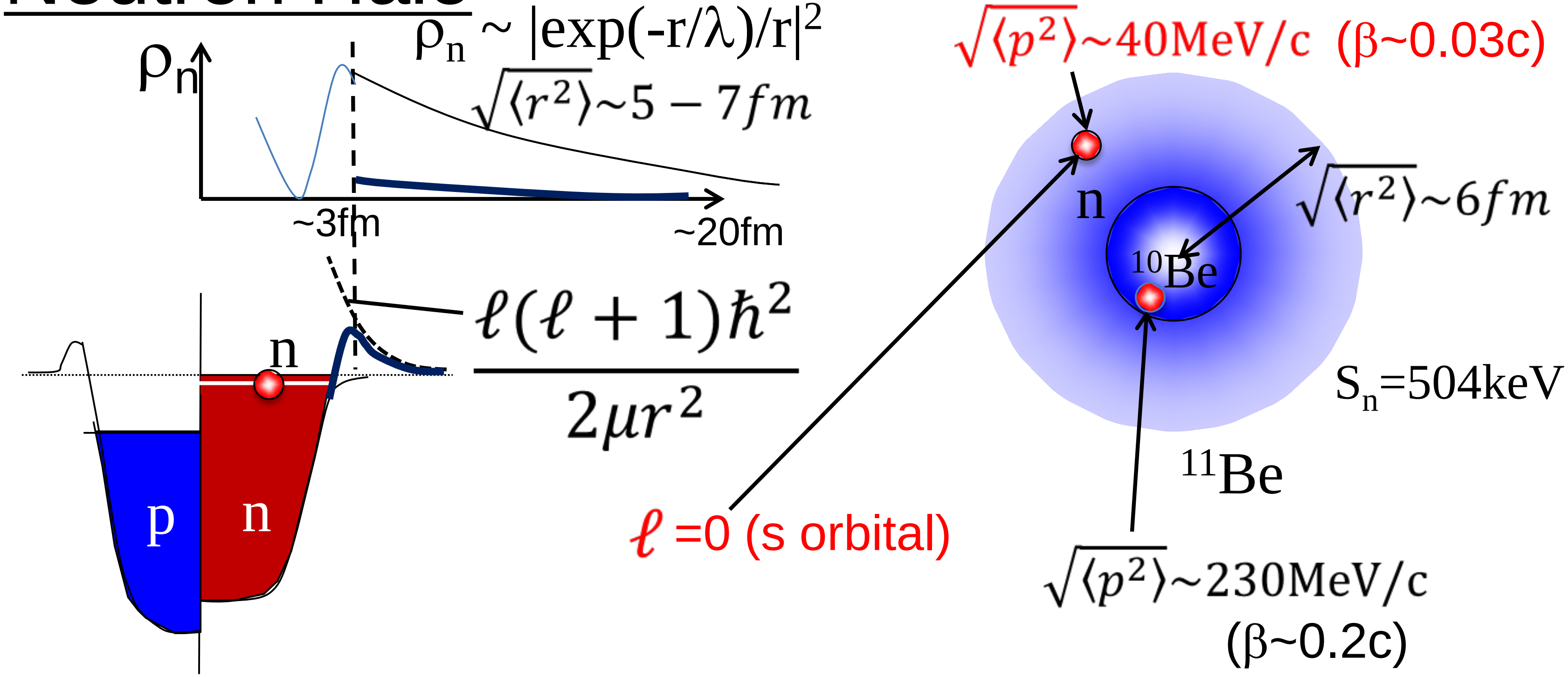


O.B. Tarasov et al., Phys. Rev. Lett. **121**, 022501 (2018).

Slide: Courtesy of N.Fukuda


Nuclei Beyond Drip Line
Neutron drip-line Nucleus
Neutron halo
Dineutron?
(new correlation)
ρ
core
n
p
halo
r
V
r_p
r_n
p
n
Cutting at A=const...
E
n-rich
Stable
N−Z
Neutron-rich Nucleus
Neutron matter
EOS
Skin
Shell Evolution?
Magicity loss,New magic number
Stable Nucleus
Shell Structure: Established
Magic Number: 2,8,20,28,50,82,126

Neutron Halo 中性子ハロー



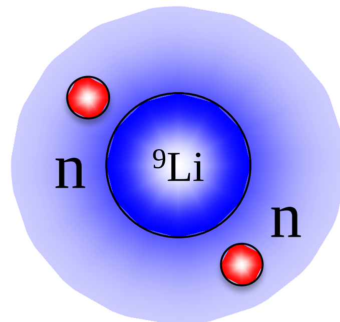
- Small S_n S_n<1MeV<<8MeV
- Extended ρ_n Distribution beyond Range of Nuclear Force

$$r \to \infty \; for \; S_n \to 0 \quad \left(\sqrt{\langle r^2 \rangle} \sim 1/S_n\right) \quad \sim 0.1nm \; at \; S_n = 1meV$$

- Small Fermi Momentum→ Small Kinetic Energy
- Orbital Angular Momentum $\ell = 0,1$ (Small Centrifugal Barrier)

⇨ Nuclear Stability At the Limit←→ Shell Evolution/Deformation ←→ Halo Structure

Two-neutron Halo



^{11}Li

リチウム11

(Z=3, N=8)

S_{2n}=0.37MeV

Borromean Ring

^{9}Li + n Barely Unbound

a_s= - (13-23) fm PLB642, 449(2006).

n + n Barely Unbound

a_s= - 18.9(4) fm

^{9}Li + n+n Bound

S_{2n}=0.37MeV <<8MeV

Few-body physics

“Dineutron cluster” in neutron-rich nuclei

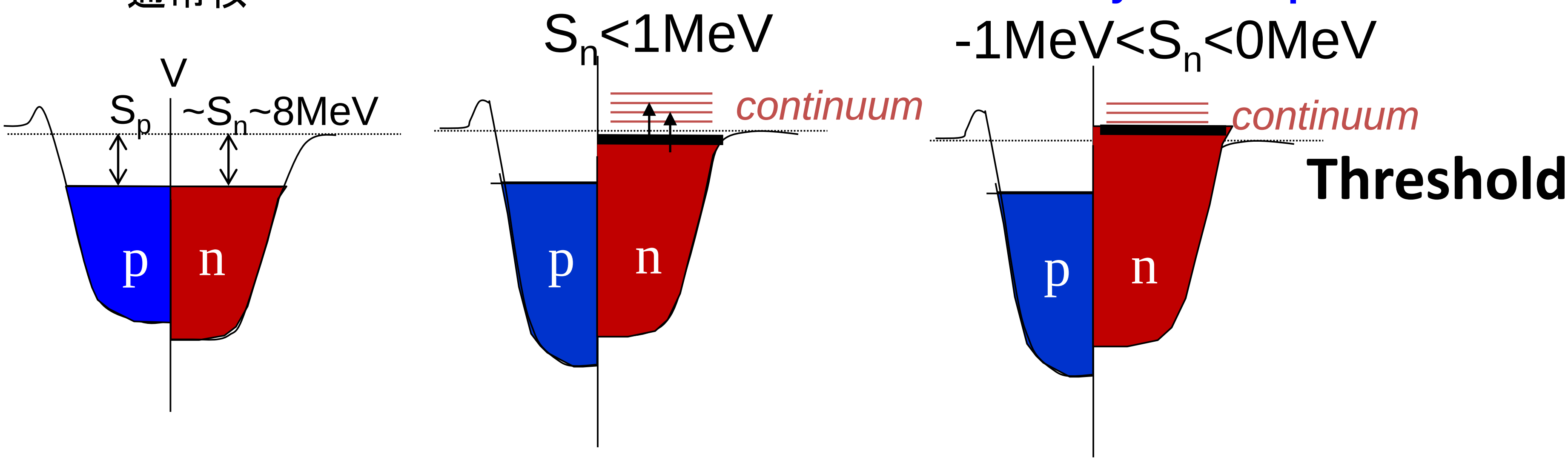
Dineutron exists in Nuclei?
“dineutron”-states can be semi-hierarchy?

Multi-neutron correlation (neutron cluster) near drip line

Ordinary Nuclei
通常核

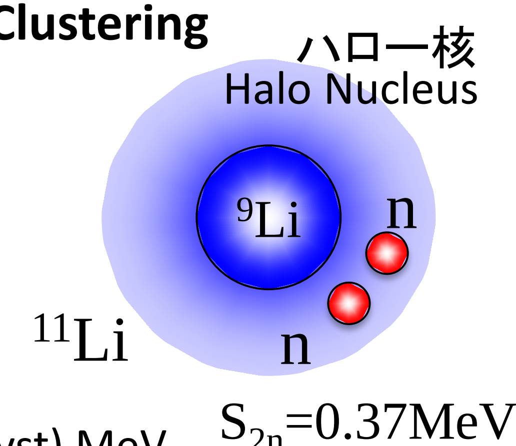
Neutron-rich Nuclei
中性子過剰核

Beyond drip line



Weakly bound/unbound nuclei --- Threshold (*Unitary limit*)→ Clustering

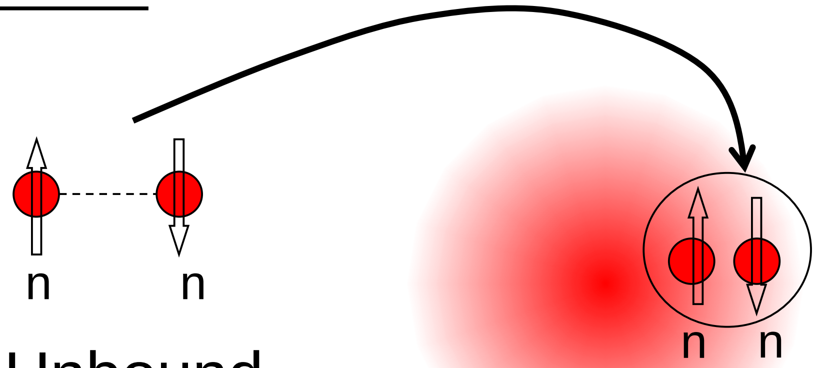
Halo Nuclei
Weakly Unbound Nuclei



^{4}n: **"Tetra neutron"** $E_{4n}=0.83\pm0.65$(stat)±1.25(syst) MeV
K.Kisamori et al., PRL116, 052501 (2016)

^{26}O: **"Weakly Unbound 2n"** ^{24}O+2n $E_{2n}= 0.018\pm0.003$(stat)±0.004(syst) MeV
Y.Kondo et al., PRL116,102503(2016).

Dineutron?



Unbound
a= -18.7 fm

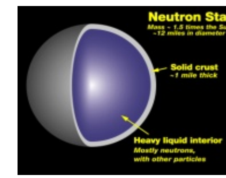
S波散乱長

S=0, T=1

A.B.Migdal
Strongly correlated "dineutron"
on the **surface** of a nucleus
Sov.J.Nucl.Phys.238(1973).

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

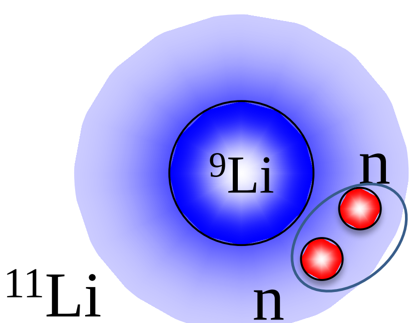
M.Matsuo
PRC73,044309(2006).
A.Gezerlis, J.Carlson,
PRC81,025803(2010)



neutron-star

Possible dineutron site

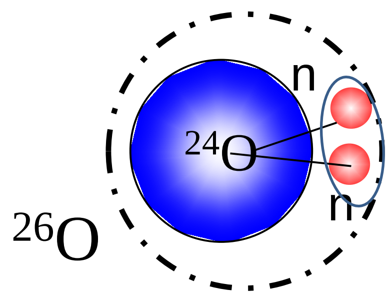
2n Halo Nuclei?

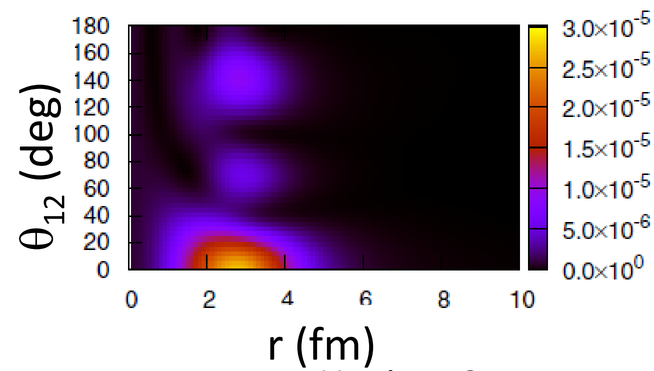


S_{2n}=0.37MeV

T.Nakamura PRL96, 252502 (2006).

2n weakly-unbound nuclei?



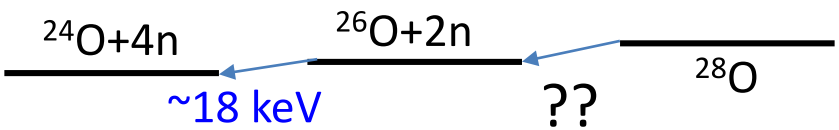


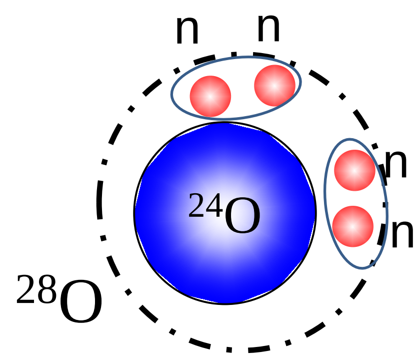
S_{2n}= –0.018(5) MeV

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

Hagino, Sagawa,
PRC93,034330(2016)

What happens if there are 'multiple' dineutrons?

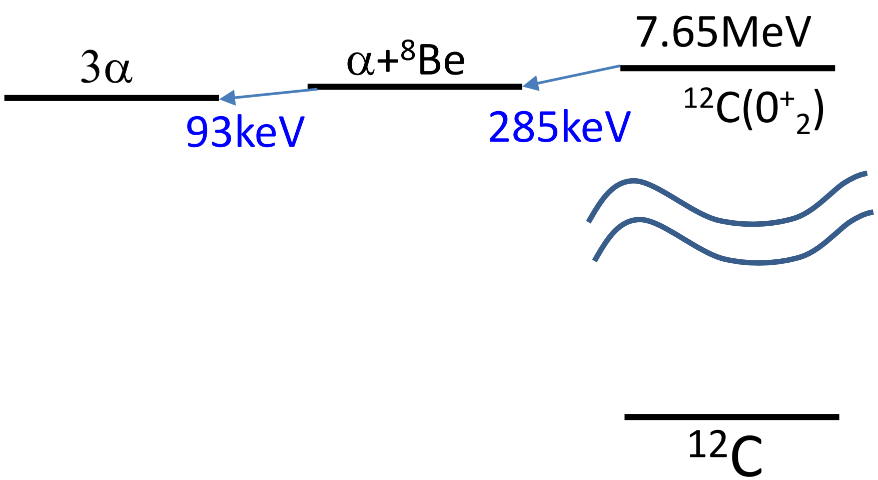




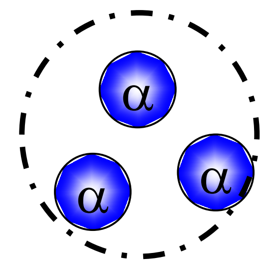
Dineutron-cluster?

Dineutron-condensation?

ダイニュートロン凝縮



Hoyle state



alpha-cluster

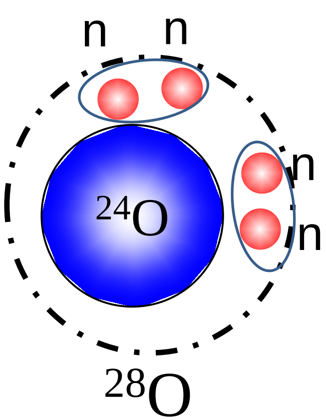
alpha-condensation?

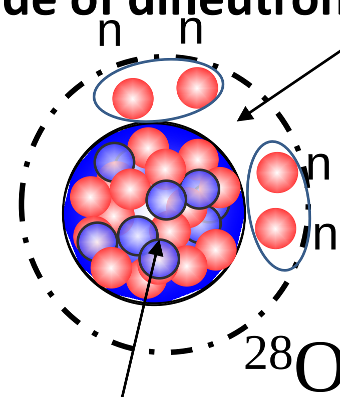
アルファ凝縮(ボーズ凝縮)

A.Tohsaki, H.Horiuchi, P.Schuck,G.Ropke, PRL 87, 192501 (2001).

Dineutron Clustering & Hierarchy

Naïve Picture





Surface-region:

Dineutron-cluster hierarchy

(made of dineutron-cluster)

Core-region:

Normal nuclear hierarchy

(made of nucleons)

Boundary between
Normal nuclear hierarchy and
Dineutron-cluster hierarchy → Obscure

Dineutron-cluster hierarchy: **Semi-hierachy**

Evolution Towards the Stability Limit

Where is the neutron drip line?

What are characteristic features of drip-line nuclei?

How does nuclear structure evolve towards the drip line?

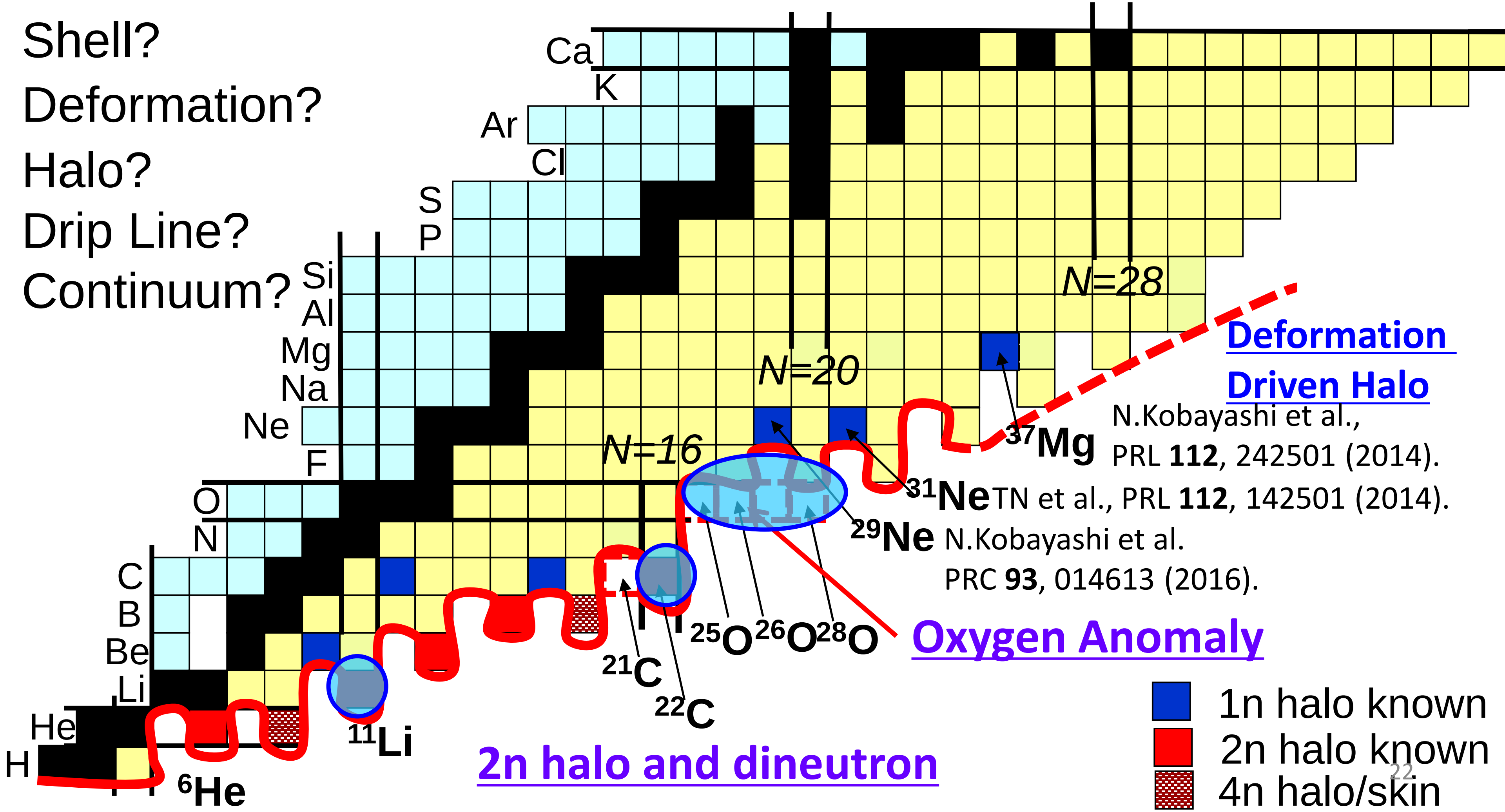
Shell?

Deformation?

Halo?

Drip Line?

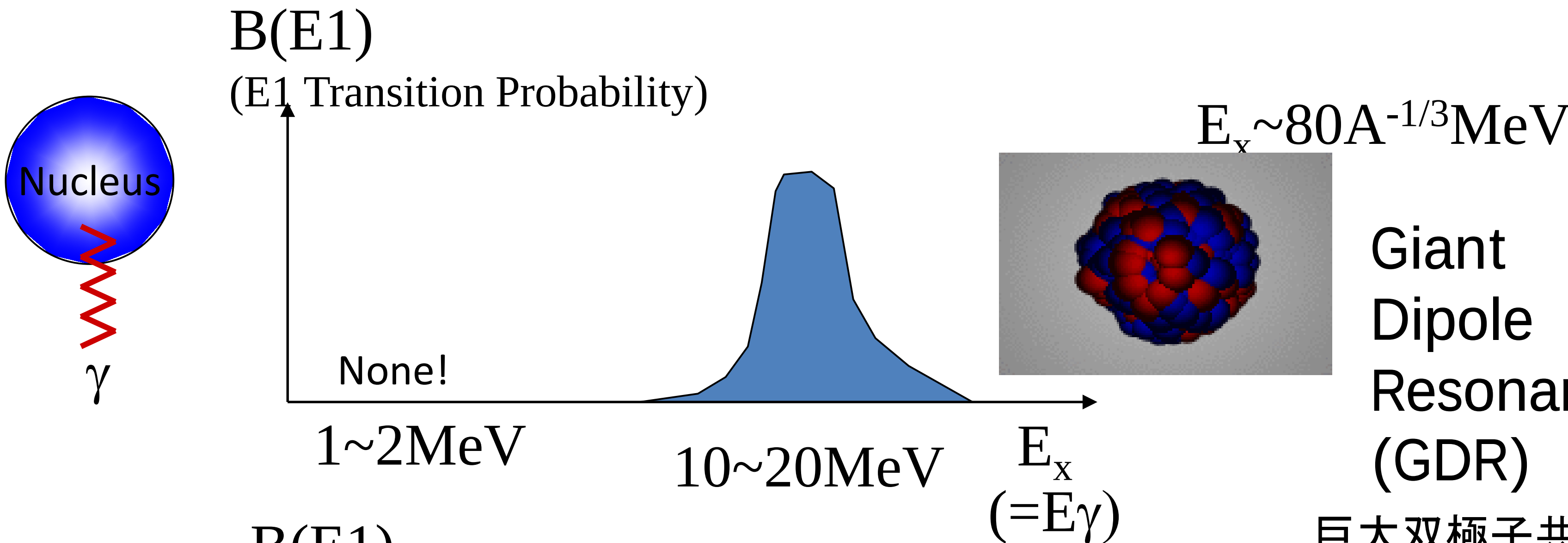
Continuum?



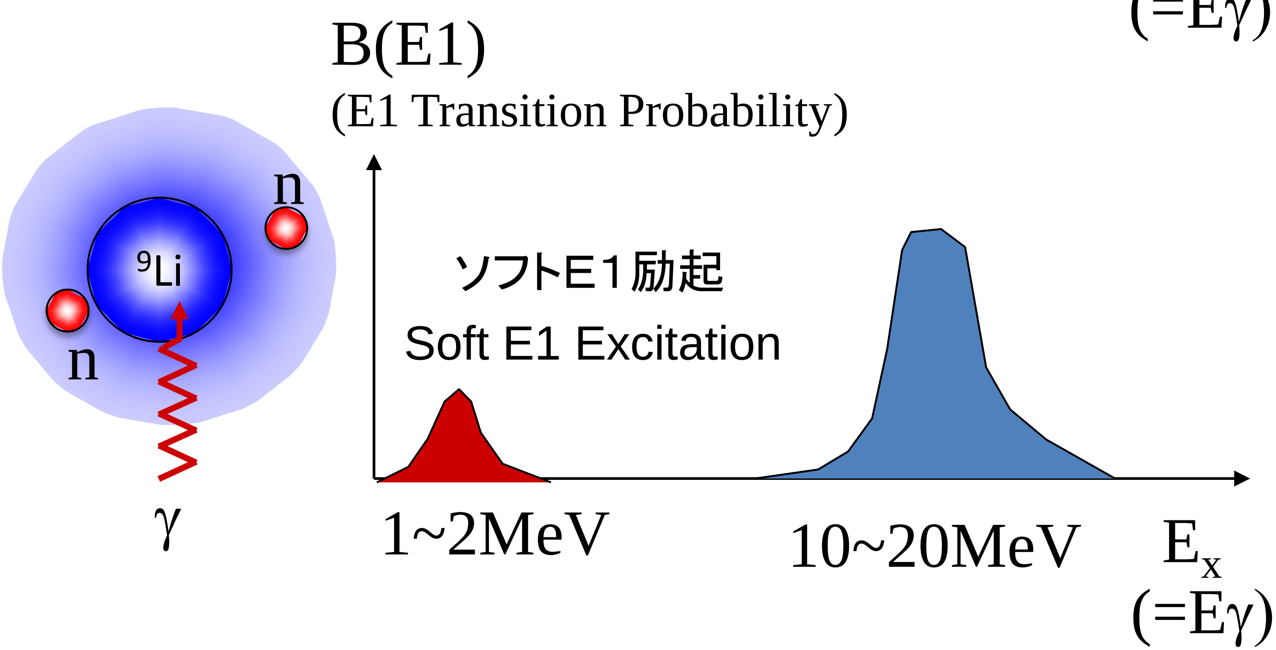
Coulomb Breakup of 2n Halo Nuclei (^{11}Li, ^{22}C)

R. Minakata, TN, Y. Kondo, Y. Togano,
S. Leblond, J.Gieblin, N.A.Orr et al.

How a nucleus responds, when it absorbs a photon?

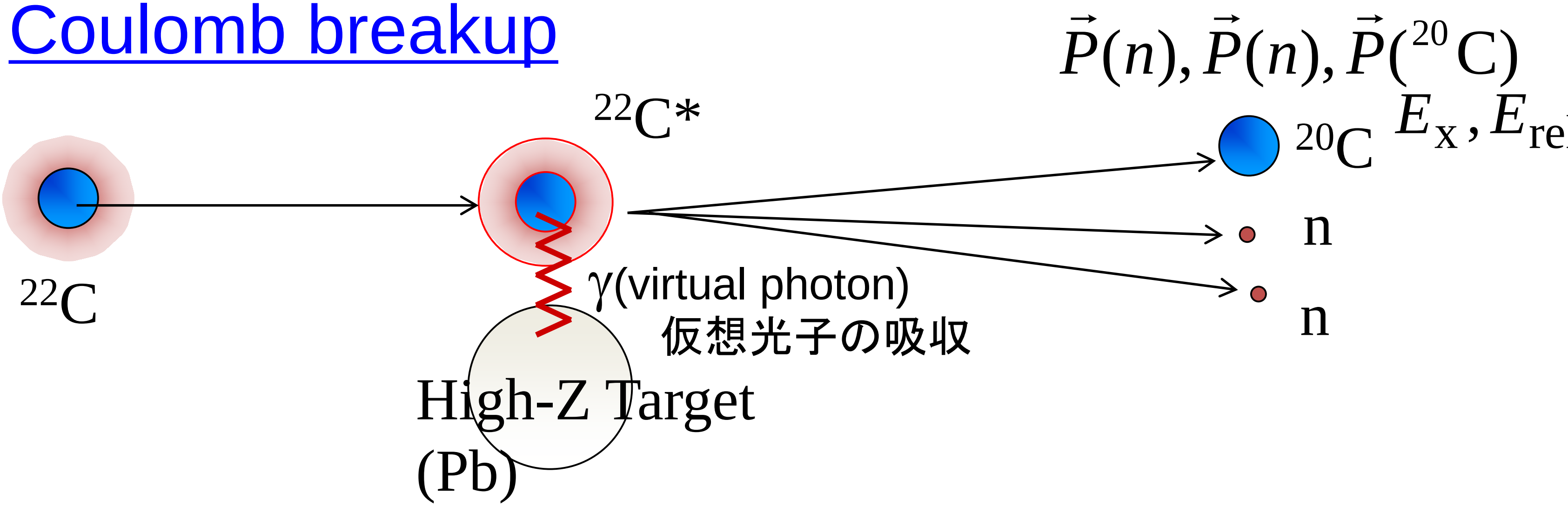


Giant
Dipole
Resonance
(GDR)
巨大双極子共鳴



クーロン分解

Coulomb breakup



Equivalent Photon Method 等価光子法

$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

断面積＝(仮想光子数)x(双極子遷移確率)

Cross section = (Photon Number)x(Transition Probability)

C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).

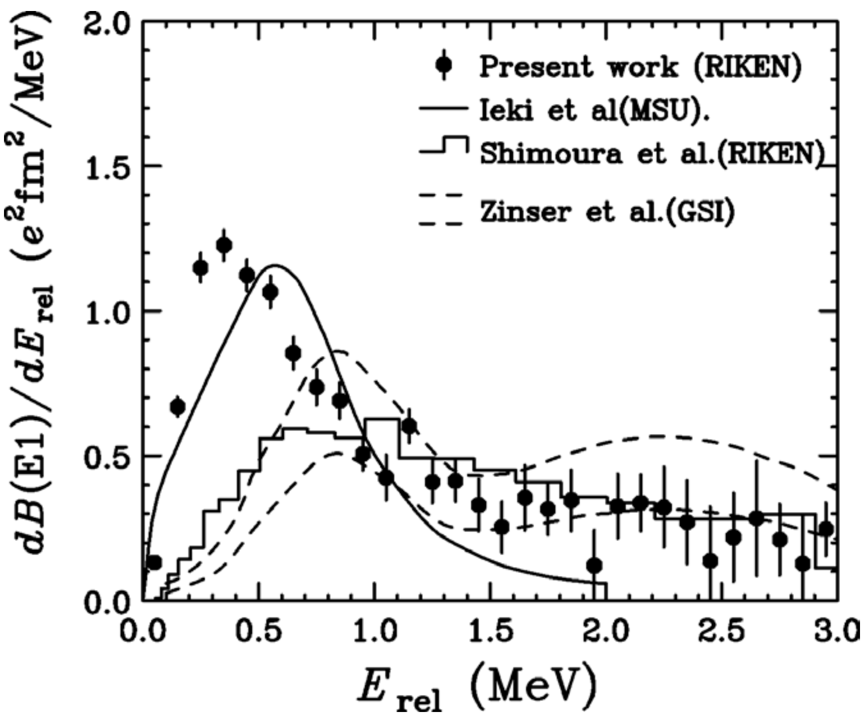
ソフト双極子励起

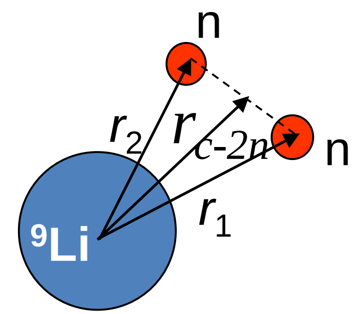
Halo → Soft E1 Excitation

(E1 Concentration at Ex<1MeV)

Coulomb Breakup of 2n Halo
→ Probe of Dineutron Correlation

^{11}**Li** T.Nakamura et al. PRL96,252502(2006).





$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x$$

$$= \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\ 2} + r_2^{\ 2} + 2(\vec{r}_1 \cdot \vec{r}_2) \right\rangle$$

$$B(E1) = 1.42 \pm 0.18\, e^2\, fm^2 (E_{\rm rel} \leq 3\text{MeV})$$

$$\rightarrow 1.78(22)\, e^2\, fm^2 \rightarrow \langle \theta_{12} \rangle = 48^{+14}_{-18}\ \text{deg}.$$

Correlation in the Ground State of ^{11}Li

Soft E1 Excitation of 2n-halo
→ dineutron-like correlation

^{22}C (Z=6,N=16)

■ 2n-Halo 巨大ハローか？Giant Halo?

- ✓ **Large Reaction Cross Section**

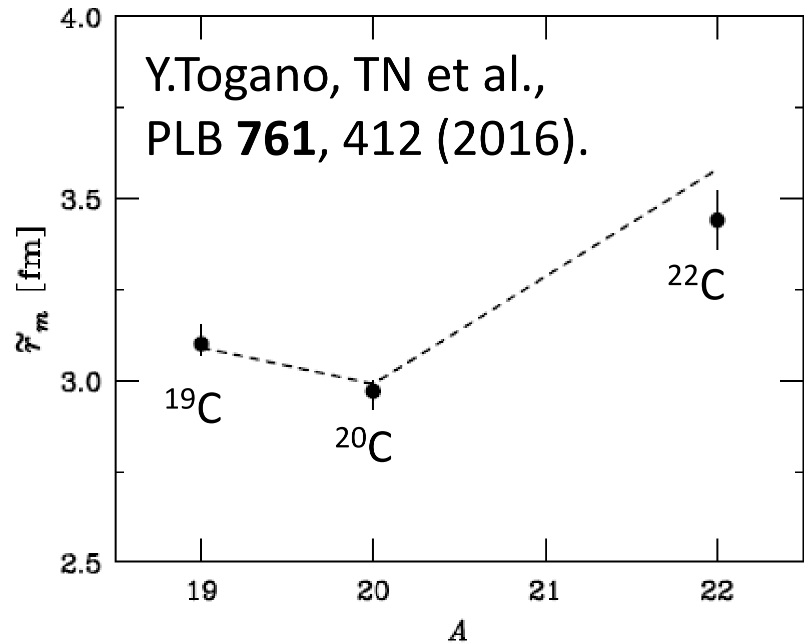
  $(\langle r_m^2 \rangle)^{1/2}$=3.44(8) fm c.f. ~3.5 fm ^{11}Li

Y. Togano, TN, et al.,PLB 761, 412 (2016).
K.Tanaka et al., PRL 104, 062701(2010).

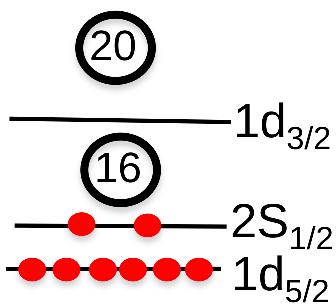
- ✓ **S_{2n}= –0.14(46) MeV**
  L.Gaudefroy et al. PRL109,202503(2012).

- ✓ **Narrow Momentum Distribution** ~73MeV/c

  N.Kobayashi et al. PRC86,054604(2012).



■ N=16 Magicity? 新魔法数？



A.Ozawa et al., PRL 84, 5493 (2000).

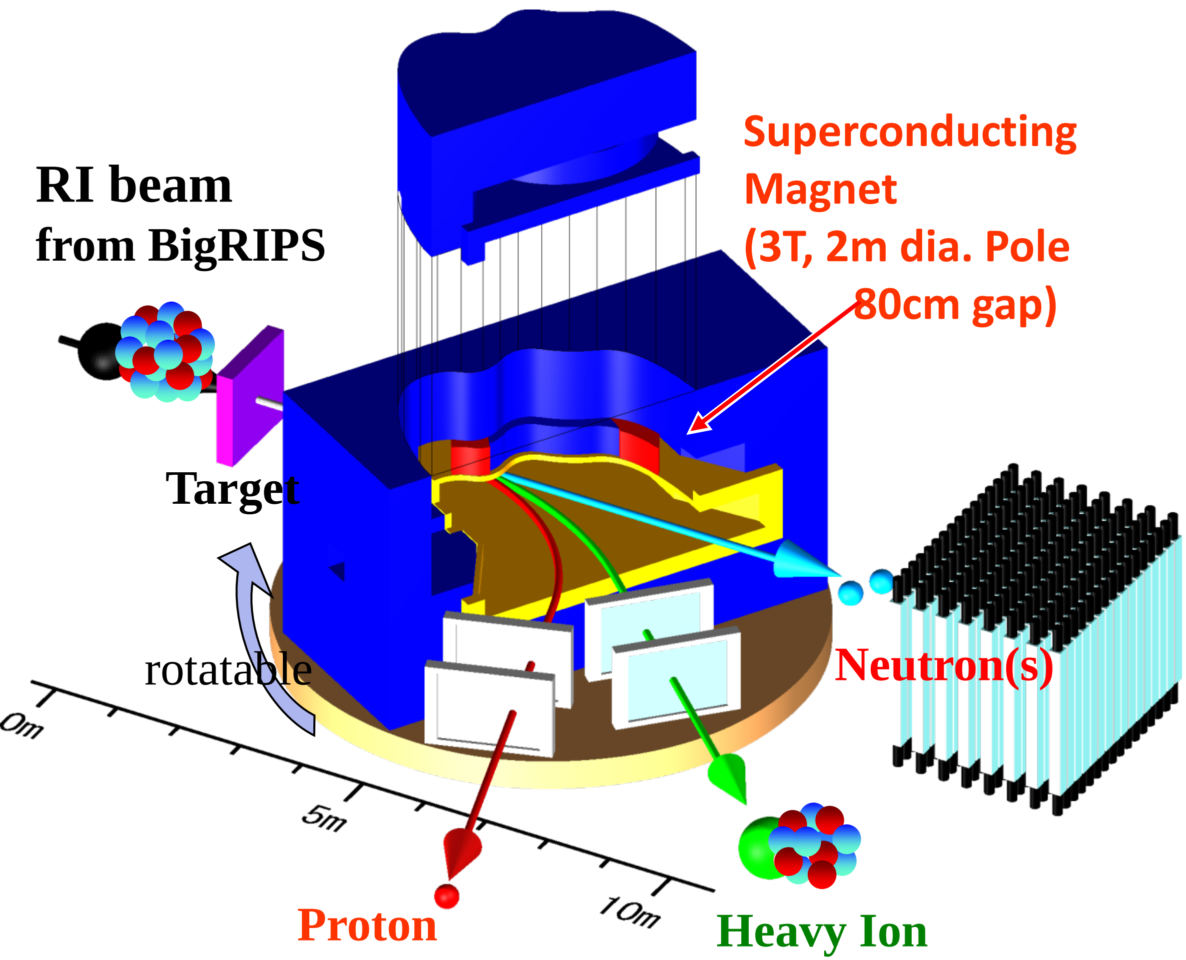
M.Stanoiu et al., PRC78,034315 (2008).

SAMURAI at RIBF/RIKEN

SAMURAI@RIビームファクトリー
理研仁科センター

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence



Large momentum acceptance

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

Good Momentum Resolution

$\Delta p/p \sim 1/1000$

→ $A/\Delta A > 100$ (>5σ)

Large Bending Angle (~60deg)

+4 Tracking Detectors

T.Kobayashi NIMB **317**, 294 (2013)

Large angular acceptance for *n*

+-8.8 deg (H) x +-4.4 deg(V)

(~50% coverage < E_{rel} ~ 5MeV)

TN, Y.Kondo, NIMB **376**, 156 (2016).

Moderate Erel Resolution

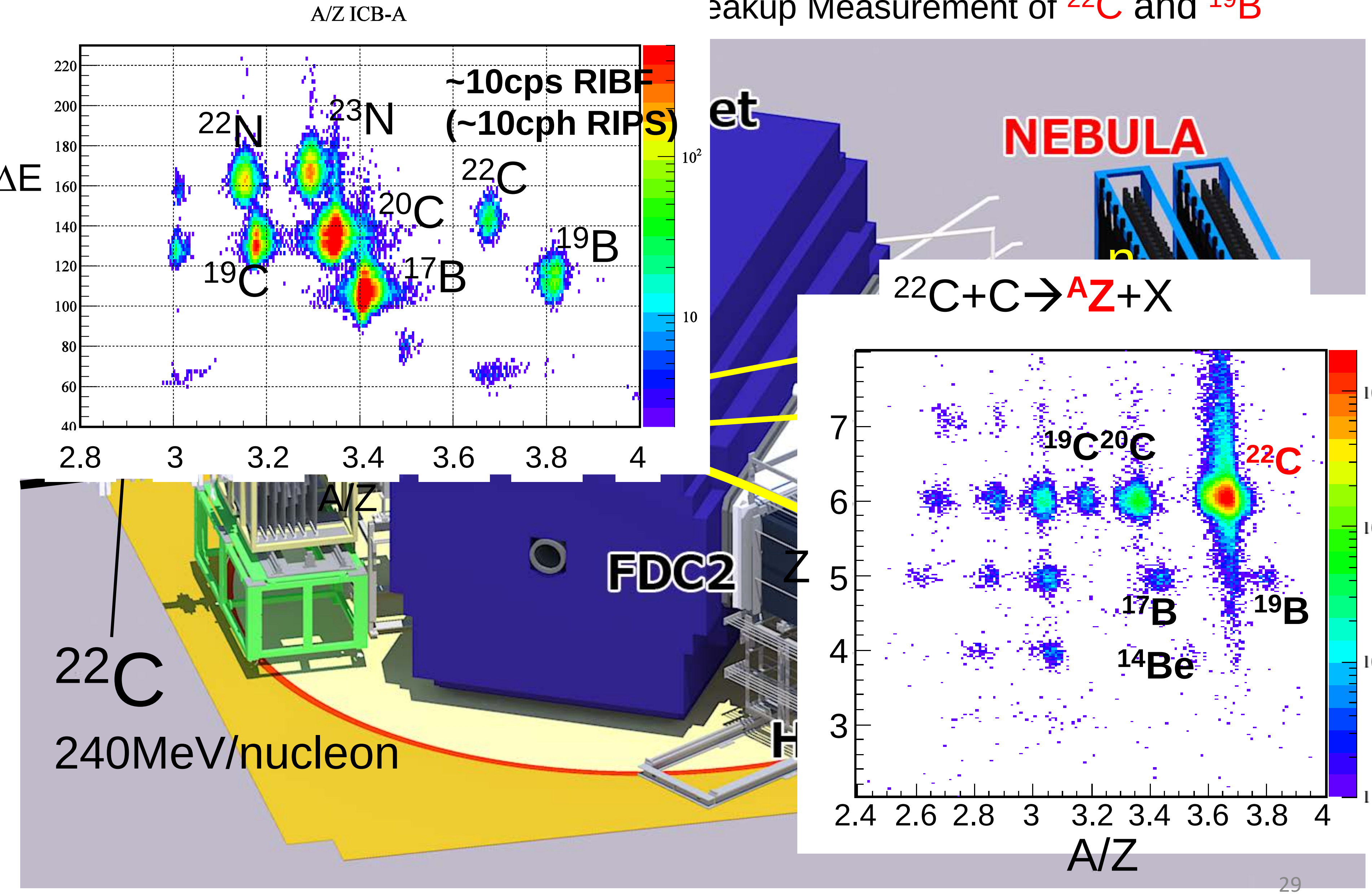
ΔE = 200 keV (σ) at E_{rel}=1MeV

Stage: Rotatable (-5 -- 95 degrees)

→Variety of Physics Opportunities

SAMURAI Experiment

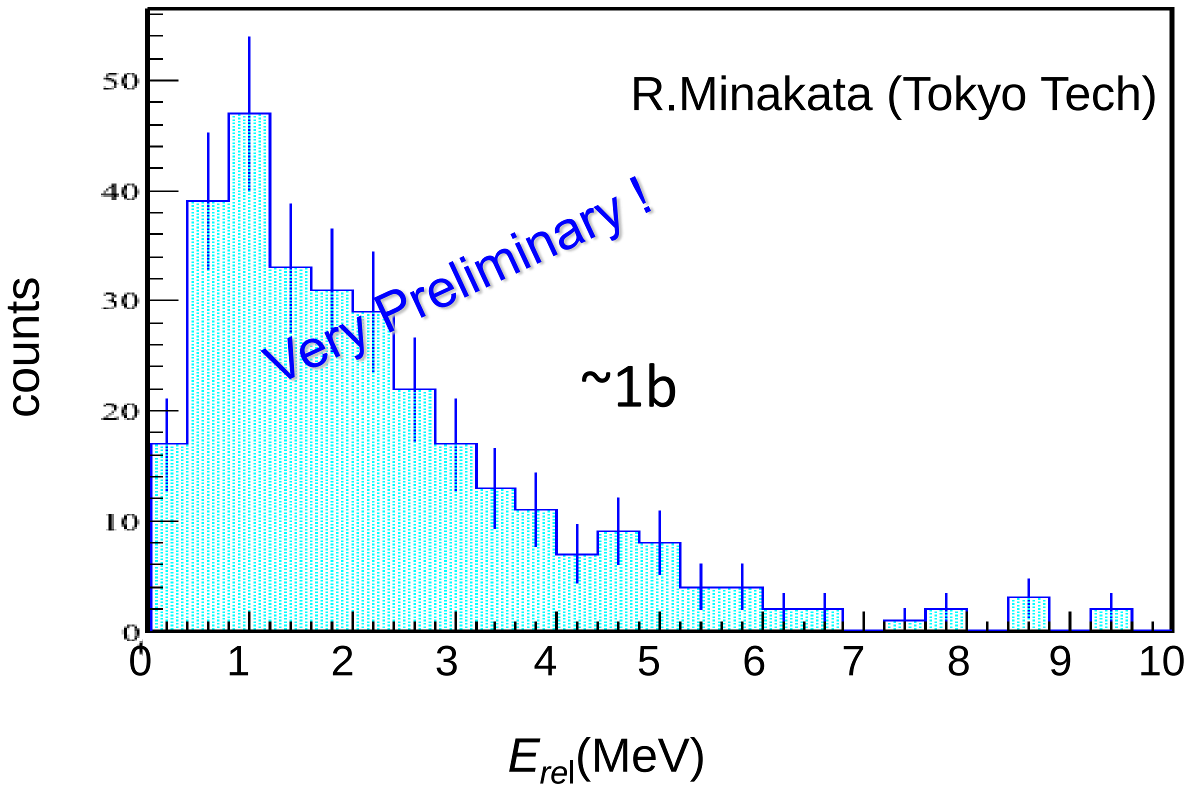
…eakup Measurement of ^{22}C and ^{19}B



Coulomb Breakup of ^{22}C (^{20}C+n+n Spectrum)

R. Minakata, T.Nakamura

$^{22}C+Pb \rightarrow {}^{22}C^* \rightarrow {}^{20}C+n+n$



Strong Soft E1 Excitation → **Evidence of Halo**

Spectroscopy of Super-heavy oxygen isotopes

--Barely Unbound 2n emitter ^{26}O

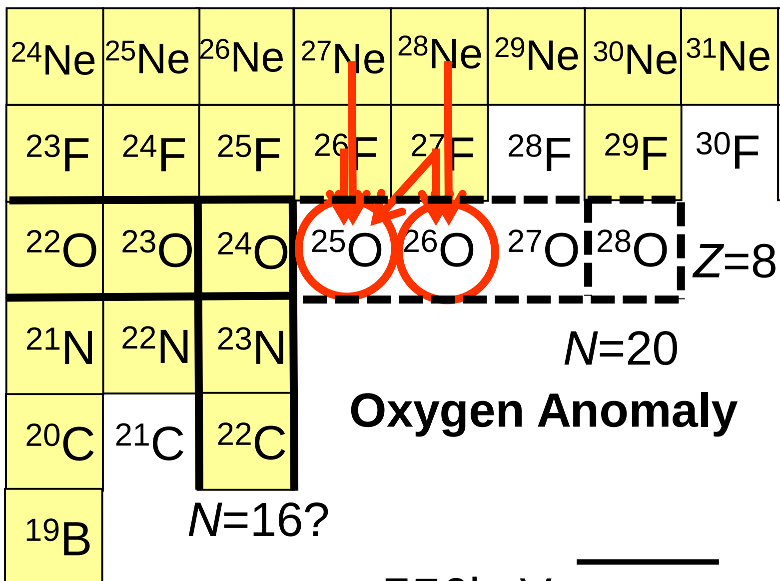
& 4n emitter ^{28}O

Yosuke Kondo, TN et al.

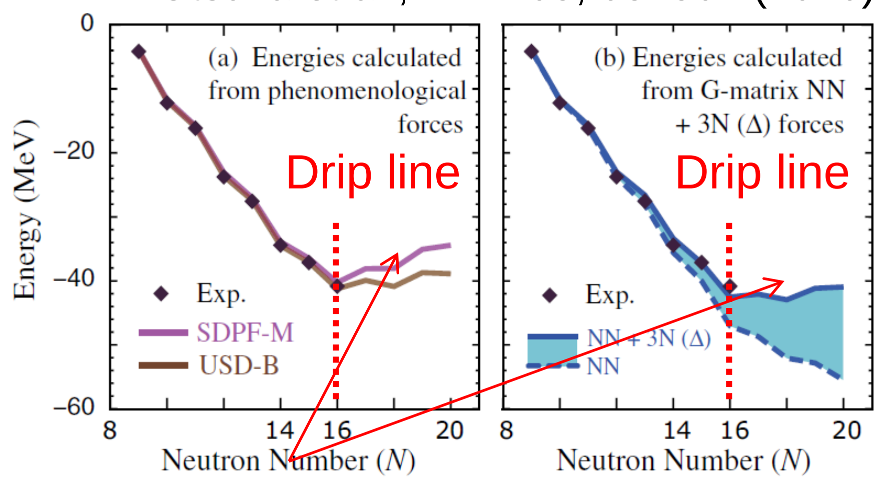
Study of unbound nuclei ^{25}O and ^{26}O at SAMURAI

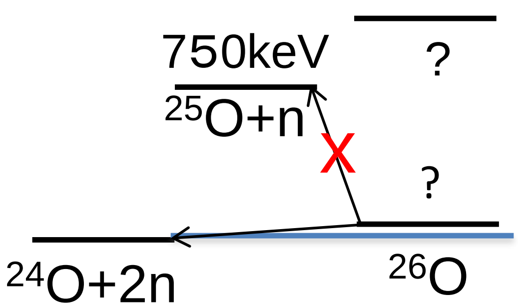
Spokesperson Yosuke Kondo

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



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





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

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).

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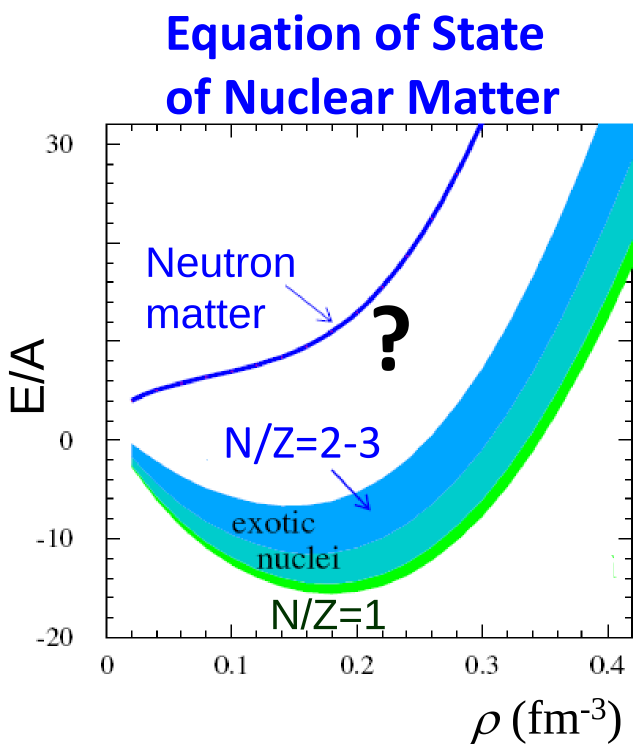
A.Volya, V.Zelevinski, PRL94,052501(2005).
K. Tsukyiyama, T. Otsuka, PTEP2015, 093D01 (2015).

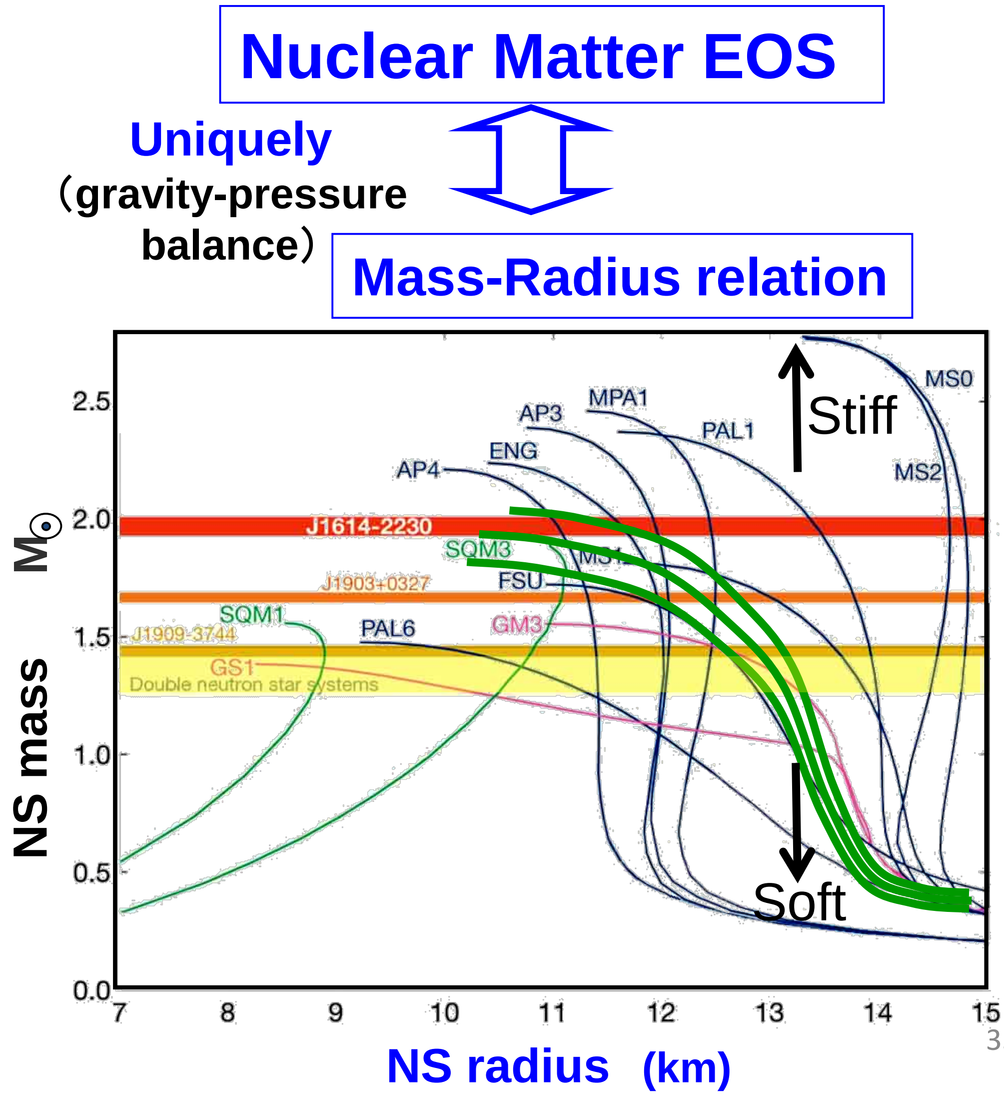
nn correlations:
L.V. Grigorenko et al., PRL111,042501(2013).
K. Hagino, H. Sagawa PRC89,014331(2014).

"Nuclear Interactions" ("3N") of very neutron-rich systems

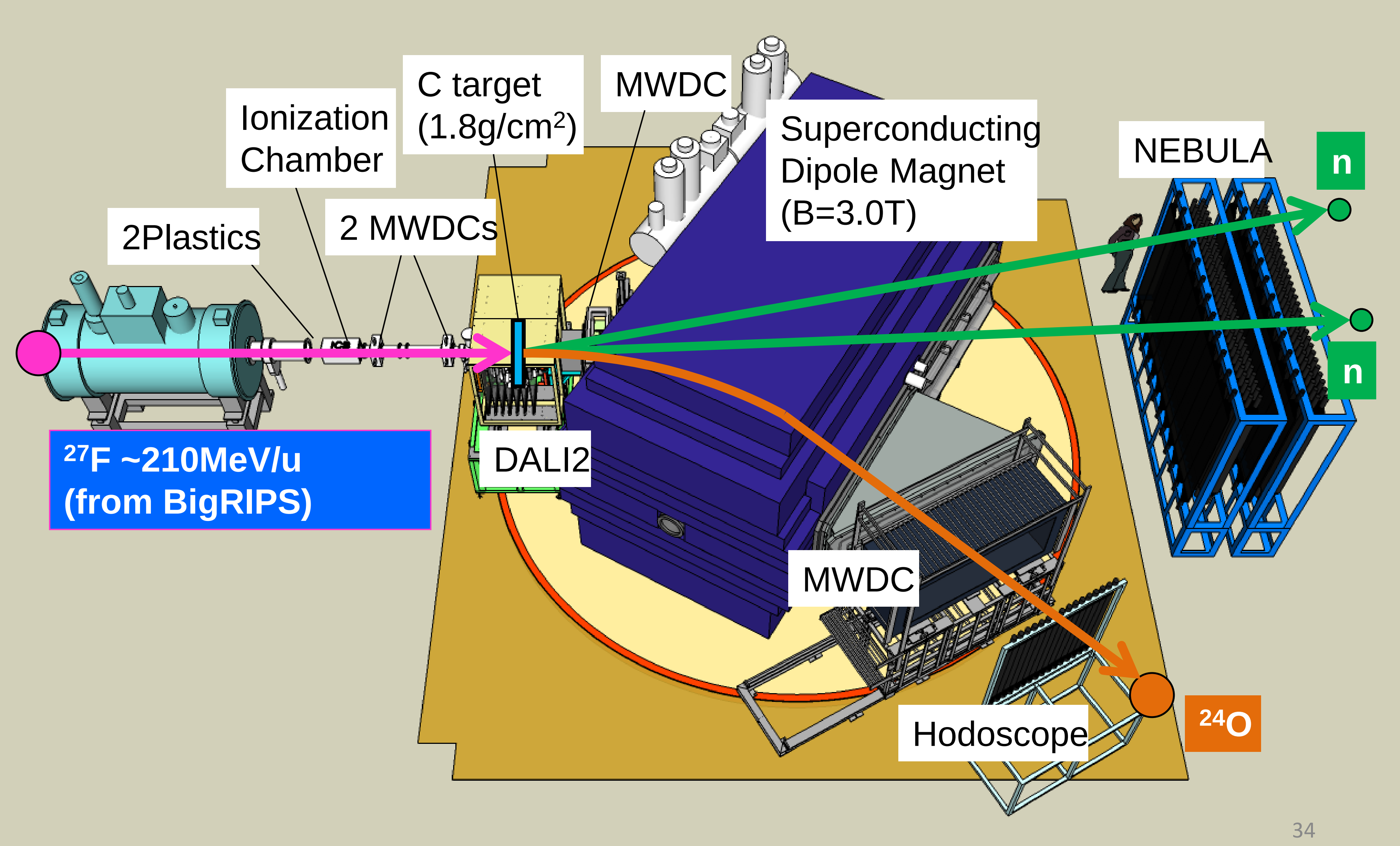
→**Equation of State (EoS)** of neutron-rich nuclear matter

→**Neutron Star** (Radius, Maximum mass, Composition)

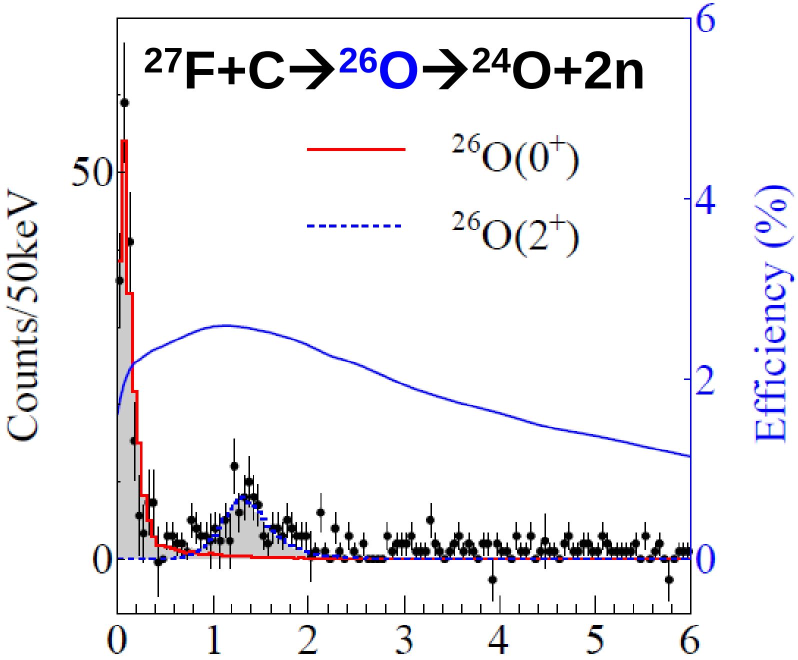




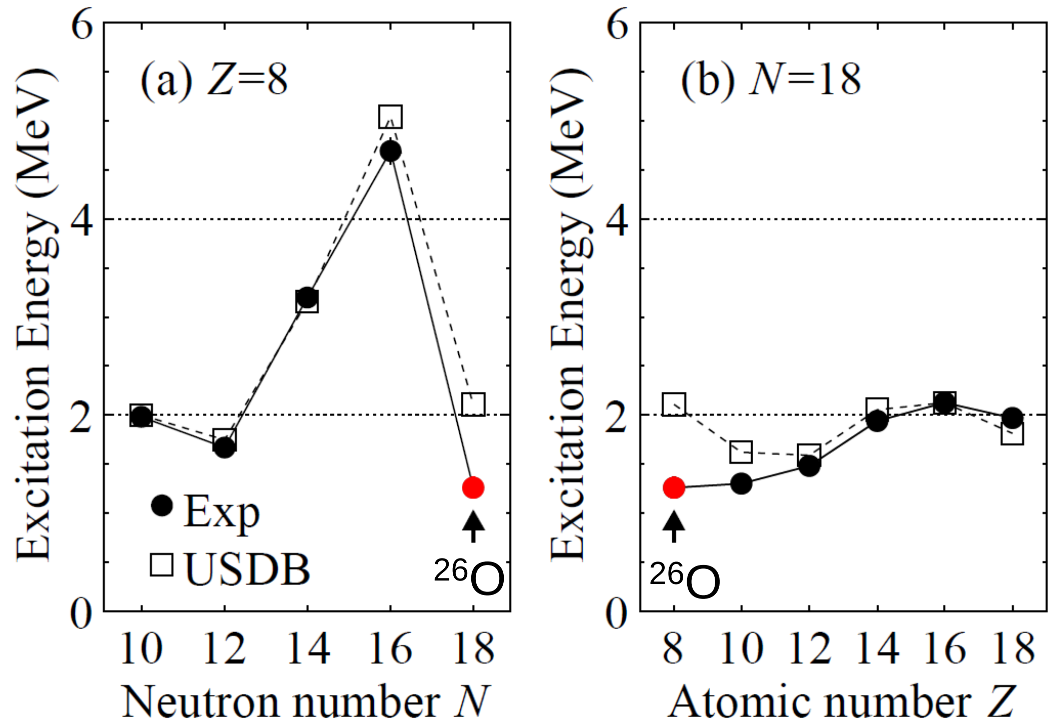
Experimental Setup at SAMURAI at RIBF



Study of ^{26}O (SAMURAI02)



Decay Energy (MeV)



Ground state (0^+)

5 times higher statistics than previous study

18±3(stat)±4(syst)keV

Finite value is determined for the first time

1st excited state (2^+)

Observed for the first time

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

N=16 shell closure is confirmed

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

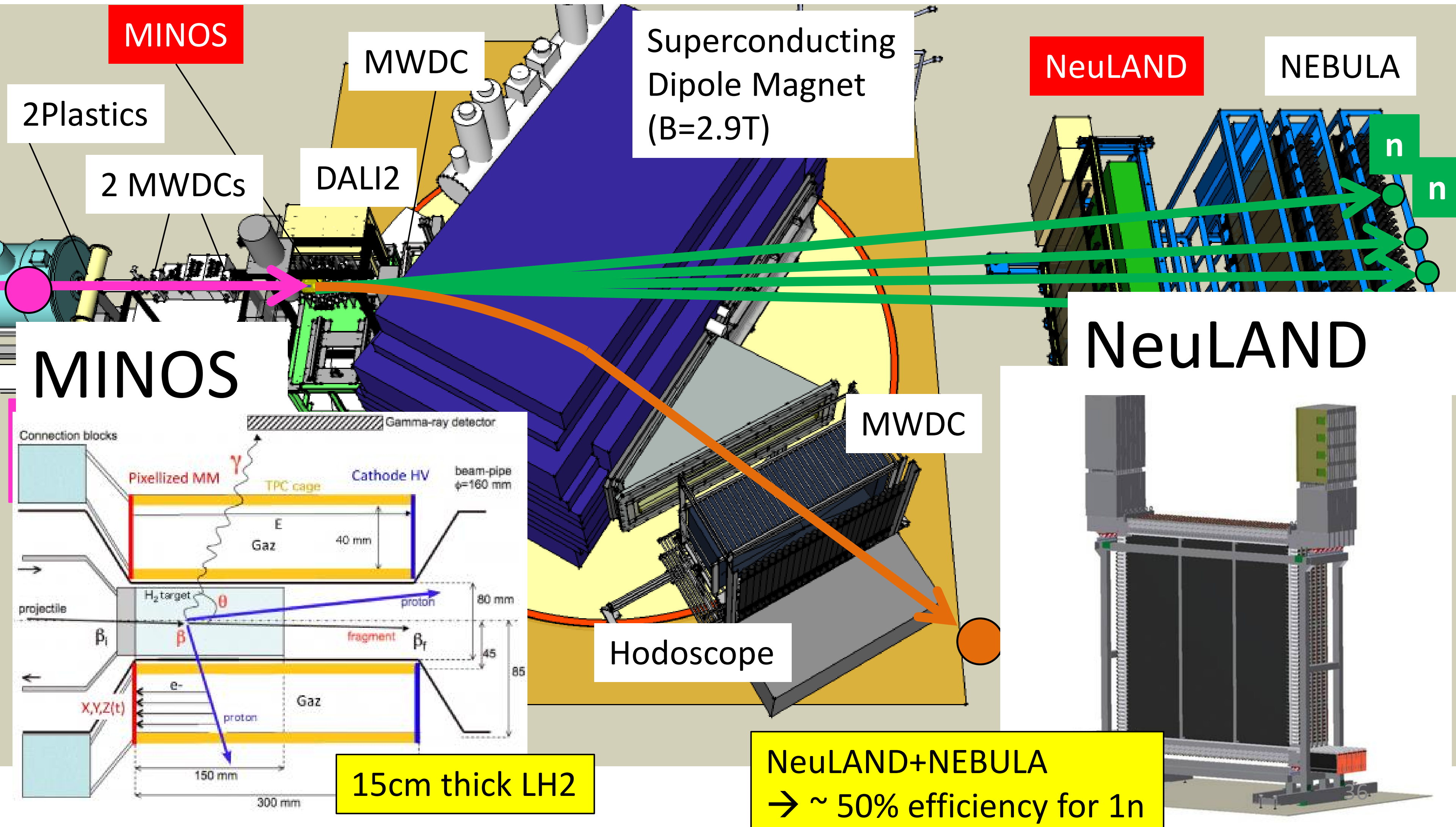
→effects of

pf shell?, **continuum**?

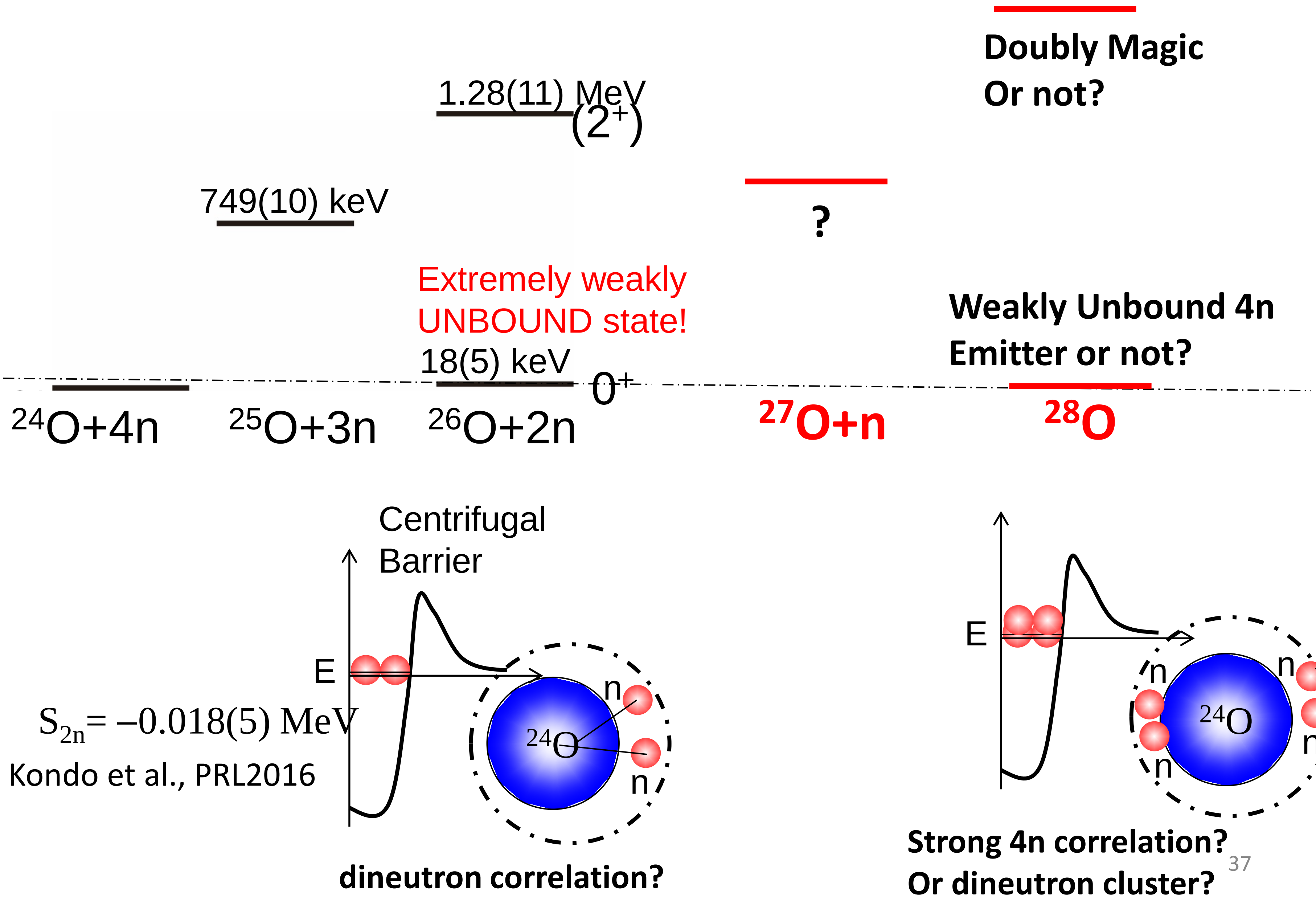
2n Correlations?, **3N force?**

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

^{28}O measurement @ RIBF-SAMURAI



Dineutron Cluster?



Summary and Outlook

✓ **Introduction**

- Why hierarchical structure exists in quantum world?
- Clustering is key to this?
- How Hierarchy is Formed? --Naïve Pictures

✓ **Dineutron Correlation in 2n Halo nuclei**

^{11}Li, ^{22}C SAMURAI: Powerful Facility for Drip Line Nuclei

✓ **Spectroscoy of Super-heavy oxygen --Barely unbound 2n emitter ^{26}O**

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

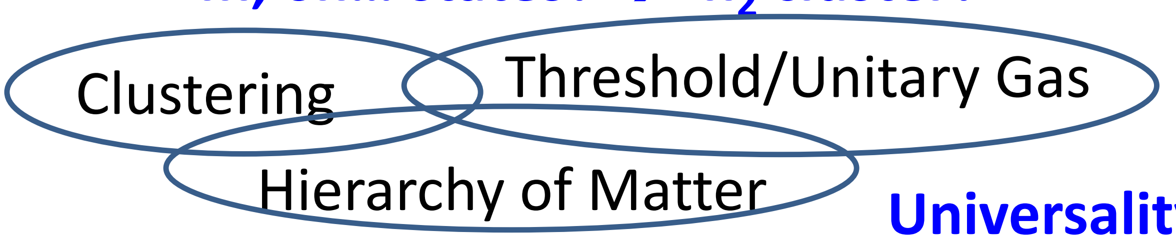
→ ^{26}O(0^+_{gs}): Very weakly unbound 2n states → Correlation? Continuum?

^{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

Near Future: Variety of spectroscopies along n-drip line

4n, 6n… states? → n_2 cluster?



Universality?

Day-one Collaboration

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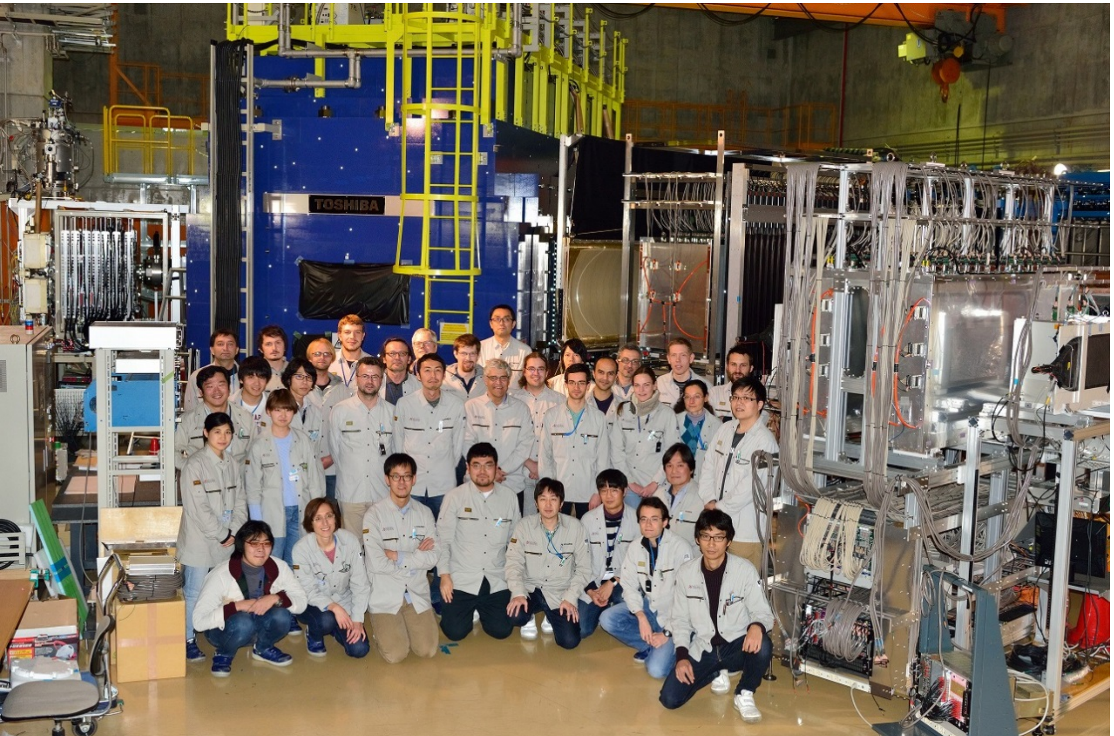
SAMURAI21 collaboration—$^{27,28}O$



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「量子クラスターで読み解く物質の階層構造」
Clustering as a window on the hierarchical structure of quantum systems

領域代表　中村隆司 P.I. Takashi Nakamura　H30-34

公募研究にぜひご応募下さい。
Your Applications and Contributions
to our Project for FY 2019-20 are Most Welcome.

All the sciences, and not just the sciences but all the efforts of intellectual kinds, are an endeavor to see the connections of the hierarchies.
Richard P. Feynman, The Character of Physical Law

For more details…

不安定核の物理

--中性子ハロー･魔法数異常から中性子星まで

基礎法則から読み解く物理学最前線8

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Review article: **“Exotic nuclei explored at In-flight Separators”**
T.Nakamura, H.Sakurai, H.Watanabe,
Progress in Particle and Nuclear Physics **97**, 53 (2017).