Breakup Reactions on Exotic Nuclei at the large acceptance spectrometer SAMURAI at RIBF

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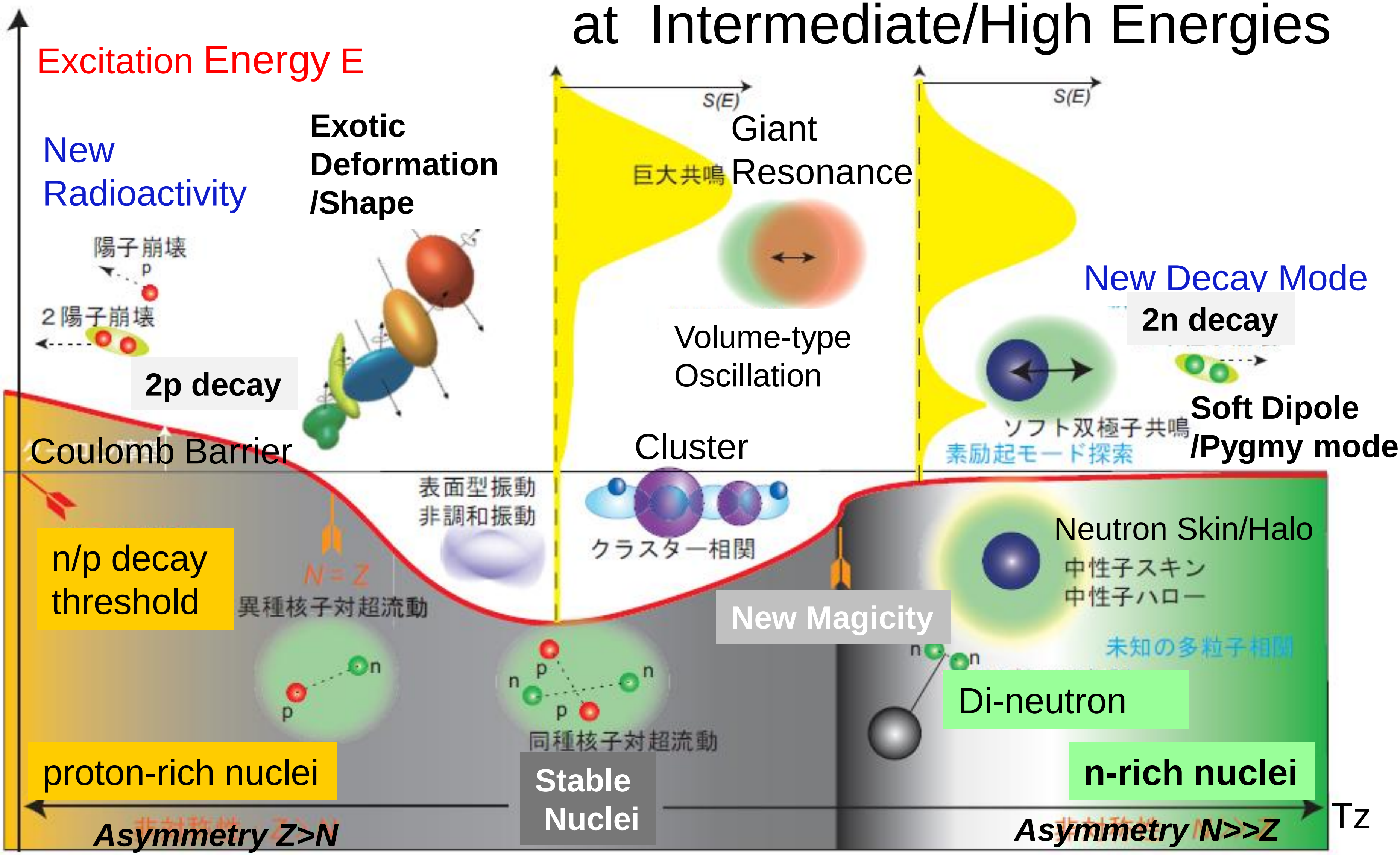
Tokyo Institute of Technology

ASY-EOS 2012
Int. Workshop on Nuclear Symmetry Energy and Reaction Mechanisms
Siracusa, Sicily, Italy

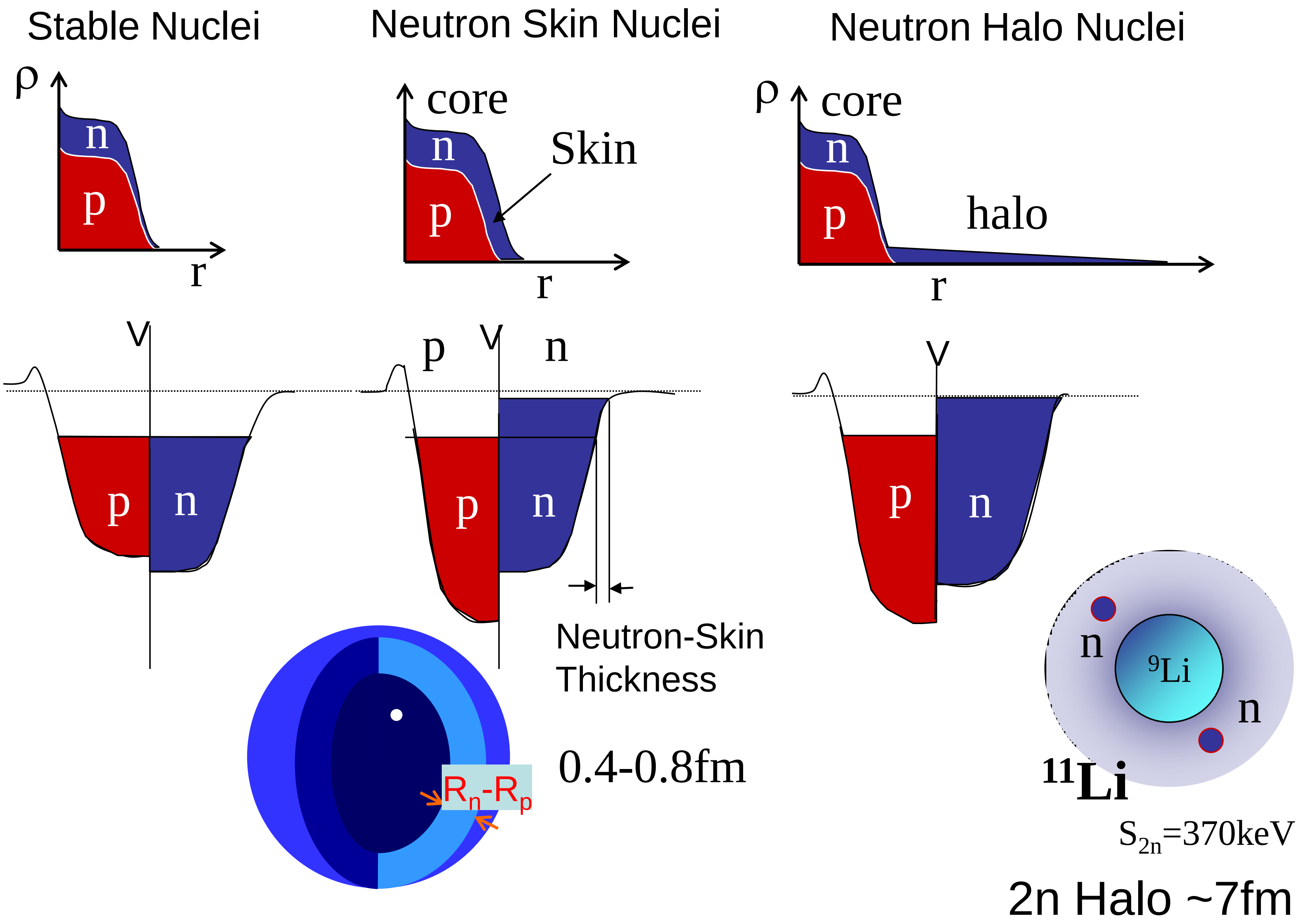
Contents

→ Breakup Reactions at Intermediate/High Energies

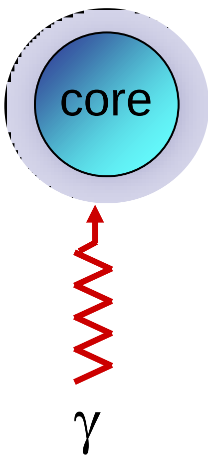


"Physics at RIBF" by Nuclear Theory Group in Japan/ Nakatsukasa et al.

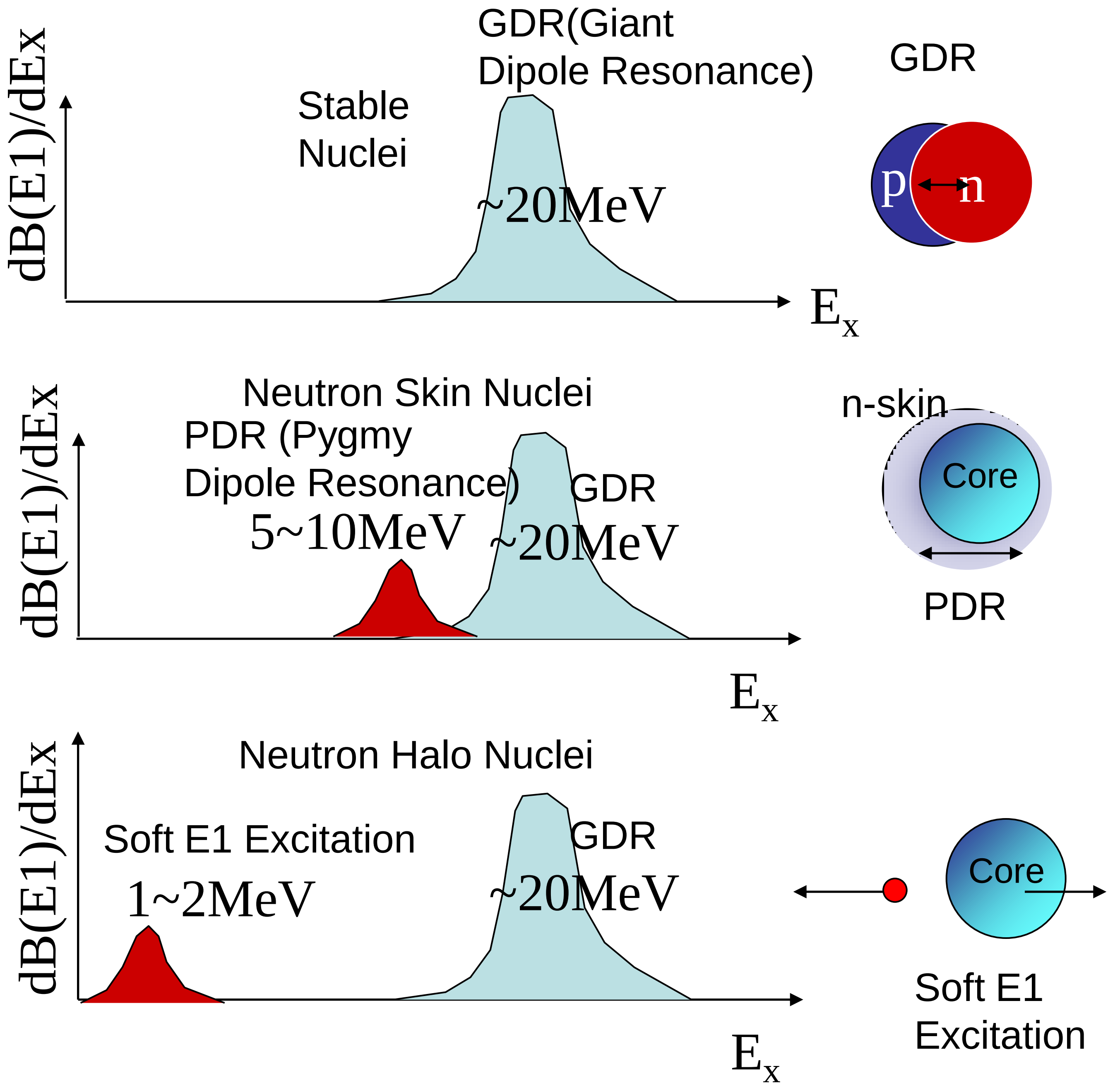
Neutron Skin/Halo



E1 Response of Nuclei



How a nucleus responds?

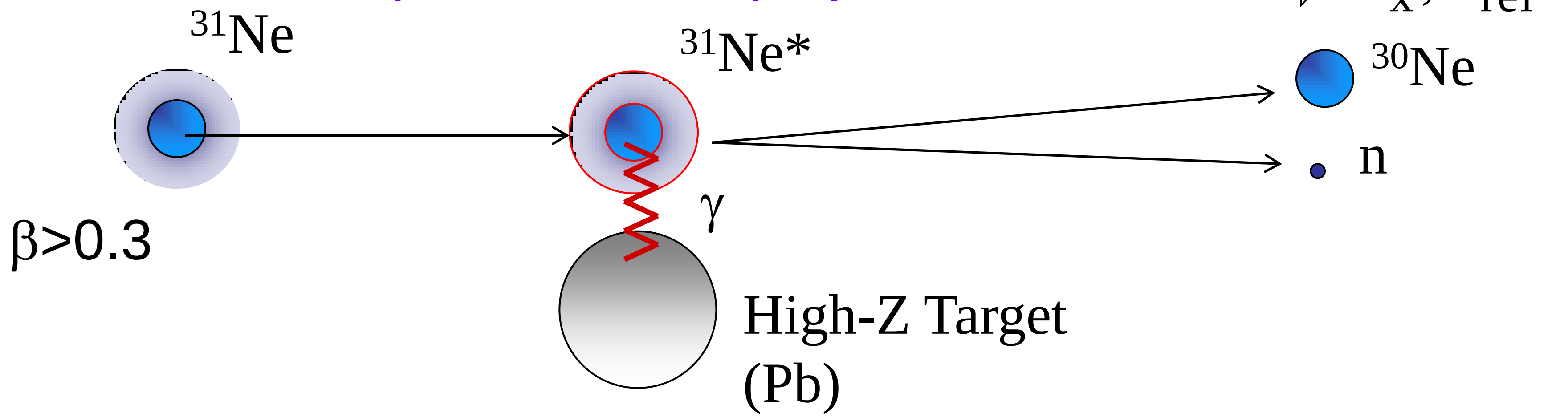


Coulomb Breakup

→Photon absorption of a fast projectile

$\vec{P}(n), \vec{P}(^{30}\mathrm{Ne})$

Invariant Mass ⇒ E_x, E_{rel}

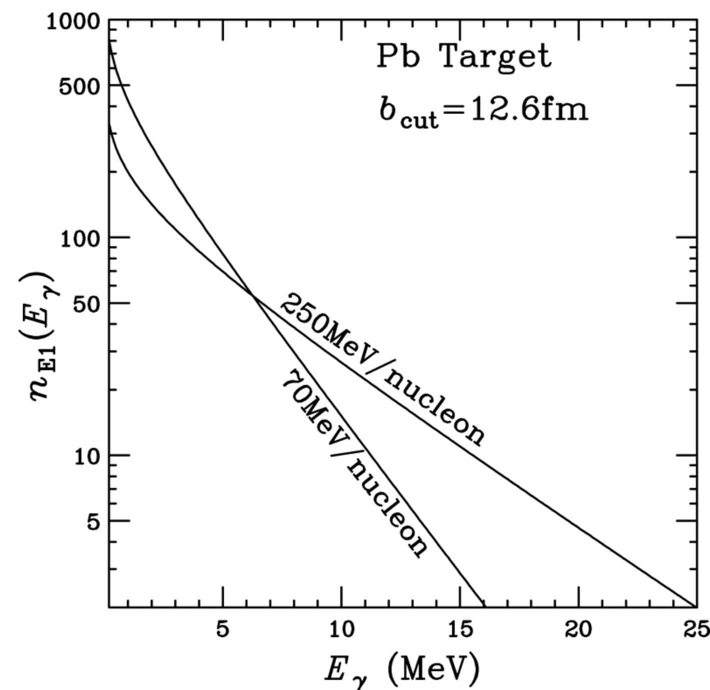


Equivalent Photon Method

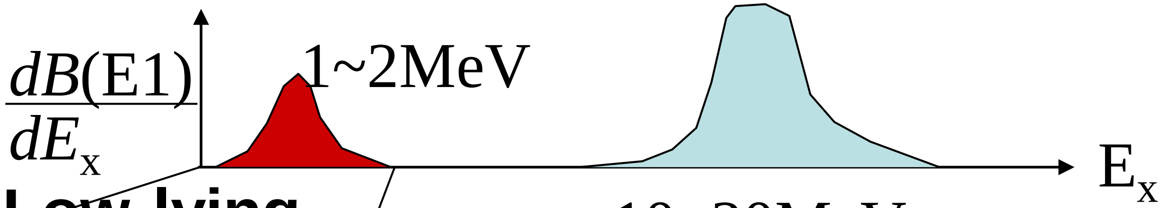
$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

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

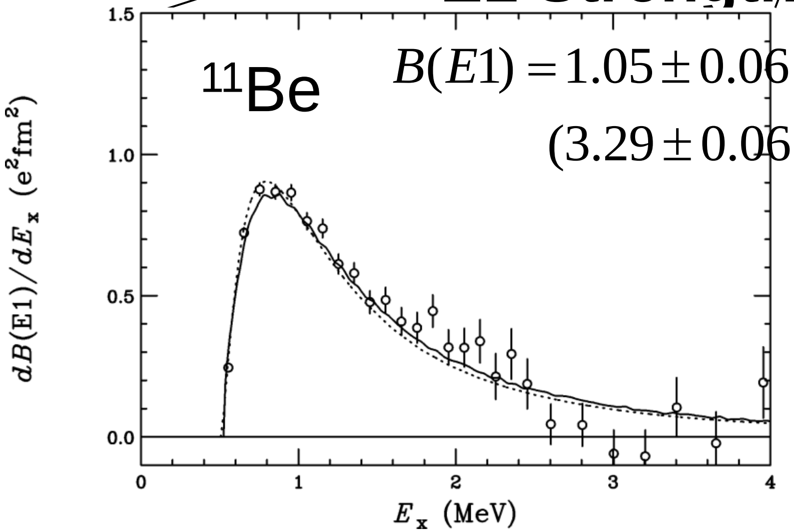
C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).



E1 Response of halo nuclei (Coulomb Breakup of 1n halo)

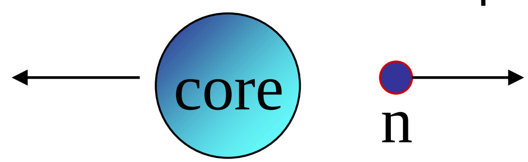


Low-lying
E1 Strength (Soft E1 excitation)

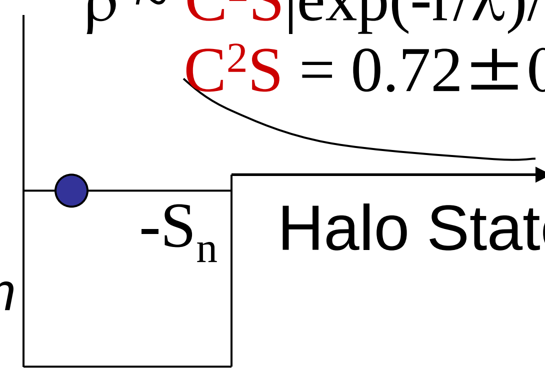


N.Fukuda, TN et al., PRC70, 054606 (2004)
TN *et al.*,PLB 331,296(1994)
Palit et al., PRC68, 034318(2003)

Direct Breakup Mechanism



$\rho \sim C^2S|\exp(-r/\lambda)/r|^2$
$C^2S = 0.72 \pm 0.04$



E1 Strength

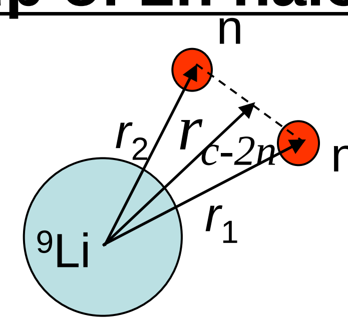
$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} r Y^1{}_m|\Phi_{gs}\rangle|^2$$
$$\propto C^2S\,|\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} r Y^1{}_m|s_{1/2}\rangle|^2$$

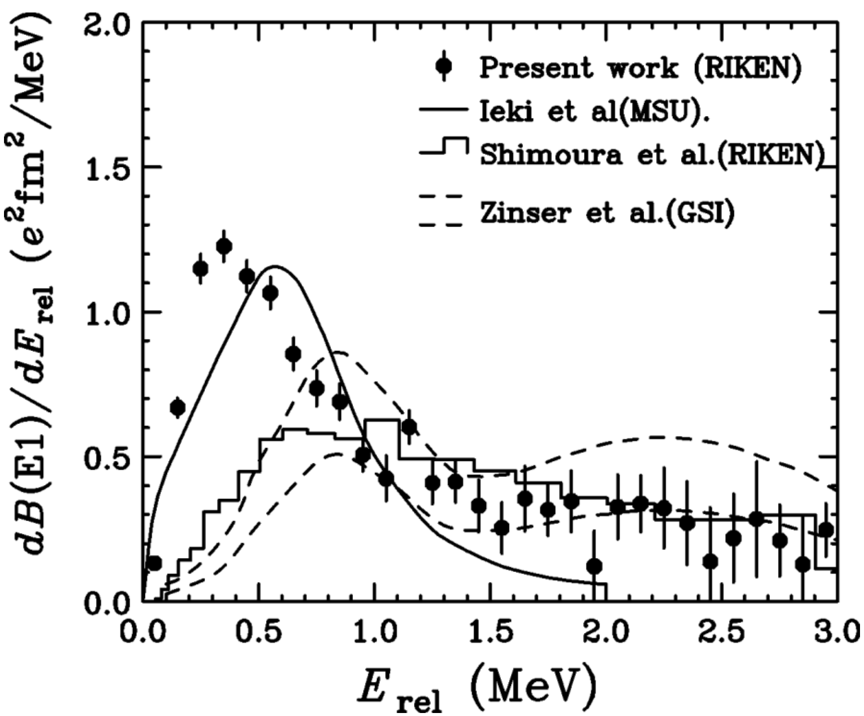
Fourier Transform

Soft E1 Excitation of 1n halo—Sensitive to S_n, l, C^2S

Dineutron Correlation in ^{11}Li (Coulomb Breakup of 2n halo)

T.Nakamura
et al. PRL96,252502(2006).



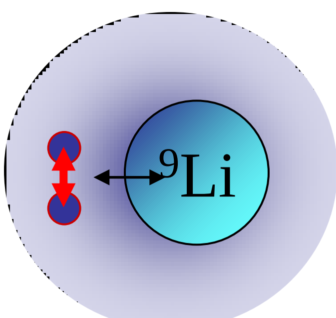


$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x$$

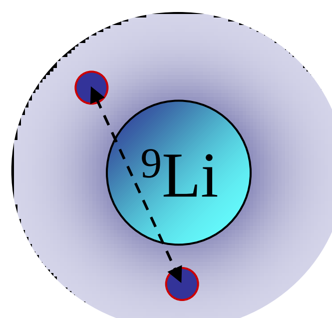
$$= \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\,2} + r_2^{\,2} + 2(\vec{r}_1 \cdot \vec{r}_2)\right\rangle$$

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

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



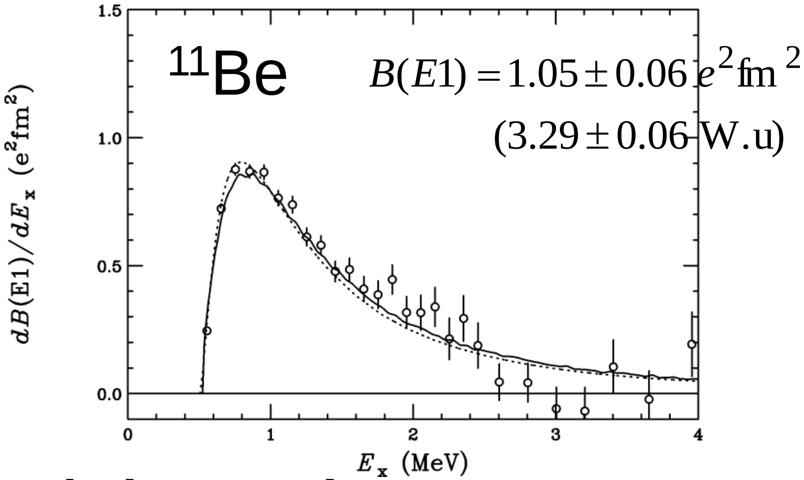
Dineutron Correlation
→Strongly Polarized
→ Strong E1 Excitation



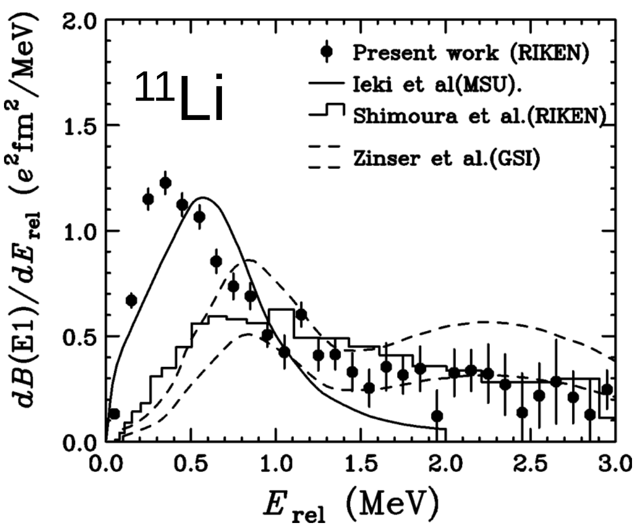
Weak 2n correlation
→Weakly Polarized
→Weak E1 Excitation

Soft E1 Excitation of 2n-halo—+dineutron-like correlation

Soft E1 Excitation for Halo Nuclei



N.Fukuda, TN et al., PRC70, 054606 (2004)

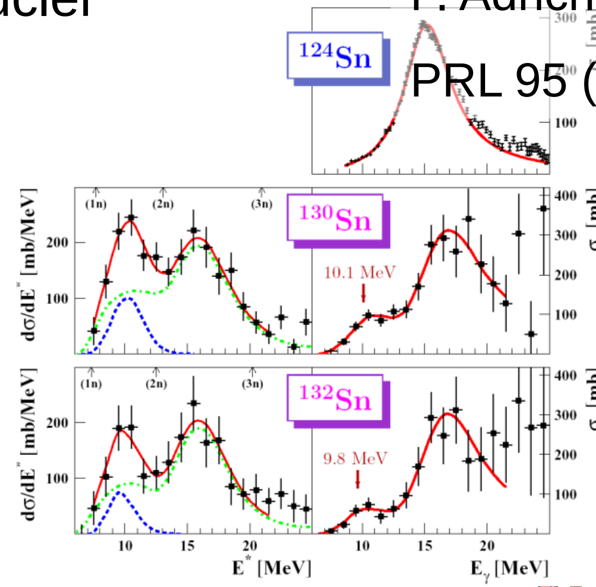


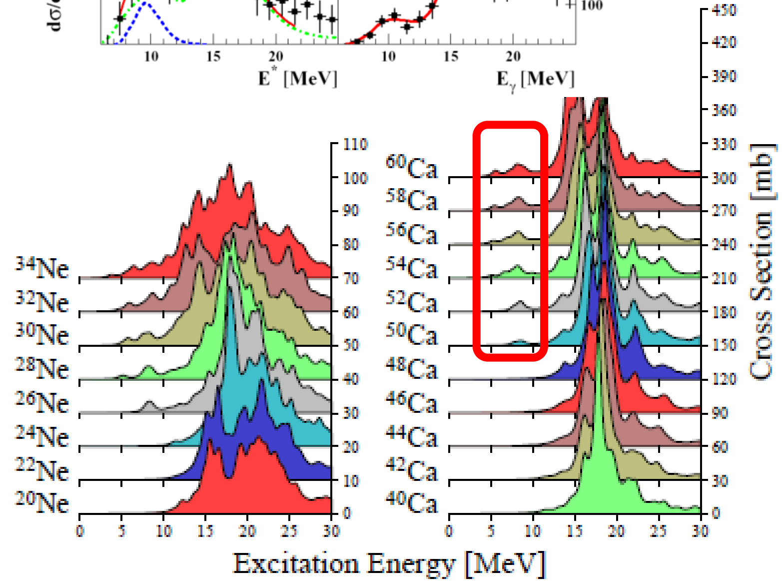
T.Nakamura et al. PRL96,252502(2006).

Pygmy Dipole Resonance for n-Skin Nuclei

P. Adrich et al.,

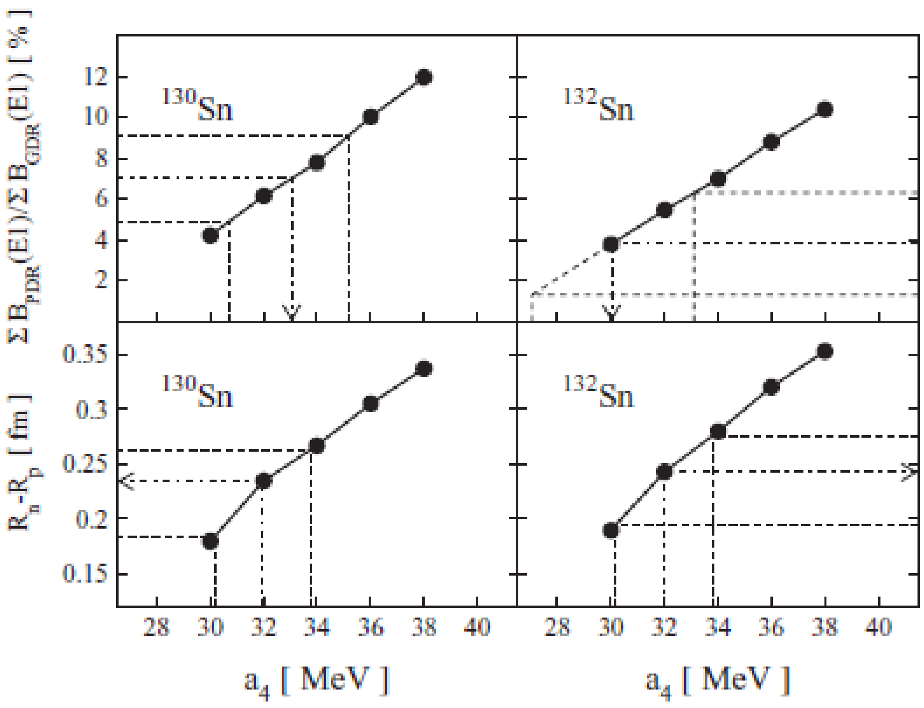
PRL 95 (2005) 132501

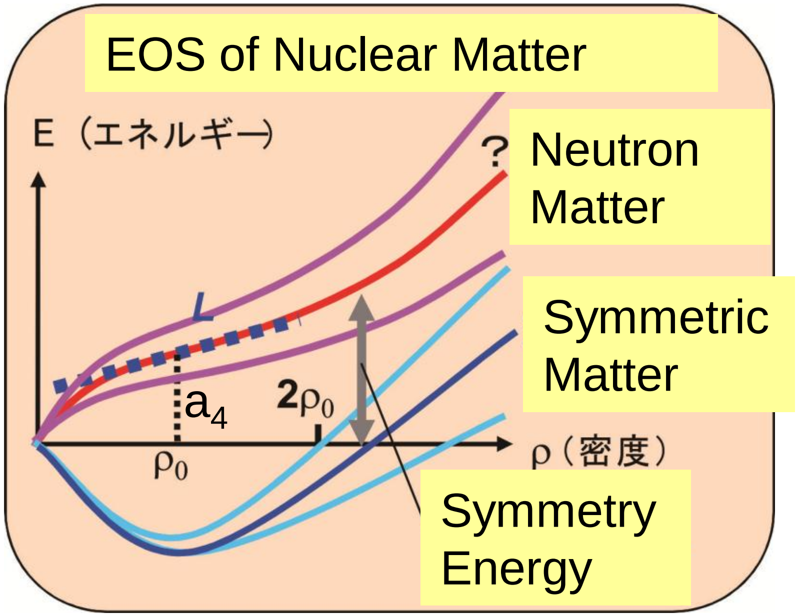




T.Inakura, T.Nakatsukasa, K.Yabana, PRC84, 021302(2011)

Pygmy Dipole Resonance
←→ Neutron Skin Thickness
←→ Equation of State of Nuclear Matter





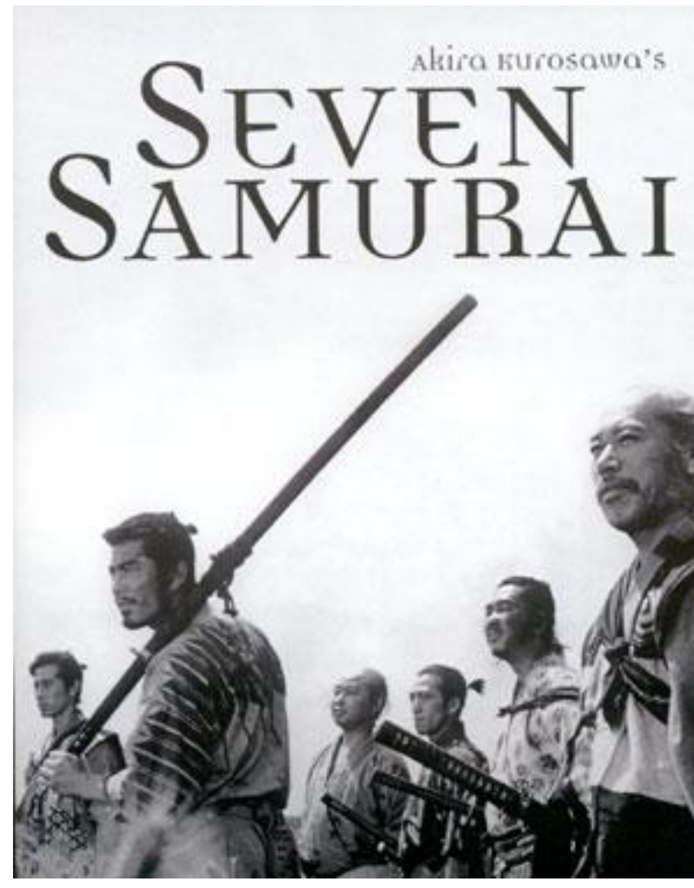
Result (*averaged ^{130,132}Sn) :*

a_4 = 32.0 ± 1.8 MeV

S(ρ) : moderate stiffness

A.Klimkiewicz et al., PRC76,051603(2006).

SAMURAI at RIBF

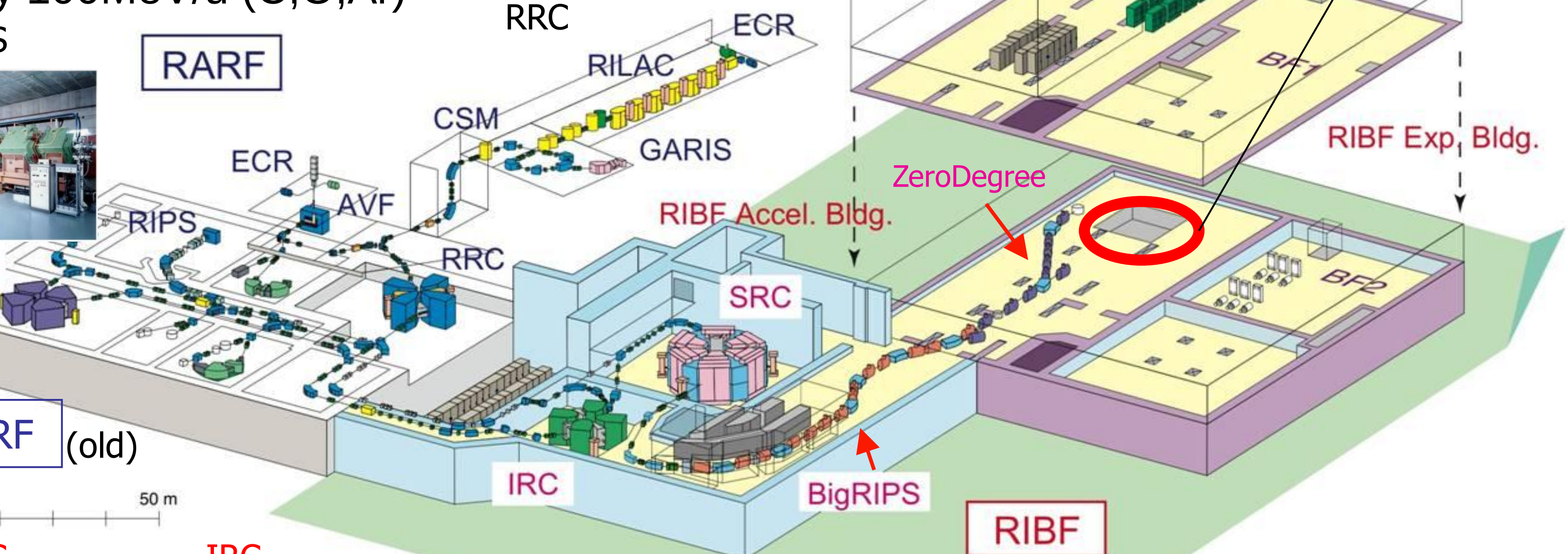


RI Beam Factory since 2007

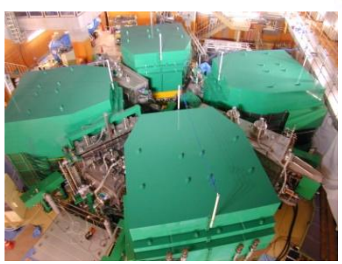
RARF since1990-
GANIL,GSI,MSU
2nd generation RI-beam
facility 100MeV/u (C,O,Ar)


RRC

RIPS

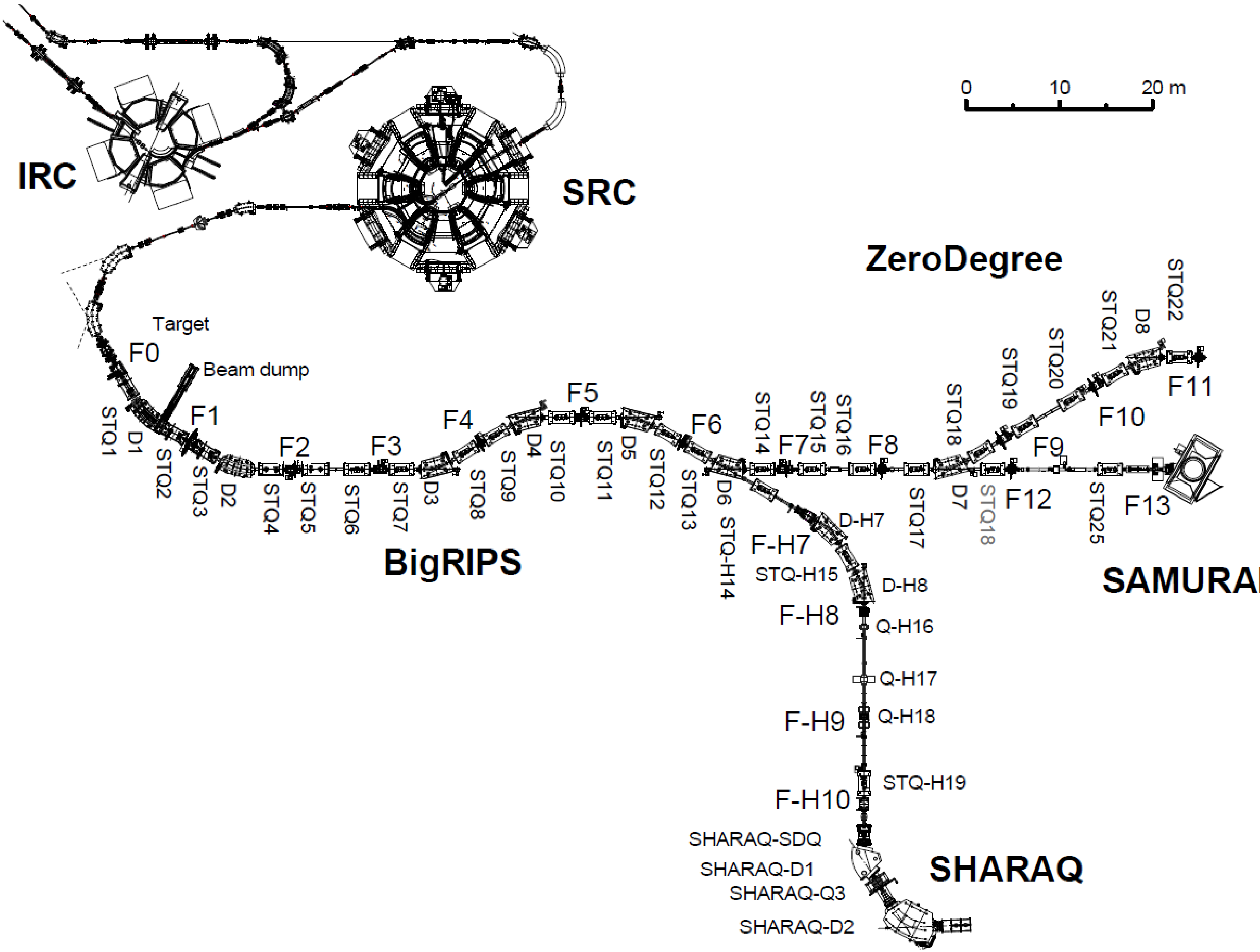



fRC


IRC



SRC

RI-beam Factory 2007-
World largest Heavy-Ion facility
3rd generation RI-Beam facility
345MeV/u up to ^{238}U
+ Large Acceptance Fragment
Separator **BigRIPS**

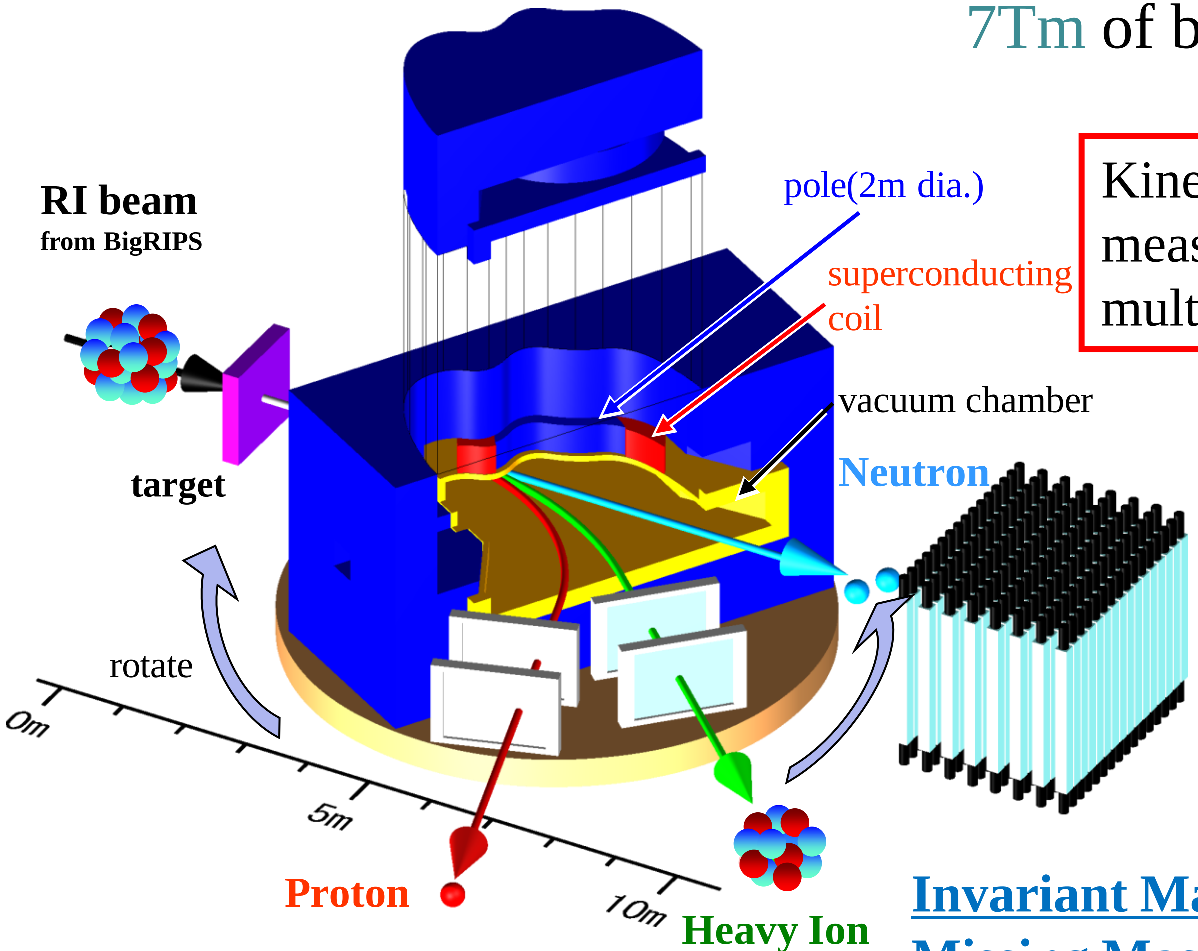


0
10
20 m
IRC
SRC
ZeroDegree
Target
F0
Beam dump
F1
F2
F3
F4
F5
F6
F7
F8
F9
F10
F11
F12
F13
STQ1
D1
STQ2
STQ3
D2
STQ4
STQ5
STQ6
STQ7
D3
STQ8
STQ9
D4
STQ10
STQ11
D5
STQ12
STQ13
D6
STQ14
STQ15
STQ16
STQ17
STQ18
D7
STQ18
STQ19
STQ20
STQ21
D8
STQ22
STQ25
BigRIPS
SAMURAI
STQ-H14
D-H7
F-H7
STQ-H15
D-H8
F-H8
Q-H16
Q-H17
F-H9
Q-H18
STQ-H19
F-H10
SHARAQ-SDQ
SHARAQ-D1
SHARAQ-Q3
SHARAQ-D2
SHARAQ

SAMURAI

-- New Spectrometer in RIBF --

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam with 7Tm of bending power

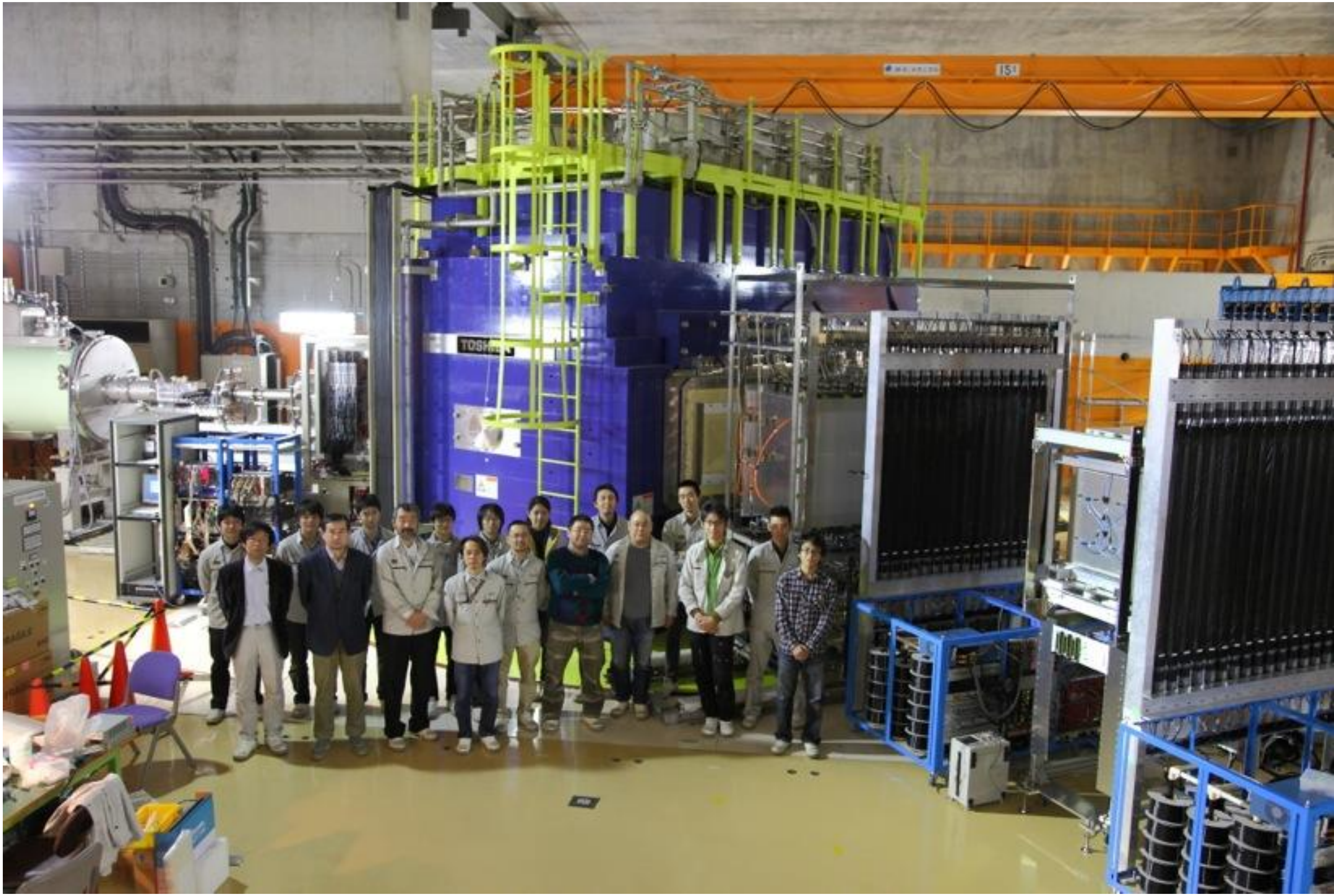


Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet
  3T with 2m dia. pole
  (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

Invariant Mass Measurement
Missing Mass Measurement

Slide: K. Yoneda



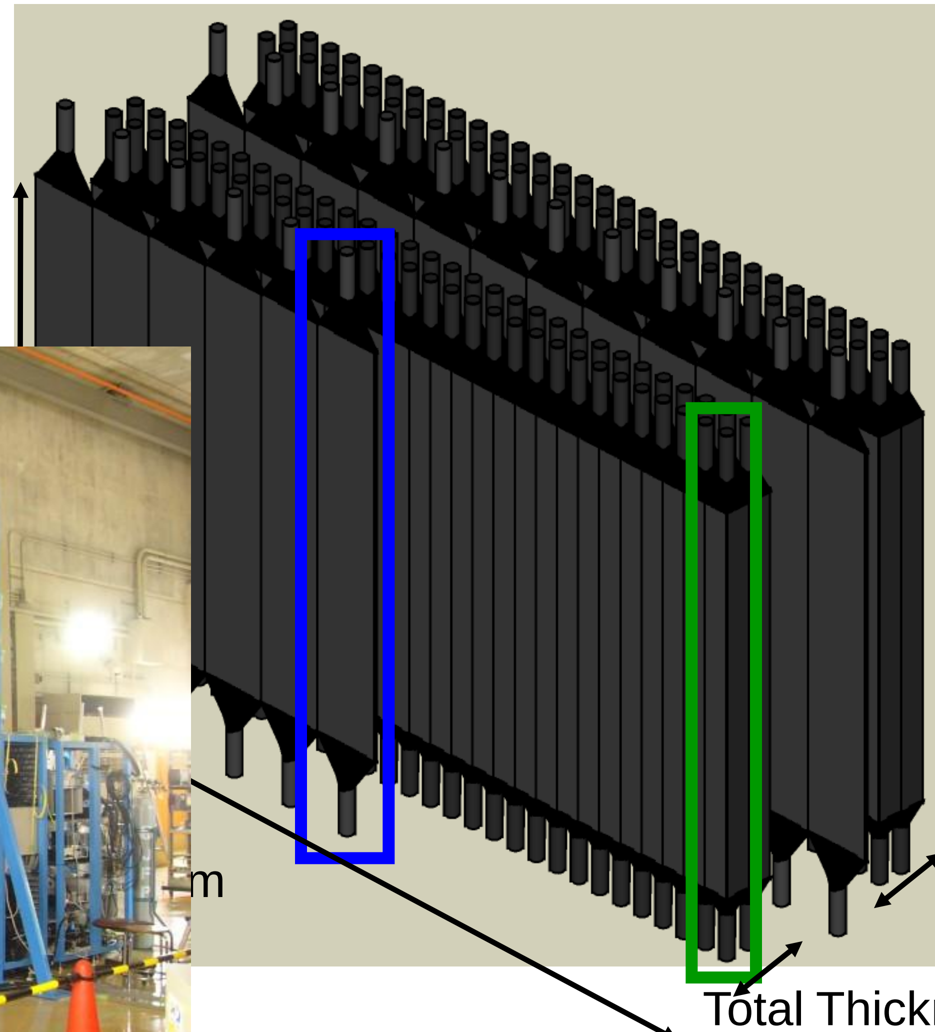
Commissioning Experiment March 2012

NEBULA

NEutron-detection system for **B**reakup of **U**nstable-nuclei with **L**arge **A**cceptance

Neutron Detectors

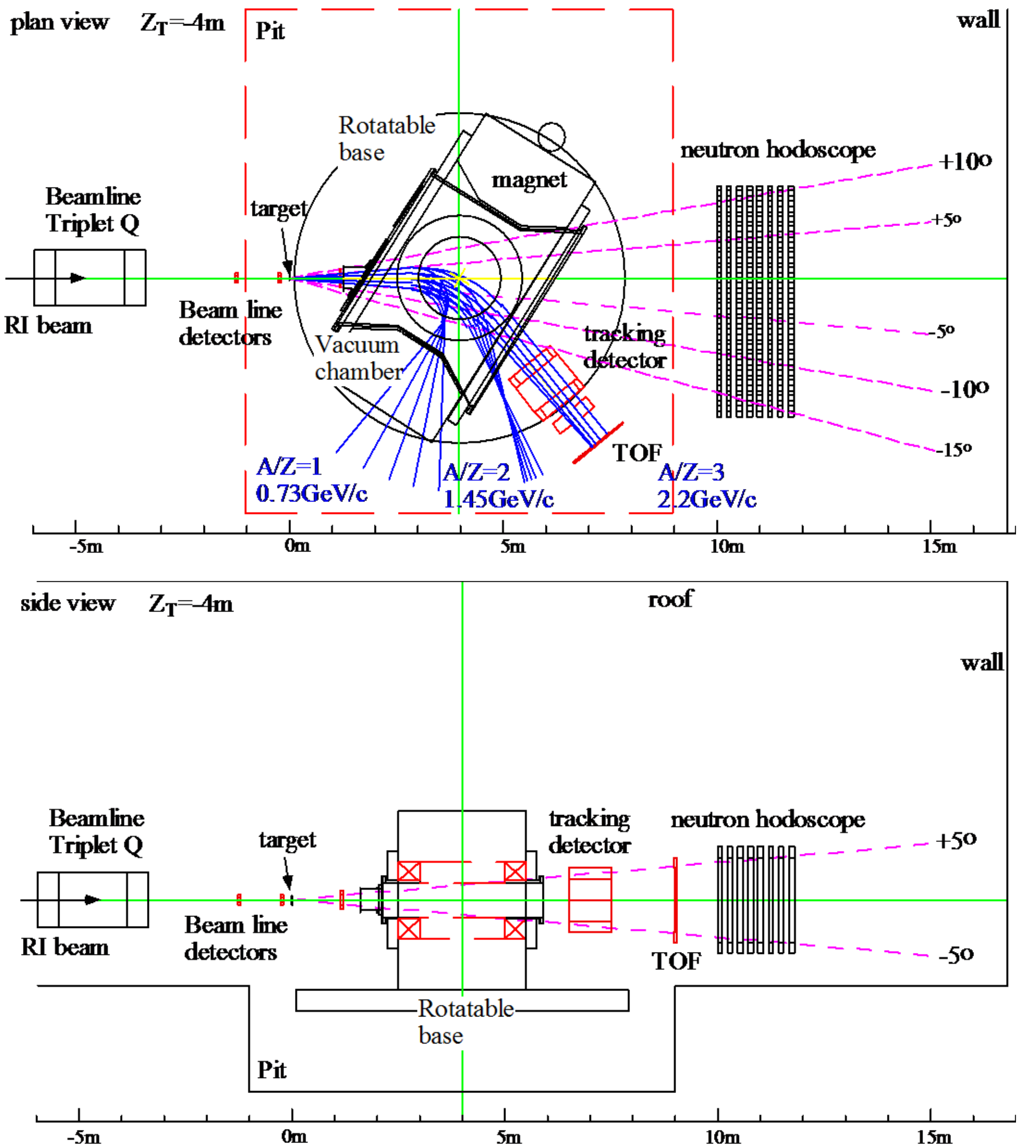
(30×2Layer) × 2Walls = 120 Modules



Total Thickness 480mm

ε(1n)~40%, ε(2n)~12%

Large acceptance



Large momentum byte

$R_{max} / R_{min} \sim 2 - 3$

(magnet rotatable)

Large angular acceptance

for neutron,

vertical – 5 degrees

horizontal – 10 degrees

(~100% coverage

up to $E_{rel} \sim 3$MeV,

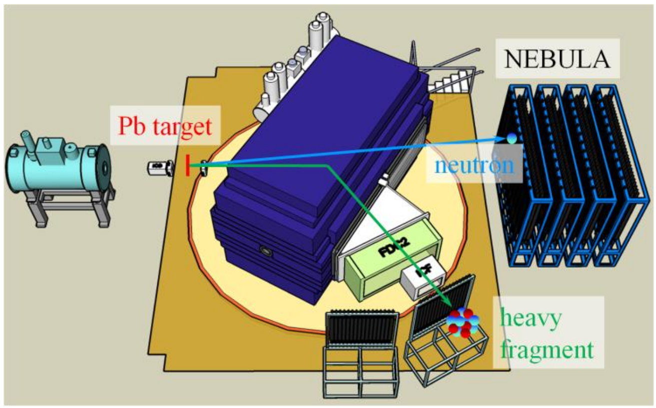
~ 50% coverage

at $E_{rel} \sim 10$ MeV)

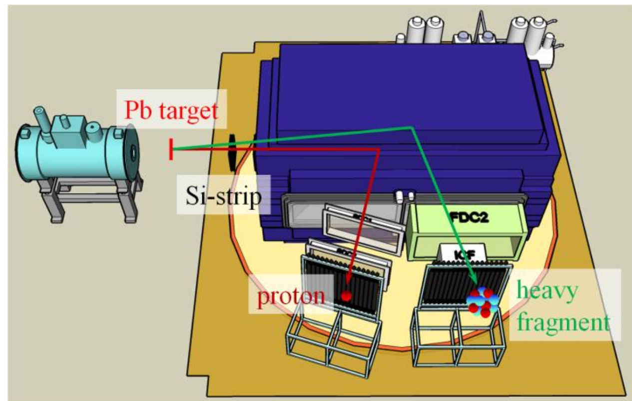
Various Configuration

SAMURAI allows a variety of modes

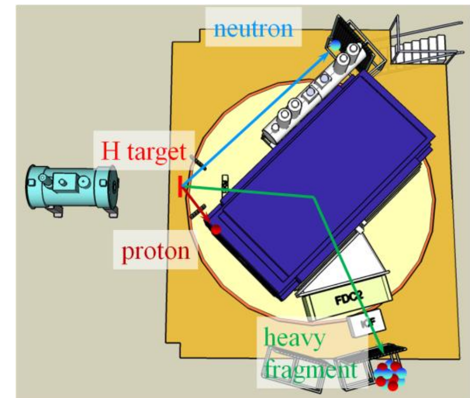
(γ, *n*) reaction: neutron-rich side



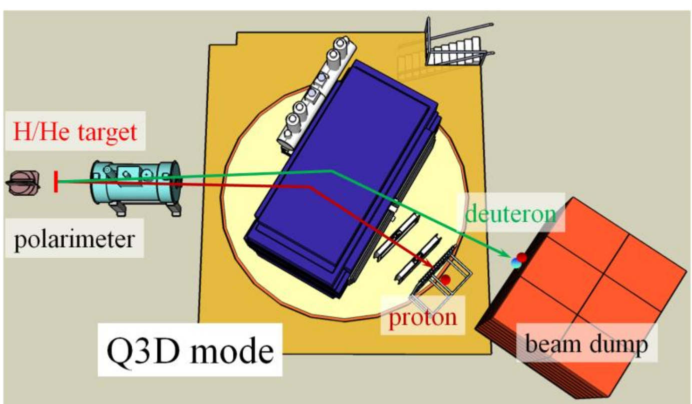
(γ, *p*) reaction: proton-rich side



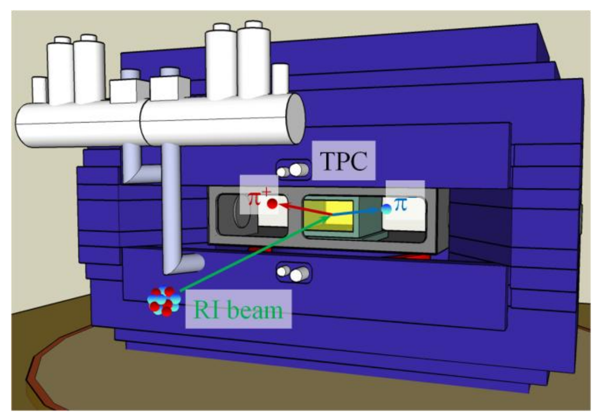
(*p*,*p'*), (*p*,2*p*), (*p*,*pn*), …



pol. *d*-induced reaction



EOS measurement



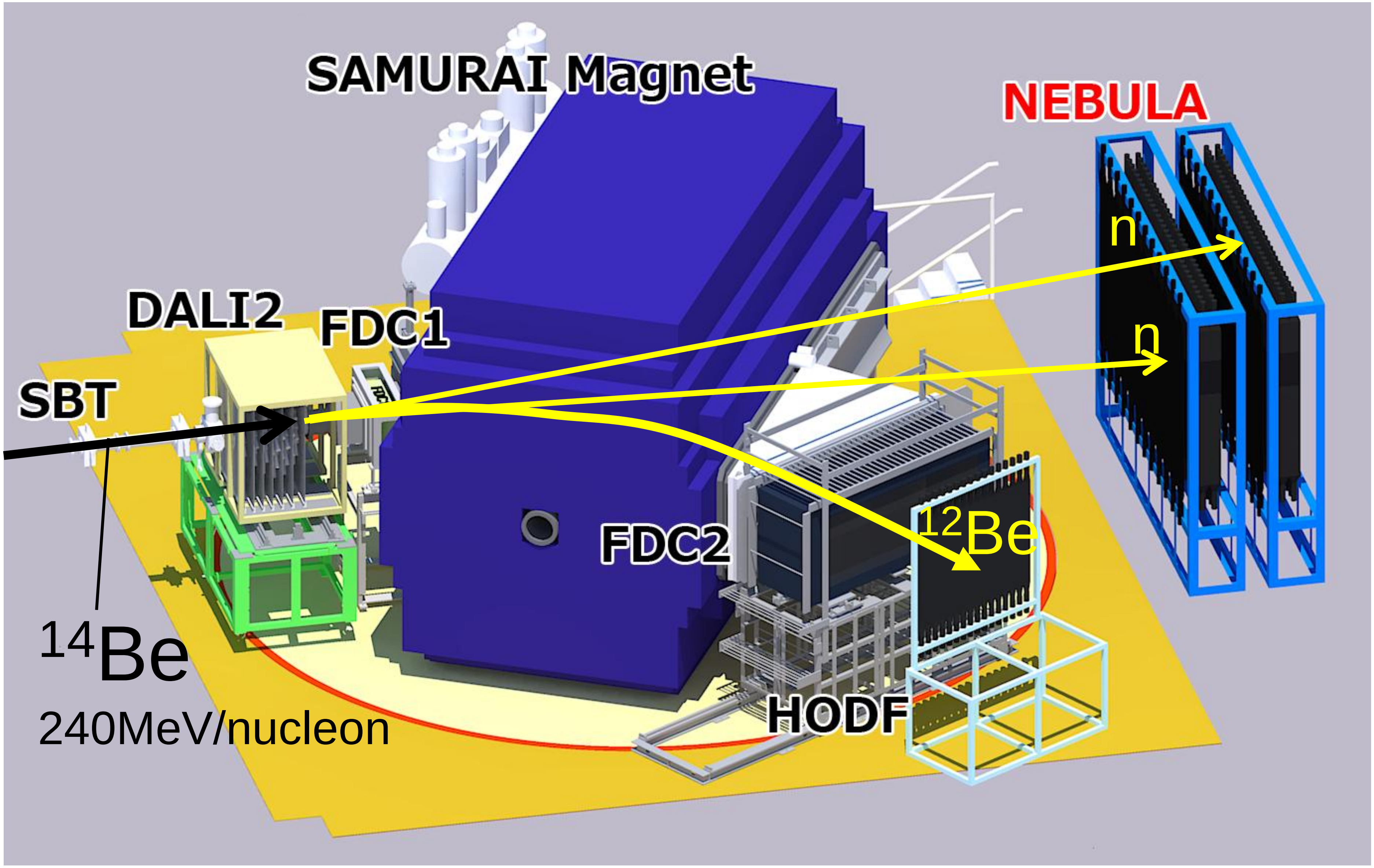
Various usage → Variety of physics subjects covered with SAMURAI

Commissioning in March 2012

- Kickoff all the detectors, DAQs for **the (γ,n) setup**
- Beam transport to SAMURAI
- Heavy ion detectors optimization
- NEBULA calibration
  - Time-zero with high-energy gamma
  - Efficiency measurement (inc. 2n cross talk) with ^{7}Li(p,n) reaction
- Brho scan for rigidity calibration
- HI-neutron coincidence measurement
  - $^{17}C \rightarrow {}^{16}C$+n ^{15}B+n
  - $^{15}C \rightarrow {}^{14}C$+n
  - $^{14}Be \rightarrow {}^{12}Be$+2n

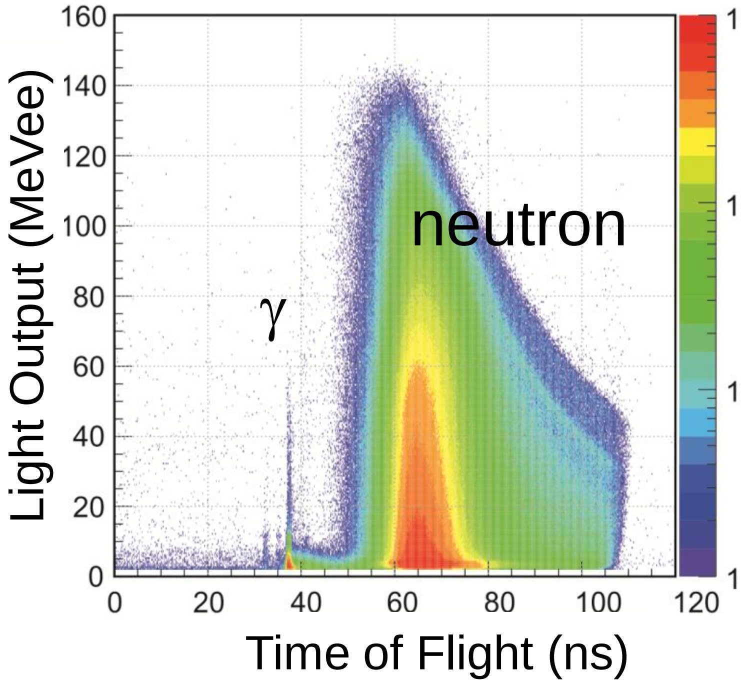
Everything worked perfectly !!

Commissioning Experiment Mar/2012

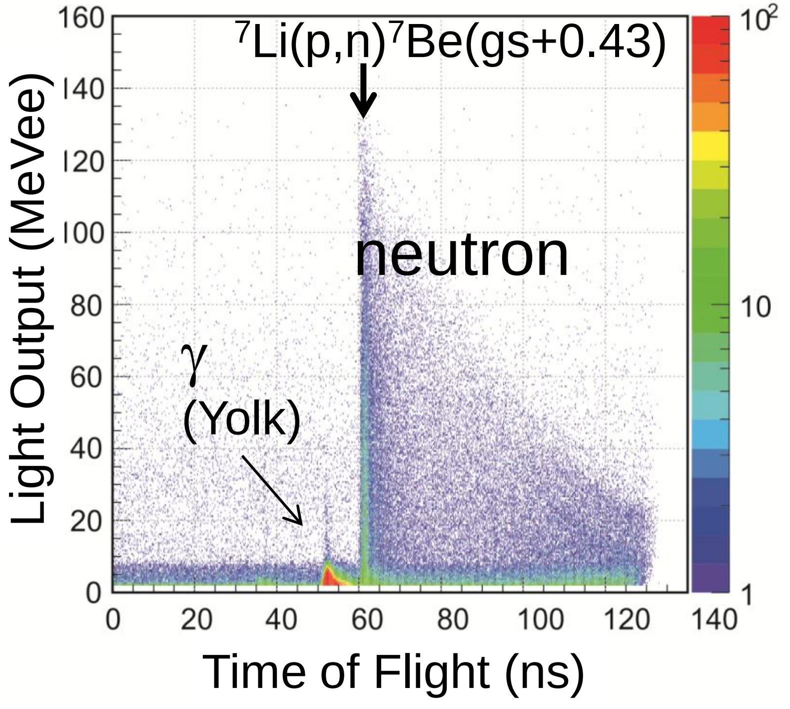


Spectra from NEBULA

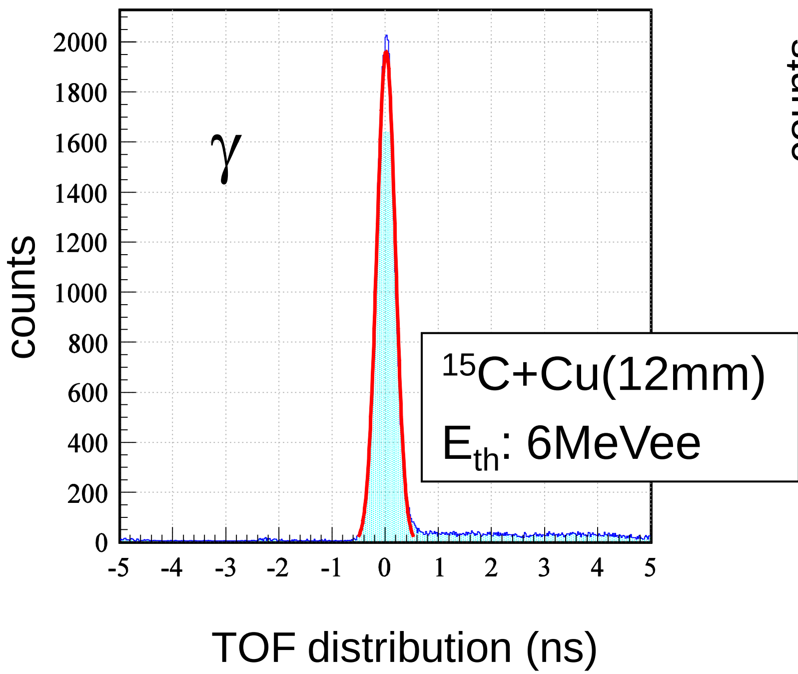
^{15}C(200MeV/u) + Cu(12mm)

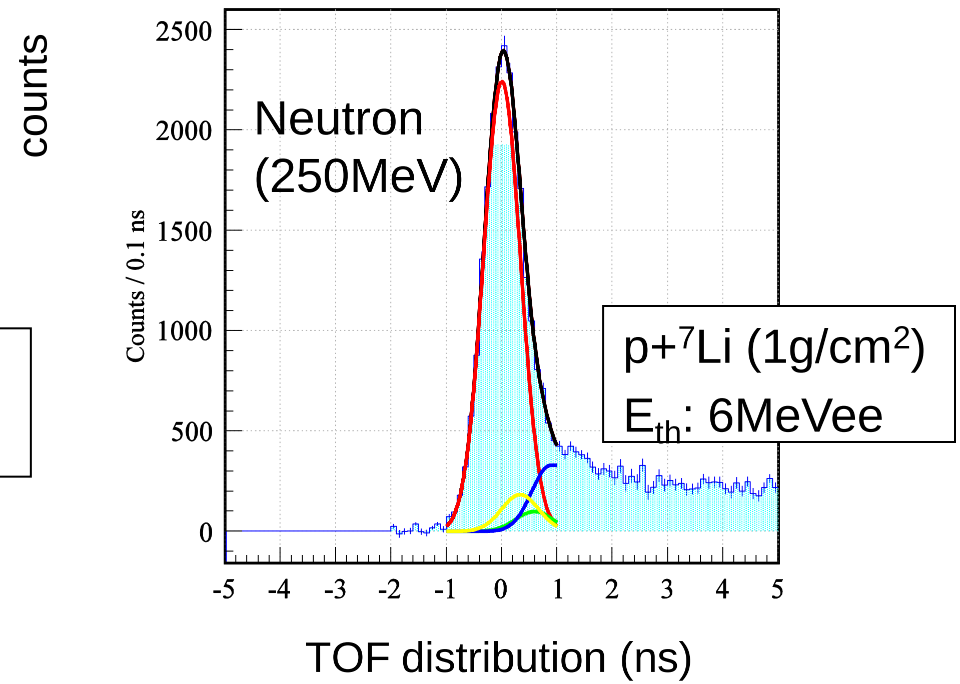


p(250 MeV)+^{7}Li(1g/cm^2)→ n



TOF resolution of NEBULA





σ_t = 171(1) ps

σ_t = 257(8) ps
(Including flight path difference ~190ps)

Day-One Experiments

May 5 – 28, 2012

- **“Spectroscopy of unbound oxygen isotopes”**
  - Spokesperson: Yosuke Kondo (Tokyo Tech)
  - Observation of unbound oxygen isotopes ^{25}O,^{26}O
- **“Exclusive Coulomb Breakup of neutron drip-line Nuclei”**
  - Spokesperson: Takashi Nakamura (Tokyo Tech)
  - Coulomb breakup of neutron-rich boron and carbon isotopes
- **“Structure of $^{18,19}B$ and $^{21,22}C$”**
  - Spokesperson: Nigel Orr/Julien Gibelin (LPC-Caen)
  - Observation of unbound states in neutron-rich B and C isotopes

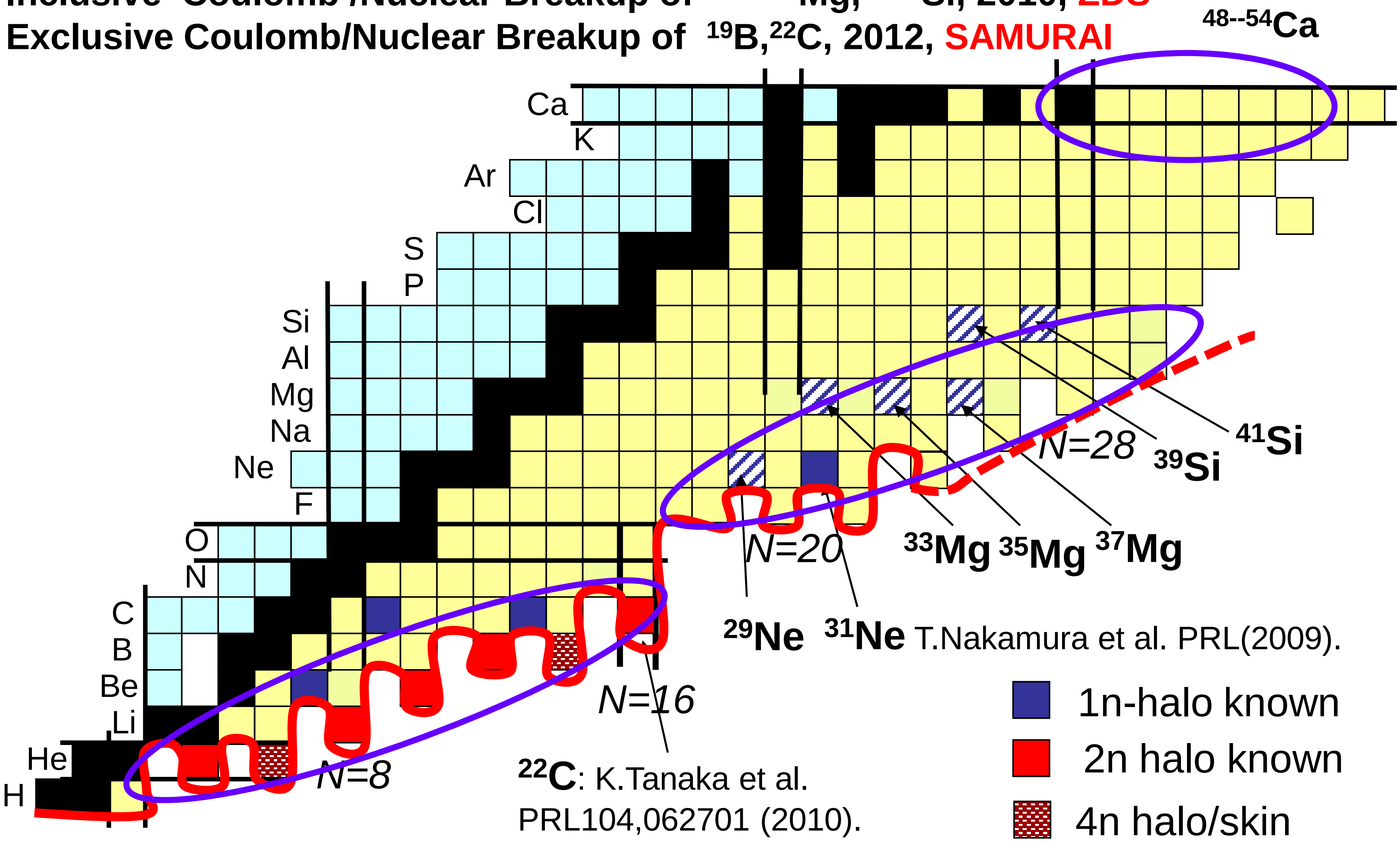
・ Successfully done

・ Data analysis is now going on

Coulomb Breakup (2008~ 2014)

Soft Dipole/ Pygmy Dipole

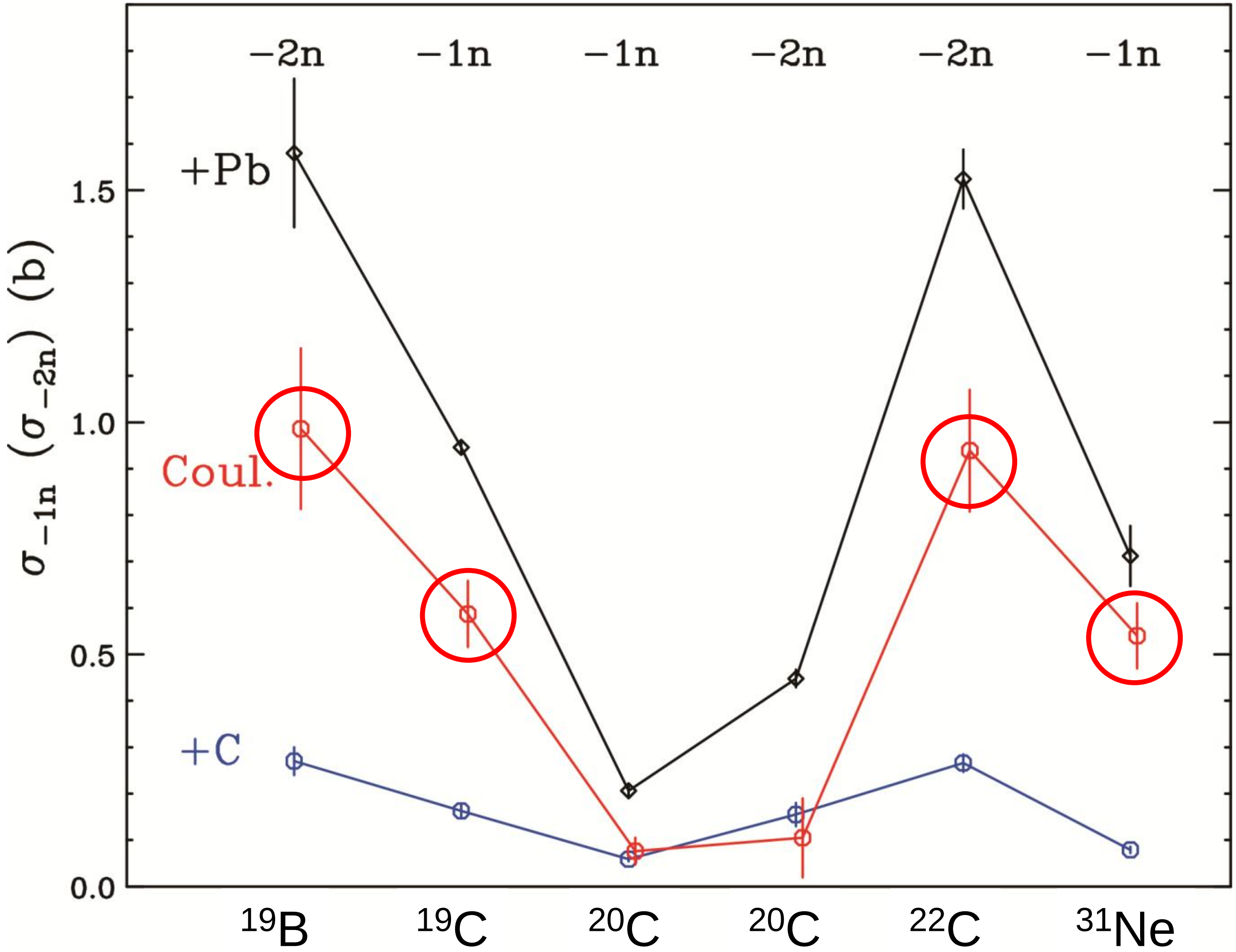
Inclusive Coulomb/Nuclear Breakup of ^{19}B,^{22}C,^{31}Ne, 2008, ZDS
Inclusive Coulomb /Nuclear Breakup of ^{33,35,37}Mg,^{39,41}Si, 2010, ZDS
Exclusive Coulomb/Nuclear Breakup of ^{19}B,^{22}C, 2012, SAMURAI



ZDS in 2008/2010:

T.Nakamura et al., PRL103,262501(2009)
N.Kobayashi, T.N. et al., arXiv1111.7196v1[nucl-ex]

"Inclusive" Coulomb breakup cross section



Evidence for

2n Halo in ^{22}C

1n Halo in ^{31}Ne

c.f. ^{19}C (known halo)

2n Halo in ^{19}B :
First Measurement

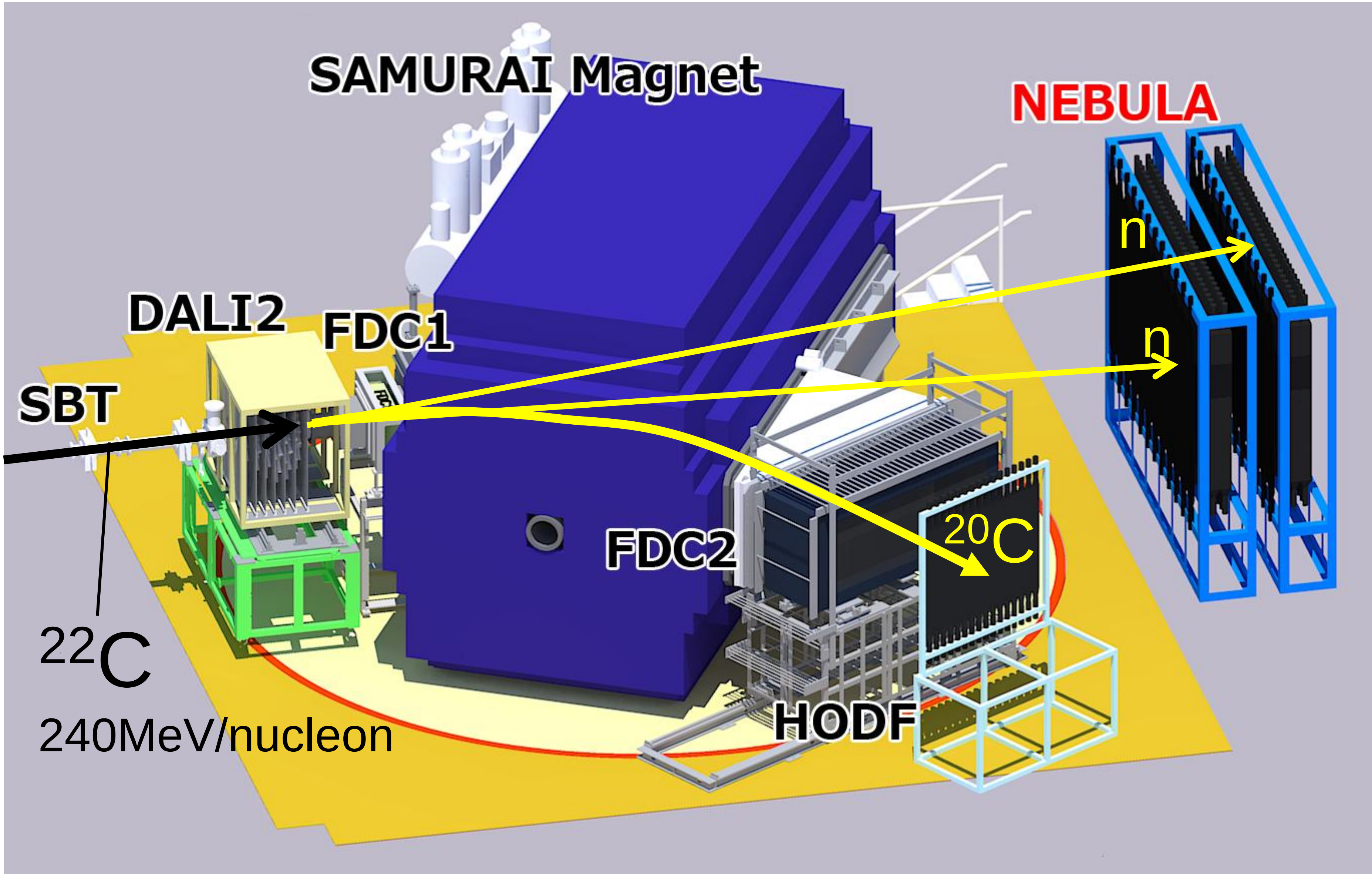
$$\sigma(E1) = \sigma(Pb) - \Gamma\sigma(C)$$

$$\Gamma = \sim 1.7 - 2.6$$

c.f. ^{22}C: Reaction cross section, K.Tanaka et al.PRL104,062701 (2010).
^{31}Ne: Reaction cross section, M. Takechi et al.PLB707, 357 (2012).

SAMURAI Experiment May/2012

First Full Exclusive Coulomb/Nuclear Breakup Measurement of ^{22}C and ^{19}B



Online Spectra from Breakup Exp.@ SAMURAI May/2012

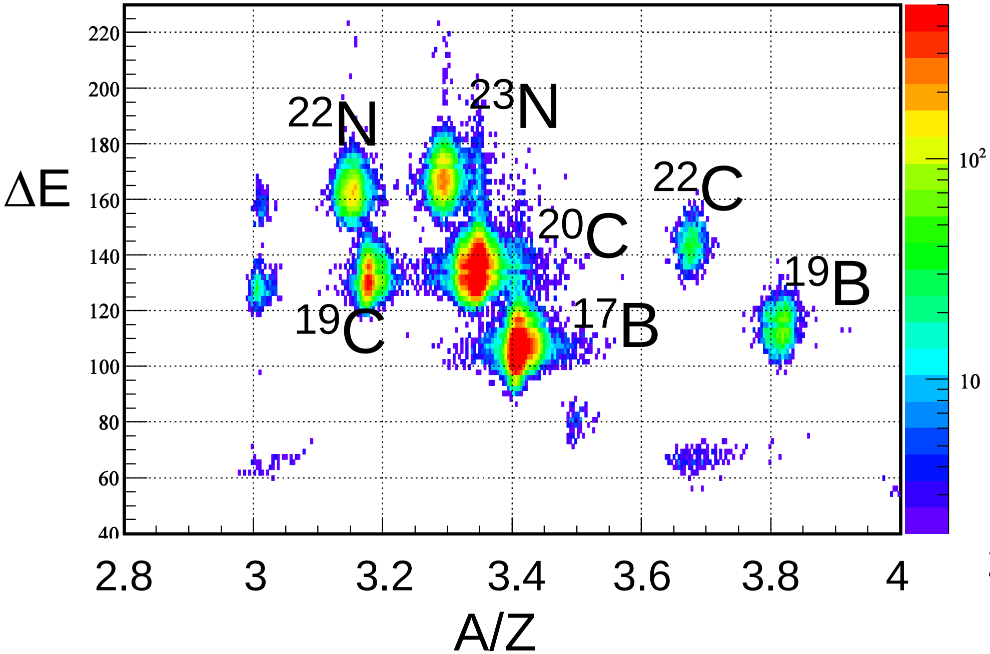
^{48}Ca 150~200pnA (Max 250pnA)

^{22}C+Pb/C→^{20}C+n+n

^{19}B+Pb/C→^{17}B+n+n

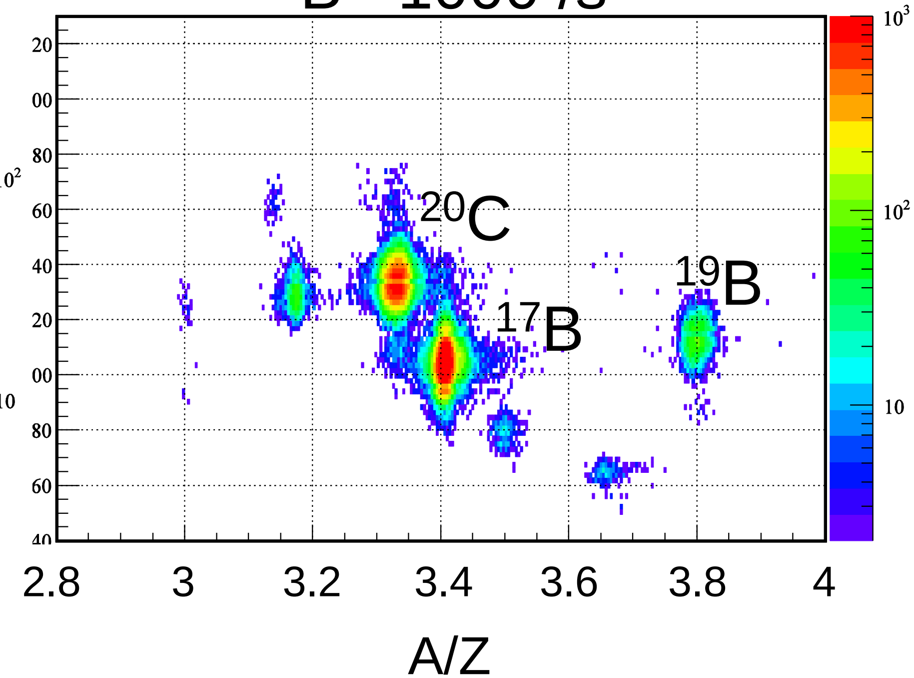
^{22}C ~15 /s

^{23}N ~100 /s



^{19}B ~100 /s

^{17}B ~1000 /s



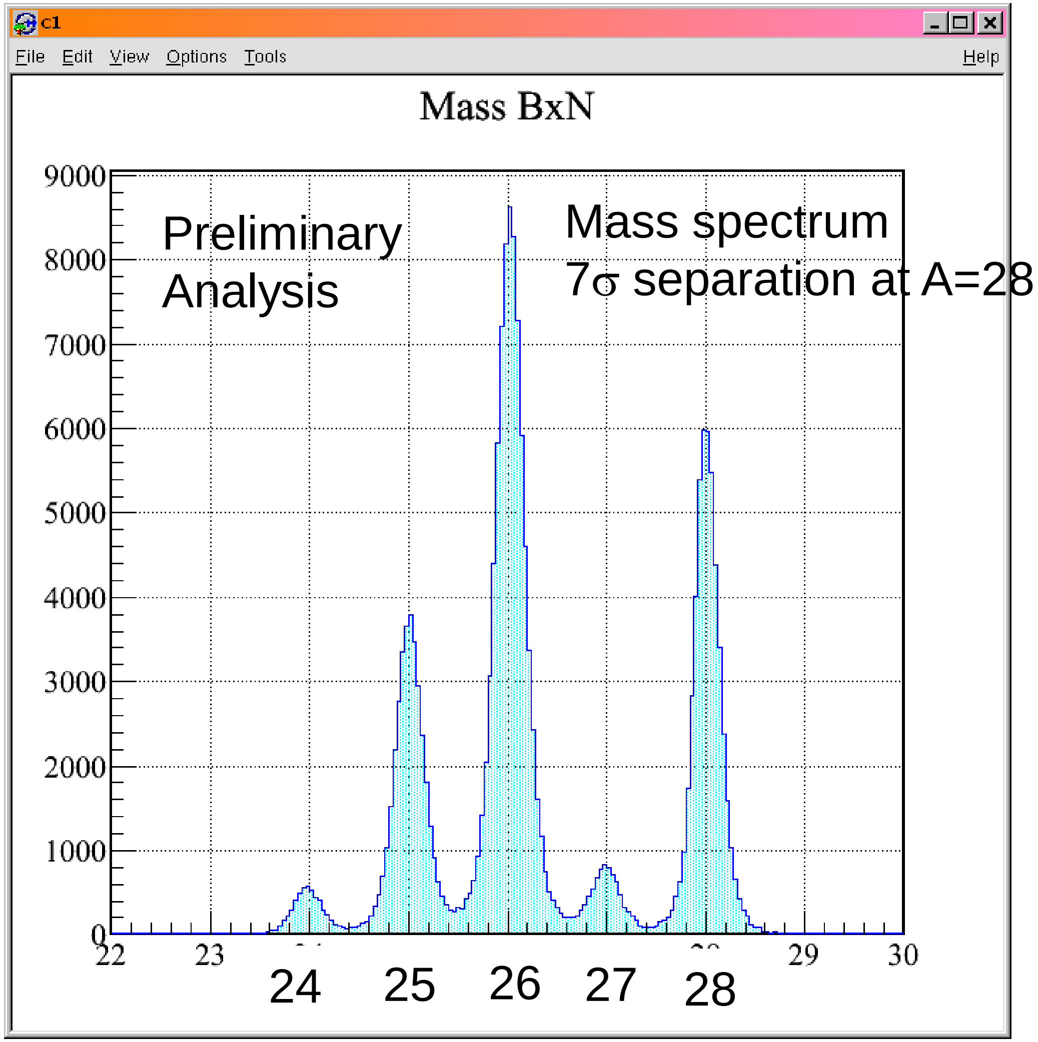
<u>High intense RIBF Beam</u>

^{22}C: **~15/s** (*c.f. 10/hour K.Tanaka,PRL2010, RIPS@RIKEN)*

Gain of ~5000!

PI Spectra at SAMURAI (May, 2012, SAMURAI/RIBF, Kondo et al)

$^{28}Ne \rightarrow {}^{A}Ne + X$



Courtesy of
Y.Kondo

neutron trigger

Summary

1 Nuclear Physics at the Limit → Breakup Reactions

Coulomb Breakup

- **Soft E1 Excitation for Halo Nuclei**

spectral-Shape, Strength of B(E1) ---- Sensitive to ℓ ,S_n,C^2S

di-neutron like correlation

c.f. T.Nakamura, Y.Kondo, p.67, Clusters in Nuclei Vol.2 (C.Beck Ed)
Lecture Notes in Physics **848**, Springer, Berlin (2012).

- Pygmy Dipole Resonance ---- Sensitive to Neutron Skin/EOS

2 SAMURAI at RIBF: Multi-purpose Wide-Acceptance Spetrometer for Unstable Nuclei

3 Commissioning Experiment: Check Basic Specifications --- Successful

4 Day-1 Experiments: Coulomb Breakup/Unbound Oxygen/ ^{21}C/^{18}B etc. ---- Successful

Construction Members

T. Kobayashi (Tohoku) ・Spokesperson
T. Motobayashi (RIKEN)・Co-spokesperson
K. Yoneda (RIKEN) ・Project manager

Construction Team Member (*Leader)

Magnet and Infrastructure:	H. Sato*, K. Kusaka, J. Ohnishi, H. Okuno, T. Kubo (RIKEN)
Vacuum system and Utilities:	H. Otsu*, Y. Shimizu (RIKEN)
Heavy ion detectors:	Y. Matsuda (Kyoto), K. Sekiguchi, N. Chiga, graduate students, T. Kobayashi* (Tohoku), H. Otsu (RIKEN)
Neutron detectors (NEBULA):	T. Nakamura*, Y. Kondo, Y. Kawada, T. Sako, R. Tanaka (Tokyo Tech), Y. Satou (Seoul National Univ.)
Proton detectors:	K. Yoneda*, Y. Togano, M. Kurokawa, A. Taketani, H. Murakami, T. Motobayashi (RIKEN), K. Kurita (Rikkyo), T. Kobayashi (Tohoku), L. Trache (Texas A&M) and the TWL collaboration
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Grazie Mille!