Symmetry-energy Studies using the SAMURAI Facility at RIBF

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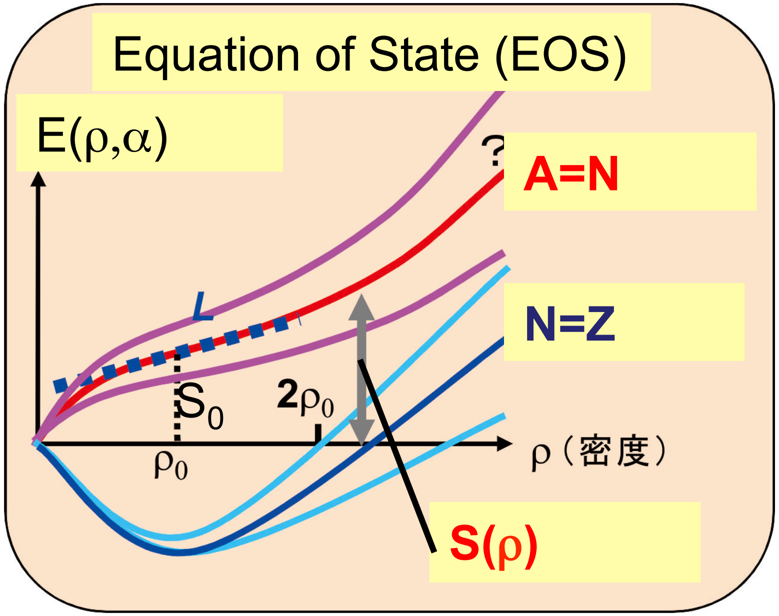
SAMURAI NAKAMURA GRP.

NuSYM13, July 22-26, 2013, MSU, USA

Contents

SAMURAI

EOS of Nuclear Matter



Difference of n and p densities

$$E(\rho,\alpha) = E(\rho,0) + S\alpha^2 + \dots \qquad \alpha = \frac{\rho_n - \rho_p}{\rho_0} \approx \frac{N-Z}{A}$$

$$S(\rho) = S_0 + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \dots$$

Symmetry Energy: S(ρ)→ **Neutron Star**

- **Nuclear Force (NN,3N)**
- **Many-body Correlations** (Superfluidity(pairing), π condensation …)

-- Wide range of **Density** $10^{-3}\rho_0$ --- $10\rho_0$ -- **Density Dependence**

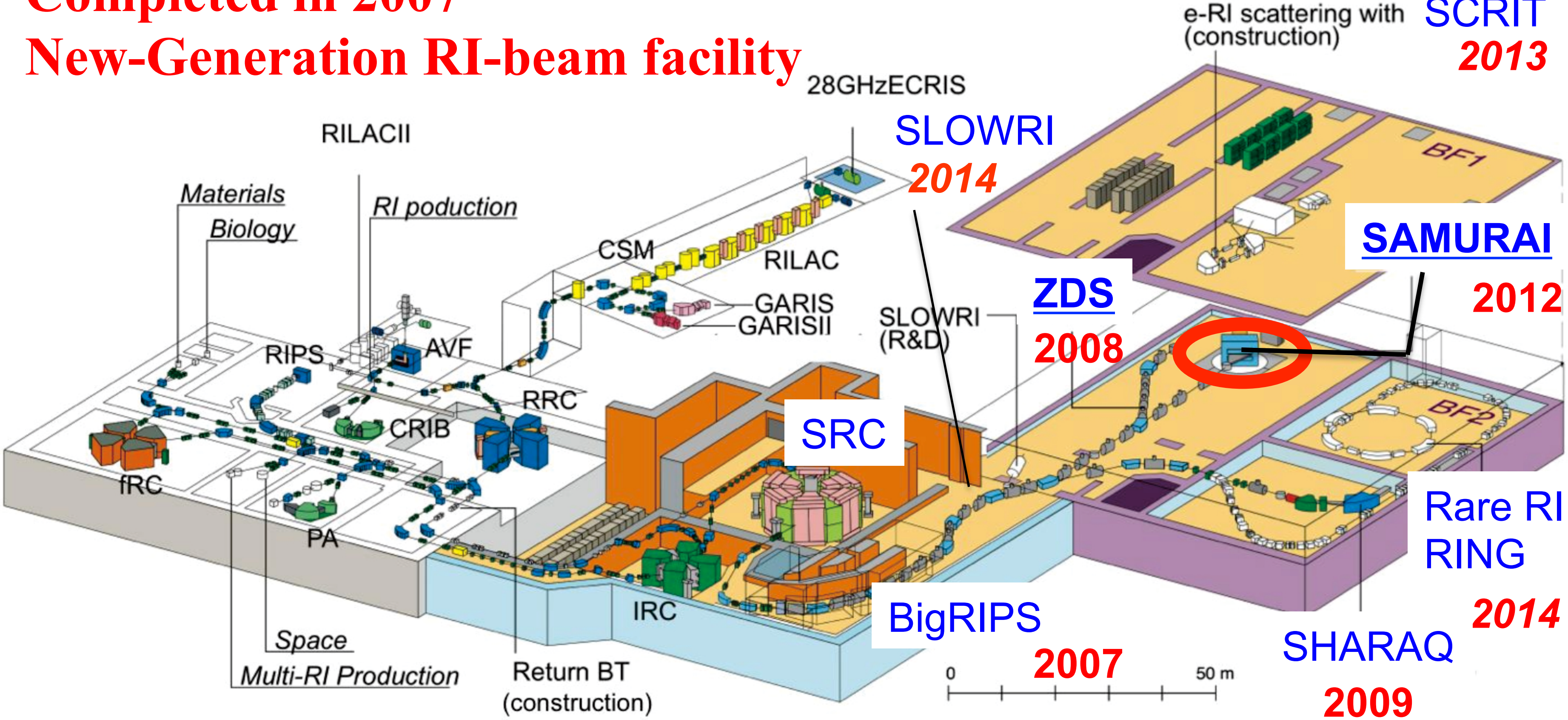
-- **Asymmetric nuclear matter** N>>Z -- **Isospin Dependence**

Neutron-rich Nuclei

→Microscopic Laboratory for Neutron-Star Physics

RIKEN RI Beam Factory (RIBF)

Completed in 2007
New-Generation RI-beam facility



SRC: World Largest Cyclotron (K=2500 MeV)

Heavy Ion Beams up to ^{238}U at 345MeV/u (Light Ions up to 440MeV/u)

eg.

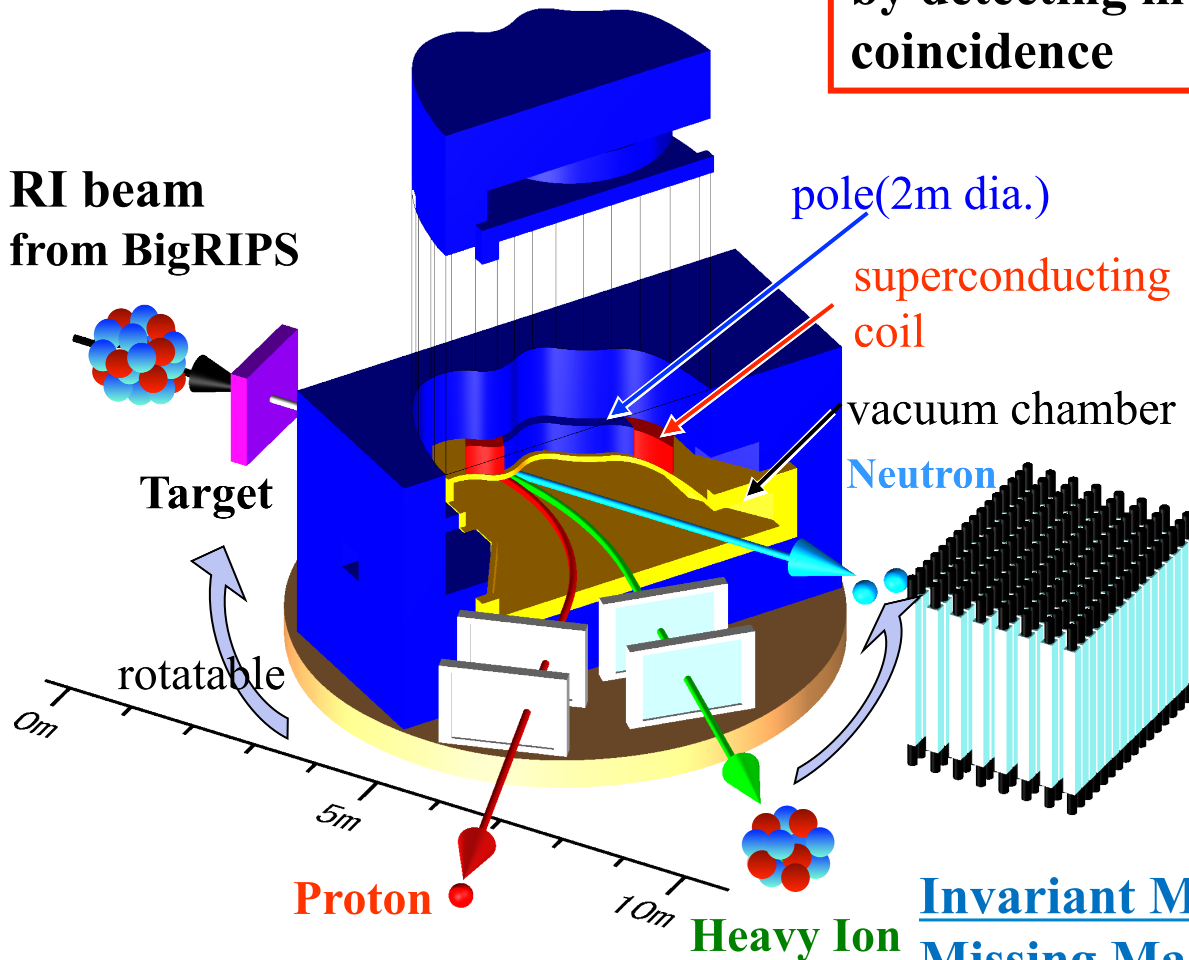
^{48}Ca beam (345 MeV/nucleon) ~200pnA (415 pnA max.)

^{238}U beam (345 MeV/nucleon) ~12pnA (15 pnA max.)

SAMURAI

Superconducting Analyzer for MUlti-particle from RAdio Isotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence



- **Superconducting Magnet**
  3T with 2m dia. Pole
  (designed resolution 1/700)
  80cm gap (vertical)
  Large Acceptance
  ±5 deg.(V) ±10 deg.(H)
  $B\rho_{max}/B\rho_{min}$~2--3
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors(**NEBULA**)
- Large Vacuum Chamber
- Rotational Stage

Invariant Mass Measurement

Missing Mass Measurement

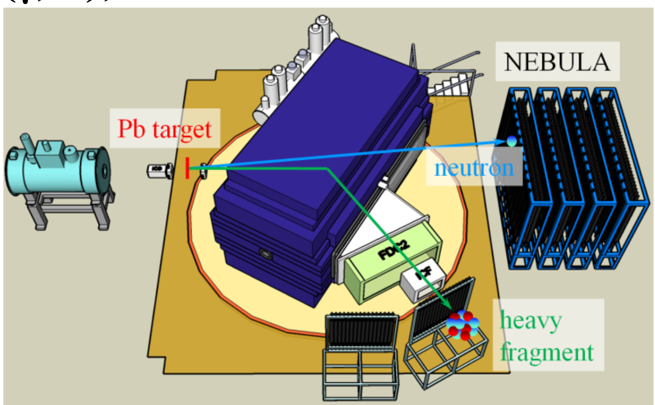
SAMURAI

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

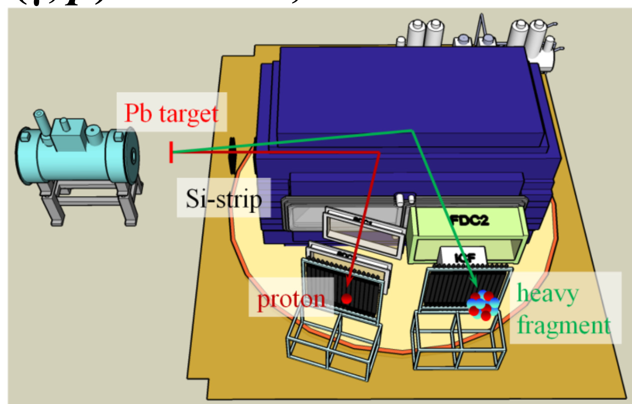
Various Configuration

SAMURAI allows a variety of modes

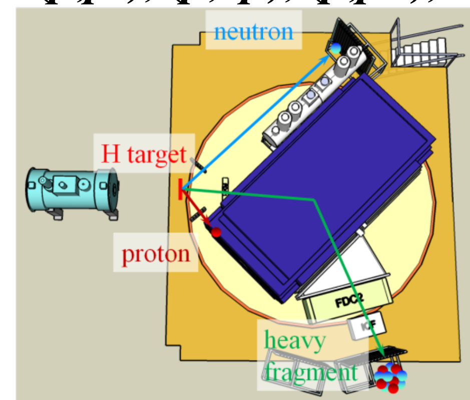
xn+HI (neutron-rich side)
(γ, *n*), unbound nuclei…



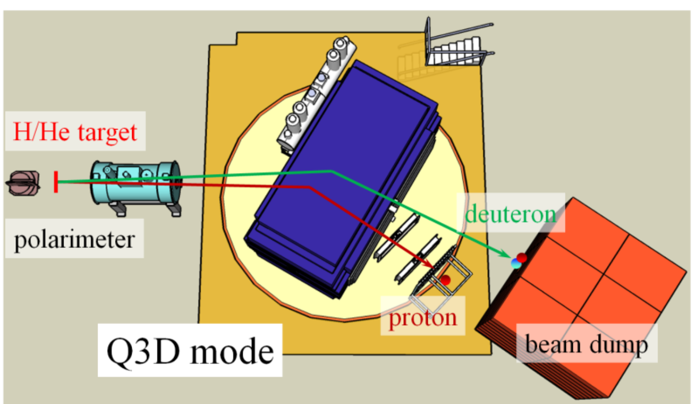
p+HI (proton-rich side)
(γ, *p*) reaction,…



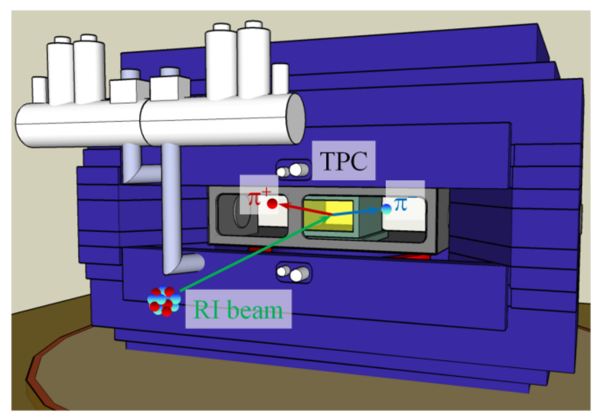
p,n(target frame)+HI
(*p*,*p'*), (*p*,2*p*), (*p*,*pn*), …



pol. *d*-induced reaction



EOS measurement

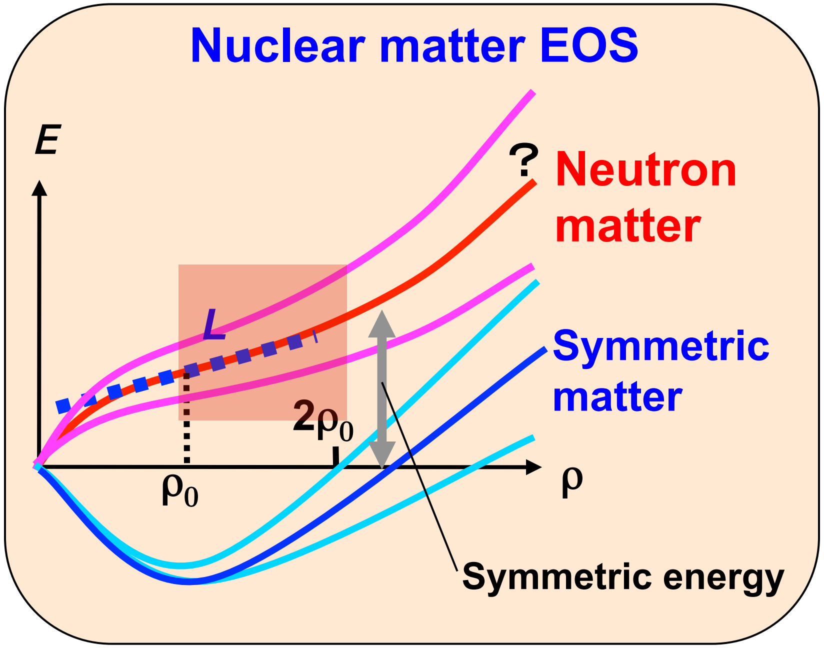


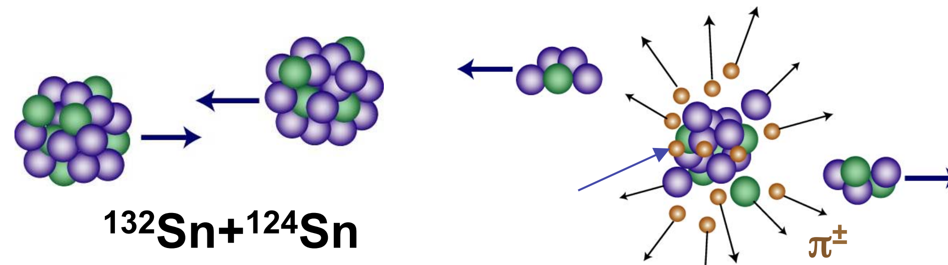
Various usage → Variety of physics subjects covered with SAMURAI

Projects at SAMURAI-I

EOS of high-density n-rich matter

Density dependence of symmetry energy in $\rho \sim 2\rho_0$ region

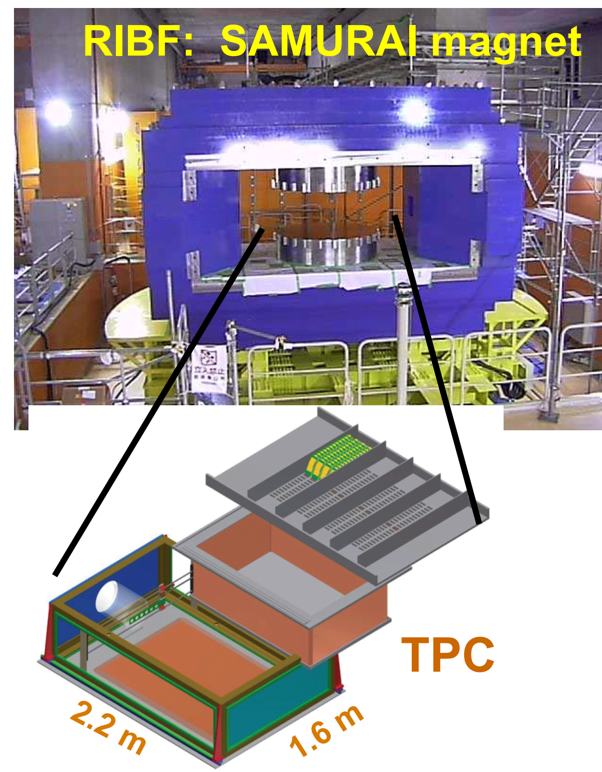




$^{132}Sn + ^{124}Sn$
$^{108}Sn + ^{112}Sn$
@ 250-300 MeV/u

n-rich high-density matter

W.Lynch,
T.Murakami,
B.Tsang et al.



Measure π^+/π^- yields from A-A collisions of various nuclei with various proton/neutron ratios

⇩

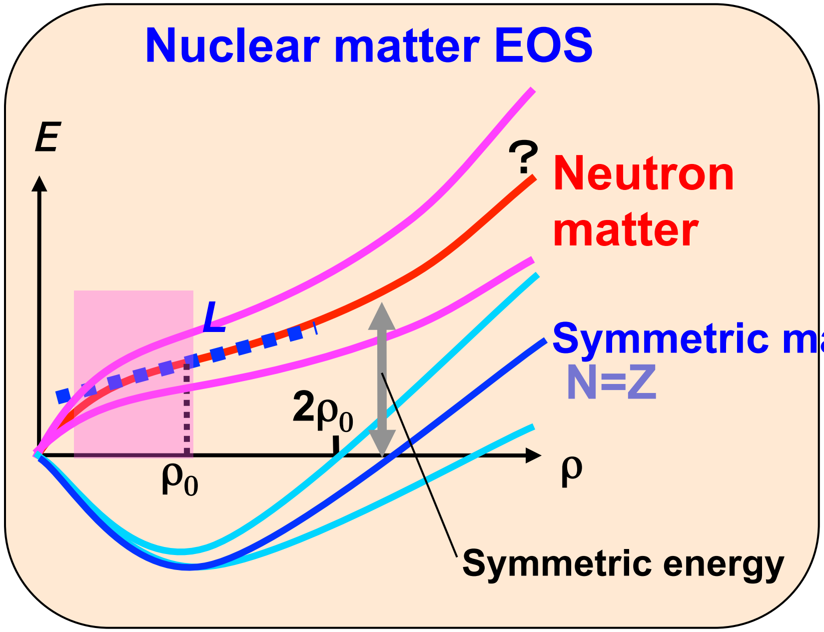
Information on symmetric energy for $\rho \sim 2\rho_0$ region

Detailed TALK by T.MURAKAMI (FRIDAY)

Projects at SAMURAI -II

Properties/EOS of low/medium density n-rich matter

EOS for $\rho \sim \rho_0$, $\rho < \rho_0$



Direct Reactions of n-rich nuclei

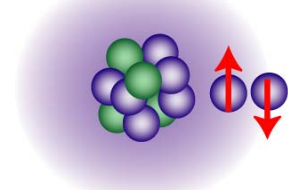
① response of n-skin nuclei

n-skin

Pigmy dipole resonance(E1)
Density oscillation (E0)

Pressure, incompressibility of EOS for n-rich matter

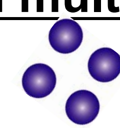
② Di-neutron correlation in low-dense neutron matter



Superfluidity (Pairing correlation)

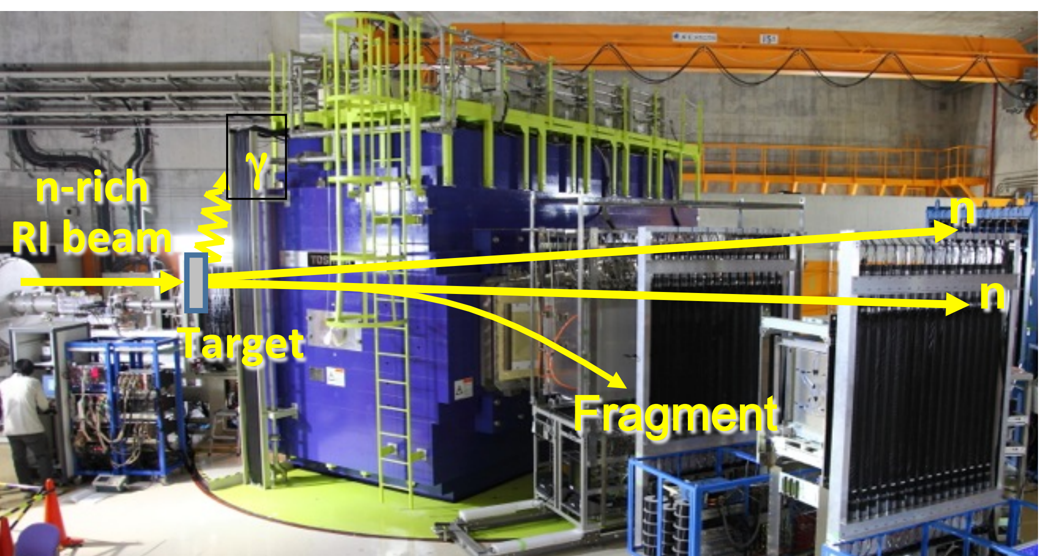
③ Unbound Nuclei / n-rich multi-nucleonic systems

4n



Nuclear force for n-rich Systems (isospin dep.)

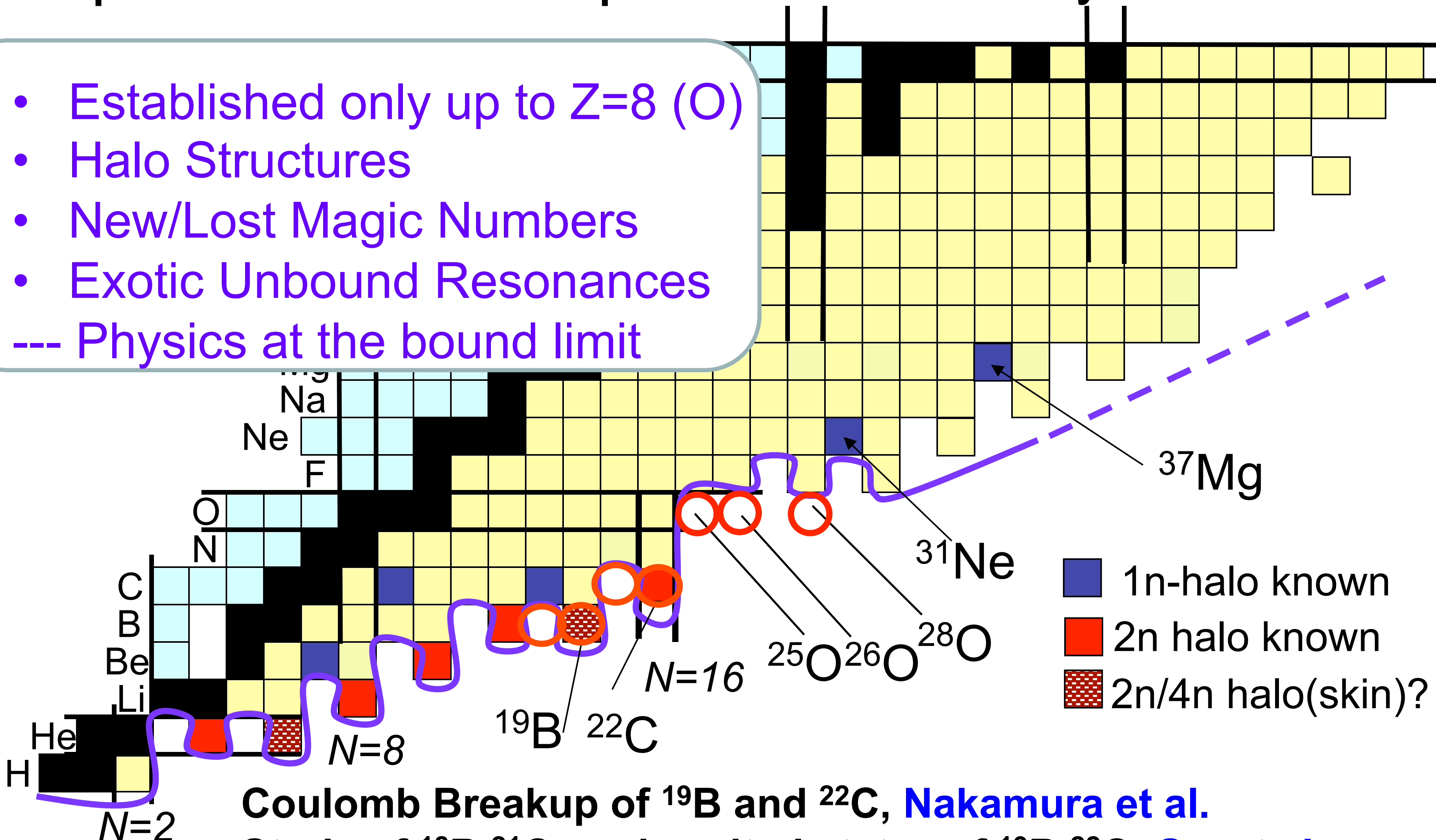
^{26,28}O etc.



Day-One Campaign Experiments at SAMURAI: Explore Neutron Drip Line --May/2012

- Established only up to Z=8 (O)
- Halo Structures
- New/Lost Magic Numbers
- Exotic Unbound Resonances

--- Physics at the bound limit



Coulomb Breakup of ^{19}B and ^{22}C, Nakamura et al.
Study of ^{18}B,^{21}C, and excited states of ^{19}B,^{22}C, Orr et al.
Structure of Unbound Oxygen Isotopes ^{25}O,^{26}O, Kondo et al.

Coulomb Breakup of ^{22}C and ^{19}B (Day-one campaign)

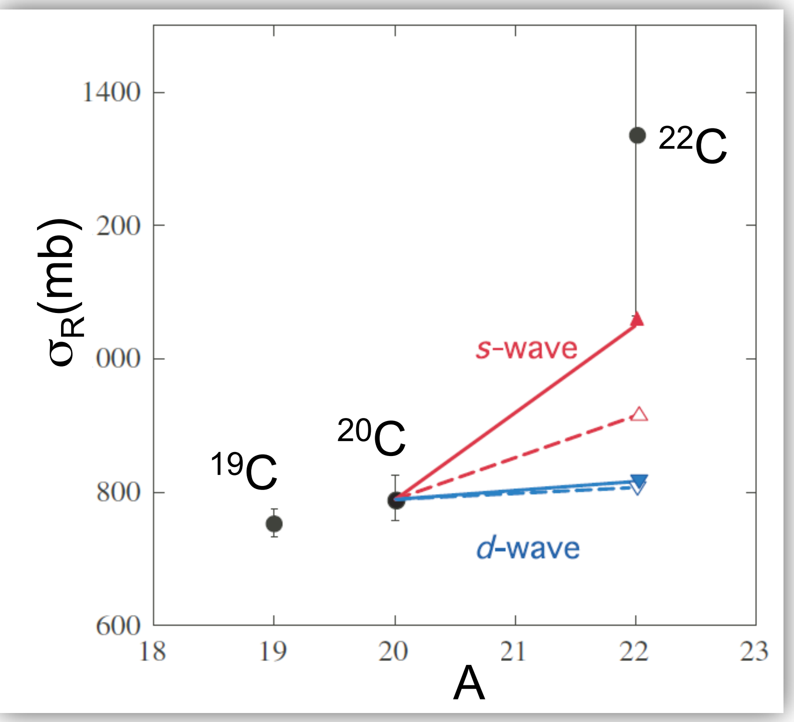
^{22}C

- ☐ Prominent 2n-Halo?

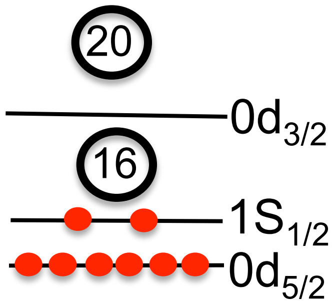
Reaction cross section measurement

$(\langle r_m^2 \rangle)^{1/2}$=5.4(9) fm   c.f. ~3.5 fm ^{11}Li

K.Tanaka et al., PRL 104, 062701(2010).



- ☐ N=16 Magicity?



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

- ☐ Heaviest s-wave dominant 2n Halo?

"Inclusive" Nuclear and Coulomb breakup at 240 MeV/nucleon

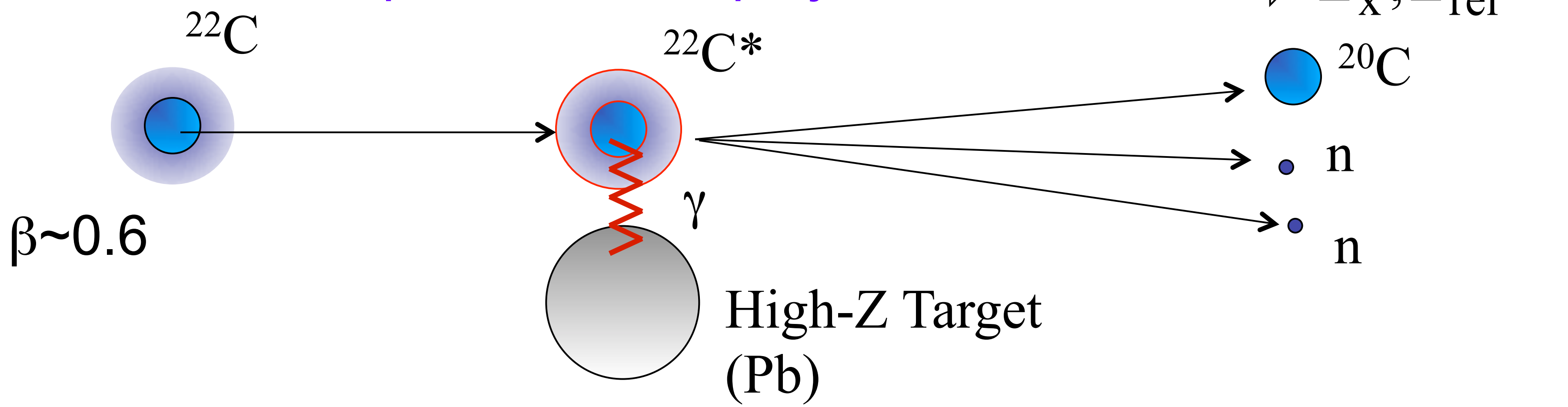
→ N=16 Magicity, 2n Halo   *N.Kobayashi et al.,PRC86, 054604 (2012).*

Coulomb Breakup

→Photon absorption of a fast projectile

$\vec{P}(n), \vec{P}(n), \vec{P}(^{20}\mathrm{C})$

Invariant Mass ⇒ E_x, E_{rel}

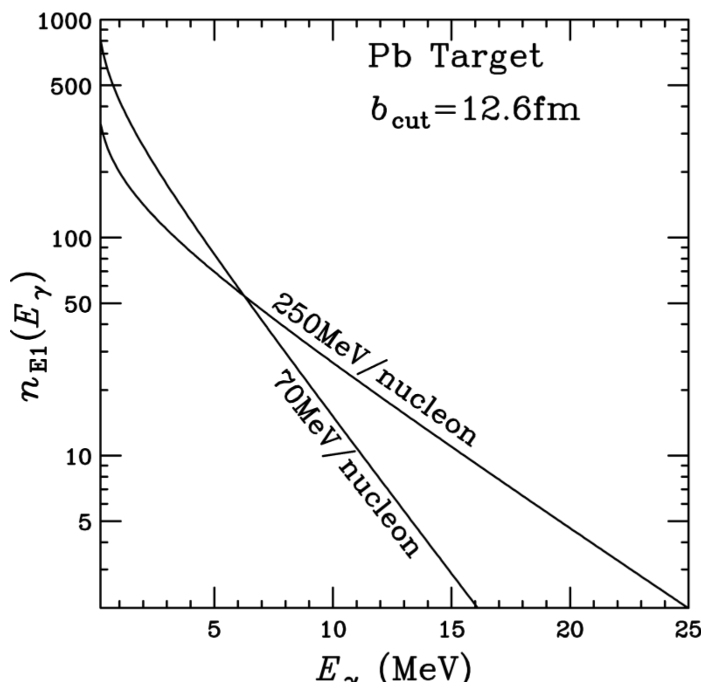


Equivalent Photon Method

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

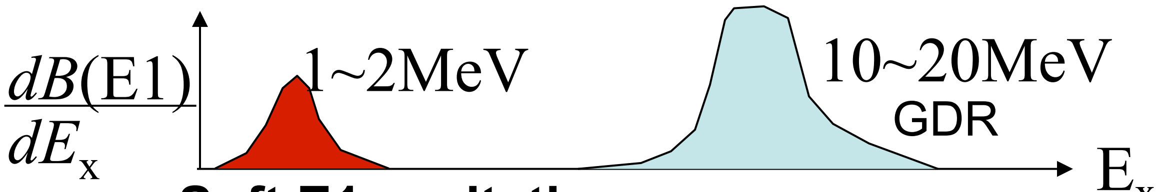
Cross section = (Photon Number)x(Transition Probability)

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



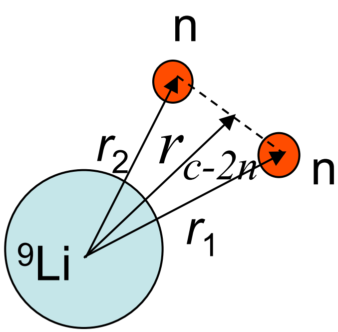
Dineutron Correlation

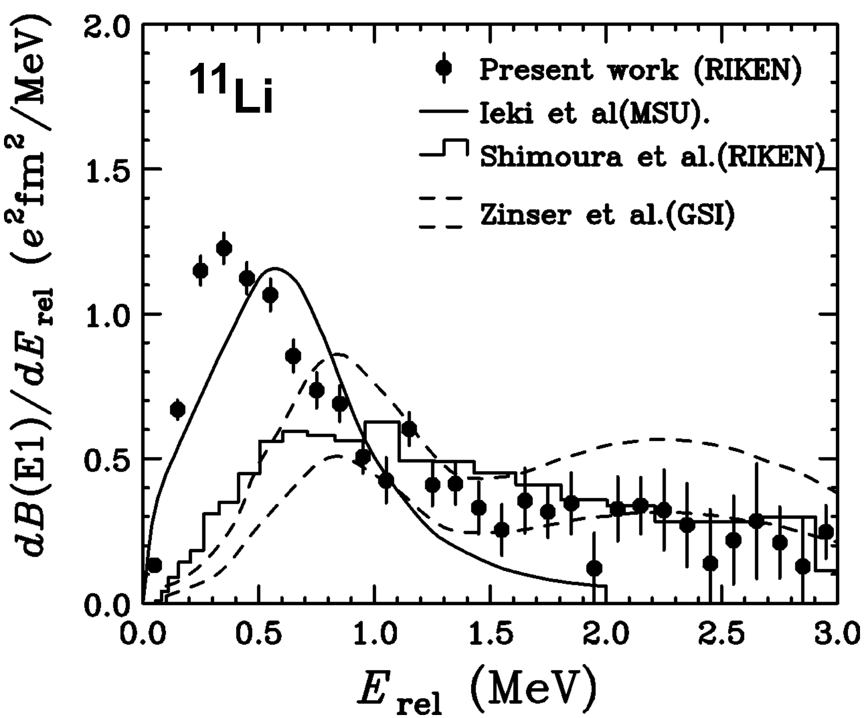
←Coulomb Breakup of 2n halo nucleus and Soft E1 Excitation



Soft E1 excitation

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





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

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

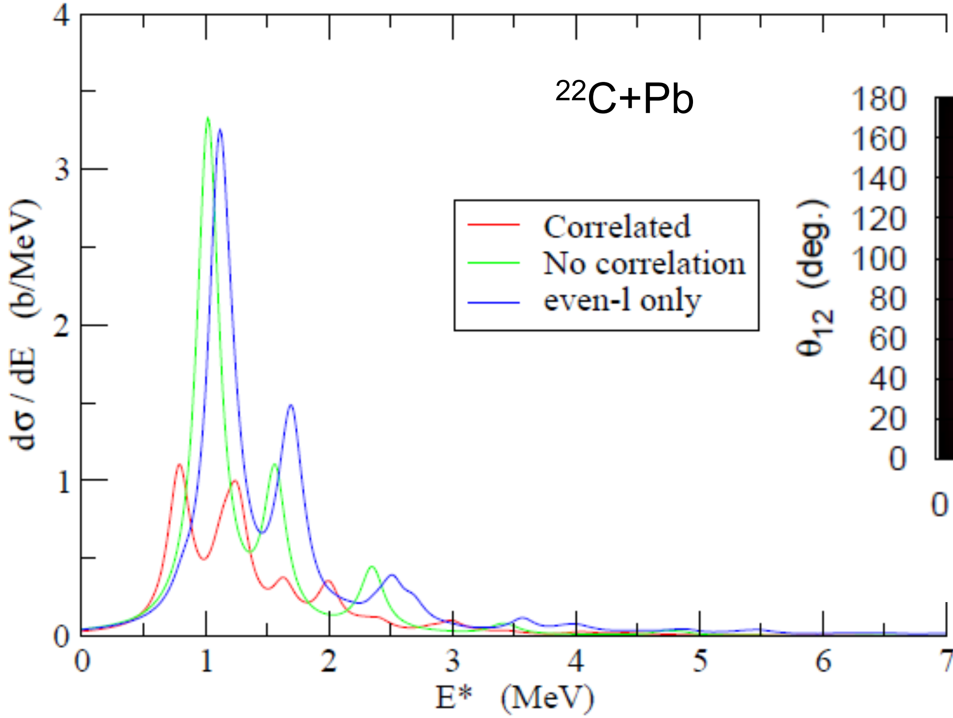
$$B(E1)=1.42\pm0.18\ e^2 fm^2 (E_{\rm rel}\leq 3\text{MeV})$$

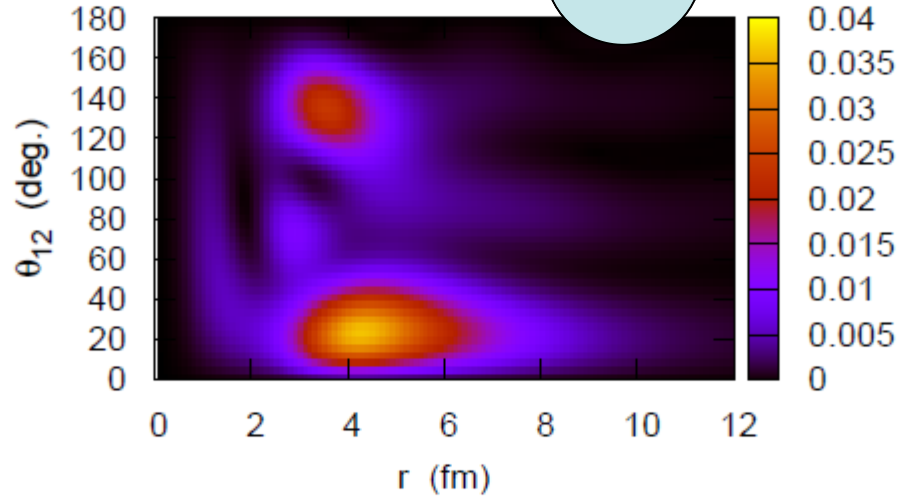
$$\rightarrow 1.78(22)\ e^2 fm^2 \rightarrow \langle\theta_{12}\rangle = 48^{+14}_{-18}\ \text{deg.}$$

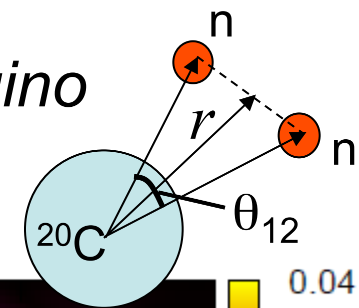
Soft E1 Excitation of 2n-halo—dineutron-like correlation

^{22}C: Theoretical Calculation *by K.Hagino*

N=16







S_{2n}=500keV

Correlated: $\alpha|(2s_{1/2})^2\rangle + \beta\,|(1d_{3/2})^2\rangle + \gamma|(2p_{3/2})^2\rangle + \gamma|(1f_{7/2})^2\rangle$ ....

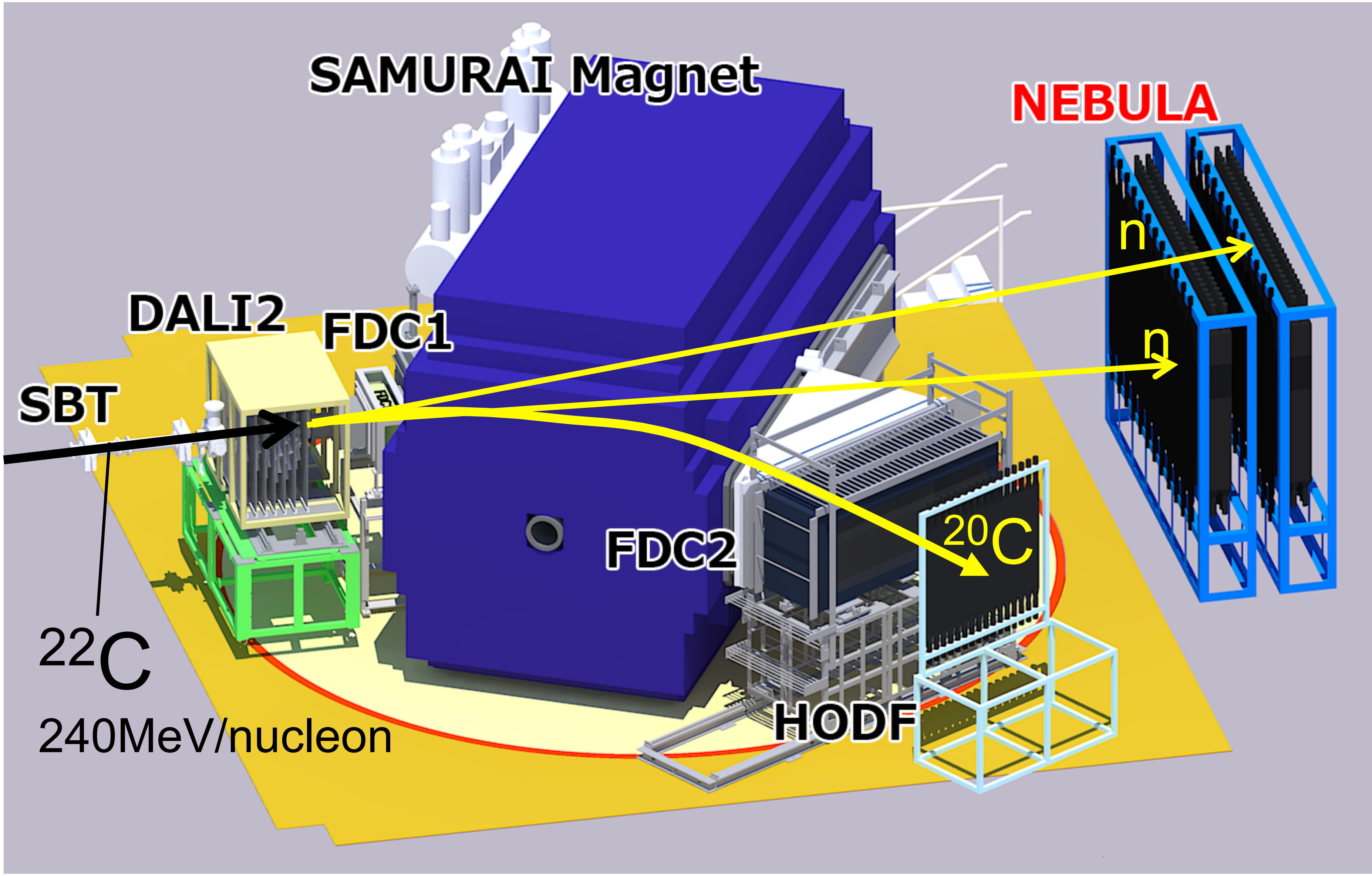
1.05b — 62.5% — 24.2% — 4.7% — 3.8%

Non-Correlated: $|(2s_{1/2})^2\rangle$

(s only) 1.66b — 100%

→Kinematically Complete Measurement of Coulomb Breakup

Experimental Setup



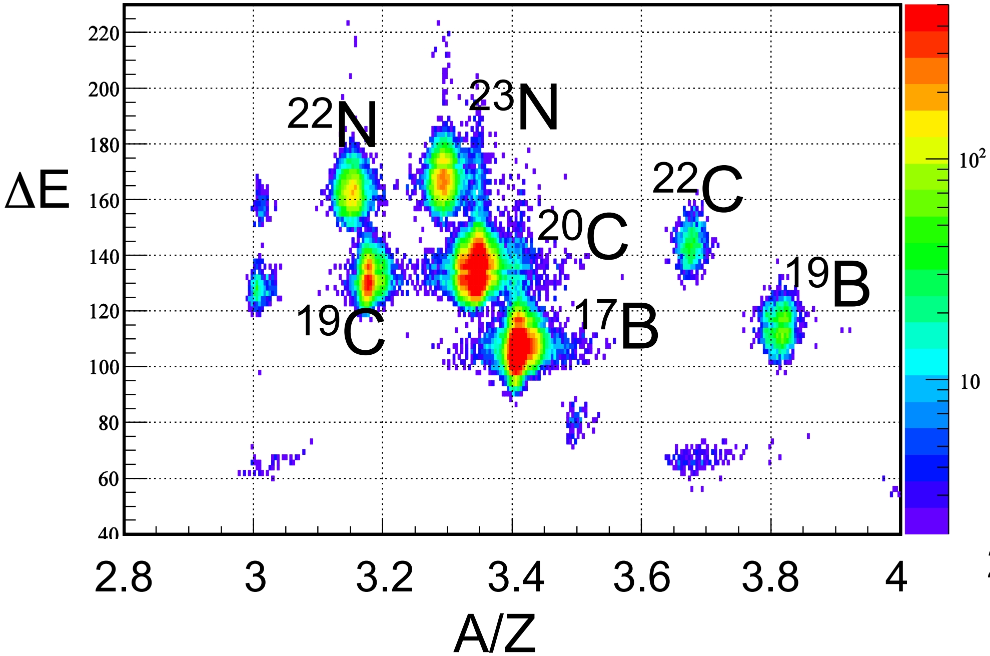
Particle Identification of RI Beams

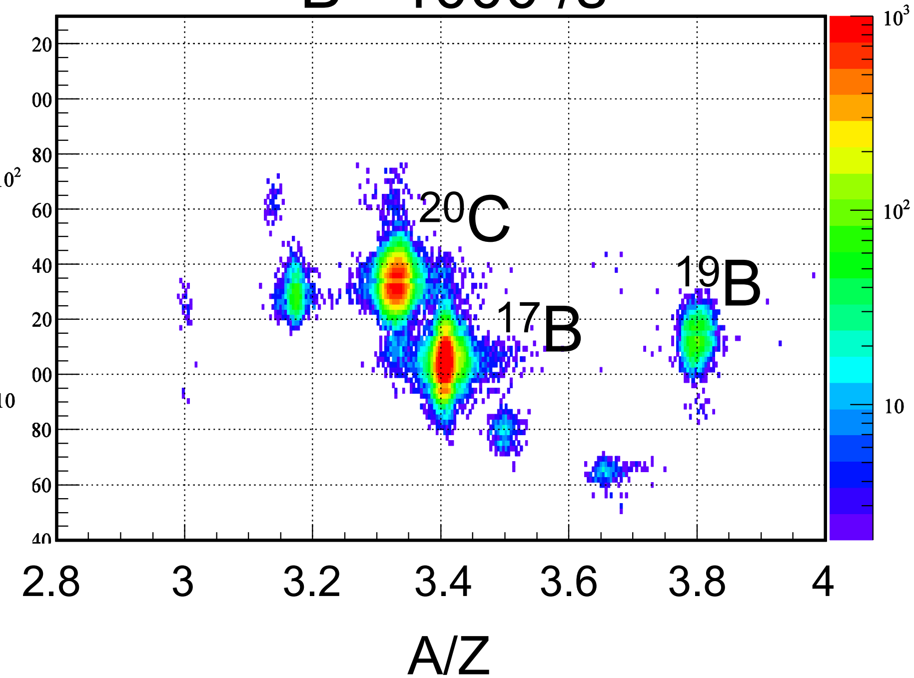
^{48}Ca 150~200pnA (Max 250pnA)

^{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





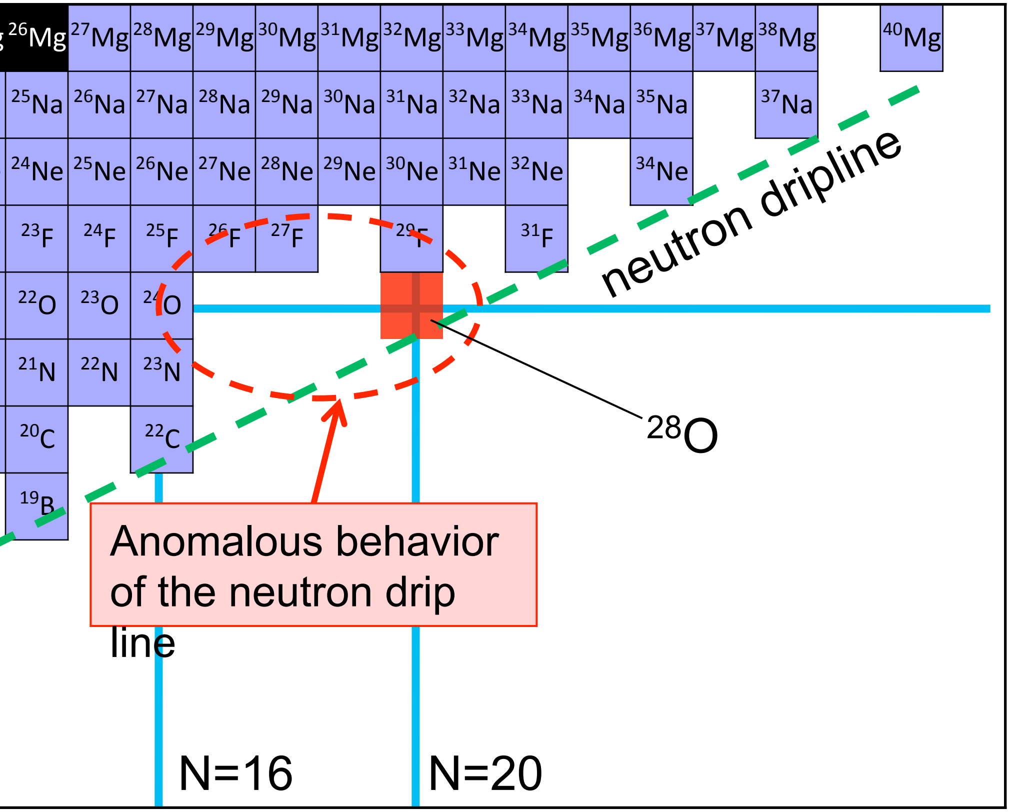
High intense RIBF Beam

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

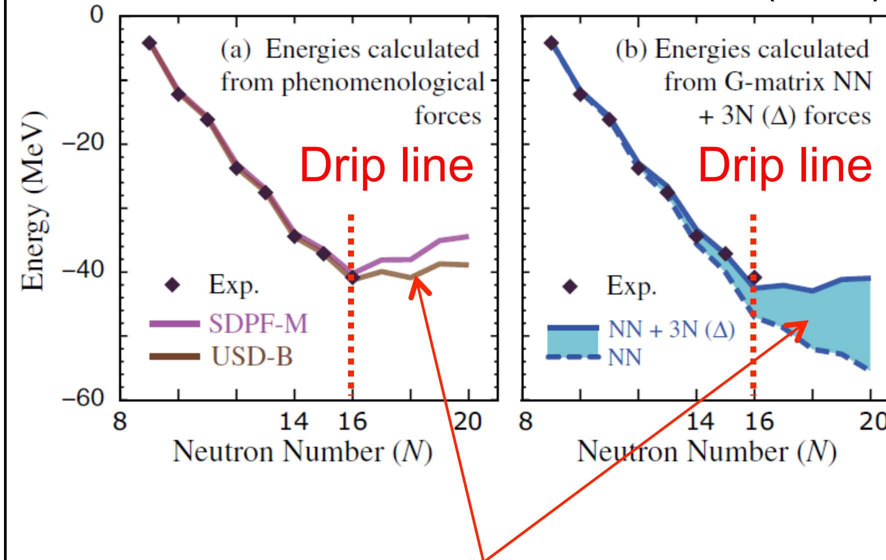
Gain of ~5000!

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

Y.Kondo et al.



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



3N Force?

I.Tews et al. (3N is important in stiff neutron-matter)

Experimental study of unbound oxygen isotopes towards ^{28}O

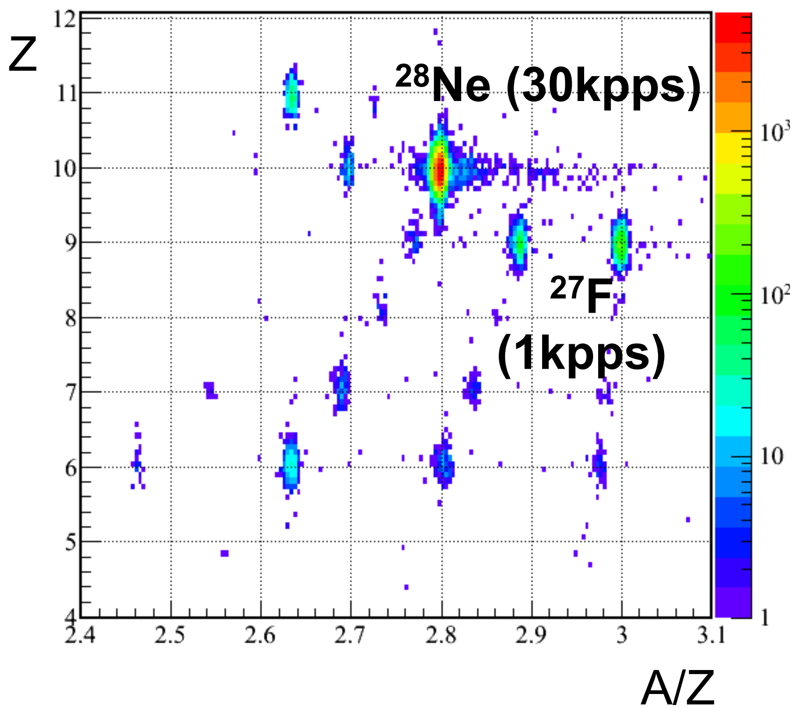
- ^{25}O and ^{26}O measurement as a 1st step

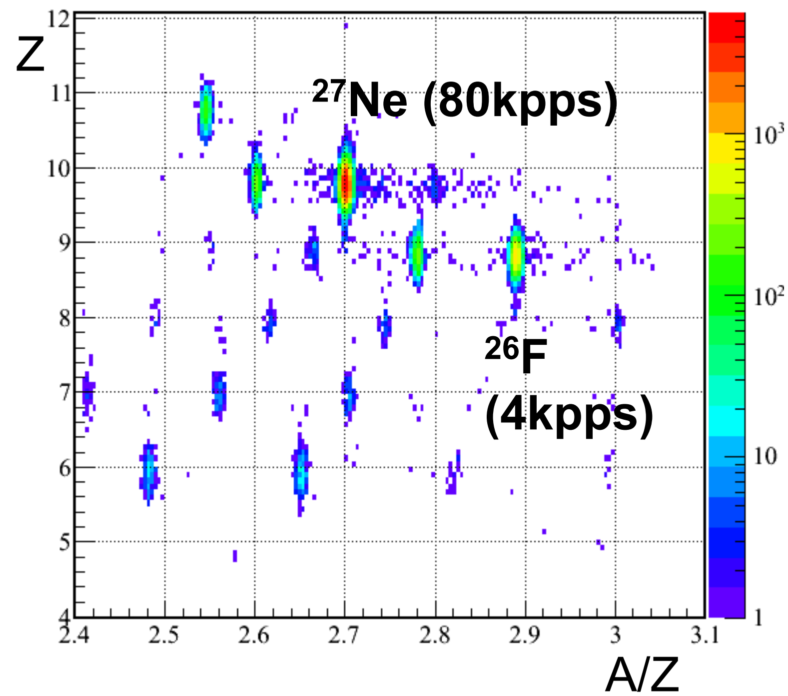
Study of unbound nuclei $^{25,26}O$
Y.Kondo et al.

One/two-proton removal reactions by using cocktail beam

- $^{27}F + C \rightarrow {}^{26}O \rightarrow {}^{24}O + 2n$
- $^{28}Ne + C \rightarrow {}^{26}O \rightarrow {}^{24}O + 2n$

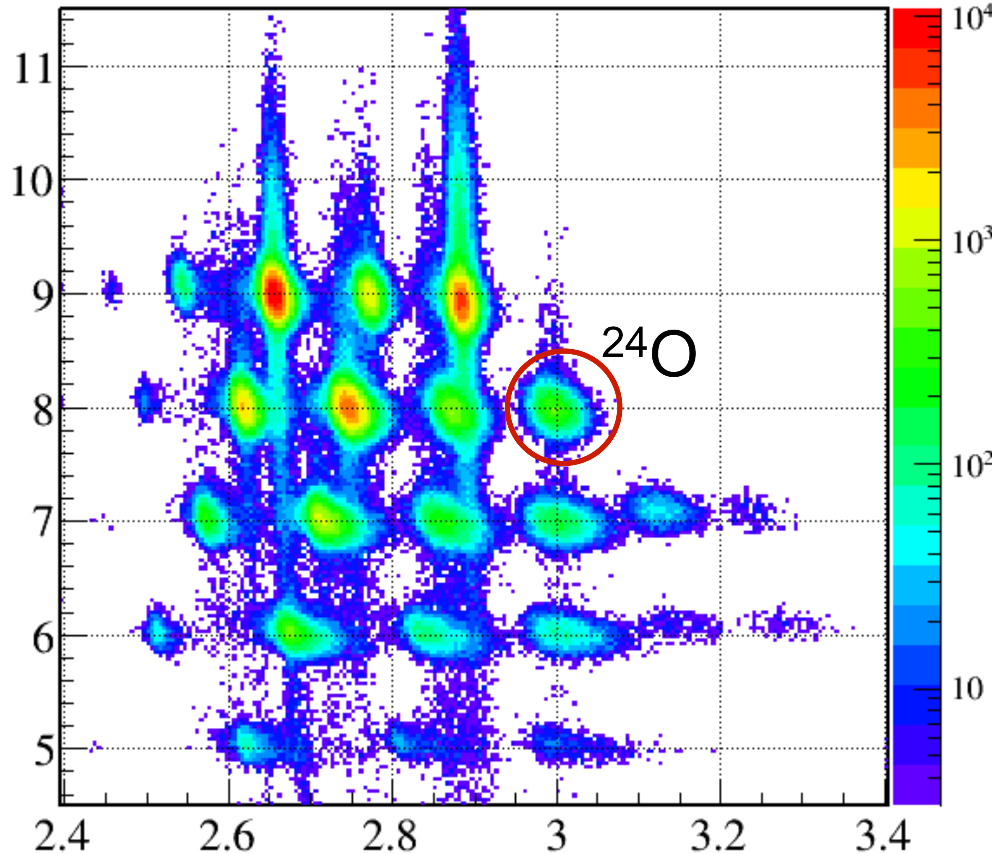
- $^{26}F + C \rightarrow {}^{25}O \rightarrow {}^{24}O + n$
- $^{27}Ne + C \rightarrow {}^{25}O \rightarrow {}^{24}O + n$





Particle ID of Fragments

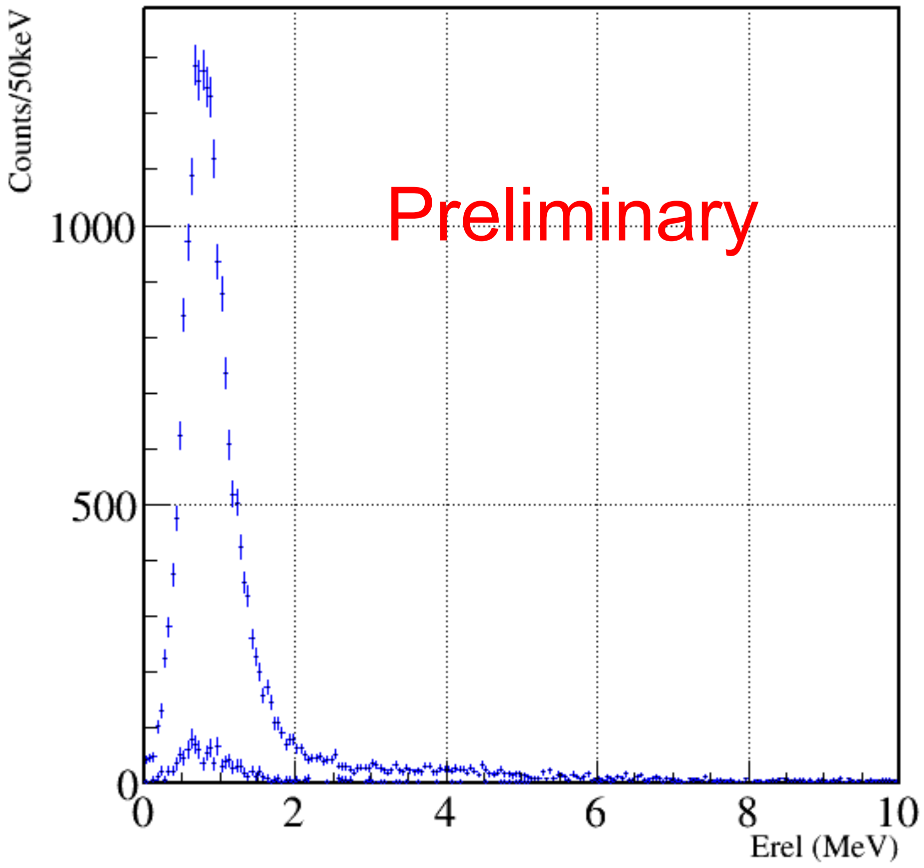
$^{26}F + C \rightarrow {}^{A}Z + X$ (neutron trigger)



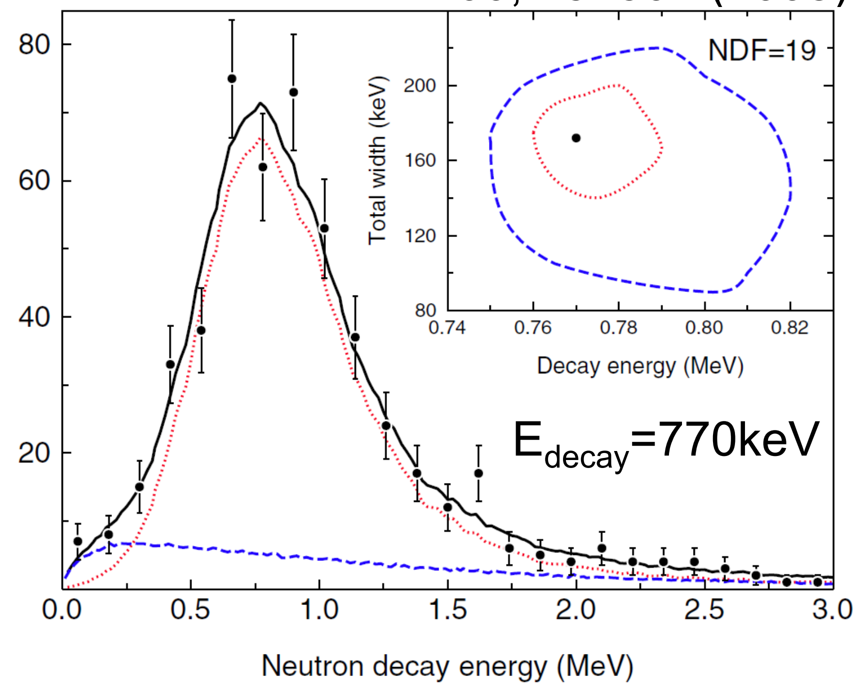
Clear Particle identification!

→ High resolving power of the SAMURAI spectrometer

Decay energy spectrum: $^{24}O+n$



C.R.Hoffman et al., PRL100, 152502 (2008)

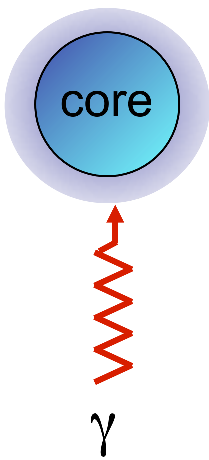


Consistent with MSU result

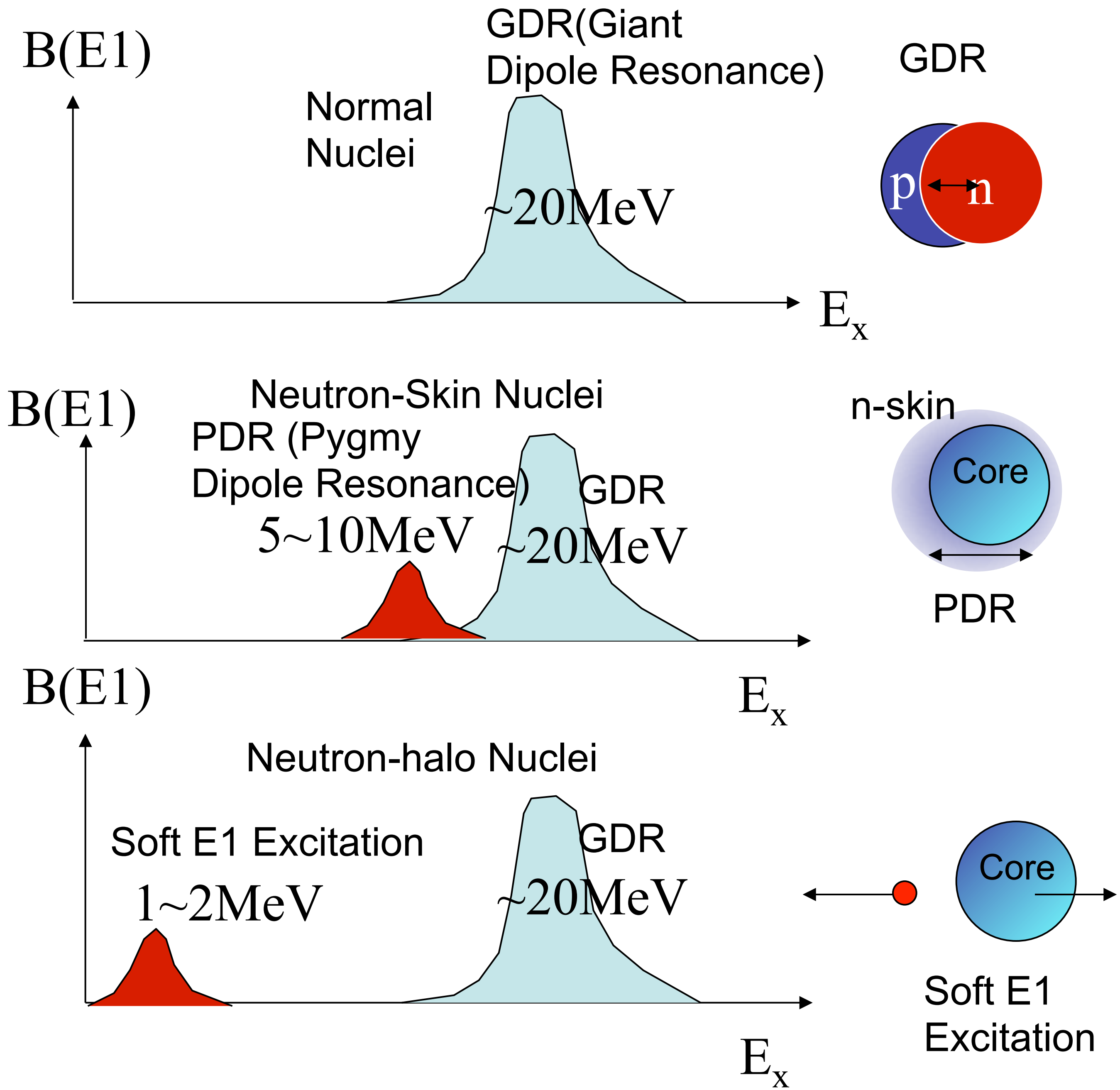
~50 times more statistics

PDR Measurements (near future project)

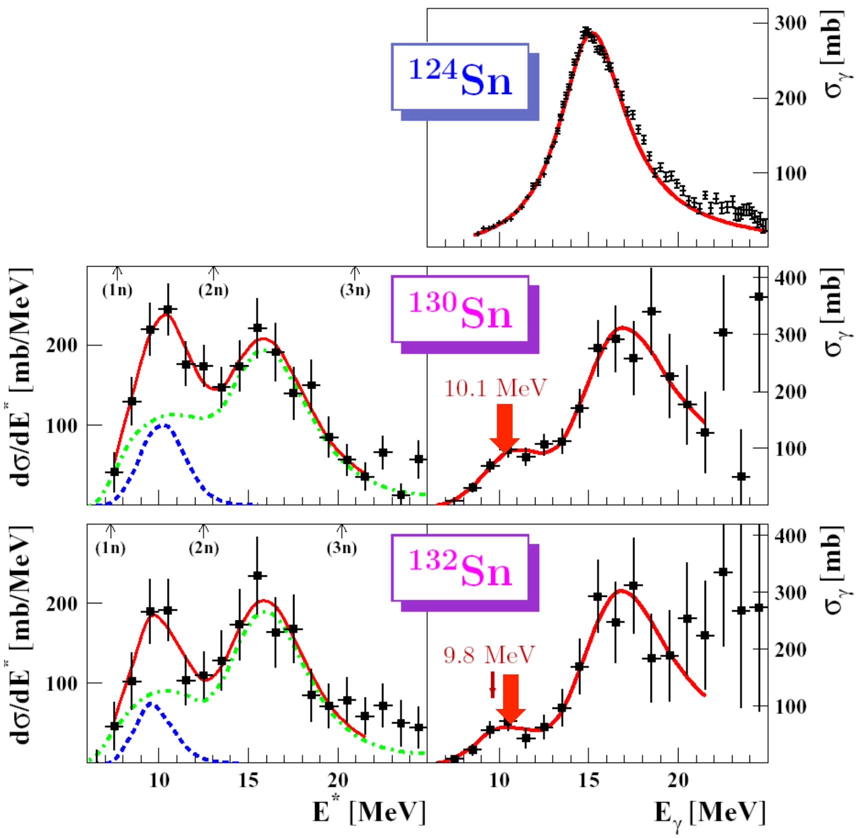
E1 Response of Nuclei



How does a nucleus respond to a γ absorption?

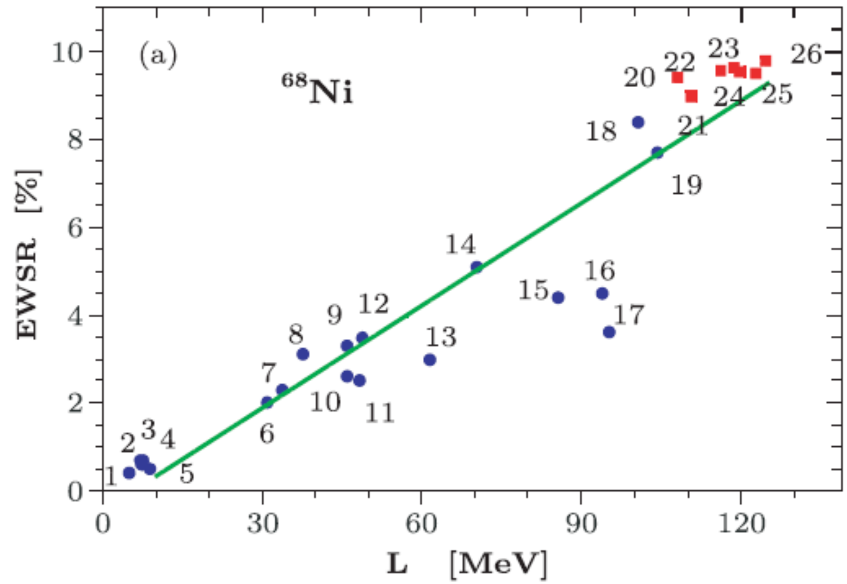


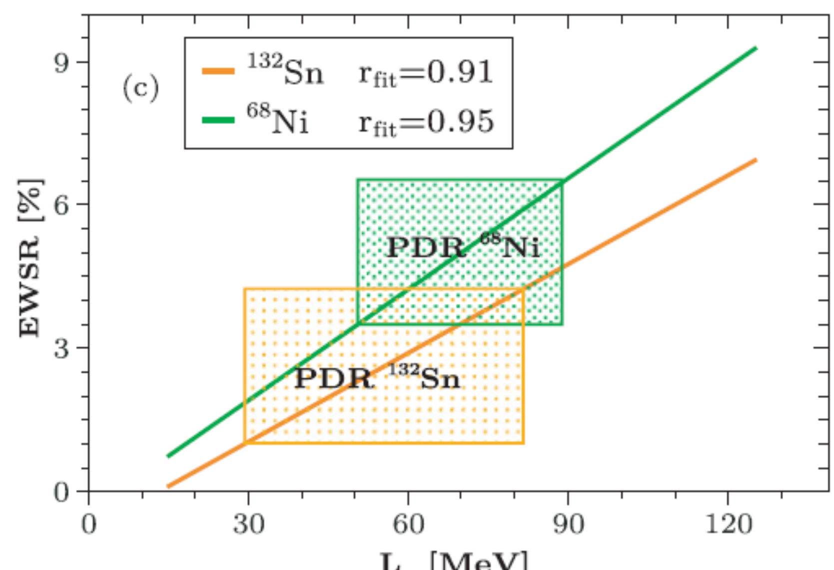
Pygmy Dipole Resonance of Neutron Skin Nuclei
(Previous work)



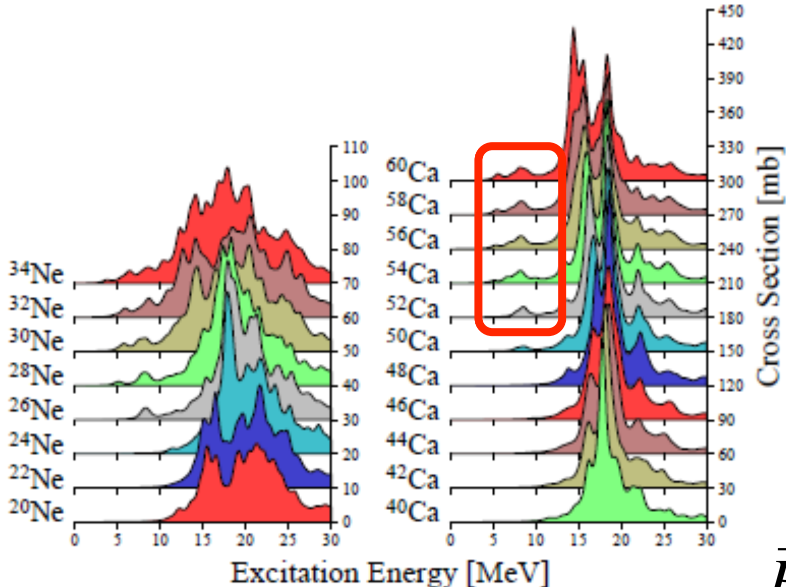
P. Adrich et al., PRL 95, 132501 (2005) .(GSI) ^{130,132}Sn

O.Wieland et al., PRL 102, 092502 (2009) . (GSI) ^{68}Ni





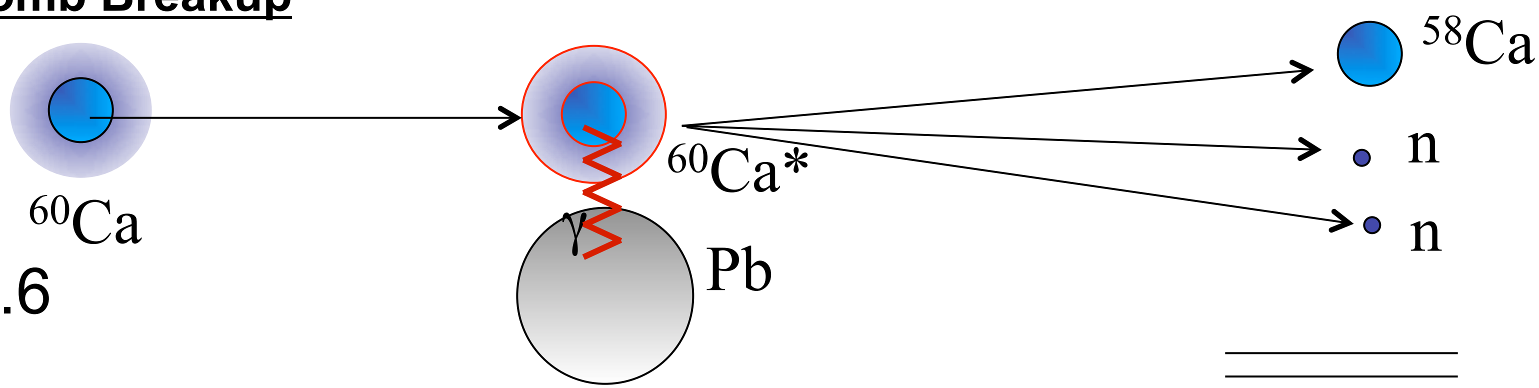
L: Pressure term of Symmetry Energy



T.Inakura, T.Nakatsukasa, K.Yabana
Phys.Rev. C 84, 021302(R) (2011)

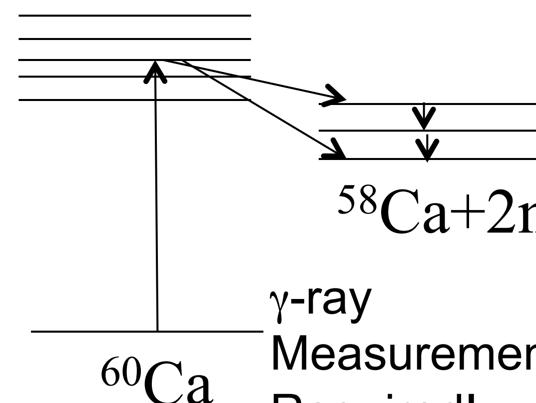
$$\vec{P}(n), \vec{P}(n), \vec{P}(^{58}\mathrm{Ca}) \Rightarrow E_{\mathrm{x}}, E_{\mathrm{rel}}$$

Coulomb Breakup



β~0.6

Invariant Mass Method



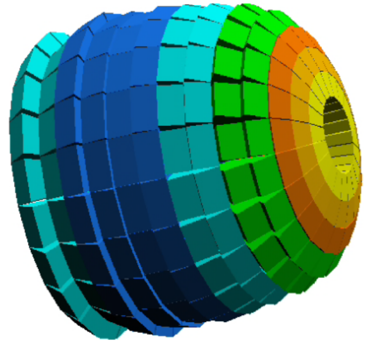
γ-ray Measurement Required!

$$M^* = \sqrt{\left(E(^{58}Ca) + E(n) + E(n)\right)^2 - \left(\vec{P}(^{58}Ca) + \vec{P}(n) + \vec{P}(n)\right)^2}$$

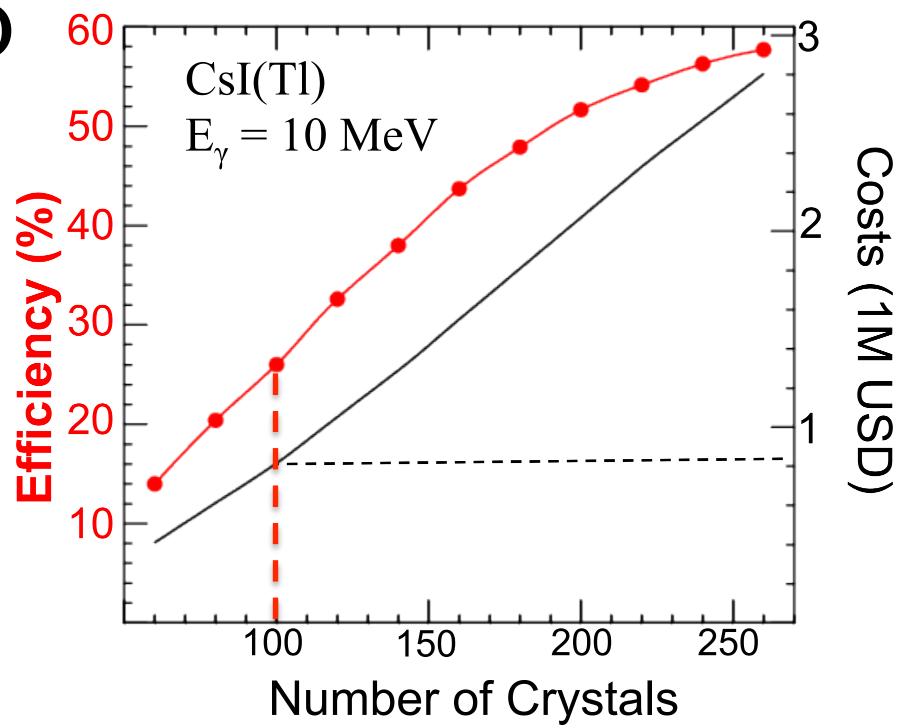
$$E_{rel} = M^* - M(^{58}Ca) - 2M(n)$$

or $$E_{rel} = M^* - (M(^{58}Ca) + \Sigma E_\gamma) - 2M(n)$$

New γ ray calorimeter at SAMURAI



- High efficiency from low to high energy γ ray
- Funded(so far): ~ 1M USD
- CsI(Tl) + APD(or PMT)
- Crystal thickness: ~25 cm



Goal: ε~40% for 10 MeV, ε~70% for 1 MeV γ ray

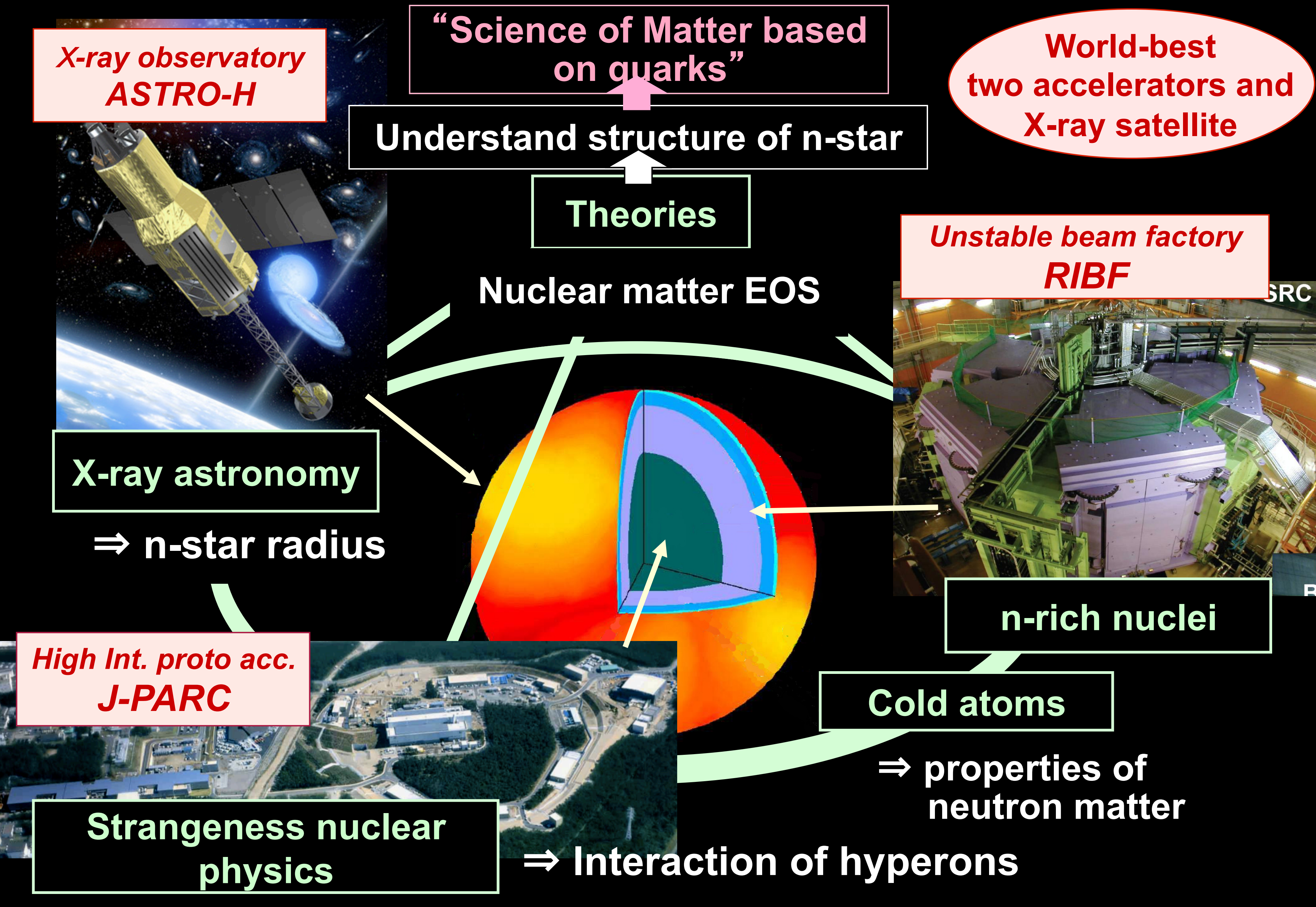
Grant-in-aid for innovative area:
“ Nuclear Matter in neutron Stars investigated by experiments and astronomical observations”
2012-2016

~10M USD

H. Tamura (Tohoku U.)

T.Takahashi (KEK), T.Murakami(Kyoto U.),
T.Nakamura(Tokyo Tech), S.Horikoshi(Tokyo.U),
T. Takahashi(JAXA),A.Onishi(YITP)

Joint project between experiments, observations, theories



Summary

1. **EOS of neutron-rich nuclear matter: Important**
2. **SAMURAI facility at RIBF at RIKEN**

   Commissioned with a great success in 2012

3. **Scientific Programs for EOS at SAMURAI**

   i) Heavy Ion Collisions

   → EOS for high dense n-rich matter →**Murakami's talk**

   ii) Direct Reactions/Breakup Reactions

   → EOS for low/medium dense n-rich matter

4. **Day-One Campaign Experiments at SAMURAI**

   Coulomb Breakup of ^{22}C and ^{19}B

   Study of Unbound Oxygen isotopes

   --successfully done

5. **Pygmy Dipole Resonance (& Other Collective Modes) for n-rich nuclei** -- RIBF-SAMURAI / FRIB

SAMURAI Dayone Experiment (May 2012)

First experimental campaign for the 3 physics programs

1. Coulomb breakup of ^{22}C and ^{19}B (T. Nakamura)
2. Study of unbound states of ^{22}C, ^{21}C, ^{19}B, ^{18}B (N. A. Orr)
3. Study of unbound nuclei ^{25}O and ^{26}O (Y. Kondo)

Collaborators

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