# Recent results at RIBF

1. Nuclear structure and astrophysics
   in-beam gamma & decay spectroscopy
2. New coming programs

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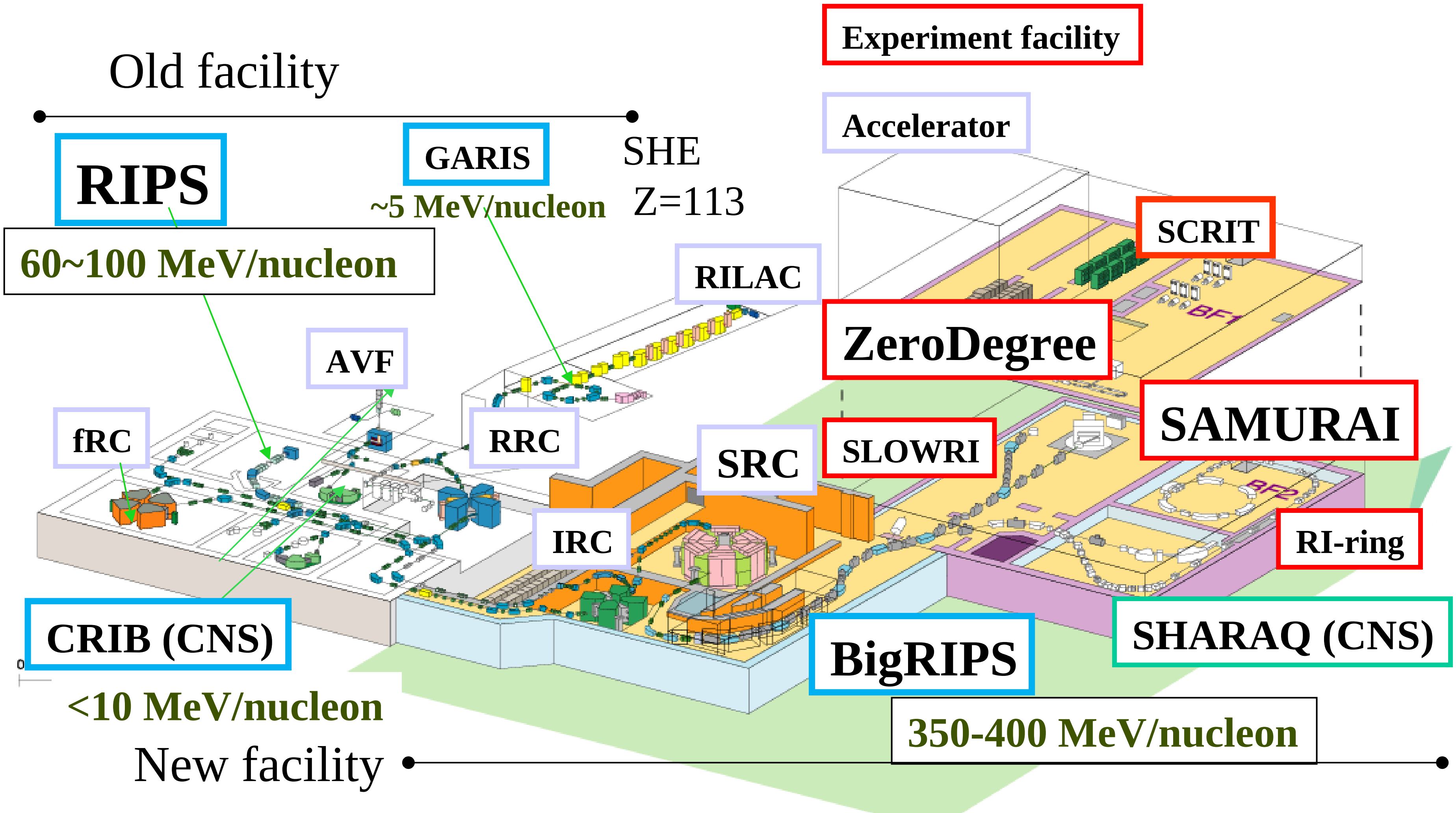
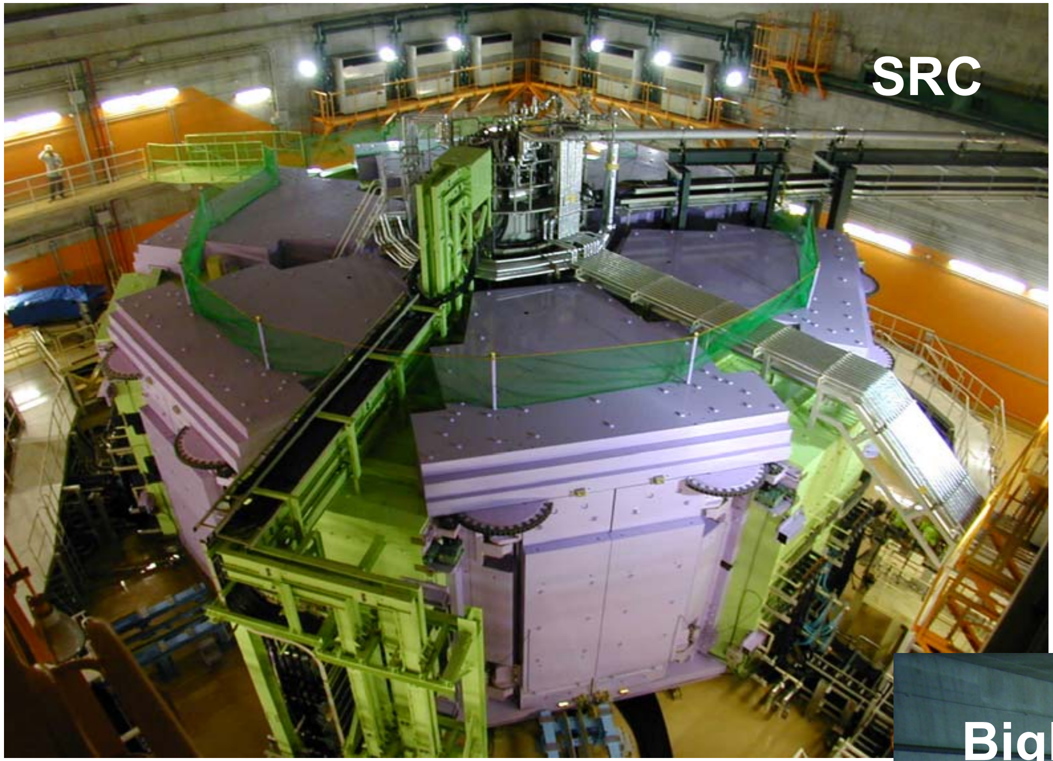
# RIKEN RI Beam Factory (RIBF)




**Intense (80 kW max.) H.I. beams (up to U) of 345*A*MeV at SRC**
**Fast RI beams by projectile fragmentation and U-fission at BigRIPS**
**Operation since 2007**




**World's First and Strongest**
**K2600MeV**
**Superconducting Ring Cyclotron**

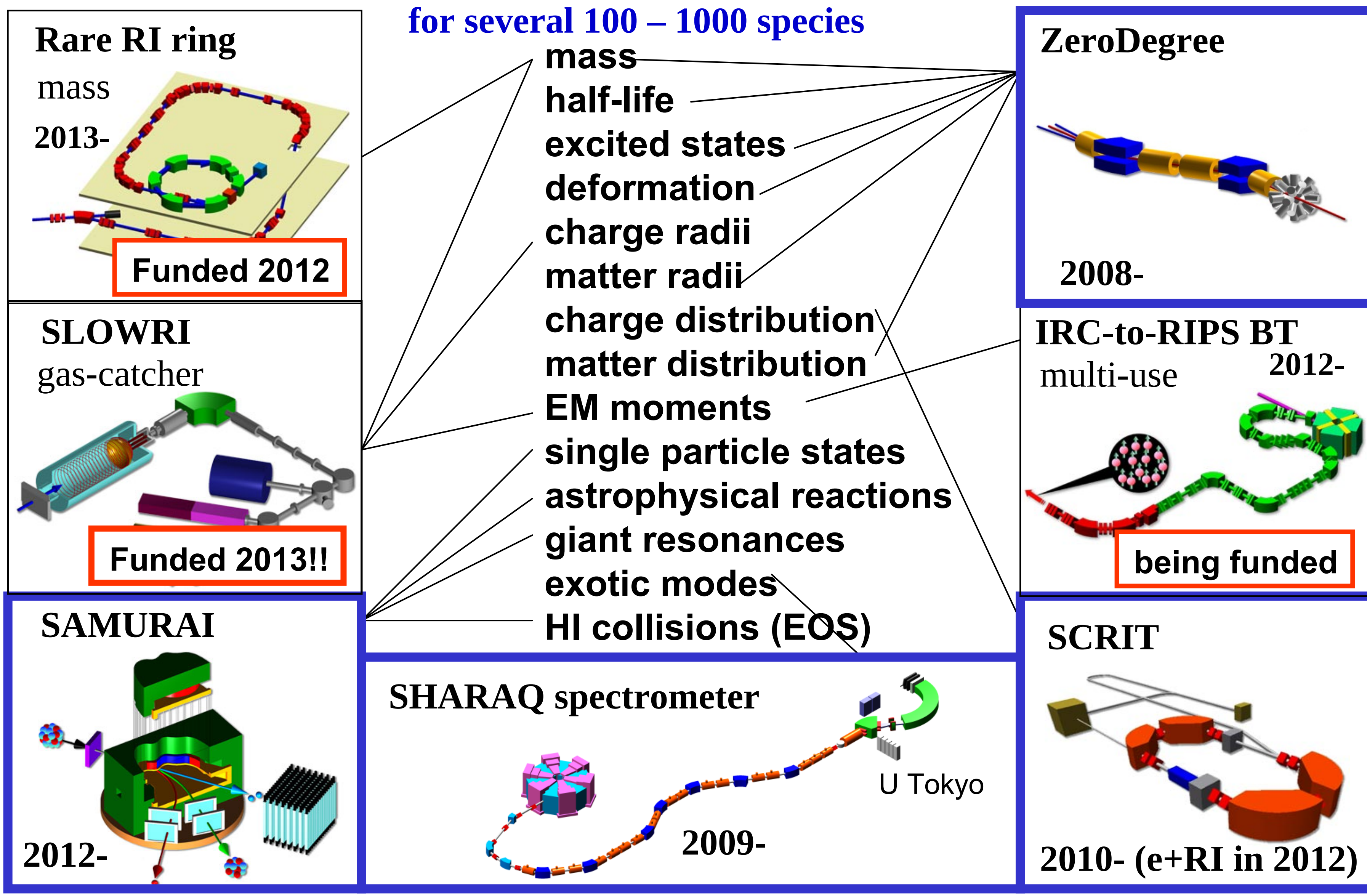
400 MeV/u Light-ion beam
345 MeV/u Uranium beam


**World's Largest Acceptance**
**9 Tm**
**Superconducting RI beam Separator**

~250-300 MeV/nucleon RIB

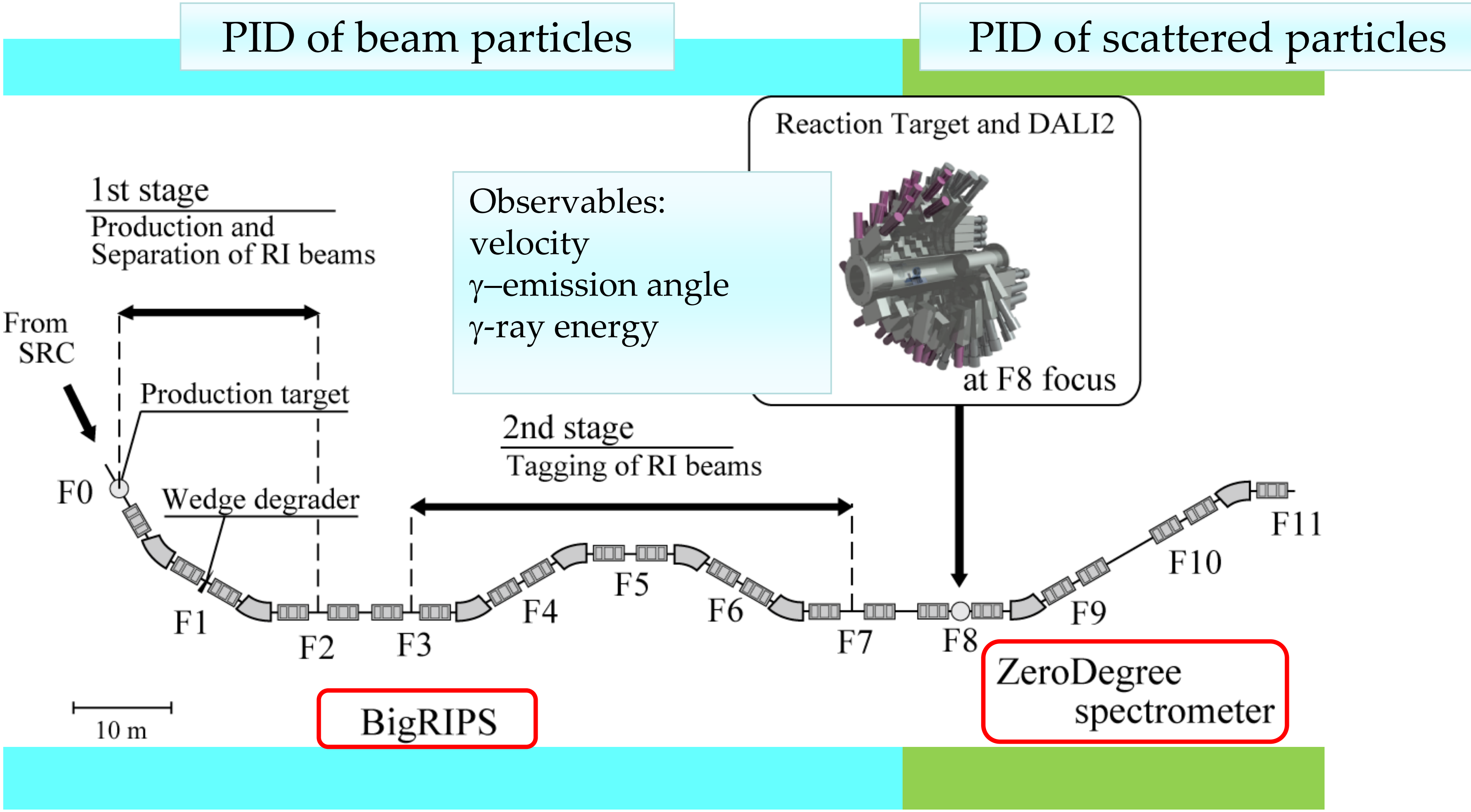
# New Experimental Devices of RIBF

To maximize the potentials of intense RI beams available at RIBF



# In-beam gamma spectroscopy

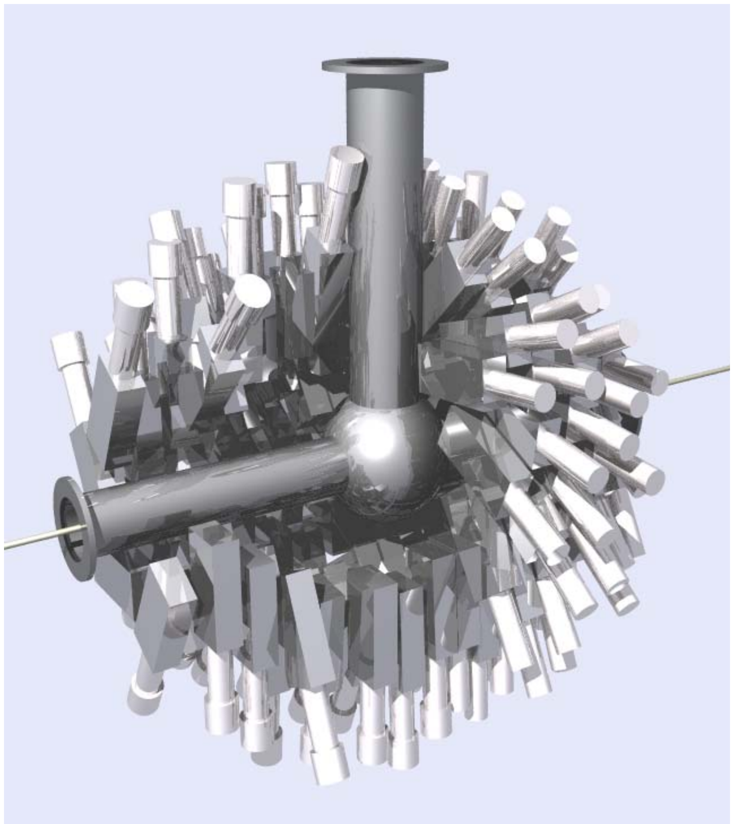
# γ-ray spectroscopy setup @ BigRIPS/ZDS




**Determine reaction channel and correct Doppler shift effects.**

# DALI2 for RIBF experiments

**D**etector **A**rray for **L**ow **I**ntensity radiation



γ-ray energy
Emission angle of γ ray
→ For Doppler-shift corrections

## Standard specification

| | |
|---|---|
| Arrangement | Hedgehog like |
| Size (cm3) | 4.5 x 8 x 16 |
| # of Detectors | 160 |
| Volume | ~ 90 liter |
| # of Layers | 16 |
| Angular resolution | ~ 8 degree |
| Energy resolution (β~0.6) | 10% @ 1MeV |
| Efficiency (β~0.6) | 20% @1MeV (24%@1MeV (β~0.3)) |
| Timing resolution | ~ 2.5ns (FWHM) |

Ref. S.Takeuchi et al., RIKEN Accel. Prog. Rep. **36**(2003)148
Ex.) S.Takeuchi et al., PRC **79**, 054319 (2009)

RIKEN NISHINA CENTER

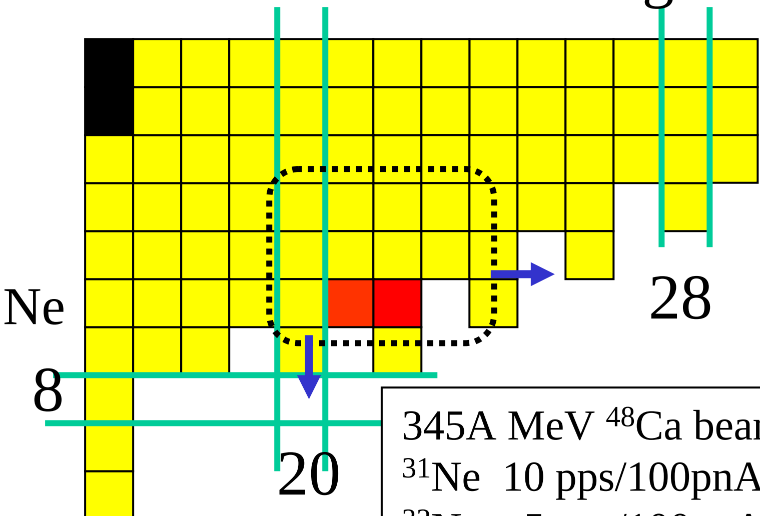
# In-beam Gamma Spectroscopy 2008-2012

| | | | |
|---|---|---|---|
| •2008 | DayOne | | |
| | **32Ne,** 31,33Na | **H. Scheit, P. Doornenbal** | |
| | | PRL 103:032501, 2009./PRC 81:041305, 2010. | |
| •2009 | Test with U (0.3-0.6 pnA) | | |
| | ~132Sn | H. Wang, N. Aoi | |
| | Test with 48Ca beam | | |
| | 32Mg etc. | K.Li, H.Scheit | |
| •2010 | 48Ca campaign | | |
| | **38,40,42Si** | **S.Takeuchi, M.Matsushita** | PRL 109:1823501 (2009) |
| | **A>36Mg** | **P. Doornenbal, H. Scheit** | in preparation |
| | **F isotopes** | **P. Doornenbal, H. Scheit** | in preparation |
| | ~Al, P | D. Steppenbeck | in preparation |
| | 33Mg | D. Bazin | |
| | 40Mg test | P. Fallon | |
| •2011 | U beam campaign | | |
| | 78Ni | K. Yoneda, D. Steppenbeck | |
| | ~132Sn | H. Wang, N. Aoi | |
| •2012 | 124Xe and 70Zn beam campaign | | |
| | **10xSn** | **A. Obertelli, P. Doornenbal** | |
| | **54Ca** | **D. Steppenbeck, S. Takeuchi** | |

# Collectivity enhancement toward the drip line in Ne and Discovery of deformed halo nucleus $^{31}$Ne

DayOne in 2008

## "Island of inversion" region

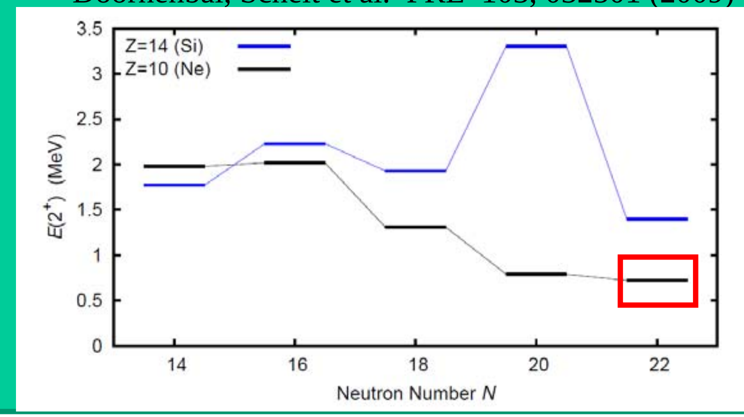



345A MeV $^{48}$Ca beam
$^{31}$Ne 10 pps/100pnA
$^{32}$Ne 5 pps/100pnA

A large deformation at Z=10-12
in spite of N=20
A pilot-region for nuclear structure
 Interplay of three ingredients:
  Weakly-bound natures
  Tensor forces
  Pairing

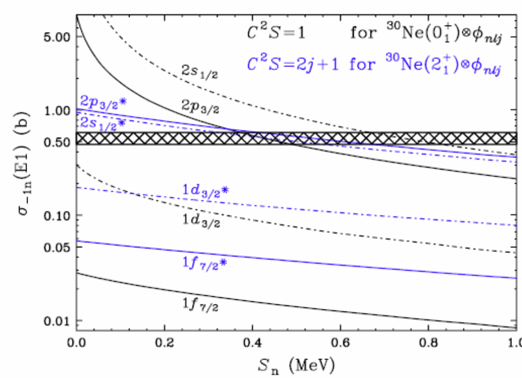
## Collectivity enhancement toward the drip line?

Doornenbal, Scheit et al. PRL 103, 032501 (2009)



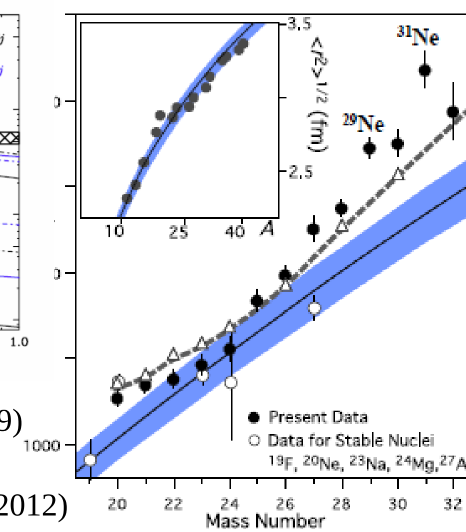

## A new candidate of halo nuclei: $^{31}$Ne

**Large Coulomb breakup cross section**



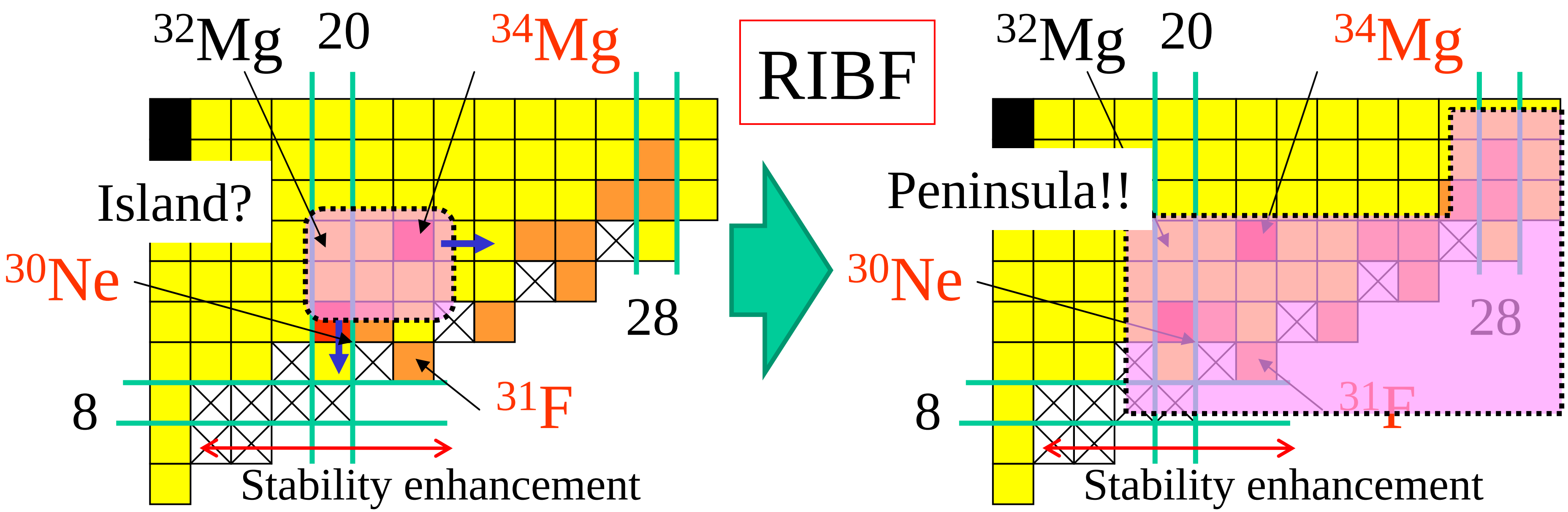

Nakamura et al., PRL 103, 262501(2009)

**Total X-section Jump at $^{29,31}$Ne**




Takechi, Otsubo et al., PLB707, 357 (2012)

# Extension of the deformation region up to the drip-line




<u>Doornenbal, Scheit, et al.</u>

Ne-32 1st excited states: PRL 103, 032501 (2009)

New states in $^{31,32,33}$Na: PRC 81, 041305R (2010)

Mg-36,-38: ARIS11; in preparation

F-29: in preparation

<u>Takeuchi et al.</u>

Si-42 : PRL109, 182501 (2012)

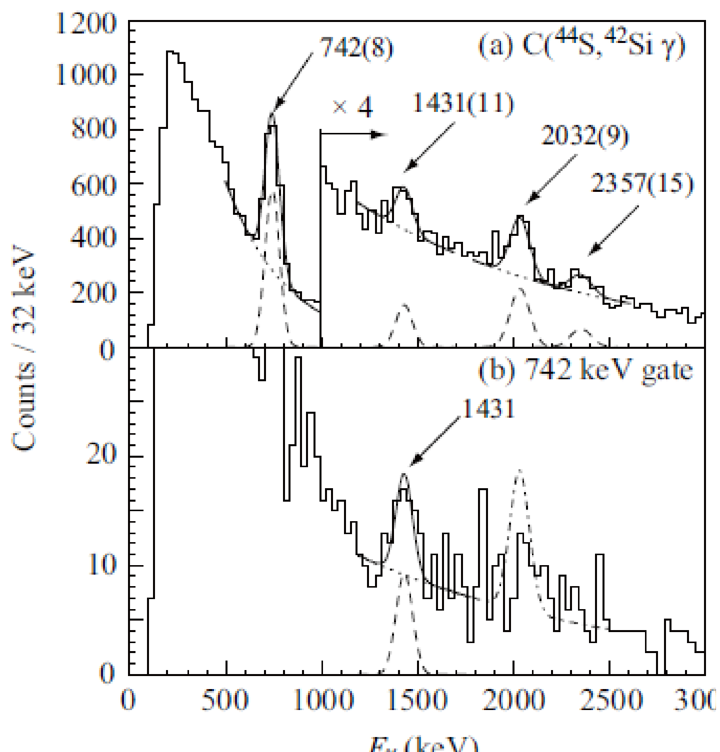
# Well developed deformation of $^{42}$Si

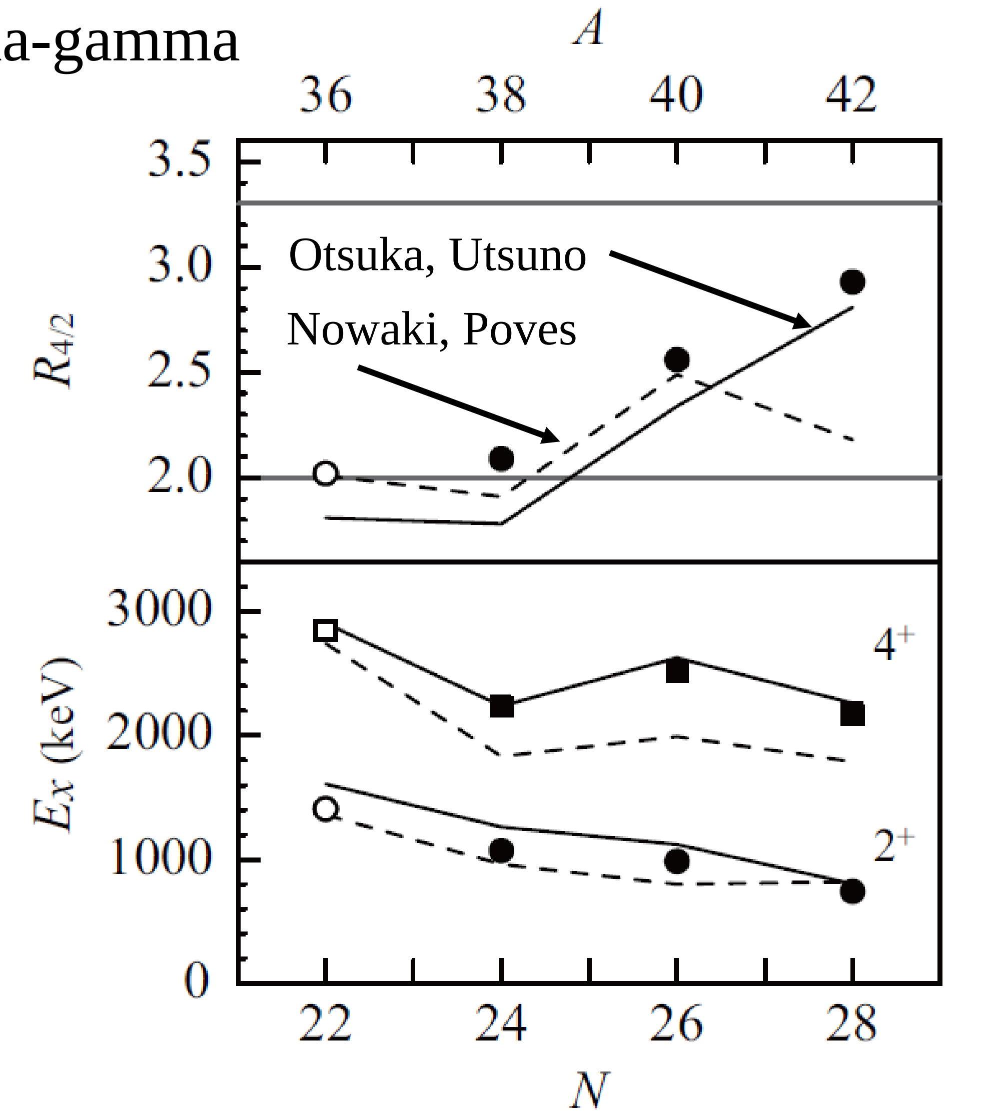
S. Takeuchi et al., PRL109, 182501 (2012)

Confirmation of 2+ energy observed at GANIL
High statistic data allows gamma-gamma Coincidence

$^{44}$S + C -> $^{42}$Si +X

E(4+)/E(2+)~3 for Si-42



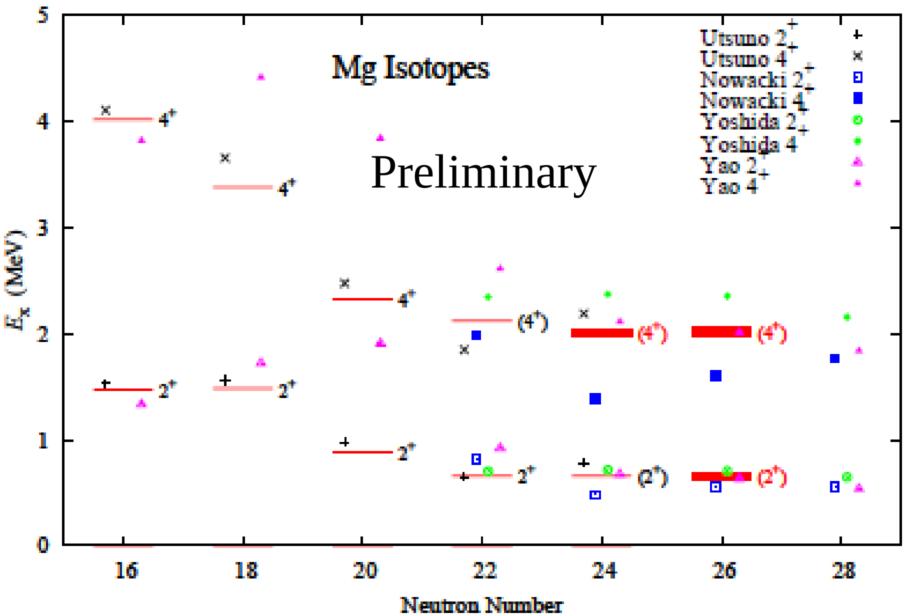



# Collectivity of the neutron-rich Mg isotopes

P. Doornenbal, et al. in preparation

$^{A}$Al -> $^{A-1}$Mg

Excitation Energy of $2^+$ and $4^+$ in Mg

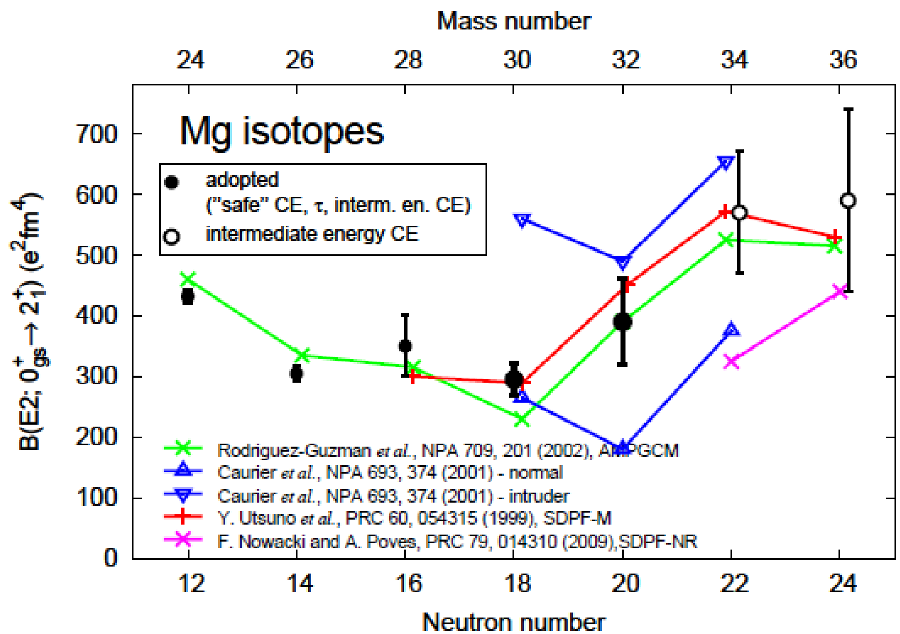



CH2, C, Pb target data

–> total inelastic cross section

B(E2) for Mg-36 590 $e^2fm^4$

Preliminary




SDPF-M: Y. Utsuno *et al.*, Phys. Rev. C 60, 054315 (1999)

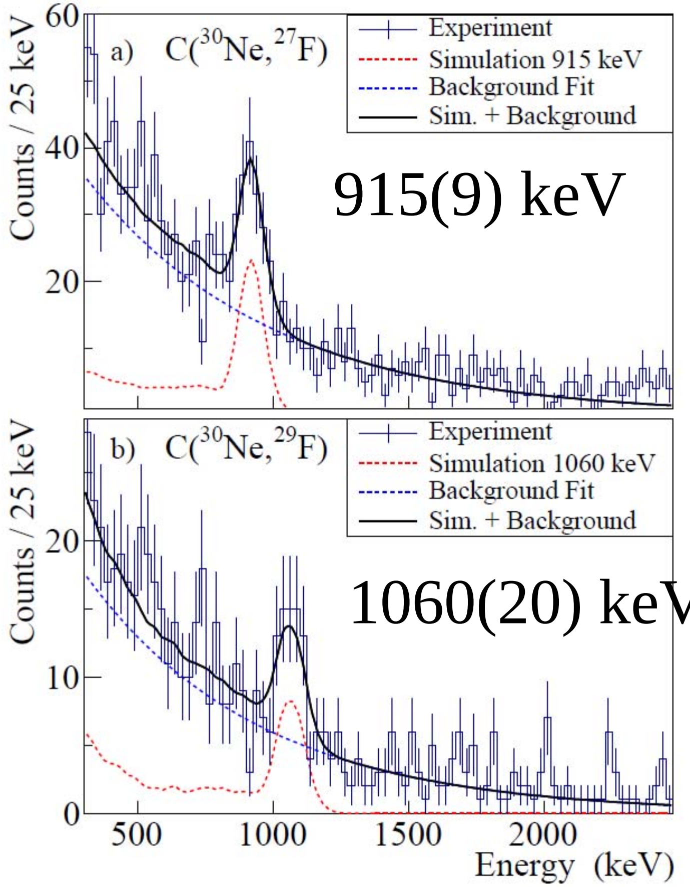
SDPF-NR ($0\hbar\omega$): F. Nowacki and A. Poves, Phys. Rev. C 79, 014310 (2009)

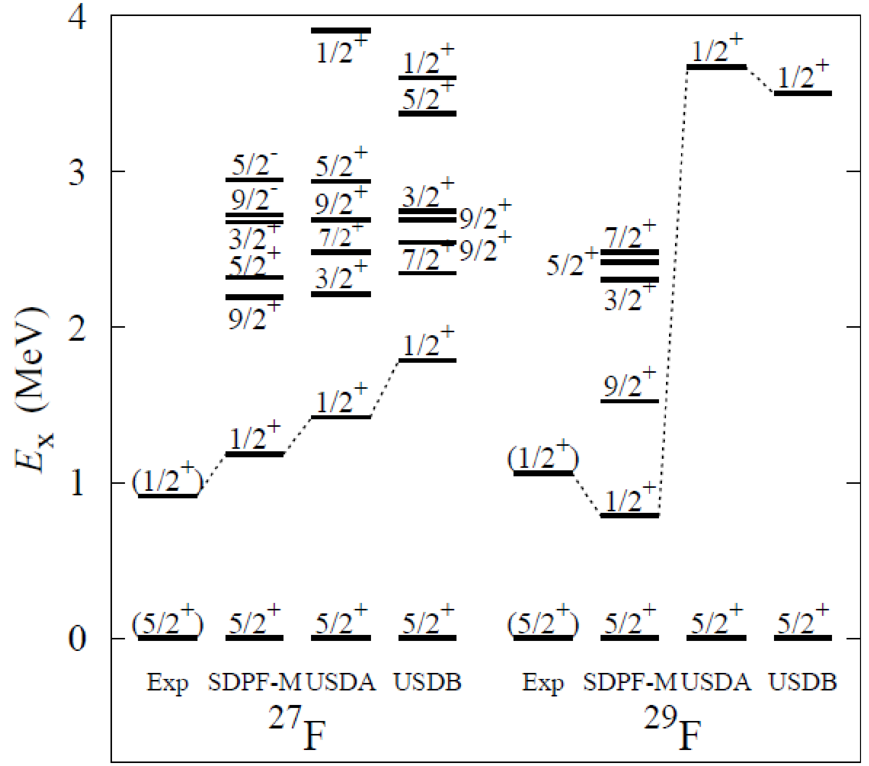
Skyrme-QRPA: K. Yoshida, Eur. Phys. J. 42, 583 (2009)

3DAMP+GCM: J. M. Yao *et al.*, Phys. Rev. C 83, 014308 (2011)

# Spectroscopy on $^{29}$F:Double-magicity of unbound O-28?

P. Doornenbal et al., in preparation




F-29 is one of “island-of-inversion” nuclei

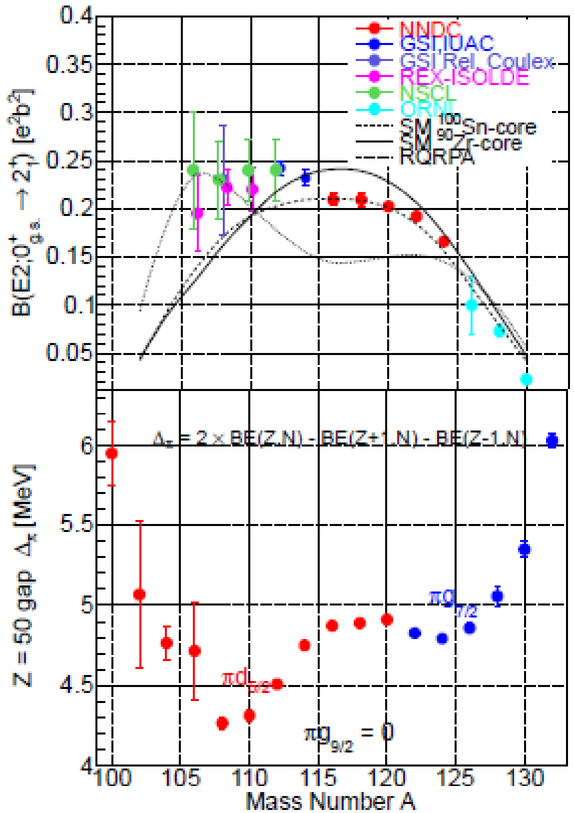
According to the Shell model by Utsuno and Otsuka,

F-29 1/2+ ~ d 5/2+ (π) x O-28(2+)

1060 keV -> E(2+) for O-28 is 2.4 MeV. C.f. 4.7 MeV for O-24

# Systematics of B(E2) for the Sn isotopes

P. Doornenbal et al., in preparation

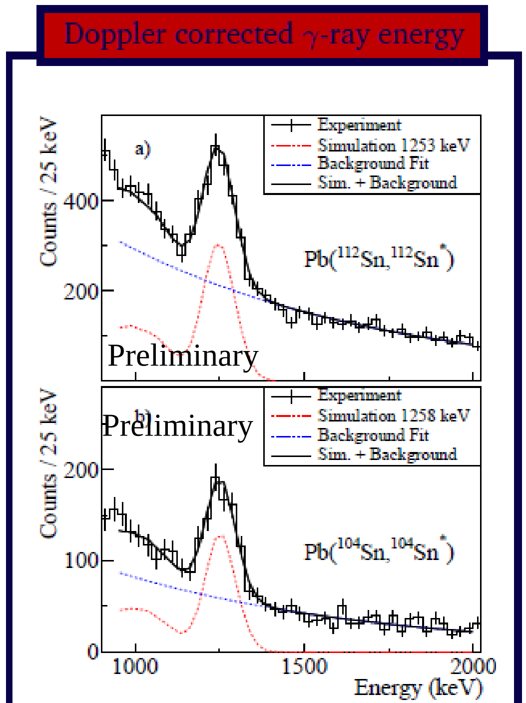



- Excitation across $N = 50$ shell
- $\alpha$-correlations
- refined tuning of proton-neutron monopoles
- reduction of the $Z = N = 50$ gap

- $^{124}$Xe, 6 pnA primary beam
- Pb($^{104}$Sn,$^{104}$Sn$^{*}$), Pb($^{112}$Sn,$^{112}$Sn$^{*}$)
- F8 target: $^{nat.}$Pb, 0.557 g/cm$^2$
- 150, 170 in front of F8 target
- 600 pps $^{112}$Sn @F11
- 168 pps $^{104}$Sn @F11
- 5;17 hours data taking
- Rates including F8 PPAC efficiencies and
- Only fully stripped ions

Sn-112

Sn-104



# Decay Spectroscopy

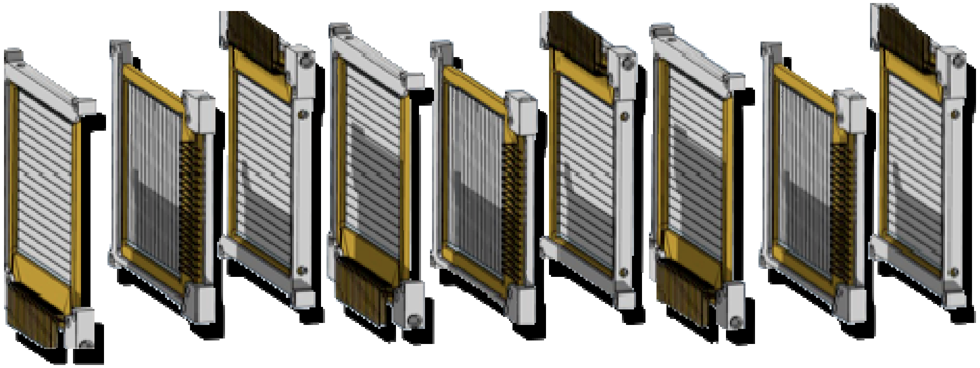
At the New Facility
BigRIPS/ZeroDegree

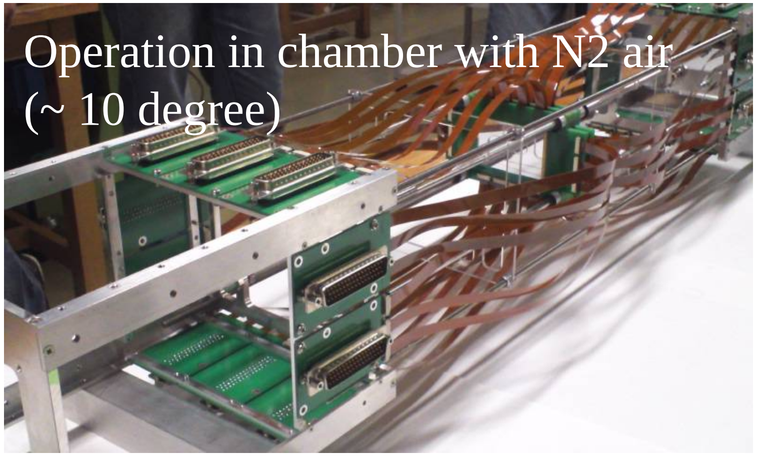
2009 Clovers+DSSSD
n-rich Nuclei with A~110

2012 Cluster-arrays+DSSSD
EURICA Project

New Silicon Detector : WAS3ABi
(Wide-range Active Silicon-Strip Stopper Array for Beta and ion detection)

Active Stopper of DSSSD
to take position correlations between HI and beta






**8 layers of DSSSD**
**(40-strips x 60 strips)**
**RIKEN/IBS/TUM**

# The First Decay Spectroscopy at RIBF

2009 Dec.

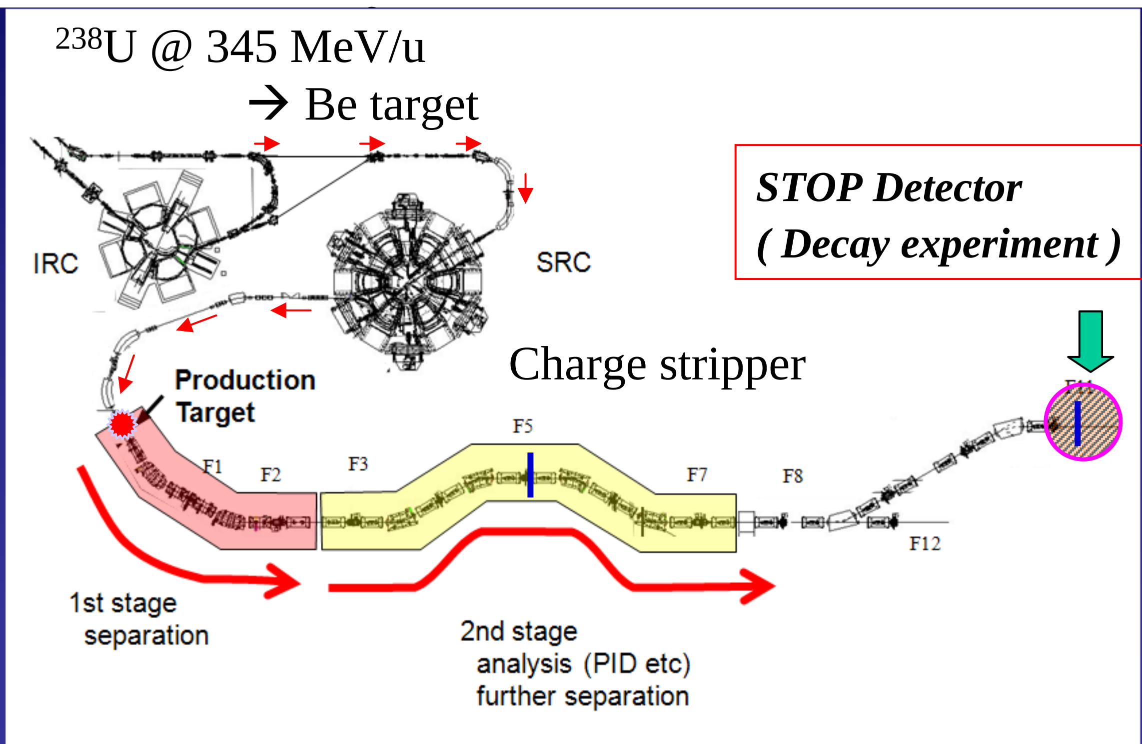
U beam to access A~110 region

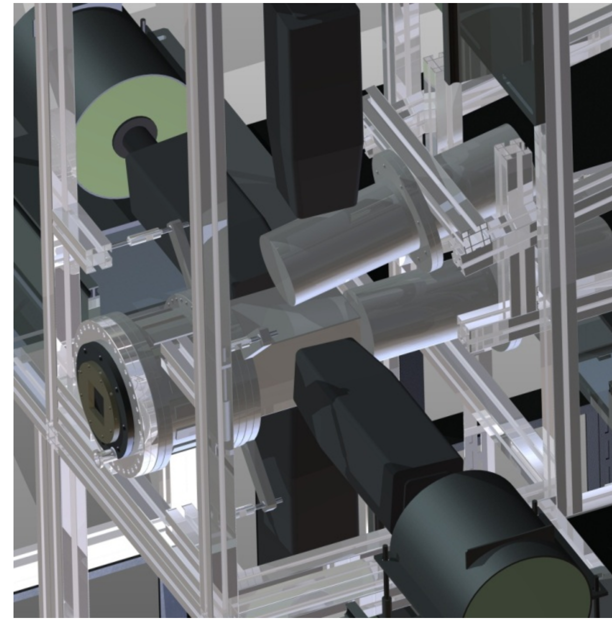
Collectivity

triaxiality, shape-coexistence, etc

Intensity 0.8 pnA max.

0.1-0.2 pnA on average



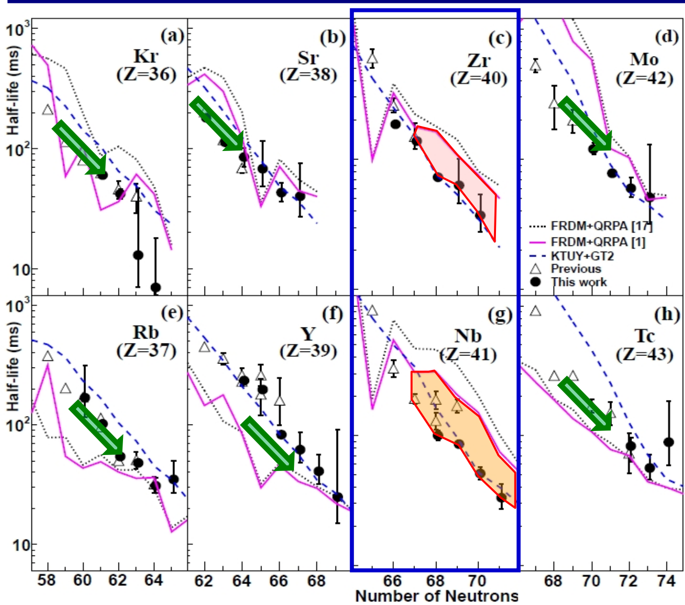
4 Clovers (RIKEN)

$LaBr_3$ (Milano)

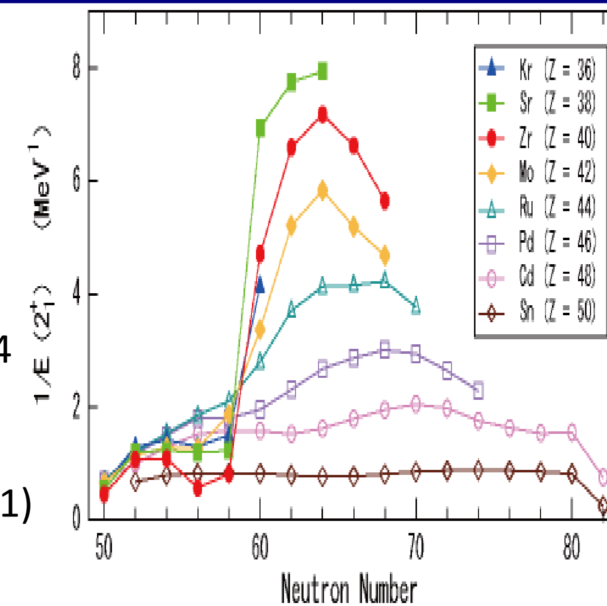
7 layers of DSSSD

(RIKEN, TUM)

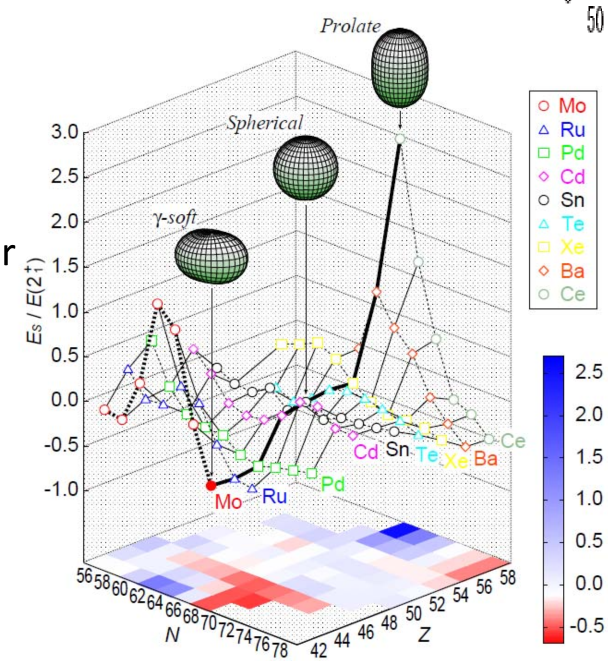
# Exotic Collective-Motions at A~110 and Their Applications to the R-process Nucleosynthesis



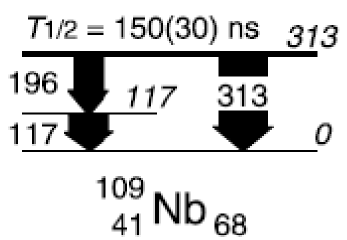

New Half-life data for 18 new isotopes
S. Nishimura et al., PRL 106, 052502 (2011)




Deformed magic N=64 in Zr isotopes
T. Sumikama et al., PRL 106, 202501 (2011)



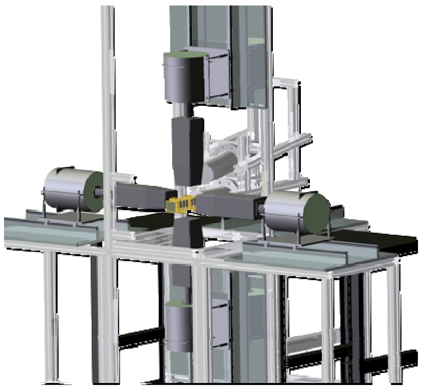

Low-lying level structure of Nb-109: A possible oblate prolate shape isomer
H. Watanabe et al., Phys. Lett. B 696, 186-190 (2011)



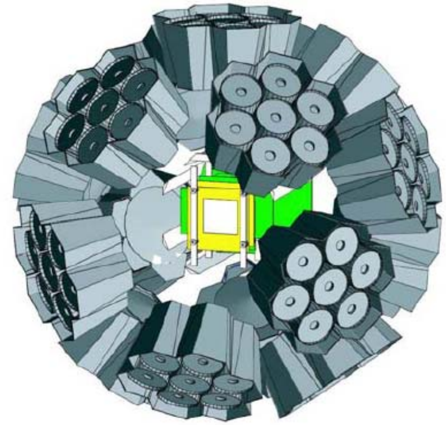

Development of axial asymmetry in neutron-rich nucleus Mo-110
H. Watanabe et al., Phys.Lett.B 704,270-275(2011)

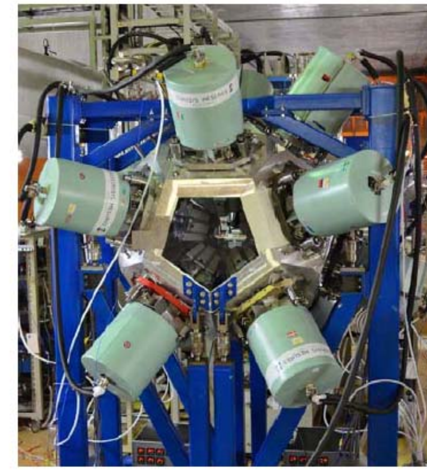
# Gain Factors from 2009 to 2012 for Decay Spectroscopy

First decay spectroscopy in 2009



EURICA setup





U-beam intensity
- 0.2 pnA → 10 pnA … <u>x 50 times</u>

Beam time …
- 2.5 days (4 papers) → 100 days … <u>x 40 times ( ~ 40 x 4 = 160 papers)</u>

Gamma-ray detector
- 4 Clover detectors (Det. Effi. ~1.5% at 0.662 MeV)
  → 12 Cluster detectors (Det. Eff. ~ 15 % at 0.662MeV) … <u>x 10 times</u>
  ( → gamma-gamma coincidence … x 100 times )

Beta counting system
- 16 x 16 pixels x 7 layers = 1792 pixels
  → 40x60 pixels x 8 layers = 19200 pixels … <u>x 4-10 times</u>
- Accept relatively higher implantation rate for $T_{1/2}$ measurement
  → <u>x 2 – 5 times</u>

- **EURICA Commissioning March, 2012**
- **EURICA Campaign has been started since June, 2012 !!**
  - **2012, June … 7 days (N=Z below $^{100}$Sn)**
  - **2012, Nov. … 30 days ($^{78}$Ni , $^{128}$Pd ,$^{136-138}$Sn )**
  - **2012, Dec. … ($^{124}$Rh, $^{115}$Nb, $^{81}$Cu, ..)**
  - **2013, May-June … EURICA Campaign (III)**

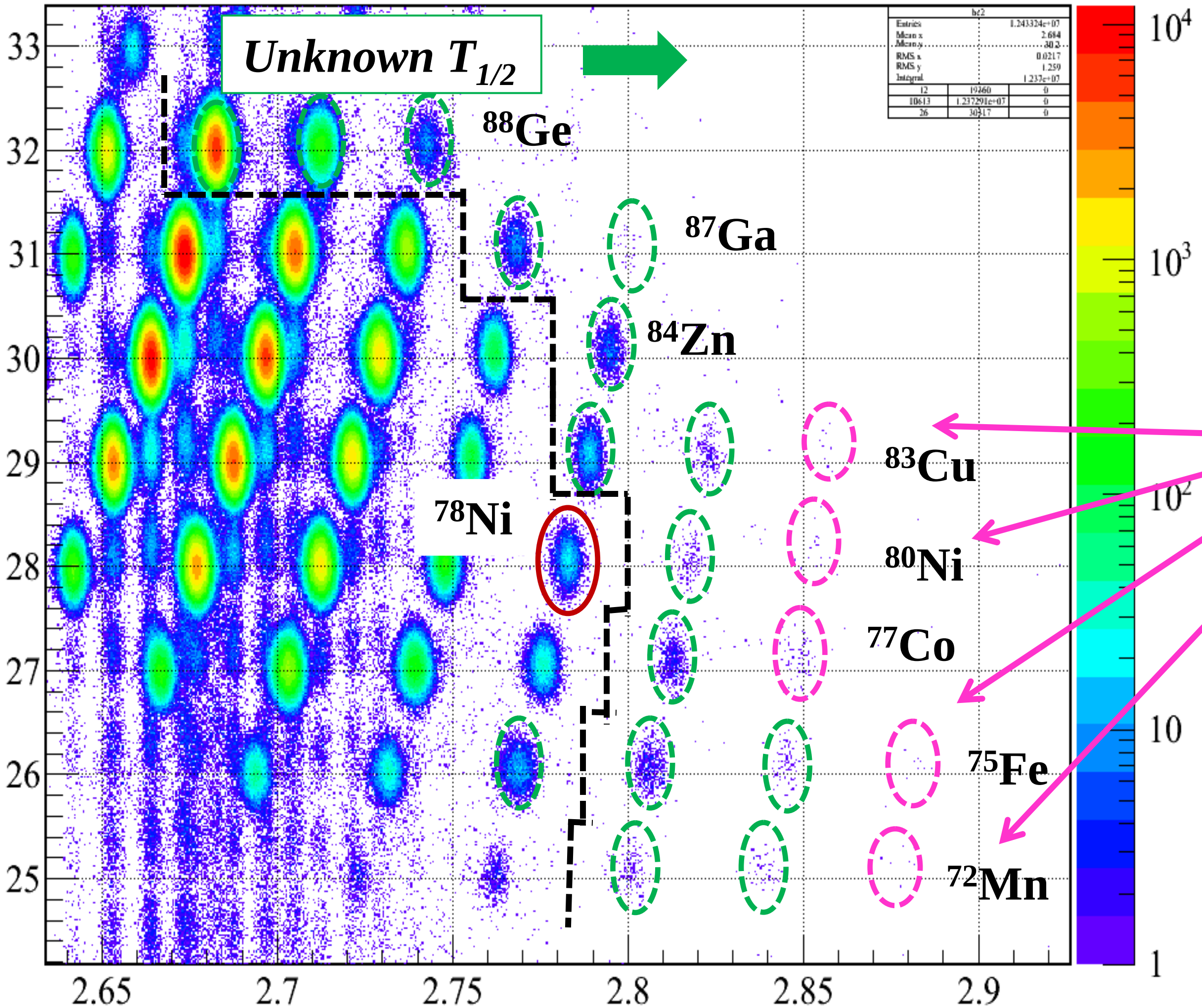
***Beta-decay half-lives**

***Excited states E(2+), E(4+), …**

***Long-lived isomers**

***Qbeta**

# Double-Magic Nuclei $^{78}$Ni (7.5 days)



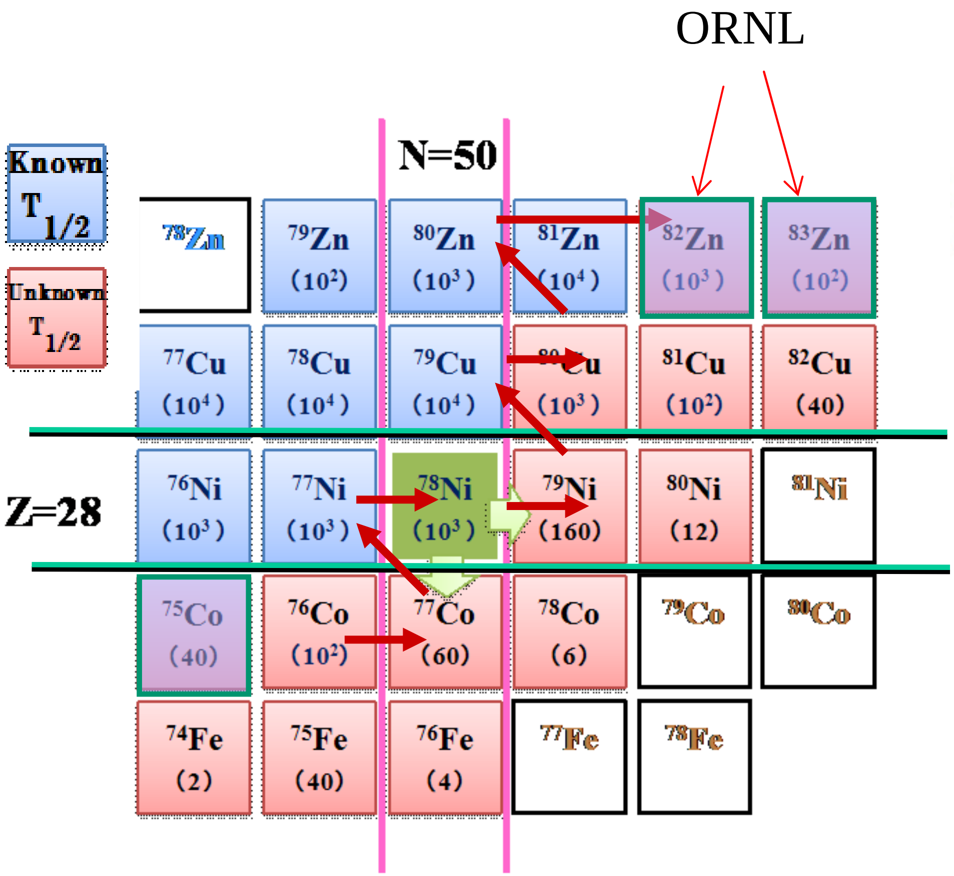

Spokesperson:
S.Nishimura

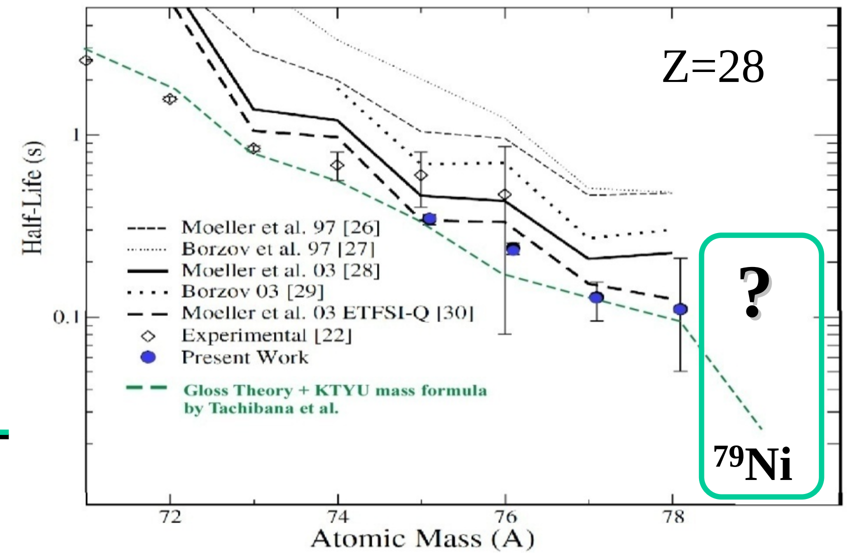
U-beam : 6 ~ 8 pnA

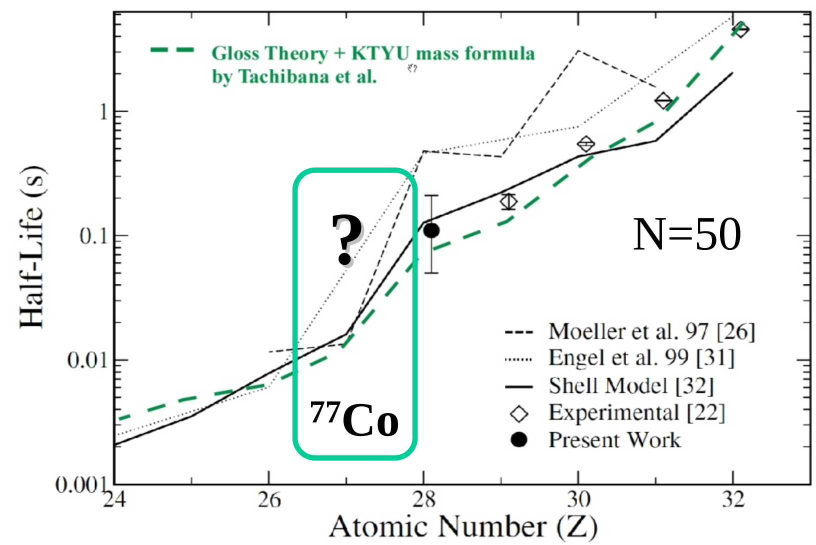
Statistics will be doubled with the $^{81}$Cu experiment (Spokesperson: Niikura)

→ ~ 10 k of $^{78}$Ni produced.

# Half-lives Measurement




□ … Not discovered

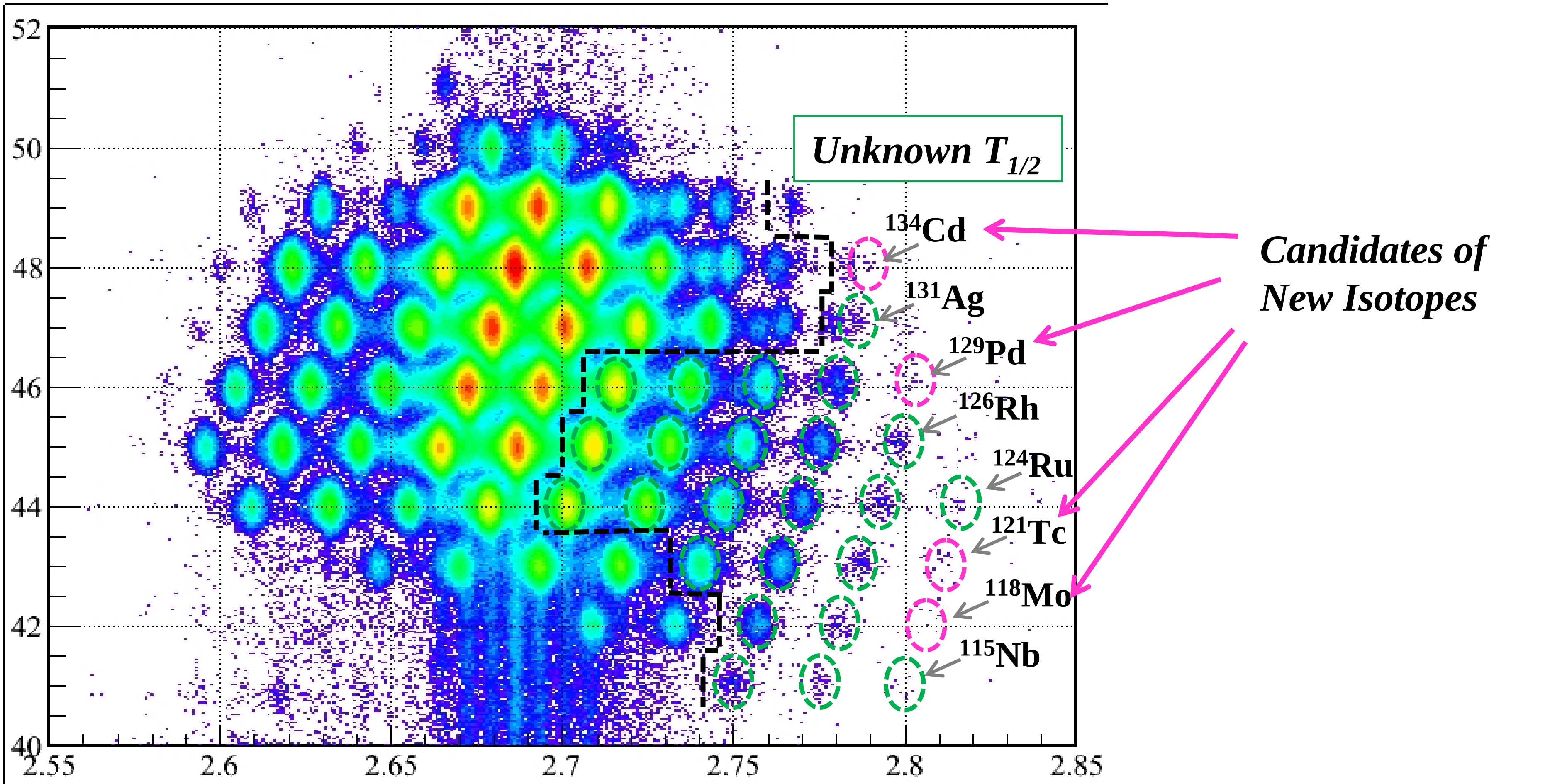
**Red … No decay information**

P.T.Hosmer et al., PRL 94, 112501(2005) mod.

# $^{128}$Pd setting (5 days)

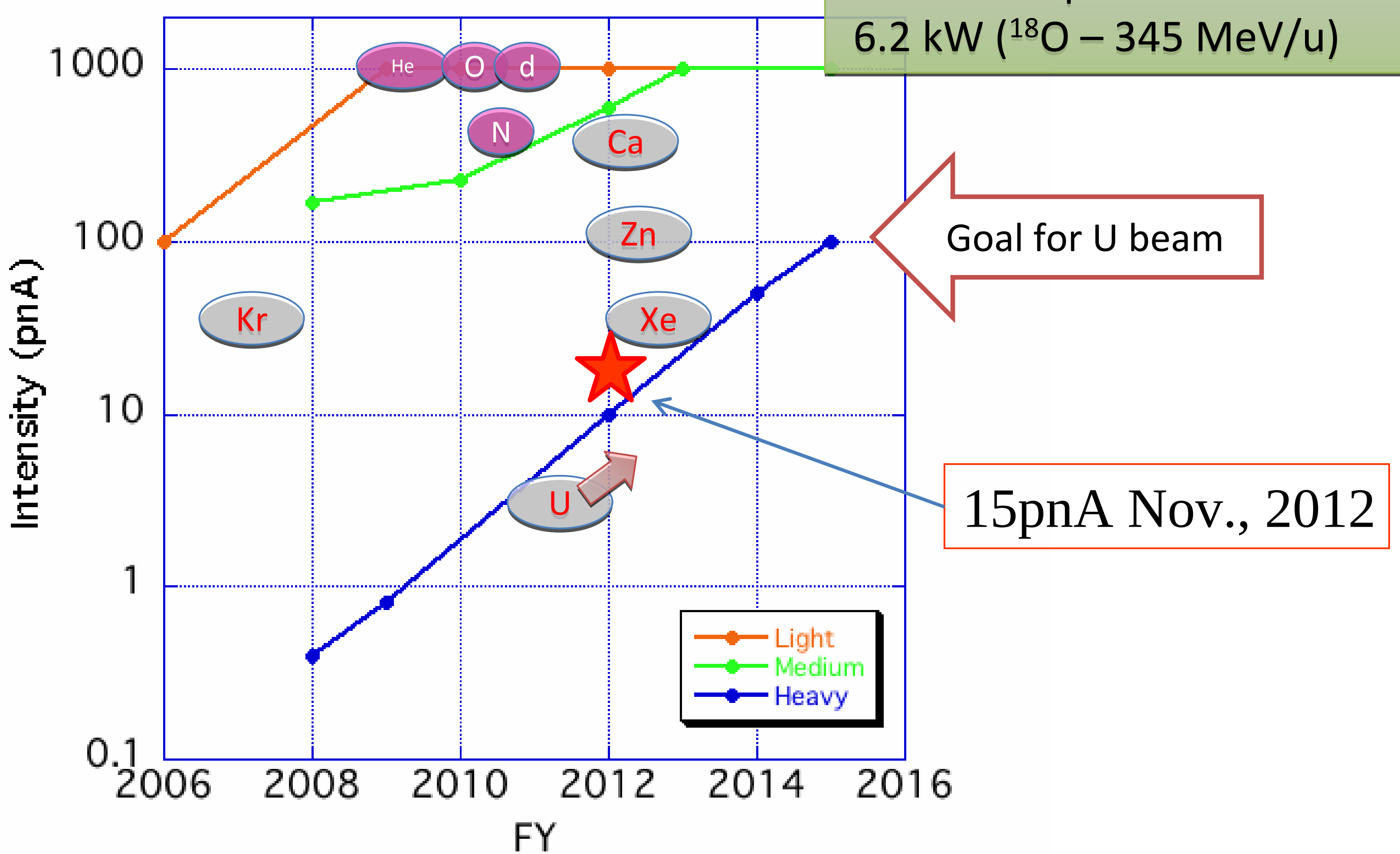
U-beam : 7 ~ 12 pnA

Spokespersons:
H.Watanabe/G.Lorusso



# Intensity records and outlook

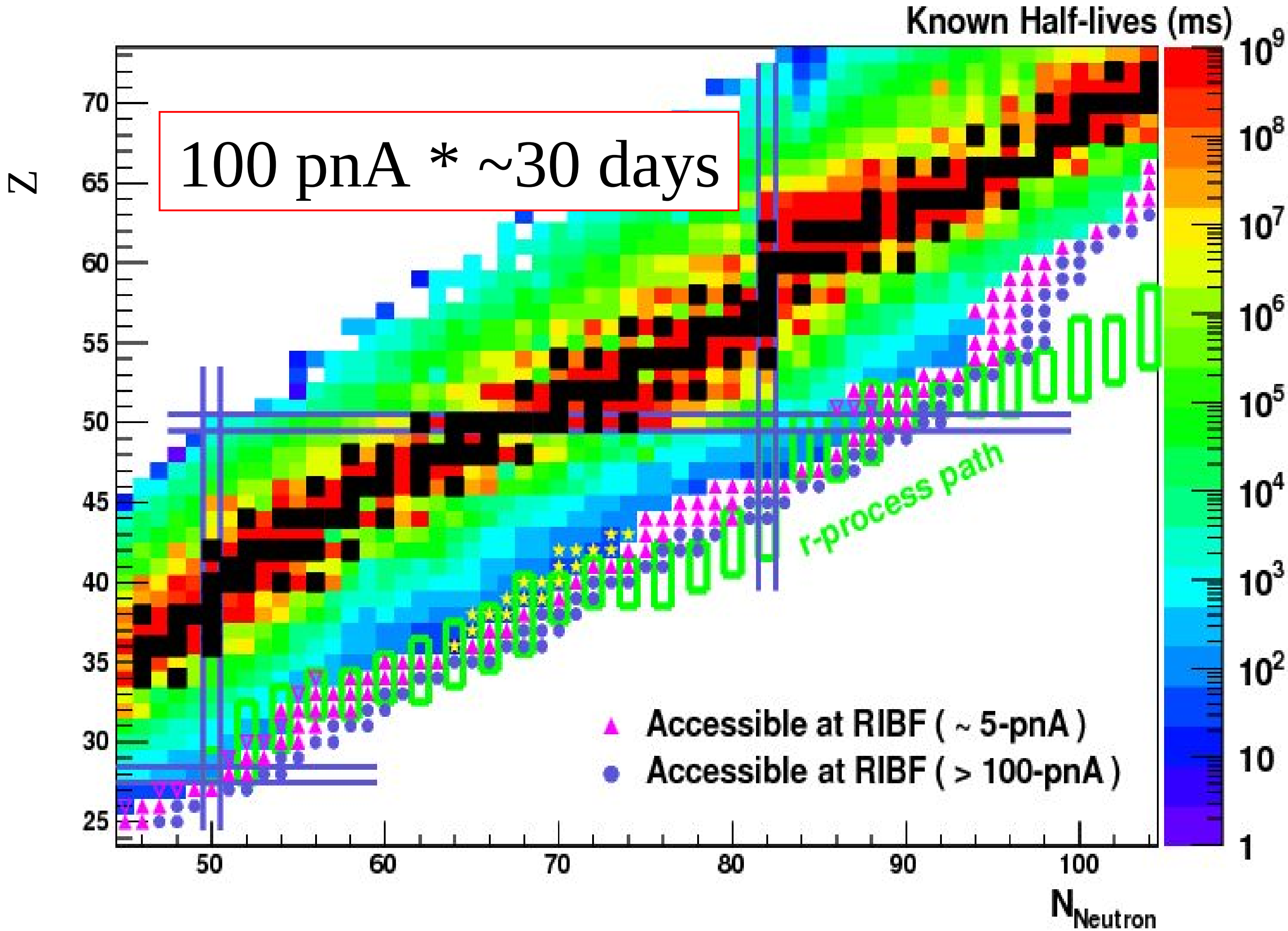
Max. beam power:
6.2 kW ($^{18}O$ – 345 MeV/u)




| | $^{48}$Ca | $^{70}$Zn | Kr | $^{124}$Xe | $^{238}$U |
|---|---|---|---|---|---|
| FY2012 plan | 150 pnA | - | 30 pnA | 10 pnA | 5 pnA |
| achieved (maximum) | 415 pnA ! (Jun. 2012) | 100 pnA ! (Jul. 2012) | '30 pnA' (Nov. 2007) | 27 pnA! (Jul. 2012) | 3.8 pnA (Dec. 2011) |

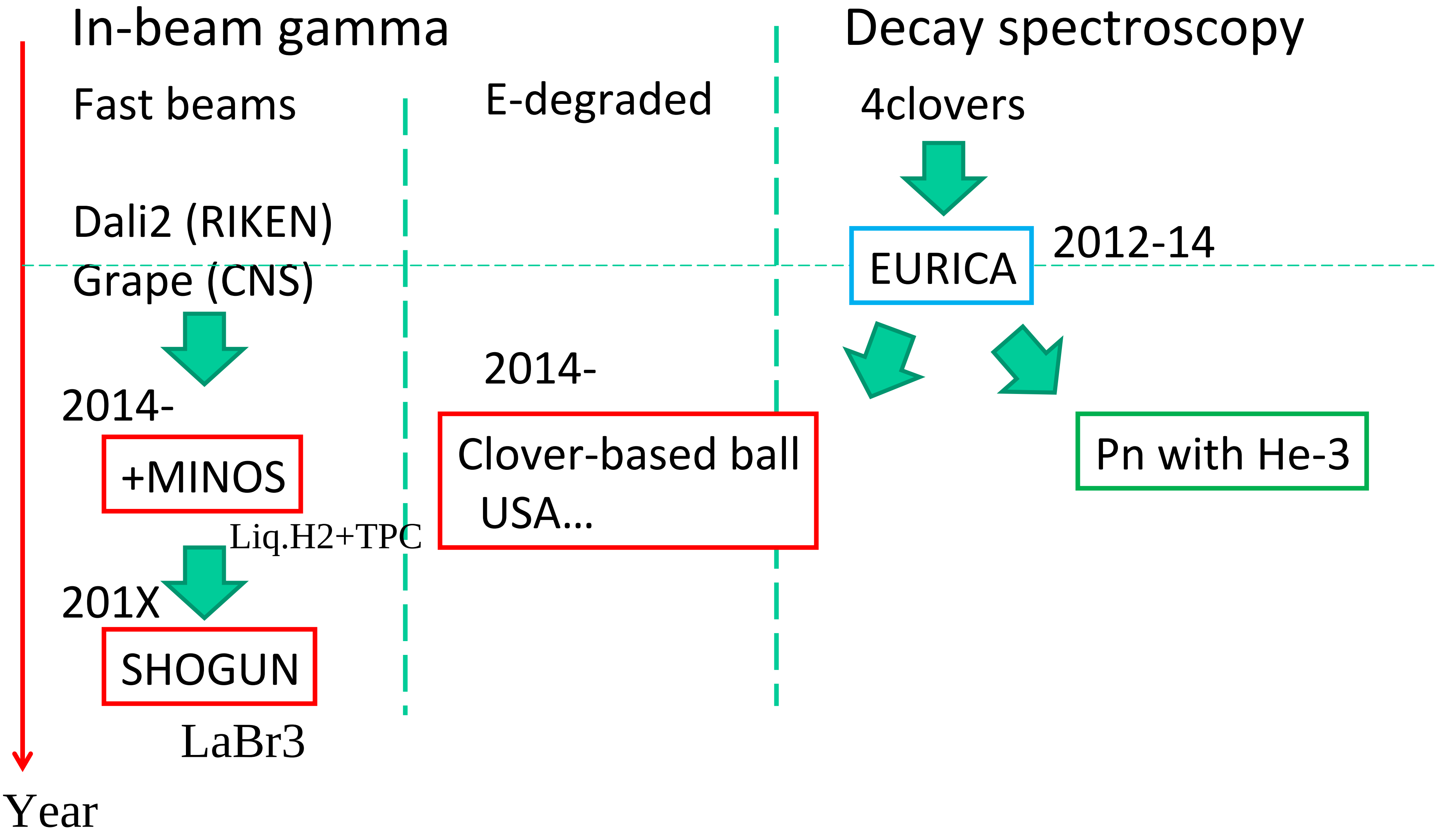
Kamigaito et al.

# In five years.. (U-beam int. ~ 100 pnA!)




**Several hundreds of new beta-decay half-lives in five years.**
**→ Significant contribution in nuclear structure and r-process nucleosynthesis.**

# Perspectives of spectroscopy for next 5 years



# SAMURAI Spectrometer **Kobayashi et al 2012-**

RIKEN NISHINA CENTER

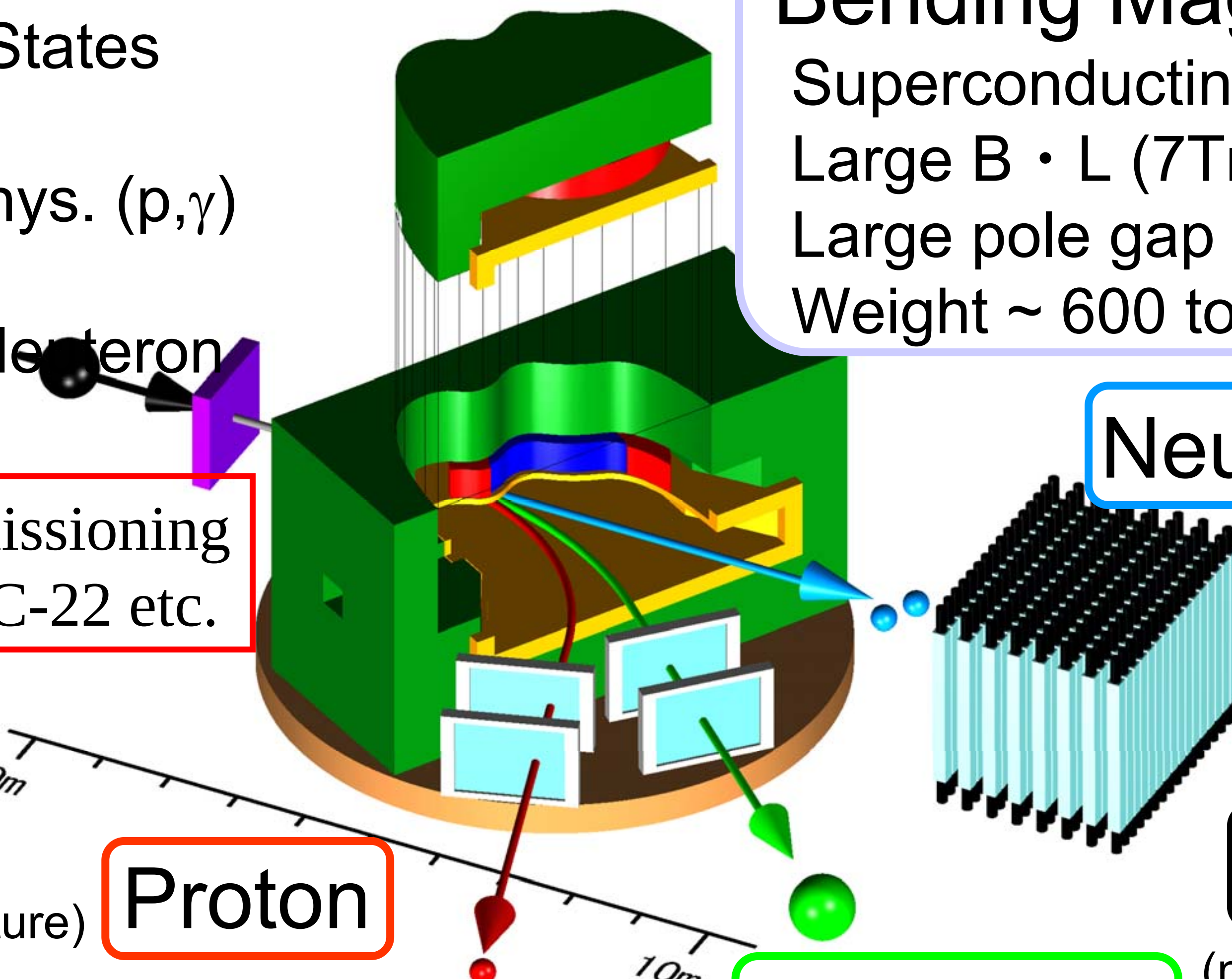
versatile spectrometer with a large superconducting magnet

Spectroscopy of
Unbound States
(p,2p)
Nucl. Astrophys. (p,$\gamma$)
Clustering
3NF w/ pol. deuteron
EoS in HIC

March Commissioning
May B-19, C-22 etc.

## Bending Magnet

- Superconducting
- Large B・L (7Tm)
- Large pole gap (80cm)
- Weight ~ 600 ton




Neutron

$\vec{d}$ setup
(not shown in picture)

Proton

Heavy Ion

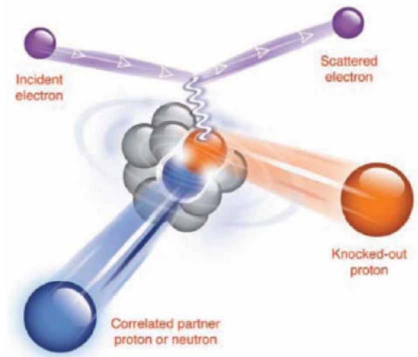
TPC
(not shown in picture)

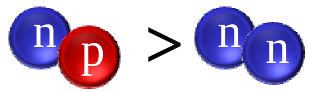
NSCL, Liverpool, TA&M joining this project

# $^{12}$C – Interesting Physics Found & Hidden

## $^{12}$C($e,e'pN$) @ 4.627 GeV

factor of 18

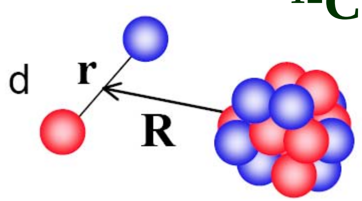



Strong *NN* tensor force
(short-range correlations)

R. Subedi et al.,Science 320 (2008) 1476.

## $^{12}$C($p$,$^3He$) , $^{12}$C($p,t$) @ 40 MeV




$\sigma_{np} / \sigma_{nn} \sim 2.4$

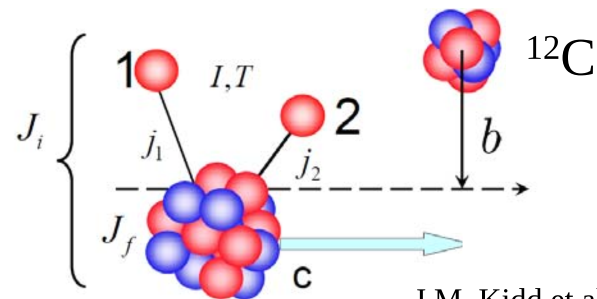
M. Yasue et al., J. Phys. Soc. Jap. 42, 367 (1977).

For $^{12}$C, 4$p$ & 4$n$ on $p_{3/2}$ shell
→No correlation: factor of 2.67 (pair counting)

**What is the behavior of *np*-correlations as a function of the relative momentum of the pair ?**

**RIBF: Nuclear Break-up reactions on C-target**

## $^{12}$C + $^{12}$C → X + anything @ 250 MeV/$u$ (inclusive)




J.M. Kidd et al., PRC 37, 2613 (1988).

| X | c 250 MeV/nucleon | |
|---|---|---|
| $^6$Li | 26.35±2.1 | |
| $^7$Li | > 17.19±1.3 | |
| $^8$Li | > 1.33±0.34 | |
| $^7$Be | 22.64±1.49 | |
| $^9$Be | 10.44±0.85 | |
| $^{10}$Be | 5.88±9.70 | -2$p$ |
| $^{11}$Be | 0.36±0.26 | |
| $^8$B | < 3.21±0.59 | |
| $^{10}$B | 47.50±2.42 | -$np$ |
| $^{11}$B | 65.61±2.55 | |
| $^{12}$B | < 0.49±0.67 | |
| $^{10}$C | 5.33±0.81 | -2$n$ |
| $^{11}$C | 55.97±4.06 | |

factor of ~ 8

Jenny Lee et al.

# *np*-Correlations & 3-body Force

**P. Navratil (TRIUMF):**

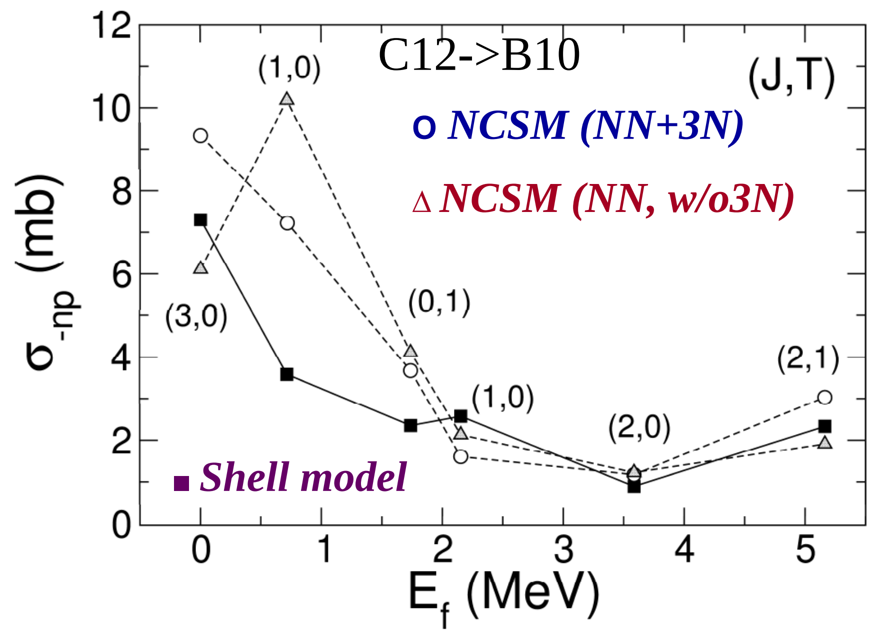
no-core shell model (NCSM) *ab initio* calculations
( including realistic 2-body interaction and 3-body forces )

**NCSM ($N_{max}$ = 6, Full hω=20) → $^{12}C$, $^{10}B$**

Same reaction Model
(J.A. Tostevin)

**Significant Increase in the T=0 Cross Sections !**

**T=0 cross section Sensitive to 3*N*-force**




J.A. Tostevin, E. Simpson, P. Navratil, paper in preparation

**Role of np-correlation & NNN Force ?**

**NCSM:** switch on/off 3-body force

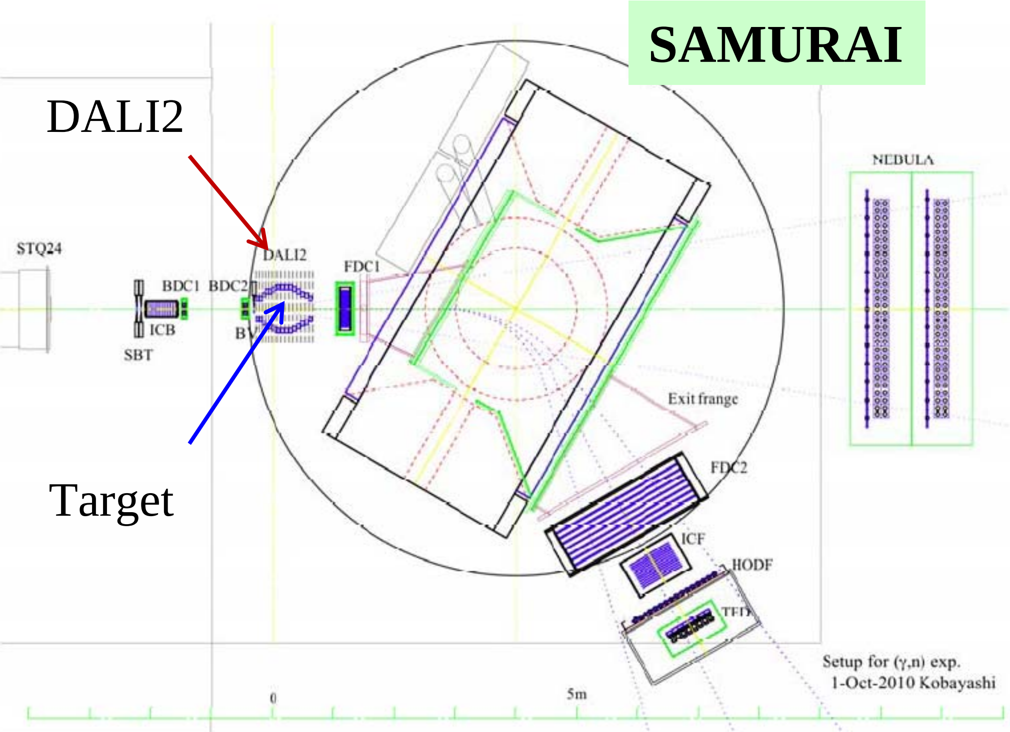
**TOSM** (tensor-optimized shell model)
T. Myo (Osaka Tech): Argonne potential for 2N, no 3N force at present

**Theories reach Bottleneck ….**
**Final-State-Exclusive Data needed !**
**- gain Detailed knowledge**
**- guide Theoretical Developments**

# RIBF: First final-state exclusive measurement of *np*-pair removal

Jenny Lee et al.

**$^{12}$C → $^{10}$B (-*np*), $^{10}$C (-2*n*), $^{10}$Be (-2*p*) @ 250 A MeV**




## γ-residues-neutron Measurement

- First quantitative study of *np*-correlation & 3-body force

✓ First detailed study of diffractive mechanism in 2N removal reaction

✓ First insight into internal structure of correlated pairs (FSI considered)

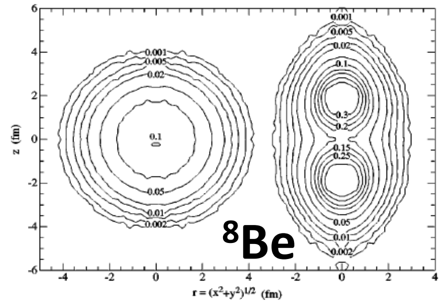
**Benchmark: New Powerful Tool of Direct *np*-removal reaction**

**SAMURAI at RIBF → Systematic & Quantitative knowledge of *np*-Correlations & 3N-force toward exotic *N*=*Z* nuclei**

# *Study of clustering in Beryllium isotopes*

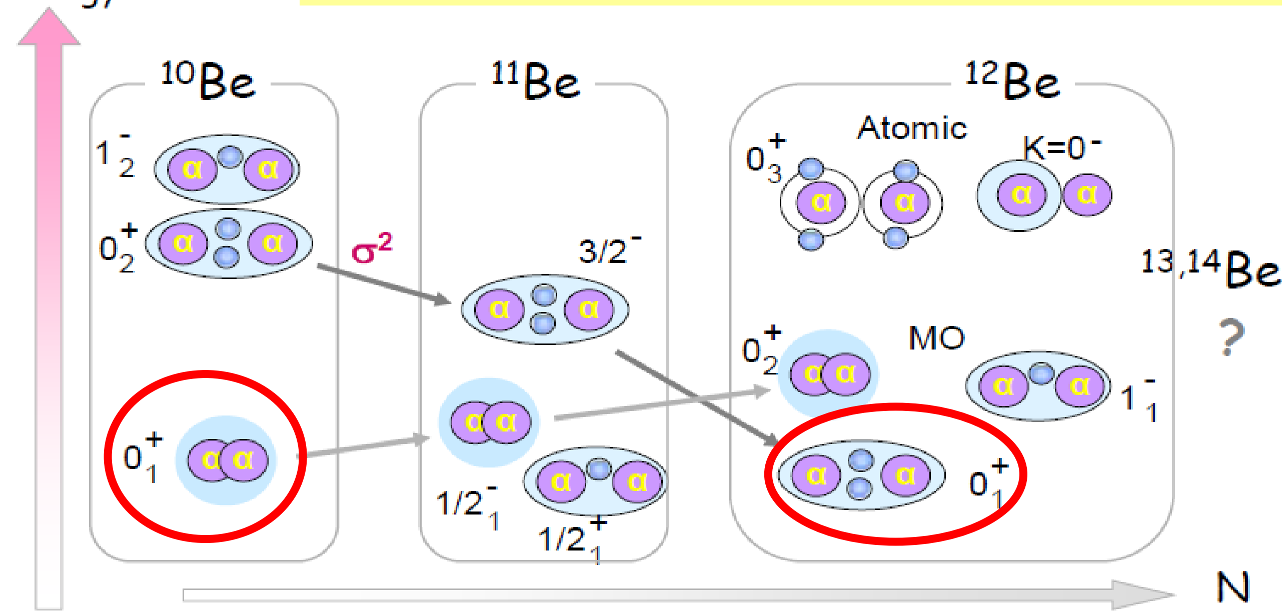
D. Beaumel et al.

- $^{8}$Be has well developed cluster structure well reproduced by *ab initio* calculations
  How about in neutron-rich isotopes ?
  What is the role of excess neutrons ?




R.B. Wiringa et al., PRC 62 (2000)

AMD Prediction:
Excess neutrons drastically changes cluster structures.

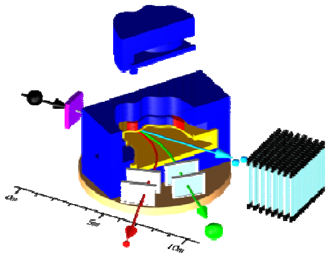



From Y. Kanada-Enyo

$^{12}$Be GS predicted to have extended cluster configuration compared to the compact $^{10}$Be

**Proposed approach: probe quantitatively the wave-function of the *ground-state* of n-rich Be isotopes using cluster QFS such as $^{10,12,14}$Be(p,pα)**

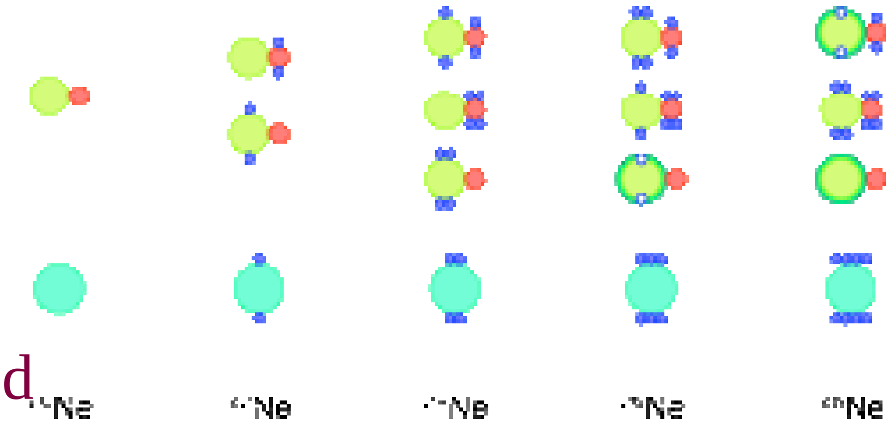
**Measured Xsections will be compared to DWIA calc. using inputs from AMD or cluster models**



# Valence neutrons expand
# Variety of cluster in light nuclei

H.Otsu et al.

1. Ne isotope



$^{20}$Ne := $^{16}$O + α

...

$^{28}$Ne := $^{24}$O + α

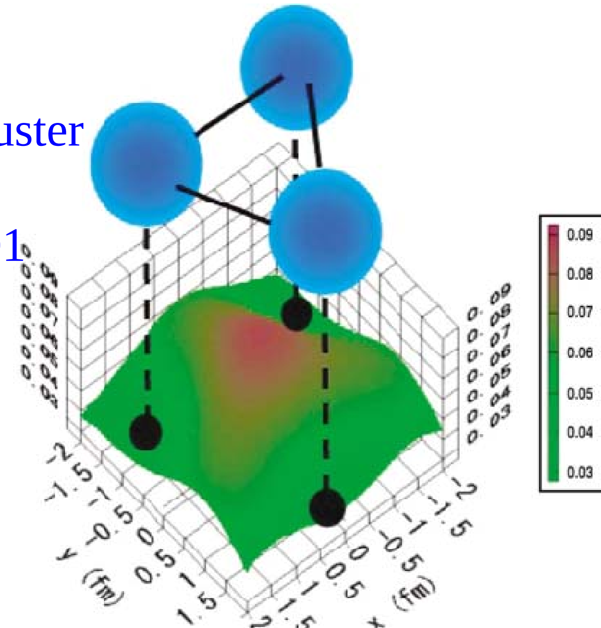
$^{28}$Ne : Discipline restored

two doubly magic cluster candidates

2. C isotope

This spring
Exp. will run

$^{14}$C Triangular Shape cluster
by N. Itagaki et. al.,
PRL 92(2004) 142501



$^{12}$C := $^{8}$Be(:= α+α) +α

$^{14}$C := $^{10}$Be(:= $^{6}$He+α) +α

$^{16}$C := $^{12}$Be(:= $^{6}$He+$^{6}$He, $^{8}$He+α) +α

$^{16}$C : Variety enlarged

3 body (triangle shape) cluster candidates

Exploration of cluster states by SAMURAI

# Summary

RIBF has started in operation since 2007.

Bunch of data for shell evolution and nuclear astrophysics are being produced via in-beam gamma spectroscopy and decay spectroscopy

Primary beam intensity is increased year by year to expand our play ground.

At the SAMURAI spectrometer, the new programs on np-correlation and clusters are starting.