B02:
Properties of neutron-rich nuclear matter with low-to-medium nuclear density
中性子過剰な中低密度核物質の物性

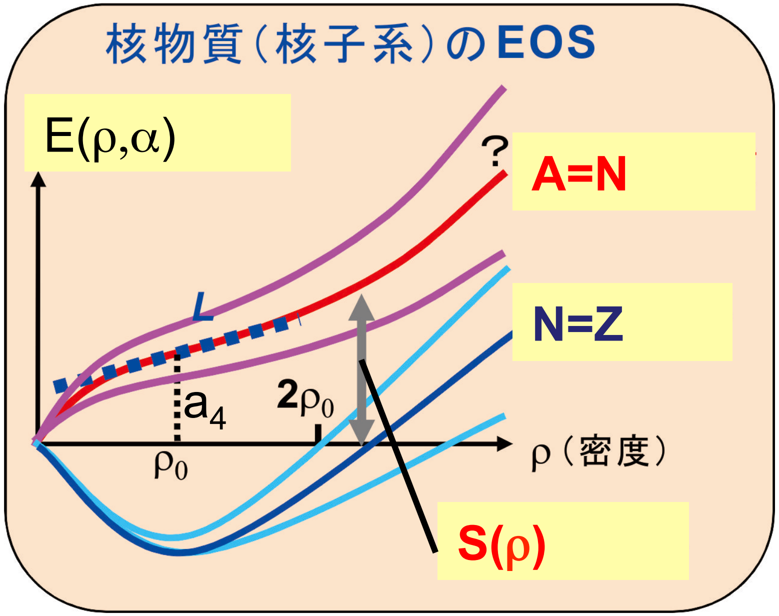
T.Nakamura, Y.Kondo, Y.Togano
Tokyo Inst. of Tech.
S.Shimoura
CNS, U. of Tokyo
T.Teranishi
Kyushu U.

中村隆司　東工大
下浦享　東大CNS
近藤洋介、栂野泰宏　東工大
寺西高　九大

実験と観測で解き明かす中性子星の核物質　キックオフシンポジウム
Kickoff Symposium “Nuclear Matter in Neutron Start Investigated by Experiments and Astronomical Observations”– Oct.26.27, 2012, @Nishina Center, RIKEN

Contents

EOS (Nucleonic Degree of Freedom)



Difference of n and p densities

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

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

Symmetry Energy: S(ρ)

EOS of nuclear matter within nucleonic D.O.F

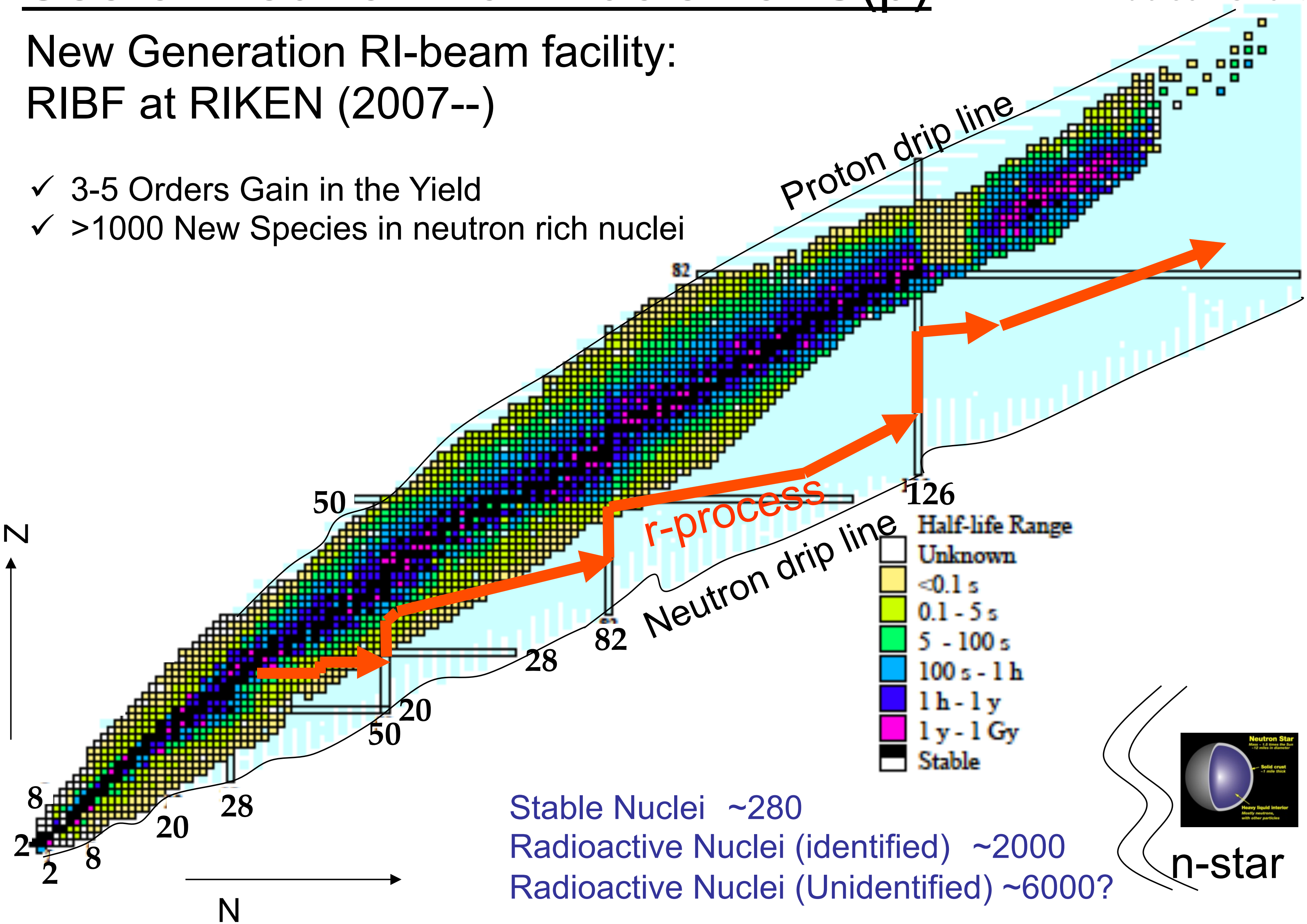
- ☐ Provide Basis of EOS with non-nucleonic D.O.F
  → Maximum density→ Composition→ Maximum Mass/Radii of N-Star
- ☐ Direct determination of EOS (within nucleonic D.O.F) can be possible using a variety of observables
- ☐ Most important but unknown term: **Symmetry Energy S(ρ)**

Neutron-rich Nuclei →Microscopic Laboratory for Neutron-Star Physics

Use of Neutron-rich Nuclei for S(ρ)

New Generation RI-beam facility:
RIBF at RIKEN (2007--)

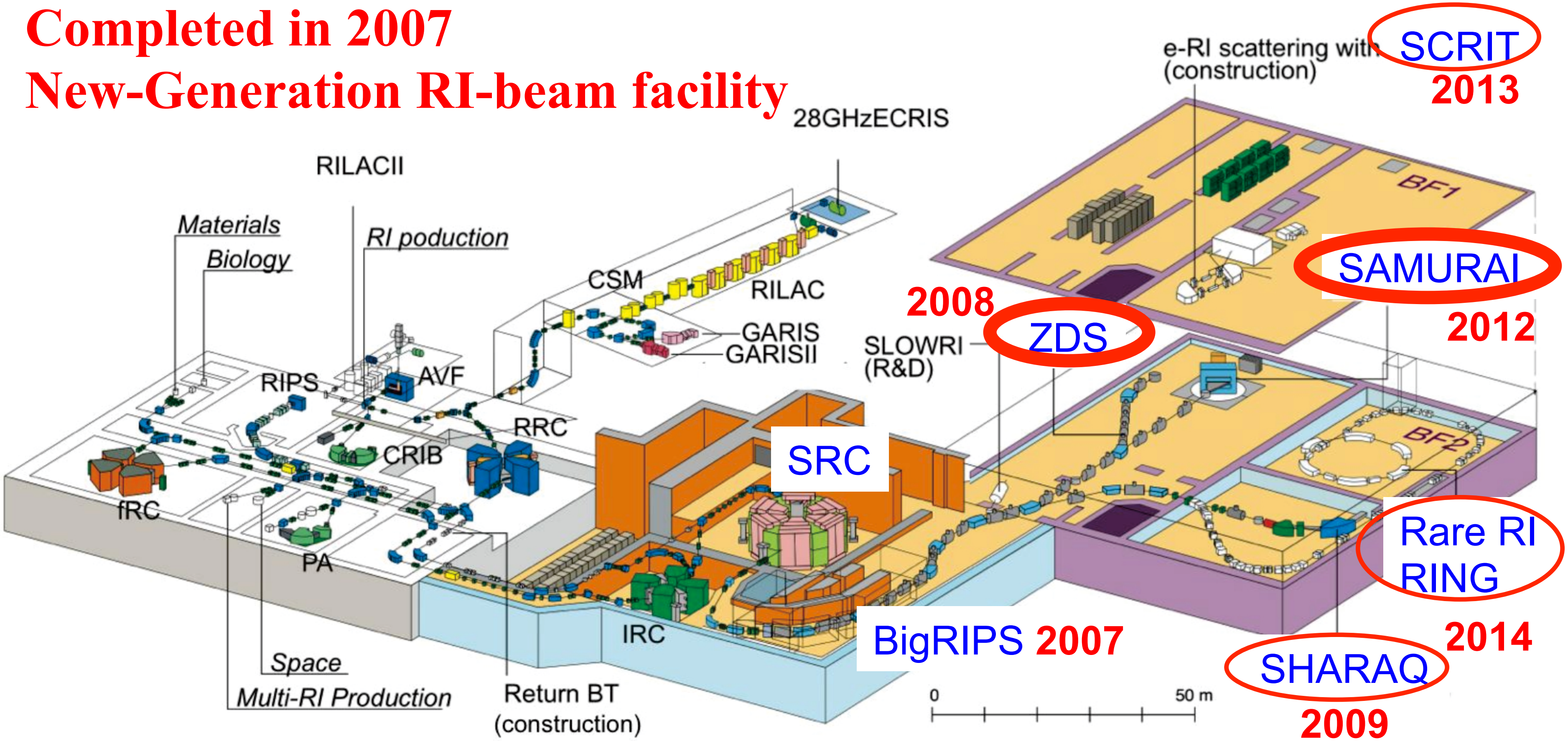
- ✓ 3-5 Orders Gain in the Yield
- ✓ >1000 New Species in neutron rich nuclei



Stable Nuclei ~280
Radioactive Nuclei (identified) ~2000
Radioactive Nuclei (Unidentified) ~6000?

RIKEN RI Beam Factory (RIBF) (2012)

Completed in 2007
New-Generation RI-beam facility



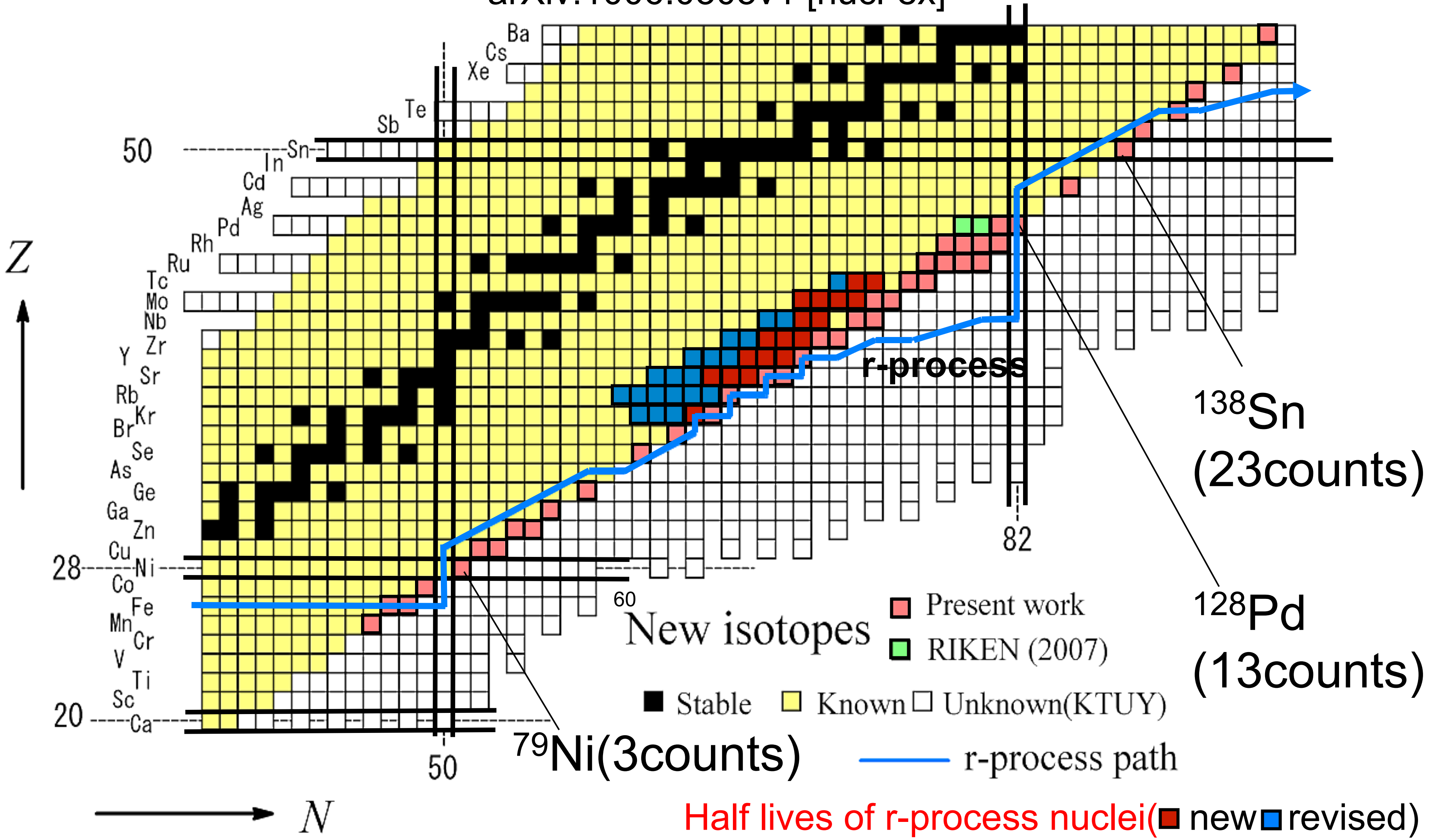
SRC: World Largest Cyclotron (K=2500 MeV)
Heavy Ion Beams up to ^{238}U at 345MeV/u (Light Ions up to 440MeV/u)

BigRIPS: Large Acceptance Fragment Separator (80mradx100mrad, dP/P:6%)

Summary of identified New Isotopes at RIBF

(~50 species)

T.Ohnishi, T.Kubo et al., JPSJ 77 (2008) 083201.
T.Ohnishi, T.Kubo et al., JPSJ,79 (2010) 073201.
arXiv:1006.0305v1 [nucl-ex]

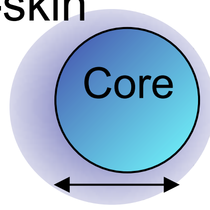


Half lives of r-process nuclei(■ new ■ revised)
Nishimura et al., PRL106,052502(2011).

How to determine the EOS?

---Projects of B02

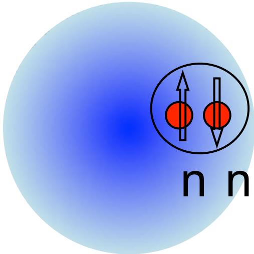
- S(ρ) : S_0, L(*pressure*), K_{sym}(*Incompressibility*)
  ← Collective Motion of Neutron-rich Nuclei



Pygmy Dipole Resonance (E1)

Breathing Mode (E0)

- Superfluidity ←Dineutron correlation of halo nuclei



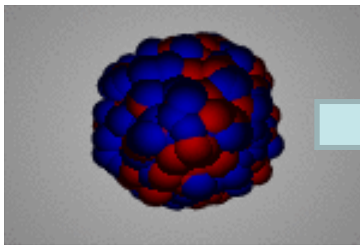
- S(ρ)←Nuclear force
  (density dependence, isospin dependence, 3-body force)
  ← tetra neutron, exotic nucleonic system
- S(ρ)←Bulk Property ← neutron skin thickness
  nuclear masses

$\square$ S(ρ) : S_0,*L*(*pressure*), K_{sym}(*Incompressibility*)
← Collective Motion of Neutron-rich Nuclei

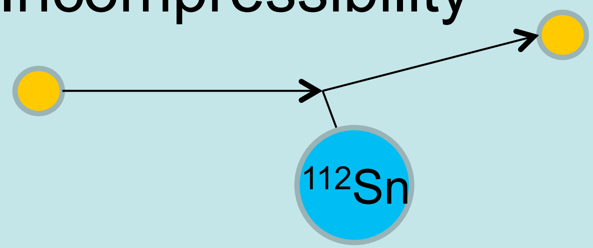
Giant Resonance: Collective Motion of Nuclei

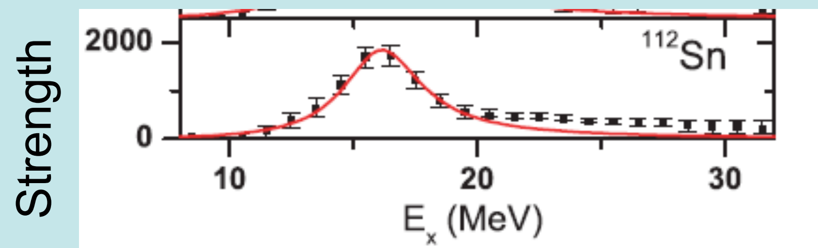
Isoscalar

Monopole
(GMR)



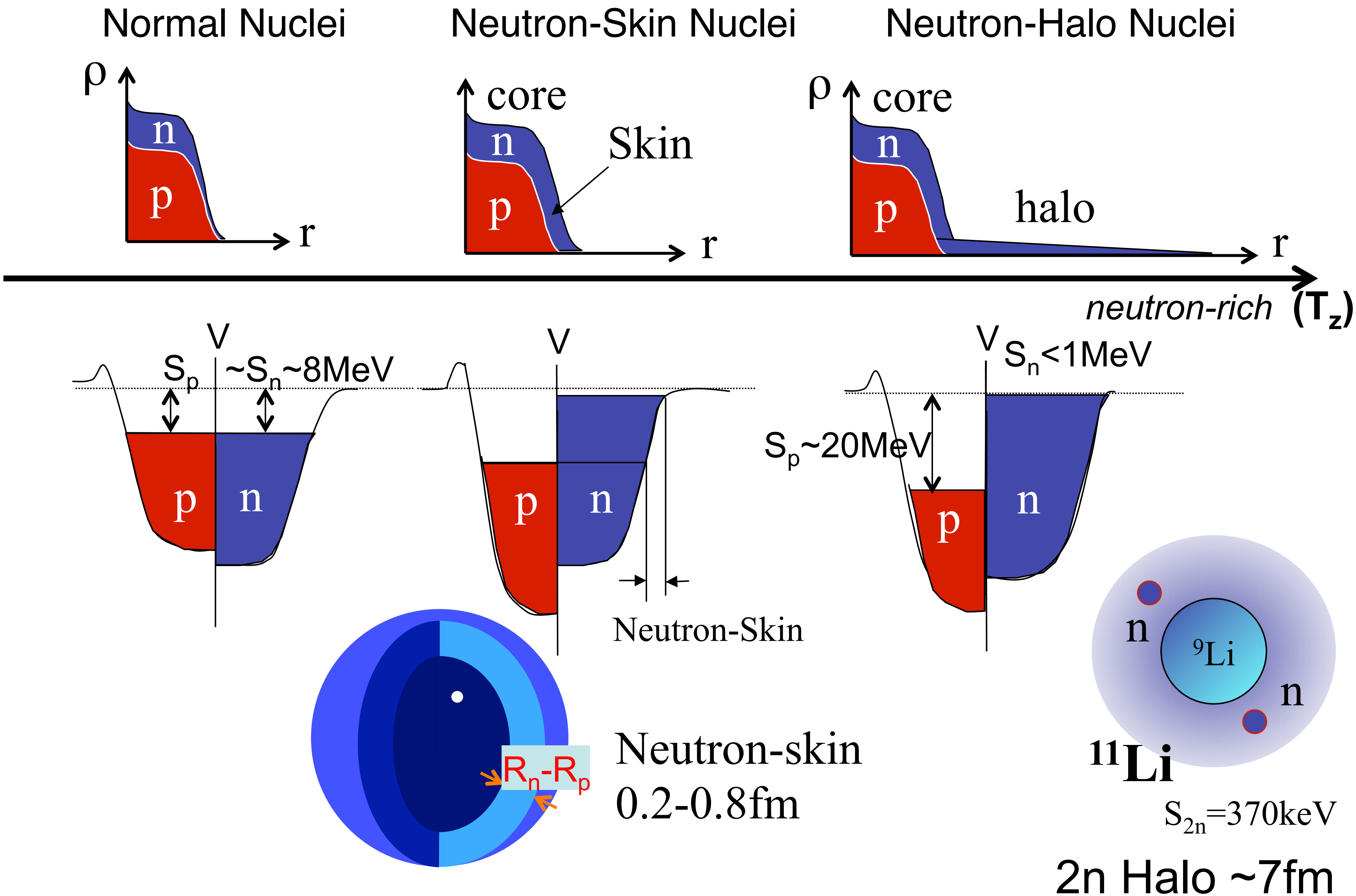
Isoscaler Giant Monopole Resonance
→Incompressibility



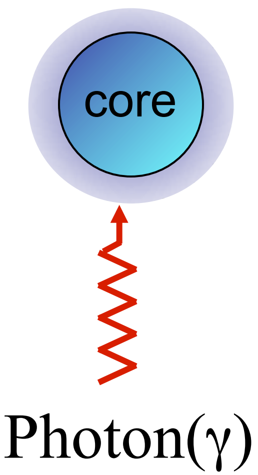


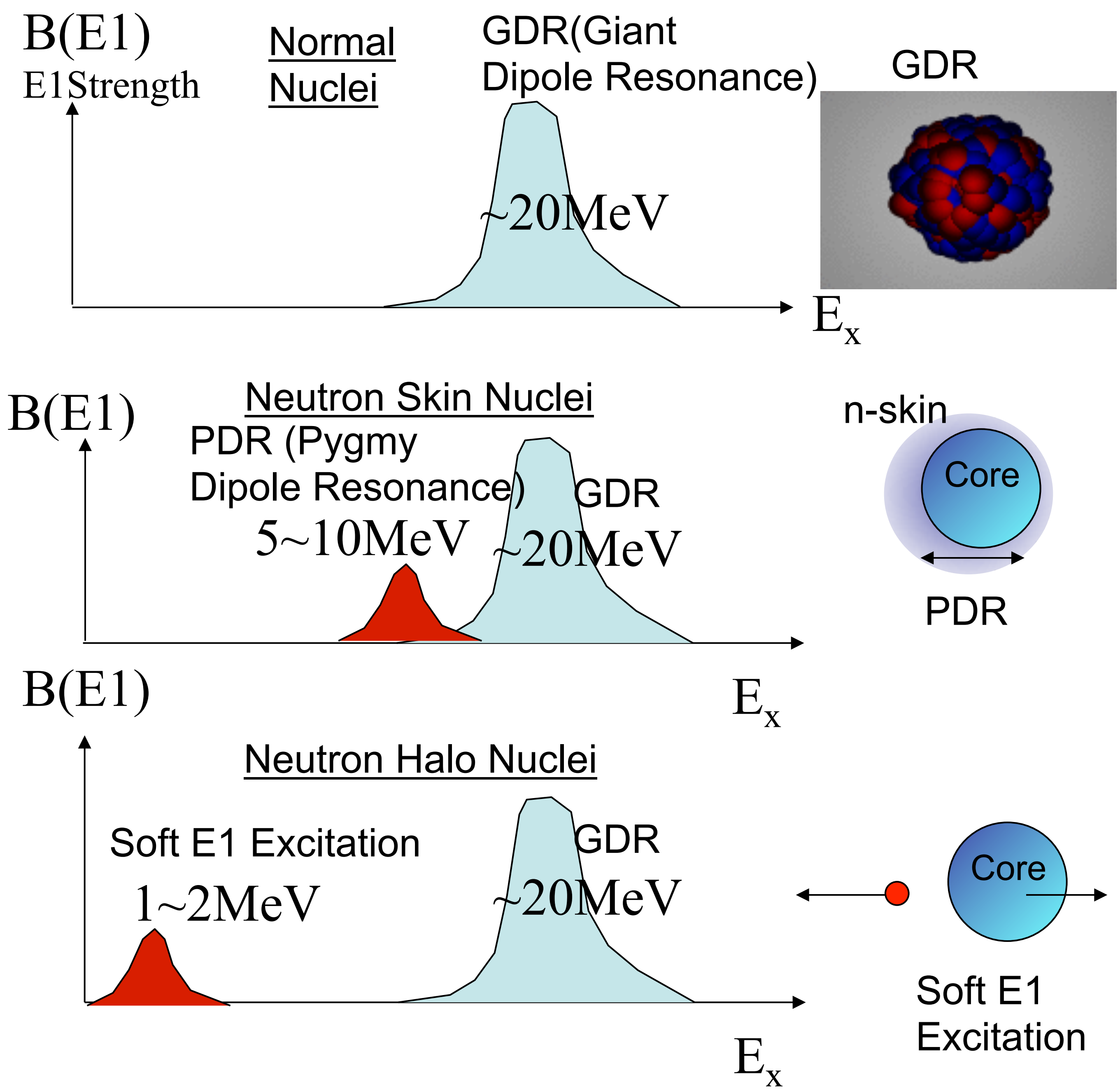
K_∞= 240(10) MeV (N=Z)
K_{sym}= -500(100) MeV
T.Li et al.,PRC81,034309(2010).
and references therin
(Data are from RCNP, Osaka)

Neutron Skin and Neutron Halo

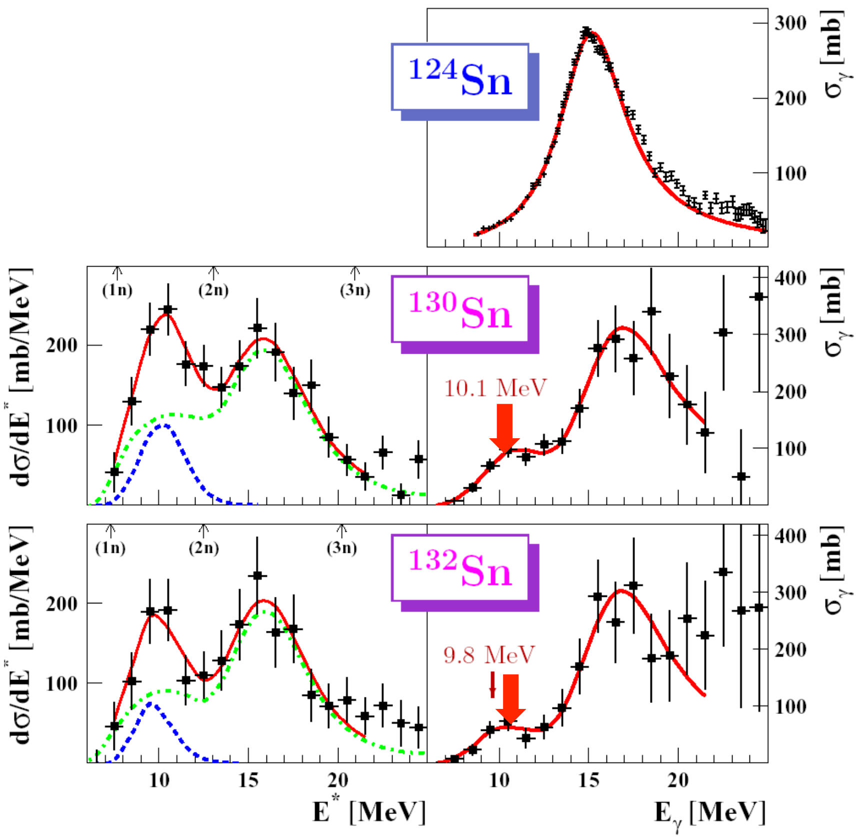


Electric Dipole Response

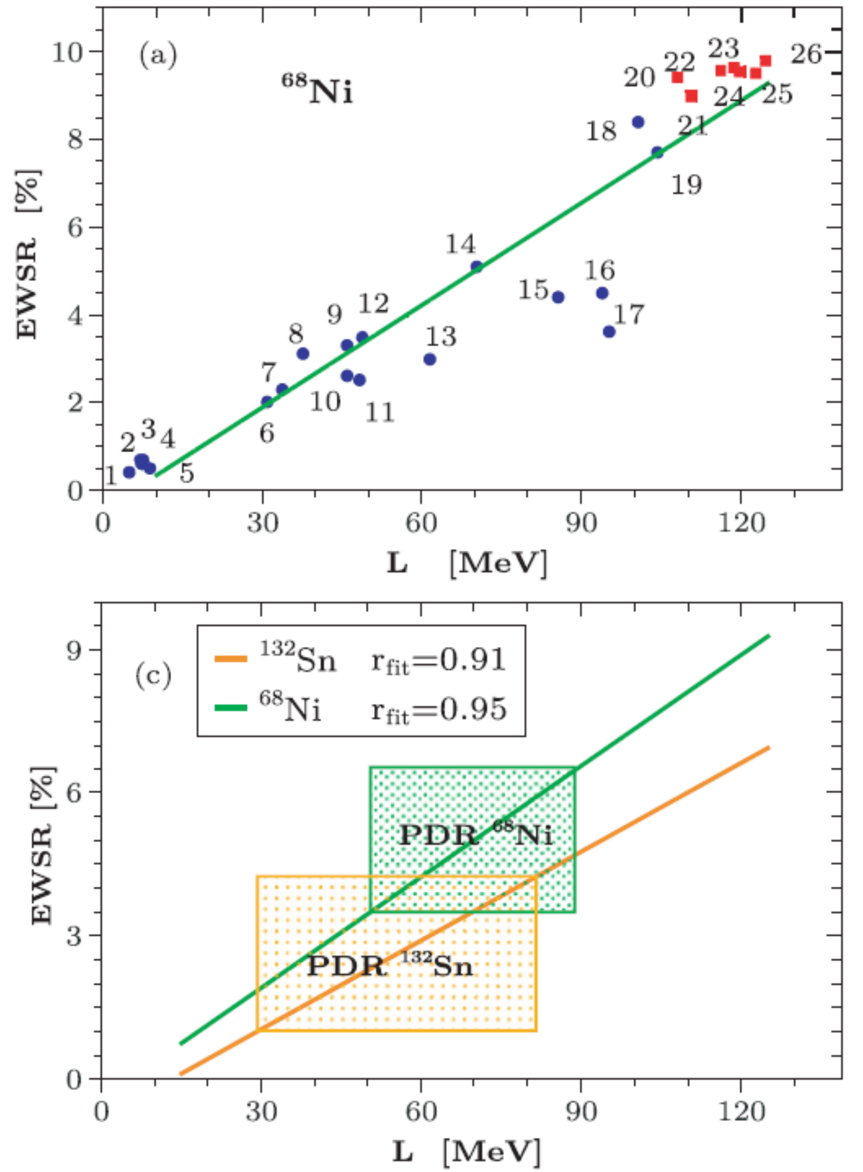




Pygmy Dipole Resonance of Neutron Skin Nuclei

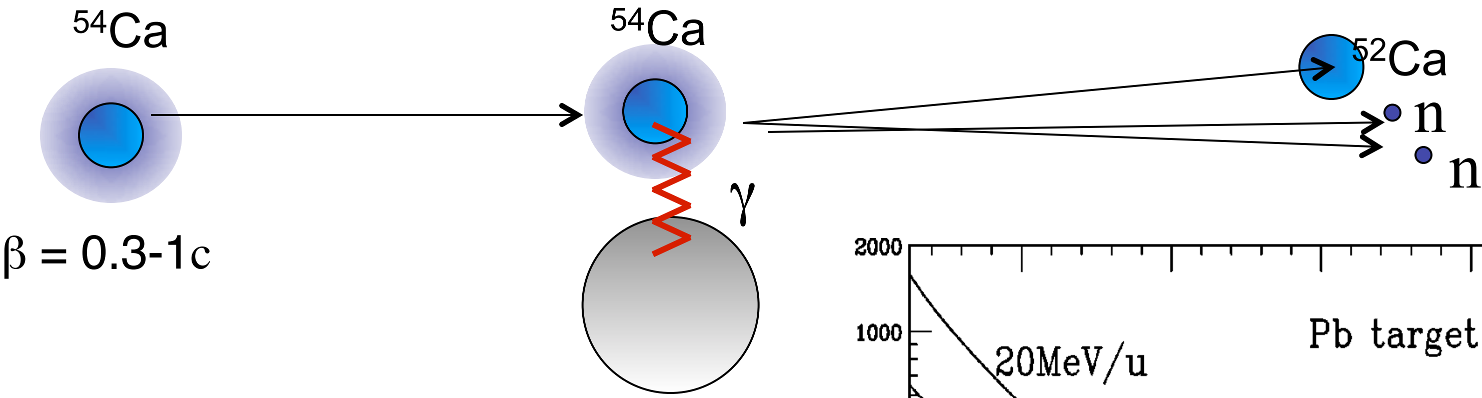


P. Adrich et al., PRL 95 (2005) 132501 (GSI) ^{130,132}Sn

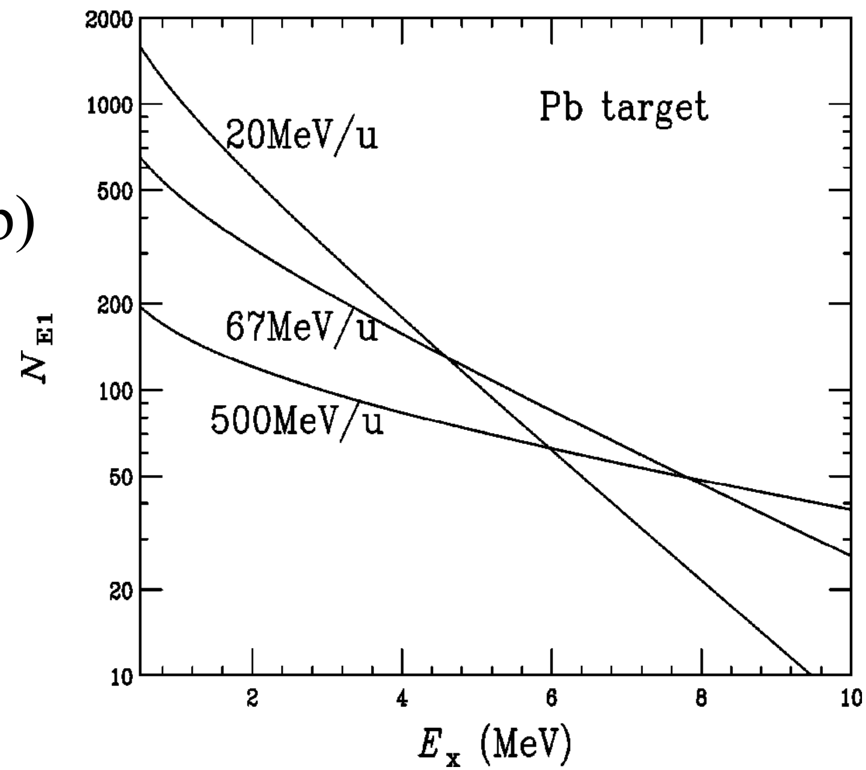


L: Pressure term

Method: Coulomb Breakup – Use of a Virtual Photon



Heavy Target (Pb)



Excitation Energy (=Photon Energy)

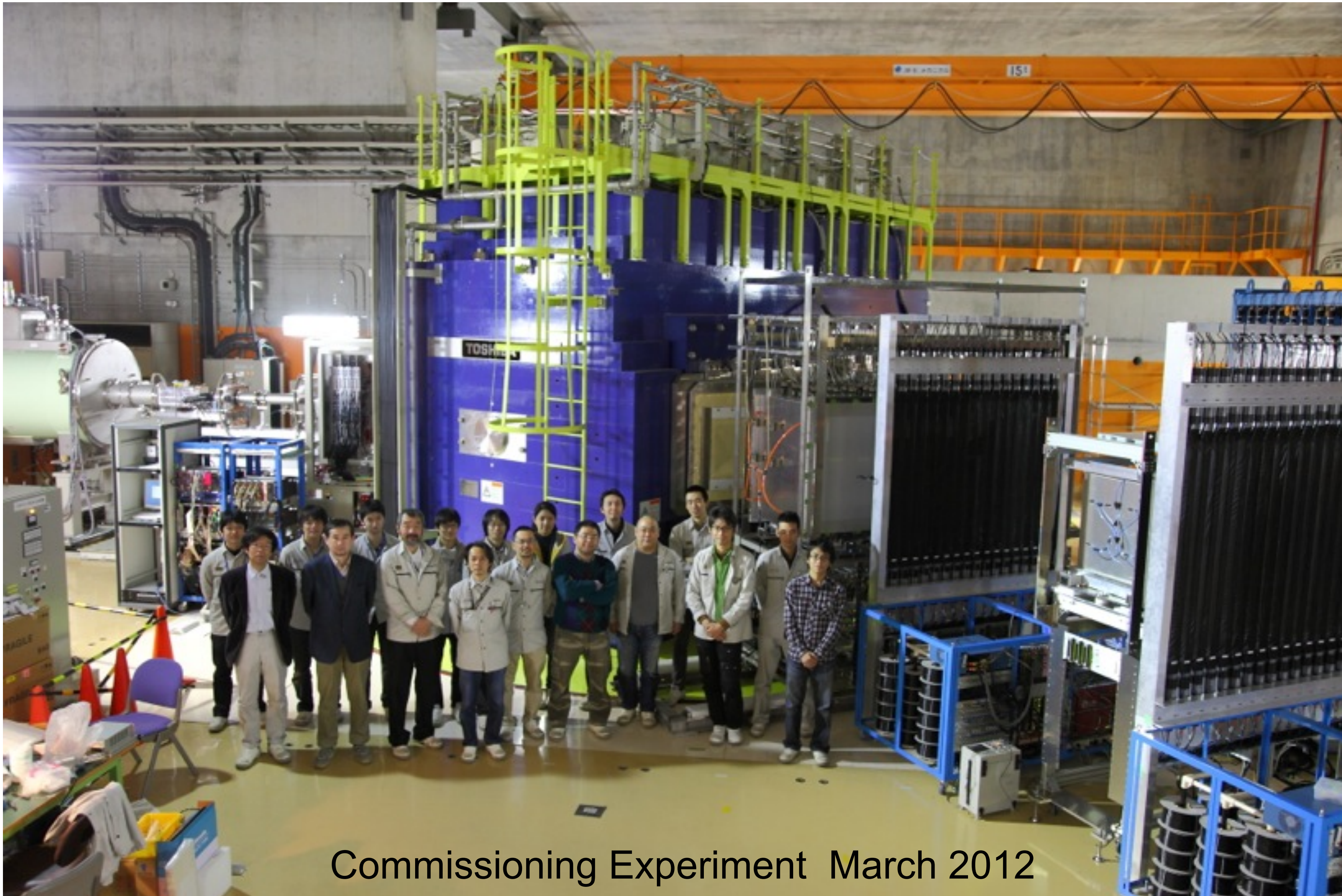
Excitation by a Virtual Photon

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

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

SAMURAI

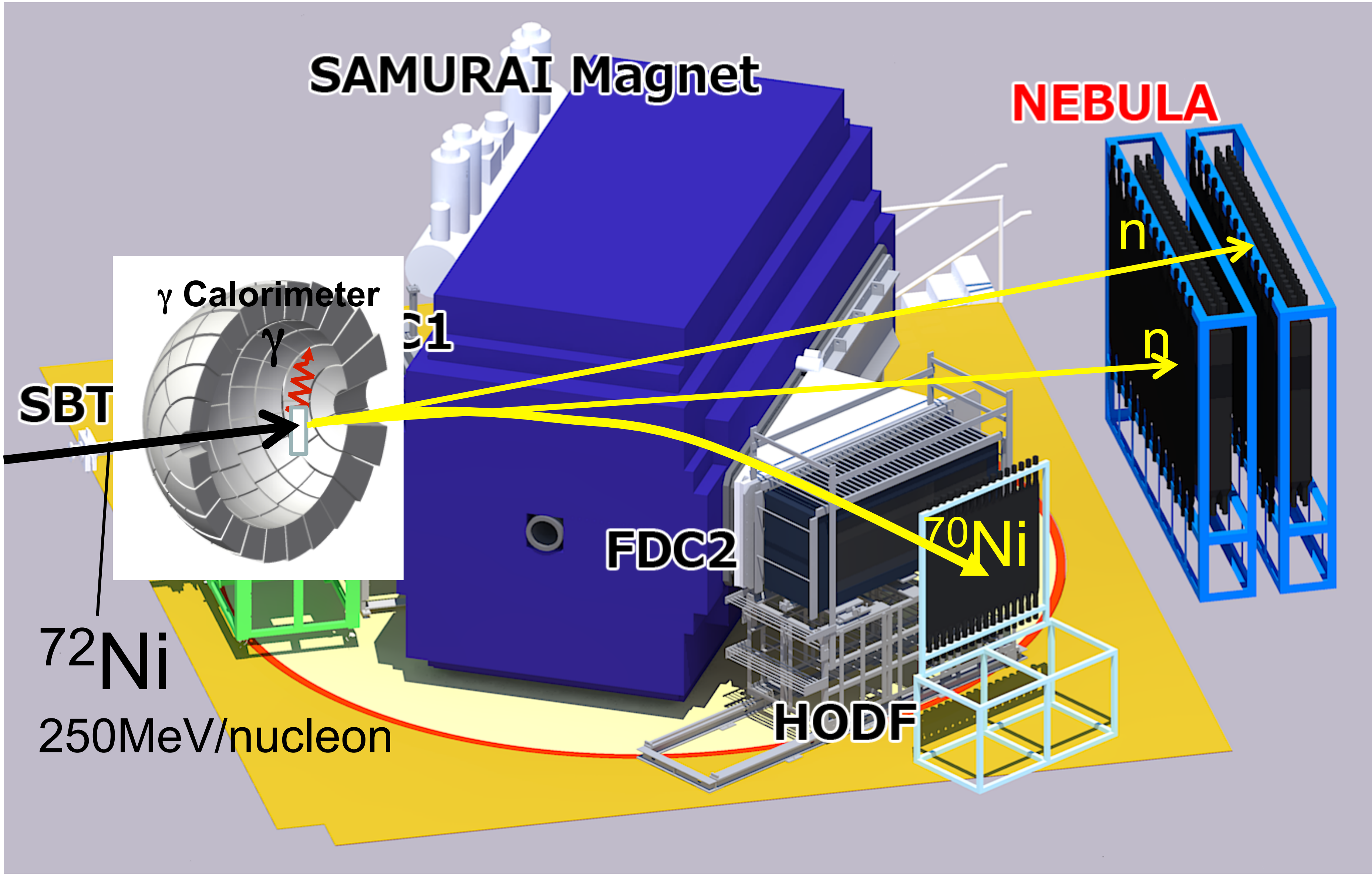
-- New Spectrometer in RIBF --



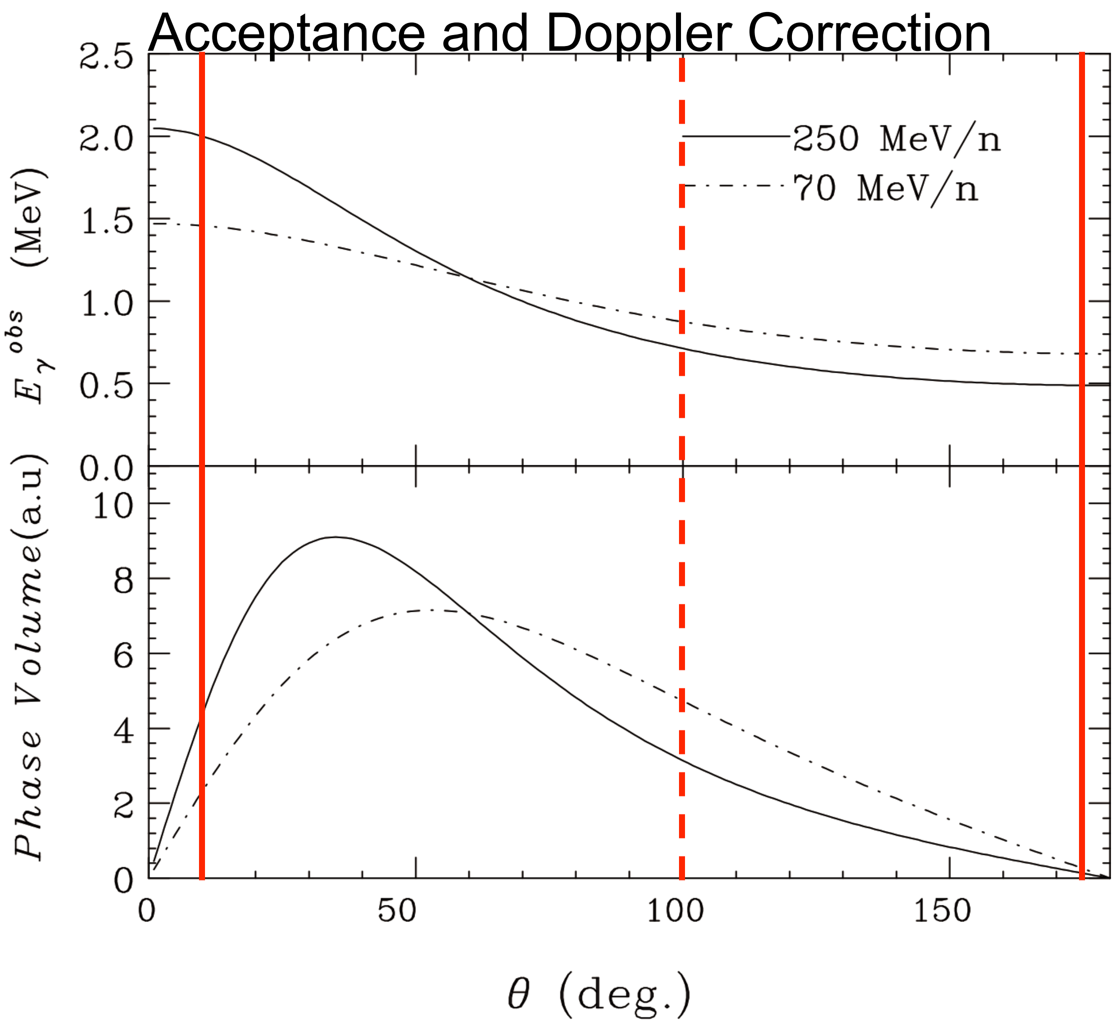
Commissioning Experiment March 2012

Slide: K. Yoneda

PDR of neutron-skin nuclei



Gamma-ray Calorimeter to be build



Building Calorimeter with almost full 4π coverage (10—170deg)

BGO or CSI
PMT or APD

by Assistant Prof. Togano

10--170 degrees: 97% coverage
10—100 degree: 83% coverage

Goal: Total intrinsic efficiency >80% for Eγ=1MeV(Lab)

□ Superfluidity

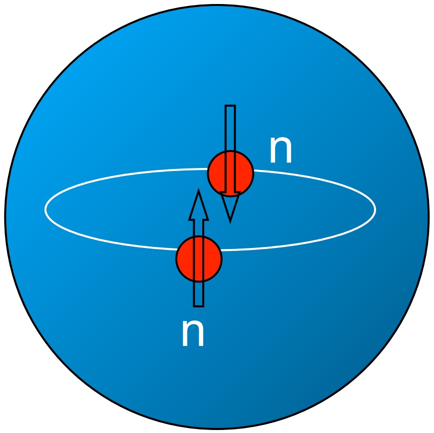
←Dineutron correlation of *halo nuclei*

---mimic Dilute Matter

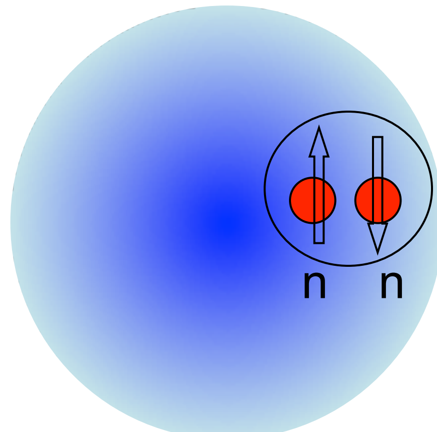
Dineutron Correlation

Migdal Sov.J.Nucl.Phys. 16,238 (1973)

BCS-like Pairing
(Long range correlation)



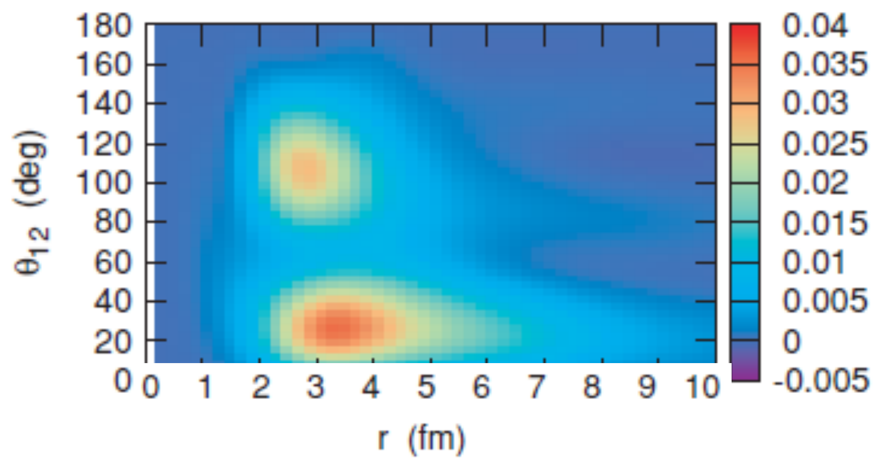
Dineutron Correlation (BEC like)
(Short range correlation)



M.Matsuo et al.
PRC73,044309(2006).

Significantant
at low densities

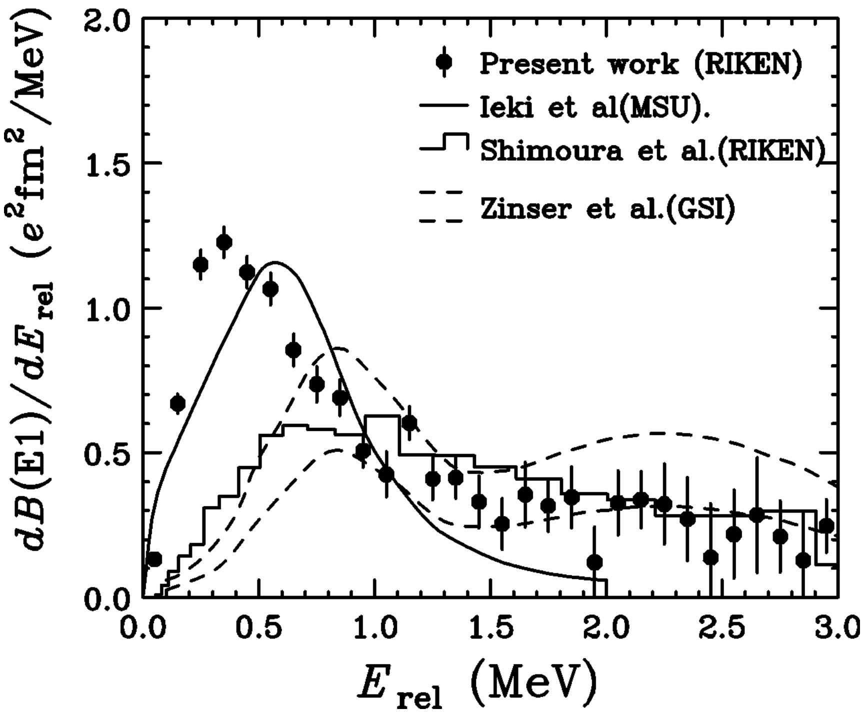
$\rho/\rho_0 \sim 10^{-4}$--10^{-1}

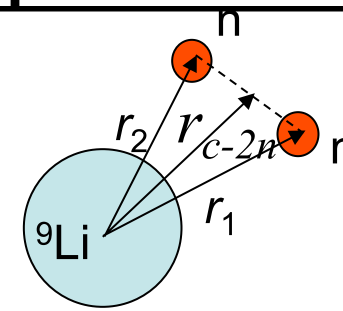


K.Hagino, H.Sagawa, J.Carbonell, P.Schuck
PRL99,022506 (2007).

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

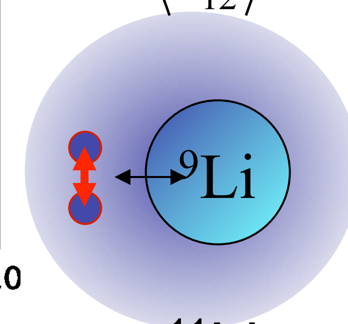
T.Nakamura
et al. PRL96,252502(2006).





$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\,2} + r_2^{\,2} + 2(\vec{r}_1 \cdot \vec{r}_2)\right\rangle$$

$$\rightarrow \langle \theta_{12} \rangle = 48^{+14}_{-18}\ \text{deg.}$$



^{11}Li

Dineutron Correlation
→Strongly Polarized
→ Strong E1 Excitation

- ☐ **Dineutron correlation in 2n halo nuclei**

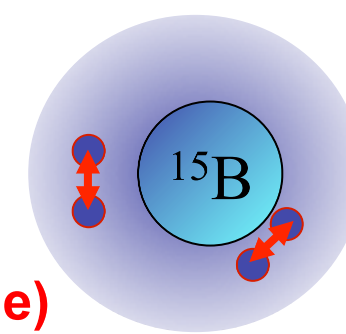
  Varying Shell,Separation energy →Varying **Density**

  ^{6}He, ^{17}B, ^{22}C, ^{34}Ne

- ☐ **Dineutron correlation in 4n halo nuclei**

  ^{8}He, ^{19}B (Establish 4n halo is also an issue)

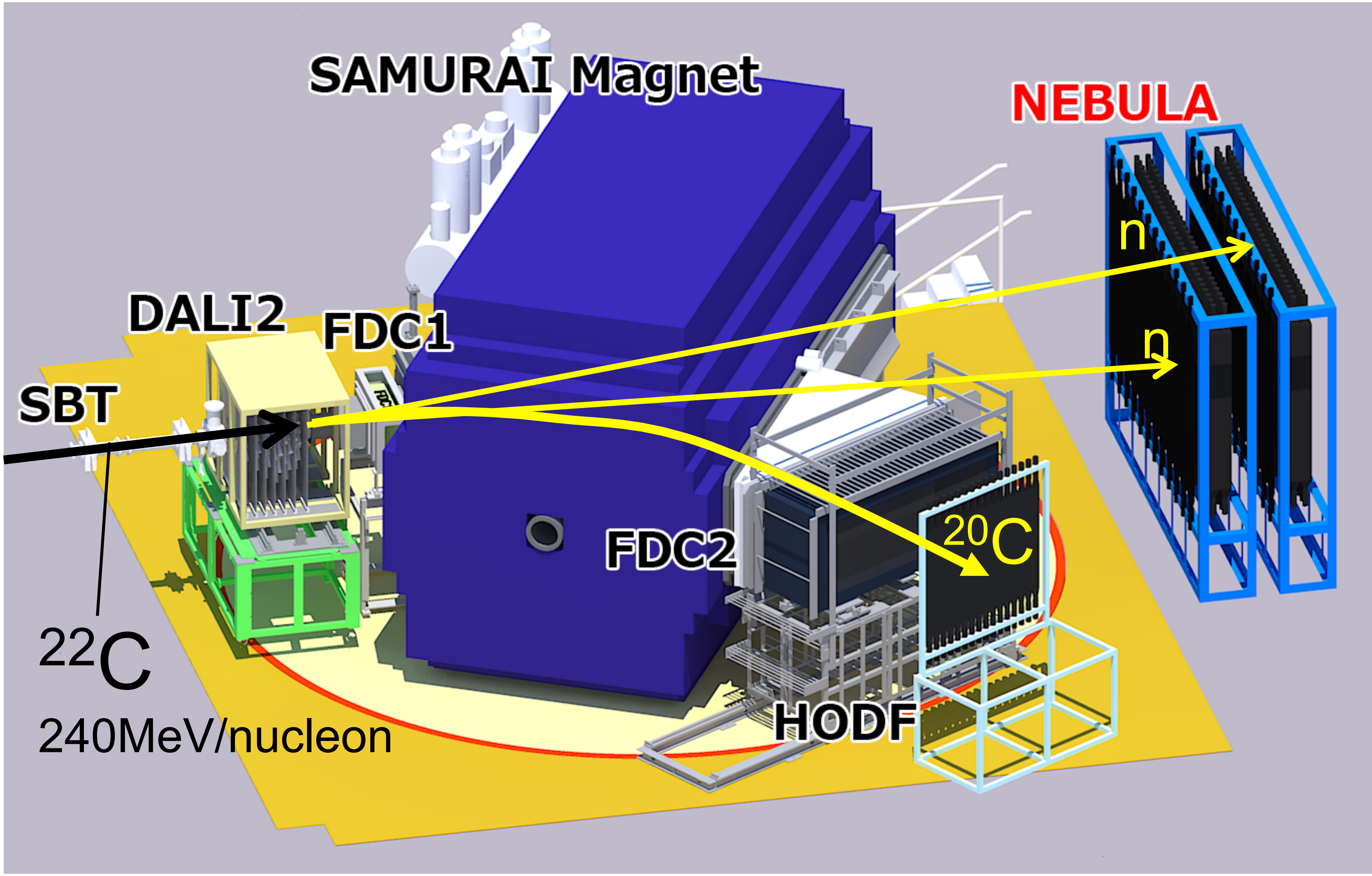
- ☐ **Dineutron correlation in neutron-skin nuclei**



^{19}B

SAMURAI Experiment May/2012

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



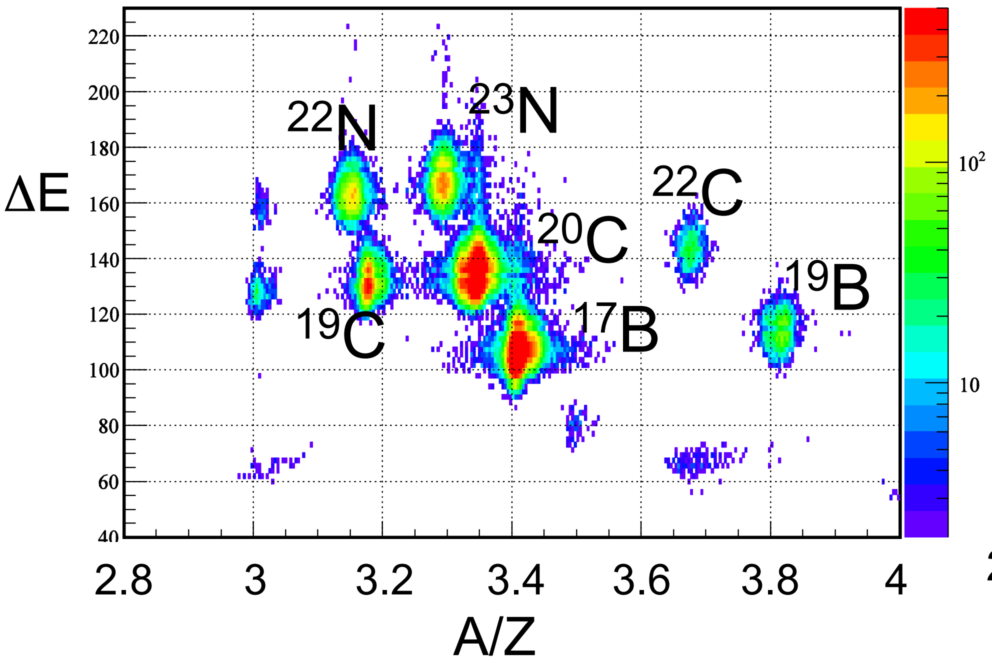
Online Spectra from Breakup Exp.@ SAMURAI May/2012

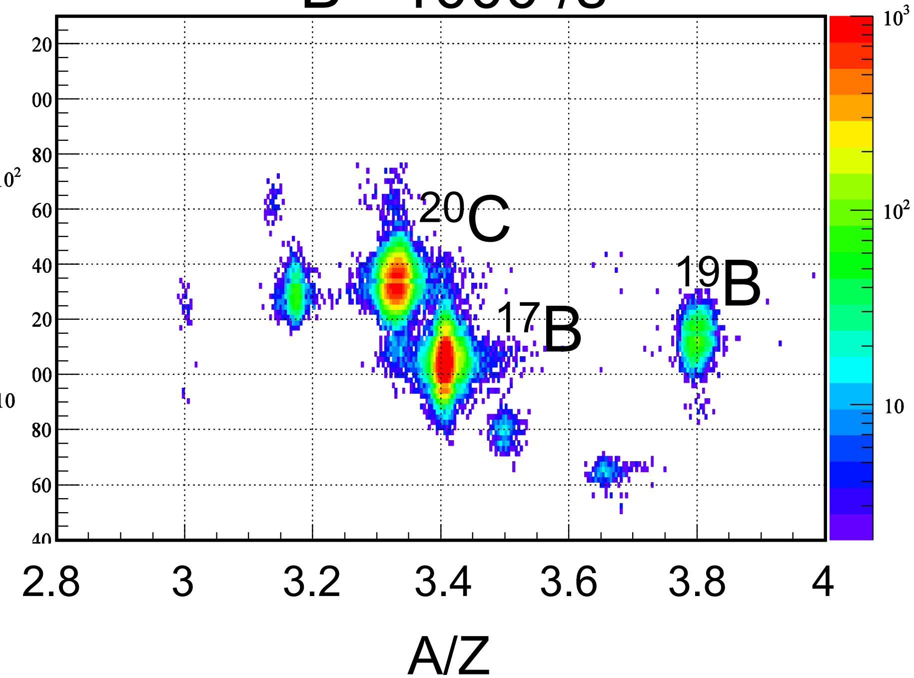
^{48}Ca 150~200pnA (Max 250pnA)

^{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





High intense RIBF Beam

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

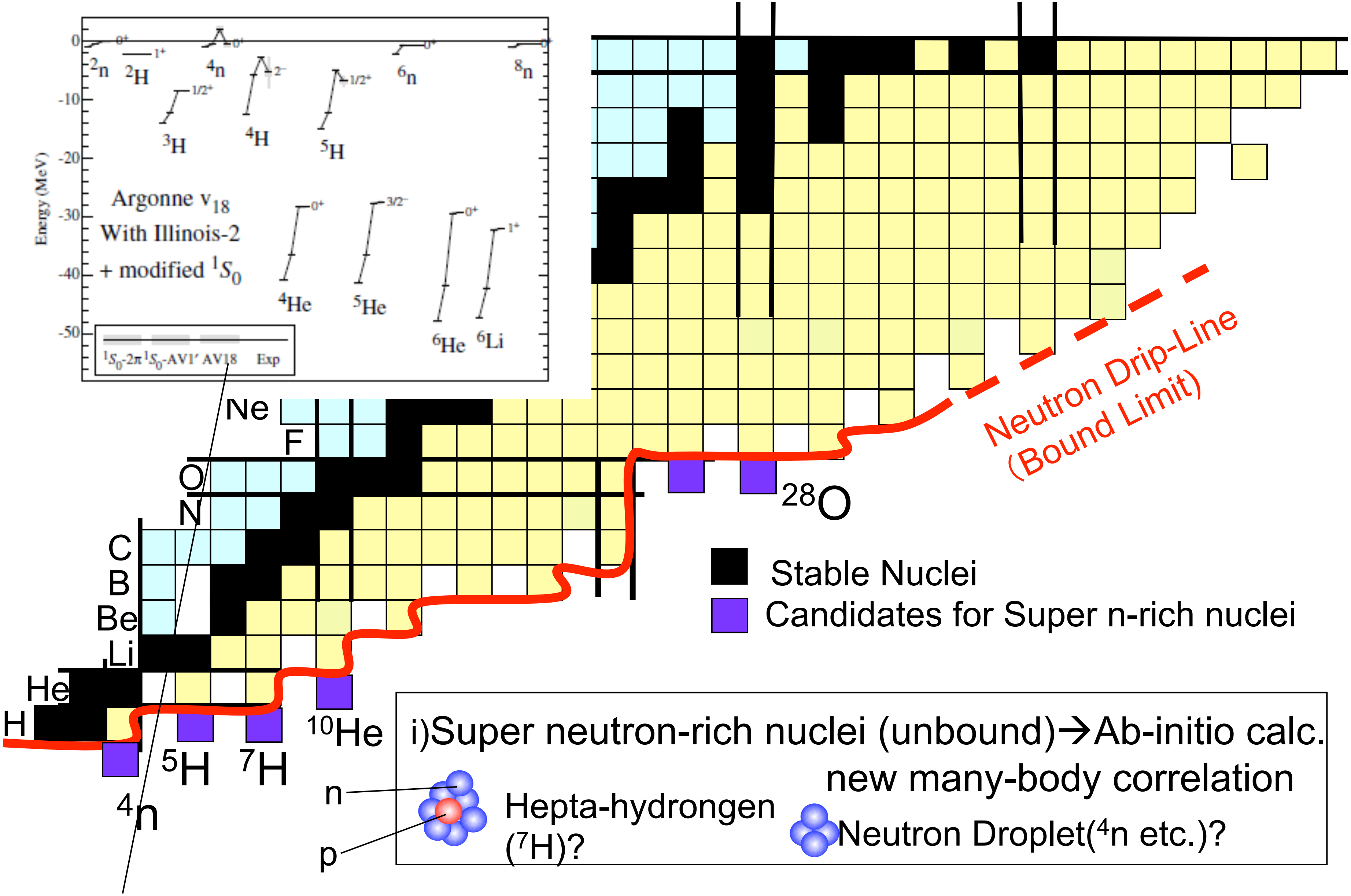
Gain of ~5000!

□ $S(\rho)$ ← Nuclear force

density dependence, isospin dependence

3-body force

← tetra neutron, exotic nucleonic system

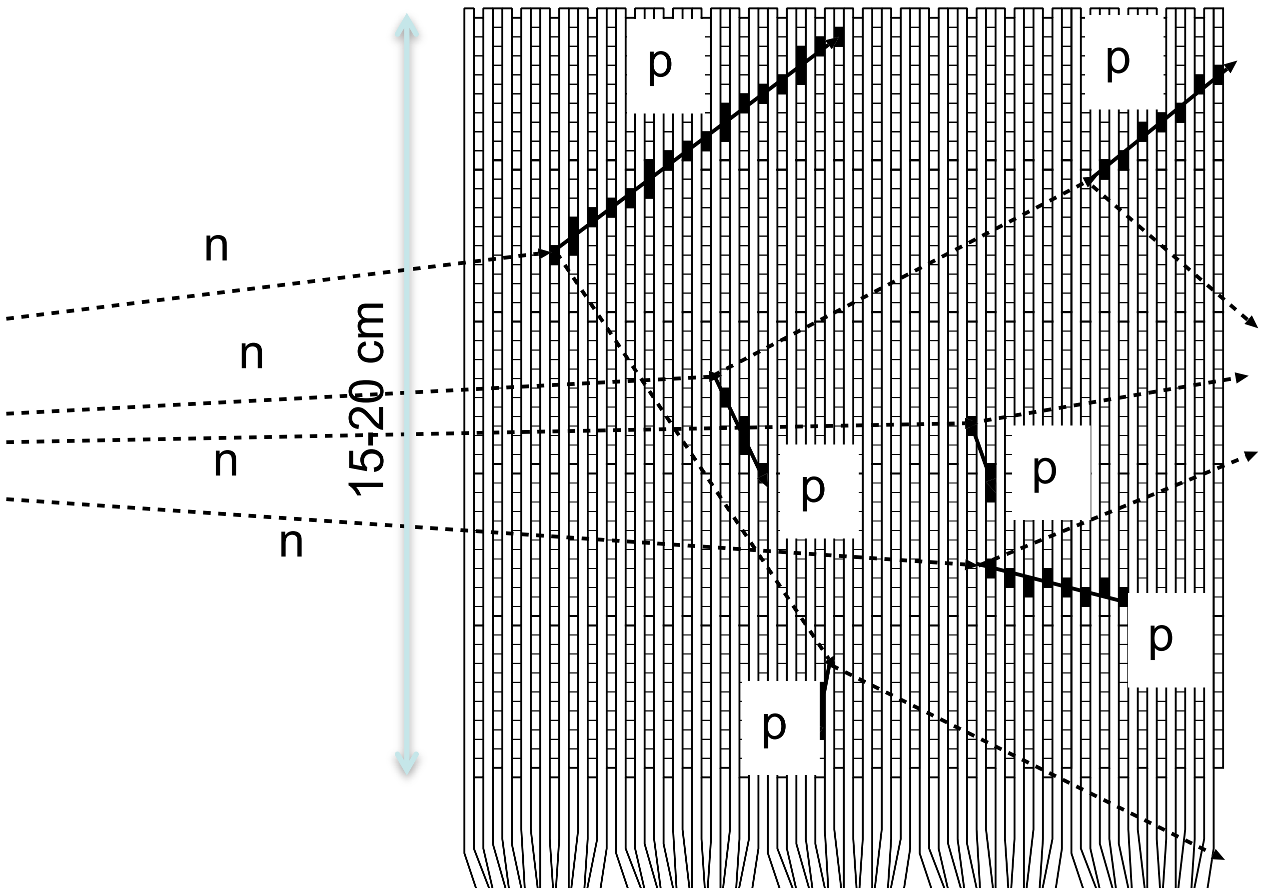


Ab-initio Calculation：S.C. Pieper,PRL90,252501(2003)

→Nuclear Force,dineutron decay

^{26,28}O（Unbound: Z=8 3-body force: Magicity? ） T.Otsuka PRL105,032501(2010)

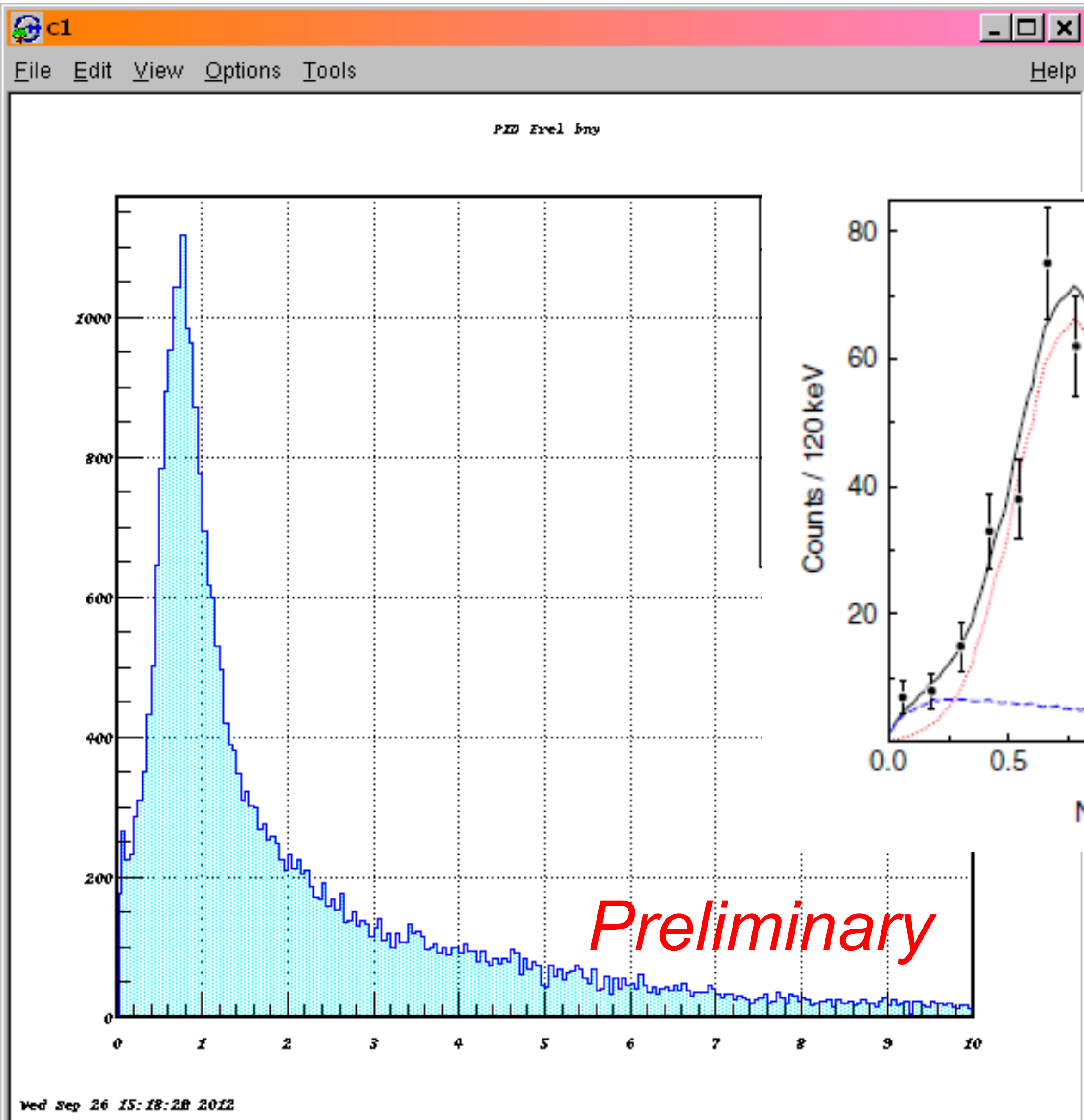
Next Generation Neutron Detector



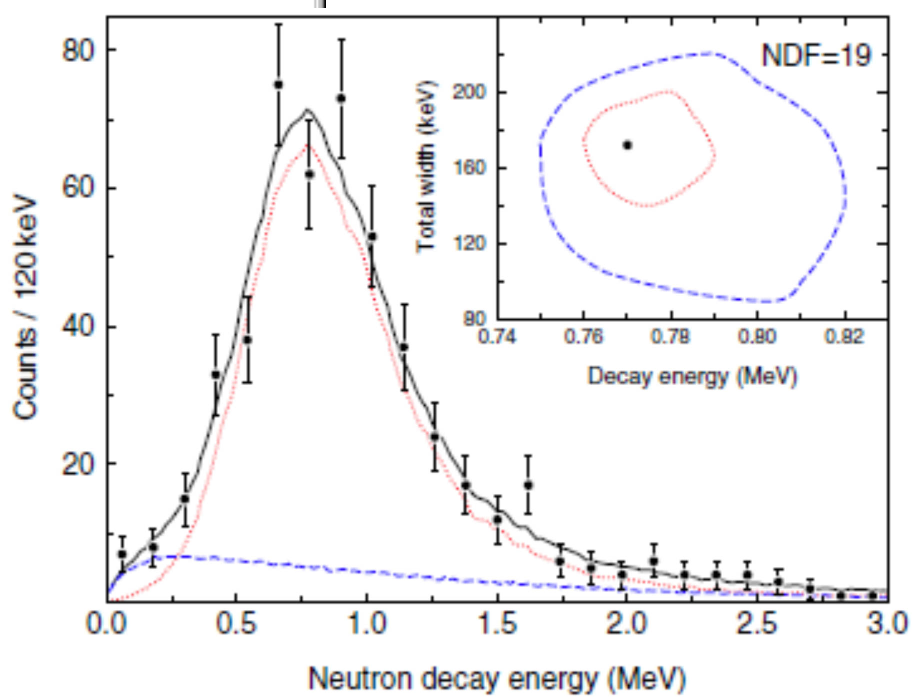
Micro-Hodoscope: 2.5 × 5 mm^2
Cubic Module: (15~20cm)^3

Prof. Shimoura
CNS, Univ. of Tokyo

$^{26}F + C \rightarrow {}^{25}O^{*} \rightarrow {}^{24}O + n + X$ Y.Kondo et al.



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



$^{27}F, {}^{28}Ne \rightarrow {}^{26}O^{*}$ Y.Kondo

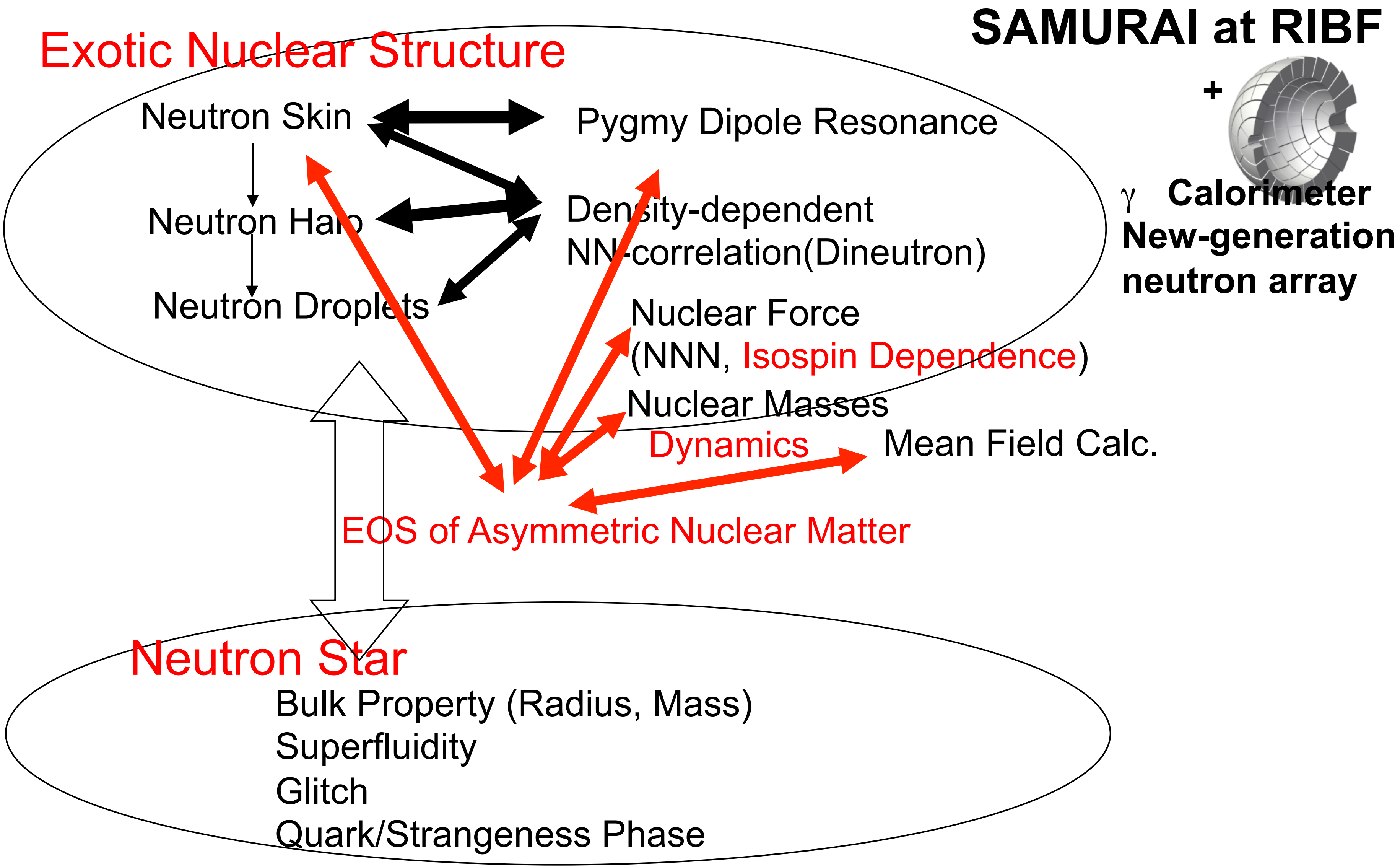
Important bench mark

In shell model with 3body force

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

Summary

Nuclear Structure using new-generation RI Beams



BUDGET:

Whole Project: 9.8 Oku-JPY (~12M USD)

B02: 1.6 Oku-JPY (~2M USD)

Gamma Calorimeter : ~1 Oku-JPY (~1.3M USD)
30% in 2013, Full in 2015

New-Generation Neutron Counter: ~0.3 Oku-JPY (~0.4M USD)
Traveling : ~0.05 Oku-JPY(~0.06M USD)
Human Resources : ~0.3 Oku-JPY(~0.4M USD)

B02: Members:

T. Nakamura: PI
"New Assistant Prof.", T.Nakamura, Y.Kondo → Gamma Calorimeter

S. Shimoura → New-generation Neutron Detectors

T. Teranishi → Collaboration in experiments

Extra Funds:
1-2M-JPY/year (10~20K USD/year) for ~10 experimenters will be selected