The ONOKORO/ESPRI project

Juzo Zenihiro (Kyoto Univ.)
for the ONOKORO/ESPRI collaboration

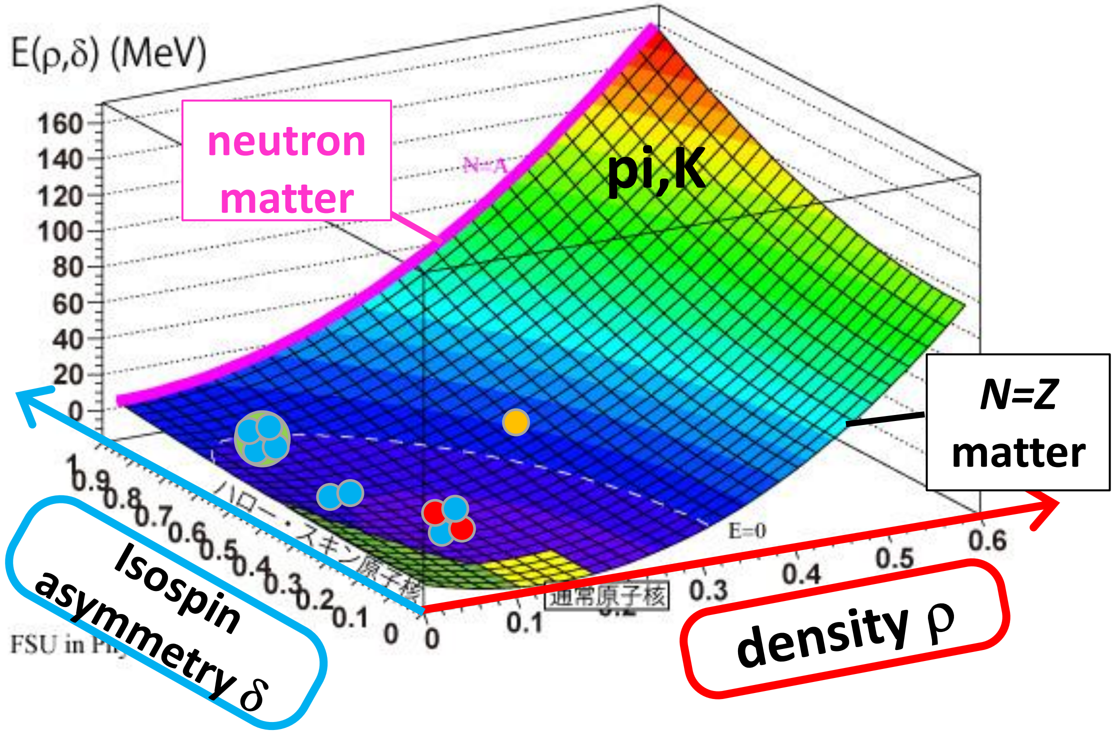
Nuclear matter

- Nuclear matter properties characterize not only finite nuclei but also <u>astrophysical phenomena</u> in our universe.

- Nuclear matter has multifaceted aspects
  - Clustering, correlation, strangeness

➔ appearance of the small amount of impurities

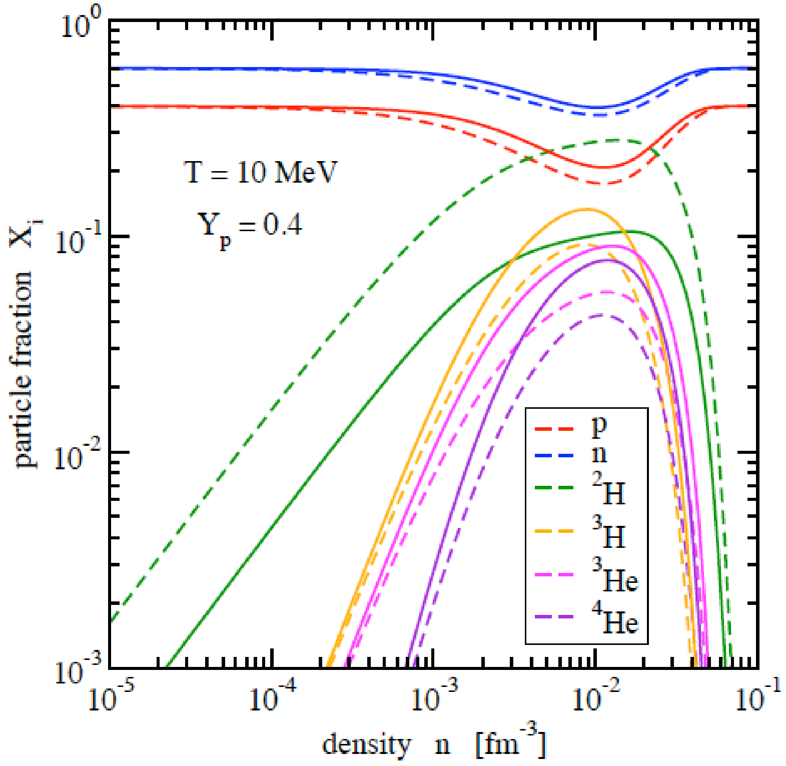
Nuclear matter EOS



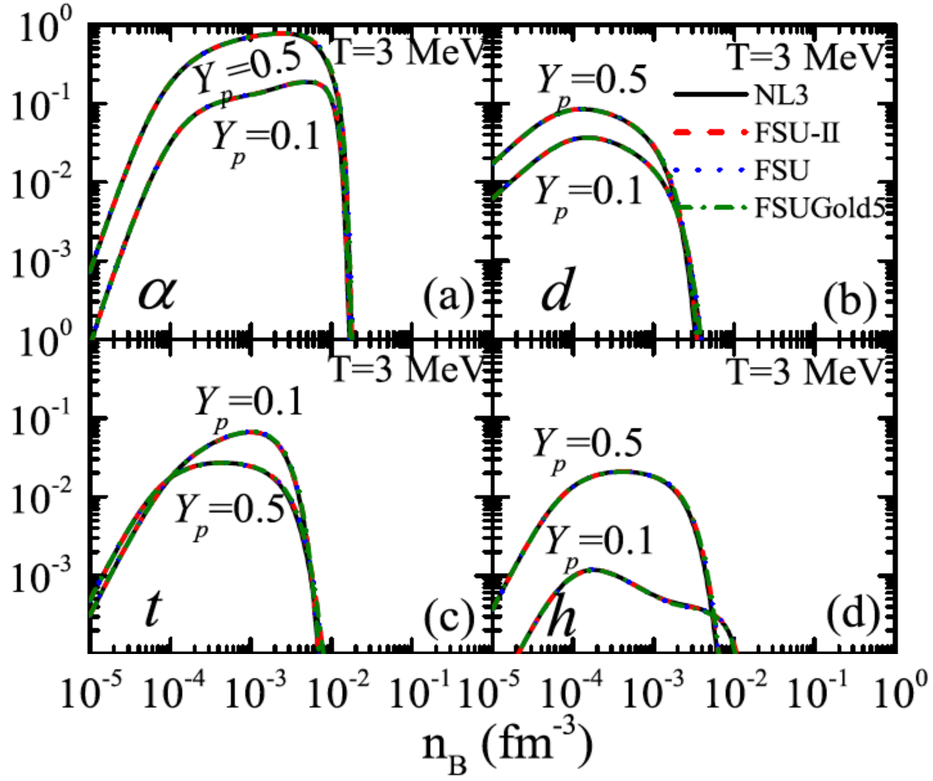
δ = (N-Z)/A

In dilute nuclear matter : $\rho < 0.1\ \rho_{sat}$

S. Typel,
J. Phys. Conf. Ser. 420, 012078 (2013)



Z.W. Zhang and L.W. Chen
Physical Review C 95, 064330 (2017)



Various light clusters (d, t, 3he, a) evolve spontaneously !!
Depends on the density and the isospin asymmetry of the pn medium.

Spontaneous cluster formation in NM

Do clusters really appear in the uniform medium?

If so, they can be a key to understand the nuclear matter.

- Small amount of impurity breaks symmetry and characterize the system.
- The nuclear system universally has a nature of non-uniformity.

New stage of Nuclear Matter Study

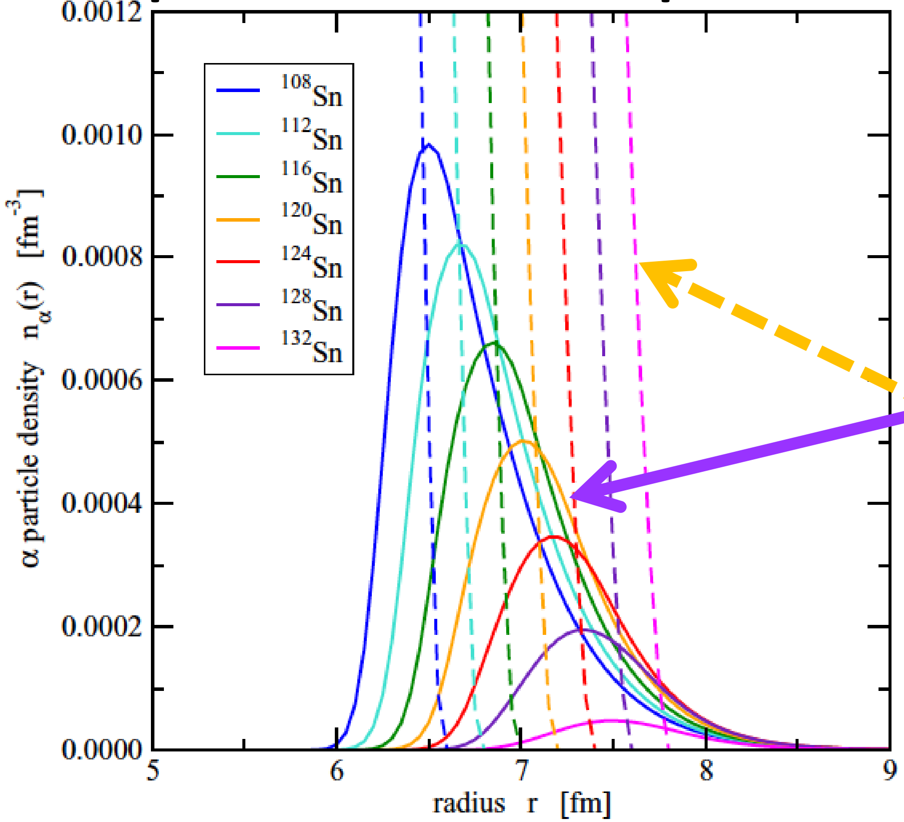
- Uniform nuclear matter (solvent, uniform) : EOS

↕ Order parameters : density, isospin asymmetry

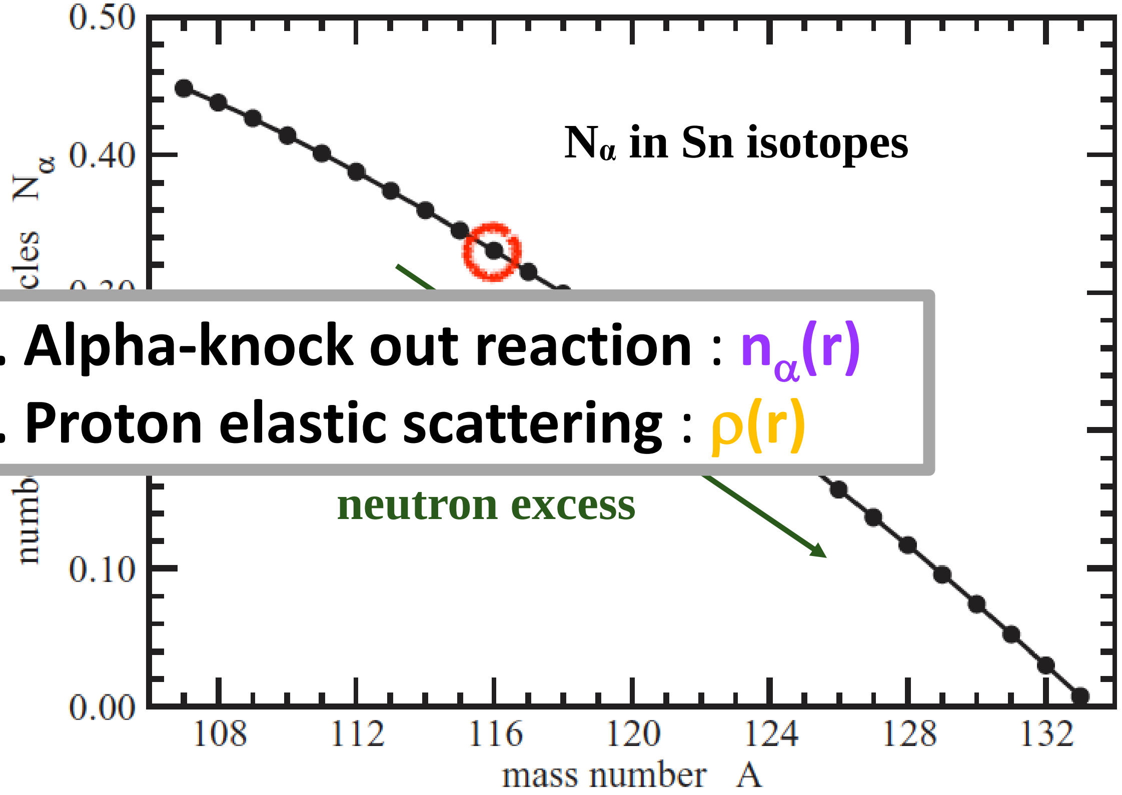
- Spontaneous emergence of clusters (colloid, non-uniform, anisotropy) : cluster formation probability

How about finite nuclei?

Dilute surface of heavy nuclei alpha clusters develop.



Decrease depending on neutron no.



1. Alpha-knock out reaction : $n_\alpha(r)$

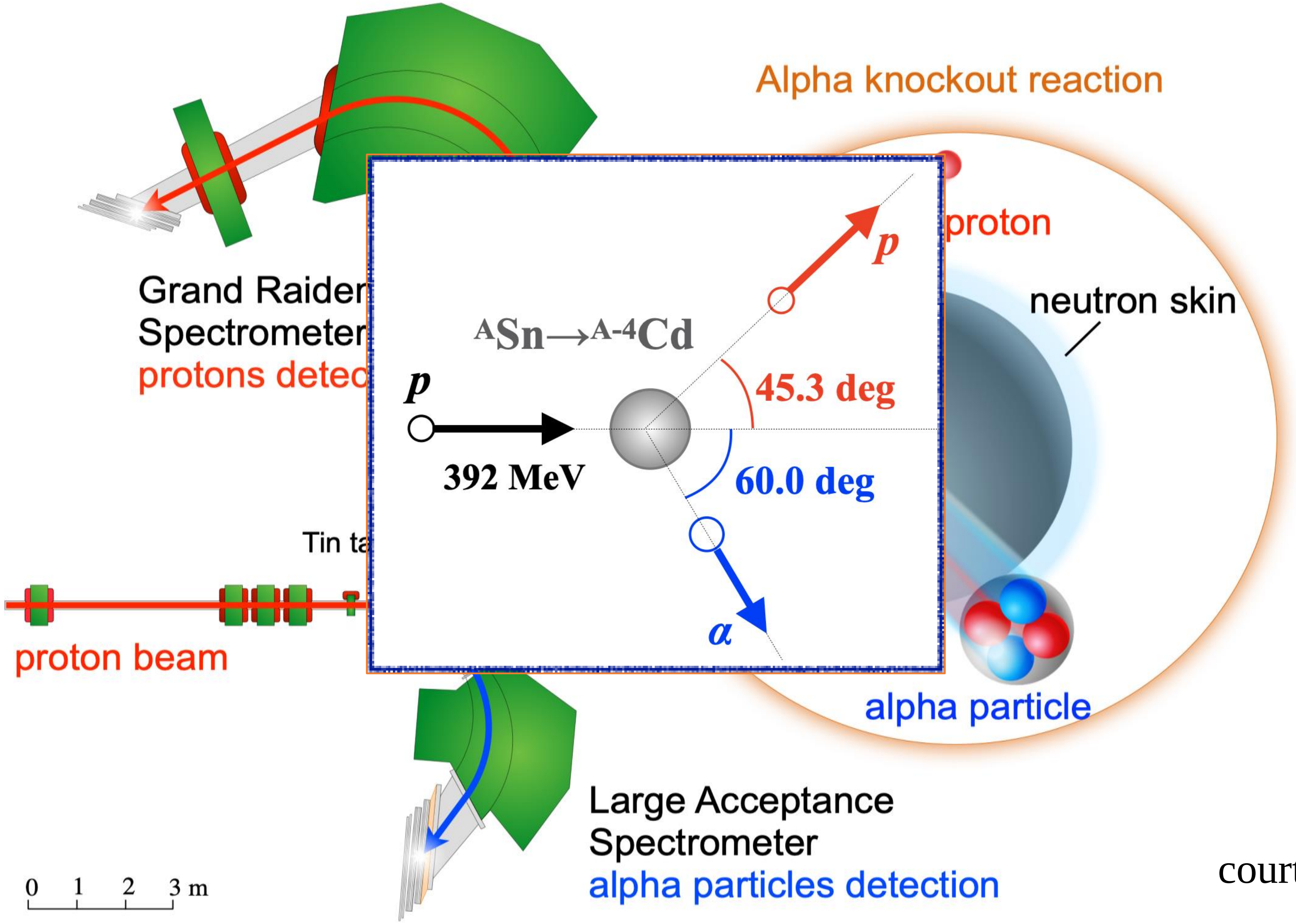
2. Proton elastic scattering : $\rho(r)$

S. Typel, PRC **89**, 064321 (2014).

Pre-ONOKORO/ESPRI

1. Pilot experiment of Sn(p,pa) @RCNP
2. p-A elastic scattering @RCNP

1. ^{112,116,120,124}Sn(p,pα) @ E_p=392 MeV

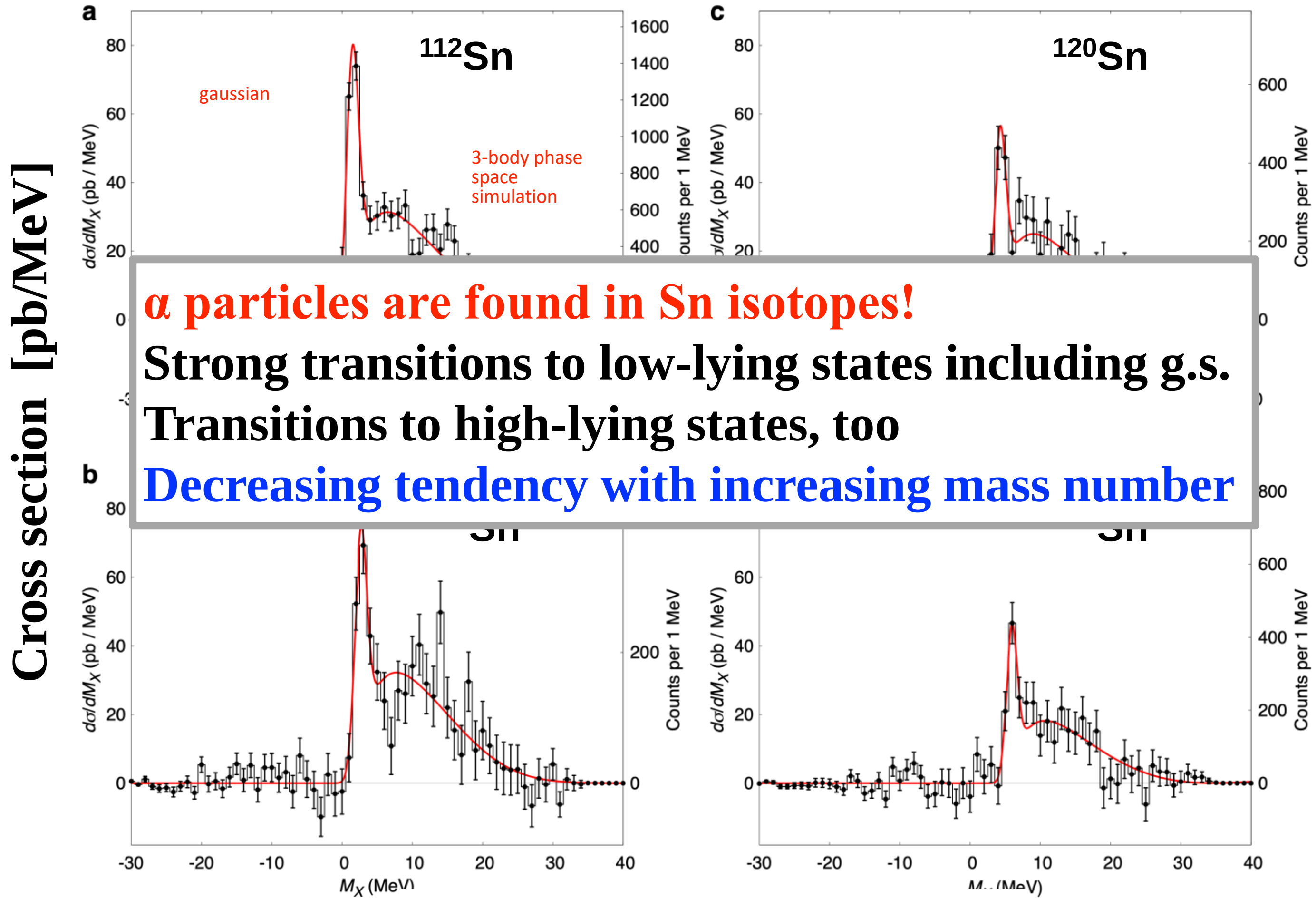


courtesy of J. Tanaka

courtesy of J. Tanaka

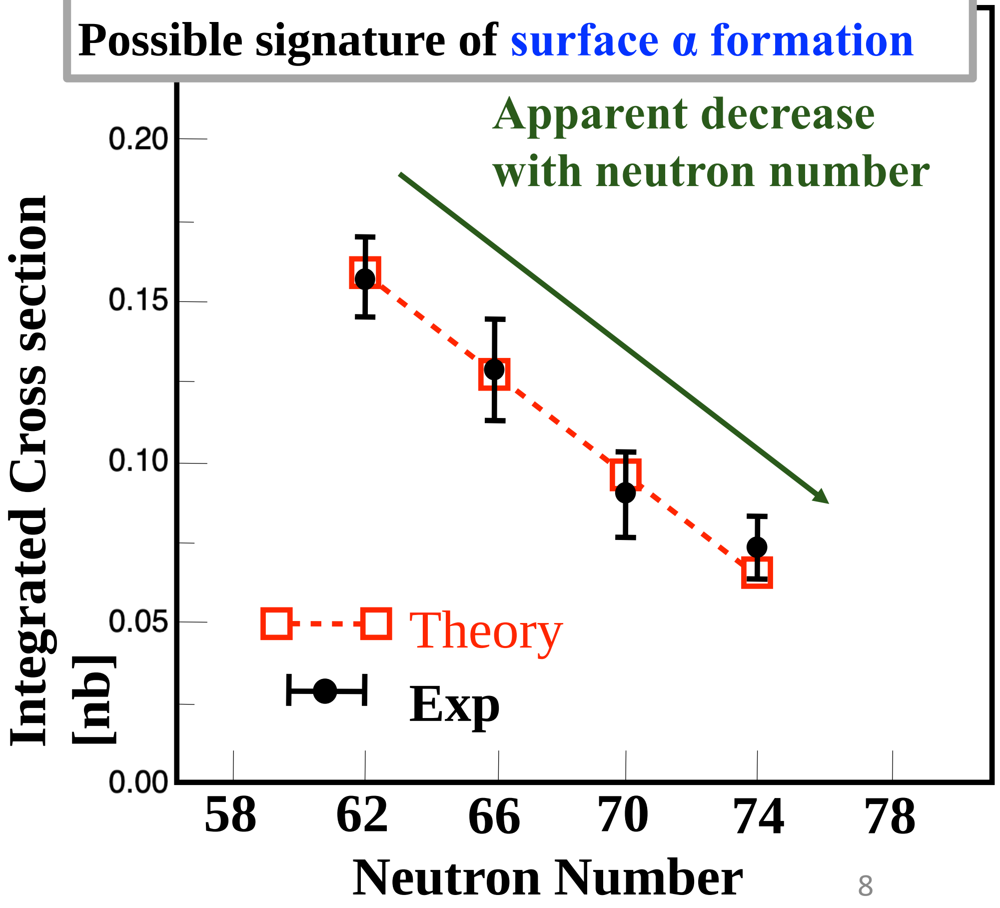
Alpha particles were detected!!

^{A}Sn(*p,pα*)$^{A-4}$Cd missing mass spectrum



α particles are found in Sn isotopes!
Strong transitions to low-lying states including g.s.
Transitions to high-lying states, too
Decreasing tendency with increasing mass number

The tendency is consistent with Typel's prediction!
Note: absolute values are normalized
Possible signature of surface α formation



REPORT

NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

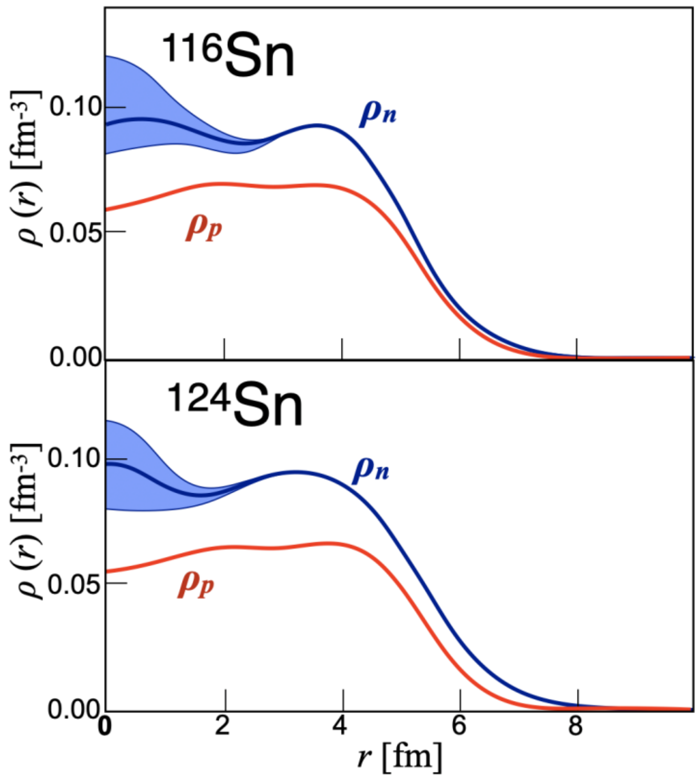
Junki Tanaka[1,2,3*], Zaihong Yang[3,4*], Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], Jianling Lou[5], Yukie Maeda[8], Yohei Matsuda[9], Kenjiro Miki[10], Shoken Nakamura[4], Kazuyuki Ogata[4,11], Valerii Panin[3], Heiko Scheit[1], Fabia Schindler[1], Philipp Schrock[12], Dmytro Symochko[1], Atsushi Tamii[4], Tomohiro Uesaka[3], Vadim Wagner[1], Kazuki Yoshida[13], Juzo Zenihiro[3,7], Thomas Aumann[1,2,14]

The surface of neutron-rich heavy nuclei, with a neutron skin created by excess neutrons, provides an important terrestrial model system to study dilute neutron-rich matter. By using quasi-free α cluster–knockout reactions, we obtained direct experimental evidence for the formation of α clusters at the surface of neutron-rich tin isotopes. The observed monotonous decrease of the reaction cross sections with increasing mass number, in excellent agreement with the theoretical prediction, implies a tight interplay between α-cluster formation and the neutron skin. This result, in turn, calls for a revision of the correlation between the neutron-skin thickness and the density dependence of the symmetry energy, which is essential for understanding neutron stars. Our result also provides a natural explanation for the origin of α particles in α decay.

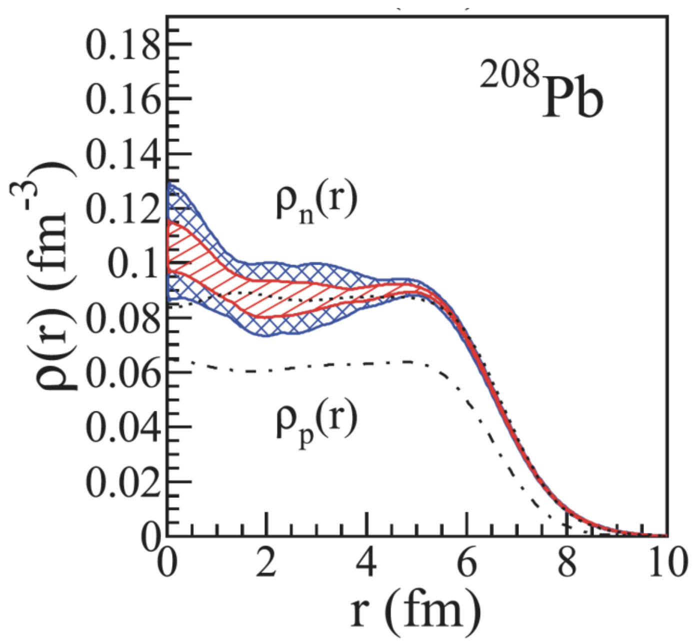
J. Tanaka, Z.H. Yang, S. Typel, K. Ogata, T. Uesaka, J. Zenihiro, T. Aumann, et al., Science 371, 260–264 (2021)

2. Proton elastic scattering: $\rho_n(r)$, $\rho_p(r)$

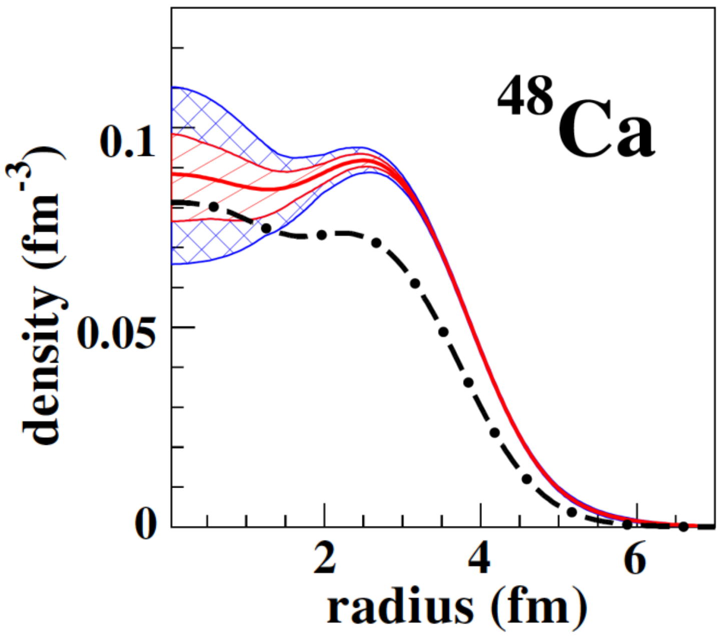
S.Terashima et al



J.Zenihiro et al.



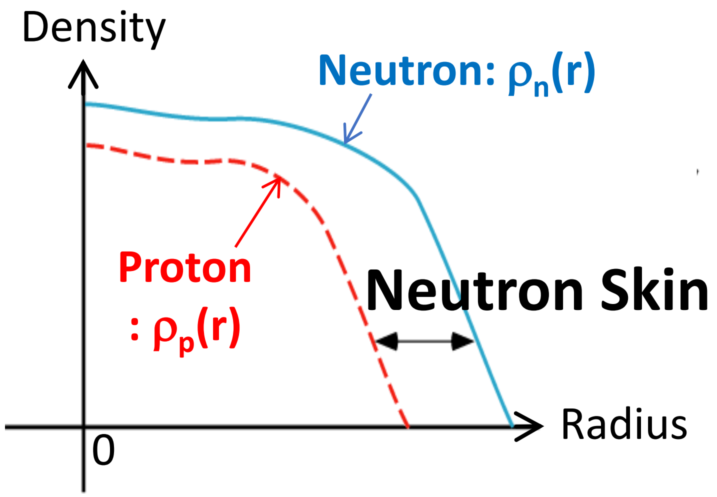
J.Zenihiro et al.



Experimentally determined density distributions from the RCNP experiments

Neutron skin structure and EOS

Finite n-rich system



Excess neutrons make
n-skin structure
➔ ^{208}Pb, ^{132}Sn, ^{48}Ca.

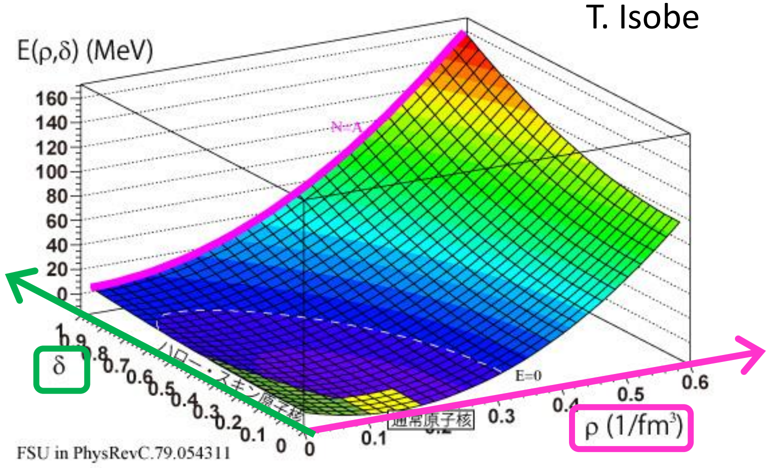
Density: ρ_m

balance

Asymmetry: δ

Infinite nuclear matter EOS

Drawn by
T. Isobe

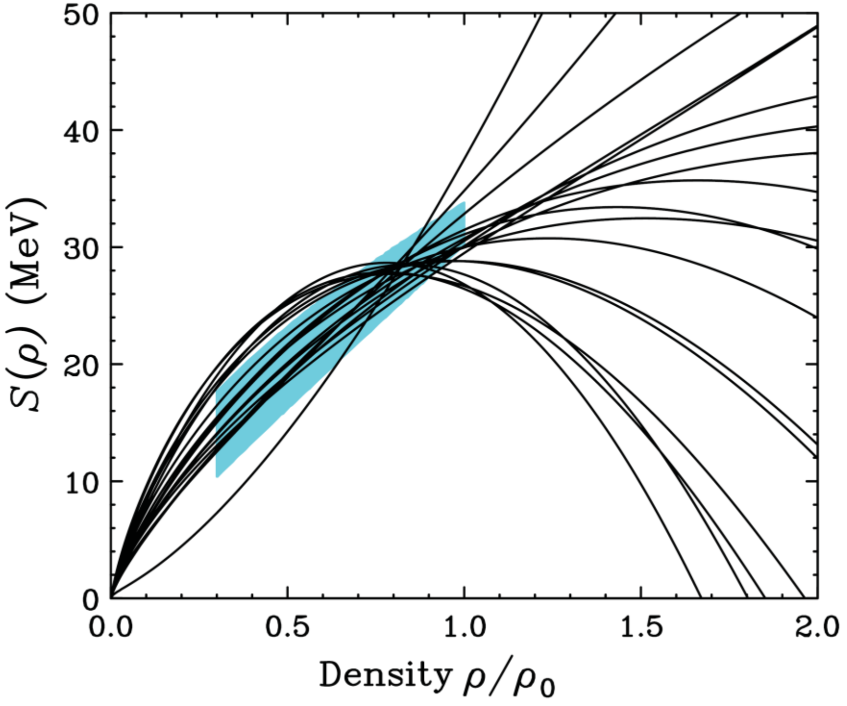


Symmetry energy

$$S(\rho) = S(\rho_{sat}) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + O(\varepsilon^3)$$

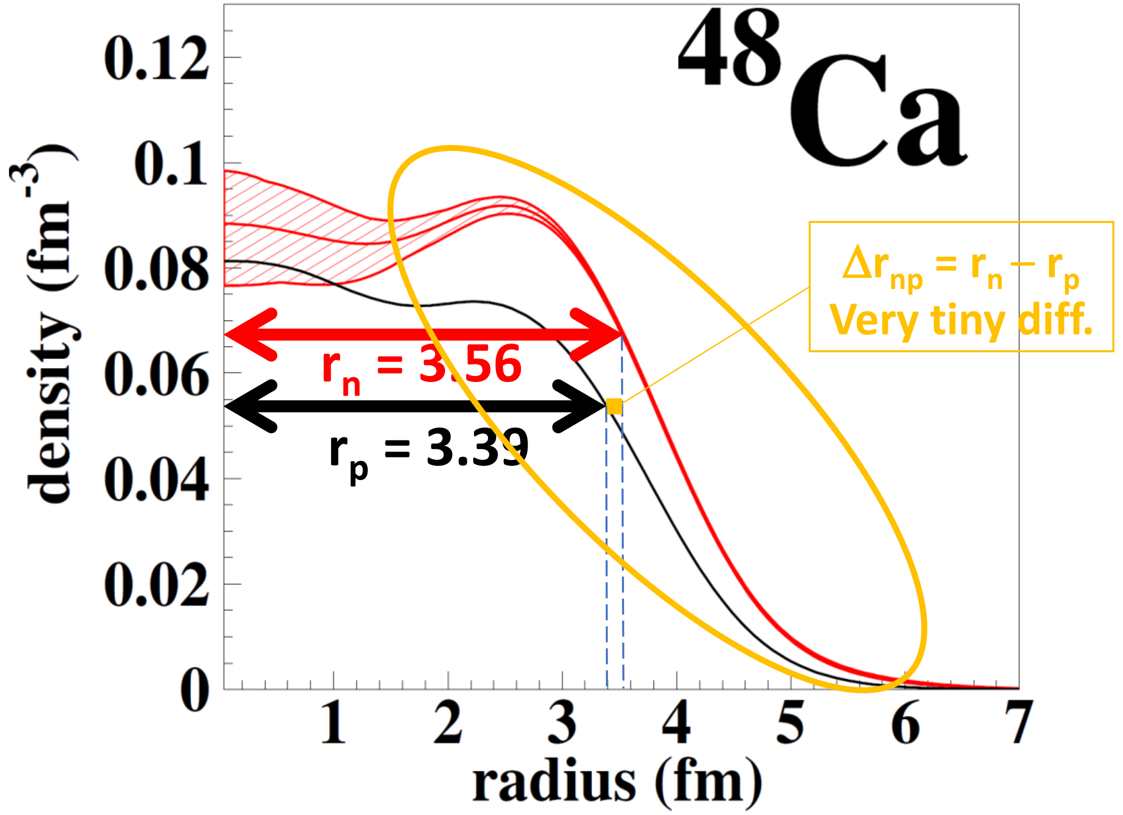
Beyond neutron skin

…But, still large uncertainty in S(ρ)



PRC 86,015803 (2012)

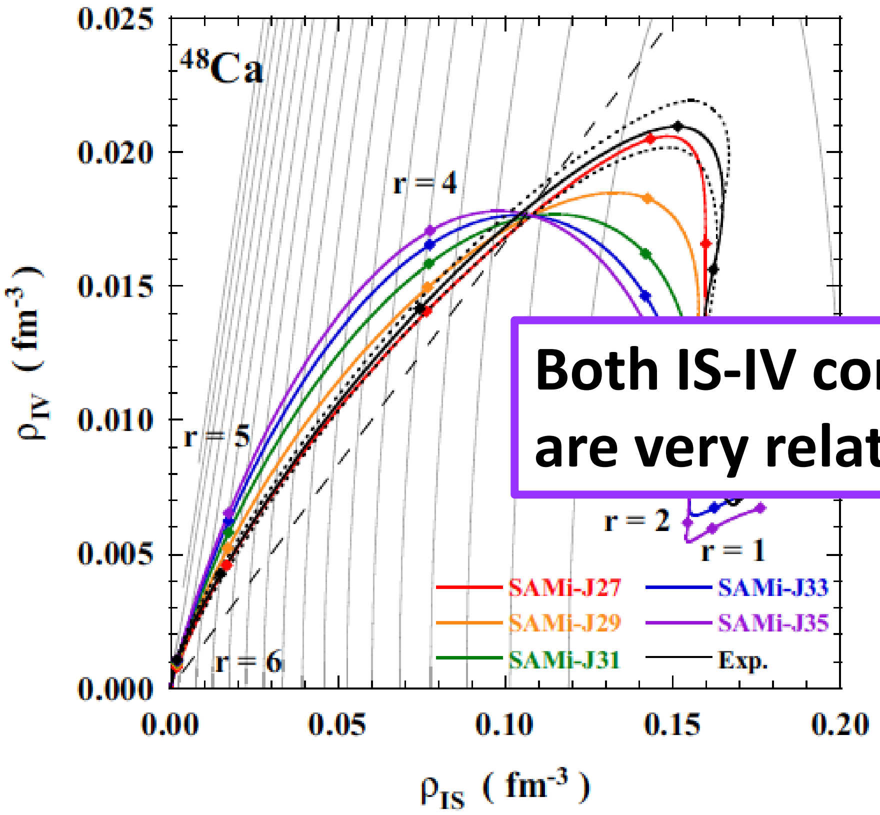
Experimental difficulties



Δr_{np} = 0.17(3) fm

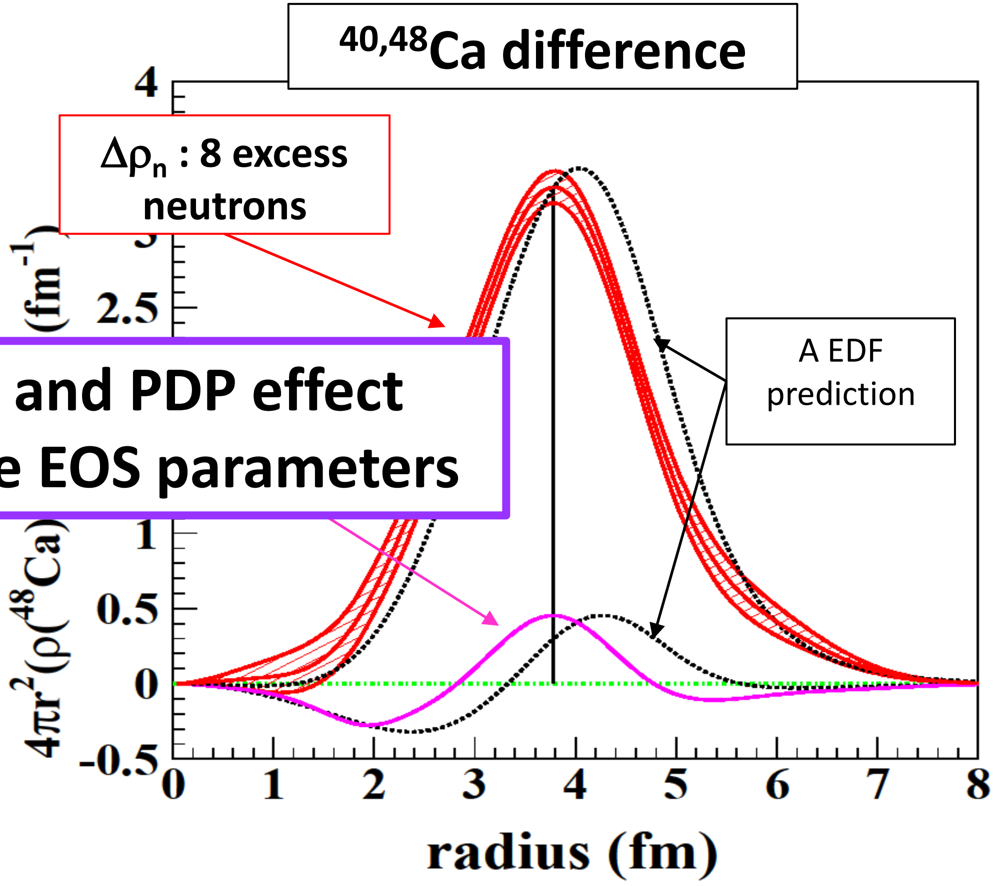
Beyond neutron skin

Isoscalar vs **Isovector** density map (IS-IV)
➔ Already introduced in the **Sagawa-san's** talk



S. Yoshida, H. Sagawa,
T. Uesaka, and J. Zenihiro

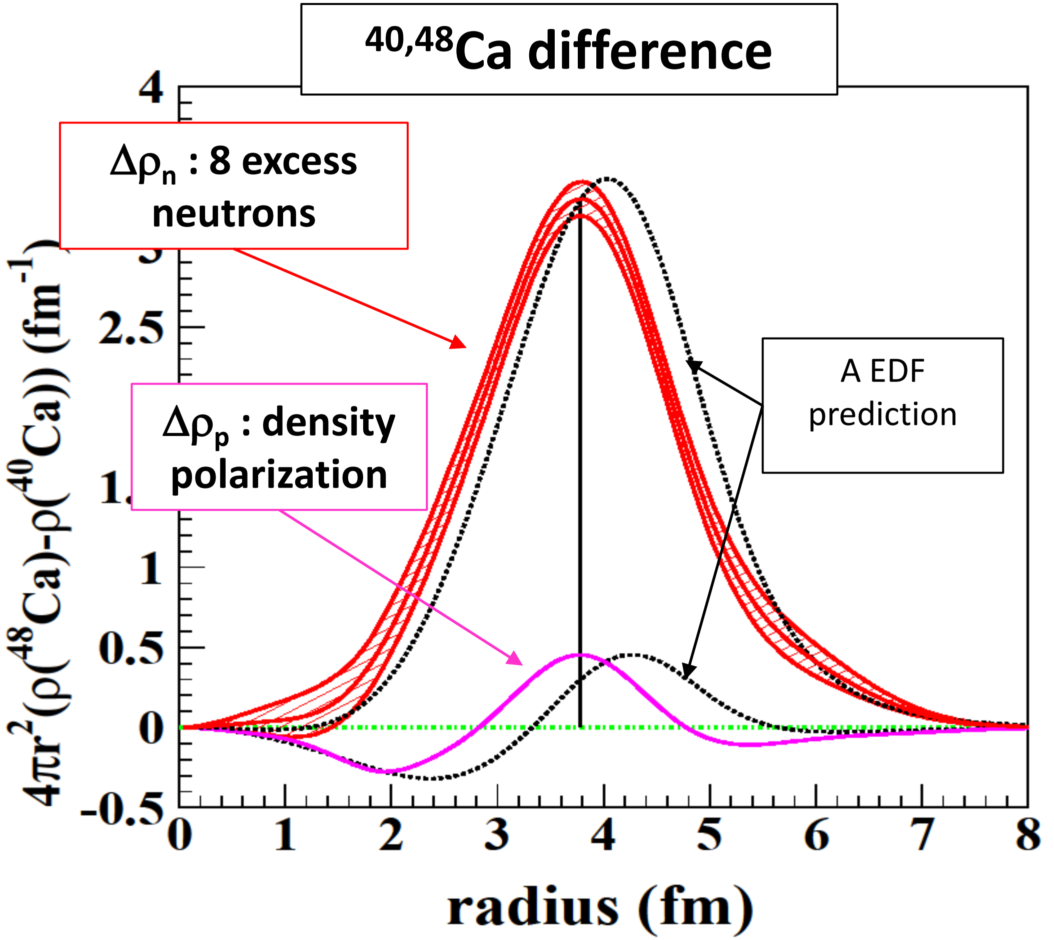
Proton density polarization (PDP) effect
by excess neutrons

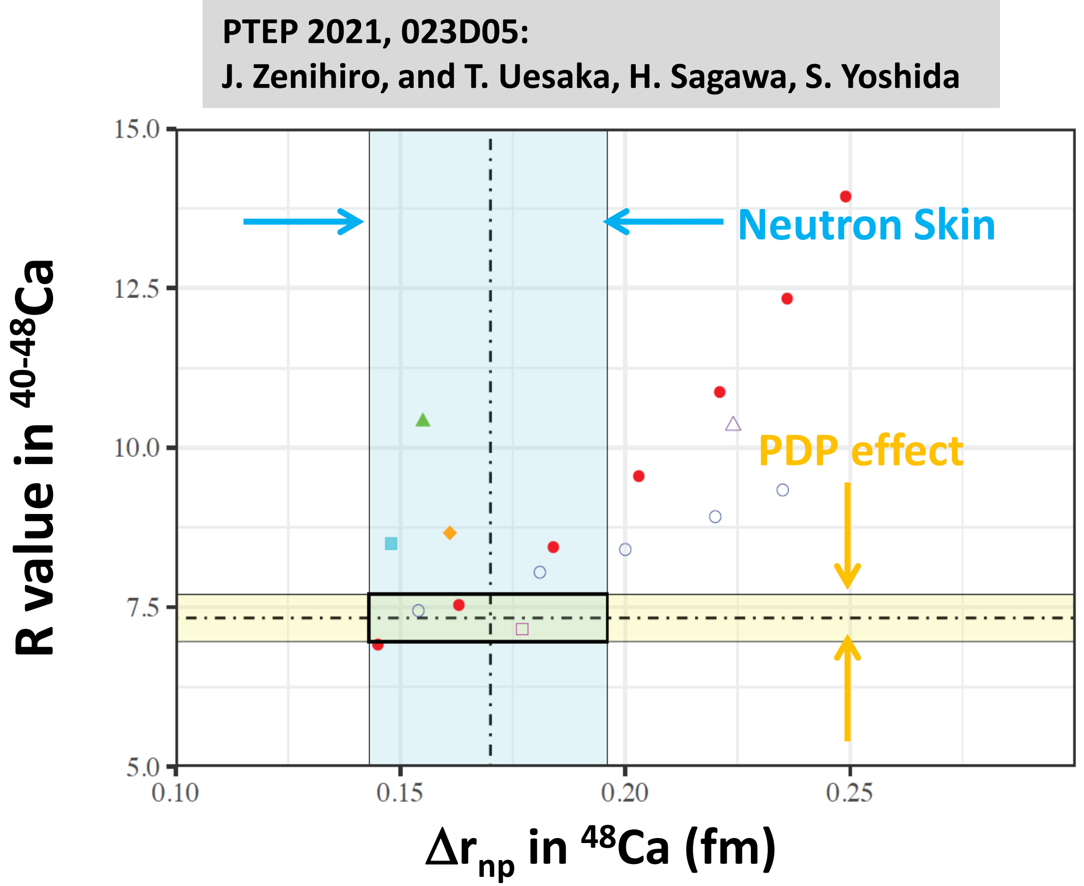


J.Zenihiro, T. Uesaka et al.

Both IS-IV correlation and PDP effect are very related to the EOS parameters

proton density polarization (PDP) effect





$$R \equiv \Delta\rho_{n,\mathrm{peak}}/\Delta\rho_{p,\mathrm{peak}} = 7.35 \pm 0.33$$

The ONOKORO/ESPRI project

1. Cluster knock-out (p,pX) X=d,t,3he,alpha reactions
2. proton elastic scattering from unstable nuclei (ESPRI/ESPRI+)

Systematic study for stable and unstable nuclei

1. Cluster knock-out reaction studies of heavy nuclei

- (p,pX) @ E/A = 200—300 MeV
  X: d, t, ^{3}He, α

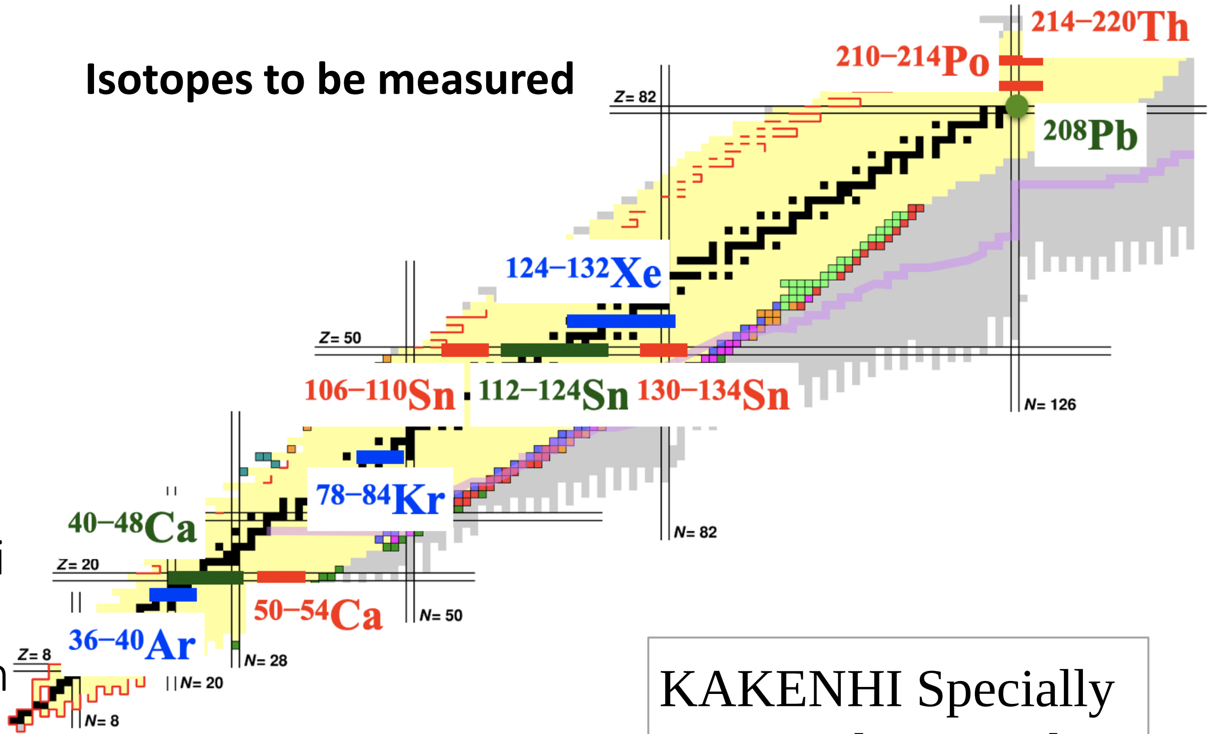
- Relative abundances of **d,t,^{3}He,α** clusters and their isotopic dependences

  - Surface α formation in heavy nuclei
    - understanding of the origin of α-decay
    - correction of n-skin vs L relation

  - Discovery of deuteron clusters in heavy nuclei

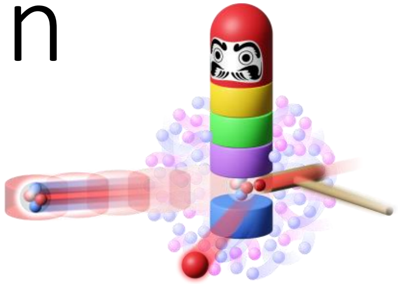
  ➔For alpha and deuteron, recently discussed in the collaboration with a help from Ogata-san, and so on.

  - First observation of the ratio of t/^{3}He clusters

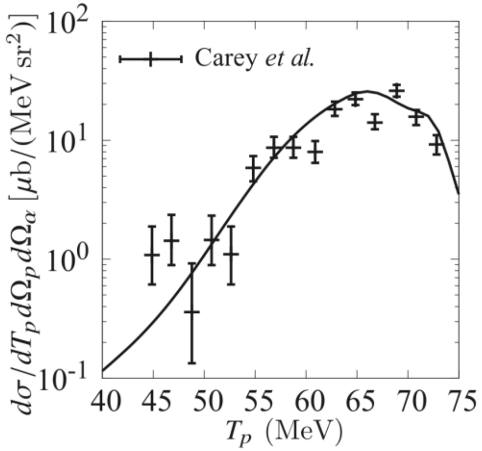


KAKENHI Specially Promoted Research
(科研費特別推進研究)
4.5 M$ / 5 years

As a new tool: Cluster knock-out reaction

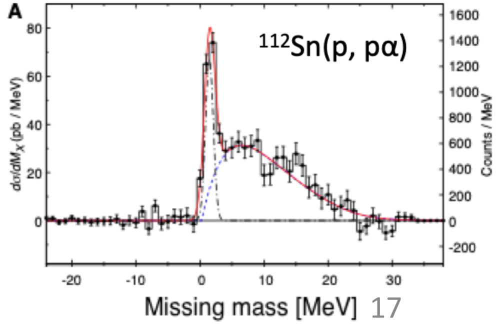


- Natural extension of successful (p,pN)-reaction studies at RIBF/RCNP
  - **RCNP** : T. Wakasa, K. Ogata, and T. Noro, PPNP 96
  - **RIBF** : Tang et al. PRL 124, Kubota et al. PRL 125, Yang et al. PRL 126, + many SEASTAR papers



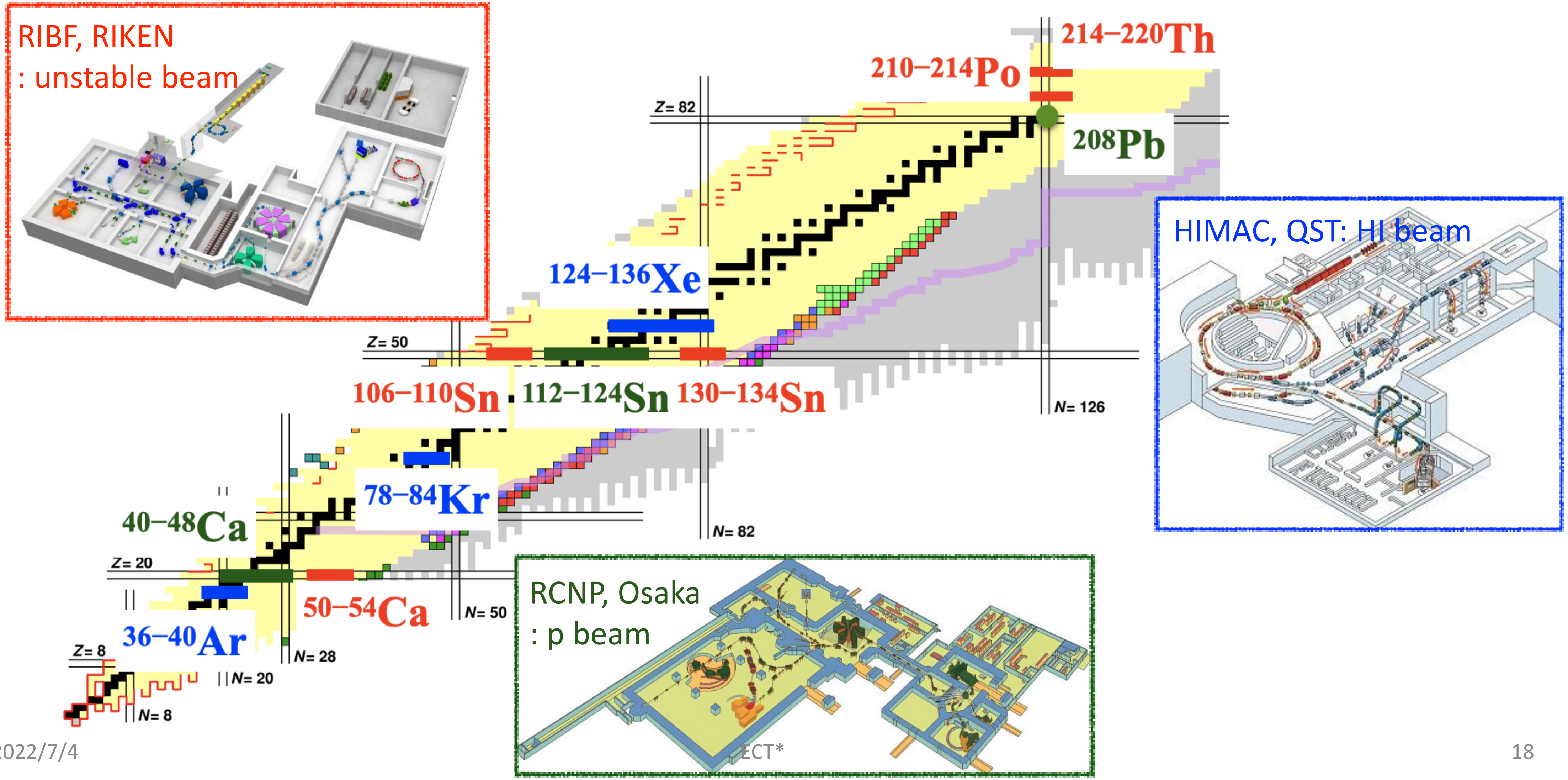
- Developments of the reaction frameworks
  - DWIA+AMD : K. Yoshida et al., PRC99 ➔ alpha knock-out
  - CDCC-DWIA : Y. Chazono et al., PRC103 ➔ d knock-out

- RCNP project for the basic data to understand the reaction mechanism w/ high resolution spectroscopy.
  - Approved (8days) and will start in FY2022.



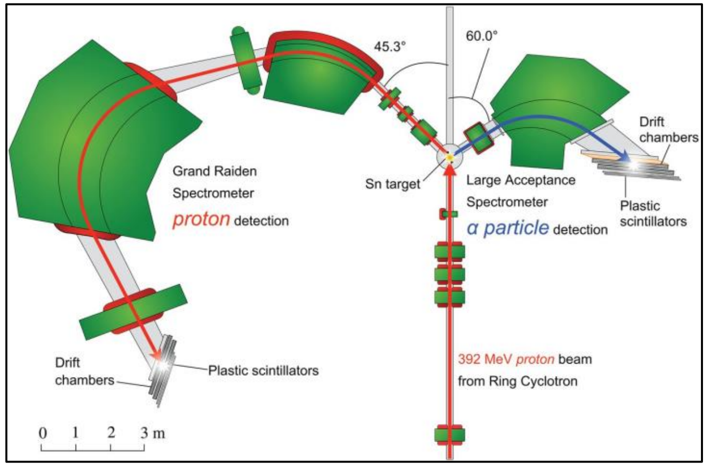
Experimental sites

E = 200—300 A MeV

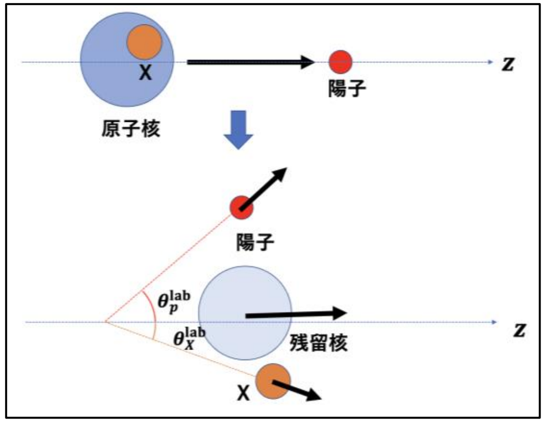


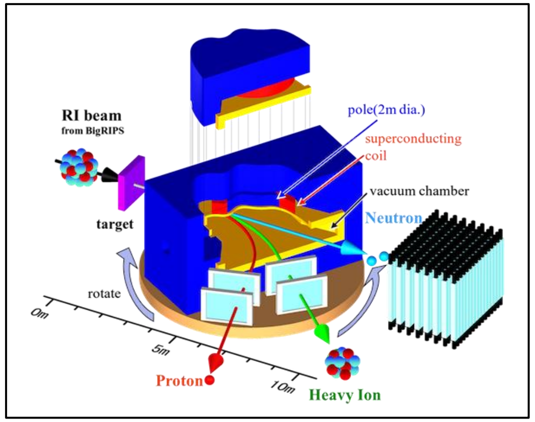
Experimental devices

RCNP：**established** w/ GR&LAS double spectrometer



RIBF, HIMAC：New recoil device **to be developed** w/ SAMURAI spectrometer @RIBF



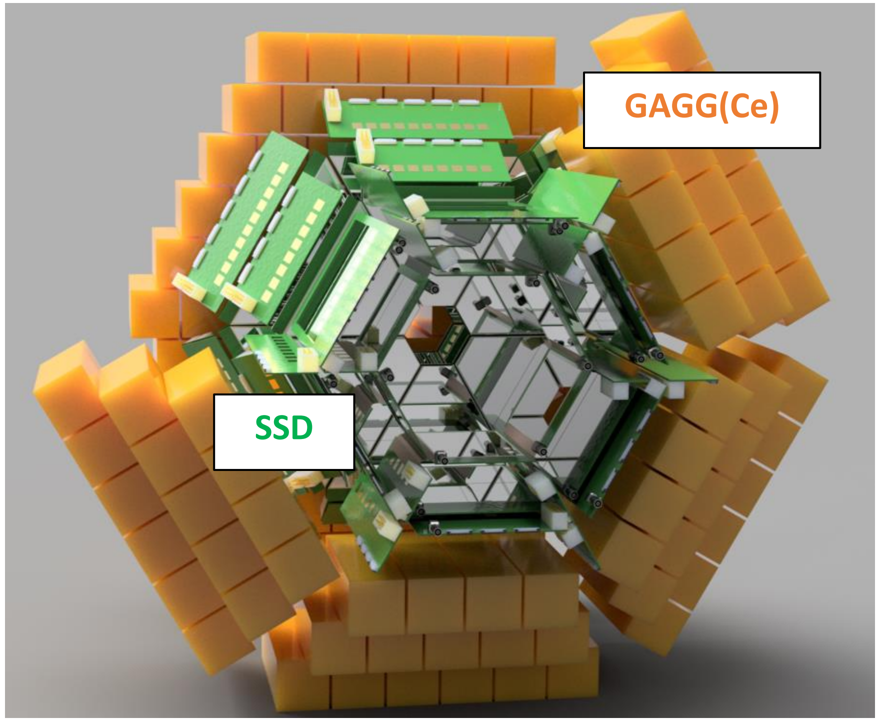


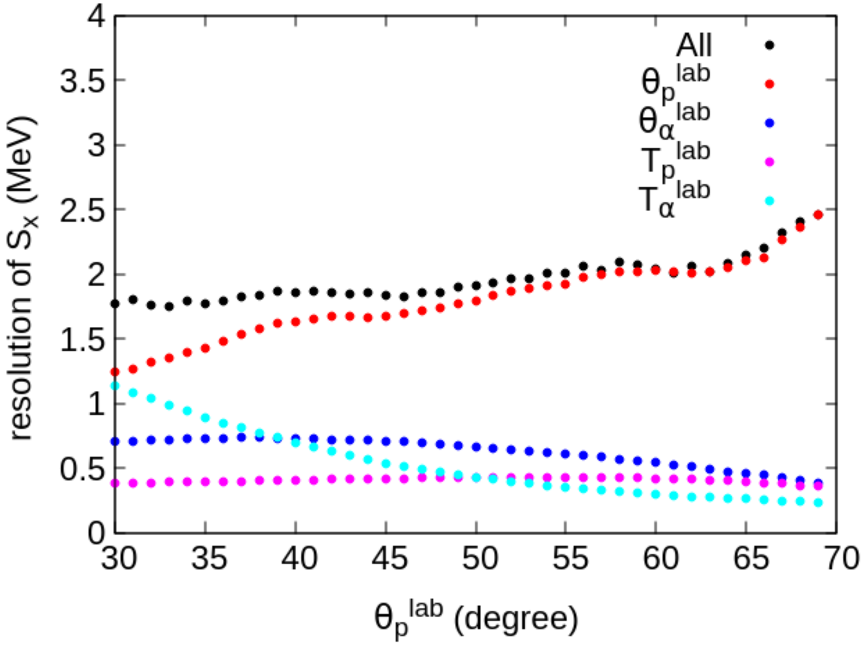
	kinematics	Cluster setting (d,t,3he,a)	Luminosity (cm)	$\Delta\Omega_p\Delta\Omega_X$ (sr^2)	ΔS_X (MeV)
RIBF	Inverse	Simultaneous	10^{27}	4	2
HIMAC	Inverse	Simultaneous	10^{30}	4	2
RCNP	normal	individual	10^{32}	10^{-4}	0.3

New telescope array : “TOGAXSI”

TOtal energy measurement by GAgg and verteX measurement by Si strips

- For the inverse kinematics measurements at HIMAC, RIBF
- Test experiment at HIMAC is ongoing. ➔ many PhD students



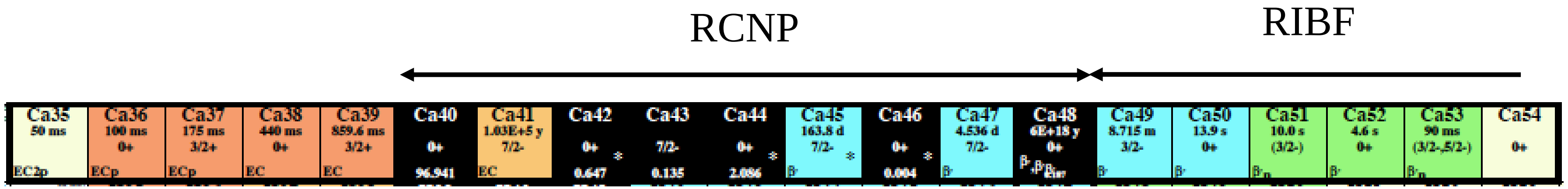


Separation energy resolution (α knockout)

Next experiments (planned in 2022~2023)

(p,pX) [X:d,t,^{3}He, α]: Ca isotopes already approved

for $^{49\text{-}52}$Ca, $^{51\text{-}54}$Sc, and $^{54\text{-}56}$Ti at RIBF
for $^{40\text{-}48}$Ca at RCNP
both spoken by T. Uesaka and J. Zenihiro



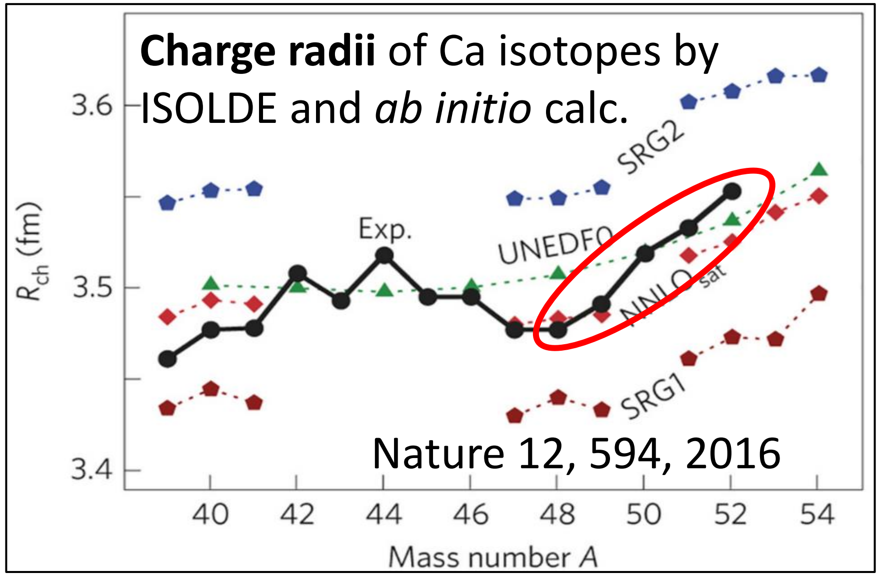
to be followed by experiments for
Sn isotopes
Pb isotopes and heavier α-decay nuclei
N=Z nuclei
:

2. Proton elastic scattering w/ RI beams

- p-A scattering in inverse kinematics with RI beams
  ➔ The ESPRI project

- Complementary experiments to the cluster knock-out reaction measurements.
    - Mainly for the study of the EOS, especially, the **symmetry energy** parameters.
    - If some structure appeared beyond the mean-field, we may be able to discuss clusters/correlations from density distributions.

  ➔ related to **Sagawa-san's talk**

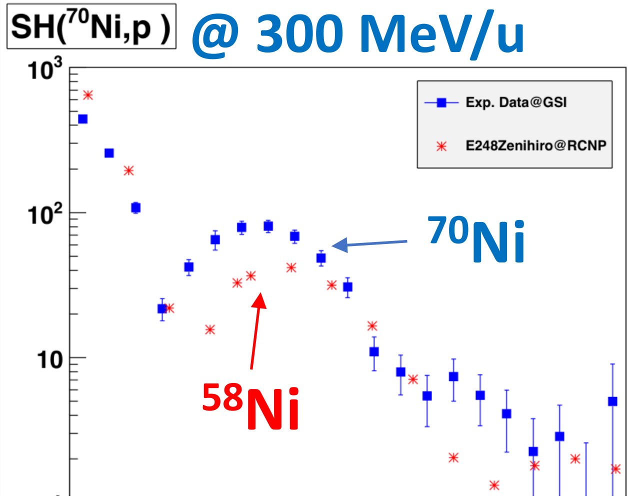


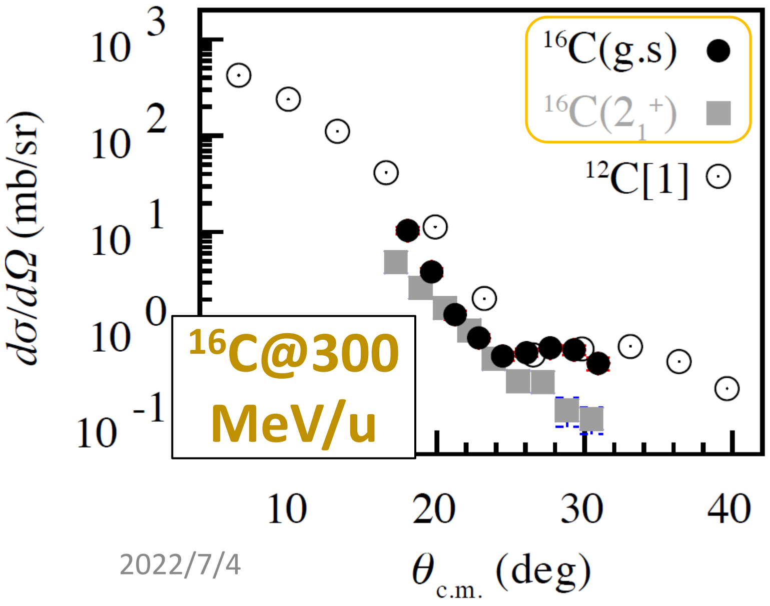
- Plan to measure proton elastic scattering for ^{52}**Ca** at RIBF, ^{108,112}Sn at RCNP, RIBF

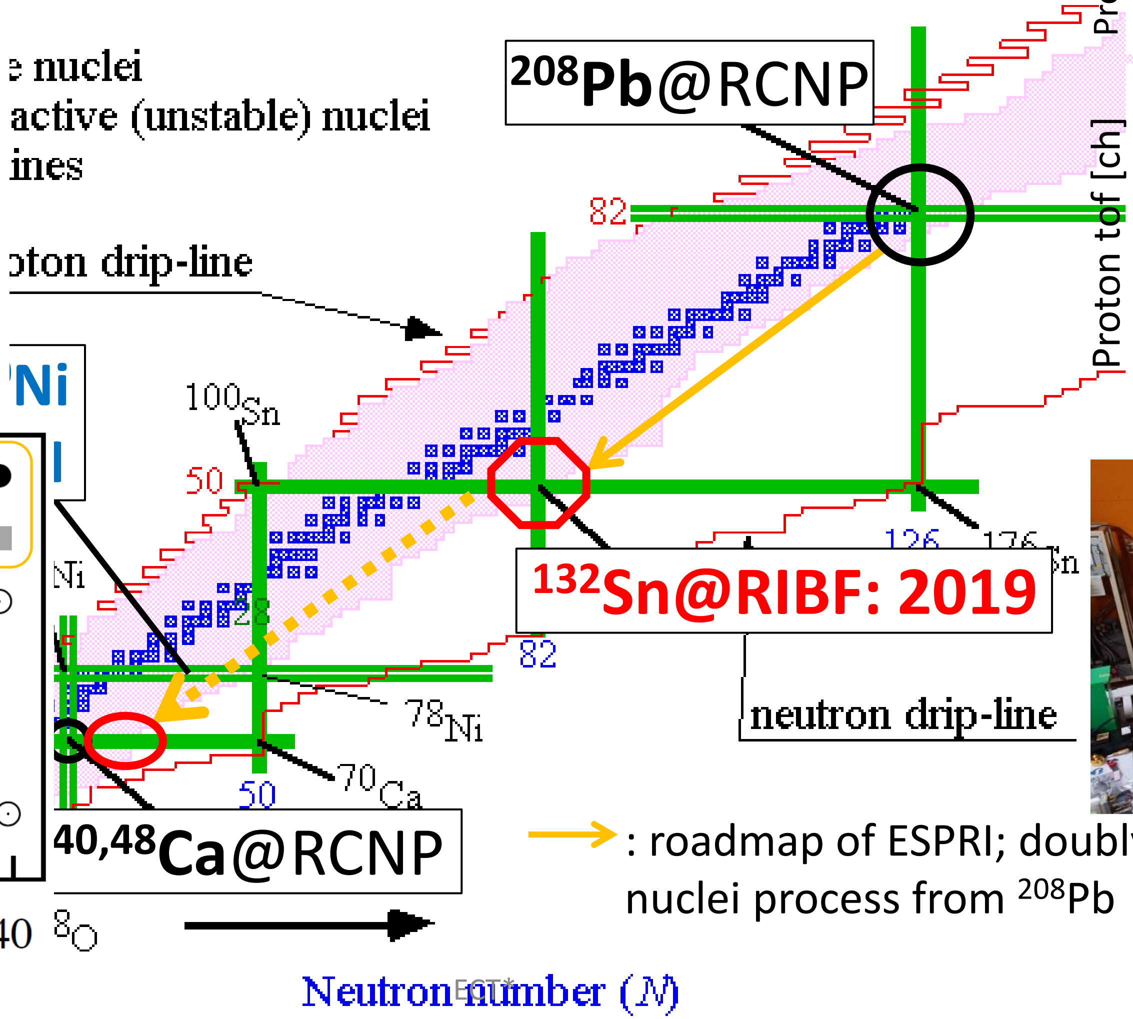
ESPRI project so far

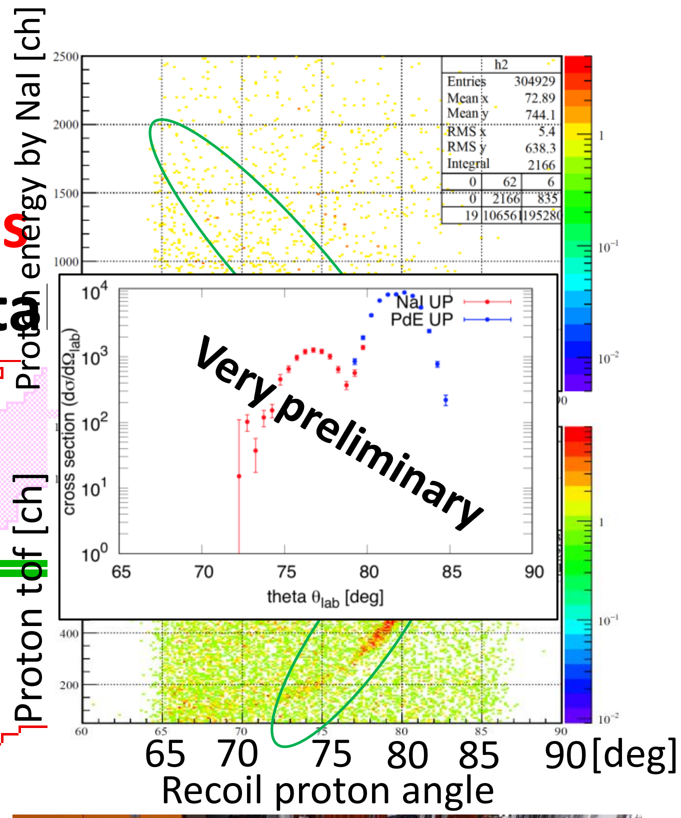
Elastic Scattering of Protons with RI beams

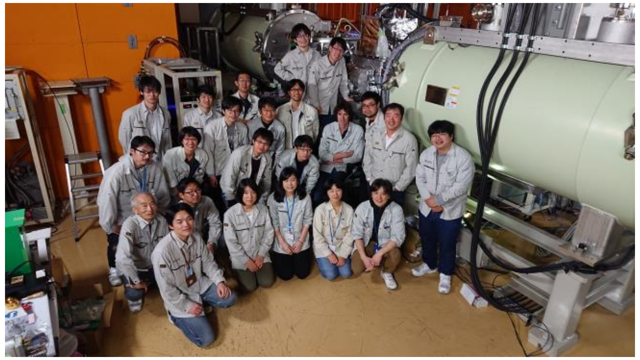
...oton elastic scattering method to **unsta**...







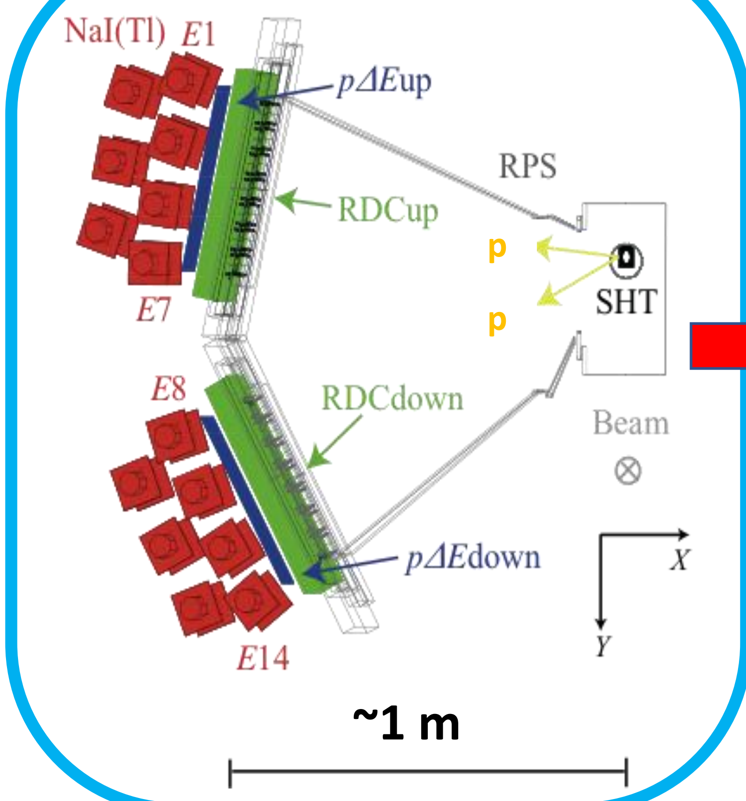




→ : roadmap of ESPRI; doubly magic nuclei process from ^{208}Pb

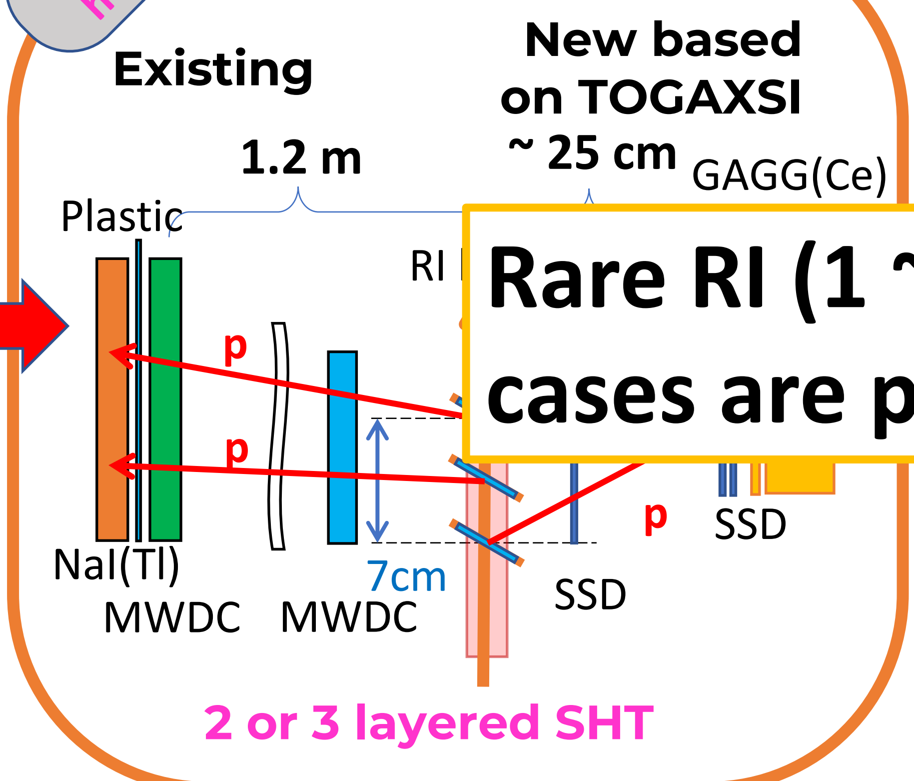
ESPRI device roadmap

16C, 132Sn done!!
w/ Existing ESPRI

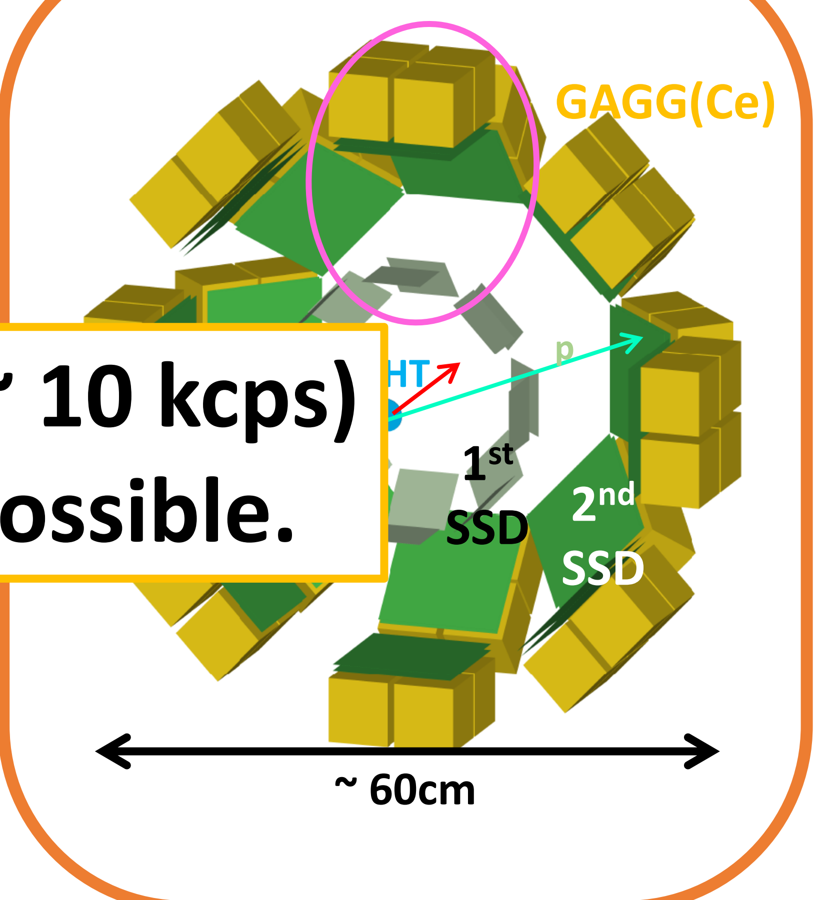


New ESPRI+ system combined w/ new SHT & telescope

Now here



2pi telescope array based on ONOKORO device

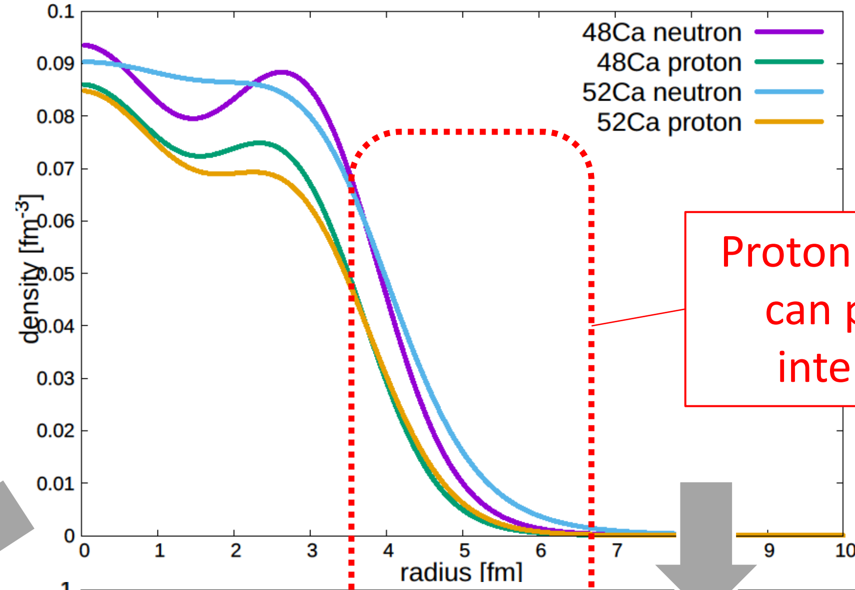


Rare RI (1 ~ 10 kcps) cases are possible.

^{48}Ca vs ^{52}Ca by RMF

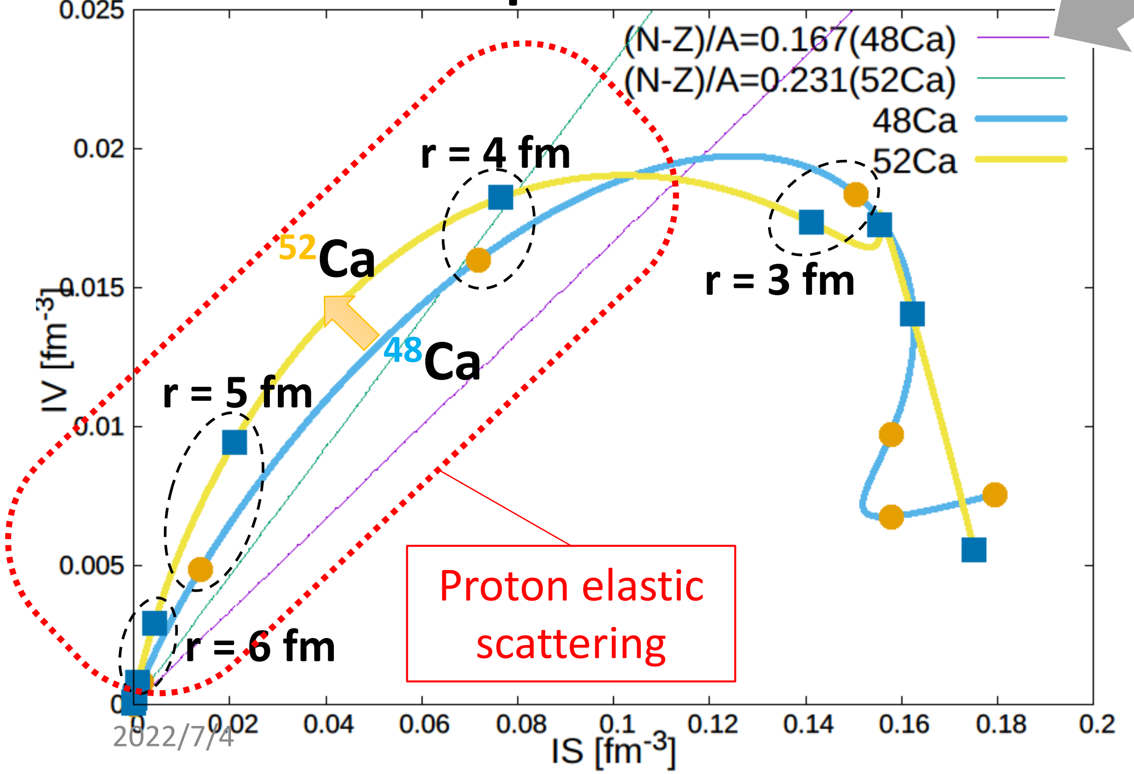
A RMF prediction (all in fm)
: r_n – r_p = skin (Δr_{np})
^{48}Ca: 3.58 – 3.37 = 0.20
^{52}Ca: 3.9 – 3.47 = 0.43

ISOLDE result :
r_p in ^{52}Ca ~3.48 fm
Reaction cross section :
Δr_{np} in ^{51}Ca ~ 0.35 fm

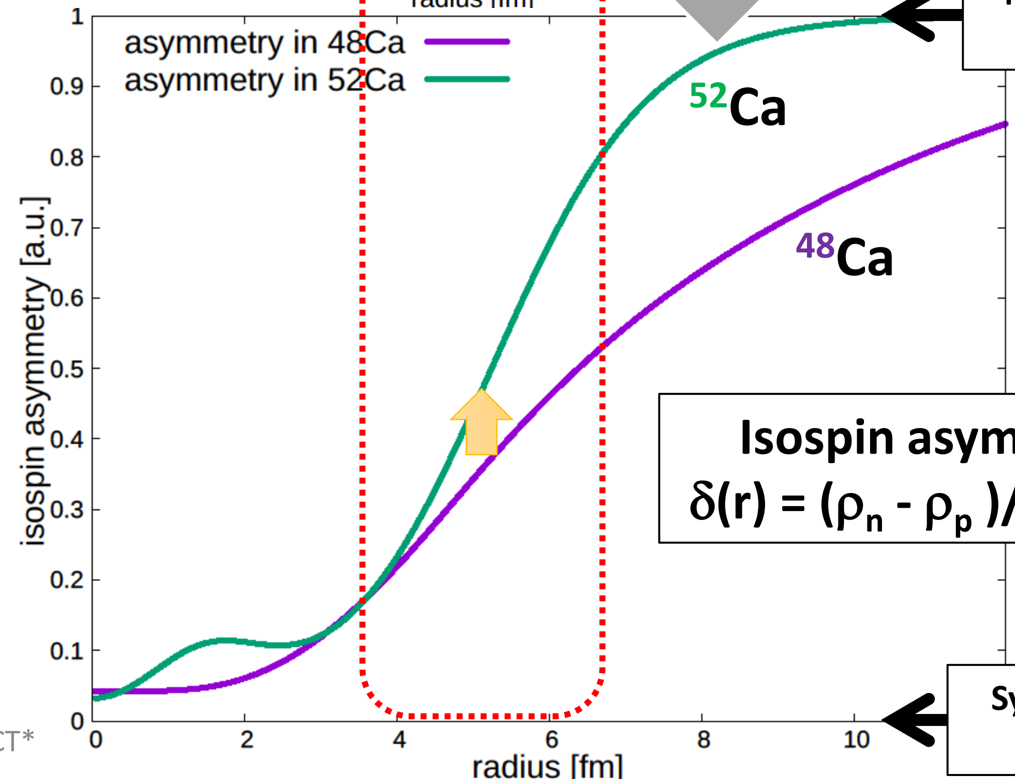


Proton elastic scattering can probe the most interesting region.

2D IS-IV map in ^{48}Ca and ^{52}Ca



Proton elastic scattering



Neutron matter

Symmetric matter

Isospin asymmetry
$\delta(r) = (\rho_n - \rho_p)/(\rho_n + \rho_p)$

PDP effect in $^{40-48,48-52}$Ca

A RMF prediction (all in fm)

Isotope : r_n – r_p = skin (Δr_{np})

^{40}Ca : 3.33 – 3.39 = -0.05

^{48}Ca : 3.58 – 3.37 = 0.20

^{52}Ca : 3.90 – 3.47 = 0.43

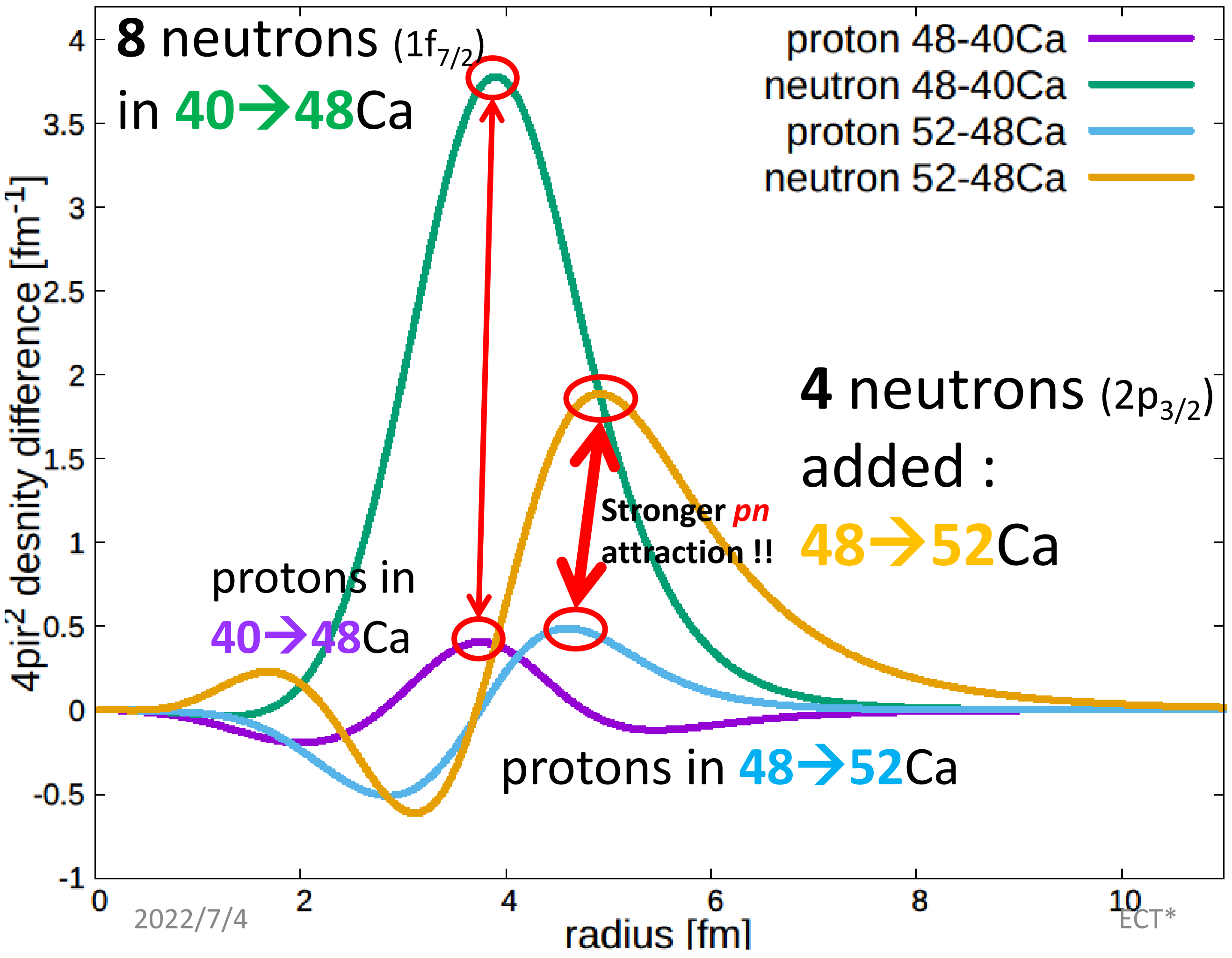
Ref.

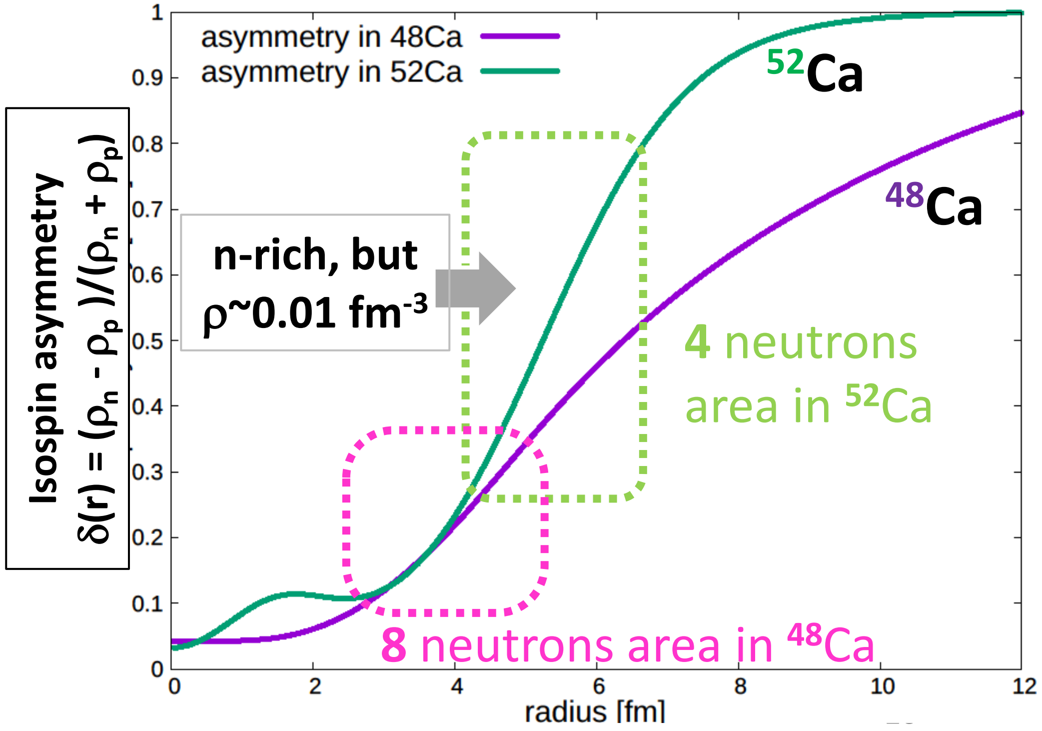
ISOLDE result :

r_p in ^{52}Ca ~3.48 fm

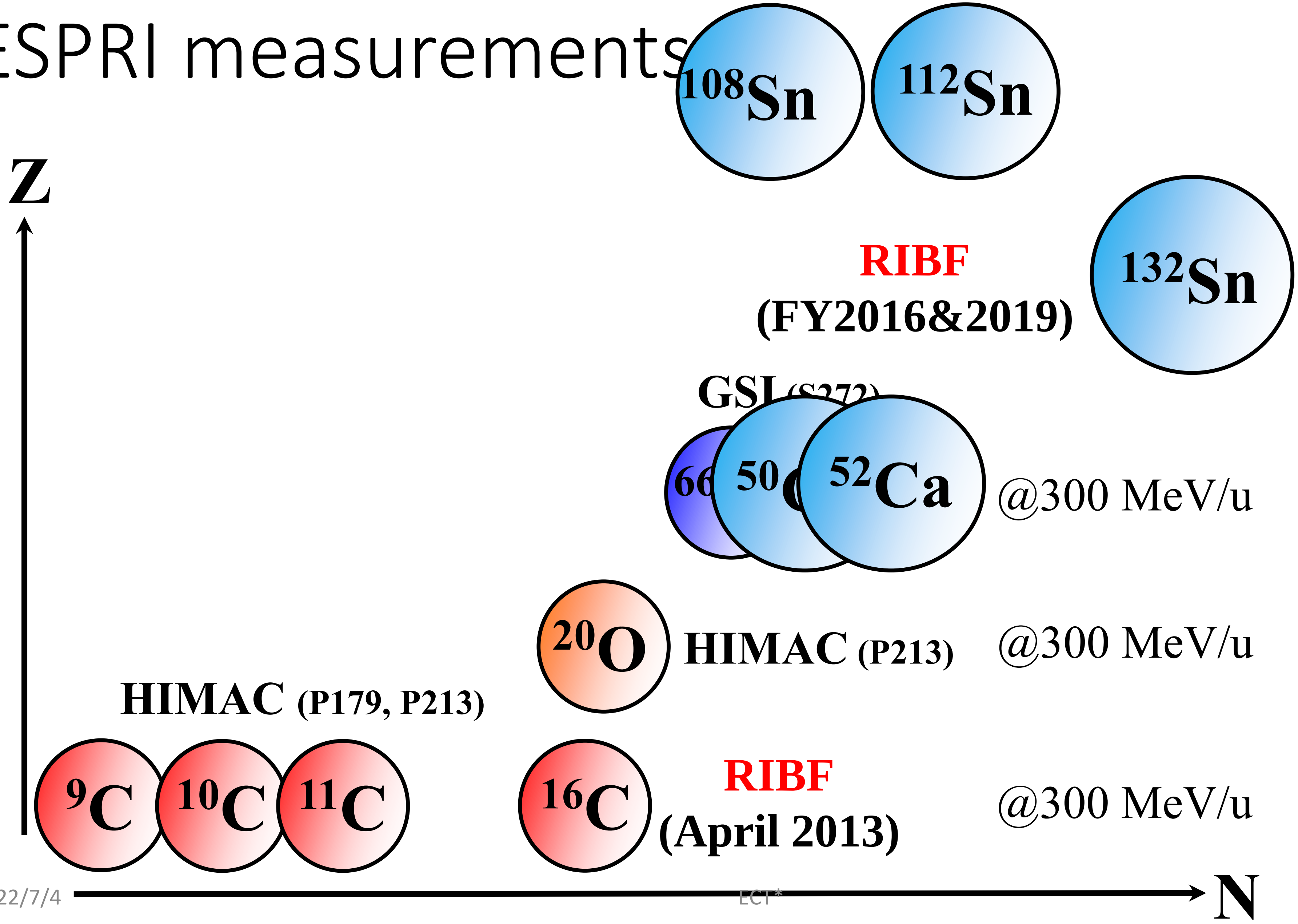
Reaction cross section :

Δr_{np} in ^{51}Ca ~ 0.35 fm





ESPRI measurements

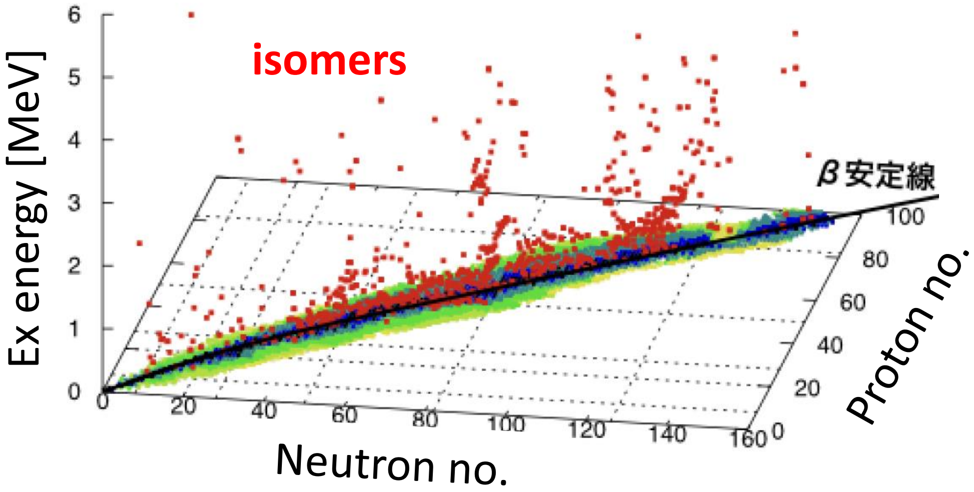


ESPRI* : isomeric-state density search

- Not the ground state!!!
  - **Elastic scattering from isomeric state nuclei**
  - **Direct determination of excited states density distributions.**

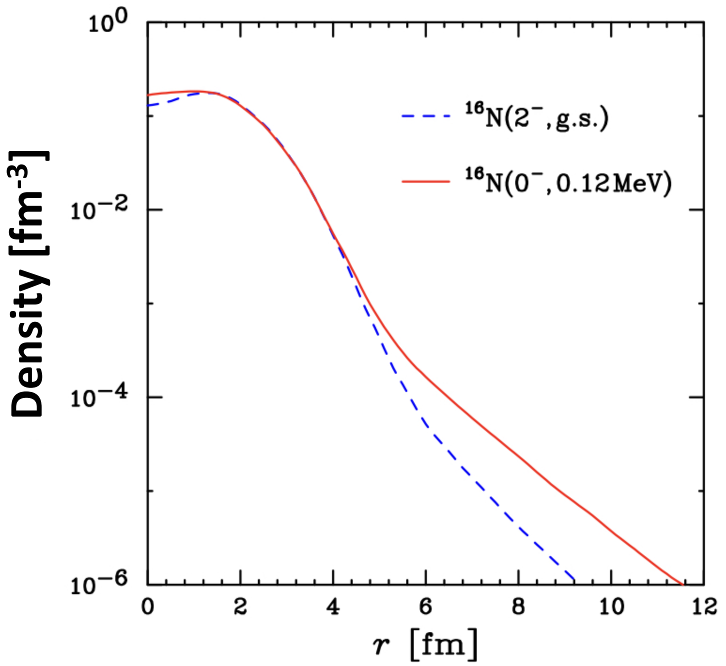
- New dof frontier : Ex energy
  - RI beams open Isospin dof
  - Isomer beams open Spin, finite temperature dof?
    - ➔ discussion w/ theorists necessary
    - EOS at finite temperature??

- Experiments planned at HIMAC
  - Development of the high-efficiency isomer tagging system
    - ASTERISQ by Dozono-san
  - Start from light isomer
    - ^{16}N(0-) isomer (ref.: ^{16,18}O, ^{16}C) : p-h pair in $\rho(r)$
  - Many interesting isomers exist!!



courtesy of Dozono-san

$^{16}N(0^-)$ case estimation



16N(0-) = 16O + p^{-1}n (0-) pair

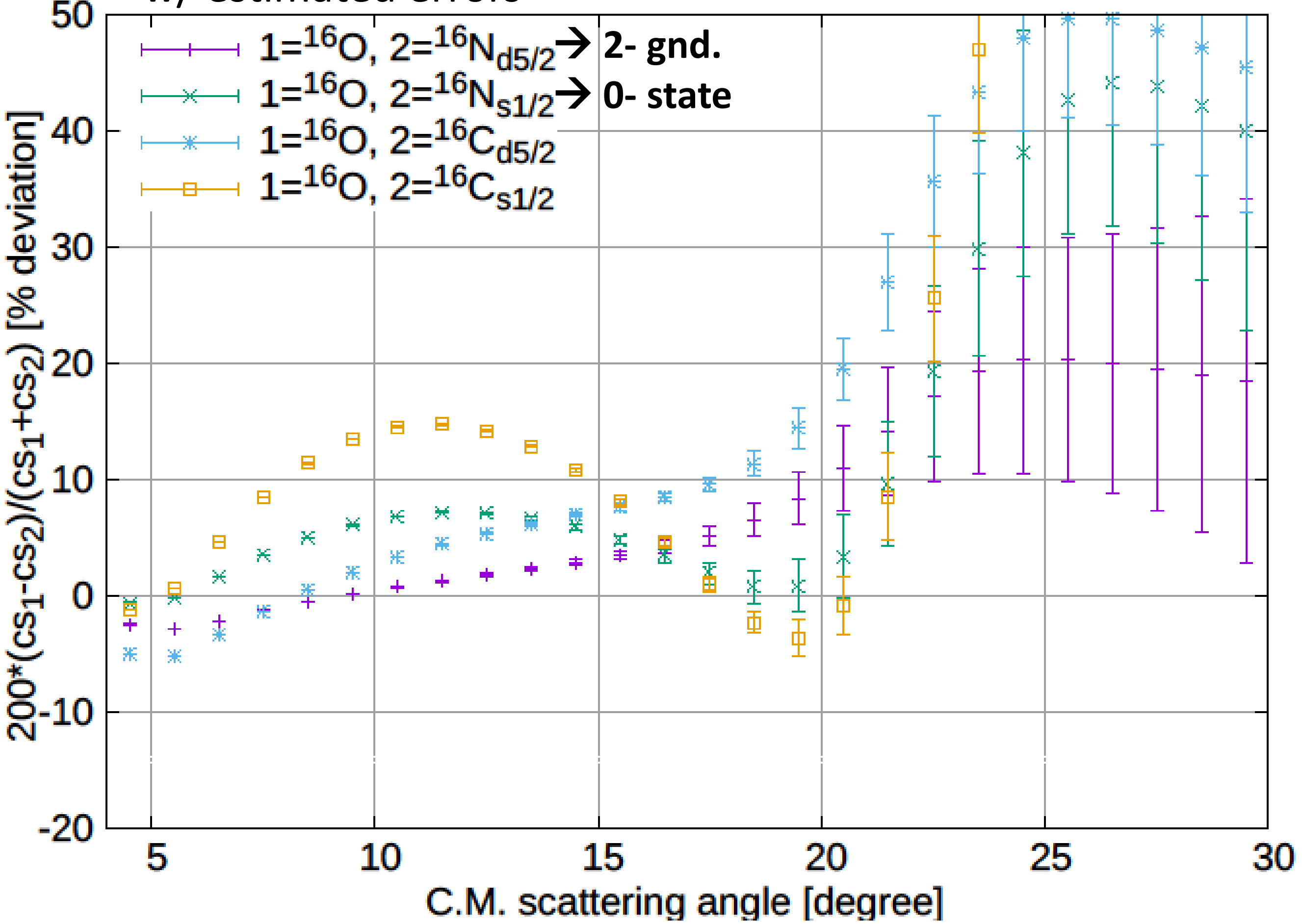
Cf.

18O(g.s.,0+) = 16O + nn (1S0) pair,

18F(g.s.,1+) = 16O +pn (3S1) pair

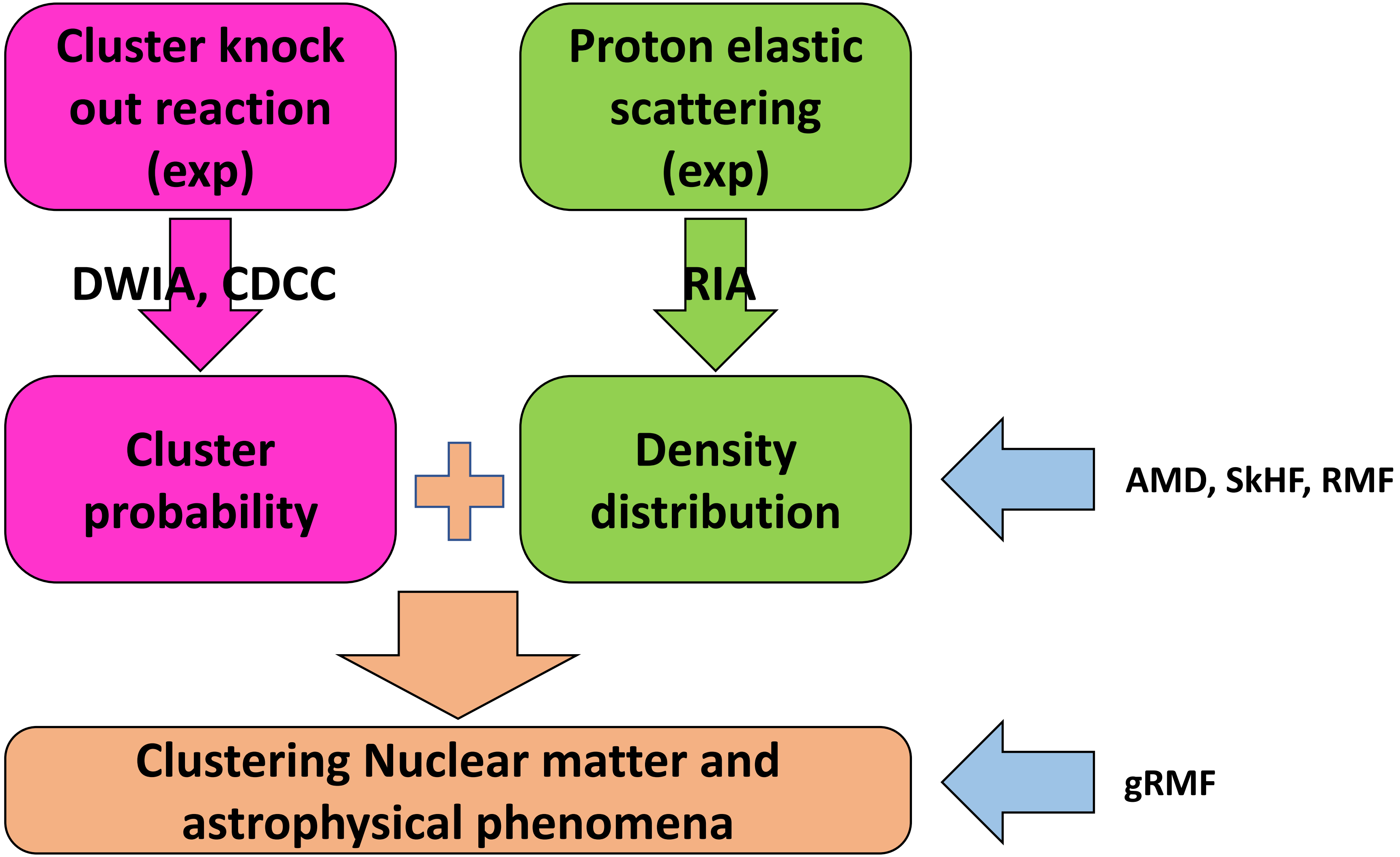
16C = 16O + (-2p, +2n)??

Cross section difference from reference nucleus ^{16}O w/ estimated errors



Summary

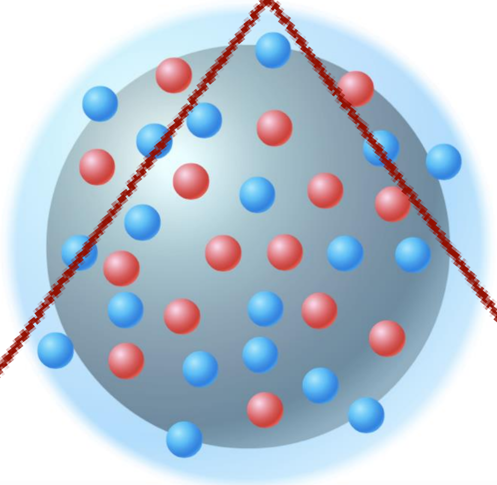
Connection between experiment and theory



Universality of clustering in nuclei

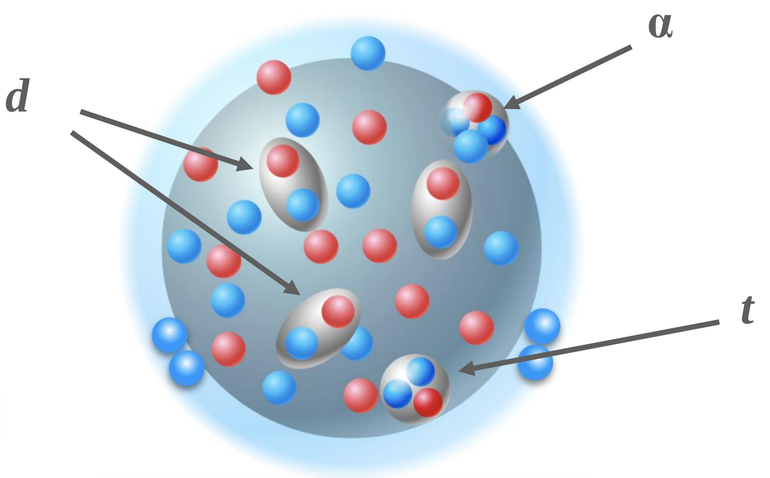
Present picture of nuclei

"Uniform" system made of independent neutrons and protons.
Cluster can be found in very limited cases of light nuclei.



New picture of nuclei
we're going to establish

"Non-uniform" system where clusters exist symbiotically with independent nucleons.
Many clusters (*d*, *t*, ^{3}He, *α*. . .) develop in all the nuclei.



Summary

- We have launched the ONOKORO/ESPRI projects.
  - Comprehensive understanding of spontaneous **cluster** formation in uniform nuclear **medium**.
    - Nuclear many-body system has a nature of non-uniformity
  - Two complementary methods are employed.
    - ONOKORO : Cluster knock-out reaction (p,pX) X=d,t,3he,a
    - ESPRI : Proton elastic scattering

- The experimental programs are ongoing at RCNP, HIMAC, RIBF
  - FY2022 in April, July : test experiments at HIMAC to check the detector (GAGG & Si) performances
  - FY2023~FY2024 : plan to perform test and physics experiments w/ the TOGAXSI telescope.

    ➔ First targets : stable and unstable Ca isotopes

- Thanks to the theoretical progresses,
  - the framework for alpha knockout reaction are now being established w/ DWIA+AMD calculations.
  - For deuteron knockout reaction, a challenging CDCC+DWIA model is being developed including breakup and/or recombination processes.

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Answer to some questions and comments in the talk

Maybe, I did not fully hear the questions and comments.

Recent DWIA + AMD model tells us

- Reaction :
  - Knock-out reaction probes only the surface regions due to the strong absorption inside the nucleus.

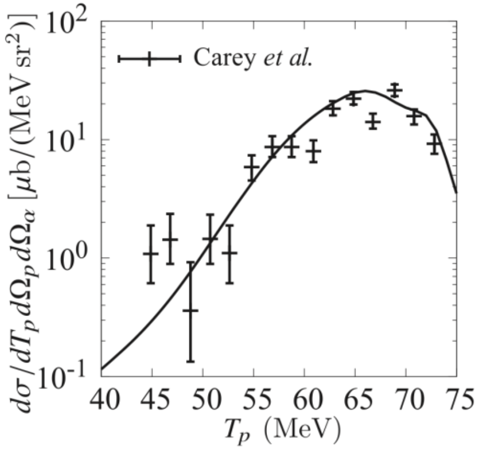
  ➔ automatically sensitive to the surface region

- Structure :
  - **Anti-symmetrization (AS)** must be included to deduce the alpha probability.
  - Otherwise, Sα is overestimated and the model cannot distinguish alpha amplitudes with mean field potentials

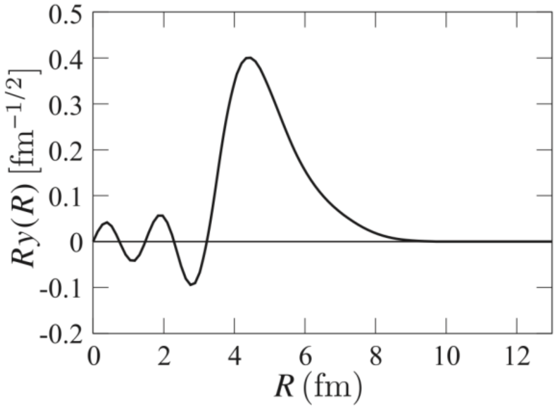
  ➔ If AS is properly included, alpha formation probability can be discussed.

- As a result, knock-out reaction can probe the surface alpha localization w/ a reliable model based on DWIA +AMD
  - K. Yoshida et al., Phys. Rev. C 100, 044601 (2019)
  - Y. Chiba and M. Kimura, Prog. Theor. Exp. Phys. 2017, 053D01 (2017).
  - About alpha decay nuclei like Po, still be careful to treat the probability.
    - C. Qi et al., Phys. Rev. C 81, 064319 (2010).
    - K. Yoshida and J. Tanaka, arXiv, 2111.07541.

^{20}Ne(p, $p\alpha$)



α cluster probability in ^{20}Ne by AMD



Reliability of the NN effective interaction for ρ(r)

- Reaction framework : RIA w/ the medium modified NN interaction
  - Dirac ***tρ***-optical potential : single folding of *NN* amplitude (***t***) & densities (*ρ*)
    - *NN* amplitude; 10 mesons’ coupling including both direct & exchange terms are tuned by free NN phase shift analysis(RLF model by C. J. Horowitz)

$$F = F^S + F^V \gamma^{\mu}_{(0)} \gamma_{(1)\mu} + F^{PS} \gamma^5_{(0)} \gamma^5_{(1)} + F^T \sigma^{\mu\nu}_{(0)} \sigma_{(1)\mu\nu} + F^A \gamma^5_{(0)} \gamma^{\mu}_{(0)} \gamma^5_{(1)} \gamma_{(1)\mu}$$

$$U = \frac{-4\pi i p_{\mathrm{lab}}}{M} [F_{S0} \rho_S + \gamma_0 F_{V0} \rho_V]$$

  - Medium modification to the *NN* amplitude
    - Phenomenological parameters; aj, bj
    - Universal form of density-dependent terms
    - At ρ=0, the same as free NN interaction

    ➔Calibrated by the scattering data of ^{58}Ni (density is known.)

$$g_j^2 \rightarrow g_j^{*2} \equiv \frac{g_j^2}{1 + a_j \rho(r)/\rho_0},$$

$$m_j \rightarrow m_j^* \equiv m_j \left(1 + b_j \rho(r)/\rho_0\right)$$

$$j = \sigma, \omega.$$

➔ The same interaction can be applied to determine the density.