～中性子星の観測と理論～
研究活性化ワークショップ 2025
2025/05/19 – 2025/05/21
理化学研究所

原子核反応で探る 状態方程式と核子対凝縮相

大田晋輔
大阪大学核物理研究センター (RCNP)

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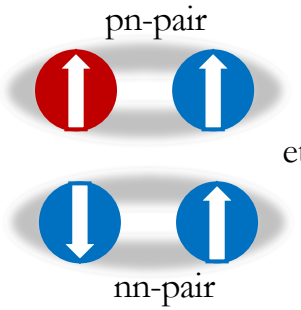
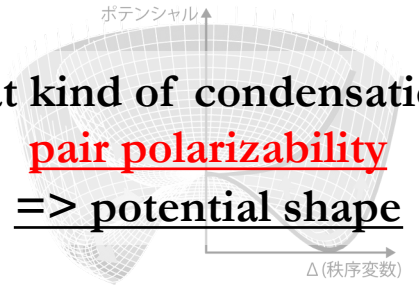
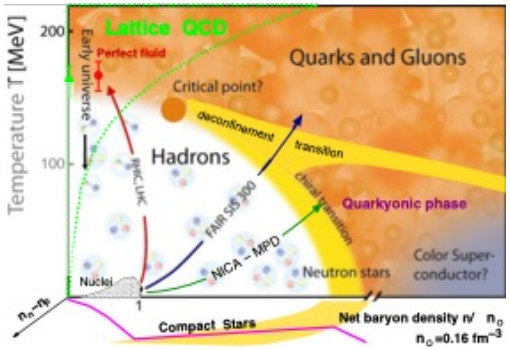




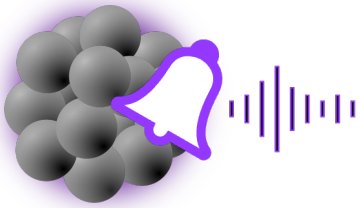
What kind of condensations?

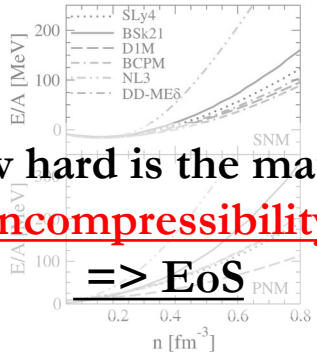
pair polarizability

=> potential shape



PHASES & PHANES Project
EQUATION OF STATE

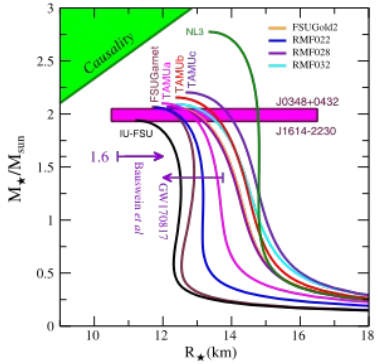




How hard is the matter?

incompressibility

=> EoS

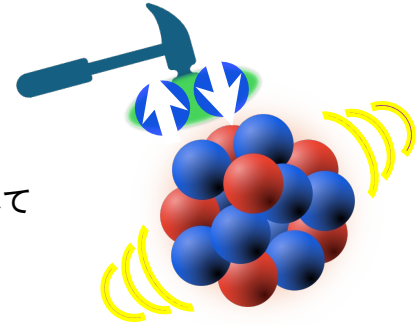


Experiment : S. Ota (RCNP), M. Dozono (Kyoto), F. Endo (RIKEN), S. Shimoura (RIKEN) et al.
Theory : K. Yoshida (RCNP), M. Matsuo (Niigata), N. Hinohara (Tsukuba) et al.

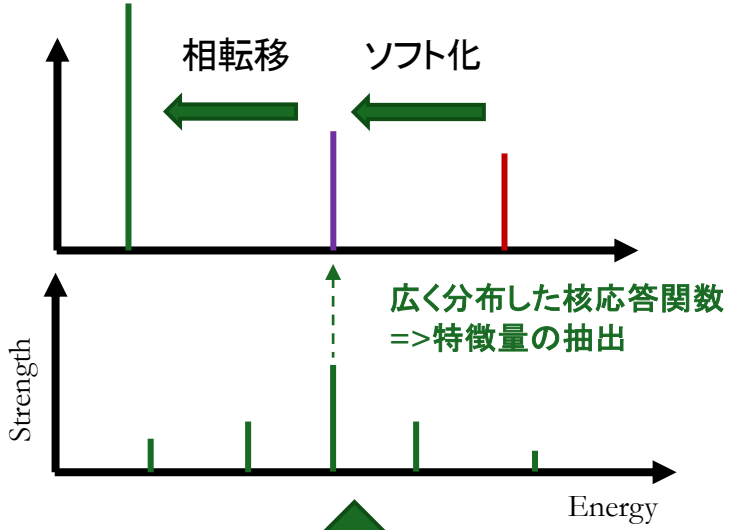
We welcome your joining!!!
(Topical and Free discussion every month)

原子核における物性の現れ

量子数や運動量移行を制御して
原子核を叩く



原子核
10fm, 300核子



力学的性質: 圧縮率
電気的性質: 双極分極率
磁気的性質: スピン応答？
流体的性質: ？

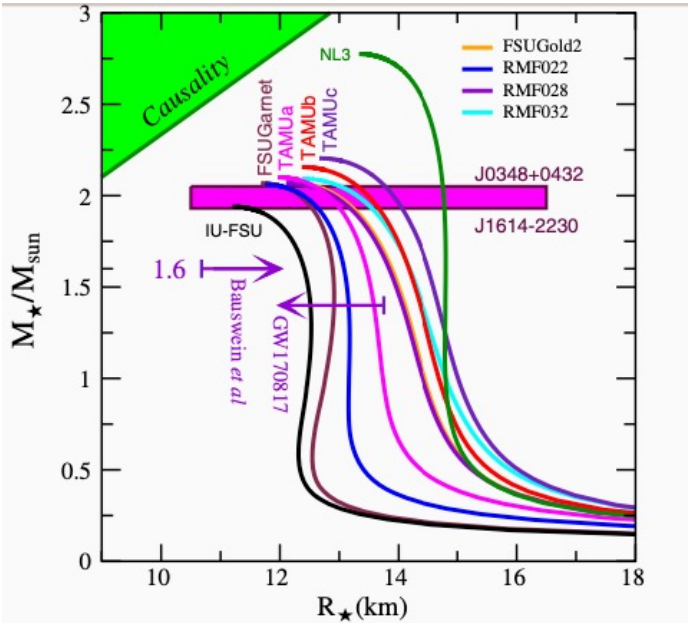
有限孤立系の特徴
殻構造、表面、変形
（質量数・荷電スピン依存性）

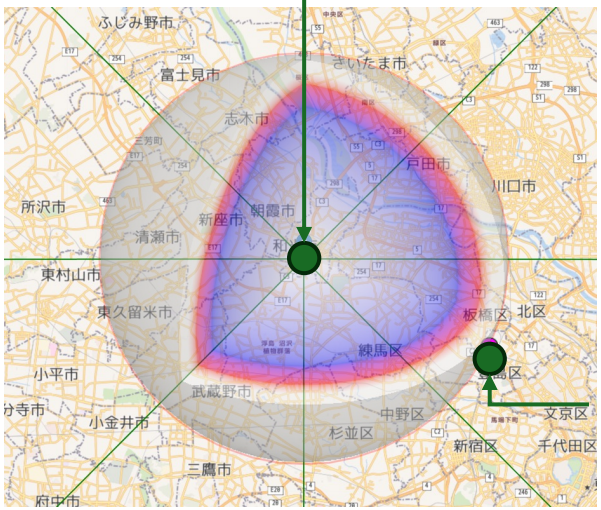
モードの断片化

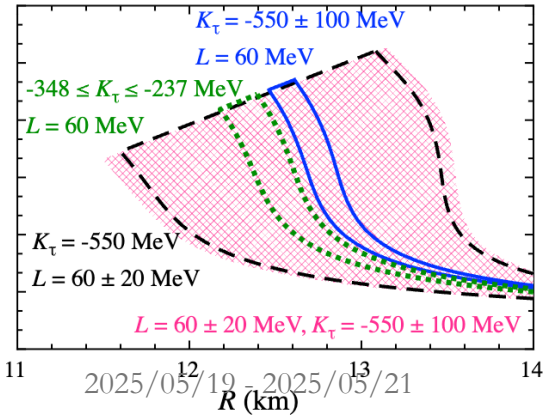
系統性から評価

巨視的系の性質

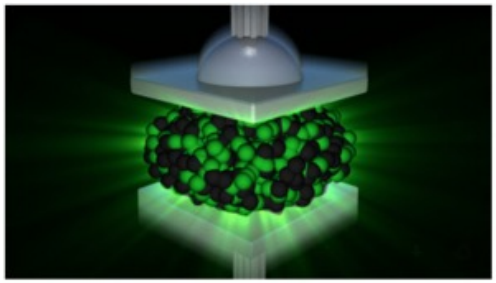
Uncertainty of EoS



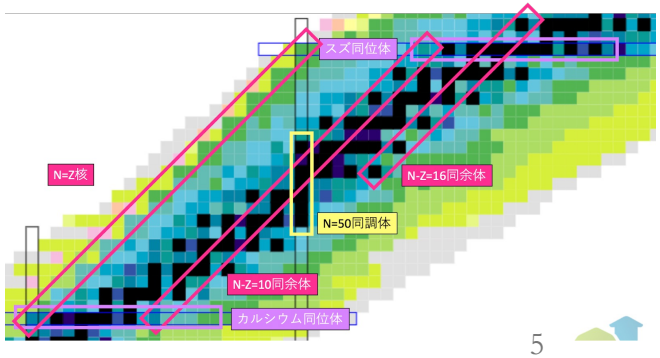




Nuclear Incompressibility

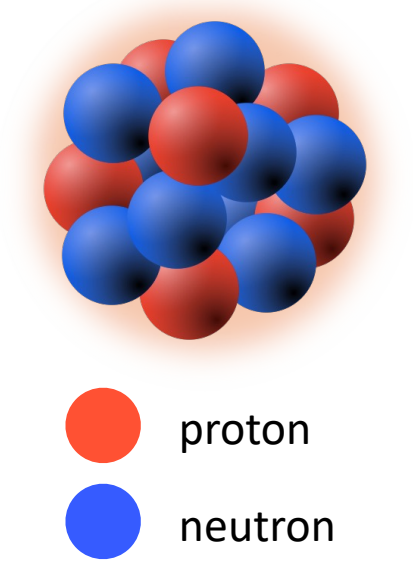


Systematic measurement



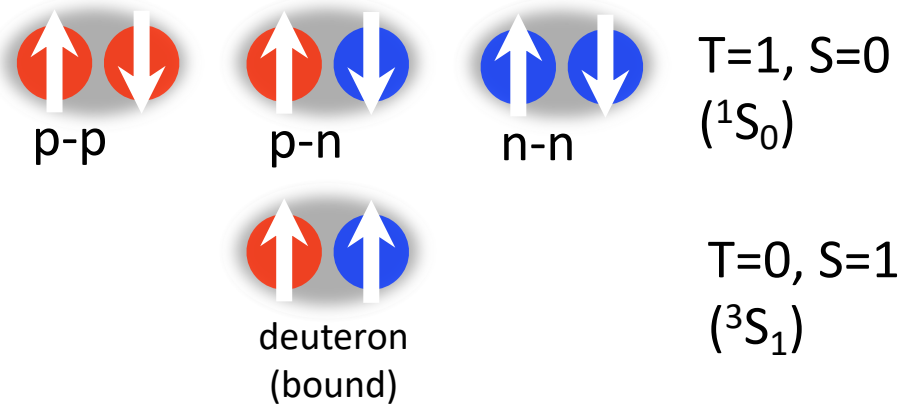
Nucleus and nucleon pair

	component	# of comp	Size	Coherence length	Spacing
Material	Electron / ion	1E23	> 1 mm	100 - 1000 Å	1-3 Å
Atomic nucleus	Proton / Neutron	1 - 300	5-7 fm	30 fm	2 fm



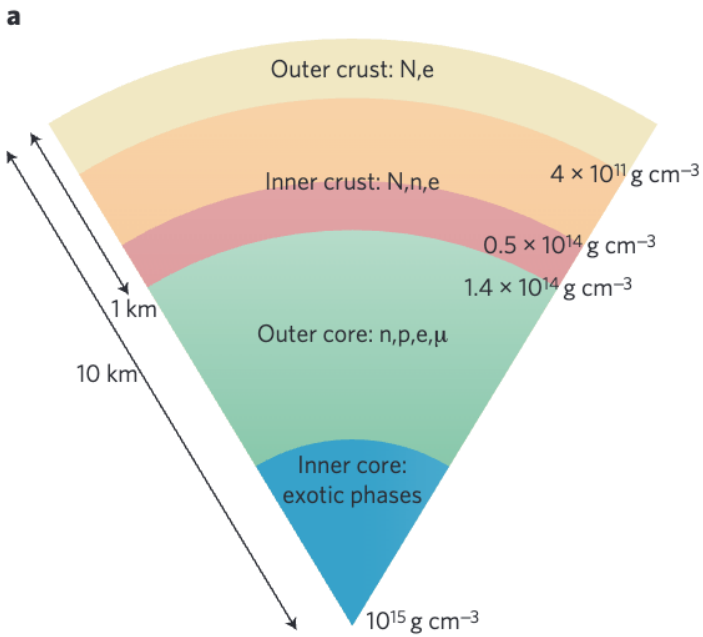
Quantum numbers of pairing correlation

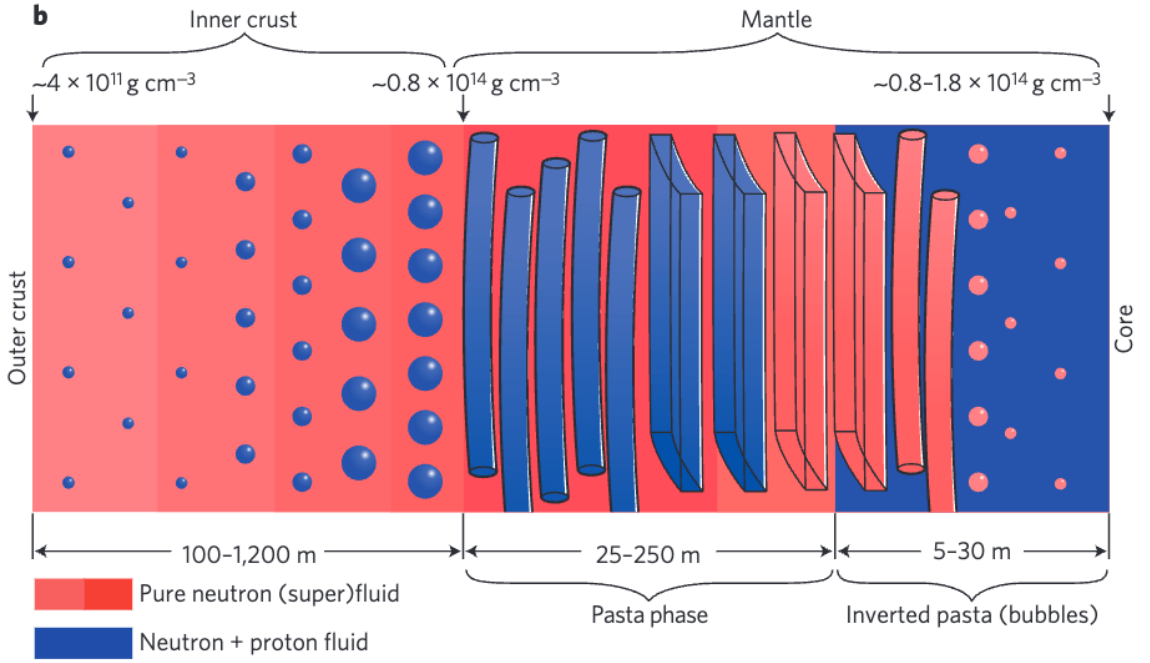
spin(S), isospin(T), space(L)



Structure of neutron star

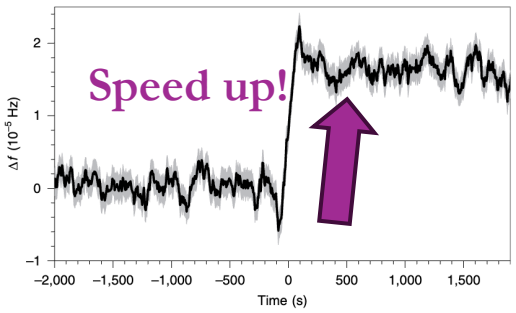
Clarify the structure and phenomena in the neutron star from terrestrial experiments

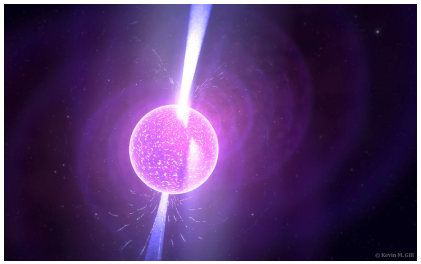




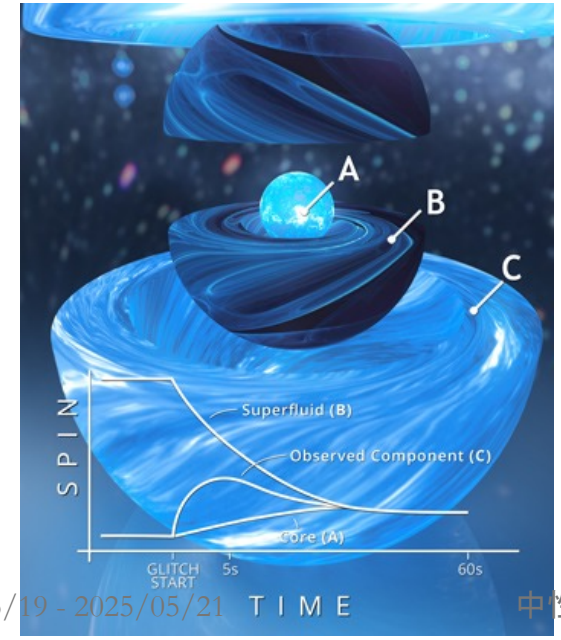
W. Neutron, Nature 2013

Observed phenomena related to neutron superfluidity



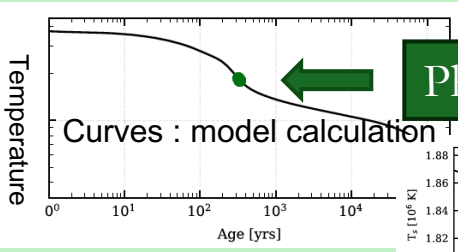


Pulser glitch requires two superfluid phases

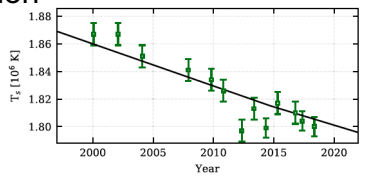


Phase transition in Cassiopeia-A

Wijngaarden+2019

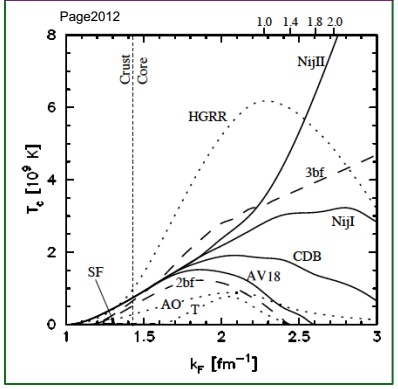


Phase transition

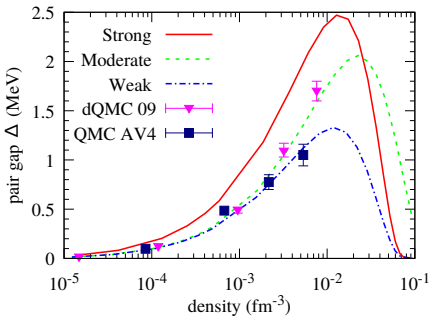


300 years old

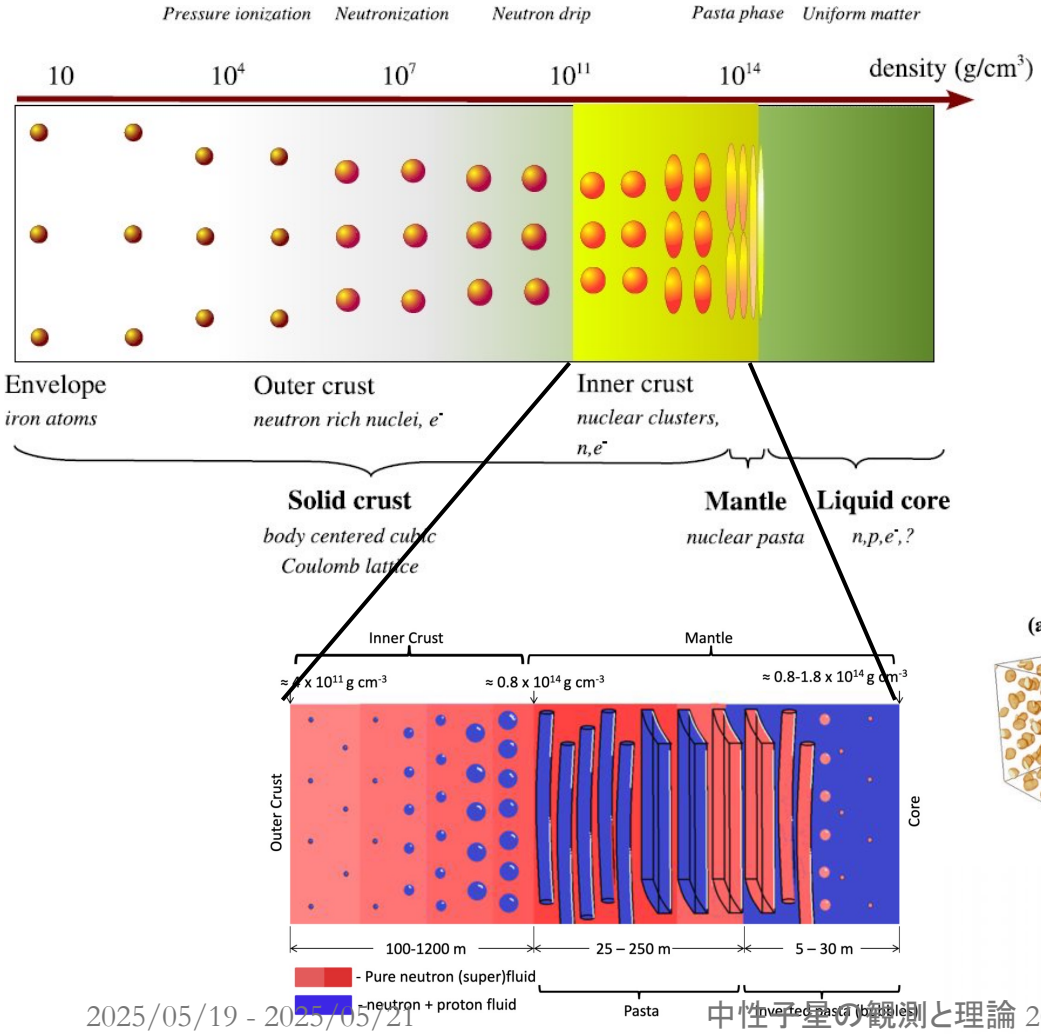
Various 3P2 gap model



Various 1S0 gap model



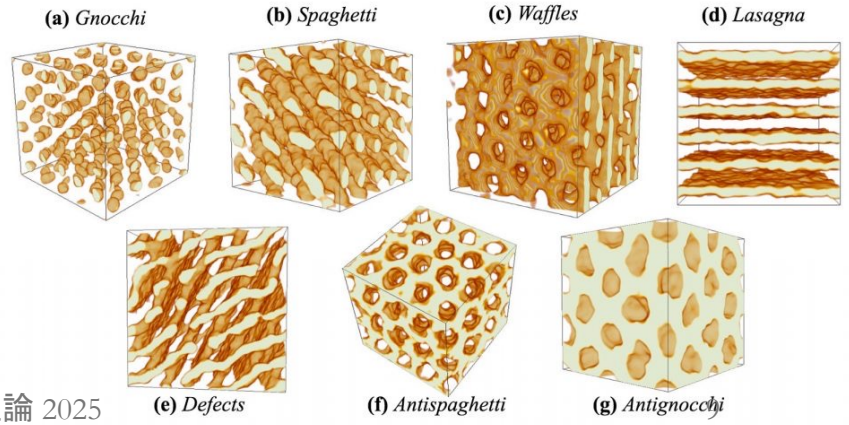
Impurity of proton makes a variety of structure



Nuclei and nuclear clusters exist in the neutron star

Pasta phase

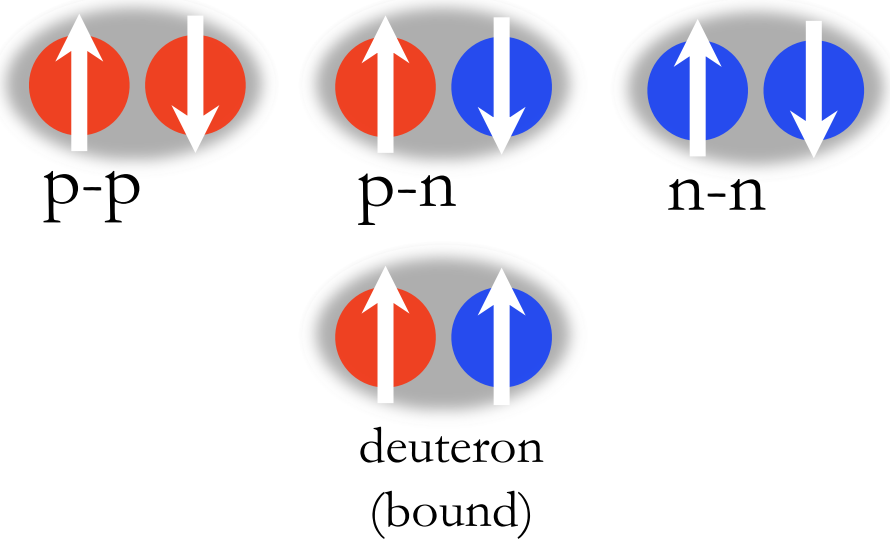
Due to the impurity of protons



Nucleon pairs

Quantum numbers of pairing correlation

spin(S), isospin(T), space(L)



	Lowest	Second
	$T=1, S=0$ $(^1S_0)$	$T=1, S=1$ $(^3P_{0,1,2})$
	$T=0, S=1$ $(^3S_1)$	$T=0, S=0$ $(^1P_1)$

What kind of pair condensation may happen?

Nucleon pair condensation?

Isovector Neutron Pair

n n

✓ L=0 superfluidity

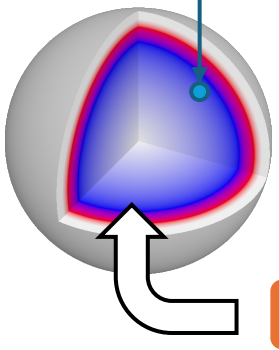
☐ Higher order?

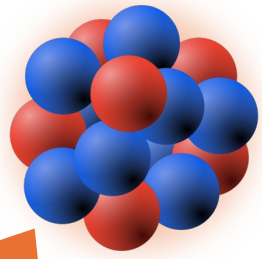
Isoscalar Proton Neutron Pair

L=0, S=1

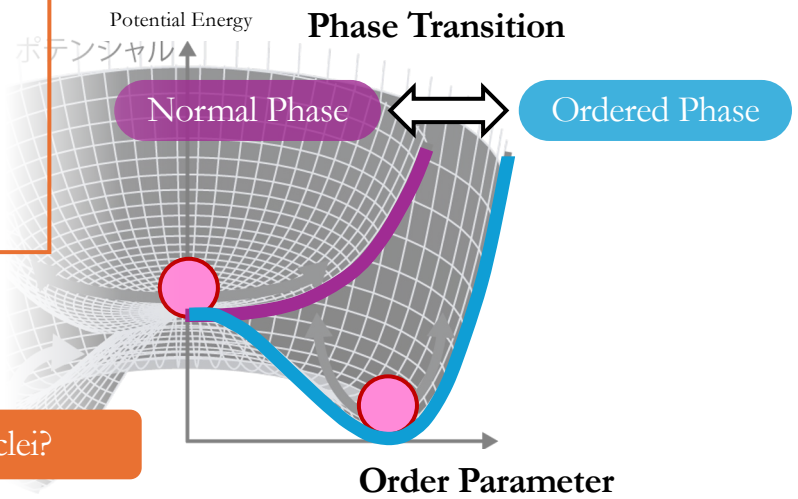
p n

?? strongly attractive
no experimental evidence





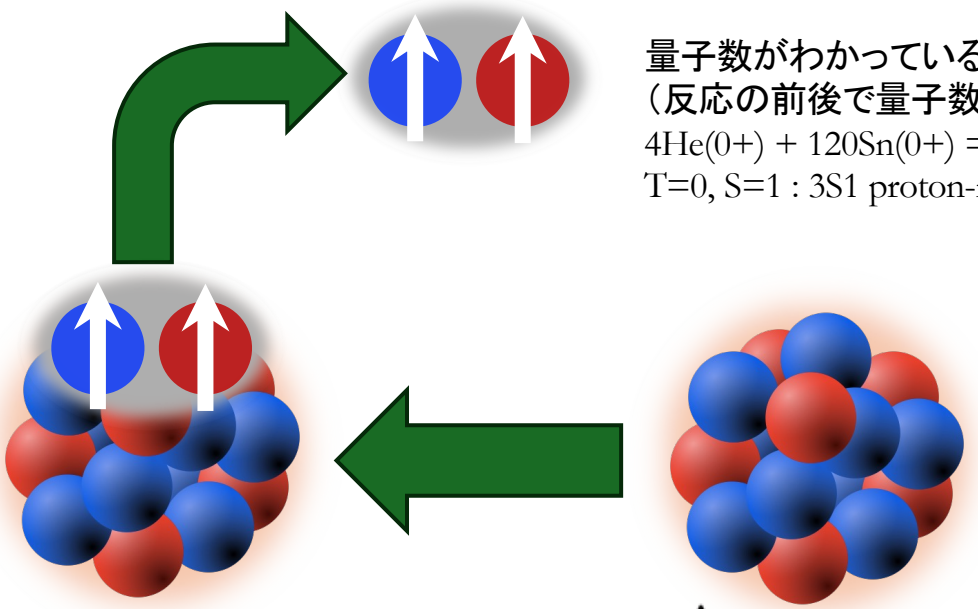
Potential shape of pair field in nuclei?



Δ>0 : Condensation
Δ=0 : Normal Phase

Δ+Curvature provides the shape of potential

“クーパー対”の移行で凝縮相を紐解く



量子数がわかっているペアをつける
（反応の前後で量子数が保存することを利用）
4He(0+) + 120Sn(0+) => 6Li(1+,T=0) + 118Sn
T=0, S=1 : 3S1 proton-neutron pair が移行した

$$\langle \mathrm{BCS}|P^{\dagger}|\mathrm{BCS}\rangle = \frac{\Delta}{G}\,.$$

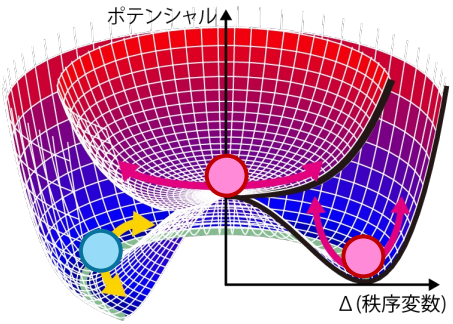
$$V = -G\,P_j^{\dagger}P_j, \qquad G \approx \frac{28}{A}\ \mathrm{MeV}.$$

Response to pair transfer
Pair rotation and vibration

Mode	Physics	Response
Phase	Gap	Rotation
Amplitude	Curvature	Vibration

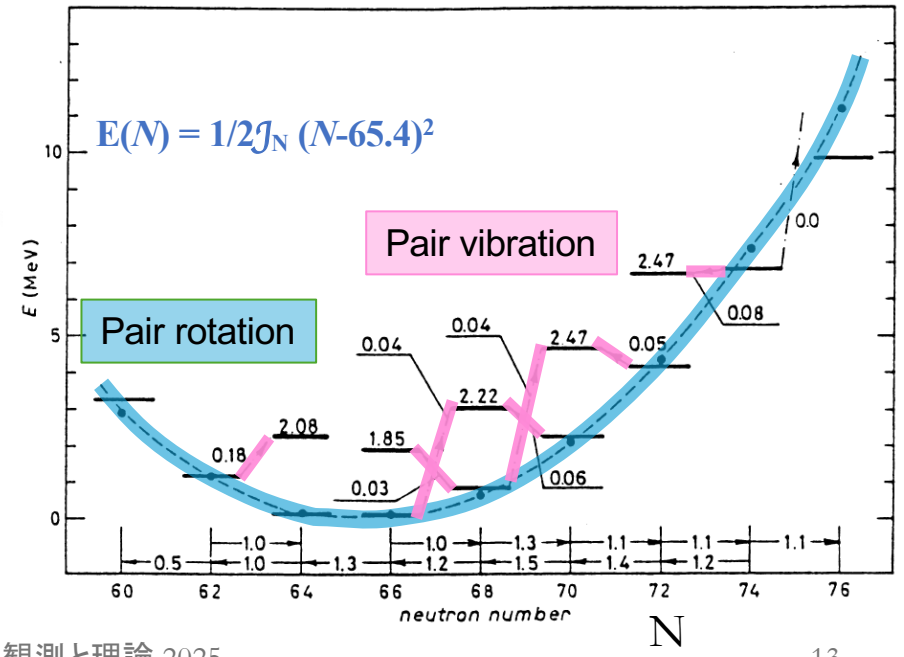
$$E_0 = U + \lambda N = \lambda N + \frac{G}{4}N^2$$
$$= \lambda N + \frac{\hbar^2}{2\mathcal{J}}N^2,$$

Symmetry breaking
Restoration => Rotational Band



$$R = \frac{\sigma(\mathrm{gs} \to \mathrm{gs})}{\sigma(\mathrm{gs} \to 2\mathrm{qp})} \approx \frac{A}{4}.$$

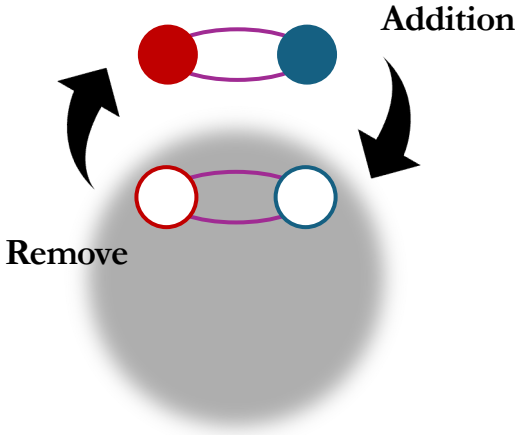
対凝縮相が発現すると
基底状態に強い遷移が観測されるはず
陽子・中性子対では未確認



For Δ=0, no information ?

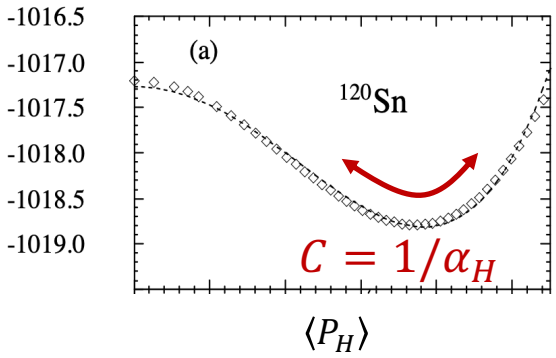
R.A. Broglia+,Phys. Rep. 335 (2000) 1-18

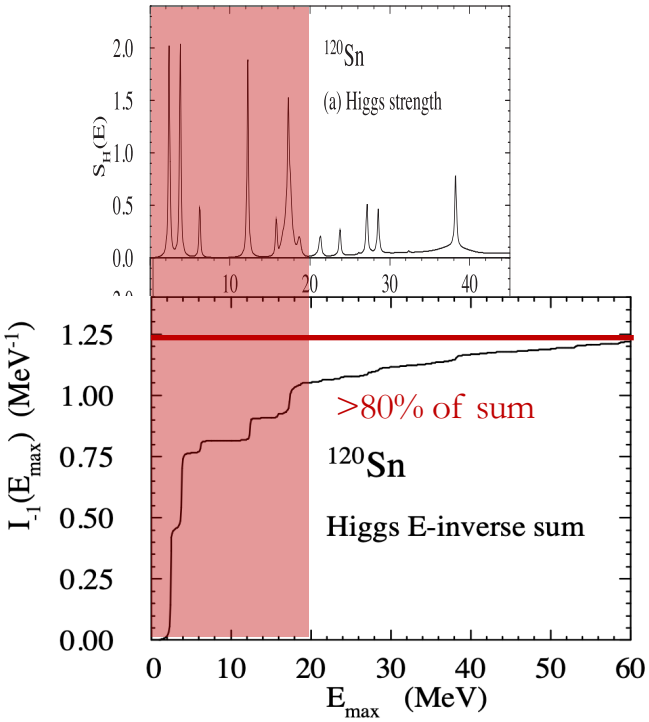
Pair polarizability
対分極率



$$P_H = P_{\mathrm{ad}} + P_{\mathrm{rm}}$$

$$I_{-1} = 2\int_{E_{\min}}^{E_{\max}} dE \frac{S_{\mathrm{H}}(E)}{E} = 2\sum_{\nu} \frac{\left|\langle \nu|\hat{P}_{\mathrm{H}}|0\rangle\right|^2}{E_\nu} = \alpha_{\mathrm{H}}$$

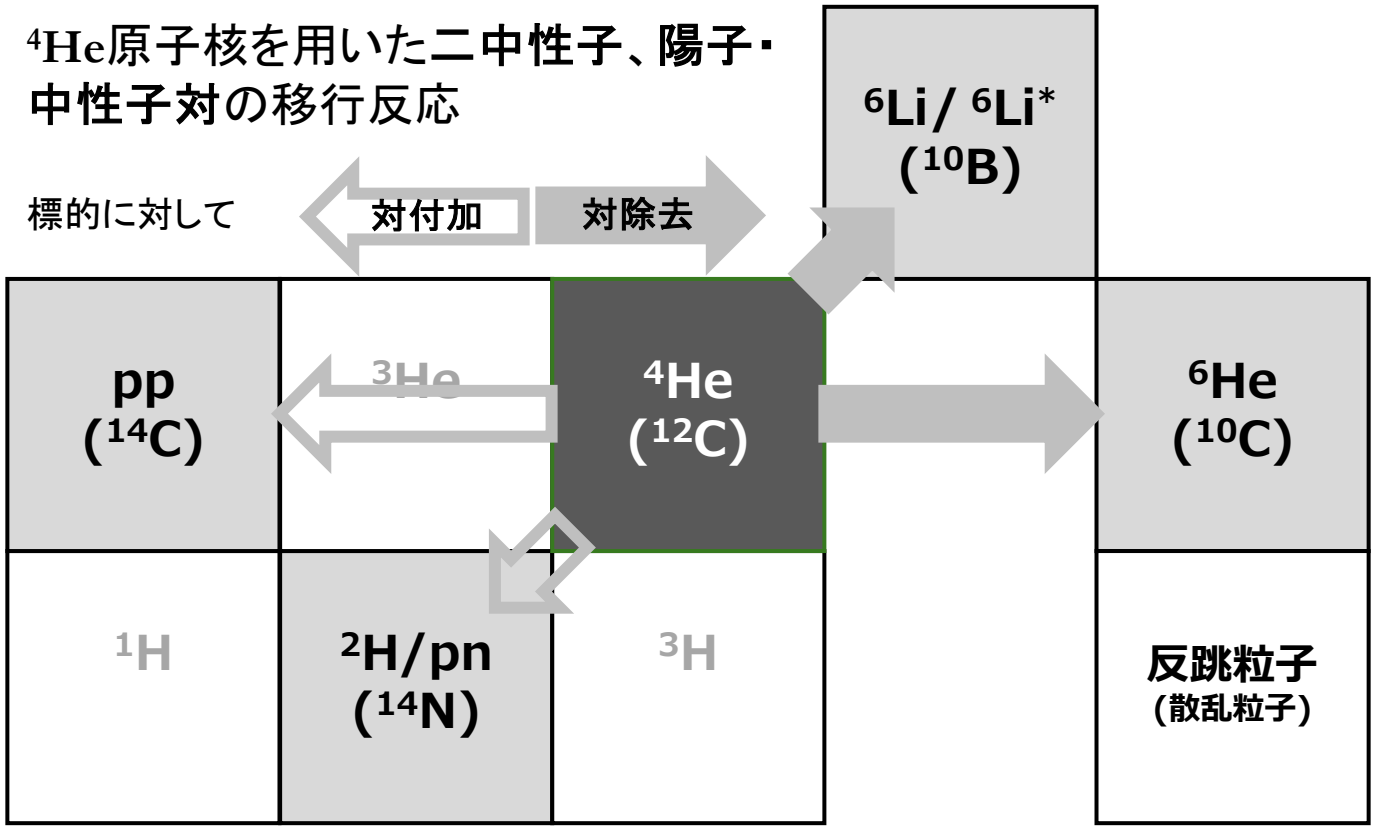




Two-nucleon additional and removal strength distributions up to 20 MeV (and more) are to be measured.

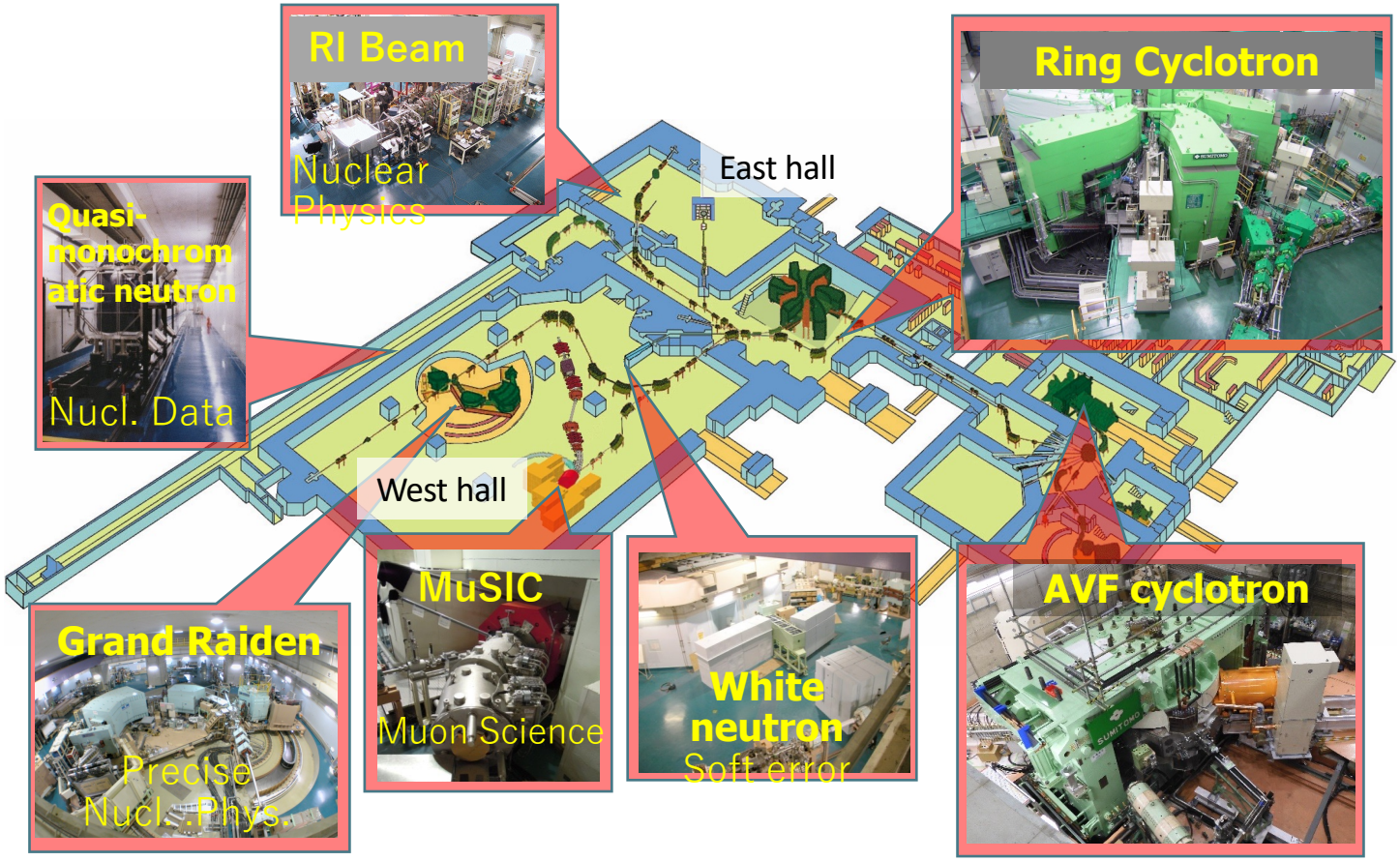
Spectroscopic tools for highly excited states

Combination of known states => Selection of quantum numbers



cf.) (1H, 3He) reactions sensitive to ΔS=0 and ΔS=1

Cyclotron facility at RCNP



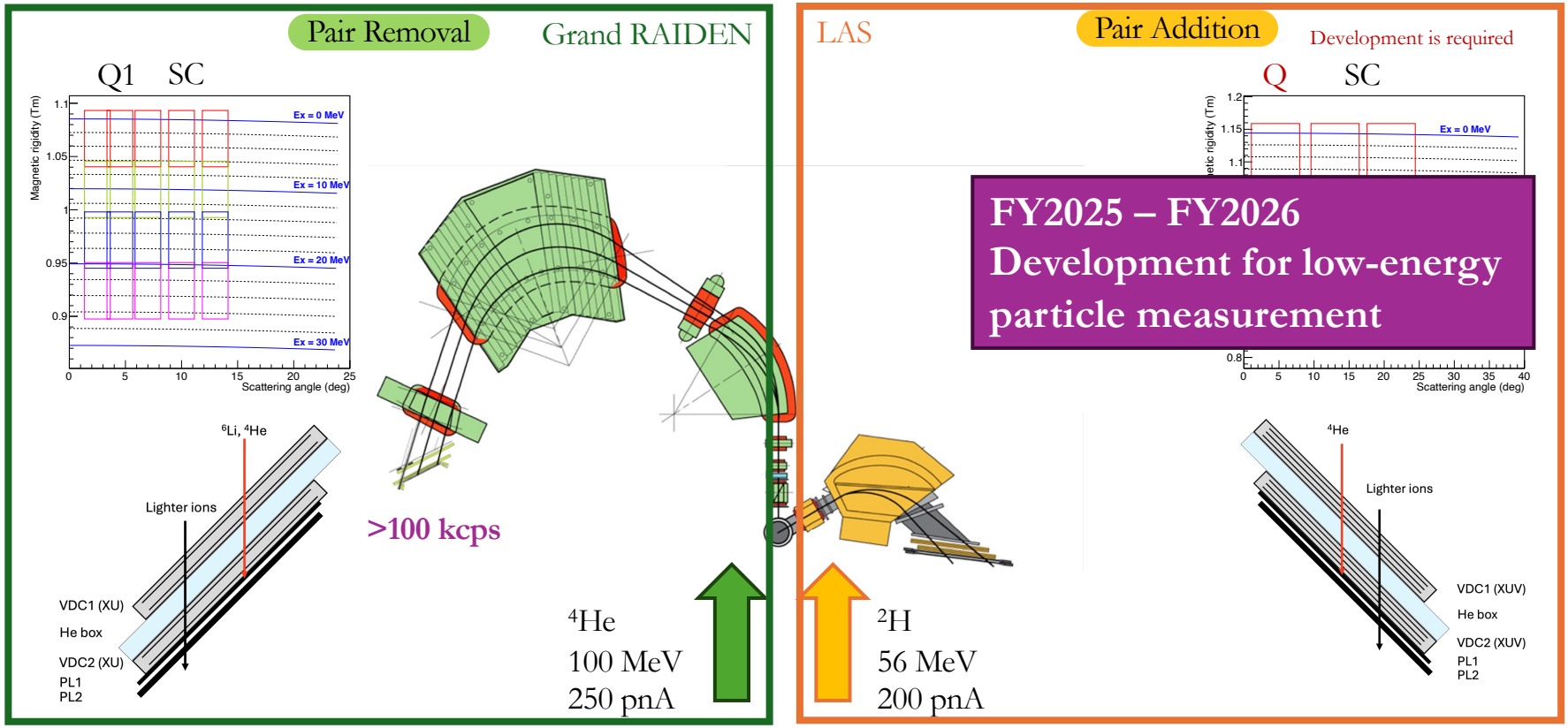
Experimental Setup

Grand RAIDEN

High resolution spectroscopy

LAS

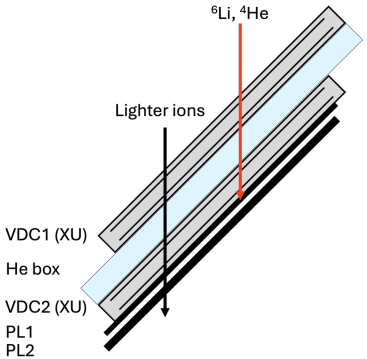
10 time wider acceptance



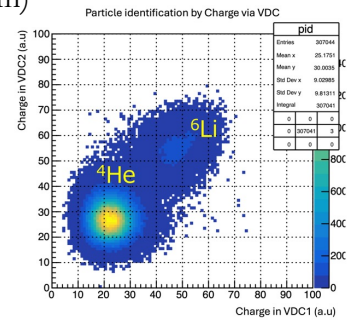
Streaming DAQ system for high-rate particles

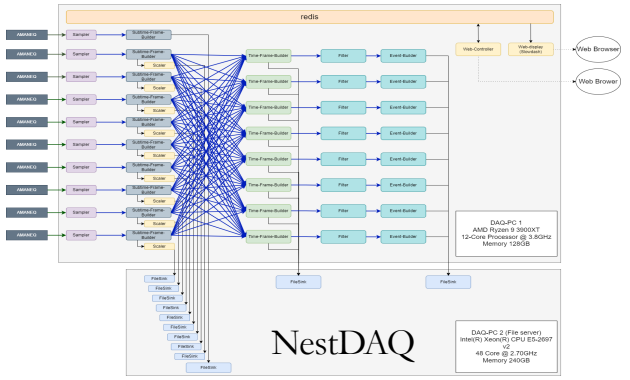
SPADI Alliance

Particle rate ~ Trigger rate due to elastic scattering
(Energy deposites in PS1 of 4He and 6Li are almost same)



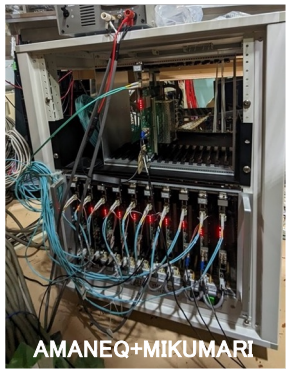
PID itself is possible using ΔE in VDC
(Confirmed during Honor seminar program)

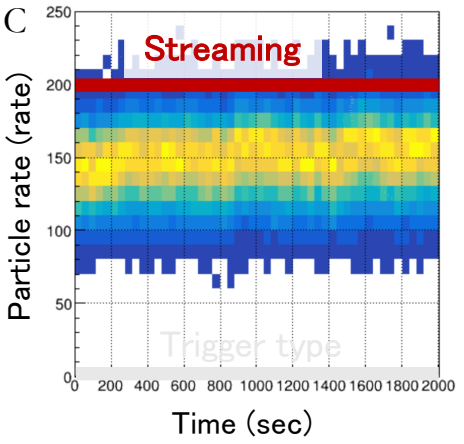




Streaming Data Acquisition system developed by SSPADI Alliance (Chair: Ota)

=> Achieved more than 200-kcps trigger equivalent
=> (a,6Li) reaction at Grand RAIDEN becomes possible





Neutron pair removal (^{4}He,^{6}He)

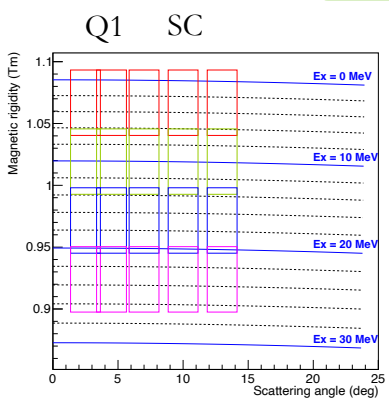
Preliminary のため削除
Grand RAIDEN での (4He,6He)反応の
測定結果

120Sn+4He => 118In+6Li @Grand Raiden

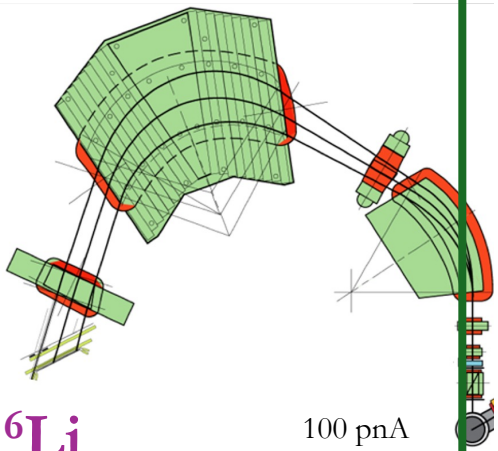
Pair Removal

Grand RAIDEN

世界最高分解能
Δp/p = 37000



運動量分析
p = qBr



^{6}Li

100 pnA

^{4}He
100 MeV

毎秒10万事象以上

対相関力は比較的強い？

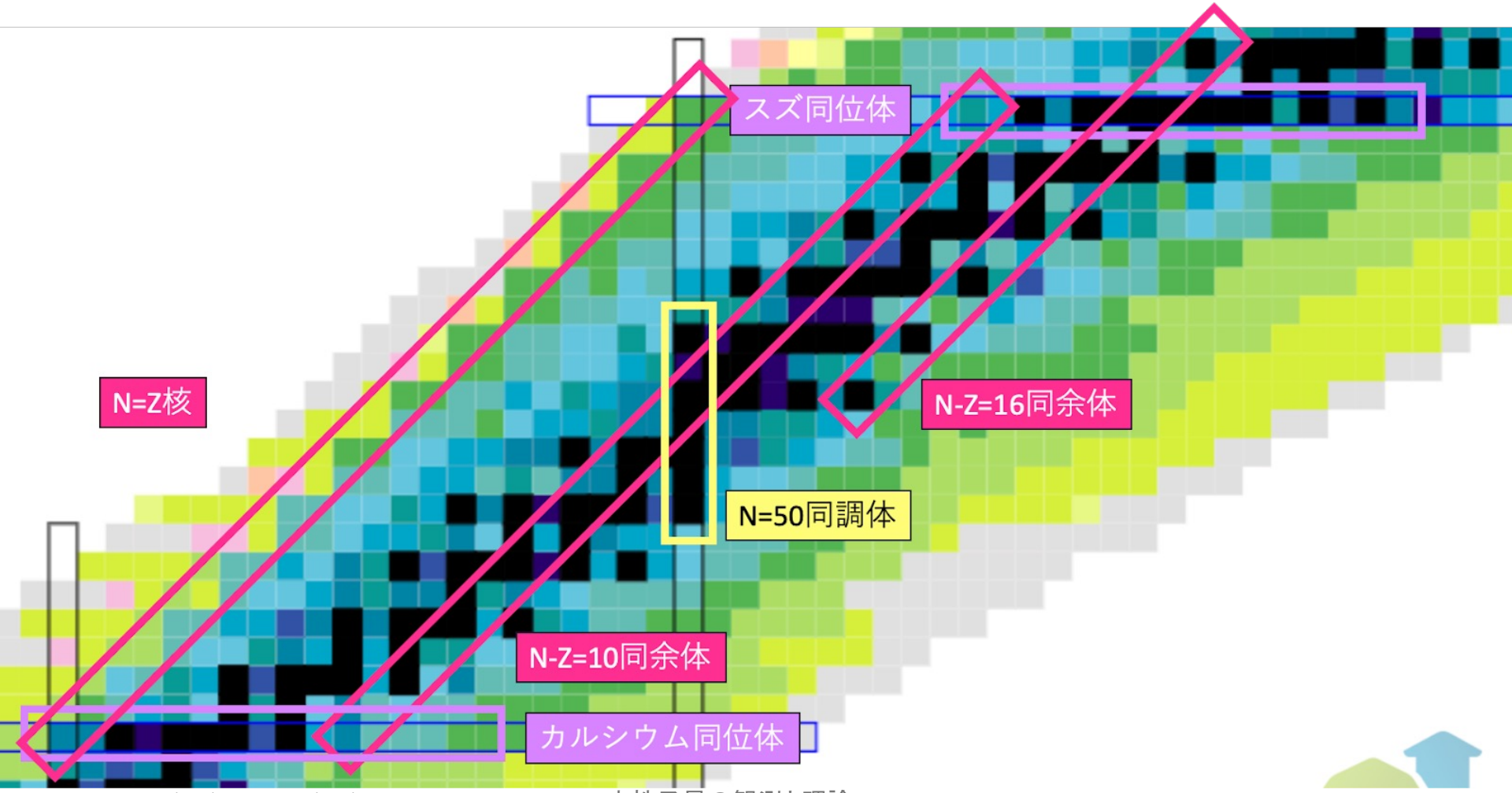
前方角度から後方まで

Preliminary のため削除
Grand RAIDEN での (4He,6Li)反応の
測定結果

超流動ぽいものはない

西岡くんらの解析結果では超流動は見つからなかったが、
比較的大きな断面積を持つ状態がありそう

Systematic measurement



Beyond BCS and other condensation

- $^3P_2$ …
  - Expected to exist in neutron star
  - Requires the new probe for measurement.
  - Searching for the candidates.
- Pion condensation
  - Unique probe of using heavy ions have been studied.
  - To be prepared for the systematic measurement.
- Cluster condensation
  - Inelastic scattering
  - Knockout reactions

Summary

- Pair potentials for n-n pair and T=0 / T=1 p-n pairs are being studied.
- Ready for systematic measurement of n-n pair removal reactions.
- Probe study of p-n pairs is ongoing.
- Development of particle detectors for LAS has just started.

- Stay tuned and please join the collaborations and/or discussions!