Proximity effect of pair correlation in the inner crust of neutron stars with Hartree-Fock-Bogoliubov theory

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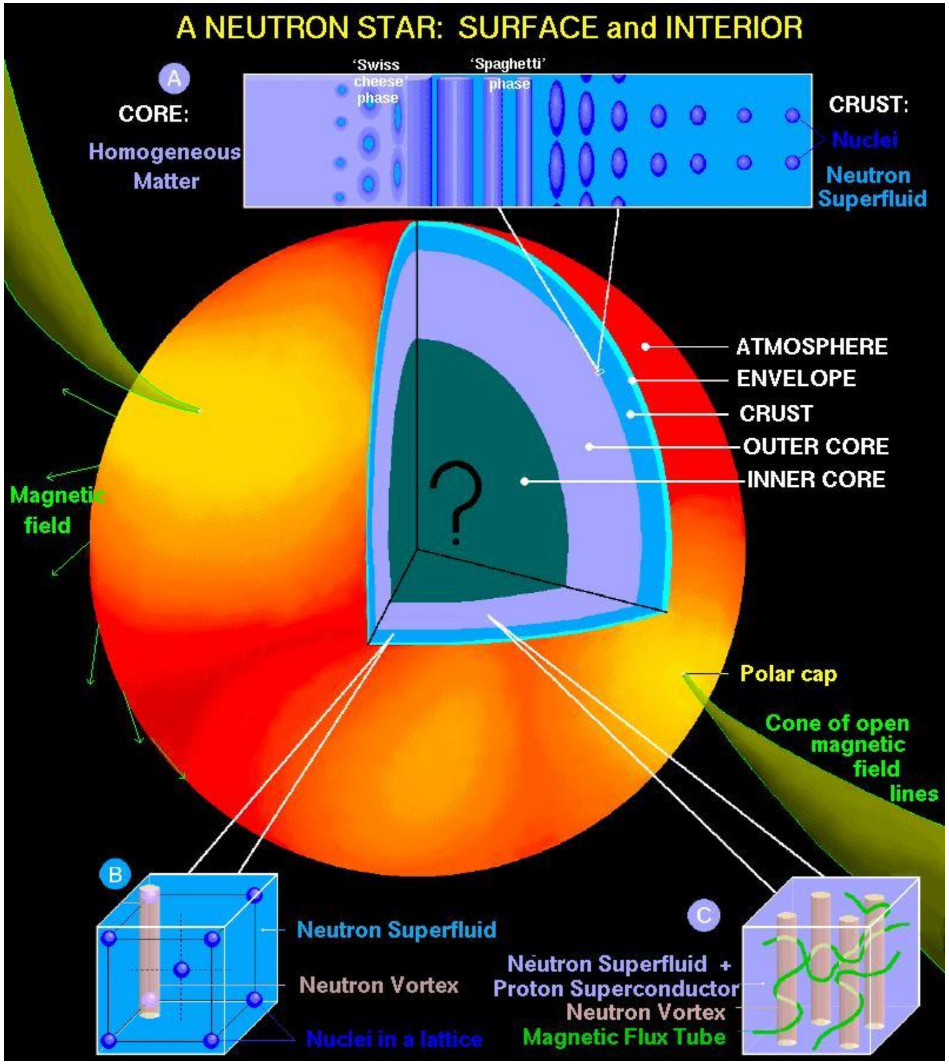
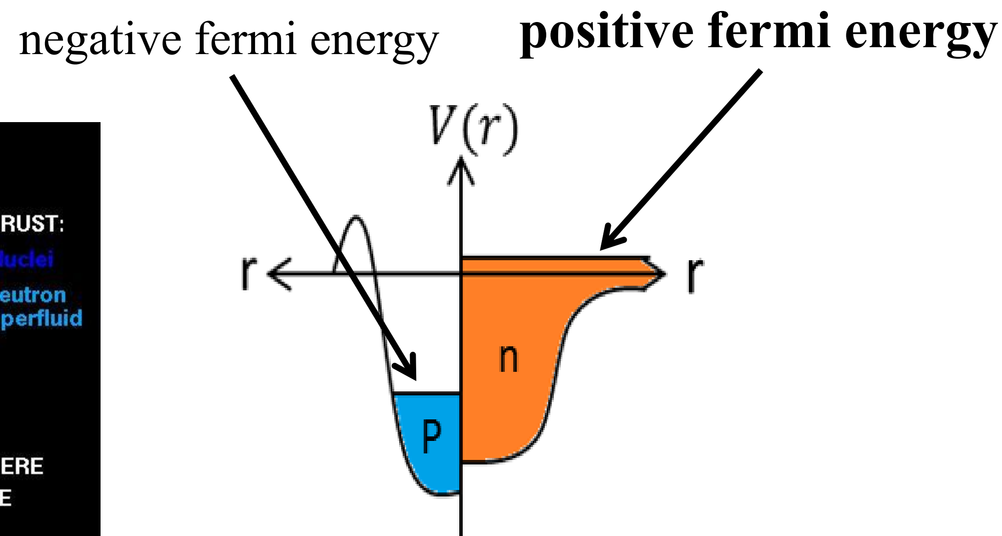
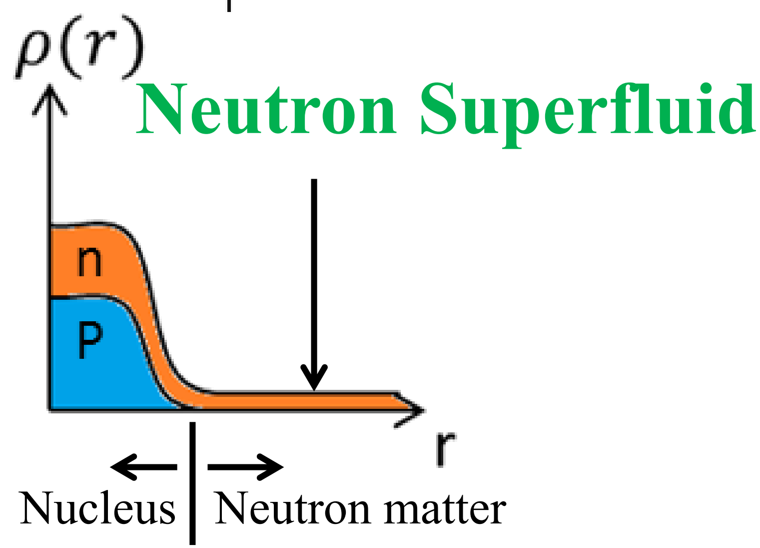
Inner crust



D. Page





N≫Z

Neutron-rich nuclei

+

Neutron Superfluid

Interplay between nuclei and neutron superfluid

- Coupling between nuclei and neutron superfluid.
  - Thermal conductivity of the inner crust.

    D. N. Aguilera, *et al*., Phys. Rev. Lett. 102, 091101(2009).
  - Microscopic QRPA analysis

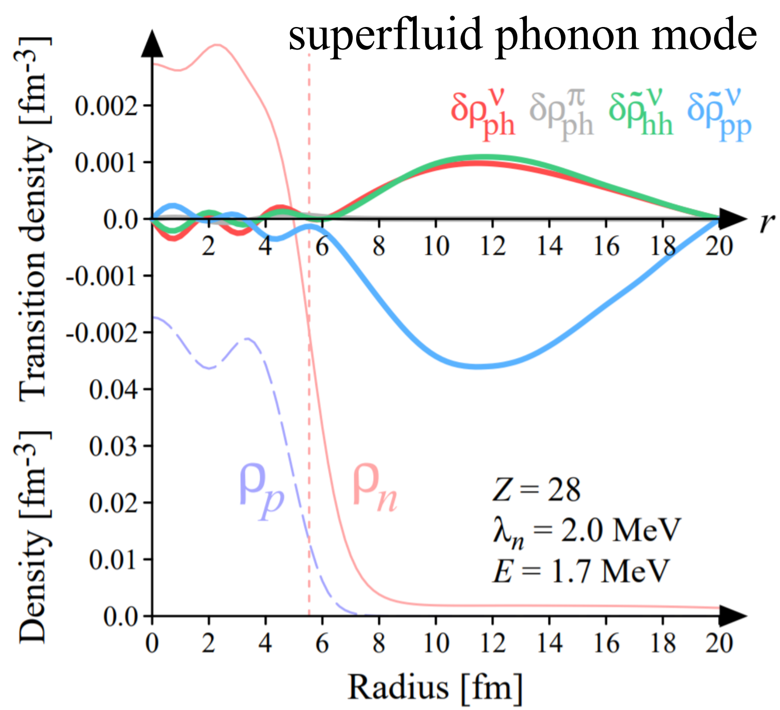
    T. Inakura and M. Matsuo, Phys. Rev. C 96, 025806(2017).

    Phonon excitation of neutron superfluid.

    The couple is weak.

In the present work

- we want to investigate paring property of the ground state.
- We study interplay between nuclei and neutron superfluid.



T. Inakura, M. Matsuo, JPS Conf. Proc. 20, 011037 (2018).

Purpose of present study

◆ The nuclei and neutron superfluid are very different matters.

Focus: proximity effect of pair correlation.

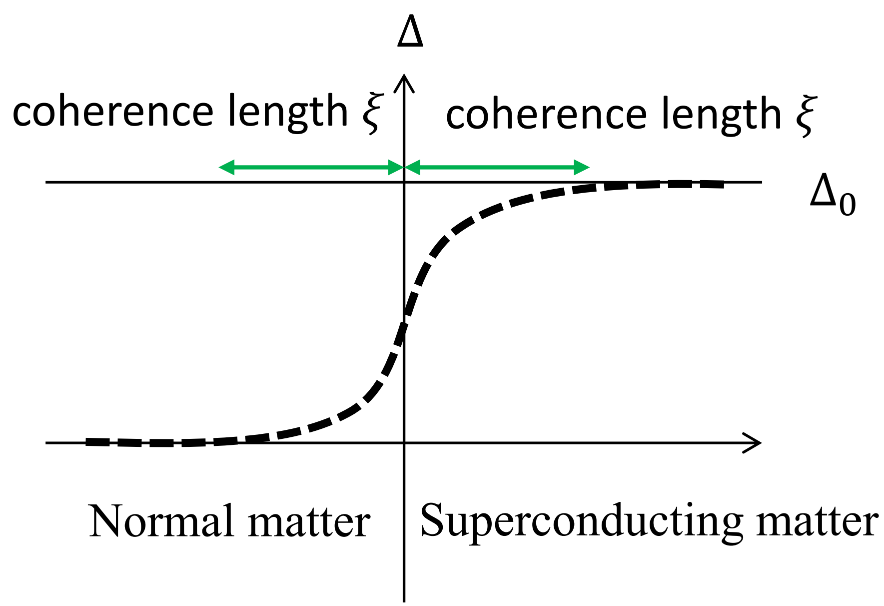
◆ In superconductivity theory, if superconducting matter and normal matter are contact, the cooper pair leaks into the normal metal.

P. D. De Gennes, Rev. Mod. Phys. 36. 225 (1964).

Proximity effect: If different superfluid matters contact, the pair correlation around the border is affected.

✔ We study how neutron-rich nuclei affect paring of neutron superfluid.

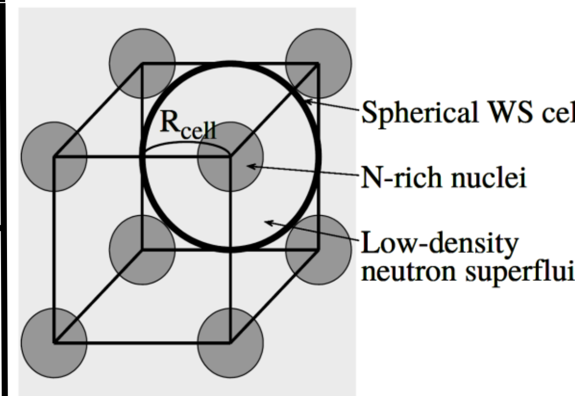
✔ We focus the proximity effect of pair correlation that appears in pair density (pair condensation).



Superconductivity of metals and alloys, P. D. De Gennes, 1999

Model

1. Spherical Wigner-Seitz cell



2. Hartree-Fock-Bogoliubov equation

$$\begin{bmatrix} h(r)-\lambda & \Delta(r) \\ \Delta(r) & -h(r)+\lambda \end{bmatrix} \begin{bmatrix} \phi_1(r) \\ \phi_2(r) \end{bmatrix} = E \begin{bmatrix} \phi_1(r) \\ \phi_2(r) \end{bmatrix}$$

3. Method

diagonalization (symmetry)

4. Fermi energy λ

We put positive λ_n to control external neutron density.
We set λ_p to express the proton number Z.

5. HF potential

Skyrme interaction: **SLy4**
SLy4 reproduce EOS of neutron matter.

E. Chabanat, *et al.*, Nucl. Phys. A635, 213 (1998).

6. Pairing correlation: DDDI

$$V_{pair,q}(r_1,r_2) = V_0\left(1-\eta\left(\frac{\rho_q}{\rho_0}\right)^{\alpha}\right)\left(\frac{1-P_\sigma}{2}\right)\delta(r_1-r_2)$$

We use two parameter set.

I. Strong paring

Reproduce:
- BCS gap
- Scattering length a=-18.5fm

$V_0 = -458.4$ MeV
$\eta = 0.845$
$\alpha = 0.59$
$\rho_0 = 0.08\ \mathrm{fm}^{-3}$

M. Matsuo, PRC(2006).
M. Matsuo, *et al.*, NPA(2007).

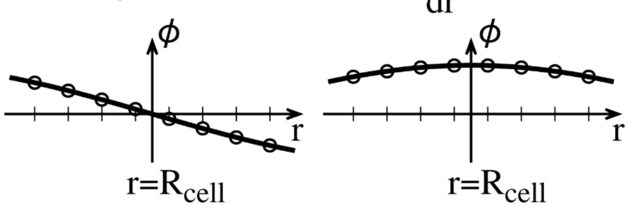
II. Weak paring

Reproduce:
- Ab-initio gap

$V_0 = -400$ MeV
η =same
α =same
ρ_0 =same

A. Dirichlet-Neumann boundly condition

odd parity: $\phi = 0$
even parity: $\frac{d\phi}{dr} = 0$



J. W. Negele and D. Vauthrin (1973).

B. Numerical detail

9-point difference method
$\Delta r = 0.2$fm

C. Cut off

$E_{max} = 60$ MeV
$l_{max} = 2 \times R_{cell}$

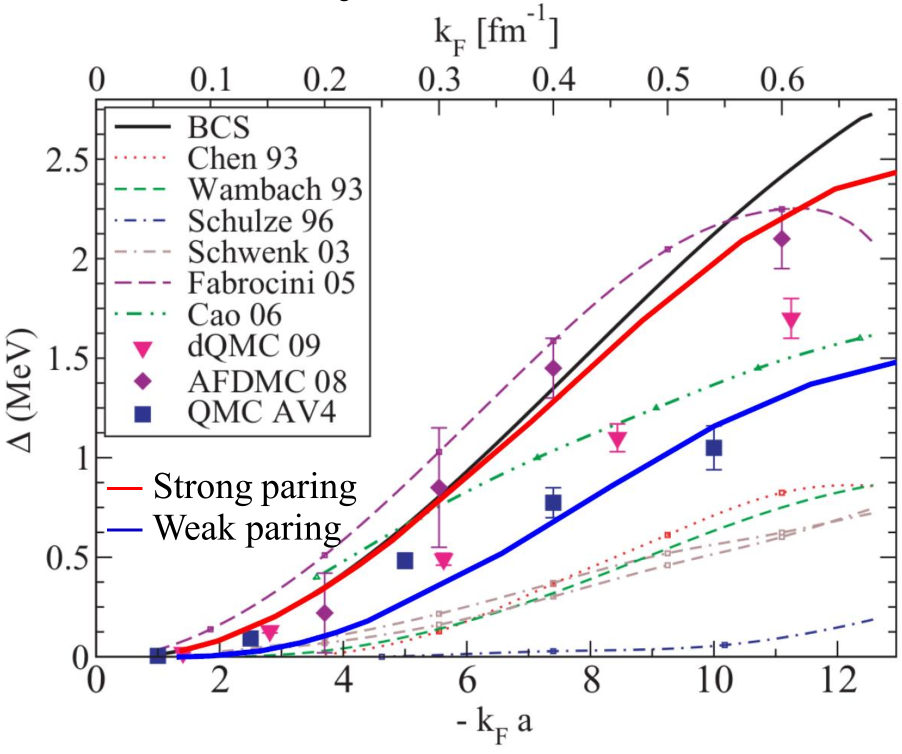
Pair gap in neutron matter

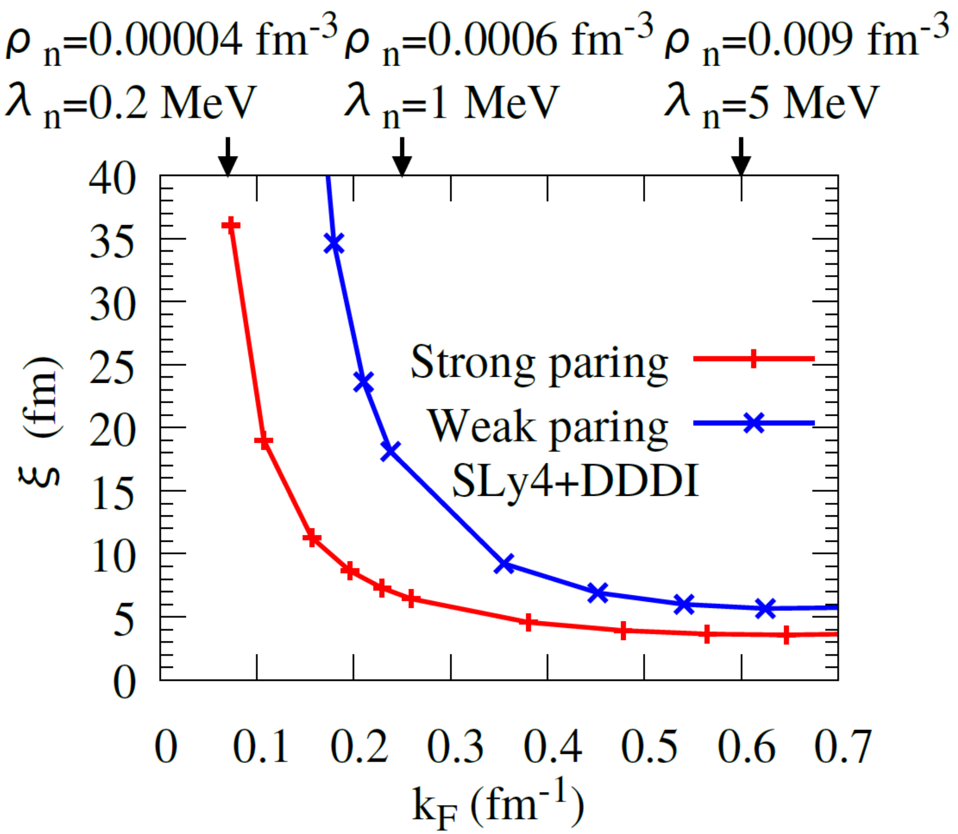
BCS gap is stronger than ab-initio gap.

Strong paring : $V_0 = -458.4\text{MeV}$

Weak paring : $V_0 = -400\text{MeV}$

The length of proximity effect ~ ξ

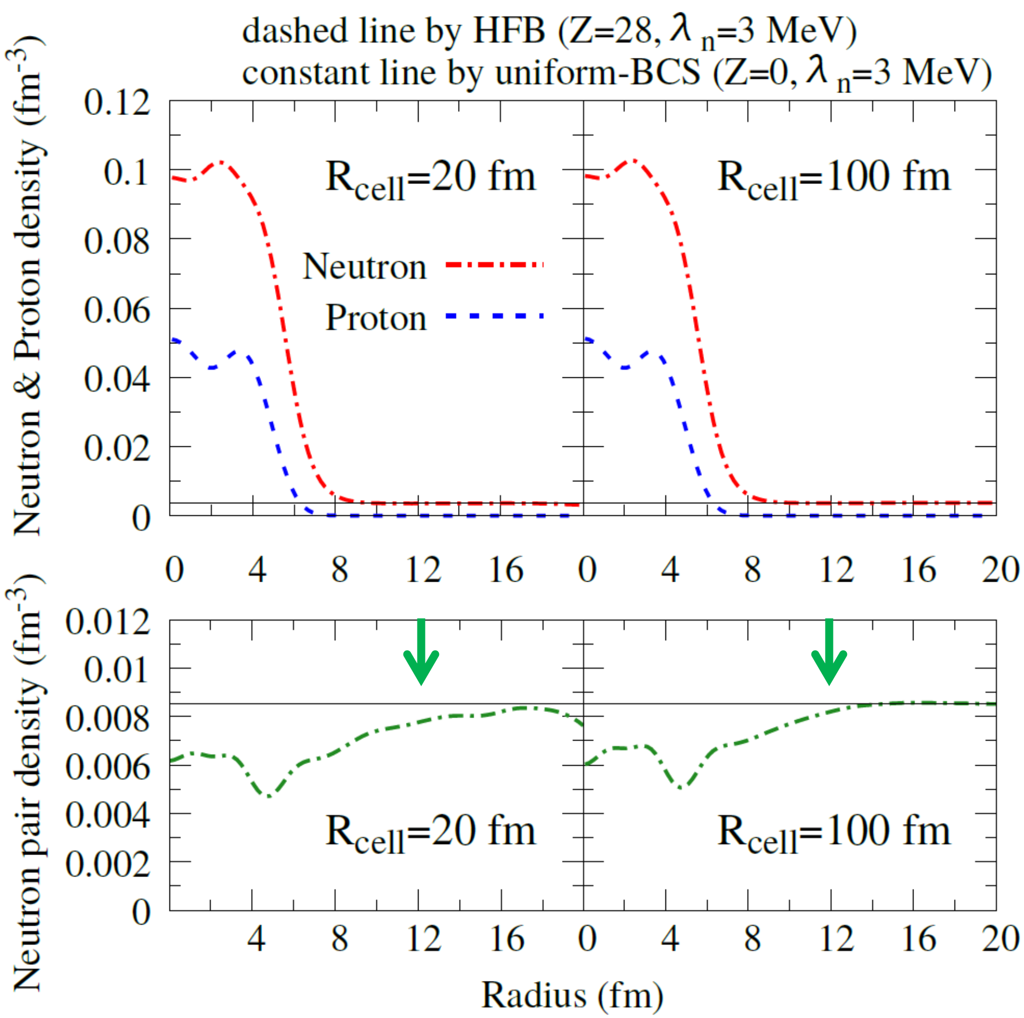




A. Gezerlis and J. Carlson, PRC (2010).

Finite size effect and proximity effect

- In order to discuss proximity effect, we want to remove the finite size effect.
- Uniform-BCS and HFB gives same result in uniform neutron matter.



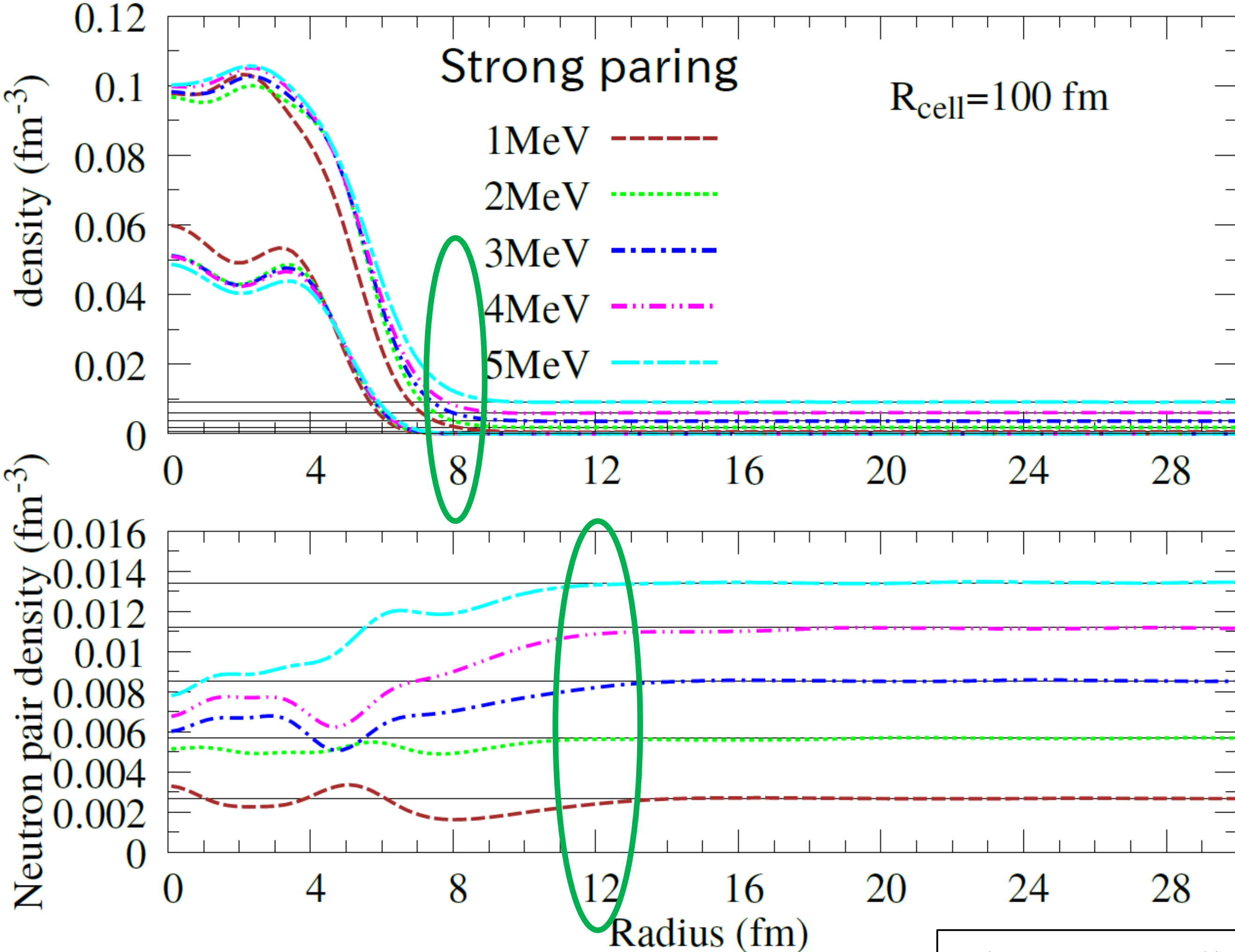
- The neutron & proton density is same in 20fm and 100fm.
- In the 20fm case, the neutron pair density does not converge.
  - ⇐ Finite size effect
- We use R_{cell} = 100fm and discuss proximity effect.

Typical result for the strong paring

Z=28(Ni)

$\lambda_n = 1 - 5\text{MeV}$

- Neutron density converge to that of uniform-BCS at ～8fm.
- Neutron pair density converge to that of uniform-BCS at ～12fm.
- The length of proximity effect is short, ～4fm.



The constant line by uniform-BCS.

The length of the proximity effect

- Pair density converges to uniform-BCS around red point.
- The coherence length describes the proximity effect very well.
- The length of proximity effect is short ~4 − 6 fm.

Woods-Saxon function

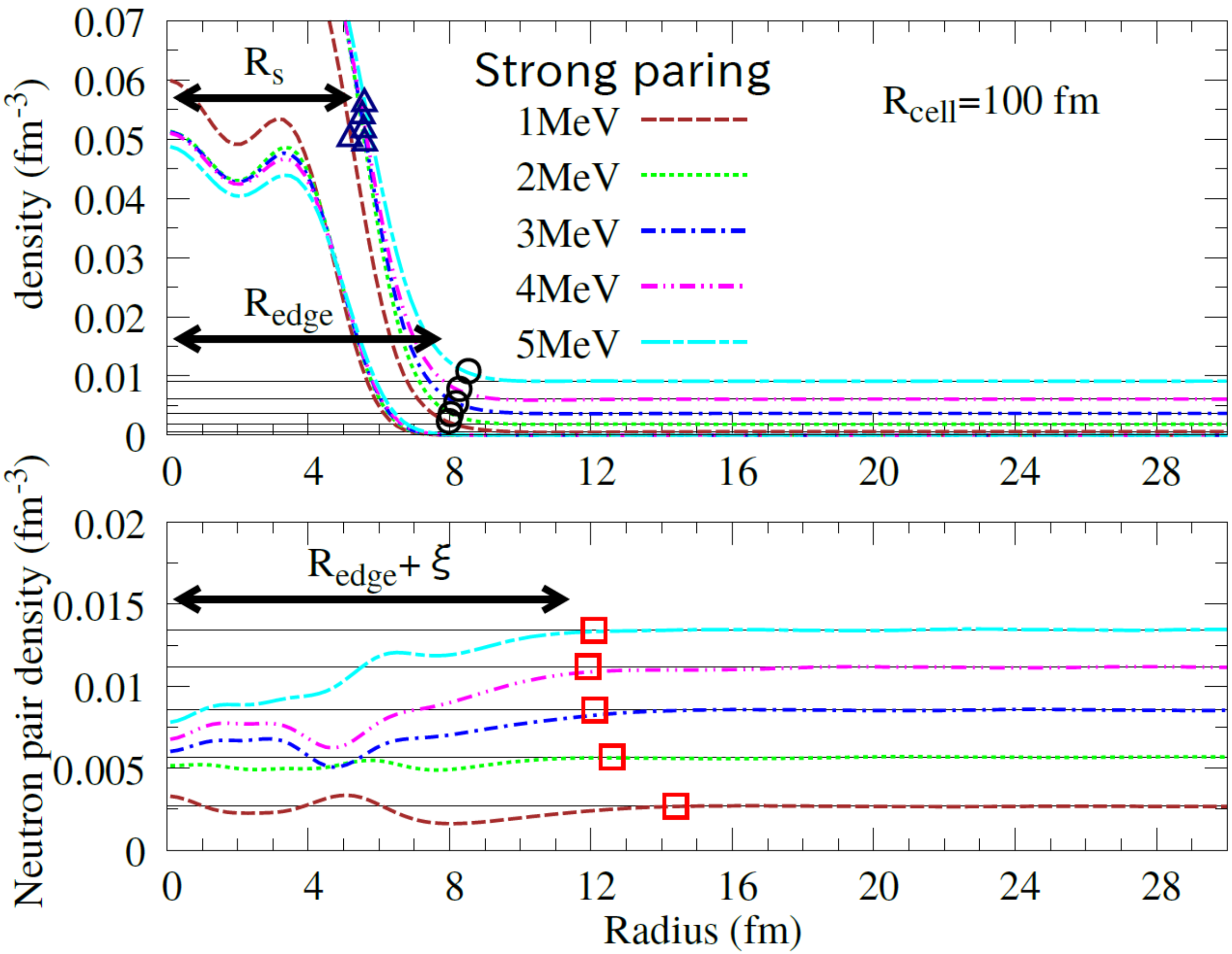
$$\left(1+\exp\left(\frac{r-R_s}{a}\right)\right)^{-1}$$

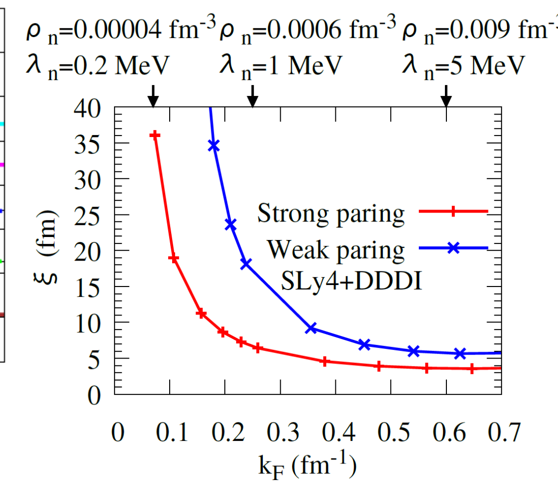
a: diffuseness

R_s:nuclear surface

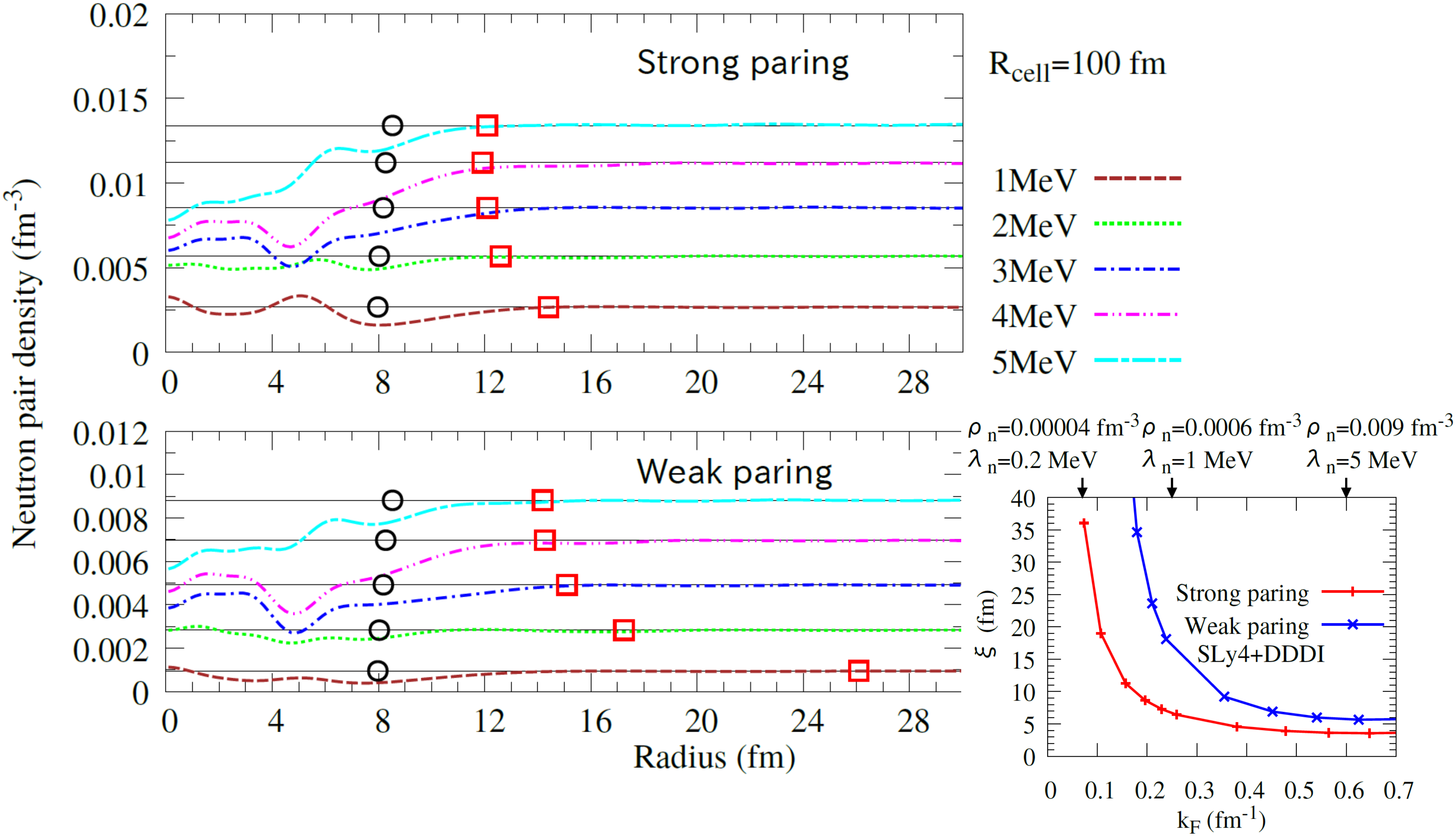
The nucleus edge:

$$R_{edge} = R_s + 4a$$

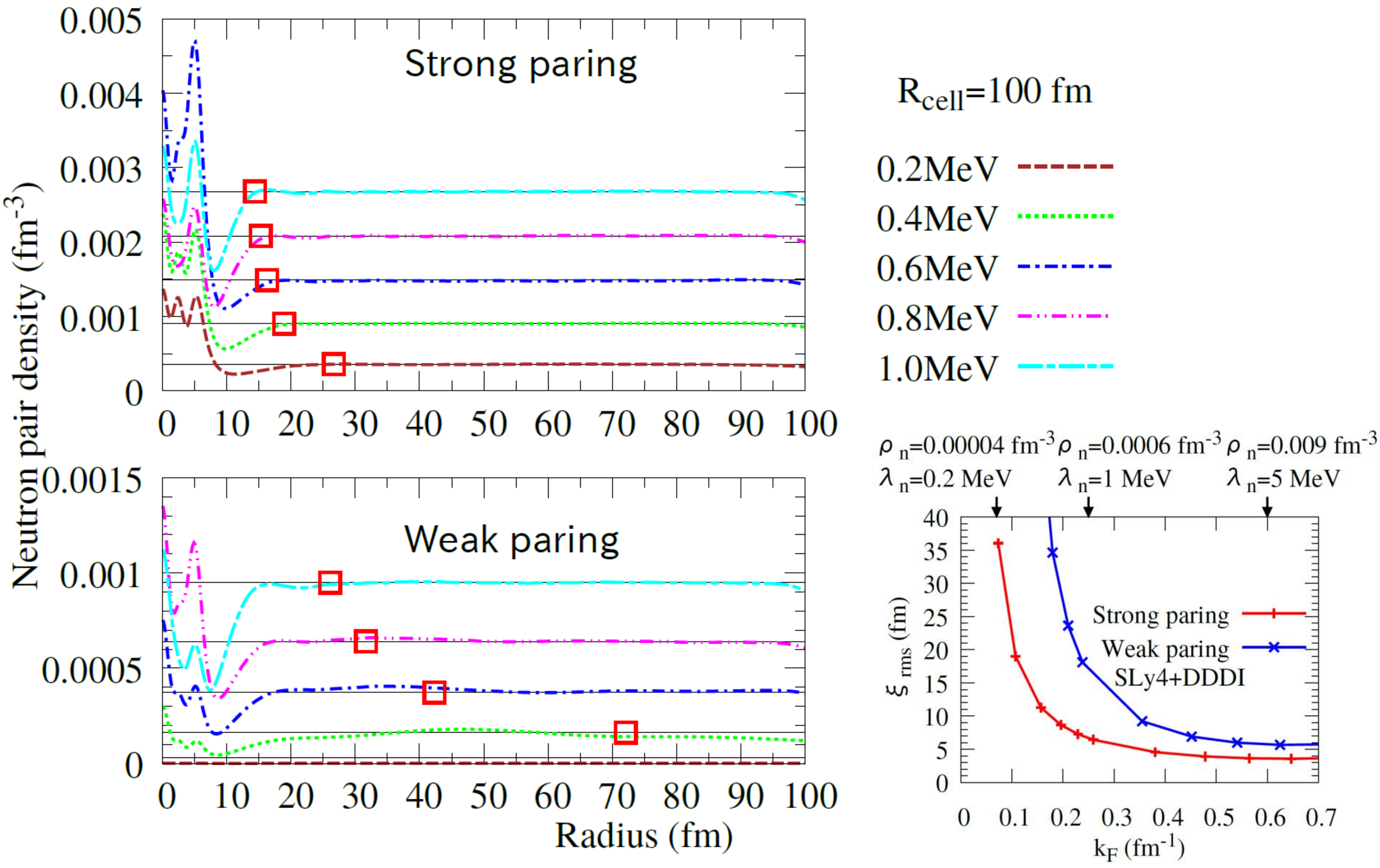




Strong paring vs weak paring $\lambda_n = 1 - 5\text{MeV}$

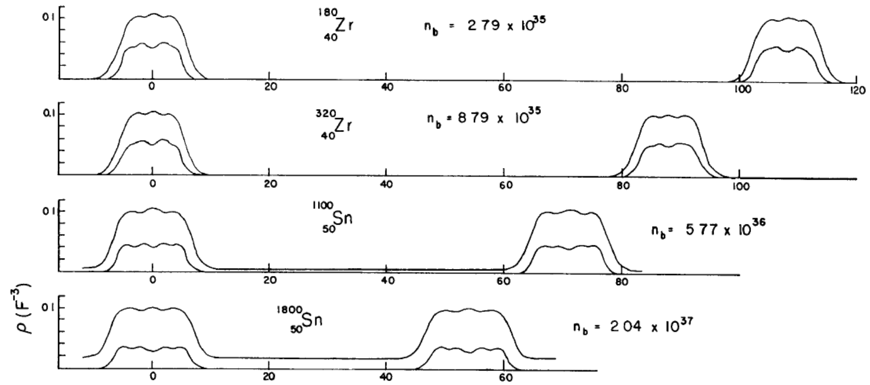


Strong paring vs weak paring
The case of low density: $\lambda_n = 0.2 - 1.0\text{MeV}$

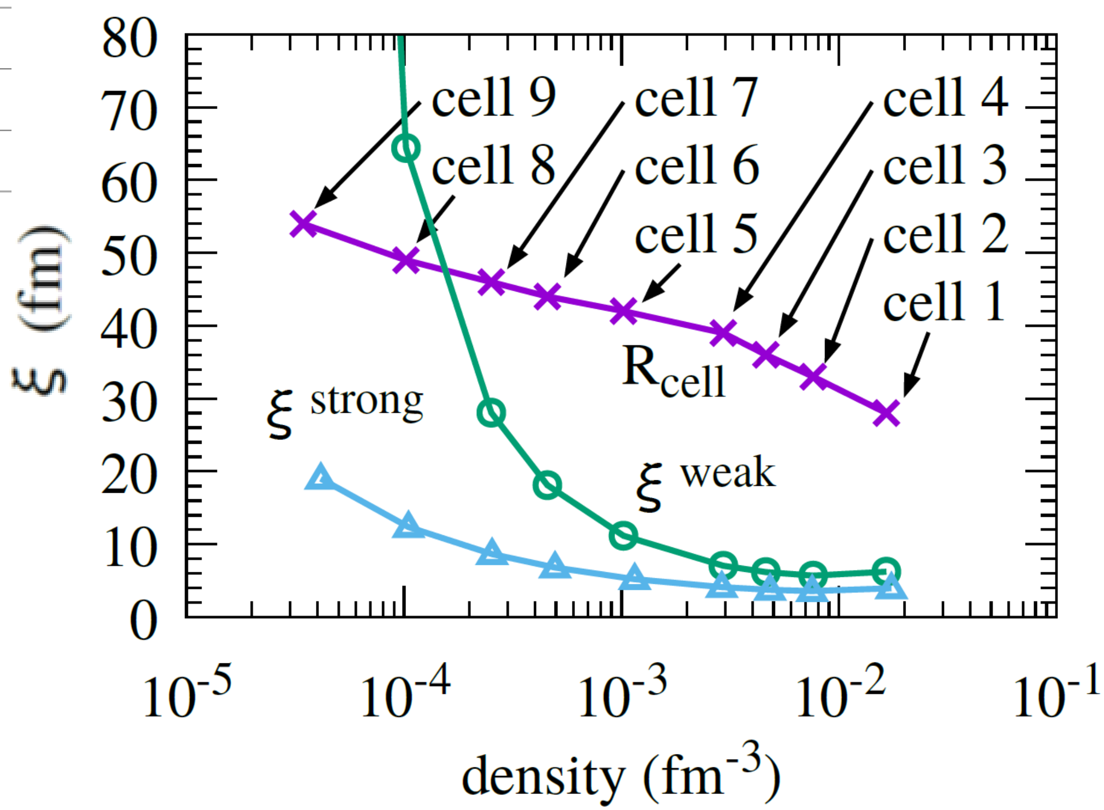


Realistic Wigner-Seitz cell: R_{cell} vs ξ

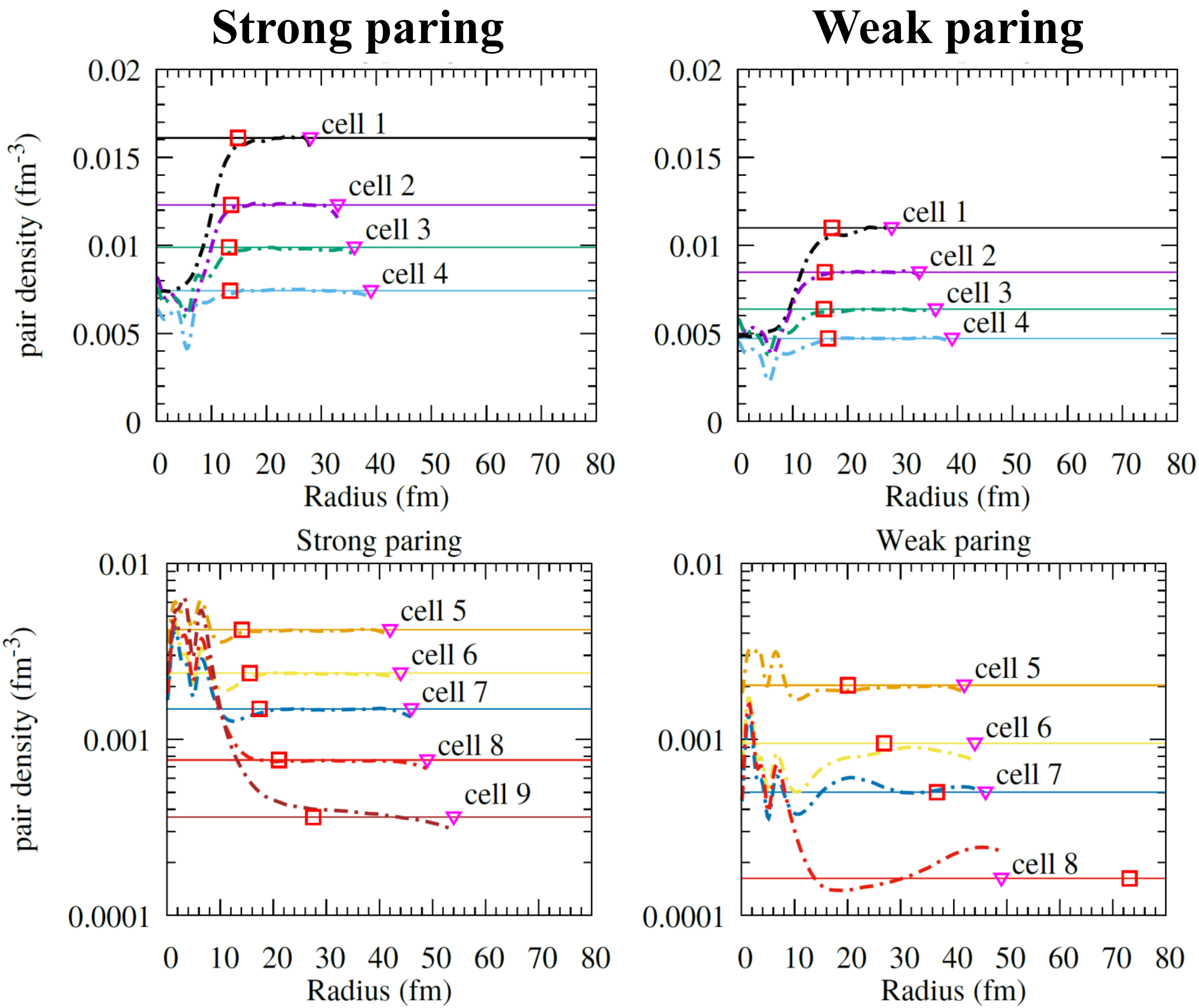
	nuclei	$\rho_{ext}(\mathrm{fm}^{-3})$	$R_{cell}(\mathrm{fm})$
1	^{1800}Sn	1.74×10^{-2}	28
2	^{1350}Sn	7.53×10^{-3}	33
3	^{1100}Sn	4.82×10^{-3}	36
4	^{950}Sn	2.89×10^{-3}	39
5	^{500}Zr	1.15×10^{-3}	42
6	^{320}Zr	4.95×10^{-4}	44
7	^{250}Zr	2.54×10^{-4}	46
8	^{200}Zr	1.05×10^{-4}	49
9	^{180}Zr	4.15×10^{-5}	54



J. W. Negele and D. Vauthrin Nucl. Phys. A 207, 298 (1973).



Realistic Wigner-Seitz cell R_{cell} vs $R_{edge} + \xi$



Conclusion

We have studied proximity effect of pair correlation in the inner crust of neutron stars.

We use strong paring (BCS gap) and weak paring (ab-initio gap).

- In the case of strong paring, proximity effect is short in the all cells.
- In the case of weak paring and low-density, proximity effect is long. In this case, pair density does not converge to uniform-BCS.

- The coupling between nuclei and neutron superfluid is weak at high density.
- But, in the case of low-density, influence of nuclei is strong. In this case, neutron superfluid in the inner crust may be different from the uniform neutron superfluid.