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Proposed Novel Route to Reach a P-wave Superfluid Fermi Gas

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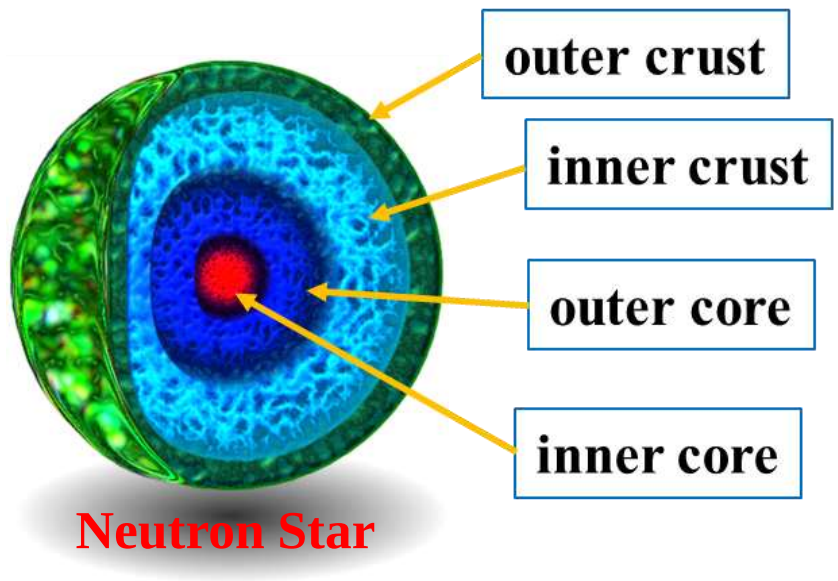
Collaborators: T. Yamaguchi & D. Inotani (Keio)

公募研究 (2015.4~2017.3)

極低温フェルミ原子気体における状態方程式の理論的決定と中性子星低密度領域への応用

- Introduction ▪ ultracold Fermi gas and neutron star
- A new proposal to reach a p-wave superfluid Fermi gas
  - parity mixing effect and p-wave pair amplitude
  - time-evolution of p-wave superfluid state
- Summary

Current possible approach by human beings (21st century)



theorists on the earth

Equation of state (EoS)

internal structure

+

TOV eq.

(Tolman-Oppenheimer-Volkoff equation)

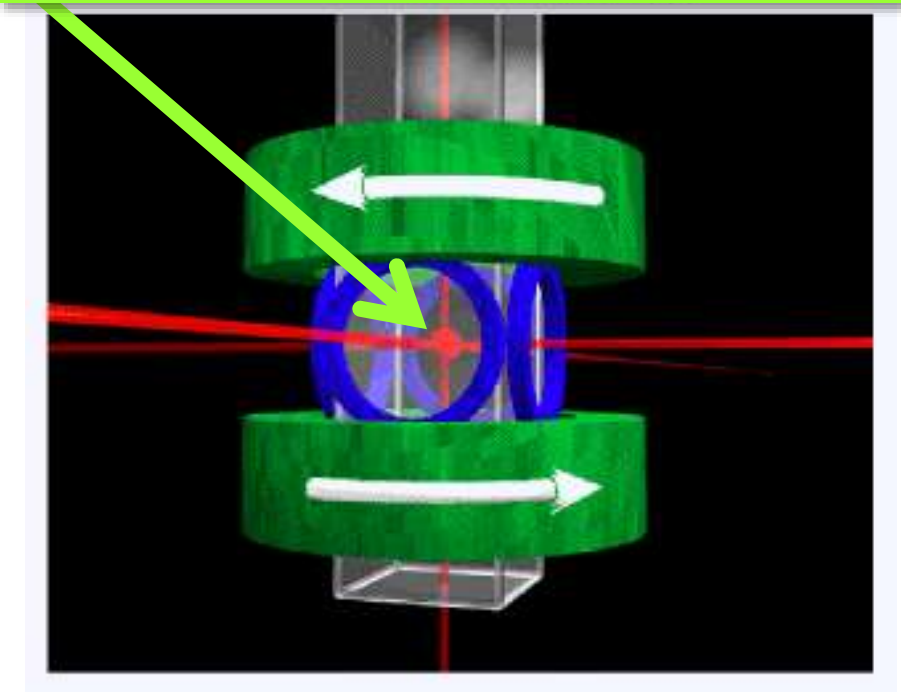
"Mass-radius (MR)" relation

Obserbavle! *Obserbavle!*

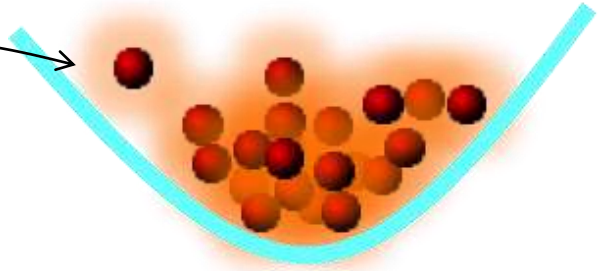
experimentalists on the earth

<u>Qur strategy</u>: Application of ultracold Fermi gas system as a quantum simulator for neutron star

Fermi atoms (^{6}Li, ^{40}K) are trapped in a magnetic/optical potential, and are cooled down to <O(μK), where quantum effects are important. In this gas system, one can tune the strength of an interaction between atoms by using a Feshbach resonance.

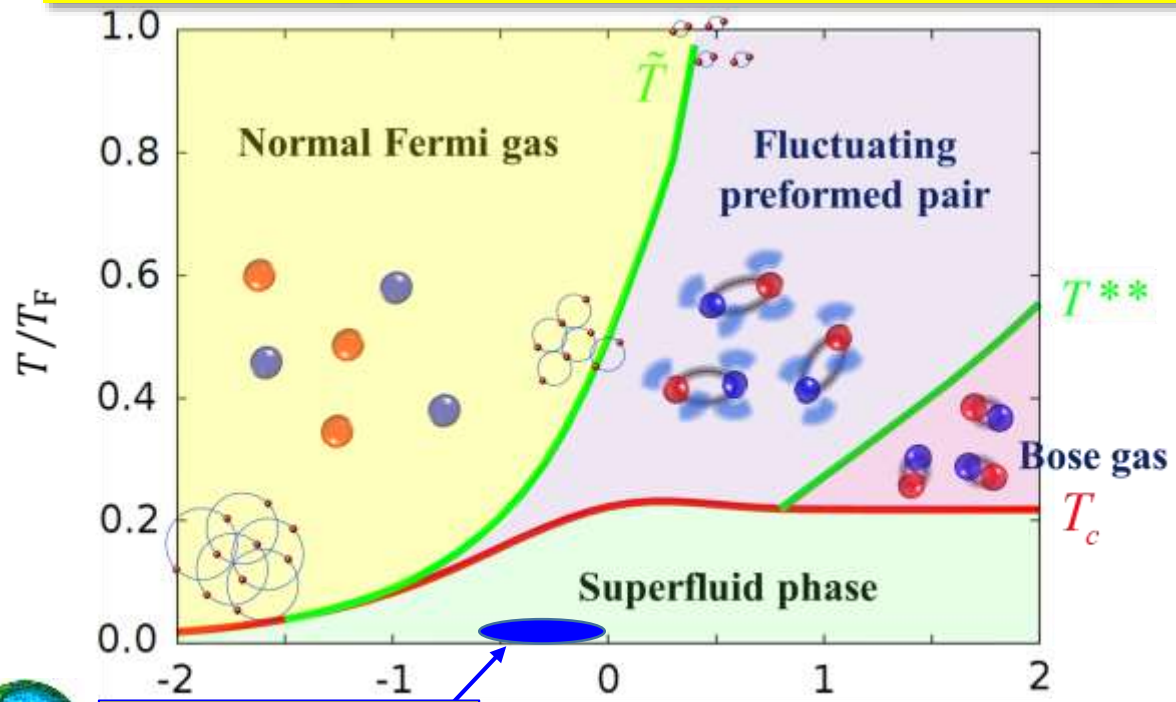


Homepage of Gonokami Lab, University of Tokyo



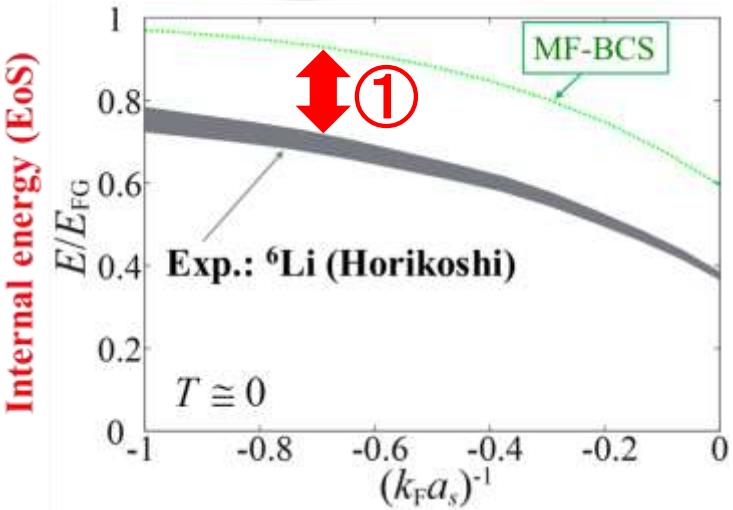
$$N = 10^5 \sim 10^8$$

Phase diagram of an ultracold Fermi gas



neutron star

pairing interaction



+

effective range r_e

cold Fermi gas ② **neutron star**

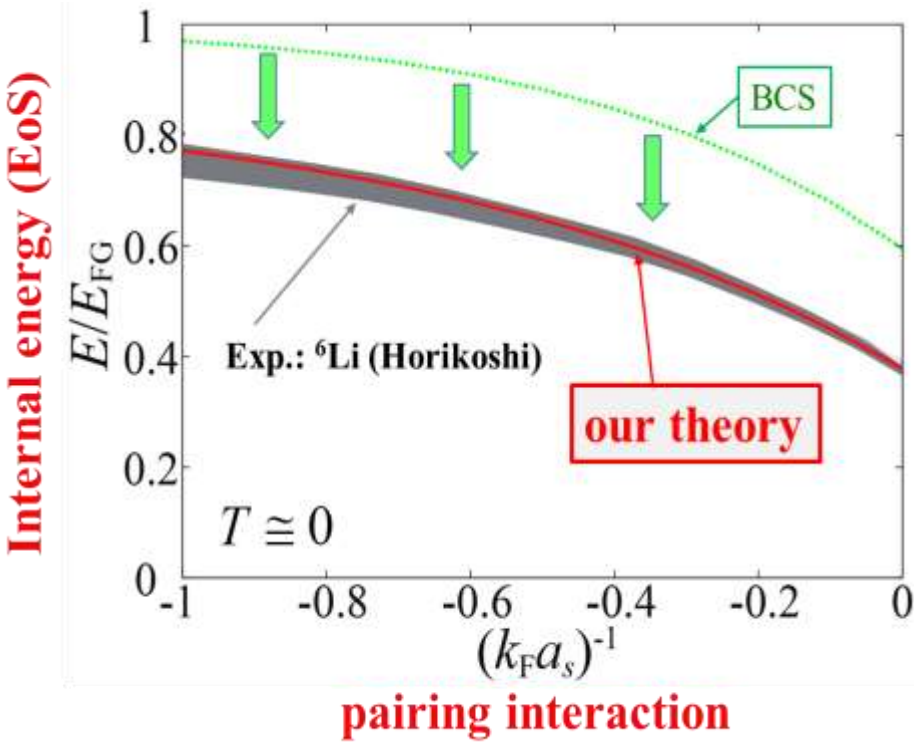
$p_F r_e \sim 0$

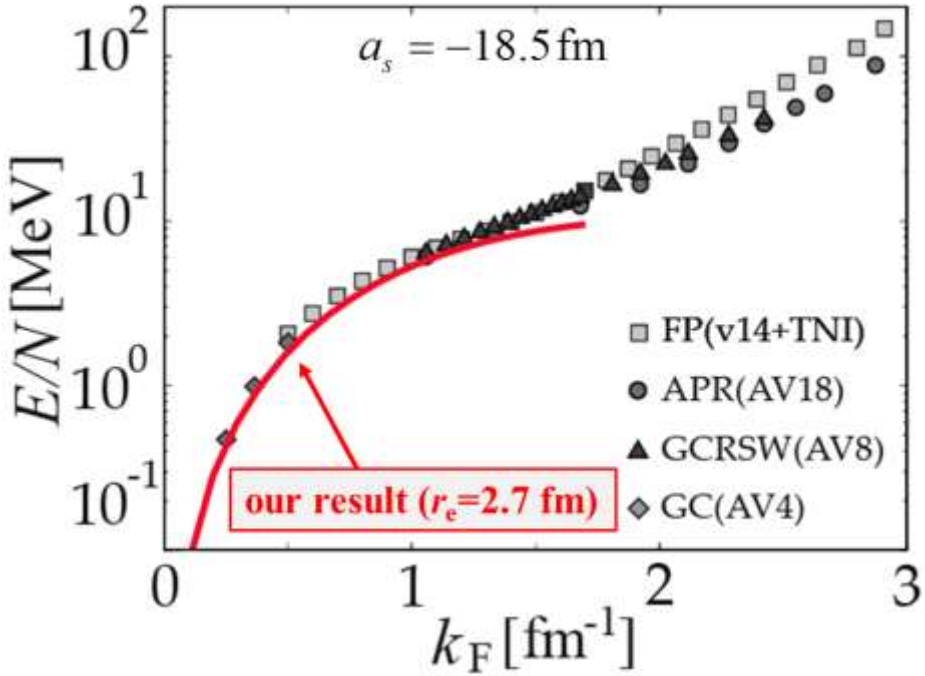
$p_F r_e \lesssim 3$

$(r_e = 2.7\text{fm})$

cold Fermi gas physics meets neutron star physics!

Cold Fermi gas EOS → **Neutron star EOS**





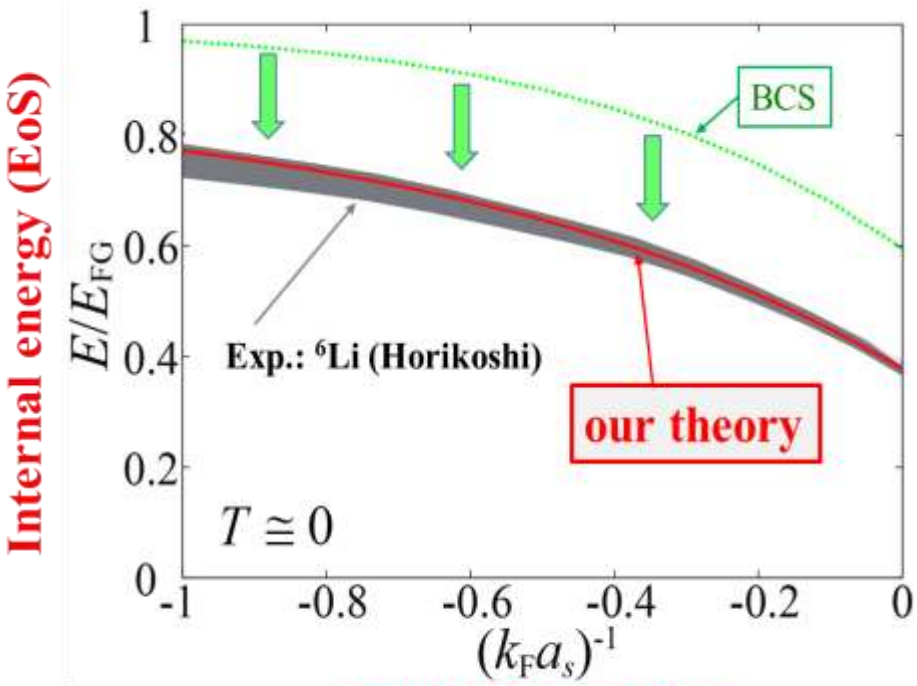
Horikoshi, Koashi, Gonokami, Tajima, Ohashi, arXiv: 1612.04026

<u>Strong-coupling theory</u>

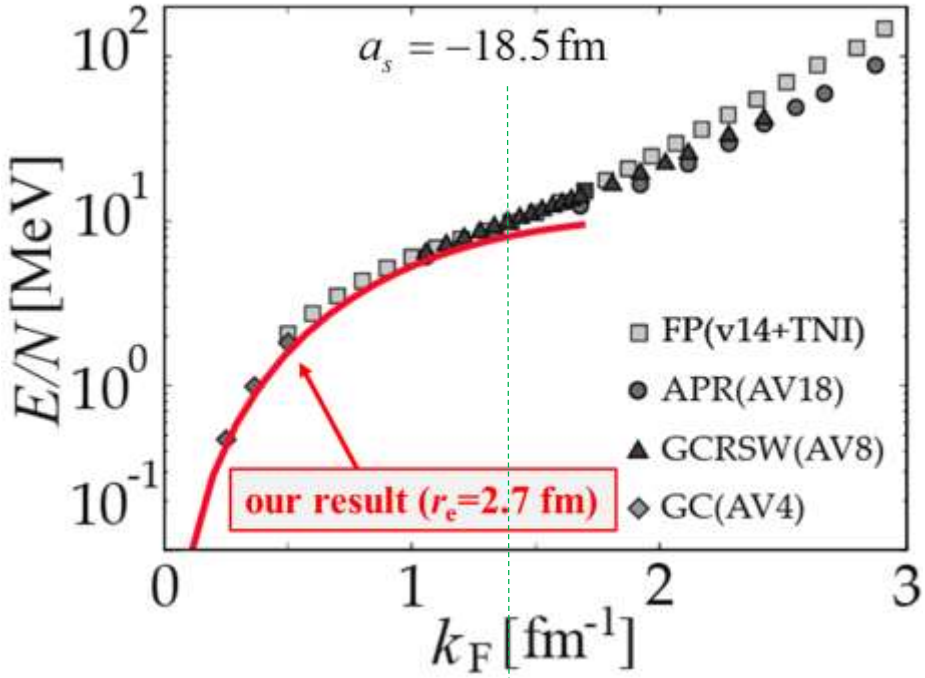
Inclusion of pairing fluctuations beyond MF level

cold Fermi gas physics meets neutron star physics!

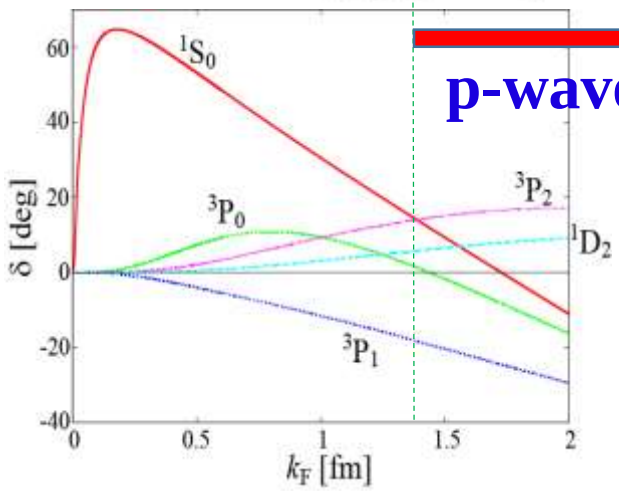
Cold Fermi gas EOS → **Neutron star EOS**



pairing interaction



p-wave SF ?



Horikoshi, Koashi, Gonokami, Tajima, Ohashi, arXiv: 1612.04026

Next strategy: approach to deeper inside neutron star using a p-wave superfluid Fermi gas

cold Fermi gas

p-wave SF

+

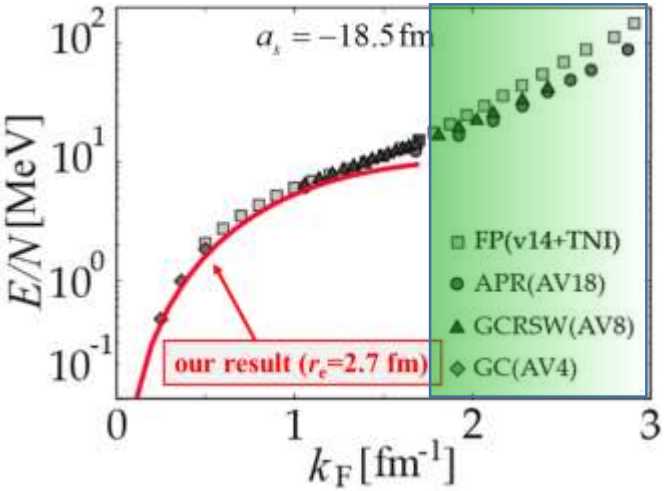
theory

difference between cold Fermi gas and neutron star physics

Neutron star

EoS

NO EXPERIMENTAL DATA!



Difficulty in achieving a p-wave superfluid Fermi gas

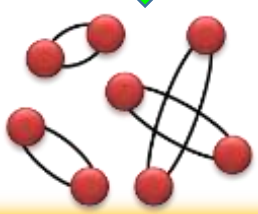
A tunable p-wave pairing interaction has been realized in an ultracold Fermi gas.

However,

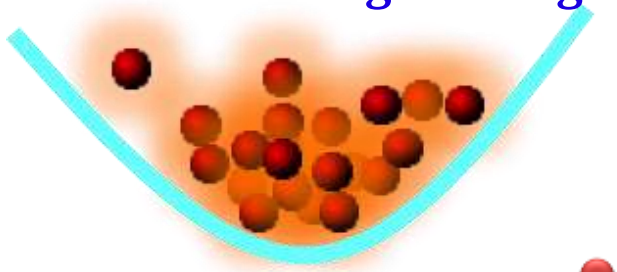
this interaction, which is necessary to form p-wave Cooper-pairs, destroys the system, before the p-wave state grows enough!

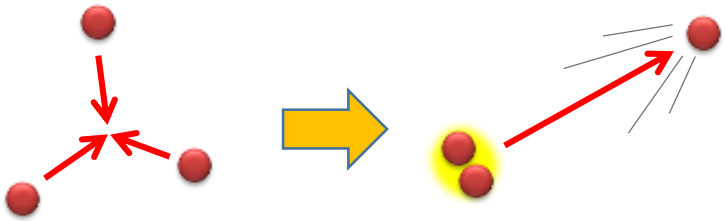
p-wave interacting Fermi gas

$T < T_c$

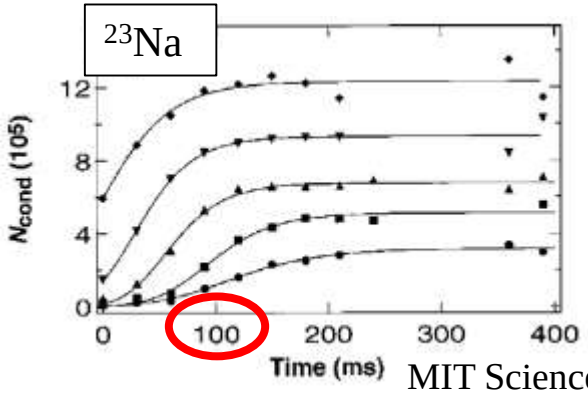


p-wave SF?





three-body particle loss



MIT Science 1998

~100 ms $\gg$ lifetime ~5-20 ms

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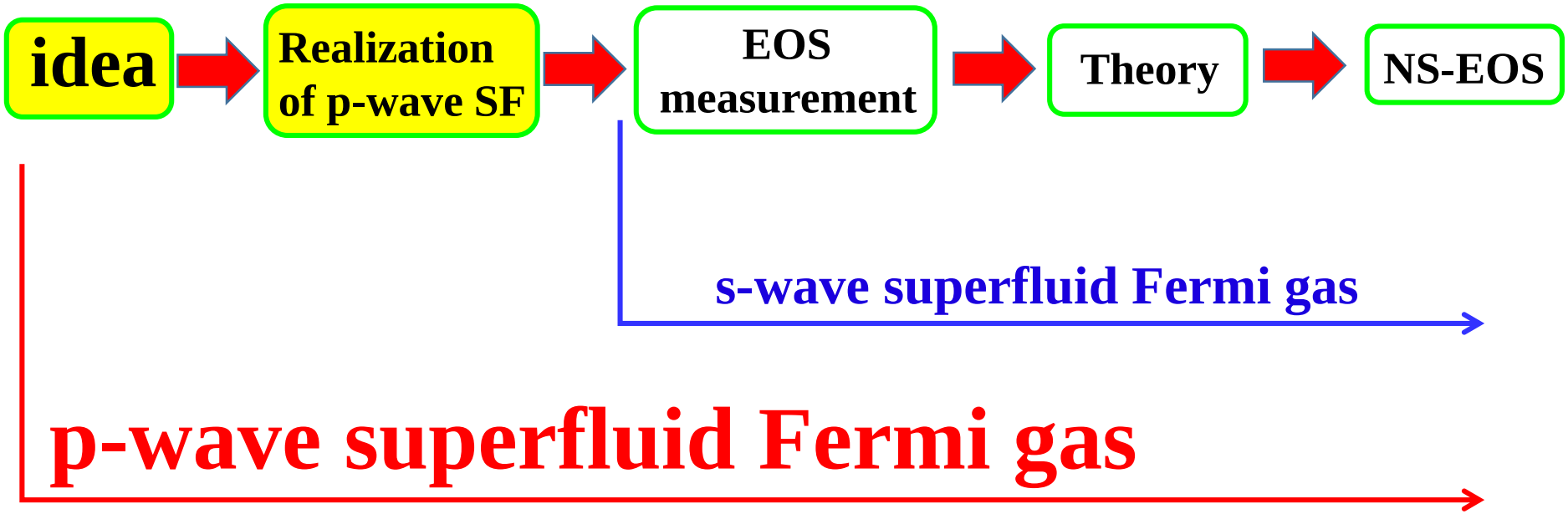


The purpose of this talk

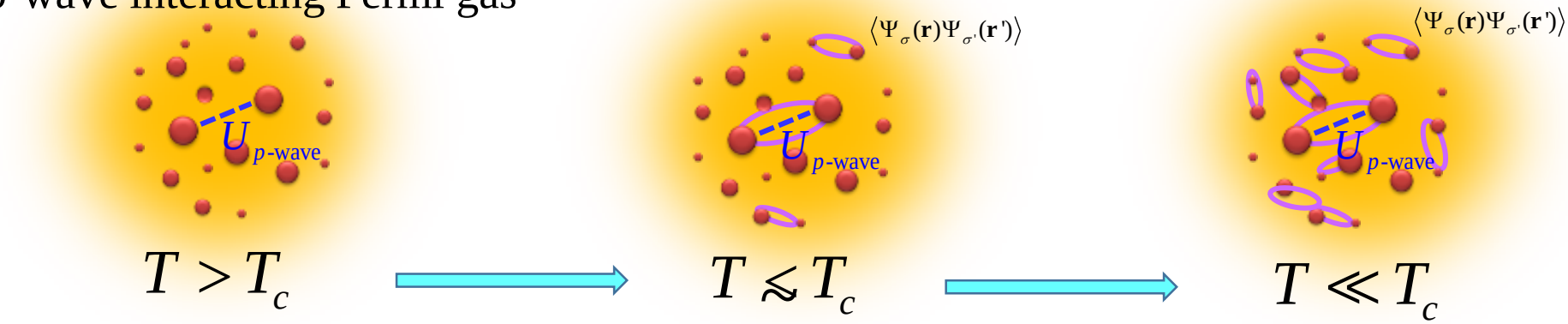
We theoretically propose <u>a novel idea to reach a p-wave superfluid Fermi gas</u>. Using this proposal, one may be able to overcome the long-standing difficulty that all the cold Fermi gas experiments aiming to realize this unconventional Fermi superfluid.

superfluid order parameter

$$\Delta(\mathbf{r},\mathbf{r}') = U(\mathbf{r}-\mathbf{r}')\langle \Psi_\sigma(\mathbf{r})\Psi_{\sigma'}(\mathbf{r}')\rangle$$

pairing interaction — **Cooper-pair amplitude**

p-wave interacting Fermi gas



$$\Delta_{p\text{-wave}} = U_{p\text{-wave}} \times 0 = 0 \qquad \Delta_{p\text{-wave}} = U_{p\text{-wave}} \times \langle \Psi_\sigma \Psi_{\sigma'} \rangle \qquad \Delta_{p\text{-wave}} = U_{p\text{-wave}} \times \langle \Psi_\sigma \Psi_{\sigma'} \rangle$$

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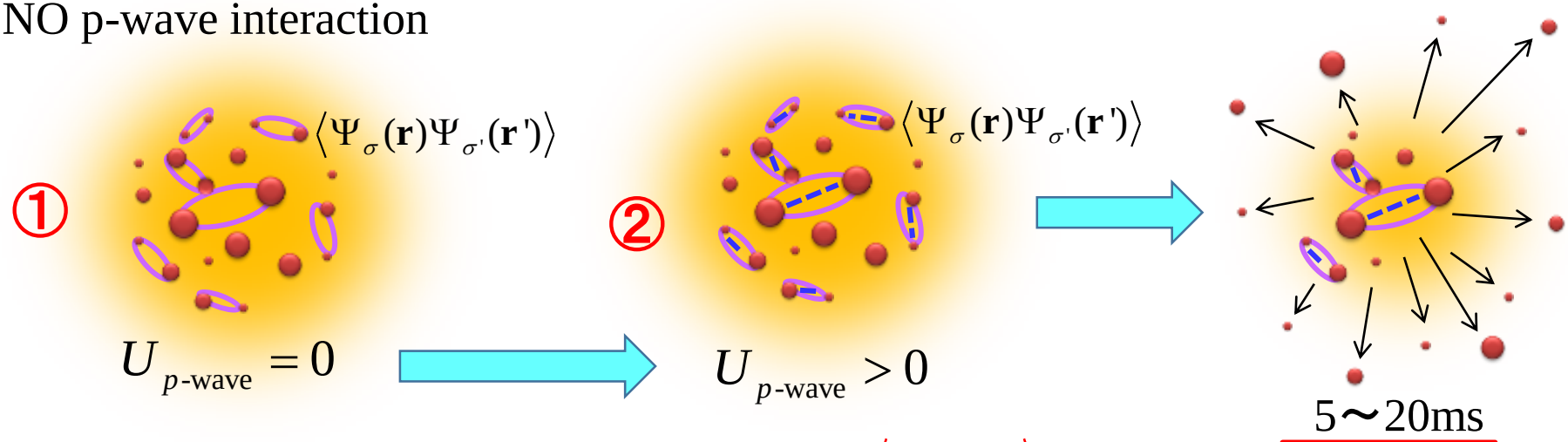
superfluid order parameter

$$\Delta(\mathbf{r},\mathbf{r}') = U(\mathbf{r}-\mathbf{r}')\langle \Psi_\sigma(\mathbf{r})\Psi_{\sigma'}(\mathbf{r}')\rangle$$

pairing interaction **Cooper-pair amplitude**

NO p-wave interaction



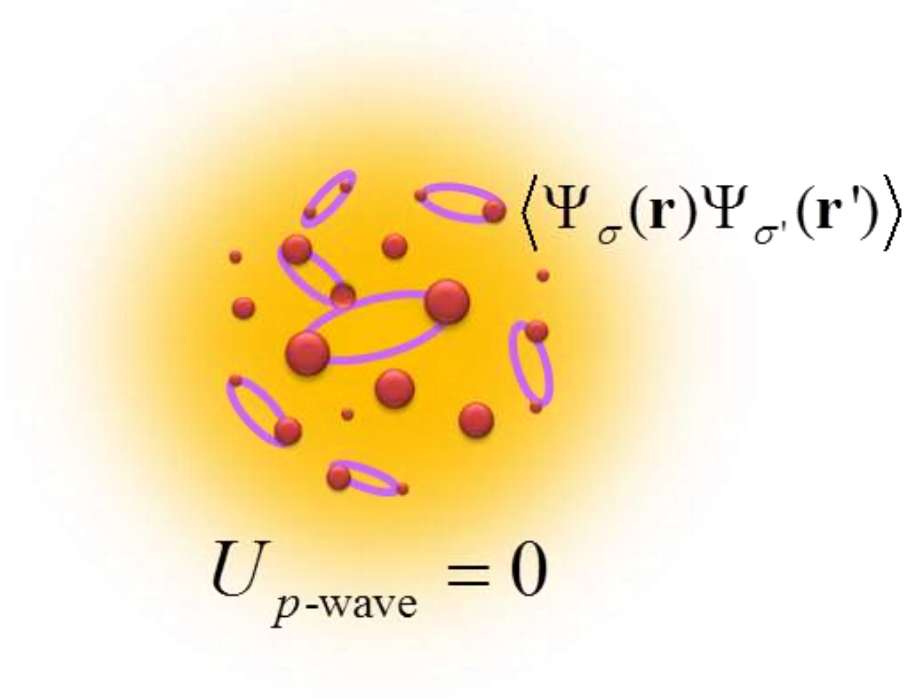
$$\Delta_{p\text{-wave}} = 0 \times \langle \Psi_\sigma \Psi_{\sigma'} \rangle = 0$$

$$\Delta_{p\text{-wave}} = U_{p\text{-wave}} \times \langle \Psi_\sigma \Psi_{\sigma'} \rangle \neq 0$$

$$\boxed{\Delta_{p\text{-wave}} > 0}$$

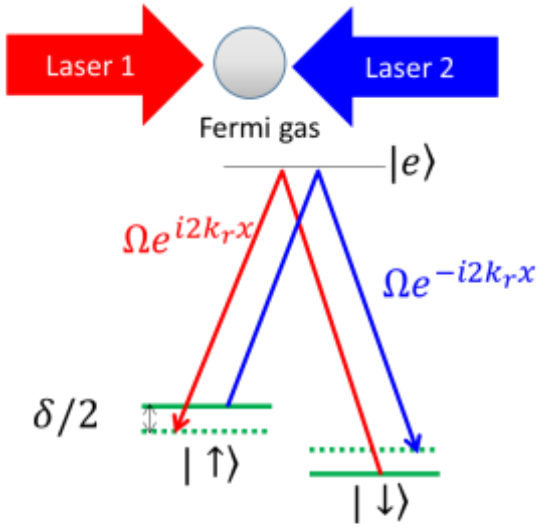
STEP 1

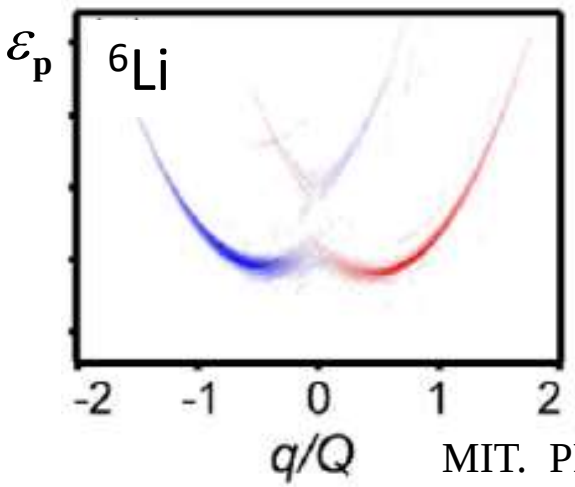
How to produce p-wave amplitude without using p-wave interaction



Parity mixing effect caused by a *synthetic* spin-orbit coupling

Cold Fermi gas physics can now introduce an *antisymmetric* spin-orbit coupling to the system by using an artificial gauge field technique.





MIT. PRL 109, 095302 (2012)

$$H_{\text{spin-orbit}} = \lambda p_z \sigma_x$$

Parity is broken!

pairing symmetry
- spin-singlet × even parity
- spin-triplet × odd parity

→ **Parity-mixing occurs!**

S-wave superfluid Fermi gas with a *synthetic* spin-orbit coupling

- Parity-broken s-wave superfluid Fermi gas

$$H=\sum_{\mathbf{p}}(c^{\dagger}_{\mathbf{p}\uparrow},c^{\dagger}_{\mathbf{p}\downarrow})\begin{pmatrix}\varepsilon_{\mathbf{p}}-\mu & \lambda p_z\\ \lambda p_z & \varepsilon_{\mathbf{p}}-\mu\end{pmatrix}\begin{pmatrix}c_{\mathbf{p}\uparrow}\\ c_{\mathbf{p}\downarrow}\end{pmatrix}-U_{s\text{-wave}}\sum_{\mathbf{p},\mathbf{p}',\mathbf{q}}c^{\dagger}_{\mathbf{p}+\mathbf{q}/2\uparrow}c^{\dagger}_{-\mathbf{p}+\mathbf{q}/2\downarrow}c_{-\mathbf{p}'+\mathbf{q}/2\downarrow}c_{\mathbf{p}'+\mathbf{q}/2\uparrow}$$

Spin-orbit coupling **S-wave pairing interaction**

- BCS-Leggett strong-coupling theory at T=0

- **s-wave superfluid order parameter**

$$\Delta_{s\text{-wave}}=-U_{s\text{-wave}}\sum_{\mathbf{p}}\left\langle c_{\mathbf{p}\uparrow}c_{-\mathbf{p}\downarrow}\right\rangle\neq 0$$

s-wave superfluid state

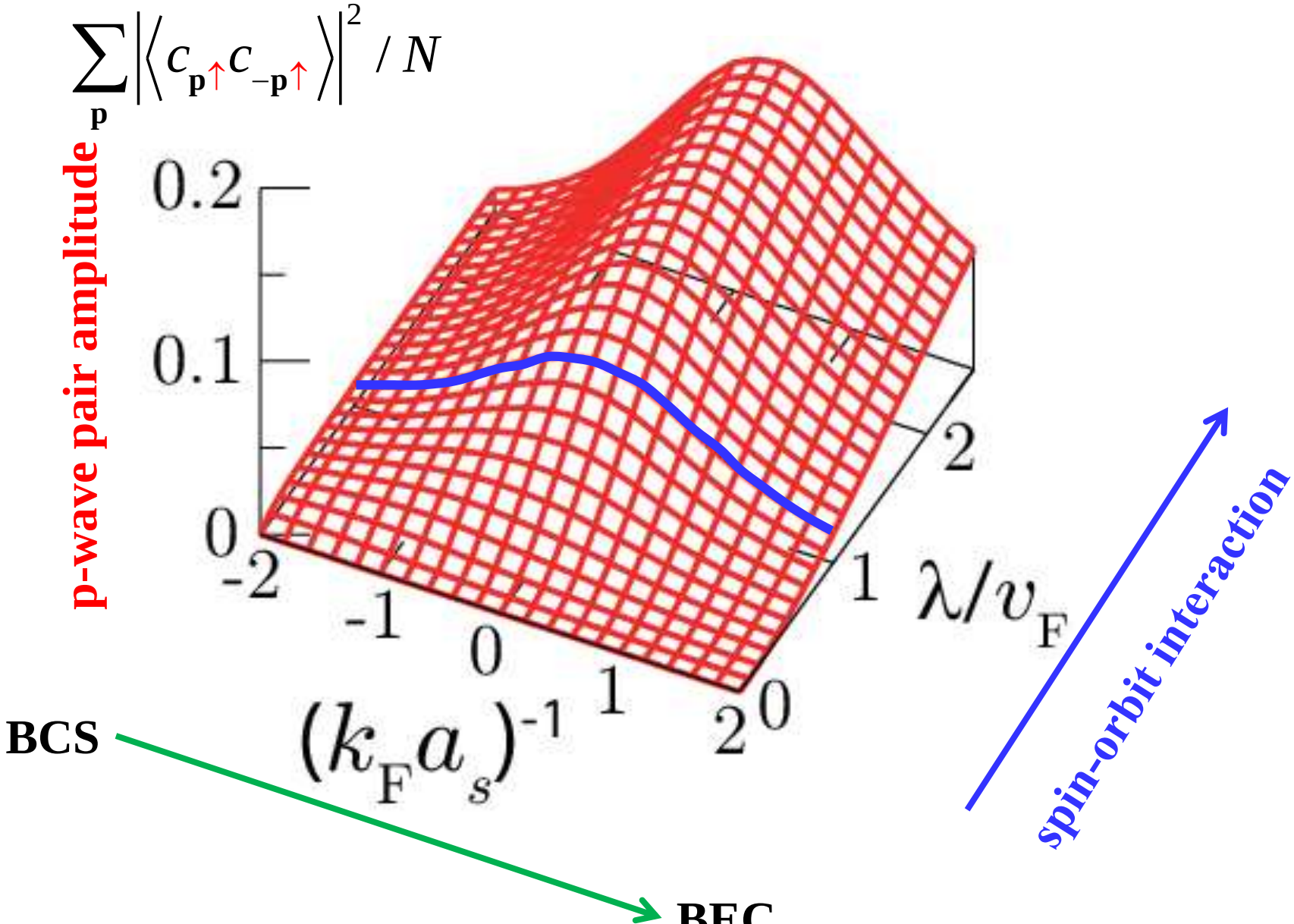
- **p-wave Cooper-pair amplitude**

$$\left\langle c_{\mathbf{p}\uparrow}c_{-\mathbf{p}\uparrow}\right\rangle=-\left\langle c_{\mathbf{p}\downarrow}c_{-\mathbf{p}\downarrow}\right\rangle=\mathrm{sgn}(p_z)\frac{\Delta_{s\text{-wave}}}{4}\sum_{\mathbf{p}}\left[\frac{1}{E^{+}_{\mathbf{p}}}-\frac{1}{E^{-}_{\mathbf{p}}}\right]\neq 0$$

$$E^{\pm}_{\mathbf{p}}=\sqrt{(\varepsilon_{\mathbf{p}}-\mu\pm\lambda\,|\,p_z\,|)^2+\Delta^2_{s\text{-wave}}}$$

- ~~**p-wave order parameter**~~

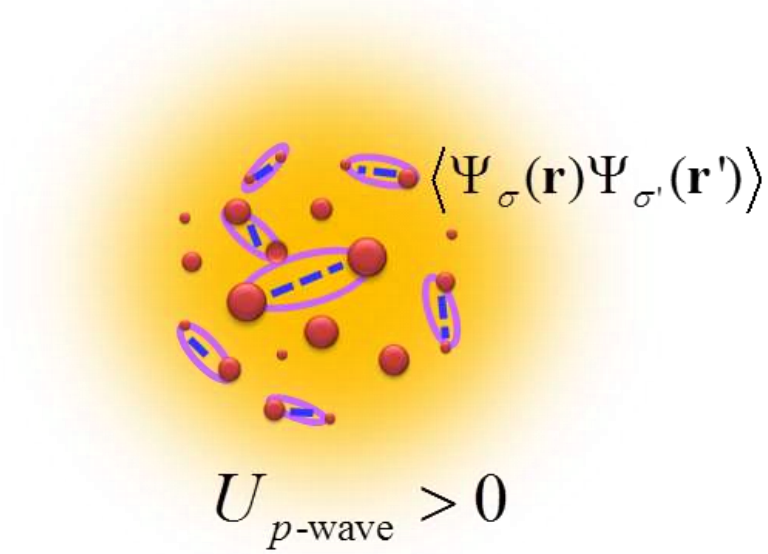
Induced p-wave Cooper-pair amplitude in the s-wave state



Yamaguchi, YO, PRA 92, 013615 (2015)

STEP 2

How to reach a p-wave superfluid state, within the lifetime, 5~20ms

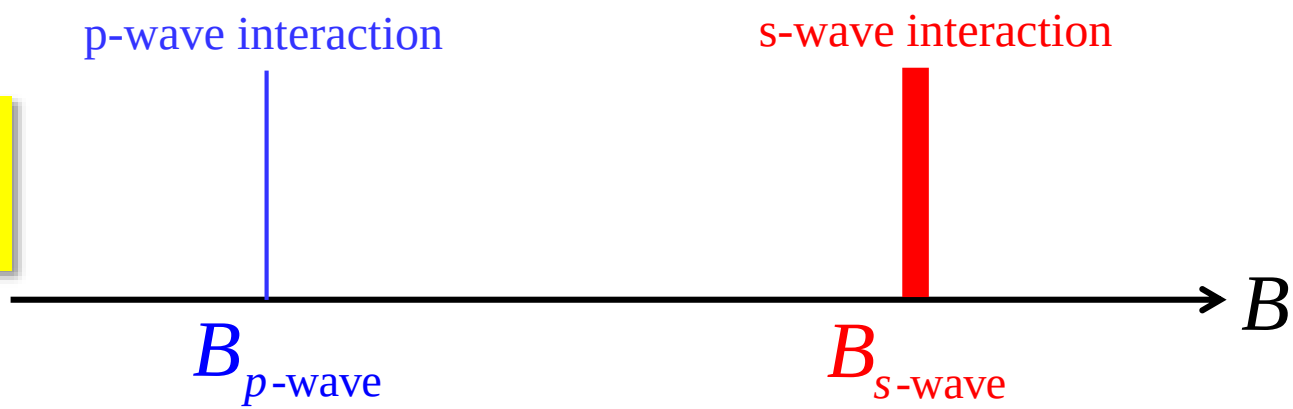


$$\Delta_{p\text{-wave}} = U_{p\text{-wave}} \times \langle \Psi_\sigma \Psi_{\sigma'} \rangle \neq 0$$

Tunable Feshbach interaction adjusted by external magnetic field

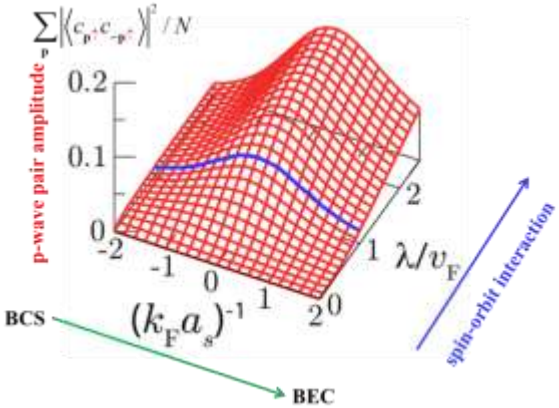
In ^{40}K and ^{6}Li Fermi gases, we can tune a pairing interaction by adjusting an external magnetic field.

Feshbach resonance



$$\Delta_{s\text{-wave}} = -U_{s\text{-wave}} \sum_{\mathbf{p}} \left\langle c_{\mathbf{p}\uparrow} c_{-\mathbf{p}\downarrow} \right\rangle \neq 0$$

$$\left\langle c_{\mathbf{p}\uparrow} c_{-\mathbf{p}\uparrow} \right\rangle =$$



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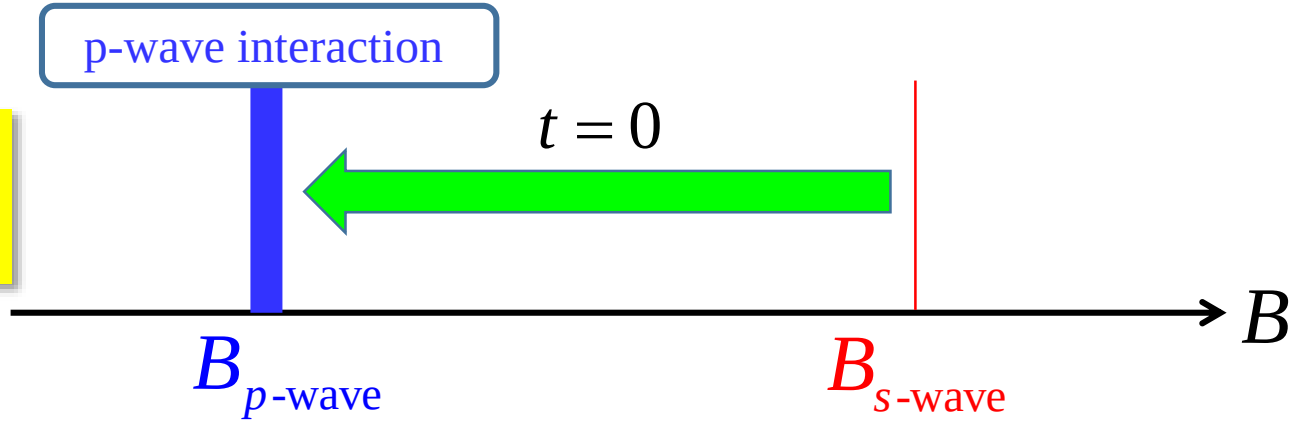
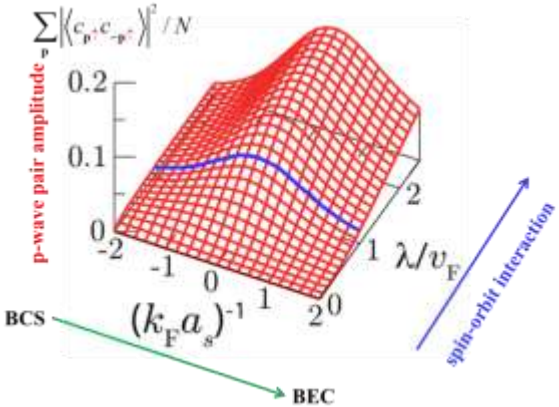


$$0! \Leftarrow \Delta_{s\text{-wave}} = -U_{s\text{-wave}} \sum_{\mathbf{p}} \left\langle c_{\mathbf{p}\uparrow} c_{-\mathbf{p}\downarrow} \right\rangle \neq 0$$

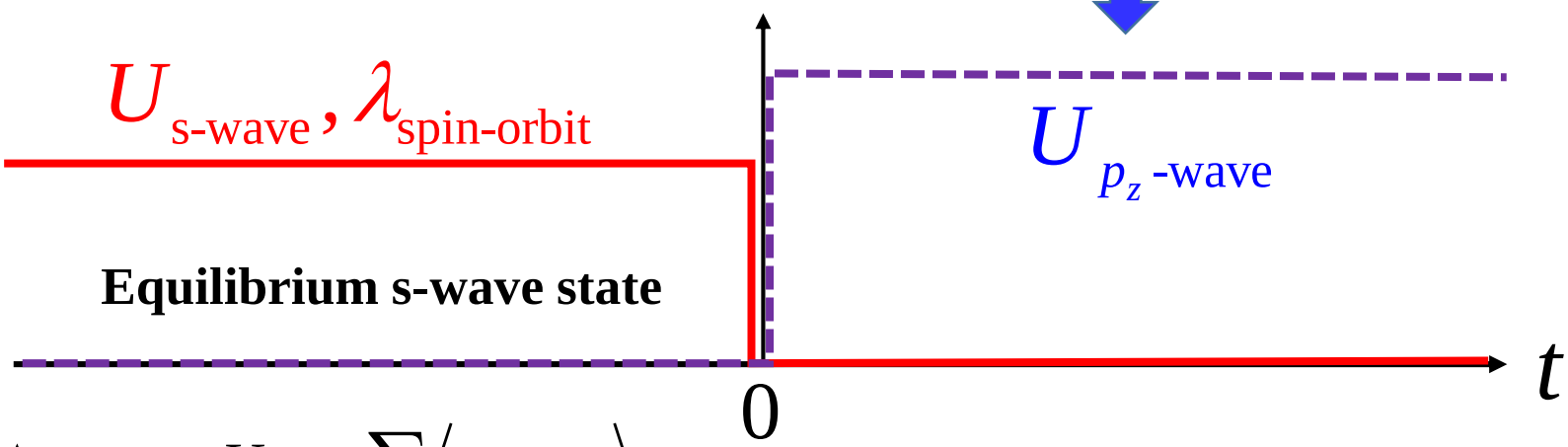
$$\Delta_{p\text{-wave}}(\mathbf{p}) = \sum_{\mathbf{p}} U_{p_z\text{-wave}}(\mathbf{p},\mathbf{p}') \left\langle c_{\mathbf{p}'\uparrow} c_{-\mathbf{p}'\uparrow} \right\rangle \neq 0 \Leftarrow \left\langle c_{\mathbf{p}\uparrow} c_{-\mathbf{p}\uparrow} \right\rangle =$$

p-wave superfluid Fermi gas !



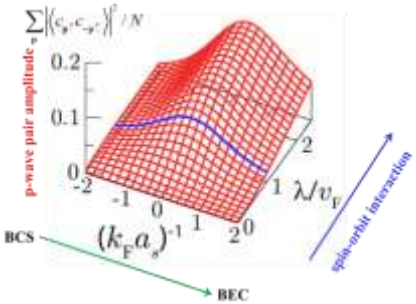
Time-dependent Bogoliubov de Gennes (TdBdG) analysis

$$i\frac{\partial \Psi_{\mathbf{p}}(t)}{\partial t} = \begin{pmatrix} \varepsilon_{\mathbf{p}} & \Delta_{p_z\text{-wave}}(\mathbf{p},t) \\ \Delta^*_{p_z\text{-wave}}(\mathbf{p},t) & -\varepsilon_{\mathbf{p}} \end{pmatrix} \Psi_{\mathbf{p}}(t)$$



$$\Delta_{s\text{-wave}} = -U_{s\text{-wave}} \sum_{\mathbf{p}} \left\langle c_{\mathbf{p}\uparrow} c_{-\mathbf{p}\downarrow} \right\rangle$$

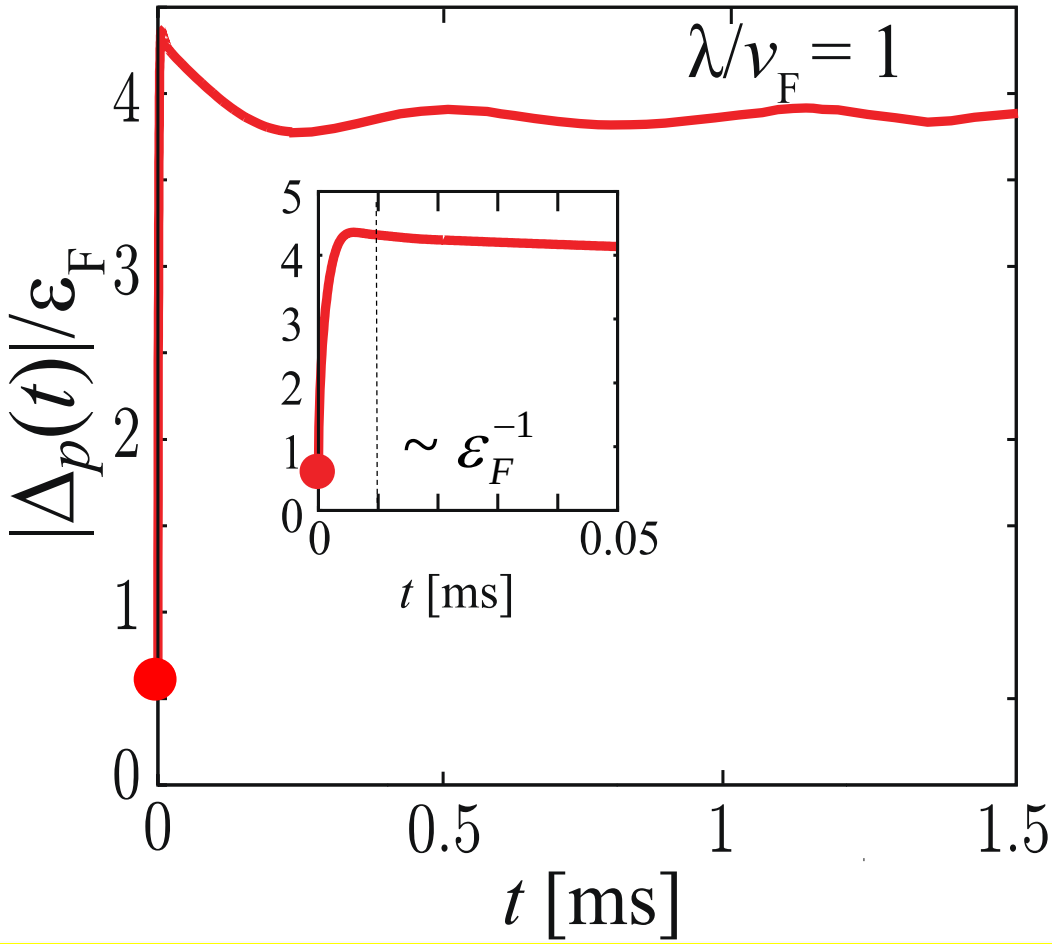
$$\left\langle c_{\mathbf{p}\uparrow} c_{-\mathbf{p}\uparrow} \right\rangle =$$



?

Time-dependent Bogoliubov de Gennes (TdBdG) analysis

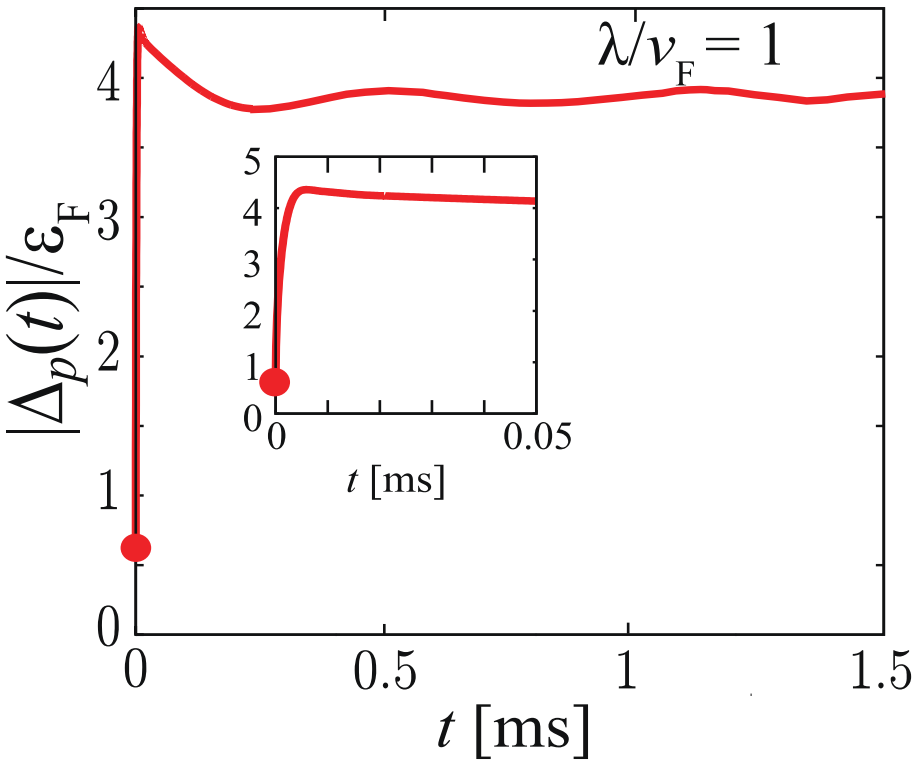
$$s\text{-wave}: (k_F a_s)^{-1} = 0 \Rightarrow p_z\text{-wave}: (k_F^3 v_p)^{-1} = 0$$



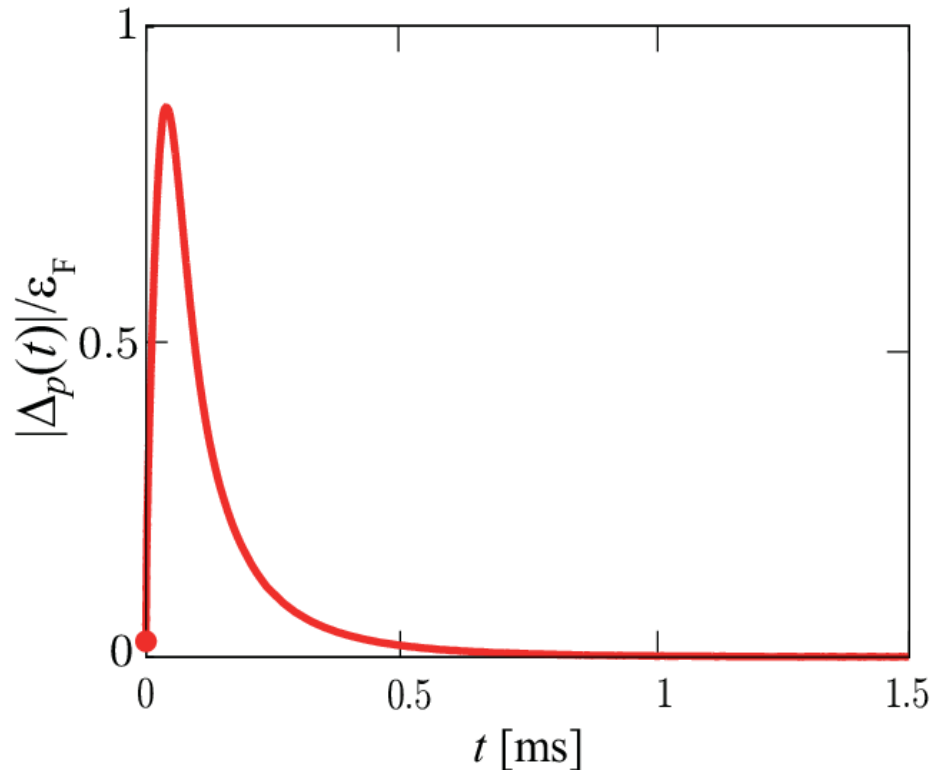
In our idea, the p-wave order parameter grows much faster than the system lifetime (~5-20ms).

Time-dependent Bogoliubov de Gennes (TdBdG) analysis

$s\text{-wave}: (k_F a_s)^{-1} = 0 \Rightarrow p_z\text{-wave: } (k_F^3 v_p)^{-1} = 0$



$s\text{-wave}: (k_F a_s)^{-1} = -1 \Rightarrow p_z\text{-wave: } (k_F^3 v_p)^{-1} = -6$

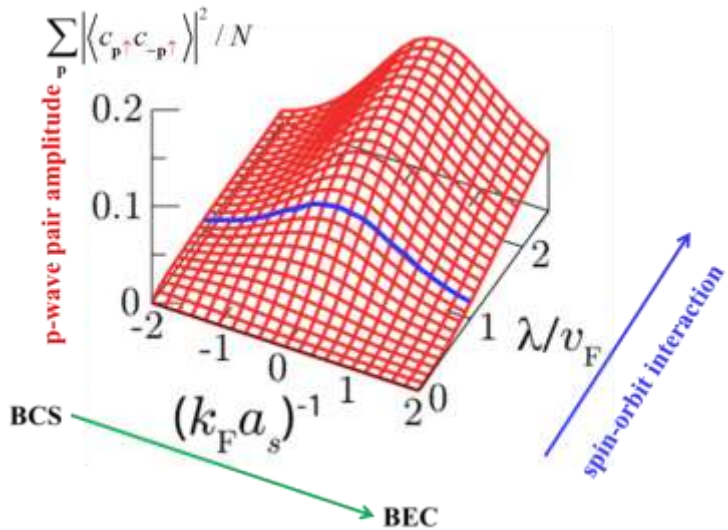


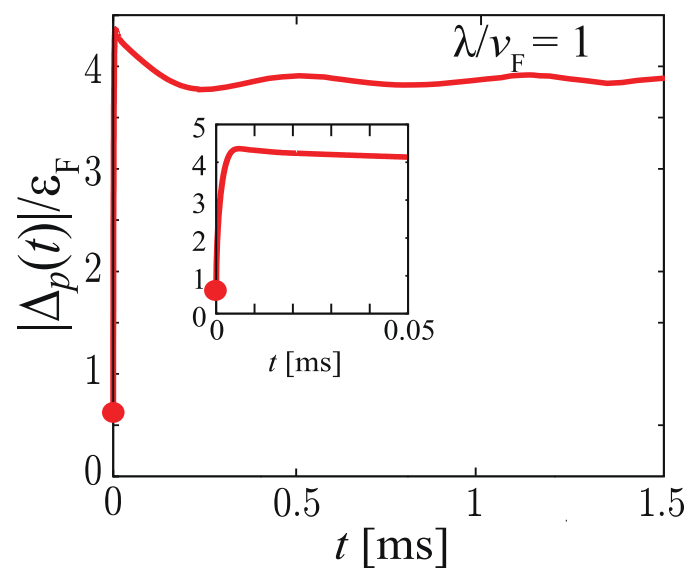
Non-vanishing $\Delta_p(t>>0)$ is obtained when the initial momentum distribution is taken to be close to that in the final equilibrium p-wave state.

Summary

We have proposed a novel idea to realize a p-wave superfluid Fermi gas. Our approach separately prepares p-wave pair amplitude without relying on any p-wave interaction, but using parity-broken spin-orbit coupling. Thus, it may overcome the current experimental difficulty (short system lifetime (=5~20 ms <<100 ms) by p-wave interaction).

p-wave Cooper-pair amplitude → **p-wave superfluid state**





Our idea involves potential importance of cold Fermi gas system for the study of non-equilibrium problems, such as PBF mechanism of neutron-star cooling.