Properties of a driven-dissipative non-equilibrium Fermi superfluid

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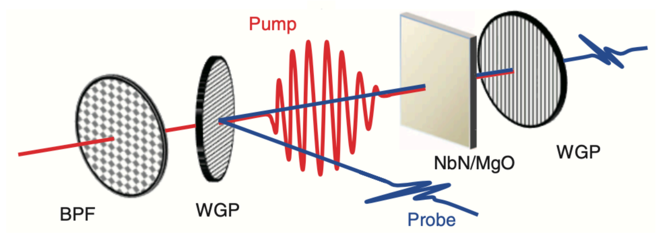
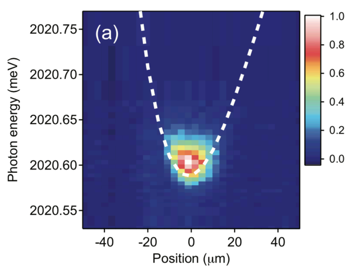
Introduction *non-equilibrium Fermi condensates*

✓ **non-equilibrium superconductivity**

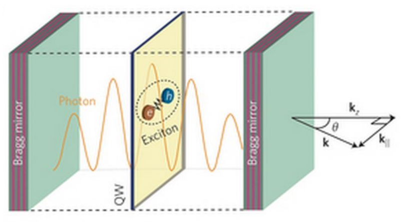


R, Matsunaga, *et al.* Science. **345**, 6201 (2014)

✓ **exciton-polariton condensates**

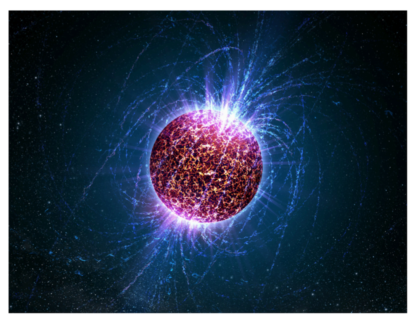


K. Yoshioka, *et al.* PRB **88**, 041201(R) (2013)

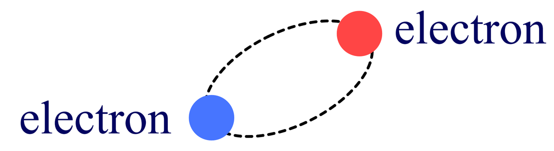


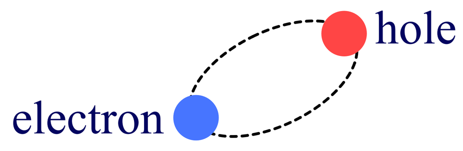
K. O. Chong, *et al.* Commun. Phys. **1**, 25 (2018)

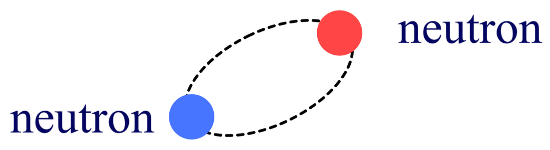
✓ **neutron star**



https://apatruno.wordpress.com/neutron-stars/







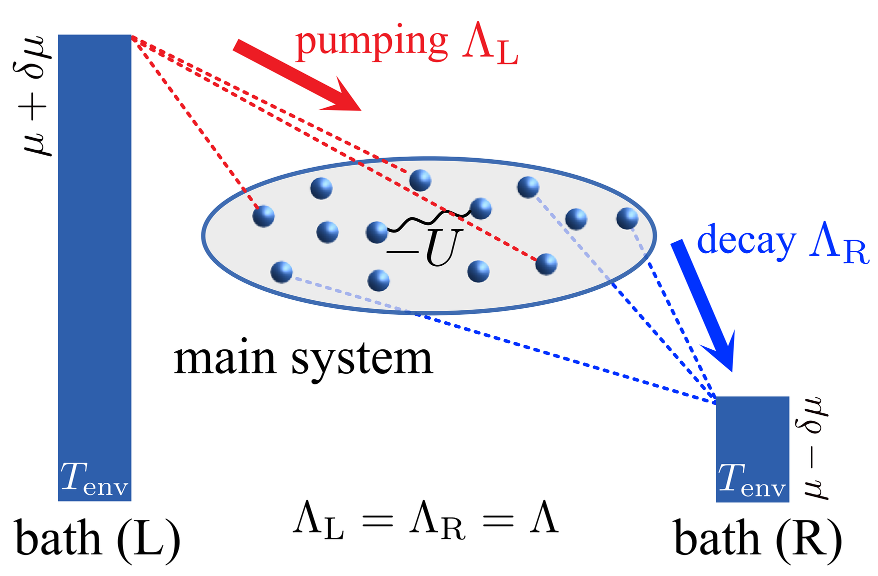
pair formation out of equilibrium $\Rightarrow$ non-equilibrium + many body effect

Summary

- We studied superfluid states in a driven-dissipative Fermi gas. By using Kadanoff-Baym equation, we derived a quantum kinetic equation, which includes both non-equilibrium and many-body effects. The fixed point of this kinetic equation gives non-equilibrium steady states.
- We found that two different states can be realized as non-equilibrium steady states. One of them is a gapless superfluid state, which is not found in a thermal equilibrium Fermi gas. However, this gapless state turned out to be unstable against superfluid fluctuations from the linear stability analysis.
- We also found that non-uniform Fulde-Ferrell like state can be realized by the non-equilibrium effects. The stability analysis of this state is our future work.

Formalism

✓ model



$\delta\mu$: non-equilibrium parameter

$$\mathcal{H}_{\rm tot}=\mathcal{H}_{\rm sys}+\mathcal{H}_{\rm env}+\mathcal{H}_{\rm mix}$$

main system

$$H_{\rm sys}=\sum_{\sigma=\uparrow,\downarrow}\int d\boldsymbol{r}\,\psi^\dagger_\sigma(\boldsymbol{r})\frac{-\nabla^2}{2m}\psi_\sigma(\boldsymbol{r})-\int d\boldsymbol{r}\left[\Delta(\boldsymbol{r},t)\psi^\dagger_\uparrow(\boldsymbol{r})\psi^\dagger_\downarrow(\boldsymbol{r})+{\rm H.c.}\right]$$

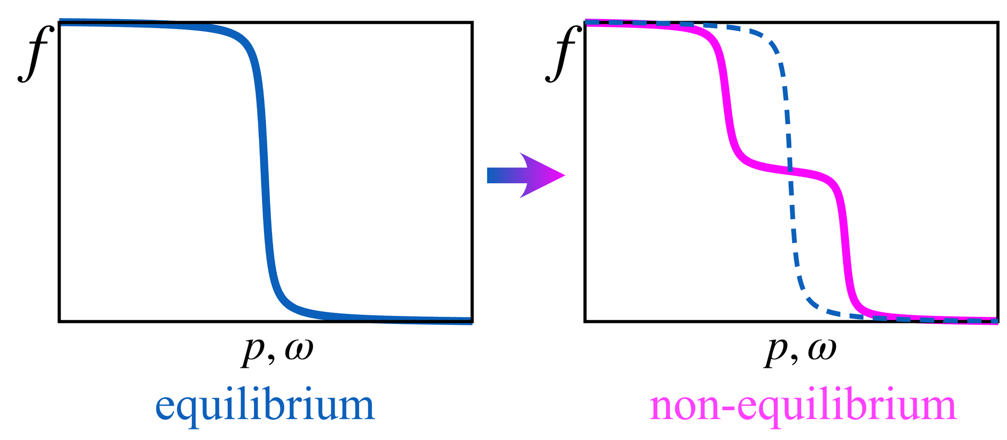
environment system

$$H_{\rm env}=\sum_{\alpha={\rm L,R}}\sum_{\sigma=\uparrow,\downarrow}\int d\boldsymbol{R}\,\phi^{\alpha\dagger}_\sigma(\boldsymbol{R})\left[\frac{-\nabla^2}{2m}-\mu_\alpha\right]\phi^\alpha_\sigma(\boldsymbol{R})$$

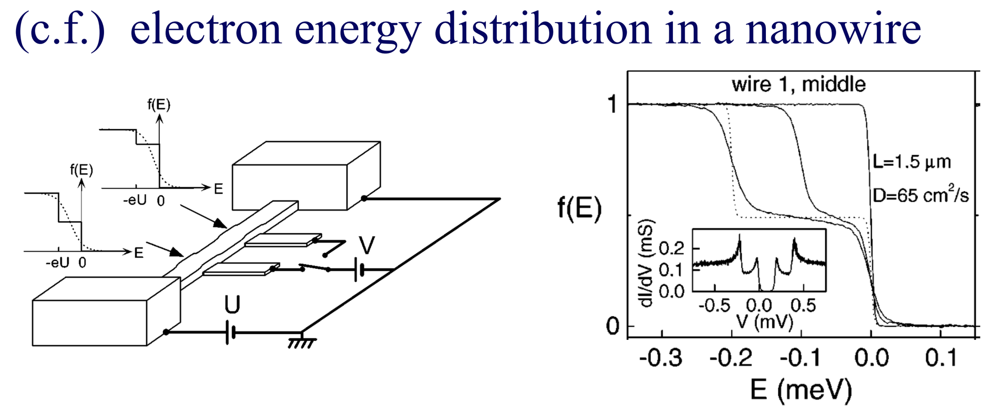
mixing term

$$H_{\rm mix}=\sum_{\alpha={\rm L,R}}\sum_{\sigma=\uparrow,\downarrow}\sum_{i=1}^{N_t}\int d\boldsymbol{r}_i\int d\boldsymbol{R}_i\left[e^{i\mu_\alpha t}\Lambda_\alpha\phi^{\alpha\dagger}_\sigma(\boldsymbol{R}_i)\,\psi_\sigma(\boldsymbol{r}_i)+{\rm H.c.}\right]$$

Atomic momentum/energy distribution



(c.f.) electron energy distribution in a nanowire



H. Pothier, S. Guéron, O. Birge, D. Esteve, and M.H. Devoret, PRL. **79**, 18 (1997)

✓ kinetic equation for the driven-dissipative Fermi gas

Nambu lesser Green's function

$$\mathcal{G}^<(\boldsymbol{r}_1t_1,\boldsymbol{r}_2t_2)=i\begin{pmatrix}\langle\psi^\dagger_\uparrow(\boldsymbol{r}_2,t_2)\psi_\uparrow(\boldsymbol{r}_1,t_1)\rangle & \langle\psi_\downarrow(\boldsymbol{r}_2,t_2)\psi_\uparrow(\boldsymbol{r}_1,t_1)\rangle\\ \langle\psi^\dagger_\uparrow(\boldsymbol{r}_2,t_2)\psi^\dagger_\uparrow(\boldsymbol{r}_1,t_1)\rangle & \langle\psi_\downarrow(\boldsymbol{r}_2,t_2)\psi^\dagger_\downarrow(\boldsymbol{r}_1,t_1)\rangle\end{pmatrix}$$

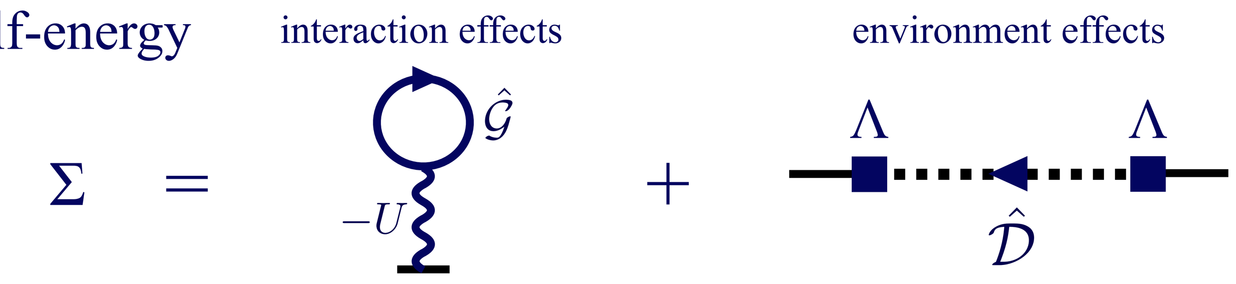
diagonal : particle density
off-diagonal : pair amplitude

Kadanoff-Baym equation

$$\left[\mathcal{G}^{-1}\mathcal{G}^<-\mathcal{G}^<\mathcal{G}^{-1}\right](\boldsymbol{p},\boldsymbol{r},t)=\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\left[\Sigma^{\rm R}\otimes\mathcal{G}^<-\mathcal{G}^<\otimes\Sigma^{\rm A}-\mathcal{G}^{\rm R}\otimes\Sigma^<+\Sigma^<\otimes\mathcal{G}^{\rm A}\right](\boldsymbol{p},\omega,\boldsymbol{r},t)$$

driving term — collision term

self-energy



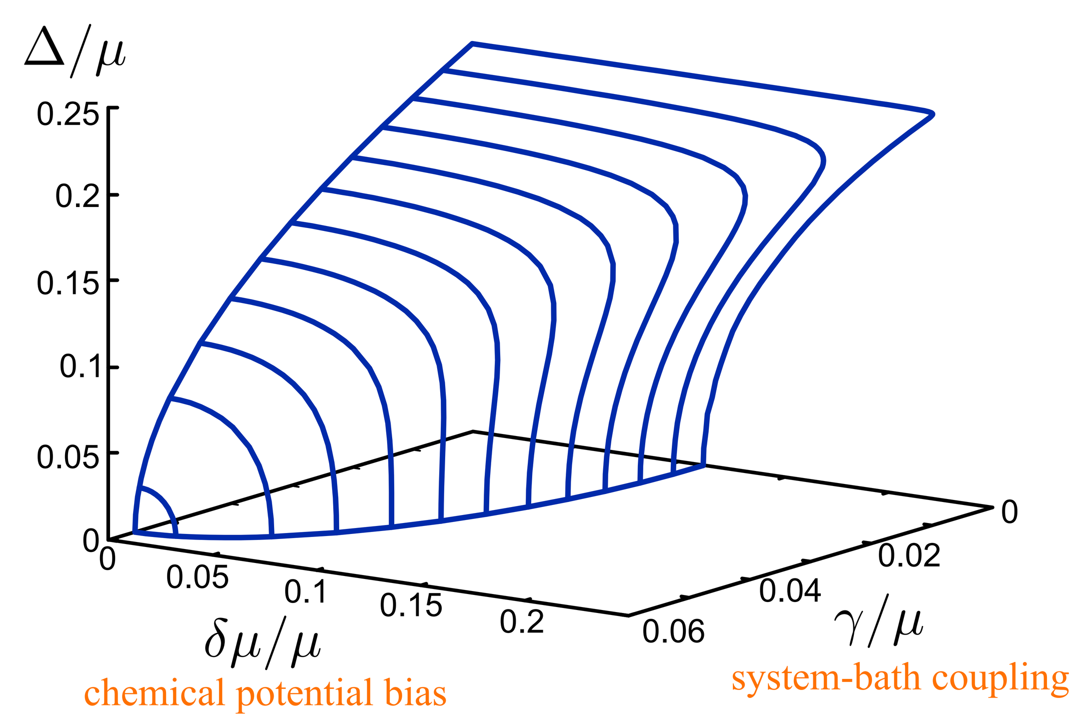
non-equilibrium steady state $\partial_t\mathcal{G}^<=0$

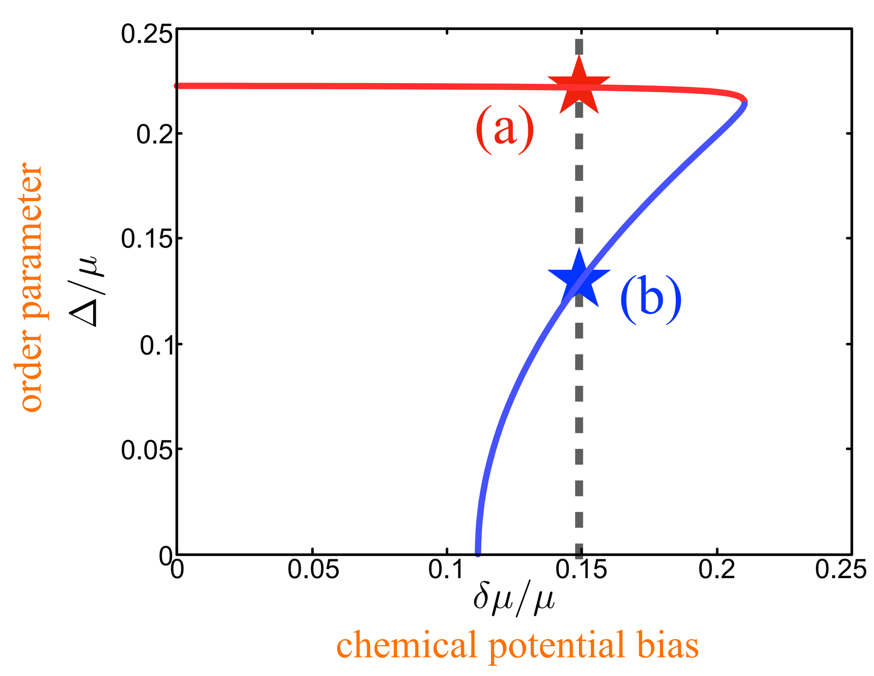
$$\Rightarrow\ \Delta_0=-iU\sum_{\boldsymbol{p}}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\mathcal{G}^<(\boldsymbol{p},\omega)_{12}$$

non-equilibrium gap equation

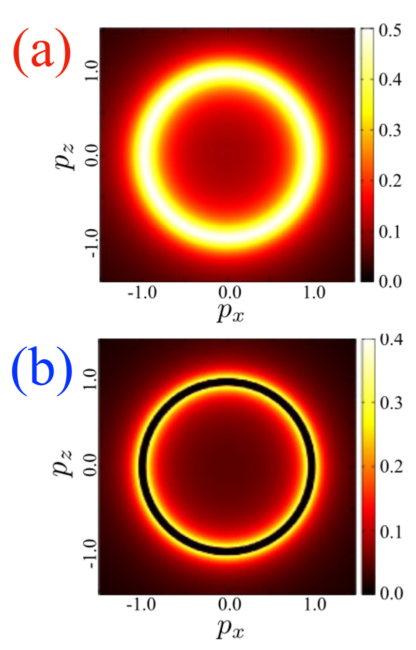
Result

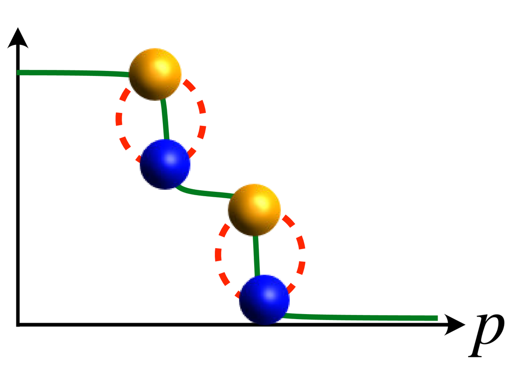
✓ non-equilibrium steady states



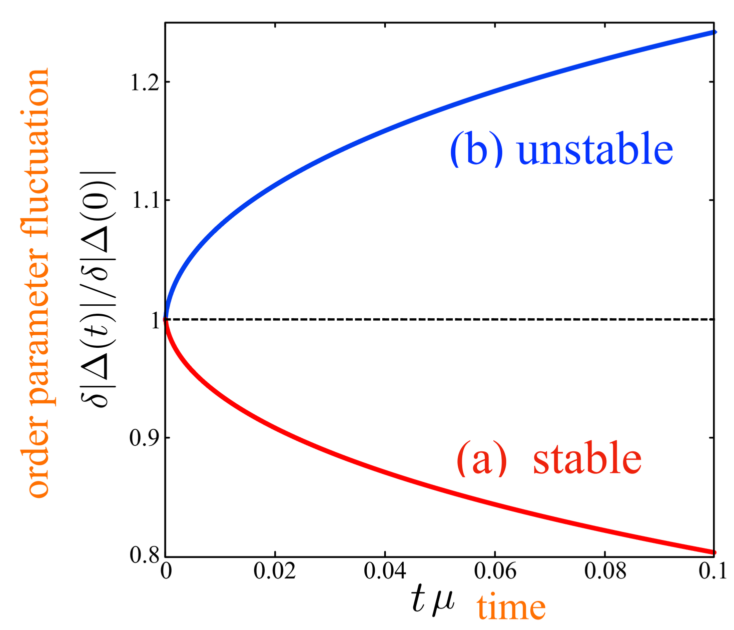


Cooper pair wave function $\langle a_{-\boldsymbol{p}\downarrow}a_{\boldsymbol{p},\uparrow}\rangle$



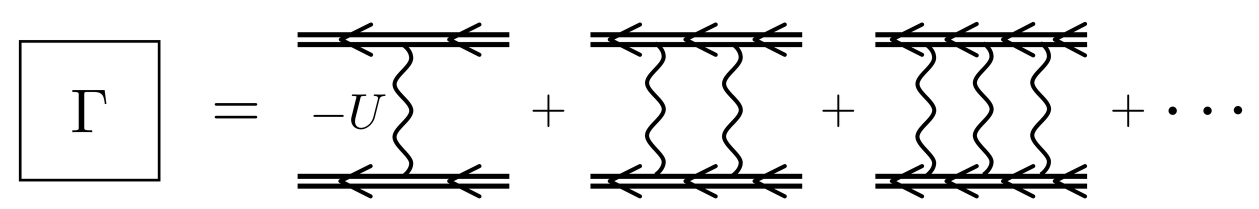


linear stability $\delta\Delta(t)=\Delta(t)-\Delta_0$



✓ exotic pairing state

non-equilibrium *T*-matrix

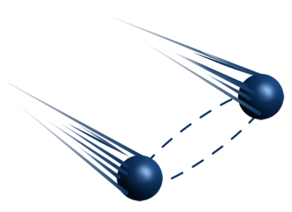


non-equilibrium propagator including environment effects

Thouless criterion

$$\left[\Gamma^{\rm R}(\boldsymbol{q}=0,\nu=0;T=T_{\rm c})\right]^{-1}=0$$

$$\left[\Gamma^{\rm R}(\boldsymbol{q}=\boldsymbol{Q},\nu=0;T=T_{\rm c})\right]^{-1}=0$$



Cooper pair with a finite center-of-mass momentum

superfluid transition temperature