Quasi-Nambu-Goldstone fermion in QGP and cold atom system

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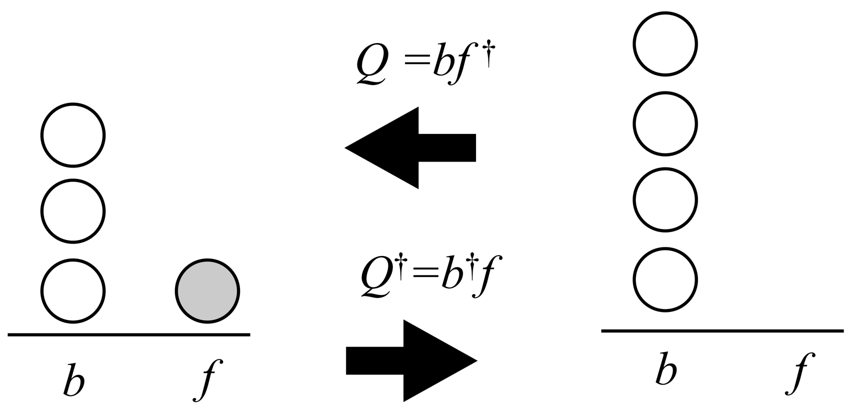
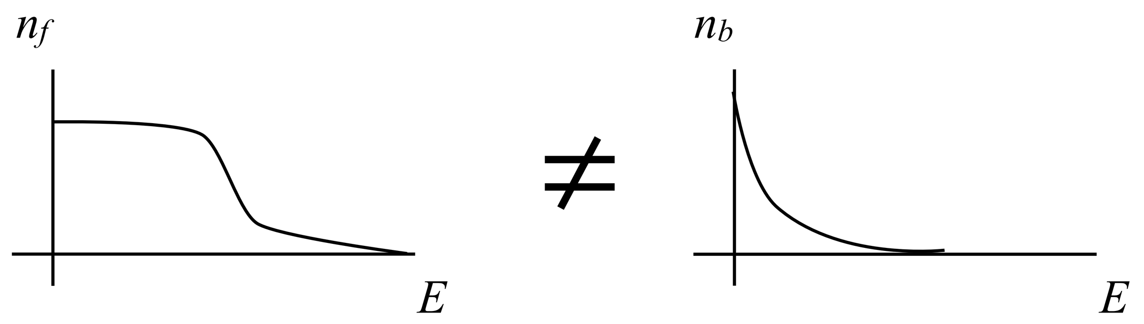
Introduction

Supersymmetry (SUSY)



SUSY: $[Q, H]=0$

SUSY is broken by matter effect.



NG mode (goldstino) appears.

V. V. Lebedev and A. V. Smilga, Nucl. Phys. B **318**, 669 (1989)
Y. Yu and K. Yang, PRL **100**, 090404 (2008)

In models which have approximate SUSY (Yukawa model, QED/QCD at high T), quasi goldstino appears.

V. V. Lebedev and A. V. Smilga, Annals of Phys. **202,** 229 (1990)
Y. Hidaka, **D. S.**, and T. Kunihiro, NPA **876**, 93 (2012)
D. S., PRD **87**, 096011 (2013)

That mode has linear dispersion relation (type-I).

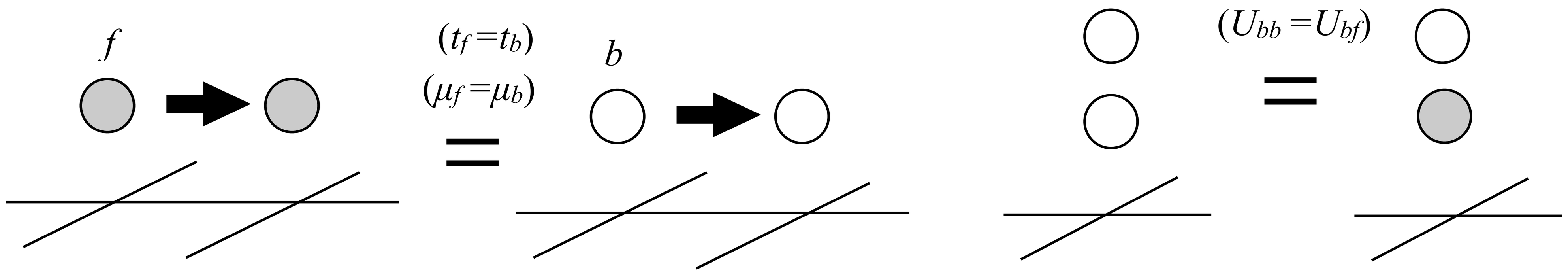
Cold atom system can be used as a **experiment station of many-body system** whose experiment is difficult.

Wess-Zumino model: Y. Yu, and K. Yang, PRL **105**, 150605 (2010)
Dense QCD: K. Maeda, G. Baym and T. Hatsuda, PRL **103**, 085301 (2009)
Relativistic QED: Kapit and Mueller, PRA **83**, 033625 (2011)

T. Shi, Y. Yu, and C. P. Sun, PRA **81**, 011604(R) (2010)

Simulate a system which has SUSY with Cold atoms!

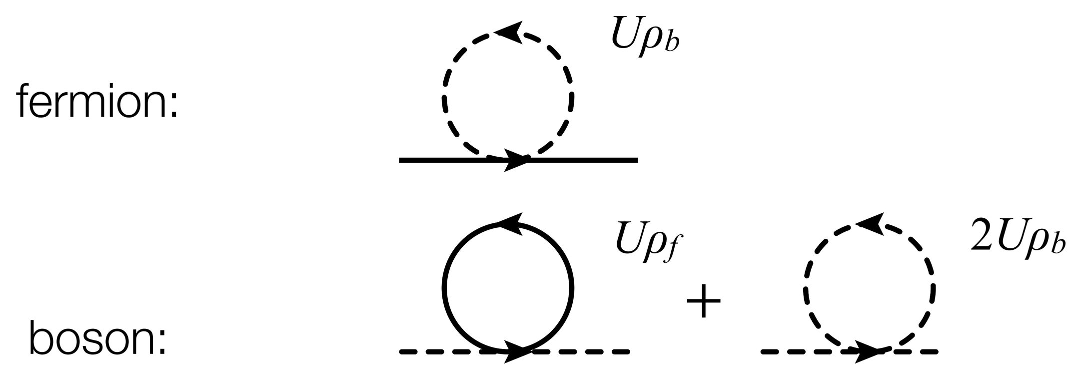
$$H_\alpha = -\sum_{\langle ij\rangle} t_\alpha a_i^{\alpha\dagger} a_j^\alpha - \mu_\alpha \sum_i a_i^{\alpha\dagger} a_i^\alpha \qquad \frac{U_{bb}}{2}\sum_i n_i^b(n_i^b-1) + U_{bf}\sum_i n_i^b n_i^f$$



Random Phase Approximation (RPA)

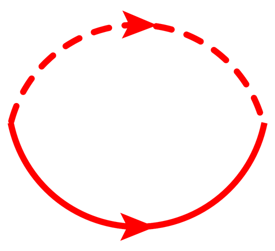
T. Shi, Y. Yu, and C. P. Sun, PRA **81**, 011604(R) (2010)

(1) the density correction to the excitation energy.



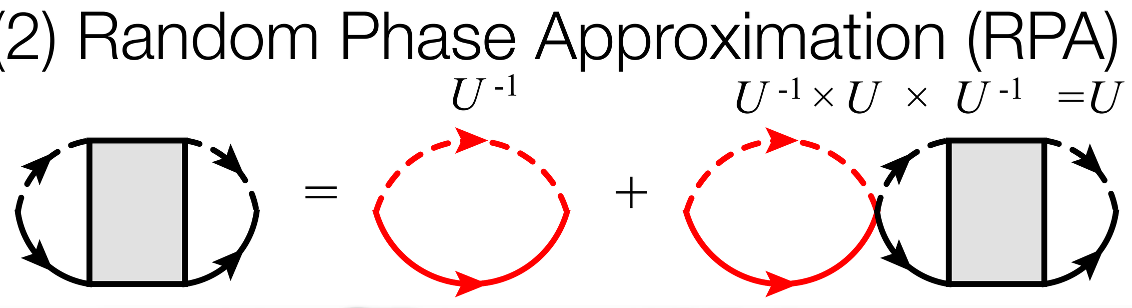
ρ_b: boson density
ρ_f: fermion density
$\rho=\rho_f+\rho_b$

the singularity at ω-$\Delta\mu$, $p\to 0$ is regularized.



(fermion term)= $\displaystyle\int \frac{d^2\mathbf{k}}{(2\pi)^2}\frac{n_F(\epsilon_{\mathbf{k}}^f)}{\omega-(\Delta\mu+t(2\mathbf{k}\cdot\mathbf{p}+\mathbf{p}^2)+U\rho)} \to U^{-1}$

(2) Random Phase Approximation (RPA)



(1), (2)

Result

Dispersion Relation	$\omega=\Delta\mu-\alpha p^2$
Strength	1

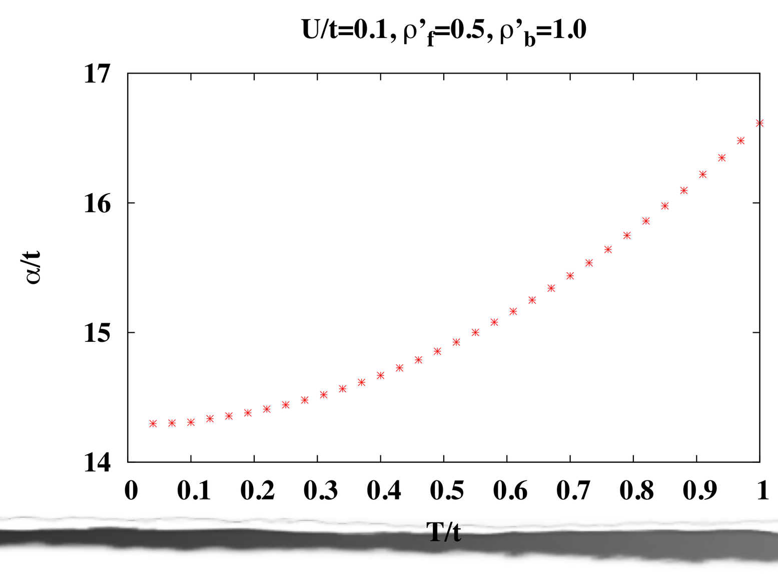
Type-II NG mode. $\displaystyle\alpha=\frac{t(\rho_b-\rho_f)}{\rho}+\frac{t^2}{\pi U\rho^2}\int_0^\infty d|\mathbf{k}||\mathbf{k}|^3(n_F(\epsilon_{\mathbf{k}}^f)+n_B(\epsilon_{\mathbf{k}}^b))$

n_B: boson distribution
n_F: fermion distribution

***T*=0 case**

$$\alpha\equiv\frac{1}{\rho}\left(\frac{4\pi t^2\rho_f^2}{U\rho}-t(\rho_f-\rho_b)\right)$$

T≠0 case

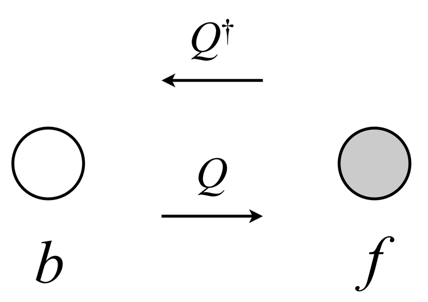


See the following for the effect of the goldstino spectrum to observable quantity: T. Shi, Y. Yu, and C. P. Sun, PRA **81**, 011604(R) (2010)

Analogy with magnon in ferromagnet

Goldstino

Charge: $Q, Q^\dagger, N, \Delta N$
Broken



Magnon in ferromagnet

Charge: M^+, M^-, M^z
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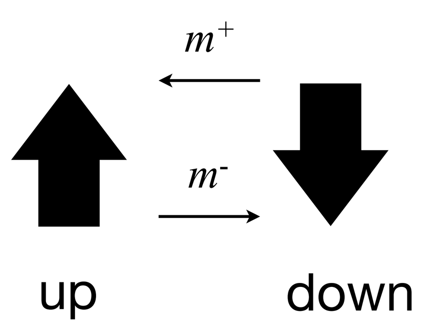

Whether the NG mode is type-I or II can be determined by checking the expectation value of commutator of the conserved charges.

Y. Hidaka, PRL **110**, 091601 (2013), H. Watanabe and H. Murayama, PRL **108**, 251602 (2012)

Analogy between the goldstino and magnon in ferromagnet is valid due to that theorem:

$\langle[Q,\rho]\rangle=0$ $\qquad$ $\langle[m^\pm, m^z]\rangle=0$

$\langle\{Q,Q^\dagger\}\rangle=\rho$ $\qquad$ $\langle[m^+,m^-]\rangle=2m_0$

$Q, Q^\dagger \rightleftarrows m_+, m_-$ $\qquad$ $\rho\rightleftarrows m_z$

Type-II dispersion relation of the goldstino can be explained by using this analogy.

By contrast, quasi goldstino in the Yukawa model, QED/QCD has a similar nature to phonon, which is type-I mode.

V. V. Lebedev and A. V. Smilga, Nucl. Phys. B **318,** 669 (1989)

Summary

- We obtained the expression of **dispersion relation** and the **strength** of the goldstino at finite T (at weak coupling, continuum limit).
- We understood the similarity between the dispersion relation of the goldstino and that of the magnon in ferromagnet by using the fact that **the (anti-)commutation relations have the same structure**.