清華大學

Tsinghua University

Landau-Beliaev Damping in a Bose-Fermi Superfluid Mixture

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Frontiers in Quantum Simulation with Cold Atoms

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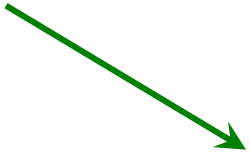
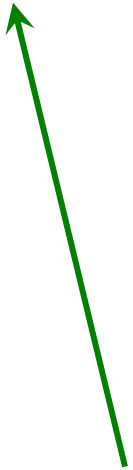
Outline

Experiment realization of
the Bose-Fermi Superfluid Mixture:
Damping of the dipole mode

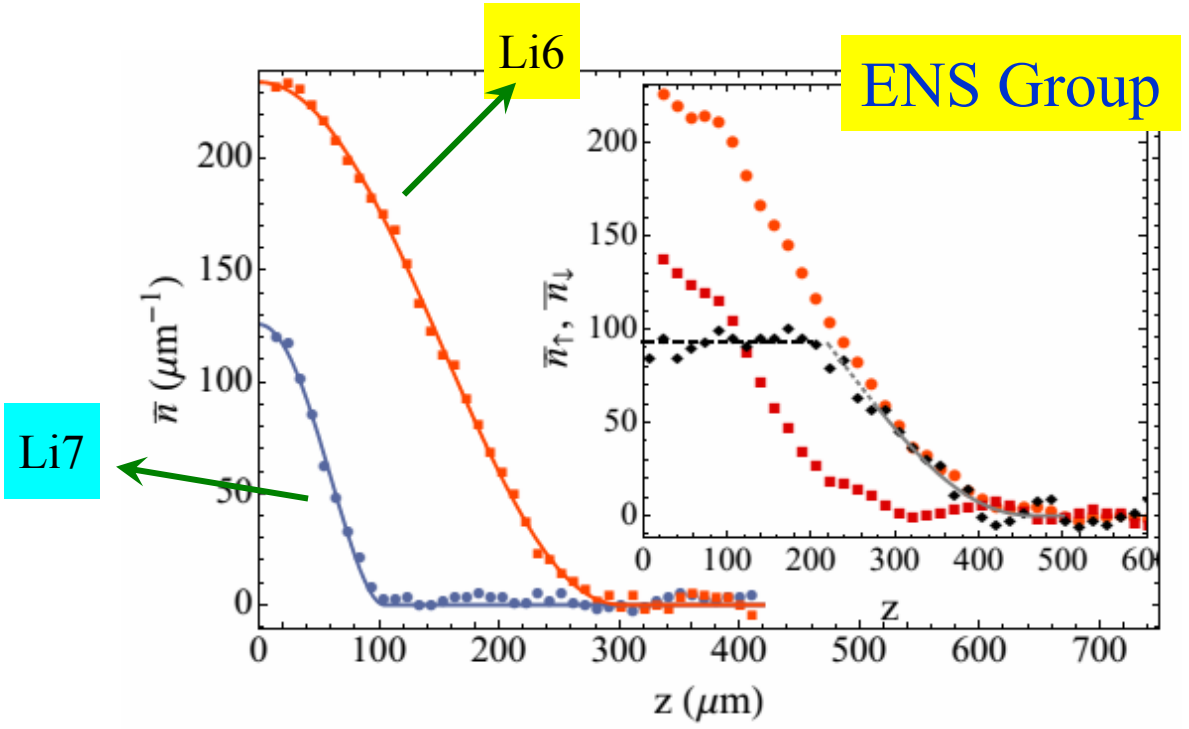


Landau-Beliaev damping
in single component BEC
High-T and low-T behavior

Landau-Beliaev damping
in Bose-Fermi Superfluid Mixture
Damping through the BCS-BEC crossover



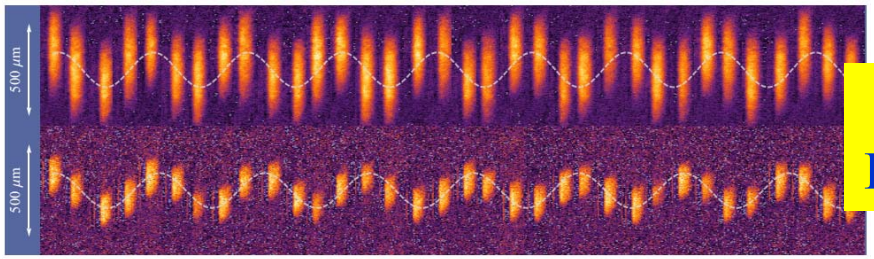
Experiment of the Bose-Fermi Superfluid Mixture



For the first time, we have
Bose superfluid mixing with Fermi superfluid

I. Ferrier-Barbut, et.al. Science, **345**, 1035 (2014)

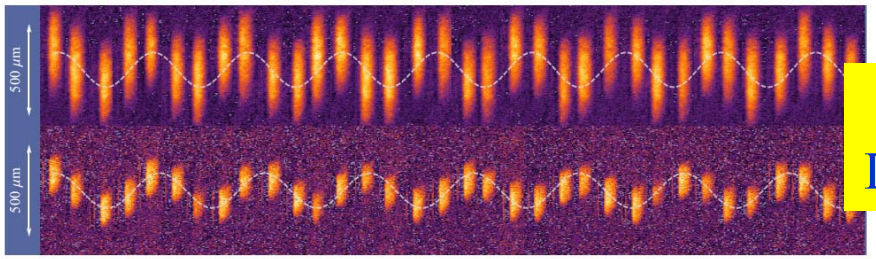
Experiment of the Bose-Fermi Superfluid Mixture



Dynamics:
Dipole Oscillation

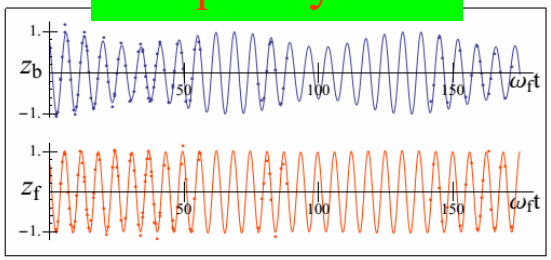
I. Ferrier-Barbut, et.al. Science, **345**, 1035 (2014)

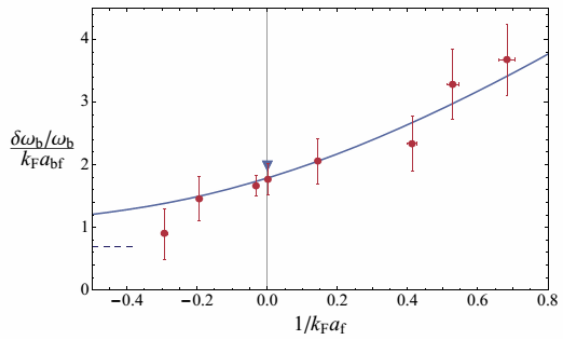
Experiment of the Bose-Fermi Superfluid Mixture



Dynamics:
Dipole Oscillation

Frequency shift

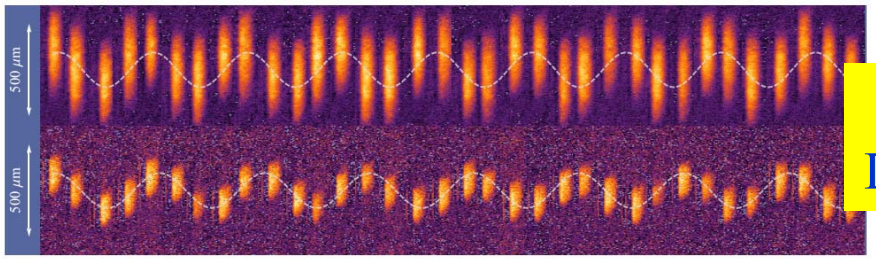




Measure the EOS of Li6

I. Ferrier-Barbut, et.al. Science, **345**, 1035 (2014)

Experiment of the Bose-Fermi Superfluid Mixture



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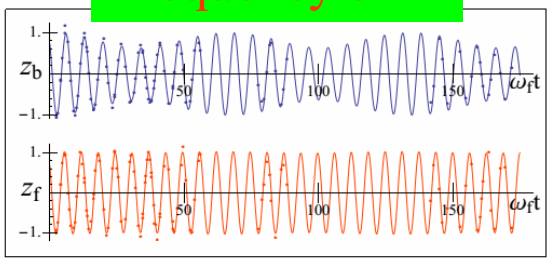
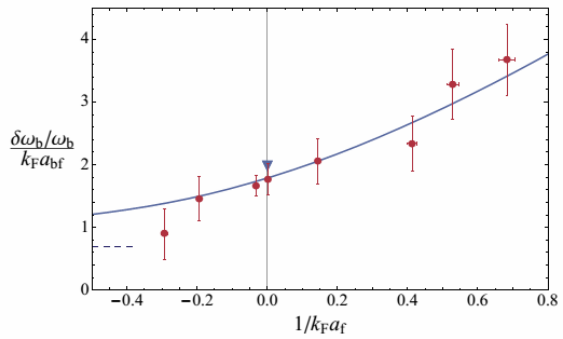
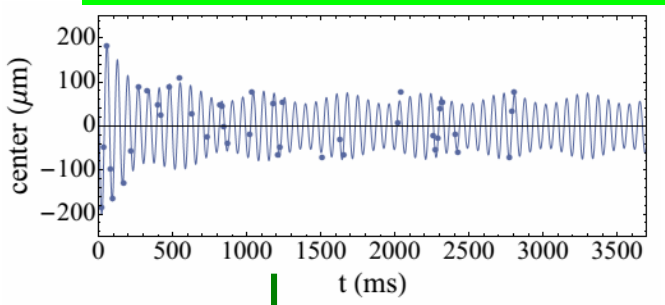


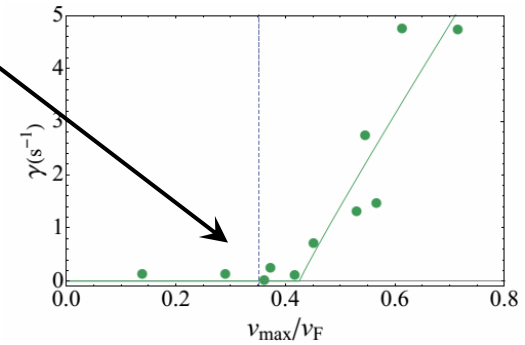


Measure the EOS of Li6

Damping of the oscillation



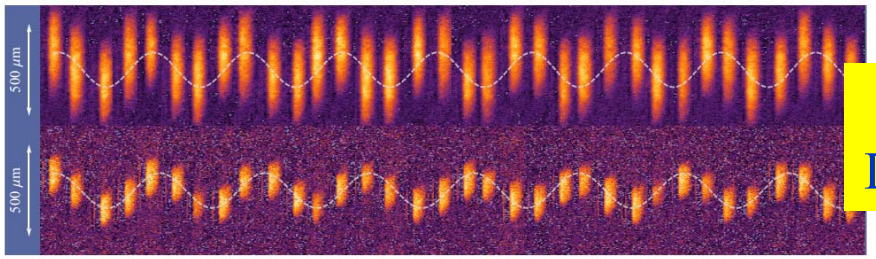
Critical velocity



Damping rate

I. Ferrier-Barbut, et.al. Science, **345**, 1035 (2014)

Experiment of the Bose-Fermi Superfluid Mixture



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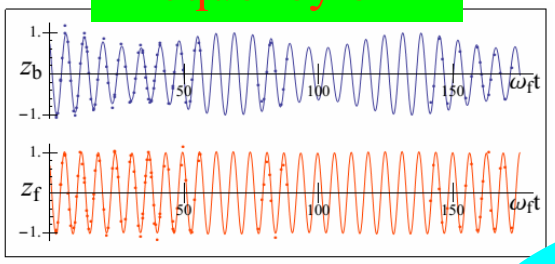
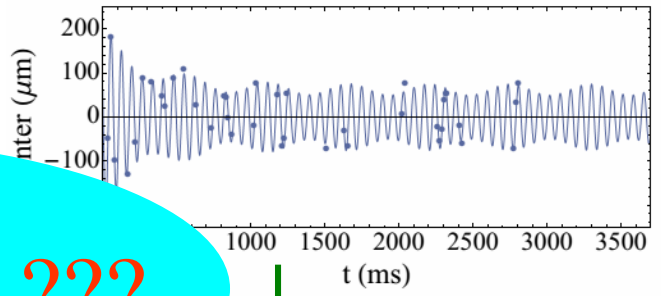
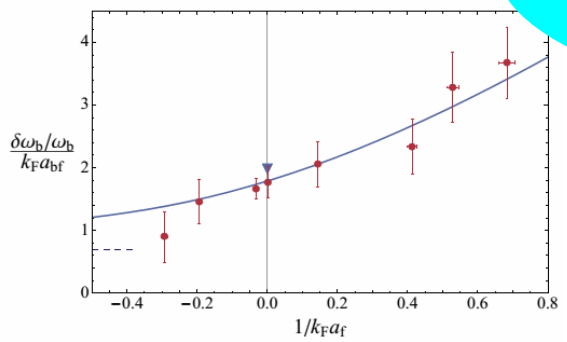


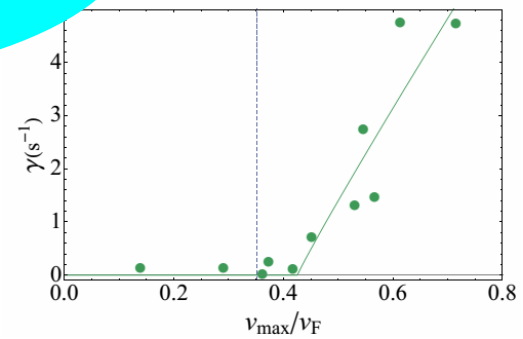
Damping of the oscillation



Why damping ???



Measure the EOS of Li6



Damping rate

I. Ferrier-Barbut, et.al. Science, **345**, 1035 (2014)

Landau-Beliaev damping in a single component BEC

$$H = \sum_{\boldsymbol{k}} \varepsilon_{\boldsymbol{k}} b_{\boldsymbol{k}}^{+} b_{\boldsymbol{k}} + \frac{1}{2}\frac{g}{V} \sum_{\boldsymbol{qpk}} b_{\boldsymbol{q}+\boldsymbol{k}}^{+} b_{\boldsymbol{p}-\boldsymbol{k}}^{+} b_{\boldsymbol{q}} b_{\boldsymbol{p}}$$

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$$b_0^{+} = b_0 = \sqrt{N_0}$$

$$b_{\boldsymbol{k}} = u_{\boldsymbol{k}} \alpha_{\boldsymbol{k}} - v_{\boldsymbol{k}} \alpha_{-\boldsymbol{k}}^{+}$$

Bogoliubov theory

$$H = \sum_{\boldsymbol{k}} E_{\boldsymbol{k}} \alpha_{\boldsymbol{k}}^{+} \alpha_{\boldsymbol{k}}$$

Quasi-particles

Landau-Beliaev damping in a single component BEC

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Quasi-particles

$$+ \frac{g\sqrt{N_0}}{V} \sum_{\boldsymbol{qk}} M_{\boldsymbol{qk}} \alpha_{\boldsymbol{q}+\boldsymbol{k}}^{+} \alpha_{\boldsymbol{q}} \alpha_{\boldsymbol{k}} + \cdots$$

$$+ \frac{g}{V} \sum_{\boldsymbol{qpk}} D_{\boldsymbol{qpk}} \alpha_{\boldsymbol{q}+\boldsymbol{k}}^{+} \alpha_{\boldsymbol{p}-\boldsymbol{k}}^{+} \alpha_{\boldsymbol{q}} \alpha_{\boldsymbol{p}} + \cdots$$

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$$+ \frac{g\sqrt{N_0}}{V} \sum_{\boldsymbol{qk}} M_{\boldsymbol{qk}} \alpha_{\boldsymbol{q}+\boldsymbol{k}}^{+} \alpha_{\boldsymbol{q}} \alpha_{\boldsymbol{k}} + \cdots$$

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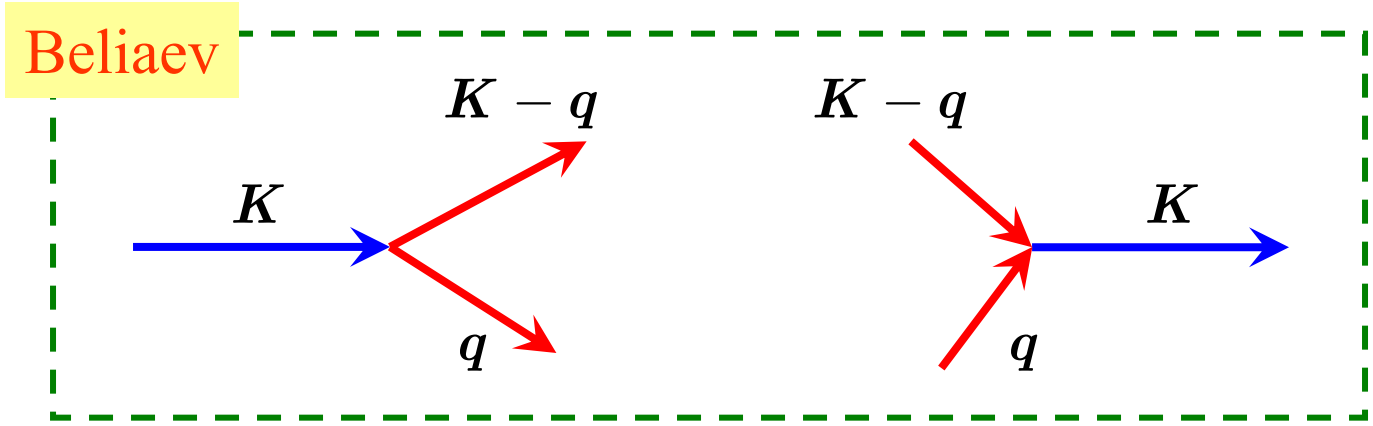
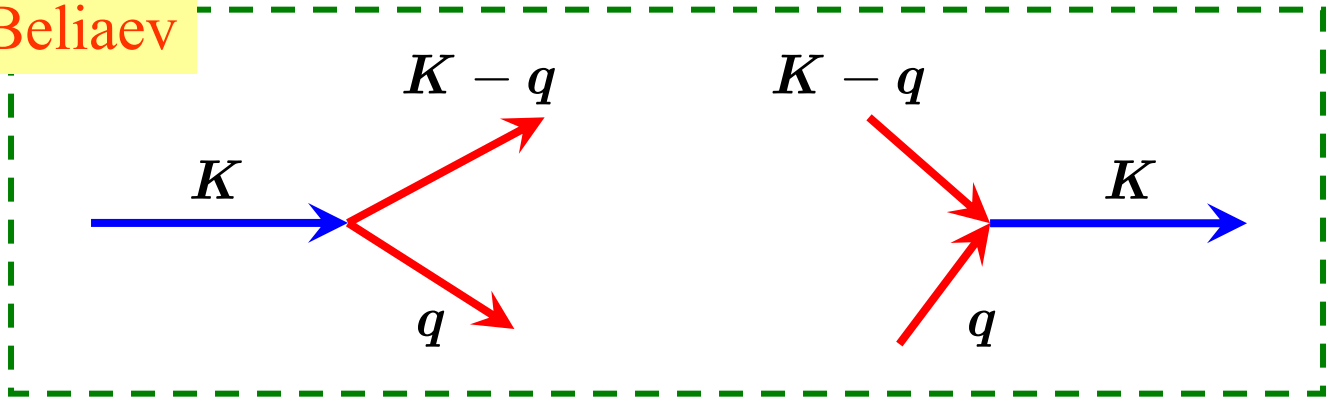
Interactions
between the quasi-particles induce the damping

Beliaev process VS Landau process



Beliaev process VS Landau process

Beliaev



$$\gamma_{\mathrm{B}} = \frac{\pi}{\hbar}\sum_{\boldsymbol{q}} \left| M_{\boldsymbol{q},\boldsymbol{K}} \right|^2 \left(1 + f^0_{\boldsymbol{q}} + f^0_{\boldsymbol{K}-\boldsymbol{q}} \right) \delta\left(E_{\boldsymbol{q}} + E_{\boldsymbol{K}-\boldsymbol{q}} - E_{\boldsymbol{K}} \right)$$

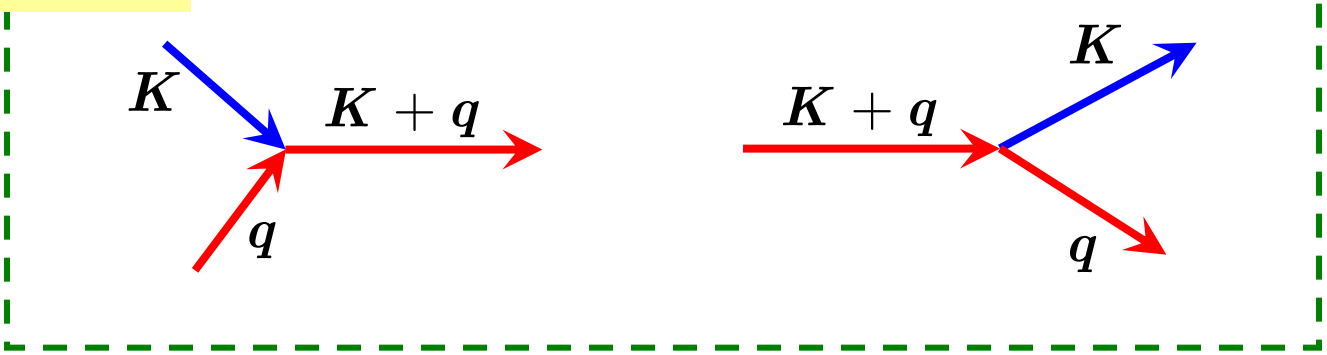
$T = 0$

$$f^0_{\boldsymbol{q}} = \frac{1}{e^{\beta E_{\boldsymbol{q}}} - 1}$$

$$\gamma_{\mathrm{B}} = \frac{\pi}{\hbar}\sum_{\boldsymbol{q}} \left| M_{\boldsymbol{q},\boldsymbol{K}} \right|^2 \delta\left(E_{\boldsymbol{q}} + E_{\boldsymbol{K}-\boldsymbol{q}} - E_{\boldsymbol{K}} \right)$$

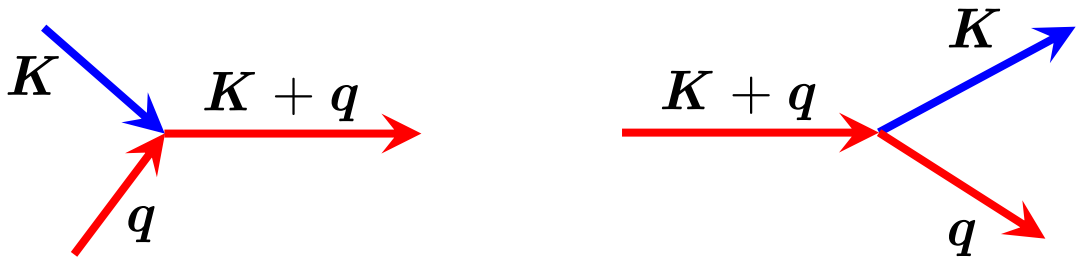
Beliaev process VS Landau process

Landau



Beliaev process VS Landau process

Landau



$$\gamma_{\mathrm{L}} = \frac{\pi}{\hbar}\sum_{\boldsymbol{q}} \left| M_{\boldsymbol{q},\boldsymbol{K}+\boldsymbol{q}} \right|^2 \left(f^0_{\boldsymbol{q}} - f^0_{\boldsymbol{K}+\boldsymbol{q}} \right) \delta\left(E_{\boldsymbol{q}} + E_{\boldsymbol{K}} - E_{\boldsymbol{K}+\boldsymbol{q}} \right)$$

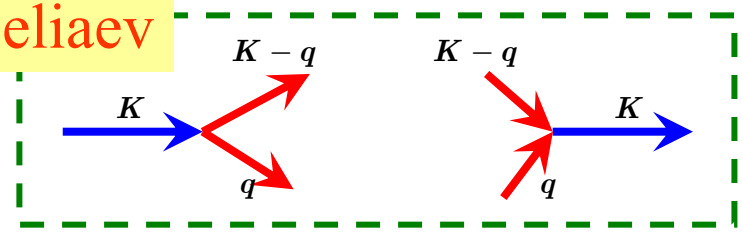
$T = 0$

$\gamma_{\mathrm{L}} = 0$

Landau-Beliaev damping in a single component BEC

Low T, Beliaev process dominate

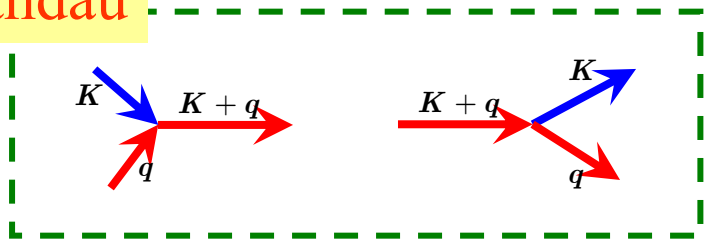
Beliaev



$$\gamma \approx \frac{3K^5}{640\pi\hbar^3 mn}, \quad T = 0$$

High T, Landau process dominate

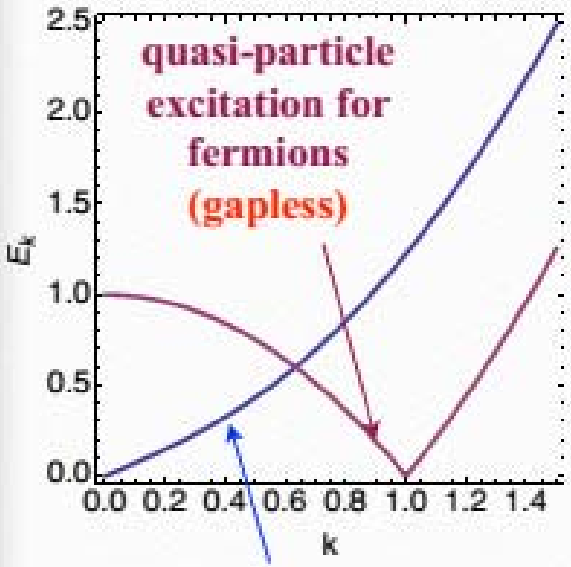
Landau



$$\gamma \approx \frac{3\pi}{8}\frac{k_{\mathrm{B}}Ta}{\hbar c}K, \quad k_{\mathrm{B}}T \gg gn$$

S.T. Beliaev, Soviet Phys. JETP, **34**, 299 (1958);
P.C. Hohenberg, P.C. Martin, Ann. Phys. (NY), **34**, 291 (1965).
W. Liu, PRL, **79**, 4056 (1997); S. Giorgini, PRA, **57**, 2949 (1998);
L.P. Pitaevskii, S. Stringari, Phys. Lett. A **235**, 398 (1997)

Quasi-particles in the Bose-Fermi Mixture

Bose superfluid and Fermi gas	Two Bose superfluids	Bose and Fermi superfluids
		

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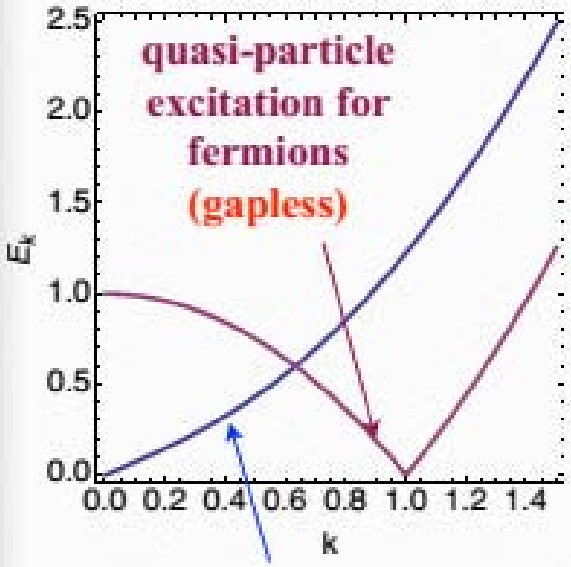	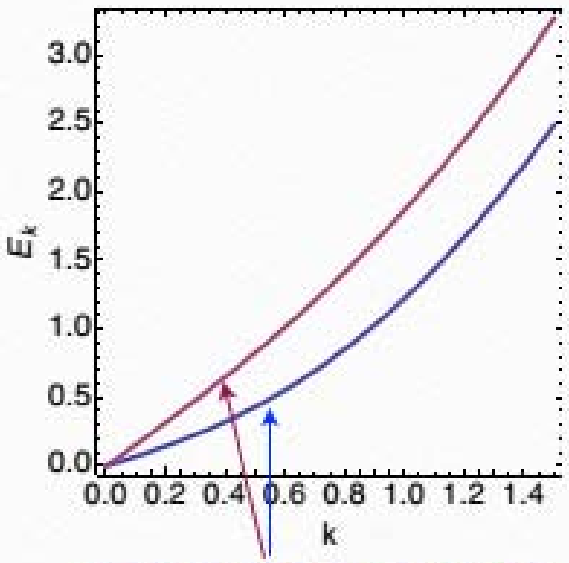	

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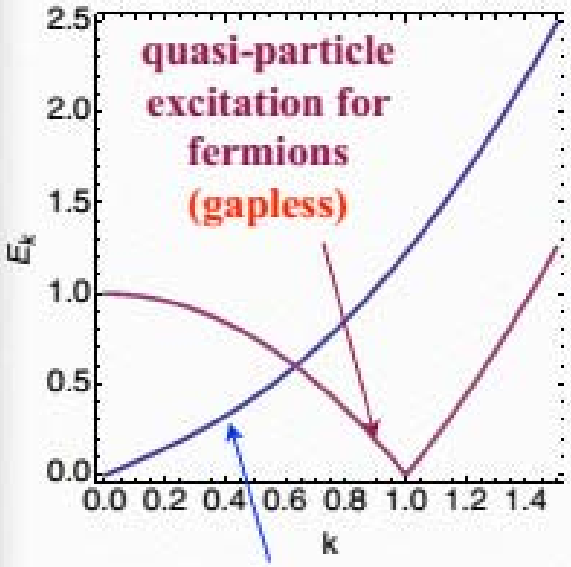
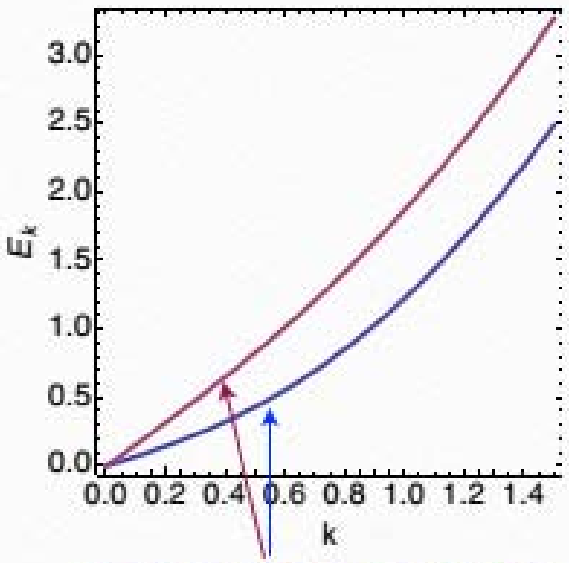
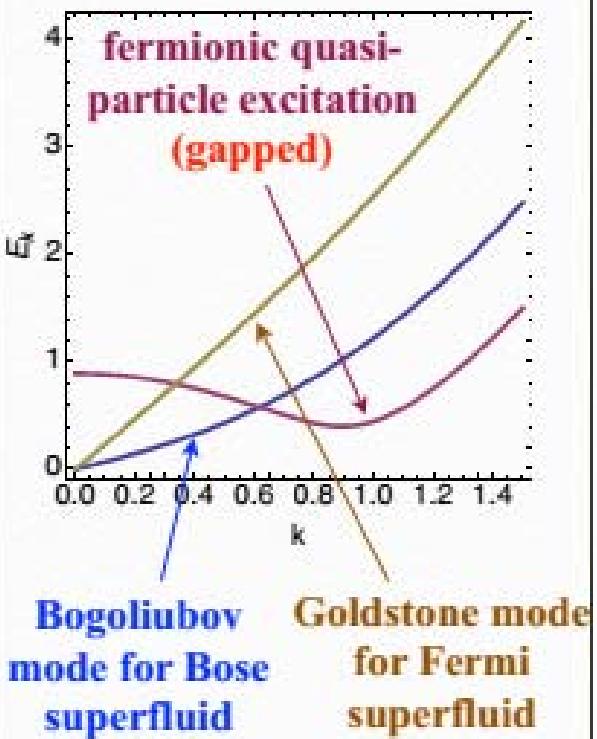
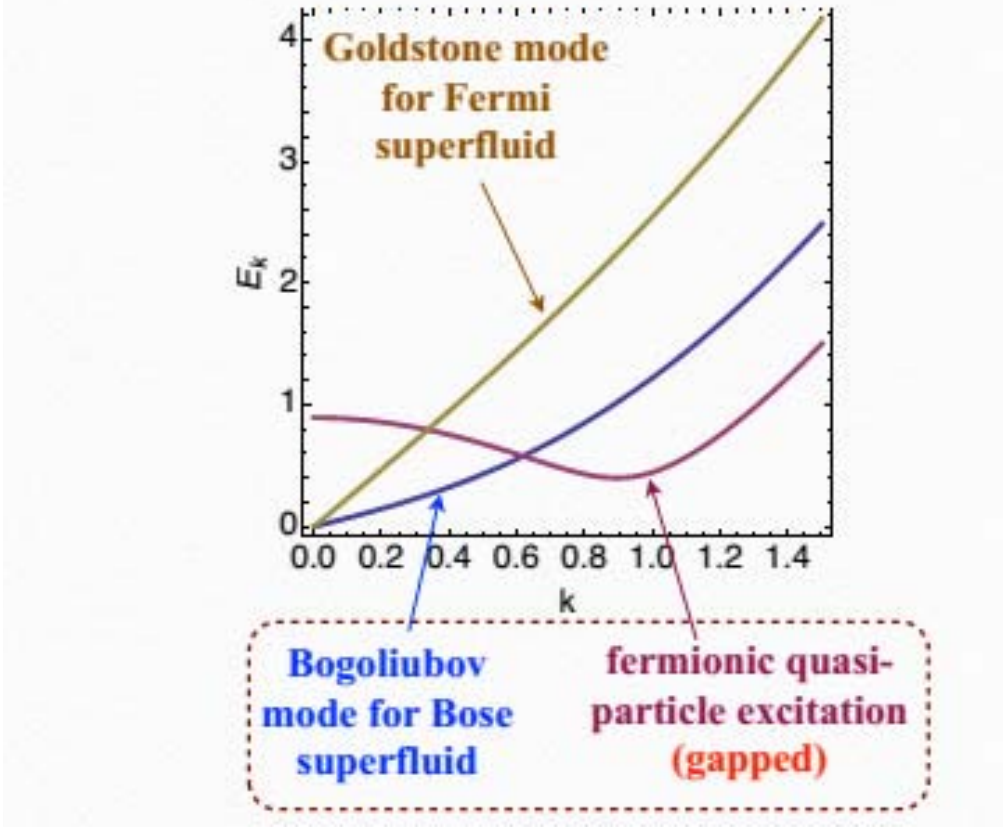
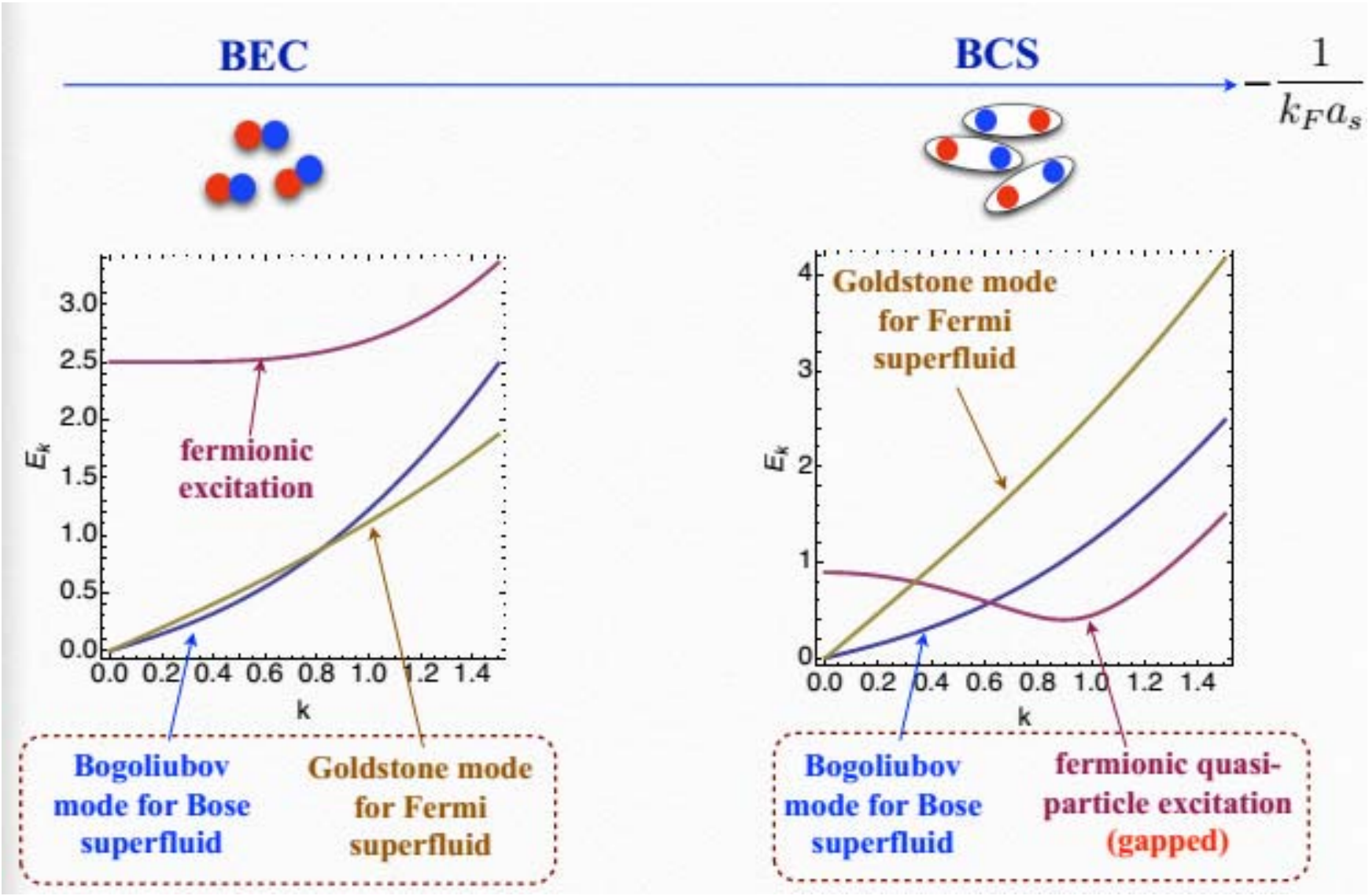
		

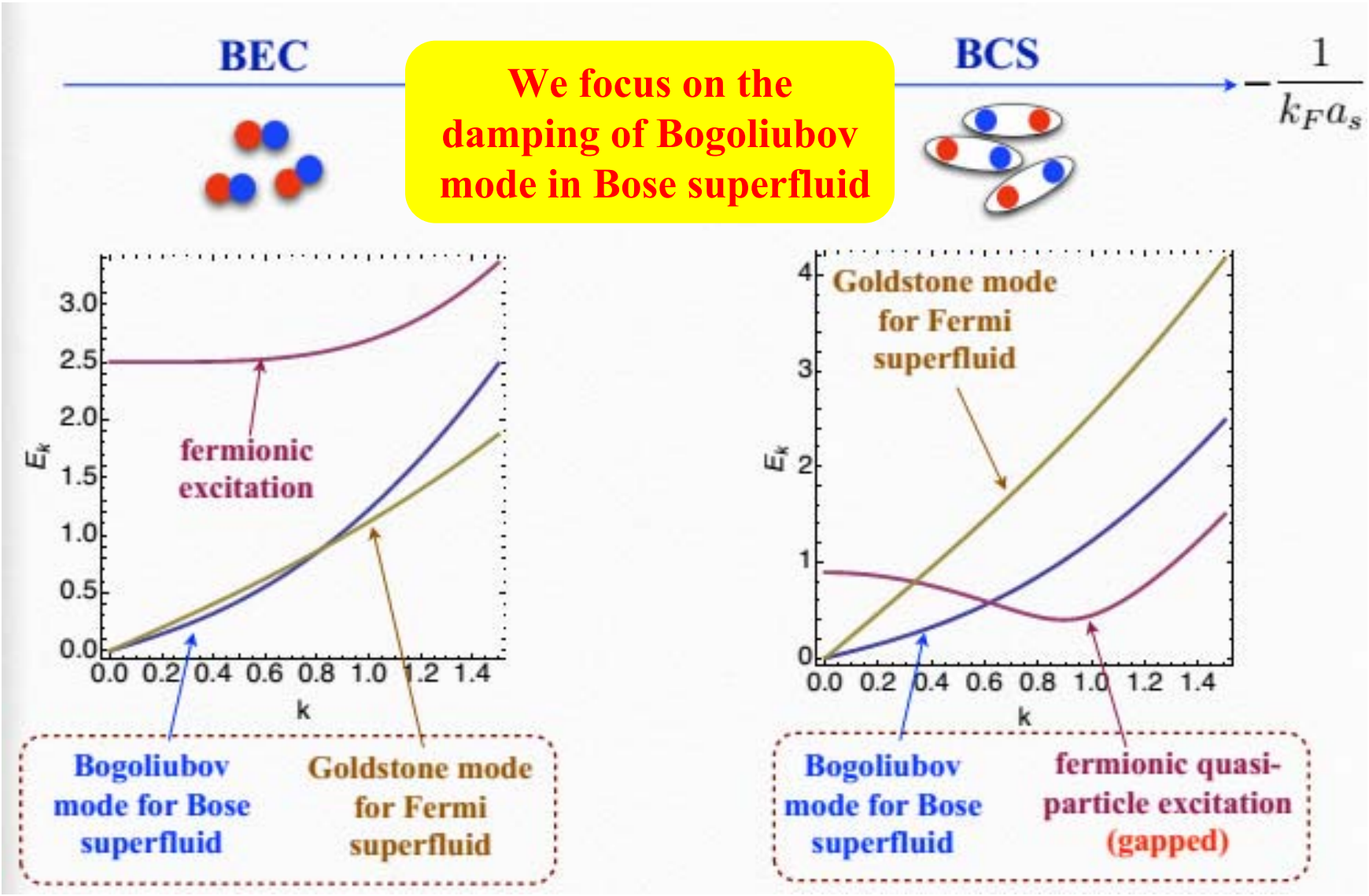
Quasi-particles in the Bose-Fermi Mixture



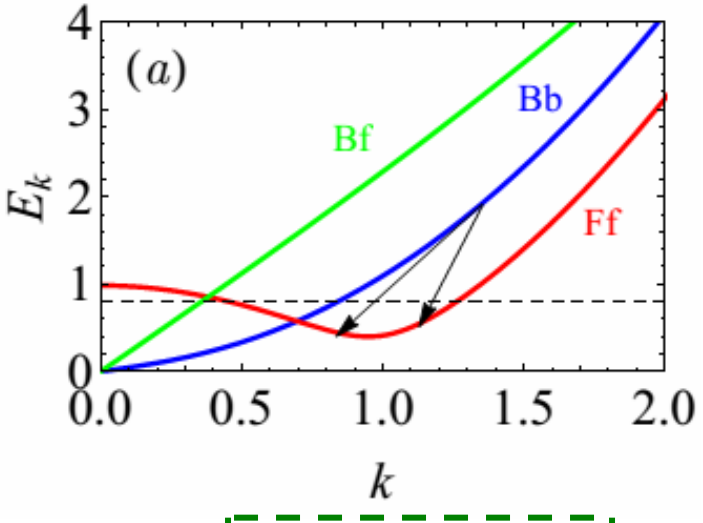
Quasi-particles in the Bose-Fermi Mixture

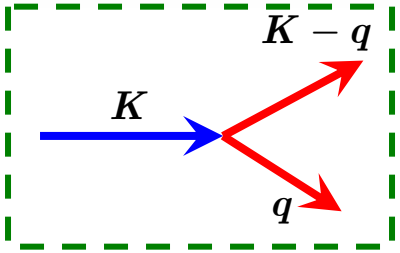


Quasi-particles in the Bose-Fermi Mixture



Beliaev damping in the Bose-Fermi superfluid mixture





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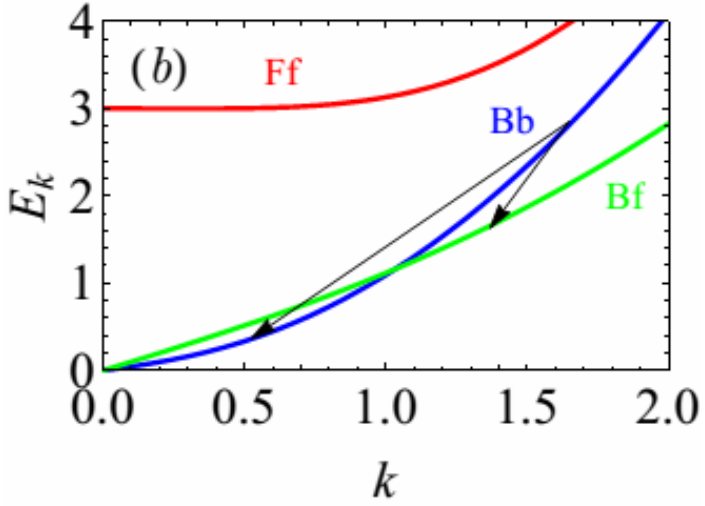
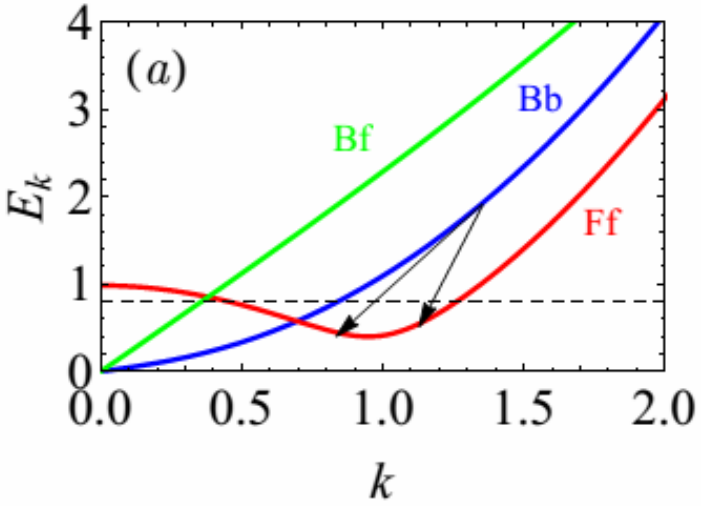
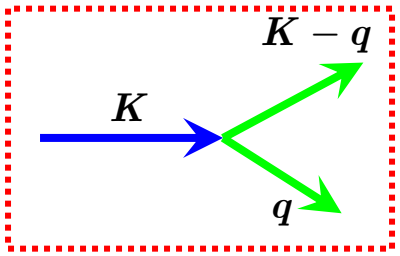
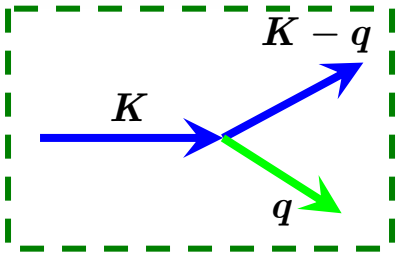
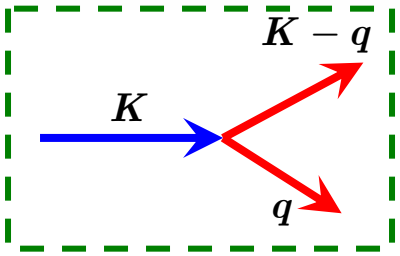








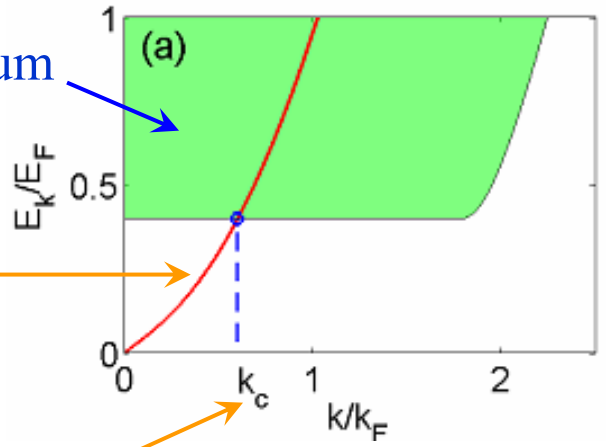


Beliaev damping in the Bose-Fermi superfluid mixture

Two-particle continuum

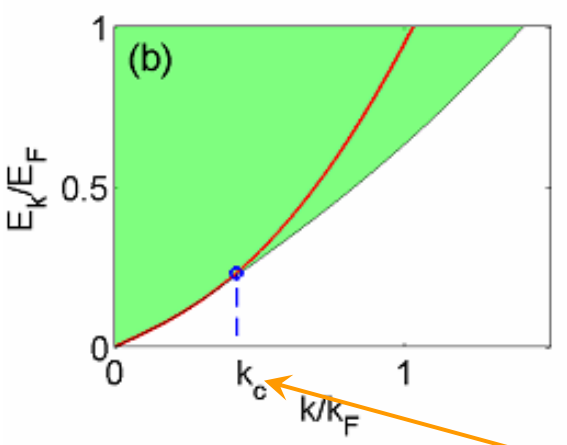
Bogoliubov mode

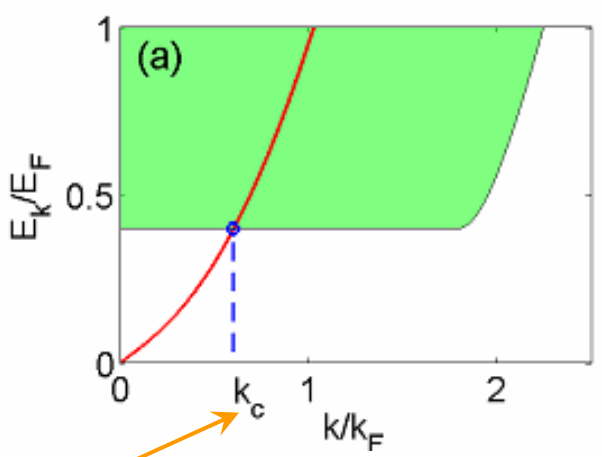
Critical momentum



$$E_{\mathrm{b}}(K_{\mathrm{c}}) = 2\Delta$$

Beliaev damping in the Bose-Fermi superfluid mixture





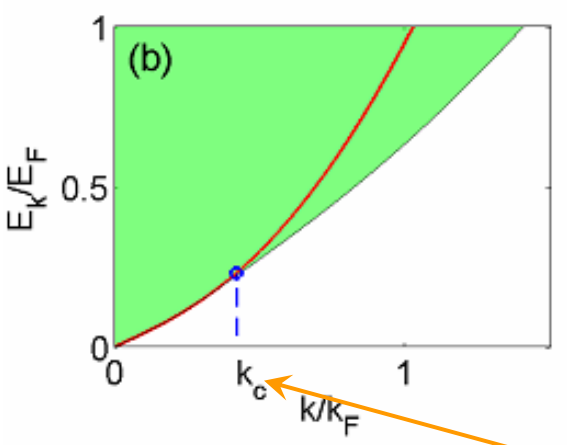
$$\left.\frac{\partial E_{\mathrm{b}}}{\partial k}\right|_{K_{\mathrm{c}}} = c_{\mathrm{m}}$$

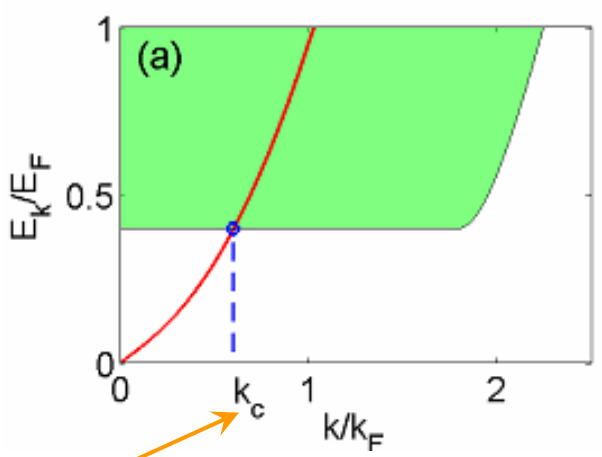
Critical momentum

$$E_{\mathrm{b}}(K_{\mathrm{c}}) = 2\Delta$$

Landau criteria for superfluid

Beliaev damping in the Bose-Fermi superfluid mixture

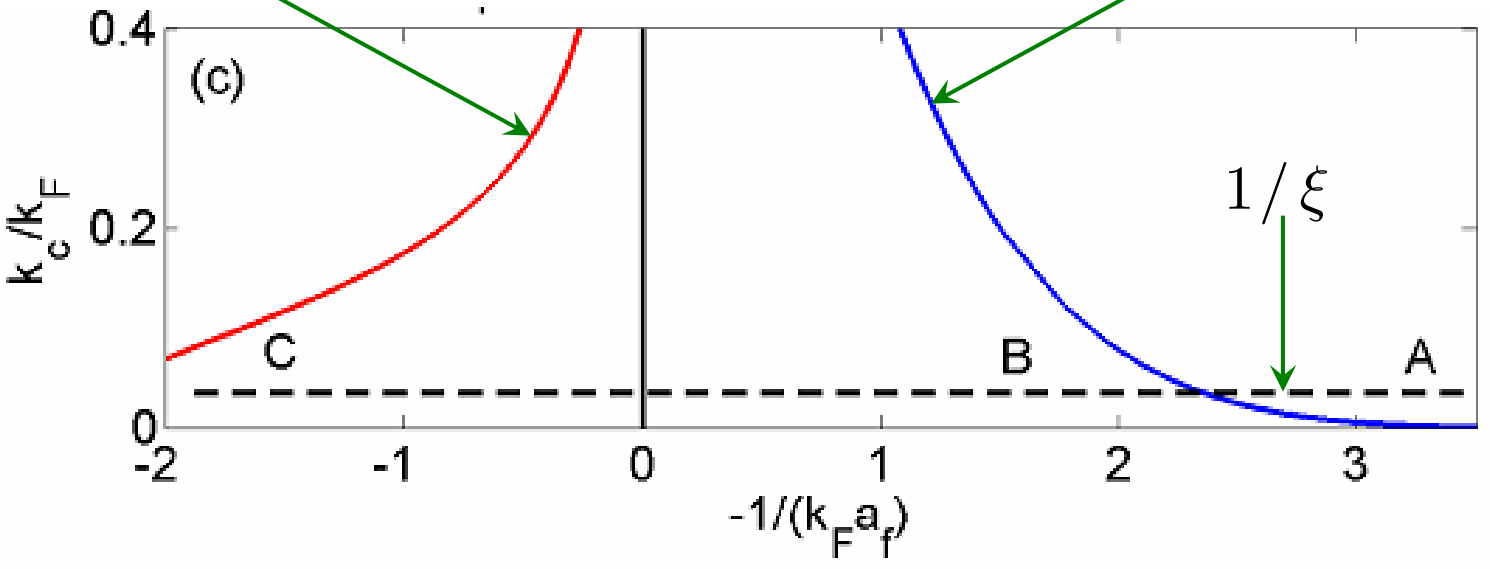




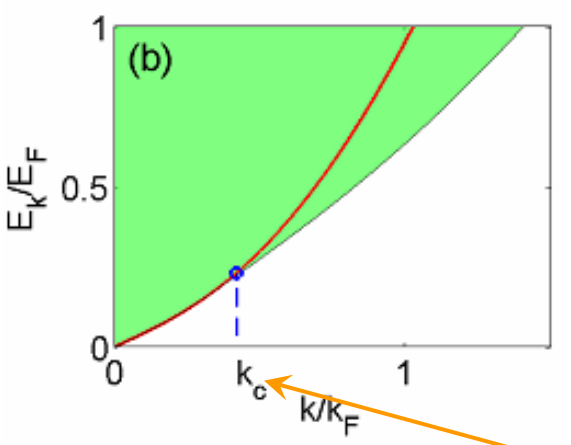
Critical momentum

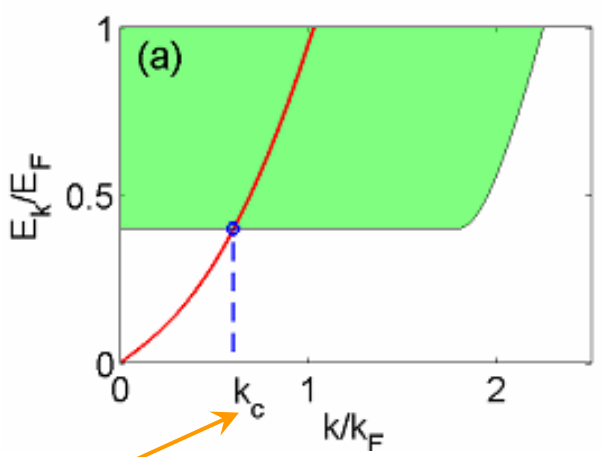
$$\left.\frac{\partial E_{\mathrm{b}}}{\partial k}\right|_{K_{\mathrm{c}}} = c_{\mathrm{m}}$$

$$E_{\mathrm{b}}(K_{\mathrm{c}}) = 2\Delta$$



Beliaev damping in the Bose-Fermi superfluid mixture





Critical momentum

$$\left.\frac{\partial E_{\rm b}}{\partial k}\right|_{K_{\rm c}} = c_{\rm m}$$

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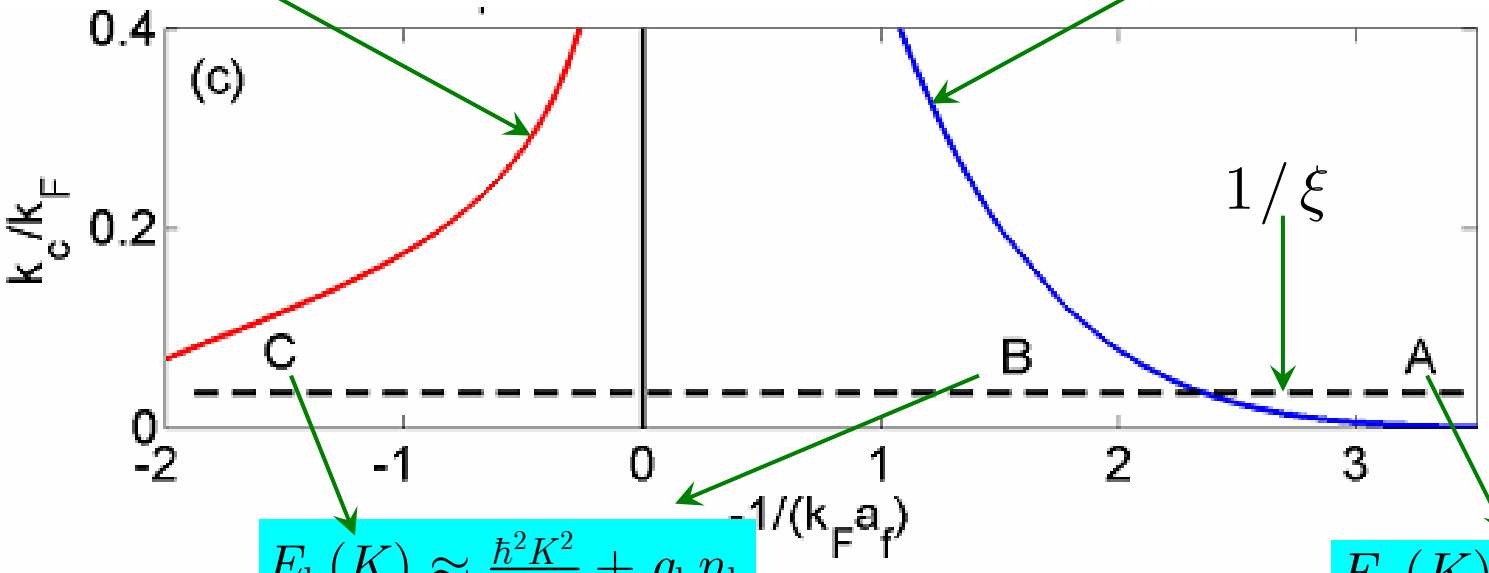


$$E_{\rm b}(K) \approx \frac{\hbar^2 K^2}{2m_{\rm b}} + g_{\rm b} n_{\rm b}$$

$$E_{\rm b}(K) \approx \hbar c_{\rm b} K$$

The Hamiltonian of the Superfluid Mixture

$$H_{\rm b} = \sum_{\boldsymbol{k}} \varepsilon^{\rm b}_{\boldsymbol{k}} b^{+}_{\boldsymbol{k}} b_{\boldsymbol{k}} + \frac{1}{2}\frac{g_{\rm b}}{V}\sum_{\boldsymbol{qpk}} b^{+}_{\boldsymbol{q}+\boldsymbol{k}} b^{+}_{\boldsymbol{p}-\boldsymbol{k}} b_{\boldsymbol{q}} b_{\boldsymbol{p}}$$

$$H_{\rm f} = \sum_{\boldsymbol{k},\sigma} \varepsilon^{\rm f}_{\boldsymbol{k}} c^{+}_{\boldsymbol{k},\sigma} c_{\boldsymbol{k},\sigma} + \frac{g_{\rm f}}{V}\sum_{\boldsymbol{qpk}} c^{+}_{\boldsymbol{q}+\boldsymbol{k},\uparrow} c^{+}_{\boldsymbol{p}-\boldsymbol{k},\downarrow} c_{\boldsymbol{q},\downarrow} c_{\boldsymbol{p},\uparrow}$$

$$H_{\rm bf} = \frac{g_{\rm bf}}{V}\sum_{\boldsymbol{qpk},\sigma} c^{+}_{\boldsymbol{q}+\boldsymbol{k},\sigma} c_{\boldsymbol{q},\sigma} b^{+}_{\boldsymbol{p}-\boldsymbol{k}} b_{\boldsymbol{p}}$$

BEC side

$$H = \sum_{\boldsymbol{k}} E_{\rm b}(\boldsymbol{k})\alpha^{+}_{\boldsymbol{k}}\alpha_{\boldsymbol{k}} + \sum_{\boldsymbol{k}} E_{\rm m}(\boldsymbol{k})\chi^{+}_{\boldsymbol{k}}\chi_{\boldsymbol{k}} + H_3^{\rm bm} + \cdots$$

BCS side

$$H = \sum_{\boldsymbol{k}} E_{\rm b}(\boldsymbol{k})\alpha^{+}_{\boldsymbol{k}}\alpha_{\boldsymbol{k}} + \sum_{\boldsymbol{k}} E_{\rm f}(\boldsymbol{k})\left(\beta^{+}_{\boldsymbol{k}}\beta_{\boldsymbol{k}} + \gamma^{+}_{\boldsymbol{k}}\gamma_{\boldsymbol{k}}\right) + H_3^{\rm bf} + \cdots$$

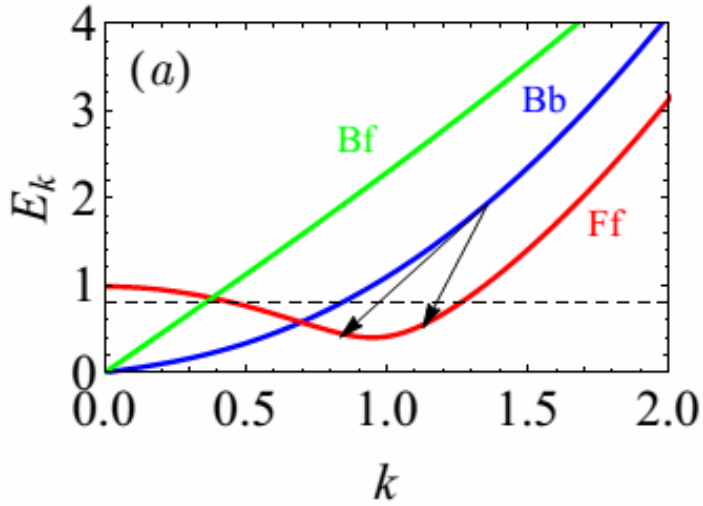
$$E_{\rm b}(\boldsymbol{k}) = \sqrt{\varepsilon^{\rm b}_{\boldsymbol{k}}\left(\varepsilon^{\rm b}_{\boldsymbol{k}} + 2g_{\rm b}n_{\rm b}\right)}$$

$$E_{\rm b}(\boldsymbol{k}) = \sqrt{\left(\varepsilon^{\rm f}_{\boldsymbol{k}} - \mu_{\rm f}\right)^2 + \Delta^2}$$

$$E_{\rm m}(\boldsymbol{k}) = \sqrt{\varepsilon^{\rm m}_{\boldsymbol{k}}\left(\varepsilon^{\rm m}_{\boldsymbol{k}} + 2g_{\rm m}n_{\rm m}\right)}$$

Beliaev damping in BCS side

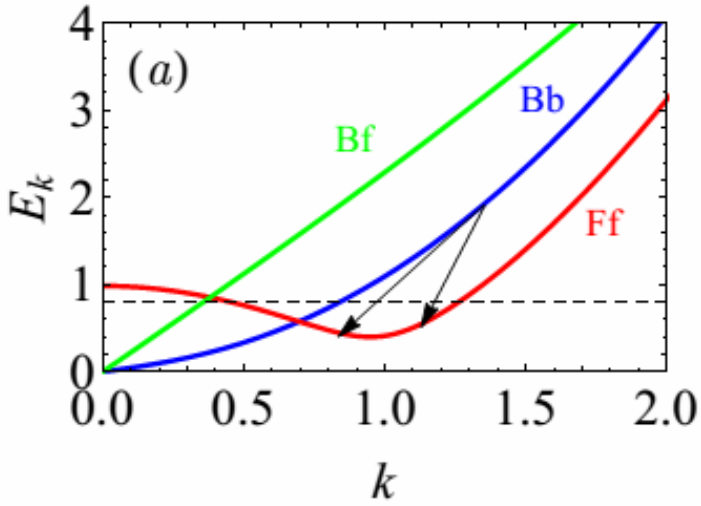
$$H = \sum_{\boldsymbol{k}} E_{\mathrm{b}}(\boldsymbol{k})\alpha_{\boldsymbol{k}}^{+}\alpha_{\boldsymbol{k}} + \sum_{\boldsymbol{k}} E_{\mathrm{f}}(\boldsymbol{k})\left(\beta_{\boldsymbol{k}}^{+}\beta_{\boldsymbol{k}} + \gamma_{\boldsymbol{k}}^{+}\gamma_{\boldsymbol{k}}\right) + H_3^{\mathrm{bf}} + \cdots$$



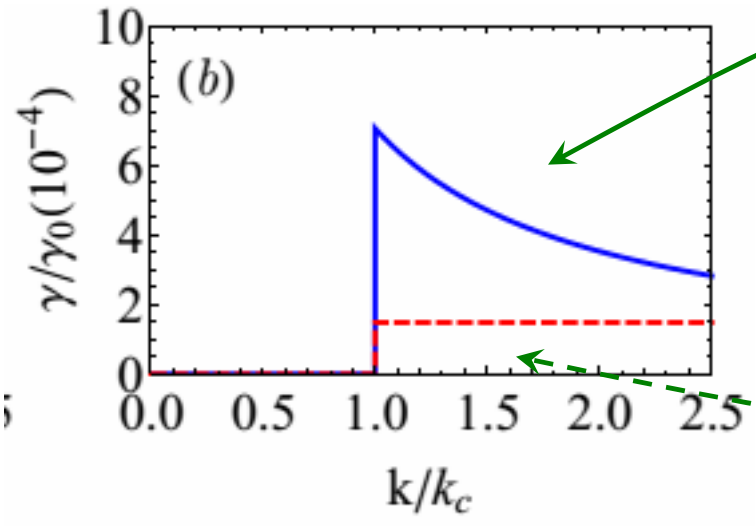
$$H_3^{\mathrm{bf}} = \frac{g_{\mathrm{bf}}\sqrt{N_{\mathrm{b}}}}{V}\sum_{\boldsymbol{qk}}\left(u_{\boldsymbol{k}}^{\mathrm{b}} - v_{\boldsymbol{k}}^{\mathrm{b}}\right)\left(u_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{f}}v_{\boldsymbol{q}}^{\mathrm{f}} + v_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{f}}u_{\boldsymbol{q}}^{\mathrm{f}}\right)\beta_{\boldsymbol{k}-\boldsymbol{q}}^{+}\gamma_{\boldsymbol{q}}^{+}\alpha_{\boldsymbol{k}} + \mathrm{h.c.}$$

Beliaev damping in BCS side

$$H = \sum_{\boldsymbol{k}} E_{\mathrm{b}}(\boldsymbol{k})\alpha_{\boldsymbol{k}}^{+}\alpha_{\boldsymbol{k}} + \sum_{\boldsymbol{k}} E_{\mathrm{f}}(\boldsymbol{k})\left(\beta_{\boldsymbol{k}}^{+}\beta_{\boldsymbol{k}} + \gamma_{\boldsymbol{k}}^{+}\gamma_{\boldsymbol{k}}\right) + H_3^{\mathrm{bf}} + \cdots$$



$$H_3^{\mathrm{bf}} = \frac{g_{\mathrm{bf}}\sqrt{N_{\mathrm{b}}}}{V}\sum_{\boldsymbol{qk}}\left(u_{\boldsymbol{k}}^{\mathrm{b}} - v_{\boldsymbol{k}}^{\mathrm{b}}\right)\left(u_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{f}}v_{\boldsymbol{q}}^{\mathrm{f}} + v_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{f}}u_{\boldsymbol{q}}^{\mathrm{f}}\right)\beta_{\boldsymbol{k}-\boldsymbol{q}}^{+}\gamma_{\boldsymbol{q}}^{+}\alpha_{\boldsymbol{k}} + \mathrm{h.c.}$$

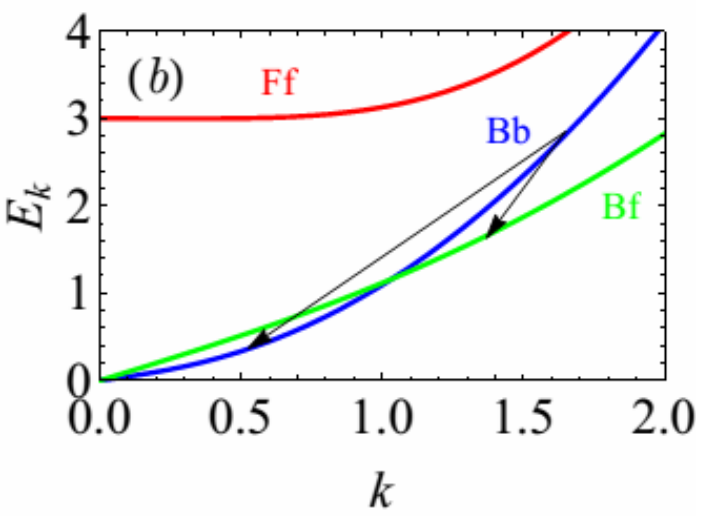


$$\gamma(\boldsymbol{K}) = \begin{cases} \dfrac{g_{\mathrm{bf}}^2 n_{\mathrm{b}}\Delta m_{\mathrm{f}}^2}{\hbar^4 K}\Theta\left(E_{\boldsymbol{K}}^{\mathrm{b}} - 2\Delta\right), & \text{regime B} \\ \dfrac{g_{\mathrm{bf}}^2 c_{\mathrm{b}}\Delta m_{\mathrm{f}}^2}{2\hbar^4 g_{\mathrm{bb}}}\Theta\left(E_{\boldsymbol{K}}^{\mathrm{b}} - 2\Delta\right), & \text{regime A} \end{cases}$$

Wei Zheng and Hui Zhai, PRL **113**, 265304 (2014)

Beliaev damping in BEC side

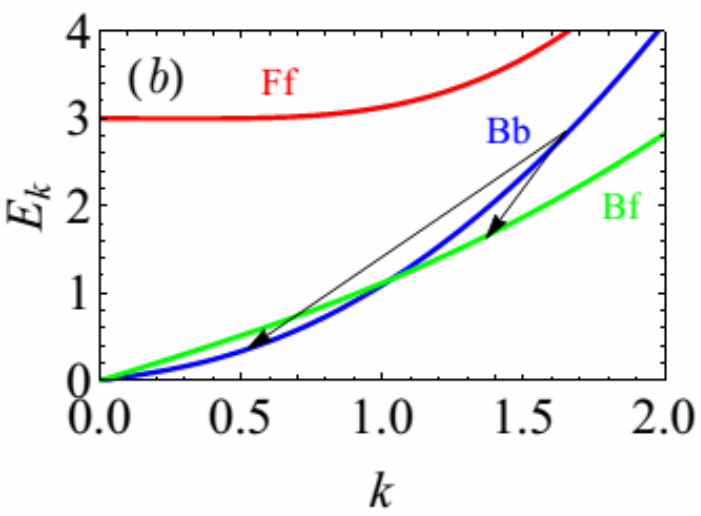
$$H = \sum_{\boldsymbol{k}} E_{\mathrm{b}}(\boldsymbol{k})\alpha_{\boldsymbol{k}}^{+}\alpha_{\boldsymbol{k}} + \sum_{\boldsymbol{k}} E_{\mathrm{m}}(\boldsymbol{k})\chi_{\boldsymbol{k}}^{+}\chi_{\boldsymbol{k}} + H_3^{\mathrm{bm}} + \cdots$$



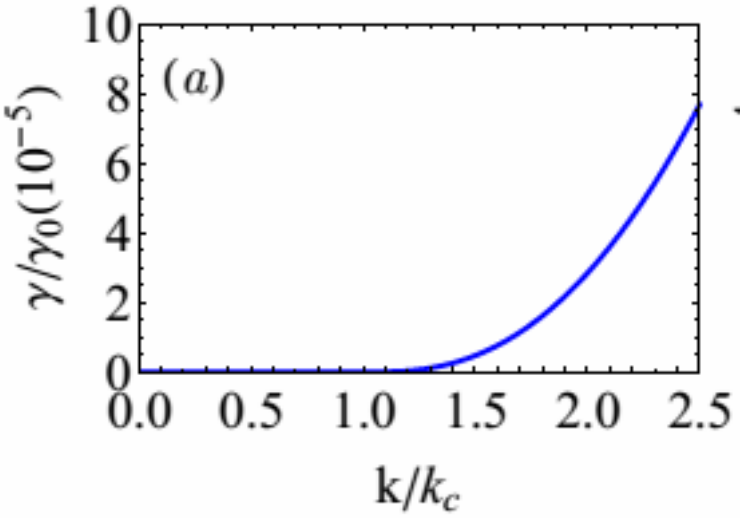
$$H_3^{\mathrm{bm}} = \frac{g_{\mathrm{mb}}\sqrt{N_{\mathrm{m}}}}{V}\sum_{\boldsymbol{qk}}\left(u_{\boldsymbol{q}}^{\mathrm{m}} - v_{\boldsymbol{q}}^{\mathrm{m}}\right)\left(u_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{b}}u_{\boldsymbol{k}}^{\mathrm{b}} + v_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{b}}v_{\boldsymbol{k}}^{\mathrm{b}}\right)\chi_{\boldsymbol{q}}^{+}\alpha_{\boldsymbol{k}-\boldsymbol{q}}^{+}\alpha_{\boldsymbol{k}} + \mathrm{h.c.}$$

Beliaev damping in BEC side

$$H = \sum_{\boldsymbol{k}} E_{\mathrm{b}}(\boldsymbol{k})\alpha_{\boldsymbol{k}}^{+}\alpha_{\boldsymbol{k}} + \sum_{\boldsymbol{k}} E_{\mathrm{m}}(\boldsymbol{k})\chi_{\boldsymbol{k}}^{+}\chi_{\boldsymbol{k}} + H_3^{\mathrm{bm}} + \cdots$$



$$H_3^{\mathrm{bm}} = \frac{g_{\mathrm{mb}}\sqrt{N_{\mathrm{m}}}}{V}\sum_{\boldsymbol{qk}}\left(u_{\boldsymbol{q}}^{\mathrm{m}} - v_{\boldsymbol{q}}^{\mathrm{m}}\right)\left(u_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{b}}u_{\boldsymbol{k}}^{\mathrm{b}} + v_{\boldsymbol{k}-\boldsymbol{q}}^{\mathrm{b}}v_{\boldsymbol{k}}^{\mathrm{b}}\right)\chi_{\boldsymbol{q}}^{+}\alpha_{\boldsymbol{k}-\boldsymbol{q}}^{+}\alpha_{\boldsymbol{k}} + \mathrm{h.c.}$$

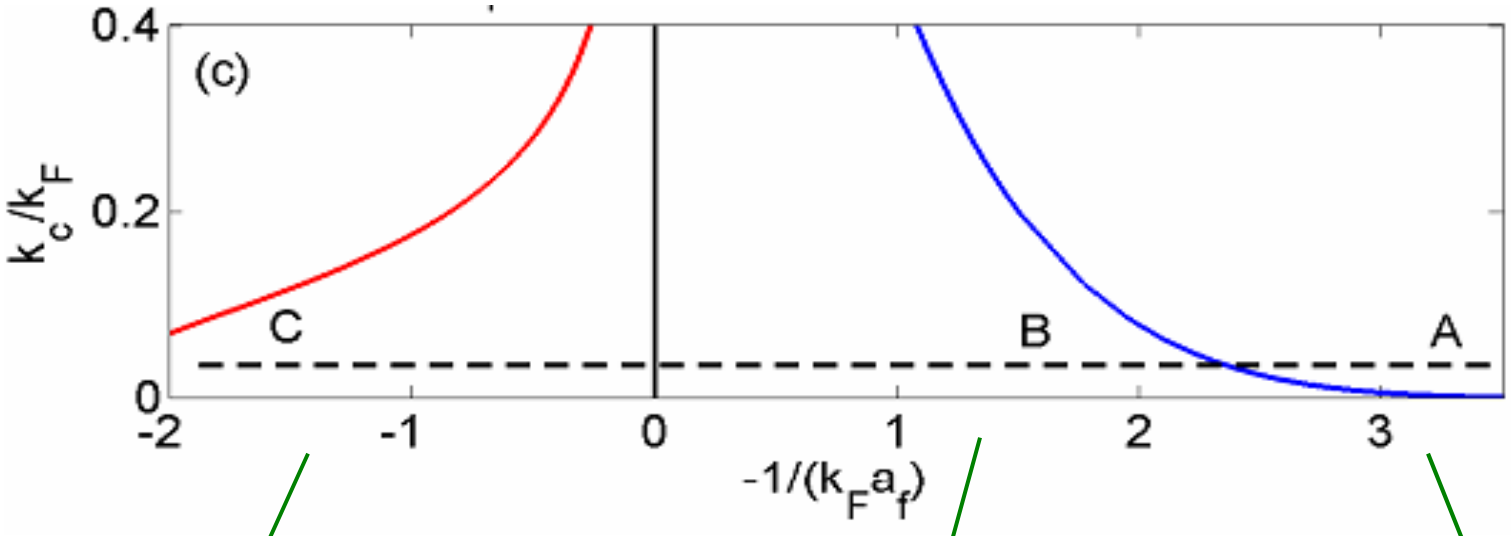


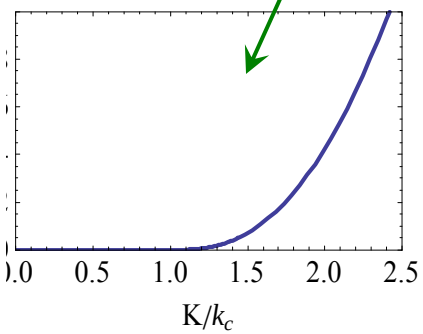
$$\gamma(\boldsymbol{K}) = \frac{2g_{\mathrm{mb}}^2 m_{\mathrm{b}} c_{\mathrm{m}}}{3\pi\hbar^4 g_{\mathrm{m}} K}\left(K - m_{\mathrm{b}}c_{\mathrm{m}}\right)^3\Theta\left(K - m_{\mathrm{b}}c_{\mathrm{m}}\right)$$

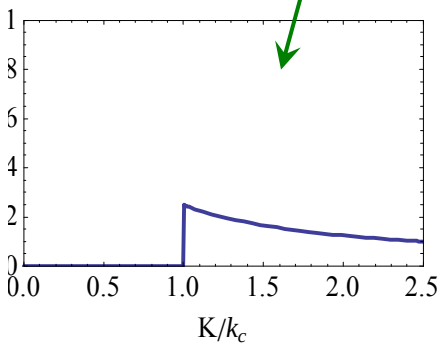
$$\approx C(\delta K)^3\,\Theta(K - K_{\mathrm{c}}), \quad \text{regime C}$$

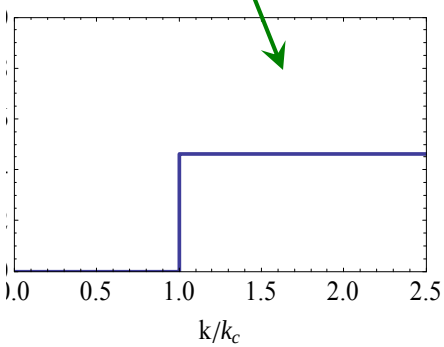
Wei Zheng and Hui Zhai, PRL **113**, 265304 (2014)

Beliaev damping through the crossover









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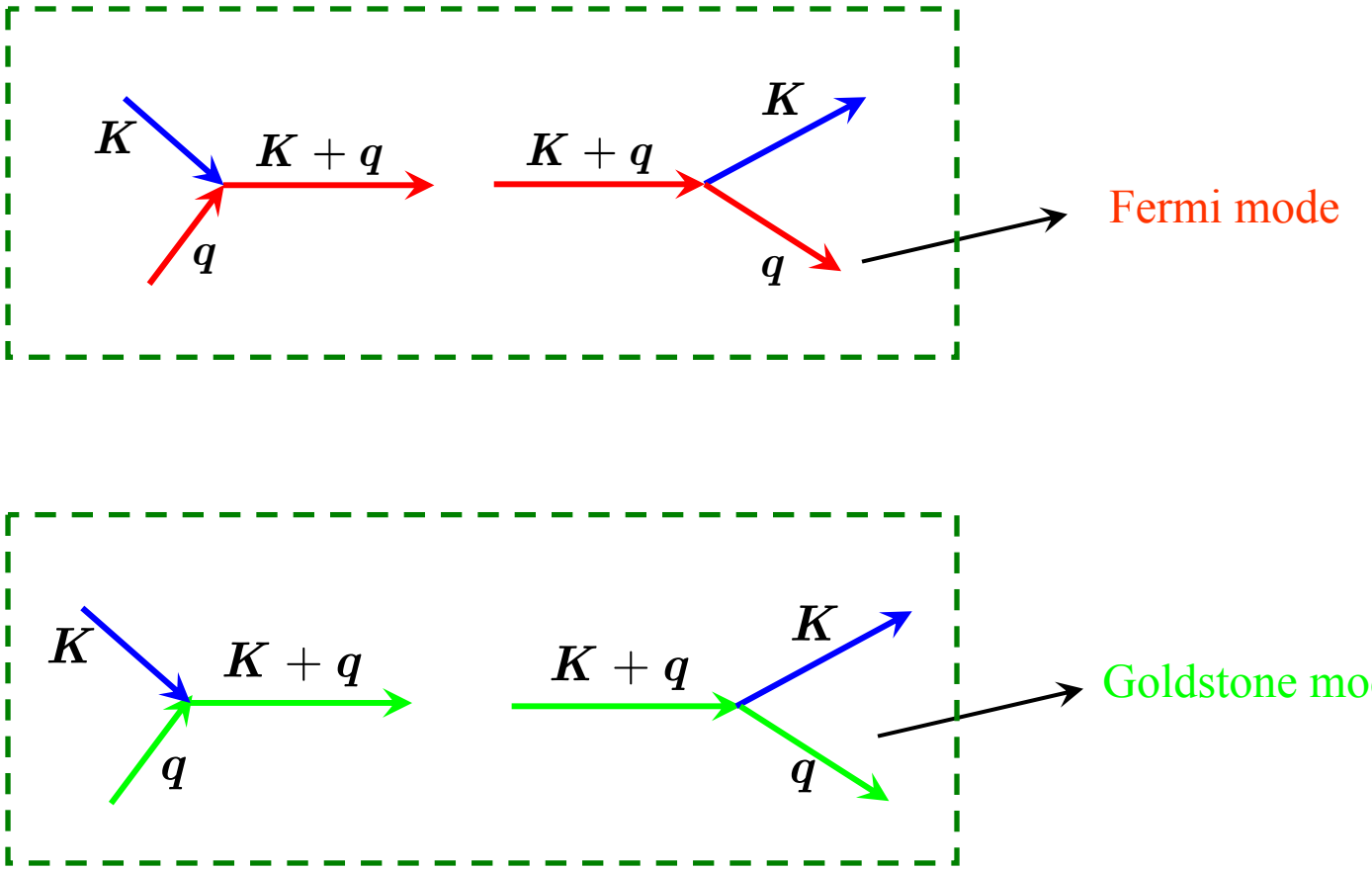
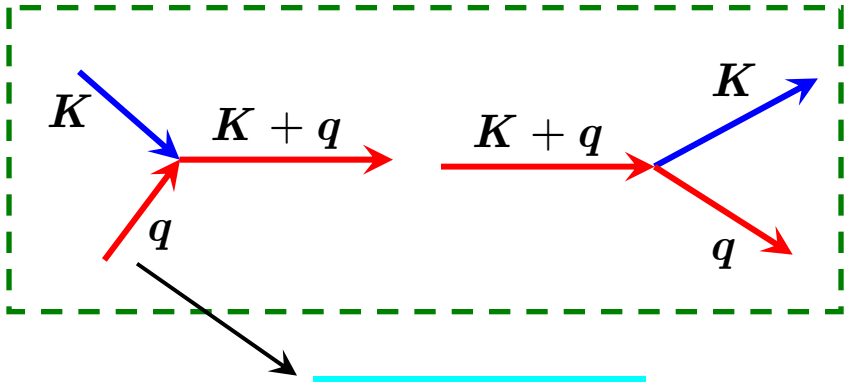
Landau damping in the mixture



No critical velocity

Landau damping in the mixture



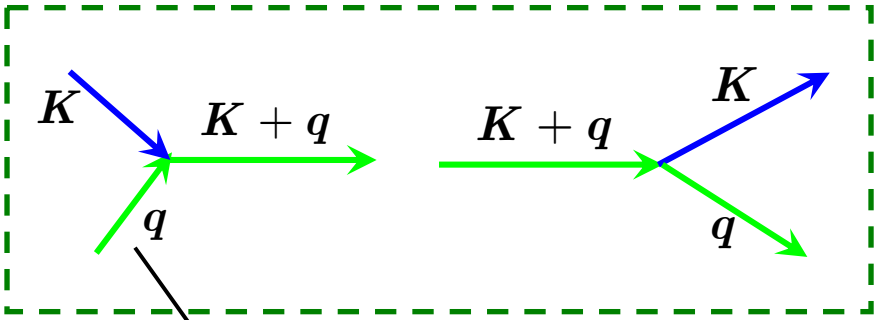
Fermi gap : Δ

When $k_{\mathrm{B}}T < \Delta$

damping is suppressed!

$$f_{\boldsymbol{q}}^{\mathrm{f}} = \frac{1}{e^{\beta E_{\mathrm{f}}(\boldsymbol{q})} + 1}$$

Landau damping in the mixture

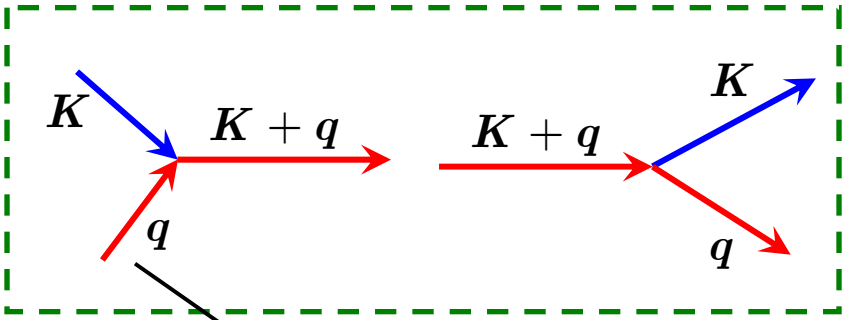


restriction: $q > q_0$

When $k_{\rm B}T < \hbar c_{\rm m} q_0$

damping is suppressed!

$$f_{\boldsymbol{q}}^{\rm b} = \frac{1}{e^{\beta E_{\rm m}(\boldsymbol{q})} - 1}$$



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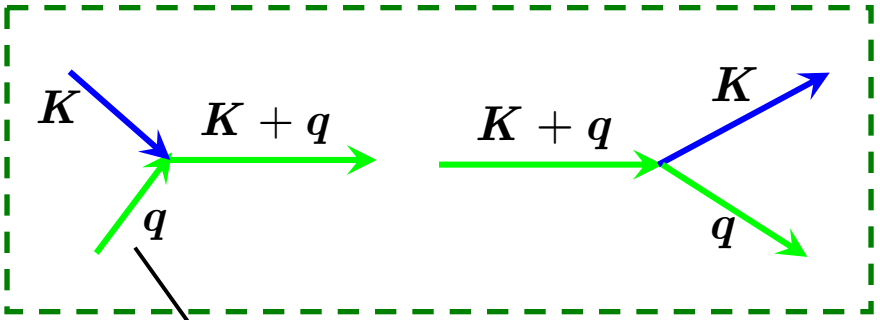

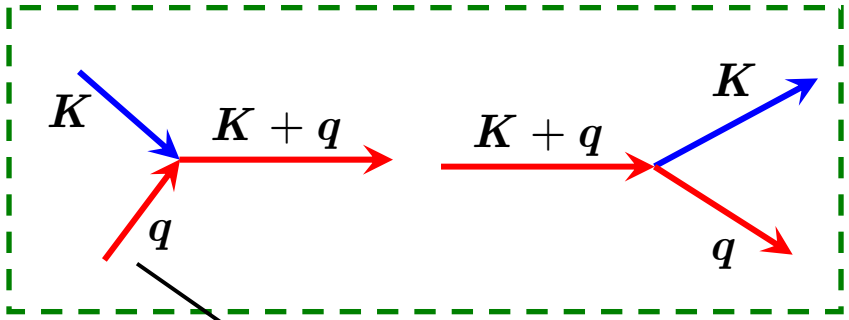

restriction: $q > q_0$

When $k_{\mathrm{B}}T < \hbar c_{\mathrm{m}} q_0$

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$$f_{\boldsymbol{q}}^{\mathrm{b}} = \frac{1}{e^{\beta E_{\mathrm{m}}(\boldsymbol{q})} - 1}$$

Dominate in BEC, Suppressed in BCS

Fermi gap : Δ

When $k_{\mathrm{B}}T < \Delta$

damping is suppressed!

$$f_{\boldsymbol{q}}^{\mathrm{f}} = \frac{1}{e^{\beta E_{\mathrm{f}}(\boldsymbol{q})} + 1}$$

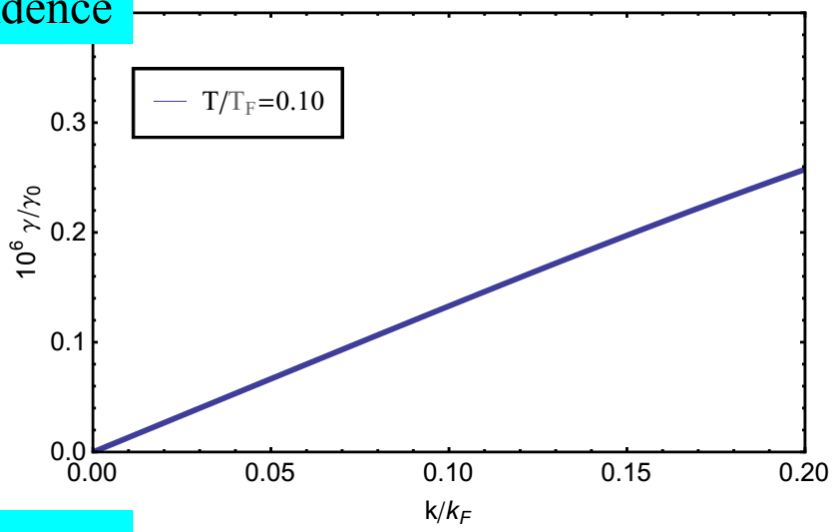
Dominate in BCS, Suppressed in BEC

Landau damping in the mixture

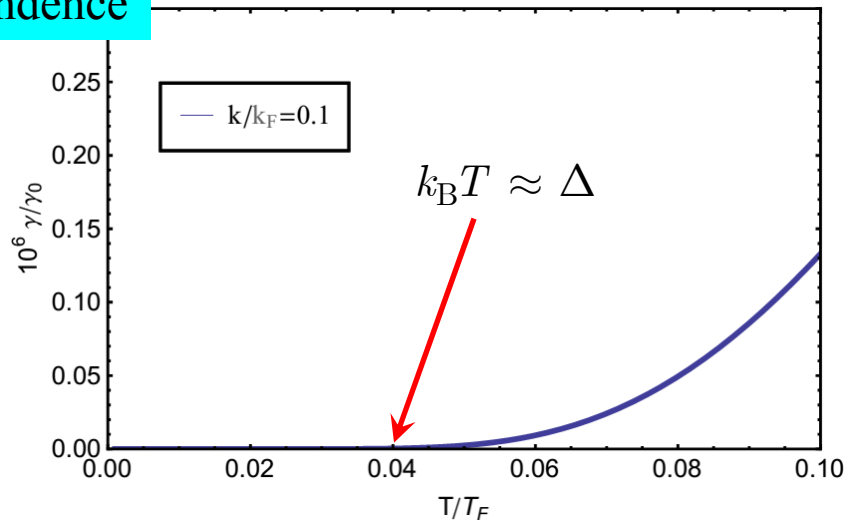
BEC side

BCS side

K-dependence



T-dependence



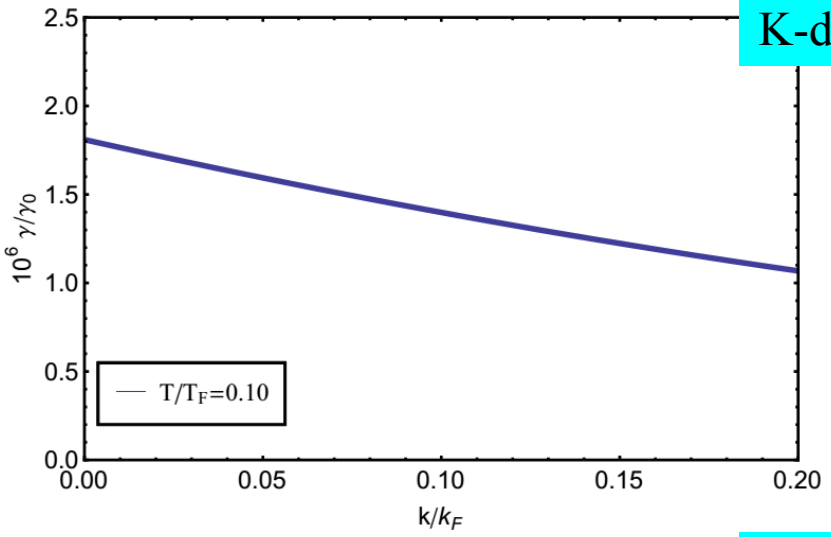
Huitao Shen and Wei Zheng, arXiv: 1502.02116

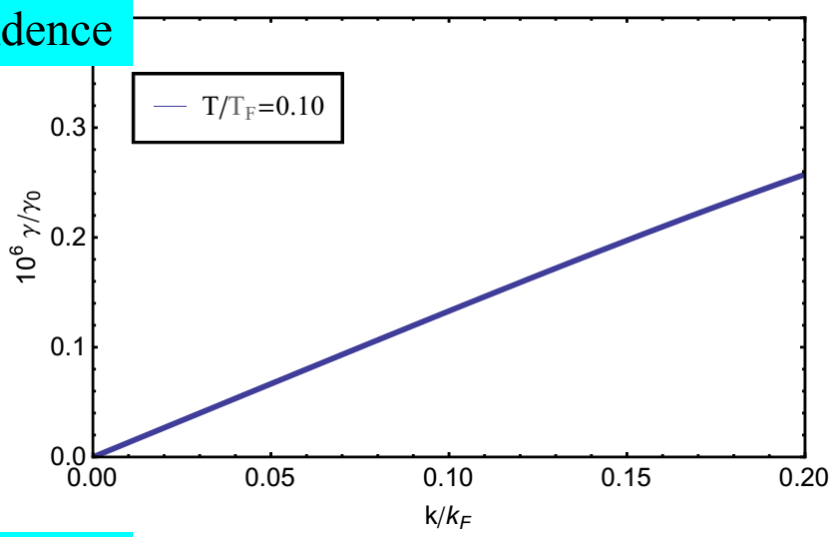
Landau damping in the mixture

BEC side

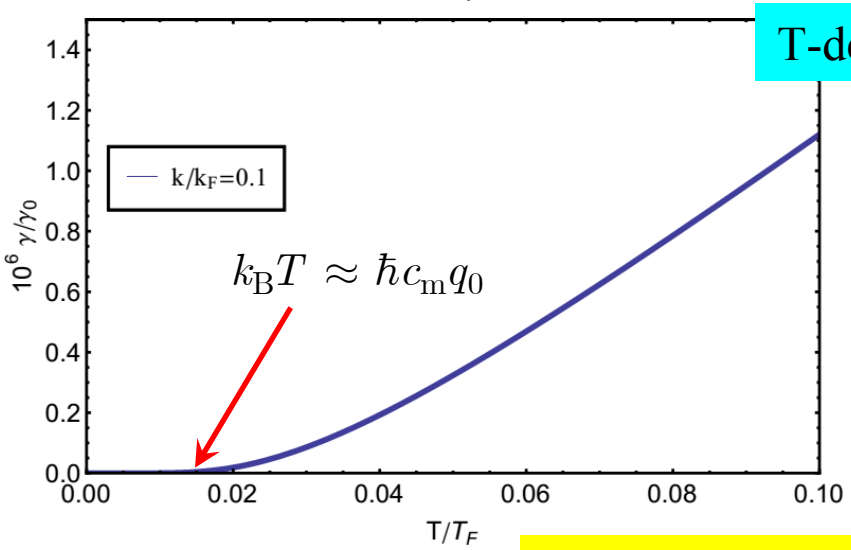
BCS side

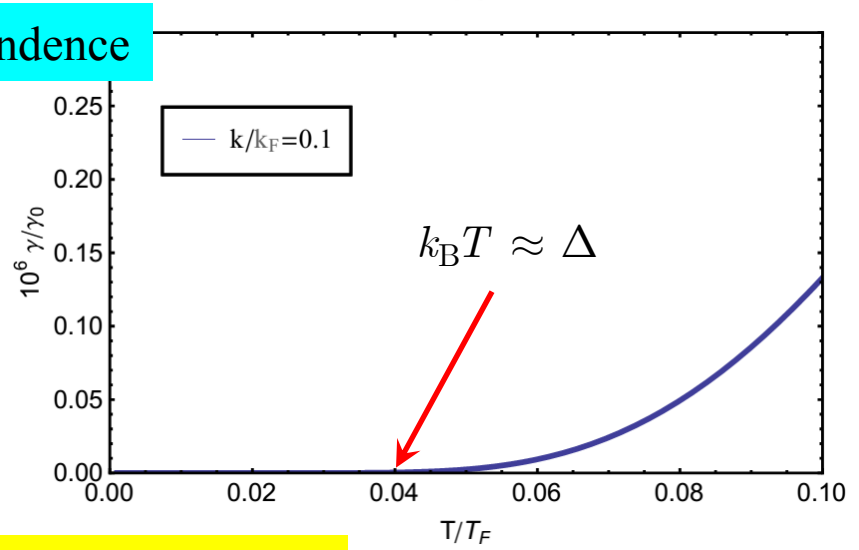
K-dependence





T-dependence



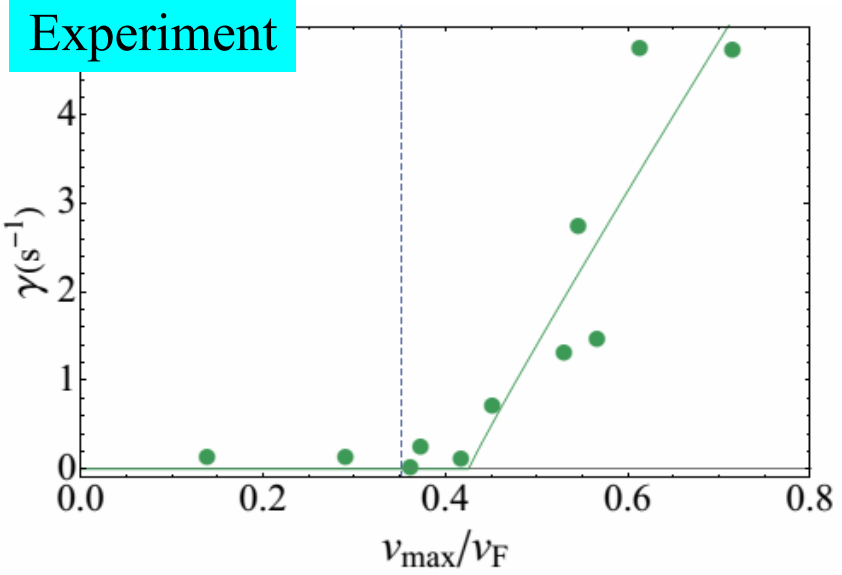


Exponentially suppressed in low-T

Huitao Shen and Wei Zheng, arXiv: 1502.02116

Compare to the experiment

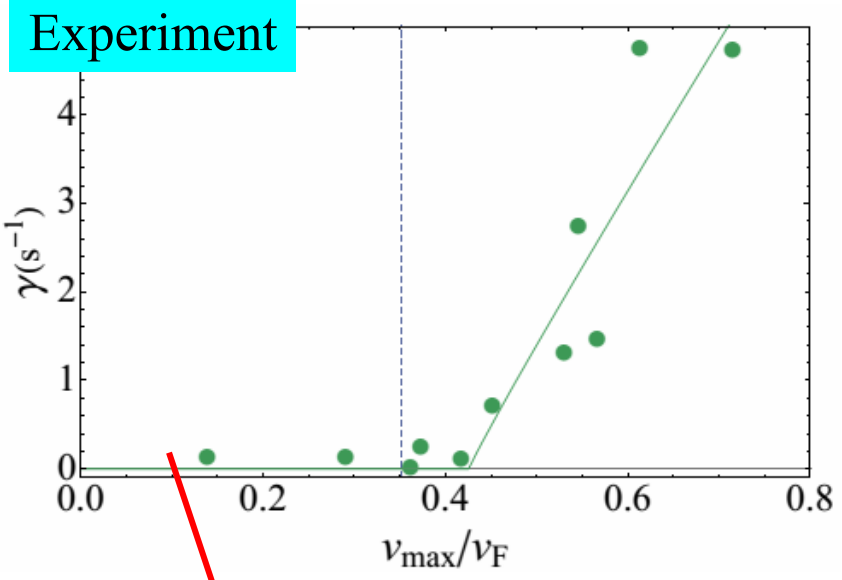
Experiment



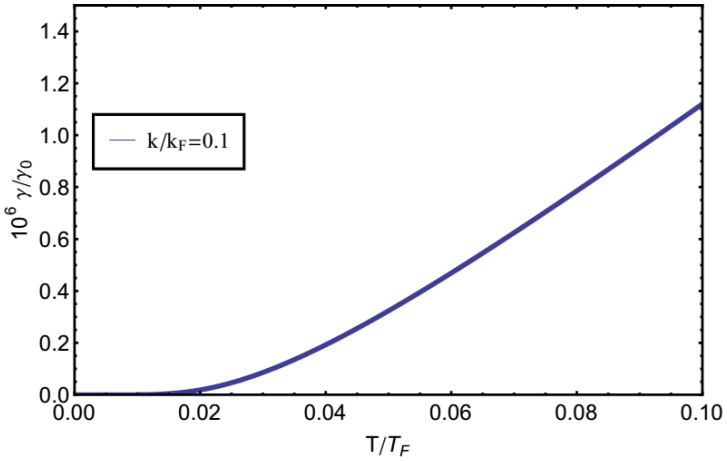
The experiment is in the unitary regime, Similar to the BEC side

Compare to the experiment

Experiment



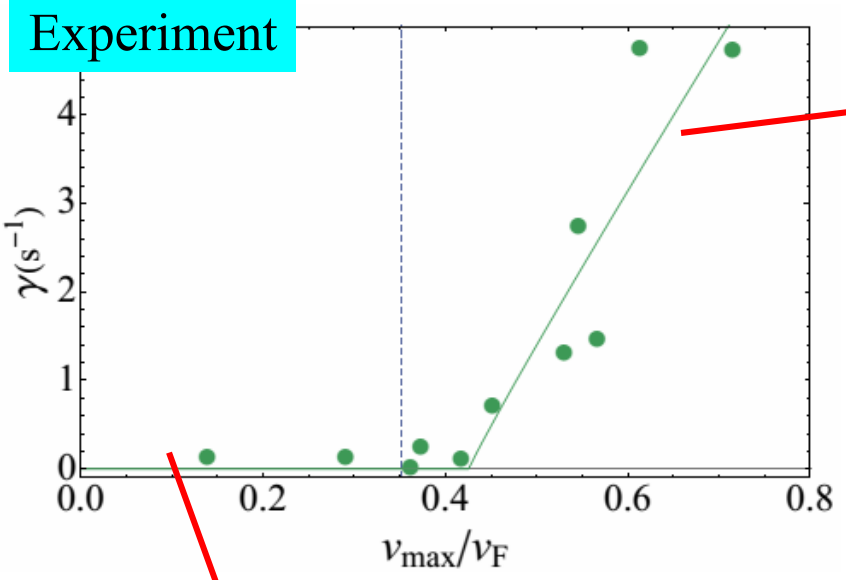
Landau damping is suppressed in low-T



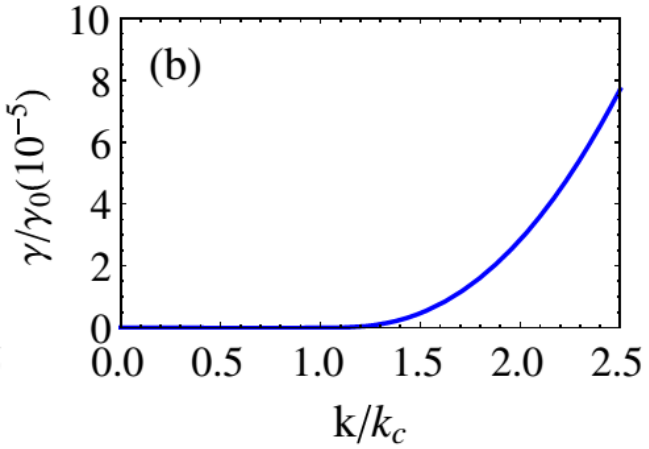
The experiment is in the unitary regime, Similar to the BEC side

Compare to the experiment

Experiment

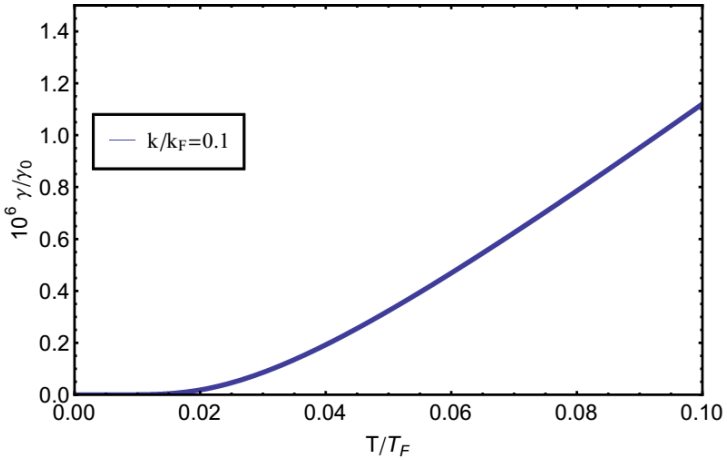


Beliaev damping dominate



critical velocity show up

Landau damping is suppressed in low-T



The experiment is in the unitary regime, Similar to the BEC side

Huitao Shen and Wei Zheng, arXiv: 1502.02116

Summary

- We try to explain the damping of the dipole oscillation by the Landau-Beliaev damping, which is due to interactions between the quasi-particles in the Bose-Fermi superfluid mixture.

- The experiment was done in a harmonic trap. One need a calculation in the trap.

- The Landau-Beliaev damping gives the quasi-particles a finite lifetime. That will affect many physical properties of the superfluid mixture, such as thermodynamics, transport.

Thank You !

And thanks to my collaborators:

Huitao Shen

Prof. Hui Zhai