Boosted 1D superconductors

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Current frontiers in condensed matter ICTS

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arxiv:1603.09478

Boosted “conventional” superconductor

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Landau critical velocity

$$v_c = \text{Min.}\left(v_s, \left(\left[\sqrt{\Delta^2+\mu^2}-\mu\right]/m\right)^{1/2}\right)$$

Sound velocity of bosonic collective mode

Fermionic (single-particle) excitations

Baym and Pethick, Phys. Rev. A 86 023602 (2012)

Boosted 1D superconductor

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What happens if the gap is zero to begin with?

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1D superconductor at T=0

No long-range order (Mermin-Wagner-Coleman theorem)

Algebraic long-range order

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What does a boost do to this kind of superconductor?

What is known?

Mean-field

Boost destroys superconductivity via Clogston-Chandrasekhar type mechanism.
Critical velocity < Landau critical velocity

T.-C. Wei and P. M. Goldbart, Phys. Rev. B 80, 134507 (2009).

Fluctuations

Interaction with walls can induce phase slips "dynamically" destroying superconductivity, finite ω and T

T. Eggel, M. A. Cazalilla and M. Oshikawa, Phys. Rev. Lett.107, 275302 (2011).

Our calculations and results

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Bosonization treatment taking into account quantum fluctuations

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Superconductivity can be strengthened upon applying a boost

Our calculations and results

Bosonization treatment taking into account quantum fluctuations

Superconductivity can be strengthened upon applying a boost

A boost can open or close gaps depending on whether the system has spinless or spin 1/2 fermions

Bosonization

Low energy theory for interacting 1D spinless Fermi system

$$\mathcal{H} = \frac{v}{2} \int dx \left[K \Pi(x)^2 + \frac{1}{K} \left(\nabla \phi(x) \right)^2 \right]$$

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K - Luttinger parameter

$$\langle O_{SU}(x)O_{SU}(x')\rangle \sim 1/|x-x'|^{1/K}$$

$$\langle O_{CDW}(x)O_{CDW}(x')\rangle \sim 1/|x-x'|^{K}$$

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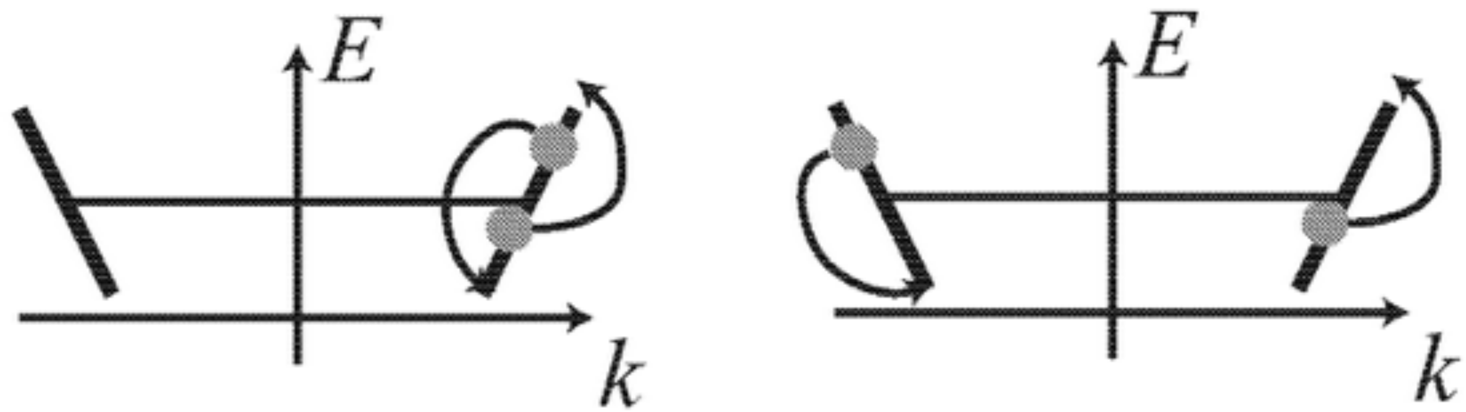
$K > 1$ attractive interactions (dominant SU order)

$K < 1$ repulsive interactions (dominant CDW order)

Bosonization



$g_4 = V(q\sim 0)$ $\quad$ $g_2 = V(q\sim 0)$

$$v = \sqrt{\left(v_F + \frac{g_4}{2\pi}\right)^2 - \left(\frac{g_2}{2\pi}\right)^2}$$

$$K = \sqrt{\frac{v^F - \left(\frac{g_2}{2\pi} - \frac{g_4}{2\pi}\right)}{v^F + \left(\frac{g_2}{2\pi} + \frac{g_4}{2\pi}\right)}}$$

Ref: Quantum physics in one dimension, Giamarchi

Application of a boost

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Momentum: $k \to k + u$

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Different Fermi speeds for left and right movers

$$v_L^F(u) = v^F(u) - w(u); v_R^F(u) = v^F(u) + w(u)$$

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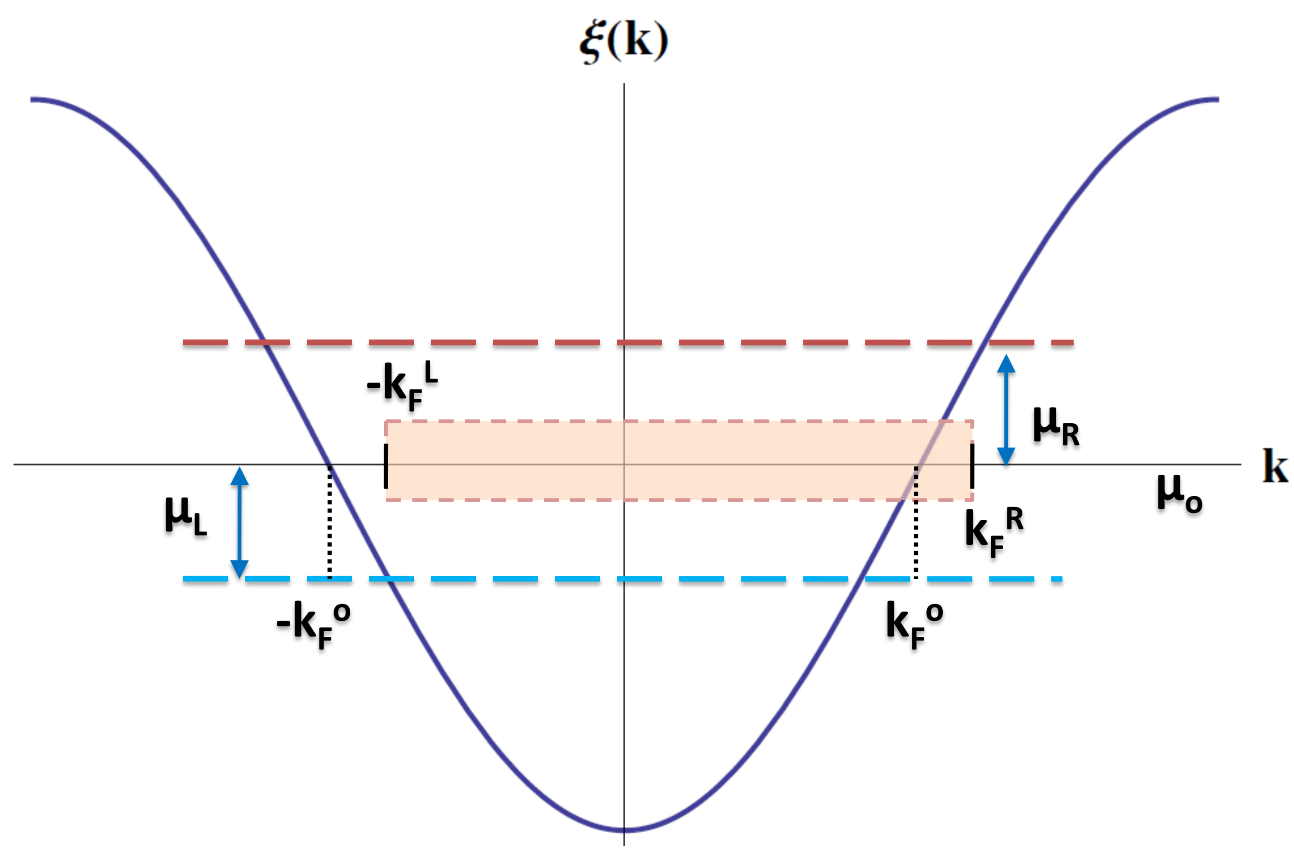

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$$\mathcal{H} = \int dx \left\{ \frac{v(u)}{2} \left[K(u)\Pi^2 + \frac{1}{K(u)} \left(\partial_x \phi\right)^2 \right] - w(u) \left[(\Pi \partial_x \phi) + (\partial_x \phi \Pi) \right] \right\}$$

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$$\begin{aligned} v(u) &= \sqrt{\left(v^F(u) + \frac{g_4}{2\pi}\right)^2 - \left(\frac{g_2}{2\pi}\right)^2}, \\ K(u) &= \sqrt{\frac{v^F(u) - \left(\frac{g_2}{2\pi} - \frac{g_4}{2\pi}\right)}{v^F(u) + \left(\frac{g_2}{2\pi} + \frac{g_4}{2\pi}\right)}} \end{aligned}$$

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g's unchanged by boost because they only depend on momentum differences

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$$\mathcal{L} = \frac{1}{2K(u)} \int dx dt \left[\frac{1}{v(u)} \left(\partial_t \tilde{\phi} \right)^2 - v(u) \left(\partial_x \tilde{\phi} \right)^2 \right]$$

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$$\tilde{\phi}(x,t) = \phi(x + w(u)t, t)$$

Galilean transformation with speed $w(u)$

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Application of a boost

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$$\langle O_{\mathrm{SU}}(x,t)O^{\dagger}_{\mathrm{SU}}(x',t')\rangle \sim e^{i2u(x-x')}\left(\frac{1}{\sqrt{[x-x'+w(u)(t-t')]^2+[v^F(u)]^2(t-t')^2}}\right)^{1/K(u)}$$

$$\langle O_{\mathrm{CDW}}(x,t)O_{\mathrm{CDW}}(x',t')\rangle \sim \cos\left[2k_F(x-x')\right]\left(\frac{1}{\sqrt{[x-x'+w(u)(t-t')]^2+[v^F(u)]^2(t-t')^2}}\right)^{K(u)}$$

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Galilean transformation with speed $w(u)$

Conformal invariance restored in terms of $\tilde{\phi}$

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for $u \ll k_F$

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Boost has no effect when the dispersion is parabolic

Application of a boost

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The same effect for spin 1/2 fermions

Application of a boost

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Superconducting pairing susceptibility

$$\chi_{\text{pair}} = \lim_{\omega\to 0} \frac{1}{\Omega} \sum_k \frac{f(\xi_k) - f(-\xi_{-k})}{\omega - \xi(k) - \xi(-k) + i\delta}$$

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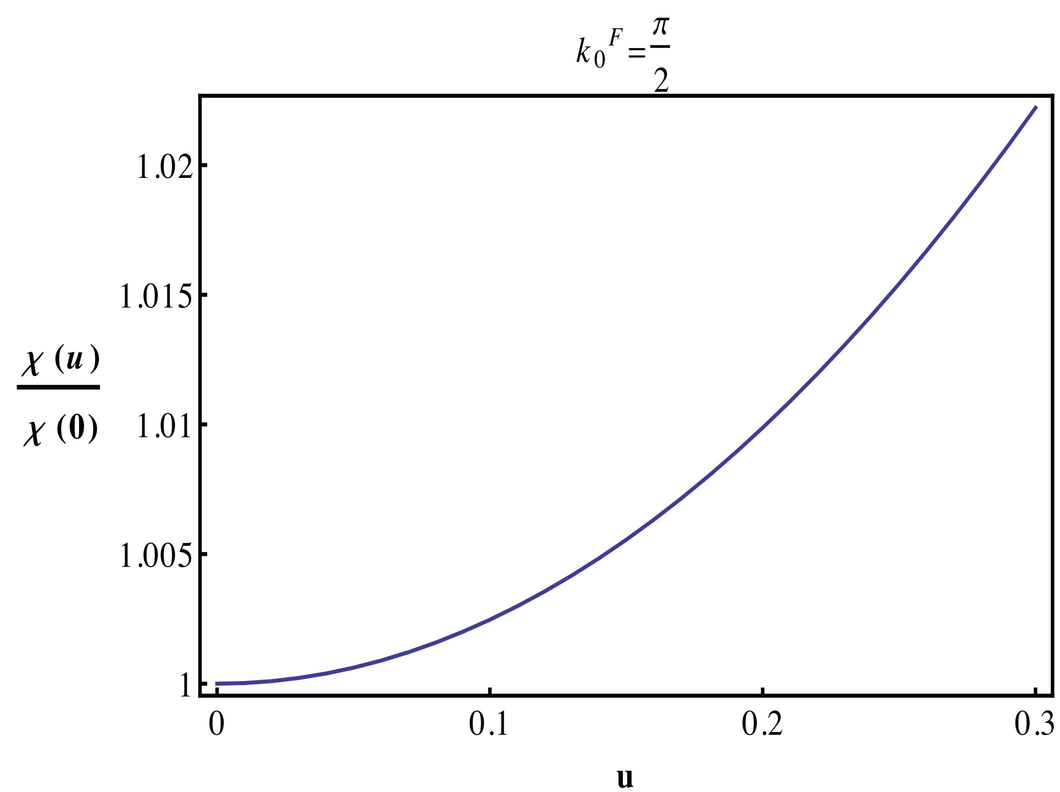

Umklapp

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for spin 1/2 fermions

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Sine-Gordon Hamiltonian

Umklapp

Umklapp

$$\mathcal{H} = \frac{v_\nu}{2} \int dx \left[K_\nu \Pi_\nu^2 + \frac{1}{K_\nu} \left(\nabla \phi_\nu\right)^2 + \frac{2 g_\nu}{2\pi a^2} \cos\left(\alpha_\nu \phi_\nu\right) \right]$$

$$\nu = \text{charge, spin}$$

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Renormalization group flows can be calculated for K and g

$$g \text{ relevant} \Rightarrow \text{gapped, } g \text{ irrelevant} \Rightarrow \text{gapless}$$

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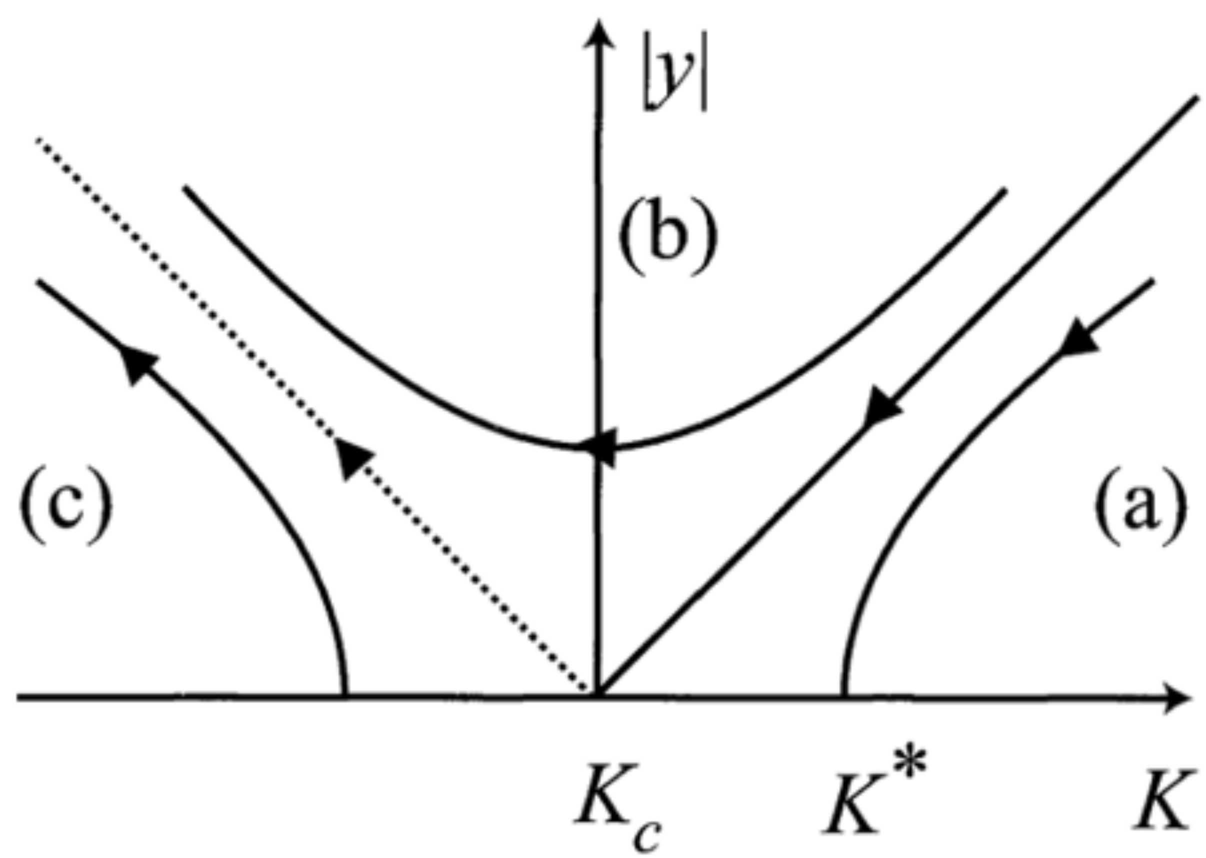

$$y = g$$

Umklapp

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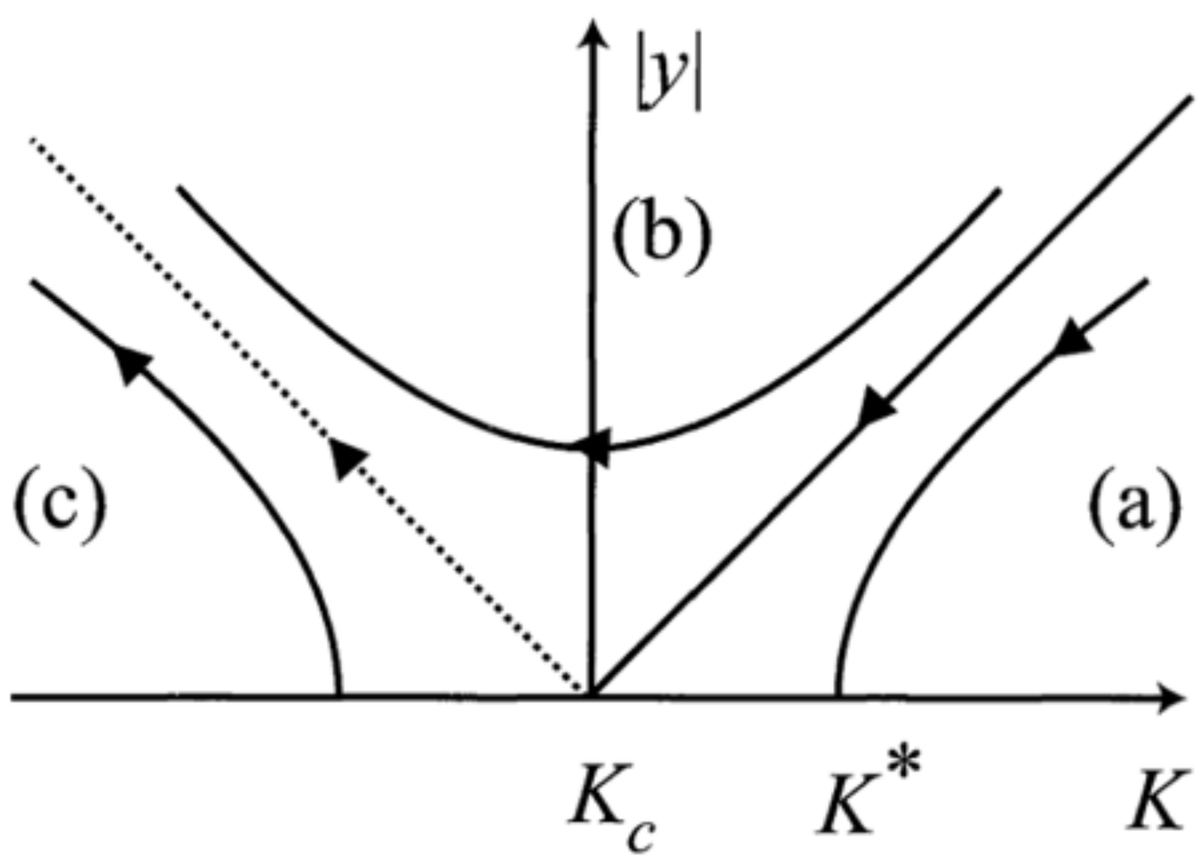

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$$K_\nu^c = \frac{8\pi}{\alpha_\nu^2}$$

$$h_\nu = 2\left(\frac{K_\nu}{K_\nu^c} - 1\right)$$

$$g_\nu^\perp = K_\nu^c g_\nu$$

$$\frac{dg_\nu^\perp}{dl} = -h_\nu g_\nu^\perp,$$

$$\frac{dh_\nu}{dl} = -\left(g_\nu^\perp\right)^2.$$

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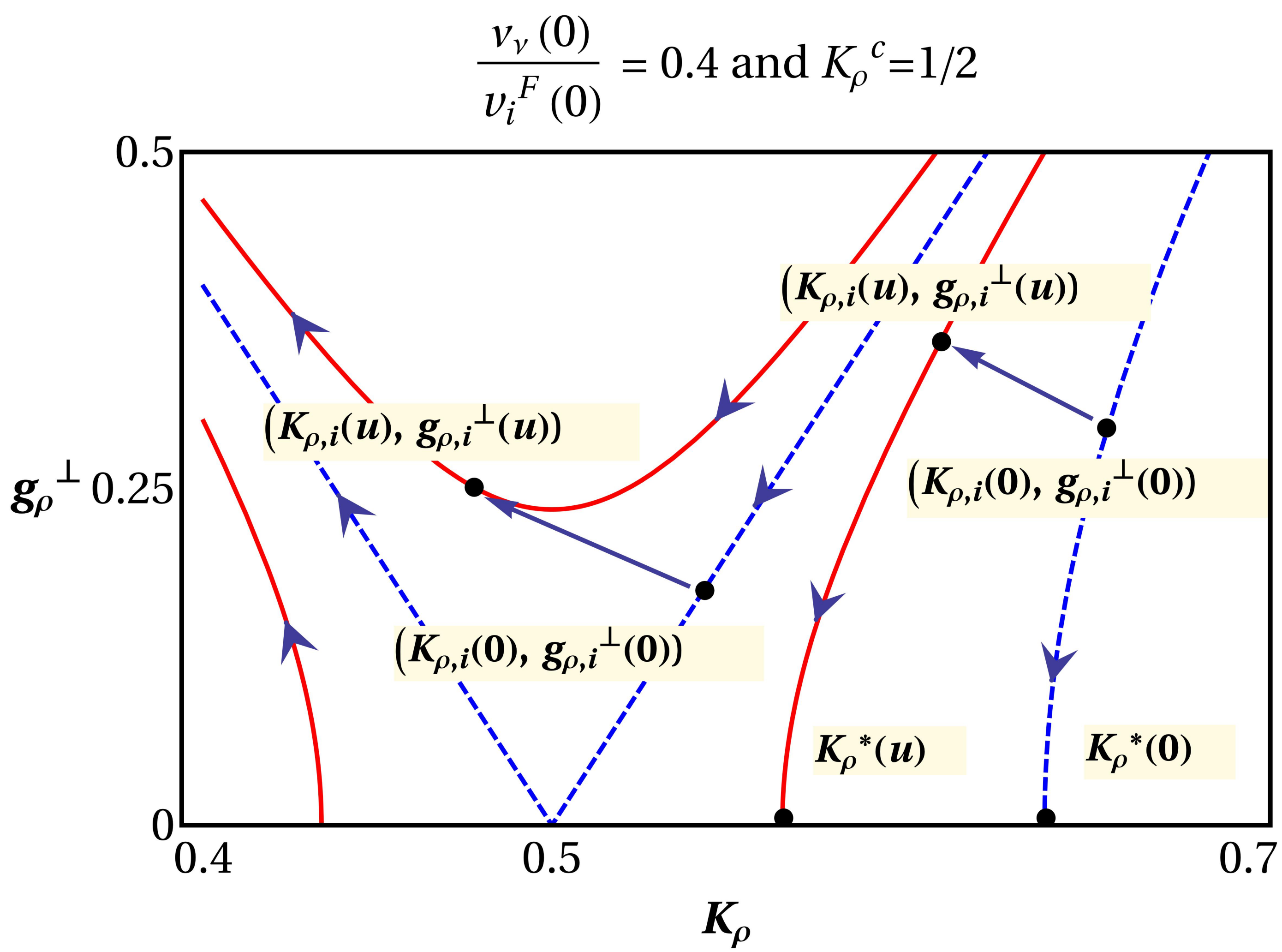
$$
\begin{aligned}
h_{\nu,i}(u) &= 2\left(\frac{K_{\nu,i}(0)}{K^c_\nu} - 1\right) - \frac{v^F_i(0)f(u)}{v_\nu(0)K^c_\nu}\left[(K_{\nu,i}(0))^2 - 1\right] \\
g^\perp_{\nu,i}(u) &= g^\perp_{\nu,i}(0)\left[1 - \frac{v^F_i(0)f(u)}{2v_\nu(0)}\left(K_{\nu,i}(0) + \frac{1}{K_{\nu,i}(0)}\right)\right].
\end{aligned}
$$

$$f(u) = -\frac{v^F_i(0) - v^F_i(u)}{v^F_i(0)}$$

Spinless fermions



Spinless fermions

Boost can open a gap

Spinless fermions

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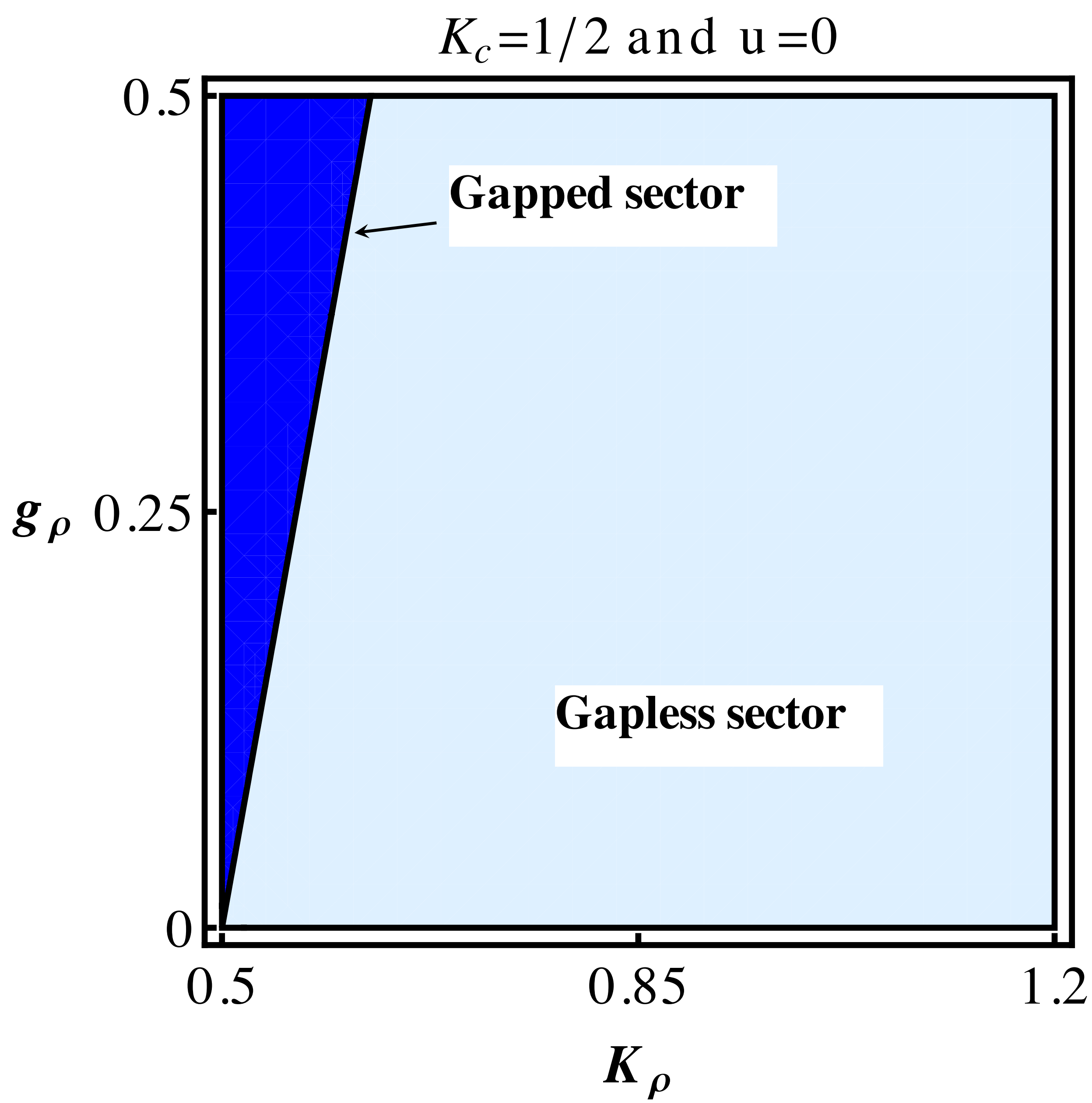

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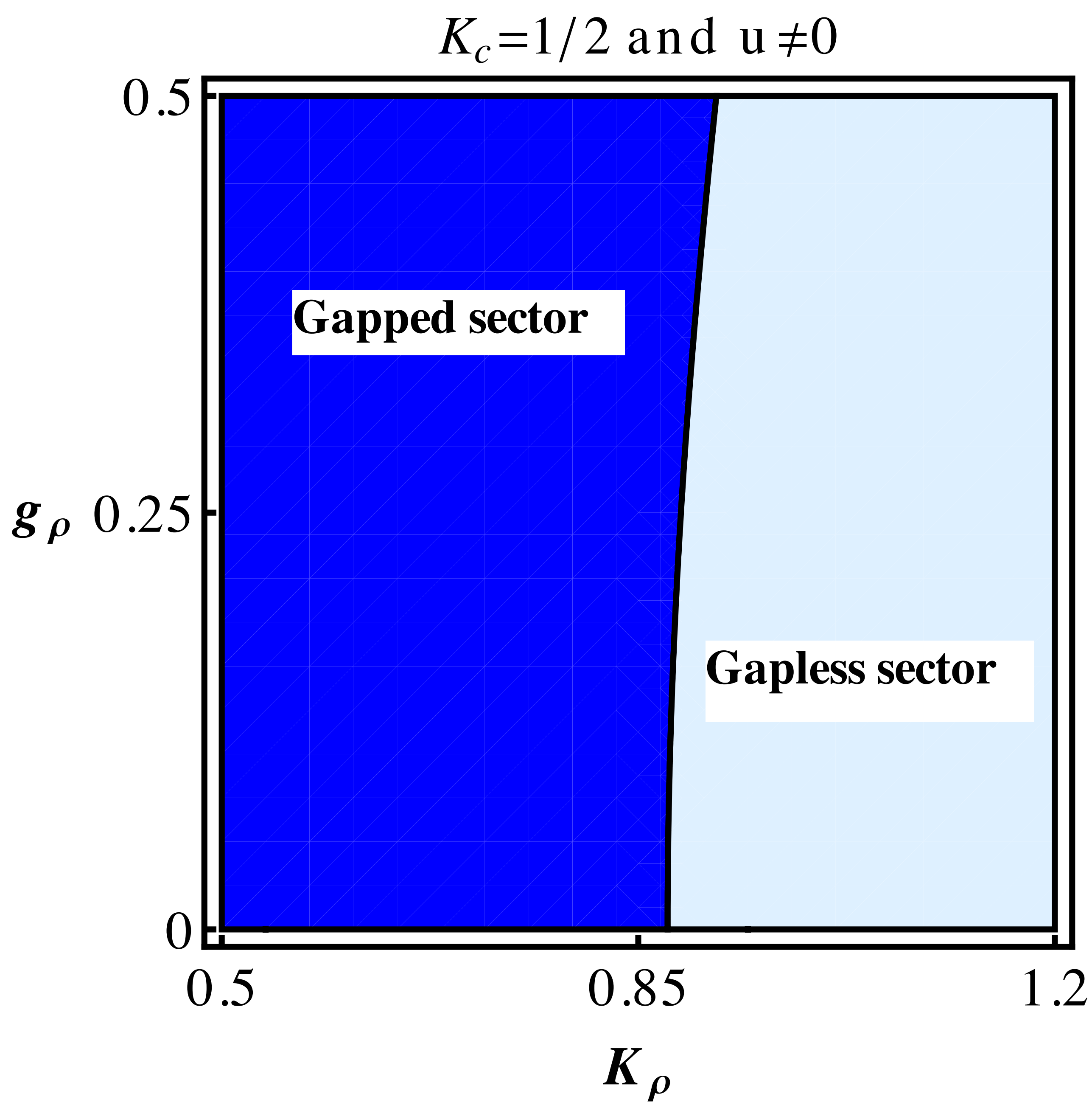

Spinless fermions

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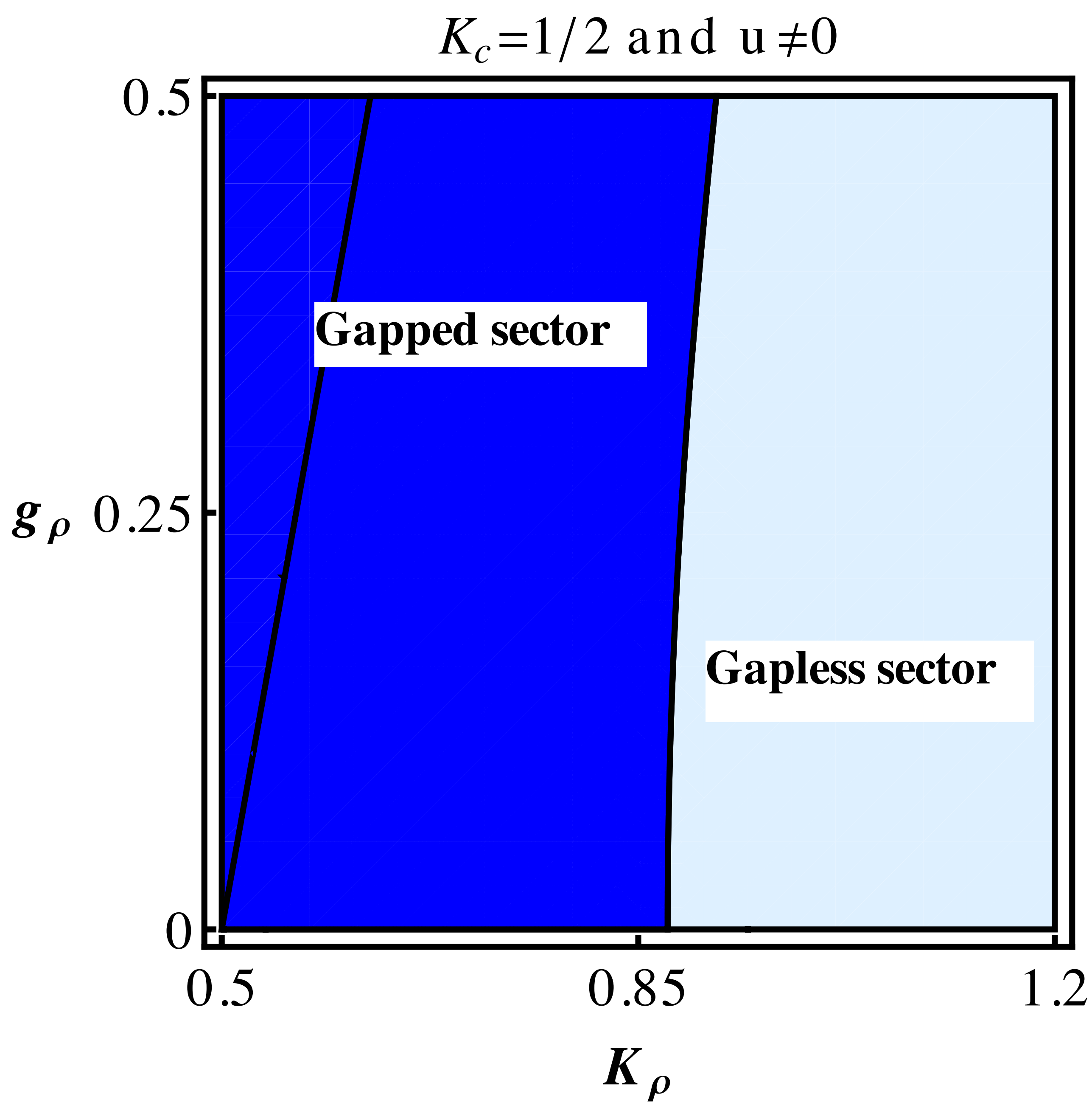
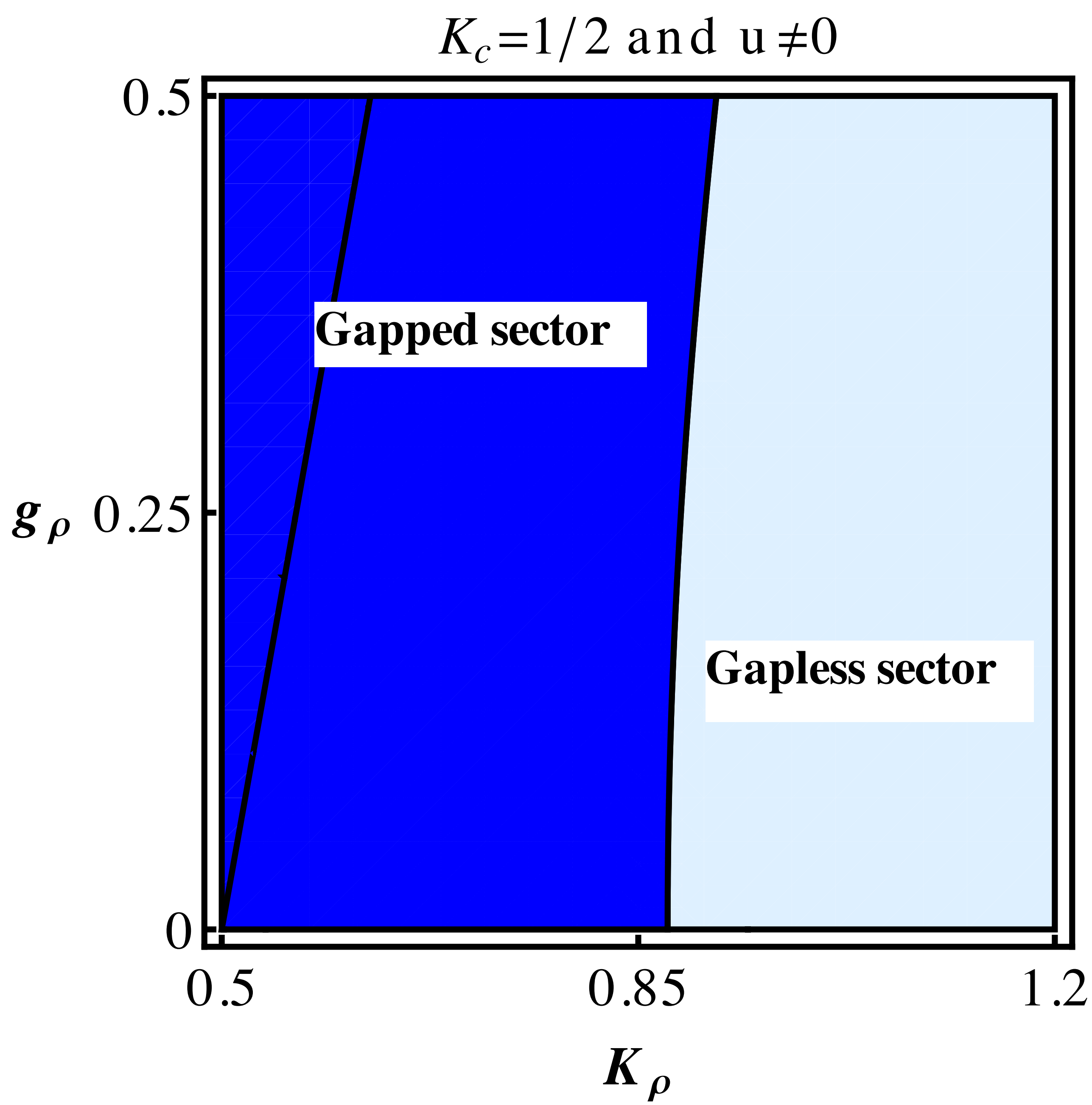
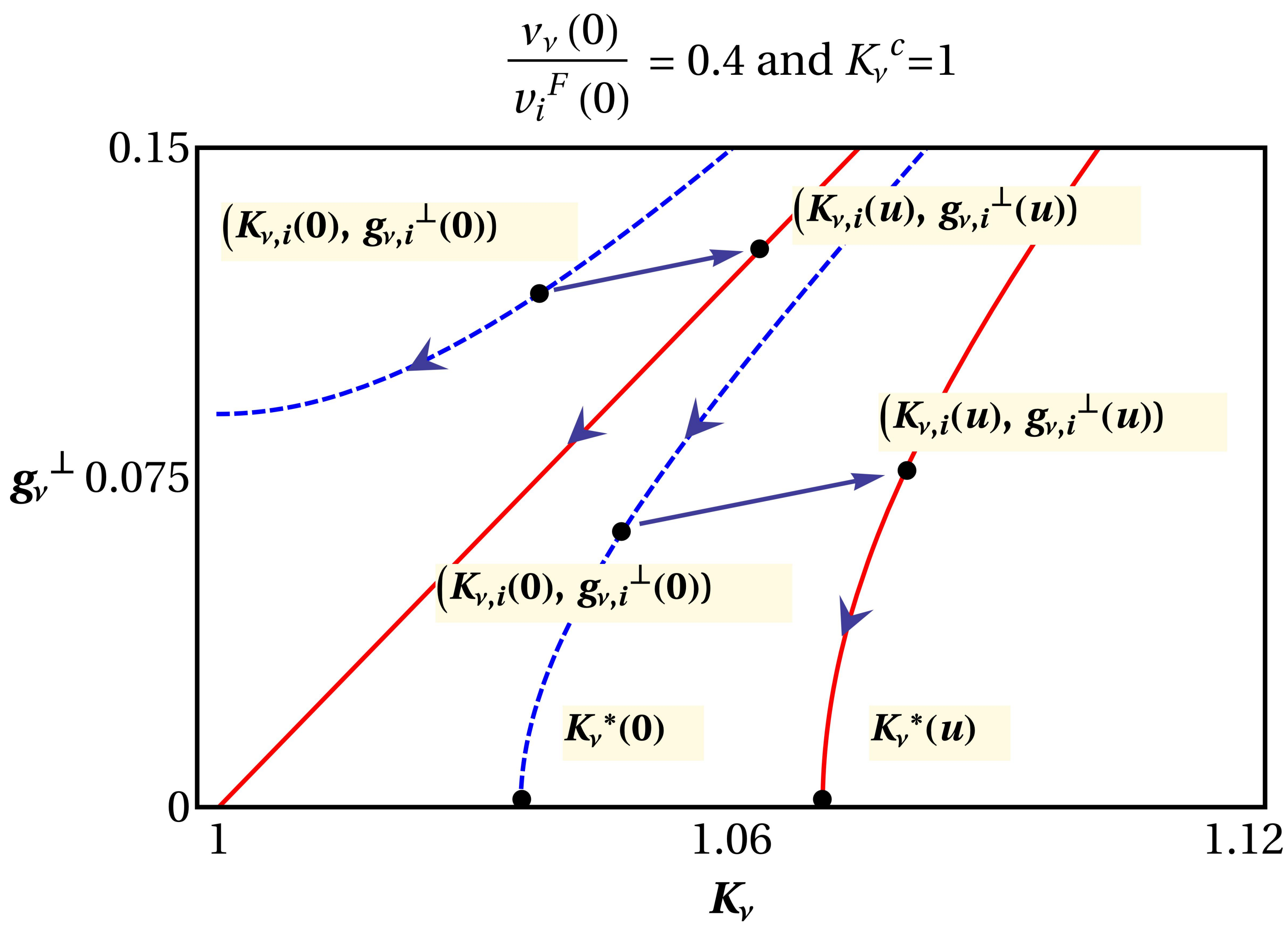


Spinless fermions



The boost can open a gap for K < 1
Possibly algebraic CDW to long-ranged CDW

Spin 1/2 fermions

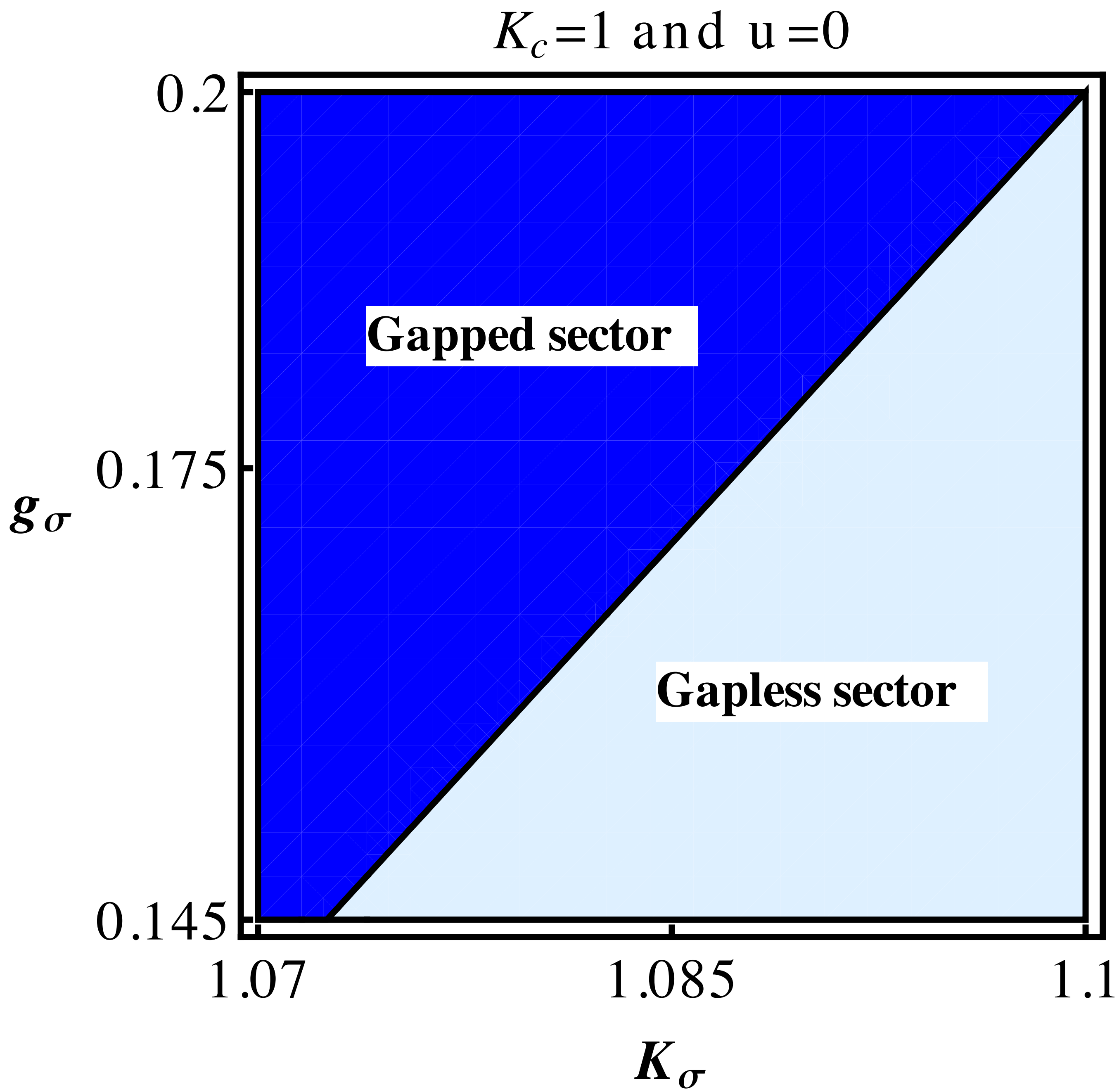


Spin 1/2 fermions

Boost can close gap

Spin 1/2 fermions

Spin 1/2 fermions



Spin 1/2 fermions

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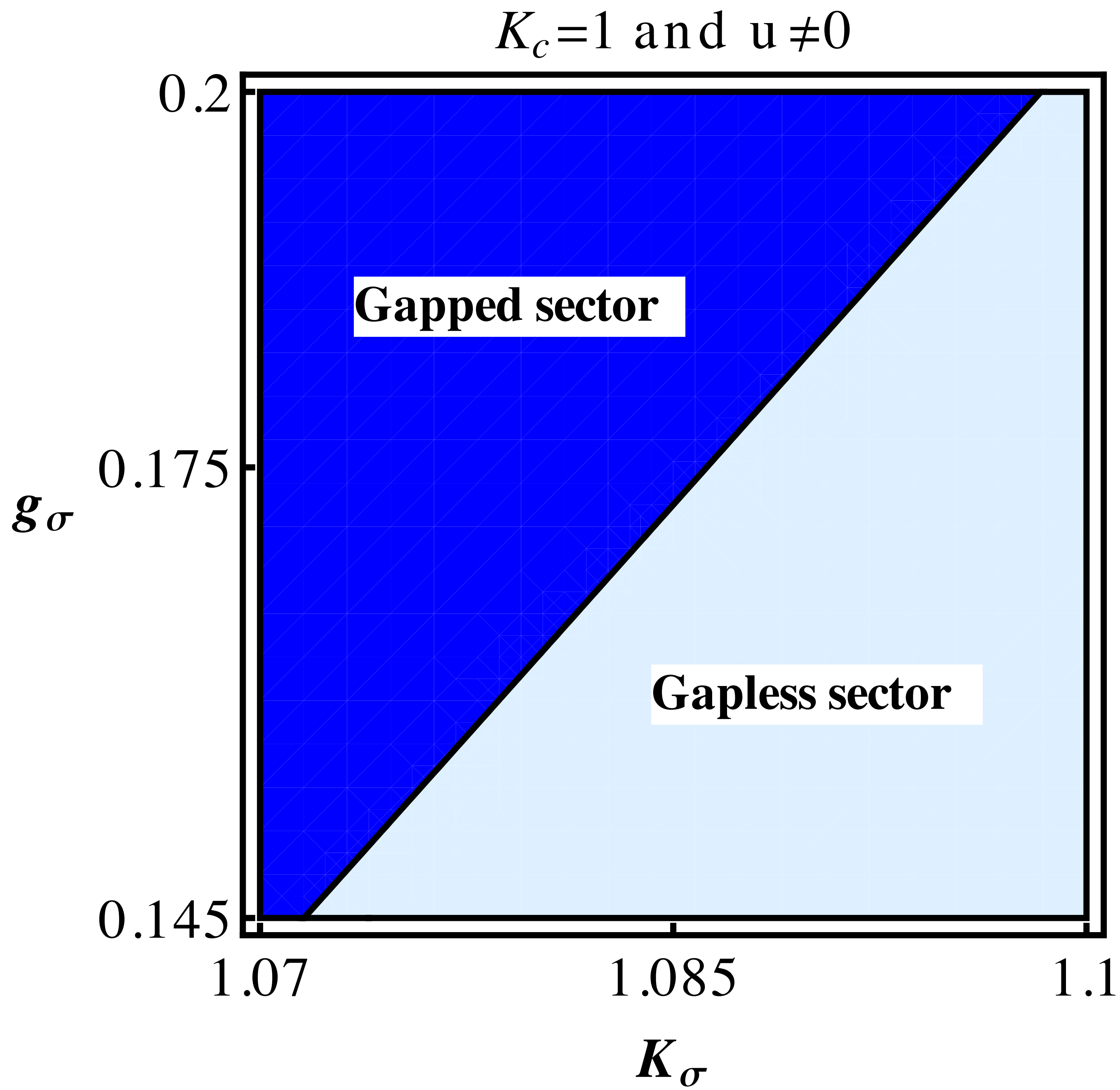

Spin 1/2 fermions

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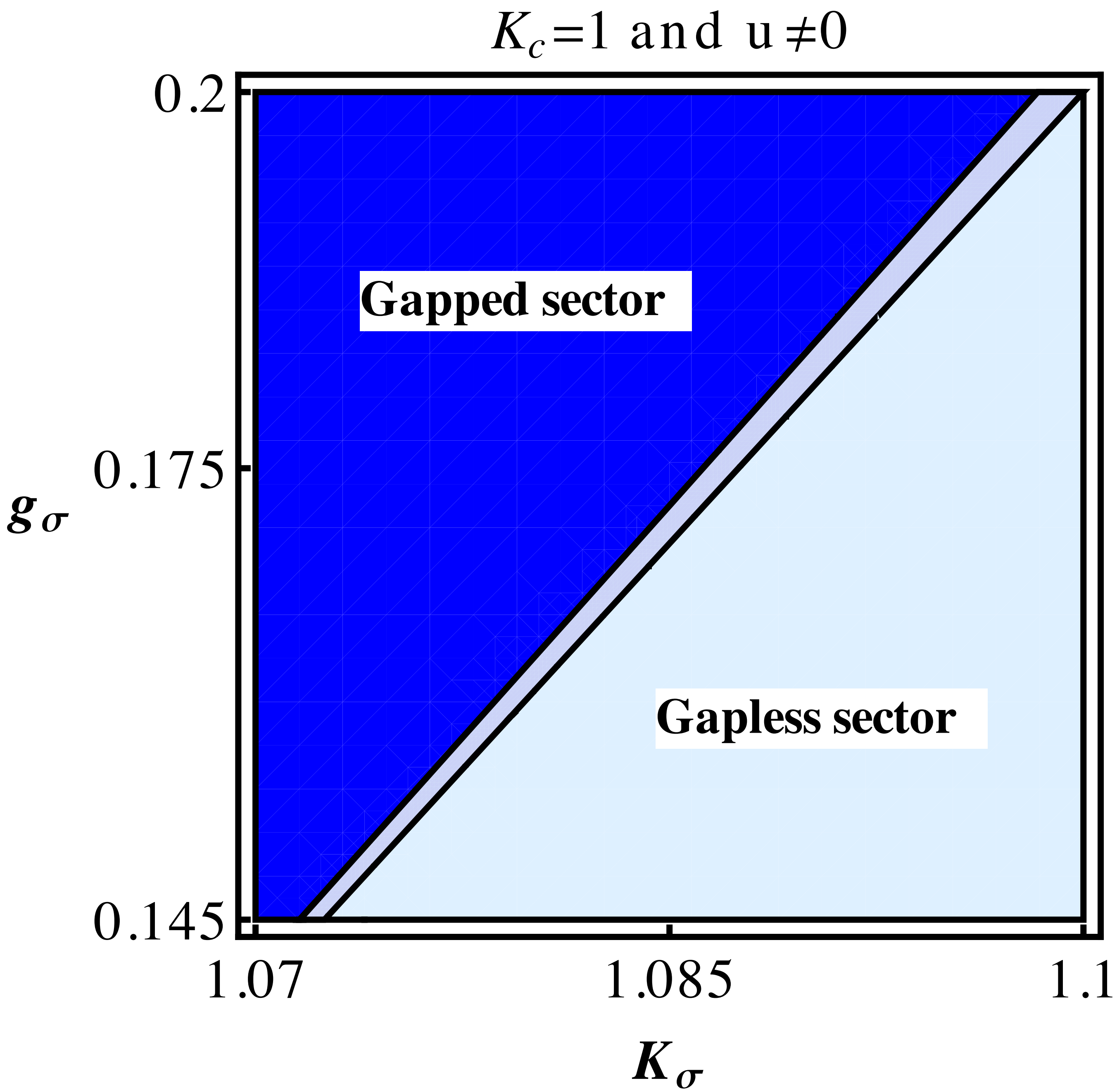
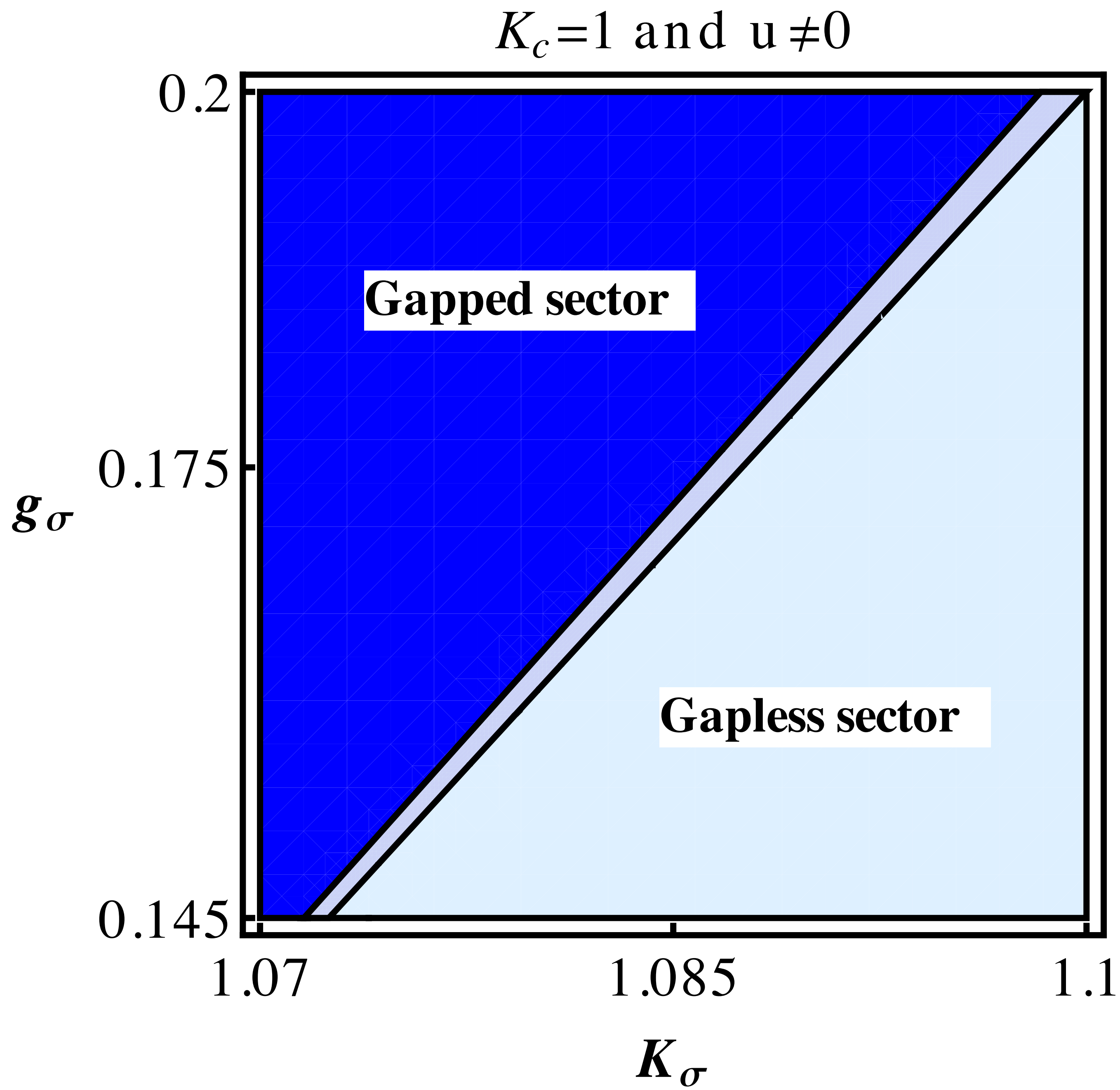


Spin 1/2 fermions



The boost can close a gap for K > 1

Spin 1/2 fermions

Interesting possibility

Unboosted system with charge and spin gap

Boost closes one of the gaps

Close charge gap but not spin gap - Luther-Emery fluid

Conclusions

- A boost has a non-trivial effect on algebraic order in 1D only for non-parabolic bands
- For a simple lattice dispersion, a boost can strengthen superconductivity (and CDW order)
- At commensurate filling, a boost can open or close gaps depending on whether the fermions are spinless or spinful
- Possible to obtain a Luther-Emery fluid by boosting starting from fully gapped state