Spin-valley collective modes of the electron liquid in graphene

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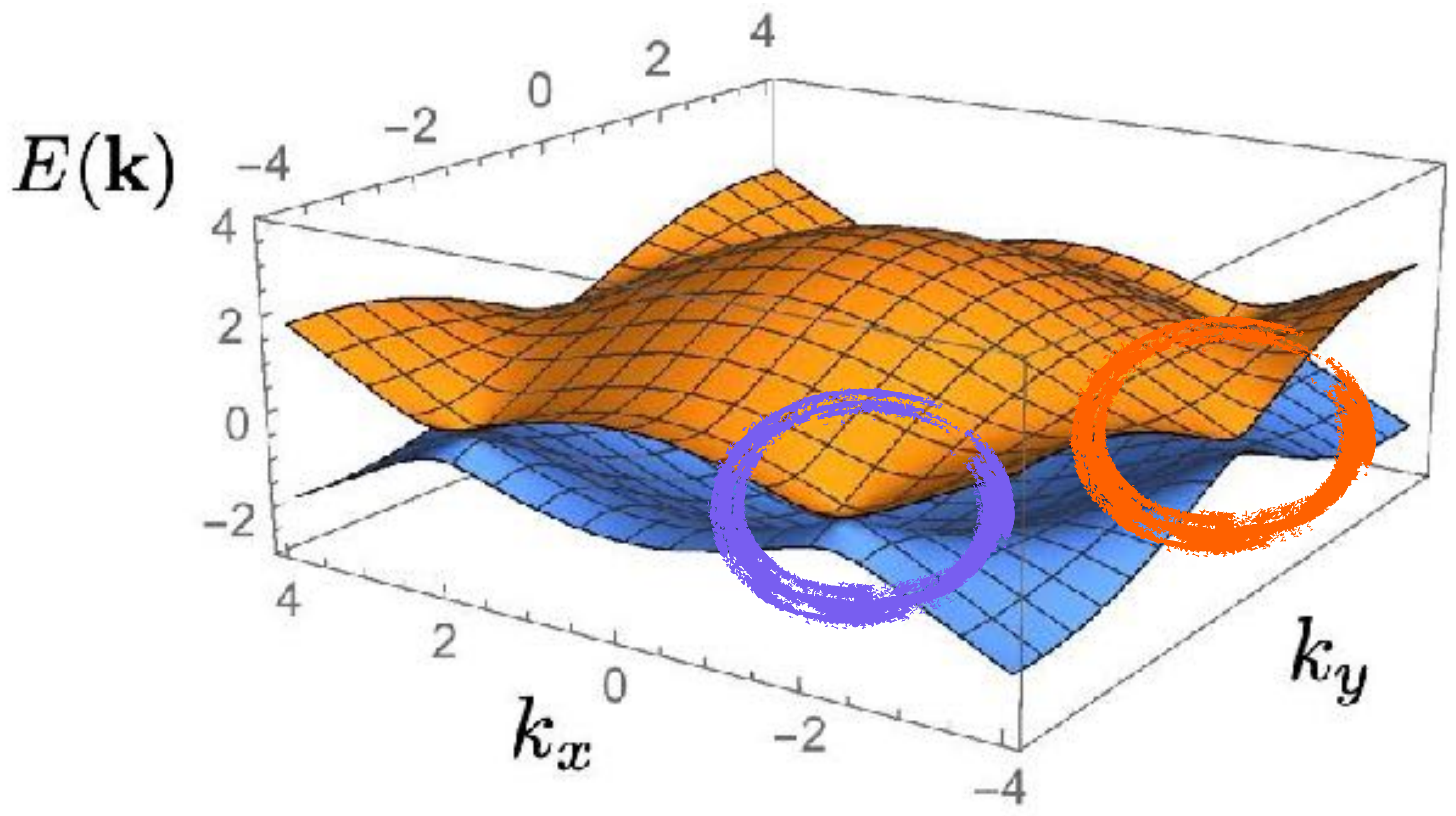
How do excitations of the spin-valley channels spread in Fermi Liquid graphene?

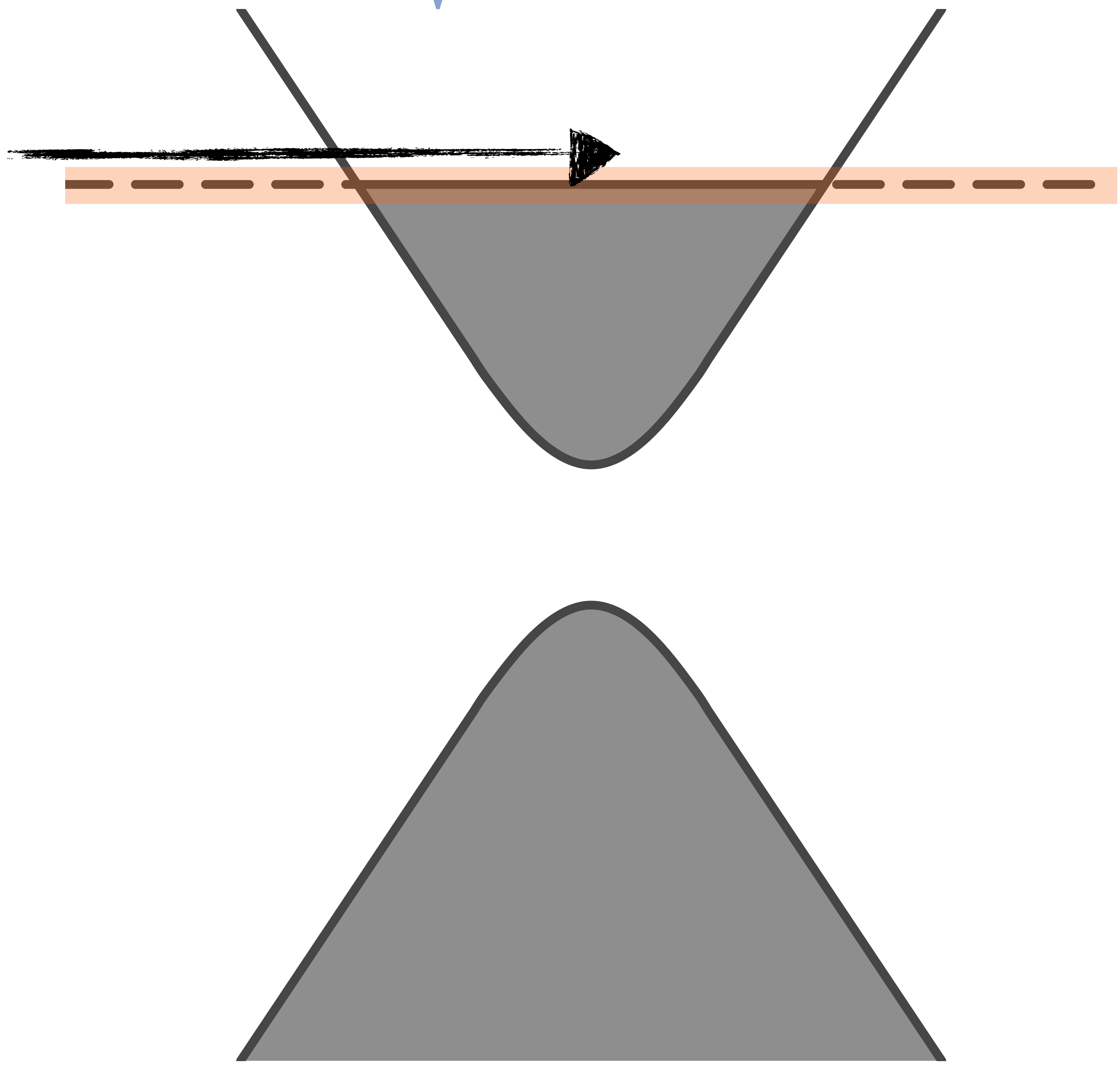
Fermi Liquid graphene

A multicomponent Fermi liquid

$$\epsilon_{ij}(\mathbf{p},\mathbf{r}) = \xi(\mathbf{p}) + \sum_{\mathbf{p}',lm} f_{ij;lm}(\mathbf{p}\cdot\mathbf{p}')\hat{\rho}_{lm}(\mathbf{r},\mathbf{p}'),$$

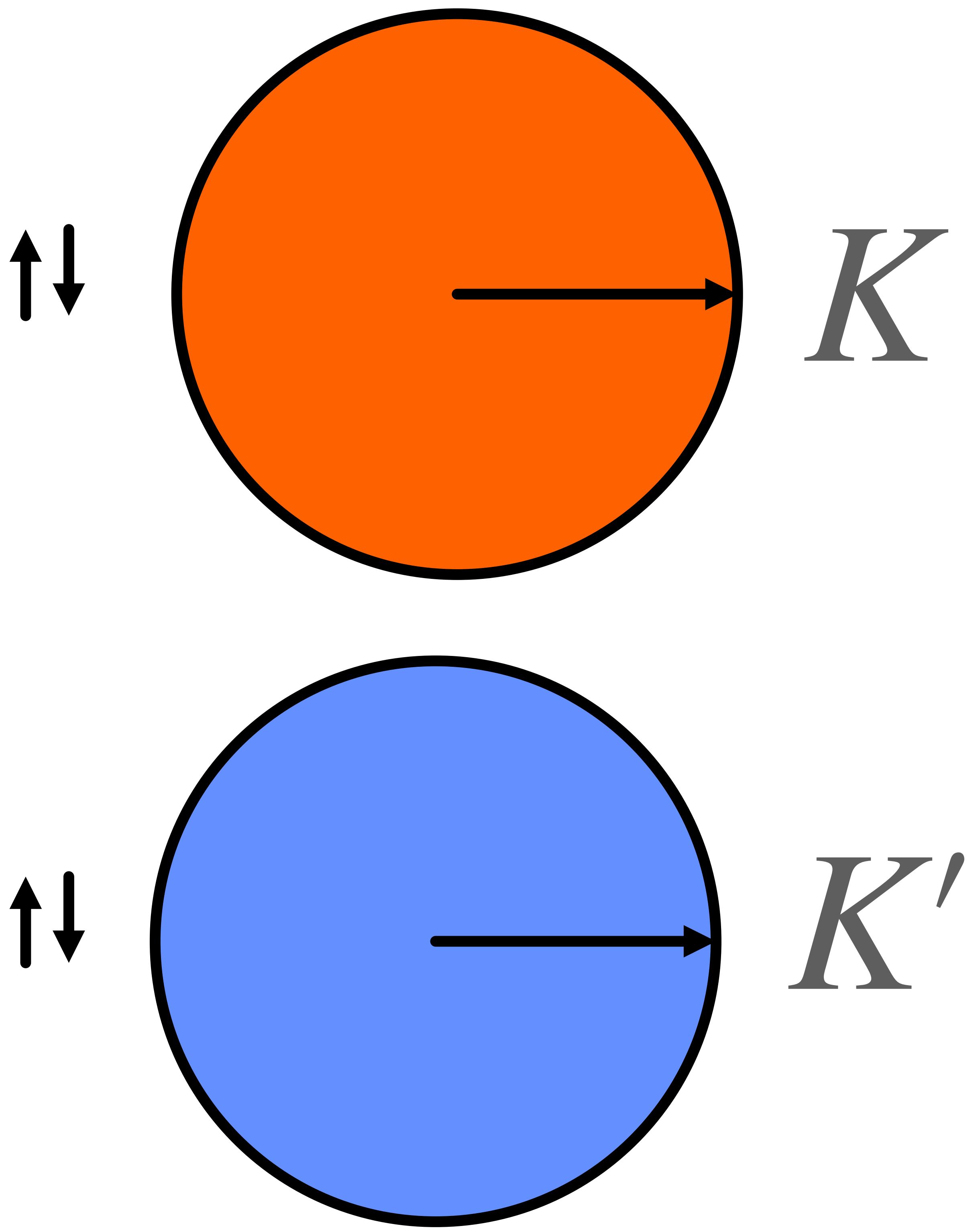


$$\xi(\mathbf{p}) = \sqrt{v^2p^2+\Delta^2} - \mu$$



- We want to construct a Fermi liquid theory of graphene without sub lattice symmetry

- We know the non-interacting dispersion but what types of interactions can we have?



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Symmetry of gapped graphene

What short ranged interactions are symmetry allowed?

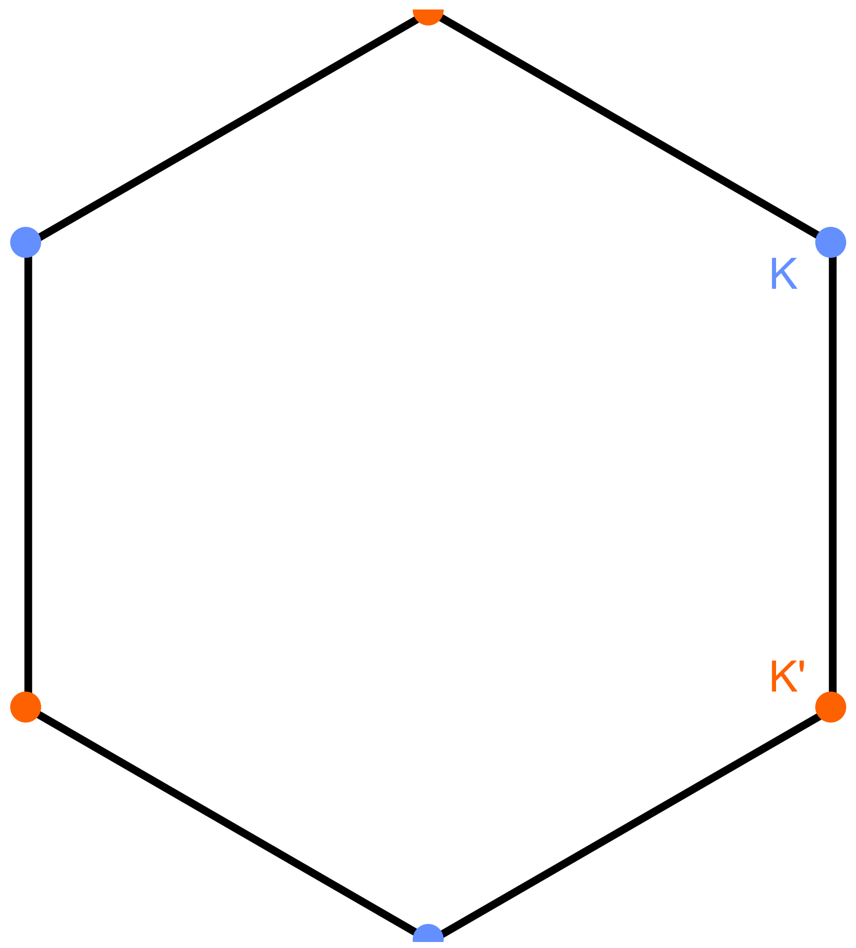
$$\hat{\Psi}_\sigma(\mathbf{r}) = \begin{pmatrix} u_{KA}(\mathbf{r}) & u_{KB}(\mathbf{r}) & u_{K'B}(\mathbf{r}) & -u_{K'A}(\mathbf{r}) \end{pmatrix} \cdot \hat{\vec{\psi}}_\sigma(\mathbf{r})$$

Low energy theory

- For the low energy theory we expand in terms of the Bloch wave functions at the Dirac points and slowly varying envelope functions
- These Bloch wave functions have well defined symmetry properties under lattice transformations

Expand around K and K' points

$$\hat{\vec{\psi}}_\mathbf{k} = \begin{pmatrix} \psi_{KA}(\mathbf{k}) \\ \psi_{KB}(\mathbf{k}) \\ \psi_{K'B}(\mathbf{k}) \\ -\psi_{K'A}(\mathbf{k}) \end{pmatrix}$$



Aleiner, Kharzeev, Tsvelik, PRB 76, 195415 (2007)

Kharitonov, PRB 85, 155439 (2012)

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Interactions from symmetry

- We can approximate the interaction constants from matrix elements of the Coulomb interaction
- Due to symmetry there are 3 independent short ranged coupling constants + long ranged part of Coulomb
- Interactions form a natural hierarchy of scales related to their characteristic length scale

$$g \propto \int u^*_{\zeta\Sigma}(r) V(|r - r'|) u_{\zeta'\Sigma'}(r')$$

Long Range

$$V(\mathbf{q})$$

Strongest

$$g_{\perp\perp} \sim V(|\mathbf{K} - \mathbf{K}'|)$$

$$g_{zz} \sim V(|\mathbf{b}|)$$

$$\tilde{g}_{00} \sim \frac{g_{zz}\Delta}{v_F |\mathbf{K} - \mathbf{K}'|}$$

Weakest

Short Range

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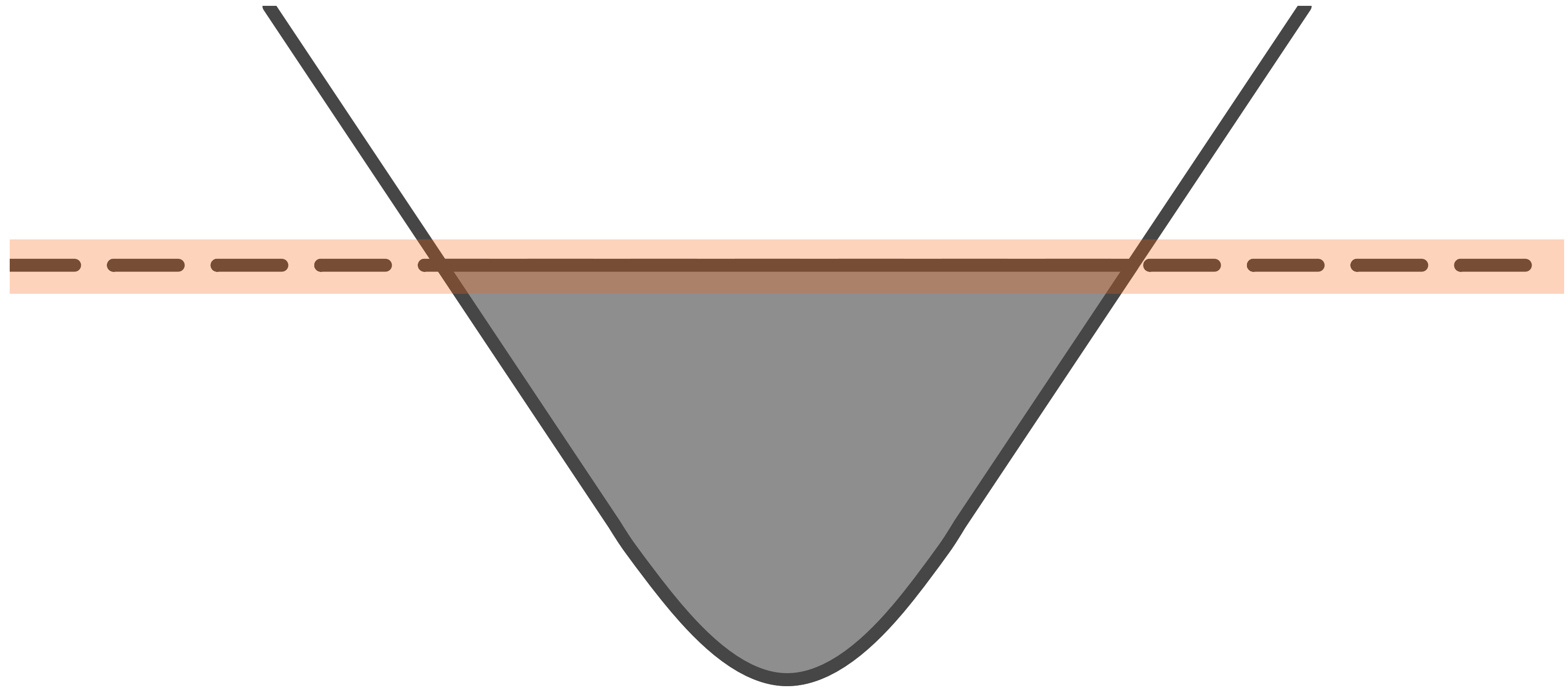
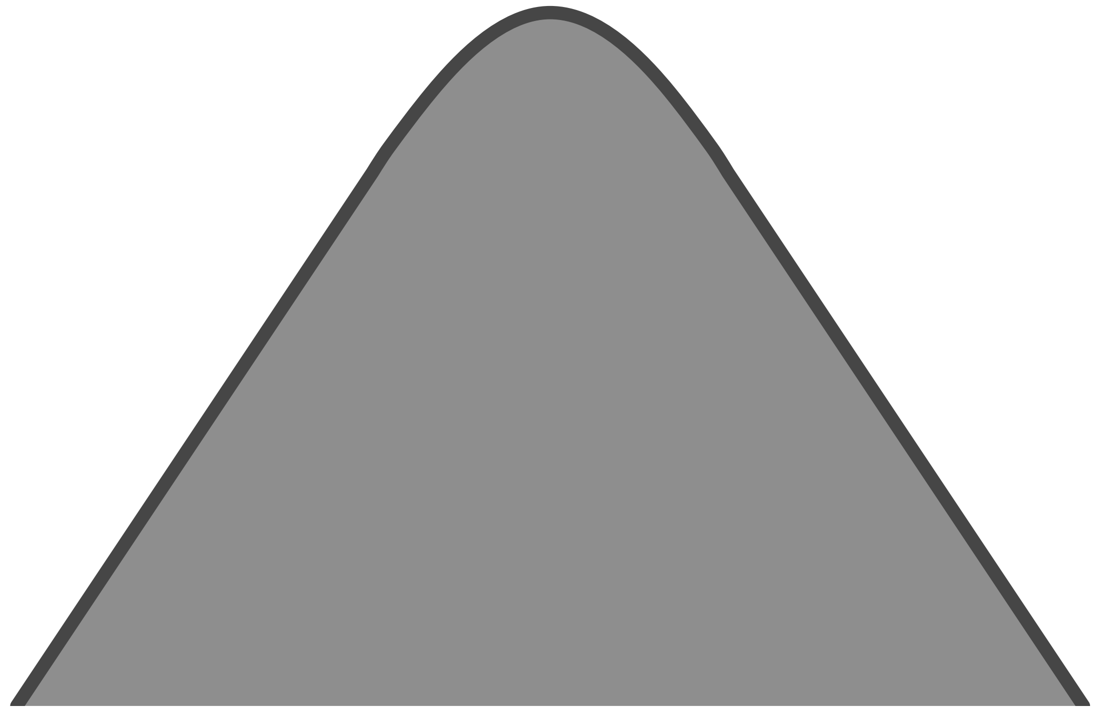
Upper band description



$$(v\mathbf{k}\cdot\Sigma + \zeta\Delta\Sigma_3)\chi_{\mathbf{k}\zeta} = \sqrt{v^2k^2+\Delta^2}\chi_{\mathbf{k}\zeta}$$



$$\begin{aligned} U(\mathbf{p},\mathbf{p}',\mathbf{q}) = {} & U^{d}_{\mathbf{p},\mathbf{p}',\mathbf{q}} + U^{s}_{\mathbf{p},\mathbf{p}',\mathbf{q}}\sigma\cdot\sigma + U^{v\parallel}_{\mathbf{p},\mathbf{p}',\mathbf{q}}\tau^{\parallel}\cdot\tau^{\parallel} \\ & + U^{vz}_{\mathbf{p},\mathbf{p}',\mathbf{q}}\tau^{3}\tau^{3} + U^{m\parallel}_{\mathbf{p},\mathbf{p}',\mathbf{q}}\tau^{\parallel}\cdot\tau^{\parallel}\sigma\cdot\sigma + U^{mz}_{\mathbf{p},\mathbf{p}',\mathbf{q}}\tau^{3}\tau^{3}\sigma\cdot\sigma, \end{aligned}$$

- Six possibly distinct short ranged interaction functions + long ranged Coulomb
    - These could be considered inputs of the theory
- Momentum dependence comes from the spinor matrix elements

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Neutral sound modes

What kills first and second sound

$$\frac{\partial \delta\rho^\mu(\mathbf{k},\mathbf{r})}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}}\delta\bar{\rho}^\mu(\mathbf{k},\mathbf{r}) + \cancel{\frac{\partial n}{\partial \epsilon}\Big|_{\bar{\epsilon}}\mathbf{v}\cdot\mathscr{F}^\mu} = \boxed{\frac{1}{G_s G_v}\,\mathrm{tr}\,\hat{X}^\mu \hat{I}[\delta\hat{\rho}]}$$

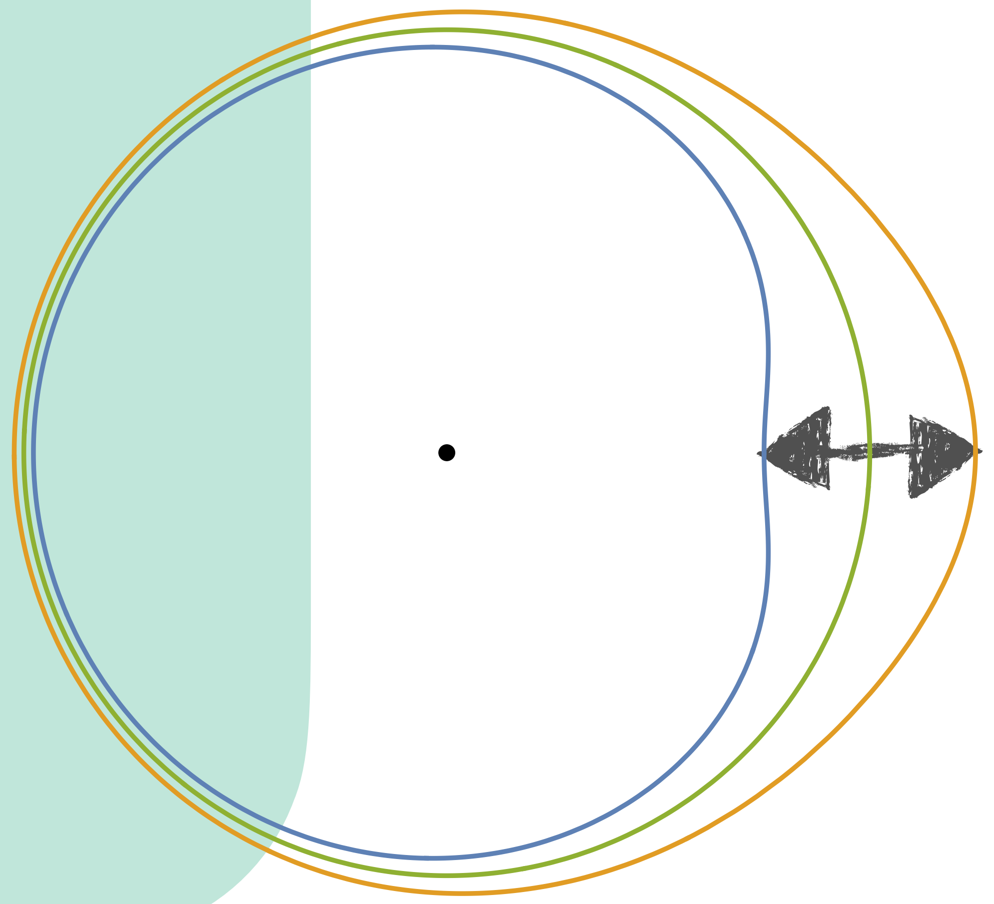
Zero Sound

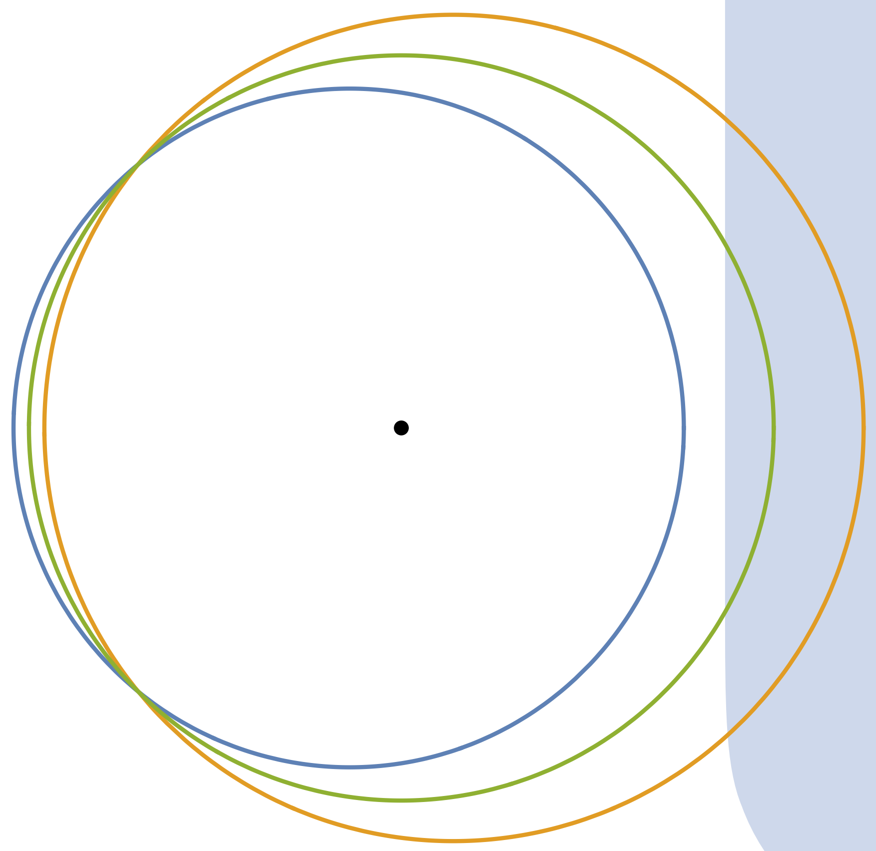
$$\omega \gg \frac{1}{\tau}$$

Collisionless

Regime generically exists at low enough temperature

Can be killed by Landau damping





Not guaranteed to exist

First Sound

$$\frac{1}{\tau_1} \ll \omega \ll \frac{1}{\tau_2}$$

Collisional

Can be killed by collisional damping

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Zero sound

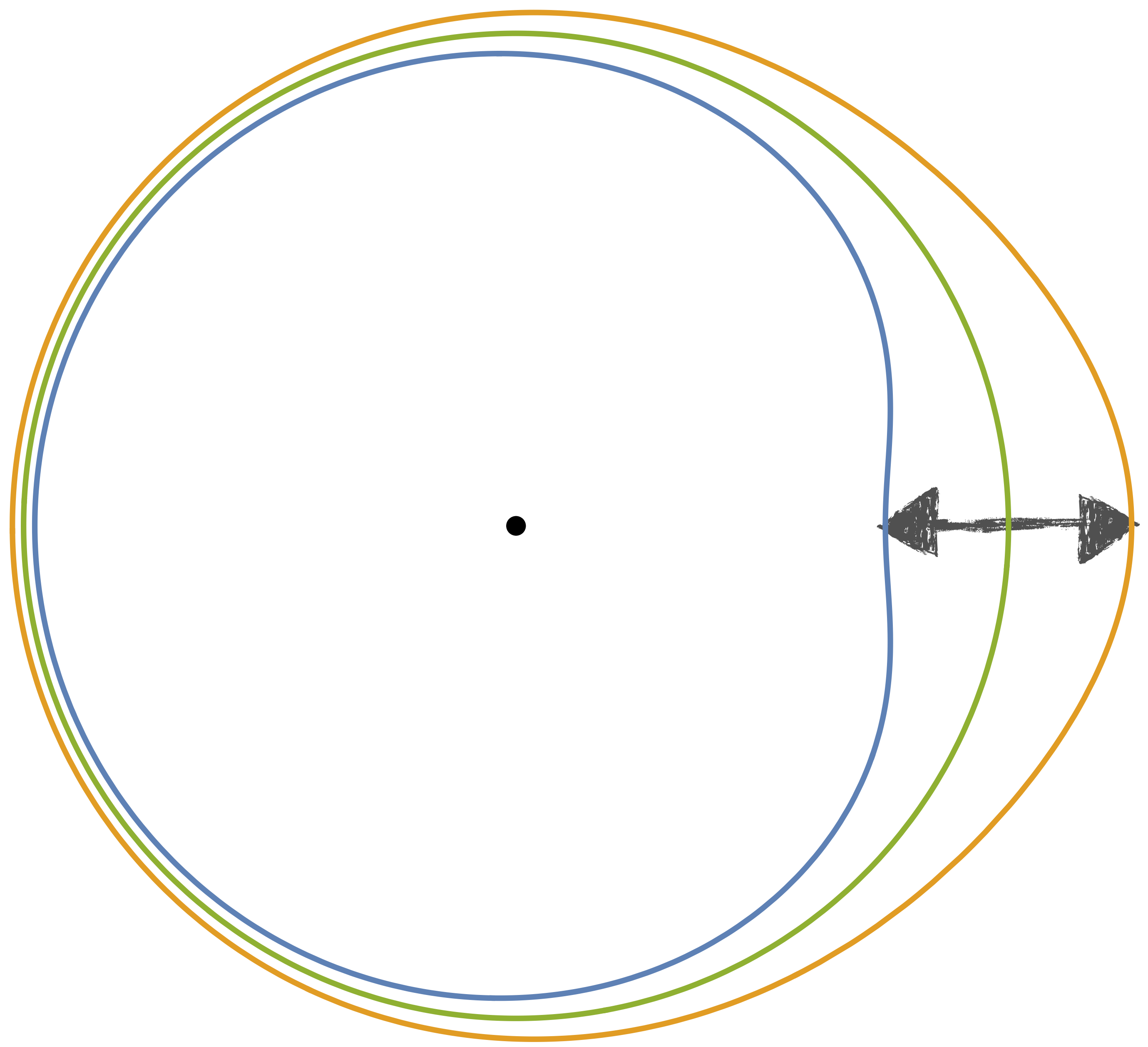
Collisionless equations for the uncharged channels

$$\frac{\partial \delta\rho^{\mu}(\mathbf{k},\mathbf{r})}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}}\delta\bar{\rho}^{\mu}(\mathbf{k},\mathbf{r}) + \frac{\partial n}{\partial \epsilon}\bigg|_{\bar{\epsilon}} \mathbf{v}\cdot\mathscr{F}^{\mu} = \cancel{\frac{1}{G_s G_v}\mathrm{tr}\,\hat{X}^{\mu}\hat{I}[\delta\hat{\rho}]}$$

$$\omega \gg \frac{1}{\tau}$$

occurs when

- Zero sound occurs in the collisionless limit
  - Sound oscillations are much faster than relaxation
  - e.g $T \to 0$ since $I \propto (T/E_F)^2$
- Relaxes through **Landau damping**



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Zero sound

Is it damped?

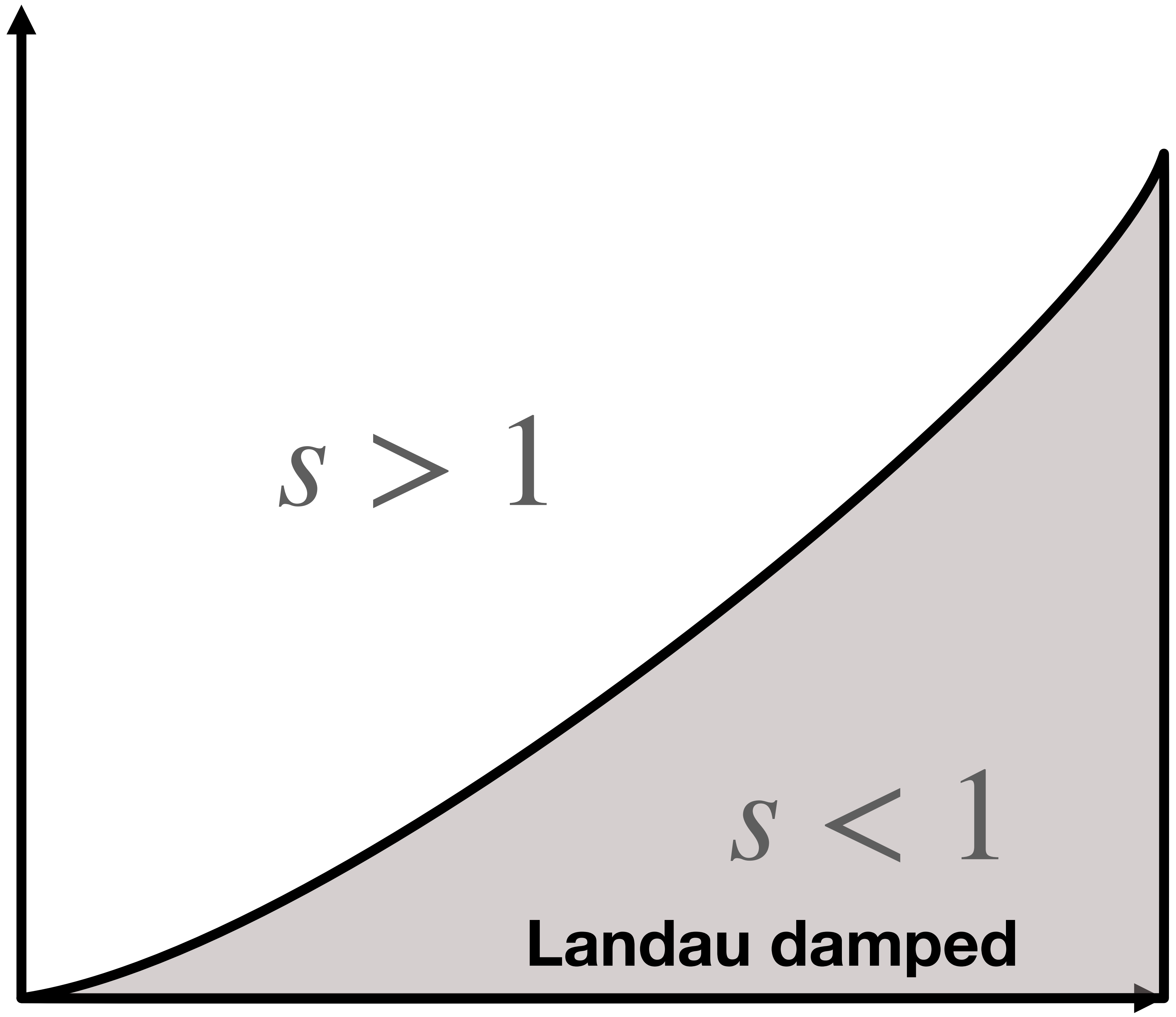
$\omega \gg \frac{1}{\tau}$

$$-i\omega\rho^{\mu}(\mathbf{k},\mathbf{q}) + i\mathbf{v}\cdot\mathbf{q}\delta\bar{\rho}^{\mu}(\mathbf{k},\mathbf{r}) = -\left.\frac{\partial n}{\partial \epsilon}\right|_{\bar{\epsilon}} \mathbf{v}\cdot\mathscr{F}^{\mu}$$

- Natural independent variable

$$|s| \equiv \left|\frac{\omega}{v_F q}\right|$$

- Solutions for $s > 1$ undamped
- Solutions for $s < 1$ Landau damped



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Absence of zero sound

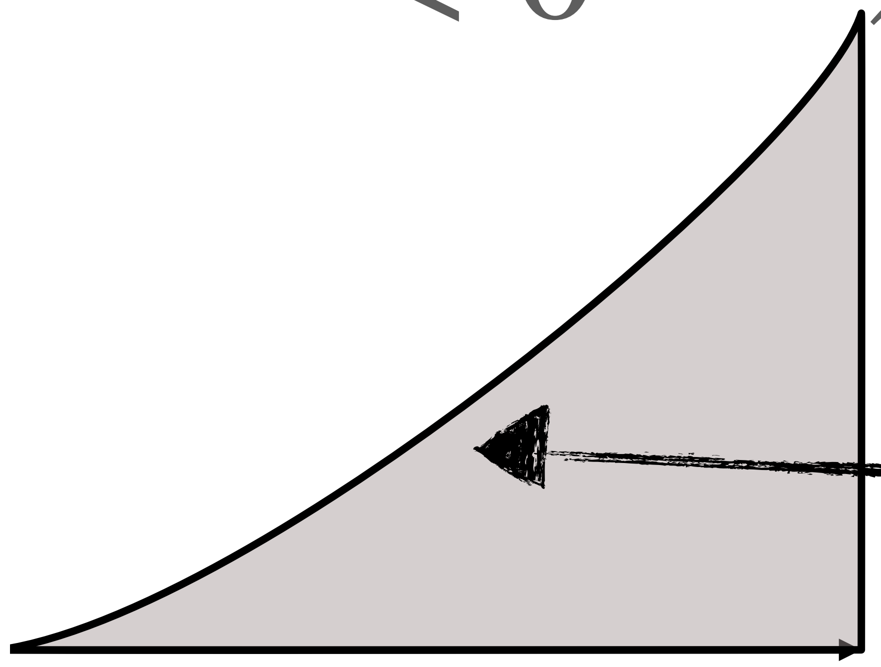
Generic Landau damping

Due to the properties of the Coulomb interaction f^μ is negative definite

$$\oint \frac{d\phi}{2\pi}(s-\cos\phi')[\nu^\mu(\phi)]^2 = \frac{G_s G_v p_F}{v_F}\oint\oint \frac{d\phi d\phi'}{2\pi}\nu^\mu(\phi) f^\mu(\phi-\phi')\nu^\mu(\phi')$$

$< 0 \implies s < 1$

< 0



Landau damped, $\omega < v_F q$

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What about first sound

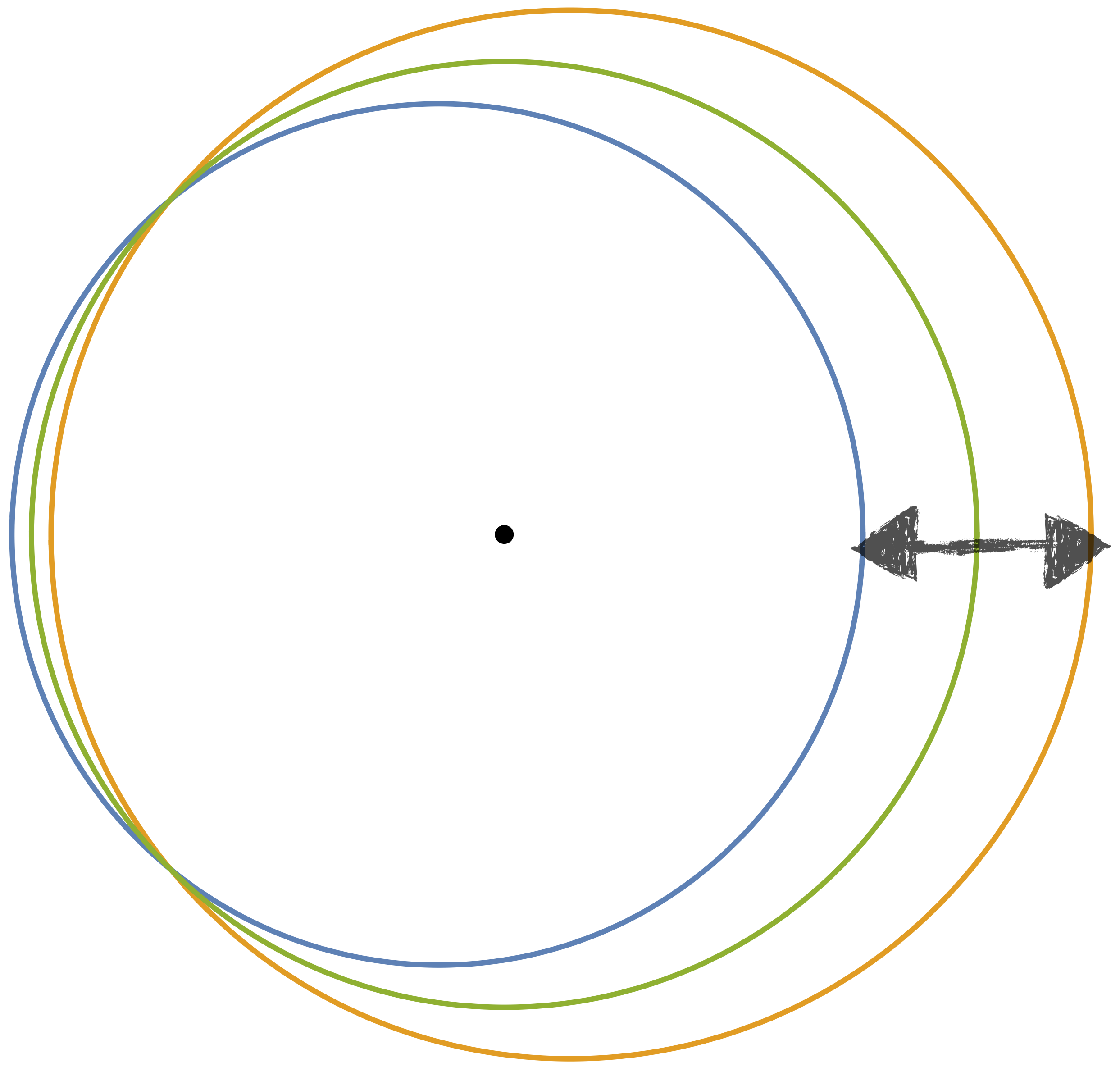
is there a hydrodynamic regime in neutral channels

$m = 0$	$\sum_p \delta\rho_p^\mu$	**Density**	**Conserved**
$m = \lvert 1 \rvert$	$\sum_p \cos\phi_{p_F}\delta\rho_p^\mu$	**Current**	
$m = \lvert 2 \rvert$	$\sum_p \cos^2\phi_{p_F}\delta\rho_p^\mu$		**Not**
	$\vdots$		

occurs when

$$\frac{1}{\tau_1} \ll \omega \ll \frac{1}{\tau_2}$$

?



- Existence of first sound rests on the behavior of the collision integral
- Specifically the relation between scattering time for different angular harmonics on the Fermi surface

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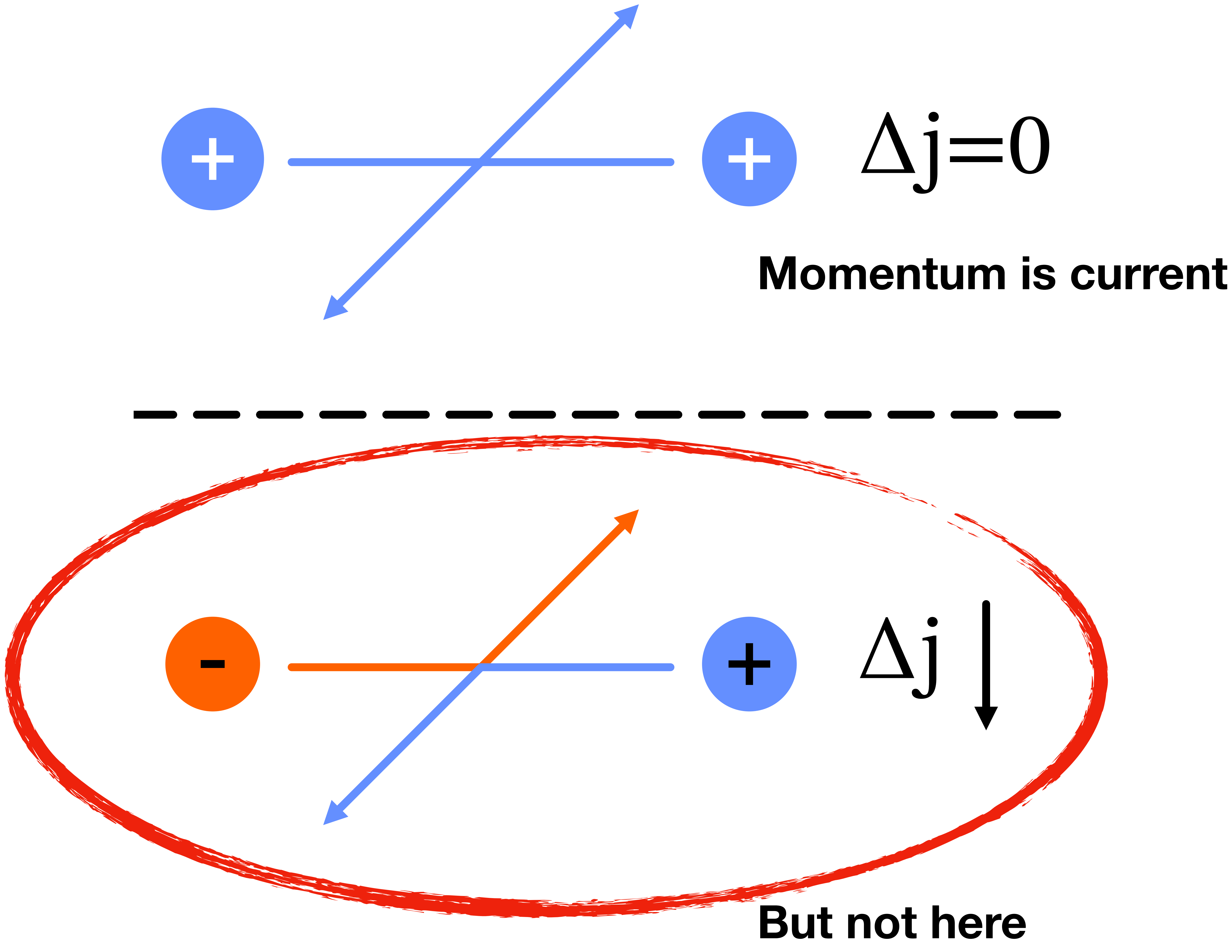
Neutral channels

How do these modes relax?



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No neutral first sound

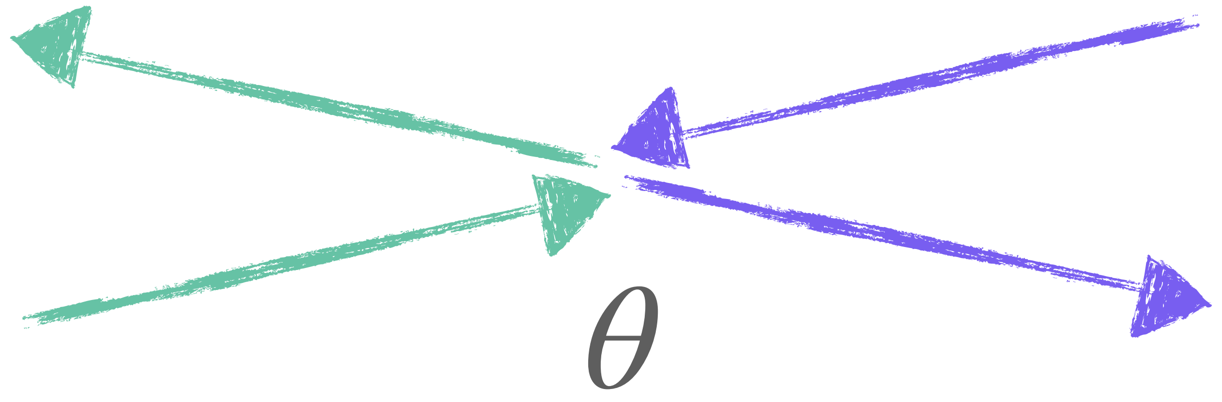
Not hydrodynamics, but diffusion

- There is no frequency regime in which neutral first sound is not overdamped

- Finite temperature transport in neutral channels is ultimately diffusive

$$\omega\tau_1 \ll 1$$

$$D^\mu \approx \frac{v_F^2}{2}\tau^\mu_{\text{tr}}(1 + F^\mu_0)$$



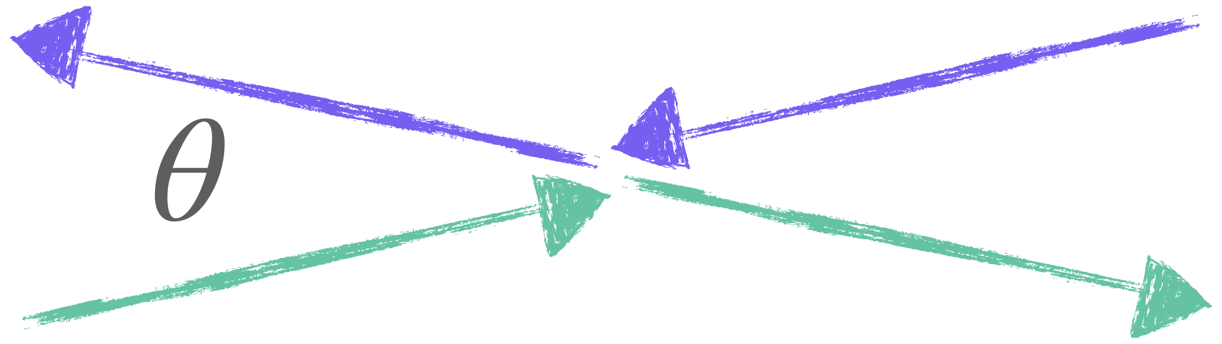
$$\cancel{\frac{1}{\tau_1} \ll \omega \ll \frac{1}{\tau_2}}$$

$$\frac{1}{\tau^\mu_1} \propto T^2\left[\ln(E_F/T) + \ln(E_F/vq_{TF})\right]$$

$$\gtrsim$$

$$\frac{1}{\tau^\mu_2} \propto T^2$$

First sound regime is “squeezed out”



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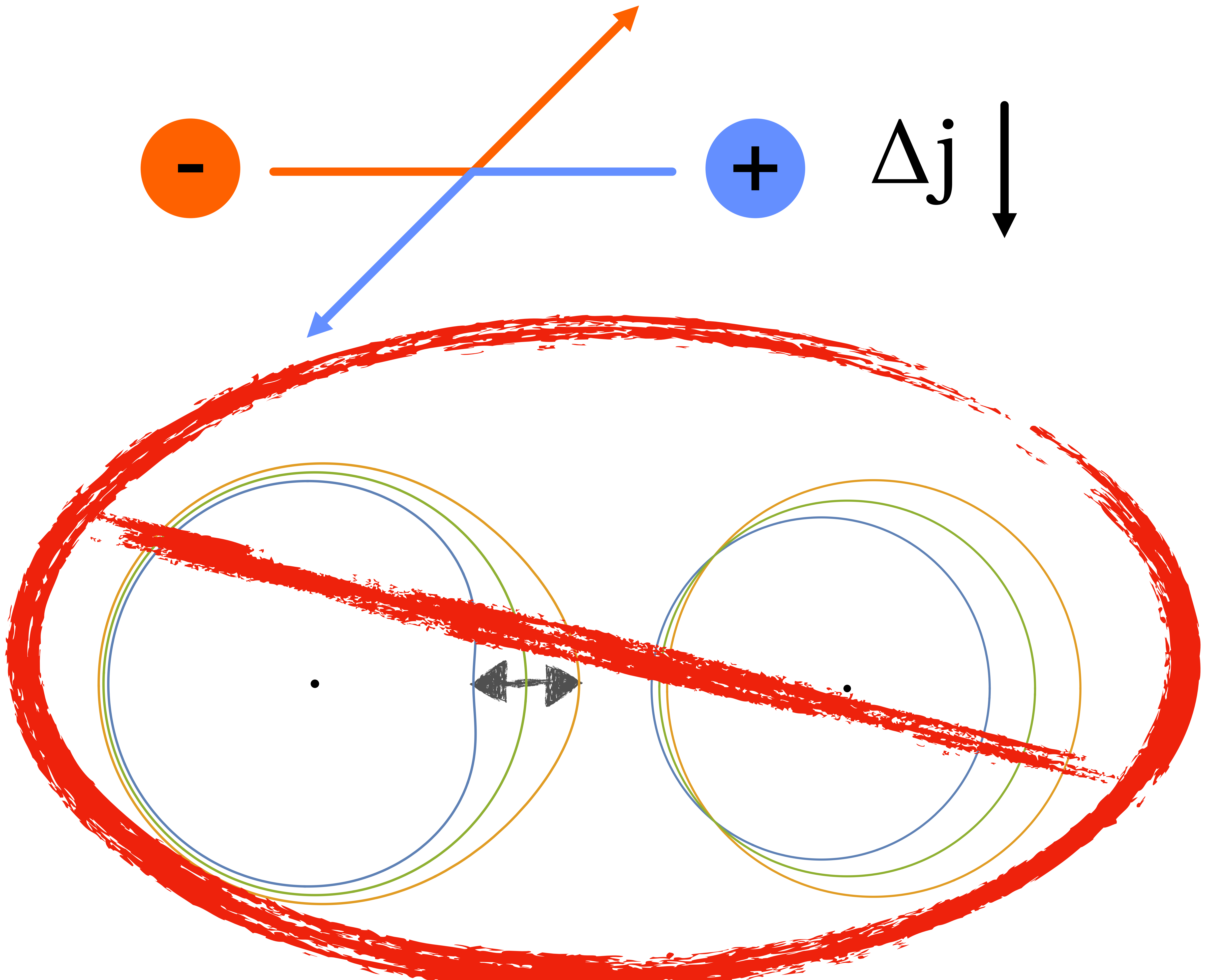
Summary

Thank you for your attention!

- Symmetry dictated Fermi liquid theory of graphene
- Neutral zero sound and first sound in graphene are absent for all spin-valley channels.
- Transport of spin-valley quantum numbers is generically diffusive



ZMR, Fal'ko, Glazman, PRB, 2020