Electromechanical properties of suspended graphene membranes

Eros Mariani

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University of Exeter (UK)

in collaboration with Felix von Oppen (FU Berlin) and Alex Pearce (Exeter)

Suspended graphene membranes

Graphene in between QED, hard and soft condensed matter

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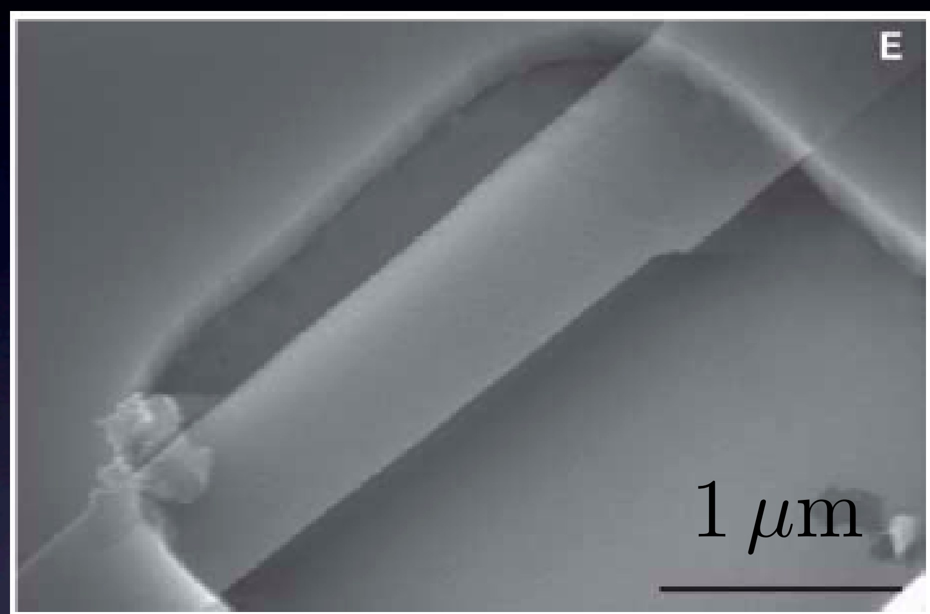
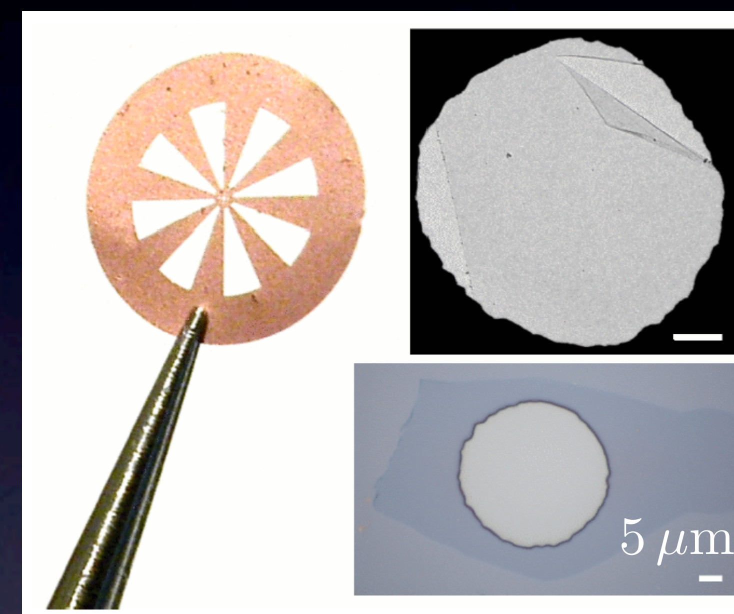
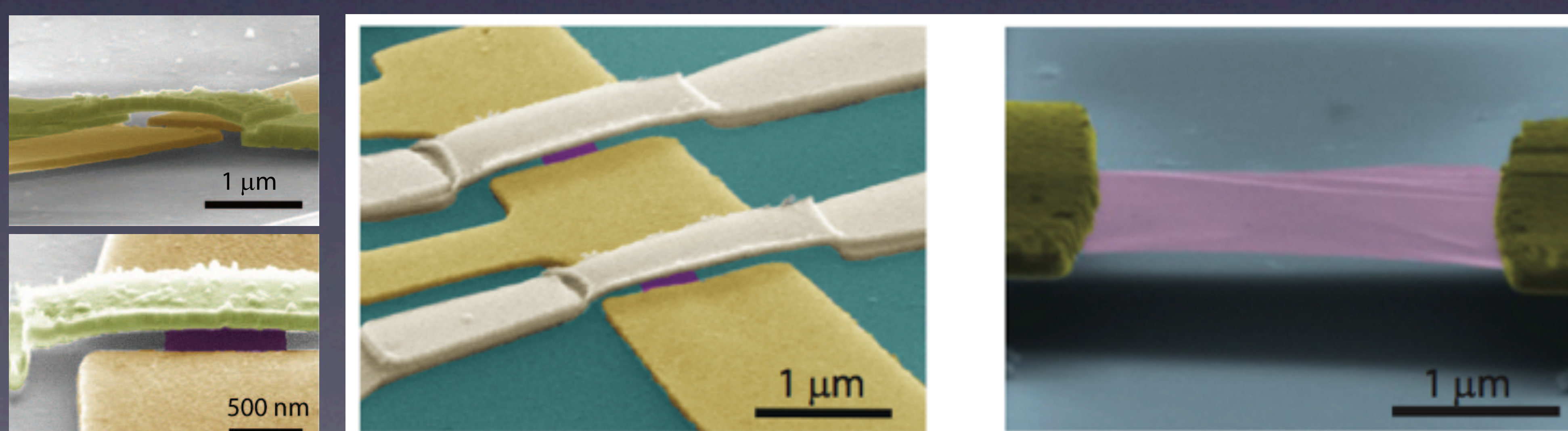
Graphene in between QED, hard and soft condensed matter



Scott-Bunch 07



Geim group 08



S. Russo, Exeter 2011

Questions

Flexural phonons VS in-plane ones?

How do phonons affect transport? Resistivity vs. T?

Deformations in mono- and bilayer membranes?

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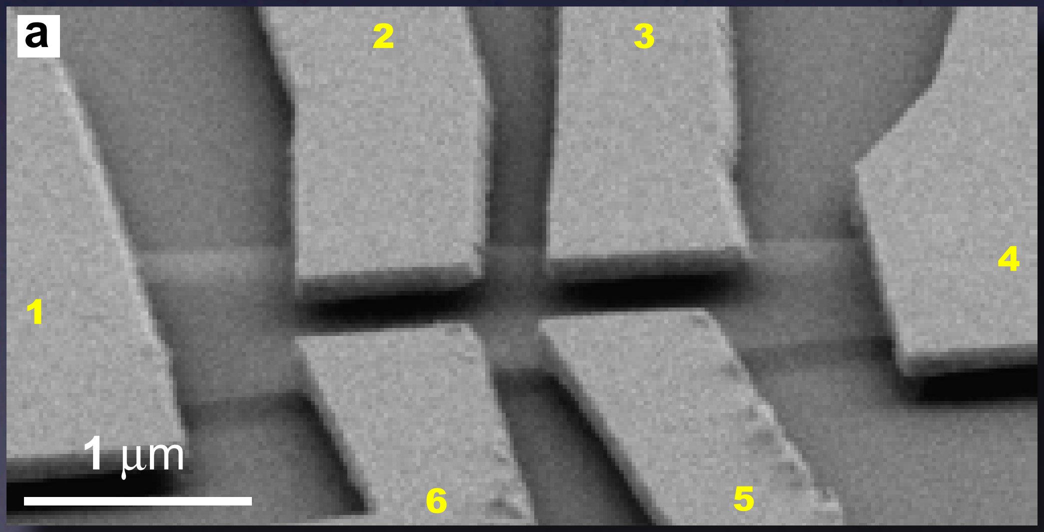
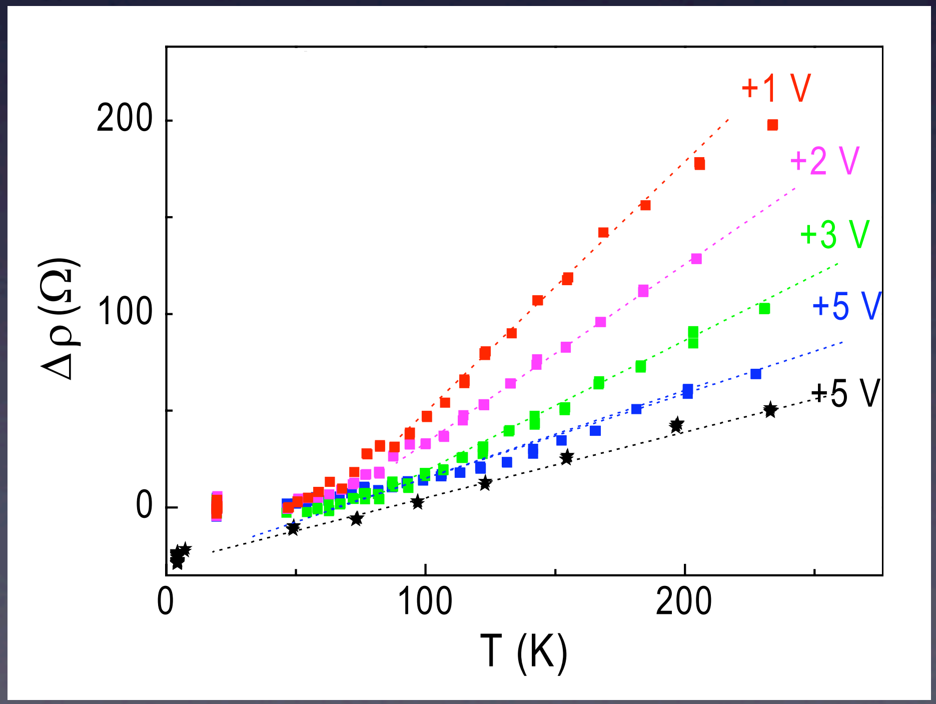




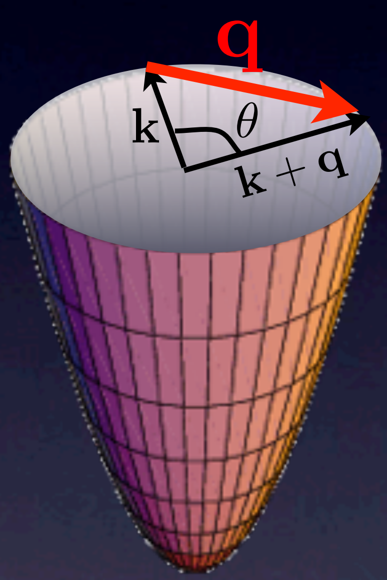
Bolotin et al, PRL 08

See also Morozov 08 and Chen 08 in non-suspended samples

TEXTBOOK

In-plane Phonon resistivity (in 2D)

$$\rho = \frac{m}{ne^2 \tau_{\rm tr}} \qquad \frac{1}{\tau_{\rm tr}} = \frac{2\pi}{\hbar} \int d\mathbf{q}\, |M_{\rm FI}|^2 \, (1-\cos\theta)\; \delta\left(\epsilon_{\mathbf{k}+\mathbf{q}} - \epsilon_{\mathbf{k}} \pm \hbar\omega_{\mathbf{q}}\right)$$



$$d\mathbf{q} \sim q^2$$

$$|M_{\rm FI}|^2 \sim q\, N_q^{(\rm Bose)} \sim q\, \frac{T}{\omega_q}$$

$$\delta(\ldots) \sim \frac{1}{q}$$

$$(1-\cos\theta) \sim q^2$$

$$T_{\rm BG} = \omega_{2k_{\rm F}}$$

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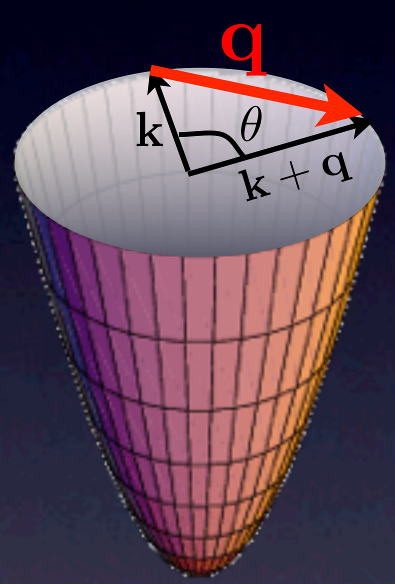

$$d\mathbf{q} \sim q^2$$

$$|M_{\rm FI}|^2 \sim q\,N_q^{\rm (Bose)} \sim q\,\frac{T}{\omega_q}$$

$$\delta(...) \sim \frac{1}{q}$$

$$(1-\cos\theta) \sim q^2$$

$$T_{\rm BG} = \omega_{2k_{\rm F}}$$

$$T \ll T_{\rm BG}$$

$$q \in [0, \frac{T}{\hbar v_{\rm ph}}]$$

$$\rho \propto T^4$$

$$T \gg T_{\rm BG}$$

$$q \in [0, 2k_{\rm F}]$$

$$\rho \propto T$$

Bloch law

TEXTBOOK

In-plane Phonon res… ty (in 2D)

$$\rho = \frac{m}{ne^2\tau_{\rm tr}}$$

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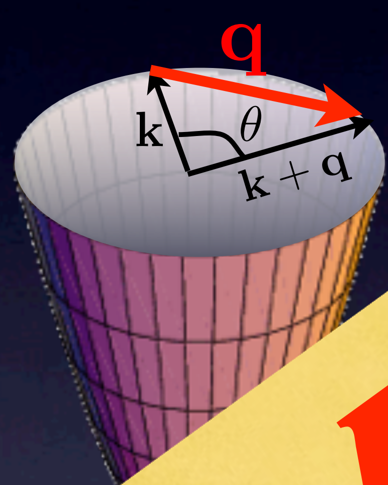


ARE WE FINISHED?

$T_{\rm BG} = \omega_2 \ldots$

$\ldots \frac{\ldots}{\hbar v_{\rm ph}}]$

$\rho \propto T^4$

$T \gg T_{\rm BG}$

$q \in [0, 2k_{\rm F}]$

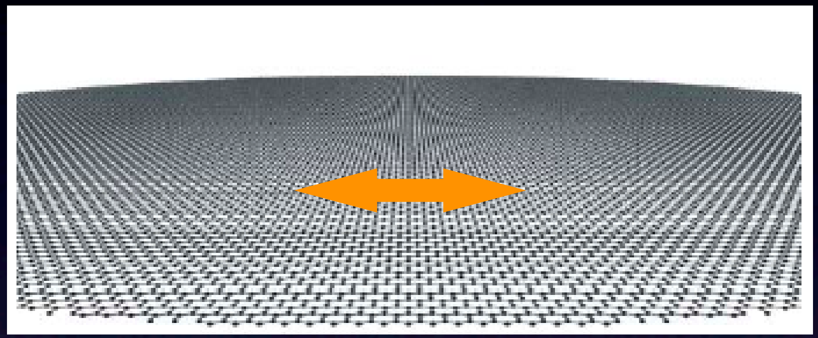
$\rho \propto T$

Bloch law

Phonons in graphene

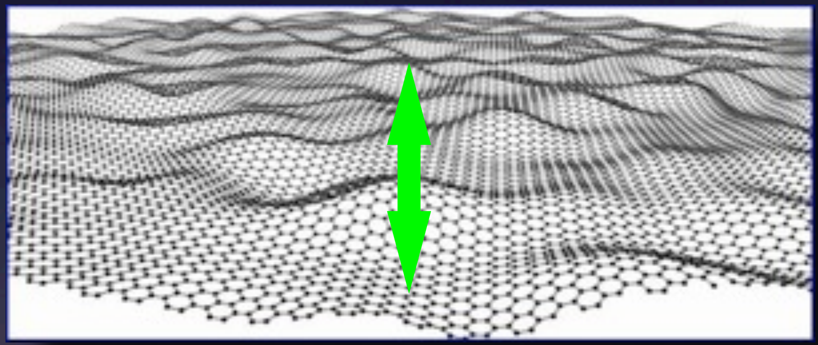
Woods '00
Katsnelson '07
Castro-Neto '07

In-plane modes



Hard to excite
Good coupling to electrons

Flexural modes



Soft to excite
Weak coupling to electrons

Q?

How do they couple to electrons?

What is their dispersion?

Electron-phonon coupling

(basic mechanism)

$$H = \mathrm{v}\begin{bmatrix} & p_x - ip_y \\ p_x + ip_y & \end{bmatrix} \begin{matrix} A \\ B \end{matrix}$$

Electron-phonon coupling

(basic mechanism)

Membrane Distortions → variation of areas (and density)

$$\rho \longrightarrow \rho + \delta\rho$$

→ Diagonal coupling

$$H^{(\mathrm{Def})}_{\mathrm{e-ph}} = \delta t_{\mathrm{on-site}}\, c^{\dagger}_j c_j$$

$$H = \mathrm{v}\begin{bmatrix} \delta t_{\mathrm{on-site}} & p_x - ip_y \\ p_x + ip_y & \delta t_{\mathrm{on-site}} \end{bmatrix} \begin{matrix} A \\ B \end{matrix}$$

Deformation potential (screened)

Electron-phonon coupling

(basic mechanism)

Membrane Distortions

→ variation of areas (and density)

$$\rho \longrightarrow \rho + \delta\rho$$

→ Diagonal coupling

$$H^{(\mathrm{Def})}_{\mathrm{e-ph}} = \delta t_{\mathrm{on-site}}\, c^{\dagger}_{j} c_{j}$$

→ Modified bond lenght, correction to hopping

$$t \longrightarrow t + \delta t$$

→ Off-diagonal coupling

$$H^{(\mathrm{Gauge})}_{\mathrm{e-ph}} = \delta t_{\mathrm{hop}}\, c^{\dagger}_{A} c_{B}$$

$$H = \mathrm{v}\begin{bmatrix} \delta t_{\mathrm{on-site}} & p_x - i p_y + \delta t_{\mathrm{hop}} \\ p_x + i p_y + \delta t_{\mathrm{hop}} & \delta t_{\mathrm{on-site}} \end{bmatrix} \begin{matrix} A \\ B \end{matrix}$$

Bond-length variation (like a gauge field)

Deformation potential (screened)

$$H = \Pi_z \otimes \sigma \cdot (\mathbf{p} - \frac{e}{c}\mathbf{A}) + V(\mathbf{r})$$

Electron Phonon Coupling

Woods & Mahan 00
Suzuura & Ando '02
Vozmediano review 2010

$$H_{e-ph} = \begin{pmatrix} g_1(u_{xx}+u_{yy}) & g_2(2u_{xy}-i(u_{xx}-u_{yy})) \\ g_2(2u_{xy}+i(u_{xx}-u_{yy})) & g_1(u_{xx}+u_{yy}) \end{pmatrix}$$

$g_1 \simeq 30\, eV$
$g_2 \simeq 1.5\, eV$

fictitious gauge field

$\mathrm{Tr}[u_{ij}] = \frac{\delta S}{S}$

relative area variation

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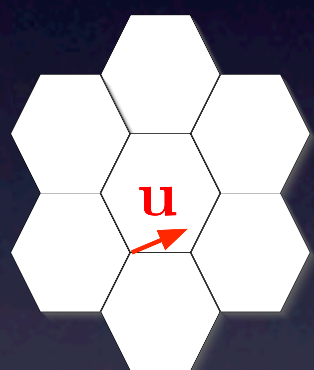

$\mathbf{u}(\mathbf{r})$
In-plane displacement

$h(\mathbf{r})$ Out-of-plane displacement

$$u_{ij} = \frac{1}{2}[\partial_i u_j + \partial_j u_i + (\partial_i h)(\partial_j h)]$$

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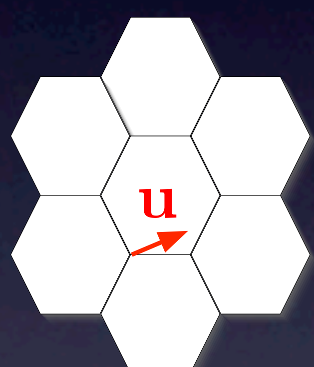
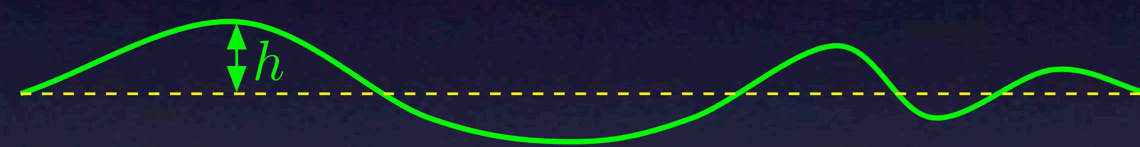


$\mathbf{u}(\mathbf{r})$
In-plane displacement

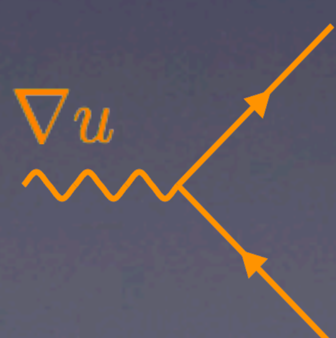


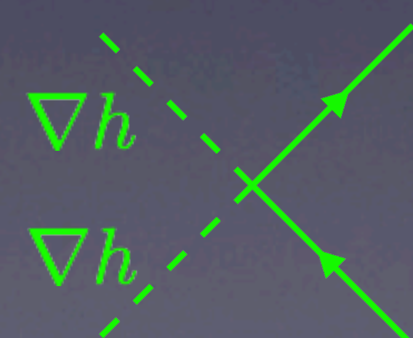
$h(\mathbf{r})$ Out-of-plane displacement

$$u_{ij} = \frac{1}{2}[\partial_i u_j + \partial_j u_i + (\partial_i h)(\partial_j h)]$$

Protected by symmetry
&
Ensures that a rotation implies no strain

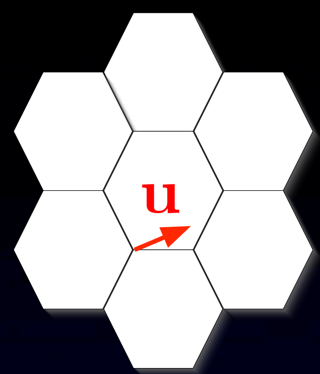
1st order in u





2nd order in h

In-plane vs Flexural phonons



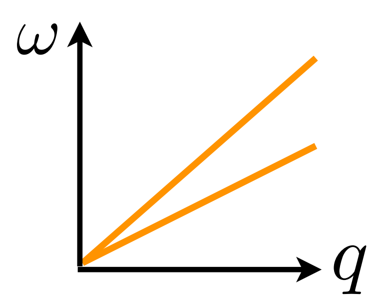
$\mathbf{u}(\mathbf{r})$

In-plane displacement

In-plane phonons

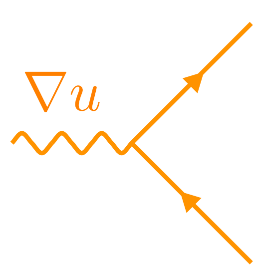
Linear dispersion

$$\omega^{(l,t)} = v^{(l,t)} q$$



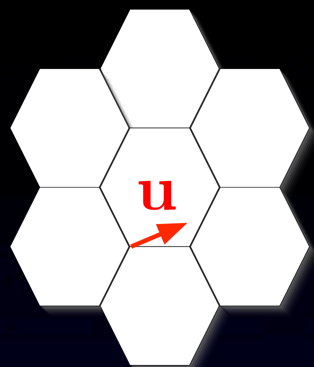
Linear coupling

$$H_{e-ph} \propto u_{ij} \sim \nabla u$$



Small DOS, Good coupling

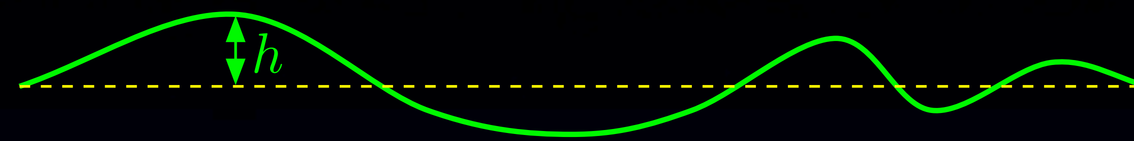
In-plane vs Flexural phonons



$\mathbf{u}(\mathbf{r})$

In-plane displacement

$h(\mathbf{r})$ Out-of-plane displacement



$$\mathcal{L} = \frac{\rho}{2}\dot{h}^2 - \frac{\kappa}{2}\left(\nabla^2 h\right)^2$$

In-plane phonons

Linear dispersion

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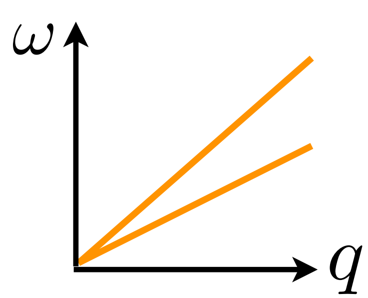

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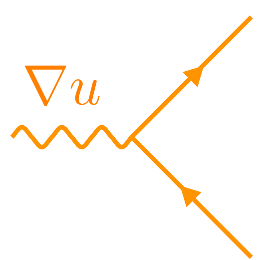

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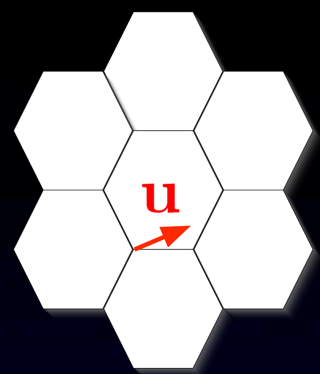
In-plane vs Flexural phonons



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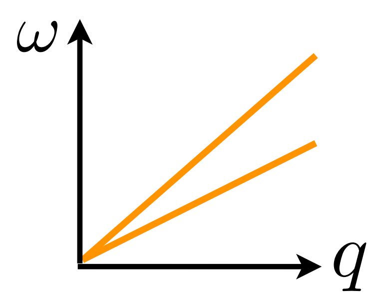

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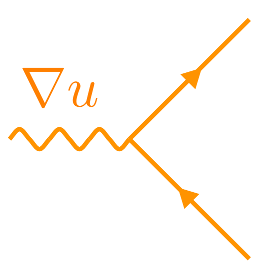
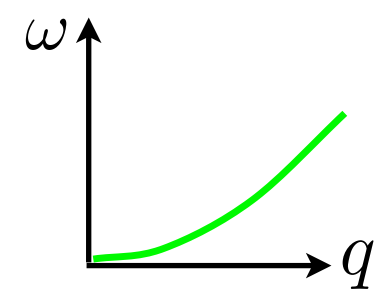


Small DOS, Good coupling

Flexural phonons

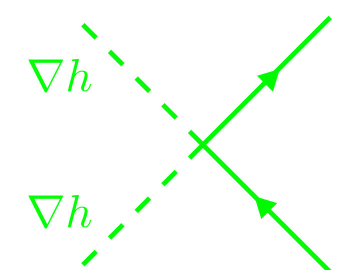
Quadratic dispersion

$$\omega^{(h)} = \alpha q^2$$



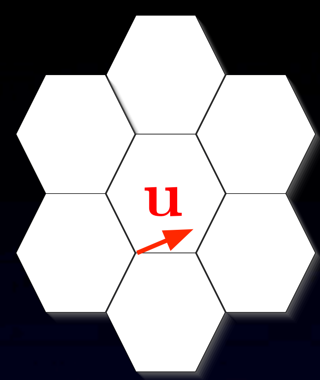
Quadratic coupling

$$H_{e-ph} \propto u_{ij} \sim (\nabla h)^2$$



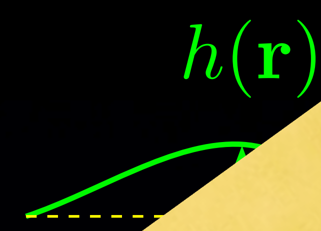
Big DOS, Poor coupling

In-plane vs Flexural phon



$\mathbf{u}(\mathbf{r})$

In-plane displacement



WHO WINS?

In-plane ph

Linear dispe

$\omega^{(l,t)}$

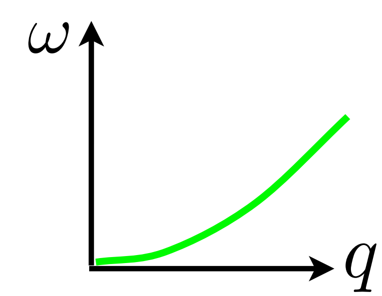
H_{e-ph}

Small DO … coupling

… phonons

… ic dispersion

$\omega^{(h)} = \alpha q^2$



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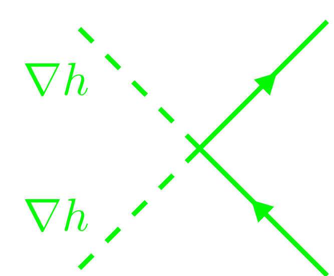
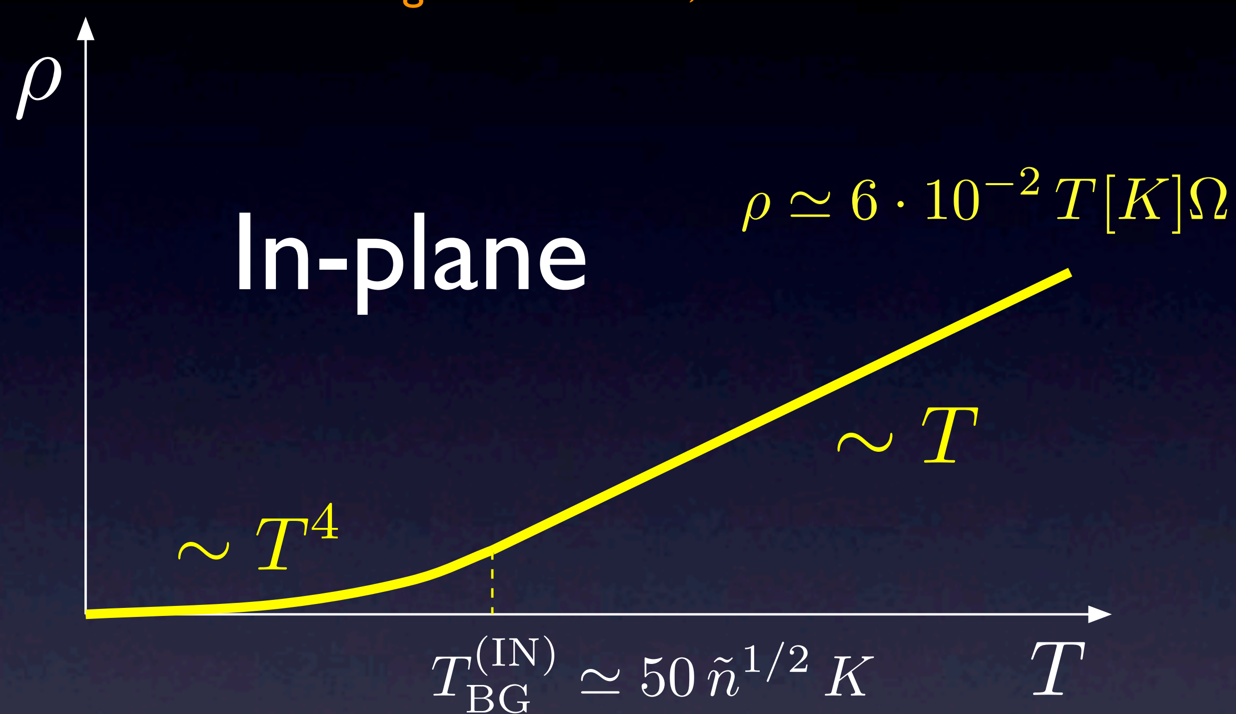
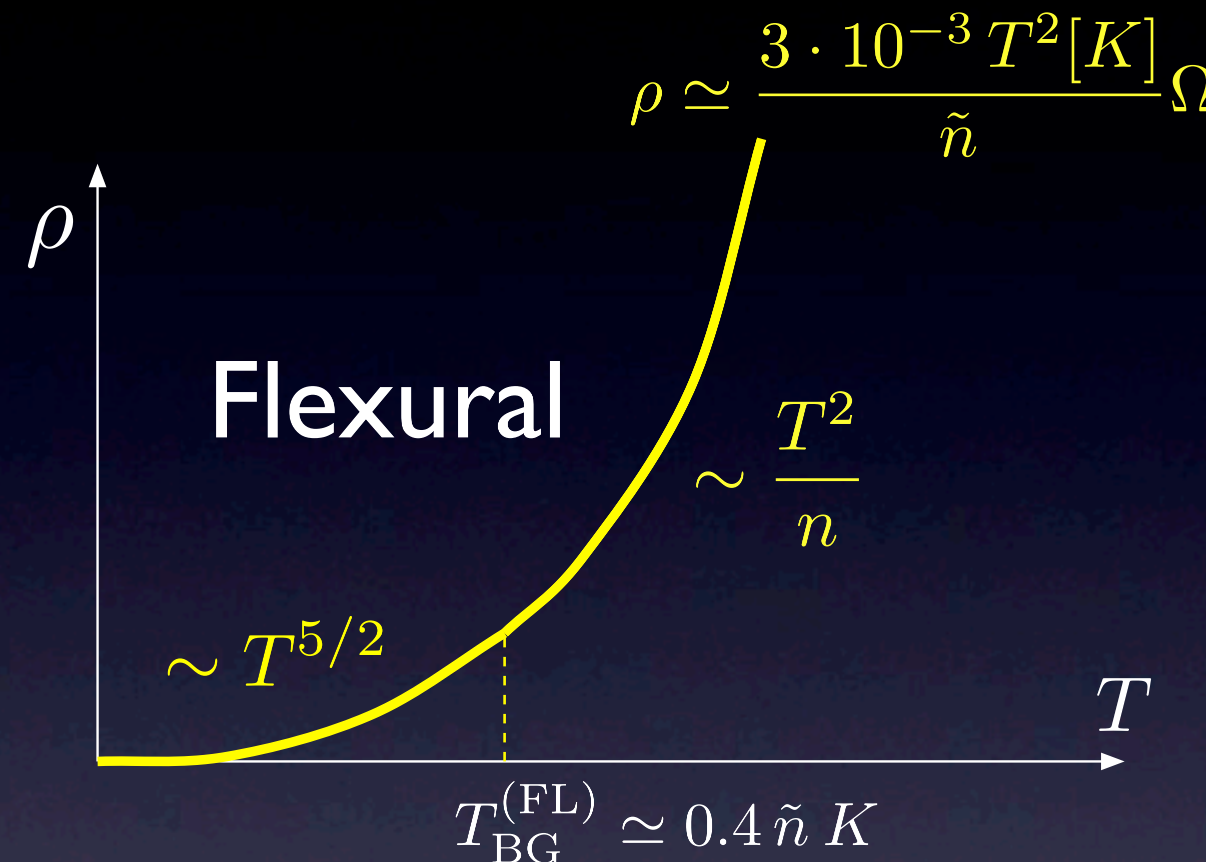


Big DOS, Poor coupling

Temperature-dependent Resistivity

Hwang & Das Sarma, PRB 2008



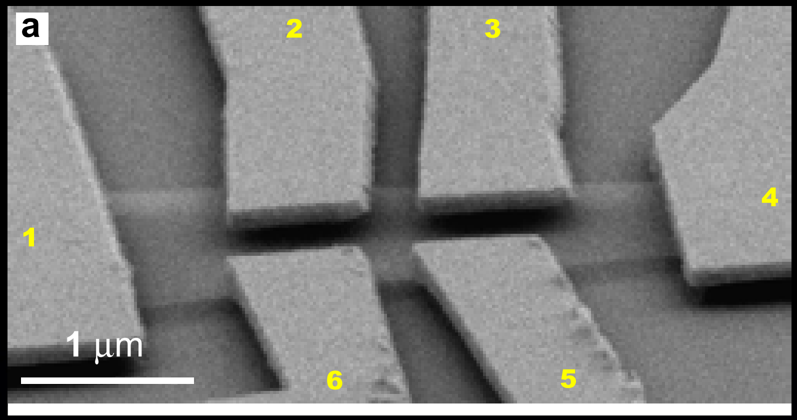


Flexural modes should dominate in-plane ones at present dopings

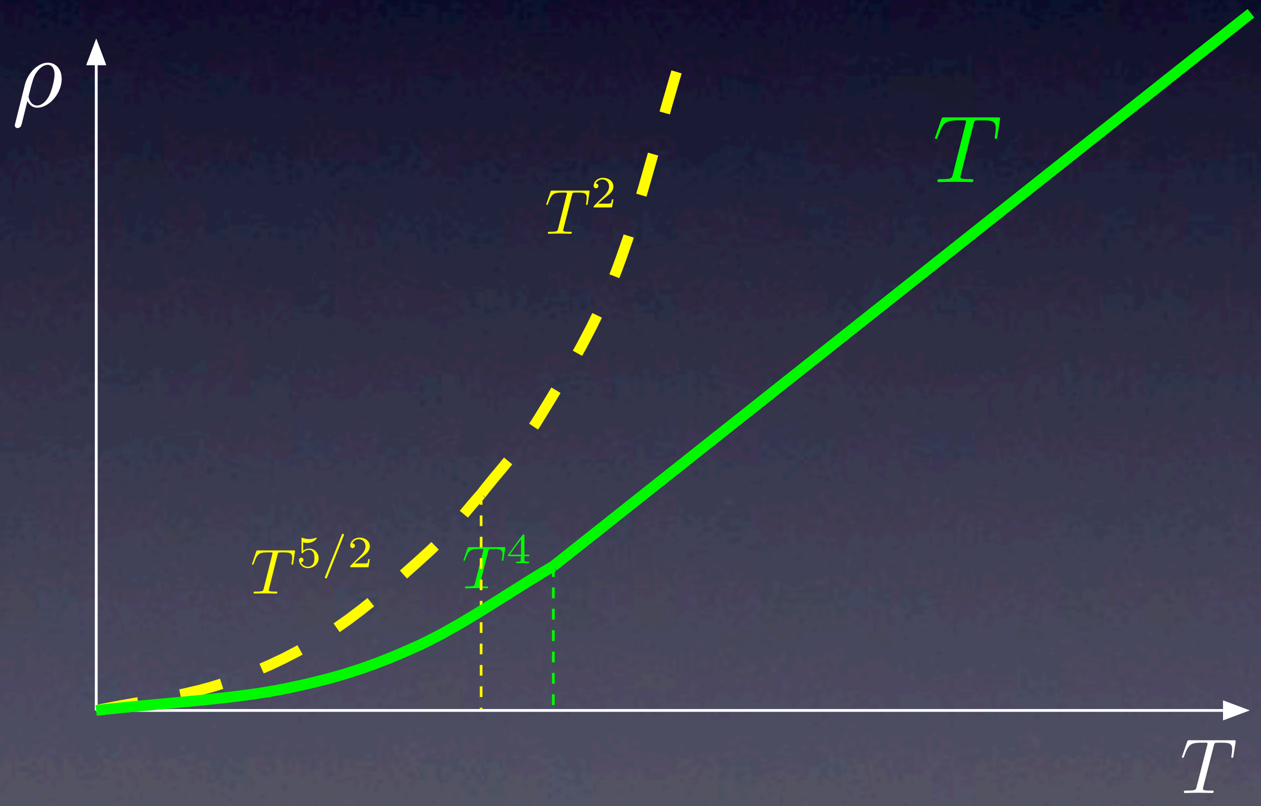
???

E. Mariani and F. von Oppen, Phys. Rev. Lett. **100**, 076801 (2008)
Phys. Rev. Lett. **100**, 249901 (2008)
Phys. Rev. B **82**, 195403 (2010)

Role of tension?

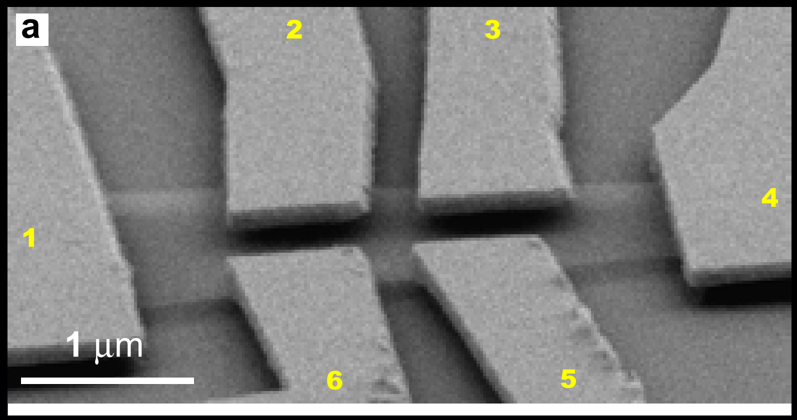


$$F_{\mathrm{bend}} \rightarrow \frac{1}{2}\int \mathrm{d}\mathbf{r}\, \kappa \left(\nabla^2 h\right)^2$$



E. Mariani and F. von Oppen, Phys. Rev. B **82**, 195403 (2010)

Role of tension?

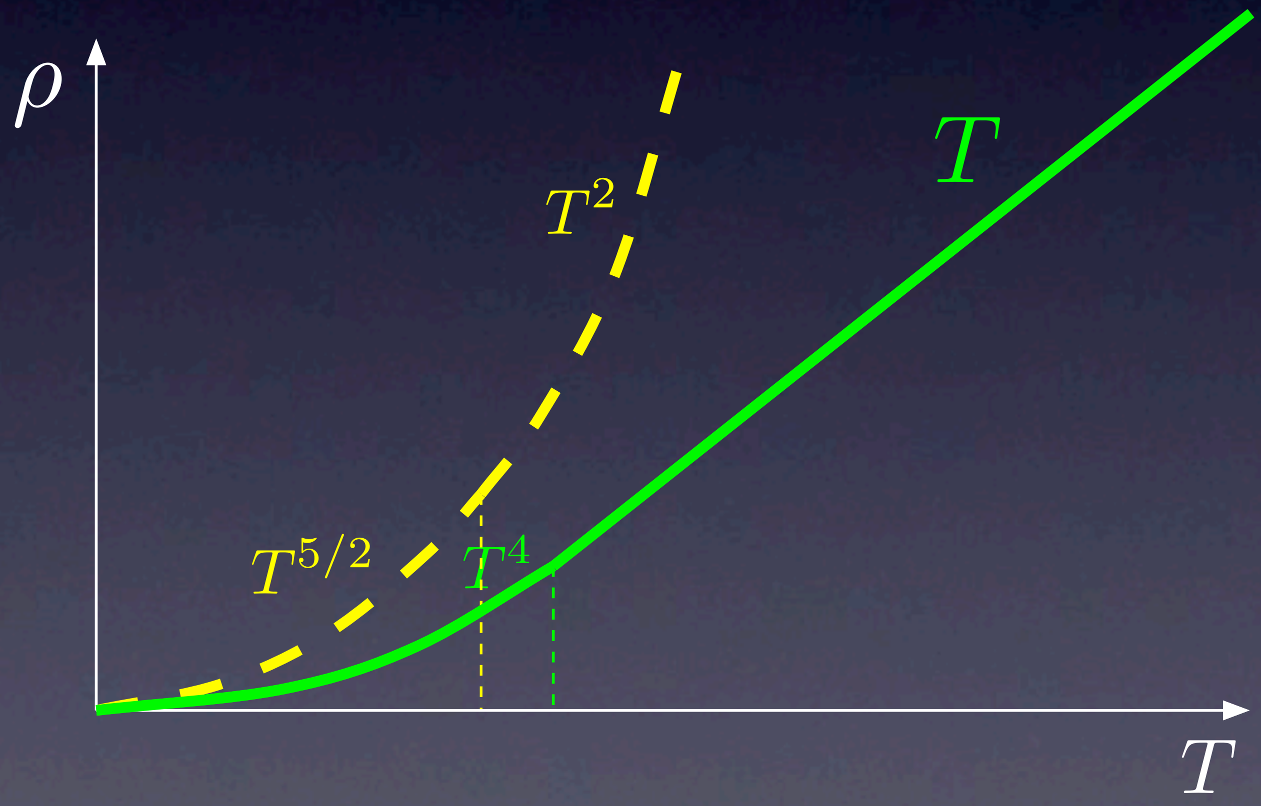


$$F_{\mathrm{bend}} \rightarrow \frac{1}{2}\int \mathrm{d}\mathbf{r}\left[\kappa\left(\nabla^2 h\right)^2 + \gamma\left(\nabla h\right)^2\right]$$

Flexural dispersion stiffening

$$\omega_q \sim q^2 \rightarrow q$$

Reduced DOS



E. Mariani and F. von Oppen, Phys. Rev. B **82**, 195403 (2010)

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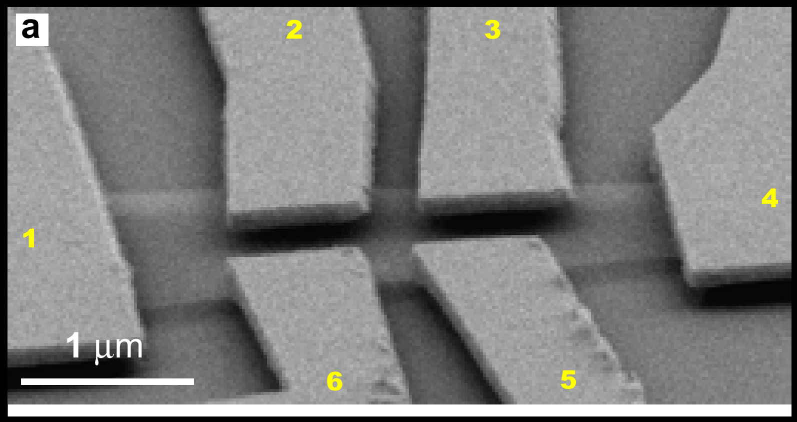

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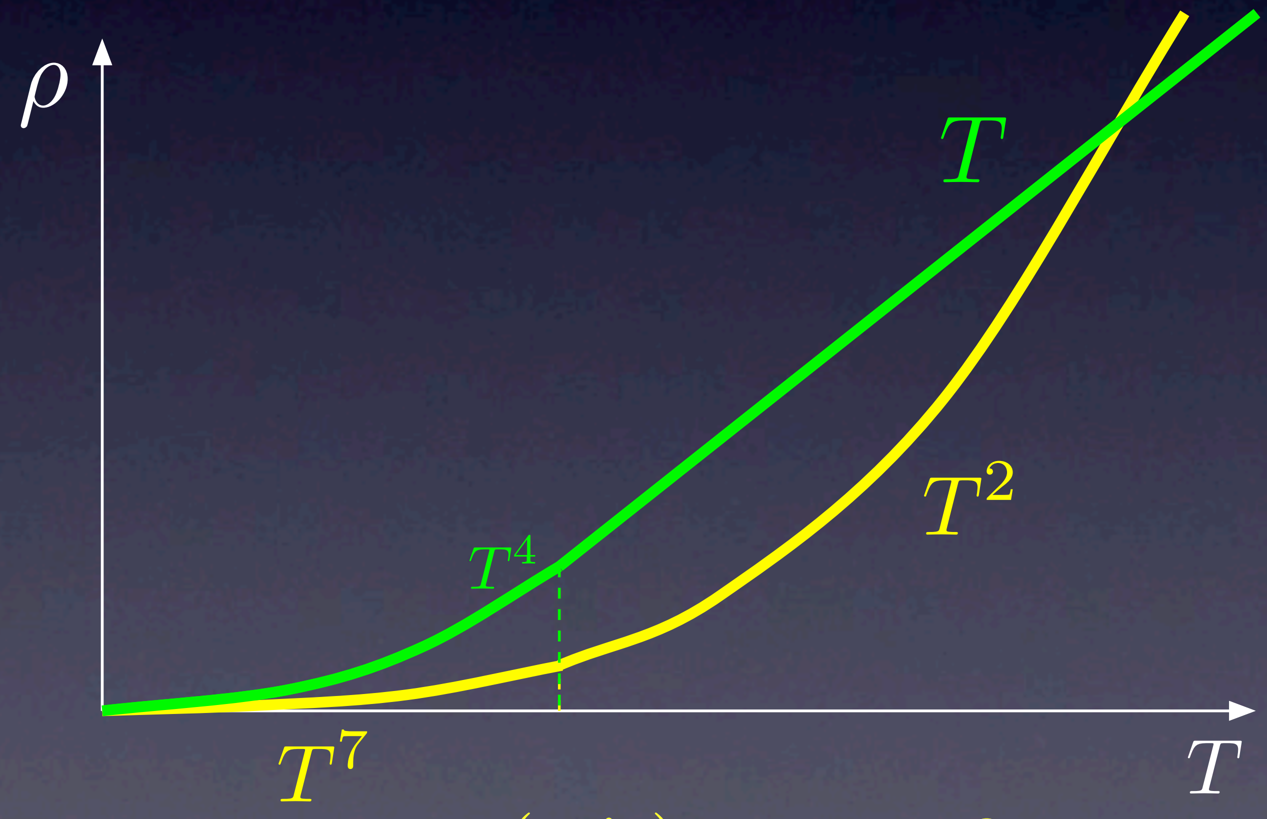
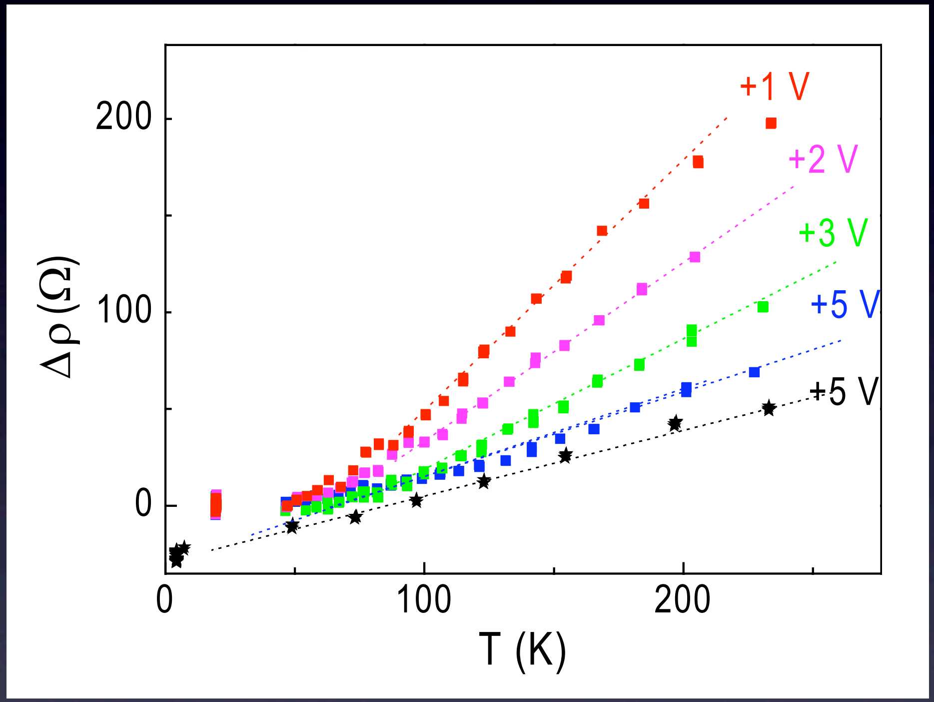


E. Mariani and F. von Oppen, Phys. Rev. B **82**, 195403 (2010)

What experiments tell us



Bolotin et al, PRL 08

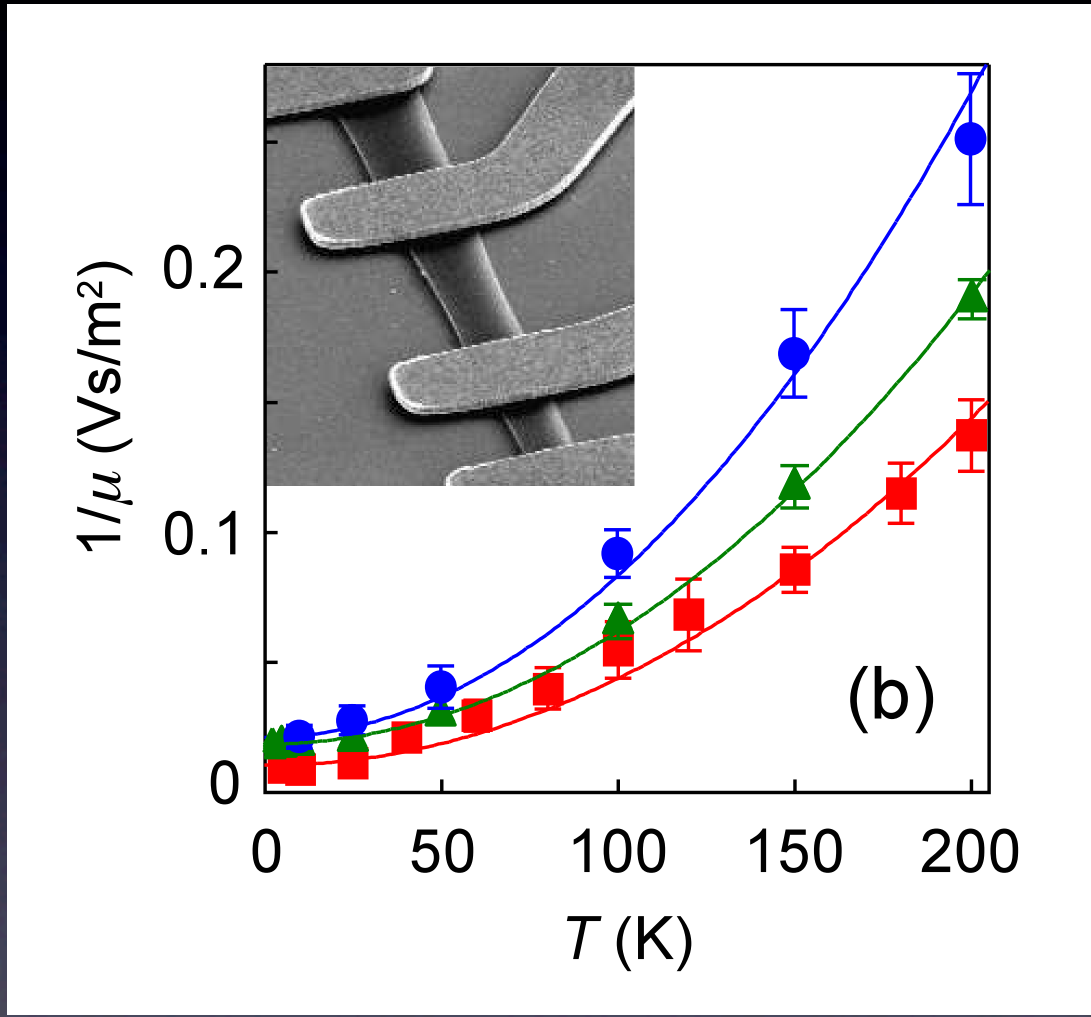
The linear T-dependence implies the presence of tension

Crossover to T^2 would allow to know the strength of tension

E. Mariani and F. von Oppen, Phys. Rev. B **82**, 195403 (2010)

One more thing...

One more thing...



E. Castro et al., Phys. Rev. Lett. **105**, 266601 (2010)

Quadratic temperature dependence observed!

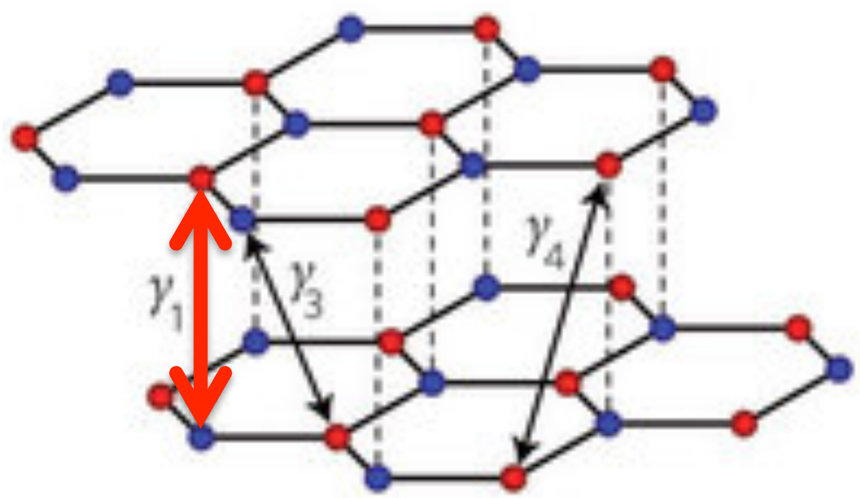
...and what about deformations in Bilayer Graphene Membranes?

EM, A. Pearce and F. von Oppen, arXiv:1110.2769

Electronic Properties of Graphene

(McCann PRL 2006)

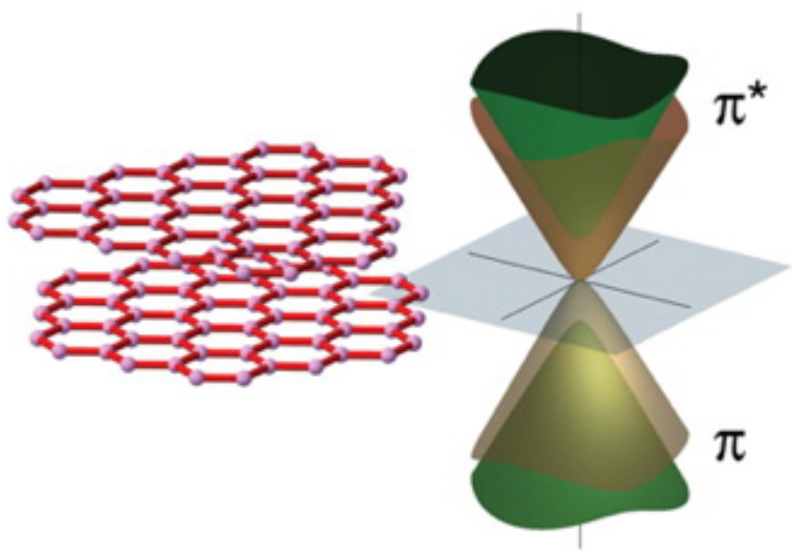
Bilayer Graphene (dominant hopping)



$$\mathcal{H} = \frac{1}{2m}\begin{bmatrix} 0 & (p^\dagger)^2 \\ p^2 & 0 \end{bmatrix} + \frac{\Delta}{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$\epsilon_{\vec{p}} = \pm\frac{1}{2m}(p_x^2 + p_y^2)$$

Δ=0



Massive Dirac Fermions

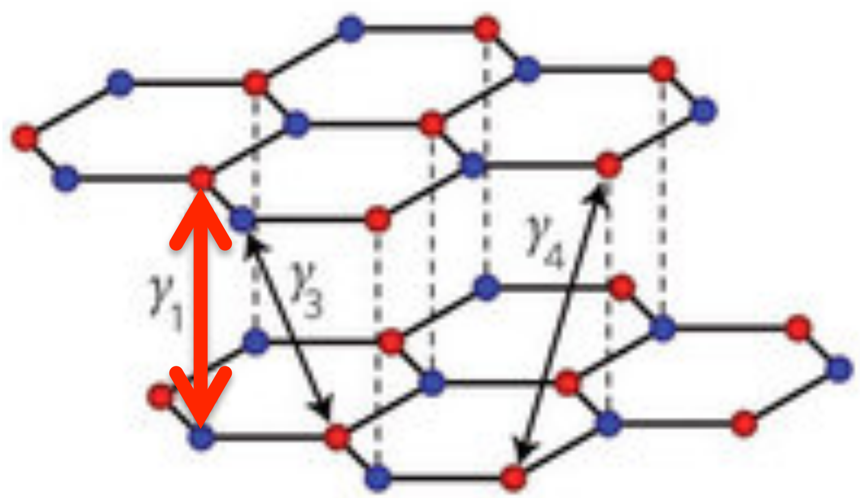
Tuneable bandgap

Berry Phase of parabolic bands $\phi=2\pi$

Electronic Properties of Graphene

(McCann PRL 2006)

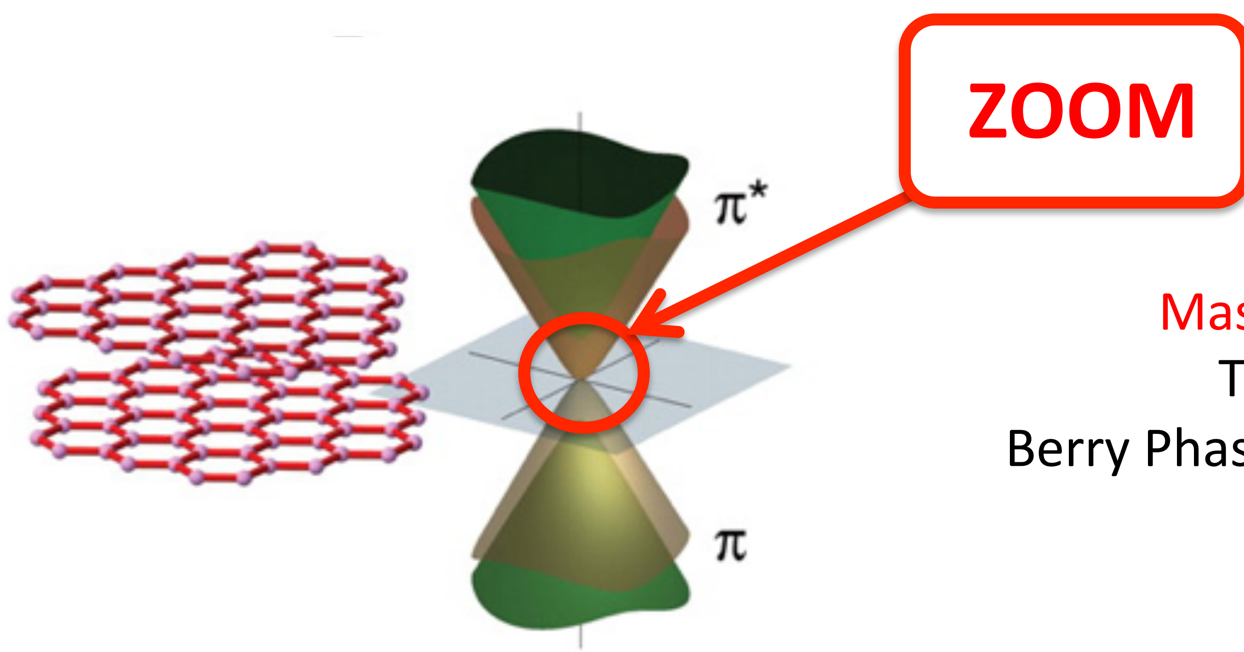
Bilayer Graphene (dominant hopping)



$$\mathcal{H} = \frac{1}{2m}\begin{bmatrix} 0 & (p^\dagger)^2 \\ p^2 & 0 \end{bmatrix} + \frac{\Delta}{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$\epsilon_{\vec{p}} = \pm\frac{1}{2m}(p_x^2 + p_y^2)$$

Δ=0



Massive Dirac Fermions

Tuneable bandgap

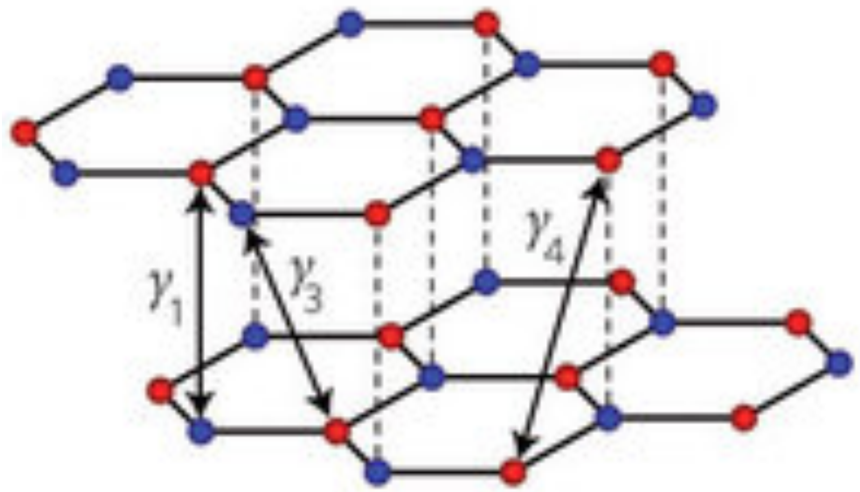
Berry Phase of parabolic bands ϕ=2π

Low Energy bandstructure of Bilayer Graphene

(McCann PRL 2006)

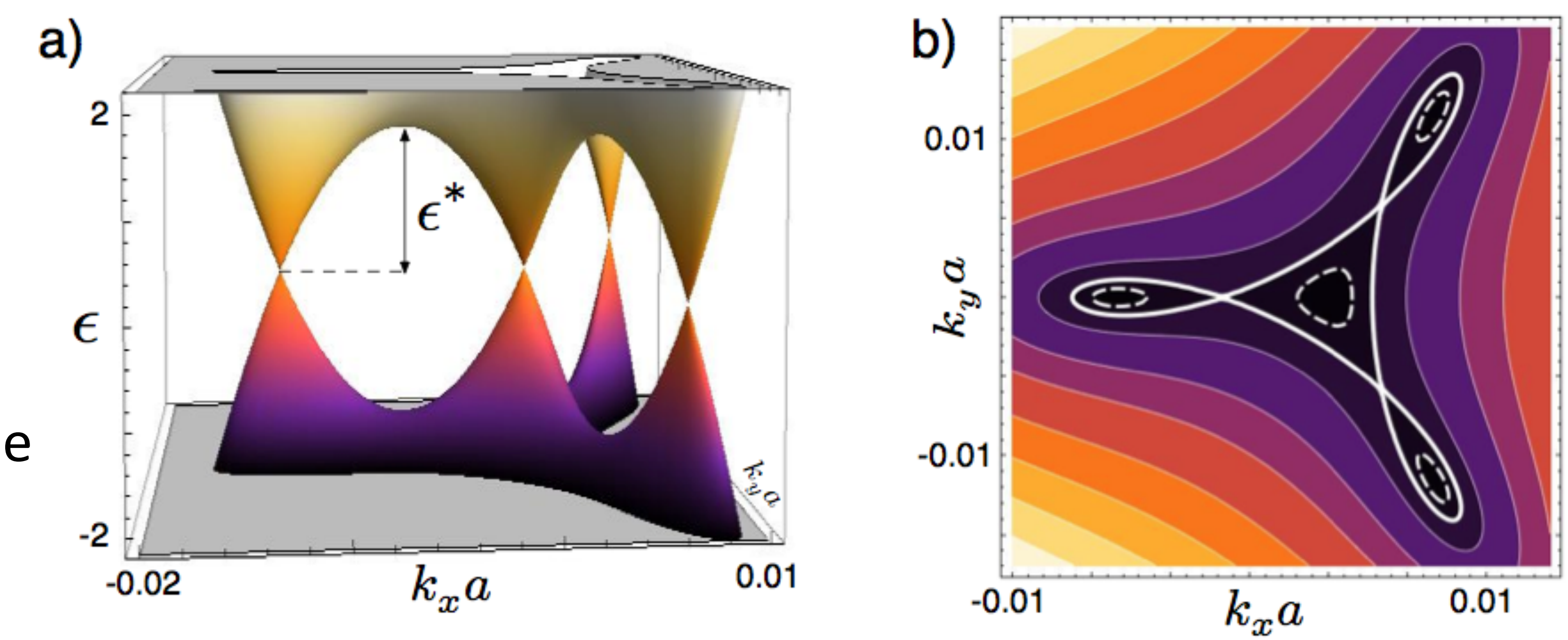
Bilayer Graphene (subdominant hoppings)
Trigonal warping

$$\mathcal{H} = \frac{1}{2m}\begin{bmatrix} 0 & (p^\dagger)^2 \\ p^2 & 0 \end{bmatrix} + v_3 \begin{bmatrix} 0 & p \\ p^\dagger & 0 \end{bmatrix}$$



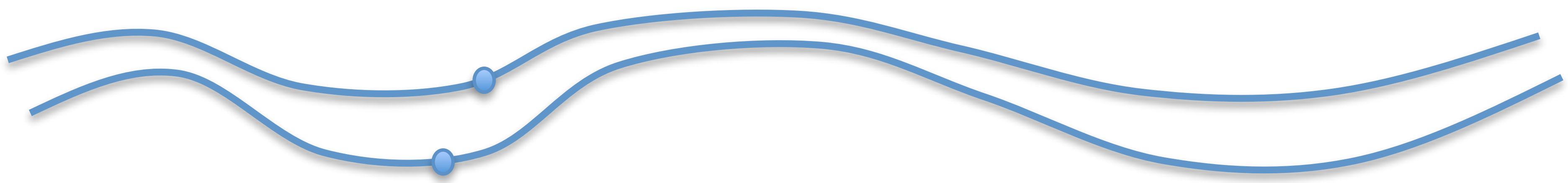
Four massless Dirac cones
at low energy ($\varepsilon^* \approx 1.6$meV)

Lifshitz Transition
Topological Transition in the
Fermi surface

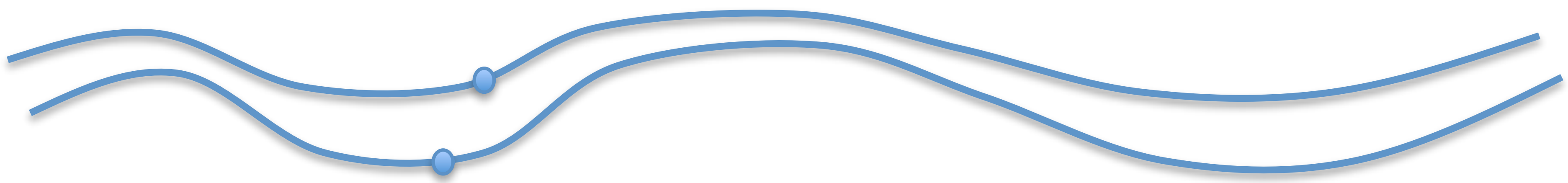


Effects in compressibility and transport measurements

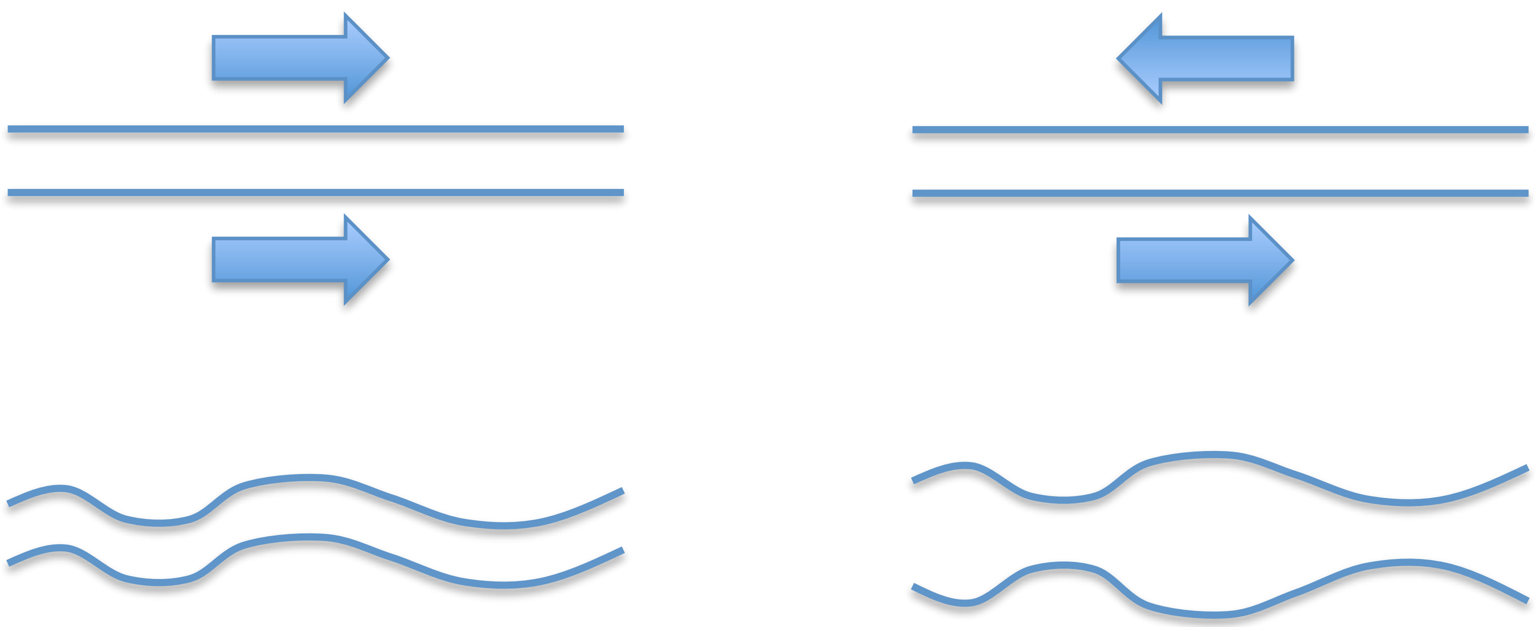
Deformations in bilayer membranes



Deformations in bilayer membranes



Generic elastic deformations decomposed into
symmetric and antisymmetric
In-plane and Flexural deformations

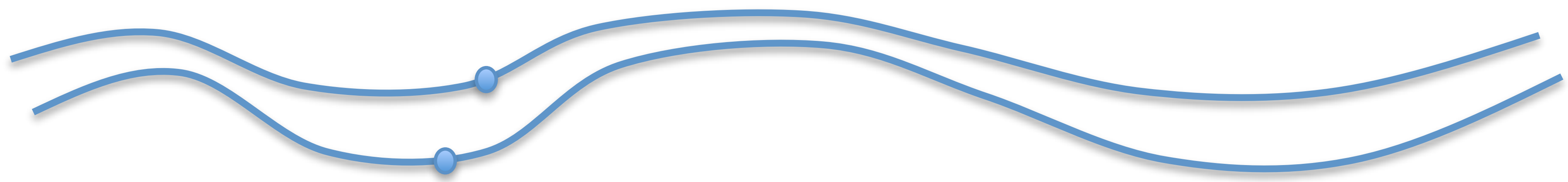


$u^{(S)}$ $u^{(A)}$

$h^{(S)}$ $h^{(A)}$

Deformations in bilayer membranes

(symmetric and antisymmetric in-plane and flexural channels)



$$H_{\text{eff}}^{(+)} = \begin{pmatrix} D^{(S)} - D^{(A)} + \frac{\Delta}{2} & v_3 P_3^{(+)} \\ v_3 P_3^{(+)\dagger} & D^{(S)} + D^{(A)} - \frac{\Delta}{2} \end{pmatrix} + \frac{1}{\gamma} \begin{pmatrix} v_1 v_4 \left(P_4^{(+)\dagger} P_1^{(+)} + P_1^{(+)\dagger} P_4^{(+)} \right) & v_4^2 \left(P_4^{(+)\dagger} \right)^2 + v_1 v_2 P_1^{(+)\dagger} P_2^{(+)\dagger} \\ v_4^2 \left(P_4^{(+)} \right)^2 + v_1 v_2 P_2^{(+)} P_1^{(+)} & v_2 v_4 \left(P_2^{(+)} P_4^{(+)\dagger} + P_4^{(+)} P_2^{(+)\dagger} \right) \end{pmatrix}$$

Where $P_j = p + F_j / v_j$

$$D_{l=1,2} = g \, \mathrm{Tr}[u_{ij}^{(l)}]$$

$$F_{l=1,2}^{(\tau)} = \frac{3}{4} a \frac{\partial t_l}{\partial a} \left[u_{xx}^{(l)} - u_{yy}^{(l)} - i\tau \left(u_{xy}^{(l)} + u_{yx}^{(l)} \right) \right]$$

$$F_3^{(\tau)} = \frac{3}{2\tilde{c}} \frac{\partial \gamma_3}{\partial \tilde{c}} \mathcal{F}[\mathbf{u}^{(S)}, \mathbf{u}^{(A)}, h^{(S)}, h^{(A)}]$$

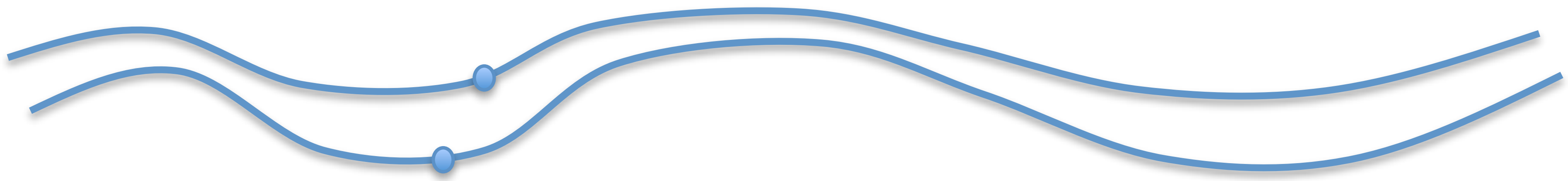
$$F_4^{(\tau)} = \frac{3}{2\tilde{c}} \frac{\partial \gamma_4}{\partial \tilde{c}} \mathcal{F}[\mathbf{u}^{(S)}, -\mathbf{u}^{(A)}, -h^{(S)}, h^{(A)}]$$

$$F_\gamma = -2 \frac{\partial \gamma}{\partial c} \left[h^{(A)} + \frac{\mathbf{u}^{(A)2}}{c} \right] .$$

$$\mathcal{F}[\mathbf{u}^{(S)}, \mathbf{u}^{(A)}, h^{(S)}, h^{(A)}] = ac \left(\partial_y h^{(S)} - i\tau \partial_x h^{(S)} \right) + \frac{a^2}{2} \left(u_{xx}^{(S)} - u_{yy}^{(S)} - i\tau \left(u_{xy}^{(S)} + u_{yx}^{(S)} \right) \right) + 2a \left(u_y^{(A)} - i\tau u_x^{(A)} \right) .$$

Deformations in bilayer membranes

(symmetric and antisymmetric in-plane and flexural channels)



$$H^{(+)}_{\rm eff} = \begin{pmatrix} D^{(S)} - D^{(A)} - \frac{\Delta}{2} & v_3 P_3^{(+)} \\ v_3 P_3^{(+)\dagger} & D^{(S)} + D^{(A)} - \frac{\Delta}{2} \end{pmatrix} + \frac{1}{\gamma} \begin{pmatrix} v_1 v_4 \left(P_4^{(+)\dagger} P_1^{(+)} + P_1^{(+)\dagger} P_4^{(+)}\right) & v_4^2 \left(P_4^{(+)\dagger}\right)^2 + v_1 v_2 P_1^{(+)\dagger} P_2^{(+)\dagger} \\ v_4^2 \left(P_4^{(+)}\right)^2 + v_1 v_2 P_2^{(+)} P_1^{(+)} & v_2 v_4 \left(P_2^{(+)} P_4^{(+)\dagger} + P_4^{(+)} P_2^{(+)\dagger}\right) \end{pmatrix}$$

Where $P_j = p + F_j / v_j$

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$$F_{l=1,2}^{(\tau)} = \frac{3}{4} a \frac{\partial t_l}{\partial a} \left[u_{xx}^{(l)} - u_{yy}^{(l)} - i\tau \left(u_{xy}^{(l)} + u_{yx}^{(l)} \right) \right]$$

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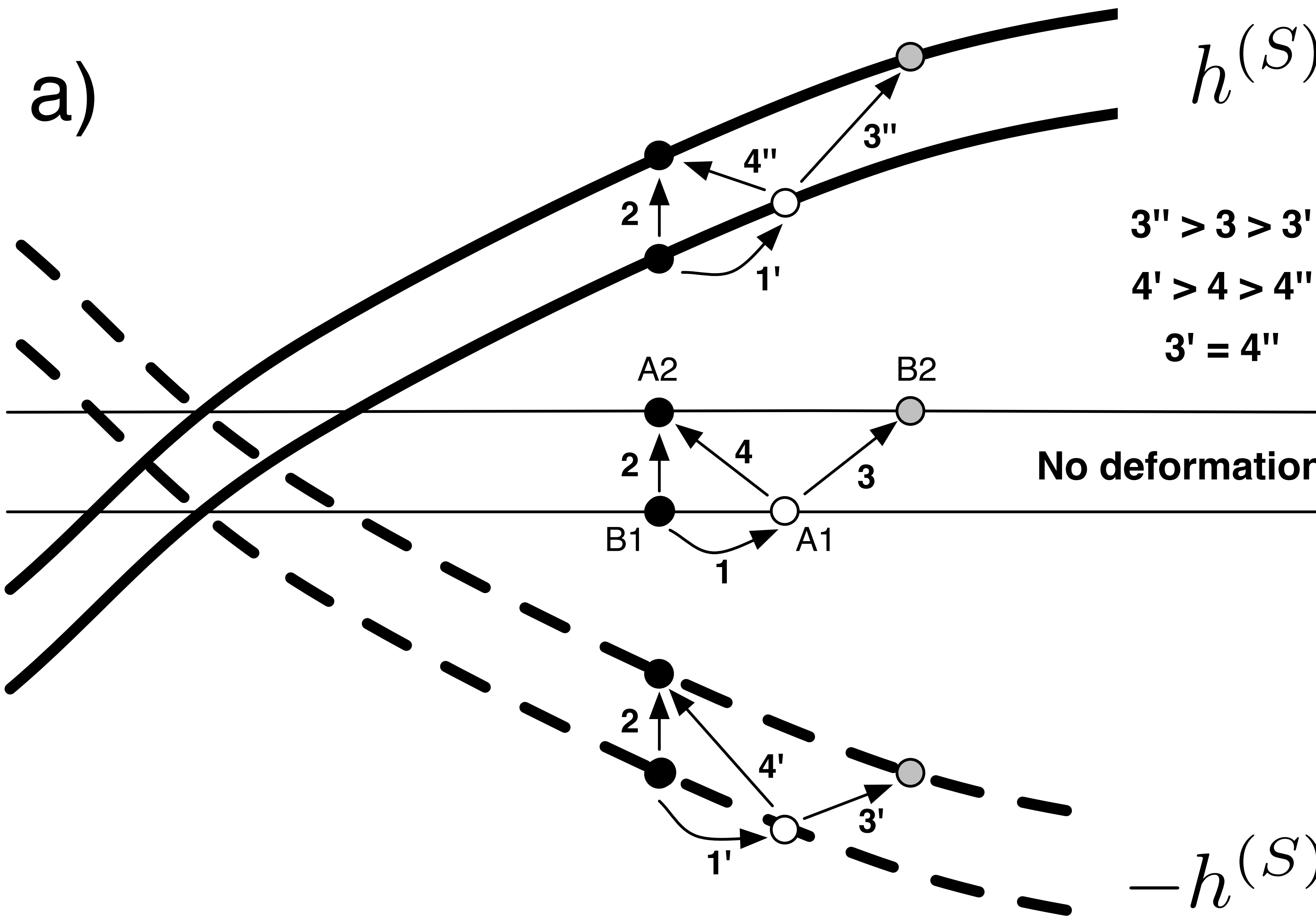
$$\mathcal{F}[\mathbf{u}^{(S)}, \mathbf{u}^{(A)}, h^{(S)}, h^{(A)}] = ac \left(\partial_y h^{(S)} - i\tau \partial_x h^{(S)} \right) + \frac{a^2}{2} \left(u_{xx}^{(S)} - u_{yy}^{(S)} - i\tau \left(u_{xy}^{(S)} + u_{yx}^{(S)} \right) \right) + 2a \left(u_y^{(A)} - i\tau u_x^{(A)} \right) .$$

Anti-symmetric deformation Potential opens band gap

Unexpected linear coupling for flexural modes


a)
$h^{(S)}$
$-h^{(S)}$
3'' > 3 > 3'
4' > 4 > 4''
3' = 4''
No deformation
A2
B2
B1
A1
1
2
3
4
1'
3''
4''
4'
3'

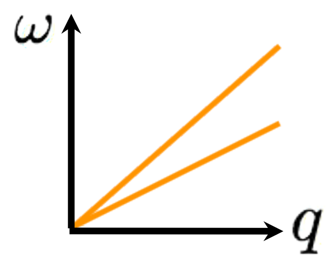
Temperature-dependent resistivity

Intralayer coupling

In-plane phonons (Viljas 2010 Min 2011)

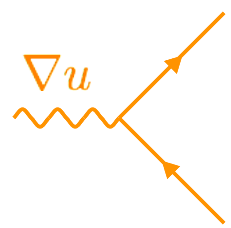
Linear dispersion

$$\omega^{(l,t)} = v^{(l,t)} q$$

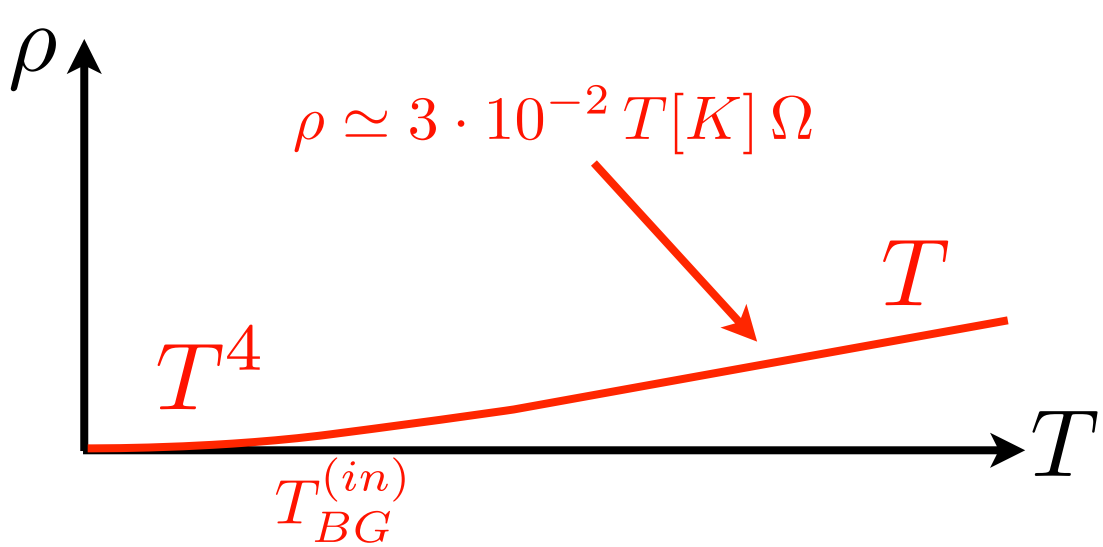


Linear coupling

$$H_{e-ph} \propto u_{ij} \sim \nabla u$$



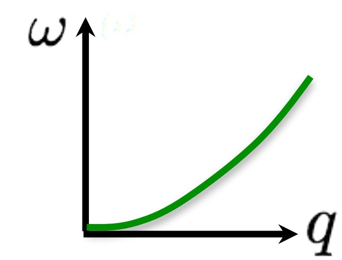
Small DOS, Good coupling



Flexural phonons (H. Ochoa 2011)

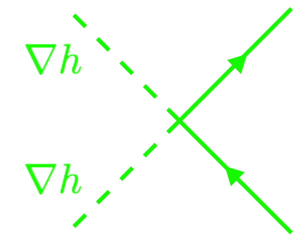
Quadratic dispersion

$$\omega^{(h)} = \alpha q^2$$

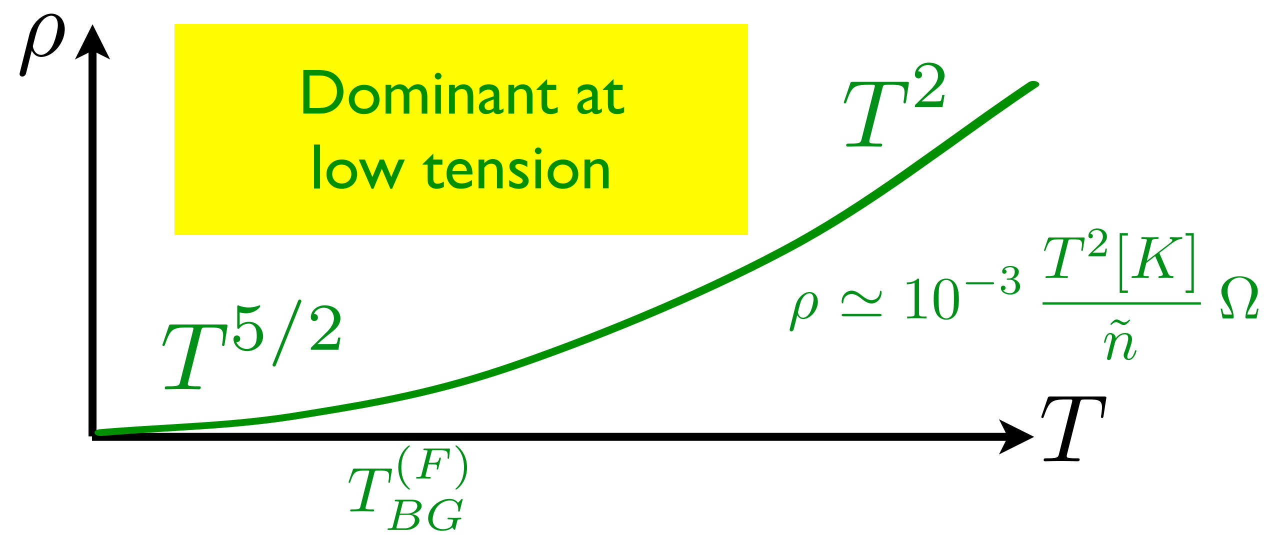


Quadratic coupling

$$H_{e-ph} \propto u_{ij} \sim (\nabla h)^2$$



Big DOS, Poor coupling

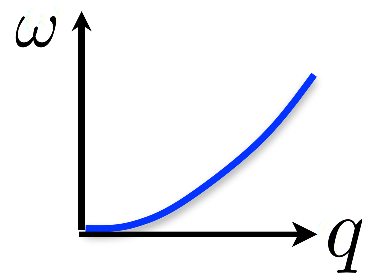


Temperature-dependent resistivity
(new interlayer gauge field contribution)

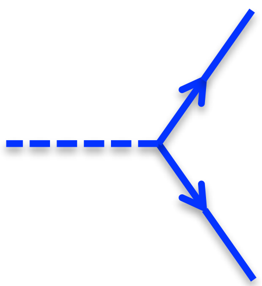
Interlayer coupling

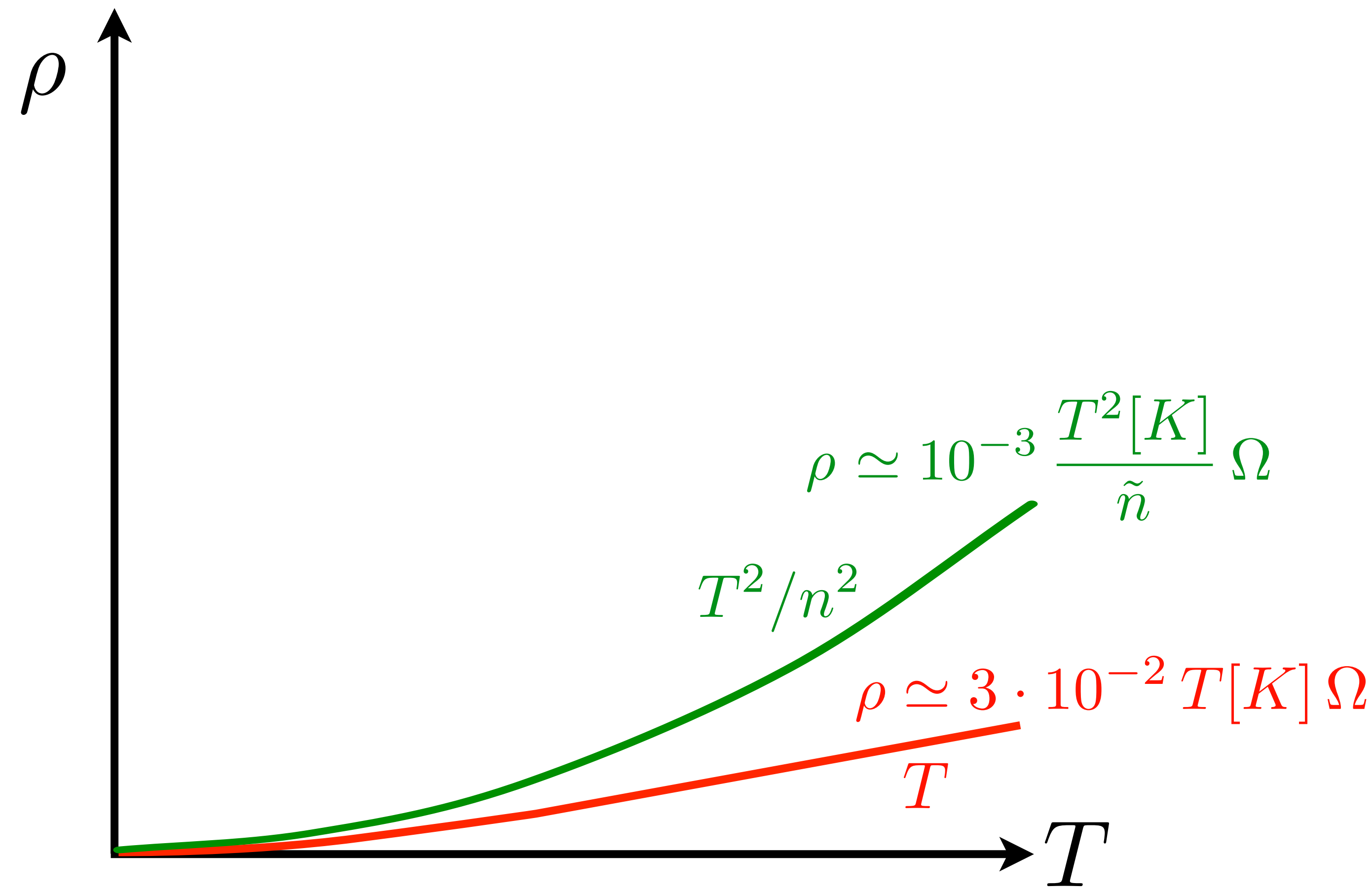
Symmetric Flexural phonons
(new linear coupling)

Quadratic dispersion
$\omega^{(h)} \propto q^2$



Linear coupling





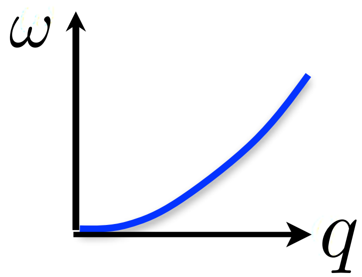
Big DOS, Strong coupling

Temperature-dependent resistivity
(new interlayer gauge field contribution)

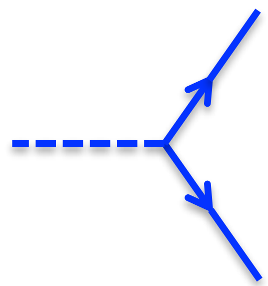
Interlayer coupling

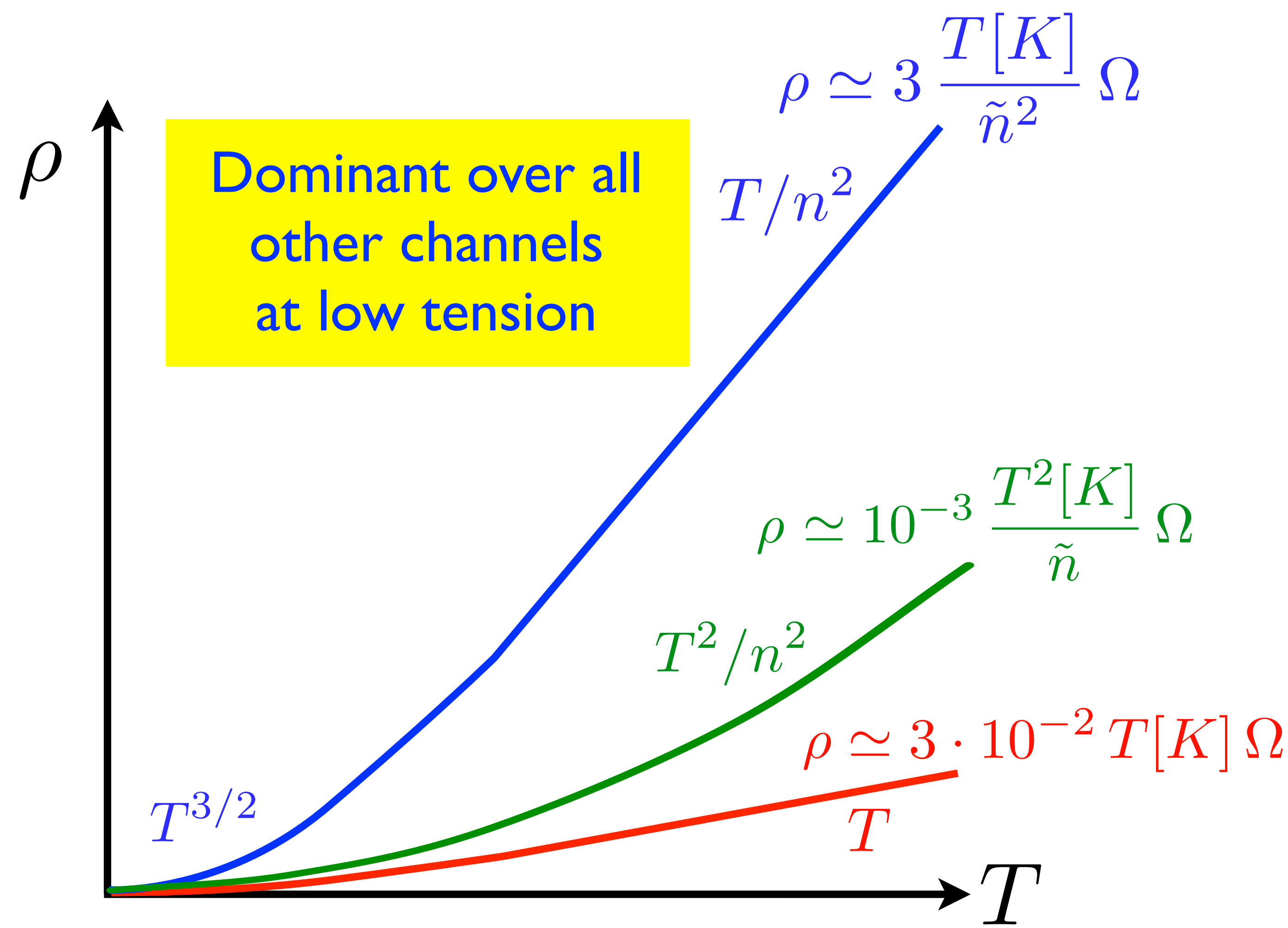
Symmetric Flexural phonons
(new linear coupling)

Quadratic dispersion
$\omega^{(h)} \propto q^2$



Linear coupling





Big DOS, Strong coupling

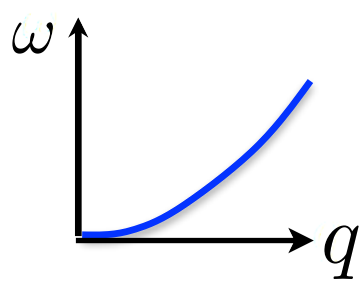
$$\rho_{q_* \ll 2k_{\rm F}} \simeq 3 \, \frac{T[K]}{\tilde{n}^2} \, \Omega$$

Temperature-dependent resistivity
(new interlayer gauge field contribution)

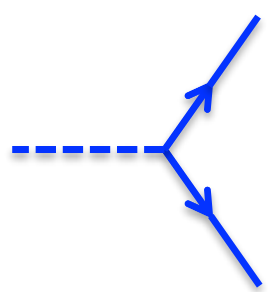
Interlayer coupling

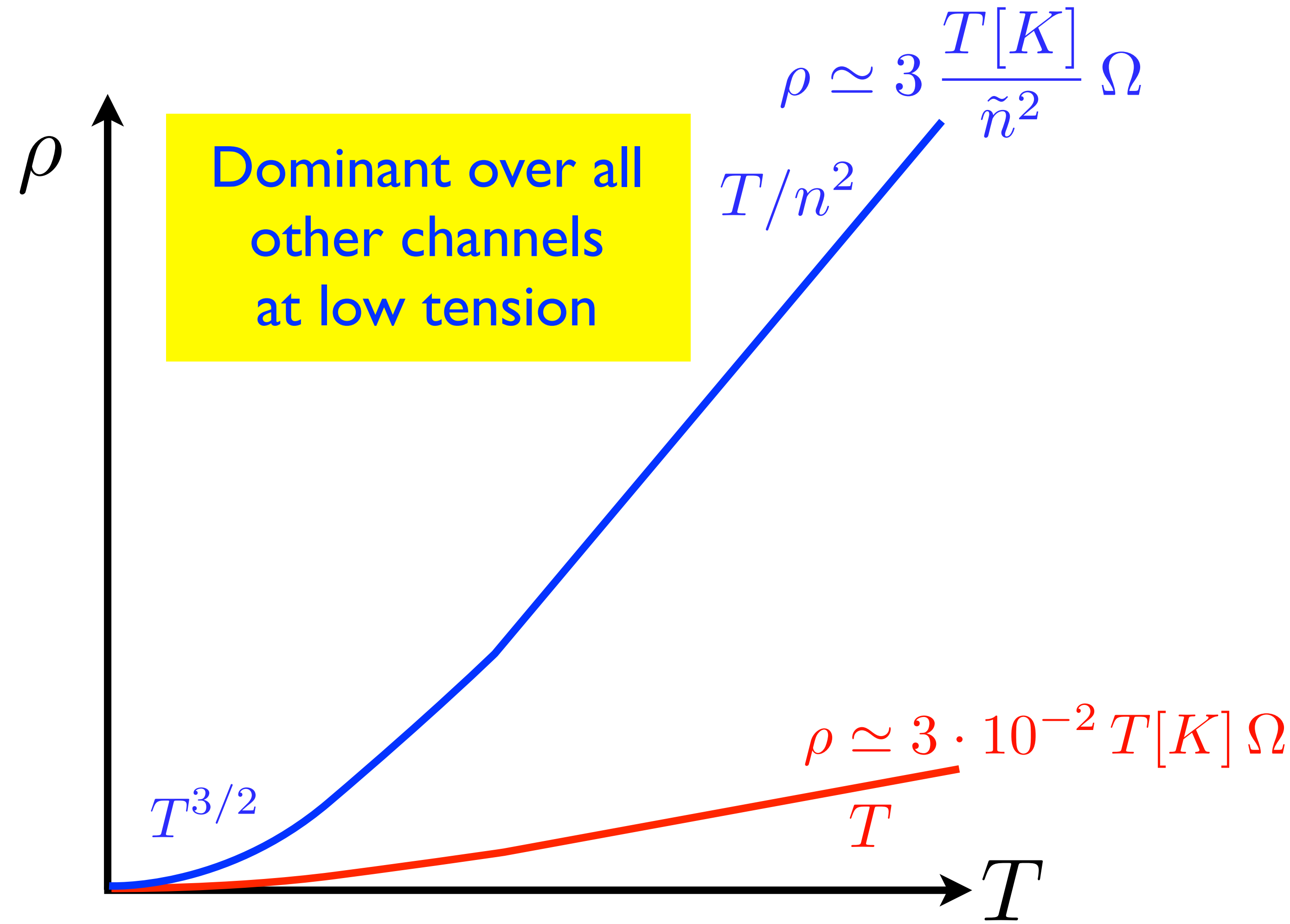
Symmetric Flexural phonons
(new linear coupling)

Quadratic dispersion
$\omega^{(h)} \propto q^2$



Linear coupling





Big DOS, Strong coupling

$$\rho_{q_* \ll 2k_{\rm F}} \simeq 3\, \frac{T[K]}{\tilde{n}^2}\, \Omega$$

Temperature-dependent resistivity (new interlayer gauge field contribution)

Interlayer coupling

Symmetric Flexural phonons (new linear coupling)

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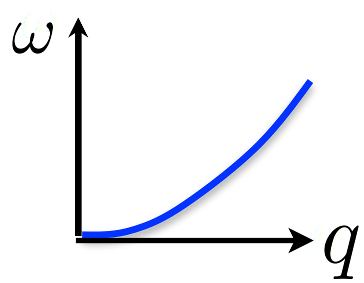
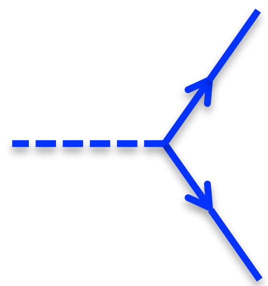


Linear coupling



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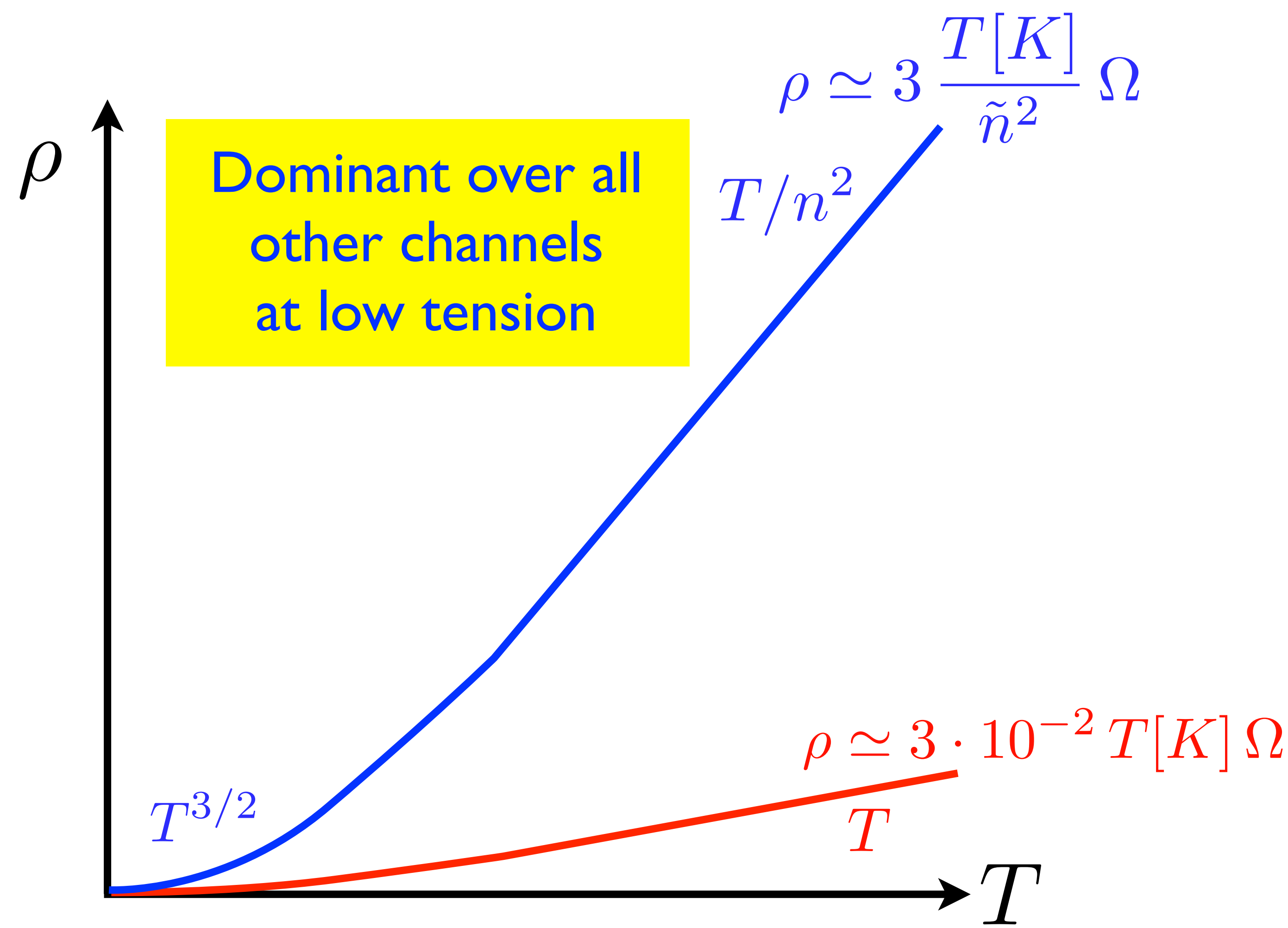


Tension

Flexural dispersion stiffening

$$\omega_q \sim q^2 \to q$$

Reduced DOS

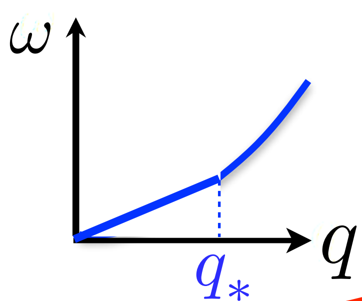
Temperature-dependent resistivity
(new interlayer gauge field contribution)

Interlayer coupling

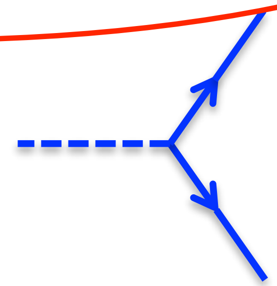
Symmetric Flexural phonons
(new linear coupling)

$\omega^{(h)} \propto q$ if $q \ll q_*$

$\omega^{(h)} \propto q^2$ if $q \gg q_*$

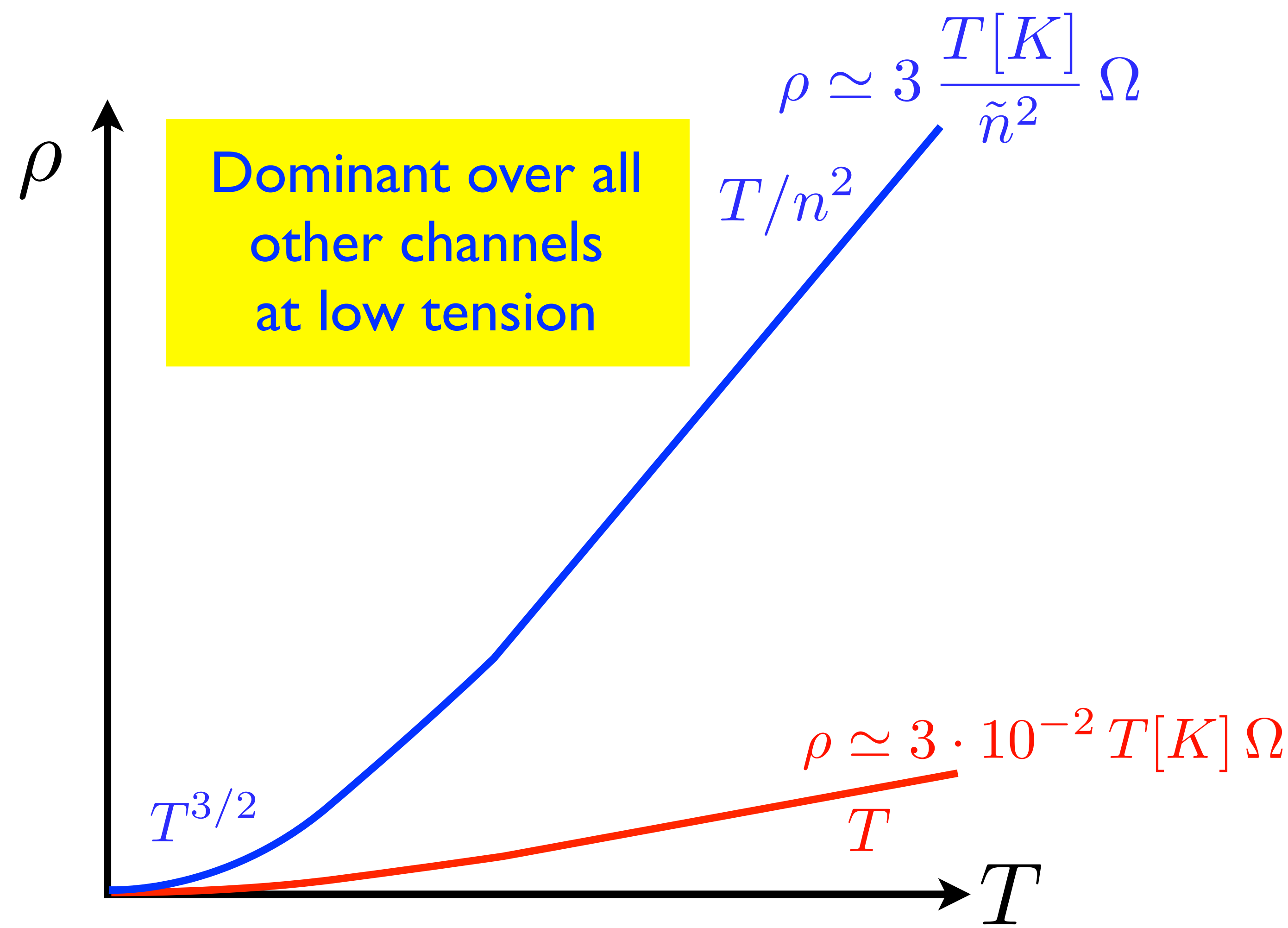


Linear coupling



Big DOS, Strong coupling

$$\rho_{q_* \ll 2k_{\rm F}} \simeq 3\,\frac{T[K]}{\tilde{n}^2}\,\Omega$$



Tension

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$$\omega_q \sim q^2 \rightarrow q$$

Reduced DOS

Temperature-dependent resistivity
(new interlayer gauge field contribution)

Interlayer coupling

Symmetric Flexural phonons
(new linear coupling)

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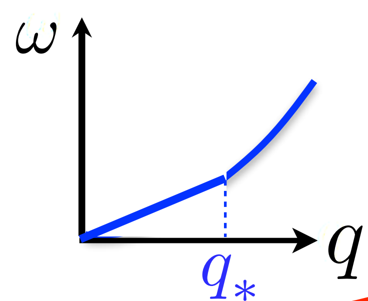
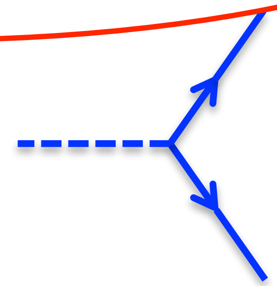
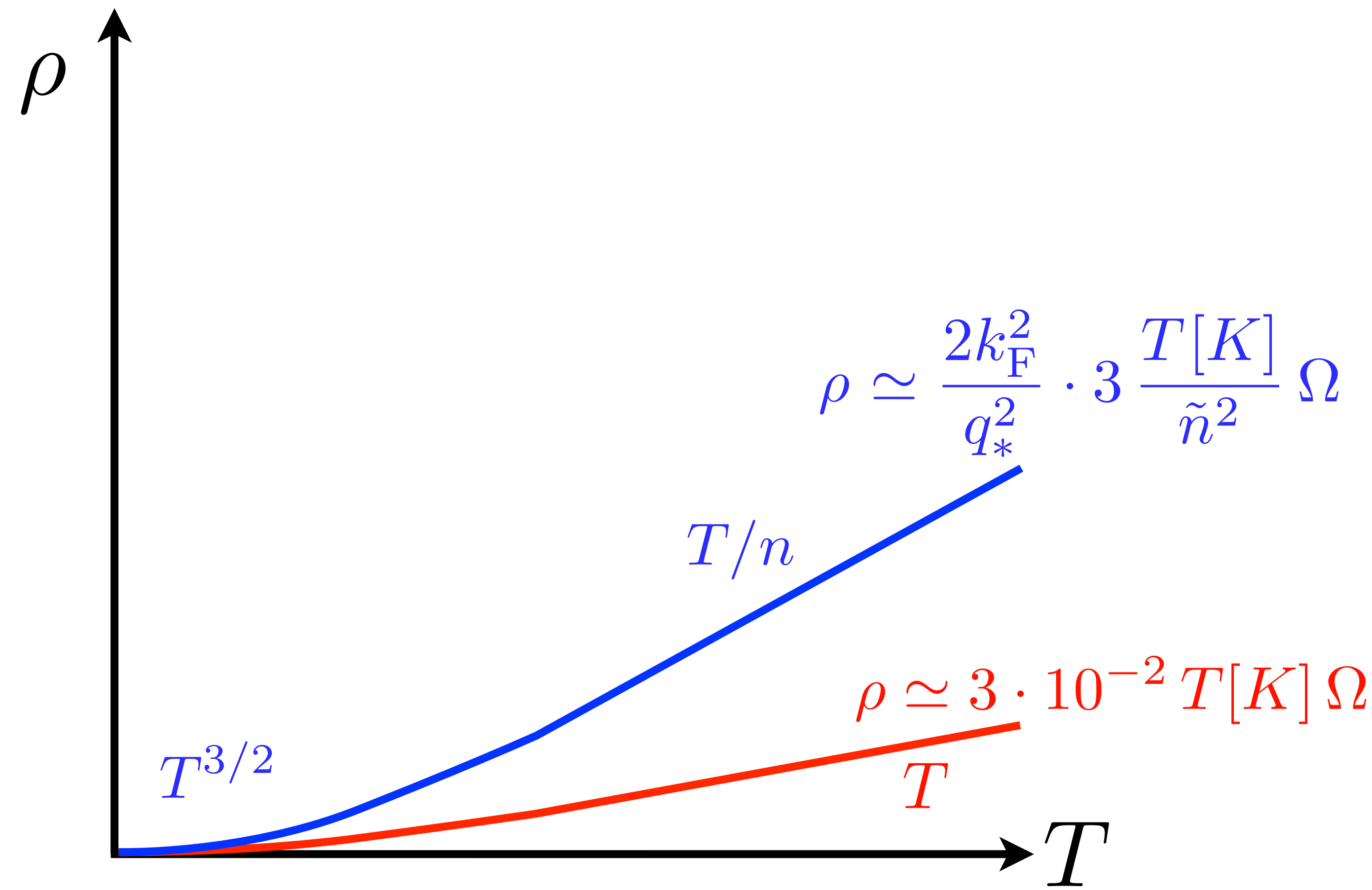


Linear coupling





Big DOS, Strong coupling

$$\rho_{q_* \ll 2k_F} \simeq 3 \frac{T[K]}{\tilde{n}^2} \Omega$$

$$\rho_{q_* \gg 2k_F} \simeq \frac{2k_F^2}{q_*^2} \cdot 3 \frac{T[K]}{\tilde{n}^2} \Omega$$

Tension

Flexural dispersion stiffening

$$\omega_q \sim q^2 \longrightarrow q$$

Reduced DOS

Temperature-dependent resistivity
(new interlayer gauge field contribution)

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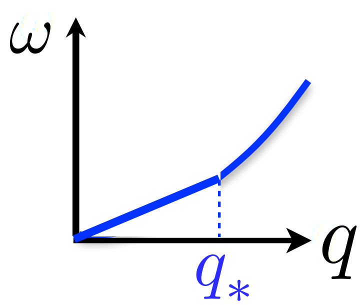
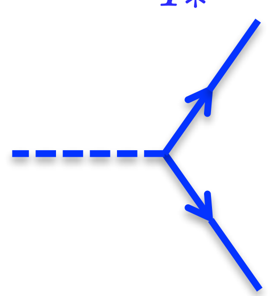
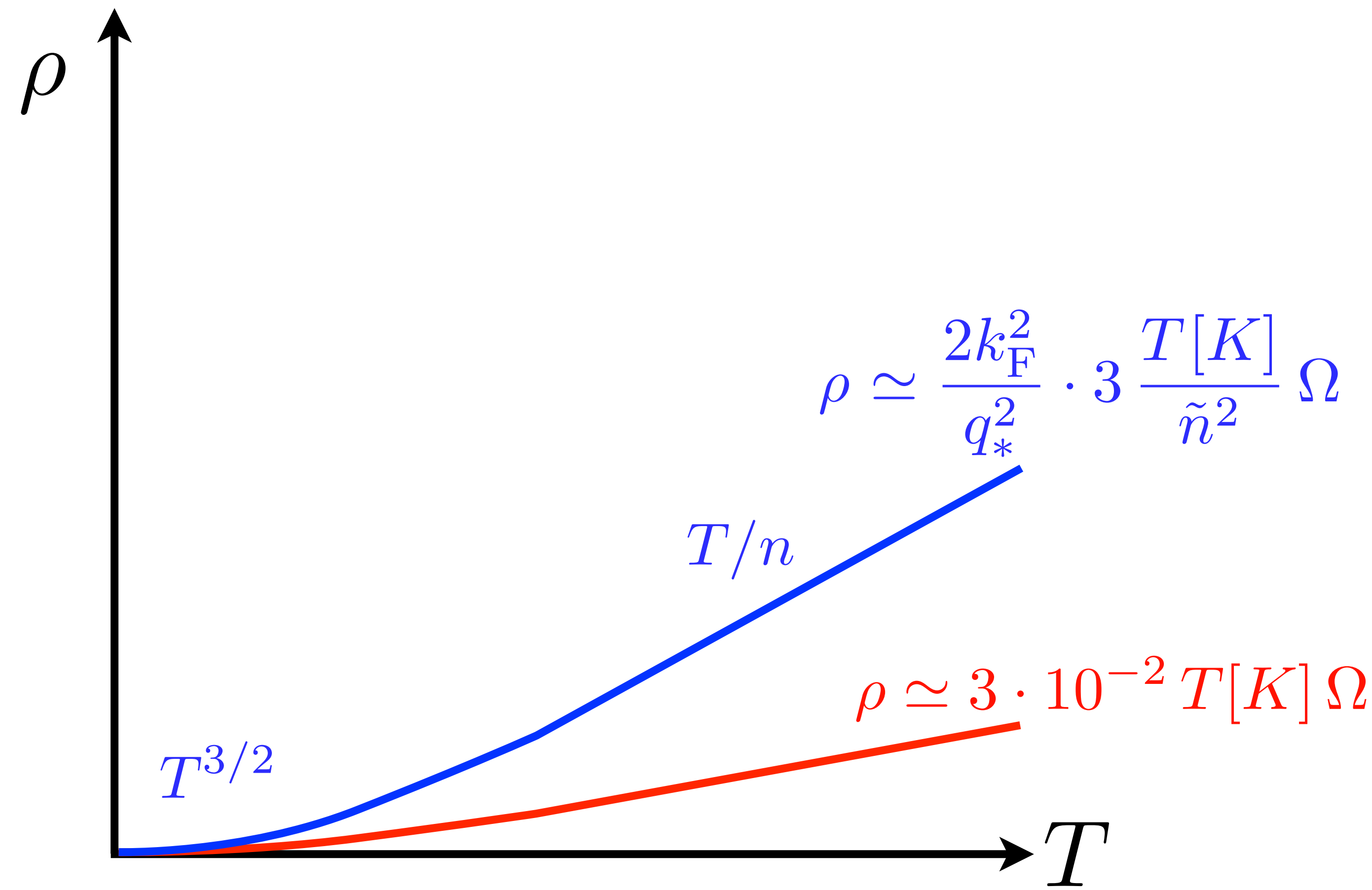


Linear coupling





Big DOS, Strong coupling

$$\rho_{q_* \ll 2k_F} \simeq 3 \frac{T[K]}{\tilde{n}^2} \Omega$$

$$\rho_{q_* \gg 2k_F} \simeq \frac{2k_F^2}{q_*^2} \cdot 3 \frac{T[K]}{\tilde{n}^2} \Omega$$

Further increase tension beyond a critical strain
$u \sim 3 \cdot 10^{-3} / \tilde{n}$
Flexural modes suppressed!

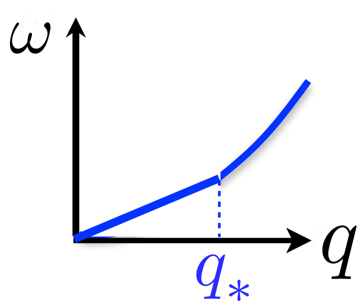
Temperature-dependent resistivity
(new interlayer gauge field contribution)

Interlayer coupling

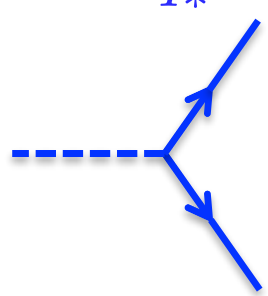
Symmetric Flexural phonons
(new linear coupling)

$\omega^{(h)} \propto q$ if $q \ll q_*$

$\omega^{(h)} \propto q^2$ if $q \gg q_*$



Linear coupling



Big DOS, Strong coupling

$$\rho_{q_* \ll 2k_F} \simeq 3 \frac{T[K]}{\tilde{n}^2} \Omega$$

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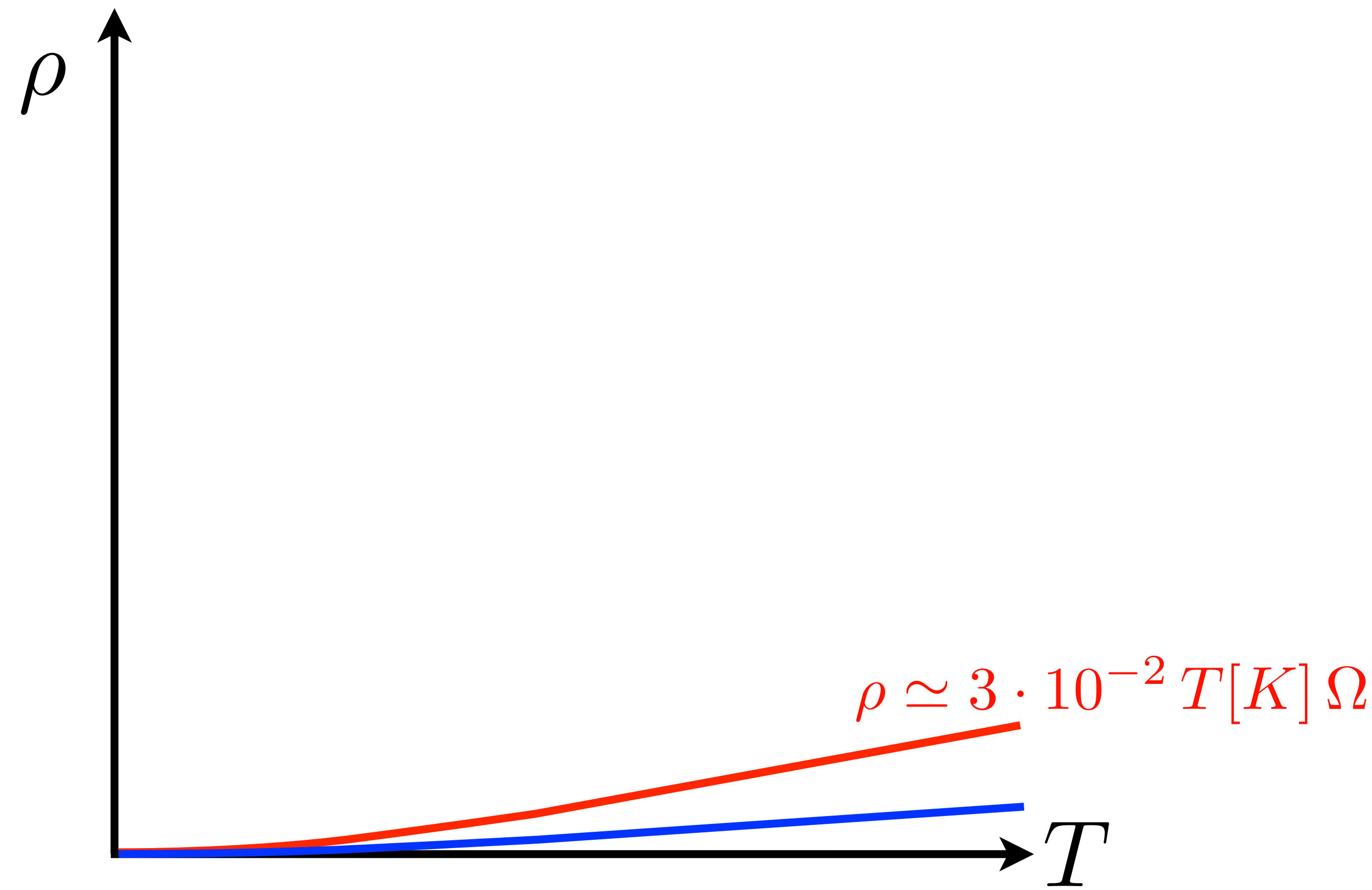


Further increase tension beyond a critical strain

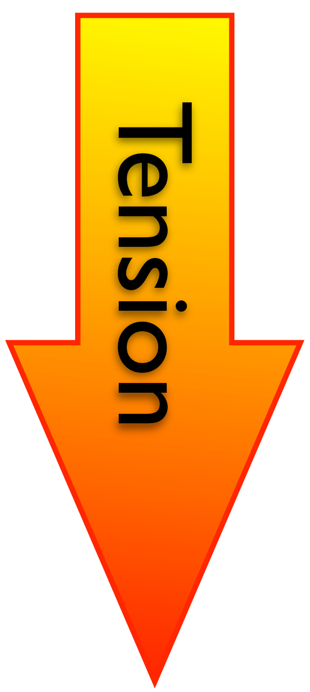
$u \sim 3 \cdot 10^{-3} / \tilde{n}$

Flexural modes suppressed!

Summary

Electron-phonon resistivity in suspended bilayers

$$\rho \propto T \quad \text{for} \quad T \gg T_{\rm BG}^{\rm (in)}$$



Flex $\rho \propto \dfrac{T}{n^2}$ if $q_* \ll 2k_{\rm F}$

$\text{strain} \sim 5 \cdot 10^{-5} \tilde{n}$

Flex $\rho \propto \dfrac{T}{n}$ if $q_* \gg 2k_{\rm F}$

$\text{strain} \sim \dfrac{3 \cdot 10^{-3}}{\tilde{n}}$

In $\rho \propto T$

Conclusions

Monolayers

In-plane VS flexural phonons

Flexural modes dominate the resistivity at low tension $\rho \propto \frac{T^2}{n}$

Bilayers

Fictitious gauge fields for generic deformations

New linear coupling for flexural modes

Resistivity linear in T: density dependence reveals tension $\rho \propto \frac{T}{n^\alpha}$

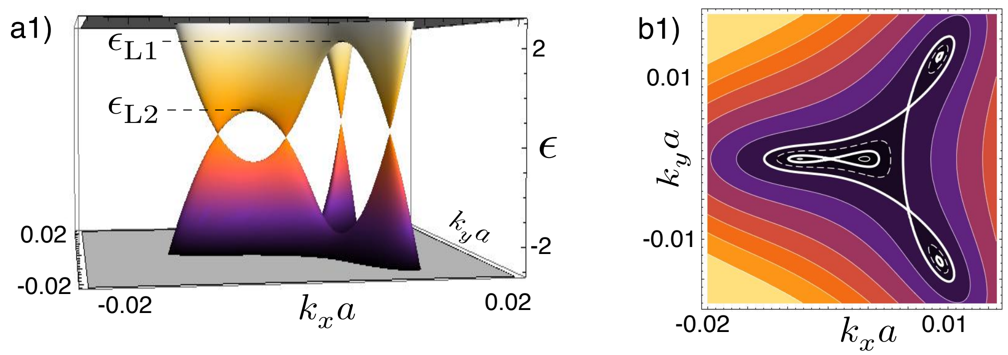
E.Mariani@exeter.ac.uk

Thank you!

Uniform gauge fields and the Lifshitz transition

Uniaxial strain, pure shear and sliding layers

J.W. Son, PRB 2011
M. Mucha-Kruczynski PRB 2011



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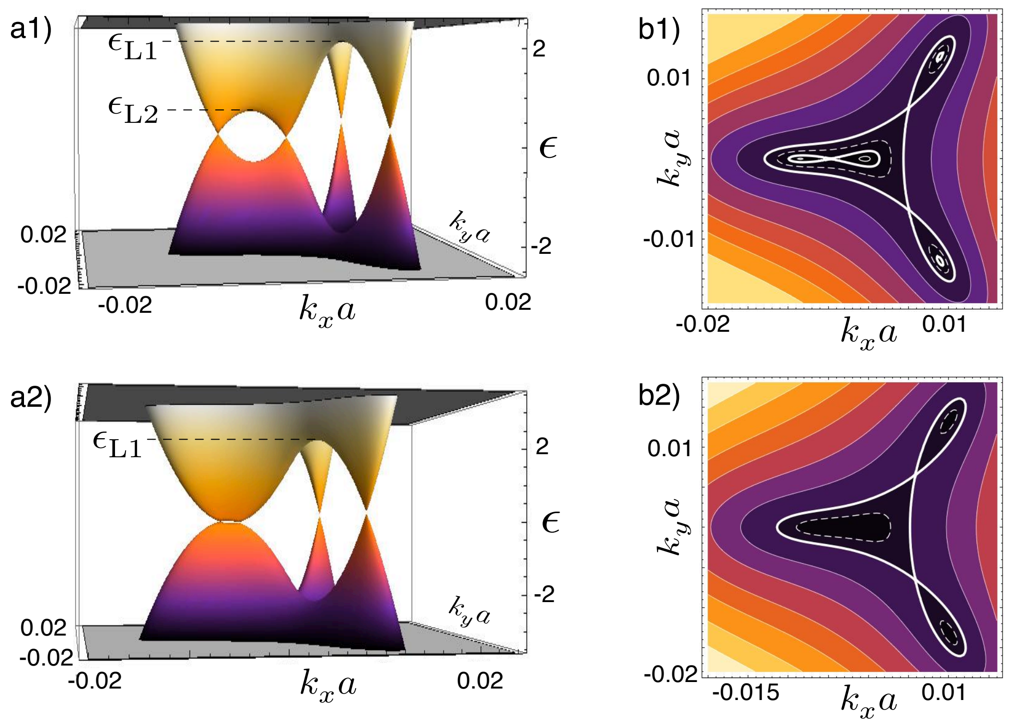

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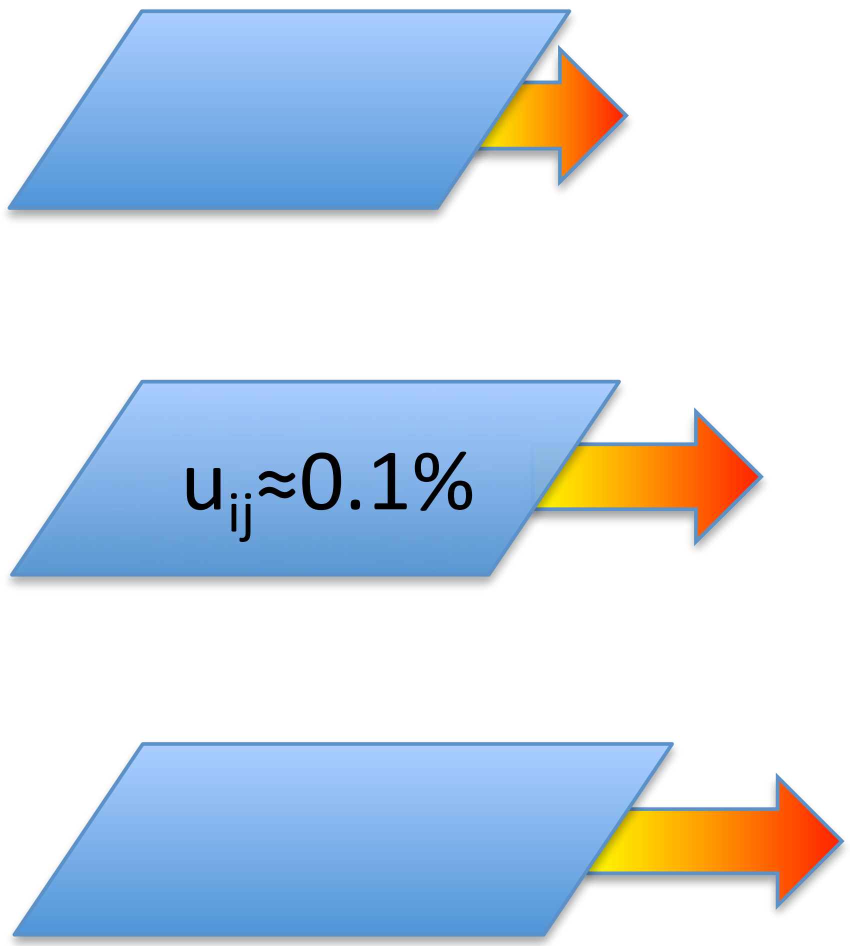
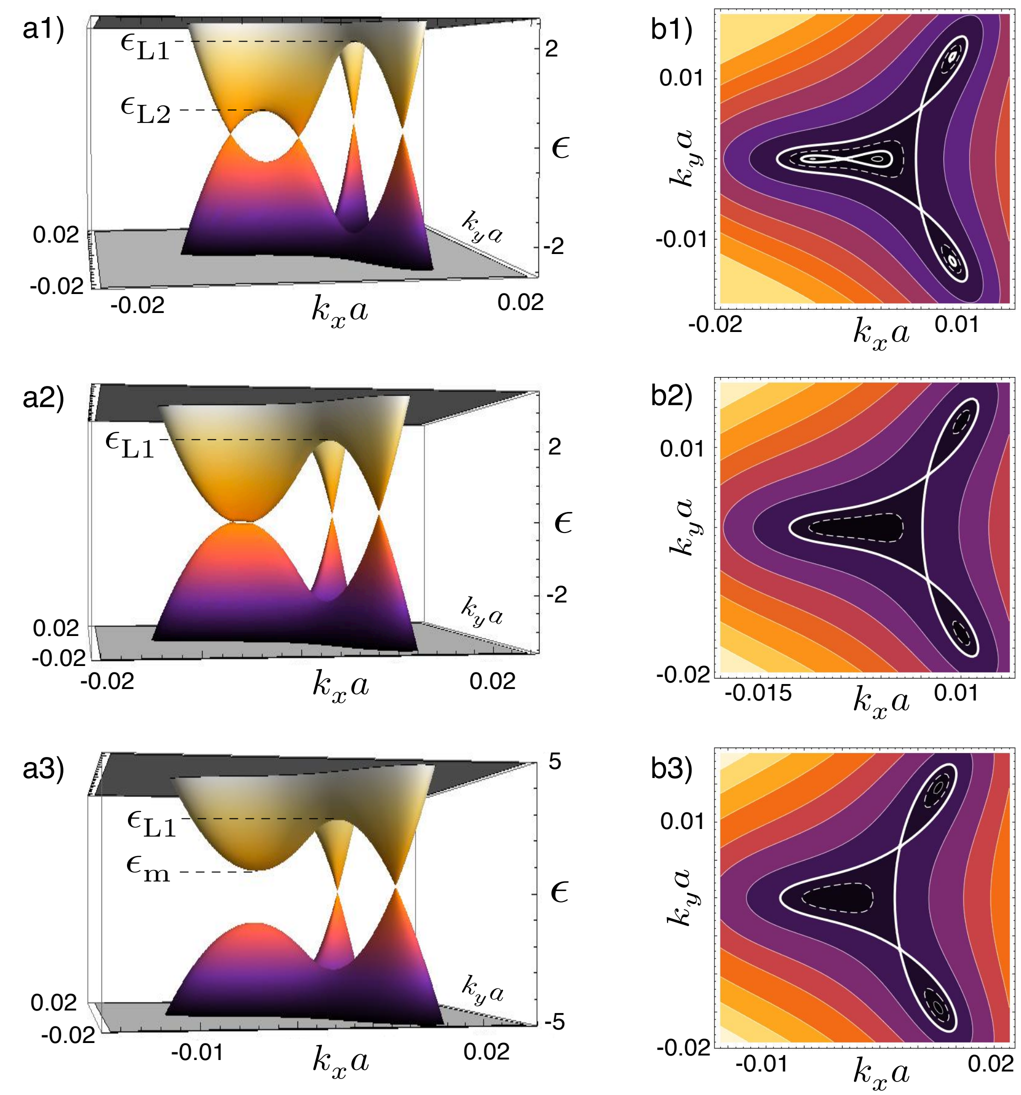
J.W. Son, PRB 2011
M. Mucha-Kruczynski PRB 2011

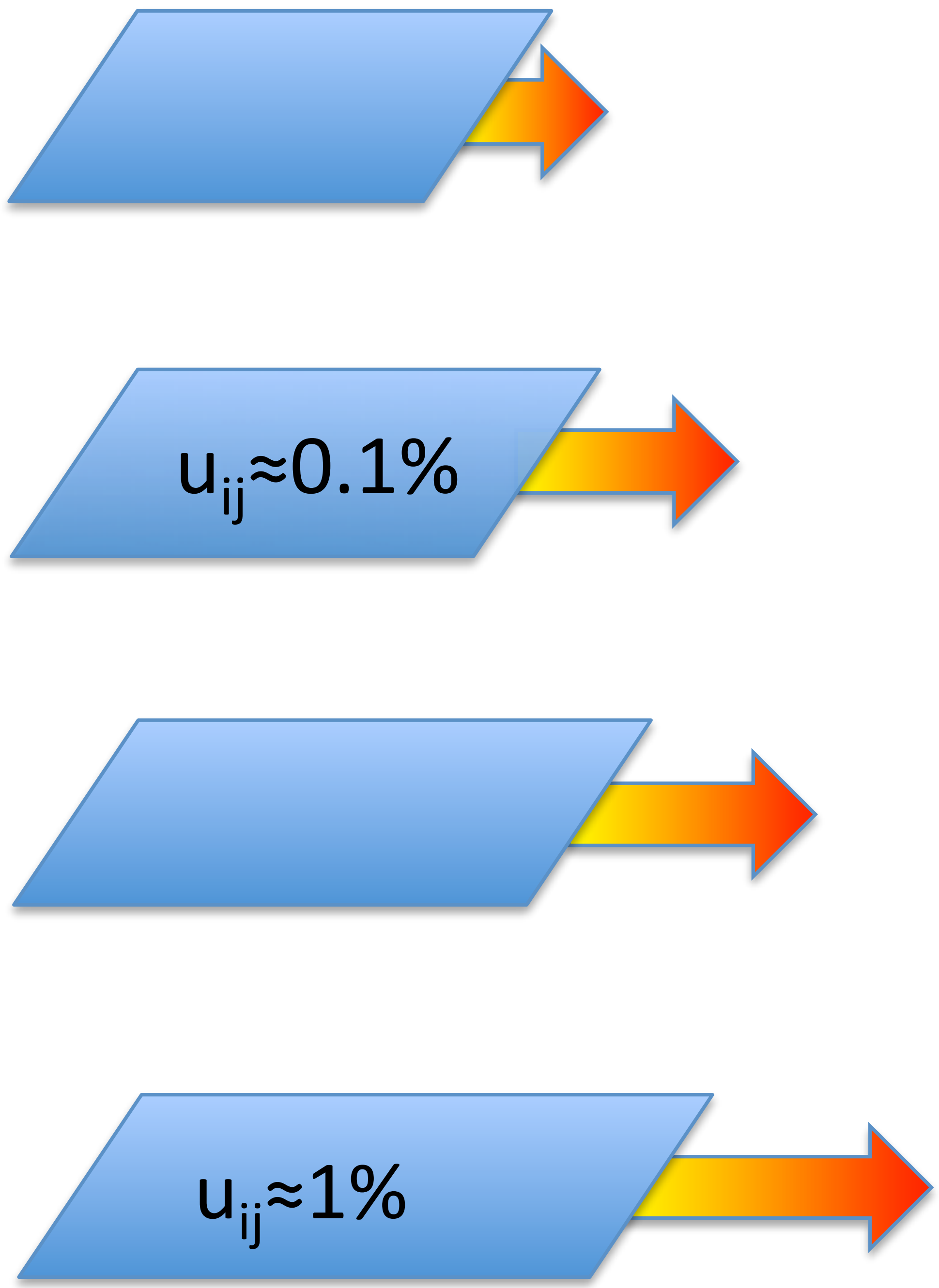


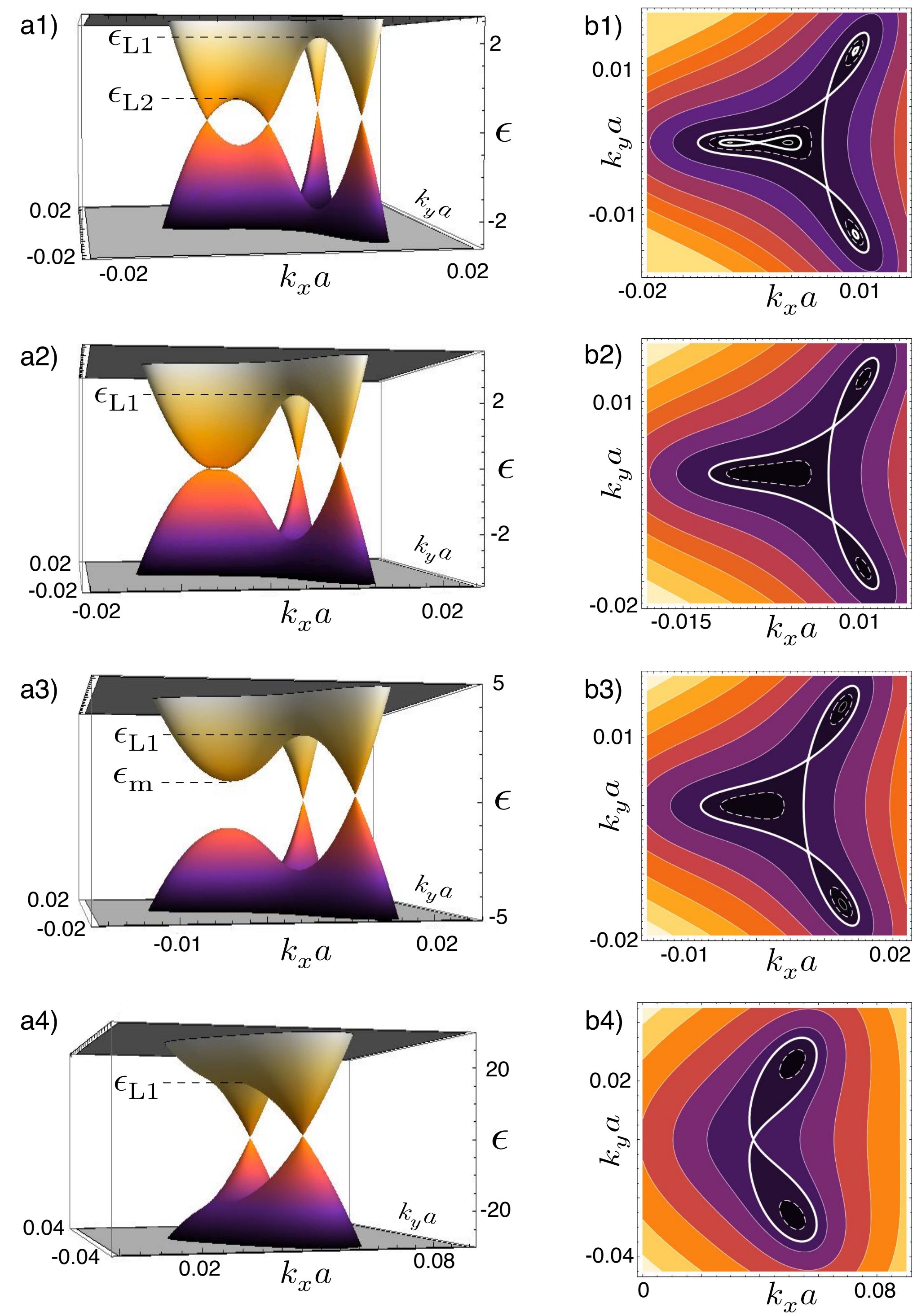


Uniform gauge fields and the Lifshitz transition

Uniaxial strain, pure shear and sliding layers

J.W. Son, PRB 2011
M. Mucha-Kruczynski PRB 2011





Uniform gauge fields and the Lifshitz transition

Uniaxial strain, pure shear and sliding layers

J.W. Son, PRB 2011
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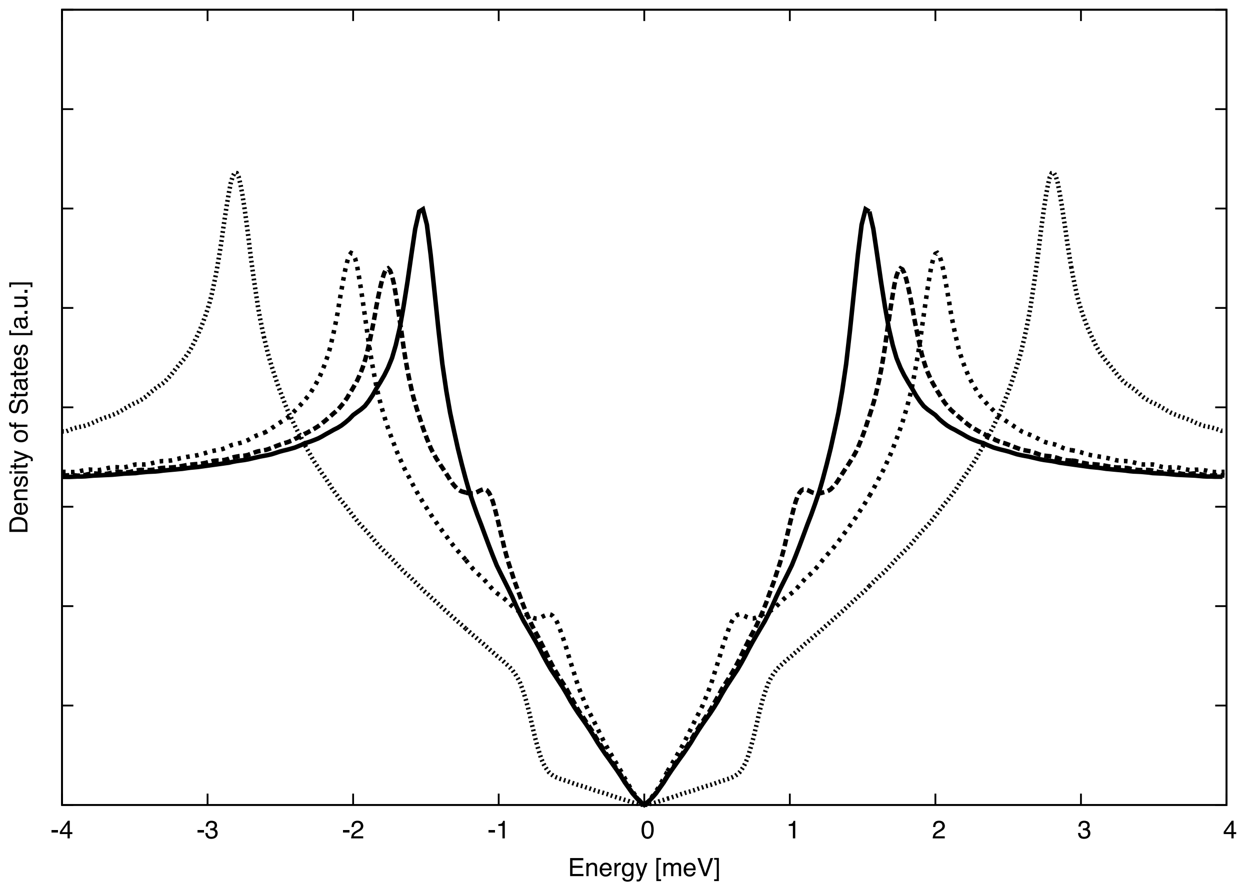
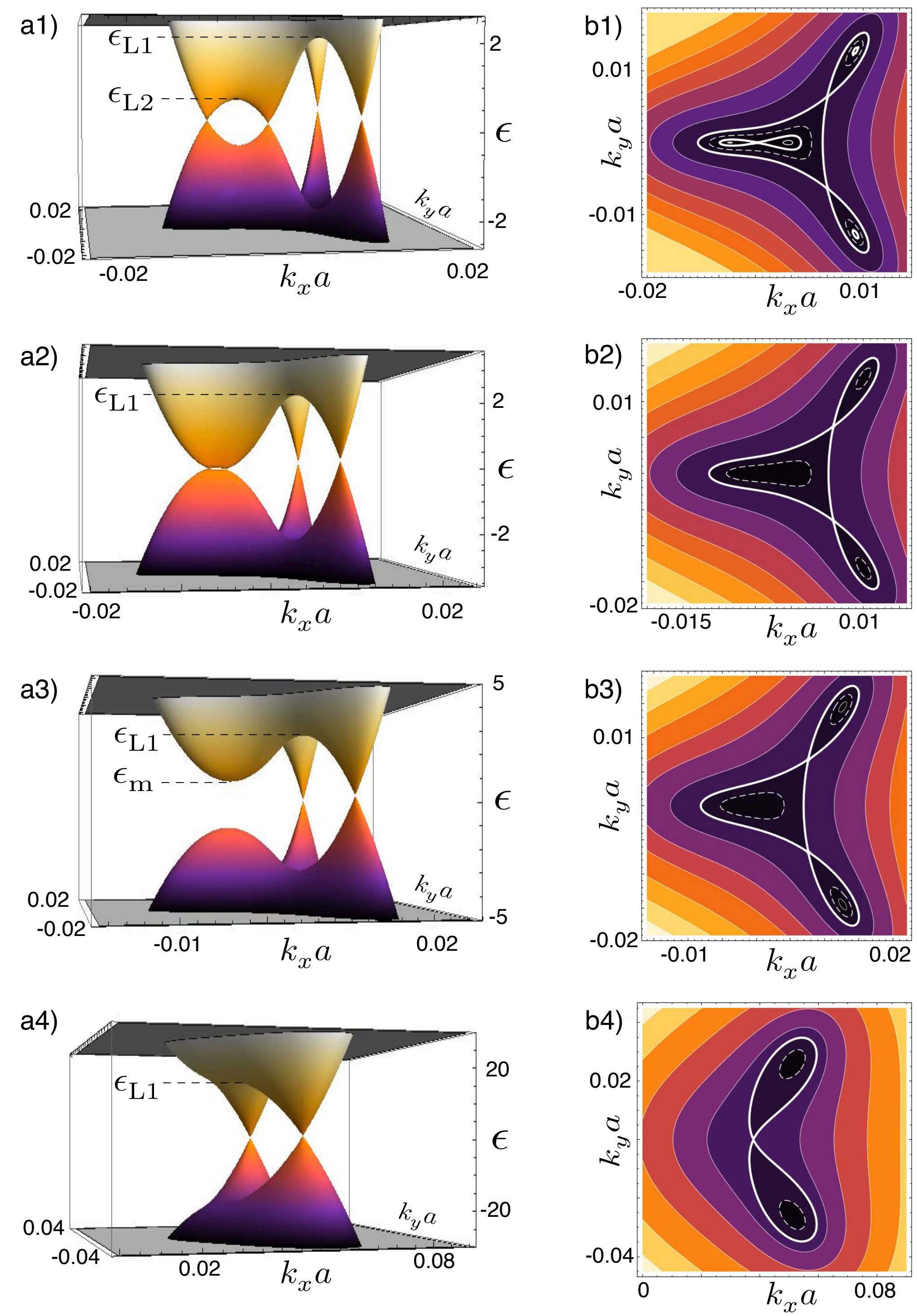
- Dramatic changes in the bandstructure
- Dirac points drift with strain – annihilation of two Dirac points!
- Tuneable Lifshitz transition





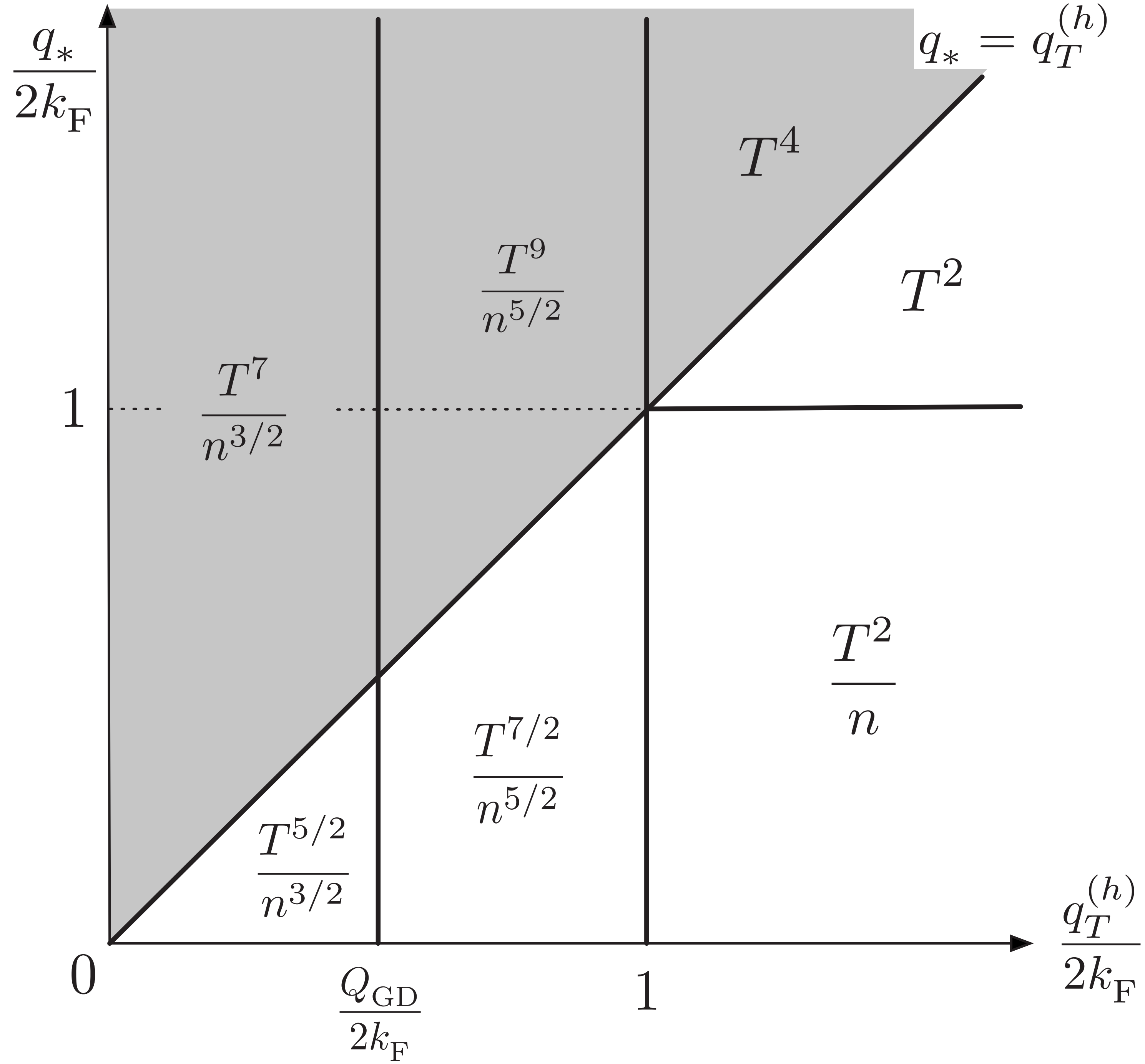


FIG. 2. The dependence of the resistivity due to scattering off flexural modes on temperature T and electron density n. The gray area identifies the region $q_* > q_T^{(h)}$ where the relevant flexural phonon dispersion is dominated by tension and $\omega_{\mathbf{q}}^{(h)} \simeq \alpha q$.

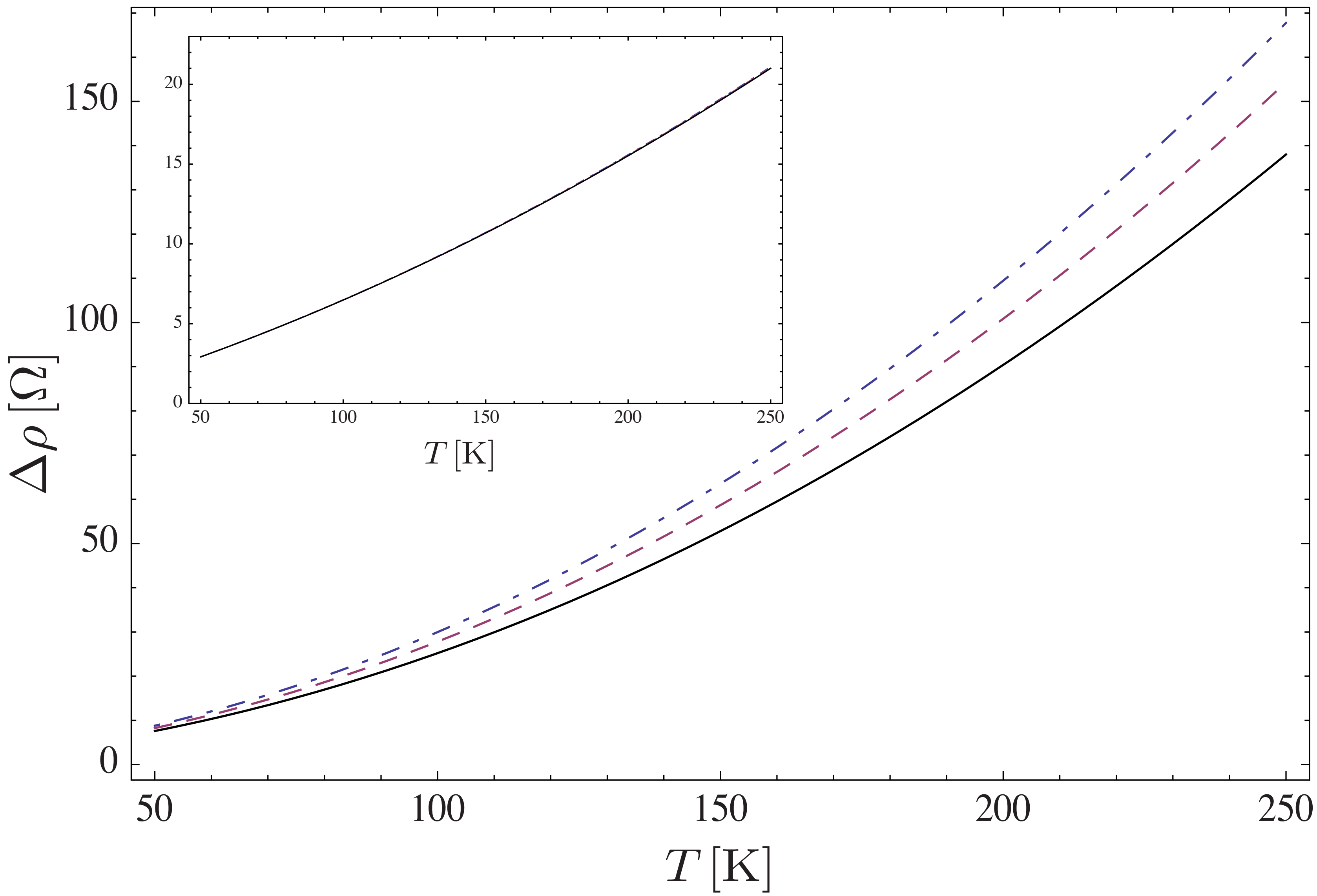


FIG. 3. (Color online) The combined contributions to the resistivity due to in-plane and flexural-phonons $\Delta\rho$ as a function of the temperature T for three different electron densities $\tilde{n} = 0.05, 0.15, 0.3$ (dashed-dotted, dashed, and continuous line, respectively). Here we assume a tension $\tilde{\gamma}=1$ and a deformation potential coupling $\tilde{g}_1=10$. Inset: same plot as in the main figure but for stronger tension $\tilde{\gamma}=20$. Notice the almost perfect linear-T scaling, independent of density.