Transport coefficients of graphene: Interplay of impurity scattering, Coulomb interaction, and optical phonons

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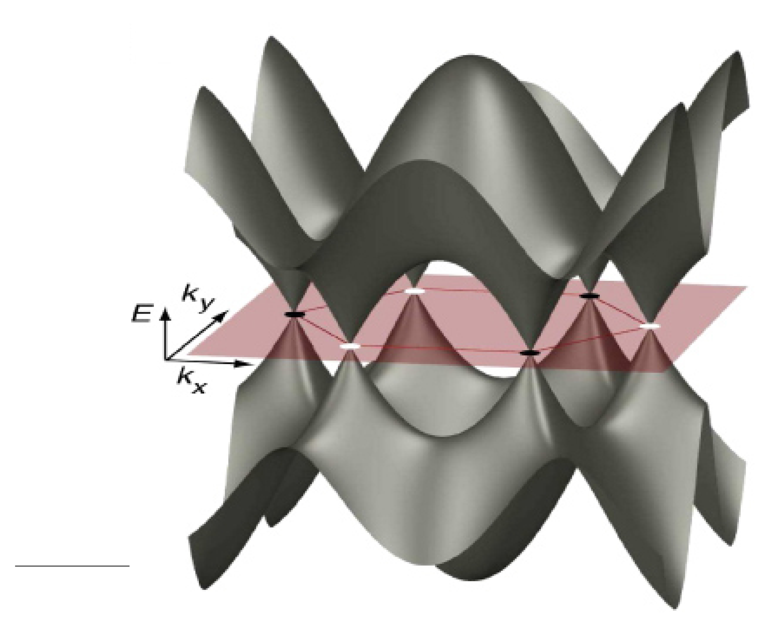
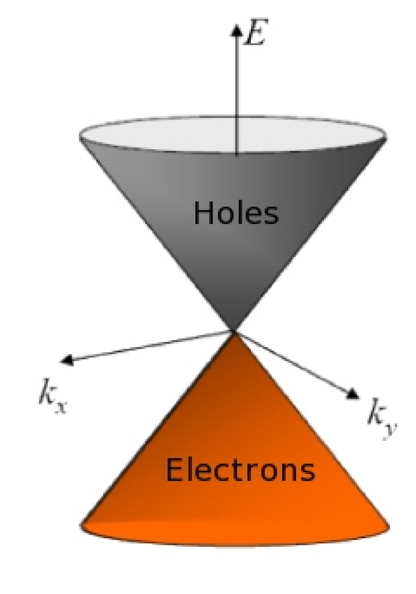
I. Introduction

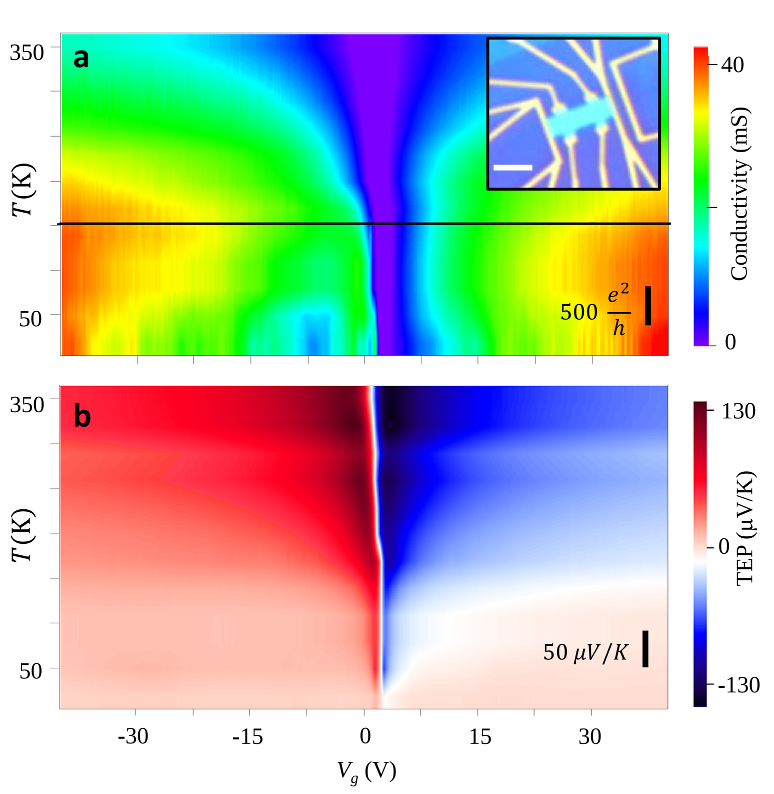


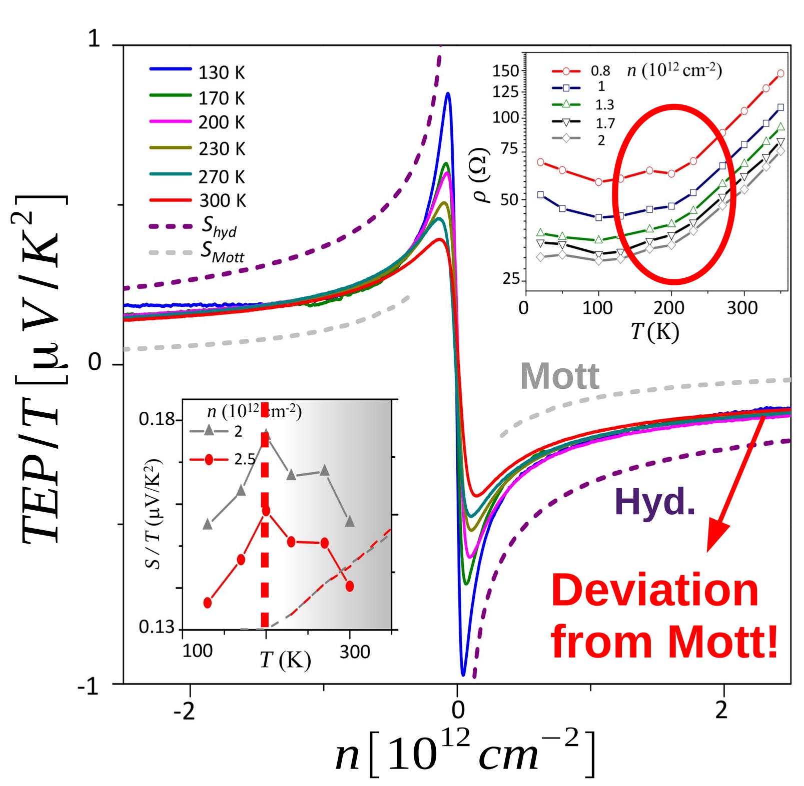


- Low-energy quasiparticles of undoped graphene – Coulomb interacting massless Dirac fermions
- At high temperature $\mu \ll k_B T$, non-Fermi-liquid transport – Inelastic **e**-**h** scattering rate $\propto k_B T/\hbar$ [Sachdev et al. 1998; Son, 2007; Fritz et al. 2008]
- Thermopower (TEP) dominated by **e**-**h**–plasma hydrodynamics with a minimal conductivity σ_Q [Hartnoll et al. 2007; Müller et al. 2008; Foster and Aleiner 2009]

Q: Can we observe hydrodynamic transport in high-quality graphene, e.g., on h-BN substrates?

- Charge puddles at low T [Adam et al. 2011]
- Non-negligible Coulomb screening effects – large fine structure constant $\alpha_{\rm int} \lesssim 1$ [Hwang et al. 2009; Ramezanali et al. 2009]
- At high T, Phonon (**ph**) scattering – A' optical phonons [Piscanec et al. 2004; Basko 2008; Attaccalite et al. 2010; Sohier et al. 2014]



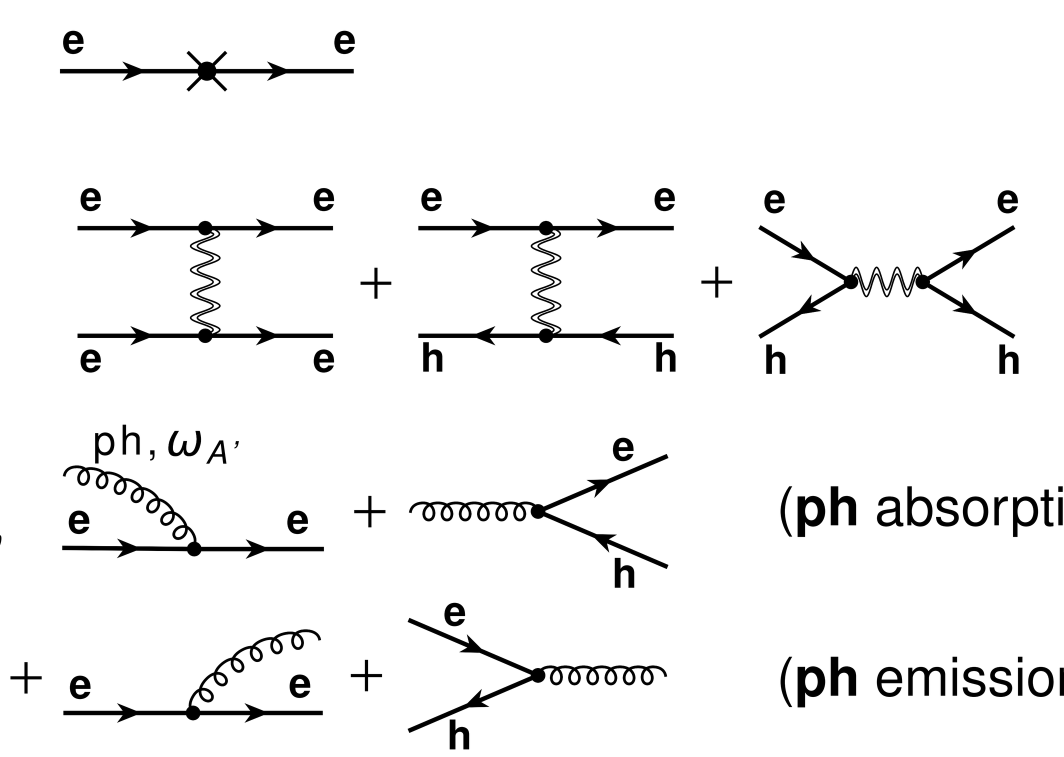


TEP Experiment: Ghahari, HYX, MSF, Kim et al., PRL

II. Boltzmann transport theory

$$\left(-\frac{df_{0,\lambda}}{d\varepsilon_{\mathbf{p}}}\right)\left[\lambda\, e\,\mathbf{v}_F\cdot\mathbf{E} - \frac{\varepsilon_{\mathbf{p}}-\mu_\lambda}{T}\mathbf{v}_F\cdot\nabla T\right] = \mathfrak{St}_{{\rm el},\lambda}[\{f_\lambda\}] + \mathfrak{St}_{{\rm int},\lambda}[\{f_\lambda\}] + \mathfrak{St}_{{\rm oph},\lambda}[\{f_\lambda\}]$$

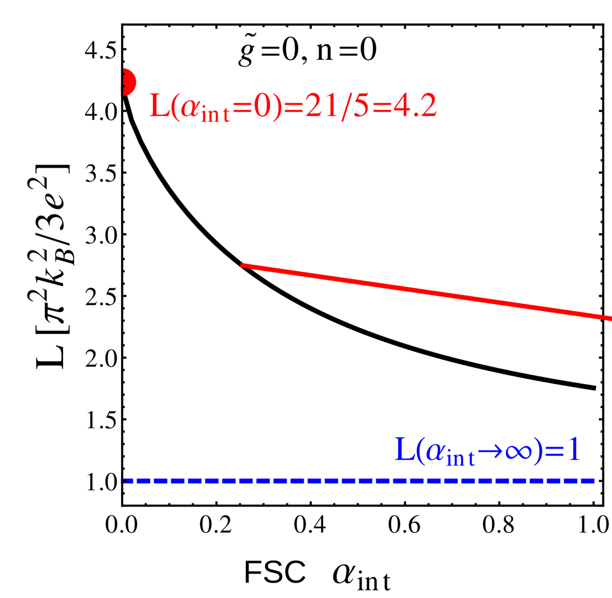
- $\lambda = +1\ (-1)$ for **e** (**h**); **E** and ∇T electric field and temperature gradient, respectively.
- $\mathfrak{St}_{{\rm el},\lambda}[\{f_\lambda\}] \sim$; $\mathfrak{St}_{{\rm int},\lambda}[\{f_\lambda\}] \sim$; $\mathfrak{St}_{{\rm opt},\lambda}[\{f_\lambda\}] \sim$

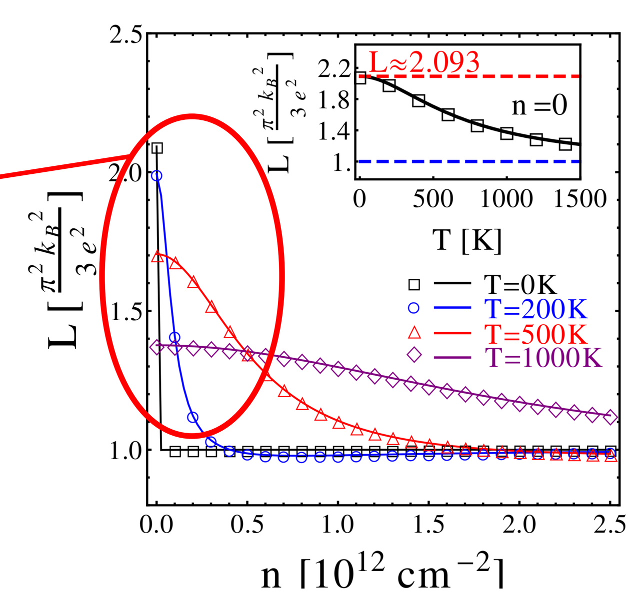


- Simplifications:
  1. Coulomb screening in the RPA approximation
  2. No e-h imbalance processes in Coulomb interactions
  3. Optical phonons (frequency $\omega_{A'} \approx 2200$ K) are dispersionless and in thermal equilibrium
- Linearized Boltzmann equation can be numerically solved by orthogonal polynomial method. [Allen 1978]

III. Disorder-limited transport

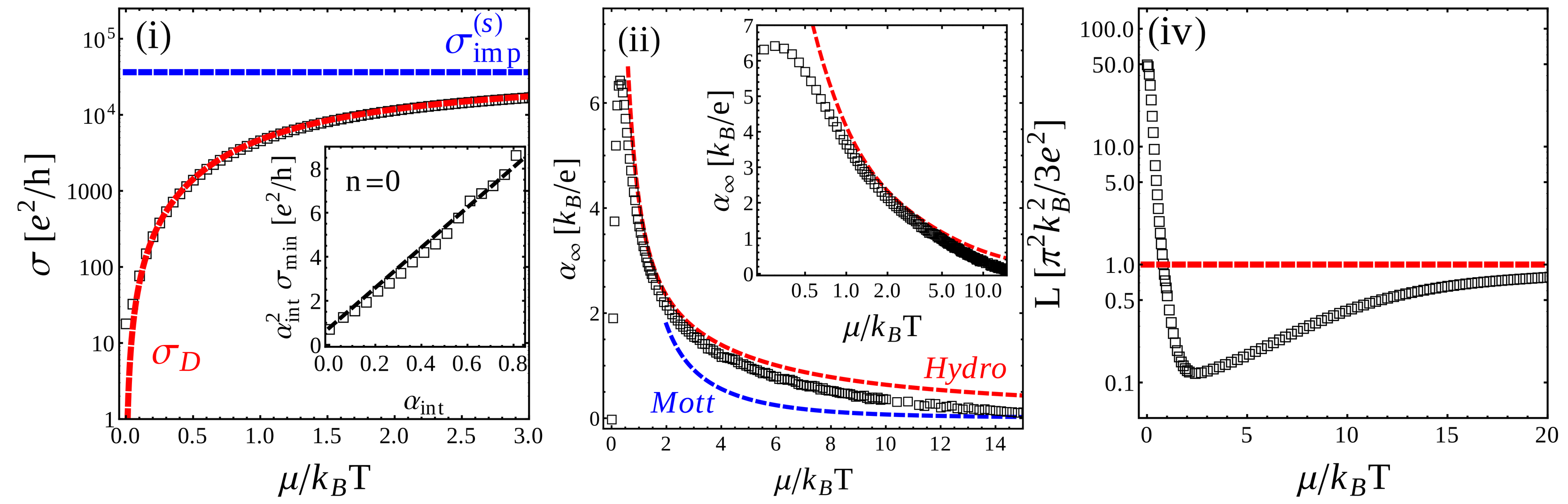
- Enhanced Lorentz ratio due to Coulomb impurities
- T, n dependence due to screening (RPA)





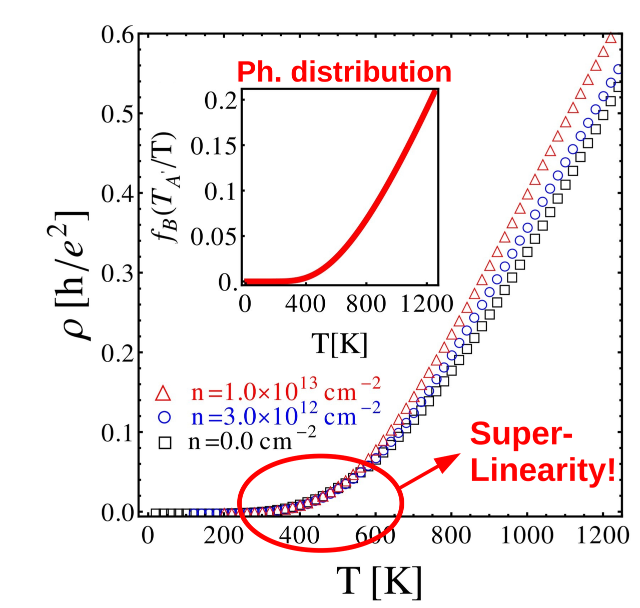
- Coulomb-impurity-only, at charge neutrality, w/o screening ($\alpha_{\rm int} \to 0$), $L/L_0 = 21/5 = 4.2$

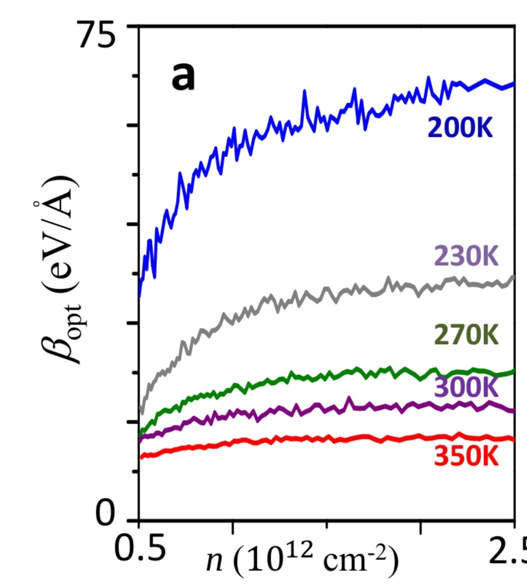
IV. Hydrodynamics to Fermi liquid crossover



- Minimal conductivity $\alpha^2_{\rm int}\,\sigma_{\rm min} \approx 0.79 + 9.13\,\alpha_{\rm int}$ at charge neutrality (Kashuba 08, Fritz *et al.*, 08 for $\alpha_{\rm int} \to 0$)
- TEP shows hydrodynamics–Fermi-liquid crossover
- Enhanced Lorentz ratio about charge neutrality

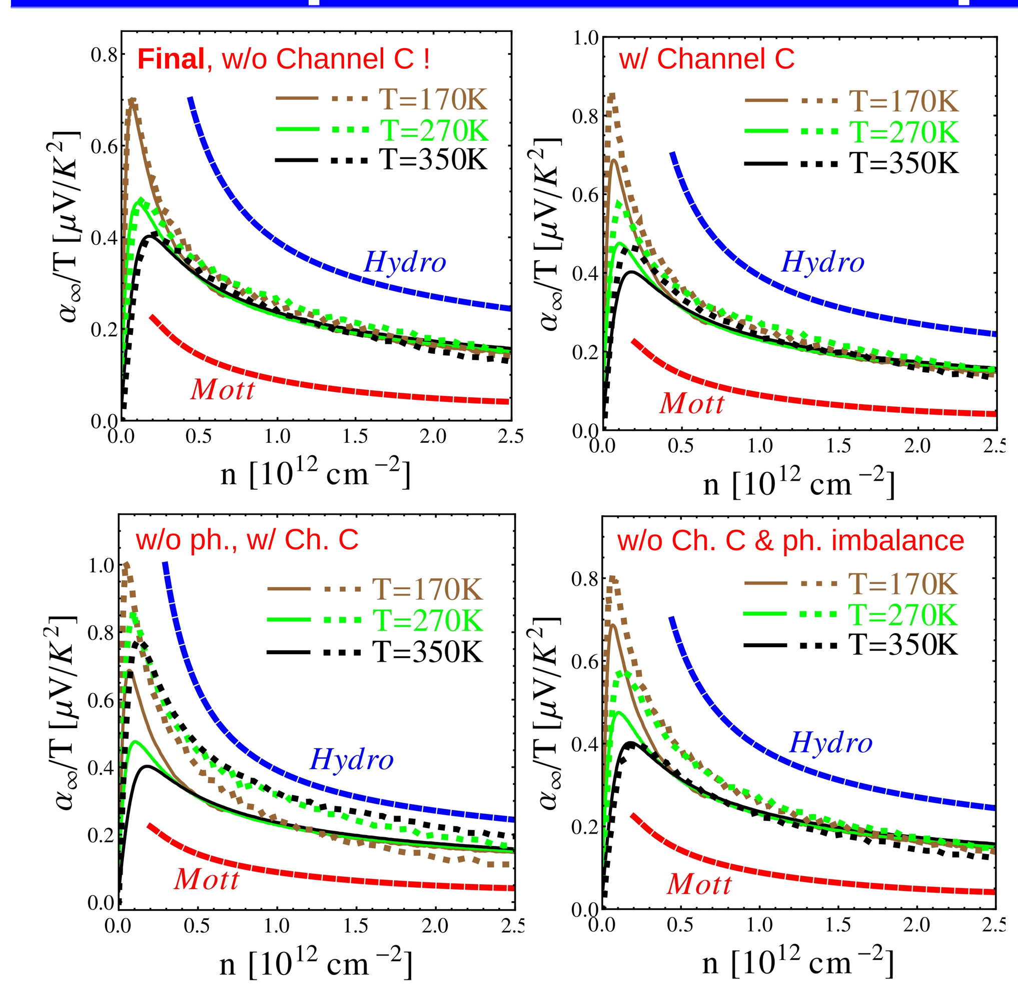
V. Optical phonon effects





- O-phonons activated at $T \sim 200$ K $\ll$ gap ~ 2200 K
- Model parameters, esp., E-ph coupling, obtained by fitting experimental conductivity data

VI. Comparison to TEP experiment



1. Quantitative agreement if excluding Channel C
2. Adding Channel C, Enhancement of hydro. (plasmons), Inconsist. with Exp.
3. Optical phonons non-negligible
4. Significant imbalance process o-ph $\leftrightarrow$ e + h