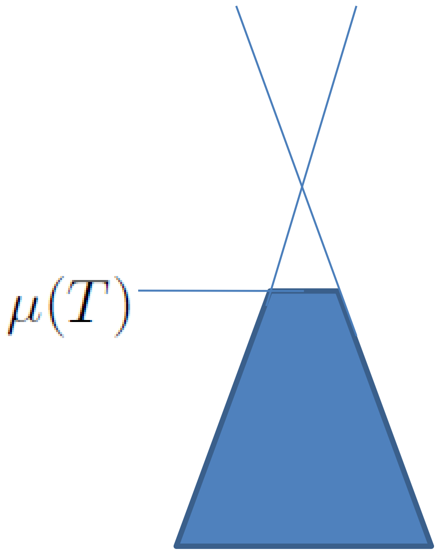
Thermodynamics of electron-hole liquids in graphene

L.A. Falkovsky
Landau Institute for Theoretical Physics

Coulomb renormalization



$$\varepsilon_s(p) = \mp vp \quad \sim \frac{e^2}{r} \quad \text{if} \quad p \sim \frac{\hbar}{r}$$

Abrikosov, Beneslsvsky 1971

Conzalez et al 1999

E. Mishchenko 2007

$$\varepsilon_s(p) = \mp vp[1 + g\ln(p_0/p)]$$

Lifsitz-Kosevich formula

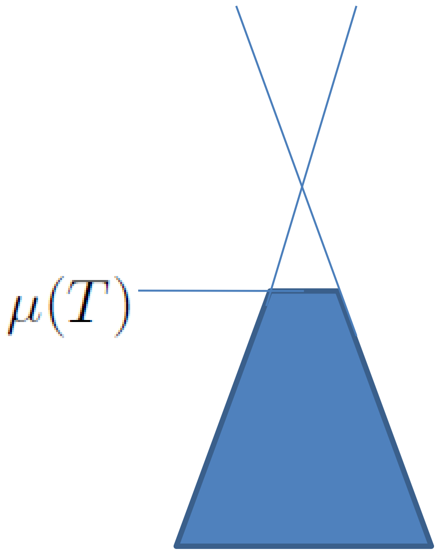
$$\tilde{M}(B) = \frac{2\pi n_0 ST}{B} \sum_{k \neq 0} \frac{\cos[kcA(\varepsilon_F)/e\hbar B]}{\sinh[2\pi^2 kc|m(\varepsilon_F)|T/e\hbar B]}$$

$$A(\varepsilon) = \pi \left(\frac{\varepsilon}{v}\right)^2 (1 - 2g\ln(p_0 v/\varepsilon)$$

$$m(\varepsilon) = \frac{1}{2\pi} \frac{dA(\varepsilon)}{d\varepsilon}$$

Coulomb renormalization

Yu, Katsnelson, Geim, Novoselov et al 2013



$$\varepsilon_s(p) = \mp vp[1 + g\ln(p_0/p)]$$

$$g = e^2/8\pi\hbar v\epsilon$$

$$p_0 \simeq 0.5 \times 10^8 \ \text{cm}^{-1}$$

$\epsilon \simeq 2.5 \div 8$

Chemical potential

$$\mu = \varepsilon_F - \frac{\pi^2}{6}\frac{T^2}{\varepsilon_F}$$

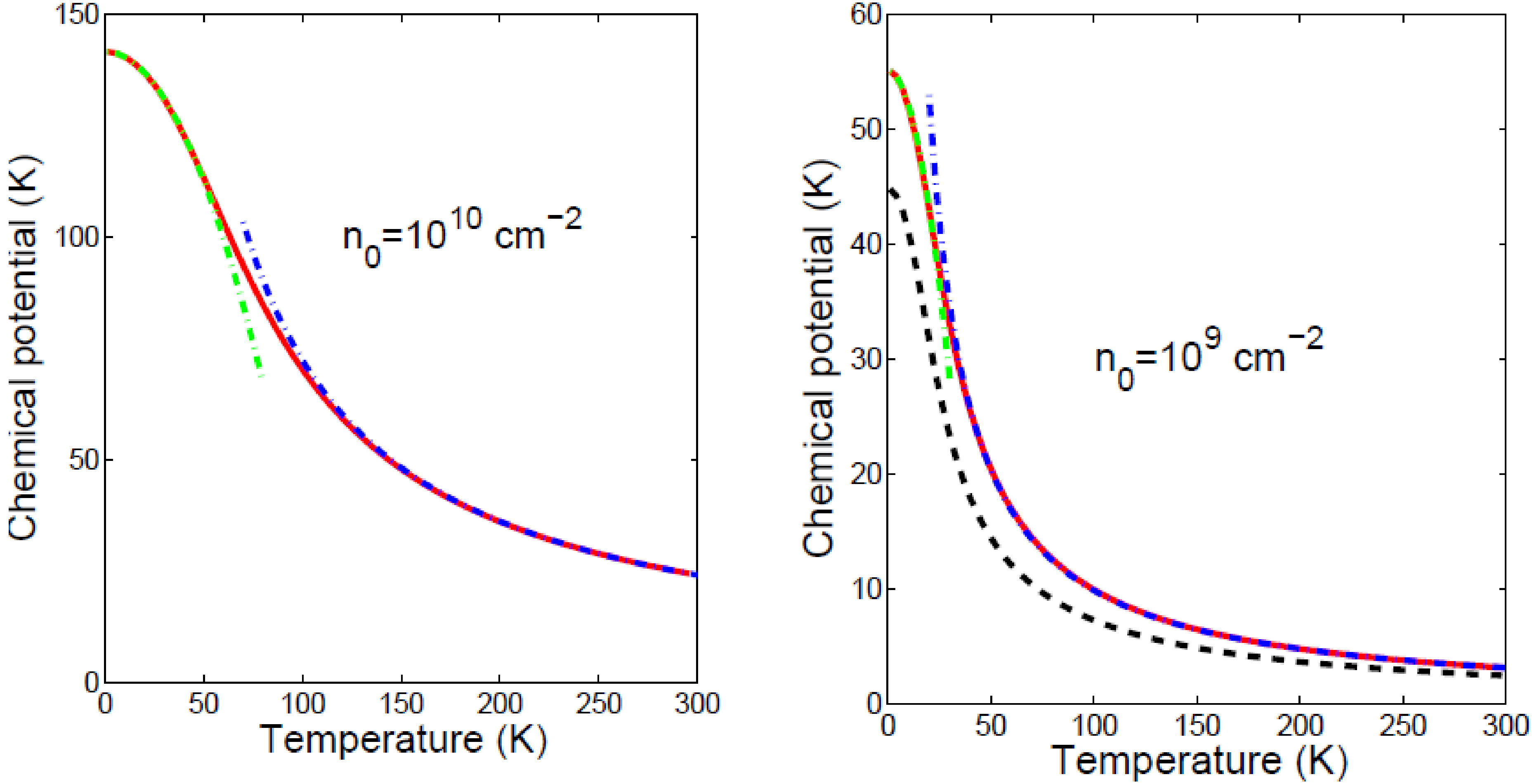
$$n_0 = \frac{p_F^2}{\pi\hbar^2} = \frac{1}{\pi}\left(\frac{\varepsilon_F}{\hbar v}\right)^2 [1 - 2g\ln(p_0 v/|\varepsilon_F|)]$$

$$\mu \gg T$$

$$|\mu| = \frac{\pi}{4\ln 2}\frac{n_0(\hbar v)^2}{T}[1 + 2g\ln(p_0 v/2T)]$$

$$\mu \ll T$$

Chemical potential



Heat capacity

$T \ll |\mu|$

$$C_S^{(e)} = \frac{2\pi S|\varepsilon_F|}{3\left(\hbar v\right)^2}T[1 - 2g\ln(p_0 v/|\varepsilon_F|)]$$

$$n_0 = \frac{p_F^2}{\pi\hbar^2} = \frac{1}{\pi}\left(\frac{\varepsilon_F}{\hbar v}\right)^2[1 - 2g\ln(p_0 v/|\varepsilon_F|)]$$

$T \gg |\mu|$

$$E = \frac{\pi^2}{6\ln 2}NT \quad \text{and} \quad C_S^{(e)} = \frac{\pi^2}{6\ln 2}N$$