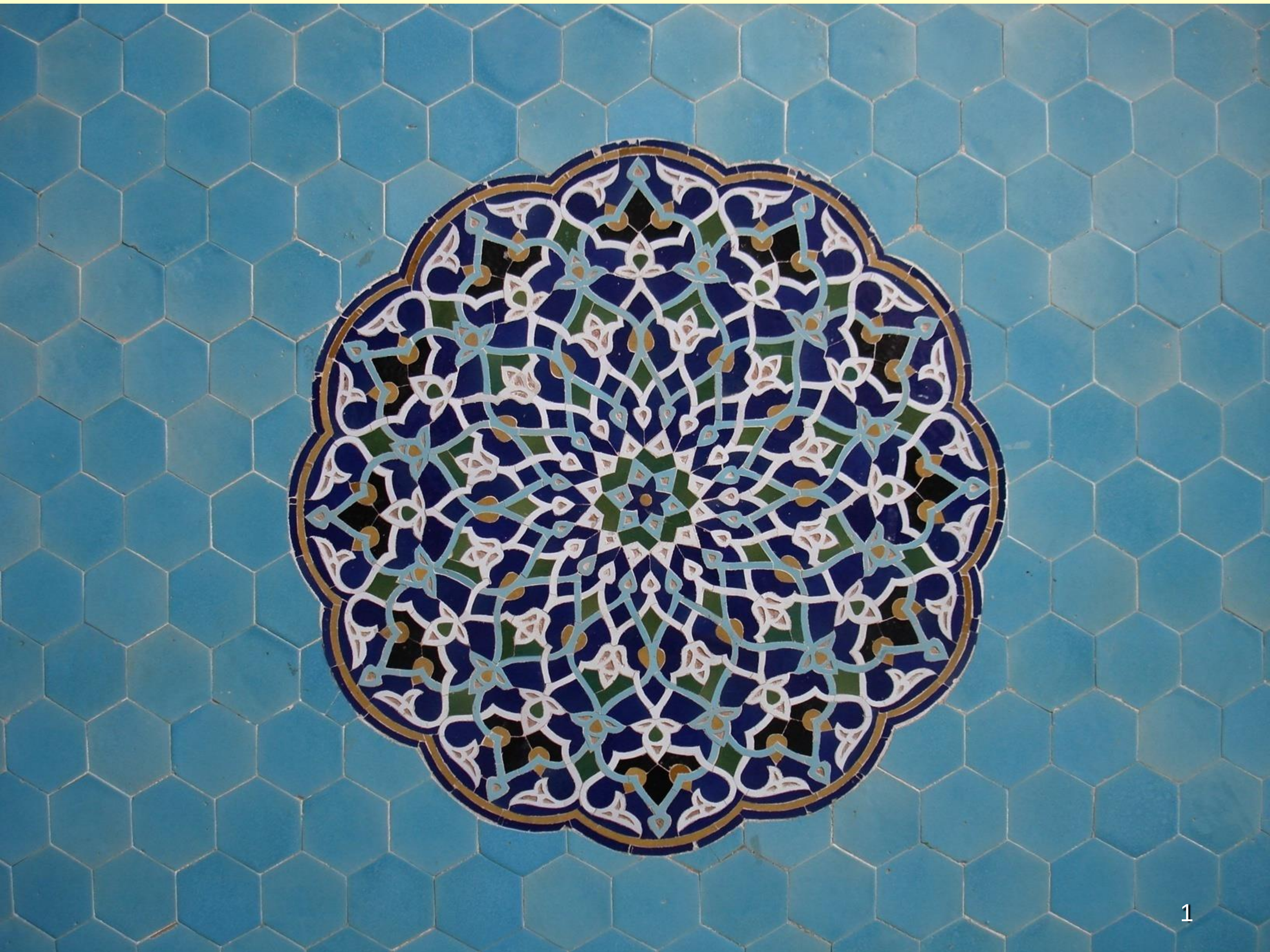

Electronic Cooling in Multilayer Epitaxial Graphene

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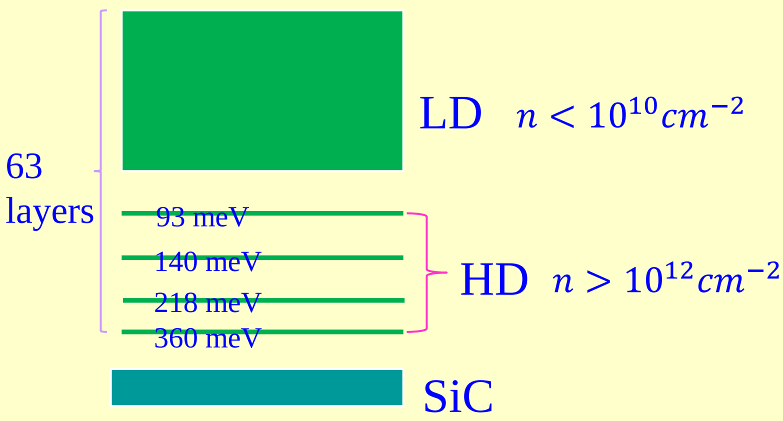
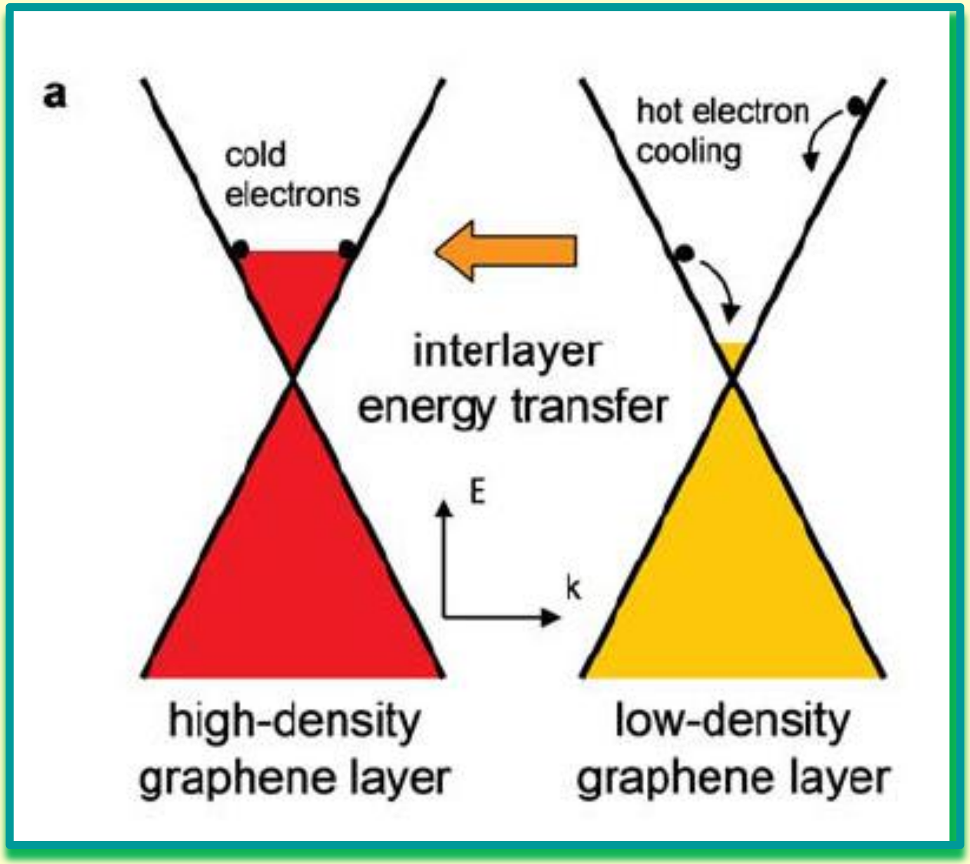
IPM
Institute for Research in Fundamental Sciences

Workshop on Nanoscale heat transport 15-16th April 2015

My purpose I:

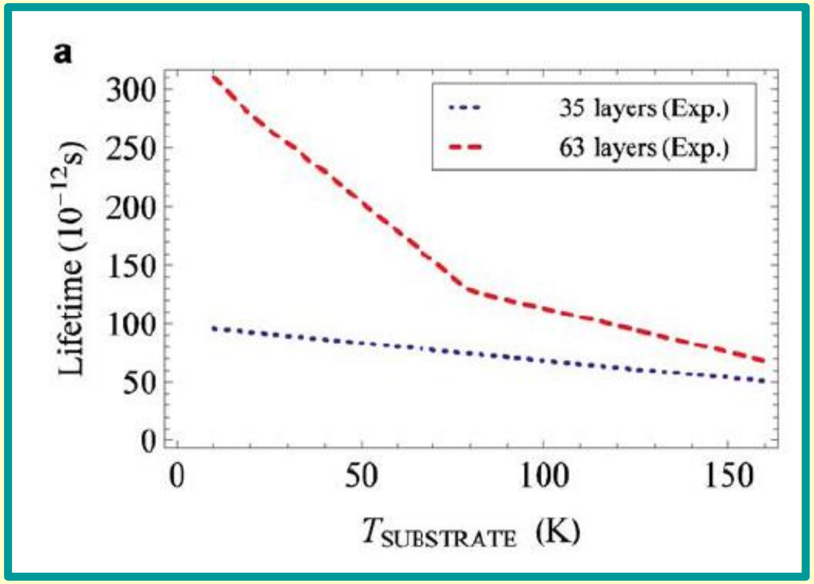


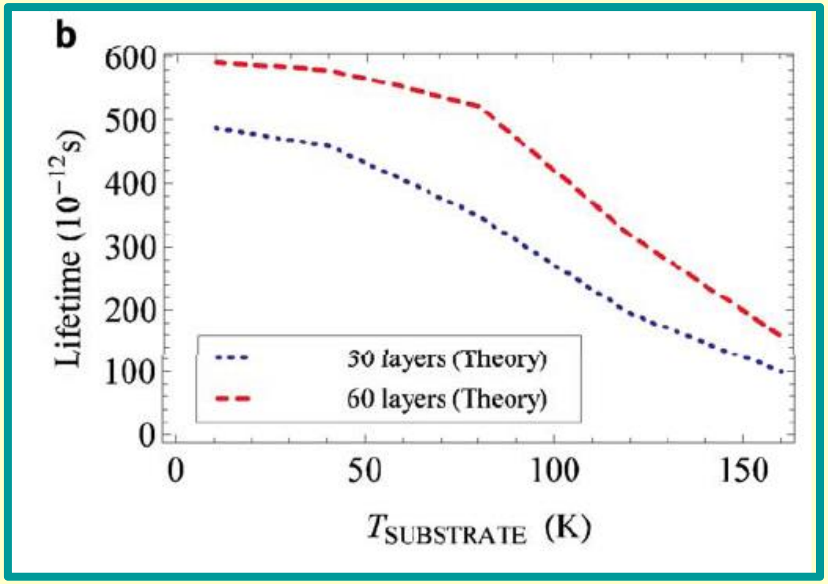


M. Mihney, J. Tolsma, C. David, D. Sun. R. Asgari, M. Polini, C. Berger, W. A. de Heer, A. H. MacDonald, T. Norris, Nature Commuin. (2015)

My purpose II:

Electronic cooling life time





M. Mihney, J. Tolsma, C. David, D. Sun. R. Asgari, M. Polini, C. Berger, W. A. de Heer, A. H. MacDonald, T. Norris, Nature Commuin. (2015)

Outlook

1. Introduction

   brief overview on electronic cooling and ultrafast spectroscopy

2. Electronic cooling and different mechanisms

   electron-phonon interactions

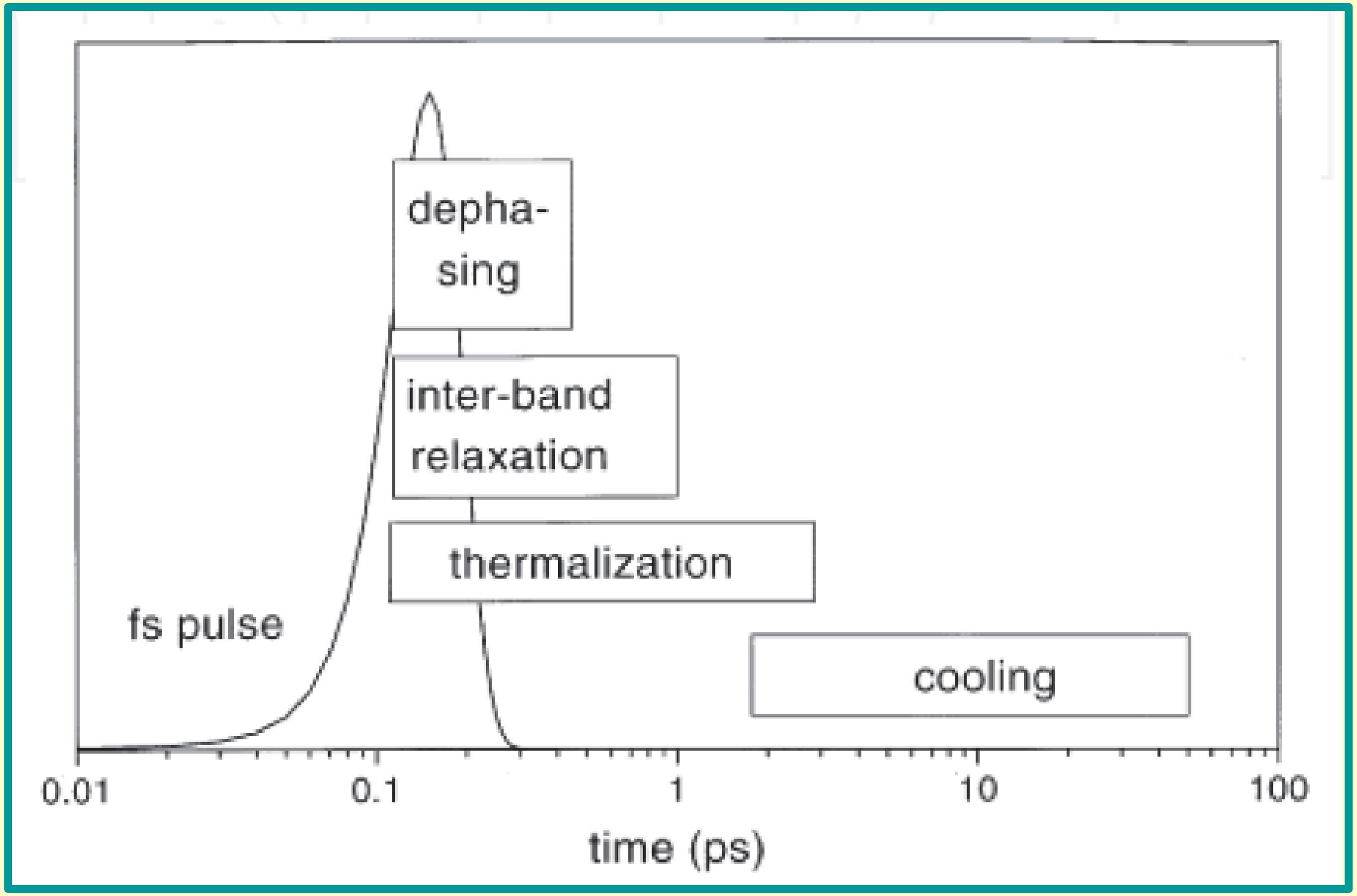
   electron-impurity interactions

   electron-electron interactions

   Multilayer epitaxial graphene

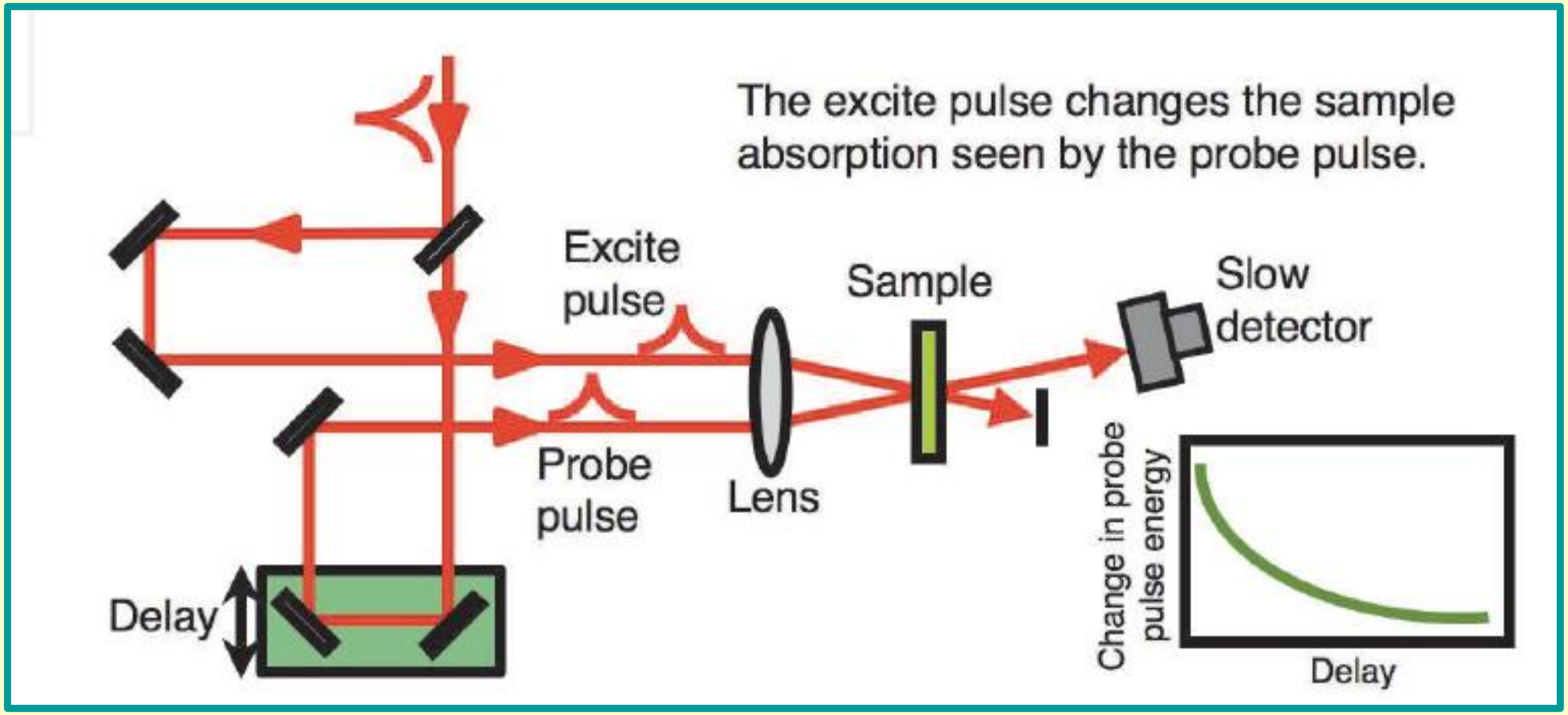
3. Conclusion

Ultrafast Spectroscopy



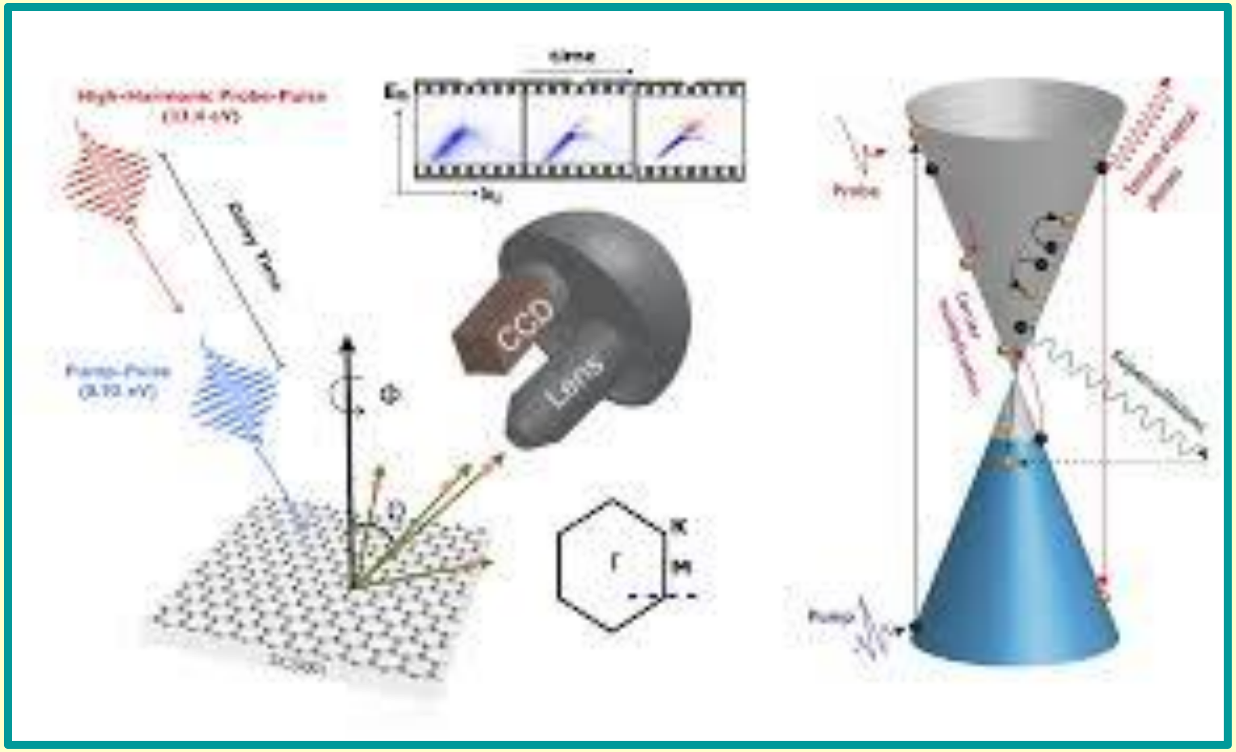
W. S. Yun, *et al*, Phys. Rev. B **85**, 033305 (2012)

Ultrafast Spectroscopy



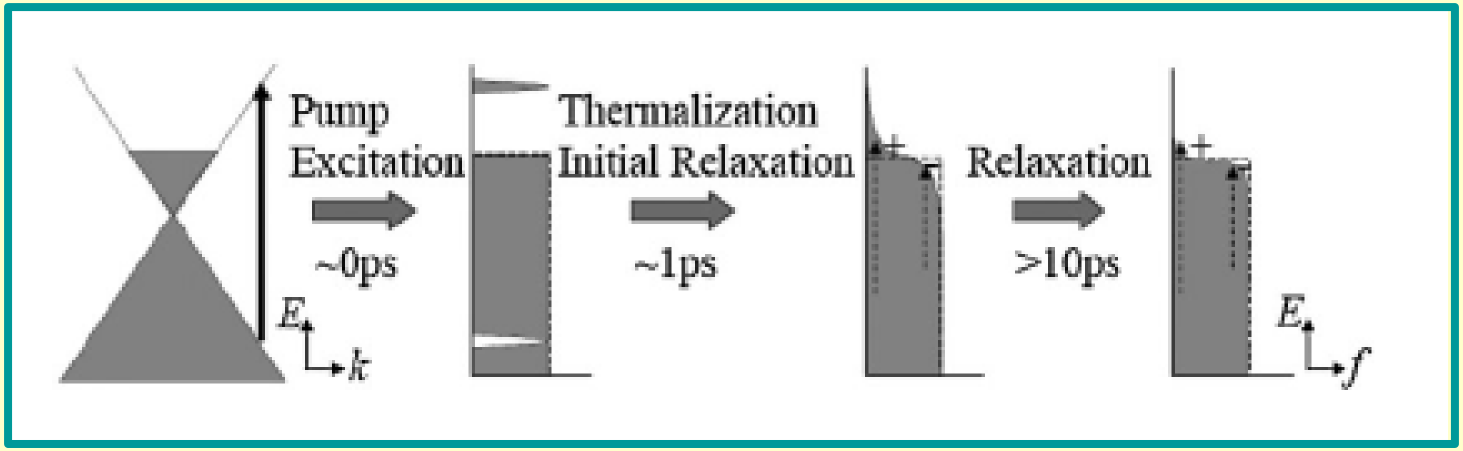
Di Xiao, *et al* , Phys. Rev. Lett. **108**,196802 (2012)

Ultrafast Spectroscopy



Ultrafast Spectroscopy

Thermalization of the hot electron



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Electron-phonon interactions

Heat transfer rate

$$Q_{e\text{-}ac} = V_d \Sigma (T_e^{\delta} - T_{ac}^{\delta})$$

$\delta = 5$ 3D metals, F. Wellstood, et al, PRB 49, 5942 (1994)

$\delta = 6$ Discorded thin film, Sergeev and Mitin , PRB 61, 6041 (2000)

$\delta = 3$ Clamped 3D but vibrations are 1D, Hekkila, PRB 77, 033401 (2008)

$\delta = 2 + d$

Electron-phonon interactions: graphene

$$Q_{e\text{-}ac} = V_d \Sigma (T_e^{\delta} - T_{ac}^{\delta})$$

$\delta = 4$ 2D graphene, Kubakadda , PRB 79, 075417 (2009)

$$Q_{e\text{-}ac} = V_d g(\mu, T_e)(T_e - T_{ac})$$

2D graphene, Bistritzer and MacDonald PRL 102, 206410 (2009)

Electron-phonon interactions: Graphene

Classical Boltzmann equation

$$\partial_t f_k^\alpha = S_{e\text{-}ph}(f_k^\alpha)$$

Scattering integral

$$S_{e\text{-}ph}(f_k^\alpha) = -\sum_{p\beta}[f_k^\alpha(1-f_p^\beta)W_{k\alpha\to p\beta} - f_p^\beta(1-f_k^\alpha)W_{p\beta\to k\alpha}],$$

Golden-rule scattering rate

$$W_{k\alpha\to p\beta} = \frac{2\pi}{\hbar}\sum_{q\gamma} w_{kp,q}^{\alpha\beta,\gamma}[(n_q^\gamma+1)\delta_{k,p+q}\delta(\epsilon_{kp}^{\alpha\beta}-\omega_q^\gamma) + n_q^\gamma\delta_{k,p-q}\delta(\epsilon_{kp}^{\alpha\beta}+\omega_q^\gamma)].$$

$$\epsilon_{kp}^{\alpha\beta} = \epsilon_k^\alpha - \epsilon_p^\beta$$

$$Q = -\partial_t\sum_{k\alpha}\epsilon_k^\alpha f_k^\alpha = -\sum_{k\alpha}\epsilon_k^\alpha S_{e\text{-}ph}(f_k^\alpha).$$

Viljas and Heillila Phys. Rev B **81**, 245404 (2010)

Electron-phonon interactions: Graphene

Electron-phonon Hamiltonian:

$$\hat{H}_{e\text{-}ac} = \sum_{k\alpha,p\beta} \sum_{q} M^{\beta\alpha}_{pk,q} c^{\dagger}_{p\beta} c_{k\alpha} (b_q + b^{\dagger}_{-q})$$

D is the coupling constant

$$M^{\beta\alpha}_{pk,q} = -\sqrt{\hbar^2/(2M\omega_q)}\, Dq \langle p\beta | e^{iq\cdot r} | k\alpha \rangle$$

$$\omega_q = \hbar c q$$

Effective interaction term

$$w^{\alpha\beta}_{kp,q} = \frac{\hbar^2}{2M\omega_q} D^2 q^2 F_{\alpha\beta}(\theta)$$

$$F_{\alpha\beta}(\theta) = (1 + s_\alpha s_\beta \cos n\theta)/2$$

$$\theta = \phi_p - \phi_k$$

Viljas and Heillila Phys. Rev B **81**, 245404 (2010)

Electron-phonon interactions: Graphene

$$Q_{\text{ind}} = -\frac{g_e A\hbar D^2}{2(2\pi)^2\rho}\sum_{\alpha\beta}\int_0^\infty dkk\int_{q_{\min}^{\alpha\beta}}^{q_{\max}^{\alpha\beta}} dqq^2 \times \frac{1+s_\alpha s_\beta y(k,q)}{\sqrt{1-[x(k,q)]^2}}|\hbar v_k^\alpha[p(k,q)/k]^{n-2}|^{-1} \times n_{ac}(\hbar cq)[f(\epsilon_k^\alpha - \hbar cq) - f(\epsilon_k^\alpha)]$$

$$p(k,q) = [s_\alpha s_\beta - s_\beta \hbar cq\gamma_1^{n-1}/(\hbar v k)^n]^{1/n} k$$

$$x(k,q) = -\{[p(k,q)]^2 - k^2 - q^2\}/(2kq)$$

$$y(k,q) = n[z(k,q)]^n - n + 1$$

$$z(k,q) = [k - qx(k,q)]/p(k,q)$$

Viljas and Heillila Phys. Rev B **81**, 245404 (2010)

Electron-phonon interactions: Graphene

Limit of the low temperature

$$k_B T_e, k_B T_{ac} \ll 2(c/v)|\mu| = k_B T_{\mathrm{BG,MLG}}$$

$$Q_{e\text{-}ac} = V_d \Sigma (T_e^\delta - T_{ac}^\delta)$$

$$\Sigma = \frac{\pi^2 D^2 |\mu| k_B^4}{15 \rho \hbar^5 v^3 c^3}$$

$$\delta = 4$$

Viljas and Heillila Phys. Rev B **81**, 245404 (2010)

Electron-phonon interactions: Graphene

For high temperature regiem

$$2(c/v)\max(|\mu|, k_B T_e) \ll k_B T_e, k_B T_{ac}$$

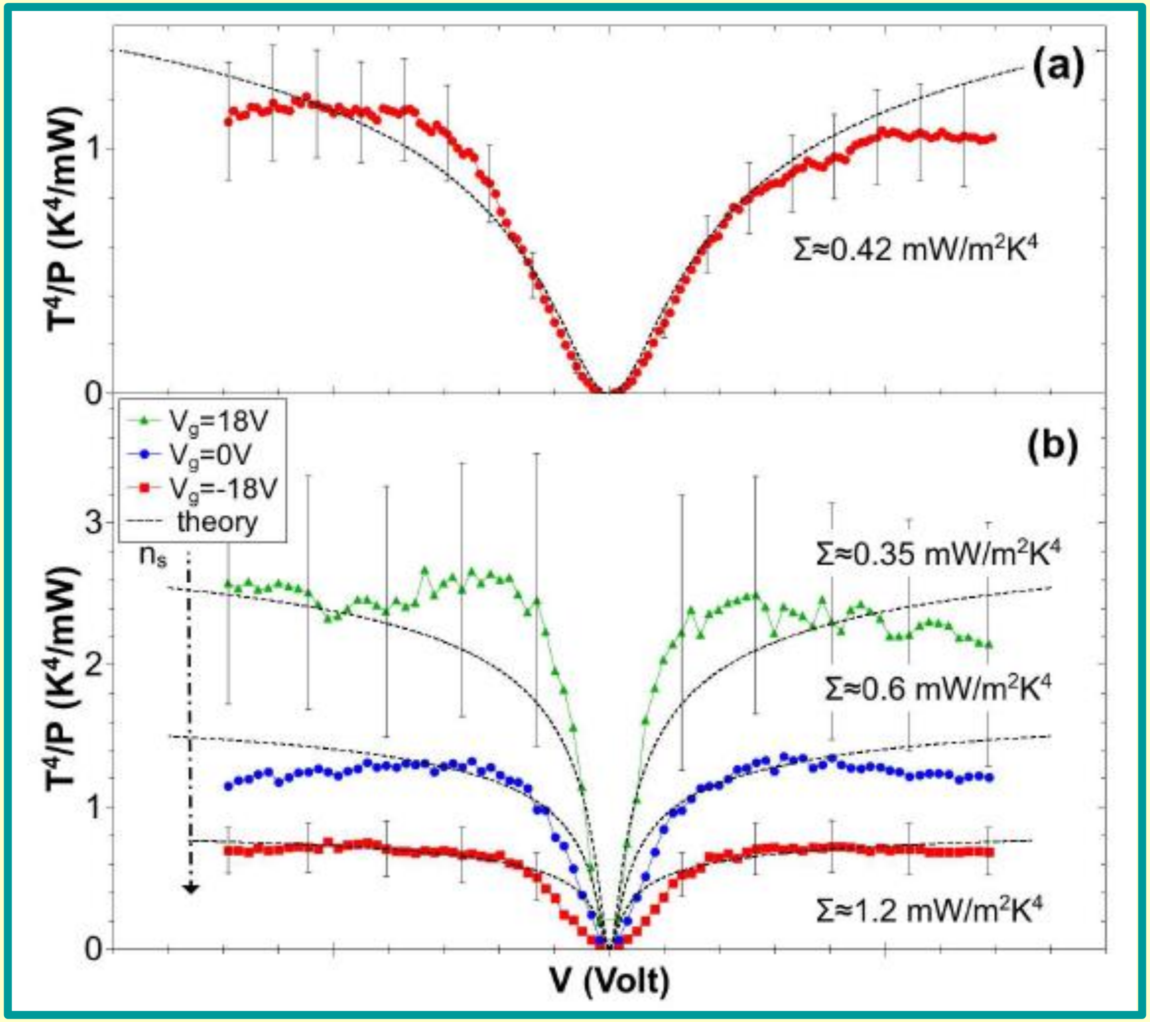
$$Q_{e\text{-}ac} = V_d\, g(\mu, T_e)(T_e - T_{ac})$$

$$g(\mu, T_e) = \frac{D^2 k_B}{30\pi\rho\hbar^5 v^6}[15\mu^4 + 30\pi^2\mu^2(k_B T_e)^2 + 7\pi^4(k_B T_e)^4]$$

$$g(\mu, T_e) \propto T_e^4$$

Viljas and Heillila Phys. Rev B **81**, 245404 (2010)

Electron-phonon interactions: Exp results



Betz et al, Phys. Rev Lett **109**, 056805 (2012)

Outlook

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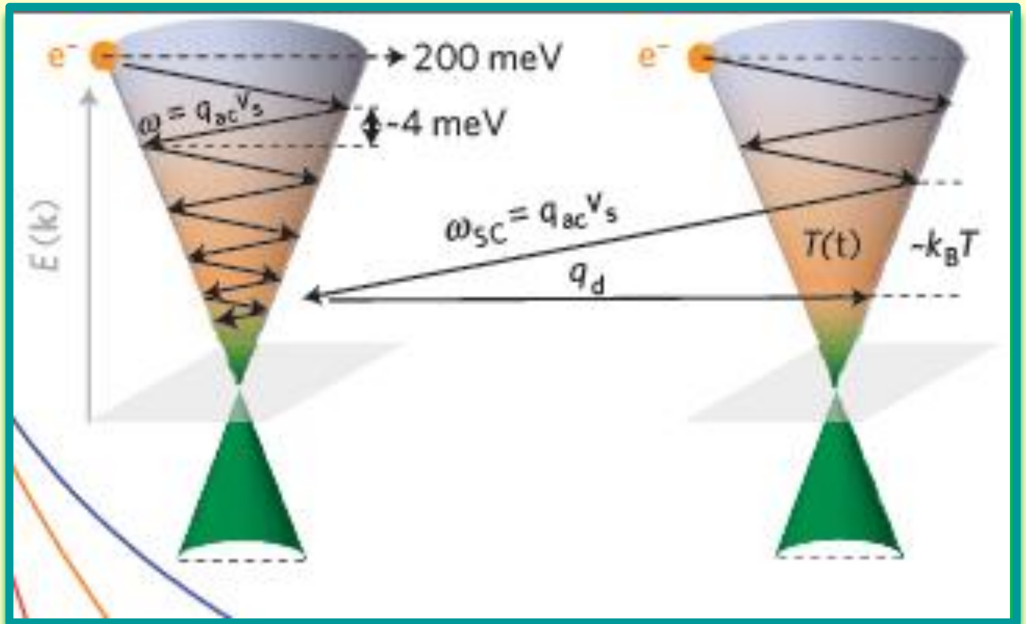
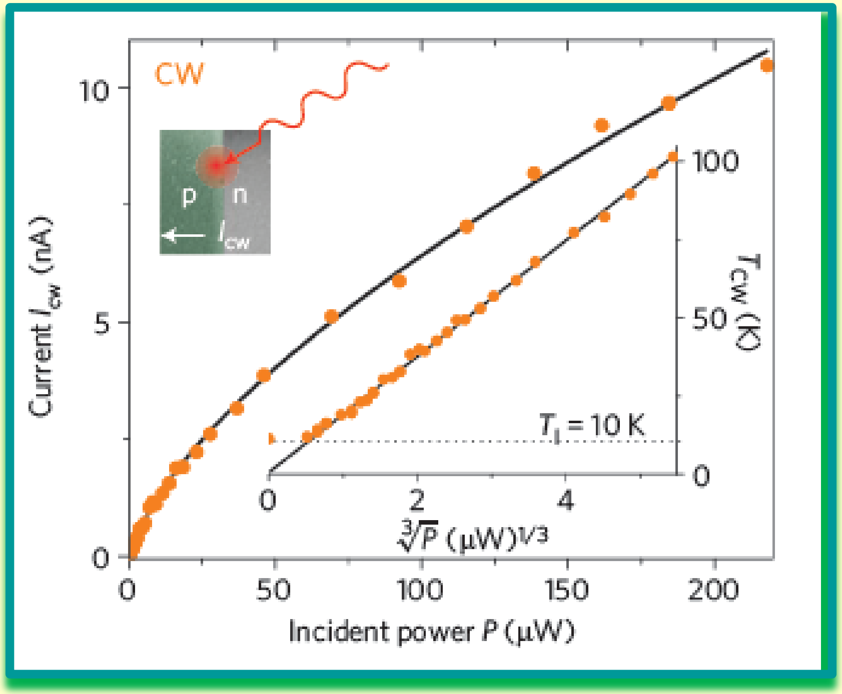
Electron-impurity interactions: supercollision



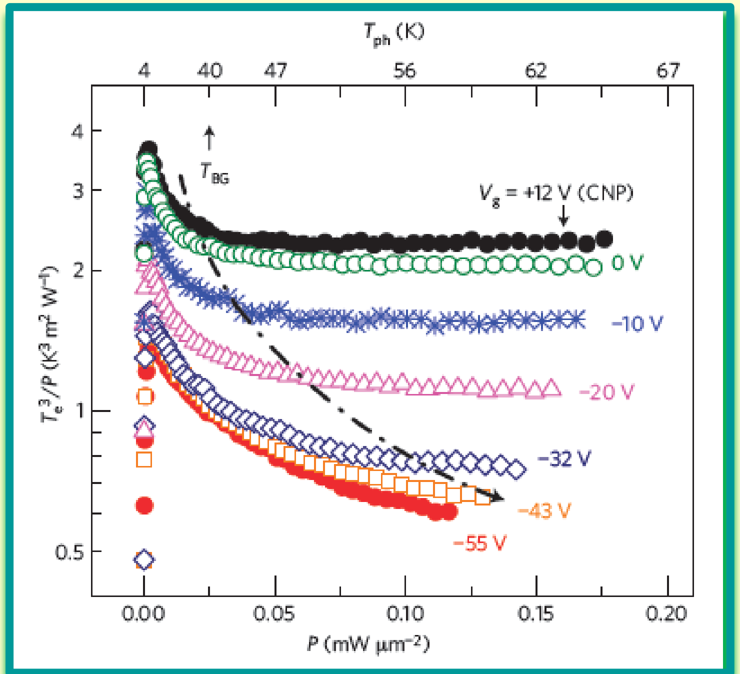
$$J_{SC} = A\,(T_e^3 - T_{ph}^3), \quad A = 9.62\,\frac{g^2 \nu^2(E_F) k_B^3}{\hbar k_F l}$$

Song, Reizer and Levitov Phys. Rev Lett, **109**, 106602 (2012)

Electron-impurity interactions: Evidences!

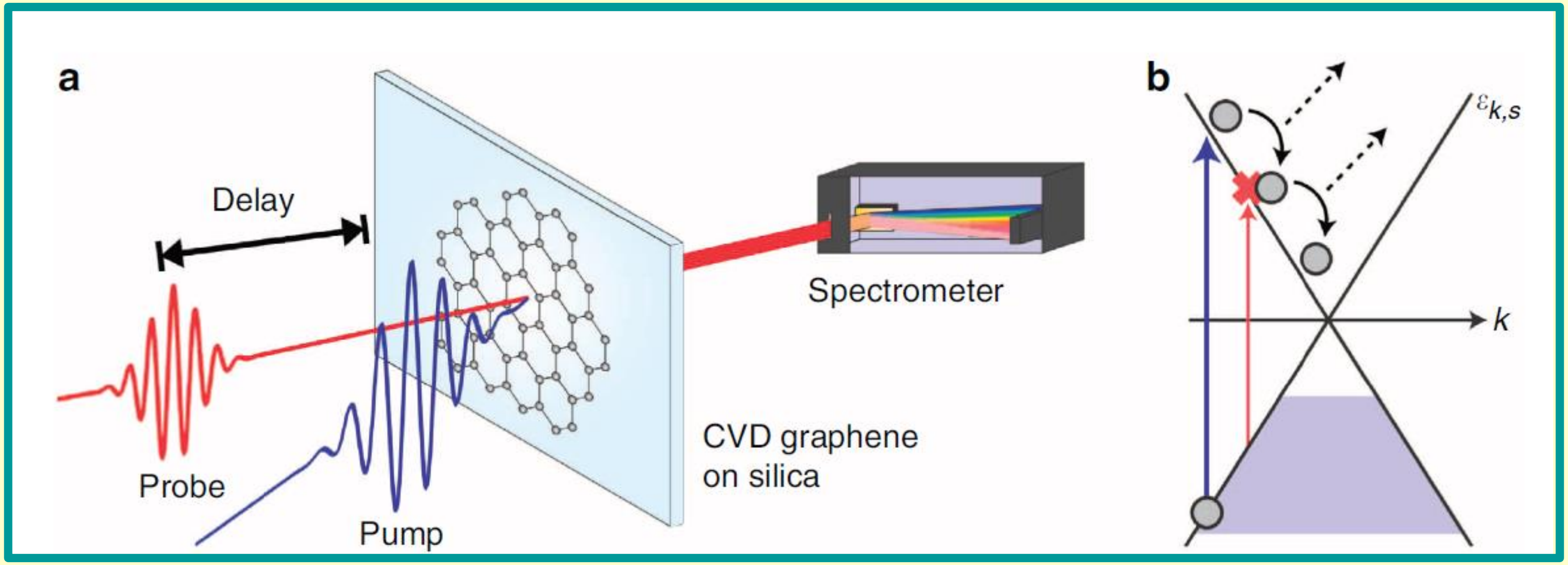


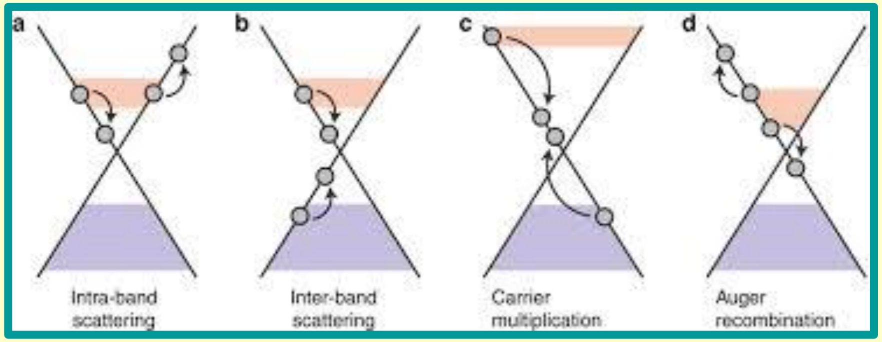
Graham et al Nature Physics (2012)



Betz et al Nature Physics (2012)

Electron-electron interactions





Brida, et al, Nature Commuin, DOI 10.1038 (2013)
Butscher, et al App. Phys. Lett **91**, 203103 (2007)
Sun et al, Phys. Rev. B **85**, 125413 (2012)

Electron-electron interactions

Semiclassical Boltzmann equation

$$\frac{\mathrm{d}f_\mu(\varepsilon_{\mathbf{k},\lambda})}{\mathrm{d}t} = \left.\frac{\mathrm{d}f_\mu(\varepsilon_{\mathbf{k},\lambda})}{\mathrm{d}t}\right|_{e-e} + \left.\frac{\mathrm{d}f_\mu(\varepsilon_{\mathbf{k},\lambda})}{\mathrm{d}t}\right|_{e-ph}$$

$$\left.\frac{\mathrm{d}f_\mu(\varepsilon_1)}{\mathrm{d}t}\right|_{e-e} = \int_{-\infty}^{\infty} d\varepsilon_2 \int_{-\infty}^{\infty} d\varepsilon_3 C_\mu(\varepsilon_1,\varepsilon_2,\varepsilon_3) \times\{[1-f_\mu(\varepsilon_1)][1-f_\mu(\varepsilon_2)]f_\mu(\varepsilon_3)f_\mu(\varepsilon_4) - f_\mu(\varepsilon_1)f_\mu(\varepsilon_2)[1-f_\mu(\varepsilon_3)][1-f_\mu(\varepsilon_4)]\}$$

Collision integral

$$C_\mu(\varepsilon_1,\varepsilon_2,\varepsilon_3) = \frac{2\pi}{\hbar}\frac{1}{S^2}\sum_{\mathbf{Q},\mathbf{k}_3} |V_{1234}^{(\mu)}|^2 \times \delta(|E-\varepsilon_1| - \hbar v|\mathbf{Q}-k_1|) \times \delta(|\varepsilon_3| - \hbar v k_3) \times \delta(|E-\varepsilon_3| - \hbar v|\mathbf{Q}-k_3| + \eta)$$

Brida, et al, Nature Commuin, DOI 10.1038 (2013)
Butscher, et al App. Phys. Lett **91,** 203103 (2007)
Sun et al, Phys. rEv. B **85**, 125413 (2012)

$E = \varepsilon_1 + \varepsilon_2$

$Q = k_1 + k_2$

Electron-electron interactions

$$\frac{df_\mu(\varepsilon_{k,\lambda})}{dt} = \left.\frac{df_\mu(\varepsilon_{k,\lambda})}{dt}\right|_{e-e} + \left.\frac{df_\mu(\varepsilon_{k,\lambda})}{dt}\right|_{e-ph}$$

$$|V^{(\mu)}_{1234}|^2 = |\mathcal{U}^{(\mu)}_{1234} - \mathcal{U}^{(\mu)}_{1243}|^2/2 + |\mathcal{U}^{(\mu)}_{1234}|^2$$

$$\mathcal{U}^{(\mu)}_{1234} = W(|\mathbf{k}_1 - \mathbf{k}_3|, \omega; t) F^{(\mu)}_{s_1,s_3}(\theta_{\mathbf{k}_3} - \theta_{\mathbf{k}_1}) F^{(\mu)}_{s_2,s_4}(\theta_{\mathbf{k}_4} - \theta_{\mathbf{k}_2})$$

$$F^{(\mu)}_{s,s'}(\theta) = [1 + ss' \exp(i\mu\theta)]/2$$

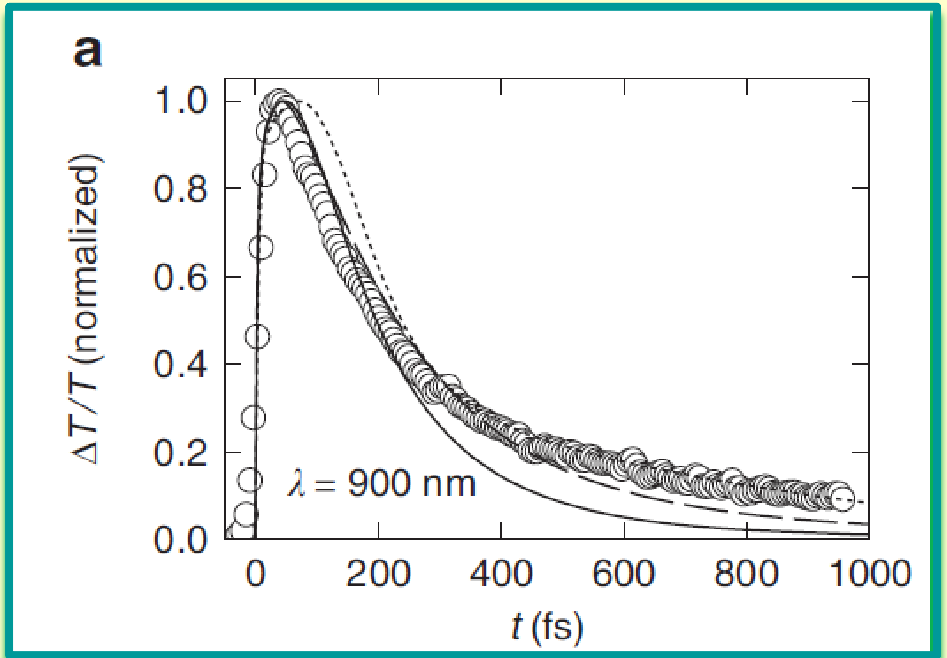
$$C_\mu(\varepsilon_1, \varepsilon_2, \varepsilon_3)|_{\text{Auger}} = \frac{1}{8\pi^2\hbar^5 v^4}\sqrt{\left|\frac{\varepsilon_2\varepsilon_3\varepsilon_4}{\varepsilon_1}\right|}\,|V^{(\mu)}_{1234}|^2$$

$$\mathrm{CM}(t) \equiv \frac{n_c(t) - n_c(-\infty)}{n_c(0) - n_c(-\infty)}$$

Brida, et al, Nature Commuin, DOI 10.1038 (2013)
Butscher, et al App. Phys. Lett **91**, 203103 (2007)
Sun et al, Phys. Rev. B **85**, 125413 (2012)

Electron-electron interactions: Delay time

$$\frac{\Delta T}{T}(\lambda, t) = \pi\alpha[f_\mu(\hbar\omega/2) - n_{\mathrm{F}}(\hbar\omega/2) - f_\mu(-\hbar\omega/2) + n_{\mathrm{F}}(-\hbar\omega/2)],$$



Brida, et al, Nature Commuin, DOI 10.1038 (2013)

Electron-electron interactions: interlayer

$$\dot{\mathbf{P}}_2 = -i[\mathbf{P}_2, H] = -i\nabla_{\mathbf{R}_2} H = \sum_{\mathbf{q}} i\mathbf{q} U_d(q) \rho^1_{\mathbf{q}} \rho^2_{-\mathbf{q}} e^{-i\mathbf{q}\cdot(\mathbf{R}_1 - \mathbf{R}_2)}$$

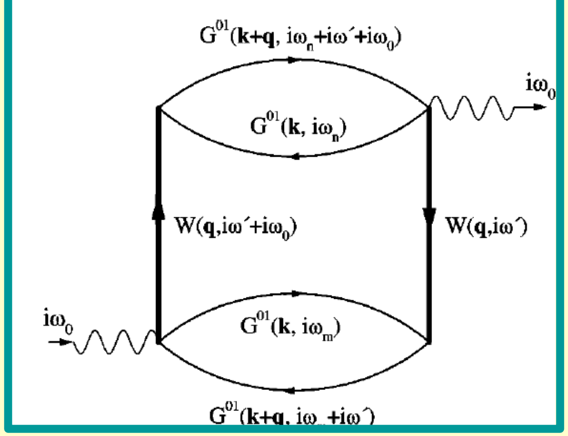
$$- e n_2 \mathbf{E}_2 + \dot{\mathbf{P}}_{2,ep} + \dot{\mathbf{P}}_{2,ei}\,.$$

$$e n_2 \mathbf{E}_2 = i \sum_{\mathbf{q}} \mathbf{q} \int_{-\infty}^{\infty} dt_1 (-i)\theta(t - t_1) \sum_{\mathbf{k},\mathbf{p}} \sum_{\mathbf{Q}}$$

$$\times e^{-i\mathbf{q}\cdot[\mathbf{R}_1(t) - \mathbf{R}_1(t_1)] + i\mathbf{Q}\cdot\mathbf{R}_1(t_1)} e^{i(1-\gamma)(\varepsilon_{k+q} - \varepsilon_k)(t - t_1)}$$

$$\times \mathrm{Tr}\{\tilde{\varrho}[U_d(q)\tilde{c}^\dagger_{\mathbf{k}+\mathbf{q}}(t)\tilde{c}_{\mathbf{k}}(t)\tilde{d}^\dagger_{\mathbf{p}-\mathbf{q}}(t)\tilde{d}_{\mathbf{p}}(t),$$

$$\times U_d(\mathbf{Q} - \mathbf{q})\tilde{\rho}^1_{\mathbf{Q}-\mathbf{q}}(t_1)\tilde{\rho}^2_{\mathbf{q}-\mathbf{Q}}(t_1)]\}.$$



Wang and Lima, Phys. Rev. B **63**, 205312 (2001)
Senger and Tanatar SSC **121**, 61 (2002)

Electron-electron interactions: Interlayer

Cooling power rate transferred between layers

$$\frac{Q^{el}}{L^2} = \frac{\hbar}{4\pi^3} \int_{-\infty}^{\infty} \omega \, d\omega \int d\vec{q} \, |v^{sc}_{LD,HD}|^2 \left[n_B(T_{LD}) - n_B(T_{HD}) \right]$$

$$\times \quad \mathrm{Im}\chi_{LD}(q,\omega,T_{LD}) \mathrm{Im}\chi_{HD}(q,\omega,T_{HD})$$

Wang and Lima, Phys. Rev. B **63**, 205312 (2001)
Flensberg and Hu, Phys. Rev. B **52**, 14795 (1995)

Electron-electron interactions

$$\chi^{(0)}(q,\omega,T) = g \lim_{\eta\to 0^+} \sum_{s,s'=\pm} \int \frac{d^2k}{(2\pi)^2} \frac{1+ss'\cos(\theta_{k,k+q})}{2} \frac{n_F(\varepsilon_{k,s}) - n_F(\varepsilon_{k+q,s'})}{\omega + \varepsilon_{k,s} - \varepsilon_{k+q,s'} + i\eta}.$$

$$\begin{aligned}\mathrm{Im}\,\chi^{(0)}(q,\omega,T) = \frac{g}{4\pi}\sum_{\alpha=\pm}\Big\{&\Theta(v_F q-\omega)q^2 f(v_F q,\omega)\big[G_+^{(\alpha)}(q,\omega,T) - G_-^{(\alpha)}(q,\omega,T)\big]\\ &+\Theta(\omega - v_F q)q^2 f(\omega, v_F q)\Big[-\frac{\pi}{2}\delta_{\alpha,-} + H_+^{(\alpha)}(q,\omega,T)\Big]\Big\}\end{aligned}$$

$$\begin{aligned}\mathrm{Re}\,\chi^{(0)}(q,\omega,T) = \frac{g}{4\pi}\sum_{\alpha=\pm}\Big\{&\frac{-2k_B T\ln[1+e^{\alpha\mu_0/(k_B T)}]}{v_F^2} + \Theta(\omega - v_F q)\\ &\times q^2 f(\omega, v_F q)\big[G_-^{(\alpha)}(q,\omega,T) - G_+^{(\alpha)}(q,\omega,T)\big]\\ &+\Theta(v_F q - \omega)q^2 f(v_F q,\omega)\Big[-\frac{\pi}{2}\delta_{\alpha,-} + H_-^{(\alpha)}(q,\omega,T)\Big]\Big\}.\end{aligned}$$

$$f(x,y) = \frac{1}{2\sqrt{x^2-y^2}}$$

$$G_\pm^{(\alpha)}(q,\omega,T) = \int_1^\infty du \frac{\sqrt{u^2-1}}{\exp\left(\frac{|v_F q u \pm \omega| - 2\alpha\mu_0}{2k_B T}\right) + 1}$$

Ramezanali, Vaziefeh, Asgari, Polini, MacDonald, J. Phys. A **42**, 214015 (2009)
Faridi, Pashangpour, Asgari, Phys. Rev. B **85**, 045410 (2012)

Electron specific heat and spin susceptibility at low temperature

$$C_V = -T\partial^2[n\delta f(T)]/\partial T^2$$

$$\delta f_{\rm int}(T\to 0) = \varepsilon_{\rm F}\frac{\pi^2}{3}\left(\frac{T}{T_{\rm F}}\right)^2\frac{\alpha_{\rm gr}[1-\alpha_{\rm gr}\xi(\alpha_{\rm gr})]}{4g}\ln\Lambda + {\rm R.T.}$$

$$\frac{1}{\chi_s(T)} = \frac{1}{n\mu_B^2}\frac{\partial^2[f_0(T,\zeta)+f_{\rm int}(T,\zeta)]}{\partial\zeta^2}\bigg|_{\zeta=0}$$

$$\begin{aligned}\delta\chi_s^{-1}(T) &= \chi_s^{-1}(T) - \chi_s^{-1}(T=0)\\ &= \frac{\varepsilon_{\rm F}\pi^2}{8n\mu_B^2}\left(\frac{T}{T_{\rm F}}\right)^2\left[\frac{g_v}{3} - \eta\ln\Lambda\right]\end{aligned}$$

Ramezanali, Vaziefeh, Asgari, Polini, MacDonald, J. Phys. A **42**, 214015 (2009)
Faridi, Pashangpour, Asgari, Phys. Rev. B **85**, 045410 (2012)

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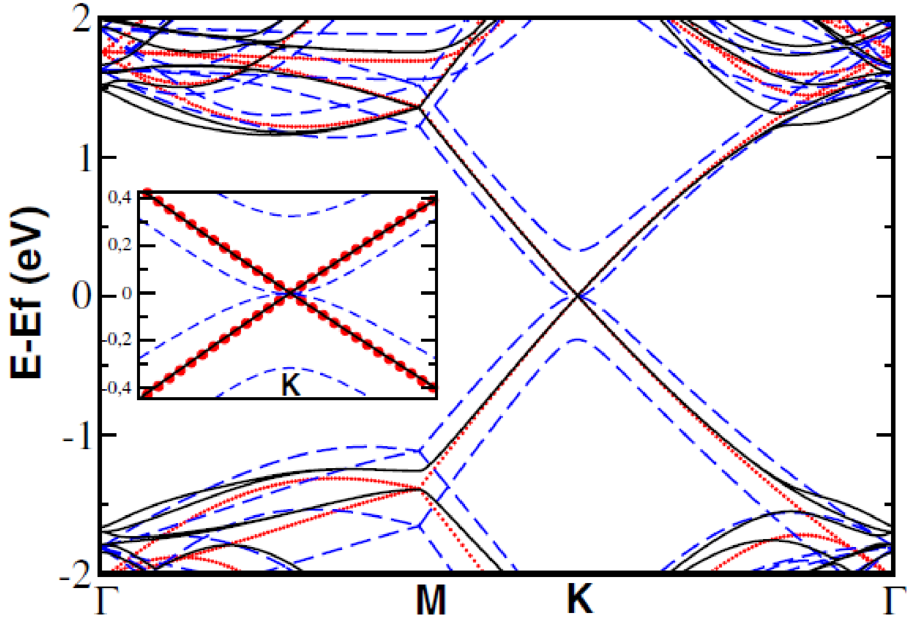
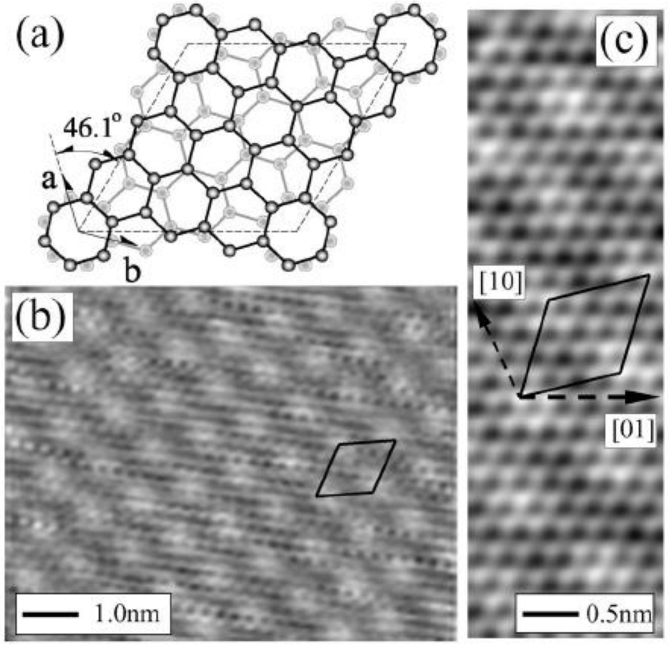
Epitaxial graphene on C-terminated SiC

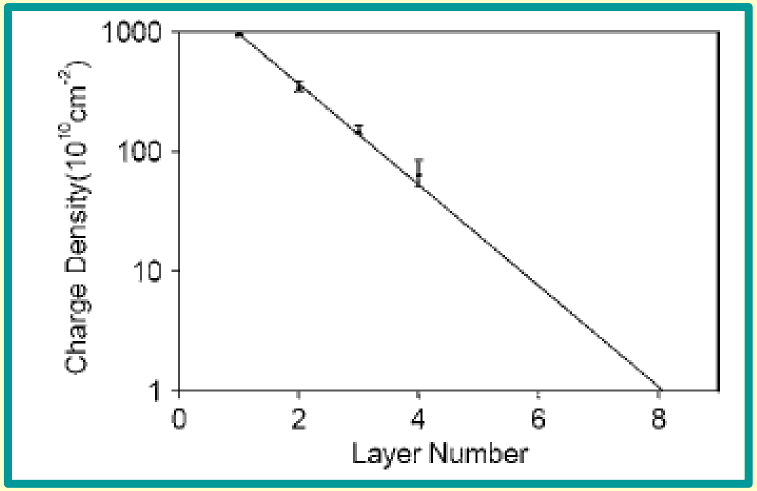




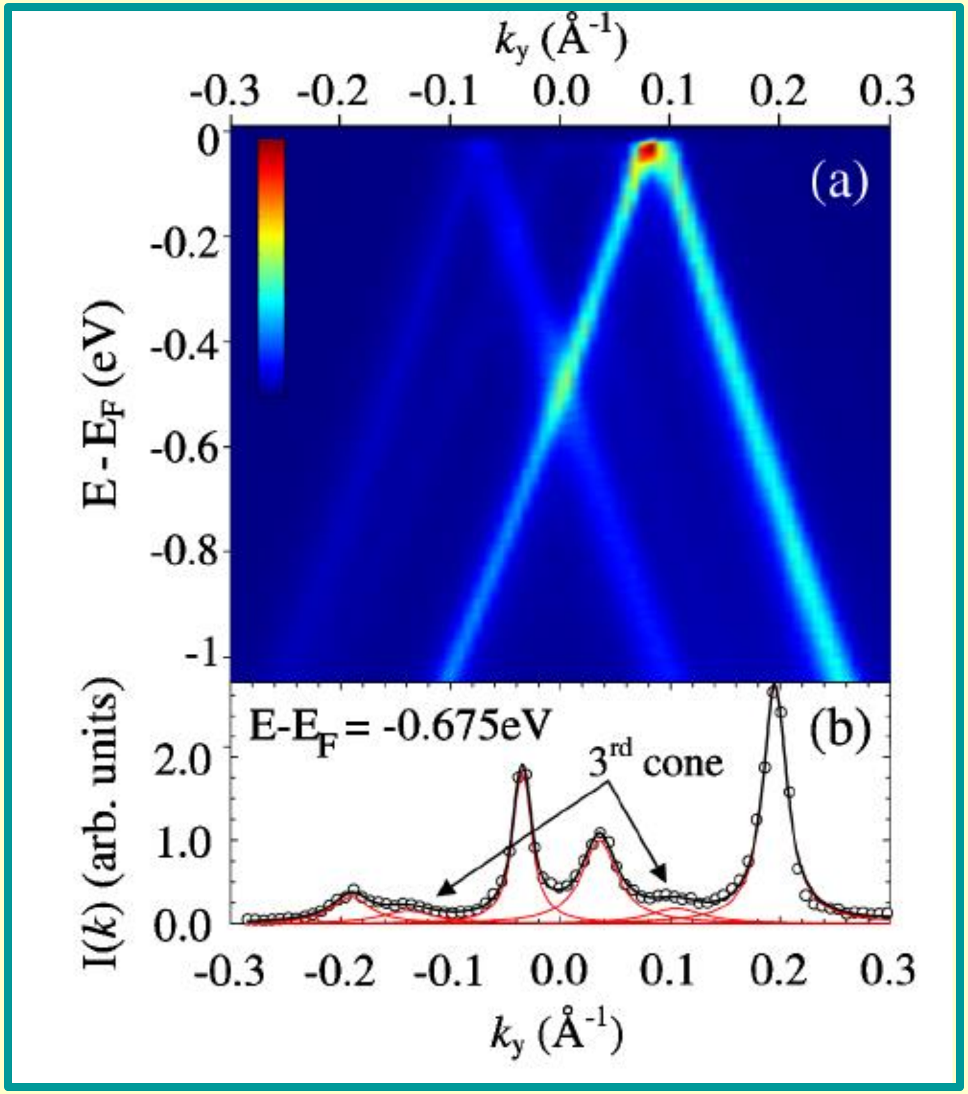
Hass, et al Phys. Rev. Lett **100**, 125504 (2008)

Epitaxial MLG on C-face SiC

Charge distributions:



Sun, et al Phys. Rev. Lett **104**, 136802 (2010)



Sprinkle, et al Phys. Rev. Lett **103**, 226803 (2009)

Electron-electron interactions: Two-layers

$$\frac{Q^{el}}{L^2} = \frac{\hbar}{4\pi^3}\int_{-\infty}^{\infty}\omega\, d\omega \int d\vec{q}\,|v^{sc}_{LD,HD}|^2\,[n_B(T_{LD}) - n_B(T_{HD})]$$
$$\times \quad \mathrm{Im}\chi_{LD}(q,\omega,T_{LD})\mathrm{Im}\chi_{HD}(q,\omega,T_{HD})$$

$$v^{sc}_{LD,HD} = v_q/\epsilon^{RPA}(q,\omega,T_{LD},T_{HD})$$

$$\epsilon^{RPA}(q,\omega,T_{LD},T_{HD}) = (1 - v_q\chi_{LD}(q,\omega,T_{LD}))(1 - v_q\chi_{HD}(q,\omega,T_{HD}))$$
$$- \; v_q^2 e^{-2qd}\chi_{LD}(q,\omega,T_{LD})\chi_{HD}(q,\omega,T_{HD})$$

M. Mihney, J. Tolsma, C. David, D. Sun. R. Asgari, M. Polini, C. Berger, W. A. de Heer, A. H. MacDonald, T. Norris, Nature Commuin. (2015)

Electron-electron interactions: two layers

$$k_{F,LD}d << 1 \text{ and } q_{HD}^{TF}/k_{F,LD} >> 1$$

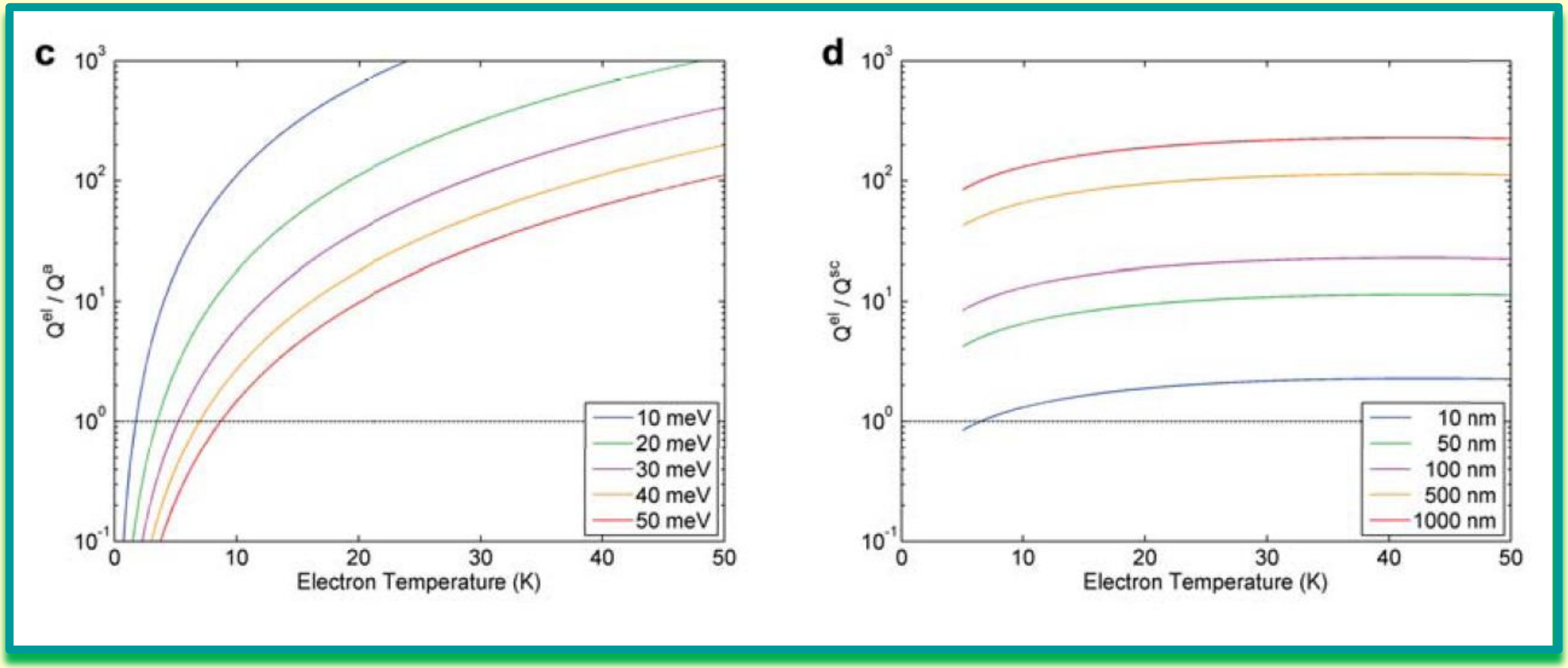
$$q_i^{TF} = q v_q \nu_i$$

$$\frac{Q^{el}}{L^2} = \frac{E_{F,LD}^4 \nu_{LD}}{2\pi^2 v_F^2 \hbar^3 \nu_{HD}} \int_0^\infty \Omega d\Omega \int_0^\infty Q dQ \left(\frac{1}{e^{\Omega/t}-1}\right)\left(\frac{\Omega}{Q}\right)^2$$

$$\frac{Q^{el}}{L^2} = -\frac{E_{F,LD}^4 \pi^2 \nu_{LD}}{15 v_F^2 \hbar^3 \nu_{HD}} t^4 \ln t.$$

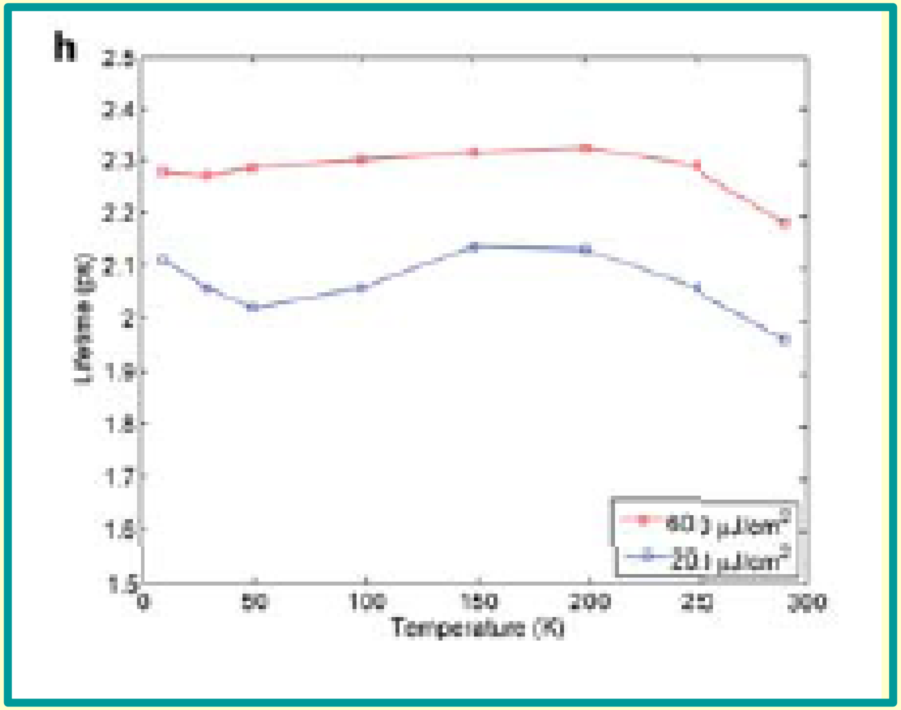
$$t = k_B T / E_{F,LD}$$

Electron-electron interactions: Interlayer



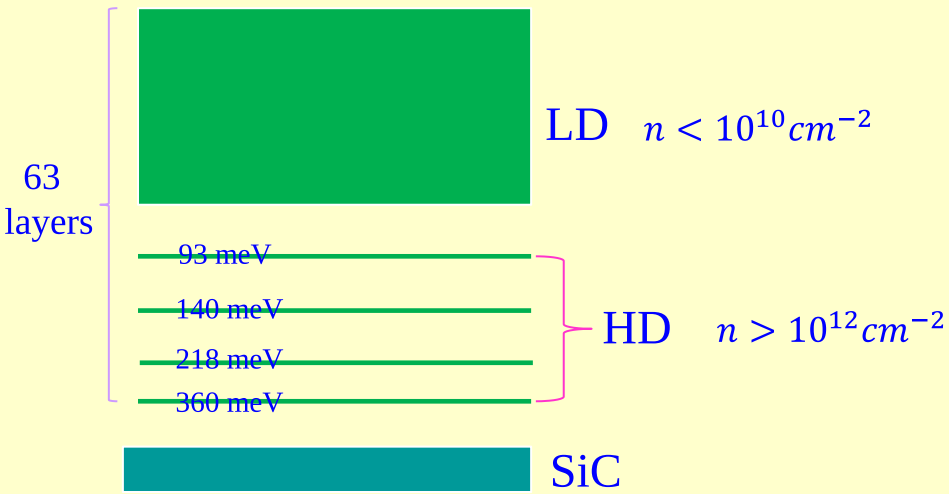
M. Mihney, J. Tolsma, C. David, D. Sun. R. Asgari, M. Polini, C. Berger, W. A. de Heer, A. H. MacDonald, T. Norris, Nature Commuin. (2015)

Cooling lifetime in MEG



$$\partial_t T_i = \left(Q_i^{ph}(T_i) + \sum_{j \neq i} Q_{ij}^{el}(T_i, T_j) \right) / \mathcal{C}_i$$

Power rate in MEG



$$Q_{ij}^{el} = \frac{\hbar}{\pi} \int_{-\infty}^{\infty} d\omega\, \omega \sum_{\vec{q}} |v_{ij}^{sc}|^2 \times [n_B(\hbar\omega/T_i) - n_B(\hbar\omega/T_j)] \times \mathrm{Im}\chi_i(q,\omega,T_i)\, \mathrm{Im}\chi_j(q,\omega,T_j)$$

$$\mathbf{v}_{ij}^{sc} = \left(\mathbf{v}^{-1} - \delta_{i,j}\, \chi_i(q,\omega,T_i)\right)_{ij}^{-1}$$

Cooling in multilayer: approximation

$$Q_{ij}^{el} = \frac{\hbar}{\pi}\int_{-\infty}^{\infty} \omega d\omega \sum_{\vec{q}} |v_{ij}^{sc}|^2 \times \frac{\hbar\omega}{4T_L^2} \frac{\delta T}{\sinh^2(\hbar\omega/2T_L)} \times \mathrm{Im}\chi_i(q,\omega,T_L)\mathrm{Im}\chi_j(q,\omega,T_L).$$

$$\epsilon^{MEG}(q,\omega) = 1 - \frac{2\pi e^2}{\kappa q} \sum_{j\in HD} \chi_j(q,\omega,T_j).$$

$$\partial_t T_{LD} = \left(\sum_{j\in HD} Q_{LD,j}^{el}(T_{HD} = T_L, T_{LD}, d_{j,LD}) \right) / \mathcal{C}_{LD}$$

$$\mathcal{C}_{LD} = 18\zeta(3)T_{LD}^2/(\pi v_F^2)$$

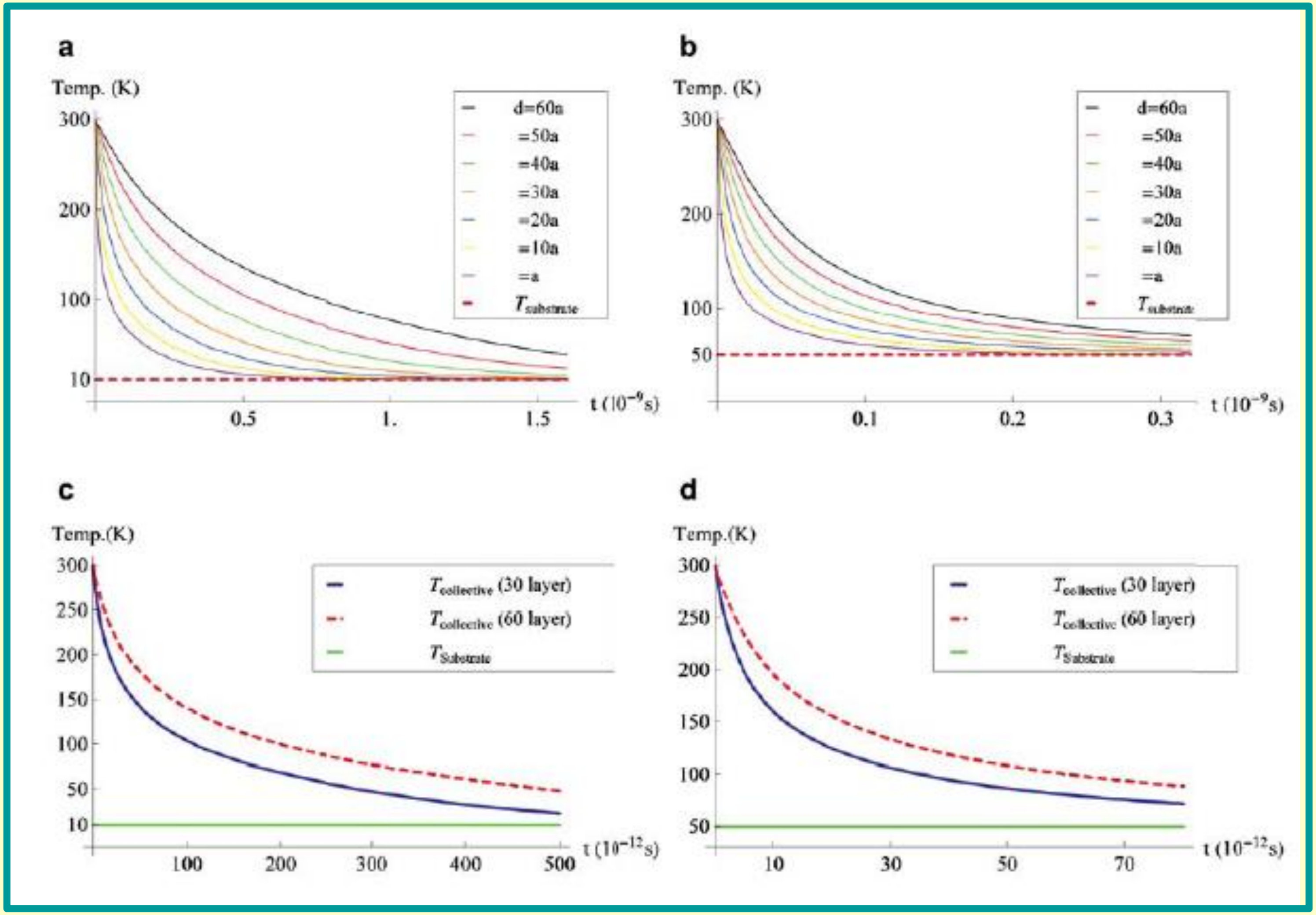
T(t) in MEG

$$\partial_t T_{LD} = \left(\sum_{j \in HD} \mathcal{Q}^{el}_{LD,j}(T_{HD} = T_L, T_{LD}, d_{j,LD}) \right) / \mathcal{C}_{LD}$$

$$\partial_t T_c = \left(\sum_{i \in LD} \sum_{j \in HD} \mathcal{Q}^{el}_{ij}(T_L, T_{LD} \to T_c, d_{ij}) \right) / N\mathcal{C}_{LD}$$

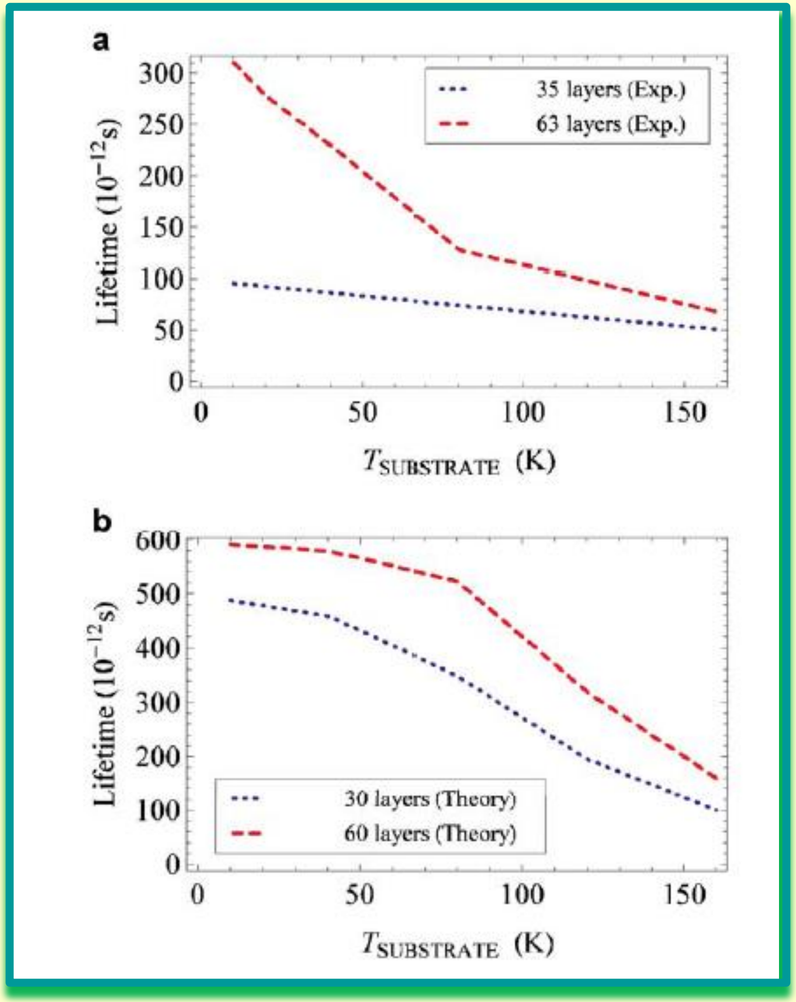
$$\mathcal{C}_{LD} = 18\zeta(3) T^2_{LD} / (\pi v^2_F)$$

T(t) in MEG



a
Temp. (K)
300
200
100
10
0.5
1.
1.5
t (10⁻⁹s)
d=60a
=50a
=40a
=30a
=20a
=10a
=a
T_substrate
b
Temp. (K)
300
200
100
50
0.1
0.2
0.3
t (10⁻⁹s)
d=60a
=50a
=40a
=30a
=20a
=10a
=a
T_substrate
c
Temp.(K)
300
250
200
150
100
50
10
100
200
300
400
500
t (10⁻¹²s)
T_collective (30 layer)
T_collective (60 layer)
T_Substrate
d
Temp.(K)
300
250
200
150
100
50
10
30
50
70
t (10⁻¹²s)
T_collective (30 layer)
T_collective (60 layer)
T_Substrate

Cooling lifetime in MEG



M. Mihney, J. Tolsma, C. David, D. Sun. R. Asgari, M. Polini, C. Berger, W. A. de Heer, A. H. MacDonald, T. Norris, Nature Commuin. (2015)

Conclusions

- Electron cooling mechanisms: e-ph, e-imp and e-e interactions
  δ =2+d ?
- Epitaxila graphene: C-face multilayer graphene on SiC substrate
  electronic cooling times ranging from a few to hundreds of picoseconds that strongly depend on the lattice temperature and the number of epitaxial graphene layers

- Developed a theory of hot-carrier equilibration based on interlayer energy transfer via screened Coulomb interactions

- Energy transfer between the LD layers is much stronger than between LD and HD layers
- The theoretically calculated thermal equilibration times are free of any fitting parameters, compare closely with the experimental relaxation times

Thanks for your attention