A New Mechanism for Coulomb Drag in Graphene

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Baltimore 03/18/2013

Justin Song & LL, arXiv:1303.3529, arXiv:1205.5257

Novel phenomena at CN

- Strong interactions, anomalous thermodynamics (Gonzales, Guinea, Vozmediano, Son, Sheehy & Schmalian, Vafek)
- New collective modes (Vafek, Mishchenko et al)
- P-conserving collisions give rise to finite resisitivity (Kashuba, Fritz, Schmalian, Mueller, Sachdev)

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- P-conserving collisions give rise to finite resisitivity (Kashuba, Fritz, Schmalian, Mueller, Sachdev)

- Strong thermopower: coupling charged and neutral modes (Hwang, Rossi, Das Sarma, Zuev et al, Wei et al, Checkelsky & Ong)
- Nonlocality mediated by neutral modes (Abanin, LL, Geim)

Couple neutral and charged modes?

Charge-compensated neutral plasma ultra-sensitive to B fields

- Continued interest in plasma physics and astrophysics
- Thermo-magnetic waves predicted and observed in 3D semimetals (Gurevich, Gelmont '66; Kopylov '78)
- Thermo-magnetic instabilities in Bismuth under T gradient. Period doubling sequence, Feigenbaum chaos (80's)

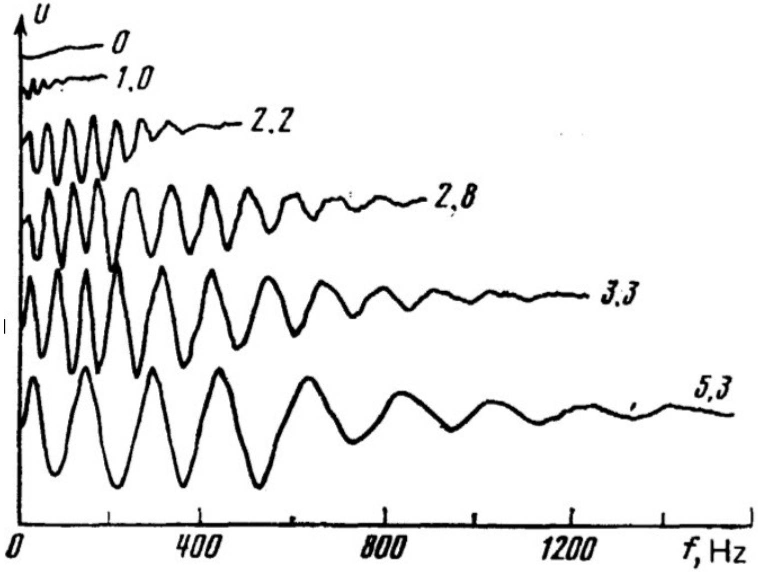

FIG. 3. Frequency dependence of the signal from the phase detector for various temperature gradients indicated at the curves in relative units. Specimen Bi2, $T = 1.7$ °K.

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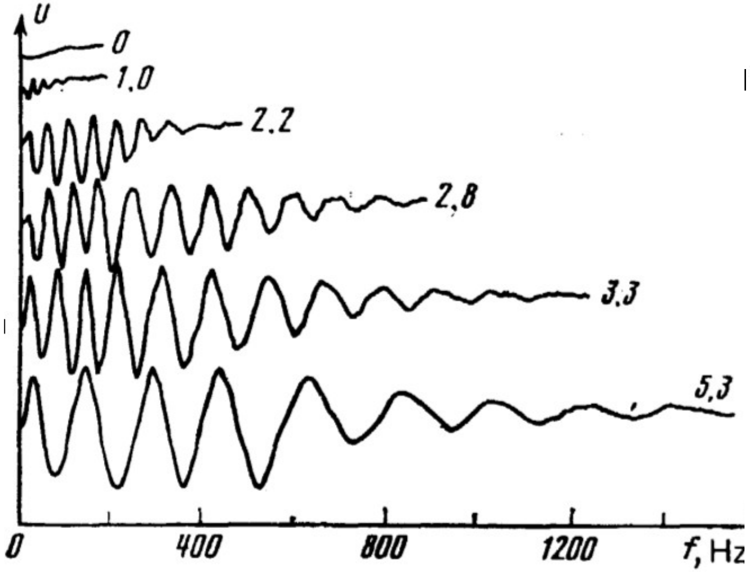

FIG. 3. Frequency dependence of the
detector for various temperature grad
curves in relative units. Specimen Bi

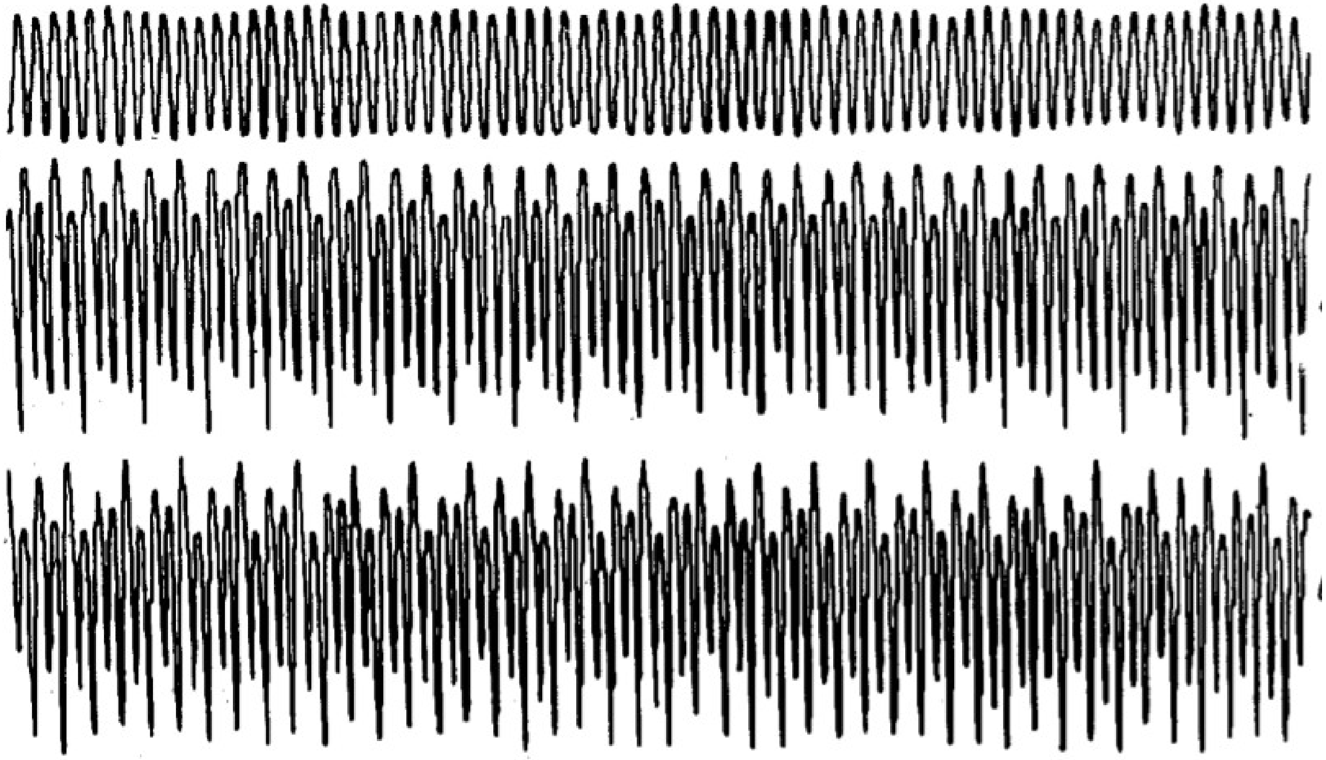

FIG. 1. "Oscilloscope traces" of the signals for three values of the direct current

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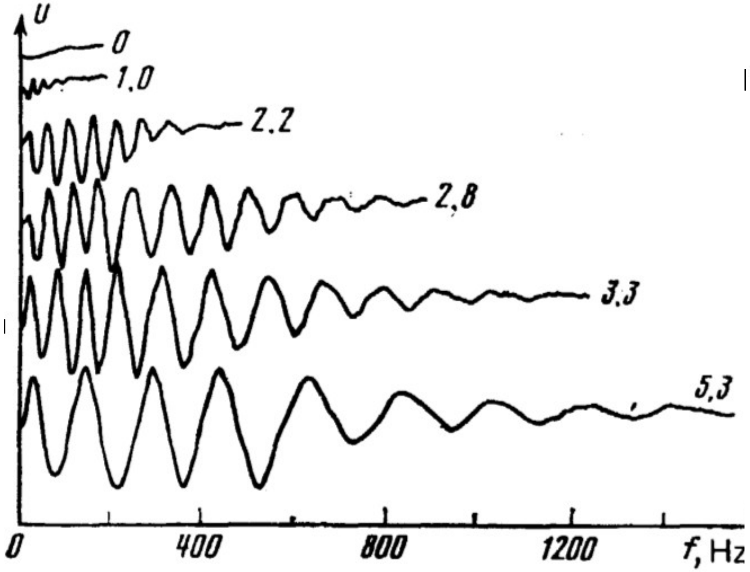

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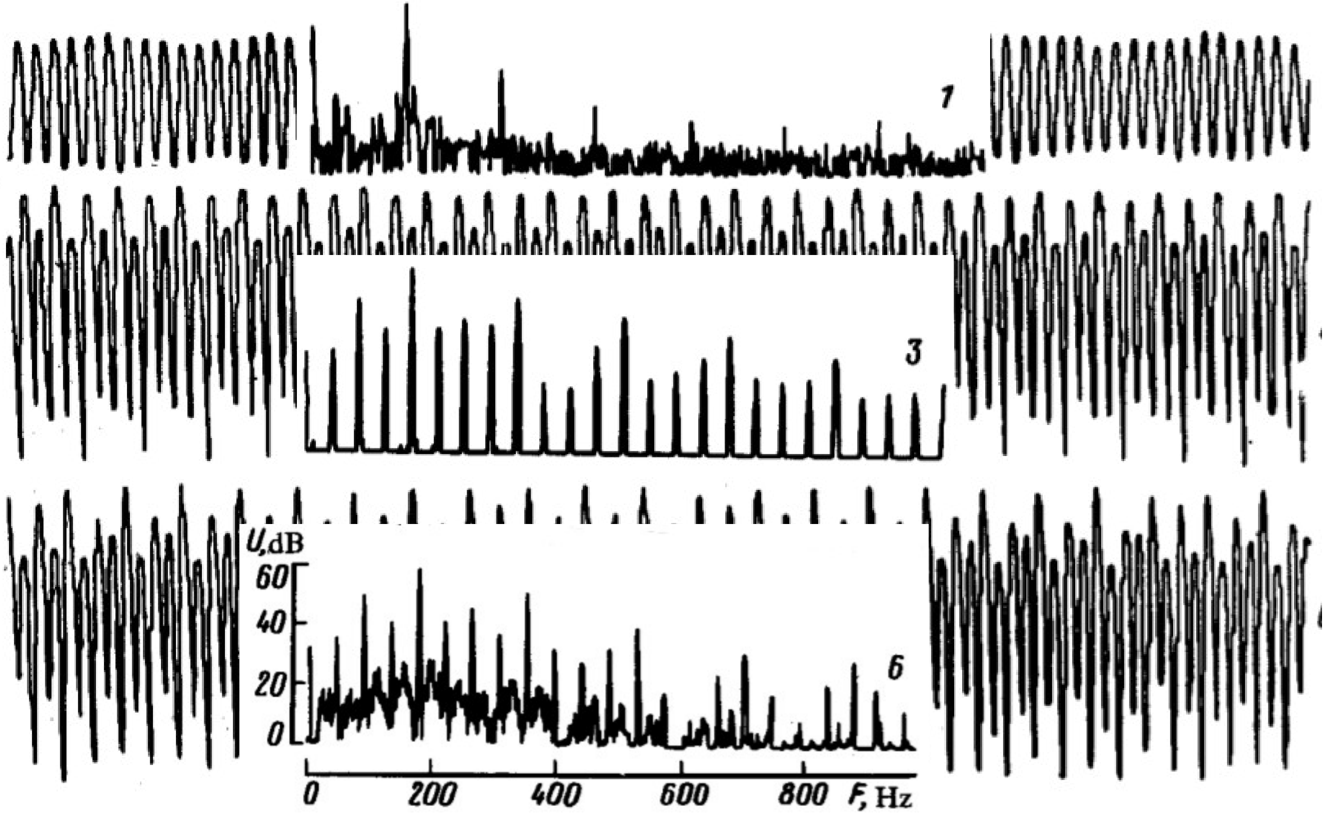

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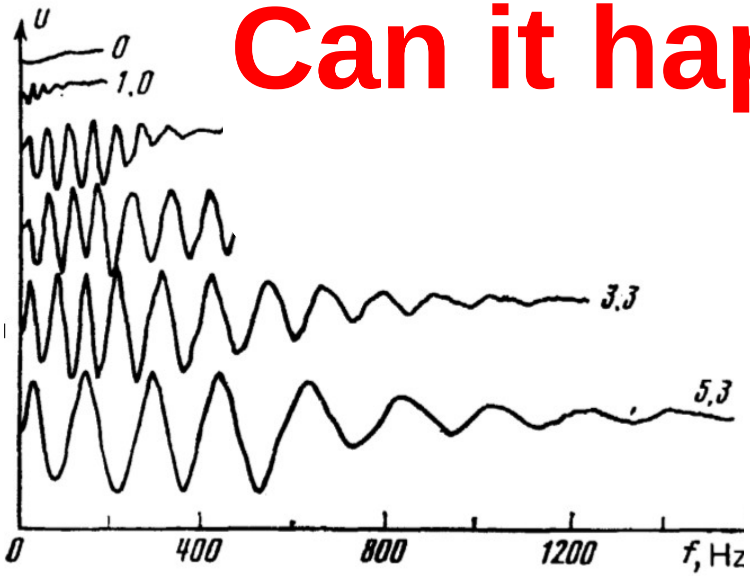
Can it happen in graphene?



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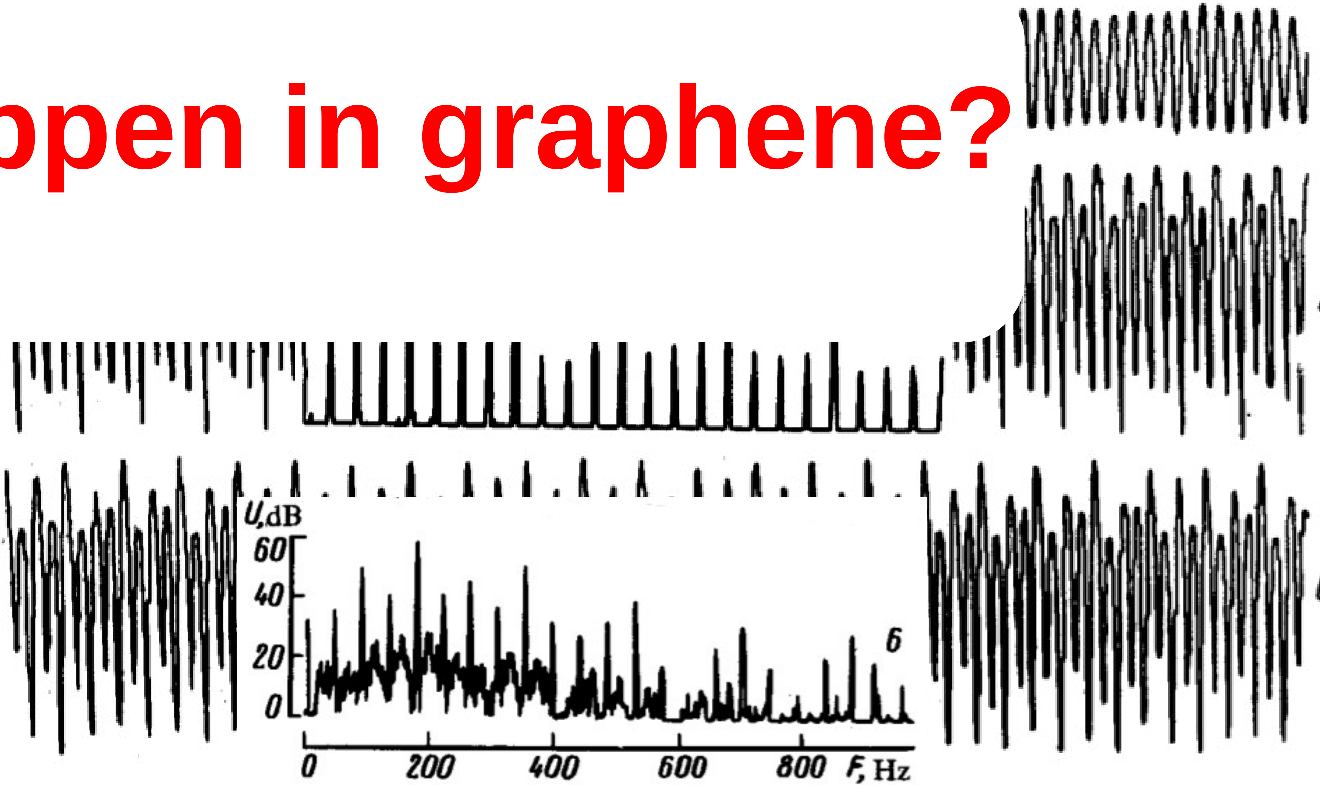

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G/hBN heterostructures: why special?

- Basic el-ph scattering leads to **very slow cooling**
- Optical phonon cooling negligible below room T (ω_o=2000K); Acoustic-phonon-dominated in a wide T range
- Different in GaAs: crossover T~20K since ω_o=400K

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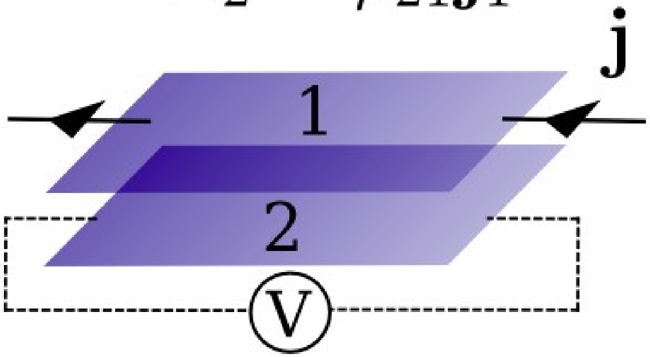
- **atomically thin, strongly interacting, nested electron gases**
- Charge-decoupled, however strongly thermally coupled
- Different layers separately contacted: drag measurements give more detailed information than single-layer measurements

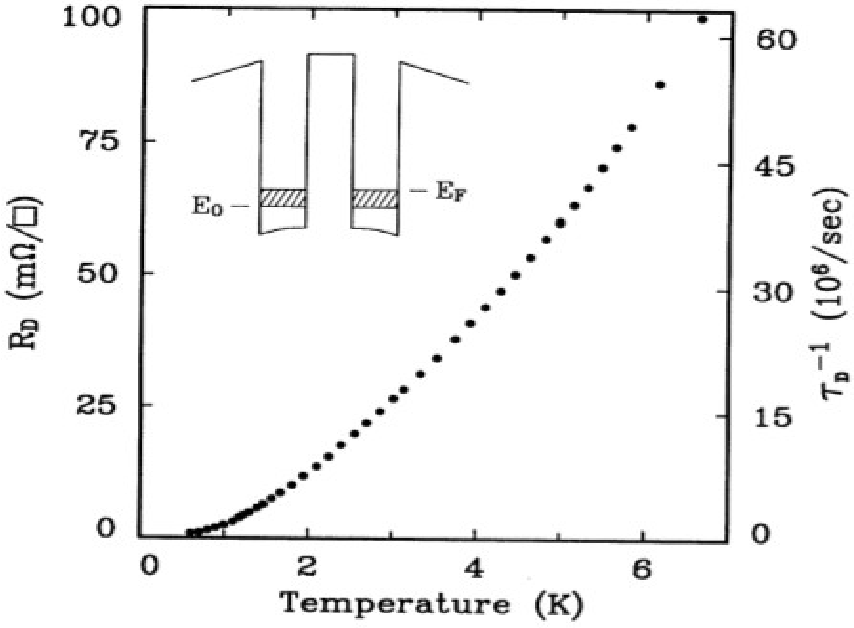
Claim: in a wide T range drag at CN dominated by energy modes

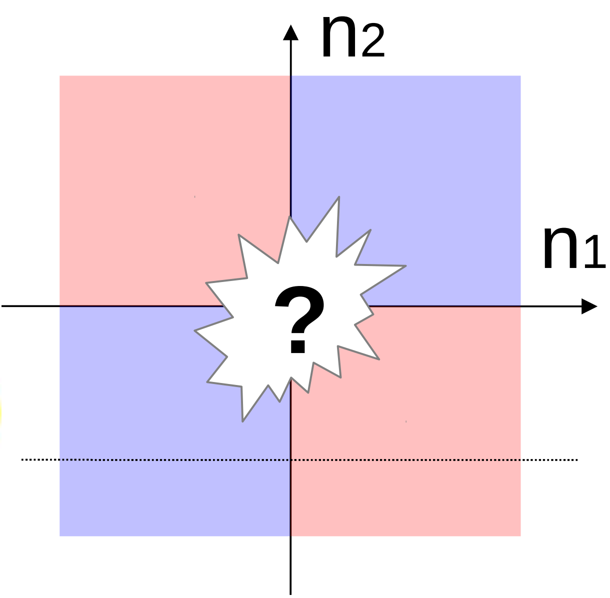
Coulomb drag in graphene

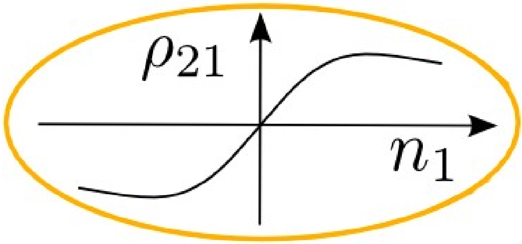
- Direct probe of interactions
- G/BN heterostructures: new 'strong coupling' regime $d \ll \lambda_F$
- Unconventional behavior *vs.* T, n
- New physics near CN

$$\mathbf{E}_2 = \rho_{21}\mathbf{j}_1$$









Gramila, Eisenstein, MacDonald, Pfeiffer, West, PRL 66, 1216 (1991)

Momentum drag: polarity, strong coupling, disorder

Theory:

W.-K. Tse and S. Das Sarma, Phys. Rev. B 75, 045333 (2007).

B. N. Narozhny, Phys. Rev. B 76, 153409 (2007).

R. Sensarma, E. H. Hwang, and S. Das Sarma, Phys. Rev. B 82, 195428 (2010).

N. M. R. Peres, J. M. B. Lopes dos Santos, and A. H. Castro Neto, Europhys. Lett. 95, 18001 (2011).

M. I. Katsnelson, Phys. Rev. B 84, 041407 (2011).

B. N. Narozhny, M. Titov, I.V. Gornyi, P.M. Ostrovsky, PRB 85, 195421 (2012)

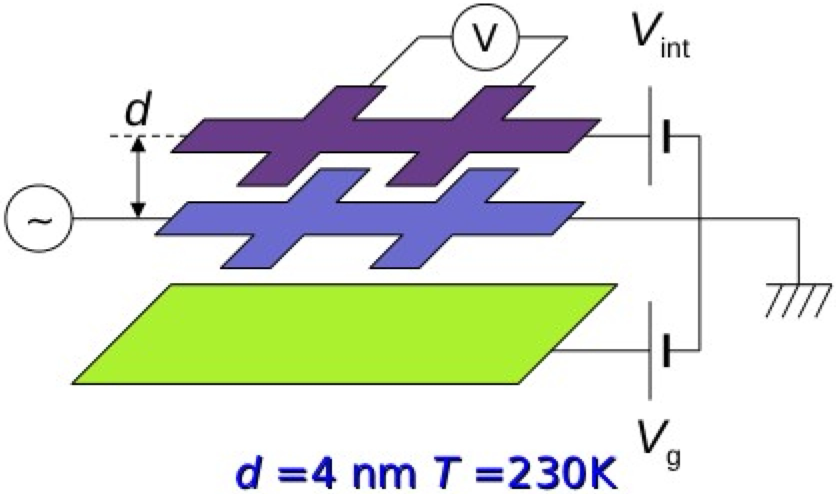
Experiment:

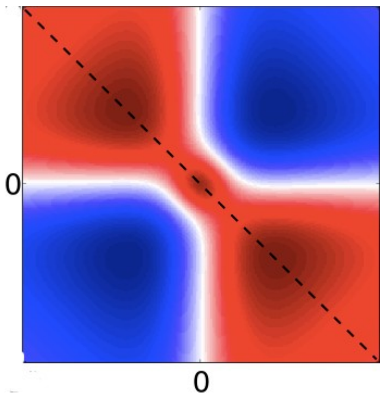
S. Kim, I. Jo, J. Nah, Z. Yao, S. K. Banerjee, and E. Tutuc, Phys. Rev. B 83, 161401(R) (2011).

R. V. Gorbachev, A. K. Geim, M. I. Katsnelson, K. S. Novoselov, T. Tudoroskiy, I. V. Grigorieva, A. H. MacDonlad, K. Wantanabe, T. Taniguchi, L. A. Ponomarenko, Nature Physics 8, 896 (2012).

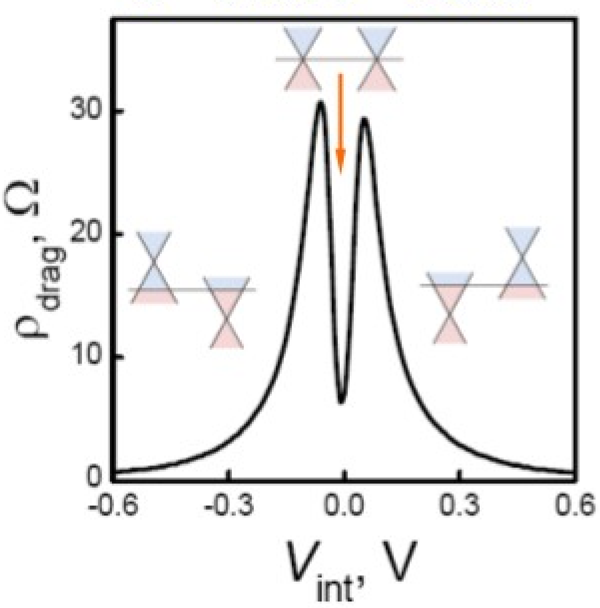
New drag mechanism at CN?

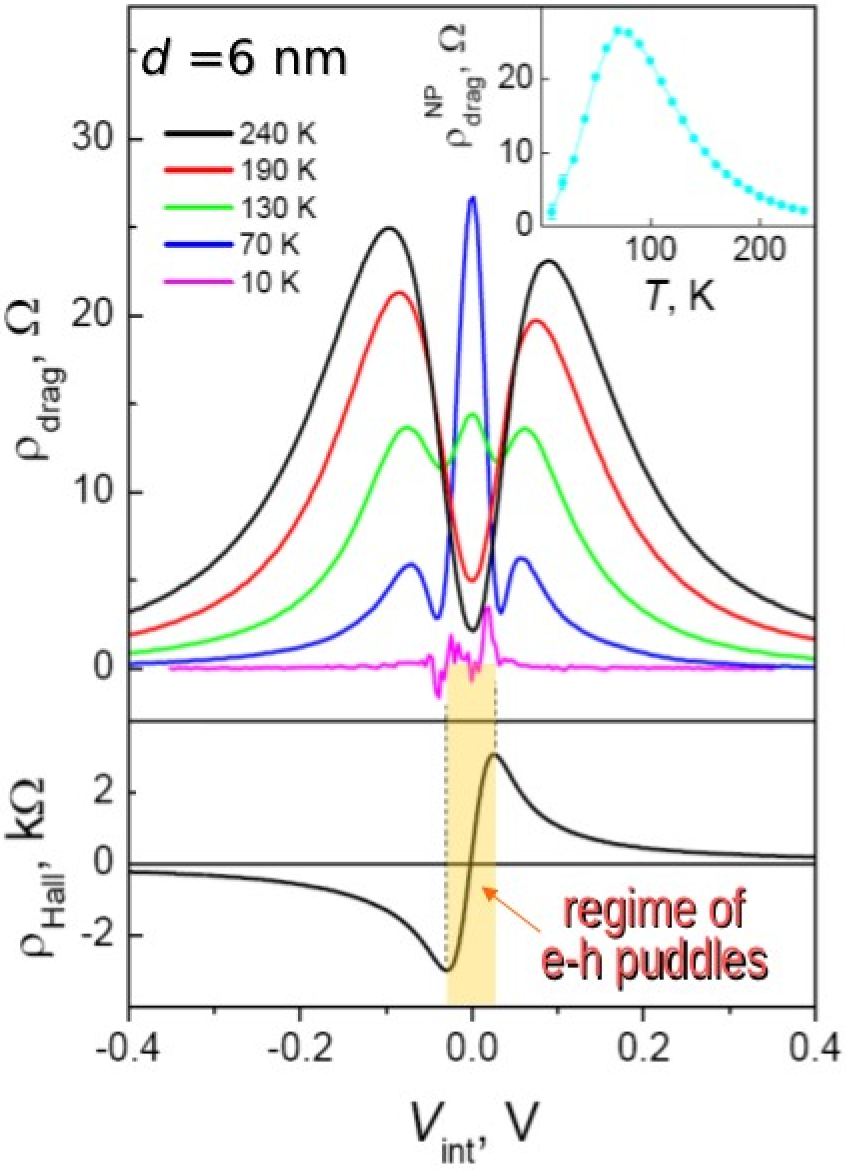
Ponomarenko et al. (2012)





d =4 nm T =230K





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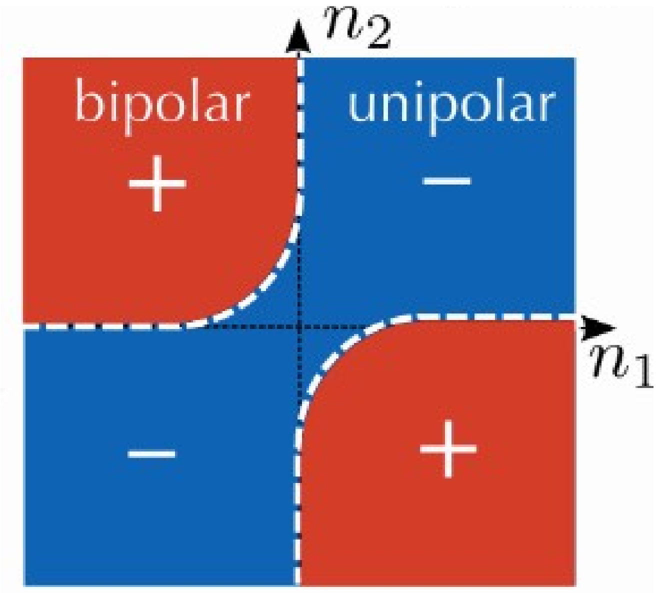
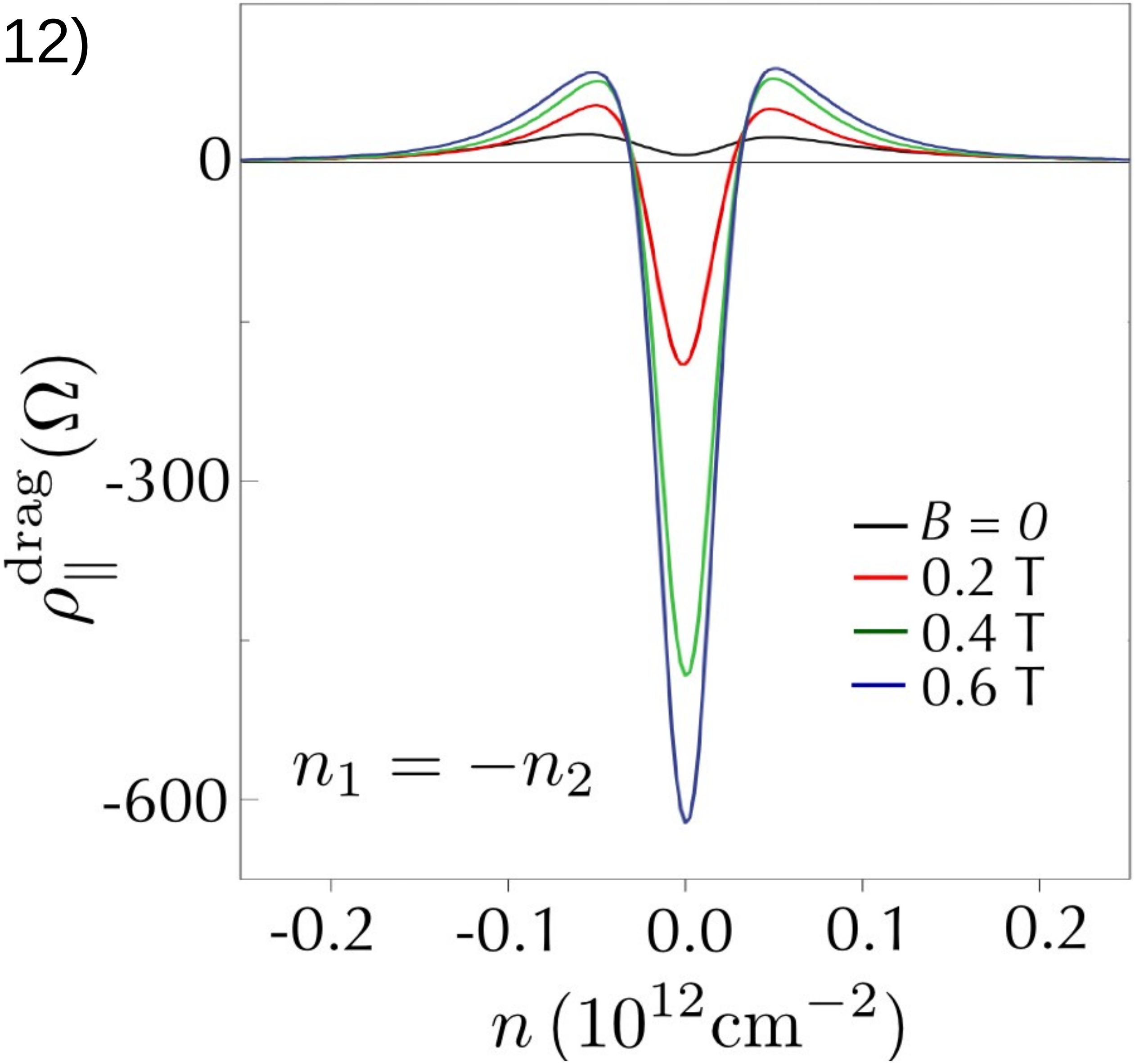
Strong negative magnetodrag peak in classically weak fields

Ponomarenko et al. (2012)

Sign reversal at B<0.1T





Energy-driven magnetodrag (E-mechanism)

- Fast interlayer scattering
  μ=100meV, T=300K, τ=1/γ=30fs

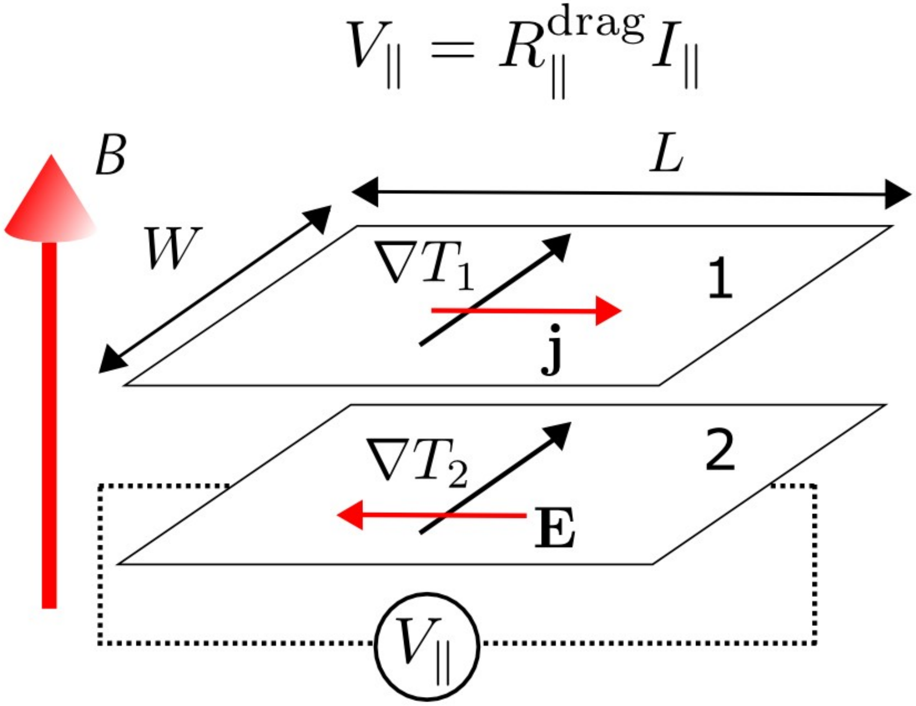
$$\mathcal{J}_{12} = \frac{6\zeta(4)}{\hbar^3 v^2}\frac{\nu_1\nu_2 k_B^4}{(\nu_1+\nu_2)^2}\left(T_1^4\ln\frac{T_0}{T_1} - T_2^4\ln\frac{T_0}{T_2}\right)$$

- Vertical energy transfer coupled to lateral charge transport

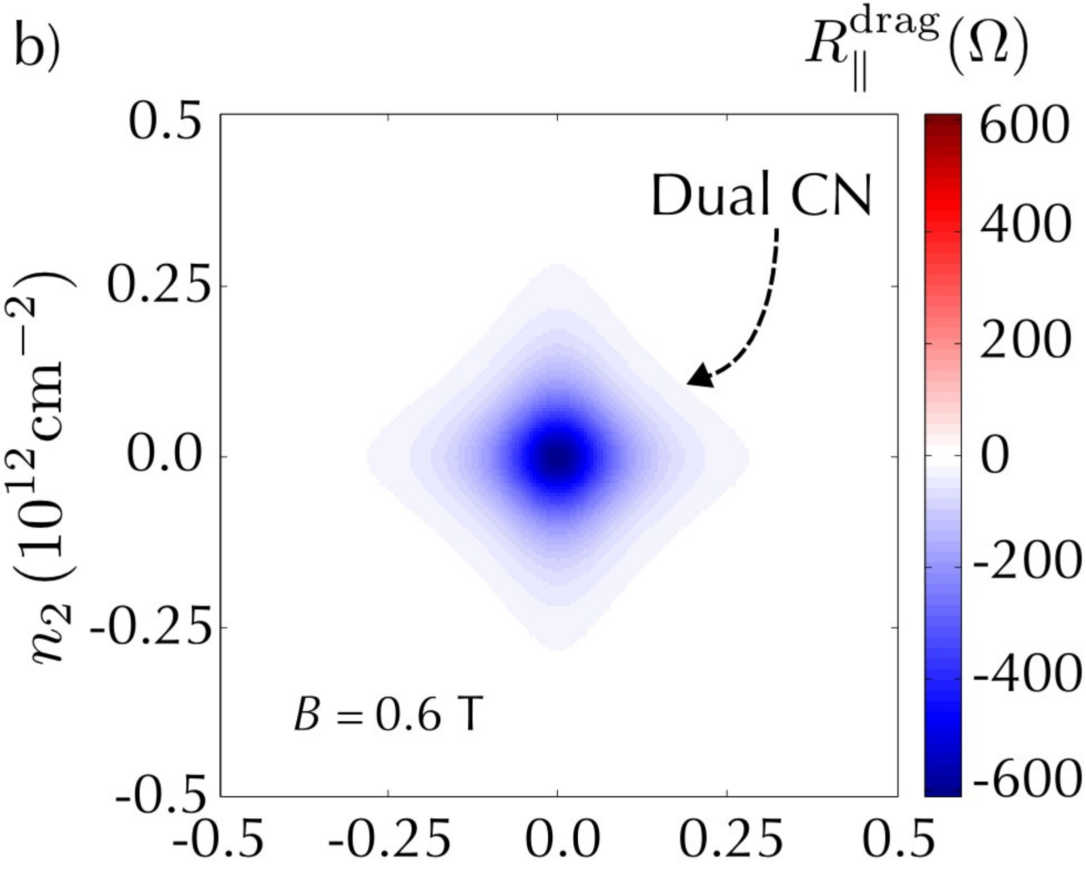
$$\gamma = \frac{1}{C_{\mathrm{el}}}\frac{d\mathcal{J}_{12}}{dT} = \frac{9\zeta(4)k_B^2T^2}{\pi\mu\hbar}\ln\frac{T_0}{T}$$

- Ettingshausen-Nernst effect: giant drag near CN

a)

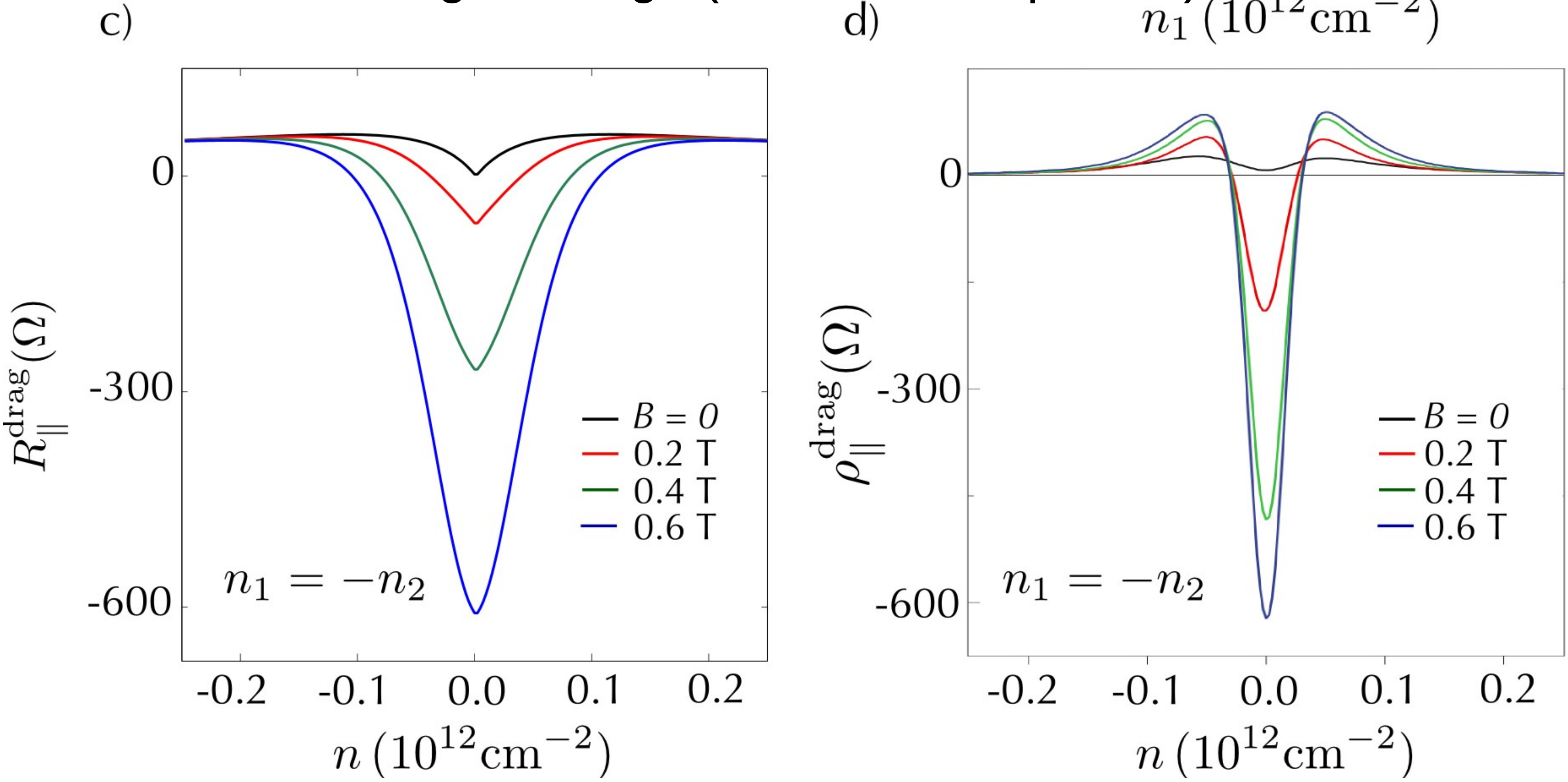


b)



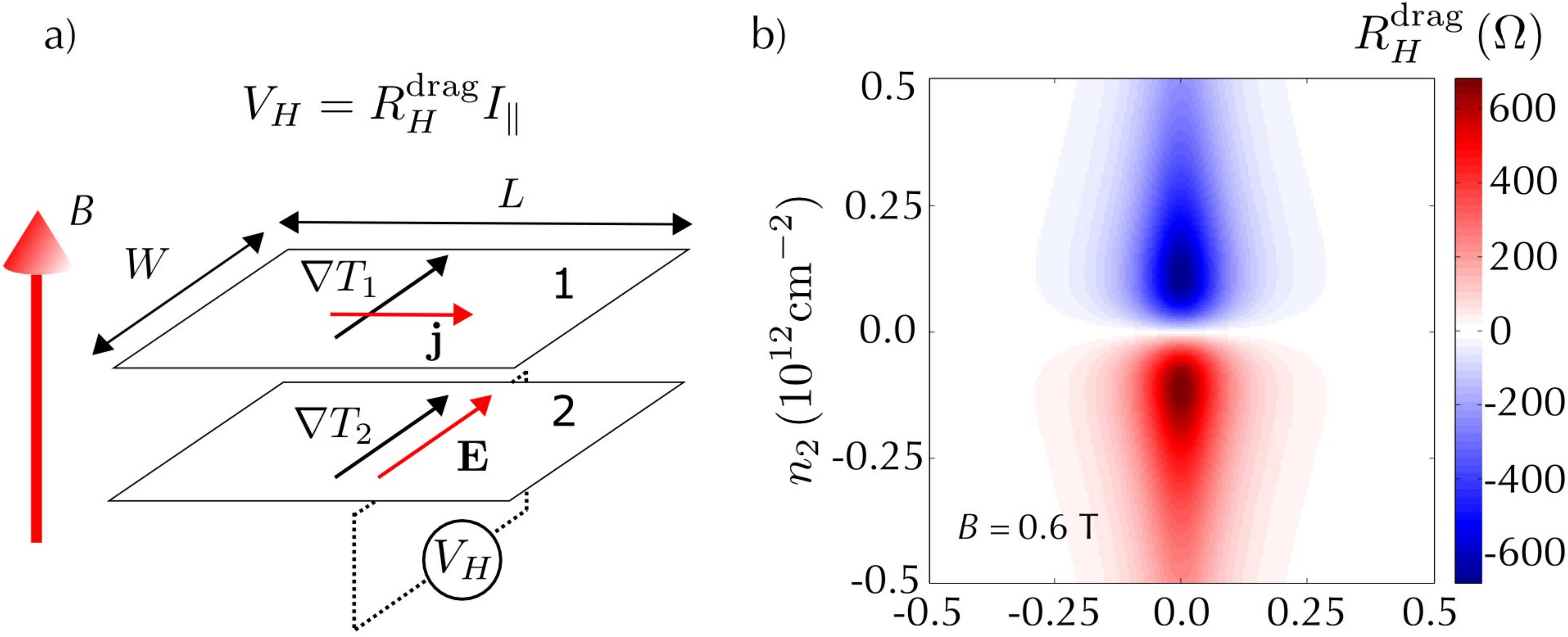
Theory vs. experiment

- Large drag values at weak fields
- Peak at CN & strong B dependence
- Negative sign (reduced dissipation!)



Hall drag at CN

- Theory of p-drag predicts zero Hall drag (Kamenev, Oreg; Bonsager, Flensberg, Hu, Jauho)
- Here: large drag values even at weak fields
- Peak at CN & strong B dependence
- No 1-2 layer symmetry

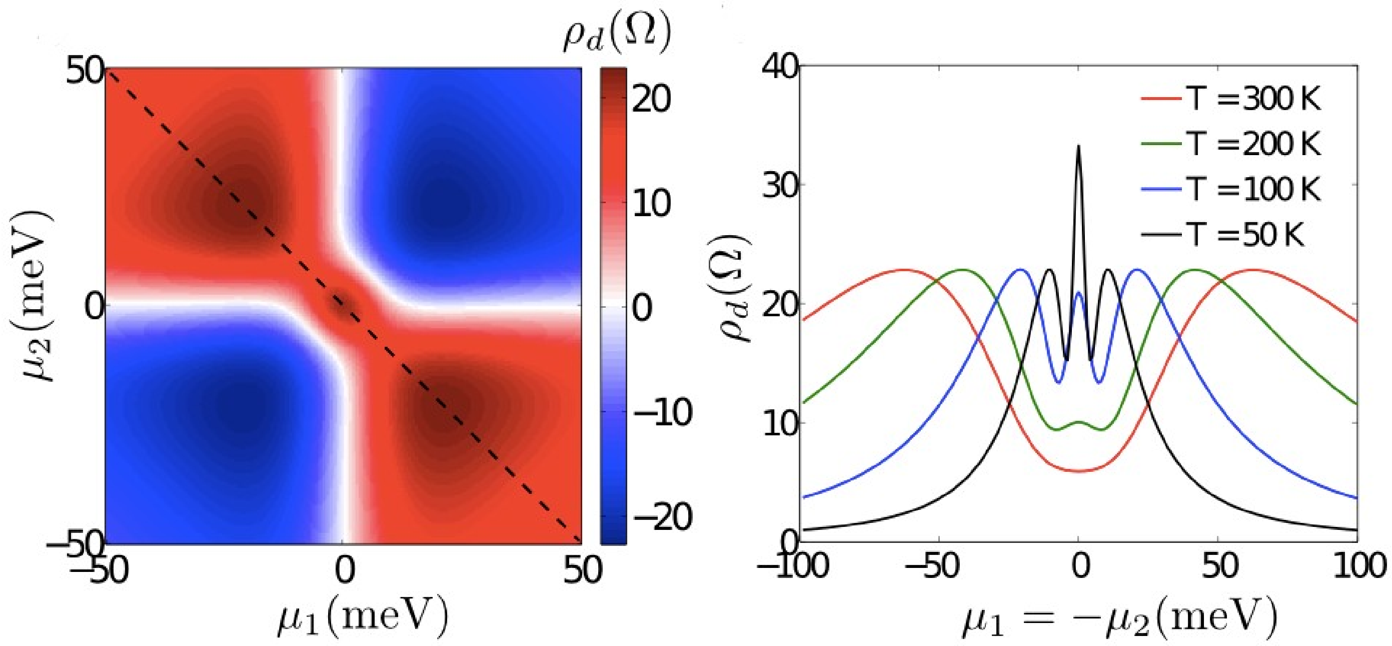


E-mechanism for drag at B=0

- No E-drag at B=0 in a uniform system

(w/ contacts acting as ideal heat sinks)

- Remnant drag due to inhomogeneities
- Active layer: local Joule-Thomson heating/cooling
- Drag voltage generated by thermopower in the passive layer



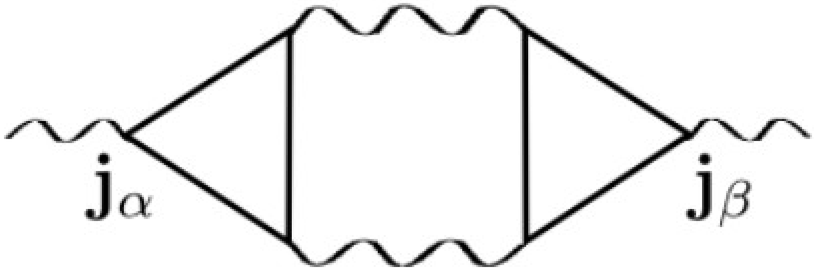
E-mechanism: microscopic analysis

$$\mathcal{H}=\sum_i\int d^2\mathbf{r}\psi_i^\dagger(\mathbf{r})\Big[-i\hbar v\sigma\cdot\nabla+\delta\mu_i(\mathbf{r})\Big]\psi_i(\mathbf{r})+\mathcal{H}_{\rm el-el}$$

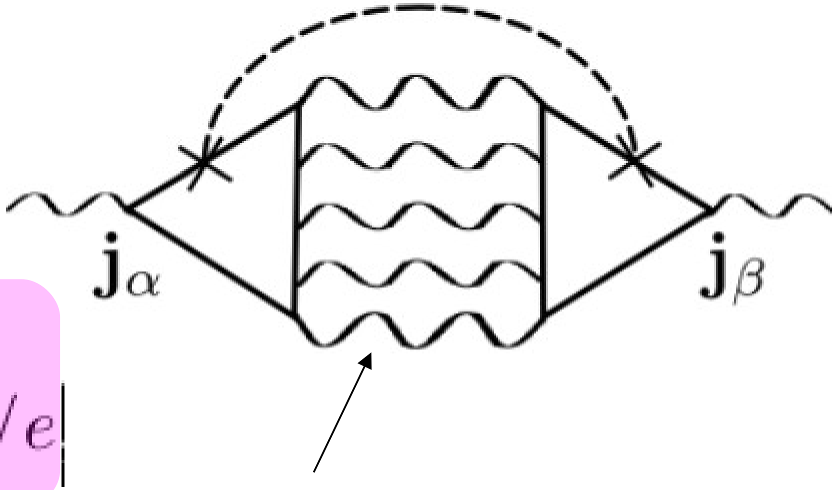
- Slow electron-lattice cooling; large cooling length (few mm)
- Large disorder correlation length for e-h puddles; ξ~100nm for G/BN
- Can use hydrodynamics
- Electron temperature apprx
- Heating linear in current (Joule-Thomson-like)
- Energy current

$$\mathbf{j}_{\rm q}(\mathbf{r})=Q(n)\mathbf{j},\quad Q[n(\mathbf{r})]=\mathcal{S}[n(\mathbf{r})]T/e$$

P-drag



E-drag at B=0



$$V_{ij}(\mathbf{q})=V^0_\mathbf{q}/[1-V^0_\mathbf{q}(\Pi_1(\mathbf{q},\omega)+\Pi_2(\mathbf{q},\omega))]$$

Hydrodynamical treatment

Entropy per particle

$$\mathbf{j}_q(\mathbf{r}) = Q(n)\mathbf{j}, \quad Q[n(\mathbf{r})] = \mathcal{S}[n(\mathbf{r})]T/e \quad Q = \frac{2\pi^2 k_B^2 T^2 \mu}{3e(\mu^2 + \Delta^2(T))}$$

$$-\nabla \kappa_1 \nabla \delta T_1 + a(\delta T_1 - \delta T_2) + \lambda \delta T_1 = -\nabla \cdot \mathbf{j}_{q,1}$$
$$-\nabla \kappa_2 \nabla \delta T_2 + a(\delta T_2 - \delta T_1) + \lambda \delta T_2 = 0$$

$$\delta T_2(\mathbf{r}) = -\frac{a}{\widehat{L}_1 \widehat{L}_2 - a^2} (\mathbf{j}_1 \cdot \nabla) Q[n_1(\mathbf{r}), T]$$
$$\mathbf{E}_2(r) = -(Q[n_2(\mathbf{r})]/T)\nabla \delta T_2$$

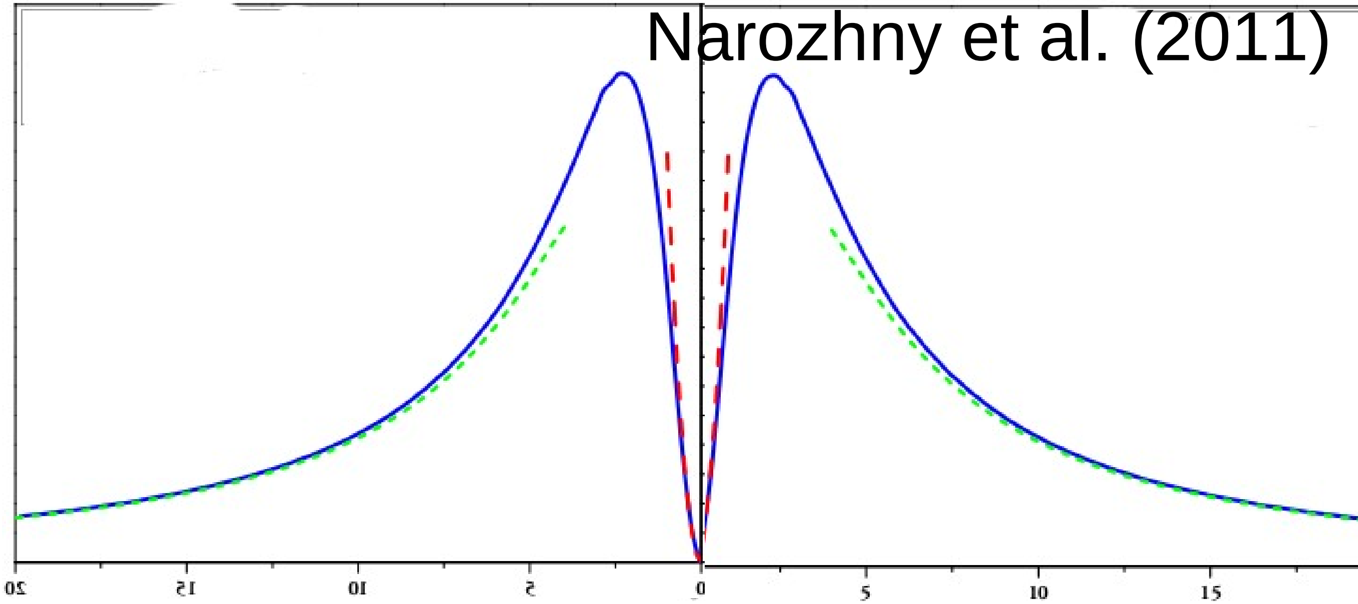
interlayer correlations

$$\rho_{21} = \frac{1}{2T\tilde{\kappa}} \frac{\partial Q}{\partial \mu_1} \frac{\partial Q}{\partial \mu_2} \sum_{\mathbf{q}} \frac{\langle \delta\mu_2(-\mathbf{q}) \delta\mu_1(\mathbf{q}) \rangle}{1 + \xi_c^2 \mathbf{q}^2}$$

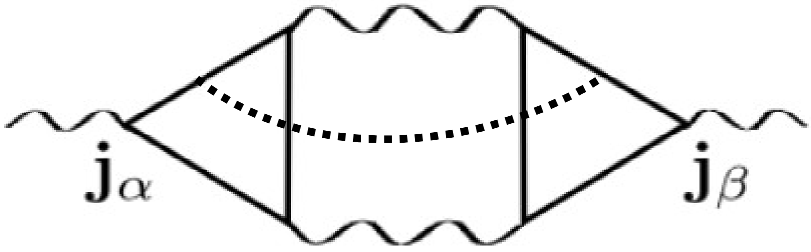
peaks at CN!

Adding the P and the E contributions

- Momentum drag sign depends on polarity
- Vanishes at CN (the E-mechanism peaks at CN)
- Finite value at CN can be restored by disorder

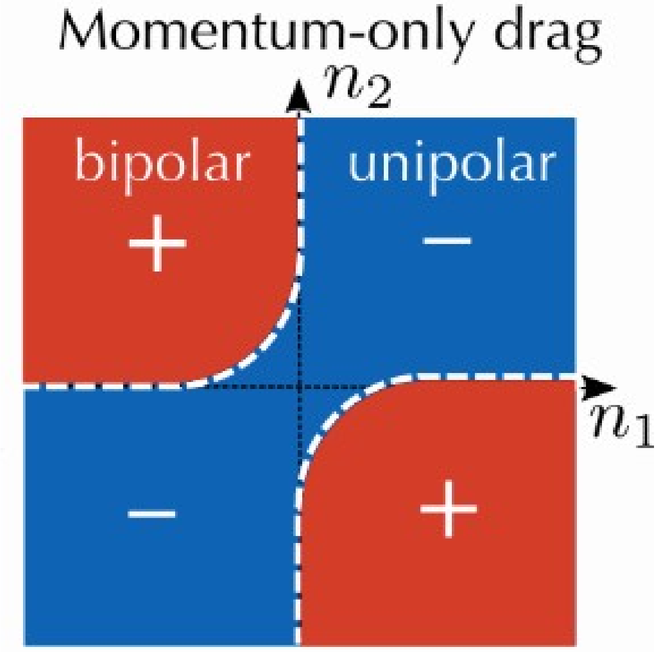


Narozhny et al. (2011)



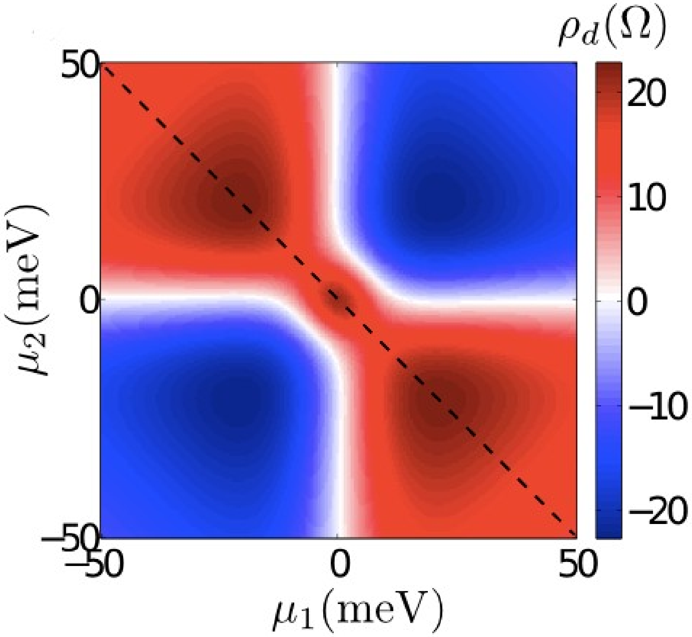
Numerical fit

$$\rho_{21}^{(\mathrm{m})} = \tilde{\rho}_{21}^{(\mathrm{m})} \frac{h}{e^2} (k_B T)^2 \frac{\mu_1}{(\mu_1^2 + \eta k_B^2 T^2)} \frac{\mu_2}{(\mu_2^2 + \eta k_B^2 T^2)}$$

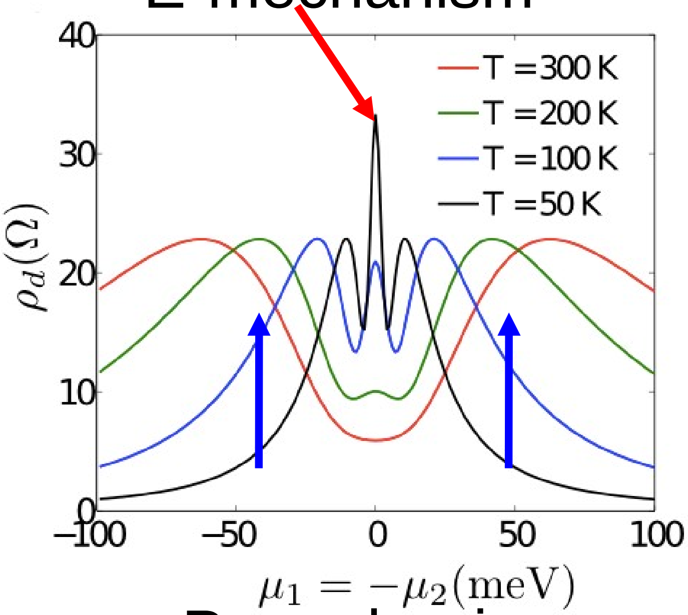


The P & E contributions combined

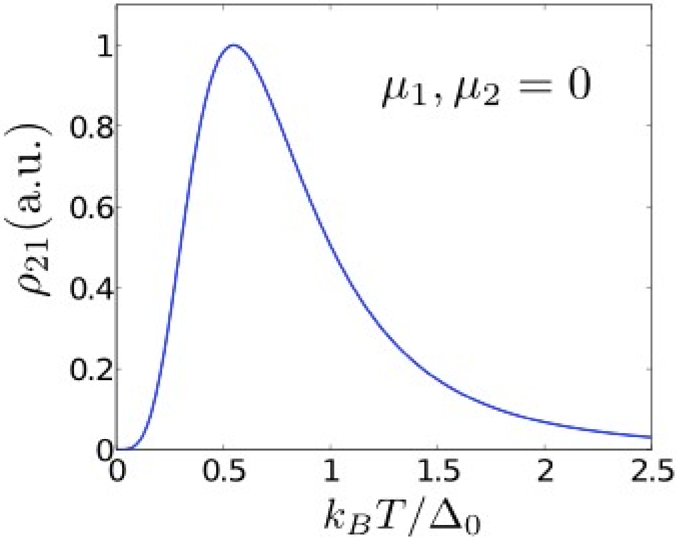
Peak structure at CN with side lobes

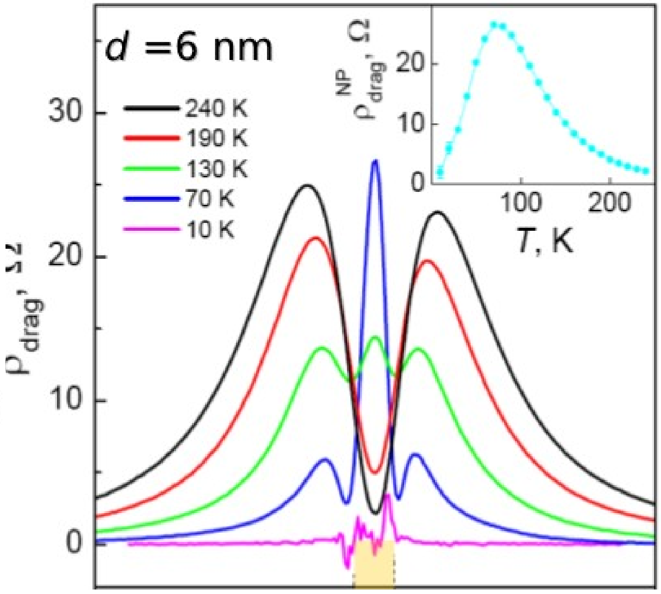


E-mechanism



P-mechanism





Nonmonotonic
T dependence
Song & LL (2012)

Manchester
experiment
(2012)

E-mechanism summary

- E-mechanism a direct probe of energy-carrying processes
- Easy to distinguish from p-mechanism: large effect where p-drag is small, sharp peak at CN
- Positive-sign peak for B=0 & non-monotonic T dependence
- Negative-sign peak for B>0
- Agrees with experiment

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- Control electron cooling & heating *in situ*
- Strong B, n and T dependence near peak: applications in sensing?