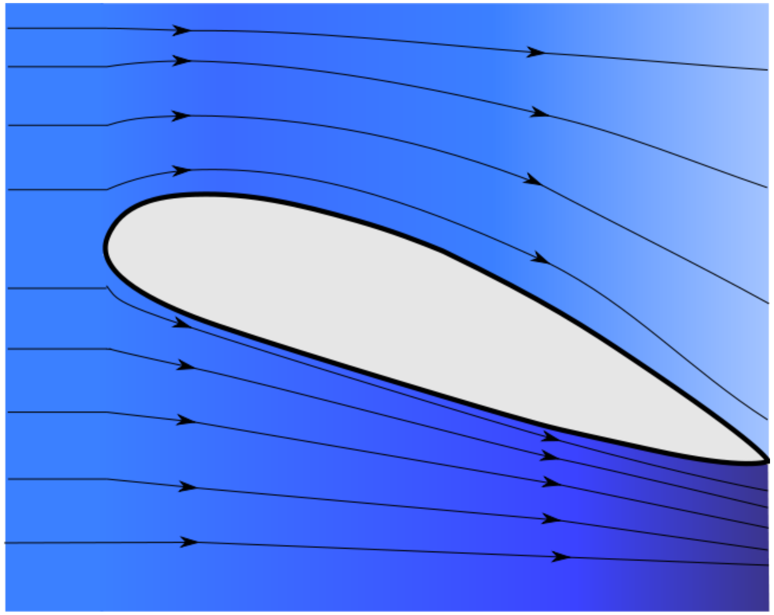
Hydrodynamic behavior of electron fluids

Fluids: chaotic on microscales, orderly on macroscales (conservation laws!)



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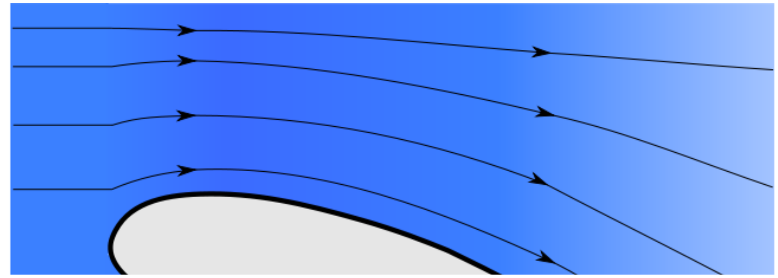

Hydrodynamics: theory of everything

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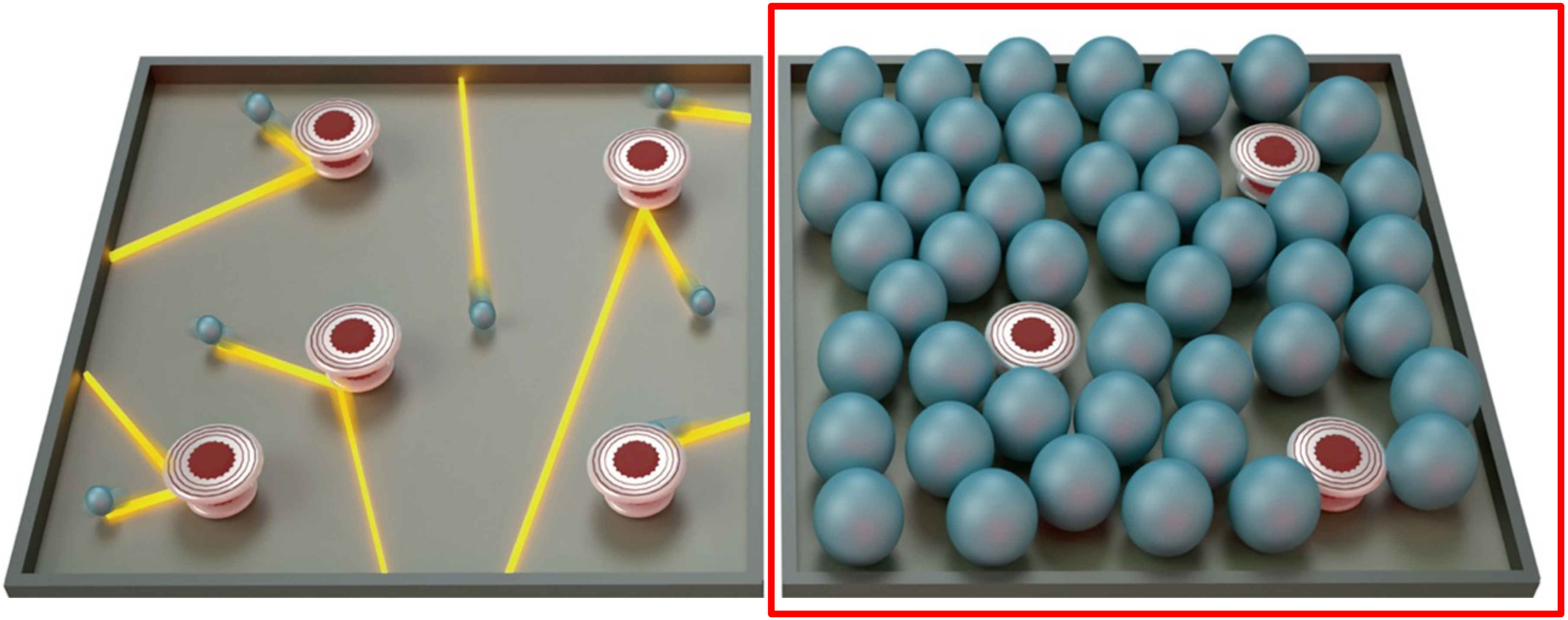
Is hydrodynamics ever relevant in metals?



credit: Andy Lucas; from: Jan Zaanen, Science 2016

- High-mobility electron systems (graphene, GaAs 2DES, $PdCoO_2$, etc):
- Non-Fermi liquids, high-Tc superconductors, strange metals

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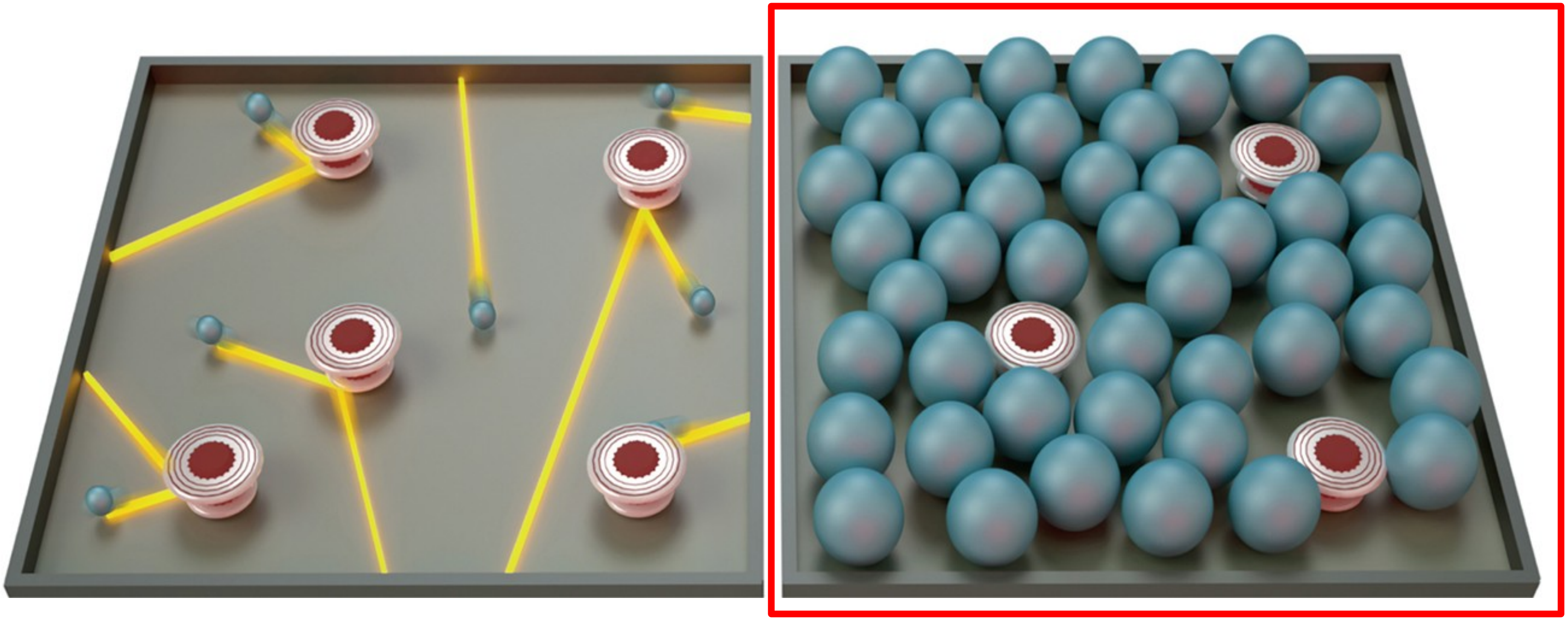

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Literature

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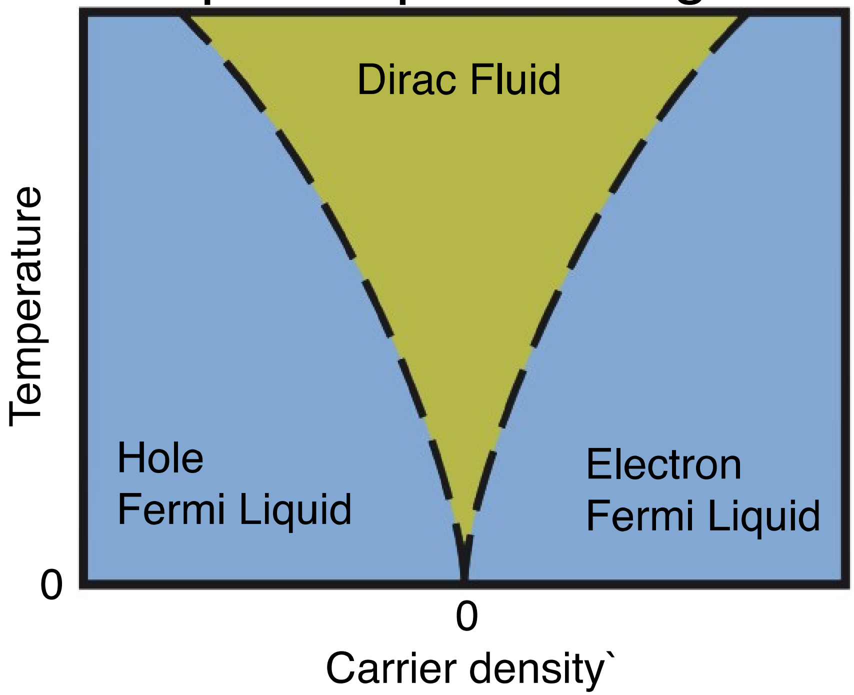
...

Viscous electron fluids in 2D systems

- Strong interactions (enhanced in 2D, graphene)
- Graphene: weak electron-phonon scattering, no Umklapp ee scattering
- Fast p-conserving ee collisions, shear viscosity

Graphene phase diagram



Sheehy and Schmalian, PRL 99, 226803 (2007)

Guo et al. 1607.07269 1612.09239 Bandurin et al. 1703.06672, Ledwith et al. 1708.01915, 1708.02376

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- **Signatures of viscous effects?**
- **New collective phenomena?**

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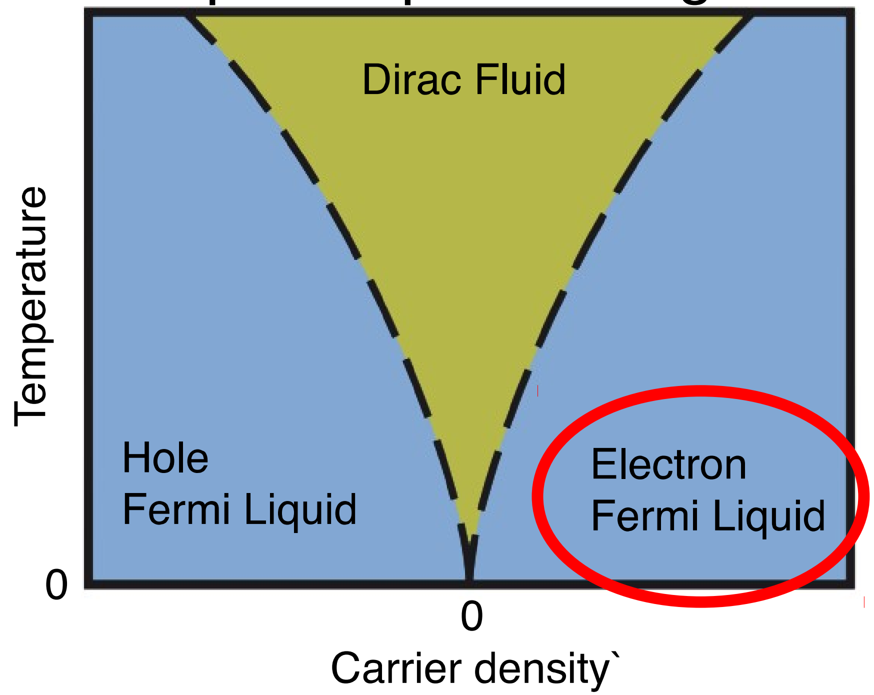

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Accessing hydrodynamic regime

- In 3He E_F~1K, strong interactions
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- Phonons: el-ph scattering relatively weak, can have $l_{ee}<l_{el\text{-}ph}$ at T>10K
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cf. typical metals, where $l_{ee} > l_{el\text{-}ph}$

New phenomena?

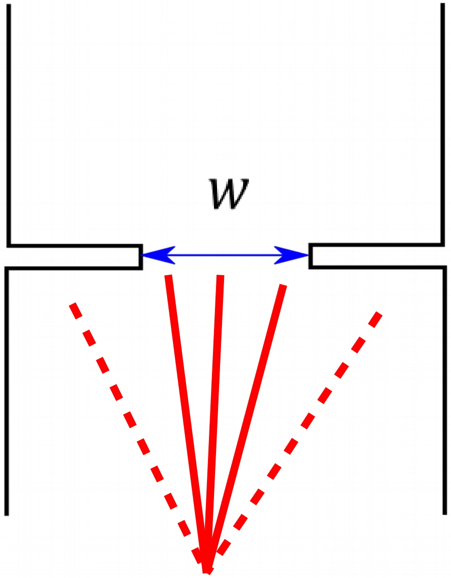
Fundamental bound for free-particle conductance

- Landauer (1957): conduction=transmission

$$G=\frac{2e^2}{h}N \qquad N=\sum_n t_n,\ \ 0<t_n\leq 1$$

- Sharvin (1965): counting phase space

$$N\approx\frac{2w}{\lambda_F},\ \ w\gg\lambda_F$$



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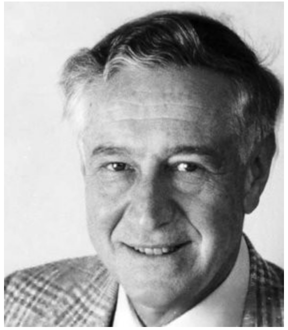

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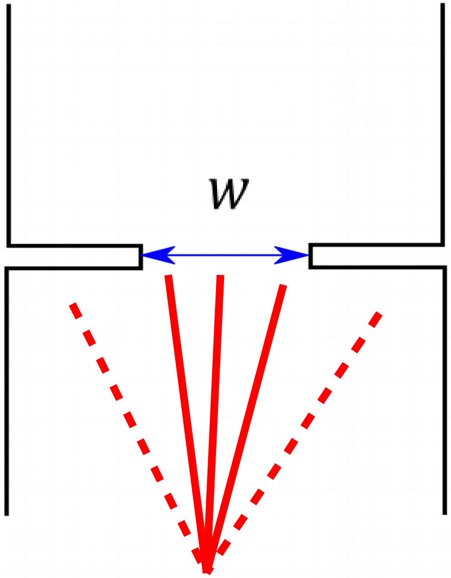
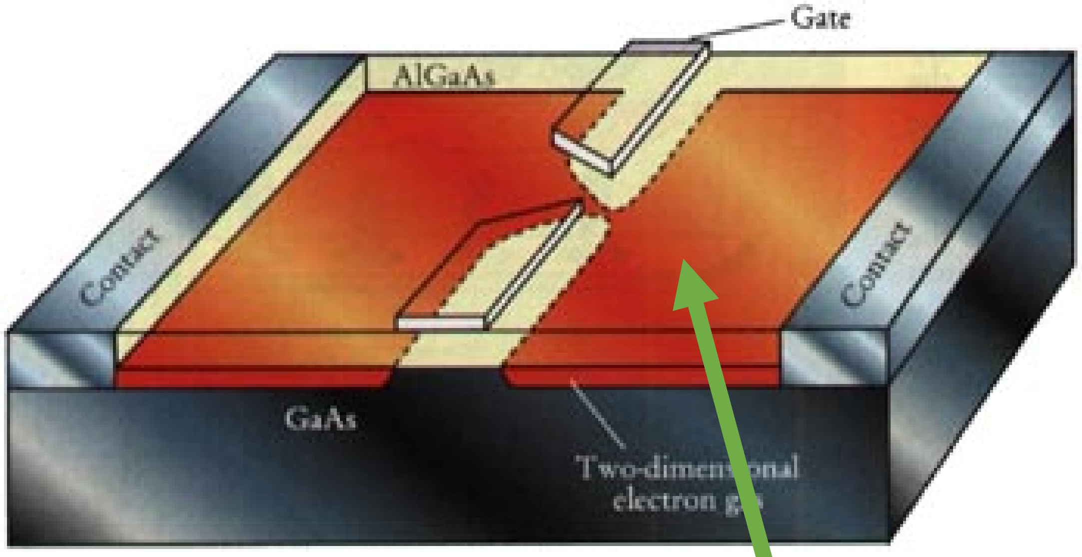
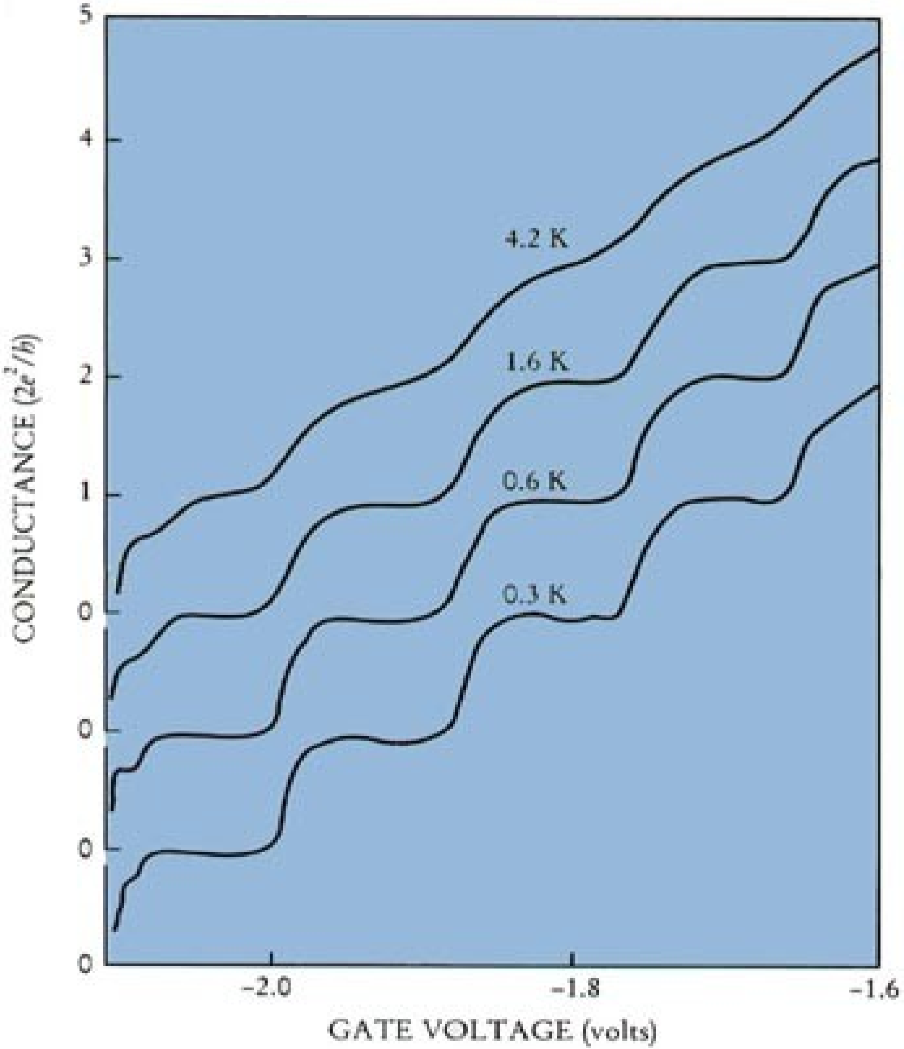


resistance=backreflection
Nonzero resistance for ballistic flow!

Experimental realization in quantum point contacts



Disorder-free



Width

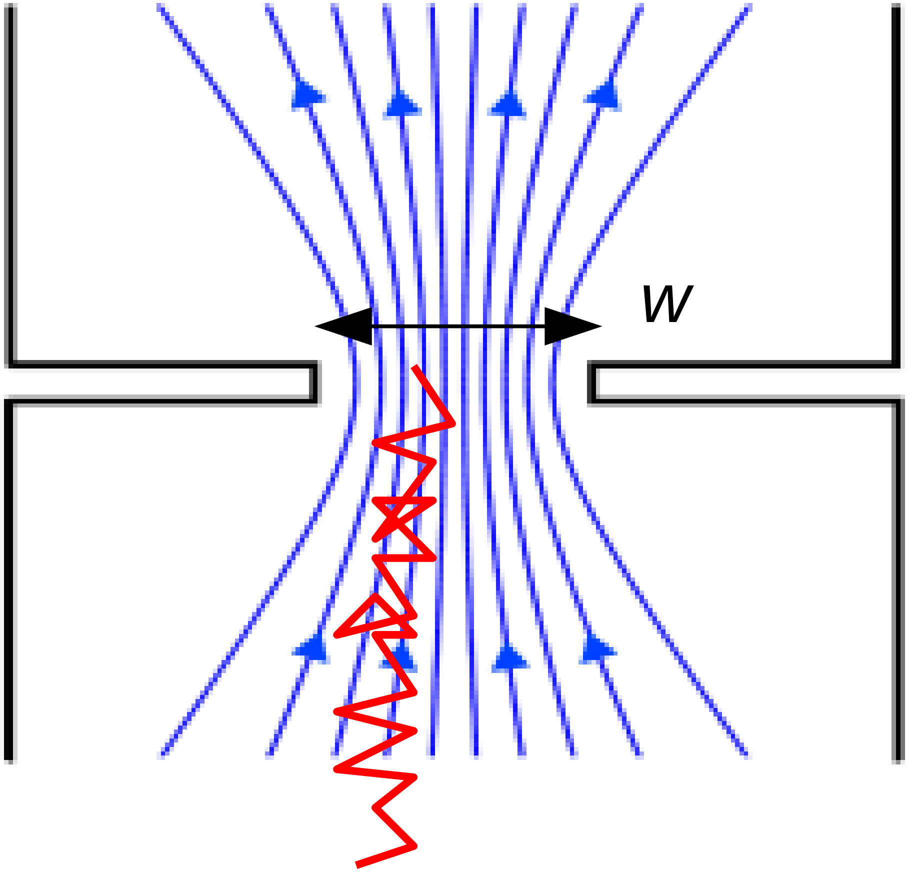
B. J. van Wees et al. Phys. Rev. Lett. **60**, 848 (1988); Phys. Rev. B **43**, 12431 (1991).

Is this really the highest conductance? No

Guo, Ilseven, Falkovich & LL, PNAS 2017

- In a viscous flow electrons cooperate to overcome the ballistic conductance bound
- Experimental realization in graphene

$$\boxed{l_{ee} \ll w}$$



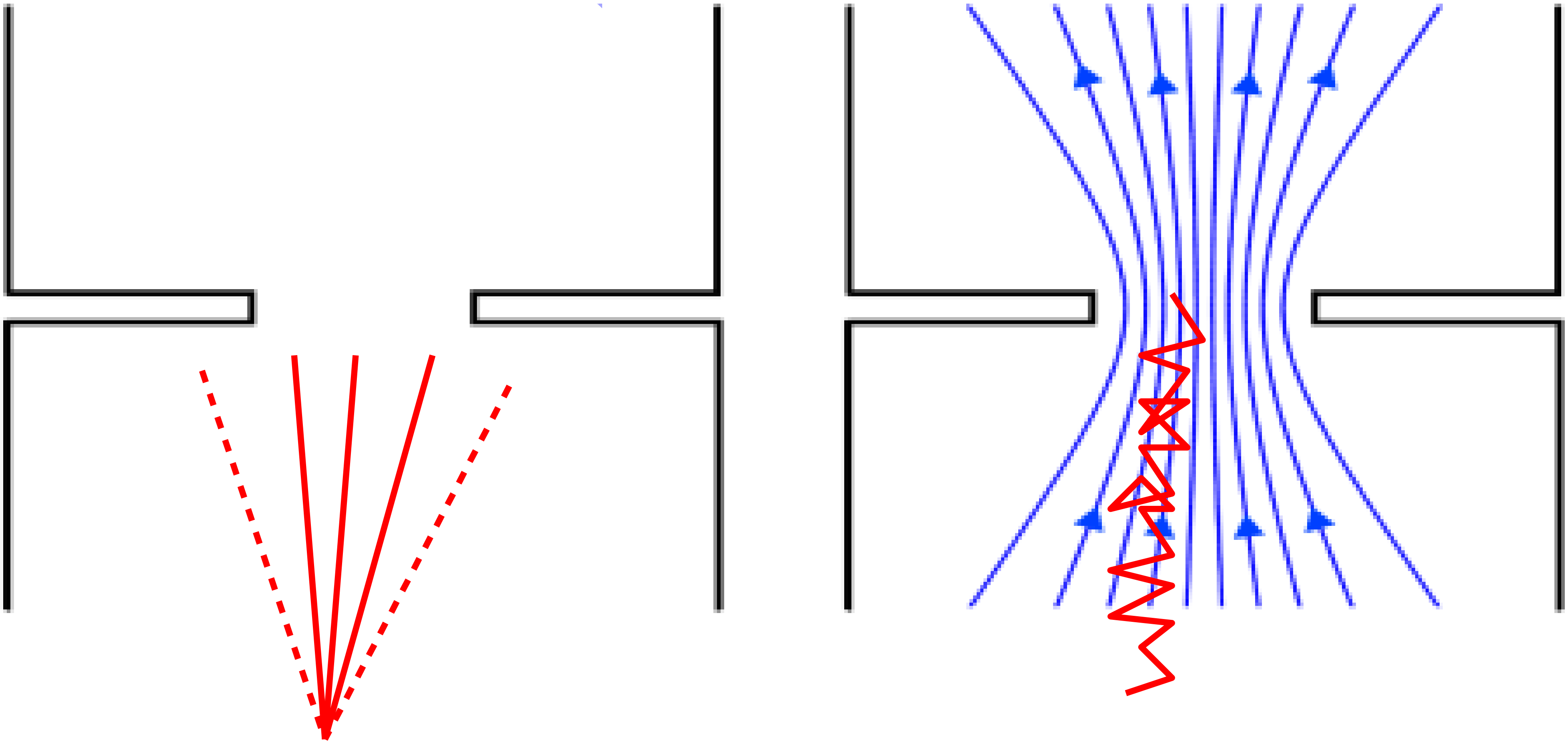
Extreme viscous limit:
conductance from Stokes eqn

$$-\nu \nabla^2 \vec{v} = \frac{e}{m} \vec{E} \qquad \nu = \frac{v_F l_{ee}}{4}$$

$$\rho = \frac{\gamma(k) m}{ne^2}, \quad \gamma(k) = \nu k^2 \qquad k = \frac{1}{w}$$

$$\boxed{G_{vis} \approx G_{ball} \frac{w}{l_{ee}} \gg G_{ball}}$$

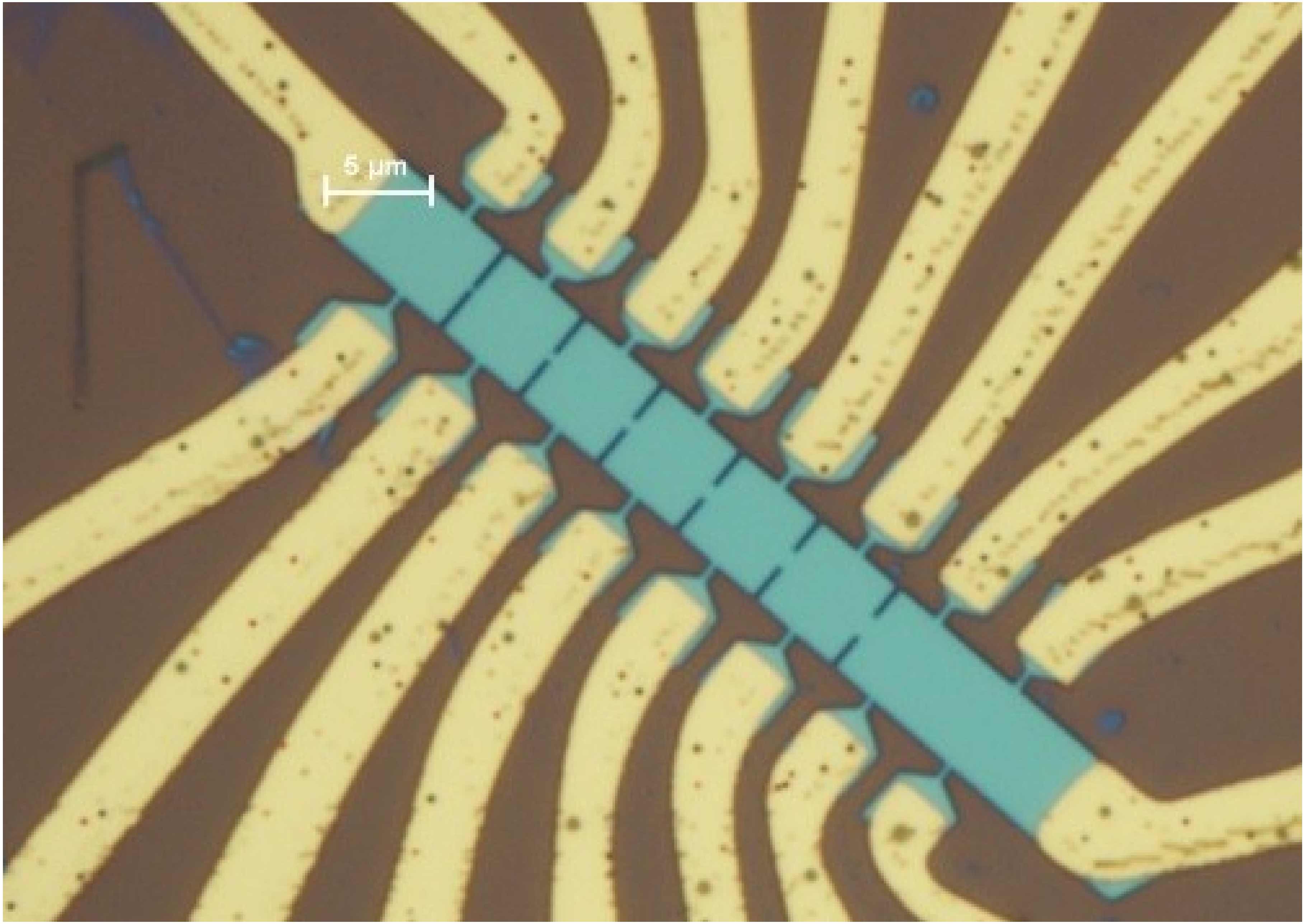
Ballistic at T=0, superballistic at T>0



- Conductance enhanced as a result of cooperative behavior
- Electrons follow zig-zag paths to avoid boundaries
- Phase space bottleneck relieved

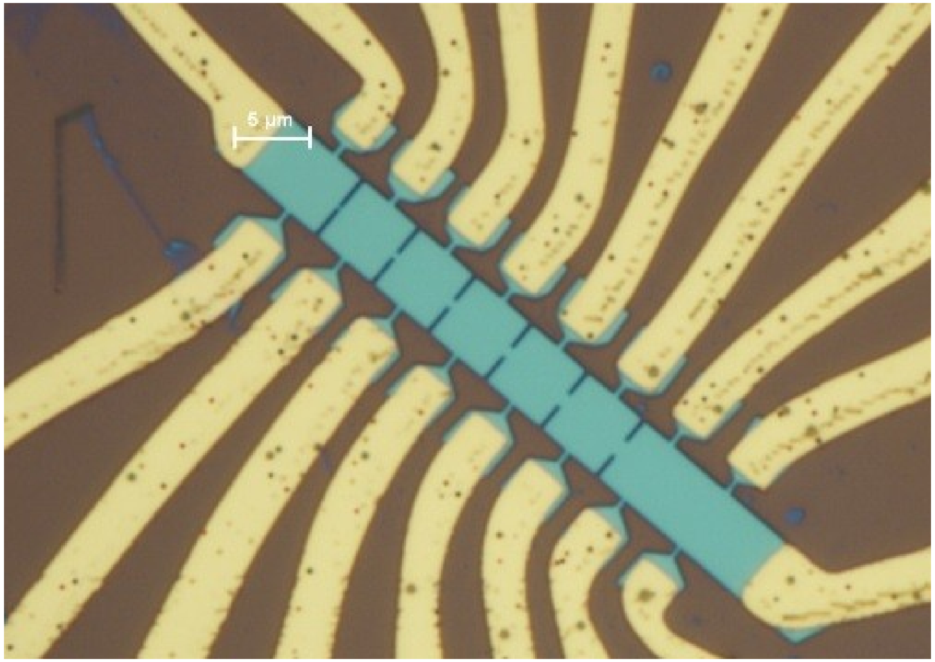
Point contacts in high mobility graphene

Bandurin et al. Nature Phys 2017

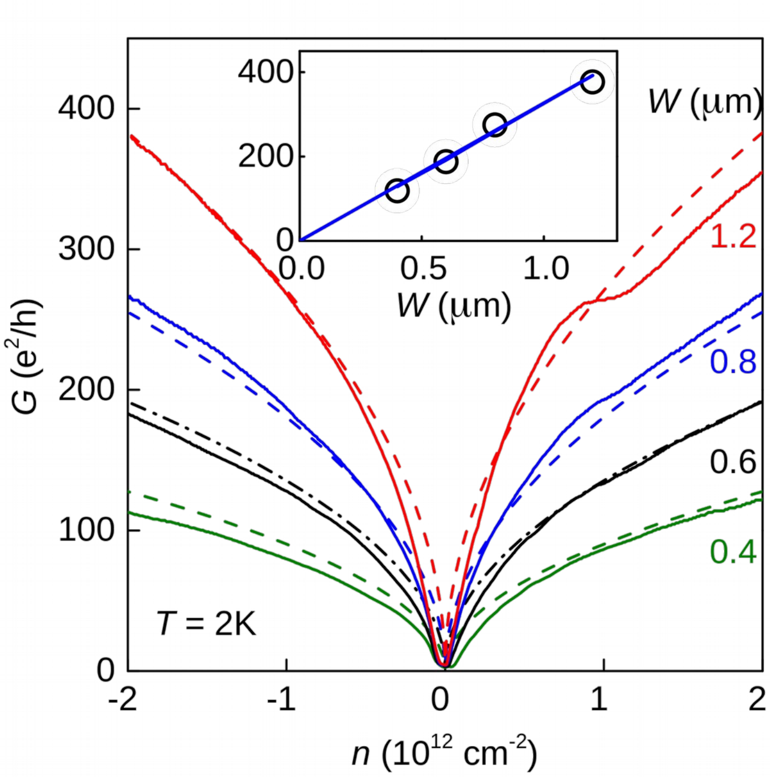


Transport measurements

Point contacts in high-mobility graphene



Ballistic transport at low T

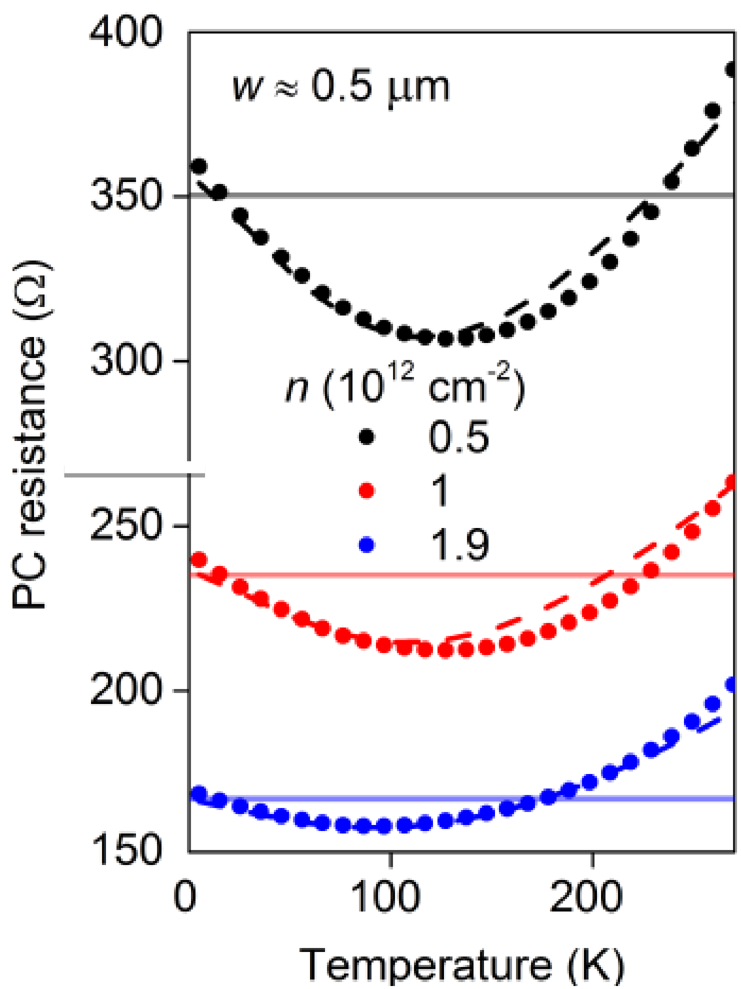


$$G_b = \frac{4e^2}{h}\frac{2w}{\lambda_F}$$

Nat Phys 2017

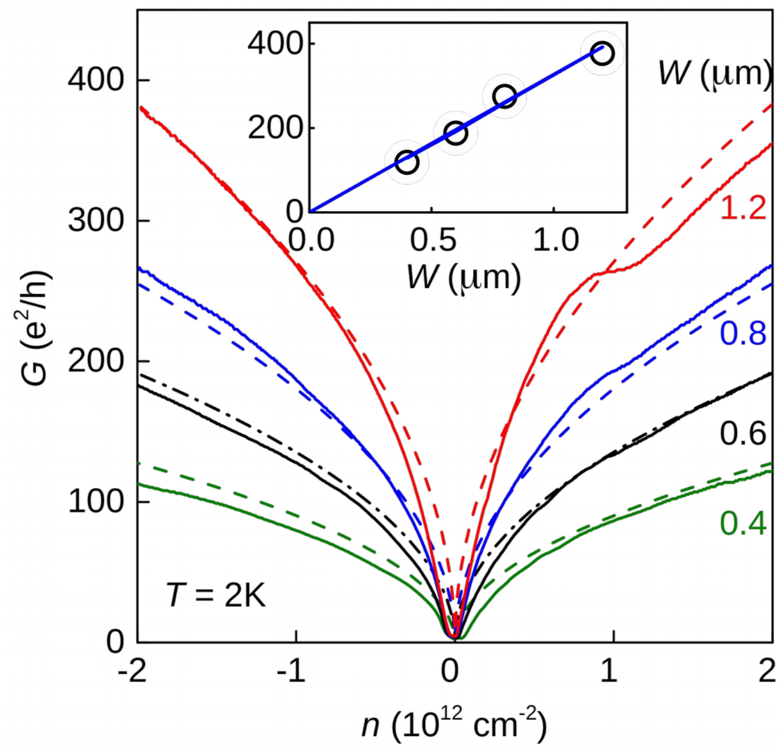
Transport measurements

Viscous flow at elevated temperatures



Semiconducting-like behavior
R values below the ballistic limit

Ballistic transport at low T



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Nat Phys 2017

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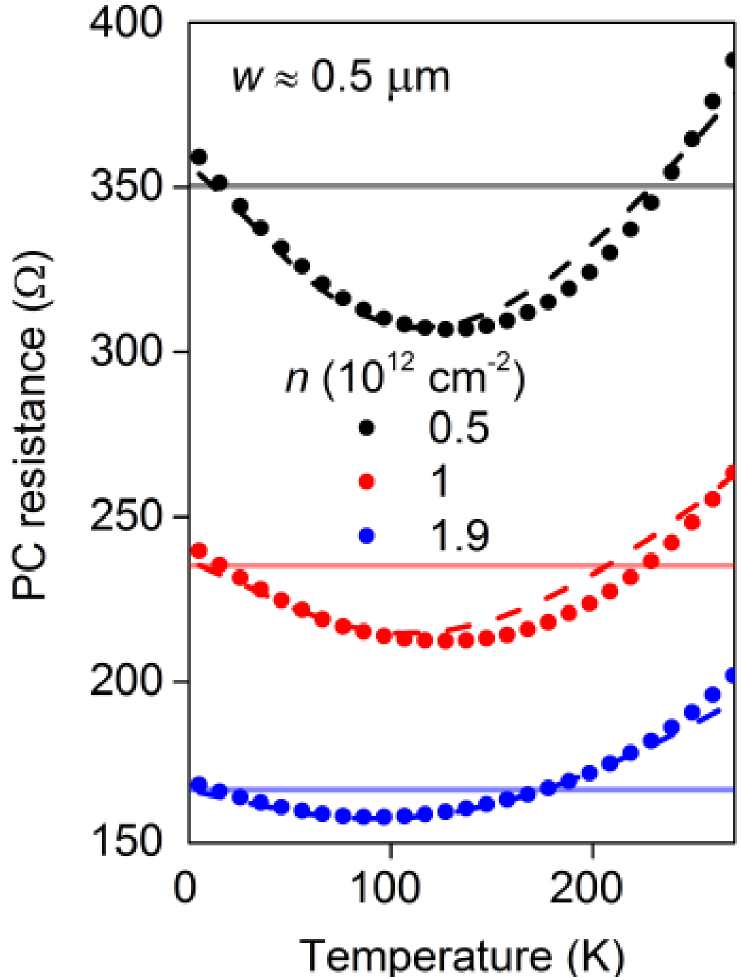
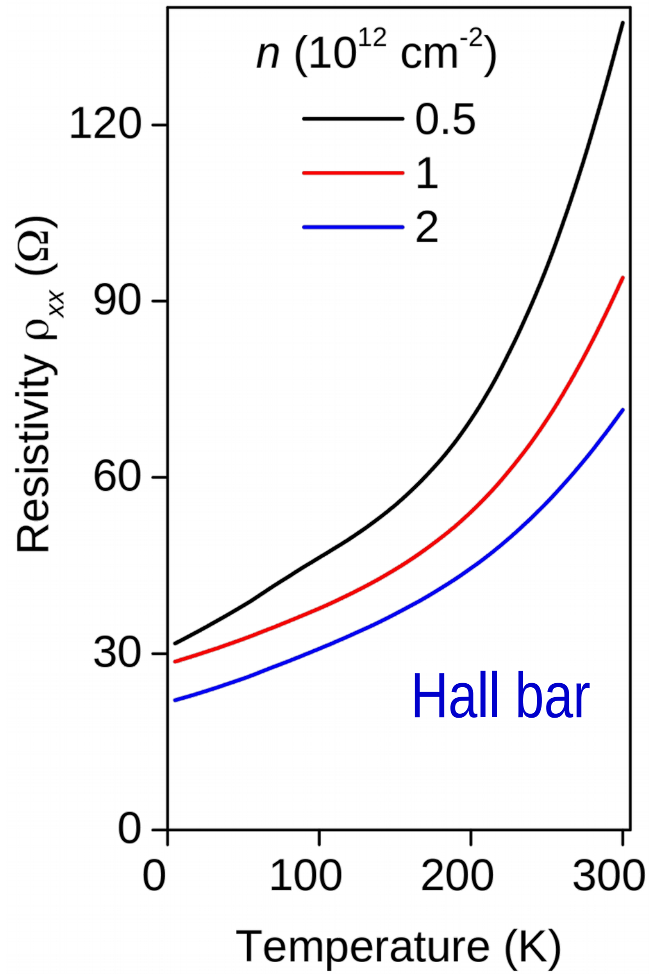




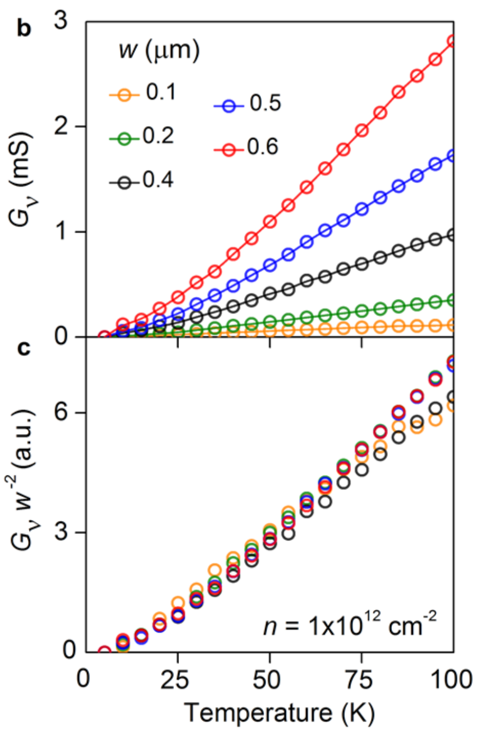
Semiconducting-like behavior
R values below the ballistic limit

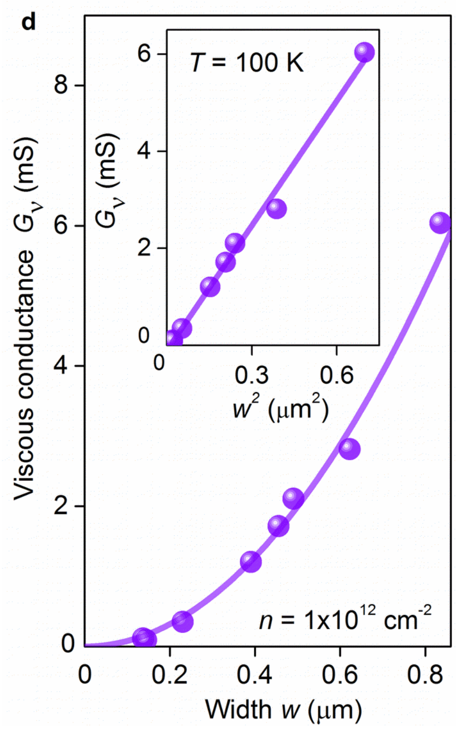
conventional behavior

Nat Phys 2017

Theory vs. measurements

- A new collective effect: hydrodynamic screening of disorder, **superballistic conductance**: **$G_{visc} > G_{ball}$**
- At crossover: ballistic and viscous **conductance additive** (no Mathiessen rule): **$G=G_{ball}+G_{visc}$**
- Probe ballistic-to-viscous crossover as a function of temperature: **good agreement with experiment**





Unconventional scaling $G_{visc} \sim w^2$

$$G_{visc} = \frac{\pi (ne)^2 w^2}{32\,\eta}$$

Together... We Can