Title: Viscous Electron Fluids: Higher-Than-Ballistic Conduction Negative Nonlocal Resistance and Vortices

Date: Aug 23, 2016 09:30 AM

URL: http://pirsa.org/16080039

Abstract:

Viscous Electron Fluids: Higher-than-Ballistic Conduction, Negative Nonlocal Resistance and Vortices

Leonid Levitov (MIT)

Low Energy Challenges in High Energy Physics
Perimeter Institute 08/23/2016

Collaboration

Haoyu Guo MIT

Andrey Shytov
Exeter UK

Gregory Falkovich
WIS Israel

Is hydrodynamics ever relevant?

- In one-comp fluid or gas a hydrodynamic approach works b/c one has 1) local equilibrium and 2) locally conserved energy and momentum
- All transport properties governed by just 3 quantities: the shear viscosity (η), the second viscosity (ζ), and the thermal conductivity (κ)

08/16/2

Is hydrodynamics ever relevant in metals?

- In one-comp fluid or gas a hydrodynamic approach works b/c one has 1) local equilibrium and 2) locally conserved energy and momentum
- All transport properties governed by just 3 quantities: the shear viscosity (η), the second viscosity (ζ), and the thermal conductivity (κ)
- Electron fluid in a solid can exchange energy and momentum with the lattice. Hydrodynamics not relevant? Not so fast...
- High-mobility electron systems (GaAs 2DES, graphene):
- Non-Fermi liquids, high-Tc superconductors, strange metals

08/16/2016

Critical electron fluids

- Interactions strong near CP (e.g. enhanced in 2D, graphene)
- Vanishing DOS but long-range interactions, strong coupling
- Fast p-conserving collisions, shear viscosity
- AdS CFT, black holes and **new collective phenomena**

VOLUME 56, NUMBER 14 1

Nonzero-temperature transport near quantum critical points

Kedar Damle and Subir Sachdev

Department of Physics, P.O. Box 208120, Yale University, New Haven, Connecticut 06520-8120

PRL **94,** 111601 (2005) PHYSICAL REVIEW LETTERS

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole F

P. K. Kovtun,[1] D. T. Son,[2] and A. O. Starinets[3]

Critical electron fluids

- Interactions enhanced in 2D, strong near DP
- Vanishing DOS but long-range interactions, strong coupling
- Fast p-conserving collisions, shear viscosity
- AdS CFT, black holes and new collective phenomena
- Near-perfect fluid: record-low viscosity – how to measure?

025301 (2009) PHYSICAL REVIEW LETTERS ULY

Graphene: A Nearly Perfect Fluid

Markus Müller,[1] Jörg Schmalian,[2] and Lars Fritz[3]

)01 (2014) PHYSICAL REVIEW LETTERS 5 14

Corbino Disk Viscometer for 2D Quantum Electron Liquids

Andrea Tomadin,[1,*] Giovanni Vignale,[2] and Marco Polini[1]

Carrier collisions vs. disorder scattering in graphene

$\gamma_{\rm ee} \sim (k_{\rm B}T)^2/E_{\rm F}$ in the degenerate limit

Near charge neutrality, the rate $\gamma_{\rm ee}$ grows

$\gamma_{\rm ee} \approx A\alpha^2 k_{\rm B}T/\hbar$, where α is the interaction strength.

Fritz, L., Schmalian, J., Müller, M. & Sachdev, S. Quantum critical transport in clean graphene. Phys. Rev. B **78**, 085416 (2008). Kashuba, A. B. Conductivity of defectless graphene. Phys. Rev. B 78, 085415 (2008).

$$\gamma_{\rm ee}^{-1} \approx 80\,{\rm fs}$$

Disorder scattering can be estimated from mean free path values, which reach a few microns at large doping

$$\gamma_{\rm p} \propto n^{-1/2} \qquad n \lesssim 10^{10}\,{\rm cm}^{-2}$$

$$\gamma_{\rm p}^{-1} \sim 0.5\,{\rm ps}$$

8/22/16

Carrier collisions vs. disorder scattering in graphene

$\gamma_{ee} \sim (k_B T)^2 / E_F$ in the degenerate limit

Near charge neutrality, the rate γ_{ee} grows

$\gamma_{ee} \approx A\alpha^2 k_B T / \hbar$, where α is the interaction strength.

Fritz, L., Schmalian, J., Müller, M. & Sachdev, S. Quantum critical transport in clean graphene. Phys. Rev. B **78**, 085416 (2008). Kashuba, A. B. Conductivity of defectless graphene. Phys. Rev. B 78, 085415 (2008).

$$\gamma_{ee}^{-1} \approx 80\,\mathrm{fs}$$

Disorder scattering can be estimated from mean free path values, which reach a few microns at large doping

$$\gamma_p \propto n^{-1/2} \qquad n \lesssim 10^{10}\,\mathrm{cm}^{-2}$$

$$\gamma_p^{-1} \sim 0.5\,\mathrm{ps}$$

8/22/16

Carrier collisions vs. disorder scattering in graphene

$\gamma_{ee} \sim (k_B T)^2 / E_F$ in the degenerate limit

Near charge neutrality, the rate γ_{ee} grows

$\gamma_{ee} \approx A\alpha^2 k_B T / \hbar$, where α is the interaction strength.

Fritz, L., Schmalian, J., Müller, M. & Sachdev, S. Quantum critical transport in clean graphene. Phys. Rev. B **78**, 085416 (2008). Kashuba, A. B. Conductivity of defectless graphene. Phys. Rev. B 78, 085415 (2008).

$$\gamma_{ee}^{-1} \approx 80\,\text{fs}$$

Disorder scattering can be estimated from mean free path values, which reach a few microns at large doping

$$\gamma_p \propto n^{-1/2} \qquad n \lesssim 10^{10}\,\text{cm}^{-2}$$

$$\gamma_p^{-1} \sim 0.5\,\text{ps}$$

8/22/16

Hydrodynamic description of electron transport

$$\gamma_{\mathrm{p}} \ll \gamma_{\mathrm{ee}}$$

Navier-Stokes equation

$$\partial_t v + (v\nabla)v - \nu\nabla^2 v = -\nabla P/mn$$

$$\nu \approx (1/2)v_{\mathrm{F}}^2\gamma_{\mathrm{ee}}^{-1}$$

$$\nu_{el} \approx 0.1\, m^2 s^{-1} \gg \nu_{honey} \approx 0.002 - 0.005\, m^2 s^{-1}$$

$$P = e\int_{n_0}^{n} \Phi(n')\mathrm{d}n'$$

Reynolds number $Re = vL/\nu$

Laminar flows (low Re), turbulent flows (high-Re)

8/22/16

Hydrodynamic description of electron transport

$$\gamma_{\mathrm{p}} \ll \gamma_{\mathrm{ee}}$$

Navier-Stokes equation

$$\partial_t v + (v\nabla)v - \nu\nabla^2 v = -\nabla P/mn$$

$$\nu \approx (1/2) v_{\mathrm{F}}^2 \gamma_{\mathrm{ee}}^{-1}$$

$$\nu_{el} \approx 0.1\, m^2 s^{-1} \gg \nu_{honey} \approx 0.002 - 0.005\, m^2 s^{-1}$$

$$P = e \int_{n_0}^{n} \Phi(n')\mathrm{d}n'$$

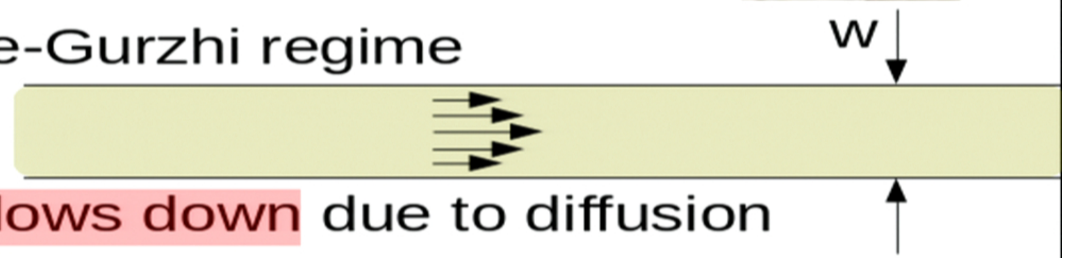
Reynolds number $Re = vL/\nu$

Laminar flows (low Re), turbulent flows (high-Re)

8/22/16

Signatures of viscous flows

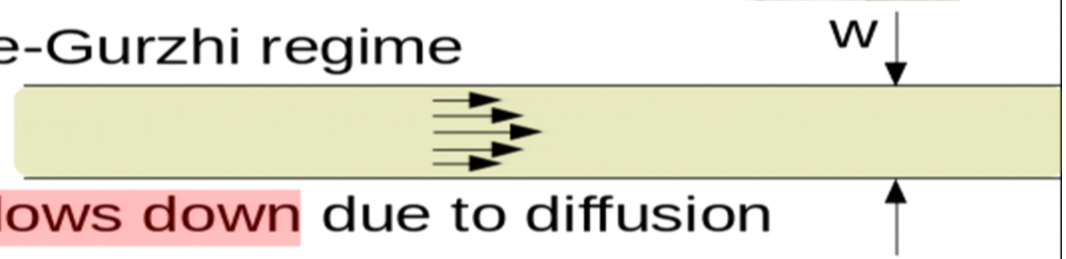
- T-dependent scattering time $\tau_{ee} \sim E_F/T^2$
- Sample width $w << l_{ee}$ (low T) Knudsen-Fuchs regime
- $w >> l_{ee}$ (higher T) Poiseuille-Gurzhi regime
- Control value τ_{ee} by current
- Gurzhi effect: p-relaxation slows down due to diffusion
- R=dV/dI vs. I first grows then decreases



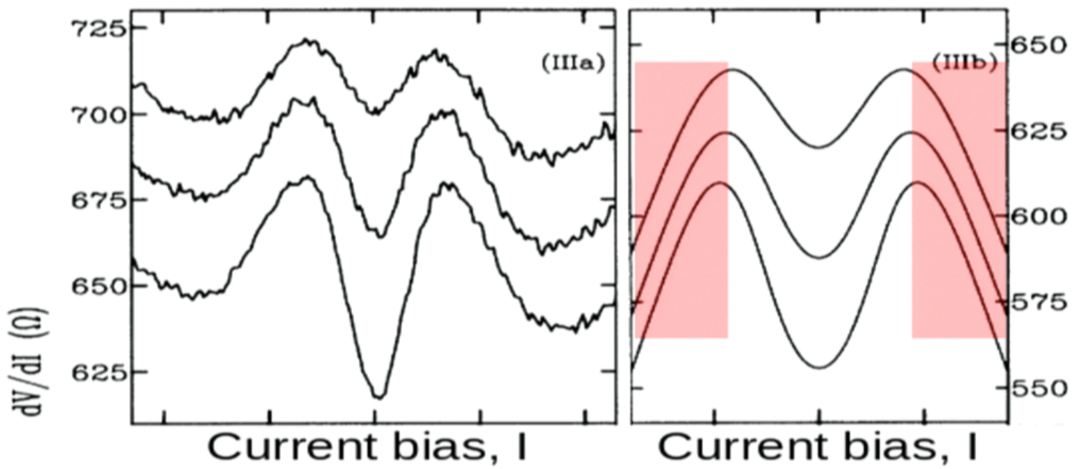
08/16/2016

Signatures of viscous flows

- T-dependent scattering time $\tau_{ee} \sim E_F/T^2$
- Sample width $w \ll l_{ee}$ (low T) Knudsen-Fuchs regime
- $w \gg l_{ee}$ (higher T) Poiseuille-Gurzhi regime
- Control value τ_{ee} by current
- Gurzhi effect: p-relaxation slows down due to diffusion
- R=dV/dI vs. I first grows then decreases



Tested in ballistic wires
de Jong & Molenkamp
1995

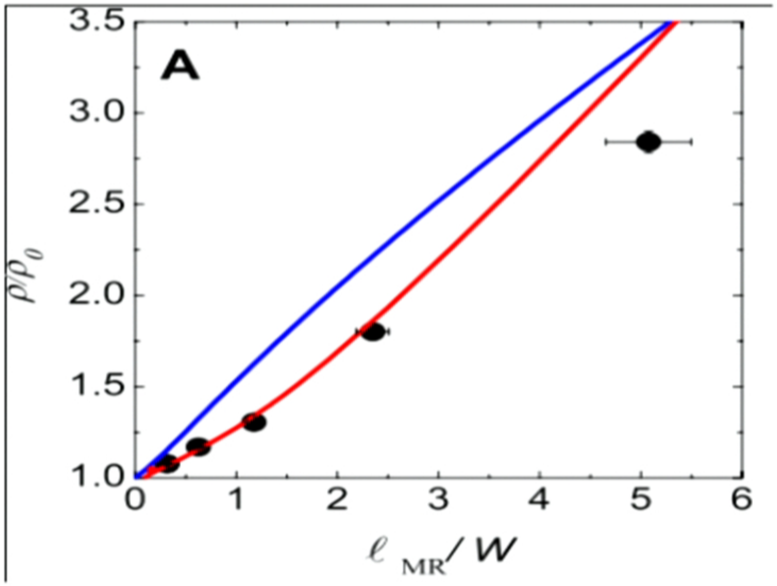


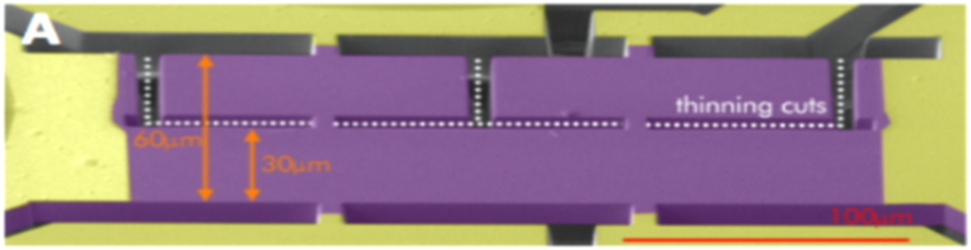
08/16/2016

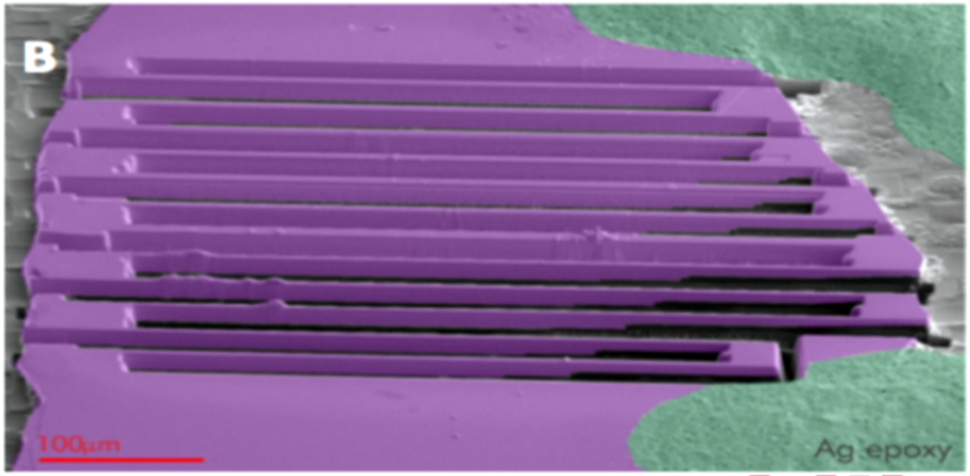
Evidence for hydrodynamic electron flow in ultra-pure $PdCoO_2$ wires

(Moll, Mckenzie, et al. Science 2016)

1) low resistivity (~ 100 nΩ cm);
2) apparent mean free paths larger than the wire width;
3) superlinear scaling ρ vs. 1/W



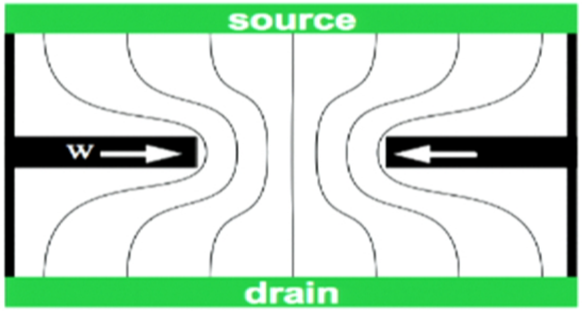


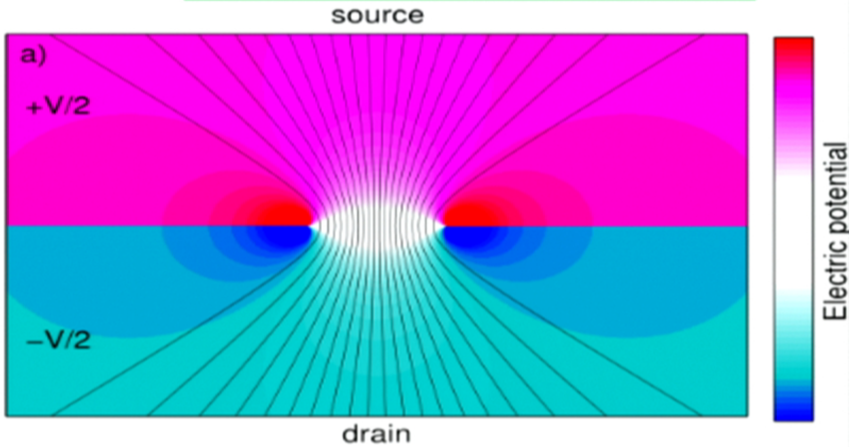


Measure viscosity in a constriction

- Viscous point contact (VPC): $l_{ee} \ll w$
- Resistance dominated by viscosity
- Characteristic scaling: $G_{viscous} \sim W^2$ vs. $G_{ballistic} \sim W$

$$R = \frac{32\eta}{\pi (ne)^2 w^2} = \frac{l_T^2}{w^2} 4\,k\Omega, \quad l_T = \frac{\hbar v}{T}$$





Other approaches:
Mueller, Schmalian, Fritz '09
Mendoza, Herrmann, Pucci '11
Tomadin, Vignale, Polini '14

2D viscous charge flow

Continuity of charge:

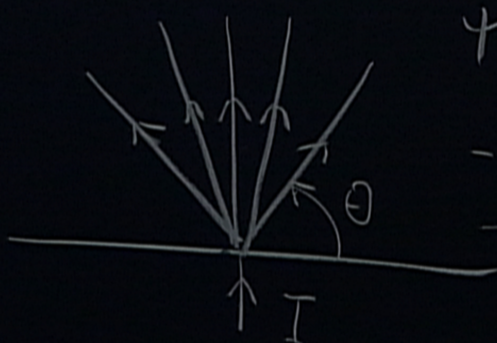
$$\nabla j = 0 \xrightarrow{\vec{j} = ne\vec{v}} \nabla \cdot \vec{v} = 0 \rightarrow \vec{v} = \hat{z} \times \vec{\nabla} \psi \quad \text{(stream function)}$$

Stokes eq. $\eta \nabla^2 \vec{v} = ne \vec{\nabla} \phi \xrightarrow{\text{rot}} (\nabla^2)^2 \psi = 0$

general soln $\psi(x,y) = \text{Re}\left(f_1(z) + \bar{z} f_2(z)\right)$ — analytic fcns, $z = x + iy$

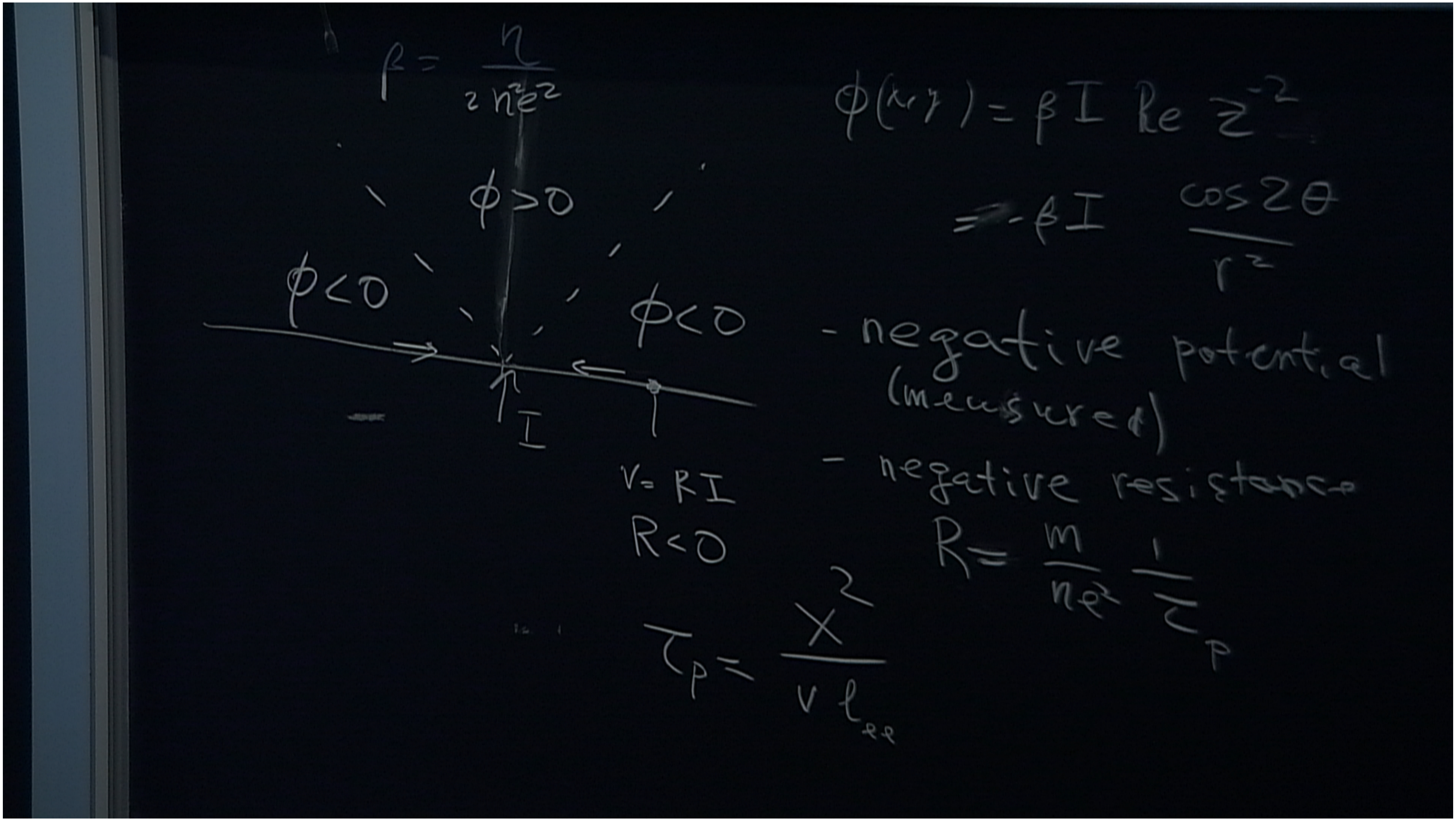
b.c. 1) $\frac{\partial \psi}{\partial \ell} = j(x)$ 2) $\frac{\partial \psi}{\partial n} = 0$ (no slip)

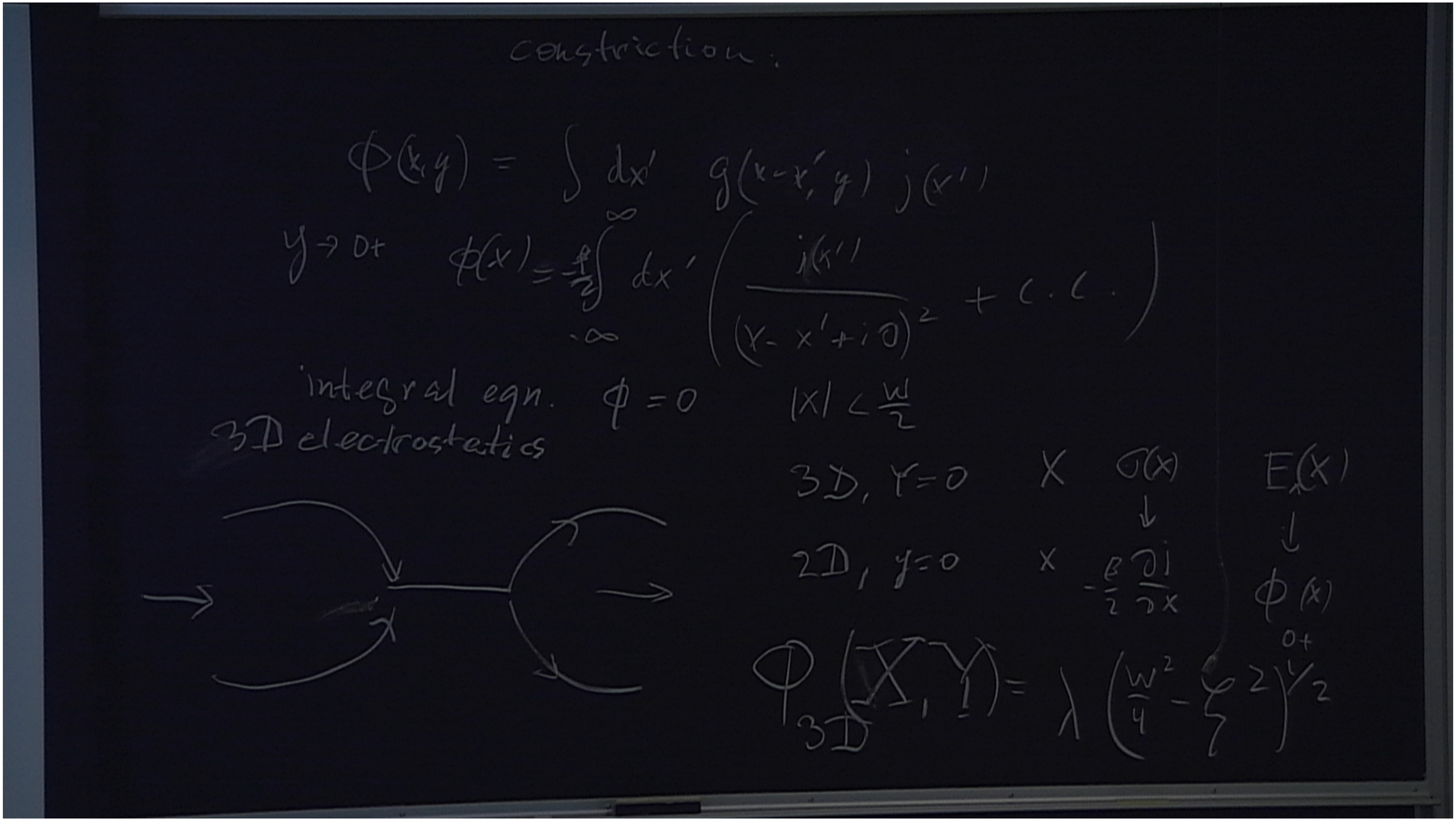
① point-like source, $y > 0$ halfplane



$$\psi(x,y) = \frac{I}{4\pi ne}\left(\sin 2\theta - 4\theta\right)$$

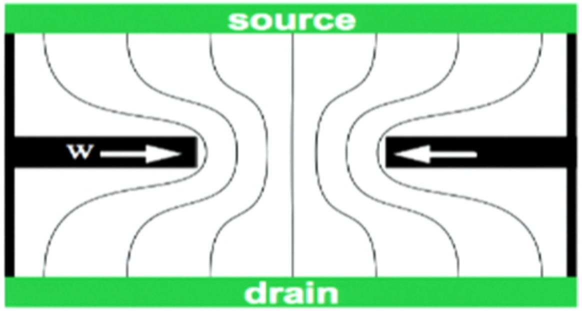
- radial flow
- directional effect (plume)


β = η / 2n²e²
φ(x,y) = βI Re z⁻²
= -βI cos 2θ / r²
φ>0
φ<0
φ<0
I
- negative potential
(measured)
- negative resistance
V = RI
R<0
R = m/ne² 1/τp
τp = x² / v lee

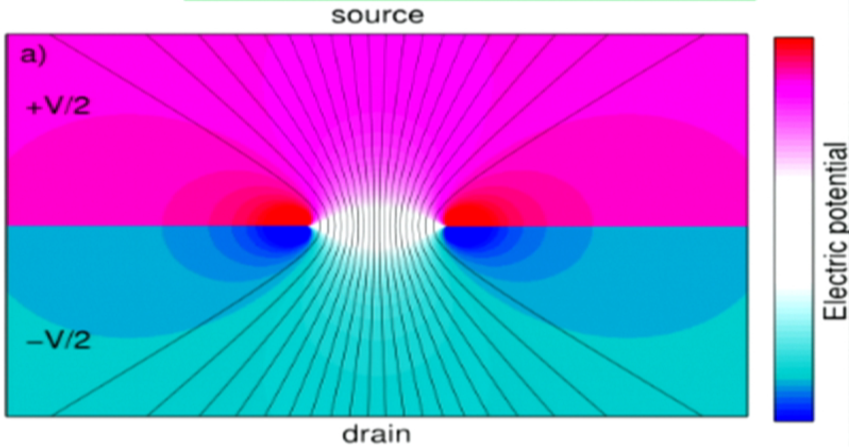

constriction:
φ(x,y) = ∫ dx' g(x−x', y) j(x')
y → 0+ φ(x) = −β/2 ∫_{−∞}^{∞} dx' (j(x') / (x − x' + i0)² + c.c.)
integral eqn. φ = 0 |x| < W/2
3D electrostatics
3D, Y=0 X σ(X) E(X)
2D, y=0 x −β/2 ∂j/∂x φ(x)
0+
φ_3D(X, Y) = λ (W²/4 − ζ²)^{1/2}

Measure viscosity in a constriction

- Viscous point contact (VPC): $l_{ee} \ll w$
- Resistance dominated by viscosity
- Characteristic scaling: $G_{viscous} \sim W^2$ vs. $G_{ballistic} \sim W$: can make $G_{visc} \gg G_{ball}$



$$R = \frac{32\eta}{\pi (ne)^2 w^2} = \frac{l_T^2}{w^2} 4\,k\Omega, \quad l_T = \frac{\hbar v}{T}$$



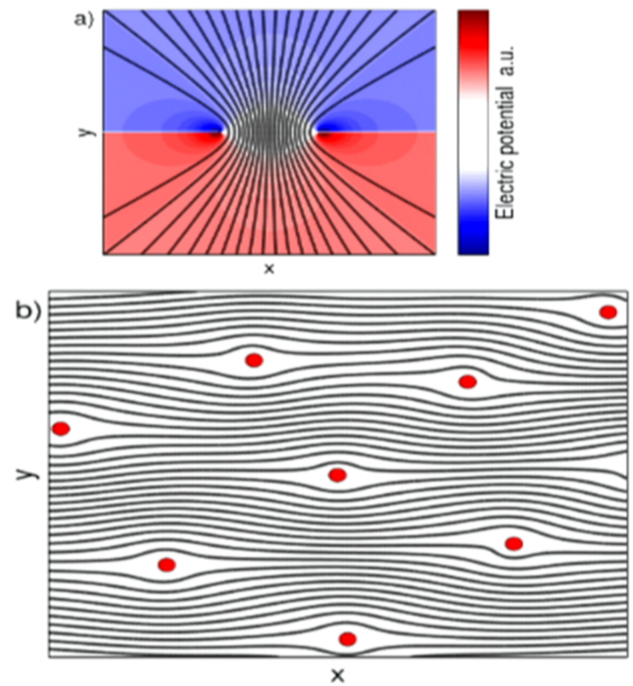
Features:

- Viscous-to-ballistic transition by varying n or T
- Conductance **higher** than $G_{ballistic}$
- Origin: zigzag trajectories, long "mean free path" $\xi = w^2/l_{ee} \gg w$
- Resistance **decreases** as temperature increases b/c $l_{ee} \sim 1/T^2$

Other approaches:
Mueller, Schmalian, Fritz '09
Mendoza, Herrmann, Pucci '11
Tomadin, Vignale, Polini '14

Higher-than-ballistic conduction

- Recall Landauer transport of degenerate fermions $G(\mu)=G_0\sum_n t_n(\mu),\ \ 0<t_n(\mu)\leq 1,\ \ G_0=\frac{e^2}{\pi\hbar}7.75\times 10^{-5}\Omega^{-1}$
- Governed by the number of channels for a constriction (Sharvin contact) $N=\sum_n t_n(\mu)=\frac{2w}{\lambda_F}$
- **Enhanced conductance of a viscous flow a result of correlated transport**
- **Cooperation:** electrons achieve jointly what they cannot accomplish individually
- Ballistic and viscous regimes realized in a single device (at T=0 and T>0)
- Similar behavior in other systems. **Flow lines bundle up in plumes and streams to circumnavigate disorder**



08/16/2016

The viscous-to-ballistic crossover

- Solve quantum kinetic eqn w full account taken of zero modes (p_x,p_y,n)

$$(\partial_t + v\nabla)f = I_{ee}(f) + I_b(f)$$

- τ-apprx for the collision integral

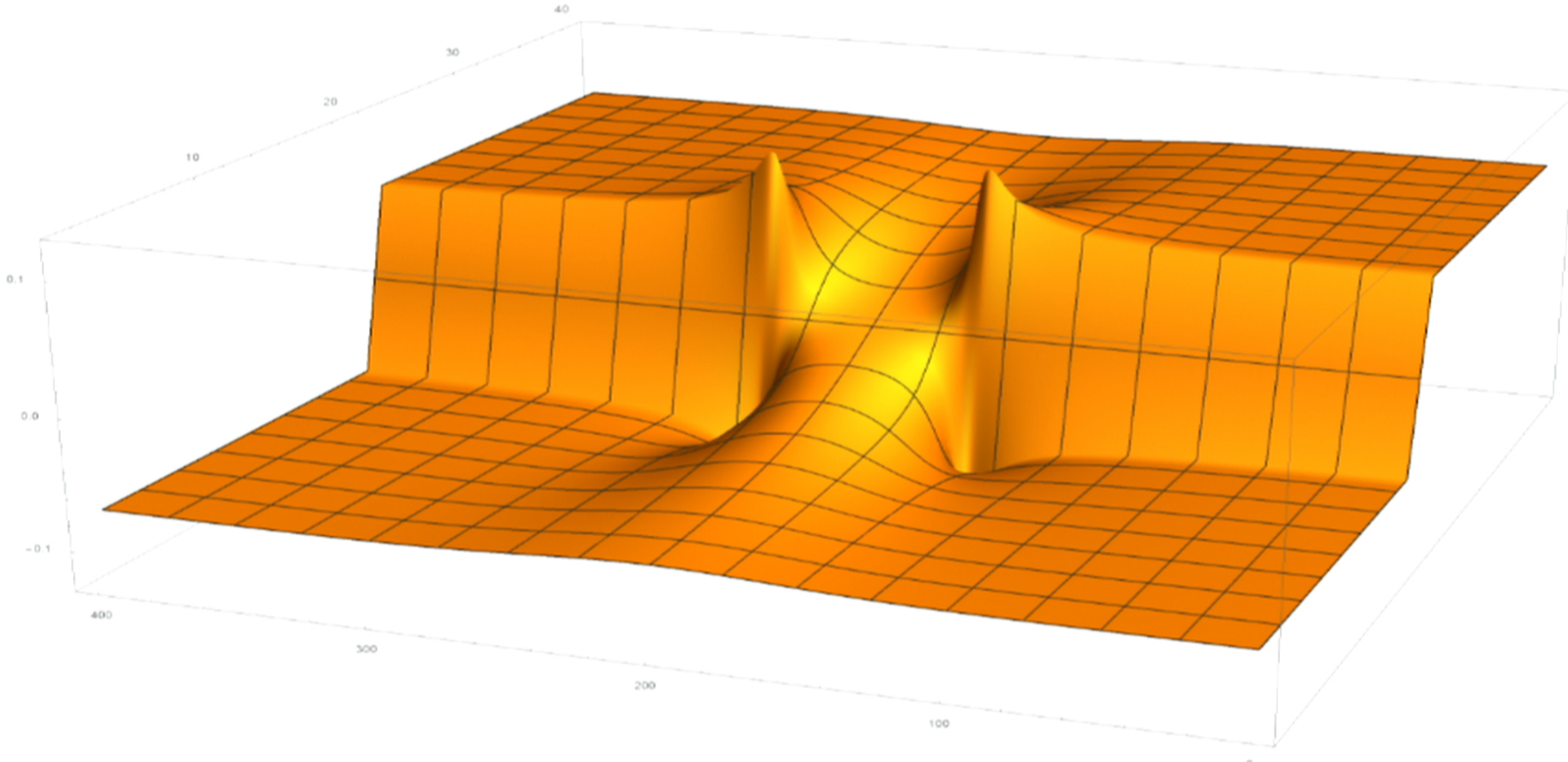
$$I_{ee} = -\gamma(f - P_3 f)$$

- Project on the 3D zero-mode subspace

$$I_b = -\alpha(x)\delta(y)P_2 f$$

08/16/2016

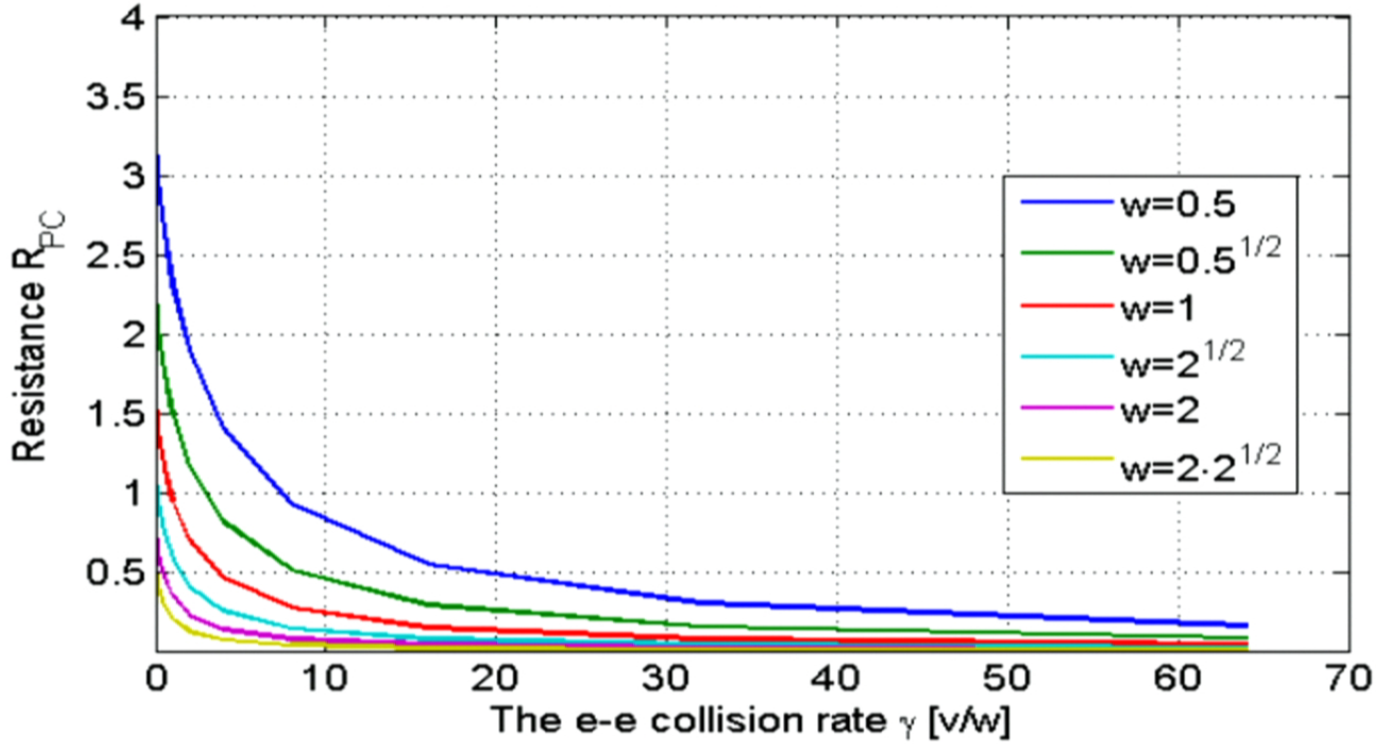
Potential distribution, high γ_{ee}



- Agrees w exact solution (hydro)
- Negative E-field at the edge

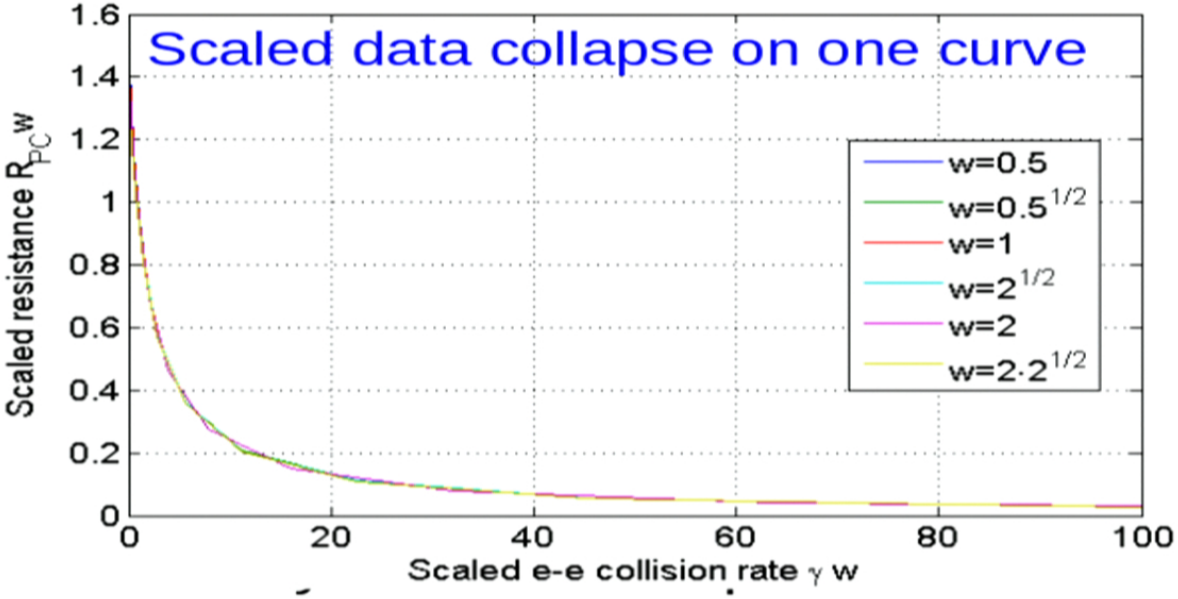
08/16/2016

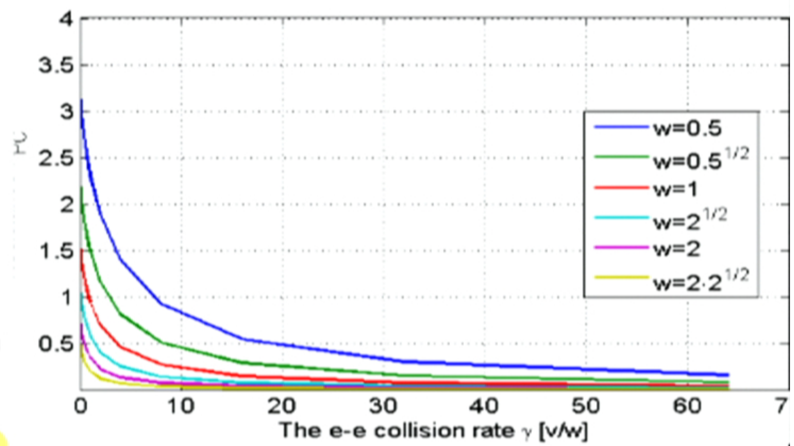
Conductance of a VPC



08/16/2016

Conductance of a VPC

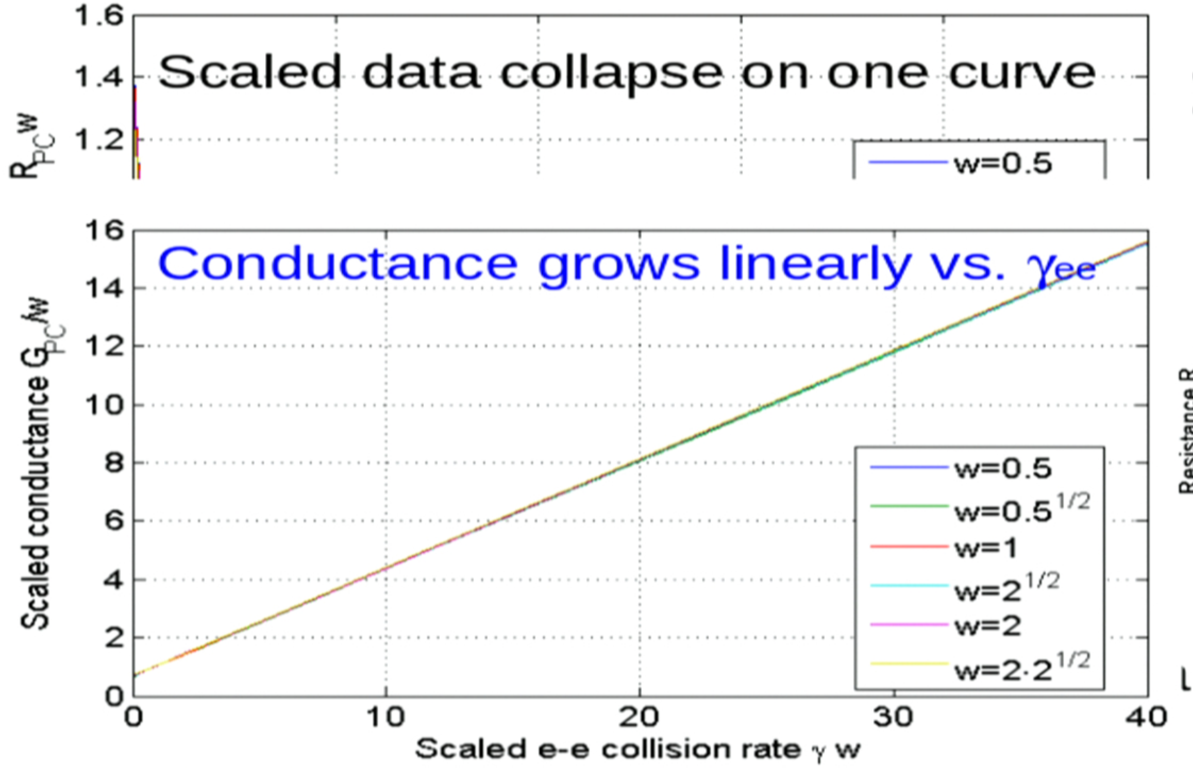


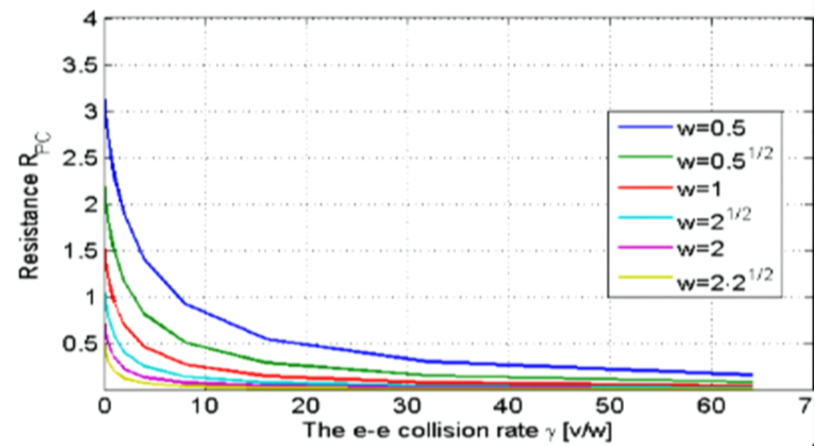


- For all γ, results expressed through a universal function of *γw/v*

08/16/2016

Conductance of a VPC





- With numerical precision find a simple linear dependence (exact solution?)

$$G_{exact} = G_{ball} + G_{hydro} = \frac{4e^2}{h} N + \frac{\pi (ne)^2 w^2}{32\eta}$$

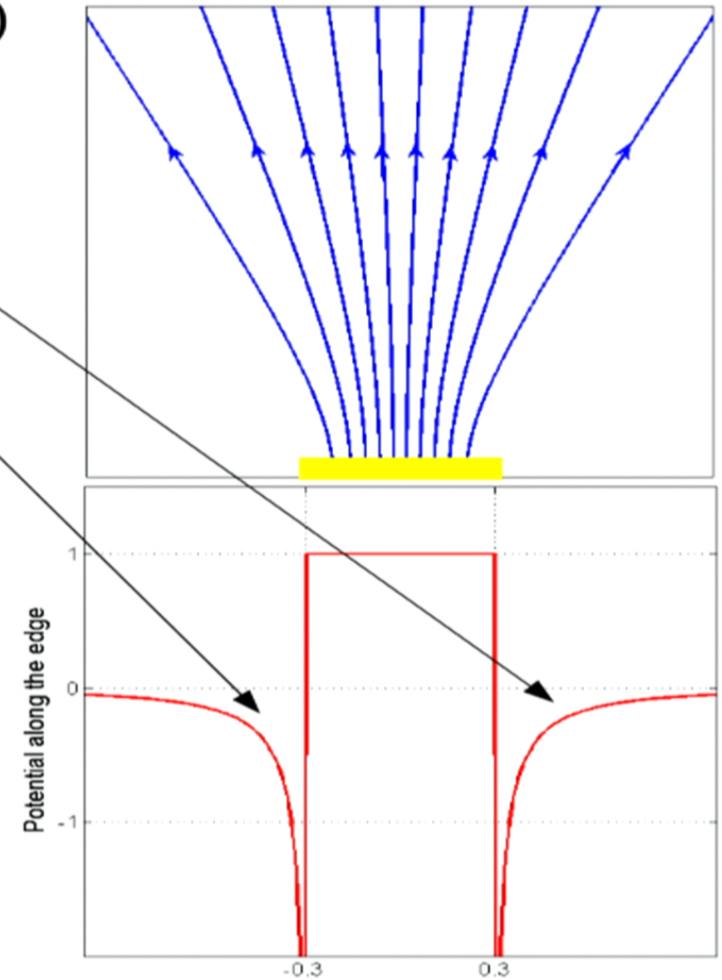
08/16/2016

Superballistic conduction summary & future

- A new collective effect: hydrodynamic screening of disorder, conductance enhancement: $G_{visc} >> G_{ball}$
- Low dissipation in the viscous limit
- Division of labor of different carriers: high-current streams and low-current buffer regions
- Ballistic and viscous conductances additive in the two cases studied (no Mathiessen rule): $G=G_{ball}+G_{hydro}$
- Probe ballistic-to-viscous crossover as a function of temperature
- How general is this behavior?
- How high G values can be reached?
- Limits on dissipation?

Current and potential for a point source

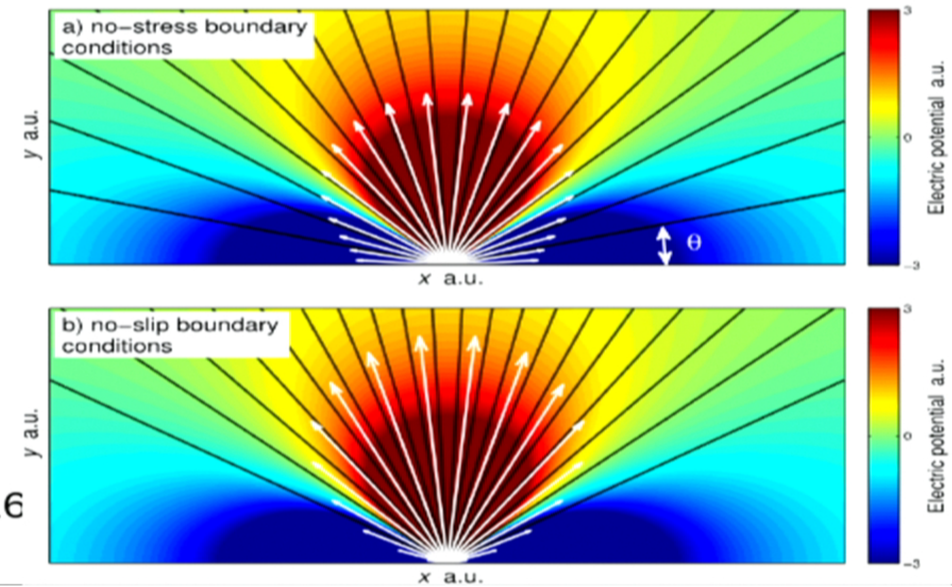
- Plumes of current (a directional effect)
- Low-current, high-vorticity regions
- E-field opposite to current, negative voltage at the edge



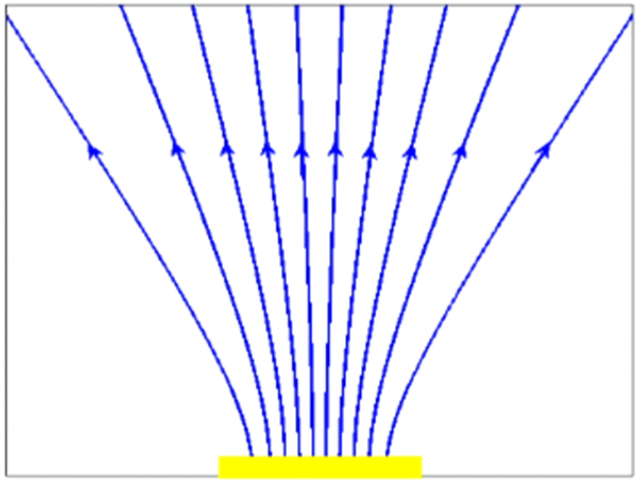
08/16/2016

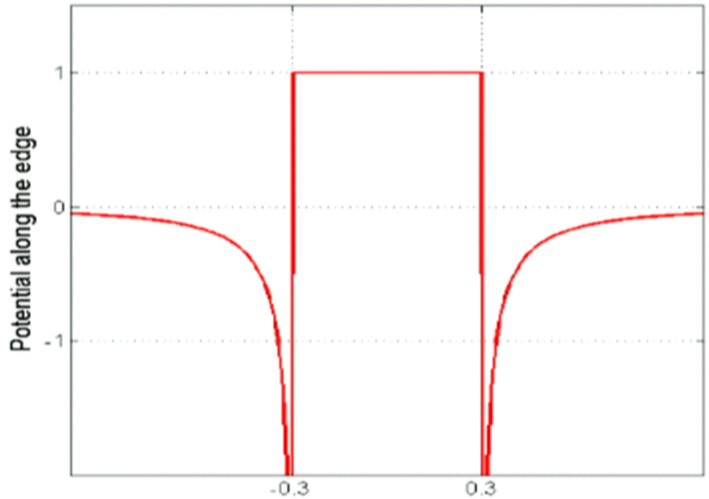
Current and potential for a point source

- Plumes of current (a directional effect)
- Low-current, high-vorticity regions
- E-field opposite to current, negative voltage at the edge
- No one-to-one relation between potentials and currents

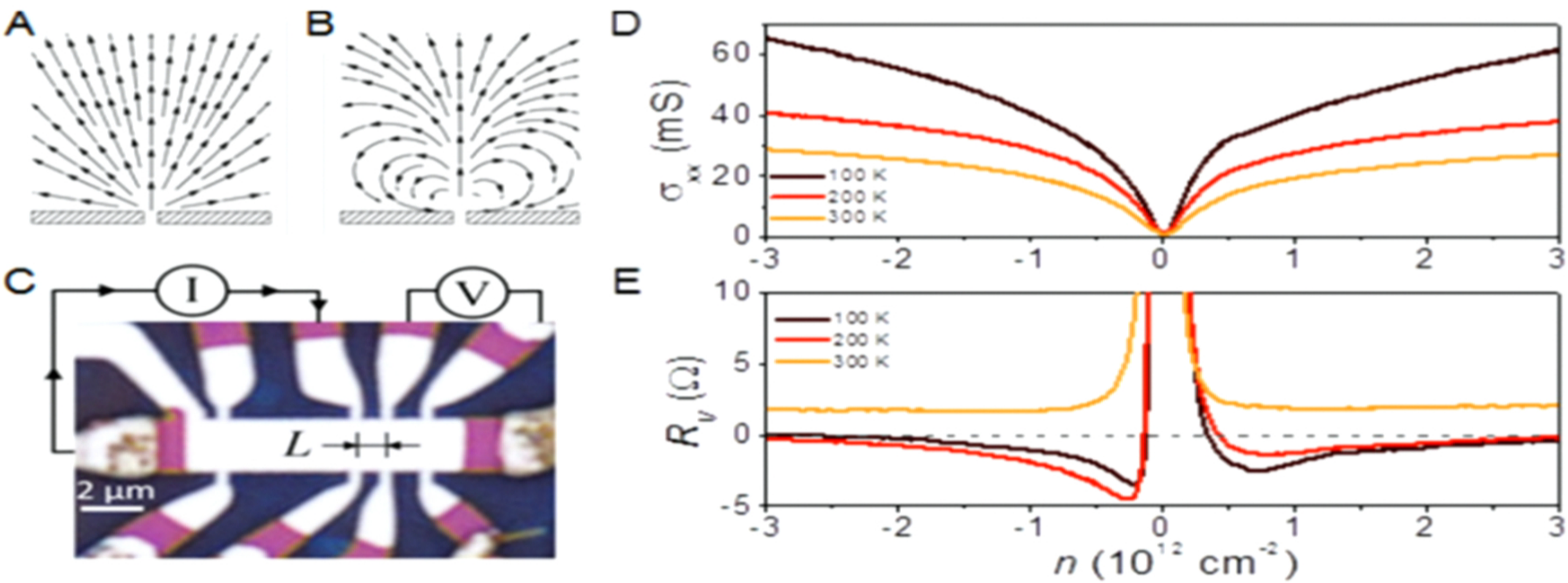


08/16





Strong V<0 in recent measurements



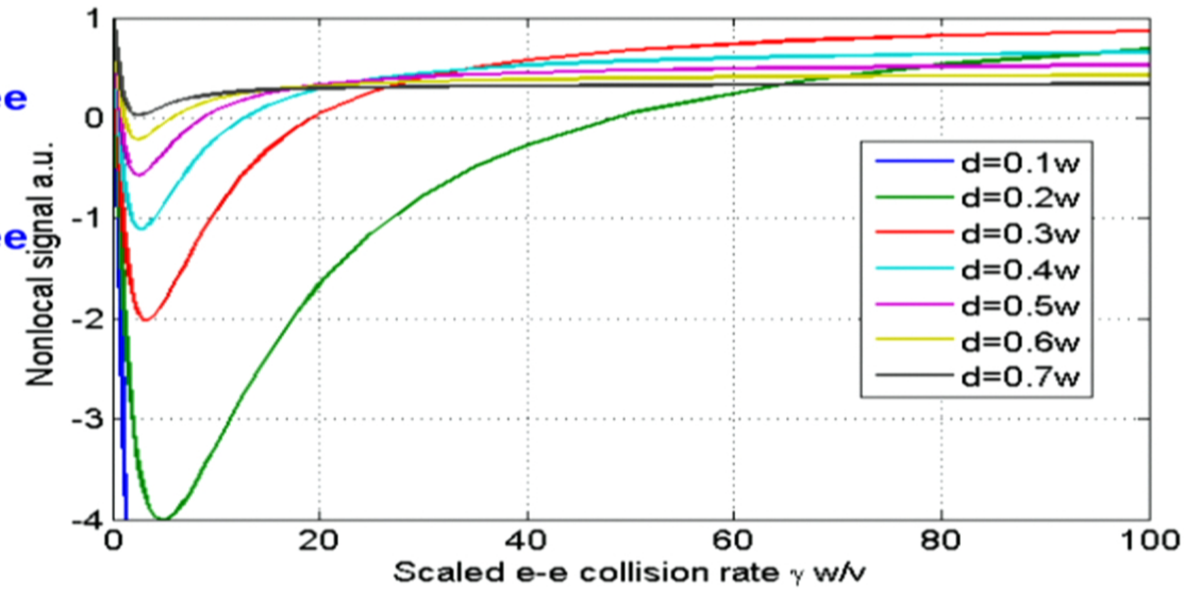
Bandurin et al (2015)

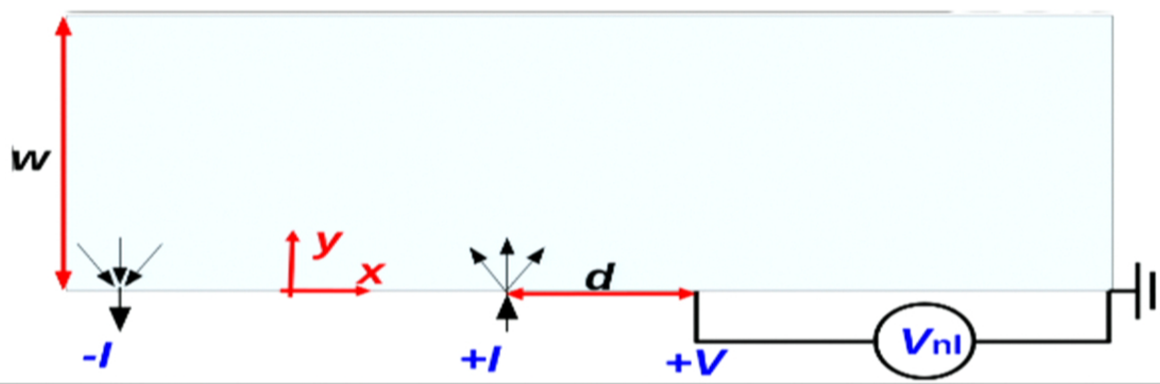
- Negative nonlocal resistance V=RI
- Negative V is strongest before reversing sign and turning positive

08/16/2016

Theory of negative nonlocal response

- Ballistic regime, V>0, small d,T, large n: $d \ll l_{ee}$
- Viscous regime, V<0, large d,T, small n: $d \gg l_{ee}$

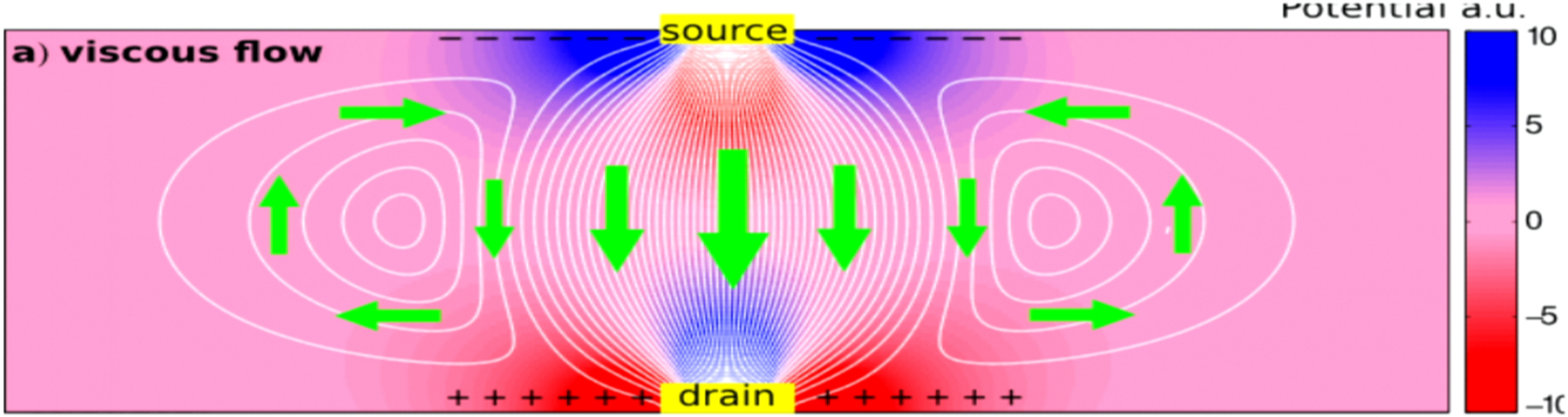




08/16/2016

Two VPC in series: nonlocal current-field relation can lead to rich spatial structures

- Vortices launched by shear flow
- Reverse E field buildup



Negative voltage needs no backflow

- Does the V<0 response **always** signal the presence of a backflow and vortices?

08/16/2016 LL & Falkovich arXiv:1508.00836 Nat Phys (2016)

Summary & Future

- The current-field relation **nonlocal** due to viscosity. **Negative voltage** as a signature of viscous flow
- Sign change as a function of position, if observed, allows to **directly measure** the viscosity-to-resistivity ratio
- **Vortices** and **backflow** launched by a shear flow
- In agreement w measurements in high-mobility graphene
- Caveats? **Other neutral modes**. Convective heat transport, negative thermoelectric effect due to **energy flow**. Control by lattice cooling?

02.05.2016

Observation of critical fluid

The breakdown of the Wiedemann-Franz law in graphene indicates convective heat propagation

(Crossno … KC Fong, Science 2016)