What is The Ultimate Conductance of Hydrodynamic Electrons?

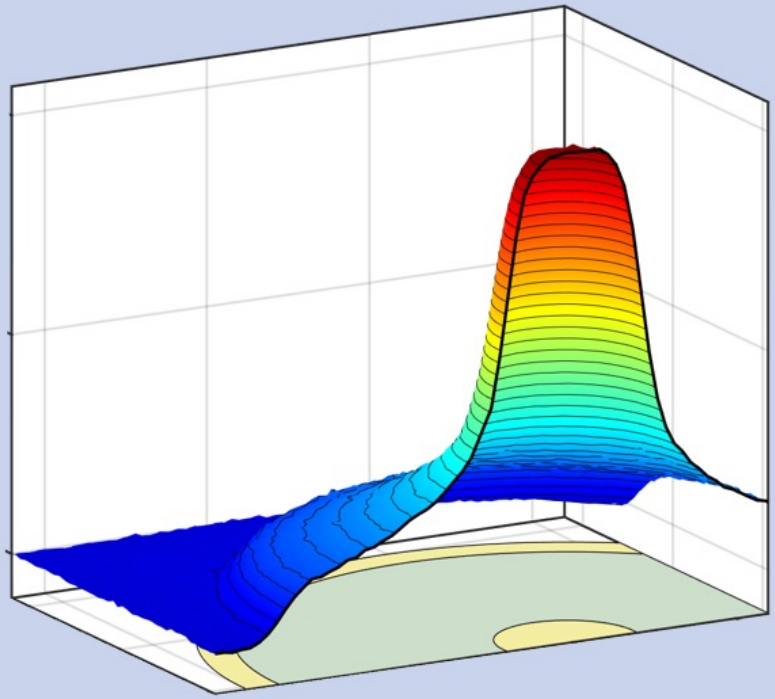
Shahal Ilani

Department of Condensed Matter Physics
Weizmann Institute of Science

Chandan Kumar

John Birkbeck

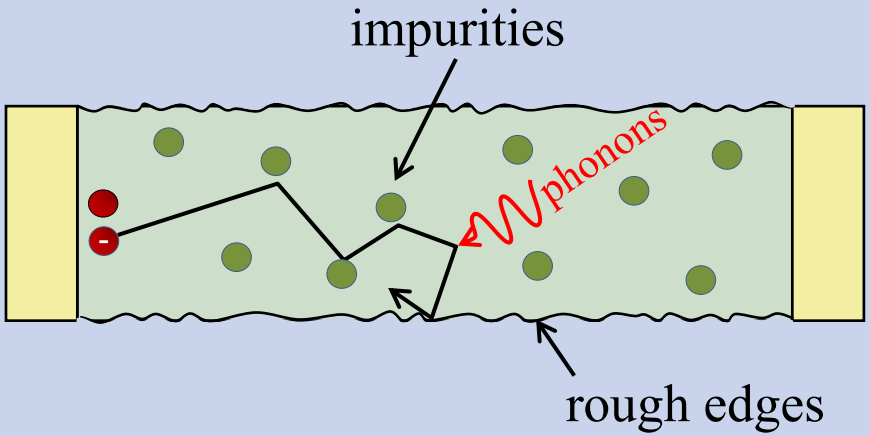
Joseph Sulpizio



Experimental collaboration: Dave Perello, Andre Geim (Manchester)
Theory collaboration: Oren Reuven, Ady Stern (Weizmnann) Thomas Scaffidi (Toronto)
hBN crystals: Takashi Taniguchi, Kenji Watanabe

Electrical resistance comes from momentum relaxation

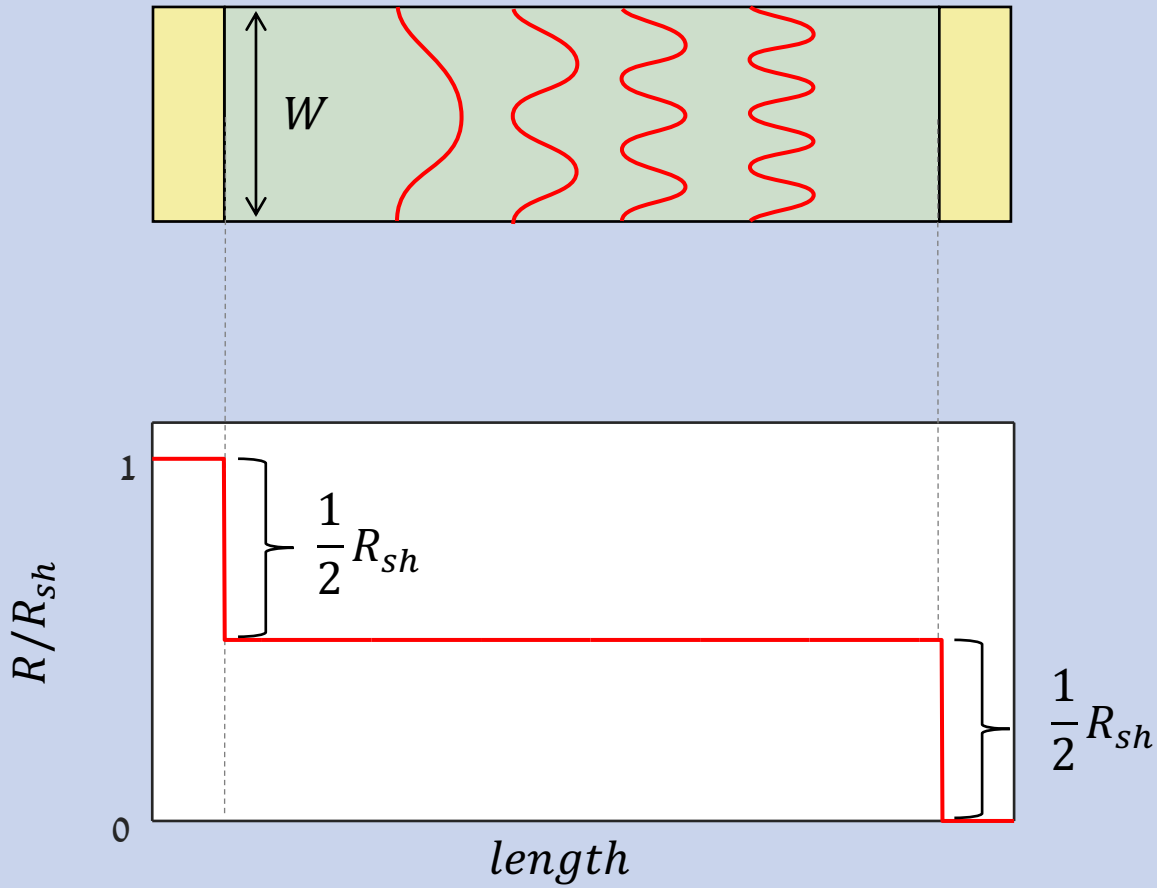
electrical resistance = momentum back-scattering



Landauer (1957) and Sharvin (1965)

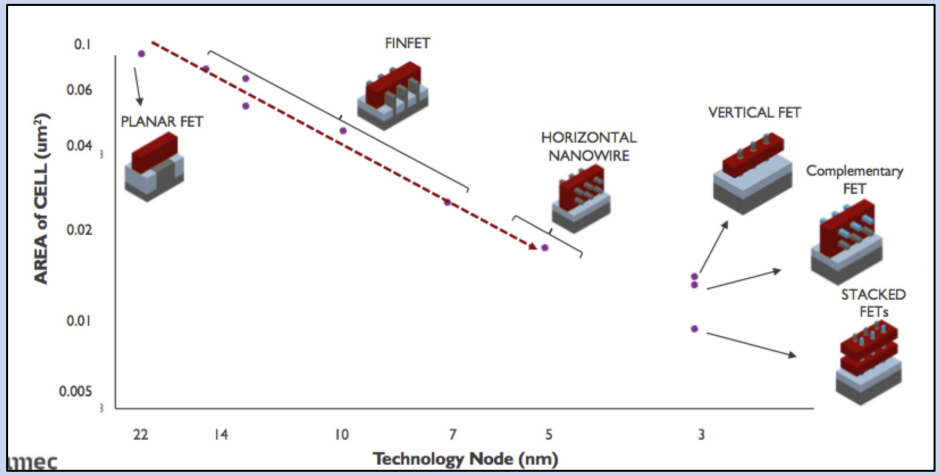
Landuer: N $= W/\lambda_F$ modes $\qquad R_{2probe} = \frac{1}{N}\frac{h}{e^2} \equiv R_{sh}$

Sharvin: At the interface with the contacts



The resistive bottleneck

Moore's law



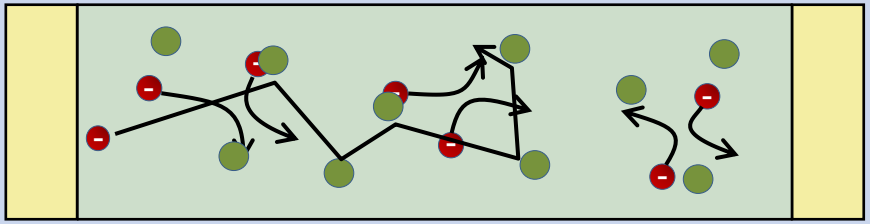
Scaling down continues

The bottleneck is the contact resistances

Ultimate bound - Landauer-Sharvin resistance

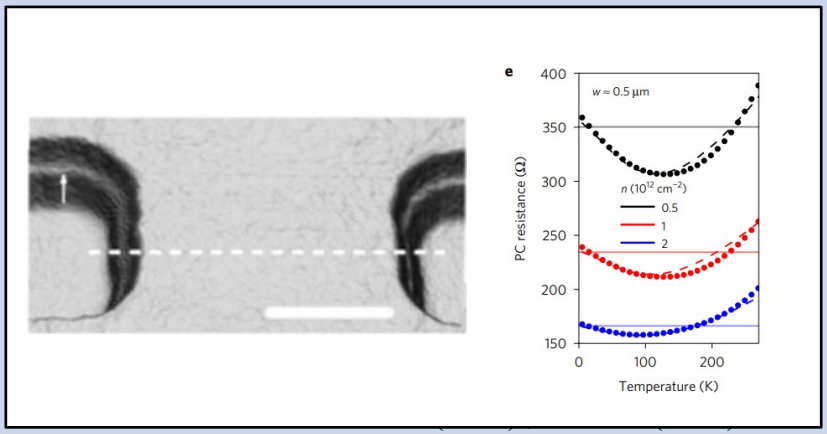
Can this fundamental limit be broken electron hydrodynamics?
By how much?

Electron hydrodynamics

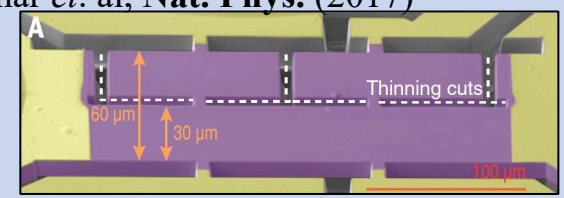


Hydrodynamics in high mobility wires

De-jong and Molenkamp, **PRB** (1994)

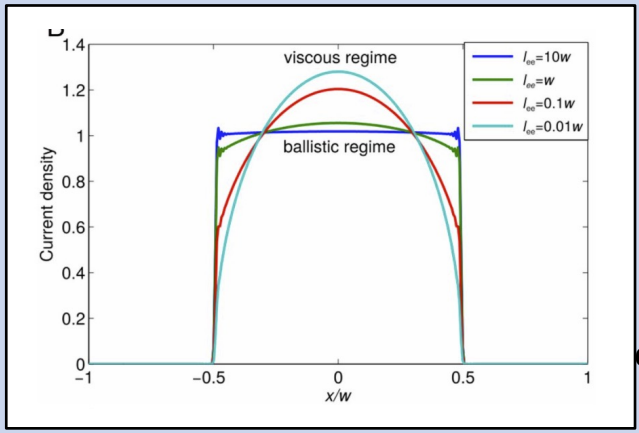


Kumar *et*. al, **Nat. Phys.** (2017)



Negative local resistance

Bandurin *et*. Al, **Science** (2016)



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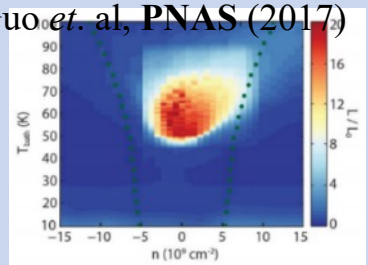
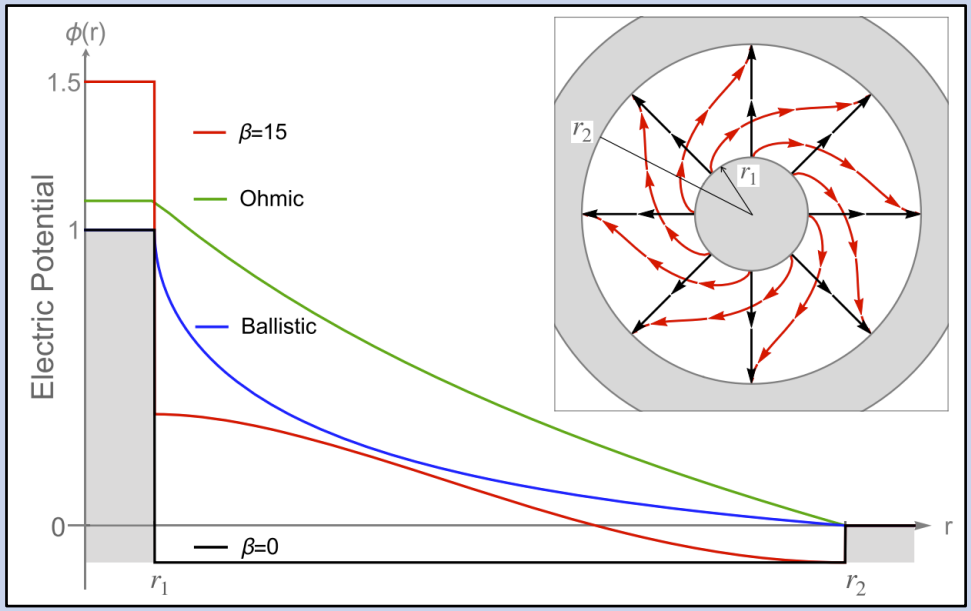
Guo *et*. al, **PNAS** (2017)



See also: Z.J. Krebs, V.W. Brar et. al, **arXiv** (2021)

Freely Flowing Currents and Electric Field Expulsion in Viscous Electronics



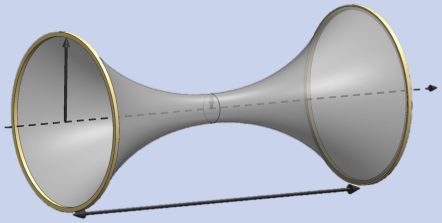
M. Shvait, A. Shytov and G. Falkovich, **PRL** (2019)

See also:

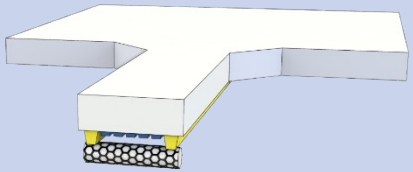
Q. Hong, M. Davidova, E. Kiselev, L. Levitov, **arXiv** (2020)

A. Levchenko, J. Schmallian, **Annal of Physics** (2020)

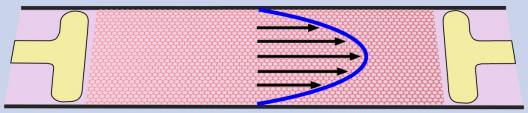
Outline



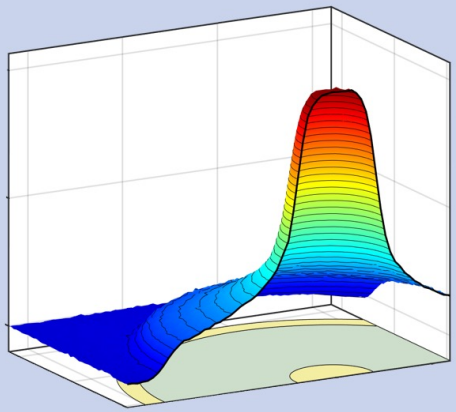
Theory: How hydrodynamics can eliminate resistance



Technique: imaging flowing Electrons



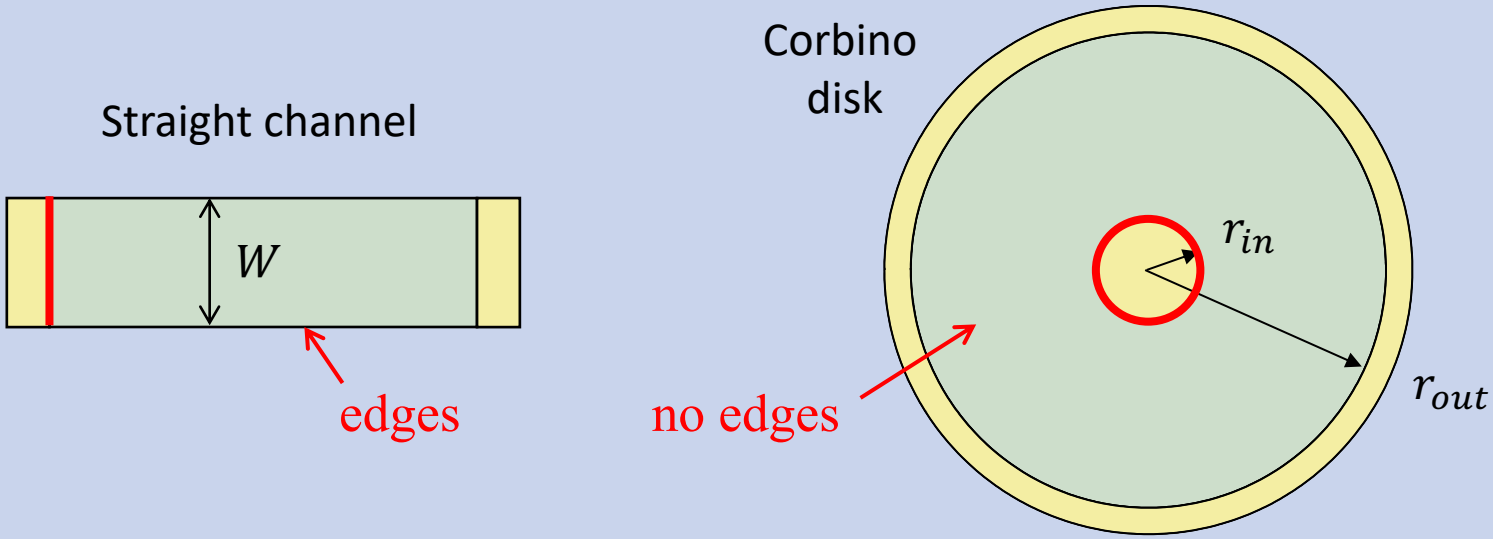
Imaging Poiseuille flow of hydrodynamic electrons



Imaging Corbino disk flow

- Ballistic
- Hydrodynamic
- Magneto - hydrodynamic

Corbino disk – Ballistic conductance

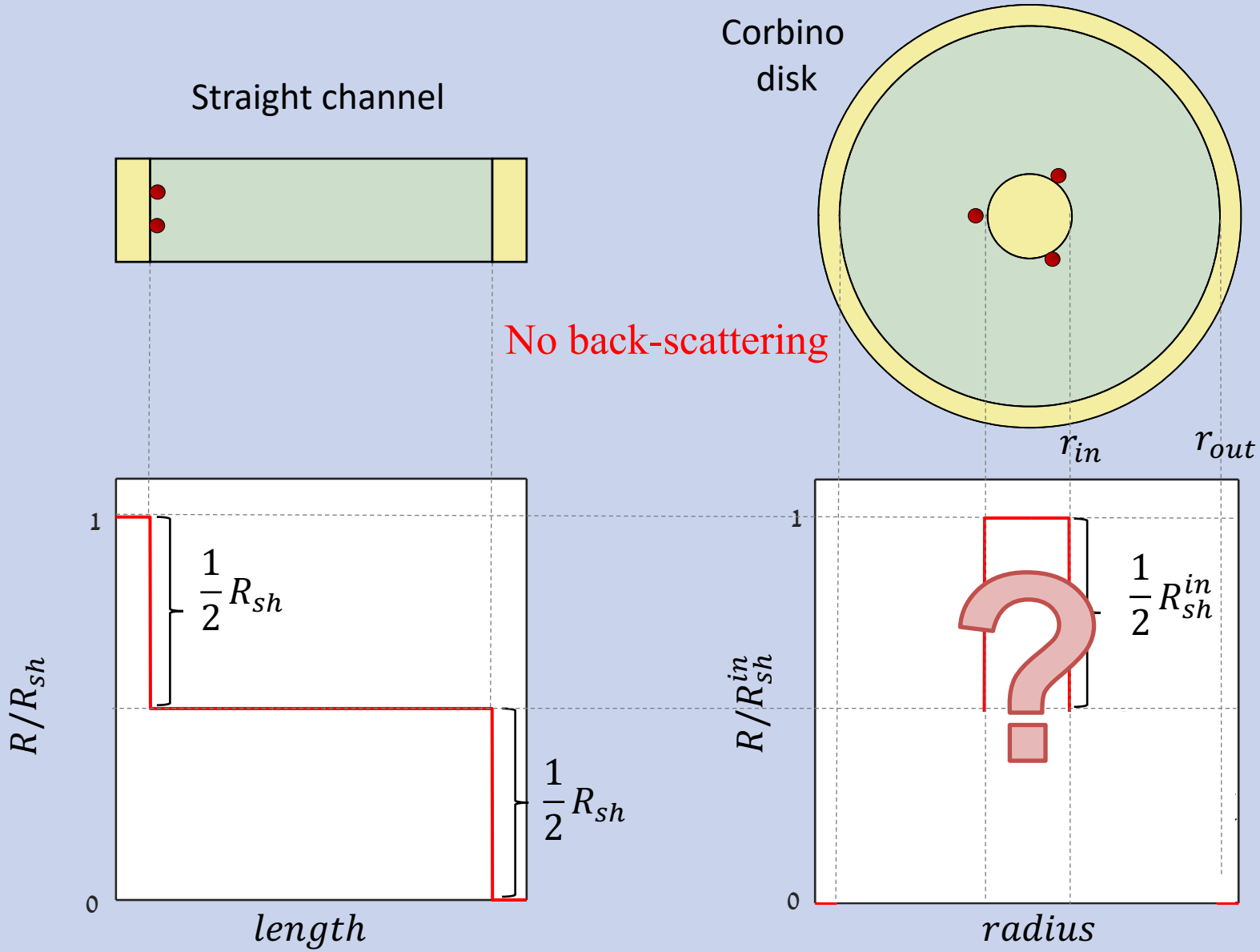


R_{2probe} given by the narrowest region of the channel

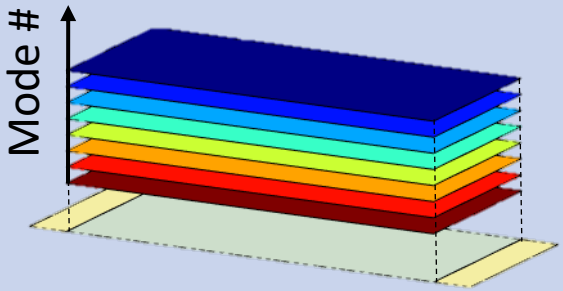
$$R_{sh} = \frac{\pi h}{4e^2}\frac{1}{k_F W}$$

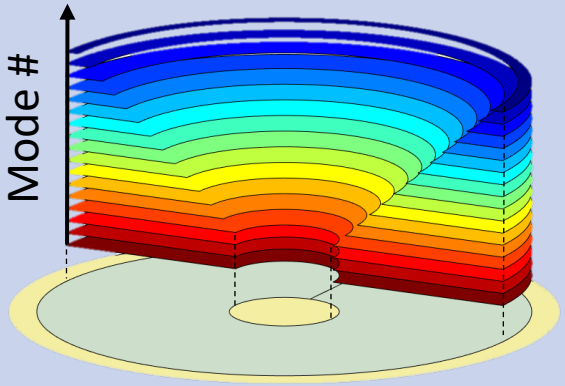
$$R_{sh}^{in} = \frac{\pi h}{4e^2}\frac{1}{k_F (2\pi r_{in})}$$

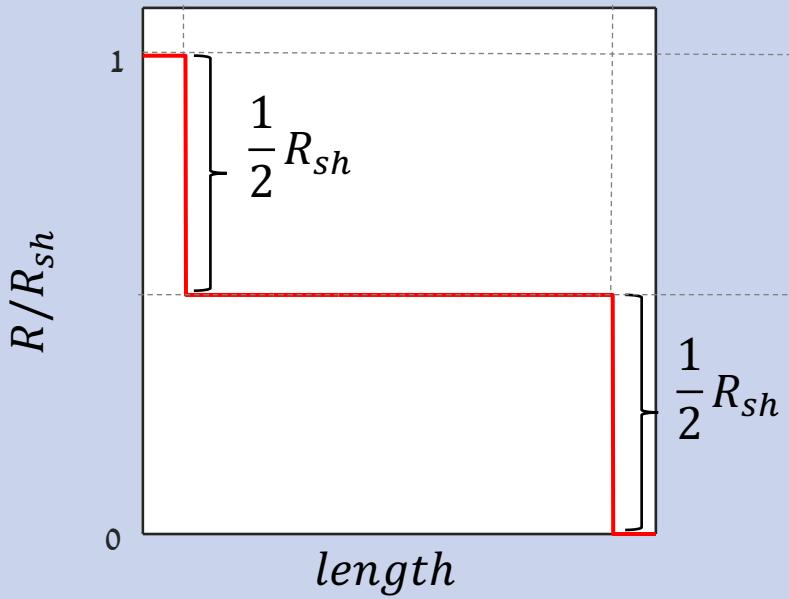
Corbino disk – Ballistic conductance

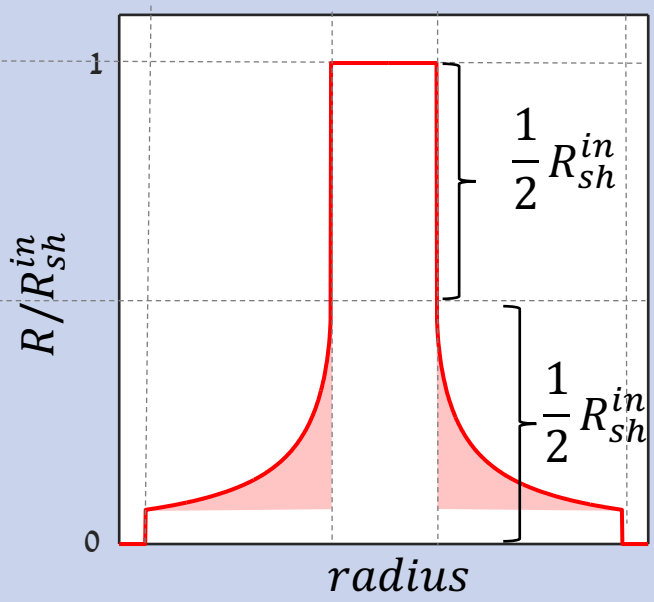


Corbino disk – Ballistic conductance







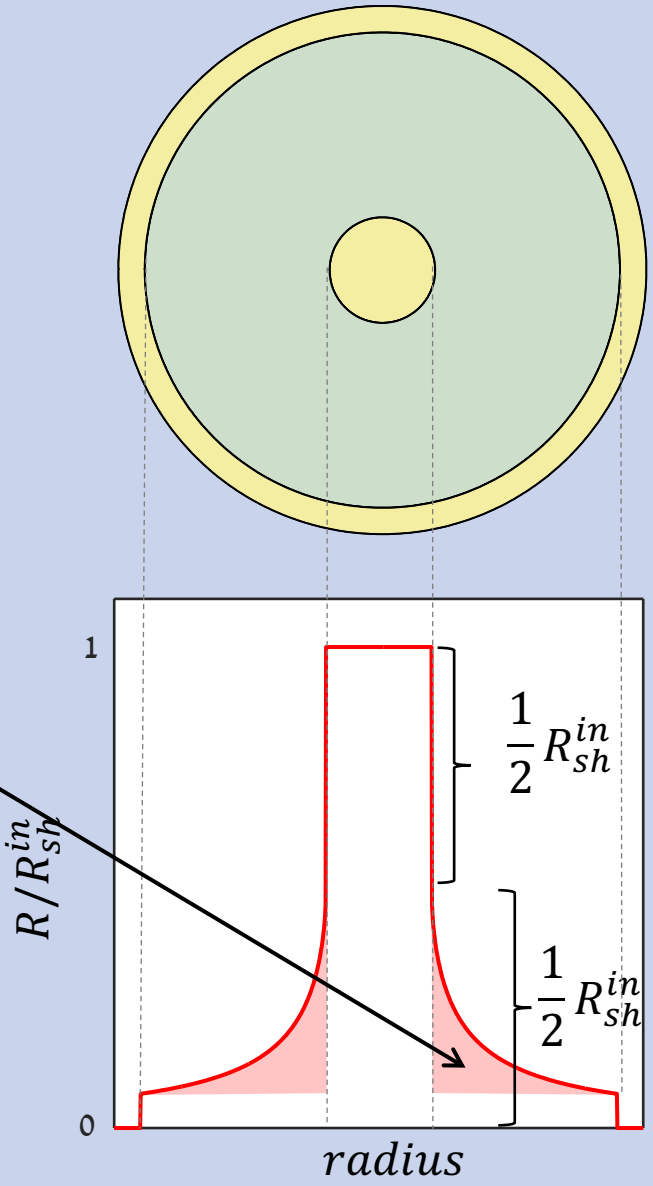


Corbino disk – Ballistic conductance

Bulk Landauer-Sharvin resistance

$$R_{LS}(r)/R_{sh}^{in} = \frac{1}{\pi}\,\mathrm{asin}\left(\frac{r_{in}}{r}\right)$$

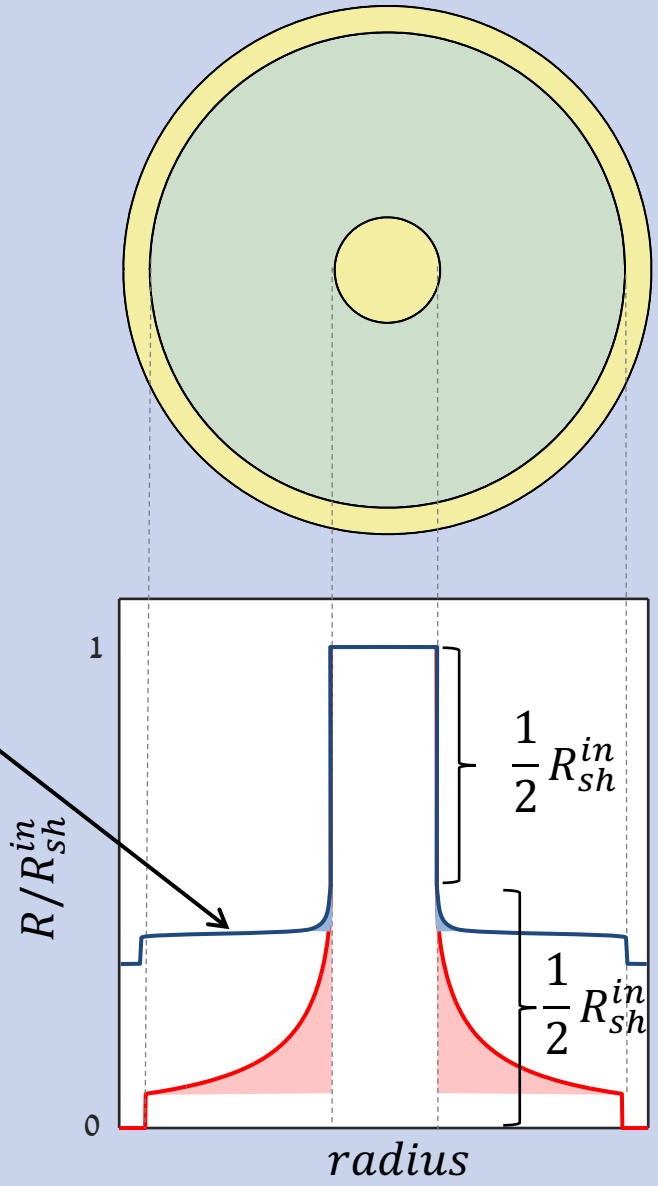
A geometrical/phase-space resistance



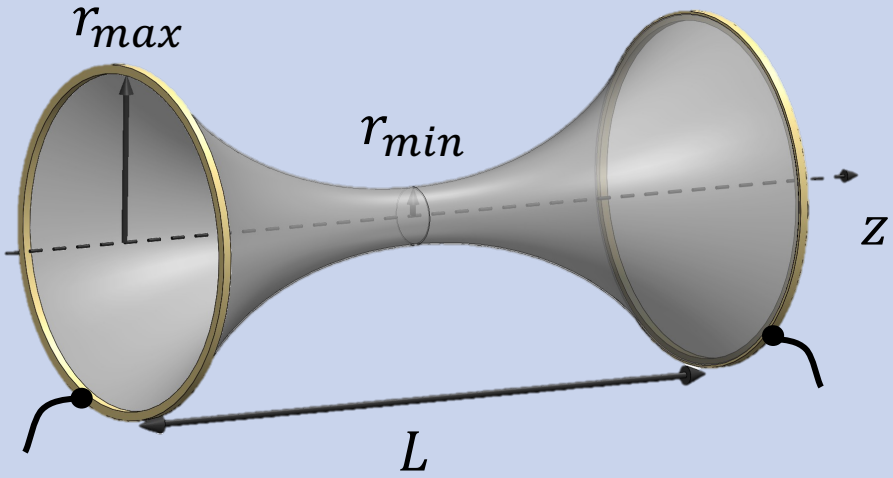
Hydrodynamics – Shavit/Shytov/Falkovich prediction

Hydrodynamically

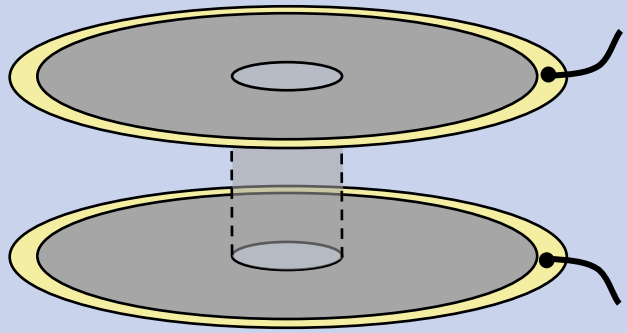
Half of the Landauer-Sharvin resistance is eliminated !!



Can Landuer-Sharvin resistance be eliminated completely?

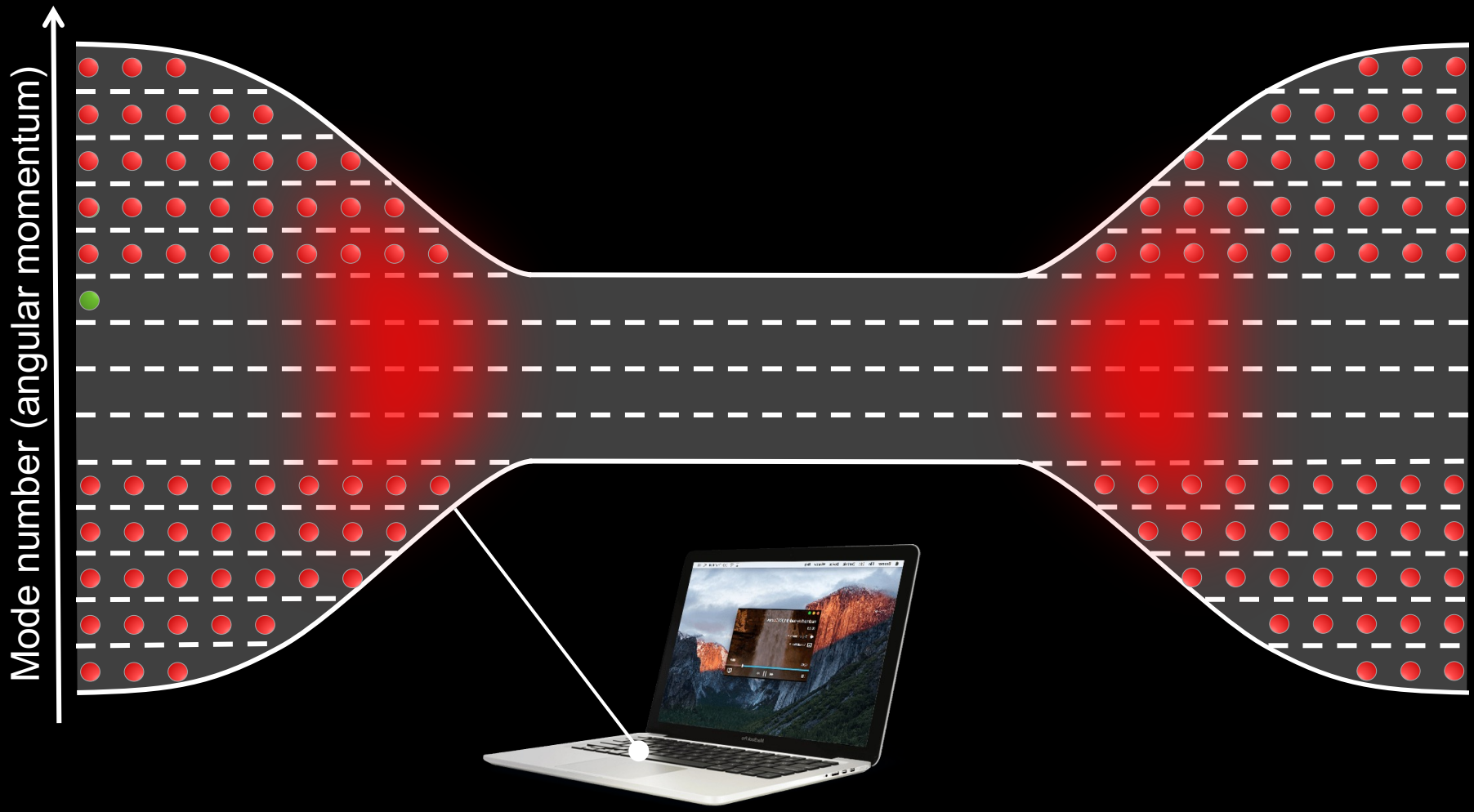


wormhole, $r(z)$



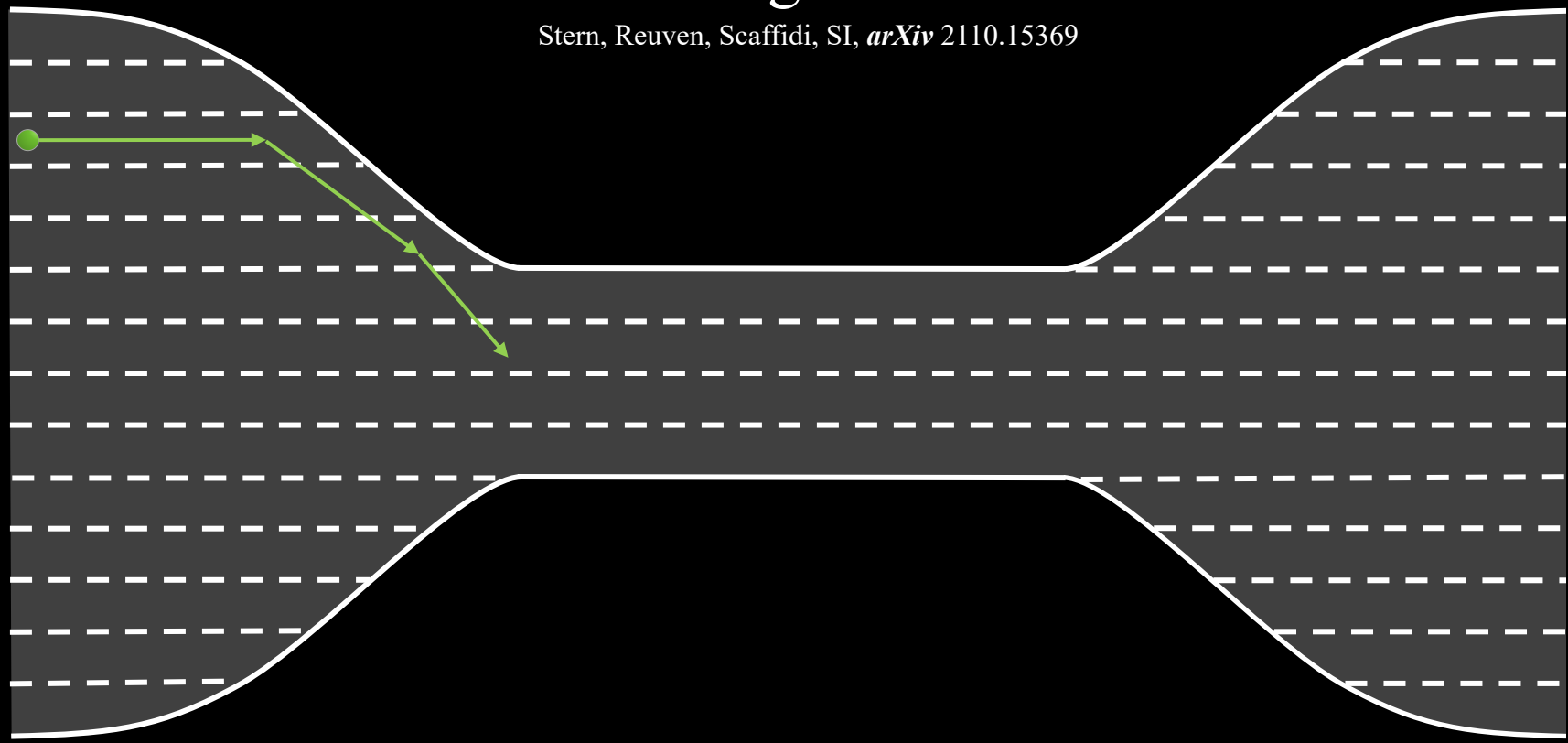
Stern, Reuven, Scaffidi, SI, ***arXiv*** 2110.15369

A quantum mechanical traffic jam



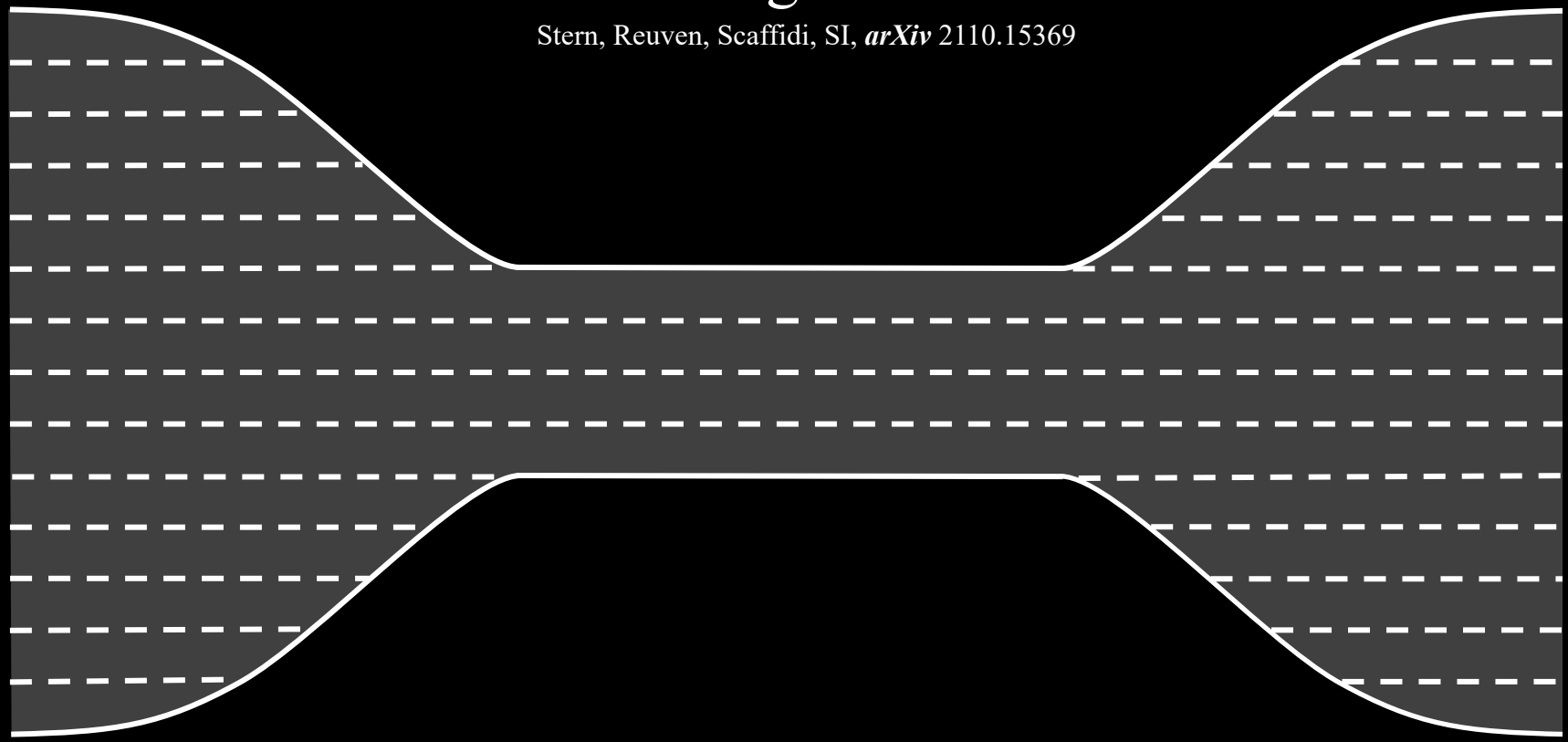
Breaking the limit

Stern, Reuven, Scaffidi, SI, ***arXiv*** 2110.15369



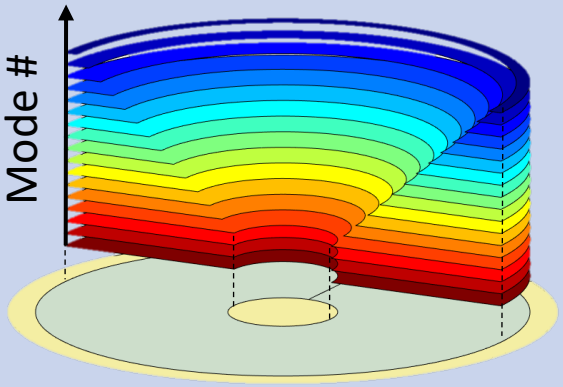
Breaking the limit

Stern, Reuven, Scaffidi, SI, ***arXiv*** 2110.15369



Corbino is an ideal half of the wormhole

Stern, Reuven, Scaffidi, SI, ***arXiv*** 2110.15369

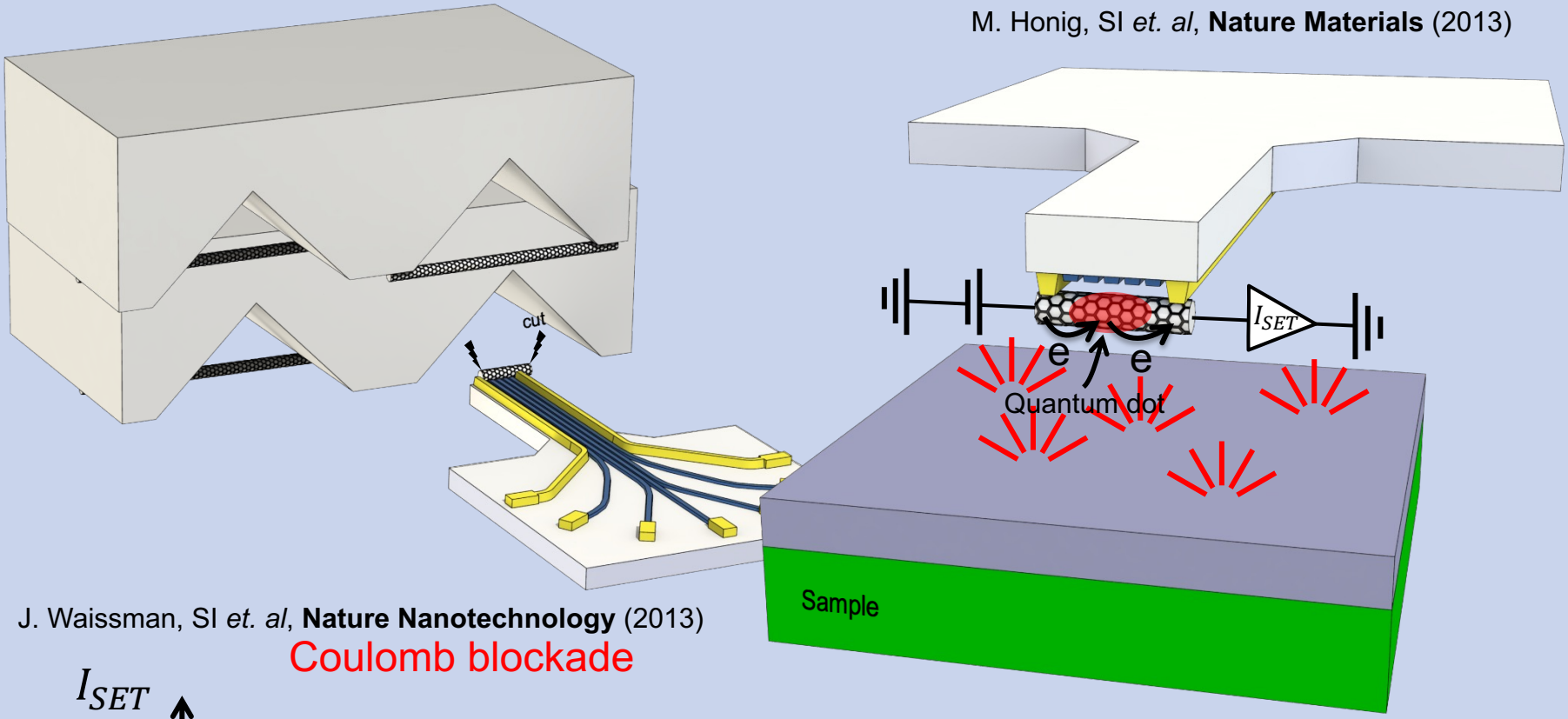


$$R_{ballistic} \sim \mathrm{r(z)}'$$

$$R_{hydro} \sim \mathrm{r(z)}''$$

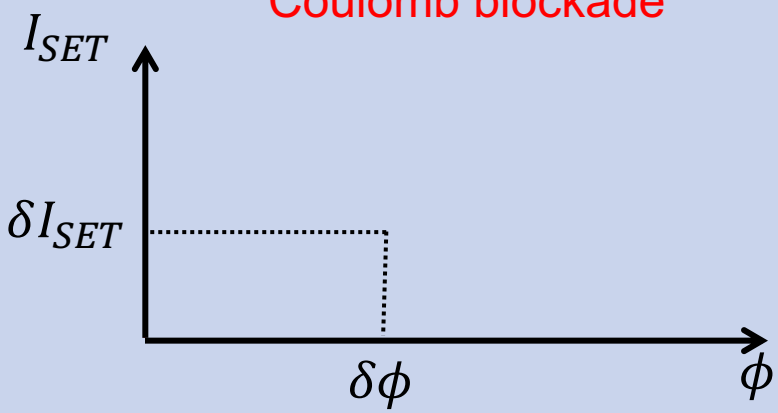
A scanning nanotube single electron transistor (SET)

M. Honig, SI *et. al*, **Nature Materials** (2013)



J. Waissman, SI *et. al*, **Nature Nanotechnology** (2013)

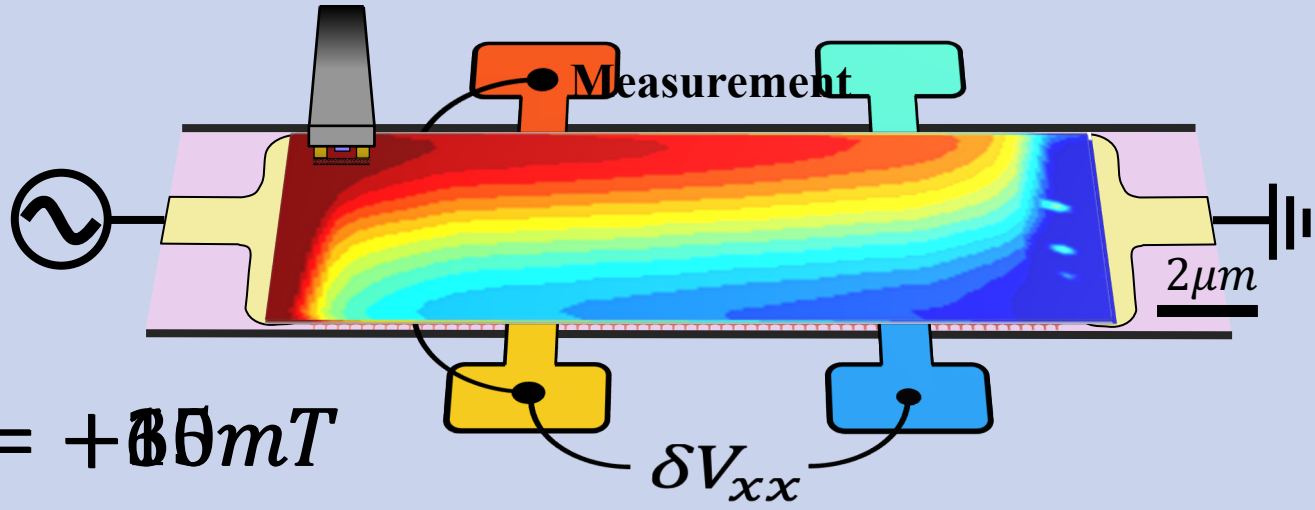
Coulomb blockade

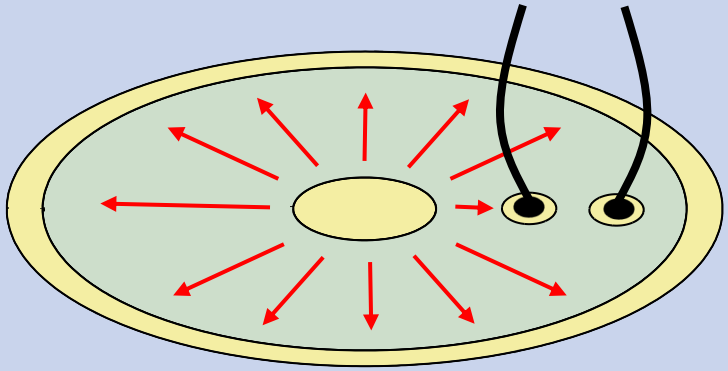


can measure:

$10^{-5} - 10^{-6}\ electron\ charge/\sqrt{Hz}$

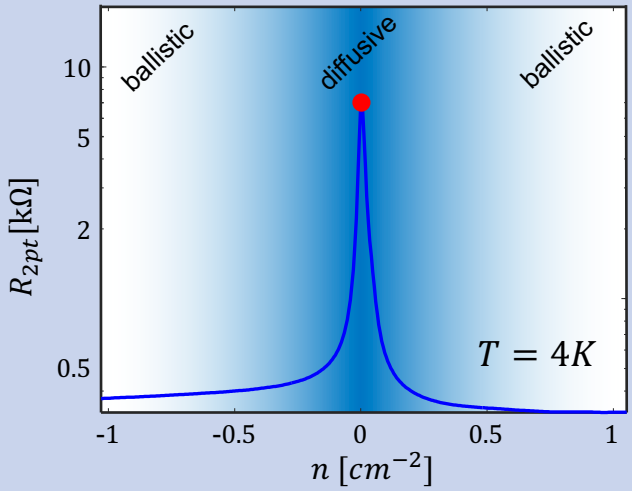
Imaging flowing electrons ("Scanning Transport")



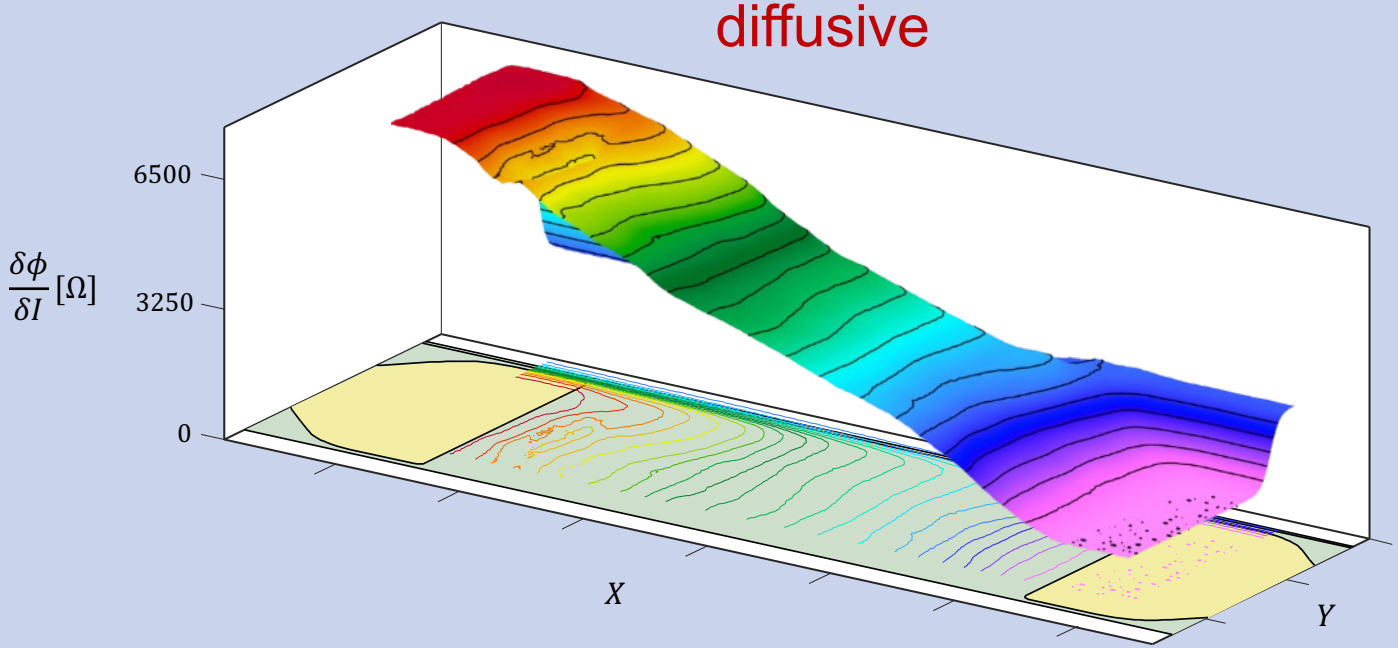


L. Ella, SI *et. al*, **Nature Nanotechnology** (2019)

Where is the resistance?

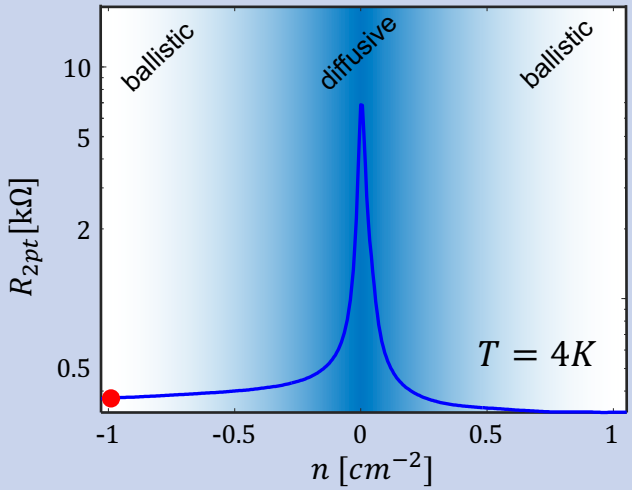


diffusive

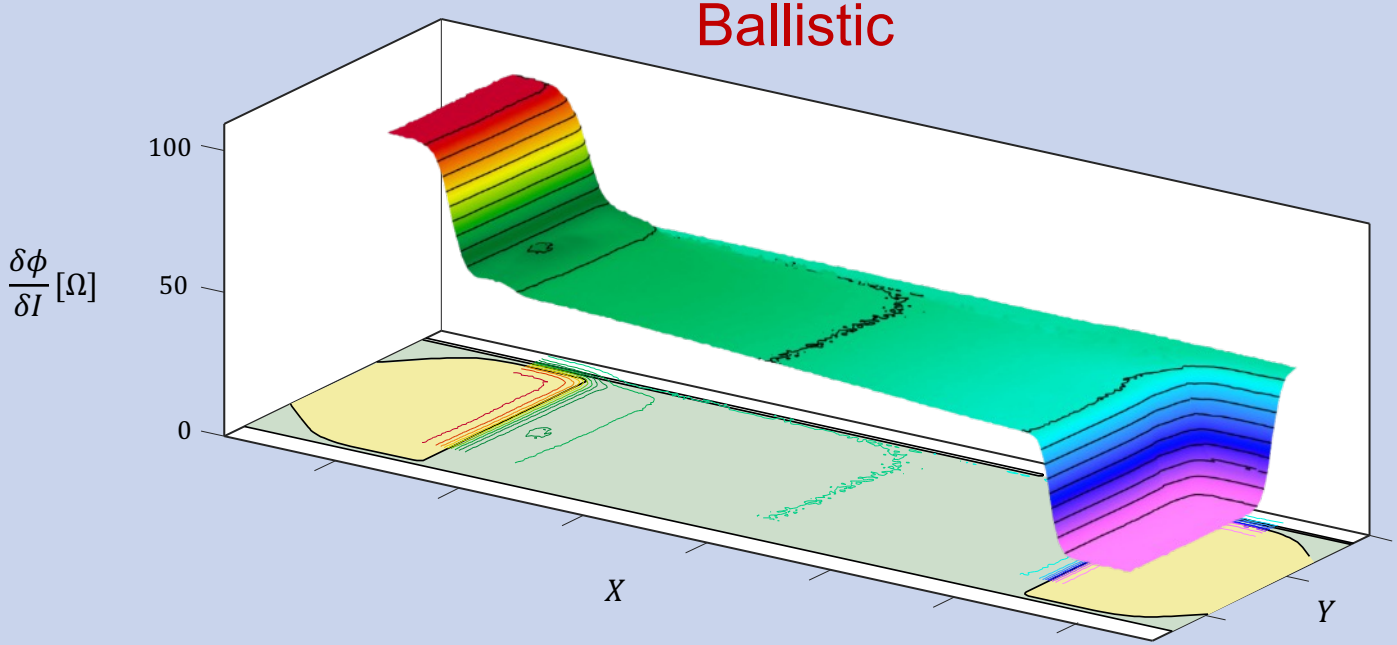


L. Ella, SI *et. al*, **Nature Nanotechnology** (2019)

Where is the resistance?

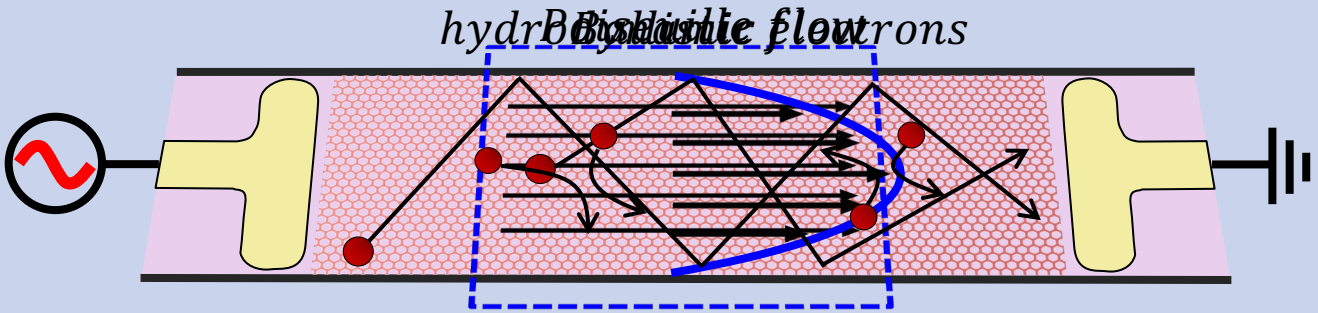


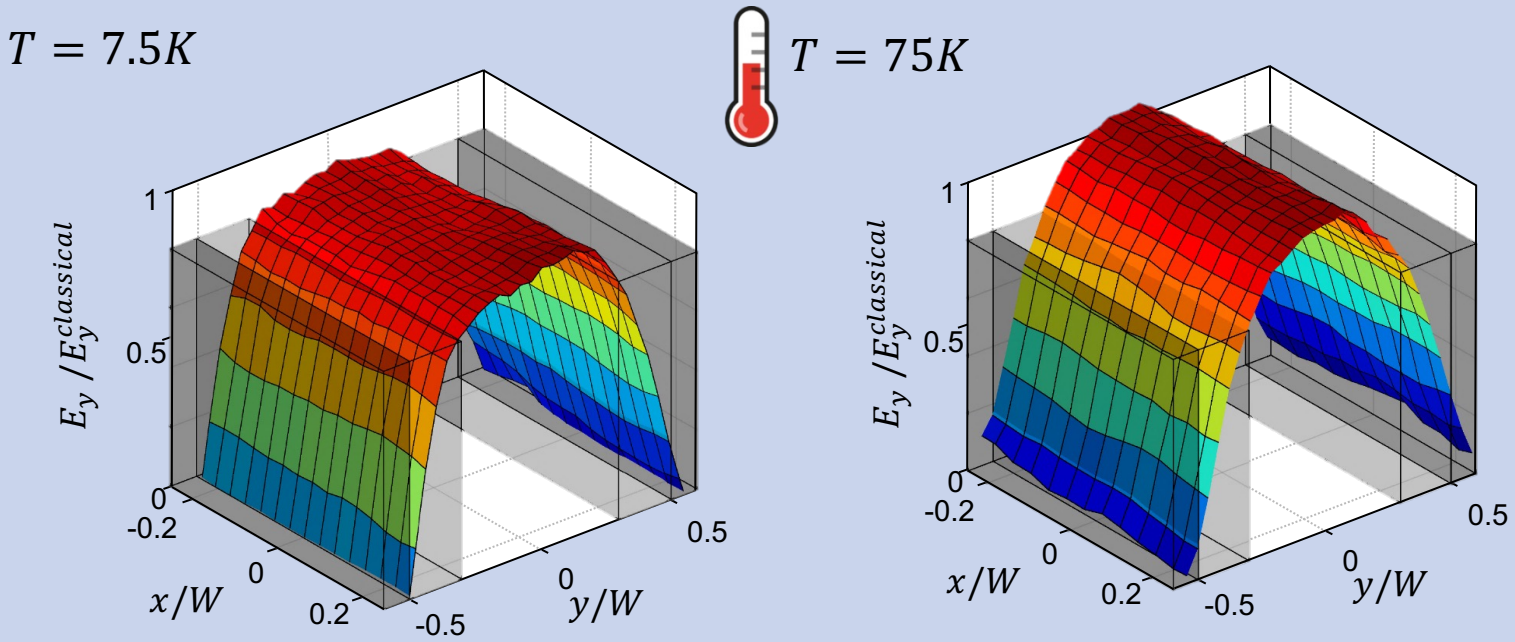
Ballistic



L. Ella, SI *et. al*, **Nature Nanotechnology** (2019)

Imaging hydrodynamic electrons in graphene

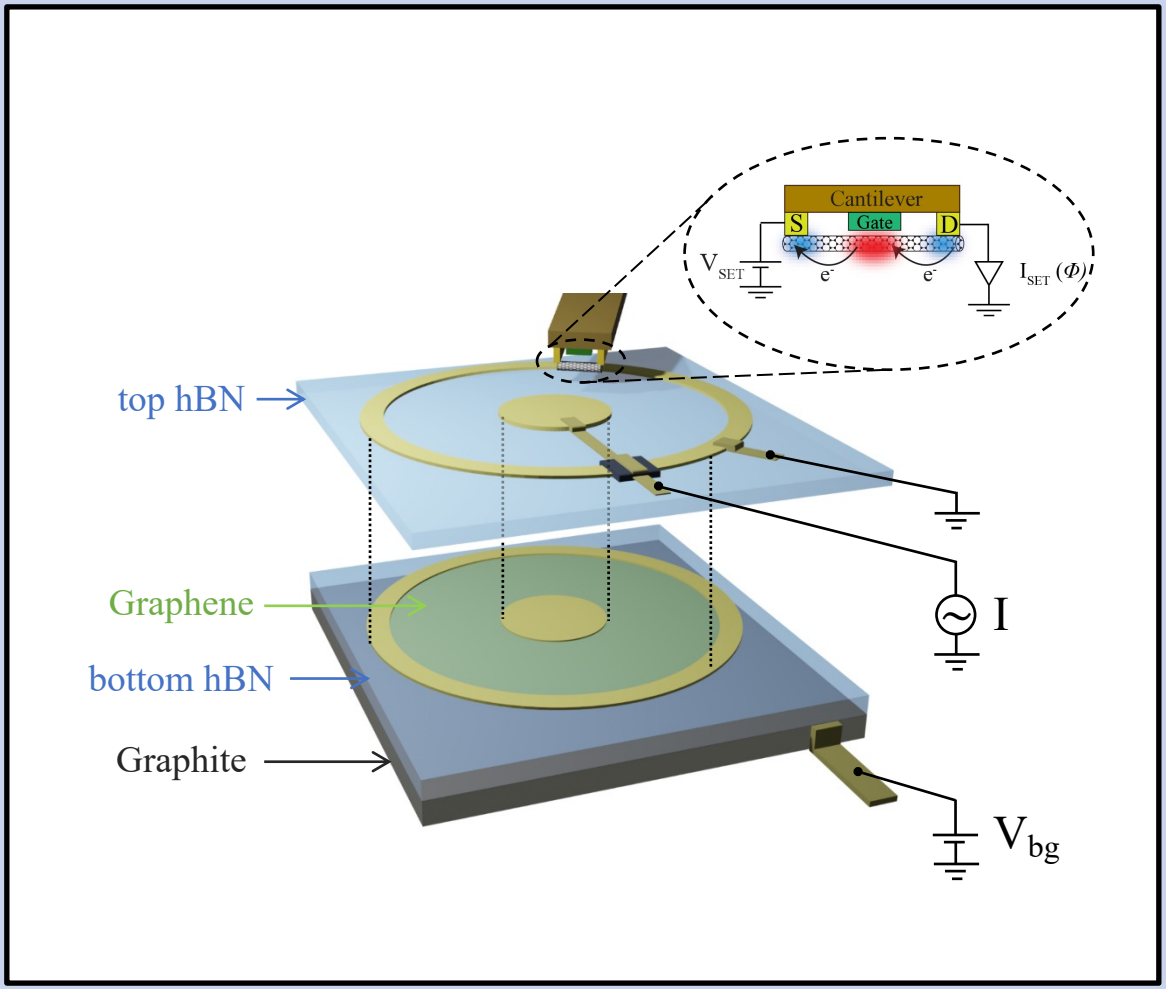




J.A. Sulpizio, SI et. al,L. Ella, A. Rozen, J. Birkbeck, D.J. Perello, D. Dutta, M. Ben-Shalom, T. Taniguchi, K. Watanabe, T. Holder, R. Queiroz, A. Stern, T. Scaffidi, A.K. Geim and SI, **Nature** 576, 75 (2019)

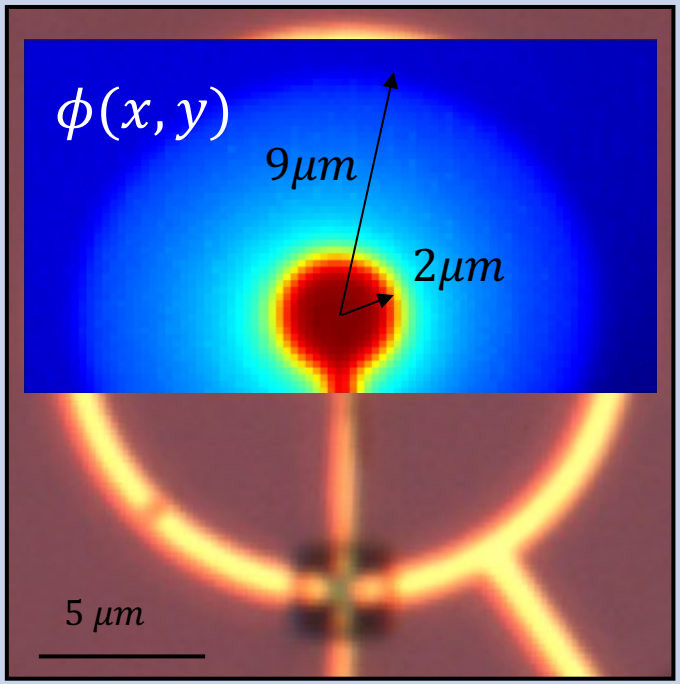
Imaging Poiseuille flow with NV centers: Ku, Yacoby et. al, **Nature** 583, 537 (2020)
See also: Jenkins, Young, Bleszynski Jayich, et. al, **arXiv** 05065 (2020)

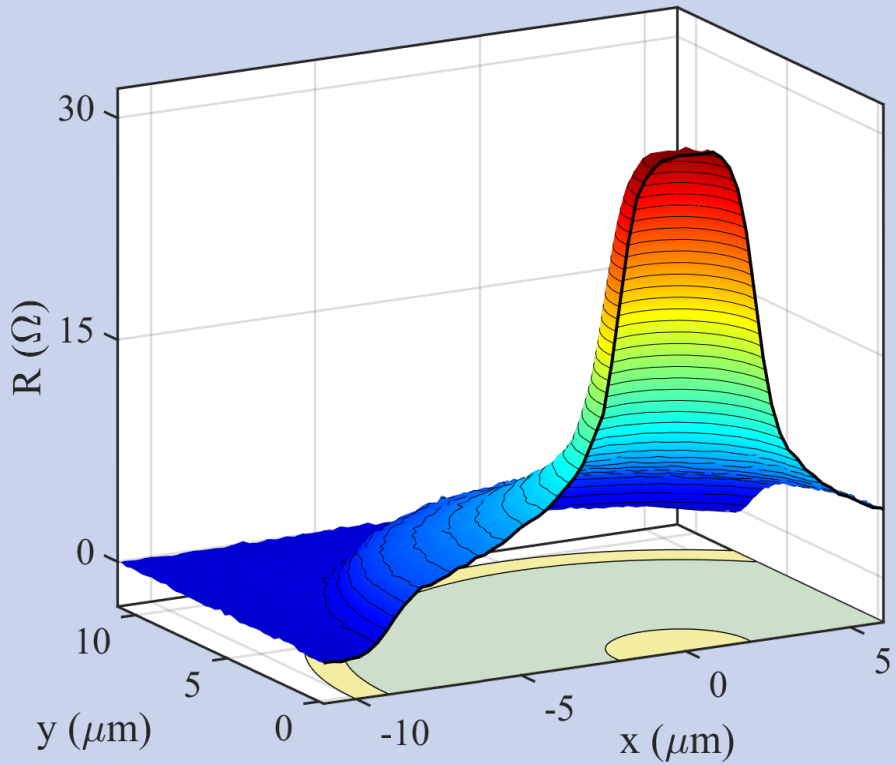
Experimental setup



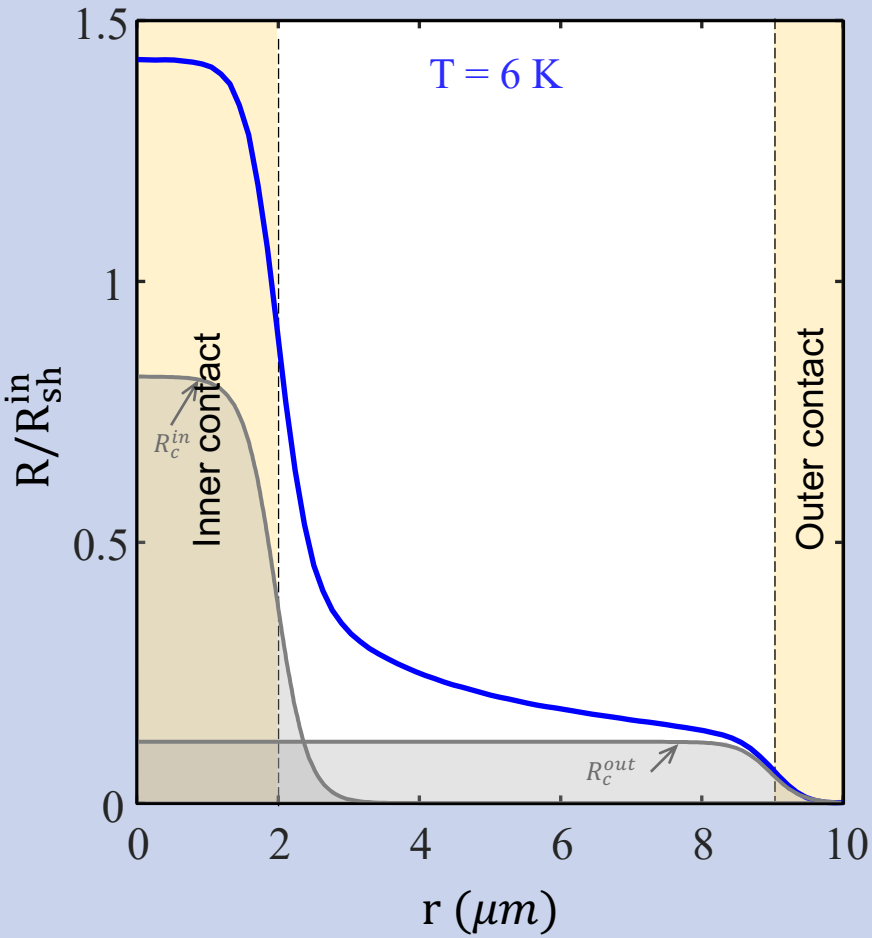
Imaging of Corbino flow

$$R(x,y) = \phi(x,y)/I$$



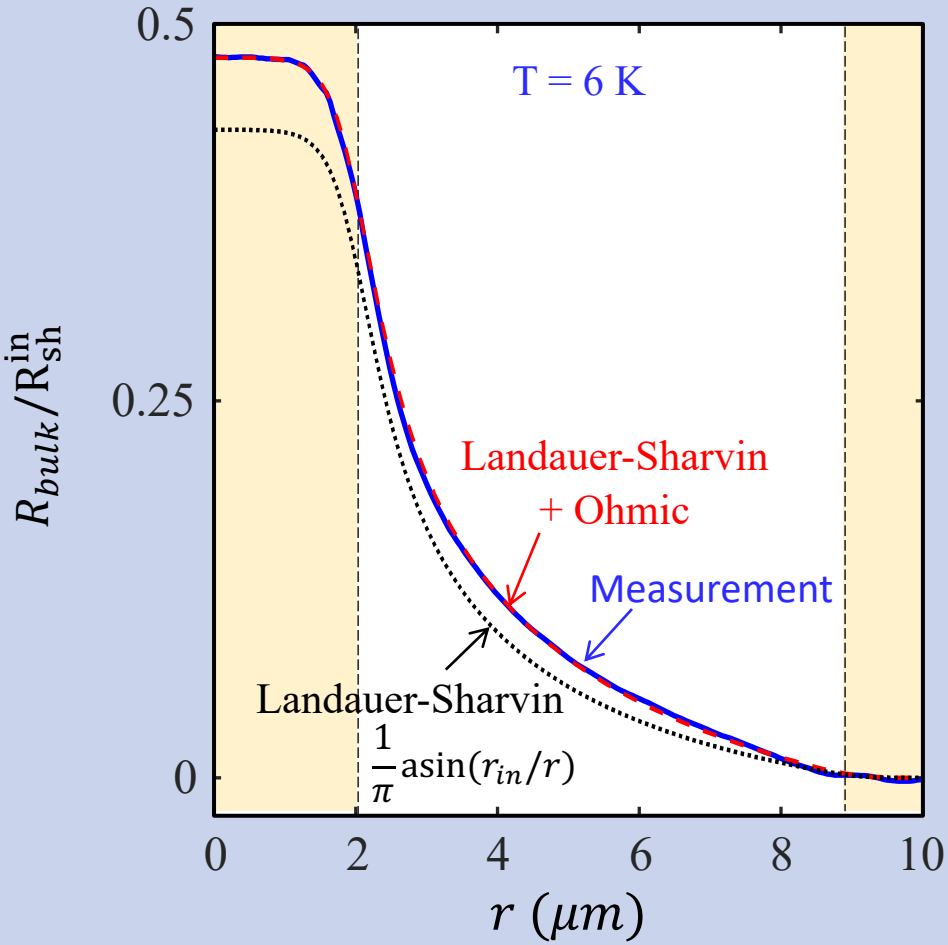


The flow profile



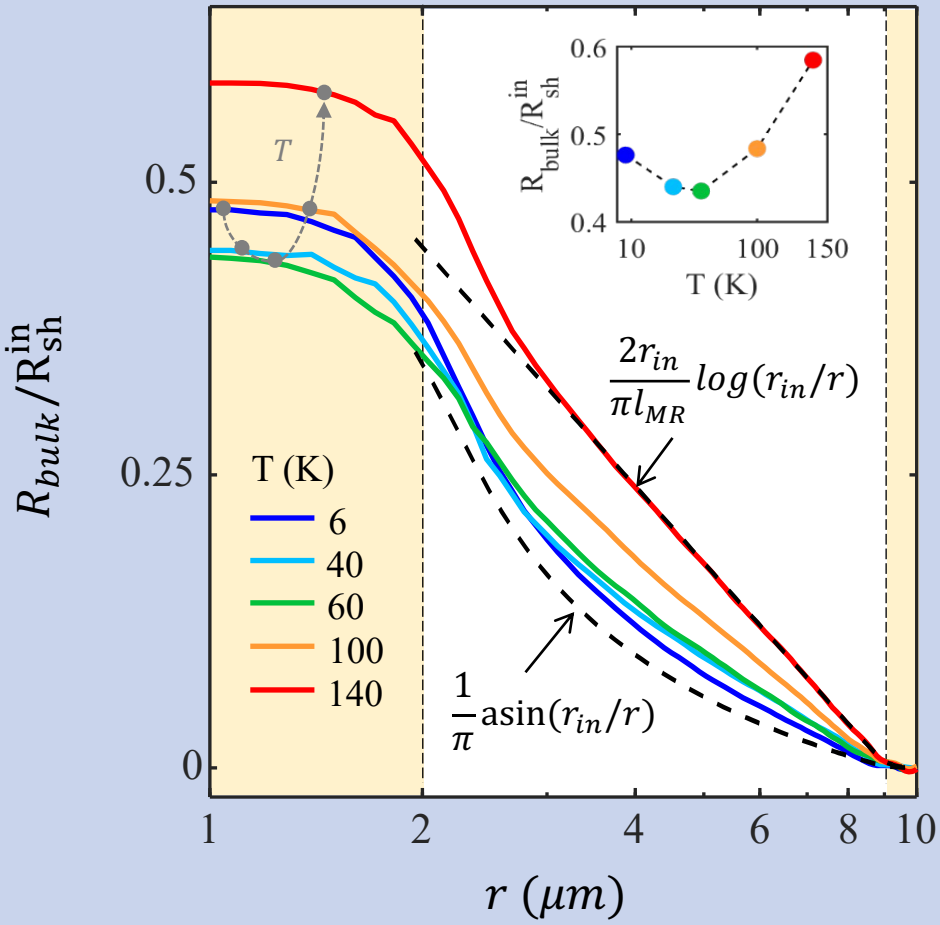
Kumar, Birkbeck, Sulpizio, Perello, Taniguchi, Watanabe, Reuven, Scaffidi, Stern, Geim, SI, ***arXiv*** *2111.06412*

Bulk resistance profile



Kumar, Birkbeck, Sulpizio, Perello, Taniguchi, Watanabe, Reuven, Scaffidi, Stern, Geim, SI, ***arXiv*** *2111.06412*

Temperature dependence



Kumar, Birkbeck, Sulpizio, Perello, Taniguchi, Watanabe, Reuven, Scaffidi, Stern, Geim, SI, ***arXiv*** *2111.06412*

A powerful identity for Corbino geometry

With azimuthal symmetry:

$$\tilde{R}(r)^{L_{MR}=\infty}_{L_{ee}=\left(l_{ee}^{-1}+l_{MR}^{-1}\right)^{-1}} = R(r)^{L_{MR}=l_{MR}}_{L_{ee}=l_{ee}} - \frac{\hbar}{2e^2 k_F l_{MR}}\log(r_{in}/r)$$

Clean-limit hydrodynamic profile

with momentum relaxing scattering

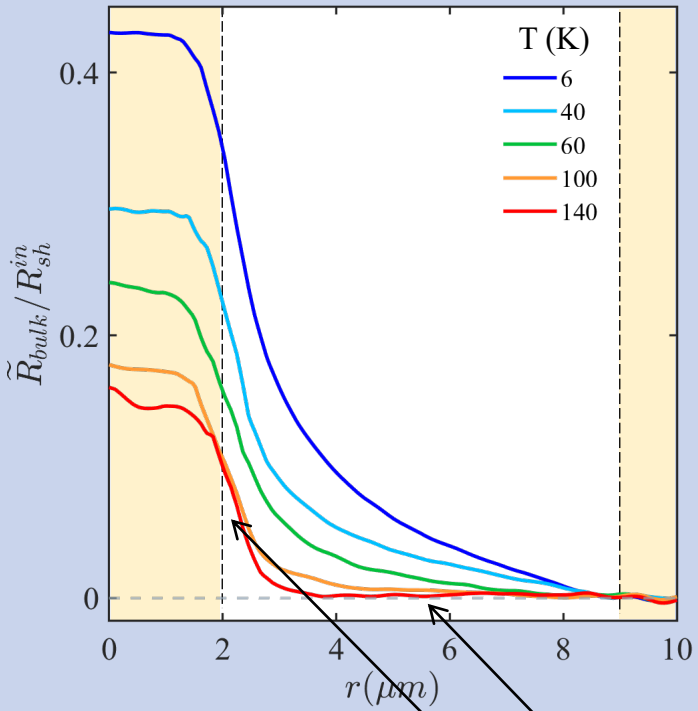
Finite B experiments give l_{MR}

Ohmic term $\tan(\theta_H) = l_{MR}/R_C$

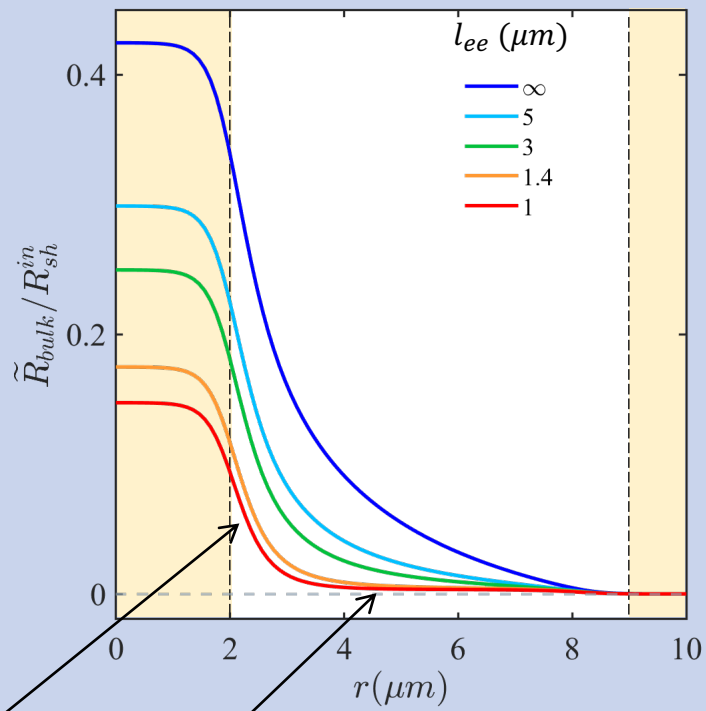
Kumar, Birkbeck, Sulpizio, Perello, Taniguchi, Watanabe, Reuven, Scaffidi, Stern, Geim, SI, ***arXiv*** *2111.06412*

Clean-limit Hydrodynamic profiles

Experiment



Theory

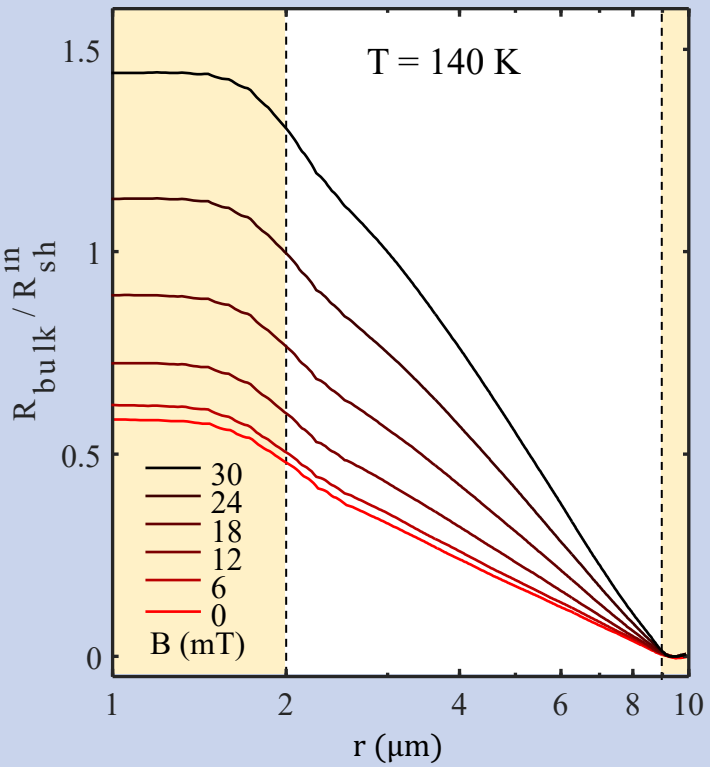


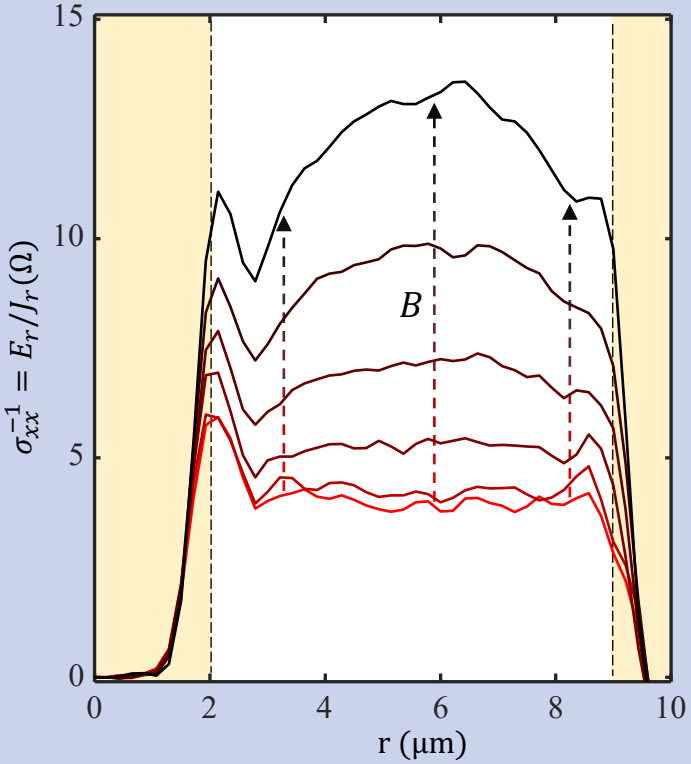
Stokes resistance $\sim \frac{l_{ee}}{r_{in}^2}$

Perfect elimination of Landuaer-Sharvin resistance

Kumar, Birkbeck, Sulpizio, Perello, Taniguchi, Watanabe, Reuven, Scaffidi, Stern, Geim, SI, ***arXiv*** *2111.06412*

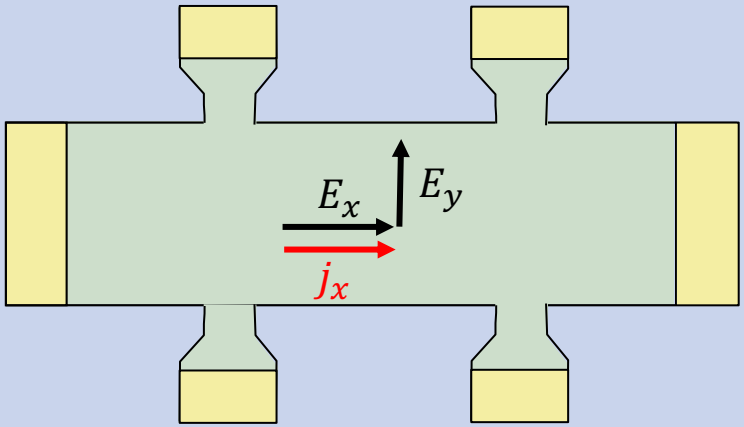
Hydrodynamics in magnetic Field

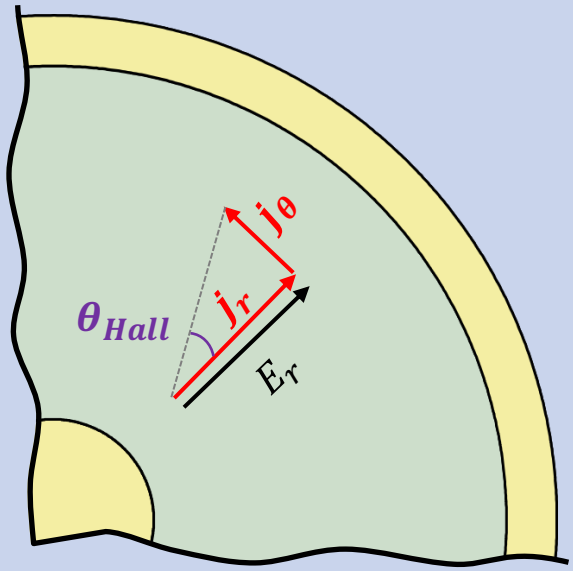




Kumar, Birkbeck, Sulpizio, Perello, Taniguchi, Watanabe, Reuven, Scaffidi, Stern, Geim, SI, ***arXiv*** *2111.06412*

What is measured in a Corbino geometry?





ρ_{xx}

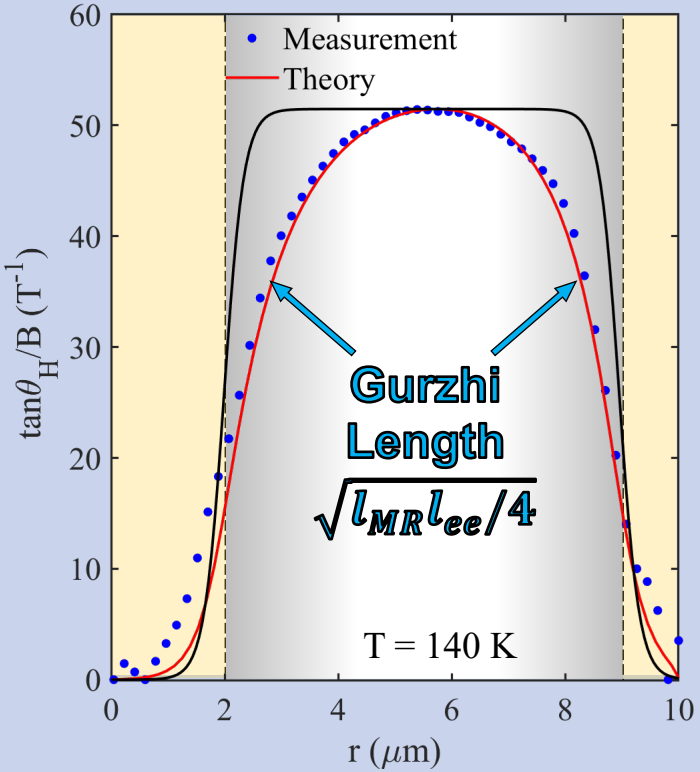
resistivity

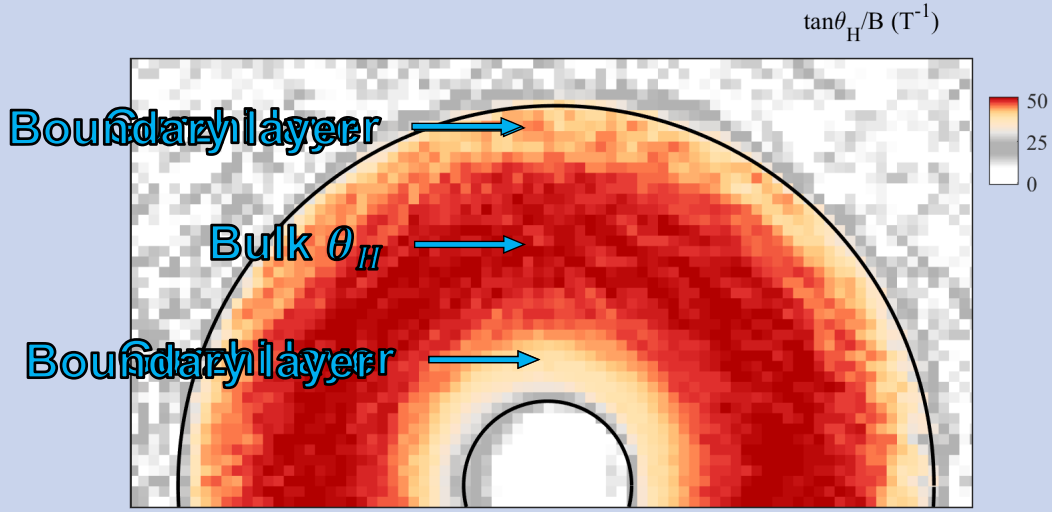
σ_{xx}^{-1}

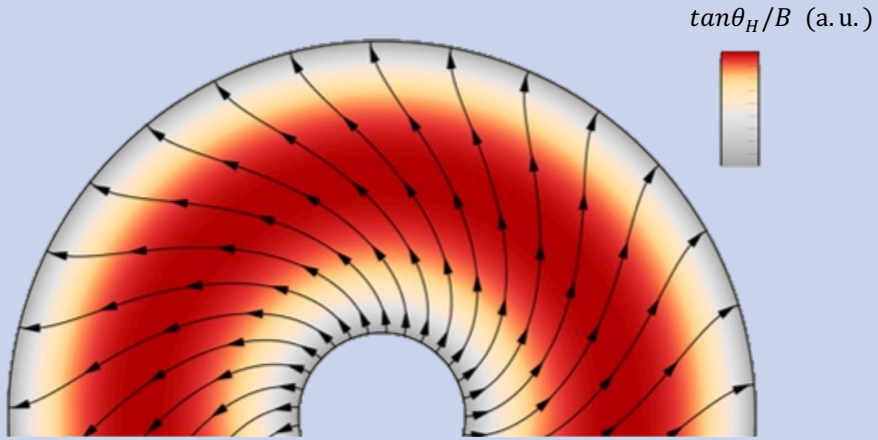
inverse conductivity

$$\sigma_{xx}^{-1} = \frac{\rho_{xx}^2 + \rho_{xy}^2}{\rho_{xx}} = \rho_{xx}(1 + \tan^2(\theta_H))$$

Flow in magnetic Field





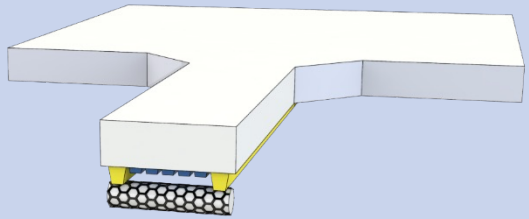


Kumar, Birkbeck, Sulpizio, Perello, Taniguchi, Watanabe, Reuven, Scaffidi, Stern, Geim, SI, ***arXiv*** *2111.06412*

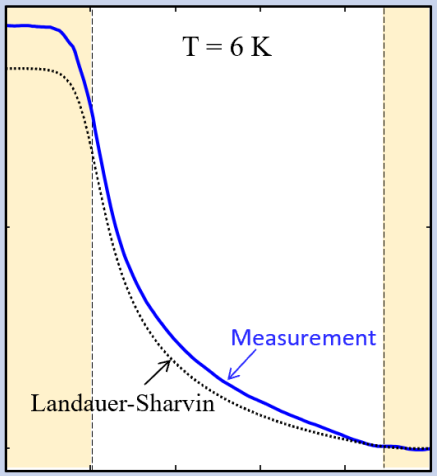
Shvait, A. Shytov and G. Falkovich, **PRL** (2019) A. Levchenko, J. Schmallian, **Annal of Physics** (2020)

Summary

Geometrical Landau-Sharvin bulk resistance

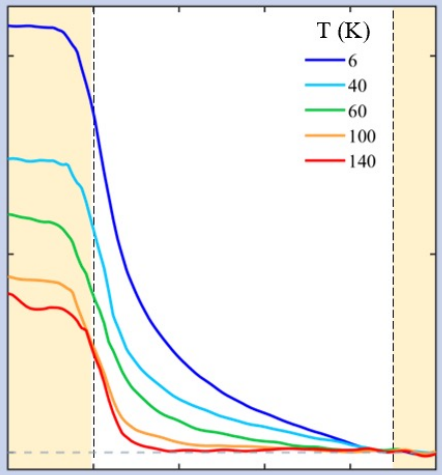


Ballistic



Observation of LS bulk resistance

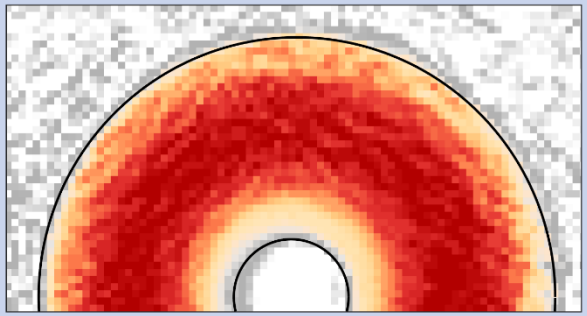
Hydrodynamic



Stokes resistance

Perfect elimination of LS resistance in the bulk

Magneto-hydrodynamic



Magnetic ‘viscometer’

Observation of the emergent Gurzhi length