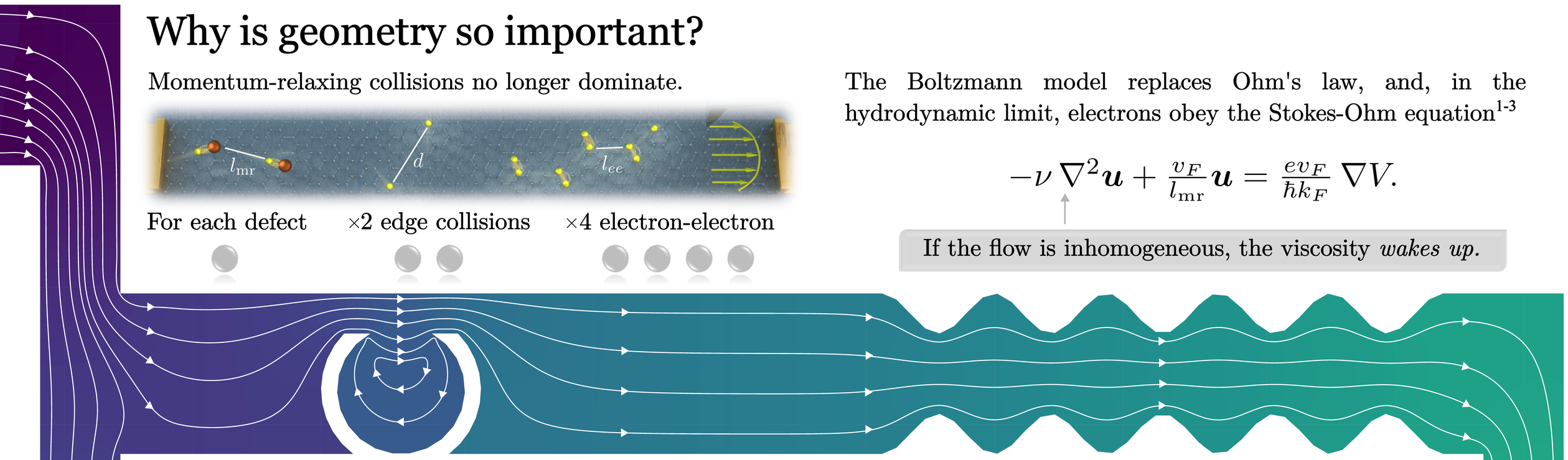
Electron hydrodynamics in graphene devices

J. Estrada-Álvarez. Supervisors: E. Díaz, F. Domínguez-Adame. GISC Departamento de Física de Materiales UCM

Electronic transport in graphene defies Ohm's law and gives rise to hydrodynamic signatures: electronic whirlpools, tunable differential resistance for terahertz applications, and superballistic conduction, which reduces device dissipation. The hydrodynamic signatures highlight the relevance of the device's geometry.

2025 PhDay Físicas



Why is geometry so important?

Momentum-relaxing collisions no longer dominate.

For each defect ×2 edge collisions ×4 electron-electron

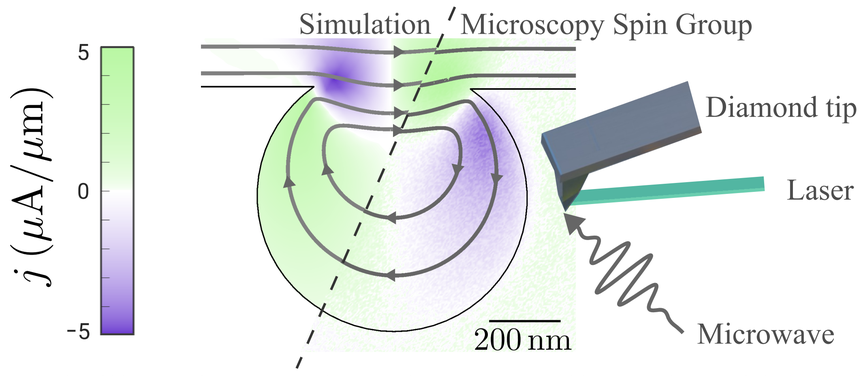
The Boltzmann model replaces Ohm's law, and, in the hydrodynamic limit, electrons obey the Stokes-Ohm equation[1-3]

$$-\nu\,\nabla^2\boldsymbol{u} + \frac{v_F}{l_{\mathrm{mr}}}\boldsymbol{u} = \frac{e v_F}{\hbar k_F}\,\nabla V.$$

If the flow is inhomogeneous, the viscosity *wakes up.*

Electronic whirlpools

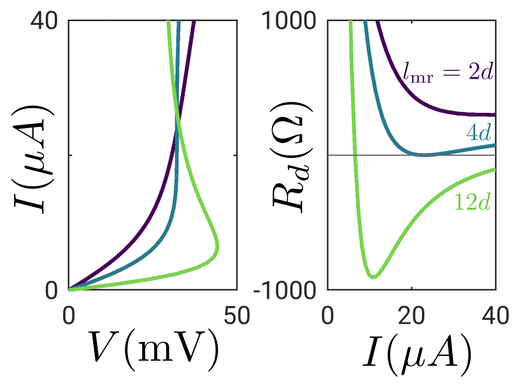
Whirlpools are a signature of non-ohmic transport. Quantum sensing with nitrogen-vacancy microscopy provides direct images.

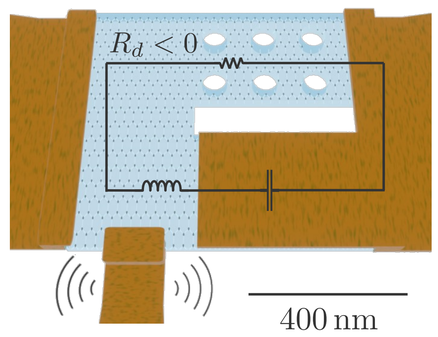


In materials like $PdCoO_2$, the anisotropy affects the whirlpool[4].

Terahertz technology

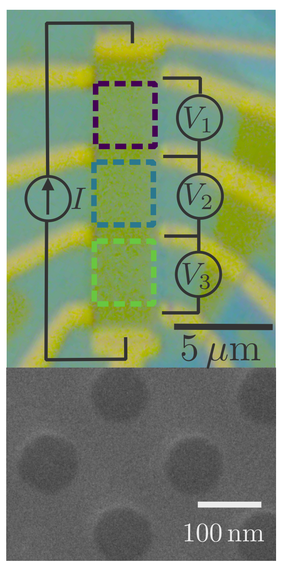
The electron viscosity decreases with current. The negative differential resistance enables amplifiers and oscillators[5].

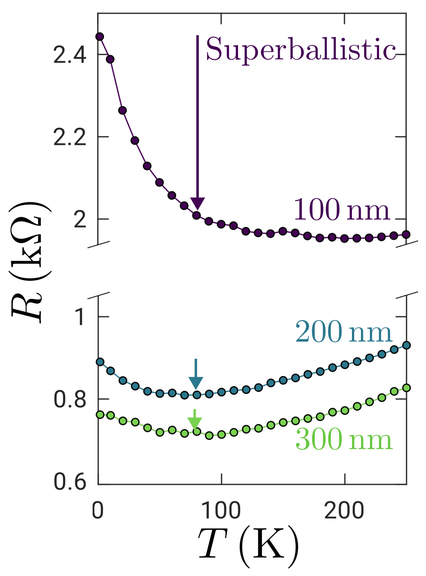


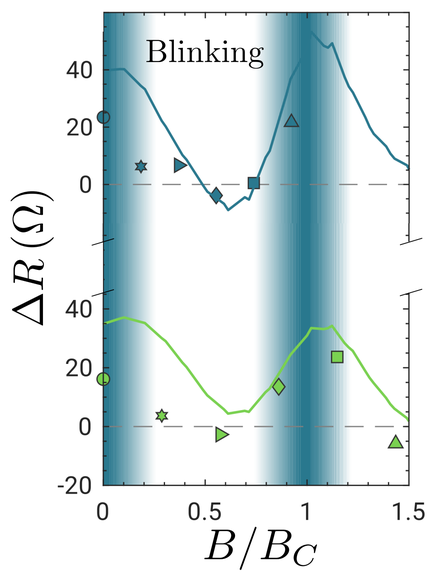


Superballistic conduction

An antidot superlattice bends the electron flow and boosts hydrodynamics[6].

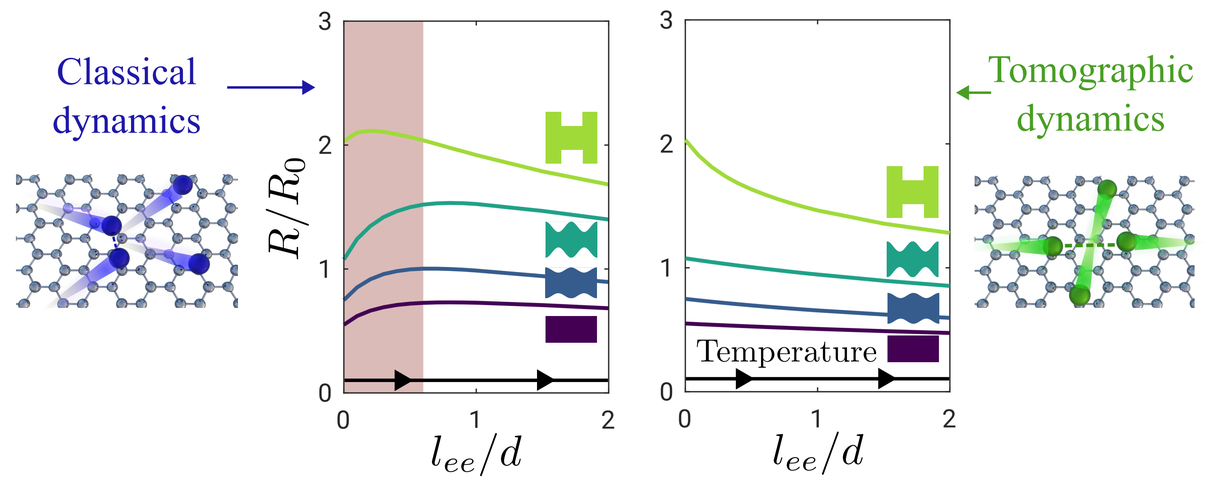






Reduced dissipation

Optimizing the device's geometry, together with electron-electron collisions, reduces resistance[7]. Tomographic dynamics for the electron collisions solve the *superballistic paradox* and further reduce the resistance[8].



The geometry determines the electrical properties. The antidot lattice enhances hydrodynamics.

Phenomena without an analog in conventional fluids: magnetic fields, anisotropy, and tomographic dynamics.

Hydrodynamics enables terahertz technology and optimized devices with reduced energy dissipation.

We acknowledge J. Salvador-Sánchez, A. Pérez, M. Amado, E. Diez; C. Ding, C. Degen for NV imaging; R. Brito and F. Bermúdez-Mendoza for discussions. Funded by the "(MAD2D-CM)-UCM" by Comunidad de Madrid, the Recovery, Transformation, and Resilience Plan, and by NextGenerationEU from the EU and AEI (PID2022-136285NB-C31), and M. Ciencia, Innovación y Universidades (Grant FPU22/01039).

ESCUELA DE DOCTORADO UNIVERSIDAD COMPLUTENSE DE MADRID

FACULTAD DE CIENCIAS FÍSICAS

Comunidad de Madrid

Plan de Recuperación, Transformación y Resiliencia

Financiado por la Unión Europea NextGenerationEU

1 J. Estrada-Álvarez *et al.* Comm. Phys. **7**, 138 (2024).
2 J. Estrada-Álvarez *et al.* Rev. Esp. Fís. **38**, 12 (2024).
3 J. Estrada-Álvarez *et al.* Sci. Rep. [accepted for publication].
4 J. Estrada-Álvarez *et al.* Phys. Rev. Res. **7**, 013087 (2025).
5 J. Estrada-Álvarez *et al.* 2D Mater. **12**, 015012 (2024).
6 J. Estrada-Álvarez *et al.* Phys. Rev. X **15**, 011039 (2025).
7 J. Estrada-Álvarez *et al.* Phys. Rev. B **111**, 075401 (2025).
8 J. Estrada-Álvarez *et al.* Phys. Rev. Lett. [accepted for publication].