Nonlocal electrodynamics in anisotropic metals

Skin effect in $PdCoO_2$

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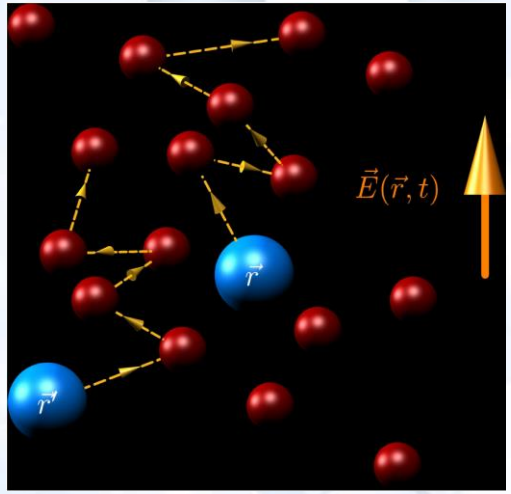
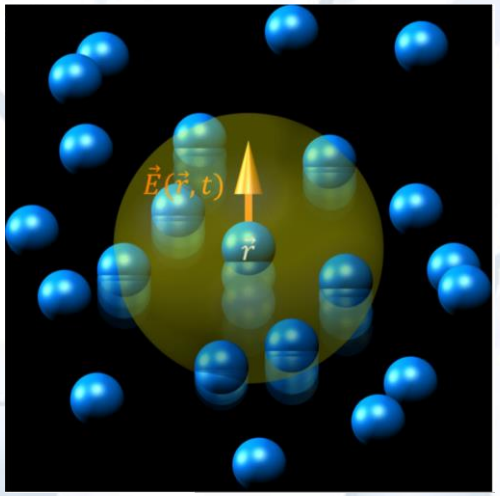
Non-diffusive electron flow: non-local response

Diffusive transport: local response



Momentum-relaxing scattering rate γ_{mr}

Non-diffusive transport: non-local response



Momentum-conserving scattering rate γ_{mc}

Inhomogeneous, retarded current in translationally invariant systems:

$$J_\alpha(\vec{r},t) = \sum_\beta \sigma_{\alpha\beta}(\vec{r}-\vec{r}',t-t')\,E_\beta(\vec{r},t)$$

Momentum dependence:

$$J_\alpha(\vec{q},\omega) = \sum_\beta \sigma_{\alpha\beta}(\vec{q},\omega)\,E_\beta(\vec{q},\omega)$$

Electron hydrodynamics[*]

$\gamma_{\mathrm{mc}} \gg \{\gamma_{\mathrm{mr}}, \omega, v_F/L\}$

Ballistic conduction

$\{\omega, v_F/L\} \gg \{\gamma_{\mathrm{mr}}, \gamma_{\mathrm{mc}}\}$

[*] See, e.g., S. Conti and G. Vignale, Phys. Rev. B **60**, 7966 (1999); G. Giuliani and G. Vignale, *Quantum Theory of the Electron Liquid*, Cambridge University Press (Cambridge, 2005); A. Lucas and K. C. Fong, J. Phys. Condens. Matter **30**, 053001 (2018); B. N. Narozhny et al., Ann. Phys.-Berlin **529**, 1700043 (2017); B. N. Narozhny, Ann. Phys.-New York **411**, 167979 (2019); I. Tokatly and O. Pankratov, Phys. Rev. B **60**, 15550 (1999); J. M. Link et al., Phys. Rev. B **93**, 235447 (2016); **98**, 195103 (2018); C. Q. Cook and A. Lucas, Phys. Rev. B **99**, 235148 (2019); D. Forcella et al., Phys. Rev. B **90**, 456 (2014)…

Viscosity of electron fluids

- Mainly observed in the **DC limit**

Materials:

- Galilean-invariant
  - Fermi liquids (liquid Helium)[1-3]
- Without Galilean invariance:
  - GaAs heterostructures[3,4]
  - Graphene[5-8,14,16,17]
  - Delafossites[9,10]
  - Semimetals[11-13,15]
  - Doped metal oxides[18]
  - Engineered nanoapertures[19]

Experiments:

- Electrical transport[3-7,11-13] and imaging[8,14]
- Thermal transport[6,11-13]
- Magnetotransport[9-11,14]
- Quantum magnetometry[15,17]
- Time-domain spectroscopy[16]
- Plasmonic resonances[18,19]

[1] W. R. Abel et al., Phys. Rev. Lett. **17**, 74 (1966)
[2] P. R. Roach and J. B. Ketterson, Phys. Rev. Lett. **36**, 737 (1976)
[3] Y. Huang et al., Cryogenics **52**, 538 (2012)
[3] L. W. Molenkamp and M. J. M. de Jong, Phys. Rev. B **49**, 5038 (1994)
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[5] D. A. Bandurin et al., Science **351** 1055 (2016)
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[9] P. J. C. Moll et al., Science **351**, 1061 (2016)
[10] N. Nandi et al., npj Quantum Mater. **3**, 66 (2018)
[11] J. Gooth et al., Nat. Comm. **9**, 1 (2018)
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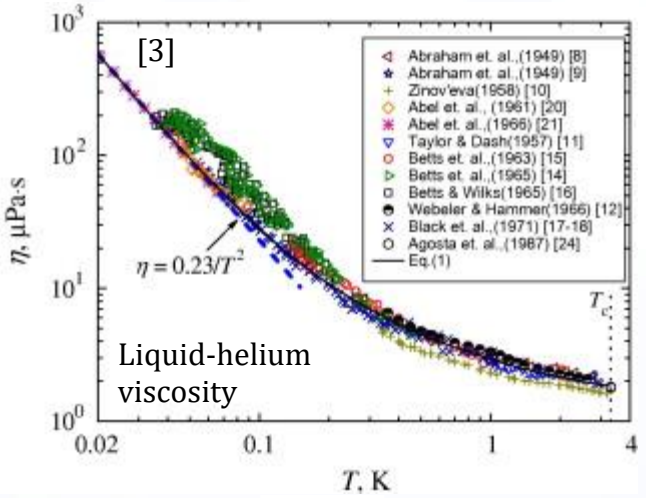
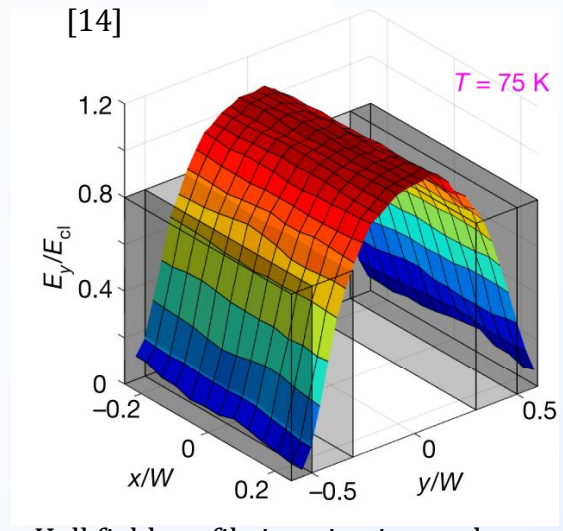
[13] A. Jaoui et al., Nat. Comm. **12**, 195 (2021)
[14] J. A. Sulpizio et al., Nature **576**, 75 (2019)
[15] U. Vool et al., arXiv:2009.04477
[16] P. Gallagher et al., Science **364**, 158 (2019)
[17] M. J. Ku et al., Nature **583**, 537 (2020)
[18] D. De Ceglia et al., Sci. Rep. 8, 1 (2018)
[19] D. Yoo et al., Nat. Comm. **10**, 1 (2019)



Liquid-helium viscosity

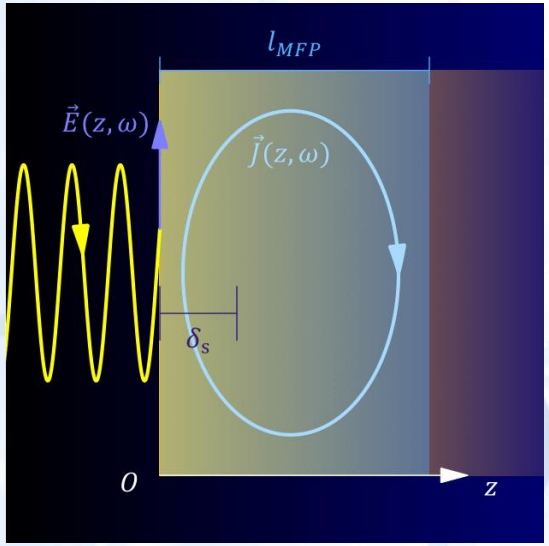


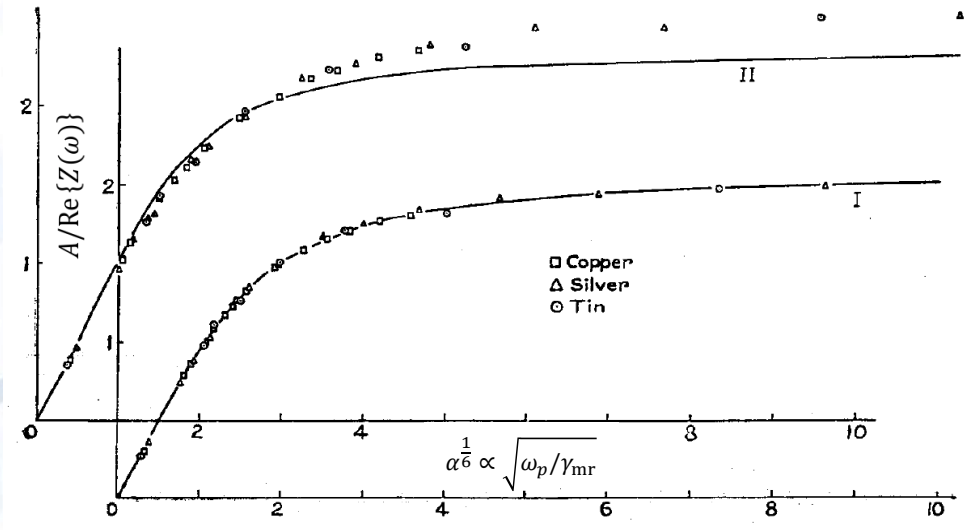
Hall field profile imaging in graphene

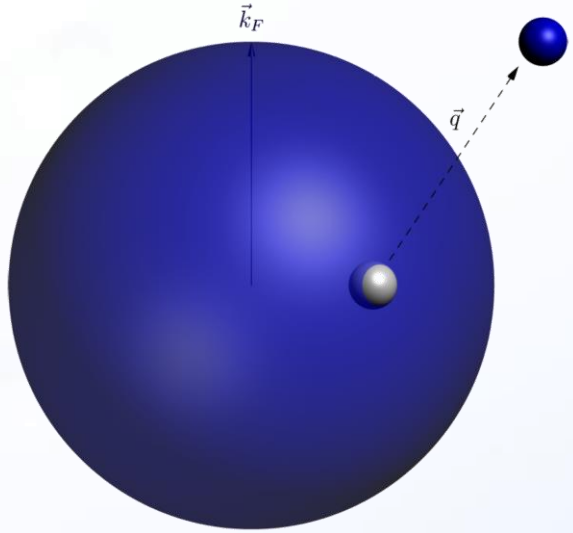
Ballistic conduction: anomalous skin effect

- Observed saturation of surface resistance $R(\omega) = \mathrm{Re}\{Z(\omega)\}$ for $l_{MFP} = v_F/\gamma_{mr} \gg \delta_s$: ballistic response[1]
- Momentum-conserving scattering (γ_{mc}) should impact results: hydrodynamic skin effect[2]
- **Fermi-surface isotropy is often assumed**[1]

$$Z(\omega) = \frac{E(z,\omega)|_{z=0^+}}{\int_0^{+\infty} dz\, J(z,\omega)}$$







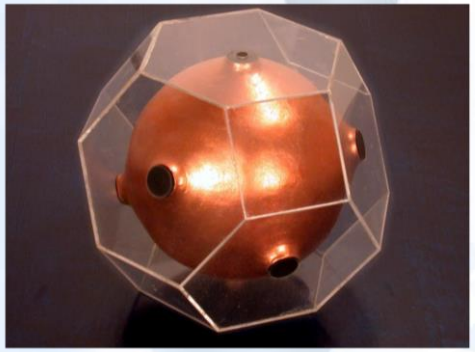
[1] A. B. Pippard, Proc. Roy. Soc. A **191**, 385-415 (1947); G. E. H. Reuter and E. H. Sondheimer, Proc. Roy. Soc. A **195**, 336 (1948); E. H. Sondheimer, Adv. Phys. **50**, 499 (2001)

[2] A. Levchenko and J. Schmalian, Ann. Phys. **419**, 168218 (2020);); D. Forcella et al., Phys. Rev. B **90**, 456 (2014); D. V., Phys. Rev. Research **3**, 023076 (2021); D. V. et al., Sci. Rep. **11**, 1 (2021); P. Matus et al., Proc. Natl. Acad. Sci. U.S.A **119**, e2200367119 (2022)

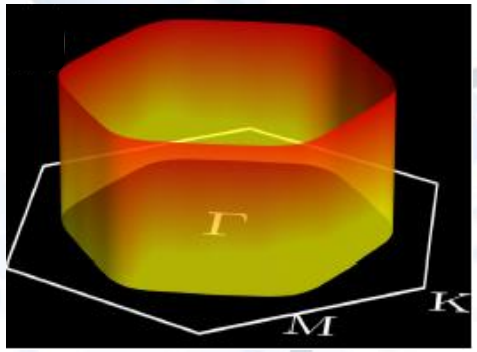
Kinetic theory for arbitrary Fermi surface

Anisotropic Fermi surfaces in high-purity metals

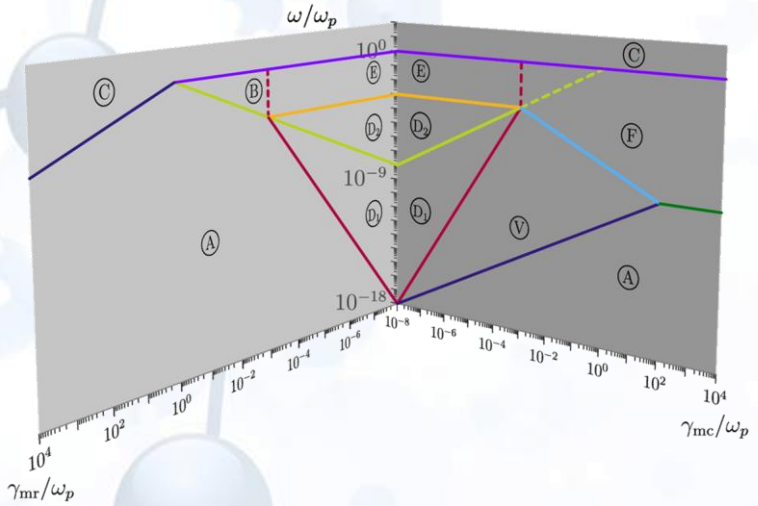
Copper[1]



$PdCoO_2$[2]



Many crossovers between diffusive, ballistic, hydrodynamic regimes as functions of γ_{mr}, γ_{mc}, ω[2]



Regimes:

Diffusive: A B

Ballistic: D_1 D_2 E

Viscous: V

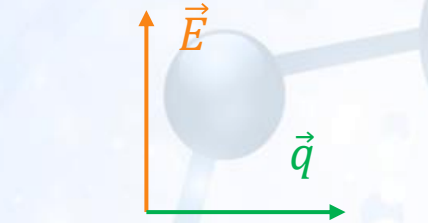
Transparent: C

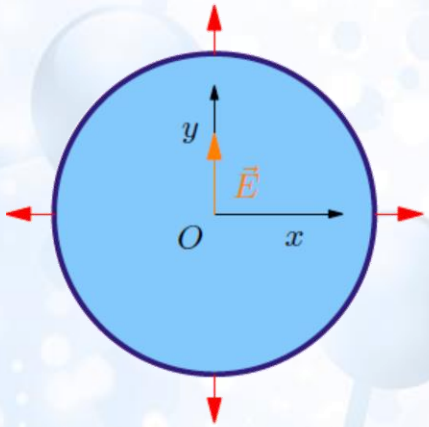
[1] Cavendish Laboratory, P2049 (Cambridge, UK)
[2] D. V. et al., arXiv:2204.13344 (2022)

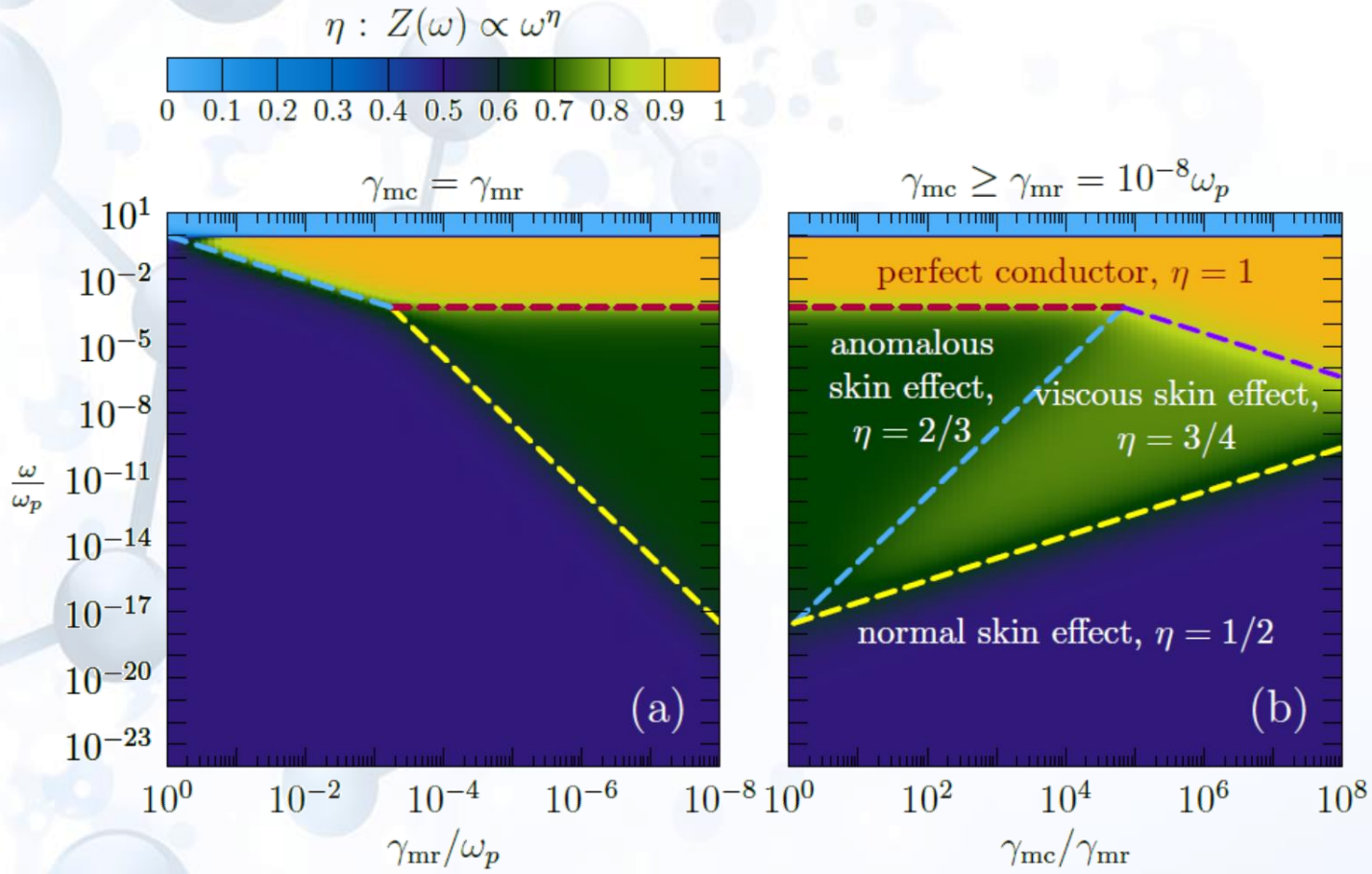
- Boltzmann equation with driving field $\vec{E}(\vec{q},\omega)$ and collision operator: $\hat{C}\chi_{\vec{k},m} = \gamma_m \chi_{\vec{k},m}$
  1. Charge conservation: $\chi_{\vec{k},0} = c_0 : \gamma_0 = 0$
  2. Momentum relaxation in spatial direction i: $\chi_{\vec{k},i} = c_0 c_i \vec{v}_{\vec{k},i}/v_{\vec{k},i} : \gamma_i = \gamma_{mr}$
  3. Momentum-conserving modes: $\chi_{\vec{k},j} : \gamma_j = \gamma_{mc}, j \neq \{0, i\}$
  4. Mirror planes in $\vec{k}$ space (e.g., polygonal or regular solid Fermi-surface shapes)

- Conductivity $\sigma_{ij}(\vec{q},\omega)$
- Skin depth $\delta_s(\omega)$
- Surface impedance $Z(\omega)$

Isotropic skin effect «phase diagram»



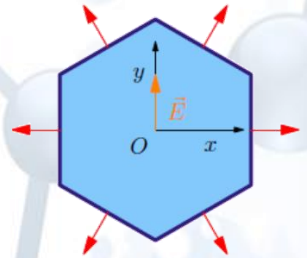


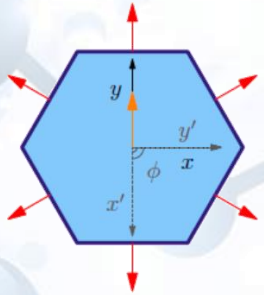


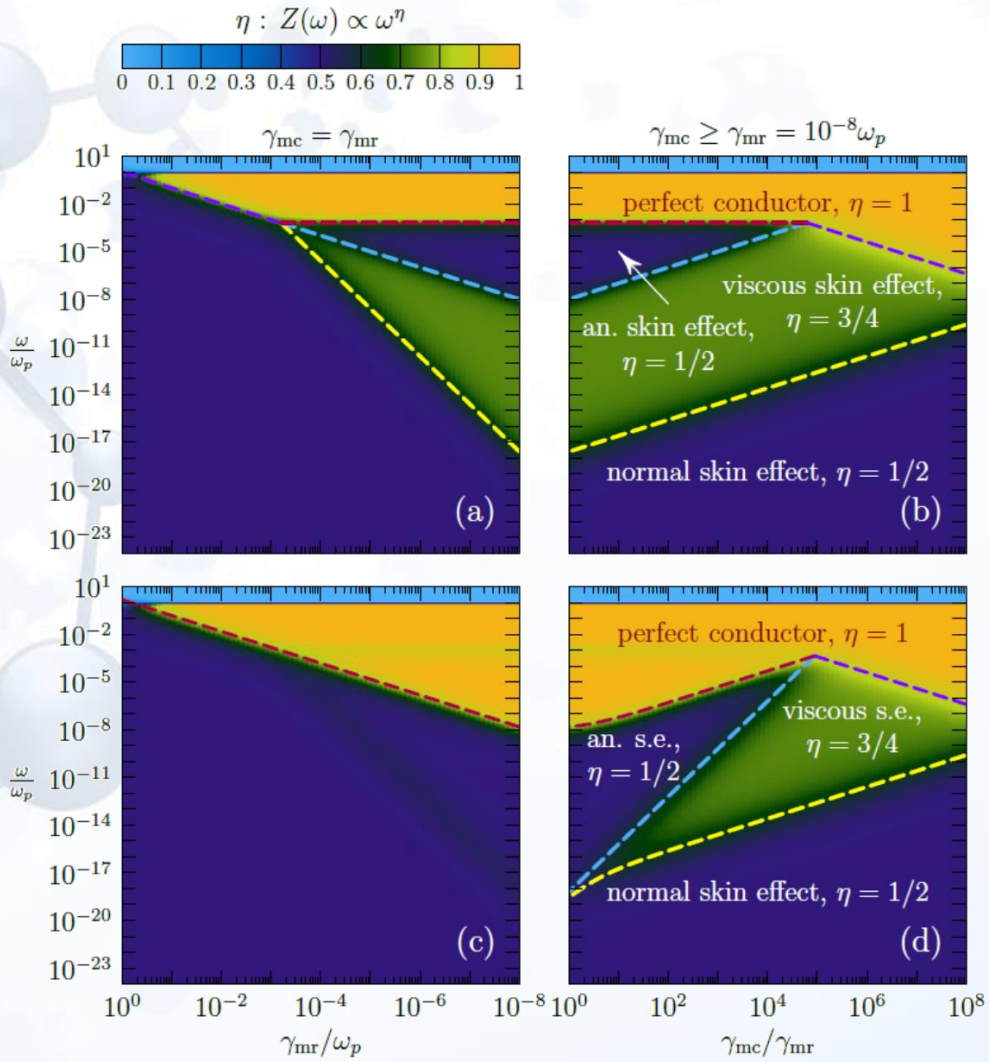
D. V. et al., arXiv:2204.13344 (2022)

Anisotropic «phase diagram»: hexagonal

- Different power law in ballistic regime due to anisotropy: $\eta = 1/2$ (cf. $\eta = 2/3$ in isotropic case)
- Quantitative boundaries for crossovers between regimes, influenced by FS shape
- **Orientational dependence** of skin effect
- $\vec{v}_{\vec{k}} \cdot \vec{q} = 0$: suppression of nonlocality for state $\vec{k}$



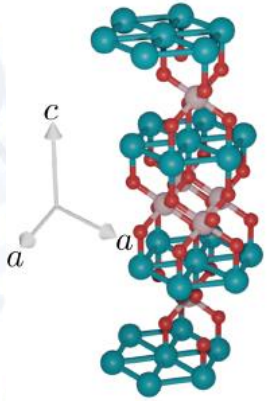


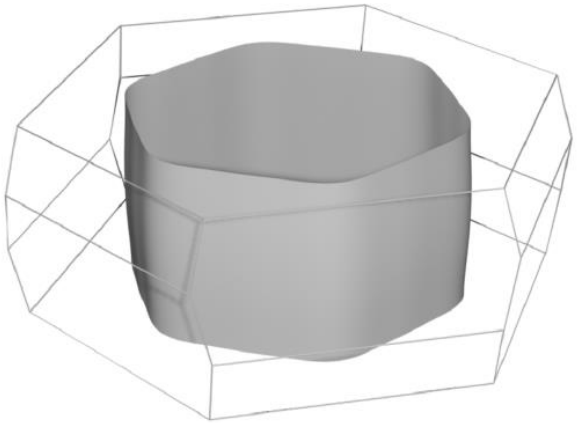


D. V. et al., arXiv:2204.13344 (2022)

Microwave experiments on $PdCoO_2$

- Delafossite: extremely long mean free path, anisotropic transport[1]
- Evidence for hydrodynamic and ballistic DC transport[2]
- Quasi-2D, polygonal-like in-plane Fermi surface[3]
- Microwave induction measurements to probe surface resistance $R(\omega)$[4]





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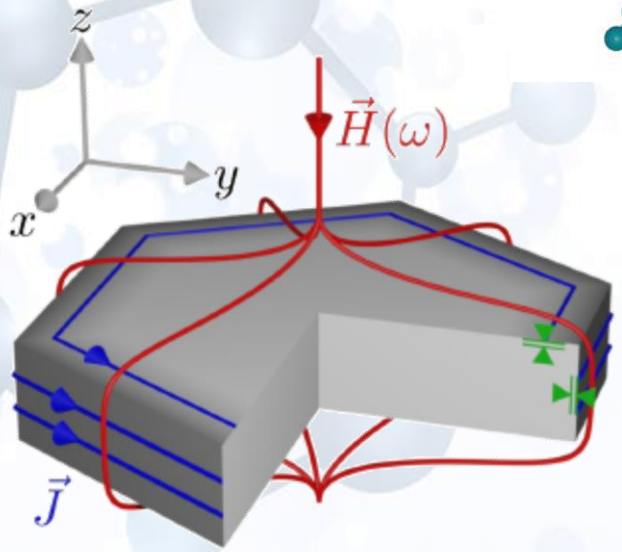
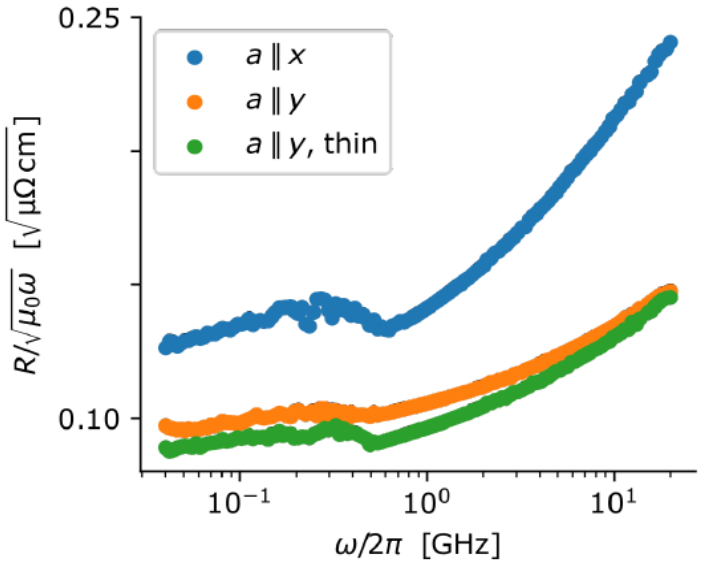
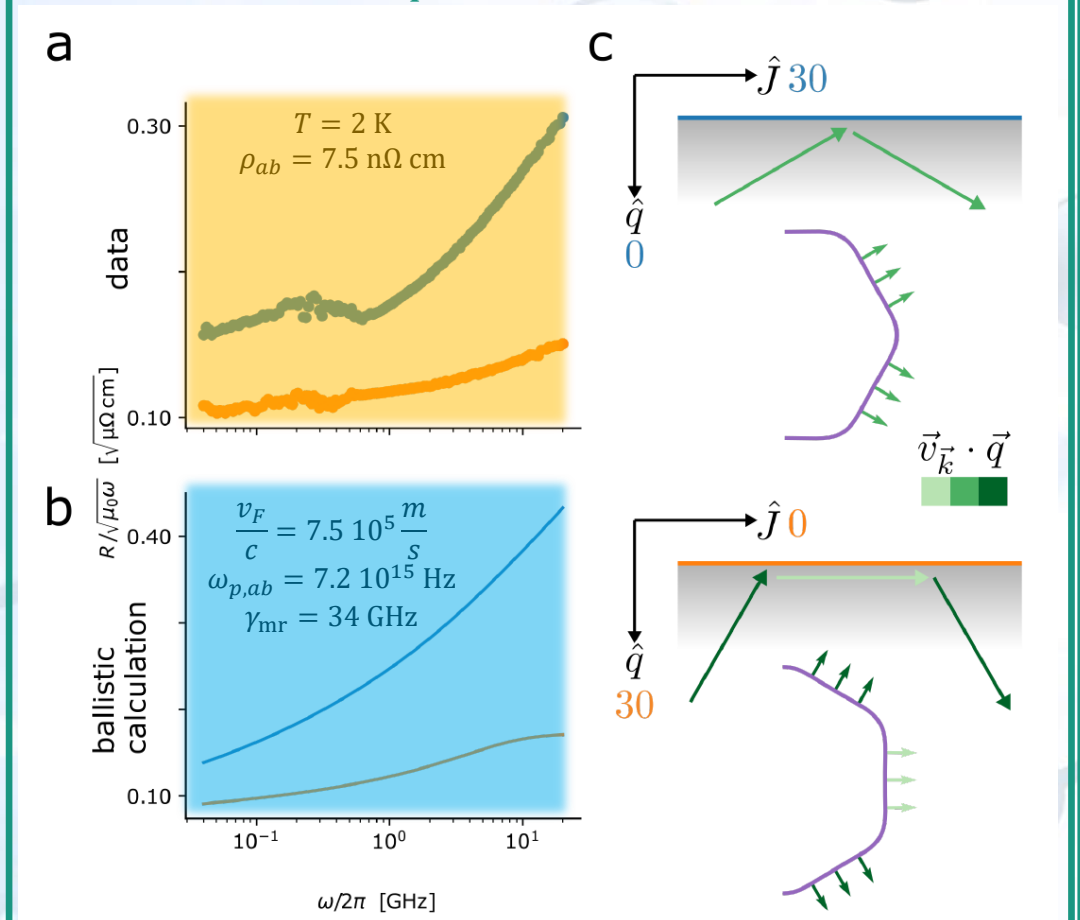




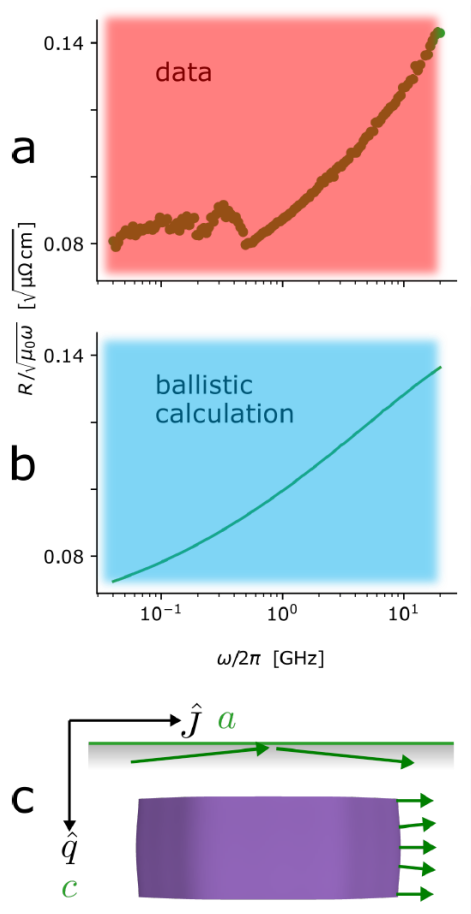
[1] T. Harada et al., APL Mat. **6**, 046107 (2018); A. P. Mackenzie, Rep. Prog. Phys. 80, 32501 (2017)
[2] P. H. McGuinness et al., Proc. Natl. Acad. Sc. USA **118**, 2113185118 (2021); P. J. W. Moll et al., Science **351**, 1061 (2016); M. D. Bachmann et al., Nat. Comm. **10**, 5081 (2019); arXiv:2103.01332 (2021)
[3] C. W. Hicks et al., Phys. Rev. Lett. 109, 116401 (2012)
[4] G. Baker et al., arXiv:2204.13344 (2022)

Microwave experiments on $PdCoO_2$

In-plane conduction



Out-of-plane conduction



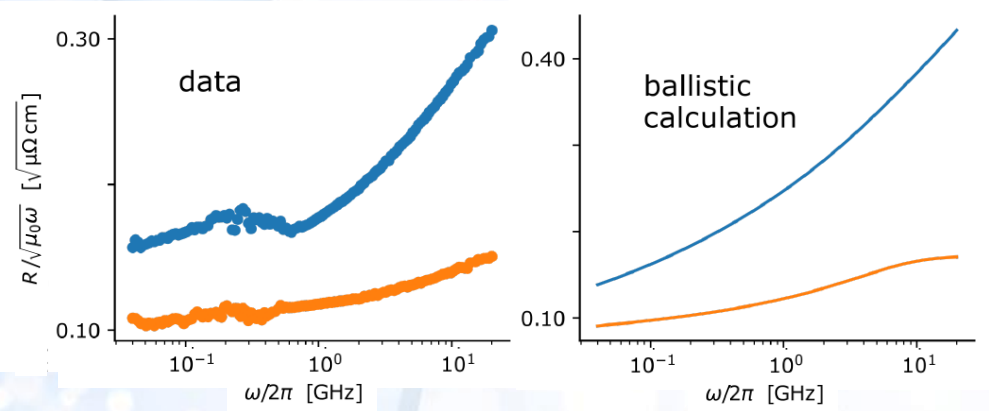
Results:

1. Orientational dependence of skin effect: anisotropic conduction
2. Out-of-plane component: $PdCoO_2$ EM response is 3D
3. Crossover from normal to **ballistic** skin effect
4. Quantitative agreement with kinetic theory
5. Constraint on scattering rates $3 < \gamma_{mc}/\gamma_{mr} < 10$

G. Baker et al., arXiv:2204.14239 (2022)

Conclusions

- Kinetic theory of electrodynamics in 2D and 3D anisotropic systems
  - Orientational dependence of surface impedance and skin depth
- Microwave spectroscopy experiments on delafossite $PdCoO_2$
  - Anisotropic skin effect observation
  - Diffusive/ballistic crossover



D. V. et al., arXiv:2204.13344 (2022)
G. Baker et al., arXiv:2204.14239 (2022)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