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Abstract:

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MAX-PLANCK-GESELLSCHAFT

Evidence for hydrodynamic electron flow in $PdCoO_2$

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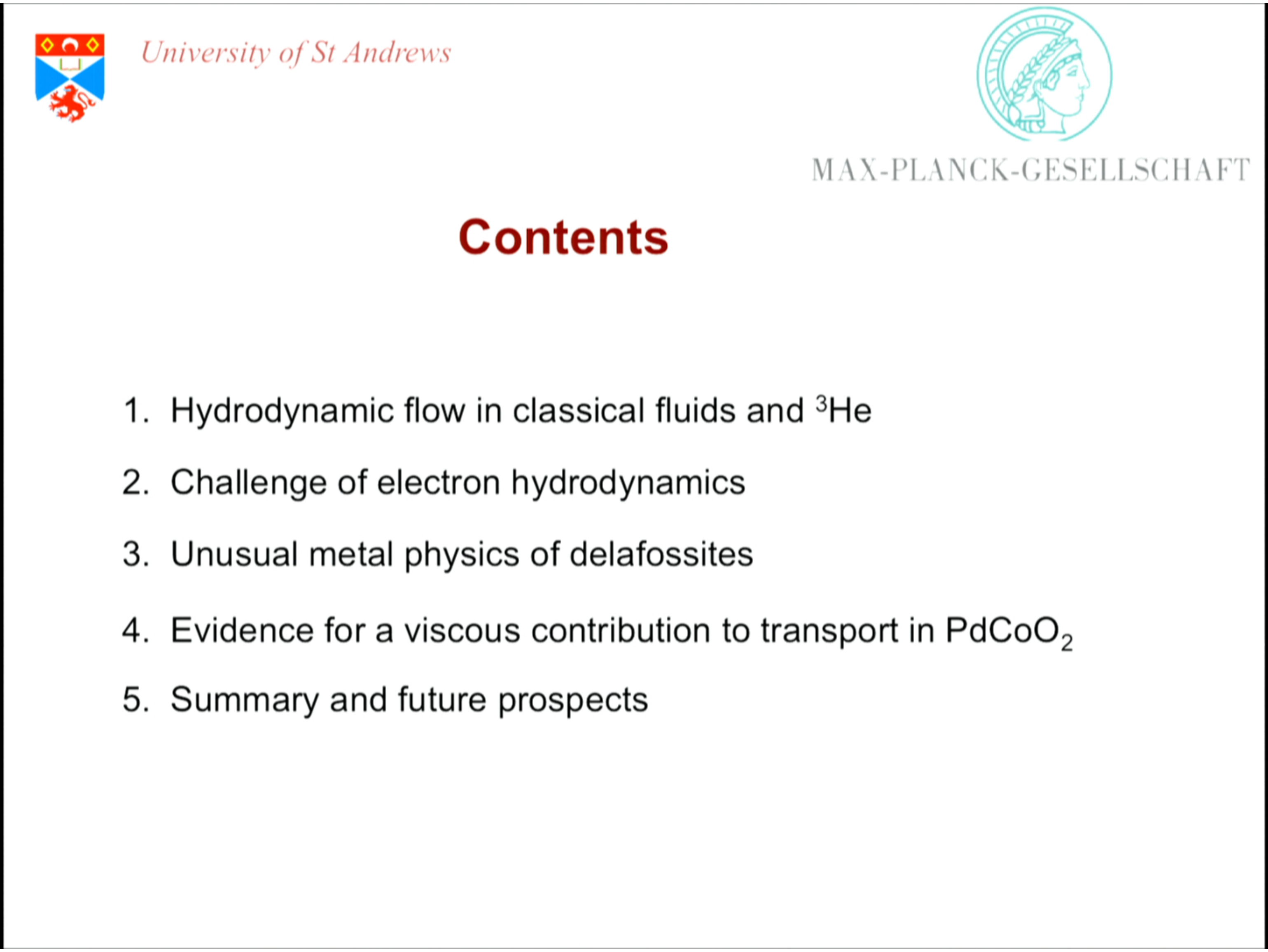
Scotland



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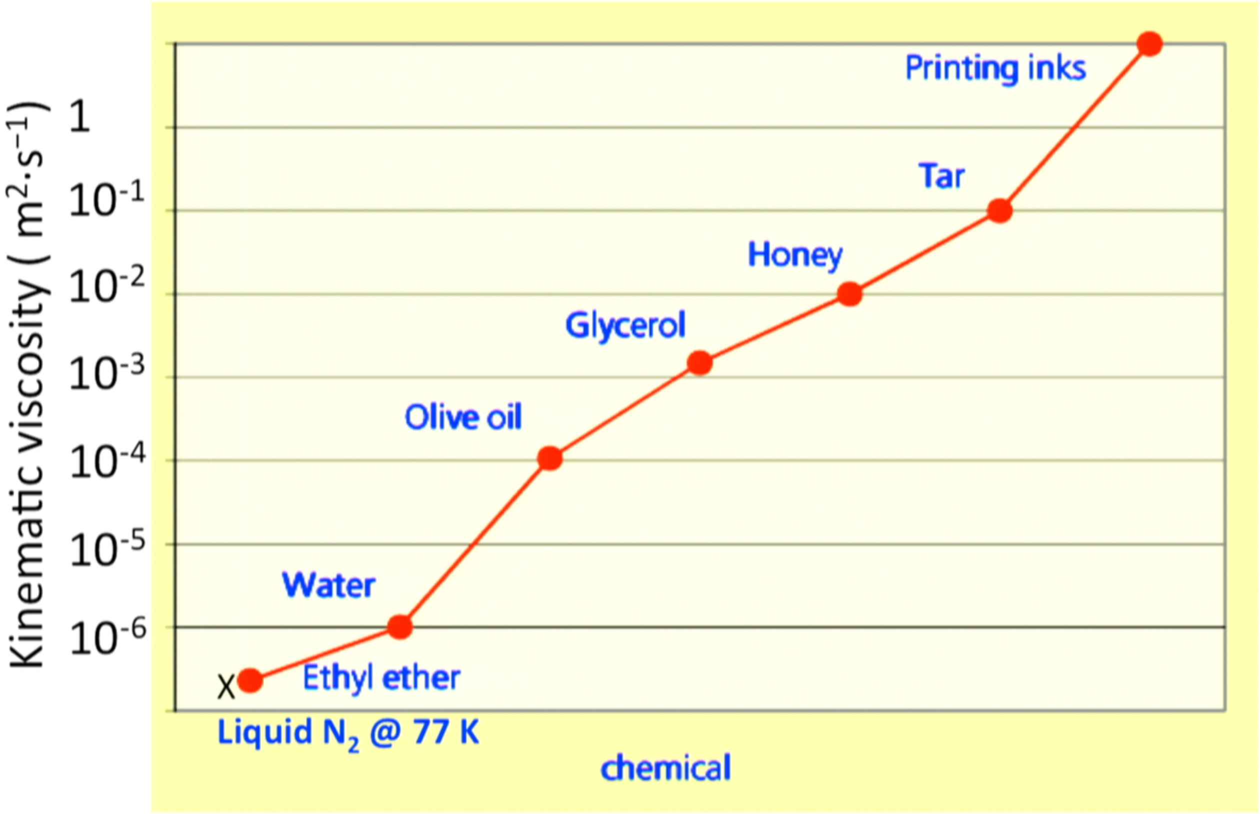
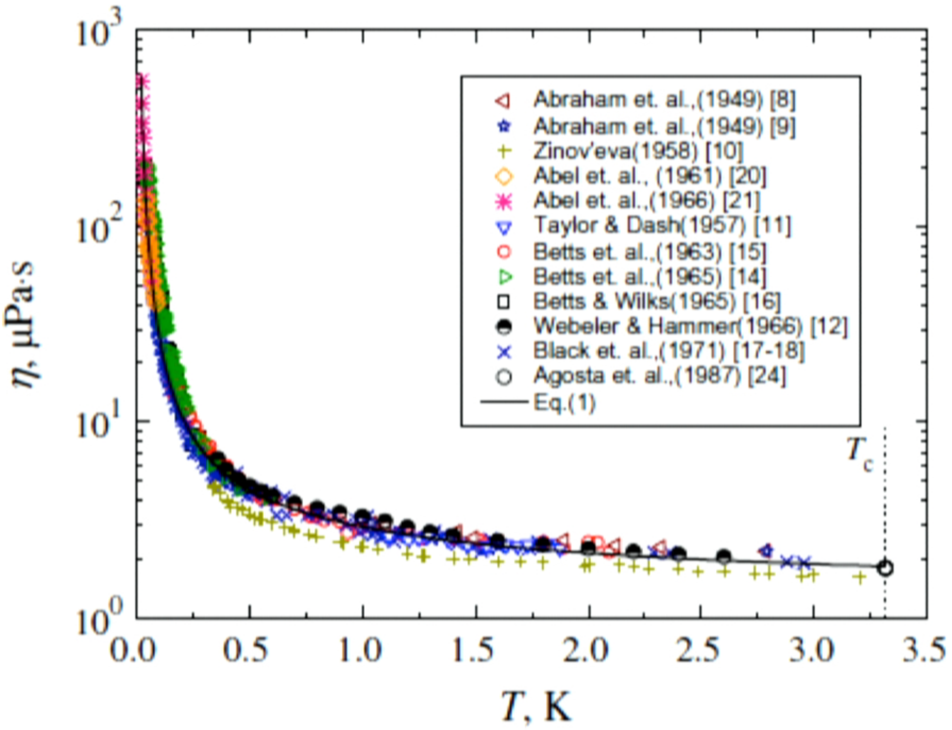
Contents

1. Hydrodynamic flow in classical fluids and ^{3}He
2. Challenge of electron hydrodynamics
3. Unusual metal physics of delafossites
4. Evidence for a viscous contribution to transport in $PdCoO_2$
5. Summary and future prospects

Viscosity of some familiar classical substances



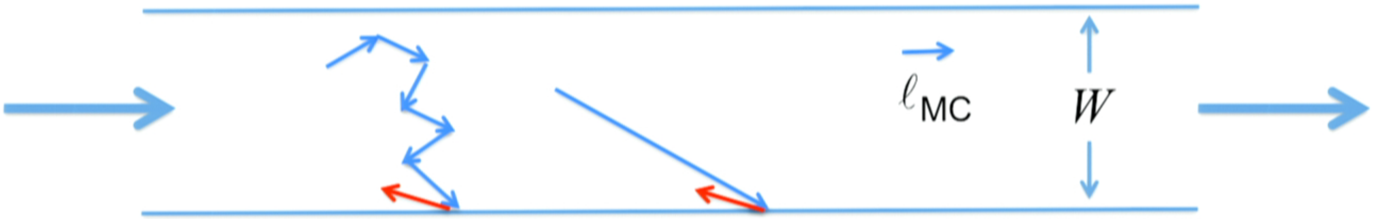
What about a quantum fluid? Consider ^{3}He



This is non-intuitive at first sight – the 'better' the fluid (lower scattering) the more viscous it becomes!

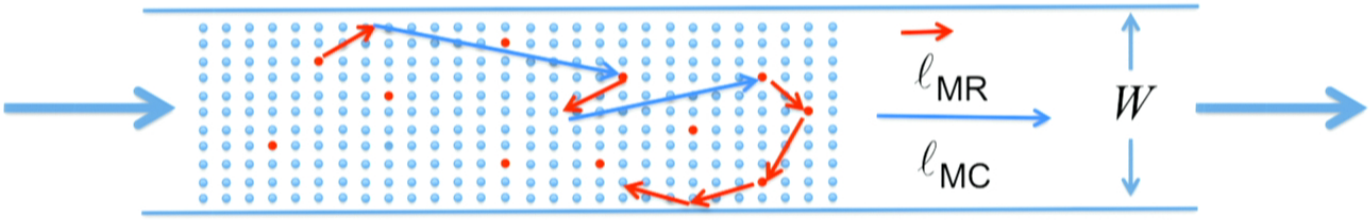
It is a very real effect though – it dictates the low temperature limit of dilution fridge operation.

Fluid flow through an empty 2D channel



- Mean free path ℓ_{MC} is for scattering of the fluid particles from each other. These events conserve the overall fluid momentum.
- Only momentum-relaxing collisions are with the outside world, i.e. at the walls of the channel.
- For longer ℓ_{MC} the particles find the walls more efficiently so the rate of momentum relaxation goes up.
- The same applies to all transverse coupling so ***η is proportional to ℓ_{MC}***. A 'pure' particle fluid with a low internal scattering rate is a viscous one!
- Most appropriate theory is based on hydrodynamics, e.g. on the Navier-Stokes equations

Electrons flowing in a normal solid are *far* from the hydrodynamic regime



- Unlike the fluid in the empty tube, electrons in solids have many ways of making collisions in the bulk that relax the momentum to the solid.
- Electron-impurity, normal electron-phonon, Umklapp electron-phonon and Umklapp electron-electron processes all relax momentum.
- One is usually FAR from the hydrodynamic in which internal collisions are frequent and momentum-conserving.
- How to proceed? In 99.9999% of cases we have ignored momentum-conserving processes completely. We parameterise flow resistance in terms of resistivity, which is a property of the solid, not of the electron fluid.

The 0.00001%

MINIMUM OF RESISTANCE IN IMPURITY-FREE CONDUCTORS

R. N. GURZHI

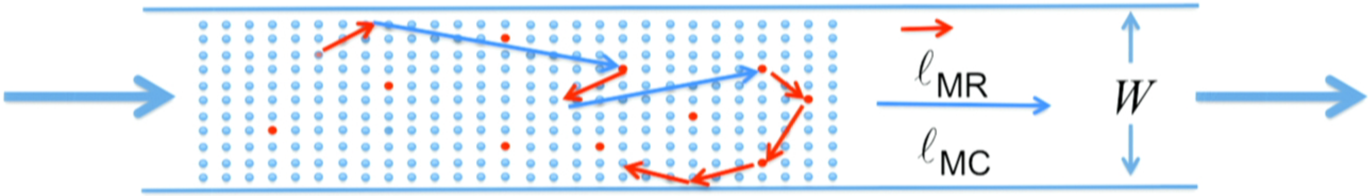
J. Exptl. Theoret. Phys. (U.S.S.R.) **44**, 771-772 (February, 1963)

HYDRODYNAMIC EFFECTS IN SOLIDS AT LOW TEMPERATURE

R. N. GURZHI

Usp. Fiz. Nauk **94**, 689–718 (April, 1968)

Key point introduced by Gurzhi: In solids, hydrodynamic effects can be parameterised in terms of the relationship between the three length scales ℓ_{MR}, ℓ_{MC} and sample dimension (here *W)*.



$\ell_{MR} << \ell_{MC} << W$

Standard theory applies;
R is determined entirely by solid resistivity ρ and usual geometrical factors

$\ell_{MC} << W << \ell_{MR}$

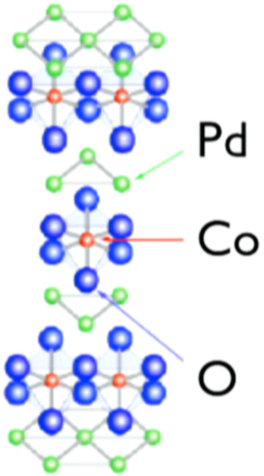
Hydrodynamic theory applies; *R* is determined entirely by fluid viscosity η, boundary scattering and 'Navier-Stokes' geometrical factors

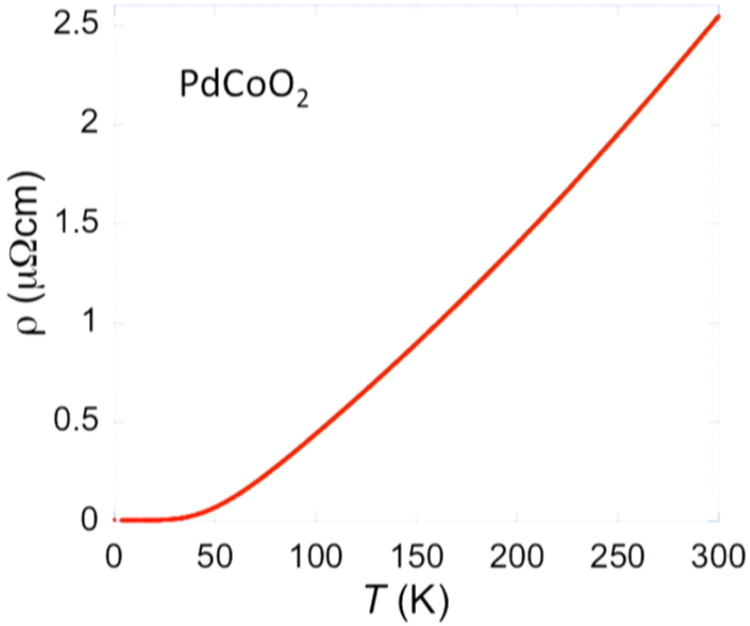
Can hydrodynamic effects be observed in a true metal?

Recall hydrodynamic condition: $\ell_{\mathrm{MC}} \ll W \ll \ell_{\mathrm{MR}}$

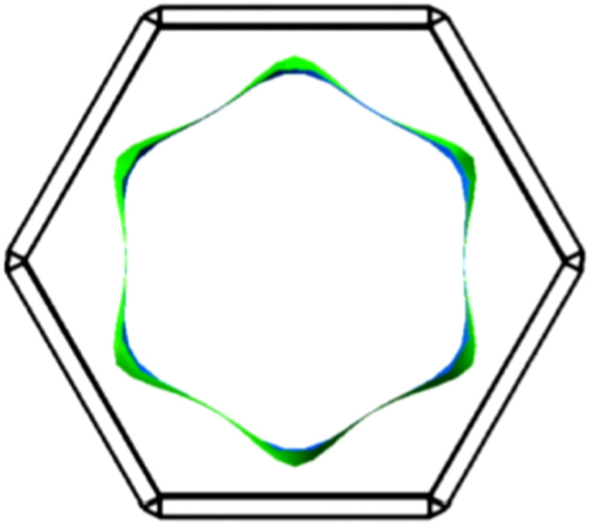
Looks extremely difficult: Must often work far below T_F so ℓ_{ee} is very long, *and* e-e Umklapp is in principle efficient. Expectation is that $\ell_{\mathrm{MC}} \gg \ell_{\mathrm{MR}}$.

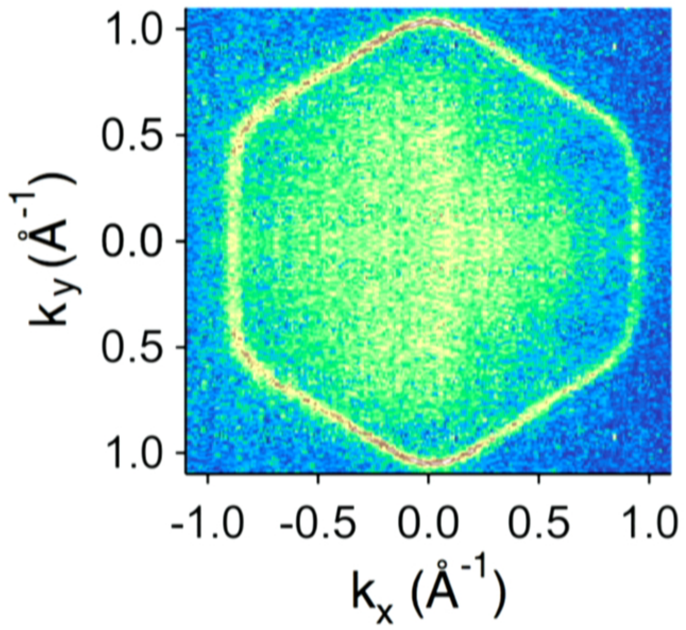
However, delafossites seem not to be standard metals.





Fermi surface of $PdCoO_2$ from calculation and ARPES

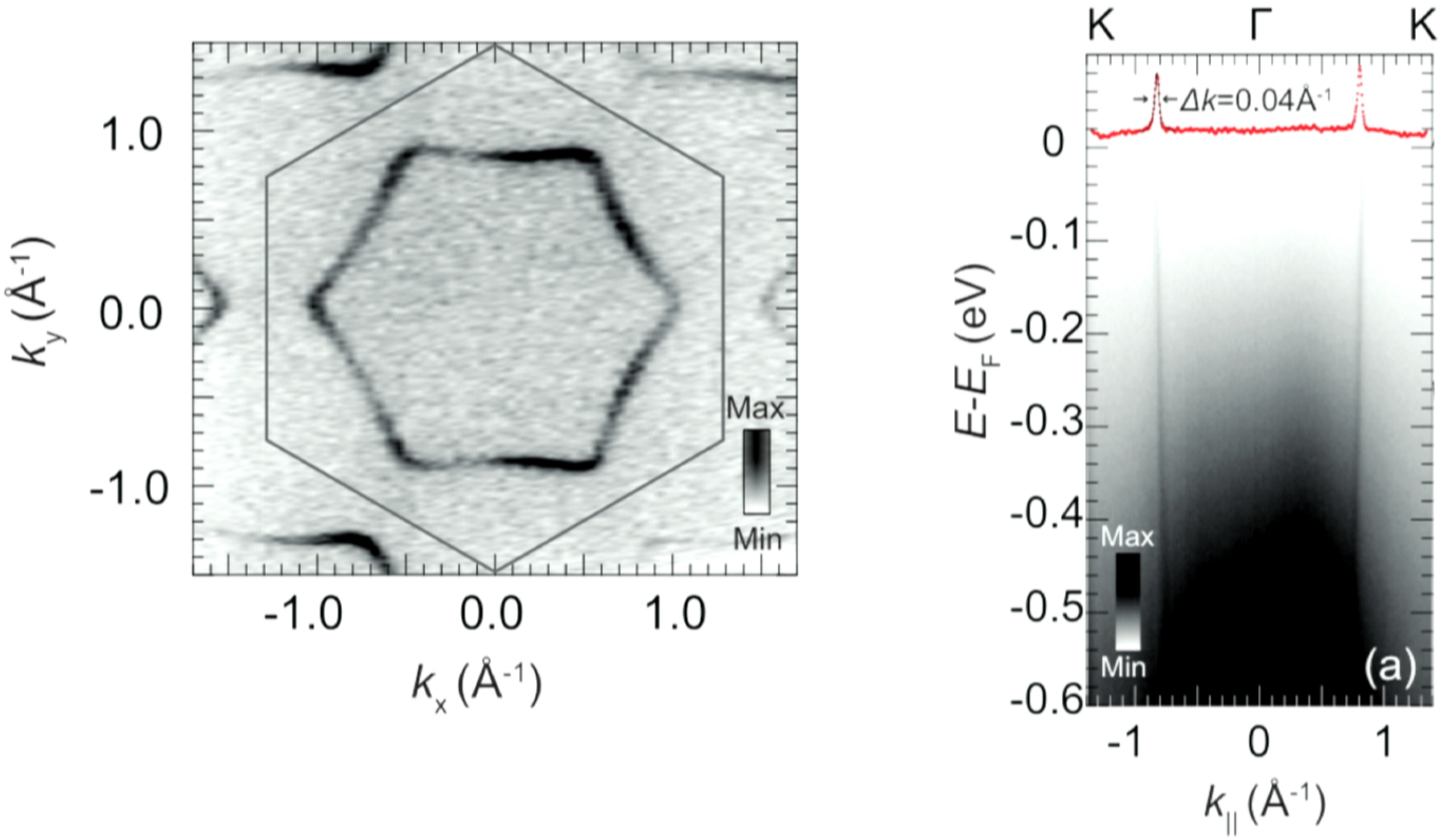




K.P. Ong, J. Zhang, J.S. Tse and P. Wu
Phys. Rev. B ***81****, 115120 (2010)*

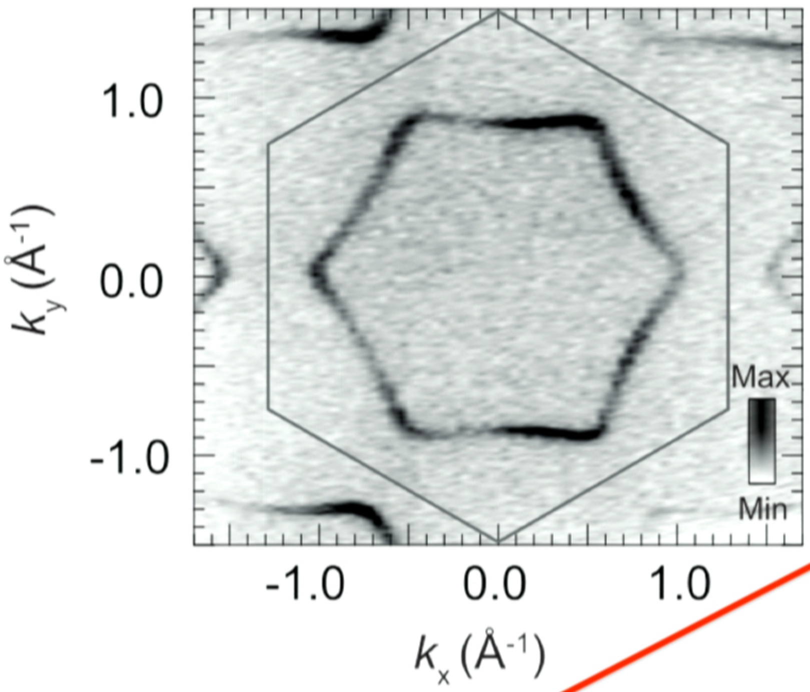
H.J. Noh, J. Jeong, E.J. Cho, S.B. Kim, K. Kim, B.I. Min and H.D. Kim, Phys. Rev. Lett. ***102****, 256404 (2009)*

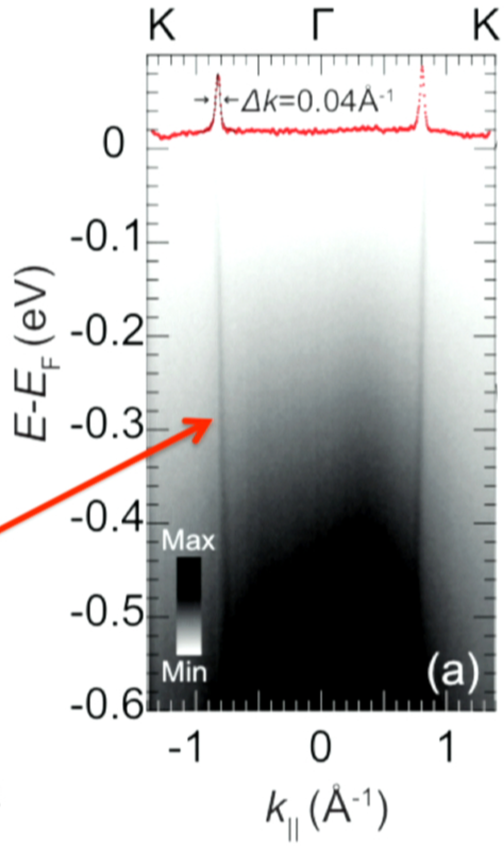
ARPES spectra from $PtCoO_2$



P. Kushwaha, V. Sunko, P. J. W. Moll, L. Bawden, J. M. Riley, N. Nandi, H. Rosner, F. Arnold, E. Hassinger, T. K. Kim, M. Hoesch, A. P. Mackenzie and P. D. C. King, Science Advances ***1****, 1500692 (2015).*

ARPES spectra from $PtCoO_2$

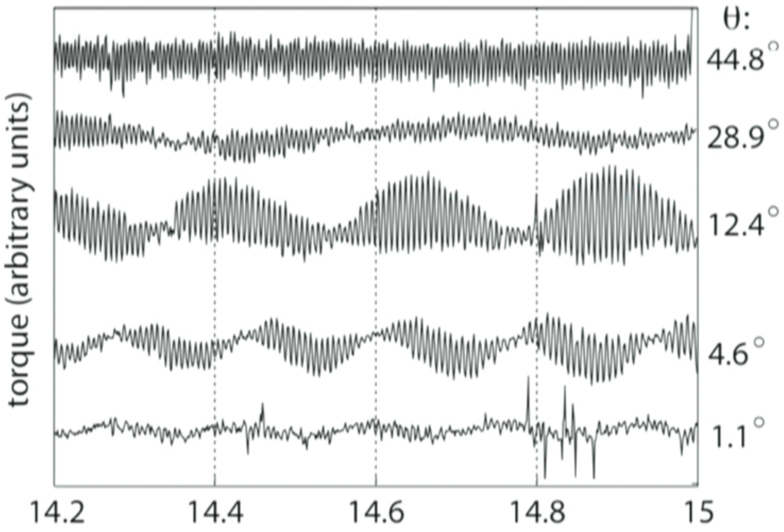




No observable boson coupling or quasiparticle peak broadening down to 5000 K below E_F

P. Kushwaha, V. Sunko, P. J. W. Moll, L. Bawden, J. M. Riley, N. Nandi, H. Rosner, F. Arnold, E. Hassinger, T. K. Kim, M. Hoesch, A. P. Mackenzie and P. D. C. King, Science Advances ***1****, 1500692 (2015).*

ARPES is consistent with the de Haas – van Alphen effect in both $PdCoO_2$ and $PtCoO_2$



Data for $PdCoO_2$

$\bar{k}_F = 0.97$ Å^{-1}

$\bar{m}^* = 1.5\ m_e$

$\bar{v}_F = 7.5 \times 10^5\ \mathrm{ms}^{-1}$

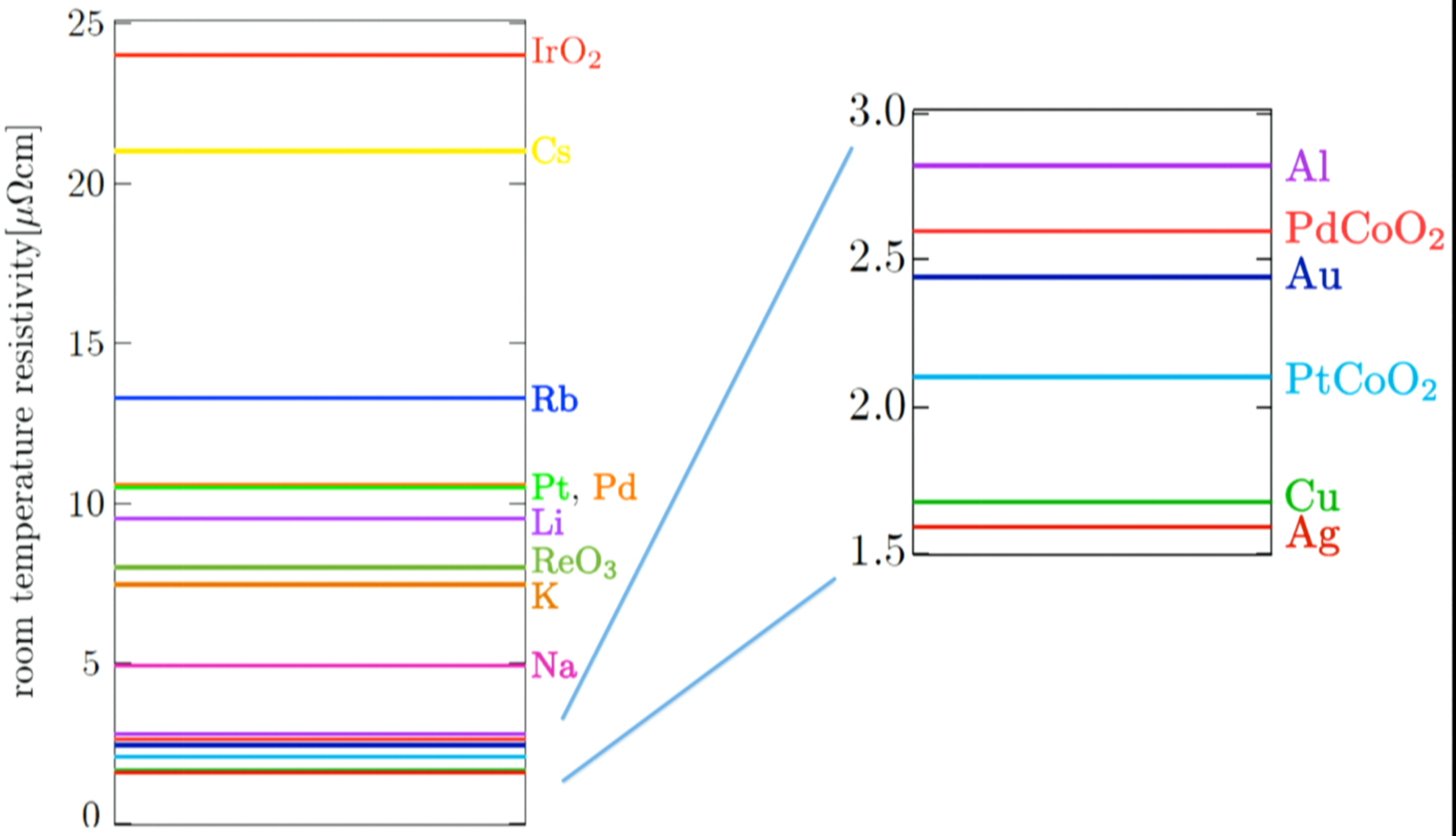
$T_F = 27000$ K

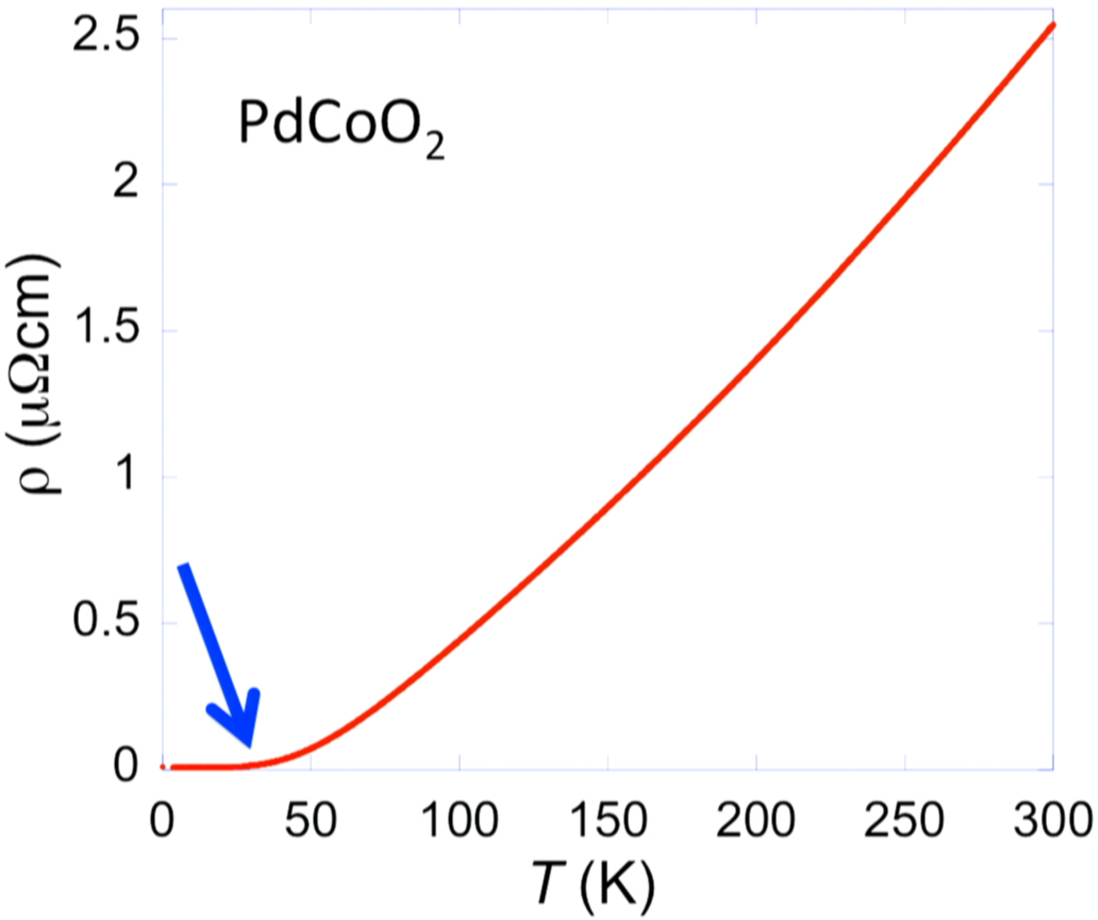
Single closed Fermi surface; no observed density wave gapping.

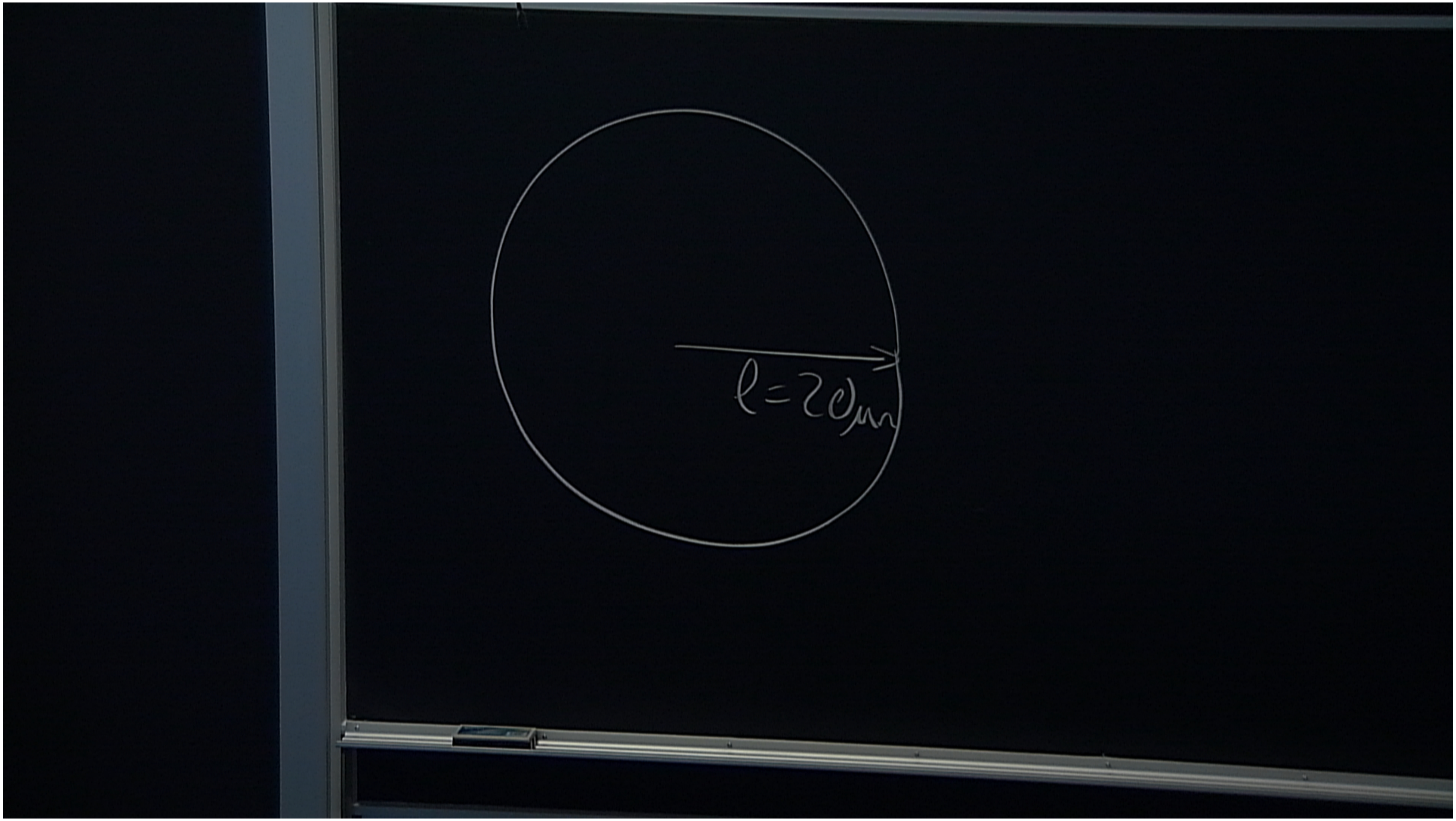
Conduction bands of Pd / $PtCoO_2$ have dominantly 4*d* / 5*d* character but nearly free electron parameters.

C.W. Hicks, A.S. Gibbs, A.P. Mackenzie, H. Takatsu, Y. Maeno & E.A. Yelland
Phys. Rev. Lett. ***109****, 116401 (2012)*

$PdCoO_2$ and $PtCoO_2$: record-breaking conductivity




PdCoO$_2$
ρ (μΩcm)
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
T (K)


$\ell = 20\mu m$

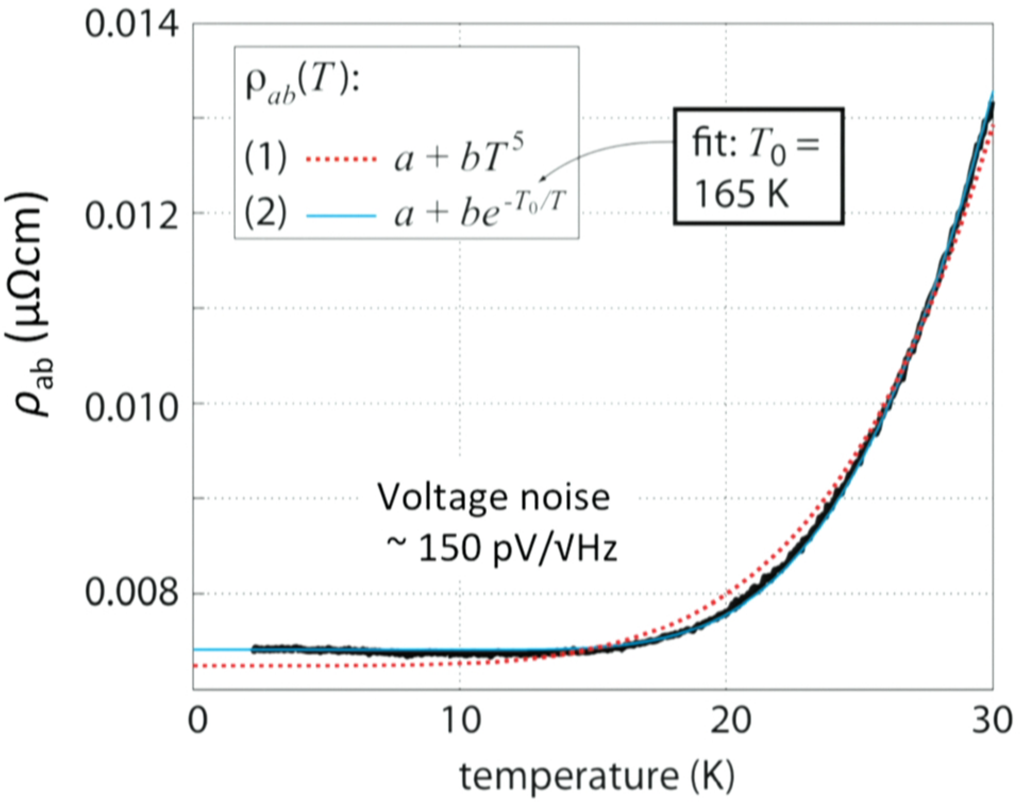
Tiny and exponential resistivity at low temperatures

Resistivity at low T is < 10 nΩcm.

Mean free path ℓ can be as much as 50 μm!

If this is naively interpreted as a defect spacing it is chemically implausible.

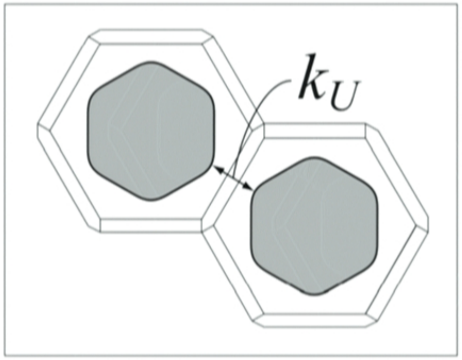
Also, $\ell_{\mathrm{dHvA}} << \ell_{\mathrm{MR}}$



C.W. Hicks, A.S. Gibbs, A.P. Mackenzie, H. Takatsu, Y. Maeno & E.A. Yelland Phys. Rev. Lett. ***109****, 116401 (2012)*

Could exponential resistivity be due to 'phonon drag'?

Idea (Peierls 1930s): phonons cannot equilibriate on the timescale of low temperature electron-phonon collisions and are dragged out of equilibrium by the electron distribution in an applied electric field at low temperatures.

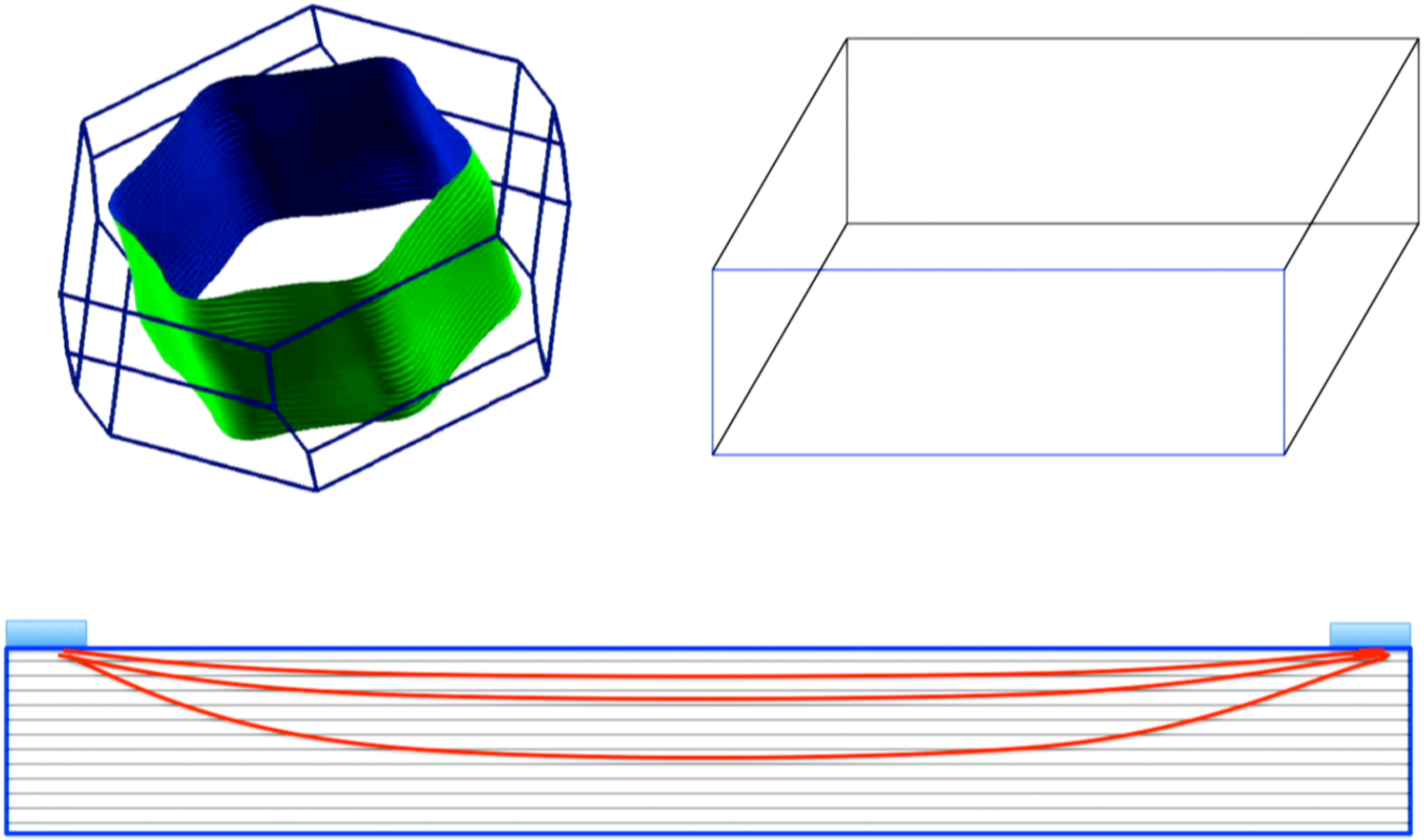


Standard el-ph scattering therefore does not relax the electron distribution's momentum at low temperatures.

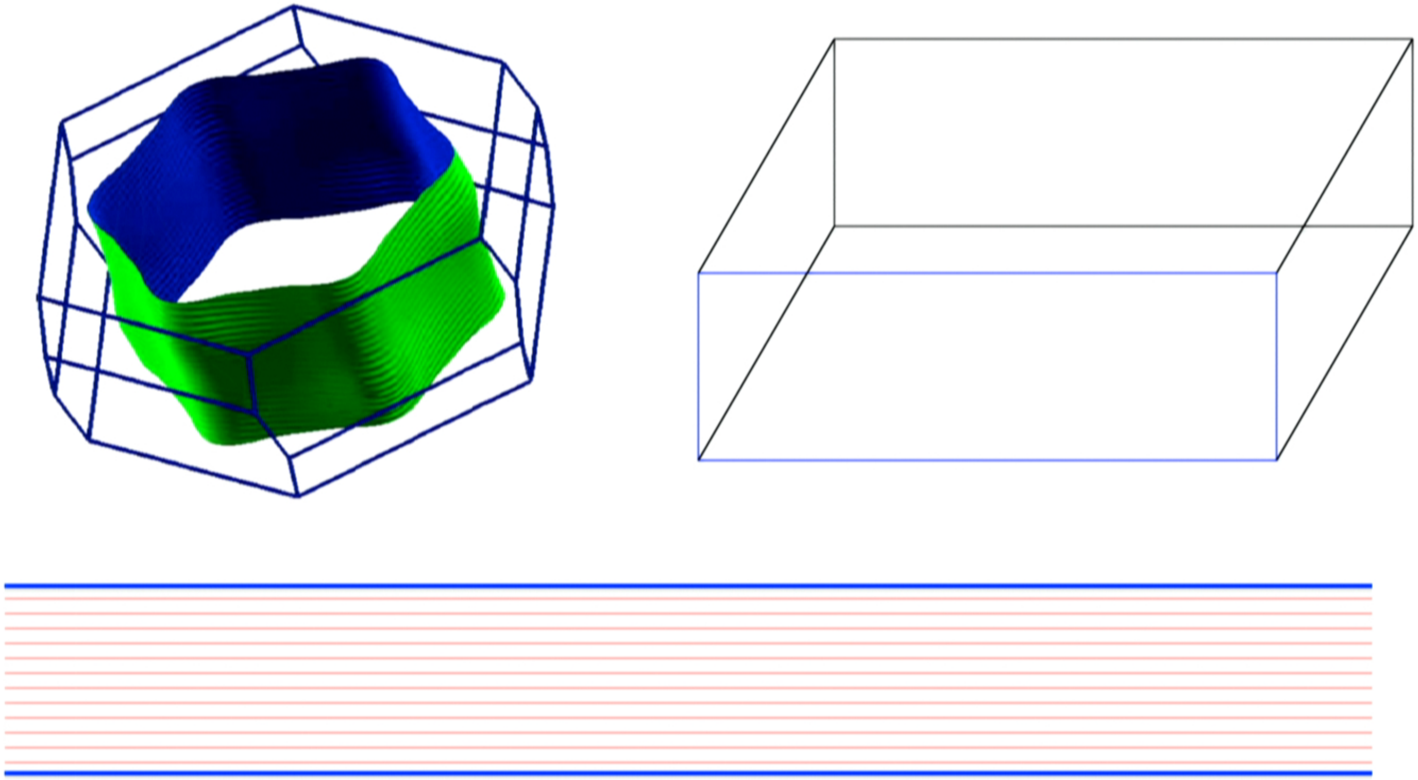
Electron-phonon Umklapp processes then have an activation temperature $T_U = \hbar c k_U$ where c is the sound velocity.

Estimating c from phonon specific heat and knowing k_U from the Fermi surface gives reasonable agreement between T_U and the measured T_o.

Note on effective dimensionality

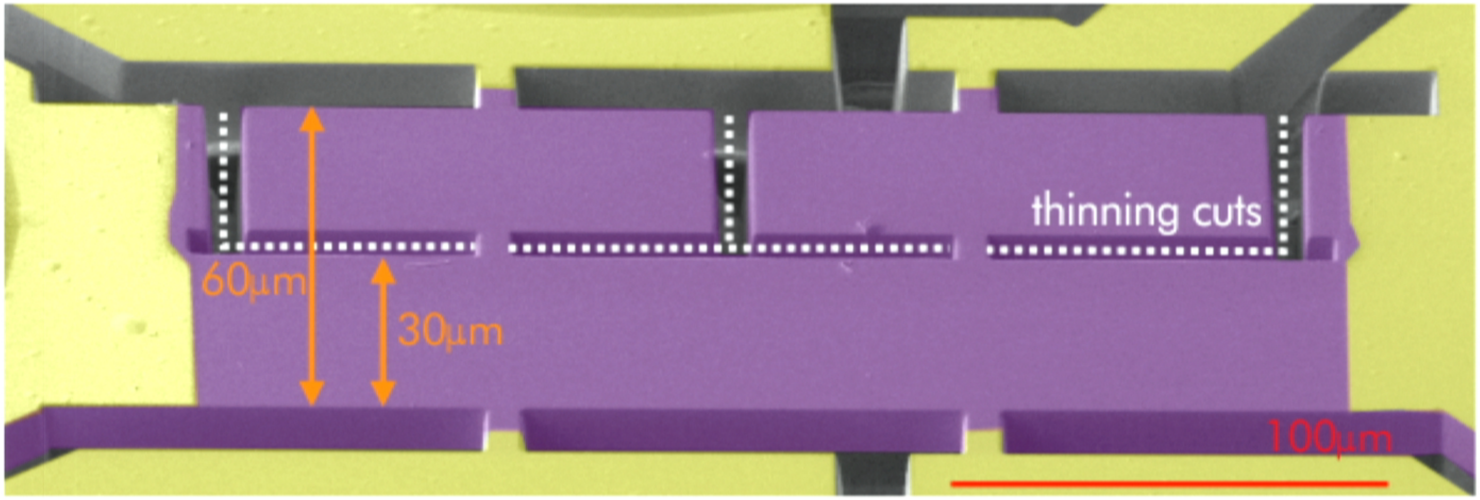


Note on effective dimensionality



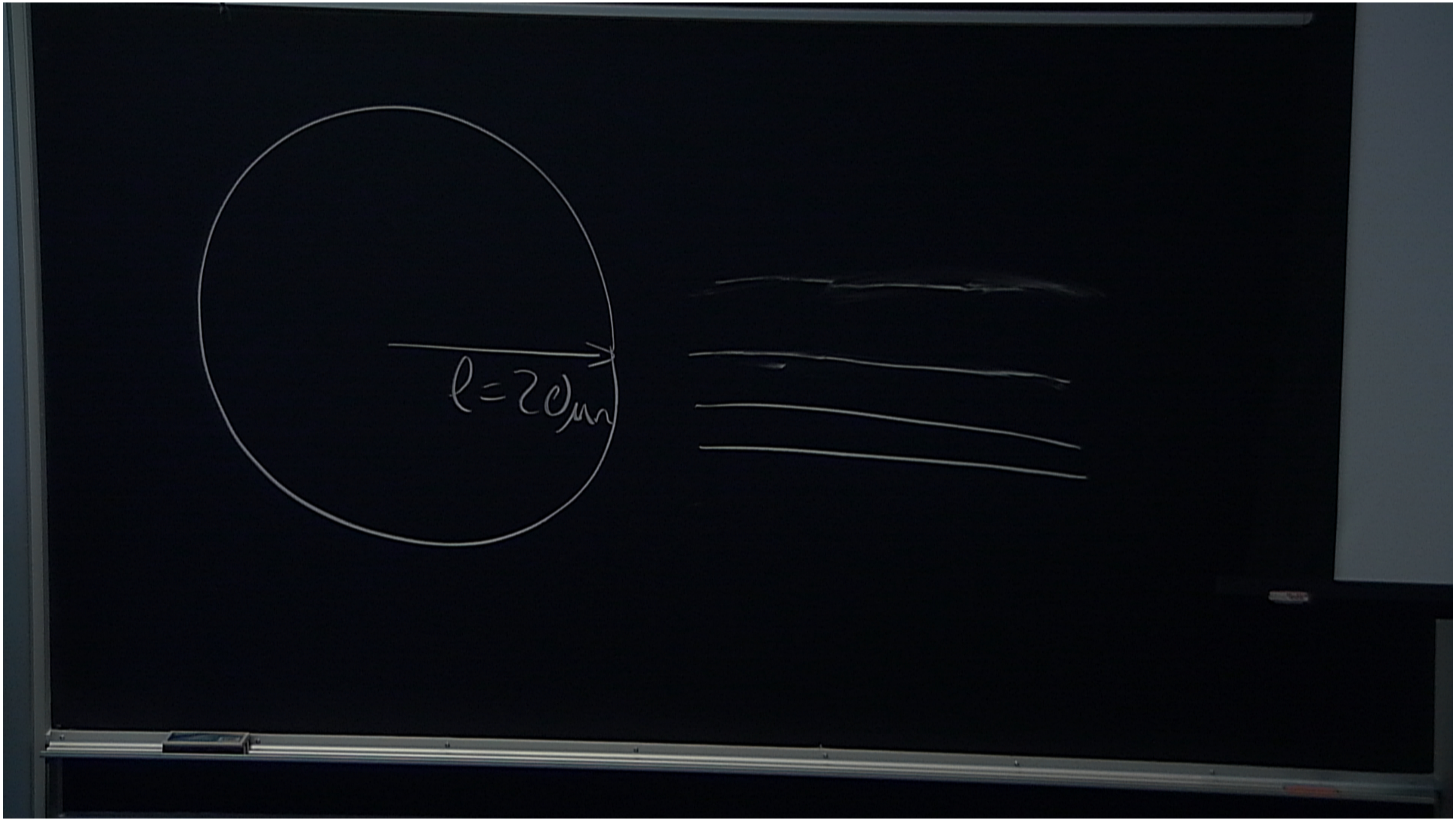
Regime can be reached in which the sample is just a large number (~ 10^4) parallel conducting layers. Analysis using 2D transport theory is then appropriate.

Carefully study the electron flow when boundary scattering at the edges of the channel becomes important



Experiment: Successively narrow the channel in factors of 2, measuring the resistance after every step.

*P.J.W. Moll, P. Kushwaha, N. Nandi, B. Schmidt and A.P. Mackenzie, Science **351**, 1061 (2016)*

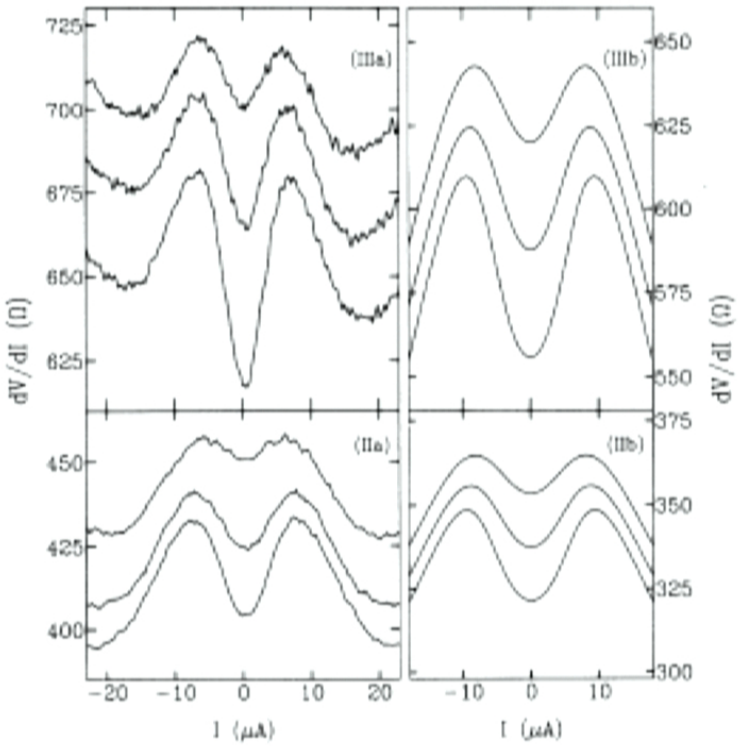

$\ell = 2\ell_{min}$

The de Jong – Molenkamp theory

Rewrite standard Boltzmann theory explicitly including momentum-conserving scattering.

Convenient and (eventually!) intuitive parameterisation in terms of the three length scales introduced by Gurzhi.

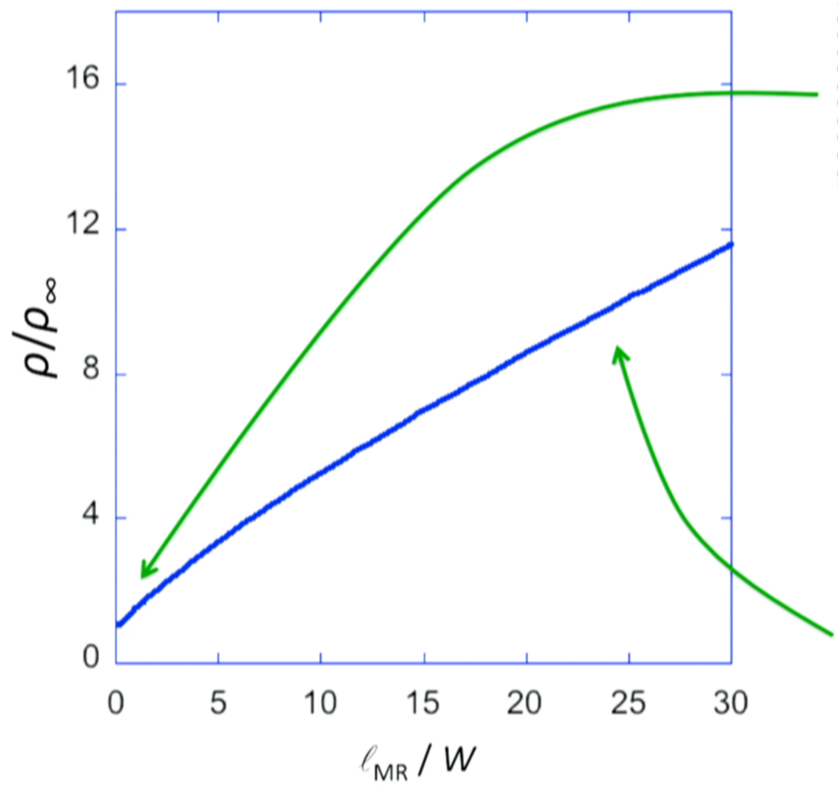
Predictive capability in principle for any combination of ℓ_{MR}, ℓ_{MC} and *W*.

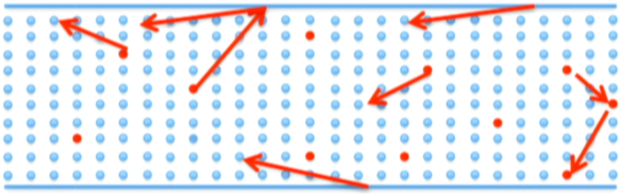


M.J.M de Jong & L.W. Molenkamp, Phys. Rev. B ***51****, 13389 (1995)*

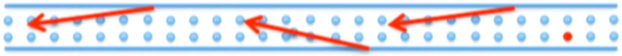
Purely ballistic theory of transport in 2D channels

C.W.J. Beenakker and H. van Houten, Solid State Phys. ***44****, 1 (1991)*





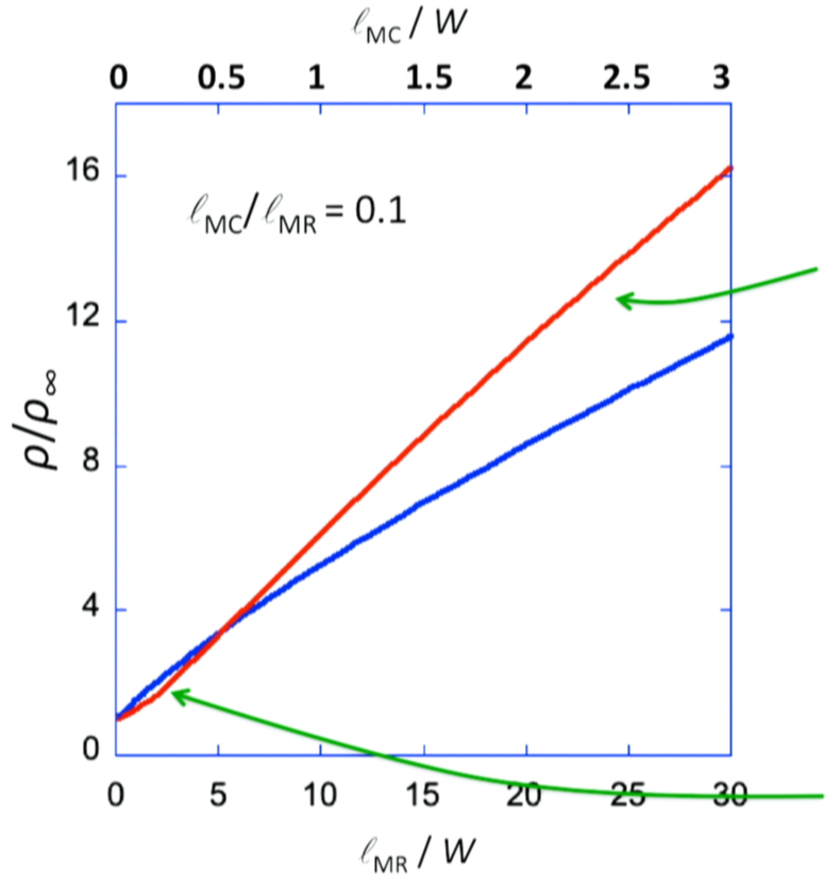
Bulk momentum relaxing scattering supplemented by extra momentum relaxing boundary scattering.



Boundary scattering dominant but sub-linear rise as a function of $1/W$ because of bias towards electrons moving parallel to boundaries.

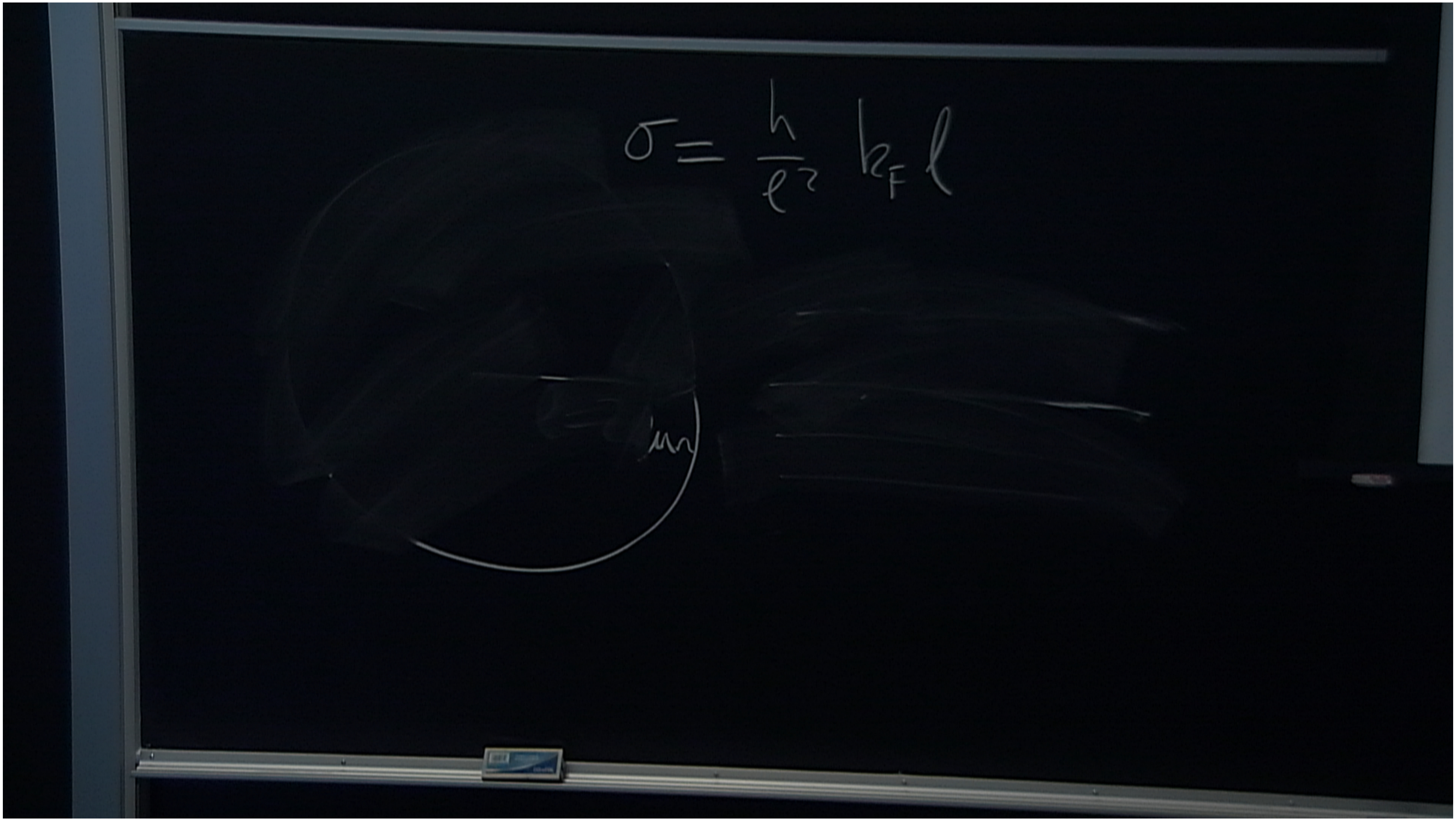
Expressed as a function of these dimensionless axes there are no free parameters

Add momentum-conserving scattering with de Jong-Molenkamp theory



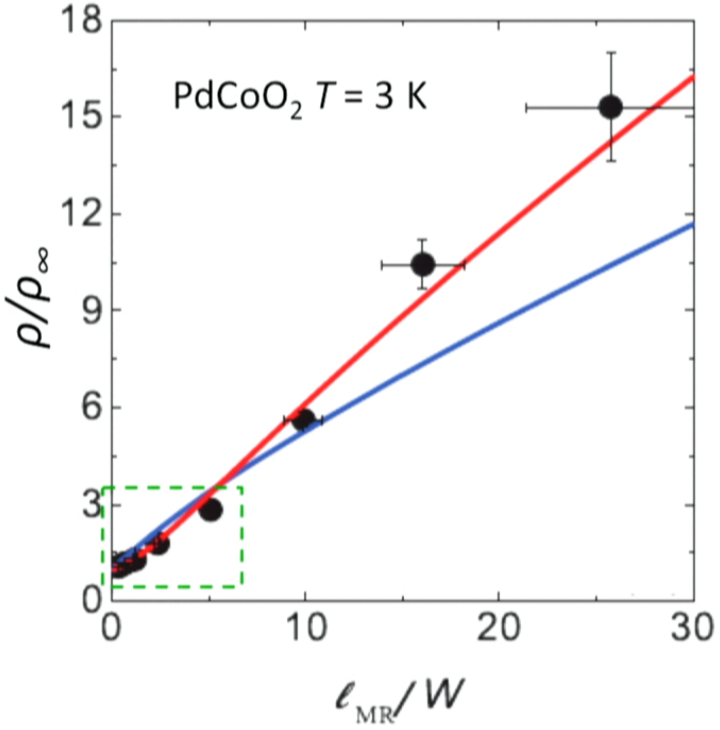
In the very narrow wires the shorter ℓ_{MC} enhances the coupling to the boundary. Crossover close to $\ell_{MC} / W = 1$; intuitively reasonable.

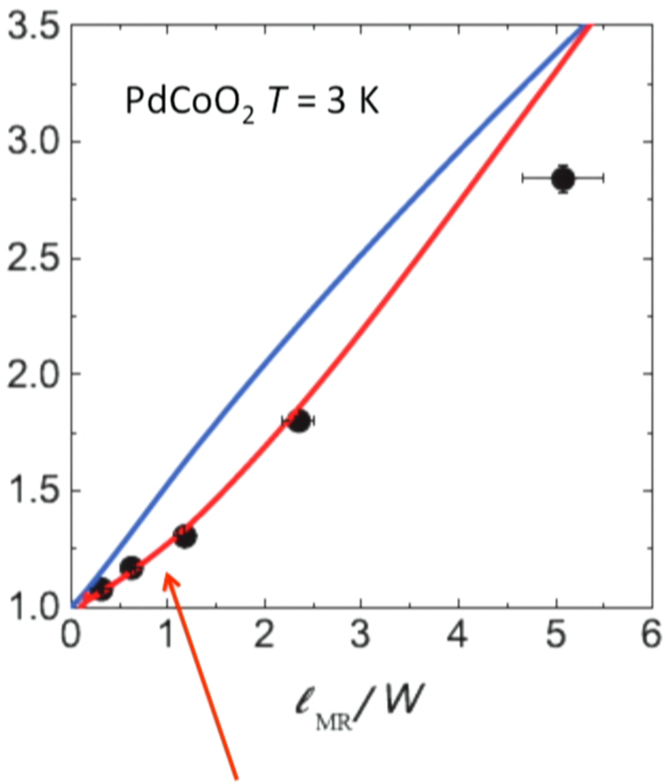
Diffusive momentum conserving scattering hinders ballistic coupling with the boundary and gives characteristic W^{-2} dependence for channel resistivity of a viscous system (equivalent to the W^{-3} dependence of channel resistance obtained by solving the Navier-Stokes equation in 2D).



$$\sigma = \frac{h}{e^2} k_F \ell$$

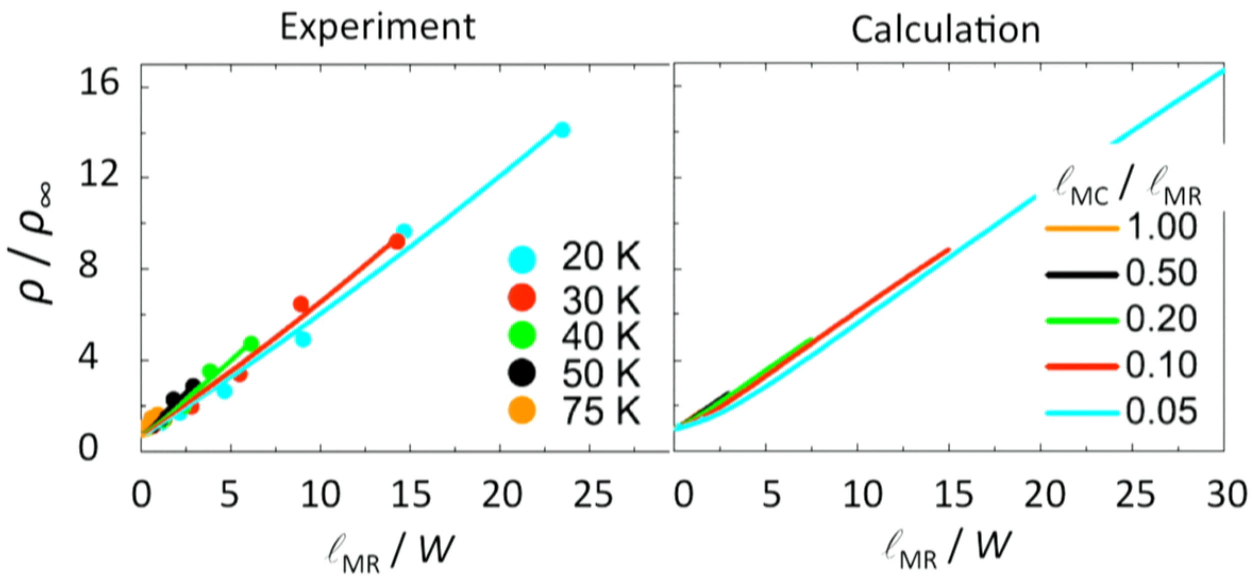
Width dependence of channel resistance analysed using the de Jong-Molenkamp theory





Curvature is the signature of a viscous contribution

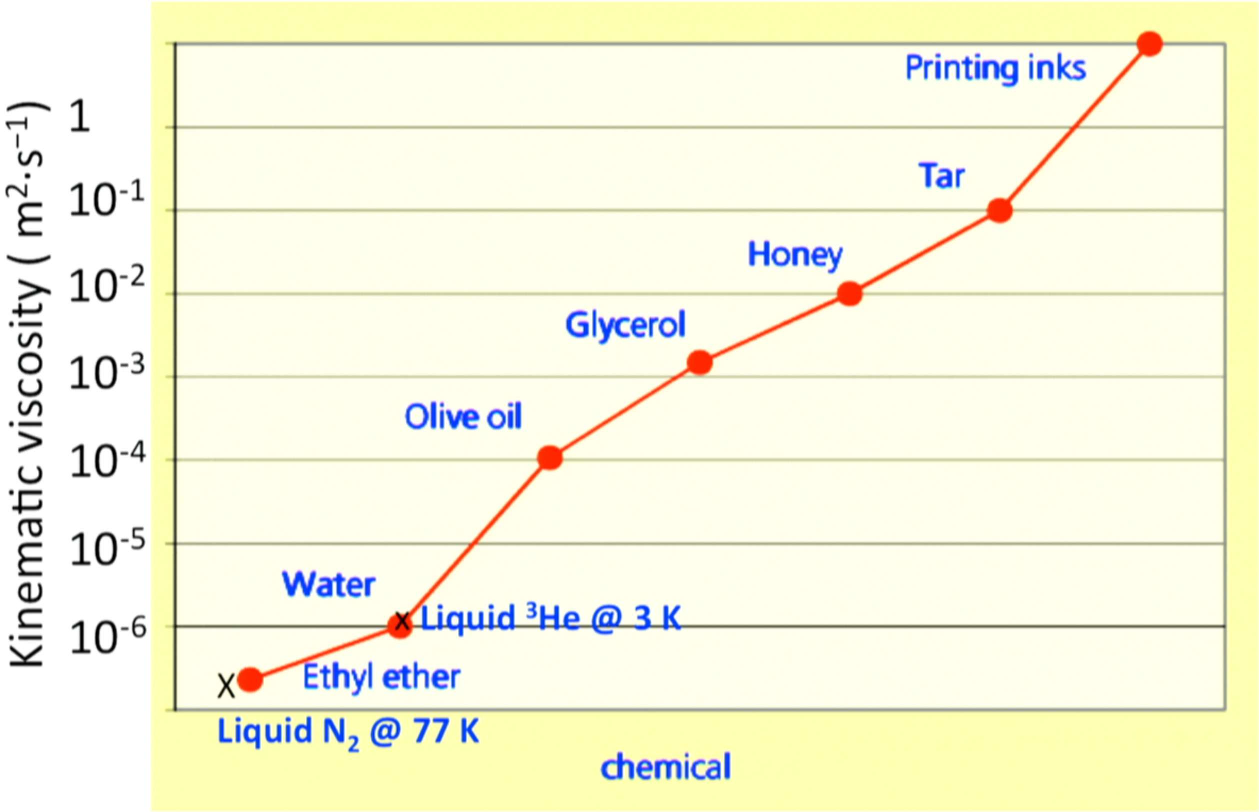
Temperature dependence of the effect



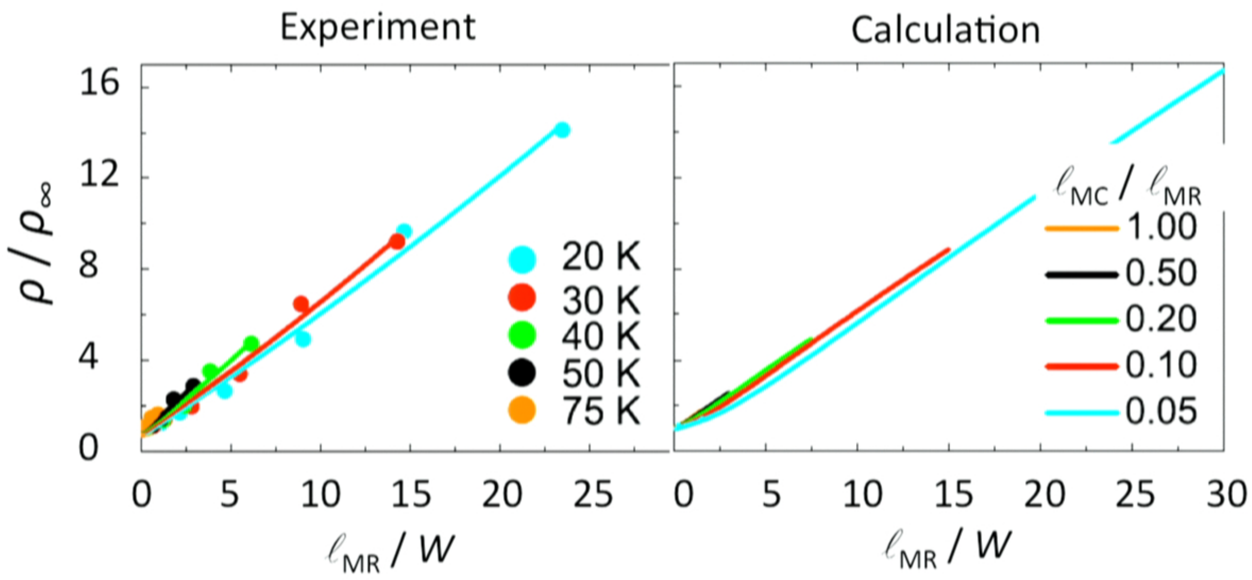
A temperature dependence is observed, which would not be expected in the absence of significant hydrodynamic effects.

However, the data imply a much weaker change of ℓ_{MC} than might be expected.

Viscosity of some familiar classical and quantum fluids



Temperature dependence of the effect



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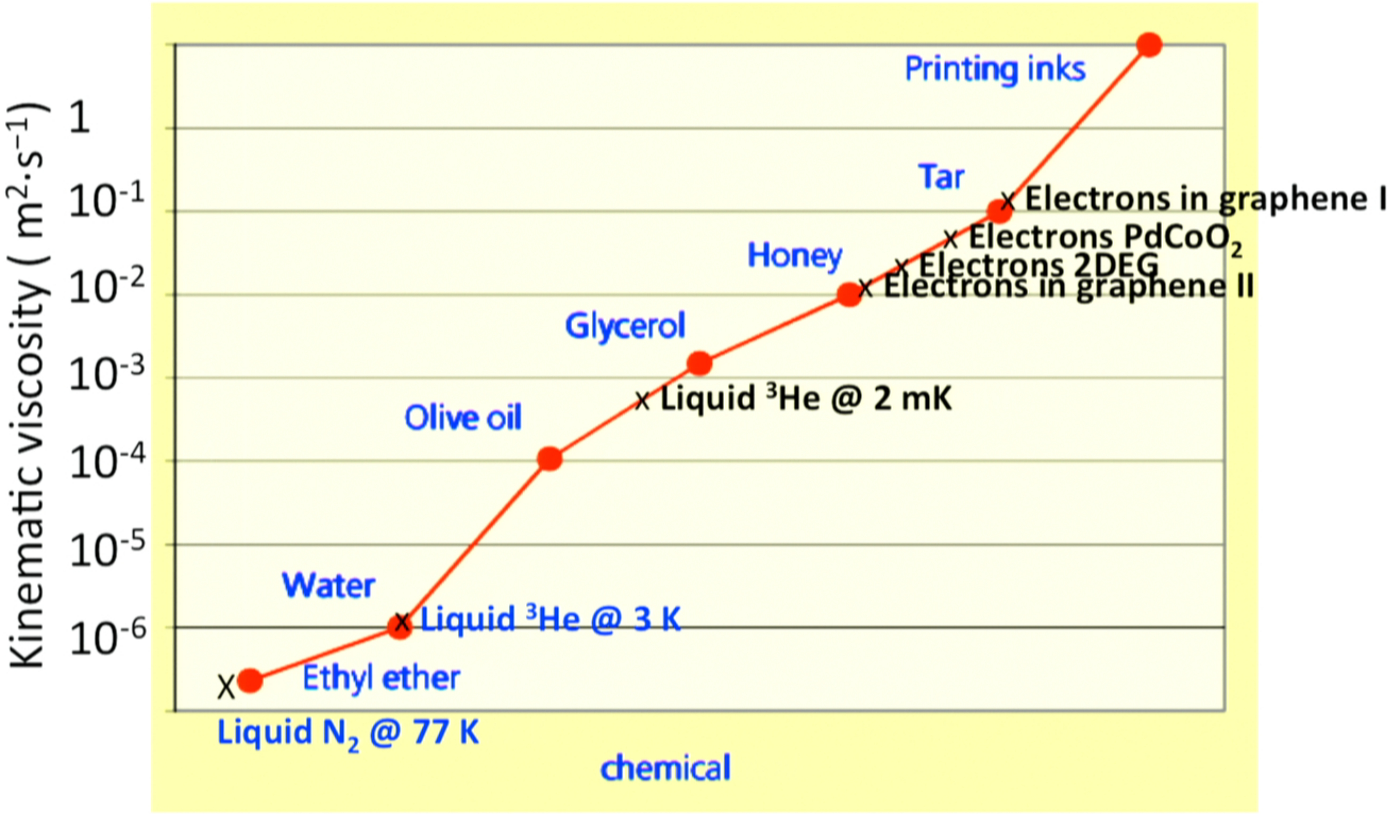
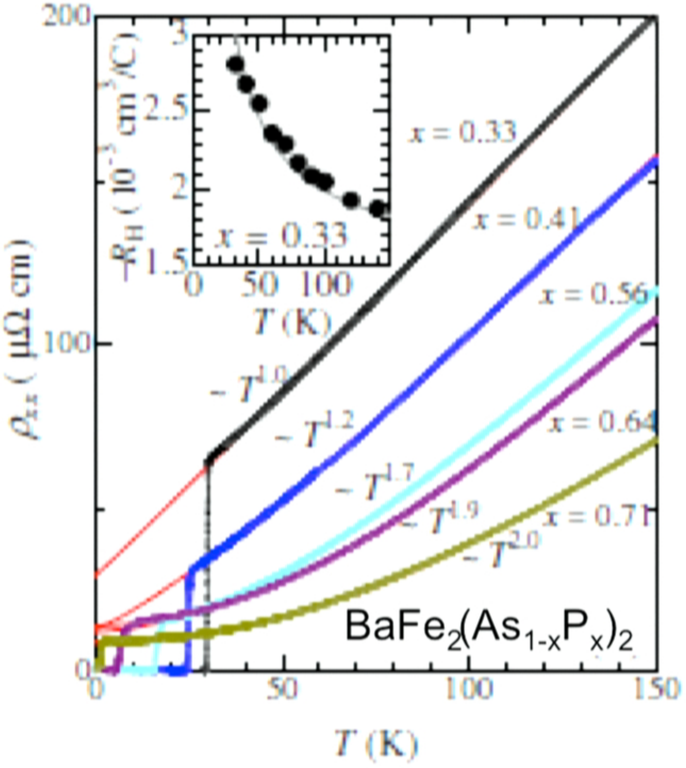


Electrons in graphene I: *D. A. Bandurin et al., Science **351**, 1055 (2016)*

Electrons in graphene II: *J. Crossno et al., Science **351**, 1058 (2016)*

Outstanding question – are hydrodynamics playing a role in transport in quantum critical electron systems?



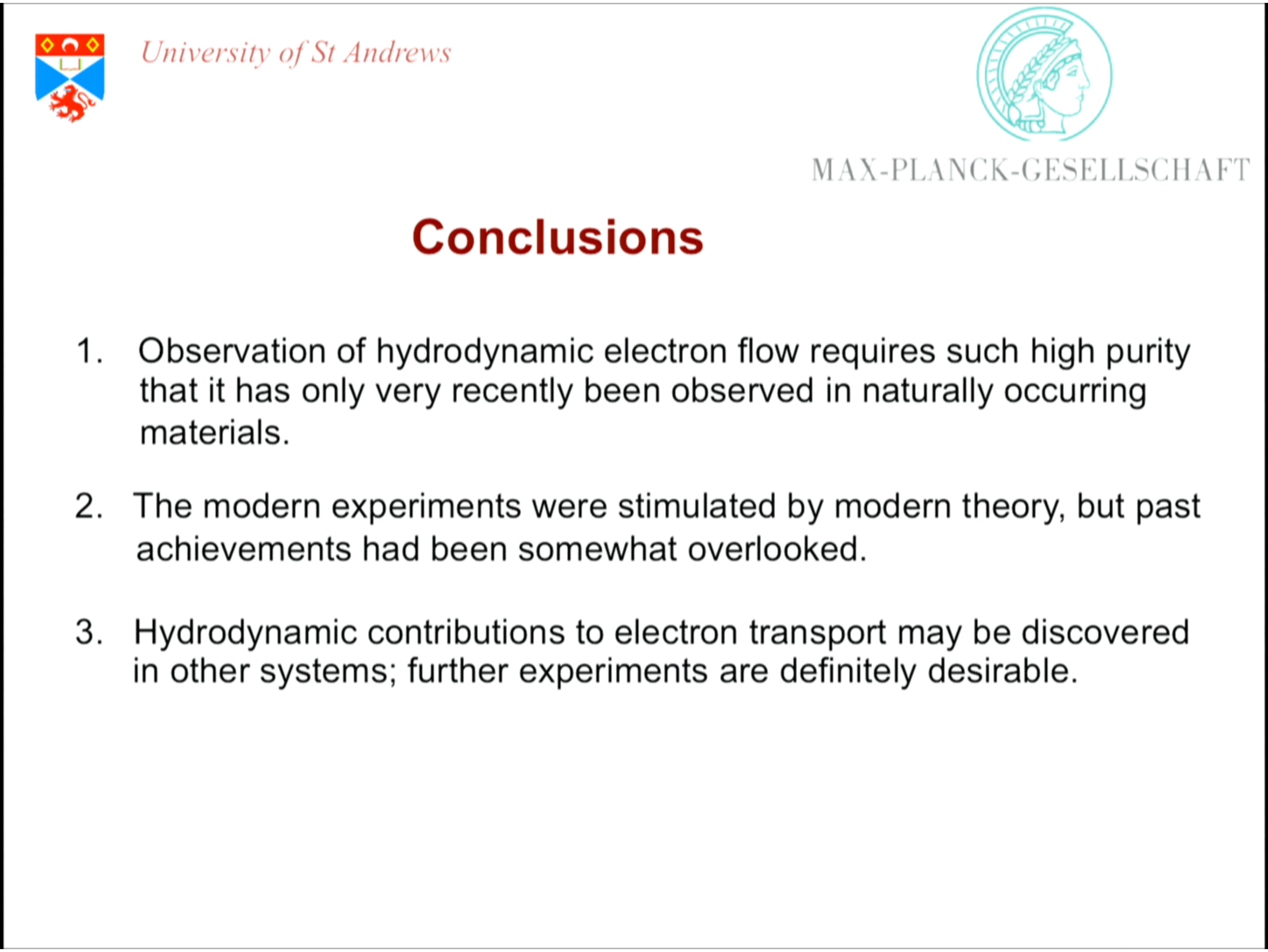
S. Kasahara et al., Phys. Rev. B ***81****, 184519 (2010)*

Cuprates, pnictides, heavy fermions, organics and even some conventional metals can be tuned to show linear resistivity.

Evidence for a universal, high scattering rate when this happens.
J.A.N. Bruin, H. Sakai, R.S. Perry & A.P. Mackenzie, Science ***339****, 804 (2013)*

Is hydrodynamics playing a role in this?
Unknown but, in principle, testable.

Also possible to extend in future to fully three-dimensional systems.



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Conclusions

1. Observation of hydrodynamic electron flow requires such high purity that it has only very recently been observed in naturally occurring materials.
2. The modern experiments were stimulated by modern theory, but past achievements had been somewhat overlooked.
3. Hydrodynamic contributions to electron transport may be discovered in other systems; further experiments are definitely desirable.