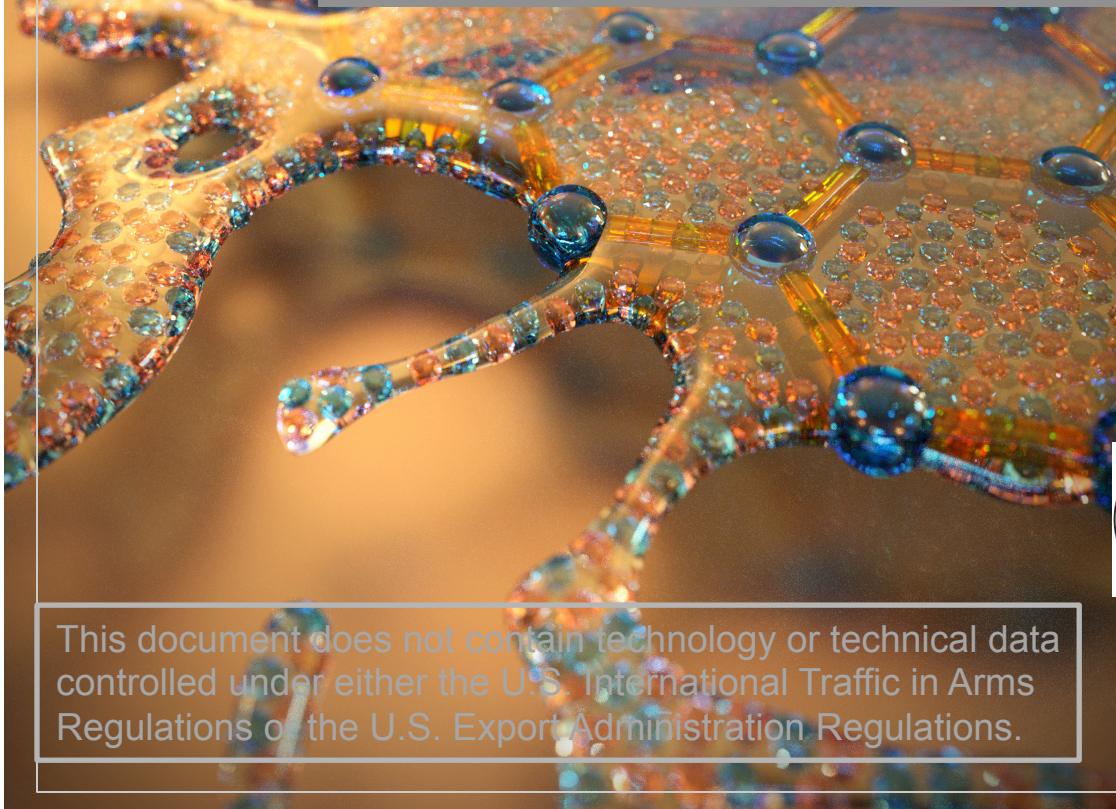




D.Englund E.Walsh D.Efetov J Crossno T.Ohki A. Lucas S Sachdev G-H.Lee P.Kim

Hydrodynamics, quantum sensor, and the search of dark matter



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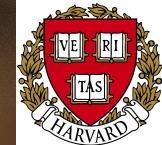
Kin Chung Fong
Quantum Information Processing
Raytheon BBN Technologies

Fermi National Accelerator Lab
April 24, 2019

Collaborators:



ICFO^R

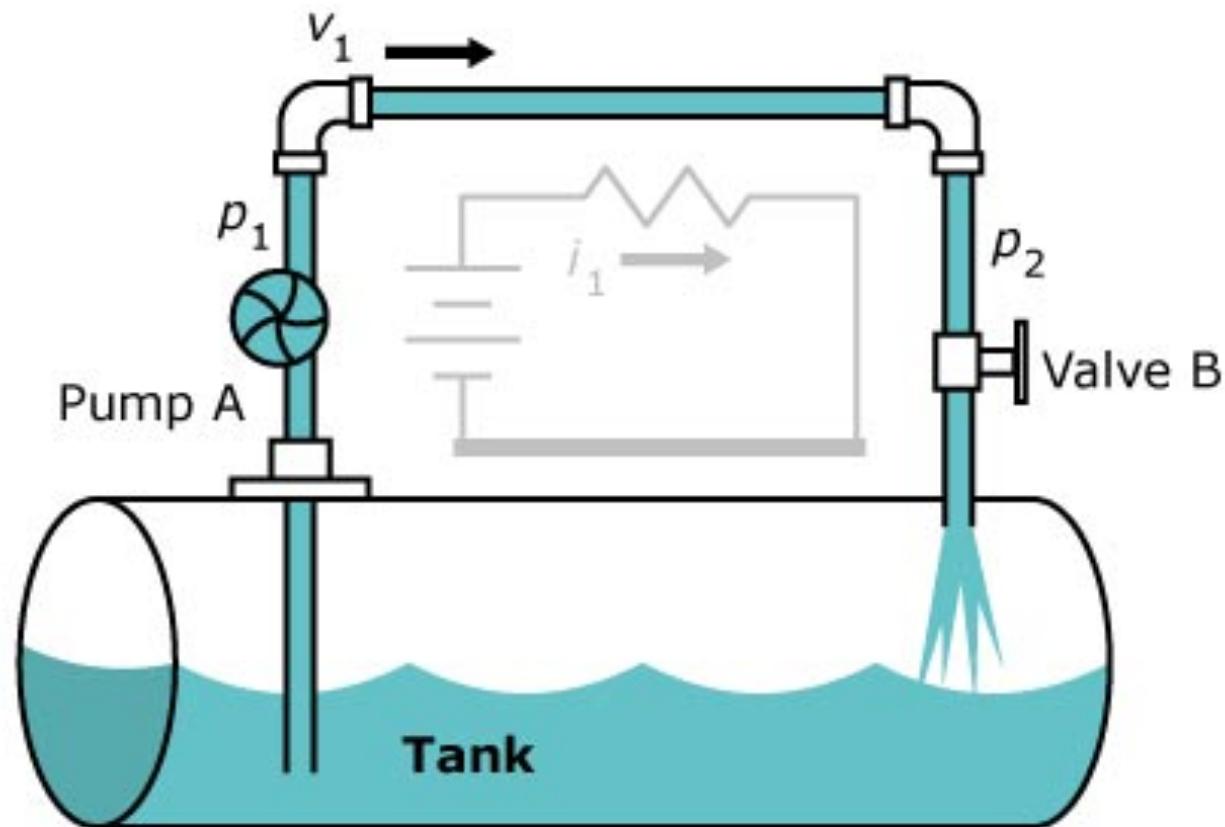


MIT

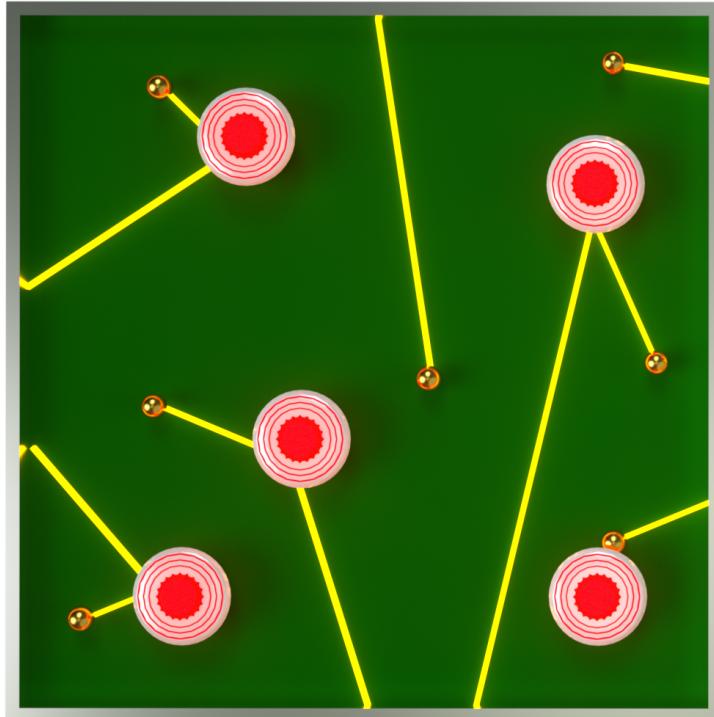


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Hydrodynamics vs. Solid State



Hydrodynamics vs. Solid State



$$\frac{d}{dt} \langle \mathbf{p}(t) \rangle = q\mathbf{E} - \frac{\langle \mathbf{p}(t) \rangle}{\tau}$$

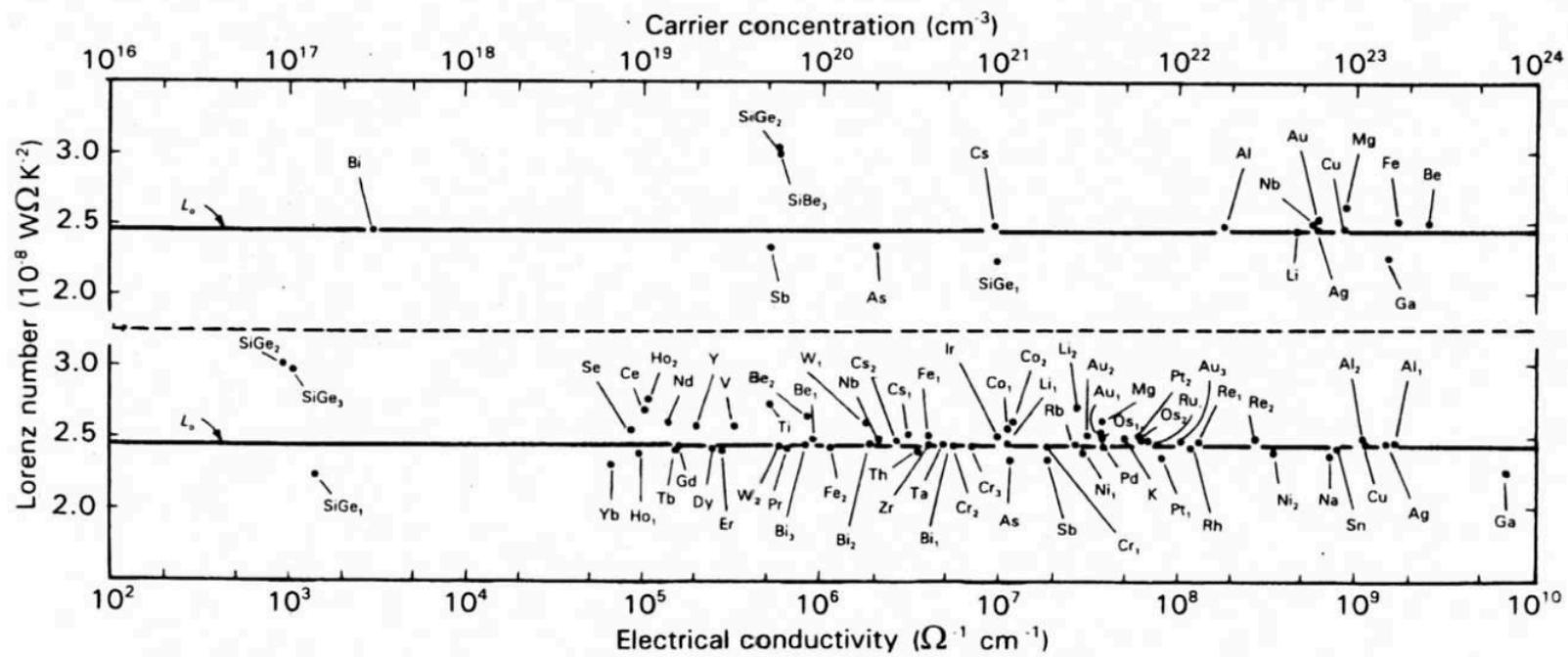
$$\mathbf{J} = \left(\frac{nq^2\tau}{m} \right) \mathbf{E}$$

$$\kappa = \frac{1}{3} c_e v^2 \tau$$

Wiedemann-Franz law

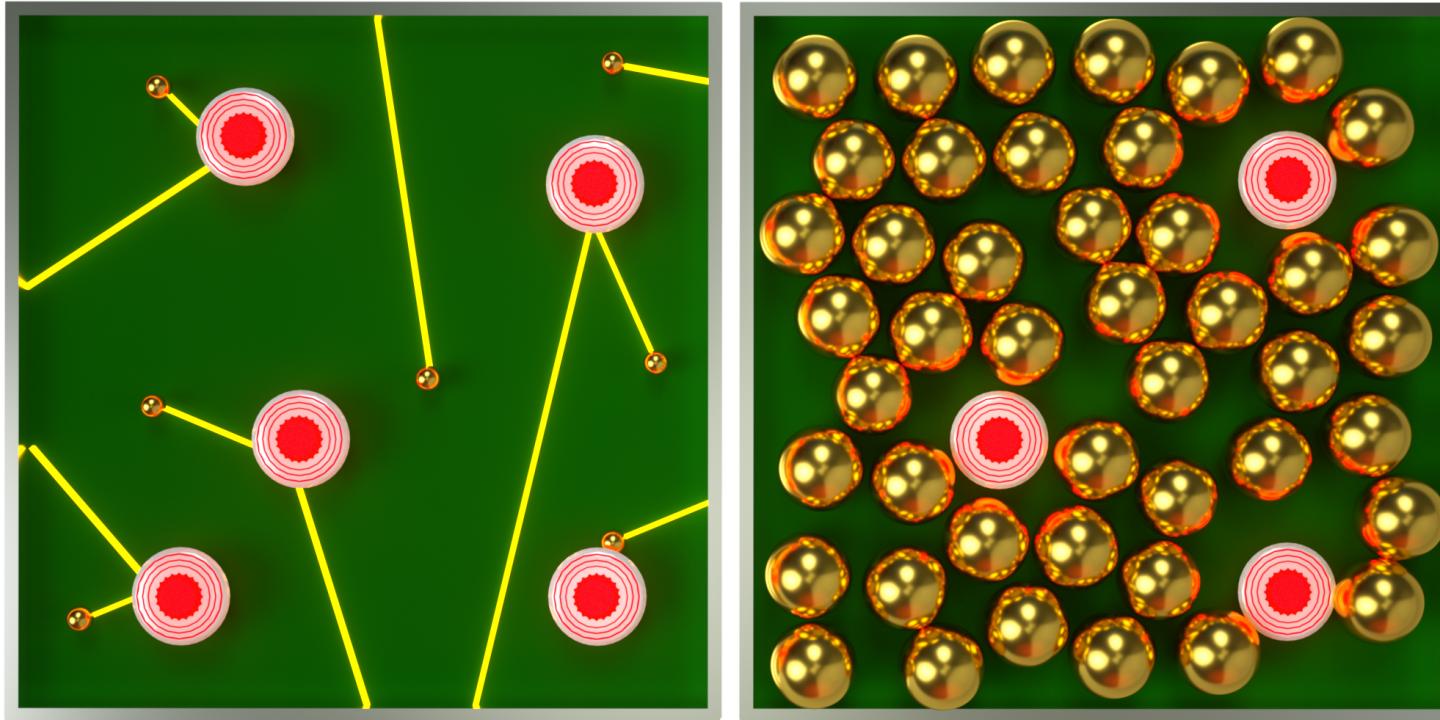
$$\frac{\kappa_{WF}}{\sigma_{elec} T} = L_0 = \frac{\pi^2}{3} \left(\frac{k_B}{e} \right)^2$$

- Independent of density, mass, mean-free-path, scattering time
- True in Drude model and Fermi liquid



Kumar, Prasad, Pohl, J. of Materials Sci. 28, 4261 (1993)

Hydrodynamics



Weakly interacting

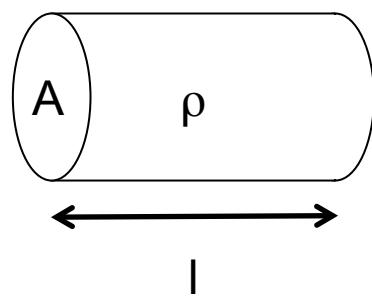
Strongly interacting

Zaanen, Science 351 (2016)

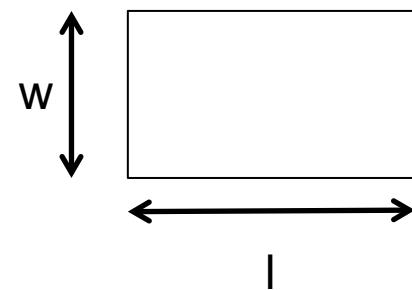
Condition of hydrodynamic description: $\tau_{ee} \ll \tau_{imp}$

Electrical resistance

Ohmic flow

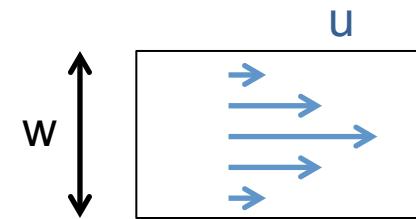


$$R = \frac{\rho l}{A}$$



$$R \propto \frac{1}{w}$$

Hydrodynamic flow



$$R = \frac{12\eta l}{n^2 e^2 w^3}$$

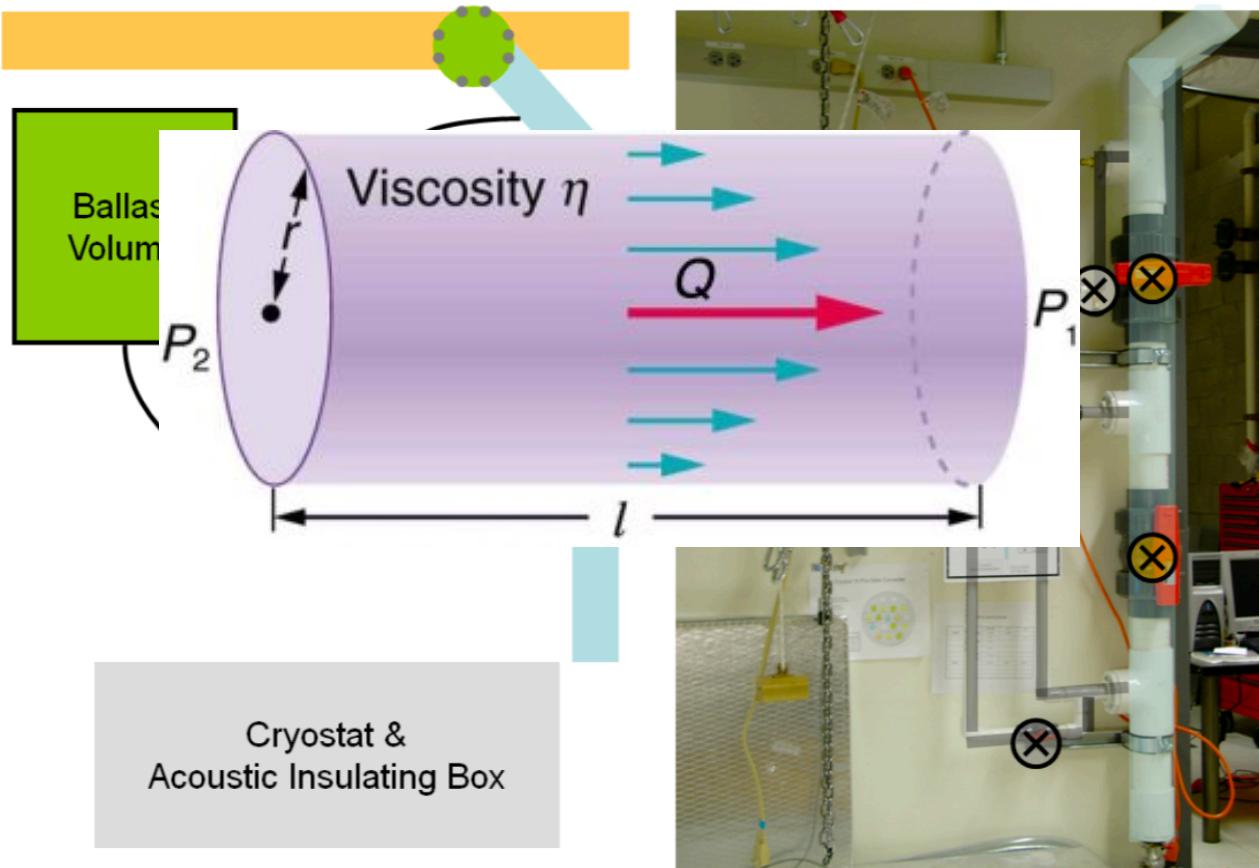
Poiseuille's flow

Poiseuille flow

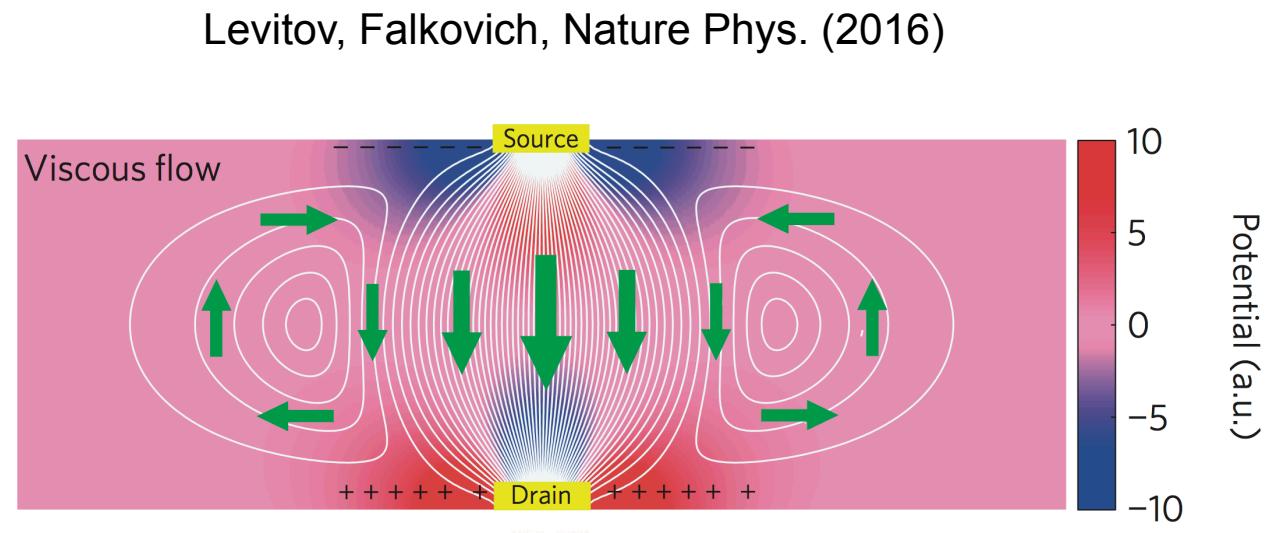
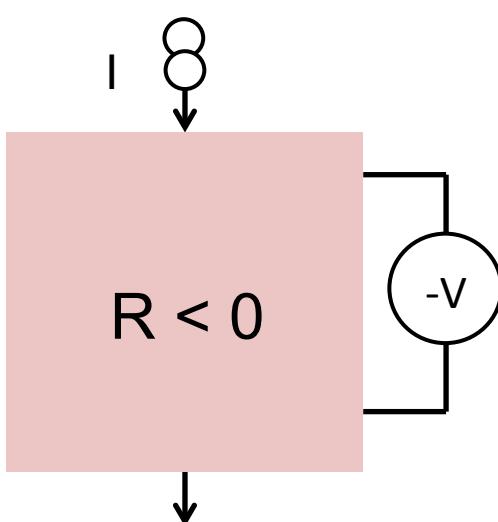
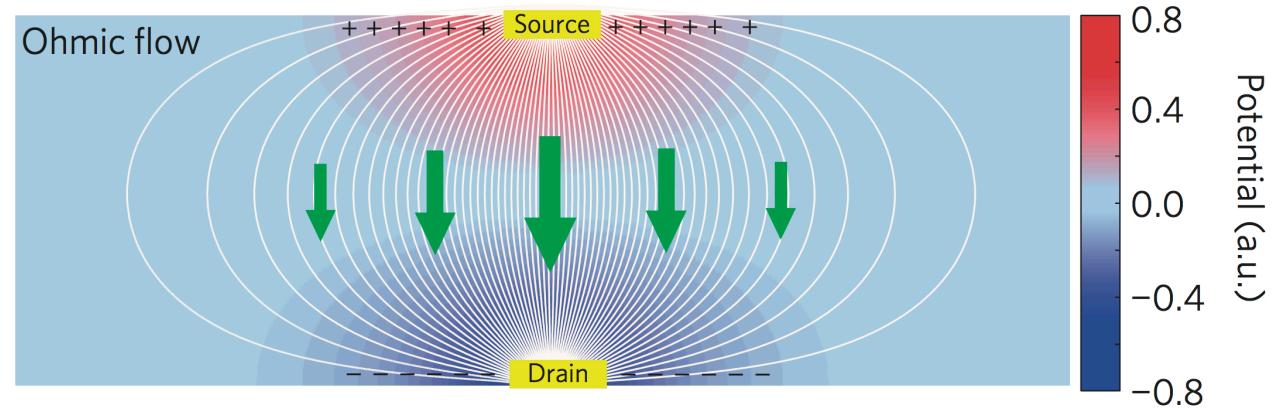
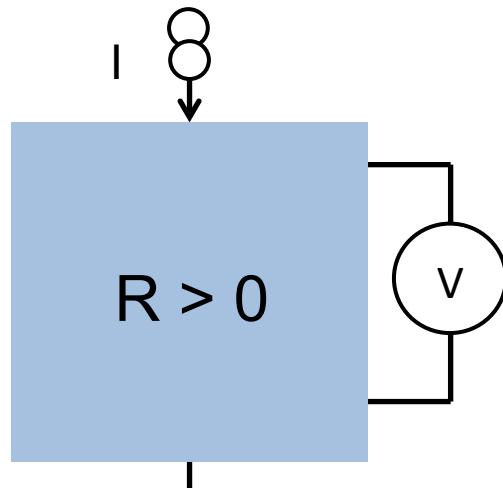
$$\frac{\Delta P}{\text{vol / time}} = \frac{8\eta l}{\pi r^4}$$

Electrical

$$R = \frac{12\eta l}{n^2 e^2 w^3}$$



Hydrodynamics in resistance measurement

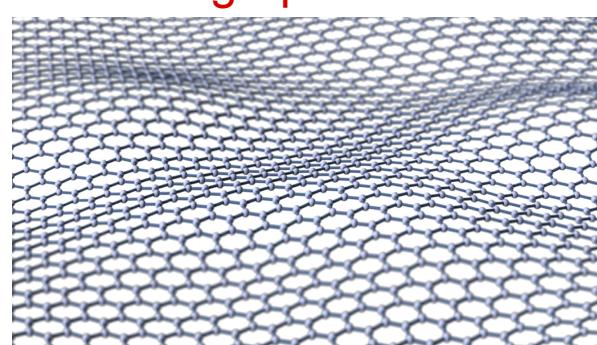
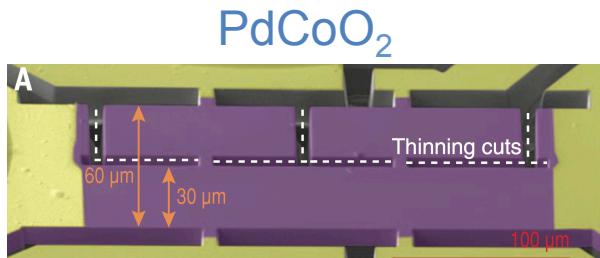


Hydrodynamics in solid

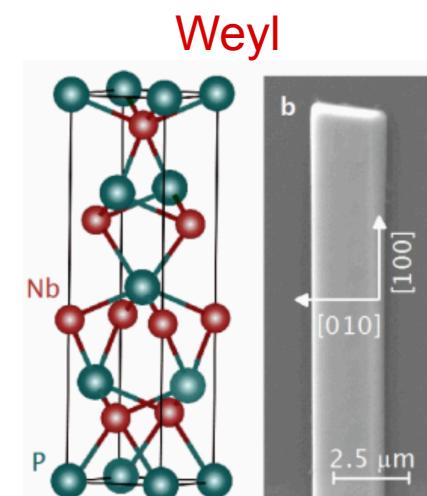
-
- R. N. Gurzhi, J. Expt. and Th. Phys. 17 521 (1963)
 - de Jong and Molenkamp, PRB 1995
 - Chow, Wei, Girvin, Shayegan PRL 1996
 - Andreev, Kivelson, Spivak, PRL 106, 256804 (2011)
 - Titov, et. al., PRL 111, 166601 (2013)
 - Apostolov, Levchenko, Andreev, PRB 89 121104 (2014)
 - Moll, et. al., Science 351, 1061 (2016)
 - Crossno, et. al. Science 351, 1058 (2016)
 - Bandurin, et. al. Science 351, 1055 (2016)
 - Kumar, et. al., Nat. Physics. 17, 521 (2017)
 - Gooth, et. al., Nature 547, 324 (2017)
 - Gooth, et. al., arXiv:1706.05925 (2017)

Hydrodynamics in solid

- R. N. Gurzhi, J. Expt. and Th. Phys. 17 521 (1963)
- GaAs { de Jong and Molenkamp, PRB 1995
 Chow, Wei, Girvin, Shayegan PRL 1996
 Andreev, Kivelson, Spivak, PRL 106, 256804 (2011)
- Coulomb drag { Titov, et. al., PRL 111, 166601 (2013)
 Apostolov, Levchenko, Andreev, PRB 89 121104 (2014)
- PdCoO₂ { Moll, et. al., Science 351, 1061 (2016)
 Crossno, et. al. Science 351, 1058 (2016)
- graphene { Bandurin, et. al. Science 351, 1055 (2016)
 Kumar, et. al., Nat. Physics. 17, 521 (2017)
- Weyl { Gooth, et. al., Nature 547, 324 (2017)
 Gooth, et. al., arXiv:1706.05925 (2017)

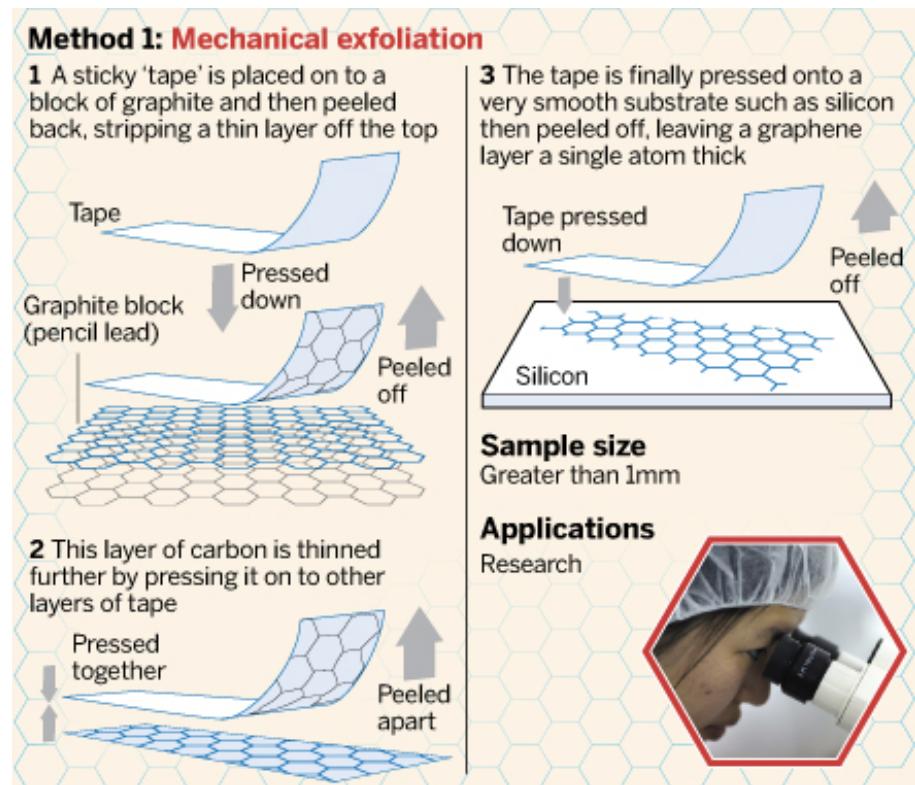
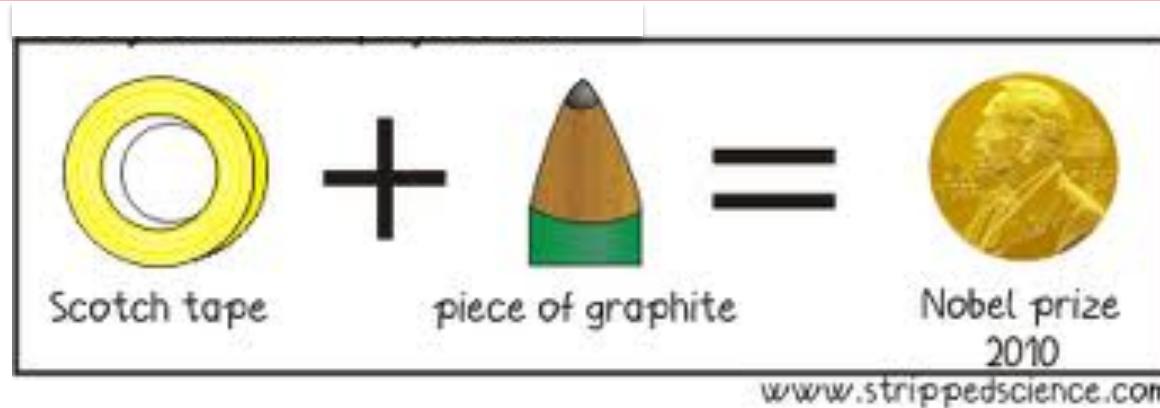


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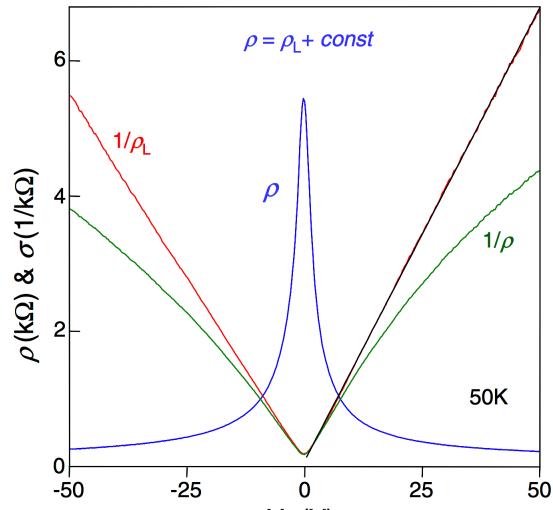
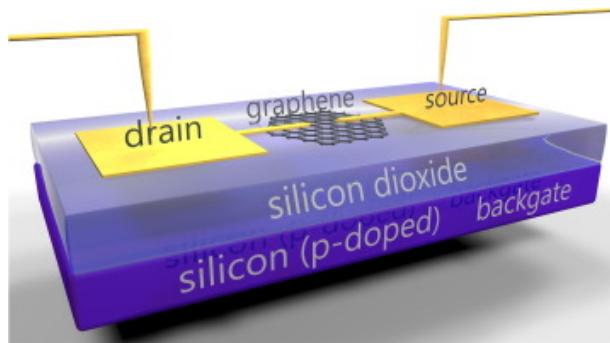


Graphene

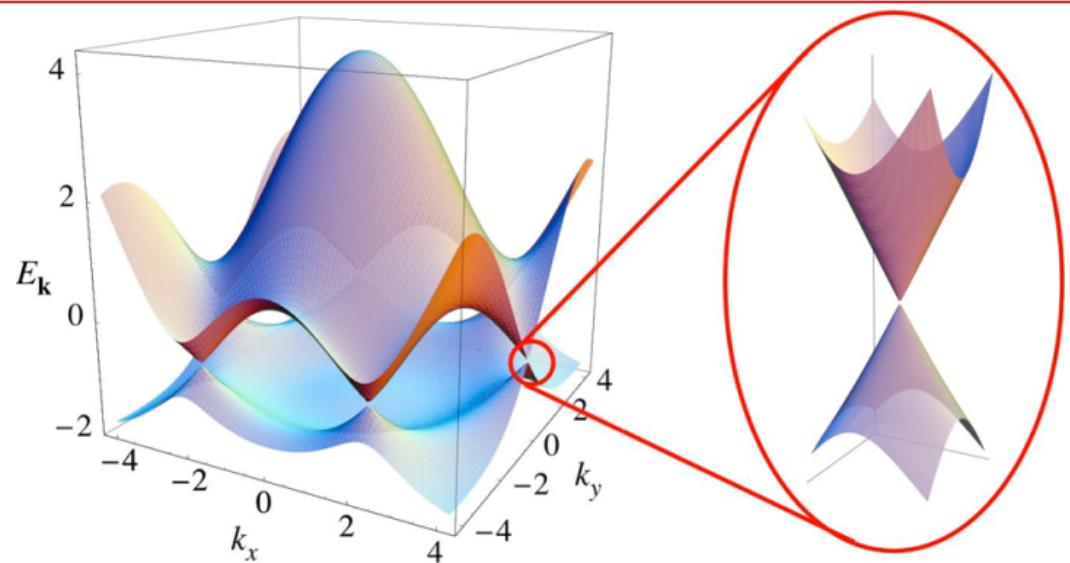
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Dirac point



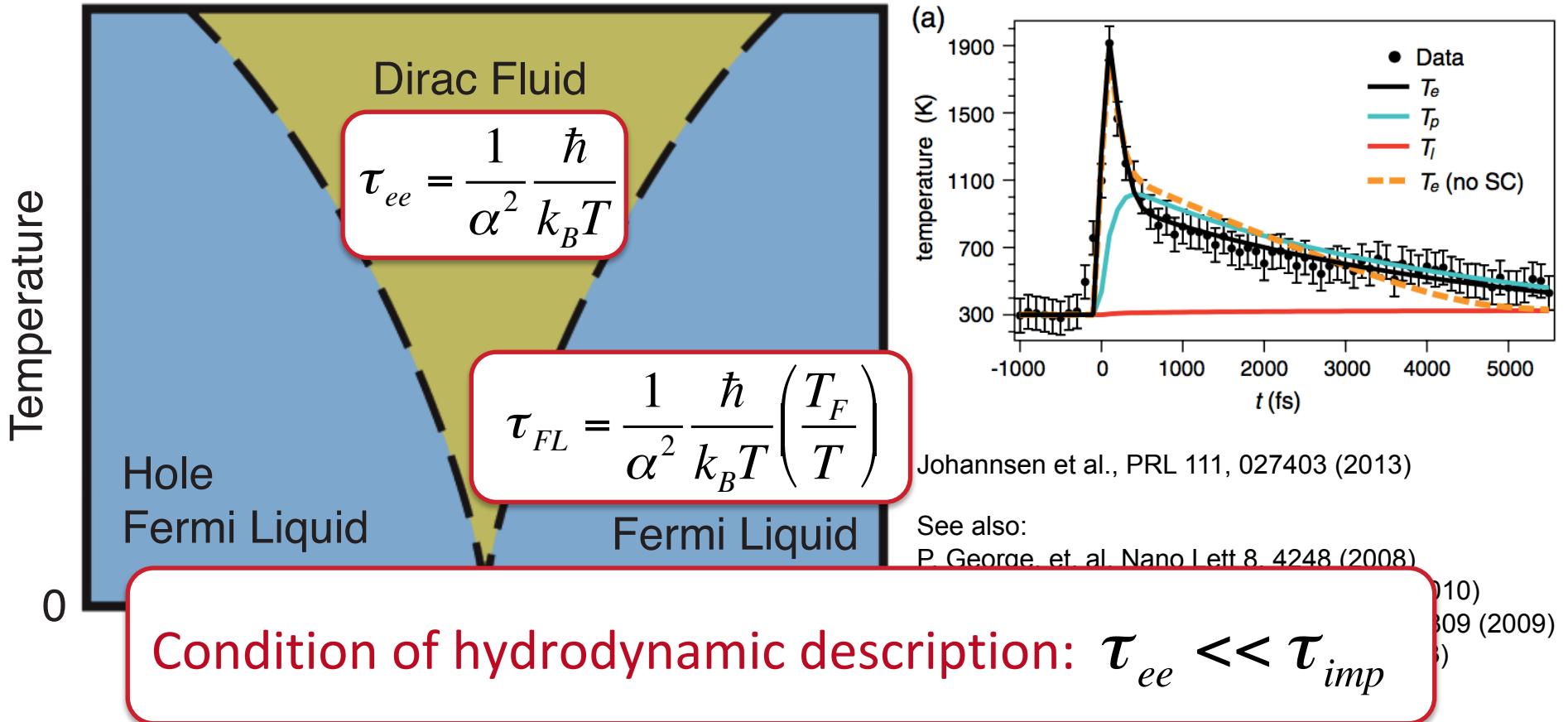
PRL 100, 016602 (2008)



Phys. Rev. 71, 622 (1947)
RMP 81, 109 (2009); 83, 407 (2011)

- $E = \hbar v_F k_F = \hbar v_F \sqrt{\pi n}$
 - Metallic
 - $DOS = 2E / (\pi(\hbar v_F)^2)$
 - Weak screening, Strong e-e interaction
- $$\alpha = \frac{Potential}{Kinetic} = \frac{e^2}{\epsilon_r \hbar v_F} \approx 0.5$$
- *Quantum criticality*

Fast e-e interaction



Sheehy and Schmalian, PRL 99, 226803 (2007)

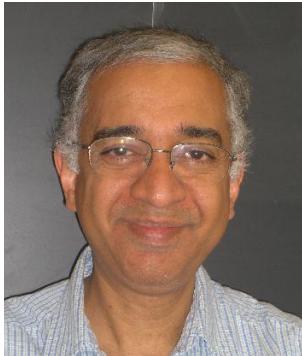
See also:

Fritz, Schmalian, Muller, and Sachdev, PRB (2008).

Muller, Fritz, and Sachdev, PRB (2008).

Foster and Aleiner, PRL (2009).

Muller, Schmalian, Fritz, PRL (2009)

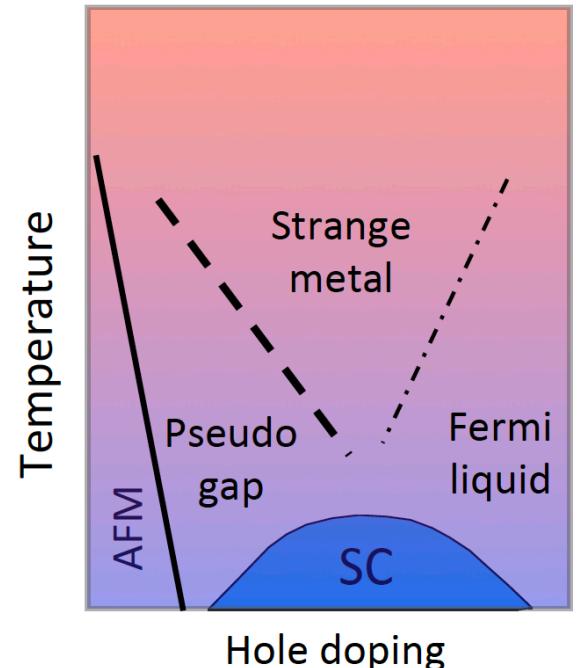


Randeria

Quantum phases without sharp quasiparticles

- * Normal state of high T_c superconductors
- * Quantum critical regimes
- * Unitary Fermi gas; BCS-BEC crossover
- * Quark-gluon plasma
- * String Theory: AdS/CFT

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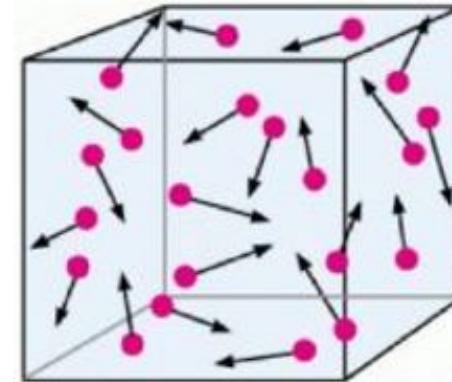


Minimum viscosity

Sharp quasiparticle:

$$l_{mfp} \gg \frac{\hbar}{p}$$

$$\frac{npl_{mfp}}{n} = \frac{\eta}{n} \gg \hbar$$



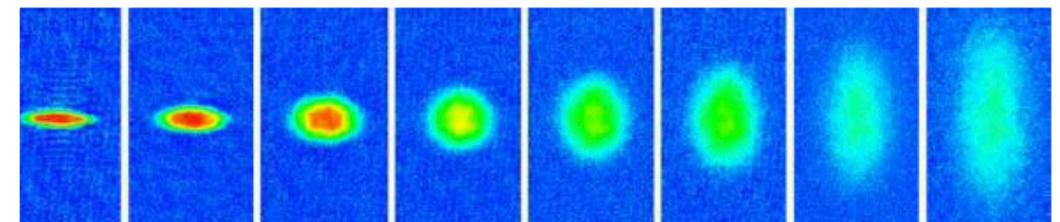
Kovtun-Son-Starinets Bound
PRL (2005)

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$$

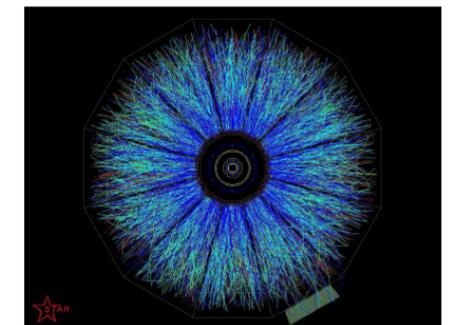
Experimental search for the “perfect fluid”

| Fluid | $T [K]$ | $\eta [Pa \cdot s]$ | $\eta/n [\hbar]$ | $\eta/s [\hbar/k_B]$ |
|---|---------------------|----------------------------|------------------|----------------------|
| H ₂ O | 370 | 2.9×10^{-4} | 85 | 8.2 |
| ⁴ He | 2 | 1.2×10^{-6} | 0.5 | 1.9 |
| ⁶ Li ($ a_s \simeq \infty$) | 23×10^{-6} | $\leq 1.7 \times 10^{-15}$ | ≤ 1 | ≤ 0.5 |
| QGP | 2×10^{12} | $\leq 5 \times 10^{11}$ | - | ≤ 0.4 |

The coldest and
The hottest fluids
ever made in
a laboratory



Unitary Fermi gas
(Thomas)

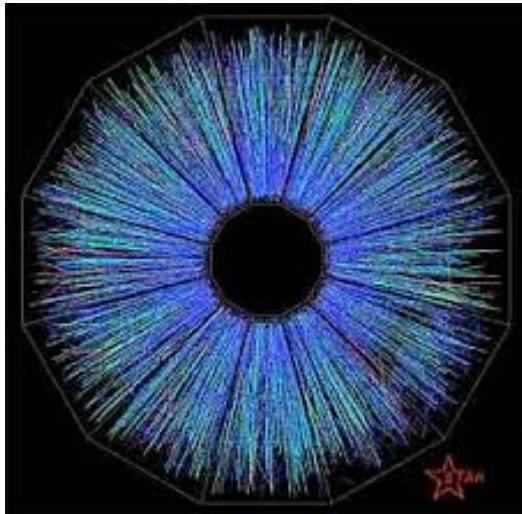


QGP
(RHIC)

Data from: T. Schafer & D. Teaney, Rept.Prog.Phys. (2009)

Hydrodynamic physics

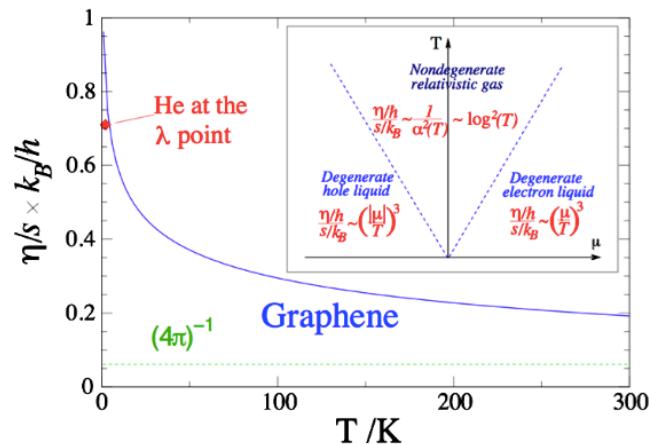
Quark-gluon plasma



RHIC: relativistic heavy ion collider

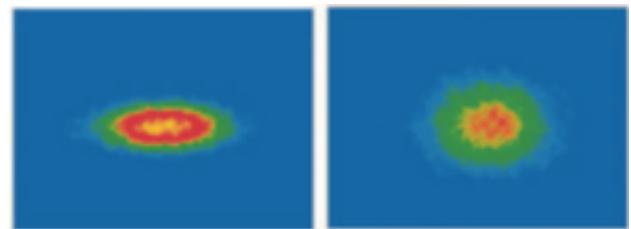
$>10^{12}$ K

Graphene



Mueller, Schmalian, Fritz,
PRL 2009

Unitary quantum gas



Cao, Elliott, Joseph, Wu,
Petricka, Schafer, Thomas,
Science 2011

1 uK

Experimental signature of Dirac fluid

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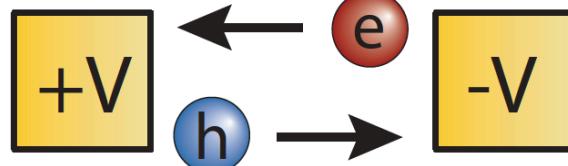
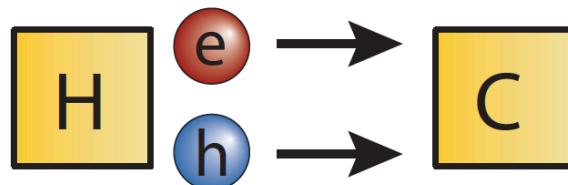
Quantum-critical relativistic magnetotransport in graphene

Markus Müller, Lars Fritz, and Subir Sachdev

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 9 June 2008; revised manuscript received 13 August 2008; published 5 September 2008)

In the quantum-critical regime $\mu \lesssim T$ we find pronounced deviations from Fermi-liquid behavior, such as a collective cyclotron resonance with an intrinsic collision-broadened width and significant enhancements of the Mott and Wiedemann-Franz ratios. Some of these results have been anticipated by a relativistic hydrodynamic theory,

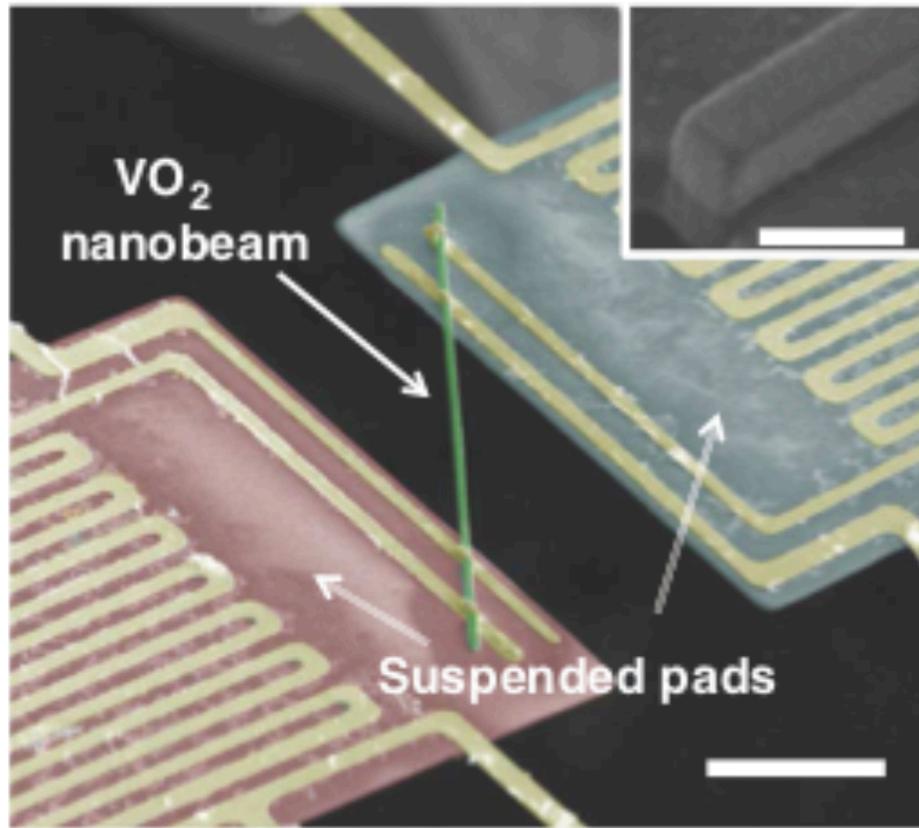


$$\frac{K_{DL}}{\sigma_{elec} T} > L_0$$

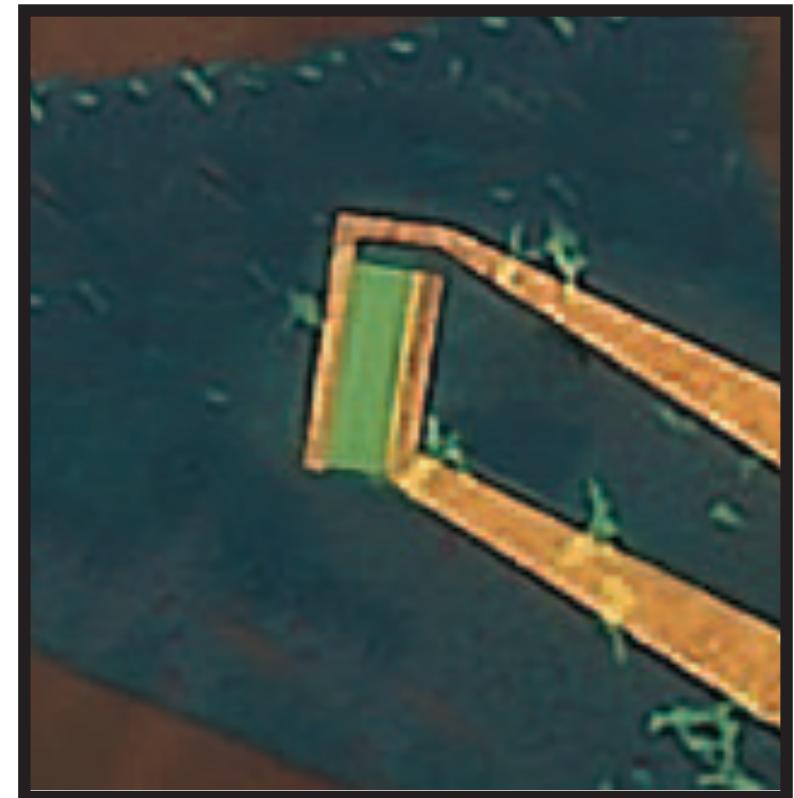
Foster and Aleiner, PRB (2009)

How to measure electrical thermal conductivity?

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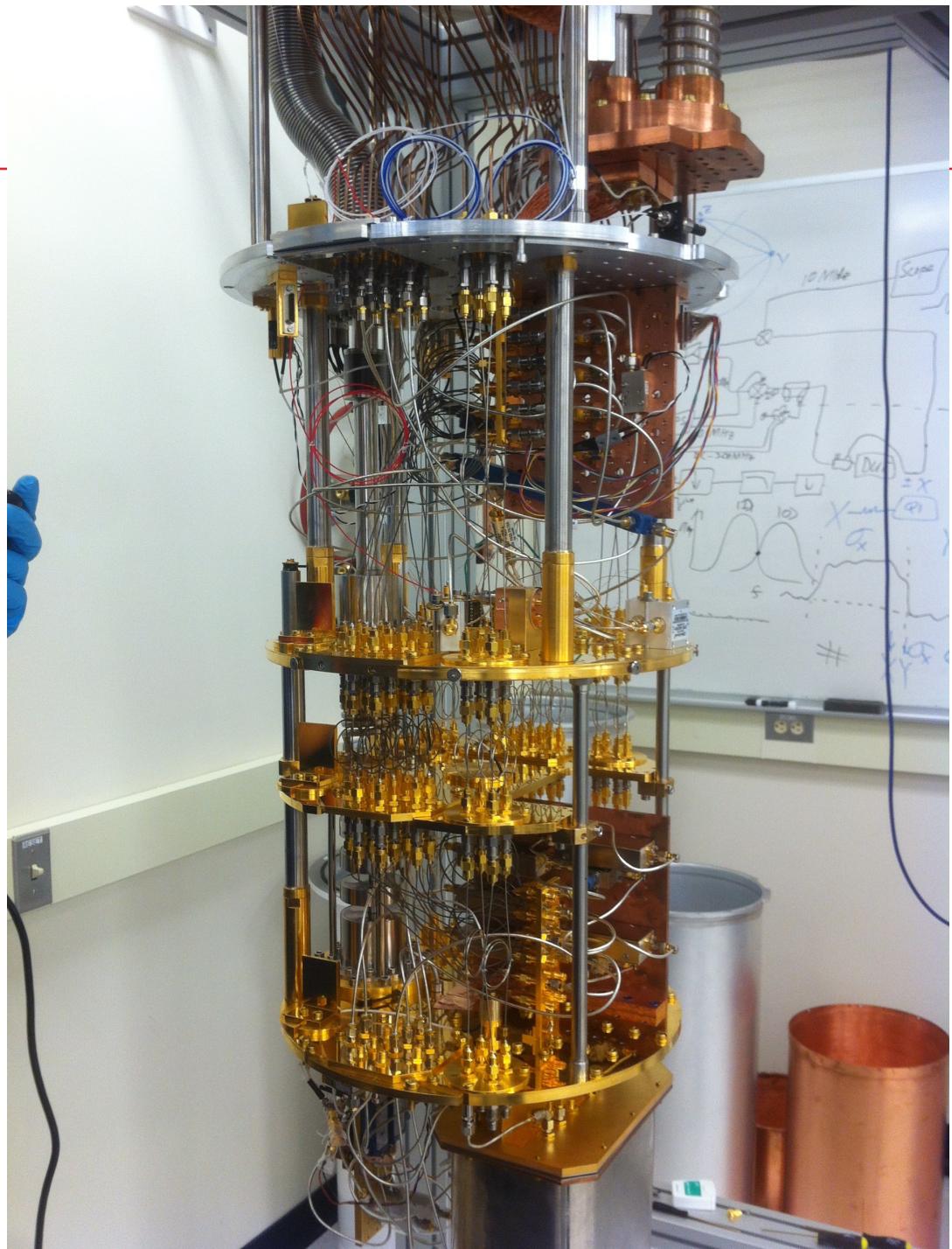
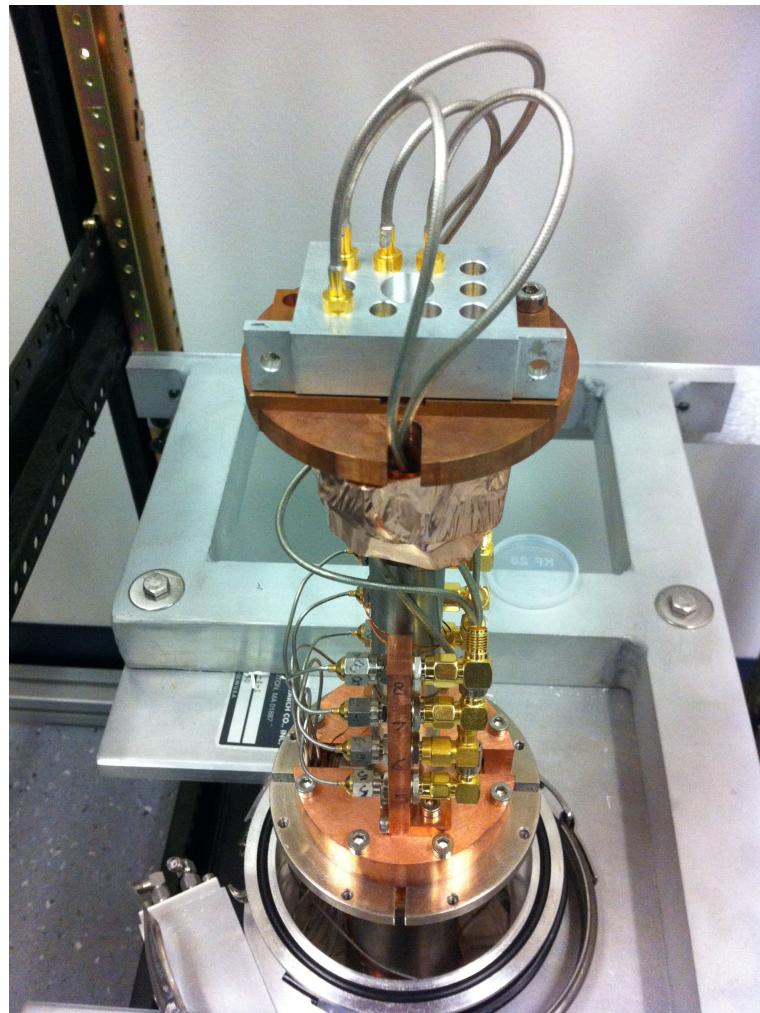


Science 355, 371 (2017)



Science 351, 1058 (2016)

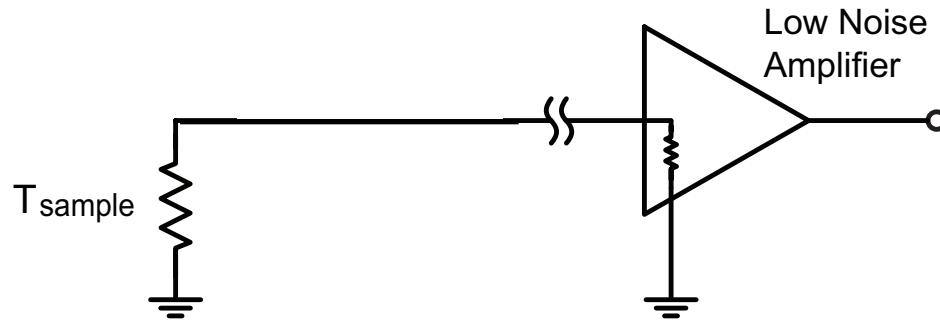
Experimental setup



kc.fong@raytheon.com

How to measure electron temperature?

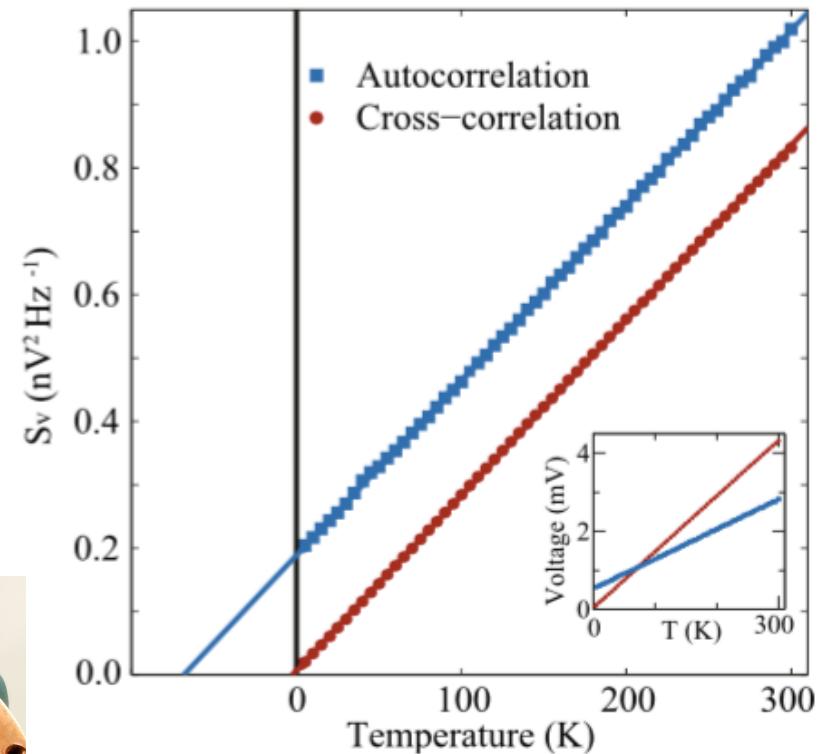
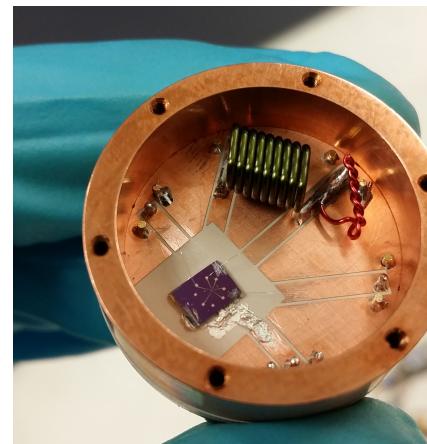
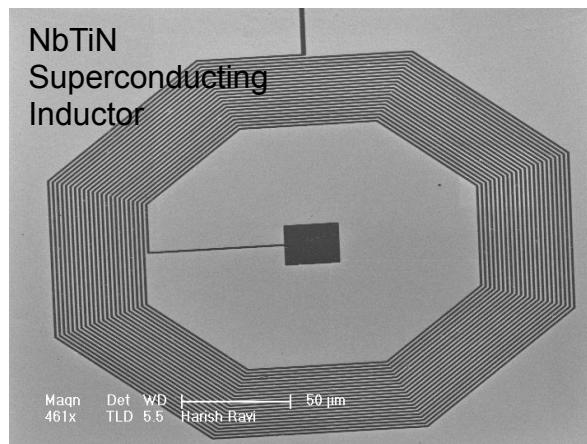
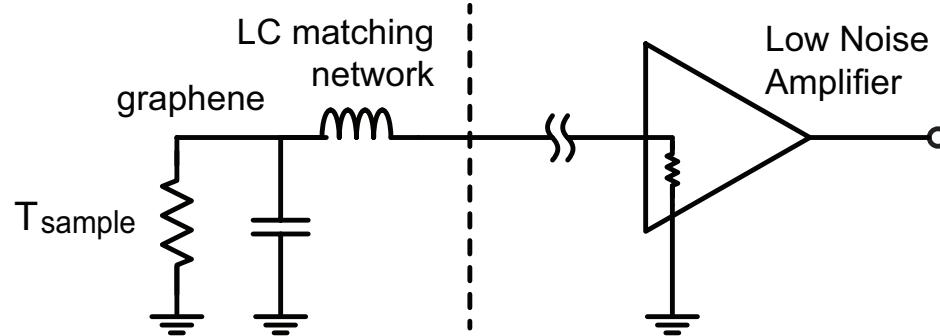
$$S_V = 4R(k_B T_e)$$



- On the order of $\sim 10 \text{ pV}$ at 1K
- Noisy!!
- Amplifier also inject noise!
- Impedance matching

Johnson noise radiometer

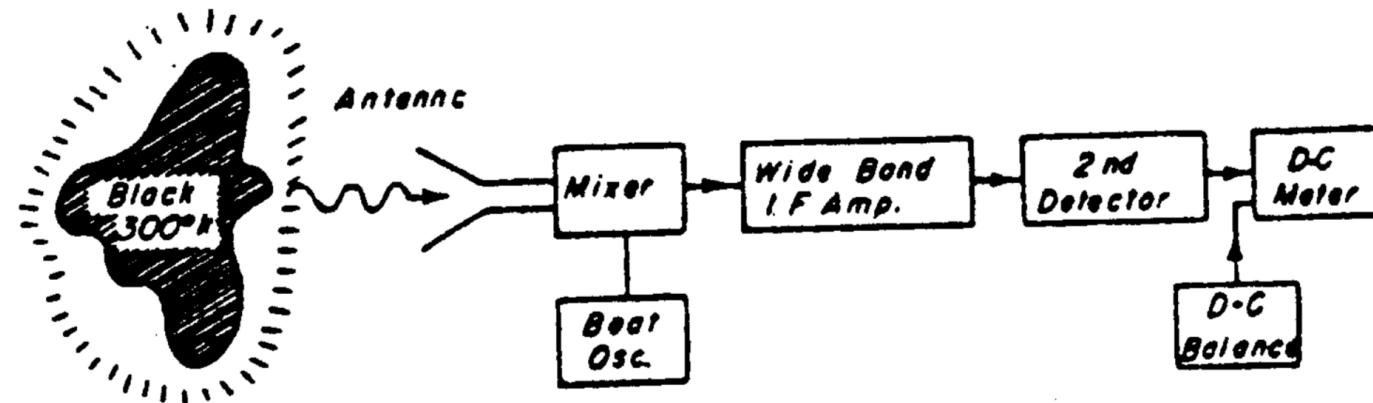
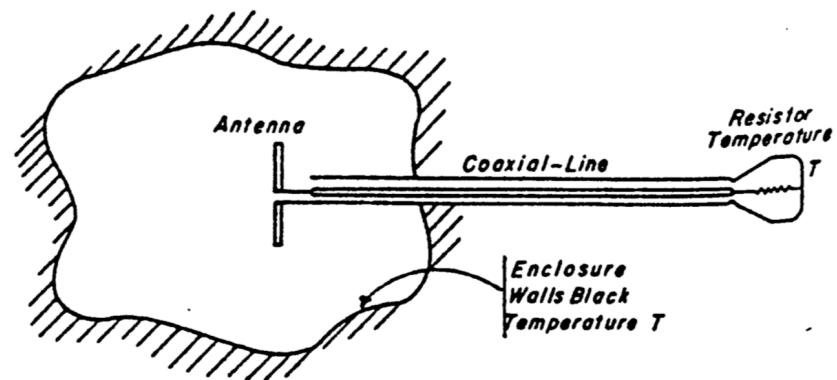
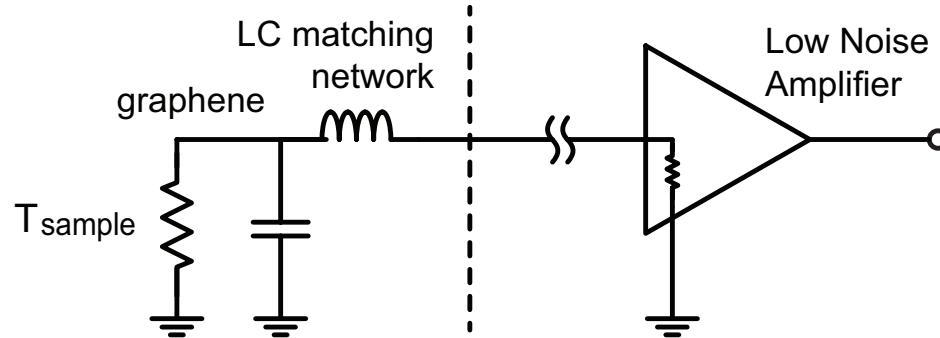
$$S_V = 4R(k_B T_e + k_B T_{sys})$$



Dicke Radiometer

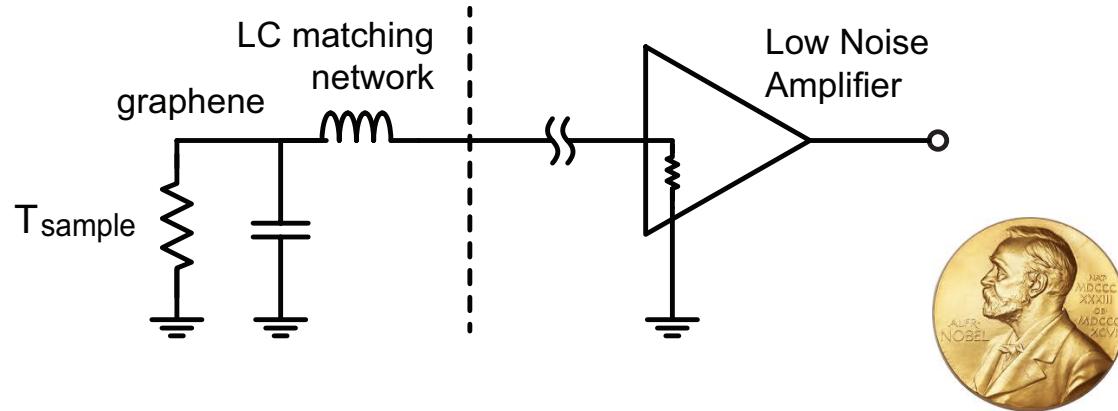
$$S_V = 4R(k_B T_e + k_B T_{sys})$$

Rev. of Sci. Inst. 17, 268 (1946)



Measuring the temperature of universe

$$S_V = 4R(k_B T_e + k_B T_{sys})$$



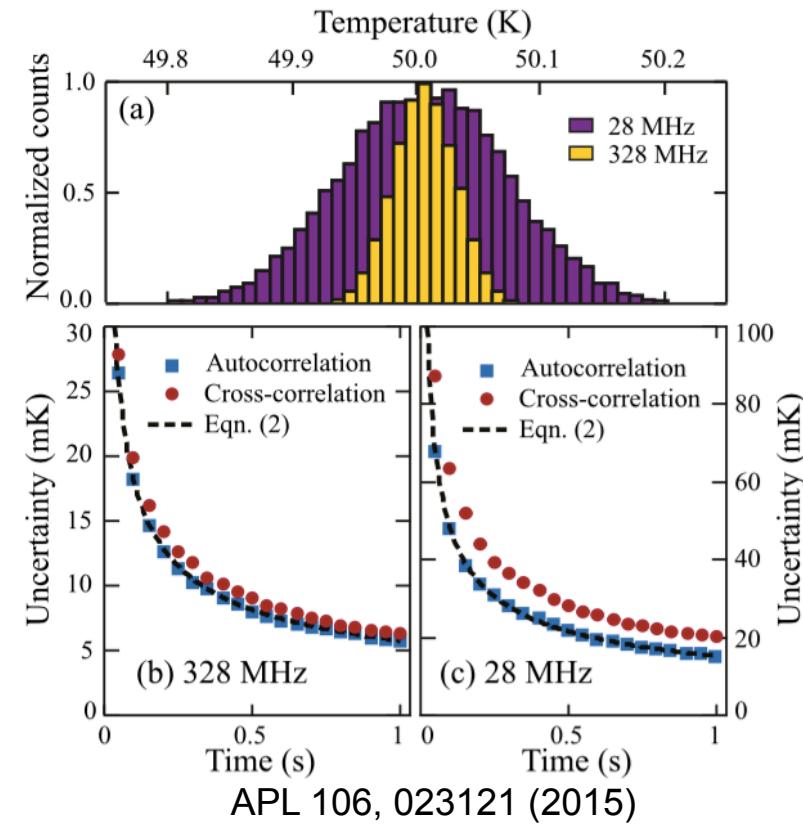
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Noise of the Johnson noise

$$S_V = 4R(k_B T_e + k_B T_{sys})$$

$$\delta T = \frac{T_e + T_{sys}}{\sqrt{\Delta f \cdot \tau}}$$

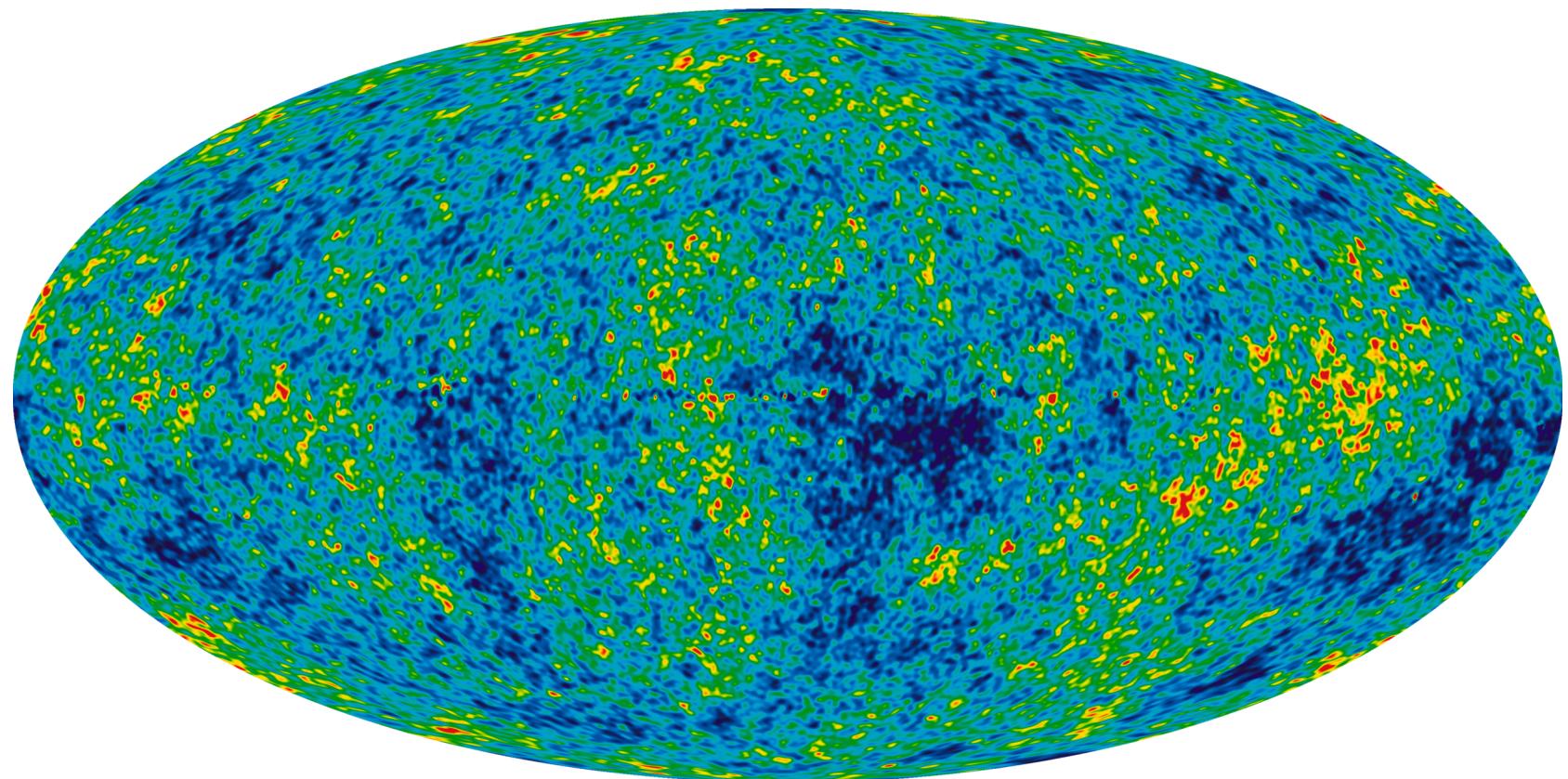


APL 106, 023121 (2015)

Temperature sensitivity $\sim \text{mK} / \text{Hz}^{1/2}$

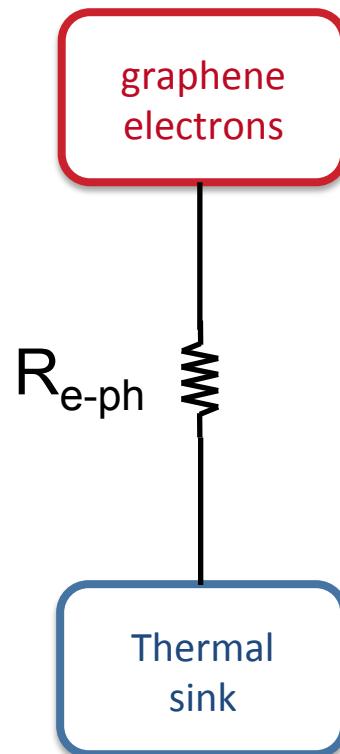
Where does our mK sensitivity stand?

$$T = 2.72548 \pm 0.00057 \text{ K}$$



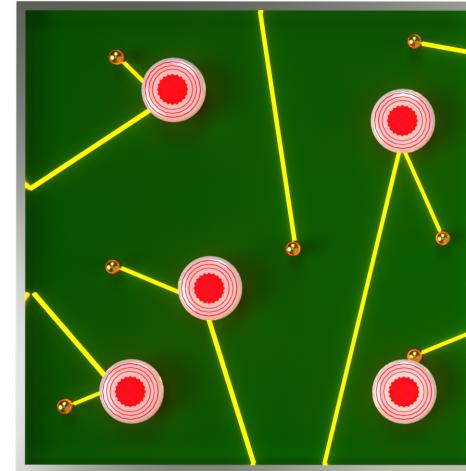
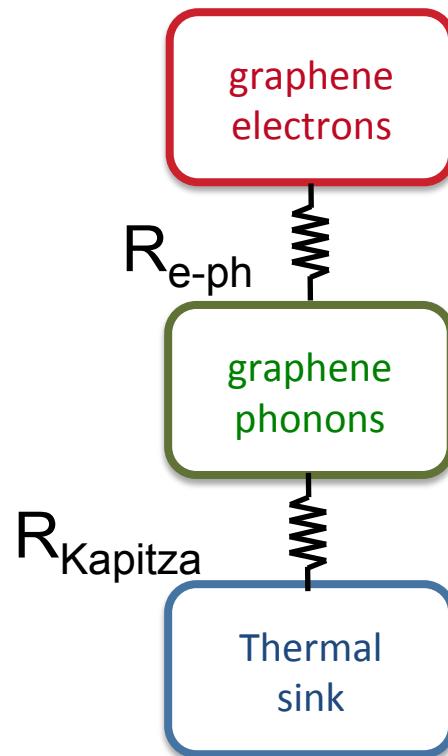
Understanding the thermal pathways

$$P_{heating} = I^2 R = G_{th} (T_e - T_{ph})$$



| Electrical | Thermal |
|------------|---------------------|
| V | T |
| I | P |
| R_{elec} | $R_{th} = 1/G_{th}$ |
| C_{elec} | C_{th} |

Electron-phonon coupling in graphene

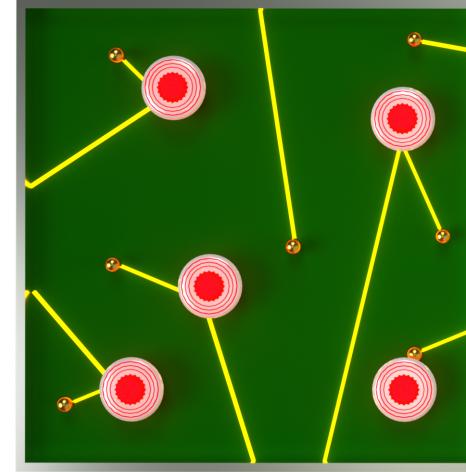
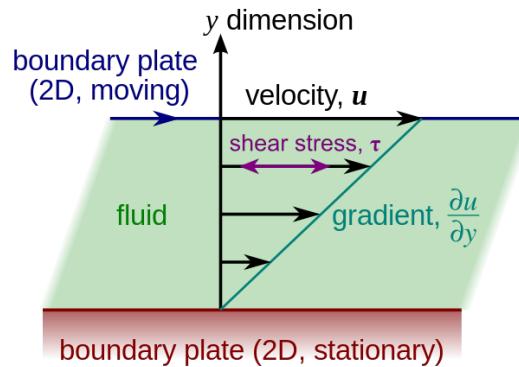


$$P_{e-ph} = A \Sigma_{e-ph} (T_e^3 - T_{ph}^3)$$

$$P_{\text{Blackbody}} = A \sigma (T_h^5 - T_c^5)$$

In metal: 0.5 nK change
for 50 W in 1 mm³
(PRL 1985, PRB 1994)

Momentum relaxation in hydrodynamics



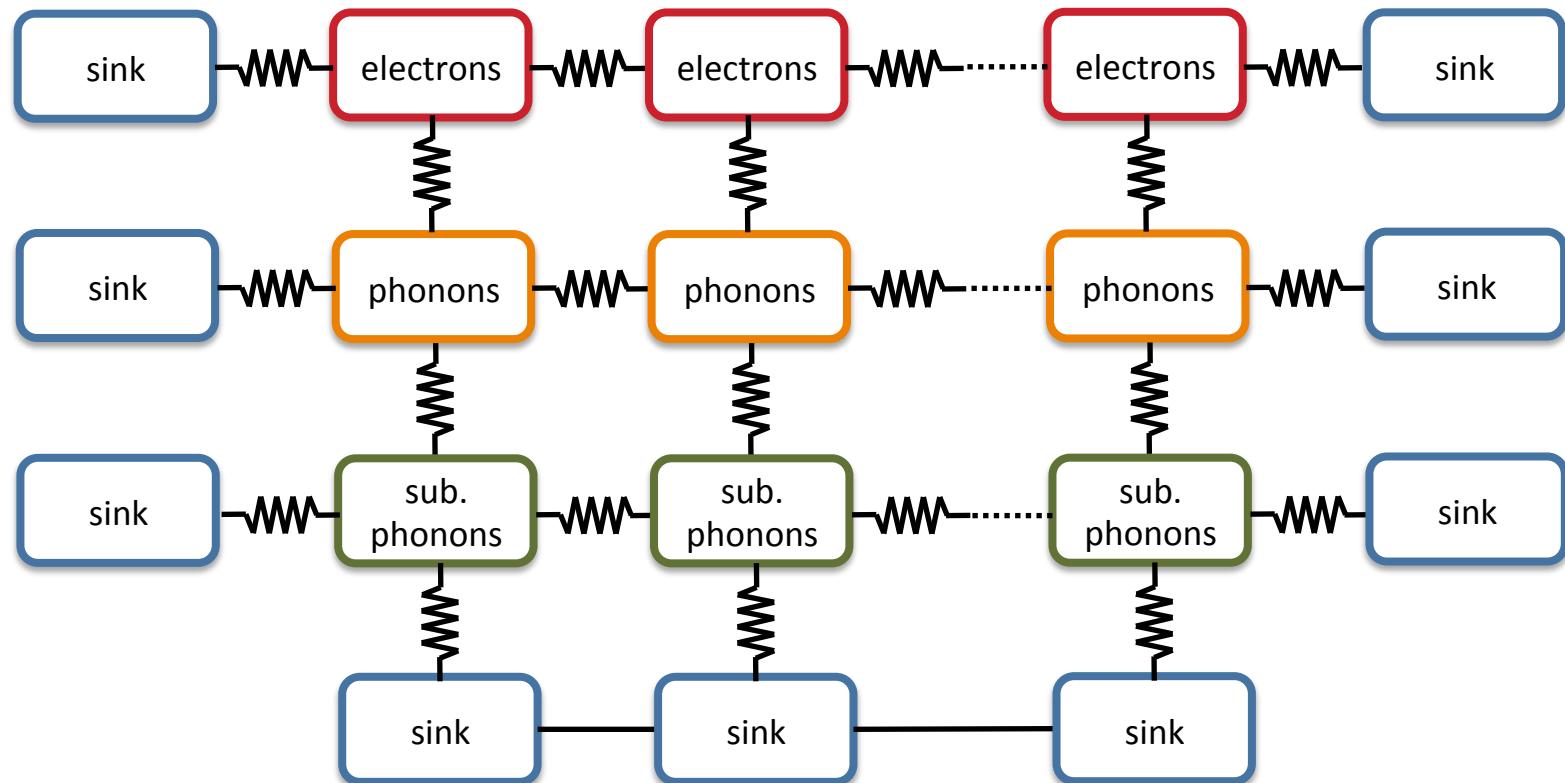
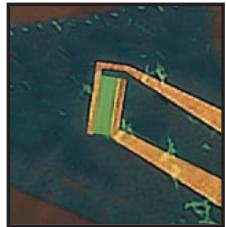
Dissipation via viscosity

$$\frac{\eta}{\rho_m} \nabla^2 u$$

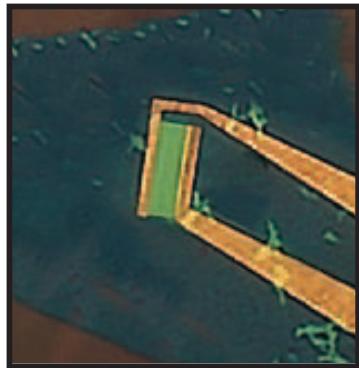
Dissipation via impurities or phonons

$$\frac{u}{\tau_{MR}}$$

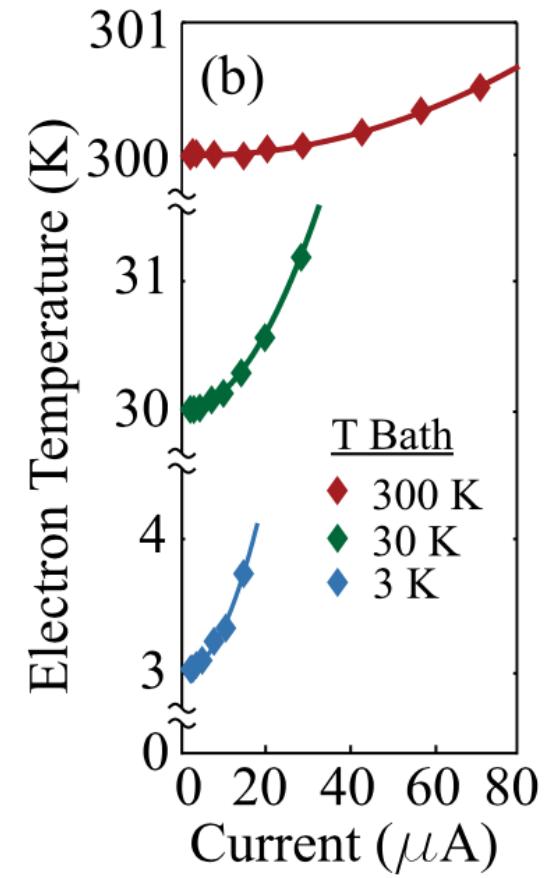
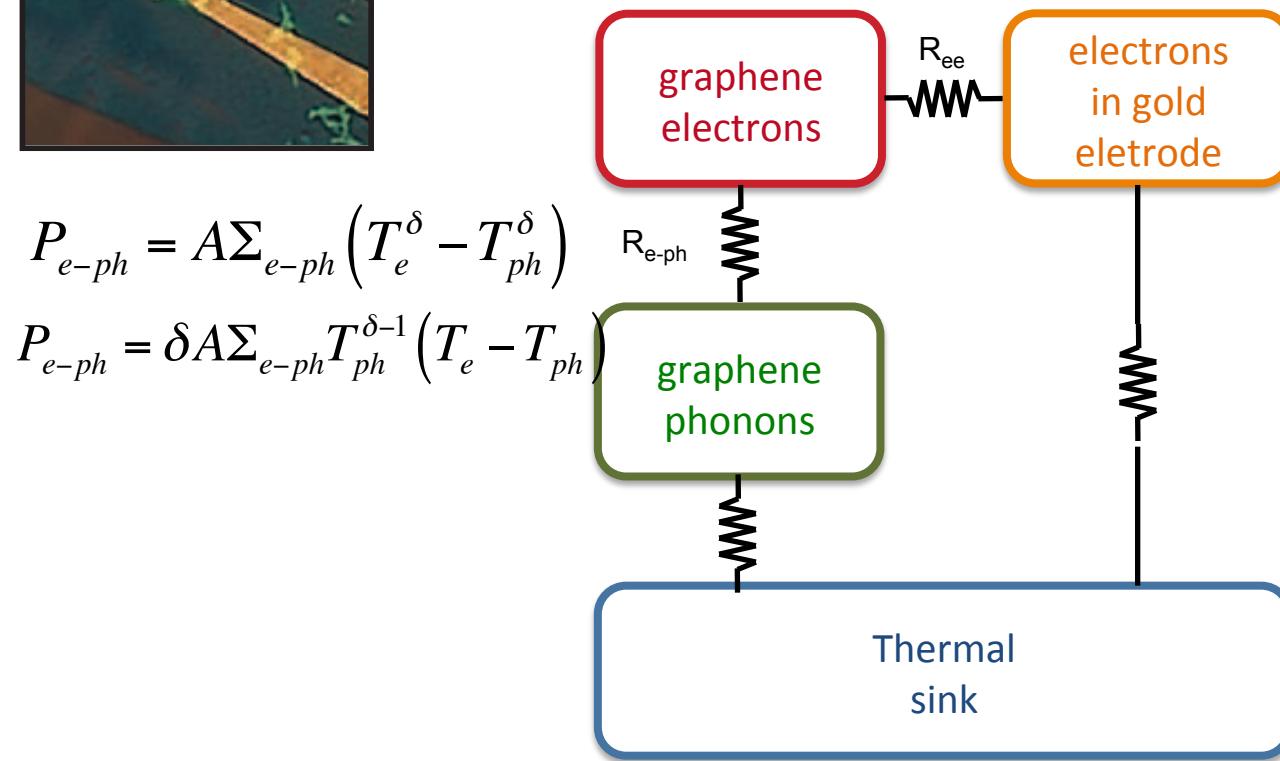
Thermal diagram



Differential thermal measurement

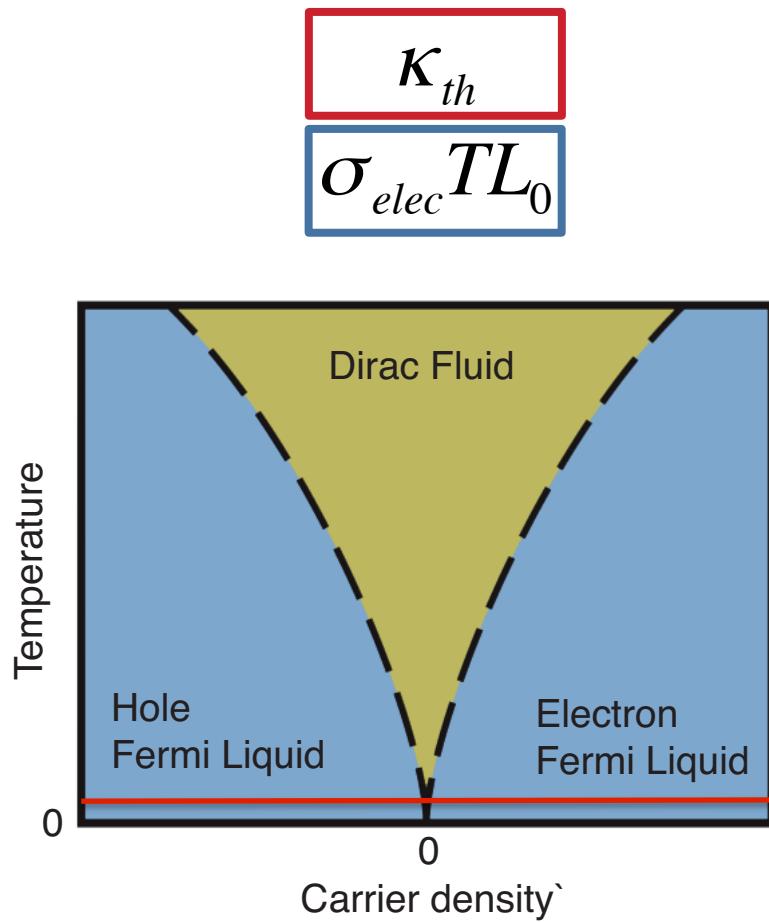


$$P_{WF} = \frac{L_0 T}{R} (T_e - T_{ph})$$



APL 106, 023121 (2015)

WF law in clean samples



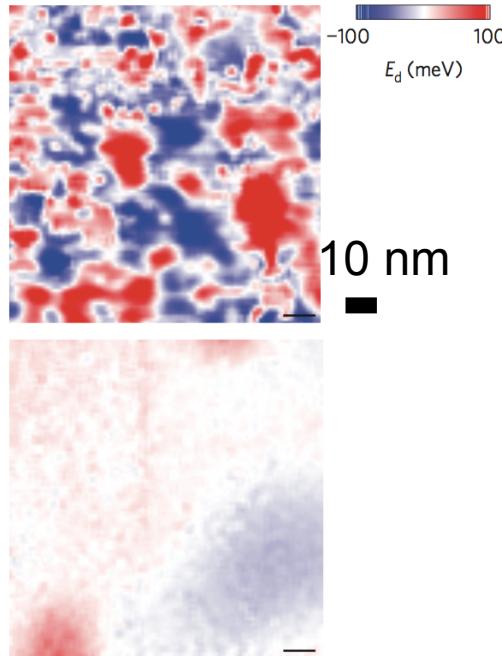
Temperature

0

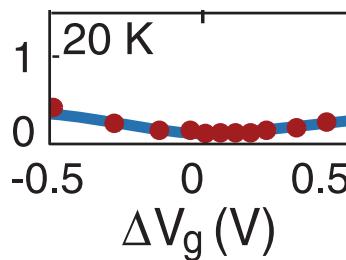
Carrier density

K_{th}

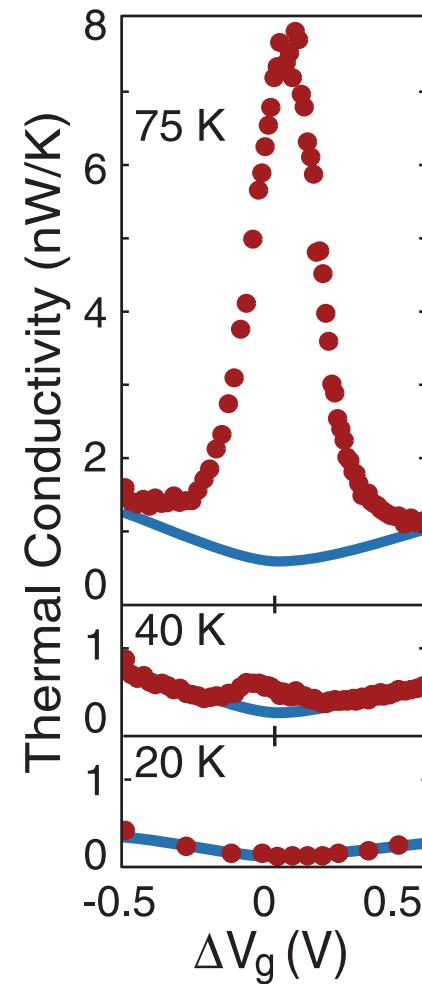
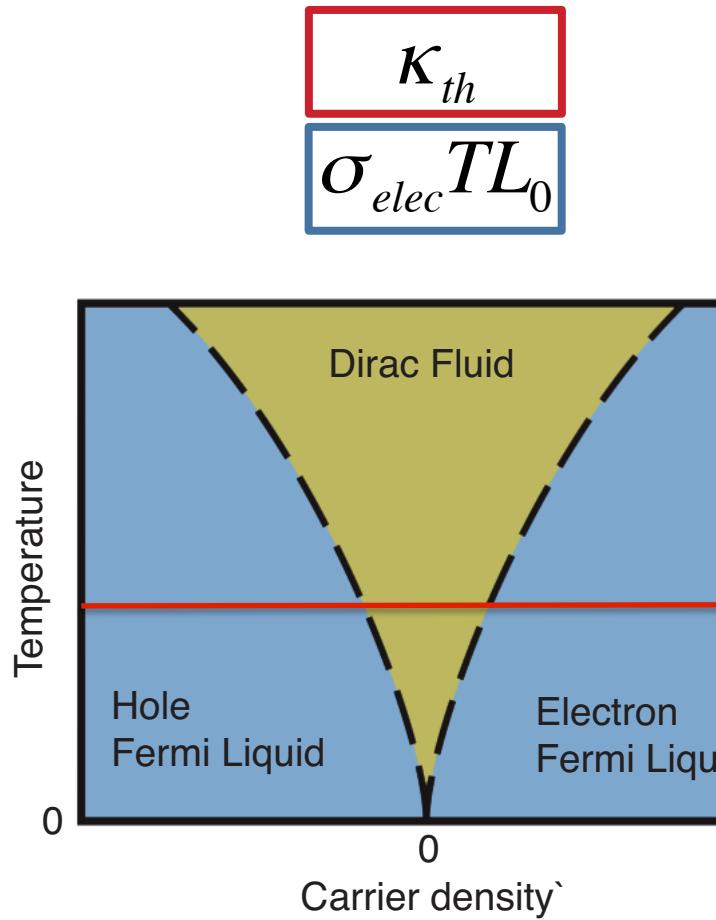
$\sigma_{elec} TL_0$



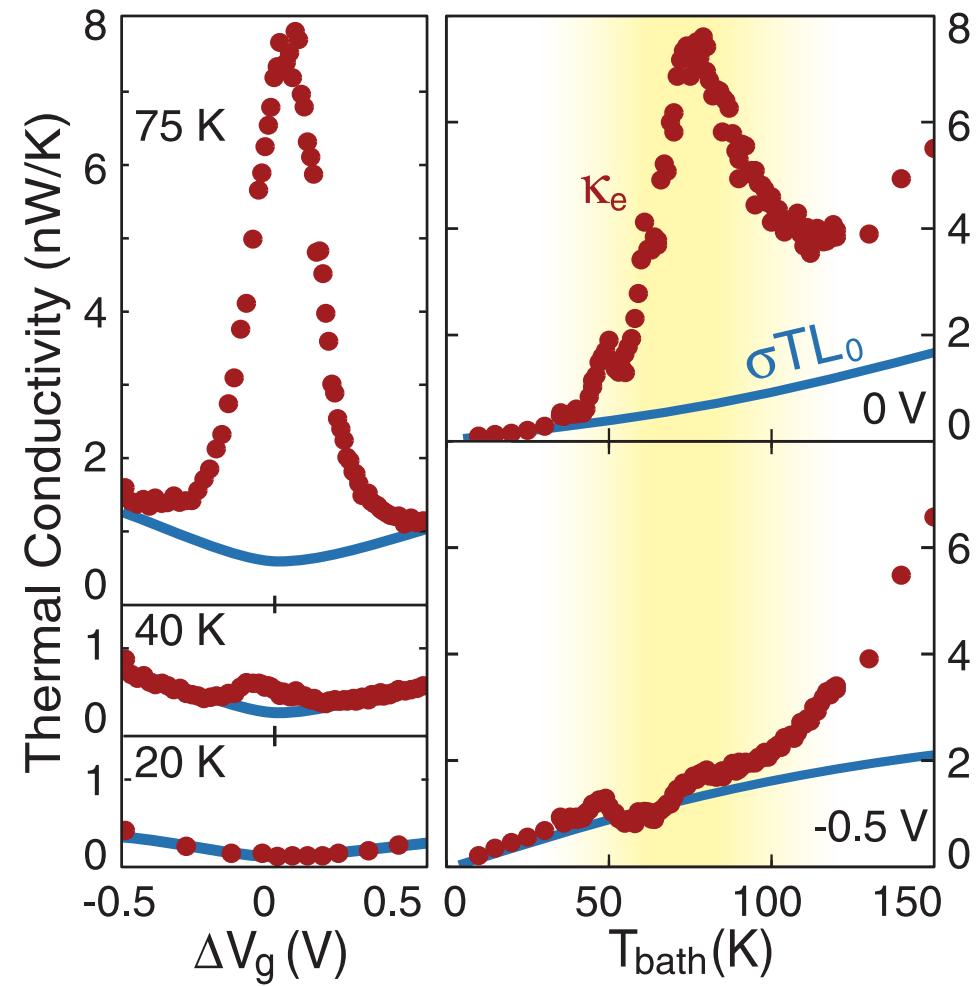
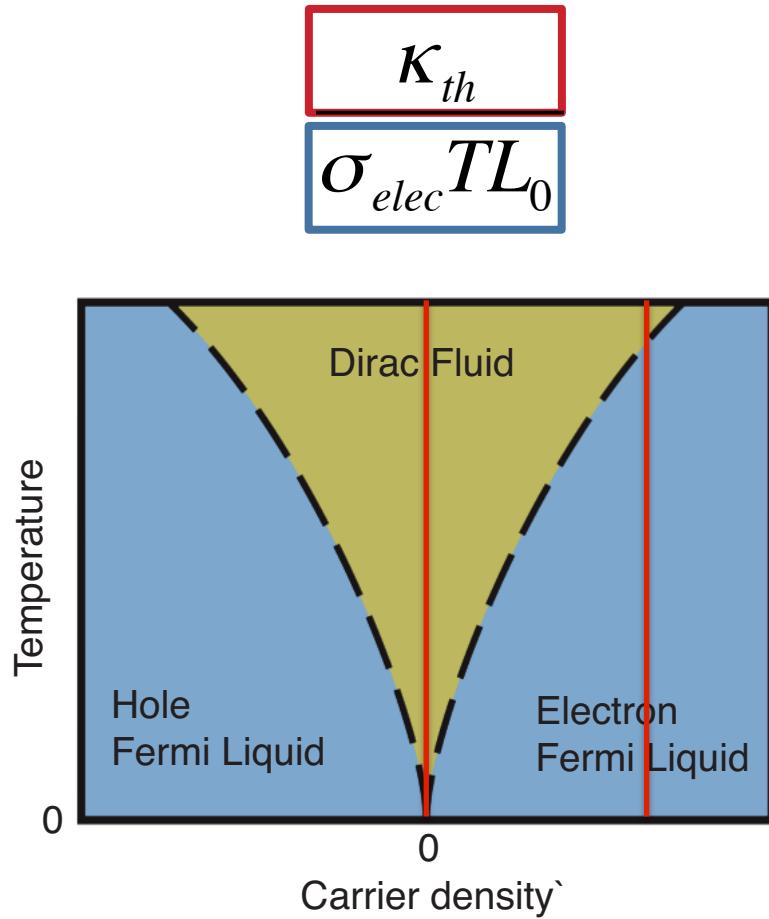
Nat Material 10, 282 (2011)
See also: Nat. Phys. 5, 722 (2009)



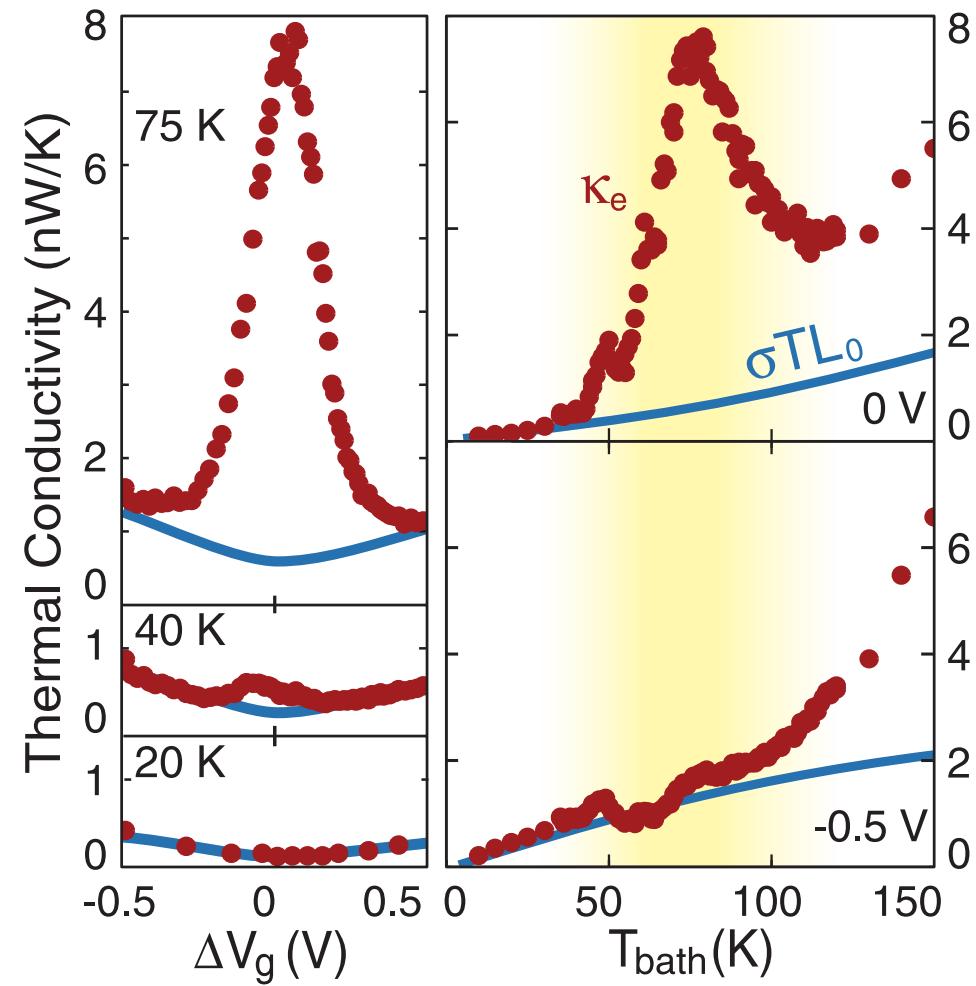
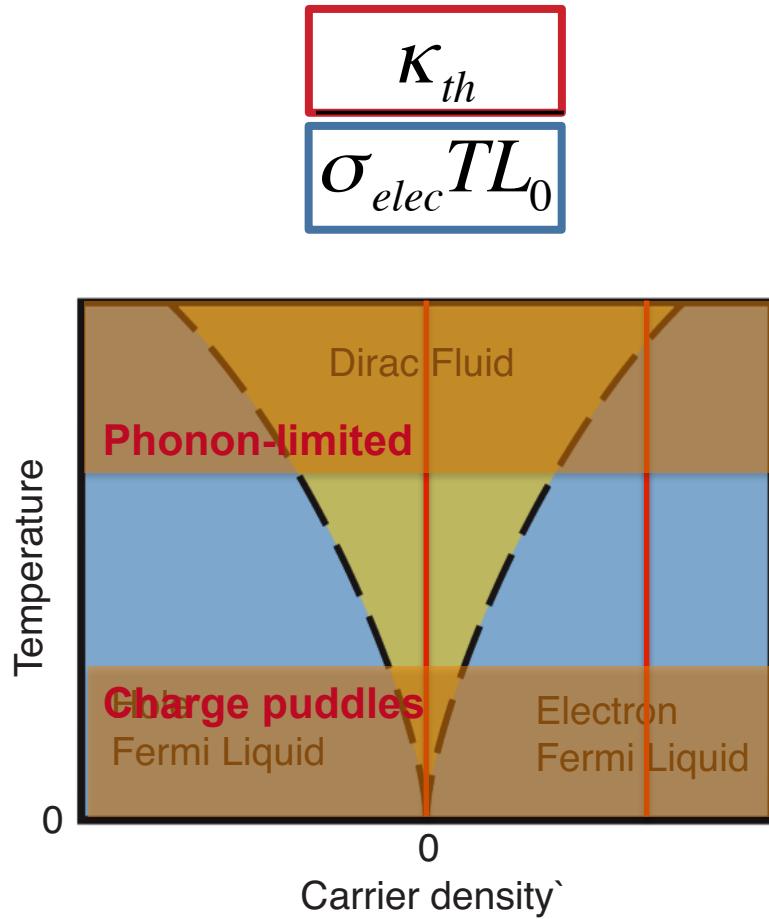
WF law in clean samples



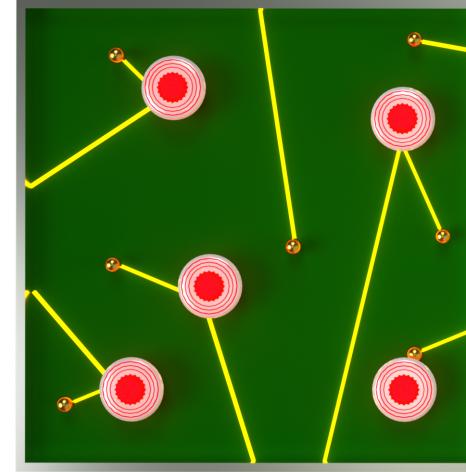
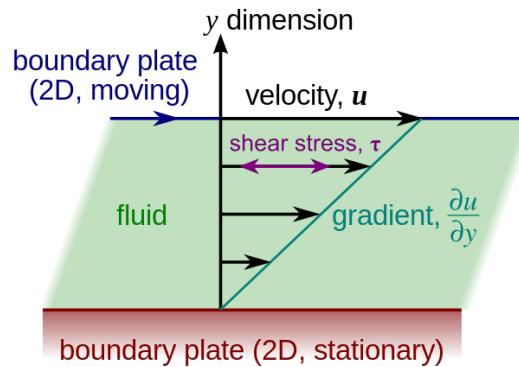
WF law in clean samples



WF law in clean samples



Momentum relaxation in hydrodynamics



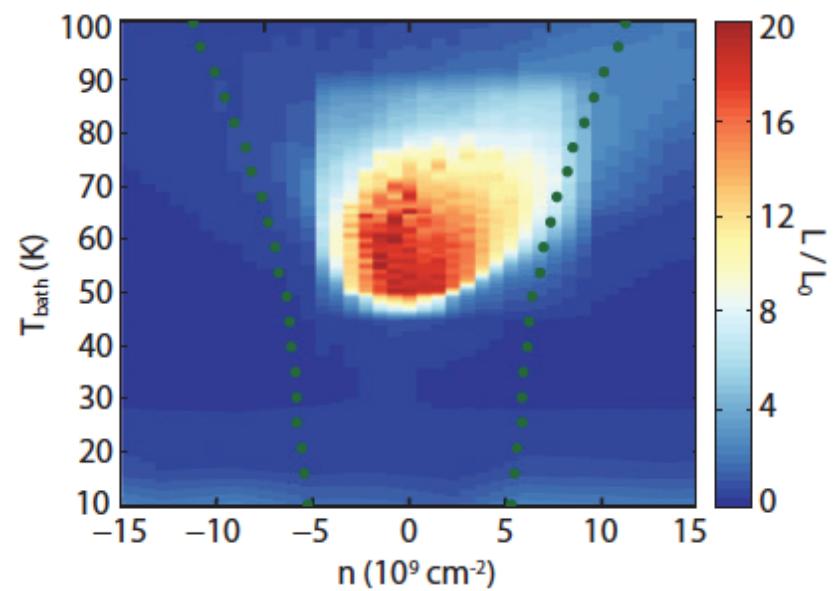
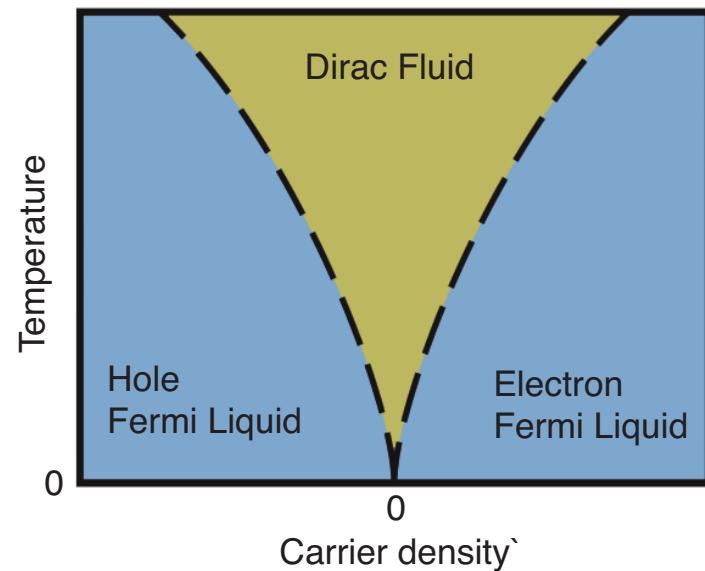
Dissipation via viscosity

$$\frac{\eta}{\rho_m} \nabla^2 u$$

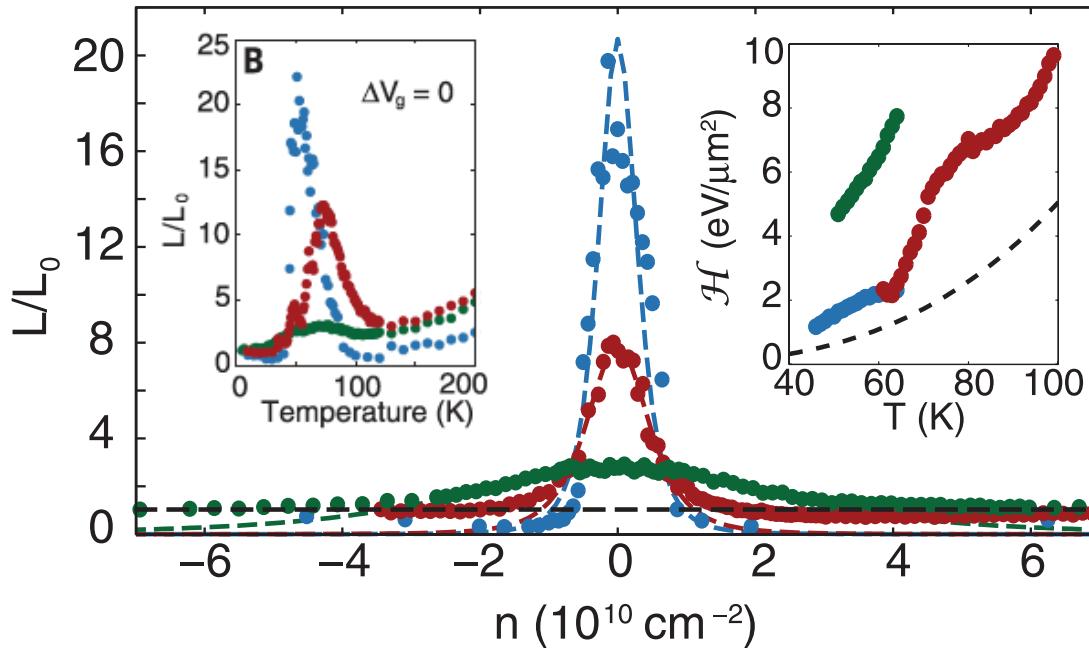
Dissipation via impurities or phonons

$$\frac{u}{\tau_{MR}}$$

Signature of Dirac Fluid



Momentum relaxation length



Andrew Lucas



Subir Sachdev

$$\mathcal{L} = \frac{\mathcal{L}_{\text{DF}}}{(1 + (n/n_0)^2)^2}$$

$$\mathcal{L}_{\text{DF}} = \frac{\mathcal{H} v_F l_m}{T^2 \sigma_{\min}} \quad \text{and} \quad n_0^2 = \frac{\mathcal{H} \sigma_{\min}}{e^2 v_F l_m}$$

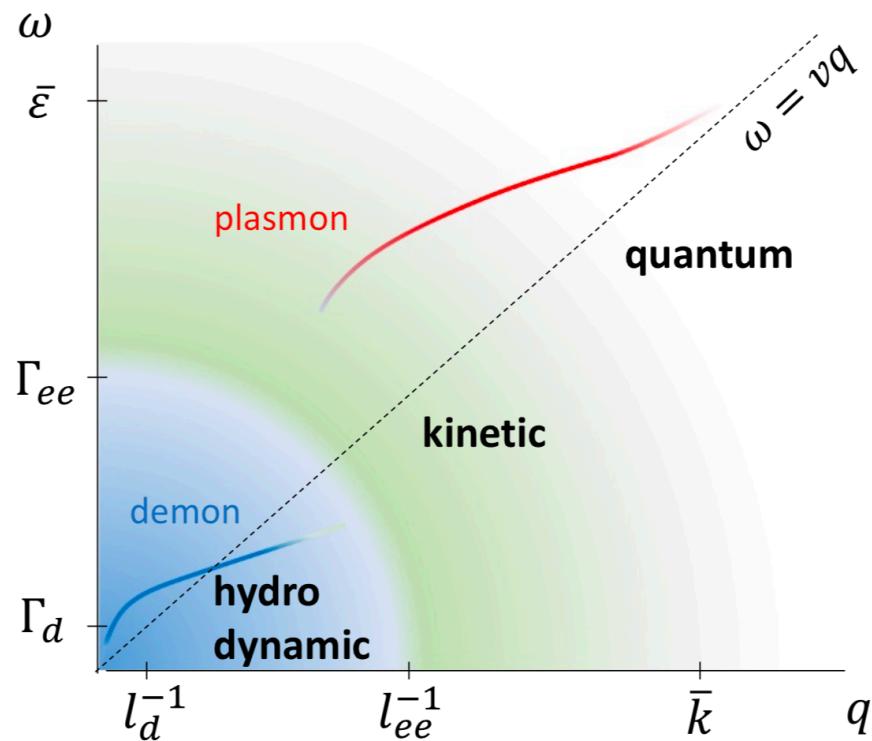
l_m = momentum relaxation length

H = Fluid enthalpy density

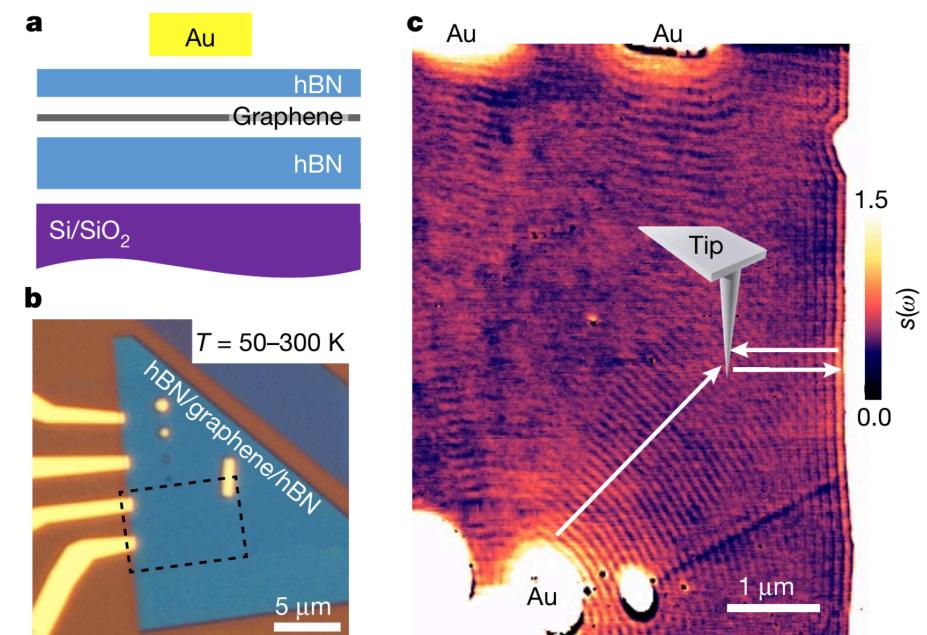
Muller *et al.*, PRB 78, 115406 (2008)
 Foster *et al.*, PRB 79, 085415 (2009)
 Lucas *et. al.*, PRB 93, 075426 (2016)

Related works:
 Principi and Vignal, PRL 115, 056603 (2015)

Second sound and plasma wave

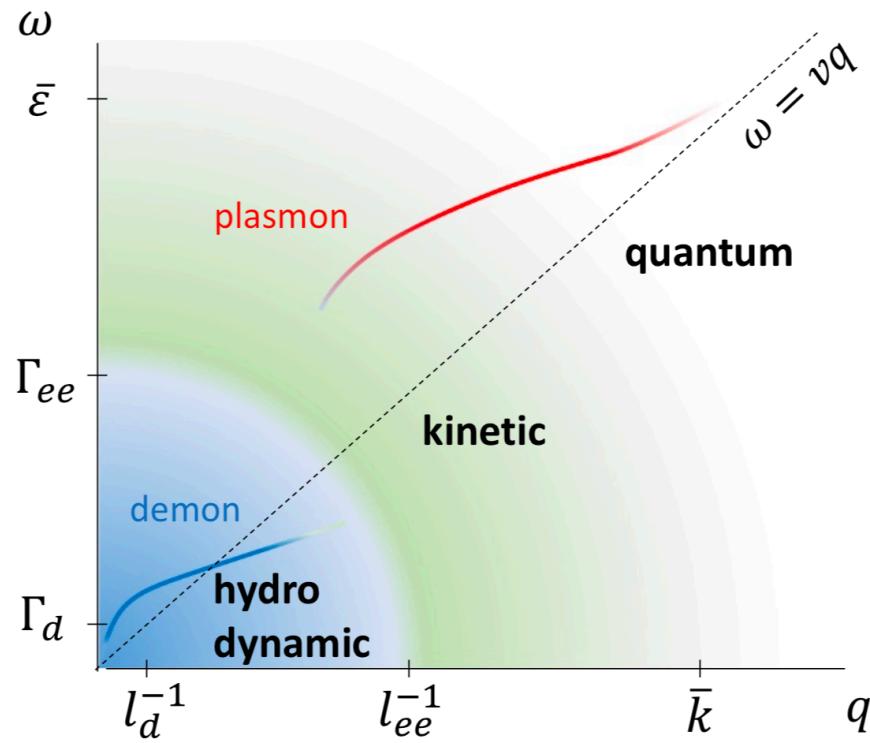


Sun, Basov, and Fogler, PNAS 115, 3285 (2018)

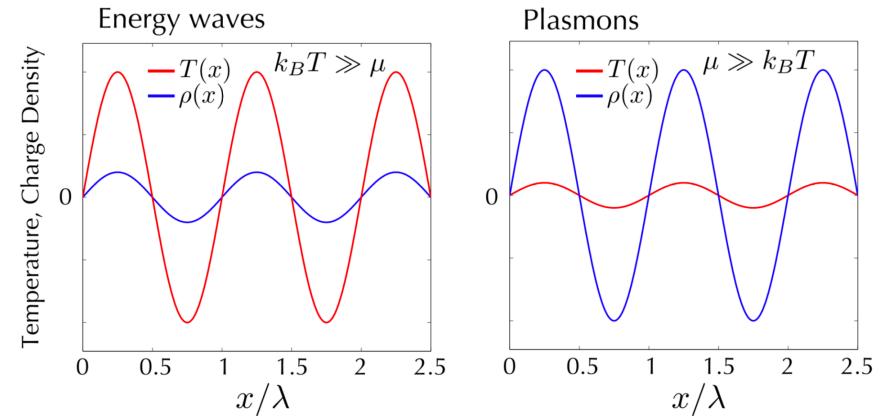


Nature 557, 530 (2018)

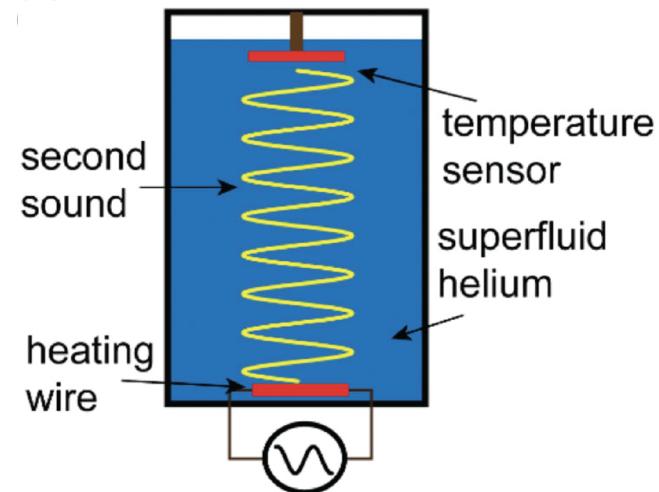
Second sound and plasma wave



Sun, Basov, and Fogler, PNAS 115, 3285 (2018)

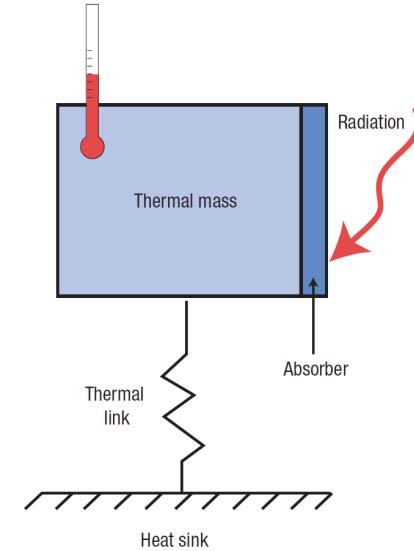
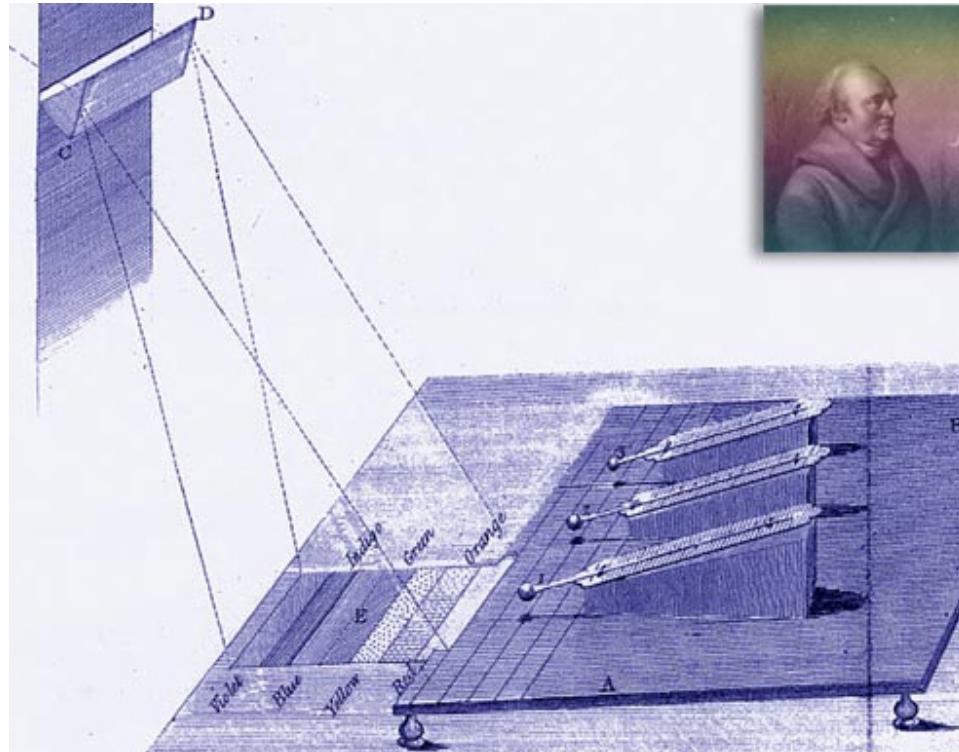


Phan-Song-Levitov, arXiv:1306.4972



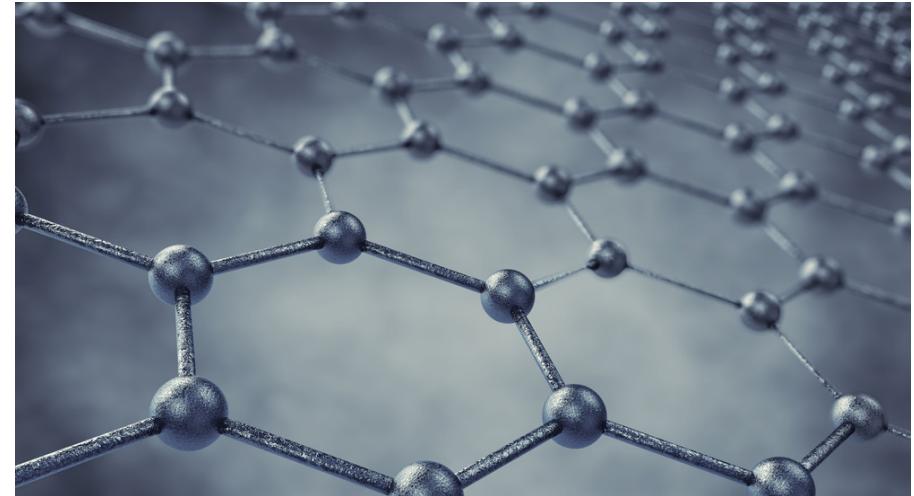
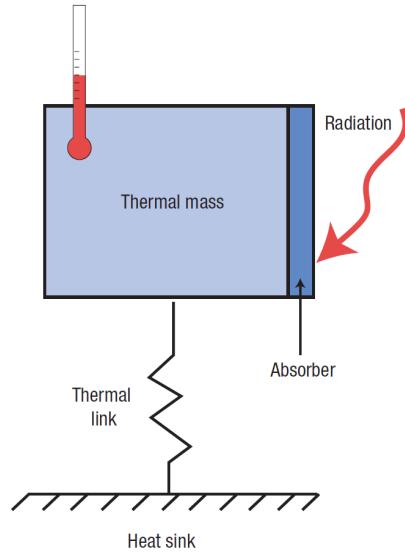
From quantum materials to quantum sensor

1800: Sir William Herschel



$$\Delta T = \frac{P}{G_{th}} \quad \Delta T = \frac{h\nu}{C_{th}}$$

Why graphene?



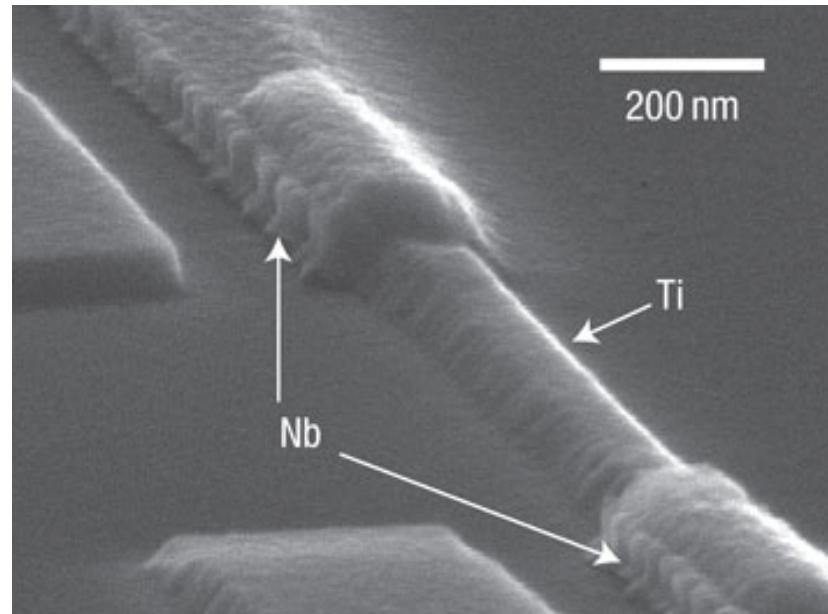
$$NEP = \sqrt{4G_{th}k_B T^2}$$

$$\Delta\epsilon \sim \sqrt{C_{th}k_B T^2}$$

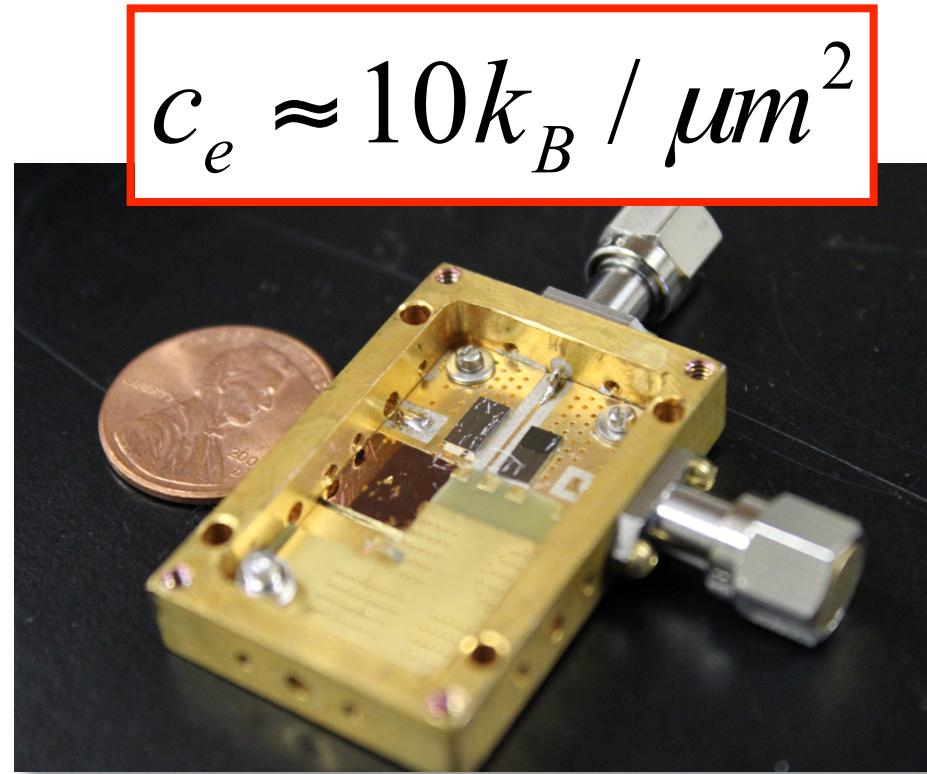
Ref:

- Vora, Kumaravadivel, Nielsen, and Du, APL 100, 153507 (2012)
- Fong and Schwab, PRX 2, 031006 (2012)
- J. Yan, et. al., Nature Nanotech. 7, 472 (2012)
- McKitterick, Prober, and Karasik, JPL 113, 044512 (2013)

Minute electronic heat capacity



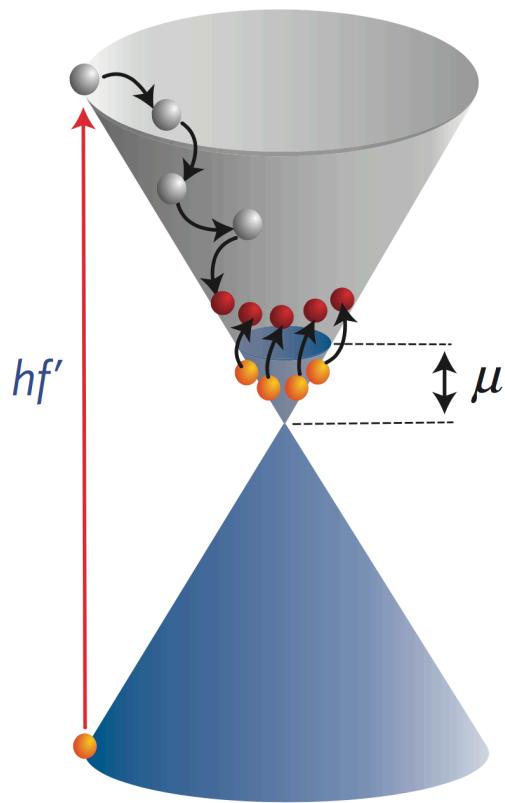
Nano-wire SPD
10000 kB at 65 mK
Nat. Nano. 3, 496 (2008)
APL 101, 052601 (2012)



$$c_e \approx DOS(\varepsilon_F) k_B^2 T$$

Graphene Bolometer
~1000 kB at 311 mK
PRX 3, 041008 (2013)

Why graphene?



Tielrooij, et. al., Nat. Phys. 9, 248–252 (2013)

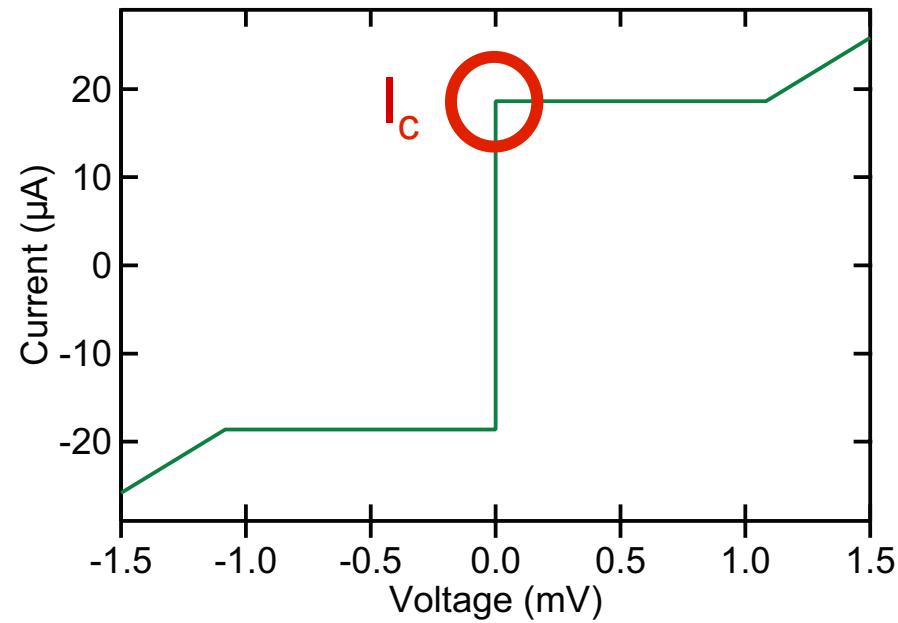
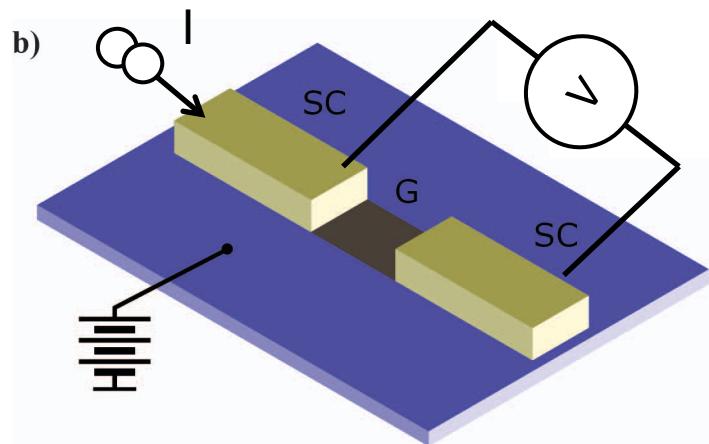
- Minute C_{th} on the order of k_B
- $DOS = 2E / (\pi(\hbar v_F)^2)$
- Small G_{th} due to weak electron-phonon coupling
- Fast thermalization due to short e-e scattering time
- Wide EM bandwidth
- High absorption efficiency with impedance matching

See also:

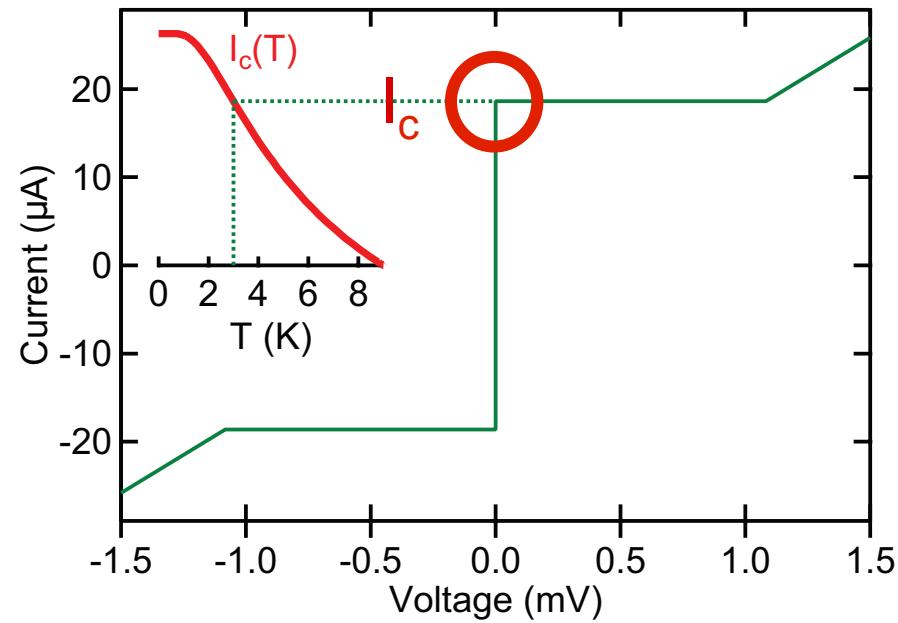
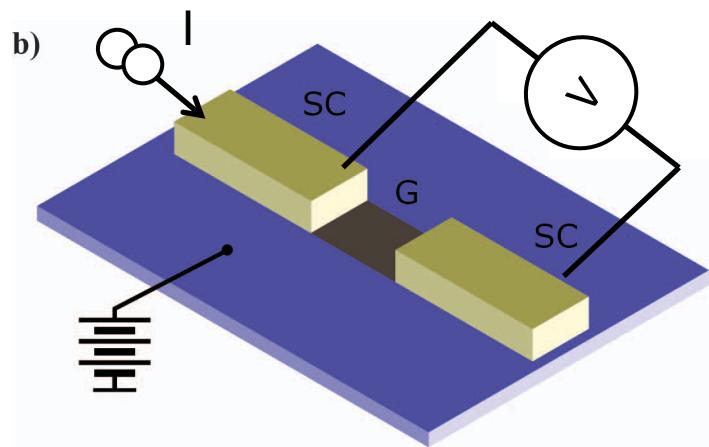
P. George, et. al. Nano Lett 8, 4248 (2008)
 Lui, Mak, Shan, Heinz, PRL 105, 127404 (2010)
 Breusing, Ropers, Elsaesser, PRL 102, 086809 (2009)
 Johannsen et al., PRL 111, 027403 (2013)

kc.fong@raytheon.com

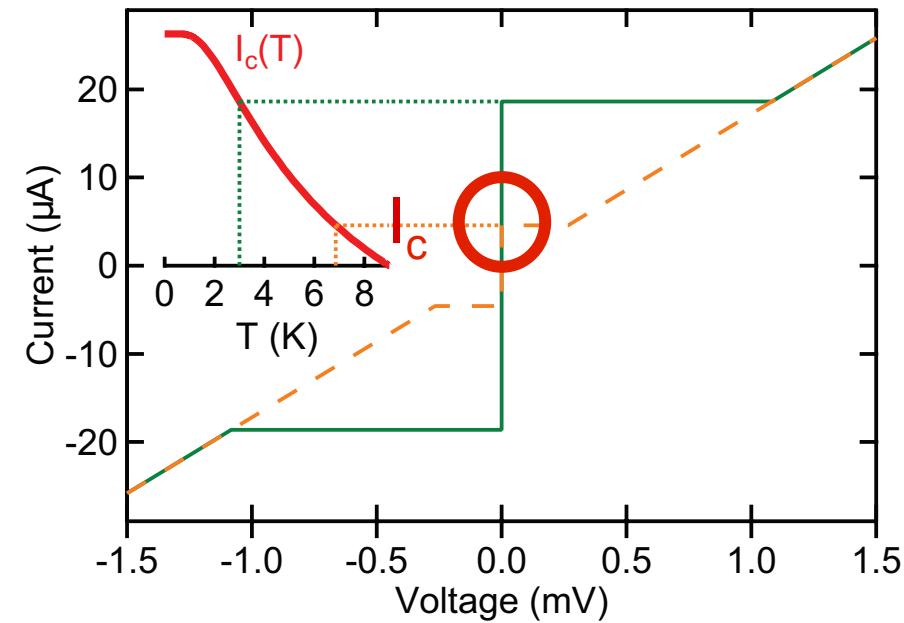
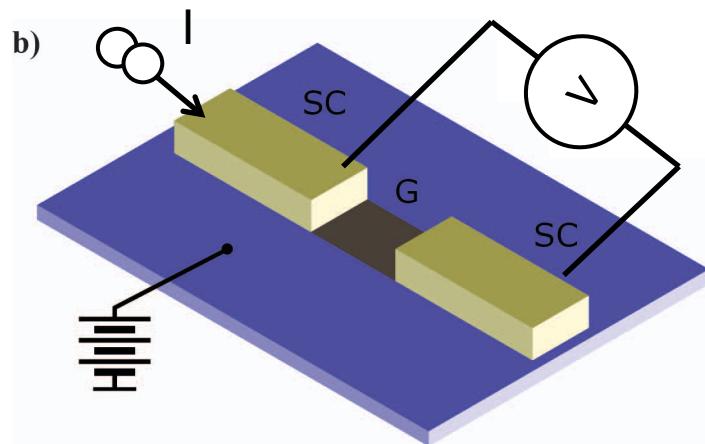
How to use graphene to sense single photon?



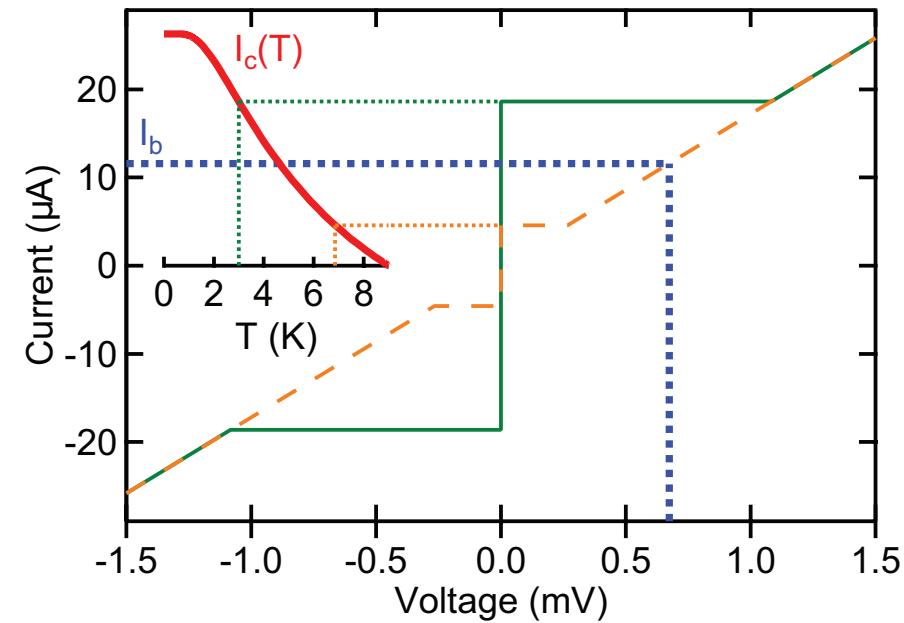
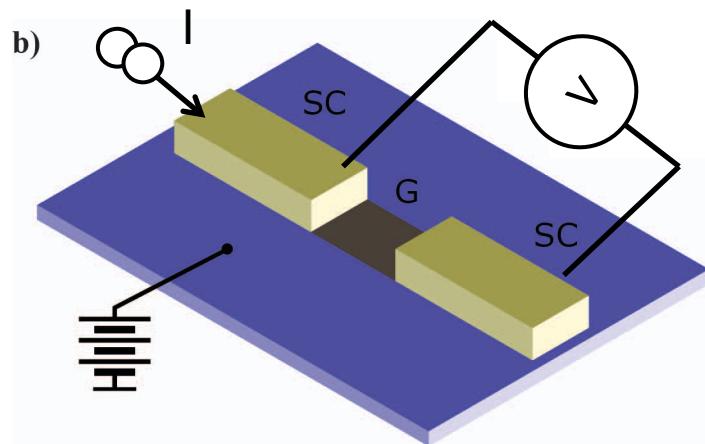
How to use graphene to sense single photon?



How to use graphene to sense single photon?



How to use graphene to sense single photon?



Applications of SNS Josephson junction

Reversing the direction of the supercurrent in a controllable Josephson junction

J. J. A. Baselmans*, A. F. Morpurgo*†, B. J. van Wees*
& T. M. Klapwijk*

* Department of Applied Physics and Material Science Center, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

When two superconductors are connected by a weak link, a supercurrent flows, the magnitude of which is determined by the difference in the macroscopic quantum phases of the superconductors. This phenomenon was discovered by Josephson¹ for the case of a weak link formed by a thin tunnel barrier: the supercurrent, I , is related to the phase difference, ϕ , through the Josephson current–phase relation, $I = I_c \sin \phi$, with I_c being the critical current which depends on the properties of the weak link. A similar relation holds for weak links consisting of a normal metal, a semiconductor or a constriction². In all cases, the phase difference is zero when no supercurrent flows through the junction, and increases monotonically with increasing supercurrent

† Present address: Department of Physics, Stanford University, Stanford, California 94305-4060, USA.

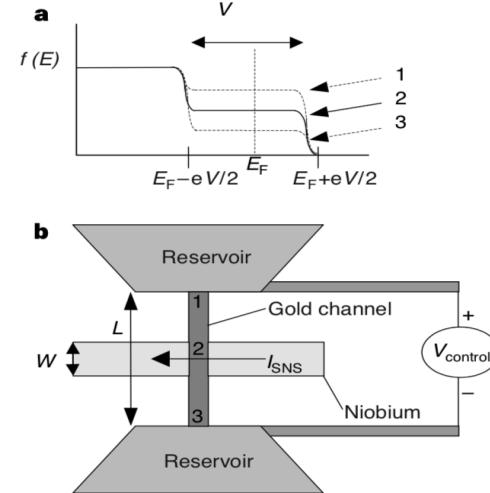


Figure 1 Electronic distribution function and the sample layout. In the bottom panel, a gold channel between two electron reservoirs is connected to two niobium superconducting leads. The control voltage across the channel induces a position-dependent electron distribution, shown in **a** for positions 1, 2 and 3 in **b**. The current through the Josephson junction is indicated by I_{SNS} .

Nature 397, 43 (1999)

See also:

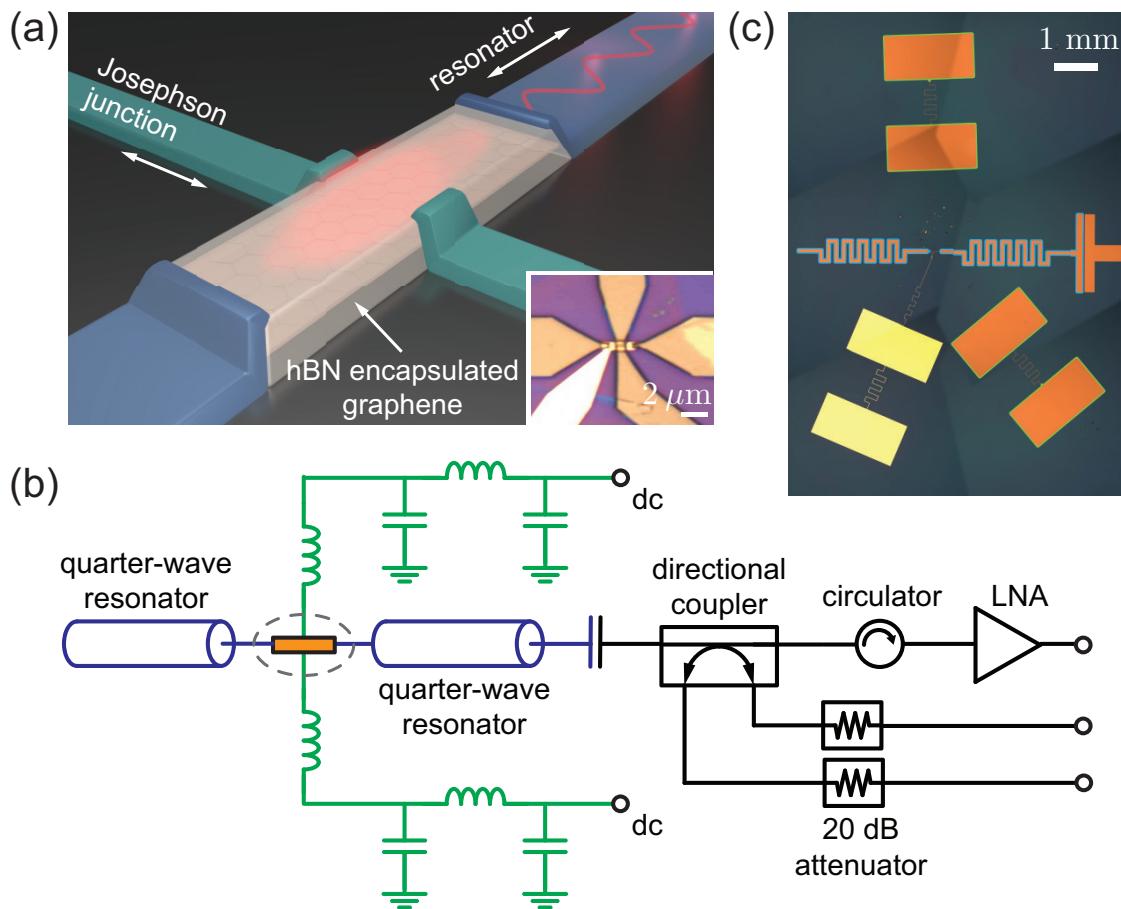
Gasparinetti, Viisanen, Saira, Faivre, Arzeo, Meschke, and Pekola, PR Applied 3, 014007 (2015)
Govenius, Lake, Tan, and Möttönen, PRL 117, 030802 (2016)

Microwave bolometer

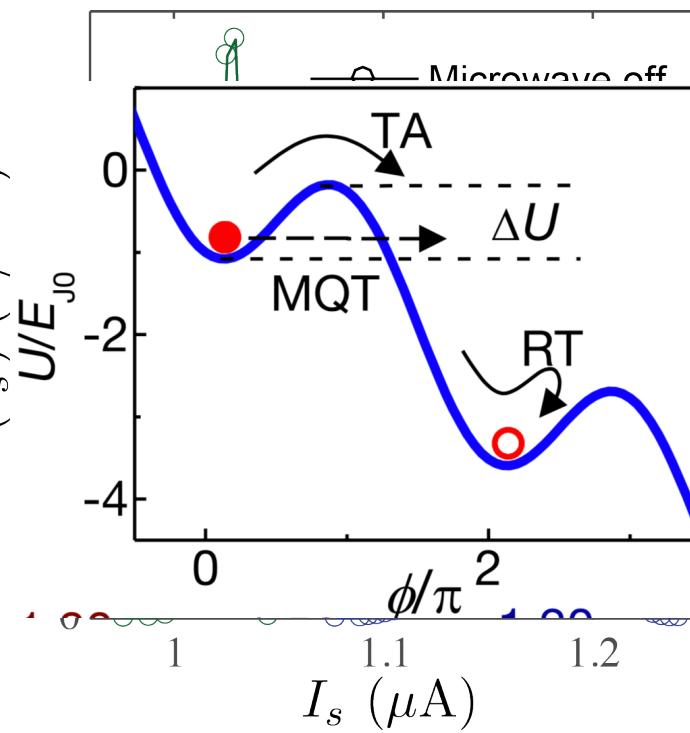
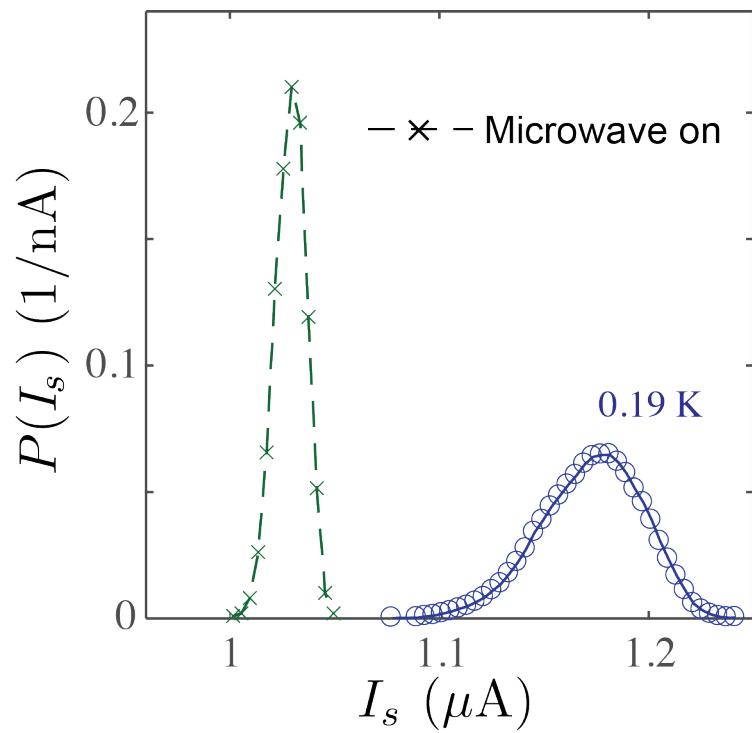


L.Ranzani

G-H.Lee

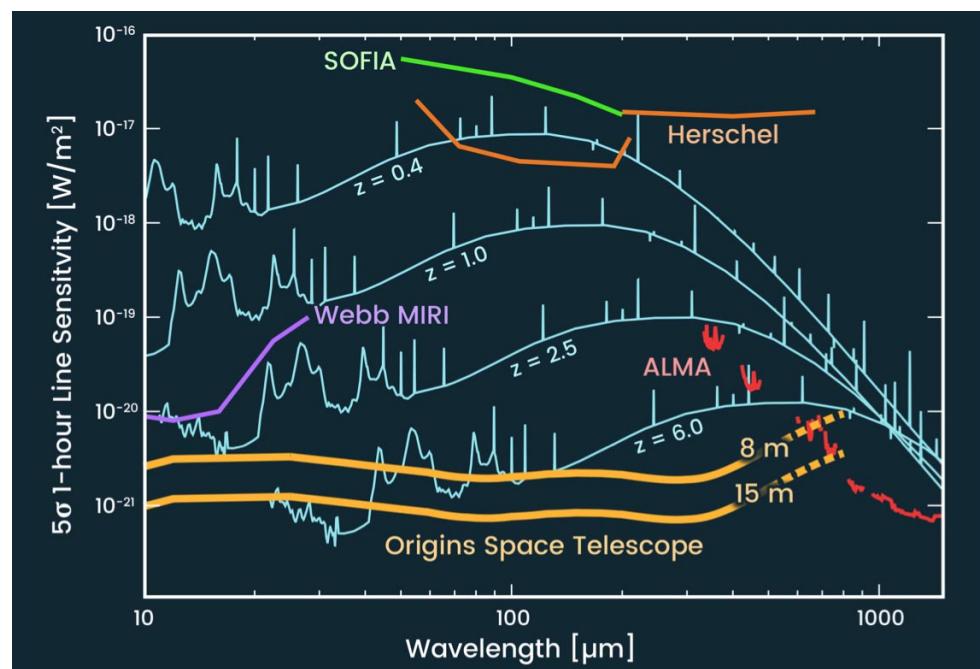
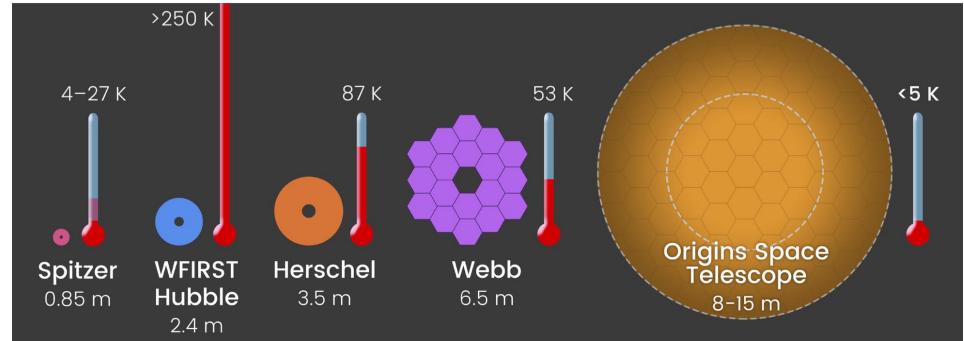
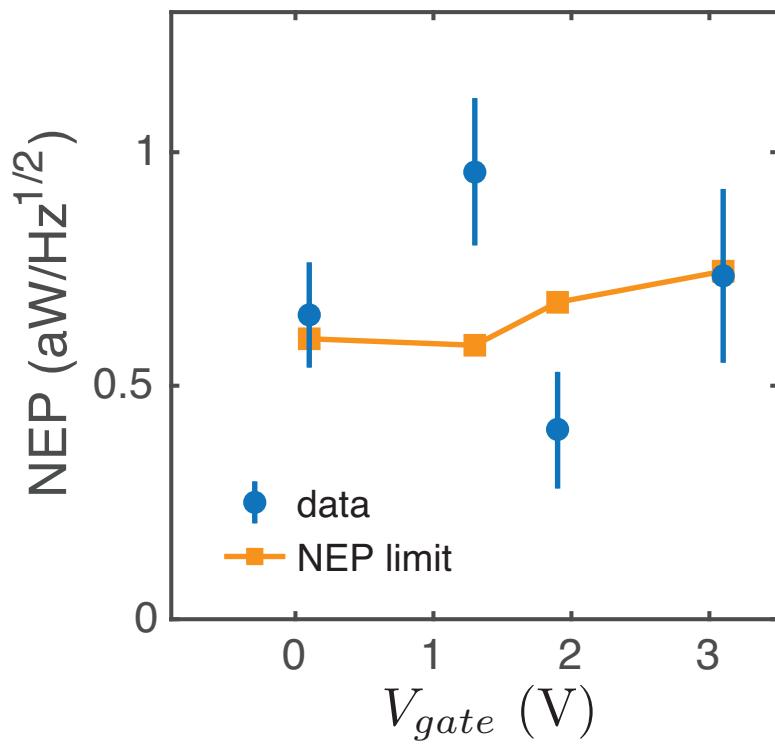


Bolometric effect

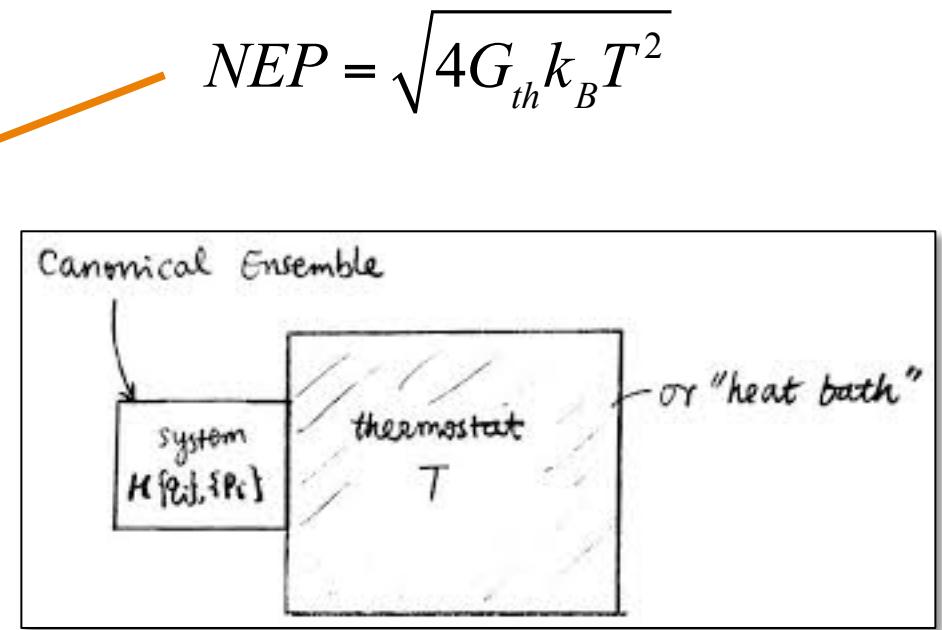
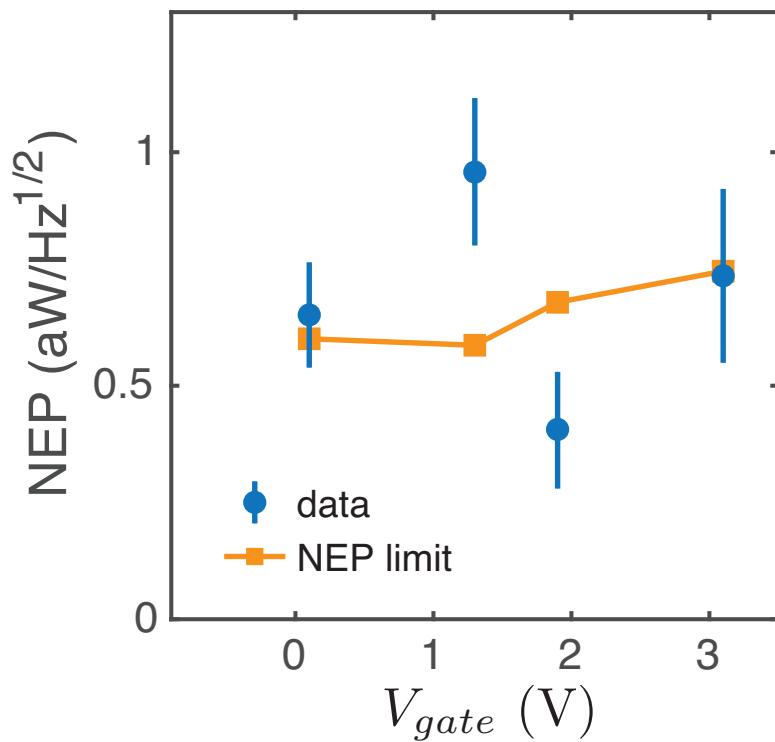


Sensitivity reaching fundamental fluctuation limit at 6e-19 W/Hz^{1/2} @ 0.2 K

Raytheon
BBN Technologies

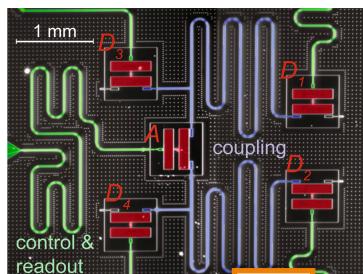


Sensitivity reaching fundamental fluctuation limit at 6e-19 W/Hz^{1/2} @ 0.2 K



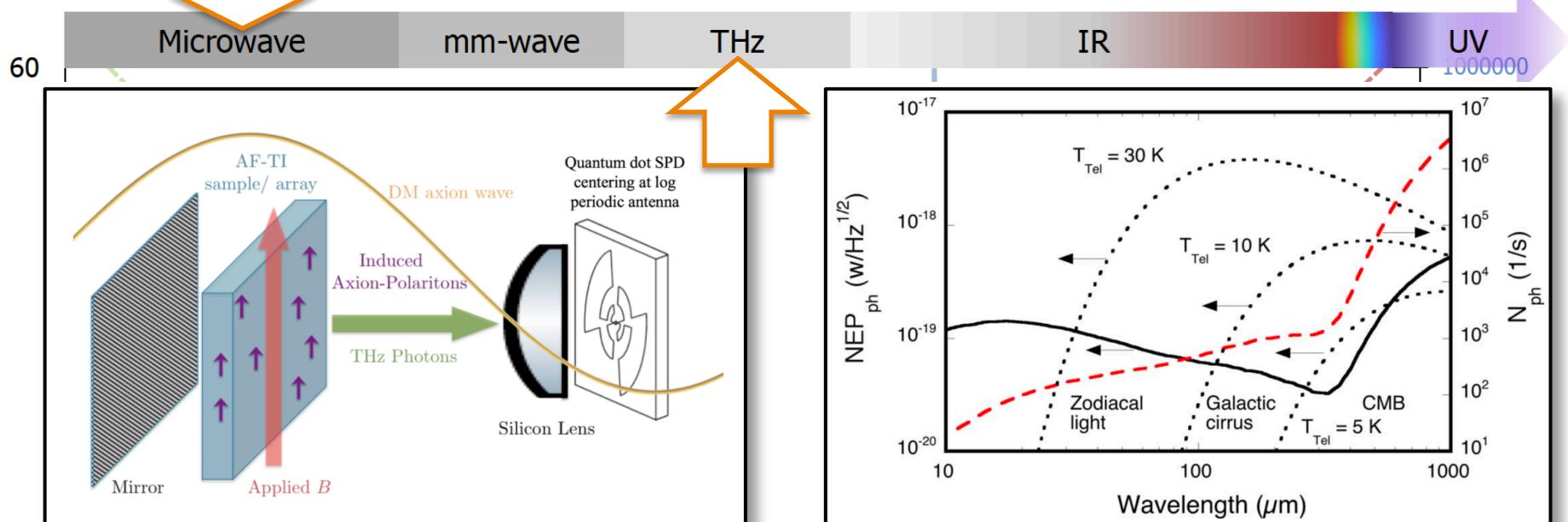
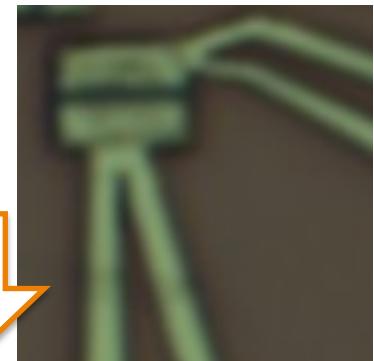
Enabling single-photon technology

npj Quantum Information 3, 16 (2017)



ASC: *Plenary Session
on Thursday*

Lower energy



arXiv:1807.08810

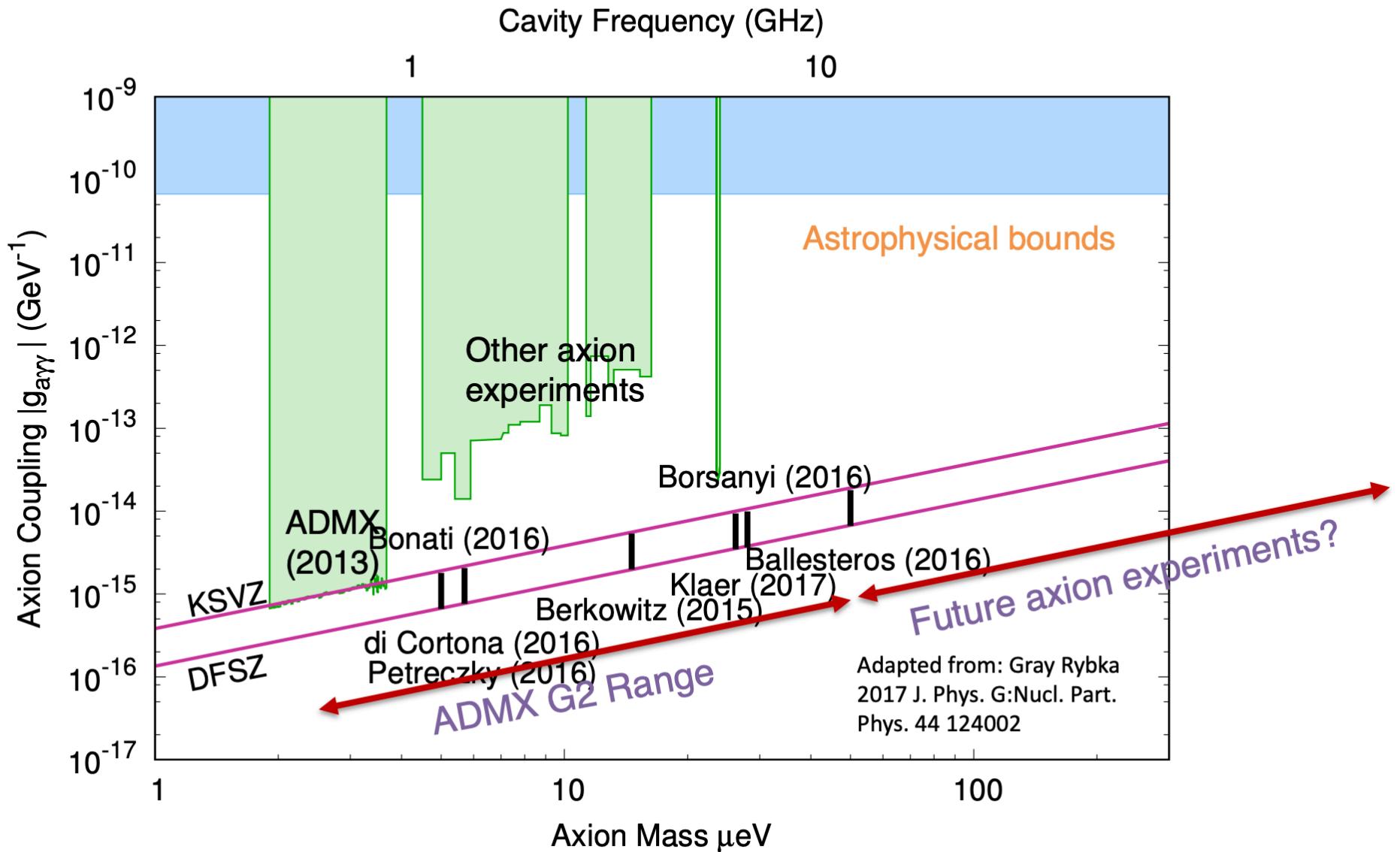
ASC: *Novel electronics (4EOr2A)*

IEEE THz 1, 97 (2011)

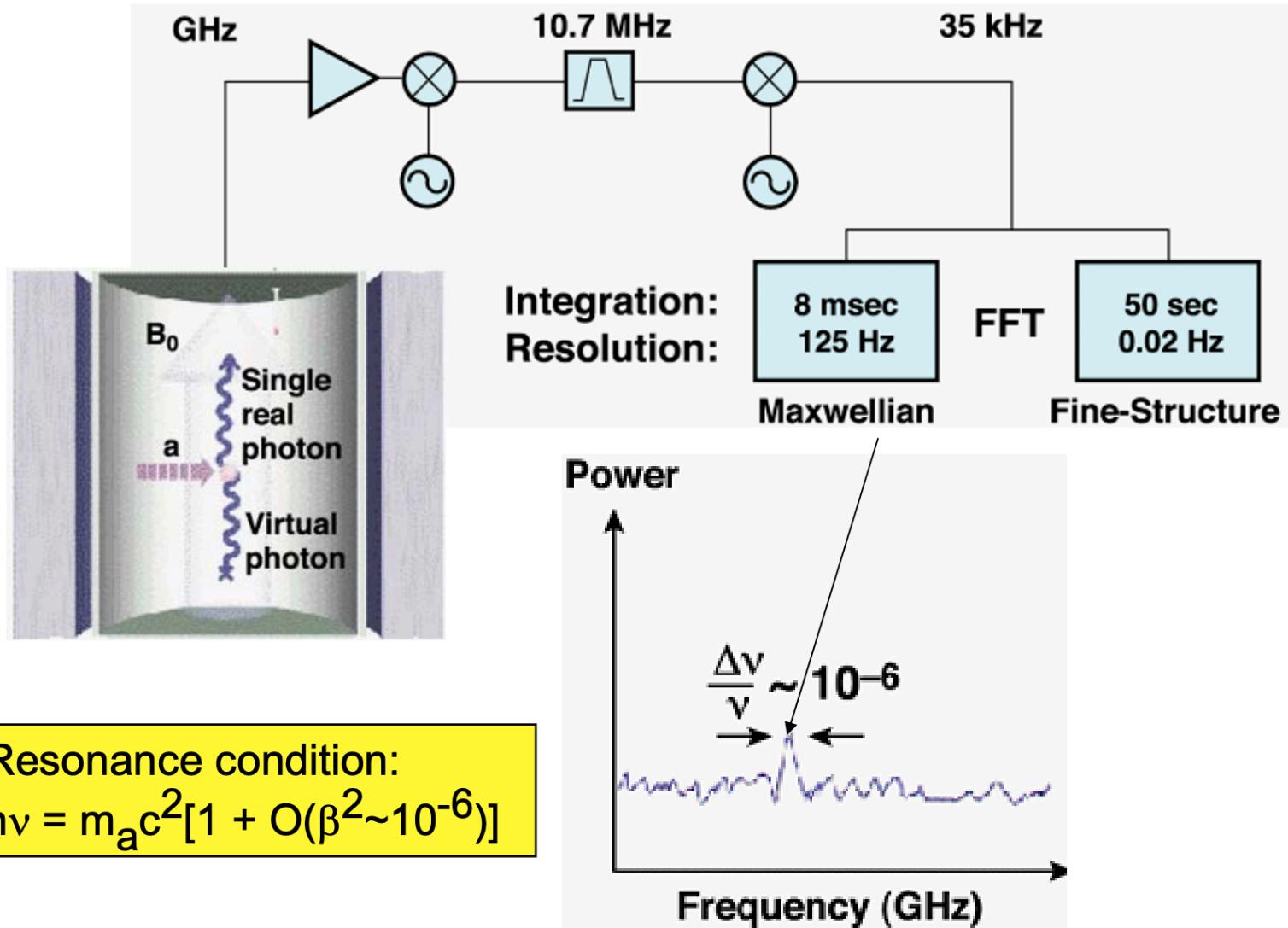
ASC: *Non-equilibrium Detectors and Mixers (1EOr2B)*

Experimental Perspective on DM Axions

Analytic and Lattice QCD predictions of the axion mass

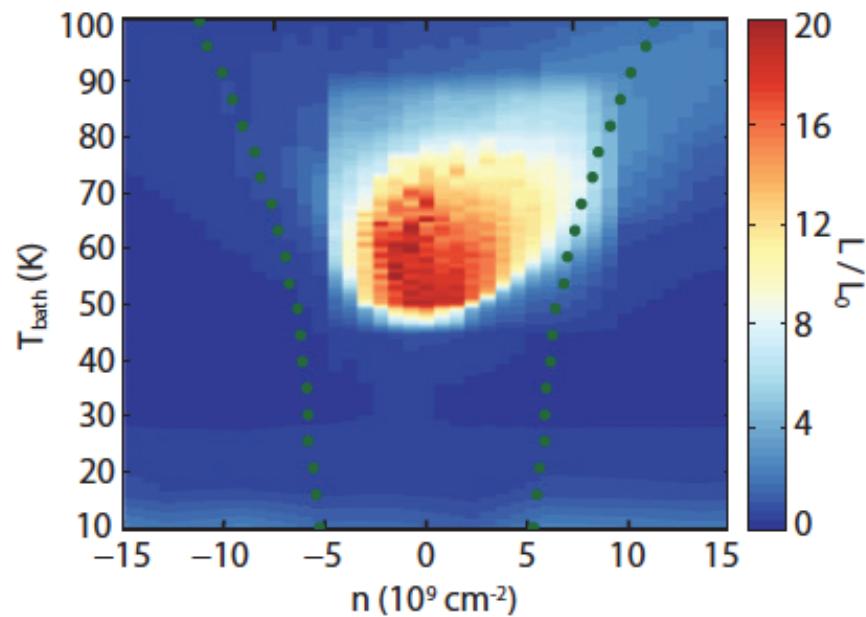


Axion Dark Matter Experiment

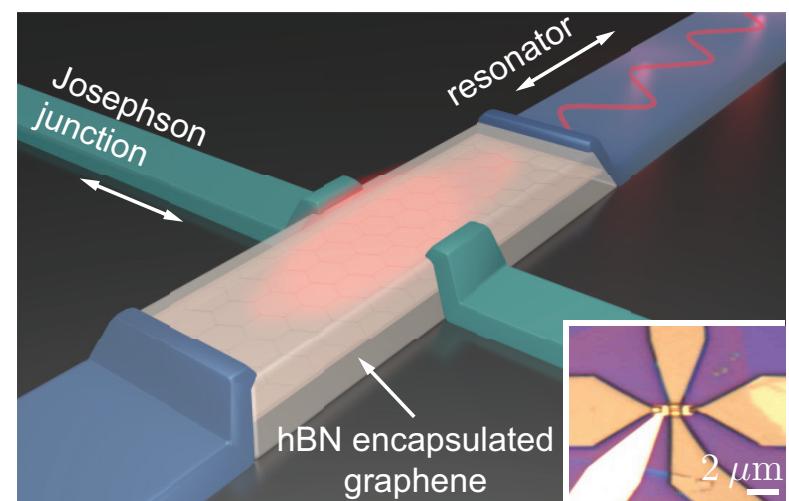


Conclusion

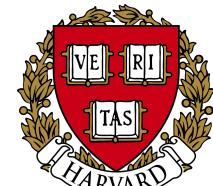
Hydrodynamics



Quantum sensor



Team works



Dirk Englund



Dmitri Efetov



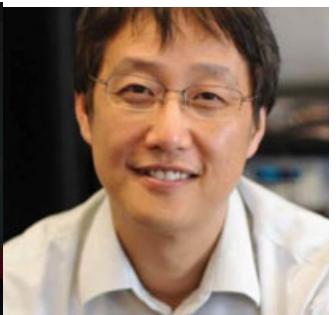
T. Ohki



Gil-ho Lee



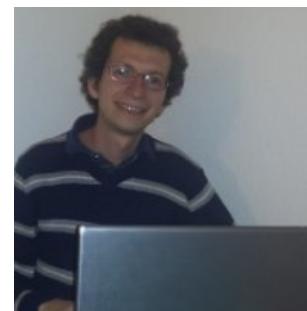
Subir Sachdev



Philip Kim



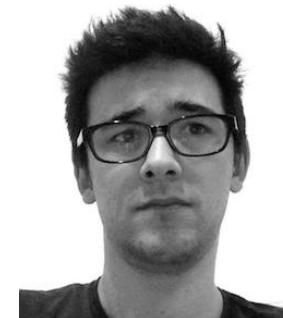
Evan Walsh



L. Ranzani



W-C. Jung



Andrew Lucas



J Crossno