University of Basel

Department of Physics

FMM 29.10.2021

Christian Scheller

Cooling Low-Dimensional Electron Systems into the Microkelvin Regime

Lev V. Levitin,[1,*] Harriet van der Vliet,[1,†] Terje Theisen,[1] Stefanos Dimitriadis,[1,‡] Marijn Lucas,[1] Antonio D. Corcoles,[1,§] Ján Nyéki,[1] Andrew J. Casey,[1] Graham Creeth,[2,¶] Ian Farrer,[3,**] David A. Ritchie,[3] James T. Nicholls,[1] and John Saunders[1]

[1] *Department of Physics, Royal Holloway, University of London, Egham TW20 0EX, UK*

[2] *London Centre for Nanotechnology, University College London, London WC1H 0AH, UK*

[3] *Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, UK*

(Dated: September 28, 2021)

arXiv:2110.01887v1 [cond-mat.mes-hall] 5 Oct 2021

University of Basel
Department of Physics

Motivation

Why go to low T ?

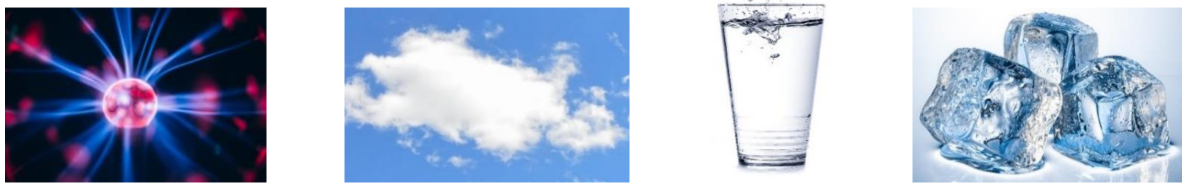
Energy (k_BT) = Temperature = disorder (TdS=dU)
Lower T $\Rightarrow$ more ordered phenomena

- Fragile FQH states
- Many-body effects (nuclear order in GaAs due to RKKY)
- Coherence
- Phase transitions
- Quasiparticles in SC (qubits, majorana)
- New physics…

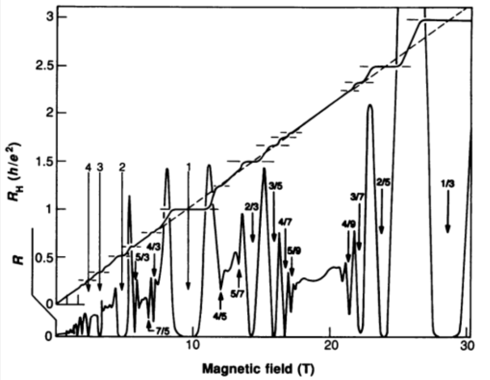
Why Semiconductor ?

Can engineer stuff as you like (gates, growth)

Phases of matter

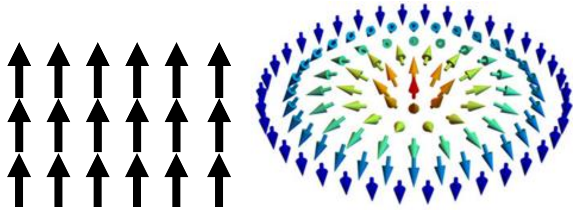


Fractional Quantum Hall effect

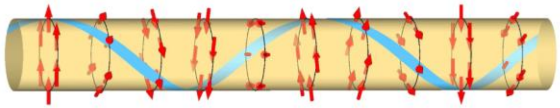


Science **248**, 1510 (1990)

Magnetic transitions

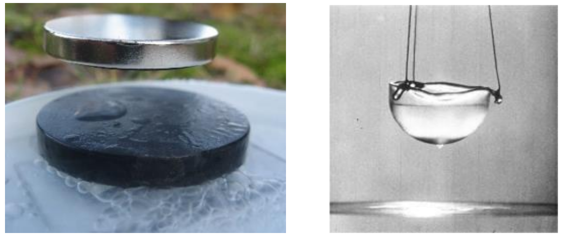


PRB **96**, 144412 (2017)

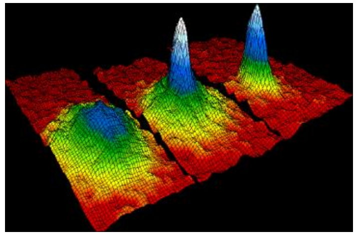


PRL **102**, 116403 (2009)

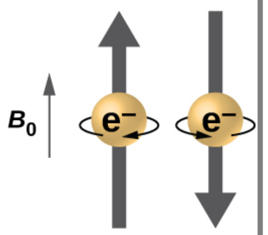
Super conductivity / fluidity



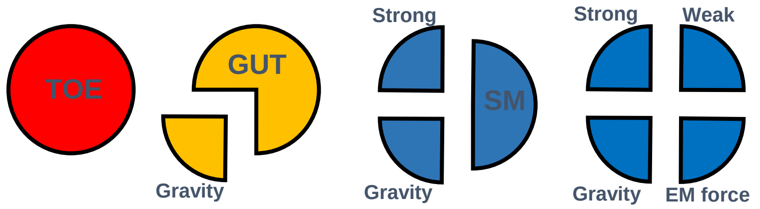
BEC



Spin + B-field



Fundamental forces



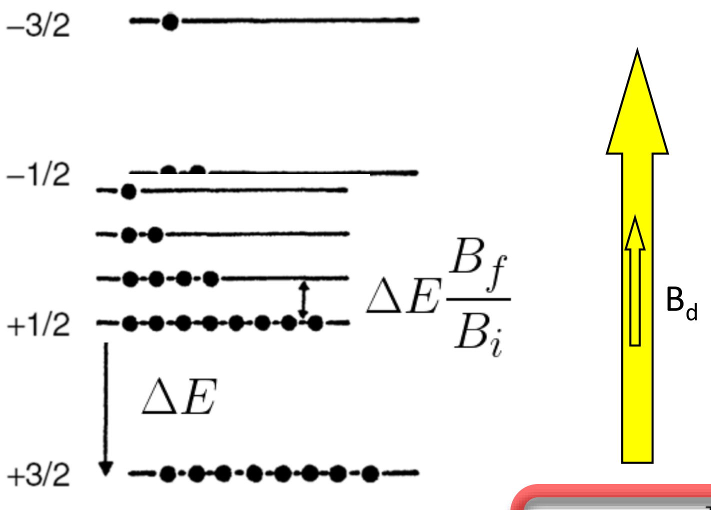
Cooling Method: AND

AND: Single shot magnetic cooling, 3 steps:

(1) magnetize and precool

(2) decouple (Al heat switch → SC) and demagnetize

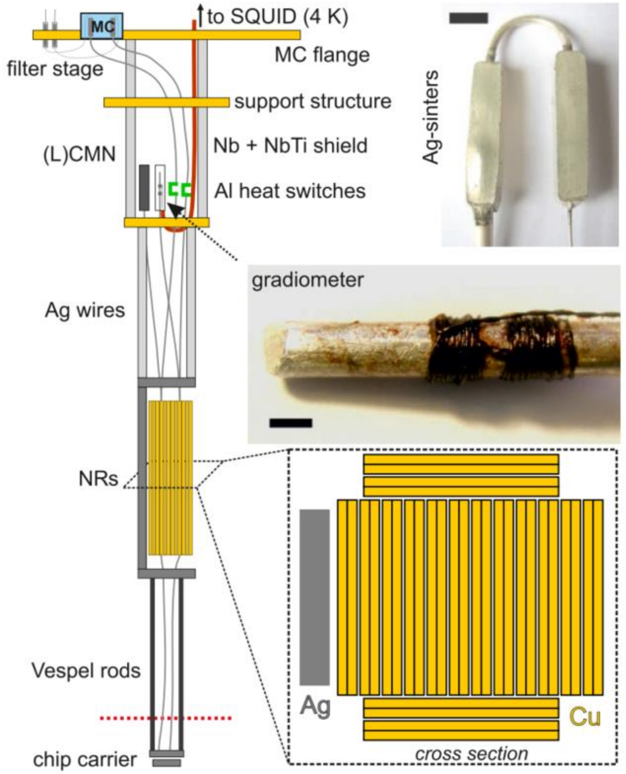
(3) warmup (experiments)



$$T_f = T_i \frac{B_f}{B_i}$$

Basel: Sample in liquid ^3He

- Parallel NR: 1 per lead

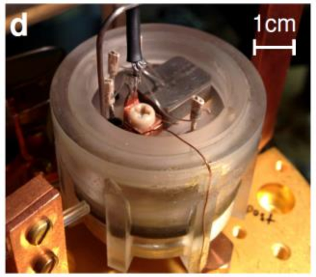


150μK in Cu plates

This work: Sample in liquid ^3He

- Bulk Cu nucl. Refrigerator
- Plastic / metal ^3He immersion cell
- 2DEG sample & noise thermometer

Plastic cell



Metal cell

300μK in ^3He bath

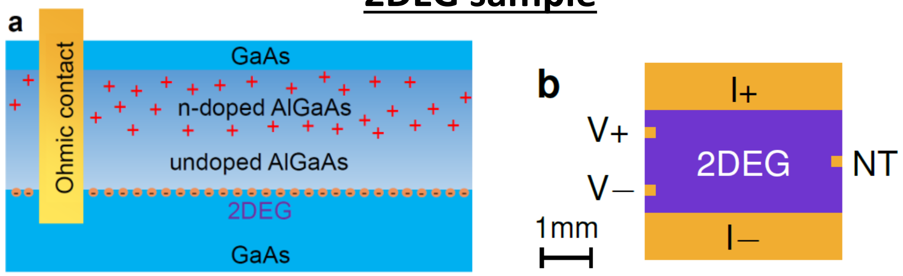
University of Basel
Department of Physics

Sample

Sample:

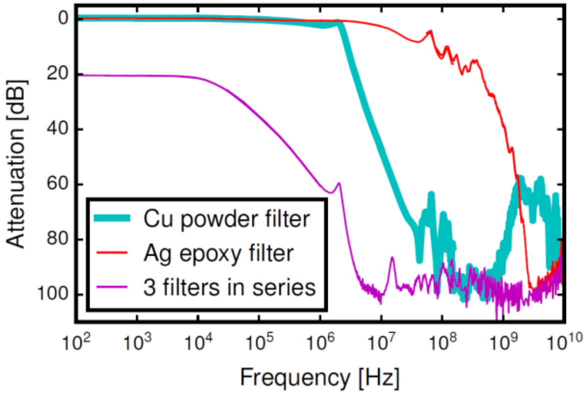
- GaAs/AlGaAs 2DEG
- Before LED: $n = 2 \cdot 10^{11} cm^{-2}$; $\mu = 1 \cdot 10^{6}$; $R_{Square} = 31\ \Omega$
- After LED: $n = 3.3 \cdot 10^{11} cm^{-2}$; $\mu = 3 \cdot 10^{6}$; $R_{Square} = 6\ \Omega$
- AuNiGe Ohmic contacts $< 1\Omega$ @ 4,2 K, become SC below 0.6 K
- Noise thermometer: Brownian motion e$^-$ in Au wire

2DEG sample

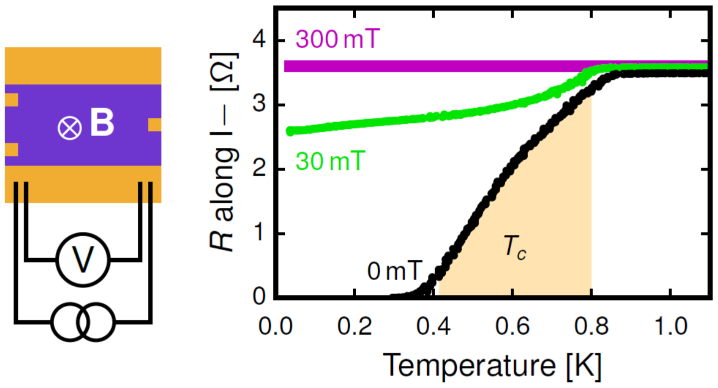


Heavy filtering

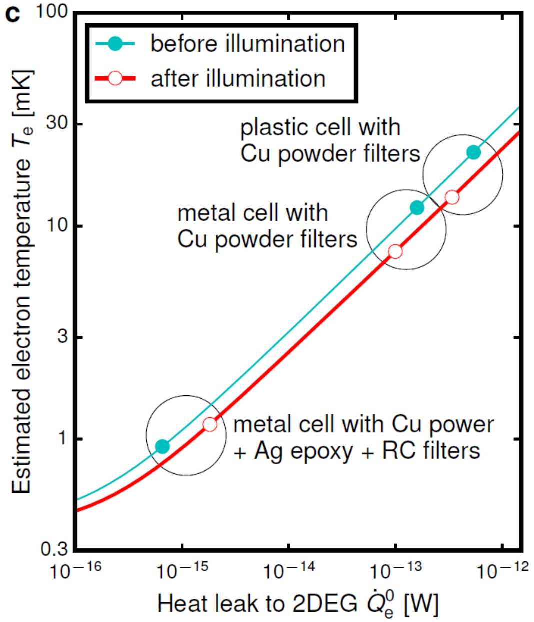
- Cu-powder
- Ag-epoxy (SC core, btw noise therm. & SQUID)
- Discrete $R = 500\ \Omega,\ C = 20\ nF$



Ohmic become superconducting



Sequential improvements

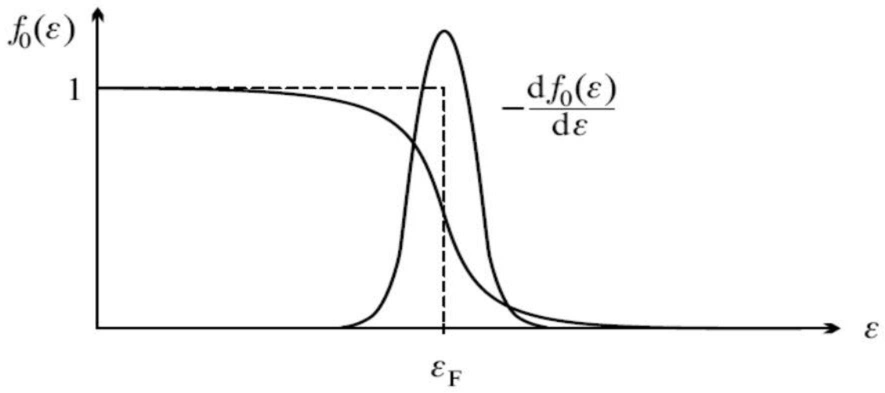


University of Basel
Department of Physics

WF – EP coupling – Kapitza

Wiedemann-Franz law:

- $\frac{\kappa}{\sigma} = L_0 \cdot T$ where $\kappa(\sigma)$: thermal (electrical) conductivity, L_0 = Lorentznumber
- $\kappa = \frac{1}{3} c_V mnl < v >$ kinetic gas theory
- $\sigma = \frac{ne^2\tau}{m} = \frac{ne^2 l}{m<v>}$ Drude model
- $c_v = \frac{\partial \epsilon}{\partial T} \propto T g(\epsilon_F)$ # excited e$^-$ @ T: $\propto g(\epsilon_F) k_B T$, each one carries energy $k_B T$
- $\dot{Q}_{WF} = L_0/(2R) \cdot (T_1^2 - T_0^2)$



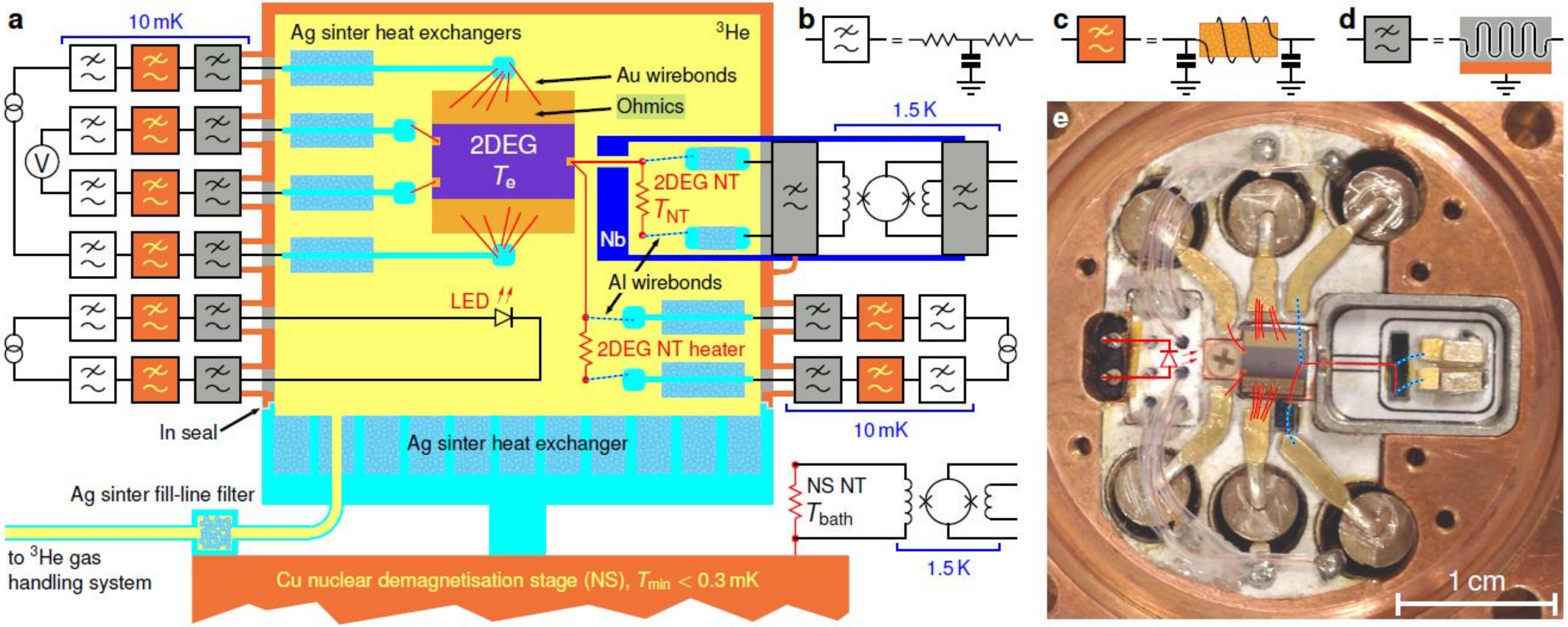
Electron phonon coupling

- $\dot{Q}_{e-ph} = \Sigma\Omega(T_1^5 - T_0^5)$
- Σ : EP coupling constant (material dependent)
- Ω : Volume

Kapitza boundary resistance

- Mismatch sound velocity
- Total internal reflection of phonons
- LHe & metal $\rightarrow$ large mismatch $\Rightarrow$ total refl. for $\alpha > 3°$
- Need sinters to cool metal in LHe (large area)
- $\dot{Q}_{Kapitza} = c_1(T_1^3 - T_0^3) + (c_2 (T_1^4 - T_0^4))$

Experimental setup



<u>Setup and measurement procedure</u>

- 1 NT (noise thermometer): Brownian motion in gold wire
- 2 heaters (resistors): 2DEG, NT (other AU wire)
- LED to change 2DEG (mobility, density, charge noise)

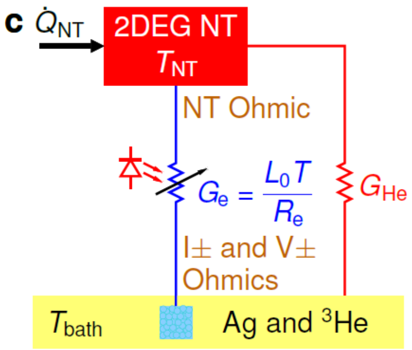
$\Rightarrow$ Measure T_{NT} vs heating $\Rightarrow$ therm. conductivity $\Rightarrow$ T_e (heat flow model)

Thermal transport

Heating noise thermometer (Au wire)

- $G_\Sigma = d\dot{Q}_{NT}/dT_{NT}$
- 2 cooling path: ohmics + 2DEG / liquid 3He
- Consider WF & Kapitza

$\Rightarrow G_\Sigma = \frac{L_0 T}{R_e} + K_2 T^2 + K_3 T^3$



Heating the 2DEG (passing current)

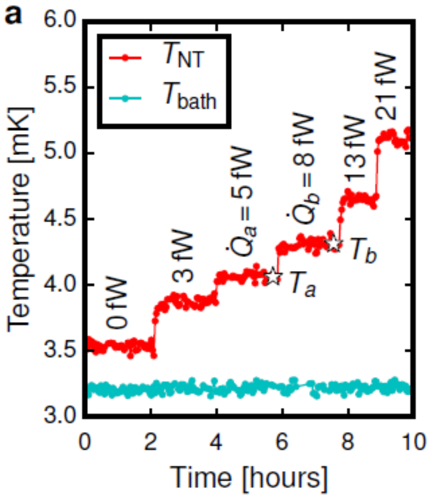
- $G_N = d\dot{Q}_e/dT_{NT}$ nonlocal therm.cond. : heat 2DEG, observe T_N
- 3rd (unknown) cooling path, not relevant below 3mK (EP cooling?)
- $G_N = (G_\Sigma + X_4 T^4)/\alpha$

Combine the two, neglect X4-term

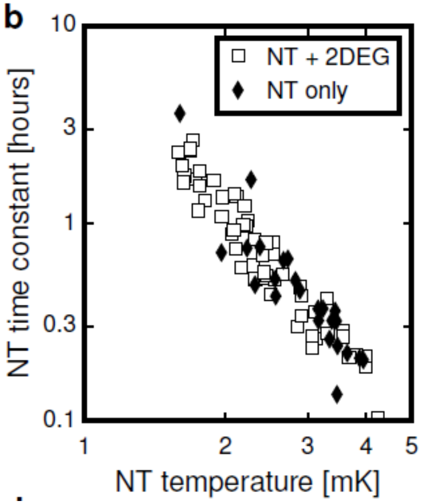
$$\dot{Q}_{NT} + \alpha \dot{Q}_e = \int_{T_{bath}}^{T_{NT}} G_\Sigma(T)\, dT = \frac{L_0}{2R_e}(T_{NT}^2 - T_{bath}^2) + \frac{K_2}{3}(T_{NT}^3 - T_{bath}^3) + \frac{K_3}{4}(T_{NT}^4 - T_{bath}^4).$$

- Heat leak: heaters off ($\dot{Q}$ is only heat leak), measure T_{NT} , T_{bath}

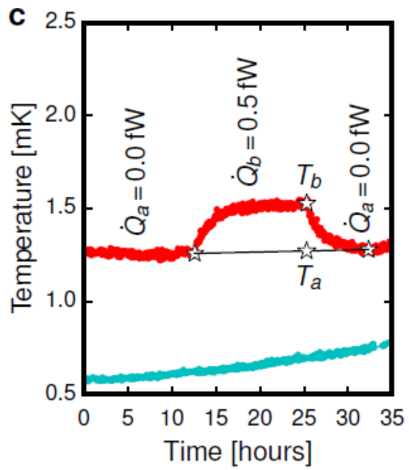
Heater step profile



Long TC @ low T



Extraction procedure @ low T

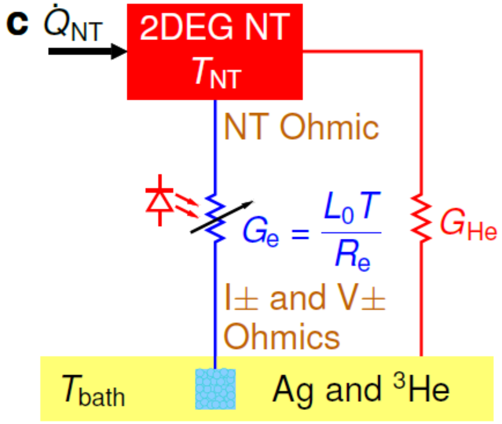


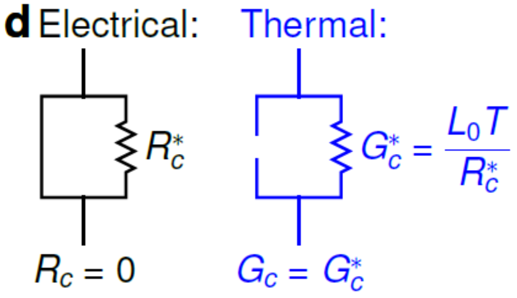
Thermal conductance

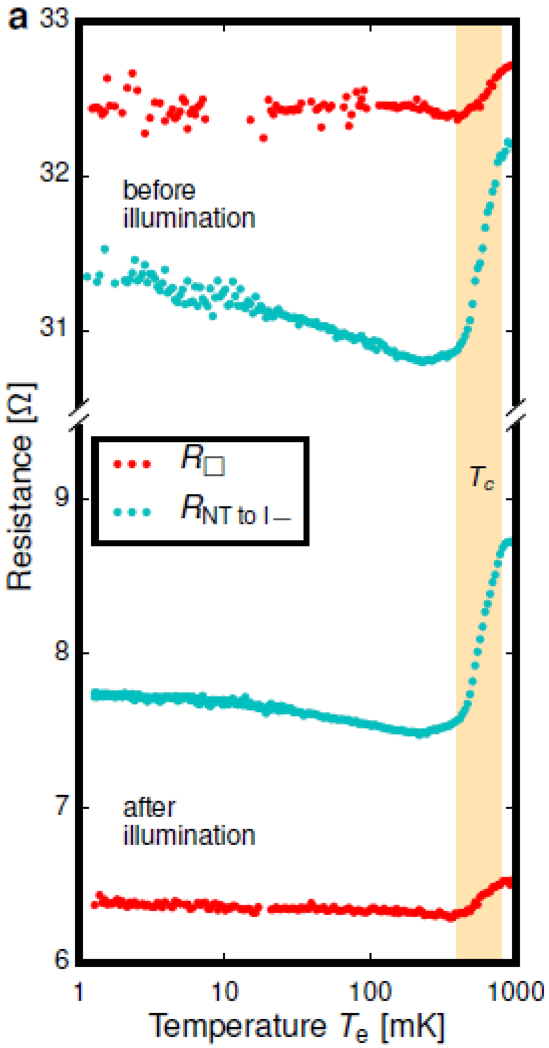
Heating noise thermometer (Au wire)

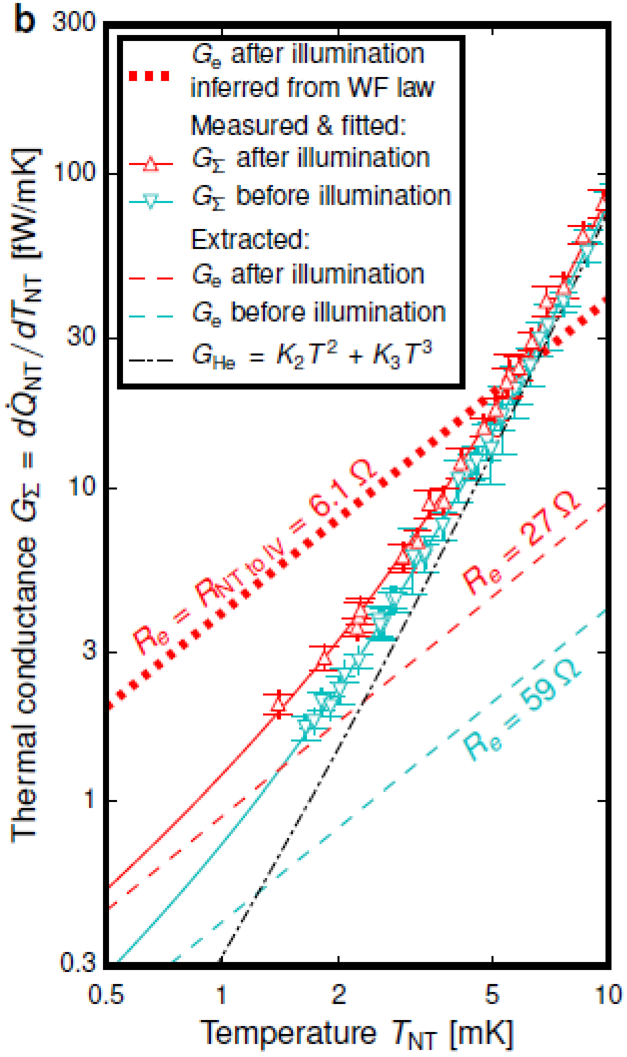
- $G_\Sigma = d\dot{Q}_{NT}/dT_{NT}$
- 2 cooling path: ohmics + 2DEG / liquid 3He
- Consider WF & Kapitza

$$\Rightarrow G_\Sigma = \frac{L_0 T}{R_e} + K_2 T^2 + K_3 T^3$$









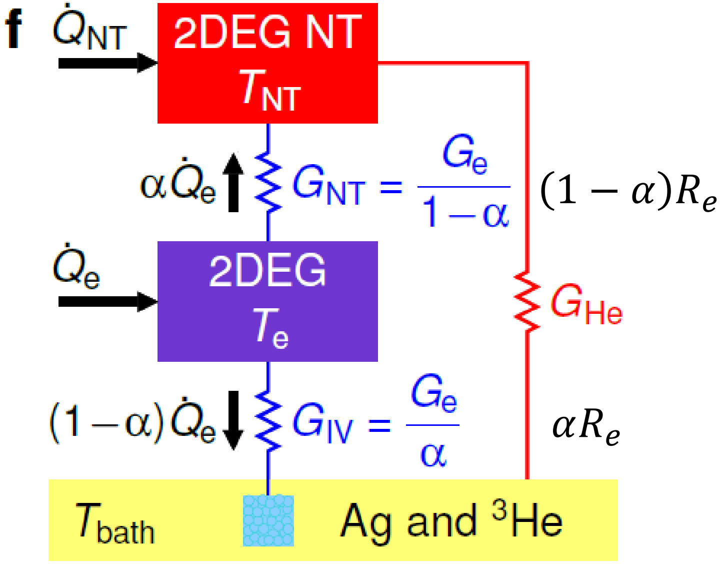
Themal model → T_e

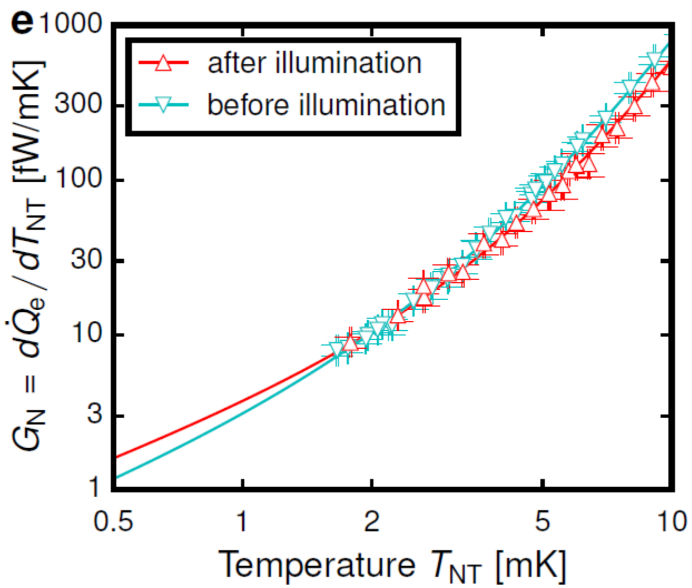
Heating the 2DEG (passing current)

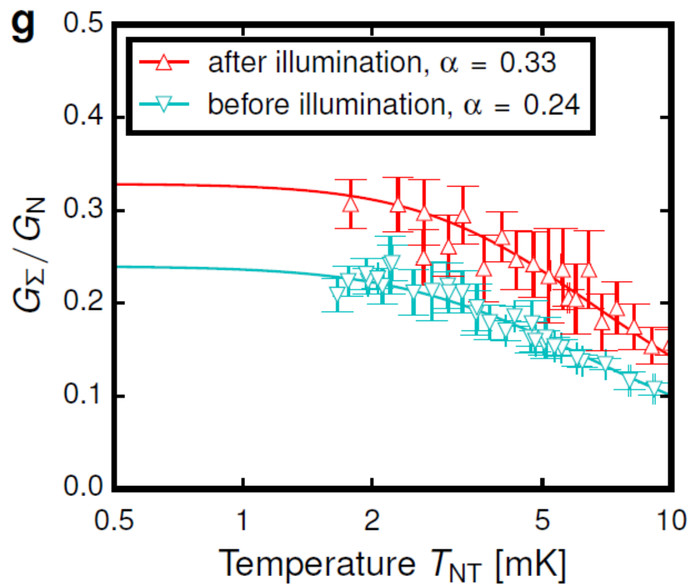
- $G_N = d\dot{Q}_e/dT_{NT}$ nonlocal therm.cond. : heat 2DEG, watch response T_N
- 3rd (unknown) cooling path, not relevant below 3mK (EP cooling?)
- $G_N = (G_\Sigma + X_4 T^4)/\alpha$

$$\dot{Q}_e = \frac{L_0}{2(1-\alpha)R_e}(T_N^2 - T_e^2) + \frac{L_0}{2\alpha R_e}(T_b^2 - T_e^2)$$

$$T_e^2 = (1-\alpha)\,T_{\rm bath}^2 + \alpha\,T_{\rm NT}^2 + 2\alpha(1-\alpha)\,R_e\dot{Q}_e/L_0$$







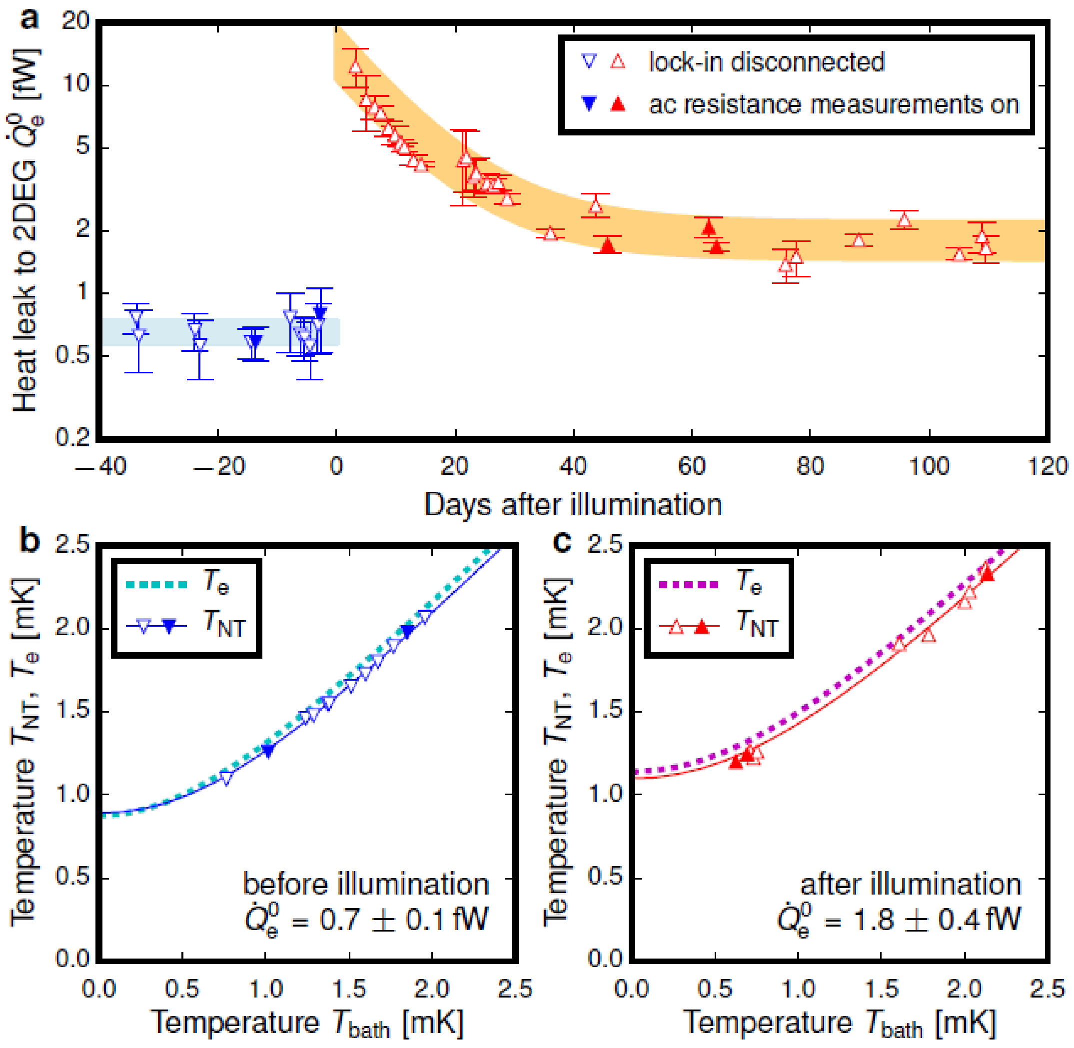
Wiedemann Franz law

$$\dot{Q} = \frac{L_0}{2R}(T_1^2 - T_0^2)$$

Results

LED illumination

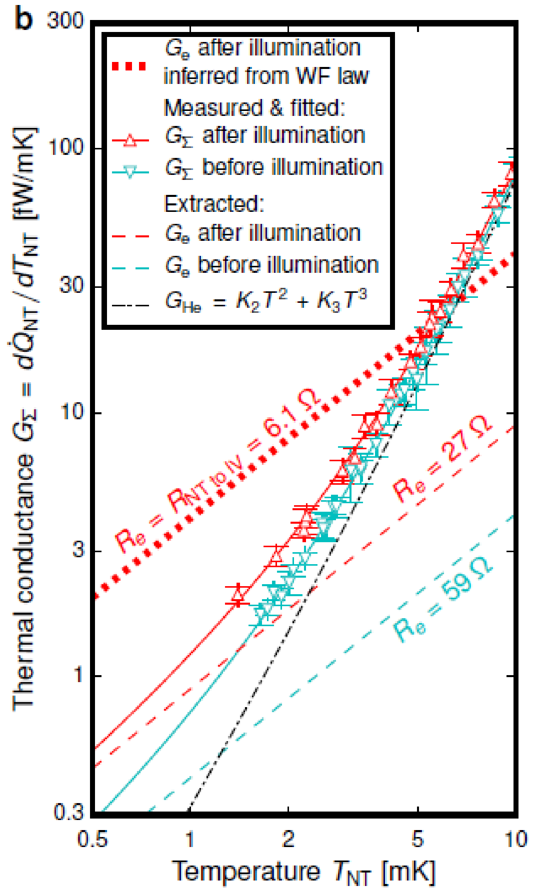
- Changes only 2DEG properties
- Large heat leak after LED, saturates after 40 days at high value
- Lowest Te before LED (0.9mK)
- HL: 0.7fW (1.9fW) before (after) LED
- T_e, T_{NT} almost identical



Critics / Conclusions

Critics

- SC Ohmics: resistance for WF from fit, not measured
  Better: Apply magnetic field (don't need to assume R)
- Very indirect temperature measurement (heat model correct?)
- Additional cooling term for 2DEG, what is it?
- Functional form of Kapitza (not measured), assumed 3rd (standard)+ 4th power ???
- Heater resistance (Au wire) not known, inferred from similar measurements
- Thermal cond. almost described by (assumed) Kapitza resistance
  Te from the small deviation



Conclusion

- Impressive work
- Result questionable