Edge State Heat Transport in the Quantum Hall Regime

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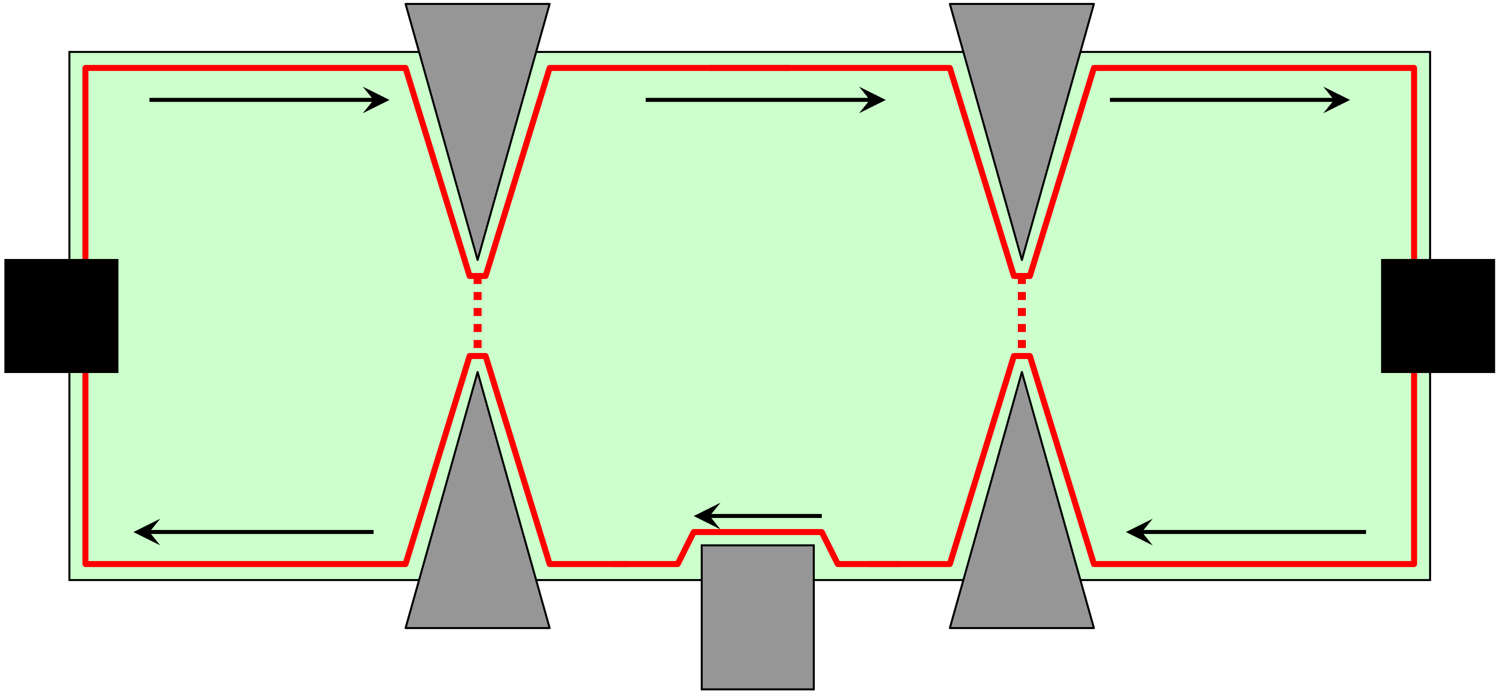
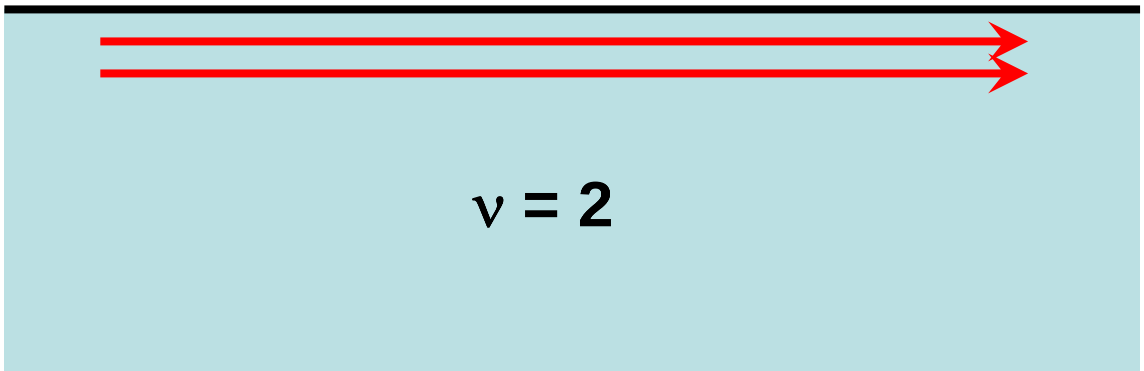
Motivation: Quantum interference devices to detect non-abelian statistics

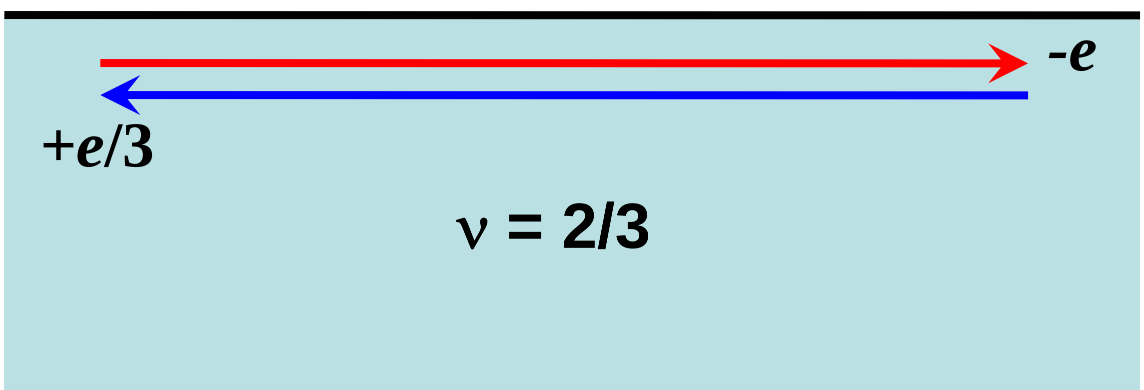


Fabry-Perot interferometer

Interferometers rely on understanding the edge



IQHE: forward modes only

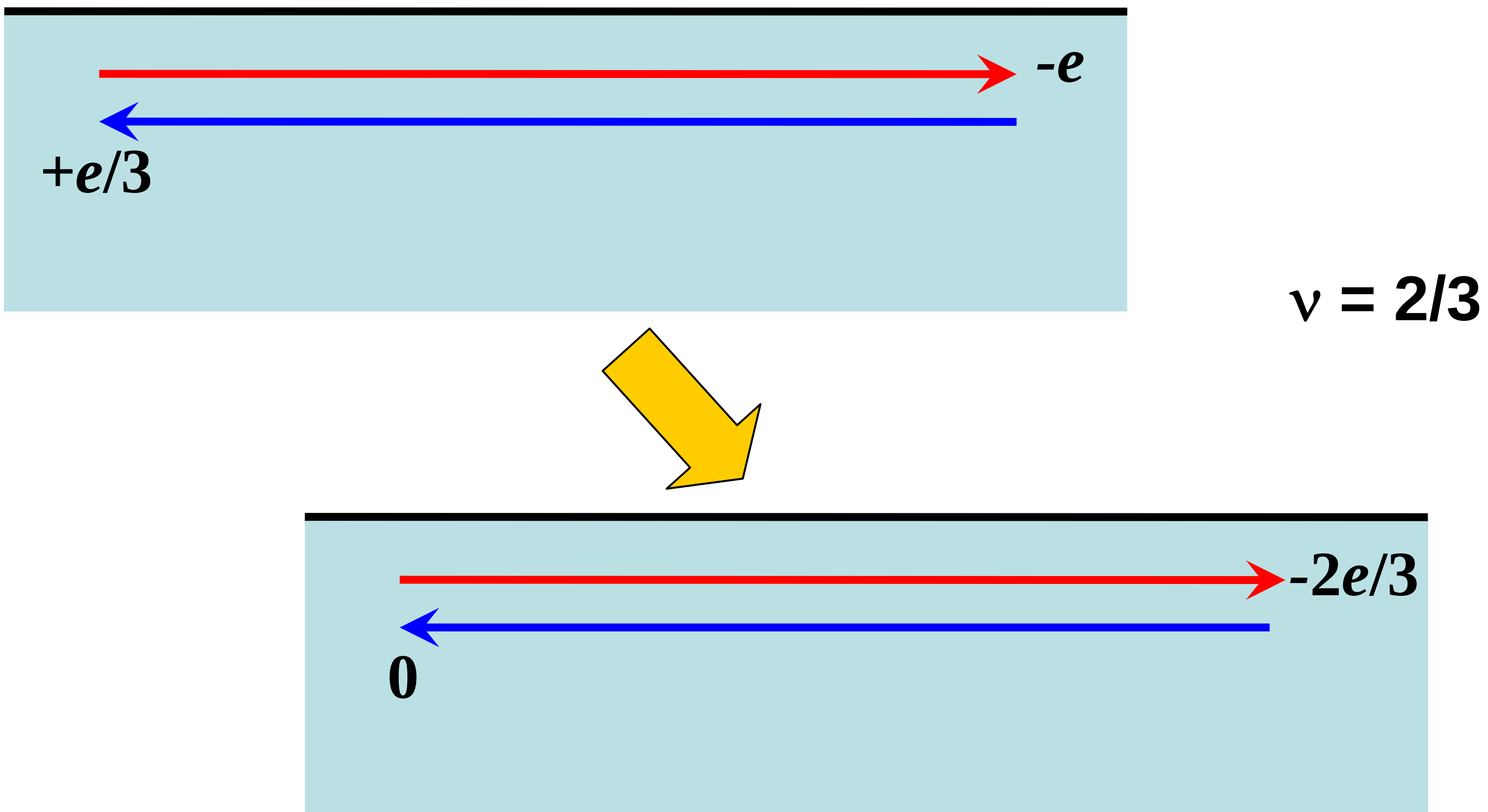


FQHE: backward modes predicted at some fractions

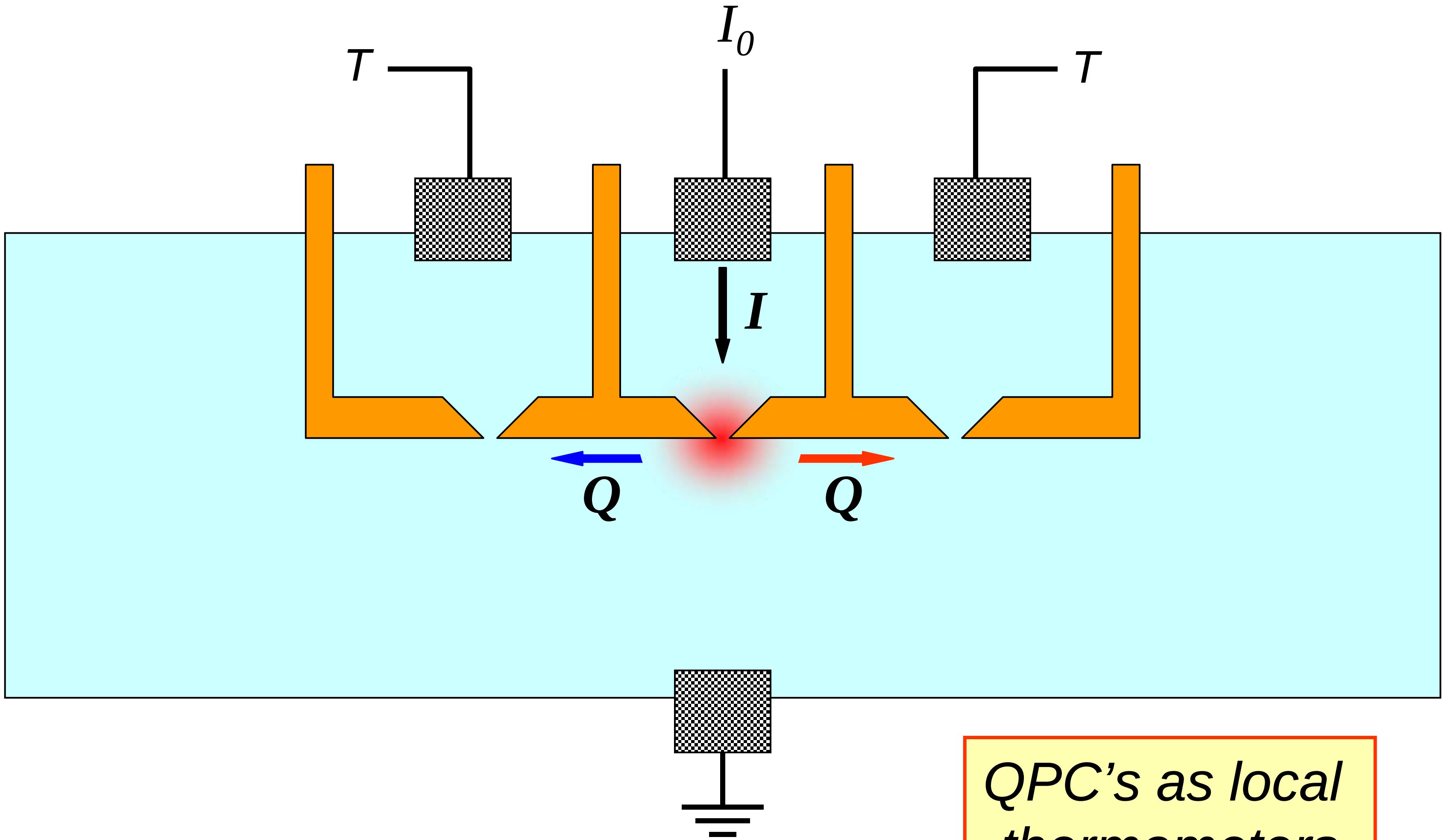
MacDonald; Wen 1990

Mode mixing due to disorder at the edge

Kane, Fisher and Polchinski 1994



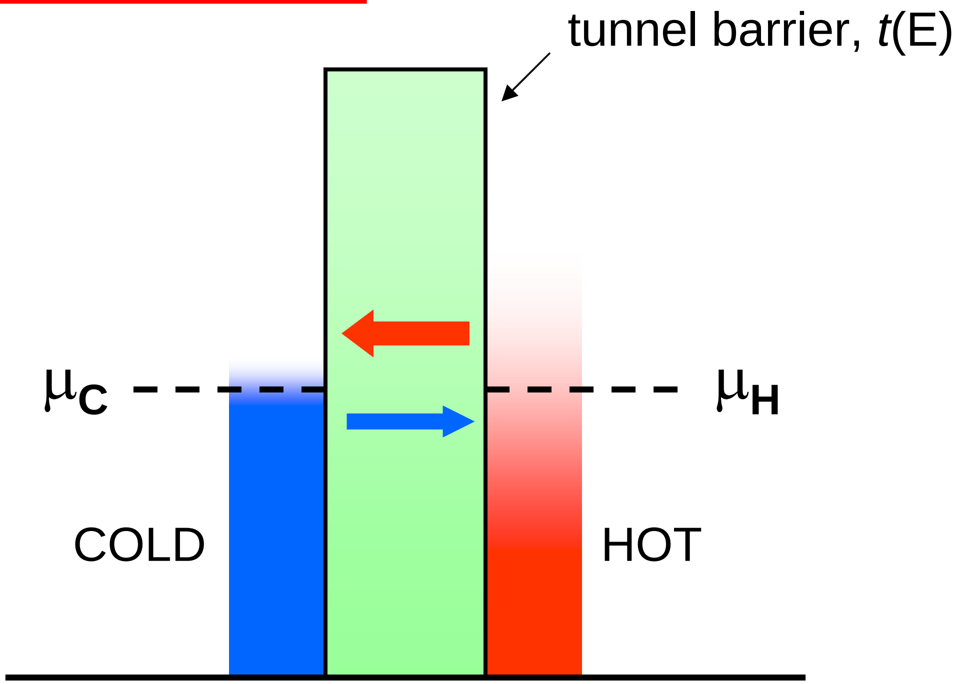
Detecting the neutral mode: Heating



QPC's as local thermometers

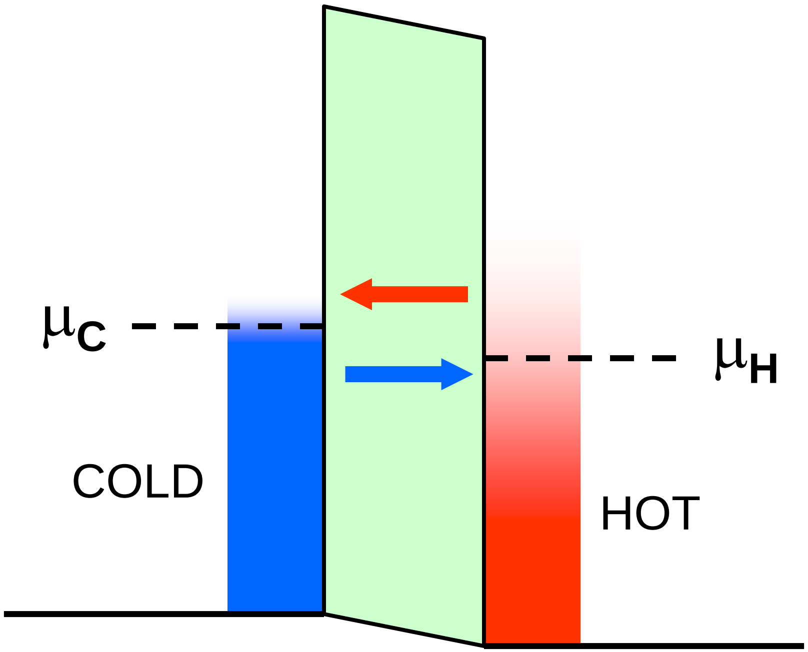
Kane & Fisher

QPC thermoelectric effect



If transmission probability is energy dependent, current flows even if $\Delta\mu$ = 0.

QPC thermoelectric effect



If no current is allowed to flow:

$$\Delta V = -S\,\Delta T$$

Mott formula

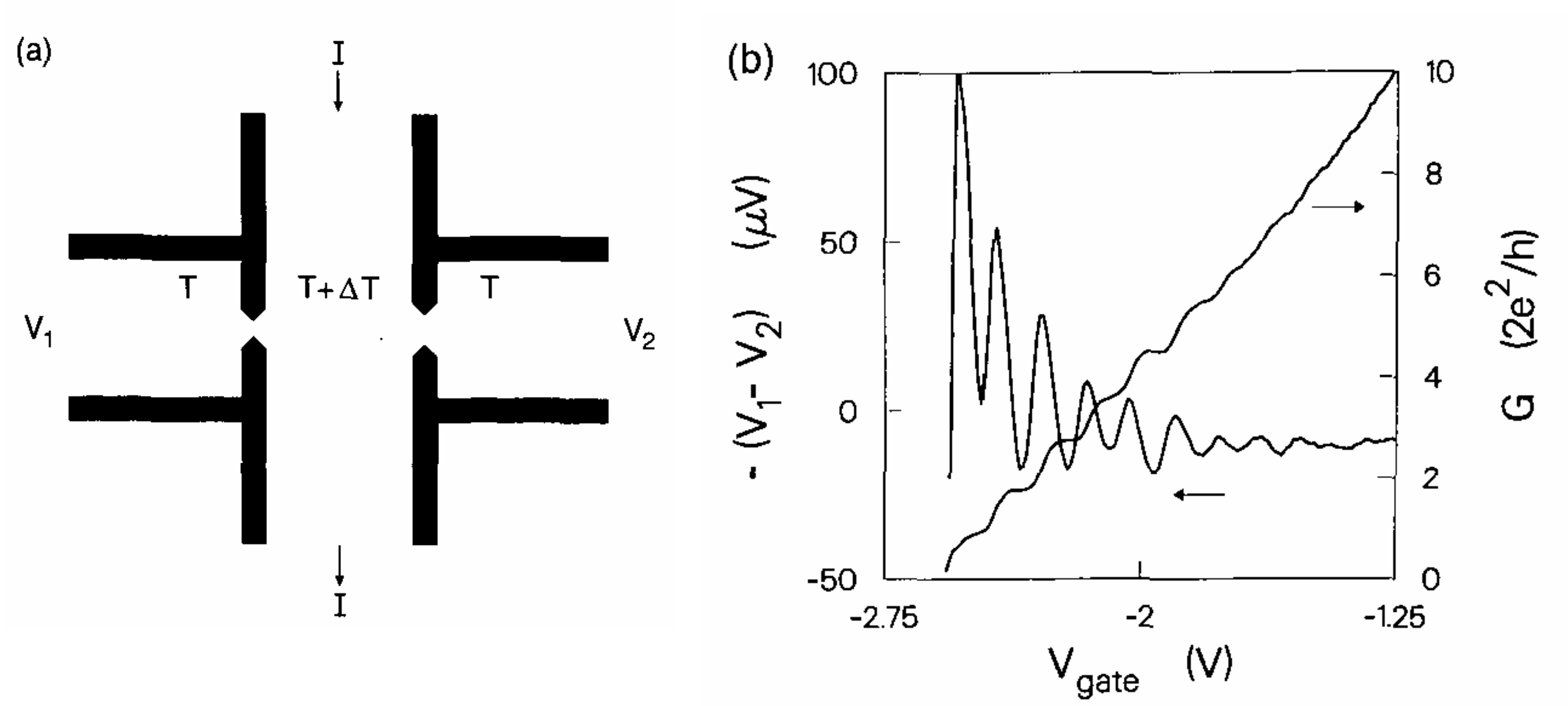
$$\begin{pmatrix} I \\ Q \end{pmatrix} = \begin{pmatrix} G & L \\ M & K \end{pmatrix} \begin{pmatrix} \Delta\mu / e \\ \Delta T \end{pmatrix}$$

$$\Delta V = \frac{L}{G} \Delta T = -S \Delta T$$

$$S = -\frac{\pi^2 k_B^2}{3e} \frac{T}{G} \frac{dG}{d\mu}$$

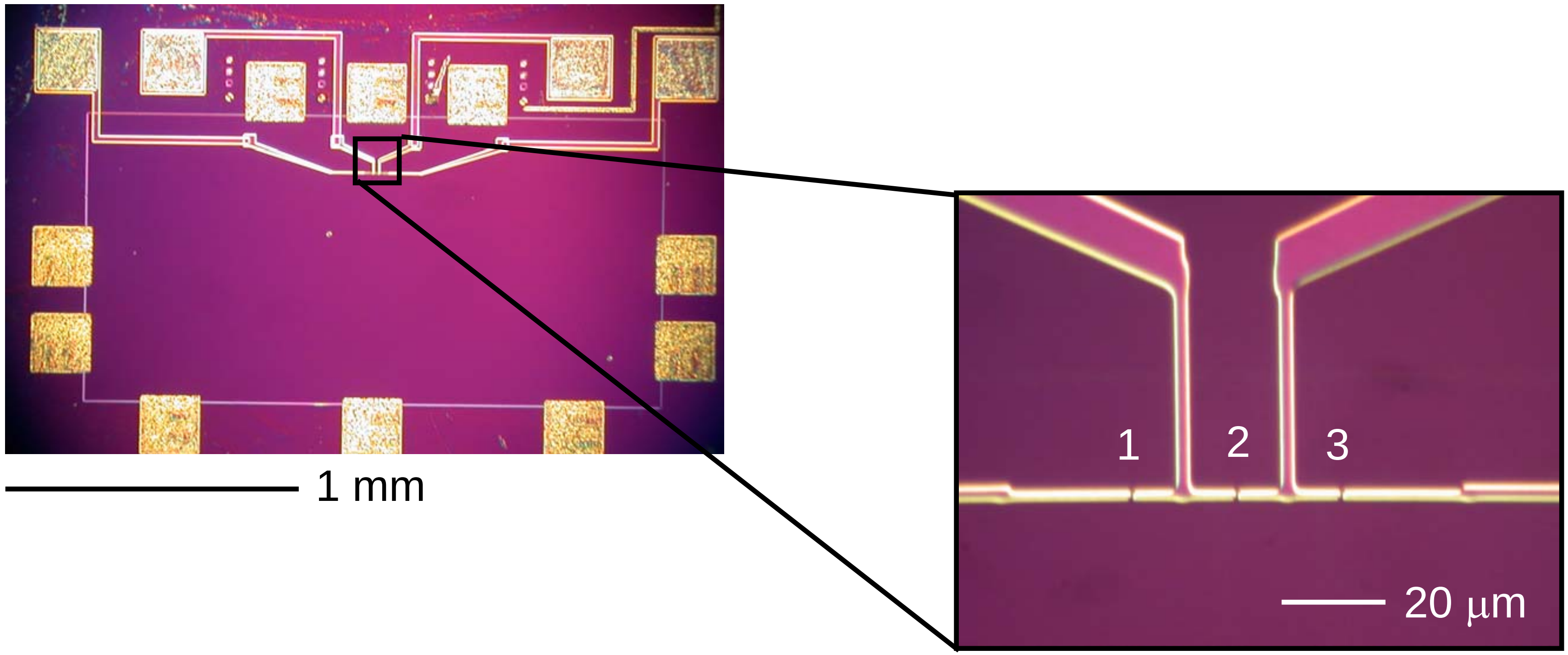
Proof of principle

Molenkamp, et al. 1990

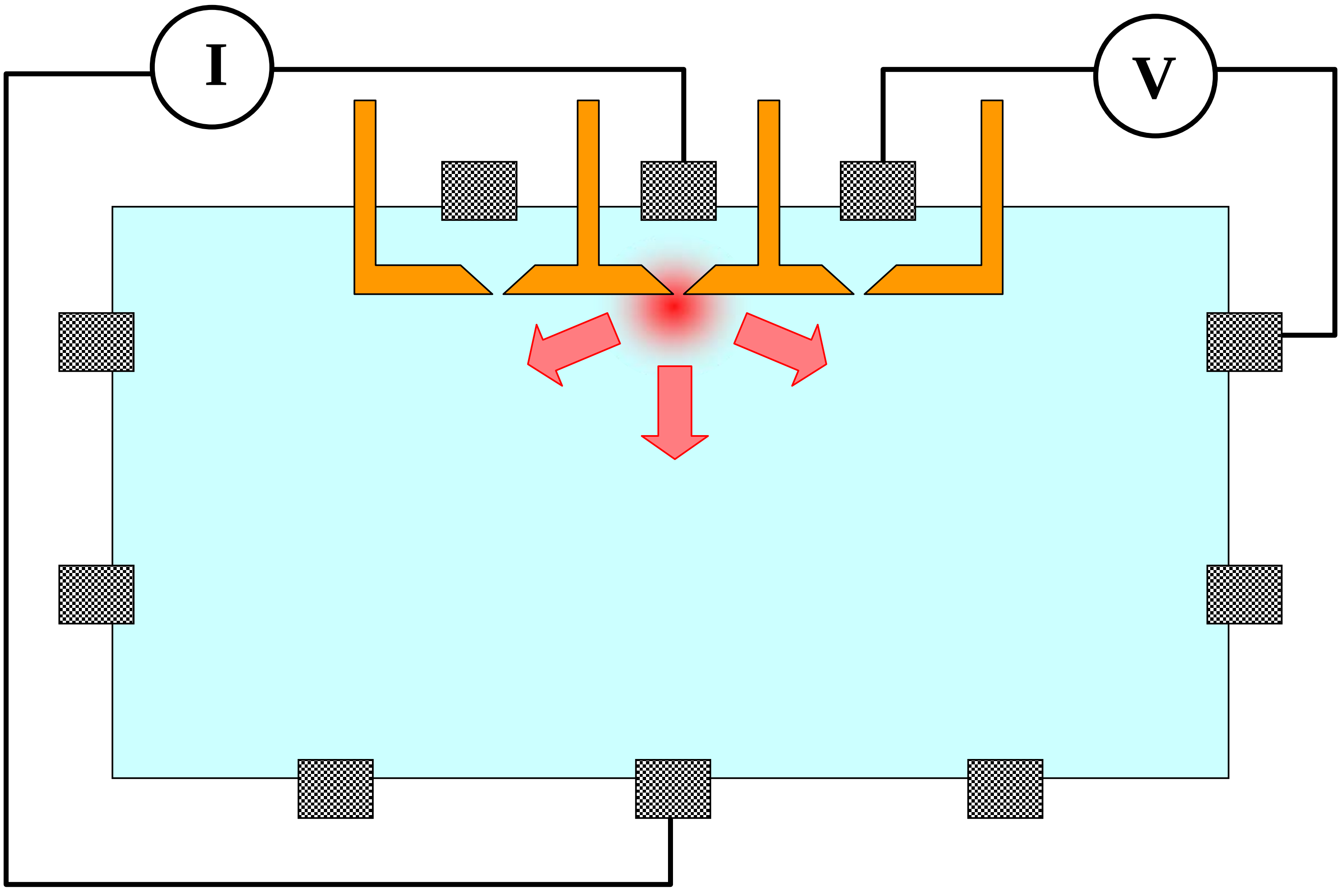


Thermovoltage oscillations align with dG/dV_g

QPC device layout

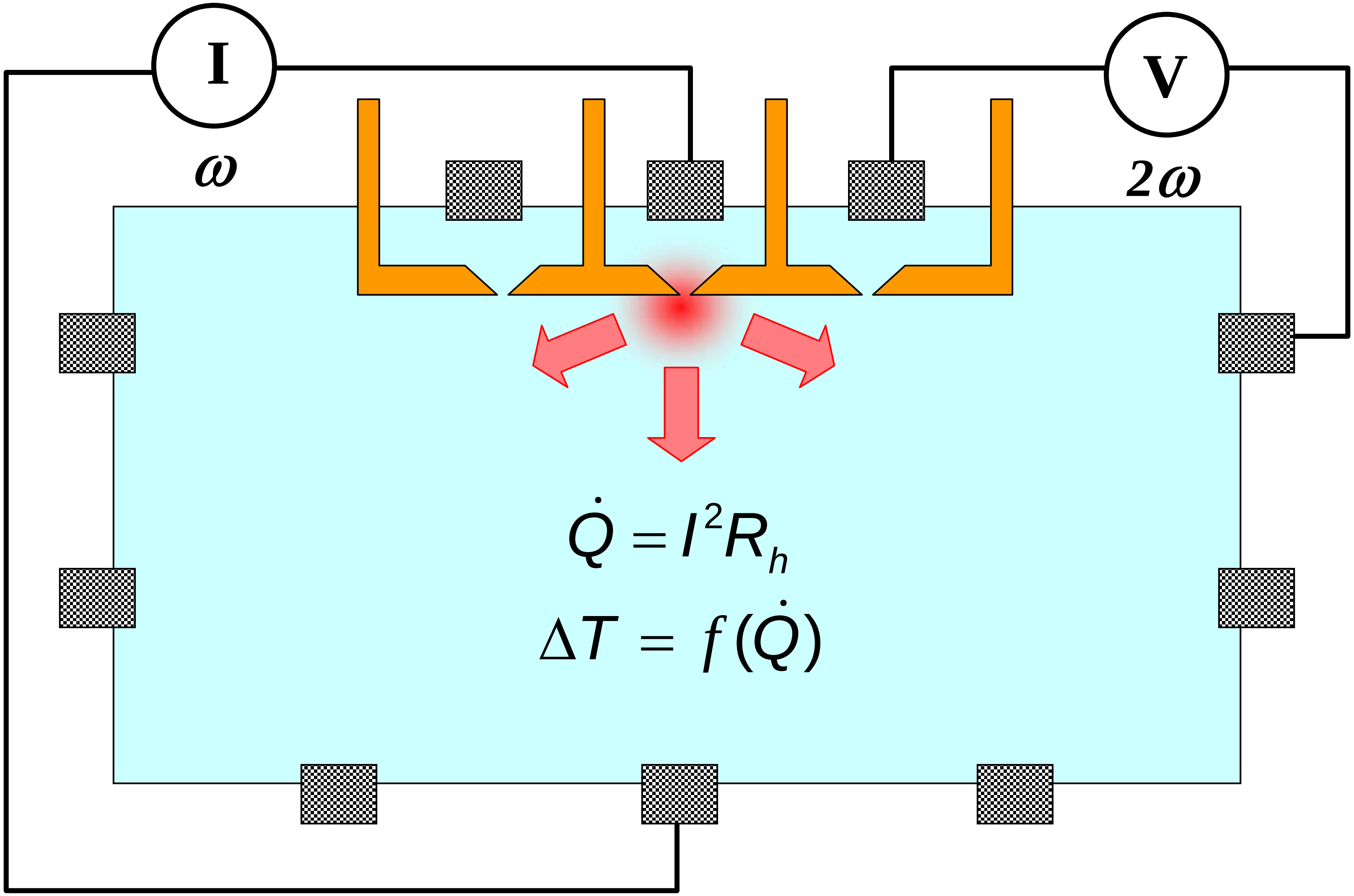


Measurement technique



How to distinguish thermopower from resistivity?

Measurement technique

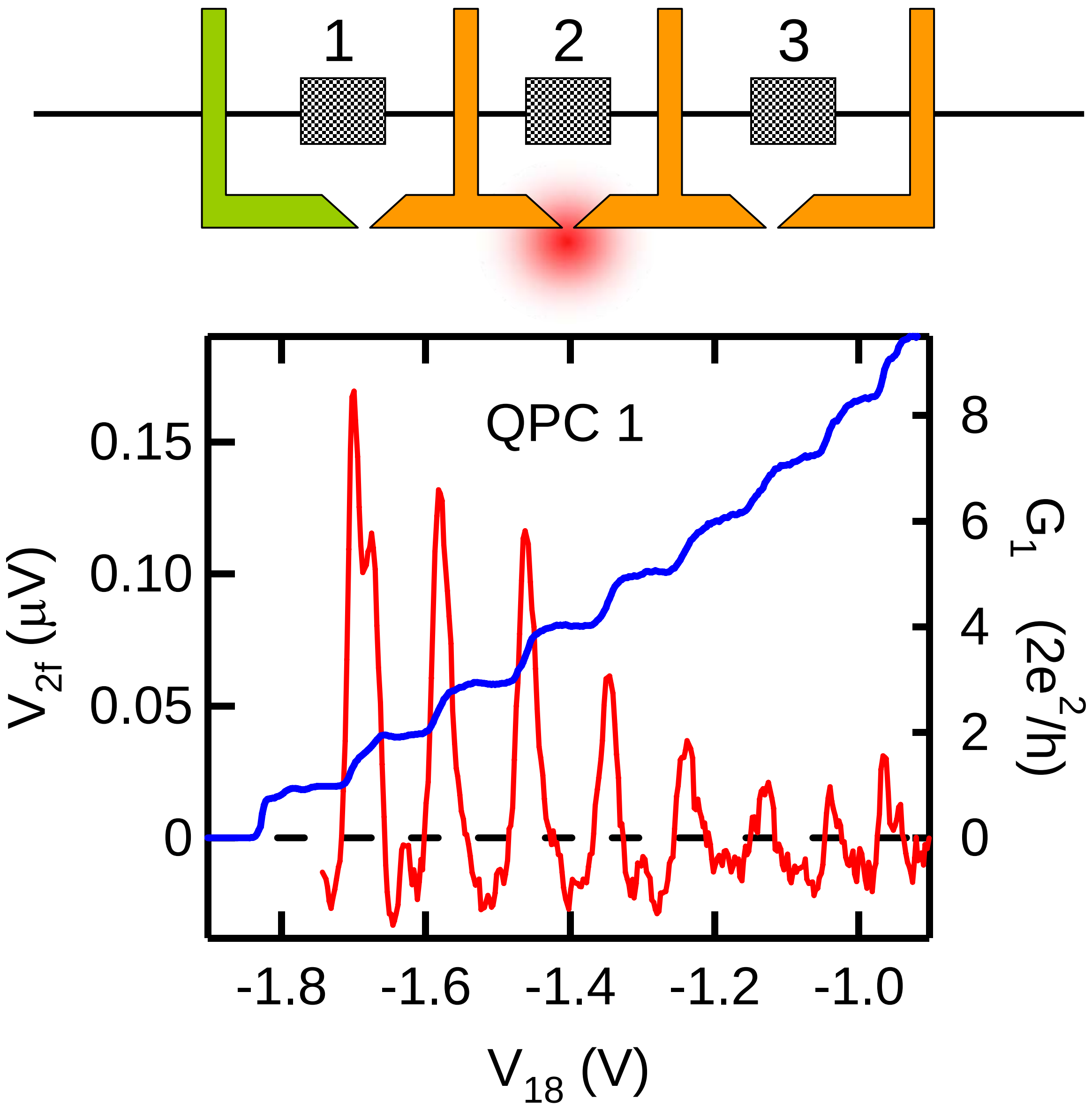


$$\dot{Q} = I^2 R_h$$

$$\Delta T = f(\dot{Q})$$

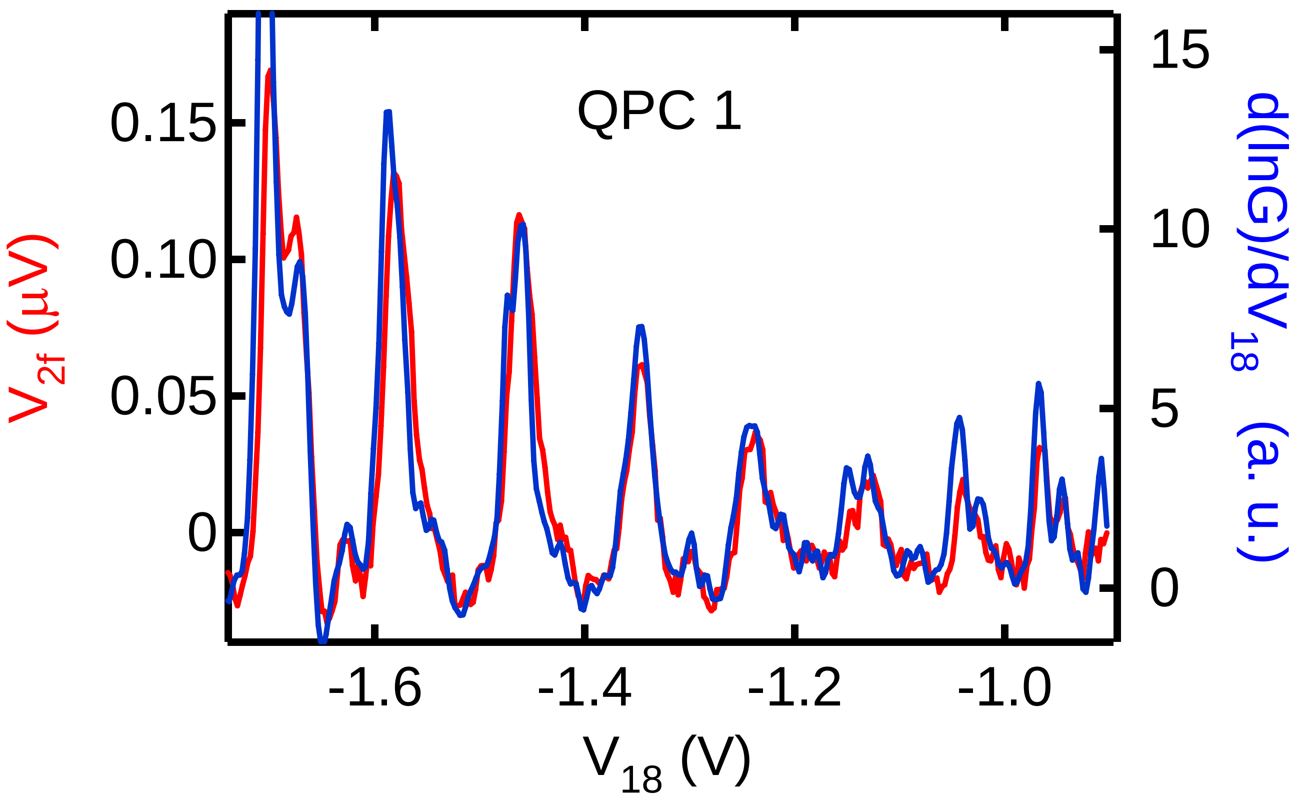
Excitation current at frequency ω, thermovoltage at 2ω

Typical B=0 results



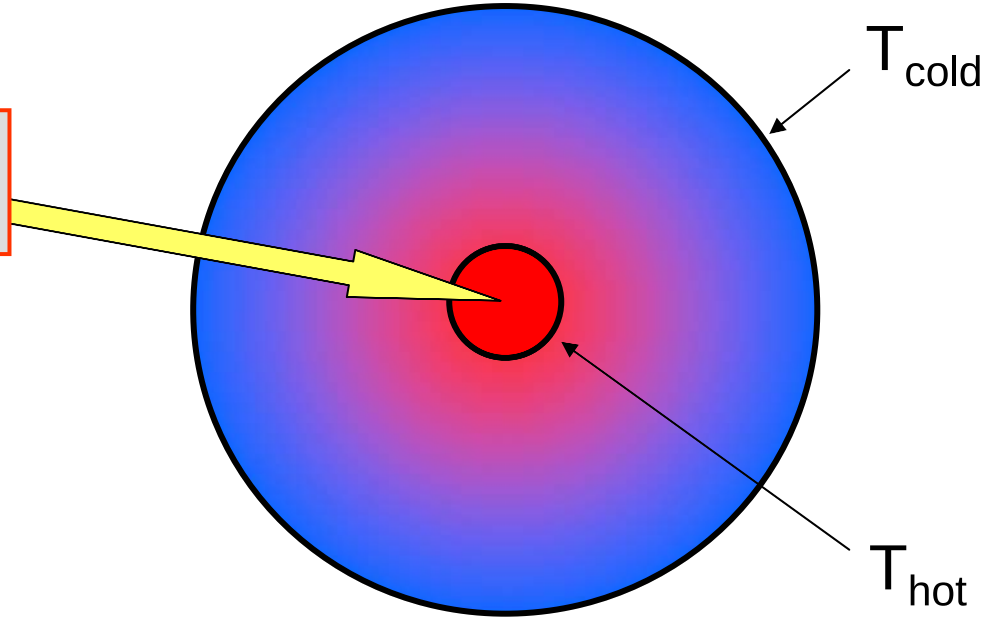
Mott's formula works at B=0

$$S = -\frac{\pi^2 k_B^2}{3e} \frac{T}{G} \frac{dG}{d\mu}$$



Crude thermal estimate

$$\dot{Q} = I^2 R$$



$$\dot{Q} = -2\pi a \, \kappa_{2D} \left.\frac{\partial T}{\partial r}\right|_{r=a}$$

$$\kappa_{2D} = L_0 T \sigma = L_0 T N e \mu$$

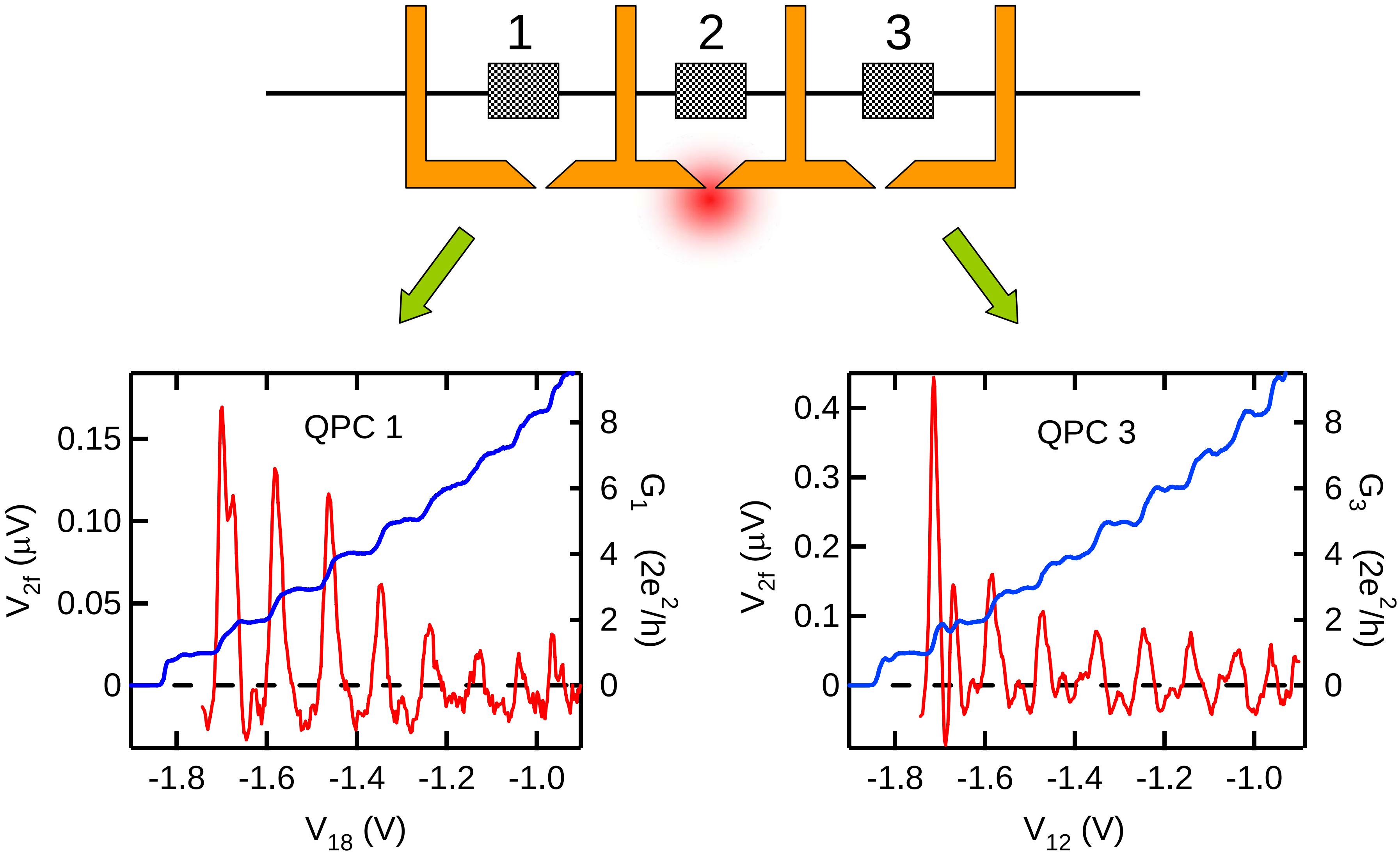
I = 50 nA, R = 8 kOhm, T_c = 60 mK
N = 1.5 x 10^{11} cm^{-2}, μ = 3 million
a = 1 μm, b = 1 mm

$$T^2 - T_{cold}^2 = \frac{\dot{Q} \ln(b/r)}{\pi L_0 \sigma}$$

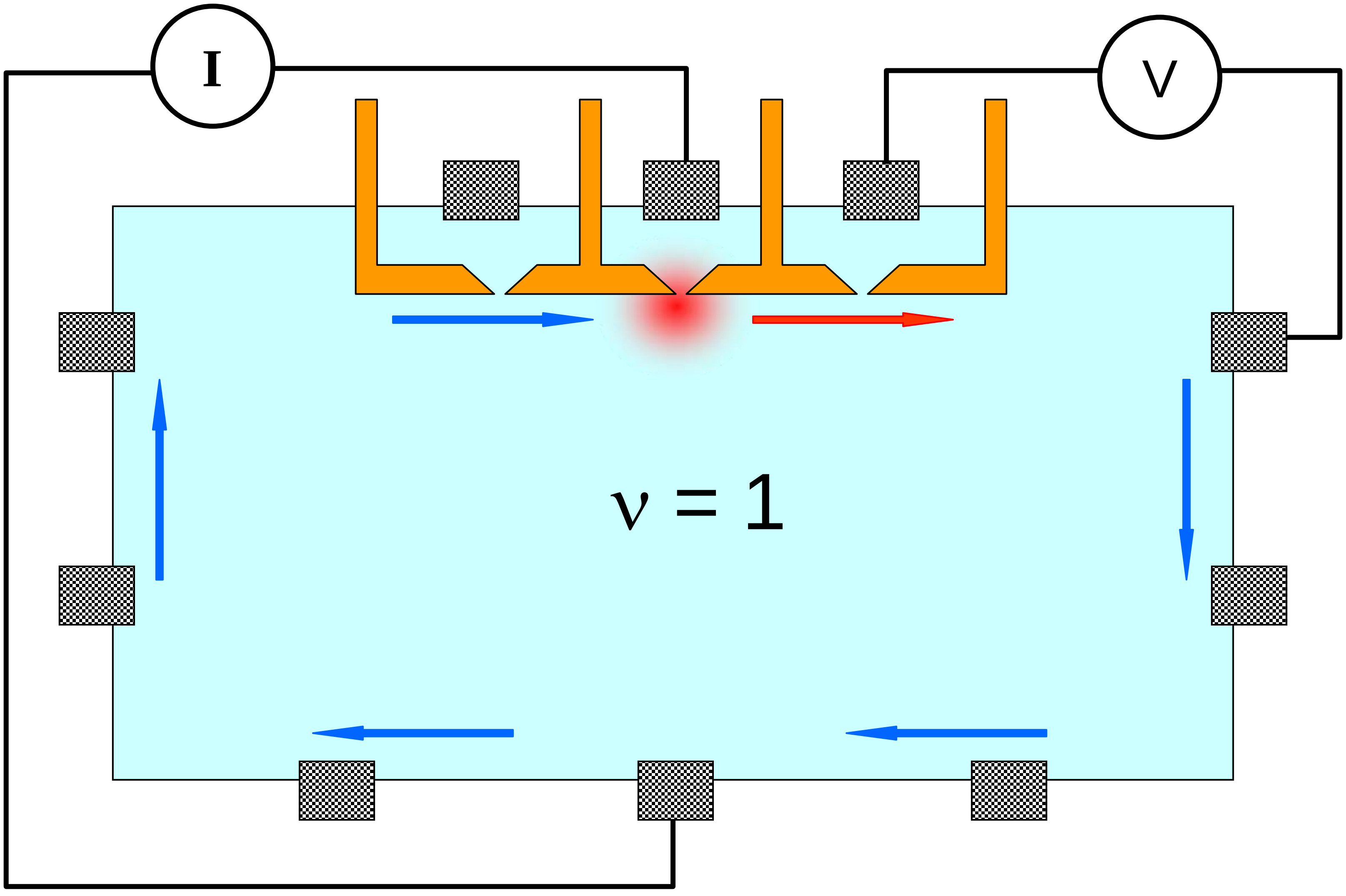
$$T(r = 1\mu m) \approx 170 \; mK$$

$$T(r = 20\mu m) \approx 130 \; mK$$

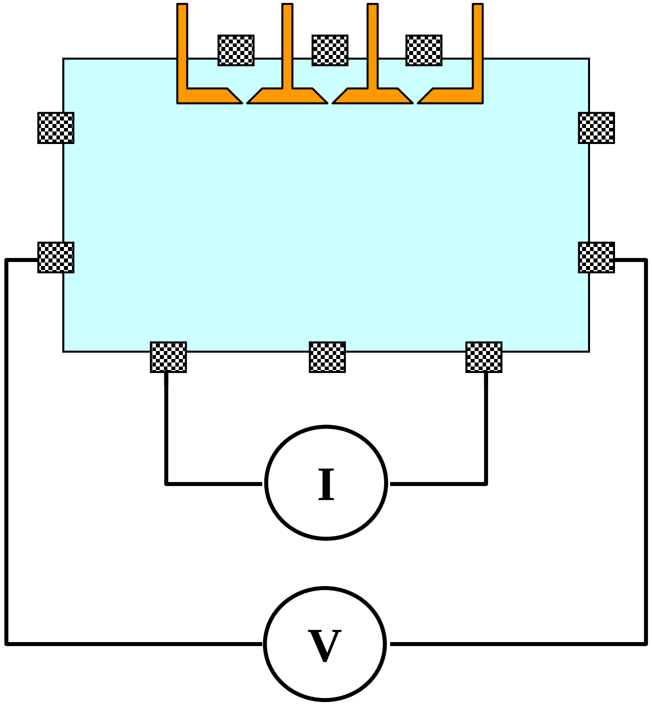
Heat goes both ways at B=0

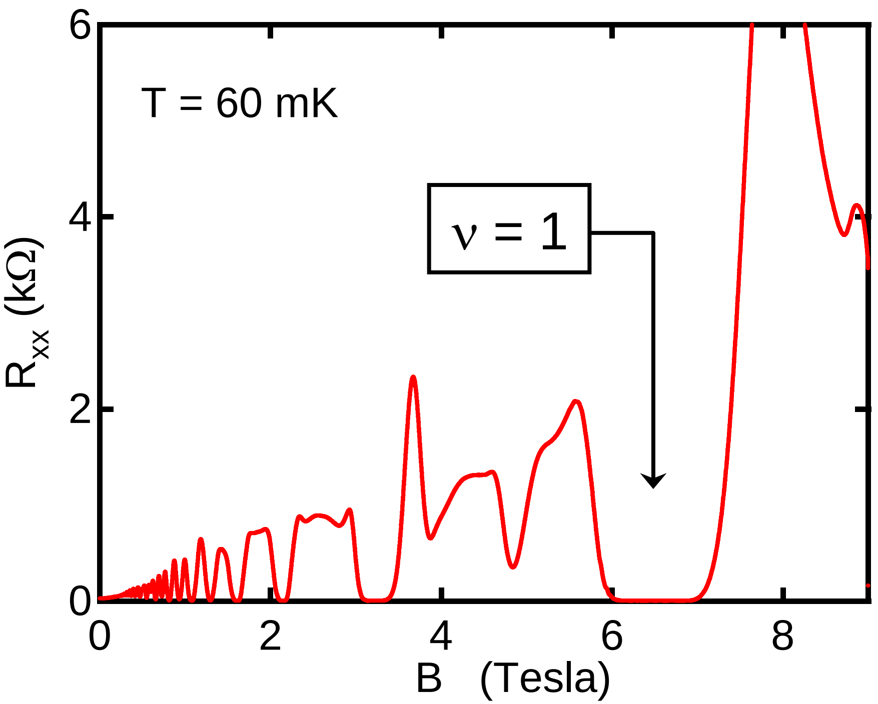


IQHE regime

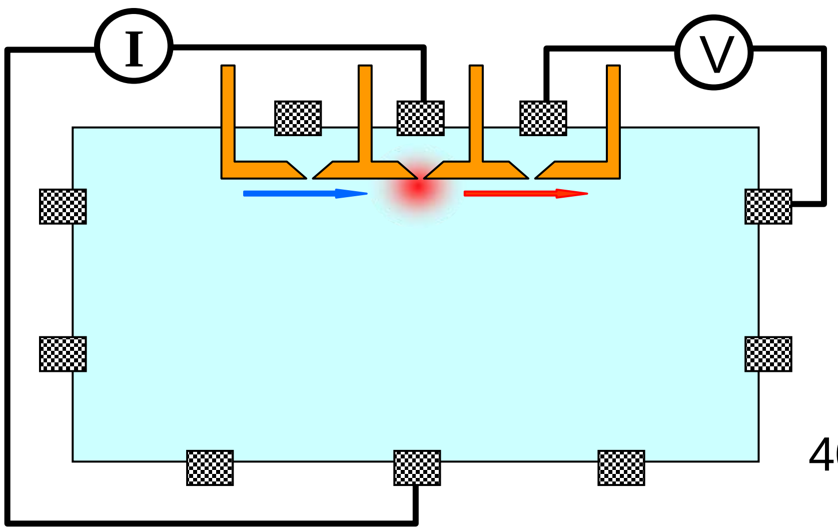


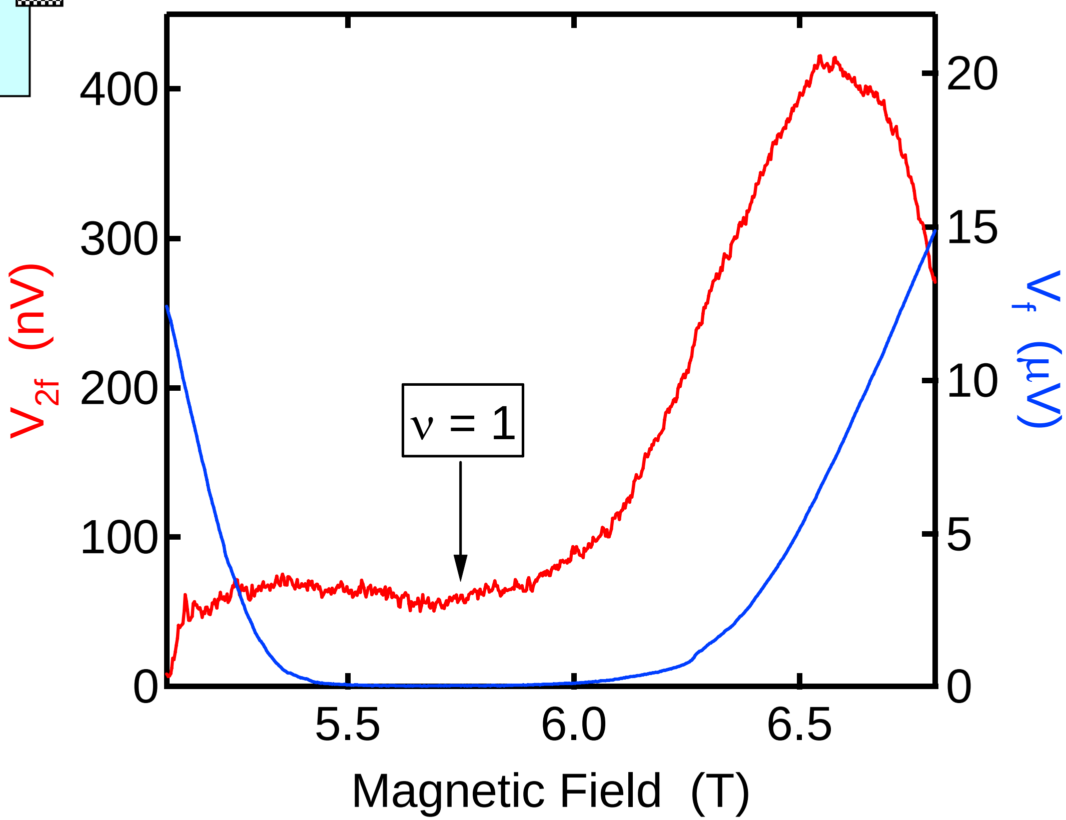
Bulk transport





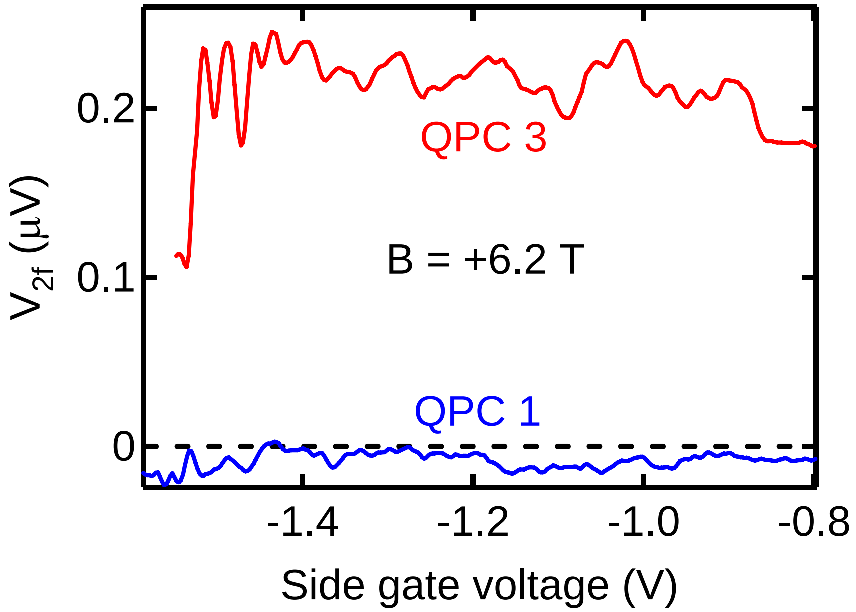
Detecting a heating signal

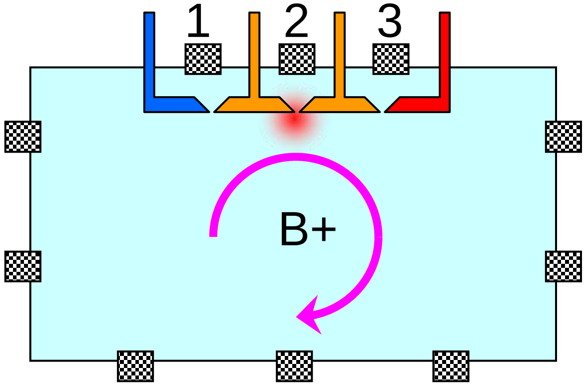




Chiral heat transport at ν = 1

I = 5 nA





Chiral heat transport at ν = 1

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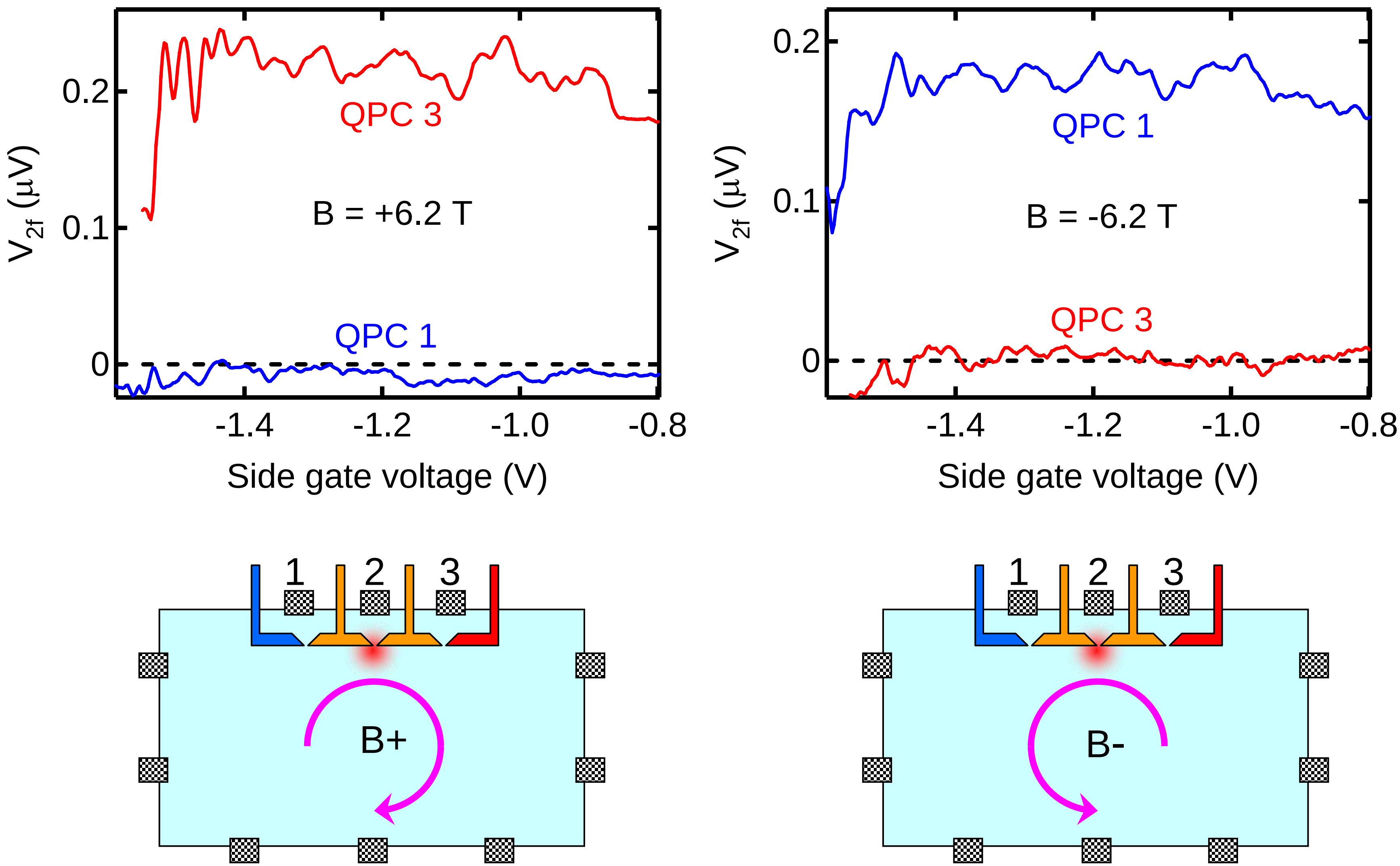
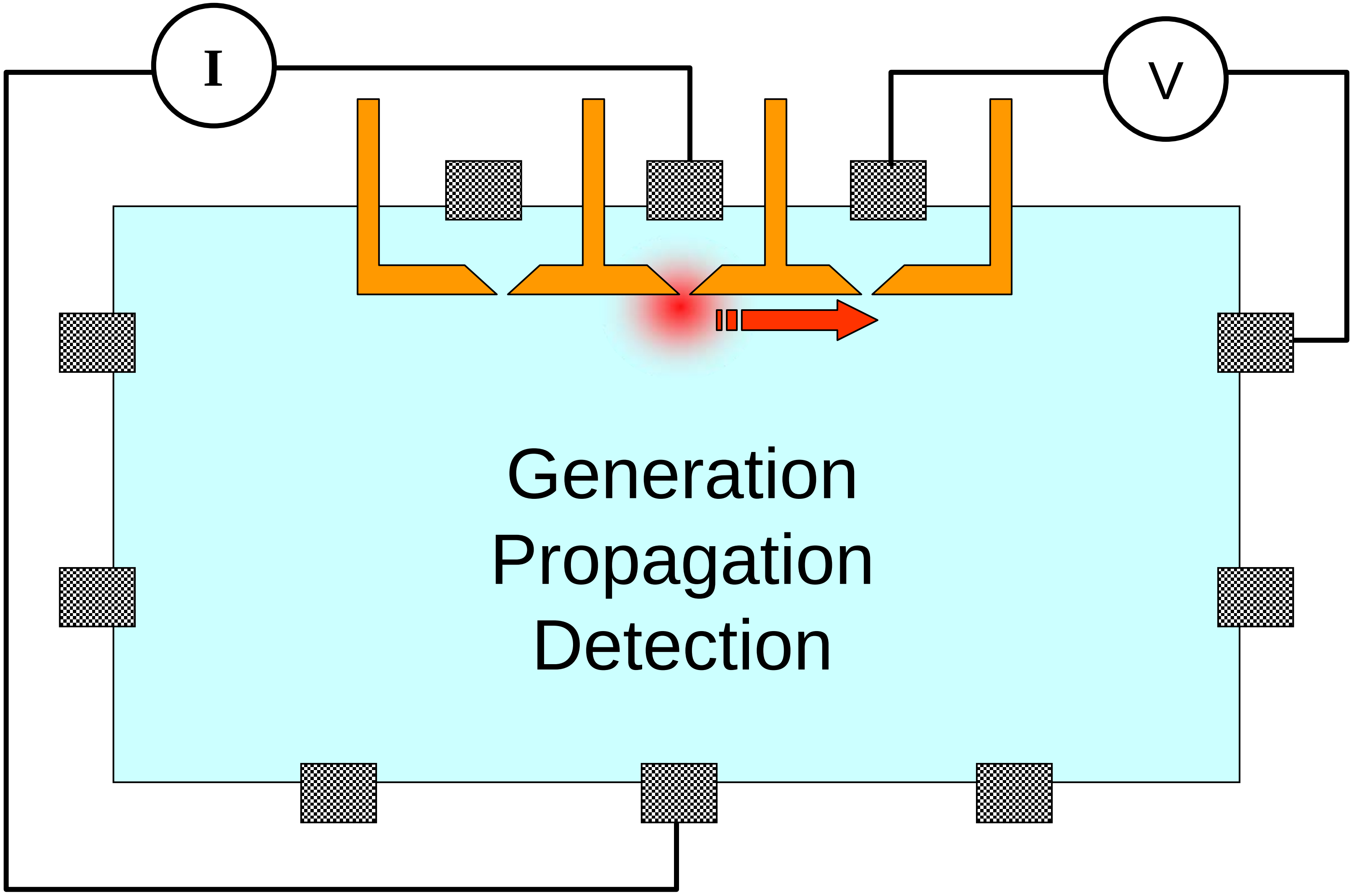
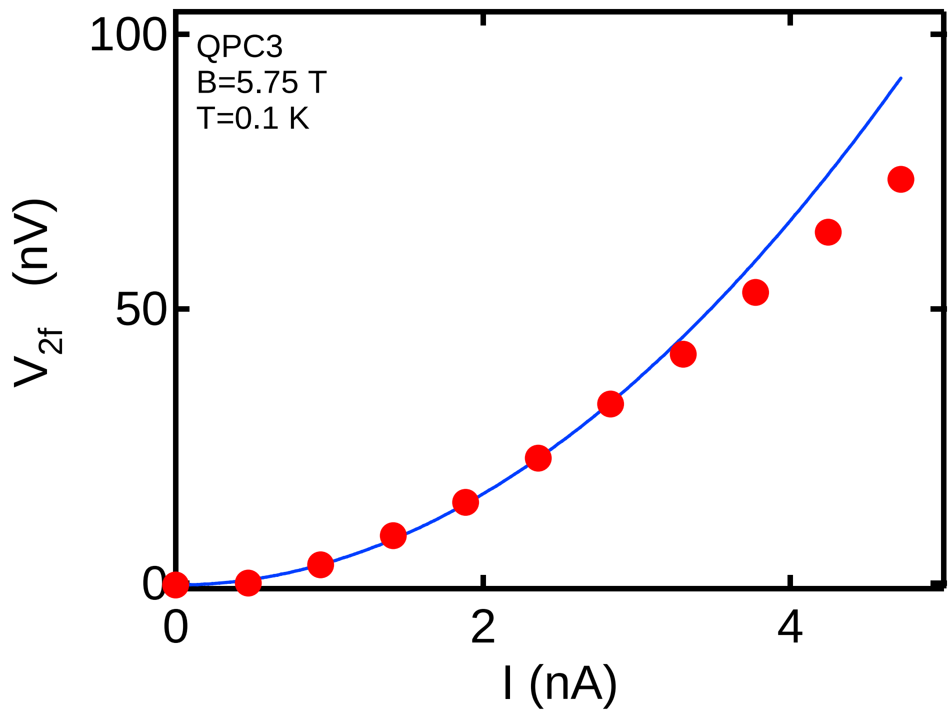


A three step process



How does the heater work?

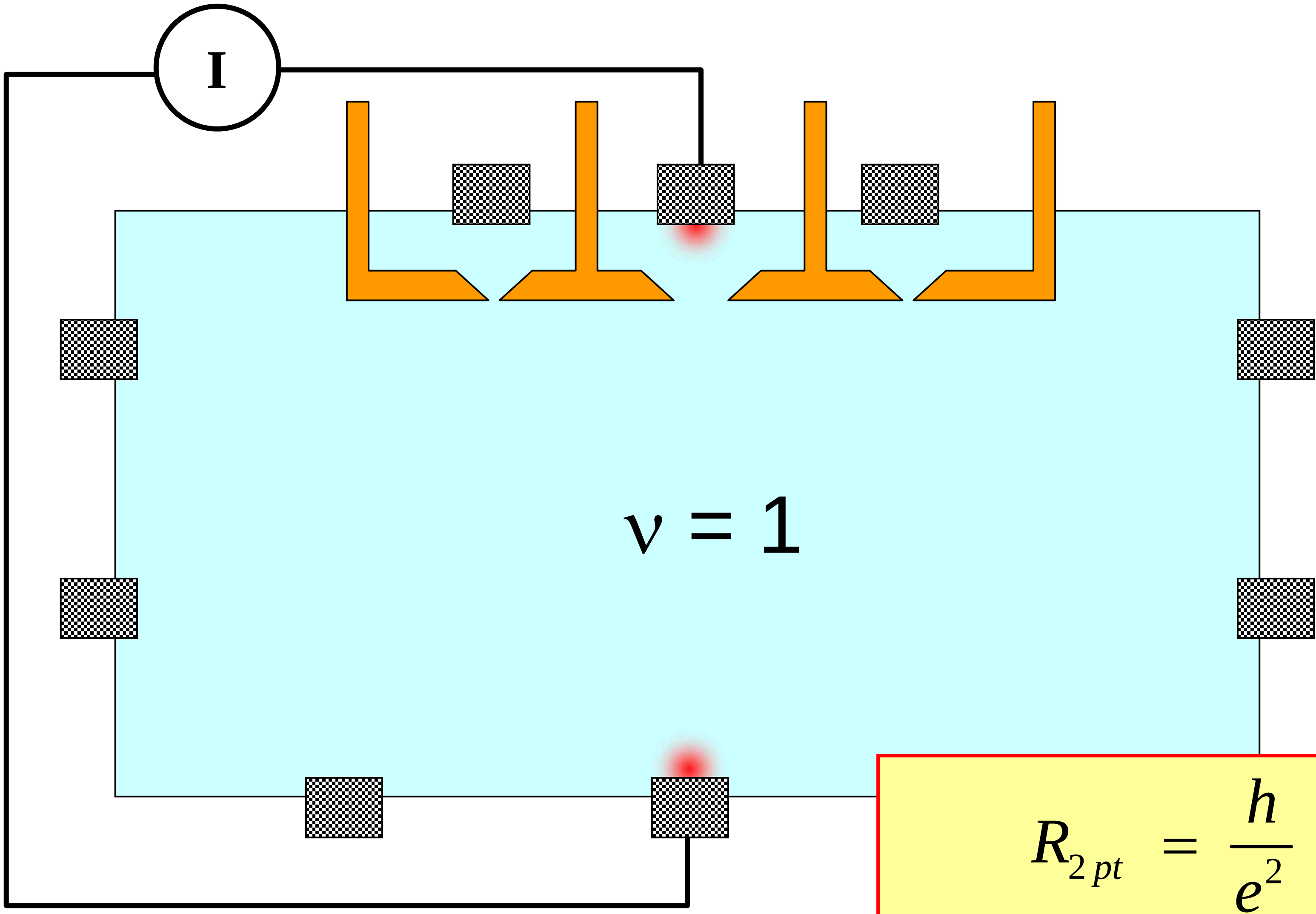
Is it heat? Current dependence of signal



$$V_{2f} \sim I^2 R$$

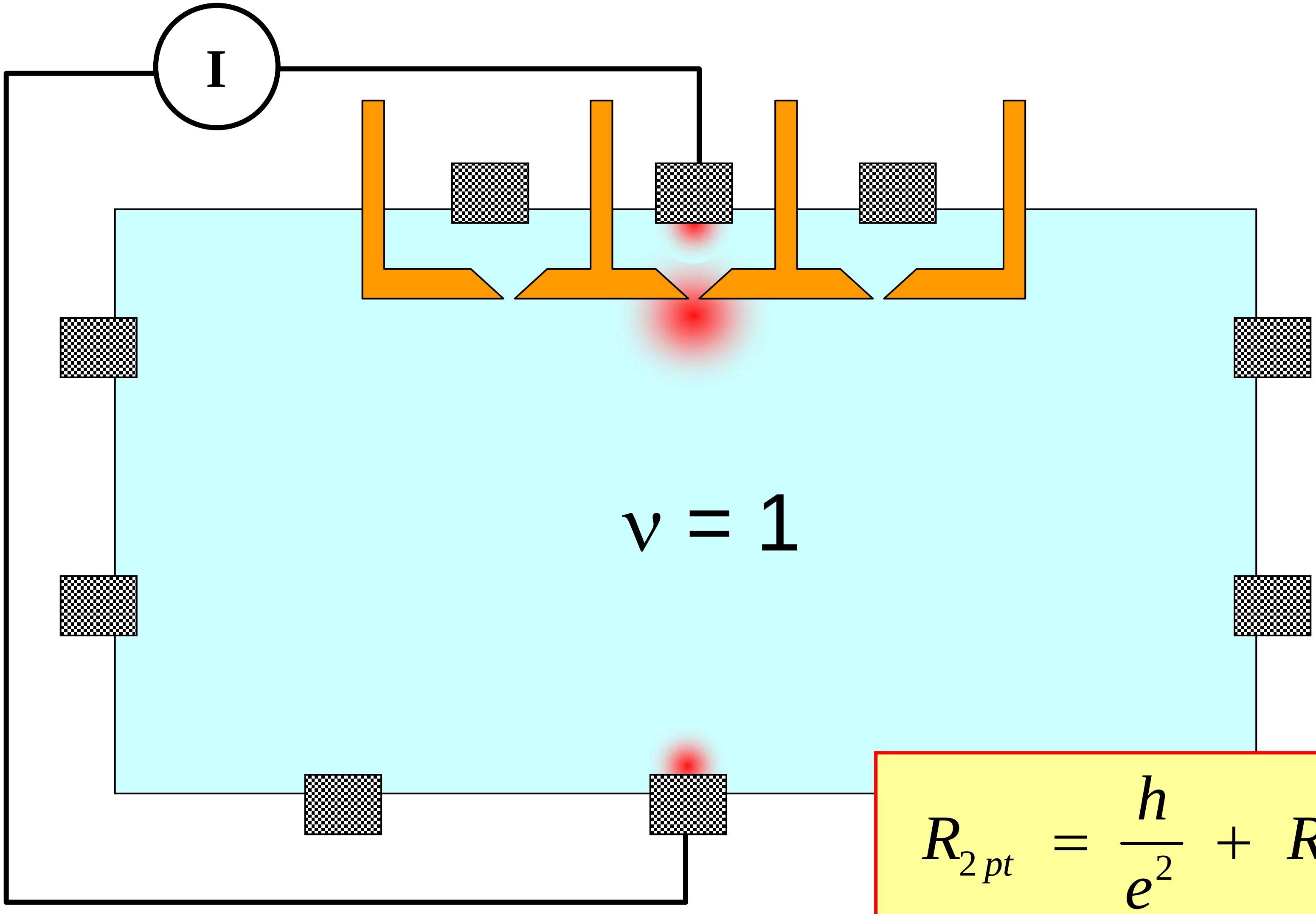
… but what R?

Hot spots in QHE regime



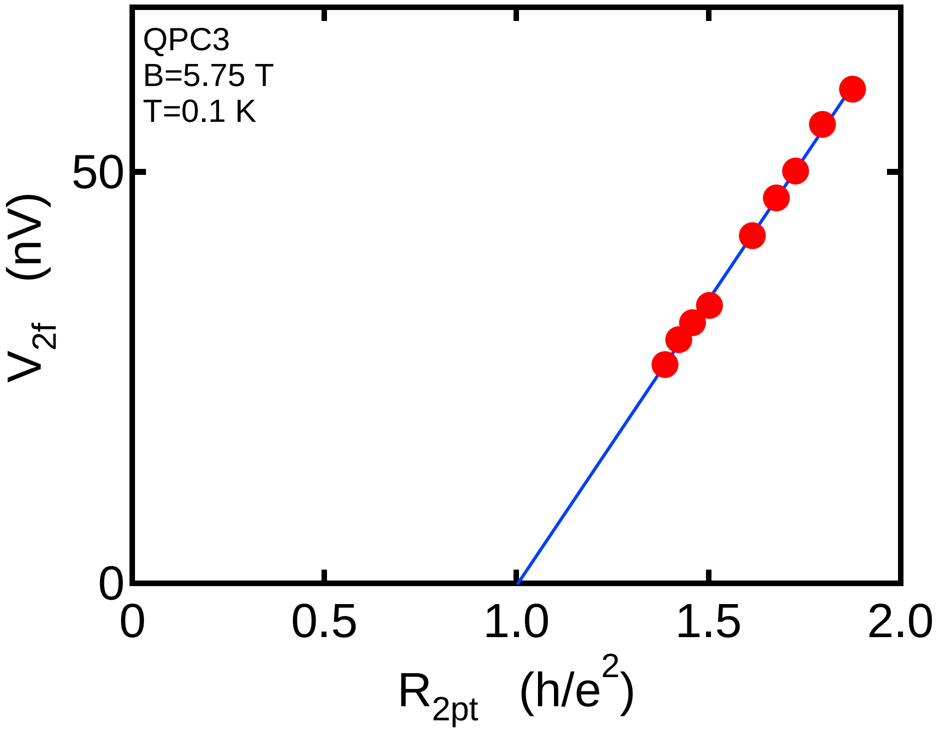
$$R_{2\,pt} = \frac{h}{e^2}$$

Hot spots in QHE regime



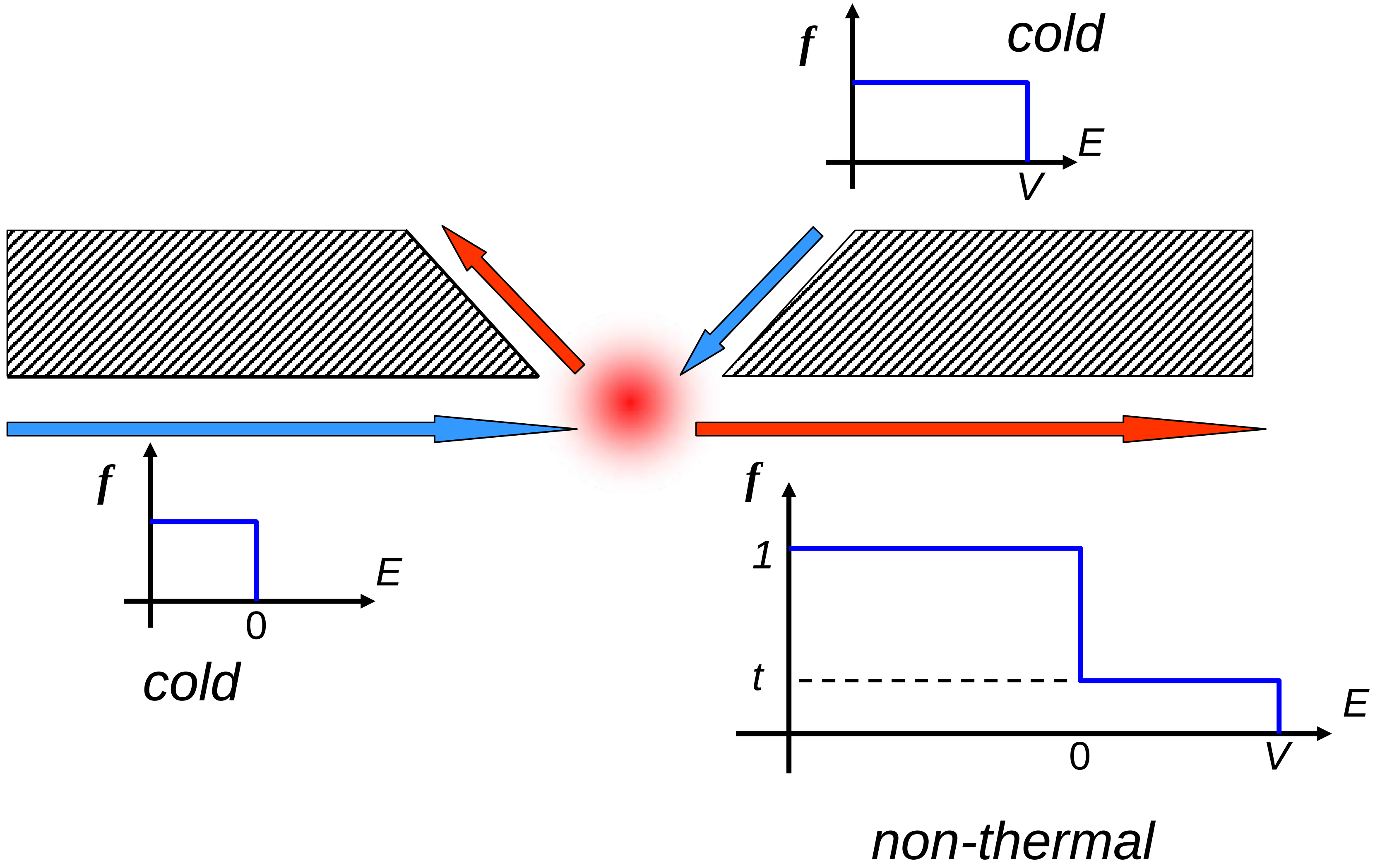
$$R_{2\,pt} = \frac{h}{e^2} + R_{QPC}$$

Heater resistance dependence of signal

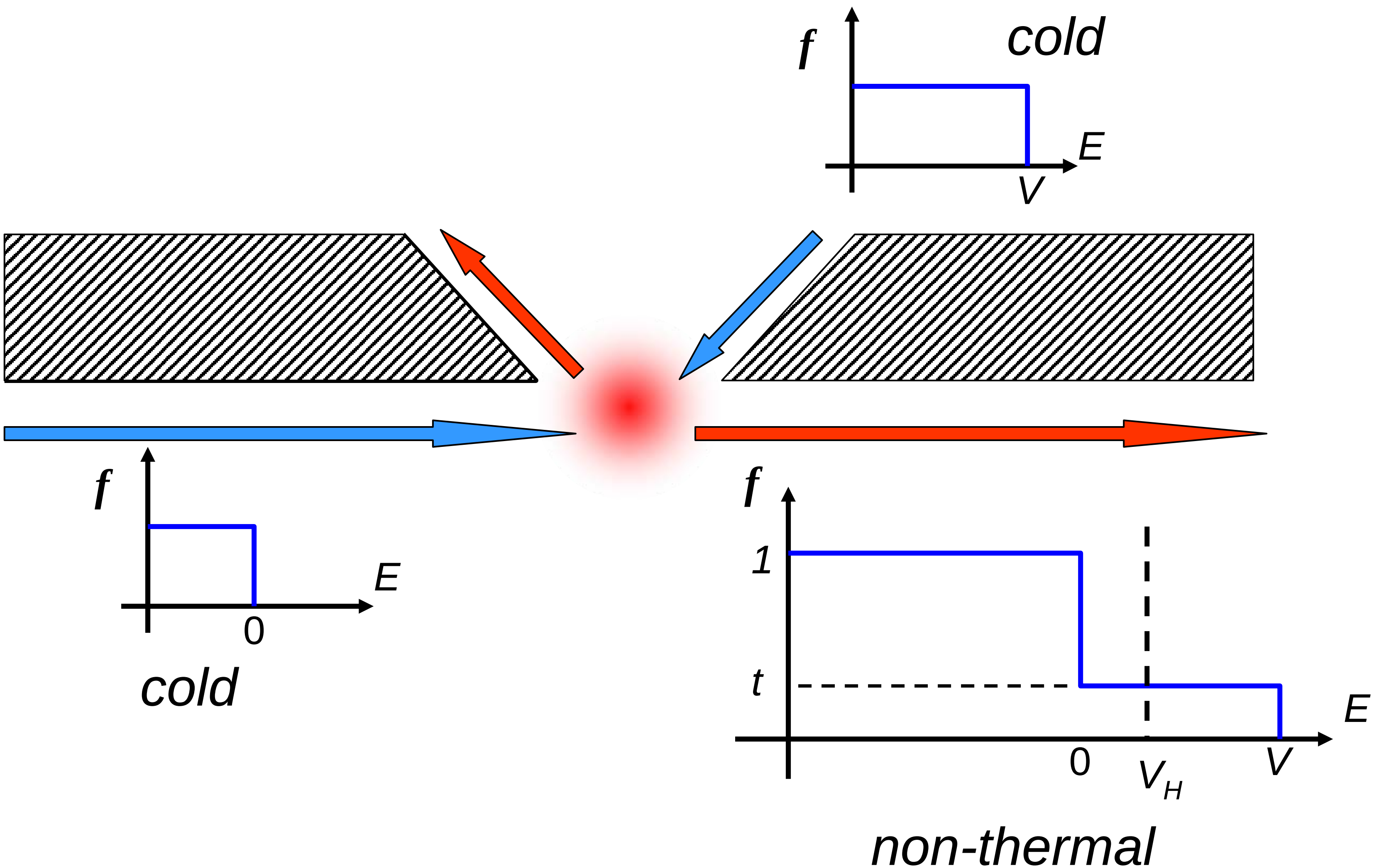


$$V_{2f} \sim I^2(R_{2pt} - h/e^2) = I^2 R_{QPC}$$

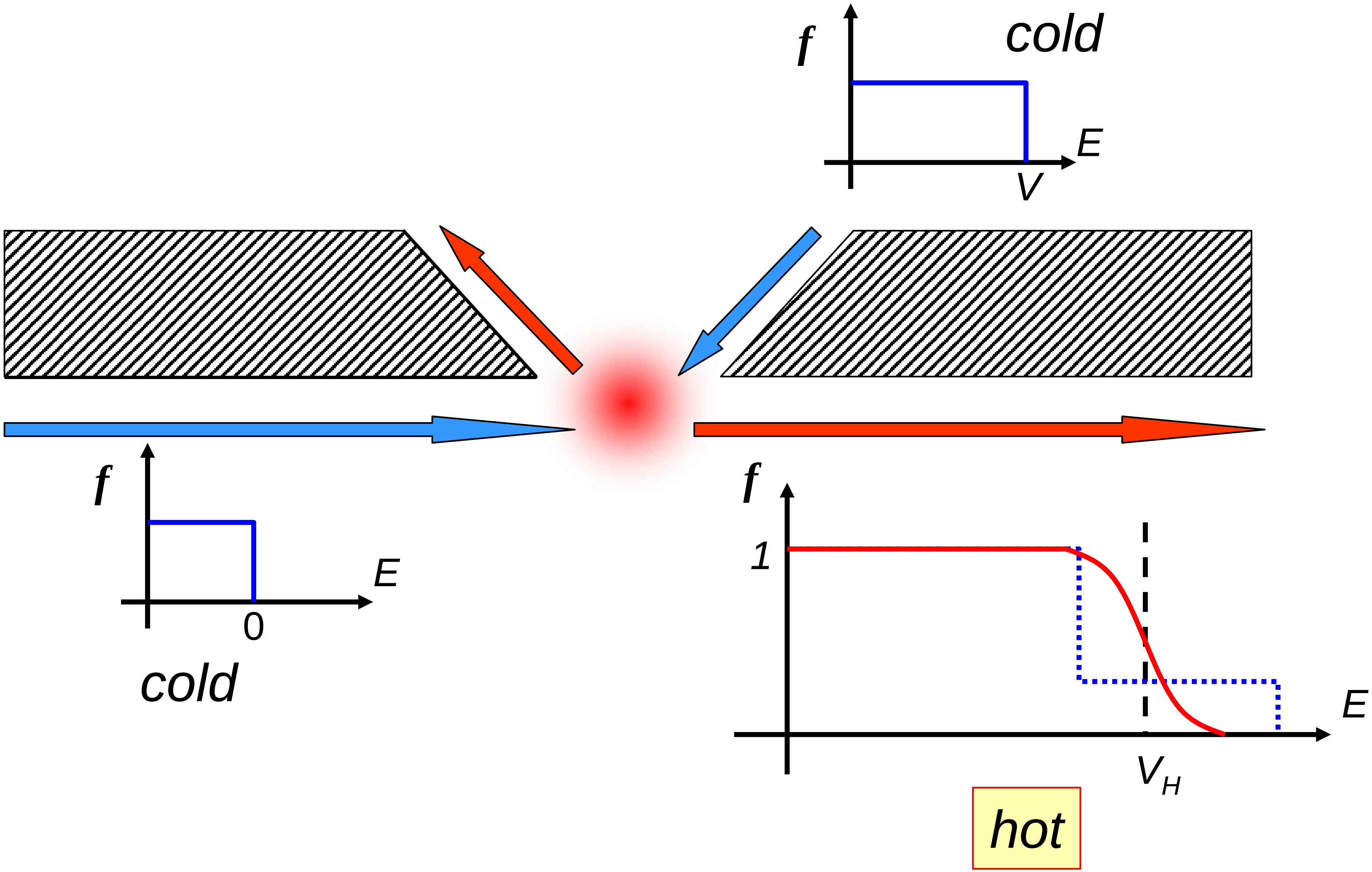
QPCs are elastic scatterers



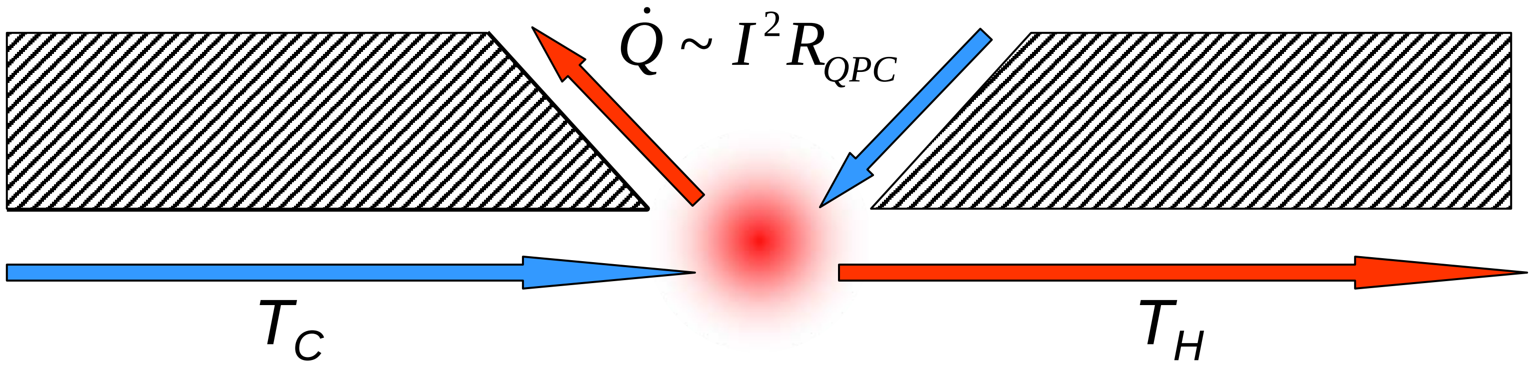
QPCs are elastic scatterers



QPCs are elastic scatterers



Simple model of heating at the edge



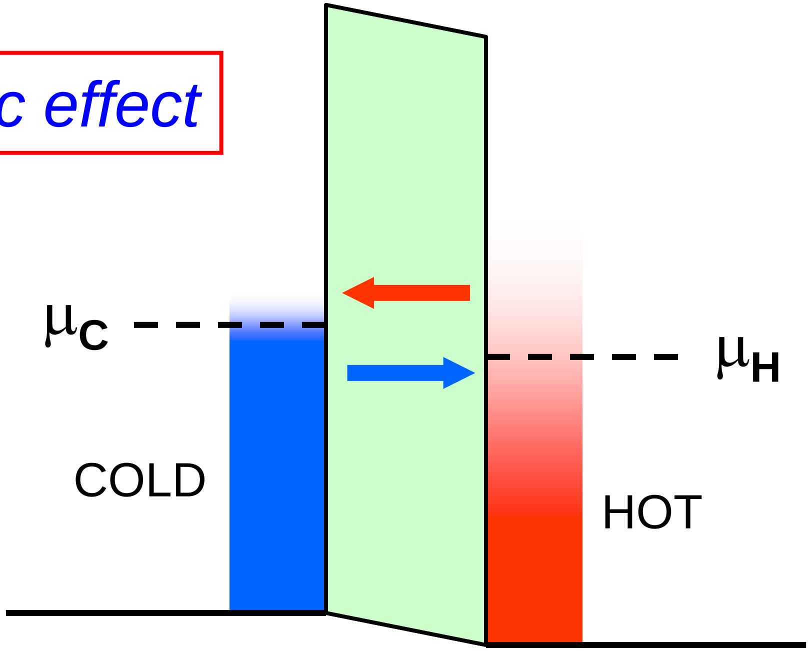
Heat flux carried by a single edge mode: $J_Q = \dfrac{\pi}{12\hbar}(k_B T)^2$

$$T_h^2 - T_c^2 = \frac{6\hbar}{\pi k_B^2} I^2 R_{QPC}$$

I = 5 nA, R = 25 kOhm, T_c = 0.1 K:
T_H = 0.8 K

How does the detector work?

QPC thermoelectric effect

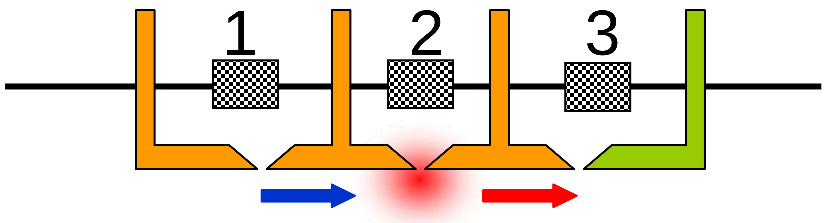


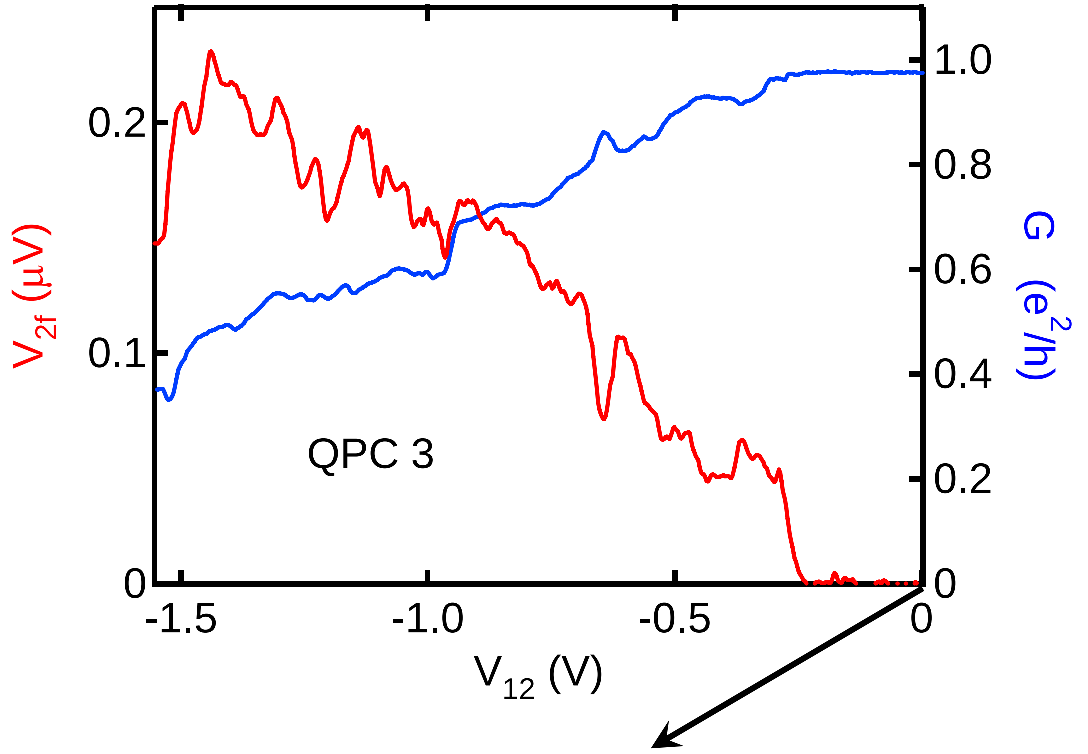
$$\Delta V = -S\,\Delta T = \alpha(V_g)\,T\,\Delta T \rightarrow \alpha(V_g)(T_h^2 - T_c^2)$$

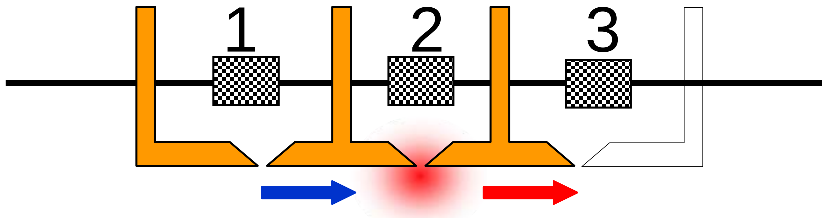
$$\Delta V = \alpha(V_g)(T_h^2 - T_c^2) = \alpha(V_g)\frac{6\hbar}{\pi k_B^2} I^2 R_{QPC}$$

$$\Delta V = const. \times I^2 R_{QPC}$$

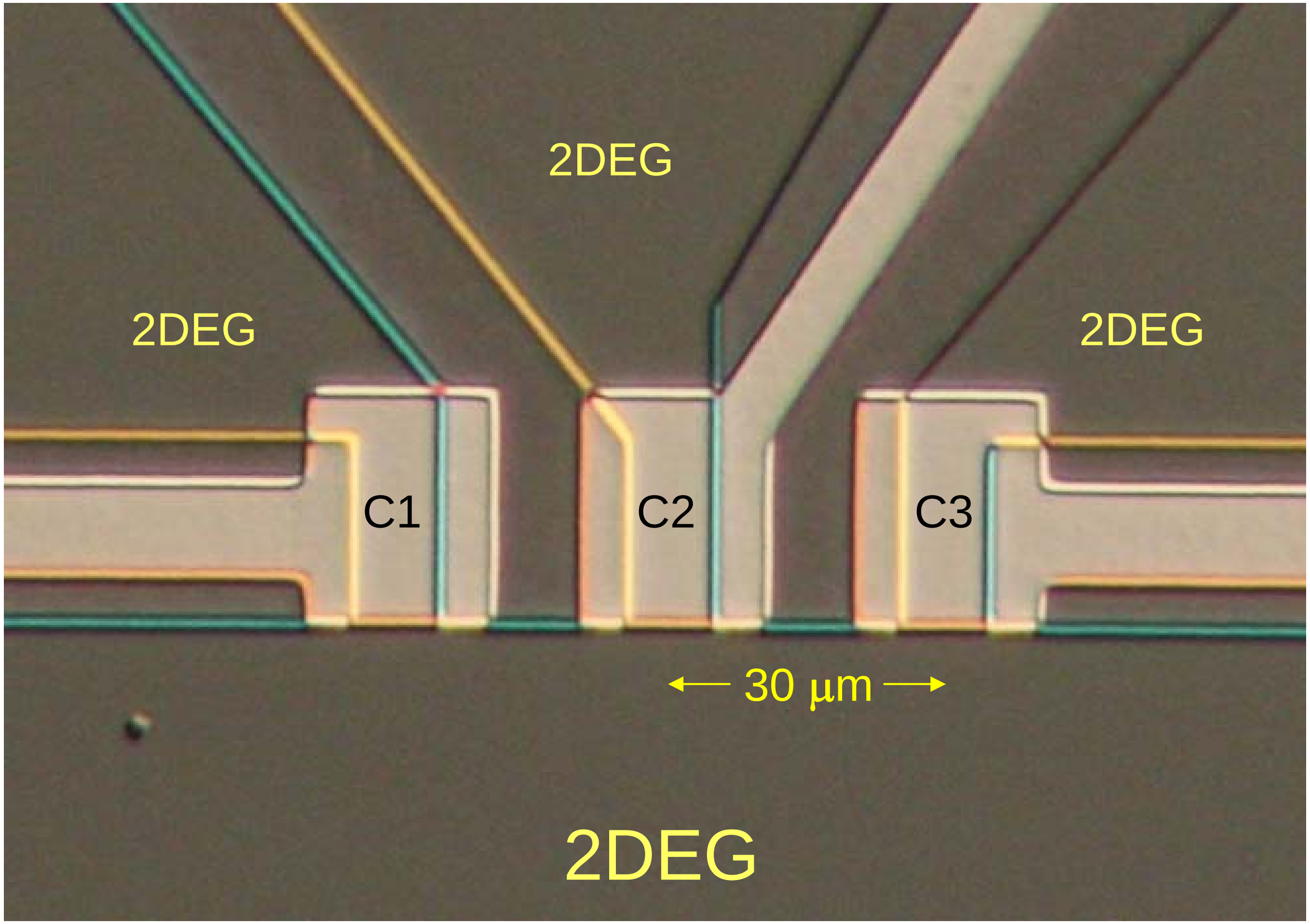
QPC detection: Not Mott?



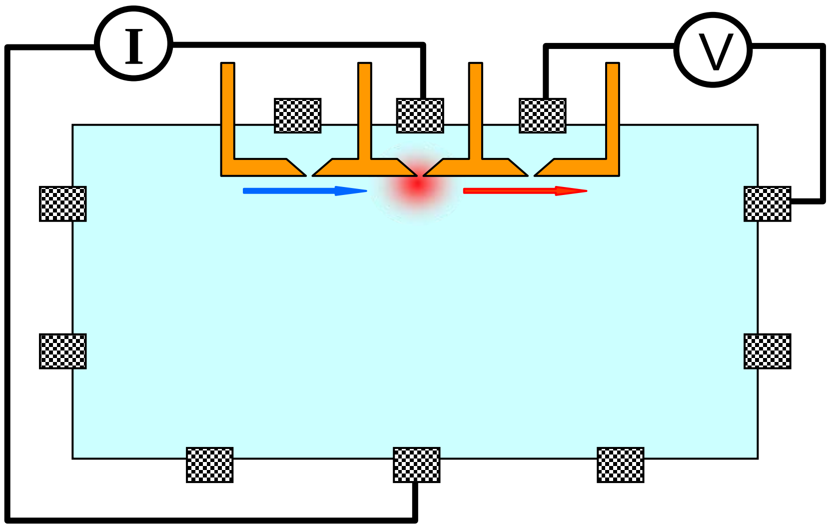


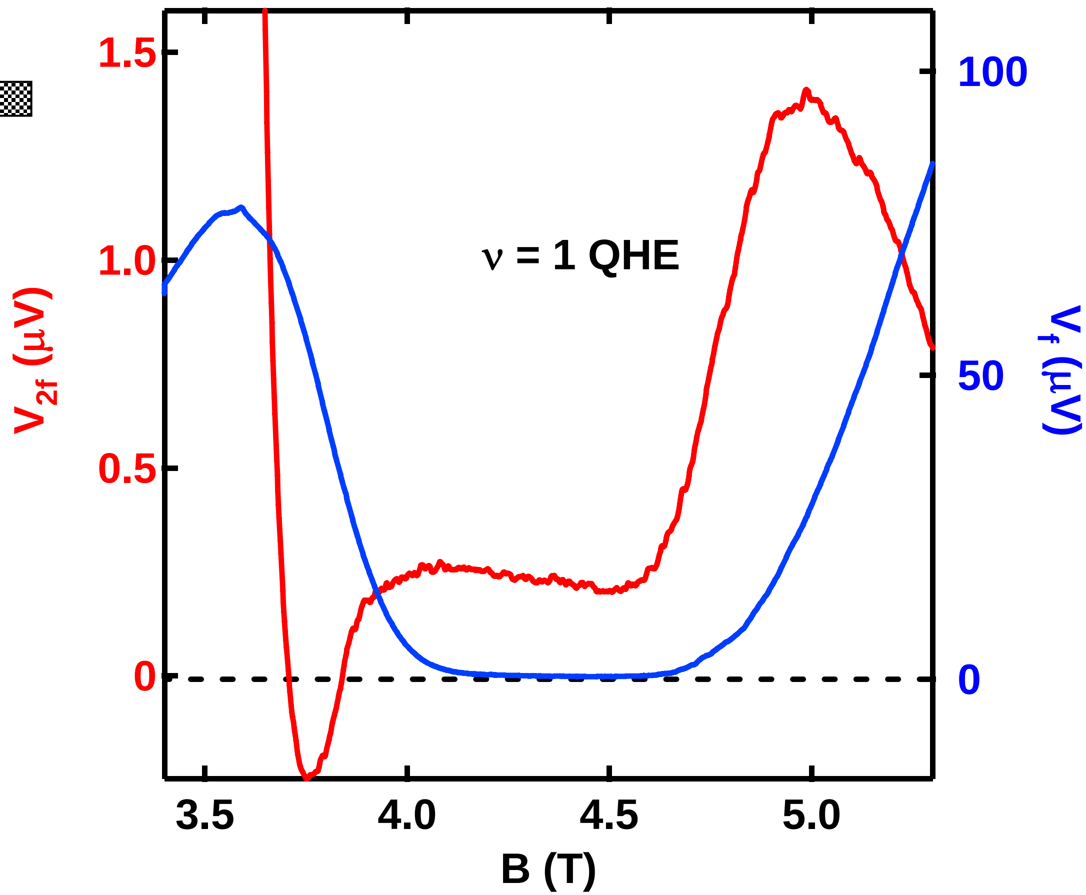


Narrow channel device



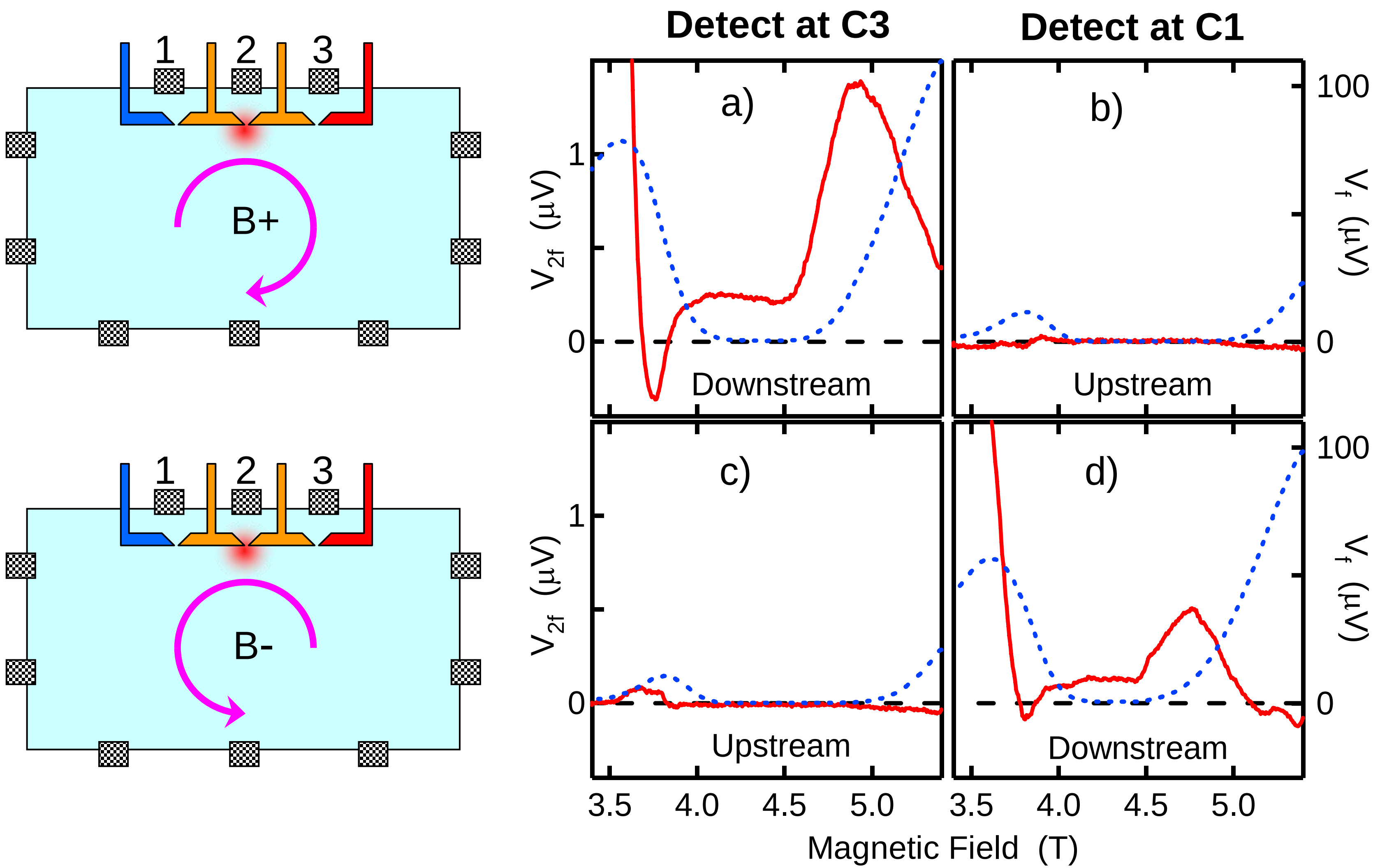
Detecting a heating signal: NC device



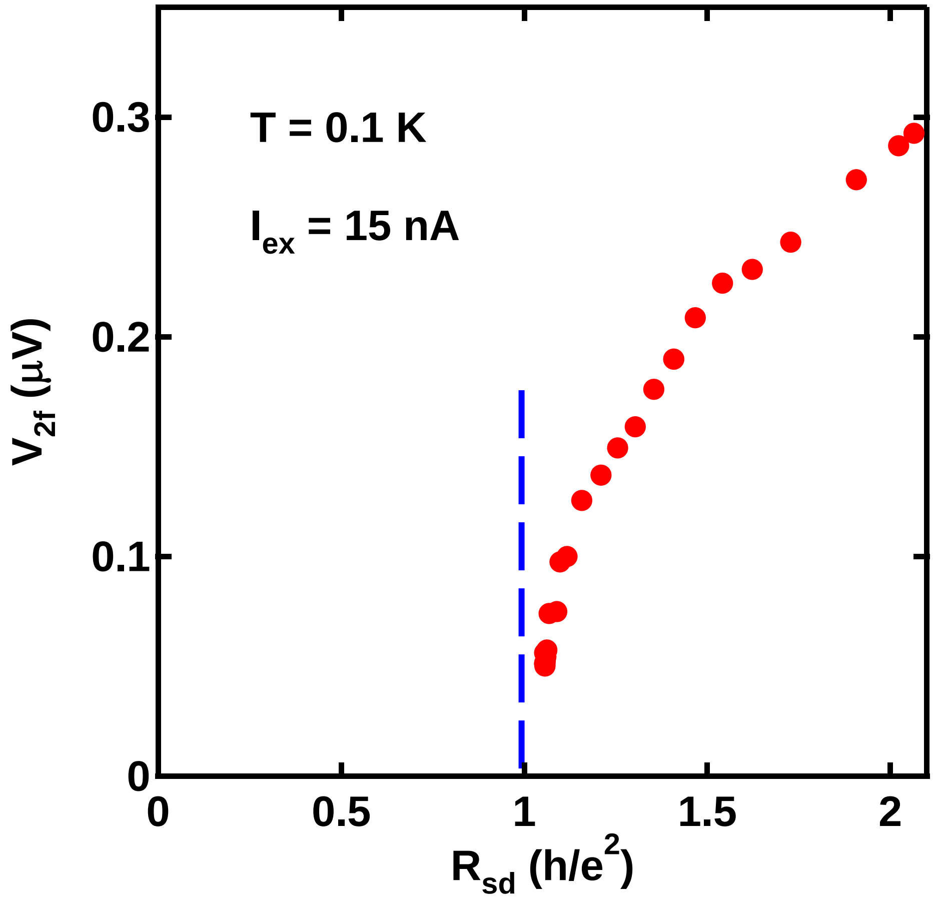


Qualitatively identical to QPC device.

Chiral heat transport at ν = 1: NC device

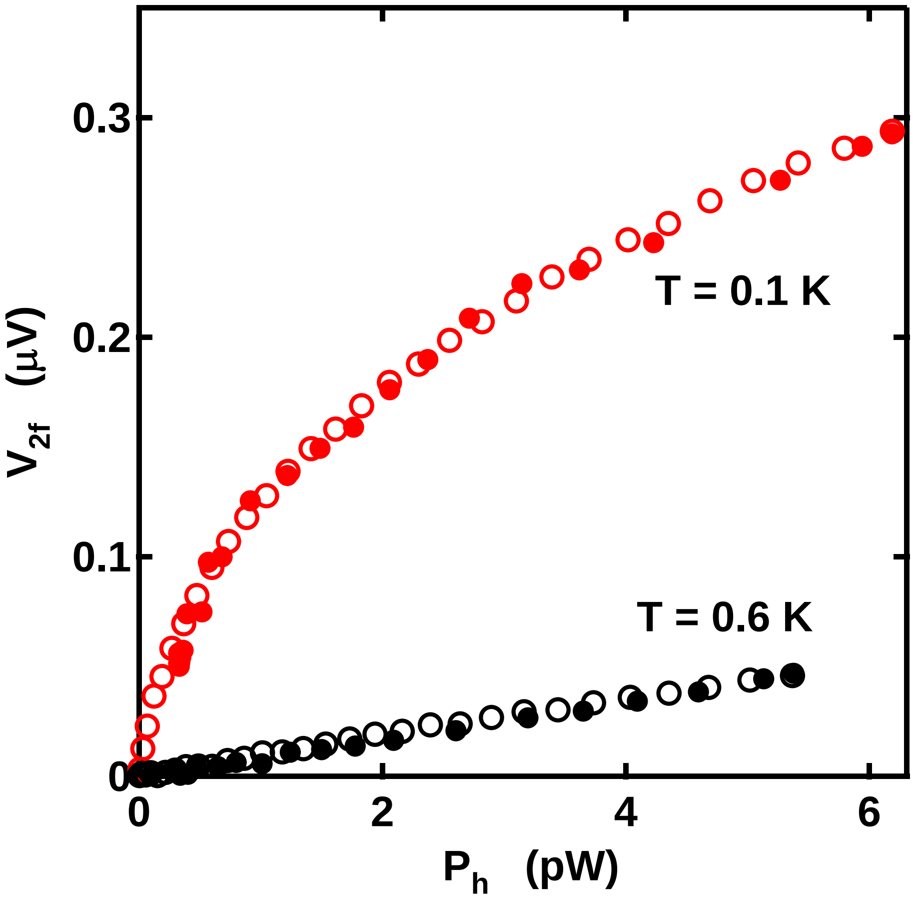


Heater resistance dependence of signal: NC device



Signal non-linear in heater power

Heater power dependence of signal: NC device



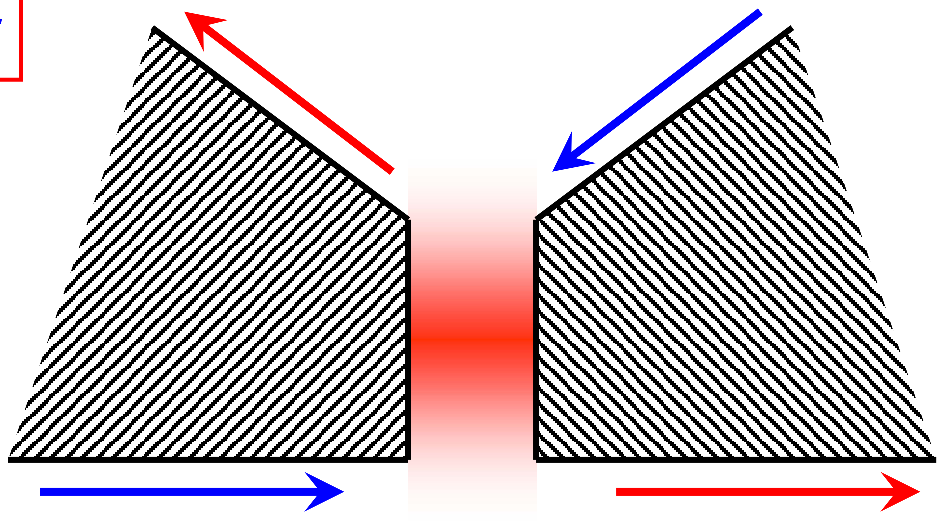
$$P_h = I^2 R$$

vary I

vary R

$$V_{2f} = f(I^2 R)$$

Model: Heater



$$P_h = I^2 R_h = A\left(T_h^4 - T_c^4\right) + B\left(T_h^2 - T_c^2\right)$$

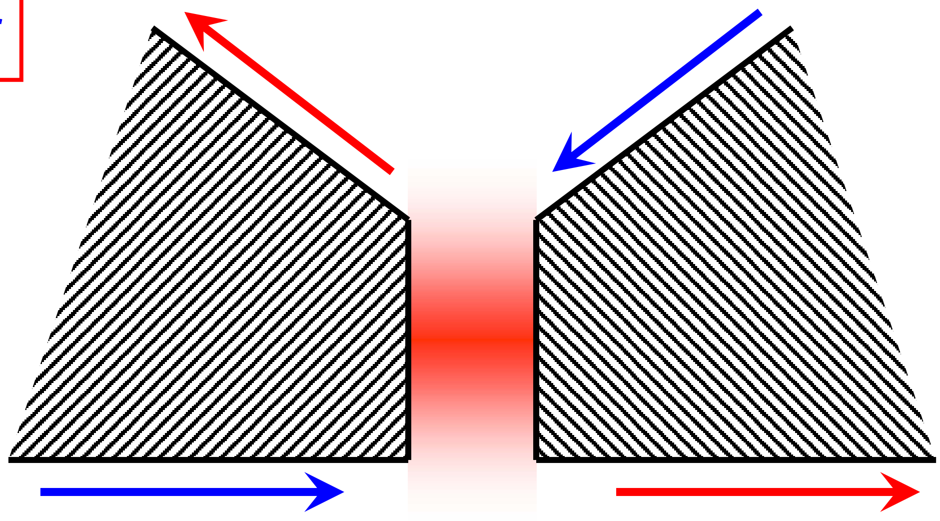
phonons edges

$$A \approx 70 \frac{fW}{\mu m^2 K^4} \times \left[\frac{e^2/h}{\sigma_{xx}}\right] \times area$$

S.M. Girvin

$$B = \frac{\pi k_B^2}{6\hbar} \approx 950 \frac{fW}{K^2}$$

Model: Heater



$$P_h = I^2 R_h = A\,(T_h^4 - T_c^4) + B\,(T_h^2 - T_c^2)$$

phonons edges

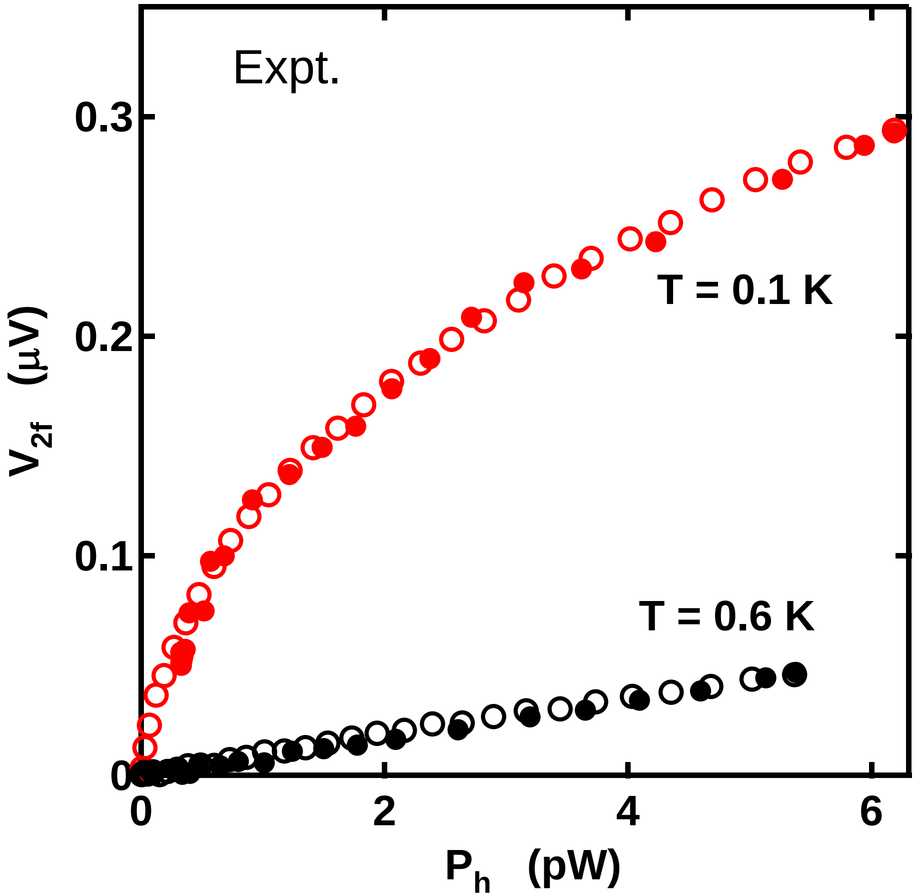
$$T^* = \sqrt{\frac{B}{A}} \approx \begin{cases} 3\,K & \text{QPC device} \\ 0.1\,K & \text{NC device} \end{cases}$$

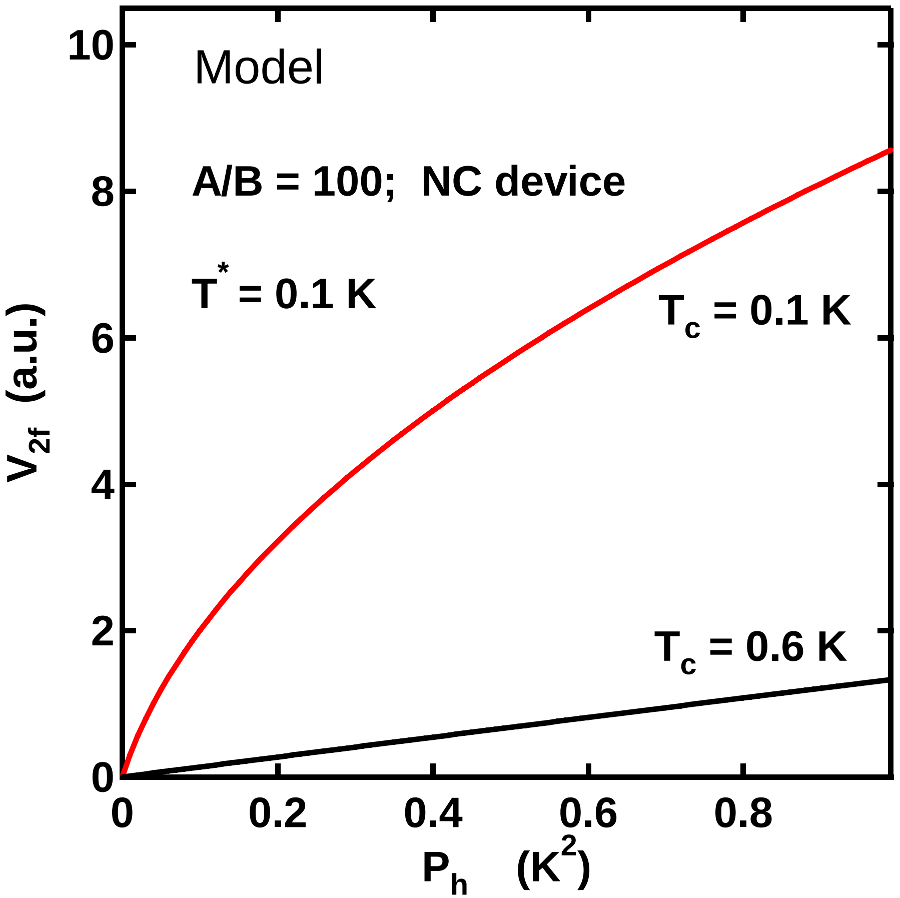
edges dominate when $T << T^*$

Model: Detector

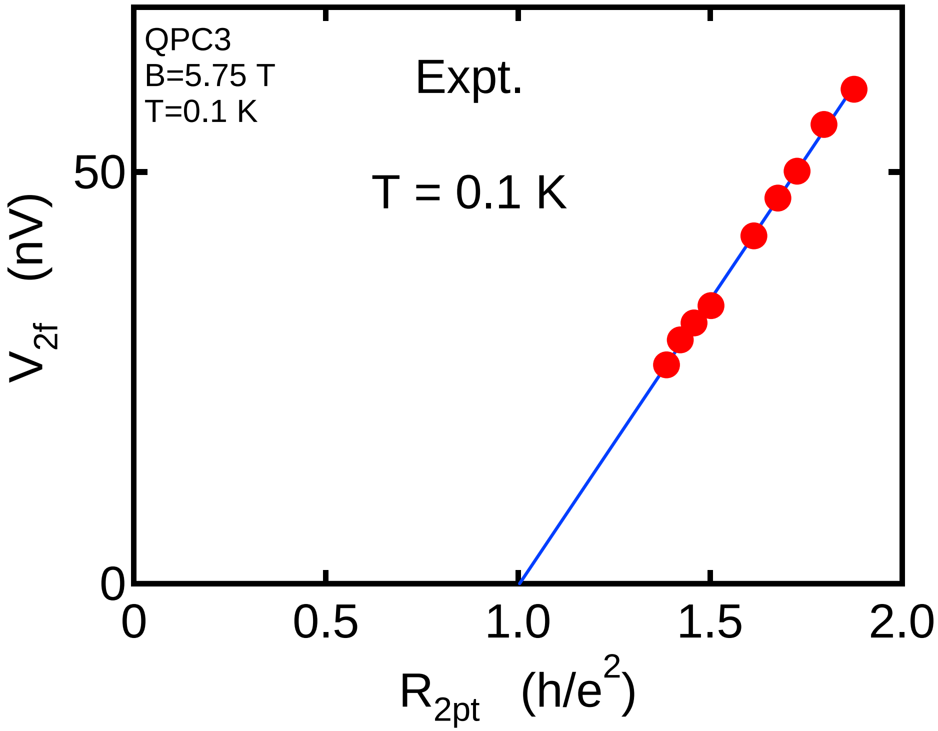
$$\Delta V = S\,\Delta T = \alpha(V_g)T\Delta T \rightarrow \alpha(V_g)(T_h^2 - T_c^2)$$

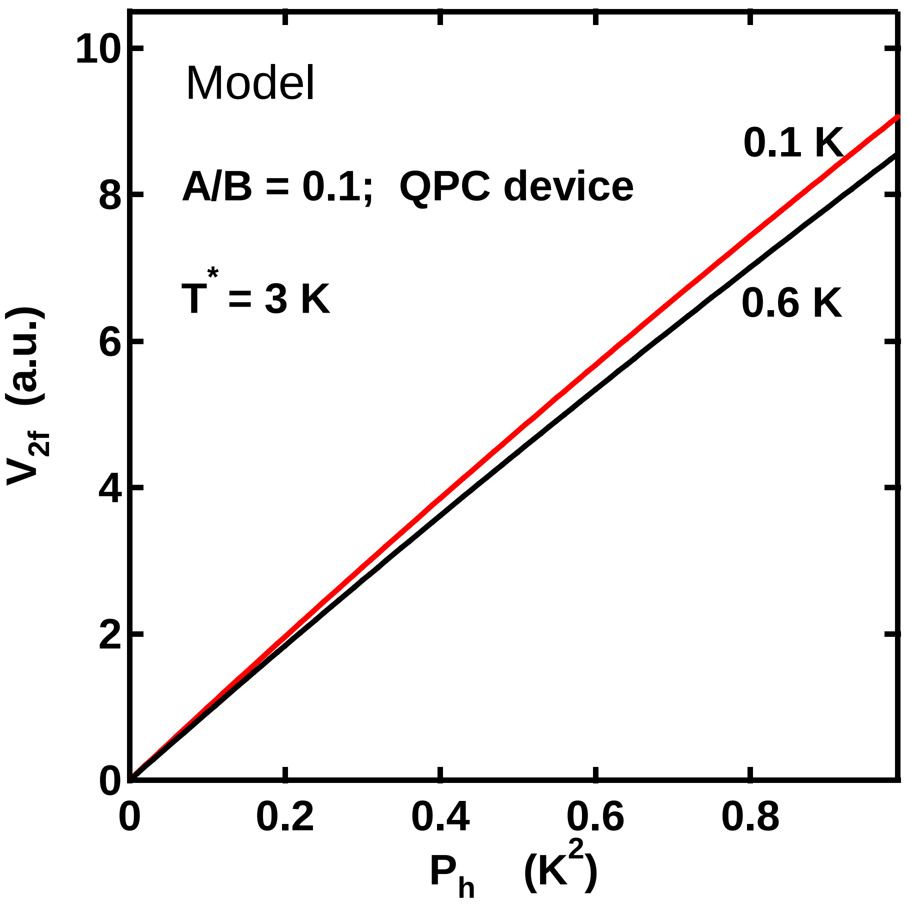
Experiment vs. Model: NC device



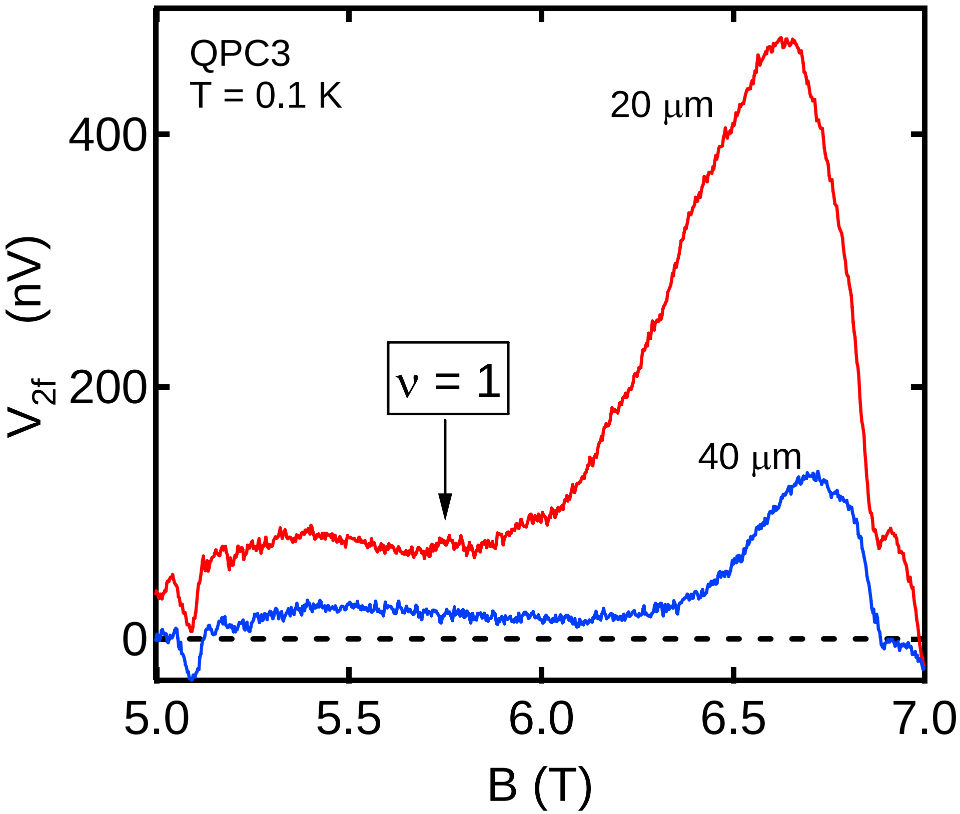


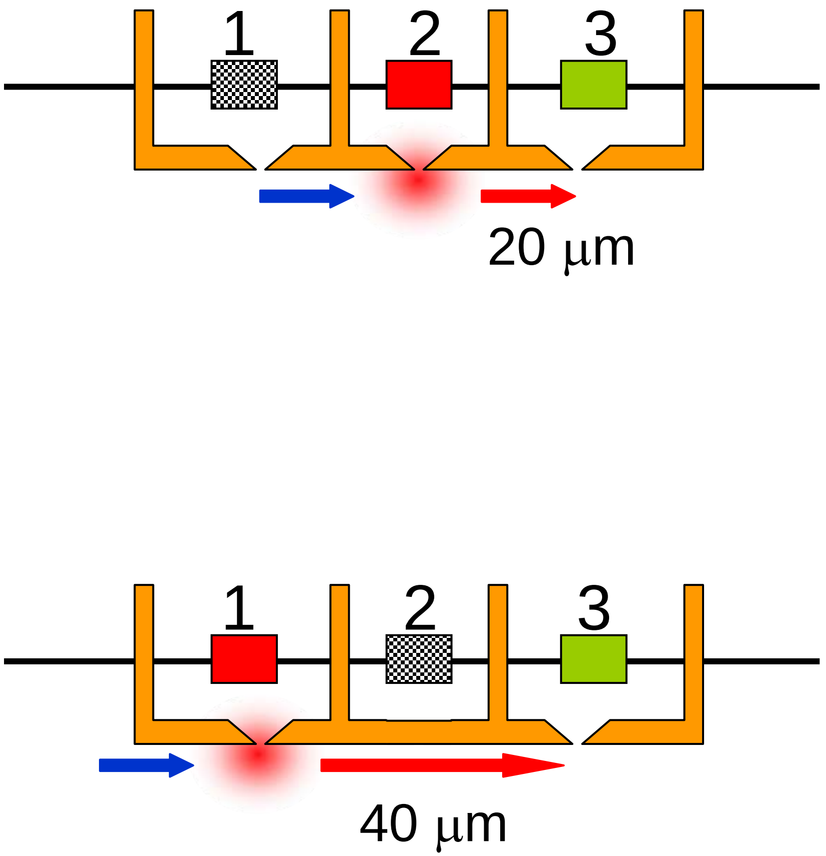
Experiment vs. Model: QPC device





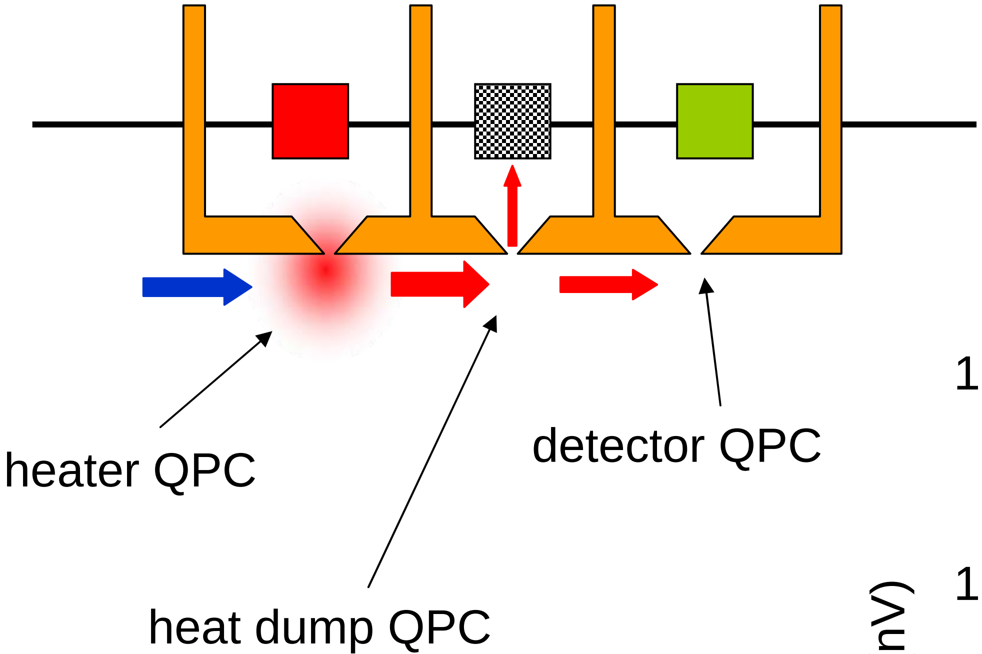
Propagation: Signal decays with distance along edge

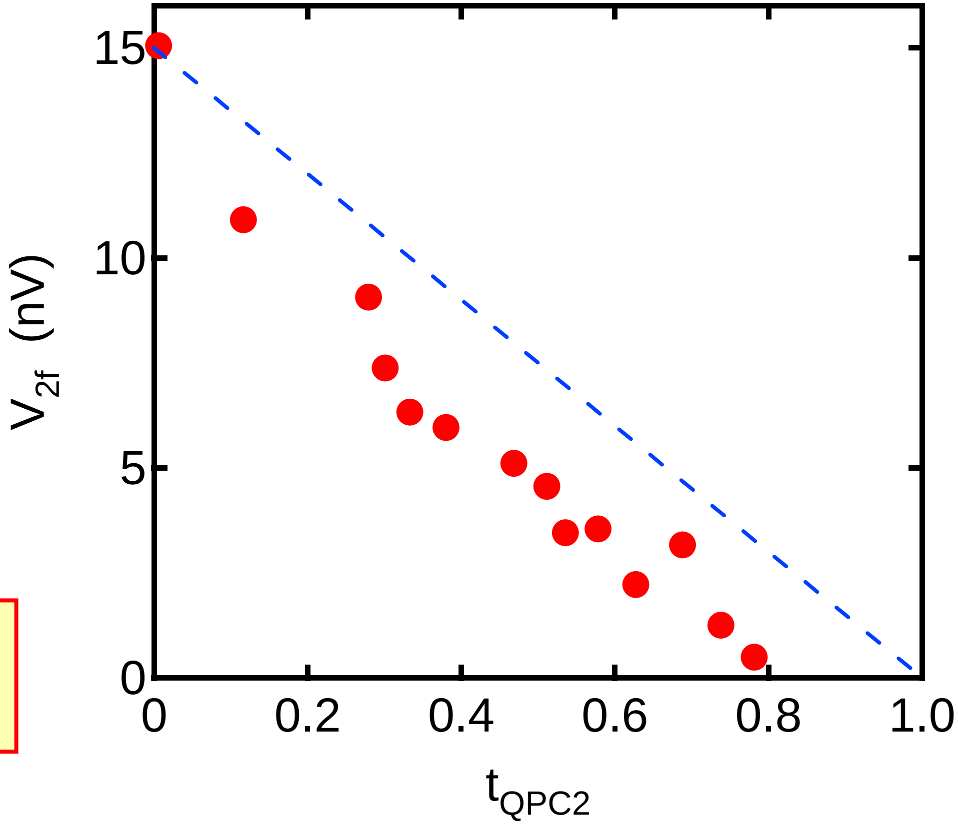




Is heat leaking into the bulk?

Allow some heat to escape midway





Strong evidence that heat transport is concentrated at the edge.

Conclusions

1. *Chiral edge state heat transport observed at* $\nu = 1$.

2. *Hot electrons cool significantly as they propagate.*

3. $\nu = 2/3$ *experiments underway.*