Heat Transport and Thermo-power in a Single-Quantum Dot Transistor

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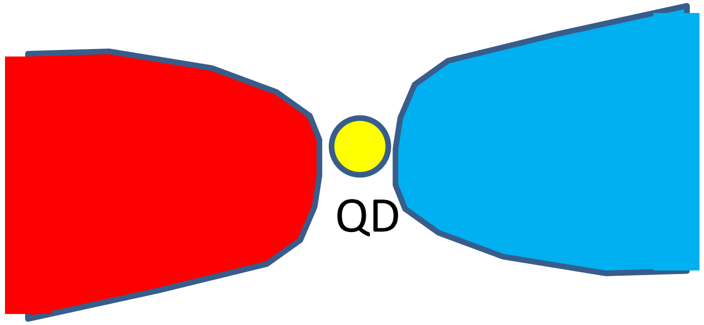


General objective:

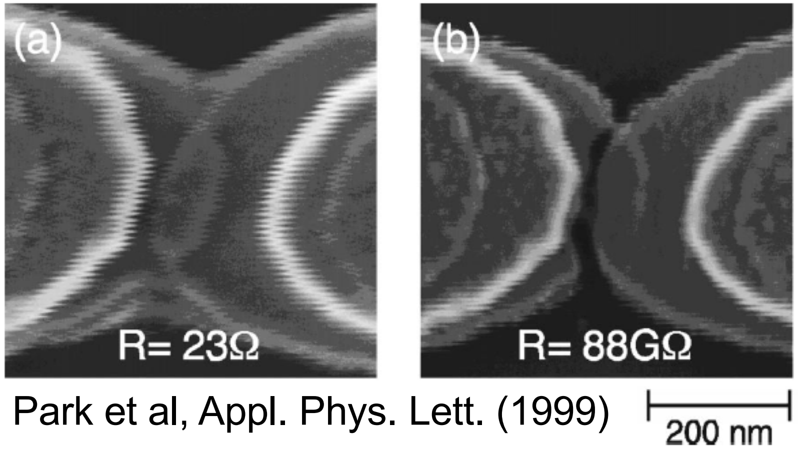
understand thermal effects in QD-based devices

Metallic quantum dot devices

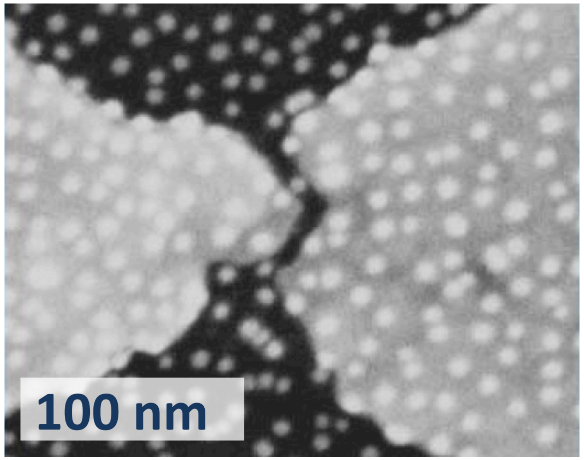
Connecting a single quantum dot

Electromigration of a metallic constriction.

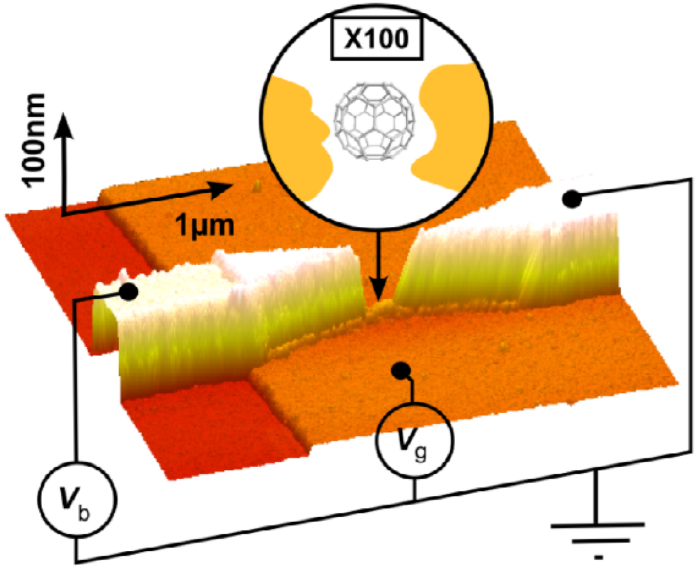
Biasing stopped when conductance drops: nm to few-nm gaps obtained



H. Park et al, Appl. Phys. Lett. (1999)



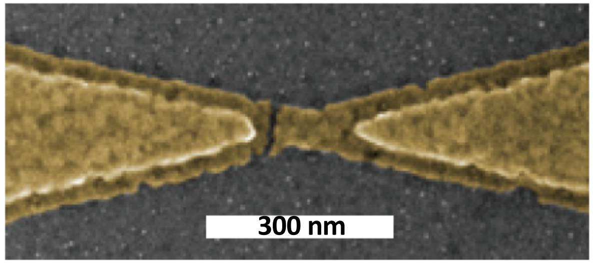
F. Kuemmeth et al., Nano Lett. (2008)



N. Roch, F. Balestro, W. Wernsdorfer et al., Nature (2008)

Quantum dot devices

Al or Pt electromigration junctions
+ 5 nm Au nanoparticles



Charging energy $E_c > 100$ meV

Level spacing $\delta \approx$ 1-10 meV

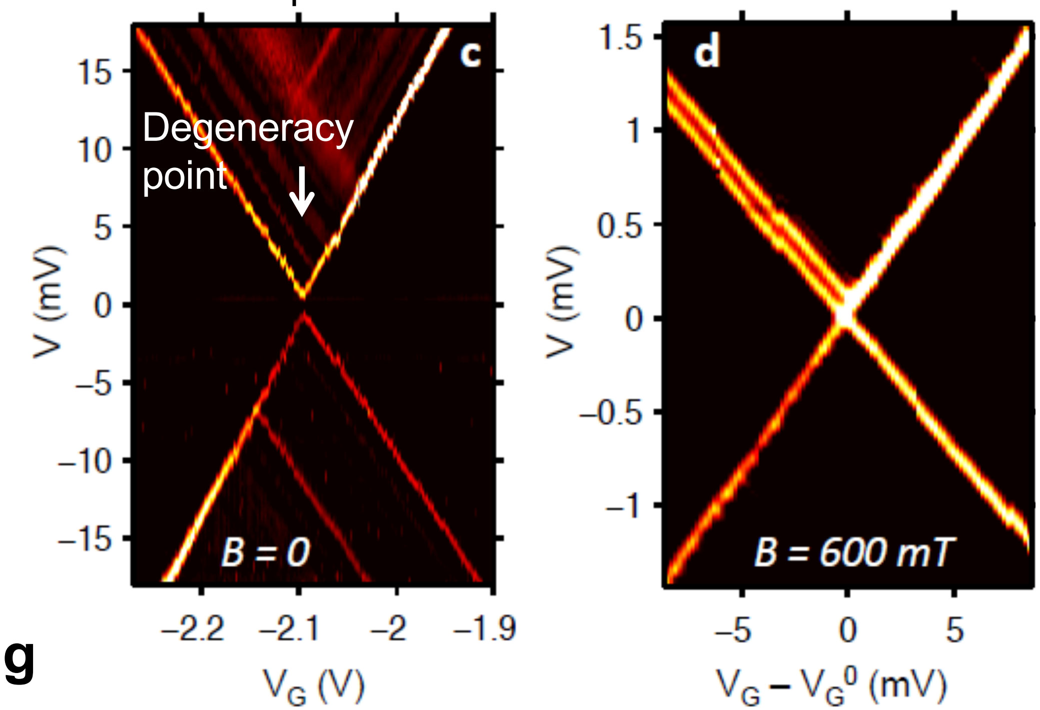
Superconducting gap Δ = 260 μeV

Tunnel coupling $\Gamma \approx$ 2 μeV

Clear hierarchy of energy scales:

$$E_c \gg \delta \gg \Delta \gg k_B T > \Gamma$$

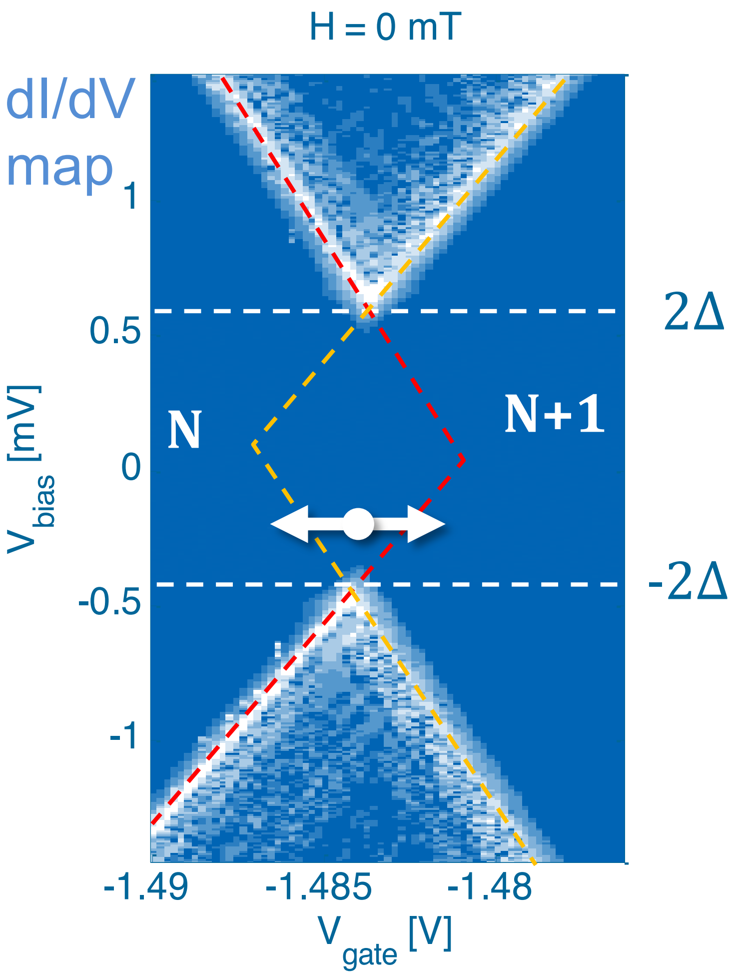
dI/dV maps

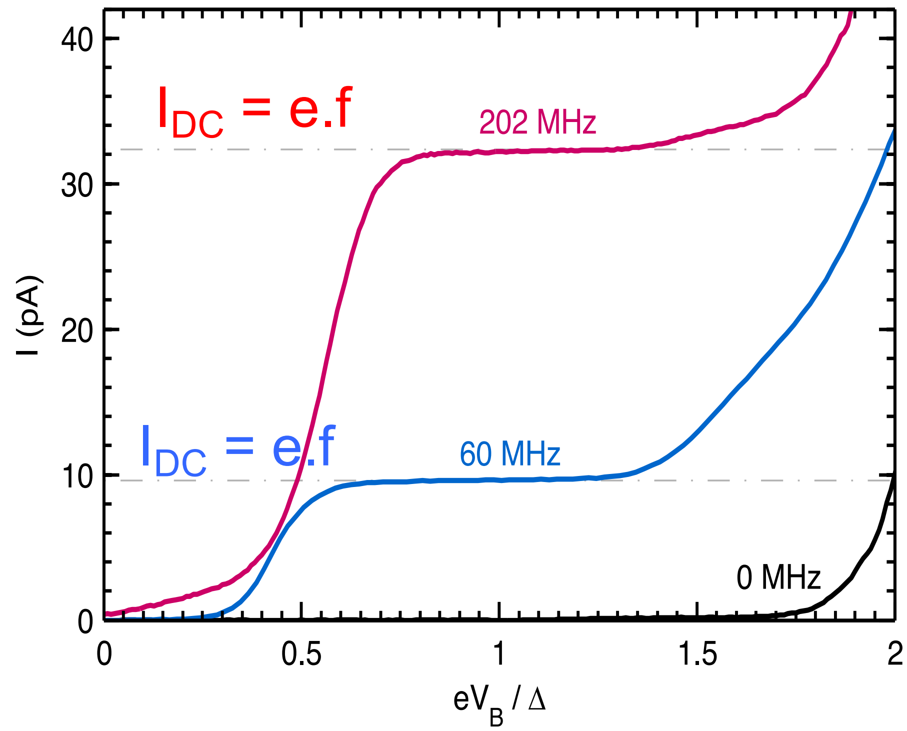


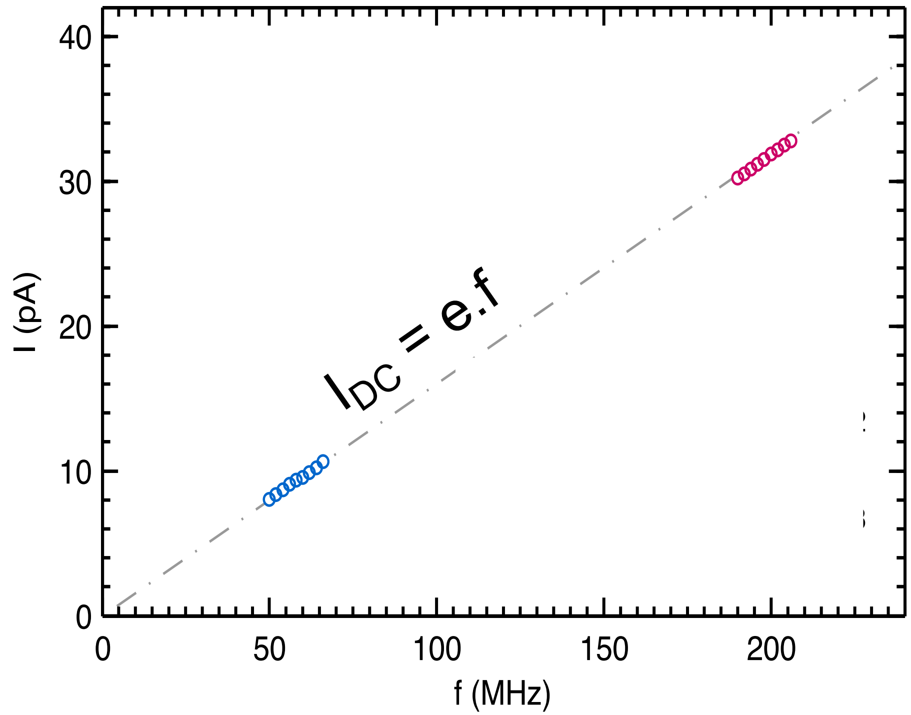
Energy spectra unmodified by gating

D. van Zanten, F. Balestro, H. Courtois, C. B. Winkelmann, PRB (2015).

A S-QD-S turnstile







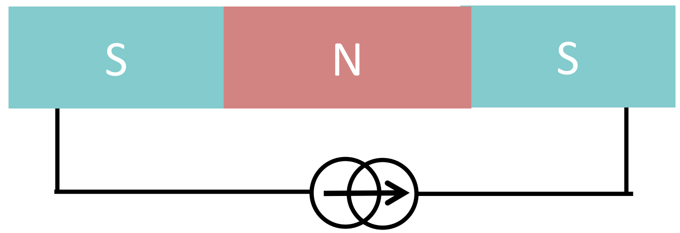
Mono-chromatic single electron source

D. van Zanten, D. M. Basko, I. M. Khaymovich, J. P. Pekola, H. Courtois, C. B. Winkelmann, PRL (2016).

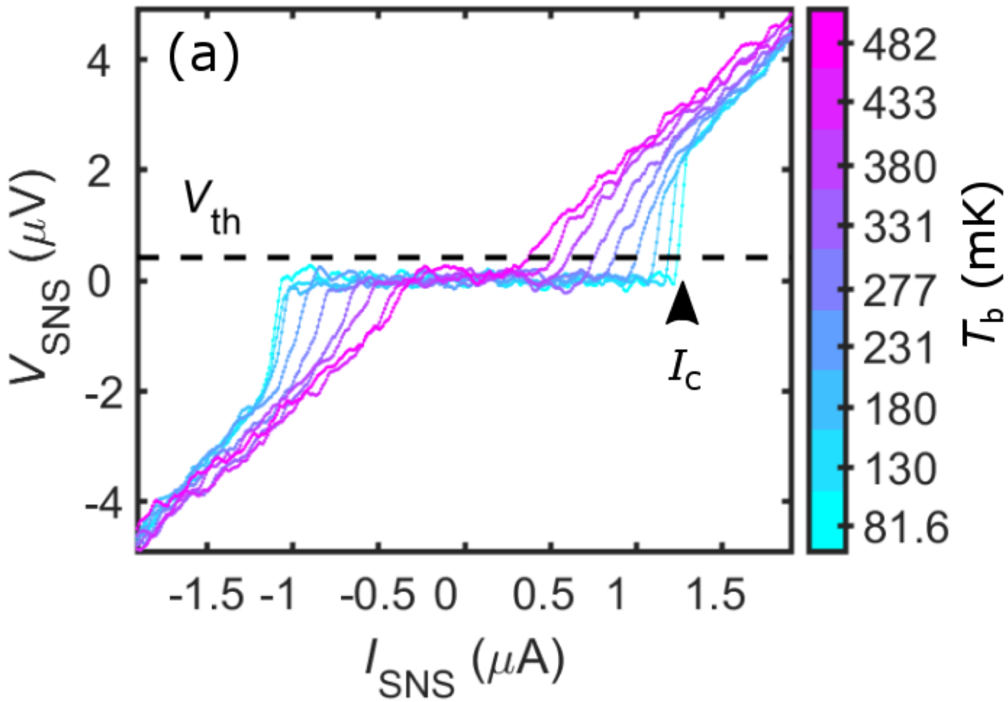
Josephson junction thermometry

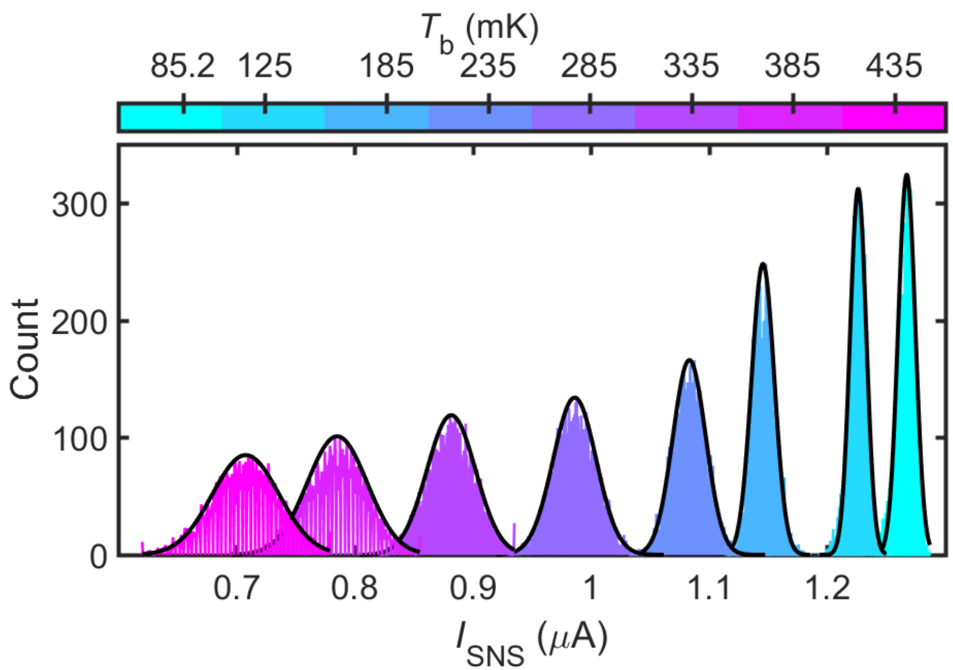
SNS Josephson junction thermometry

Zero-resistance Josephson coupling between two S through a N



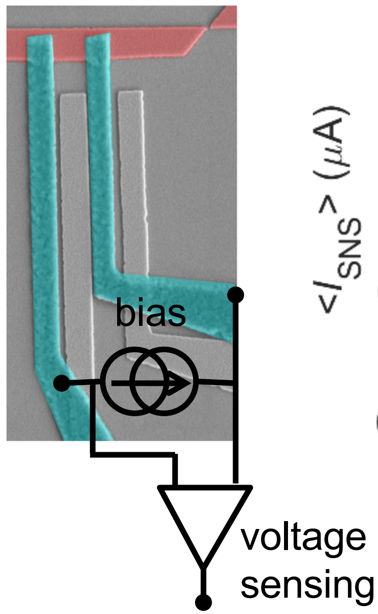
Critical current temperature dependence used as an electronic thermometer.

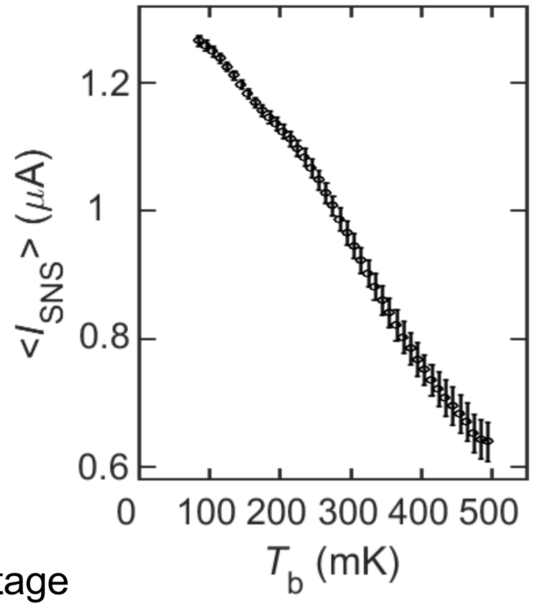




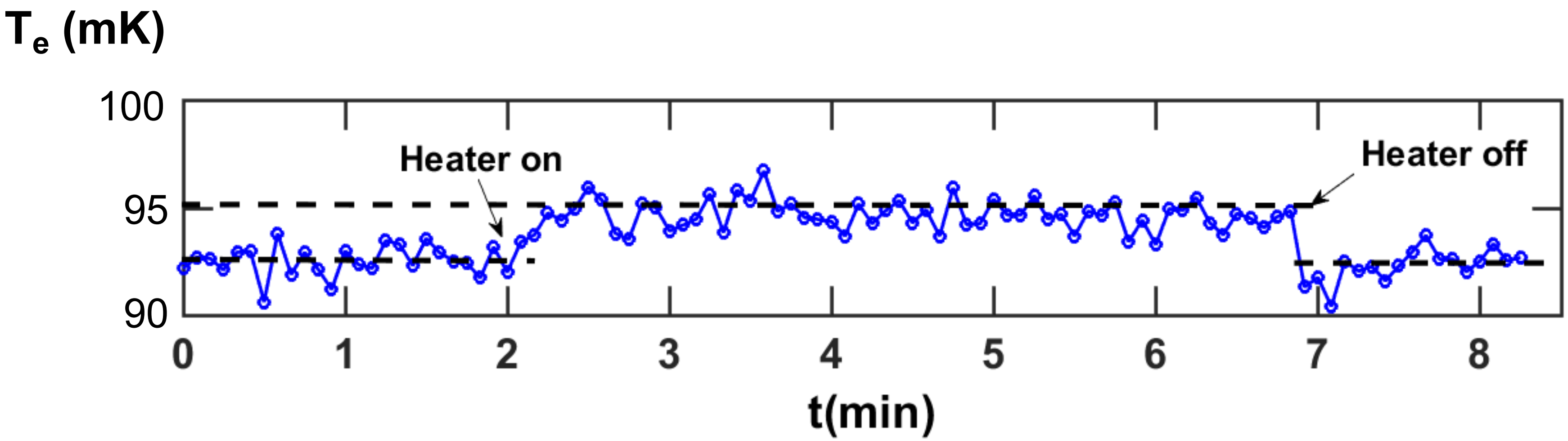
Performance of the SNS thermometer

Calibration against the bath.
Noise = 200 μK/$\sqrt{Hz}$





Direct Joule heating of the N part (100 aW):



Heat transport in a single quantum dot

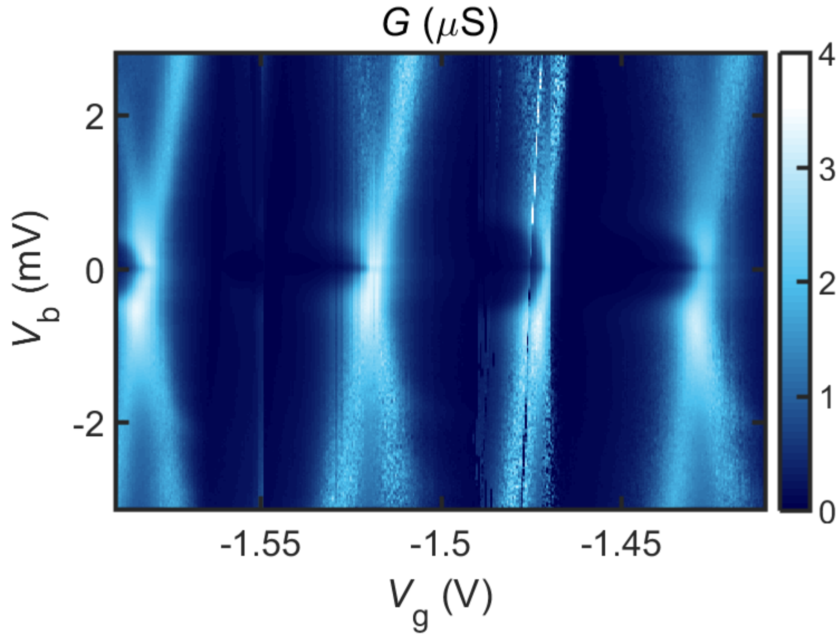
Heat transport through a QD junction

Bulky, well thermalized drain

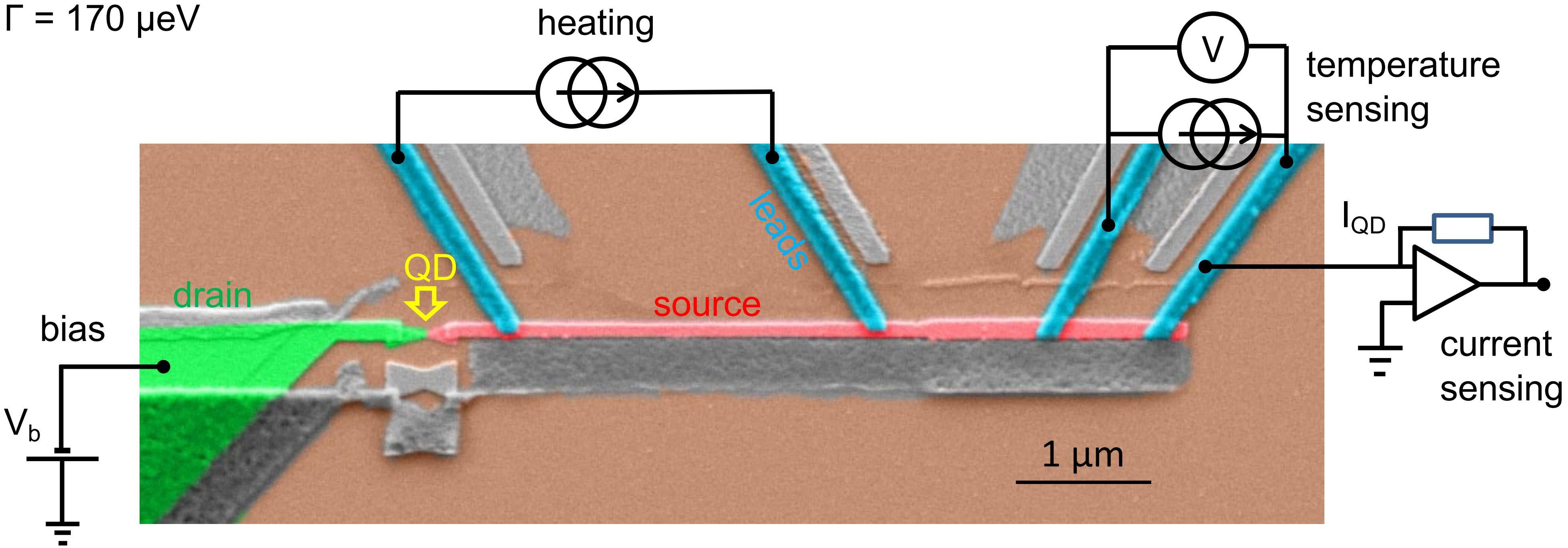
Metallic (Au) nanoparticule as a QD

Small source

S leads in clean contact: SNS junctions, thermal isolation



E_c = 4 meV
Γ = 170 μeV



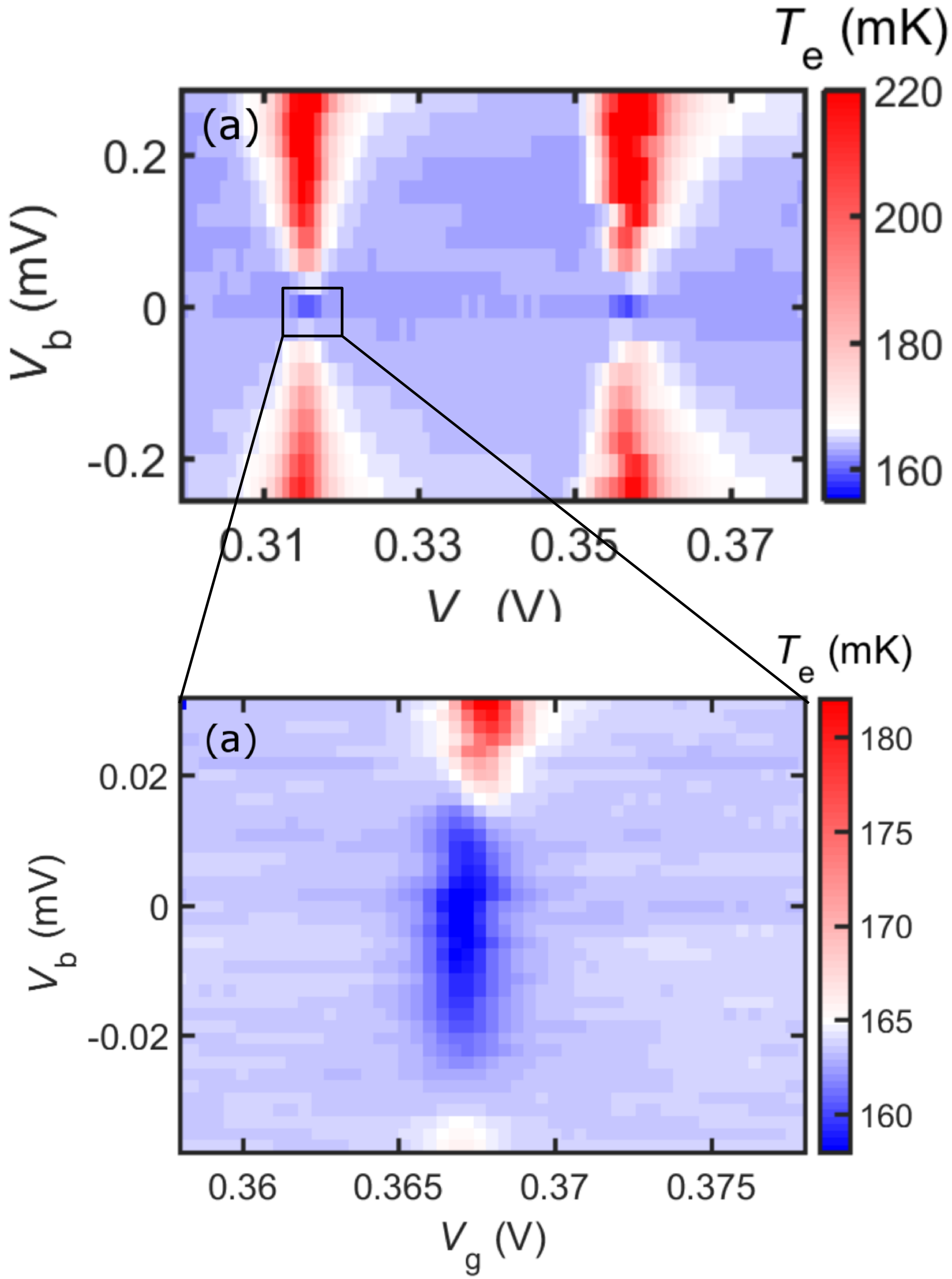
Coulomb blockaded temperature map

Bias & heat (6 fW) bias : Coulomb diamond structure in T_e map.

Local quasi-equilibrium
e^--ph coupling / Joule heat.

Lower T at degeneracy point because of improved thermal conductance of the QD junction.

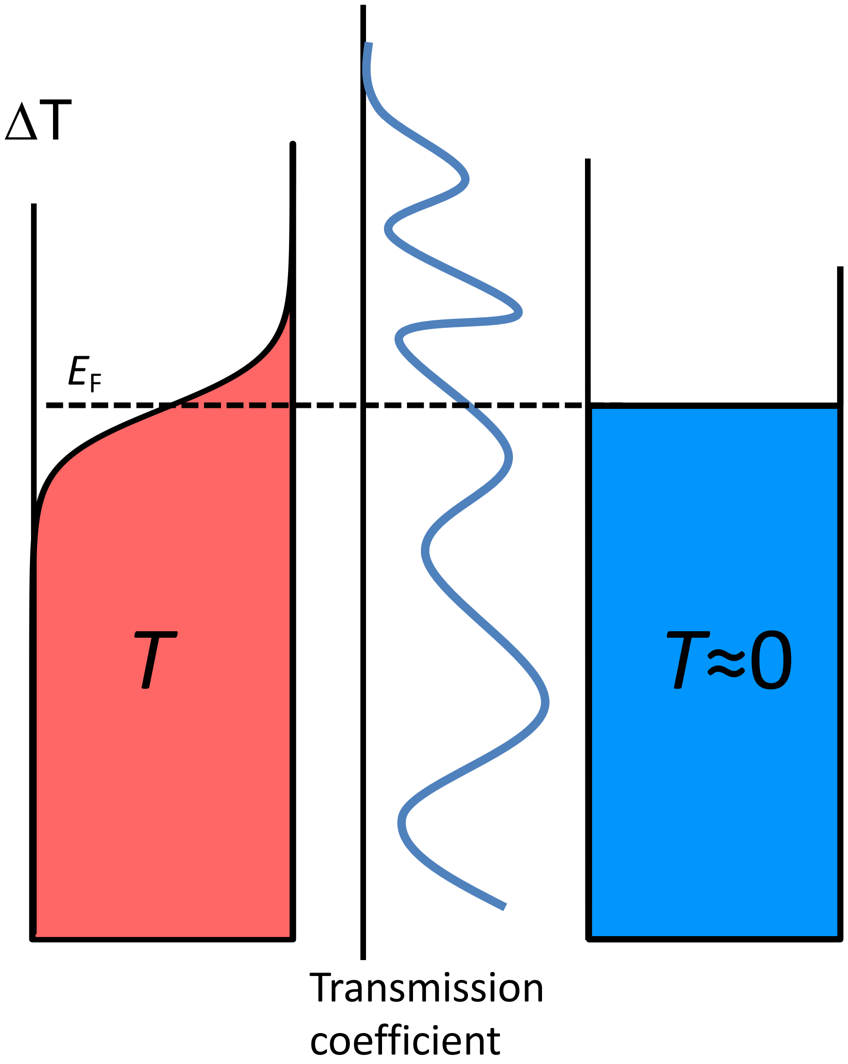
B. Dutta et al. (2019)



Thermopower of a Kondo-correlated quantum dot junction

Thermo-voltage and thermo-power

Two reservoirs with a temperature difference ΔT



Thermo-voltage and thermo-power

Two reservoirs with a temperature difference ΔT

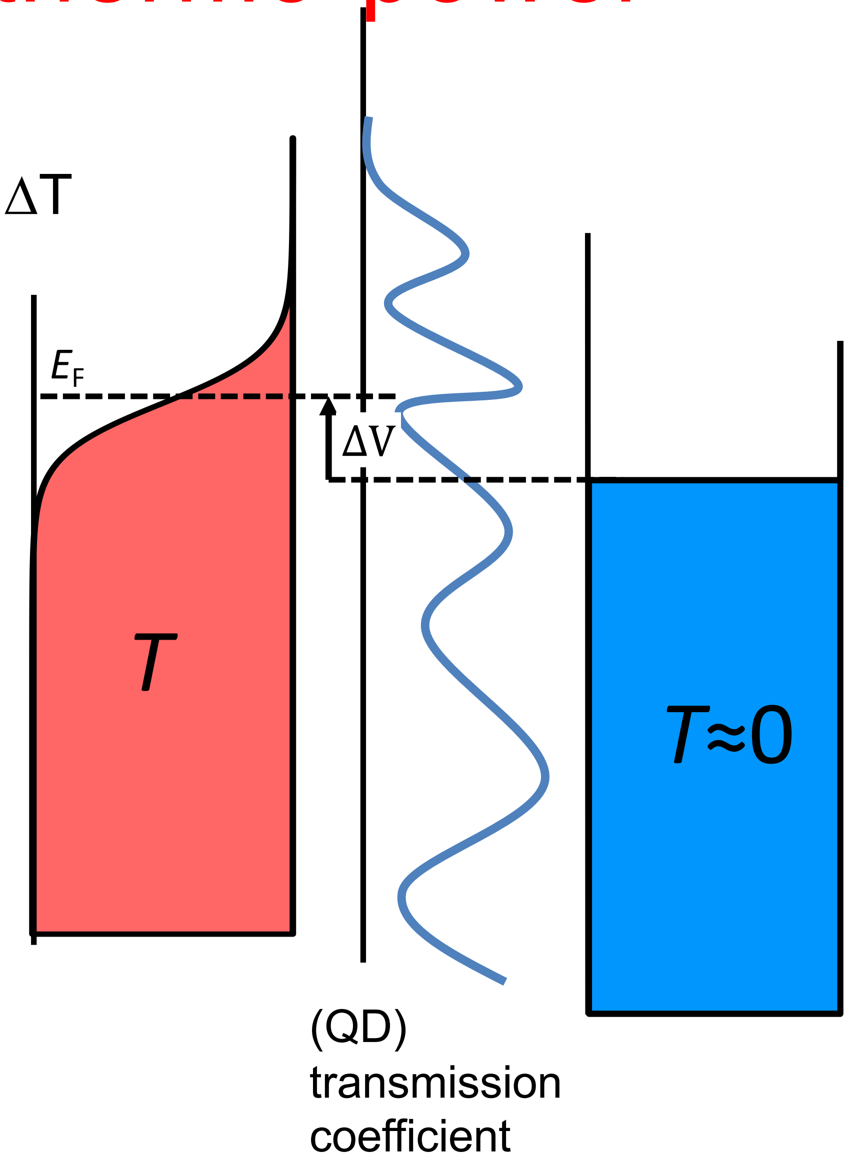
Thermovoltage ΔV

Seebeck coefficient (thermopower):

$$S = \left.\frac{\Delta V}{\Delta T}\right|_{I=0}$$

Mott's law: $$S = -eL_0 T \left[\frac{\partial \ln\big(G(E)\big)}{\partial E}\right]_{E=E_F}$$

Thermopower is related to electron-hole asymmetry.



Early experiment on thermopower of a quantum dot junction

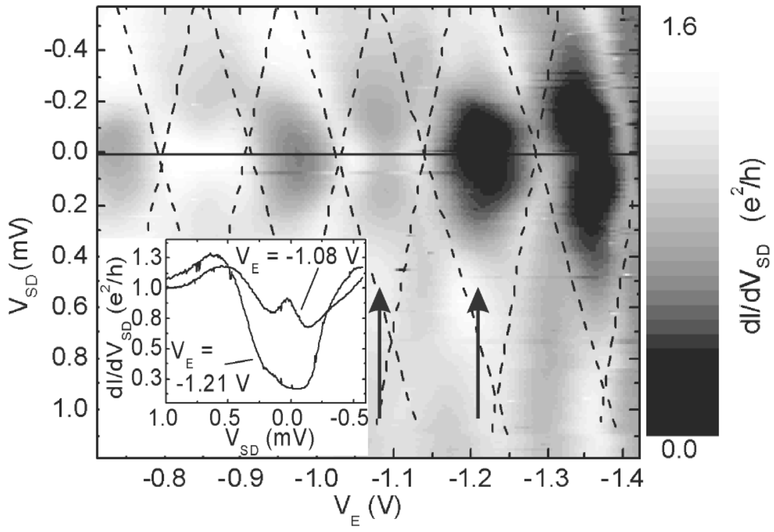


FIG. 2. Grey-scale plot of the differential conductance as a function of the QD potential ($\propto V_E$) and the externally applied bias voltage across the QD (V_{SD}). Alternating regimes of low and high conductance are observed between each successive conductance peak within the CB diamonds (dashed lines). Inset: Bias-voltage (V_{SD}) depending traces of the differential conductivity of the dot for $V_E = -1.08$ V and $V_E = -1.21$ V [indicated by arrows].

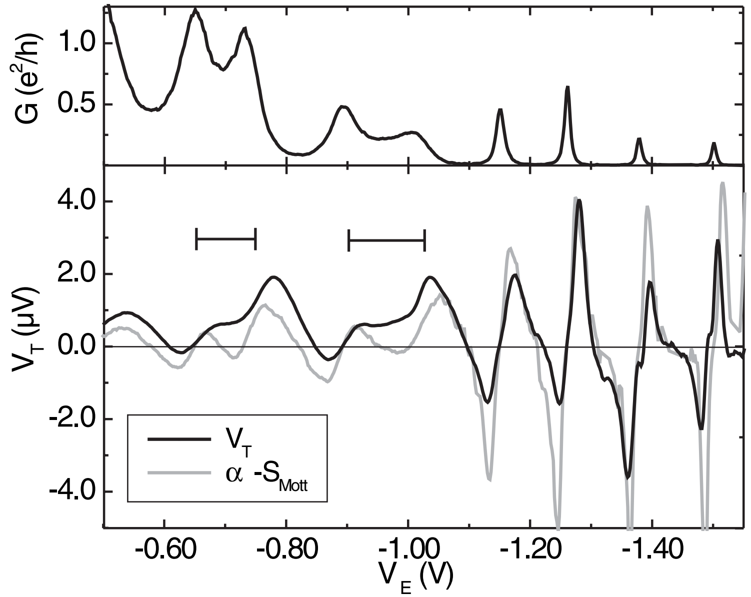
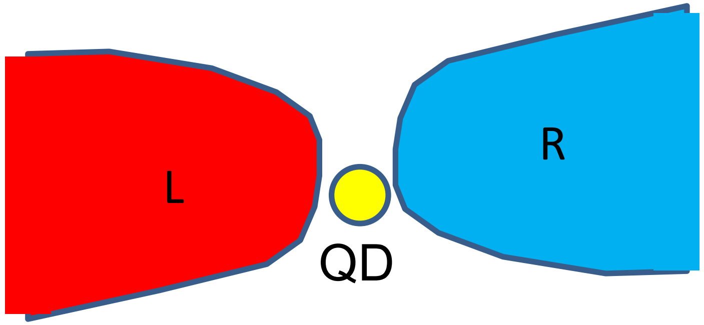


FIG. 3. Comparison of the thermovoltage measurement (V_T), the conductance (G), and the calculated thermopower S_{Mott} as expected from the Mott relation [Eq. (2), where $E \propto (-eV_E)$] as a function of applied gate voltage V_E. The horizontal bars indicate the regions of spin correlations within the gate-voltage range of strong coupling of the quantum dot to the leads ($V_E > -1.1$ V).

R. Scheibner, H. Buhmann, D. Reuter, M. N. Kiselev, and L. W. Molenkamp, PRL 95, 176602 (2005)

Thermoelectric effect and conductance



Hamiltonian for single Anderson impurity model with two leads α:

$$H = \sum_{\sigma} \varepsilon_0 d_\sigma^\dagger d_\sigma + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow + \sum_{k\alpha\sigma} \varepsilon_{k\sigma} c_{k\alpha\sigma}^\dagger c_{k\alpha\sigma} + \sum_{k\alpha\sigma} t_\alpha \left(c_{k\alpha\sigma}^\dagger d_\sigma + H.c. \right)$$

QD level energy $\varepsilon_0(V_g)$ *charging* *kinetic energy in leads* *tunneling leads <-> dot*

NRG impurity spectral function A(E) plays the role of a transmission coefficient

$$G(T) = G_0 I_0(T) \qquad I_n(T) = \int_{-\infty}^{+\infty} -\frac{\partial f(E,T)}{\partial E} E^n A(E,T) dE$$

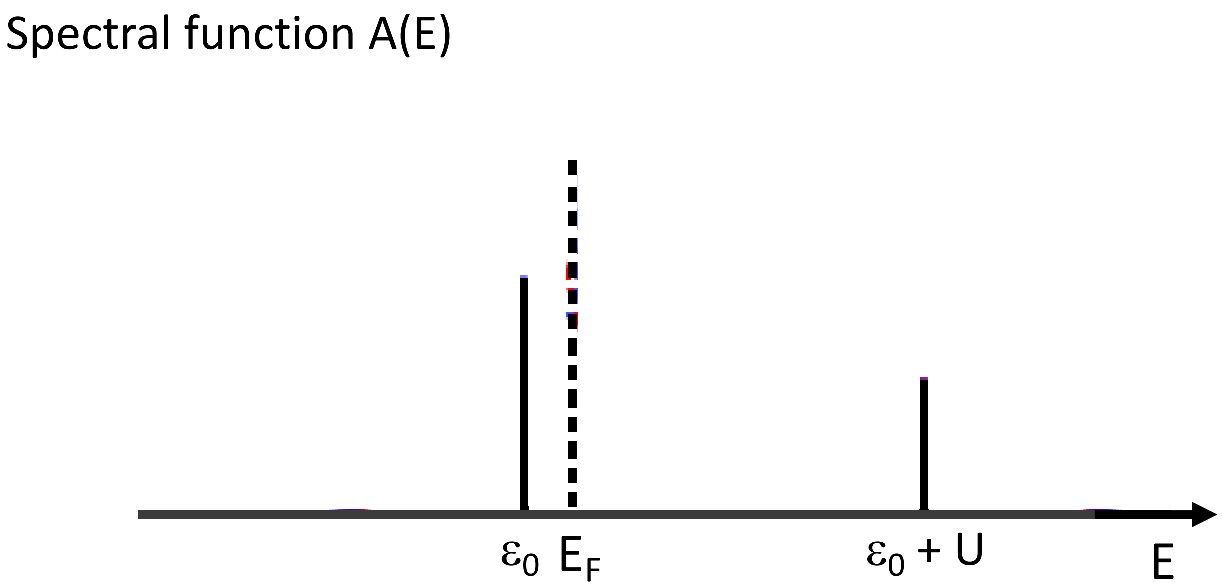
E : excitation energy with respect to E_F

Thermopower $S(T) = -\frac{1}{|e|T} \frac{I_1(T)}{I_0(T)}$ related to $\left.\frac{dA}{dE}\right|_{E_F}$

T. Costi, V. Zlatic, PRB 81, 235127 (2010)

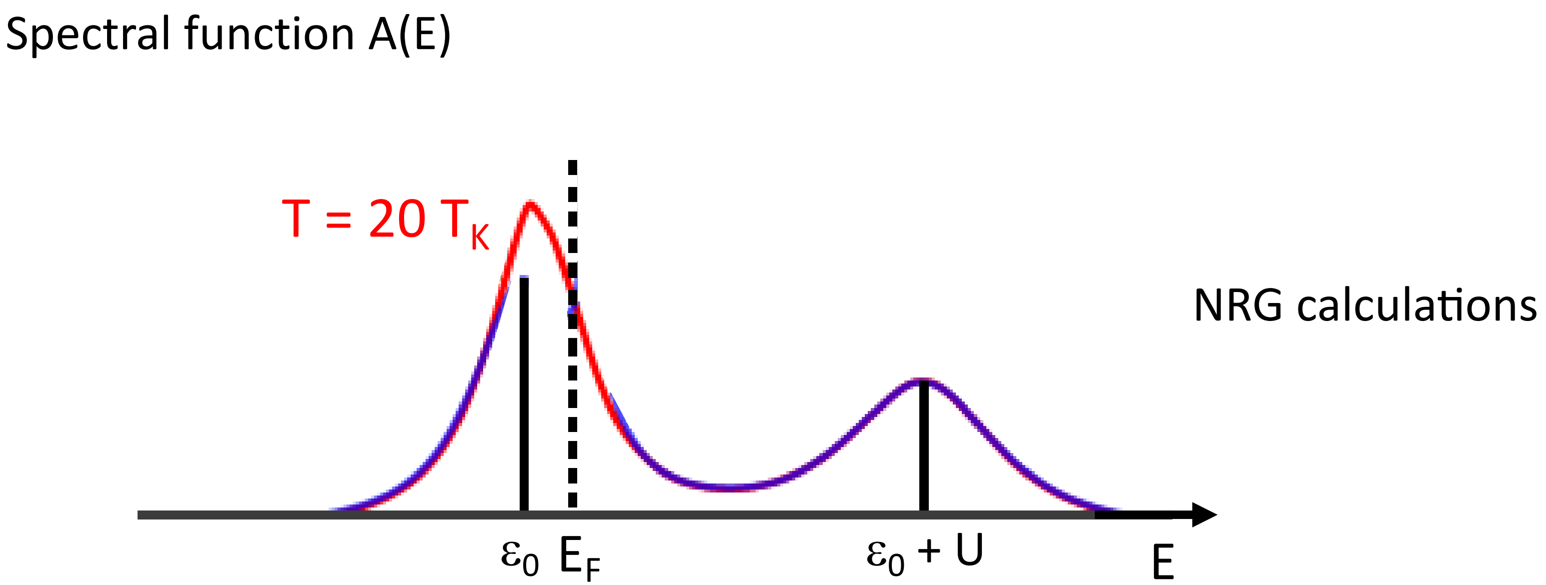
A quantum dot

Energy levels in the QD



A quantum dot coupled to leads

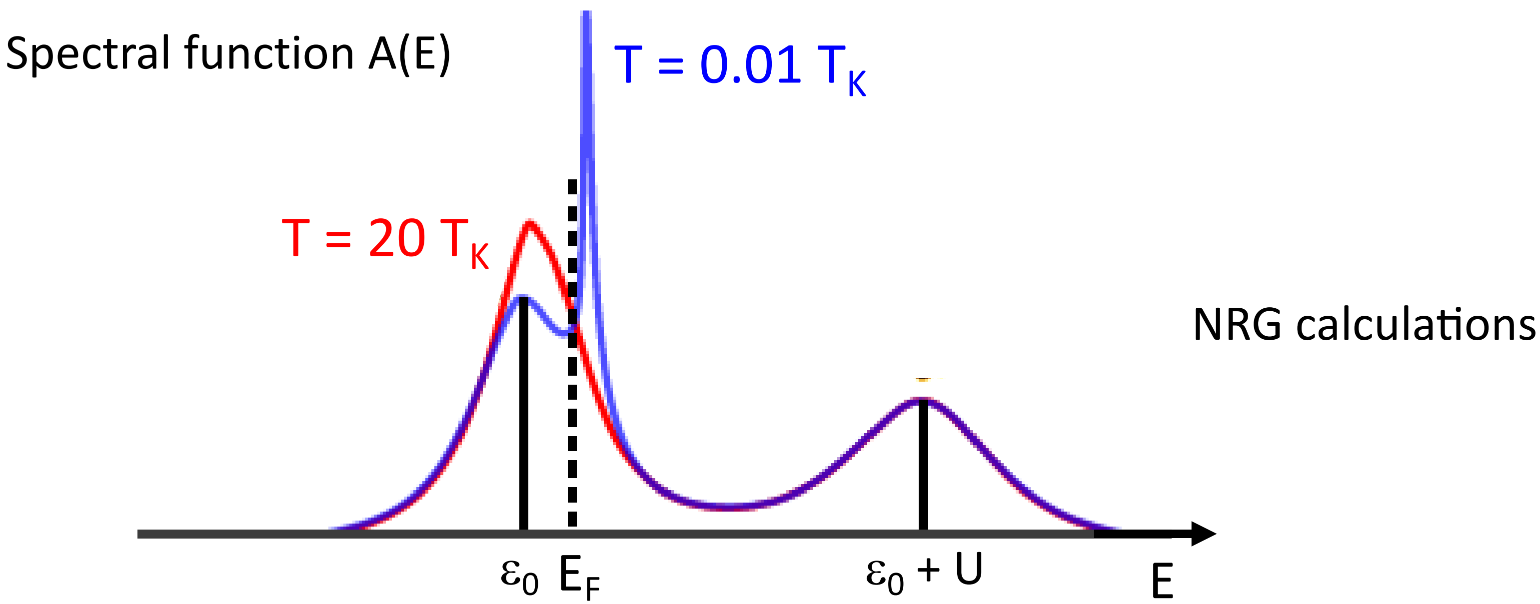
Energy levels in the QD smeared by the tunnel coupling to leads



The Kondo effect

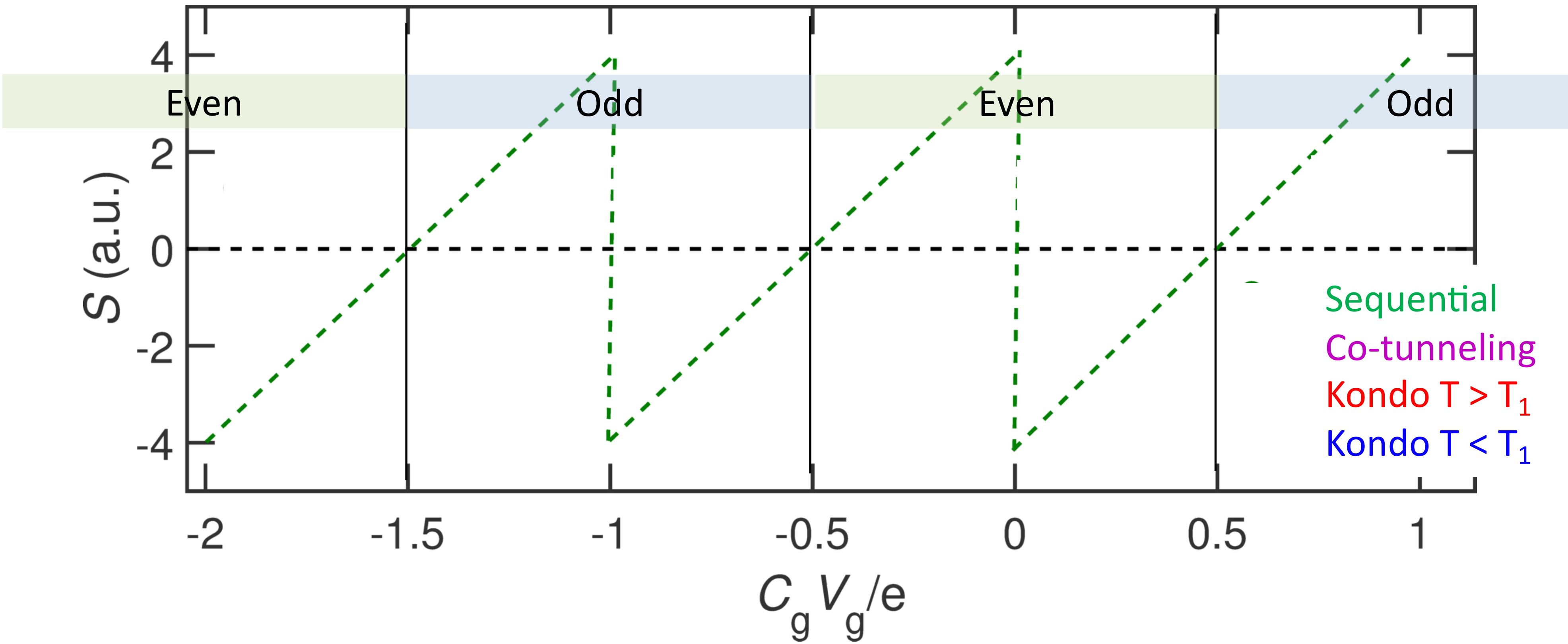
Energy levels in the QD smeared by the tunnel coupling to leads

At $T < T_K$: tunneling resonance of width $k_B T_K$ in the spectral function near E_F



Theory: thermopower of a QD junction

Sequential tunnelling: sawtooth in thermopower



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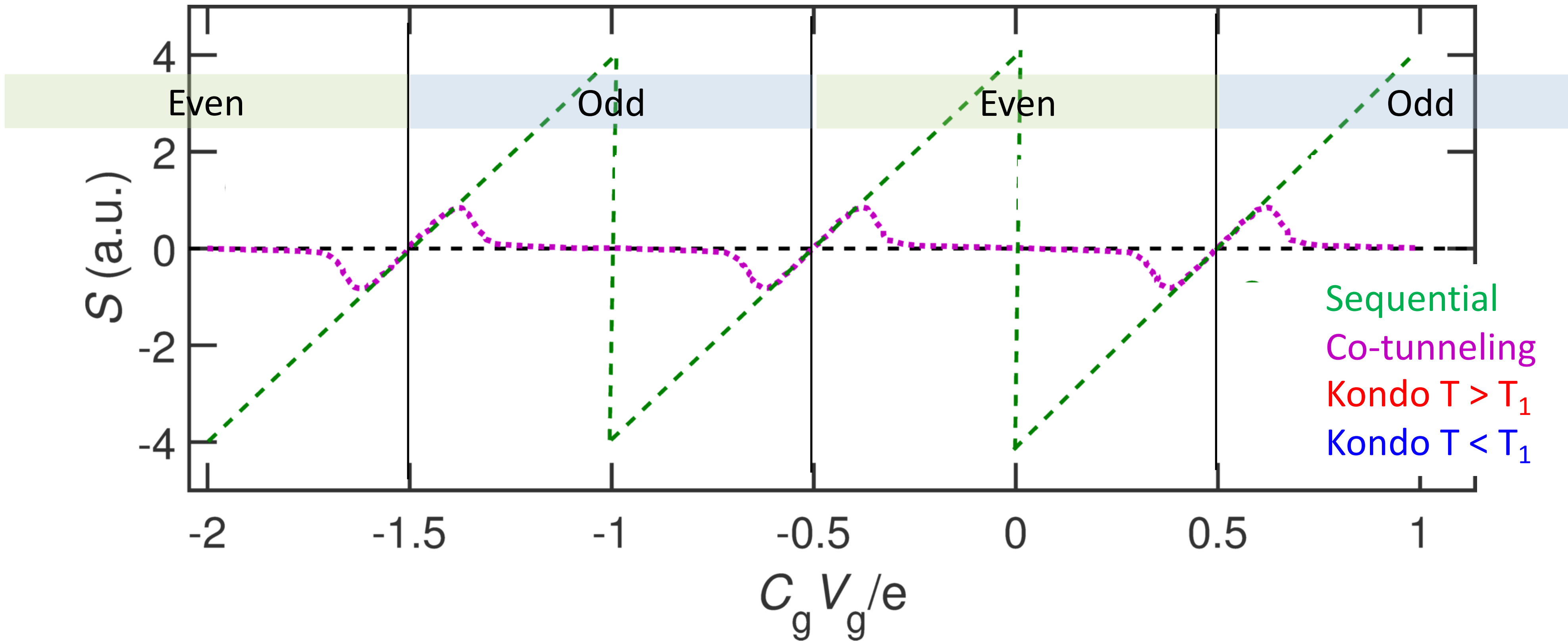
Sequential tunnelling: sawtooth in thermopower

Moderate coupling and strong blockade: co-tunnelling cancels the thermopower



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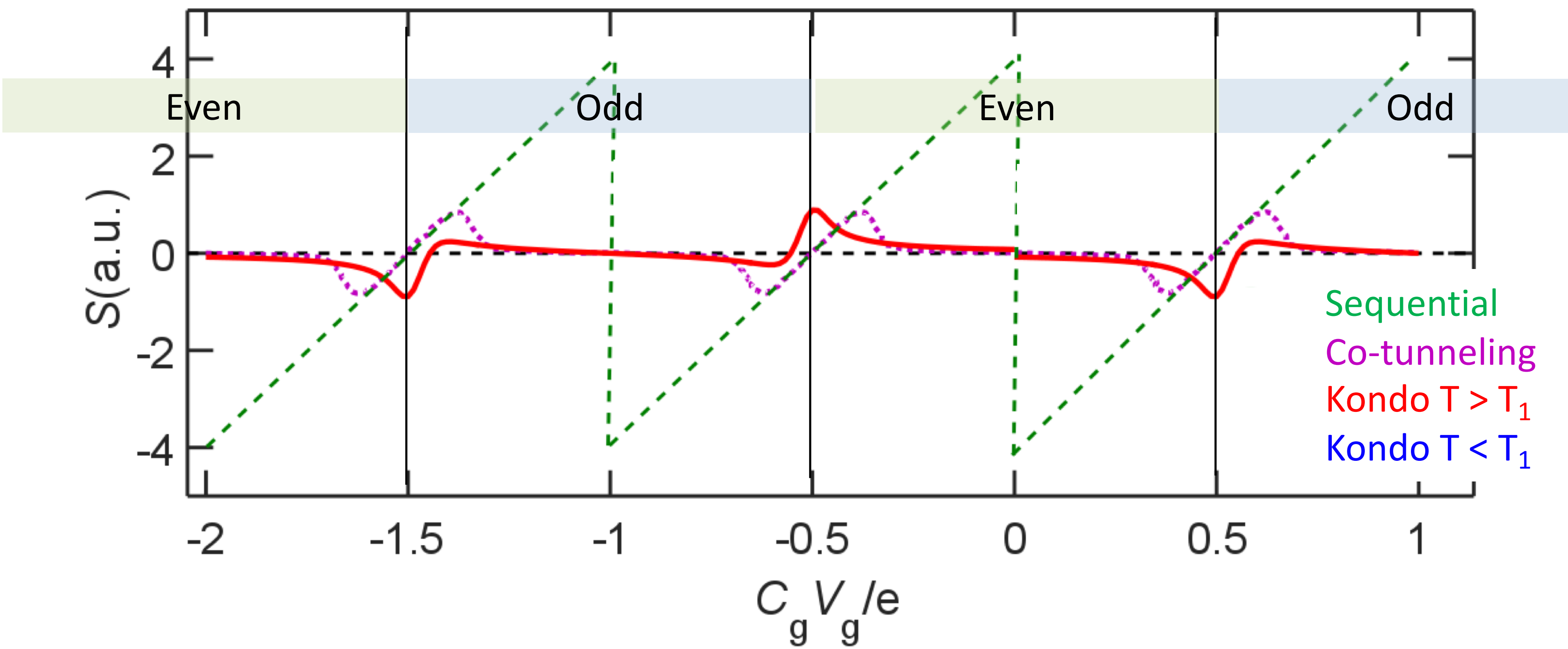
Kondo effect appears at stronger coupling and low temperature: 2e-periodicity



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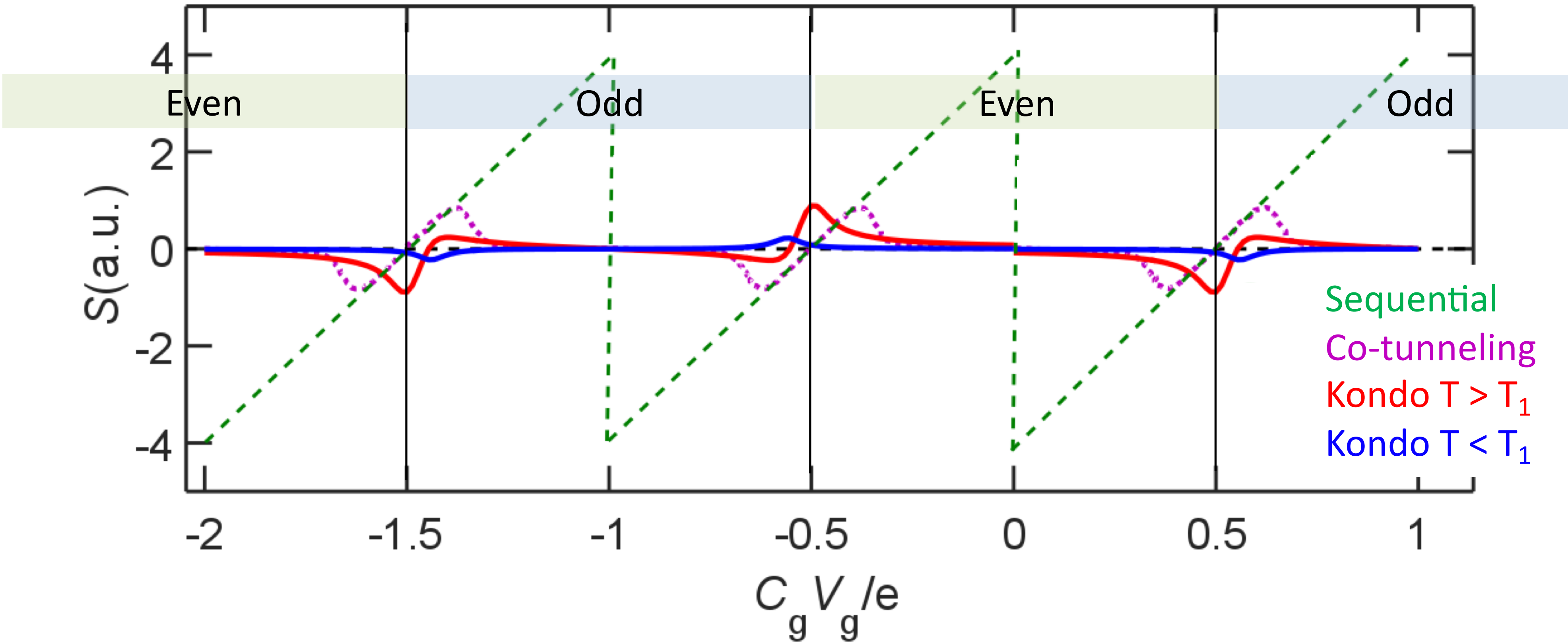
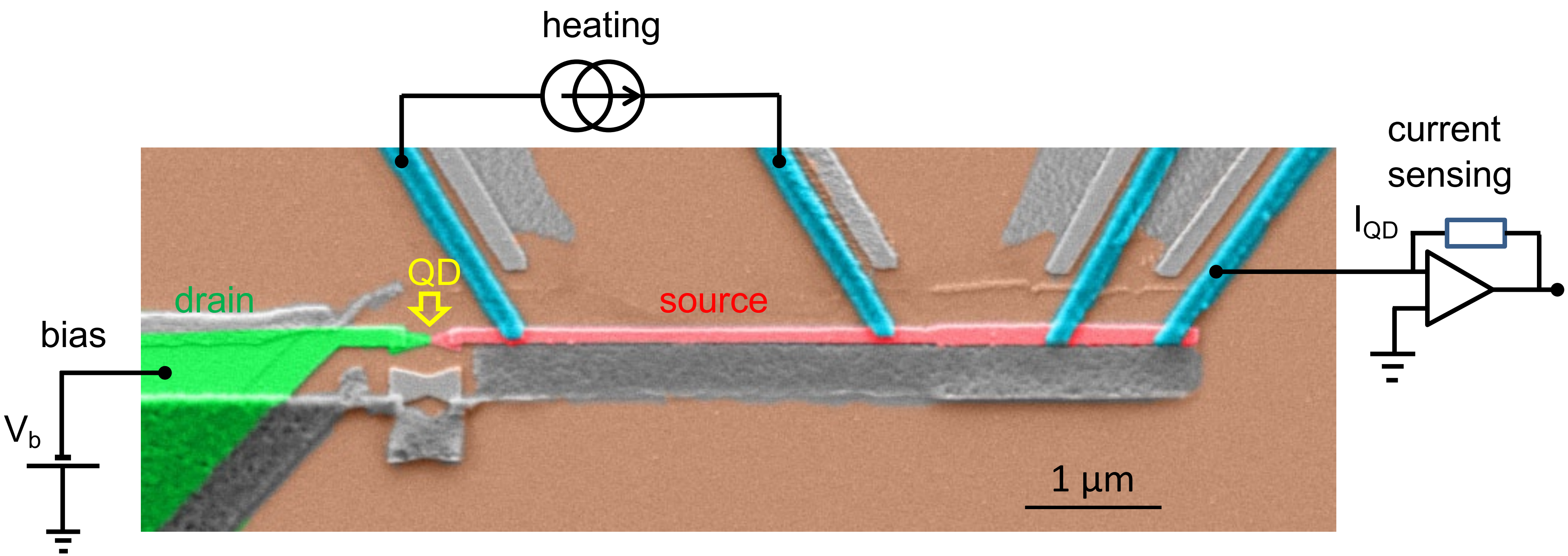
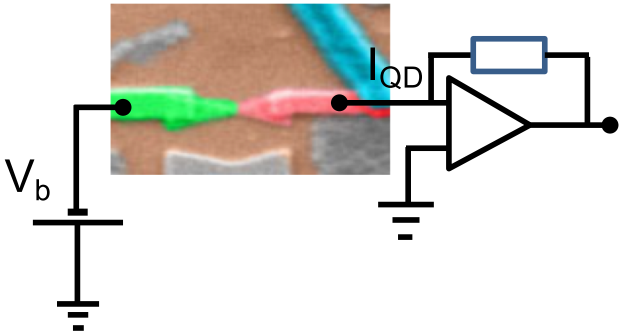


Experiment:
Thermopower of a QD junction

Similar but different sample from heat transport experiment



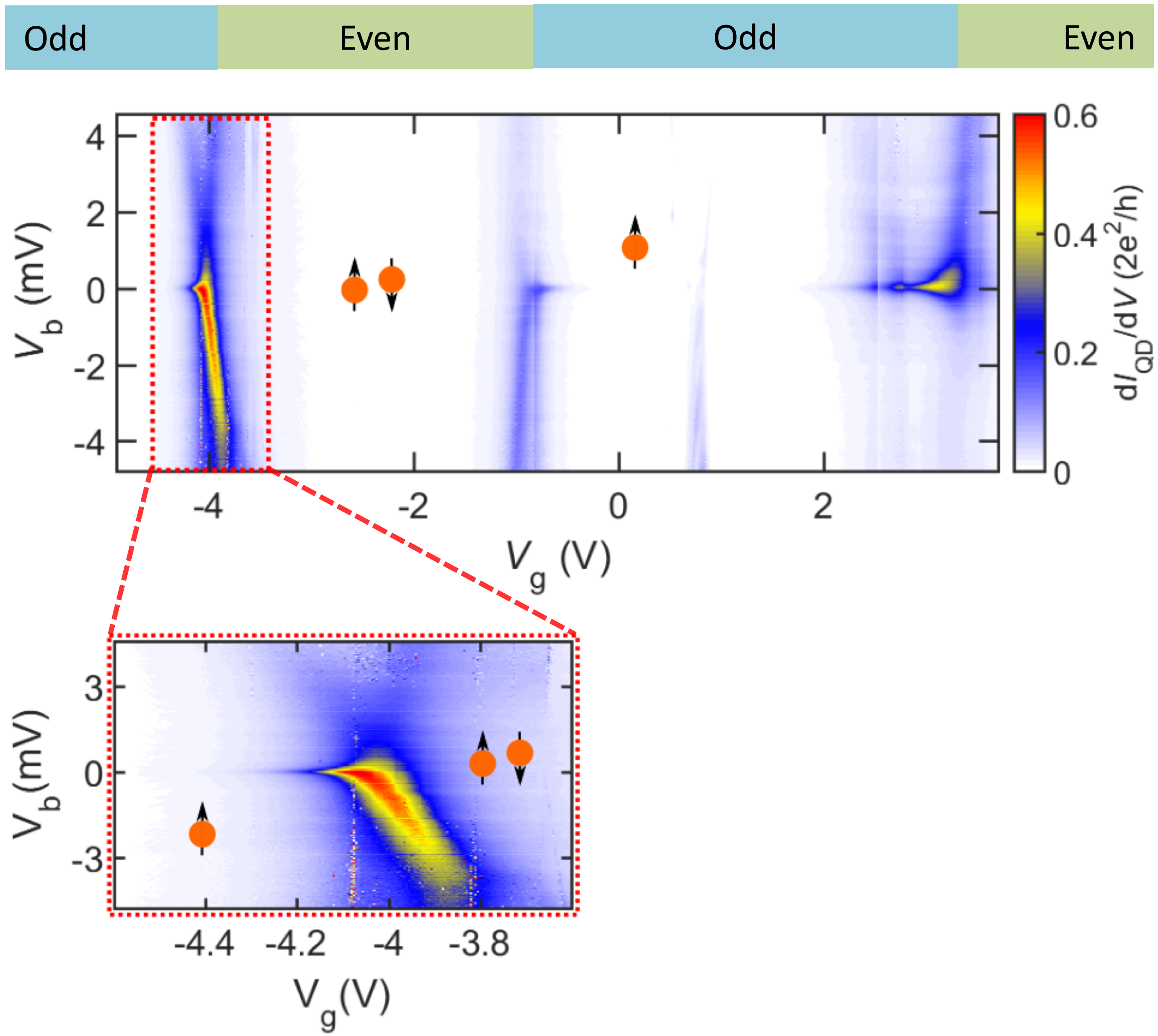
A quantum dot in the Kondo regime



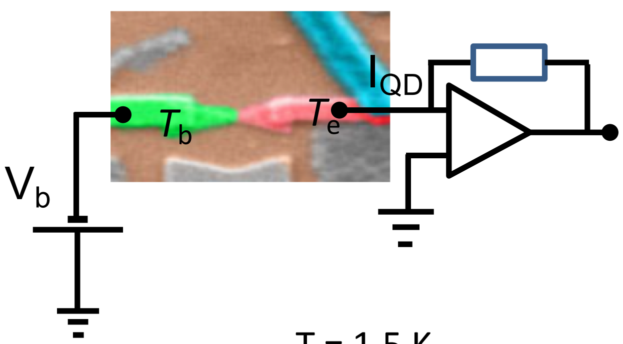
charging energy
U = 58 meV = 670 K

Strong tunnel coupling to one lead
Γ = 2.6 meV = 30 K

Assymetric coupling
Γ'/Γ = 0.002

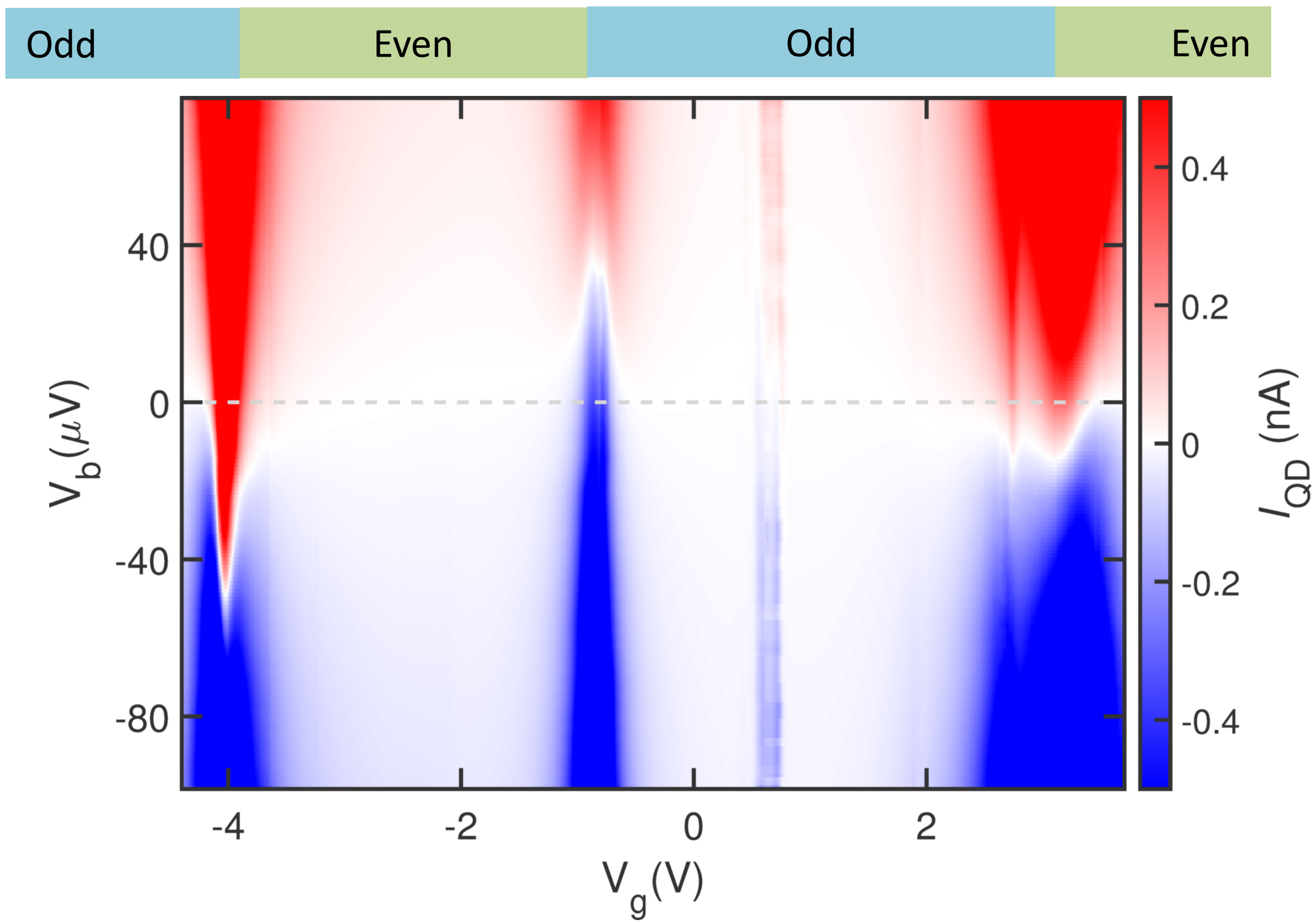


Current map in the Kondo regime

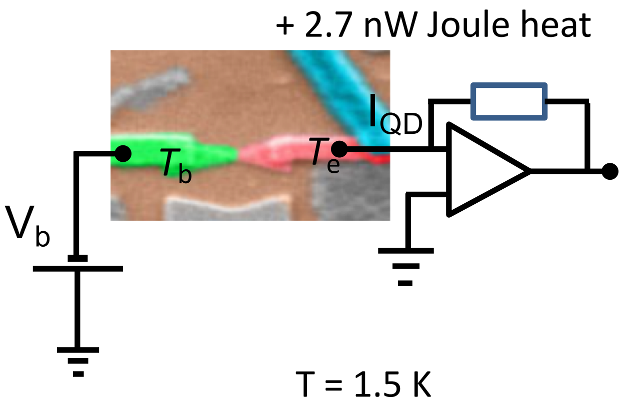


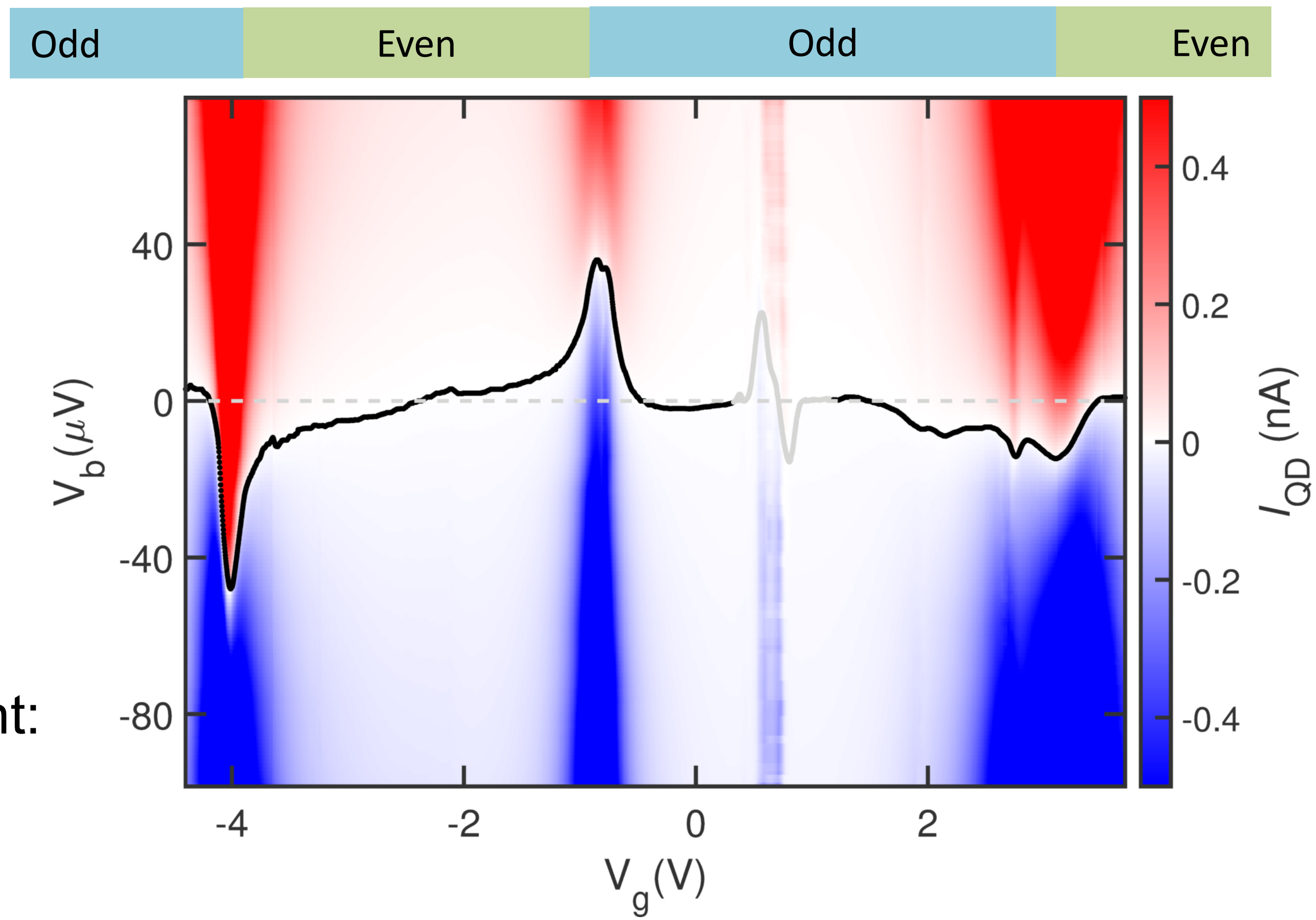
T = 1.5 K

Very high impedance!



Thermovoltage in the Kondo regime





Thermopower defined as minus bias at zero current:

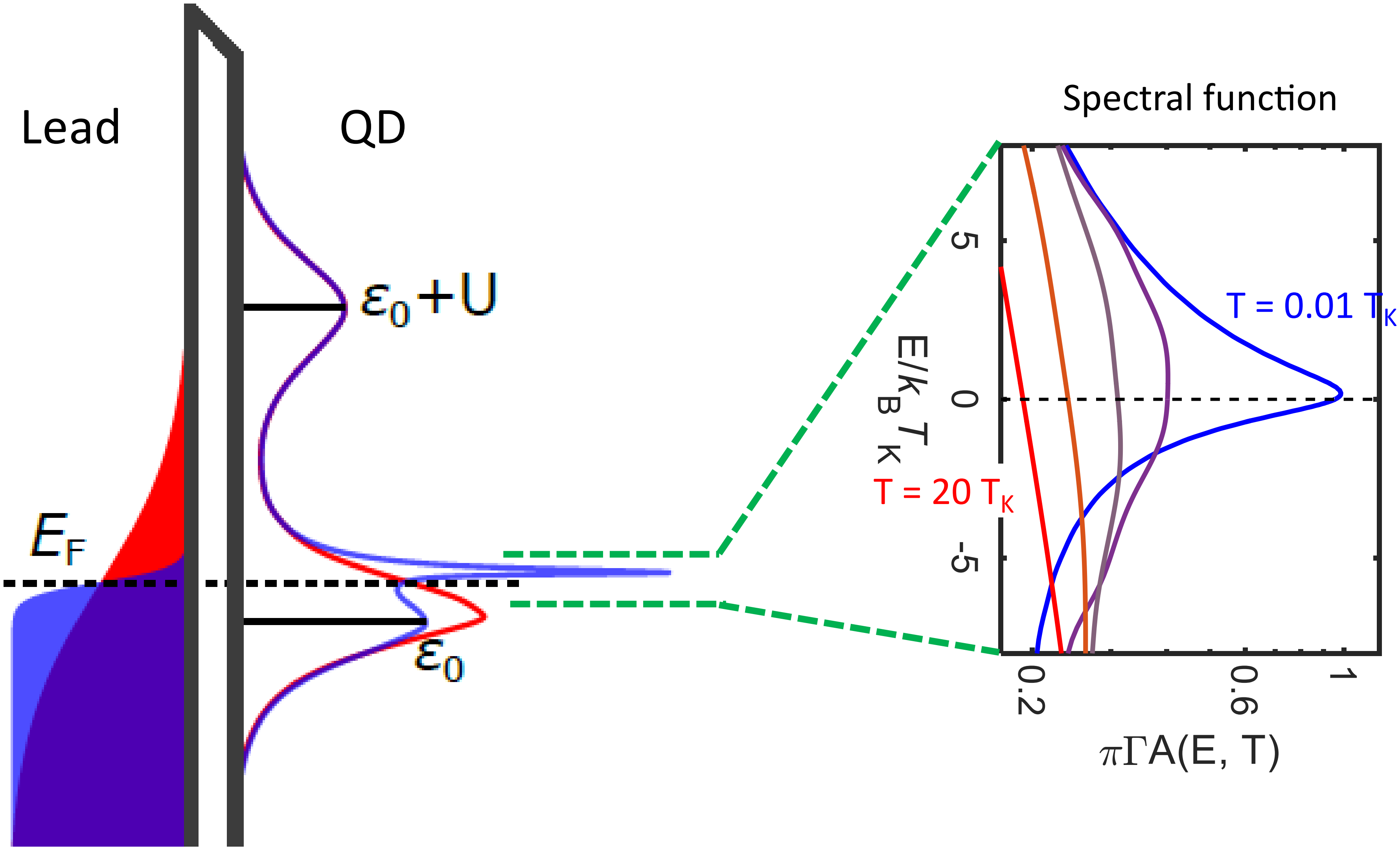
$$-V_{th} = [V_b]_{I_{QD}=0}$$

2e-periodic in gate-induced charge demonstrates electron-hole assymetry

See also A. Svilans, M. Josefsson, A. M. Burke, S. Fahlvik, C. Thelander, H. Linke, M. Leijnse, PRL (2018).

Spectral function

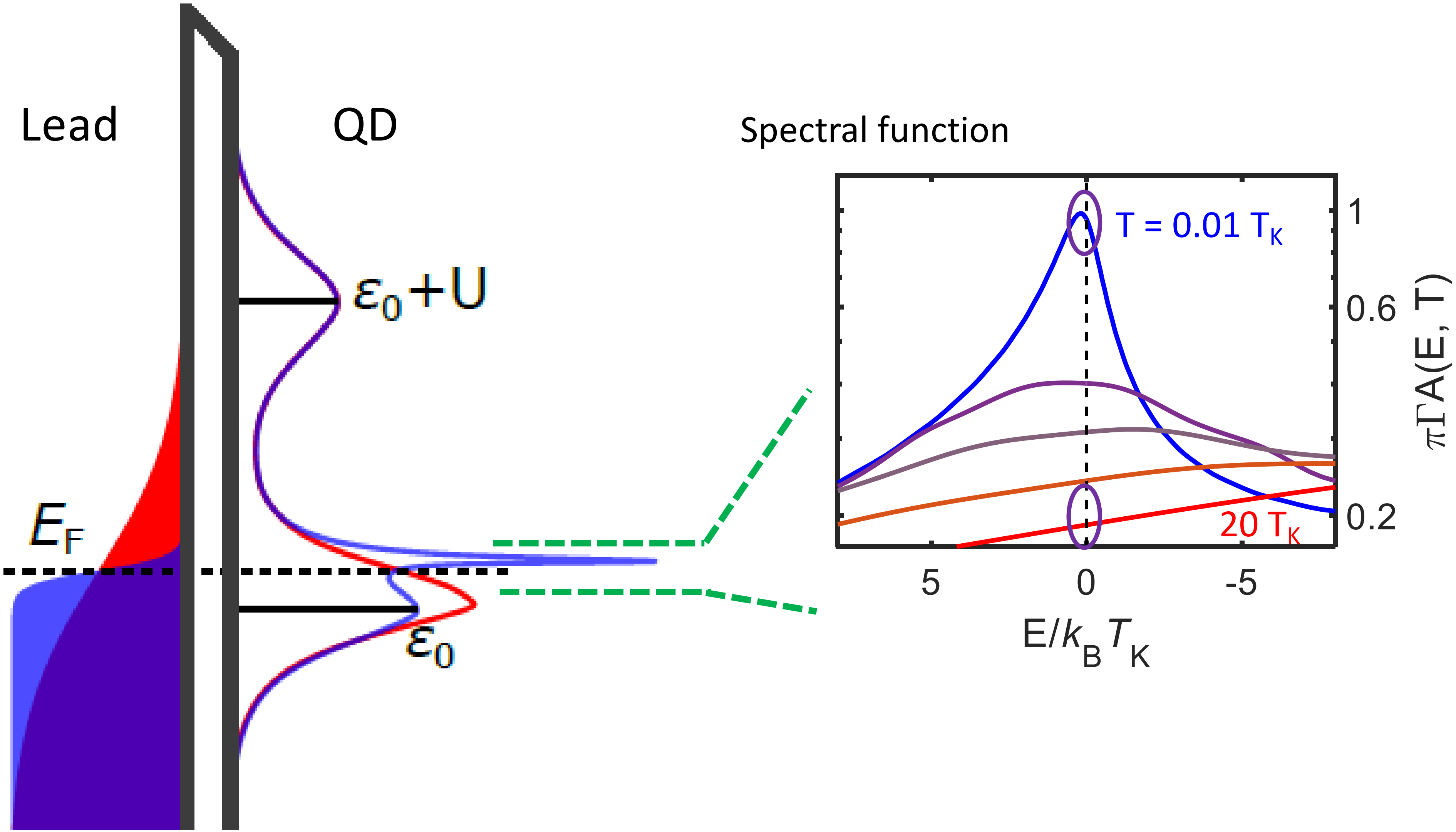
Kondo resonance shifted by about $k_B T_K$ from E_F



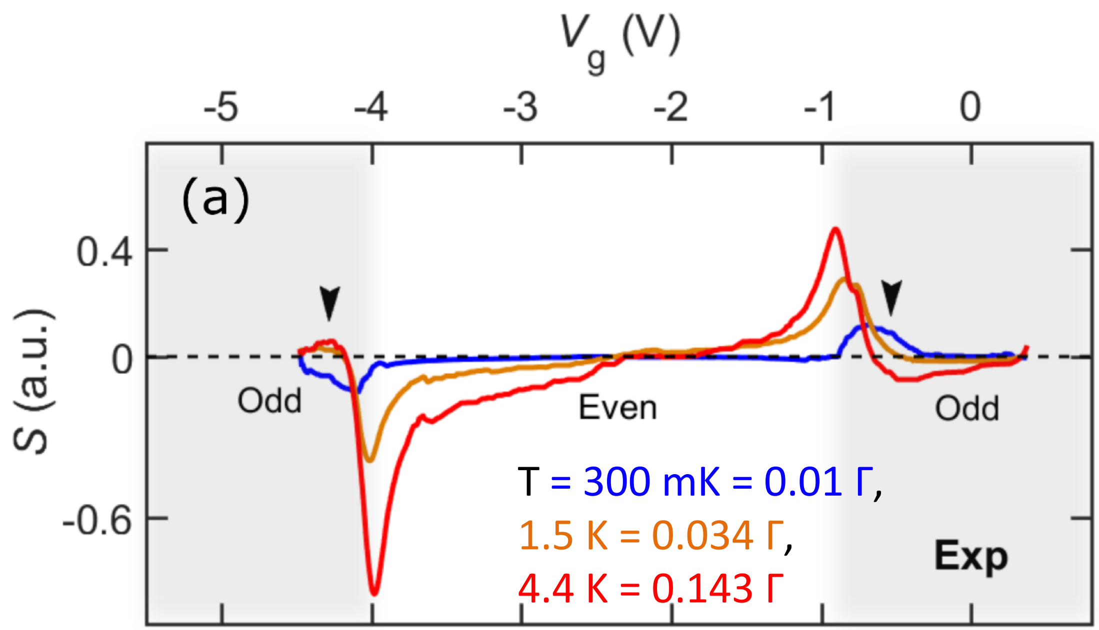
Spectral function

Kondo resonance shifted by about $k_B T_K$ from E_F:

sign change of thermopower with temperature expected



Sign reversal of the thermopower



Sign change of S with increasing temperature in odd states only

B. Dutta, D. Majidi, A. García Corral, P. A. Erdman, S. Florens, T. A. Costi, H. Courtois & C. B. Winkelmann, Nano Lett. (2019).

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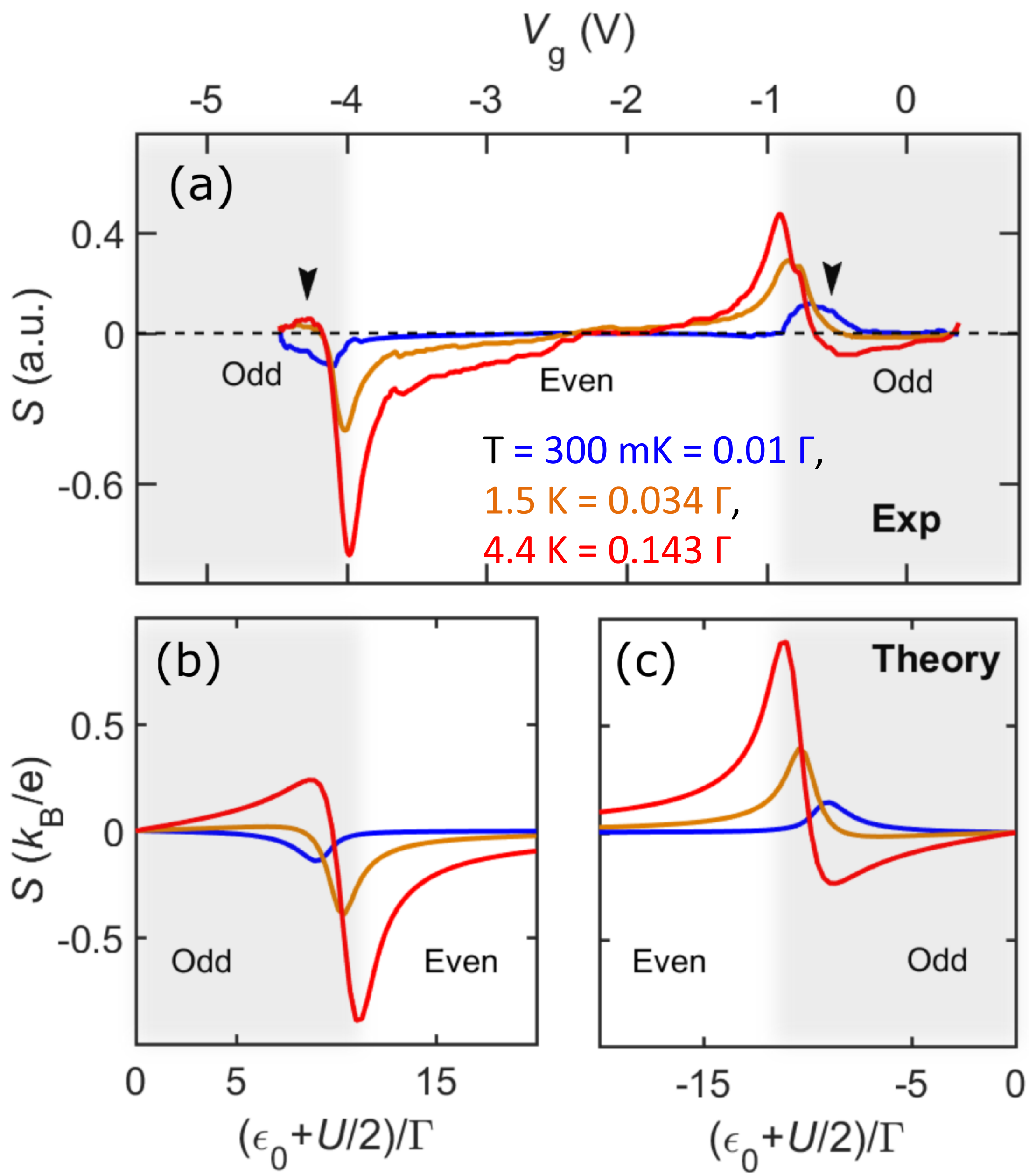


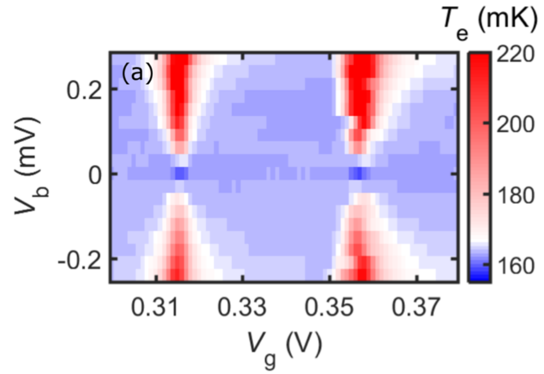
Sign change of S with increasing temperature in odd states only.

Good agreement with model, proof of Kondo origin.

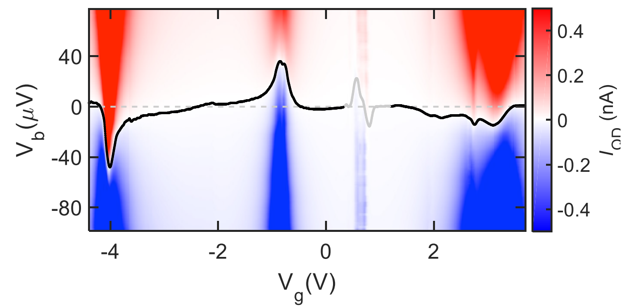
B. Dutta, D. Majidi, A. García Corral, P. A. Erdman, S. Florens, T. A. Costi, H. Courtois & C. B. Winkelmann, Nano Lett. (2019).

Summary, acknowledgements

Josephson current electronic thermometry used to measure heat transport in a QD



Thermopower of a QD in the Kondo regime shows how the Kondo resonance is shifted from the Fermi level



Bivas Dutta, Danial Majidi, Alvaro Garcia-Corral, Serge Florens, Clemens Winkelmann, Institut Néel

Jukka Pekola, Aalto University, Helsinki

Theo C. Costi, Jülich

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