NANO LUND

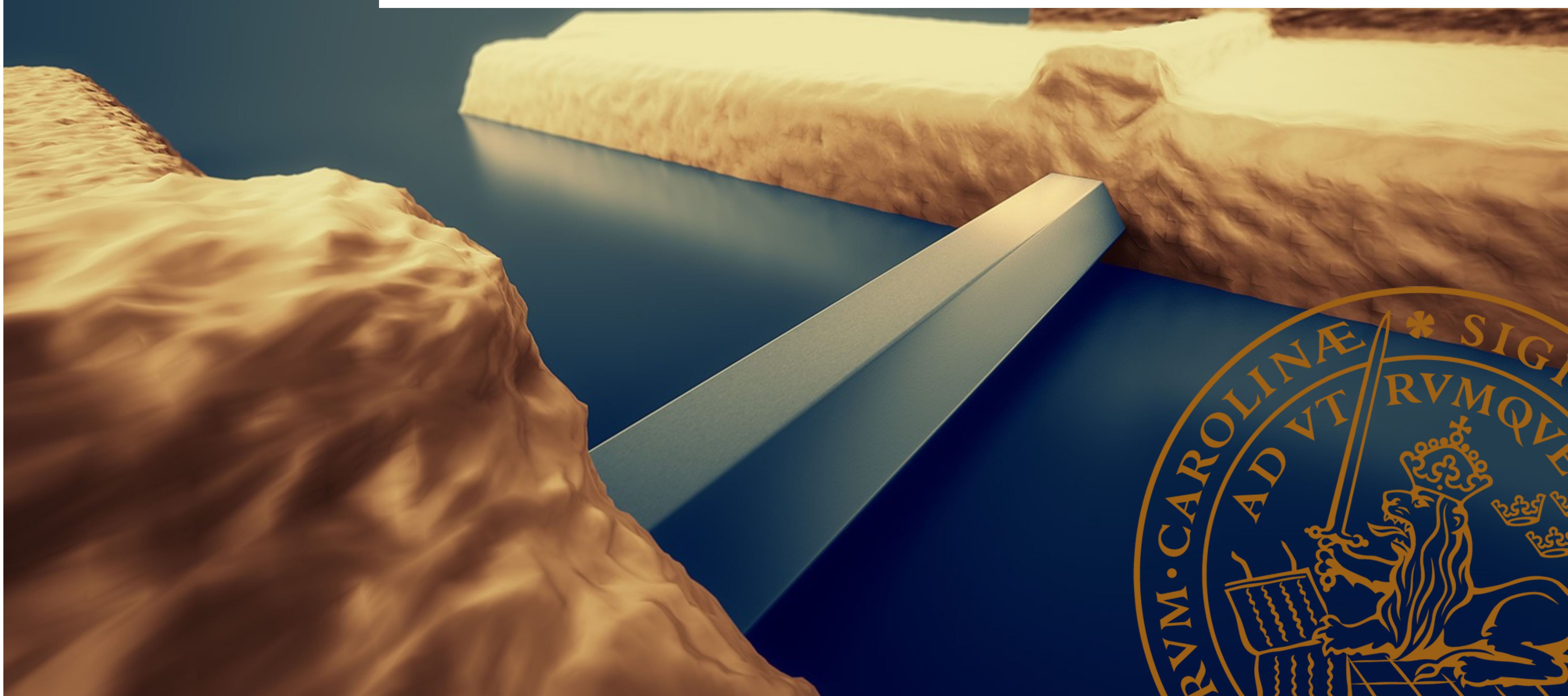
AT THE FOREFRONT OF NANOSCIENCE

LUND UNIVERSITY

Optimal power and efficiency of a quantum-dot heat engine

MARTIN JOSEFSSON, A. SVILANS, A. BURKE, E. HOFFMAN, S. FAHLVIK, C. THELANDER, M. LEIJNSE, H. LINKE

QTD Espoo, June 25th, 2019



Outline

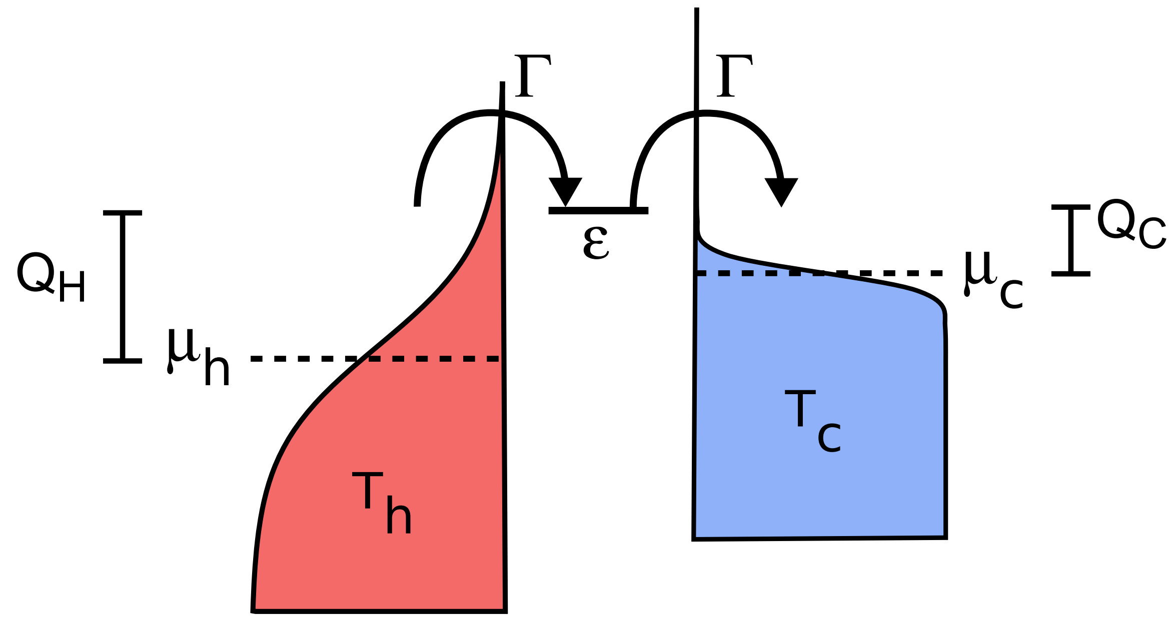
LUND UNIVERSITY | NANOLUND AT THE FOREFRONT OF NANOSCIENCE

- QD heat engine + motivation
- Theory & Experimental setup
- Power
- Efficiency

Further reading

M. Josefsson et al. Nature Nanotechnology **13**, 920 (2018)
M. Josefsson et al. arXiv:1903.12618

QD Heat Engine



Transmission $\propto \delta(E - \varepsilon)$

Energy filtering → net particle/energy flux

Electronic efficiency limits (QD):

Overall maximum

$$\eta_C = 1 - \frac{T_C}{T_H}$$

PNAS **93**, 7436 (1996), PRL **89**, 116801 (2002)
PRL **94**, 096601(2005)

At maximum power

$$\eta_{CA} = 1 - \sqrt{\frac{T_C}{T_H}} \approx \frac{\eta_C}{2}$$

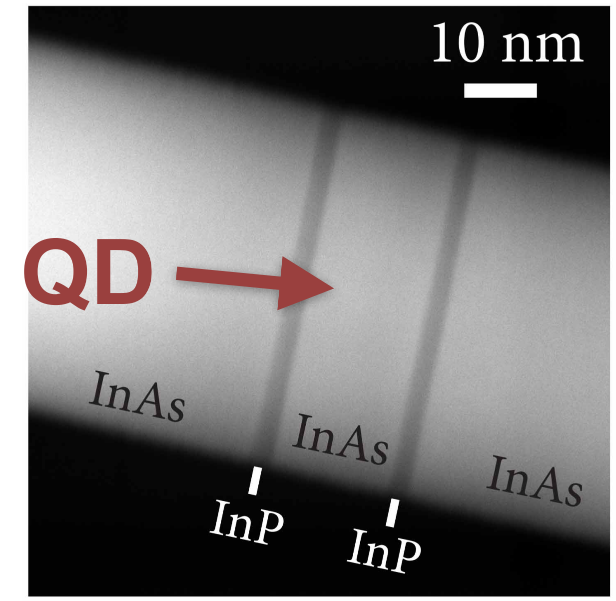
EPL **85**, 60010 (2009)
PRB **78**, 161406 (2008)

Experiments

The QD

InP-segment in a InAs nanowire

Band-gap offset confines electrons



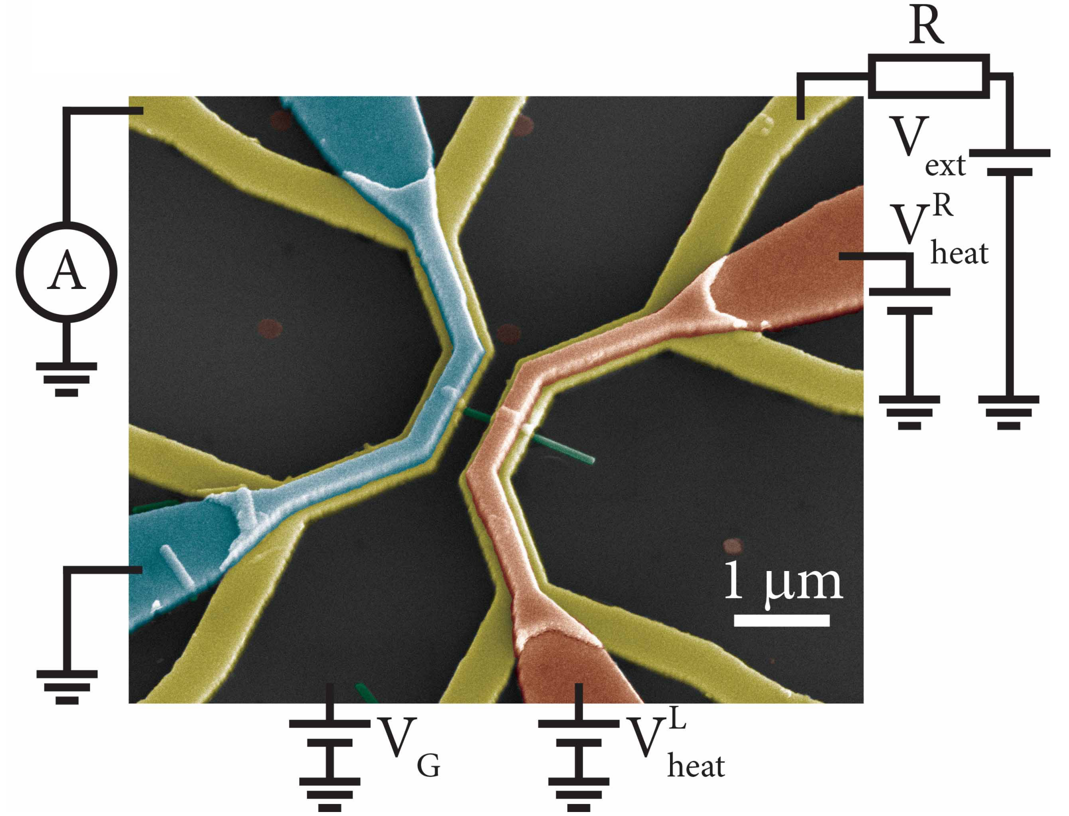
Circuitry

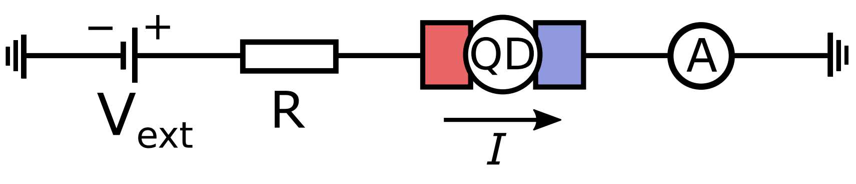
Metallic contacts

”Top-heaters” used for thermal biasing

$\Delta T = T_H - T_C$ and/or V_{ext} generates a current

External load R





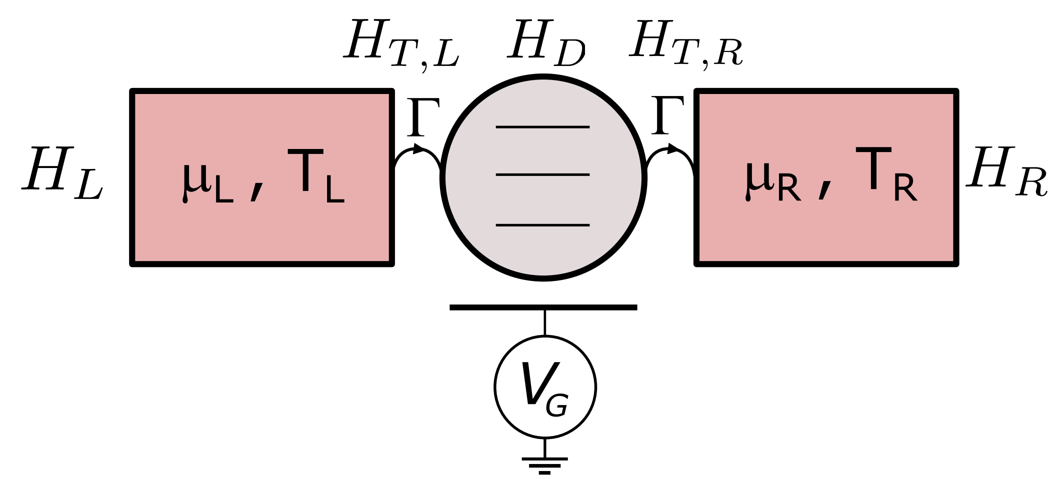
Theory

$$\eta = \frac{P}{J_Q}$$

Measured (→ P)

Calculated (→ J_Q)

$$H = H_D + \sum_r H_r + \sum_r T_{T,r}$$

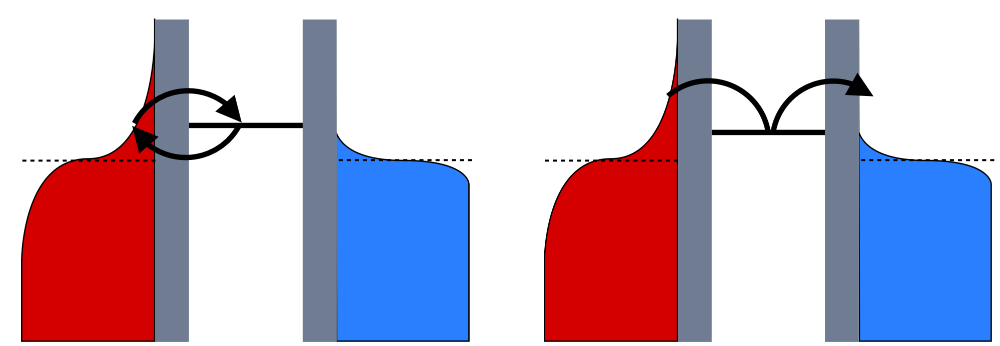


Anderson model

- Small Γ, large e-e interactions

Real-time diagrammatics

- Master equations
- Keep terms up to Γ^2
    - Charge current
    - Heat current (no phonons)



Fluctuations Cotunneling

Leijnse, Wegewijs, PRB **78**, 235424 (2008)
N. Gergs et al. PRL **120,** 017701 (2018)

Lund University | NanoLund
AT THE FOREFRONT OF NANOSCIENCE

Conductance and power

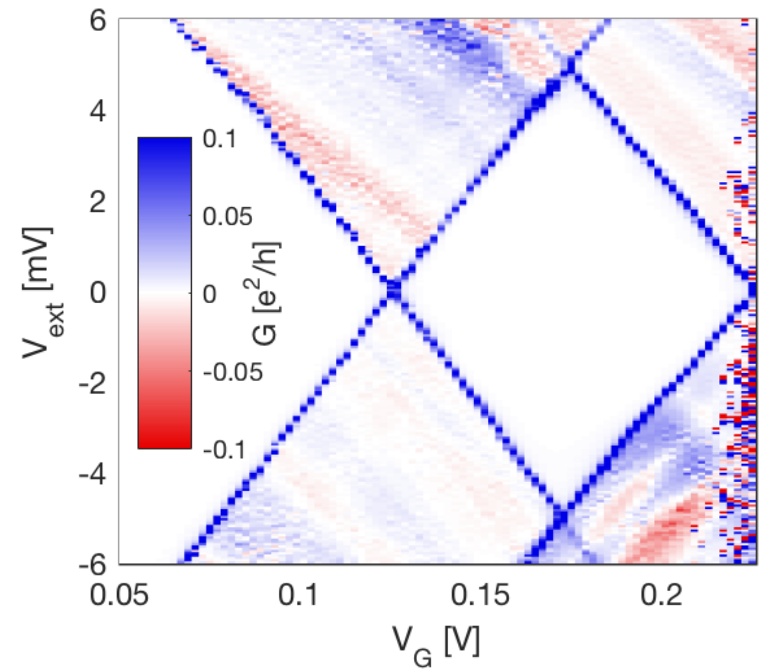
Device characterization

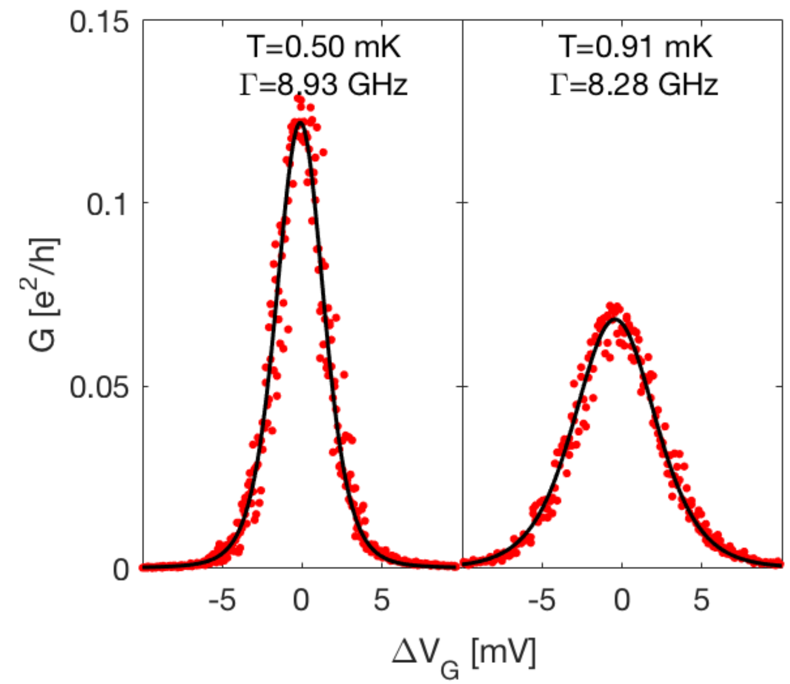
NanoLund — At the forefront of nanoscience
Lund University

Conductance ($\Delta T = 0$):

E_C and α from stability diagram

Γ from $G(V_G)$ (fit)

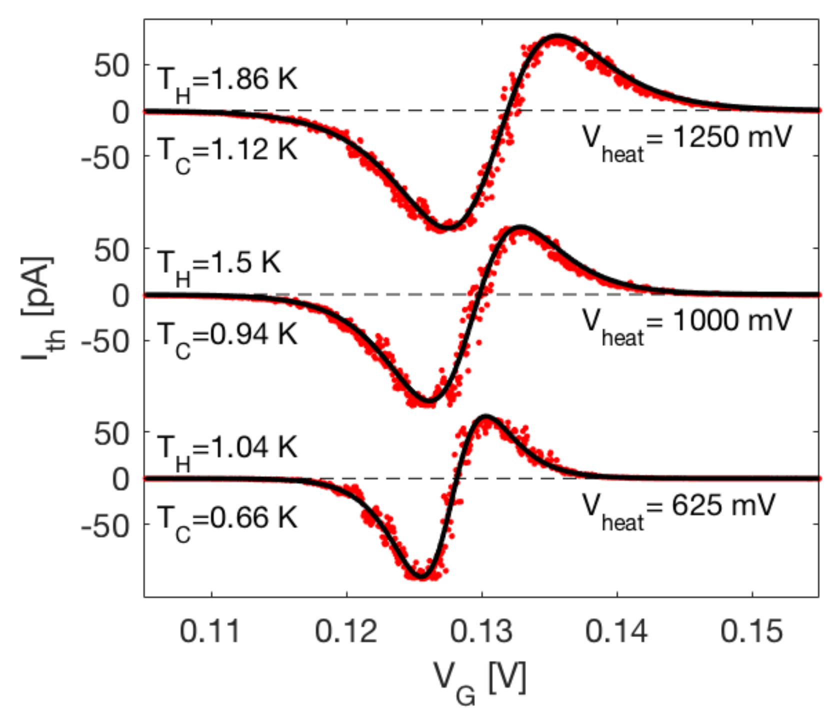




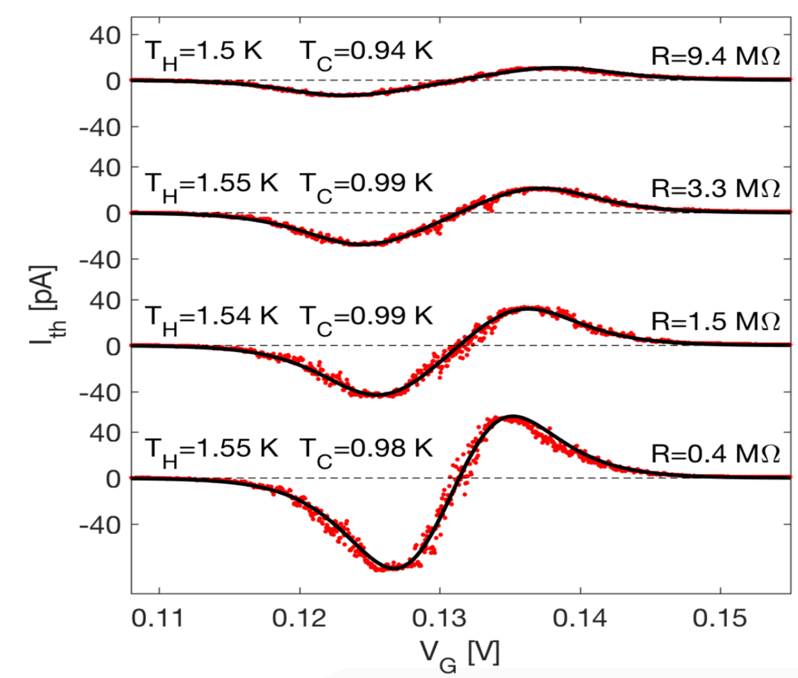
Thermocurrent ($\Delta T > 0$):

T_H and T_C from $I(V_G)$ (fit)

Repeated for each $I(V_G)$



R = 0



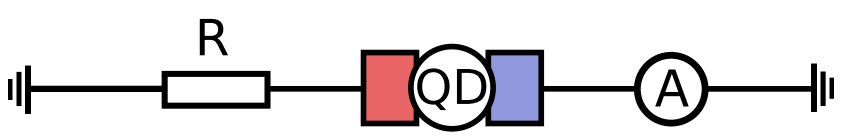
$V_{heat} = 1V$

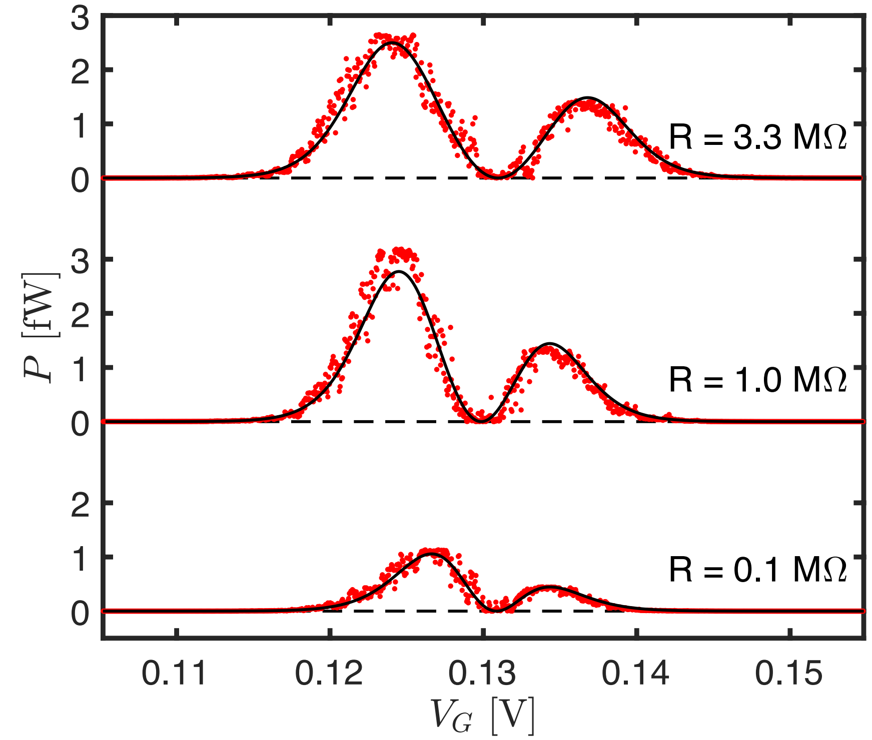
Nat. Nano. **13**, 920 (2018)

Power & Load Matching 1

Remove V_{ext} - attach load.

Only power generation P>0



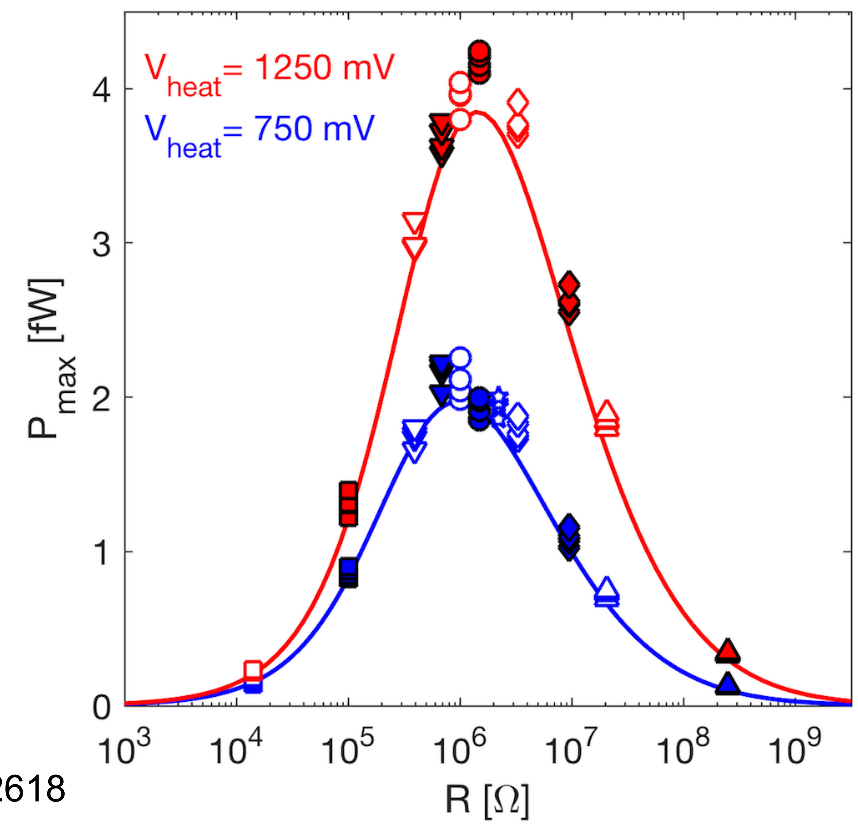


Optimal load (theory)

Linear response and sequential tunneling

$$R_P \approx 2.507 \frac{k_B(T_H + T_C)}{2\hbar\Gamma} \frac{h}{e^2}$$

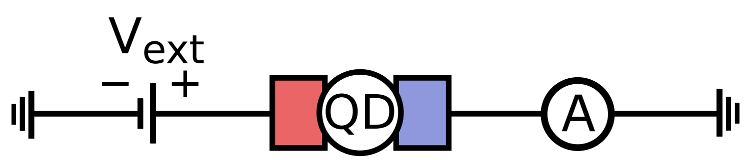
Non-linear and second order effects: ~ 1%

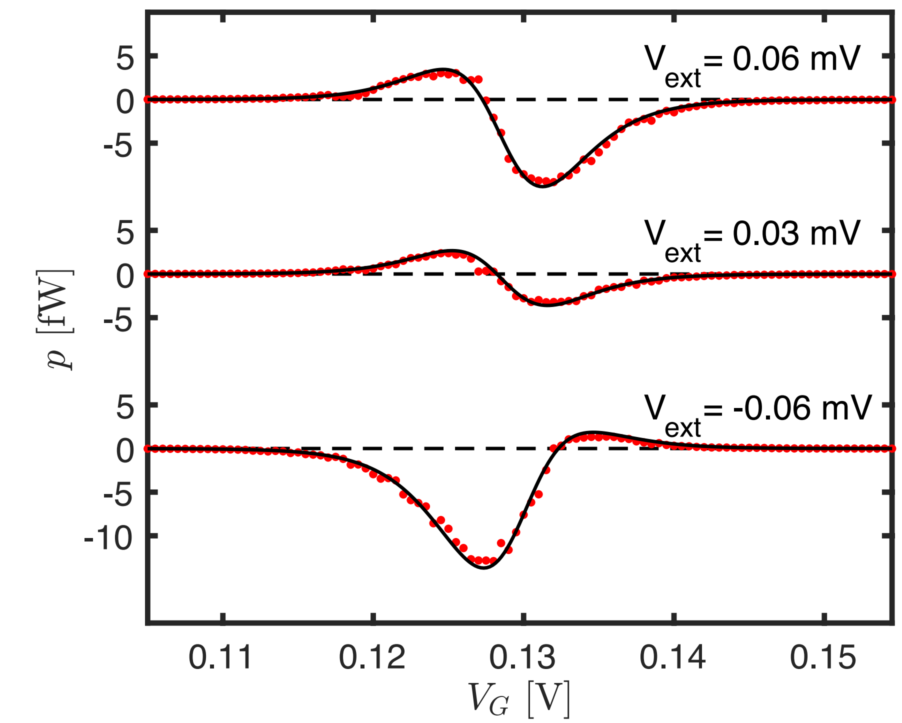


Nat. Nano. **13**, 920 (2018) & arXiv:1903.12618

Power 2

Use V_{ext} to simulate a load: $$P = -IV_{ext}$$

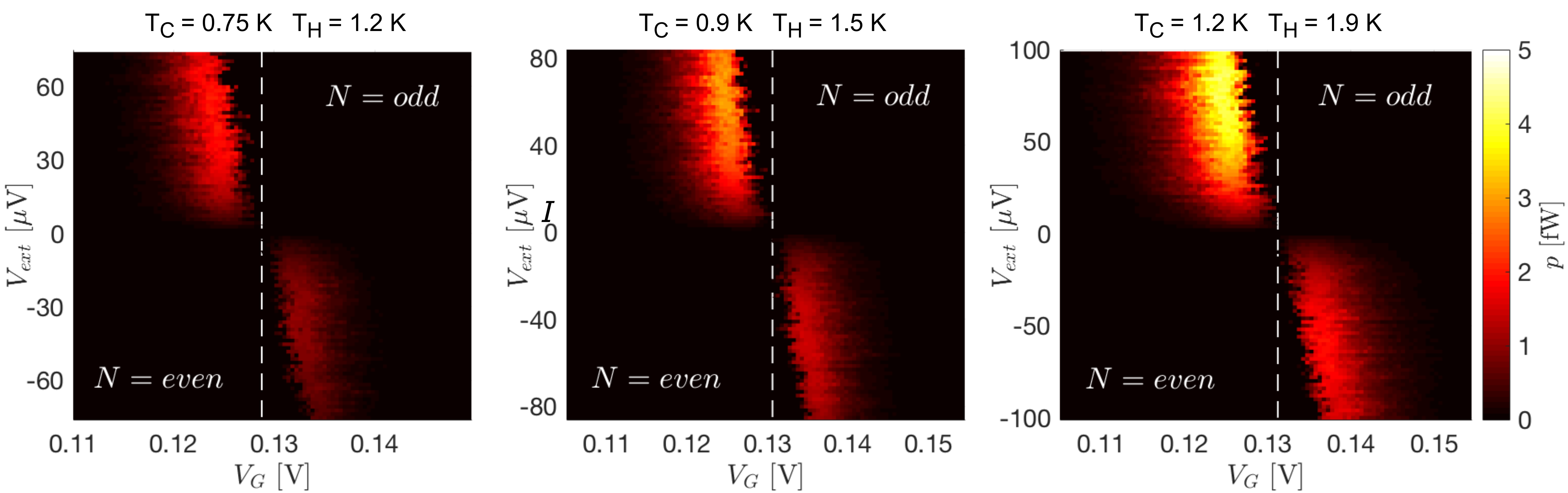




Two modes of operation:

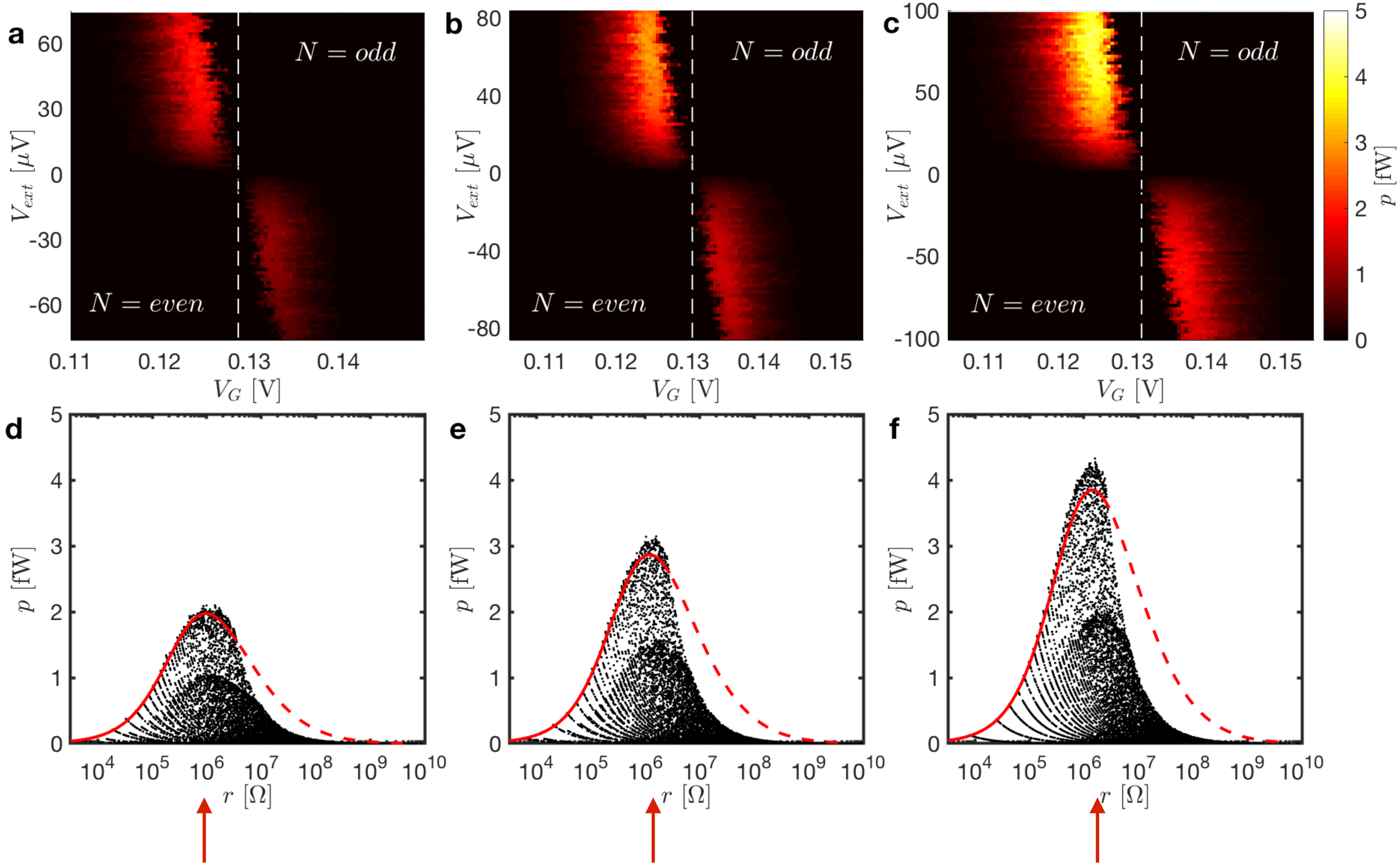
$P > 0$ generator

$P < 0$ refrigerator



Load Matching 2

Find optimal load from *P* vs *I/V$_{ext}$*



Efficiency

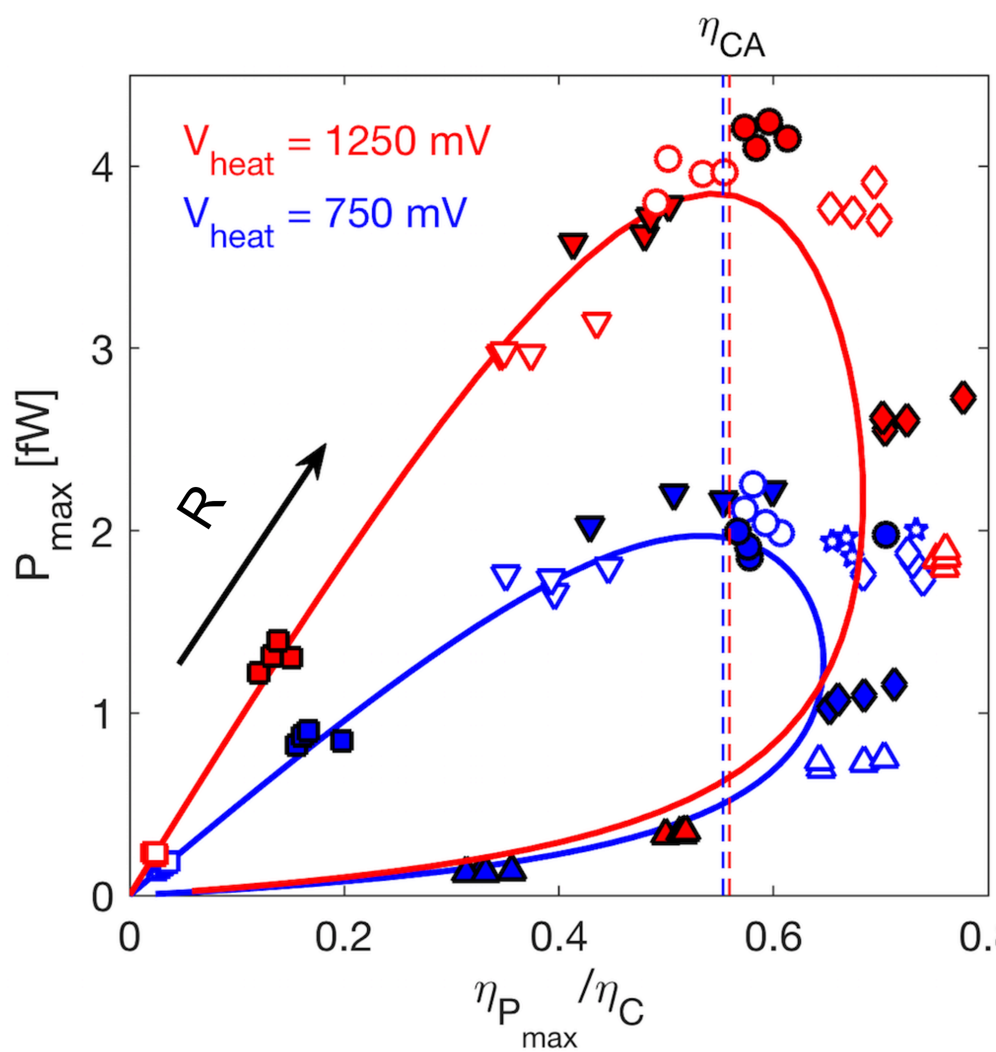
Efficiency

Our device

Focus on V_G optimized for P

Curzon-Ahlborn efficiency η_{CA} at maximum *P*

$\eta \sim 0.7\eta_C$ at P=50% of max P



First high efficiency estimates in a real device!

$$\eta = \frac{P}{J_Q}$$

Measured

Calculated

Nat. Nano. **13**, 920 (2018)

Efficiency - second order

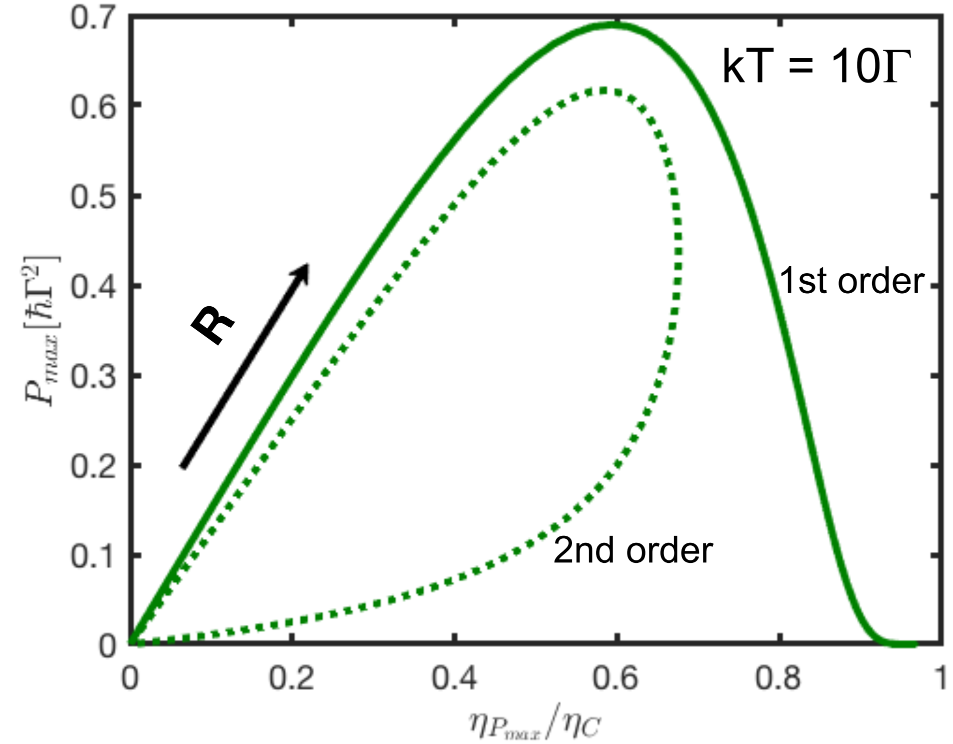
General anderson QDs

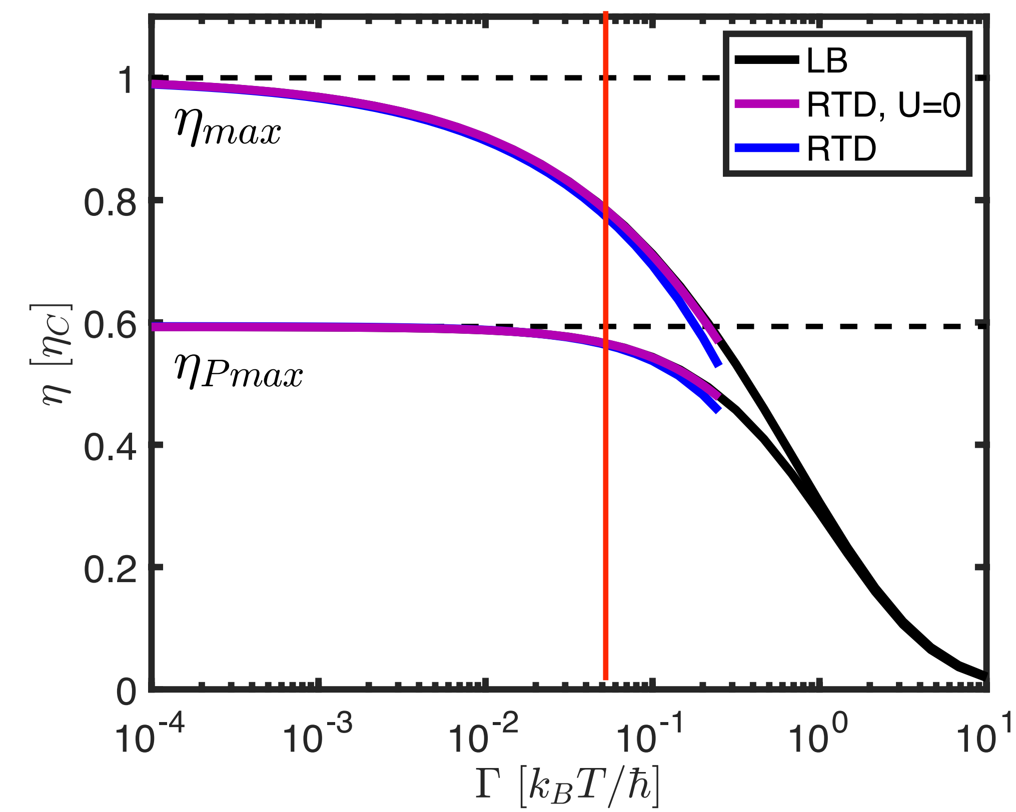
Second order effects - broadening

Max η for our device 70-80% of η_C

η at max P less sensitive

Second order effects important!



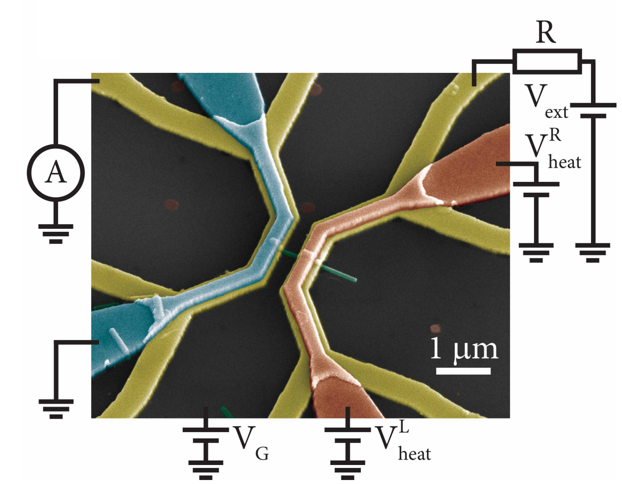


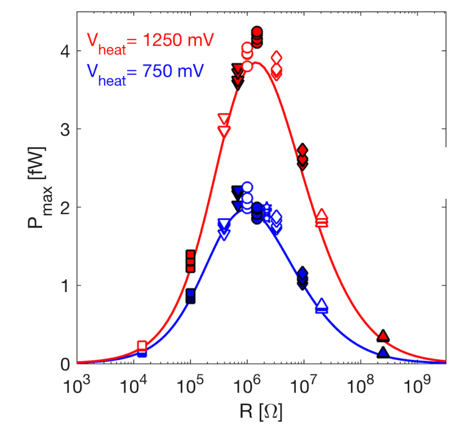
arXiv:1903.12618

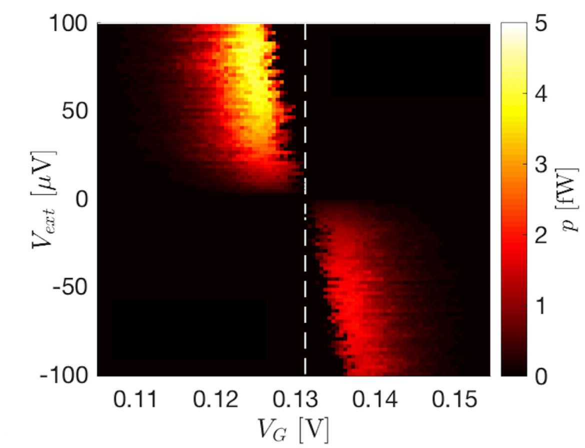
Summary

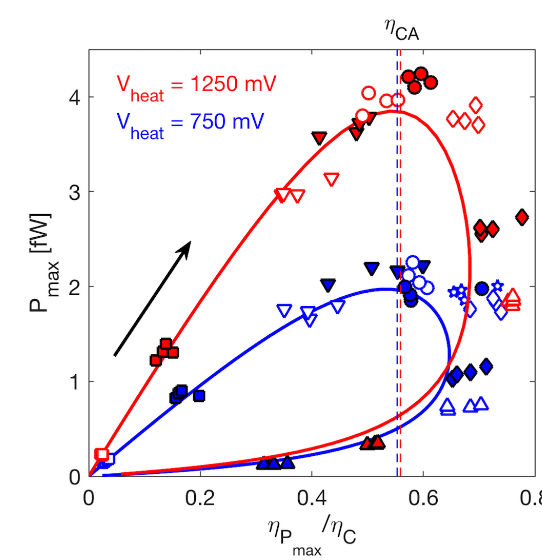
NANOLUND
AT THE FOREFRONT OF NANOSCIENCE
LUND UNIVERSITY

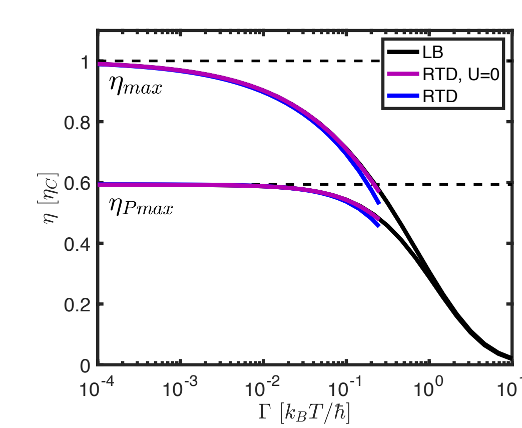
- Theory and experiments on a single QD heat engine
- Load matching - several options
- $\eta = \eta_{CA}$ when R is optimized for high power
- $\eta \sim 0.7\eta_C$ when R is optimized for high power
- Second order tunneling important for η











Nat. Nano. **13**, 920 (2018) & arXiv:1903.12618

LUND UNIVERSITY

NANOLUND

AT THE FOREFRONT OF NANOSCIENCE