nanosystems initiative munich

Paul-Drude-Institut
für Festkörperelektronik

Electron-Phonon Interaction in Nanoelectronic Circuits
toward the control of single phonons

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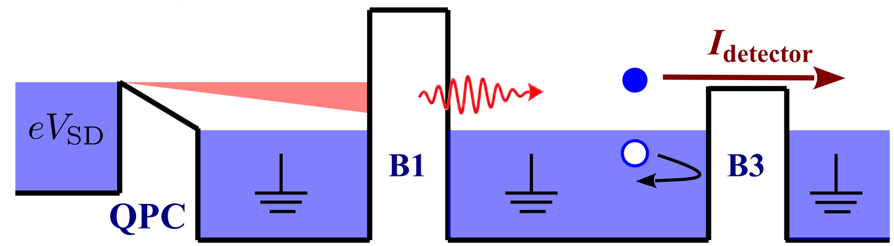
Deutsche Forschungsgemeinschaft

CeNS
Center for NanoScience | LMU

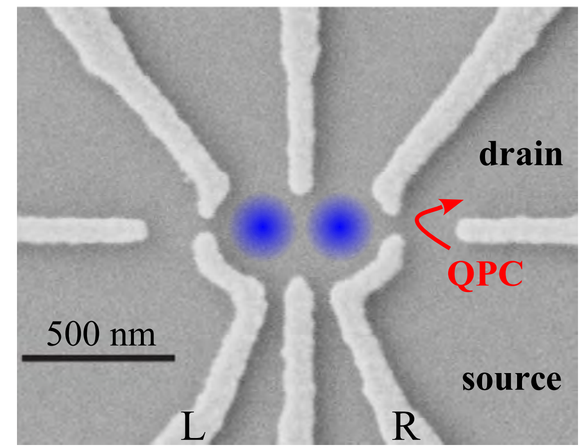
SFB 631

Phonon meets Electron

- electron-phonon interaction in 2D, one electron at a time...

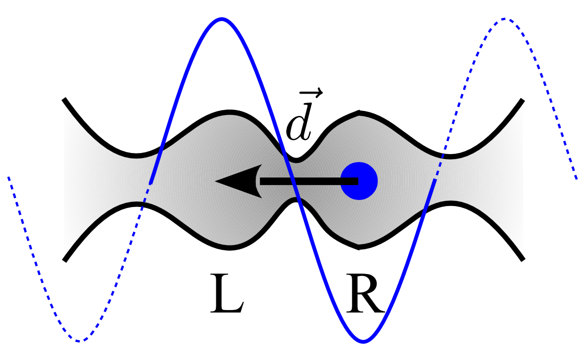


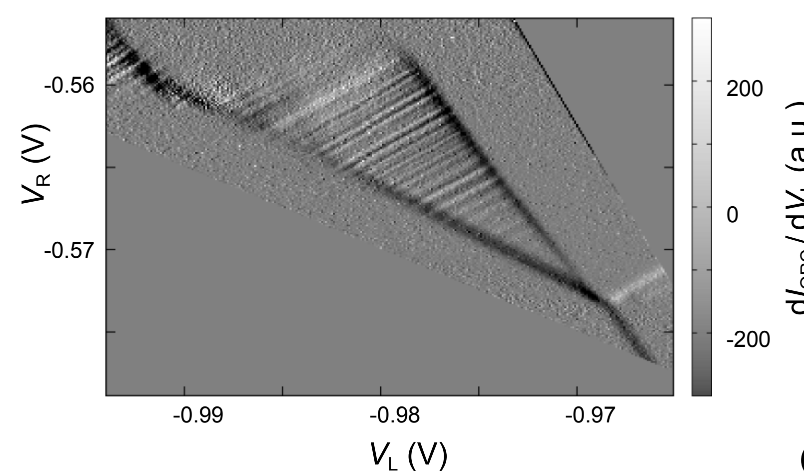
- influence of confinement in nanostructures



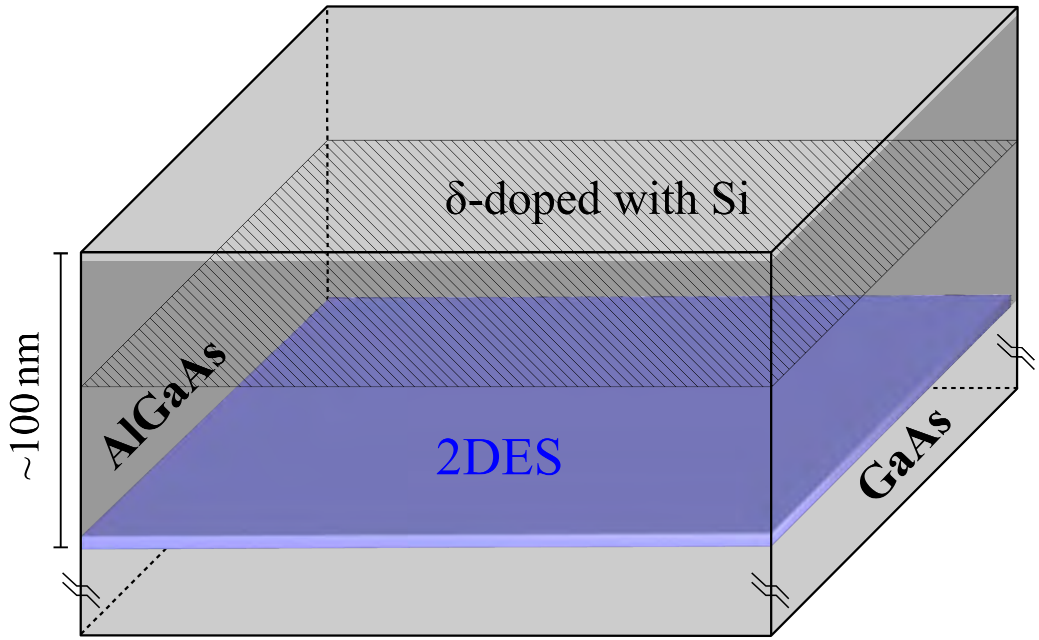
- coherent electron-phonon interaction

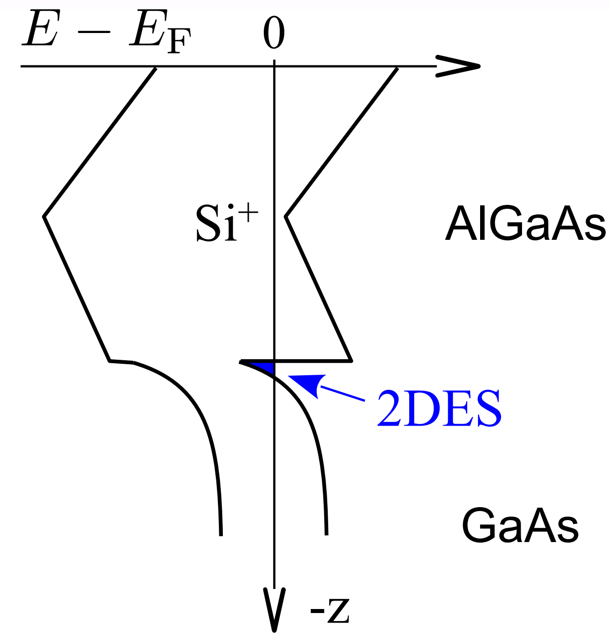
- control of single phonons ?



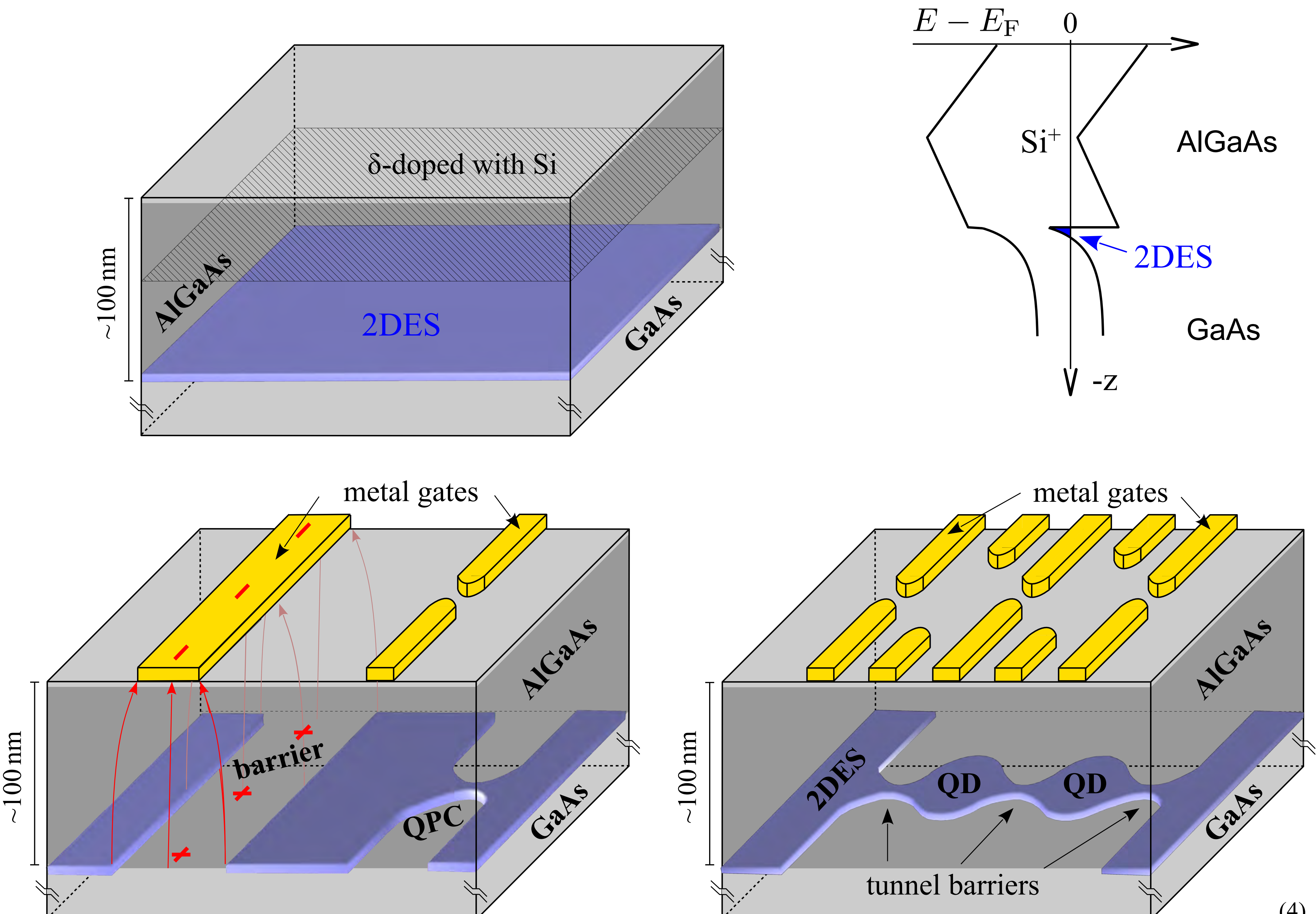


introduction – samples

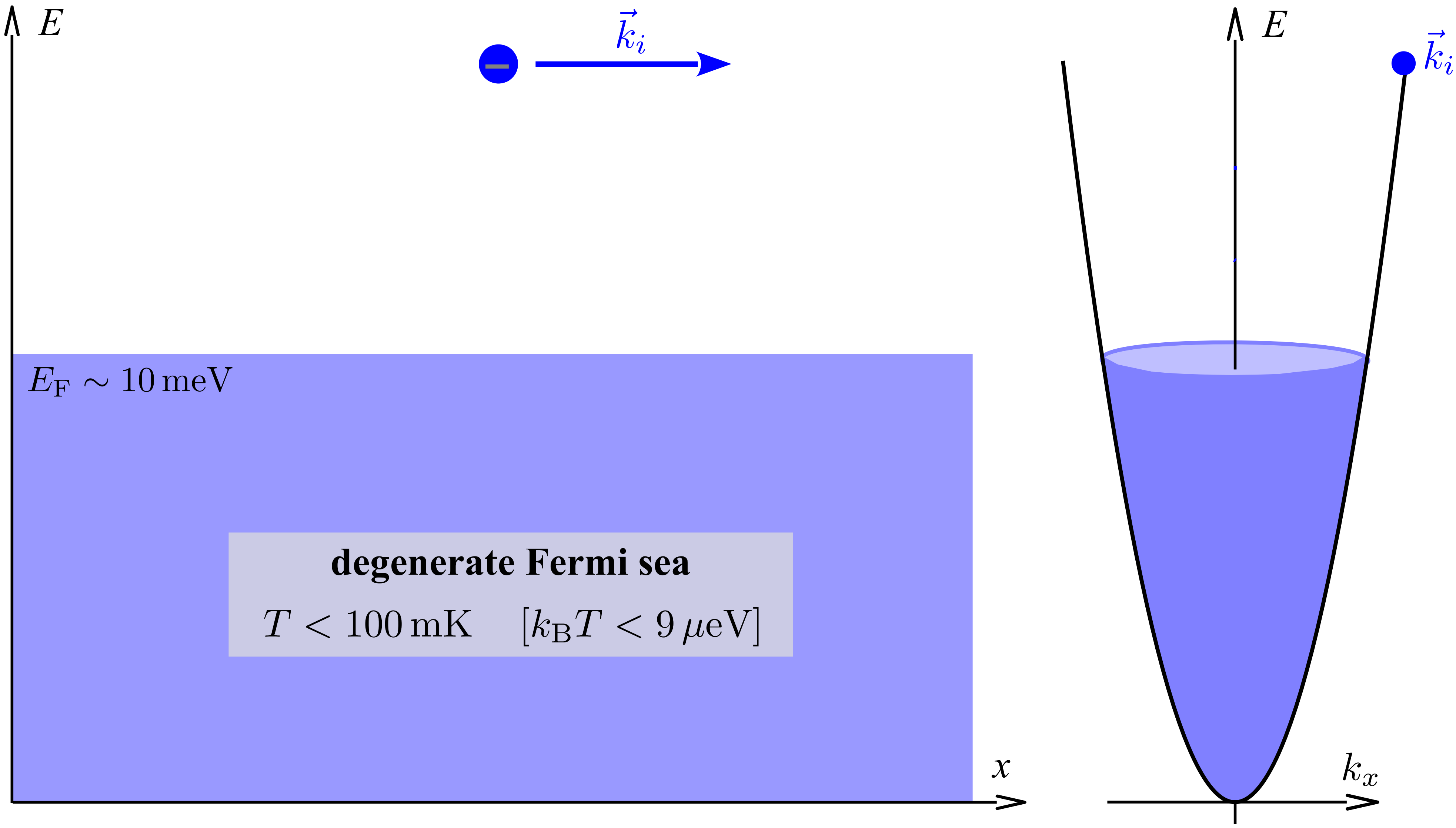




Werner Wegscheider
wafers
@ ETH Zürich

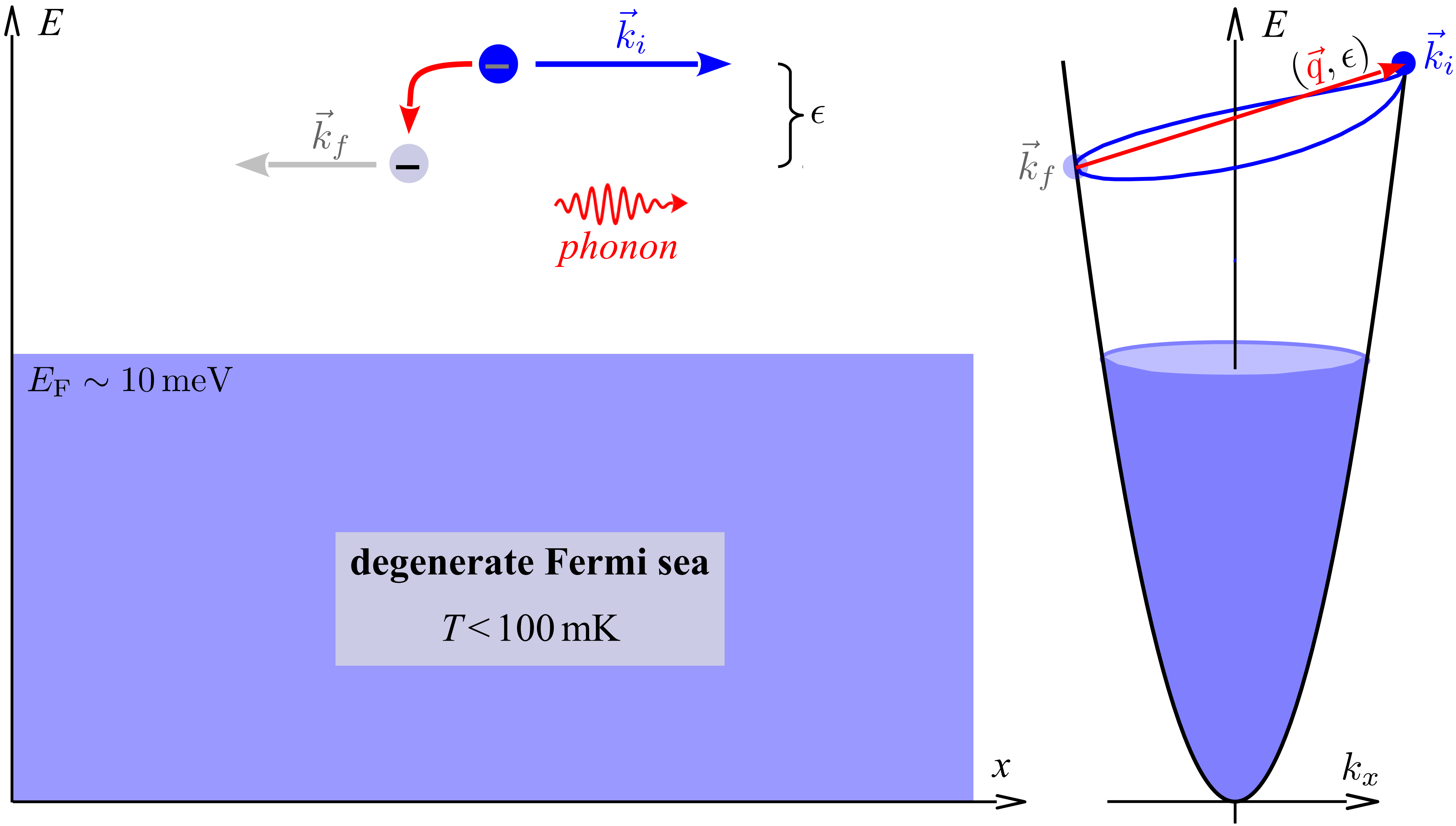

δ-doped with Si
AlGaAs
2DES
GaAs
~100 nm
$E - E_\mathrm{F}$
0
Si^+
AlGaAs
2DES
GaAs
-z
metal gates
barrier
QPC
AlGaAs
GaAs
~100 nm
metal gates
2DES
QD
QD
tunnel barriers
AlGaAs
GaAs
~100 nm

electron-phonon interaction in 2D; one electron at a time...



electron energy in real space

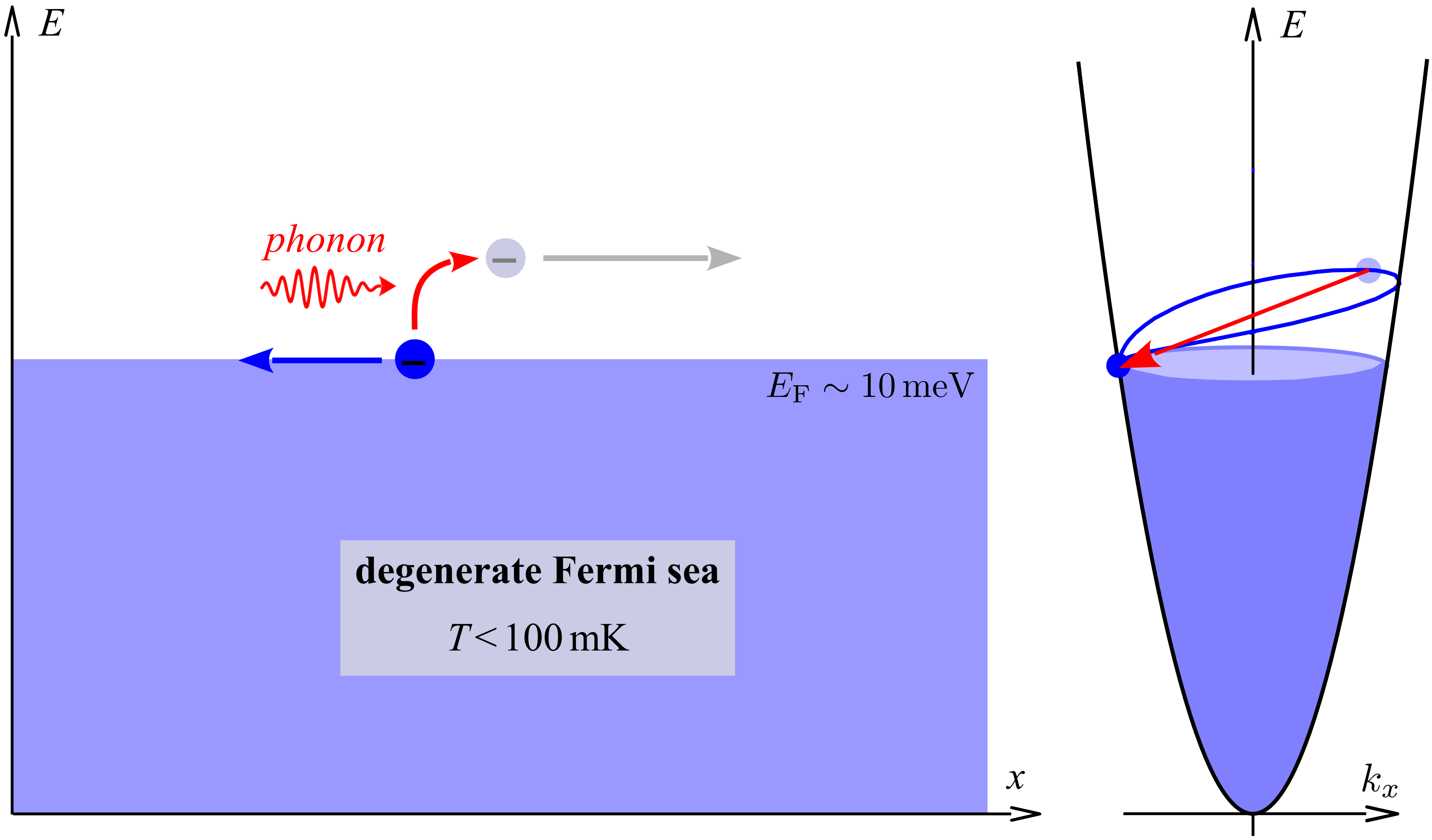
& in k-space



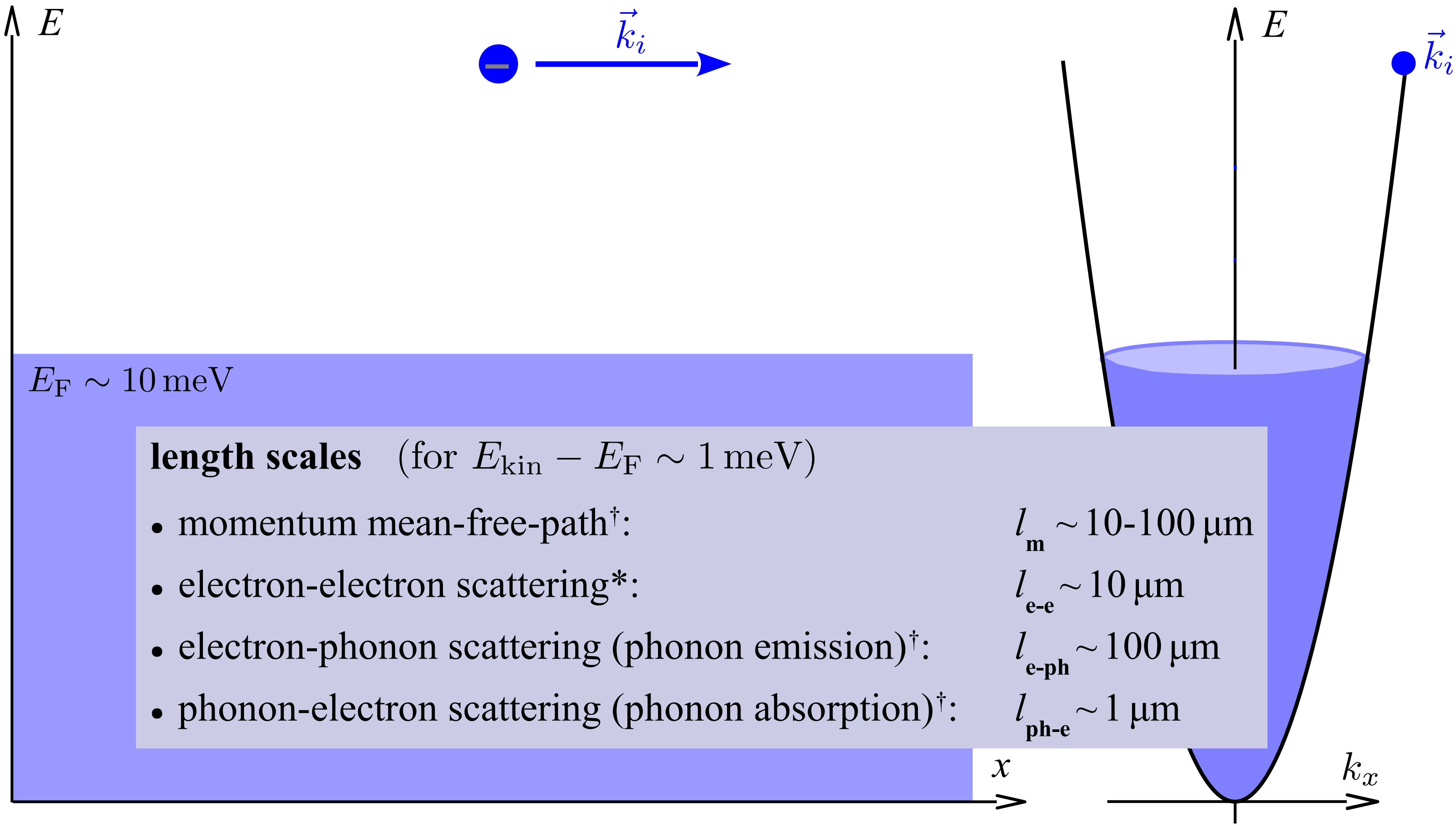
energy transfer: $\epsilon = \hbar^2/2m\left(\vec{k}_i^2 - \vec{k}_f^2\right)$

momentum transfer: $\vec{k}_f - \vec{k}_i = \vec{q}$

phonon dispersion: $\epsilon = \hbar|\vec{q}|v_{\mathrm{ph}}$



E
phonon
$E_{\mathrm{F}} \sim 10\,\mathrm{meV}$
degenerate Fermi sea
$T < 100\,\mathrm{mK}$
x
E
k_x



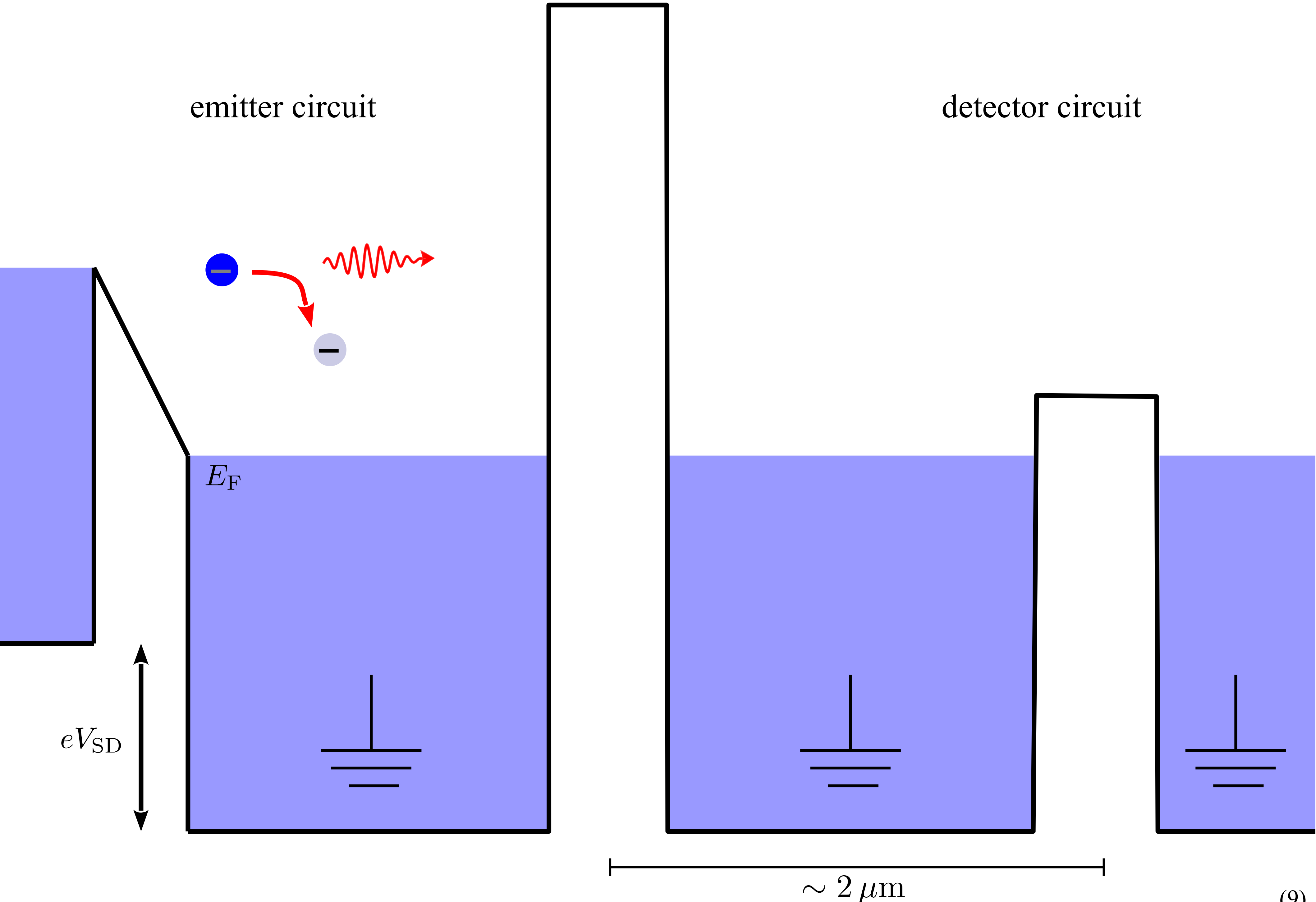
length scales $(\text{for } E_\mathrm{kin} - E_\mathrm{F} \sim 1\,\mathrm{meV})$

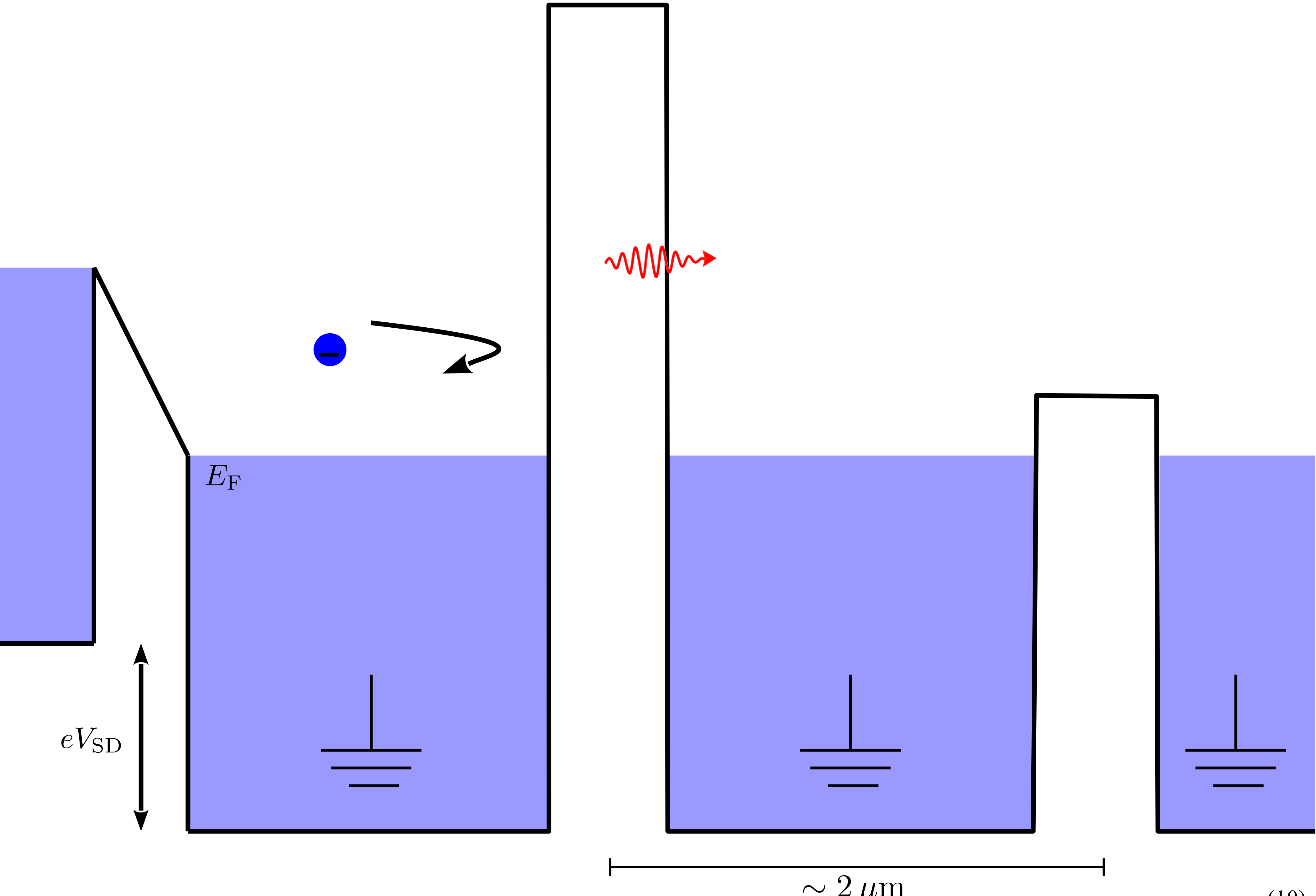
- momentum mean-free-path†: $l_\mathbf{m} \sim 10\text{-}100\,\mu\mathrm{m}$
- electron-electron scattering*: $l_\mathbf{e\text{-}e} \sim 10\,\mu\mathrm{m}$
- electron-phonon scattering (phonon emission)†: $l_\mathbf{e\text{-}ph} \sim 100\,\mu\mathrm{m}$
- phonon-electron scattering (phonon absorption)†: $l_\mathbf{ph\text{-}e} \sim 1\,\mu\mathrm{m}$

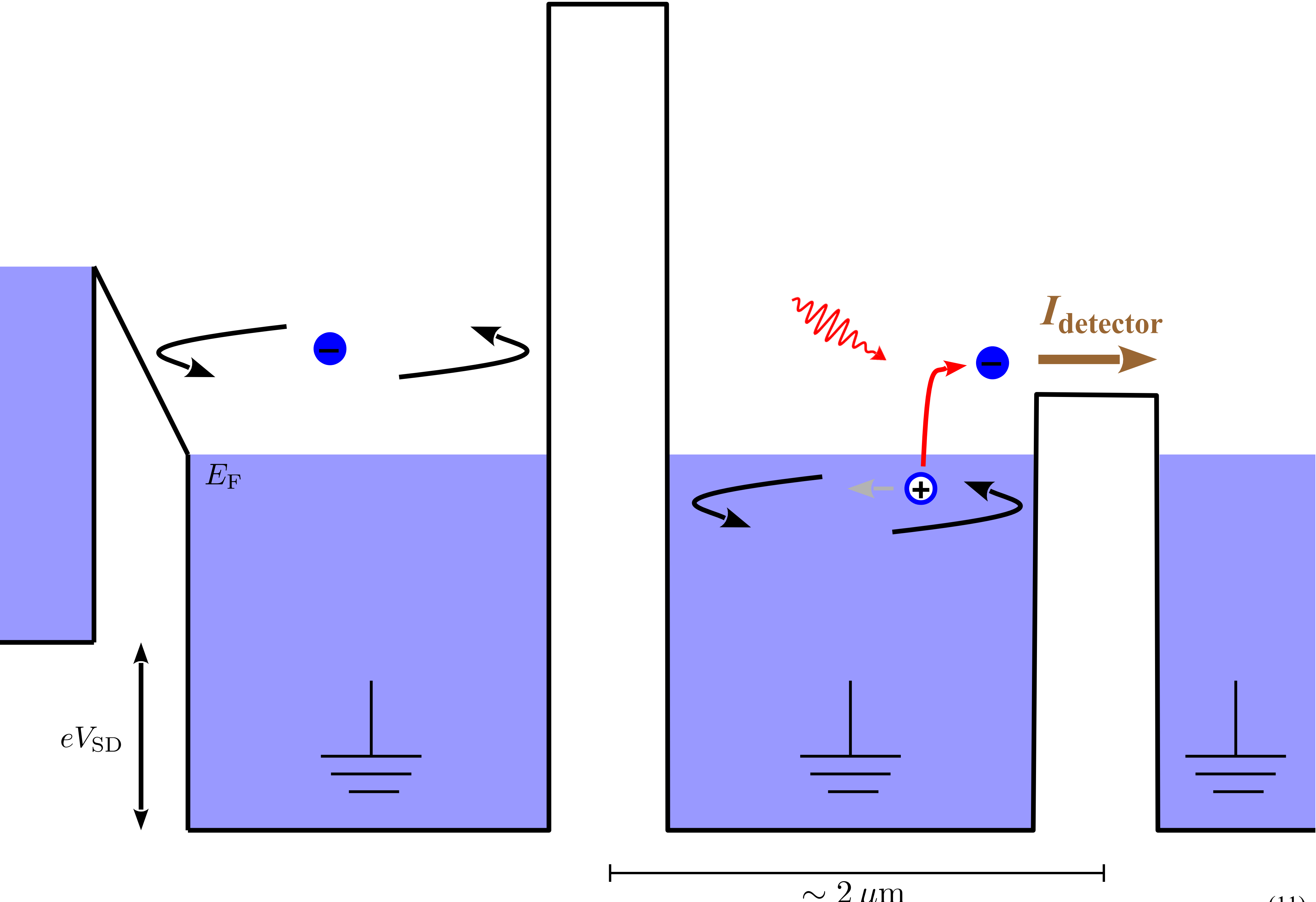
* *D. Taubert et al.: Phys. Rev. B* ***82****, 161416(R) (2010)*
Phys. Rev. B ***83****, 235404 (2011)*
J. Appl. Phys. ***109****, 102412 (2011)*

† *Schinner et al.:*
Phys. Rev. Lett. ***102****, 186801 (2009)*

design of an electron-phonon scattering (in 2D) experiment



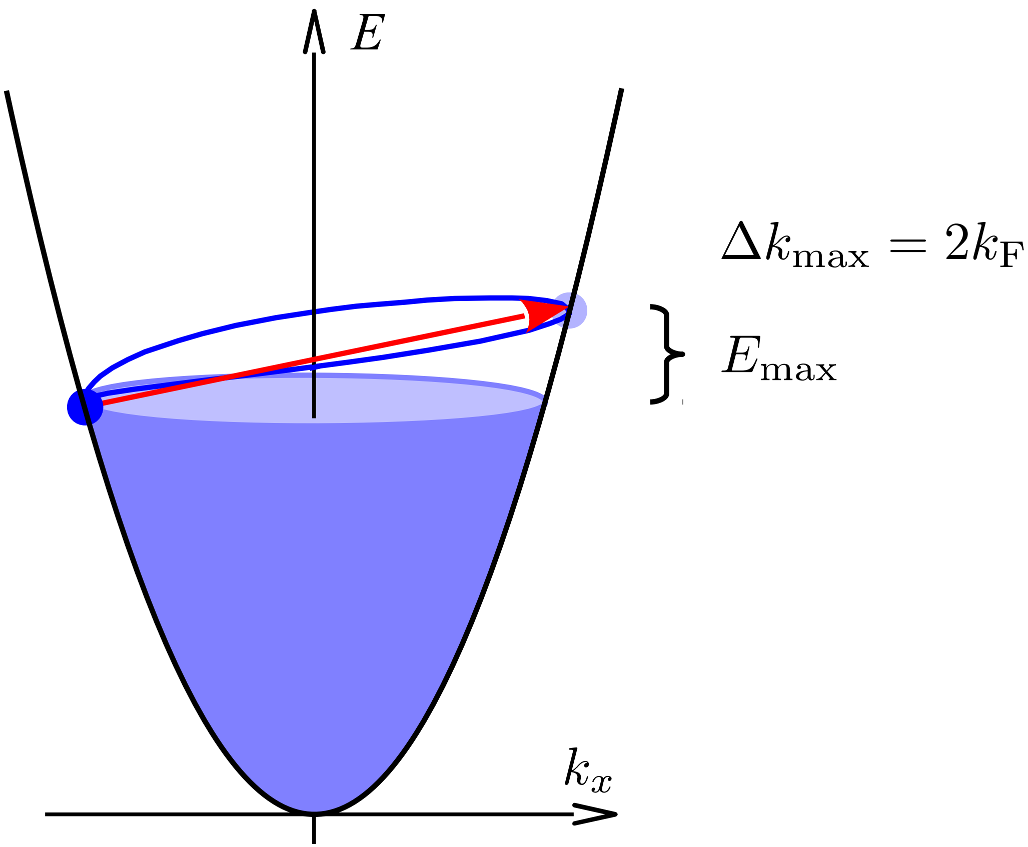

E_{F}
eV_{SD}
$\sim 2\,\mu\mathrm{m}$

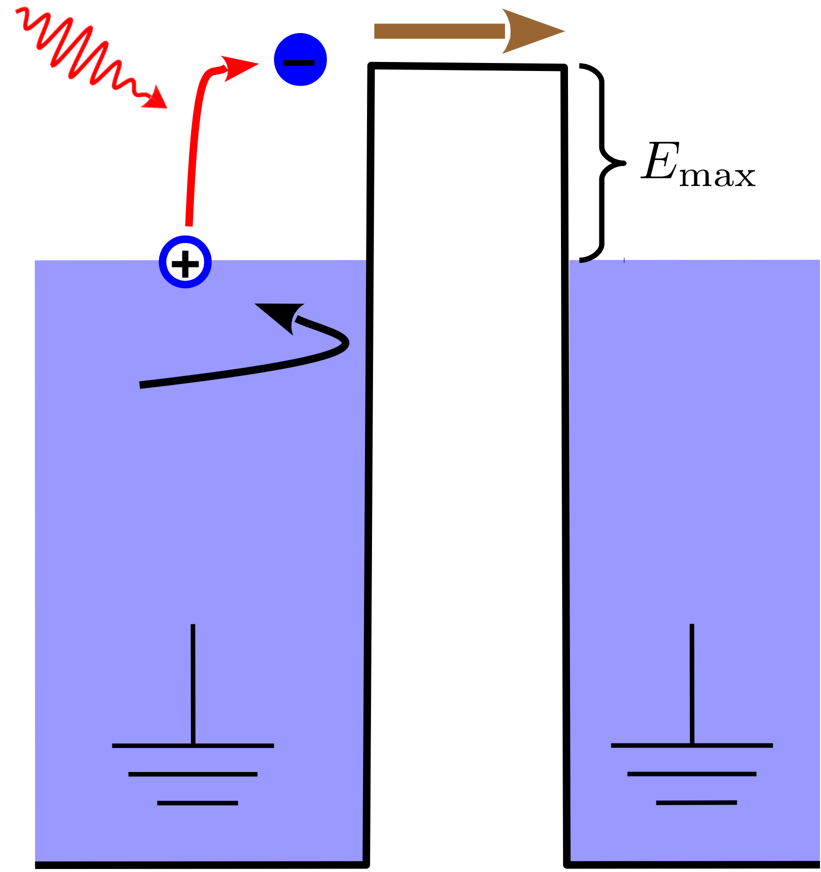


I_{detector}
E_{F}
eV_{SD}
$\sim 2\,\mu\mathrm{m}$

electron back scattering → maximum momentum & energy transfer

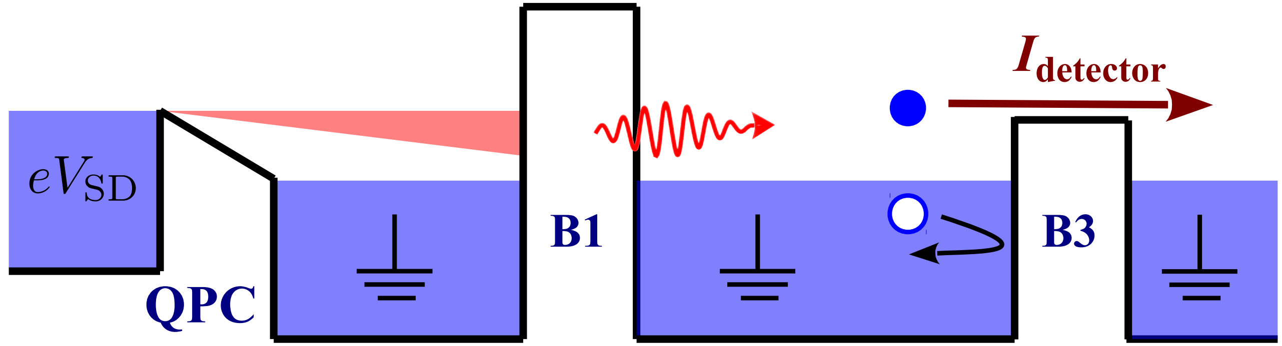
$$\boxed{E_{\mathrm{max}} \simeq \hbar 2 k_{\mathrm{F}} v_{\mathrm{s}}^{\mathrm{max}}}$$

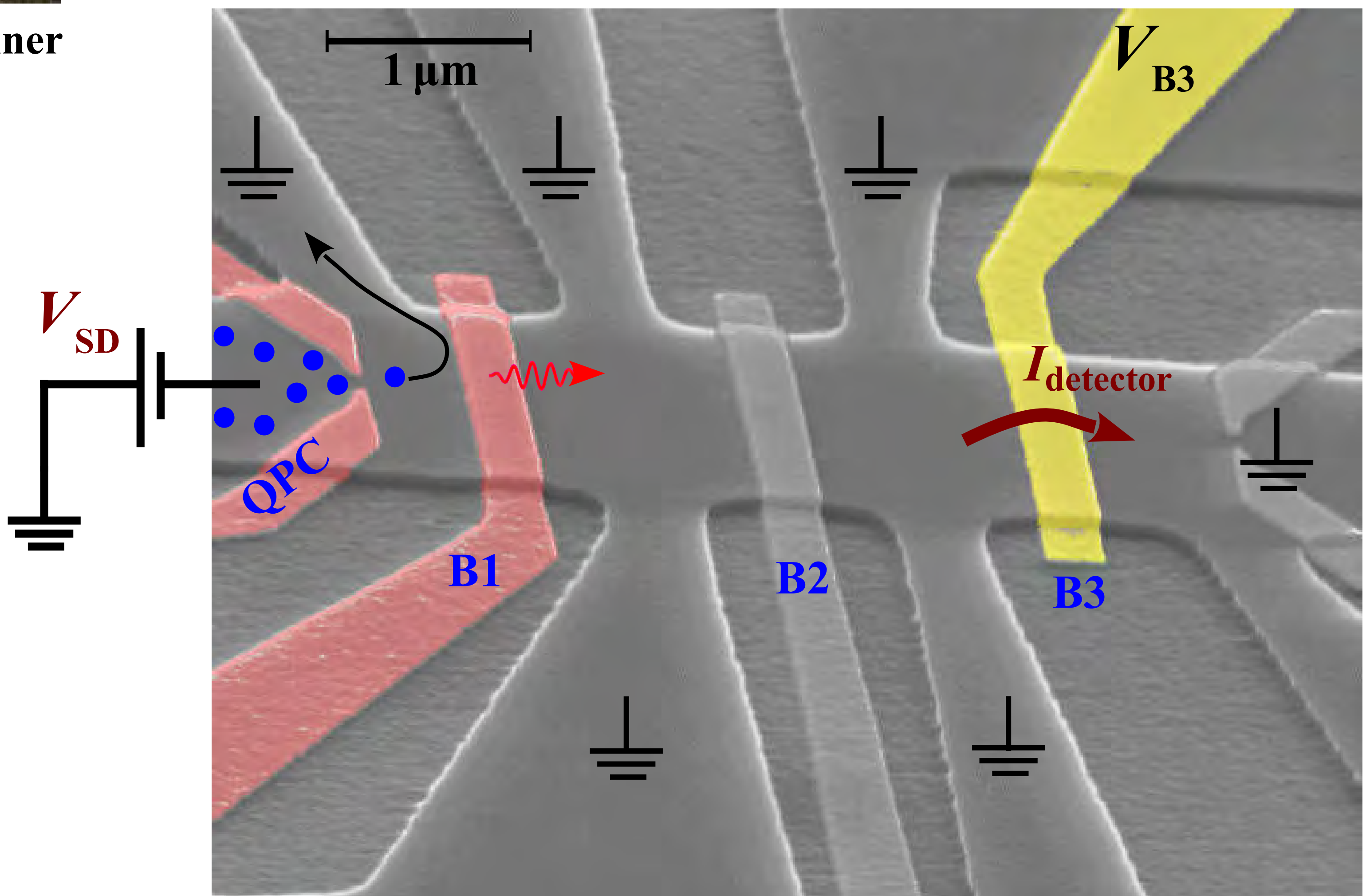




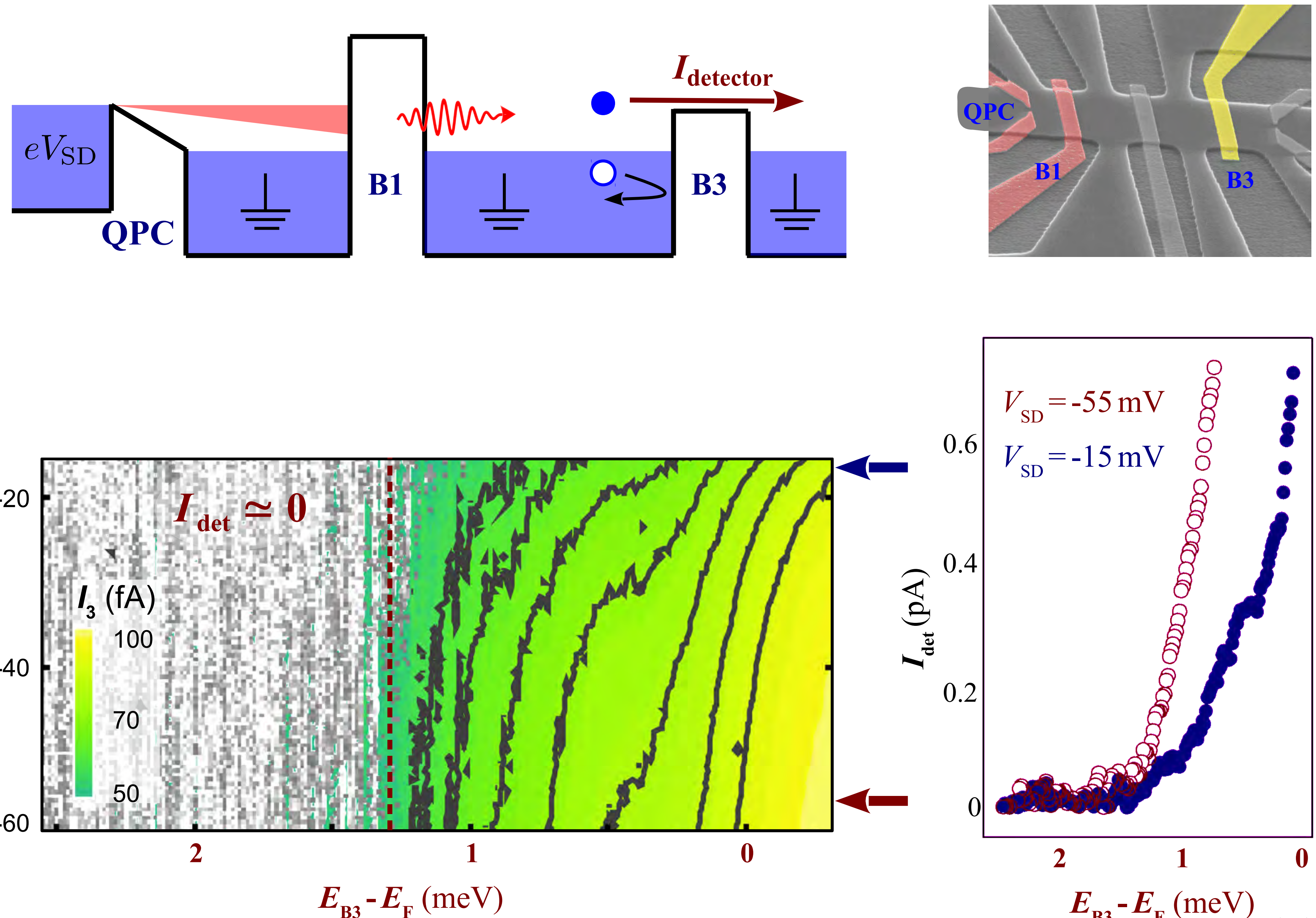
→ phonon mediated current only for detector barrier hight < E_{F}+E_{max}

Georg Schinner



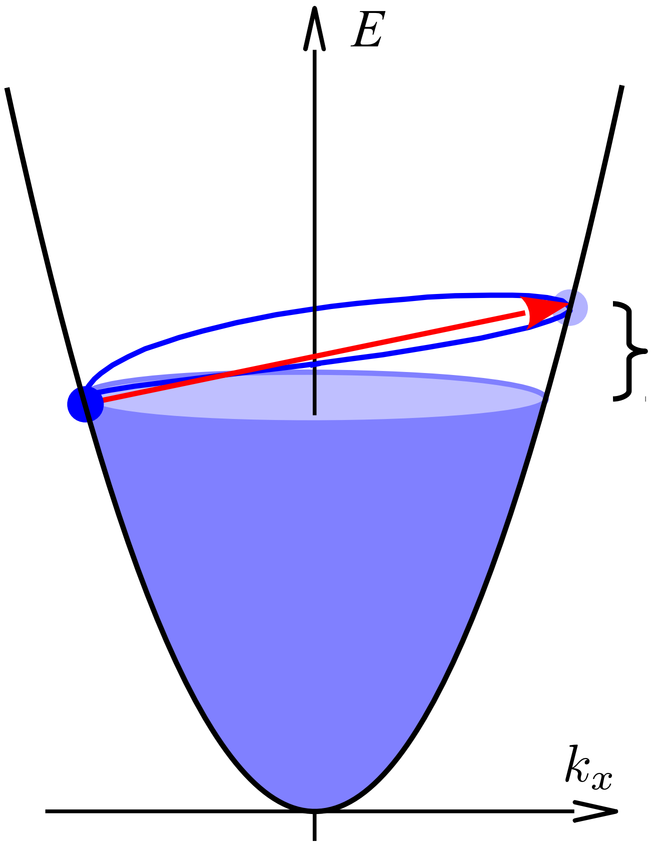


Schinner et al., Phys. Rev. Lett. ***102****, 186801 (2009)*



eV_SD
QPC
B1
I_detector
B3
QPC
B1
B3
I_det ≃ 0
I_3 (fA)
100
70
50
V_SD (mV)
-20
-40
-60
2
1
0
E_B3 - E_F (meV)
V_SD = -55 mV
V_SD = -15 mV
0.6
0.4
0.2
0
I_det (pA)
2
1
0
E_B3 - E_F (meV)

$$\boxed{E_{\mathrm{max}} \simeq \hbar 2 k_{\mathrm{F}} v_{\mathrm{s}}^{\mathrm{max}}}$$



$$\left.\begin{array}{l} \Delta k_{\mathrm{max}} = 2k_{\mathrm{F}} \\ E_{\mathrm{max}} \simeq 1.3\,\mathrm{meV} \end{array}\right\} \Rightarrow \quad v_{\mathrm{s}}^{\mathrm{max}} \simeq 6000\,\frac{\mathrm{m}}{\mathrm{s}}$$

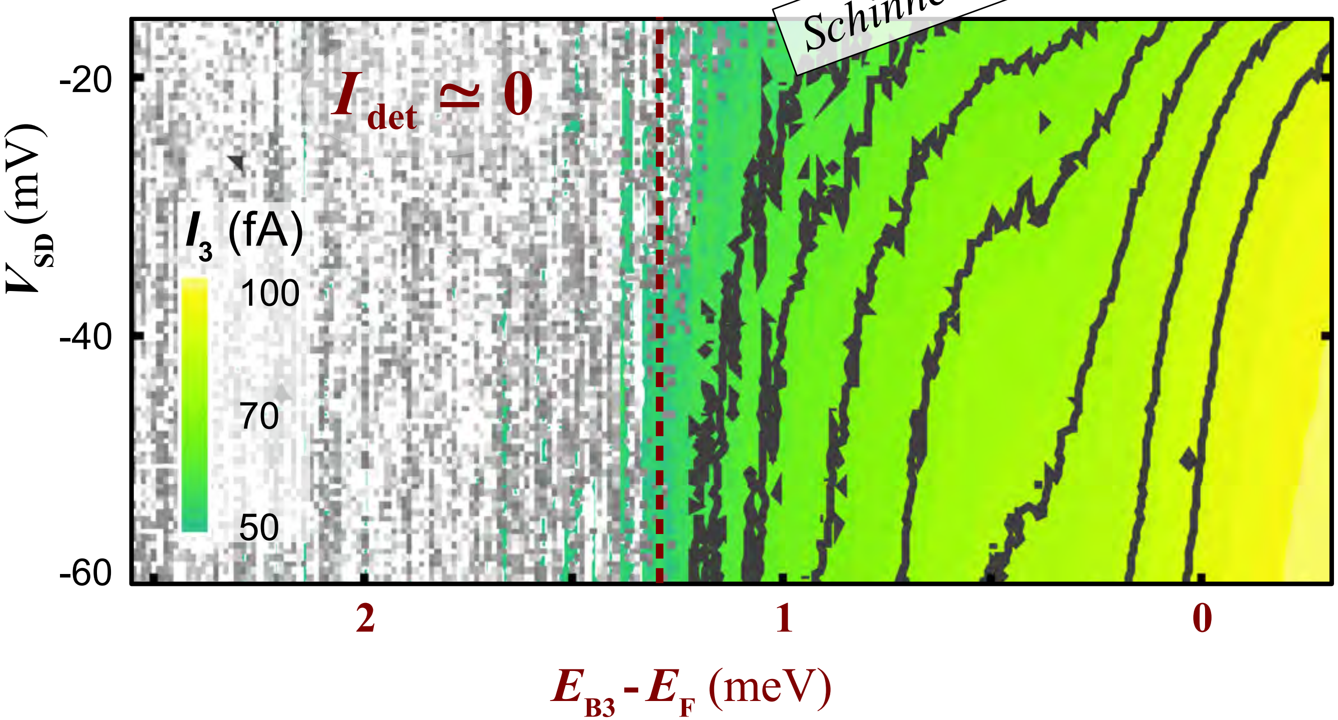
vertical onset of detector current ↔ upper bound of … momentum

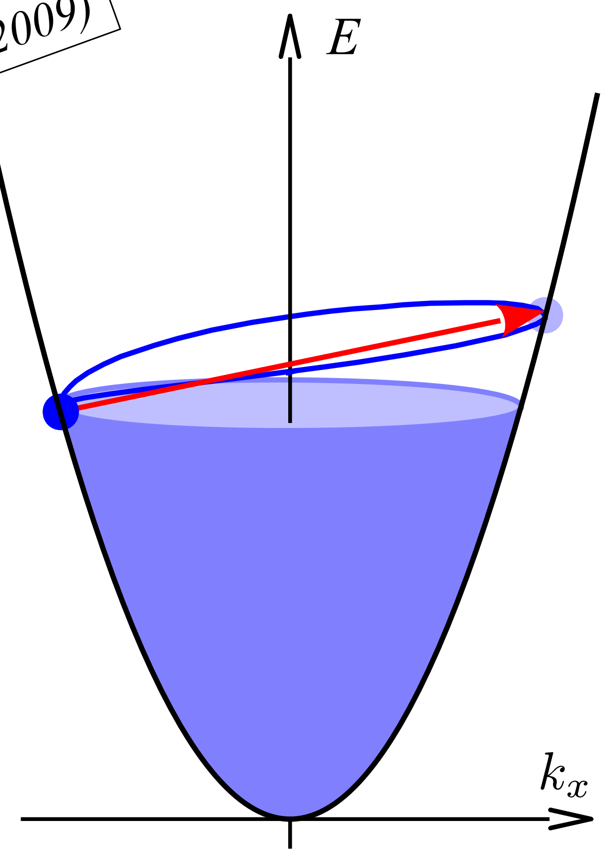
corresponds to electrons back… …n

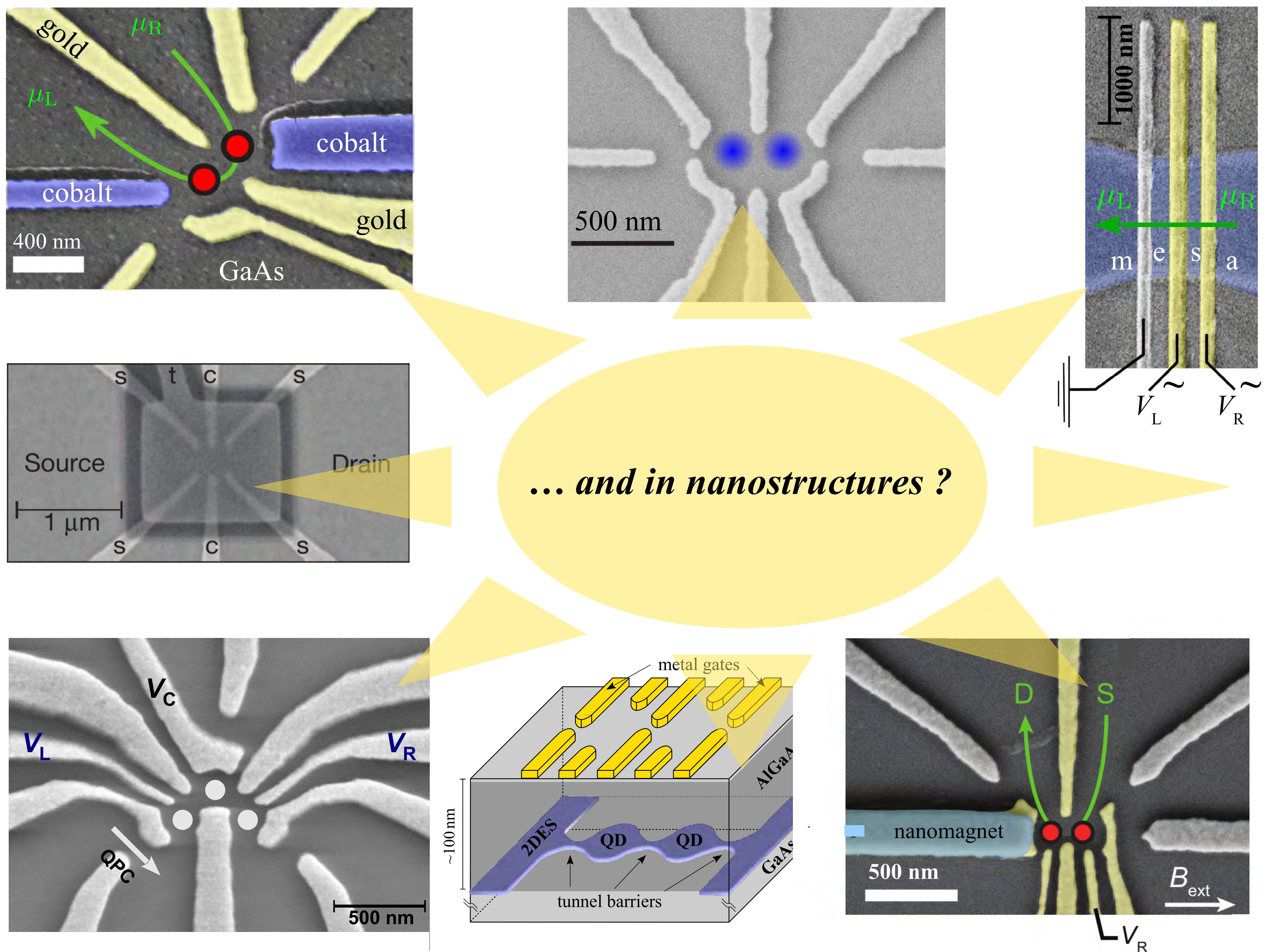
$\ldots = 6000 \, \frac{\mathrm{m}}{\mathrm{s}}$

electron-phonon interaction matters in driven mesoscopic circuits

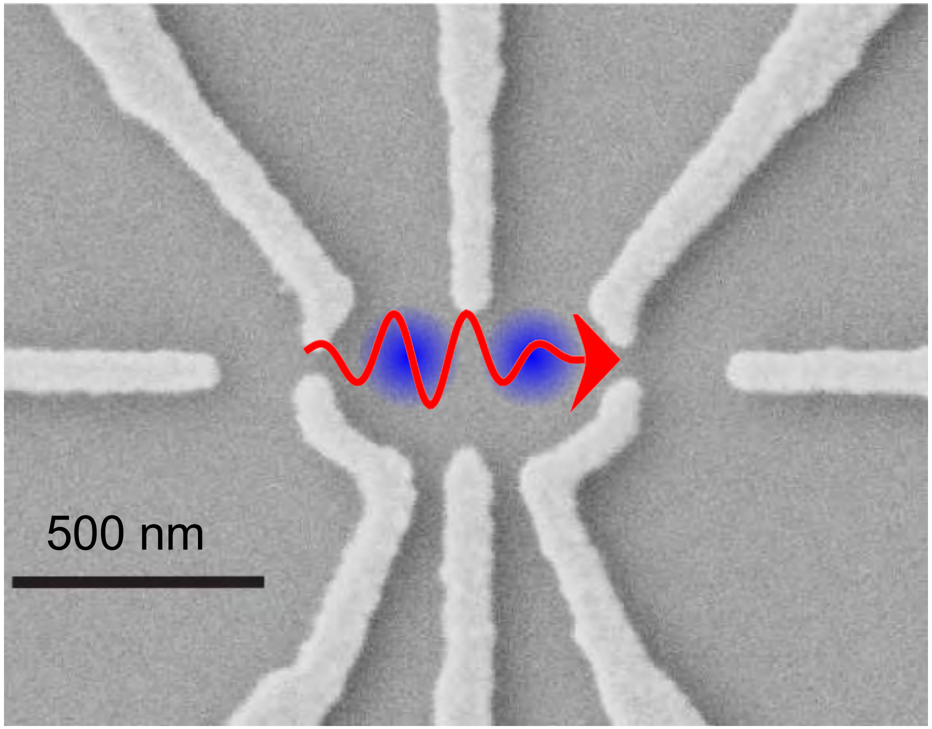
Schinner et al., PRL **102**, 186801 (2009)







gold
μ_R
μ_L
cobalt
cobalt
gold
400 nm
GaAs
500 nm
1000 nm
μ_L
μ_R
m e s a
V_L
V_R
s t c s
Source
Drain
1 μm
s c s
... and in nanostructures ?
V_C
V_L
V_R
QPC
500 nm
metal gates
2DES
QD
QD
~100 nm
tunnel barriers
D
S
nanomagnet
500 nm
B_{ext}
V_R

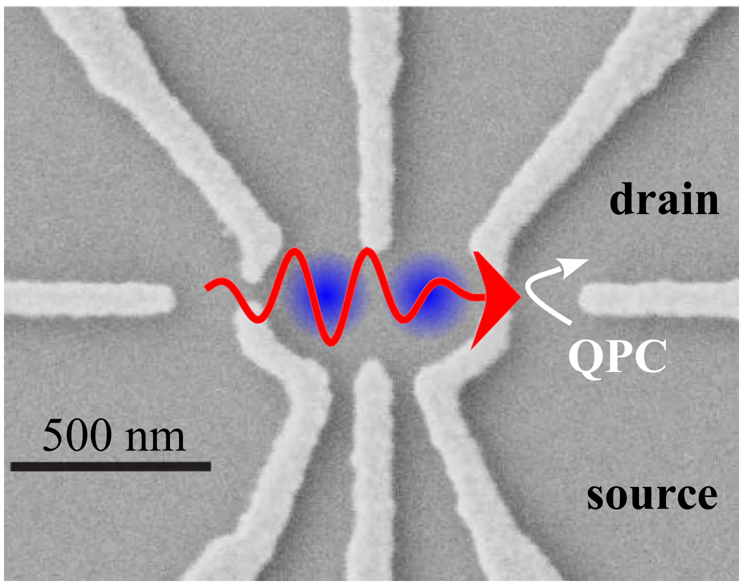


how is the electron-phonon interaction affected, if the phonon wavelength is comparable to the structure size ?

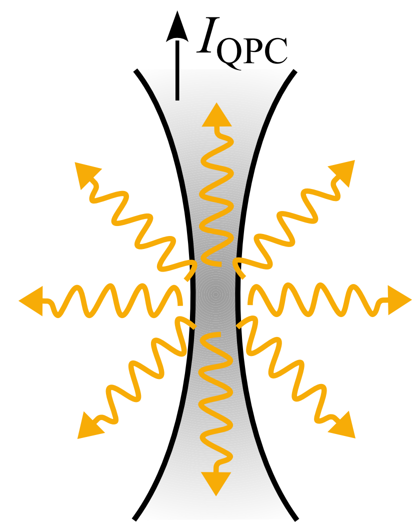
phonon energies: 50 μeV – 1 meV ⟷ phonon wavelength: 20 nm – 500 nm

electron confinement

… enhances overlap of electron and phonon wavefunctions

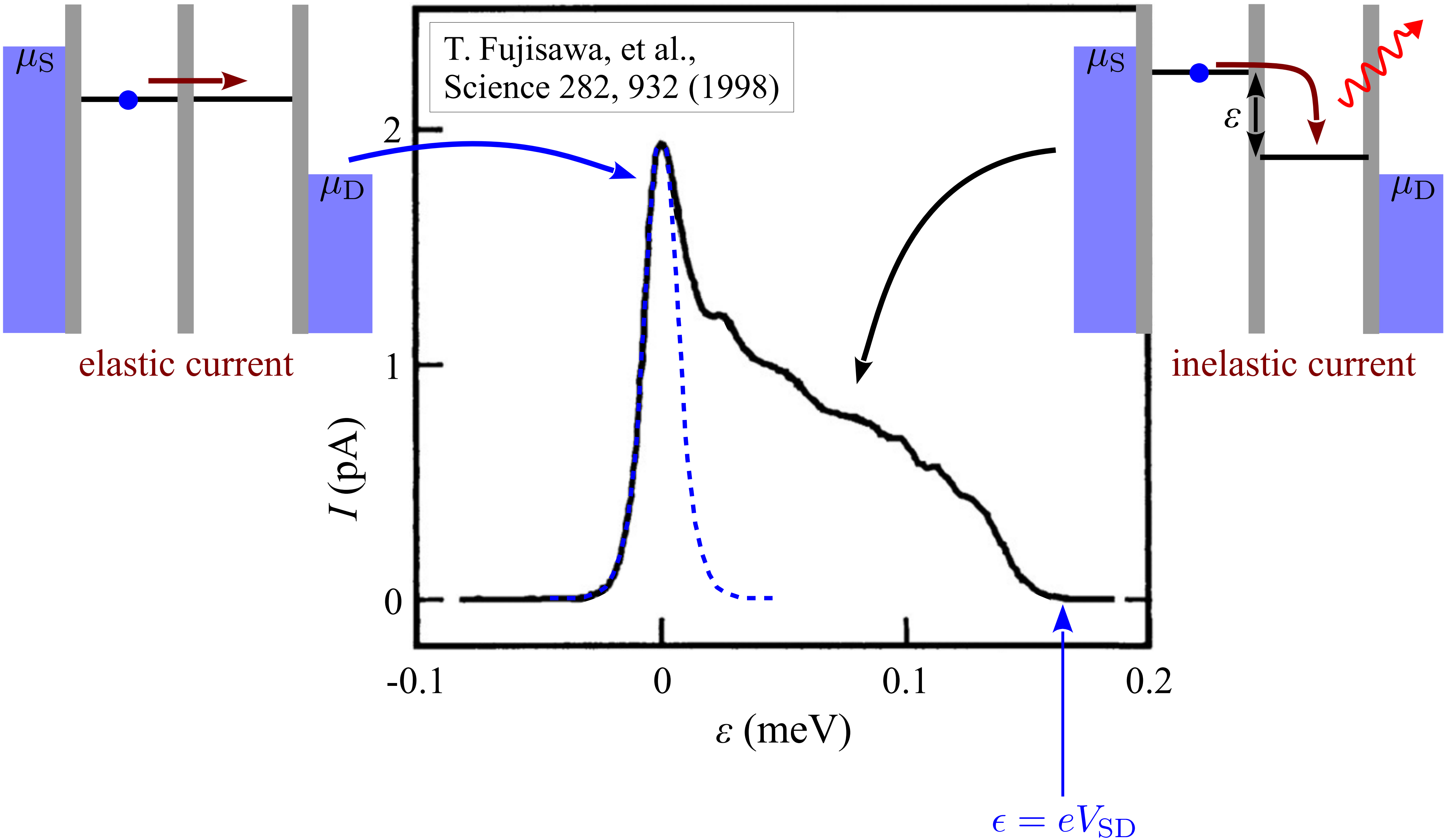


… relaxes momentum conservation law $\Delta k \sim \dfrac{2\pi}{\Delta x}$



(1) enhanced electron-phonon interaction
(2) relative phase between electron and phonon wave functions matters

phonon emission in a double quantum dot (DQD)



phonon dispersion: $\epsilon = \hbar|\vec{q}|v_{\mathrm{ph}}$

Interaction with the environment

can change the

quantum mechanical phase

of a system

dephasing / decoherence

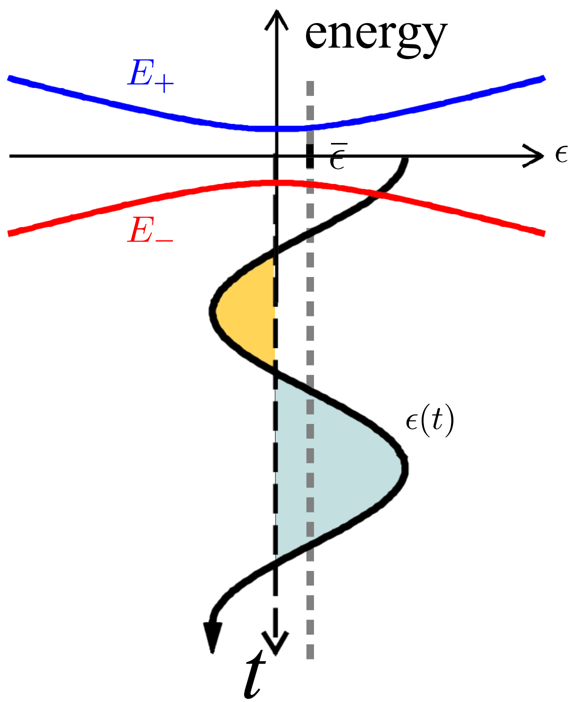
coherent dynamics

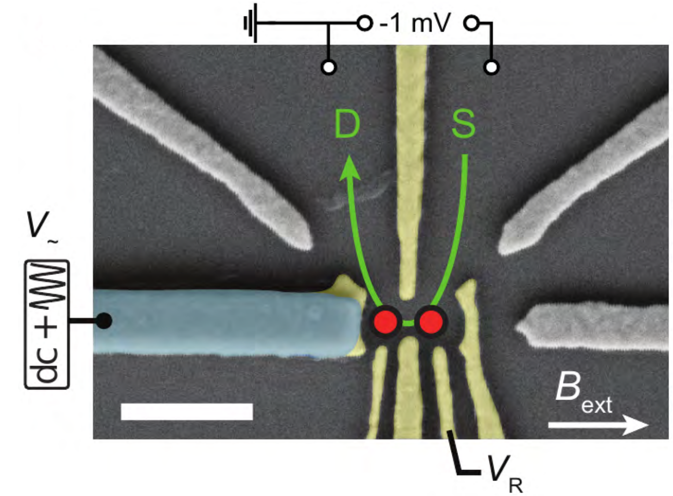
<u>early proposals related to coherent electron-phonon interaction in solids:</u>

A. Miller and **E. Abrahams**, Phys. Rev. 120, 745 (1960)
[*phonons induced electron hopping between impurities*]

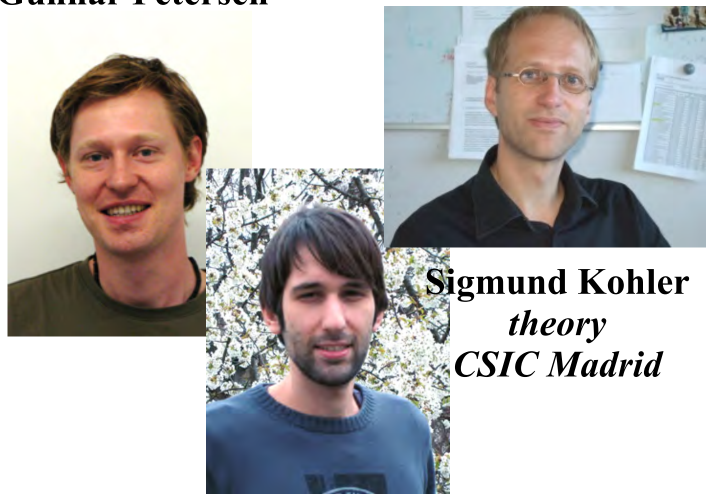
J. Imry, Tunneling in Solids, Chap. 36. Proc. 1967 NATO Advanced Study Institute. New York, Plenum: 563 (1969)
[*very general, tunneling involving defects in solids*]

determine electron-phonon coupling from decoherence





DQD charge qubit

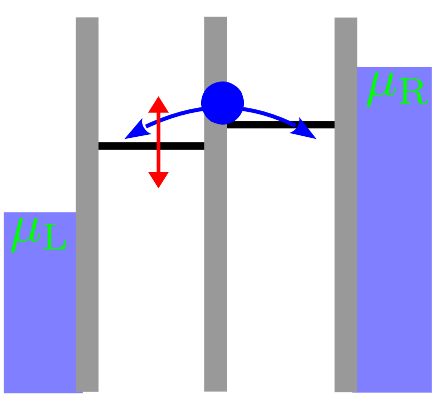


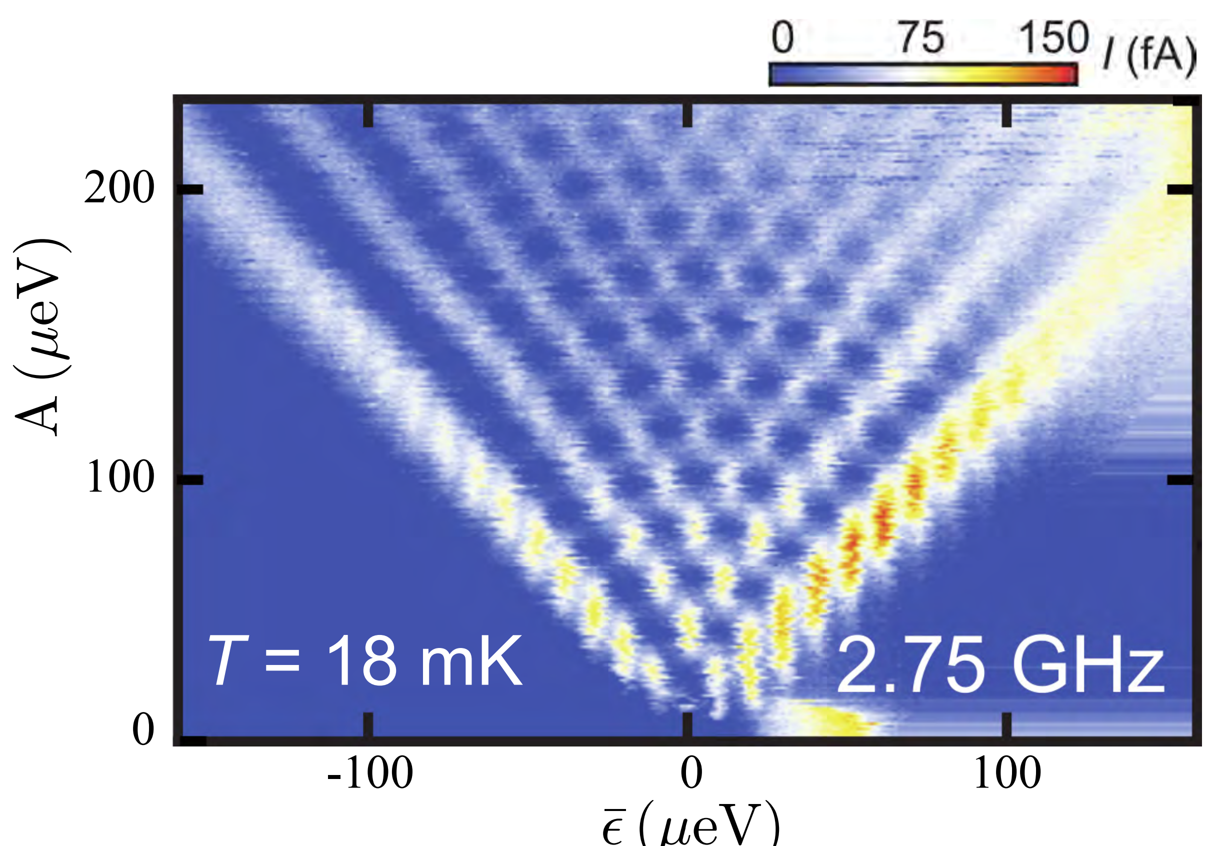
Gunnar Petersen

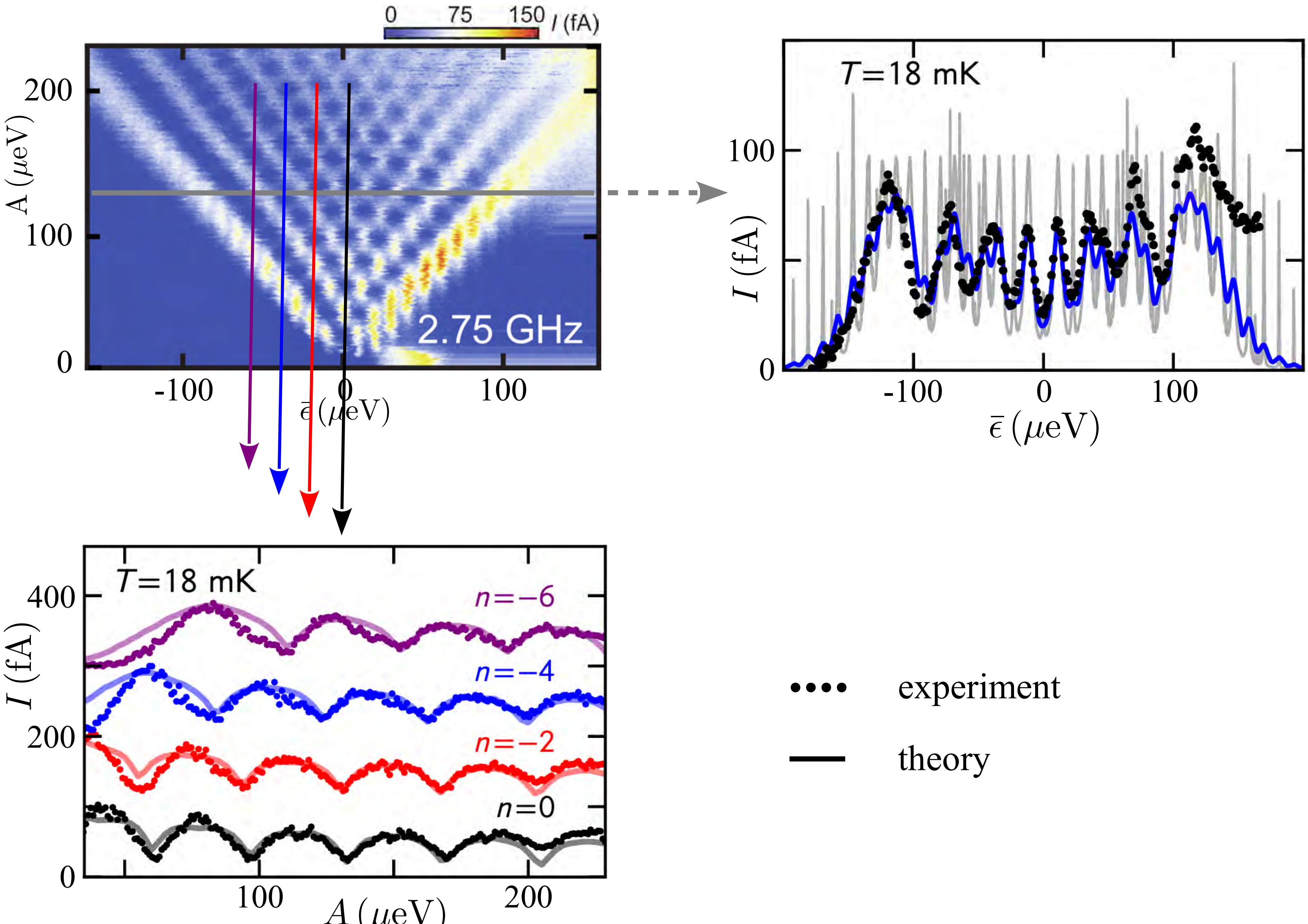
Florian Forster

Sigmund Kohler
theory
CSIC Madrid

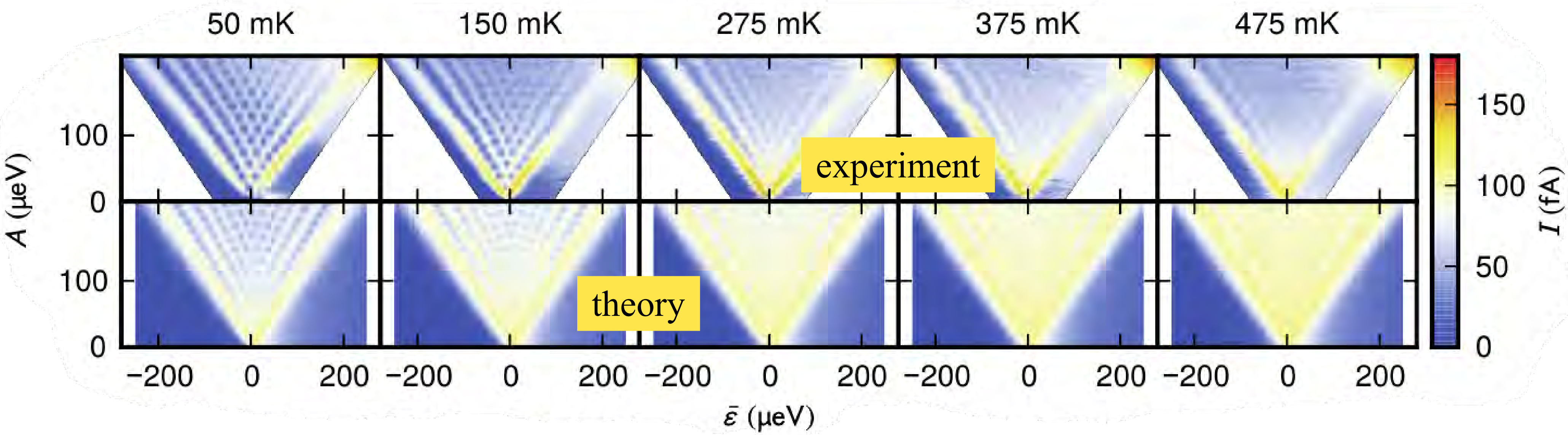
$$\epsilon = \bar{\epsilon} + A f(t)$$

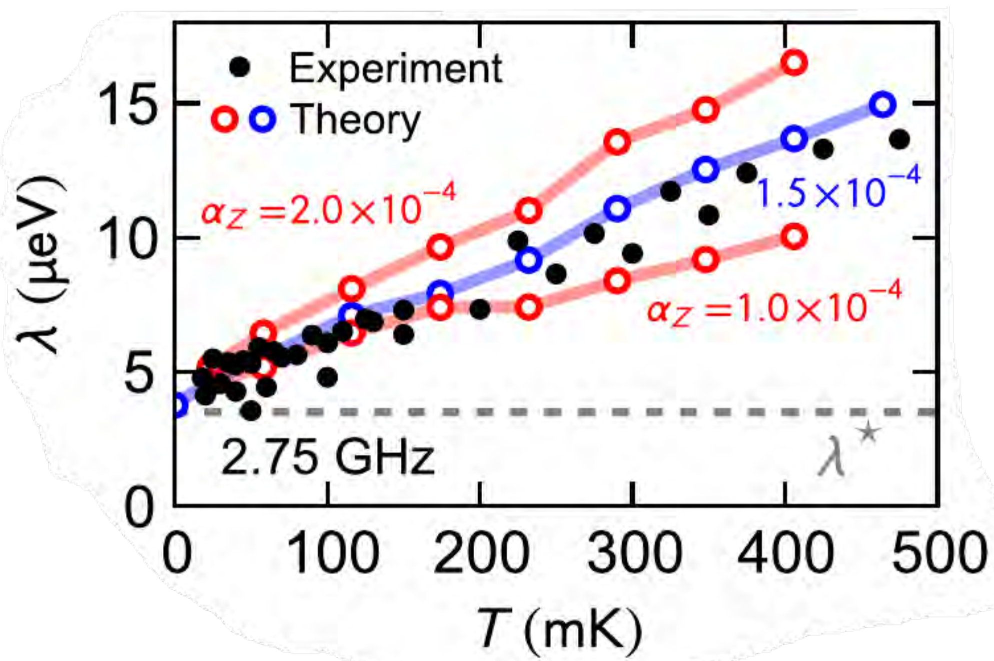






0
75
150
I (fA)
2.75 GHz
A (μeV)
200
100
0
-100
0
100
$\bar{\epsilon}$ (μeV)
T=18 mK
I (fA)
100
0
-100
0
100
$\bar{\epsilon}$ (μeV)
T=18 mK
n=−6
n=−4
n=−2
n=0
I (fA)
400
200
0
100
200
A (μeV)
experiment
theory





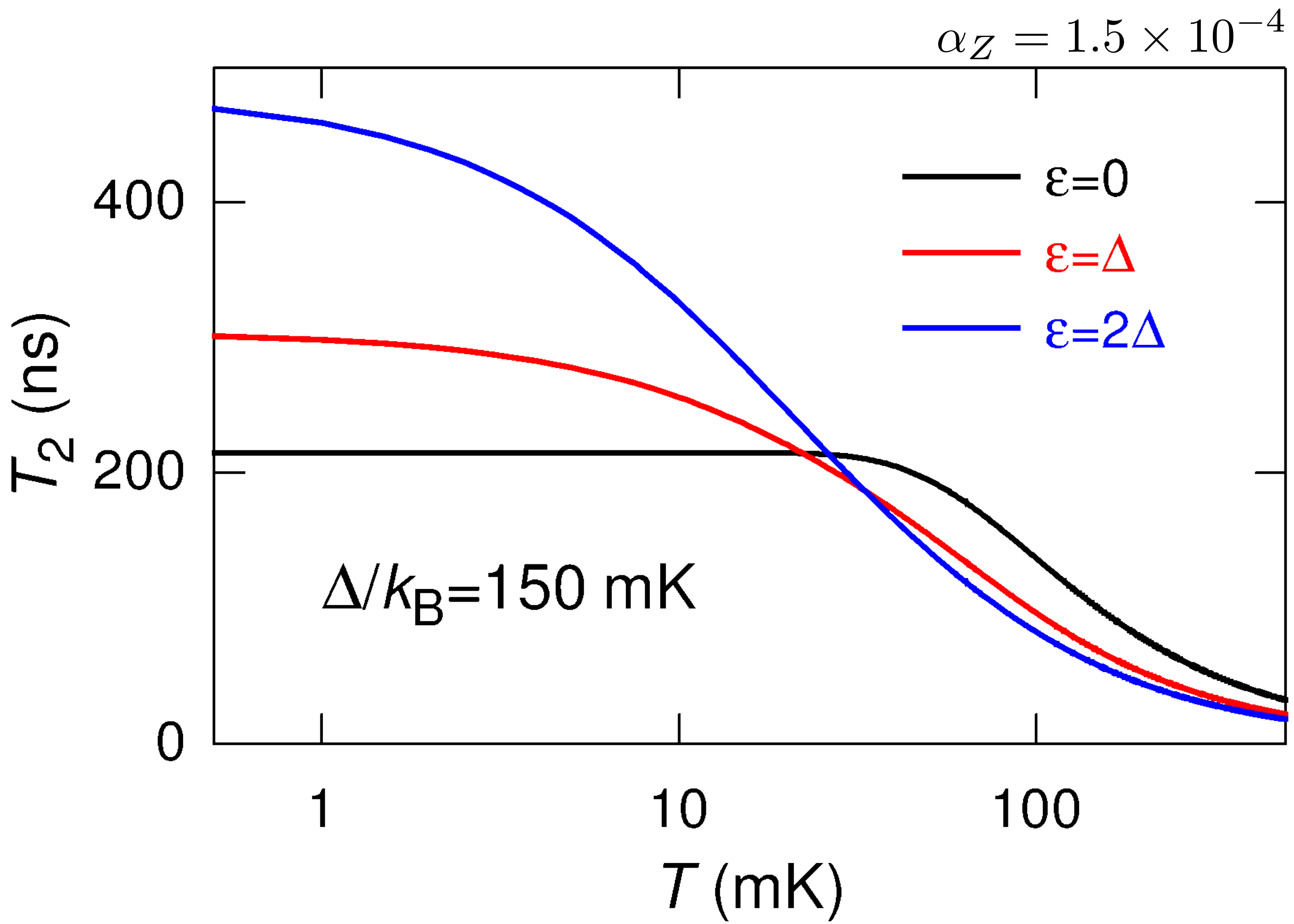
•••• experiment

— theory

Forster et al.: Phys. Rev. Lett. ***112****, 116803 (2014)*

coherence time of our two-electron [undriven] charge qubit

$$T_2^{-1} = \frac{\pi \alpha_Z}{\hbar}\left(\frac{2\bar{\epsilon}^2}{E^2} + \frac{\Delta^2}{2E}\coth\left(\frac{E}{2k_\mathrm{B}T}\right)\right) ; \quad E = \sqrt{\Delta^2 + \bar{\epsilon}^2}$$



Forster et al.: *Phys. Rev. Lett.* ***112***, 116803 (2014)

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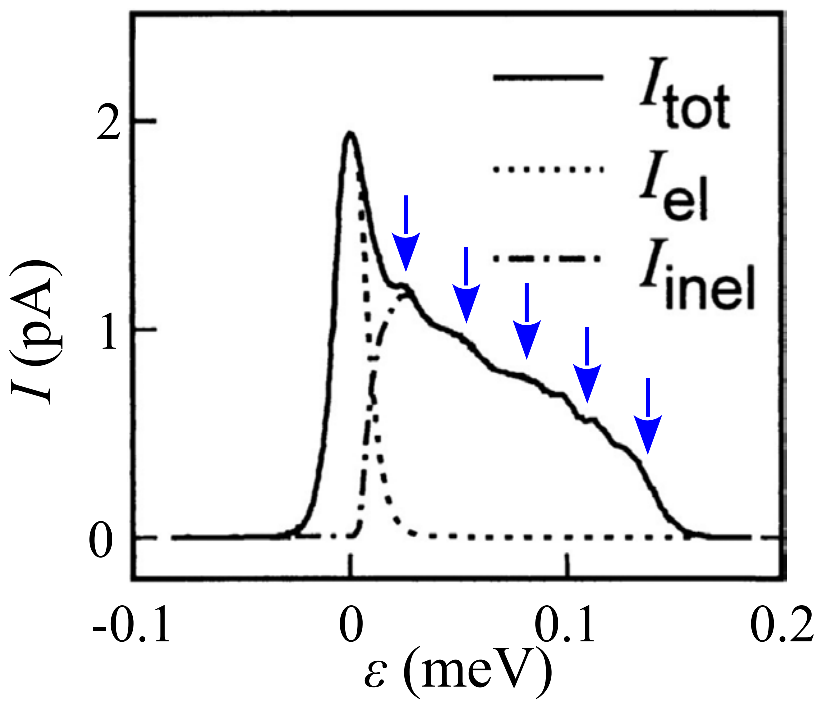
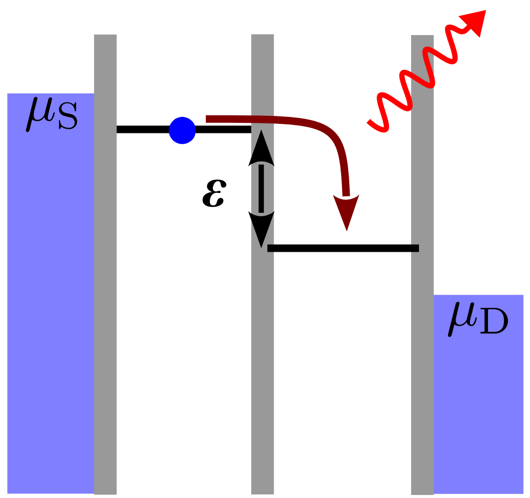
coherent phonon emission in a DQD

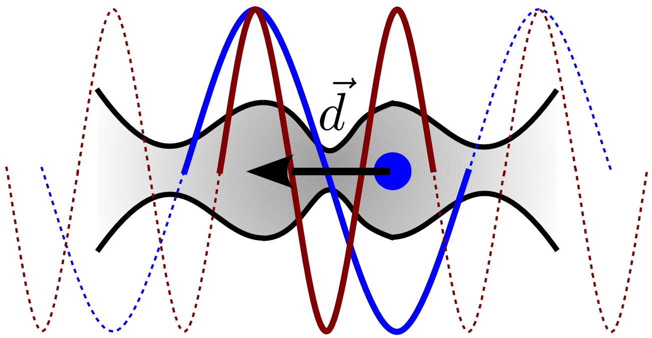
T. Fujisawa, et al., Science 282, 932–935 (1998):
Spontaneous emission spectrum in double quantum dot devices.





theory: **T. Brandes**, Physics Reports 408, 315 – 474 (2005):
Coherent and collective quantum optical effects in mesoscopic systems.

Fermi's golden rule:



electron-phonon interaction matrix element

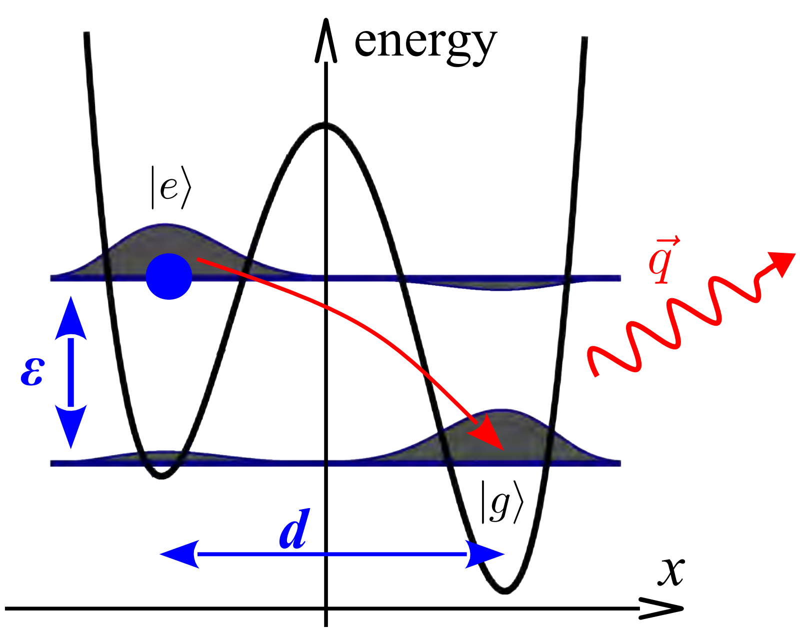
phonon anihil. & creation op.

electron wave funct.

$$\hat{H}_{\text{int}} = \frac{t_c}{\epsilon} \sum_{\vec{q},\mu} \lambda_{\vec{q},\mu} \boxed{e^{i\vec{q}\cdot\vec{d}}} \left(\hat{a}_{\mu,\vec{q}} + \hat{a}^{\dagger}_{\mu,-\vec{q}}\right) \left(|g\rangle\langle e| + h.c.\right)$$

phonon branches

phase factor

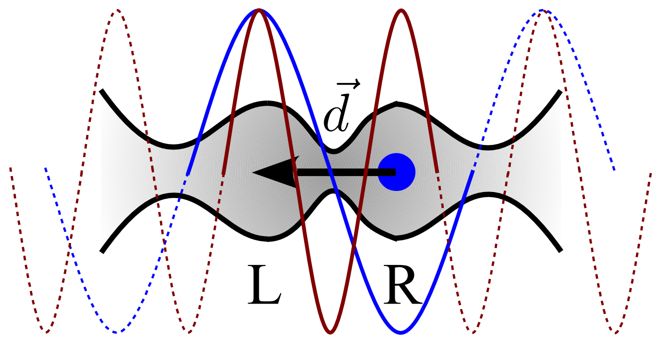


period of interference pattern:

$$\vec{d} \cdot \vec{q} \equiv N 2\pi \;\Rightarrow$$

$$\Delta\epsilon = 2\pi\, \hbar v_{\text{ph}} \frac{|\vec{q}|}{\vec{d}\cdot\vec{q}}$$

using energy conservation: $\epsilon = \hbar |\vec{q}| v_{\text{ph}}$

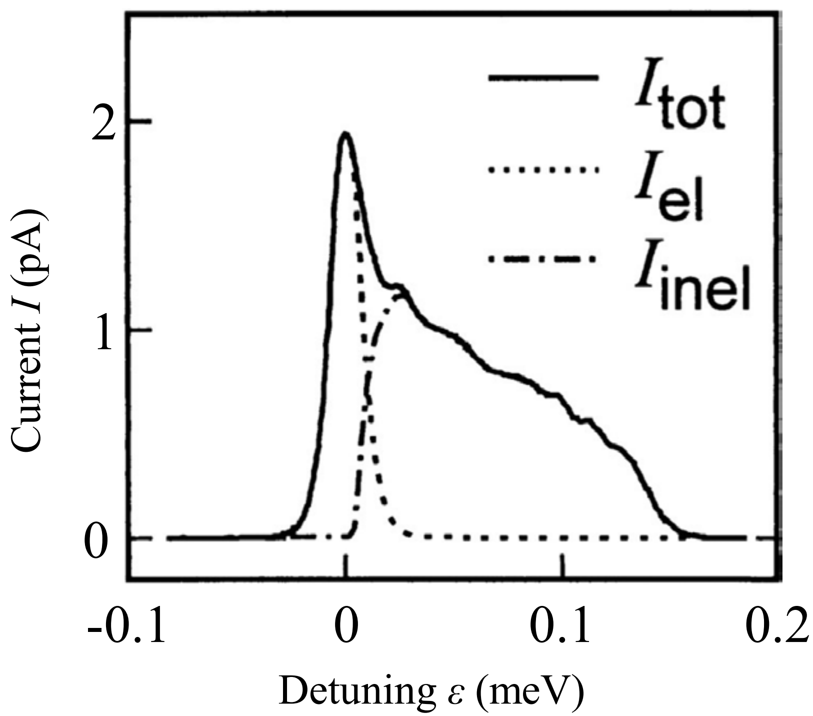


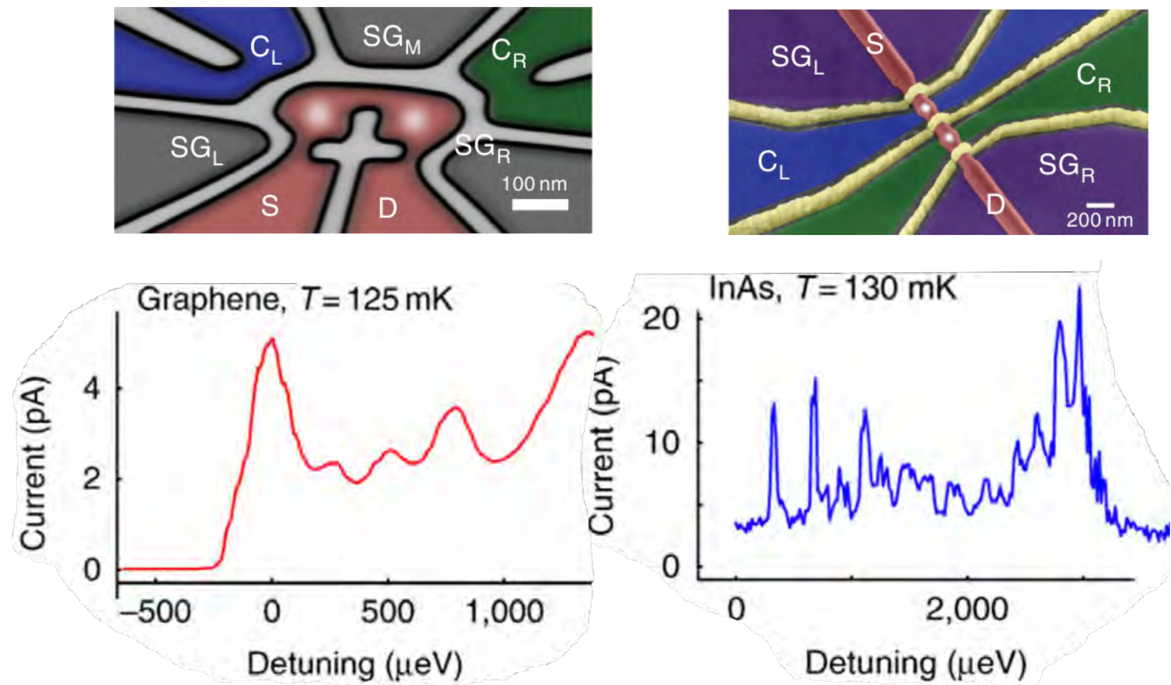
- phonon wavelengths are typically in the order or smaller than the distance of QDs
- **photon wavelengths are much longer ⇒** $\Delta\varphi_{\mathrm{photon}} = 0$
- **here: phonon mediated interaction**

coherent phonon emission in a DQD

T. Fujisawa, et al., Science 282, 932–935 (1998):
Spontaneous emission spectrum in double quantum dot devices.

P. Roulleau, et al., Nat Commun 2 (2011):
Coherent electron–phonon coupling in tailored quantum systems.



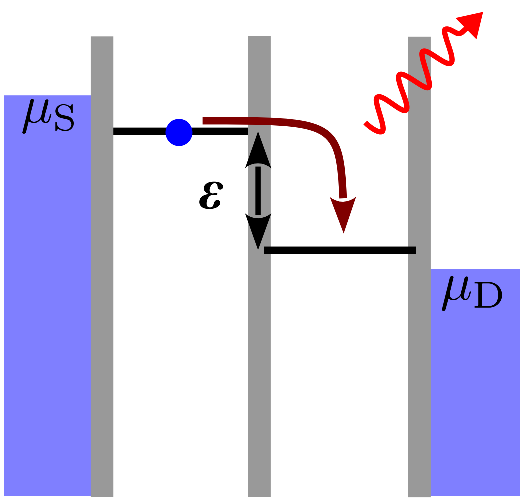


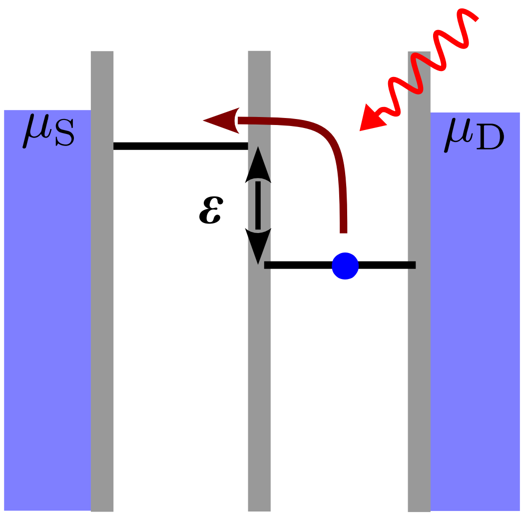
<u>observation:</u> the non-equilibrium current through a double QD oscillates as a function of energy detuning ε, i.e. the energy of the **emitted phonons**.

<u>theory:</u> **T. Brandes**, Physics Reports 408, 315 – 474 (2005):
Coherent and collective quantum optical effects in mesoscopic systems.

can we do the same for phonon absorption ?

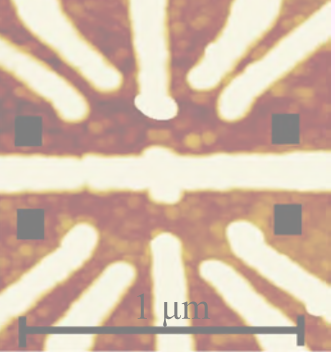
emission ↔ absorption

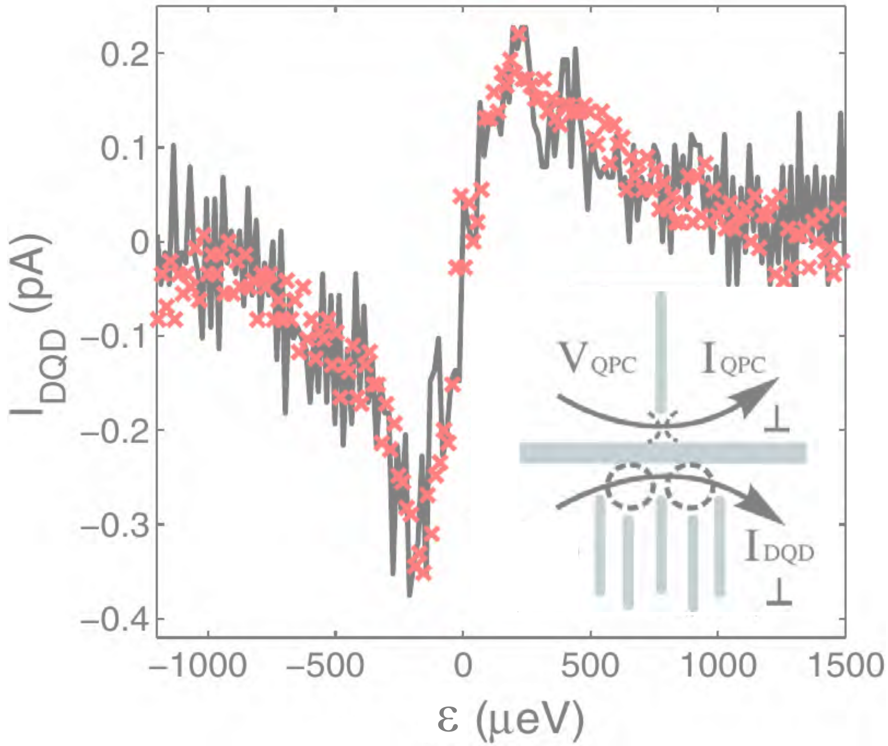


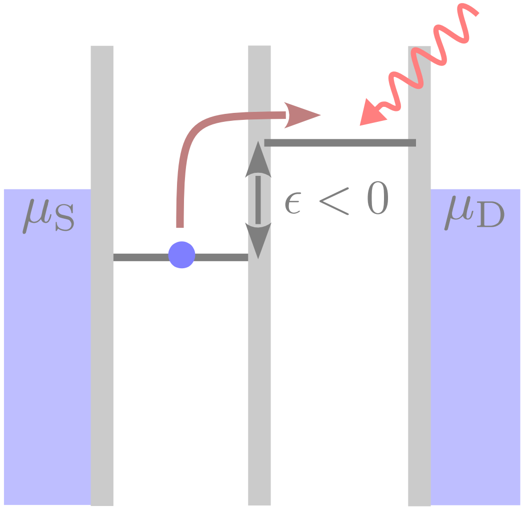


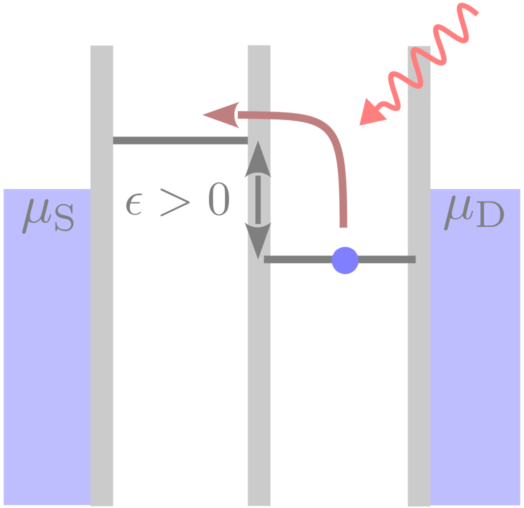
phonon source **phonon detector**

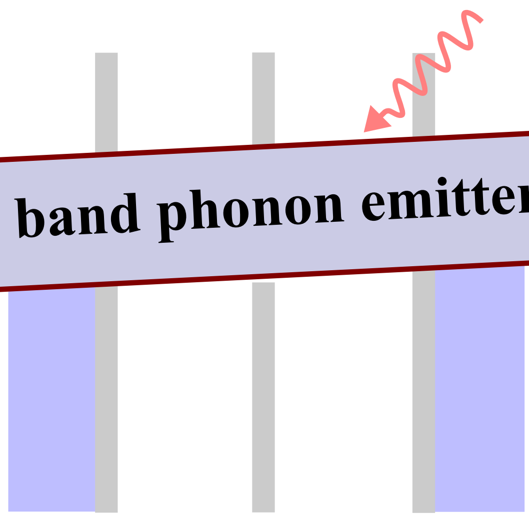
phonon driven current through a DQD (quantum ratchet)

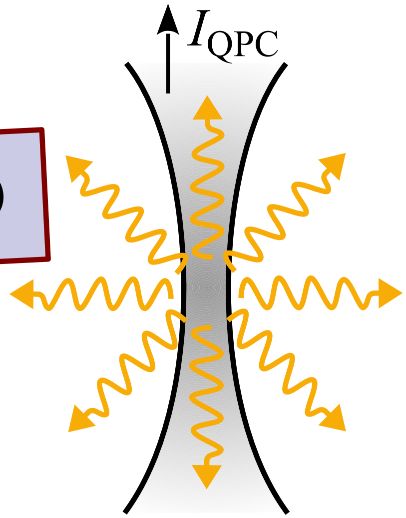






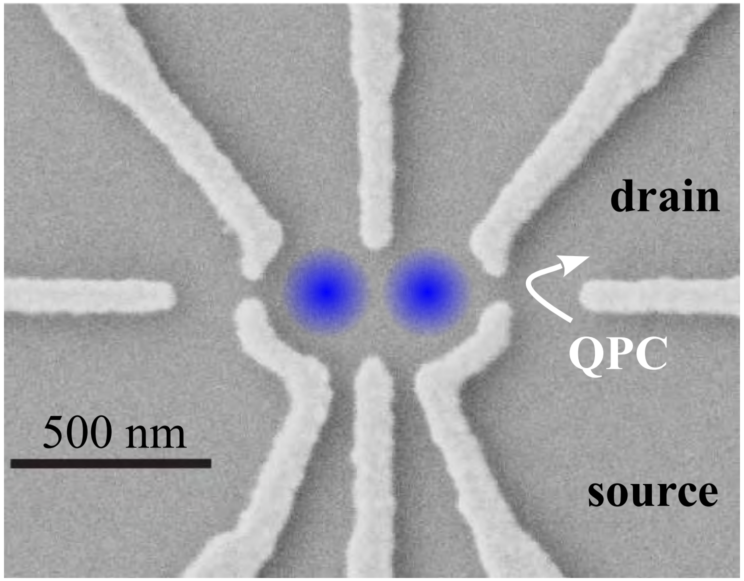


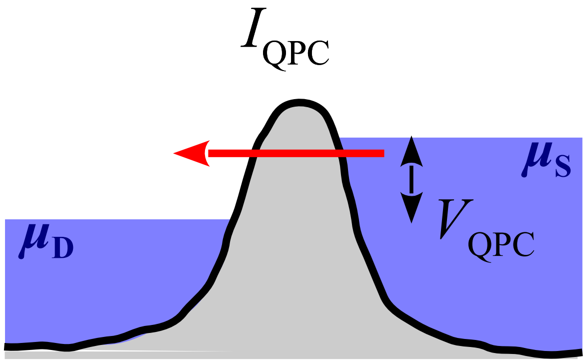


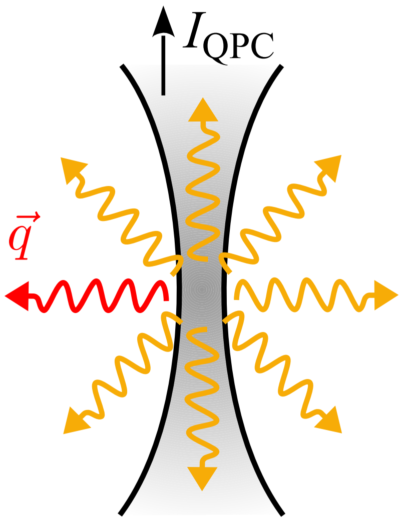


a driven QPC can act as a broad band phonon emitter ($E_{max} = eV_{SD}$)

Khrapai et al.:
Phys. Rev. Lett. ***97****, 176803 (2006)*
Phys. Rev. Lett. ***99****, 096803 (2007)*

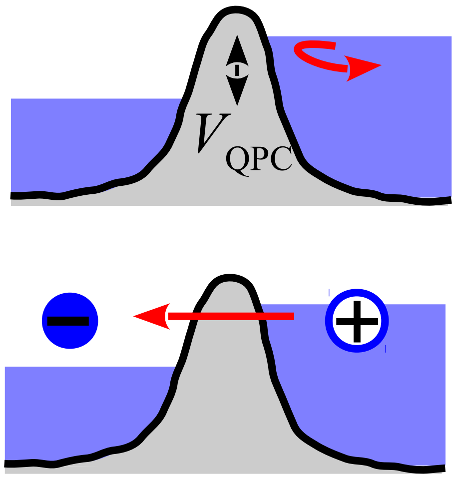

drain
QPC
500 nm
source


I_{QPC}
μ_S
μ_D
V_{QPC}


I_{QPC}
$\vec{q}$

quantum point contact (QPC) as phonon source

transmission: $0 < T \ll 1 \Rightarrow$ **local charge fluctuations**



piezoelectric effect

deformation potential

$\Rightarrow$ **phonon emission**

$E_{\mathrm{ph}} \leq eV_{\mathrm{QPC}}$

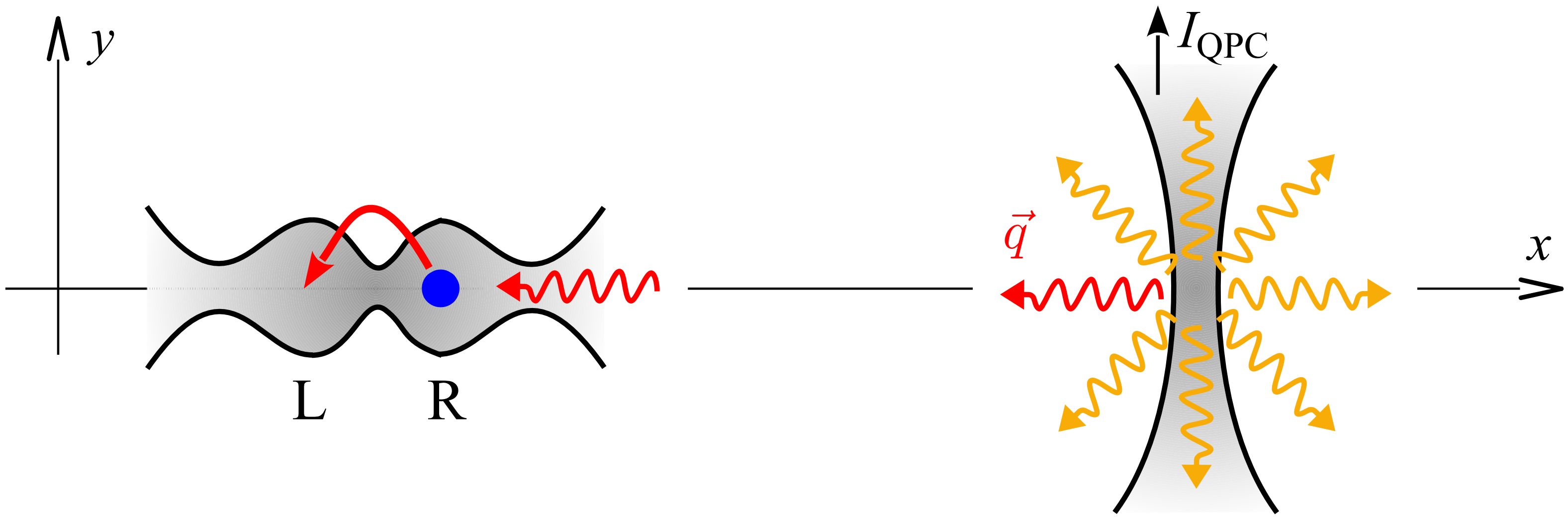
our model (Aash Clerk):

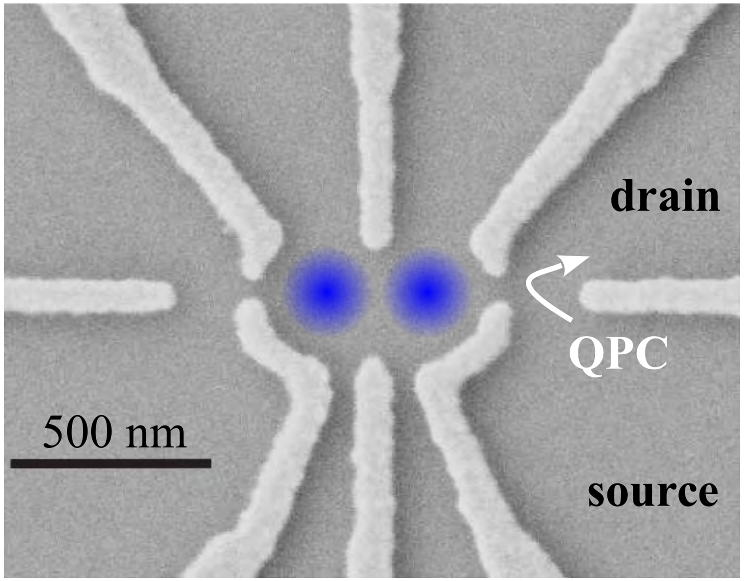
- **standard scattering theory**
  $\Rightarrow$ charge noise spectrum of the QPC.

- link the QPCs charge noise to its phonon emission spectrum (using **Keldysh Green functions** of the acoustic phonons to first order in the electron-phonon coupling to the QPC).

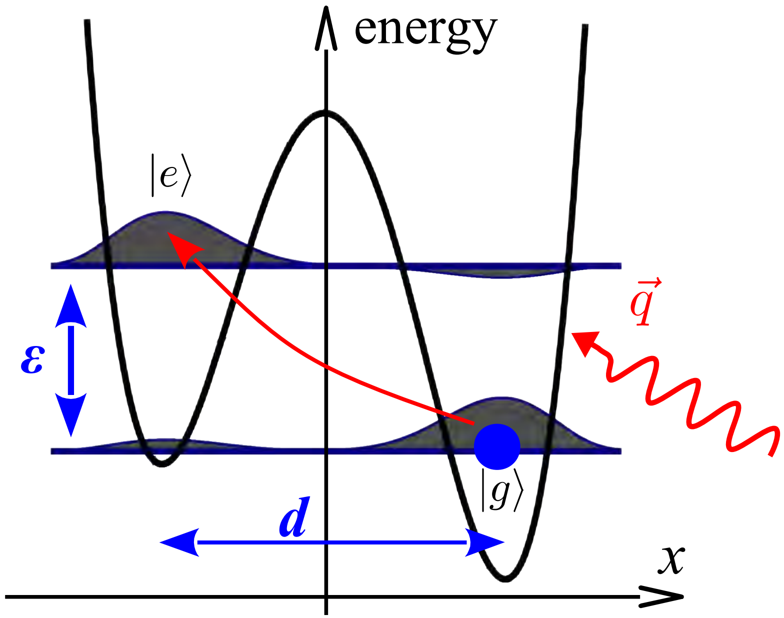
Aashish Clerk
theory
@ McGill, Canada

Nature Phys. 8, 522 (2012)


y
L
R
$I_{\rm QPC}$
$\vec{q}$
x


drain
QPC
500 nm
source

Fermi's golden rule:



electron-phonon interaction matrix element

phonon anihil. & creation op.

electron wave funct.

$$\hat{H}_{\text{int}} = \frac{t_c}{\epsilon} \sum_{\vec{q},\mu} \lambda_{\vec{q},\mu} \boxed{e^{i\vec{q}\cdot\vec{d}}} \left(\hat{a}_{\mu,\vec{q}} + \hat{a}^{\dagger}_{\mu,-\vec{q}}\right)\left(|g\rangle\langle e| + h.c.\right)$$

phonon branches

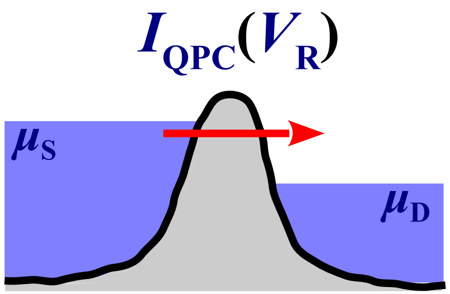
phase factor

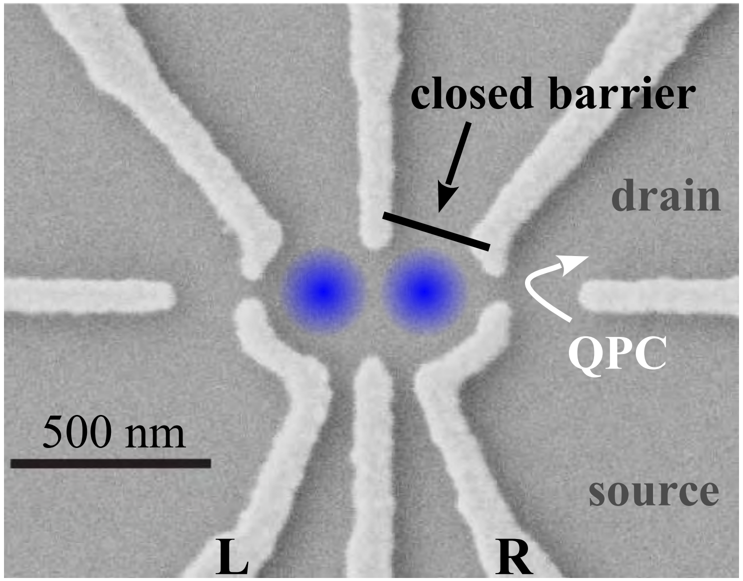
our model (Aash Clerk):

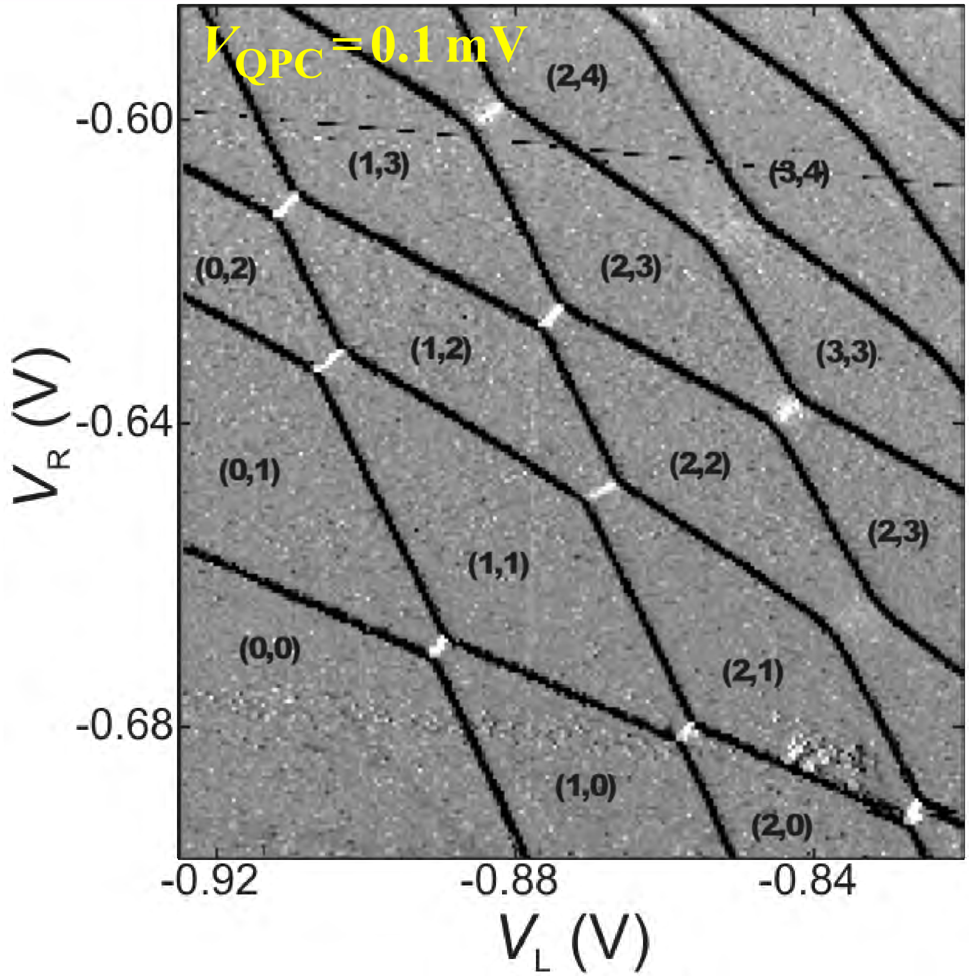
- **Golden rule rates** for electron-phonon interaction in the double QD (only piezoelectric coupling) [as in *].
- **standard elasticity theory** [as in **] but in addition account for **anisotropy of** sound velocities and polarizations, include **screening effects**

* T. Brandes & B. Kramer: Physical Review Letters **83**, 3021 (1999).
** K. Jasiukiewicz: Semicond. Sci. Technol. **13**, 537 (1998).

sensitive measurement of phonon absorption: QPC as charge detector ...





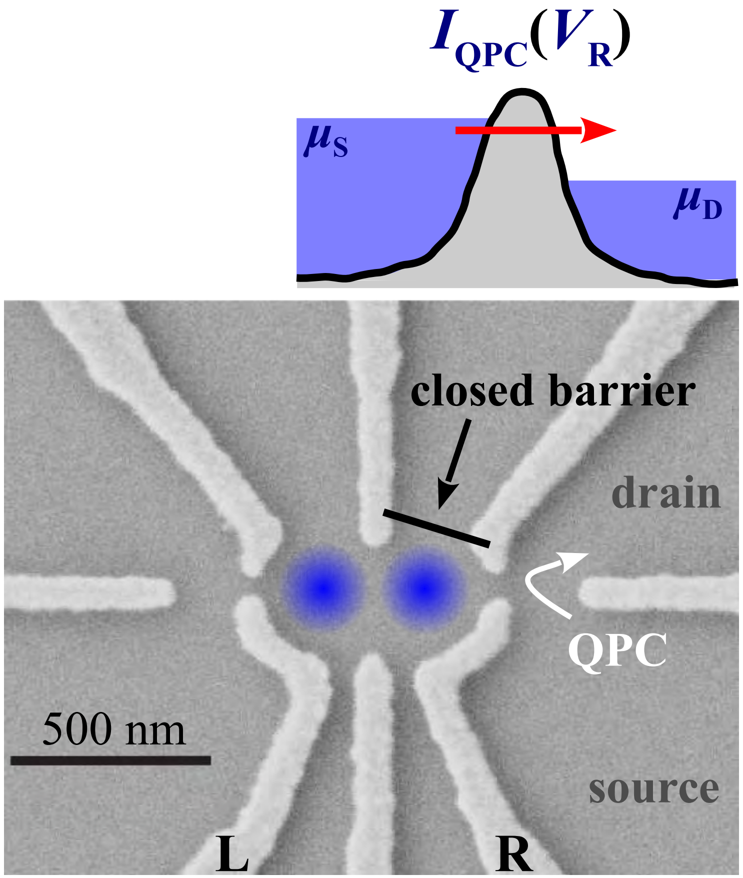


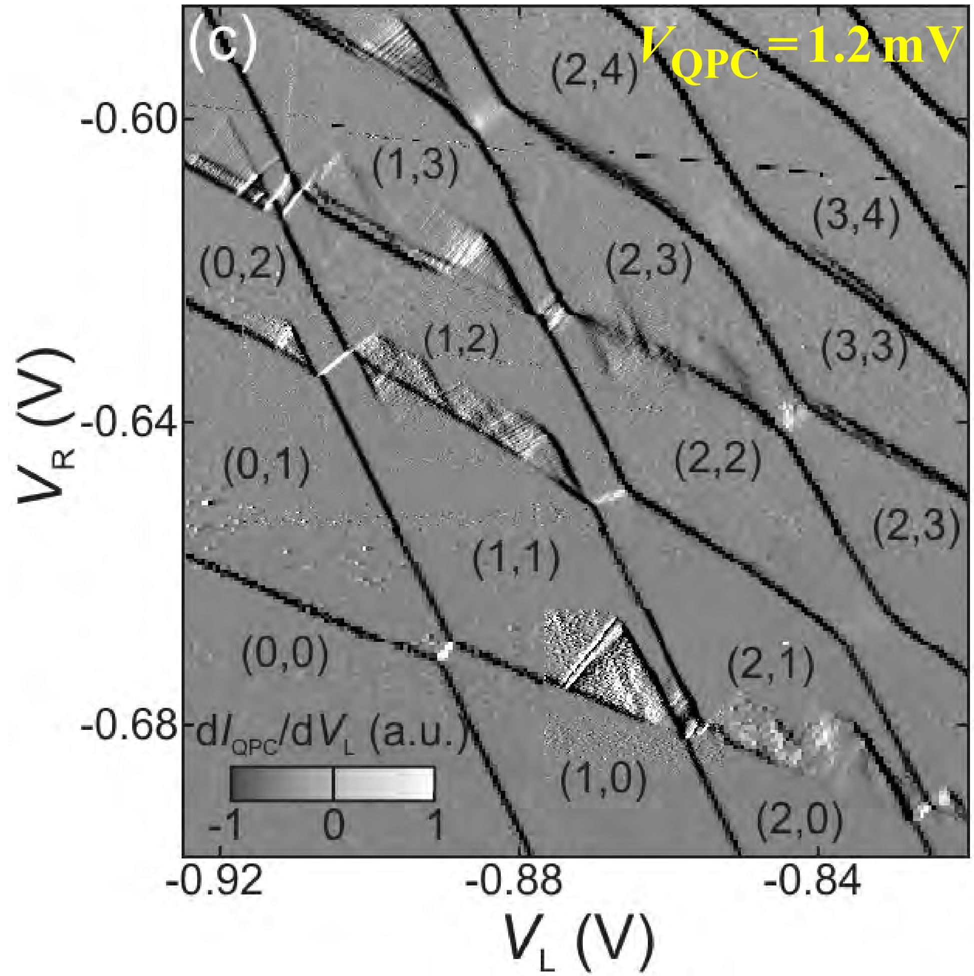
Daniela Taubert

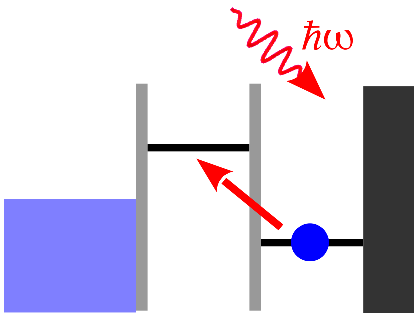
measured is the **transconductance**: $\dfrac{\mathrm{d}I_{\mathrm{QPC}}}{\mathrm{d}V_{\mathrm{L}}}$ (a.u.)

proportional to changes of the the steady state occupation of the DQD

… to measure the steady state occupation of the DQD





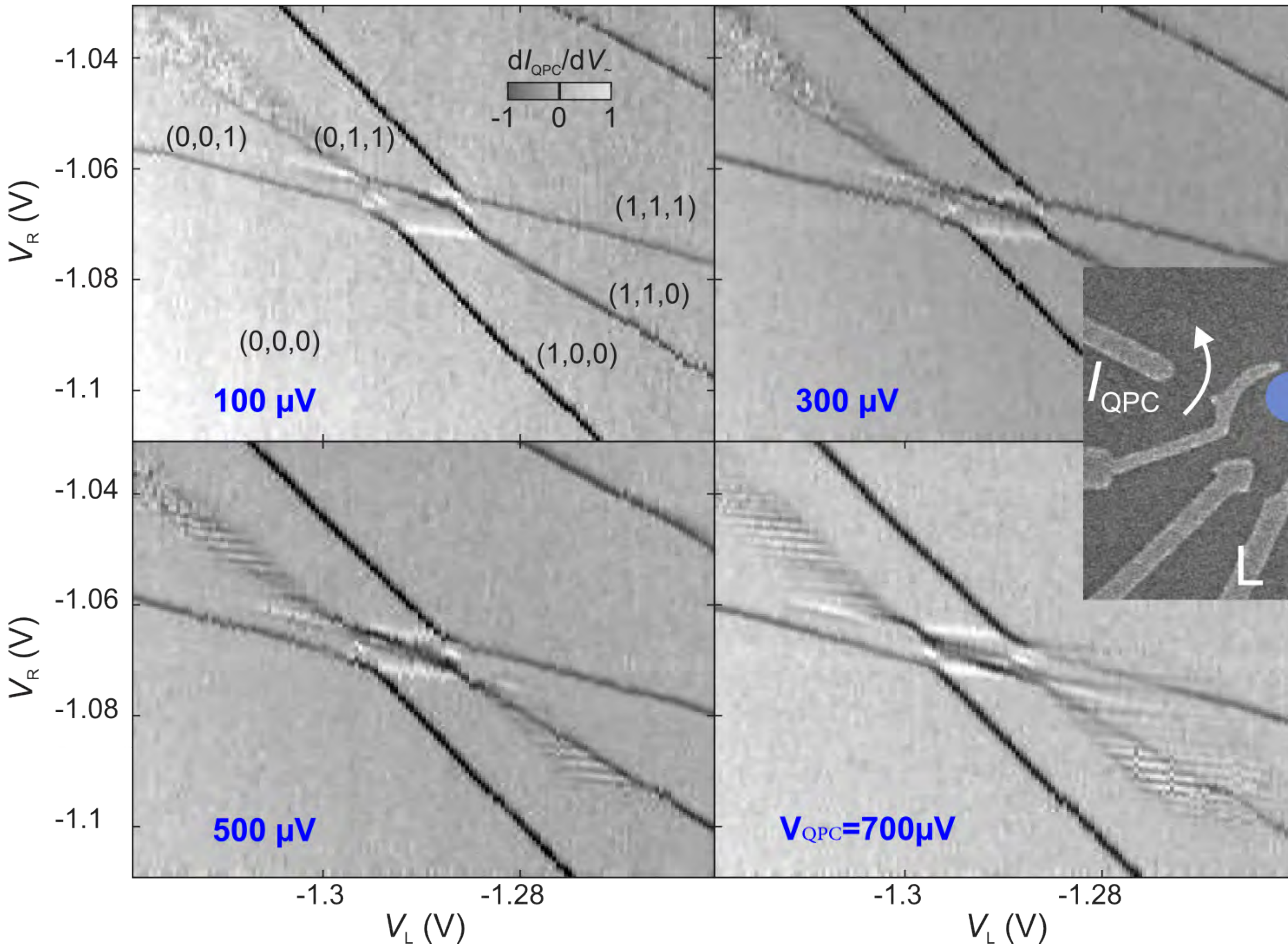


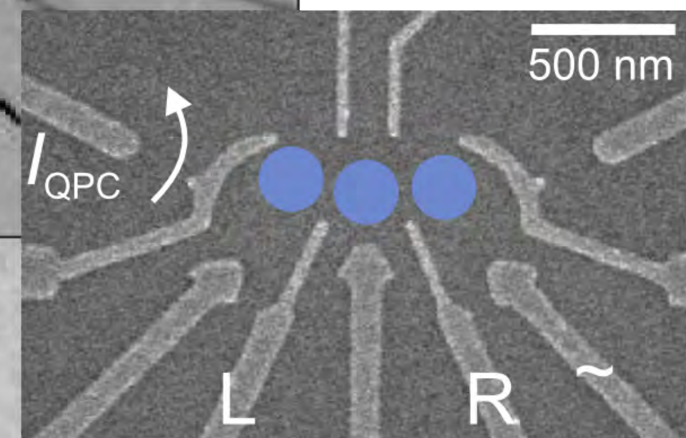
QPC charge detector:

- is a voltage biased 1D-tunnel barrier
- acts as a **broad band phonon emitter**
- re-absorption of phonons at the DQD cause **detector backaction**

literature: Khrapay et al.: PRL **97**, 176803 (2006); Schinner et al.: PRL **102**, 186801 (2009); Harbusch et al.: PRL **104**, 196801 (2010); Prokudina et al.: PRB **82**, 201310(R) (2010)

same effect observed in a triple quantum dot

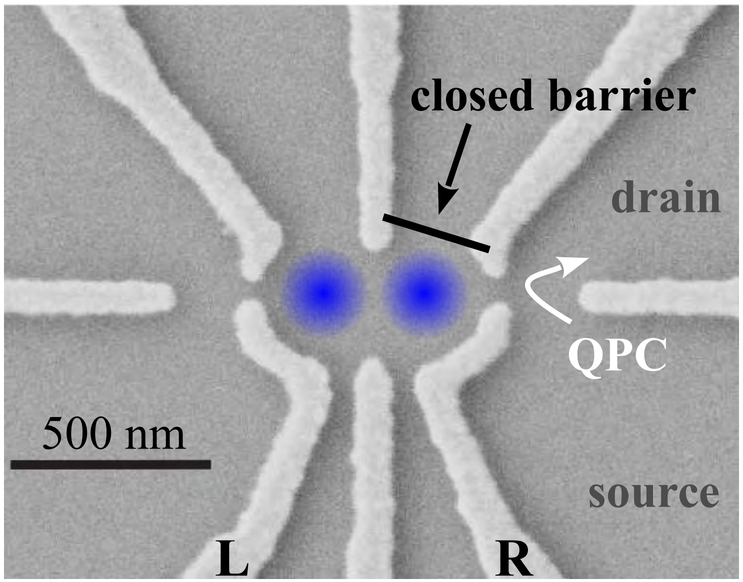


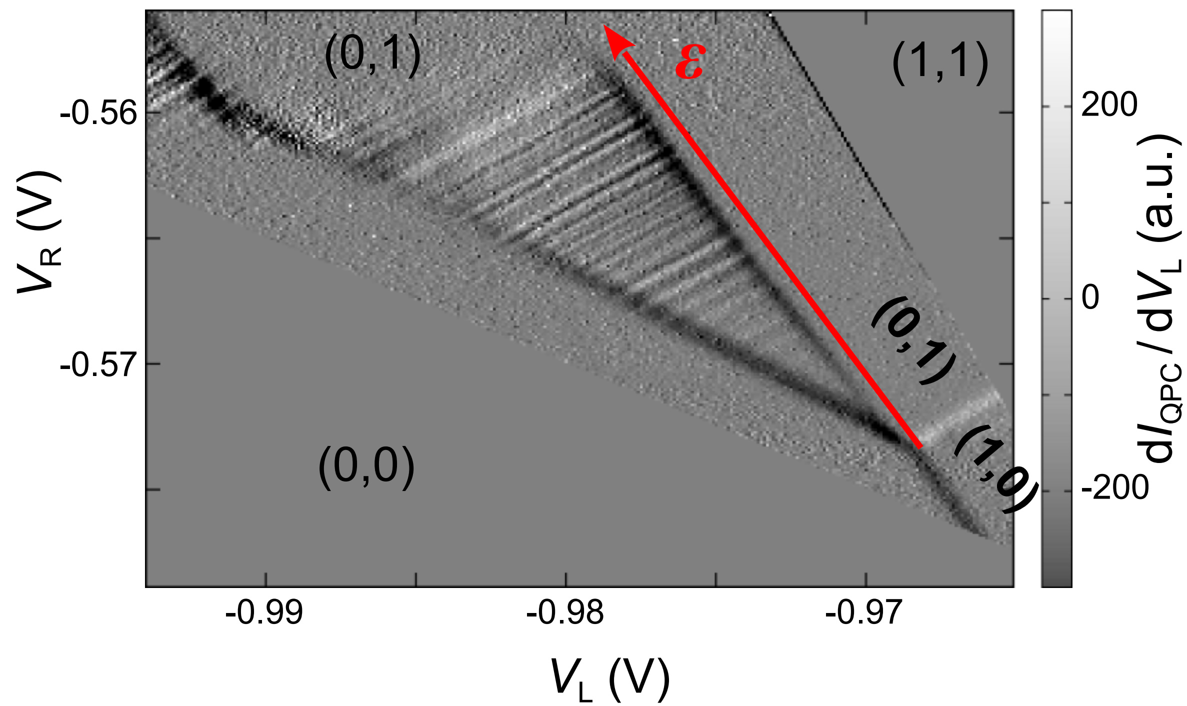


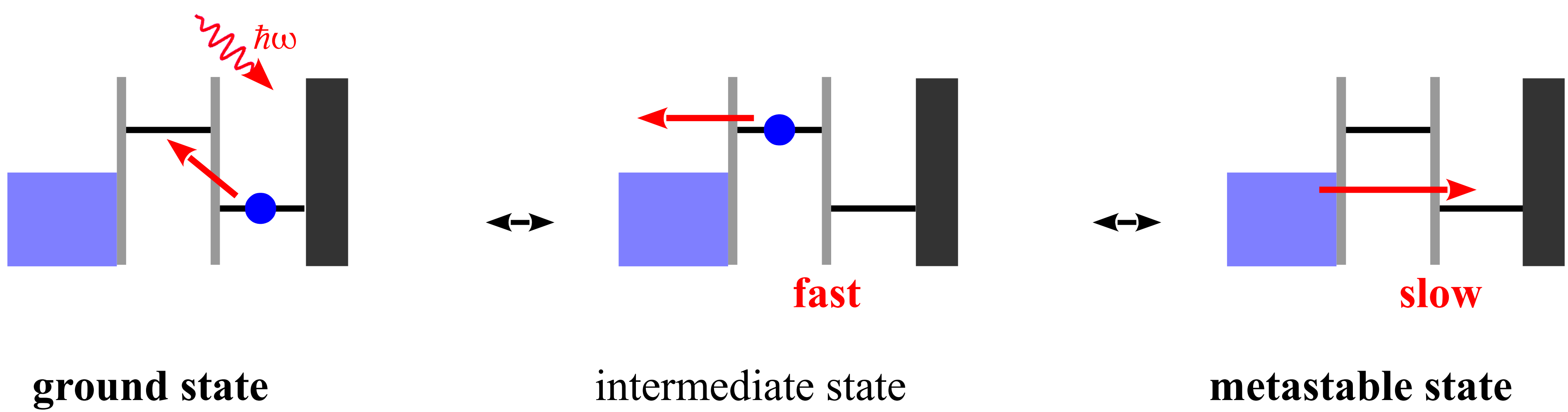
Andy Sachrajda
experiments
@ NRC, Canada

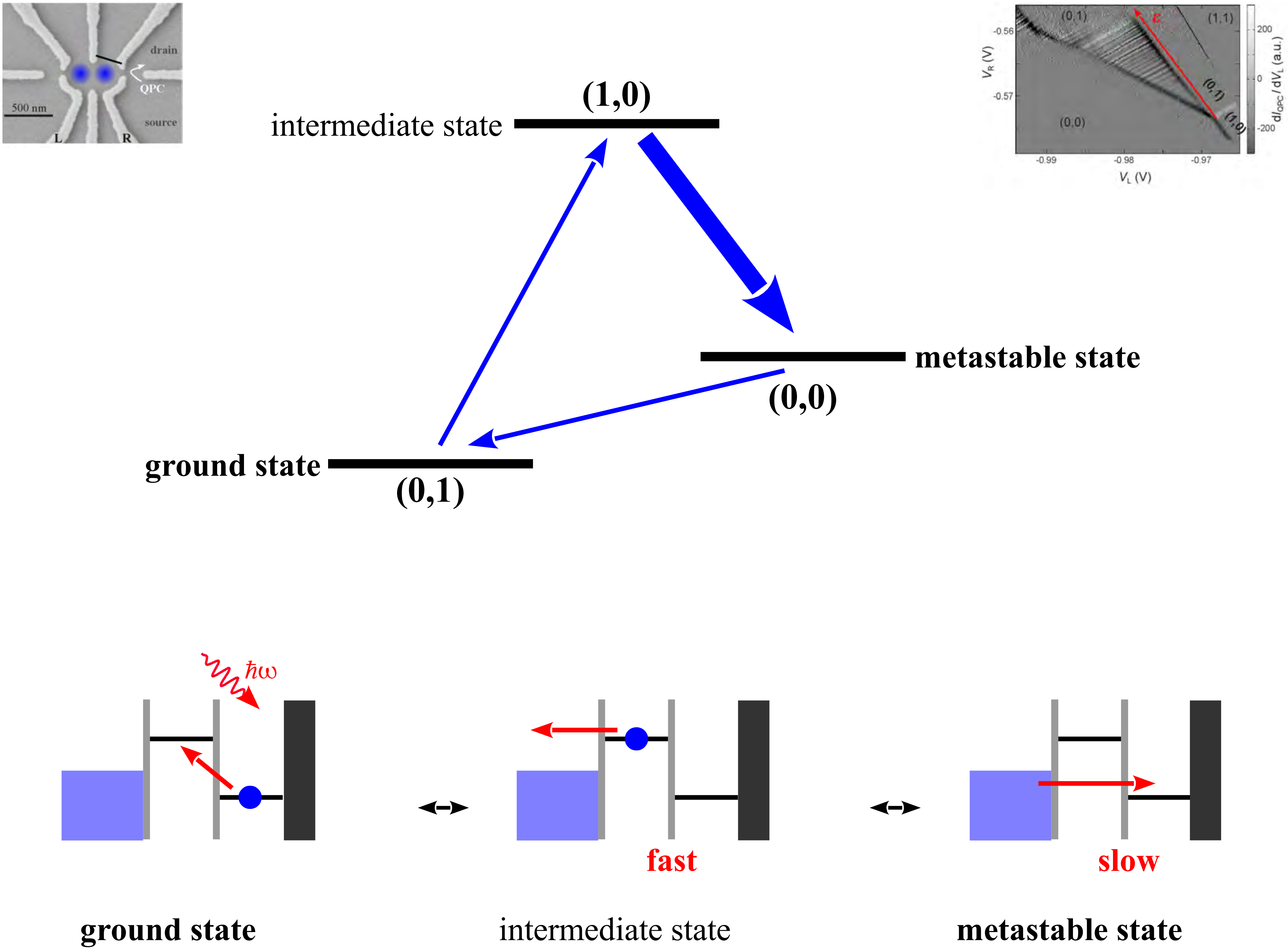
data from Andy Sachrajda's group, NRC Canada

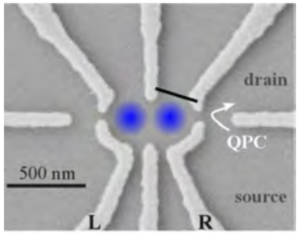
Nature Phys. ***8****, 522 (2012)*

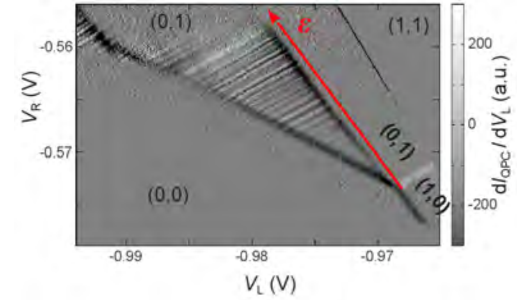

closed barrier
drain
QPC
500 nm
source
L
R

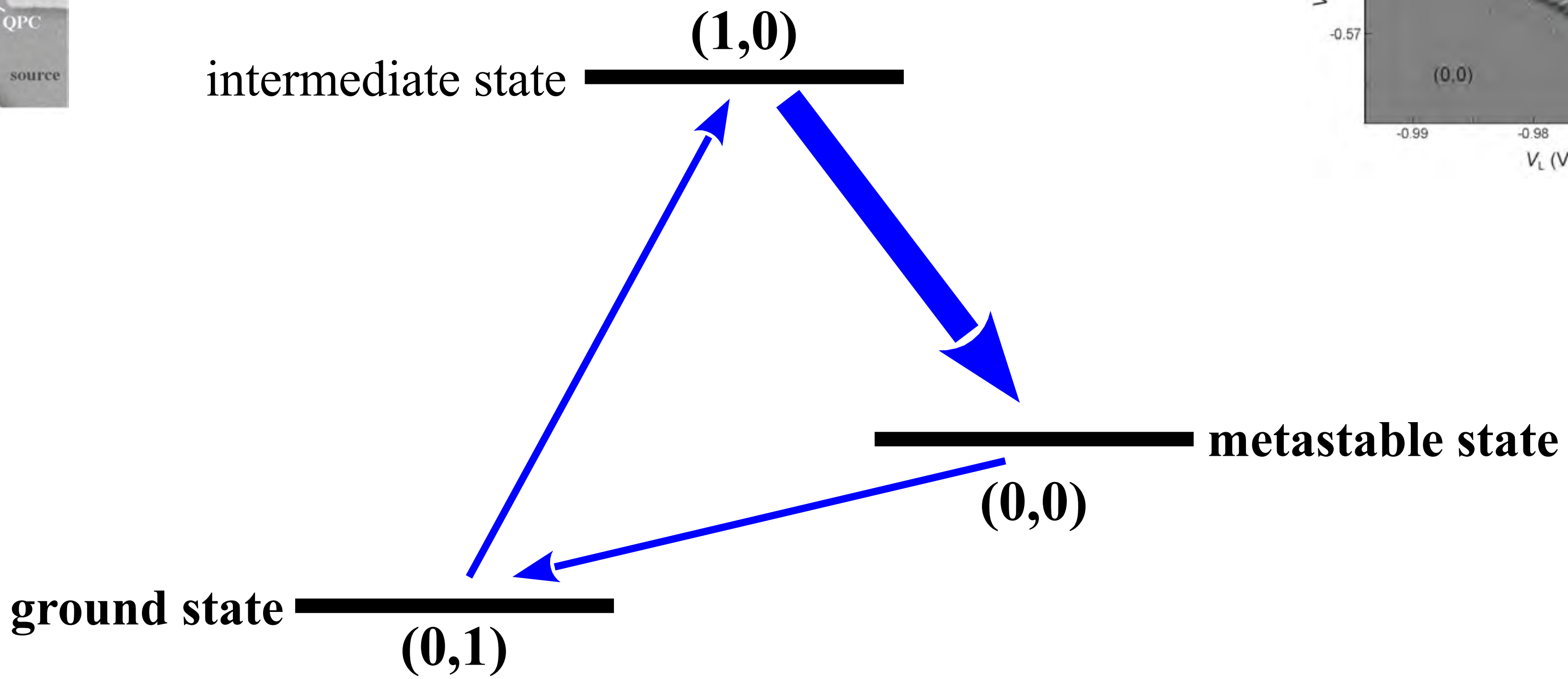

(0,1)
(1,1)
ε
(0,1)
(1,0)
(0,0)
-0.56
-0.57
V_R (V)
-0.99
-0.98
-0.97
V_L (V)
200
0
-200
dI_{QPC} / dV_L (a.u.)


ħω
fast
slow
ground state
intermediate state
metastable state


drain
QPC
500 nm
source
L
R
(0,1)
ε
(1,1)
-0.56
-0.57
V_R (V)
(0,1)
(1,0)
(0,0)
-0.99
-0.98
-0.97
V_L (V)
200
0
-200
dI_{QPC} / dV_L (a.u.)
(1,0)
intermediate state
metastable state
(0,0)
ground state
(0,1)
$\hbar\omega$
fast
slow
ground state
intermediate state
metastable state

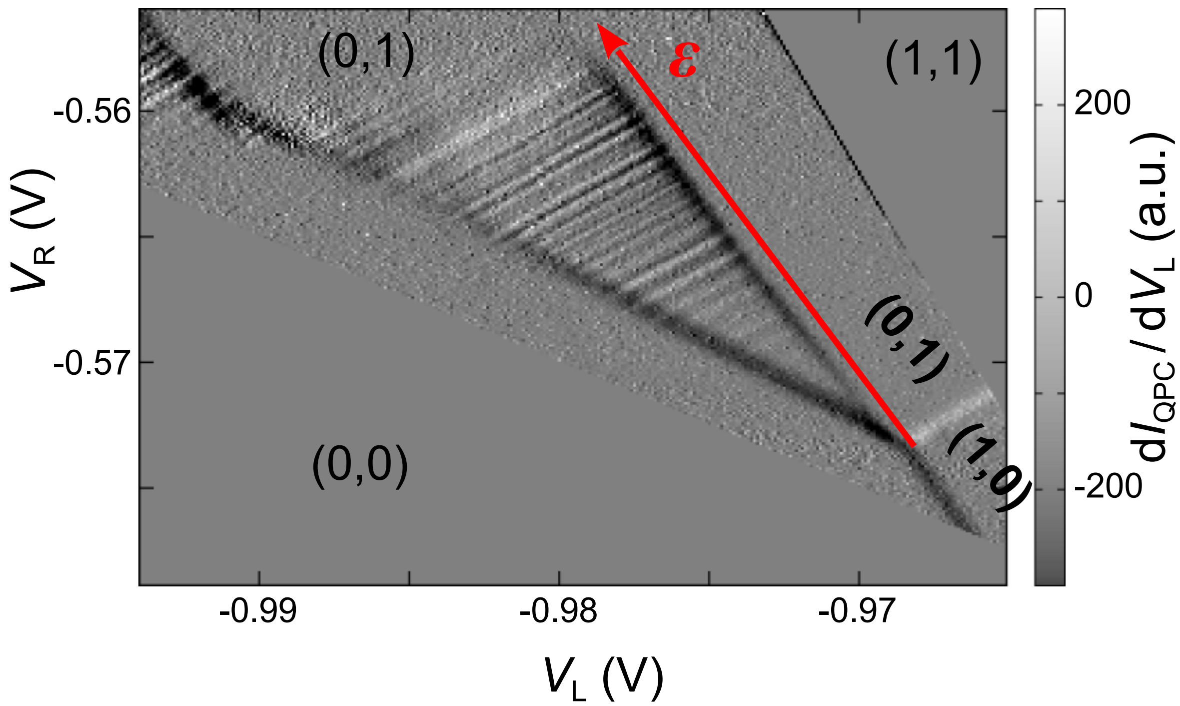


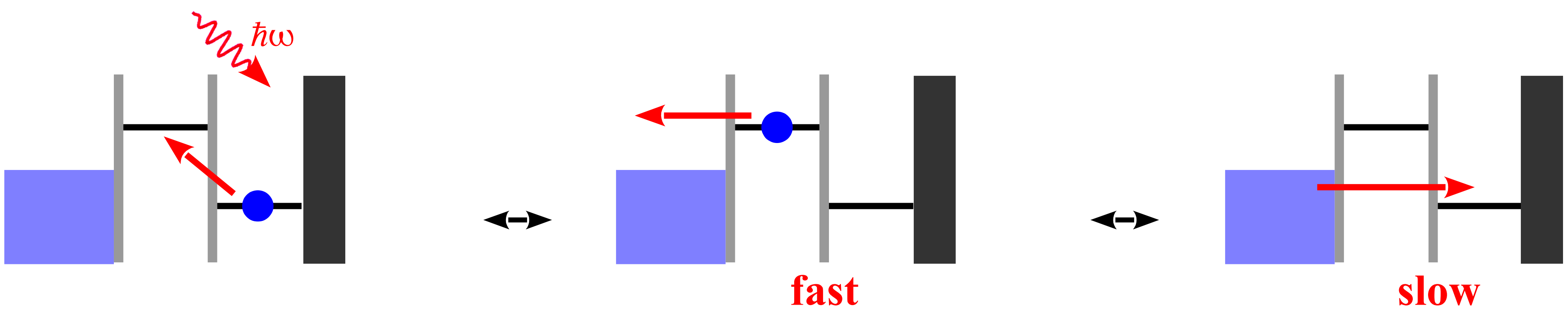




our model (Aash Clerk):

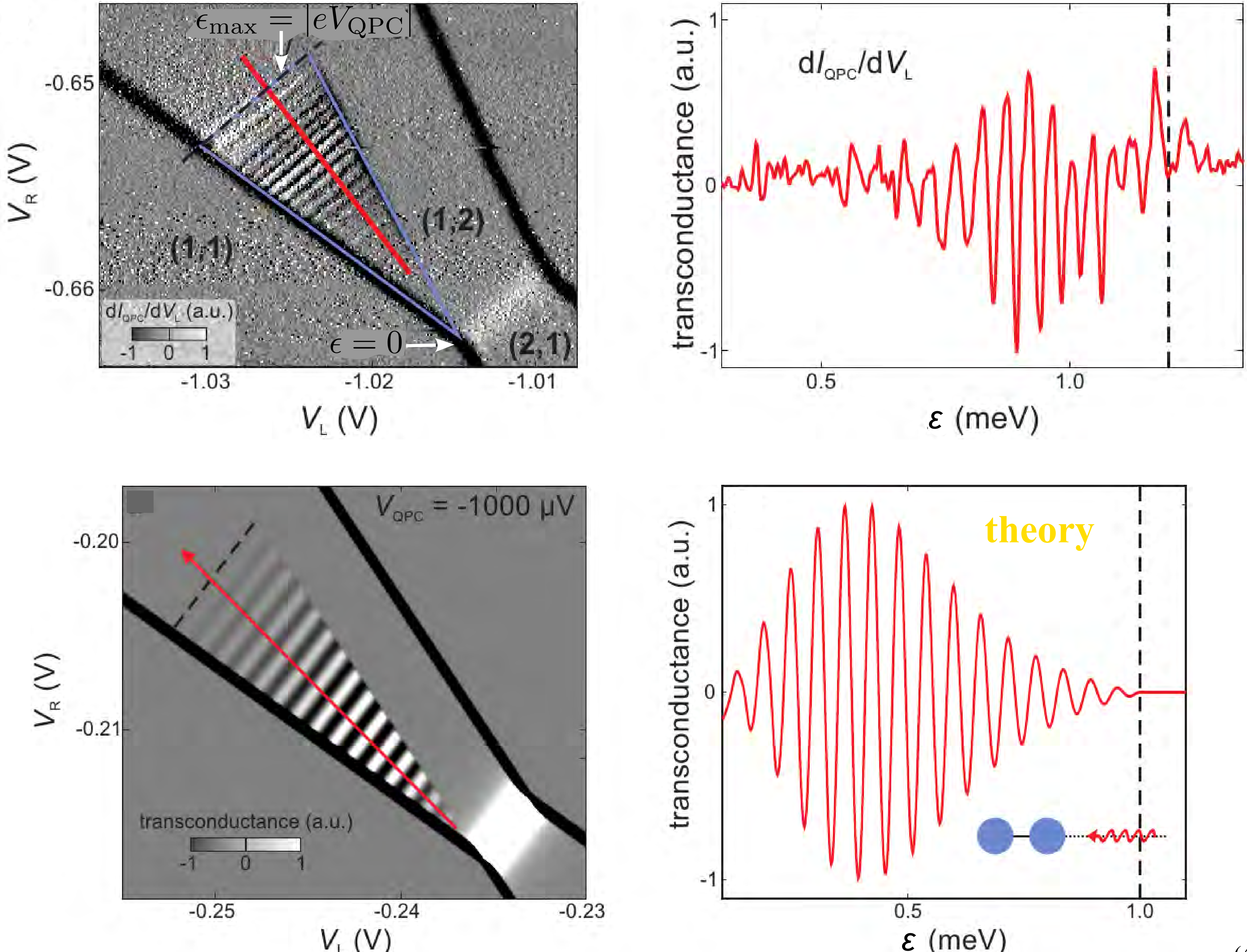
- master equation approach considering the three relevant double QD states.





- **constructive interference:** considerable occupation of excited configuration (0,0)
- **destructive interference:** ground state configuration (0,1) is always occupied

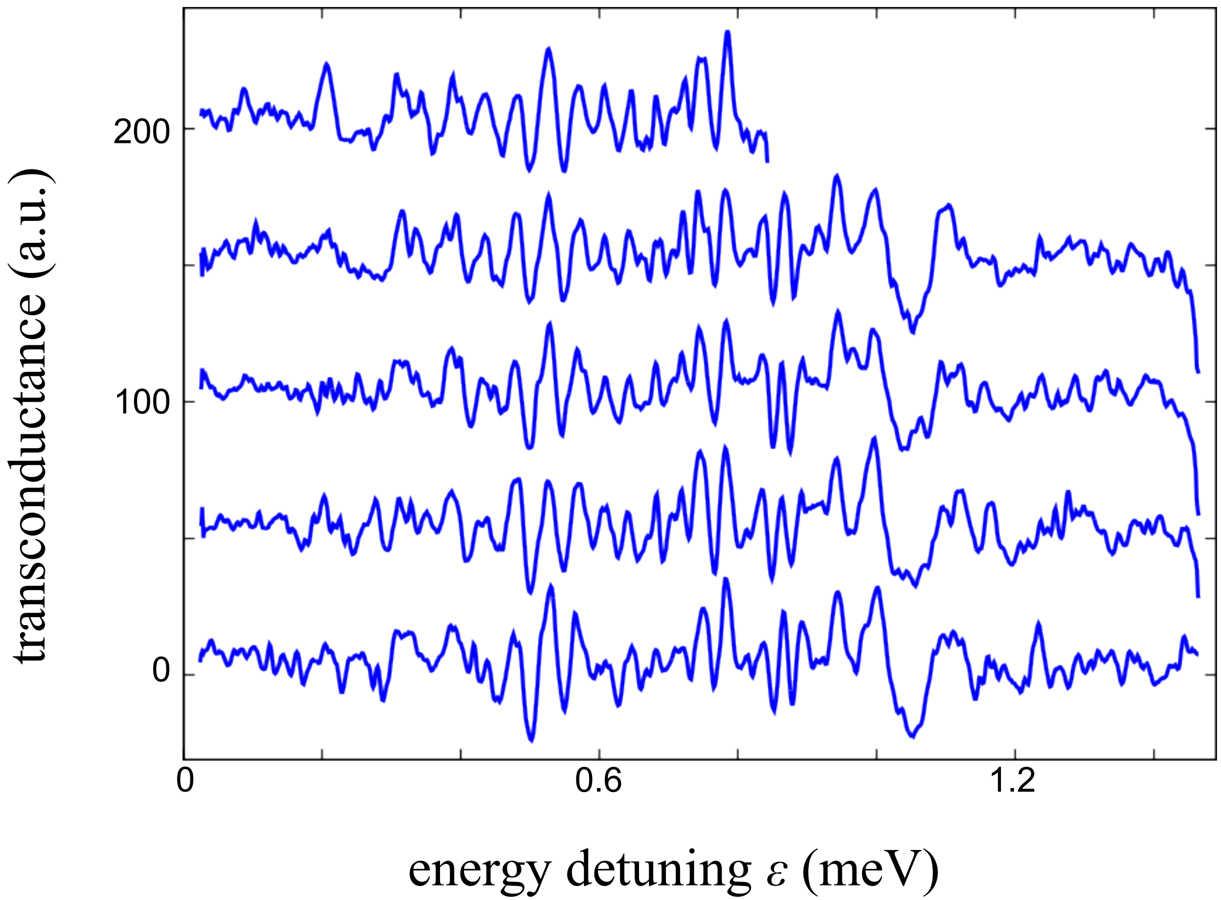
- the intermediate state (1,0) is short living and does not contribute to the detector signal



$\epsilon_{\max} = |eV_{\mathrm{QPC}}|$
$\epsilon = 0$
(1,1)
(1,2)
(2,1)
dI_{QPC}/dV_L (a.u.)
-1 0 1
V_R (V)
-0.65
-0.66
-1.03
-1.02
-1.01
V_L (V)
dI_{QPC}/dV_L
transconductance (a.u.)
1
0
-1
0.5
1.0
ε (meV)
V_{QPC} = -1000 μV
-0.20
-0.21
-0.25
-0.24
-0.23
transconductance (a.u.)
-1 0 1
theory

reproducable beating patterns

repeated measurements:



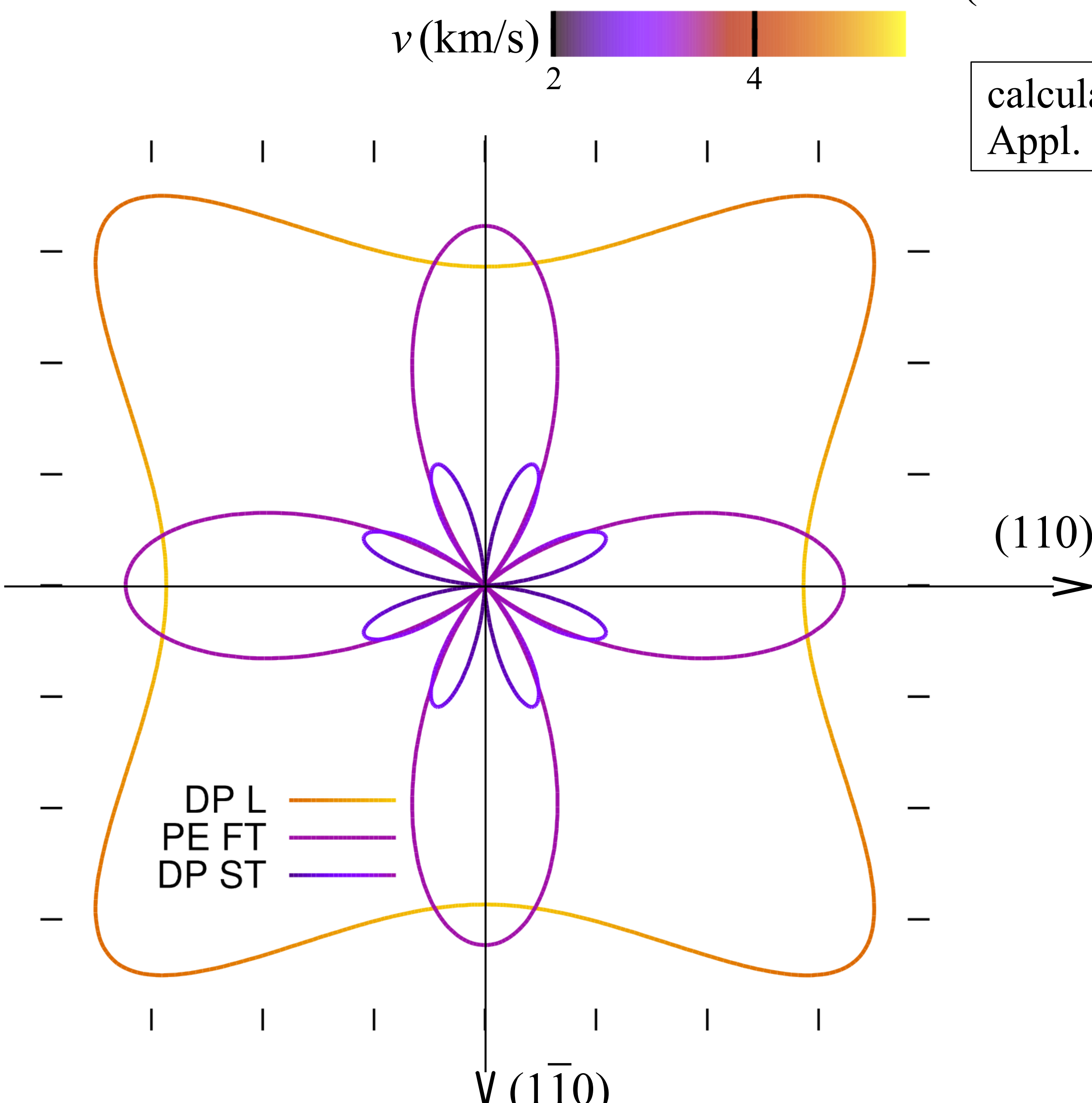
contributions of different phonon modes including deformation potential and piezoelectric coupling...

most relevant acoustic phonon modes

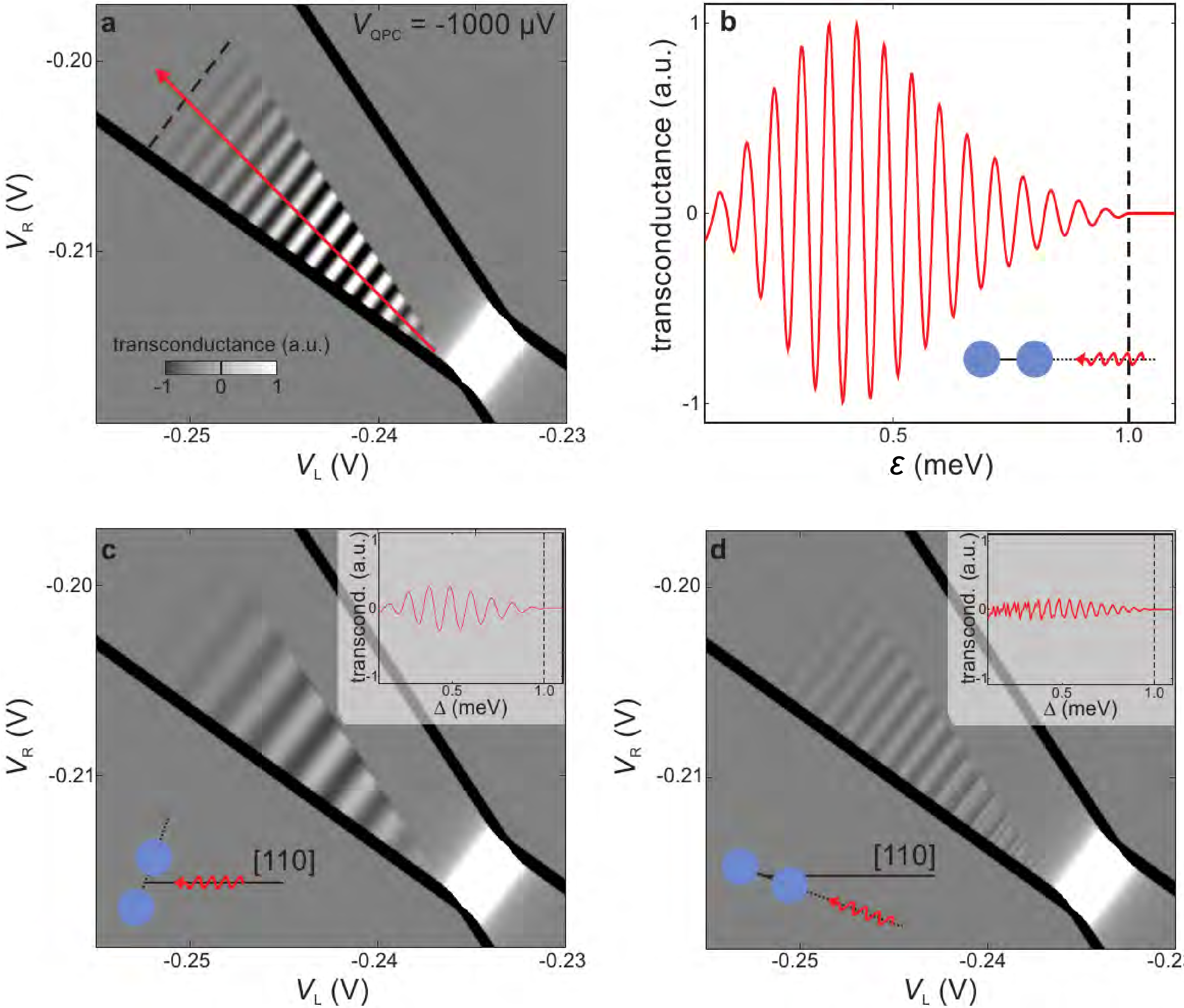
acoustic phonons in GaAs:

phonon focusing
(radius ∝ emission strength)

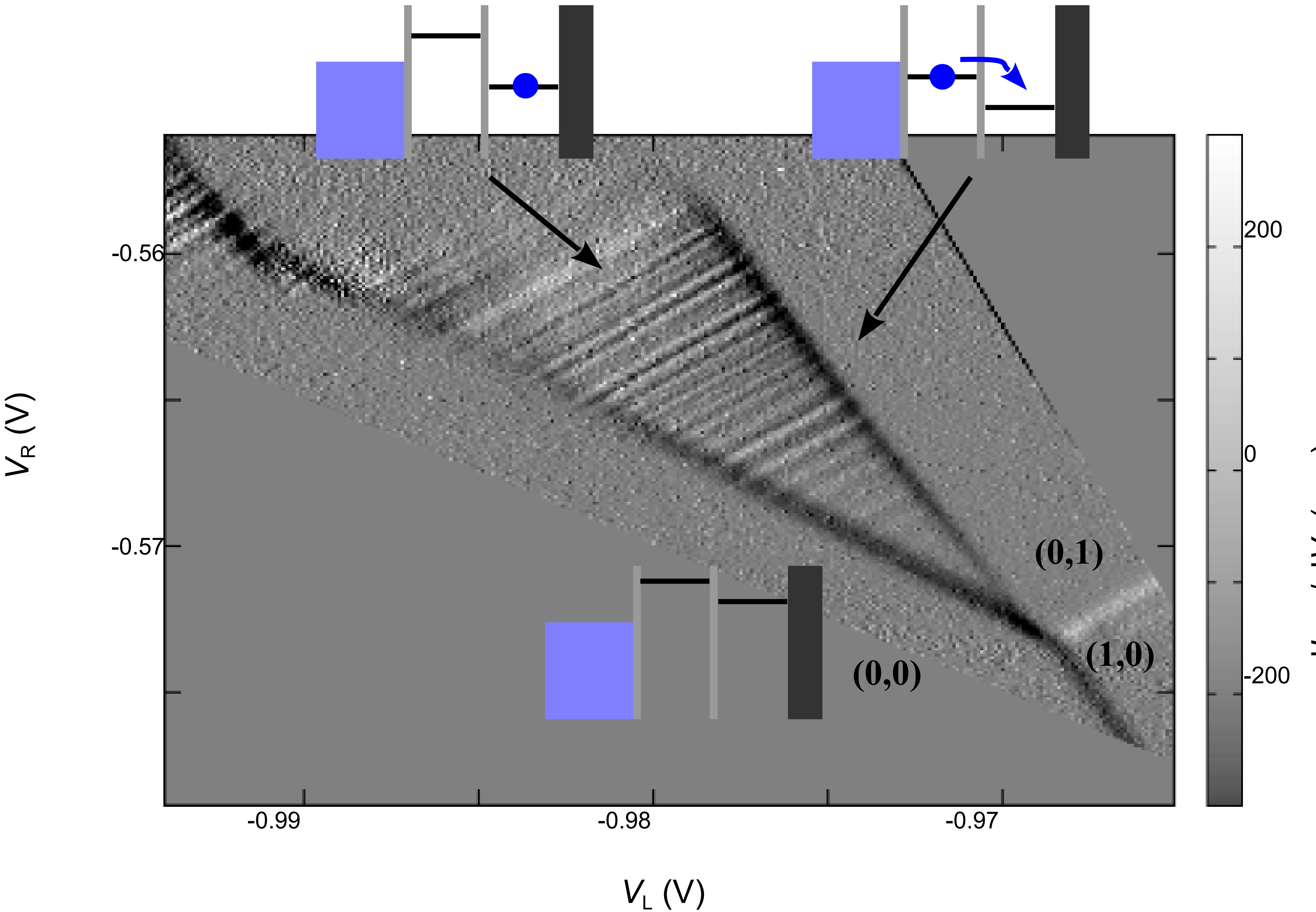
calculated after: J.S. Blakemore, Appl. Phys. 53, R123 (1982)

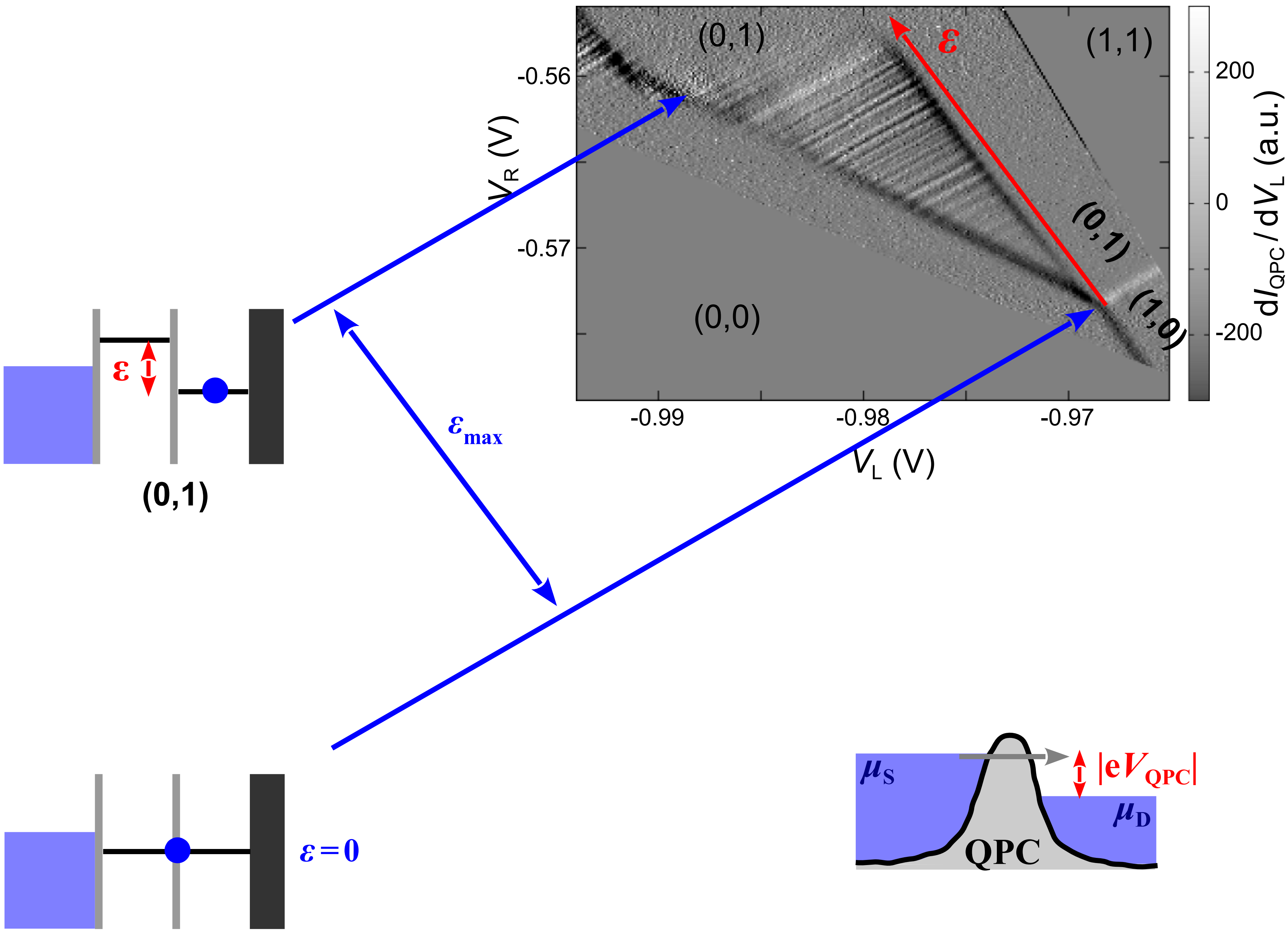


model calculations for different geometries

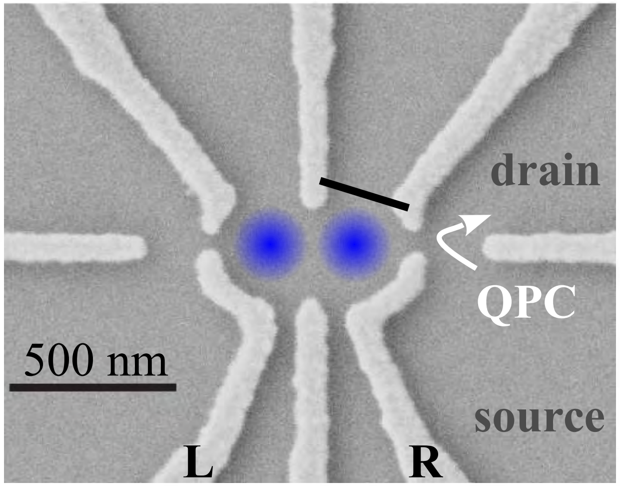


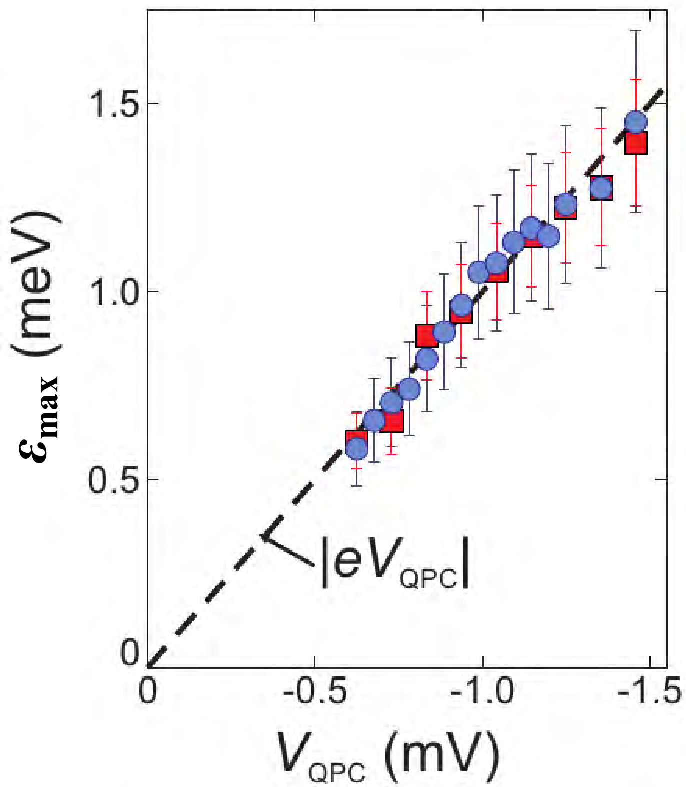
geometry of back action region

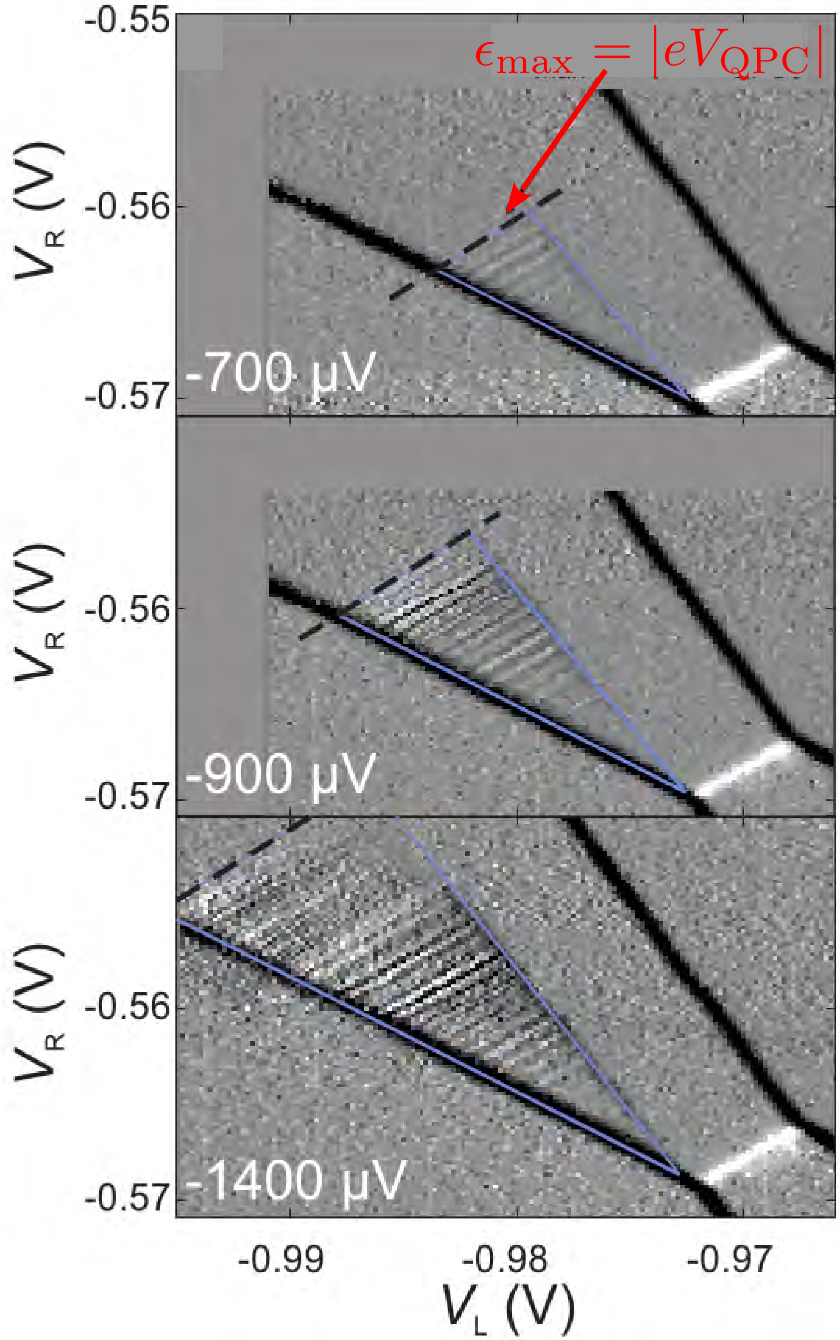


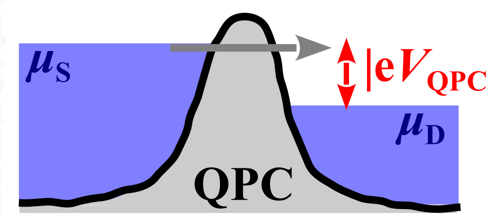

(0,1)
(1,1)
ε
-0.56
-0.57
V_R (V)
(0,0)
(0,1)
(1,0)
-0.99
-0.98
-0.97
V_L (V)
200
0
-200
dI_{QPC}/dV_L (a.u.)
ε
(0,1)
ε_{max}
$\varepsilon = 0$
μ_S
μ_D
$|eV_{QPC}|$
QPC

maximum triangle size as a function of V_{SD}









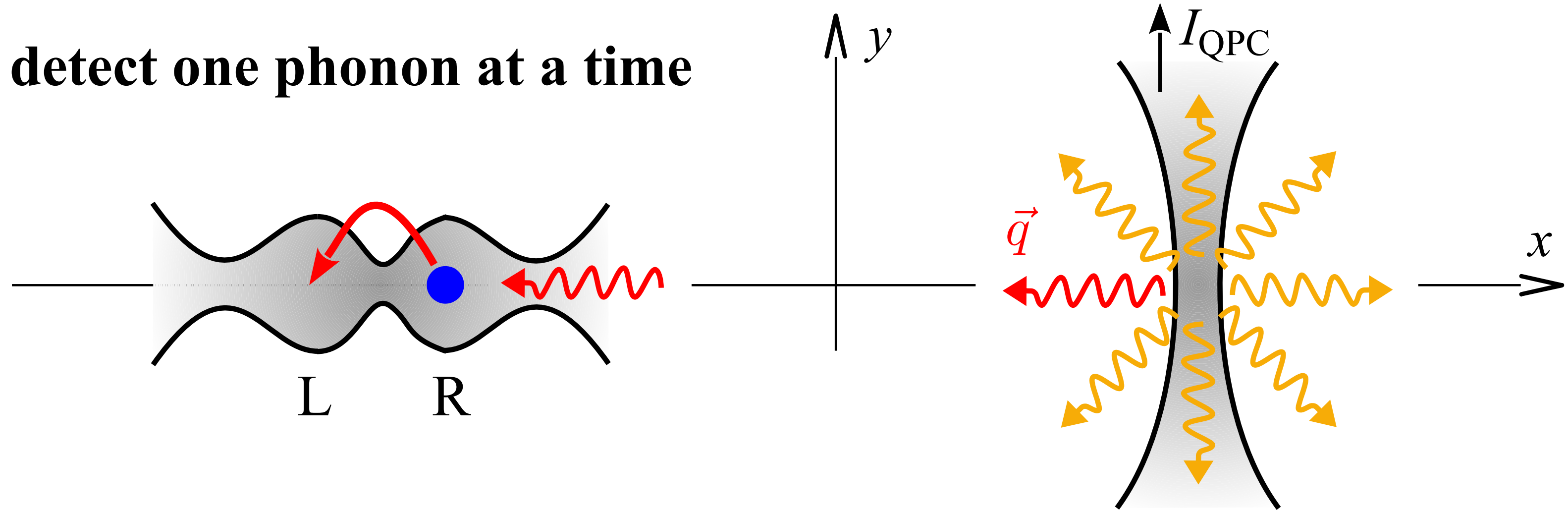
$$\epsilon_{\max} = |eV_{\mathrm{QPC}}|$$

$\Downarrow$

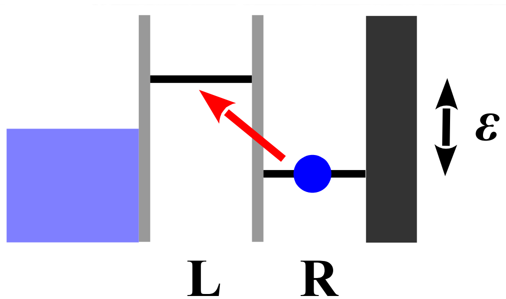
QPC is the energy source!

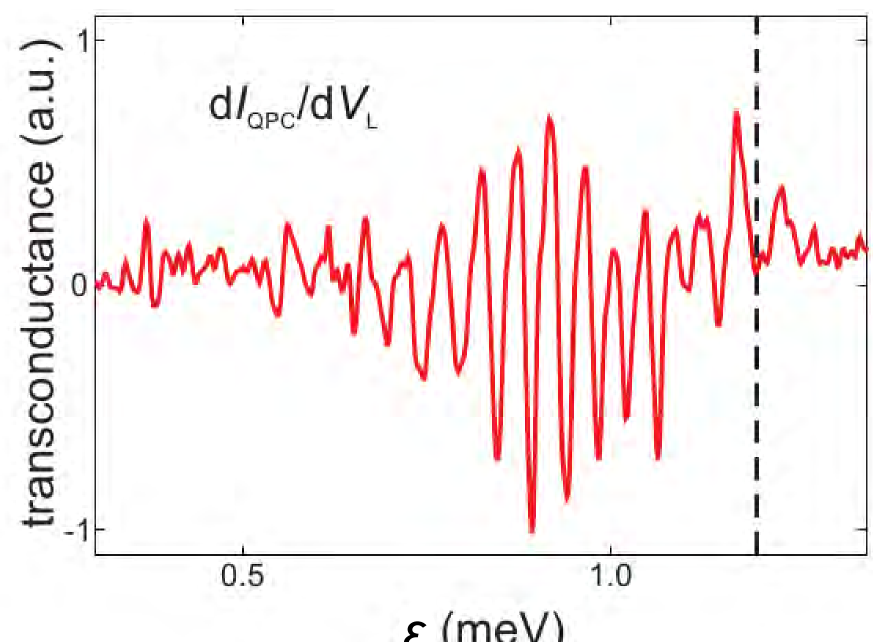
coupled quantum dots as single-phonon detector

- **we detect one phonon at a time**



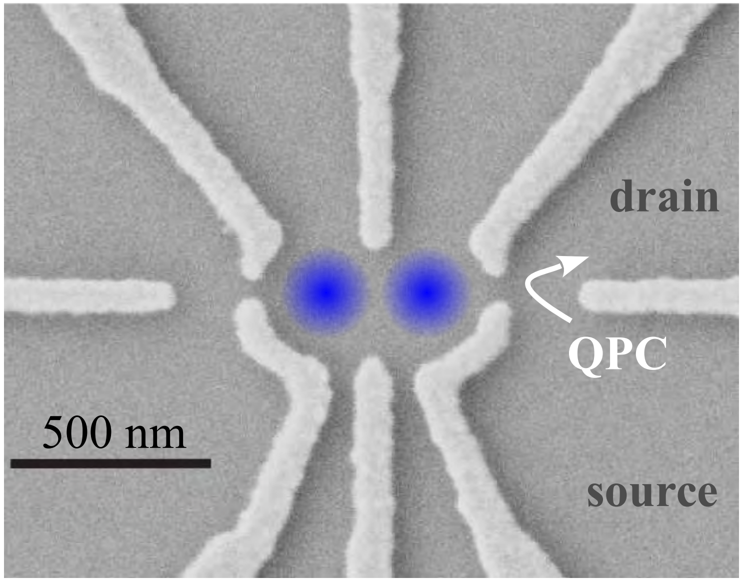
- **we can tune ε and, hence, measure the phonon spectrum**

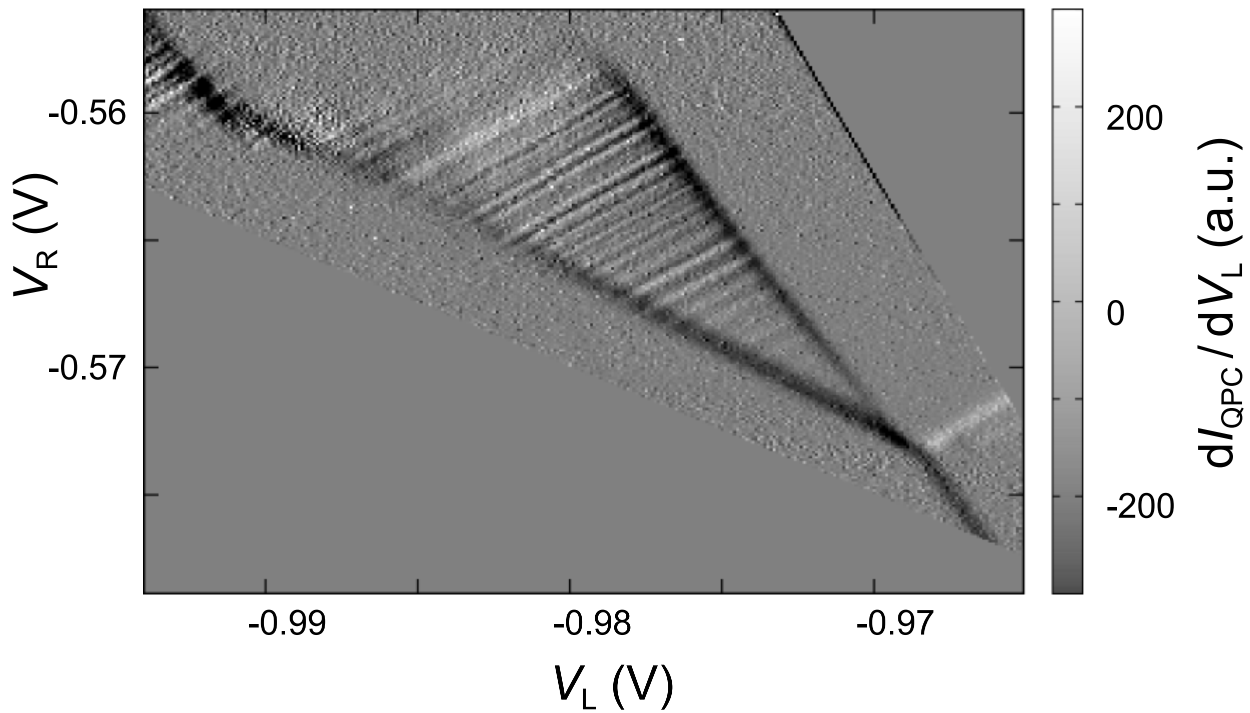




- **we are sensitive to different phonon modes**

SUMMARY – OUTLOOK





- **electron-phonon interaction is relevant in non-equilibrium mesoscopic circuits**
- **coherent electron-phonon coupling is accessible**
- **can we control single phonons ?**

Phys. Rev. Lett. ***102**, 186801 (2009)*
Phys. Rev. Lett. ***112**, 116803 (2014)*
Nature Phys. ***8**, 522 (2012)*