Towards quantum single electronics on liquid helium

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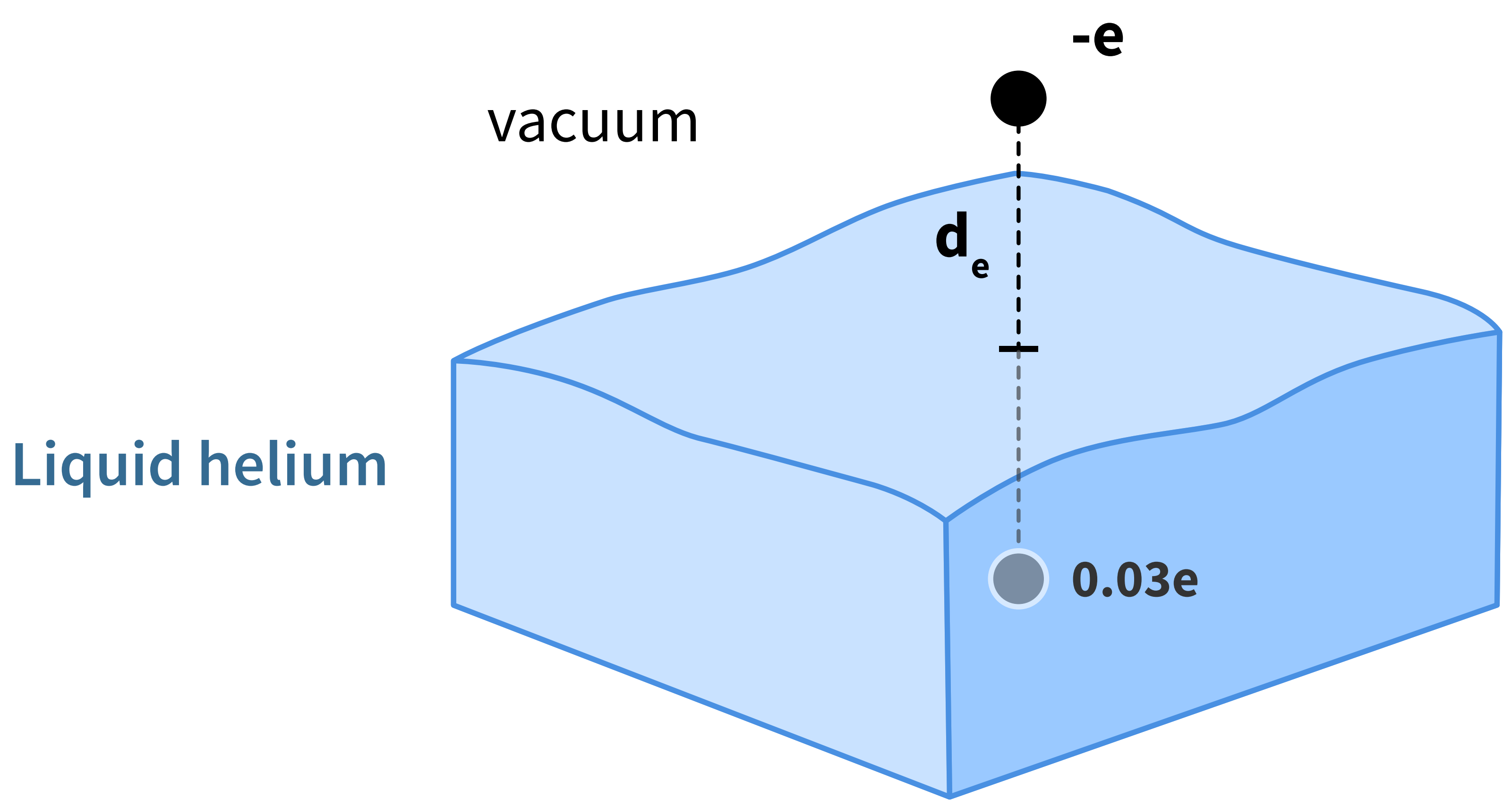
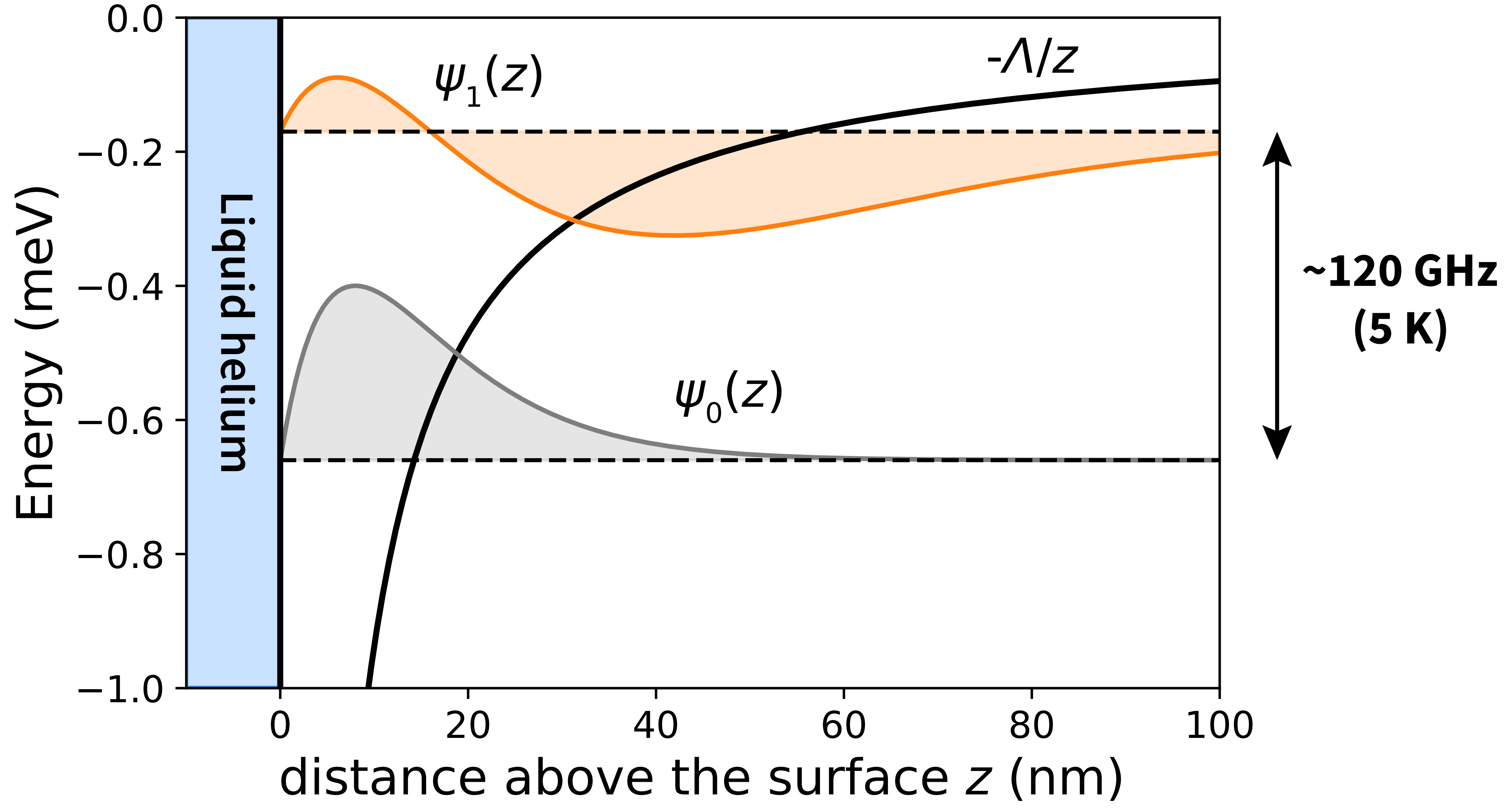
Electrons on helium





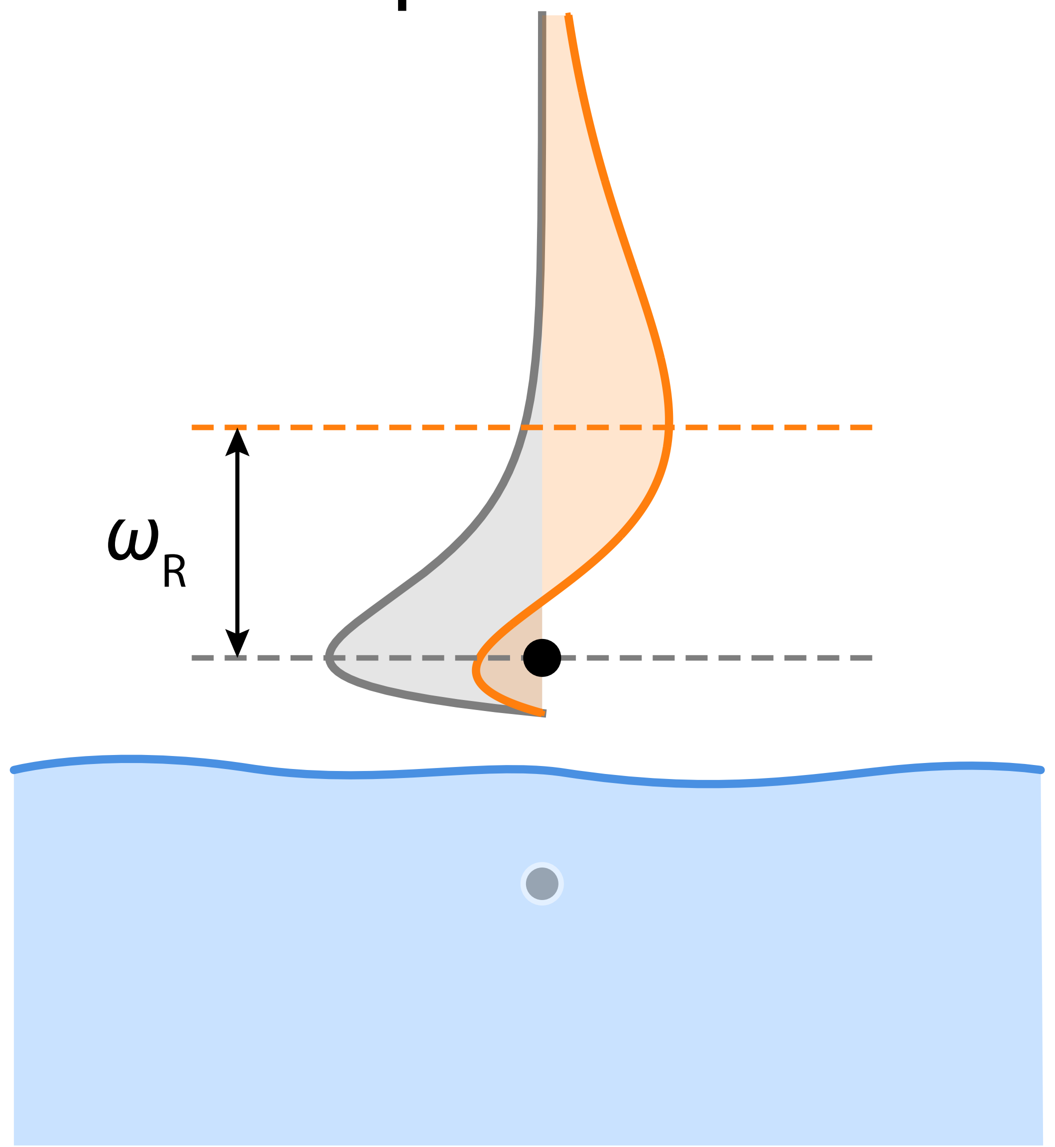
- Very high mobilities: $\mu > 10^7$ cm^2/(V s)
- Low densities: $n_s \approx 10^6$ - 10^9 cm^{-2}
- Almost no screening: long range Coulomb interactions

"1D Hydrogen atom" with Rydberg series of states

$$E_n = -\frac{m_e \Lambda^2}{2\hbar^2 n^2} \; (n = 1, 2, 3\ldots)$$

E_0 = - 0.66 meV (~ 160 GHz, 7.6 K)
E_1 = - 0.17 meV (~ 40 GHz, 1.9 K)

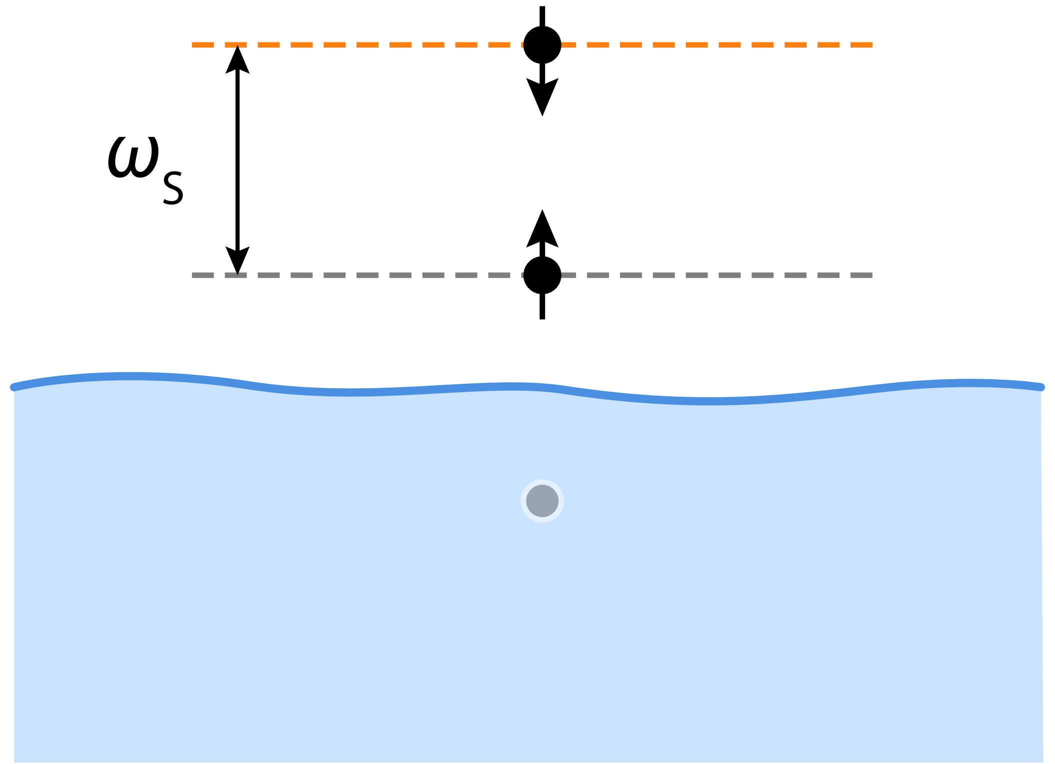
Qubit platforms with electrons on helium



Rydberg states

$\omega_R/2\pi = 120$ GHz

P.M. Platzman and M.I. Dykman
Science **284**(5422), pp.1967 (1999)

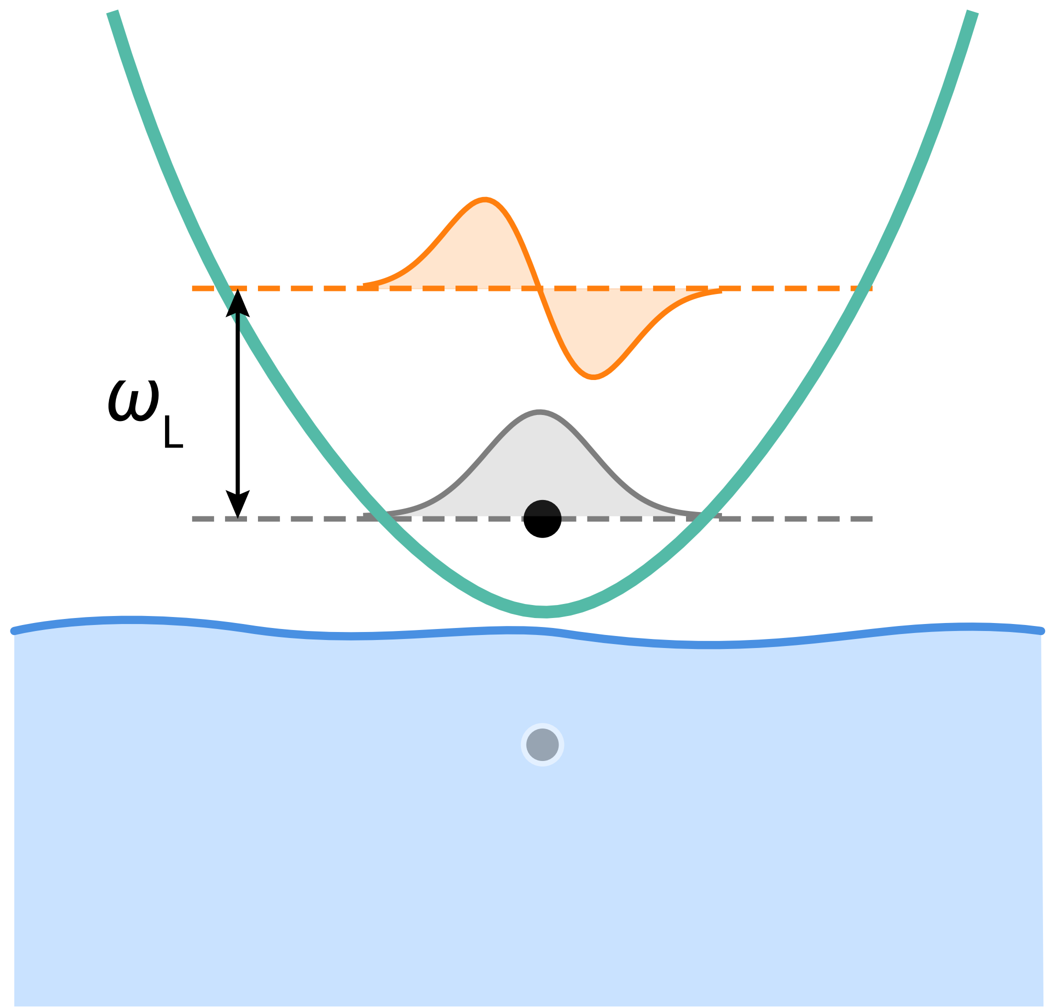


Spin states

$\omega_s/2\pi = 5$ GHz at $B = 0.2$ T

$(T_2 \approx 1.5$ s$)$

S. A. Lyon, *Phys. Rev. A* **74**, 052338 (2006)



Lateral motional states

$\omega_s/2\pi = 5$ GHz

D.I. Schuster et al., *Phys. Rev. Lett.* **105**, 040503 (2010)

D. Konstantinov - OIST (Okinawa)
A.Chepelianskii - Universite Paris-Sud

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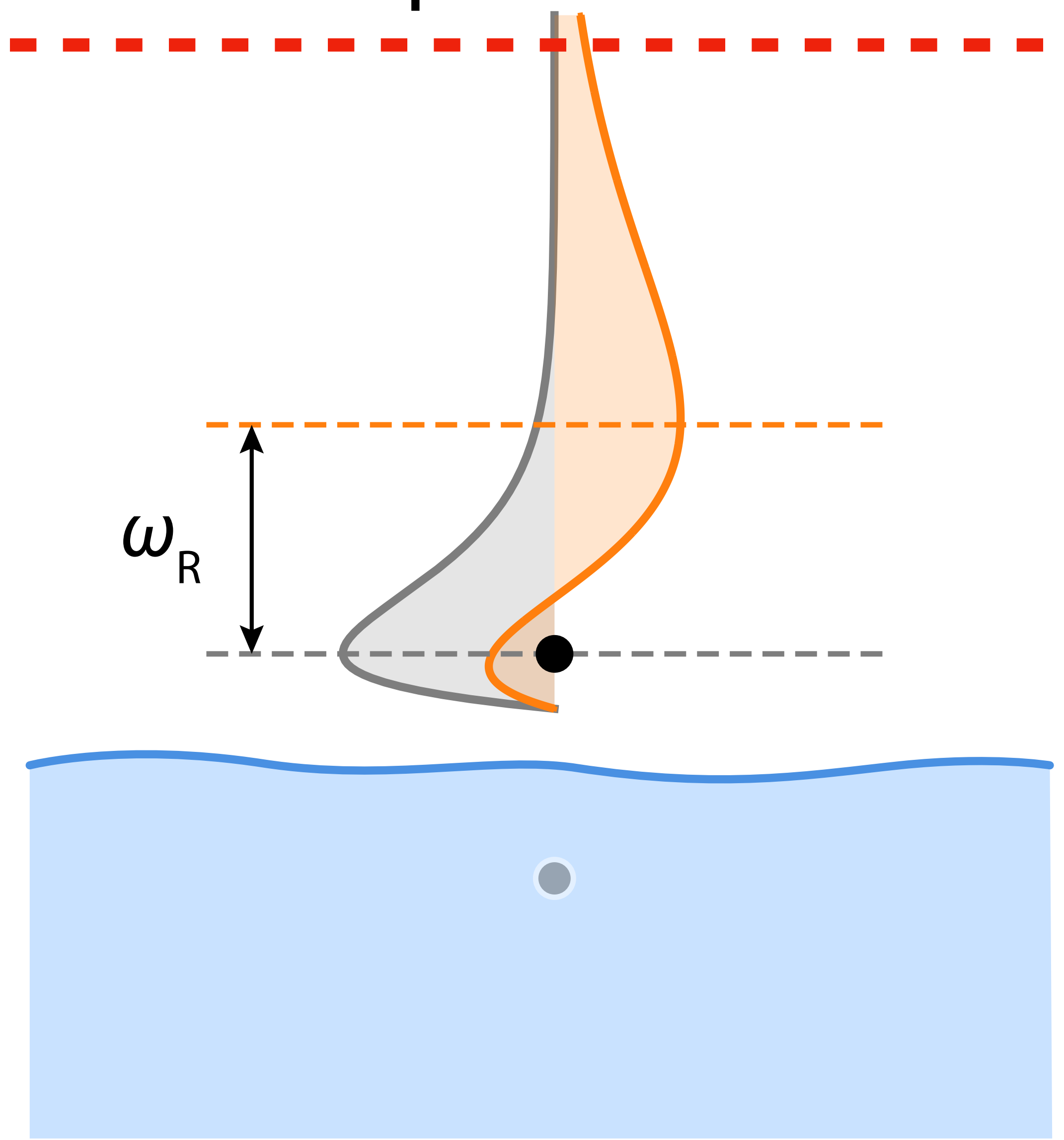

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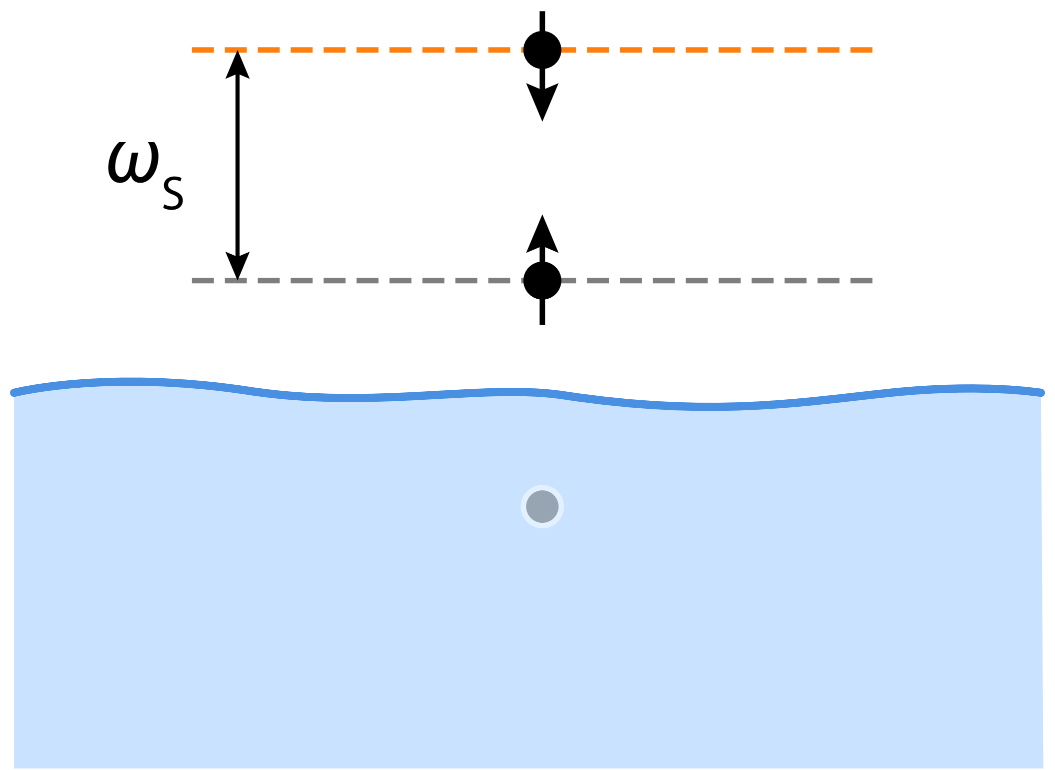

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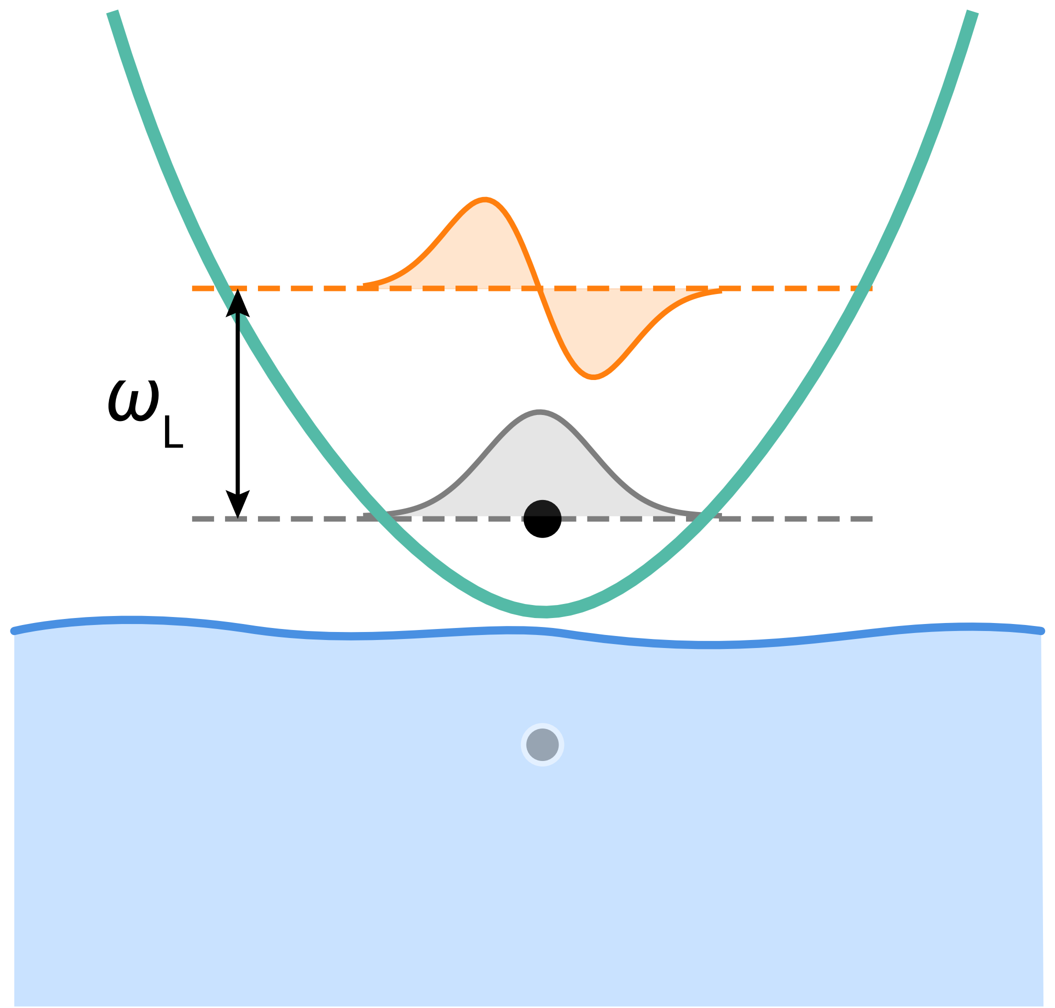

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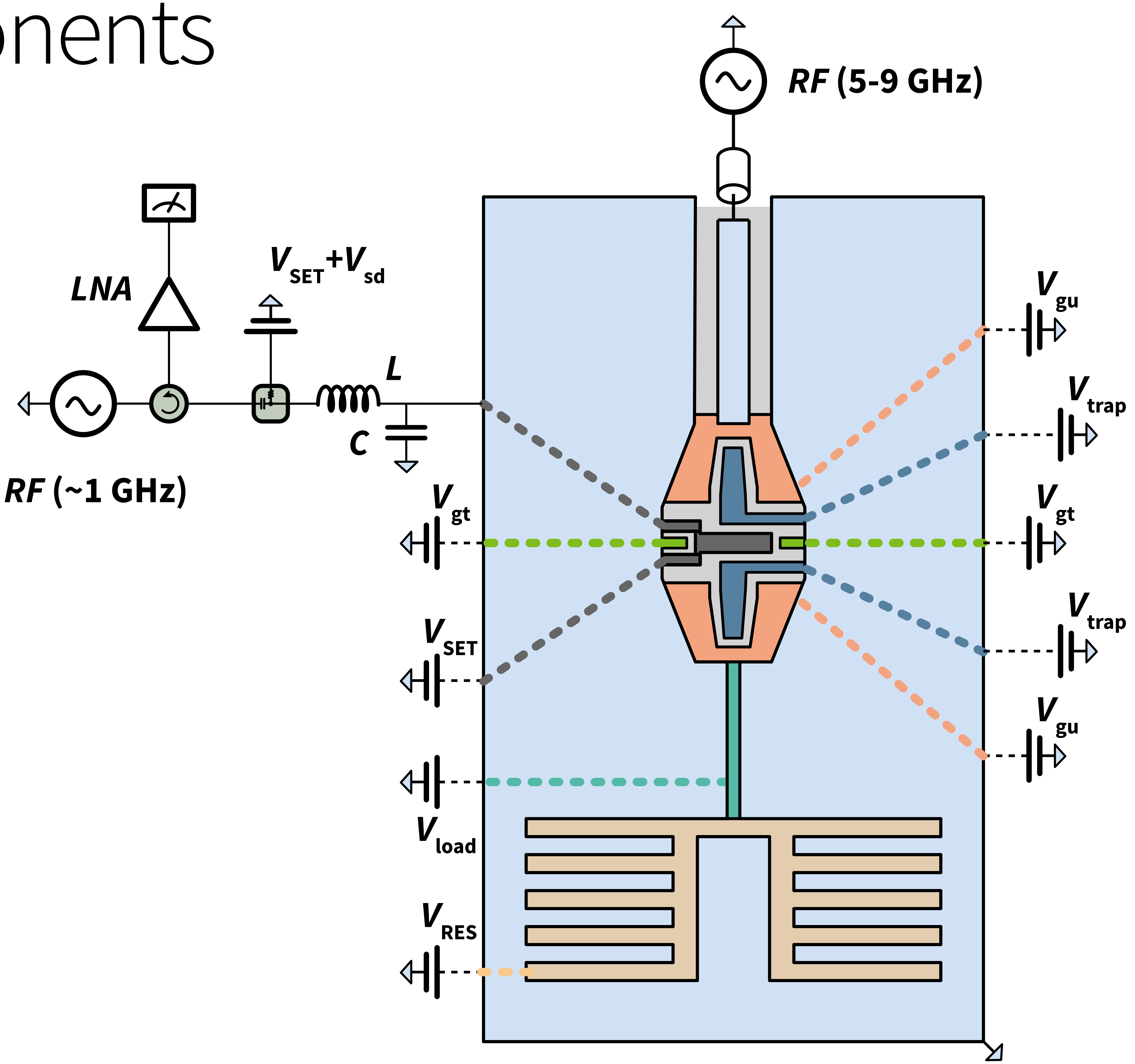
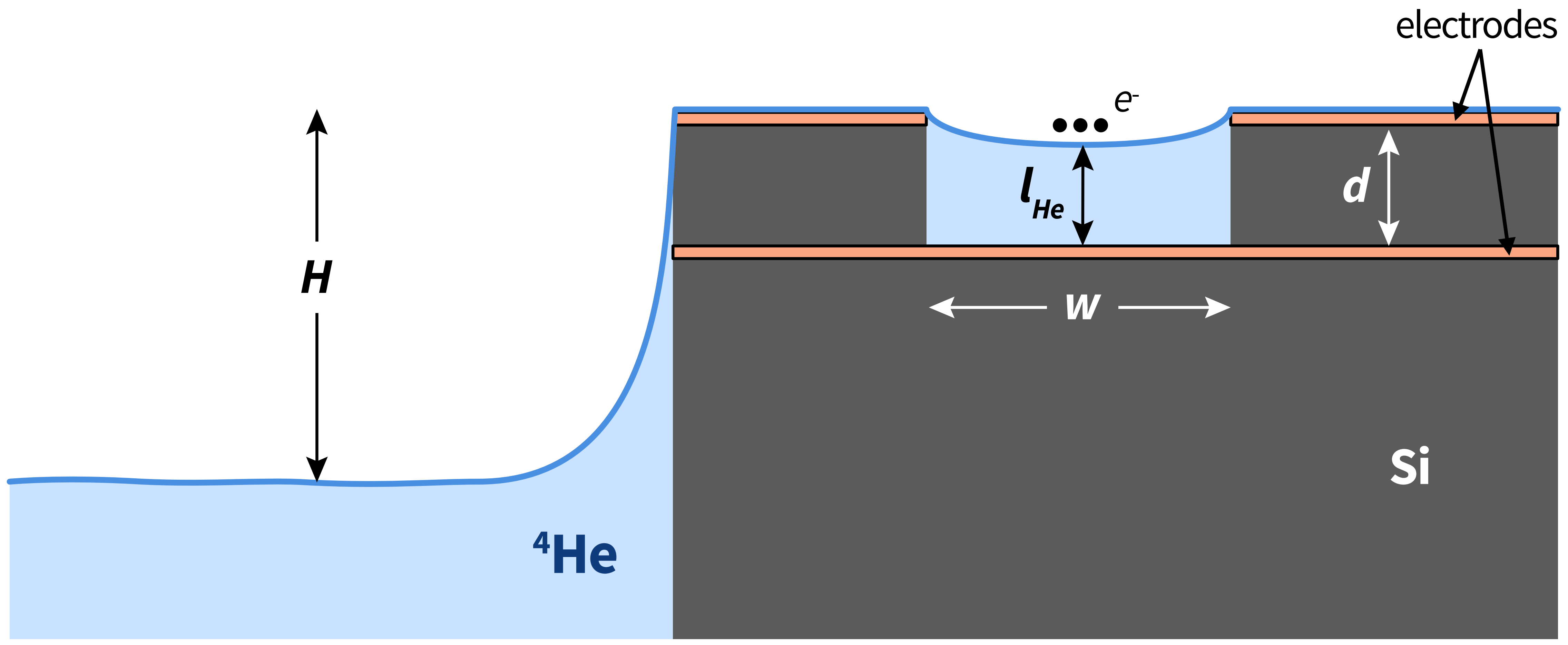
Device main components

1. **Electron storage/isolation**
2. **Single electron trap**
3. **MW excitation**
4. **Read-out scheme**
5. **Decoherence**



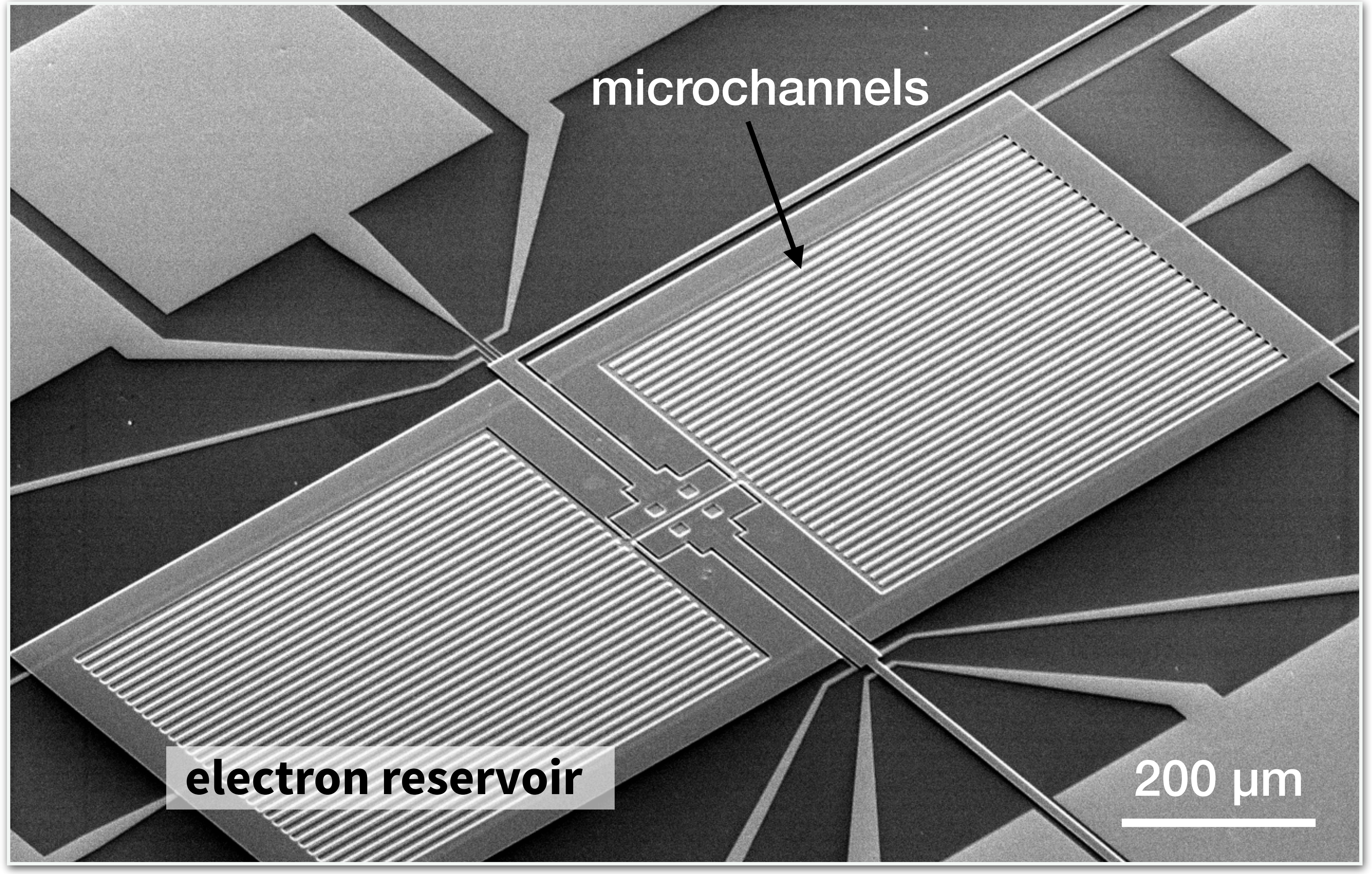
Electron storage/isolation



microstructures filled by capillary action of superfluid ^{4}He

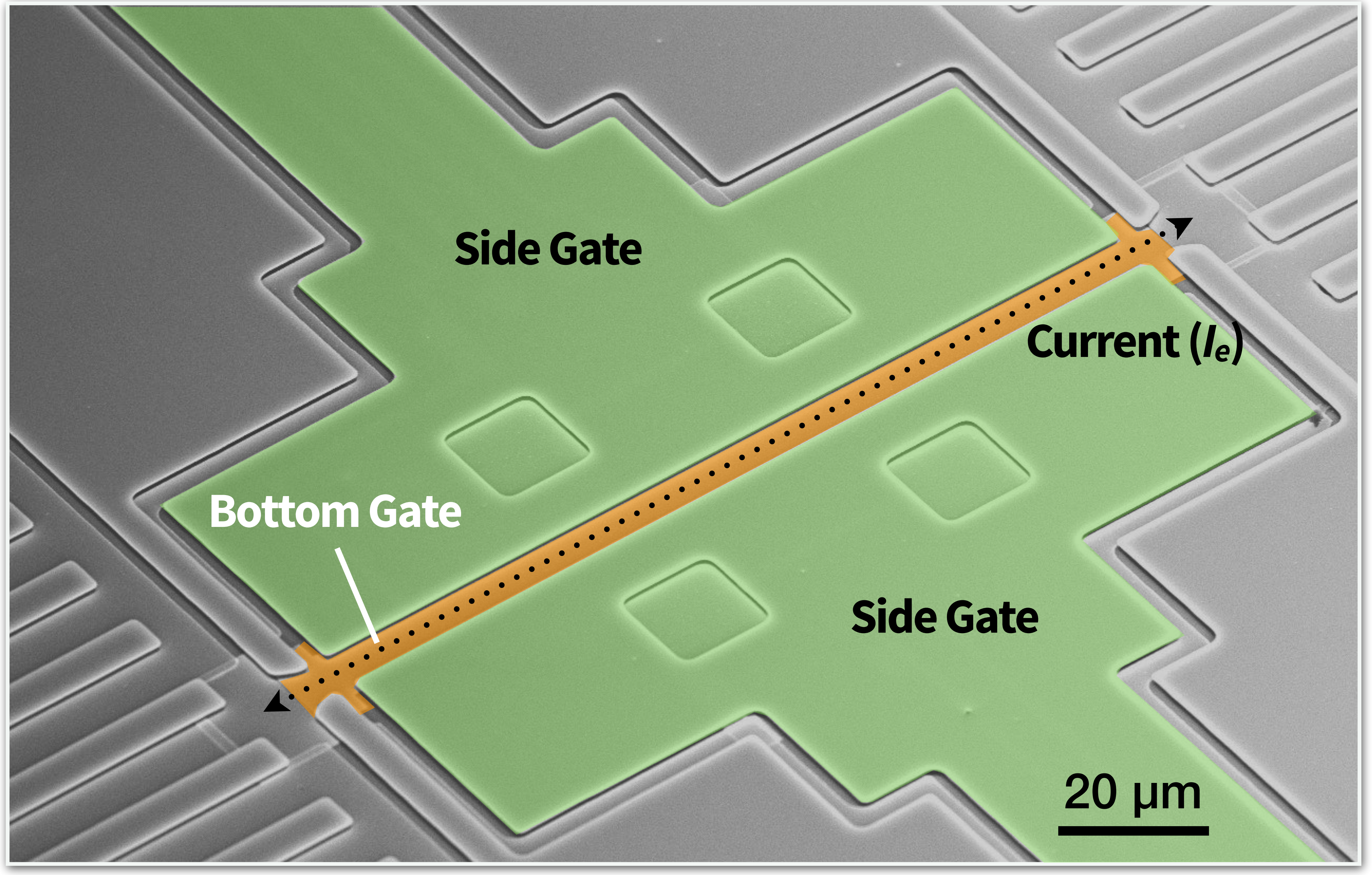
$$l_{He} = d - \frac{w^2}{8}\frac{\rho g H}{\alpha_t}$$

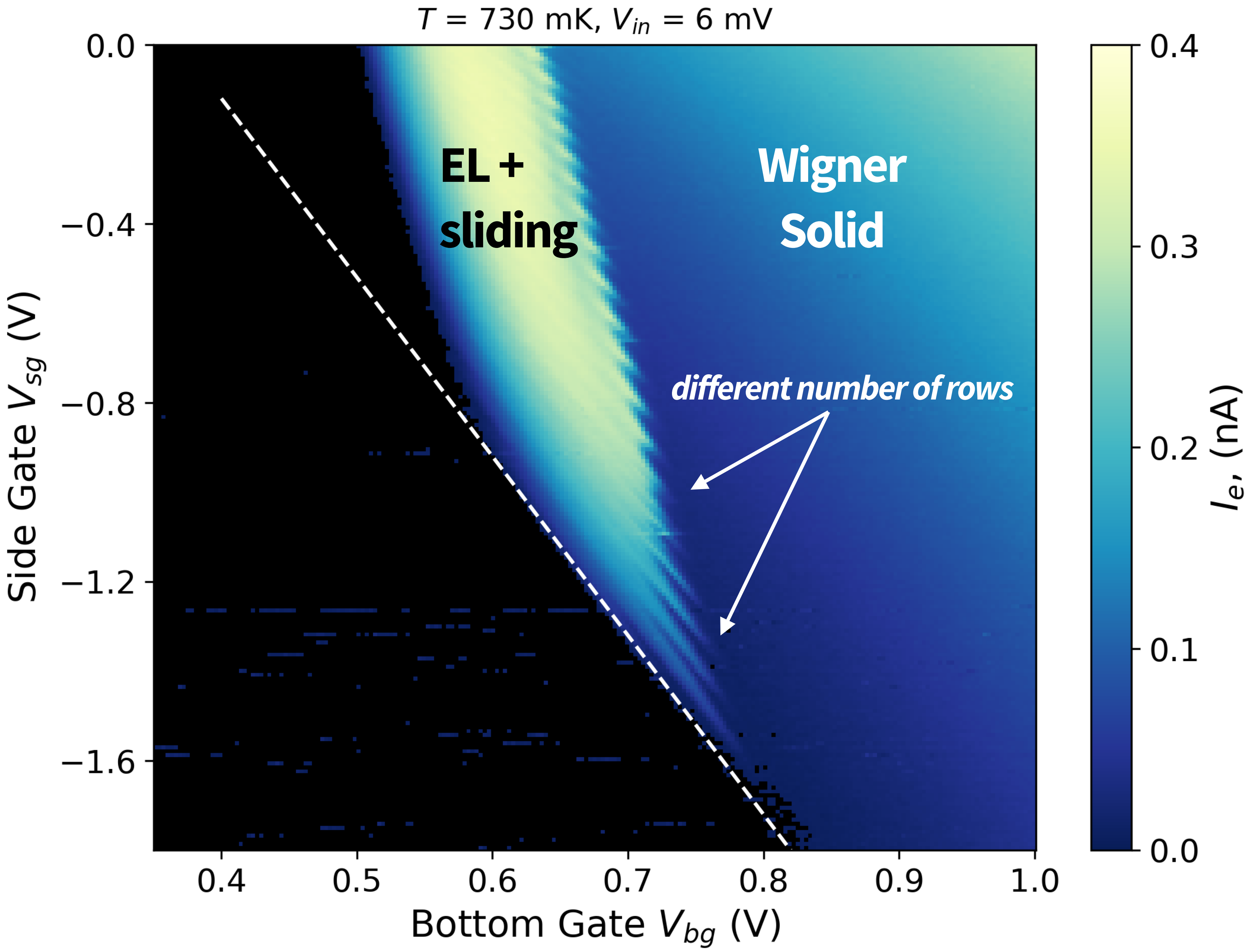
α_t - surface tension of liquid helium
ρ - density liquid helium



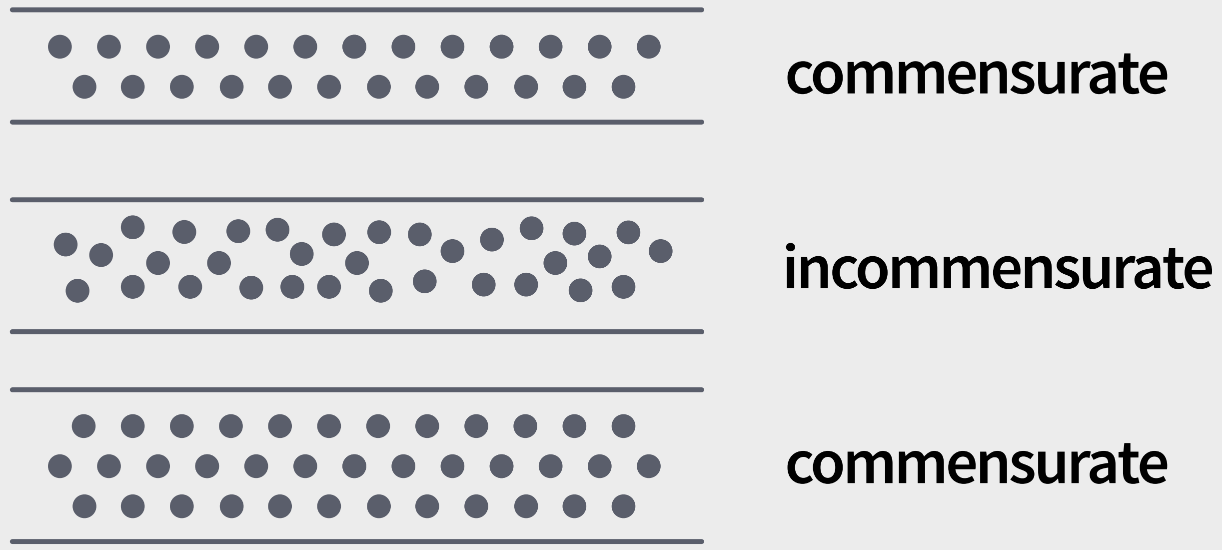
Electron Reservoirs:
Set of long helium microchannels is used to store electrons

Microchannel device





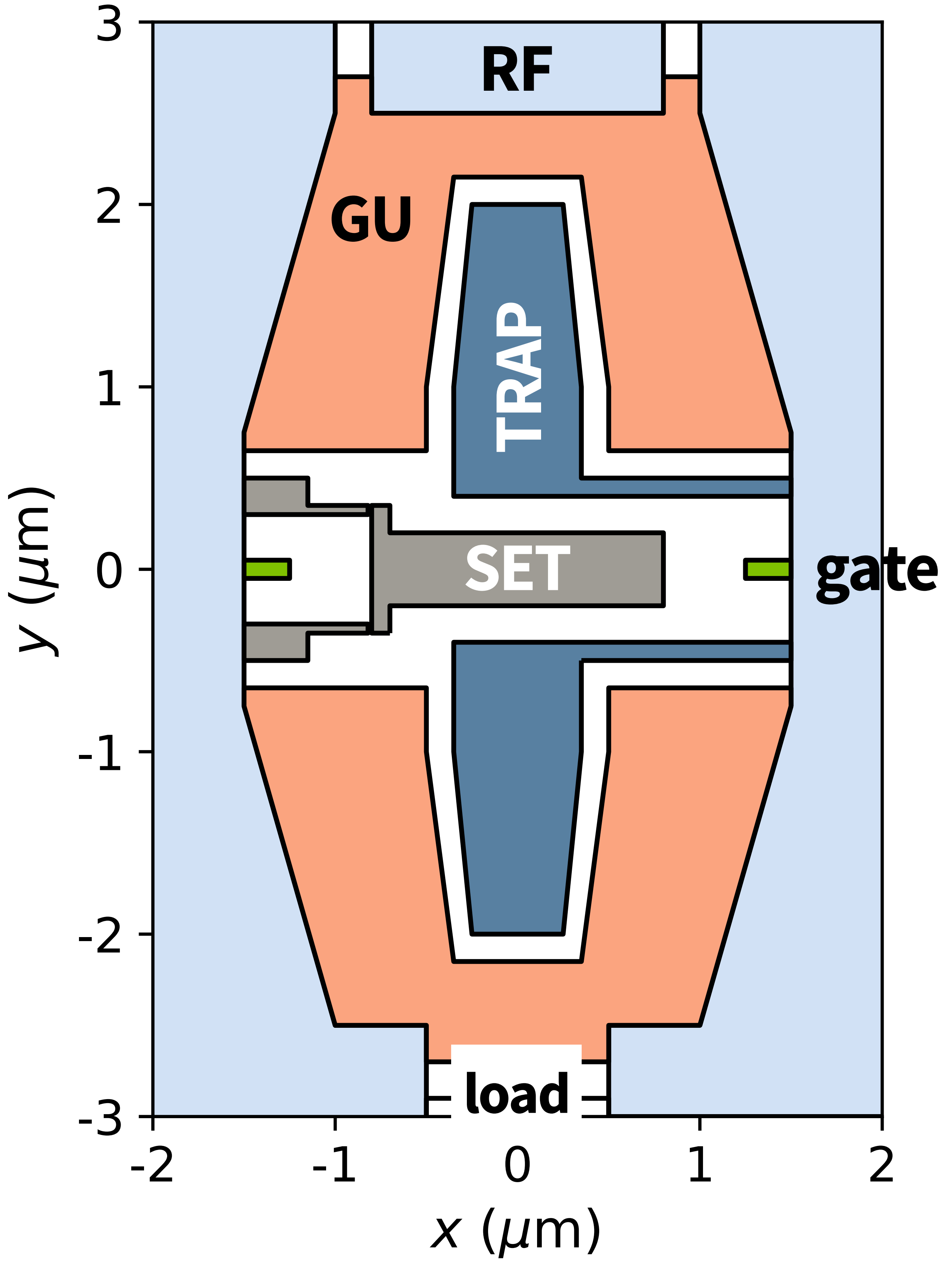
At structural transitions between adjacent N_y increased lattice defects reduce positional order. Therefore the Bragg ripplon scattering weakens and the electron mobility increases.

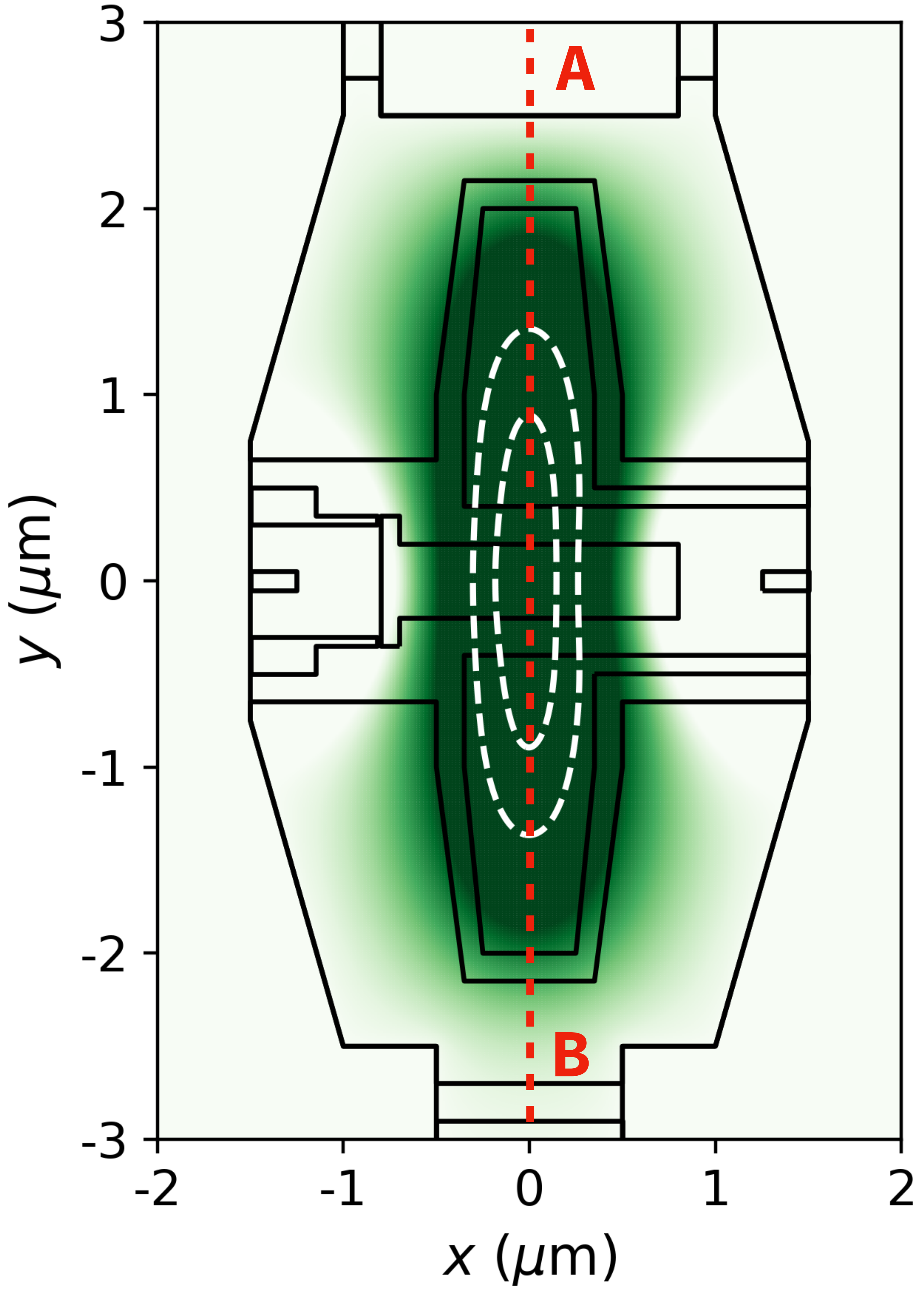


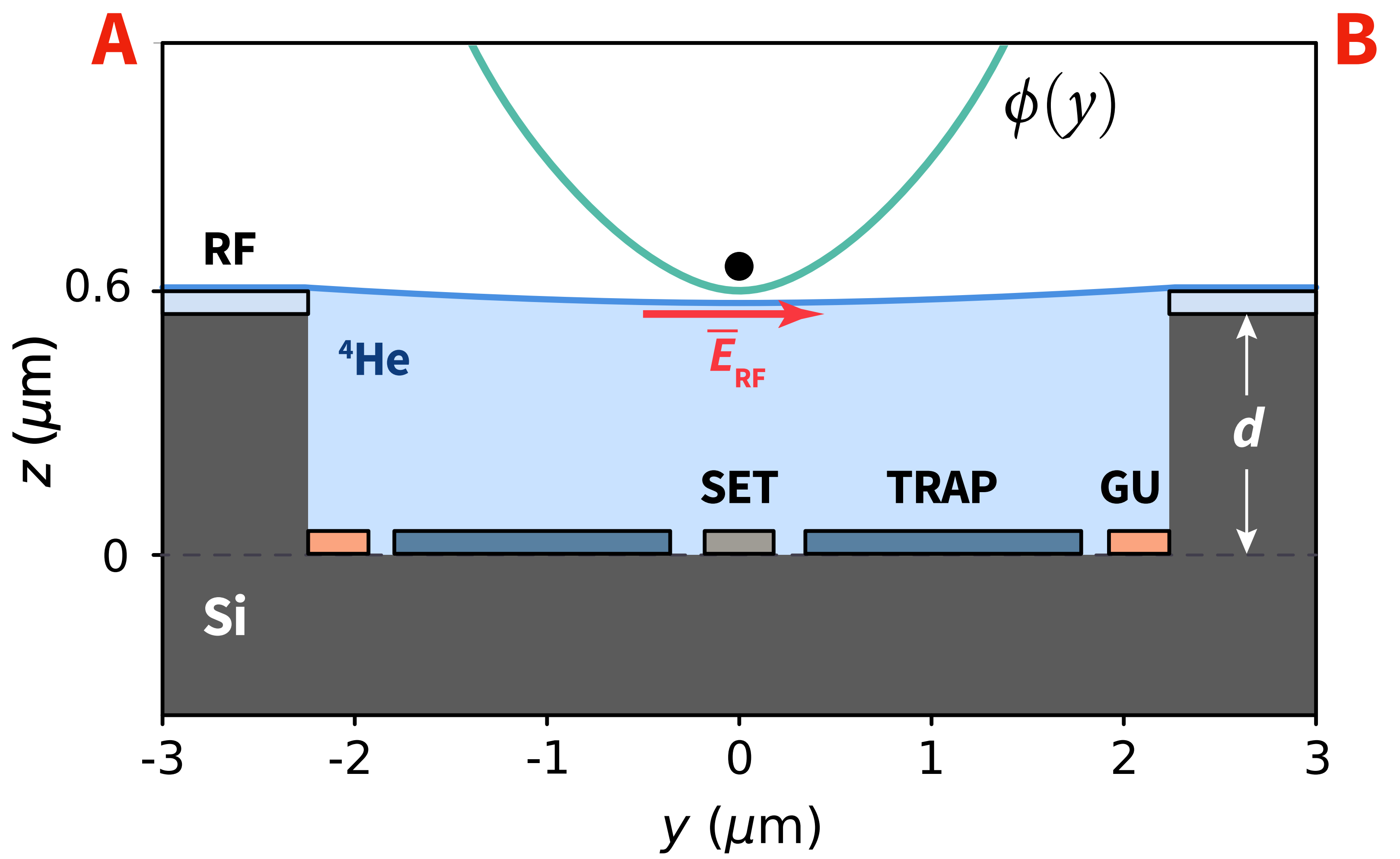
see more in *PRL* **116**, 20680 (2016) and *PRB* **94**, 045139 (2016)

Single electron trap

trap size 3 x 5 μm²







Finite Element Modelling

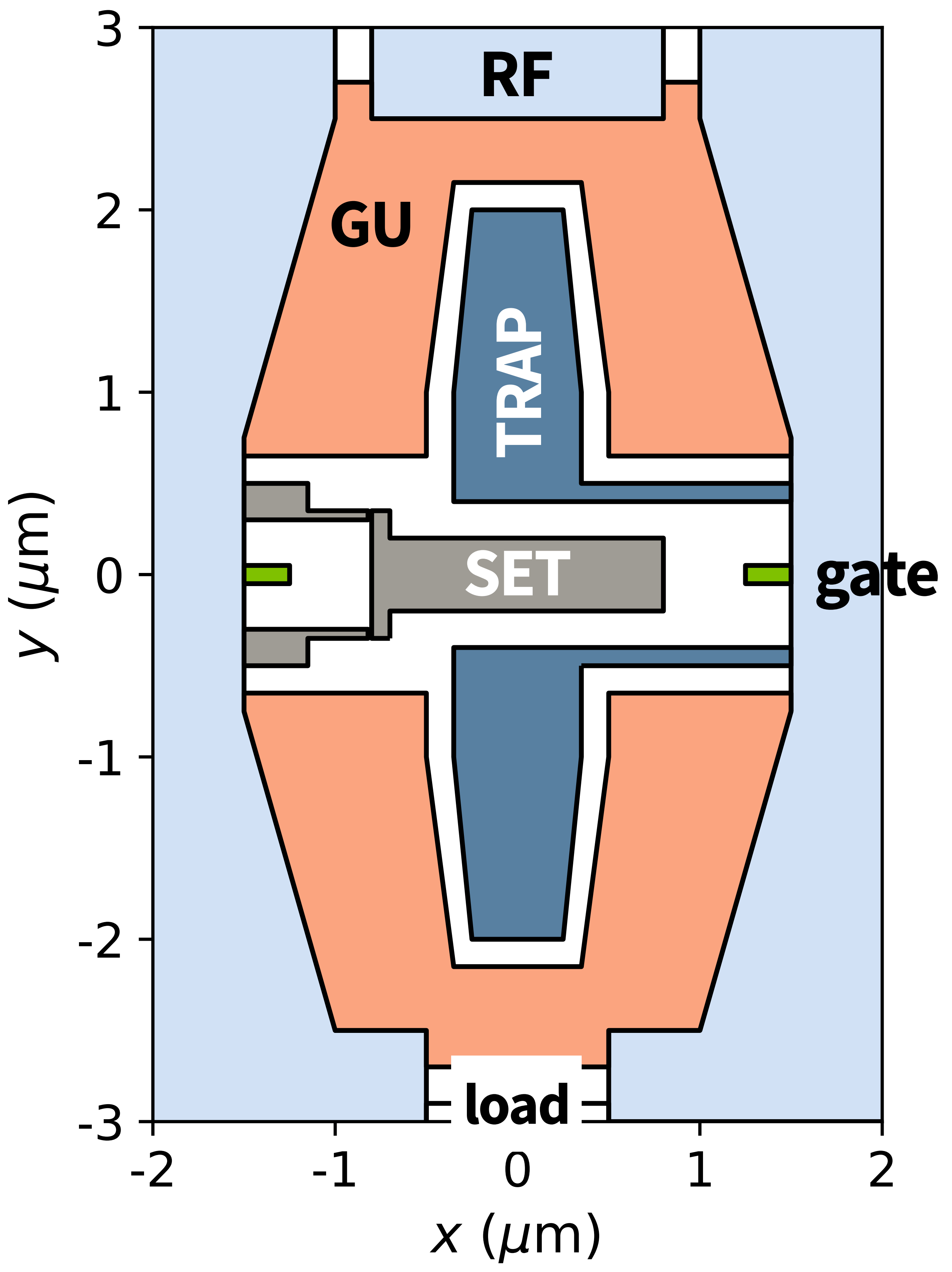
trap potential $\Delta\phi(x, y, z) = 0$

energy states $-\dfrac{\hbar^2}{2m}\nabla^2\psi + V(x, y, d_{He})\psi = E\psi$

Single electron counting with SET

P. Glasson et al., *J. Phys. Chem. Solids*, *66*(8-9), pp.1539-1543 (2005)
E. Rousseau et. al., *Phys. Rev. B* **79** 045406 (2009)

Single electron trap



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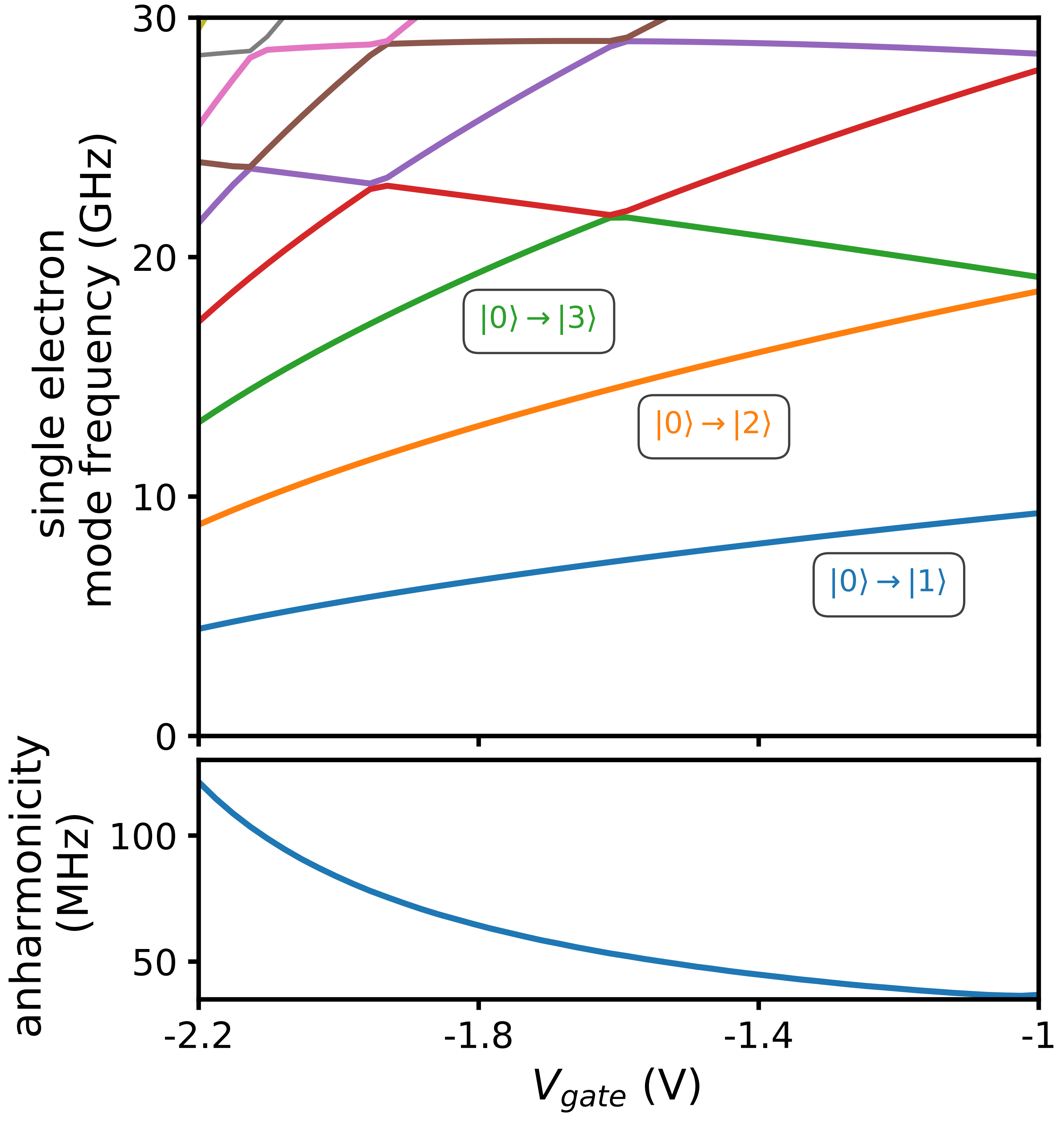
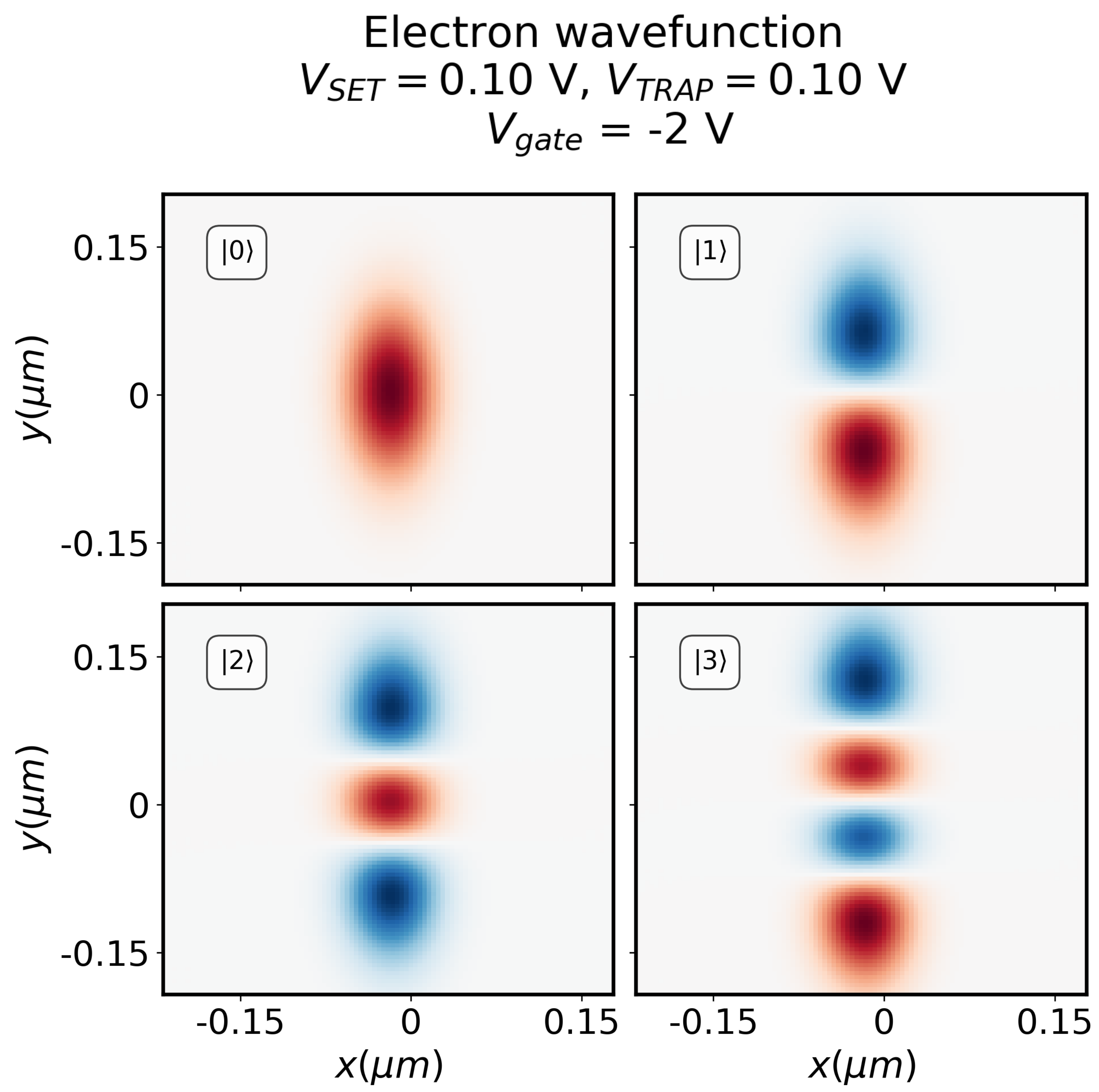
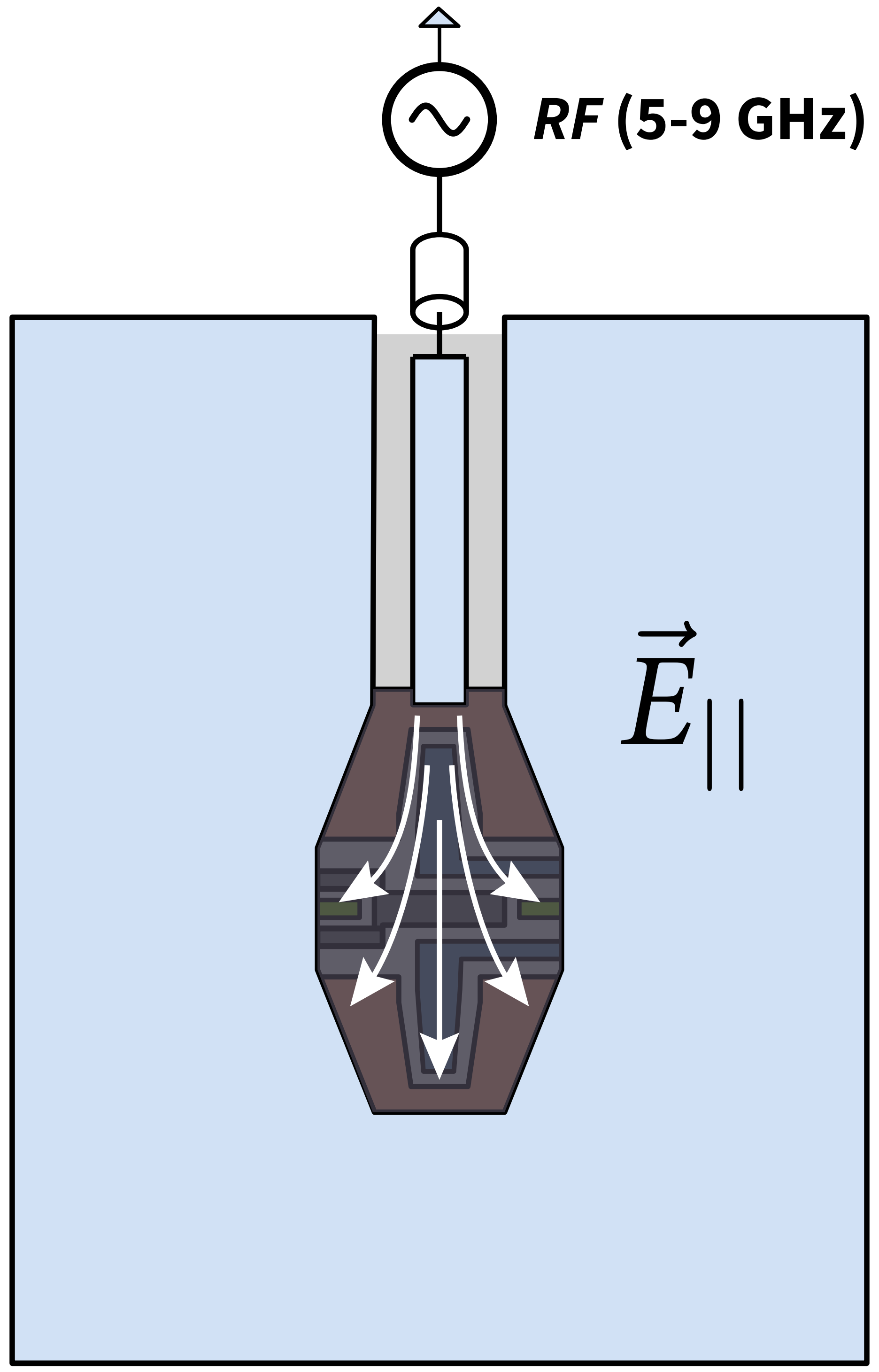


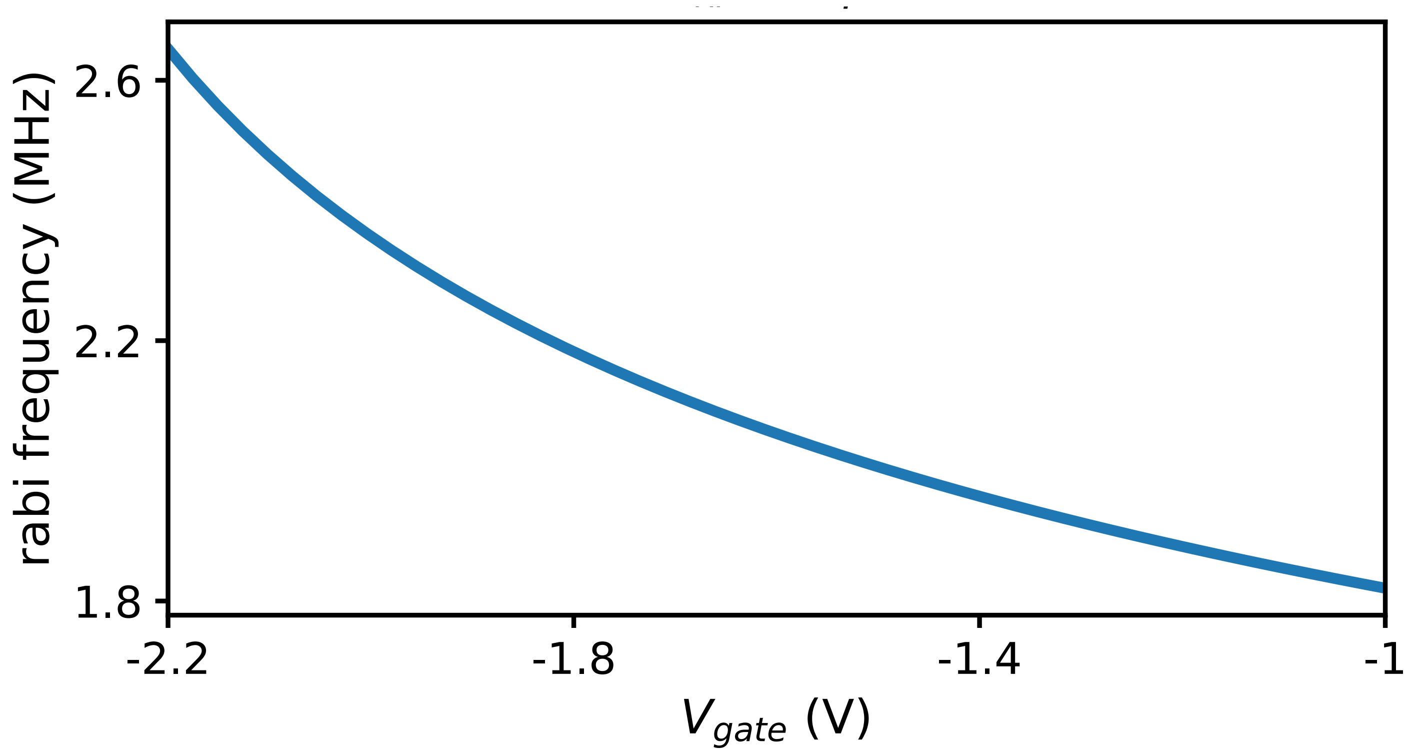


MW excitation



Coplanar waveguide

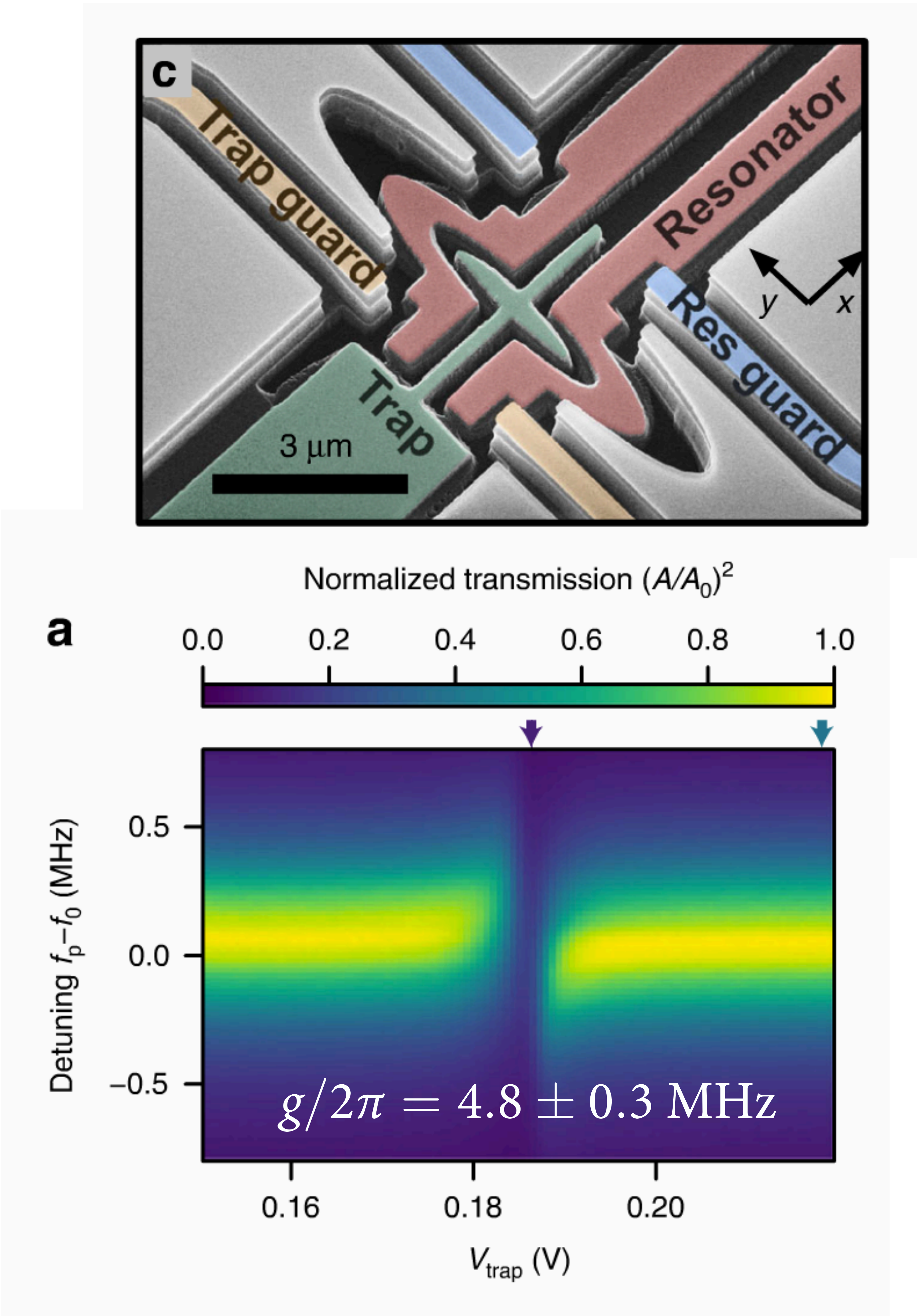
Electric field $E_{||} = 2 \cdot 10^{-2}$ MV/m per V



coupling constant (Rabi frequency)

$$g/2\pi = -\vec{d} \cdot \vec{E}_{||}/h = 2.4 \text{ MHz for } V_{\mathrm{RF}} = 10\mu\mathrm{V}$$

G. Koolstra et al., *Nat.Comm.* **10**, 5323 (2019)



Decoherence mechanisms

1. Decay via two-ripplon process
$$\Gamma_{2r}^{(\mathbf{q})} \approx 5 \cdot 10^2\mathrm{Hz}$$

2. Decay via phonons
$$\Gamma_{ph}^{(\mathbf{Q})} \approx 3 \cdot 10^4\mathrm{Hz}$$

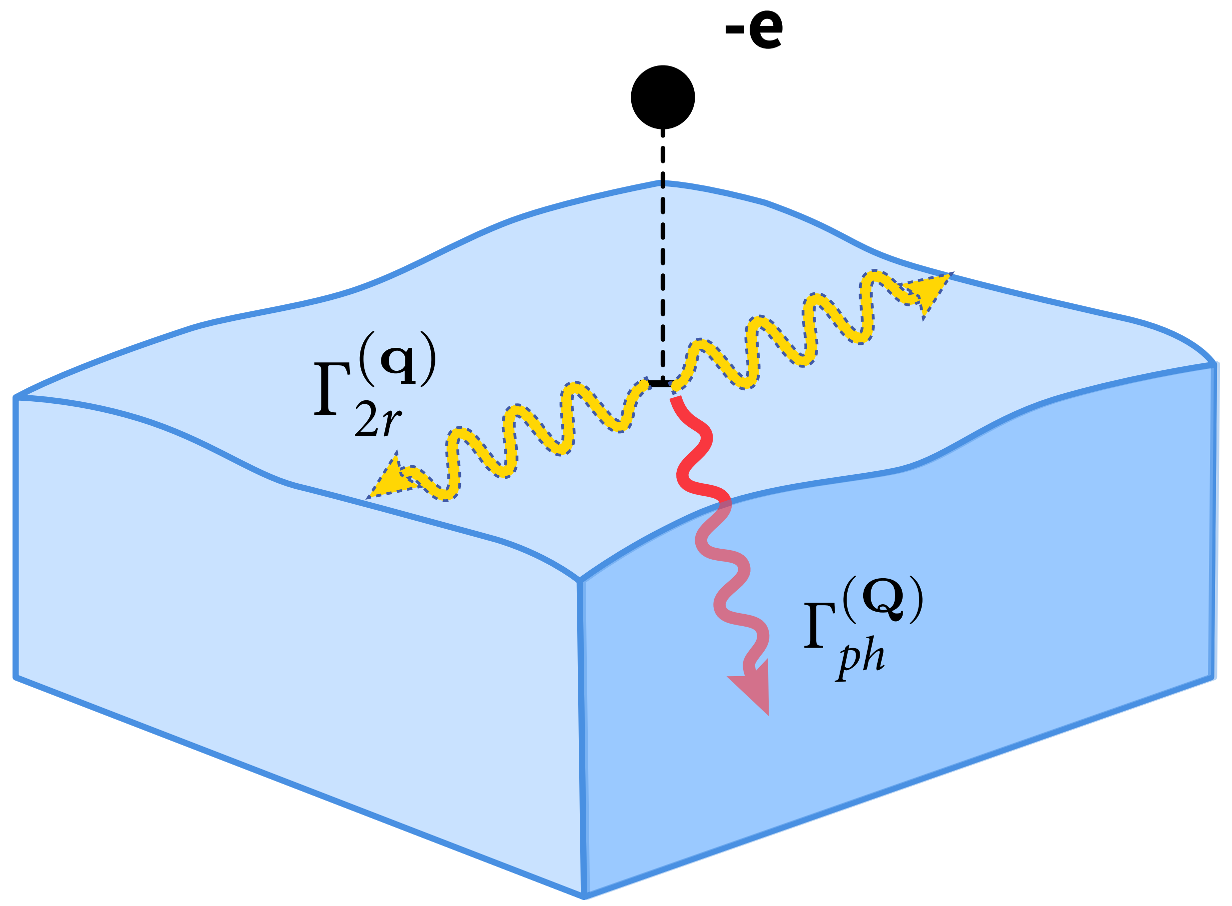
3. Electron dephasing

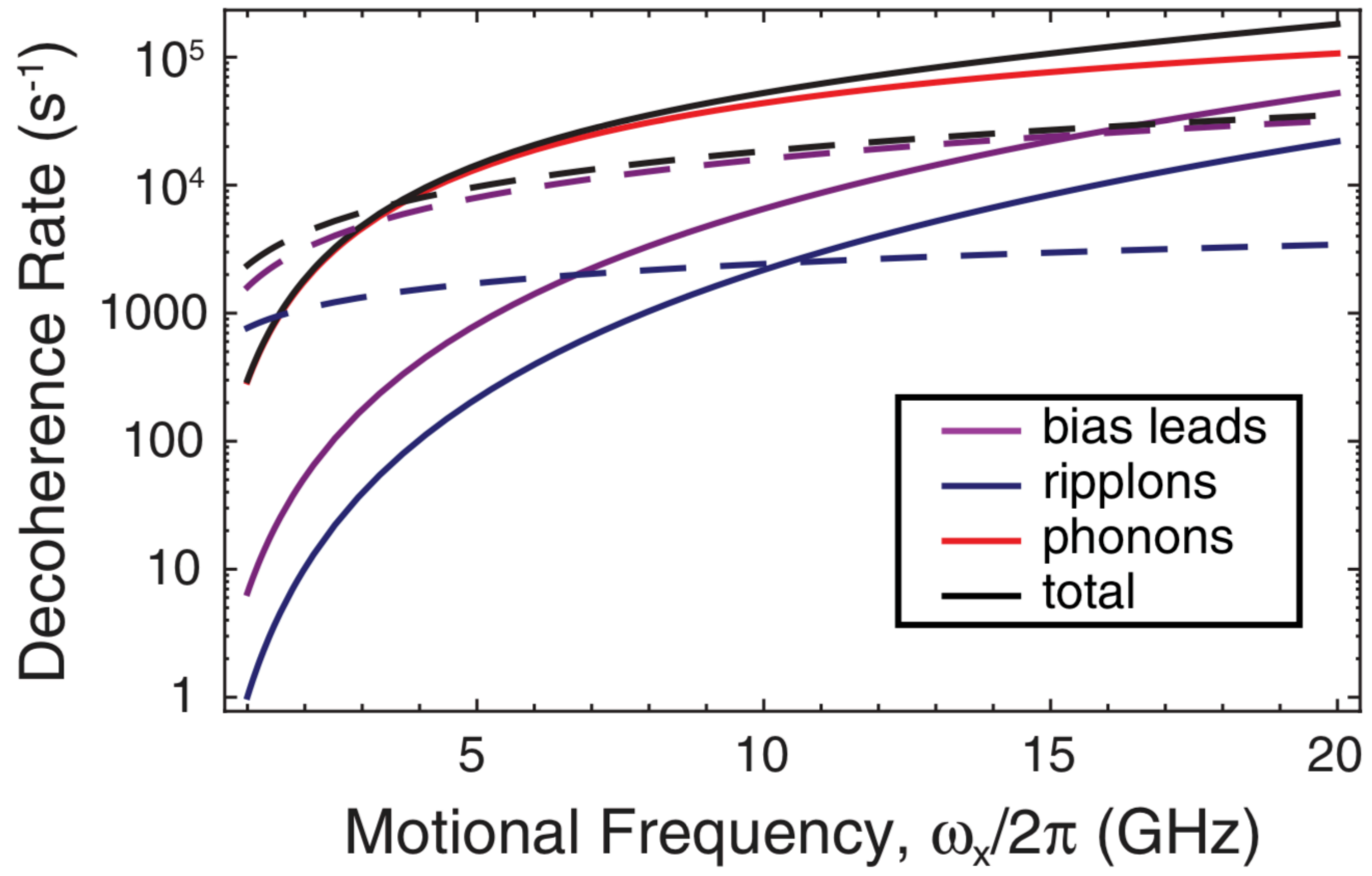
thermal Johnson noise $\Gamma_J^{(\varphi)} < 100\mathrm{Hz}$

1/f charge noise $\Gamma_{1/f}^{(\varphi)} \approx 10^4\mathrm{Hz}$

$$g \gg \Gamma_{2r}^{\mathbf{q}}, \Gamma_{ph}^{\mathbf{Q}}, \Gamma_J^{\varphi}, \Gamma_{1/f}^{\varphi}$$

M. Dykman et al., *Phys. Rev. B.* **67**, 155402 (2003)



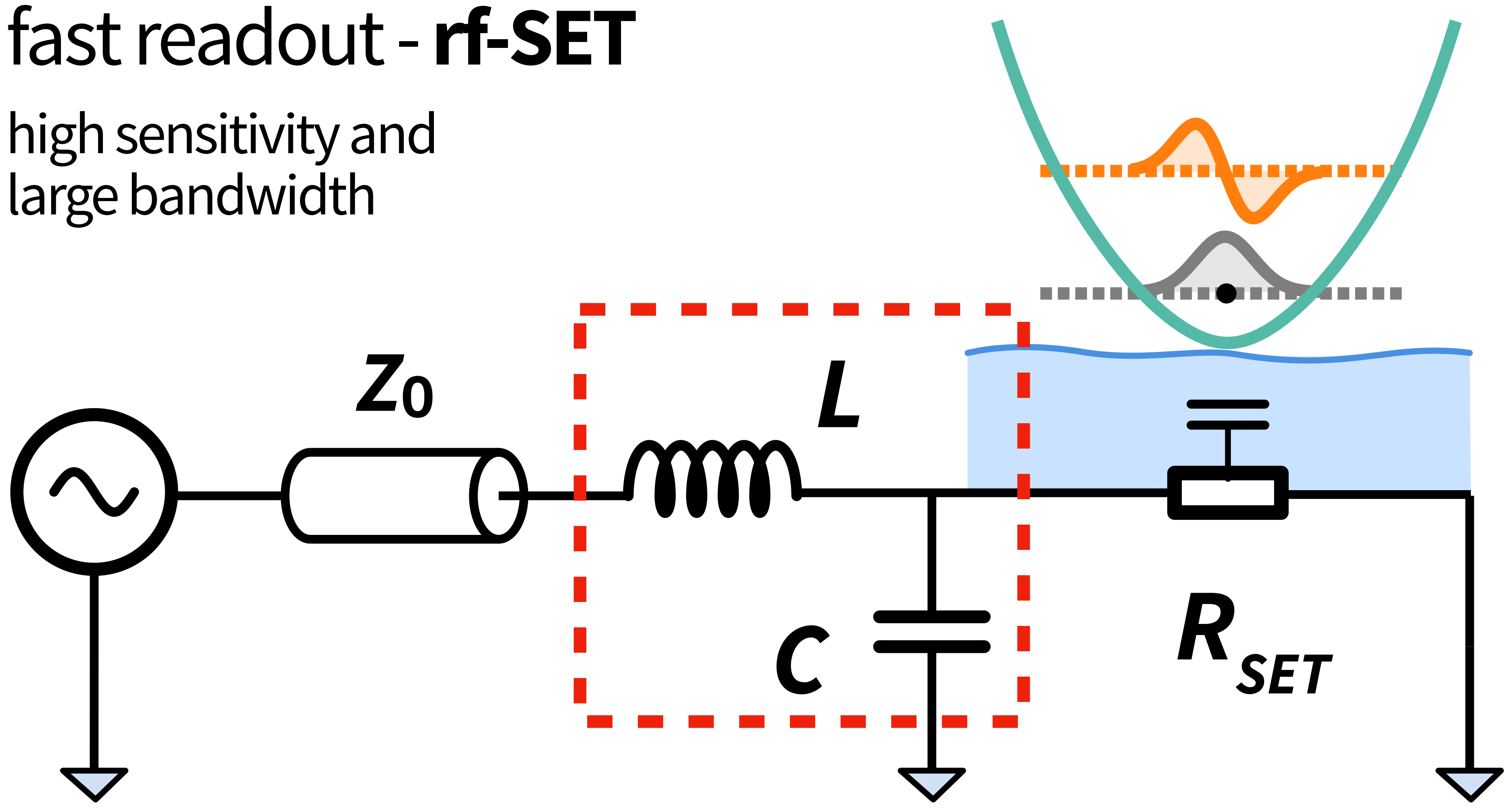


D.I. Schuster et al., *Phys. Rev. Lett.* **105**, 040503 (2010)

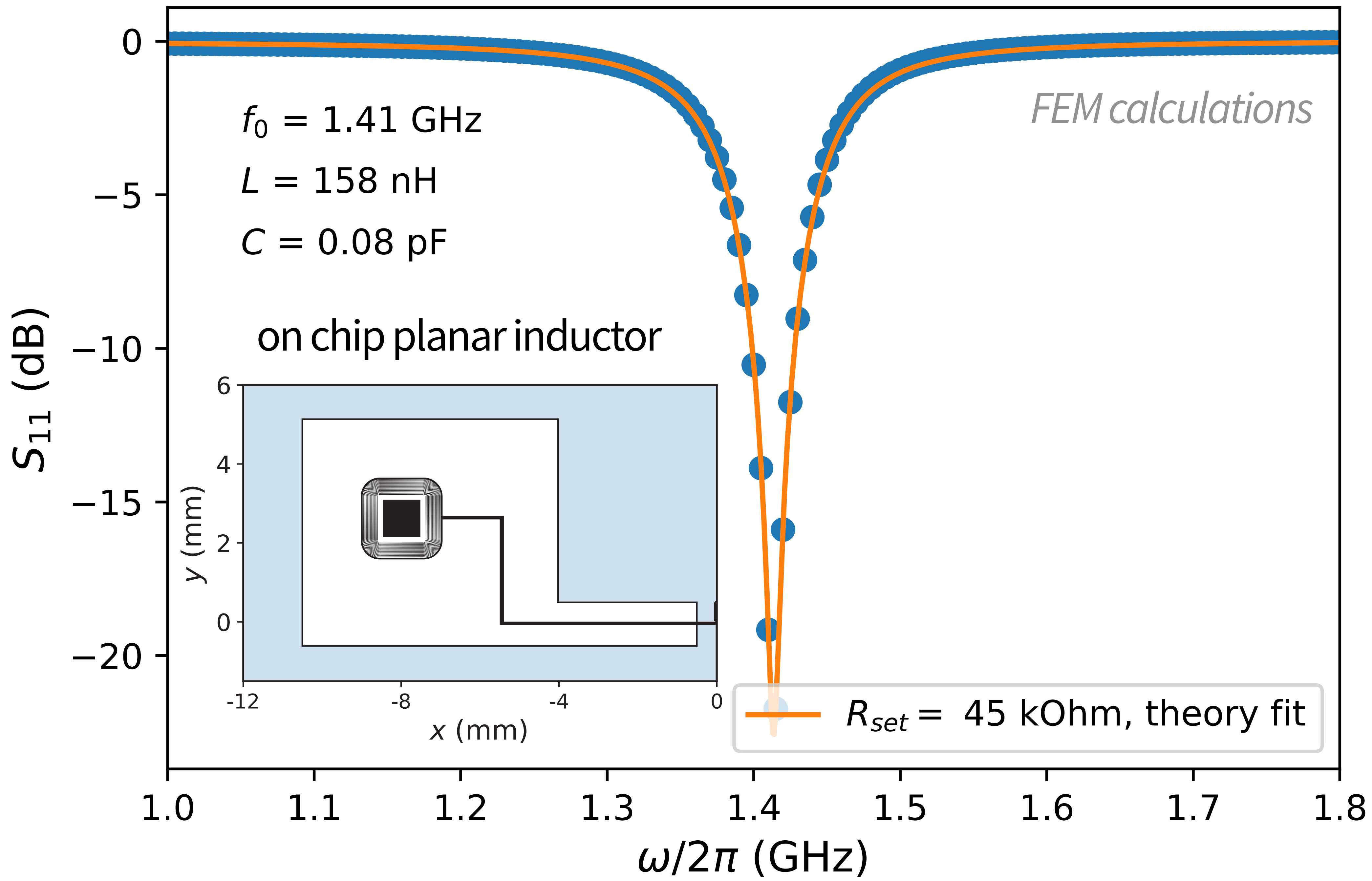
Read-out scheme

fast readout - rf-SET

high sensitivity and
large bandwidth



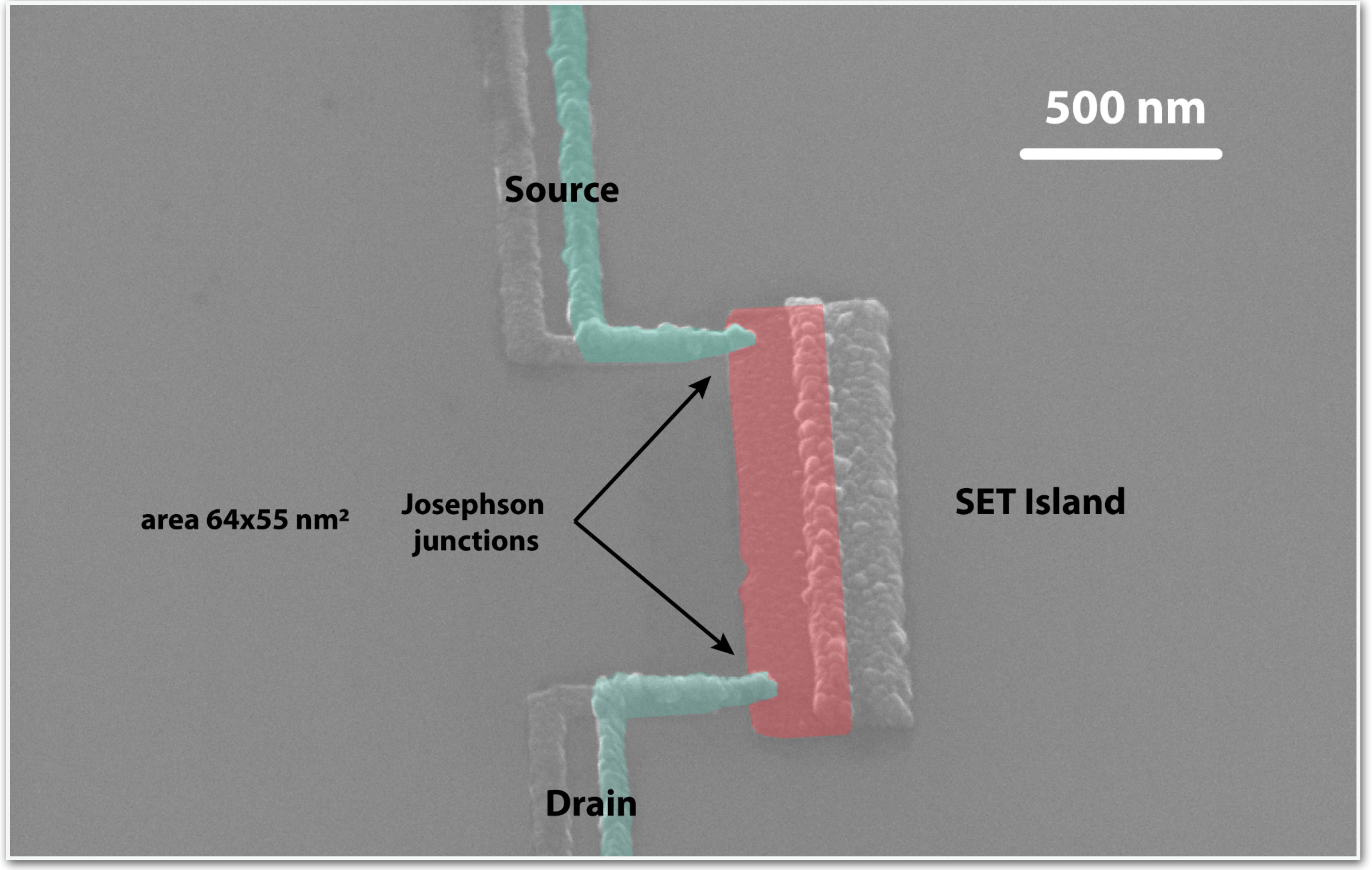
tank circuit
$\omega_0 = 1/\sqrt{LC}$ $\quad R_{\mathrm{SET}} = 45\ \mathrm{k}\Omega$

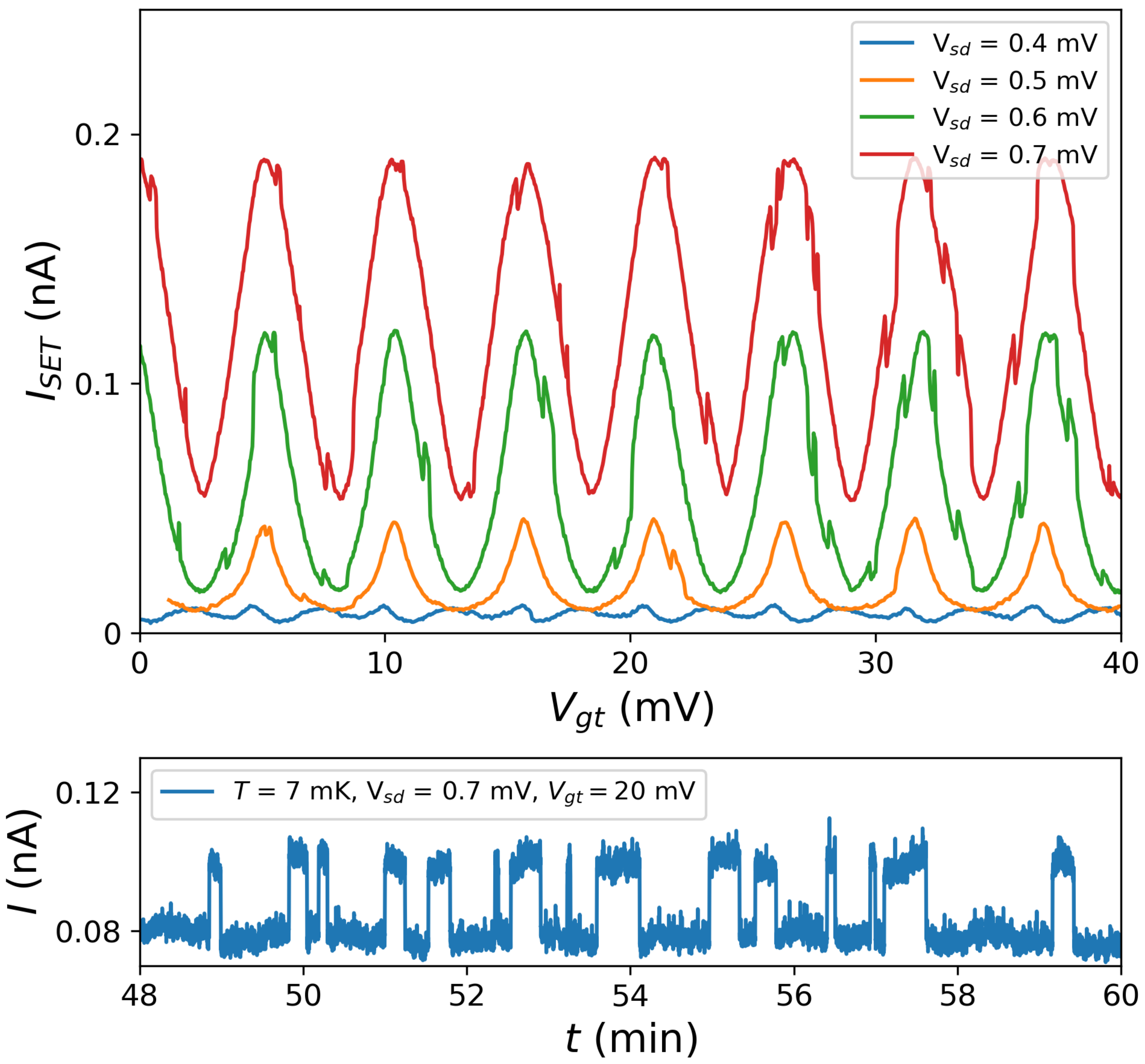


		motional states $\omega_e/2\pi = 5$ GHz	Rydberg states $\omega_R/2\pi = 120$ GHz
Induced charge difference	Δq	0.002 e	0.02 e
SET sensitivity (shot noise limit)	δq	1.3×10^{-6} e$/\sqrt{\mathrm{Hz}}$	
measurement time	$t_m = (\delta q/\Delta q)^2$	0.4 μs	4 ns
SET backaction	t_{mix}	1.2 μs	0.3 μs

$t_m < t_{mix}$

SET (dc measurements)

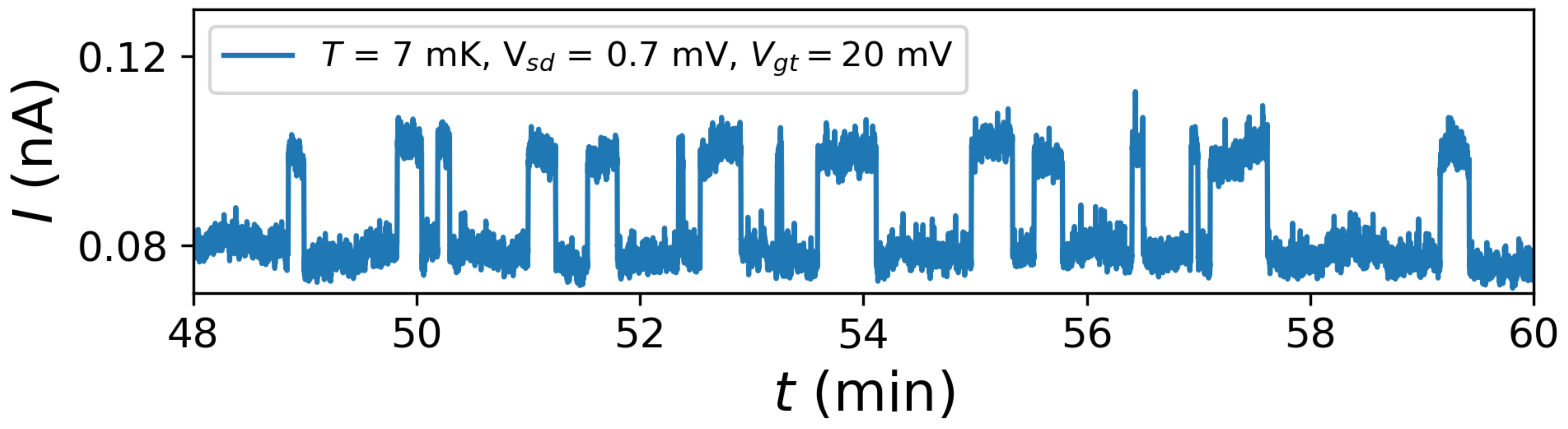


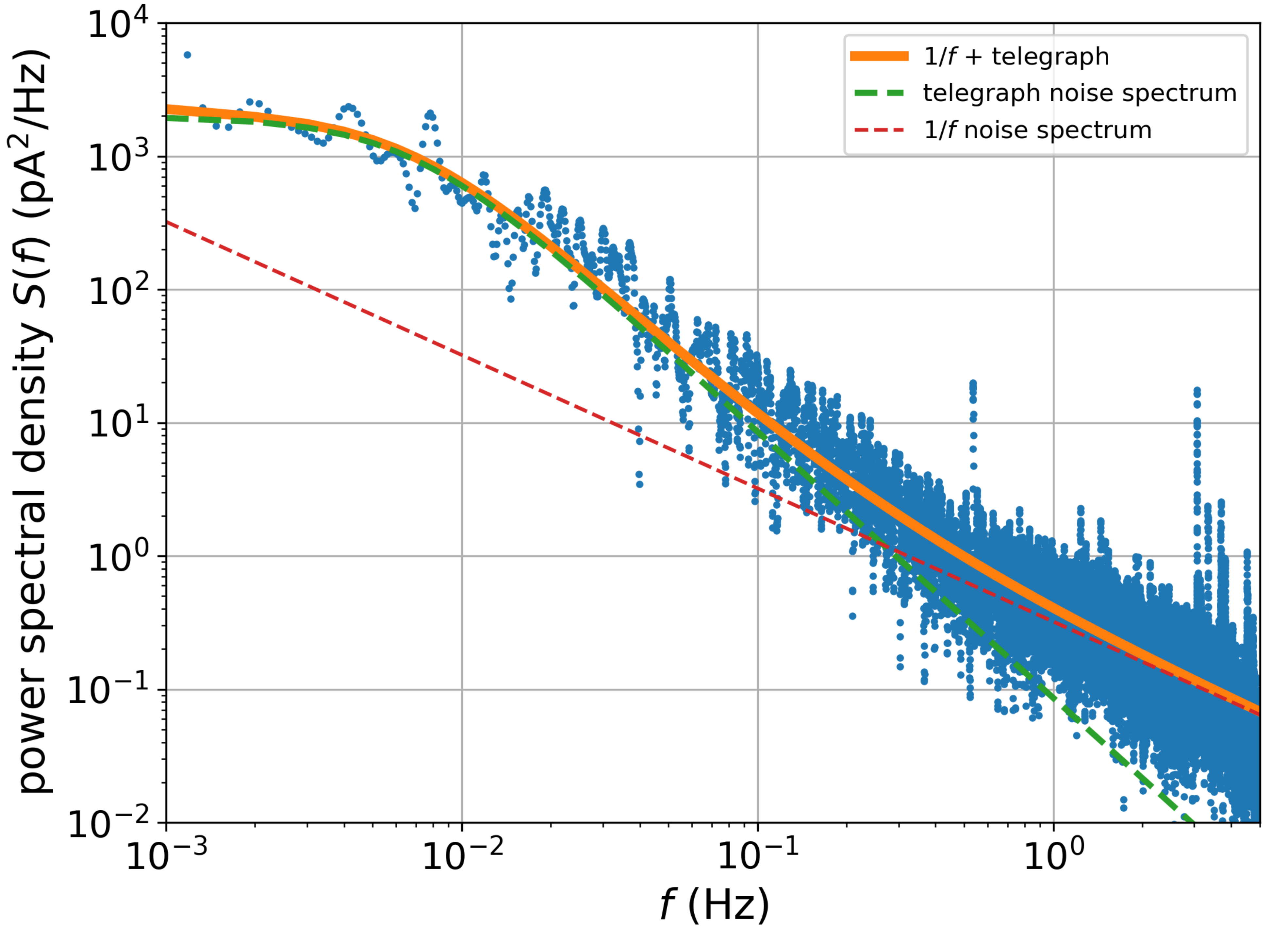


SET parameters

Δ	E_c	$E_{\sum}$	C_1	C_2	C_g
180 μeV	165 μeV	0.46 fF	0.24 fF	0.19 fF	0.03 fF

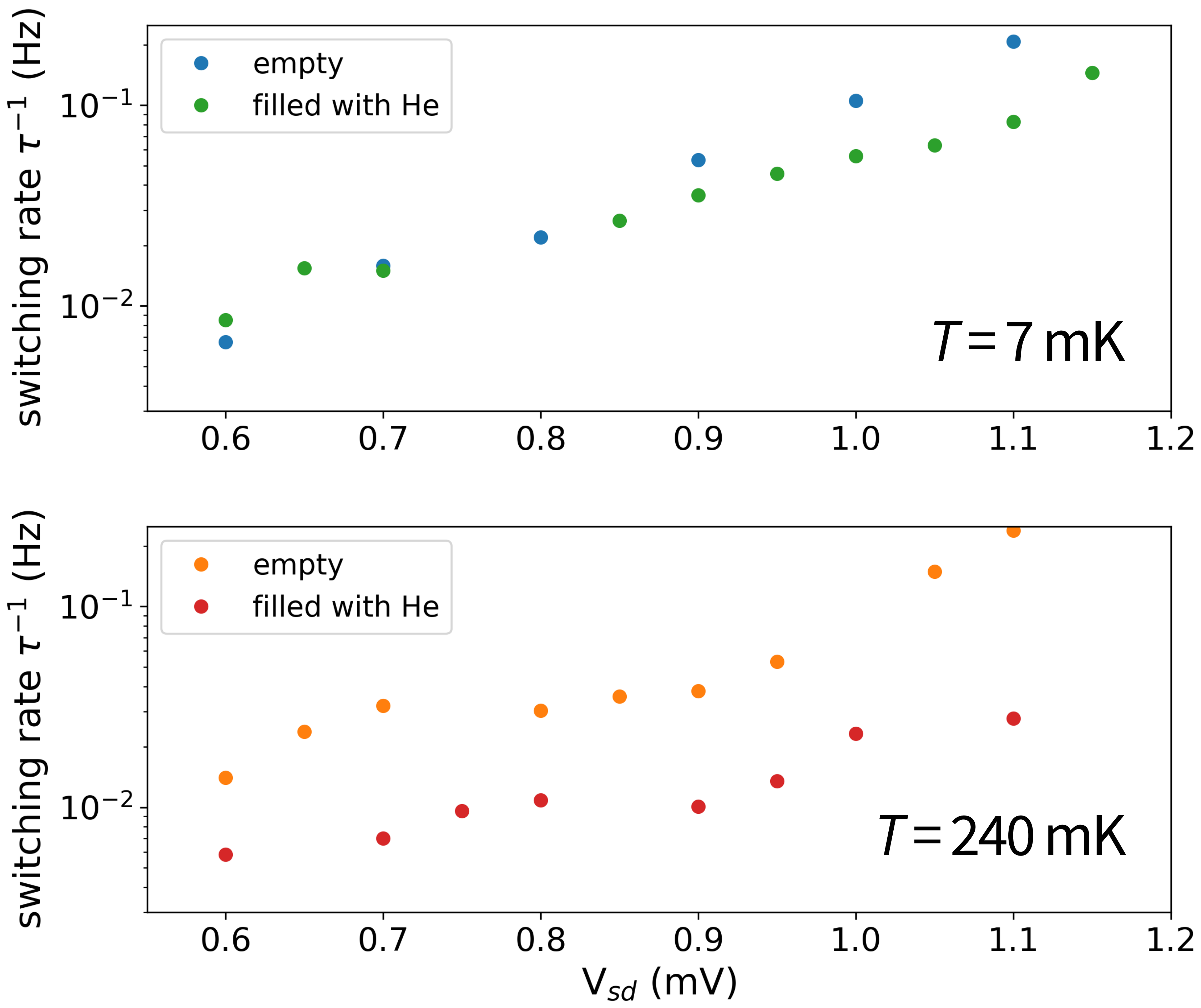
TLS thermalisation with liquid He





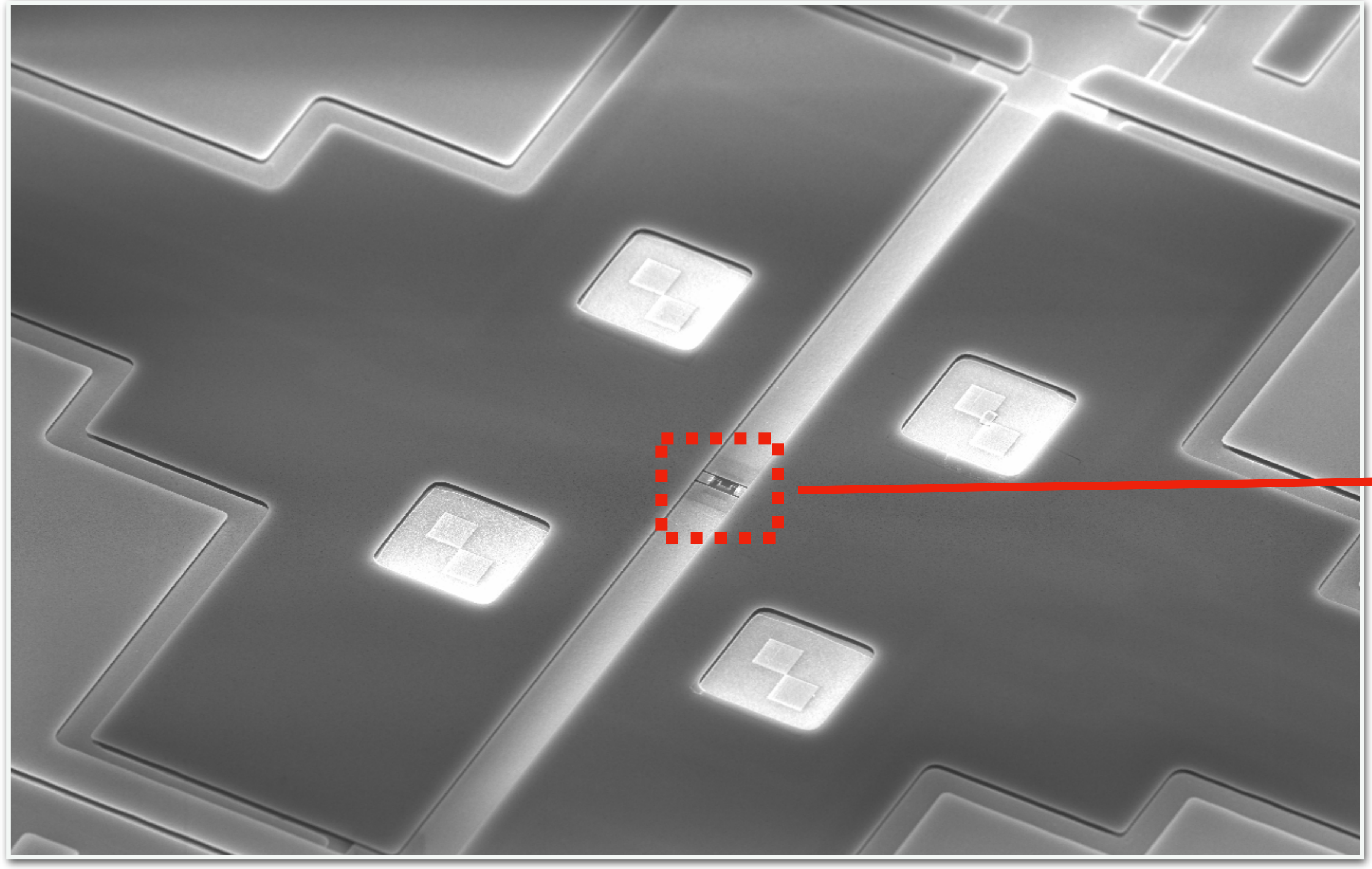
telegraph noise - TLS coupled to SET
telegraph noise has Lorentzian shape

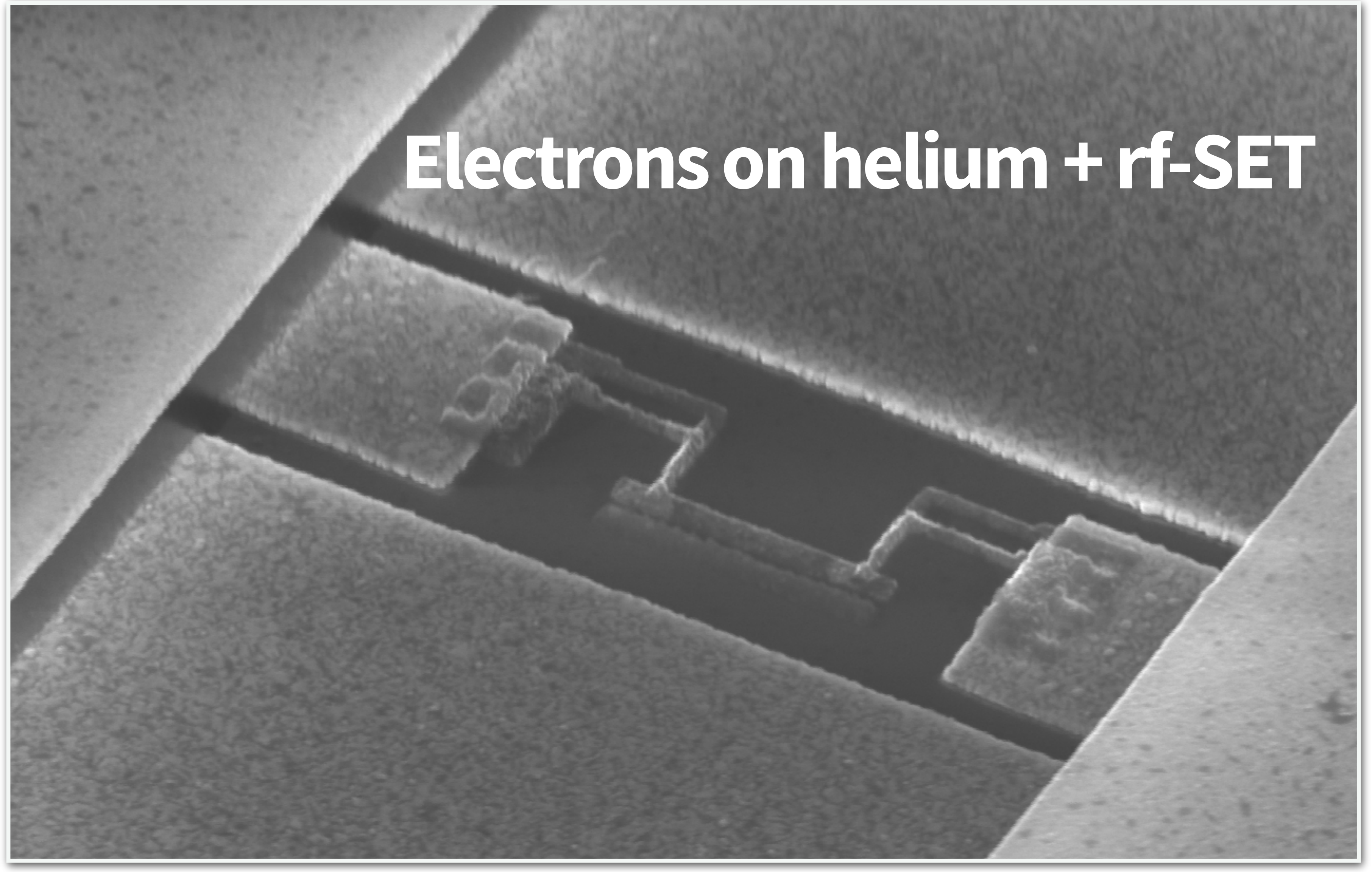
$$S(\omega) \propto \frac{\tau}{1 + \omega^2 \tau^2} \qquad \tau^{-1} \text{ - switching rate}$$



What do we do next?

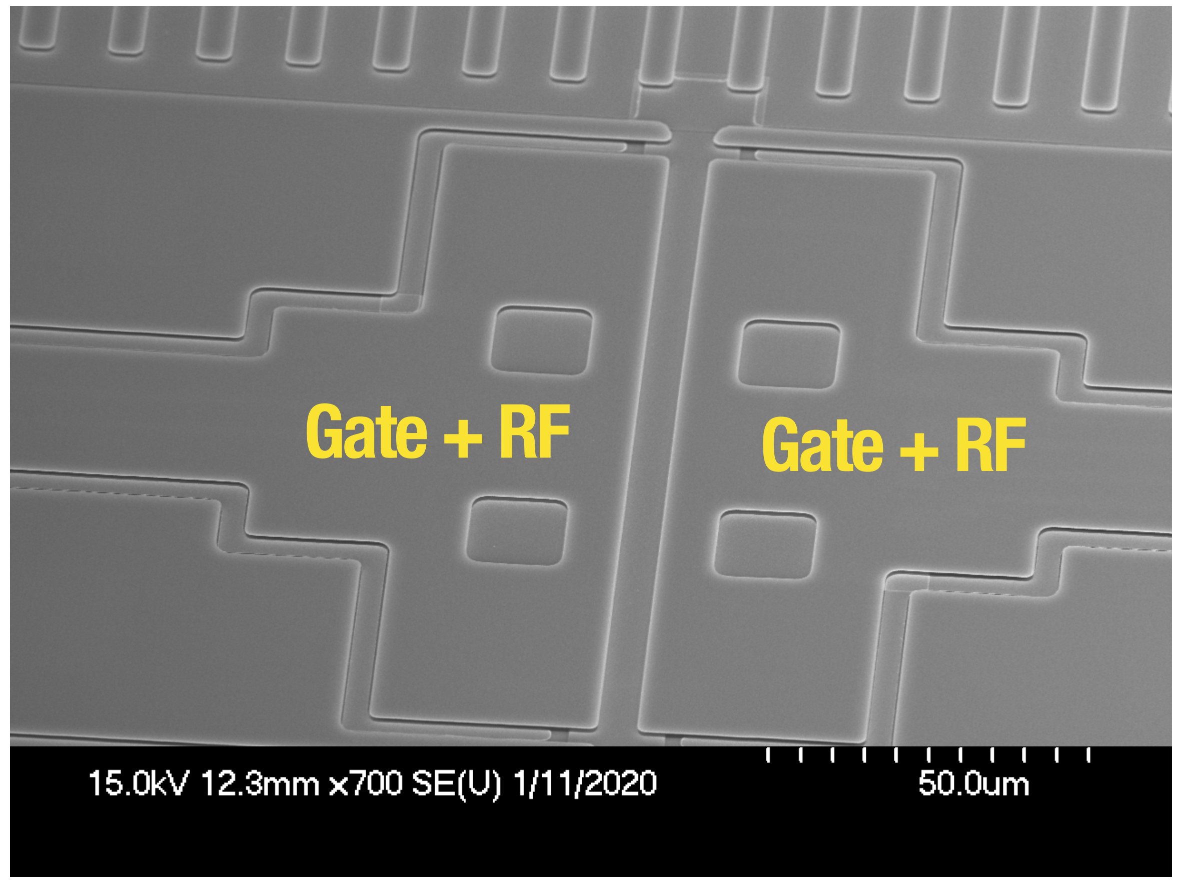
1. Experiments with rf-SET to optimise its performance
2. Integrating rf-SET device into electrons on helium experiments
3. Single electron detection with rf-SET

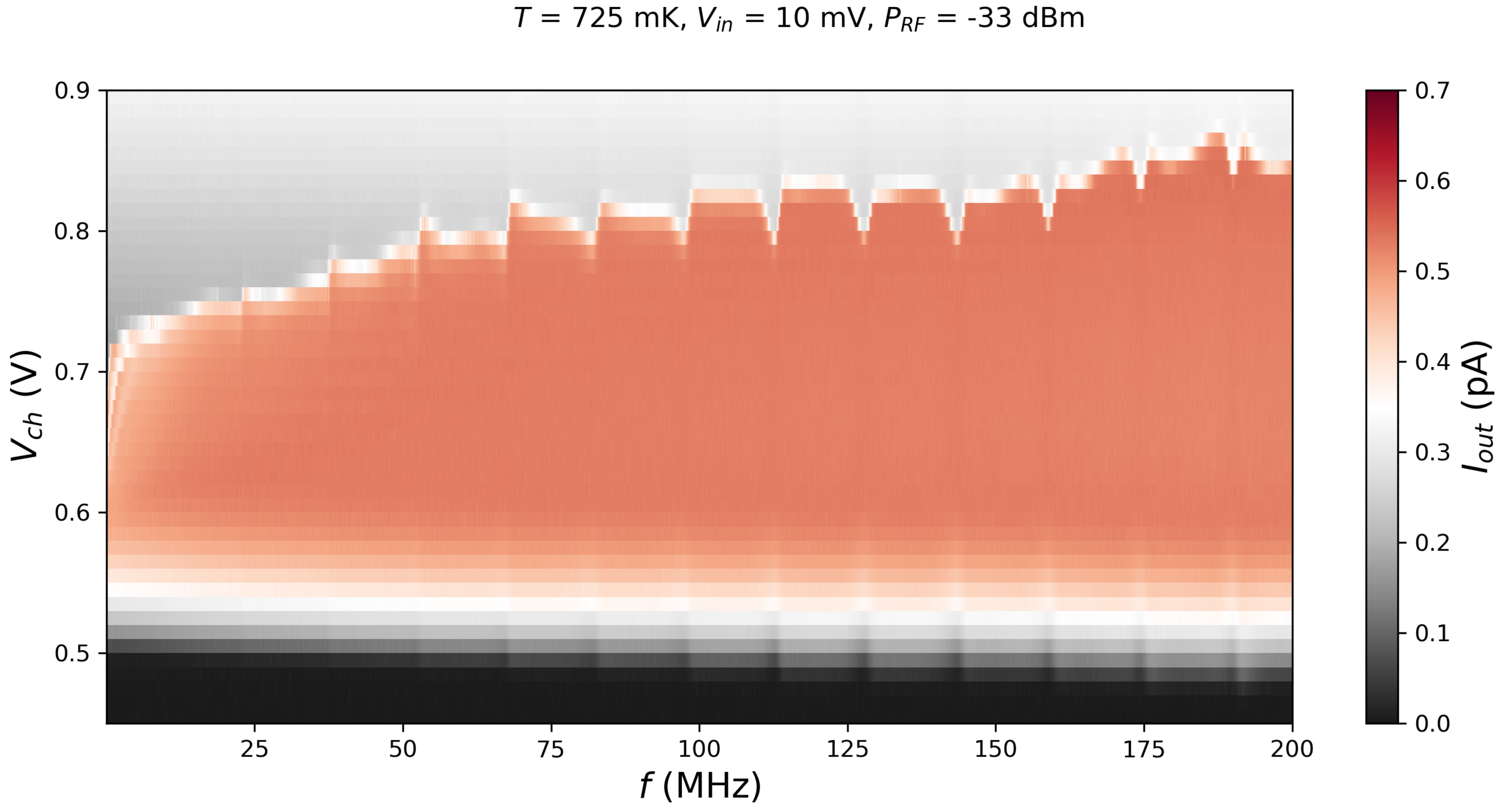


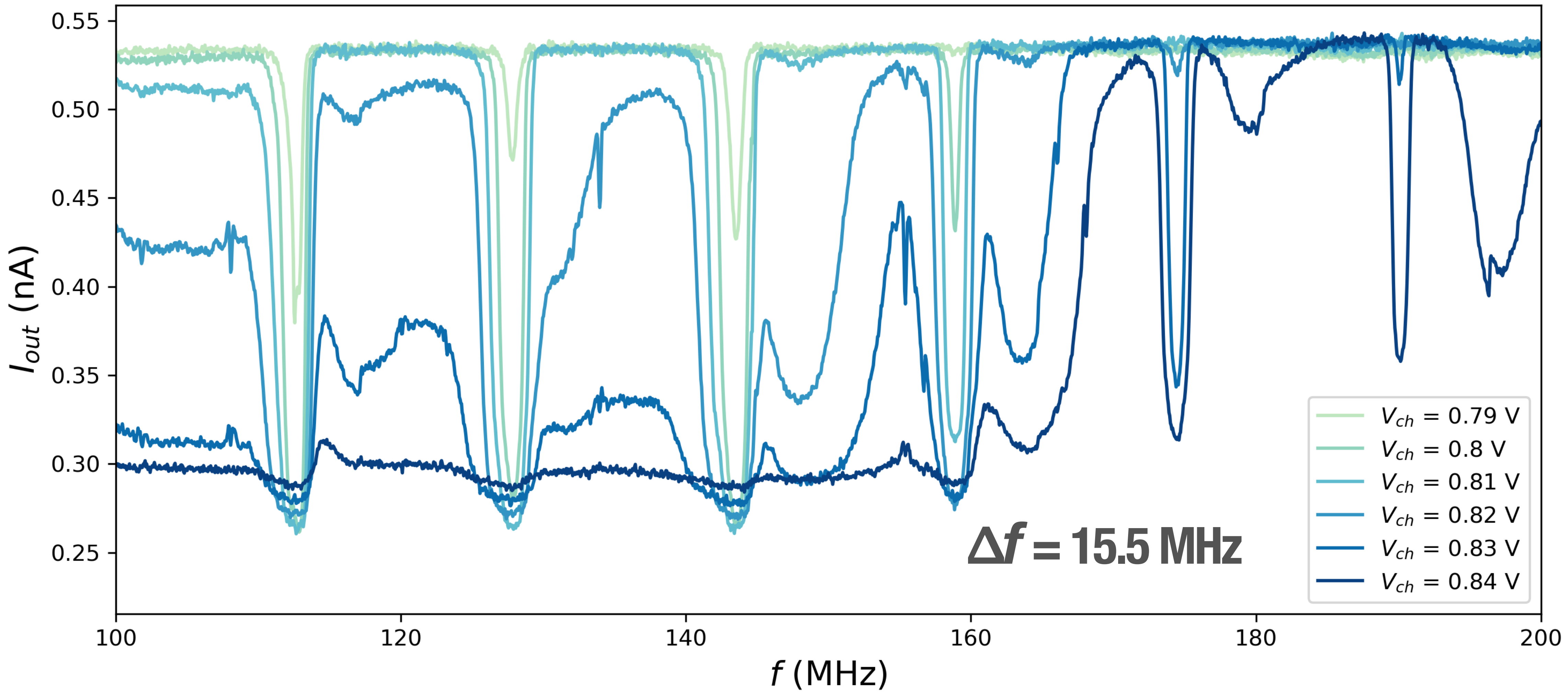


New resonant features

central microchannel width 5 μm
depth 0.8 μm







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Gate + RF