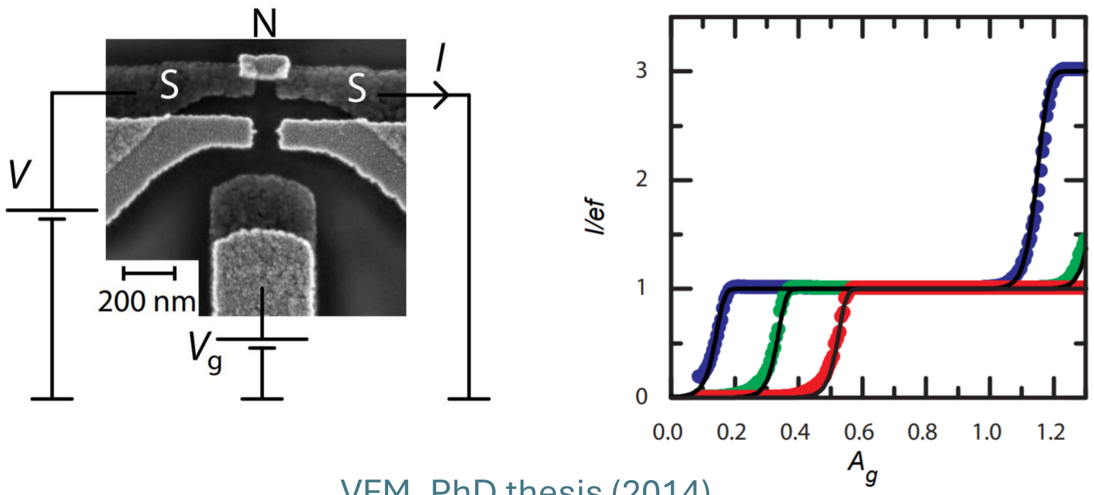
Charging energy and Coulomb diamonds

2025-06-29

Ville Maisi, Lund University

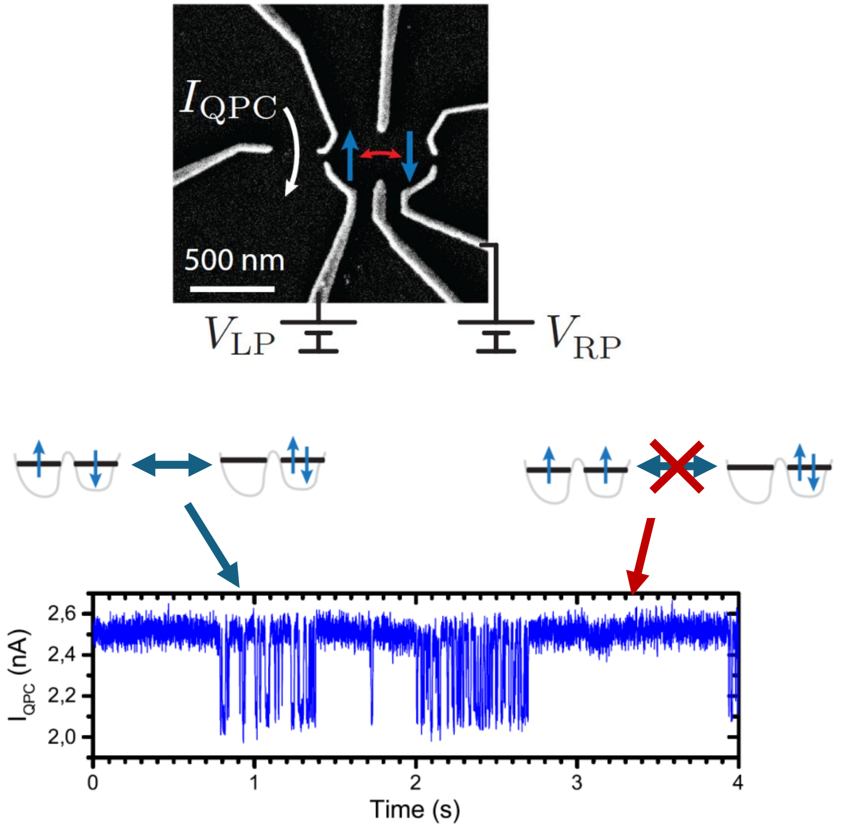
A couple of example systems I've worked with

- Metallic islands



[VFM, PhD thesis (2014)]

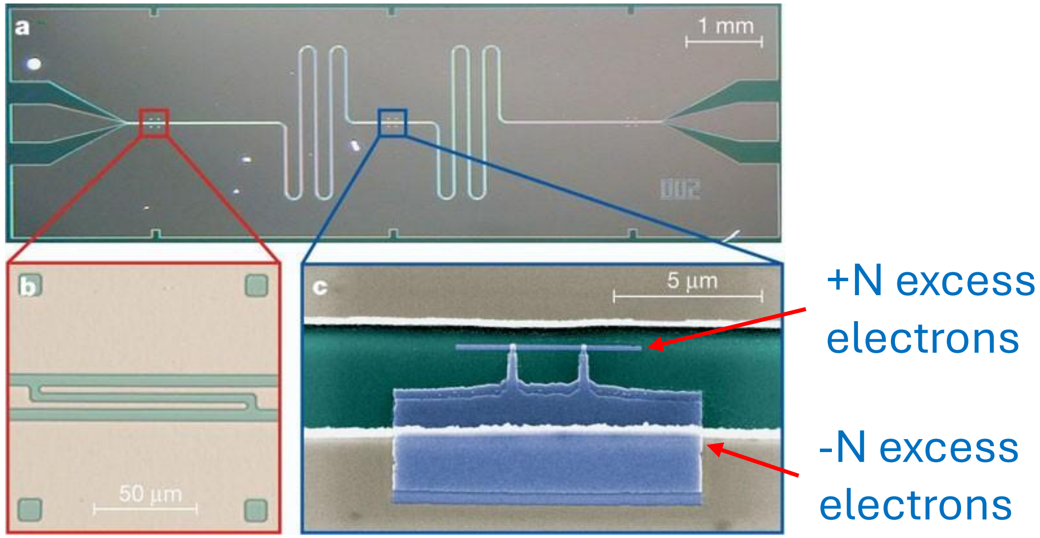
- Quantum dots (QDs)



[VFM et al, Phys. Rev. Lett. 116, 136803 (2016)]

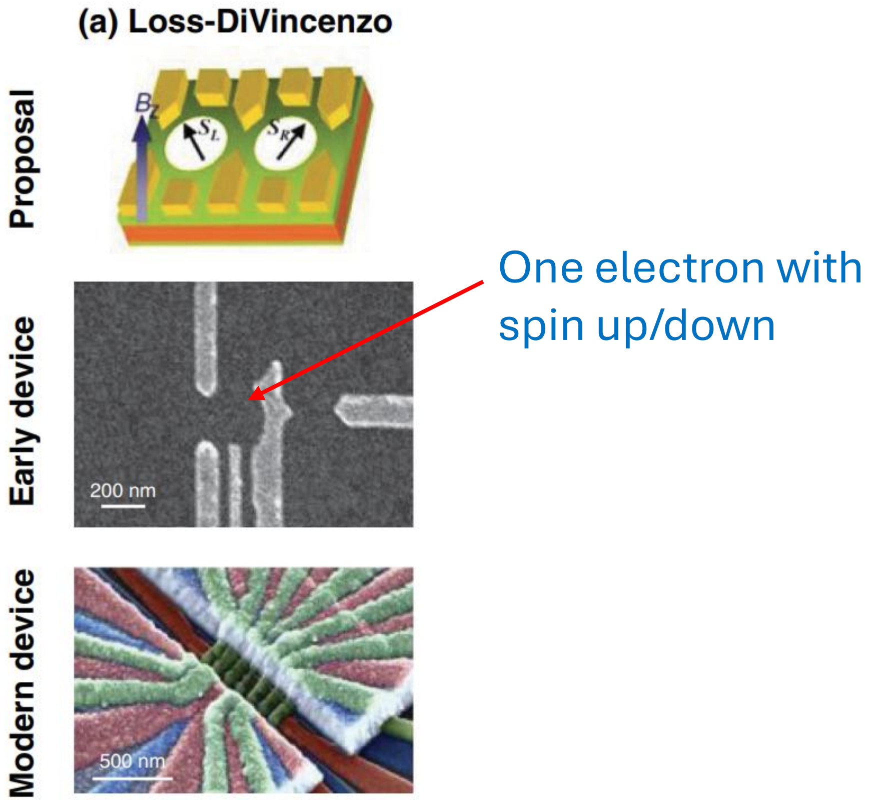
Basis for Transmon and Spin Qubits

- Superconducting qubits with metallic islands:



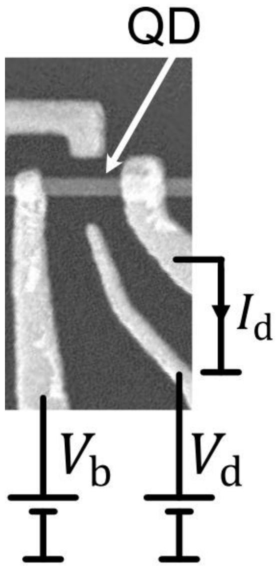
A. Wallraff et al. Nature **431,** 162 (2004).

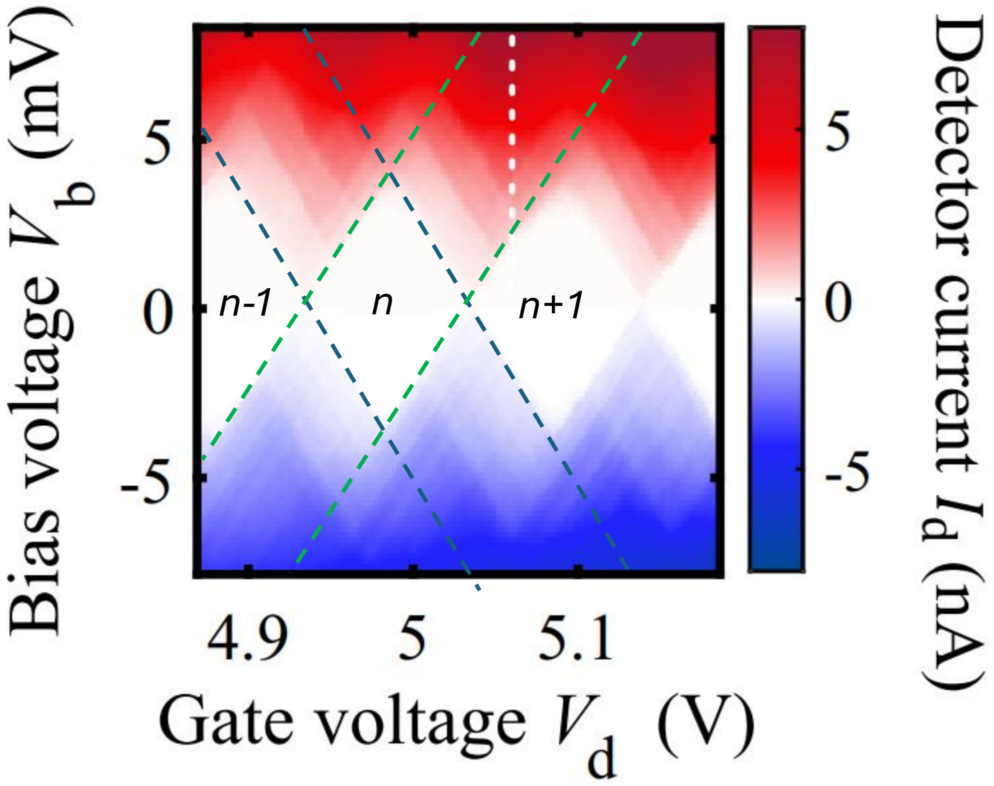
- Spin Qubit in QDs:



G. Burkard et al. Rev. Mod. Phys. **95,** 025003-1 (2023).

“Coulomb diamonds”

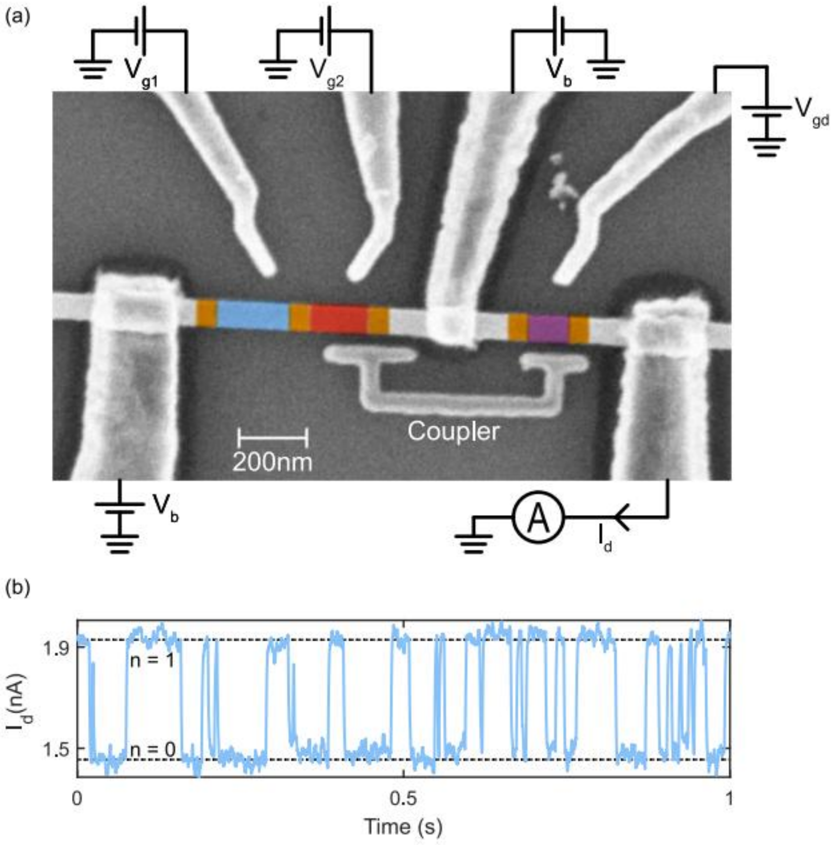


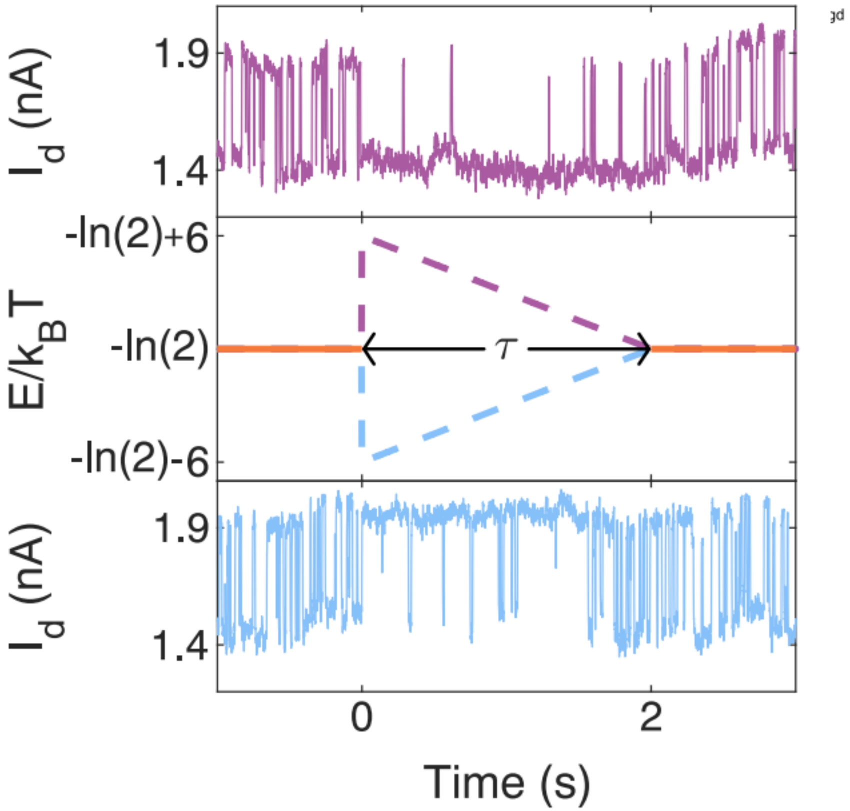


Example from
S. Haldar et al. Phys. Rev. Lett. **134,** 02301 (2025).

Charge detection

-Converting information to work

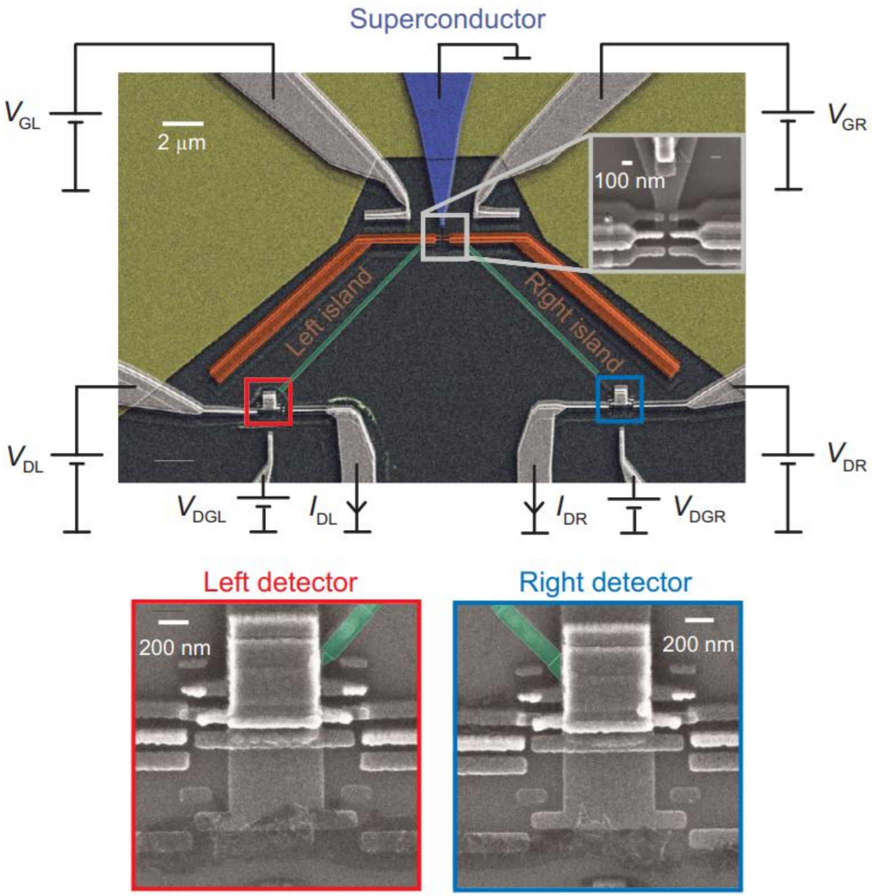




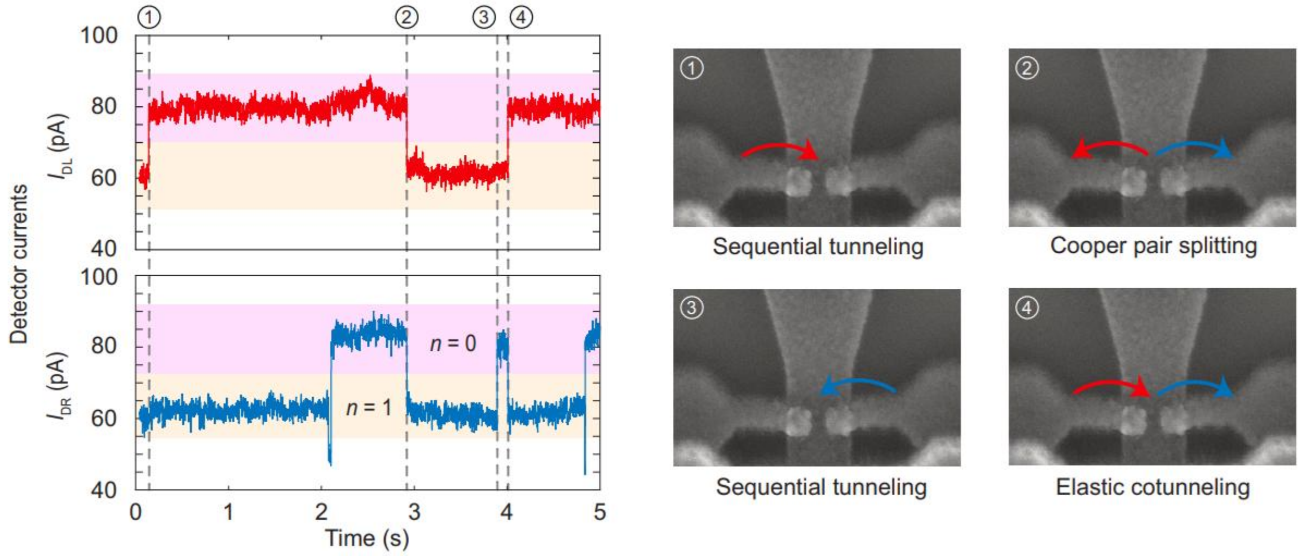
D. Barker et al. Phys. Rev. Lett. **128,** 040602 (2022).

Charge detection

-Splitting Cooper pairs



Two charge detectors resolving different tunnelling processes



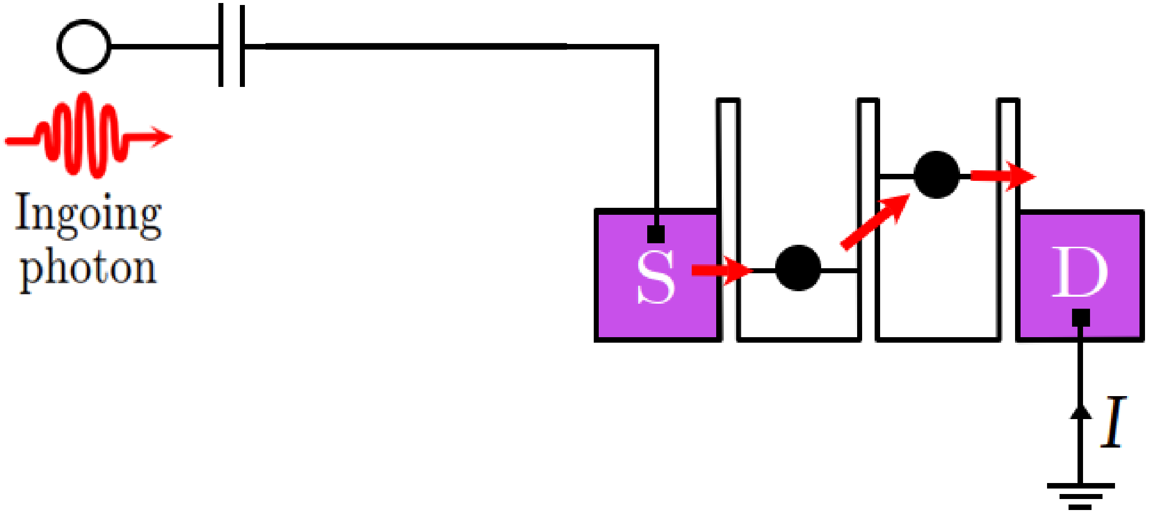
A. Ranni et al. Nature Commun. **12,** 6358 (2021).

Double quantum dot interacting with microwave resonator

2025-06-29

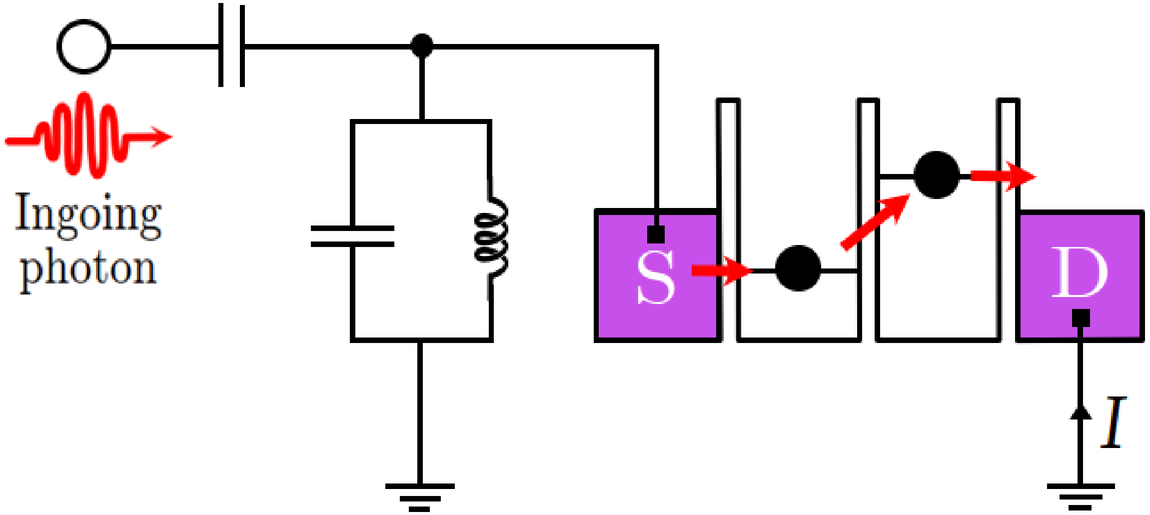
Ville Maisi, Lund University

Double quantum dot as a photodiode



Early studies as spectroscopy tool -> Quantum efficiency ~10^{-4} %:
Van der Wiel et al. Rev Mod- Phys. 75, 1 (2002).

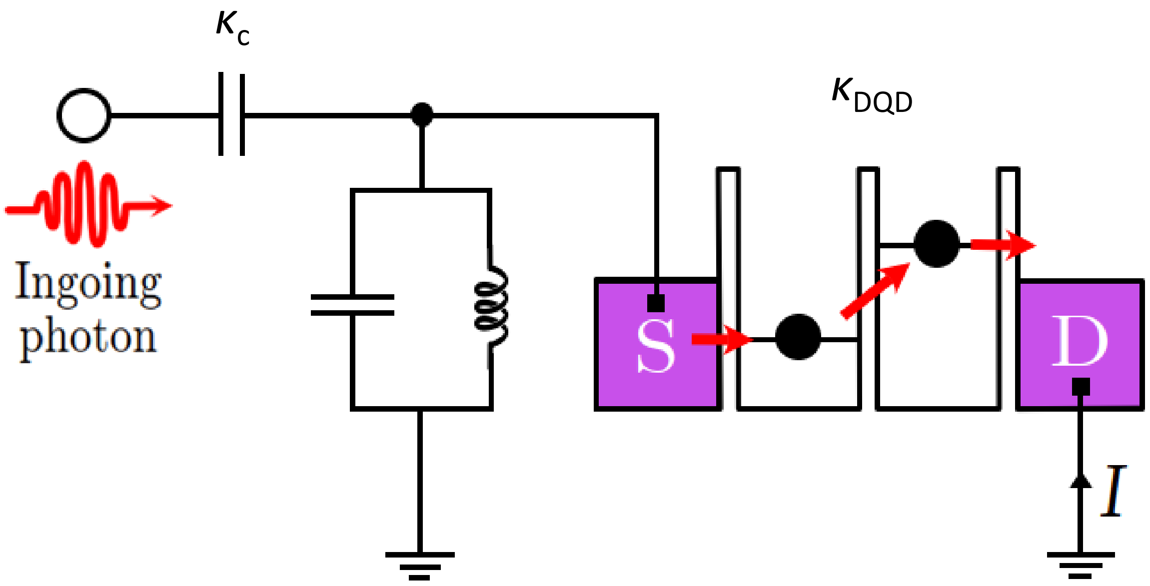
Double quantum dot as a photodiode



C. H. Wong and M. G. Vavilov, Phys. Rev. A **95,** 012325 (2017):

Near unity quantum efficiency reachable with matching the input and semiconductor DQD coupling rates

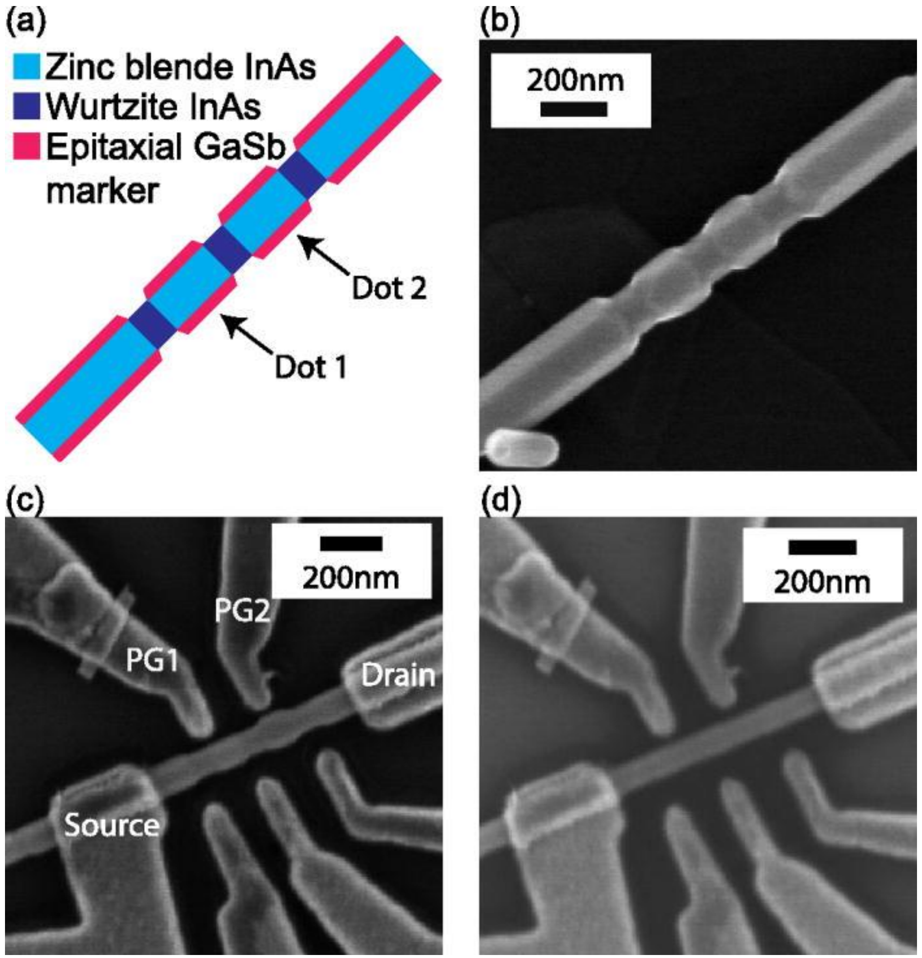
Double quantum dot as a photodiode



C. H. Wong and M. G. Vavilov, Phys. Rev. A **95,** 012325 (2017):

Near unity quantum efficiency reachable with matching the input and semiconductor DQD coupling rates

Double Quantum Dots (DQDs)

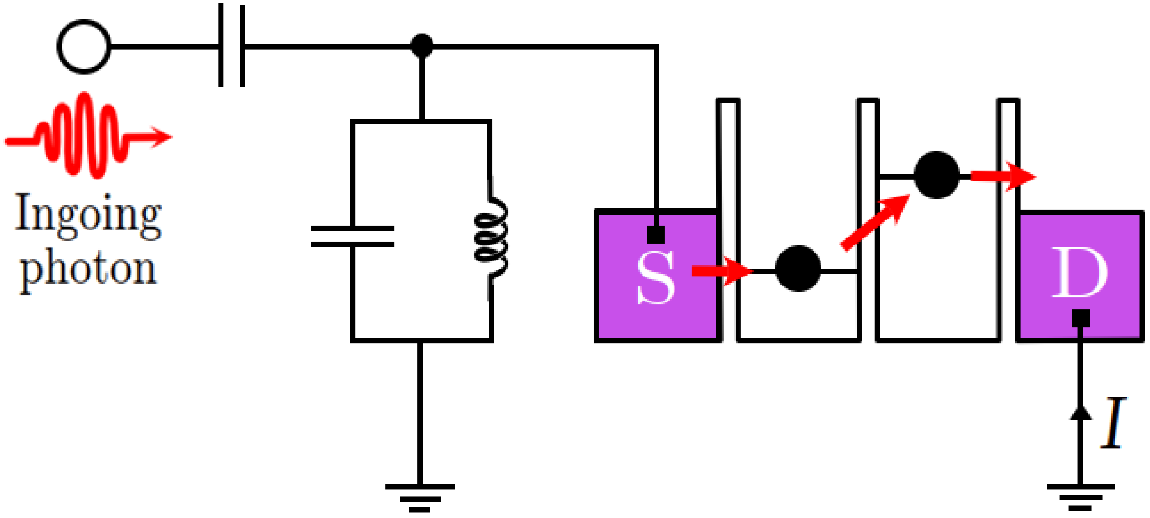


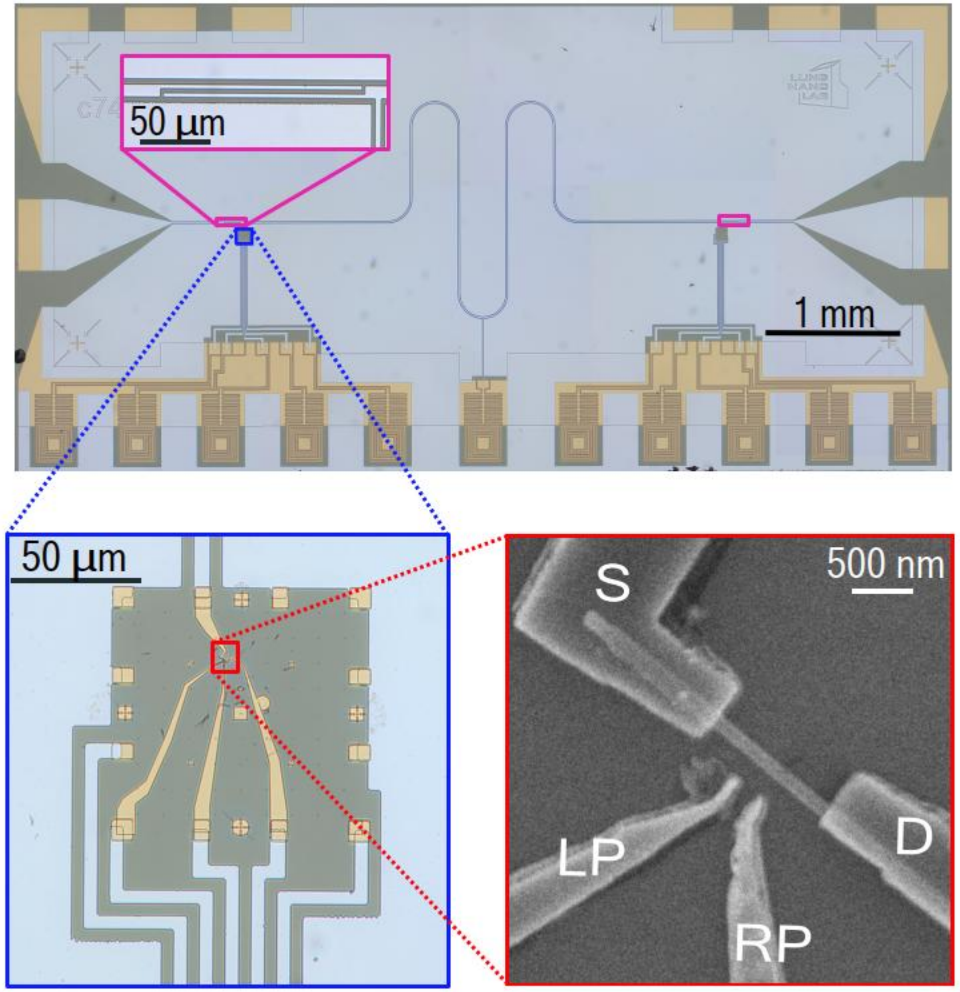
-Charging energies can be calculated the same way, just lengthier to do.

-The tunnelling between two dots is conceptually very different as it takes place from one quantized state to another one.
-> Qubit.

D. Barker et al, Appl. Phys Lett. **114,** 183502 (2019).

Double quantum dot as a photodiode

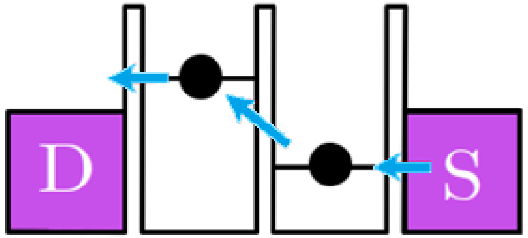




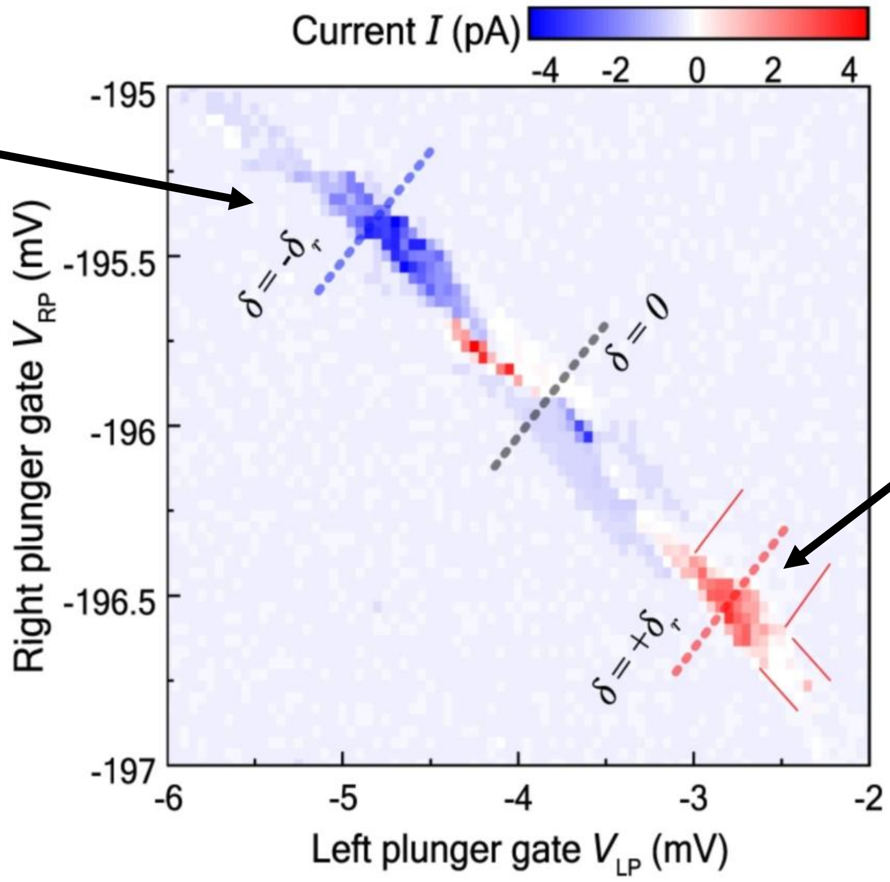
W. Khan, P. P. Potts, S. Lehmann, C. Thelander, K. A. Dick, P. Samuelsson, VFM, Nature Comm. **12,** 5130 (2021).

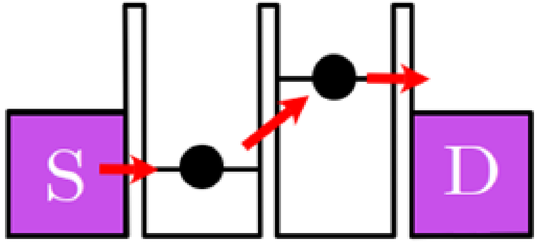
Energy detuning response

Photons in with constant power at resonator resonance frequency



Reverse detuning





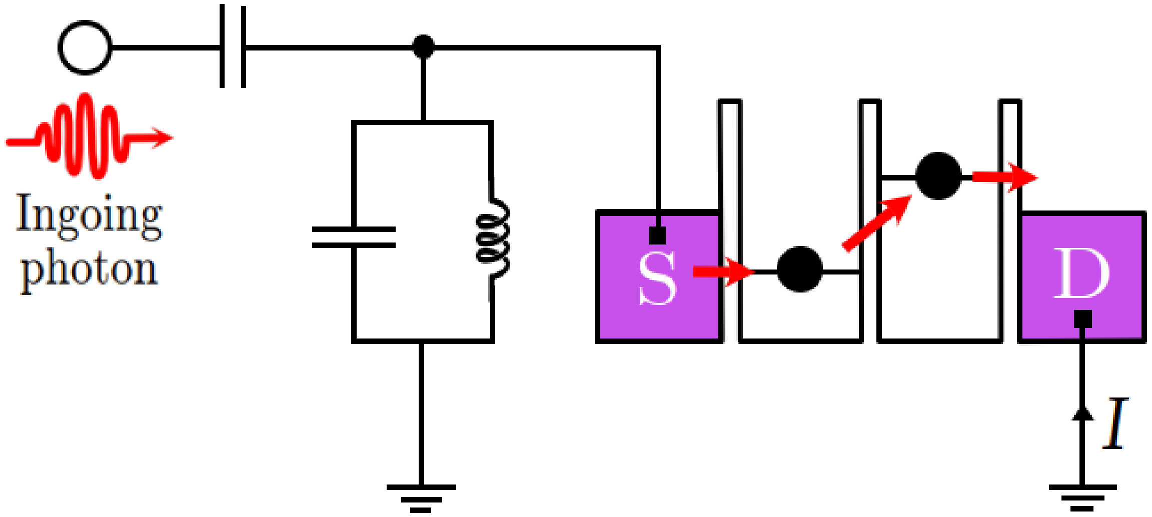
Forward detuning

W. Khan, P. P. Potts, S. Lehmann, C. Thelander, K. A. Dick, P. Samuelsson, VFM, Nature Comm. **12,** 5130 (2021).

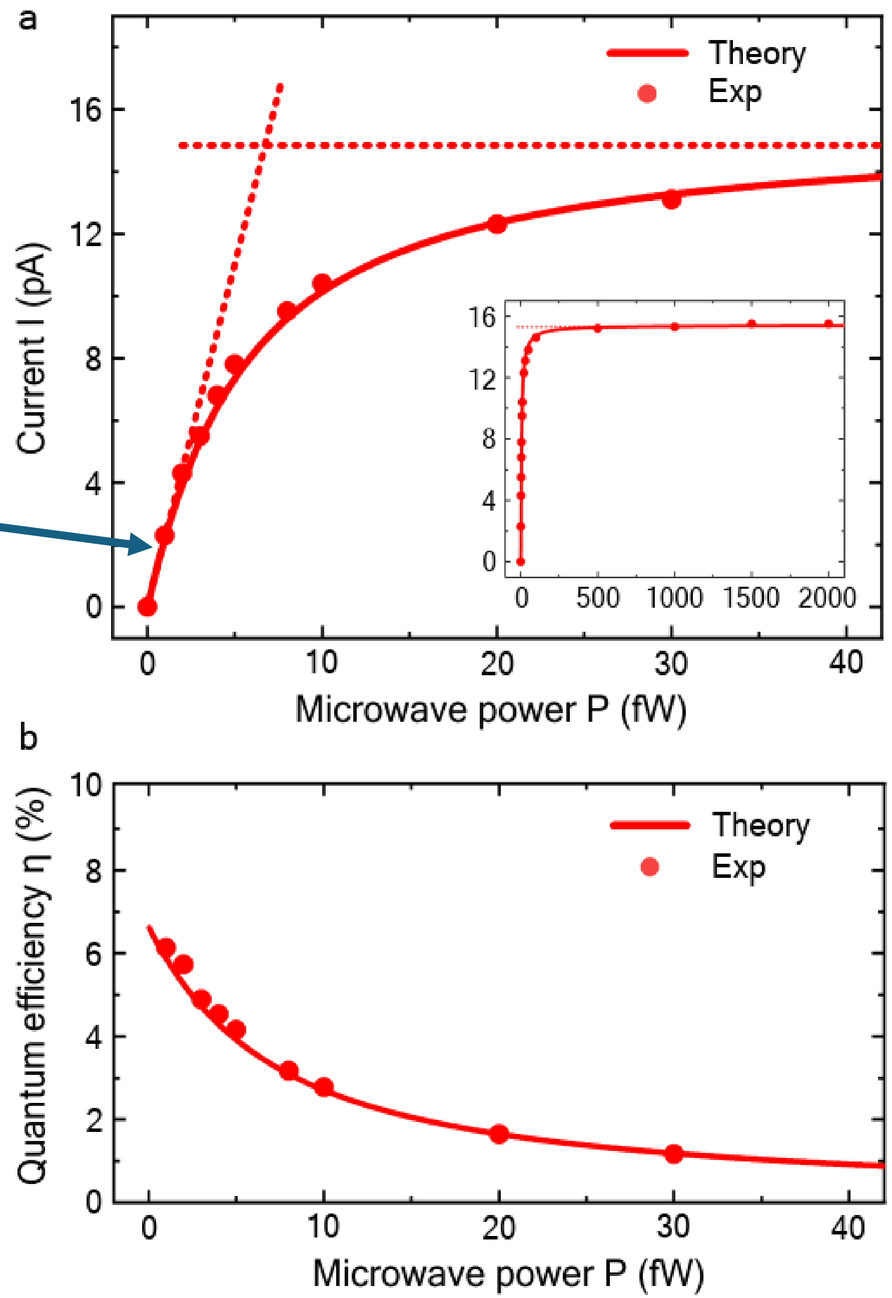
Quantum Efficiency

the fraction of photons that yields us an electron

$$\eta \equiv \frac{I/e}{\dot{N}} = \frac{I/e}{P/hf_r}$$



η = 6 %

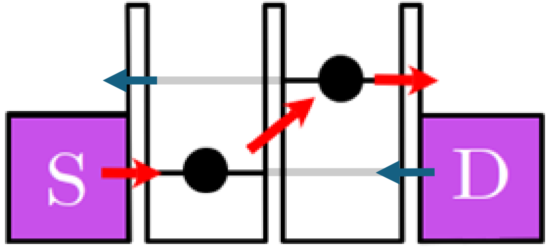


W. Khan, P. P. Potts, S. Lehmann, C. Thelander, K. A. Dick, P. Samuelsson, VFM, Nature Comm. **12,** 5130 (2021).

Towards High Quantum Efficiency

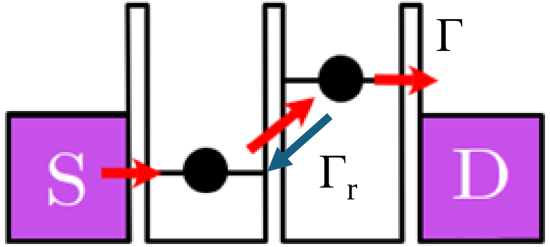
DQD matches the resonator coupling $\kappa_{DQD} = \kappa$

High directivity: electron tunnel to the right direction, i.e. low hybridization of the DQD states



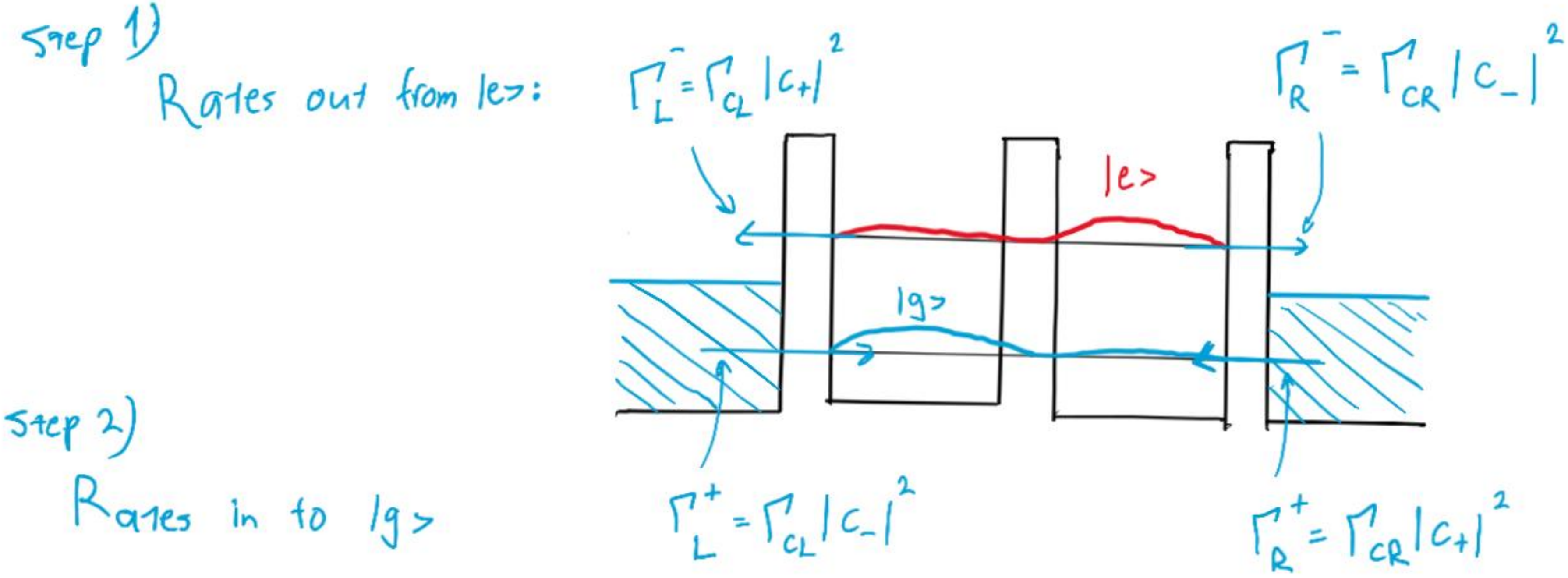
$$\eta = \frac{\kappa_c}{\kappa} \times \frac{4\,\kappa_{DQD}\,\kappa}{(\kappa_{DQD} + \kappa)^2} \times \frac{\Gamma}{\Gamma + \Gamma_r} \times p_f$$

Tunneling out from DQD Γ much faster than relaxation Γ_r



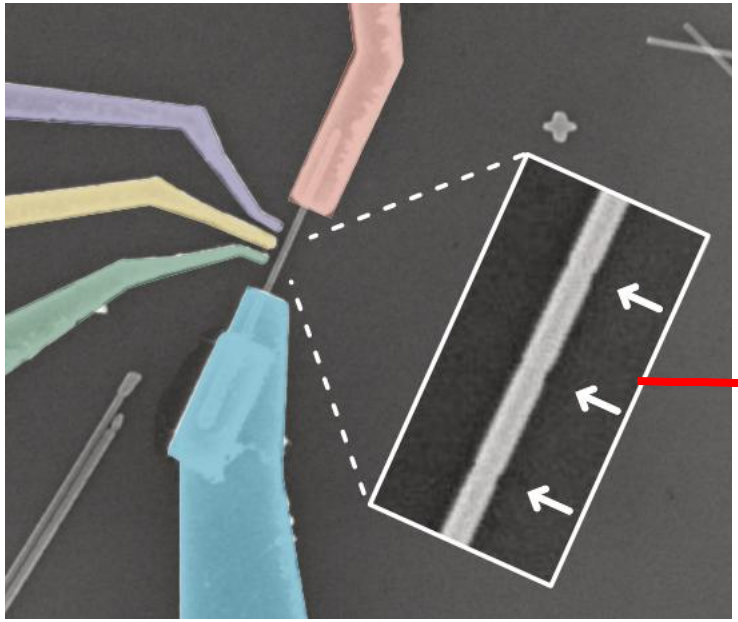
Bare resonator coupling dominated by one input $\kappa_L = \kappa$: low internal losses, no other ports

Coherent and incoherent tunnelling in the same system – directivity of the photodiode

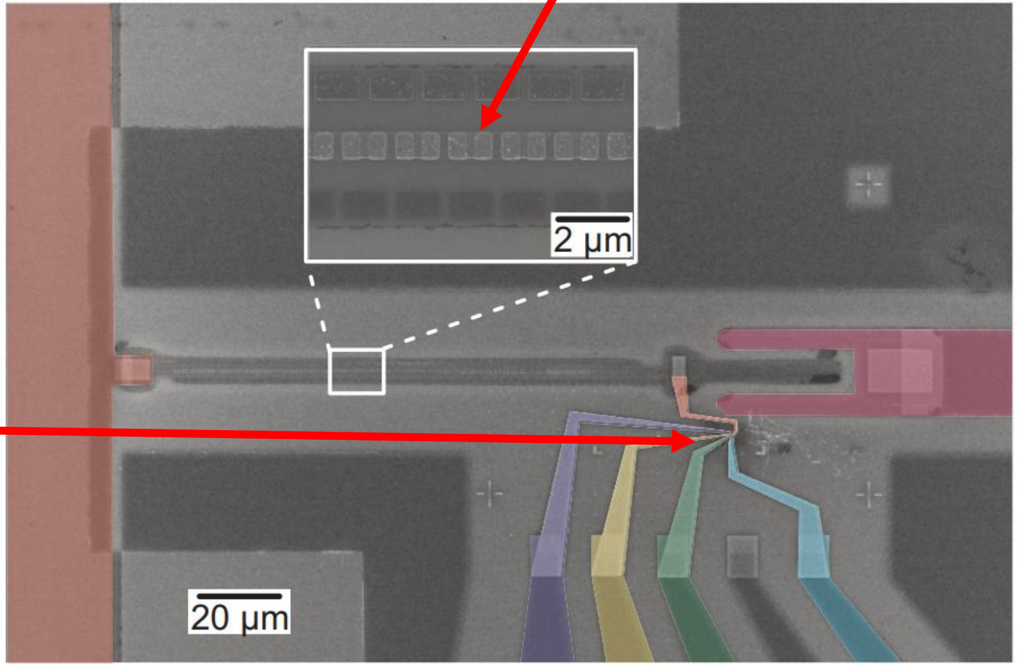


DQD interacting coherently with a resonator

Microwave resonator – Josephson junctions give rise to inductance L



DQD

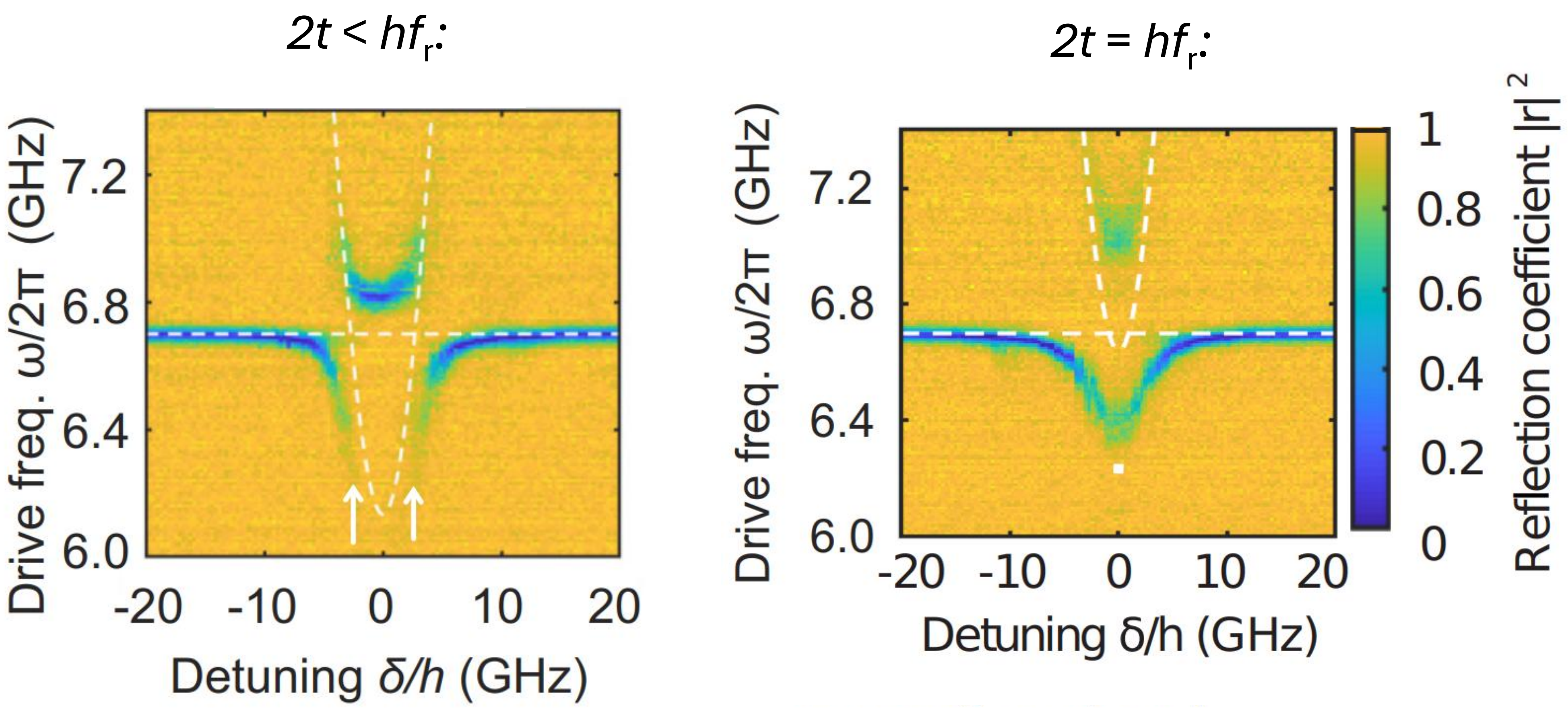


Microwave signal in

Reflected signal out. Measured to probe the system

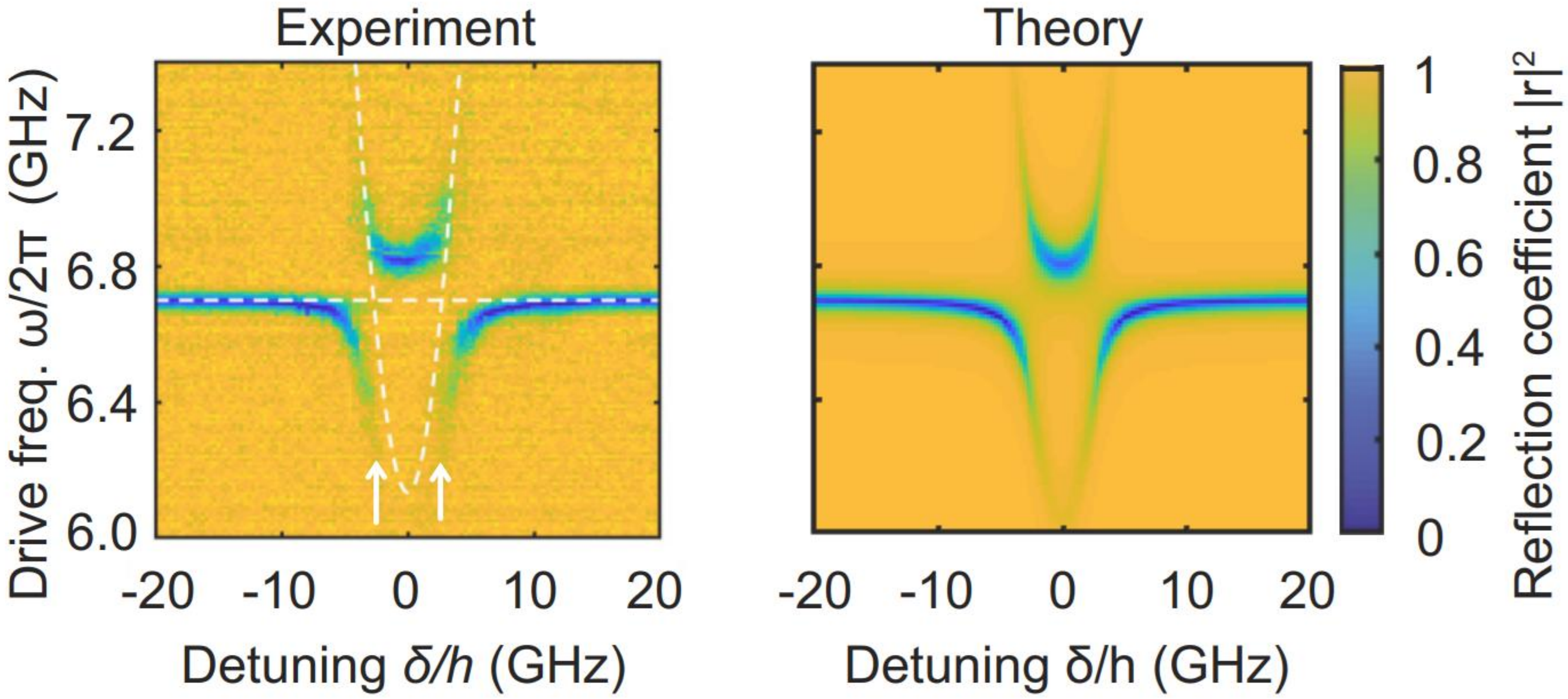
A. Ranni et al, Phys Rev. Research **6,** 043134 (2024).

Measured reflection coefficient $|r|^2 = P_{out}/P_{in}$



A. Ranni et al, Phys Rev. Research **6,** 043134 (2024).

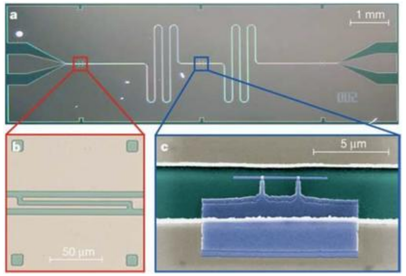
Measured reflection coefficient $|r|^2 = P_{out}/P_{in}$

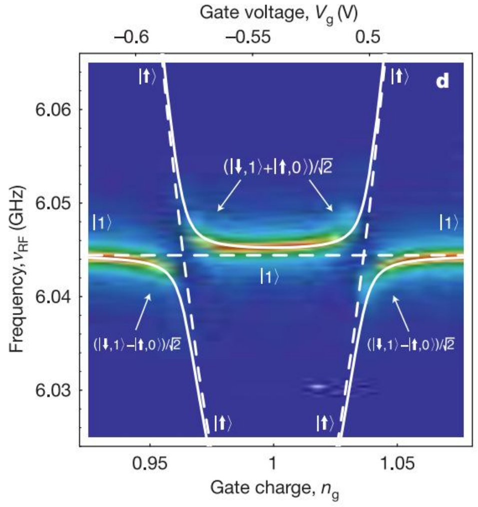


A. Ranni et al, Phys Rev. Research **6,** 043134 (2024).

The Jaynes-Cummings formalism we looked at works for many systems!

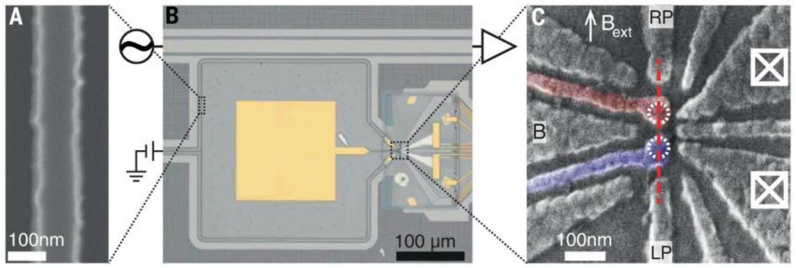
Superconducting qubits:

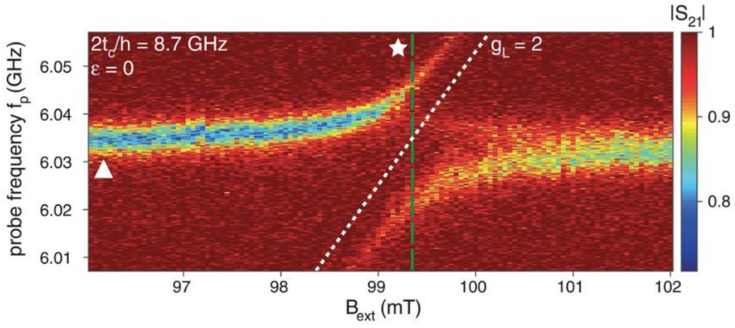




A, Wallraff et al, Nature **431,** 162 (2004)

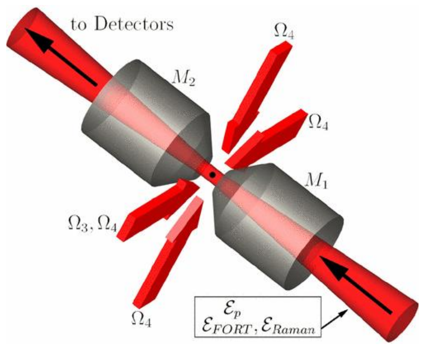
Spin qubits:

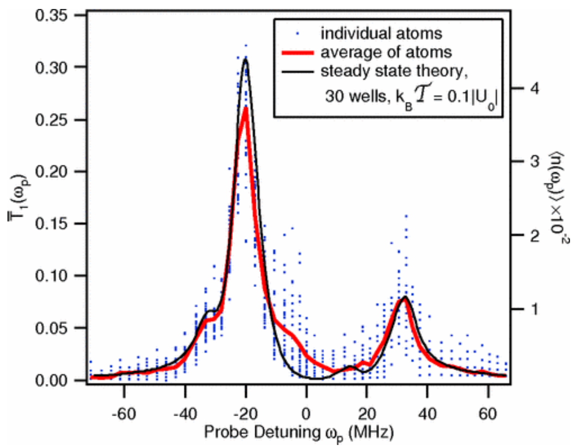




N. Samkharadze et al, Science **359,** 1123 (2018)

Atoms in optical cavities:





A. Boca et al, Phys. Rev. Lett. **93,** 233603 (2004)