

Circuit quantum electrodynamics with semiconductor quantum dots

Gianluca Rastelli



Istituto Nazionale
di Fisica Nucleare

TIFPA

Trento
Institute for
Fundamental
Physics and
Applications



Outline

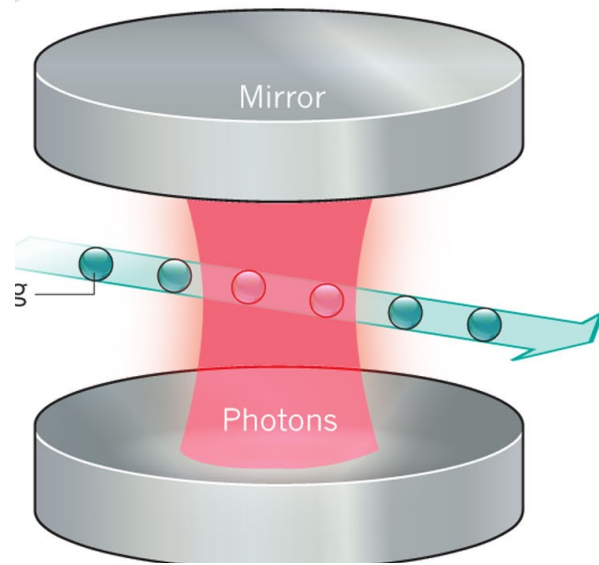
1. Overview of circuit QED with quantum dots
2. Generation of entangled microwave photons using superconducting nanodevices
3. Photodetection and quantum nondemolition with quantum dots

1. Overview of circuit QED **with quantum dots**

Circuit Quantum Electrodynamics (QED)

Cavity QED

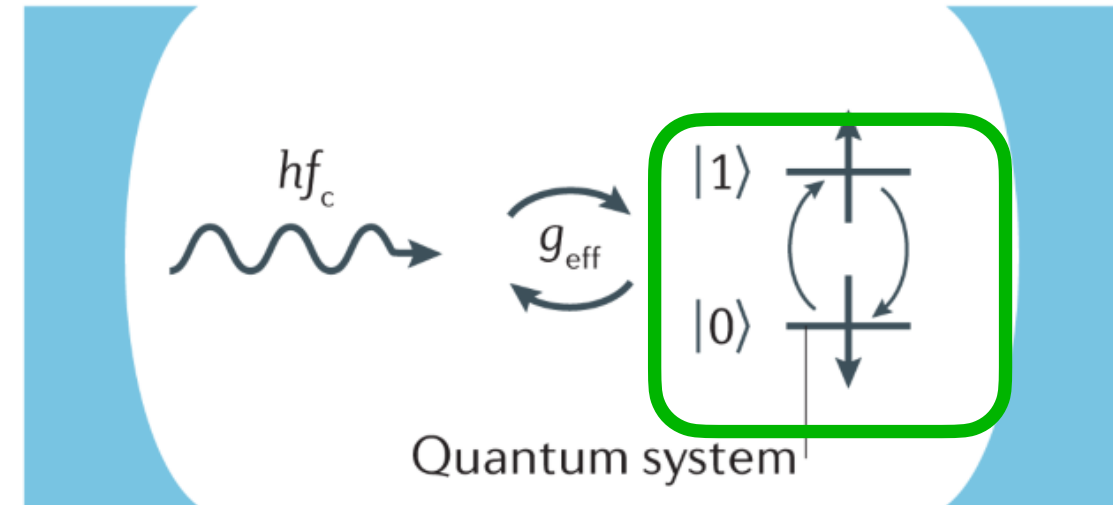
optical cavity coupled to a single atom



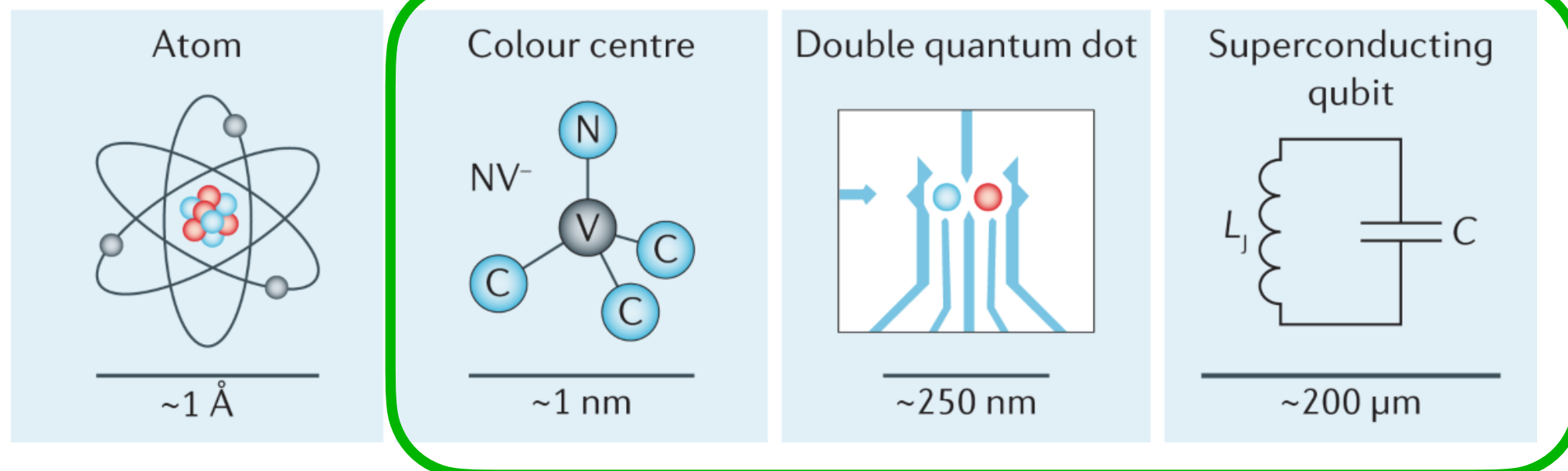
S. Haroche, *Rev. Mod. Phys.* **85**, 1083 (2013)

Circuit QED

microwave cavity coupled to qubits



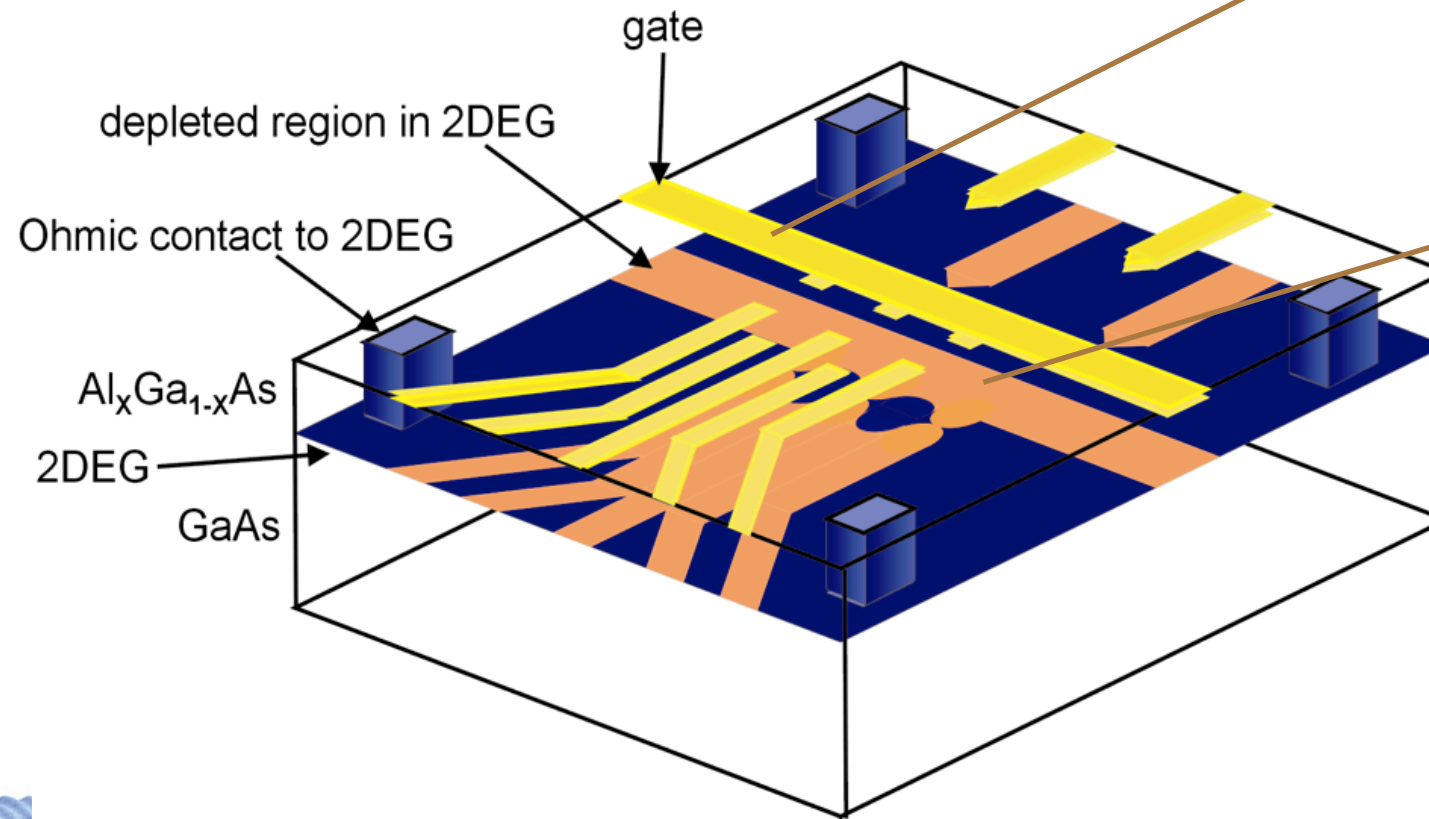
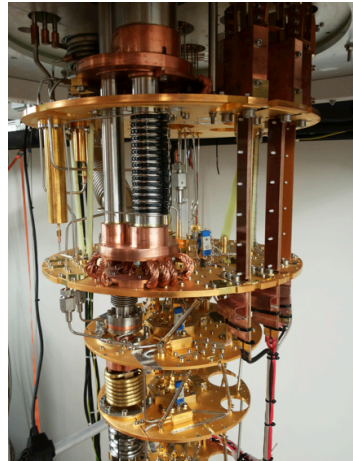
A. Blais et al., *Rev. Mod. Phys.* **93**, 025005 (2021)



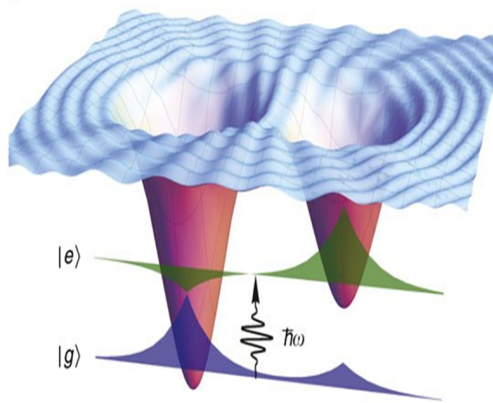
G. Burkard et al., *Nat. Rev. Phys.* **2**, 129 (2020)

All-electrical semiconductor quantum dots

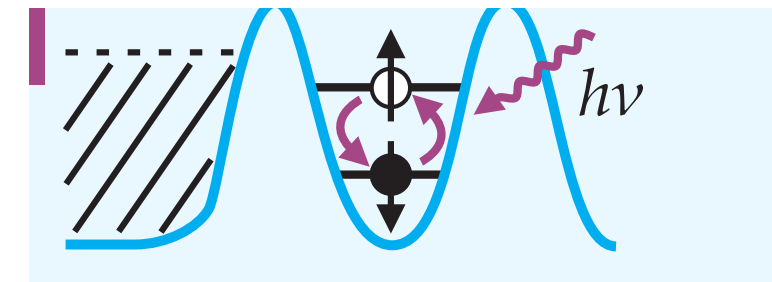
Example: **Double Quantum Dot (DQD)**



charge degree



spin degree



L.P. Kouwenhoven et al., *Rep. Prog. Phys.* **64**, 701 (2001)

W. G. van der Wiel et al., *Rev. Mod. Phys.* **75**, 1 (2002)

R. Hanson et al., *Rev. Mod. Phys.* **79**, 1217 (2007)

L. Vandersypen & M. Eriksson, *Physics Today* **72**, 8 (2019)

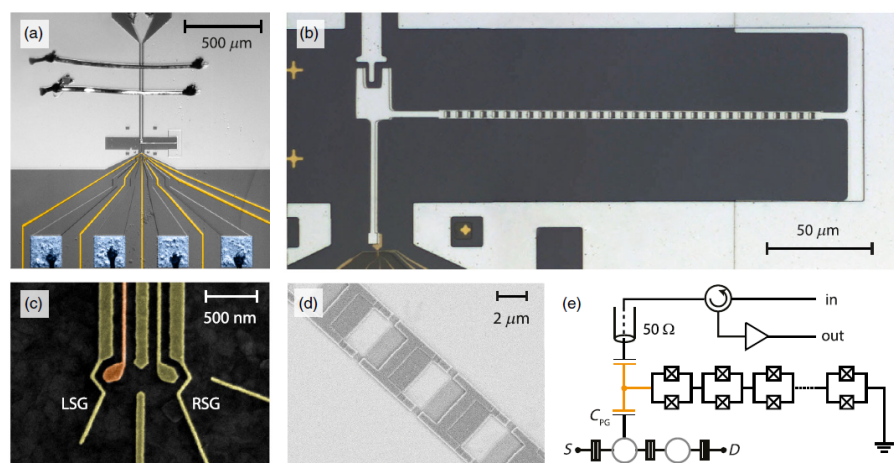
A. Chatterjee et al., *Nat. Rev. Phys.* **3**, 157 (2021)

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

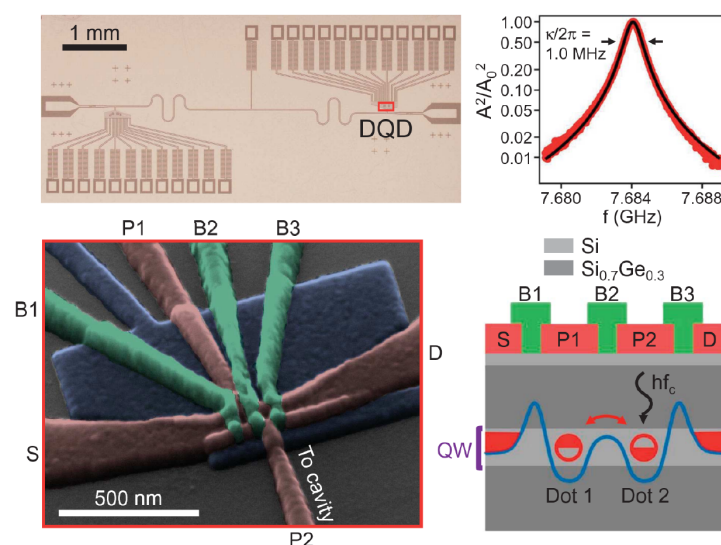
Circuit QED with quantum dots

Experimental groups: Kontos, Wallraff/Ihn/Ensslin, Petta, Vandersypen, Scarlino, etc.

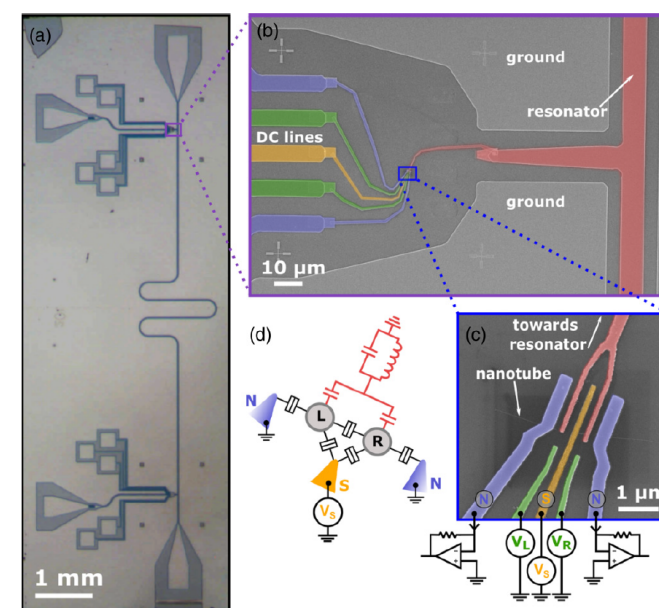
Charge-photon in strong coupling



A. Stockklauser et al., *Phys. Rev. X* **7**, 011030 (2017)

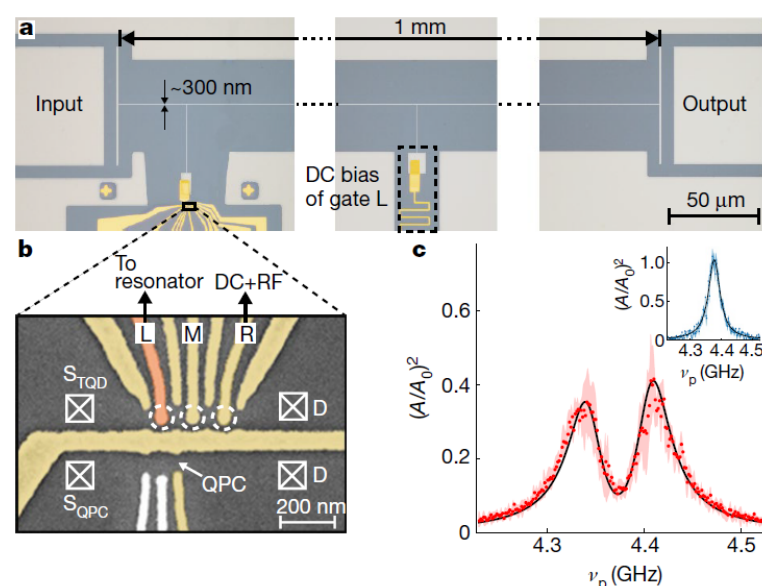


X. Mi et al., *Science* **355**, 156 (2017)

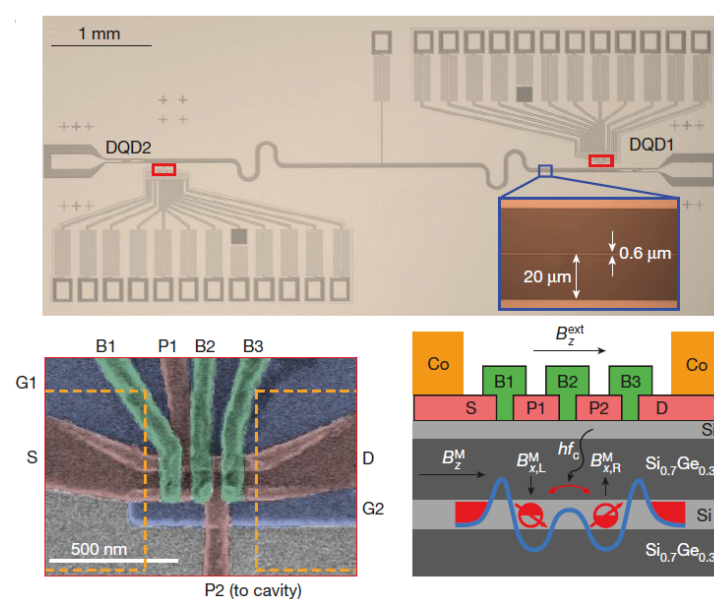


L.E. Bruhat et al, *Phys. Rev. B* **98**, 155313 (2018)

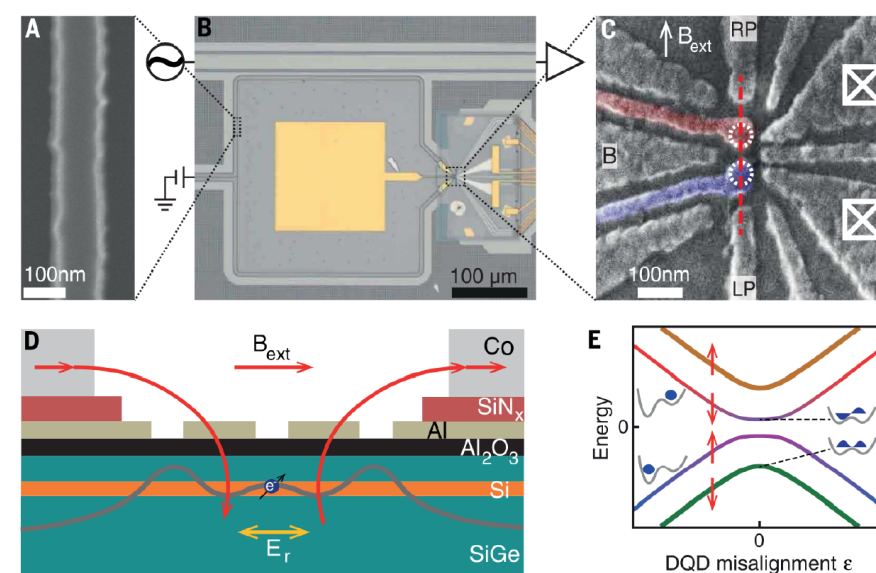
Spin-photon in strong coupling



A. Landig etl al., *Nature* **560**, 7717 (2018)



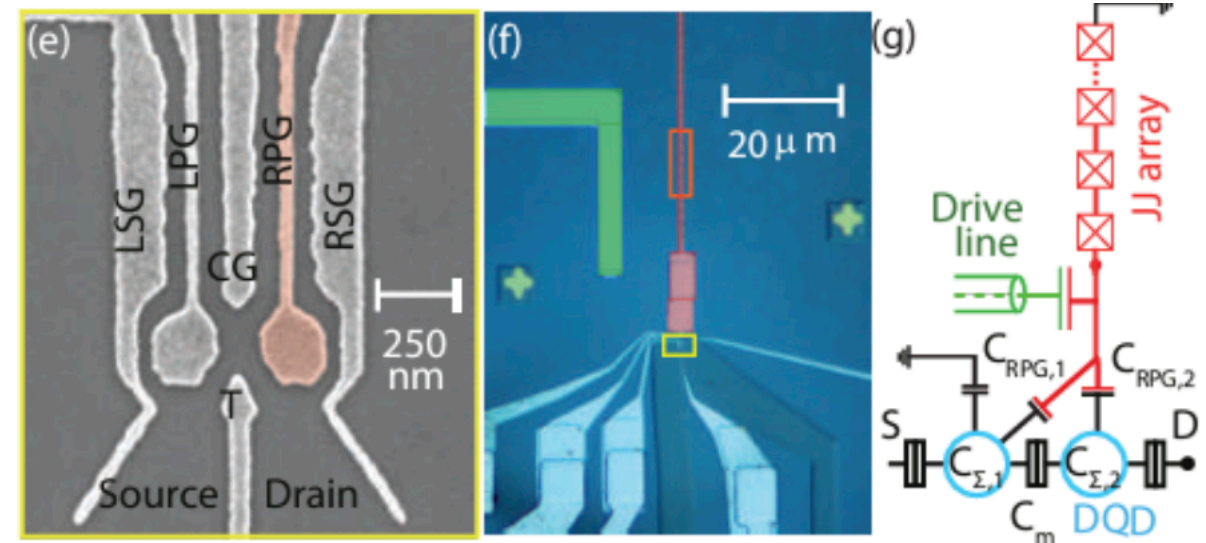
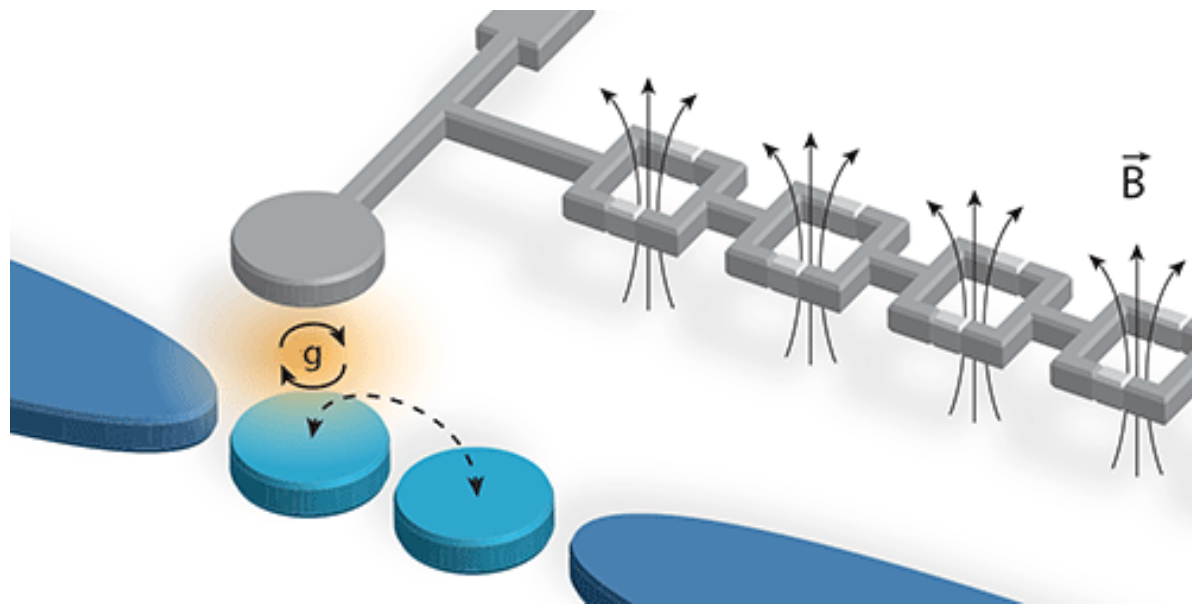
X. Mi et al., *Nature* **555**, 7698 (2018)



N. Samkharadze et al., *Science* **359**, 6380 (2018)

Circuit QED with quantum dots

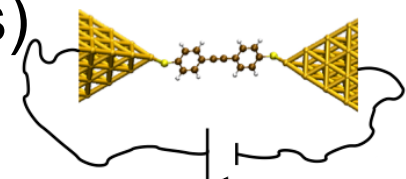
Charge-photon in *ultra* strong coupling



P. Scarlino et al., *PRX* **12**, 031004 (2022)

Motivations

- platform for quantum computation (qubit interactions mediated by photons, etc.)
- quantum simulators: models of matter-light interaction (fermions)
- quantum transport in coherent nanoconductors (single molecular junctions)



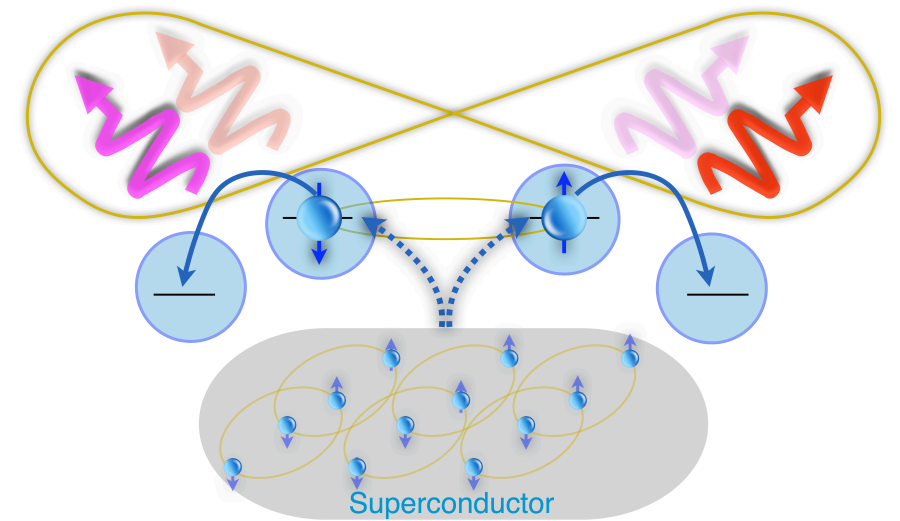
Our works

Quantum transducers sources / detectors of individual photons in microwave range

- photon entanglement using superconducting nanostructures

Entangled photon-pair emission in waveguide
circuit QED from a Cooper pair splitter

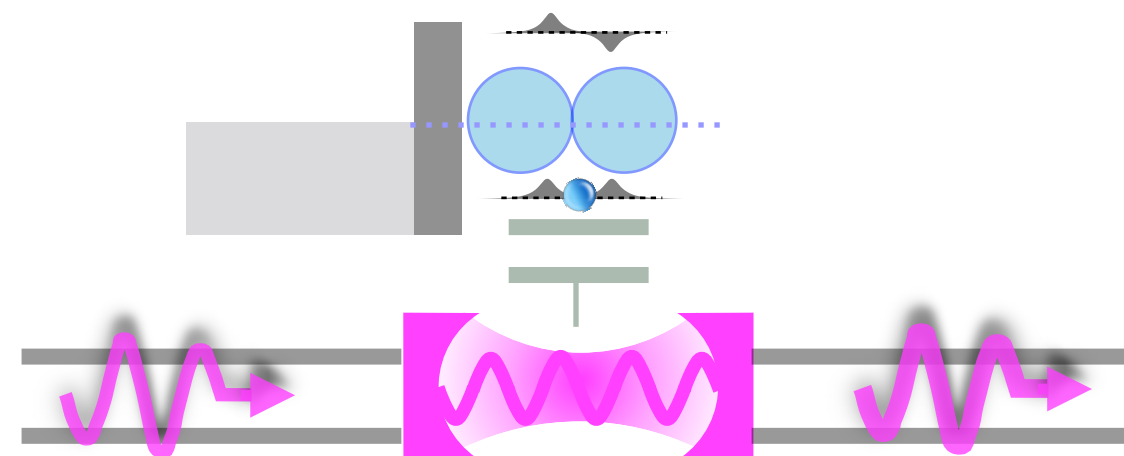
M. Governale, C. Schönenberger, P. Scarlino, **G.R.**
PRX Quantum **6**, 020339 (2025)



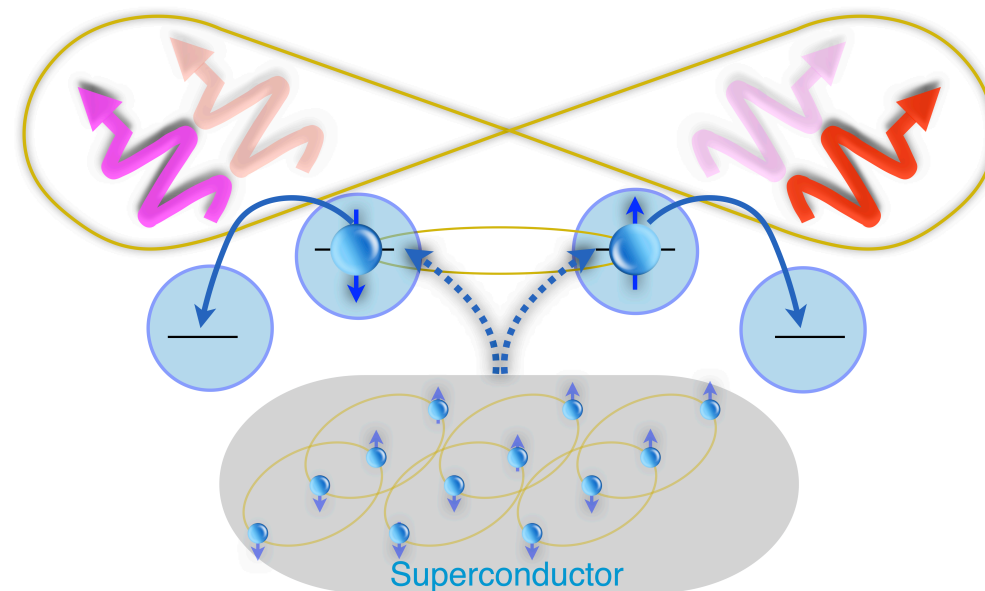
- detection of single microwave photons

Quantum nondemolition detection of single
microwave photons with quantum dots

S. Matern, A. Biella, P. Scarlino, I. Carusotto, **G.R.**
(to be submitted)



2. Generation of entangled microwave photons using superconducting nanodevices



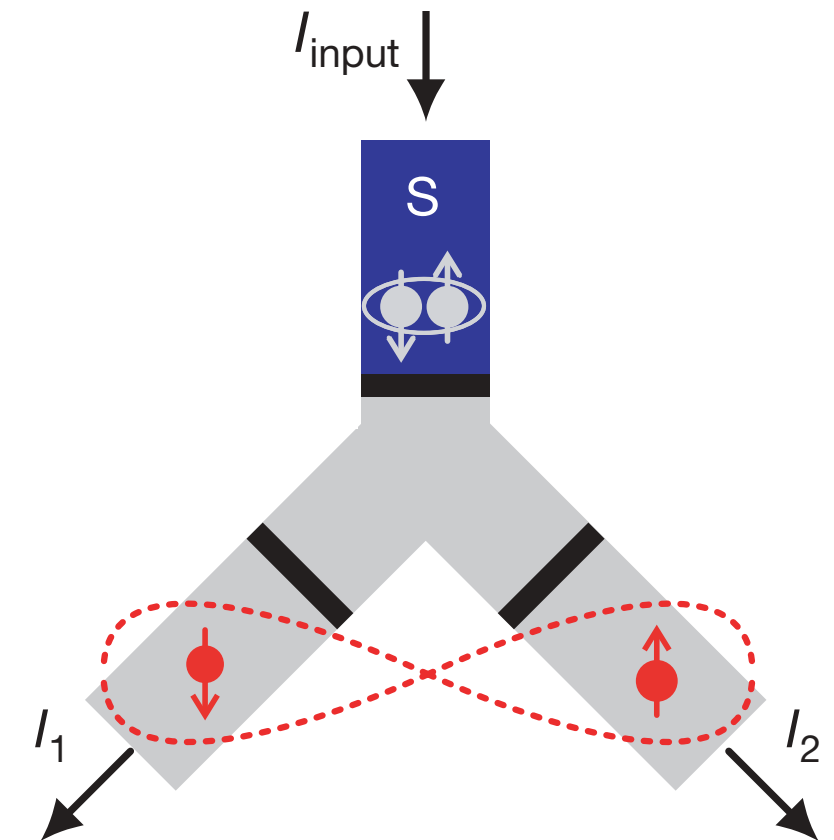
Cooper pair splitter (CPS)

Early theoretical proposals

P. Recher, E. V. Sukhorukov, D. Loss, *PRB* **63**, 165314 (2001)

G. Lesovik, T. Martin, G. Blatter, *EPJB* **24**, 287 (2001)

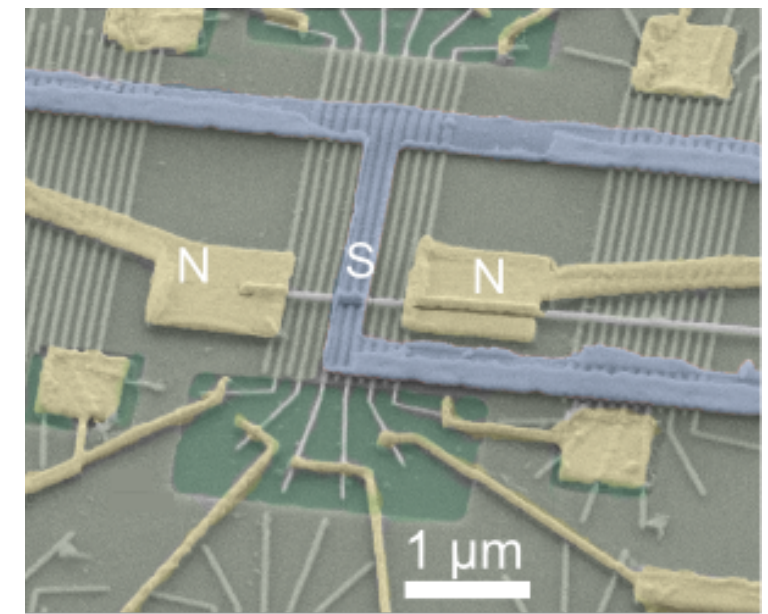
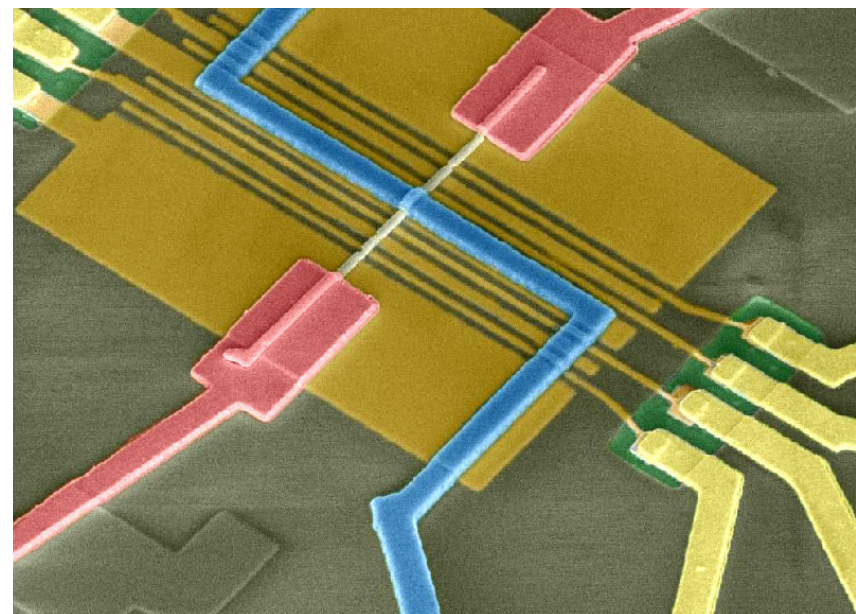
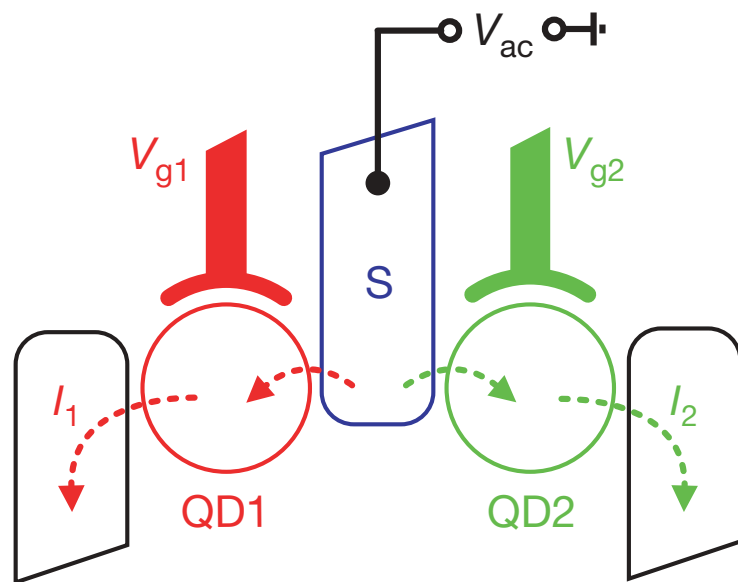
M. Chtchelkatchev, G. Blatter, G. B. Lesovik, T. Martin, *PRB* **66**, 161320 (2002)



First experiments: NWs a CNTs

L. Hofstetter, S. Csonka, J. Nygård, C. Schonenberger, *Nature* **461**, 960 (2009)

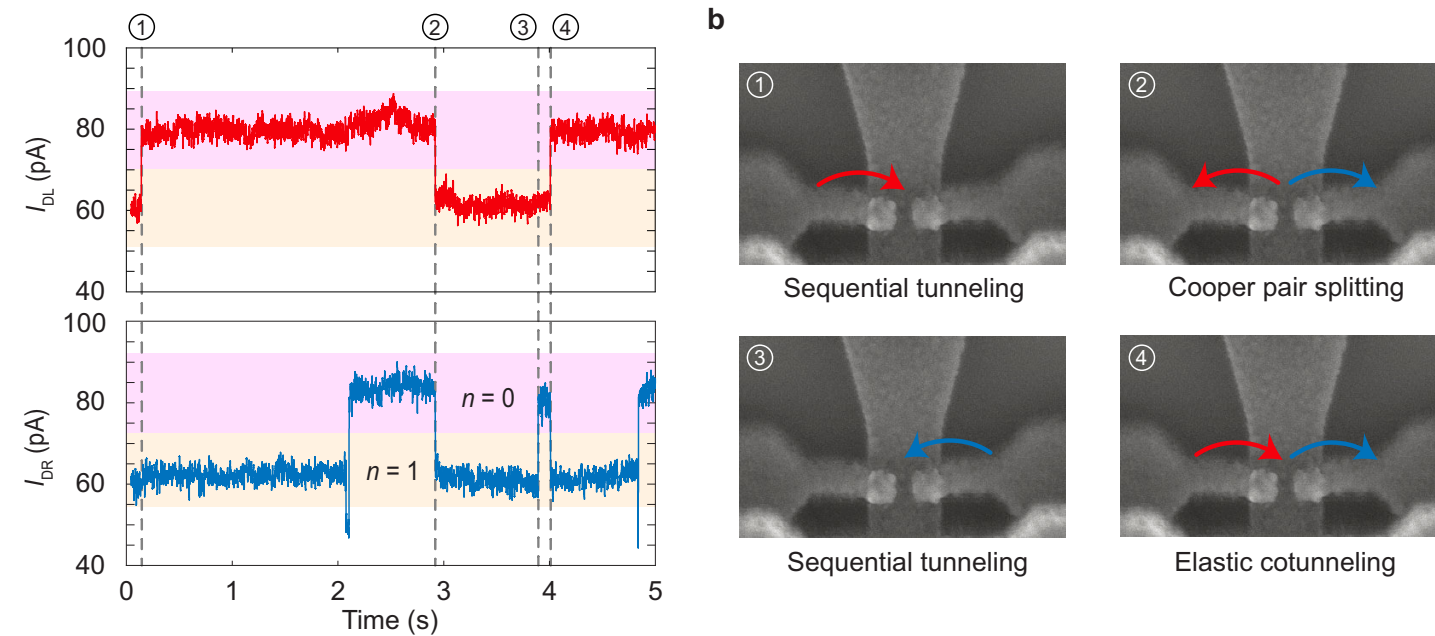
L. G. Herrmann, F. Portier, P. Roche, A. L. Yeyati, T. Kontos, C. Strunk, *PRL* **104**, 026801 (2010)



CPS: recent experiments

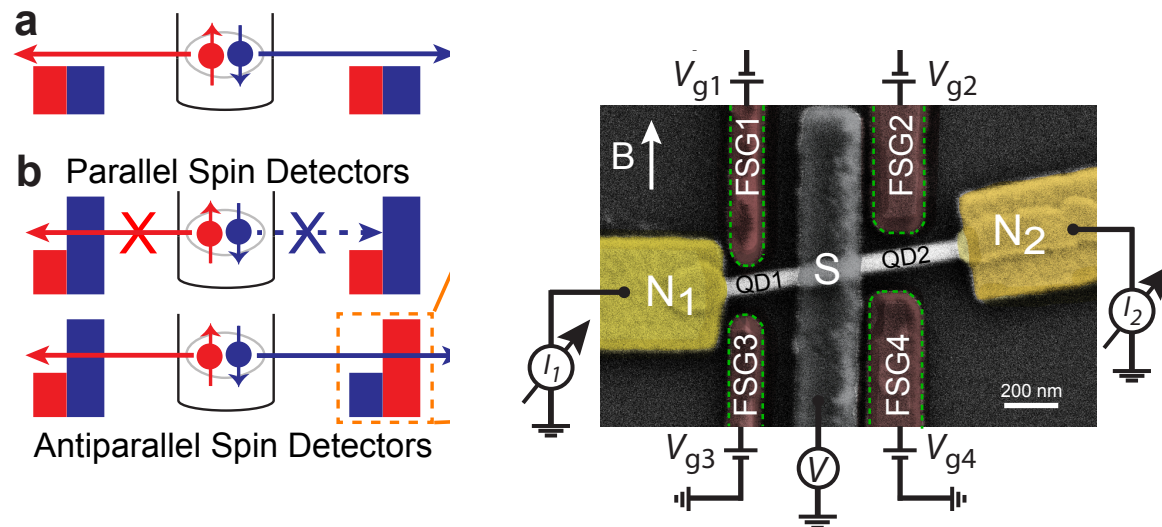
Real-time observation of Cooper pair splitting showing strong non-local correlations

A. Ranni, F. Brange, E. Mannila, C. Flindt, V. Maisi, *Nat. Commun.* **12**, 6358 (2021)



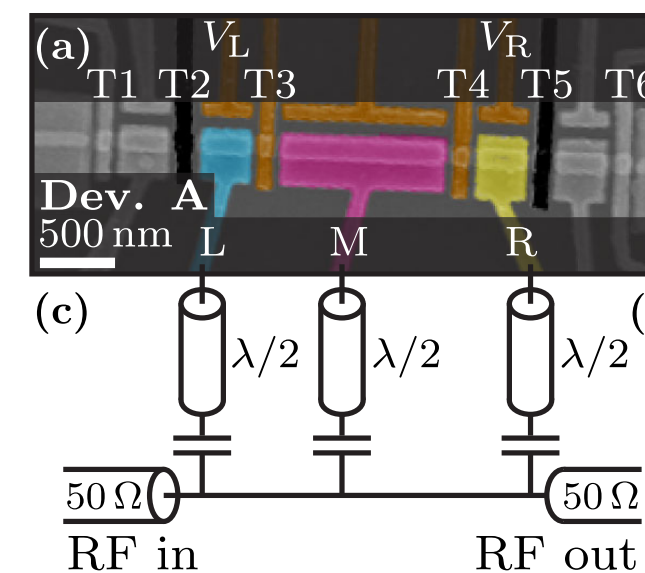
Spin cross-correlation experiments in an electron entangler

A. Bordoloi, V. Zannier, L. Sorba, C. Schönenberger, A. Baumgartner, *Nature* **612**, 454 (2022)



Controllable Single Cooper Pair Splitting in Hybrid Quantum Dot Systems

D. de Jong, C. G. Prosko, L. Han, F. K. Malinowski, Y. Liu, L. P. Kouwenhoven, W. Pfaff, *Phys. Rev. Lett.* **131**, 157001 (2023)



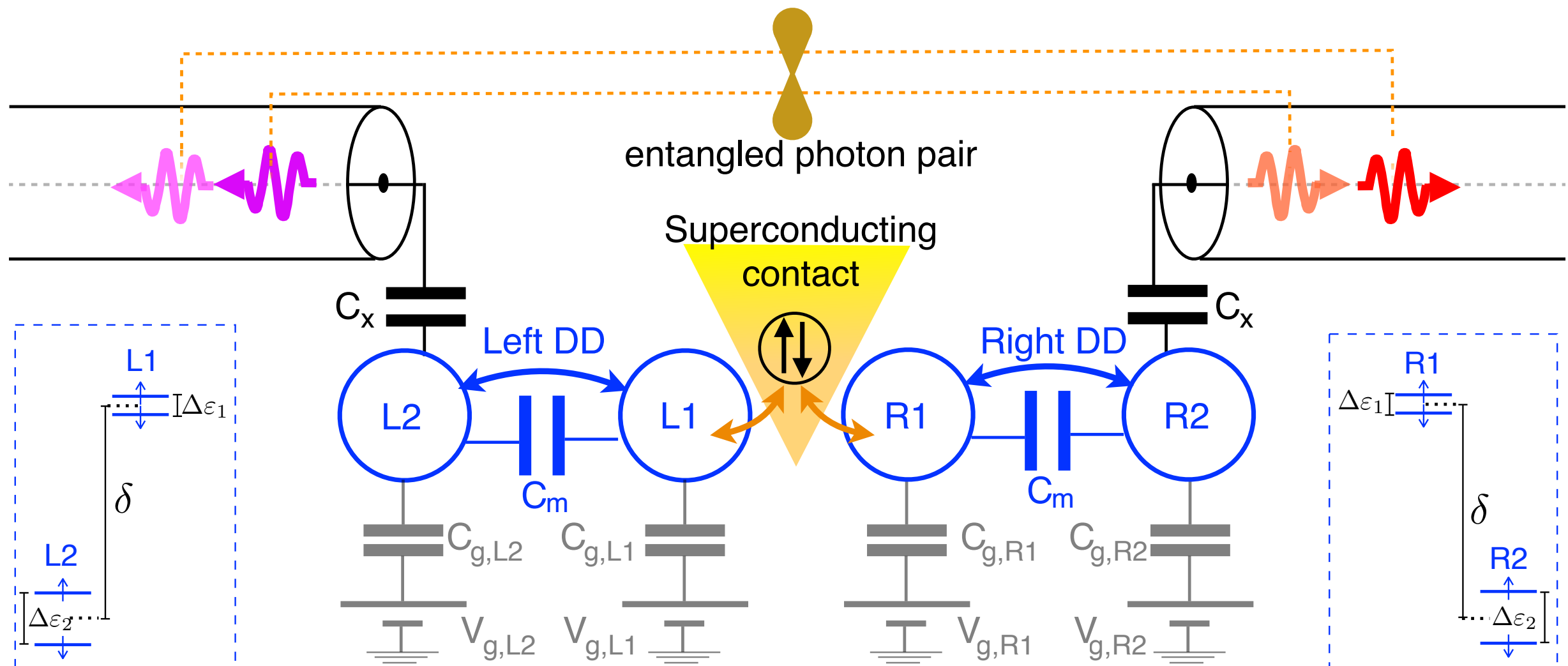
....but entanglement observation still missing!

Our proposal

Cooper pair splitter with double quantum dots



transfer entanglement to photon pairs in waveguide circuit QED

PRX Quantum **6**, 020339 (2025)

CPS with two DQDs

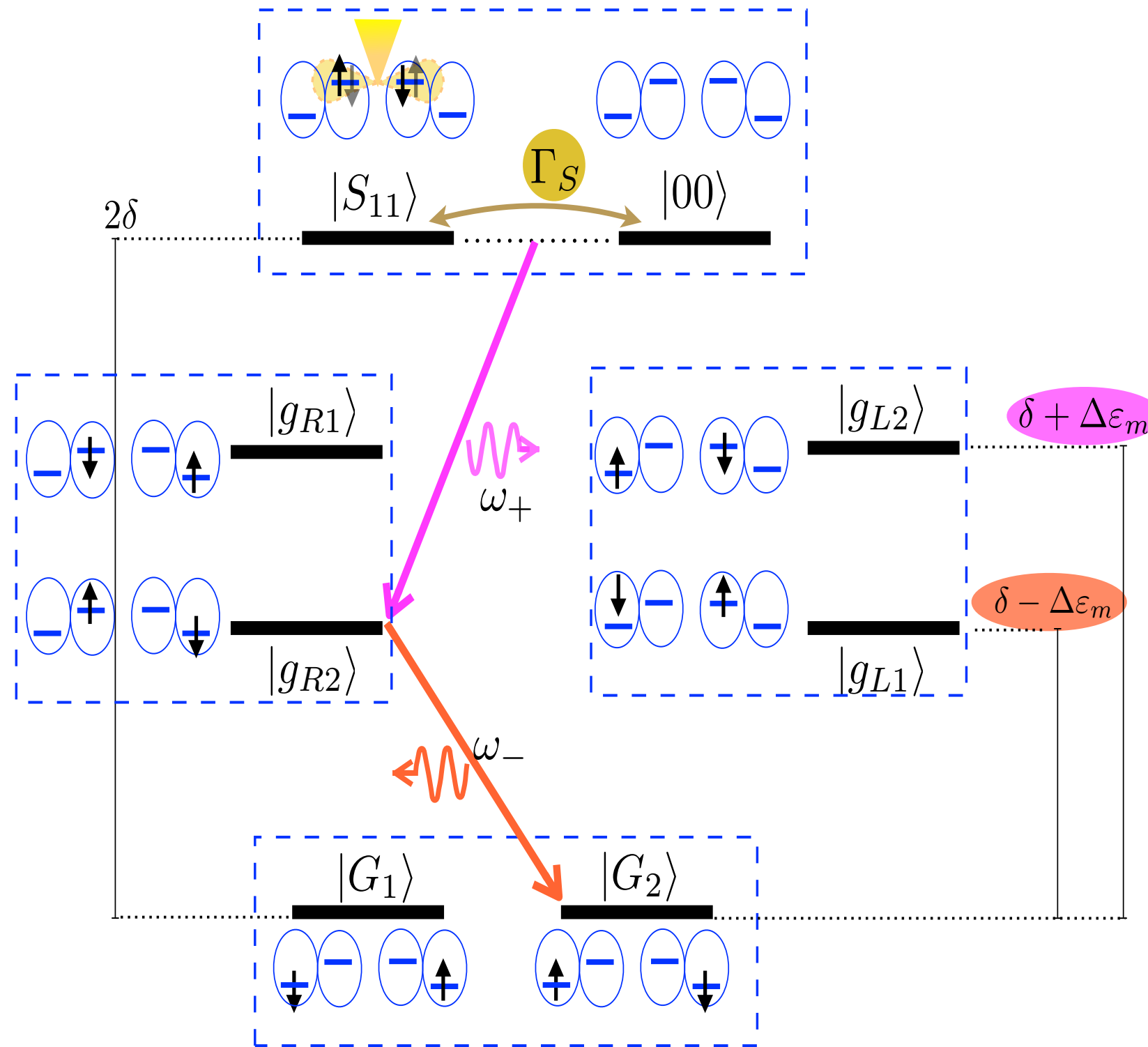
$$\hat{H}_{CPS} = -\Gamma_S |0\rangle\langle S_{11}| + \text{H.c.}$$

Γ_S = nonlocal pairing

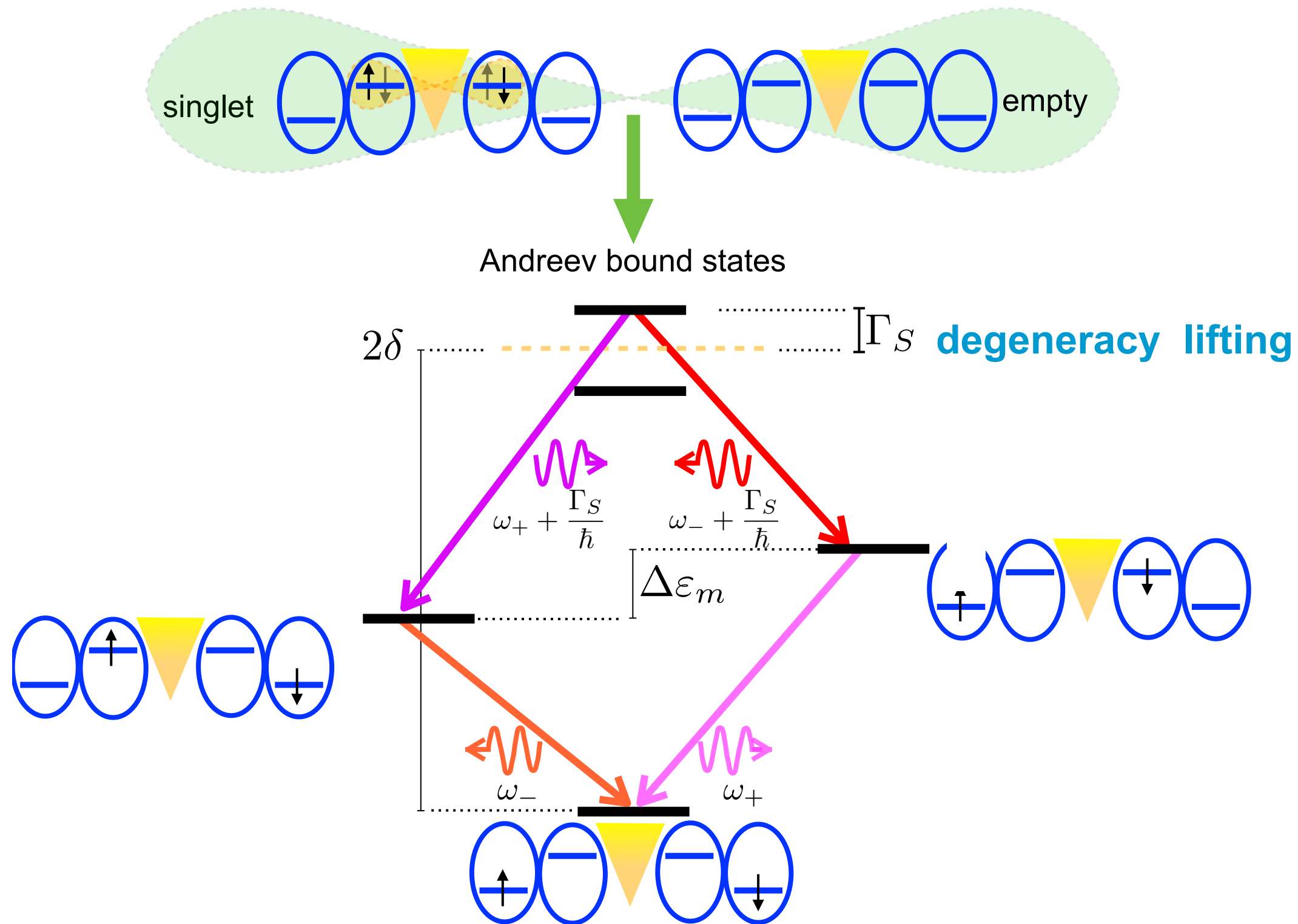
δ = double quantum dot detuning

$\Delta\varepsilon_m = (\Delta\varepsilon_2 - \Delta\varepsilon_1) / 2$
diff. between the Zeeman splittings

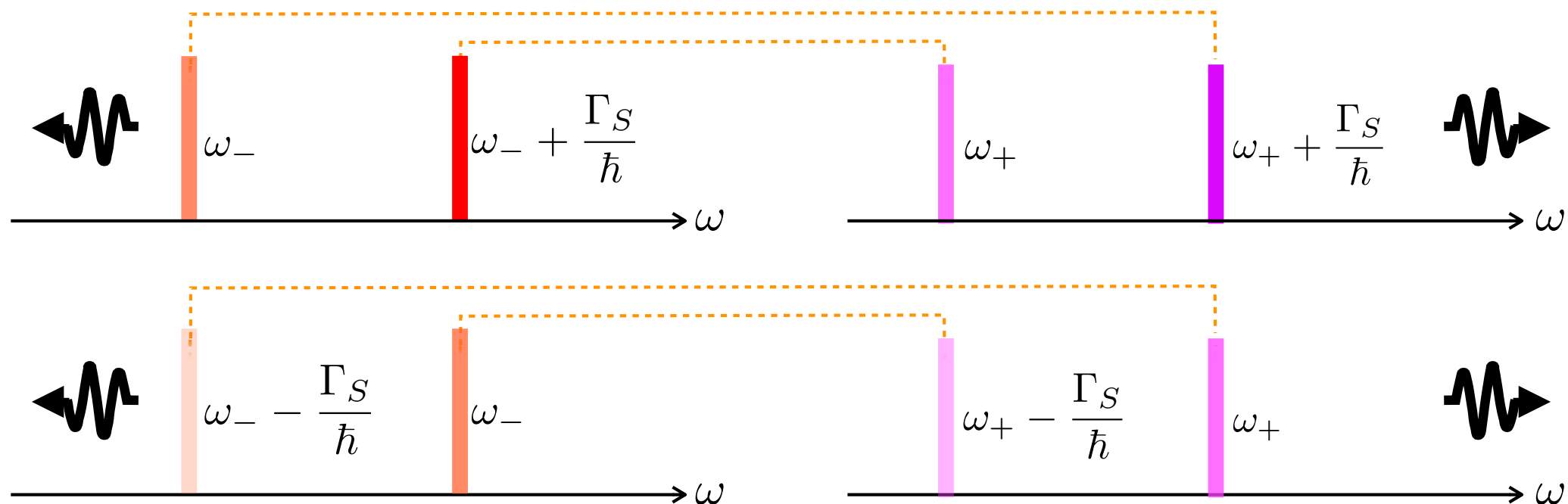
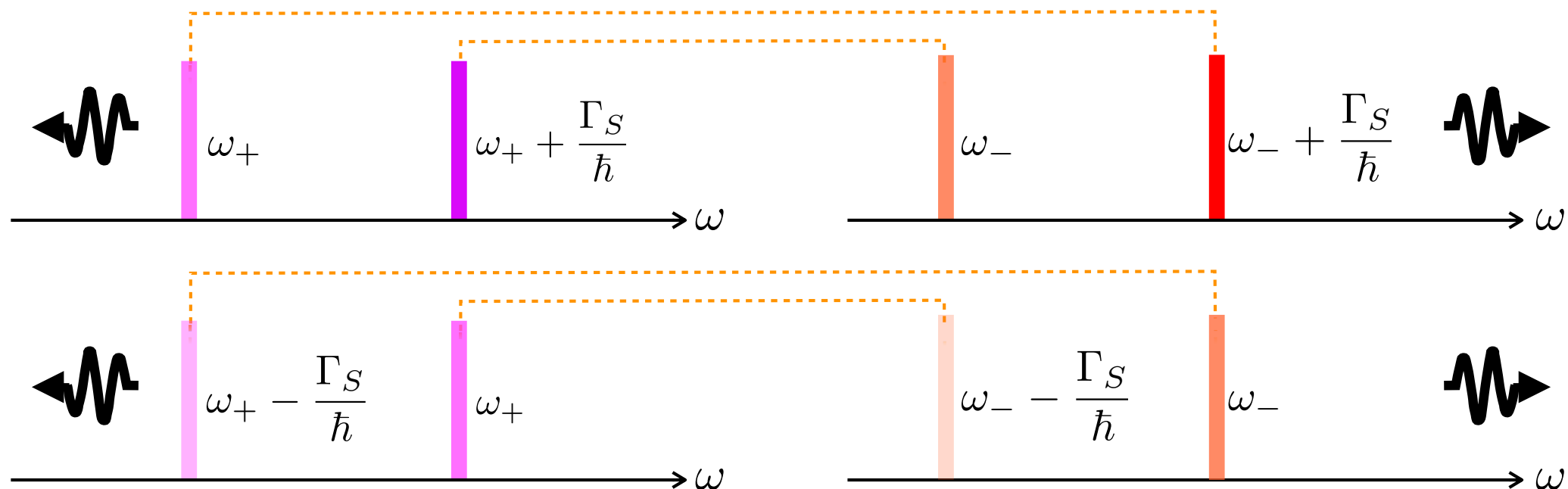
$$\hbar\omega_{\pm} = \delta \pm \Delta\varepsilon_m$$



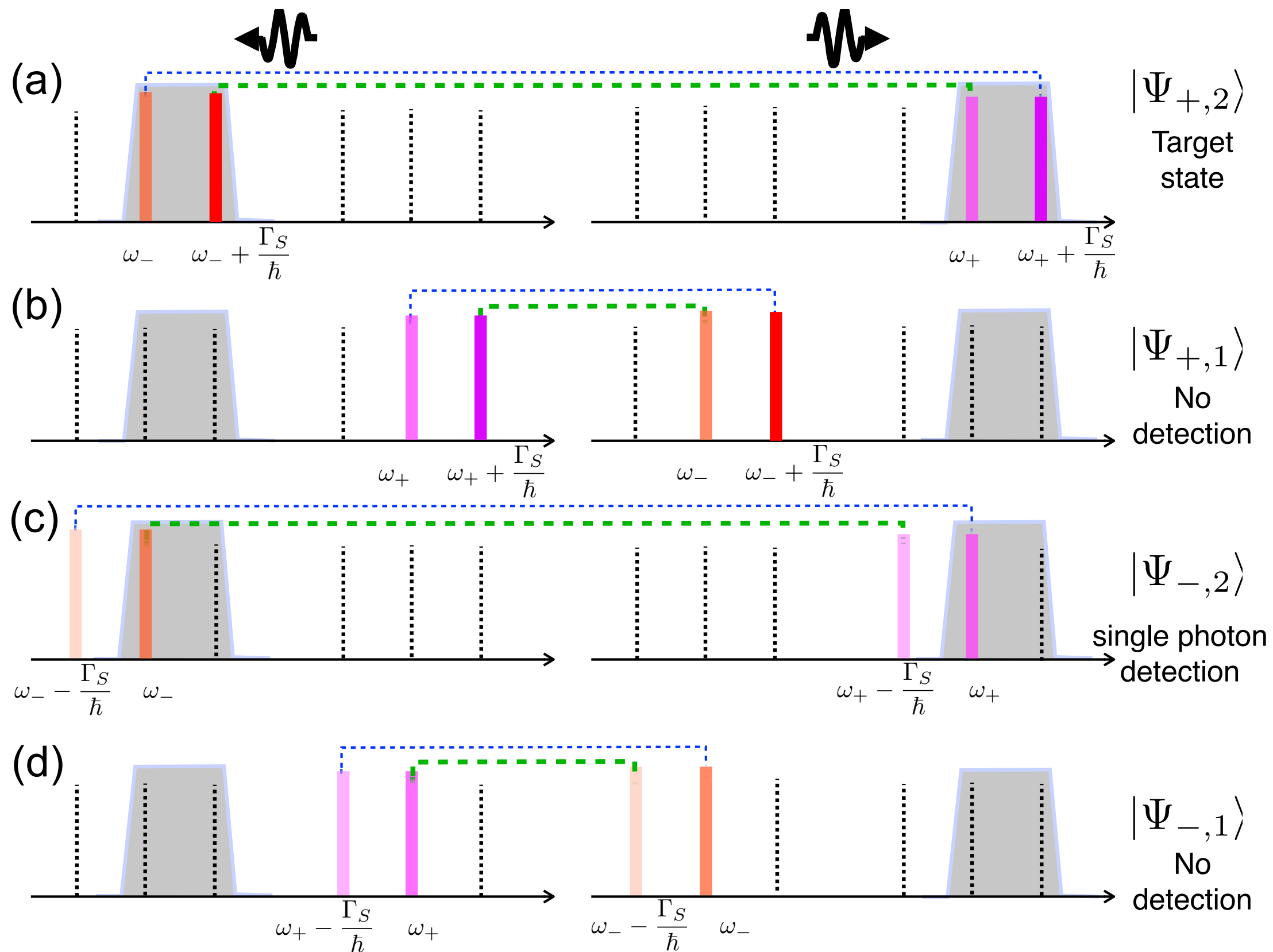
Nonlocal Andreev bound states



Frequency entangled photon pairs



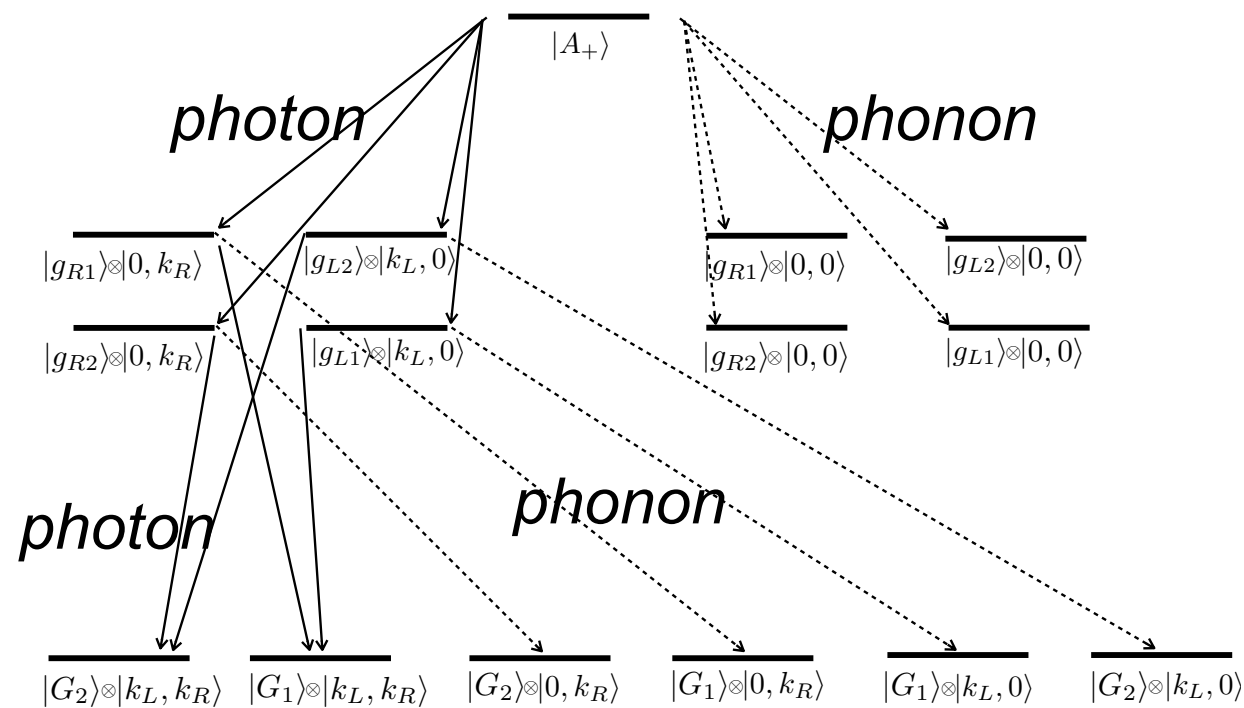
Detection by frequency filtering



(Quantum tomography in frequency space)

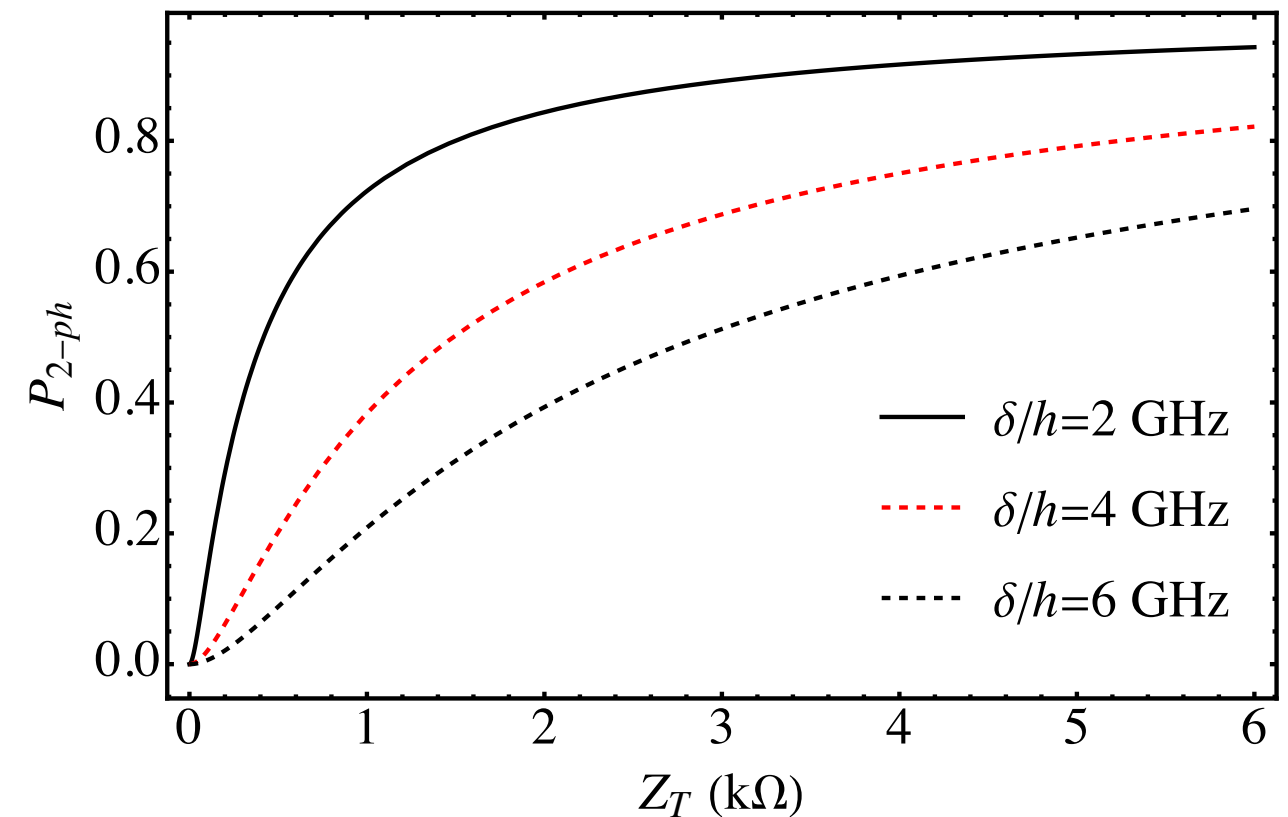
Cascade with phonon relaxation

Photon vs Phonon



Efficiency

(GaAs/AlGaAs)

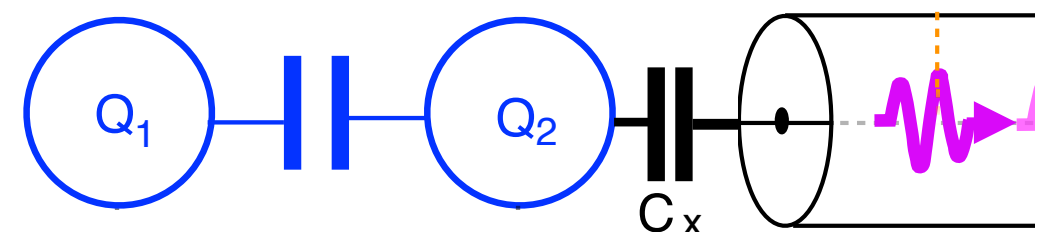


$$\gamma_{phot} \approx \left(\frac{t_{12}}{\delta} \right)^2 \left(\frac{C_x}{C_{eff}} \right)^2 \frac{Z_T}{R_K} \left(\frac{\Delta E}{\hbar} \right) \quad \text{vs} \quad \gamma_{phon} \approx \left(\frac{t_{12}}{\delta} \right)^2 J_{phon}(\delta)$$

t_{12} = DQD tunneling coupling (dipole)

Z_T = characteristic impedance of the transmission line

$R_K = h/e^2$ quantum resistance



Experimental feasibility

range of parameters

$1/h$	δ	t_{12}	$\Delta\varepsilon_1, \Delta\varepsilon_2$	$\Delta\varepsilon_m$	Γ_S
GHz	2 – 10	$\lesssim 0.3$	0.25 – 0.75	$\lesssim 0.5$	$\lesssim 0.25$

Charge dephasing

at large detuning in GaAs ≈ 50 MHz ,

P. Scarlino et al., *PRL* **122**, 206802 (2019)
P. Scarlino et al., *PRX* **12**, 031004 (2022)

Spin relaxation and dephasing

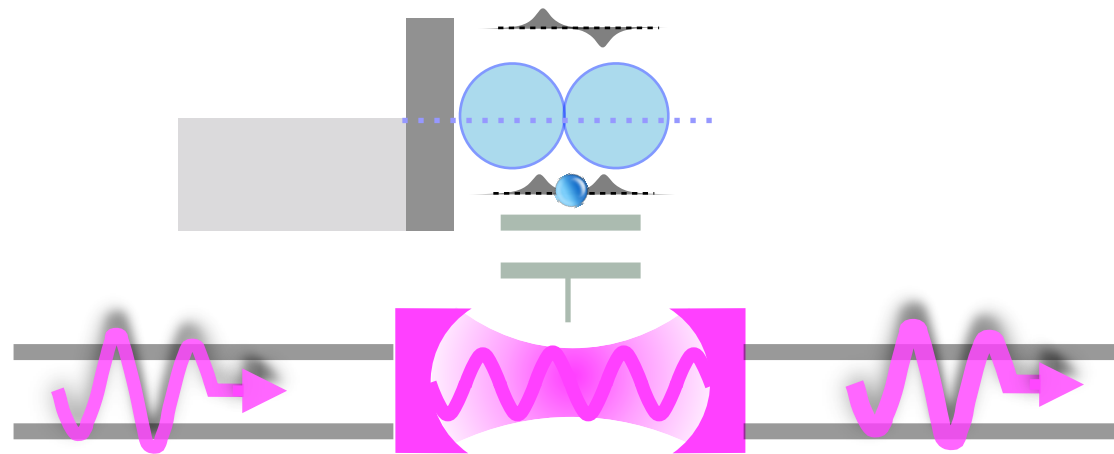
relaxation
single QD ~ 1 KHz

Ga-As P. Scarlino et al., *PRL* **113**, 256802 (2014)
Si A. Zwanenburg et al., *RMP* **85**, 961 (2013)
Ge W. I. L. Lawrie et al., *Nano Letters* **20**, 7237 (2020).

dephasing
 $1\mu s < T_2 < 100\mu s$

Ge N. W. Hendrickx et al., *Nature* **591**, 580 (2021).
Si (purified) M. Veldhorst et al., *Nat. Nanotechn.* **9**, 981 (2014)

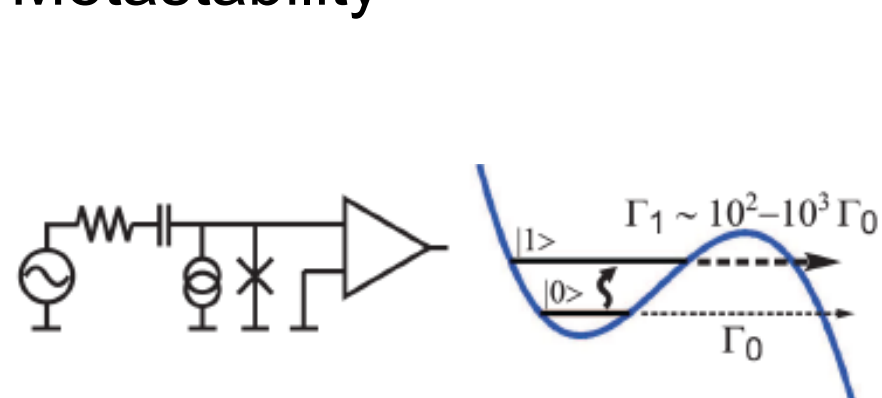
3. Photodetection and quantum nondemolition with quantum dots



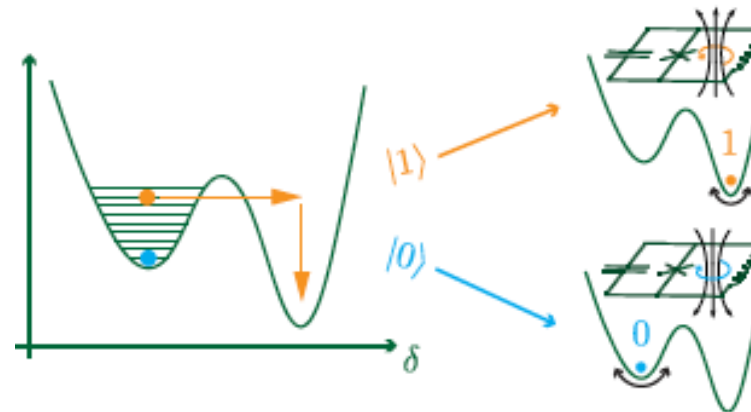
Single microwave photon detection

State of the art: Josephson junction circuits and qubits

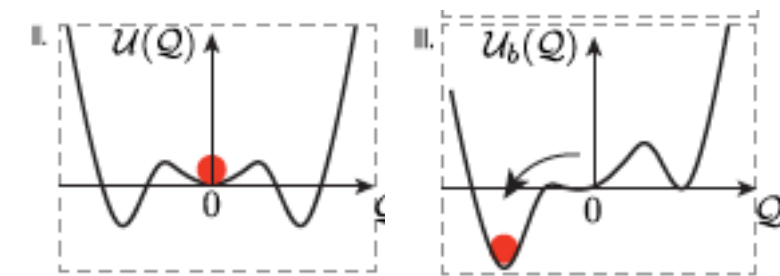
Metastability



Y.-F. Chen et al., Phys. Rev. Lett. 107, 217401 (2011)
 A.L. Pankratov et al., npj Quantum Inf. 8, 61 (2022)
 A.L. Pankratov et al., Nat. Commun. 16, 3457 (2025)

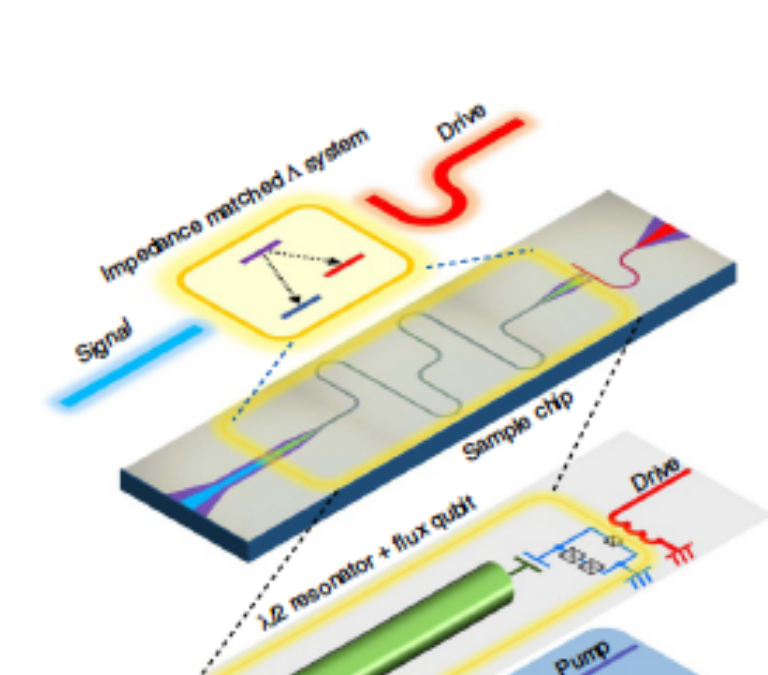


A. Opremcak et al., Science 361, 1239 (2018)
 A. Opremcak et al., Phys. Rev. X 11, 011027 (2021)

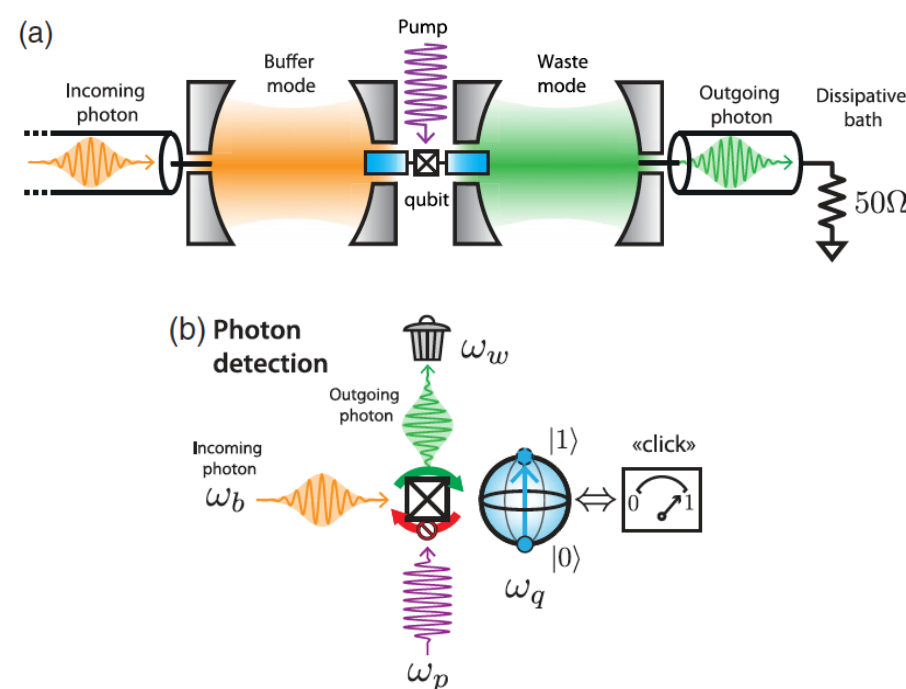


K. Petrovnin et al.,
 PRX Quantum 5, 020342 (2024)

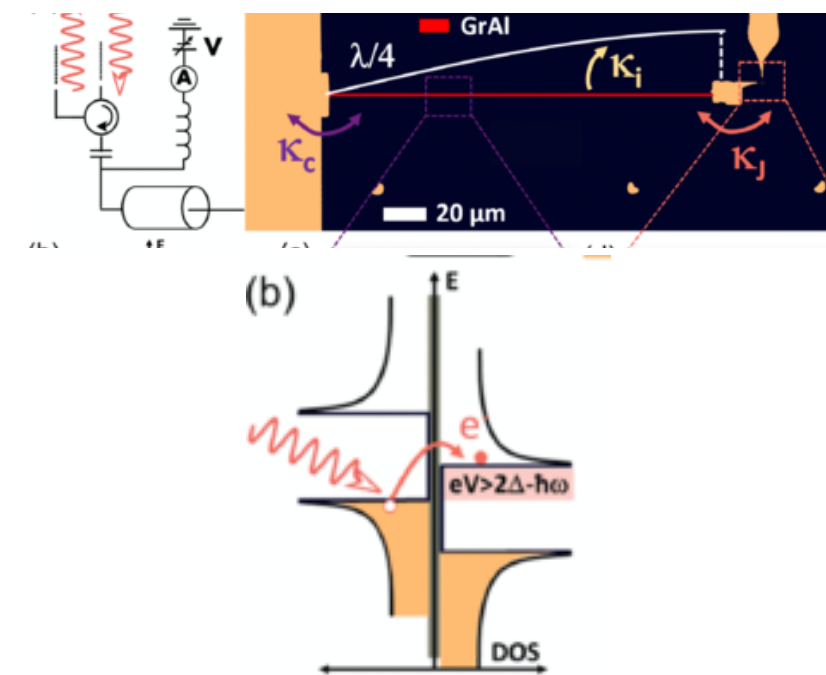
Engineered dissipation



K. Inomata, et al., Nat. Commun. 7, 12303 (2016)



R. Lescanne et al., PRX 10, 021038 (2020)

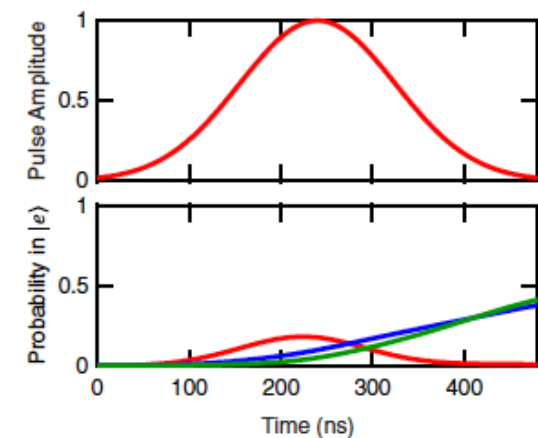


O. Stanisavljević et al., PRL 133, 076302 (2024)

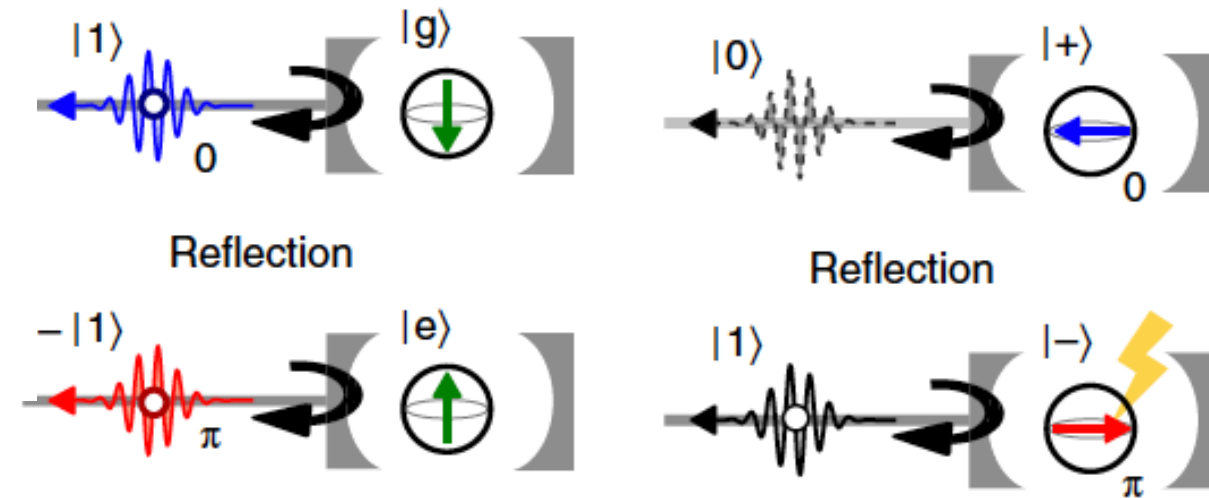
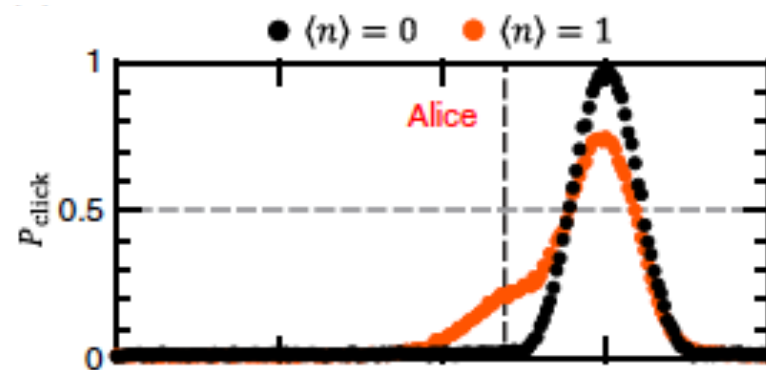
Single microwave photon detection

State of the art: Josephson junction circuits and qubits

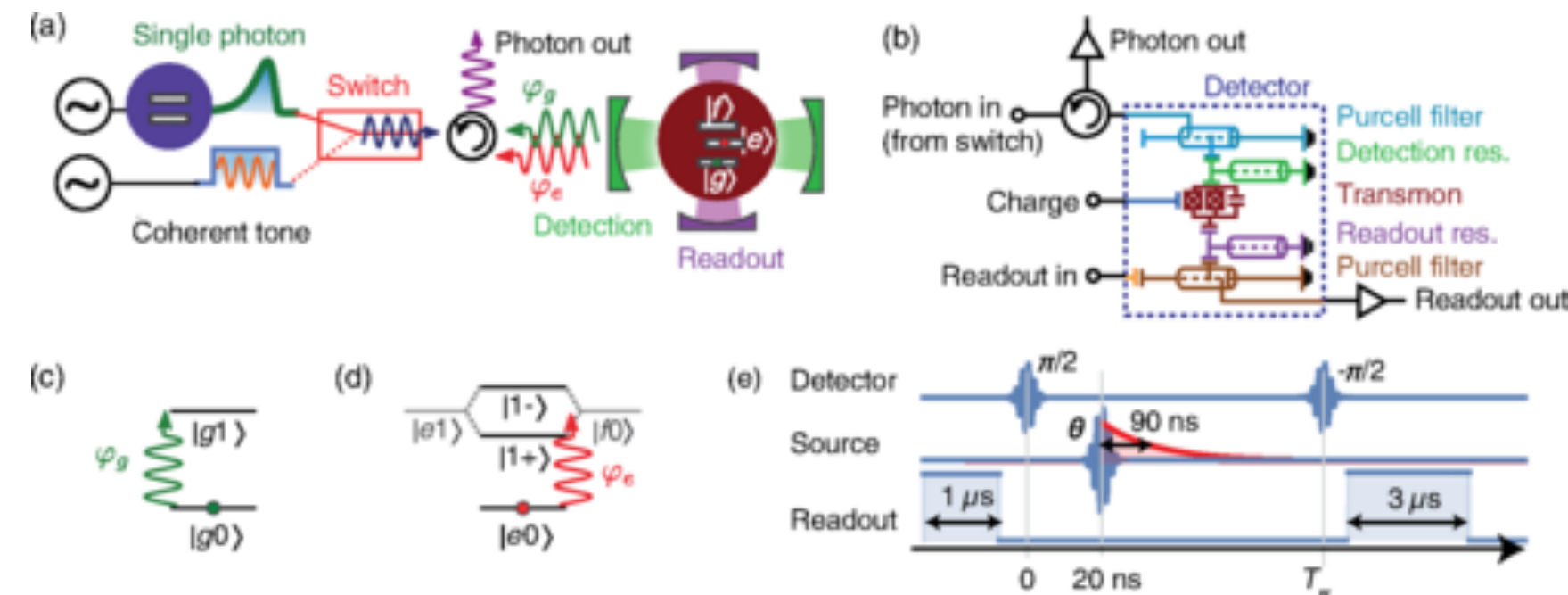
QND with superconducting qubit (dispersive interaction)



A. Narla et al., PRX 6, 031036 (2016)



S. Kono et al., Nature Phys. 14, 546 (2018)

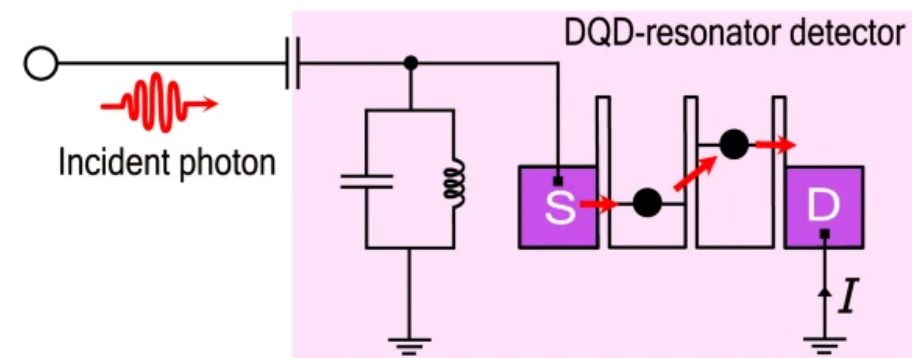


J.-C. Besse et al., PRX 8, 021003 (2018)

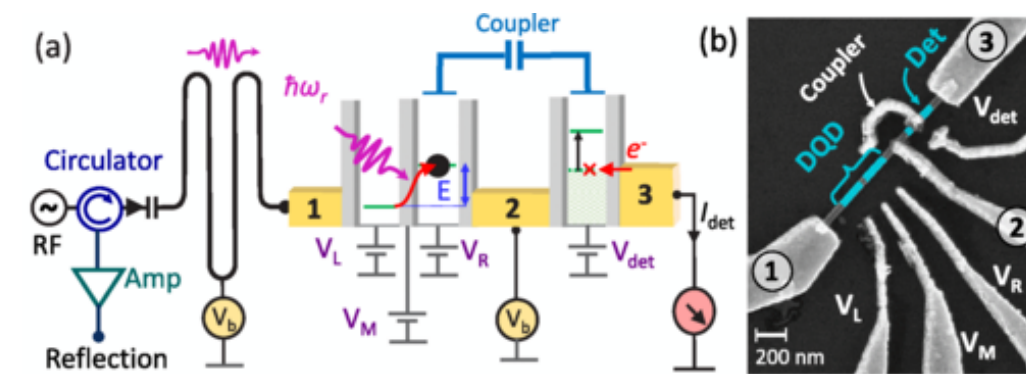
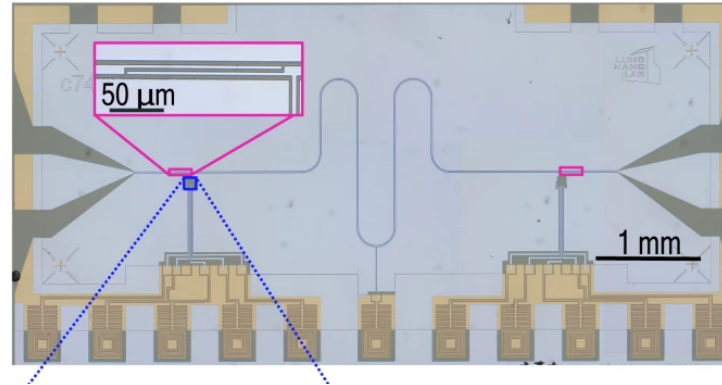
Single microwave photon detection

State of the art: quantum dots

Photon-assisted tunneling (Maisi's group)

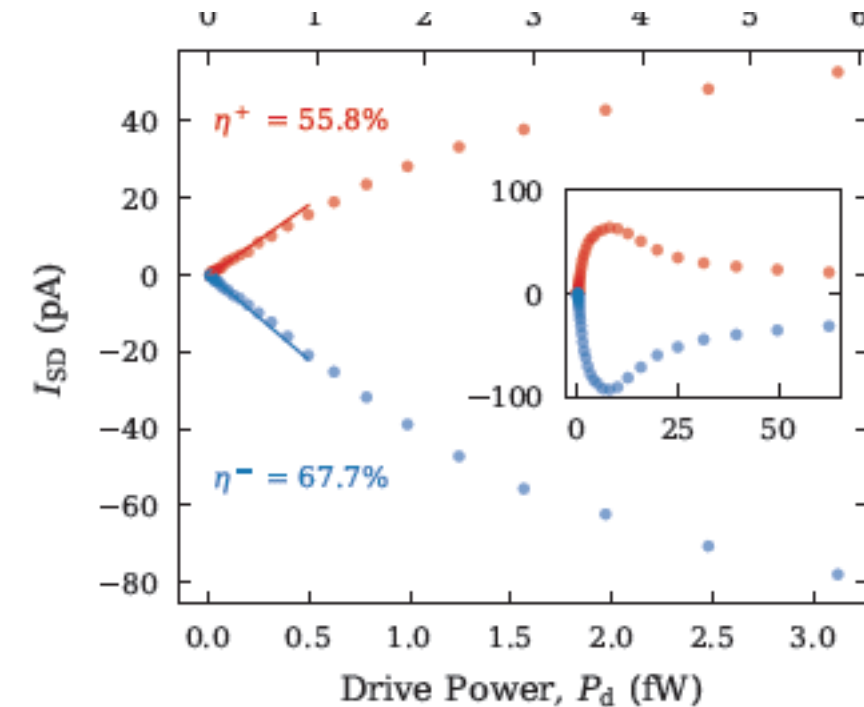
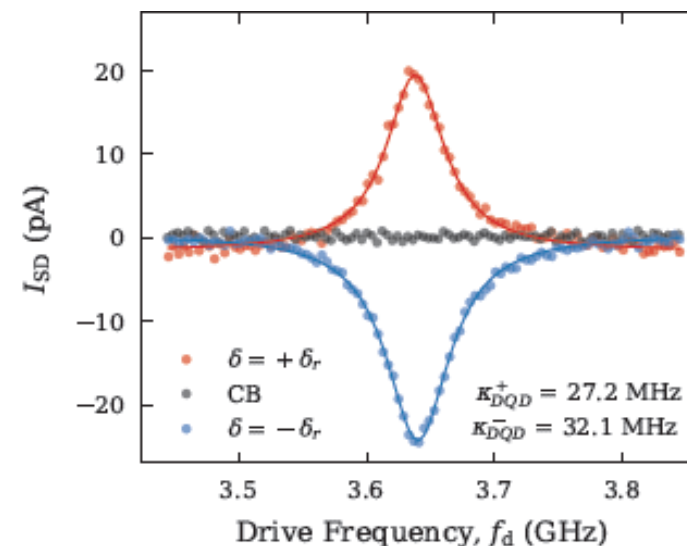
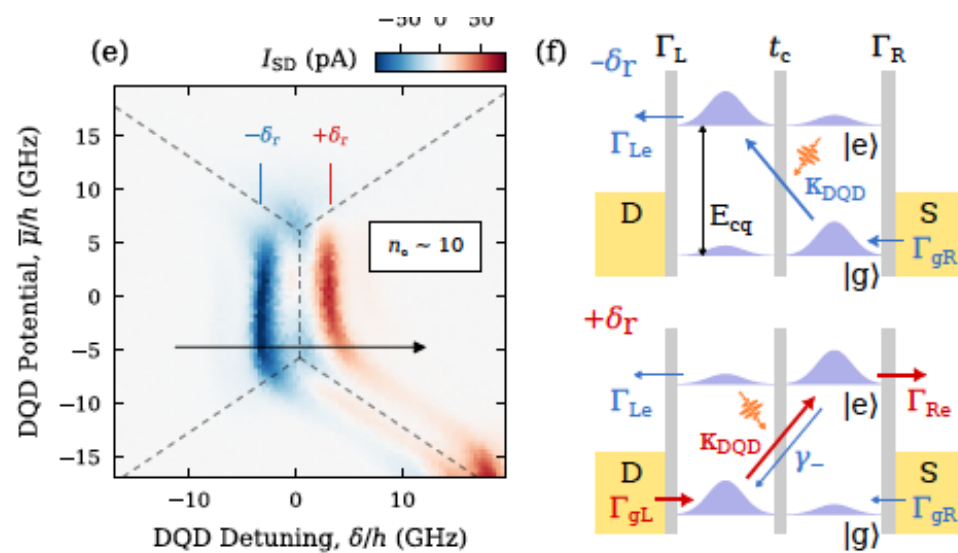


W. Khan et al., Nat. Comm. 12, 5130 (2021)



S. Haldar et al., PRL 133, 217001 (2024)

High-Efficiency Tunable Microwave Photon (Scarlino's group)

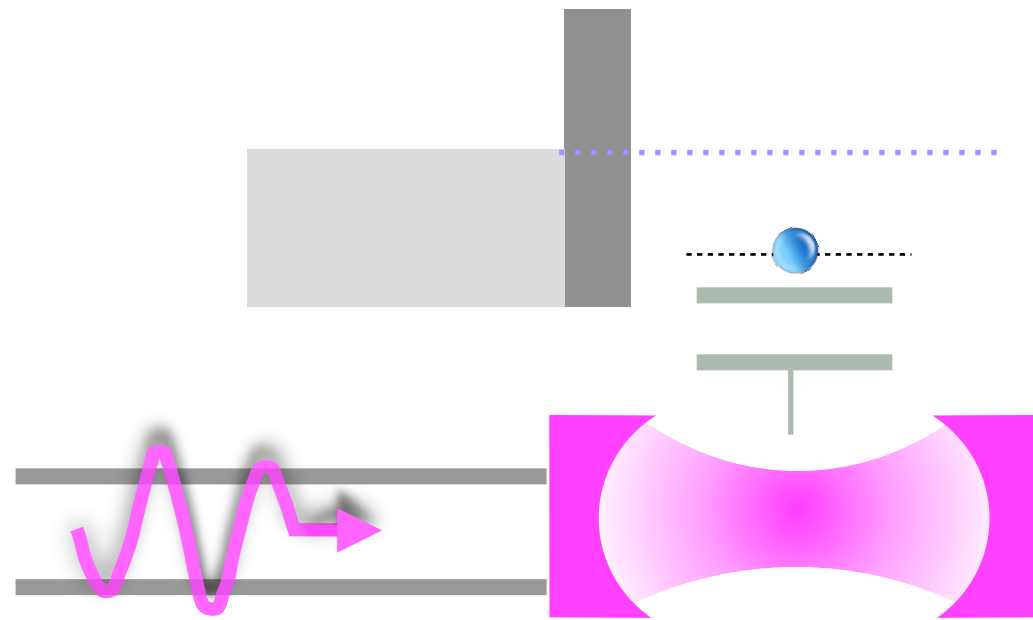


F. Opplinger et al., arxiv.org/abs/2506.19828

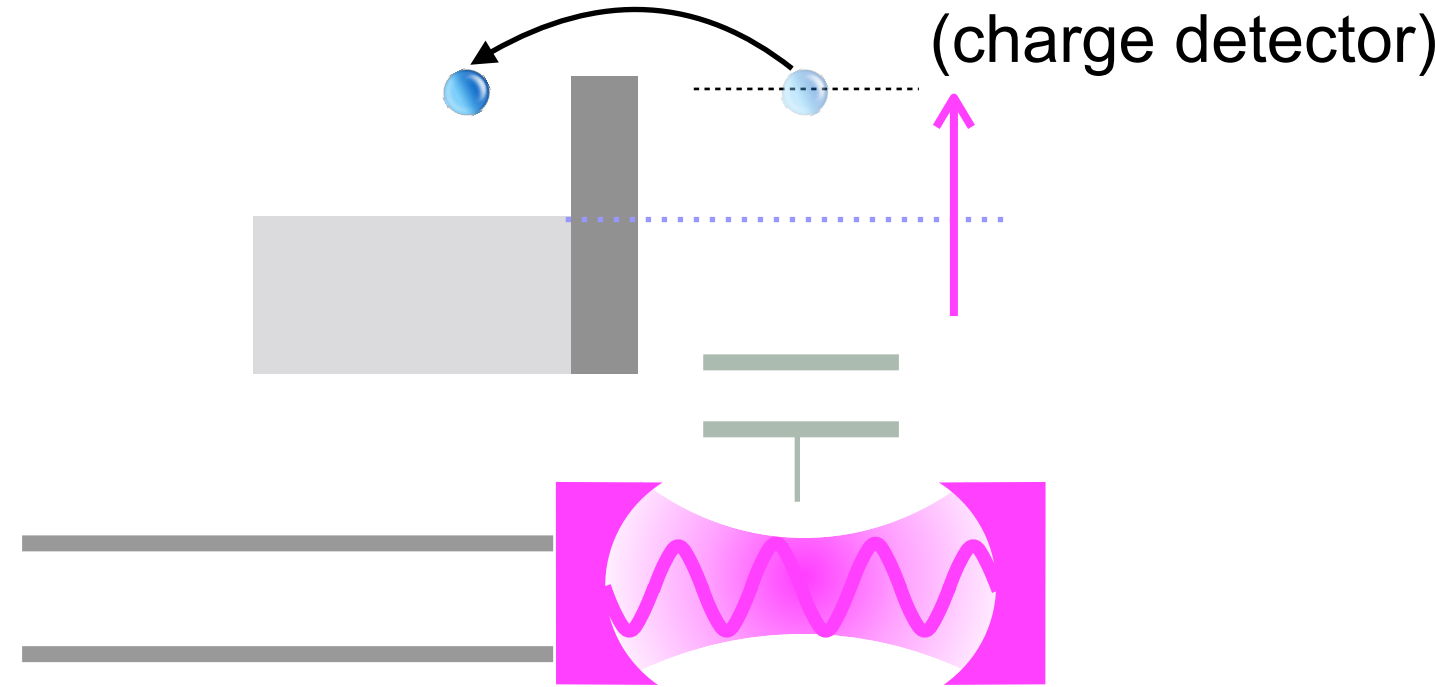
see also review A. Ghirri et al., Sensors 20, 4010 (2020)

Our proposal

dispersive interaction between a DQD and a cavity



$$H_{cQED} = \varepsilon \hat{n}_D + \hbar \omega_c \hat{n}_c + \lambda \hat{n}_D \hat{n}_c$$



Tunneling dynamics with dispersive interaction

$$\begin{aligned} \mathcal{L}_d[\hat{\rho}]/\Gamma_{QD} = & -f_0 \left[\left\{ \hat{\Pi}_0 \hat{d} \hat{d}^\dagger; \hat{\rho} \right\} - 2\hat{\Pi}_0 \hat{d}^\dagger \hat{\rho} \hat{d} \hat{\Pi}_0 \right] - f_\lambda \left[\left\{ \hat{\Pi}_1 \hat{d} \hat{d}^\dagger; \hat{\rho} \right\} - 2\hat{\Pi}_1 \hat{d}^\dagger \hat{\rho} \hat{d} \hat{\Pi}_1 \right] \\ & - (1 - f_0) \left[\left\{ \hat{\Pi}_0 \hat{d}^\dagger \hat{d}; \hat{\rho} \right\} - 2\hat{\Pi}_0 \hat{d} \hat{\rho} \hat{d}^\dagger \hat{\Pi}_0 \right] - (1 - f_\lambda) \left[\left\{ \hat{\Pi}_1 \hat{d}^\dagger \hat{d}; \hat{\rho} \right\} - 2\hat{\Pi}_1 \hat{d} \hat{\rho} \hat{d}^\dagger \hat{\Pi}_1 \right] \\ & + [f_0 + f_\lambda] \left(\hat{\Pi}_0 \hat{d}^\dagger \hat{\rho} \hat{d} \hat{\Pi}_1 + \hat{\Pi}_1 \hat{d}^\dagger \hat{\rho} \hat{d} \hat{\Pi}_0 \right) + [2 - f_0 - f_\lambda] \left(\hat{\Pi}_0 \hat{d} \hat{\rho} \hat{d}^\dagger \hat{\Pi}_1 + \hat{\Pi}_1 \hat{d} \hat{\rho} \hat{d}^\dagger \hat{\Pi}_0 \right) \end{aligned}$$

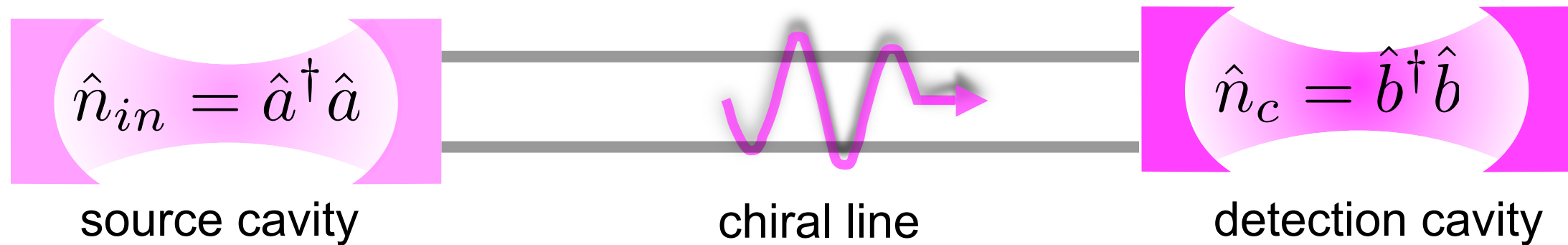
$$f_0 = f(\epsilon) \quad (\text{Fermi function}) \quad f_\lambda = f(\epsilon + \lambda) \quad \hat{\Pi}_0 = |0\rangle \langle 0| \quad \hat{\Pi}_1 = |1\rangle \langle 1|$$

(single photon regime)

Theoretical model

Quantum cascade model

C.W. Gardiner, PRL **70**, 2269 (1993)
H.J. Carmichael, PRL **70**, 2273 (1993)



$$\begin{aligned} \mathcal{L}_{cas}[\hat{\rho}] = & -\gamma_{in} \left[\left\{ \hat{a}^\dagger \hat{a}, \hat{\rho} \right\} - 2\hat{a} \hat{\rho} \hat{a}^\dagger \right] - \gamma_c \left[\left\{ \hat{b}^\dagger \hat{b}, \hat{\rho} \right\} - 2\hat{b} \hat{\rho} \hat{b}^\dagger \right] \\ & - 2\sqrt{\gamma_{in} \gamma_c} \left[\hat{b}^\dagger \hat{a} \hat{\rho} + \hat{\rho} \hat{a}^\dagger \hat{b} - \hat{b} \hat{\rho} \hat{a}^\dagger - \hat{a} \hat{\rho} \hat{b}^\dagger \right] \end{aligned}$$

Tracing the line:
dissipative nonreciprocal
interaction

Charge detector

$$\mathcal{L}_{det}[\hat{\rho}] = -\gamma_{det} \left[\hat{X} \hat{\sigma}^\dagger \rho \hat{\sigma}^- - \frac{1}{2} \left\{ \hat{X} \hat{\sigma}^- \hat{\sigma}^+, \hat{\rho} \right\} \right]$$

$$\hat{\sigma}^+ = |1_d\rangle \langle 0_d| \quad \hat{\sigma}^- = |0_d\rangle \langle 1_d|$$

$$\hat{X} = 1 - \hat{n}_d$$

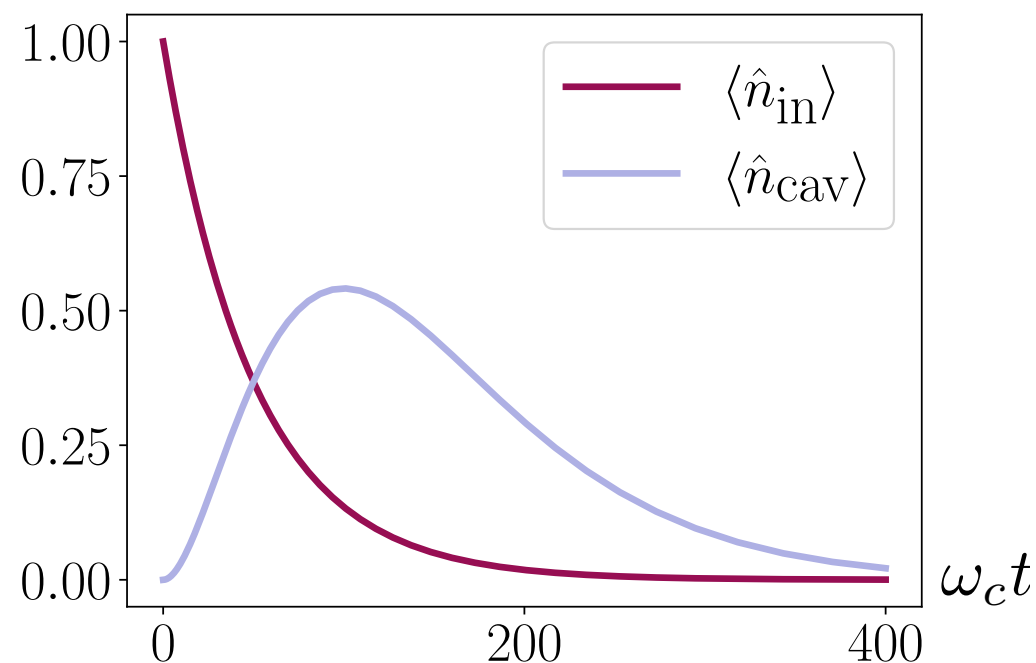
Master equation

$$\frac{d\hat{\rho}}{dt} = -i \left[H_{cQED} + \hbar \omega_{in} \hat{n}_{in}, \rho \right] + \mathcal{L}_d[\hat{\rho}] + \mathcal{L}_{cas}[\hat{\rho}] + \mathcal{L}_{det}[\hat{\rho}]$$

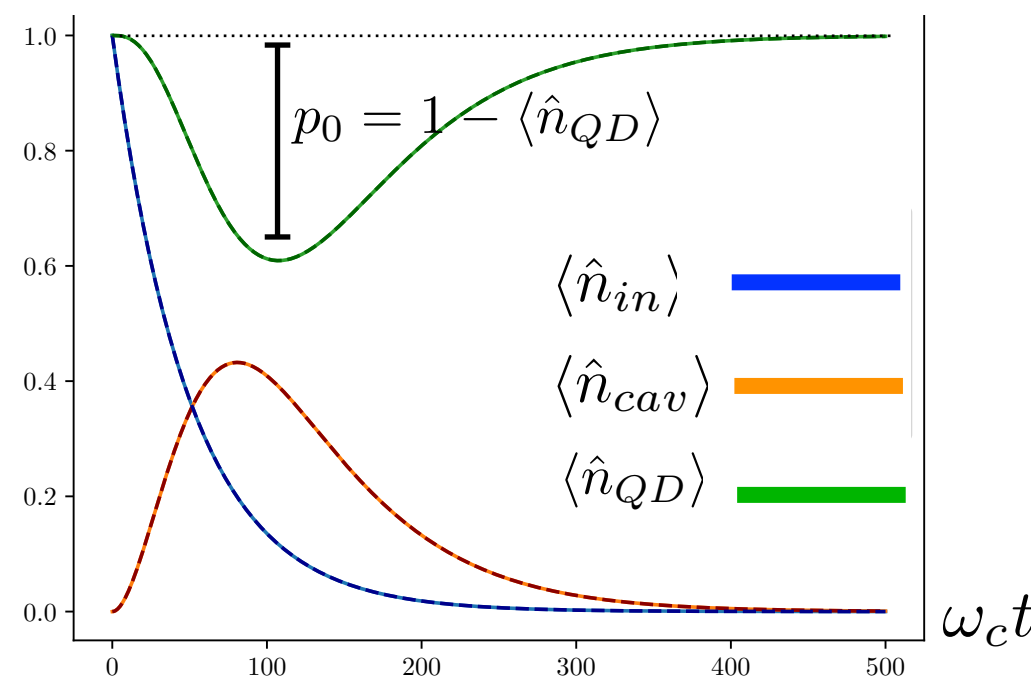
Photon-charge conversion

Resonant case

Check: no interaction with QDs



Dispersive interaction with QDs



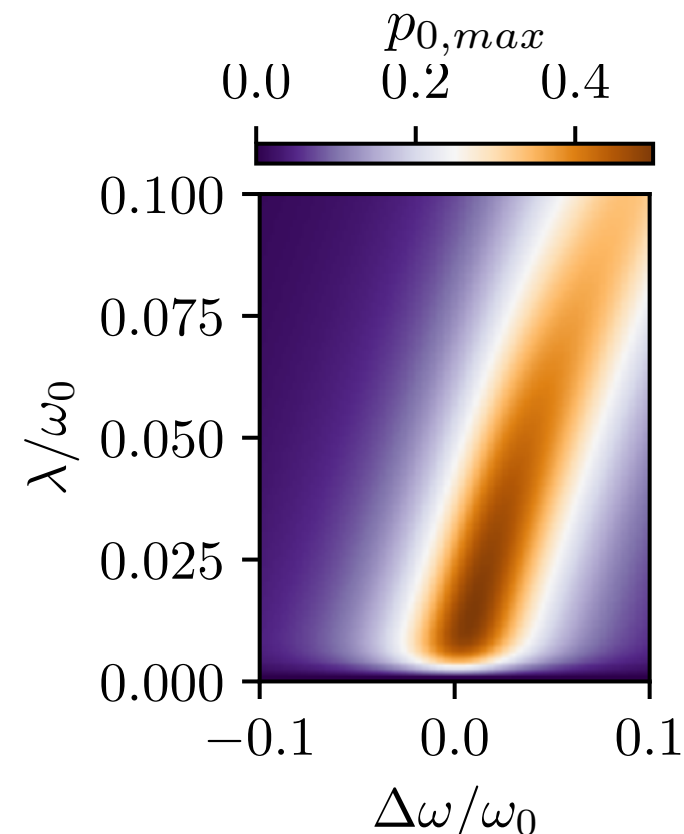
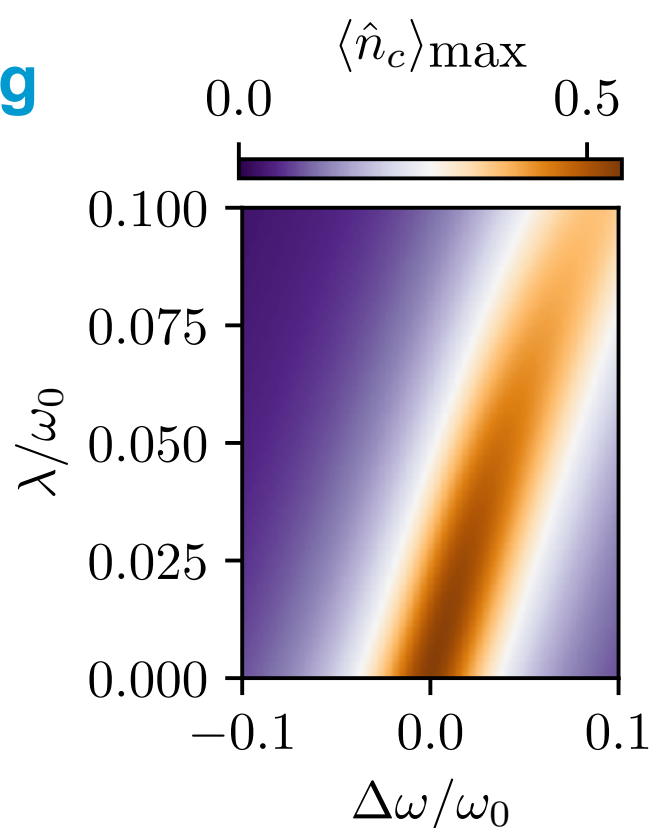
Detuning

$$\gamma/\omega_c = 0.01$$

$$\Gamma_{QD}/\omega_c = 0.04$$

$$\lambda/\omega_c = 0.05$$

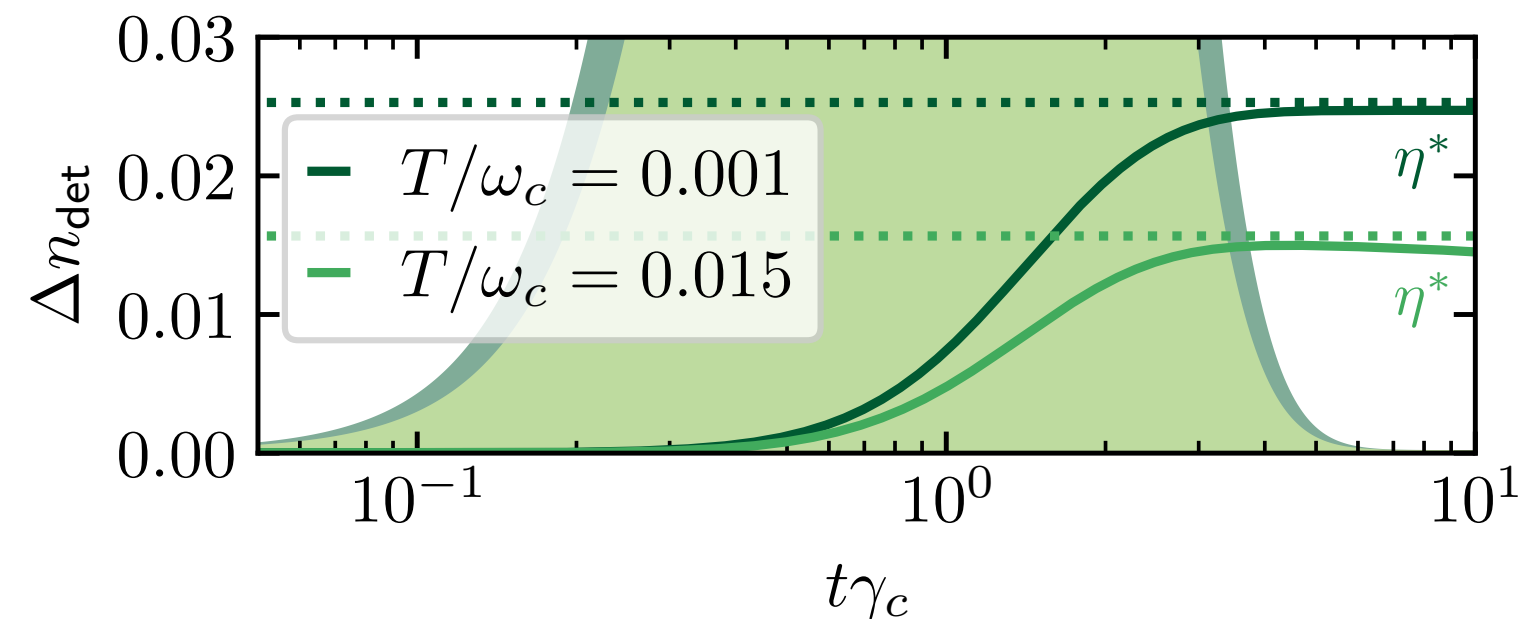
$$T/\omega_c = 0.001$$



Efficiency

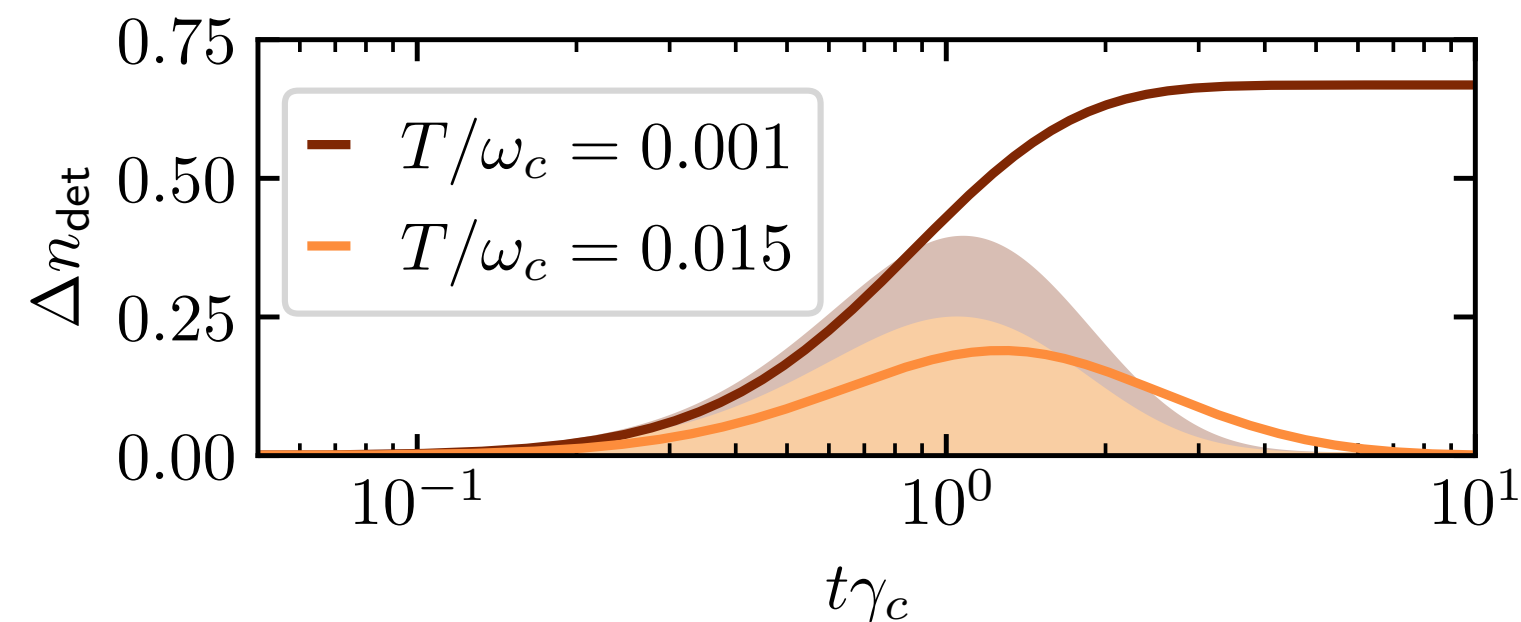
$$\Delta n_{\text{det}} = \langle \hat{n}_{\text{det}}(t) \rangle - \langle \hat{n}_{\text{det}}^{(\lambda=0)}(t) \rangle$$

$$\eta = \max_t \Delta n_{\text{det}}(t) ,$$



$$\eta^* = \gamma_{\text{det}} \int_0^{+\infty} dt \Delta p_0(t)$$

(dotted lines)



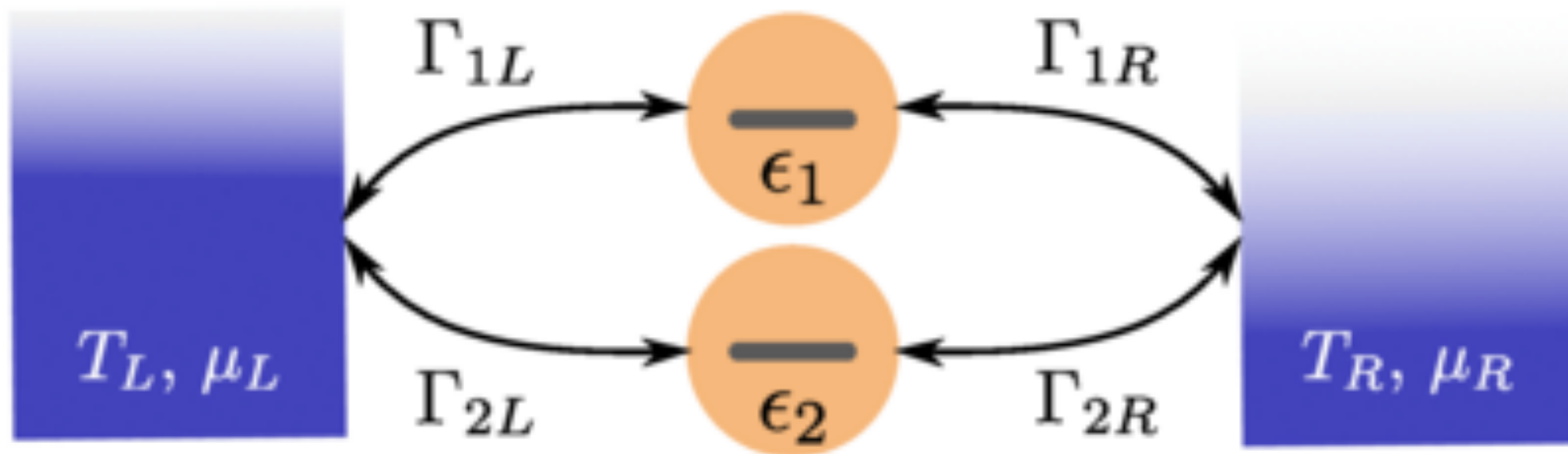
$$\begin{aligned} \gamma/\omega_c &= 0.01 \\ \Gamma_{QD}/\omega_c &= 0.02 \\ \lambda/\omega_c &= 0.022 \\ \gamma_{\text{det}} &= 0.01\Gamma_{QD} \end{aligned}$$

A different scheme (?)

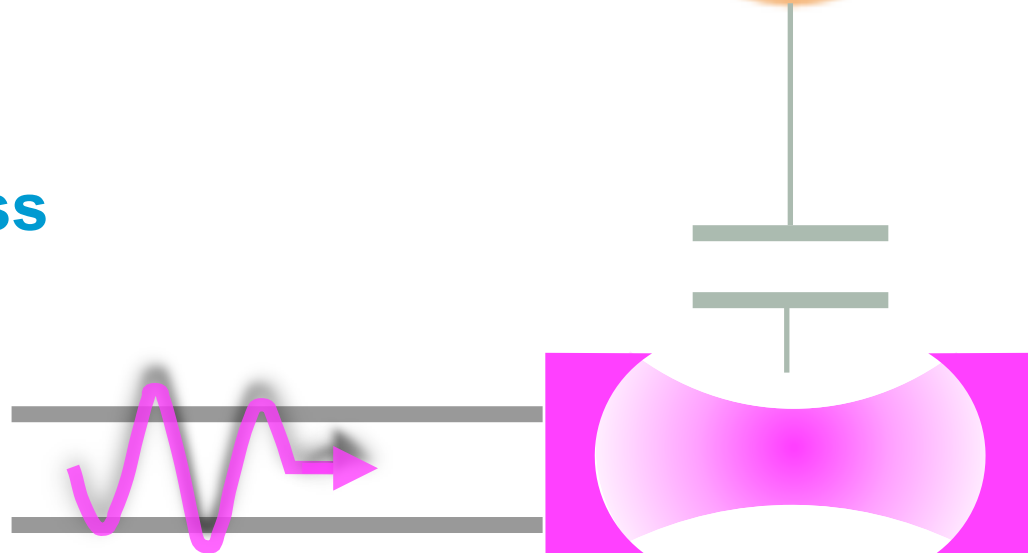
Metastability and quantum coherence assisted sensing in interacting parallel quantum dots

S. Matern, K. Macieszczak, S. Wozny, M. Leijnse ,

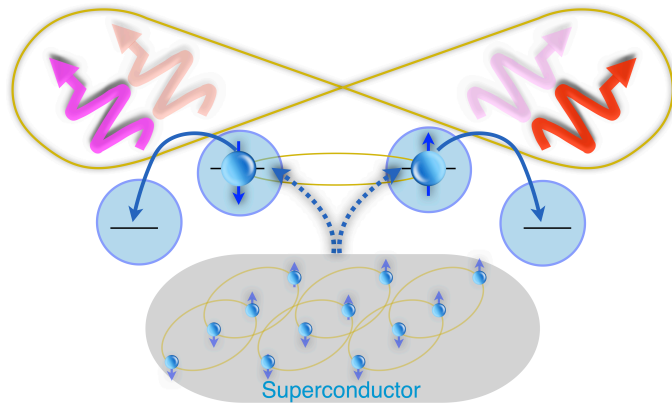
PRB **107**, 125424 (2023)



Work in progress



Summary



Entangled photon-pair emission in waveguide circuit QED
from a Cooper pair splitter

M. Governale, C. Schönenberger, P. Scarlino, **G.R.**
PRX Quantum **6**, 020339 (2025)



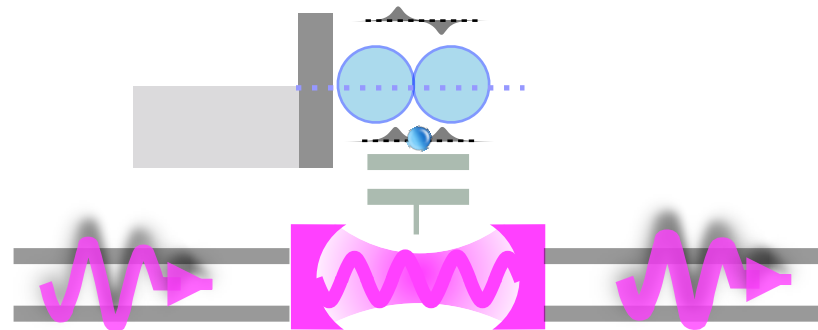
Michele Governale
Victoria University of Wellington (NZ)



Christian Schönenberger
University of Basel (CH)



Pasquale Scarlino
EPFL, Lausanne (CH)



QND detection of single microwave photons with
quantum dots

S. Matern, A. Biella, P. Scarlino, I. Carusotto, **G.R.**
(to be submitted)



Stephanie Matern



Alberto Biella



Iacopo Carusotto

BEC CNR-INO, Trento

*Thank you for the
attention*