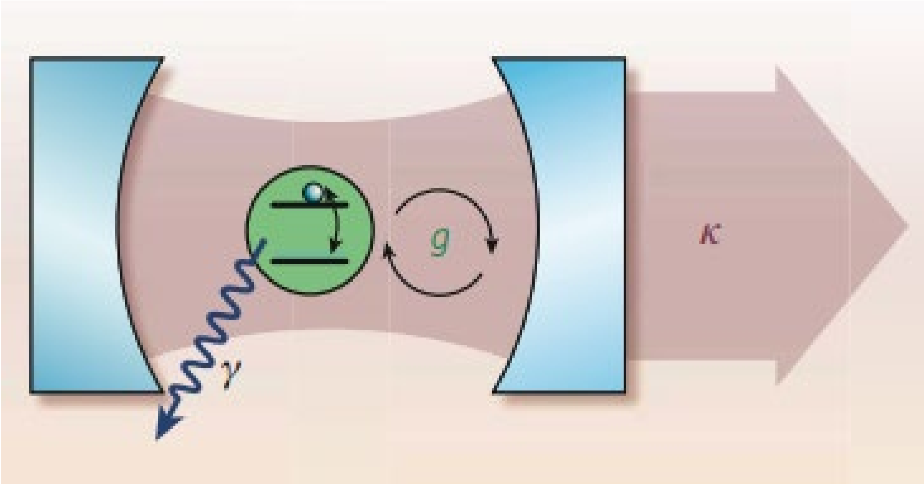
In-situ Tuning of the Electric Dipole Strength of a Double Dot Charge Qubit: Charge Noise Protection and Ultra Strong Coupling

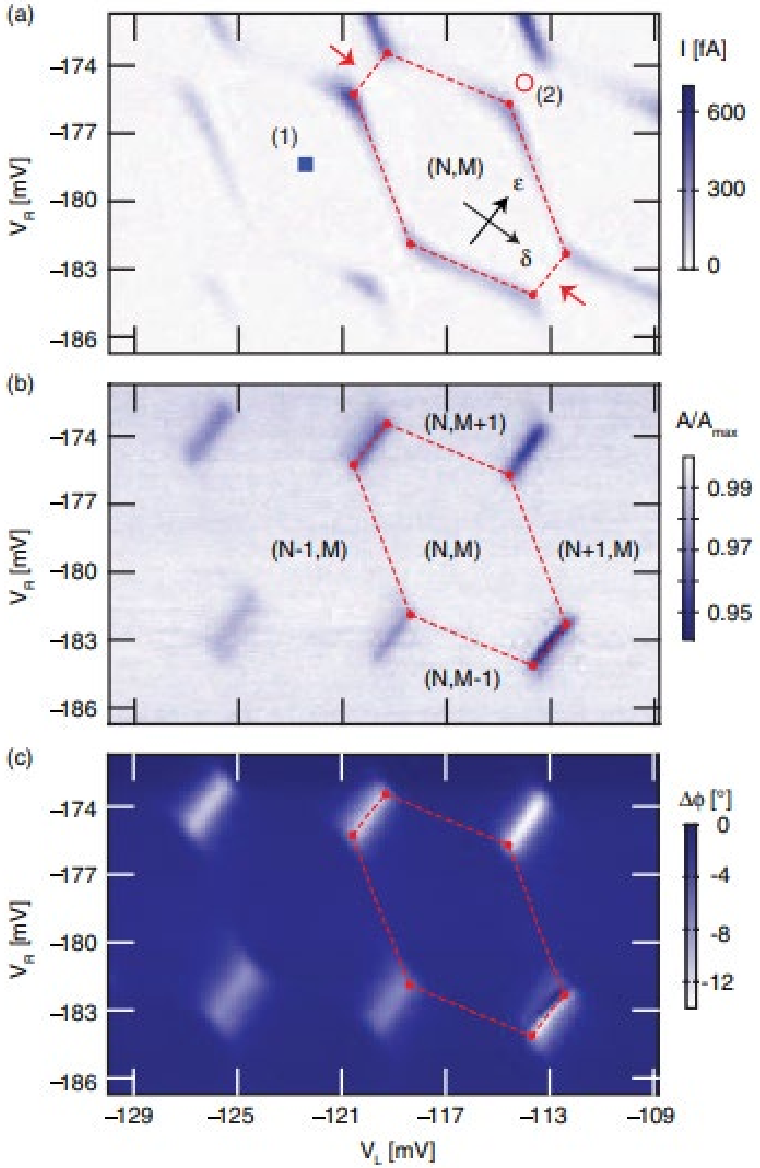
Scarlino, P., Ungerer, J. H., van Woerkom, D. J., Mancini, M., Stano, P., Muller, C., ... & Wallraff, A.
(2021) arXiv preprint arXiv:2104.03045.

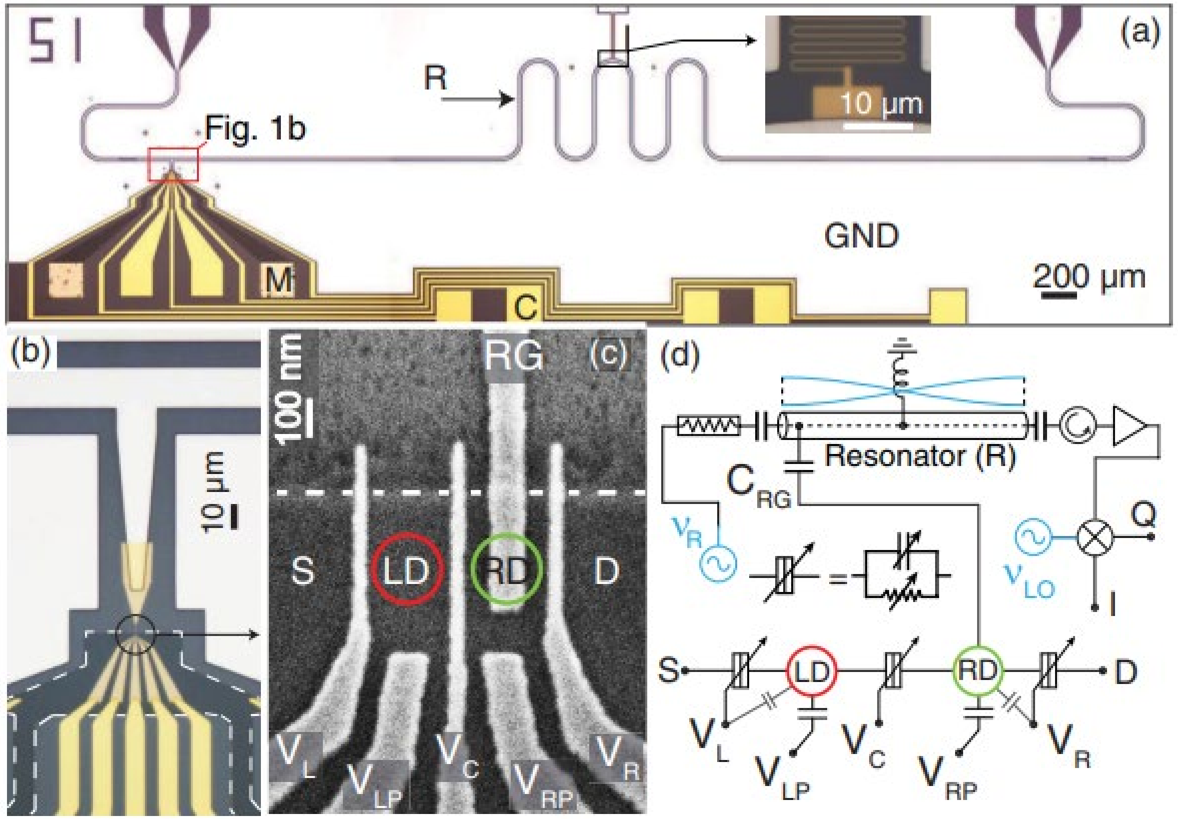
Journal Club 29/04/2022 Aldo Tarascio

Coupling a QD to a resonator

- Enables:
  - QND qubit readout
  - Charge to photon conversion
  - Qubit/qubit coupling
  - …and more!
- Requires:
  - Strong Coupling (g > κ, γ)



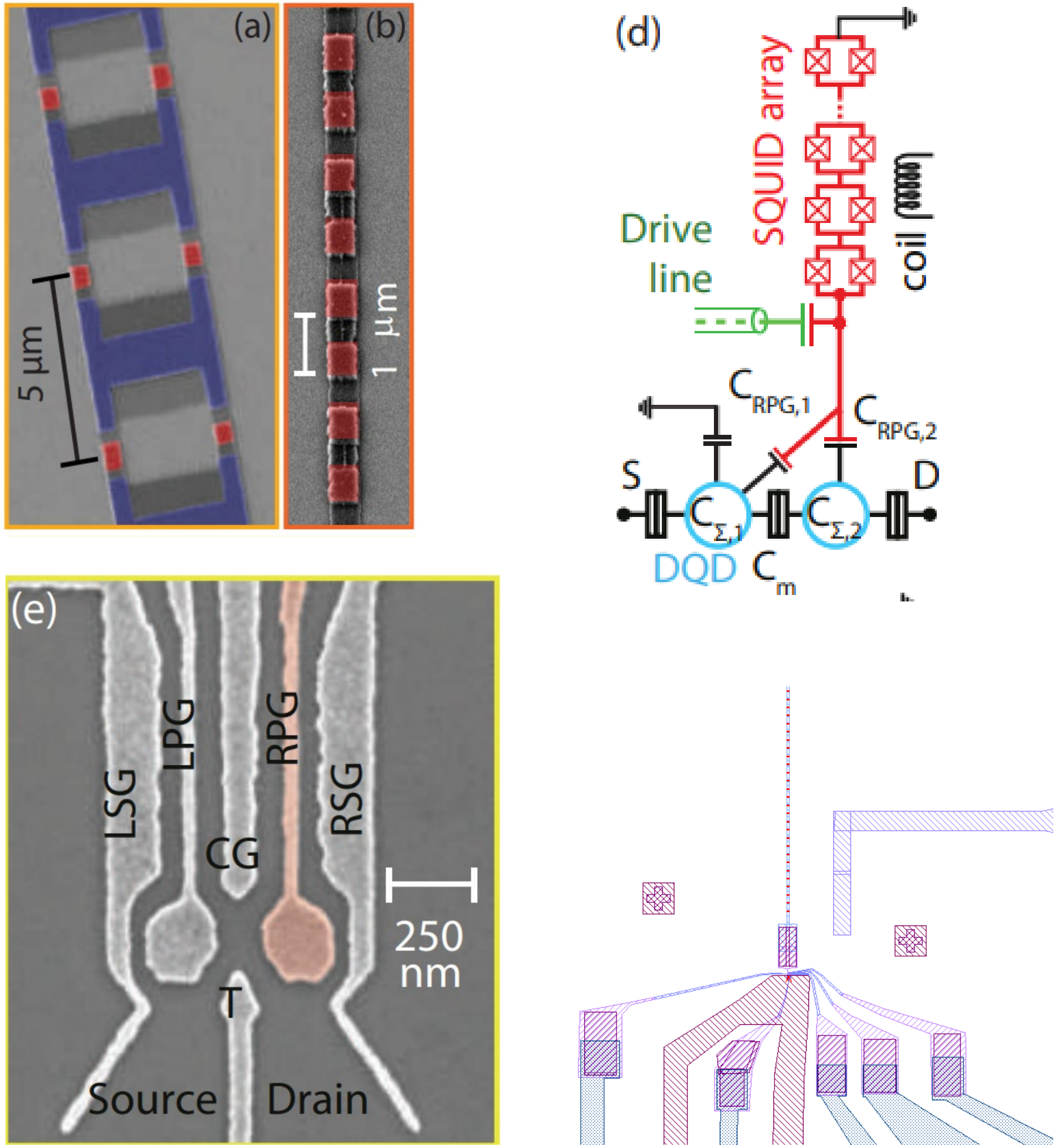




Alexandre Blais, Ren-Shou Huang, Andreas Wallraff, S. M. Girvin, and R. J. Schoelkopf Phys. Rev. A 69, 062320 (2004)

High Z resonators

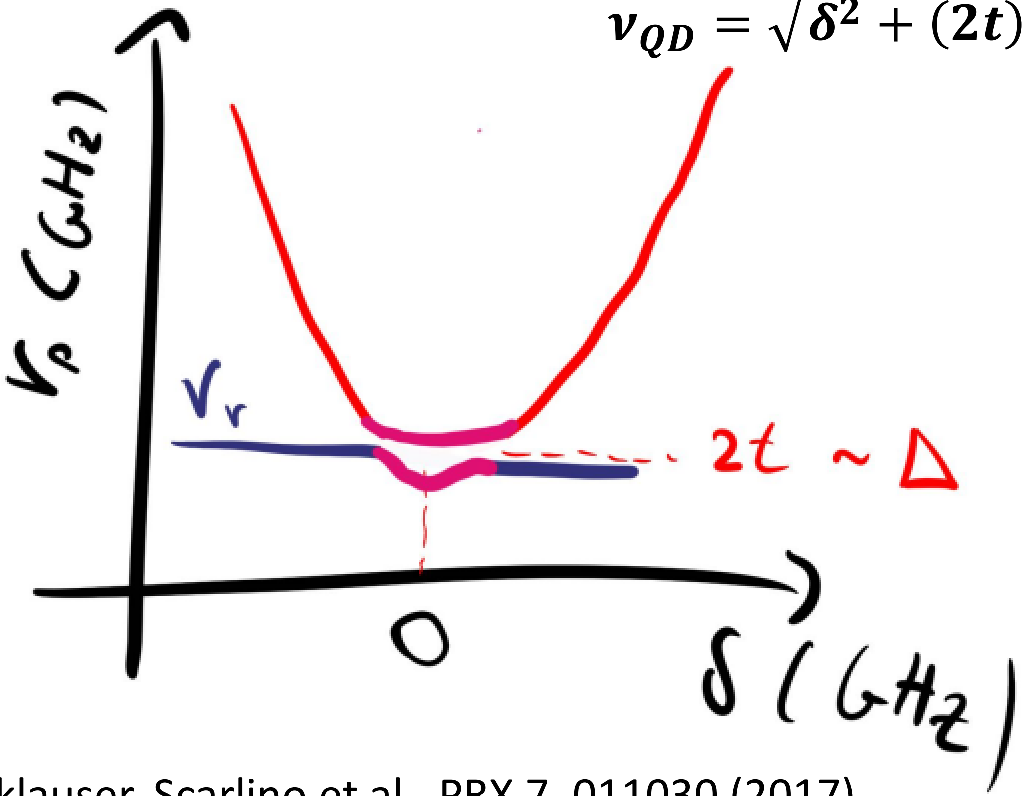
- $g \propto \sqrt{Z_r} = \sqrt{L_r/C_r}$
- Josephson Junctions have high impedance without extra Capacitance
- SQUID allow for tunable resonators

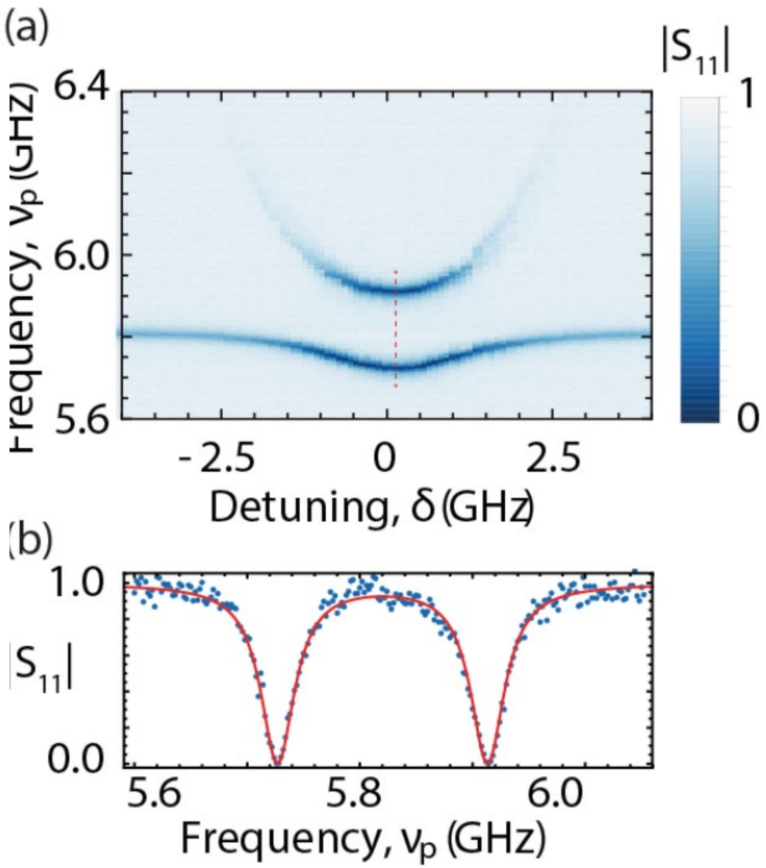


Altimiras et al., APL 103, 212601 (2013).
Masluk et al., PRL 109, 137002 (2012).

Resonant interaction

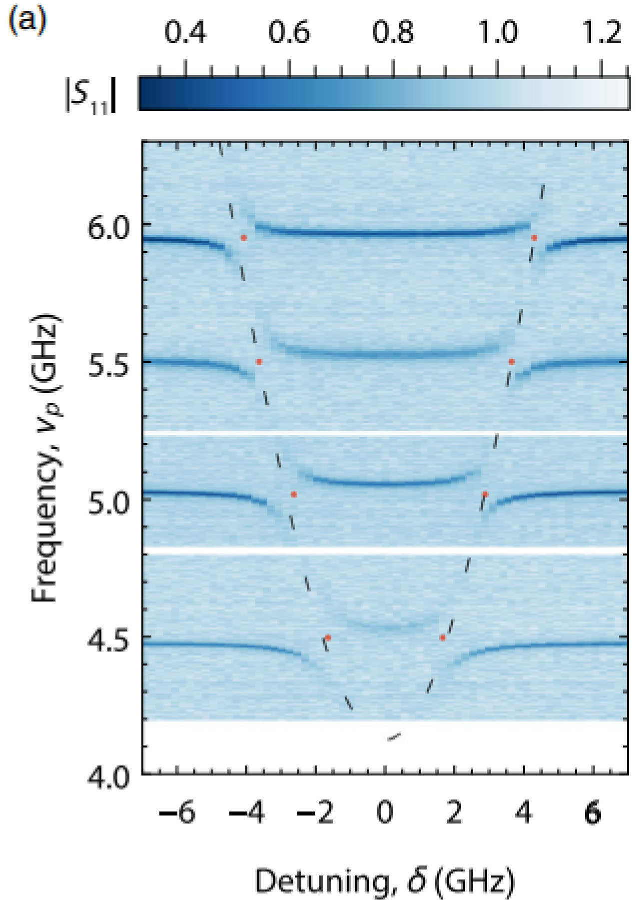
$$\nu_{QD} = \sqrt{\delta^2 + (2t)^2}$$





Stockklauser, Scarlino et al., PRX 7, 011030 (2017)
Scarlino, van Woerkom, et al., Phys. Rev. Lett. 122, 2068092 (2019)

Two tone spectroscopy



Stockklauser, Scarlino et al., PRX 7, 011030 (2017)

Maximizing g even more

- Reducing the resonator intrinsic capacitance
- Increasing the lever arm C_{QD-res}/C_{QD}
- Increase the DQD electric dipole moment- How?

$$\hbar\omega_{QD} = \sqrt{\epsilon^2 + \Delta^2} \quad \nu_{QD} = \sqrt{\delta^2 + (2t)^2}$$

$$\delta\epsilon = e\delta V_g \frac{C_{G1}-C_{G2}}{C_{outside}} \frac{C_{tot}-C_{mutual}}{C_{tot}+C_{mutual}} \Rightarrow g = \hbar\omega_r \sqrt{\frac{2e^2}{\hbar}} \times \eta \frac{C_{G1}-C_{G2}}{C_{out}}$$

$$\eta \equiv \frac{C_{tot}-C_{mutual}}{C_{tot}+C_{mutual}}$$

Supplementary Fig 2

$\boldsymbol{\eta}$ in charge stability diagrams

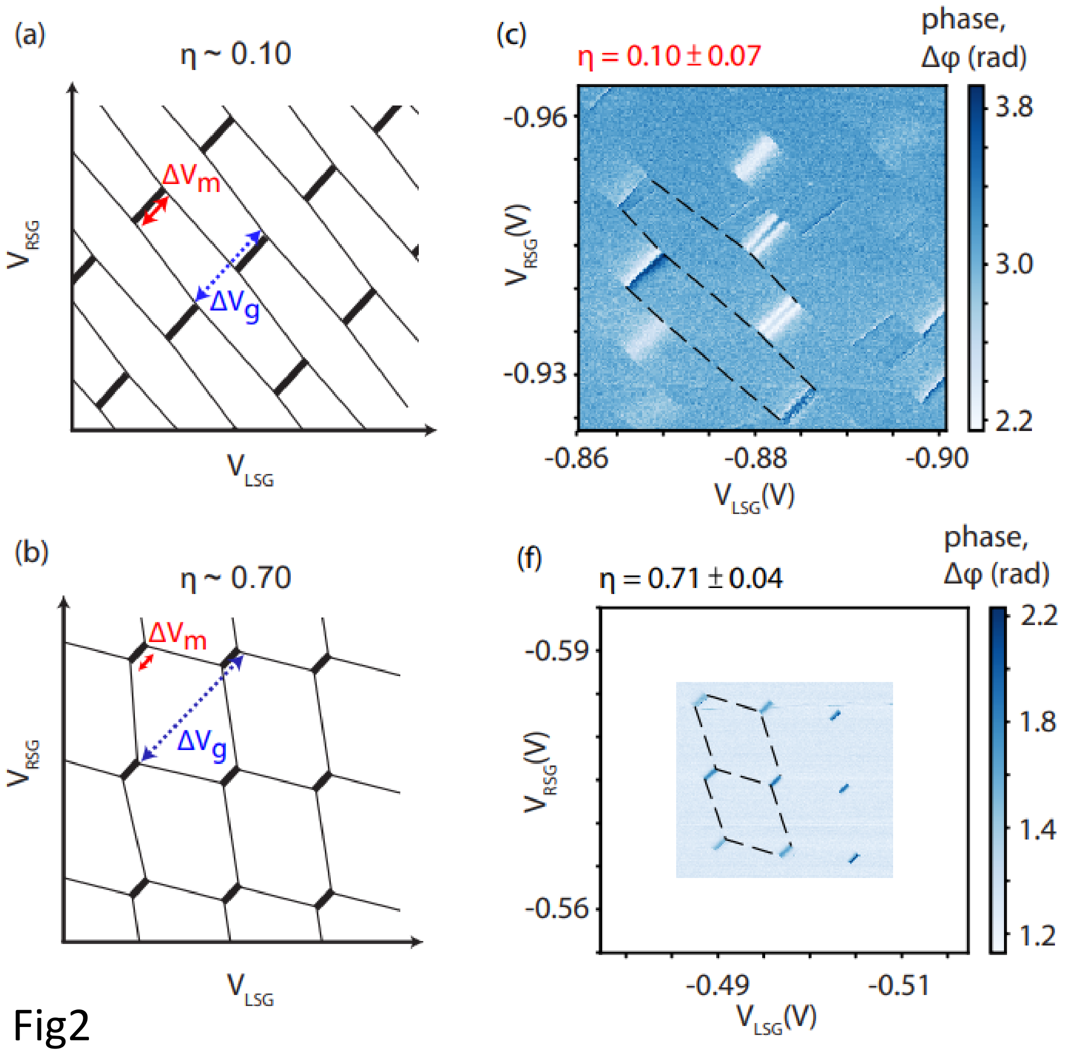
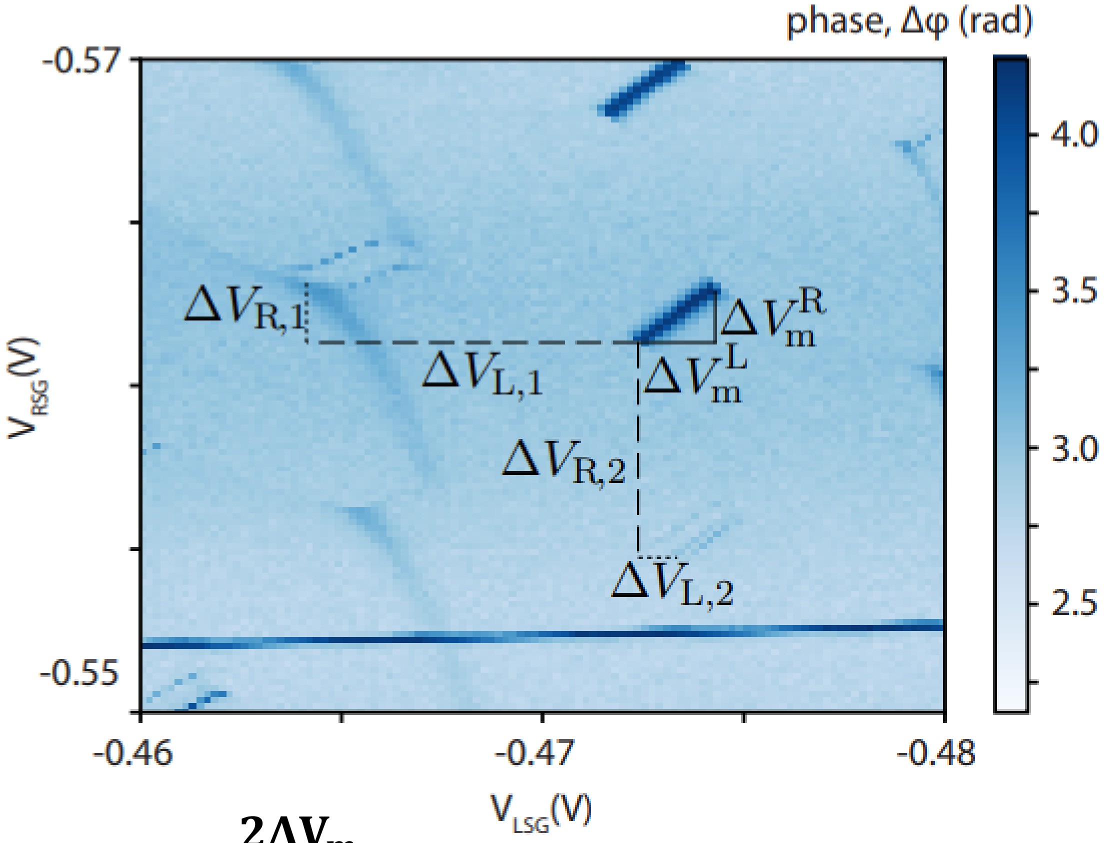
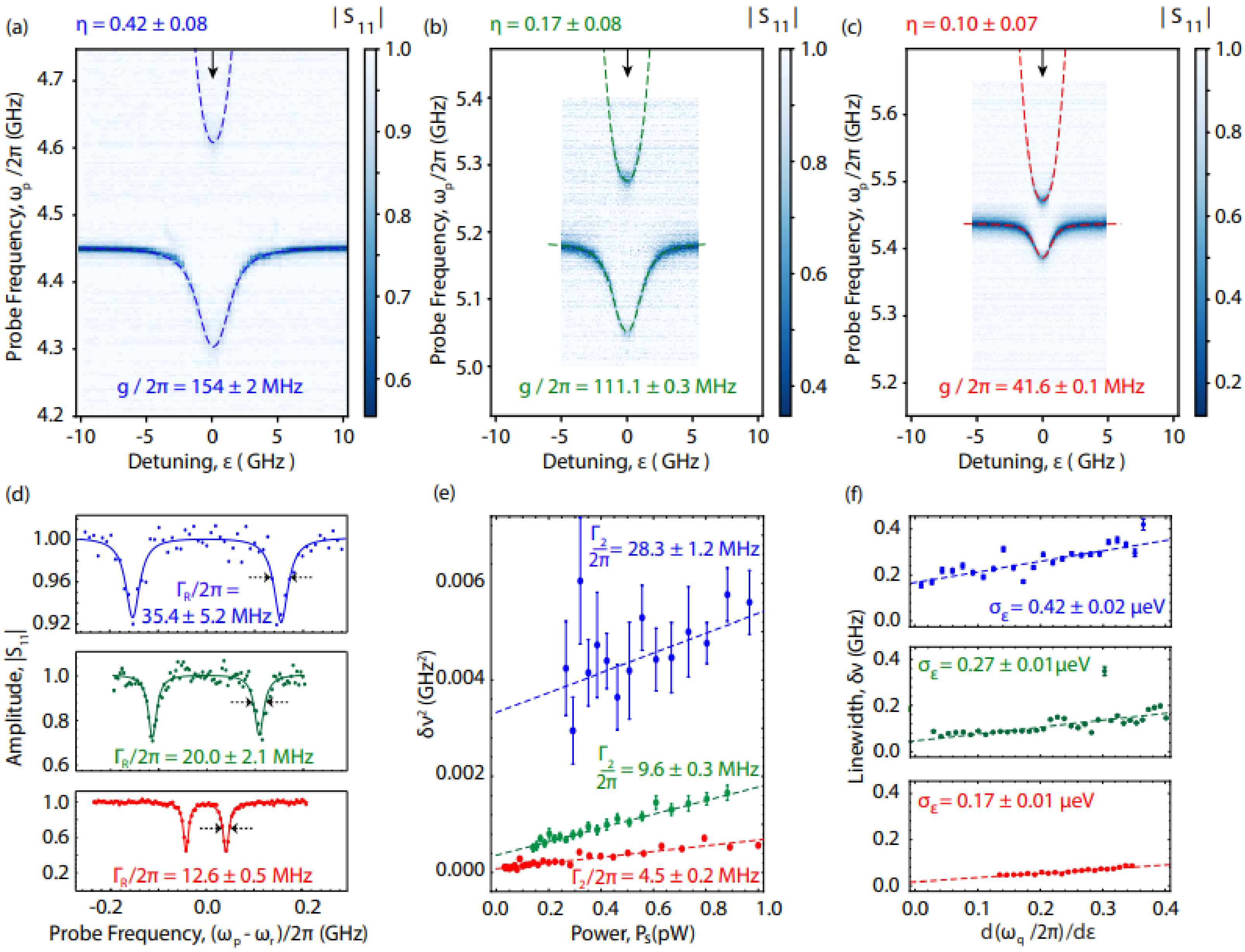


Fig2

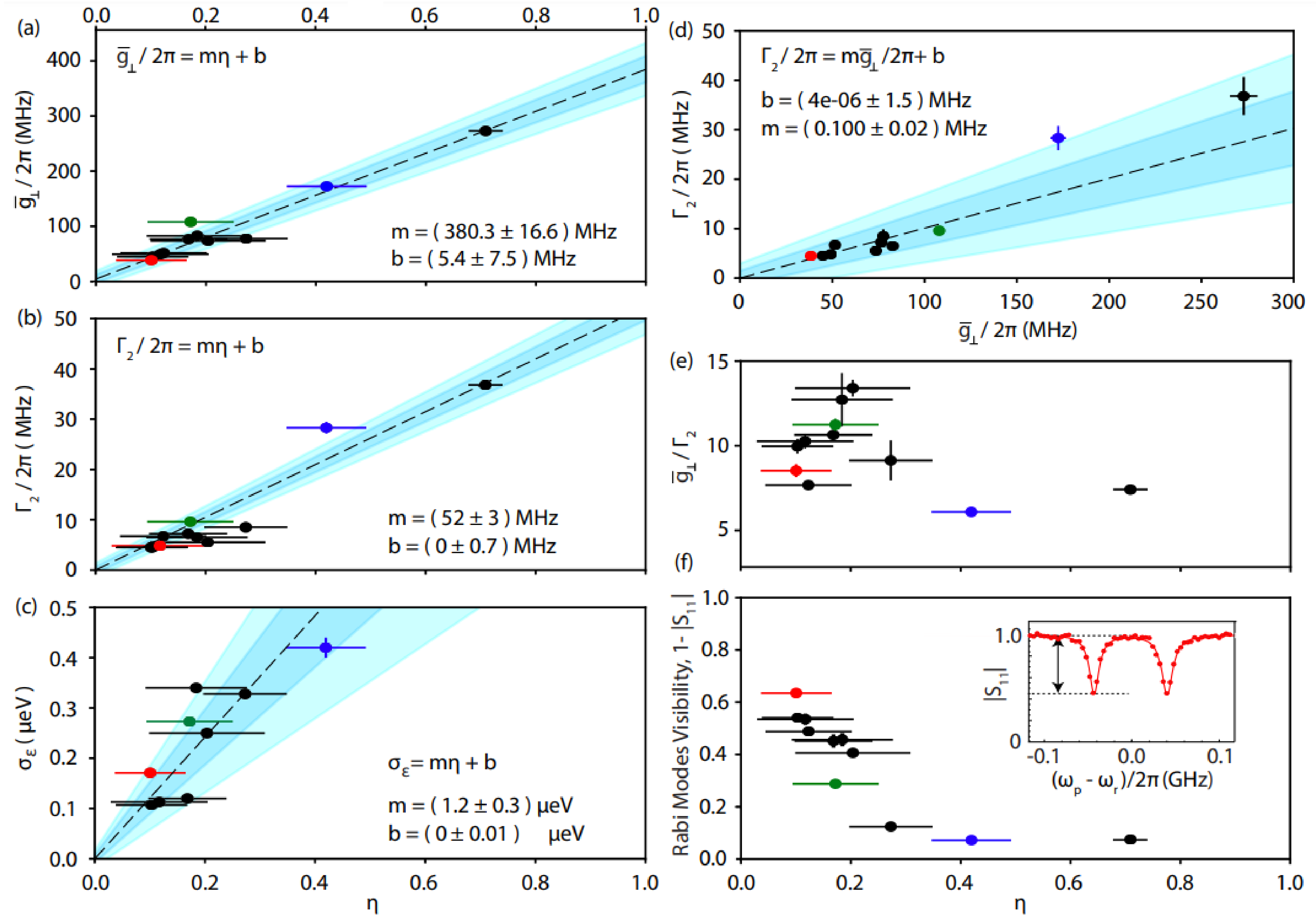


$$\boldsymbol{\eta = 1 - \frac{2\Delta V_m}{\Delta V_g}}$$

Dipole strength and coherence

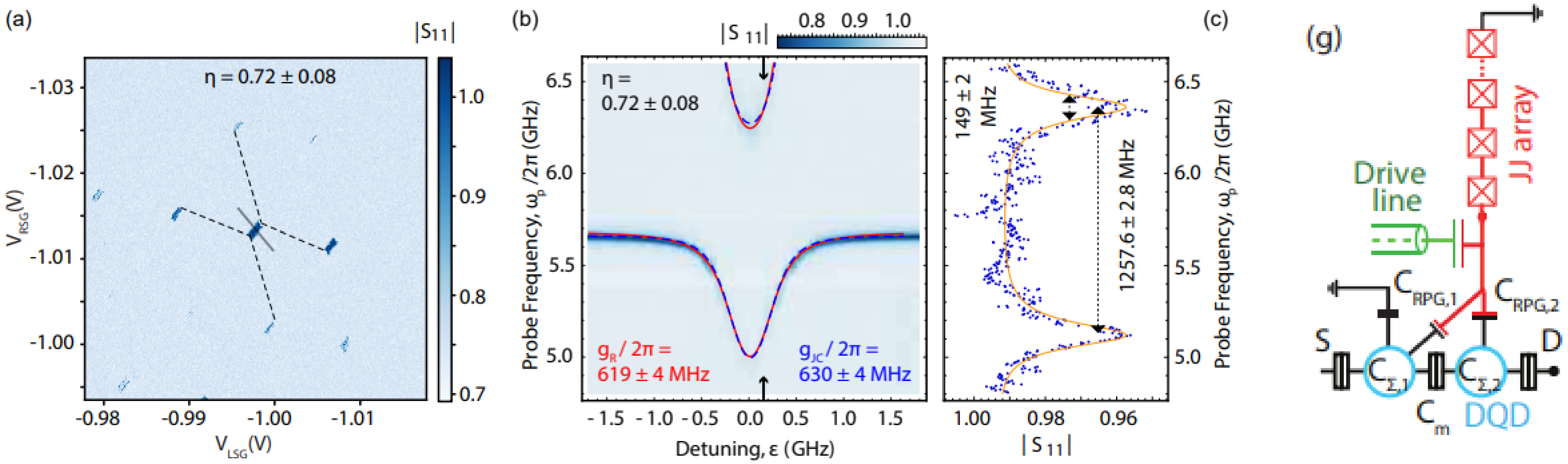


Comparing different configurations



$$\bar{g}_\perp = g \frac{\Delta}{\omega_r} \frac{5GHz}{\omega_r / 2\pi}$$

Ultra Strong coupling regime



Conclusions

For small eta

- $g/2\pi \sim 40$ MHz
- $\Gamma_2/2\pi \sim 3$ MHz ($T_2 \sim 53$ns)

For large eta

- $g/2\pi \sim 625$ MHz
- $\Gamma_2/2\pi \sim 149$ MHz ($T_2 \sim 1$ns)

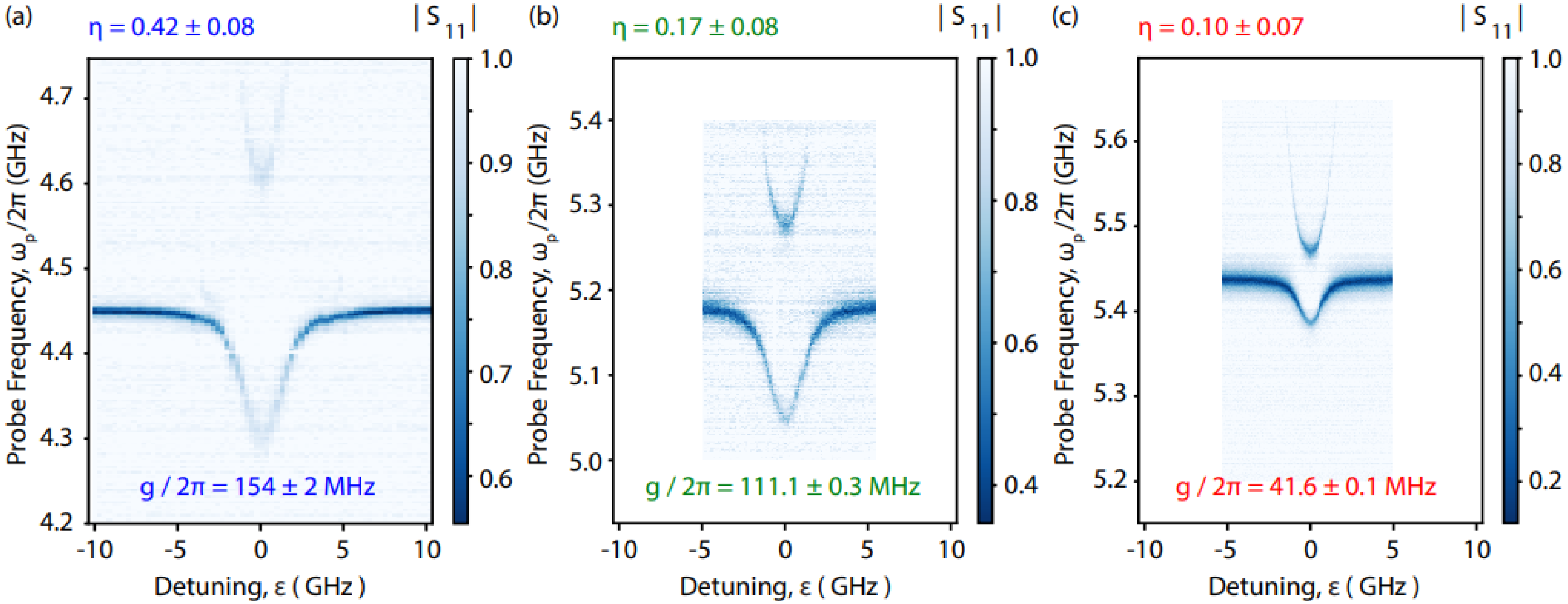
In the same kind of device you can change wildly coupling and coherence!

Defining charge noise sensitivity

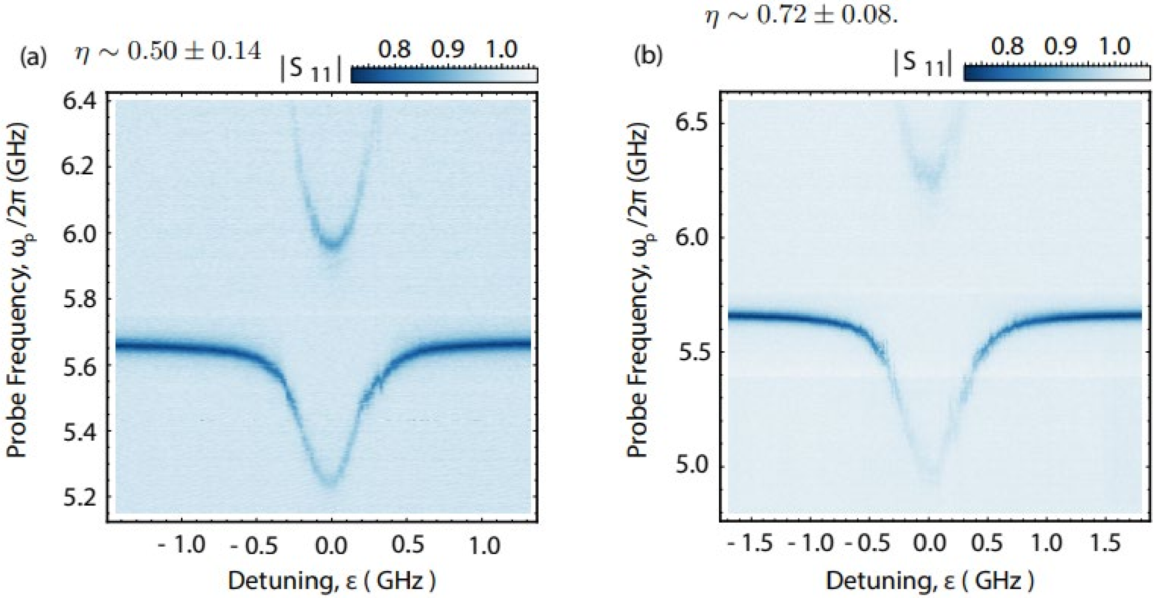
$$\ln c_{\mathrm{lin}}^{1/f}(\tau) = -\tau^2 \left(\frac{\partial \hbar\omega_{\mathrm{q}}}{\partial \epsilon}\right)^2 \left(\frac{\partial \epsilon}{\partial V_{\mathrm{G}}}\right)^2 A \ln\left(\frac{\omega_{\mathrm{c}}}{\omega_{\mathrm{ir}}}\right) \equiv -\tau^2 \left(\frac{\partial \hbar\omega_{\mathrm{q}}}{\partial \epsilon}\right)^2 \sigma_\epsilon^2 \equiv -(\Gamma_\varphi \tau)^2. \quad (11)$$

decay process	coupling	noise	decay type	dependence on qubit configuration	sensitivity	suppression
pure dephasing	linear	singular	Gaussian	$\frac{\epsilon}{\sqrt{\epsilon^2+\Delta^2}}$	$\partial_V \epsilon$	η
	linear	regular	exponential	$\frac{\Delta^2}{\epsilon^2+\Delta^2}$	$(\partial_V \epsilon)^2$	η^2
	quadratic	low-freq.	algebraic	$\frac{\Delta^2}{(\epsilon^2+\Delta^2)^{3/2}}$	$(\partial_V \epsilon)^2$	η^2
	quadratic	high-freq.	exponential	$\frac{\Delta^2}{(\epsilon^2+\Delta^2)^{3/2}}$	$(\partial_V \epsilon)^2$	η^2
relaxation	linear	resonant	exponential	$\frac{\Delta^2}{\epsilon^2+\Delta^2}$	$(\partial_V \epsilon)^2$	η^2

figure of merit	formula	dominant noise: linear-singular	dominant noise: other
coupling to cavity	g	η^1	
coherence time	$T_2^* = 1/\Gamma_\varphi$	η^{-1}	η^{-2}
quality factor	$Q = g/\Gamma_\varphi$	η^0	η^{-1}
cooperativity	$g^2/\Gamma_\varphi \kappa$	η^1	η^0

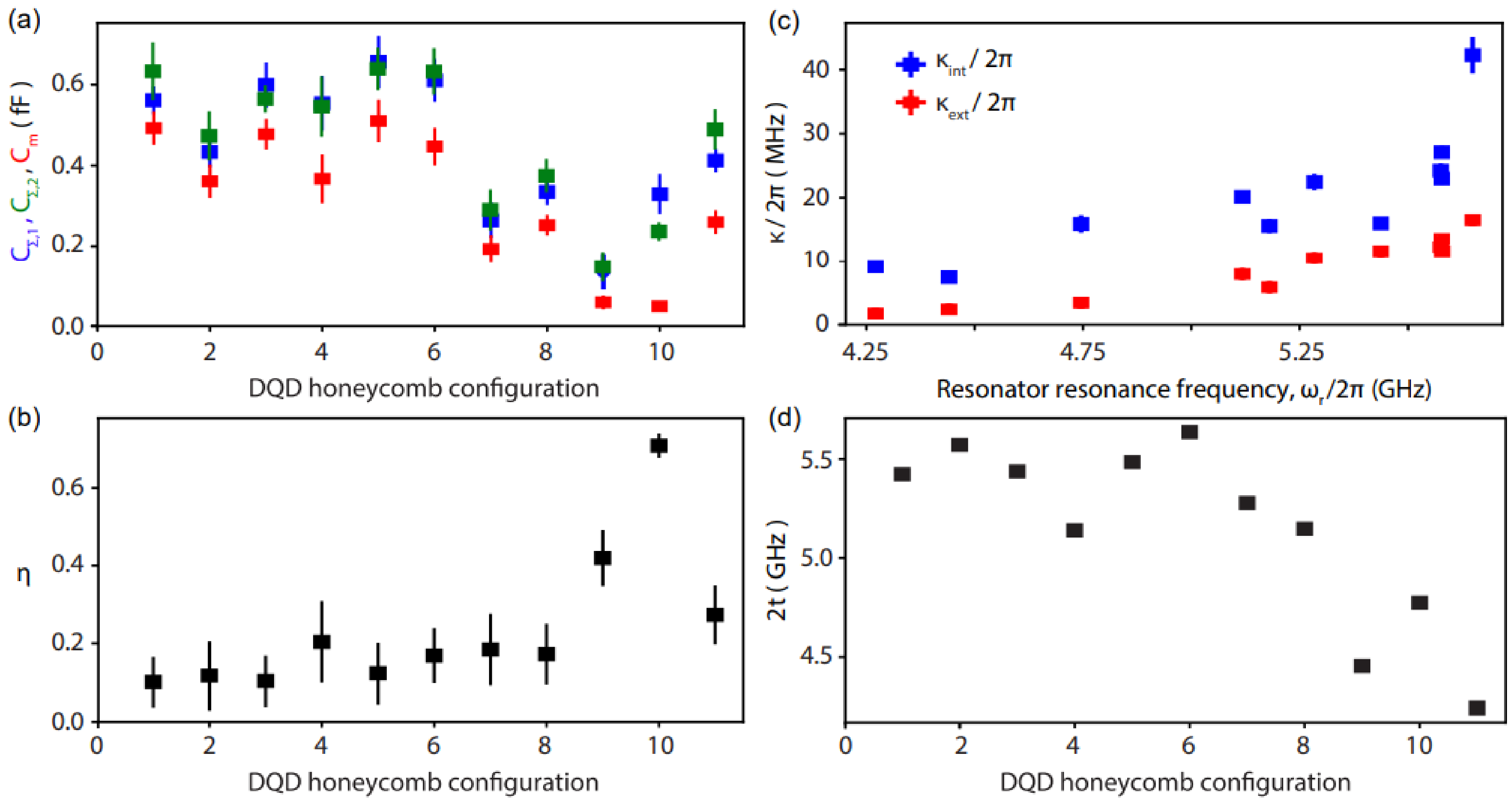


*SQUID device



*JJ device

SQUID Resonator quality



Crazy large table

index	$C_{\Sigma,1}$ [fF]	$C_{\Sigma,2}$ [fF]	C_m [fF]	η	$g/2\pi$ [MHz]	$\Gamma_2/2\pi$ [MHz]	σ_ϵ [μeV]	$\Delta/2\pi$ [MHz]	$\omega_r/2\pi$ [MHz]
1	0.561±0.034	0.634±0.071	0.488±0.041	0.101±0.064	41.63±0.06	4.5±0.2	0.171±0.006	5420.8±0.2	5437.0±0.1
2	0.433±0.037	0.474±0.061	0.358±0.041	0.117±0.088	54.9±0.1	4.8±0.2	0.113±0.009	5568.6±0.3	5575.6±0.14
3	0.599±0.056	0.565±0.034	0.473±0.038	0.103±0.065	48.8±0.2	4.5±0.2	0.107±0.007	5435.1±0.5	5578.6±0.11
4	0.554±0.068	0.41±0.075	0.364±0.060	0.204±0.105	75.7±0.2	5.5±0.2	0.250±0.008	5137.4±0.4	5117.6±0.14
5	0.656±0.065	0.70±0.053	0.506±0.052	0.123±0.079	56.4±0.5	6.7±0.2	-	5482±3	5578.4±0.4
6	0.611±0.053	0.54±0.058	0.443±0.046	0.168±0.071	86.3±0.2	7.2±0.2	0.120±0.007	5633.5±0.4	5649.0±0.2
7	0.265±0.045	0.31±0.051	0.191±0.034	0.184±0.092	87.2±0.4	6.5±0.8	0.34±0.007	5276±1	5283.7±0.6
8	0.333±0.031	0.27±0.041	0.250±0.026	0.172±0.078	111.1±0.3	9.6±0.3	0.273±0.005	5145±1	5180.3±0.2
9	0.136±0.045	0.32±0.037	0.058±0.017	0.419±0.073	153.6±1.9	28.3±1.2	0.42±0.02	4453±4	4440.9±0.3
10	0.330±0.050	0.20±0.023	0.048±0.007	0.709±0.031	260.5±3.5	36.8±0.9	-	4772.7±9	4745.5±0.9
11	0.412±0.029	0.20±0.050	0.257±0.029	0.273±0.076	65.9±0.7	8.5±1.1	0.328±0.005	4243±2	4271.6±0.2

index	$V_{CG}(mV)$	$V_{SD}(mV)$	$V_{LS}(mV)$	$V_{RS}(mV)$
1	-0.823	-0.623	-0.88132	-0.946477273
2	-0.823	-0.623	-0.883236	-0.937345455
3	-0.823	-0.727	-0.884445	-0.789789091
4	-0.823	-0.818	-0.69147	-0.751603636
5	-0.847	-0.847	-0.671525	-0.6412
6	-0.882	-0.882	-0.60214	-0.648681818
7	-0.936	-0.936	-0.79571	-0.593763636
8	-0.982	-0.982	-0.576544	-0.613915909
9	-1.04	-1.04	-0.473037	-0.562018182
10	-1.05	-1.05	-0.49628	-0.574921818
11	-1.03	-1.03	-0.525558	-0.494352727