Probing intermediate scale quantum circuits

including cross-talk, thermal excitations, dissipation, dephasing, background transmission and noise

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Theory: Juha Leppaekangas

February 8th 2019

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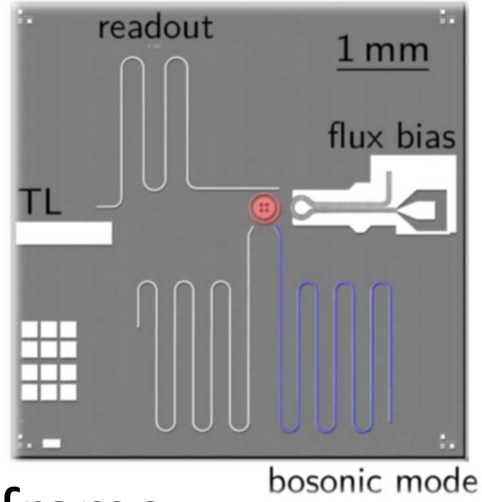
Engineering qubit-resonator coupling

$$\hat{H}_{\text{eff}}/\hbar = \boxed{\omega_{\text{eff}}\hat{a}^\dagger\hat{a}} + \boxed{\frac{\eta_2}{2}\frac{\hat{\sigma}_z}{2}} + \frac{g}{2}\left(\hat{\sigma}^+ + \hat{\sigma}^-\right)\left(\hat{a}^\dagger + \hat{a}\right)$$

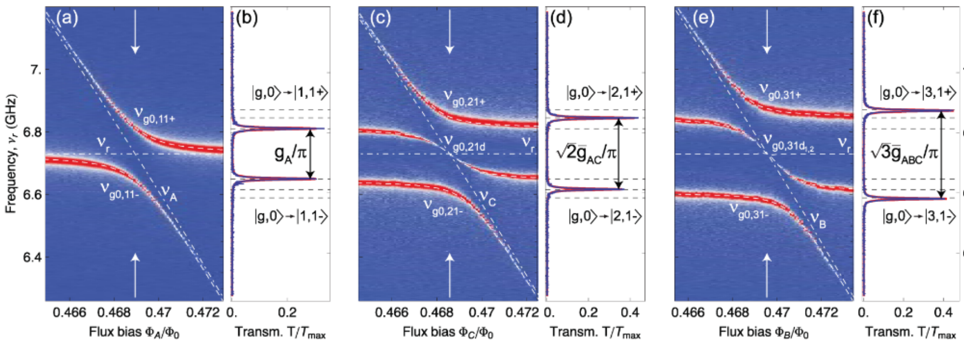
Braumüller *et al.*
Nat. Commun. **8**, 779 (2017)



Ultra-strong coupling by moving into the rotation frame

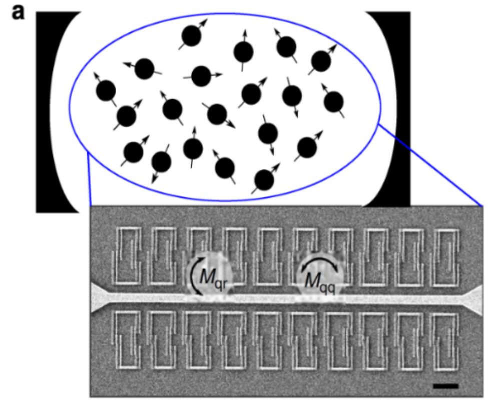
This work: increase number of (strongly) coupled qubits

J. M. Fink, et al., PRL 103, 083601 (2009)



N=3

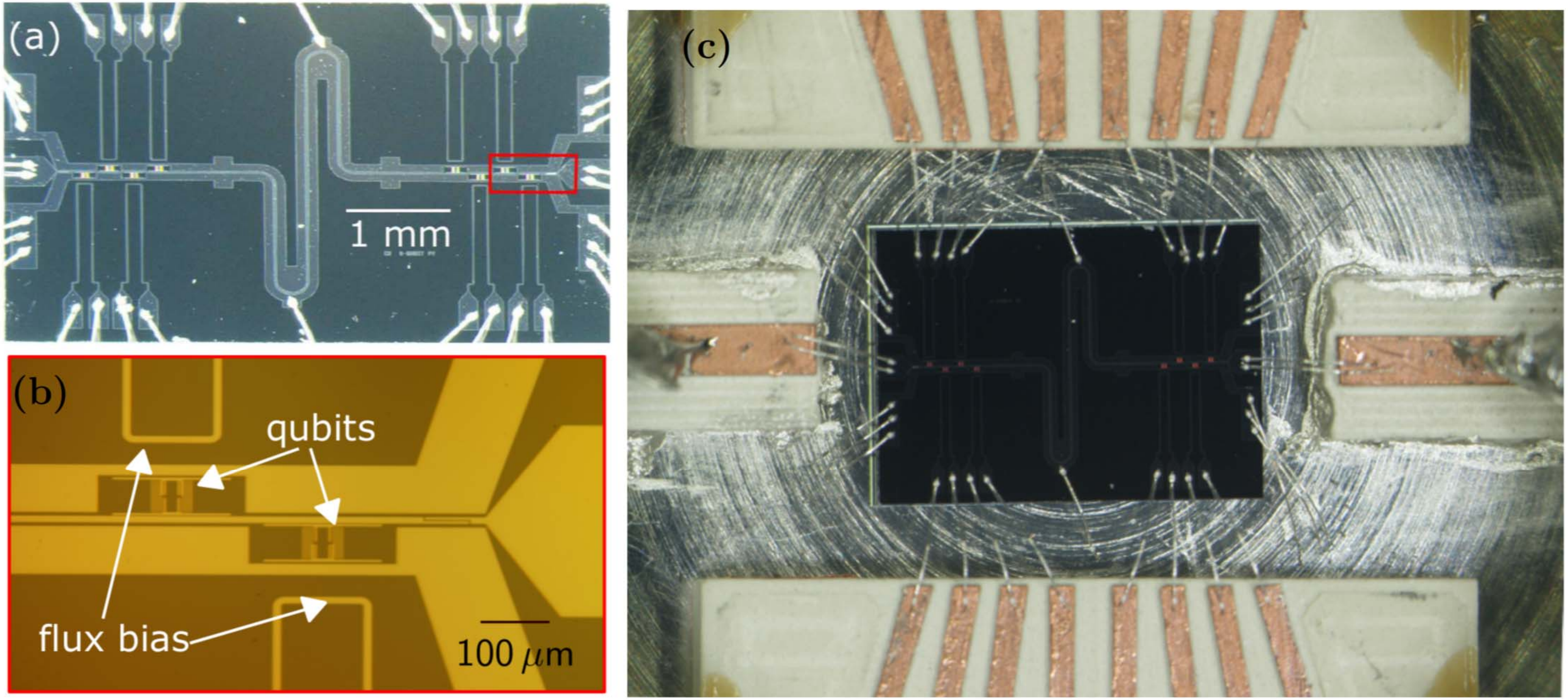
P. Macha, Nat Comm 5, 5146 (2014



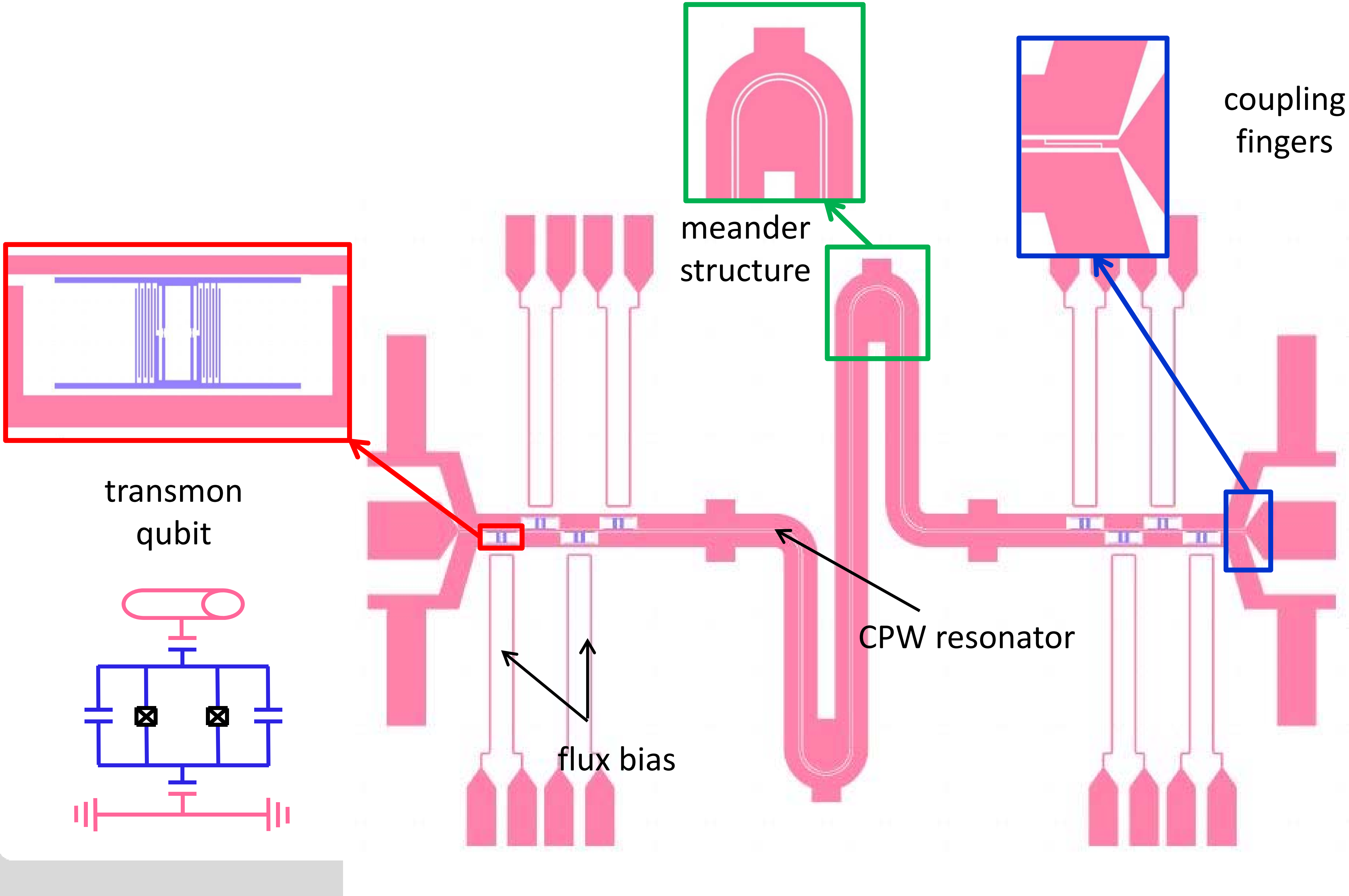
N=8

Note: testbed for resonators coupled to discrete TLS

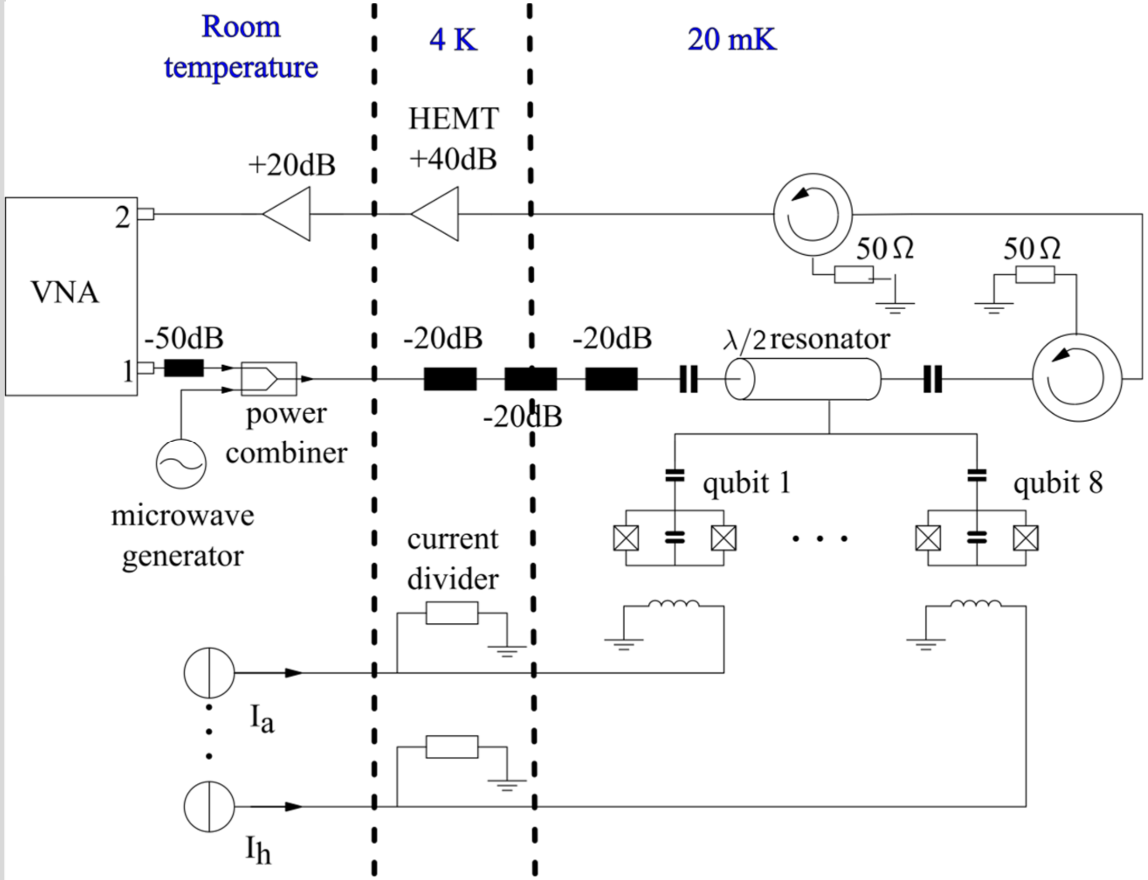
Bonded and packaged chip

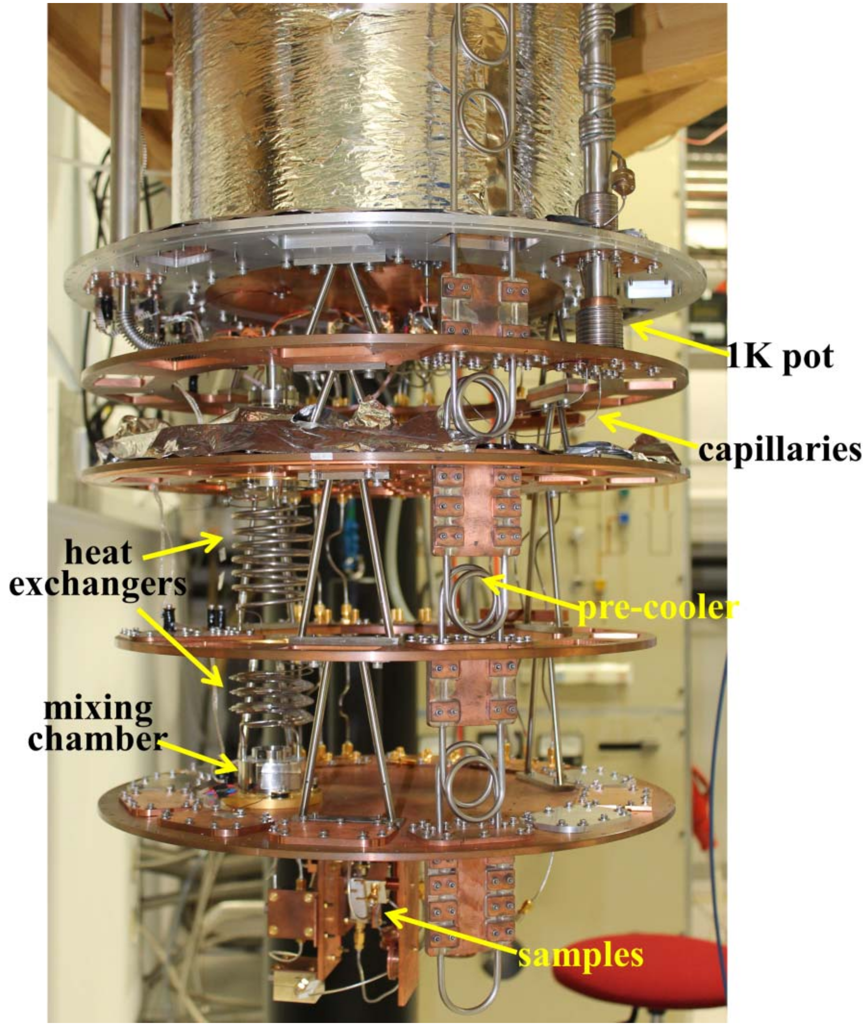


Sample design: eight qubits and one resonator



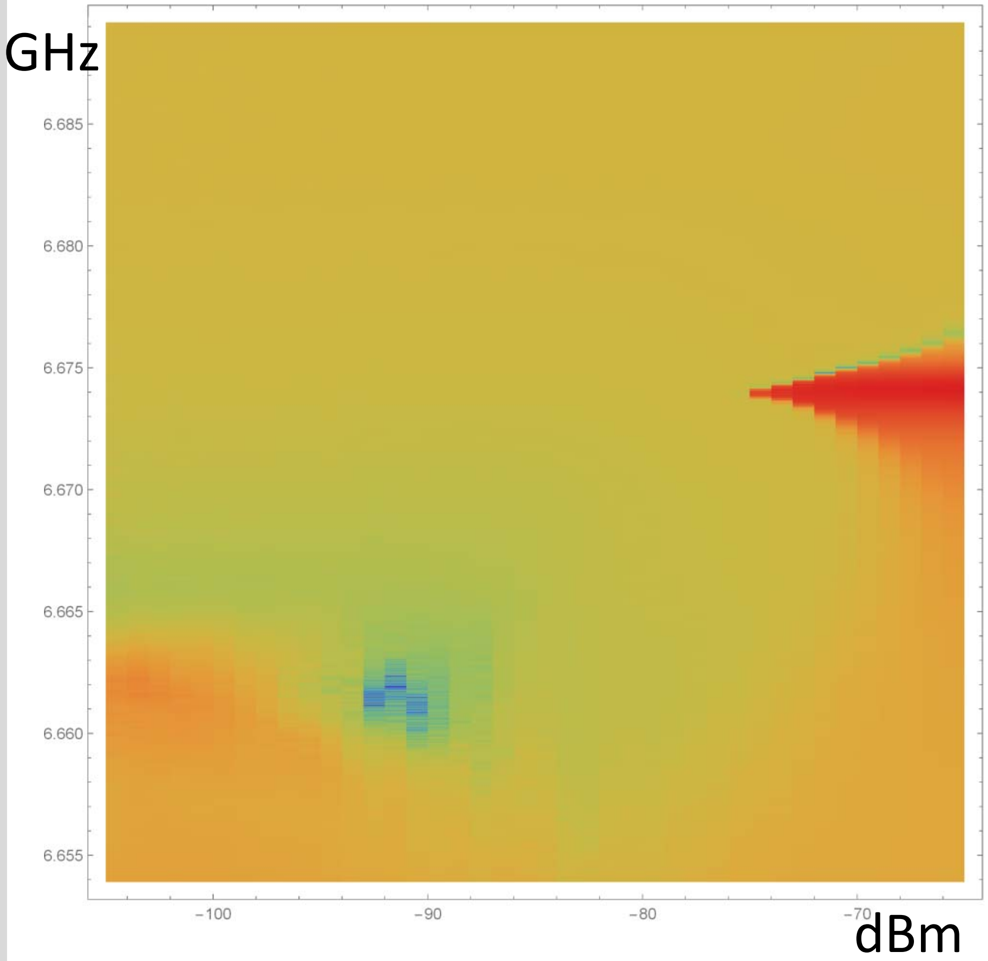
Measurement setup

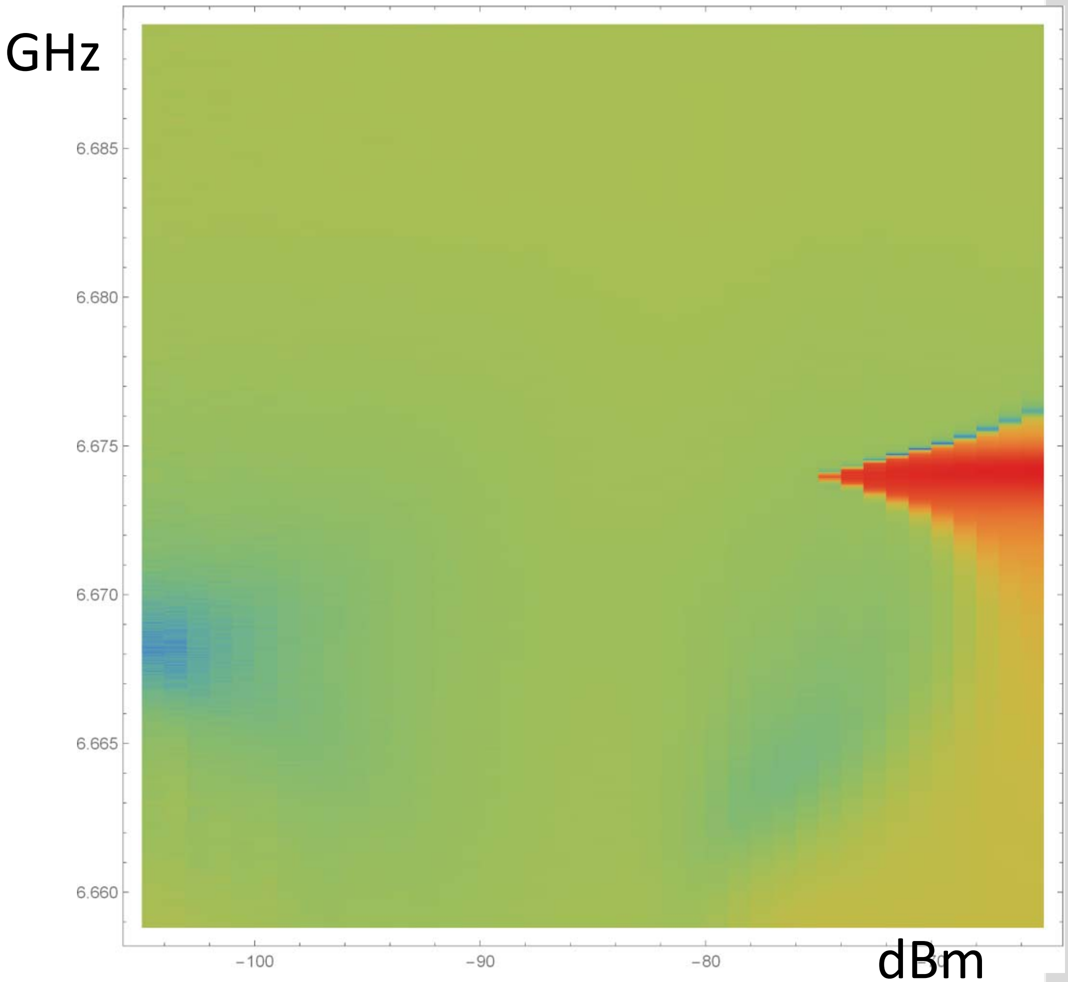




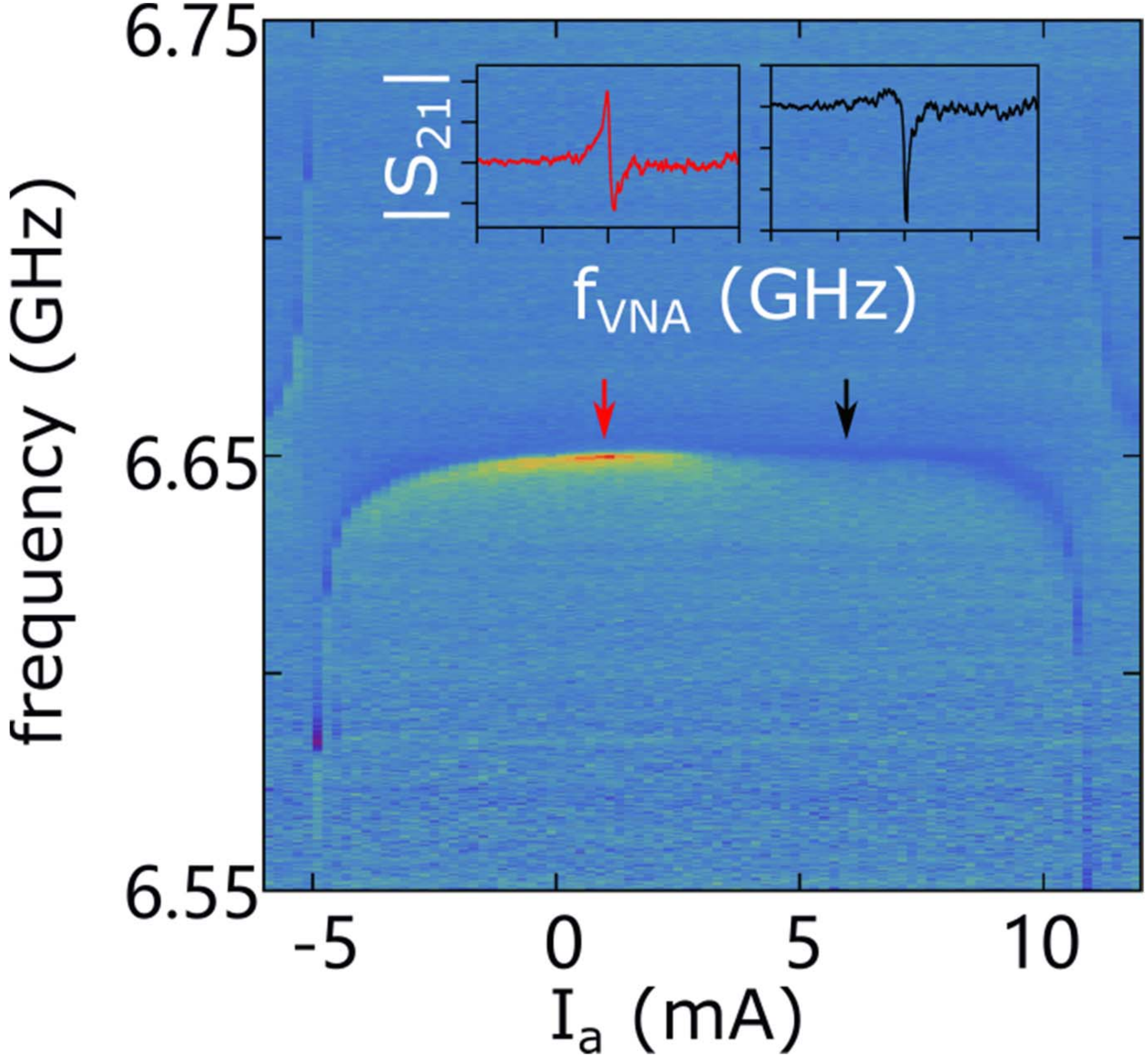
Inside charcoal coated cylinder at base

Power sweep (For 2 different conditions)





Spectroscopy under DC bias sweep



Experimental findings

Spectra (peak, dip, signal, frequency shift) depend on

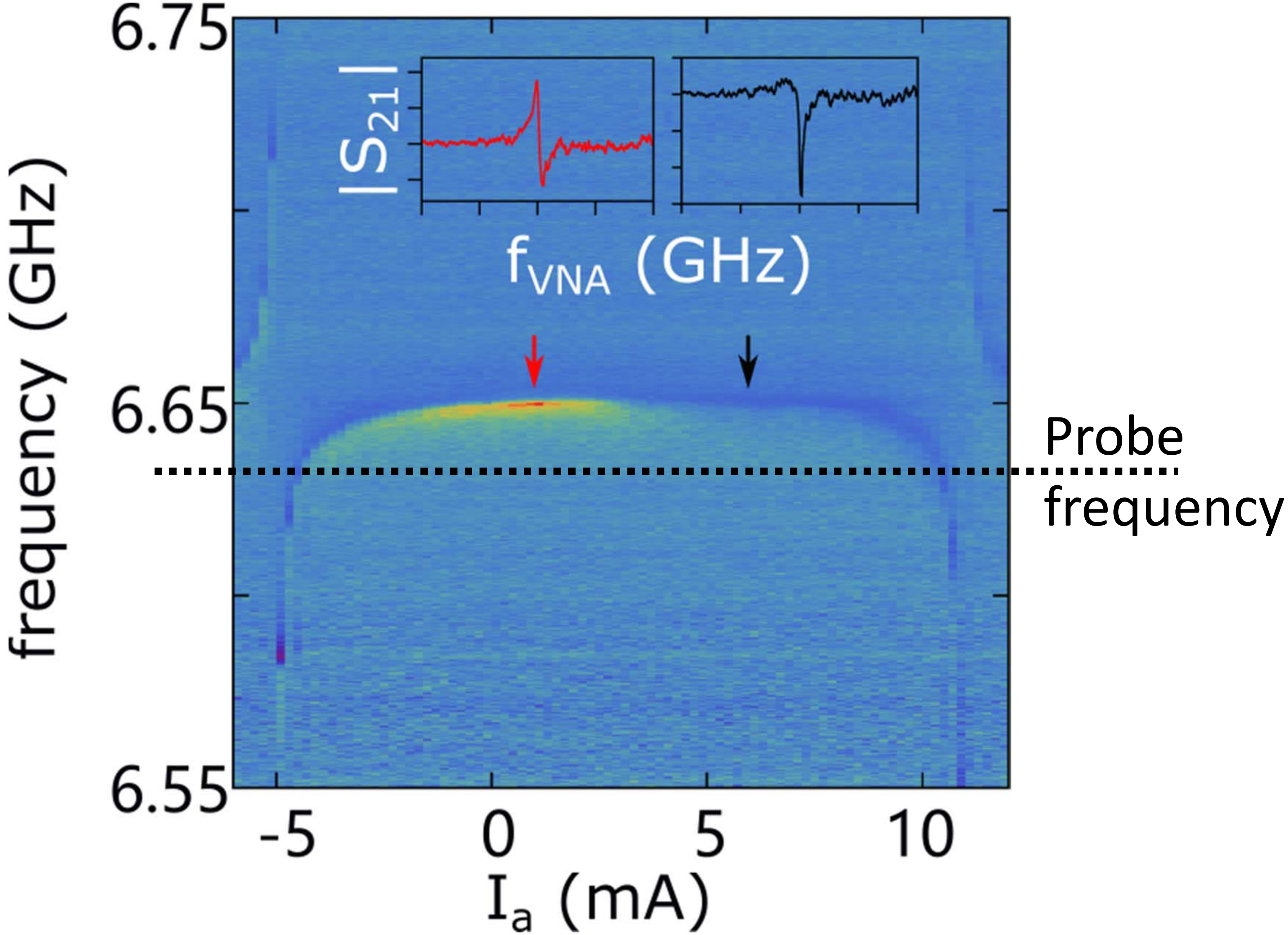
- Qubit rest frequencies f_1, f_2, ….
- Measurement temperature T
- Probe power P
- Total bias current I applied to chip

General observation:

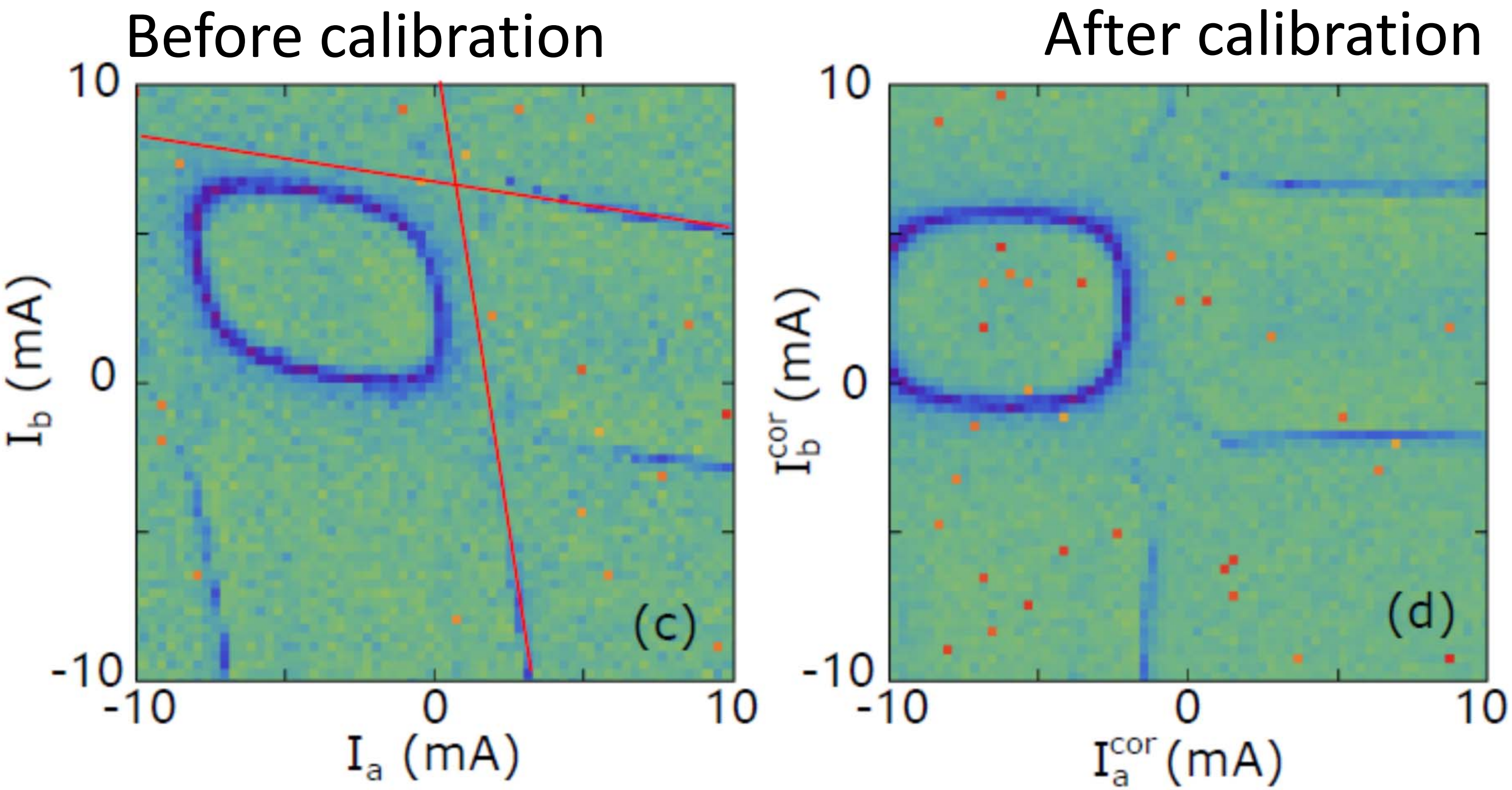
- low $T, P, I \rightarrow S_{21}$ has peak
- Higher $T, P, I \rightarrow S_{21}$ has dip (resonance inversion)

→ **What's happening...?**

1. step: crosstalk calibration



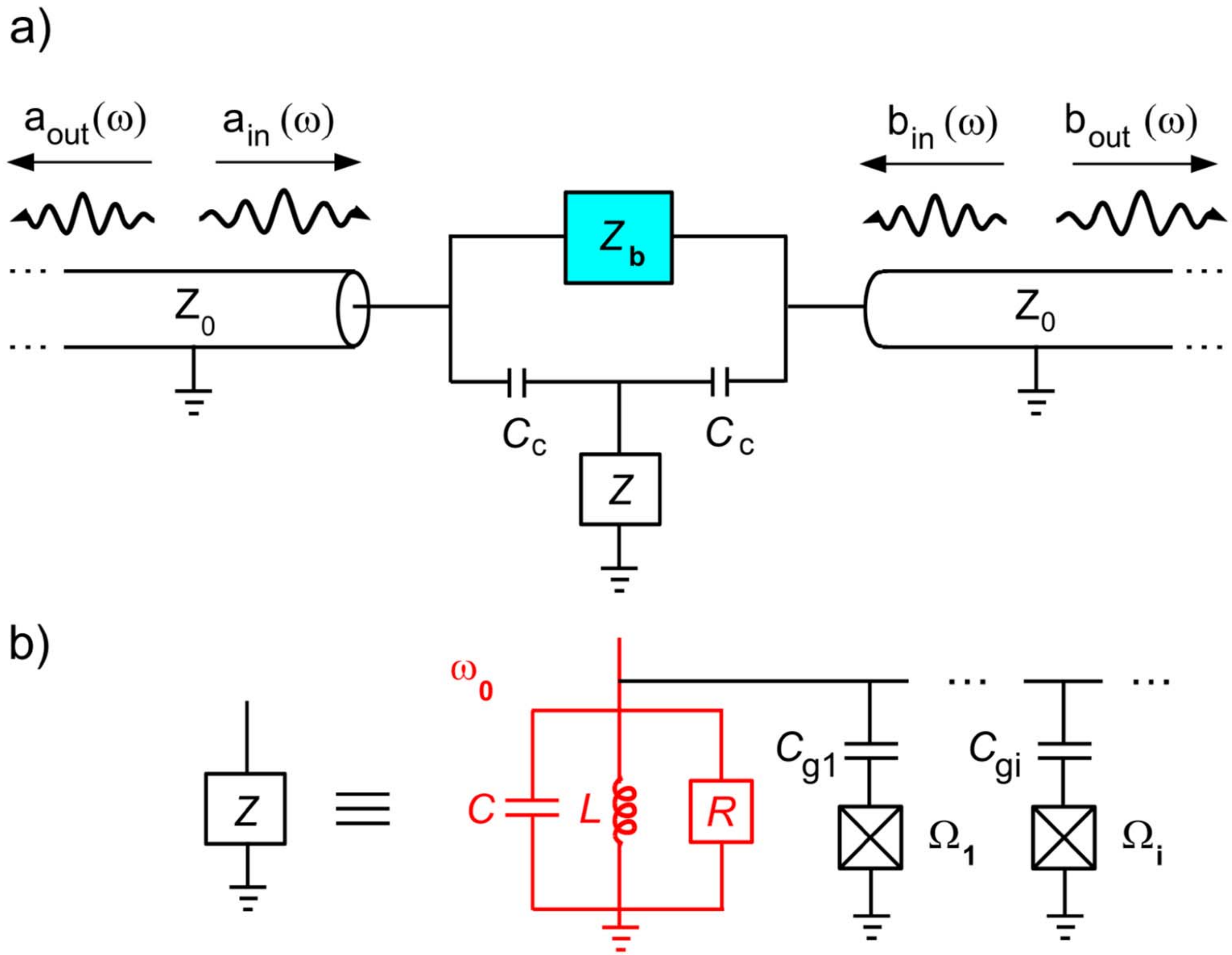
Removing crosstalk, adding local control



$$\begin{pmatrix} \Delta\Phi_1 \\ \vdots \\ \Delta\Phi_8 \end{pmatrix} = \begin{pmatrix} M_{1a} & M_{1b} & \cdots & M_{1h} \\ \vdots & \vdots & \ddots & \vdots \\ M_{8a} & M_{8b} & \cdots & M_{8h} \end{pmatrix} \begin{pmatrix} \Delta I_a \\ \vdots \\ \Delta I_h \end{pmatrix}$$

Compute mutual inductive couplings for correction current in all eight lines

2. step: Need quantitative circuit model of chip



Background Z_b

Cavity Z

Consider cavity transmission, background transmission, and background dissipation

Recall: Cavity-qubit oscillator

Tavis Cummings

$$\hat{H}_0 = \hbar\omega_0 \hat{a}^\dagger \hat{a} + \hbar \sum_{i=1}^{n} \frac{\Omega_i}{2} \hat{\sigma}_z^i + \sum_{i=1}^{n} \hbar g_i \left(\hat{a}^\dagger \hat{\sigma}_-^i + \hat{a} \hat{\sigma}_+^i \right)$$

Dispersive Hamiltonian (1Q)

$$\hat{H}_0 = \hbar \left(\omega_0 + \frac{g^2}{\Delta} \hat{\sigma}_z \right) \hat{a}^\dagger \hat{a} + \frac{\hbar}{2} \left(\Omega_0 + \frac{g^2}{\Delta} \right) \hat{\sigma}_z$$

For N qubits

$$\hat{H}_0 = \hbar \left(\omega_0 + \sum_{i=1}^{n} \frac{g_i^2}{\Delta_i} \hat{\sigma}_z \right) \hat{a}^\dagger \hat{a} + \frac{\hbar}{2} \sum_{i=1}^{n} \left(\Omega_0 + \frac{g_i^2}{\Delta_i} \right) \hat{\sigma}_z$$

For Transmons replace

$$\frac{g^2}{\Delta} \hat{\sigma}_z \hat{a}^\dagger \hat{a} \leftarrow \left(\frac{g^2}{\Delta} - \frac{g^2}{\Delta - E_C/\hbar} \right) \hat{\sigma}_z \hat{a}^\dagger \hat{a}$$

Recall: interaction transmission line with circuits

Photon field operators at cavity
$$\hat{a}_{\text{out}}(t) = \sqrt{\gamma}\hat{a}(t) - \hat{a}_{\text{in}}(t)$$
$$\hat{b}_{\text{out}}(t) = \sqrt{\gamma}\hat{a}(t) - \hat{b}_{\text{in}}(t)$$

Cavity photon operator $\hat{a}\,(t)$, and decay rate
$$\gamma = \left(\frac{C_{\text{c}}}{C + 2C_{\text{c}}}\right)^2 \frac{Z_0}{Z_{LC}}\omega_0$$

Now: include (non-dissipative) background transmission

$$\hat{a}_{\text{out}}(t) = \sqrt{\gamma}\hat{a}(t) - \frac{1}{1+2i\epsilon}\hat{a}_{\text{in}}(t) - \frac{2i\epsilon}{1+2i\epsilon}\hat{b}_{\text{in}}(t)$$
$$\hat{b}_{\text{out}}(t) = \sqrt{\gamma}\hat{a}(t) - \frac{1}{1+2i\epsilon}\hat{b}_{\text{in}}(t) - \frac{2i\epsilon}{1+2i\epsilon}\hat{a}_{\text{in}}(t)$$

Reactive response of parallel inductor
(for parallel capacitor $\varepsilon \rightarrow -\varepsilon$)
$$\epsilon = \frac{Z_0}{\omega_0 L_{\text{b}}} = \frac{Z_0}{|Z_{\text{b}}(\omega_0)|}$$

Scattering amplitude with background transmission

Valid for linear cavity, and also for cavity-transmon if

- dispersive limit w/o qubit transitions
- Transitions are slow, accounted for by statistical averaging

$$
\begin{aligned}
s_{11} &= -\frac{1}{1+2i\epsilon} + \frac{\gamma}{\gamma + i(\omega_0 - \omega)} \\
&= \frac{2\epsilon\gamma + \omega - \omega_0}{(-i+2\epsilon)\left[\gamma + i(\omega_0 - \omega)\right]}.
\end{aligned}
$$

$$
\begin{aligned}
s_{12} &= \frac{2\epsilon}{i-2\epsilon} + \frac{\gamma}{\gamma + i(\omega_0 - \omega)} \\
&= \frac{\gamma + 2\epsilon(\omega_0 - \omega)}{(1+2i\epsilon)\left[\gamma + i(\omega_0 - \omega)\right]}
\end{aligned}
$$

As non-dissipative system $|s_{11}|^2 + |s_{12}|^2 = 1$

3rd step: account for dissipation and fluctuation (finite T)

- Include dissipation in **cavity** and **background**:
  - add finite resistivity to background by replacing $\varepsilon \rightarrow \varepsilon - i\varepsilon_d$ (valid for $\varepsilon_d \ll \varepsilon$)
  - Add intrinsic dissipation to cavity by replacing $\omega_0 \rightarrow \omega_0 - i\omega_d$ corresponds to LCR circuit with energy decay rate

$$\frac{1}{RC} = 2\omega_\mathrm{d}$$

- Include fluctuations to **cavity**
  - Only relevant for non-linear cavity (otherwise cancel out)
  - Simulate driven cavity-transmon via Lindblad master simulation decay and excitation rate to TL

$$\gamma^- = \gamma\left[1 + \frac{1}{\exp\left(\frac{\hbar\omega_0}{k_\mathrm{B}T}\right) - 1}\right] \qquad \gamma^+ = \gamma\left[\frac{1}{\exp\left(\frac{\hbar\omega_0}{k_\mathrm{B}T}\right) - 1}\right]$$

Recall: Fano resonance

Spectral response of a resonant system is asymmetric around the resonance frequency due to an interference effect between two scattering amplitudes:

- Scattering through a background with a constant (or wide) state density
- Scattering through a discrete (or narrow) energy-level

Total scattering amplitude $|s|$ and spectral density $|s|^2$

$$|s| \propto \frac{|q+\eta|}{\sqrt{1+\eta^2}} \quad , \quad |s|^2 \propto \frac{(q+\eta)^2}{1+\eta^2} \, ;$$

With η broadening-normalized drive frequency with respect to the resonance frequency $\eta = (\omega_0 - \omega)/(\Gamma/2)$

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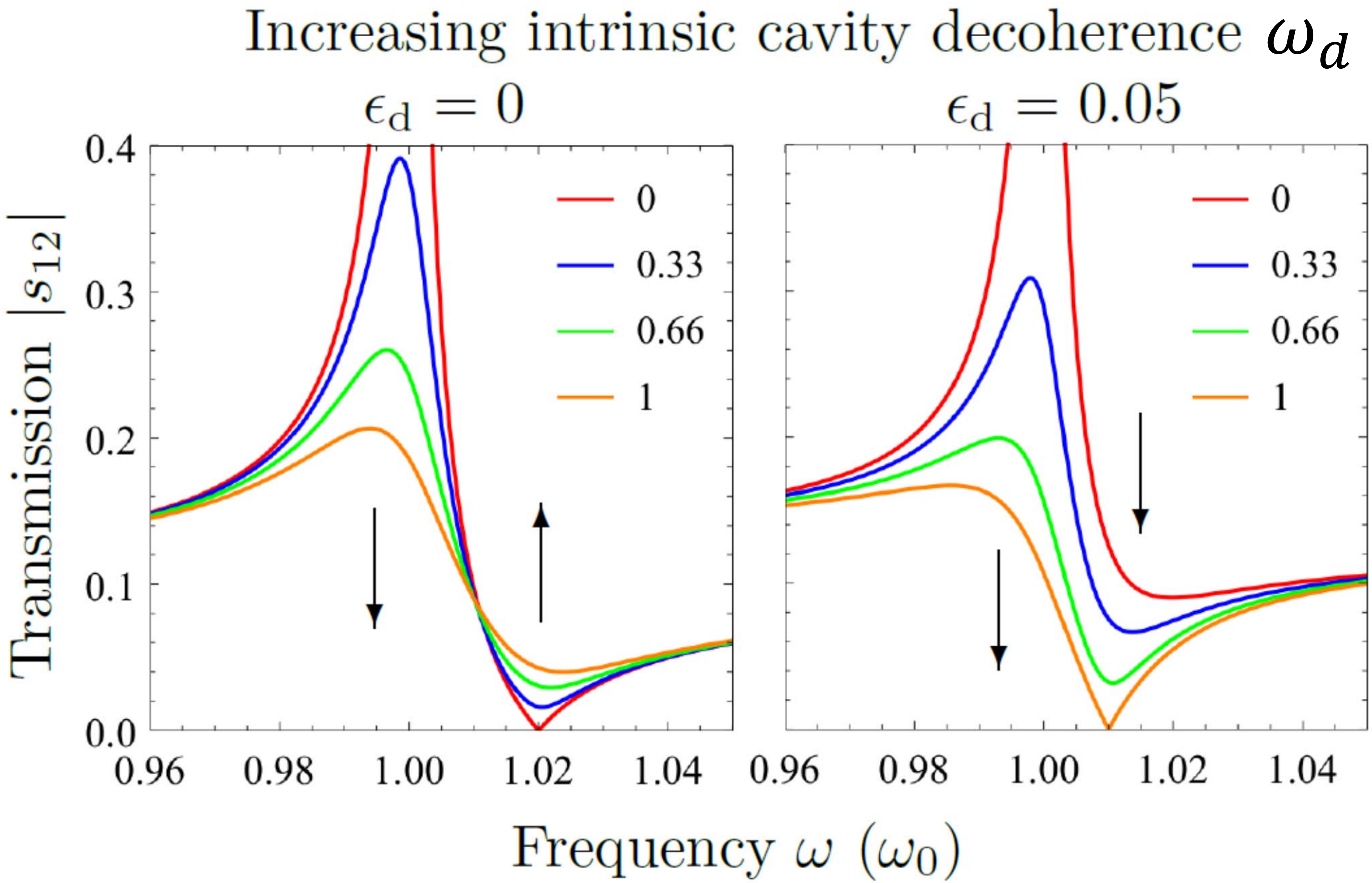
Fano resonance of linear oscillator



Weak background transmission

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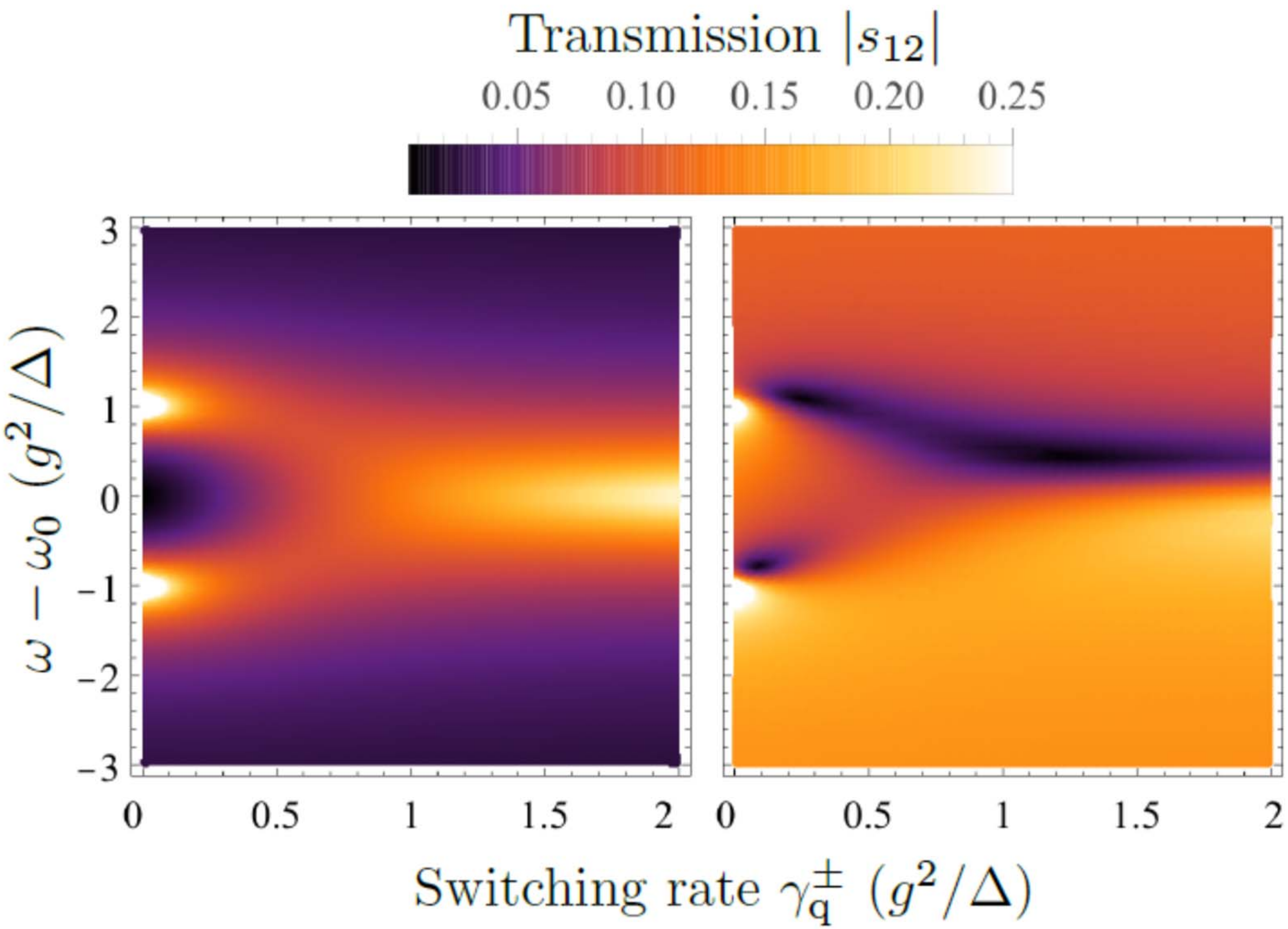
Transmission across JC oscillator with a dispersive shift and cavity fluctuations

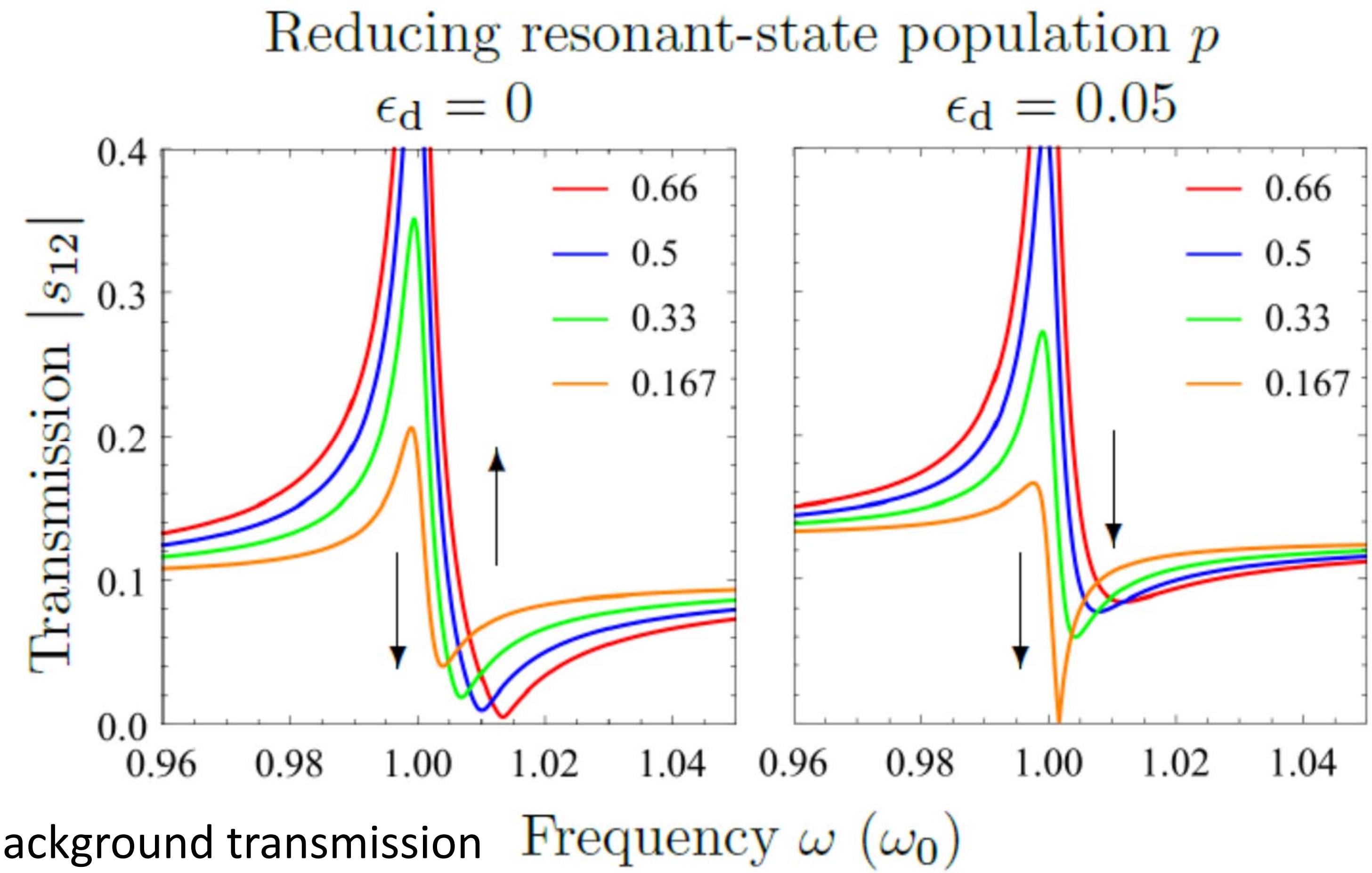


w/o background transmission w/ dissipative background

Reduced resonant-state population

Due to transmon excitations to states with dispersive shifts far away from the broadened resonance

Very similar to photon-blockade due to thermal photons



Weak background transmission

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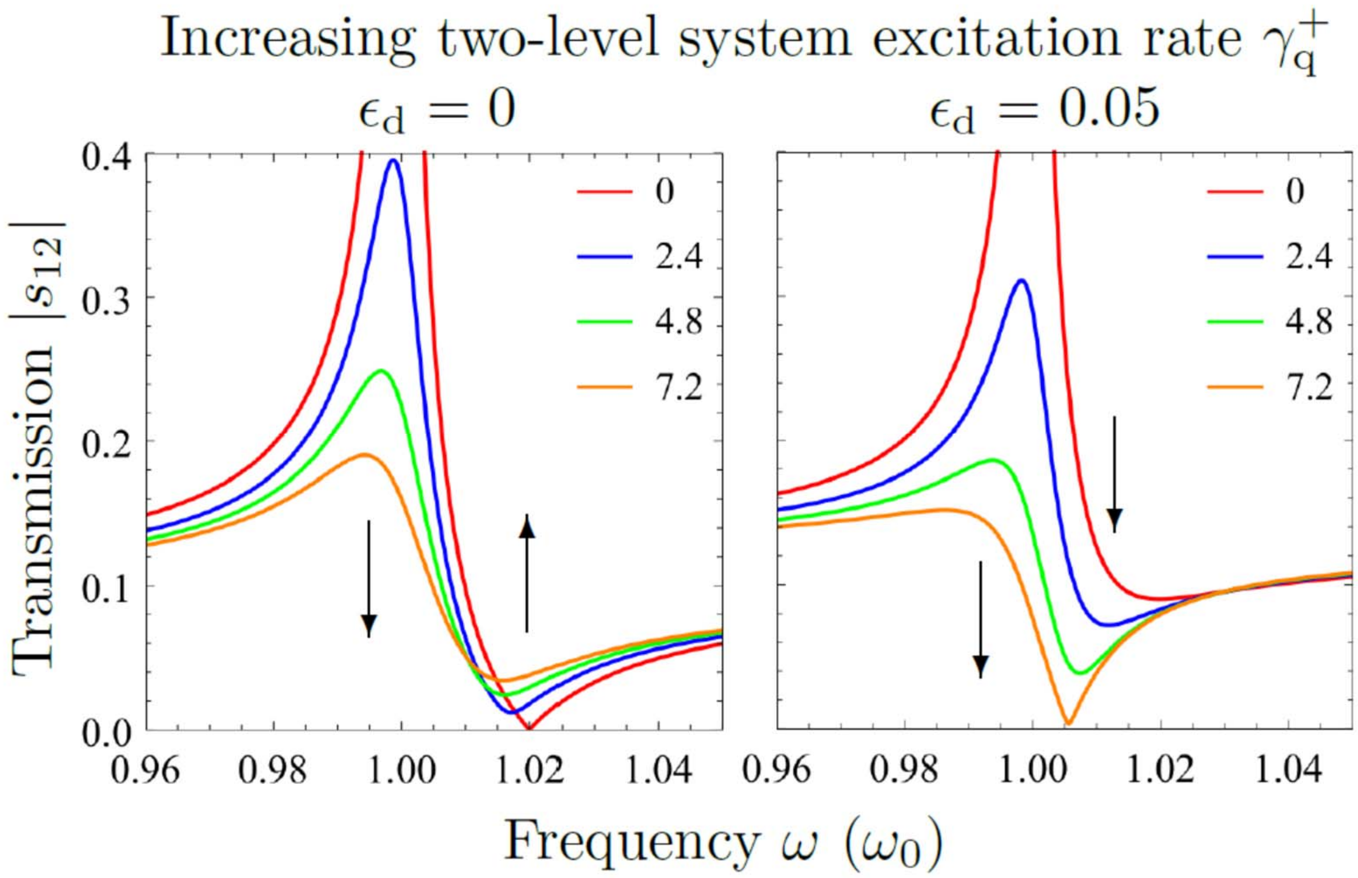
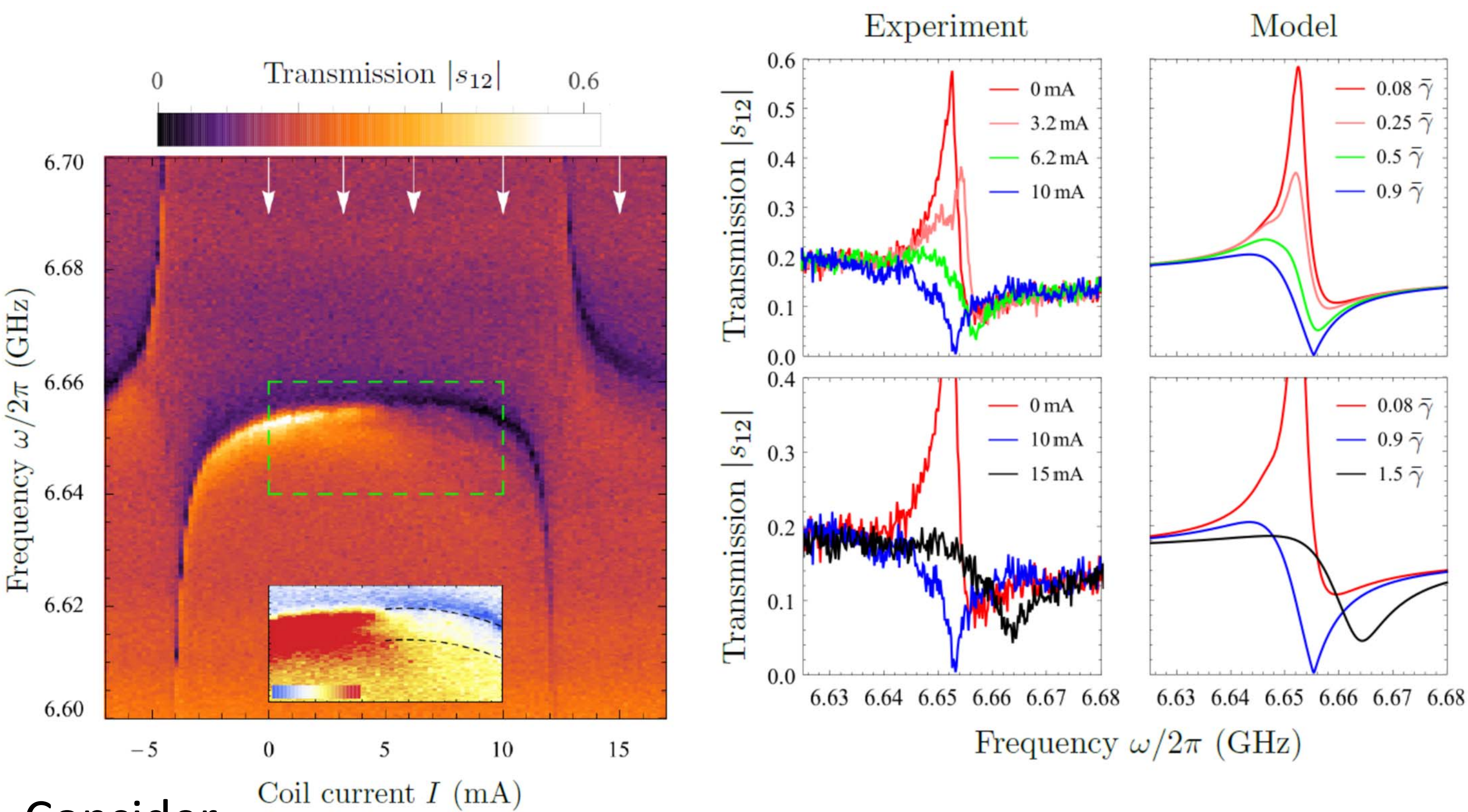
Cavity dephasing

Due to fast two-level system switching induces dephasing of the signal propagating through the cavity



Weak background transmission

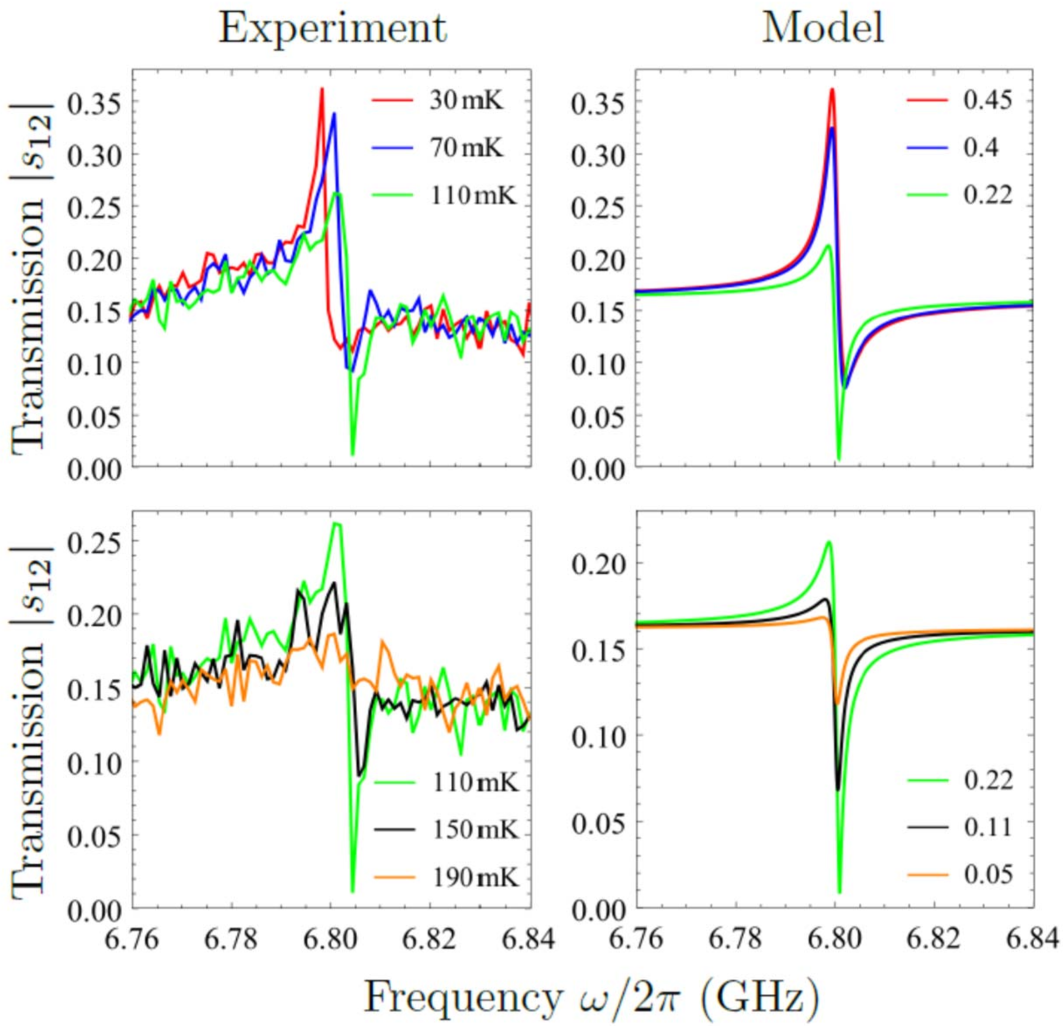
Experiment versus theory



Consider

- Microwave background with dissipation
- Heated TC oscillator (via bias current) cause cavity dephasing

Transmission at different base temperatures



Resonance inversion as function of temperature

Extract reactive and dissipative background

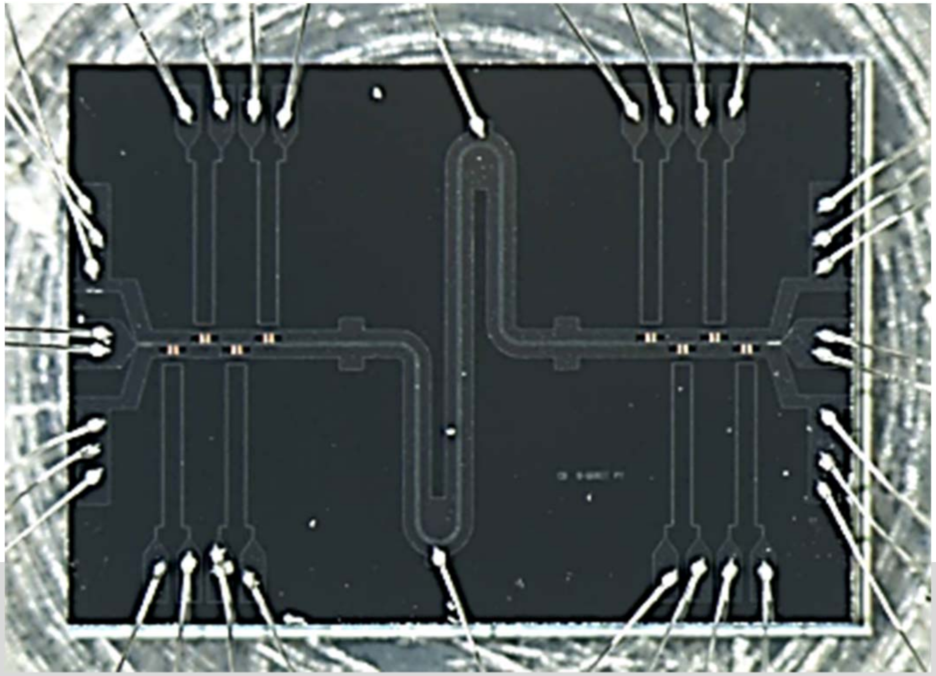
- From off-resonance background transmission and resonance transformation obtain background impedance

$$Z_{\mathrm{b}} = 1/i\omega C_{\mathrm{b}} + R_{\mathrm{b}}$$

→ C_{b}=47 fF and R_{b}=370 Ω

Capacitive coupling from DC bias (couple to TL port via box walls)

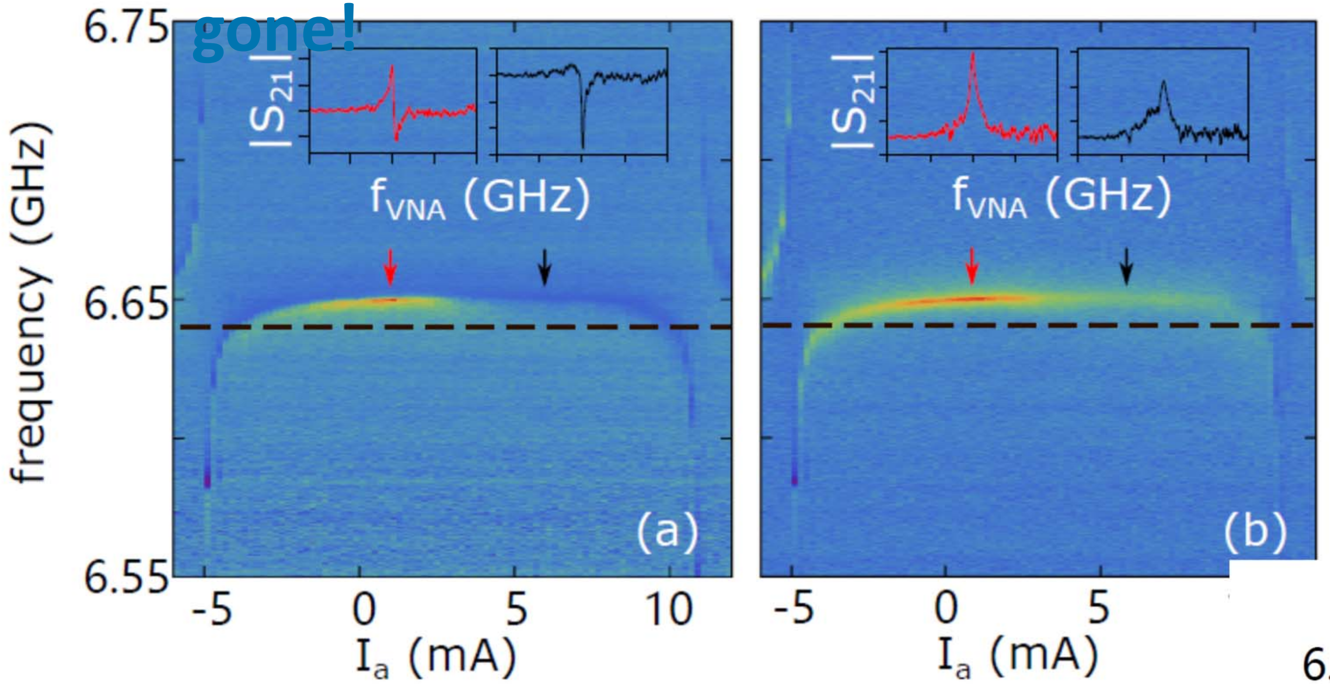
Resistance close to free space (emission to free space)



Subtracting the background transmission

Before and after correction

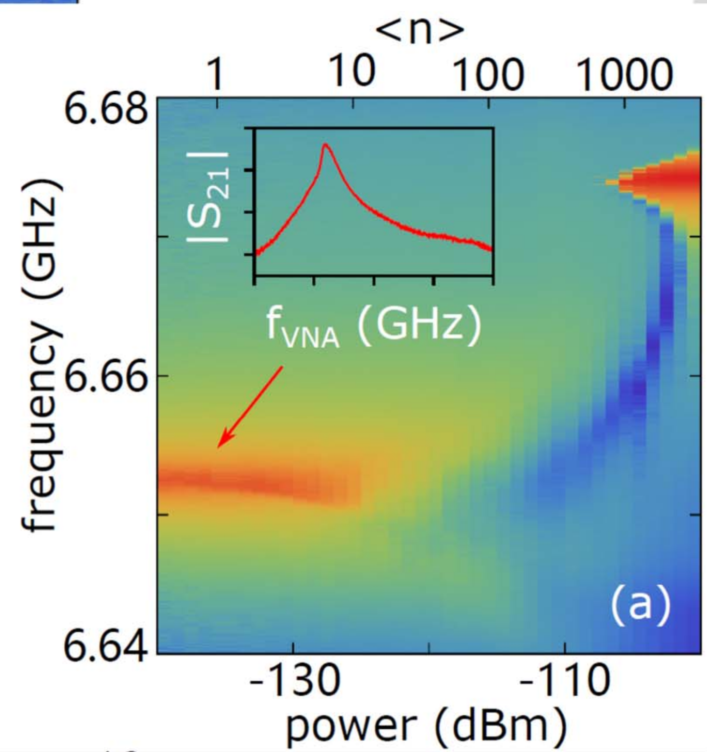
gone!



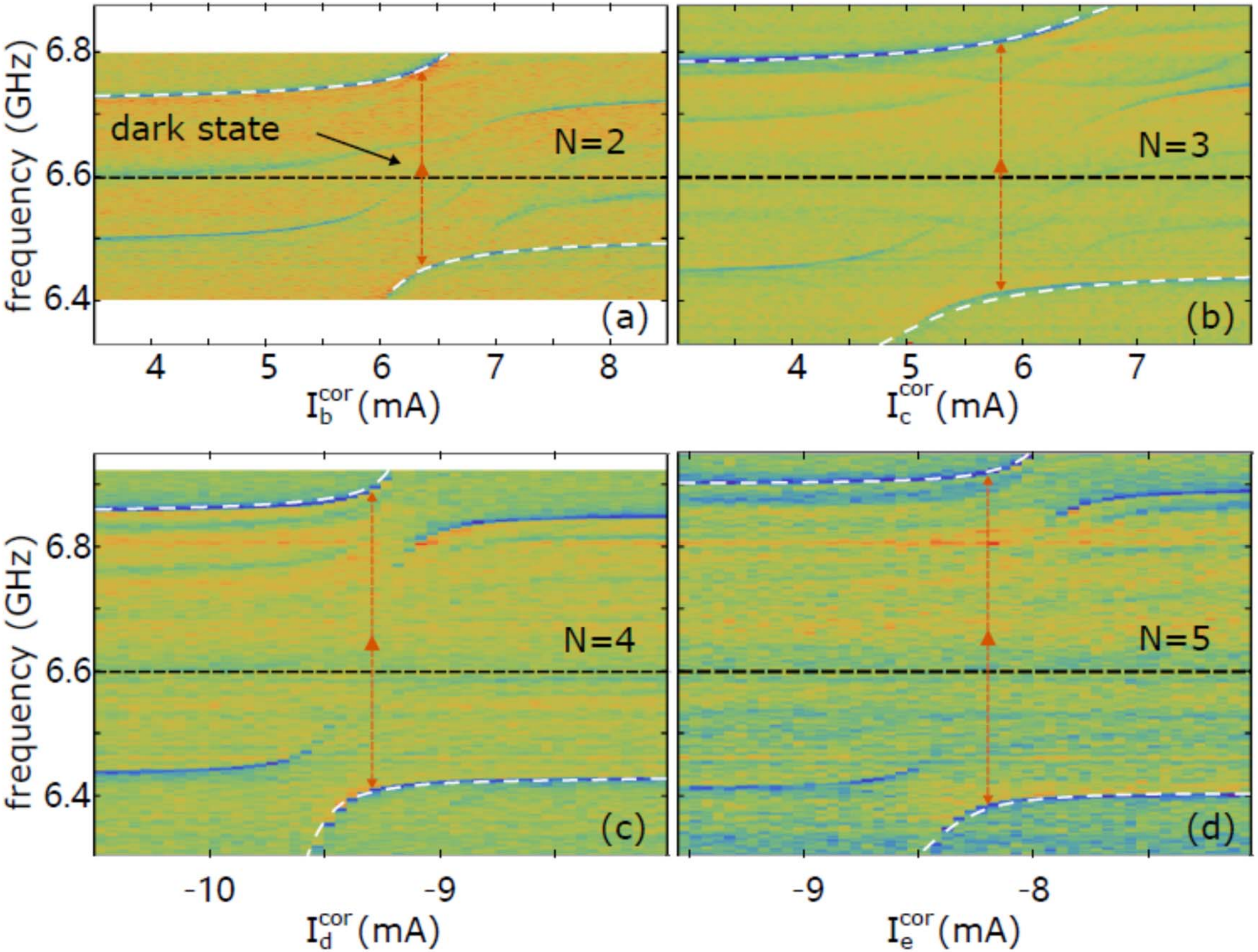
→ Dip (resonance inversion) is gone

Power scan w/ all qubits far detuned

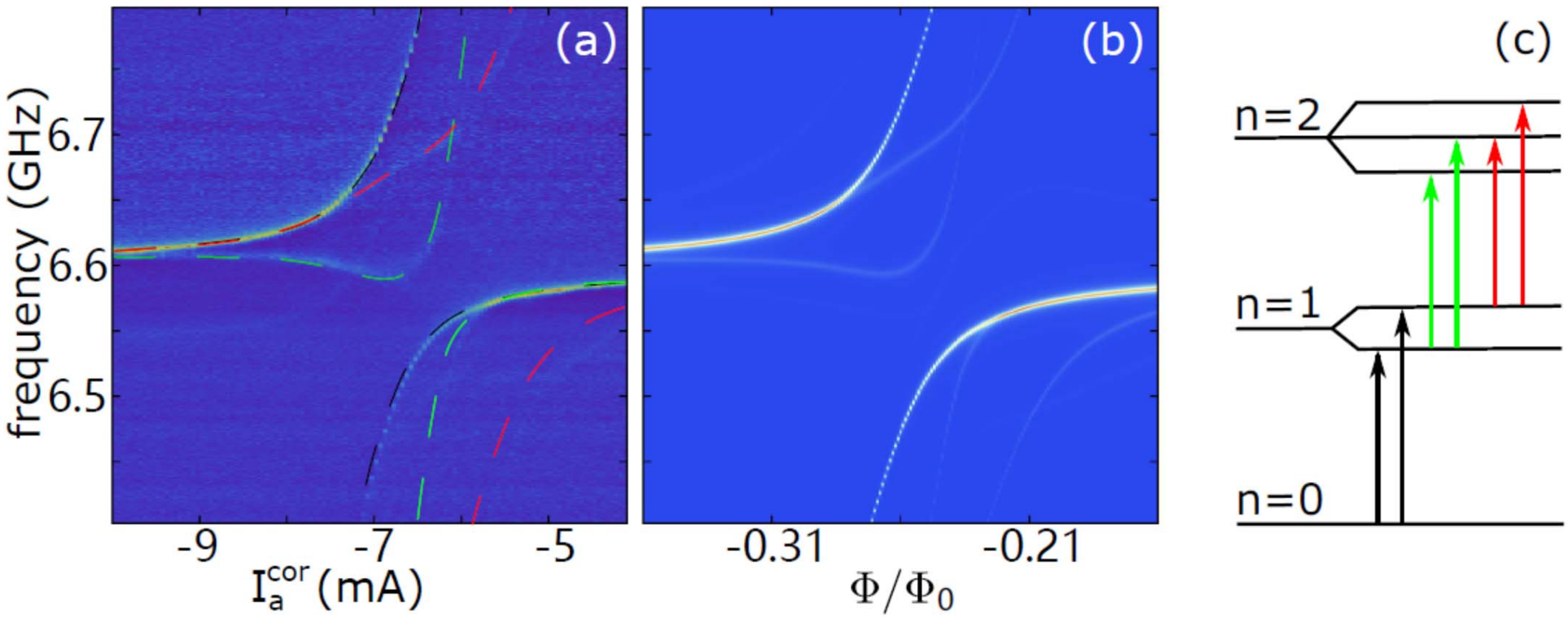
Photon-dressed resonator frequency changes from low to high powers in transmission height and frequency



Back to quantum simulator of TC model
→ multiple qubits on resonance with the cavity

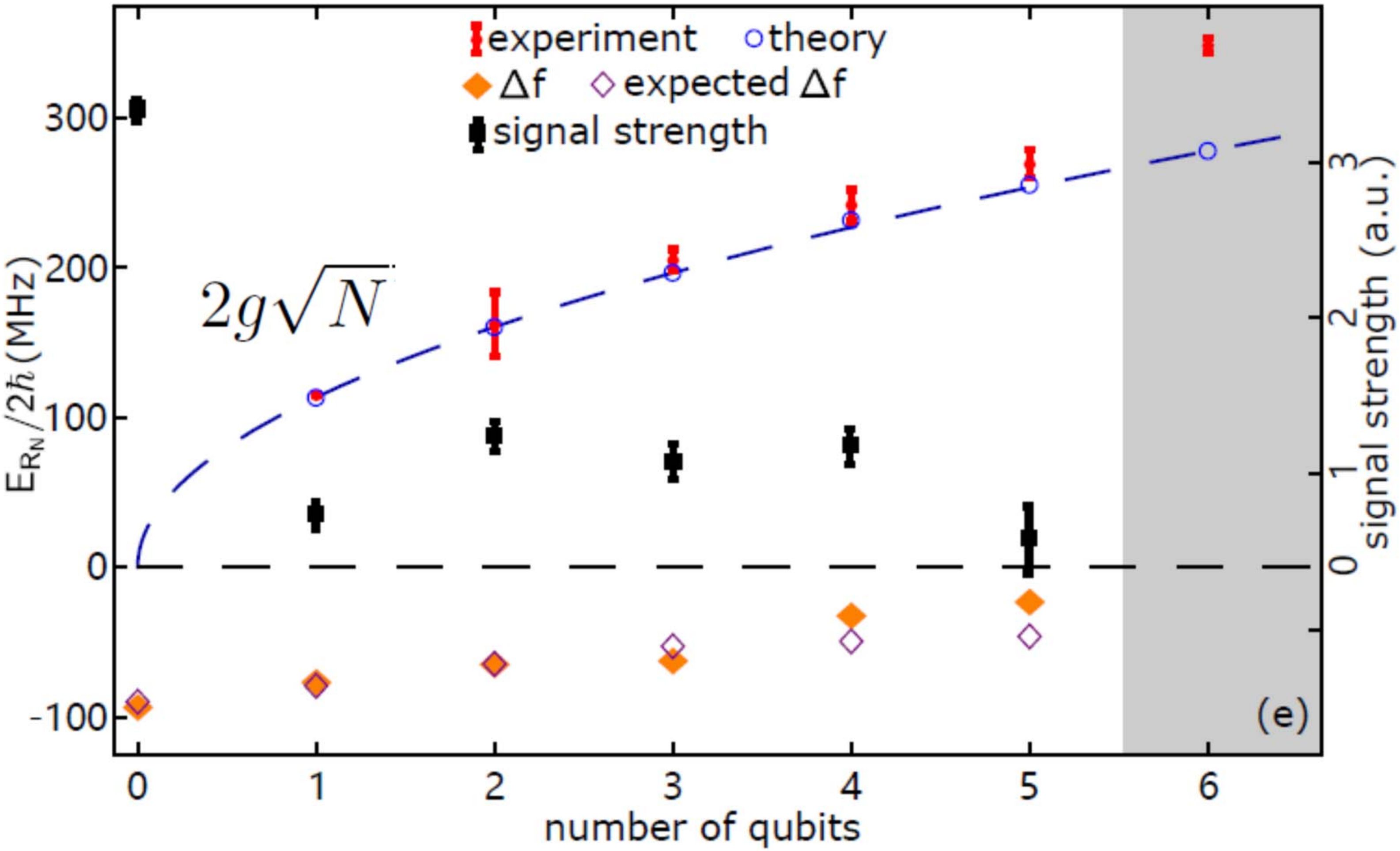


Higher level population → thermal photon population



Master equation simulation by QuTiP for three-level artificial atom interacting with a resonator which has an average thermal photon population of 0.1 photons

Vacuum Rabi splitting, center frequency shift and signal



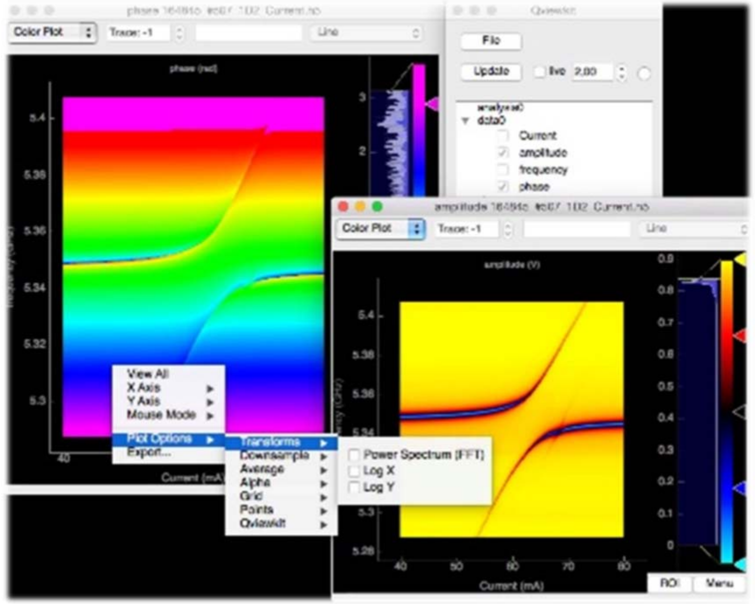
Dispersive shift $\sum_{i=N+1}^{8} g_i^2/\Delta_i$

Signal $|S_{21}| \propto \kappa_c/(\gamma_{eff}+\kappa_c)$

Unfinished challenges (tbd coming weeks)

- Signal strength dependence on # qubits
- Individual versus ensemble decay as fct. of #qubit
- Role of higher levels in spectra
- Correlate **peak inversion and signal reduction** with temperature and thermal photon population
- Extract qubit T1, T2 from data

Circle fit routine on GitHub



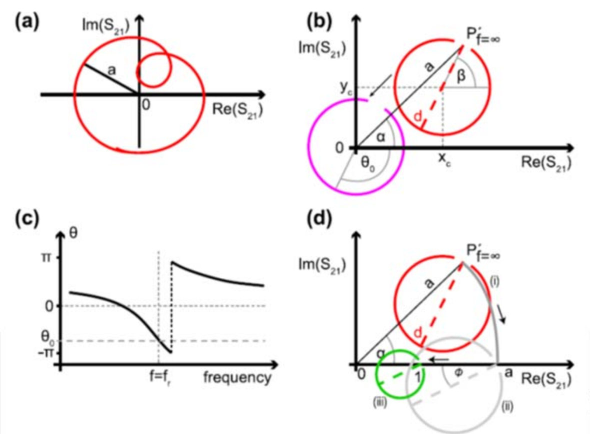
Open-source software QKIT

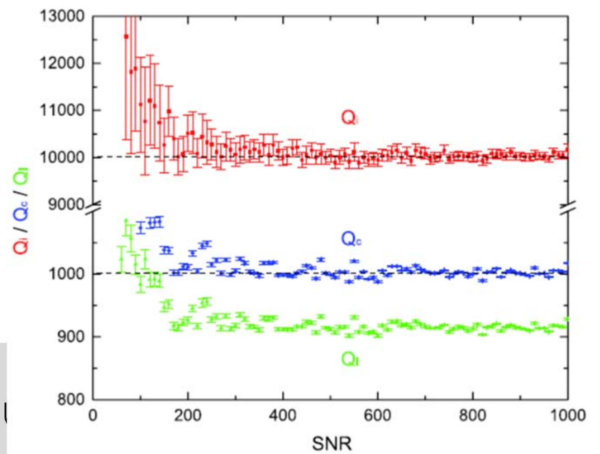
https://github.com/qkitgroup/qkit

- Python notebooks
- hdf5 data storage
- Flexible data viewer
- Instrument drivers, fitting classes

git.io/qkit

- Incl. circle fit routine (Probst *et al.*, Rev. Sci. Instr. 2015)





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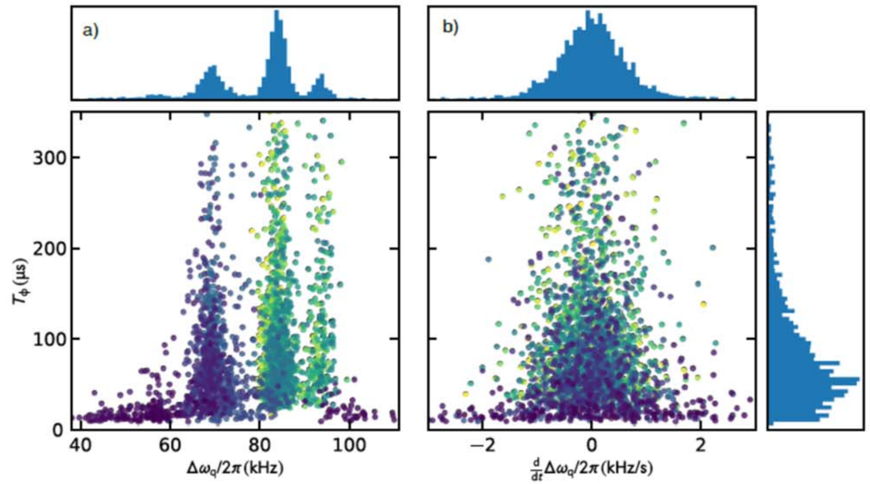
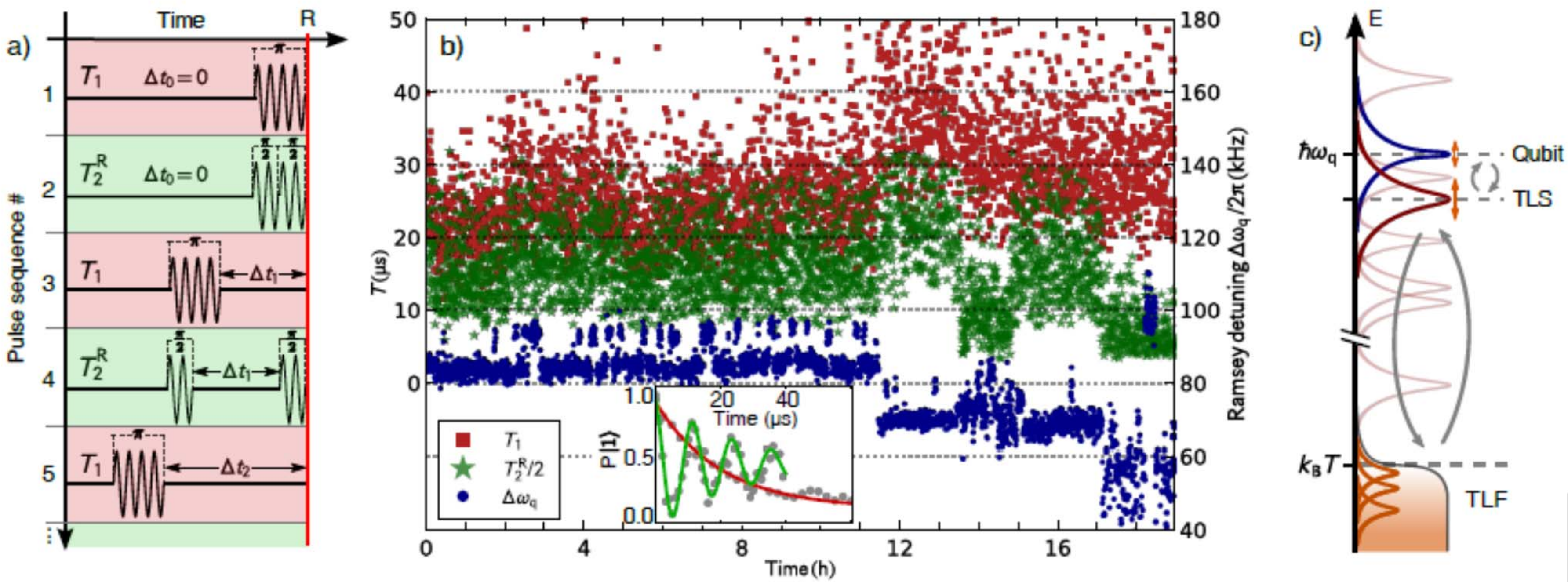
Correlating decoherence in transmon qubits

Low frequency burst noise in coherence and transition frequency
Correlation and spectral noise analysis

S. Schloer *et al.*, arXiv:1901.05352



Apply to high Q resonators?



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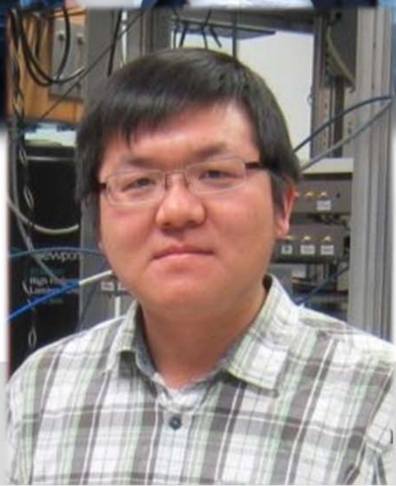

Lingzhen Guo

Michael Marthaler

Take home

- ✓ Model with reactive and dissipative background transmission
- ✓ Remove Fano interference by background calibration
- ✓ Local control of up to eight qubits interacting with one cavity
- ✓ Sqrt(N) coupling enhancement up to 5(6) qubits observed
- → Control + readout of intermediate scale qubit circuit under noise

→ Juha Leppaekangas et al., *Resonance inversion in a superconducting cavity coupled to artificial atoms and a microwave background*, arXiv:1807.09567
→ Ping Yang et al., *Probing the Tavis-Cummings level splitting with intermediate-scale superconducting circuits*, arXiv:1810.00652

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14th European Conference on Applied Superconductivity
1st-5th September 2019, SEC, Glasgow