A dissipatively stabilized Mott insulator of photons

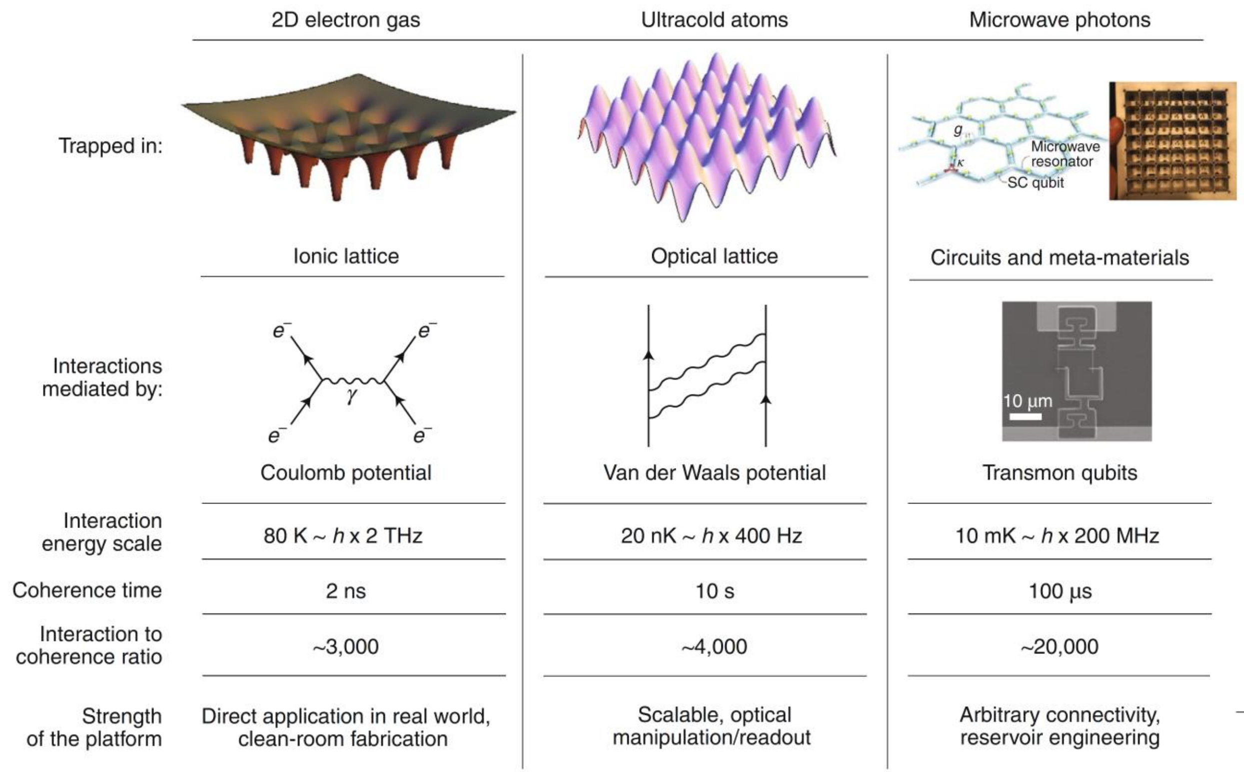
Ruichao Ma, Brendan Saxberg , Clai Owens , Nelson Leung , Yao Lu ,
Jonathan Simon & David I. Schuster

Motivation

- Thermalization of a condensed matter system, when in contact with a reservoir
- Anderson 1958: Some Quantum states (strongly disordered, isolated) (sometimes) do not self thermalize (Many-Body-Localization (MBL))
- MBL is non ergodic: State stays close to its initial state for infinite amount of time
- Problem: It is very hard to determine the ordering dynamics of the Hamiltonian in this regime.
- Synthetic quantum materials can be used to investigate this behaviour (Quantum simulation)
- Photonic systems offer tunability, strong correlation and long coherence time.

https://de.wikipedia.org/wiki/Philip_Warren_Anderson

Iacopo Carusotto, Andrew A. Houck , Alicia J. Kollár, Pedram Roushan, David I. Schuster and Jonathan Simon, „Photonic materials in circuit quantum electrodynamic
(2020)



	2D electron gas	Ultracold atoms	Microwave photons
Trapped in:	Ionic lattice	Optical lattice	Circuits and meta-materials
Interactions mediated by:	Coulomb potential	Van der Waals potential	Transmon qubits
Interaction energy scale	80 K ~ *h* x 2 THz	20 nK ~ *h* x 400 Hz	10 mK ~ *h* x 200 MHz
Coherence time	2 ns	10 s	100 µs
Interaction to coherence ratio	~3,000	~4,000	~20,000
Strength of the platform	Direct application in real world, clean-room fabrication	Scalable, optical manipulation/readout	Arbitrary connectivity, reservoir engineering

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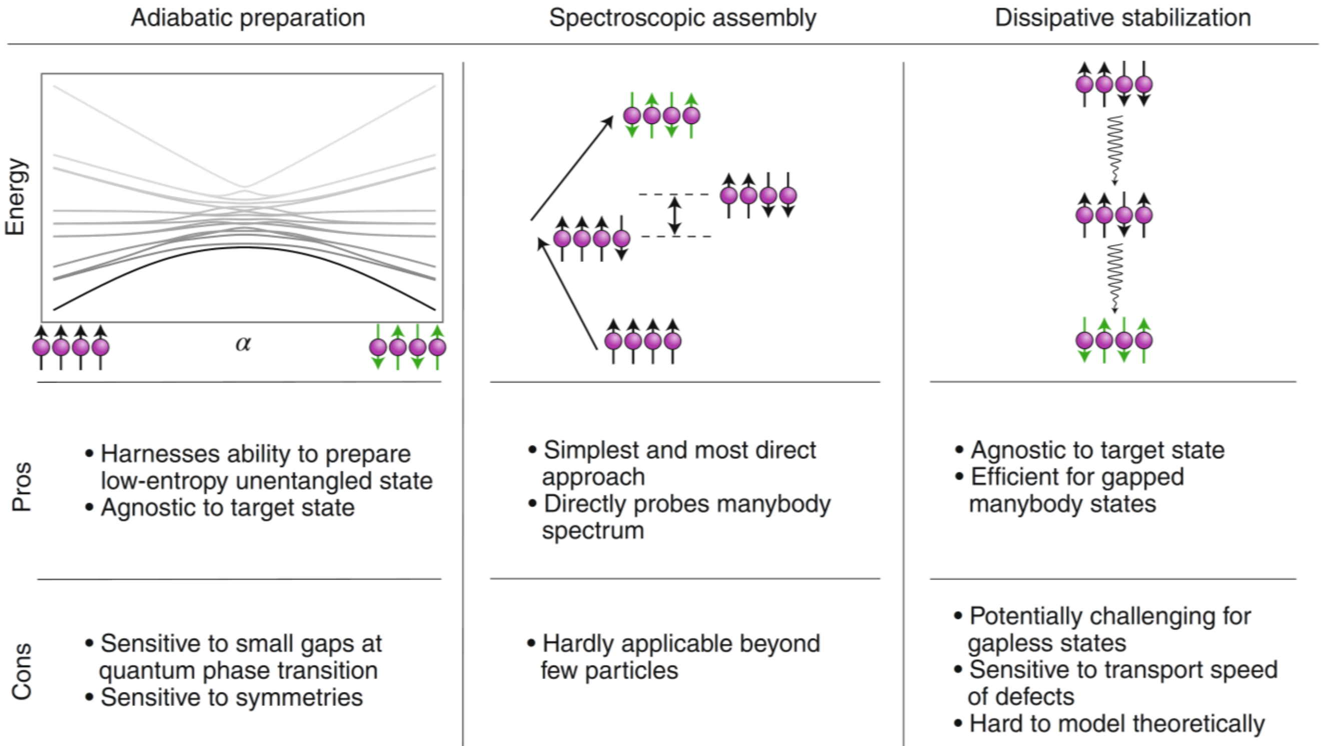

	Adiabatic preparation	Spectroscopic assembly	Dissipative stabilization
Pros	• Harnesses ability to prepare low-entropy unentangled state • Agnostic to target state	• Simplest and most direct approach • Directly probes manybody spectrum	• Agnostic to target state • Efficient for gapped manybody states
Cons	• Sensitive to small gaps at quantum phase transition • Sensitive to symmetries	• Hardly applicable beyond few particles	• Potentially challenging for gapless states • Sensitive to transport speed of defects • Hard to model theoretically

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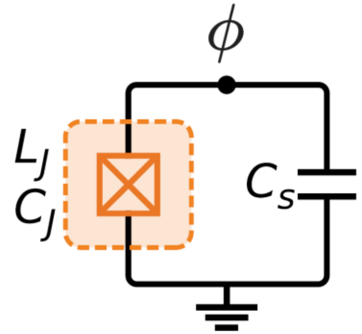
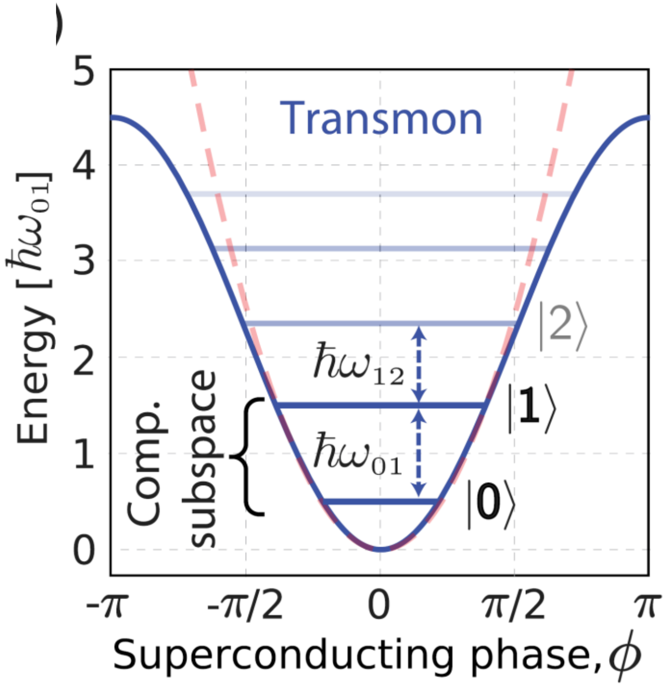
From LC-circuit to Transmon qubit





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Energy of an electronic device $E(t) = \int_{-\infty}^{t} V(t')I(t')dt'$

Capacitance	**Inductance**	**Josephson junction**
$I = C\dot{V}$ $Q(t) = \int_{-\infty}^{t} I(t')dt'$ $n = \frac{Q}{2e}$ $E_C = \frac{e^2}{2C}$ ➡ $E_C = \frac{e^2}{2(C_S + C_J)}$ $Q = C\dot{\Phi}$	$V = L$ [illegible] $\Phi(t) = \int_{-\infty}^{t}$ [illegible] $t')$ $\phi = \frac{2\pi\Phi}{\Phi_0}$ $E_L = \frac{\Phi_0^2}{4\pi^2}$ [illegible]	$V = \frac{\hbar}{2e}\frac{d\phi}{dt}$ $I = I_{crit}\sin(\phi)$ $E_J = \frac{I_C\Phi_0}{2\pi}$ $E_J = E_J(\phi_e) = 2E'_J\lvert\cos(\phi_e)\rvert$

$H = 4E_C n^2 + \frac{1}{2}E_L\phi^2$ $\quad H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) = \hbar\omega_r\left(m + \frac{1}{2}\right)$ $\quad \omega_r = \frac{\sqrt{8E_L E_C}}{\hbar}$

⬇

$H = 4E_C n^2 - E_J\cos(\phi)$ $\quad H = \sqrt{8E_C E_J}\left(m + \frac{1}{2}\right) - E_J - \frac{E_C}{12}\left(6m^2 + 6m + 3\right)$ $\quad \alpha = E_{12} - E_{01} = -E_C$

Qubit coupling

$$\frac{H_{JC}}{\hbar} = \omega_r \left(m_r + \frac{1}{2} \right) + \omega_q \left(m_q + \frac{1}{2} \right) + g(a_q^\dagger a_r + a_q a_r^\dagger)$$

Coupling Hamiltonian for a qubit and a resonator

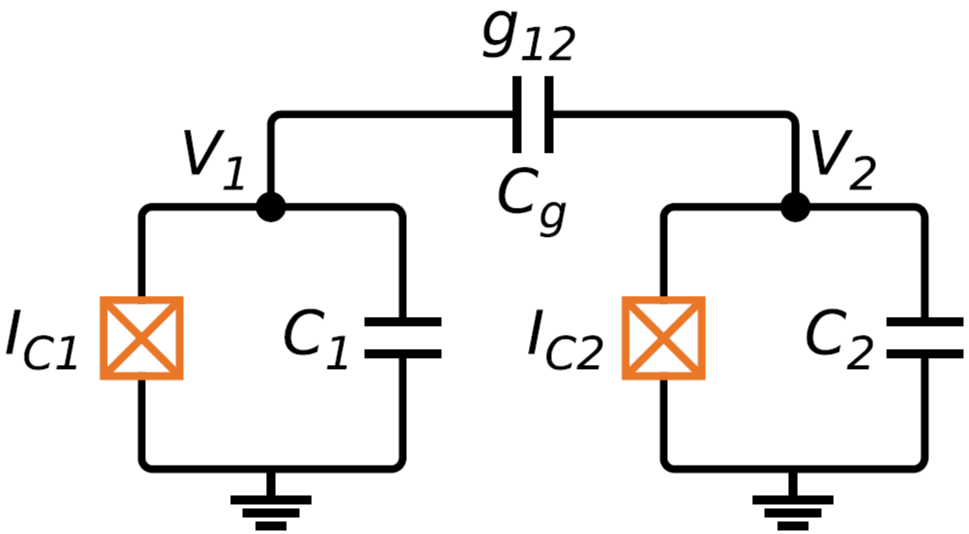
Capacitative qubit coupling

$$a^\dagger |m\rangle = \sqrt{m+1}\,|m+1\rangle$$

$$a\,|m\rangle = \sqrt{m}\,|m-1\rangle$$

Qubit readout

$$g = \frac{\omega_{01} C_g}{2 C_\Sigma}$$



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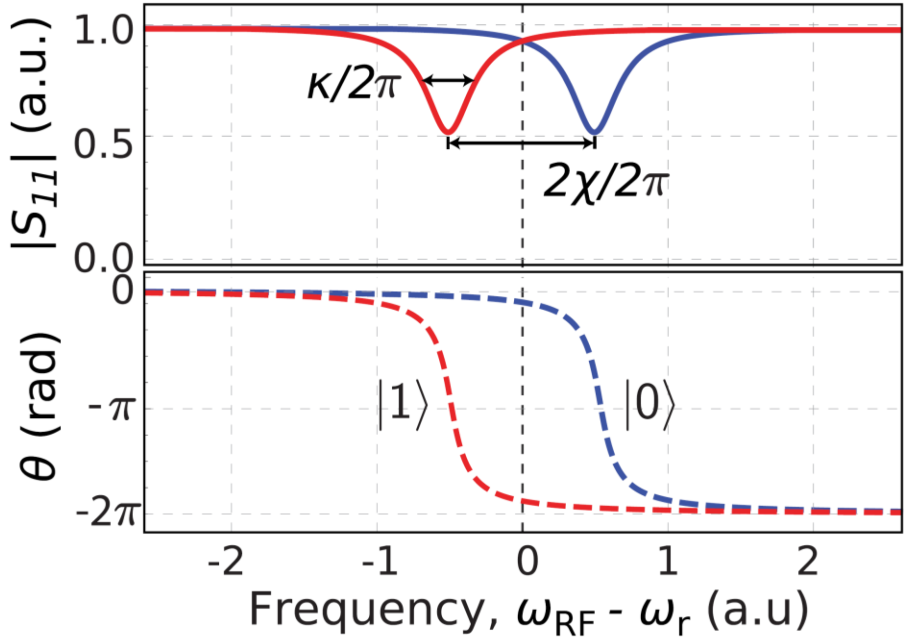
Dispersive approximation
(no photon exchange, only frequency shift)

$$\Delta >> g$$

$$\Delta = |\omega_q - \omega_r|$$



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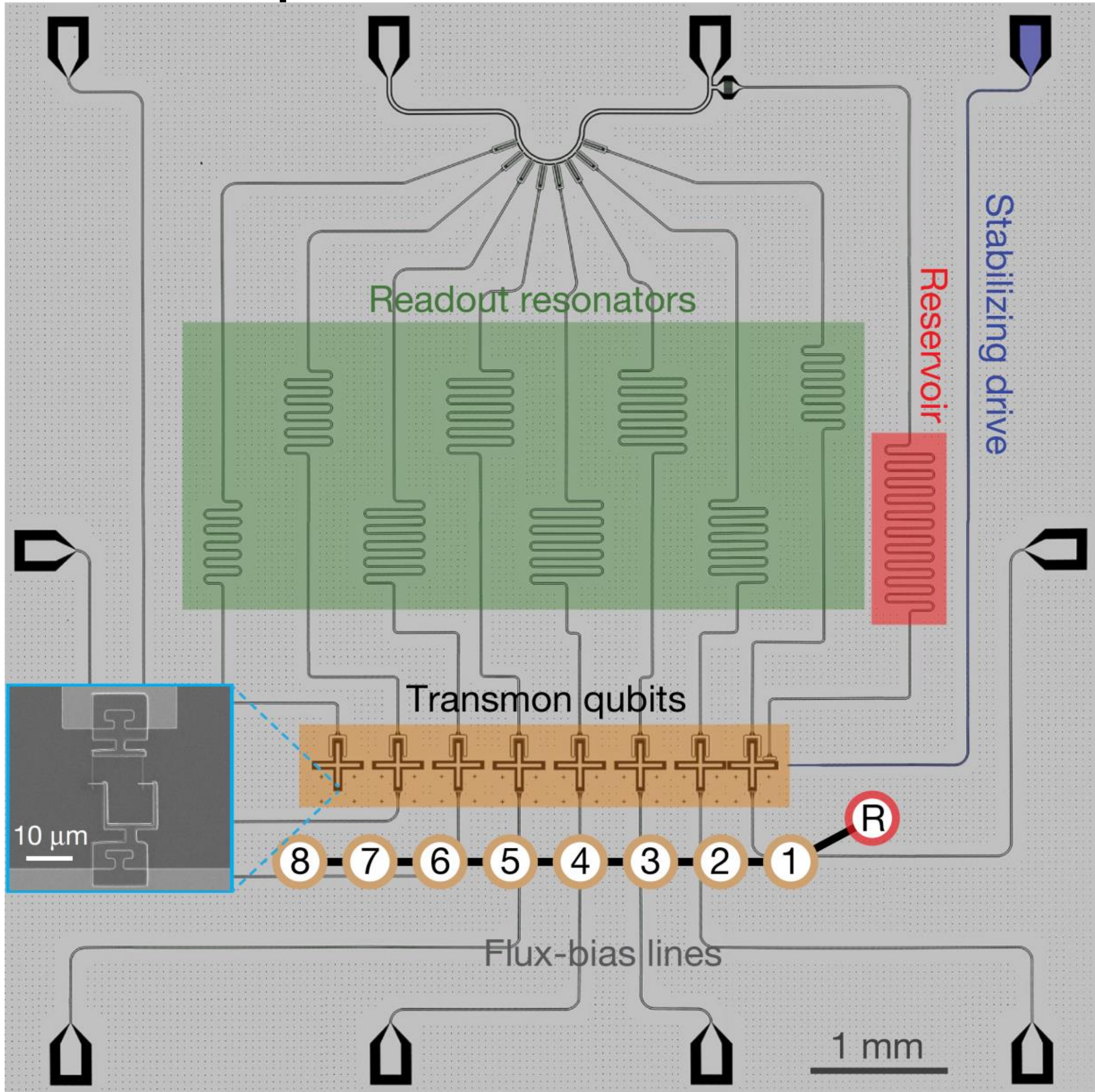
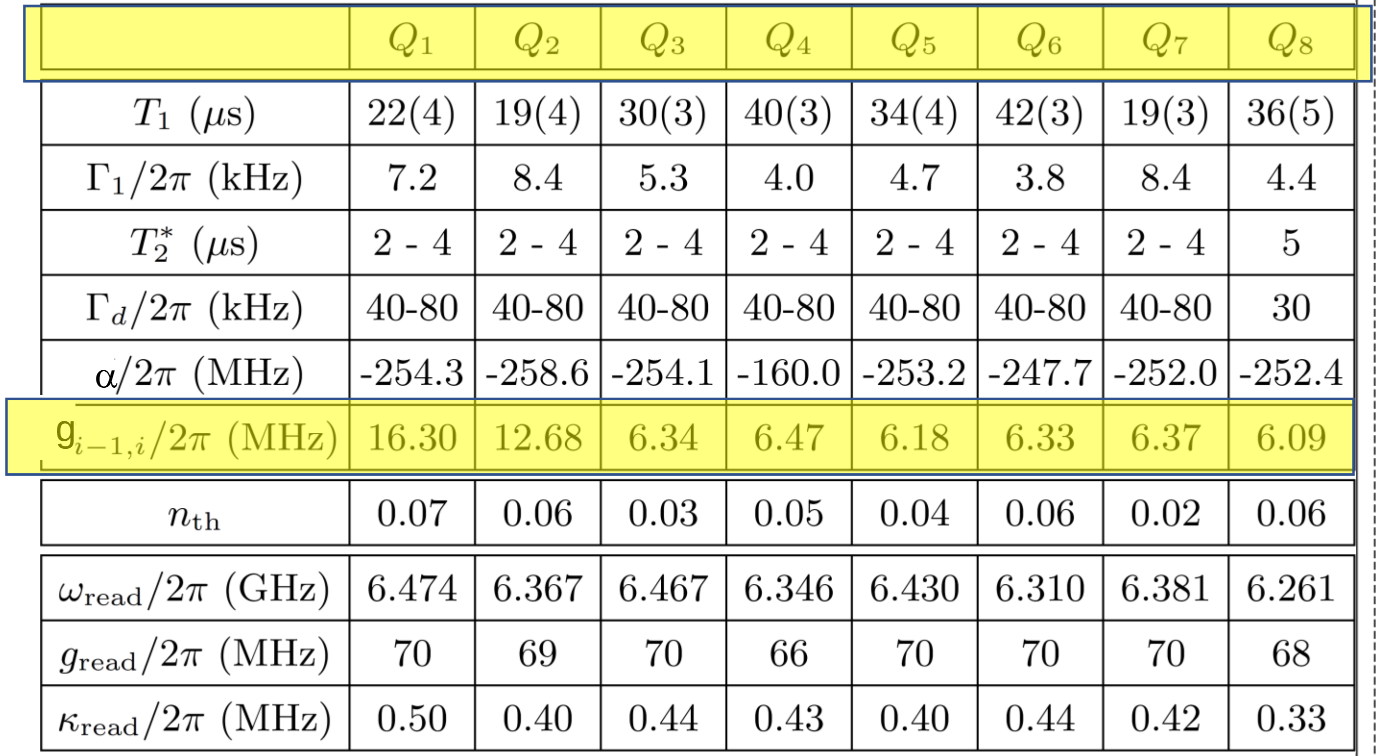
Experimental setup

- **Cooling** with dilution refrigerator
- **Radiation** shields
- **Transmon** qubit: Aluminum josephson junctions
- **Tuning** of qubits: Flux-Bias lines and external DC-coil
- Qubit capacitative **coupling** (non neighbouring coupling is supressed by an order of magnitude)
- **Readout** of qubits: Reflectance of input signal, while resonators are spectrally seperated
- **Stabilizing** drive excites Q1



Experimental setup



	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8
T_1 (μs)	22(4)	19(4)	30(3)	40(3)	34(4)	42(3)	19(3)	36(5)
$\Gamma_1/2\pi$ (kHz)	7.2	8.4	5.3	4.0	4.7	3.8	8.4	4.4
T_2^* (μs)	2 - 4	2 - 4	2 - 4	2 - 4	2 - 4	2 - 4	2 - 4	5
$\Gamma_d/2\pi$ (kHz)	40-80	40-80	40-80	40-80	40-80	40-80	40-80	30
$\alpha/2\pi$ (MHz)	-254.3	-258.6	-254.1	-160.0	-253.2	-247.7	-252.0	-252.4
$g_{i-1,i}/2\pi$ (MHz)	16.30	12.68	6.34	6.47	6.18	6.33	6.37	6.09
n_{th}	0.07	0.06	0.03	0.05	0.04	0.06	0.02	0.06
$\omega_{\mathrm{read}}/2\pi$ (GHz)	6.474	6.367	6.467	6.346	6.430	6.310	6.381	6.261
$g_{\mathrm{read}}/2\pi$ (MHz)	70	69	70	66	70	70	70	68
$\kappa_{\mathrm{read}}/2\pi$ (MHz)	0.50	0.40	0.44	0.43	0.40	0.44	0.42	0.33

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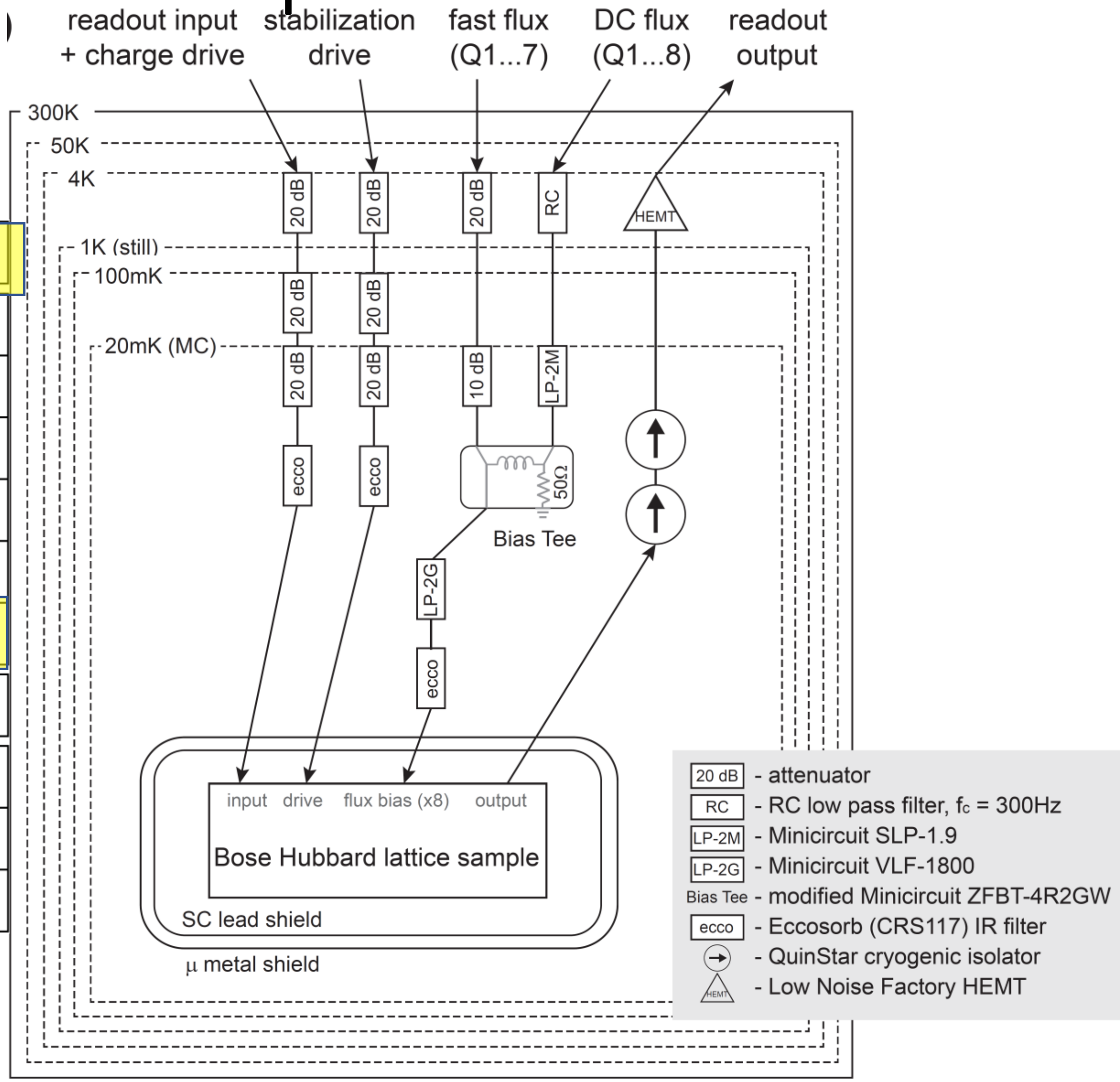

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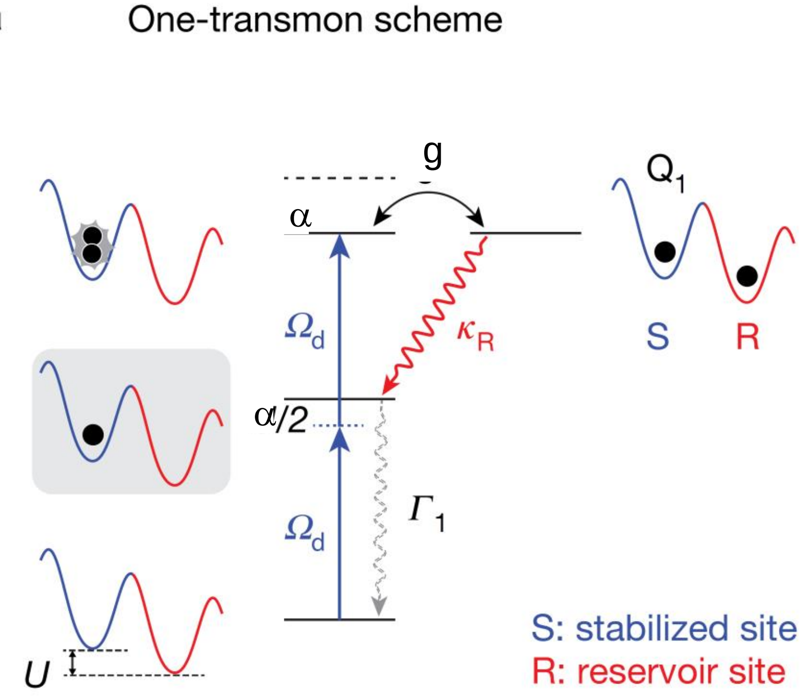
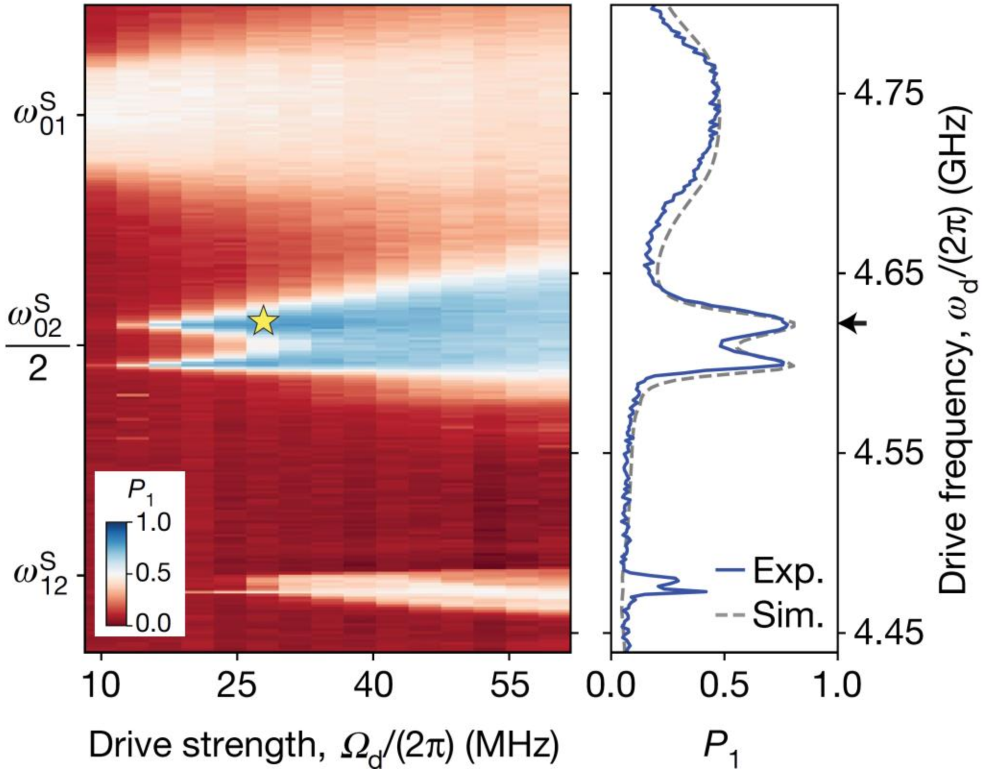
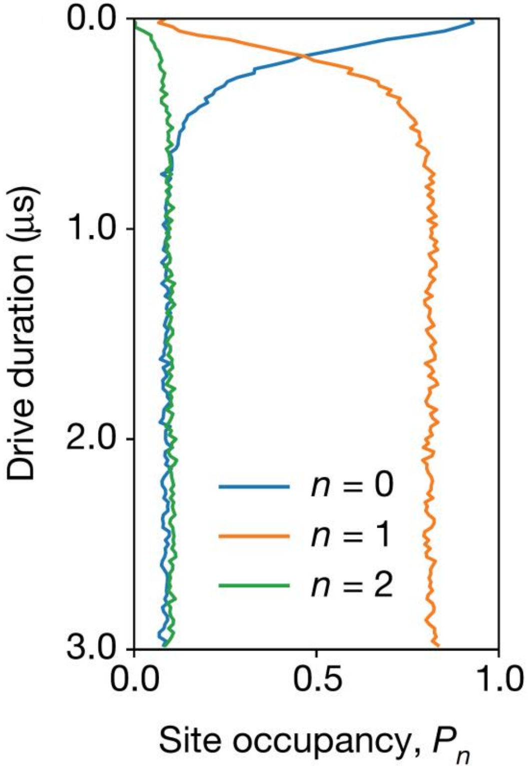
One Transmon scheme

- Two photon transition: Decay into one photon state
- Excitation at 0->1 energy gives a max occupation of 0.5 (two level laser)
- Low Drive Strength: Single photon decay too high
- High Drive Strength: Lossy resonator decay too small

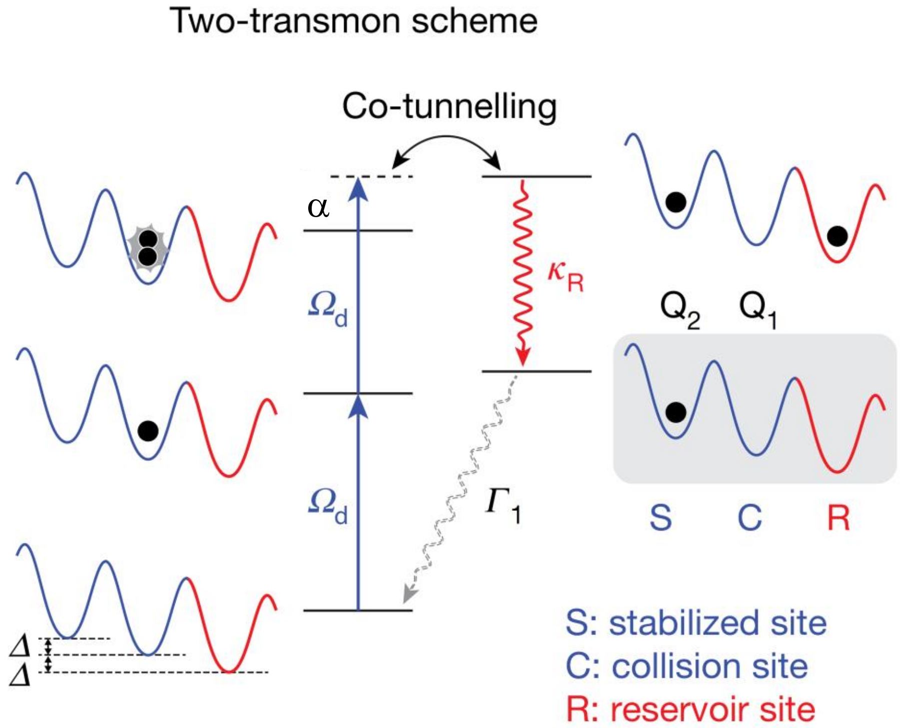


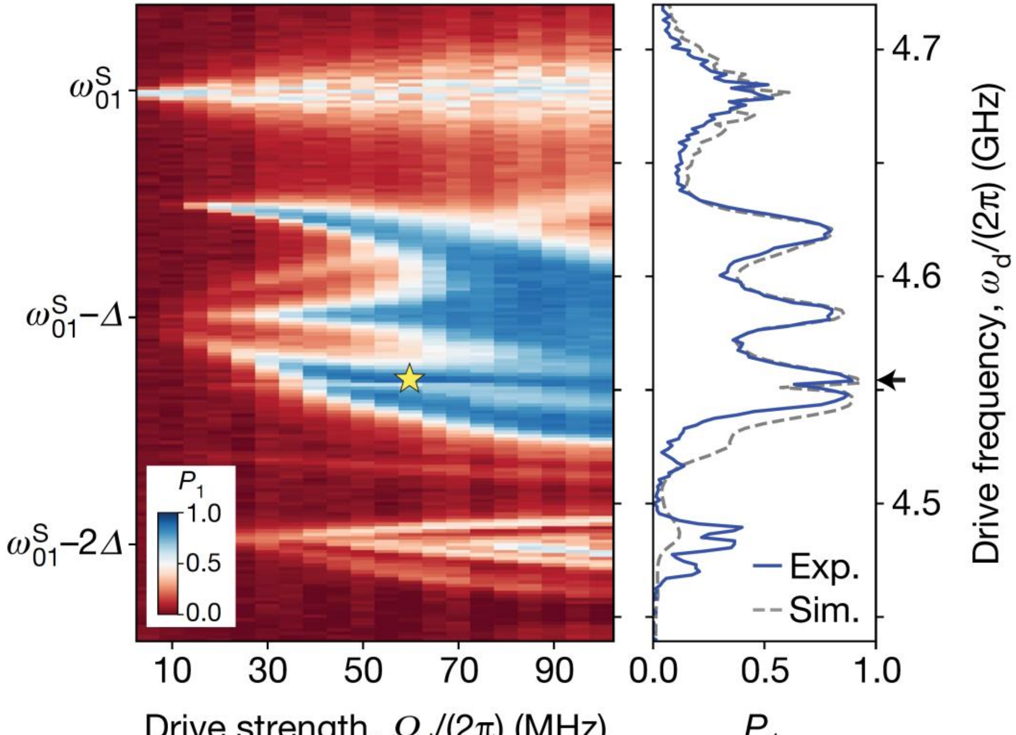


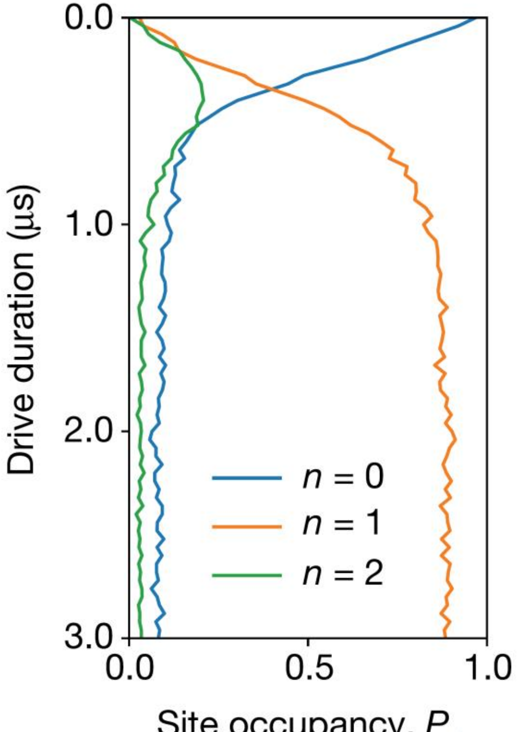


Two Transmon scheme

- Excitation with energy corresponding to 0->1 transition of collision state
- Elastic collision of two photons, one into S, the other into R (seperated by 2Δ)
- Photon insertion irreversible: Δ=2π100MHz



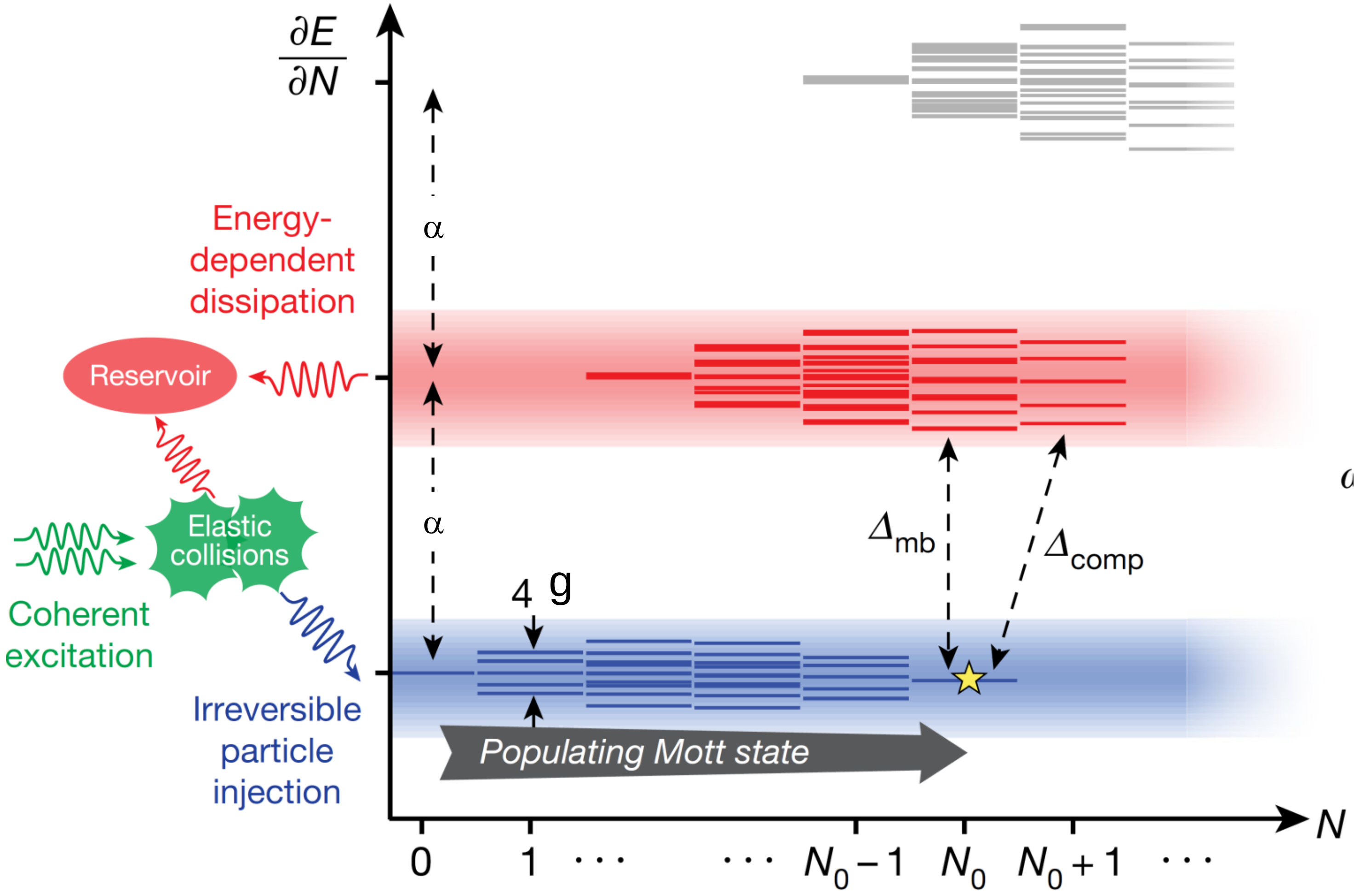




Mott insulator

$$H_{BH} = \sum_{\langle i,j \rangle} g_{i,j} a_i^{\dagger} a_j + \frac{\alpha}{2} \sum_i n_i(n_i - 1) + \sum_i \hbar\omega_p n_i$$

- Incompressible state of N photons
- Many-body Gap allows specific state of the system
- Varying energy in blue or red band due to interaction g
- Mott insulator: Insulator which should be a conductor according to band structure (odd (1) number of photons per lattice site)



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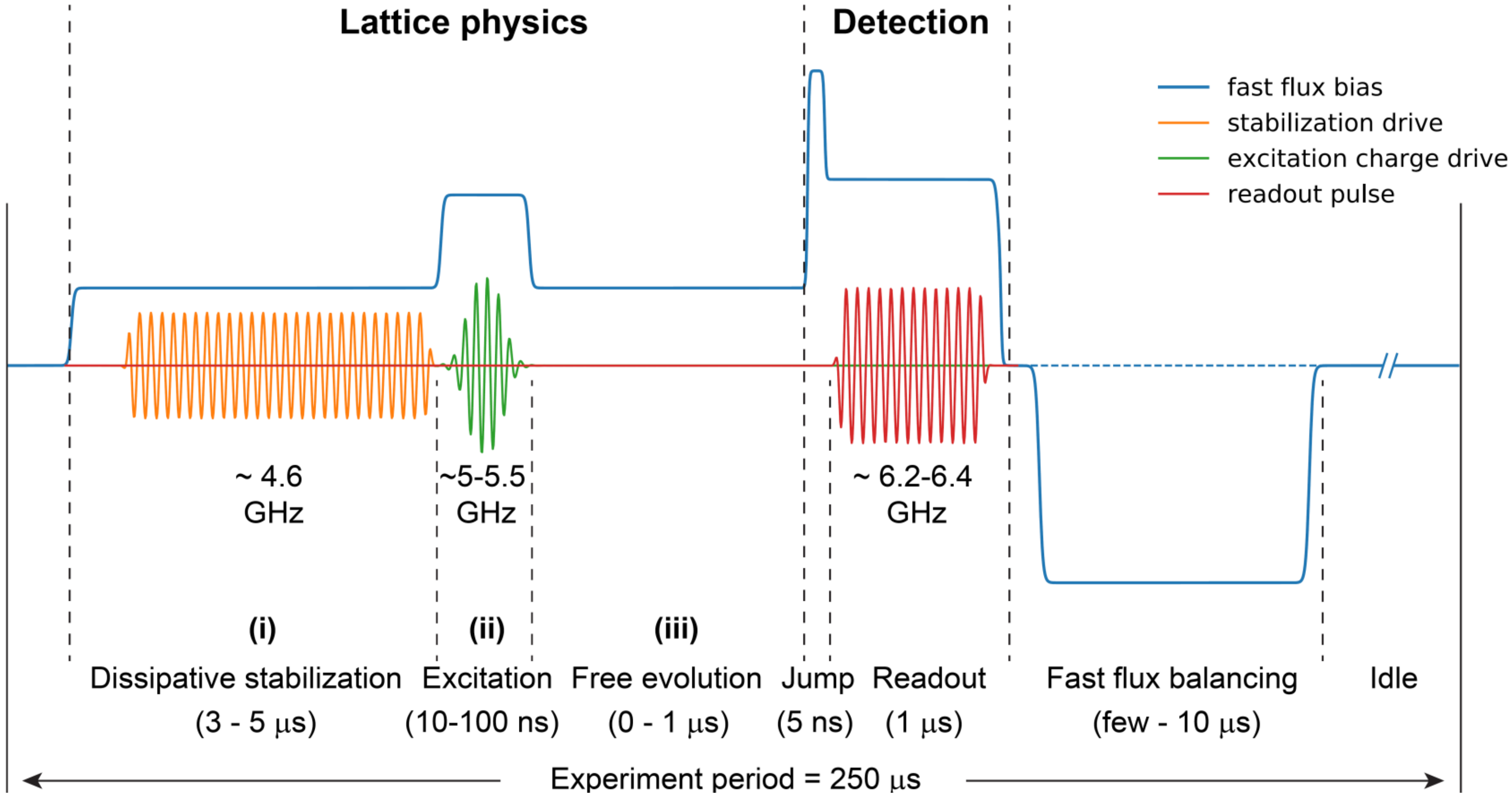
Experimental sequence

- Fast flux bias for ns accuracy tuning
- Detuning to freeze the current state
- Idle: Time before new sequence in order to decay back to the ground state



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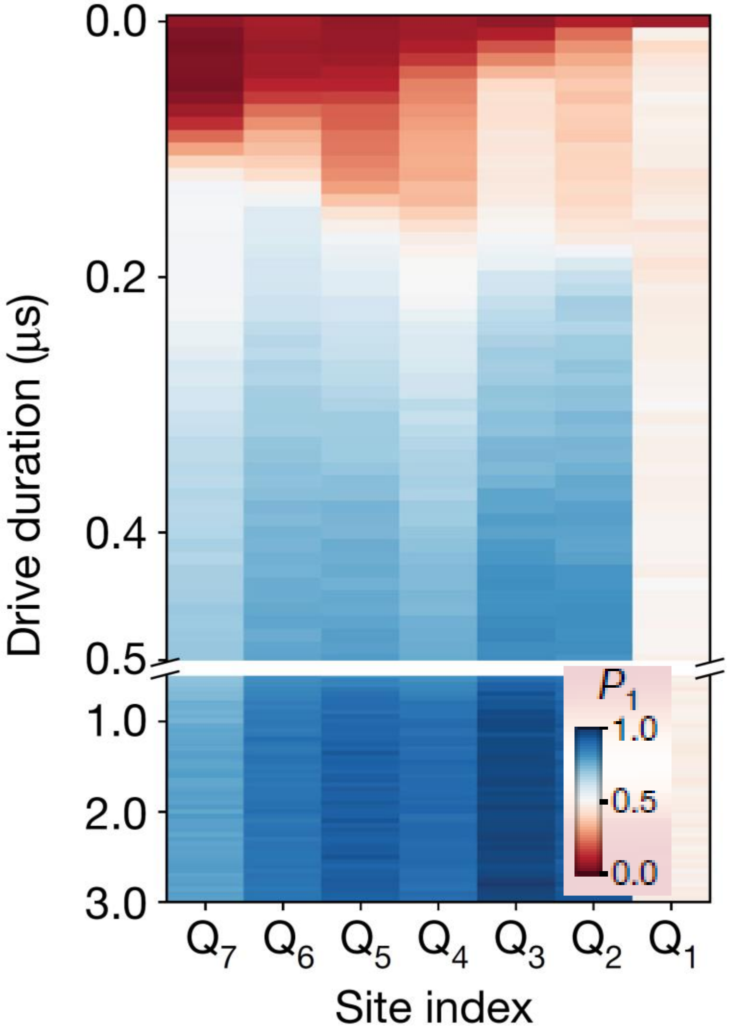
Stabilization and hole dynamics of the lattice



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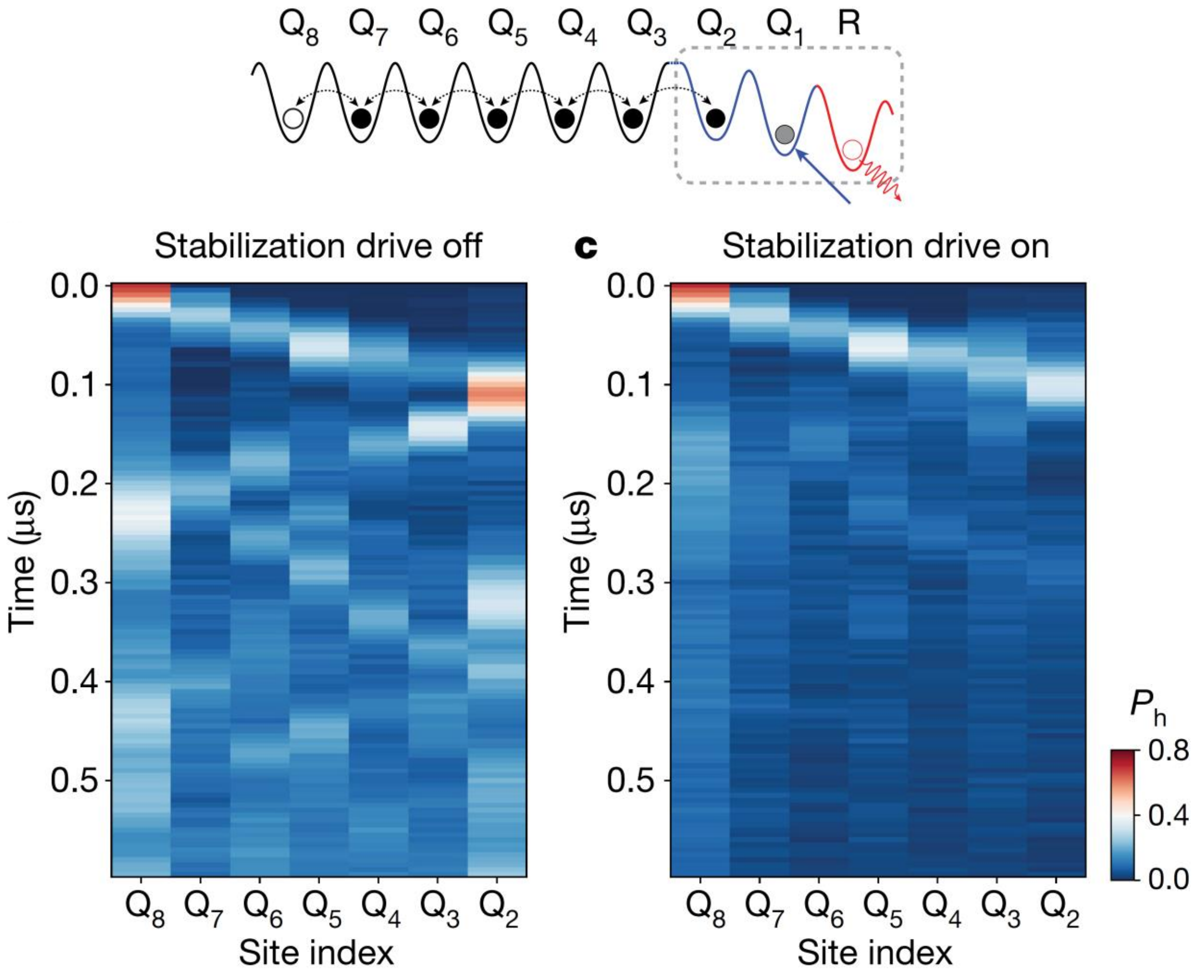

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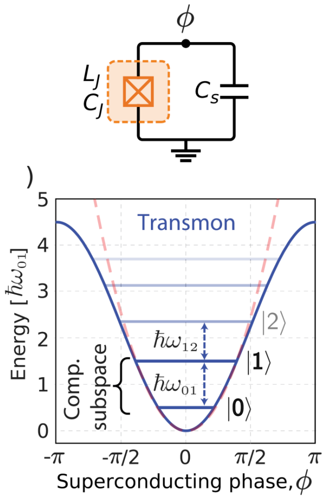
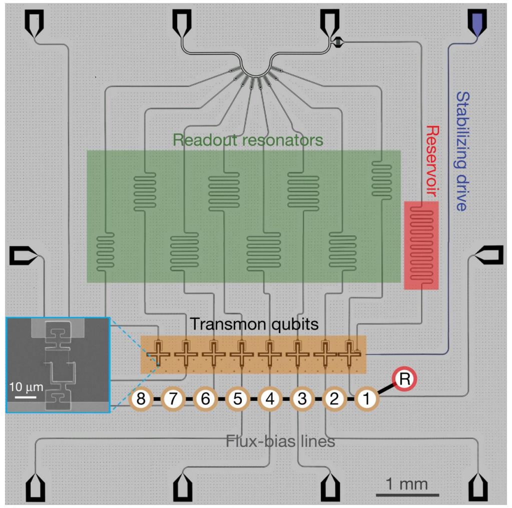
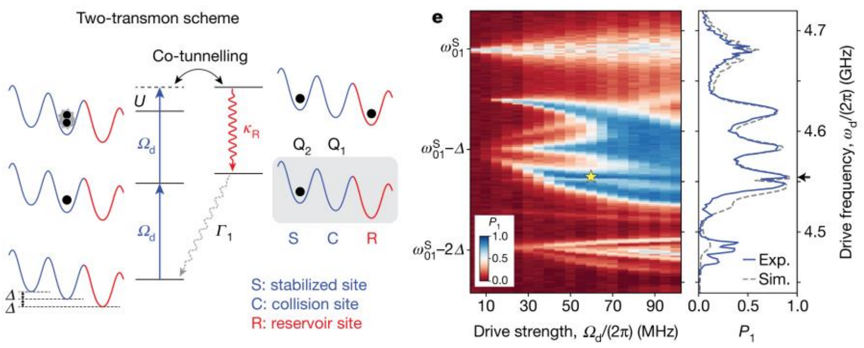
Hole dynamics of the lattice:

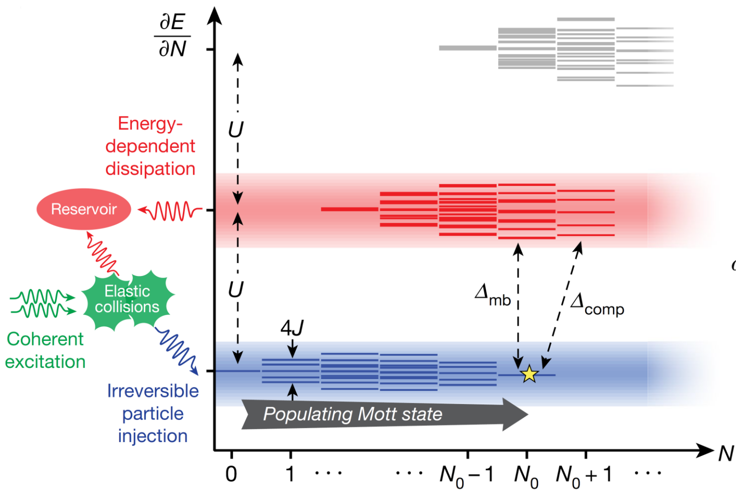
- Q8 is detuned during stabilization
- Tuning Q8 back to resonance shows dynamic hole behaviour

Summary


ϕ
L_J
C_J
C_S
)
Transmon
Energy [$\hbar\omega_{01}$]
5
4
3
2
1
0
$|2\rangle$
$\hbar\omega_{12}$
$|1\rangle$
$\hbar\omega_{01}$
$|0\rangle$
Comp. subspace
-π
-π/2
0
π/2
π
Superconducting phase, ϕ


Readout resonators
Reservoir
Stabilizing drive
Transmon qubits
10 µm
8
7
6
5
4
3
2
1
R
Flux-bias lines
1 mm


Two-transmon scheme
Co-tunnelling
U
Ω_d
Ω_d
κ_R
Γ_1
Δ
Δ
Q_2
Q_1
S
C
R
S: stabilized site
C: collision site
R: reservoir site
e
ω_{01}^S
$\omega_{01}^S-\Delta$
$\omega_{01}^S-2\Delta$
P_1
1.0
0.5
0.0
10
30
50
70
90
Drive strength, $\Omega_d/(2\pi)$ (MHz)
0.0
0.5
1.0
P_1
Exp.
Sim.
4.7
4.6
4.5
Drive frequency, $\omega_d/(2\pi)$ (GHz)


$\frac{\partial E}{\partial N}$
U
U
Energy-dependent dissipation
Reservoir
Elastic collisions
Coherent excitation
Irreversible particle injection
$4J$
Δ_{mb}
Δ_{comp}
Populating Mott state
0
1
N_0-1
N_0
N_0+1
N

References

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