Departments of Physics
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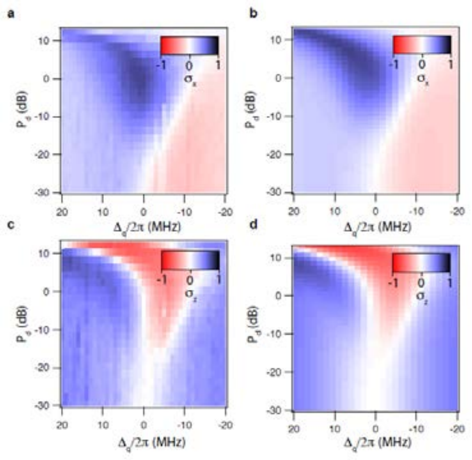
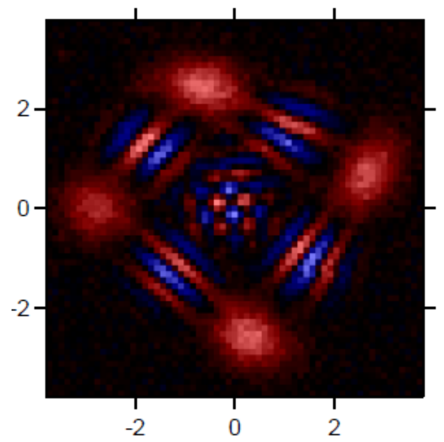




Quantum Reservoir Engineering

Towards Quantum Simulators with Superconducting Qubits

SMG
Claudia De Grandi
(Yale University)
Siddiqi Group
(Berkeley)

Noise and Dissipation: Friend or Foe?

Clerk et al. *Rev. Mod. Phys.* **82**, 1155 (2010)

Challenge: Quantum state control in the presence of noise and dissipation

How do we correct <u>non</u>-unitary errors?

$$\rho' = \sum_j E_j \rho E_j^\dagger; \qquad \sum_j E_j^\dagger E_j = I$$

Challenge: Quantum state control in the presence of noise and dissipation

How do we correct non-unitary errors?

$$\rho' = \sum_j E_j \rho E_j^\dagger; \qquad \sum_j E_j^\dagger E_j = I$$

'Active' feedback: classical measurement result fed back to controller which applies a unitary that is conditioned on measurement result.

Challenge: Quantum state control in the presence of noise and dissipation

How do we correct non-unitary errors?

$$\rho' = \sum_j E_j \rho E_j^\dagger; \qquad \sum_j E_j^\dagger E_j = I$$

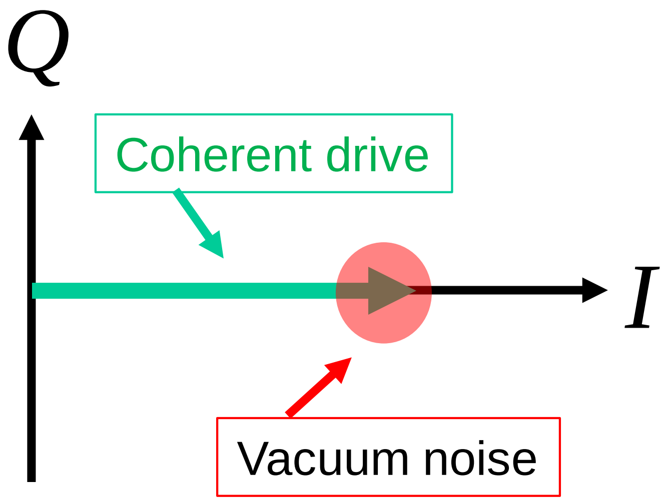
'Autonomous' feedback: embedded into the system as a quantum 'bath'

Paradox:
We can use dissipation as a tool to create and maintain coherence. (Poyatos et al. PRL 1996)

Interference between coherent drives and quantum noise of bath can be useful.

(Murch et al. PRL 2012)

Example: Photon shot noise in a driven damped cavity



Interference leads to amplitude fluctuations

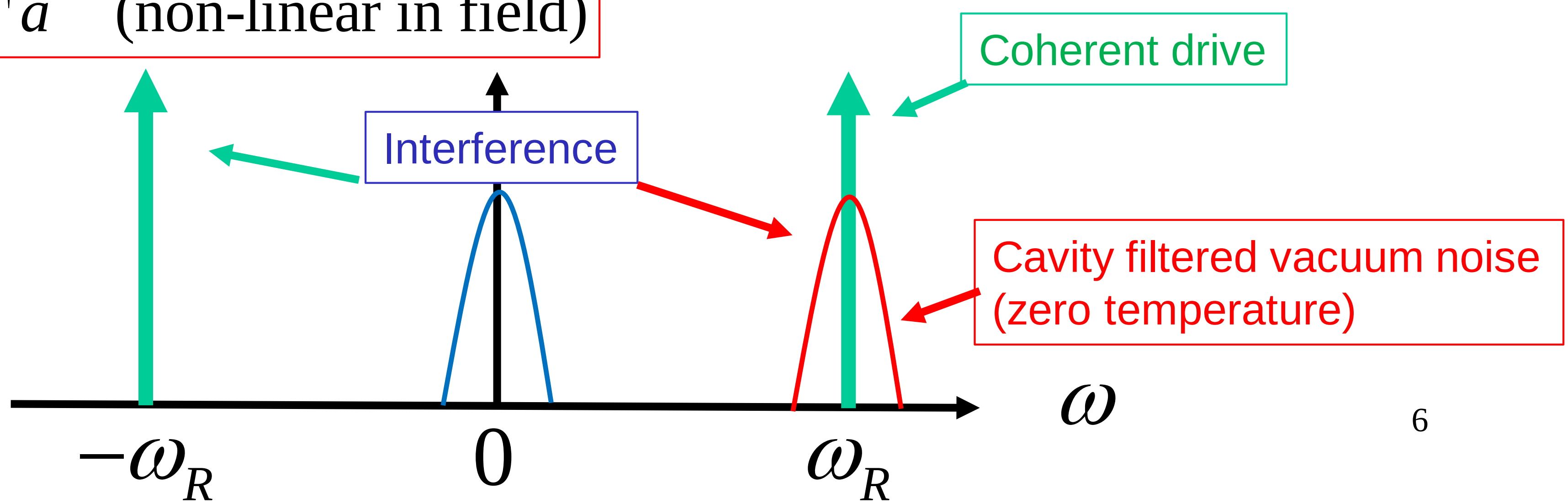
$$\left\langle (\hat{n}-\bar{n})^2 \right\rangle^{1/2} = \bar{n}^{1/2}$$

'Rectification of vacuum noise'

$$\left\langle \hat{n}(t)\hat{n}(0) \right\rangle = \bar{n}^2 + \bar{n}\, e^{-\frac{\kappa}{2}|t|}$$

Nota Bene

$\hat{n} = a^\dagger a$ (non-linear in field)



Example: Photon shot noise in a driven damped cavity

'Rectification of vacuum noise' when drive is **red detuned** from cavity

Spectral density of shot noise moves up to positive frequencies

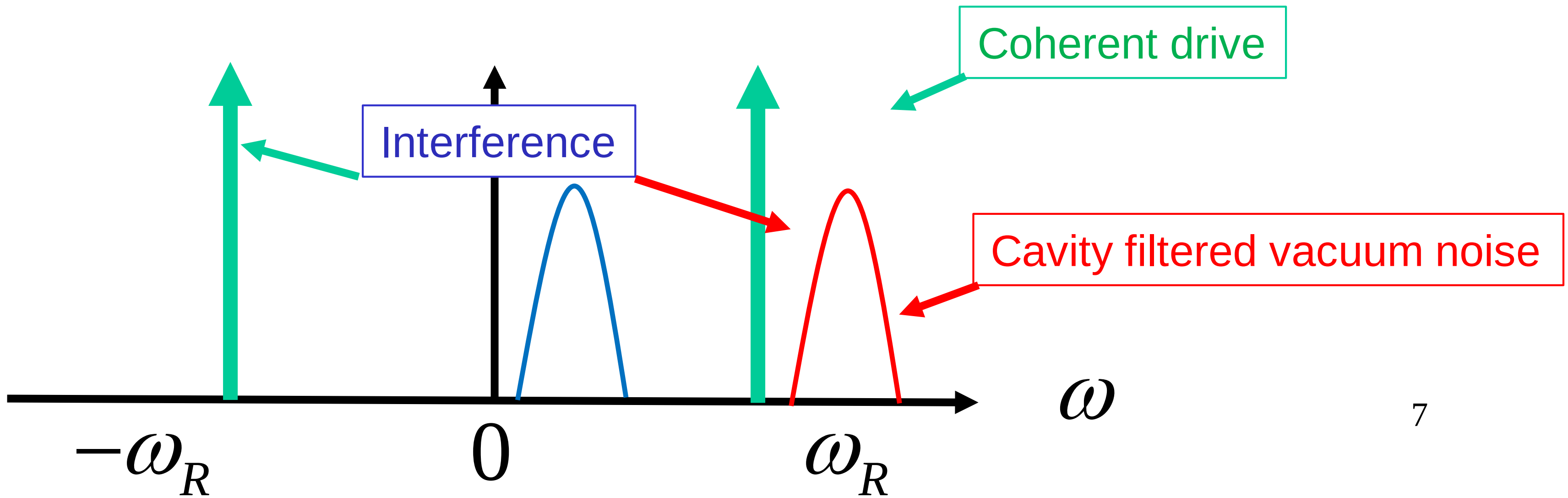
Bath can absorb energy (by Raman scattering of pump photon up to cavity)

Bath cannot emit energy

$$V = \chi \, O_{\text{system}} \, (\hat{n} - \bar{n})$$

shot noise

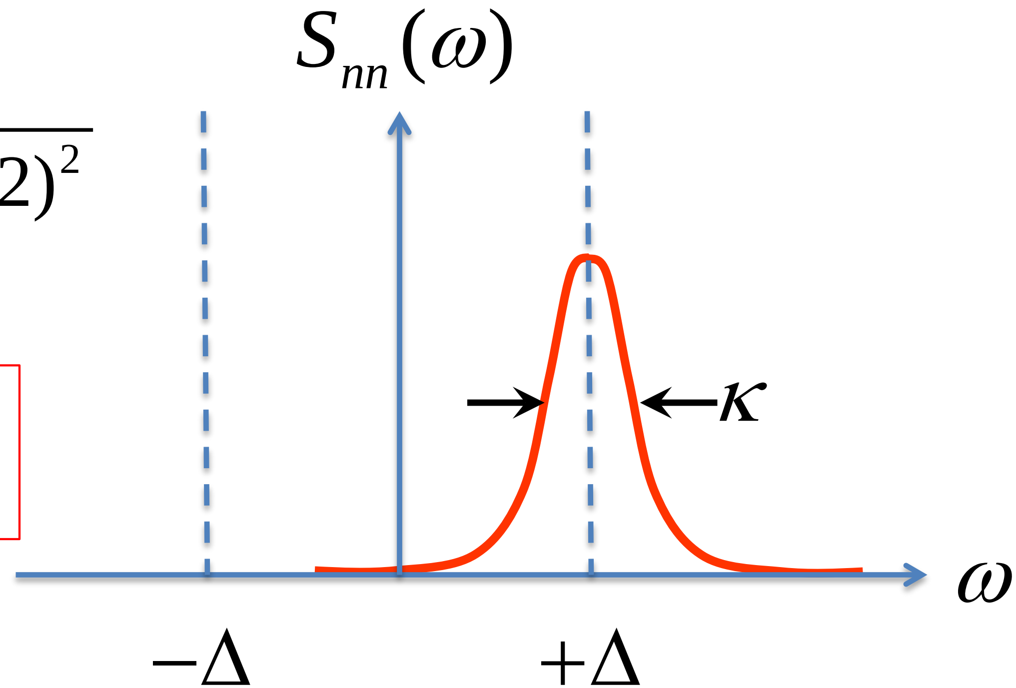
Cooling!



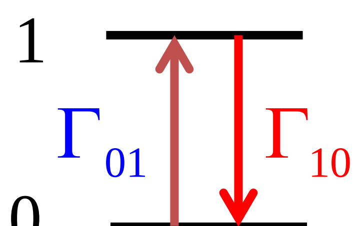
Shot noise spectral density for drive red-detuned by distance Δ

Clerk et al. *Rev. Mod. Phys.* **82**, 1155 (2010)

$$S_{nn}(\omega) = \bar{n}\frac{\kappa}{(\omega-\Delta)^2+(\kappa/2)^2}$$



Quantum shot noise spectral density is ASYMMETRIC



$\Gamma_{10} = \chi^2 S_{nn}(+\Delta)$ bath absorbs

$\Gamma_{01} = \chi^2 S_{nn}(-\Delta)$ bath emits

Fermi Golden Rule Picture: Clerk et al. *Rev. Mod. Phys.* **82**, 1155 (2010)

Autonomous Feedback: Quantum Reservoir Engineering

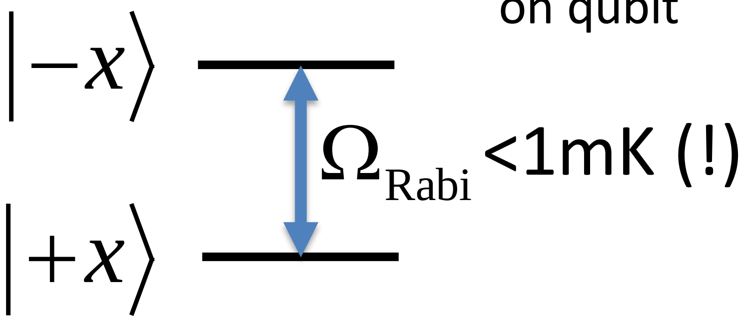
We can use photon shot noise to 'cool' a qubit to any point on the Bloch sphere, e.g. $|+x\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right)$

$$H = -\Omega_{\text{Rabi}}\,\sigma^X + \chi\,\sigma^Z\,(\hat{n} - \bar{n})$$

Rabi drive on qubit

dispersive coupling

shot noise of driven cavity



Dissipator 'cools' qubit via jump operator:

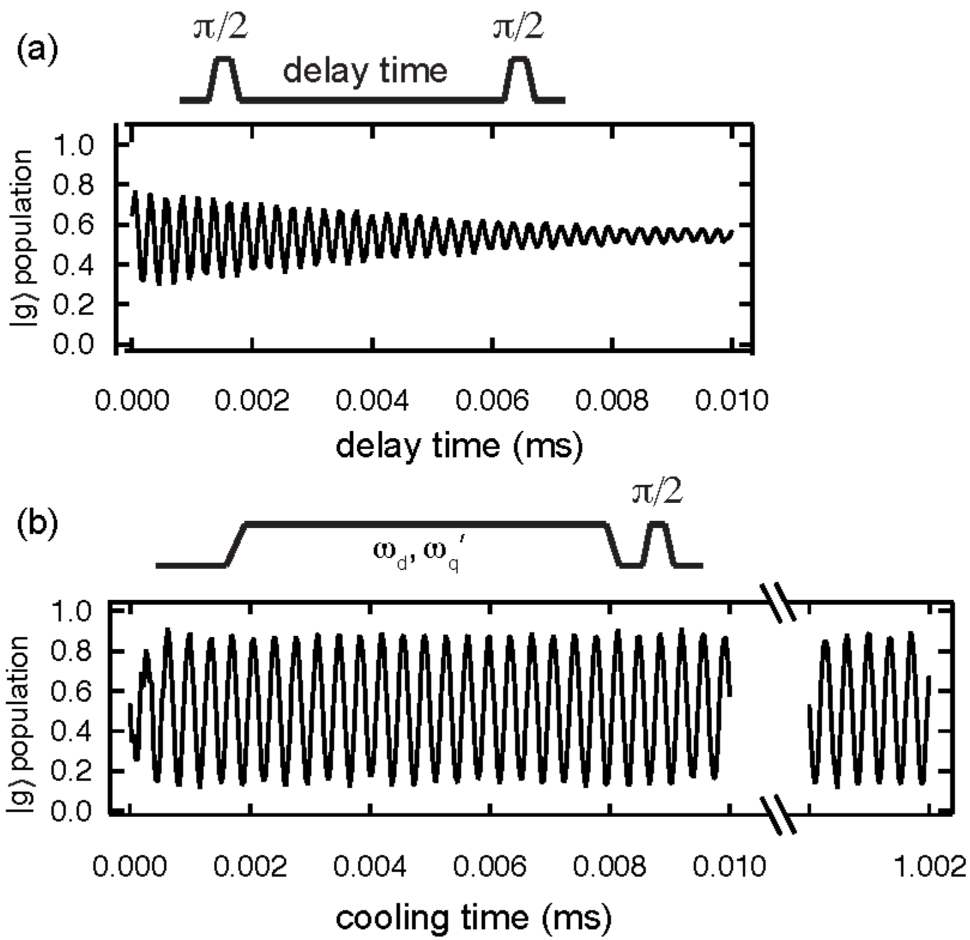
$$c = |+x\rangle\langle -x|$$

'Cavity-assisted quantum bath engineering'
(*Phys. Rev. Lett.* 2012)

Berkeley: K. W. Murch, S. J. Weber, I. Siddiqi
Yale: U. Vool, D. Zhou, SMG

Two qubit entanglement:
S. Shankar et al. (Devoret)
Nature (2013).

Quantum Reservoir Engineering to create persistent Ramsey fringes



Dissipator 'cools' qubit via jump operator:

$$c = \left|+x\right\rangle\left\langle -x\right|$$

$$T_{\text{eff}} \sim 150\,\mu\text{K}$$

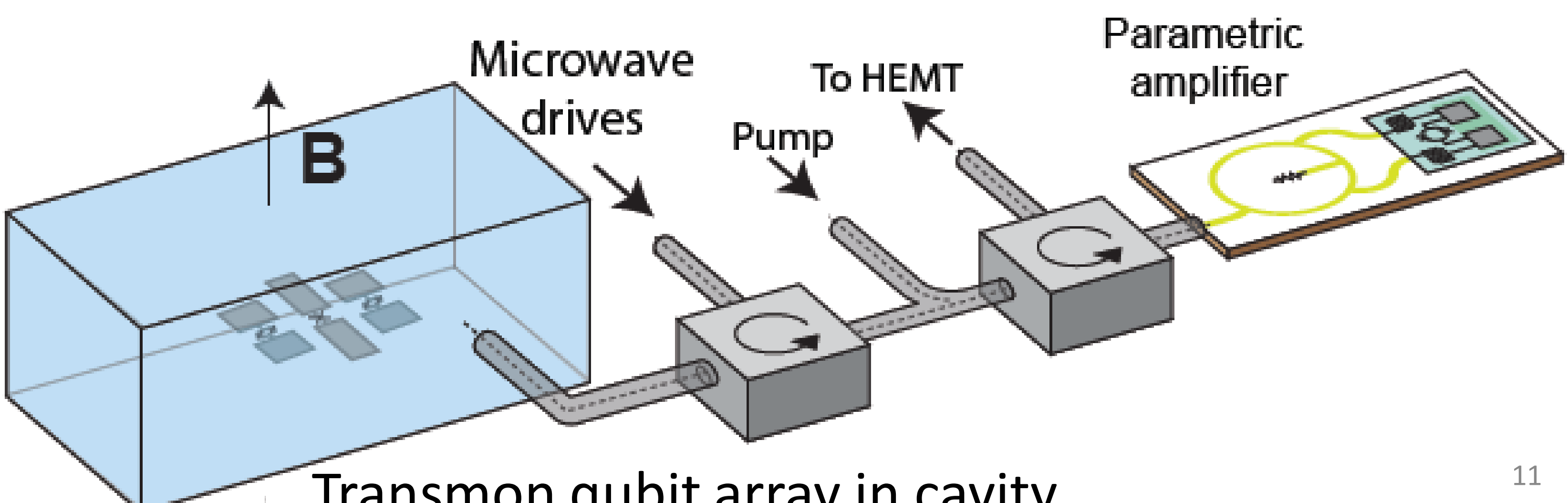
Persistent Ramsey fringes (with enhanced visibility)

Murch et al. PRL (2012)

Canonical Ensemble Quantum Simulator for 1D Bose-Hubbard Model

<u>Berkeley</u>:
Shay Hacohen-Gourgy
Vinay Ramasesh
Irfan Siddiqi

<u>Yale</u>:
Claudia De Grandi
SMG



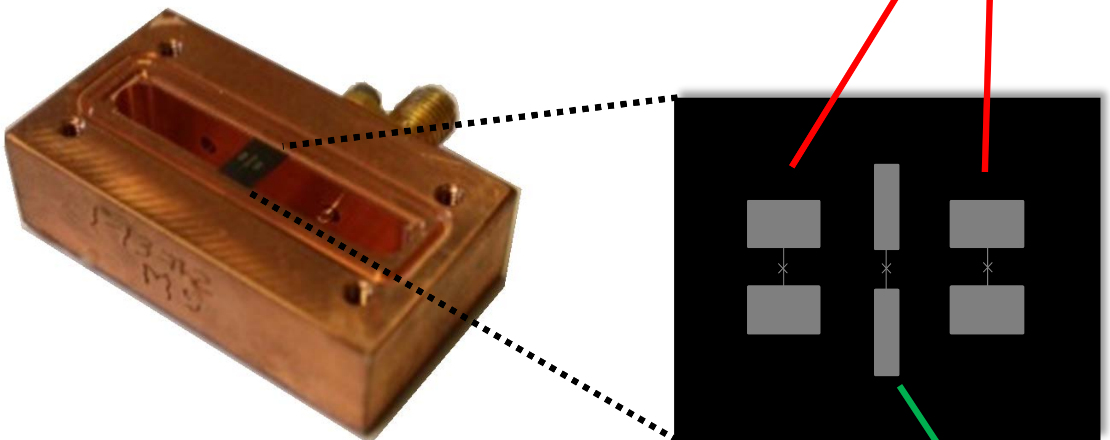
Transmon qubit array in cavity

End qubits flux-tunable (SQUIDs)

$\omega_L = 2\pi \times 5.058$ GHz

$\omega_R = 2\pi \times 5.161$ GHz

$\alpha_L = \alpha_R = -2\pi \times 214$ MHz



Middle qubit fixed (single-junction)

$\omega_M = 2\pi \times 4.856$ GHz

$\alpha_M = -2\pi \times 240$ MHz

Cavity

$\omega_M = 2\pi \times 7.116$ GHz

$\kappa = 2\pi \times 10$ MHz

Couplings

$g_1 = 2\pi \times 0.149$ GHz

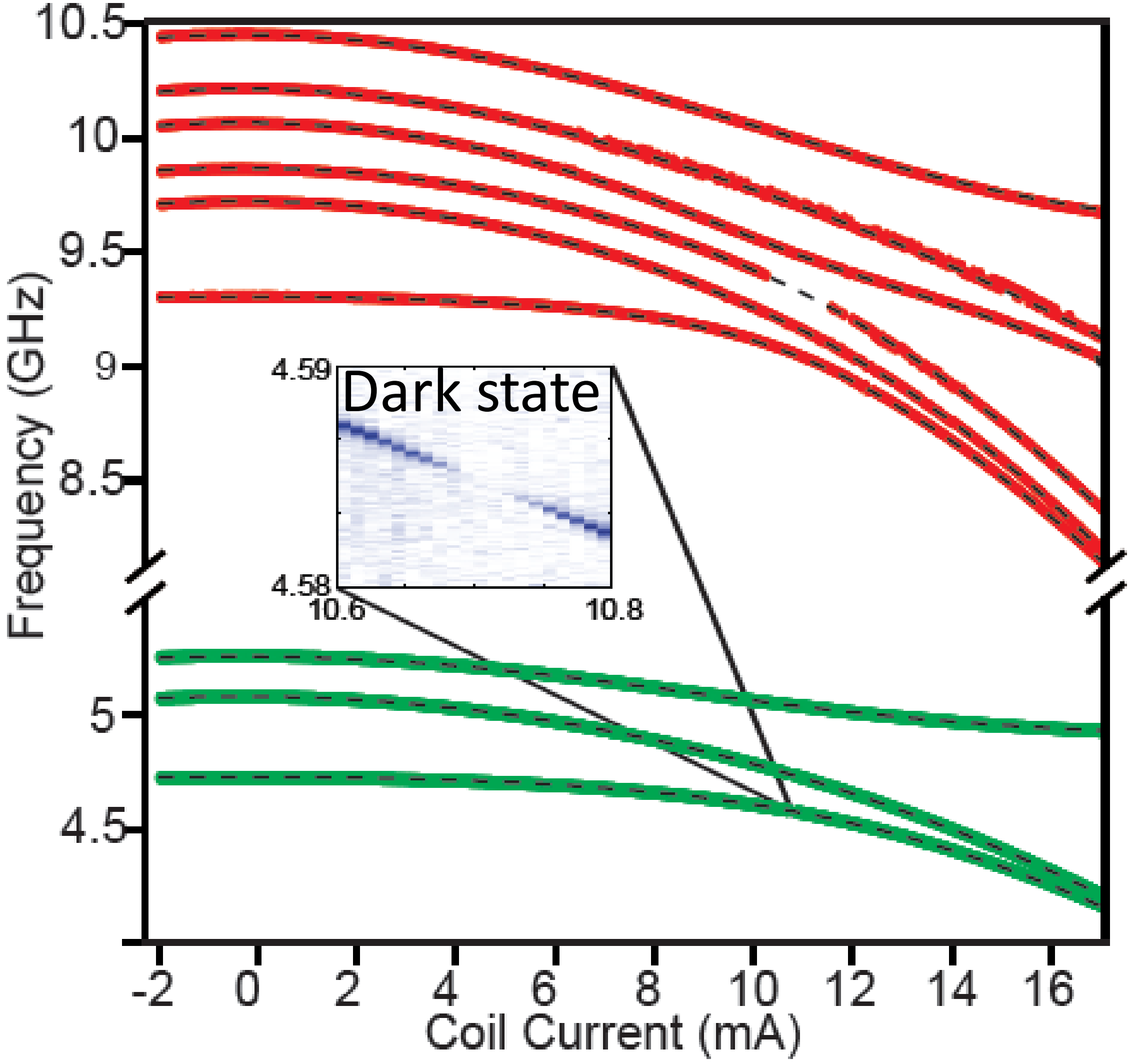
$g_2 = 2\pi \times 0.264$ GHz

$g_3 = 2\pi \times 0.145$ GHz

$J_{12}, J_{23} = 2\pi \times 0.177$ GHz

$J_{13} = 2\pi \times 0.026$ GHz

First 9 excited levels of three-transmon array



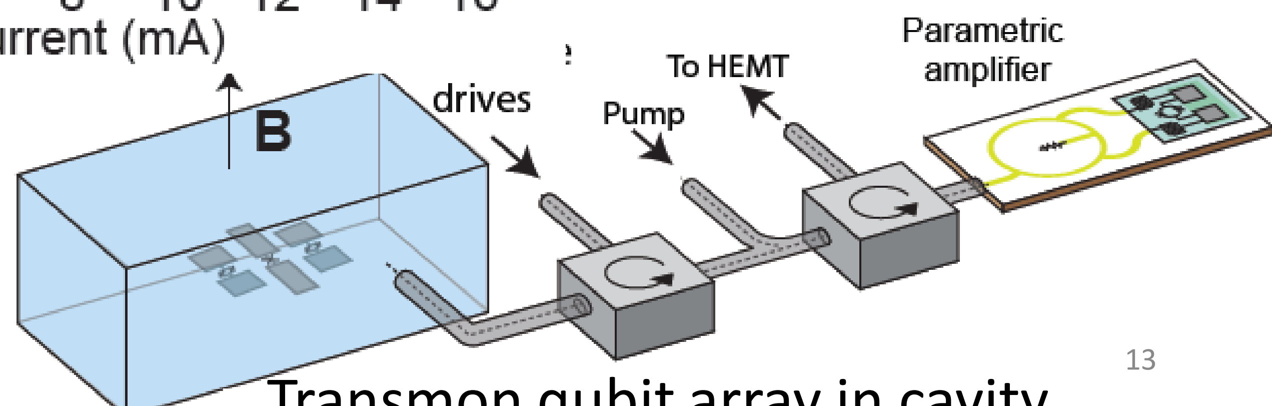
F — 2 boson manifold

E — 1 boson manifold

------ Theory fit

$J \sim 180\text{MHz}$

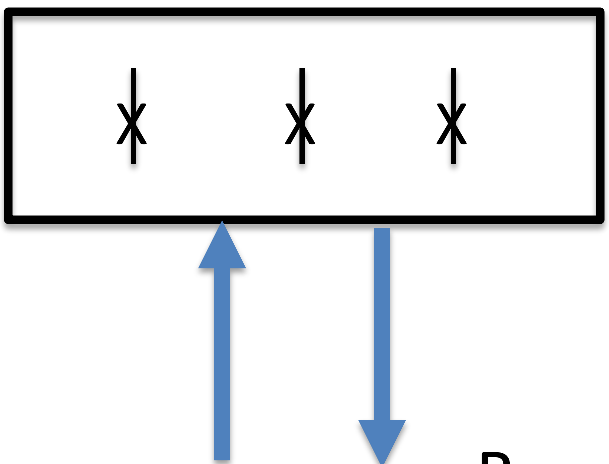
$\alpha \sim 240\text{MHz}$



Transmon qubit array in cavity

Canonical Ensemble Quantum Simulator for 1D Bose-Hubbard Model

Engineer bath to remove entropy and energy but <u>not</u> bosons!
[cf. Jake Taylor 'Chemical Potential for Light']



$$\left[H_0, \sum_j b_j^\dagger b_j\right] = 0$$

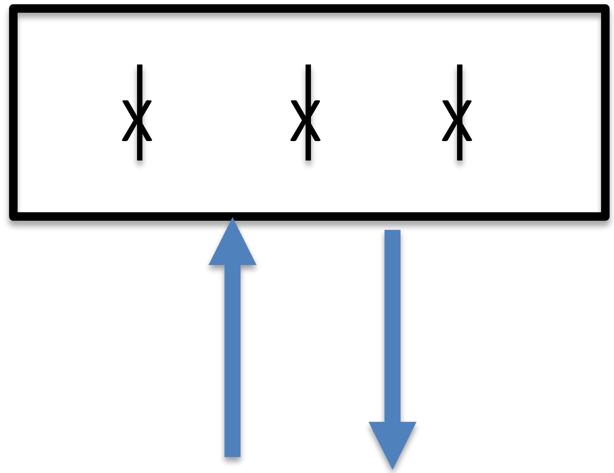
Bose-Hubbard Model

$$H_0 = \sum_j \omega_j b_j^\dagger b_j + \sum_{jk} J_{jk} b_j^\dagger b_k - \frac{1}{2}\sum_j \alpha_j b_j^\dagger b_j^\dagger b_j b_j$$

site energy

boson hopping
(dipole coupling)

Hubbard U<0



Couple Bose-Hubbard lattice to cavity photons to create dissipation

$$H_0 = \omega_Q a^\dagger a + \sum_j \omega_j b_j^\dagger b_j + \sum_{jk} J_{jk} b_j^\dagger b_k + g_j (a b_j^\dagger + a^\dagger b_j)$$

$$V = -\frac{1}{2} \sum_j \alpha_j b_j^\dagger b_j^\dagger b_j b_j$$

N.B. $\left[H_0, \sum_j b_j^\dagger b_j \right] \neq 0$

Diagonalize Quadratic H_0

$$H_0 = \omega_Q a^\dagger a + \sum_j \omega_j b_j^\dagger b_j + \sum_{jk} J_{jk} b_j^\dagger b_k + g_j (a b_j^\dagger + a^\dagger b_j)$$

$$a = \Lambda_{00} A + \sum_j \Lambda_{0j} B_j$$

$$b_k = \Lambda_{k0} A + \sum_j \Lambda_{kj} B_j$$

$$H_0 = \tilde{\omega}_Q A^\dagger A + \sum_j \tilde{\omega}_j B_j^\dagger B_j$$

$$H_0 = \tilde{\omega}_Q A^\dagger A + \sum_j \tilde{\omega}_j B_j^\dagger B_j$$

Quartic Term becomes (in RWA):

$$V = -\frac{1}{2}\sum_j \alpha_j b_j^\dagger b_j^\dagger b_j b_j$$

$$V \sim -\sum_{ijkl} \alpha_{ijkl} B_i^\dagger B_j^\dagger B_k B_l + A^\dagger A \sum_{ij} \chi_{ij} B_i^\dagger B_j + \chi_0 A^\dagger A^\dagger A A + \ldots$$

Normal modes scatter due to Hubbard interactions

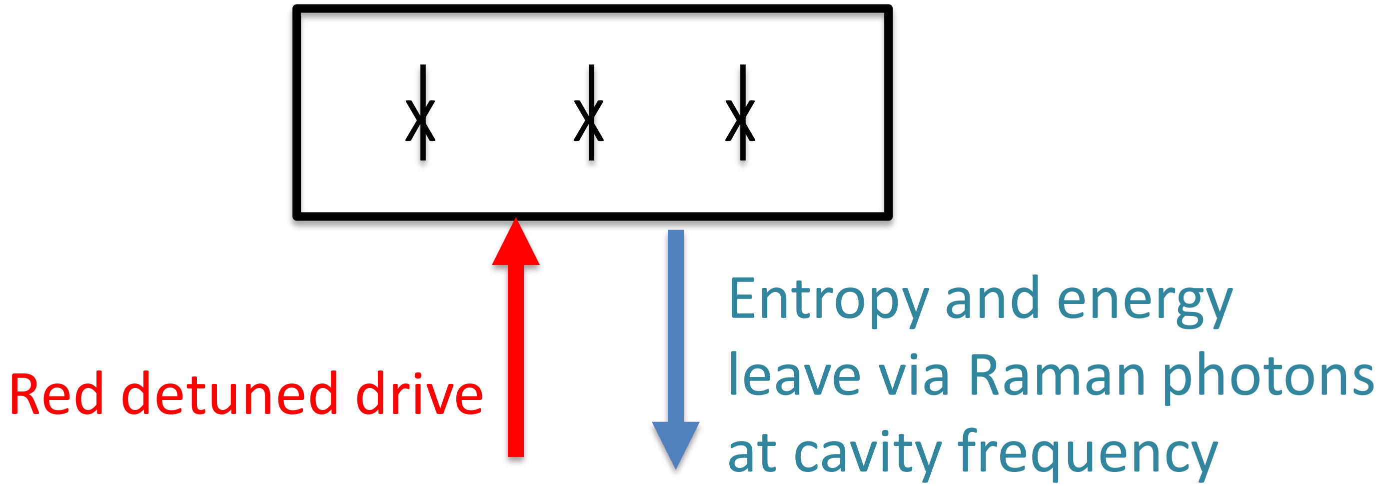
Dispersive coupling of (dressed) cavity to normal modes

Small cavity self-Kerr

$$\left[H_0 + V, \sum_j B_j^\dagger B_j \right] = 0^*$$

(Fine print re. Purcell effect)

Quantum Bath Engineering for 1D Bose-Hubbard Model



$$A^\dagger A \sum_{ij} \chi_{ij} B_i^\dagger B_j = \hat{n} \sum_{ij} \chi_{ij} B_i^\dagger B_j$$

Shot noise fluctuations cause cooling transitions which conserve particle number.

$$A^\dagger A \sum_{ij} \chi_{ij} B_i^\dagger B_j = \hat{n} \sum_{ij} \chi_{ij} B_i^\dagger B_j$$

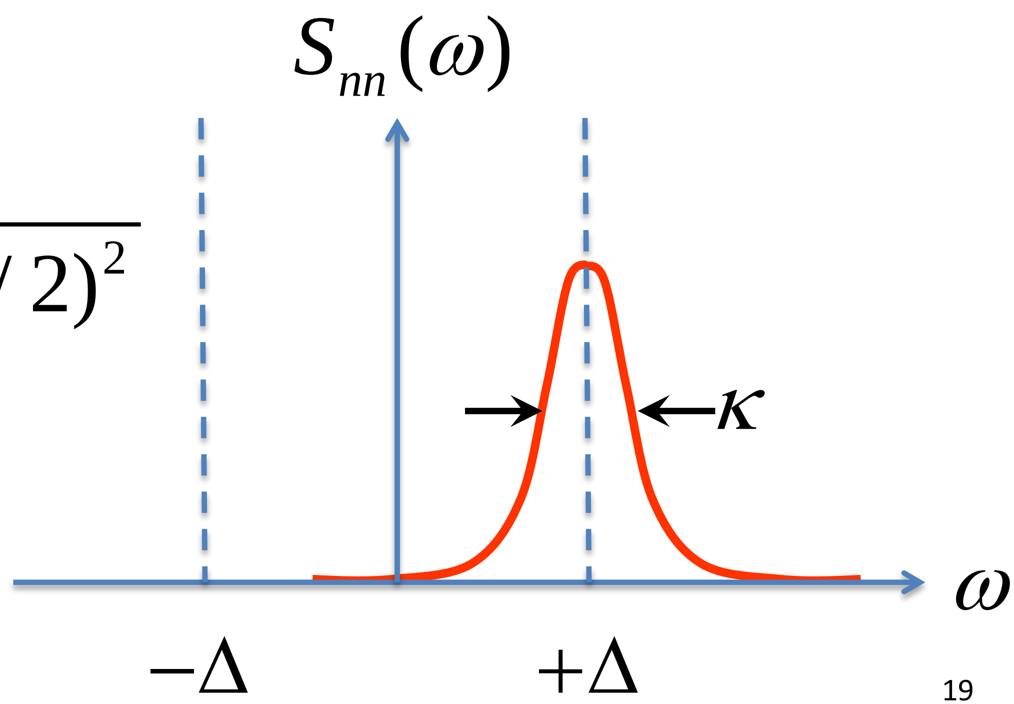
Shot noise fluctuations cause cooling transitions which conserve particle number.

Fermi Golden Rule cooling rate

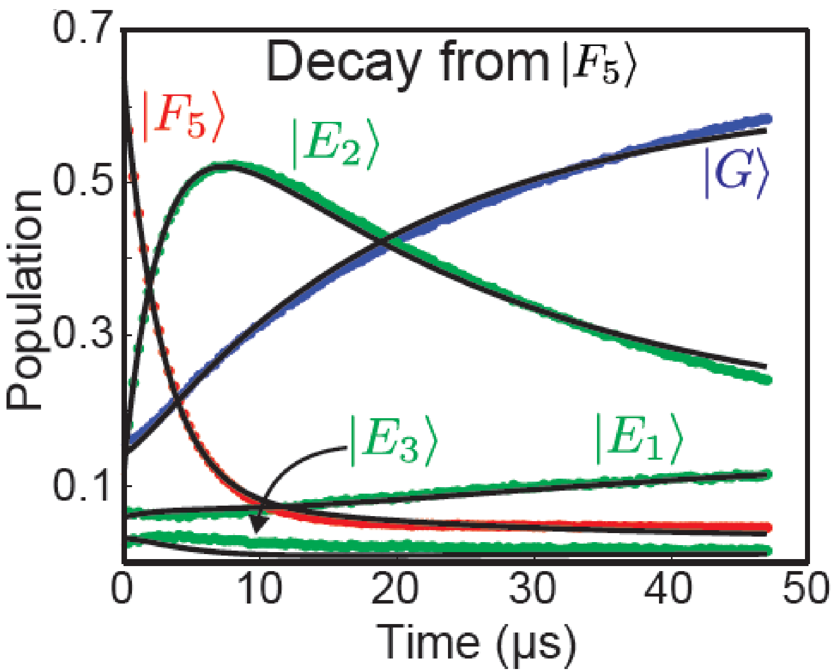
$$\Gamma_{1\to 2} = \left| \left\langle \Psi_2 \right| \sum_{ij} \chi_{ij} B_i^\dagger B_j \left| \Psi_1 \right\rangle \right|^2 S_{nn}(\omega_1 - \omega_2)$$

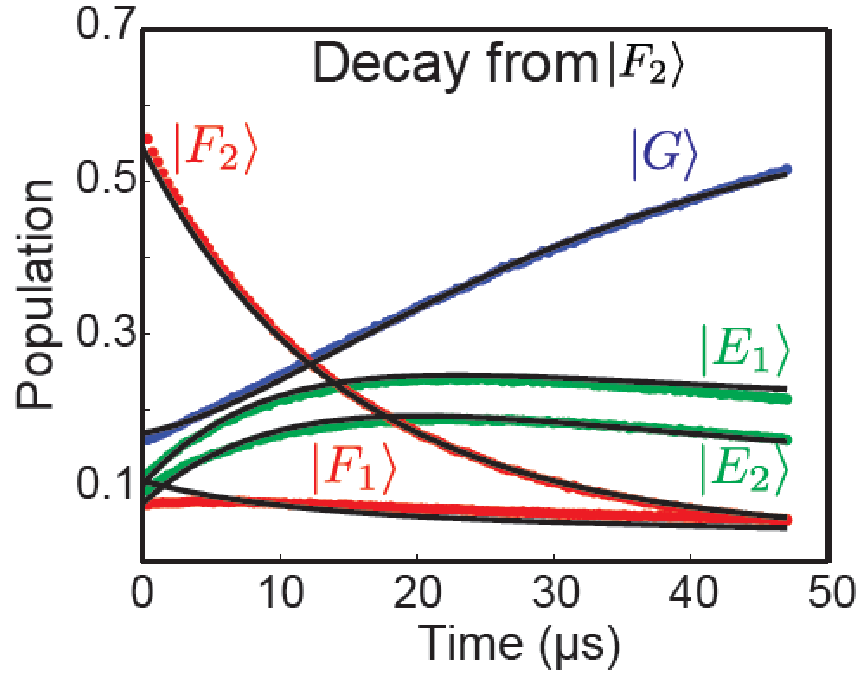
$$S_{nn}(\omega) = \bar{n} \frac{\kappa}{(\omega - \Delta)^2 + (\kappa/2)^2}$$

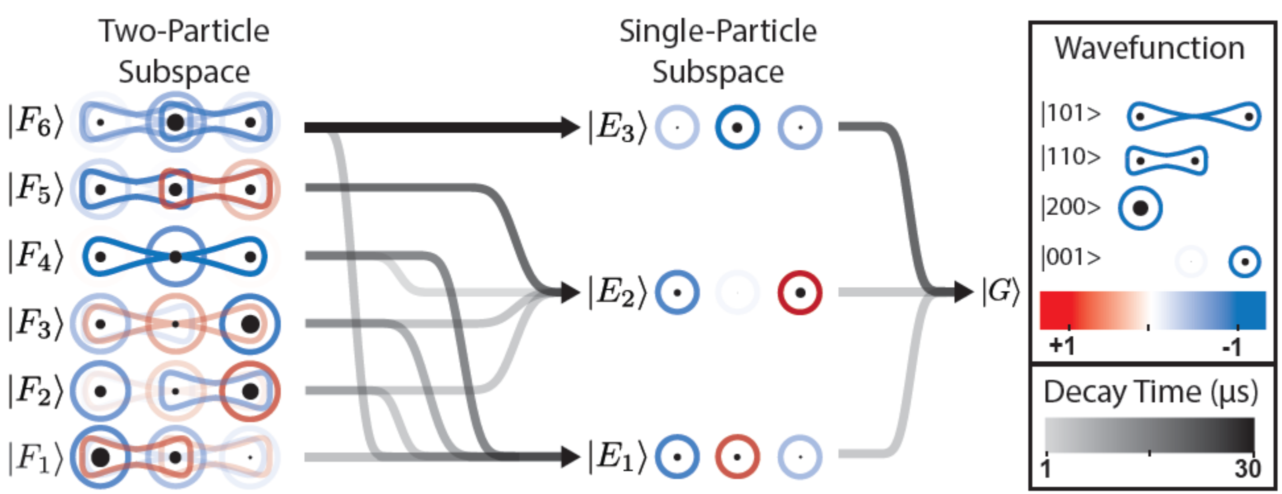
Drive detuning



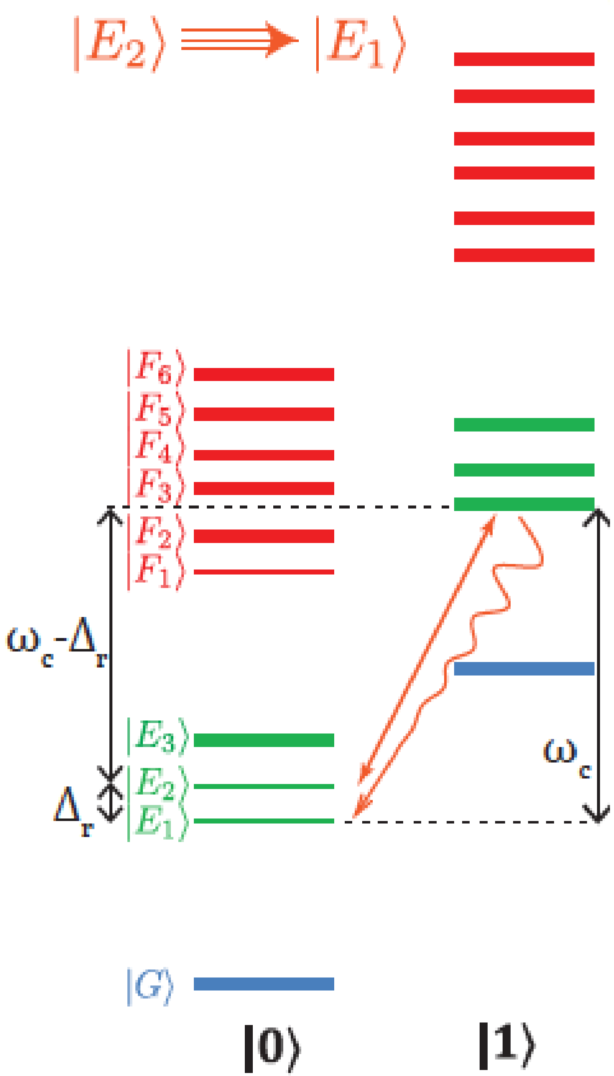
NATURAL DECAY DYNAMICS

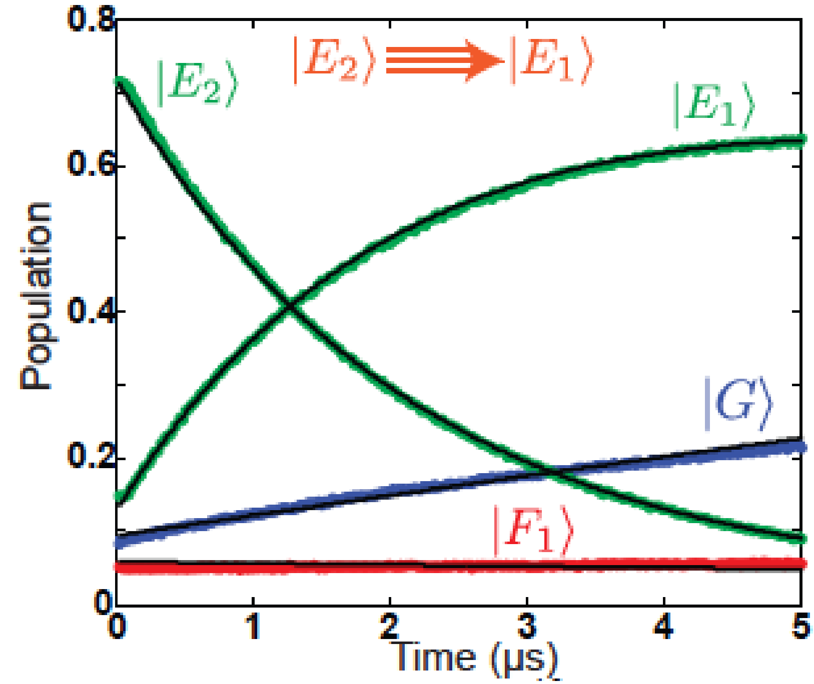






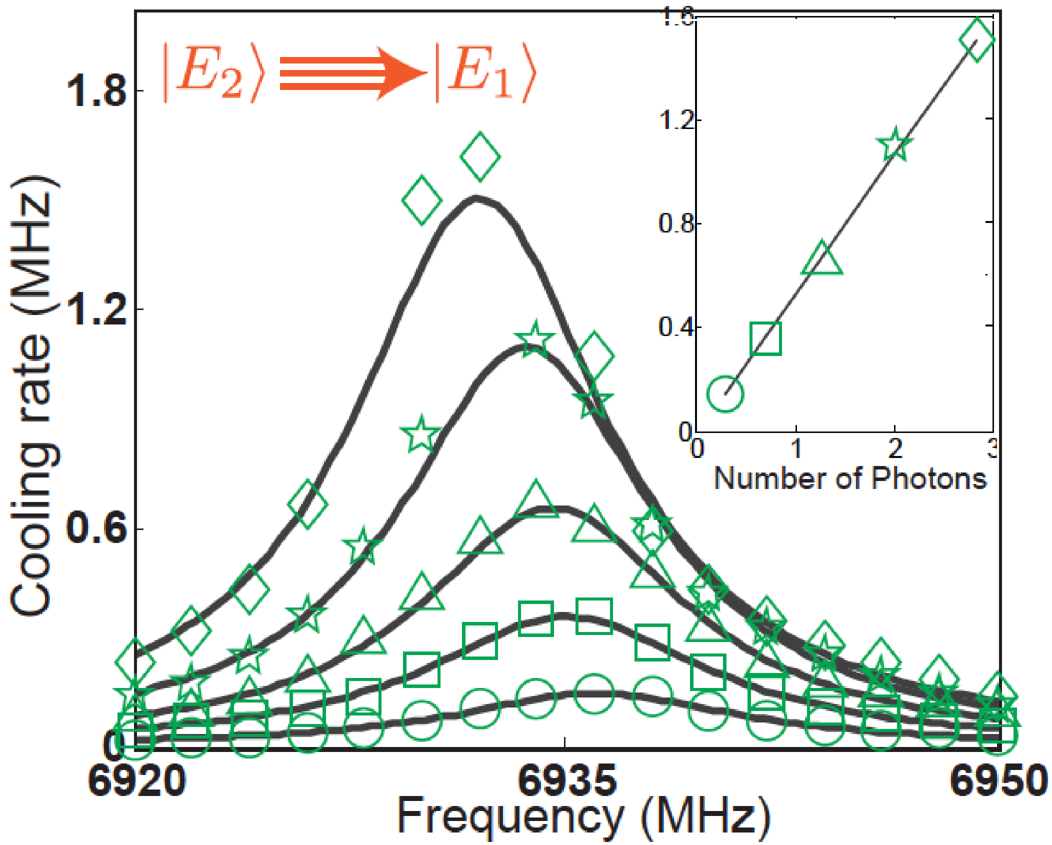
COOLING

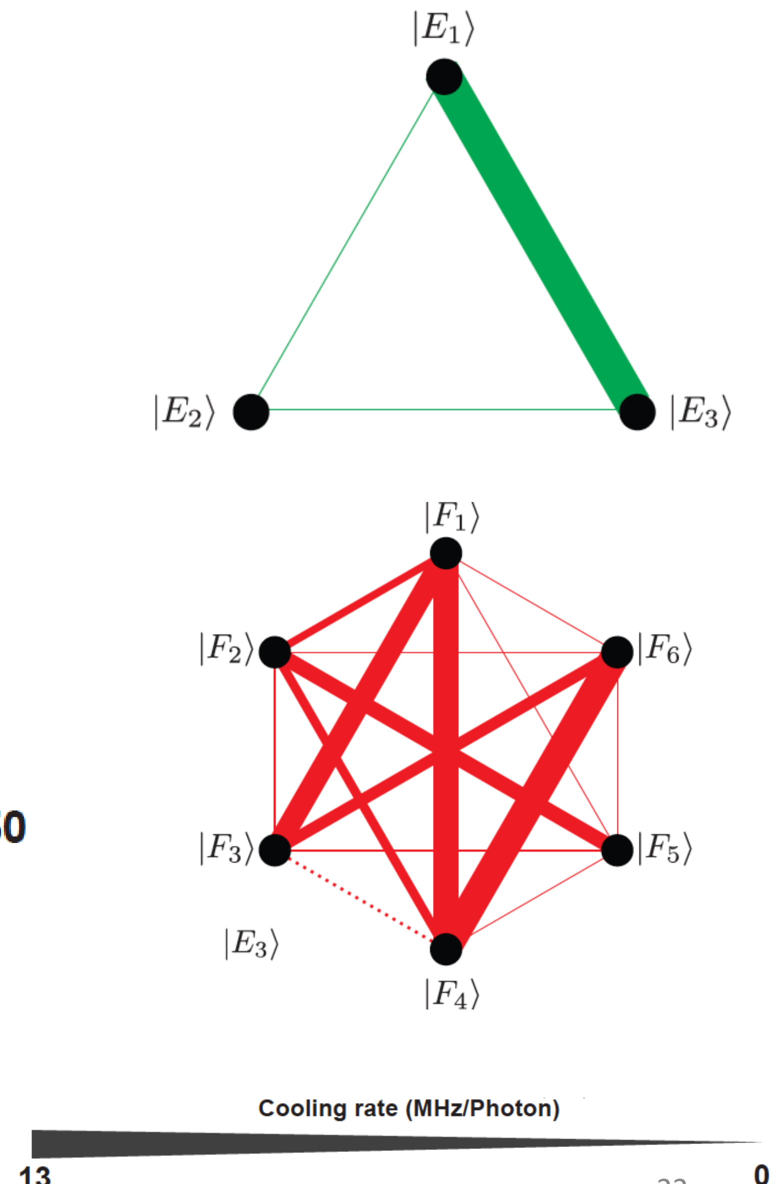




- Coherent drives transfer excitations between subspaces
- Cooling drives transfer excitations within a subspace
- **ACCESS DARK STATES**

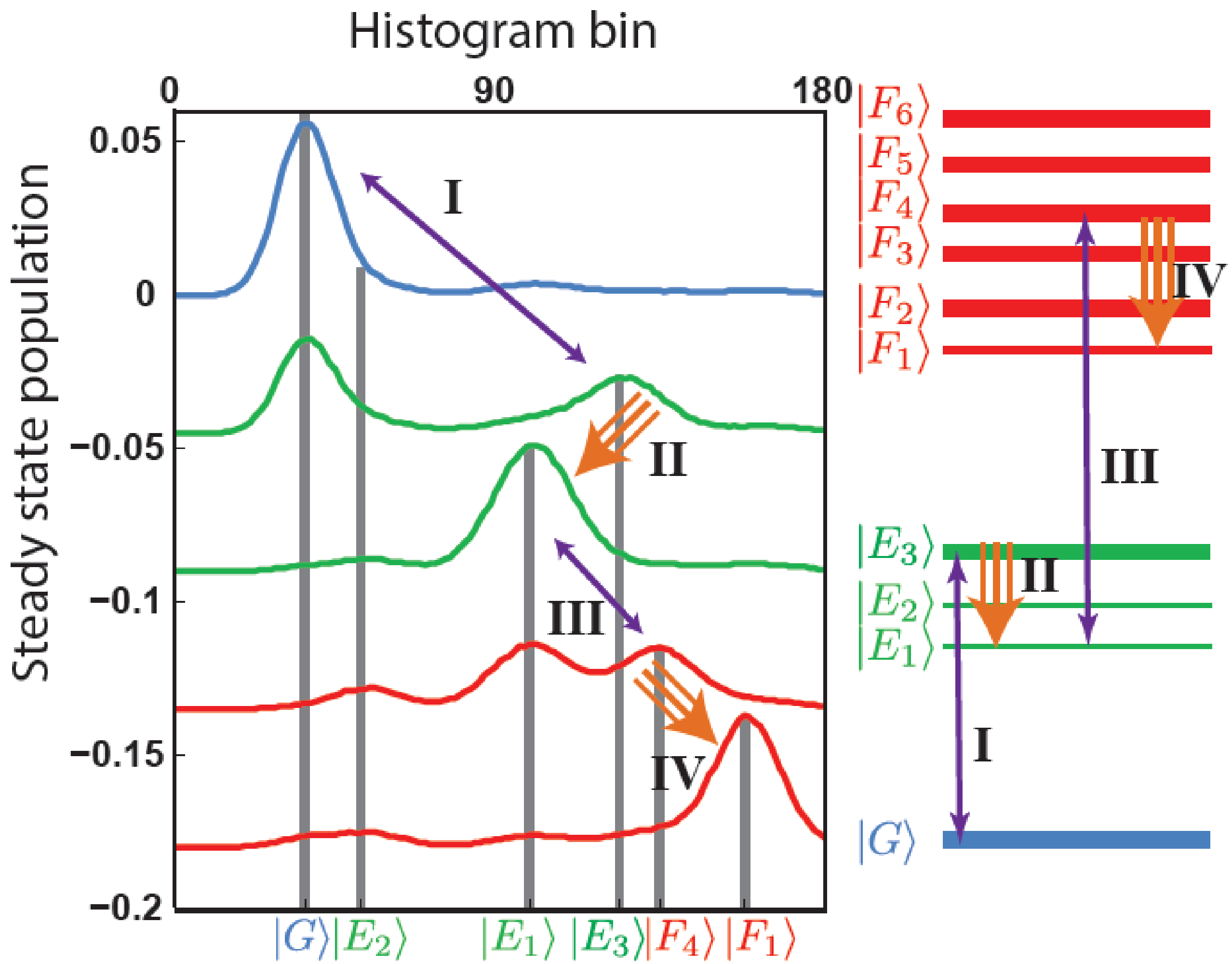
COOLING RATES





$$R_{i\to f} = 4\alpha^2\bar{n}|M_{if}|^2\frac{\kappa}{(\Delta E_{if}-\Delta_r)^2+(\kappa/2)^2}$$

STATE STABILIZATION: |F$_1$>



- Can stabilize any many-body eigenstate
- Preserves particle number in Bose-Hubbard Model

PERSPECTIVES

- STATE SYMMETRY CAN FACILITATE COOLING/QBE
- COOLING OF QUBIT CHAINS
  - PREPARE & HOLD N-BODY EIGENSTATE (EG. RESET)
  - DISSIPATIVE BOSE-HUBBARD PHYSICS
  - ACCESS DARK STATES
  - ENERGY FLOW / THERMODYNAMICS
  - QUANTUM EMULATION IN LONG-CHAINS / ARRAYS
- FOR FUTURE QUANTUM SIMULATOR NEED:
  - ABILITY TO MEASURE LOCAL QUBIT CORRELATORS IN MANY-BODY STATE

EXTRA SLIDES BEYOND HERE

Dissipation and decoherence are caused by coupling to quantum and thermal noise of the surrounding reservoir.

Example: $$H = \frac{\omega_{\mathrm{q}}}{2}\sigma^z + \hat{F}(t)\sigma^x$$

Classically the noise correlator is real: $$G_{FF}(t) \equiv \left\langle \hat{F}(t)\hat{F}(0) \right\rangle$$

and hence its spectral density $$S_{FF}(\omega) \equiv \int dt\, e^{i\omega t} \left\langle \hat{F}(t)\hat{F}(0) \right\rangle$$

is symmetric in frequency: $$S_{FF}(\omega) = S_{FF}(-\omega)$$

Not true quantum mechanically because: $$\left[\hat{F}(t), \hat{F}(0) \right] \neq 0$$

Example: $H = \omega_{\mathrm{q}} \sigma^{z} + \hat{F}(t) \sigma^{x}$

$\left[\hat{F}(t), \hat{F}(0) \right] \neq 0$ Implies $\hat{F}(t)\hat{F}(0)$ is <u>not</u> Hermitian

and so the noise correlator $G_{FF}(t) \equiv \left\langle \hat{F}(t)\hat{F}(0) \right\rangle$ is complex

and hence its spectral density $S_{FF}(\omega) \equiv \int dt e^{i\omega t} \left\langle \hat{F}(t)\hat{F}(0) \right\rangle$

can be <u>asymmetric</u> in frequency: $S_{FF}(\omega) \neq S_{FF}(-\omega)$

harmonic oscillator example:

$$\hat{F} = F_{\text{ZPF}}\left(\hat{b} + \hat{b}^{\dagger}\right)$$

$$G_{FF}(t) \equiv \left\langle \hat{F}(t)\hat{F}(0) \right\rangle = F_{\text{ZPF}}^2 \left[\left\langle \hat{b}(t)\hat{b}^{\dagger}(0) \right\rangle + \left\langle \hat{b}^{\dagger}(t)\hat{b}(0) \right\rangle \right]$$

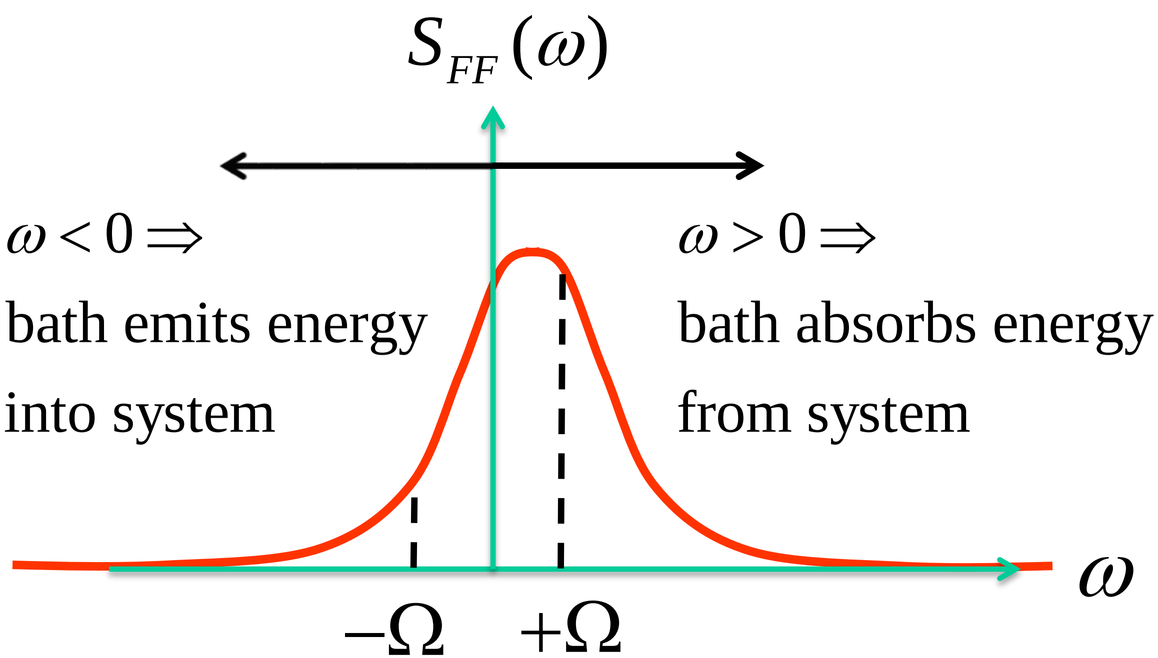
$$G_{FF}(t) = F_{\text{ZPF}}^2 \left[\left(n_{\text{B}} + 1\right) e^{-i\omega_0 t} + n_{\text{B}} e^{+i\omega_0 t} \right]$$ (is complex)

$$S_{FF}(\omega) = 2\pi \left[\left(n_{\text{B}} + 1\right)\delta(\omega - \omega_0) + n_{\text{B}}\delta(\omega + \omega_0) \right]$$ (is asymmetric)

Stimulated emission (bath absorbs)

Absorption (bath emits)

quantum noise NOT (necessarily) symmetric in frequency:

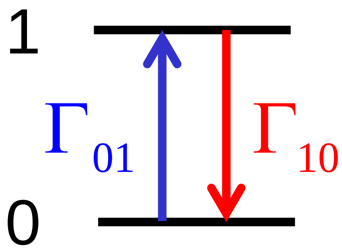


In thermal equilibrium:
(or pseudo-equilibrium)

$$\frac{S_{FF}(+\Omega)}{S_{FF}(-\Omega)} = e^{\beta\hbar\Omega} \quad = 1 \text{ for } \hbar \to 0$$

Fermi's Golden Rule in terms of noise spectral density

Example: $$H = \frac{\omega_q}{2}\sigma^z + \hat{F}(t)\sigma^x$$



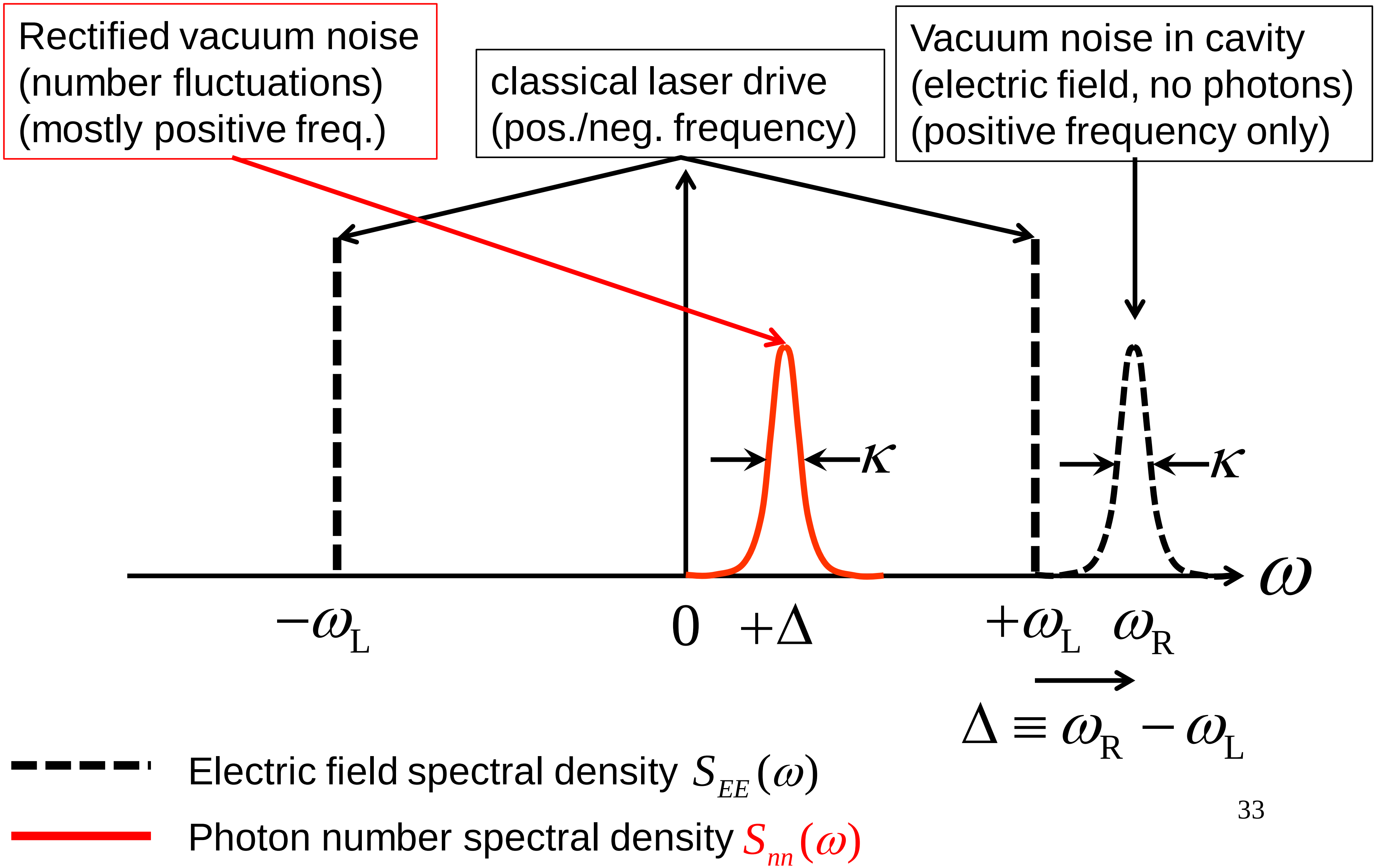
$$\Gamma_{10} = S_{FF}(+\omega_q) \text{ bath absorbs}$$

$$\Gamma_{01} = S_{FF}(-\omega_q) \text{ bath emits}$$

For quantum noise picture of FGR see:

Clerk et al. *Rev. Mod. Phys.* **82**, 1155 (2010)

Shot noise as 'rectified vacuum noise'



Rabi experiment: decoherence of driven qubit in rotating frame:

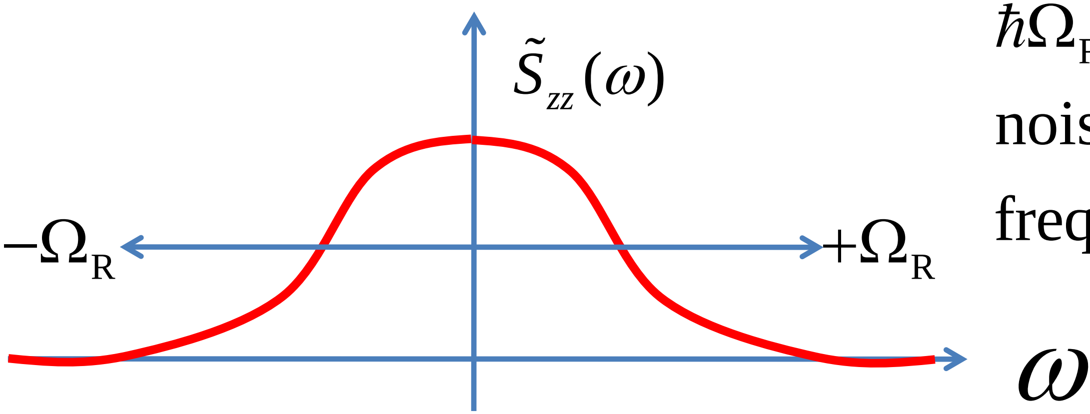
$$H = \frac{\Omega_{\mathrm{R}}}{2}\sigma^x + \frac{1}{2}U(t)\left[\vec{\xi}(t)\bullet\vec{\sigma}\right]U^\dagger(t)$$

G. Ithier, et al., *Phys. Rev. B* **72**, 134519 (2005).

$$\boxed{\frac{1}{T_{\mathrm{Rabi}}} = \frac{3}{4}\frac{1}{T_1} + \frac{1}{2}\frac{1}{T_\varphi(\Omega_{\mathrm{R}})}}$$

$$\frac{1}{T_\varphi(\Omega_{\mathrm{R}})} = \frac{1}{4}\left\{\tilde{S}_{zz}(+\Omega_{\mathrm{R}}) + \tilde{S}_{zz}(-\Omega_{\mathrm{R}})\right\} \approx \frac{1}{T_\varphi}$$

but can be smaller if Rabi rate is high



$\hbar\Omega_{\mathrm{R}} \ll k_B T$

noise is classical so symmetric in frequency (and probably non-eq.)

Choose cavity drive detuning to match mechanical oscillator frequency

$$\Delta \equiv \omega_{\mathrm{R}} - \omega_{\mathrm{L}} = \Omega_{\mathrm{M}}$$

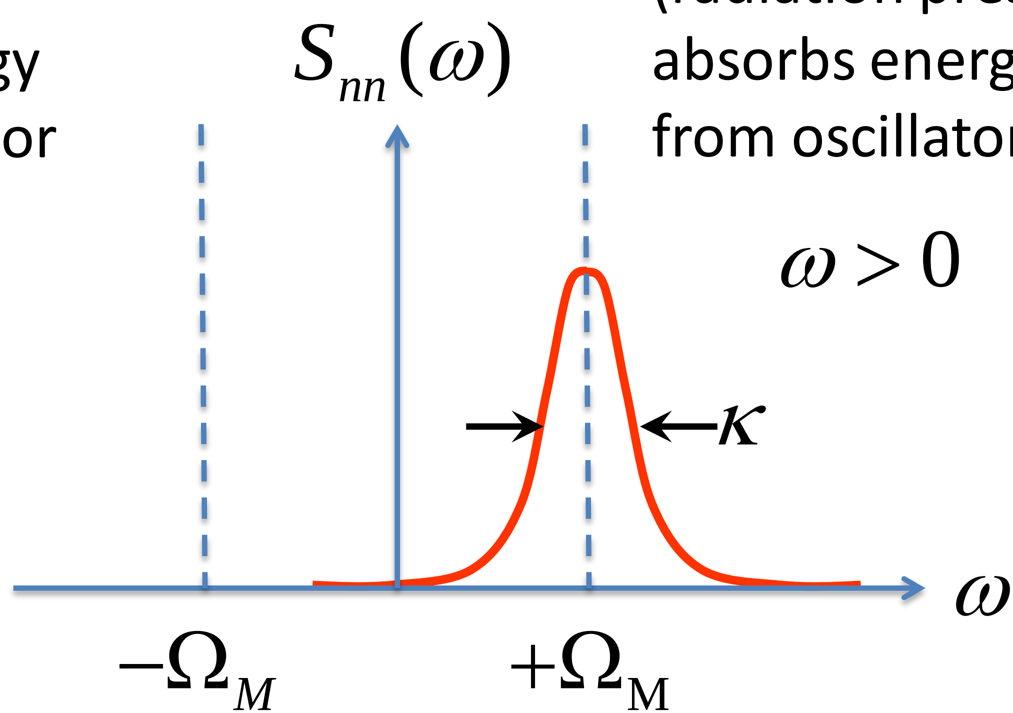
Resolved sideband limit: $+\Omega_{\mathrm{M}} > \kappa \Rightarrow$ noise is <u>cold</u>

Shot noise emits energy into oscillator

$\omega < 0$

Shot noise (radiation pressure) absorbs energy from oscillator

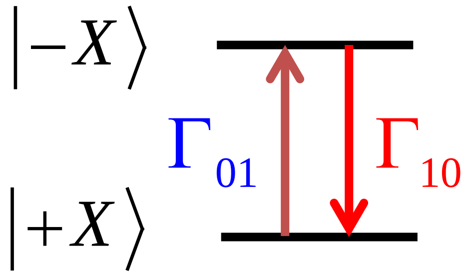
$\omega > 0$



Fermi's Golden Rule in terms of noise spectral density

$$H = -\Omega_{\text{Rabi}}\,\sigma^X + \chi\,\sigma^Z\,(\hat{n} - \bar{n})$$

shot noise of driven cavity



$$\Gamma_{10} = \chi^2 S_{nn}(+\Omega_R) \quad \text{bath absorbs}$$

$$\Gamma_{01} = \chi^2 S_{nn}(-\Omega_R) \quad \text{bath emits}$$

For quantum noise picture of FGR see:

Clerk et al. *Rev. Mod. Phys.* **82**, 1155 (2010)