COLLÈGE DE FRANCE 1530

Chaire de Physique Mésoscopique
Michel Devoret
Année 2009, 12 mai - 23 juin

CIRCUITS ET SIGNAUX QUANTIQUES (II)

QUANTUM SIGNALS AND CIRCUITS (II)

Cinquième Leçon / *Fifth Lecture*

09-V-1

VISIT THE WEBSITE OF THE CHAIR OF MESOSCOPIC PHYSICS

http://www.college-de-france.fr

then follow
Enseignement > Sciences Physiques > Physique Mésoscopique > Site web

or

http://www.physinfo.fr/lectures.html

PDF FILES OF ALL LECTURES ARE POSTED ON THESE WEBSITES

Questions, comments and corrections are welcome!

write to "phymeso@gmail.com"

09-V-2

CALENDAR OF SEMINARS

May 12: Daniel Esteve, (Quantronics group, SPEC-CEA Saclay)
Faithful readout of a superconducting qubit

May 19: Christian Glattli (LPA/ENS)
Statistique de Fermi dans les conducteurs balistiques : conséquences expéri-mentales et exploitation pour l'information quantique

June 2: Steve Girvin (Yale)
Quantum Electrodynamics of Superconducting Circuits and Qubits

June 9: Charlie Marcus (Harvard)
Electron Spin as a Holder of Quantum Information: Prospects and Challenges

June 16: Frédéric Pierre (LPN/CNRS)
Energy exchange in quantum Hall edge channels

June 23: Lev Ioffe (Rutgers)
Implementation of protected qubits in Josephson junction arrays

09-V-3

CONTENT OF THIS YEAR'S LECTURES

OUT-OF-EQUILIBRIUM NON-LINEAR QUANTUM CIRCUITS

1. Introduction and review of last year's course
2. Non-linearity of Josephson tunnel junctions
3. Readout of qubits
4. Amplification of quantum signals: detecting RF photons
5. Dynamical cooling and quantum error correction
6. Defying the fine structure constant: the prospect of the observation of Bloch oscillations.

09-V-4

LECTURE V : STATE PREPARATION OF SUPER CONDUCTING ARTIFICIAL ATOMS AND CAVITIES

1. Interaction between atom excitation and photons
2. Measuring photon number with an atom
3. Principle of dynamical cooling
4. Cooling and population inversion of fluxonium

09-V-5

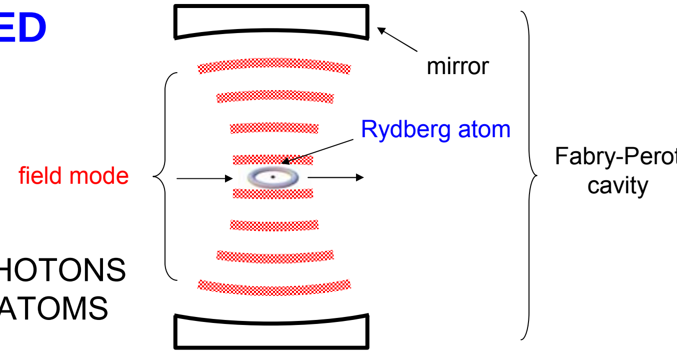
OUTLINE

1. Interaction between atom excitation and photons
2. Measuring photon number with an atom
3. Principle of dynamical cooling
4. Cooling and population inversion of fluxonium

09-V-5a

CAVITY QED

Haroche and Raimond
"Exploring the Quantum"
(Oxford University Press, 2006)

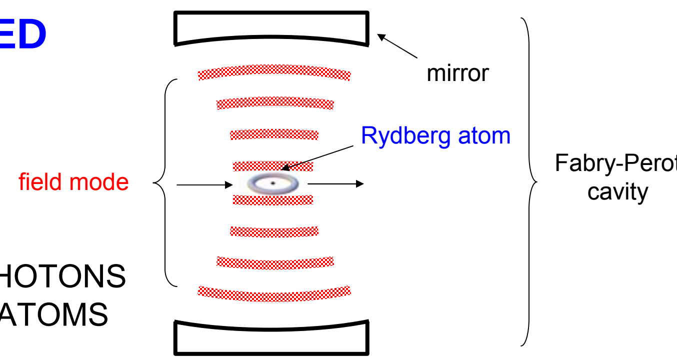


STANDING PHOTONS
AND FLYING ATOMS

09-V-6

CAVITY QED

Haroche and Raimond
"Exploring the Quantum"
(Oxford University Press, 2006)



STANDING PHOTONS
AND FLYING ATOMS

ATOMS MEASURE
PHOTON NUMBER

09-V-6a

CAVITY QED

Haroche and Raimond
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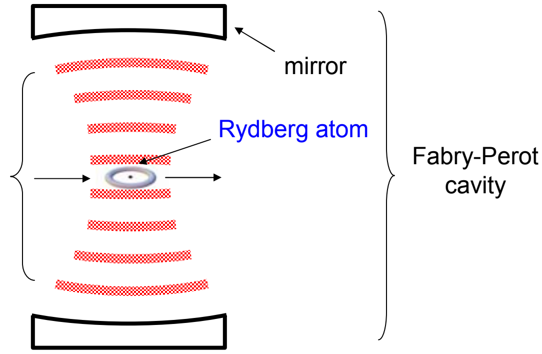


STANDING PHOTONS AND FLYING ATOMS

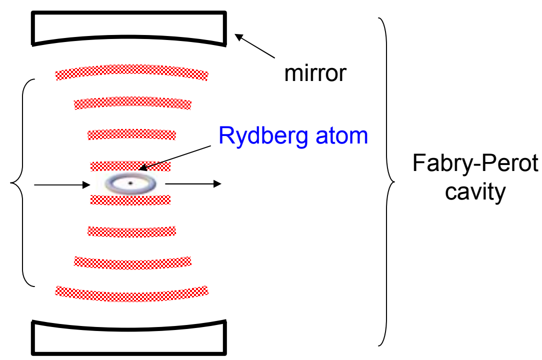
ATOMS MEASURE PHOTON NUMBER

$$\hat{H} = \hat{H}_{field} + \hat{H}_{atom} + \hat{H}_{coupling}$$

09-V-6b

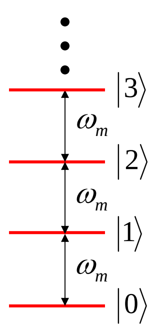
CAVITY QED

Haroche and Raimond
"Exploring the Quantum"
(Oxford University Press, 2006)



STANDING PHOTONS AND FLYING ATOMS

ATOMS MEASURE PHOTON NUMBER



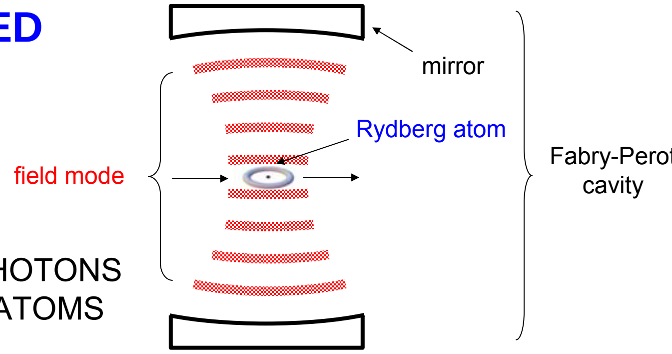
$$\hat{H} = \hat{H}_{field} + \hat{H}_{atom} + \hat{H}_{coupling}$$

$$\hat{H}_{field} = \hbar\omega_m \hat{a}^{\dagger}\hat{a}$$

09-V-6c

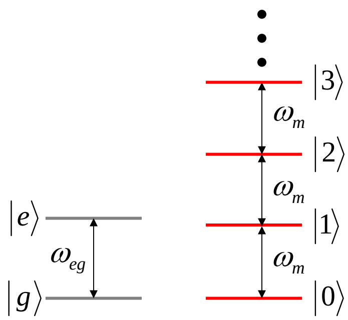
CAVITY QED

Haroche and Raimond
"Exploring the Quantum"
(Oxford University Press, 2006)



STANDING PHOTONS AND FLYING ATOMS

ATOMS MEASURE PHOTON NUMBER



$$\hat{H} = \hat{H}_{field} + \hat{H}_{atom} + \hat{H}_{coupling}$$

$$\hat{H}_{field} = \hbar\omega_m \hat{a}^\dagger \hat{a}$$

$$\hat{H}_{atom} = \hbar\omega_{eg}\hat{\sigma}_+\hat{\sigma}_-$$

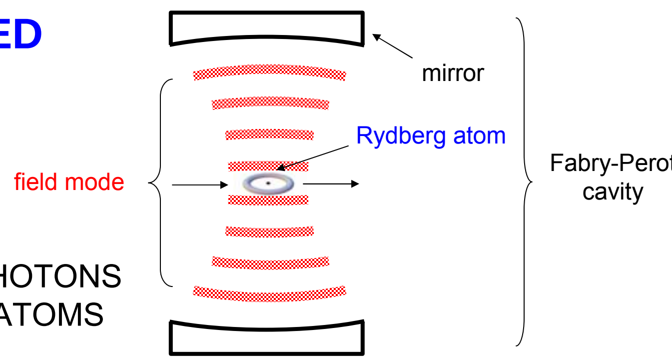
$\hat{\sigma}_+ = |e\rangle\langle g|$

$\hat{\sigma}_- = |g\rangle\langle e|$

09-V-6d

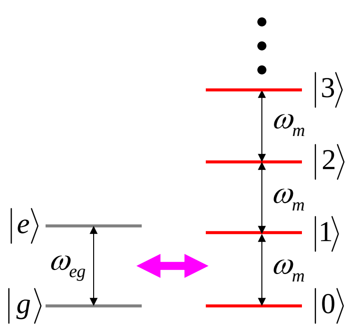
CAVITY QED

Haroche and Raimond
"Exploring the Quantum"
(Oxford University Press, 2006)



STANDING PHOTONS AND FLYING ATOMS

ATOMS MEASURE PHOTON NUMBER



$$\hat{H} = \hat{H}_{field} + \hat{H}_{atom} + \hat{H}_{coupling}$$

$$\hat{H}_{field} = \hbar\omega_m \hat{a}^\dagger \hat{a}$$

$$\hat{H}_{atom} = \hbar\omega_{eg}\hat{\sigma}_+\hat{\sigma}_-$$

$\hat{\sigma}_+ = |e\rangle\langle g|$

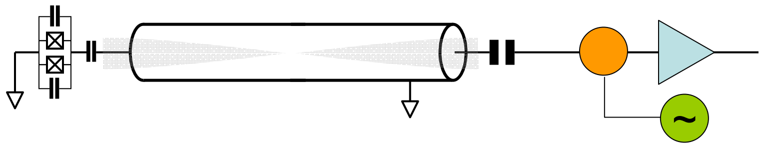
$\hat{\sigma}_- = |g\rangle\langle e|$

$$\hat{H}_{coupling} = g\hat{a}\hat{\sigma}_+ + \text{h.c.}$$

09-V-6e

CIRCUIT QED: STANDING ATOMS (I)

Transmon artificial atom | Cavity | Control and readout

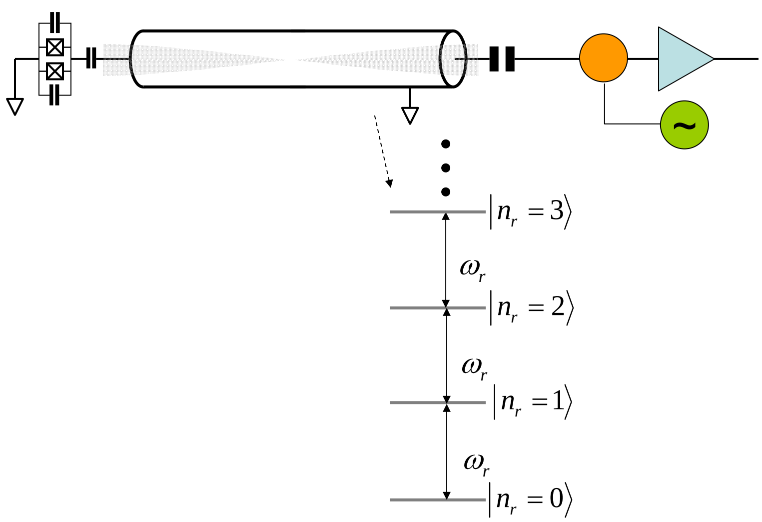


STANDING PHOTONS | PROPAGATING PHOTONS

09-V-7

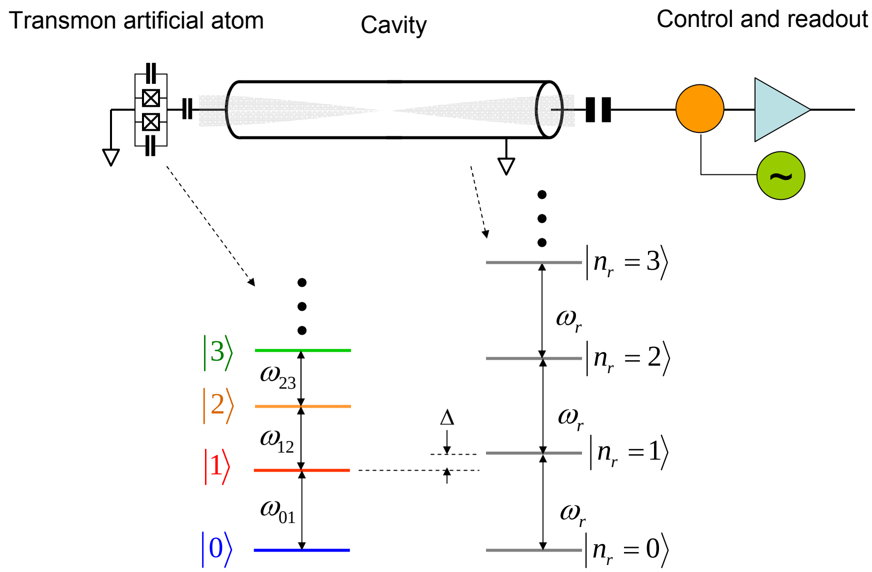
CIRCUIT QED: STANDING ATOMS (I)

Transmon artificial atom | Cavity | Control and readout



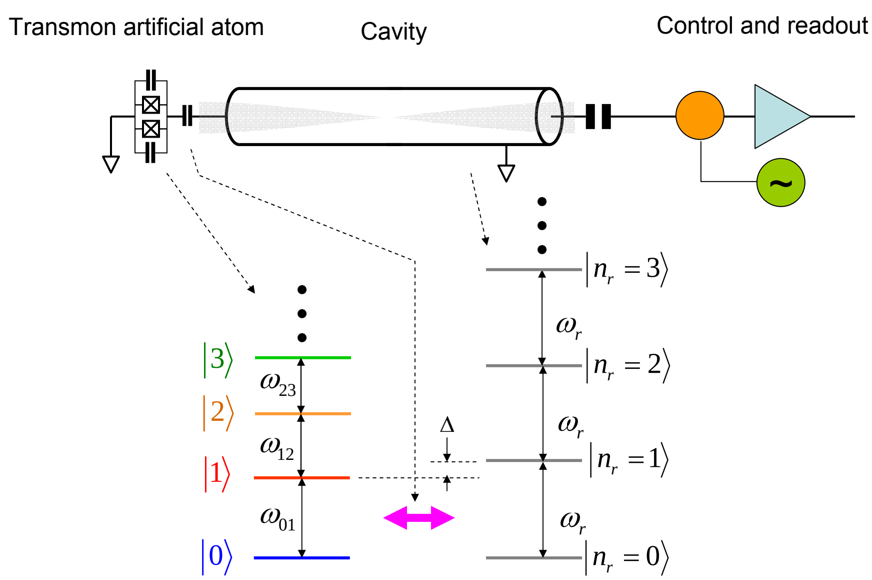
09-V-7a

CIRCUIT QED: STANDING ATOMS (I)

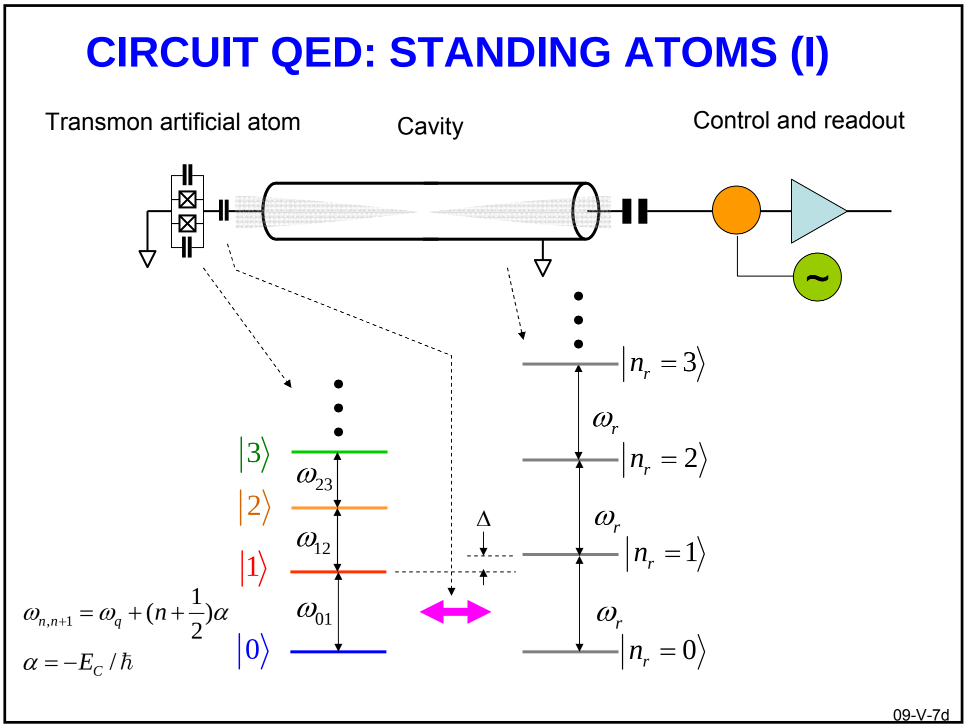


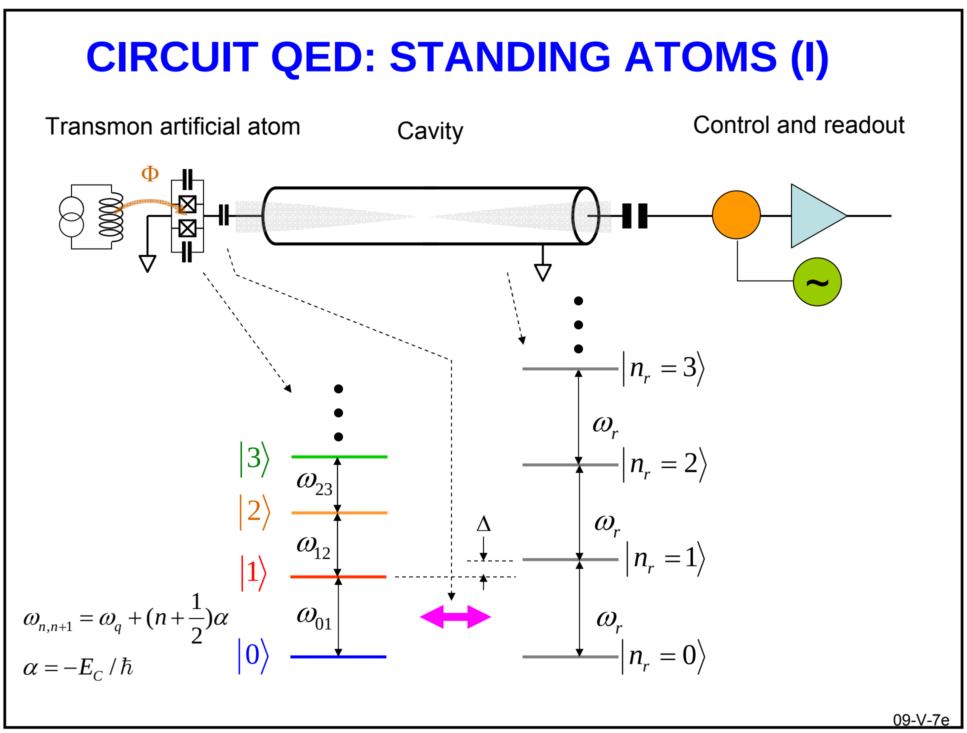
09-V-7b

CIRCUIT QED: STANDING ATOMS (I)

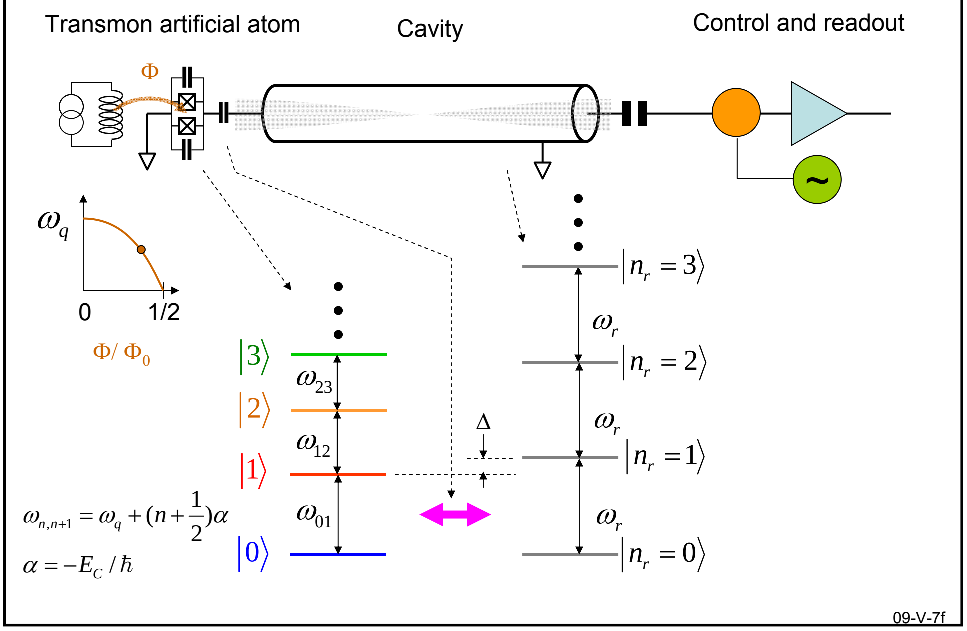


09-V-7c

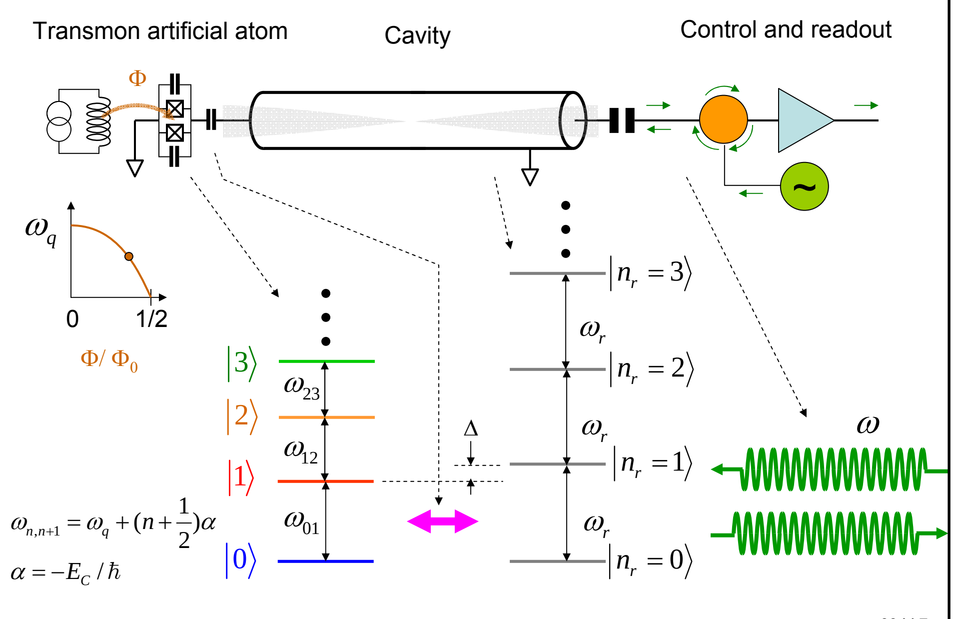

CIRCUIT QED: STANDING ATOMS (I)
Transmon artificial atom
Cavity
Control and readout
~
|n_r = 3⟩
|n_r = 2⟩
|n_r = 1⟩
|n_r = 0⟩
ω_r
ω_r
ω_r
Δ
|3⟩
|2⟩
|1⟩
|0⟩
ω_23
ω_12
ω_01
$\omega_{n,n+1} = \omega_q + (n + \frac{1}{2})\alpha$
$\alpha = -E_C / \hbar$
09-V-7d


CIRCUIT QED: STANDING ATOMS (I)
Transmon artificial atom
Cavity
Control and readout
Φ
~
|n_r = 3⟩
|n_r = 2⟩
|n_r = 1⟩
|n_r = 0⟩
ω_r
ω_r
ω_r
Δ
|3⟩
|2⟩
|1⟩
|0⟩
ω_23
ω_12
ω_01
$\omega_{n,n+1} = \omega_q + (n + \frac{1}{2})\alpha$
$\alpha = -E_C / \hbar$
09-V-7e

CIRCUIT QED: STANDING ATOMS (I)



CIRCUIT QED: STANDING ATOMS (I)



TRANSMON + CAVITY, DISPERSIVE LIMIT

$$\frac{\hat{H}}{\hbar} = \underbrace{\omega_q \hat{c}^\dagger \hat{c} + \frac{1}{2}\alpha\left(\hat{c}^\dagger \hat{c}\right)^2}_{\text{ATOM}} + \underbrace{g\left(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger\right)}_{\text{COUPLING}} + \underbrace{\omega_r \hat{a}^\dagger \hat{a}}_{\text{FIELD}}$$ + damping + drive

$$\left[\hat{c}, \hat{c}^\dagger\right] = 1$$

$$\left[\hat{a}, \hat{a}^\dagger\right] = 1$$

$$\left[\hat{a}, \hat{c}\right] = 0$$

09-V-8

TRANSMON + CAVITY, DISPERSIVE LIMIT

Idea: treat non-linear term as a perturbation

$$\frac{\hat{H}}{\hbar} = \underbrace{\omega_q \hat{c}^\dagger \hat{c} + \frac{1}{2}\alpha\left(\hat{c}^\dagger \hat{c}\right)^2}_{\text{ATOM}} + \underbrace{g\left(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger\right)}_{\text{COUPLING}} + \underbrace{\omega_r \hat{a}^\dagger \hat{a}}_{\text{FIELD}}$$ + damping + drive

$$\left[\hat{c}, \hat{c}^\dagger\right] = 1$$

$$\left[\hat{a}, \hat{a}^\dagger\right] = 1$$

$$\left[\hat{a}, \hat{c}\right] = 0$$

09-V-8a

TRANSMON + CAVITY, DISPERSIVE LIMIT

$$\frac{\hat{H}_{\text{lin}}}{\hbar} = \omega_q \hat{c}^\dagger \hat{c} + g\left(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger\right) + \omega_r \hat{a}^\dagger \hat{a}$$

+ damping + drive

HARMONIC ATOM — COUPLING — FIELD

$$\left[\hat{c}, \hat{c}^\dagger\right] = 1$$

$$\left[\hat{a}, \hat{a}^\dagger\right] = 1$$

$$\left[\hat{a}, \hat{c}\right] = 0$$

09-V-8b

TRANSMON + CAVITY, DISPERSIVE LIMIT

$$\frac{\hat{H}_{\text{lin}}}{\hbar} = \omega_q \hat{c}^\dagger \hat{c} + g\left(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger\right) + \omega_r \hat{a}^\dagger \hat{a}$$

+ damping + drive

HARMONIC ATOM — COUPLING — FIELD

$$\frac{\hat{H}_{\text{lin}}}{\hbar} = \omega'_q \hat{C}^\dagger \hat{C} + \omega'_r \hat{A}^\dagger \hat{A}$$

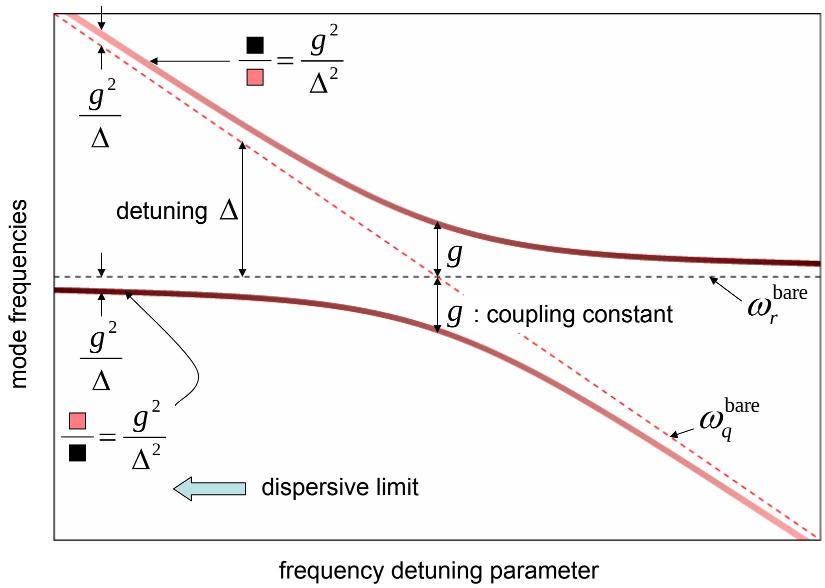
$$\left[\hat{C}, \hat{C}^\dagger\right] = 1$$

$$\left[\hat{A}, \hat{A}^\dagger\right] = 1$$

$$\left[\hat{A}, \hat{C}\right] = 0$$

09-V-8c

COUPLED OSCILLATORS



09-V-9

RETAIN SECULAR PART OF PERTURBATION

$$\hat{c} \cong \left(1-\frac{g^2}{2\Delta^2}\right)\hat{C} + \frac{g}{\Delta}\hat{A}$$

$$\hat{c}\hat{c}^{\dagger} \cong \left(1-\frac{g^2}{\Delta^2}\right)n_q + \frac{g^2}{\Delta^2}n_r + \text{non-secular terms}$$

renormalization of anharmonicity

self-Kerr

$$\frac{\alpha}{2}\left(\hat{c}\hat{c}^{\dagger}\right)^2 \cong \frac{\alpha\left(1-2\frac{g^2}{\Delta^2}\right)}{2}n_q^2 + 2\alpha\frac{g^2}{\Delta^2}n_r n_q + \frac{\alpha}{2}\frac{g^4}{\Delta^4}n_r^2$$

+ non-secular terms
+ higher order terms

09-V-10

TRANSMON + CAVITY, DISPERSIVE LIMIT

$$\frac{\hat{H}}{\hbar} = \omega_q \hat{c}^\dagger \hat{c} + \frac{1}{2}\alpha\left(\hat{c}^\dagger \hat{c}\right)^2 + g\left(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger\right) + \omega_r \hat{a}^\dagger \hat{a}$$

+ damping + drive

$$n_q = \hat{C}^\dagger \hat{C}$$

$$n_r = \hat{A}^\dagger \hat{A}$$

$$\frac{\hat{H}_{\text{lin}}}{\hbar} = \omega_q' \hat{C}^\dagger \hat{C} + \omega_r' \hat{A}^\dagger \hat{A}$$

$$\Delta = \omega_q - \omega_r \gg g$$

$$\frac{\hat{H}_{\text{eff}}}{\hbar} = \omega_q' n_q + \frac{1}{2}\alpha n_q^{\,2} + \omega_r' n_r + 2\alpha \frac{g^2}{\Delta^2} n_q n_r$$

09-V-11

TRANSMON + CAVITY, DISPERSIVE LIMIT

$$\frac{\hat{H}}{\hbar} = \omega_q \hat{c}^\dagger \hat{c} + \frac{1}{2}\alpha\left(\hat{c}^\dagger \hat{c}\right)^2 + g\left(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger\right) + \omega_r \hat{a}^\dagger \hat{a}$$

+ damping + drive

$$n_q = \hat{C}^\dagger \hat{C}$$

$$n_r = \hat{A}^\dagger \hat{A}$$

$$\frac{\hat{H}_{\text{lin}}}{\hbar} = \omega_q' \hat{C}^\dagger \hat{C} + \omega_r' \hat{A}^\dagger \hat{A}$$

$$\Delta = \omega_q - \omega_r \gg g$$

$$\frac{\hat{H}_{\text{eff}}}{\hbar} = \omega_q' n_q + \frac{1}{2}\alpha n_q^{\,2} + \omega_r' n_r + 2\alpha \frac{g^2}{\Delta^2} n_q n_r$$

READOUT OF QUBIT

$$\left(\omega_r' + 2\alpha \frac{g^2}{\Delta^2} n_q\right) n_r = \left(\omega_r' + \chi_q\right) n_r$$

09-V-11a

TRANSMON + CAVITY, DISPERSIVE LIMIT

$$\frac{\hat{H}}{\hbar} = \omega_q \hat{c}^\dagger \hat{c} + \frac{1}{2}\alpha\left(\hat{c}^\dagger \hat{c}\right)^2 + g\left(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger\right) + \omega_r \hat{a}^\dagger \hat{a}$$ + damping + drive

$$n_q = \hat{C}^\dagger \hat{C}$$

$$\frac{\hat{H}_{\text{lin}}}{\hbar} = \omega_q' \hat{C}^\dagger \hat{C} + \omega_r' \hat{A}^\dagger \hat{A}$$

$$n_r = \hat{A}^\dagger \hat{A}$$

$$\Delta = \omega_q - \omega_r \gg g$$

$$\frac{\hat{H}_{\text{eff}}}{\hbar} = \omega_q' n_q + \frac{1}{2}\alpha n_q^{\ 2} + \omega_r' n_r + 2\alpha \frac{g^2}{\Delta^2} n_q n_r$$

MEASURMENT OF # PHOTONS

$$\left(\omega_q' + \ldots. + 2\alpha \frac{g^2}{\Delta^2} n_r\right) n_q = \left(\omega_r' + \ldots + \chi_r n_r\right) n_q$$

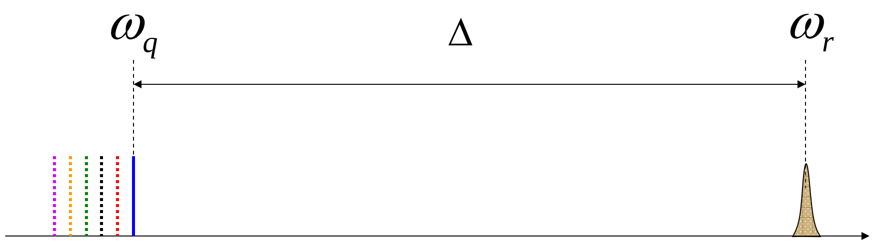
09-V-11a

OUTLINE

1. Interaction between atom excitation and photons
2. Measuring photon number with an atom
3. Principle of dynamical cooling
4. Cooling and population inversion of fluxonium

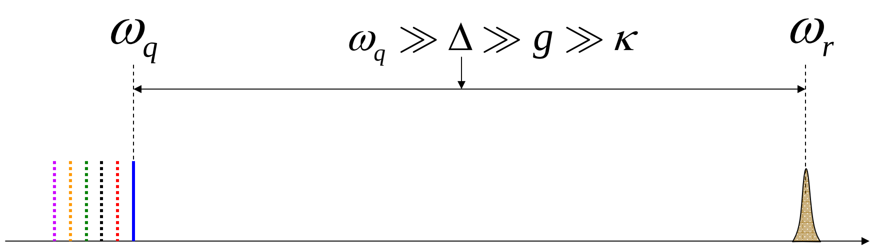
09-V-5b

T=0 AND CONDITIONAL TRANSITIONS



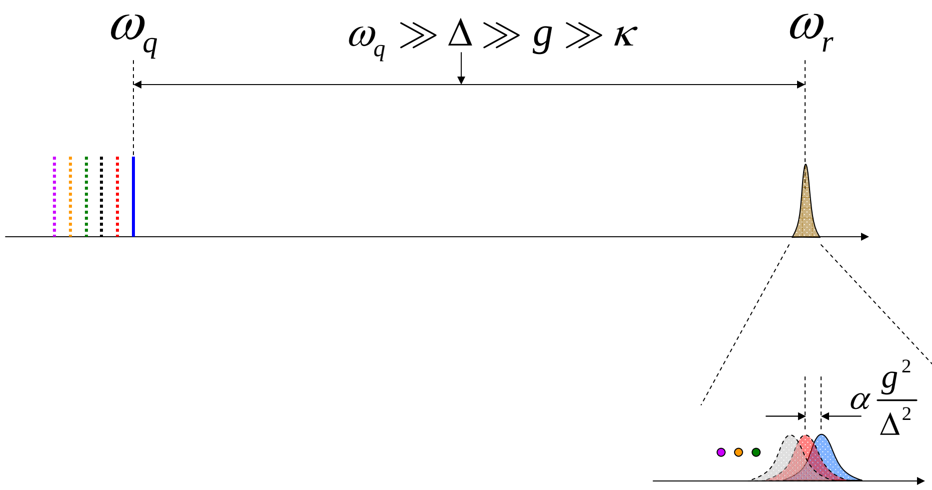
09-V-12

T=0 AND CONDITIONAL TRANSITIONS



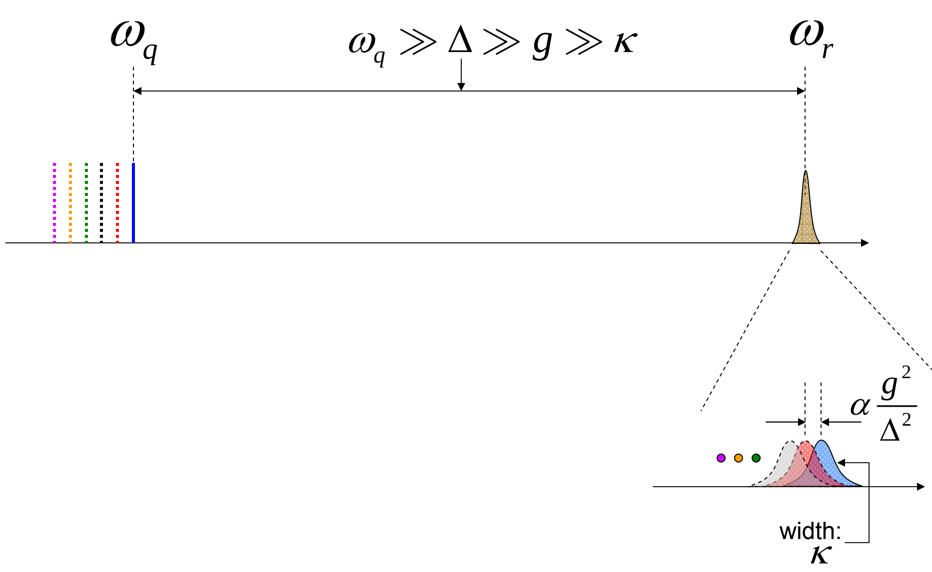
09-V-12a

T=0 AND CONDITIONAL TRANSITIONS



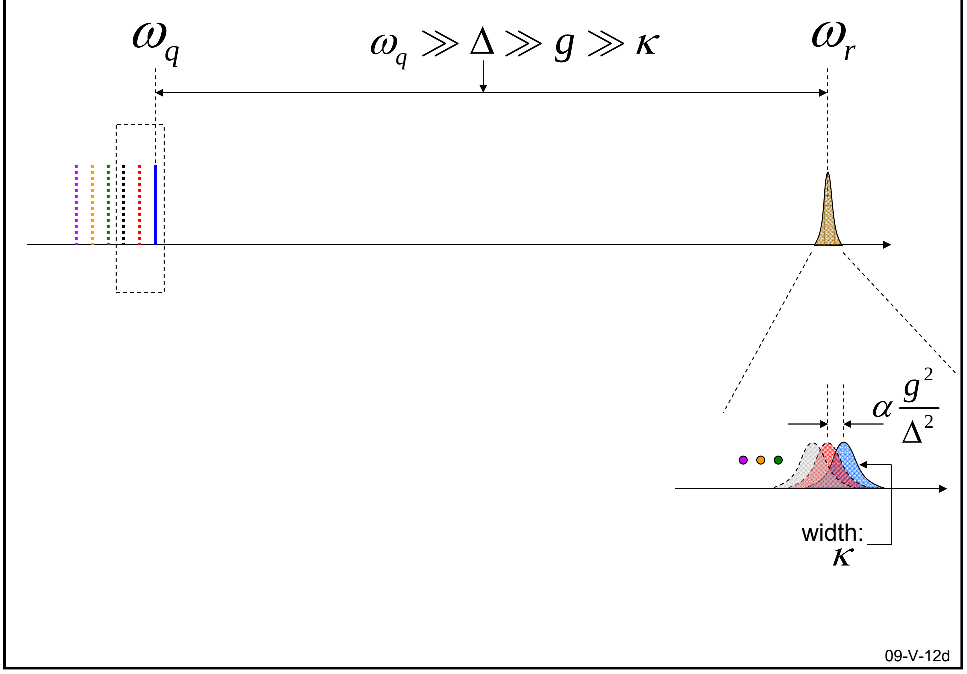
09-V-12b

T=0 AND CONDITIONAL TRANSITIONS

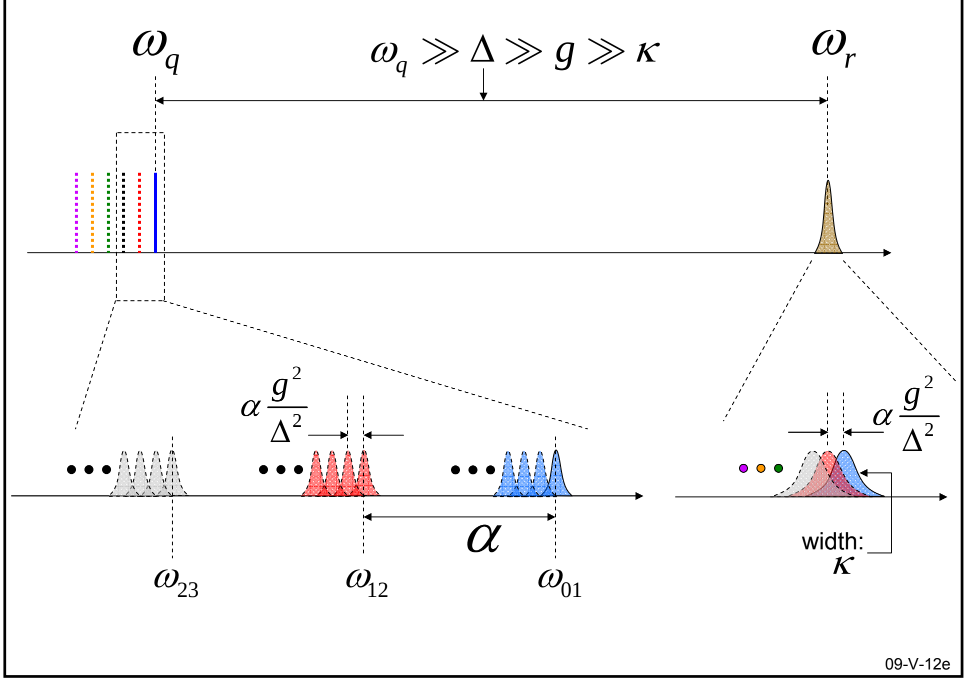


09-V-12c

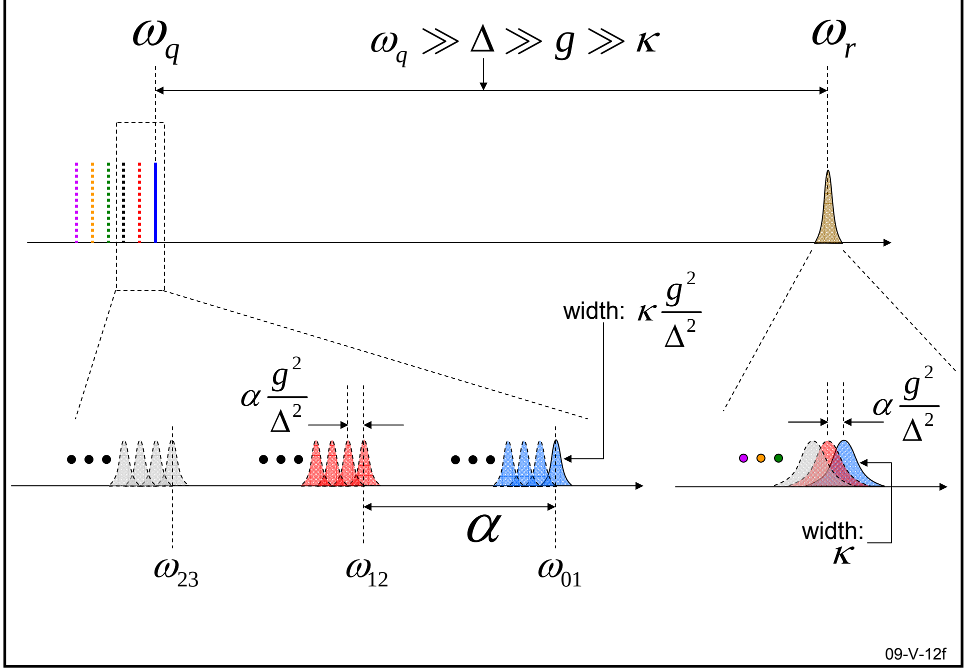
T=0 AND CONDITIONAL TRANSITIONS



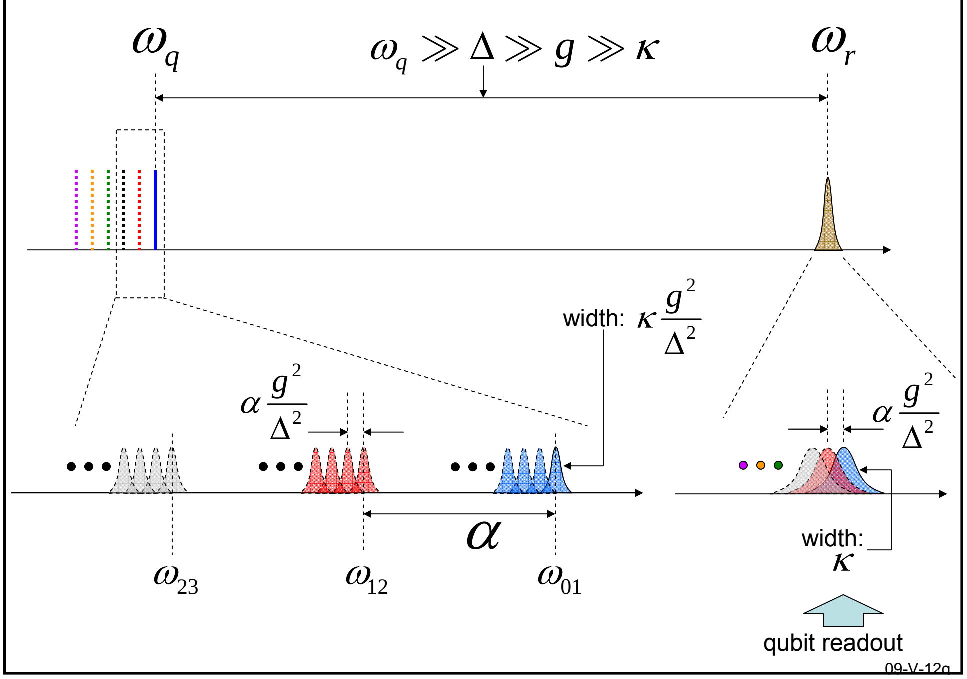
T=0 AND CONDITIONAL TRANSITIONS

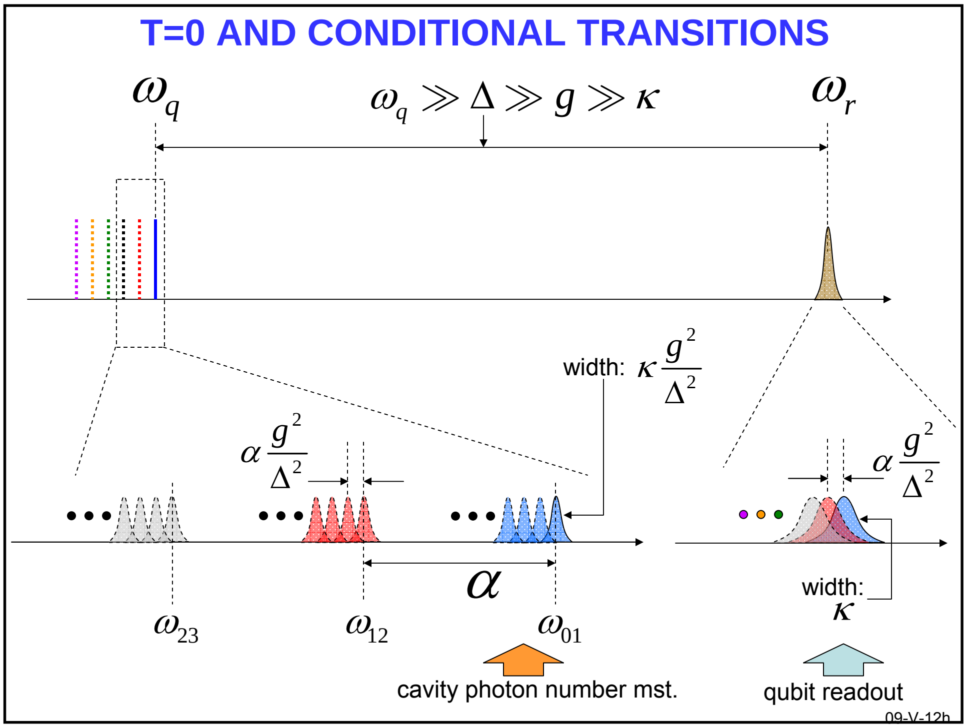


T=0 AND CONDITIONAL TRANSITIONS

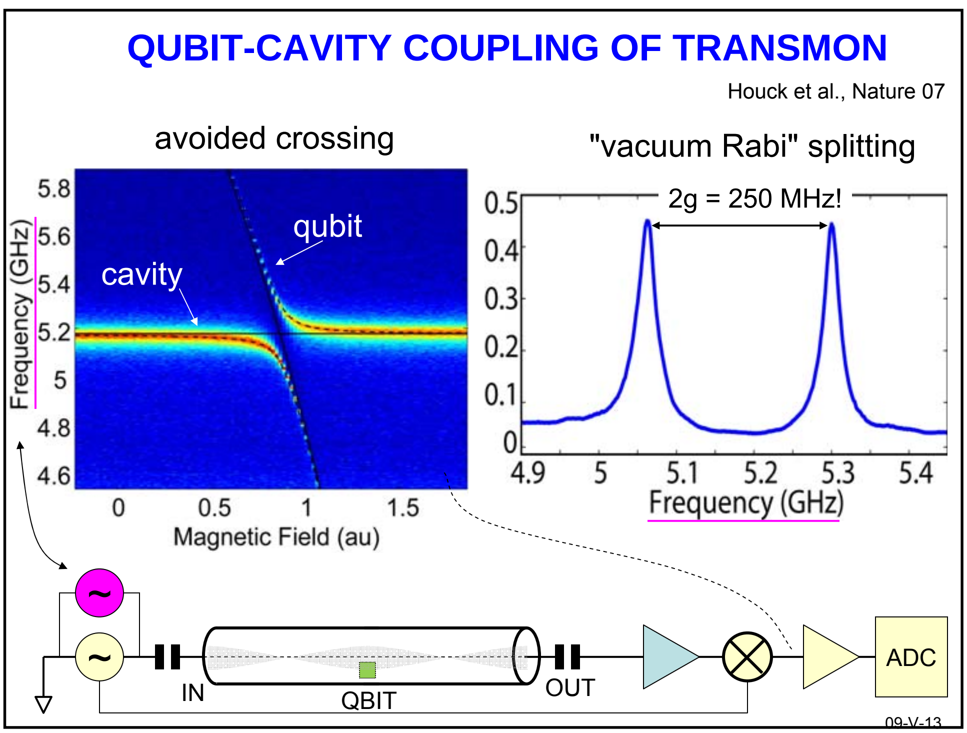


T=0 AND CONDITIONAL TRANSITIONS

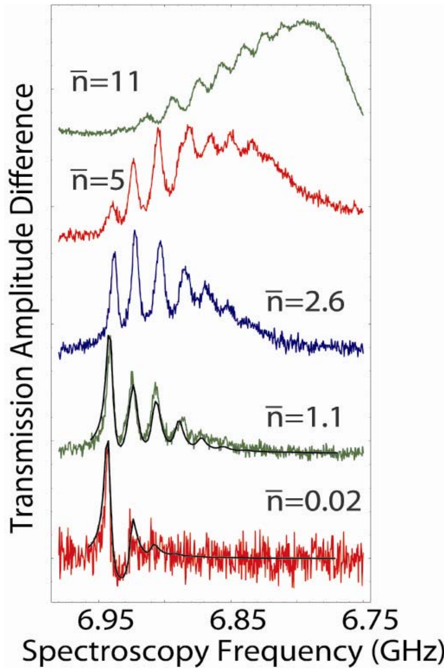




T=0 AND CONDITIONAL TRANSITIONS
ω_q
$\omega_q \gg \Delta \gg g \gg \kappa$
ω_r
width: $\kappa \frac{g^2}{\Delta^2}$
$\alpha \frac{g^2}{\Delta^2}$
$\alpha \frac{g^2}{\Delta^2}$
α
width: κ
ω_{23}
ω_{12}
ω_{01}
cavity photon number mst.
qubit readout
09-V-12b



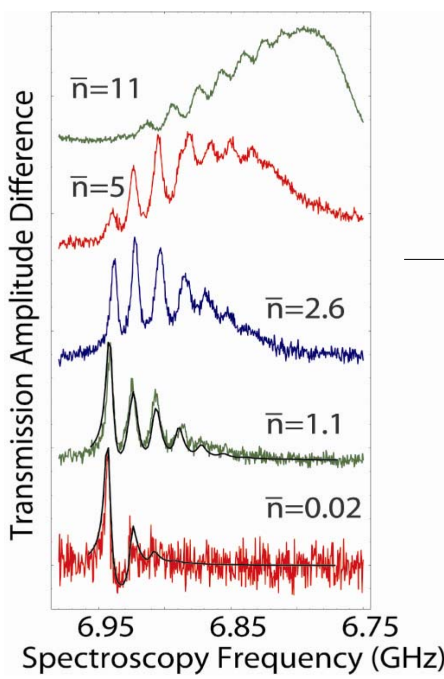
QUBIT-CAVITY COUPLING OF TRANSMON
Houck et al., Nature 07
avoided crossing
"vacuum Rabi" splitting
qubit
cavity
Frequency (GHz)
Magnetic Field (au)
2g = 250 MHz!
Frequency (GHz)
IN
QBIT
OUT
ADC
09-V-13



RESOLVING PHOTON NUMBER IN CAVITY

Houck et al., Nature 07

09-V-14



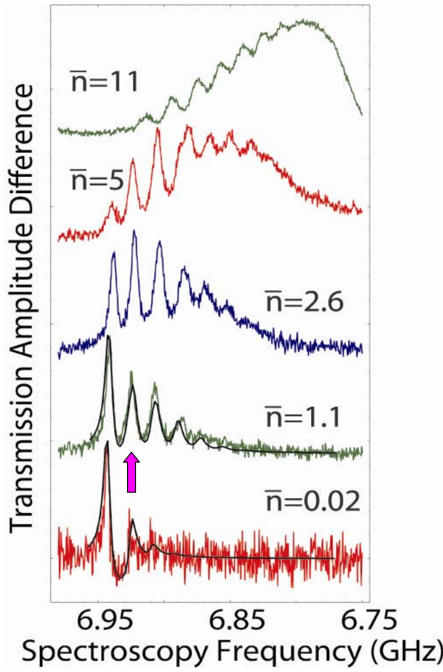
RESOLVING PHOTON NUMBER IN CAVITY

$$P(n) = \frac{(\bar{n})^n}{n!} e^{-\bar{n}}$$

- Mean shifts
- Peaks are Poisson distributed
- Peaks get broader $\propto n$

Houck et al., Nature 07

09-V-14a



RESOLVING PHOTON NUMBER IN CAVITY

CONDITIONAL QUBIT ROTATION POSSIBLE!

PREPARATION OF ARBITRARY FOCK STATE SUPERPOSITION IN A CAVITY (UCSB)

Hofheinz et al. (2008, 2009)

09-V-14b

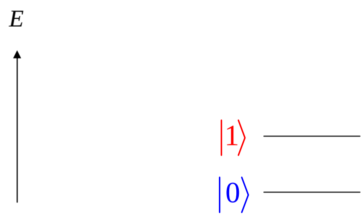
OUTLINE

1. Interaction between atom excitation and photons
2. Measuring photon number with an atom
3. Principle of dynamical cooling
4. Cooling and population inversion of fluxonium

09-V-5c

EQUILIBRIUM COOLING

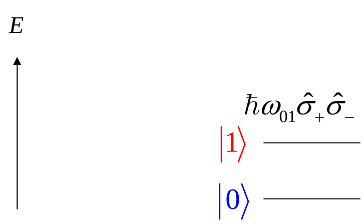
EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)



09-V-15

EQUILIBRIUM COOLING

EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)



09-V-15a

EQUILIBRIUM COOLING

EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)

E

$\hat{\sigma}_+ = |1\rangle\langle 0|$

$\hat{\sigma}_- = \hat{\sigma}_+^\dagger$

$\sigma_x = \hat{\sigma}_+ + \hat{\sigma}_-$

$\hbar\omega_{01}\hat{\sigma}_+\hat{\sigma}_-$

$|1\rangle$

$|0\rangle$

09-V-15b

EQUILIBRIUM COOLING

EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)

E

$\hbar\omega_{01}\hat{\sigma}_+\hat{\sigma}_-$

$|1\rangle$

$|0\rangle$

bosonic bath

$\sum_k \hbar\omega_k \hat{a}_k^\dagger \hat{a}_k$

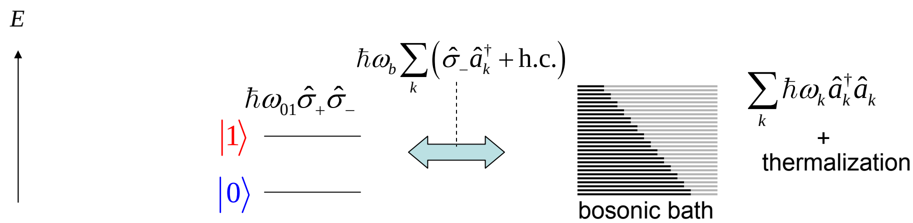
+

thermalization

09-V-15c

EQUILIBRIUM COOLING

EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)



09-V-15d

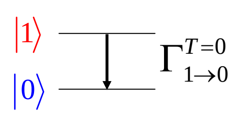
EQUILIBRIUM COOLING

$$\Gamma_{1\to 0}^{T=0} = \frac{2\pi}{\hbar}\left(M_{1,n=0\to 0,n=1}\right)^2 \sum_k \delta\left(\hbar\omega_k - \hbar\omega_{01}\right)$$

$$= \frac{2\pi}{\hbar}\left(\hbar\omega_c\right)^2 \frac{d\mathcal{N}\left(\omega_{01}\right)}{dE}$$

$$= h\omega_c^2 \frac{d\mathcal{N}\left(\omega_{01}\right)}{dE}$$

Fermi's Golden Rule



09-V-16

EQUILIBRIUM COOLING

$$\Gamma_{1\to 0}^{T=0} = \frac{2\pi}{\hbar}\left(M_{1,n=0\to 0,n=1}\right)^2 \sum_k \delta\left(\hbar\omega_k - \hbar\omega_{01}\right)$$

$$= \frac{2\pi}{\hbar}\left(\hbar\omega_c\right)^2 \frac{d\mathcal{N}\left(\omega_{01}\right)}{dE}$$

$$= h\omega_c^2 \frac{d\mathcal{N}\left(\omega_{01}\right)}{dE}$$

Fermi's Golden Rule

$$\Gamma_{1\to 0}^{T} = \Gamma_{1\to 0}^{T=0} \frac{1}{1-\exp\left(\dfrac{-\hbar\omega_{01}}{k_B T}\right)}$$

Emission

$$\Gamma_{0\to 1}^{T} = \Gamma_{0\to 1}^{T=0} \frac{1}{\exp\left(\dfrac{\hbar\omega_{01}}{k_B T}\right)-1}$$

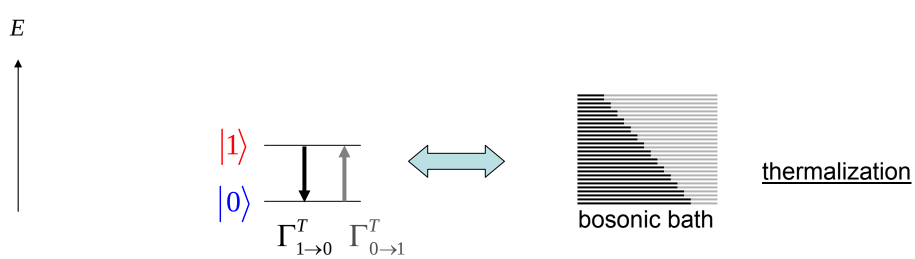
Absorbtion

Einstein's theory of A and B coefs.

09-V-16a

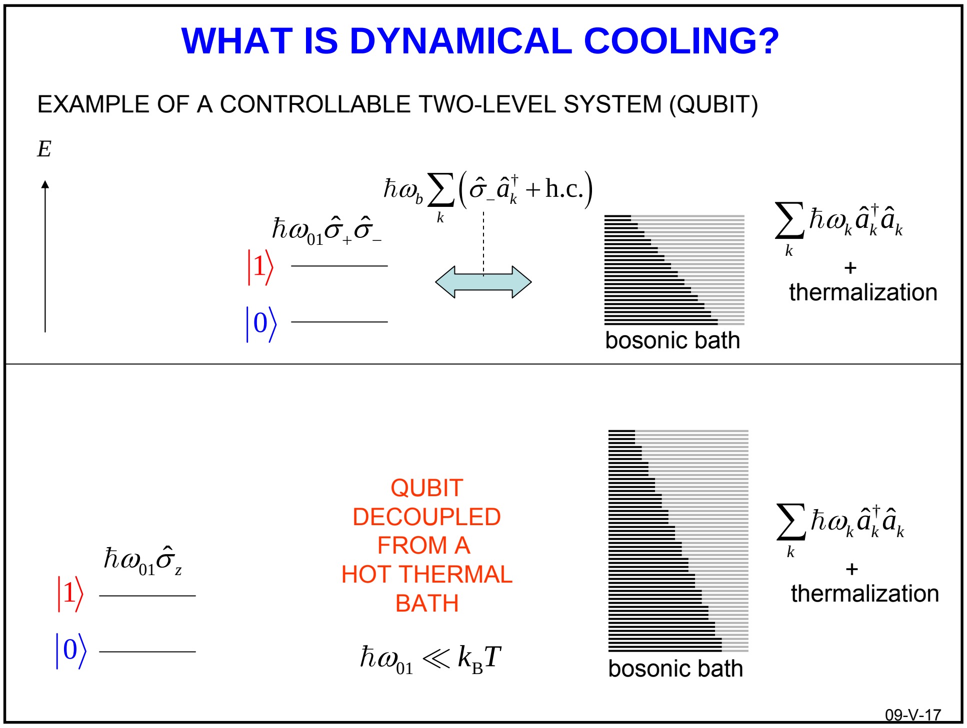
EQUILIBRIUM COOLING

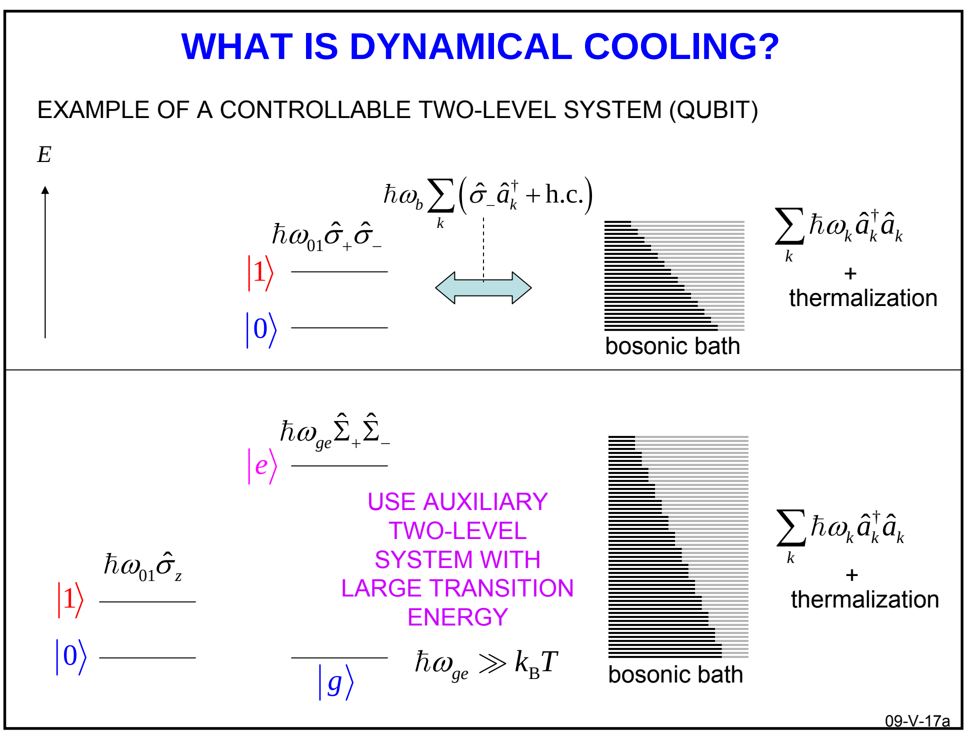
EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)



$$\frac{\Gamma_{0\to 1}^{T}}{\Gamma_{1\to 0}^{T}} = \exp\left(\frac{\hbar\omega_{01}}{k_B T}\right)$$

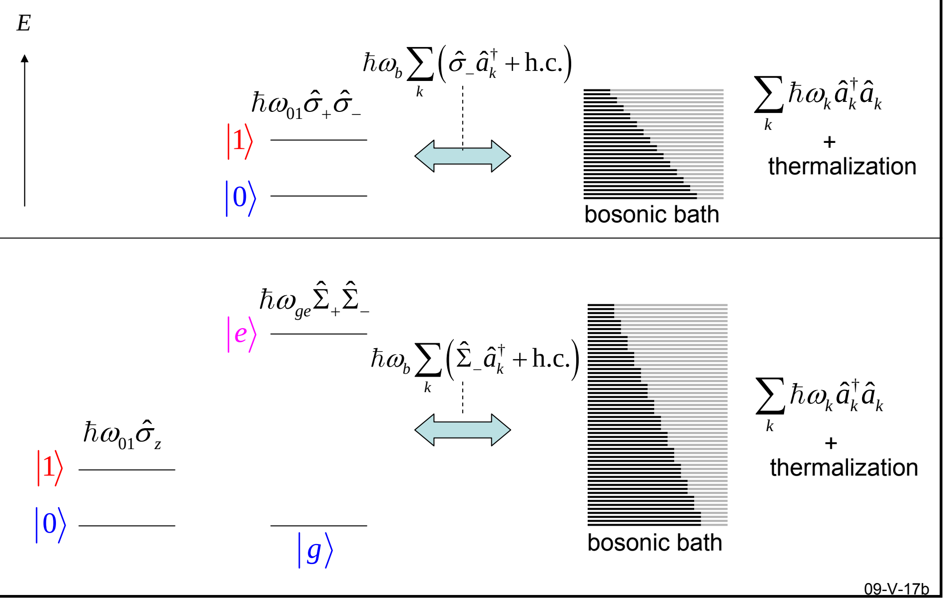
09-V-16b


WHAT IS DYNAMICAL COOLING?
EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)
E
$\hbar\omega_{01}\hat{\sigma}_{+}\hat{\sigma}_{-}$
$|1\rangle$
$|0\rangle$
$\hbar\omega_{b}\sum_{k}\left(\hat{\sigma}_{-}\hat{a}_{k}^{\dagger}+\mathrm{h.c.}\right)$
bosonic bath
$\sum_{k}\hbar\omega_{k}\hat{a}_{k}^{\dagger}\hat{a}_{k}$
+
thermalization
$\hbar\omega_{01}\hat{\sigma}_{z}$
$|1\rangle$
$|0\rangle$
QUBIT DECOUPLED FROM A HOT THERMAL BATH
$\hbar\omega_{01} \ll k_{\mathrm{B}}T$
bosonic bath
$\sum_{k}\hbar\omega_{k}\hat{a}_{k}^{\dagger}\hat{a}_{k}$
+
thermalization
09-V-17


WHAT IS DYNAMICAL COOLING?
EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)
E
$\hbar\omega_{01}\hat{\sigma}_{+}\hat{\sigma}_{-}$
$|1\rangle$
$|0\rangle$
$\hbar\omega_{b}\sum_{k}\left(\hat{\sigma}_{-}\hat{a}_{k}^{\dagger}+\mathrm{h.c.}\right)$
bosonic bath
$\sum_{k}\hbar\omega_{k}\hat{a}_{k}^{\dagger}\hat{a}_{k}$
+
thermalization
$\hbar\omega_{ge}\hat{\Sigma}_{+}\hat{\Sigma}_{-}$
$|e\rangle$
USE AUXILIARY TWO-LEVEL SYSTEM WITH LARGE TRANSITION ENERGY
$\hbar\omega_{01}\hat{\sigma}_{z}$
$|1\rangle$
$|0\rangle$
$|g\rangle$
$\hbar\omega_{ge} \gg k_{\mathrm{B}}T$
bosonic bath
$\sum_{k}\hbar\omega_{k}\hat{a}_{k}^{\dagger}\hat{a}_{k}$
+
thermalization
09-V-17a

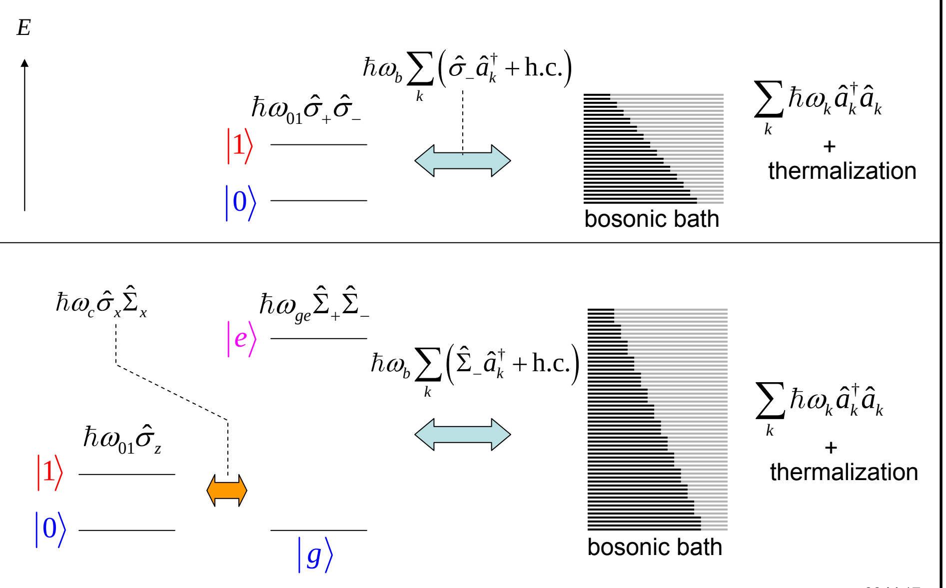
WHAT IS DYNAMICAL COOLING?

EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)



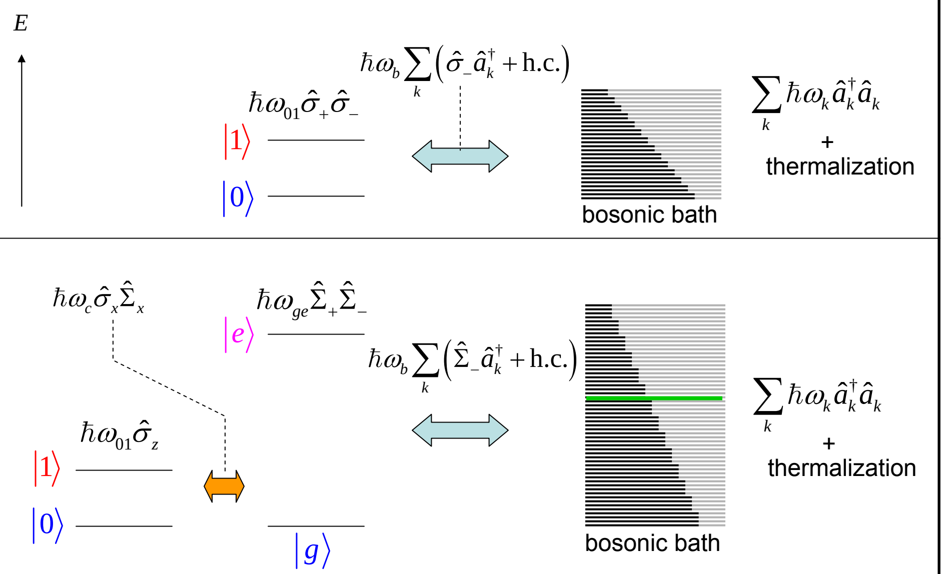
WHAT IS DYNAMICAL COOLING?

EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)



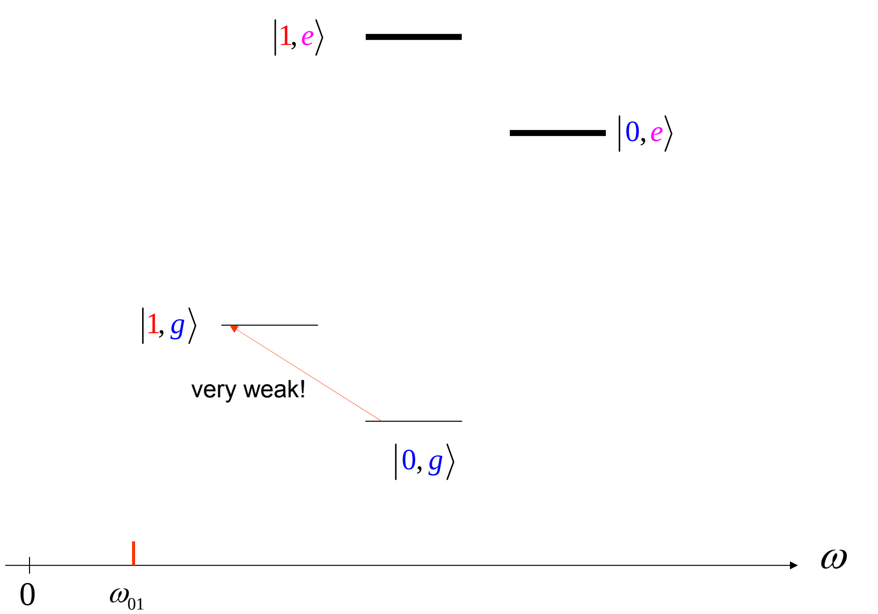
WHAT IS DYNAMICAL COOLING?

EXAMPLE OF A CONTROLLABLE TWO-LEVEL SYSTEM (QUBIT)



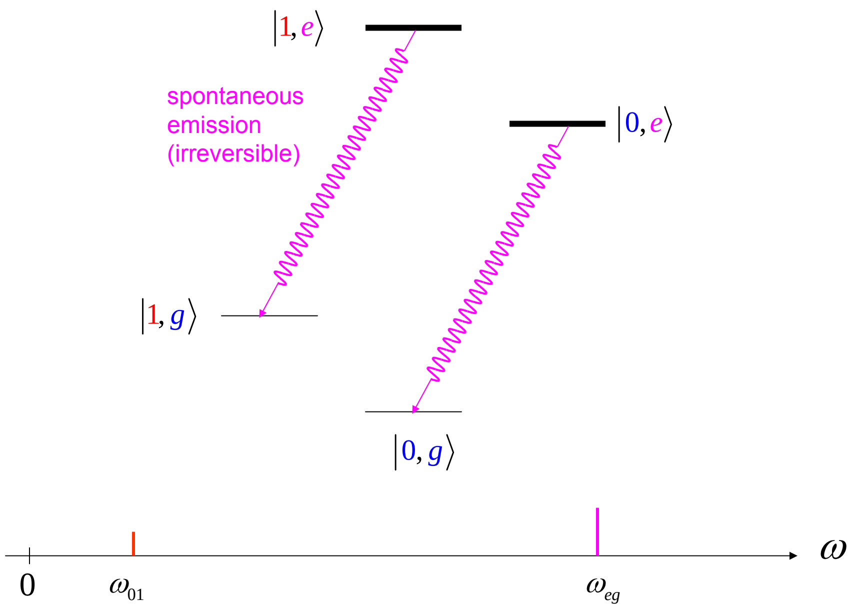
09-V-17d

COOLING BY IRRADIATION!



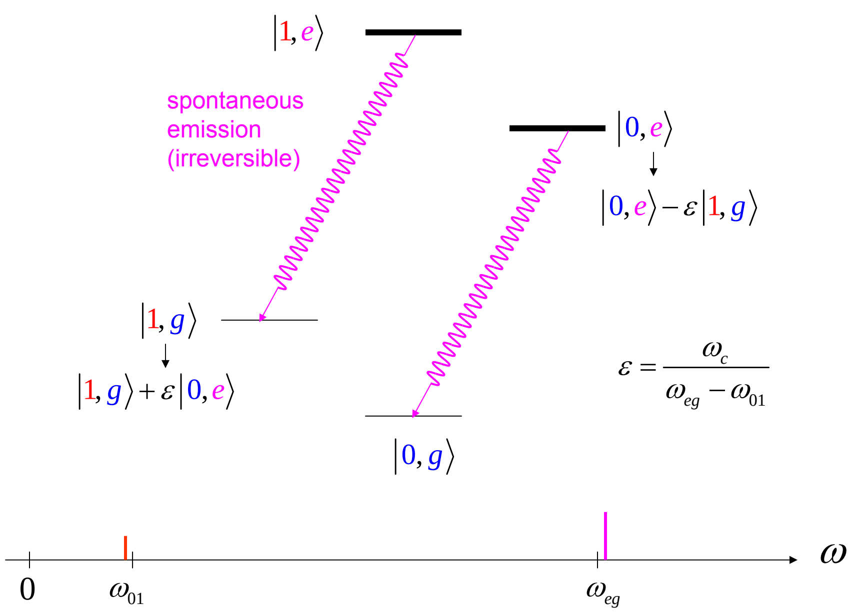
09-V-18

COOLING BY IRRADIATION!



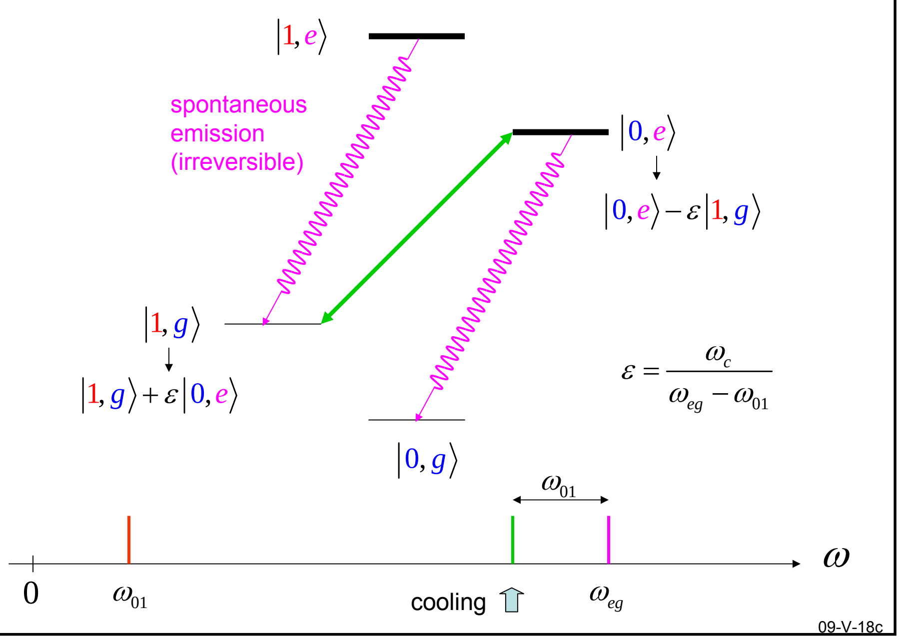
09-V-18a

COOLING BY IRRADIATION!

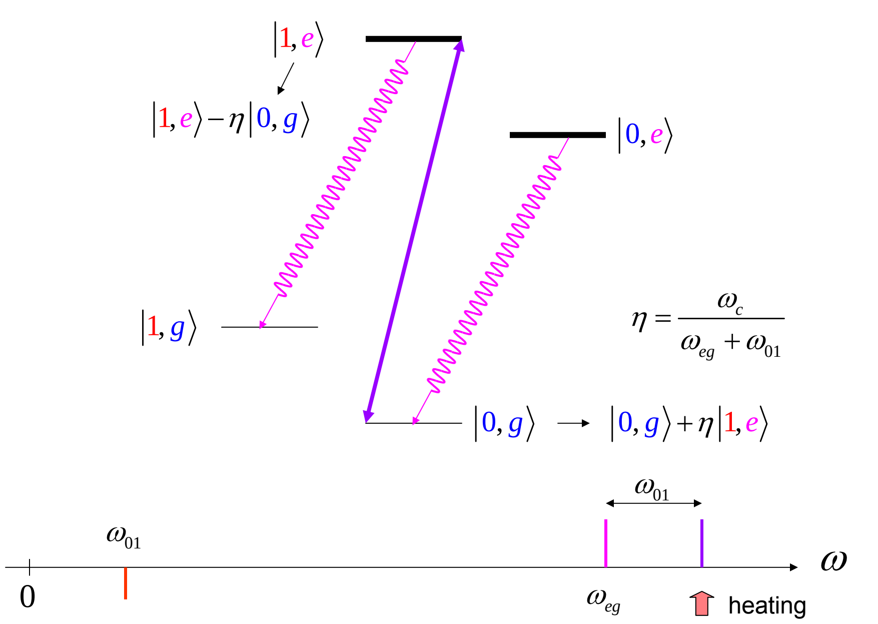


09-V-18b

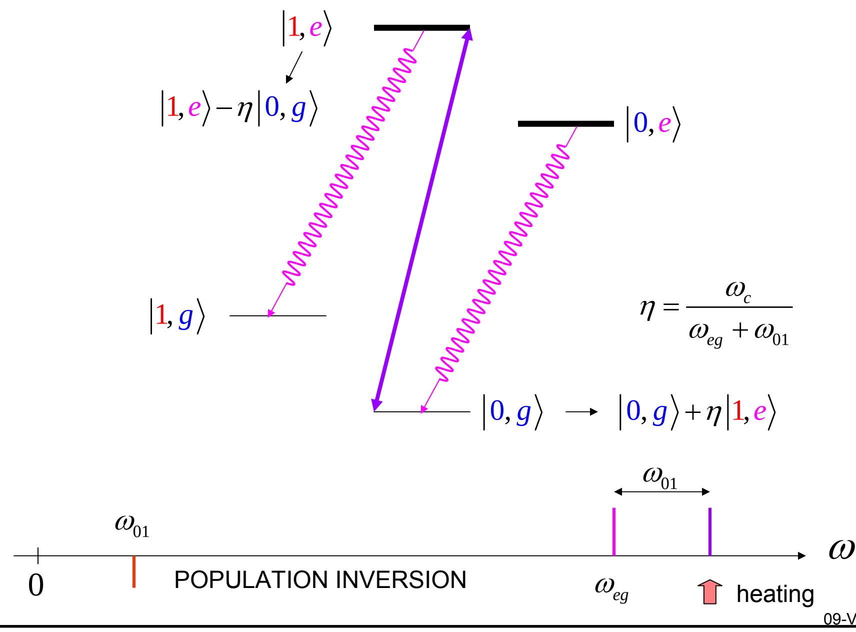
COOLING BY IRRADIATION!



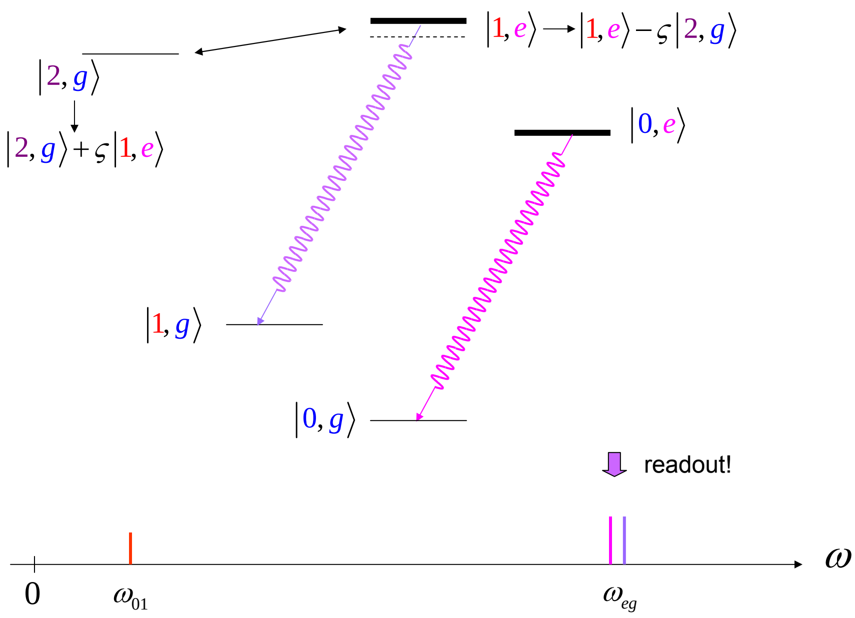
HEATING AND POPULATION INVERSION



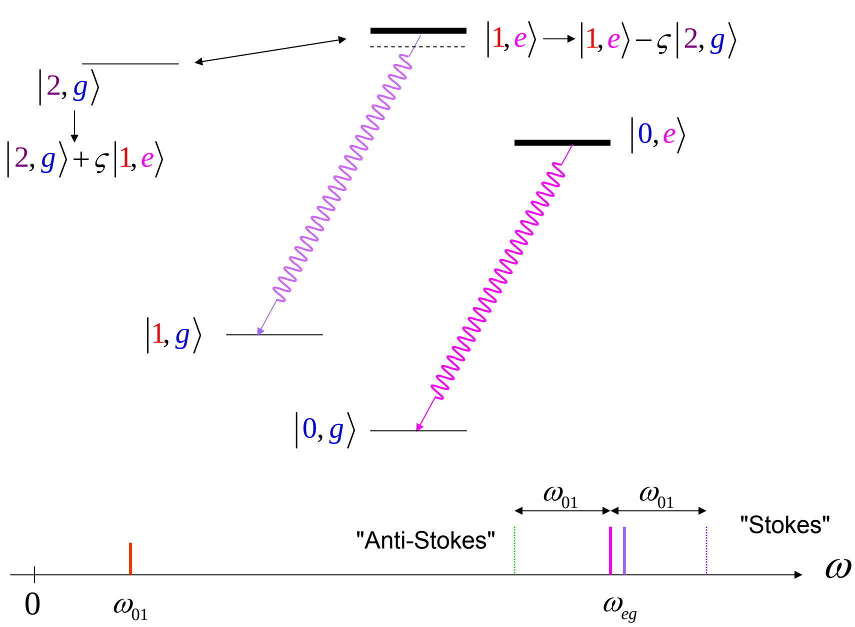
HEATING AND POPULATION INVERSION



READOUT



LINK WITH RAMAN PROCESSES



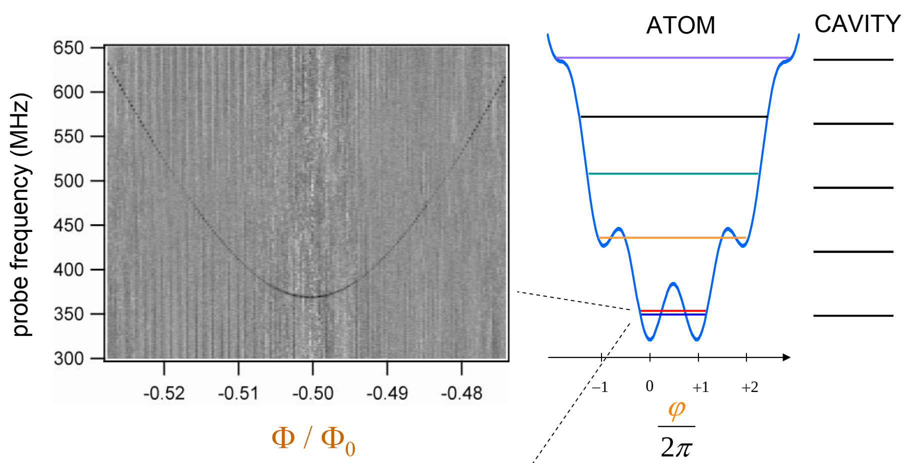
09-V-18g

OUTLINE

1. Interaction between atom excitation and photons
2. Measuring photon number with an atom
3. Principle of dynamical cooling
4. Cooling and population inversion of fluxonium

09-V-5d

MEASUREMENT OF 0-1 TRANSITION FOR THE FLUXONIUM NEAR HALF-FLUX QUANTUM

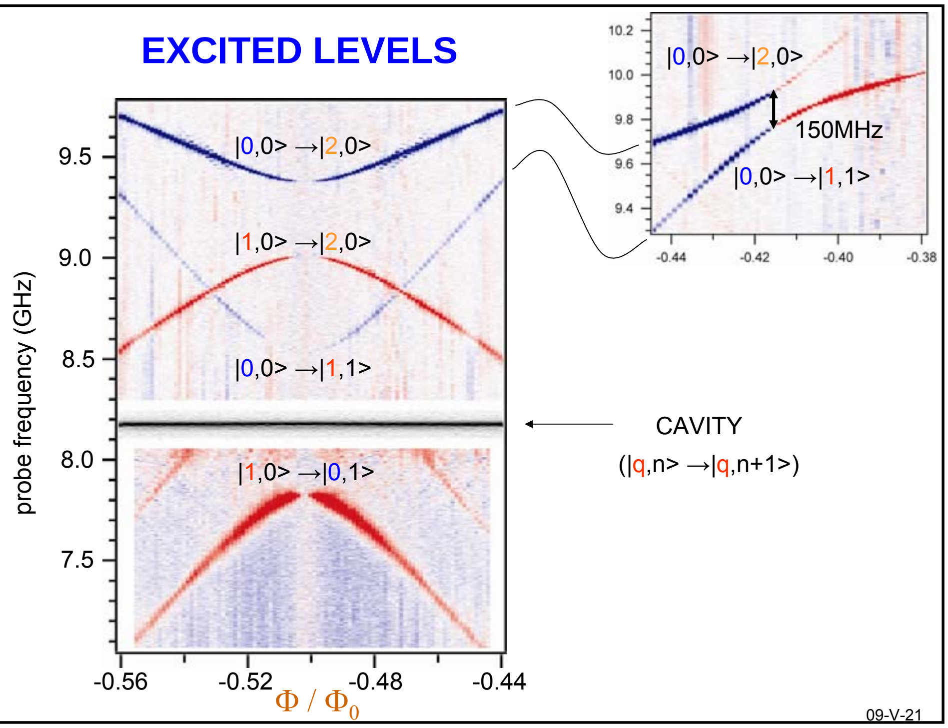


20mK → 400MHz

Koch et al., PRL 103, 217004 (2009)
Manucharyan et al., Science 326, 113 (2009)

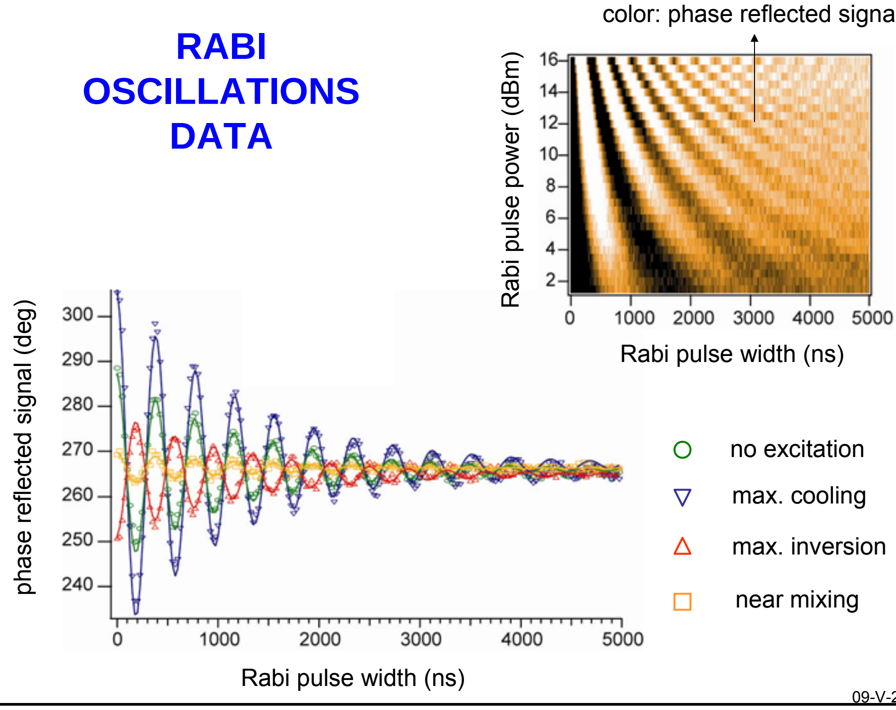
09-V-20

EXCITED LEVELS



09-V-21

RABI OSCILLATIONS DATA



09-V-22

END OF PRESENTATION