國立清華大學
NATIONAL TSING HUA UNIVERSITY

2018 AMO Summer School

# Quantum optics with superconducting artificial atom


許耀銓
Io-Chun, Hoi

# Outline

1. Introduction to quantum electrical circuits
2. Introduction to superconducting artificial atom
3. Quantum optics with superconducting artificial atom
- Single atom scattering
- Single-Photon Router
- An artificial atom in front of a mirror
- Amplification without population inversion

# Introduction to quantum electrical circuits

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# Conventional electrical circuits

Basic elements:

First transistor 1947

Fig. from Intel

Dual-core Intel processor

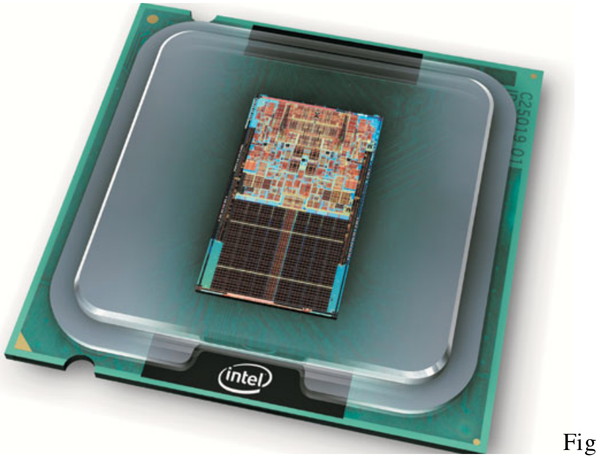


Fig. from Intel

Properties:

*Deterministic

*No quantum mechanics

*No superposition principle

*No quantization of fields

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# Quantum electrical circuits

Macrosopic system

Coherent superposition states:

Charge $Q$

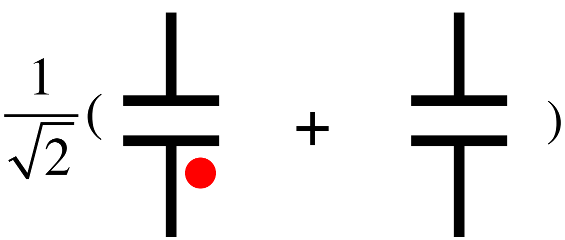
Flux $\Phi$

Properties:

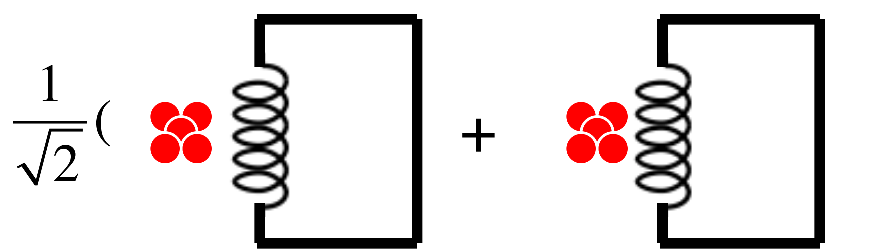
The superposition states collapse when measure.

Probabilistic character.

Charge on a capacitor:



Current or magnetic flux in an inductor:



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# Introduction to superconducting artificial atom

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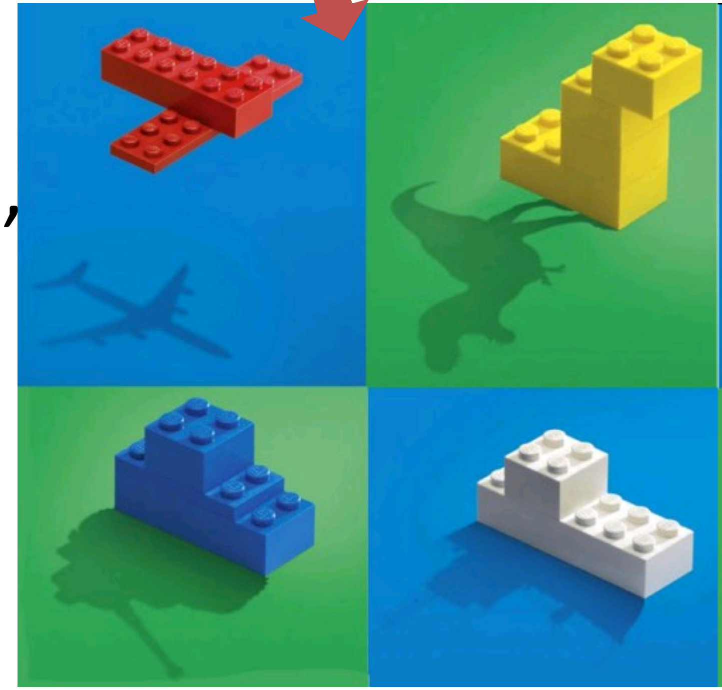
# Superconducting circuits are like LEGOS

**What's good about circuits?**

- **Circuits are like LEGOs!**



a few elementary building blocks,
gazillions of possibilities!

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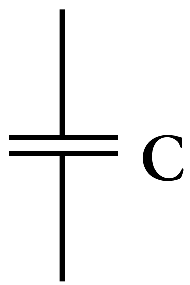
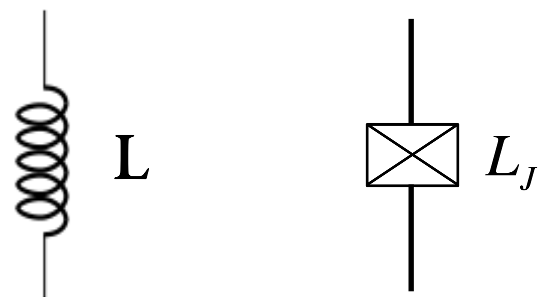
# Basic Elements of Superconducting Circuits

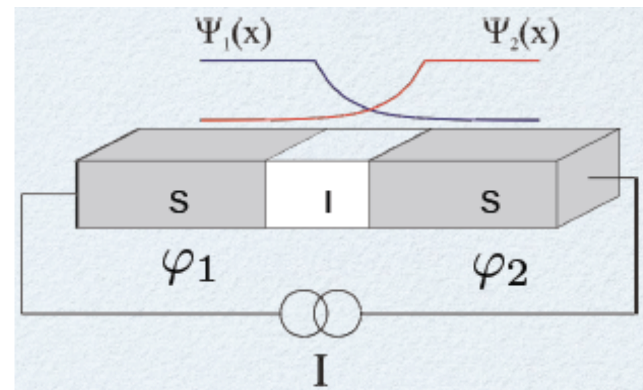
Dissipationless!

Josephson Junction:
Non-disspative
nonlinear inductance

Tunnel barrier between
two superconductors




Capacitance

Inductance

$$I = I_c \sin\phi \qquad \frac{d\phi}{dt} = \frac{2e}{\hbar}V$$

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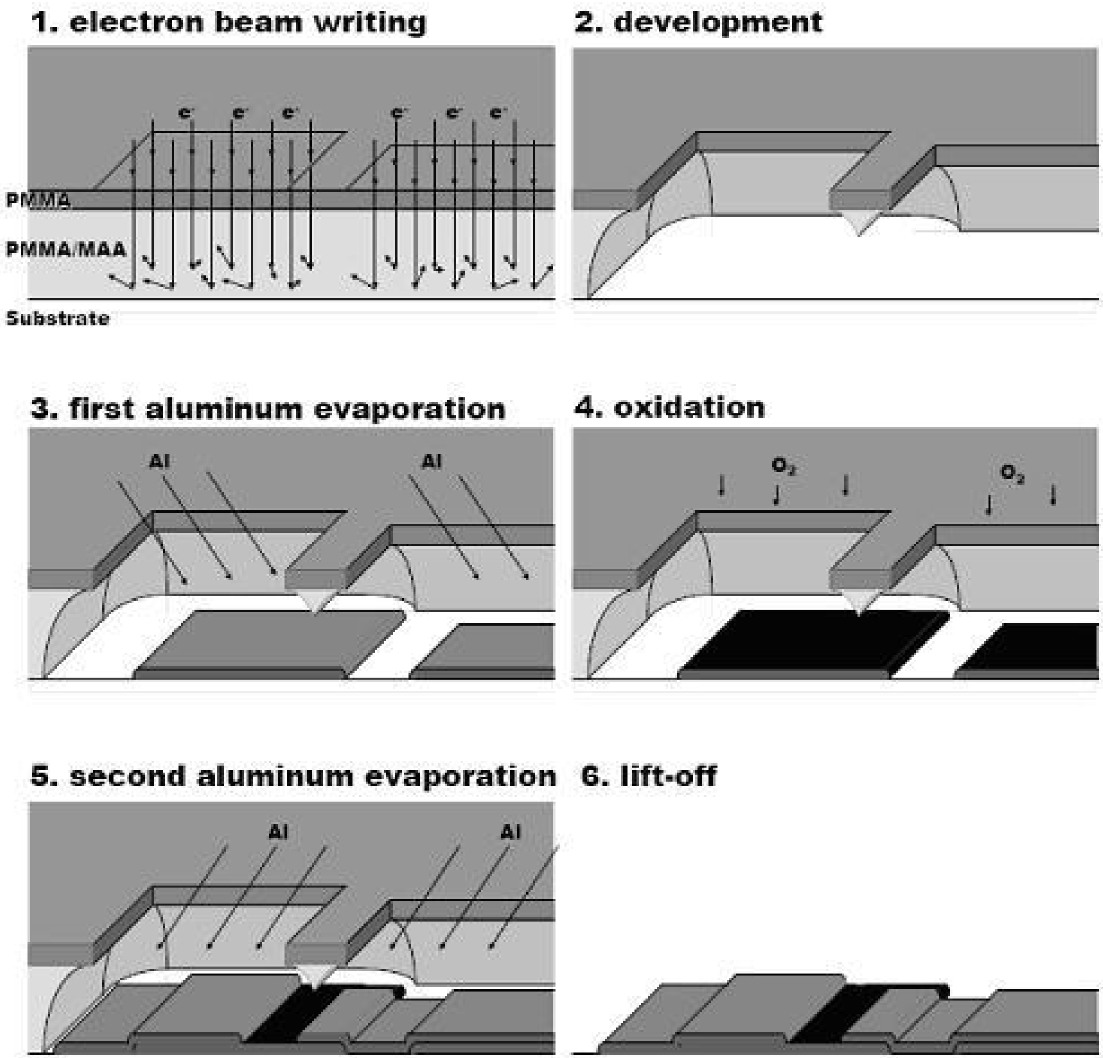
# Fabrication of Josephson Junction

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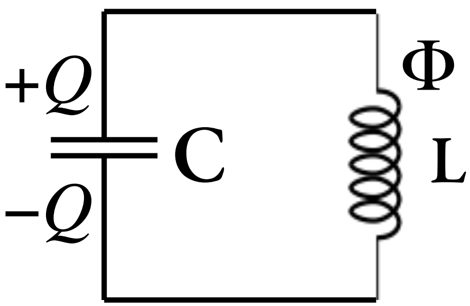
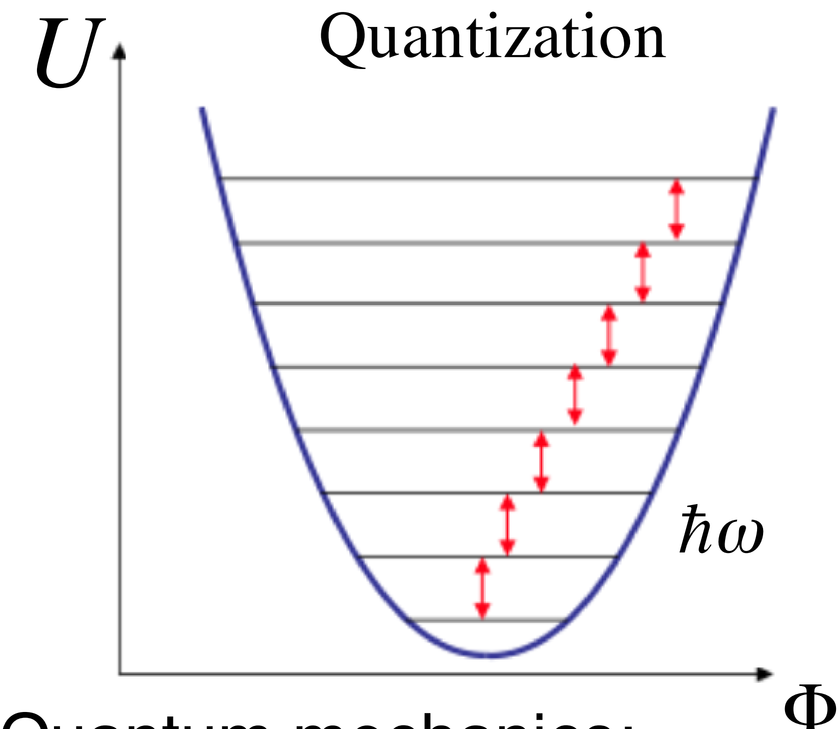
# Constructing linear quantum electrical circuits




$$\omega = \frac{1}{\sqrt{LC}} \sim GHz$$




## Classical physics:

$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

$$H = \frac{p^2}{2m} + \frac{1}{2}kx^2$$

Analogy with a moving particle in a harmonic potential

## Quantum mechanics:

$$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L} \quad H = \hbar\omega(a^\dagger a + \frac{1}{2}) \quad \left[\hat{\Phi},\hat{Q}\right] = i\hbar$$

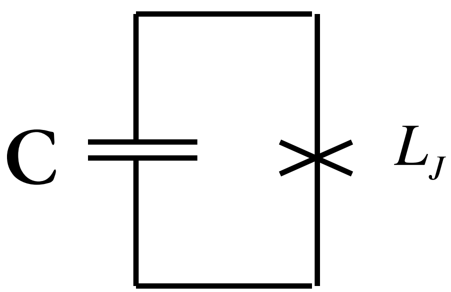
M. H. Devoret, A. Wallraff, and J. M. Martinis. Superconducting qubits: A short review. http://arxiv.org/abs/cond-mat/0411174v1, 2004.

# Constructing nonlinear Quantum circuit:

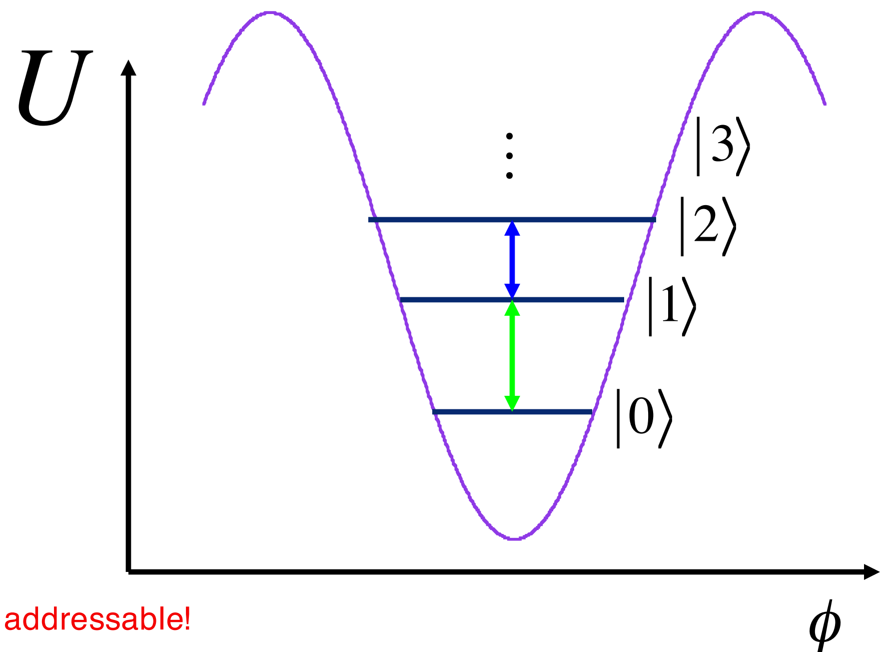
## Artificial atom

Replace linear inductance by Josephson junction (Nonlinear inductance)

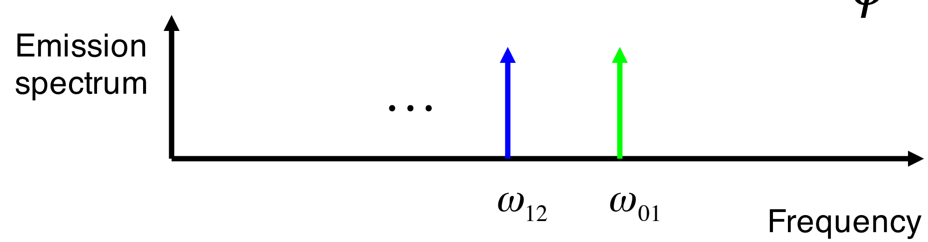
$$U = -E_J \cos\phi$$




$$L_J = \frac{\hbar}{4eI_c \left| \cos\left( \pi \frac{\Phi_{ext}}{\Phi_0} \right) \right|}$$




Transition become addressable!




Anharmonicity:
$\alpha = \omega_{01} - \omega_{12}$

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# How to operate electrical circuits quantum mechanically?

## Avoid dissipation

Avoid broaden energy levels

## Work at low temperatures

Provide reset of the circuit(Ground state)

$$k_B T << \hbar\omega << \Delta_s$$ Superconducting gap energy

$\omega / 2\pi \sim 4 - 8GHz$ $T @ mK$

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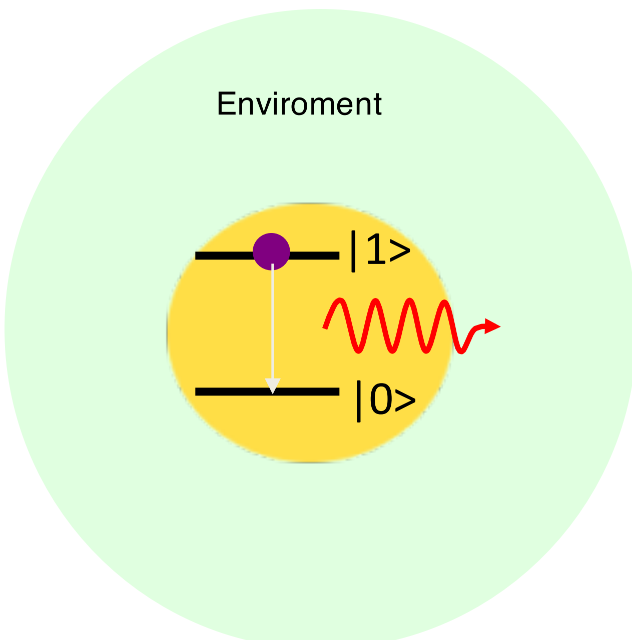
# Decoherence of artificial atom

(Effect from the environment)

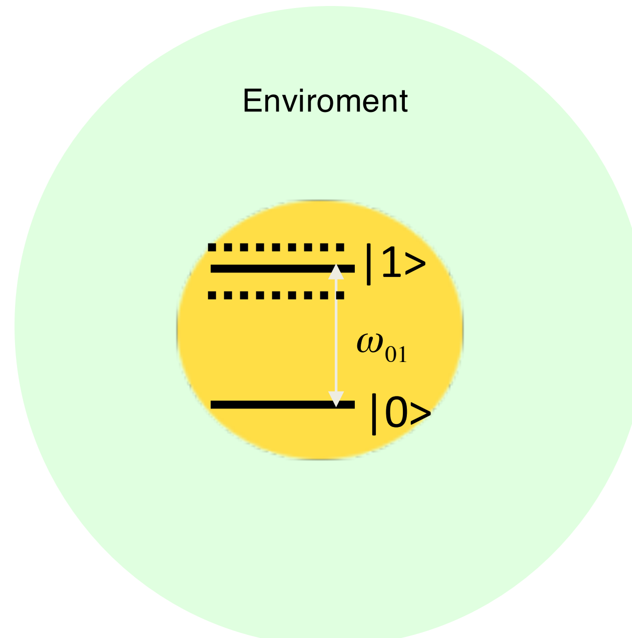
Relaxation rate $\Gamma_{01}$




Random switching

$|1\rangle \rightarrow |0\rangle$

Pure dephasing rate $\Gamma_{\varphi}$




$\omega_{01} \rightarrow \omega_{01} + \delta\omega_{01}(t)$

Phase randomization $e^{-i\omega_{01}t}$

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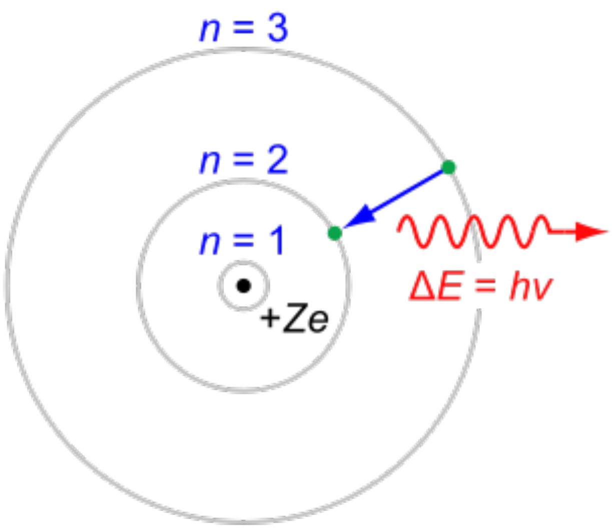
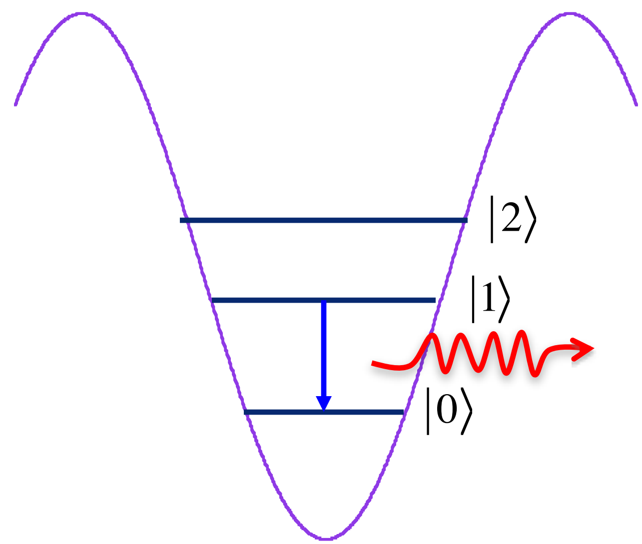
# Studying/Engineering the matter-light interaction




Natural atom

Optical photons

Superconducting artificial atom

Microwave photons

Compare with optical photon, the frequency of microwave photon is $10^6$ less.

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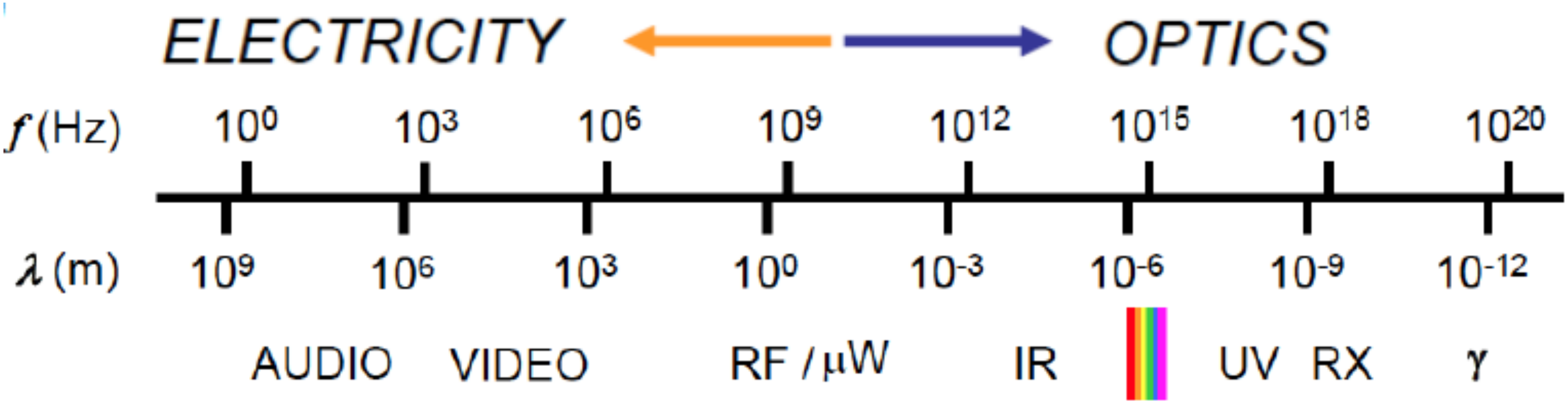
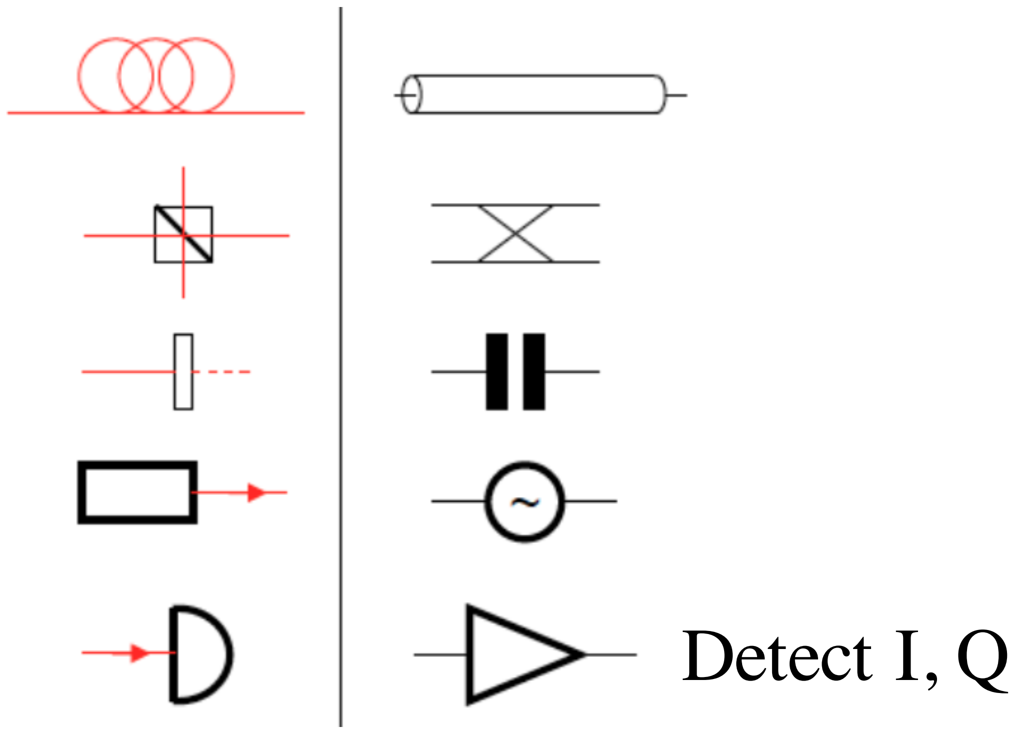

ELECTRICITY
OPTICS
f (Hz)
10^0
10^3
10^6
10^9
10^12
10^15
10^18
10^20
λ (m)
10^9
10^6
10^3
10^0
10^-3
10^-6
10^-9
10^-12
AUDIO
VIDEO
RF / μW
IR
UV
RX
γ

# Comparison of the toolboxes

Quantum optics | Superconducting circuits




Optical photons | Microwave photons

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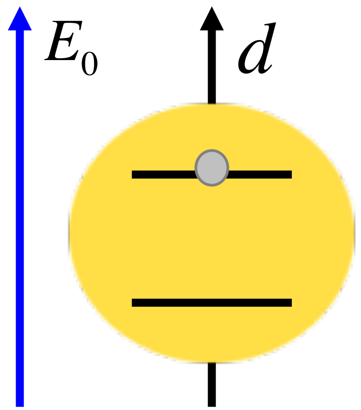
# Advantages of quantum circuit




Atom-light interaction on single photon level

1. Photons and "atom" interaction can be engineered
2. The photons can be guided by waveguides; beam alignment is not needed.
3. Standard on-chip fabrication technique
4. Tunable transition energy of the "atom"
5. Mechanical stable

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# Quantum optics with superconducting artificial atom

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# Resonant scattering

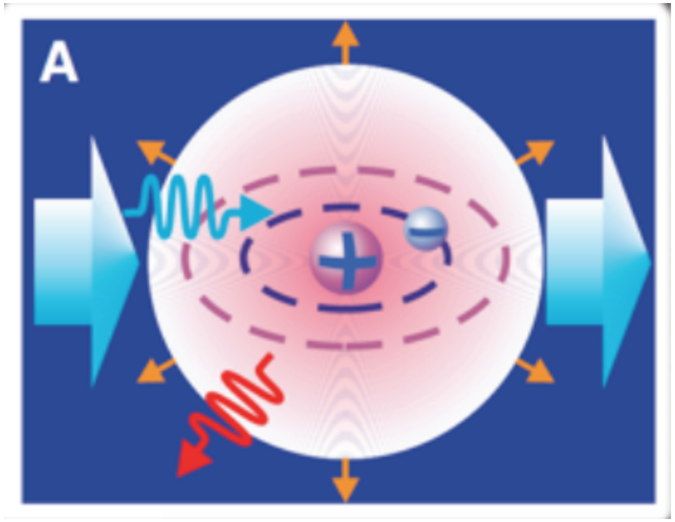
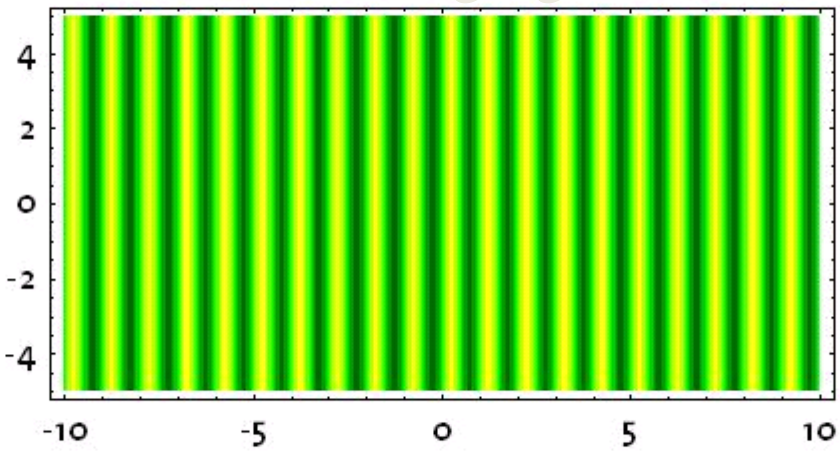


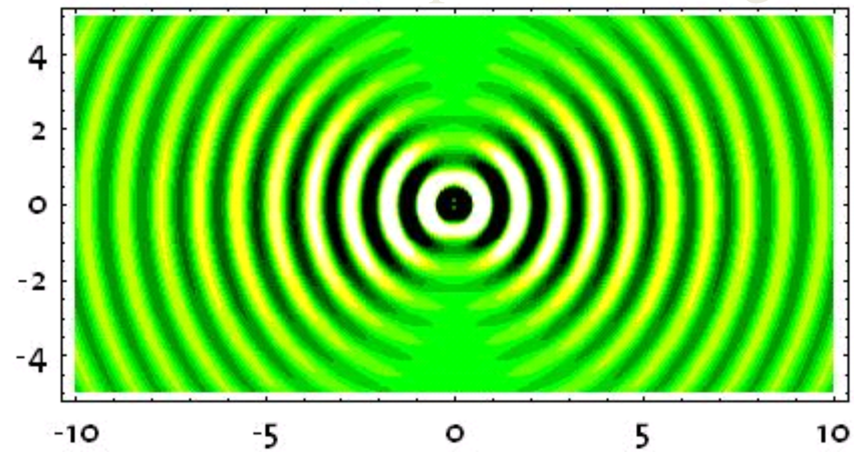

Fig: O. Astafiev, *et al*. **327**, 840 Science (2010)

# Resonant scattering in 3D space

Incoming light




Atom/dipole emits light



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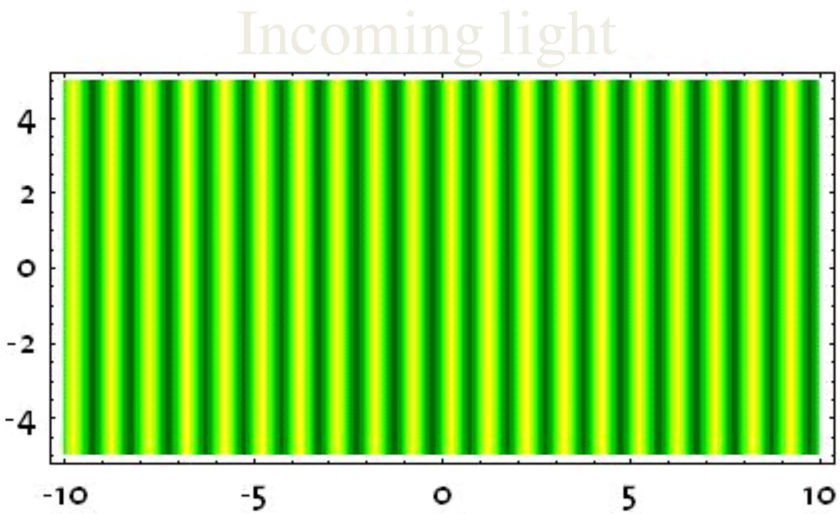
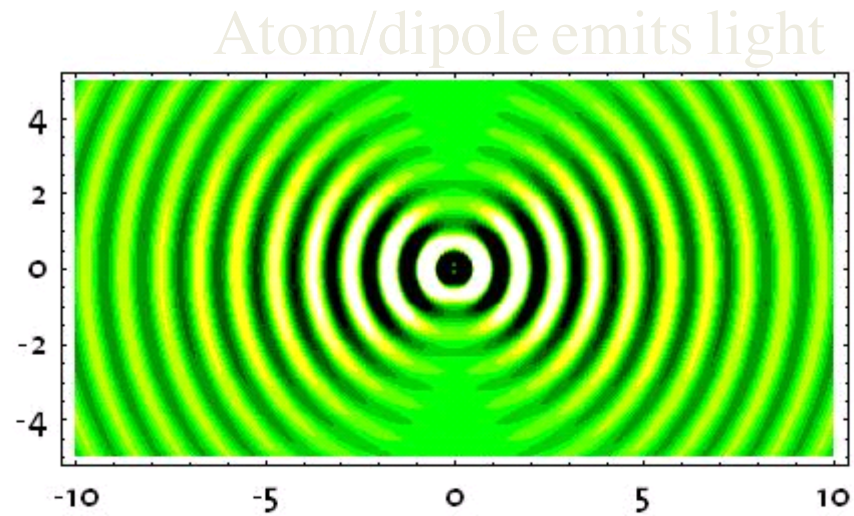
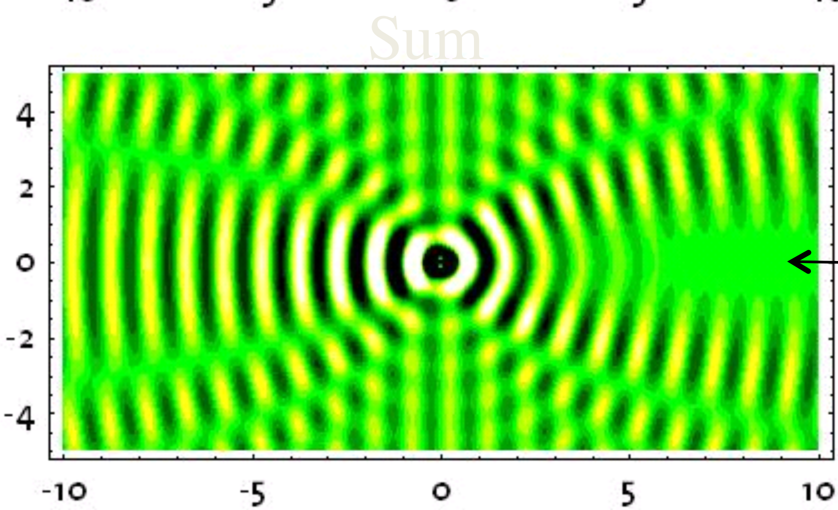
# Resonant scattering in 3D space



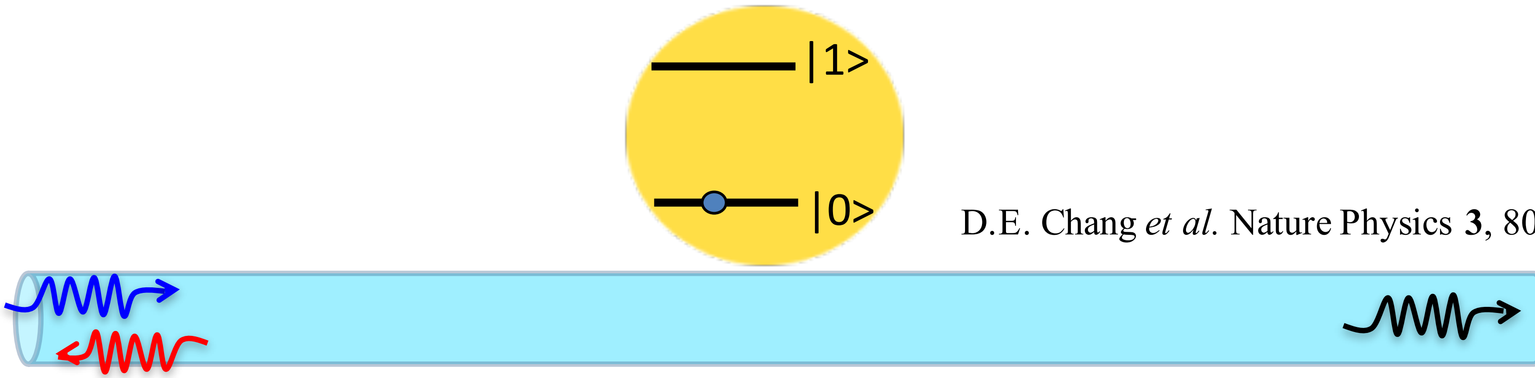

The extinction signal is due to interference

G. Wrigge *et al*. Nature Phys. **4**, 60 (2008). M. Tey *et al*. Nature Phys. **4**, 924 (2008).

Spatial mode mismatch

Fig. from U. Håkanson

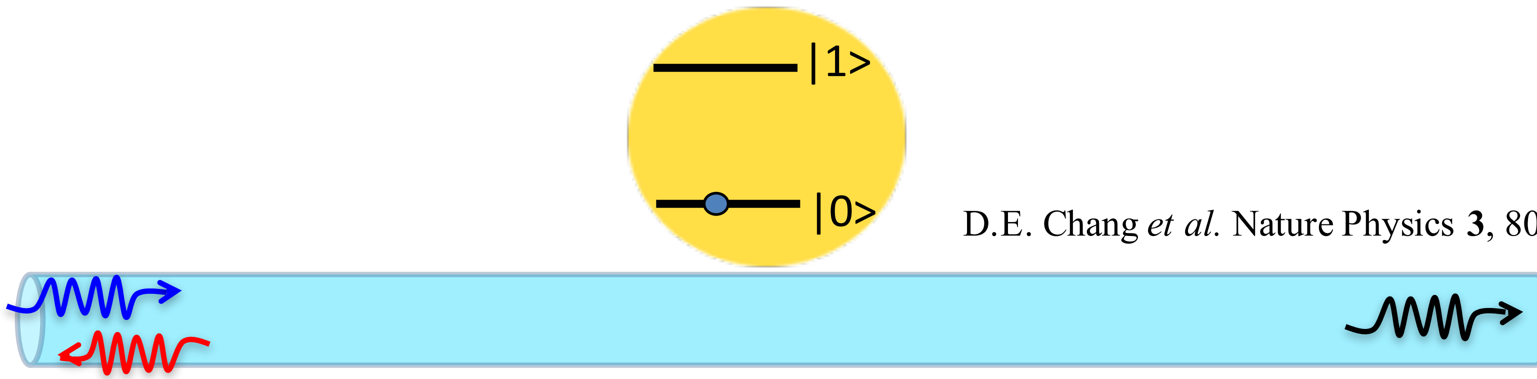
# Resonant scattering in 1D waveguide




D.E. Chang *et al.* Nature Physics **3**, 807(2007)

Fully coherent: no transmission, perfect reflection.

# Resonant scattering in 1D waveguide




D.E. Chang *et al.* Nature Physics **3**, 807(2007)

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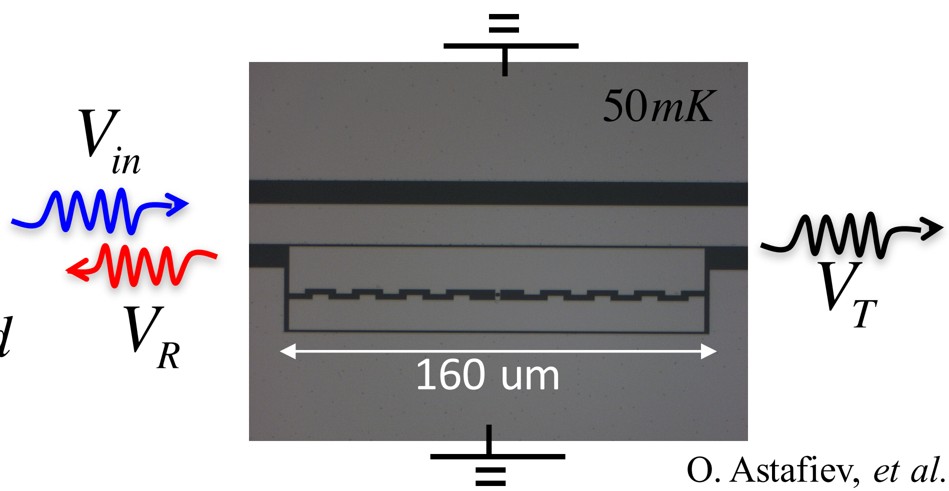


Point like atom/dipole! $\lambda >> d$

$\lambda \sim cm$ Wavelength of EM field

$d \sim \mu m$ Size of "atom"

Relaxation dominated by transmission line.

O. Astafiev, *et al.* **327**, 840 Science (2010)
IoChun, Hoi *et al.* PRL **107**, 073601 (2011)

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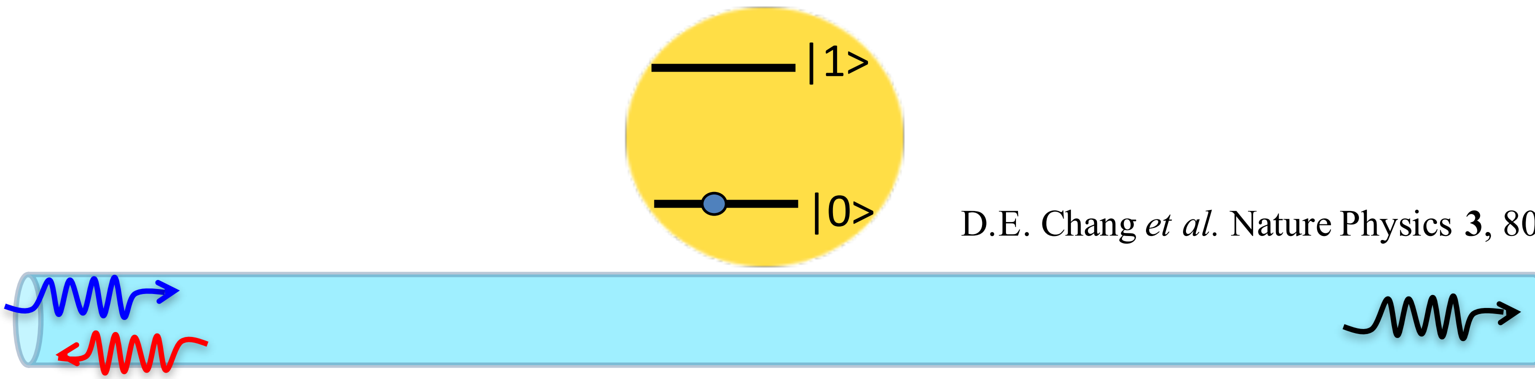
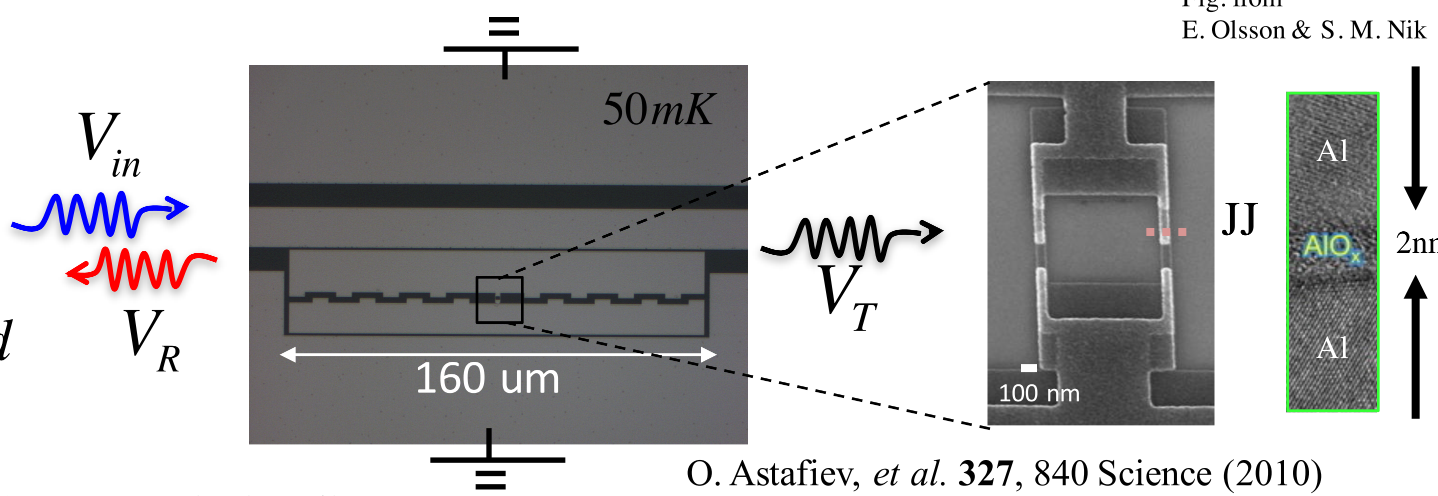
# Resonant scattering in 1D waveguide




D.E. Chang *et al.* Nature Physics **3**, 807(2007)

Fully coherent: no transmission, perfect reflection.

Fig. from
E. Olsson & S. M. Nik

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Relaxation dominated by transmission line.

O. Astafiev, *et al.* **327**, 840 Science (2010)
IoChun, Hoi *et al.* PRL **107**, 073601 (2011)

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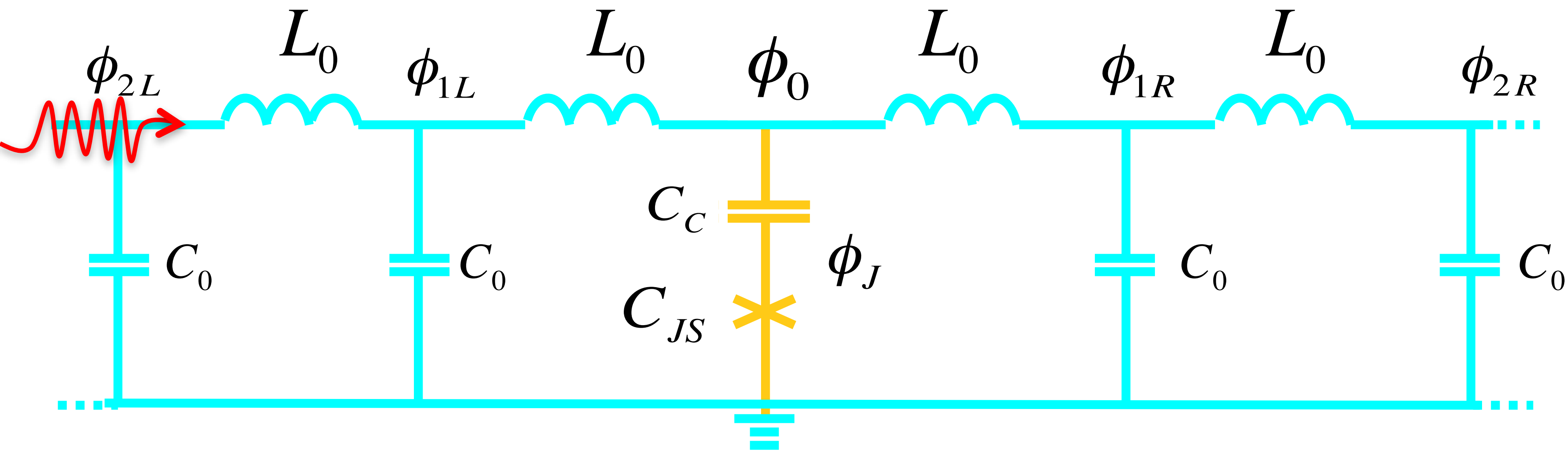
# Quantum circuit model




Relaxation rate into 1D transmission line,
indicates the strength of coupling!

$$\Gamma_{10} \simeq \frac{\omega_{01}^2 C_c^2 Z}{4C_\Sigma} \qquad C_\Sigma = C_c + C_{JS} \qquad Z = \sqrt{\frac{L_0}{C_0}}$$

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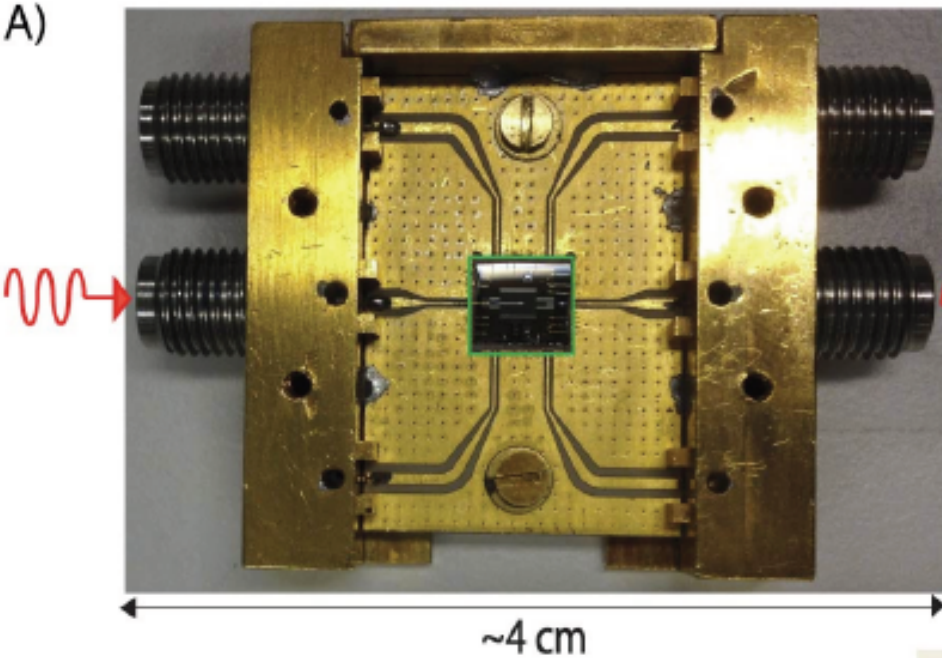
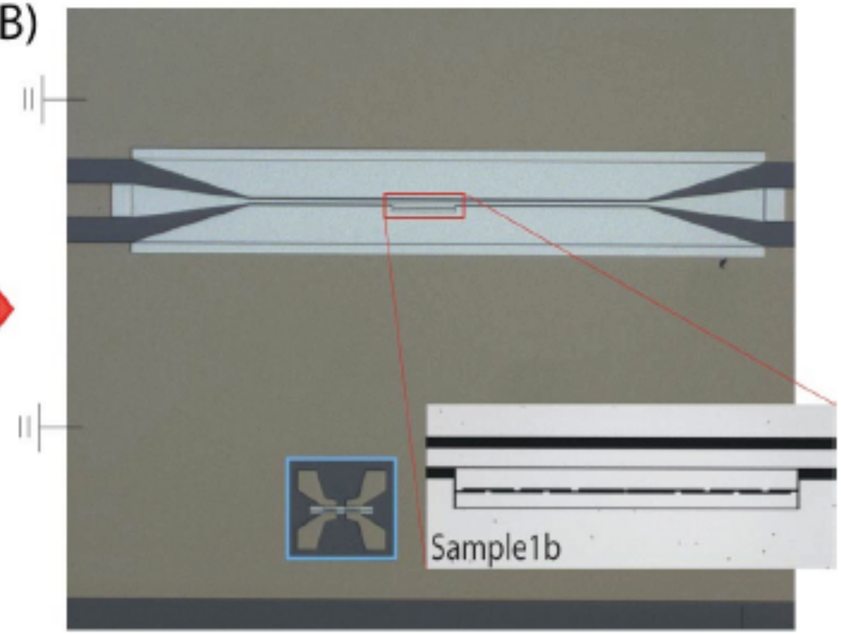
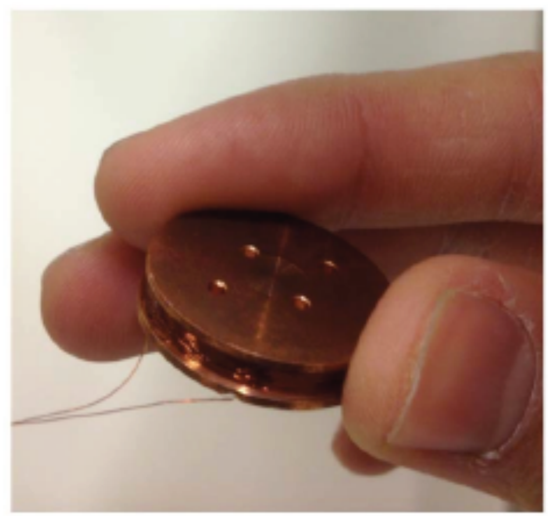
A)




B)



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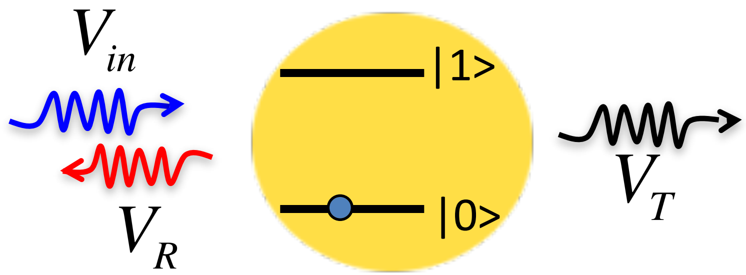
# Transmission and reflection

$$r = \frac{\langle V_R \rangle}{\langle V_{in} \rangle}$$




$$t = \frac{\langle V_T \rangle}{\langle V_{in} \rangle}$$

Reflection coefficient

$$r = -\frac{\Gamma_{10}}{2\gamma_{10}}\left[\frac{1 - i\delta\omega_p / \gamma_{10}}{1 + \left(\delta\omega_p / \gamma_{10}\right)^2 + \Omega_p^2 / \Gamma_{10}\gamma_{10}}\right]$$

Transmission coefficient

$$t = 1 + r$$

n resonance, low power

$$\left|r\left(\delta\omega_p = 0, \Omega_p \ll \gamma_{10}\right)\right| = \frac{\Gamma_{10}}{2\gamma_{10}} = \frac{1}{1 + 2\Gamma_\varphi / \Gamma_{10}}$$

$\delta\omega_p$ :Detuning
$\Gamma_{10}$ :Relaxation
$\Gamma_\varphi$ :Pure dephasing
$\gamma_{10} = \Gamma_{10} / 2 + \Gamma_\varphi$

Strong interaction limit:

$$\Gamma_{10} \gg \Gamma_\varphi \qquad \left|r\left(\delta\omega_p = 0, \Omega_p \ll \gamma_{10}\right)\right| \simeq 1$$

Fully coherent.

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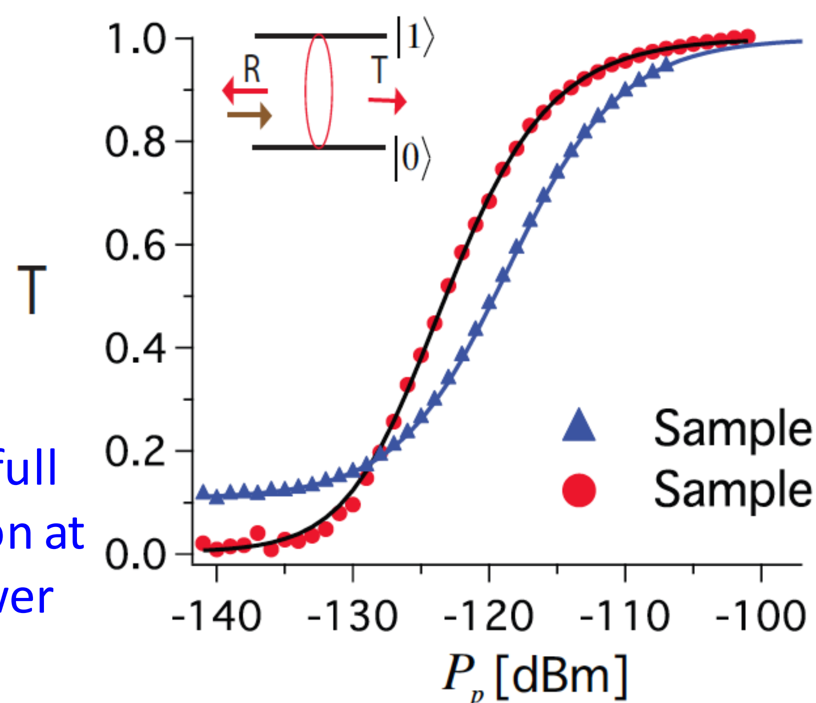
# Saturation of transmission

$$T = |t|^2$$




Almost full transmission at high power

Almost full reflection at low power

$$\langle N_P \rangle = \frac{P_P}{\hbar\omega_P(\Gamma_{10}/2\pi)}$$

Nonlinear nature of the atom!

| Sample | $E_J/h$ | $E_C/h$ | $E_J/E_C$ | $\omega_{10}/2\pi$ | $\omega_{21}/2\pi$ | $\Gamma_{10}/2\pi$ | $\Gamma_\phi/2\pi$ | Ext. |
|---|---|---|---|---|---|---|---|---|
| 1 | 12.7 | 0.59 | 21.6 | 7.1 | 6.38 | 0.073 | 0.018 | 90% |
| 2 | 10.7 | 0.35 | 31 | 5.13 | 4.74 | 0.041 | 0.001 | 99% |

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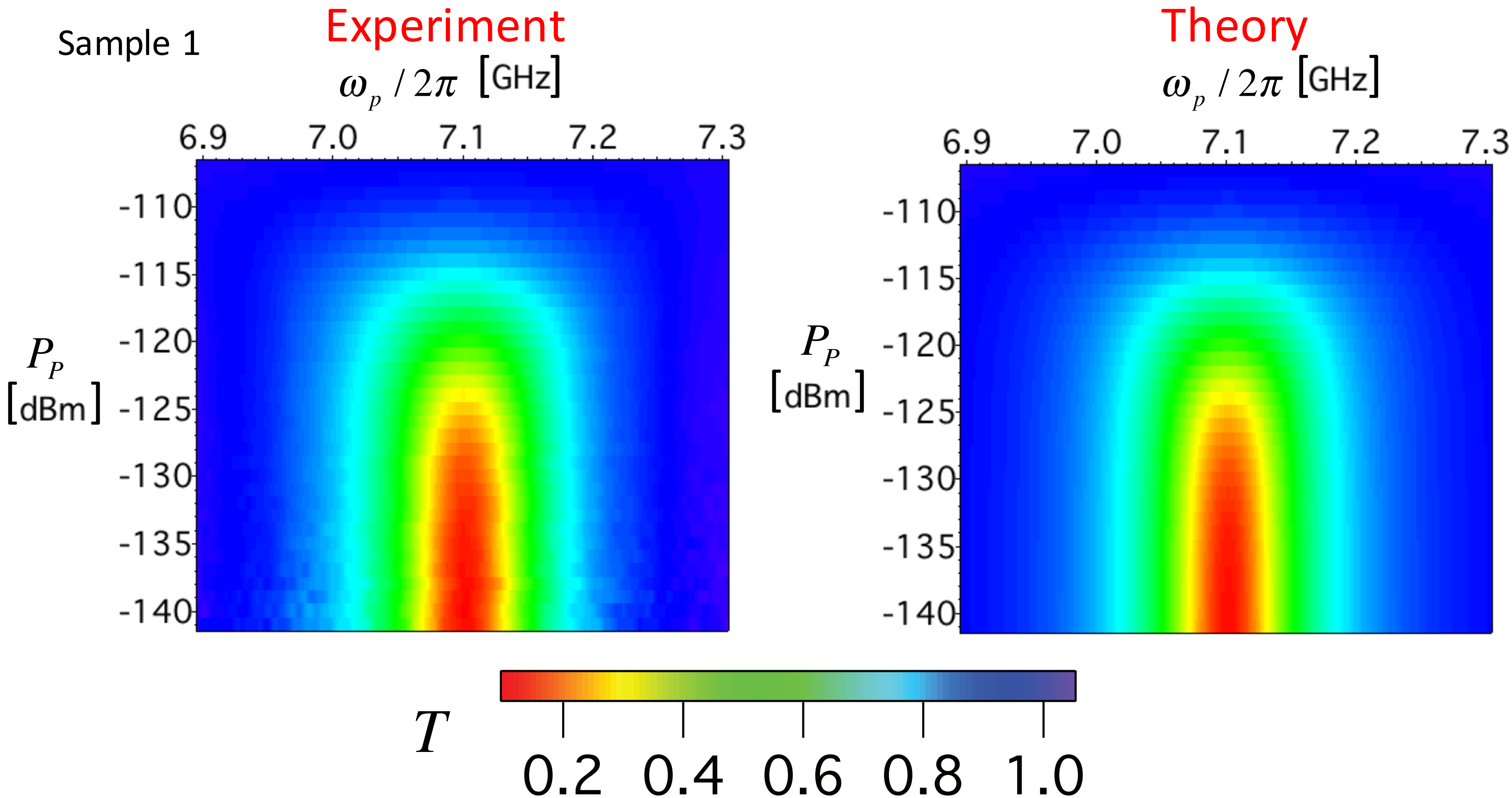
# Transmission comparing to theory

Sample 1

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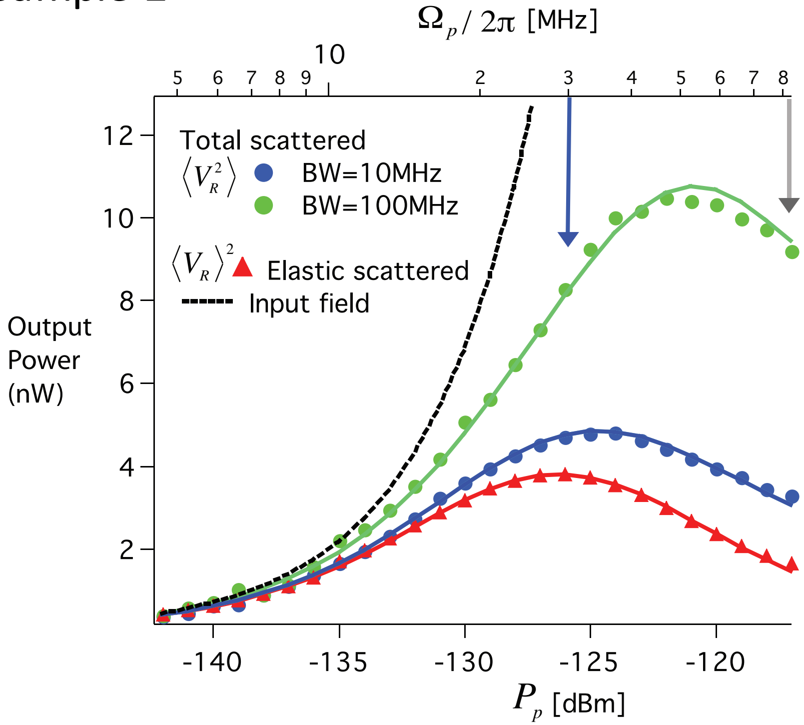
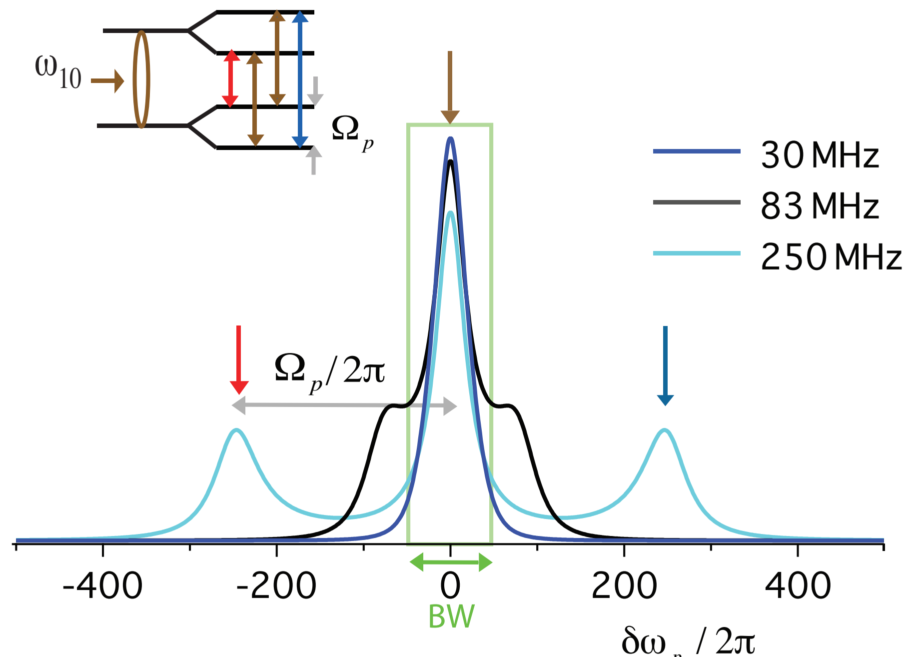
# Coherent vs Incoherent scattering

Sample 2




$$\Omega_p \ll \gamma_{10}$$

$$\langle V_{in} \rangle^2 \simeq \langle V_R \rangle^2 \simeq \langle V_R^2 \rangle \quad |r_{p,1}| \sim 1$$

I.-C. Hoi *et al.* Phys. Rev. Lett. **108**, 263601(2012)

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# Two-Tone Spectroscopy

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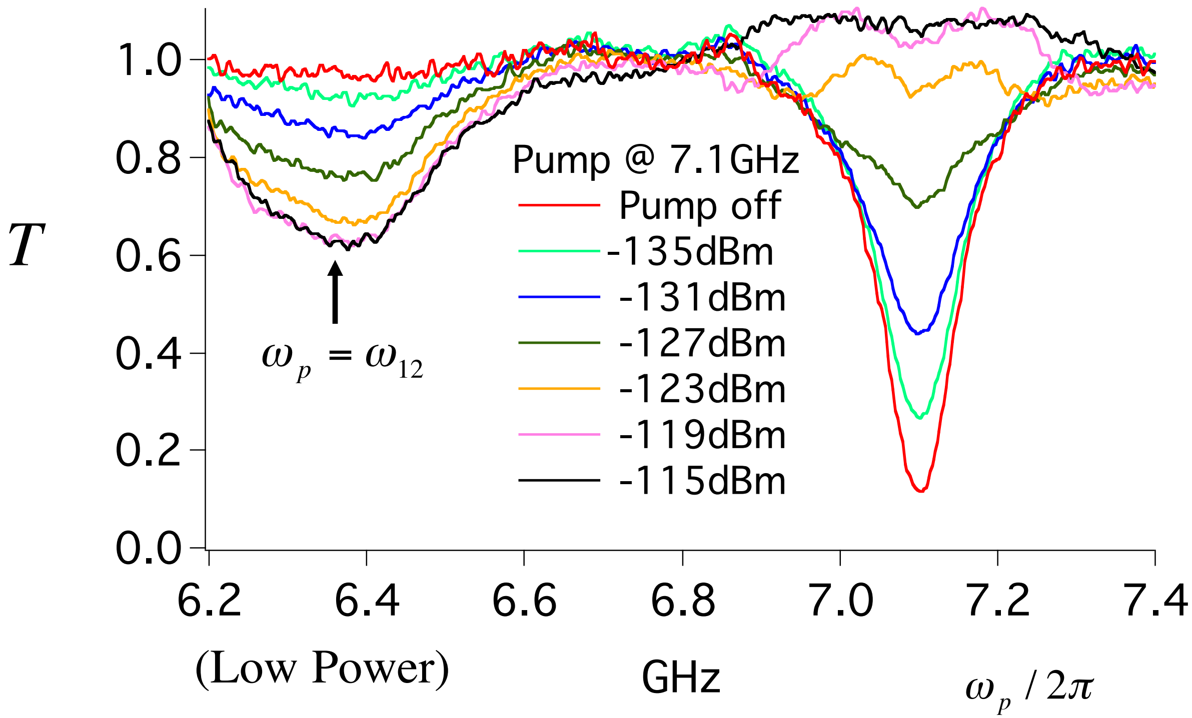
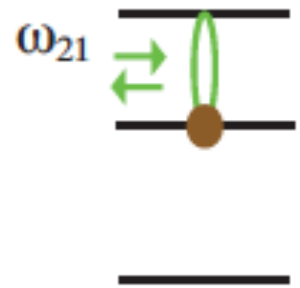
# Higher level effect




Anharmonicity:
$\alpha = \omega_{01} - \omega_{12} \simeq 720\text{MHz}$

$\omega_{12} / 2\pi = 6.38GHz$
$\omega_{10} / 2\pi = 7.1GHz$

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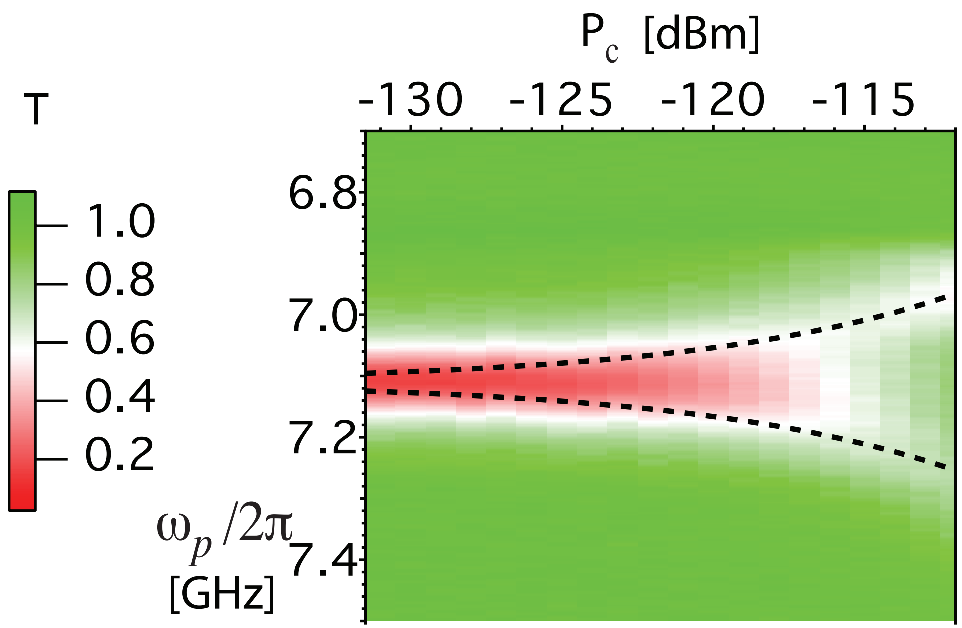
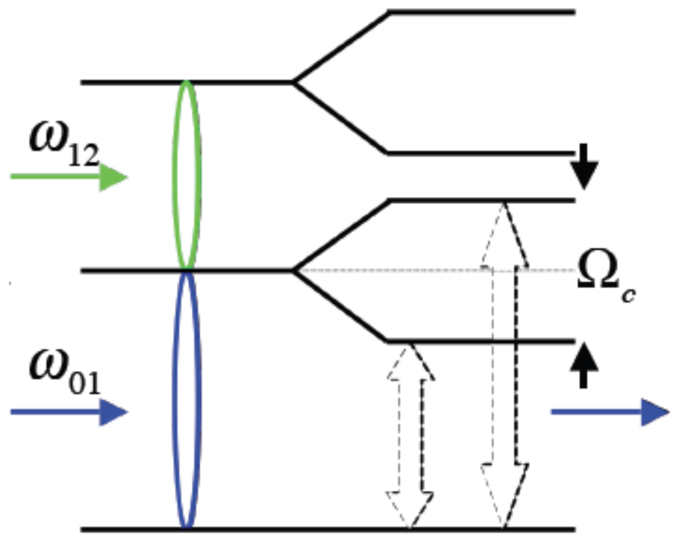
# Autler-Townes Splitting




$\Omega_P \ll \gamma_{10}$

A. A. Abdumalikov, Jr *et al.* PRL **104**, 193601 (2010)

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# The Single-Photon Router

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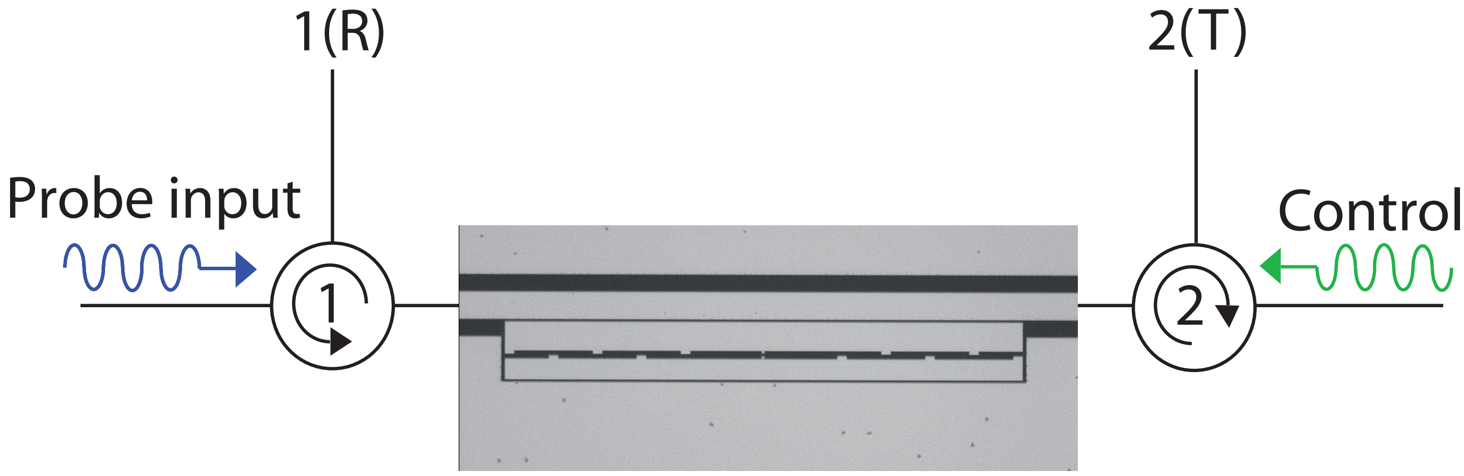
# The Single-Photon Router




By turning on or off the control tone, we can decide which port the input photons go to.

I.-C. Hoi *et al.* PRL **107**, 073601 (2011)

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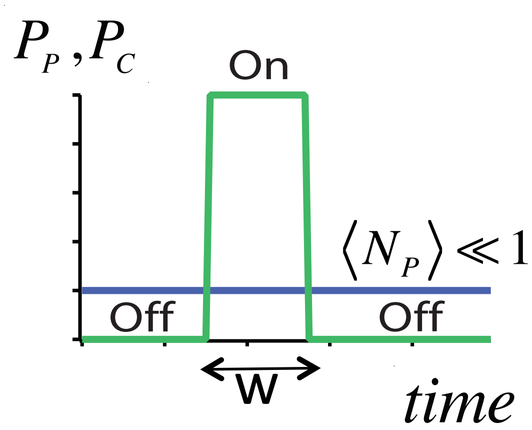
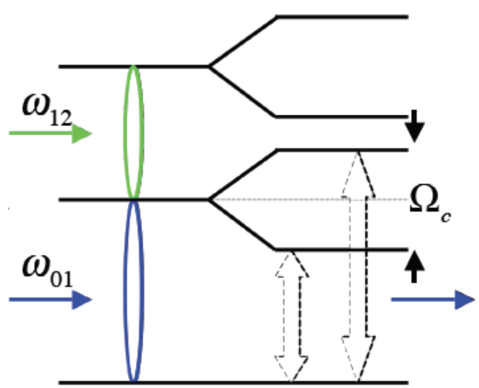
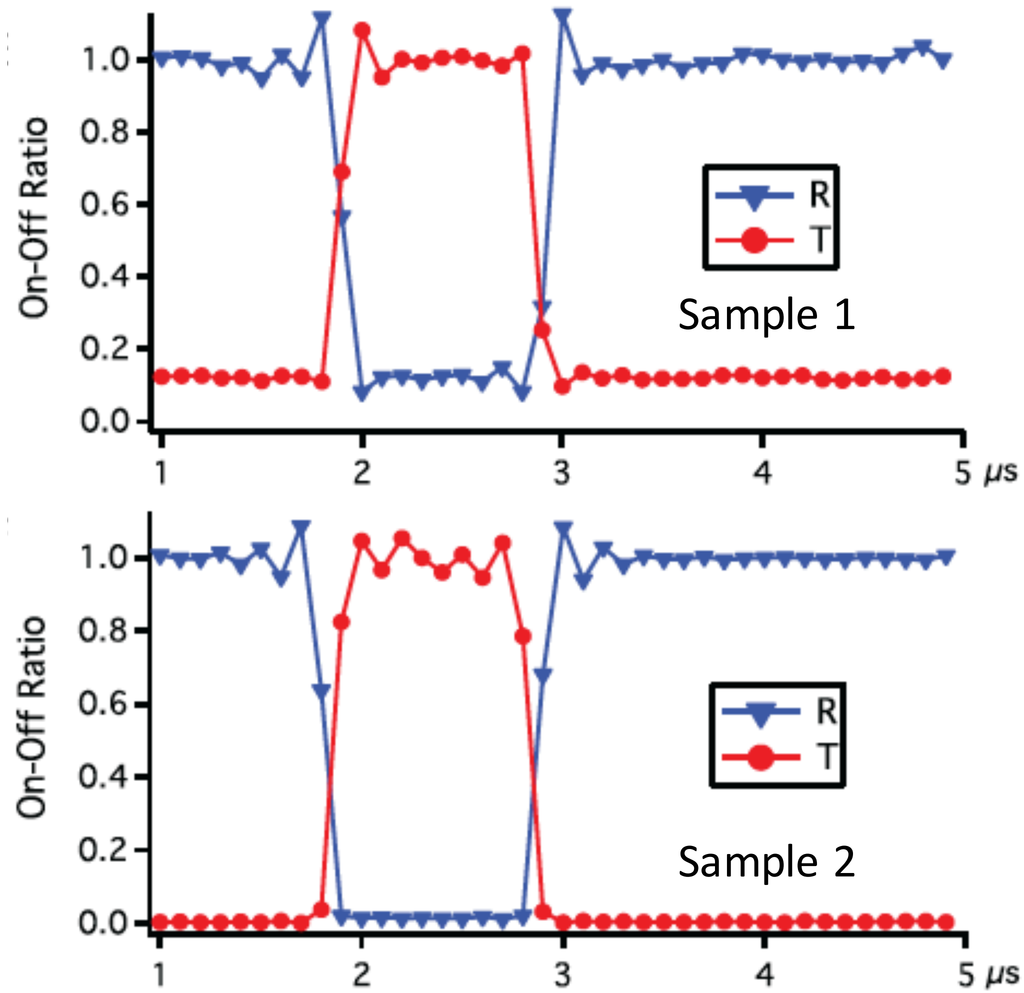
# Measuring both T and R simultaneously

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# An artificial atom in front of a mirror

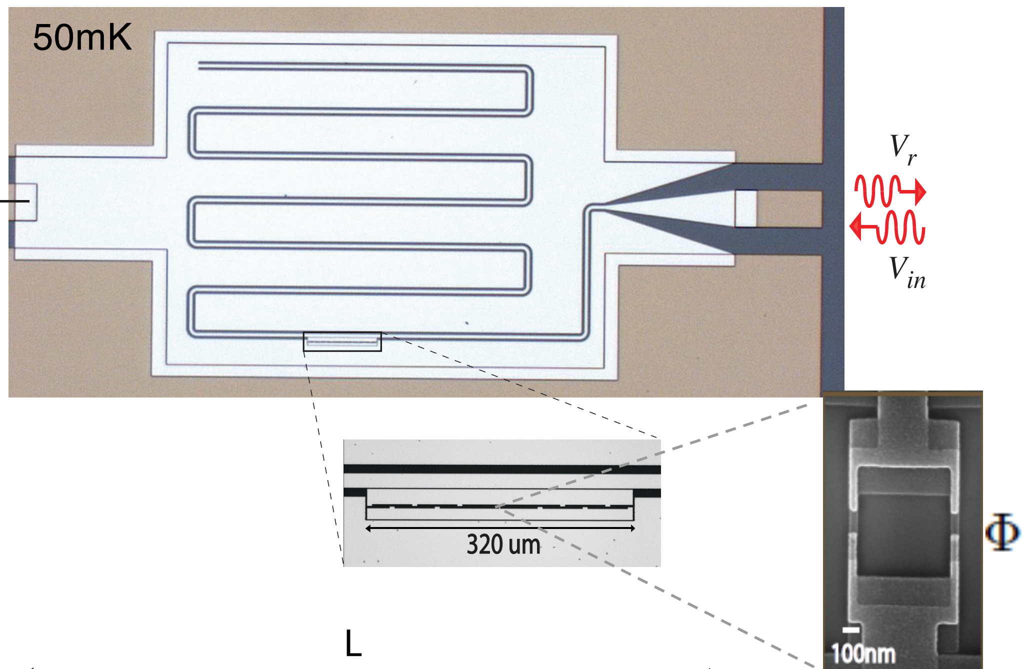
I.-C. Hoi *et al.* Nature Physics **11**, 1045-1049 (2015)

Io-Chun Hoi

國立清華大學
NATIONAL TSING HUA UNIVERSITY

# An artificial atom in front of a mirror

a)

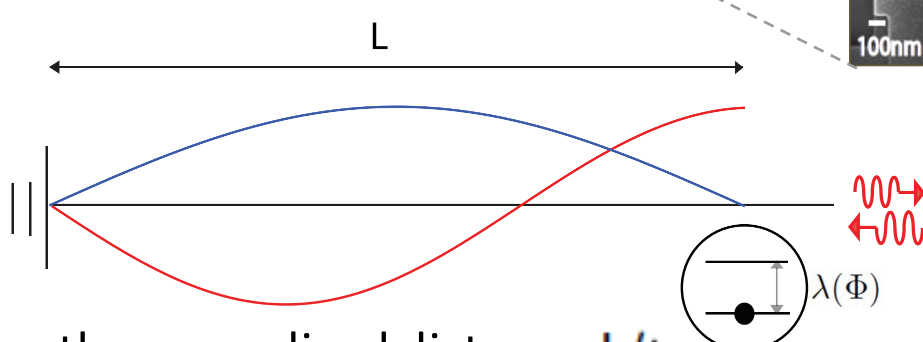



Reflection coefficient:

$$r_p = \frac{\langle V_R \rangle}{\langle V_{in} \rangle}$$

Single ion:
J. Eschner Nature, 413, 495 (2001)

b)




Changing the normalized distance: $L/\lambda$

Mirror shapes the modes of the vacuum that couple to atom.

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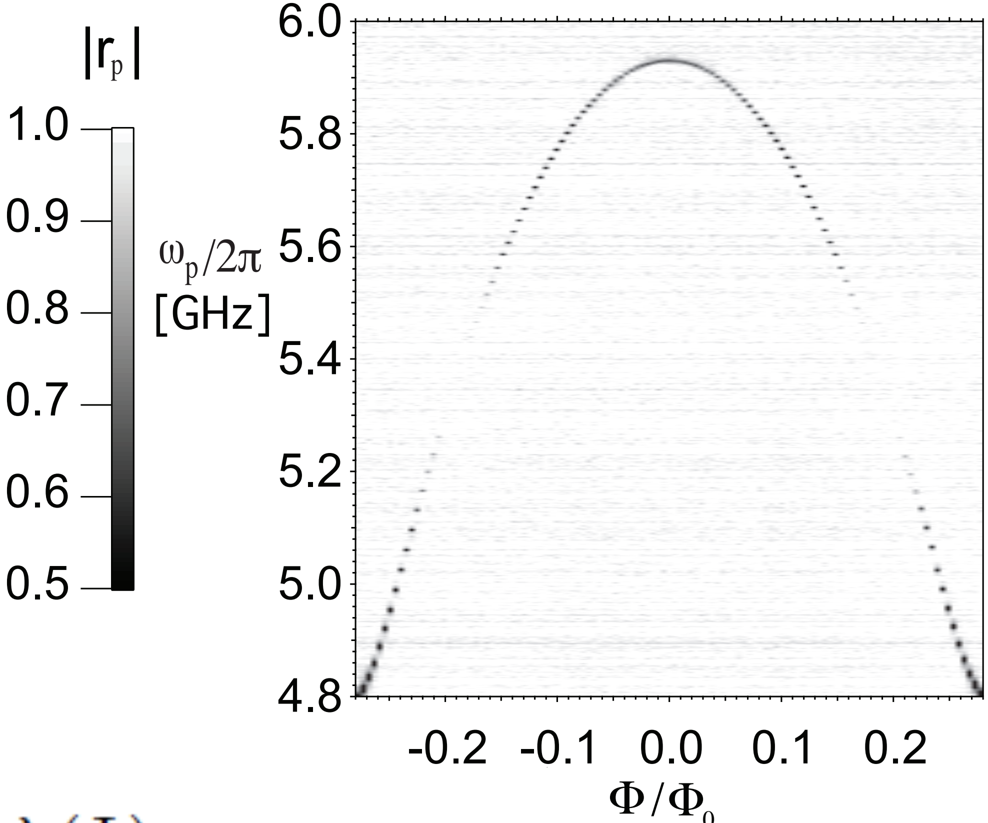
# Changing the spontaneous emission rate

$\Omega_p \ll \gamma$

Weak drive:

Experimental data




$\lambda(\Phi)$

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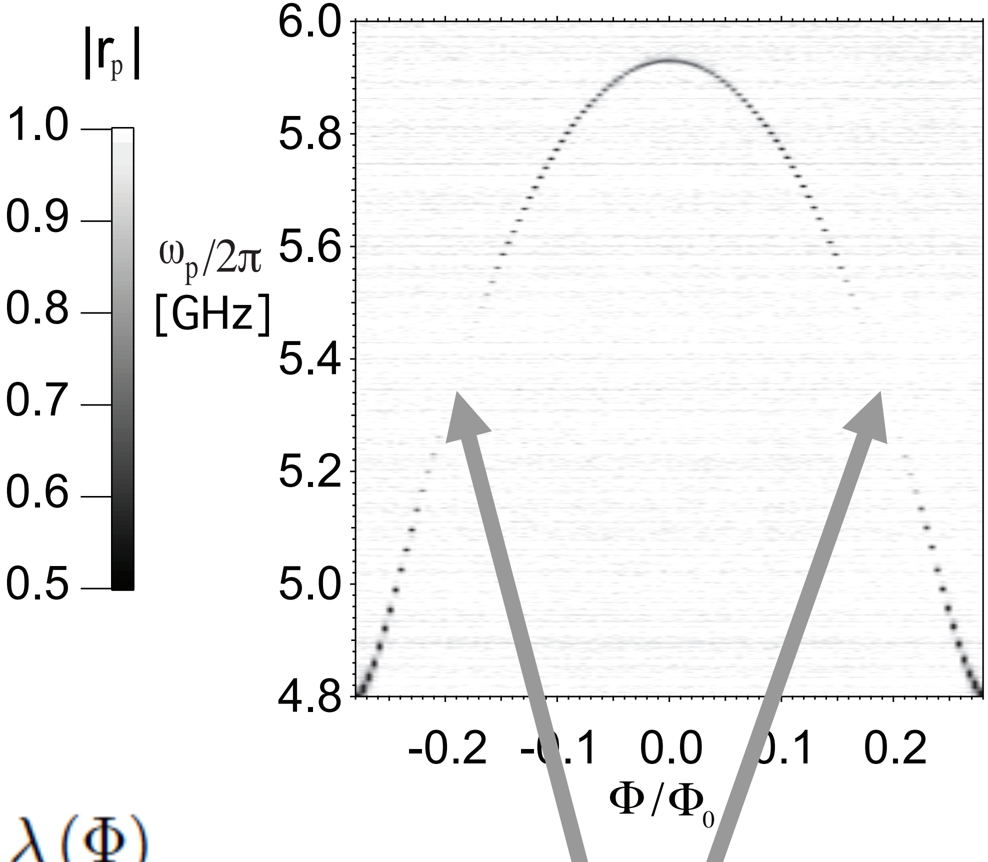
# Changing the spontaneous emission rate

$\Omega_p \ll \gamma$

Weak drive:

Experimental data




$\lambda(\Phi)$

$L = \lambda/2$ Atom decoupled from vacuum fluctuations at node.

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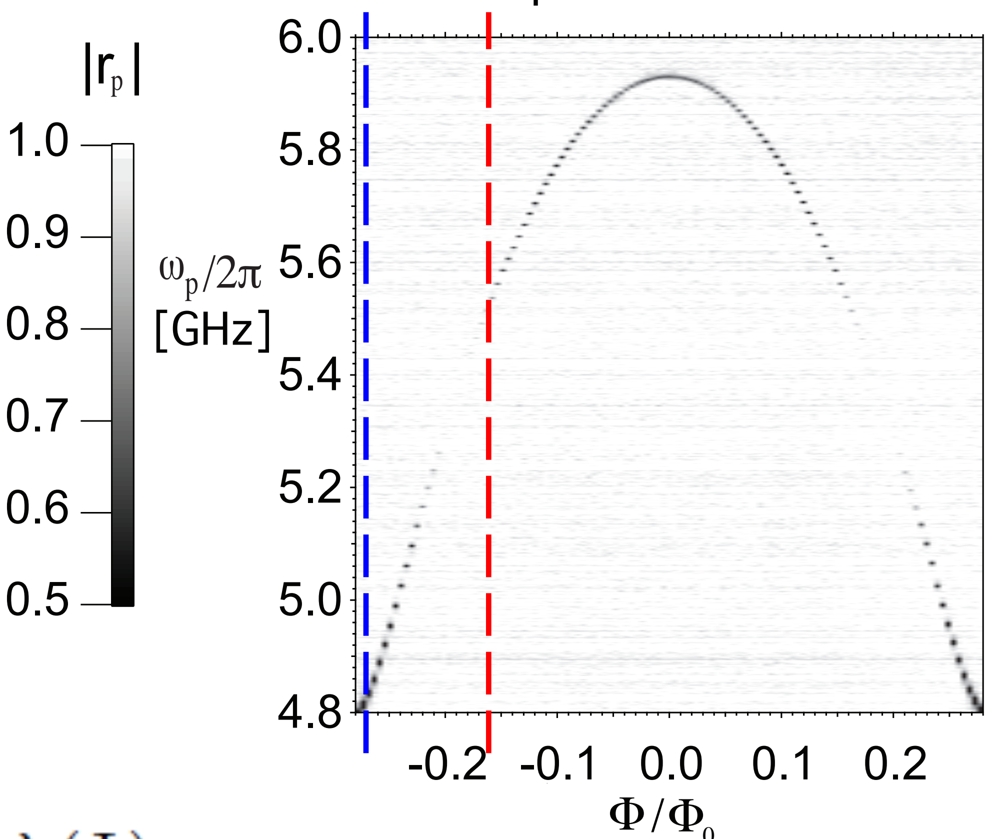
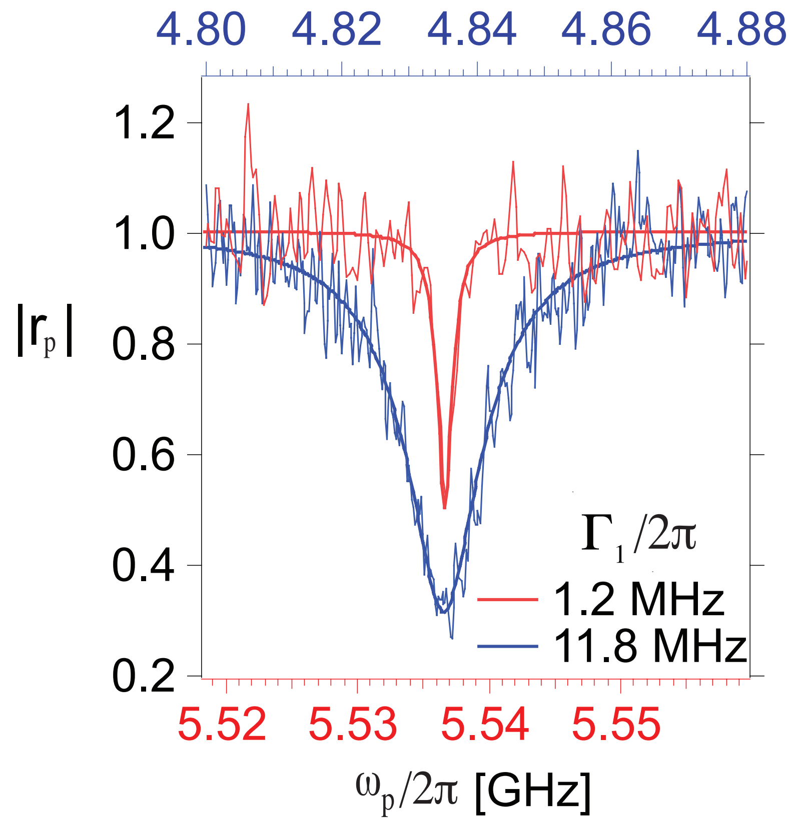
# Changing the spontaneous emission rate

$\Omega_p \ll \gamma$

Weak drive:

Experimental data




$\lambda(\Phi)$

$$L = \lambda/2$$

Atom decoupled from vacuum fluctuations at node.

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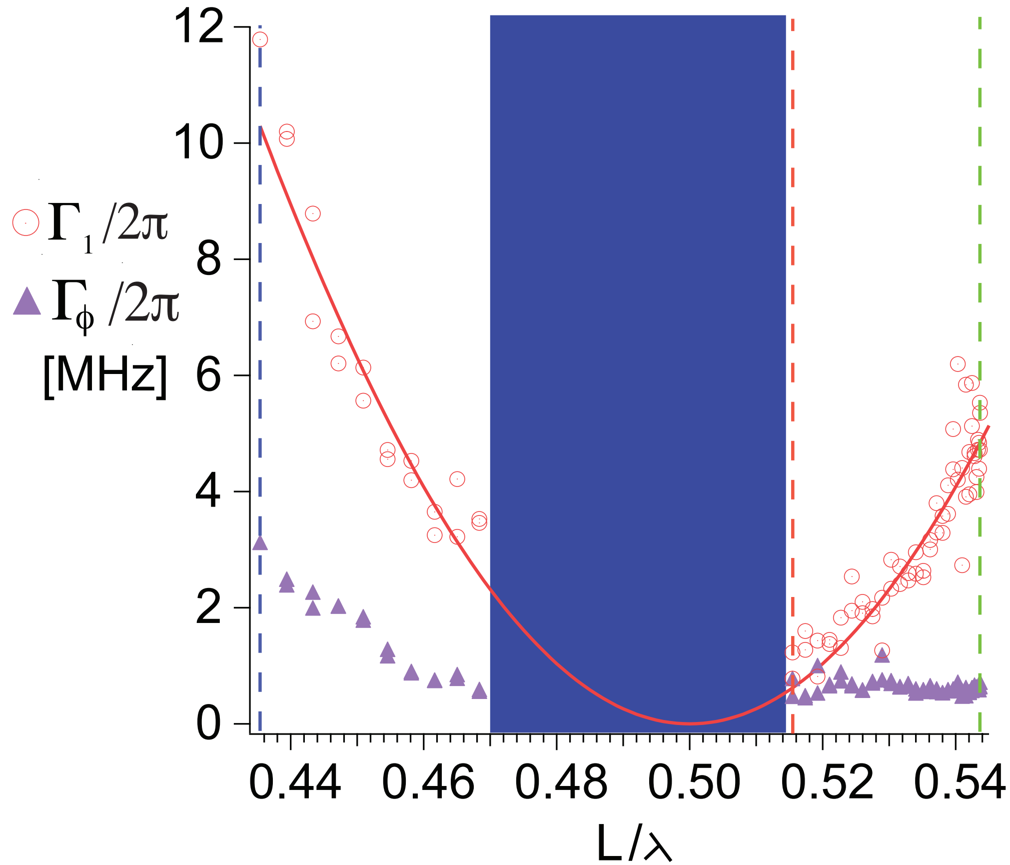
# Spontaneous emission rate as a function of normalized distance

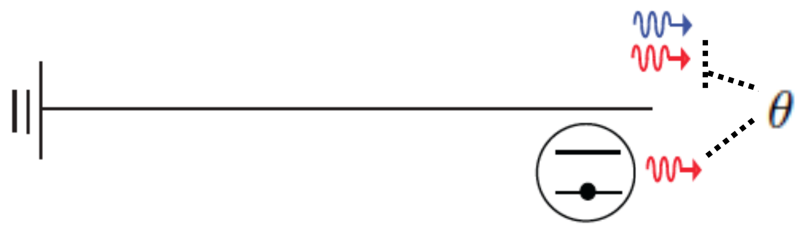



$$\Gamma_1(\Phi) = 2\Gamma_{1,b}\cos^2[\theta(\Phi)/2]$$

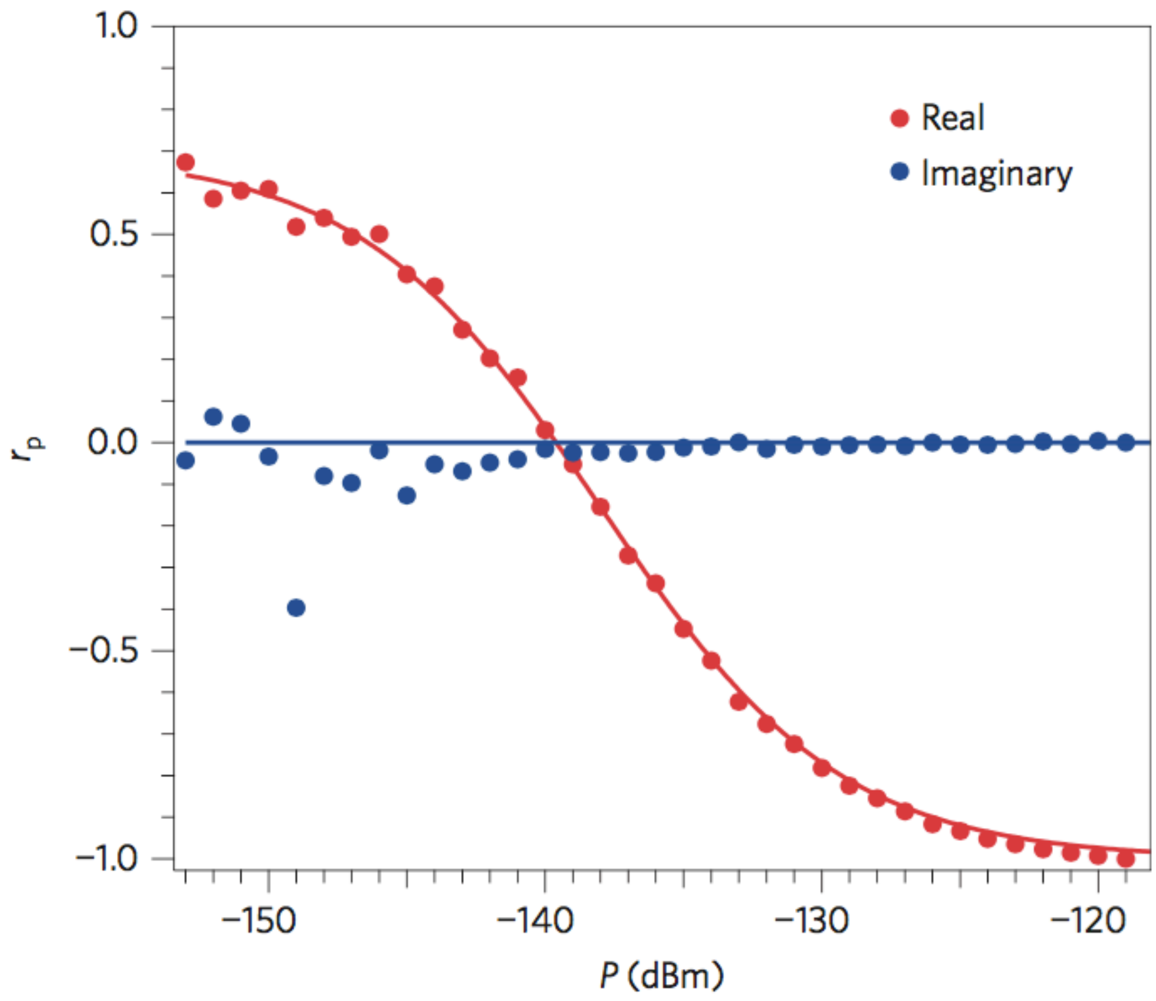
$$\theta(\Phi) = 2 \times [2\pi L/\lambda(\Phi)] + \pi$$

$\Gamma_{1,b}$: relaxation rate of bare atom

$\theta$: phase difference between scattered field from the same atom



# Calibrating atom-field coupling K

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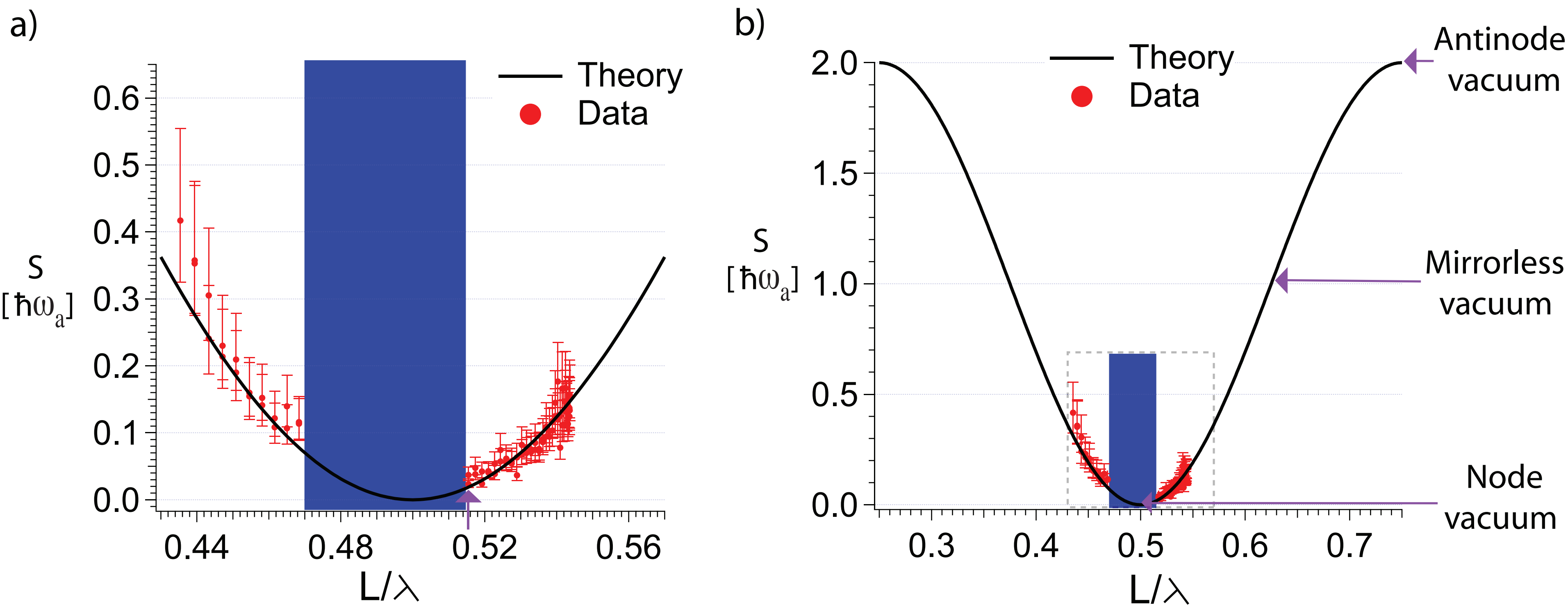
# Probing quantum vacuum fluctuations from spontaneous emission rate




$$\Gamma_1 = k^2 S$$

$$S = 2\hbar\omega_a \cos^2[\theta(\Phi)/2]$$

k: coupling constant

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