國立清華大學
NATIONAL TSING HUA UNIVERSITY

Quantum Optics with Propagating Microwaves in Superconducting Circuits

Io-Chun Hoi
許耀銓

Outline

Motivation: Quantum network

Introduction to superconducting circuits

Quantum nodes

- The single-photon router
- The cross-Kerr phase shift
- The photon-number filter
- The quantum spectrum analyzer

Quantum Network

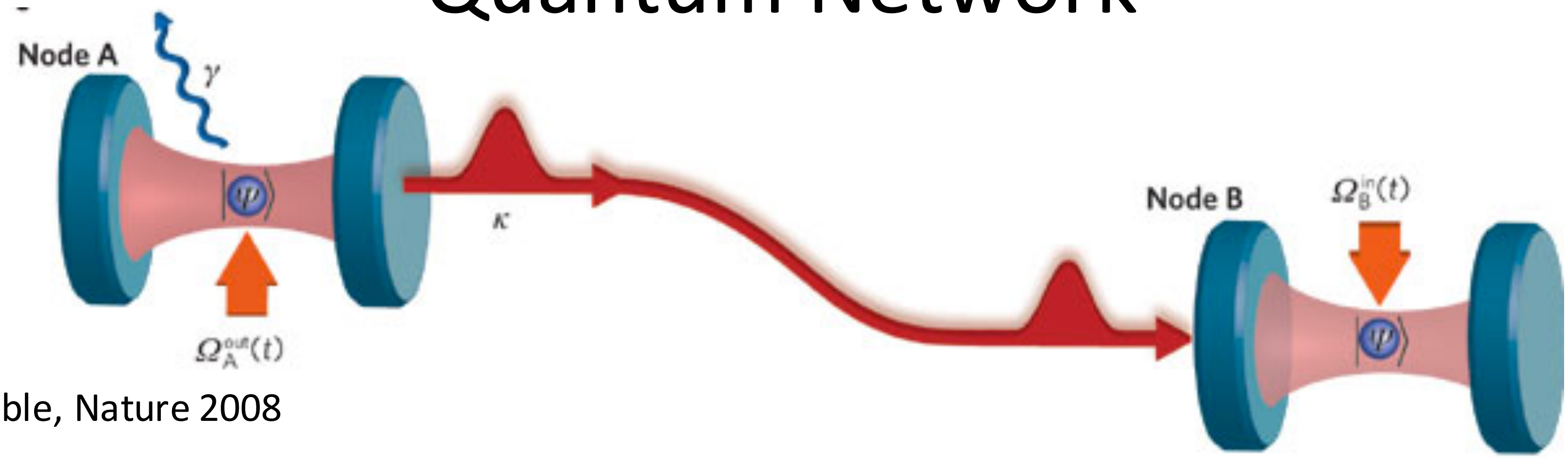
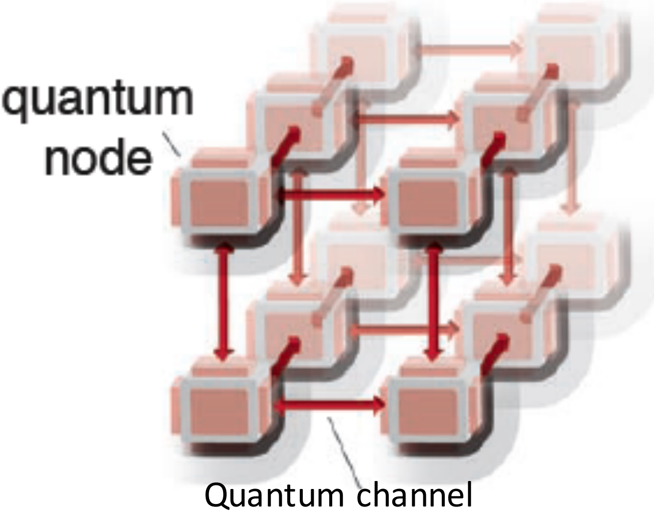


Fig. Kimble, Nature 2008

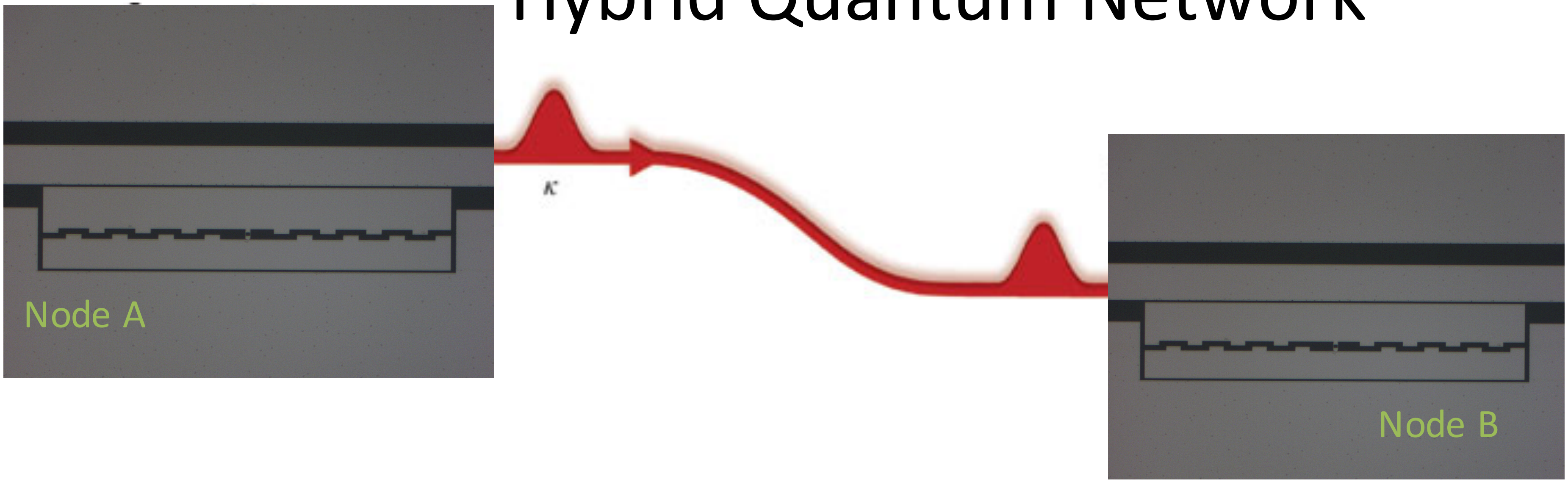


Quantum node:
Generating, processing, routing, storing, reading out quantum information.

Quantum channel:
Distributing quantum information.

Enabling large scale quantum computing and quantum communication.

Hybrid Quantum Network



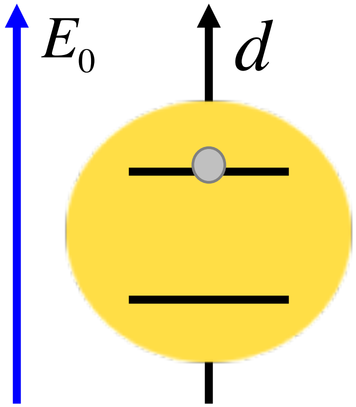
Telecom photons to distribute quantum information

Quantum node: superconducting circuits

Microwave-optical interface is needed

R.W. Andrews, *et al.* Nature Physics **10**, 321 (2014)
Y. Kubo *et al.* PRL **105**, 140502 (2010)

Advantages of superconducting circuits

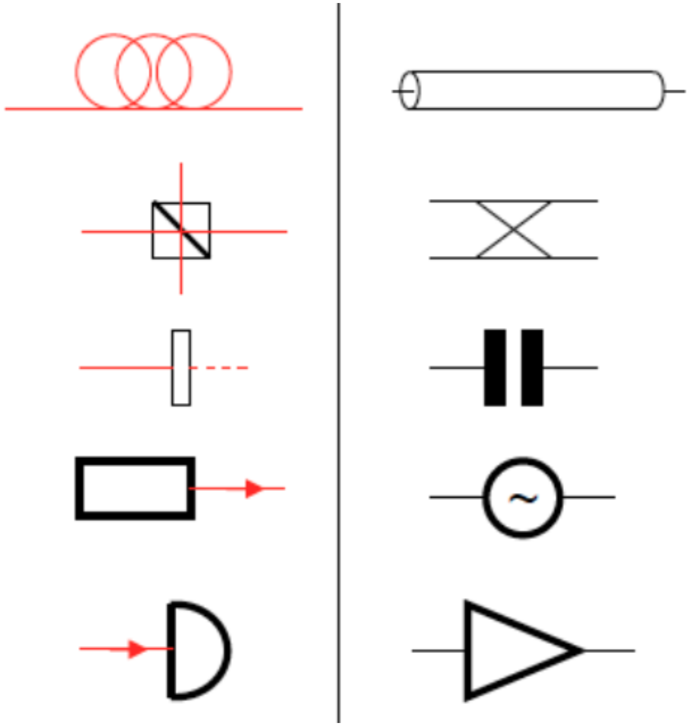


Atom-light interaction on single photon level

1. Photons and "atom" interaction can be engineered
2. Standard on-chip fabrication technique
3. Tunable transition energy of the "atom"
4. Mechanical stable

Comparison of the toolboxes

Quantum optics | Superconducting circuits



Optical photons | Microwave photons

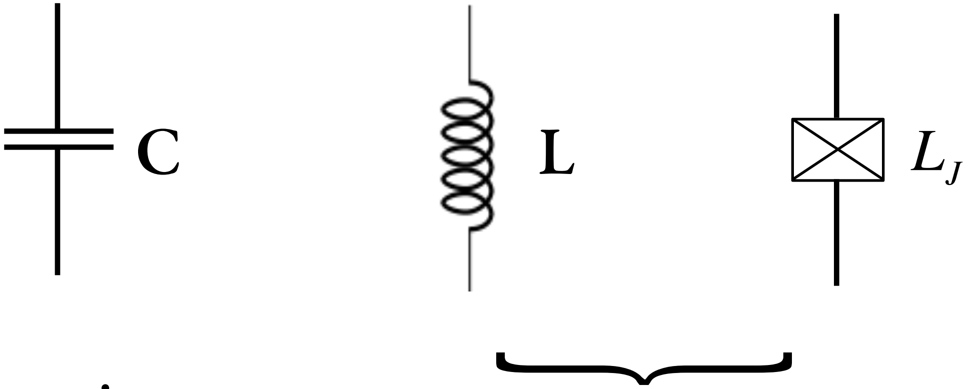
Introduction to Superconducting Circuits

Io-Chun Hoi

Basic Elements of Superconducting Circuits

Dissipationless!

Josephson Junction:
Non-disspative
nonlinear inductance



Capacitance

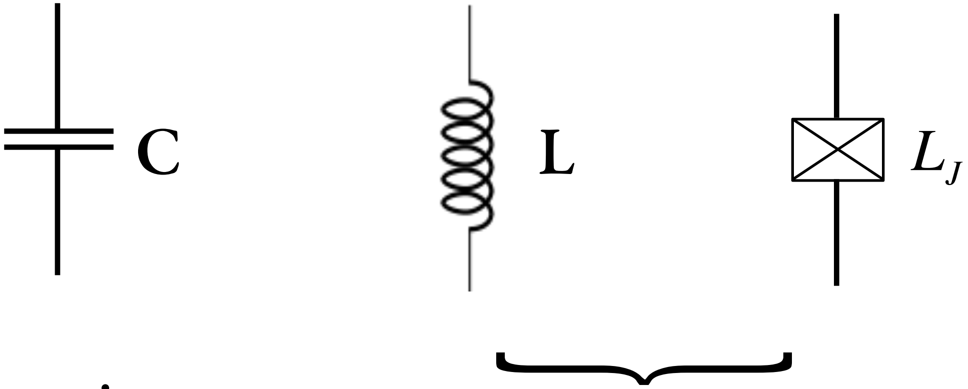
Inductance

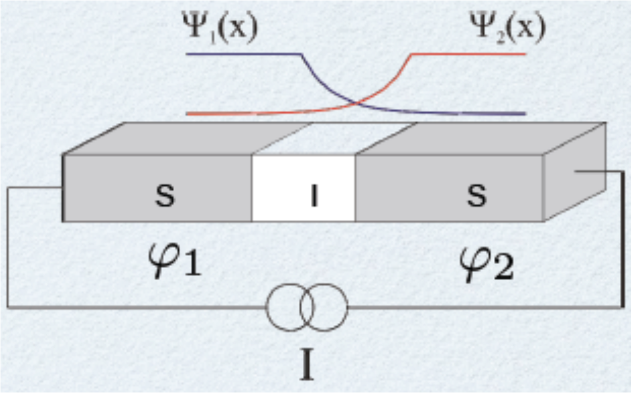
Basic Elements of Superconducting Circuits

Dissipationless!

Josephson Junction:
Non-disspative
nonlinear inductance

Tunnel barrier between
two superconductors



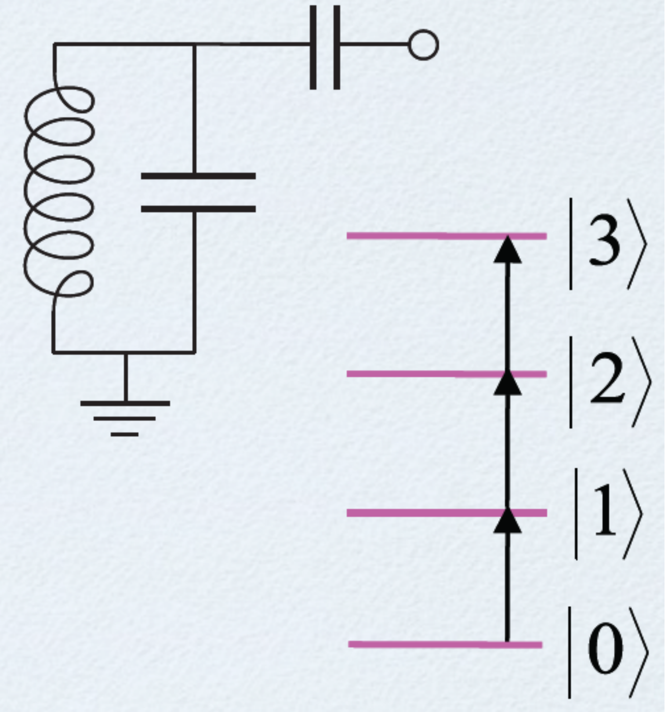


Capacitance

Inductance

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

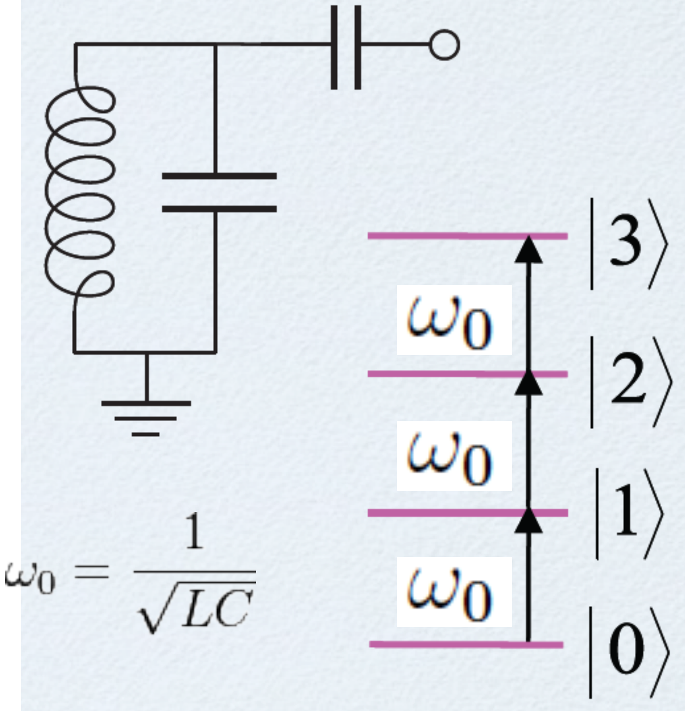
Artificial Atom Based on Quantized Superconducting Circuits



LC Harmonic oscillator

$f \sim 5GHz \sim 240mK$

Artificial Atom Based on Quantized Superconducting Circuits



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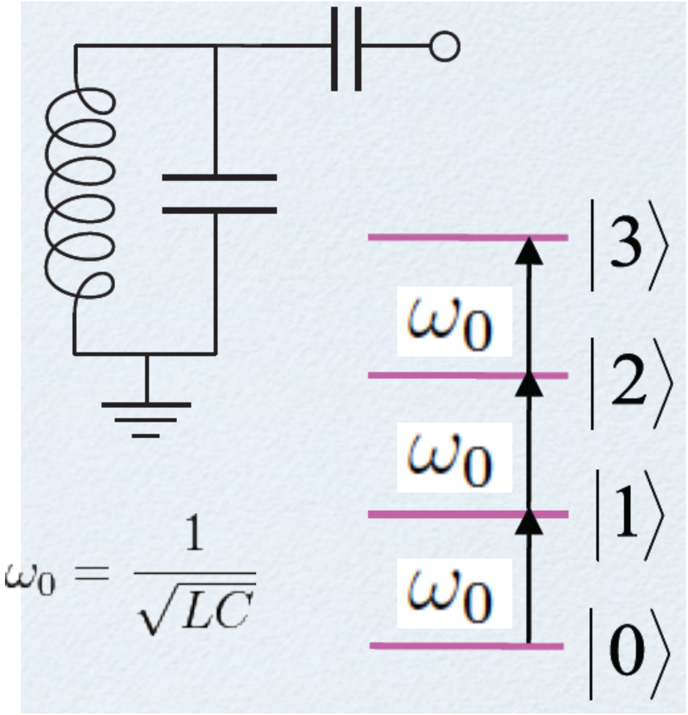

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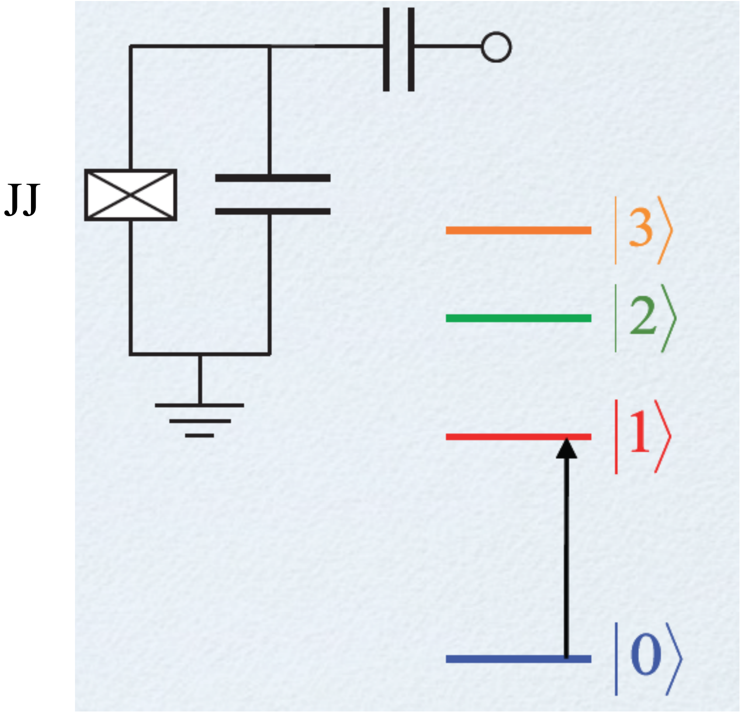
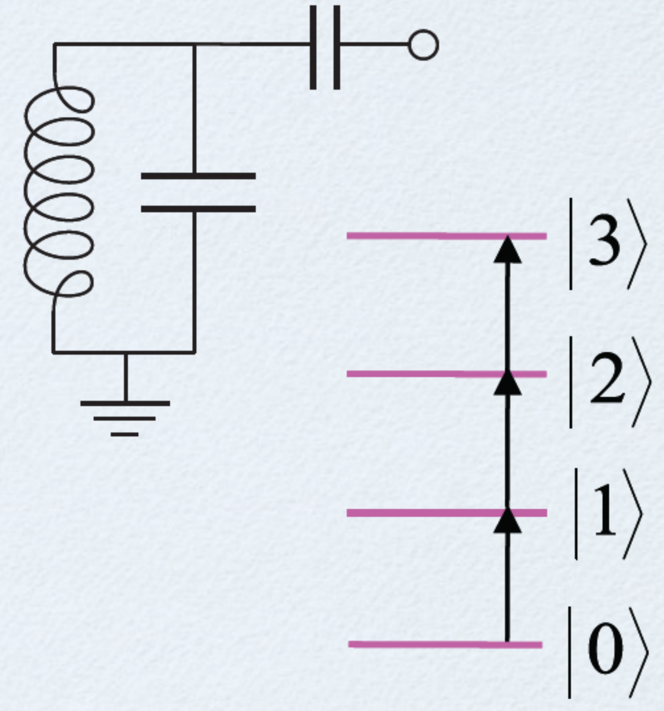


JJ is a nonlinear disspationless inductor
Nonlinearity makes the circuit anharmonic and addressable.

Artificial Atom Based on Quantized Superconducting Circuits



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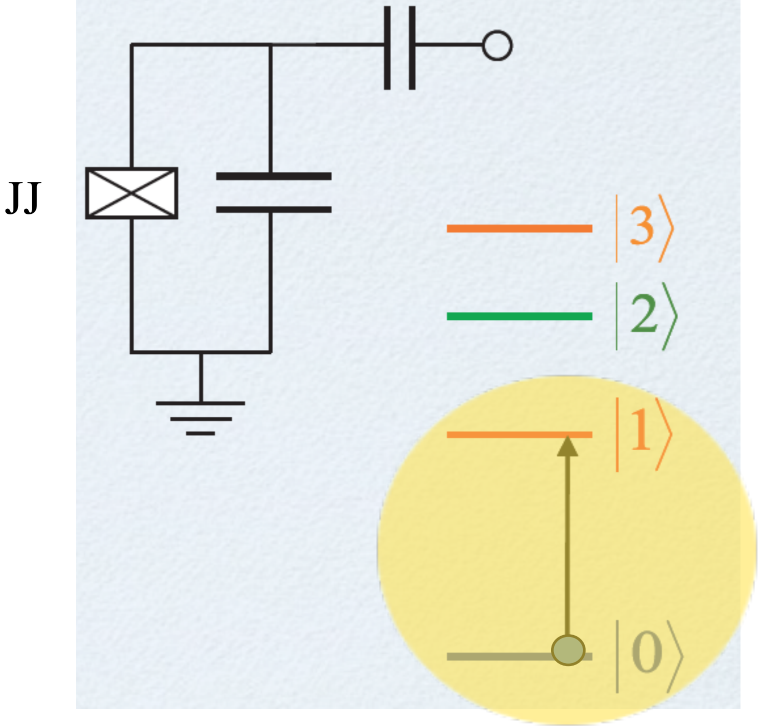

$hf_{10} >> k_B T$

$T @ mK$

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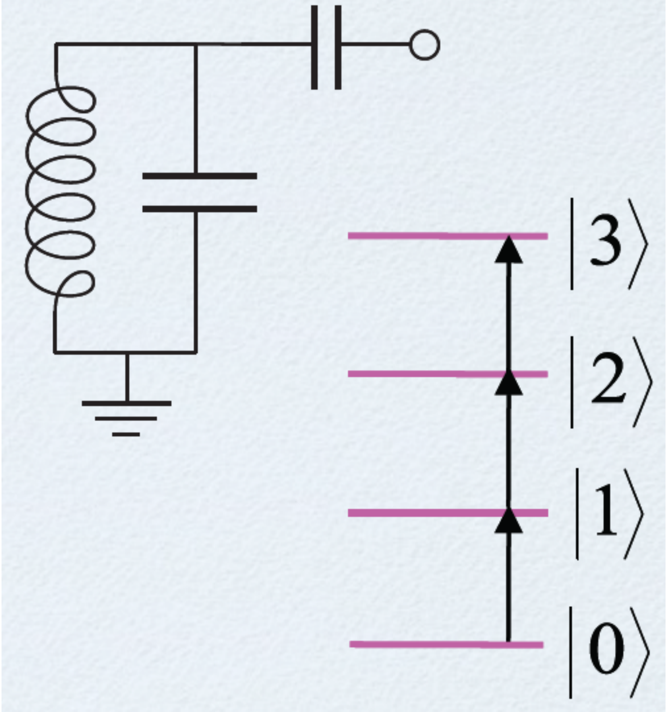
Artificial Atom Based on Quantized Superconducting Circuits



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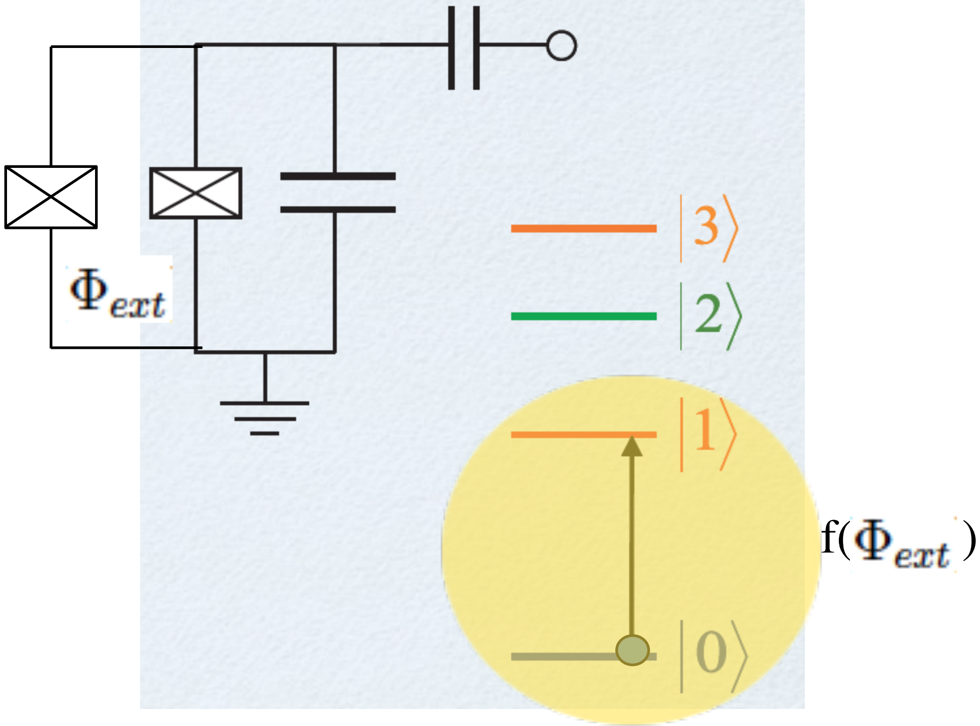


Tunable transition frequency by flux Φ_{ext} through the SQUID loop.

Resonant scattering

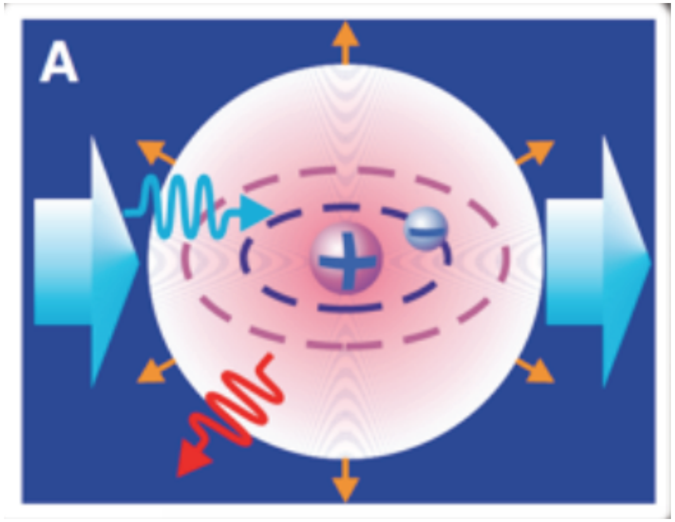
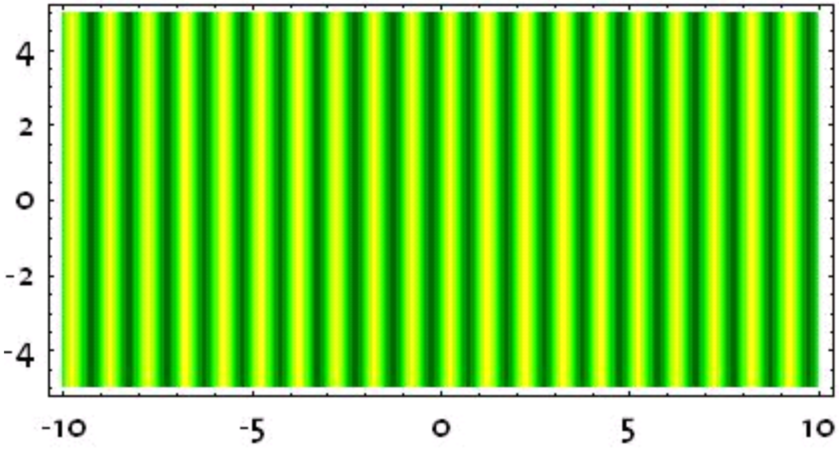


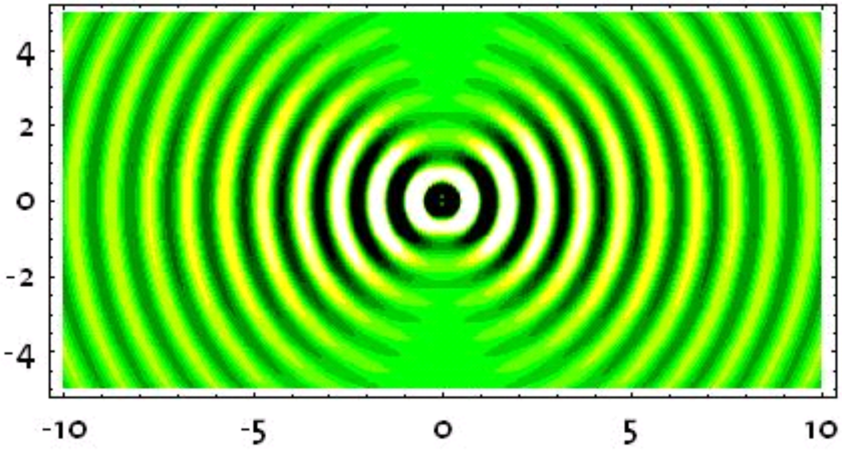
Fig: O. Astafiev, *et al.* **327**, 840 Science (2010)

Resonant scattering in 3D space

Incoming light



Atom/dipole emits light



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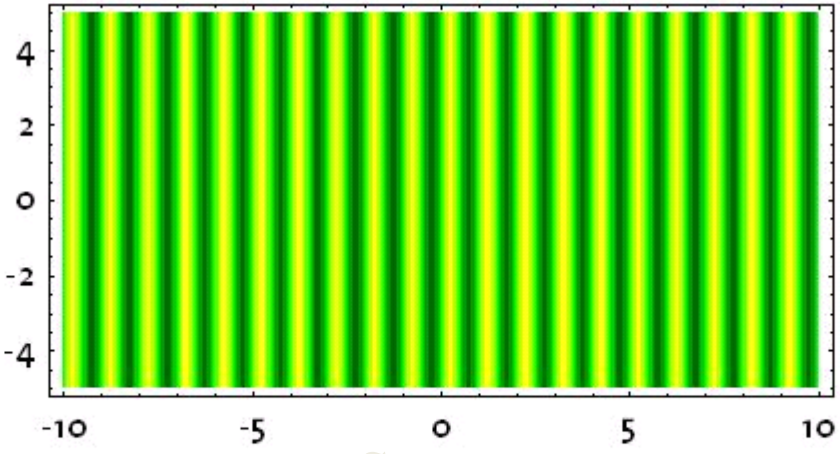

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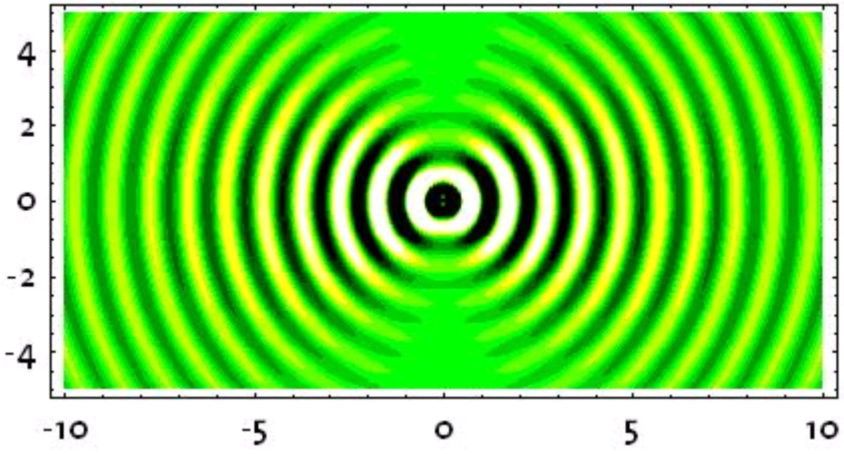
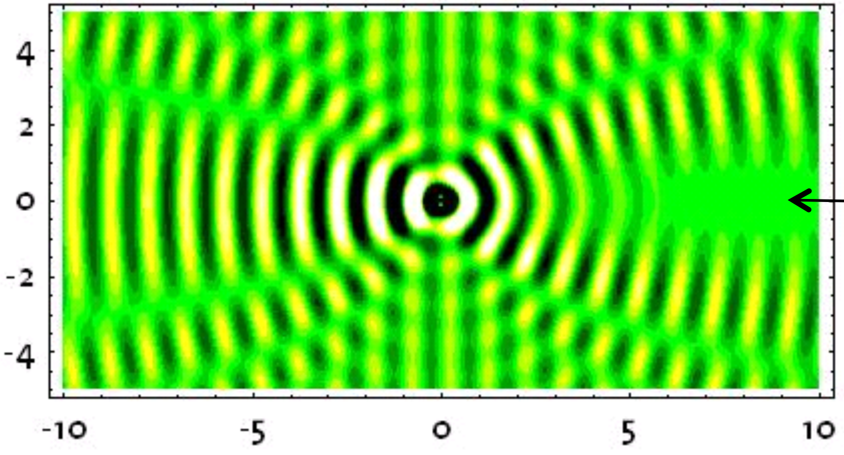


Sum



The extinction signal is due to interference

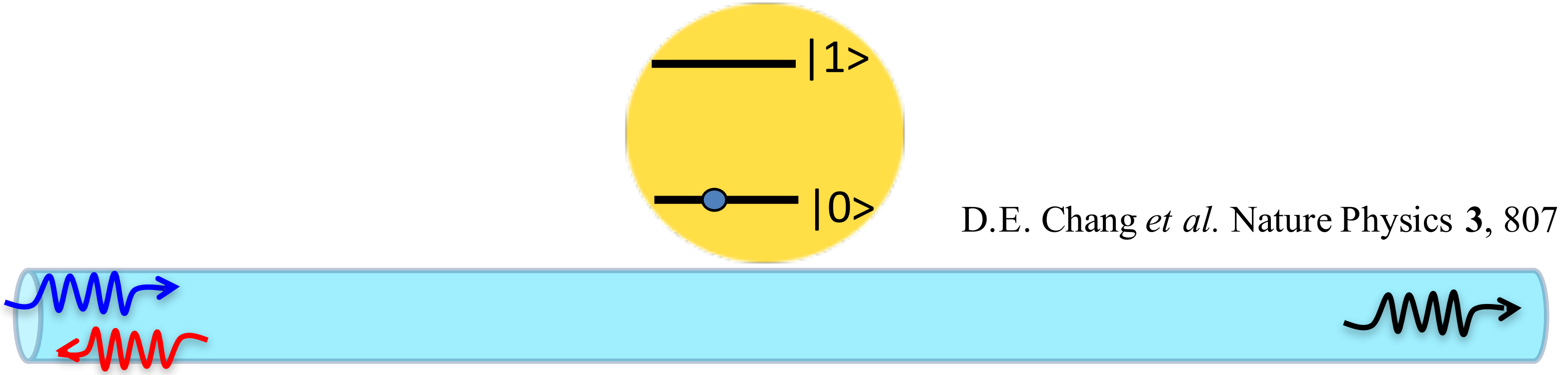
G. Wrigge *et al*. Nature Phys. **4**, 60 (2008). M. Tey *et al*. Nature Phys. **4**, 924 (2008).

Spatial mode mismatch

Fig. from
U. Håkanson

Io-Chun Hoi

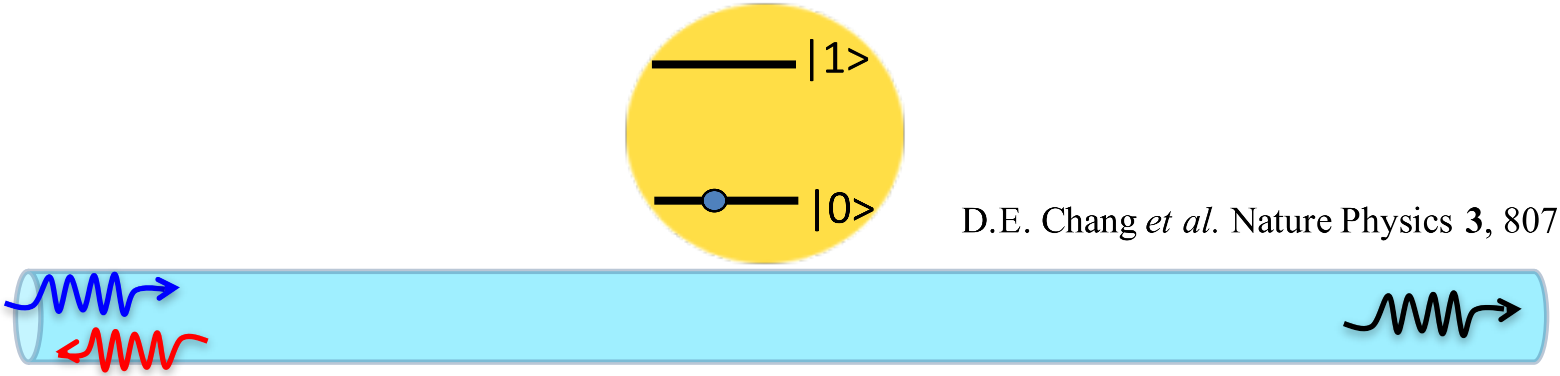
Resonant scattering in 1D waveguide



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

Fully coherent: no transmission, perfect reflection.

Resonant scattering in 1D waveguide



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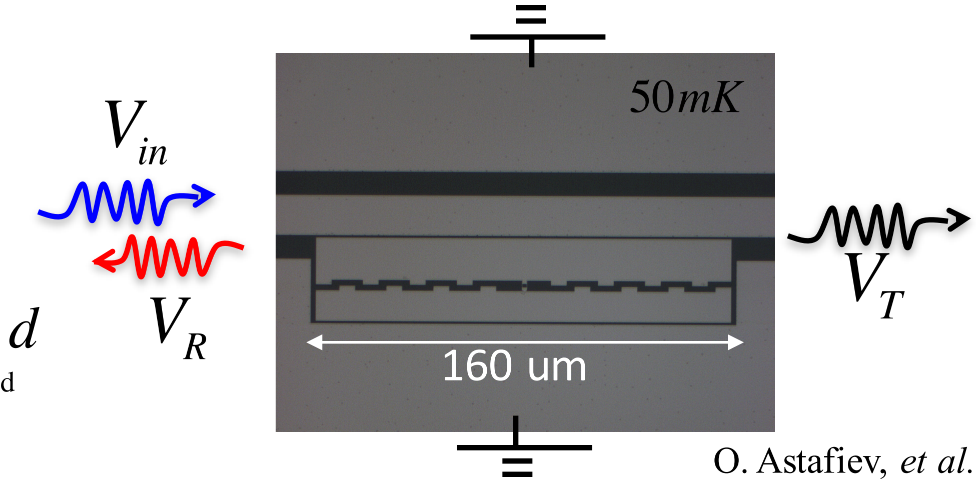

Point like atom/dipole! $\lambda >> d$

$\lambda \sim cm$ 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)

Resonant scattering in 1D waveguide

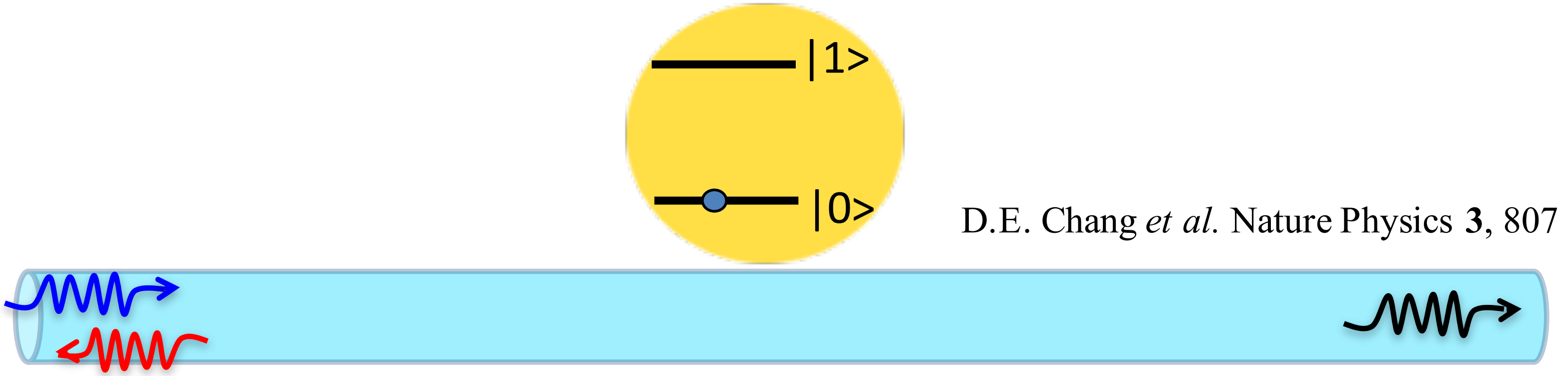

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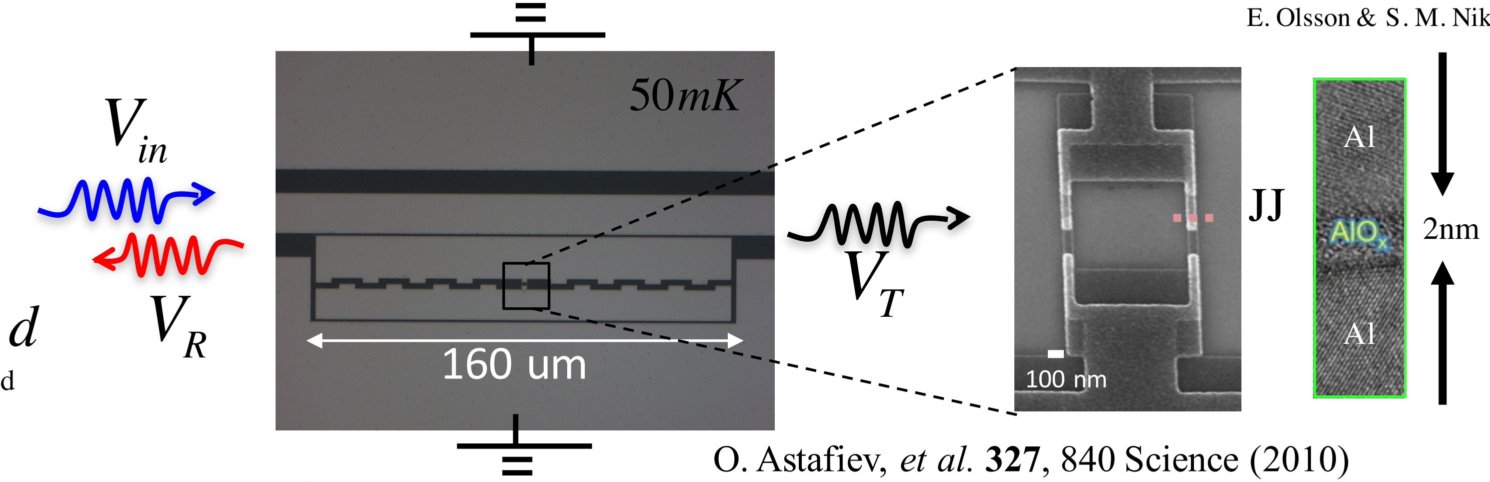
Fig. from
E. Olsson & S. M. Nik



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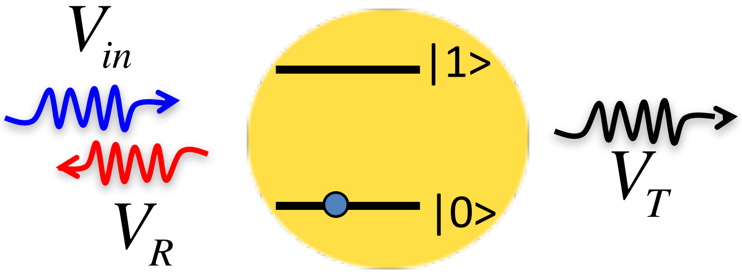
O. Astafiev, *et al.* **327**, 840 Science (2010)
IoChun, Hoi *et al.* PRL **107**, 073601 (2011)

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
Γ_{10} :Relaxation
Γ_φ :Pure dephasing
$\gamma_{10} = \Gamma_{10}/2 + \Gamma_\varphi$

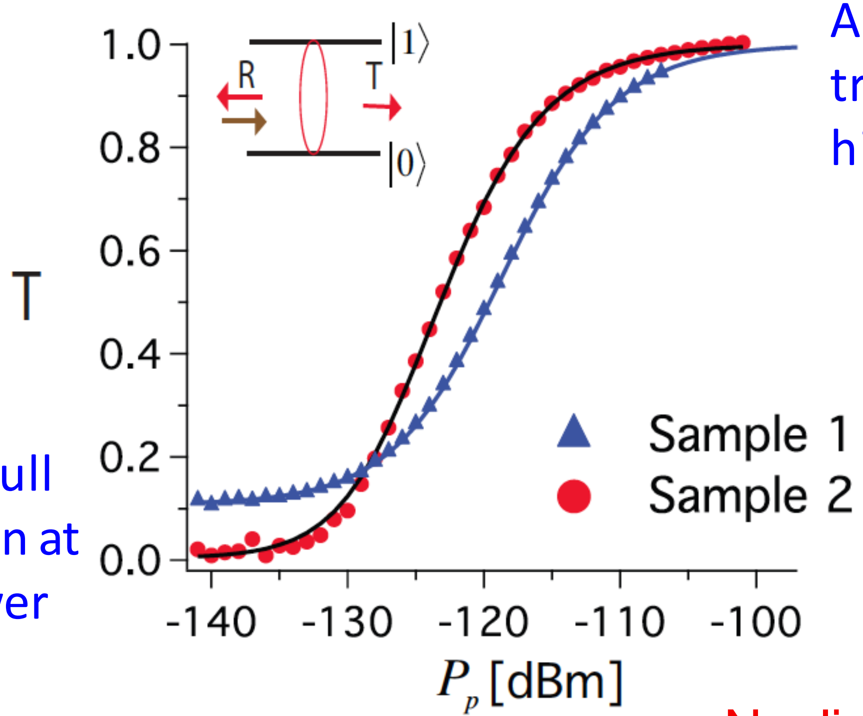
Strong interaction limit:

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

Fully coherent.

Saturation of transmission

$$T = |t|^2$$



Almost full transmission at high power

Almost full reflection at low power

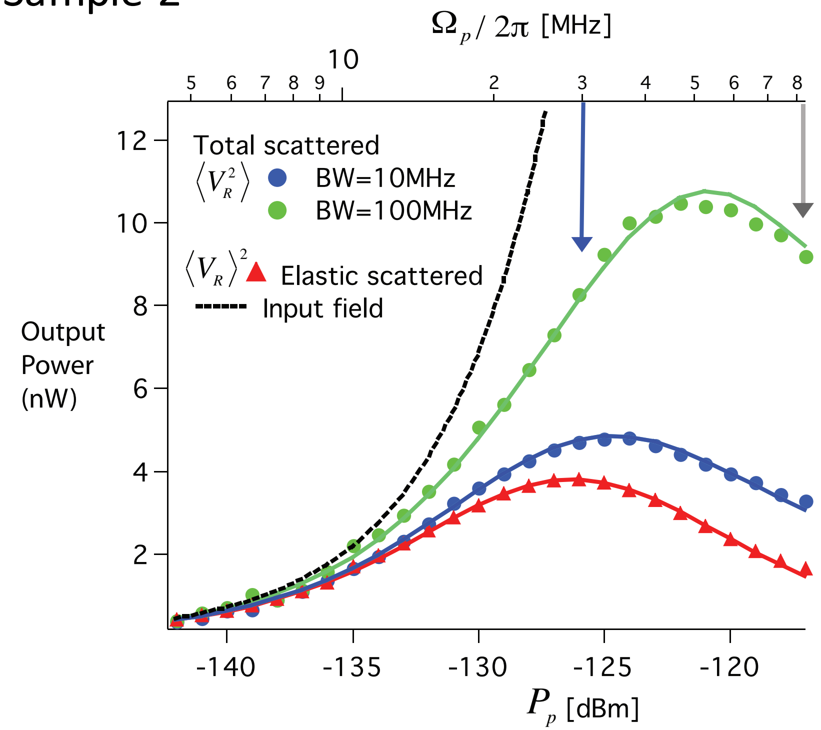
$$\langle N_P \rangle = \frac{P_P}{\hbar\omega_P(\Gamma_{10}/2\pi)}$$

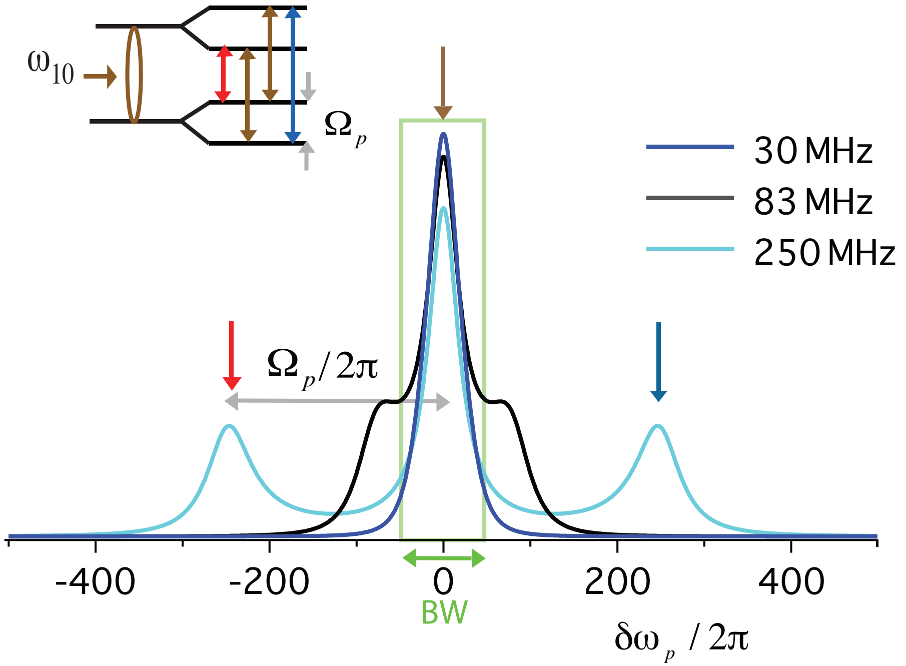
Nonlinear nature of the atom!

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%

Coherent vs Incoherent scattering

Sample 2



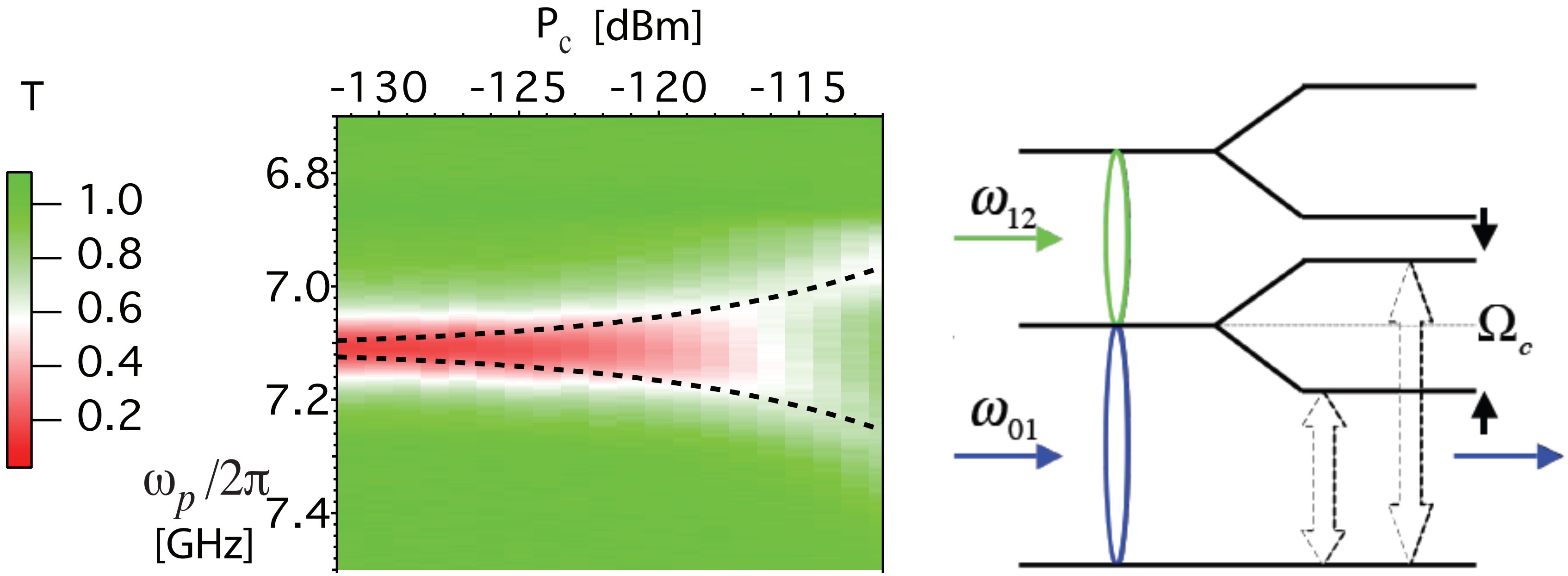


$$\Omega_p \ll \gamma_{10}$$

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

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

Autler-Townes Splitting



$\Omega_P \ll \gamma_{10}$

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

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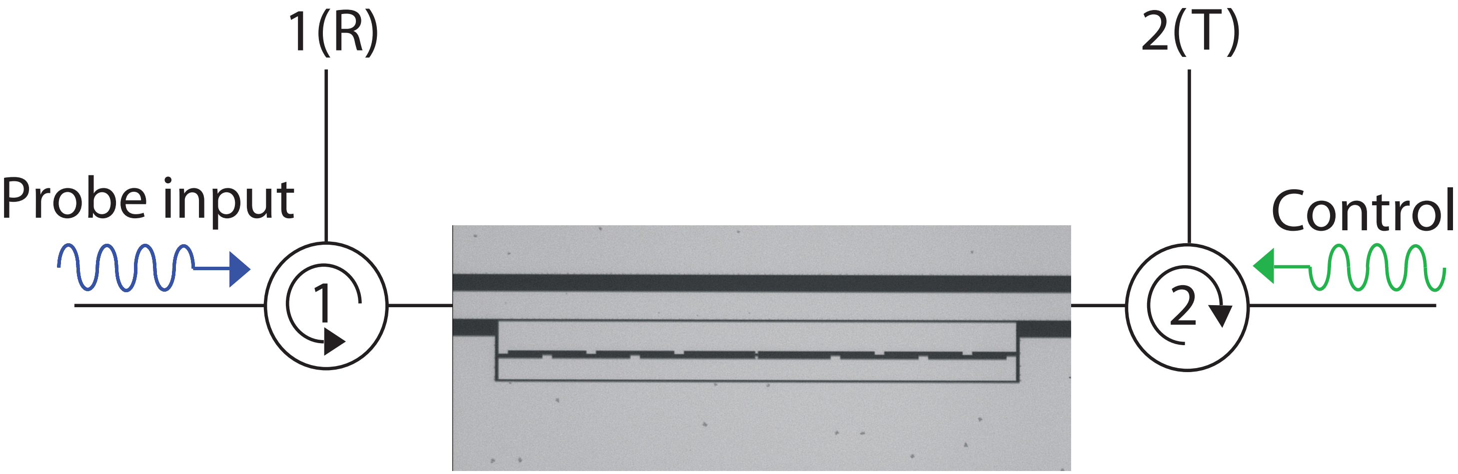
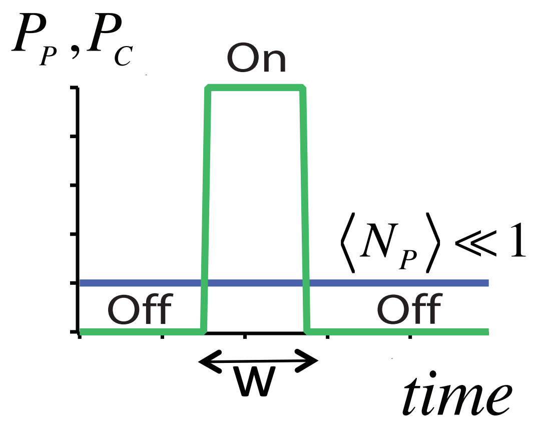
The Single-Photon Router

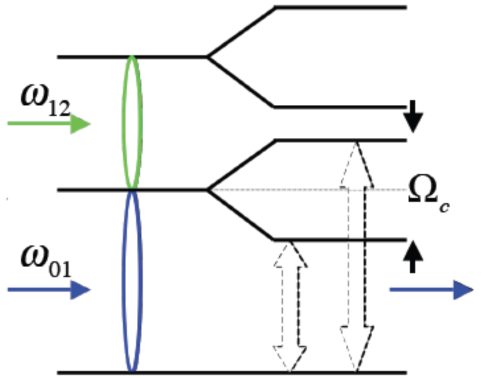


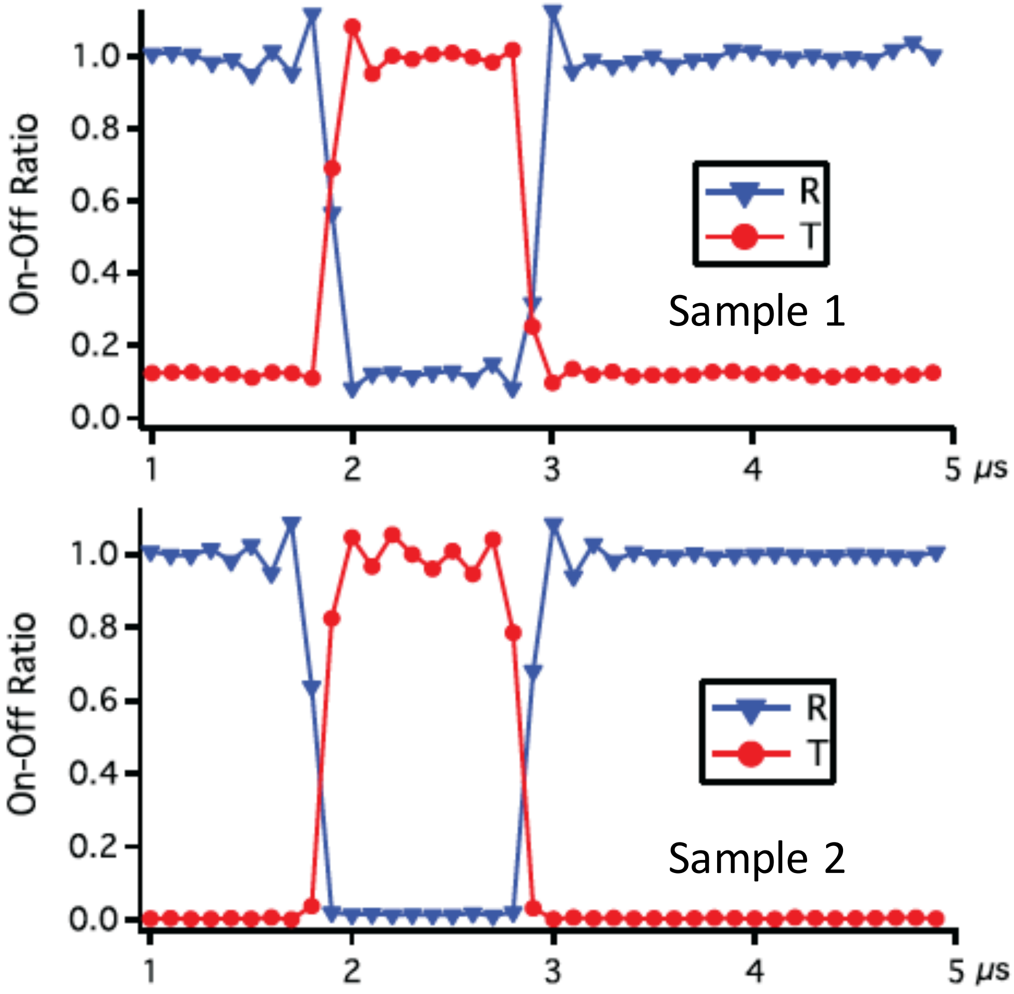
By turning on or off the control tone, we can decide which port the input photons go to.

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

Measuring both T and R simultaneously







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Photon-Photon interaction via a three-level atom

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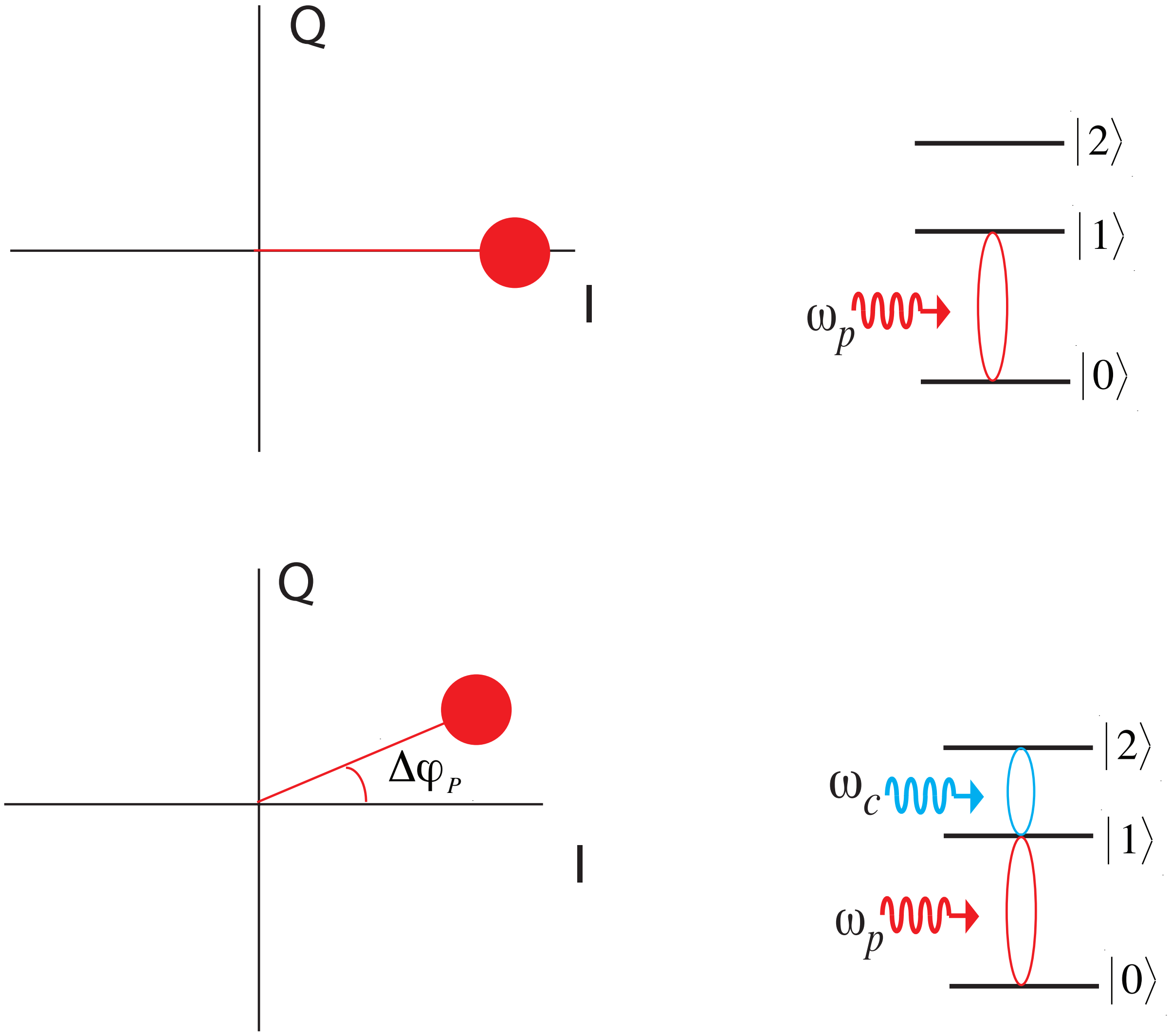
Photon-Photon interaction via a three-level atom



$\Delta\varphi_P$

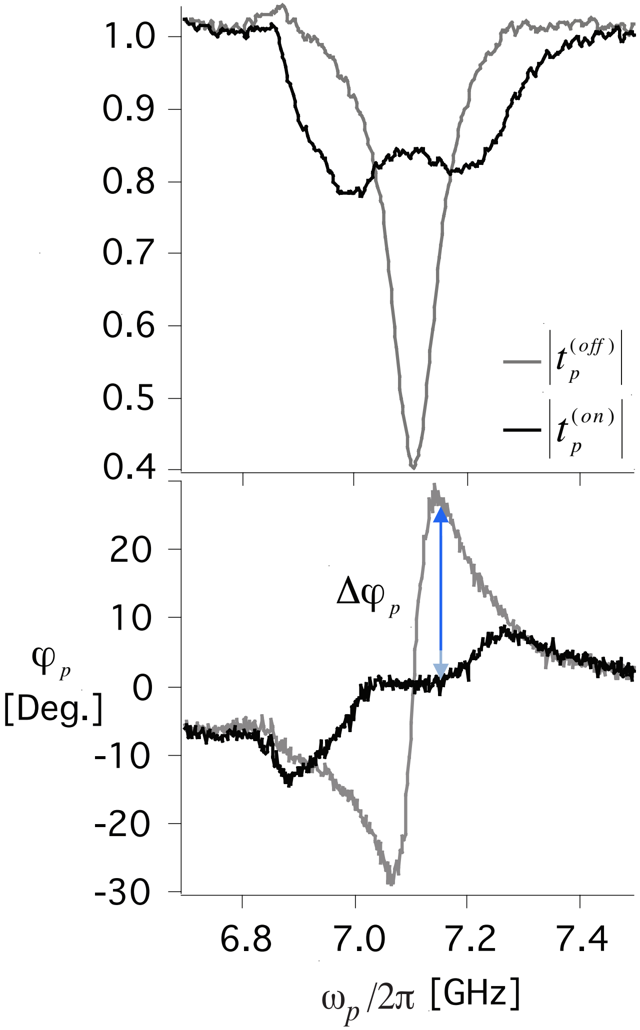
Parameters

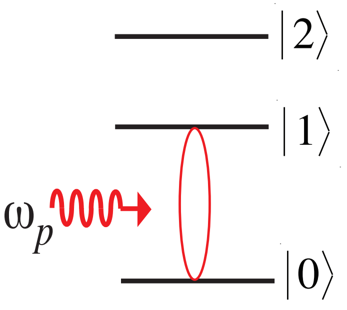
$P_P, P_C, \omega_P, \omega_C$

$\omega_C = \omega_{21}$

Io-Chun Hoi

Photon-Photon interaction via a three-level atom





$$\Delta\varphi_P$$

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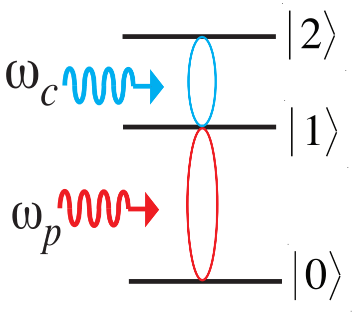

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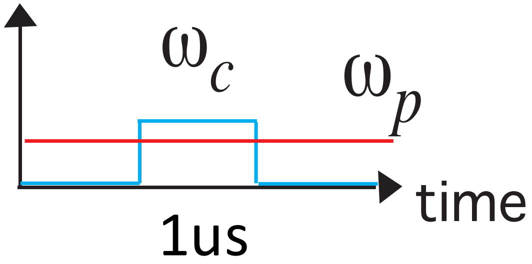
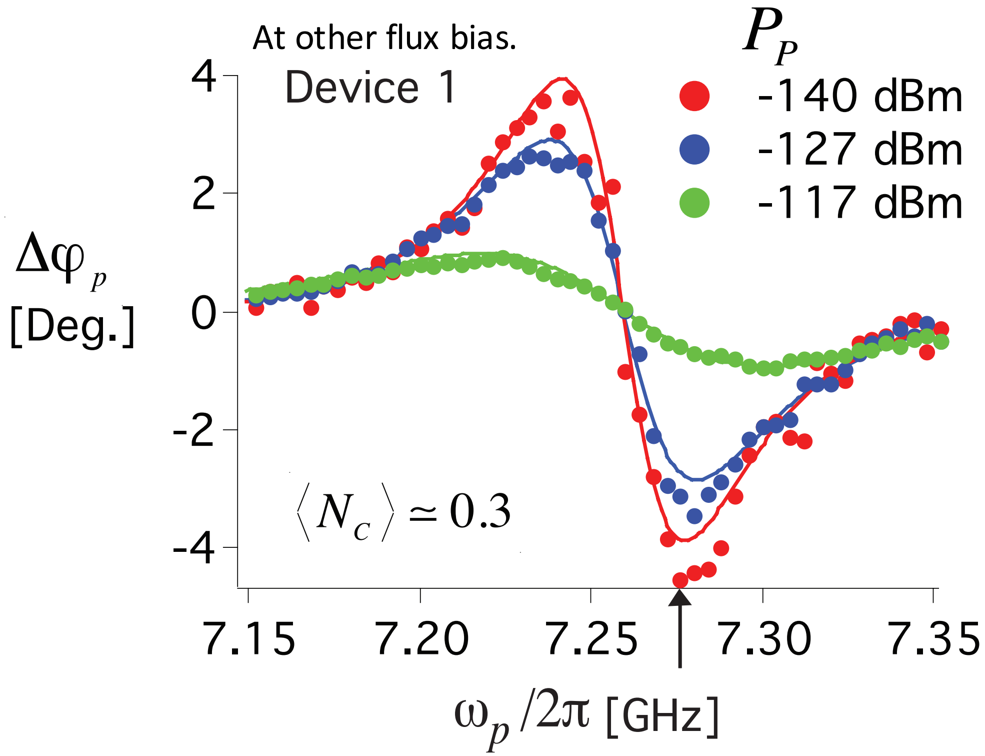
Nonlinear interaction between two microwaves





$$\langle N_C \rangle = \frac{P_C}{\hbar\omega_C(\Gamma_{21}/2\pi)}$$

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

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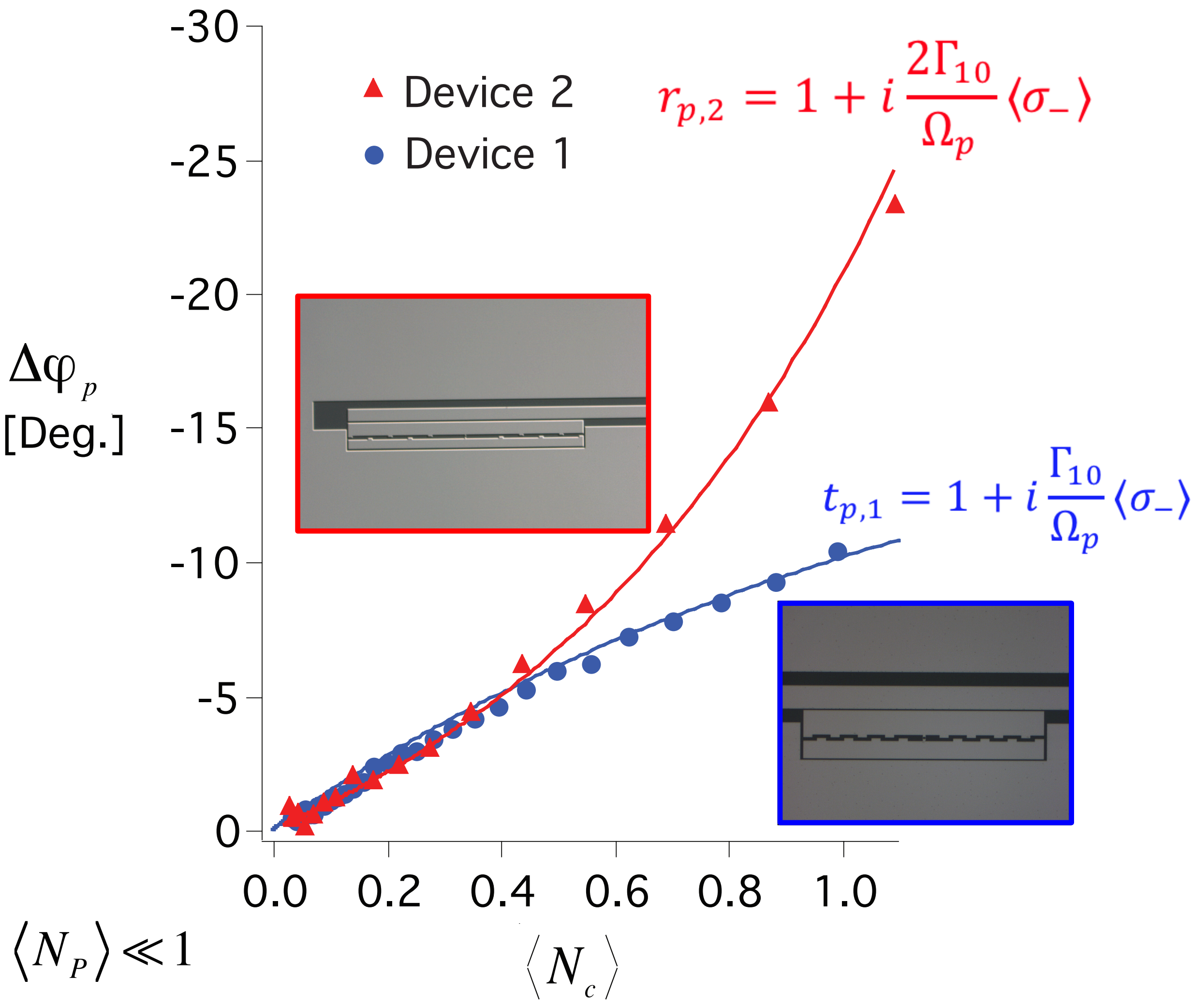
The Giant Cross-Kerr Phase Shift

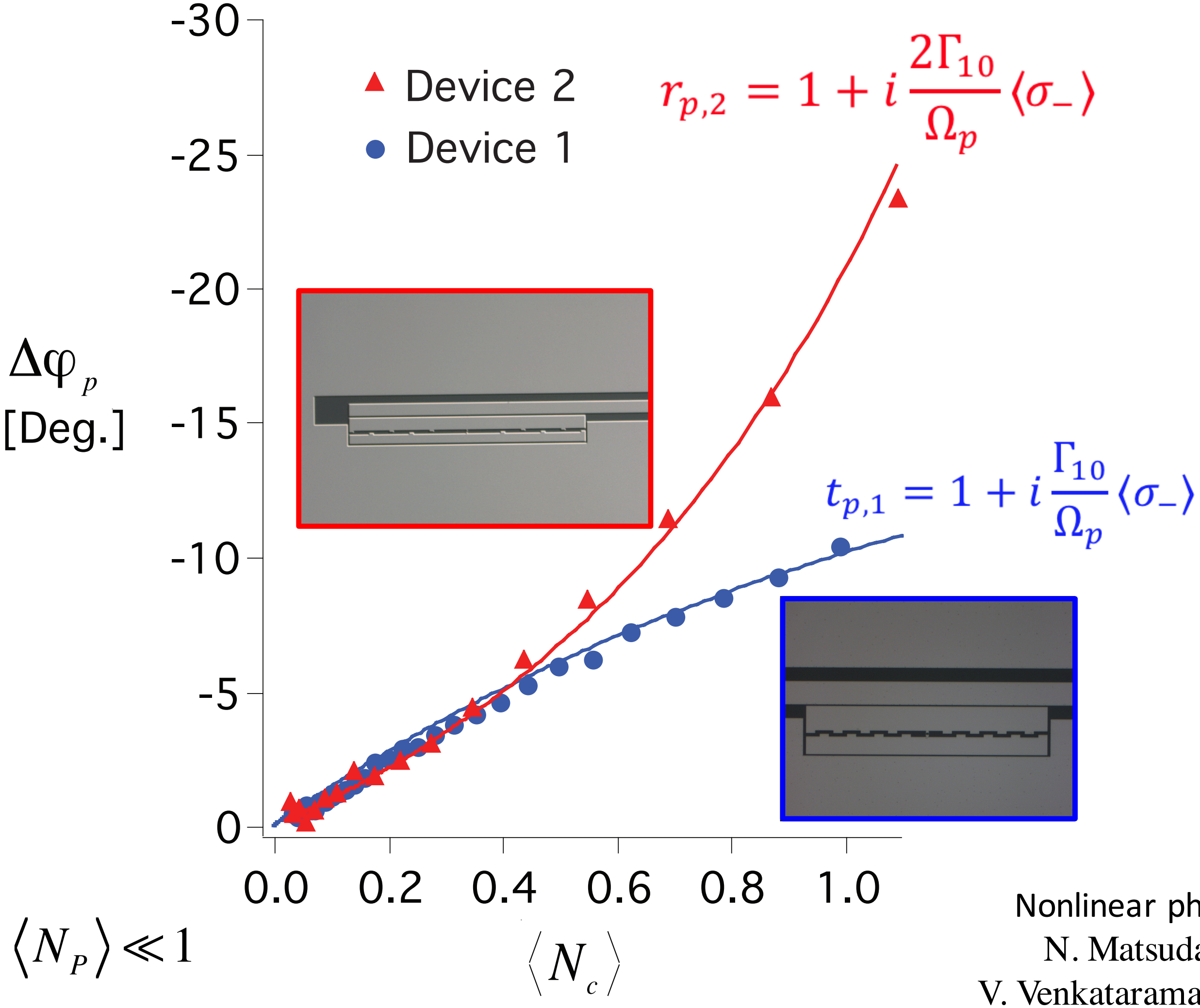


$\langle N_P\rangle \ll 1$

$$\Delta\varphi_p \propto \langle N_C\rangle$$

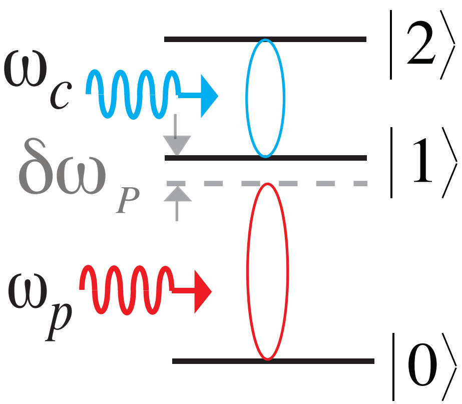
I.-C. Hoi *et al.* PRL **111,** 053601 (2013)

The Giant Cross-Kerr Phase Shift



$\langle N_P \rangle \ll 1$

Kerr medium



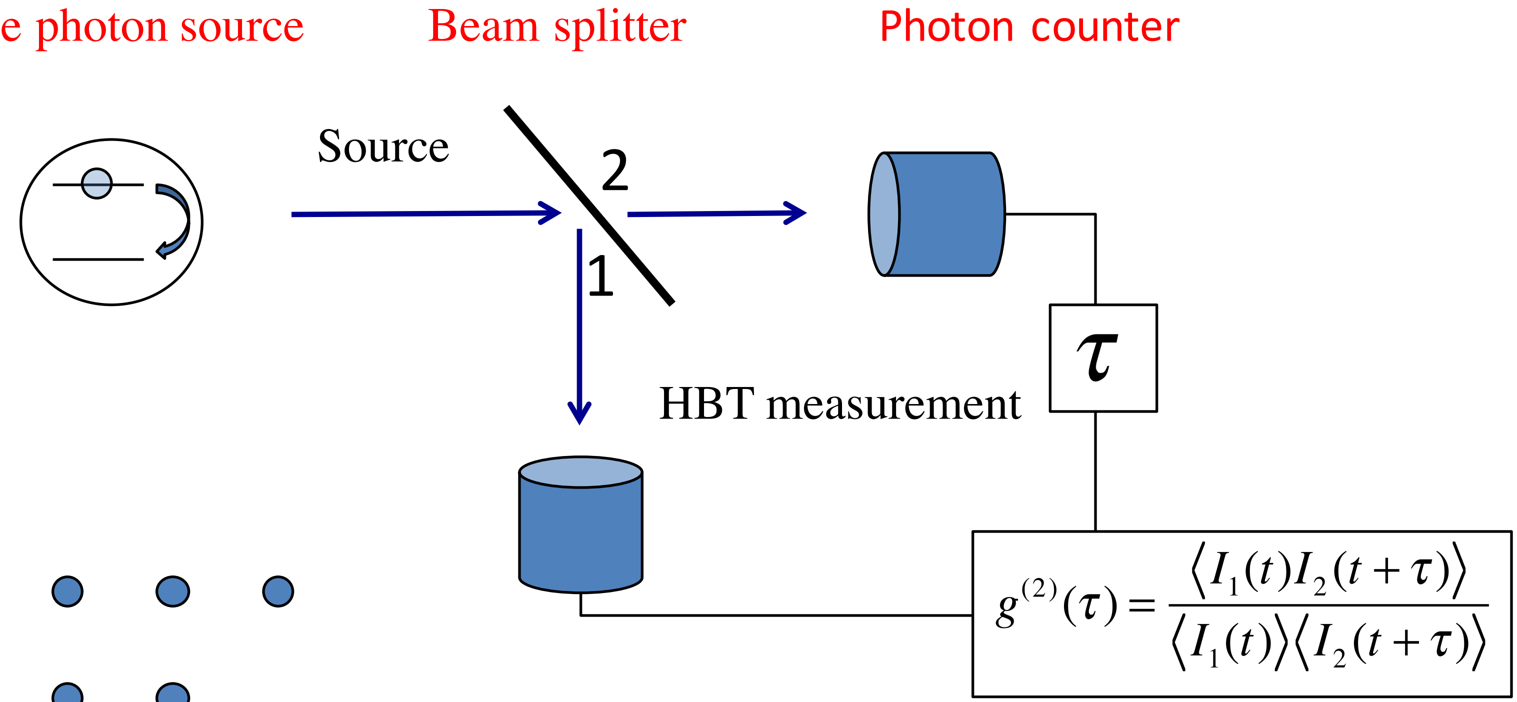
$$\Delta\varphi_p \propto \langle N_C \rangle$$

I.-C. Hoi *et al.* PRL **111,** 053601 (2013)

Nonlinear photonic crystal fibres, 0.05 degrees/photon
N. Matsuda, *et al.* Nature Photonics **3**,95(2009)
V. Venkataraman, *et al.* Nature Photonics **7**,138 (2012)

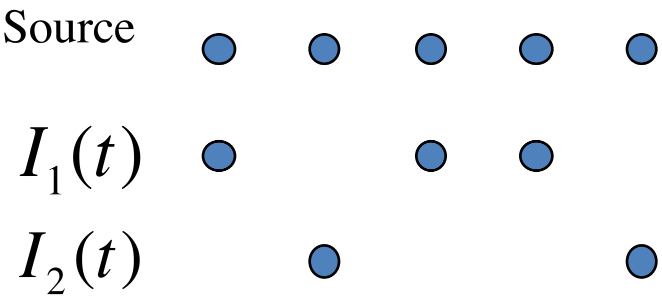
What is the photon statistics of the scattered field?

Intensity-Intensity Correlation



$$g^{(2)}(\tau) = \frac{\langle I_1(t) I_2(t+\tau) \rangle}{\langle I_1(t) \rangle \langle I_2(t+\tau) \rangle}$$

Second-order correlation function

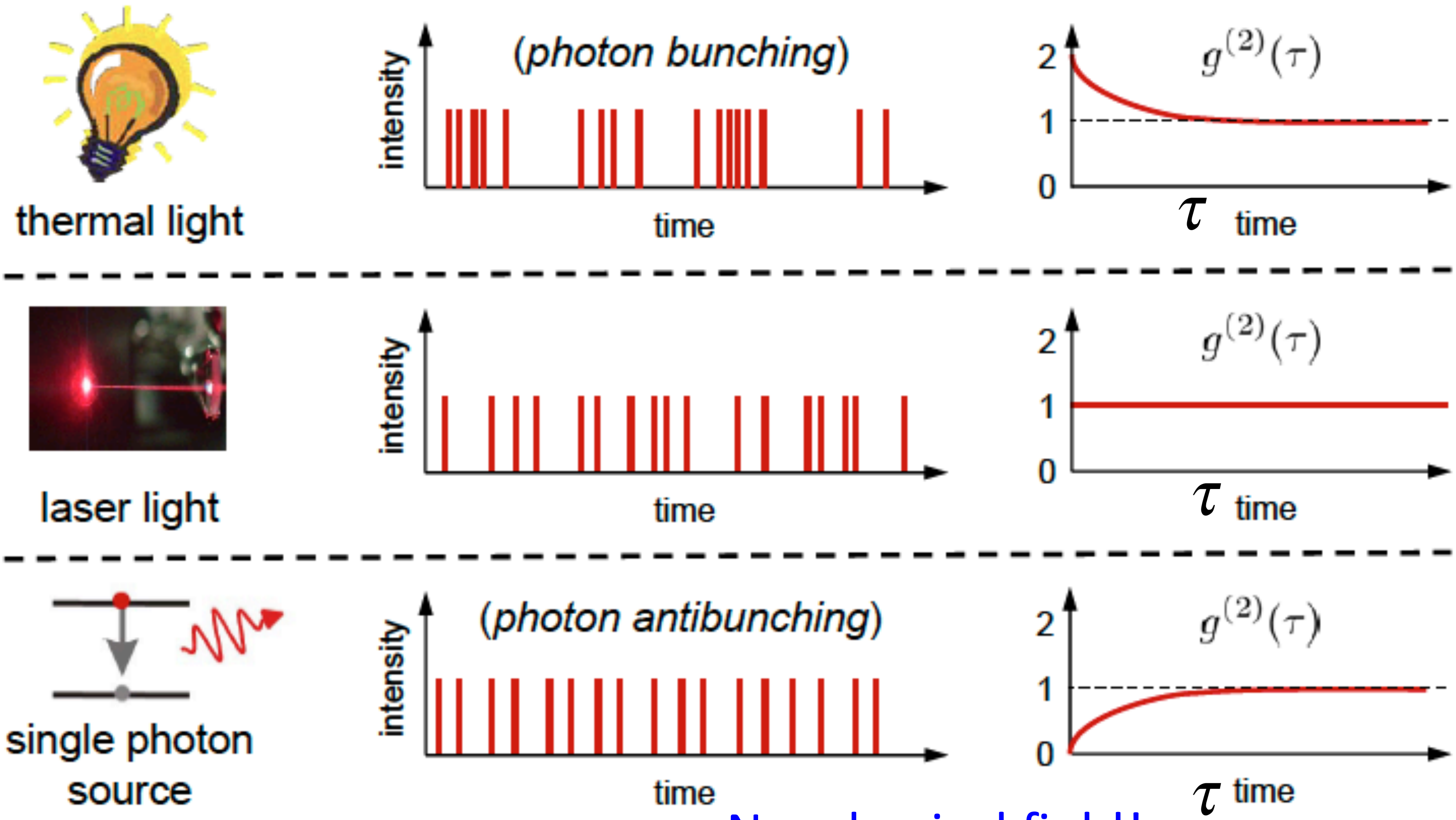


Hanbury Brown-Twiss
Nature **177**, 27 (1956)

Photon statistics from second order correlation function

A comparison between different light sources:

Coherent state



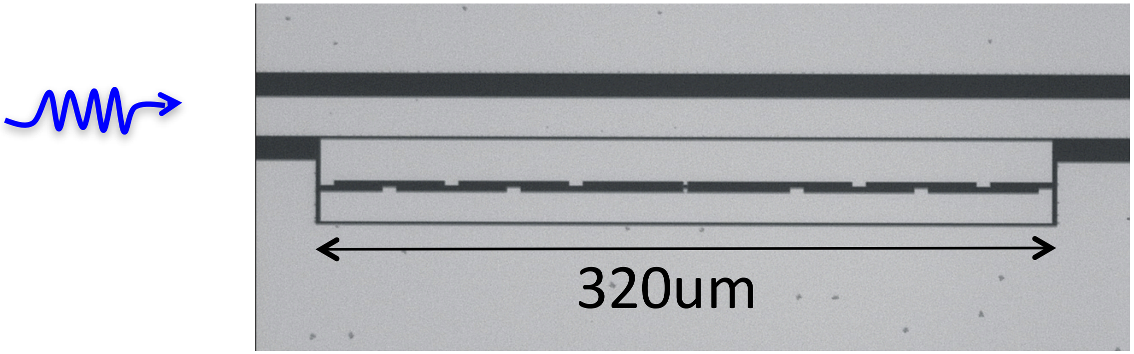
Nonclassical field!

ESONN 2010 lecture

Photon number filter

Poisson probability distibution

$$\left|V_{in}\right\rangle = a_0\left|0\right\rangle + a_1\left|1\right\rangle + a_2\left|2\right\rangle + \ldots$$



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

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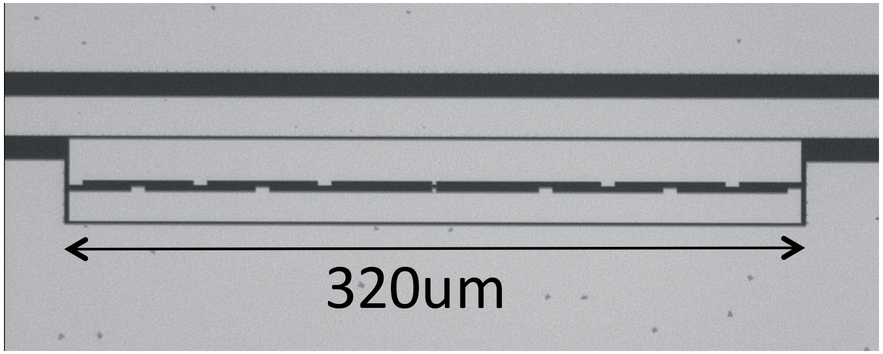


$$\left|V_{R}\right\rangle = r_0\left|0\right\rangle + r_1\left|1\right\rangle$$

Antibunching!

$$\left|V_{T}\right\rangle = t_0\left|0\right\rangle + t_1\left|1\right\rangle + \underset{\text{small}}{t_2}\left|2\right\rangle + \ldots$$

Bunching!

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

Second-order coherence of microwaves

Hanbury Brown-Twiss measurement of output state

Commercial ”beam splitter”

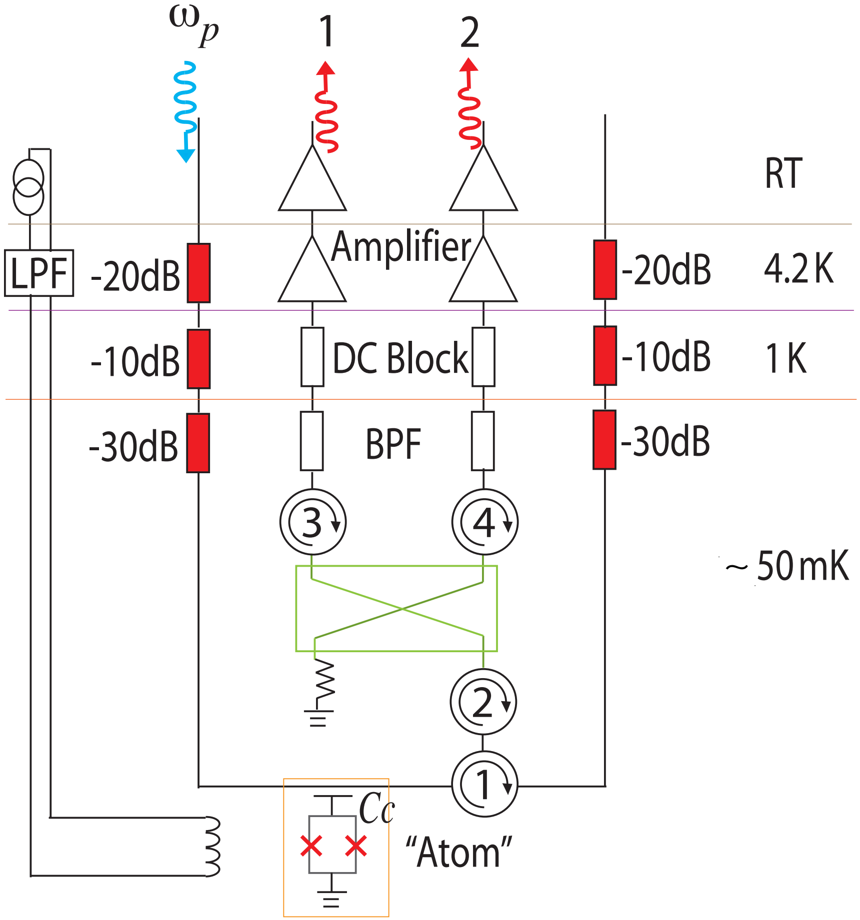
Noise temperature of detection chain is about 7K

Noise of two amplifier is uncorrelated.

$$g^{(2)}(\tau) = 1 + \frac{\langle \Delta P_1(t)\Delta P_2(t+\tau)\rangle}{\left[\langle P_1(t)\rangle - \langle P_{1N}(t)\rangle\right]\left[\langle P_2(t)\rangle - \langle P_{2N}(t)\rangle\right]}$$

Covariance

$$\Delta P_1 \Delta P_2 \equiv \left[P_1 - \langle P_1\rangle\right]\left[P_2 - \langle P_2\rangle\right]$$

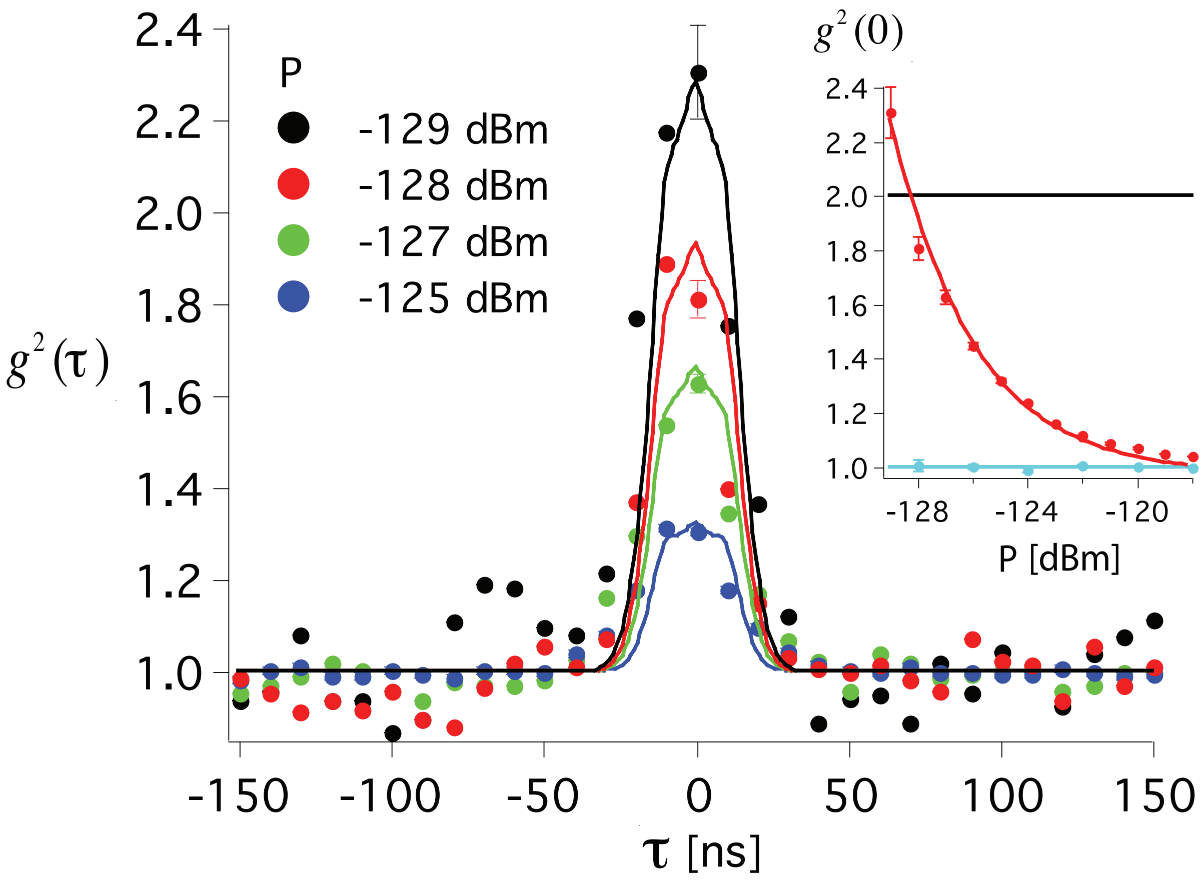


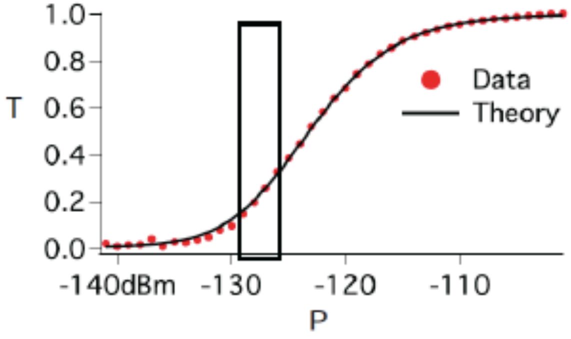
Gabelli *et al*. PRL **93** 056801(2004)

D. Bozyigit *et al.* Nature Phys. **7**, 154(2011)

C. Lang *et al.* Nature Phys. **9**, 345(2013)

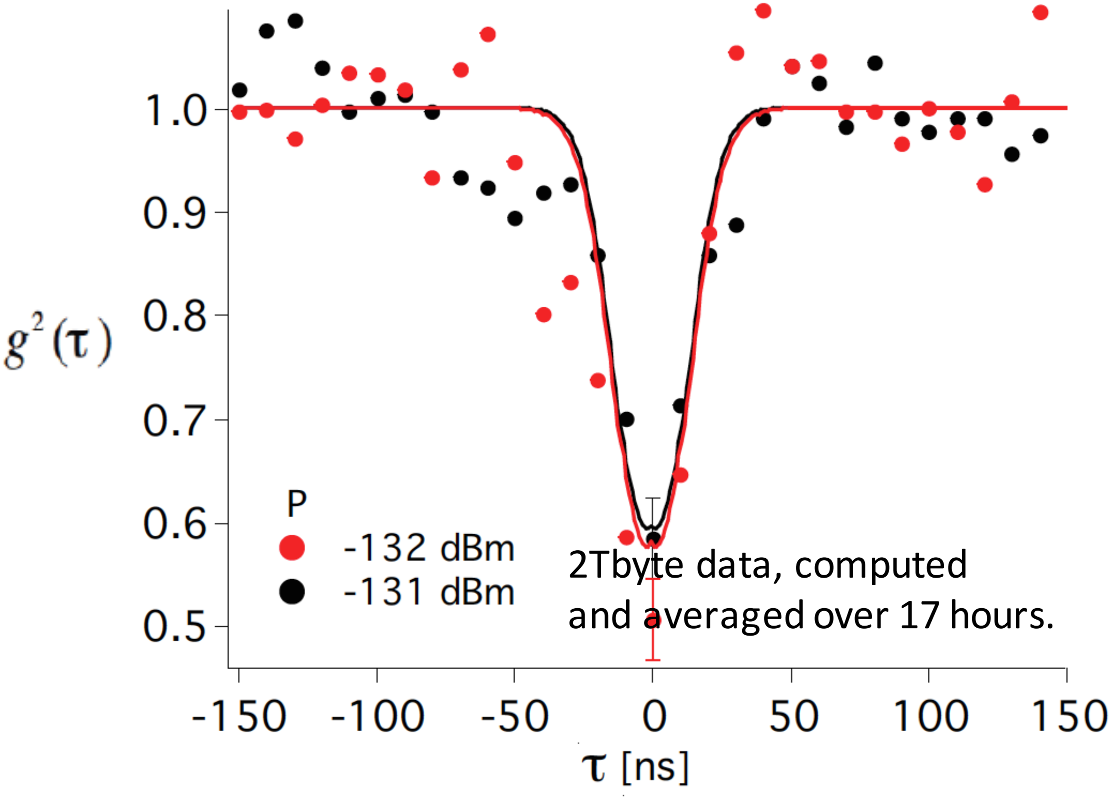
Transmitted field: Superbunching Statistics



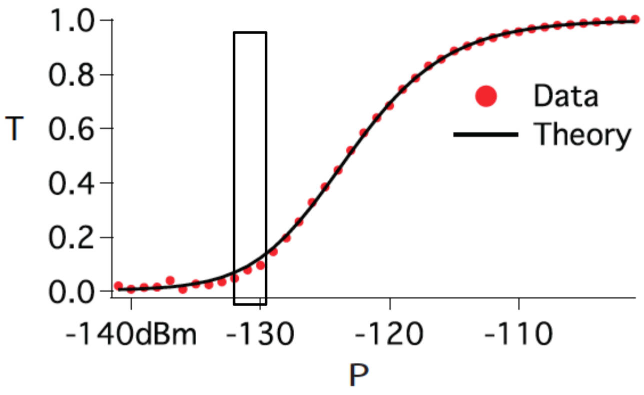


$$g^{(2)}(\tau = 0) = 2.31 \pm 0.09 > 2$$

Reflected field: Antibunching Statistics



2Tbyte data, computed and averaged over 17 hours.

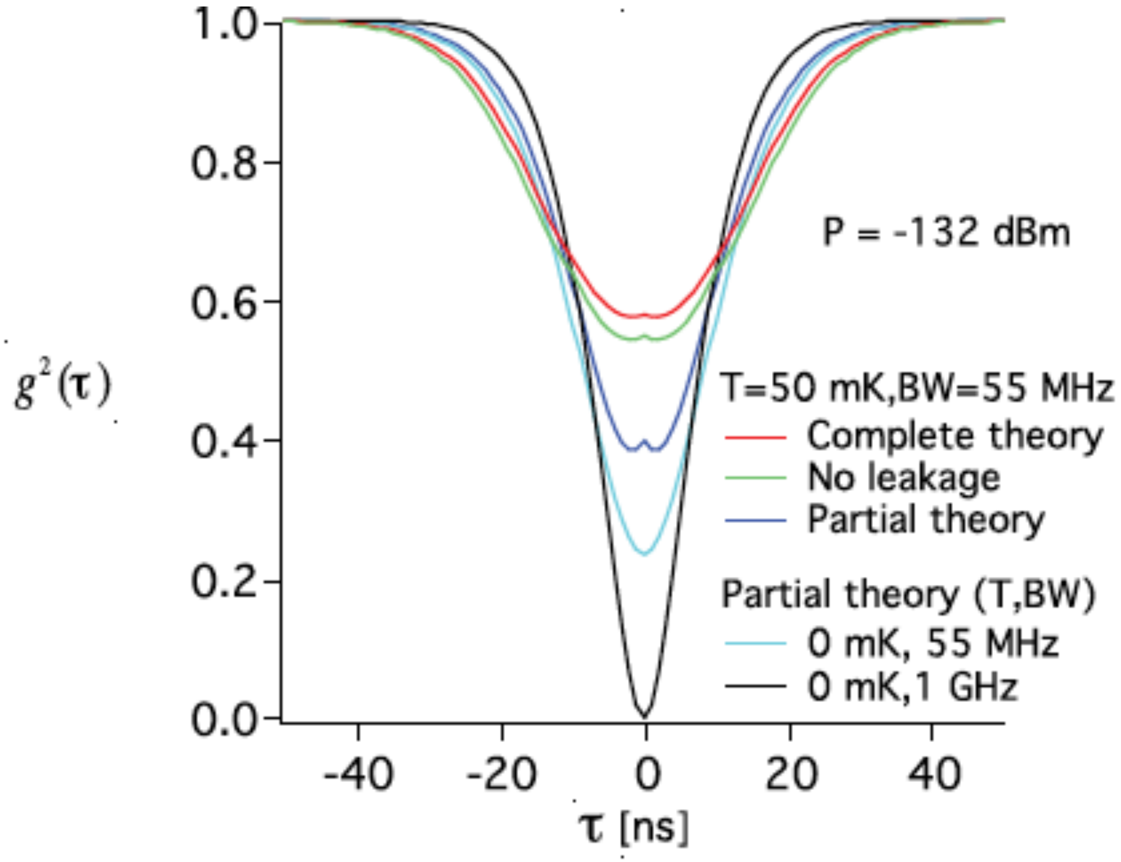


$$g^{(2)}(0) = 0.51 \pm 0.05$$

The antibunching behavior reveal quantum nature of light!

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

Reflected field: Theory



An artificial atom in front of a mirror

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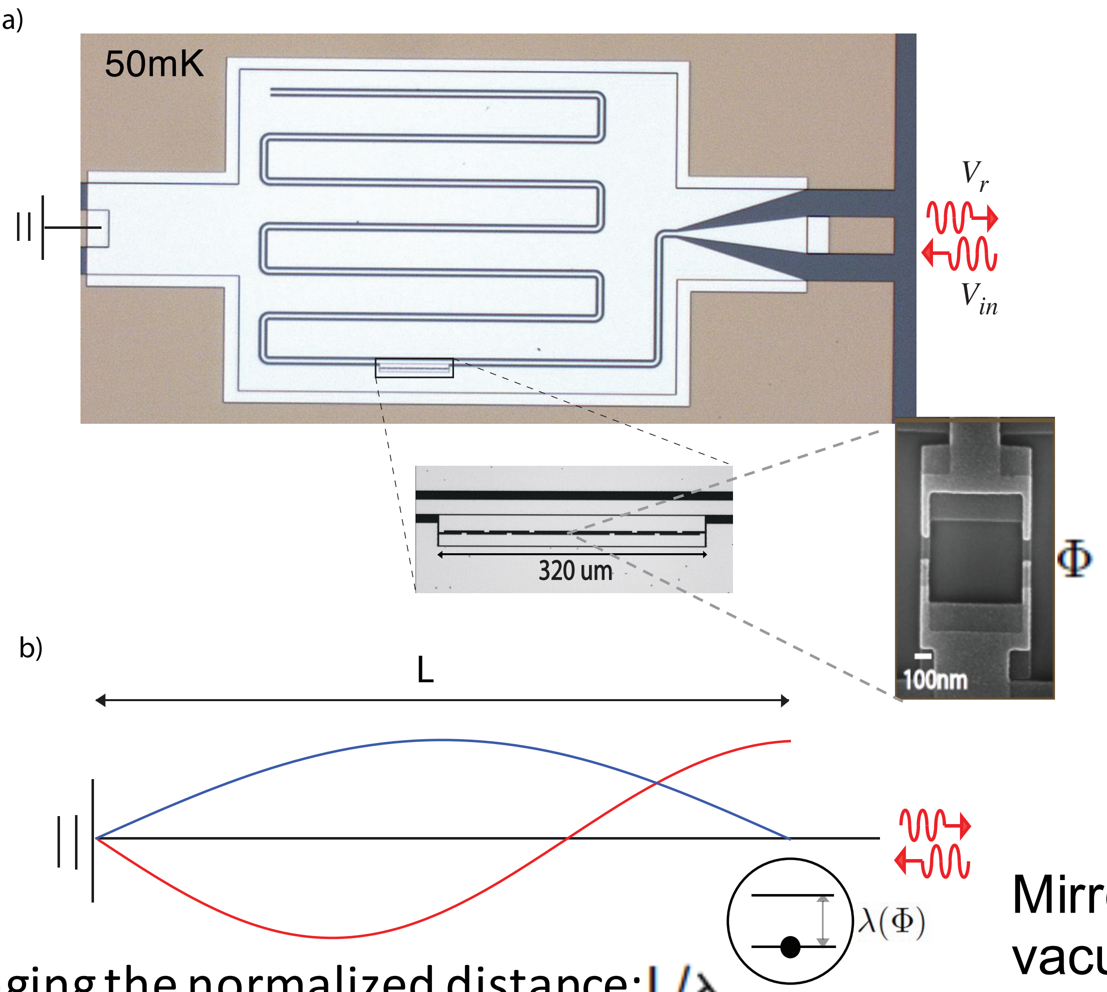
An artificial atom in front of a mirror



Reflection coefficient:

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

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

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

Changing the normalized distance: L/λ

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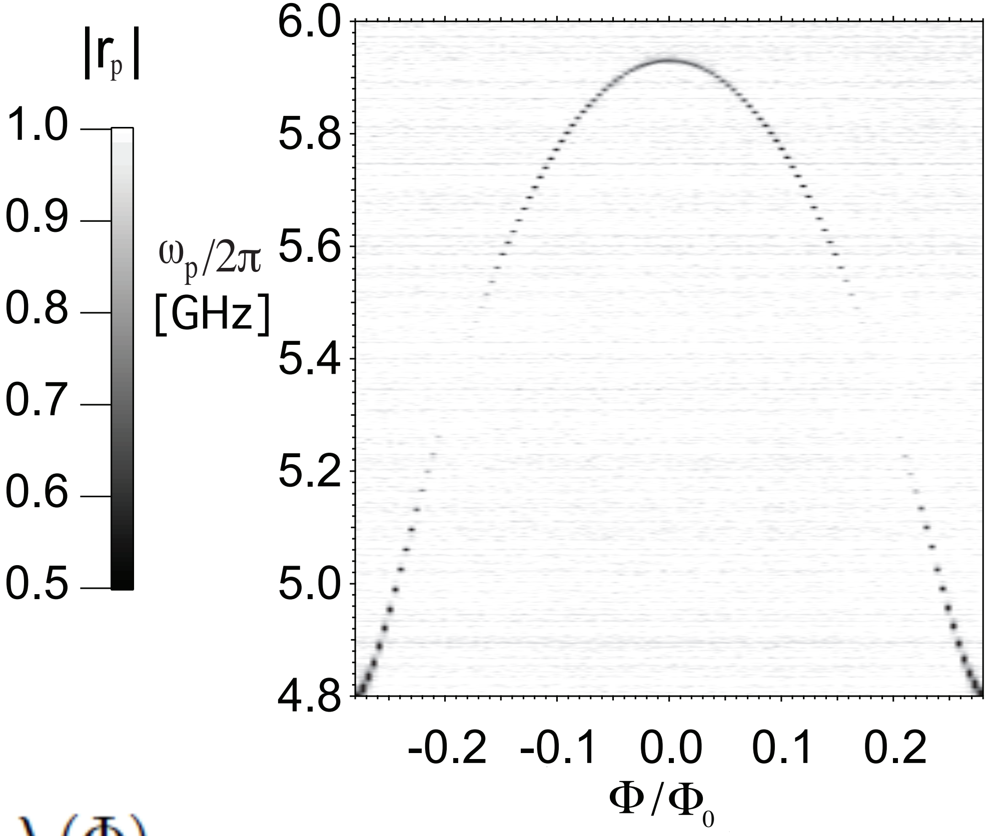
Changing the spontaneous emission rate

$\Omega_p \ll \gamma$

Weak drive:

Experimental data



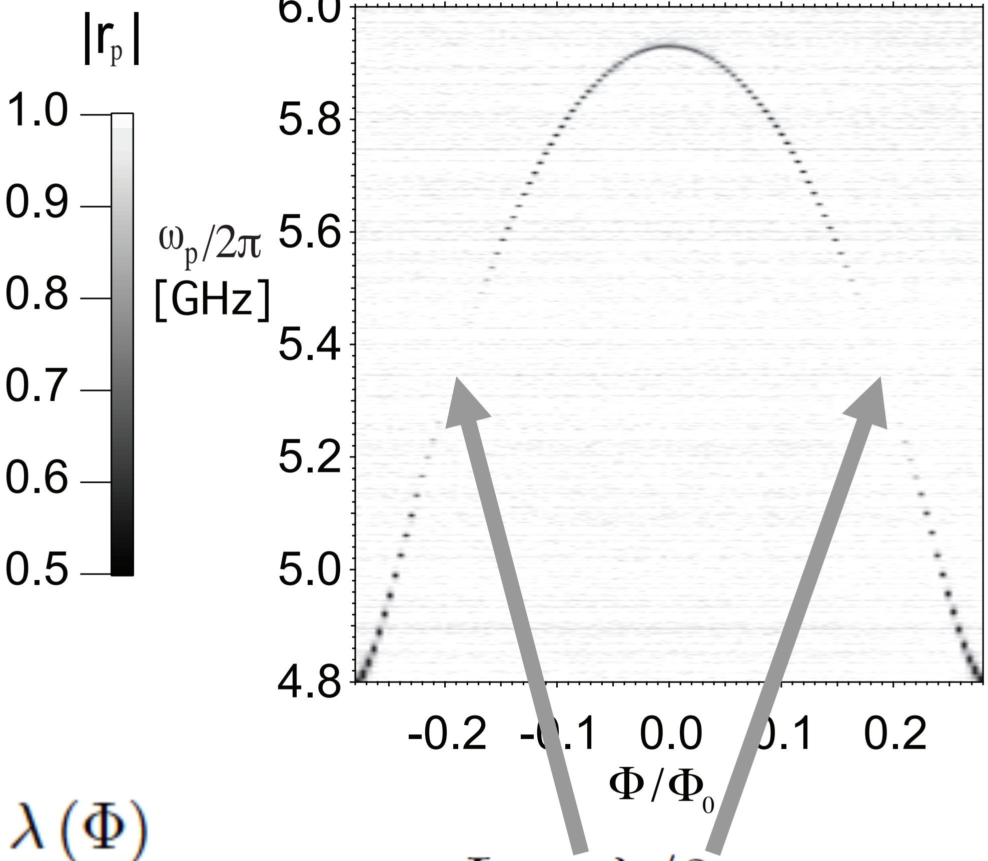
$\lambda(\Phi)$

Changing the spontaneous emission rate

$\Omega_p \ll \gamma$

Weak drive:

Experimental data



$\lambda(\Phi)$

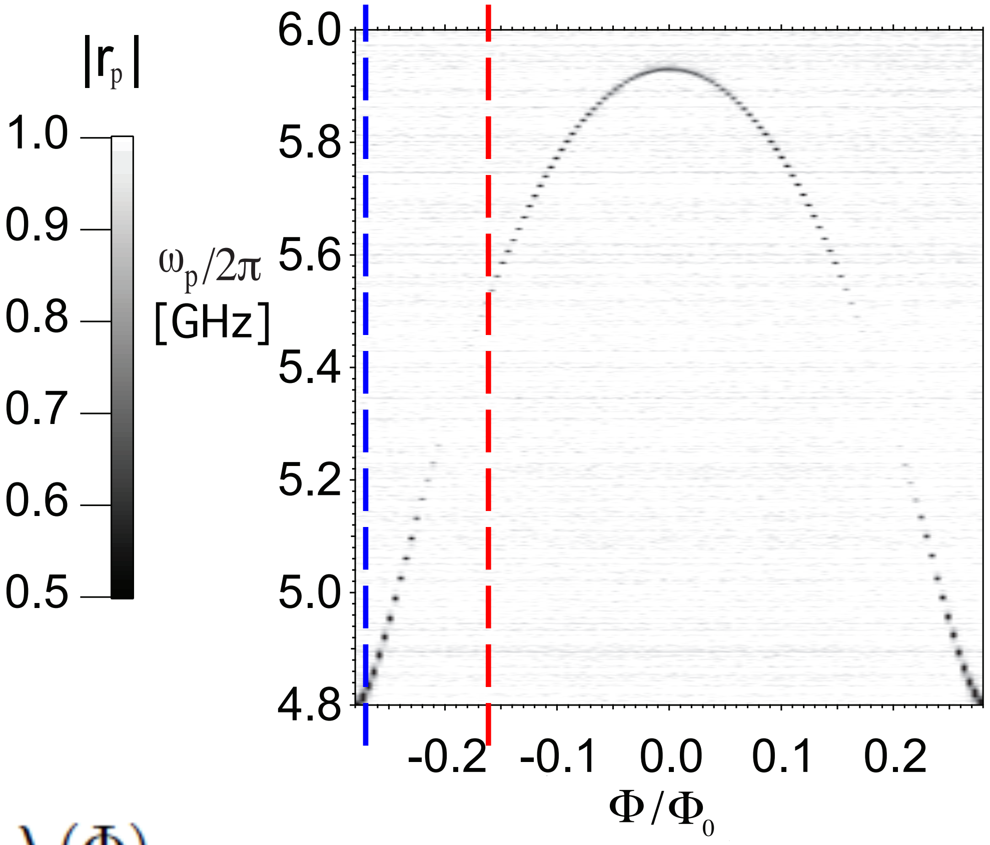
$L = \lambda/2$ Atom decoupled from vacuum fluctuations at node.

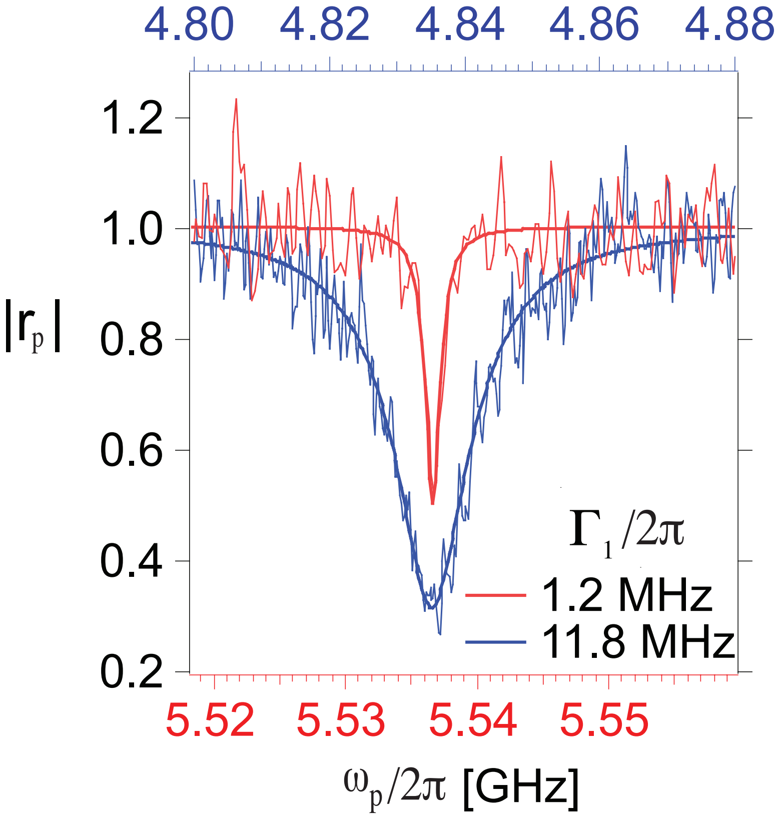
Changing the spontaneous emission rate

$\Omega_p \ll \gamma$

Weak drive:

Experimental data





$\lambda(\Phi)$

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

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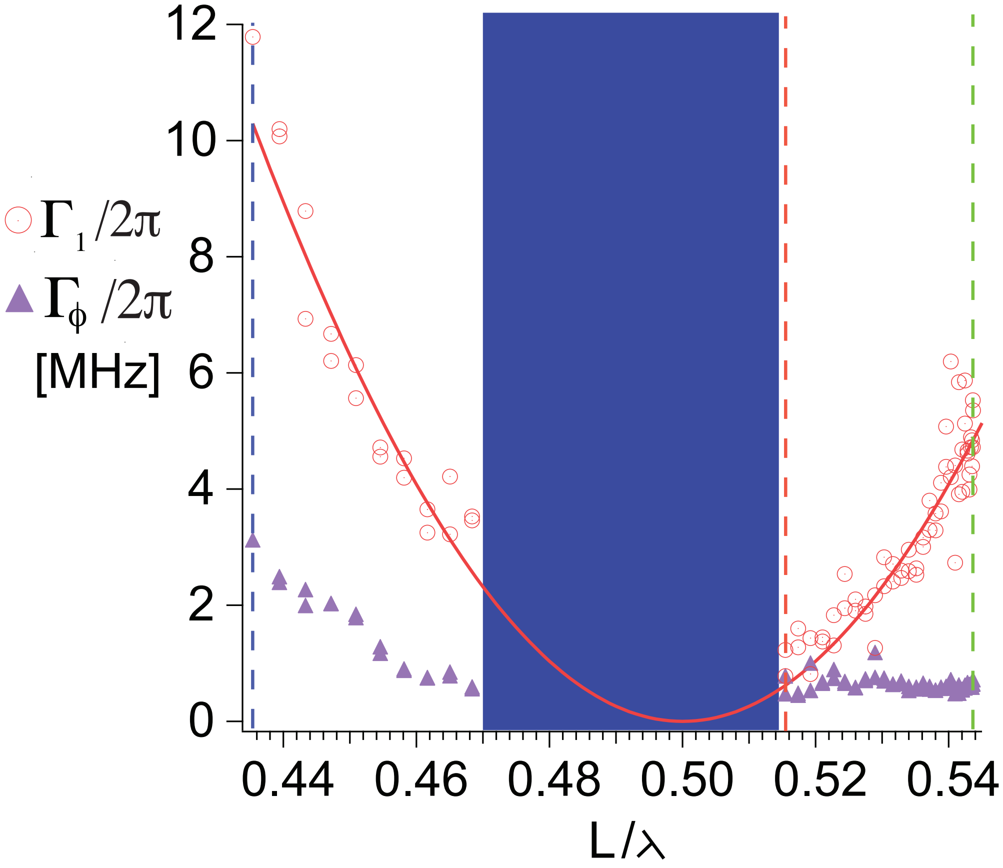
Spontaneous emission rate as a function of normalized distance

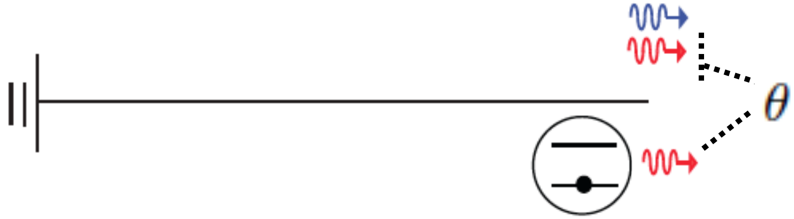


$$\Gamma_1(\Phi) = 2\Gamma_{1,b}\cos^2[\theta(\Phi)/2]$$

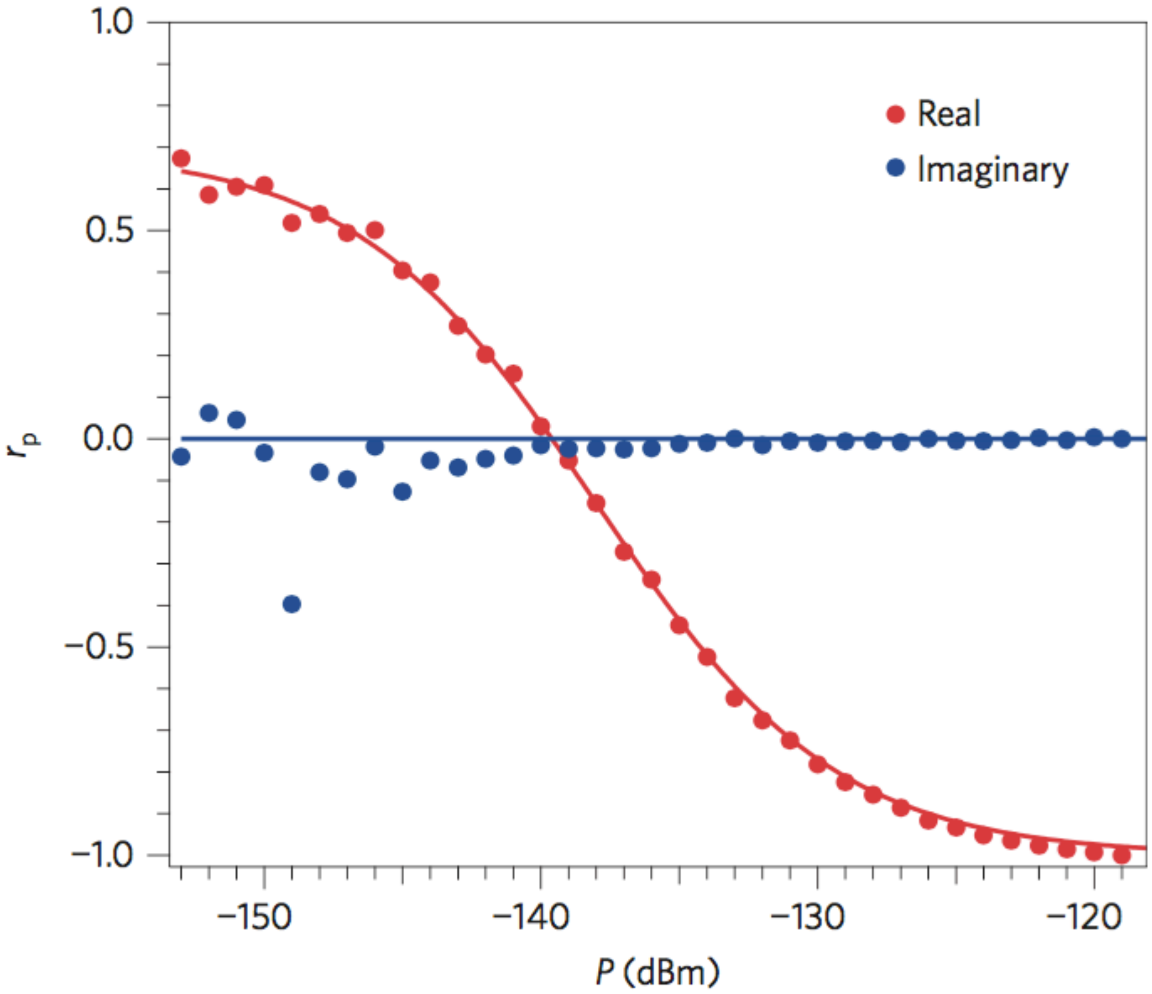
$$\theta(\Phi) = 2 \times [2\pi L/\lambda(\Phi)] + \pi$$

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

θ: phase difference between scattered field from the same atom



Calibrating atom-field coupling K



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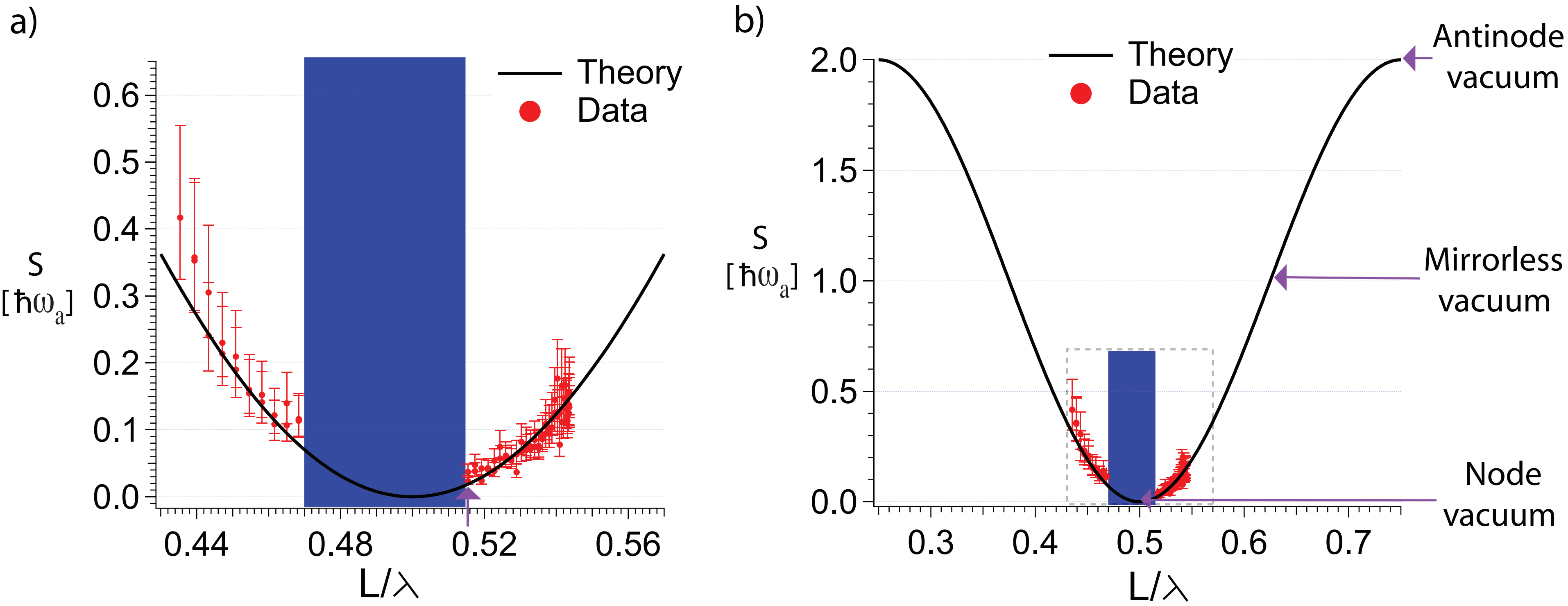
Probing quantum vacuum fluctuations from spontaneous emission rate



— $\Gamma_1 = k^2 S$

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

k: coupling constant

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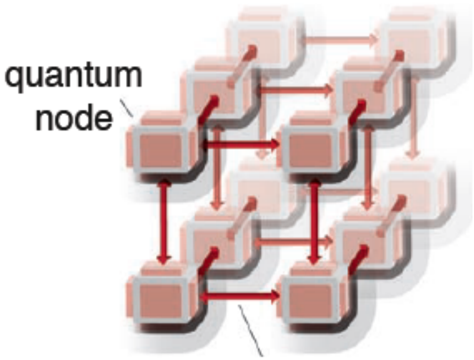
Conclusion

Quantum node:
Generating, processing, routing quantum information.



The photon-number filter (Generating)
The cross-Kerr phase shift (Processing: phase gate)
The single-photon router (Routing)
The quantum spectrum analyzer (Probing fluctuation)

I.-C. Hoi *et al.* Physical Review Letters, **107**, 073601 (2011)
I.-C. Hoi *et al.* Physical Review Letters, **108**, 263601 (2012)
I.-C. Hoi *et al.* Physical Review Letters, **111**, 053601 (2013)
I.-C. Hoi *et al.* Nature Physics doi:10.1038/nphys3484 (2015)

Io-Chun Hoi

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Postdoc, PhD student, Master student wanted!