國立清華大學
NATIONAL TSING HUA UNIVERSITY

2015 AMO Summer School

Quantum Optics with Propagating Microwaves in Superconducting Circuits II

許耀銓
Io-Chun, Hoi

Outline

Quantum applications

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

Quantum network

Resonant scattering in 1D waveguide

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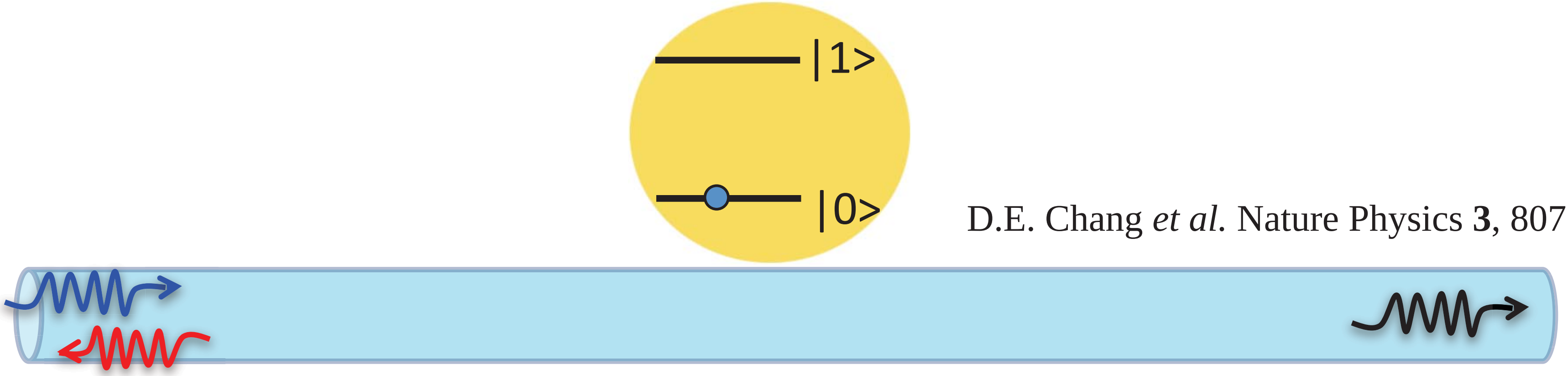
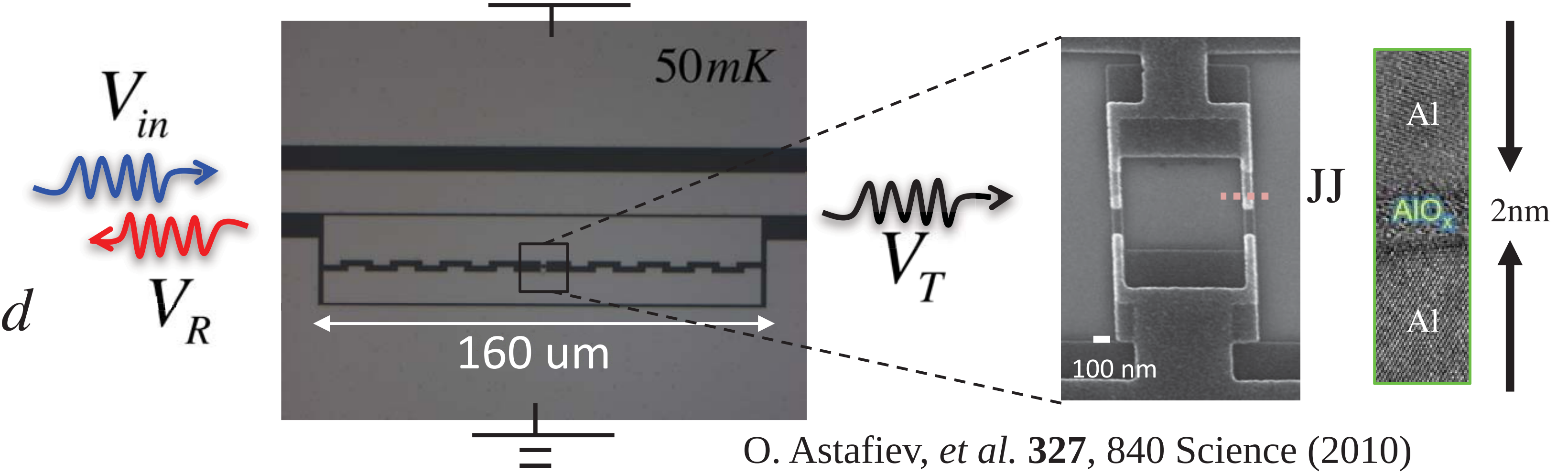
Resonant scattering in 1D waveguide



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

Fully coherent: no transmission, perfect reflection.

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



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

$\lambda \sim cm$ Wavelength of EM field

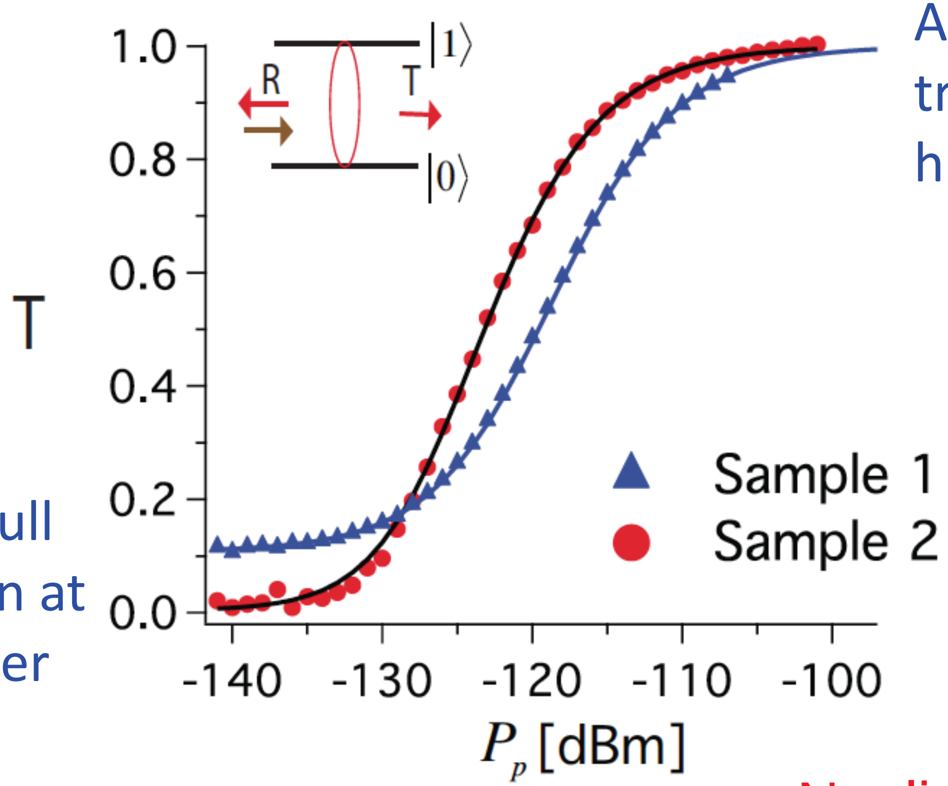
$d \sim \mu m$ Size of "atom"

elaxation dominated by transmission line.

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

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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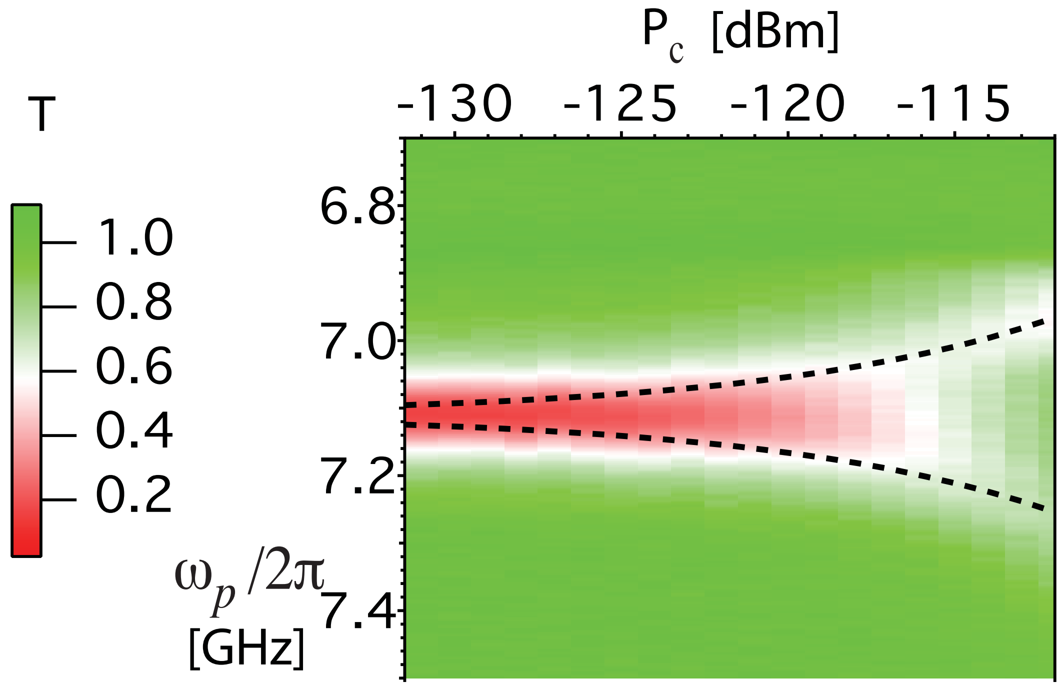
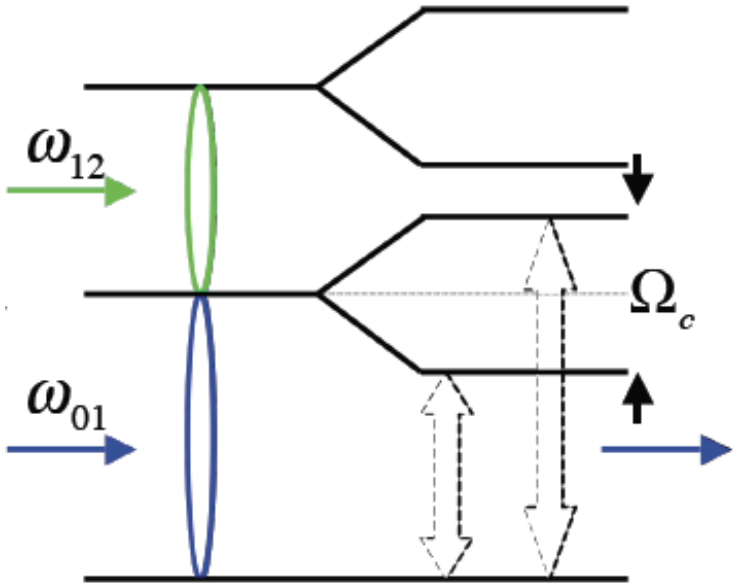
Autler-Townes Splitting



$\Omega_P \ll \gamma_{10}$

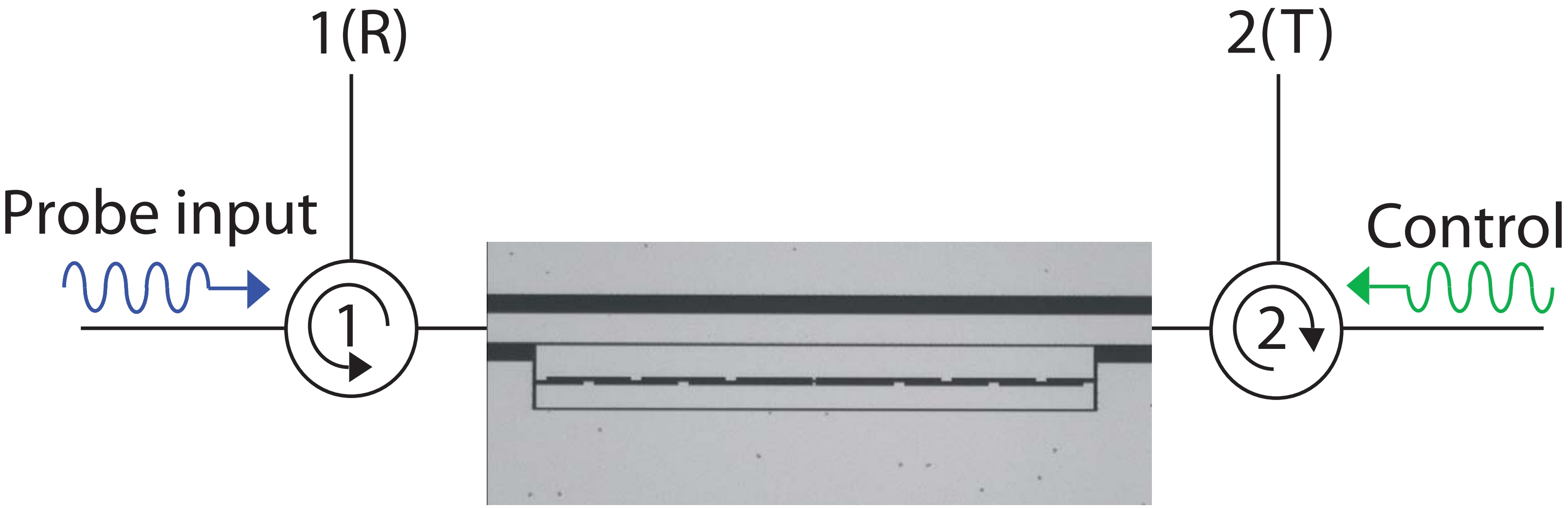


A. A. Abdumalikov, Jr *et al.* PRL **104**, 193601 (2010)

The Single-Photon Router

Io-Chun Hoi

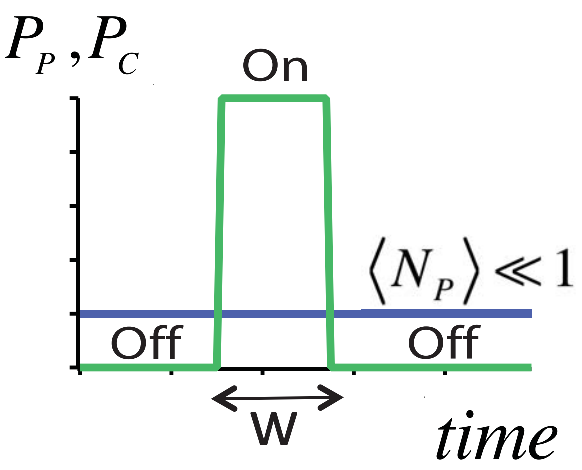
The Single-Photon Router

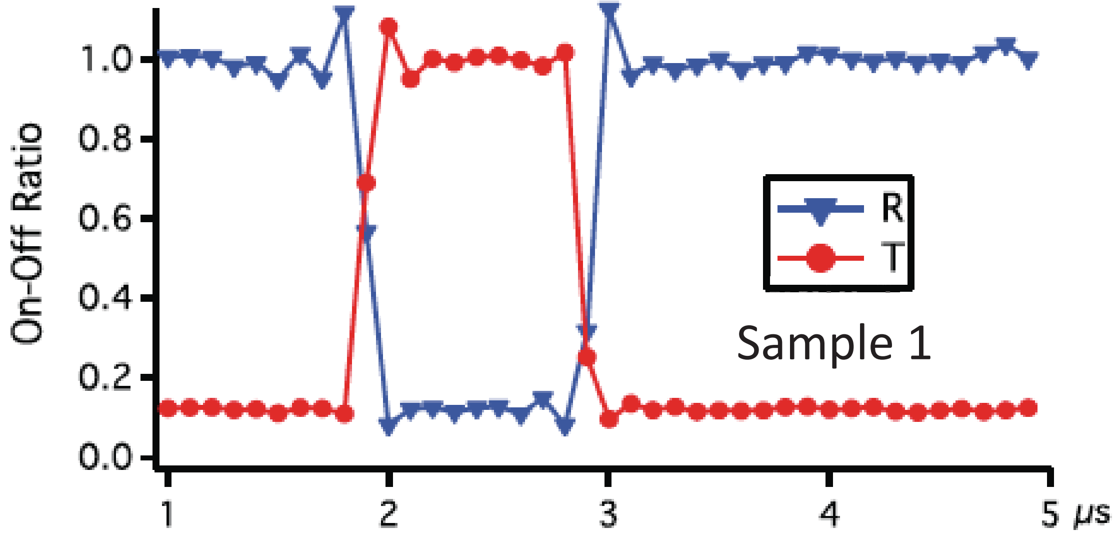


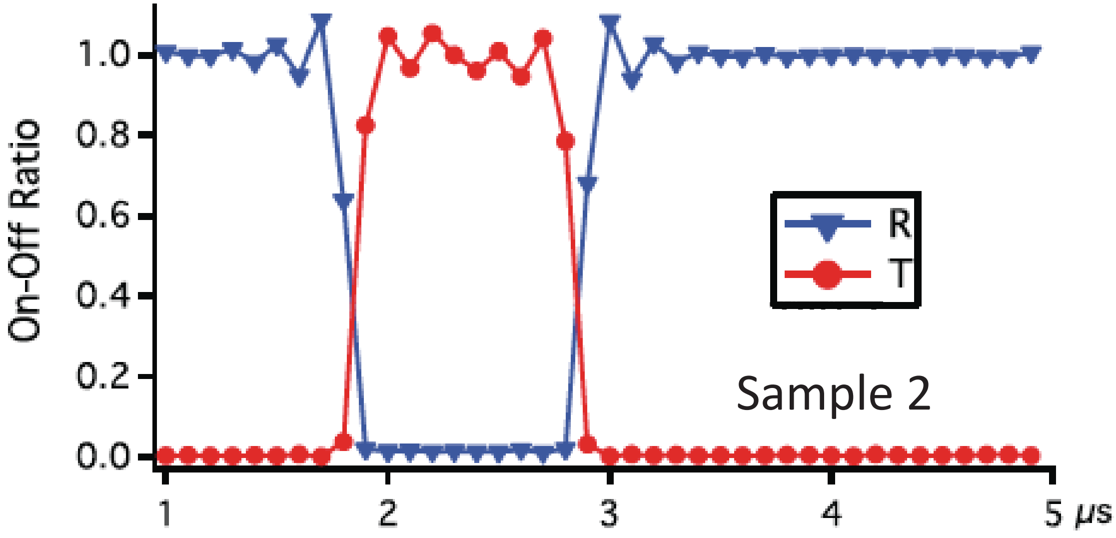
By turning on or off the control tone, we can decide which port the input photons go to.

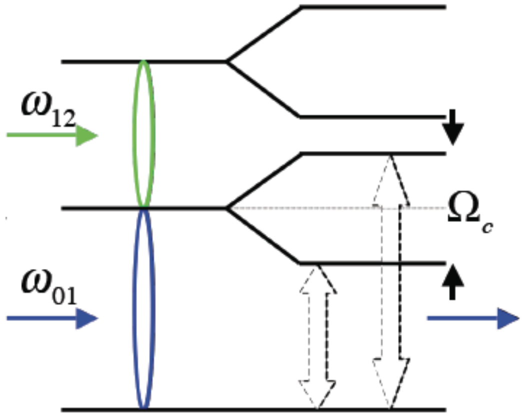
I.-C. Hoi *et al.* PRL **107**, 073601 (2011)

Measuring both T and R simultaneously



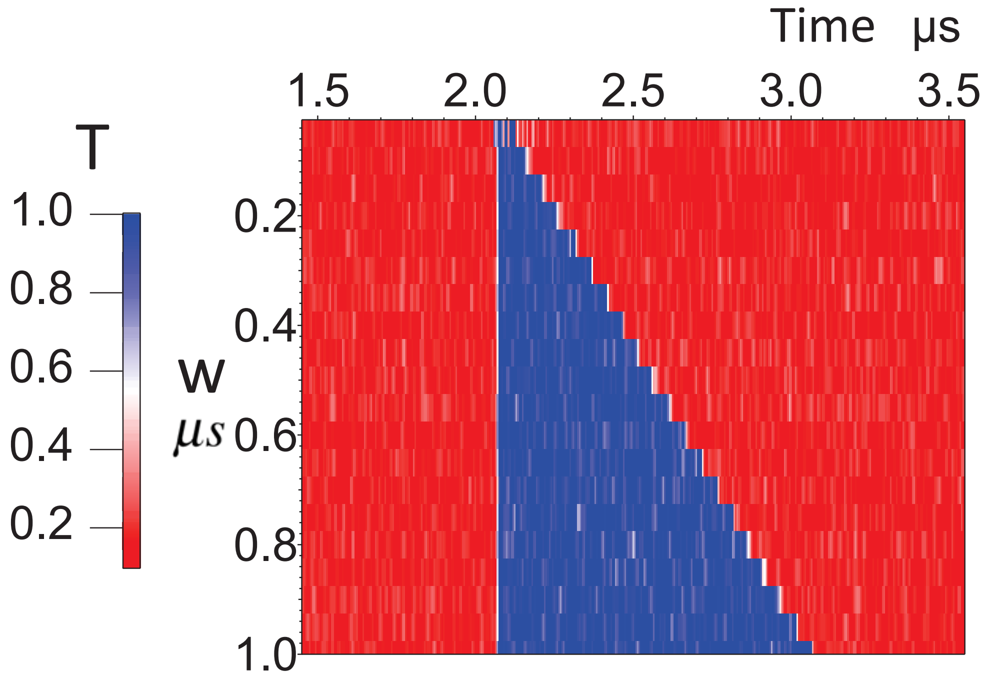






Fast photon router

Transmittance for different pulse times: 50ns to 1μs



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Fast photon router

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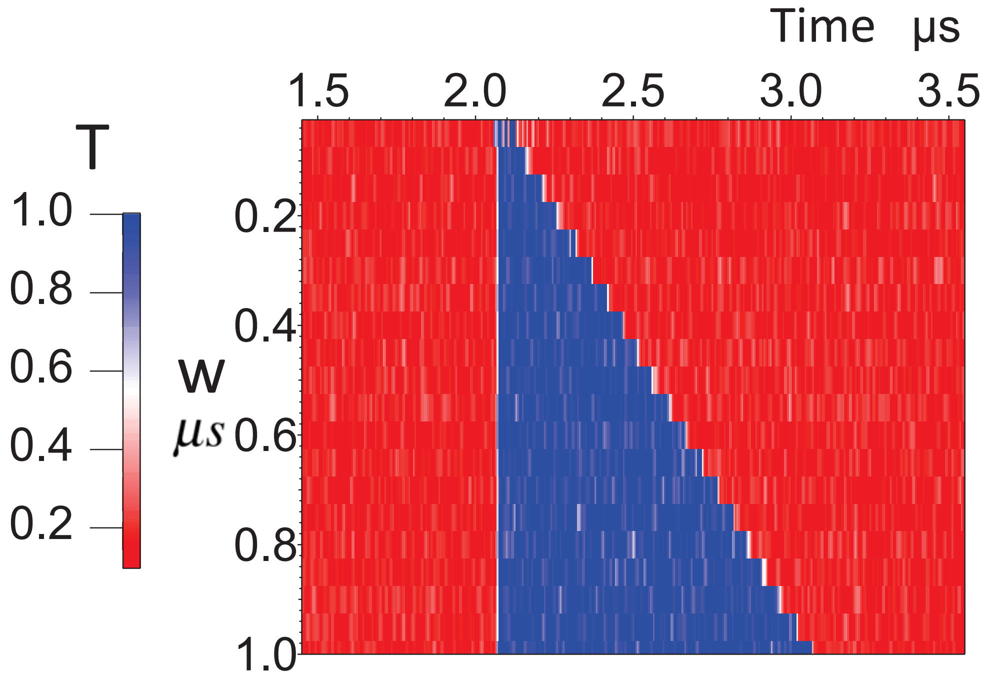
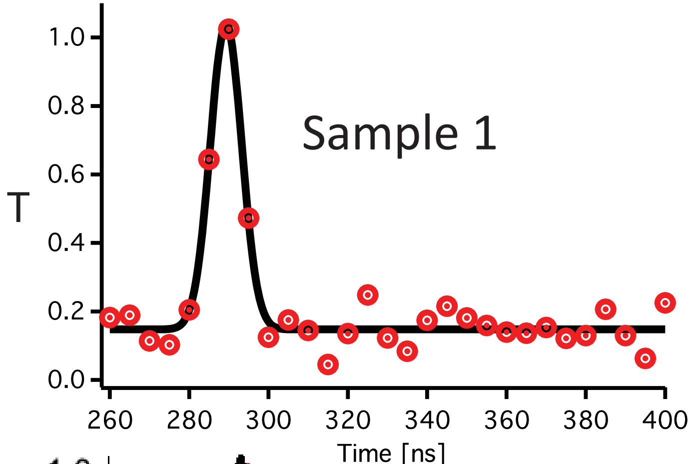
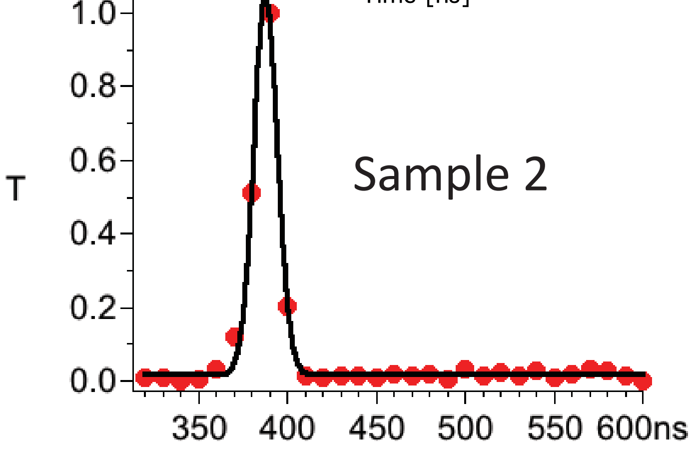


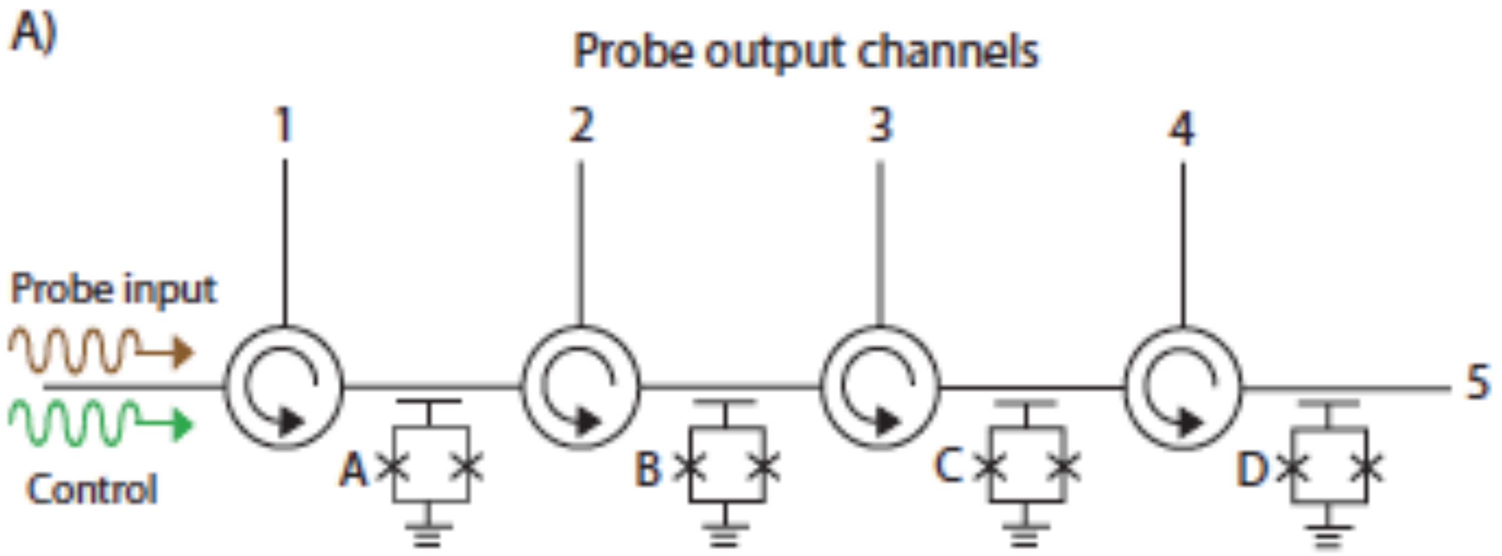
10 ns gaussian pulse times





Routing photons on the 10 ns scale, limited by $1/\Gamma_{10} \sim 2ns$

Multiple Port Photon Router



B)

ω_A ω_B ω_C ω_D	Off Off Off Off	On Off Off Off	On On Off Off	On On On Off	On On On On
Output	1	2	3	4	5

Photon-Photon interaction via a three-level atom

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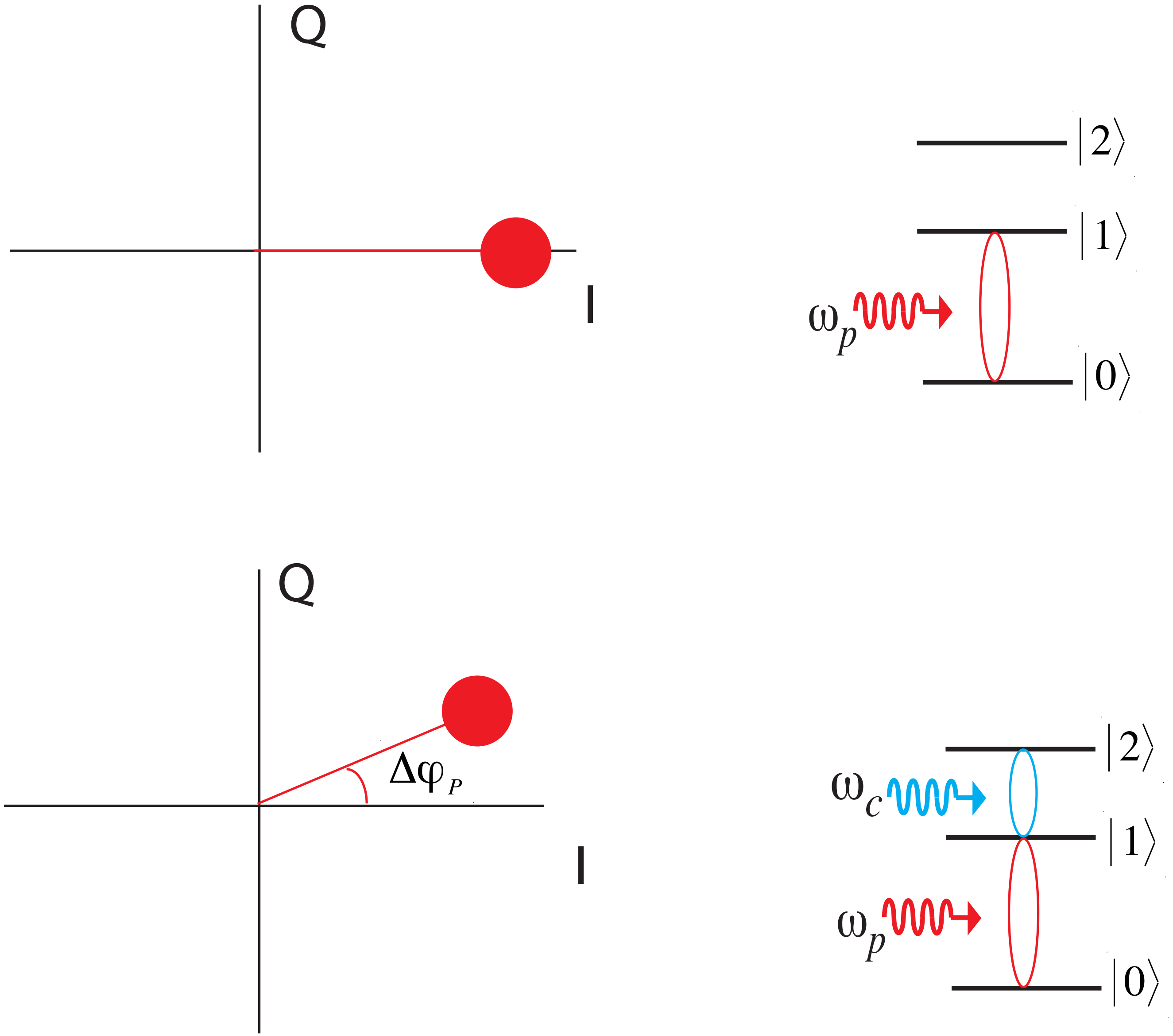
Photon-Photon interaction via a three-level atom



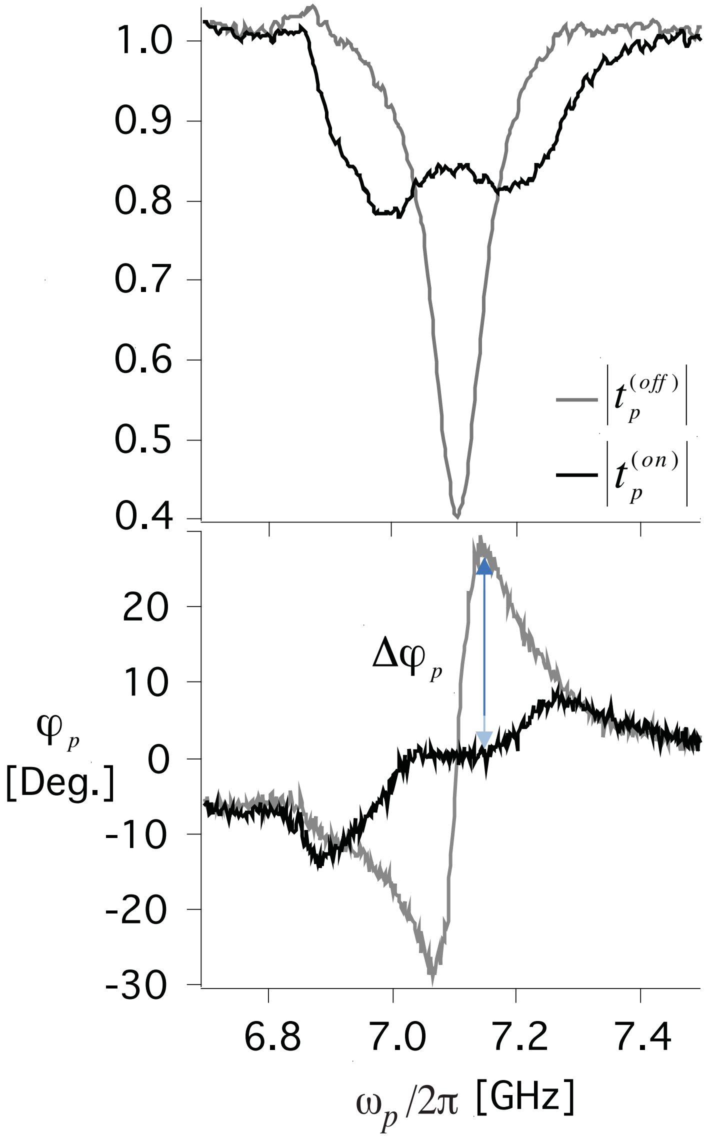
$$\Delta\varphi_P$$

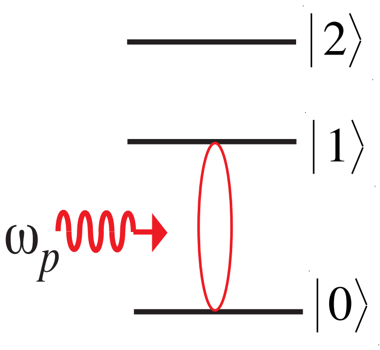
Parameters

$$P_P, P_C, \omega_P, \omega_C$$

$$\omega_C = \omega_{21}$$

Photon-Photon interaction via a three-level atom





$\Delta\varphi_P$

Parameters

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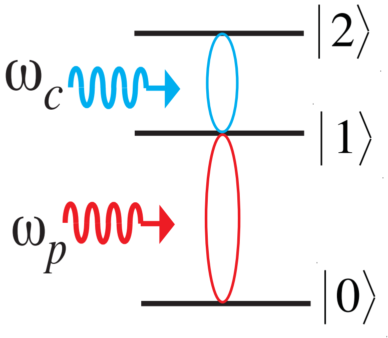
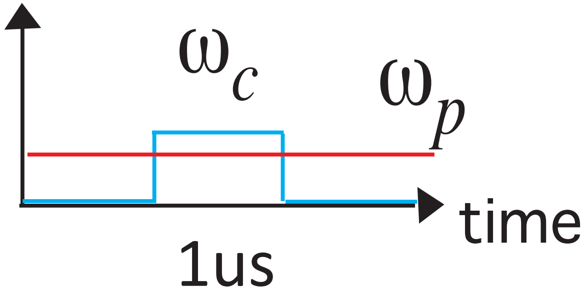
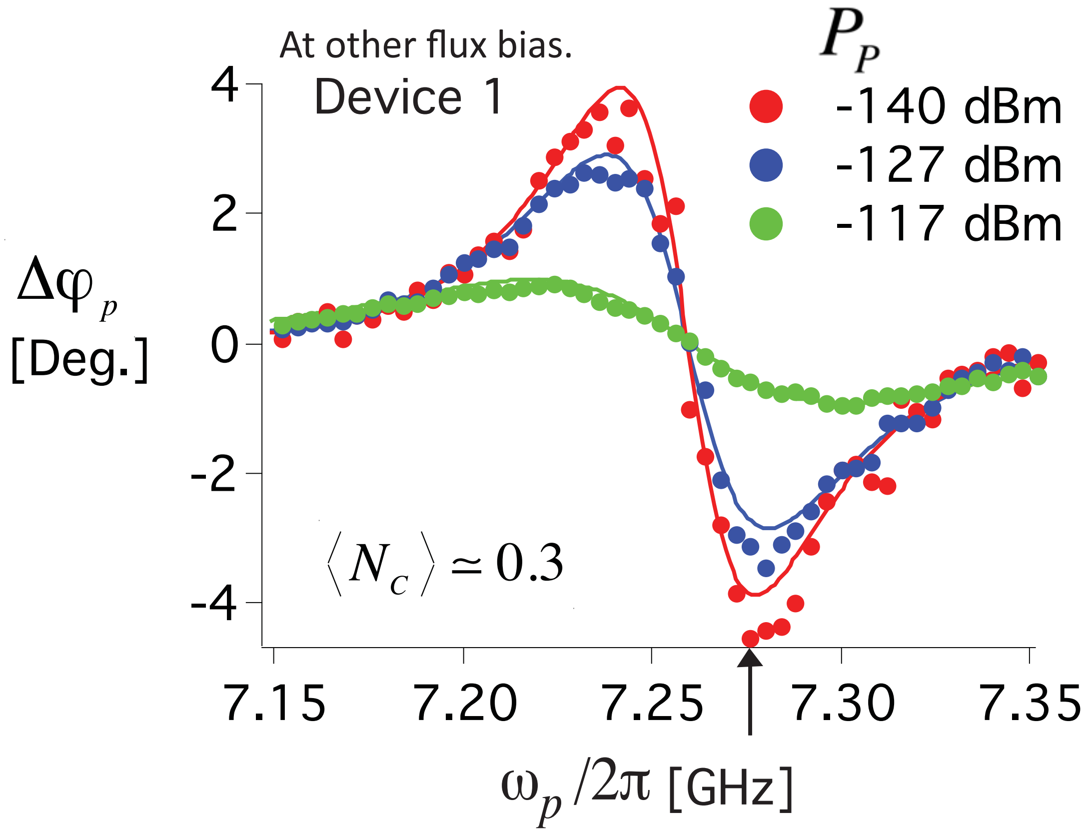


Nonlinear interaction between two microwaves

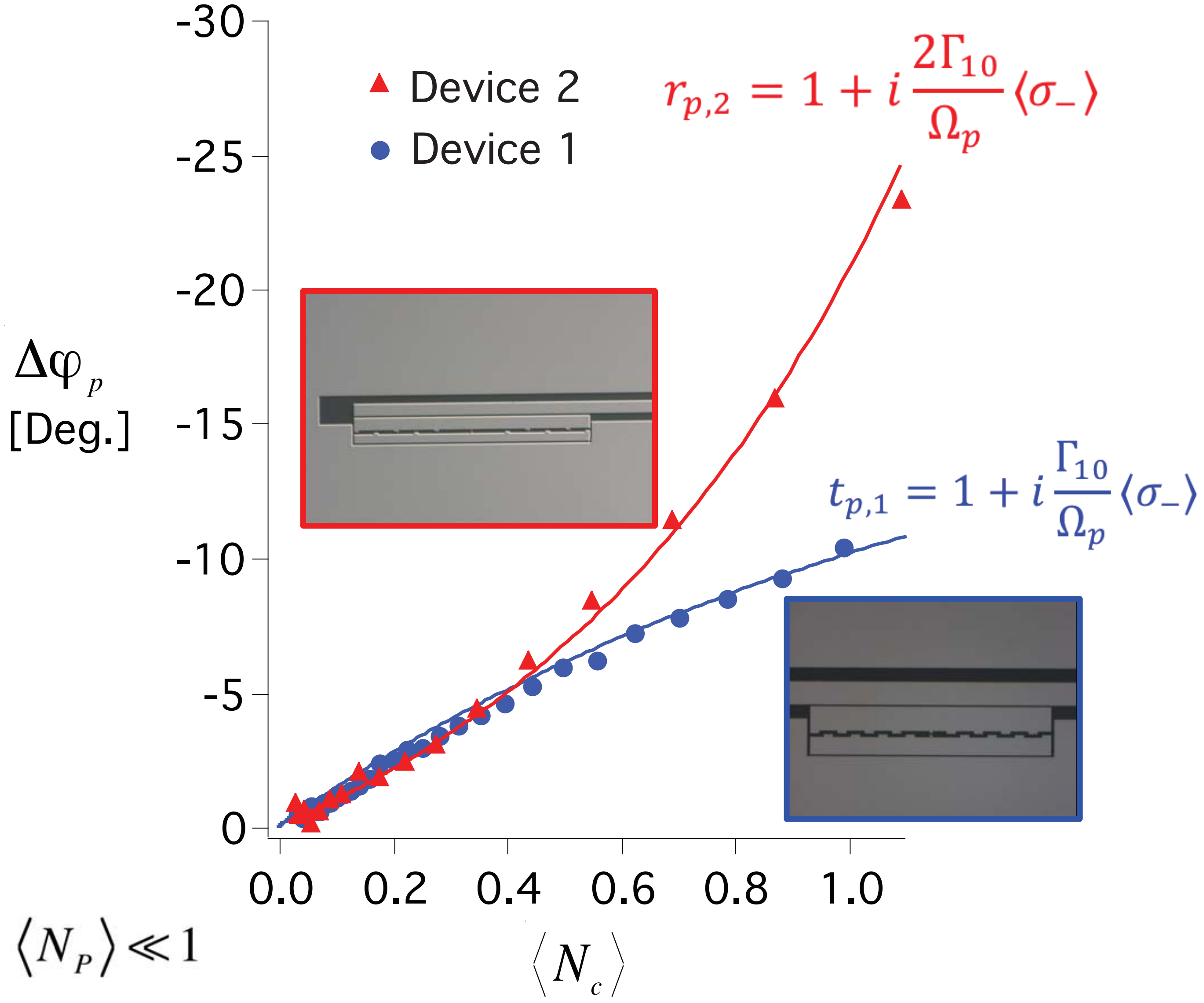




$$\langle N_C\rangle = \frac{P_C}{\hbar\omega_C(\Gamma_{21}/2\pi)}$$

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

The Giant Cross-Kerr Phase Shift

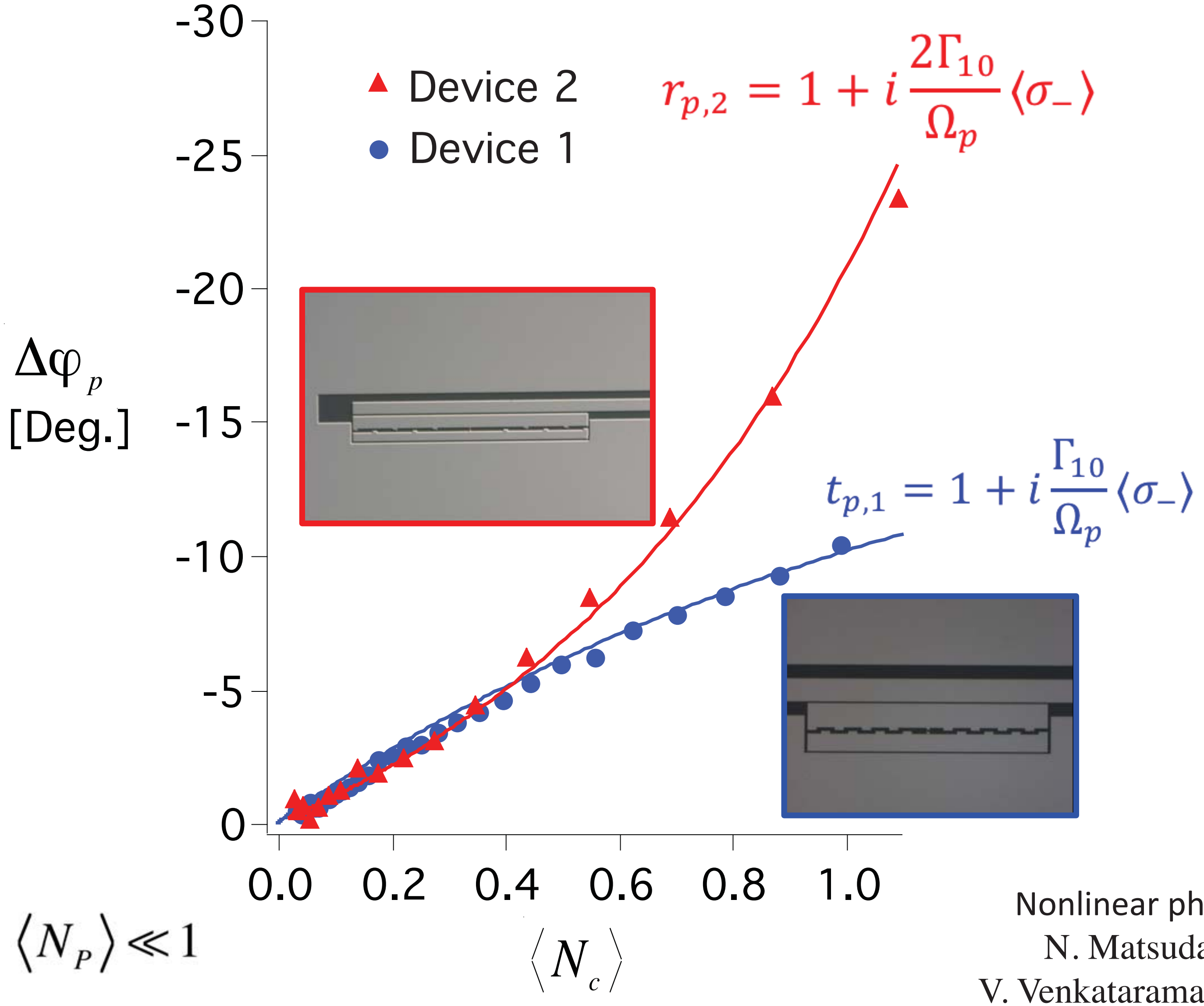


$\langle N_P \rangle \ll 1$

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

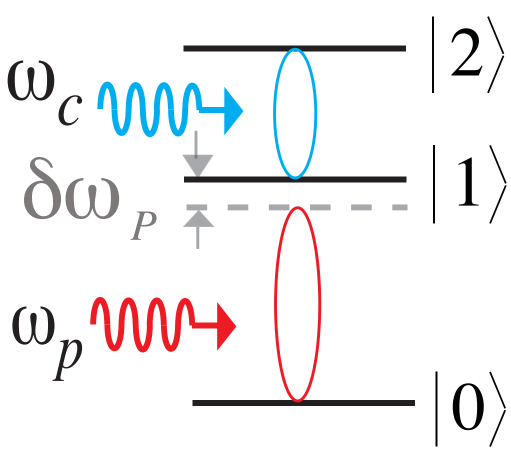
I.-C. Hoi *et al.* PRL **111,** 053601 (2013)

The Giant Cross-Kerr Phase Shift



$\langle N_p\rangle \ll 1$

Kerr medium

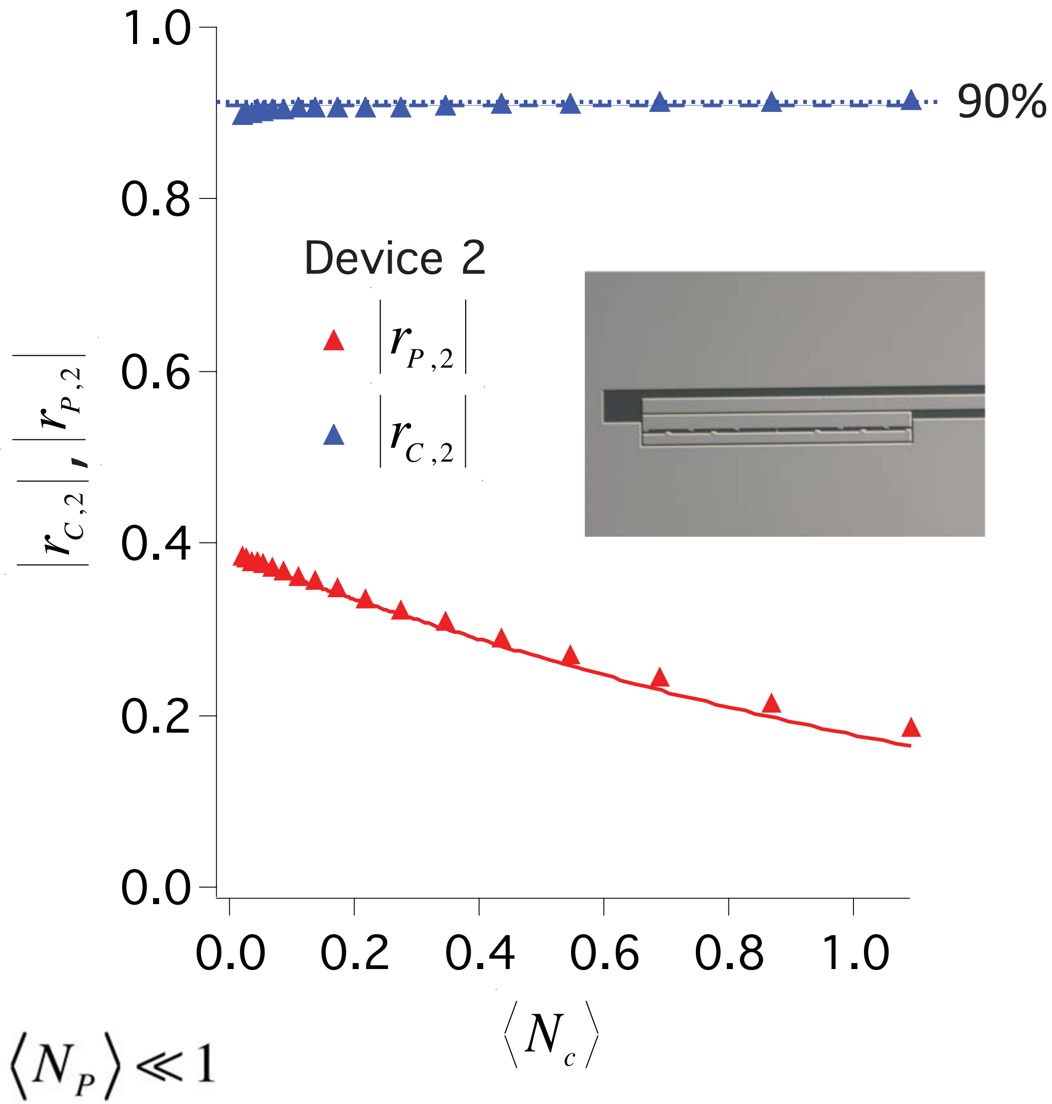


$$\Delta\varphi_p \propto \langle N_C\rangle$$

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)

Simultaneously measured control and probe fields

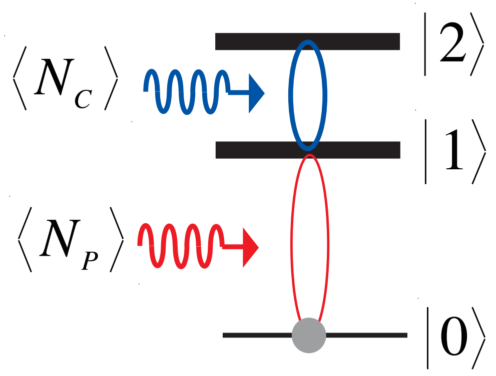


$\langle N_P \rangle \ll 1$

Possible for QND measurement of propagating photons.

S. R. Sathyamoorthy *et al.* Arxiv 1308.2208, (2013)

$$|r_{p,2}| = \left| 1 - \frac{2}{1 + 2\Gamma_{\phi,10}/\Gamma_{10}} \right|$$



Power broadening, increases dephasing.

$\langle N_C \rangle$and $\langle N_P \rangle$are conserve.

Quantum nondemolition detection of propagating microwave photons

Detect photons without being destroyed?

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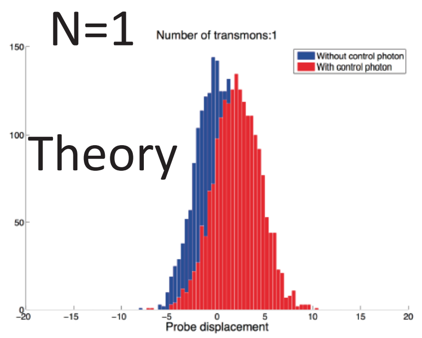
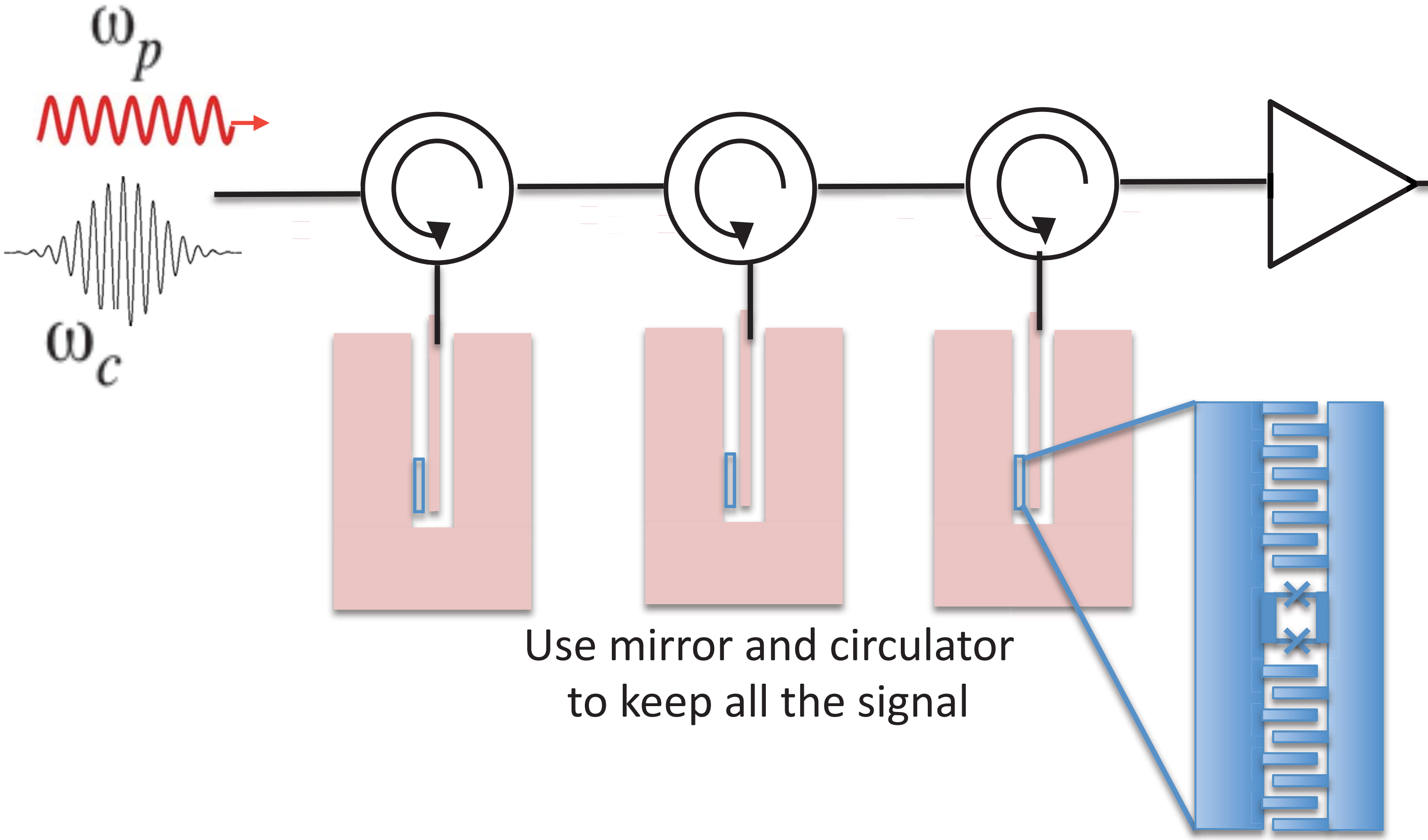
QND detection of propagating microwave photon


N=1

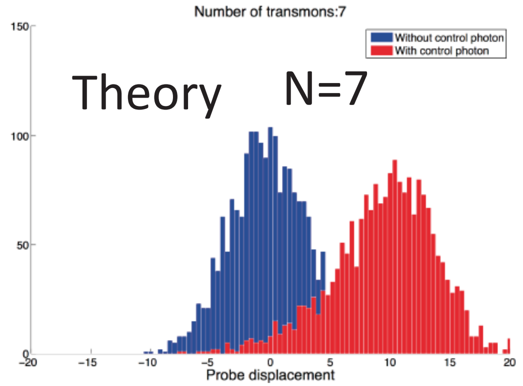
Theory

Probe displacement



Heterodyne detection

Use mirror and circulator to keep all the signal


Theory

N=7

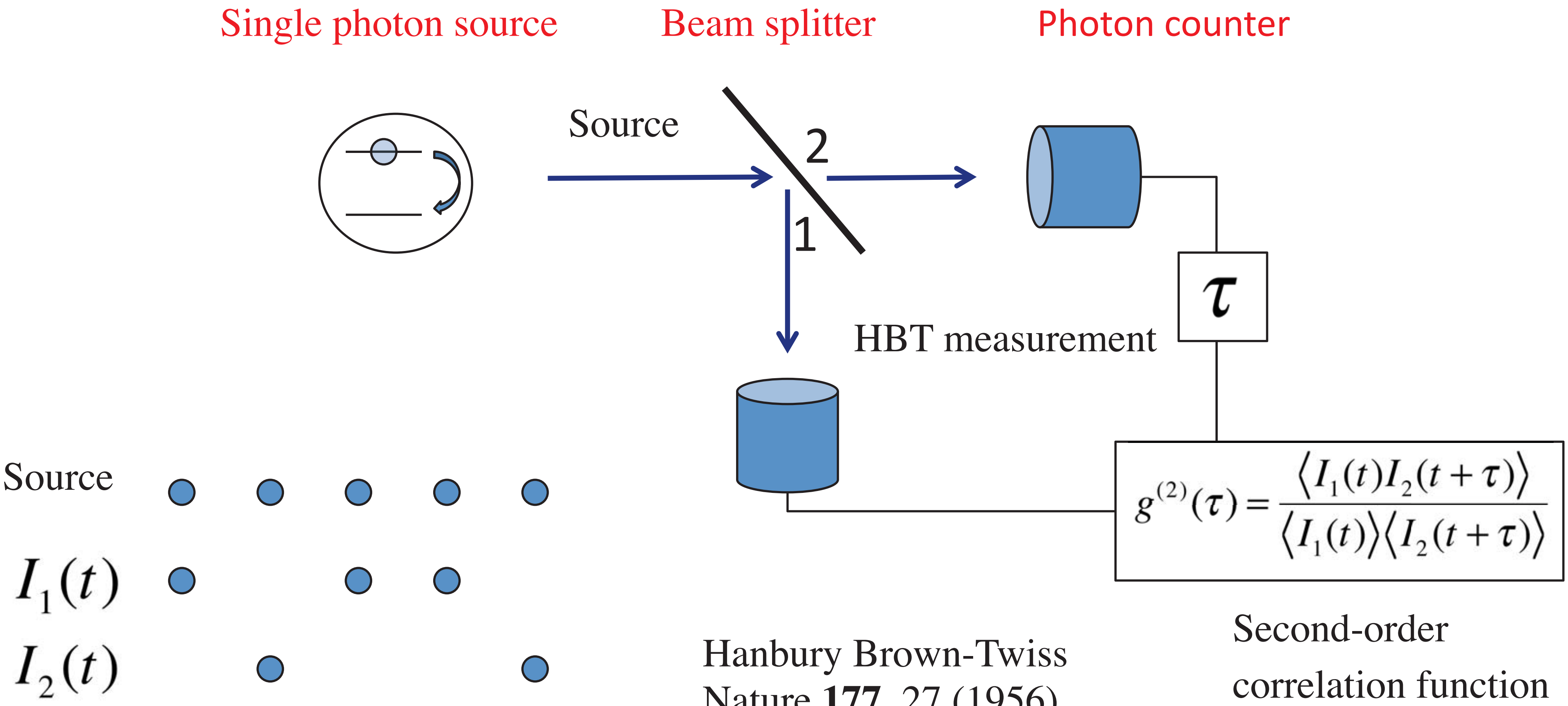
Probe displacement

N: number of transmon

Theory proposal: S.R. Sathyamoorthy et al. PRL 112, 093601 (2014)

What is the photon statistics of the scattered field?

Intensity-Intensity Correlation



Single photon source

Beam splitter

Photon counter

Source

2

1

τ

HBT measurement

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

Source

$I_1(t)$

$I_2(t)$

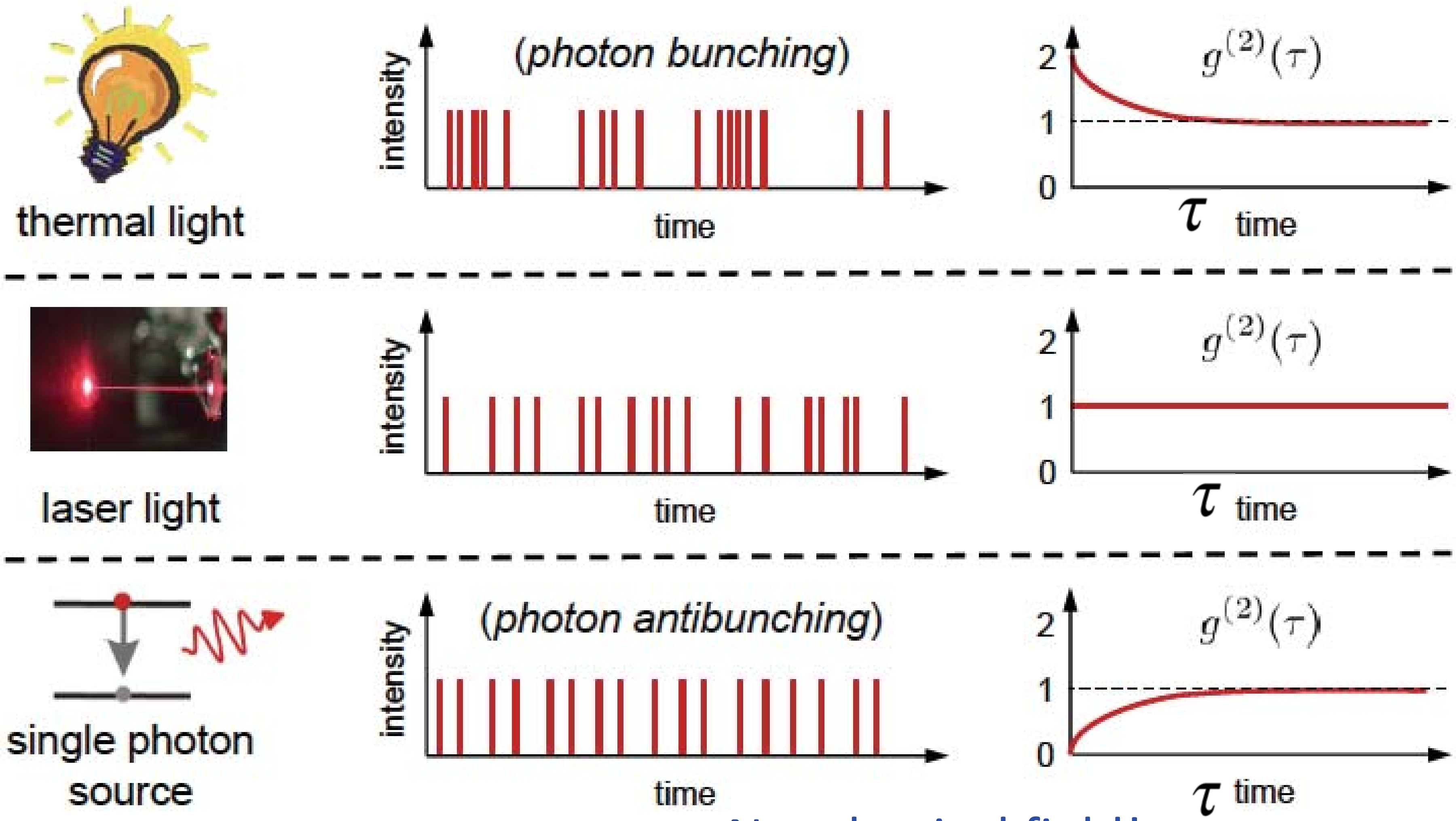
Hanbury Brown-Twiss
Nature **177**, 27 (1956)

Second-order
correlation function

Photon statistics from second order correlation function

A comparison between different light sources:

Coherent state



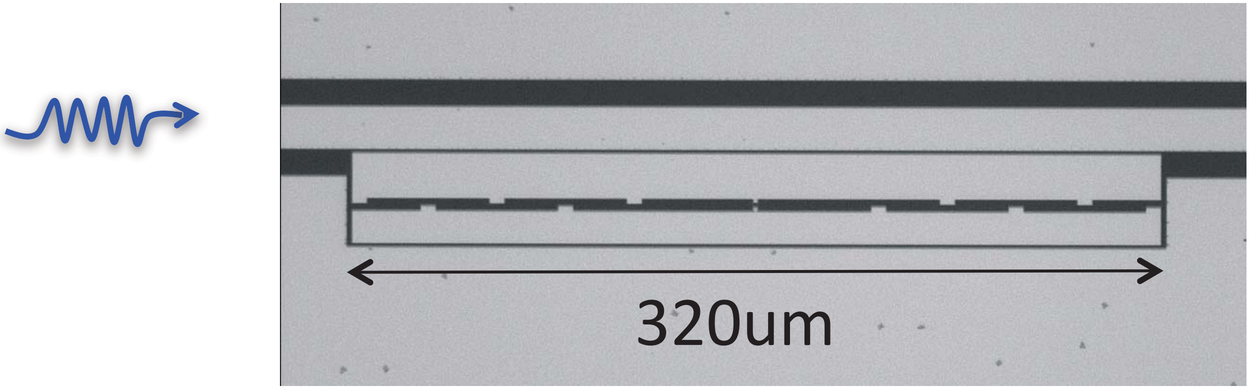
Nonclassical field!

ESONN 2010 lecture

Photon number filter

Poisson probability distibution

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

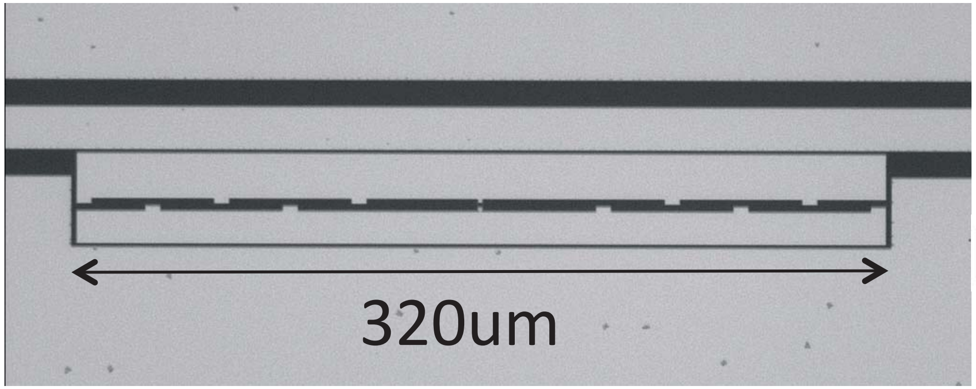


D.E. Chang *et al*., Nature Physics **3**, 807 (2007)

Photon number filter

Poisson probability distibution

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



$$\left|V_R\right\rangle = r_0\left|0\right\rangle + r_1\left|1\right\rangle$$

Antibunching!

$$\left|V_T\right\rangle = t_0\left|0\right\rangle + t_1\left|1\right\rangle + t_2\left|2\right\rangle + \ldots$$

Bunching!

small

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”

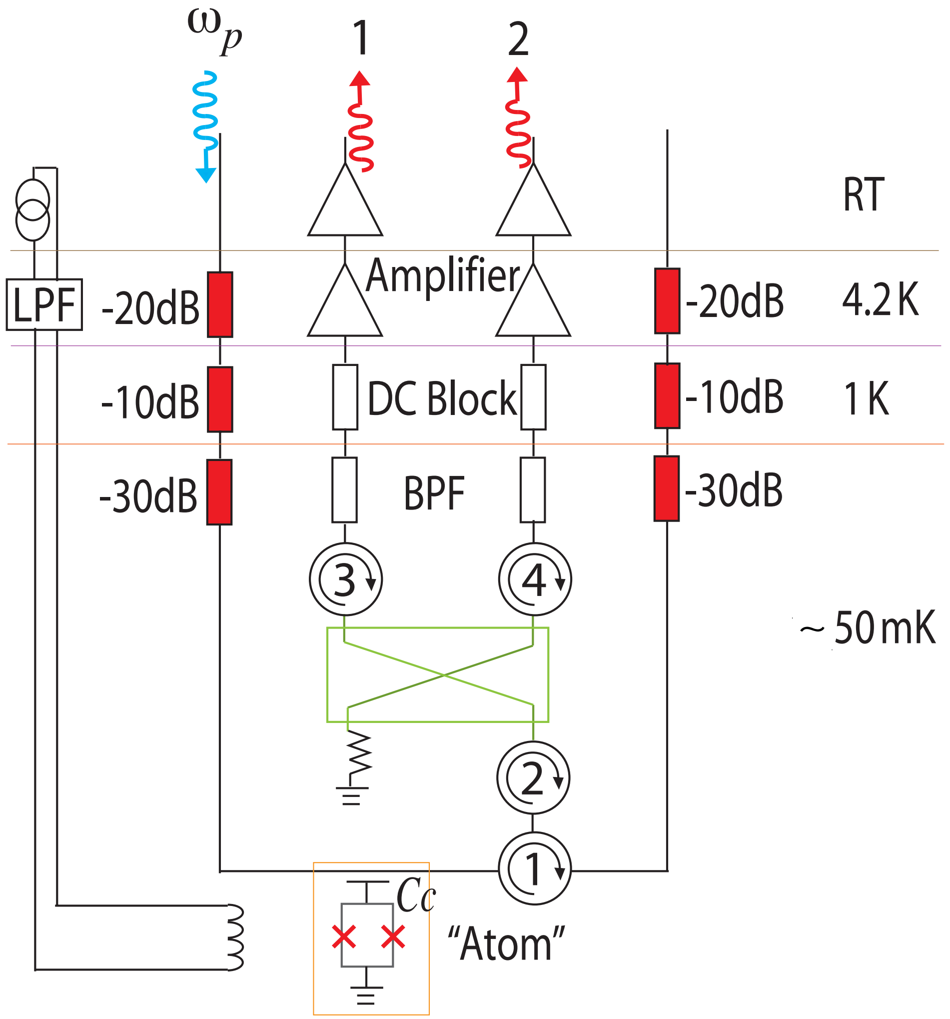
Noise temperature of detection chain is about 7K

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

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

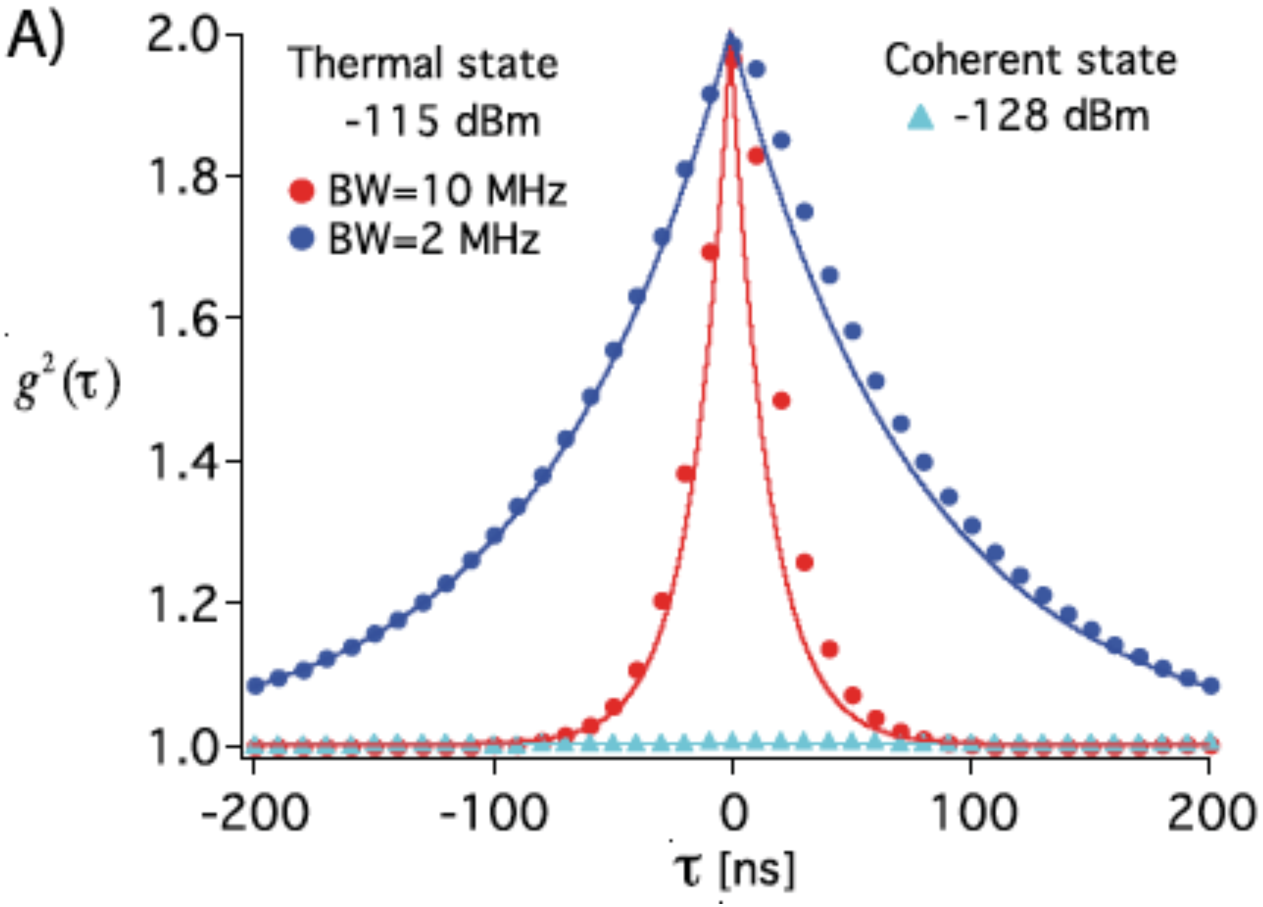


Gabelli *et al*. PRL **93** 056801(2004)

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

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

Thermal field



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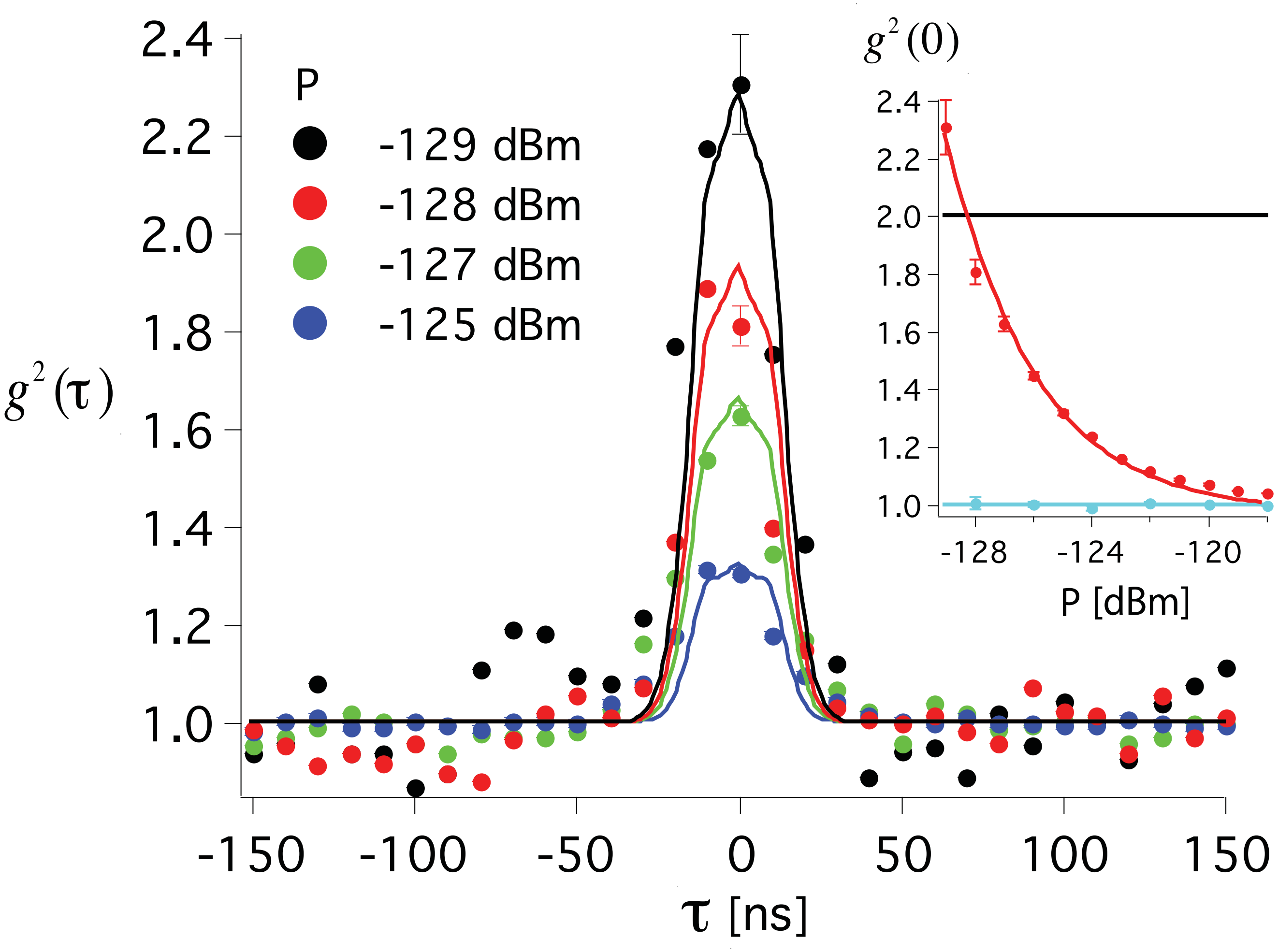
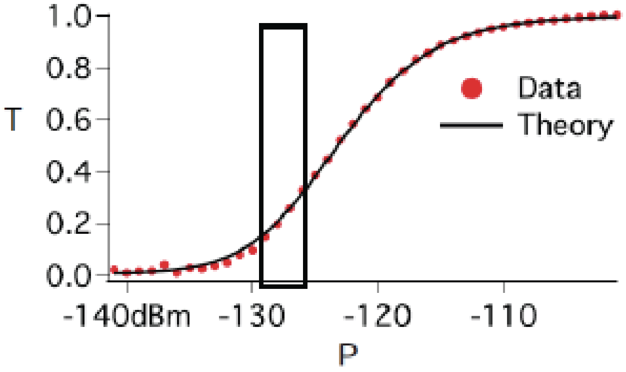
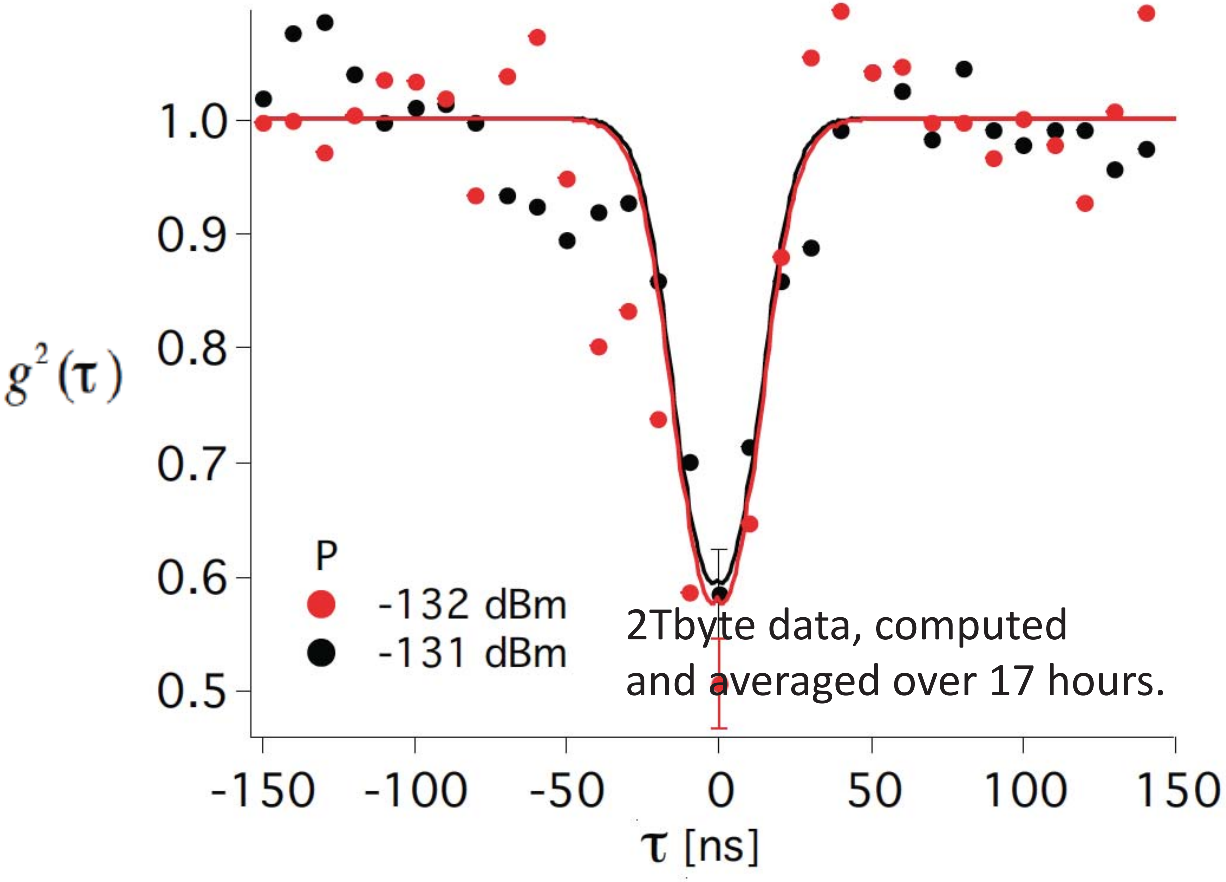
Transmitted field: Superbunching Statistics



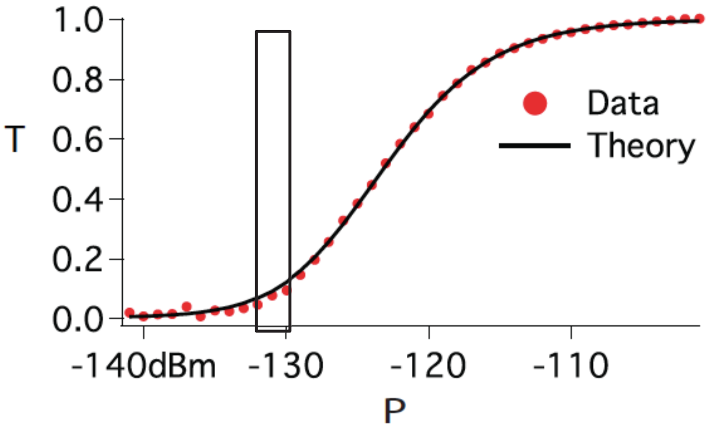


$$g^{(2)}(\tau=0)=2.31\pm0.09>2$$

Reflected field: Antibunching Statistics



2Tbyte data, computed and averaged over 17 hours.

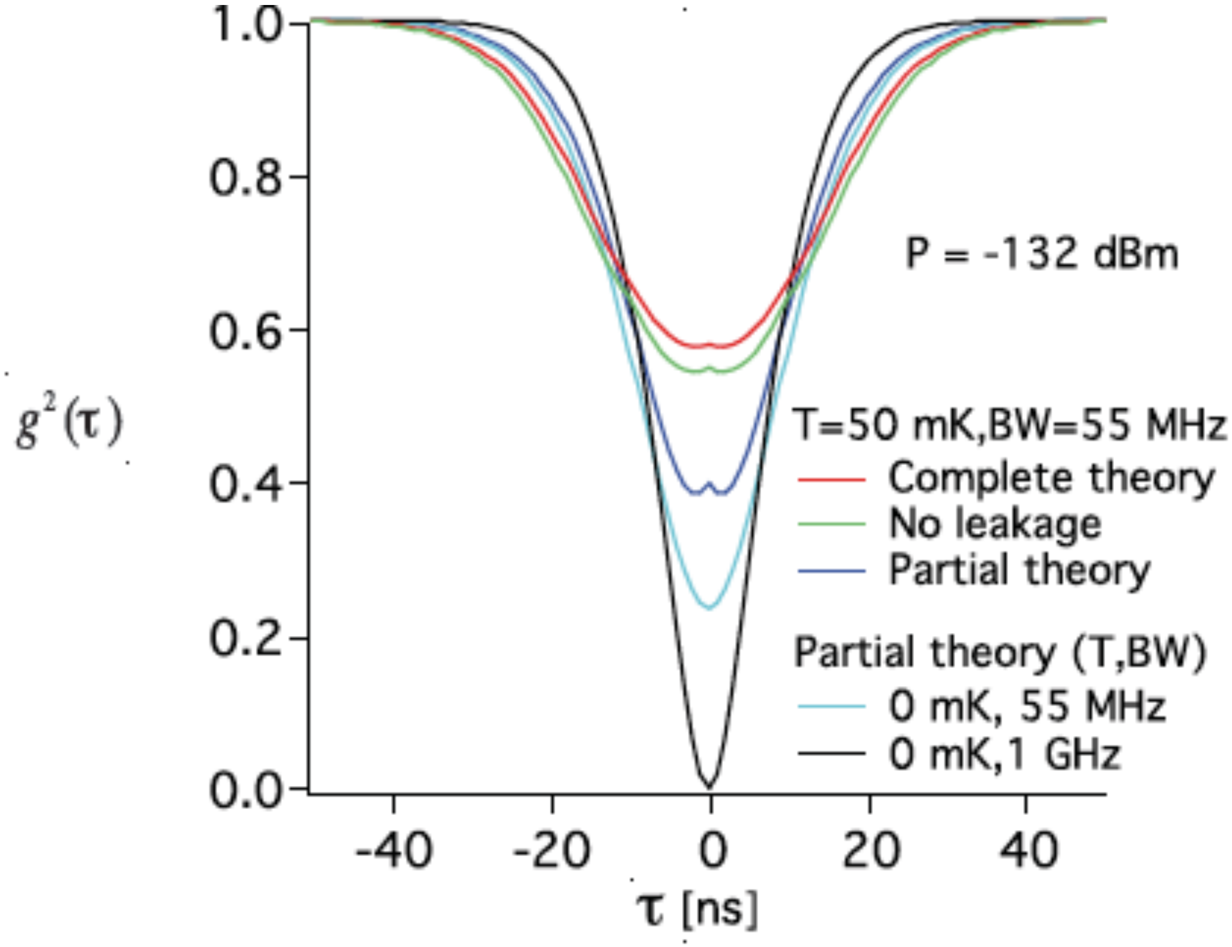


$$g^{(2)}(0) = 0.51 \pm 0.05$$

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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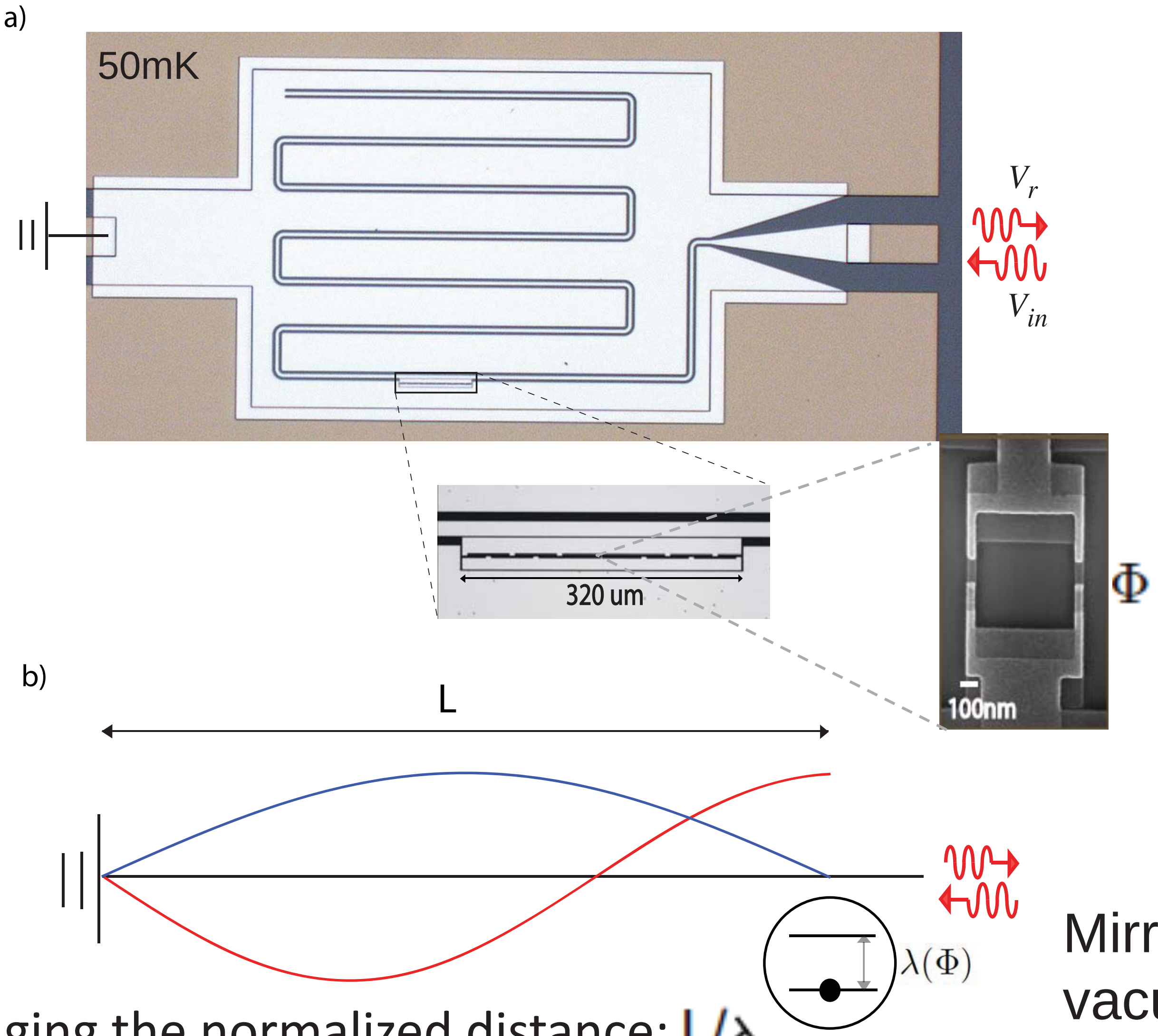
An artificial atom in front of a mirror



Reflection coefficient:

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

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

Changing the normalized distance: L/λ

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

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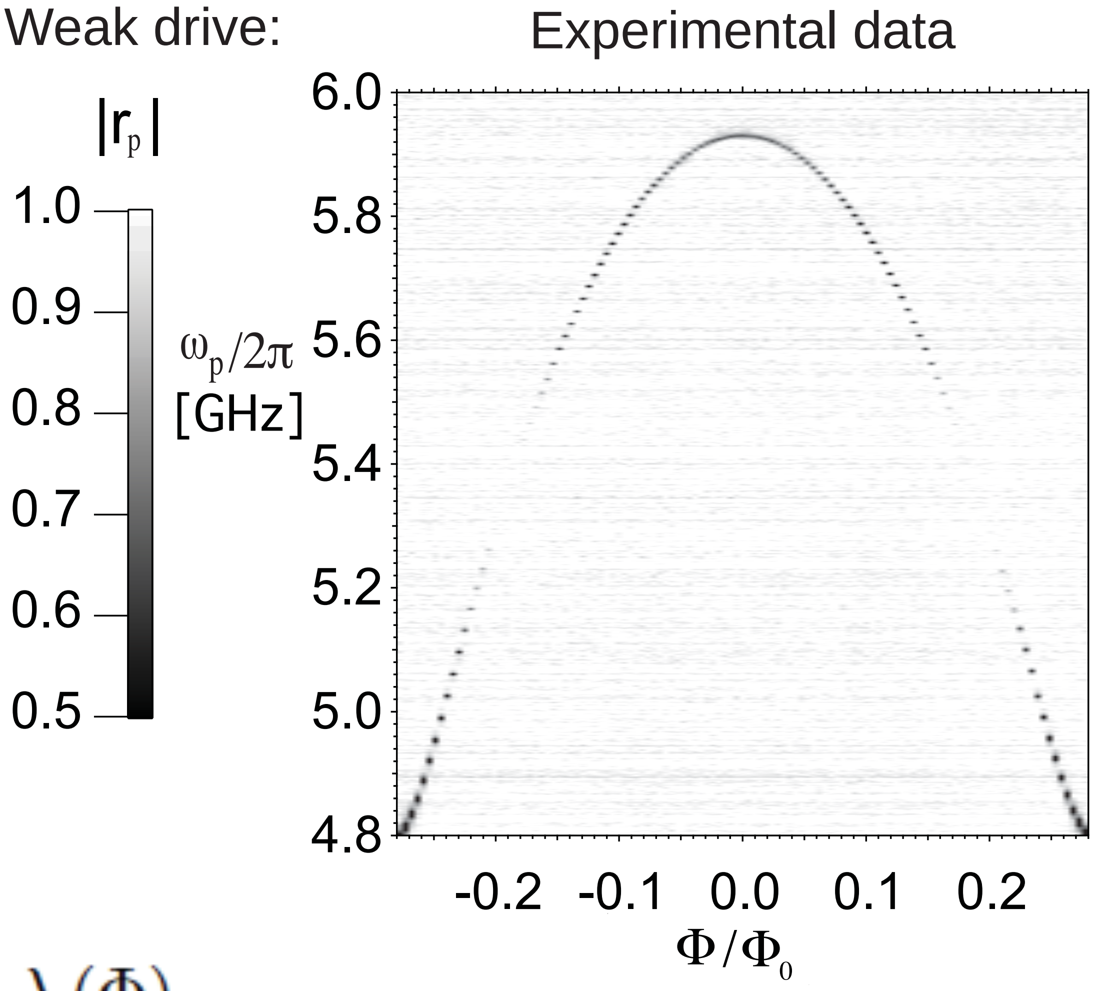
Changing the spontaneous emission rate

Weak drive:

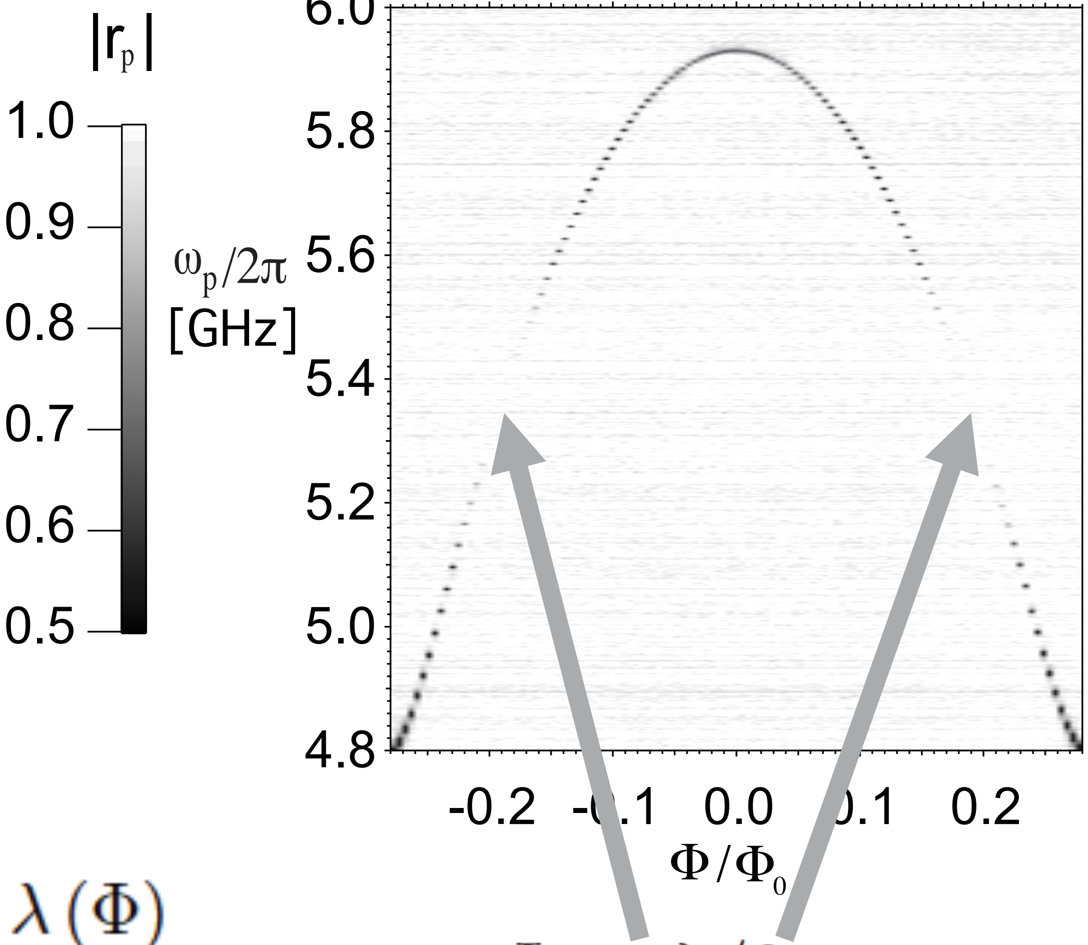


$\lambda(\Phi)$

Changing the spontaneous emission rate

Weak drive:

Experimental data



$\lambda(\Phi)$

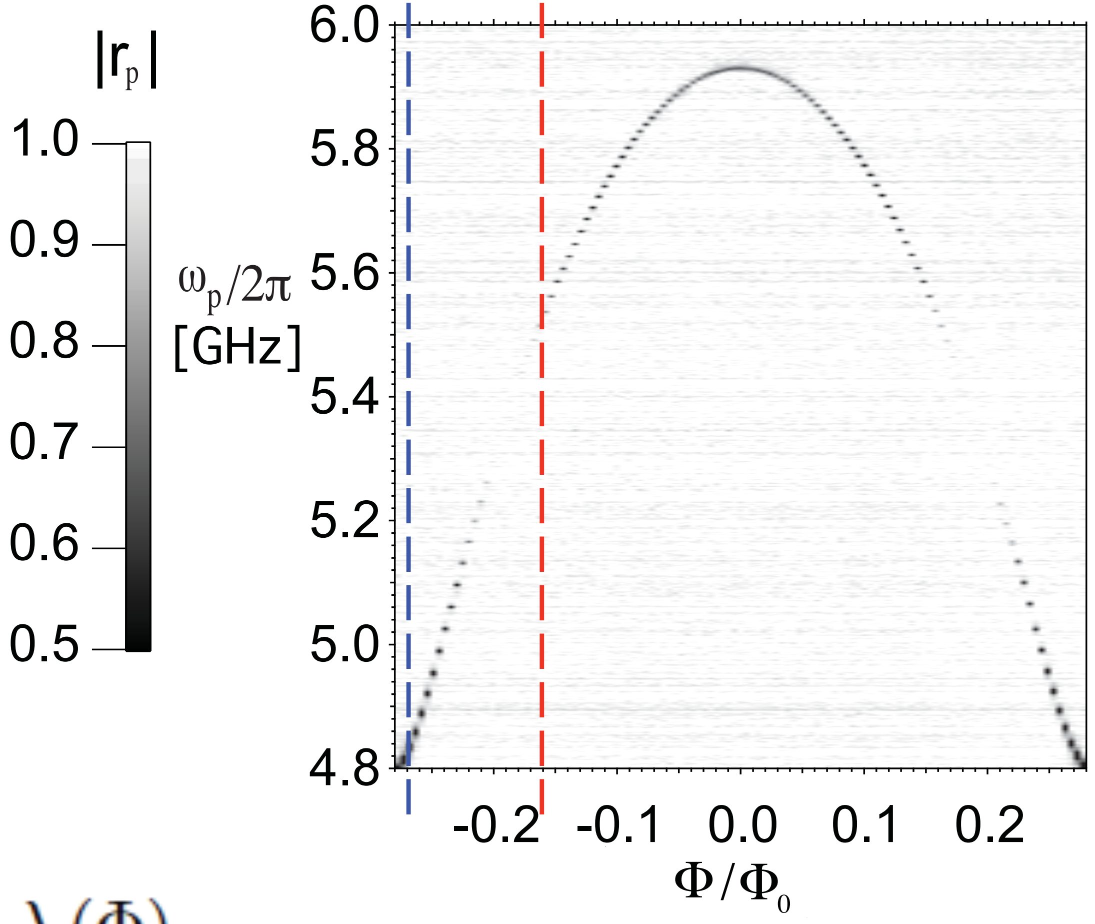
$L = \lambda/2$

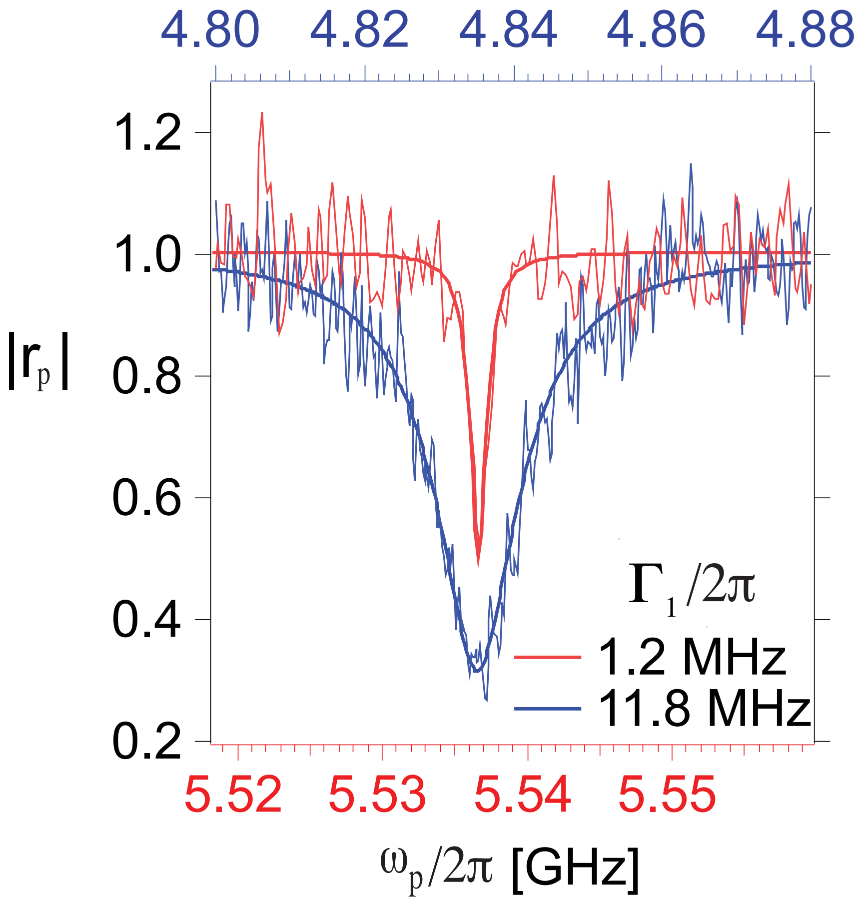
Atom decoupled from vacuum fluctuations at node.

Changing the spontaneous emission rate

Weak drive:

Experimental data





$\lambda(\Phi)$

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

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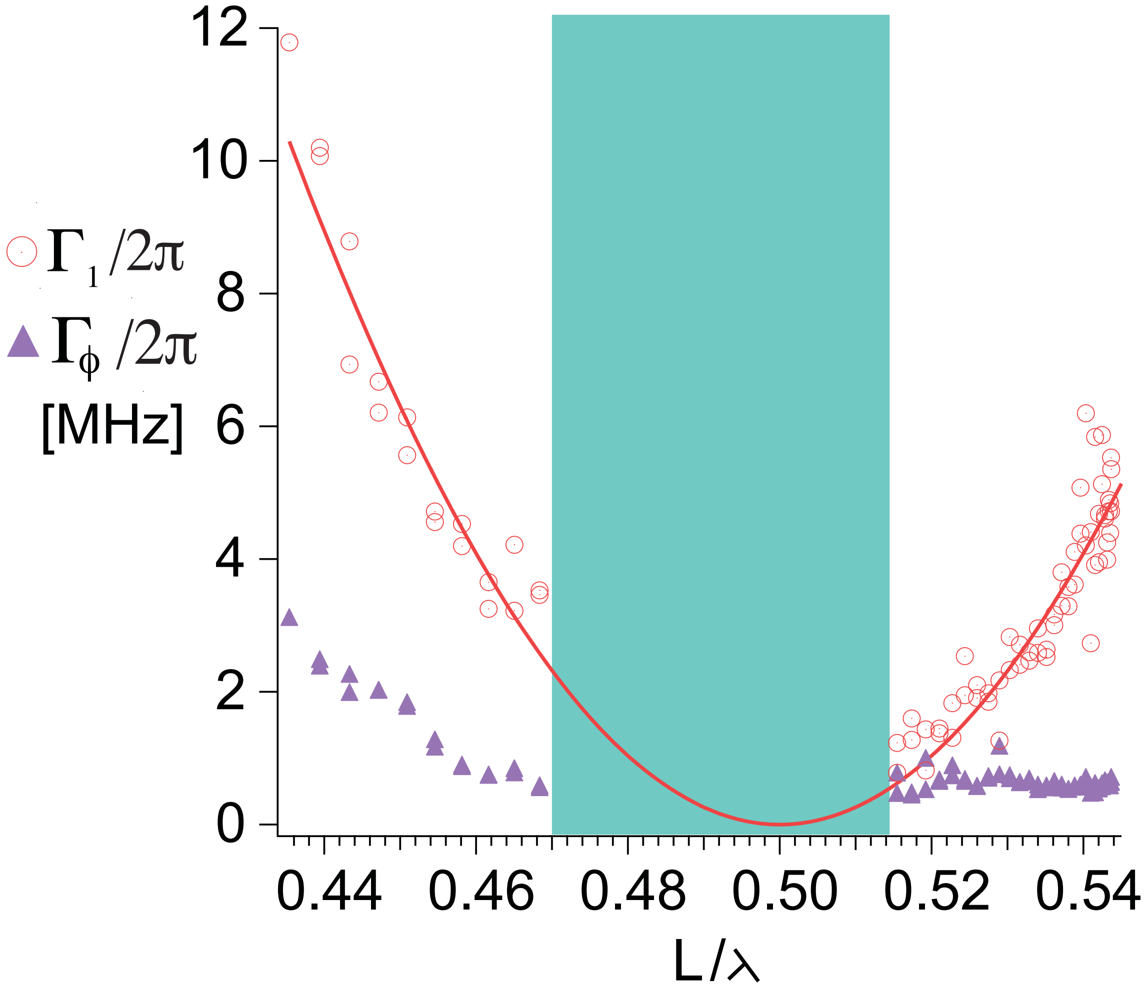
Spontaneous emission rate as a function of normalized distance

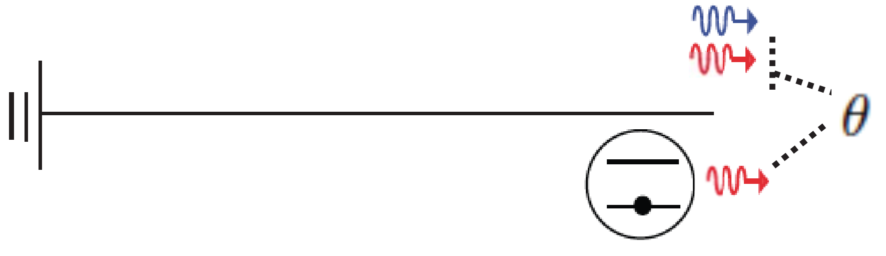


$$\Gamma_1(\Phi) = 2\Gamma_{1,b}\cos^2[\theta(\Phi)/2]$$

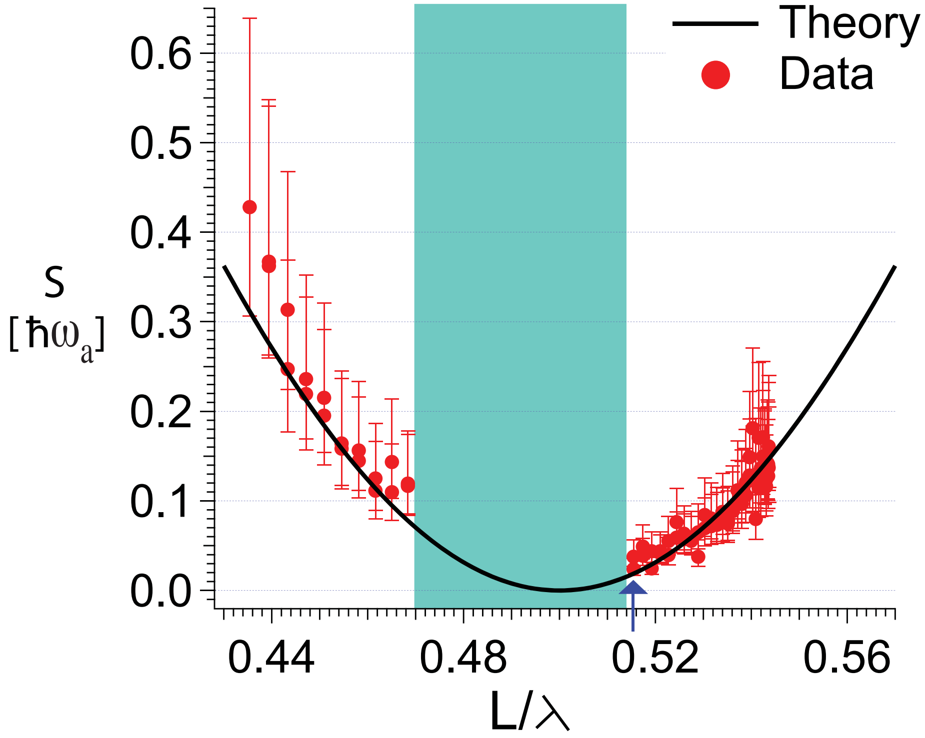
$$\theta(\Phi) = 2 \times [2\pi L/\lambda(\Phi)] + \pi$$

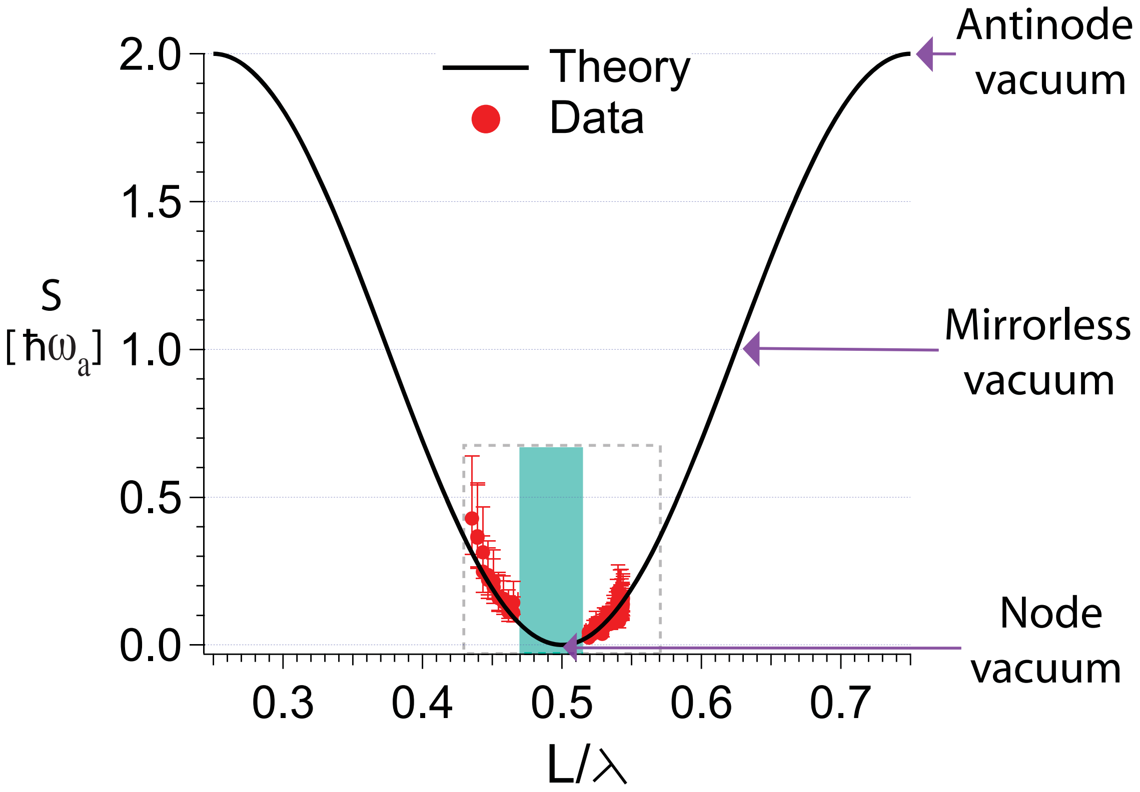
$\Gamma_{1,b}$: relaxation rate of bare atom

θ : phase difference between scattered field from the same atom



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

Photon mediated interactions between distant artificial atoms

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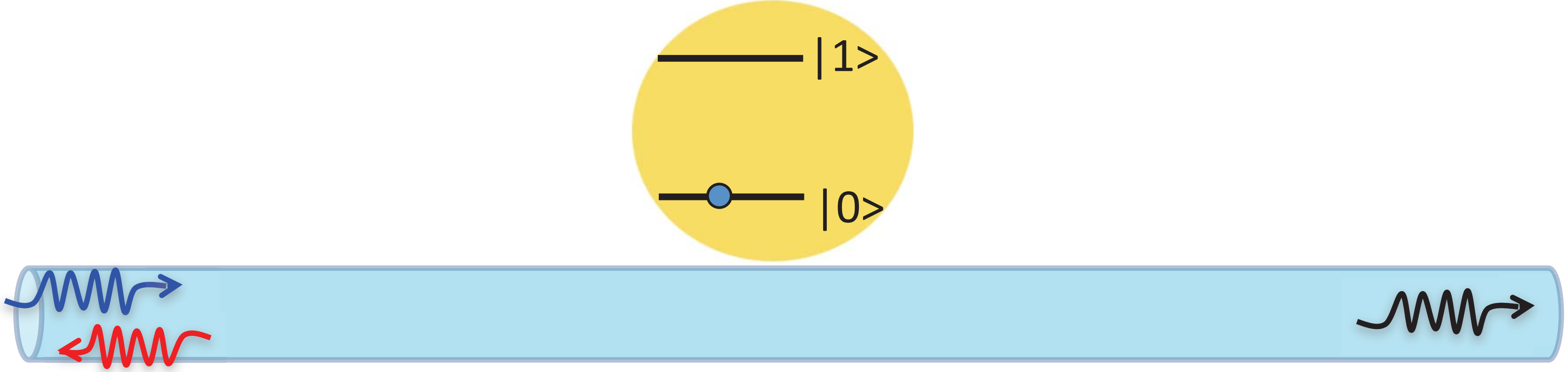
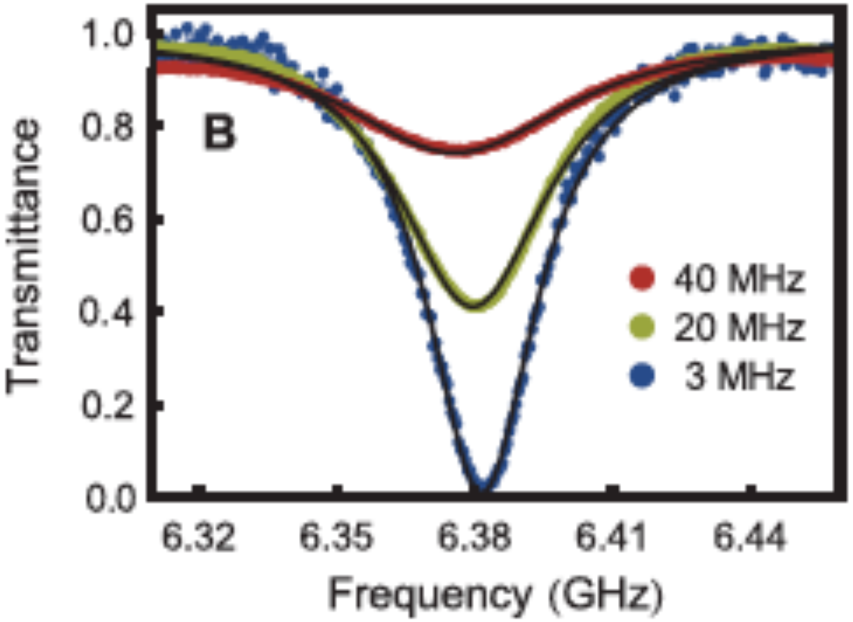
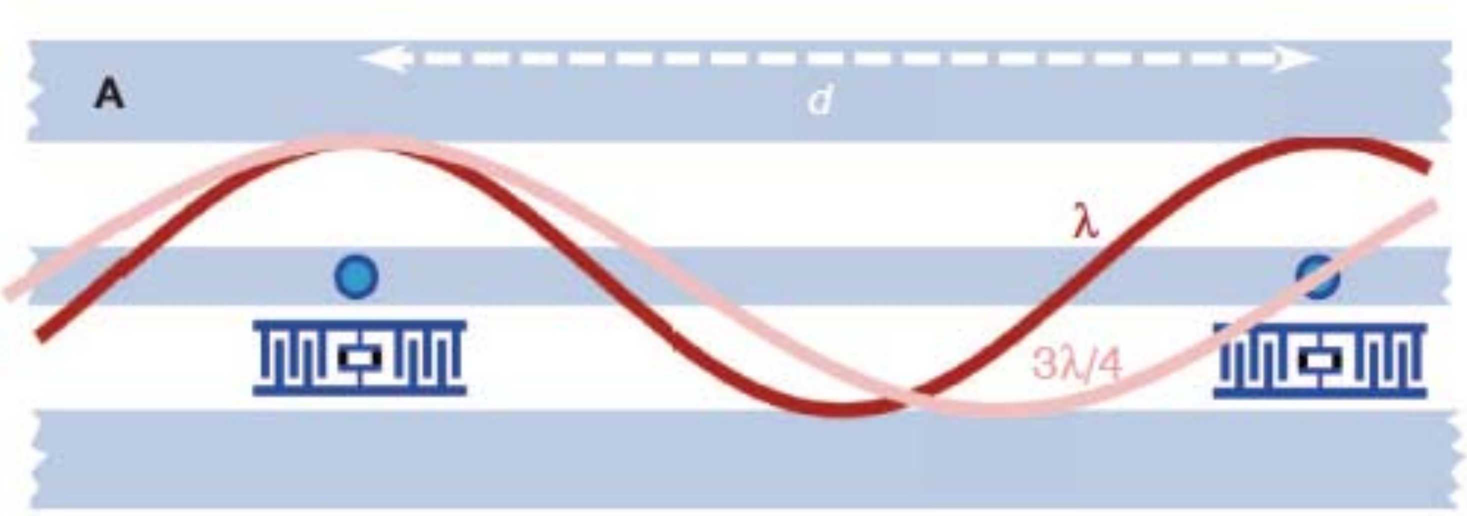


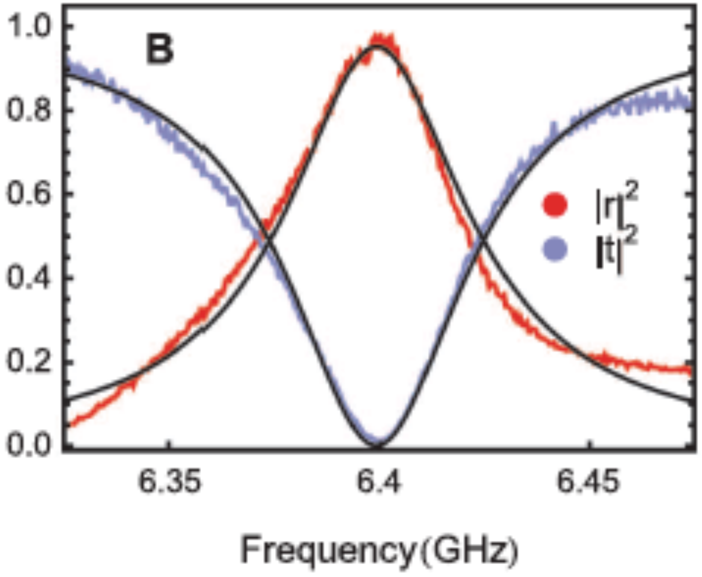
Fully coherent: no transmission, perfect reflection.



$\gamma_1/2\pi \approx 26 \pm 1$ MHz

Super-and subradiance at $d \sim \lambda$



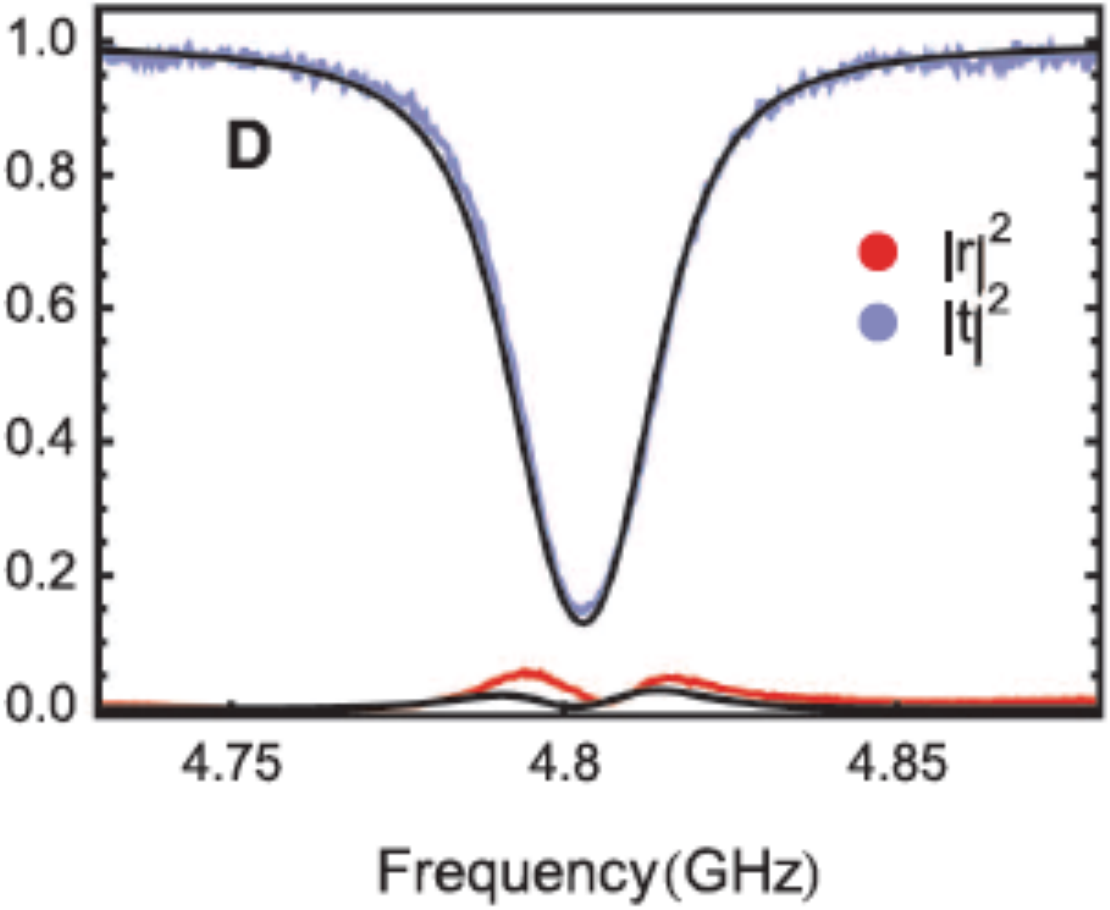


$$\Gamma_B/2\pi \sim 52 \pm 1 \text{ MHz}$$

$$\Gamma_B = 2\gamma_1$$

A.F. V. Loo *et al.* Science. **342**, 1494(2013)

$d \sim 3\lambda/4$



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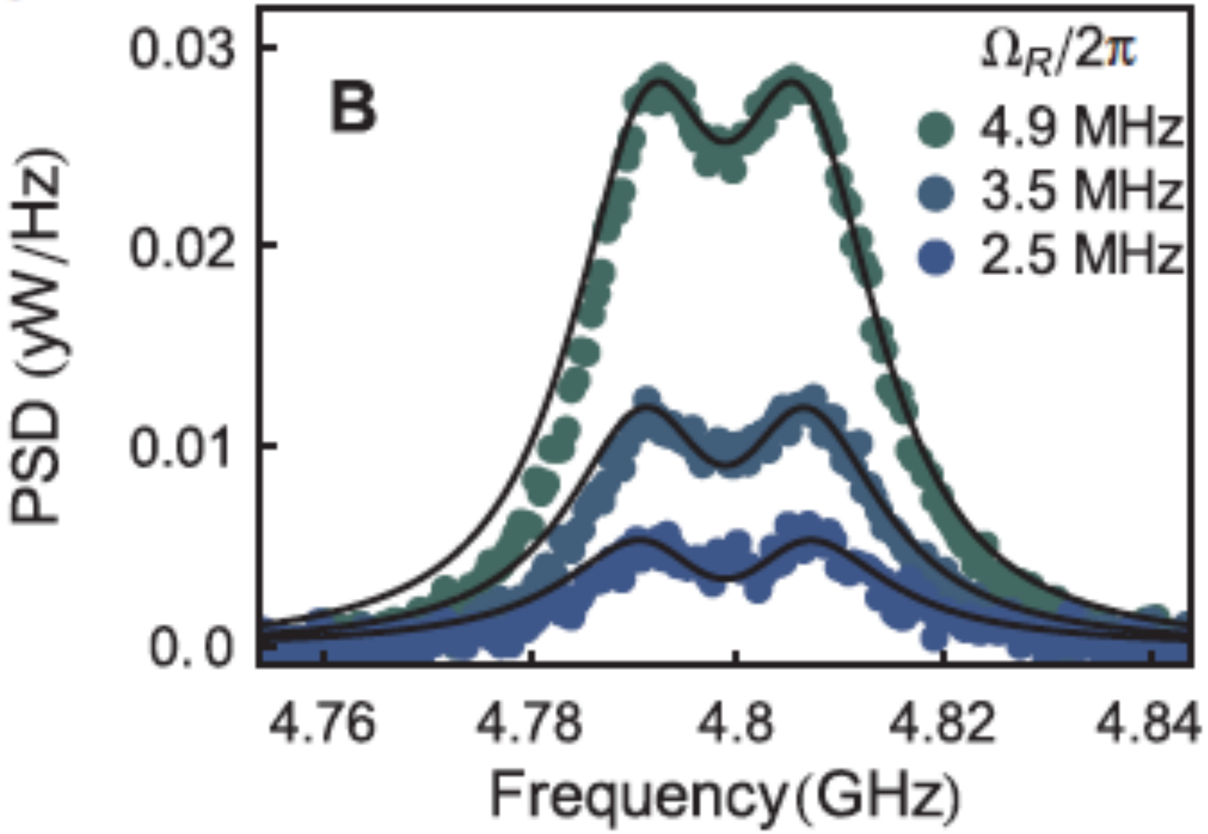
342, 1494(2013)

$d \sim 3\lambda/4$

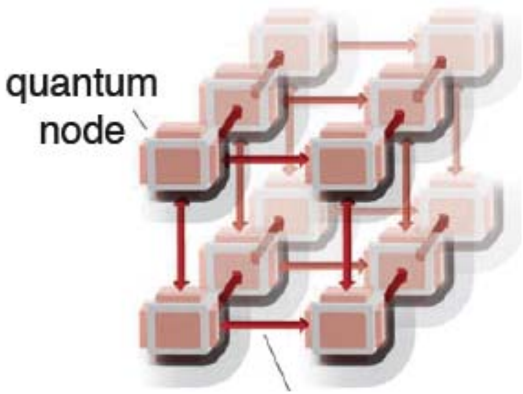


Double-peak split by 15MHz exchange interaction J, mediated by virtual photons.

A.F. V. Loo *et al.* Science. **342**, 1494(2013)

Summary I

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.* Accepted in Nature Physics (2015)
Arxiv 1410.8840
A.F. V. Loo *et al.* Science **342**, 1494(2013)

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Quantum Network

Io-Chun Hoi

Quantum Network

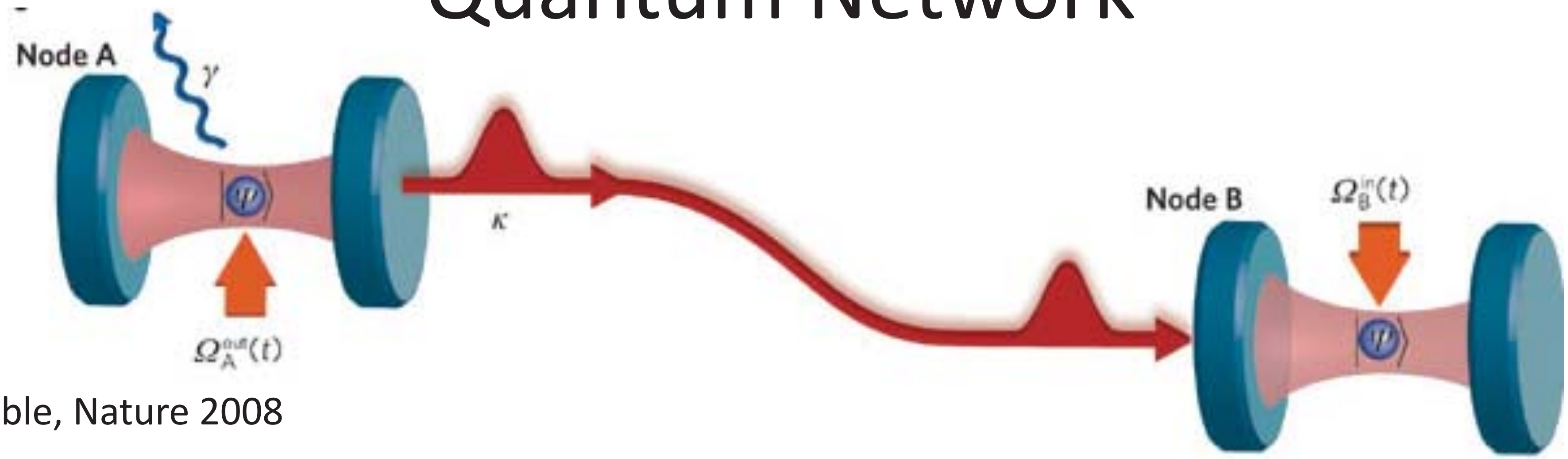
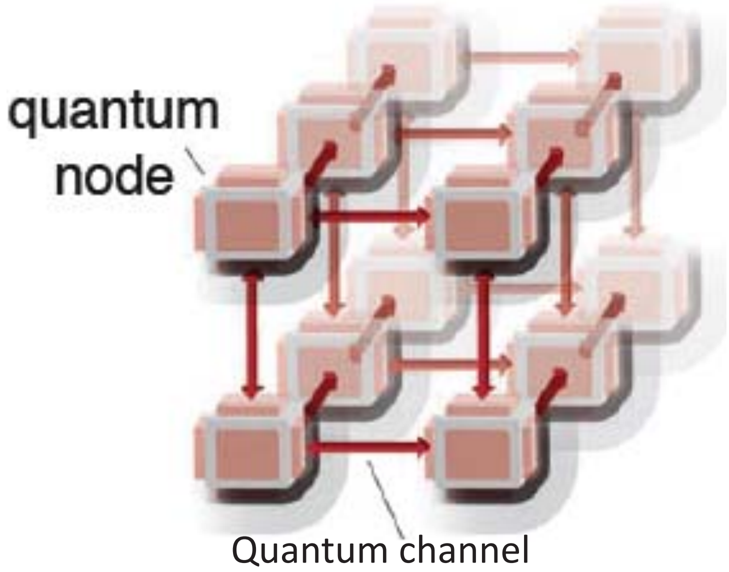


Fig. Kimble, Nature 2008

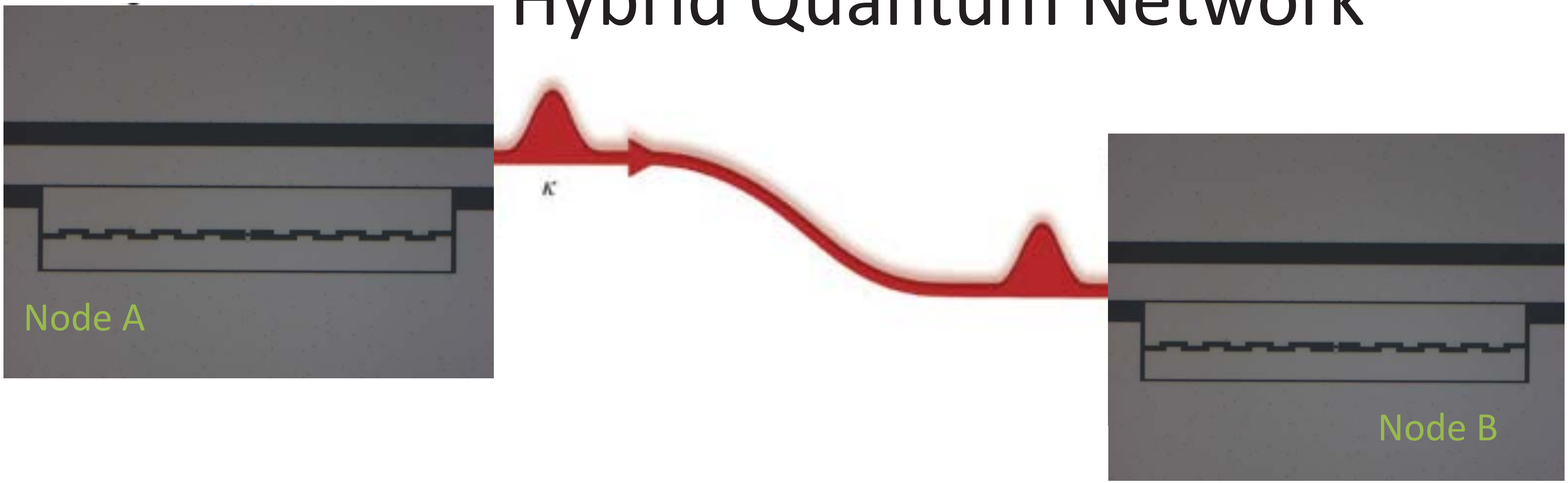


Quantum node:
Generating, processing, routing, storing, reading out quantum information.

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

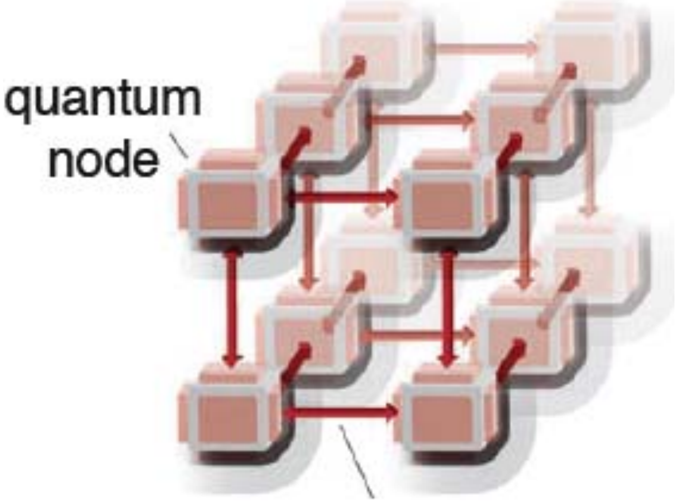
Microwave-optical interface is needed

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

Conclusion

Quantum nodes:

Routing photons with 99% on-off ratio
Giant Cross-Kerr phase shift.
Generate antibunching and superbunching microwaves.



Probing the quantum vacuum fluctuations.
Photon mediated interactions

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