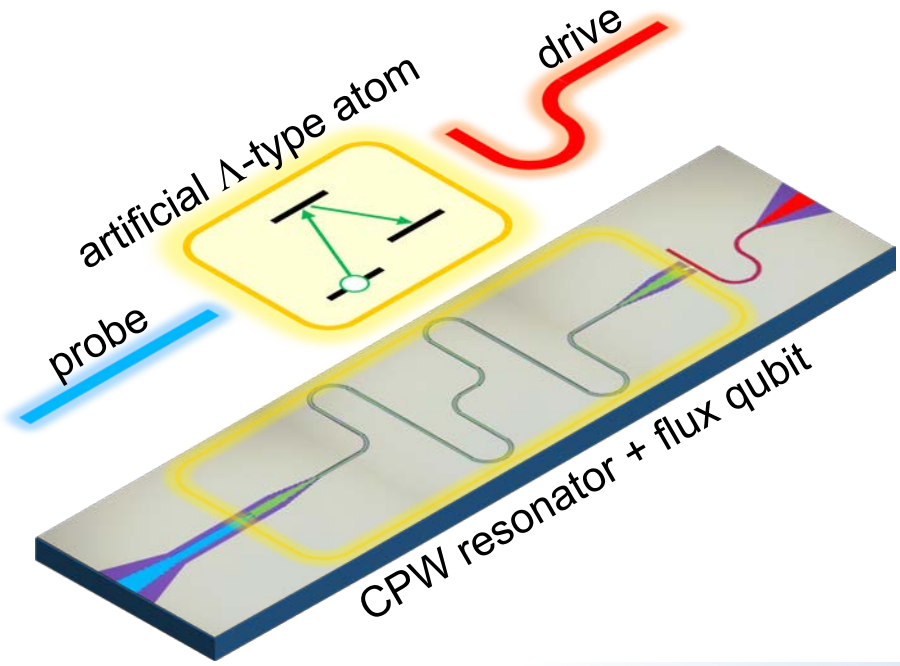
17th International Workshop on Low Temperature Detectors

LTD17
July 17-21, 2017
Kurume, Fukuoka, Japan

Single Microwave-Photon Detector based on Superconducting Quantum Circuits



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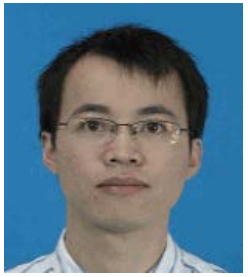
CEMS

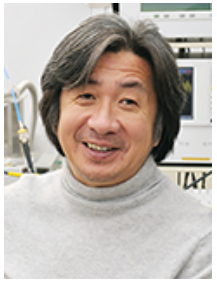
RIKEN

Collaborators

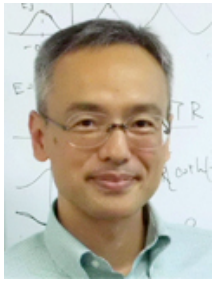
- Kazuki Koshino（Tokyo Medical and Dental Univ.）
- Zhirong Lin（CEMS, RIKEN）
- William D. Oliver（MIT Lincoln Laboratory）
- Jaw-Shen Tsai（Tokyo Univ. of Science/CEMS, RIKEN）
- Tsuyoshi Yamamoto（NEC Smart Energy Lab.）
- Yasunobu Nakamura（RCAST Univ. of Tokyo/CEMS, RIKEN）


Prof. Koshino


Dr. Lin


Prof. Tsai

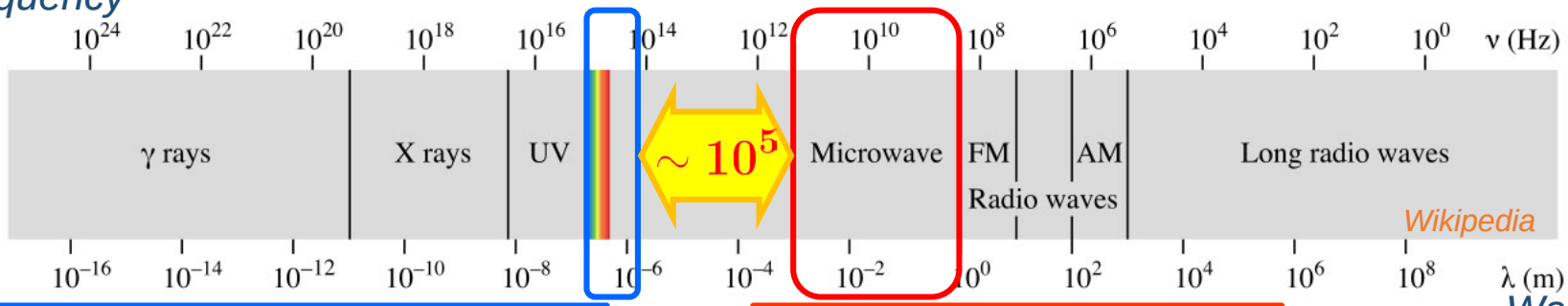

Dr. Yamamoto


Prof. Nakamura

Content

Quantum information processing with photons

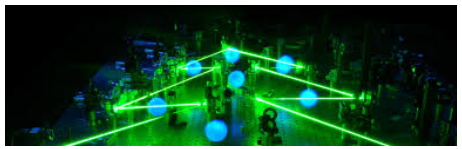
← *Frequency*

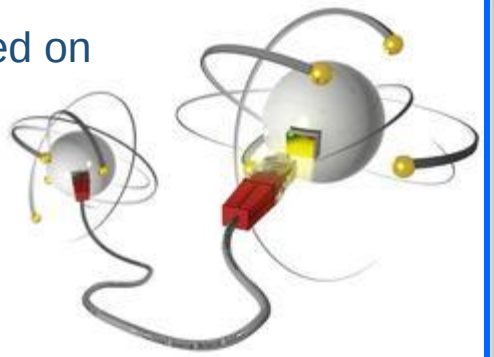


Wavelength →

■ Optical photons (~ visible light)

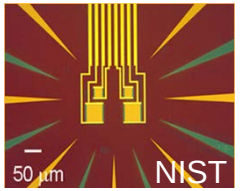
- Communication based on a single photon
- Quantum optics



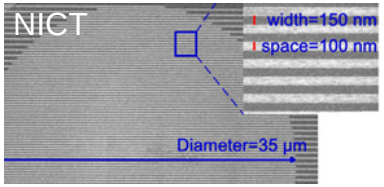


Single photon detectors

APD
η ~ 30 %

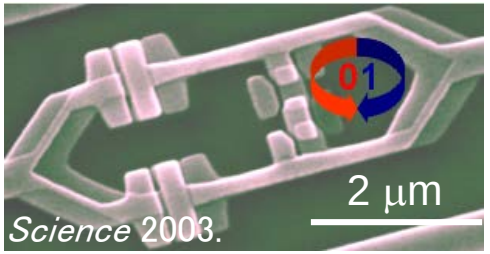


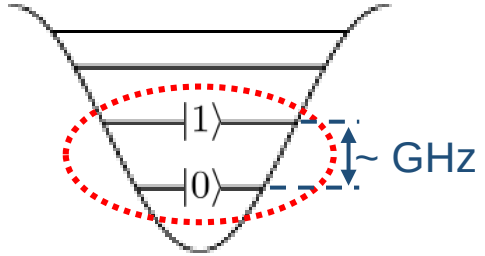
TES
η > 90 %



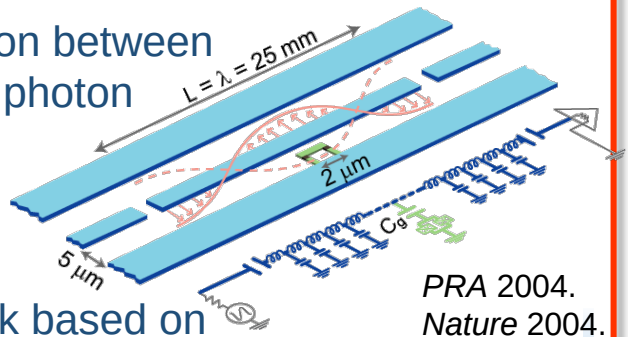
SSPD
η > 90 %

■ Microwave photons





✓ Coherent interaction between a qubit and a MW photon



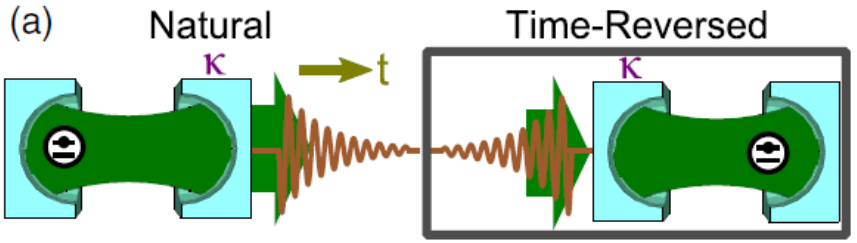
PRA 2004.
Nature 2004.

- Flying qubit
- Quantum network based on MW photons, etc…

Single photon detector

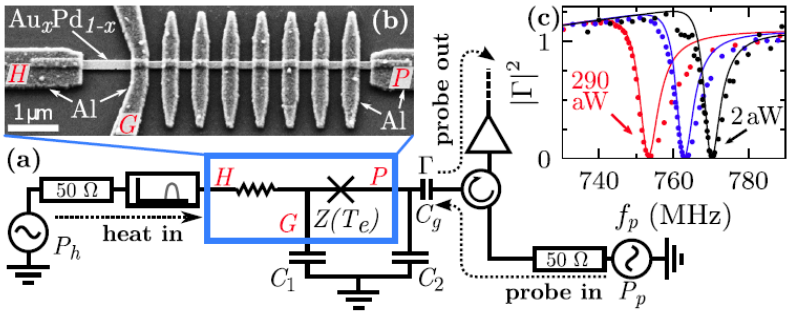
Photon detectors in MW domain

- **Harmonic oscillator mode** [J. Wenner *et al.*, *PRL* (2014)]



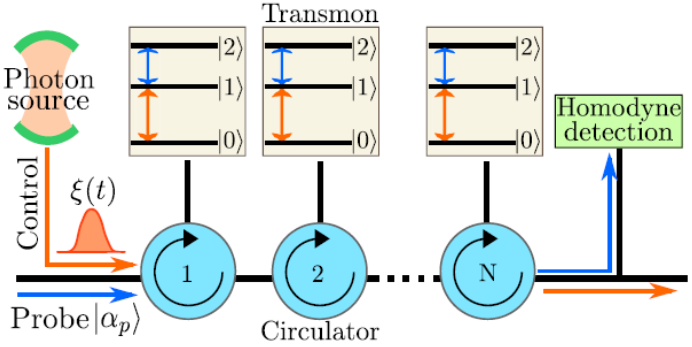
- ✓ Efficiency = 0.994
- ✓ Precise photon pulse shaping
- ✓ Time-dependent control of system parameters

- **MW nanobolometer** [J. Govenius *et al.*, *PRL* (2016)]



- ✓ Efficiency ~ 0.56 (for ~200 photons ~ 1.1 zJ)
- ✓ No single-photon sensitivity
- ✓ Dead time: ~100 μs

- **Three-level cascaded system** [S. R. Sathyamoorthy *et al.*, PRL (2014)]

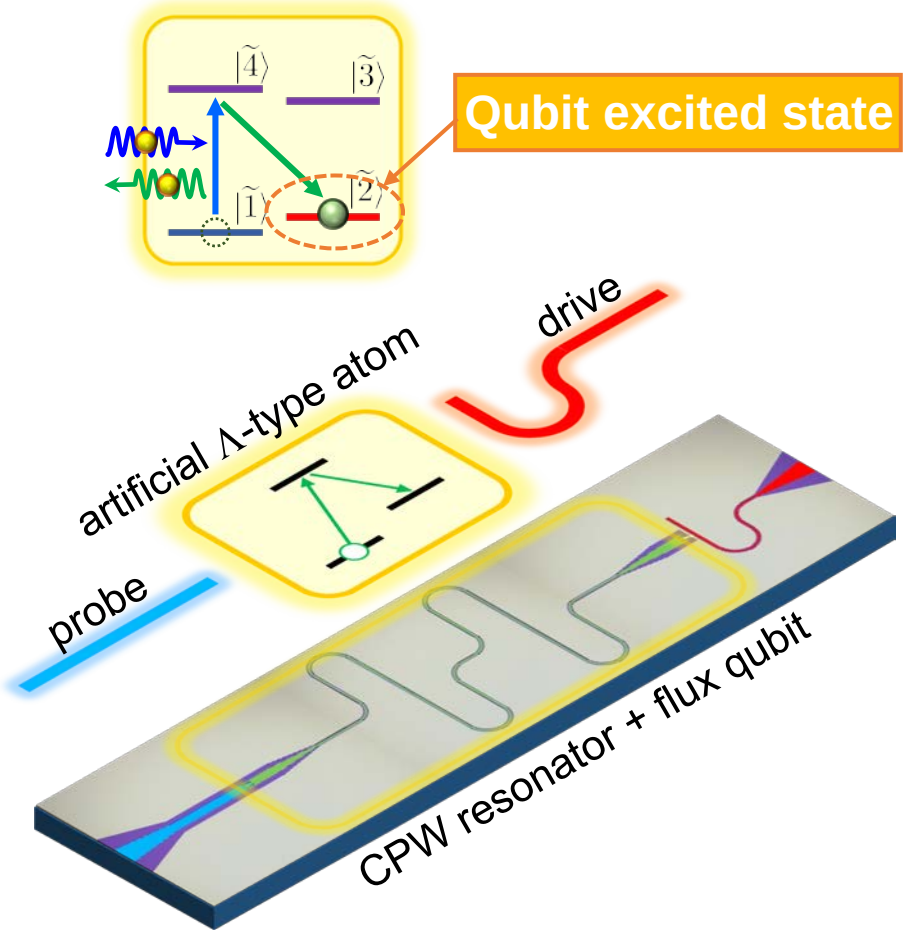


- ✓ Efficiency > 0.9 (theoretically)
- ✓ QND measurement
- ✓ Chain of transmons connected via circulators

Single photon detection in MW domain

- **Impedance-matched Λ system**

K. Koshino, K. I. *et al., PRL* (2013)
K. Inomata *et al., PRL* (2014)



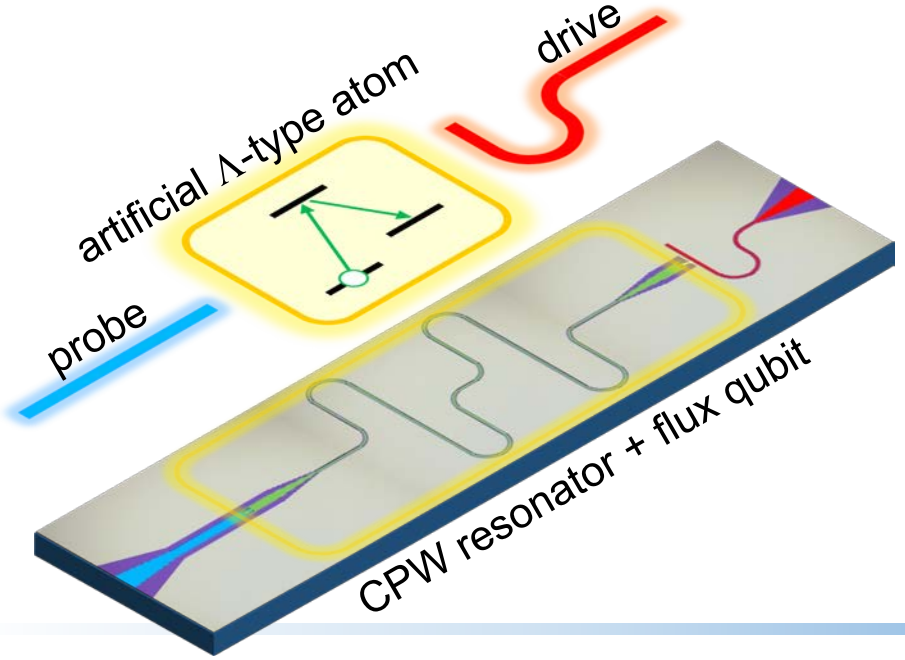
- ✓ Sensitivity to single MW photon
- ✓ Efficiency: ~ 0.66（theory > 0.9）
- ✓ Dead time: short（reset pulse）
- ✓ Dark count: ~0.014
- ✓ Free from photon pulse shaping
- ✓ No time-dependent control of params

K. Koshino, K. I *et al*., *PRA* (2015)
K. Inomata *et al*., *Nat. Commun.* (2016)

Time-gate operation

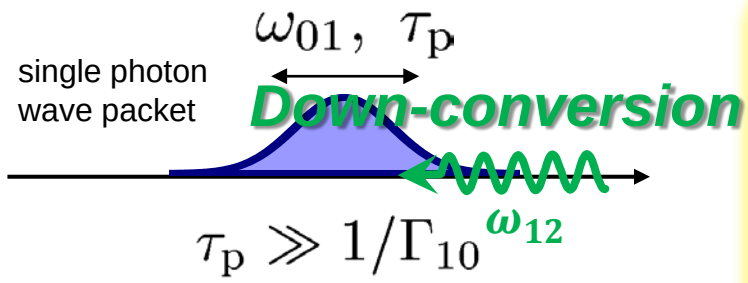
Content

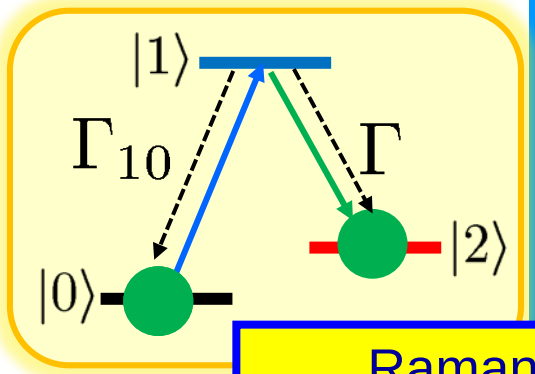
1. Motivation
2. **Impedance-matched Λ system (artificial Λ-type atom)**
3. Single microwave-photon detection
4. Summary



Impedance-matched Λ system

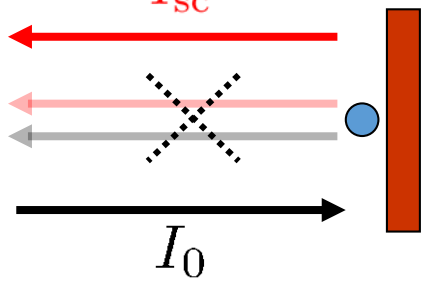
1D waveguide





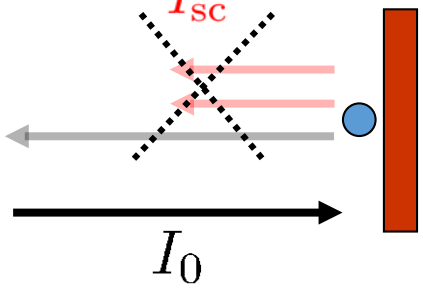
Raman transition
with ~100% efficiency

$\Gamma = 0$



Perfect reflection

$\Gamma = \Gamma_{10}$



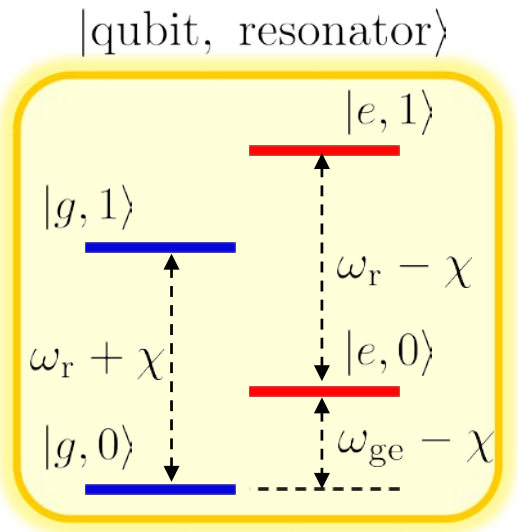
Perfect absorption
(Impedance matching)

Impedance-matched Λ system

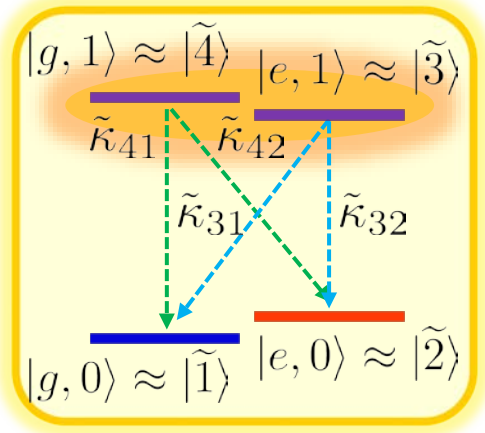
- Deterministic down-converter
- Single photon detector
- Single photon memory

K. Koshino, *PRA* (2009, 2010).

Impedance-matched Λ system using dressed states



Rotating frame at ω_d

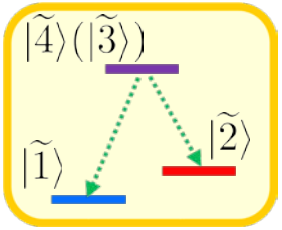


$$\omega_{|g,1\rangle} = \omega_r - \omega_d + \chi$$
$$\omega_{|e,1\rangle} = \omega_r + \omega_{ge} - 2\omega_d - 2\chi$$
$$\omega_{|e,0\rangle} = \omega_{ge} - \omega_d - \chi$$
$$\omega_{|g,0\rangle} = 0$$

$$\tilde{\kappa}_{41} = \tilde{\kappa}_{42} \text{ or } \tilde{\kappa}_{31} = \tilde{\kappa}_{32}$$

Impedance matching

Artificial Λ-type atom



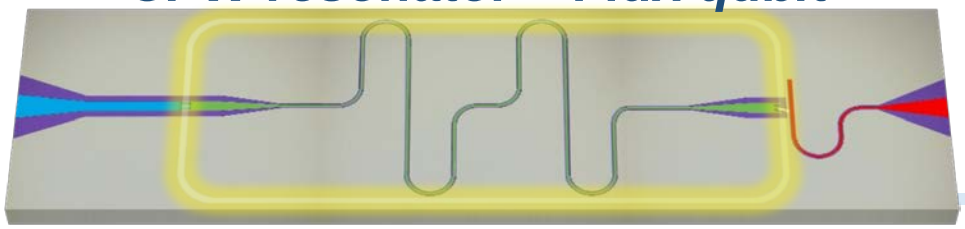
Probe

Drive

- ✓ Perfect absorption
- ✓ Deterministic down-conversion

K. Koshino *et al.*, *PRL* (2013).
K. Koshino *et al.*, *NJP* (2013).
K. Inomata *et al.*, *PRL* (2014).

CPW resonator + Flux qubit

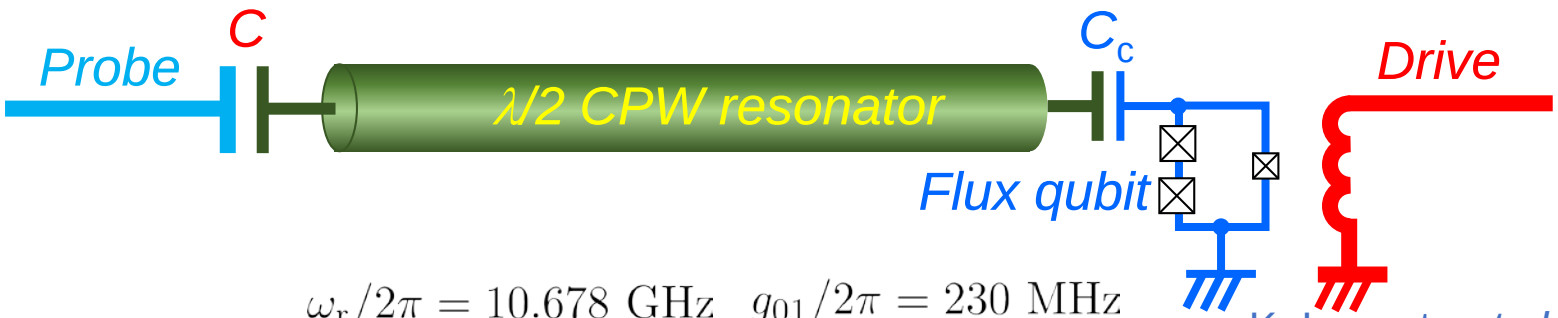


Qubit drive

P_d, ω_d

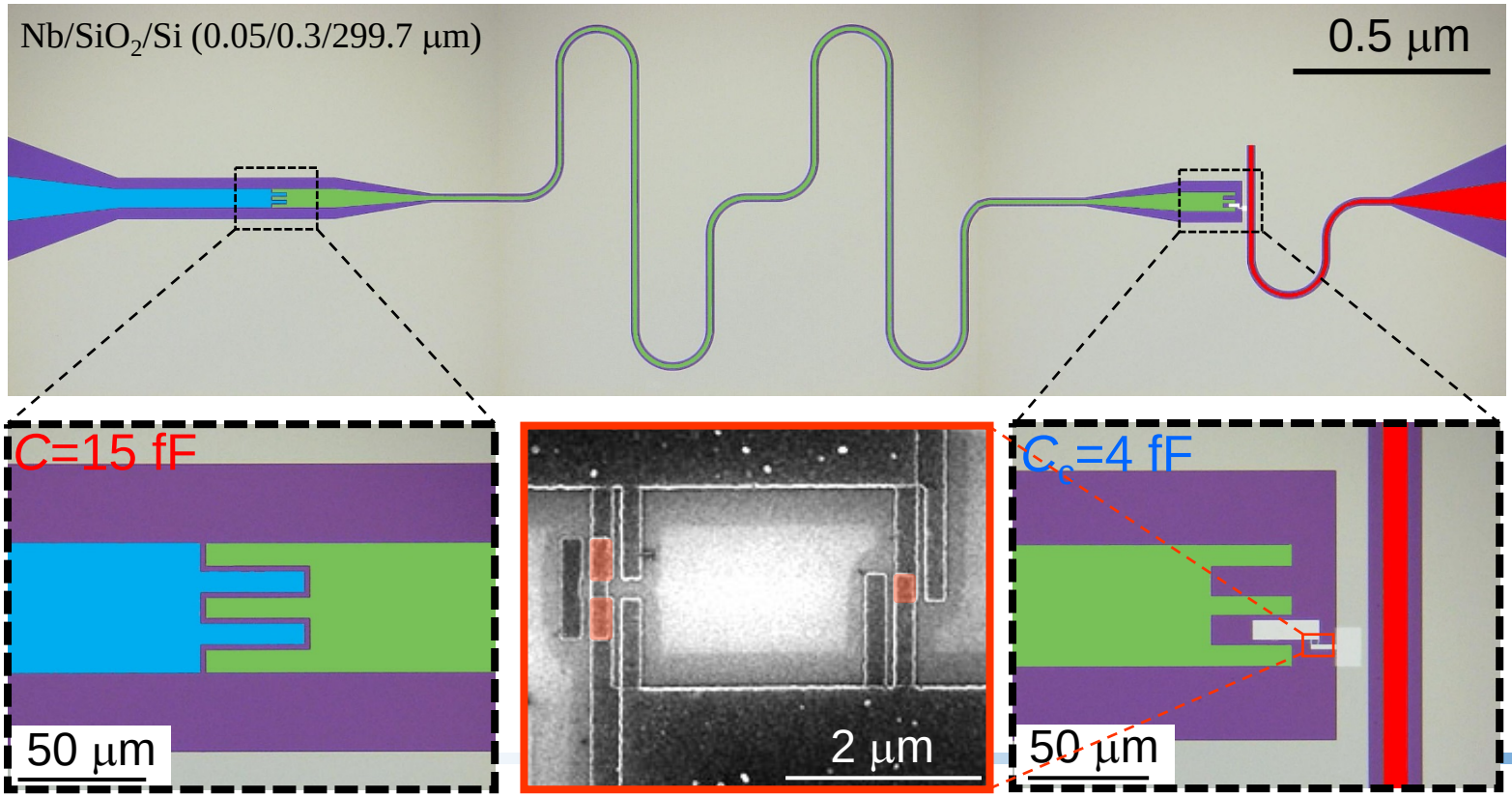
$$\delta\omega_d = \omega_{ge} - \omega_d < 2\chi$$

Device

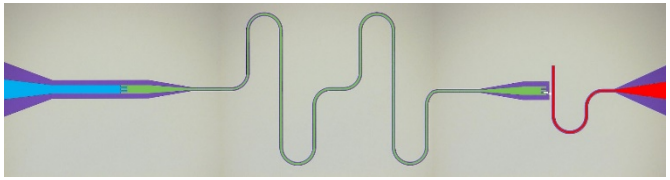


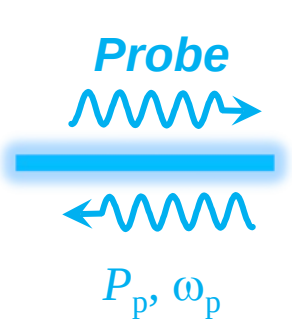
$\omega_r/2\pi = 10.678$ GHz $g_{01}/2\pi = 230$ MHz
$\omega_{ge}/2\pi = 5.461$ GHz $\chi/2\pi = 40$ MHz

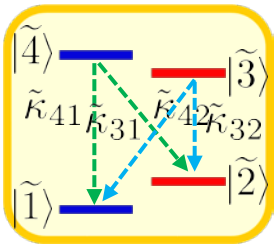
K. Inomata *et al.*, *PRB* (2012)
K. Inomata *et al.*, *PRL* (2014)

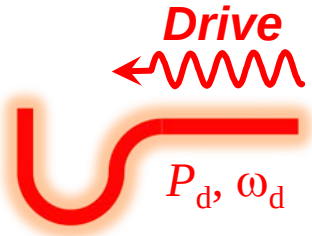


Absorption of incident microwave

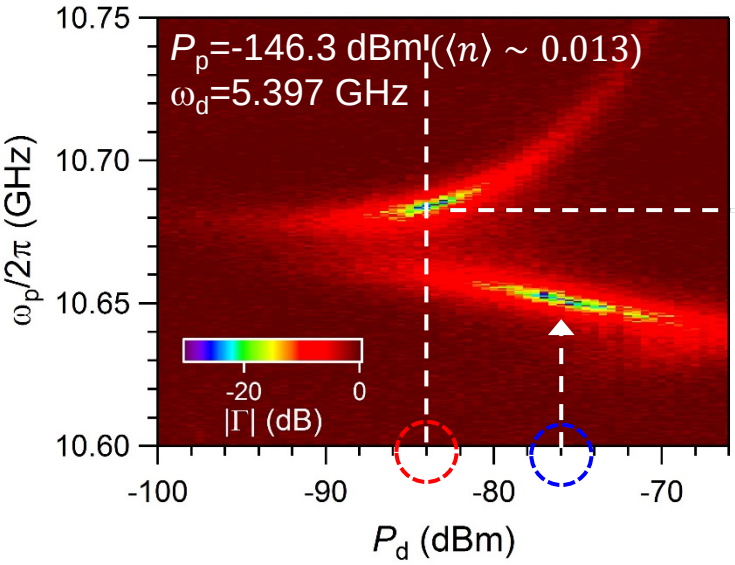


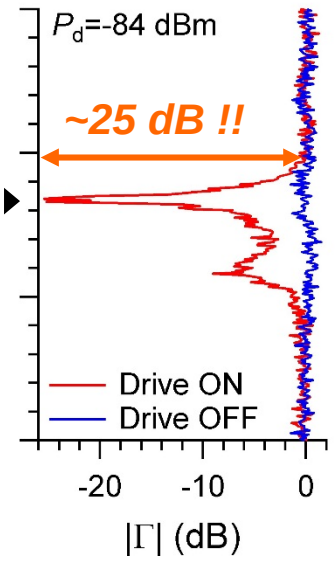


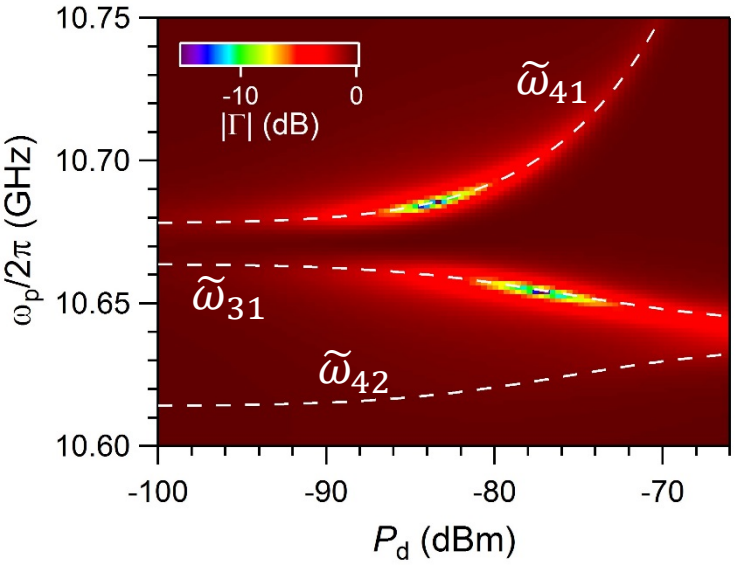




$\delta\omega_d/2\pi = 64$ MHz

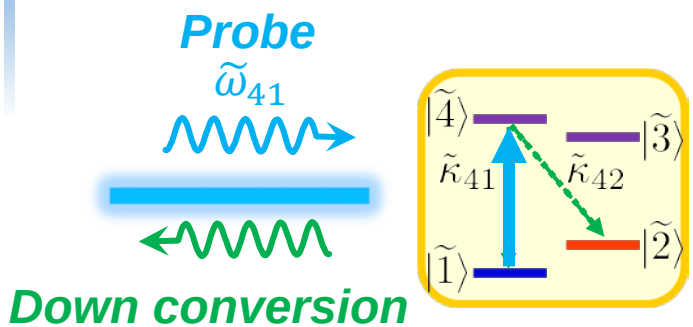


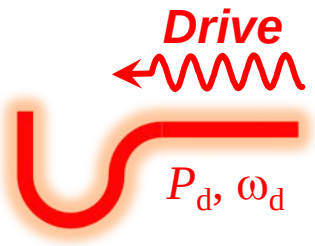




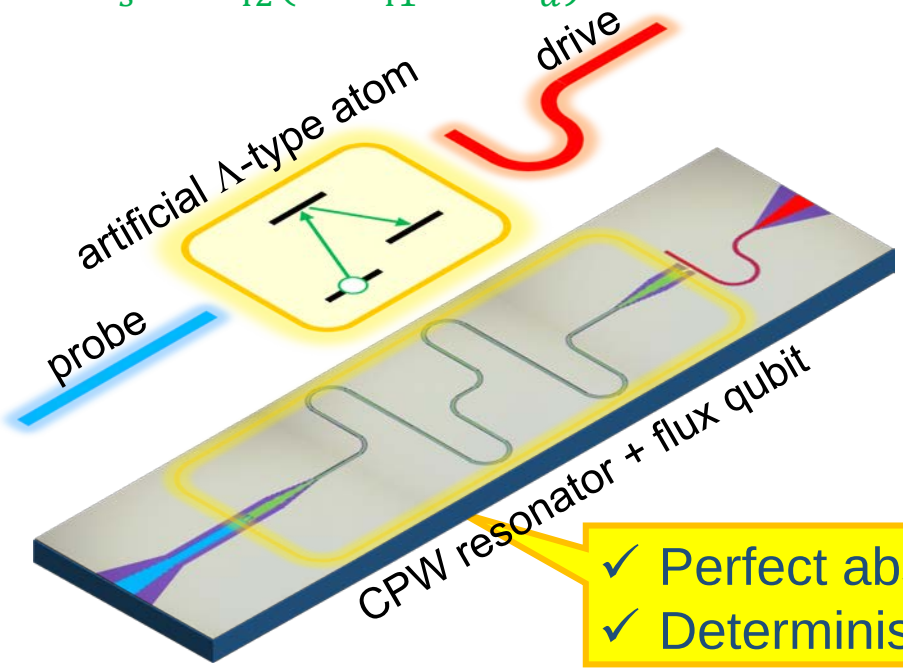
K. Inomata *et al.*, *PRL* (2014)

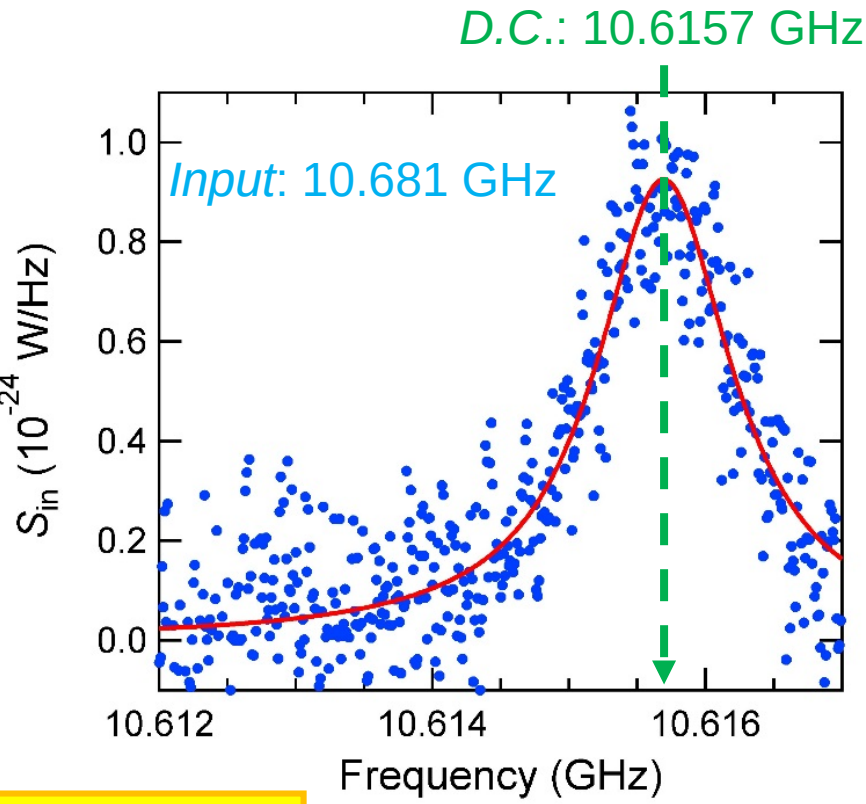
Down-converted spectrum





$\delta\omega_d/2\pi = 64$ MHz



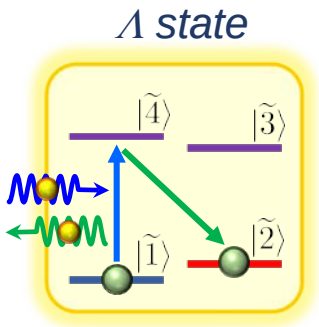


✓ Perfect absorption
✓ Deterministic down-conversion

Artificial Λ-type atom

K. Inomata *et al.*, *PRL* (2014)

Content



Device & Measurement setup

- **Resonator**

  $\omega_0/2\pi \quad = \quad 10.256$ GHz

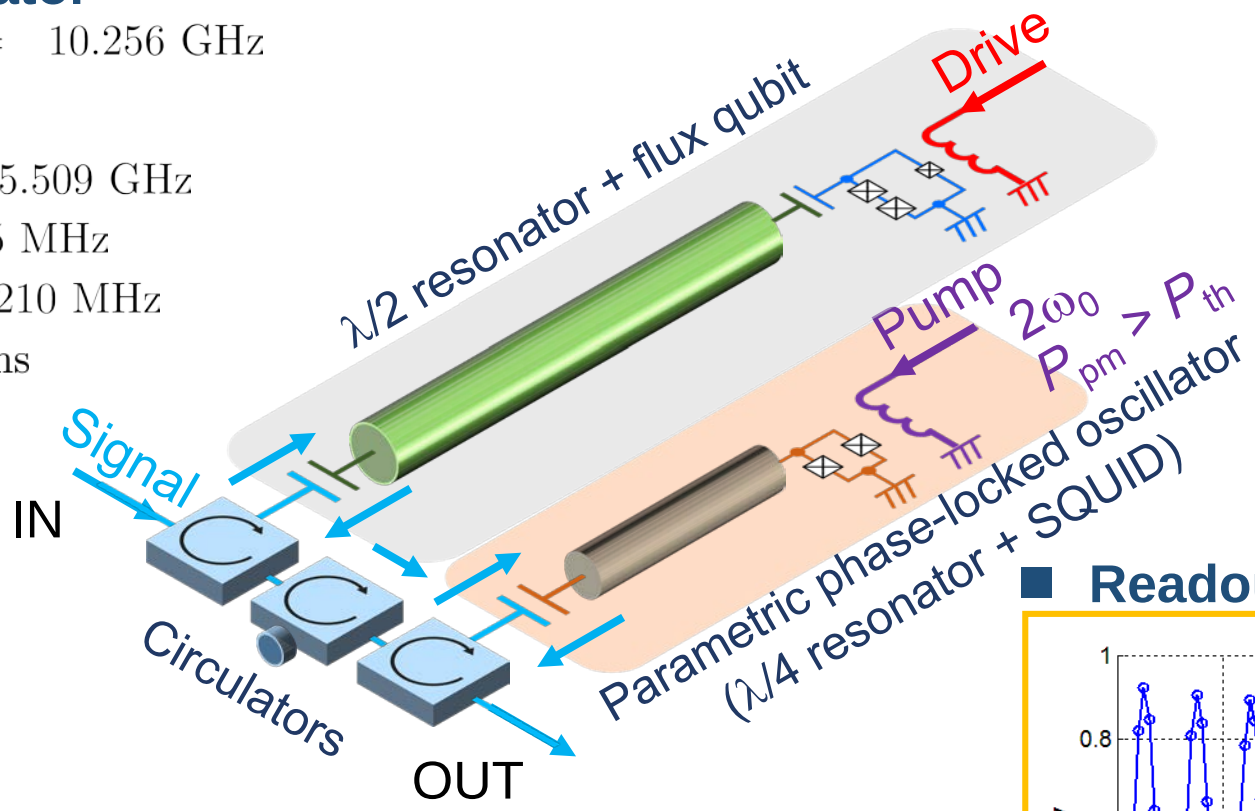
- **Qubit**

  $\omega_{ge}/2\pi = 5.509$ GHz

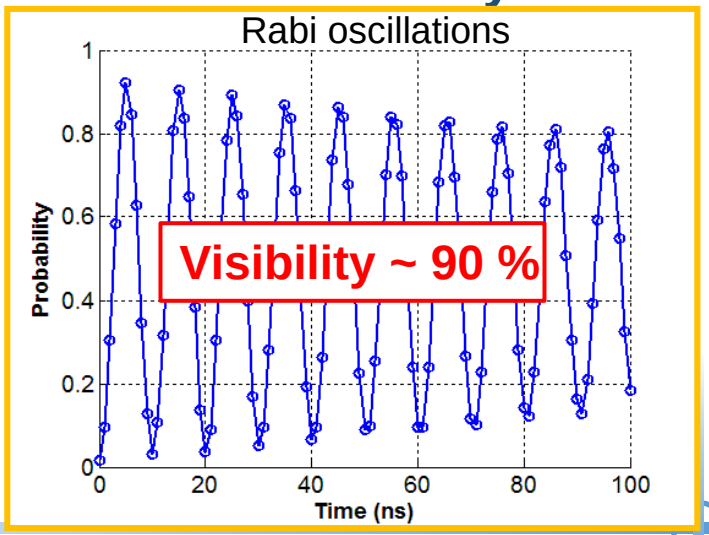
  $\chi/2\pi = 35$ MHz

  $g_{01}/2\pi = 210$ MHz

  $T_1 \sim 900$ ns

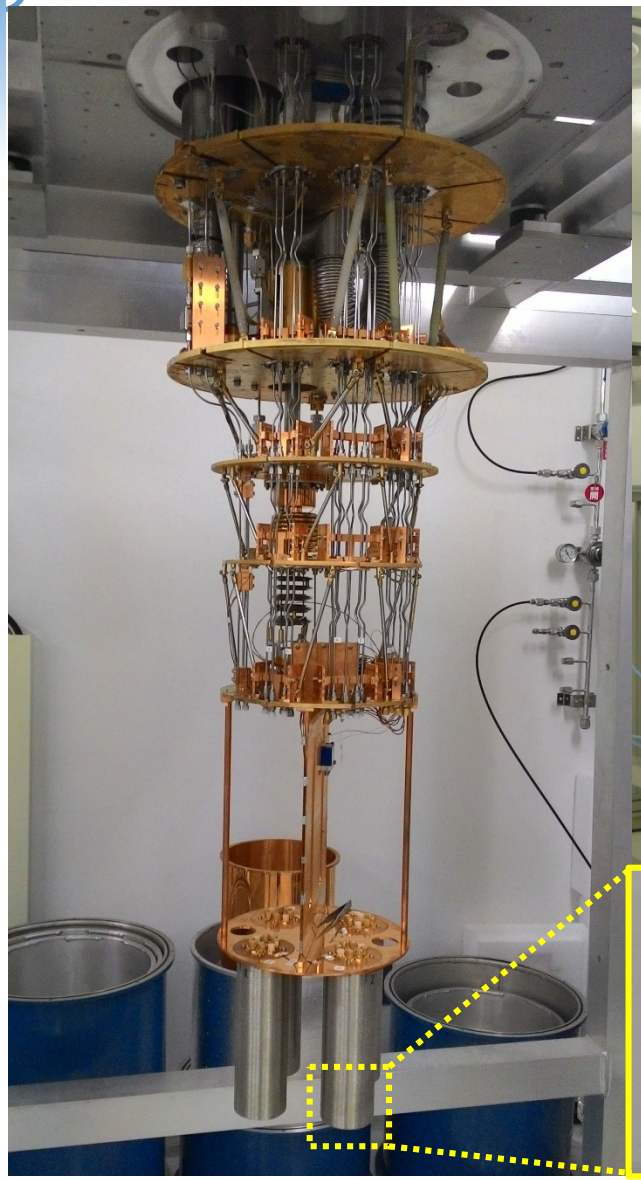


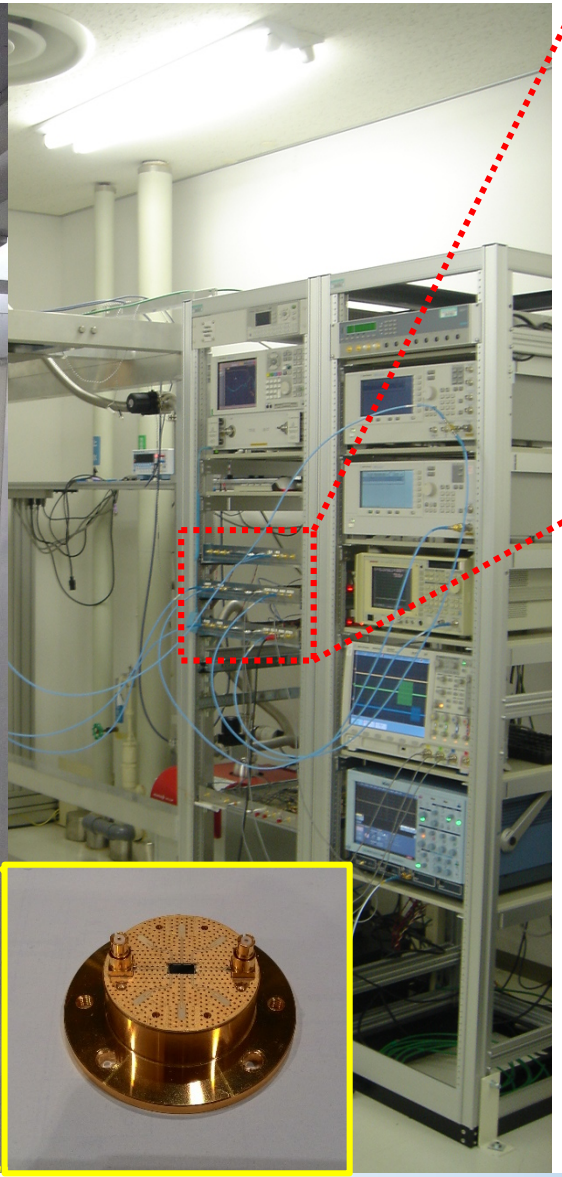
- **Readout visibility**

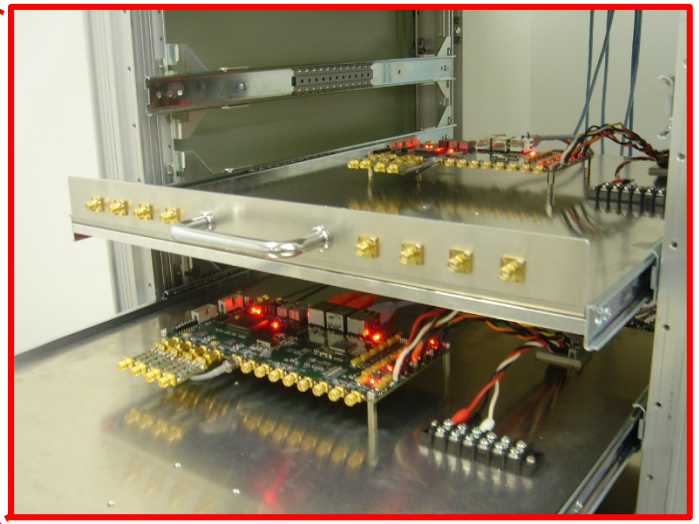


Z. R. Lin *et al.*, *Nat. Commun.* (2014)

Device & Measurement setup







Triton 200 (Oxford)

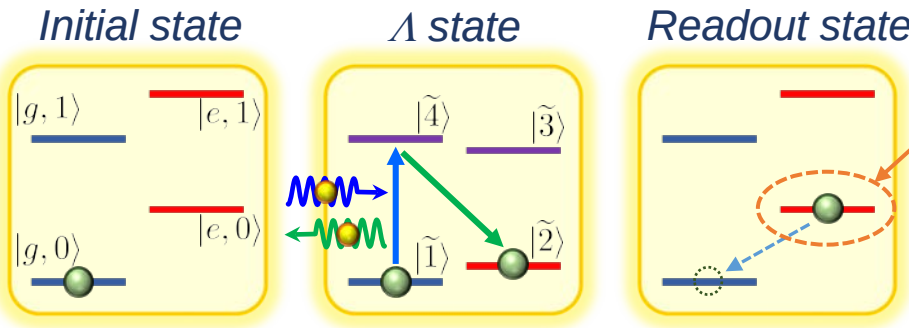
- ✓ Base temperature: 10 mK
- ✓ Input MW line: 20
- ✓ Output MW line with a HEMT: 4

GHzDAC (designed by J. Martinis)

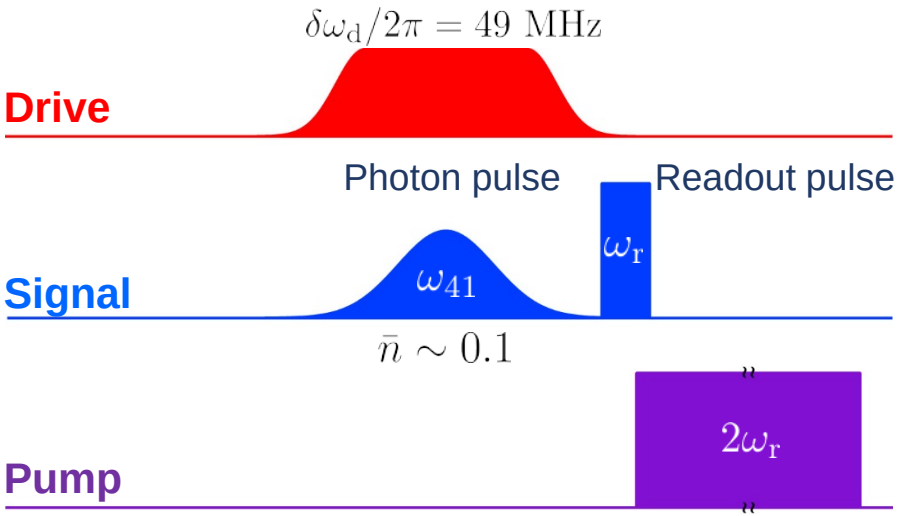
- ✓ 1GSa/s
- ✓ Pulse shaping with ns precision

Pulse sequence for itinerant photon detection

Pulse Sequence



Qubit excited state



Photon-detection efficiency

Photon pulse (Gaussian pulse)

$\bar{n} \sim 0.1$

✓ *Probability of the vacuum*

$$P(0) = \exp(-\bar{n})$$

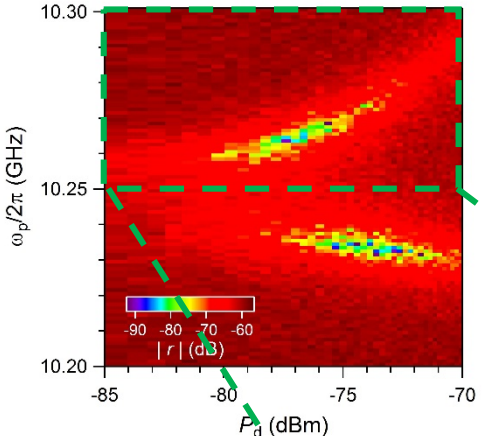
✓ *Efficiency of photon detection*

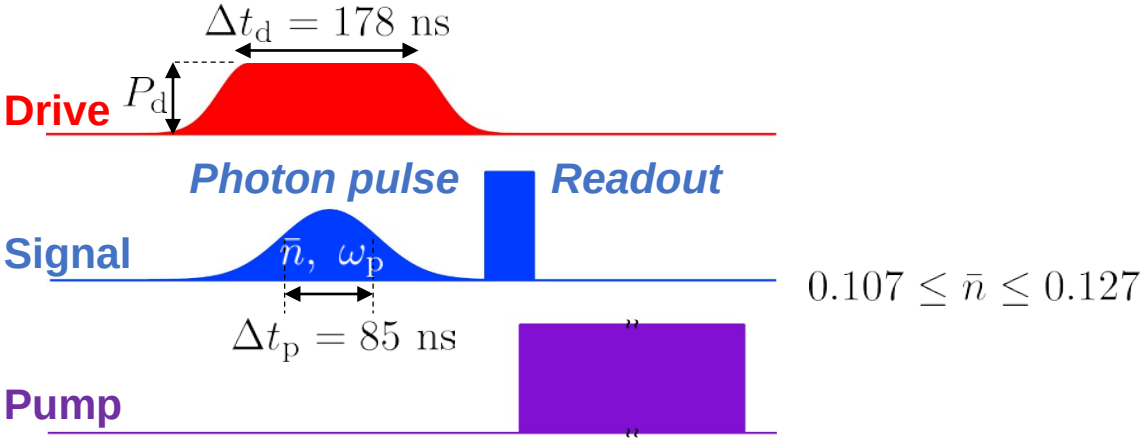
$$\eta \sim \frac{P(|1\rangle)}{1 - P(0)}$$

$P(|1\rangle)$: probability for "*click*"

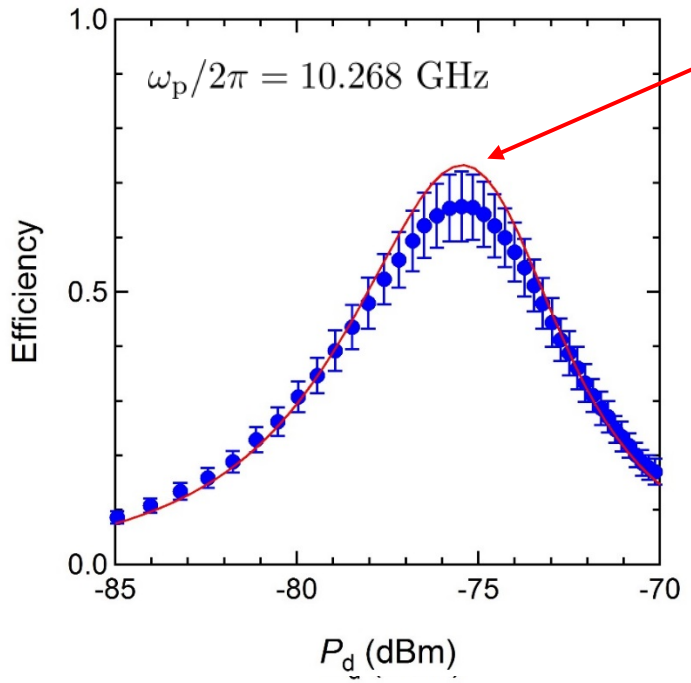
K. Inomata *et al*., *Nat. Commun*. (2016)

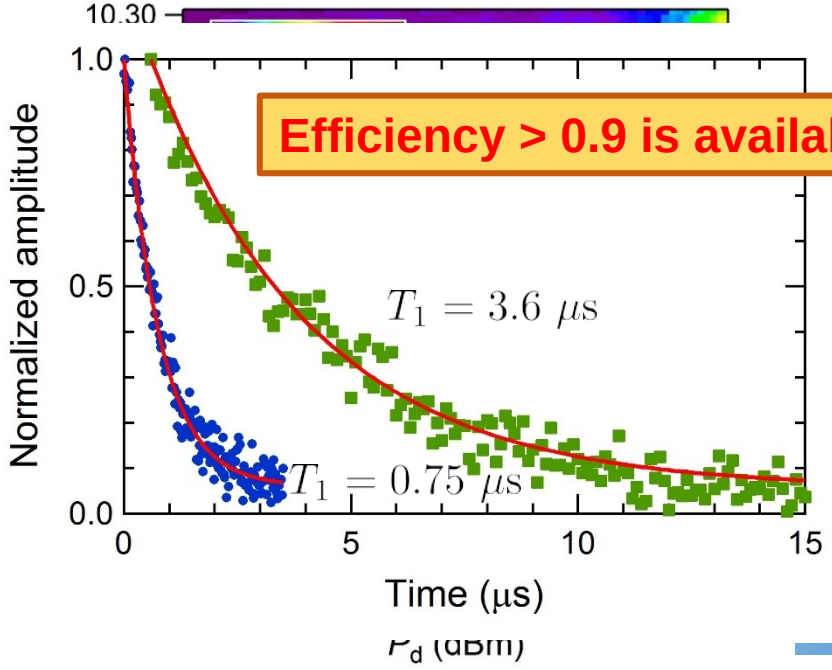
Itinerant photon detection using Z-matched Λ system





Maximum Efficiency: 0.66 ±0.06





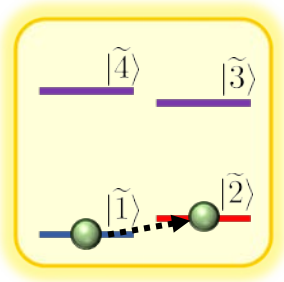
Efficiency > 0.9 is available!!

K. Inomata *et al*., *Nat. Commun*. (2016)

Dark count probability

- **Nonadiabatic & thermal transition of a qubit**

Λ state



Nonadiabatic transition

Drive

ON

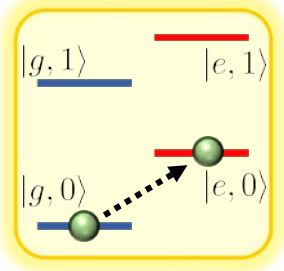
✓ *Depending on* P_{d}

OFF

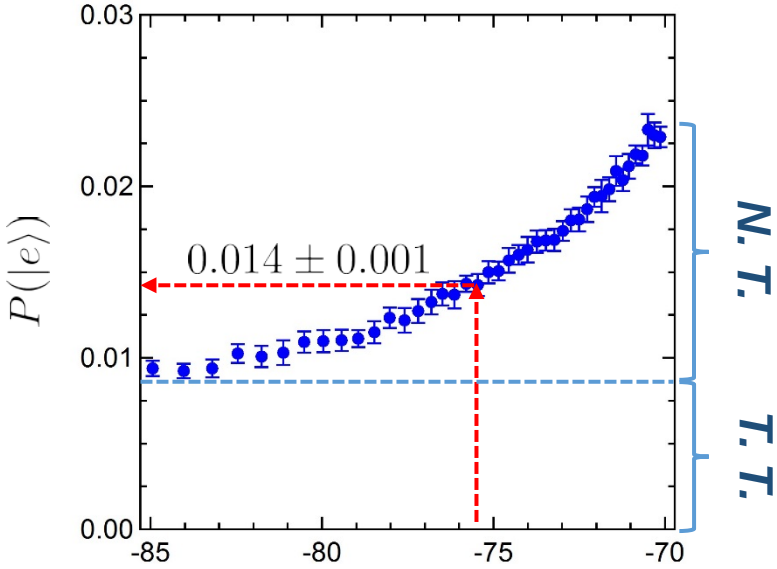
✓ *Constant*

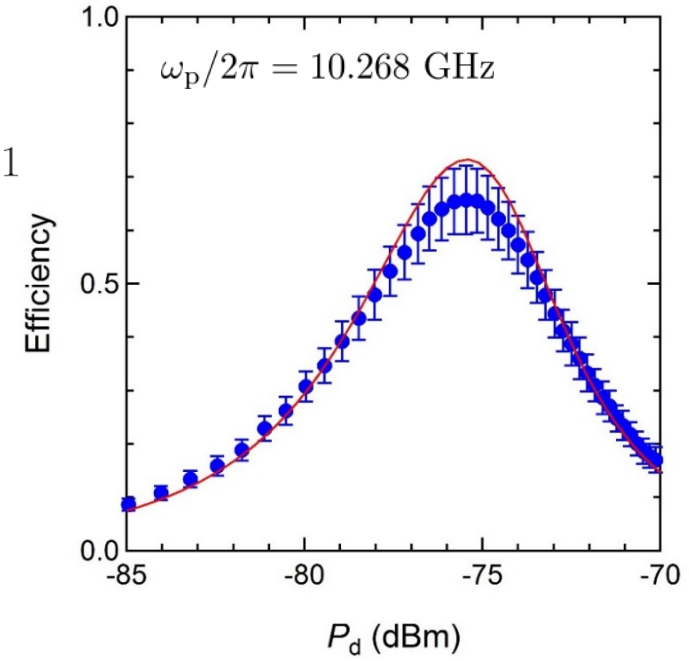
$P(|e\rangle) = 0.008 \pm 0.001$

Initial state



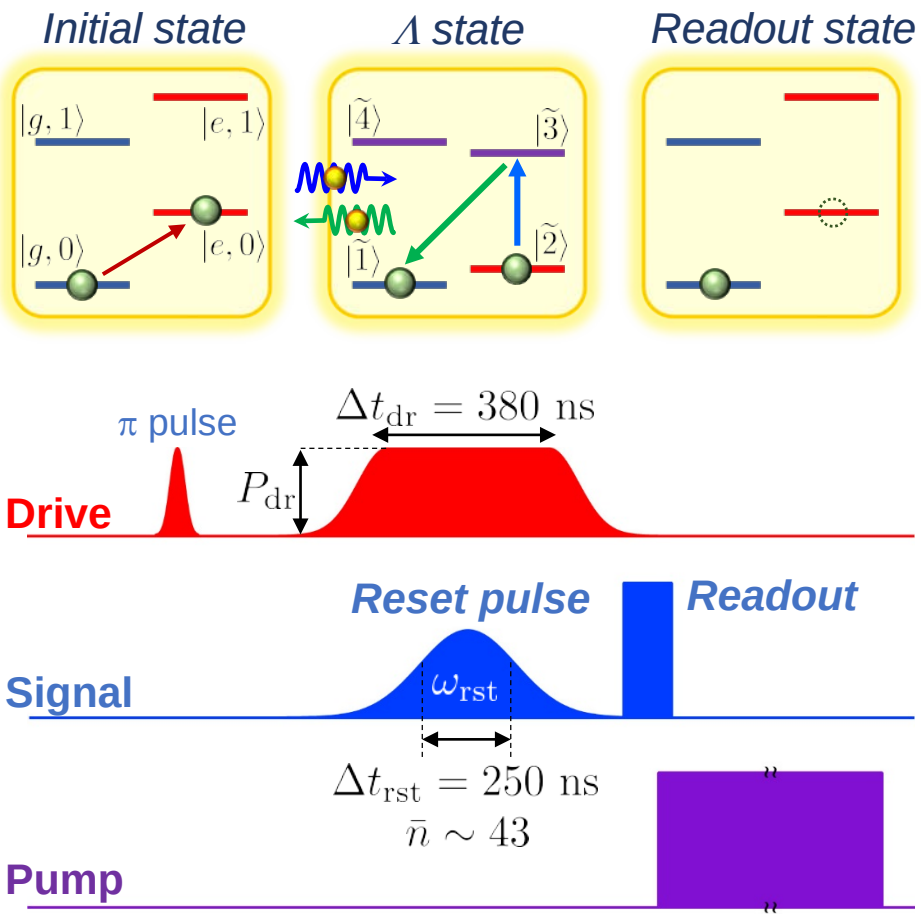
Thermal transition





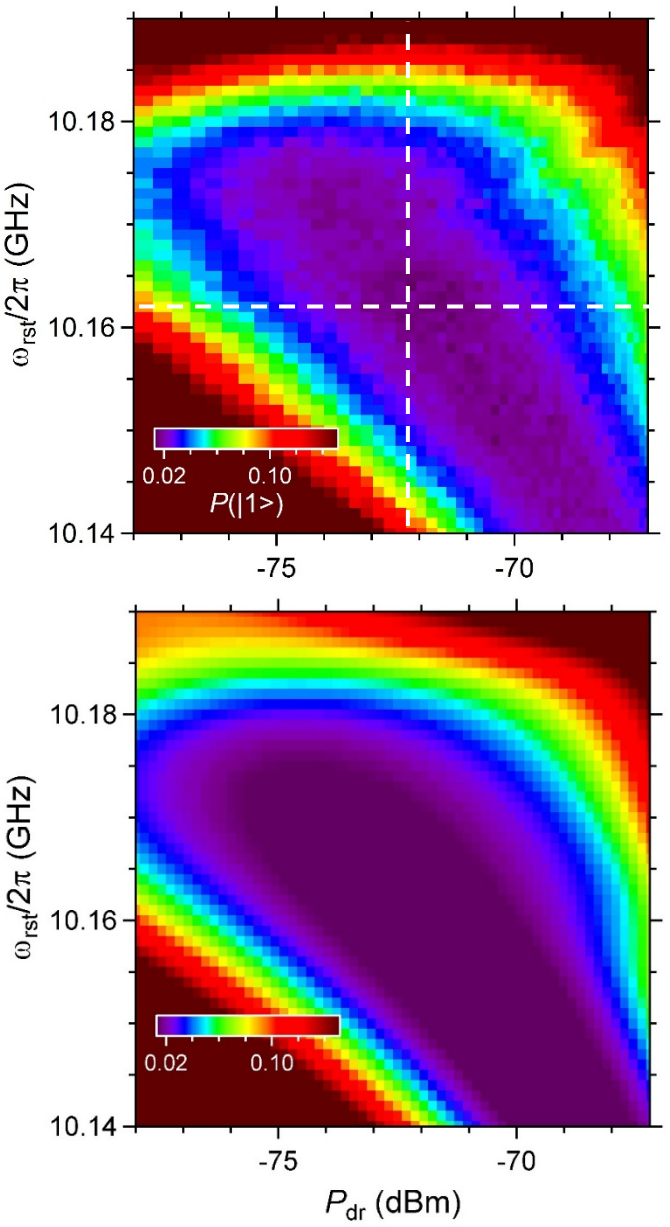
K. Inomata *et al.*, *Nat. Commun.* (2016)

Reset of the system

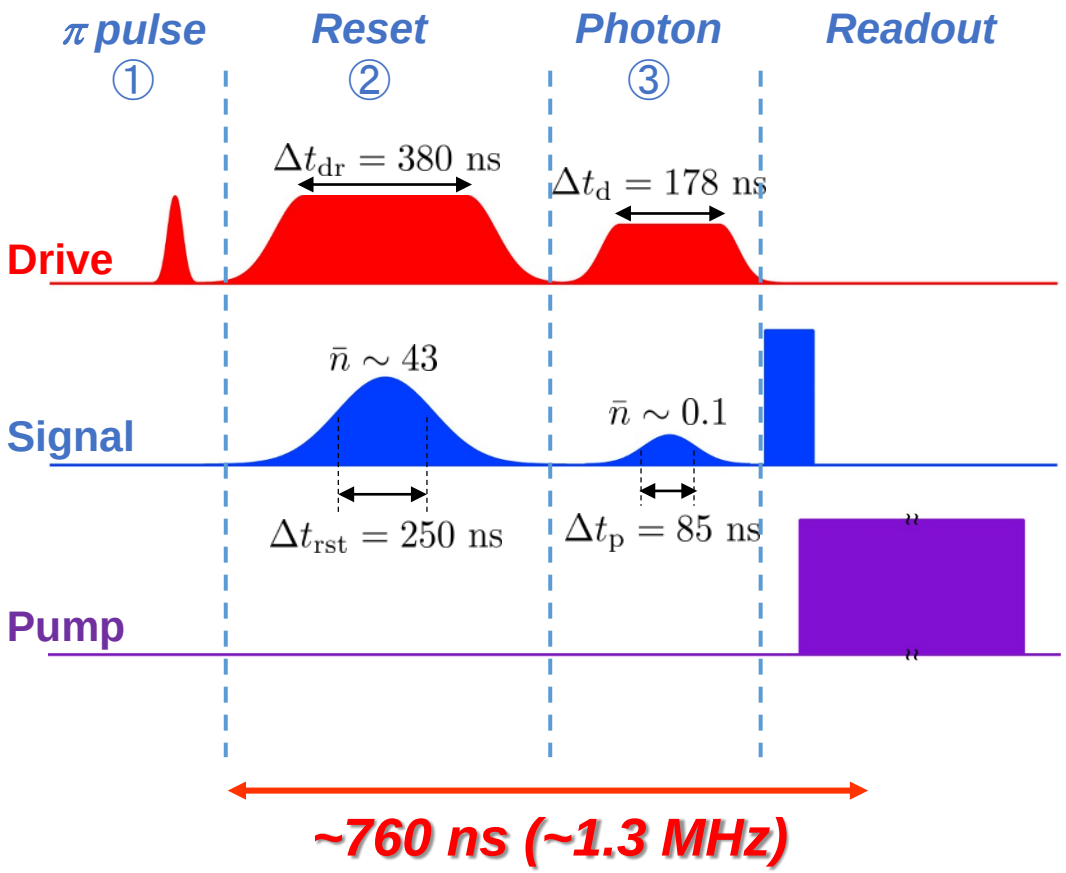


✓ Op

cf. *v*



Photon detection with a reset pulse



Pulse sequence	① + ② + ③	② + ③	③
Efficiency	0.667±0.060	0.666±0.062	0.670±0.059

Summary

- ✓ Demonstration of itinerant-photon detection using an artificial Λ-type atom.
- ✓ Single-photon detection efficiency = 0.66 ± 0.06.
- ✓ Demonstration of "*reset*" of the system.
- ✓ Repetition time for the photon detection ~ 1.3 MHz.
- ✓ Dark count probability = 0.014 ± 0.001.