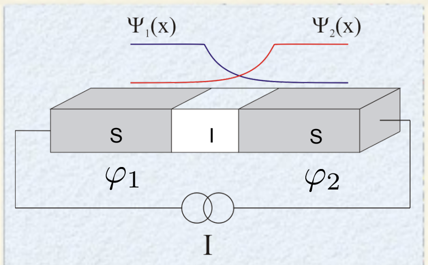
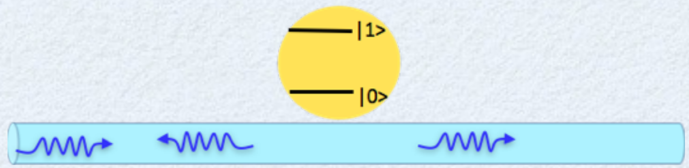
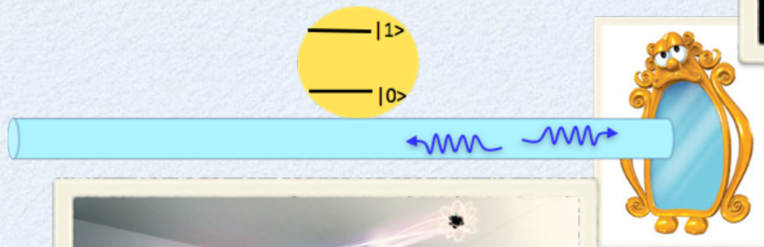
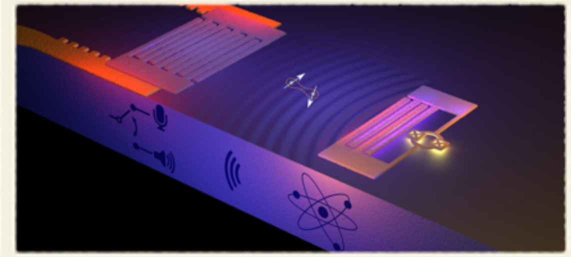
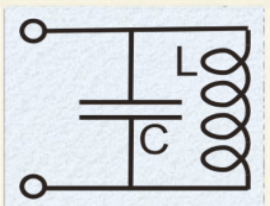
Waveguide QED with Photons and Phonons

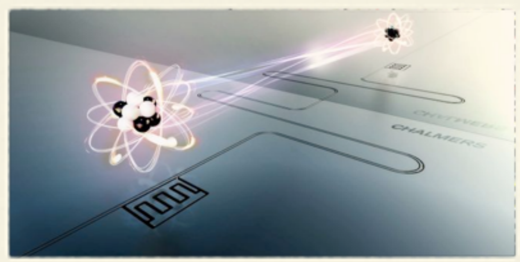


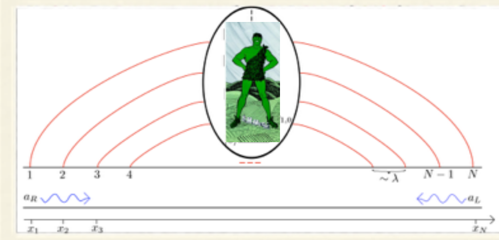


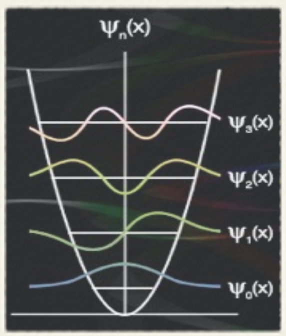












Göran Johansson
Applied Quantum Physics Laboratory, MC2
Chalmers University of Technology

Mesoscopic Transport and Quantum Coherence
5-8th of August 2017, Espoo, Finland

MC2
Microtechnology and Nanoscience


LT28
28th International Conference
on Low Temperature Physics
9–16 August 2017, Gothenburg Sweden
CHALMERS
NORWAY
Gulf of
Bothnia
Baltic
Sea
North
Sea
Gotland
Öland
LATVIA
LITHUANIA
Göteborg
Borås
Jönköping
Helsinki
Bergen
Stavanger
Lillehammer
Mora
Falun
Gävle
Sundsvall
Hudiksvall
Borlänge
Västervik
Visby
Oskarshamn
Kalmar
Växjö
Karlskrona
Riga
Ventspils
Liepāja
Klaipėda
Turku
Tampere
Pori
Rauma
Lahti
Kotka
Jelgava
Šiauliai
Nässjö

Starts in August

Ingrid Strandberg

Superradiance
Qu. Plasmonics

Applied Quantum Physics – Theory Division
Quantum Optics Circuit QED subgroup:

Theory

Göran Johansson

Post-docs

Microwave
CV Quantum
Computing

Fernando
Quijandria

Relativistic
Quantum
Information

Robert Jonsson

Quantum
Plasmonics

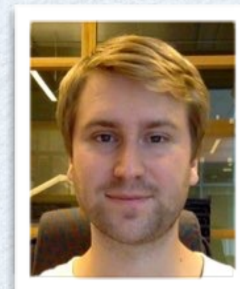
Benjamin
Rousseaux

PhD students

Photon
Sources
QND Photon
Detection

Sankar
Sathyamoorthy

Quantum SAW



Andreas Ask

Emely Wiegand

$$\Phi(x,t) = \sqrt{\frac{\hbar Z_0}{4\pi}} \int_0^\infty \frac{d\omega}{\sqrt{\omega}} \left(a_\omega^{\text{in}} e^{-i(-k_\omega x + \omega t)} + a_\omega^{\text{out}} e^{-i(k_\omega x + \omega t)} + \text{H.c.}\right), \quad (1)$$

Close collaboration with experimentalists in **Quantum Device Physics Laboratory**:

Experiment

Per Delsing

Jonas Bylander

Waveguide Quantum Optics with Artificial Atoms

- Artificial atoms are engineered
- Explore new parameter regimes, hard to reach with natural atoms

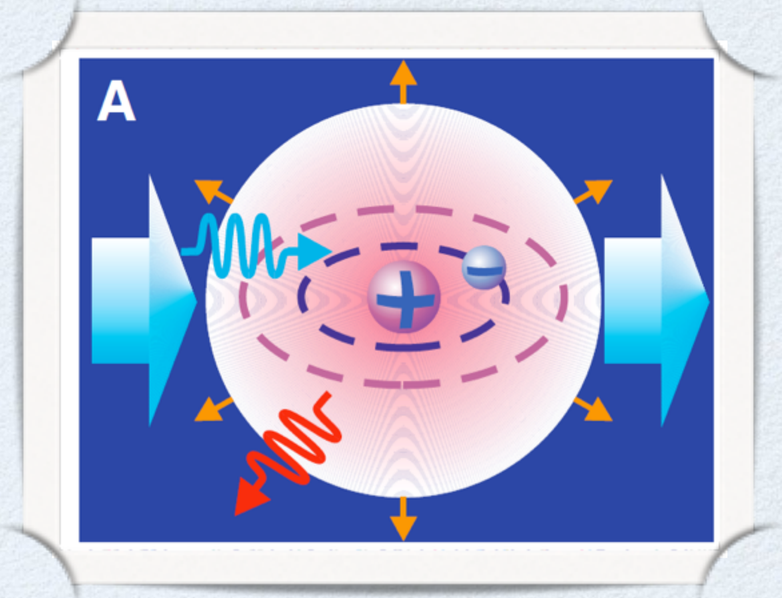
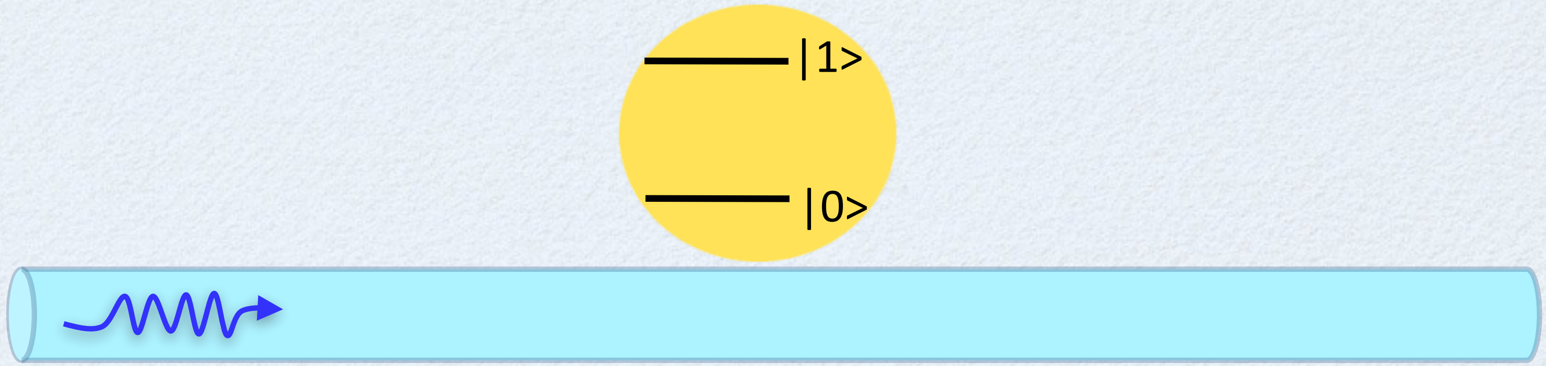
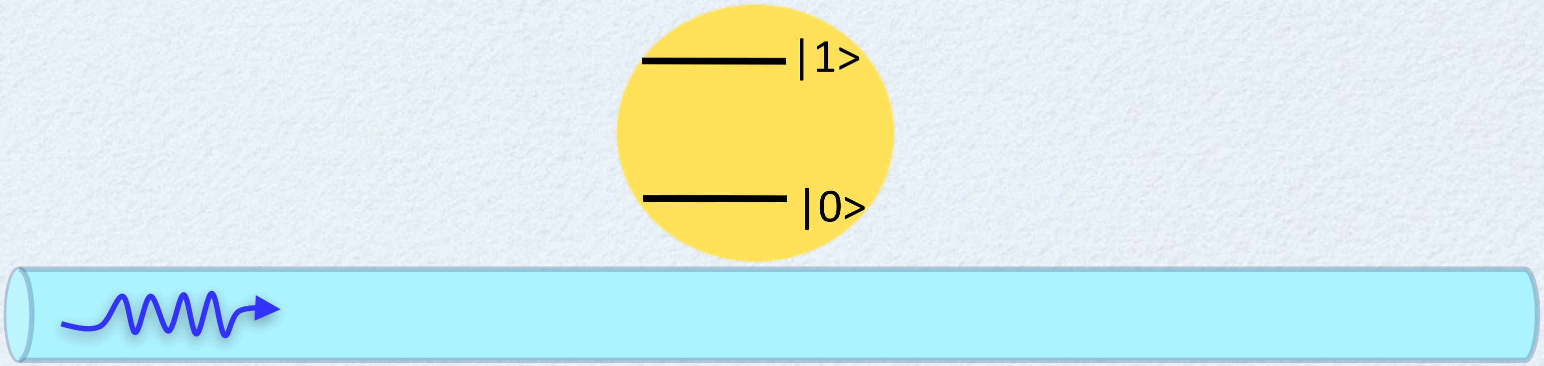


Fig: Astafiev et al., Science (2010). NEC

Single-atom scattering

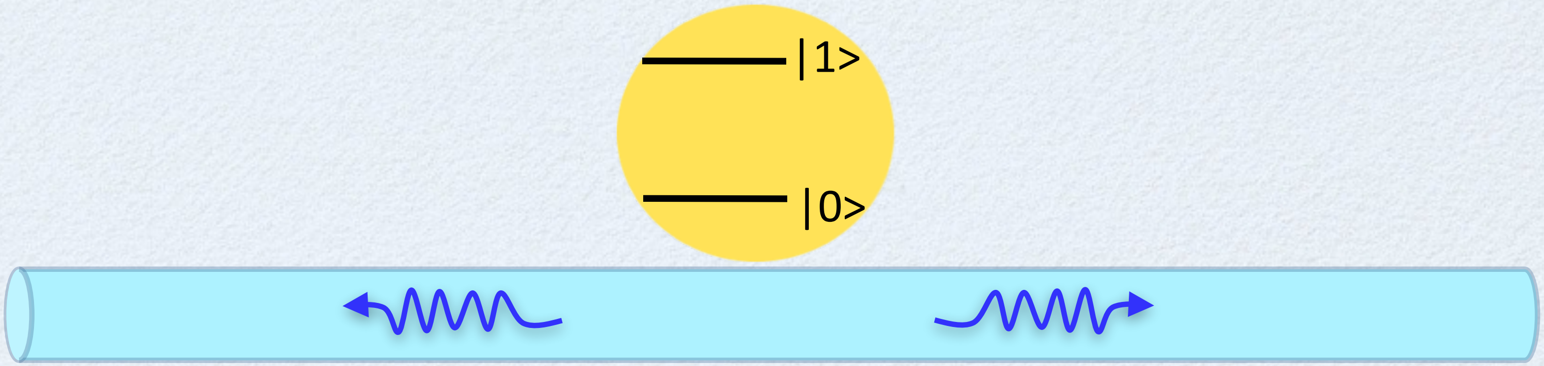


Single-Atom Scattering



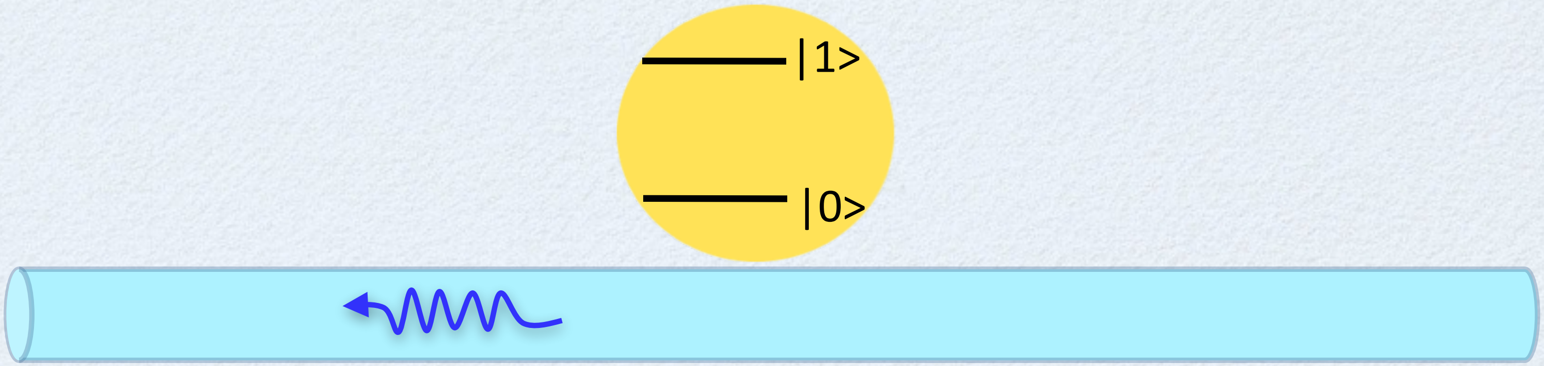
- What is the maximum reflection of a single photon/phonon from a single atom in 1D?

Single-Atom Scattering



- What is the maximum reflection of a single photon/phonon from a single atom in 1D?
  - My first guess: 50% due to spontaneous emission in random direction

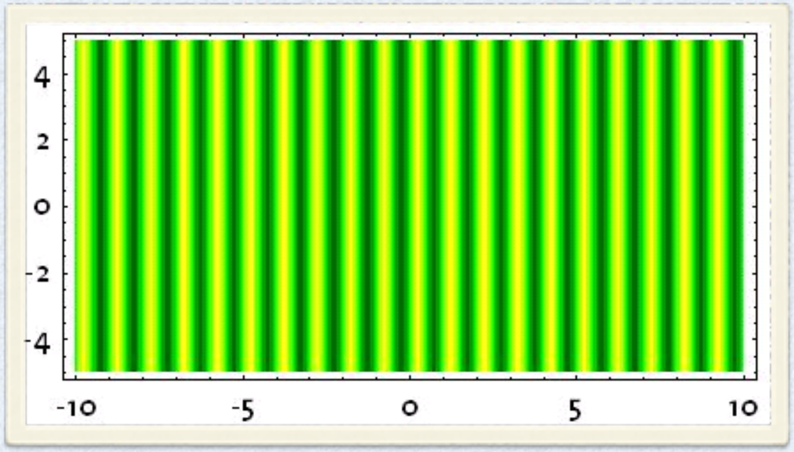
Single-atom scattering



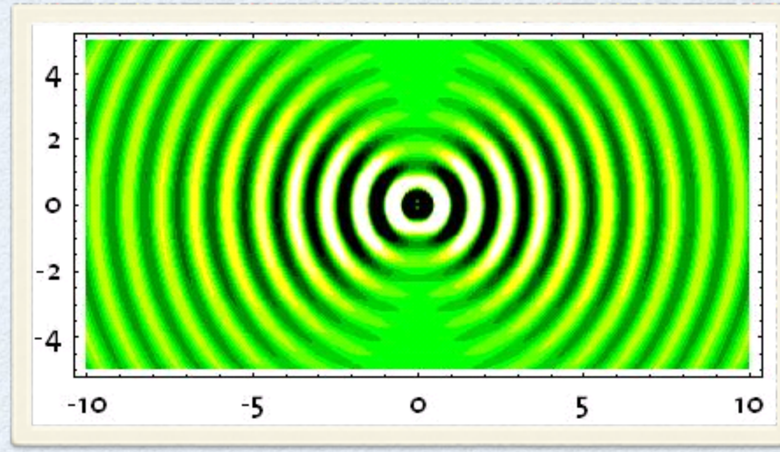
- What is the maximum reflection of a single photon/phonon from a single atom in 1D?
  - My first guess: 50% due to spontaneous emission in random direction
  - Fully coherent: 100% due to destructive interference in forward direction

Atom/dipole in open space

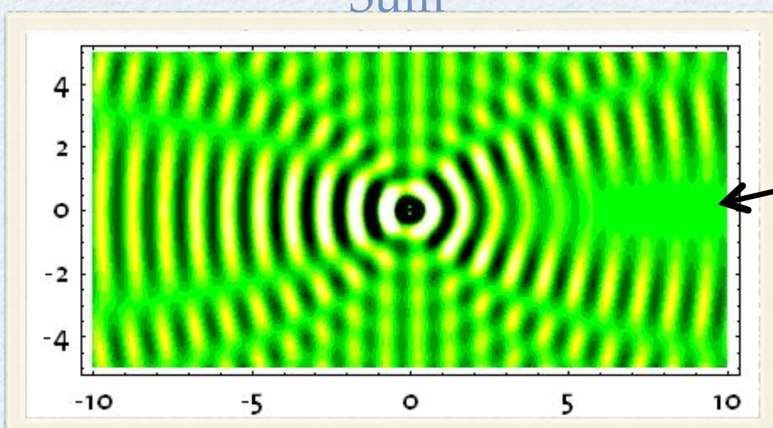
Incoming light



Atom/dipole emits light



Sum

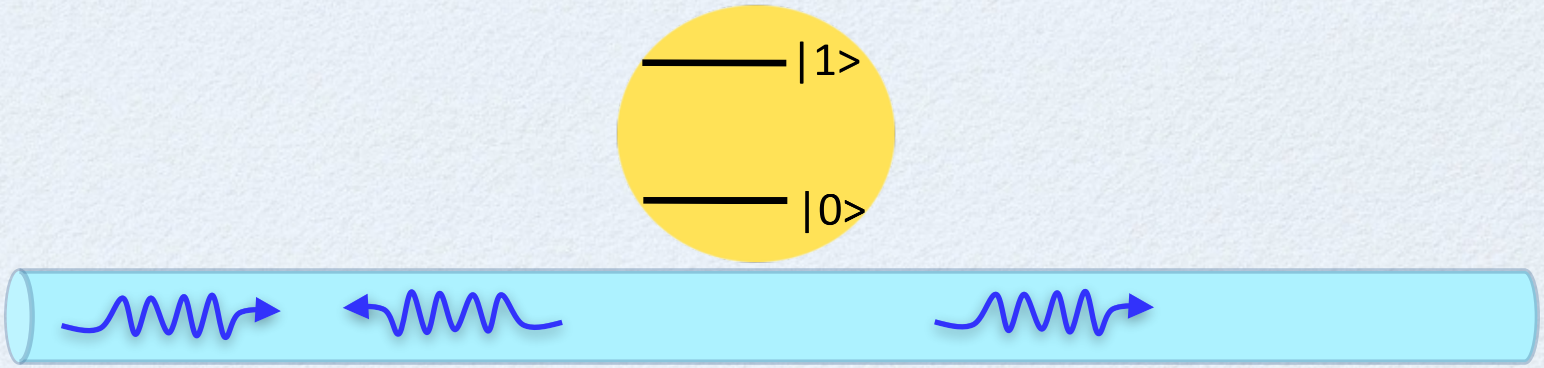


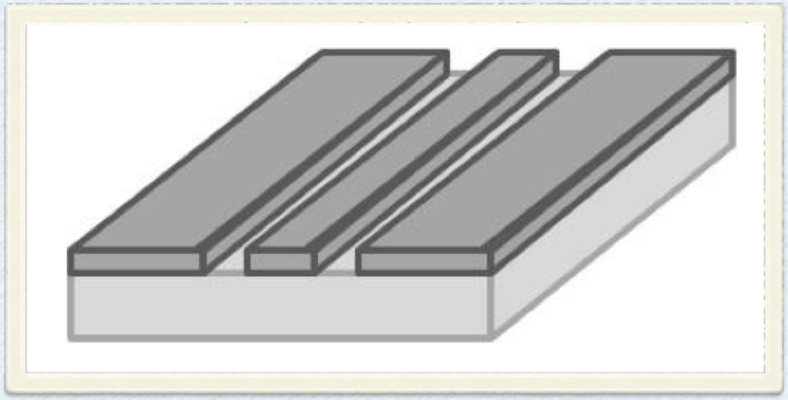
There is perfect extinction in the forward direction due to destructive interference

Figs. from:
U. Håkanson, V. Sandoghdar *et al.*, Phys. Rev. B **77**, 155408 (2008)

G. Wrigge et al. *Nature Phys.* **4**, 60 (2008). <12% extinction
M. Tey et al. *Nature Phys.* **4** 924 (2008).

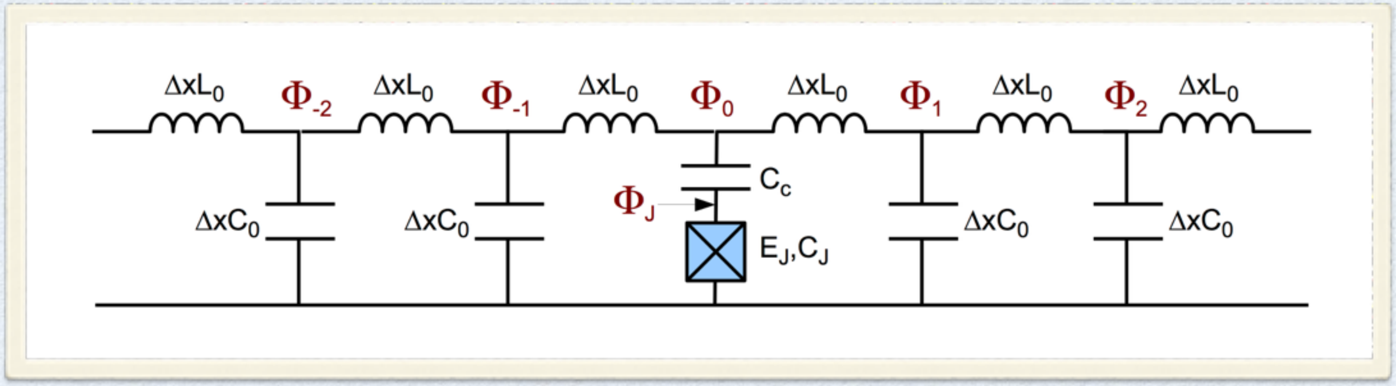
WAVEGUIDE + ATOM IN CQED



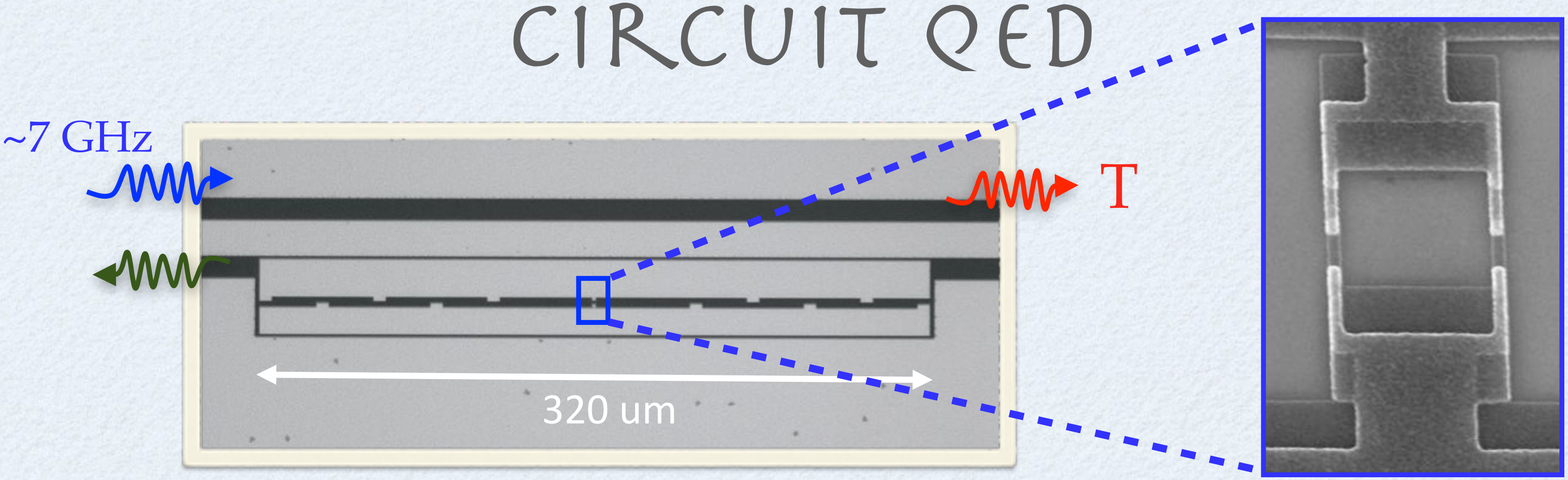


1D open space: Coplanar waveguide
(a squashed coaxial cable)

Equivalent circuits including the artificial atom

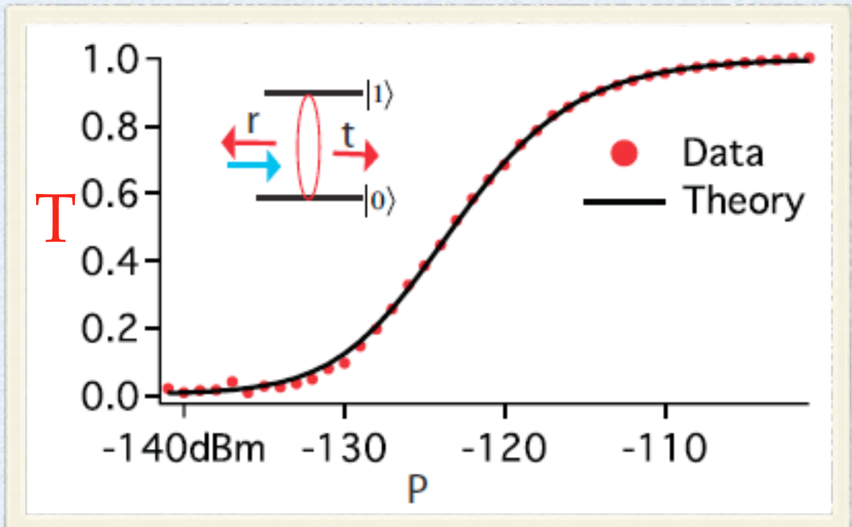


Single-atom scattering in circuit QED



Coupling:
96 MHz

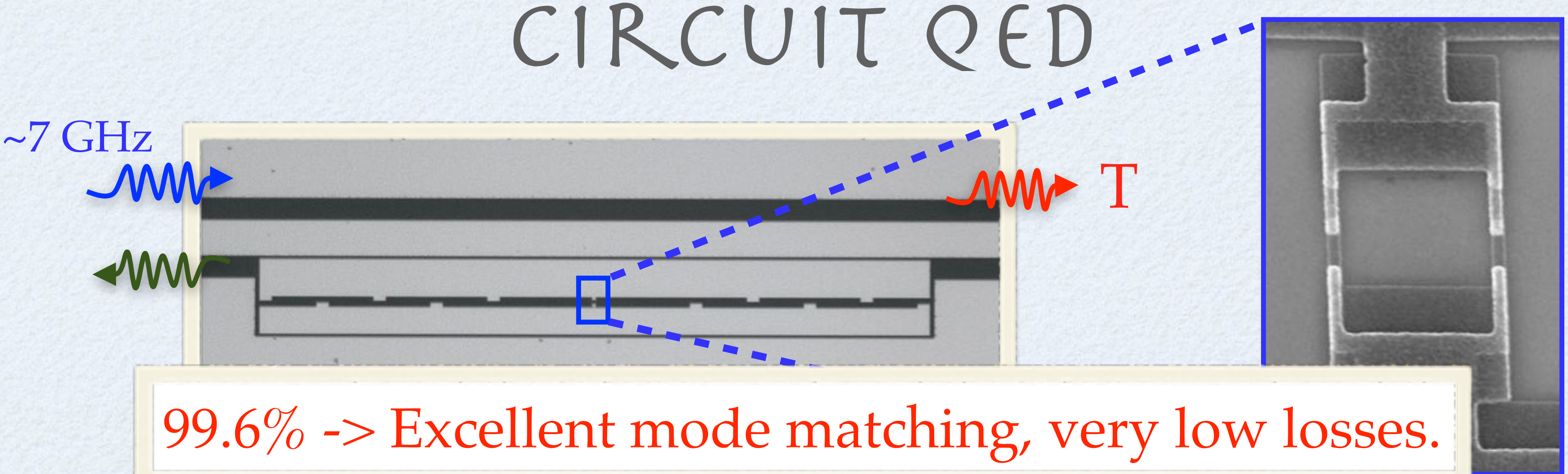
99.6%
reflection



Extinction in forward direction:
Flux qubit: >94%
Astafiev *et al.*, Science (2010).
Abdumalikov *et al.*, PRL (2010)
NEC/RIKEN
Theory: Chang *et al.*,
Nature Physics (2007);
Peropadre *et al.*, NJP (2013)

Io-Chun Hoi, C. M. Wilson, G. Johansson, T. Palomaki,
B. Peropadre, P. Delsing, *Phys. Rev. Lett.* **107**, 073601 (2011).

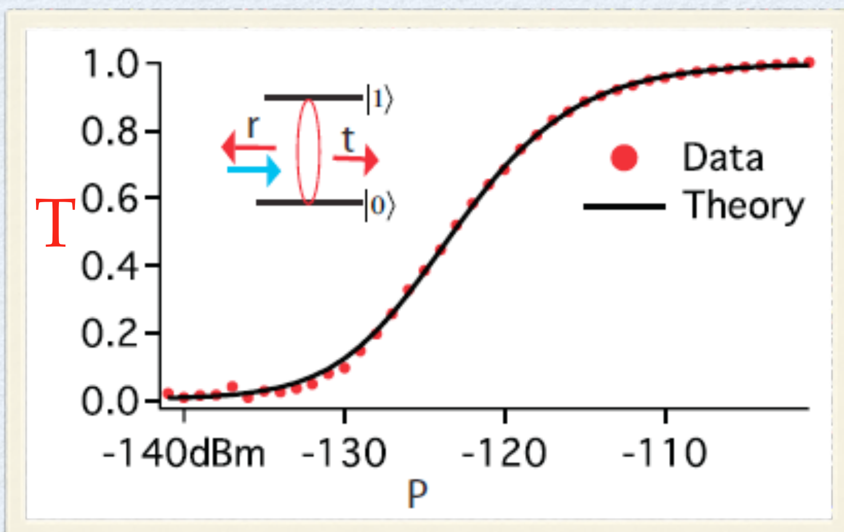
Single-atom scattering in circuit QED



99.6% -> Excellent mode matching, very low losses.

Coupling:
96 MHz

99.6%
reflection



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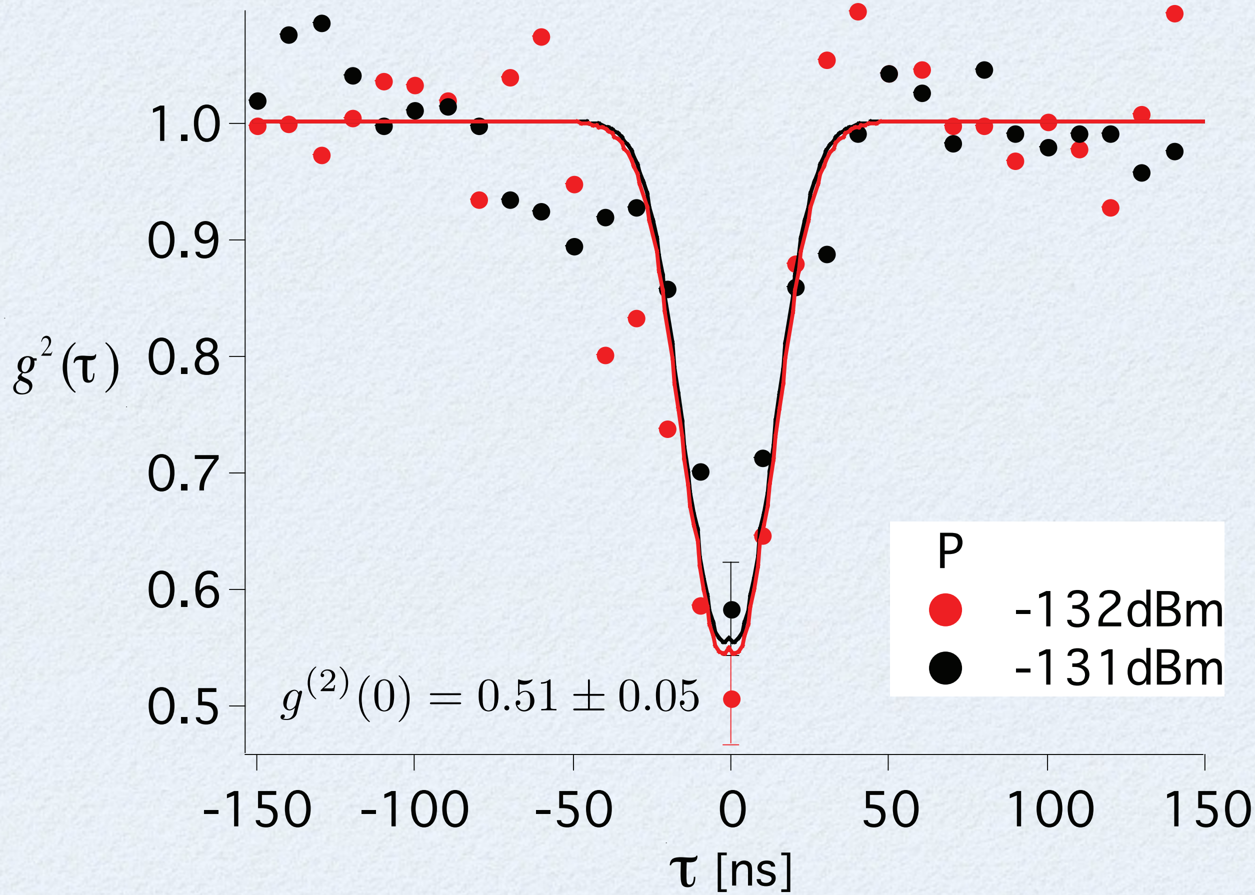
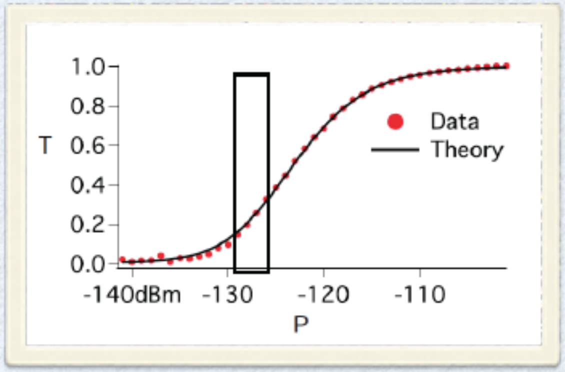
Io-Chun Hoi, C. M. Wilson, G. Johansson, T. Palomaki, B. Peropadre, P. Delsing, *Phys. Rev. Lett.* **107**, 073601 (2011).

OBSERVATION OF ANTIBUNCHING

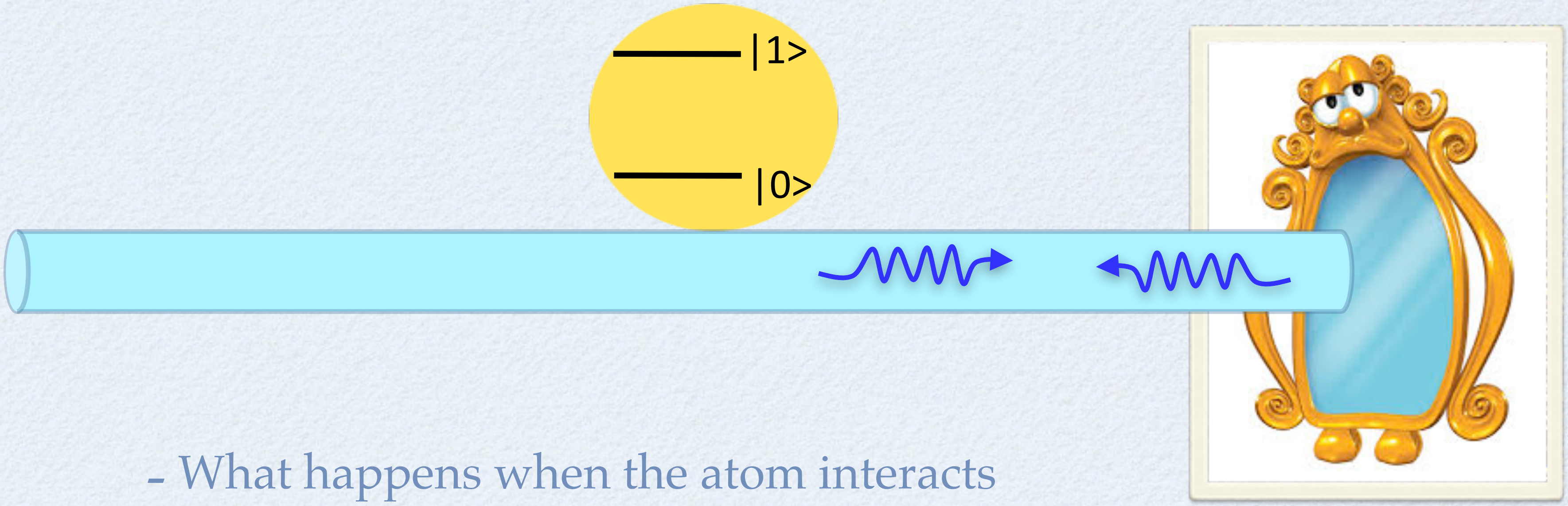




- Observe antibunching of reflected mode
  (~ 2 TB of data, processed at ~30 MB/s for 17 hours)
  - n > 1 states "filtered out"

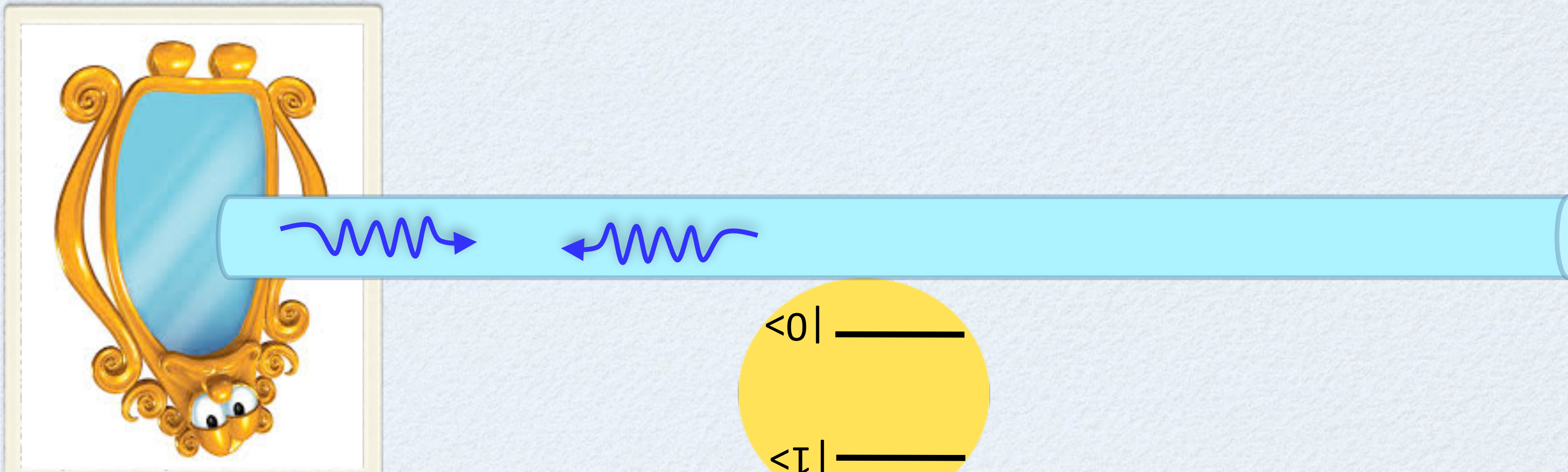
Io-Chun Hoi, Tauno Palomaki, GJ,
Joel Lindkvist, Per Delsing, C. M. Wilson, PRL (2012)

AN ATOM IN FRONT OF A MIRROR



- What happens when the atom interacts with its mirror image?

AN ATOM IN FRONT OF A MIRROR



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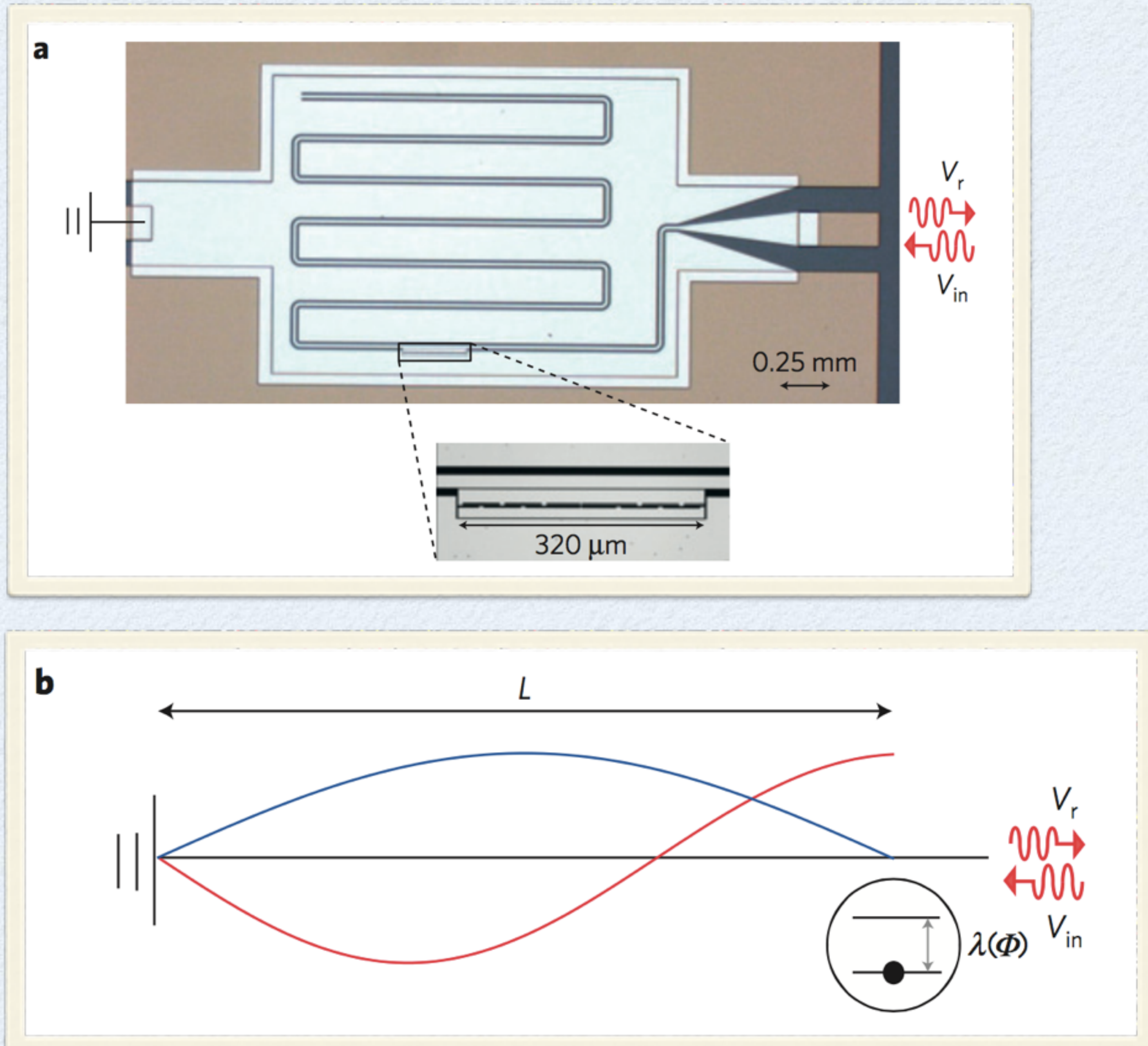
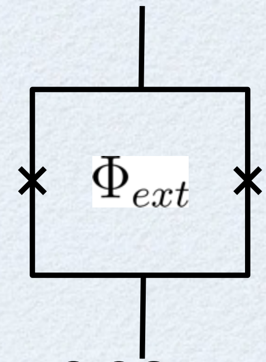
AN ATOM IN FRONT OF A MIRROR



Frequency tunable with external flux

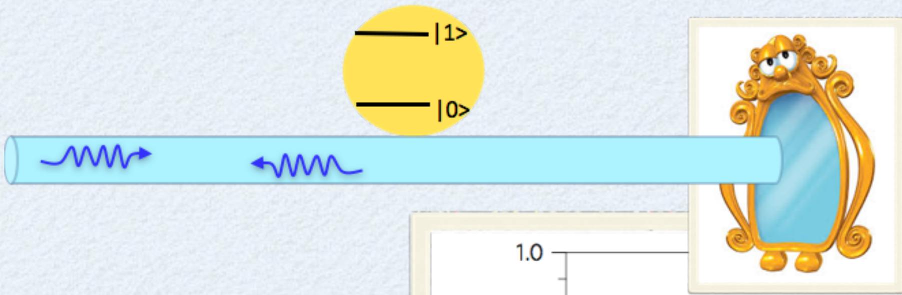


DC SQUID

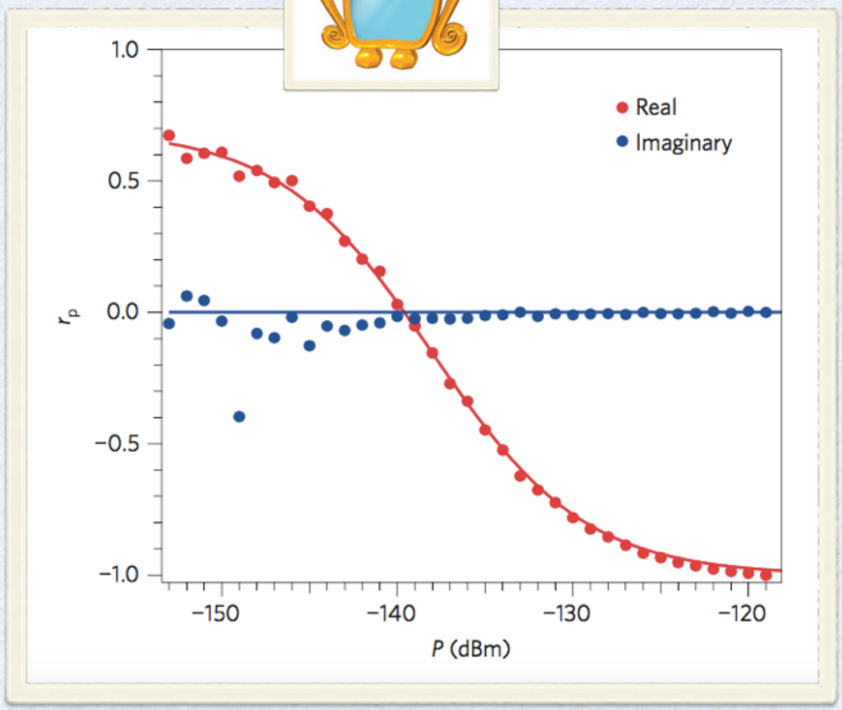
$$L_J = \frac{\Phi_0}{2\pi} \frac{1}{2I_0 \left|\cos \frac{\varphi_{ext}}{2}\right|}$$

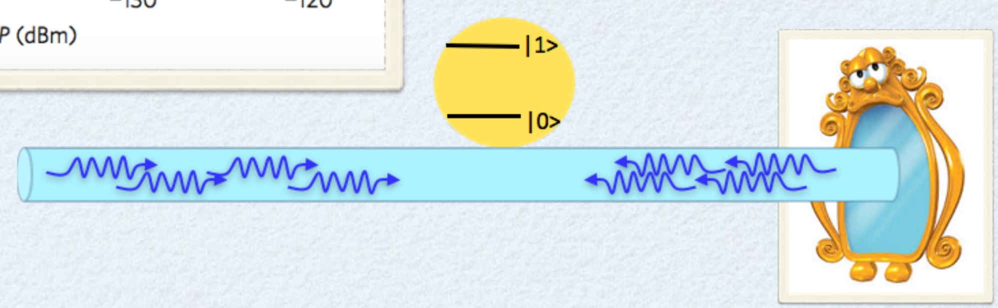
$$\varphi_{ext} = \frac{2\pi\Phi_{ext}}{\Phi_0}$$

Reflection Amplitude vs Power

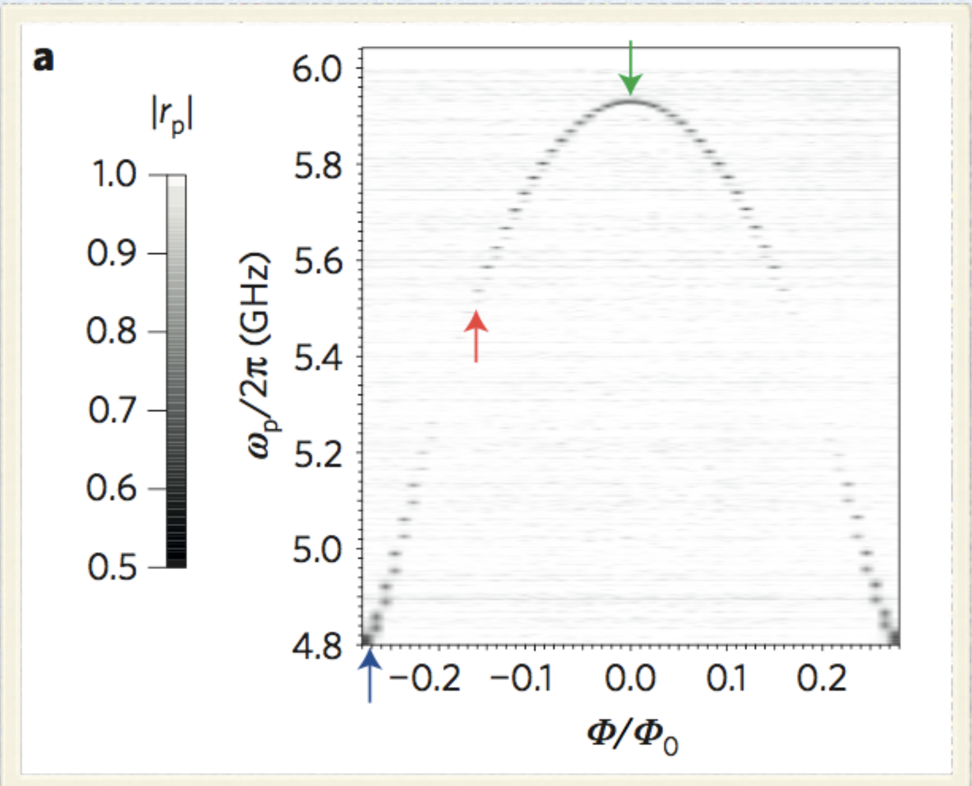


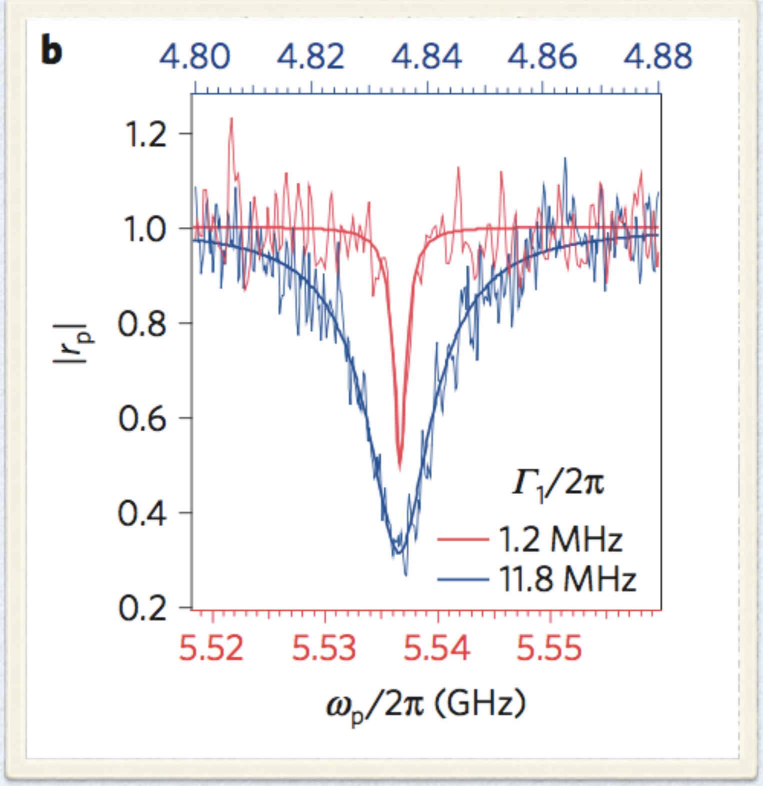
<1 due to dephasing





LOW POWER REFLECTION



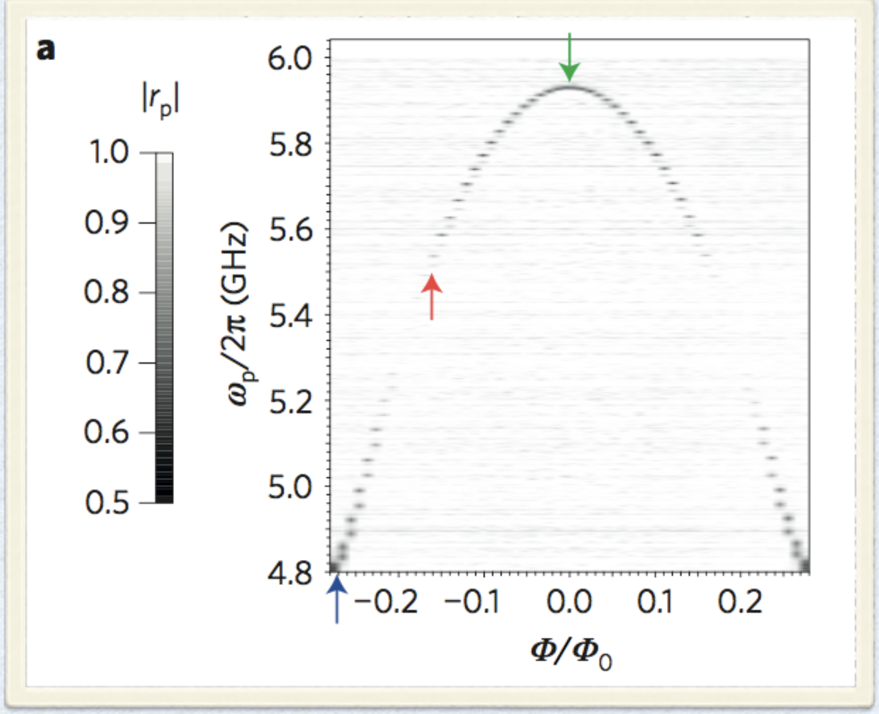


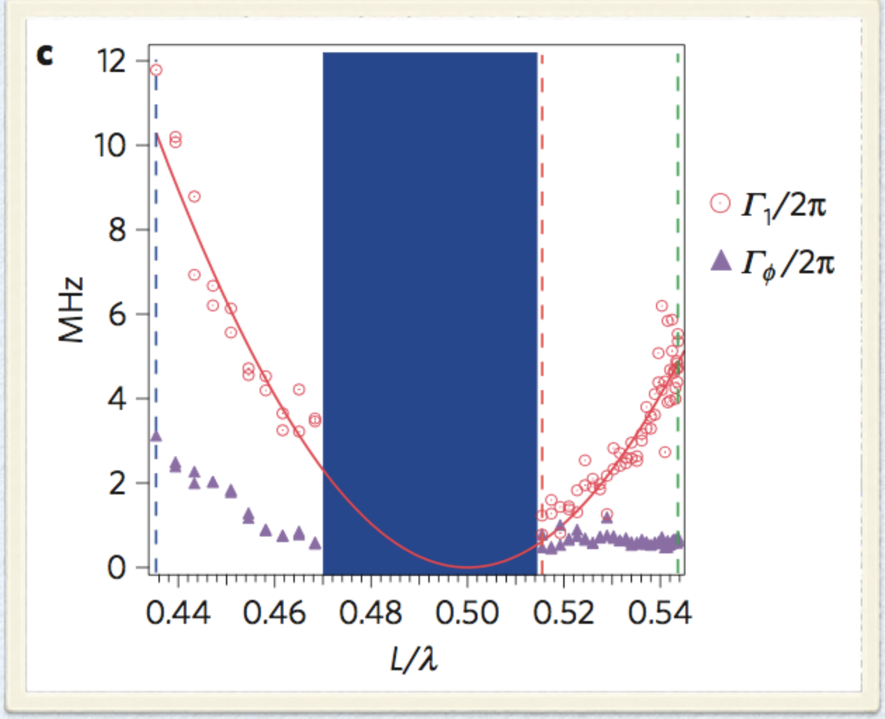
Frequency tunable with external flux

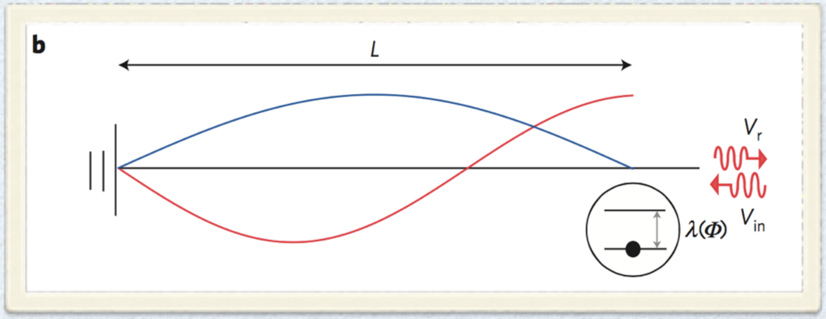
Resonance width gives atom lifetime Γ_1^{-1}

Measuring the lifetime

Measured lifetime changes a factor of 10





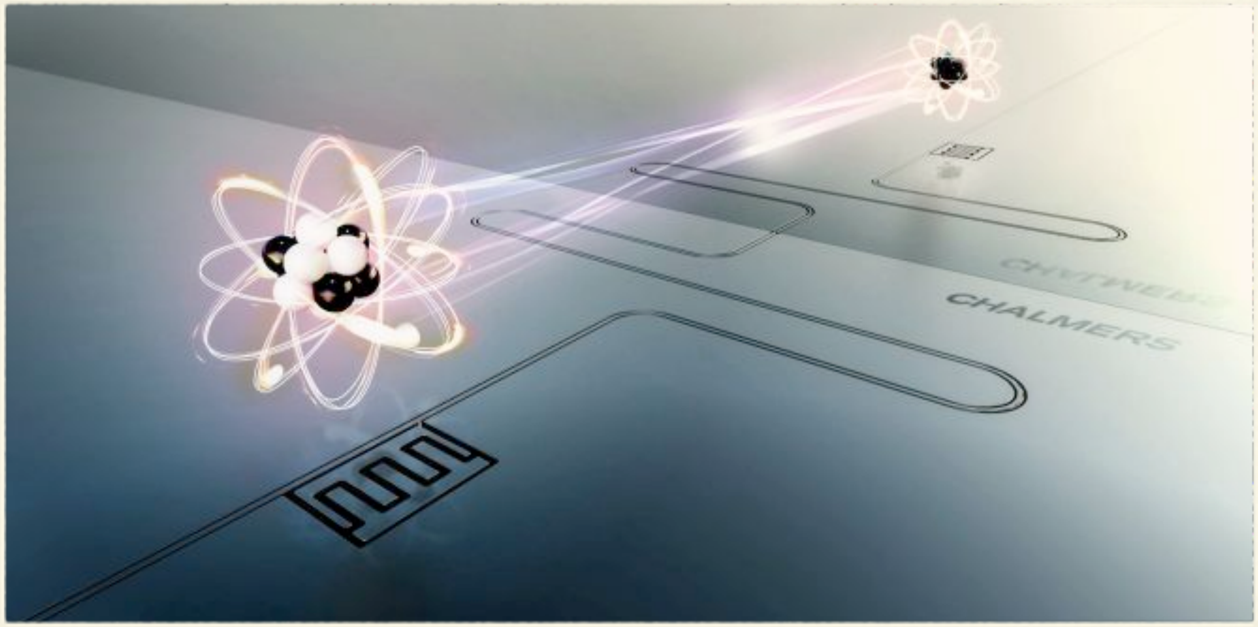


An Atom in Front of a Mirror


Io-Chun Hoi
now Taiwan


Chris Wilson
Waterloo


Per Delsing



nature physics

ARTICLES

PUBLISHED ONLINE: 28 SEPTEMBER 2015 | DOI: 10.1038/NPHYS3484

Probing the quantum vacuum with an artificial atom in front of a mirror

I-C. Hoi[1,2,3], A. F. Kockum[1,4], L. Tornberg[1], A. Pourkabirian[1], G. Johansson[1], P. Delsing[1]* and C. M. Wilson[5]*

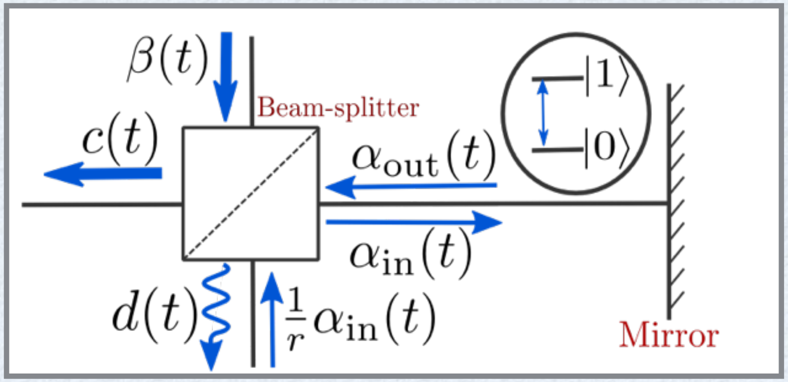

Anton
Frisk Kockum,
now RIKEN


Lars Tornberg,
now Volvo

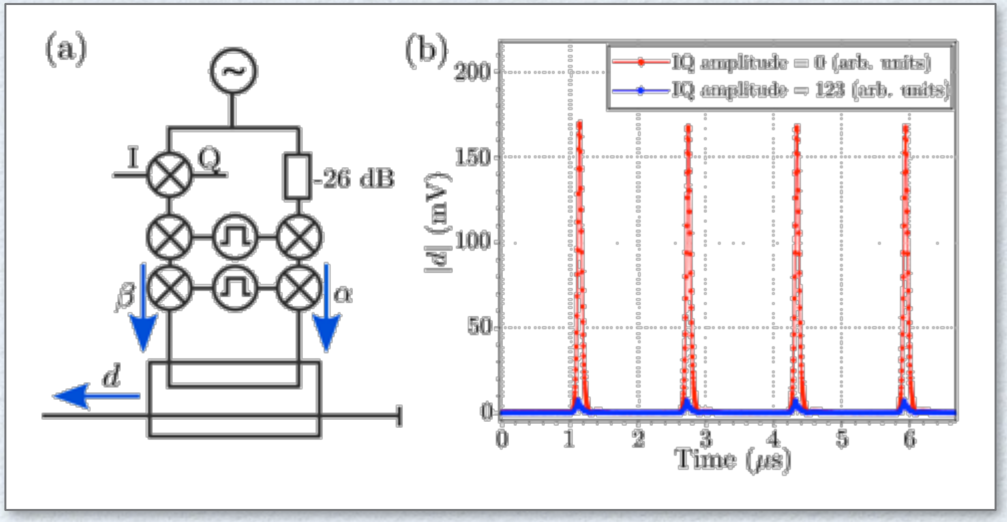
Single Photon Generator (without cavity)

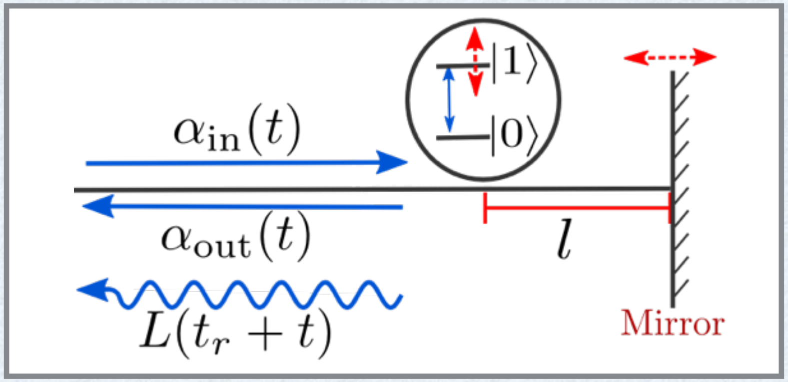
Sankar

Andreas



Cancellation of input pulse up to -34 dB





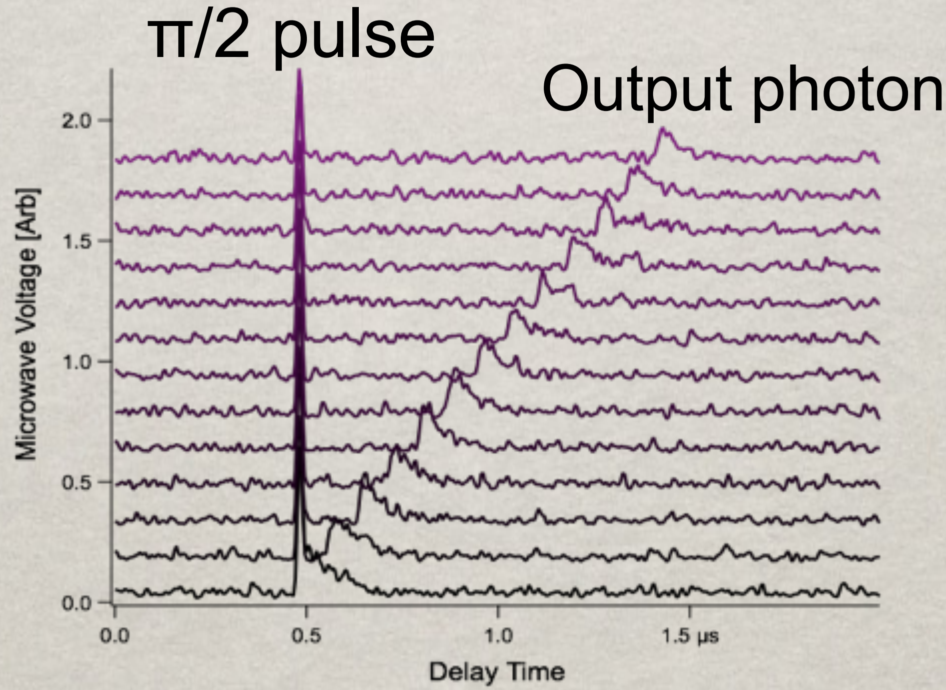
"Atom in front of a mirror"

Sankar Raman Sathyamoorthy, Andreas Bengtsson,
Steven Bens, Michaël Simoen, Per Delsing, and Göran Johansson,
Physical Review A ***93****, 063823 (2016)*

Shaped, on-demand microwave single-photon generator

P. Forn-Díaz,[1,2,3] C. W. Warren,[1] C. W. S. Chang,[1] A. M. Vadiraj,[1] and C. M. Wilson[1]

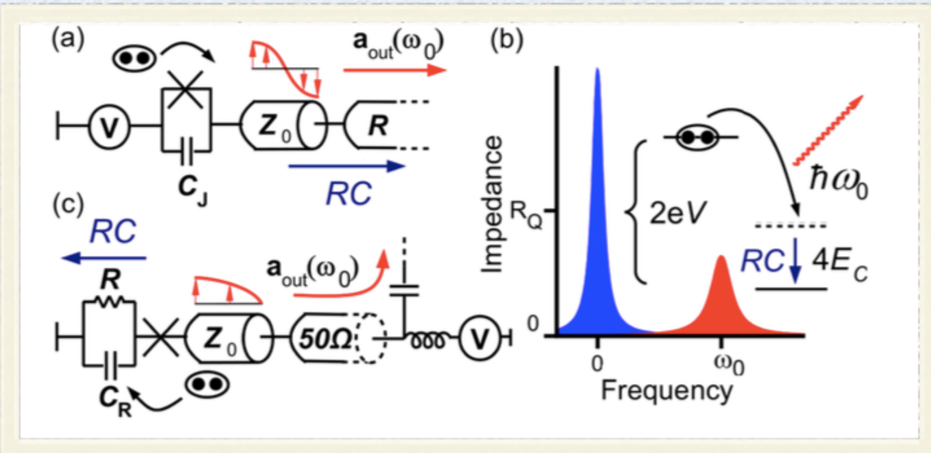
arXiv: 1706.06688

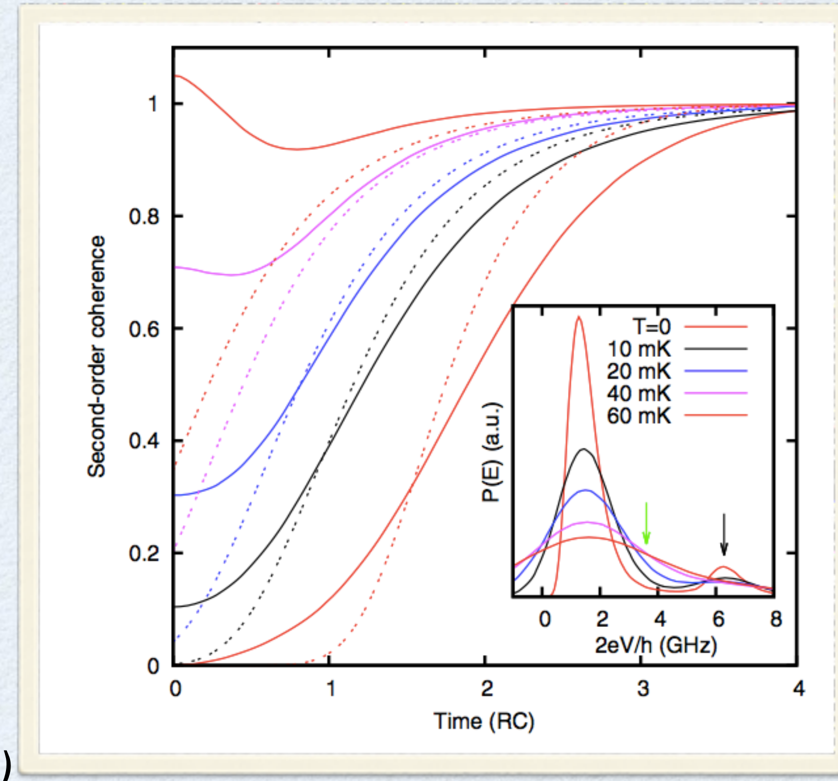


UNIVERSITY OF WATERLOO

IQC

A voltage biased Josephson junction





Juha Leppäkangas, Mikael Fogelström,
Alexander Grimm, Max Hofheinz,
Michael Marthaler, and Göran Johansson
Physical Review Letters ***115****, 027004 (2015)*

A collaboration with Karlsruhe and Grenoble.

More theory details:
Juha Leppäkangas, Mikael Fogelström, Michael Marthaler, and Göran Johansson
Physical Review B ***93****, 014505 (2016)*

How long are the photons?

100 MHz coupling strength between atom and TL

~10 ns pulse length – photon duration

The typical microwave photon is 3 meters long

(The voltage biased source could give cm-scale photons)

Quantum Optics

$v \lesssim 299792458$ m/s

10 ns = 3 m

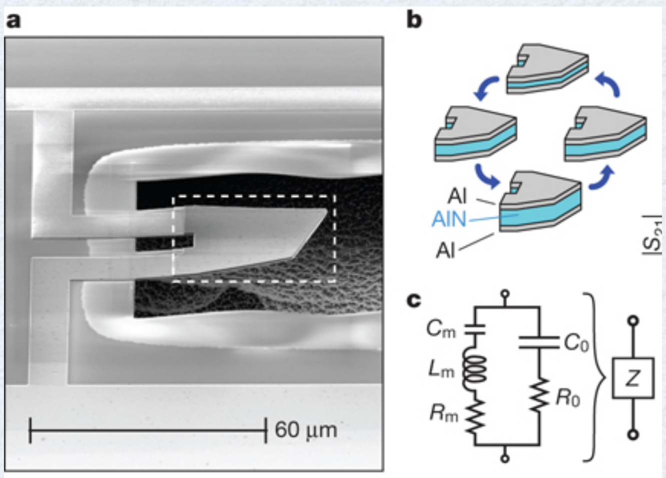
Quantum Acoustics

$v \approx 3000$ m/s

10 ns = 30 μm

Studies of Mechanical Systems at the Single Quantum Level

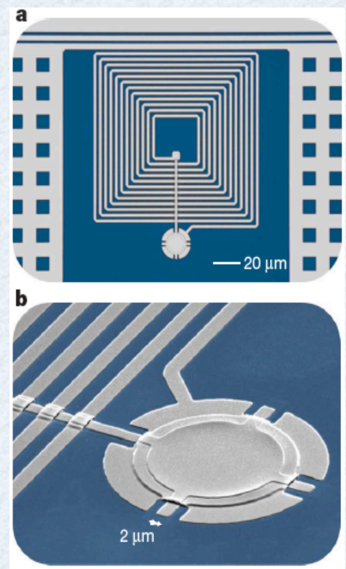
2010
First ground state macroscopic mechanical mode ~ 6 GHz



A. D. O'Connell *et al.*, Nature **464**, 697 (2010)

Piezoelectric bulk resonator
Read out by phase qubit
UCSB

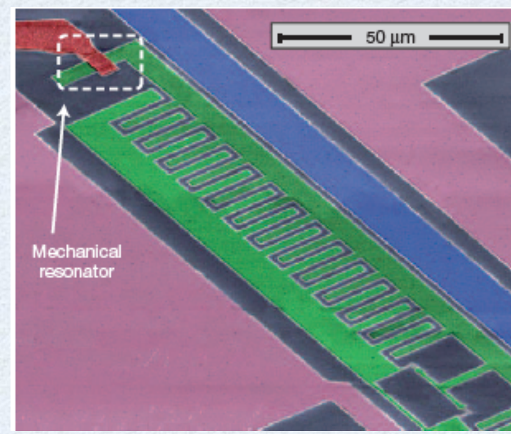
2011
First ground state cooling of low frequency mode ~10 MHz



J.D. Teufel *et al*. Nature, **471**, 204 (2011)

Drum capacitor as part of an LC-resonator
JILA

2013
Coupling a qubit to low frequency mode 10 MHz



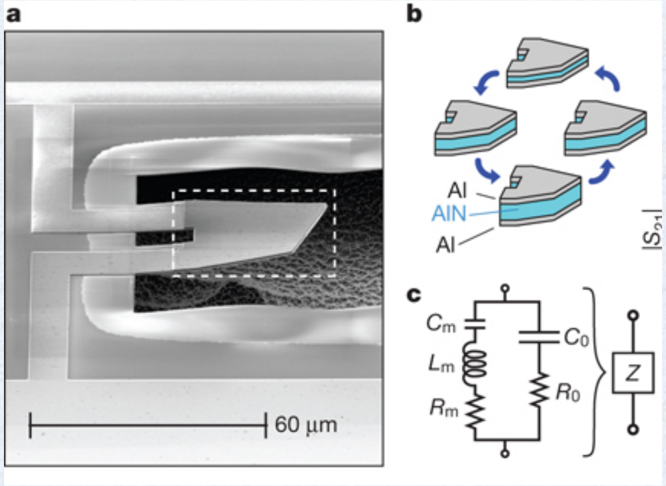
J.-M., Pirkkalainen, Nature **494**, 211 (2013)

Mechanical resonator coupled to a transmon and cavity
Helsinki

Studies of Mechanical Systems at the Single Quantum Level

These are all localized mechanical modes.
We want to investigate **propagating** modes.

2010
First ground state macroscopic mechanical mode ~ 6 GHz



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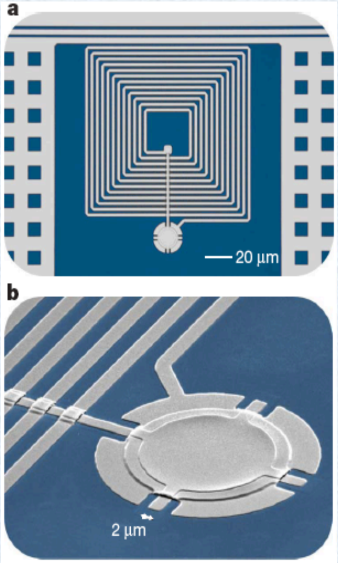

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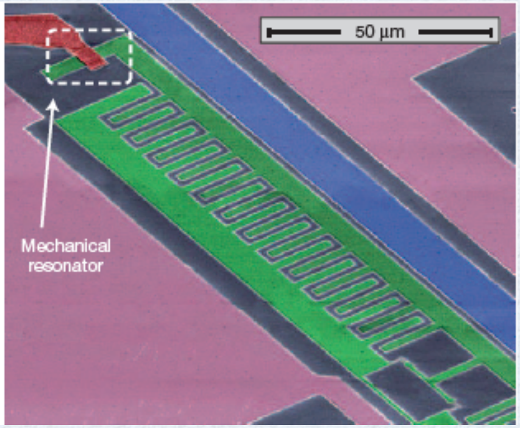

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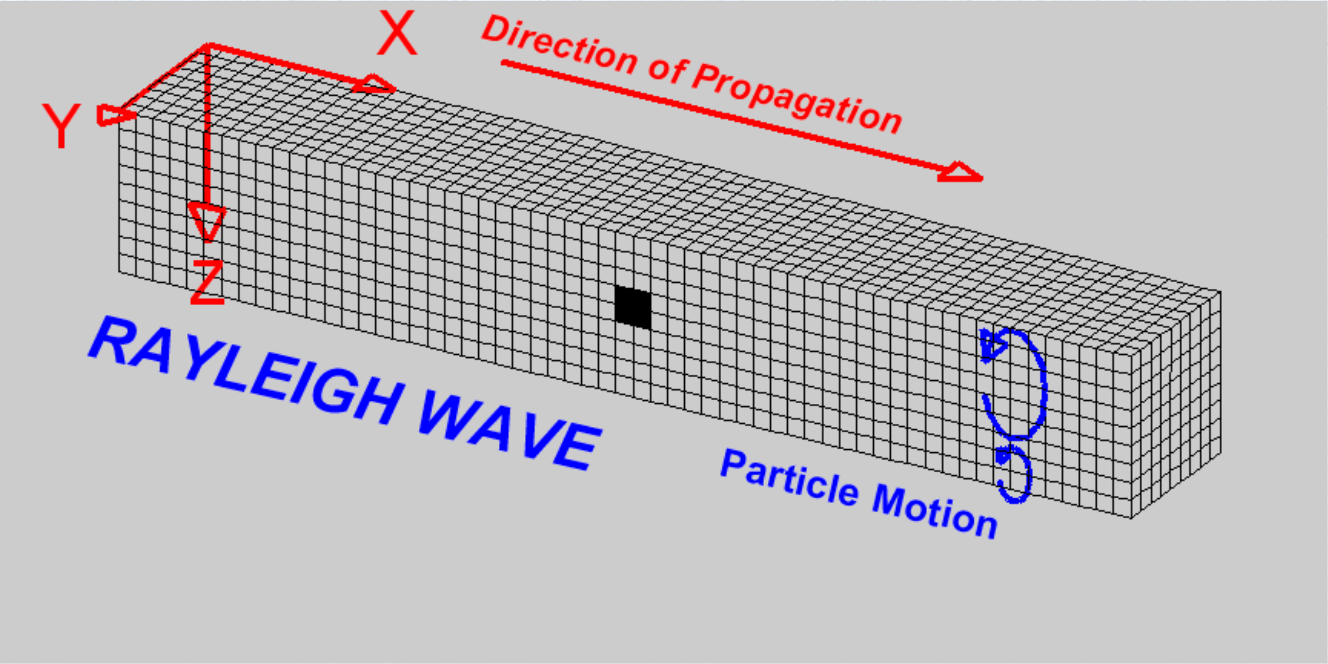
Mechanical resonator coupled to a transmon and cavity
Helsinki

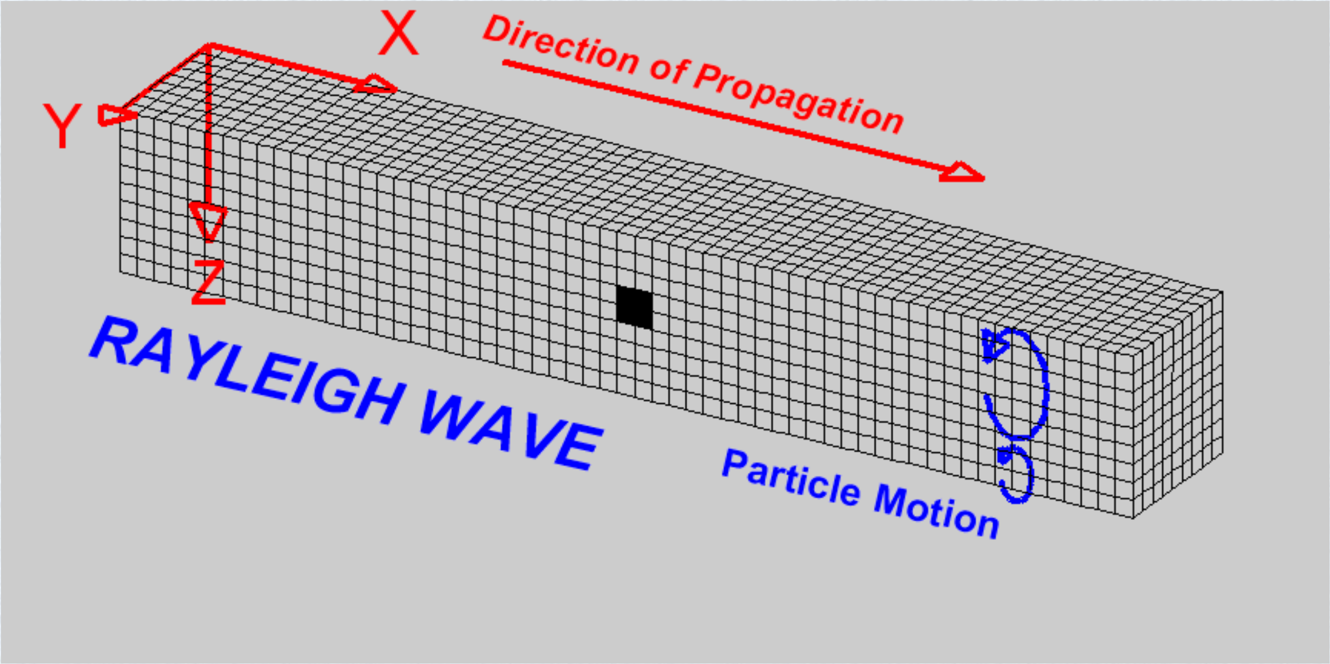
Surface Acoustic Waves (SAW)



Animation: L. Braile, Purdue University

Rayleigh, Proc. London Math. Soc., (1885)

Surface Acoustic Waves (SAW)



Animation: L. Braile, Purdue University

Rayleigh, Proc. London Math. Soc., (1885)

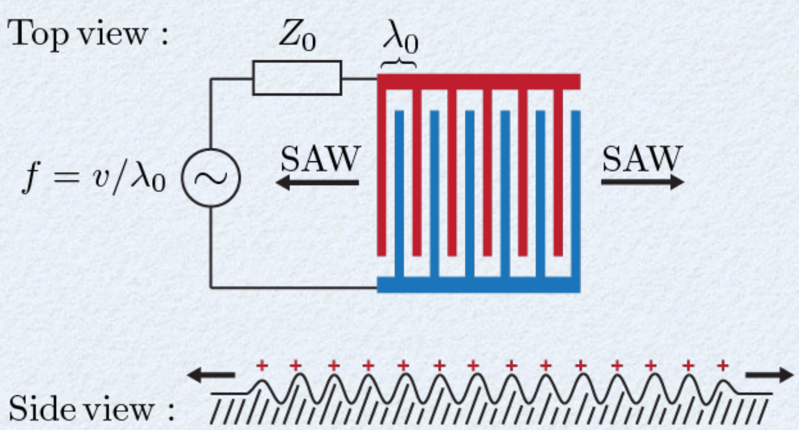
Generating and detecting SAW with an IDT

- Piezoelectric substrate (**GaAs**, quartz, $LiNbO_3$…)
- Propagation speed: v ≈ 3000 m/s
- $f \approx 5$ GHz, $\lambda \approx 600$ nm

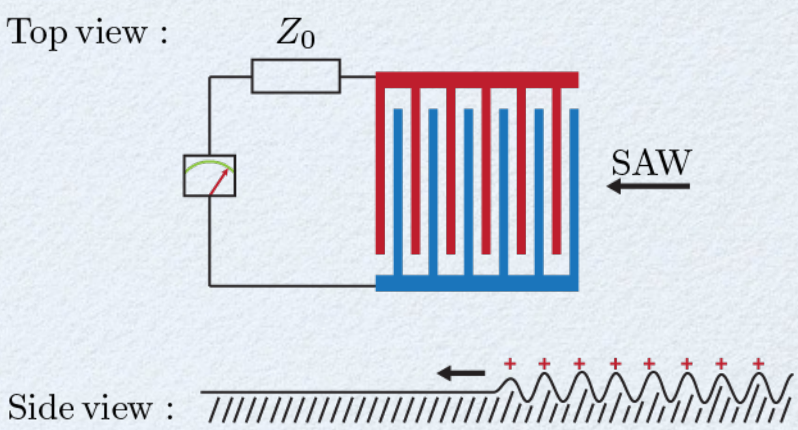
Used for delay lines and to fit band pass filters on-chip.

- Generator and receiver:

The Interdigital Transducer (IDT)

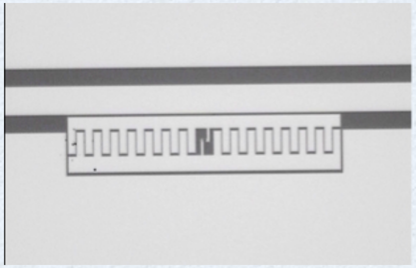


Datta, *Surface Acoustic Wave devices*, 1986

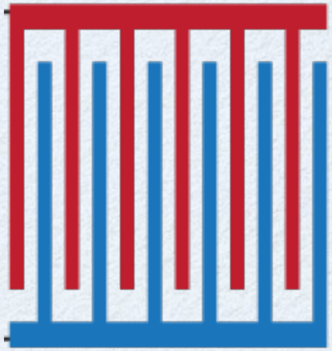


Morgan, *Surface acoustic wave filters*, 2007

Coupling SAW to a transmon

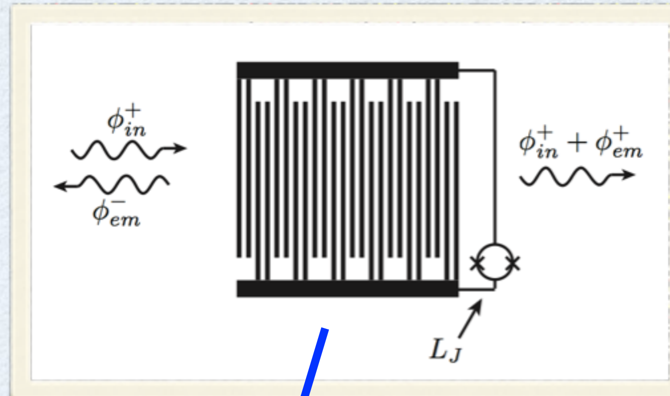


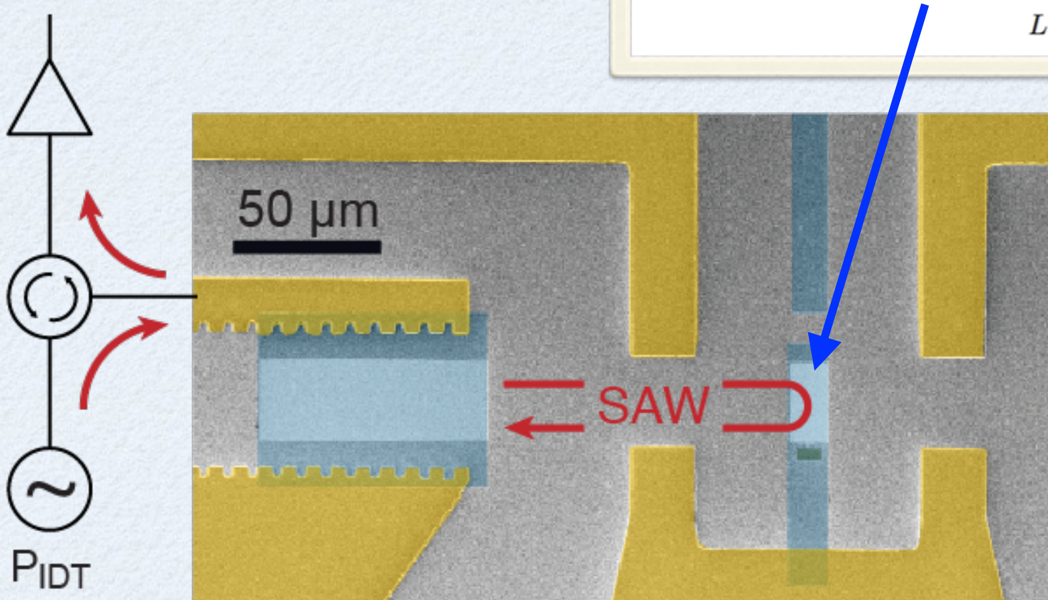
$\approx$



Superconducting atom + surface acoustic waves

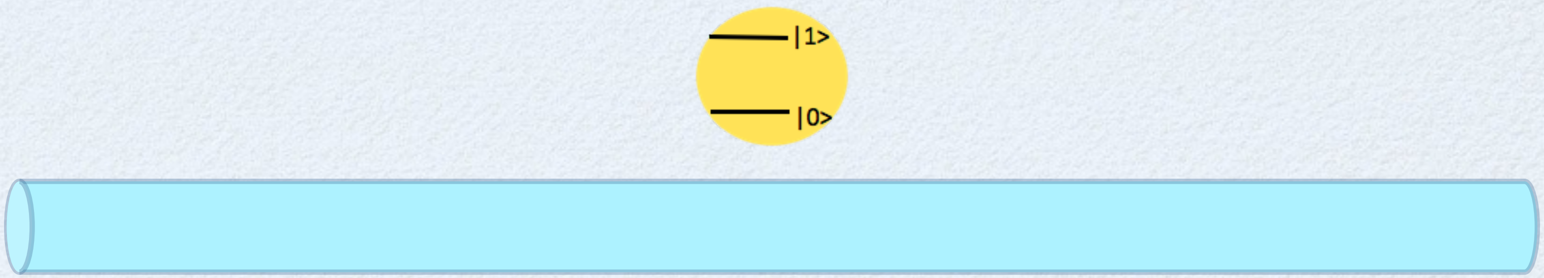
Transmon frequency: ~4.8 GHz
Coupling: 38 MHz
SAW wavelength 600 nm
Transmon size: 20 wavelengths
Negligible dephasing



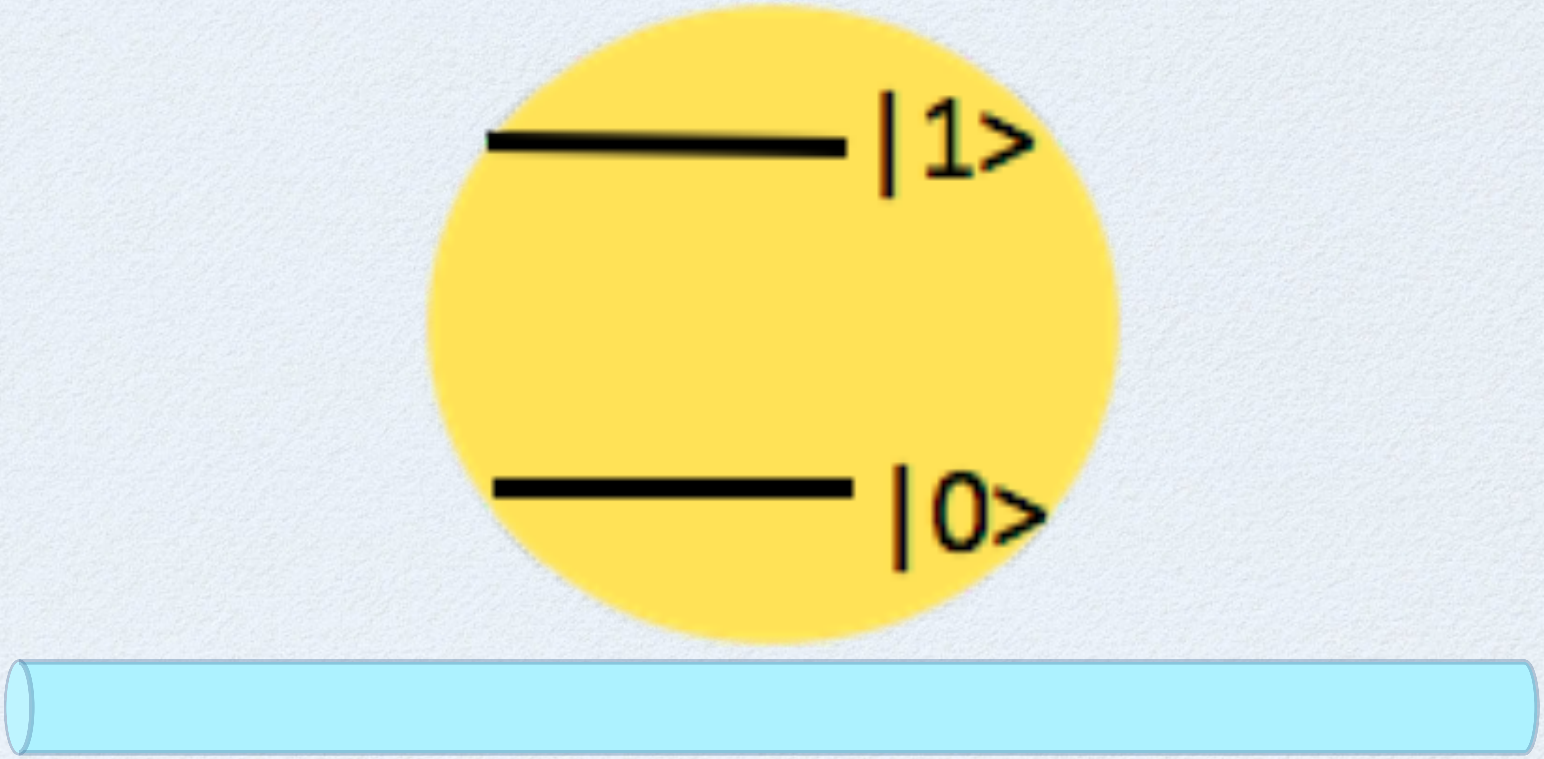


Martin V. Gustafsson, Thomas Aref, Anton Frisk Kockum, Maria K. Ekström, Göran Johansson, Per Delsing, *Science* **346**, 207 (2014)

The Giant Atom



THE GIANT ATOM

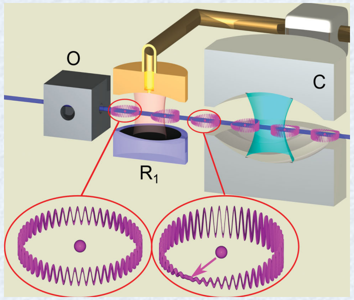


Typical atom sizes vs light wavelength

Atom, optical light

$$r \approx 10^{-10}\,\mathrm{m}$$
$$\lambda \approx 10^{-8} - 10^{-7}\,\mathrm{m}$$

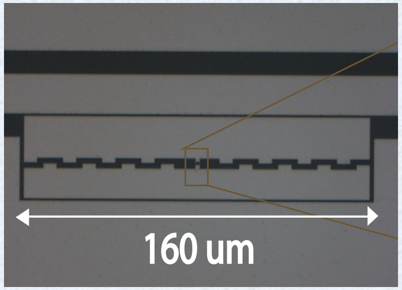
Rydberg atom, microwaves



$$r \approx 10^{-8} - 10^{-7}\,\mathrm{m}$$
$$\lambda \approx 10^{-3} - 10^{-1}\,\mathrm{m}$$

Haroche, Nobel Lecture, RMP (2013)

Transmon, microwaves

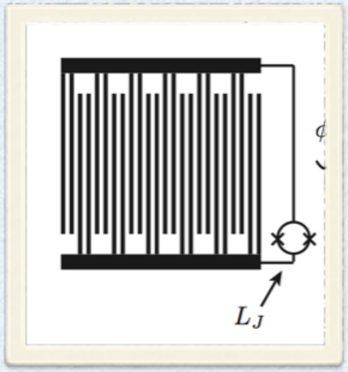


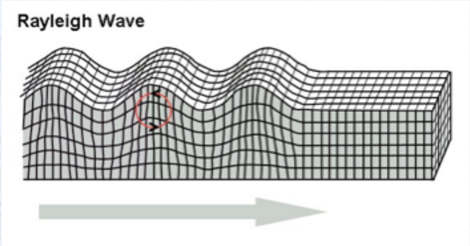
Picture by I.-C. Hoi

$$l \approx 10^{-5} - 10^{-4}\,\mathrm{m}$$
$$\lambda \approx 10^{-3} - 10^{-1}\,\mathrm{m}$$

Transmon, surface acoustic waves

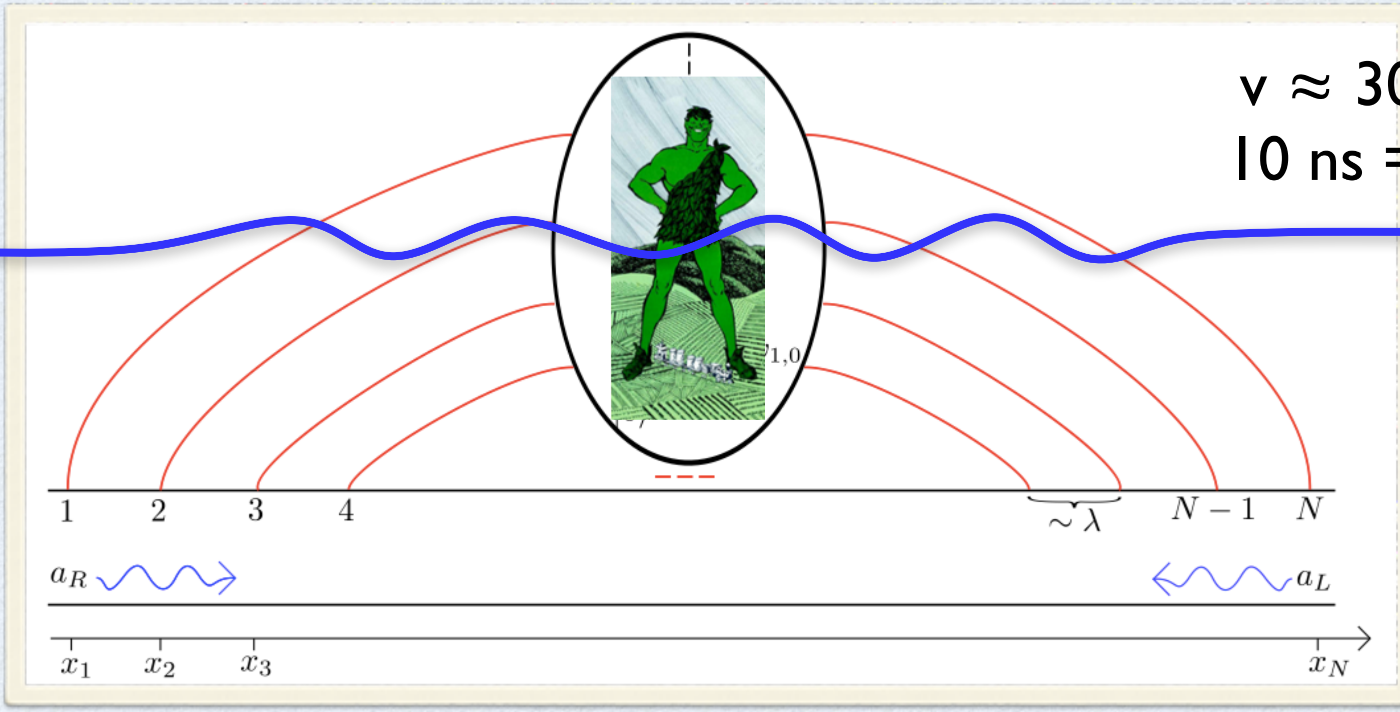
$$l \approx 10^{-5} - 10^{-4}\,\mathrm{m}$$
$$\lambda \approx 10^{-6}\mathrm{m}$$





Martin V. Gustafsson, Thomas Aref, Anton Frisk Kockum, Maria K. Ekström, Göran Johansson, Per Delsing, Science **346**, 207 (2014)

Interference of spontaneous emission



v ≈ 3000 m/s
10 ns = 30 μm

Interference from many emission points – antenna theory
Frequency dependent coupling

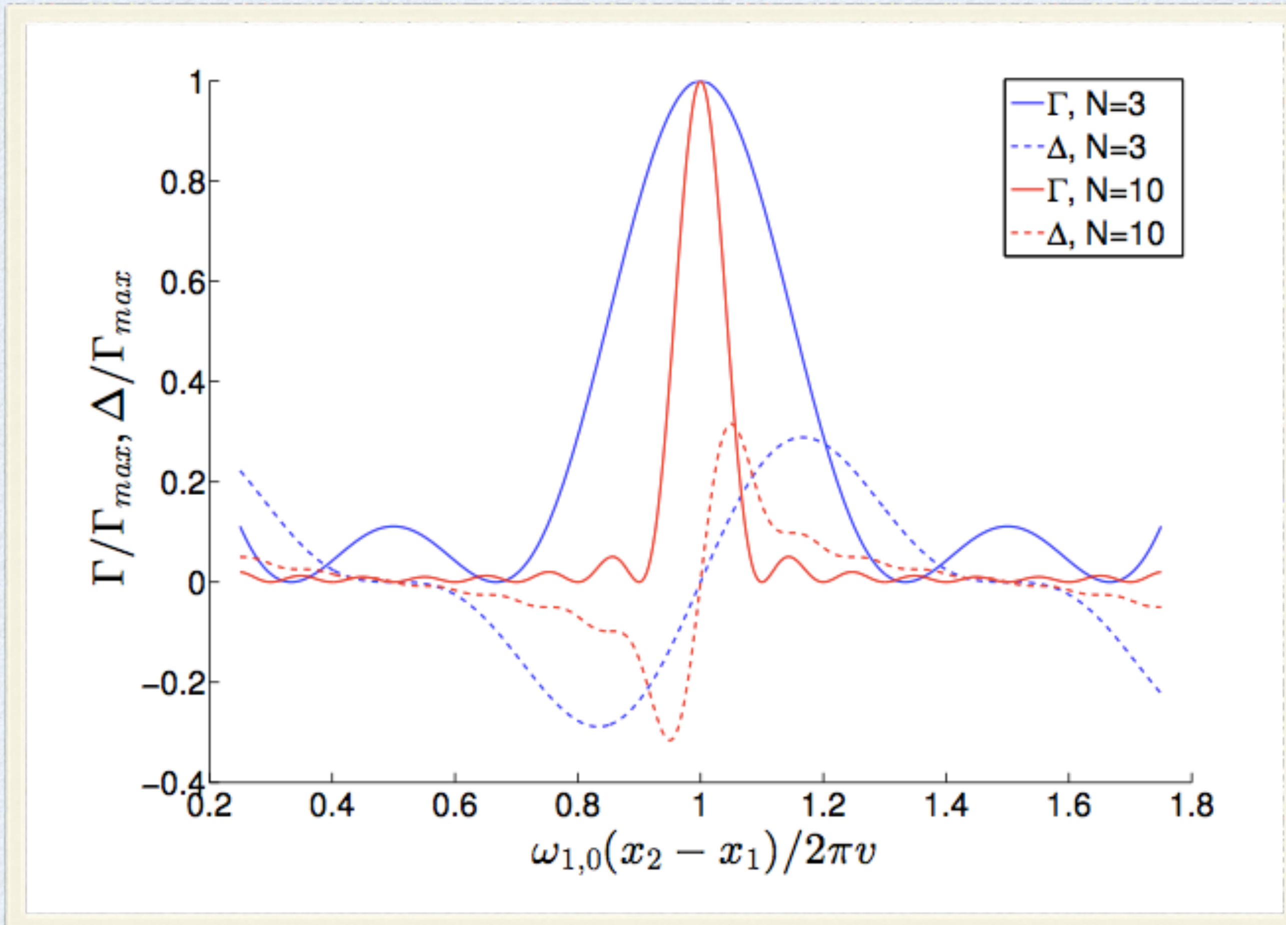
$$\phi_k = \omega_{1,0}(x_{k+1} - x_k)/v$$

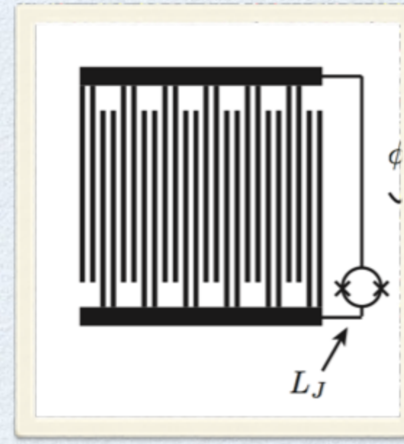
weak coupling: $\omega \approx \omega_{1,0}$

$$\Gamma_{1,0} = \left| \sum_{k=1}^{N} \sqrt{\gamma_k} \exp\left(i \sum_{j=1}^{k-1} \phi_j \right) \right|^2$$

Anton Frisk Kockum, Per Delsing, Göran Johansson, PRA (2014)

Atom with tunable coupling



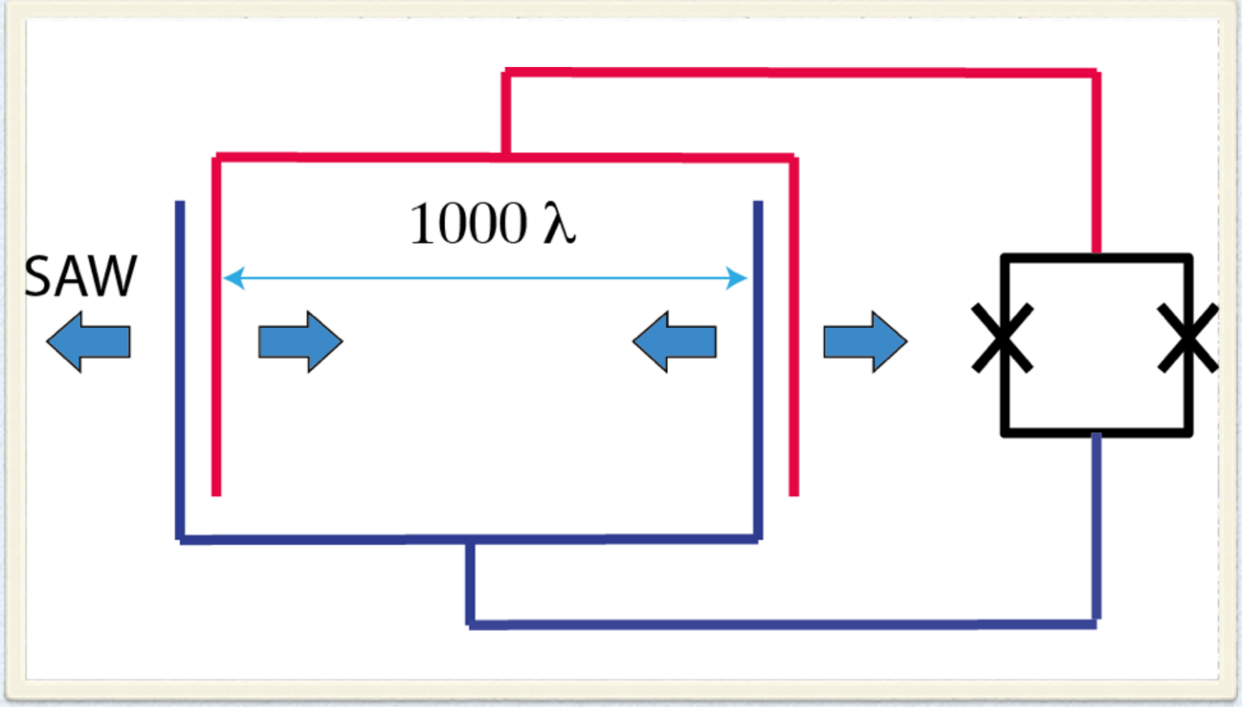


Tune atom frequency by changing the magnetic flux through the SQUID

Decay rate and Lamb shift depends on the detuning between the atom and the IDT

Anton Frisk Kockum, Per Delsing, Göran Johansson, PRA (2014)

Phonons – shorter than one atom



Delay time

$$T = 1000\frac{\lambda}{v}$$

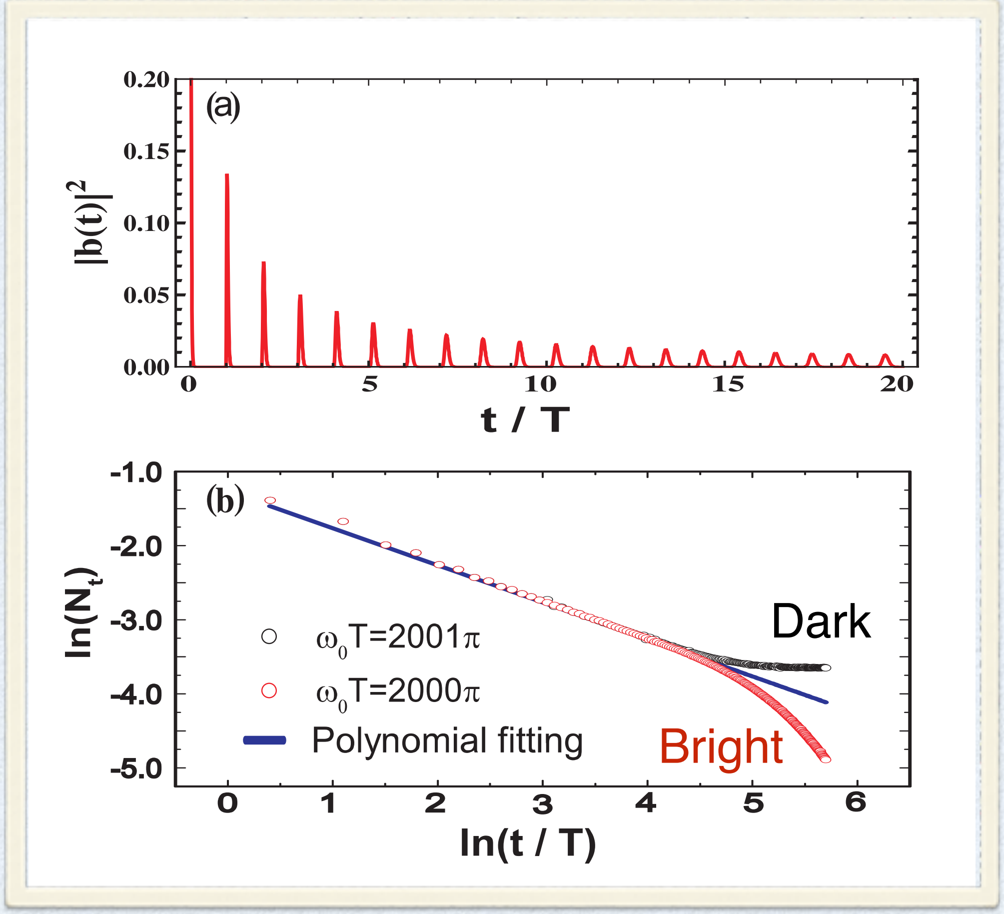
Decay in one point faster than the delay

$$T > \frac{1}{\gamma}$$

L. Guo, A. Grimsmo, A. F. Kockum, M. Pletyukhov, G. Johansson, PRA 95, 053821 (2017) [ Editor's suggestion]

See also: Dorner & Zoller PRA (2002) and Pichler & Zoller PRL (2016) (Atom in front of a mirror, at long distance.)

Polynomial spontaneous emission with delay and revivals



$$E(t) \approx E(0)\frac{1}{2\sqrt{\pi}}\left(\frac{t}{T}\right)^{-1/2}$$

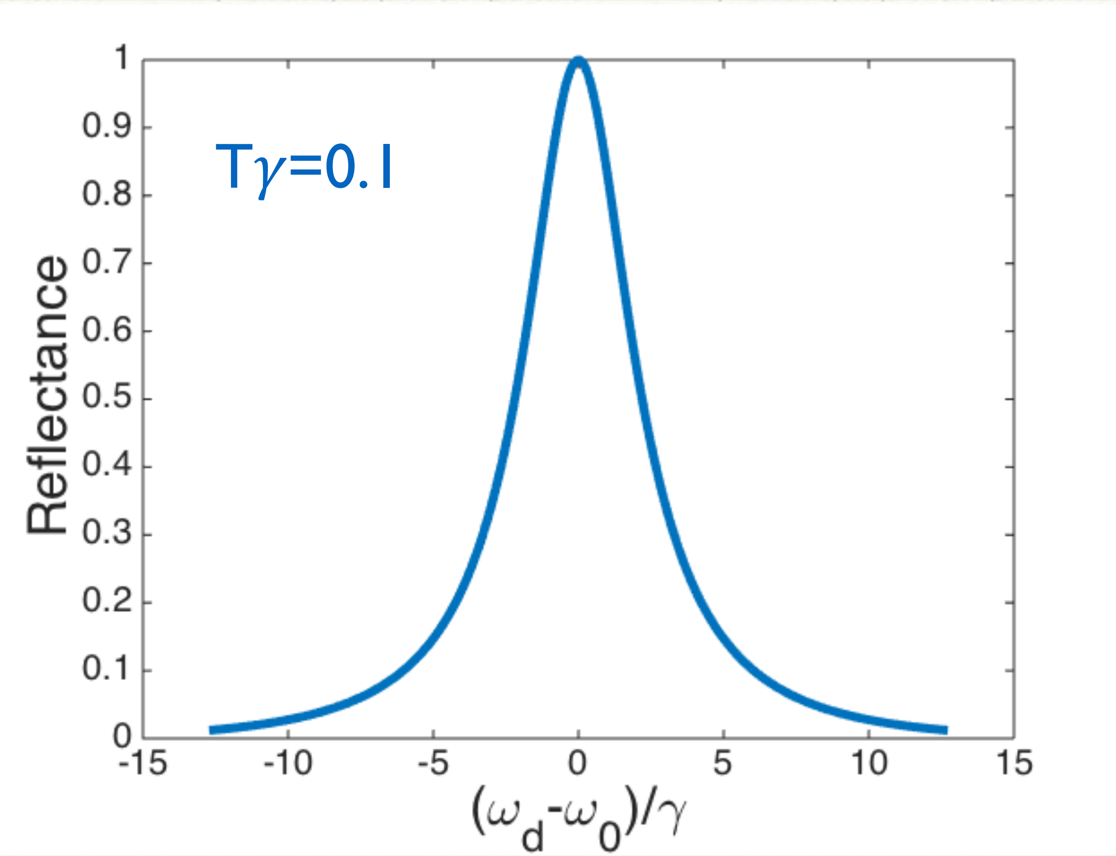
No dependence on γ (!)

Lingzhen Guo
Now in Karlsruhe

L. Guo, A. Grimsmo, A. F. Kockum, M. Pletyukhov, G. Johansson, PRA 95, 053821 (2017) [Editor's suggestion]

Reflectance (weak driving)

$$\mathcal{R} = \frac{\gamma^2(1+\cos\omega_d T)^2}{[(\omega_d-\omega_0)-\gamma\sin\omega_d T]^2+\gamma^2(1+\cos\omega_d T)^2}$$



Full reflection:

$$\omega_d = \omega_0 + \gamma\sin(\omega_d T)$$

No reflection:

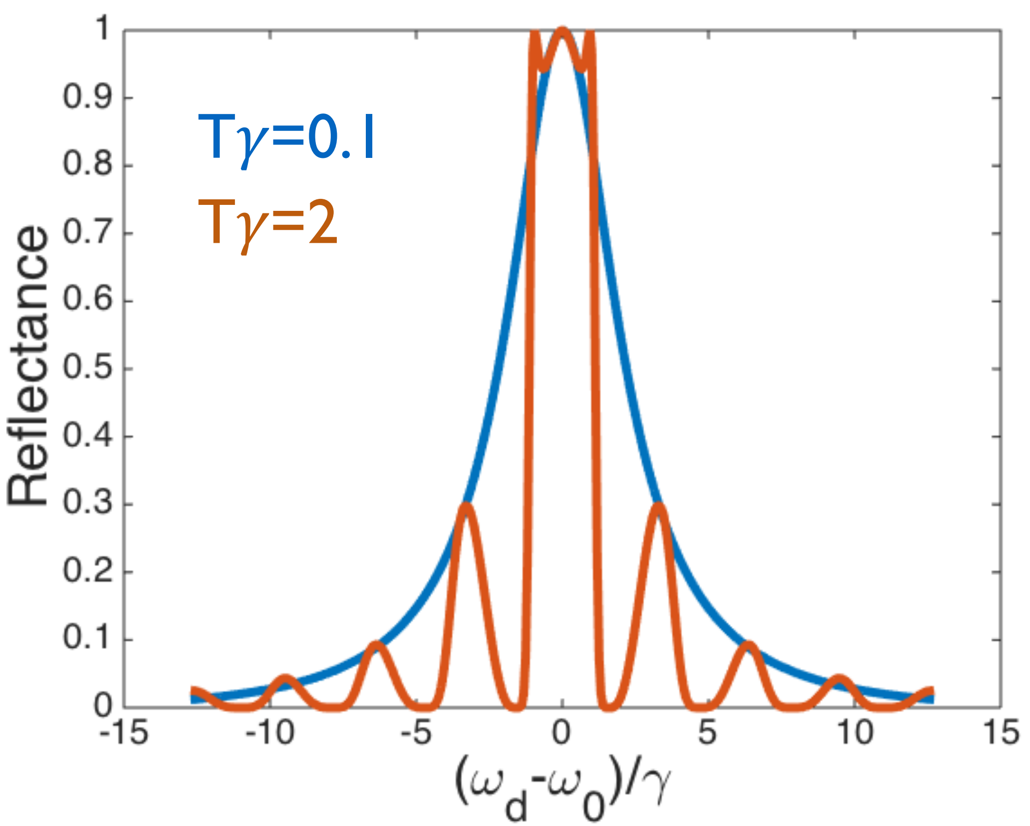
$$\omega_d T = (2n+1)\pi$$

Dark state:

$$\omega_0 T = (2n+1)\pi$$

Reflectance (weak driving)

$$\mathcal{R} = \frac{\gamma^2(1+\cos\omega_d T)^2}{[(\omega_d - \omega_0) - \gamma\sin\omega_d T]^2 + \gamma^2(1+\cos\omega_d T)^2}$$



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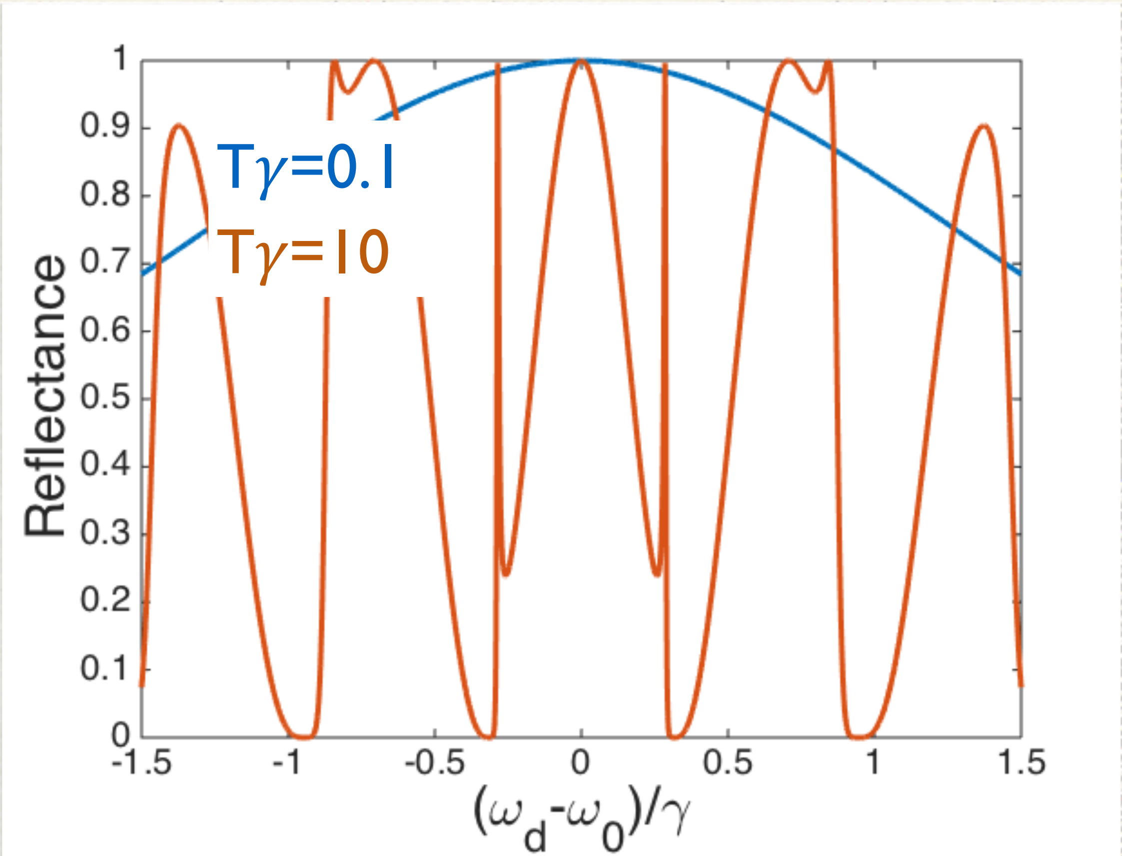

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$$\omega_d T = (2n+1)\pi$$

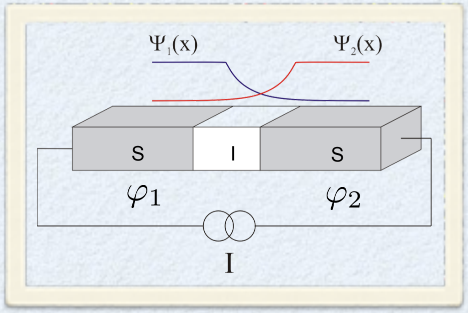
Dark state:

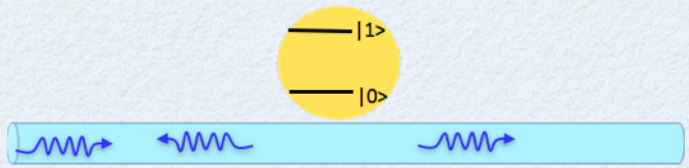
$$\omega_0 T = (2n+1)\pi$$

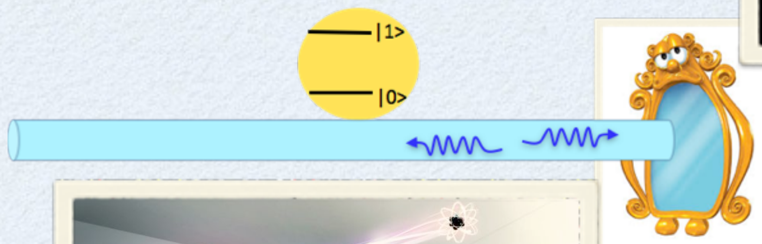
SUMMARY

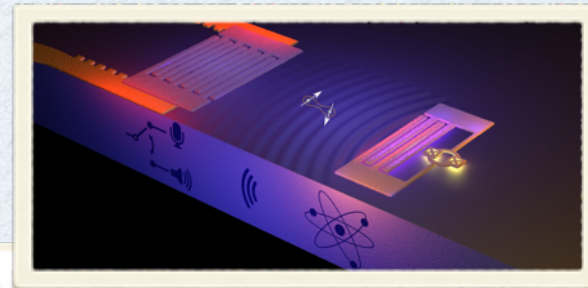
- **Artificial Atom(s) in open 1D transmission lines:**
  - Strong stable coupling of an artificial atom to a 1D transmission line
  - Antibunching in the reflected field - non-classical microwaves
  - Probing the vacuum fluctuations in front of a mirror Changing the lifetime 10 times
  - Single photon sources without cavities
  - Coupling to SAW gives a giant atom
  - Two-legged atom has non-exponential decay

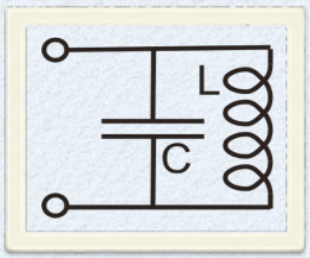
Thank you for your attention!

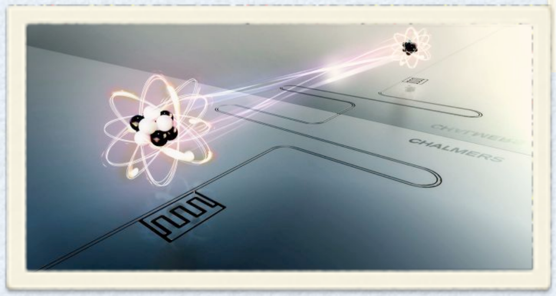


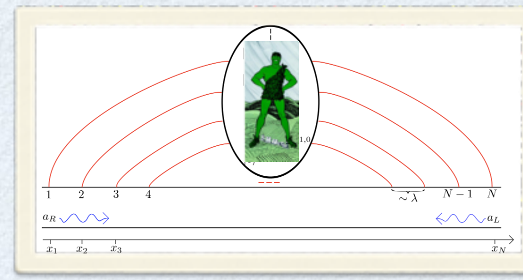


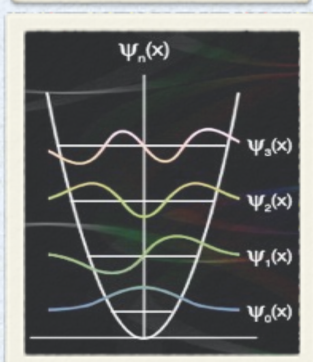












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Mesoscopic transport and quantum coherence
5-8th of August 2017, Espoo, Finland