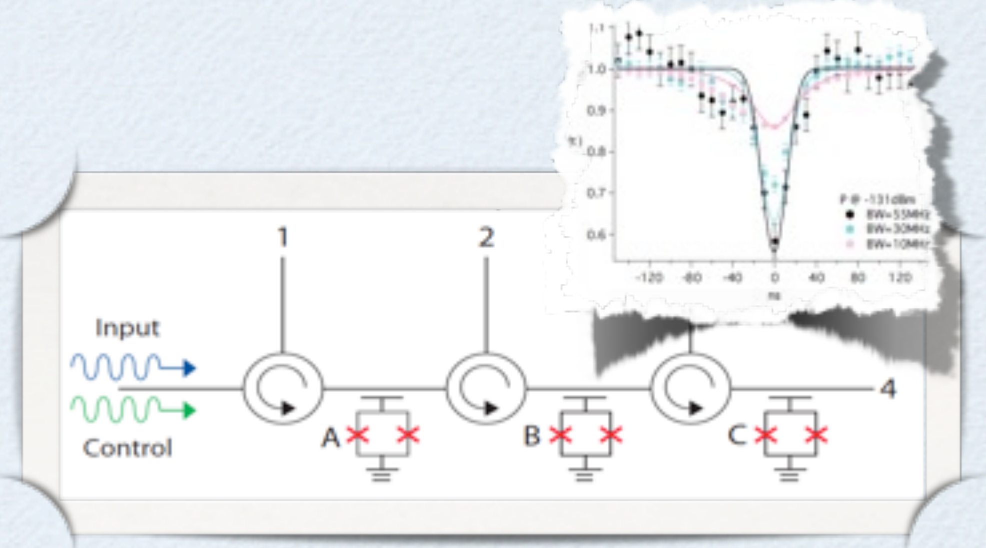
Controlling Quantum Physics

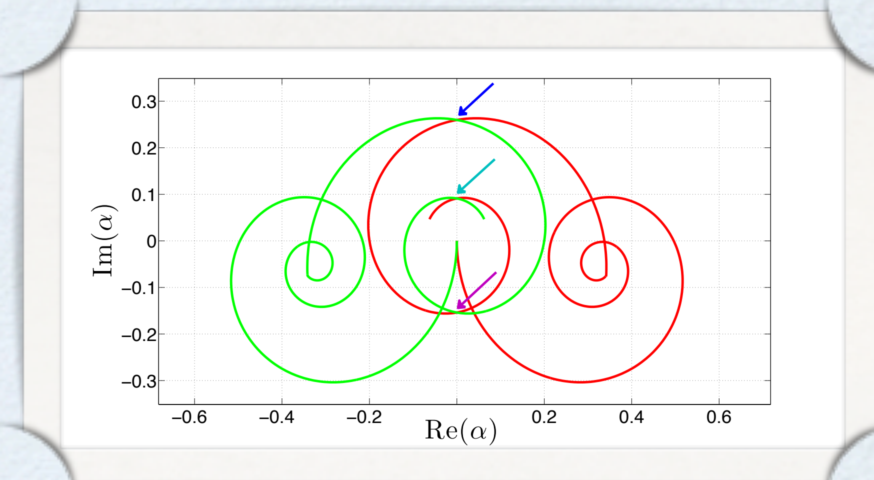
in Superconducting Circuits

Göran Johansson
Chalmers University of Technology

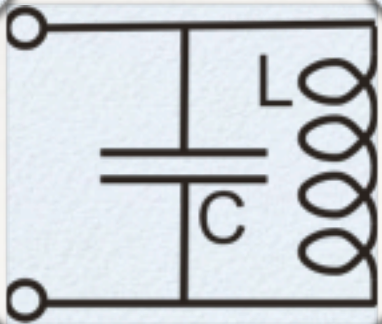
KITP workshop on
Control of Complex Quantum Systems
10th of January 2013



Photon Routing, Anti-bunching and Parity Measurement



Quantum Mechanics and Electrical Circuits

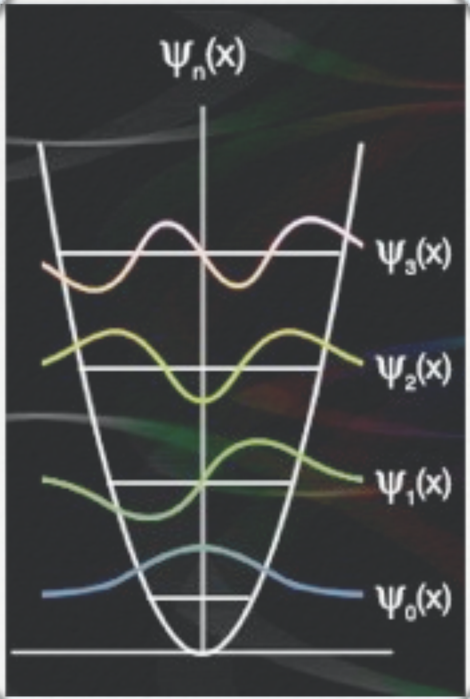


An LC-oscillator in the microwave regime

f=5 GHz --> hf / k_B = 240 mK

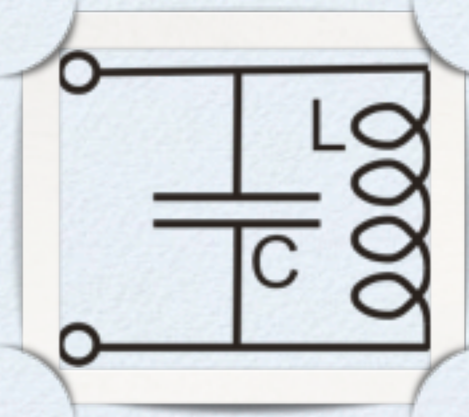
Low temperatures needed!

(300 K --> 6.3 THz)



A QM harmonic oscillator:
- Quantized Amplitudes
- Zero point motion

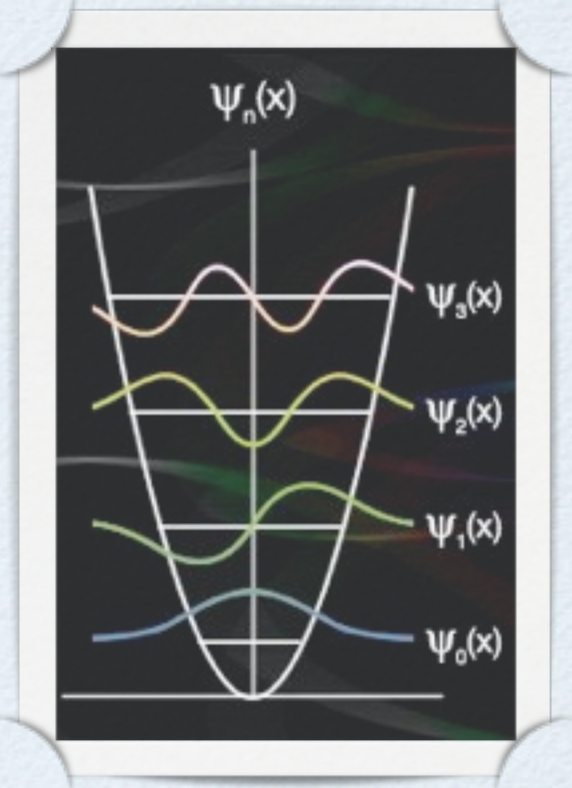
Quantum Mechanics and Electrical Circuits



An LC-oscillator in the microwave regime

Low temperatures – also with microwave equipment installed

Resistance / dissipation gives level broadening -> Minimize dissipation!



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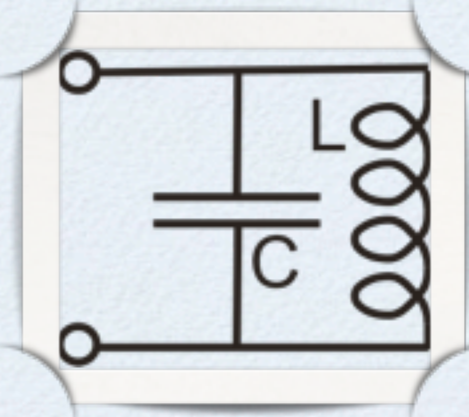
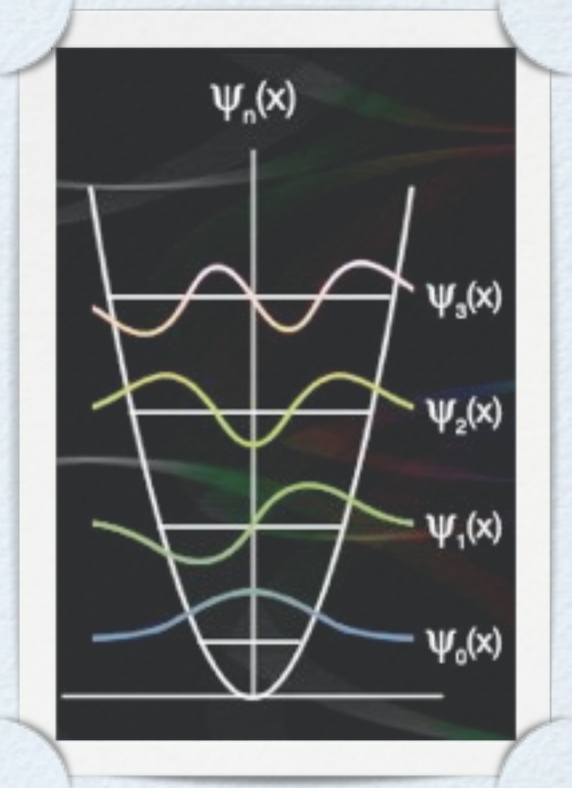


An LC-oscillator in the microwave regime

Low temperatures – also with microwave equipment installed

Resistance / dissipation gives level broadening -> Minimize dissipation!

Nonlinearity needed for quantum effects in average quantities.



A QM harmonic oscillator:
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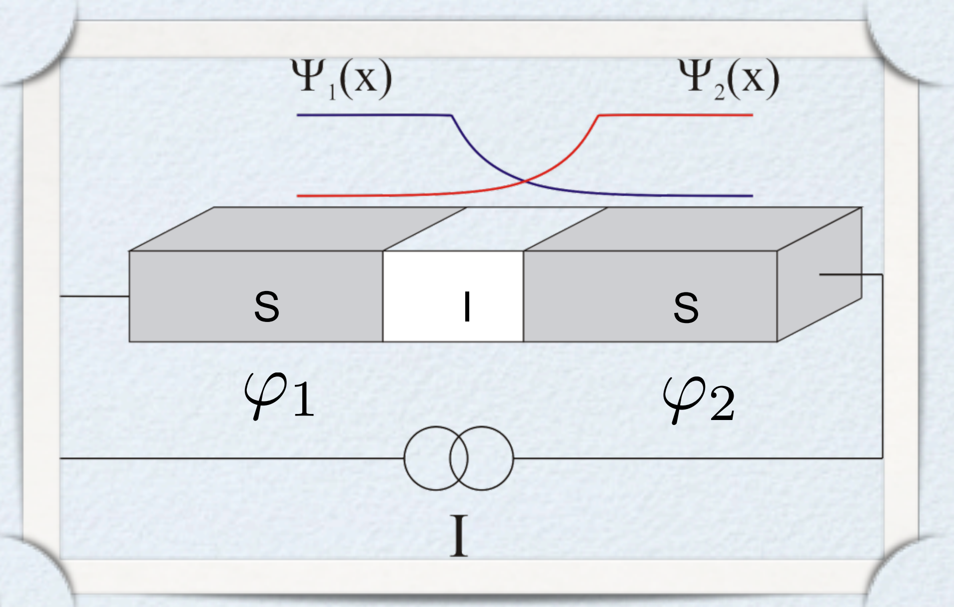
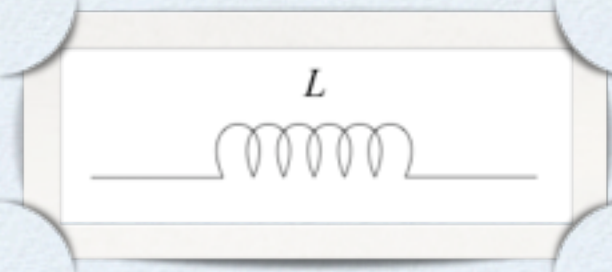
THE JOSEPHSON JUNCTION

- Tunnel junction between superconductors
- Current determined by phase difference of wave function on each side
- A nonlinear (almost) dissipationless inductor



Inductor:



$$V = L\,\dot{I}$$

$$I = \frac{1}{L}\int V\,dt' = \frac{\Phi}{L}$$

Josephson Junction:

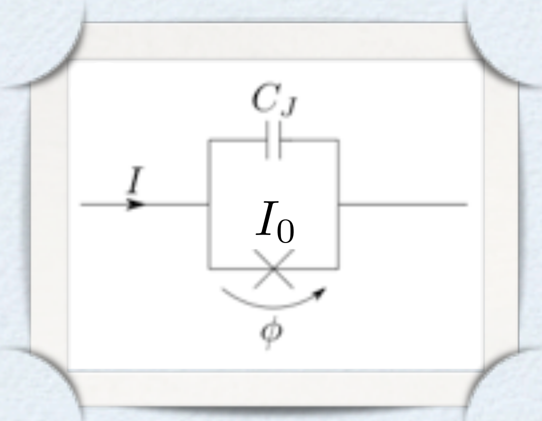
$$I = I_0 \sin\left(2\pi\frac{\Phi}{\Phi_0}\right)$$

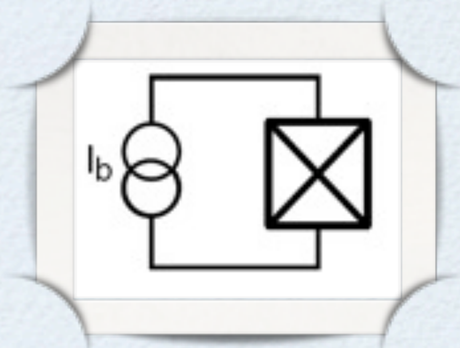
$$\Phi = \varphi_2 - \varphi_1 \qquad \Phi_0 = \frac{h}{2e}$$

Electrical circuits -> Classical mechanics

Simplest circuit: A current biased Josephson junction

Josephson junction





$$I_b = I_0 \sin\left(2\pi \frac{\Phi(t)}{\Phi_0}\right) + C_J \ddot{\Phi}(t)$$

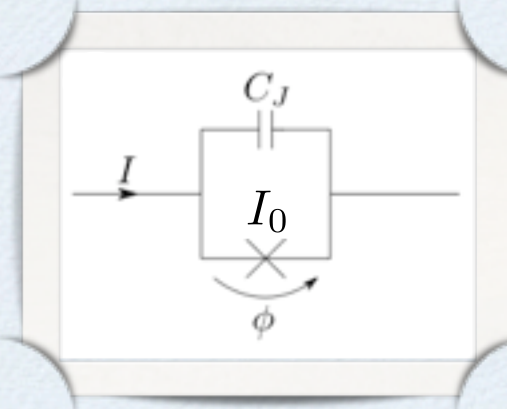
Kirchoff's rules <->

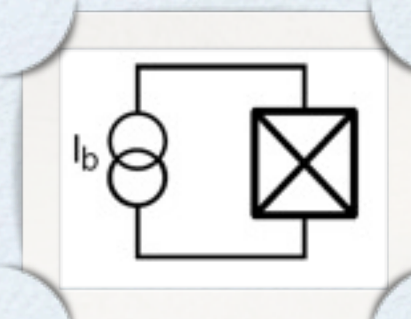
Dynamics of a fictitious phase particle with coordinate φ and mass C_J moving in a "tilted washboard" potential

Electrical circuits -> Classical mechanics

Simplest circuit: A current biased Josephson junction

Josephson junction





$$C_J \ddot{\Phi} = I_b - I_0 \sin\left(2\pi \frac{\Phi(t)}{\Phi_0}\right)$$

Kirchoff's rules <->

Dynamics of a fictitious phase particle with coordinate φ and mass C_J moving in a "tilted washboard" potential

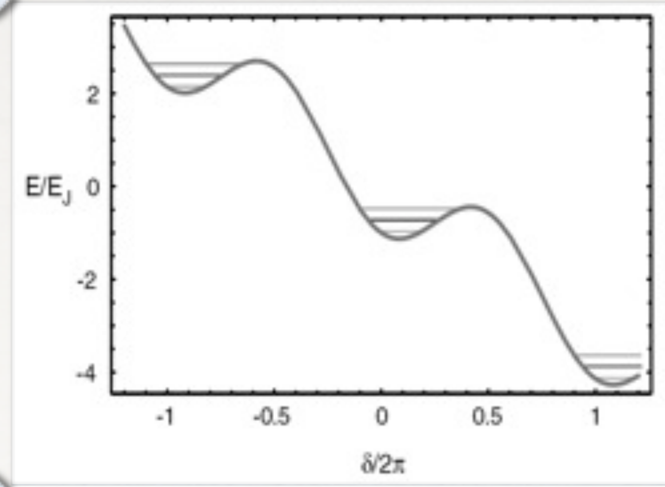
Classical Mechanics -> Quantum Mechanics

Eqs of motion -> Lagrangian -> Hamiltonian

Kinetic energy $$K(\Phi) = \frac{1}{2} C_J \dot{\Phi}^2$$

Potential energy

$$U(\Phi) = -I\Phi + E_J \left[\cos\left(2\pi \frac{\Phi}{\Phi_0} \right) - 1 \right]$$



Lagrangian $$L = K - U$$

Canonical momentum $$p = \frac{\partial L}{\partial \dot{\Phi}}$$

$$E_J = \frac{\Phi_0}{2\pi} I_0$$

Hamiltonian $$H = \frac{\partial L}{\partial \dot{\Phi}} \dot{\Phi} - L = \frac{p^2}{2C_J} + U(\Phi)$$

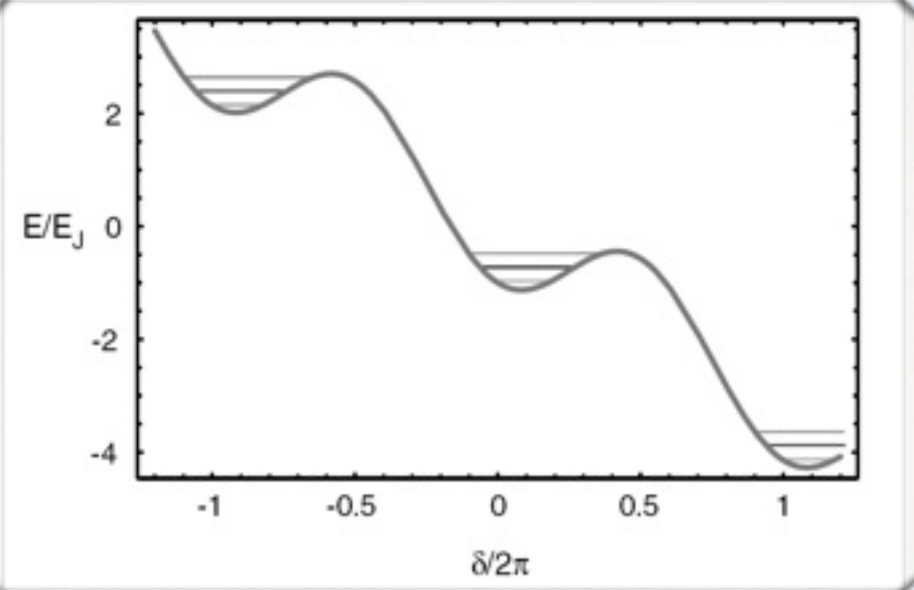
Canonical quantization $$[\Phi, p] = i\hbar$$

Classical -> Quantum

Quantum Network Analysis:
Yurke and Denker PRA 1984
Devoret, Les Houches 1997

Quantum Mechanics and Electrical Circuits

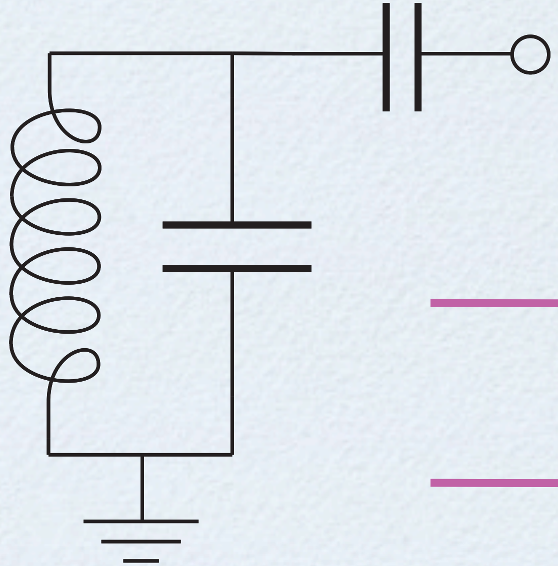
The quantum description ***is relevant***.
MQT experiment:
Devoret, Martinis, Clarke, PRL (1985)

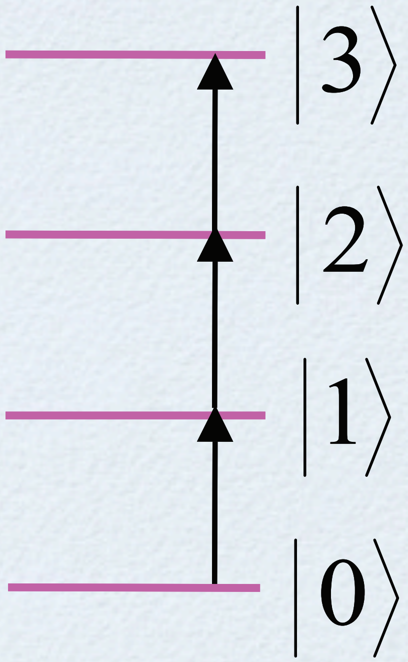


First superconducting qubit 1998 by Nakamura et al at NEC.
Today multi-qubit algorithms in Santa Barbara, Yale, Zürich, Saclay, ...
Also artificial atoms and circuit QED.

Artificial Atoms – Quantum Bits

- Quantized electrical circuit
- Harmonic oscillator is not a qubit
- Nonlinearity makes the circuit anharmonic and addressable
- Small JJ is a good nonlinear inductor





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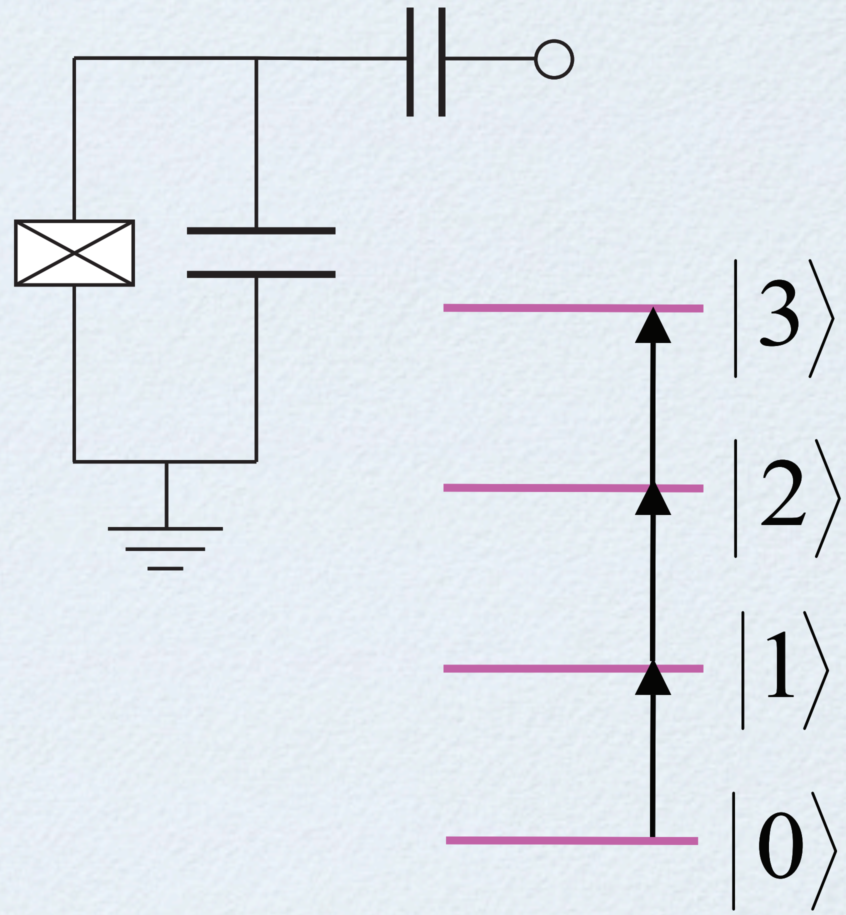

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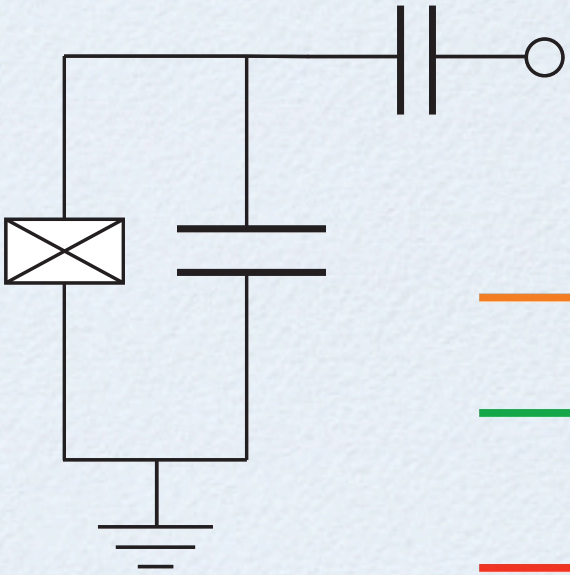
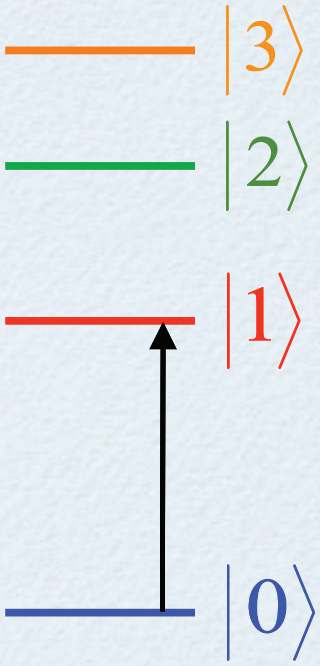




Microwave Quantum Optics

Strong Scattering from
an Artificial Atom

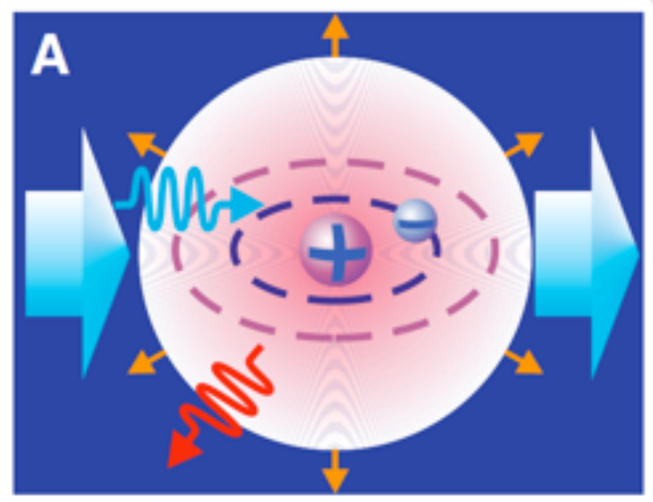
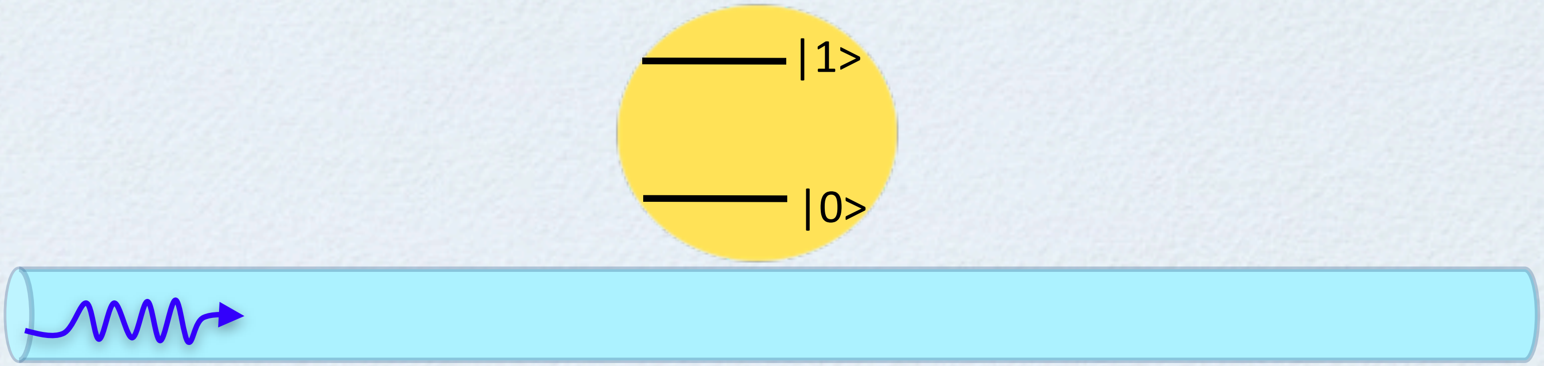
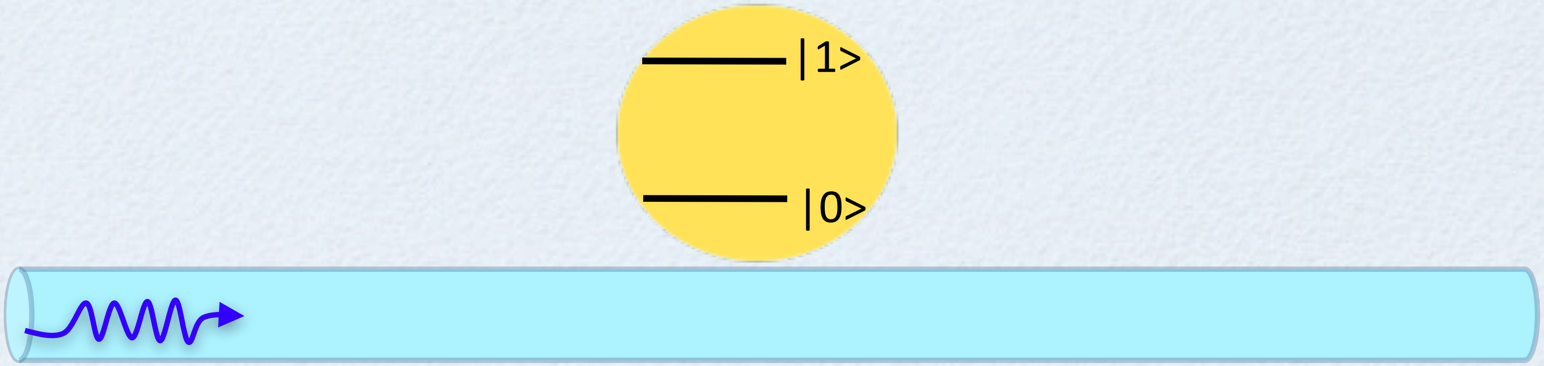


Fig: Astafiev et al., Science (2010).

Single-Atom Scattering

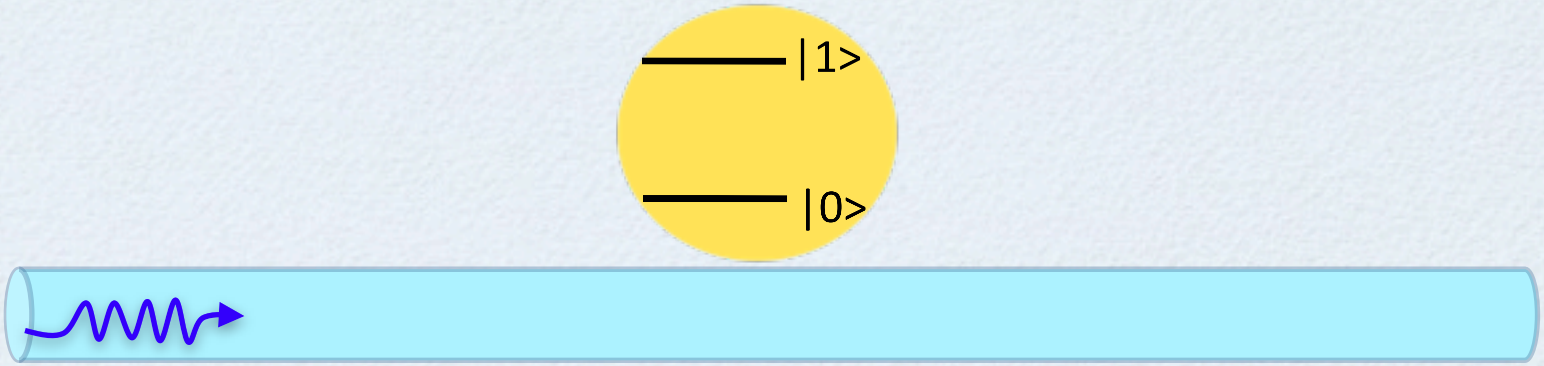


Single-Atom Scattering



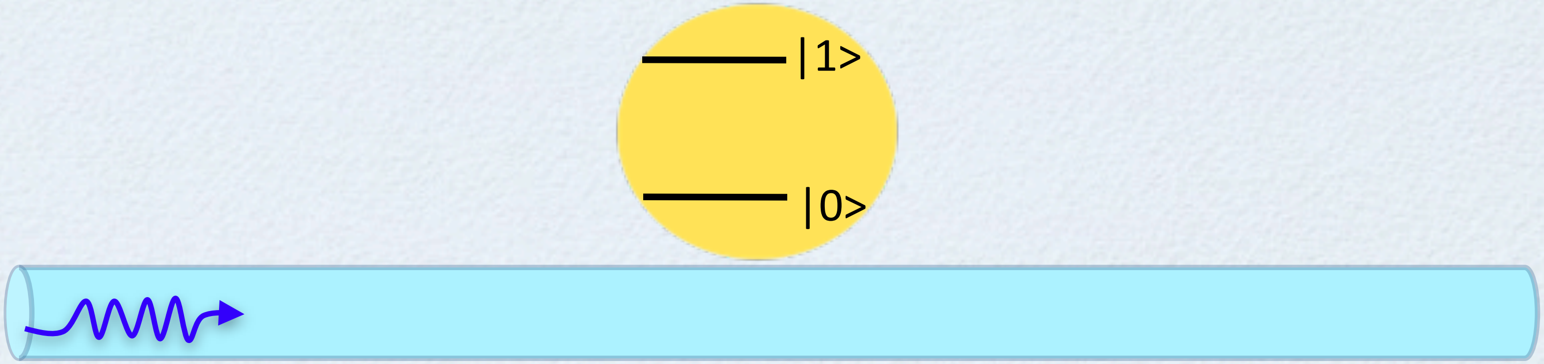
- What is the maximum reflection of a single photon from a single atom in 1D?

Single-Atom Scattering



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

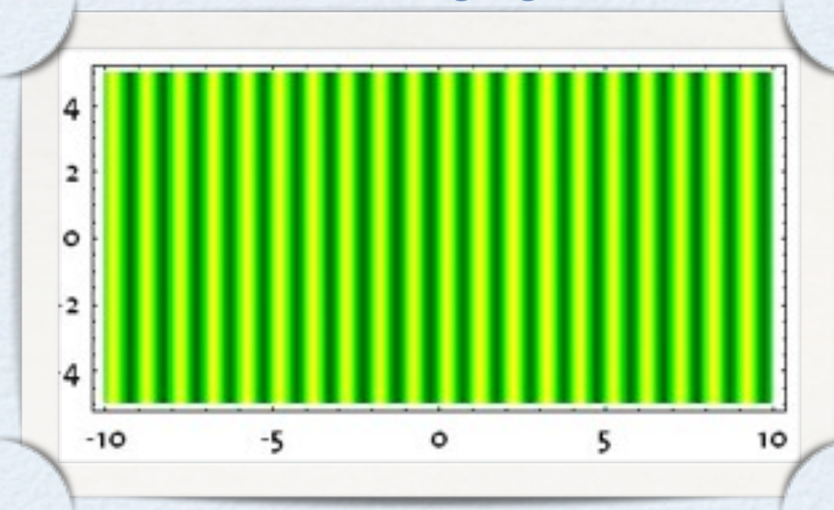
Single-Atom Scattering



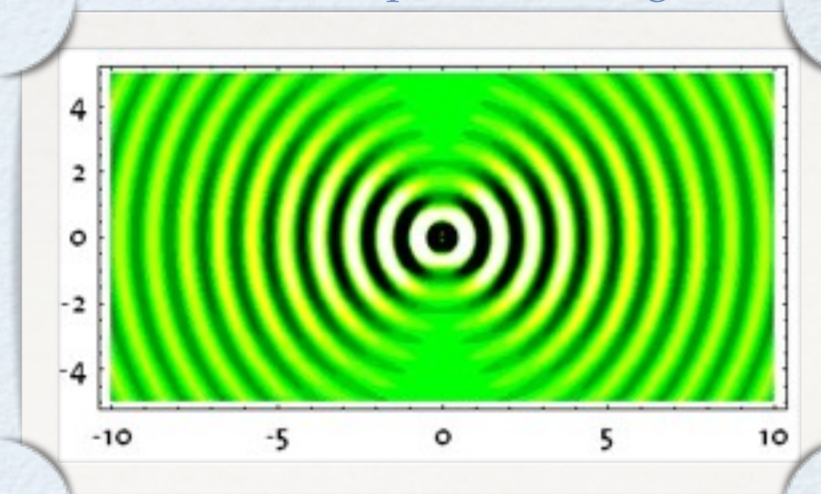
- What is the maximum reflection of a single photon from a single atom in 1D?
  - First guess: 50% due to spontaneous emission in random direction
  - Fully coherent: 100% due to destructive interference in forward direction

Atom/Dipole in open space

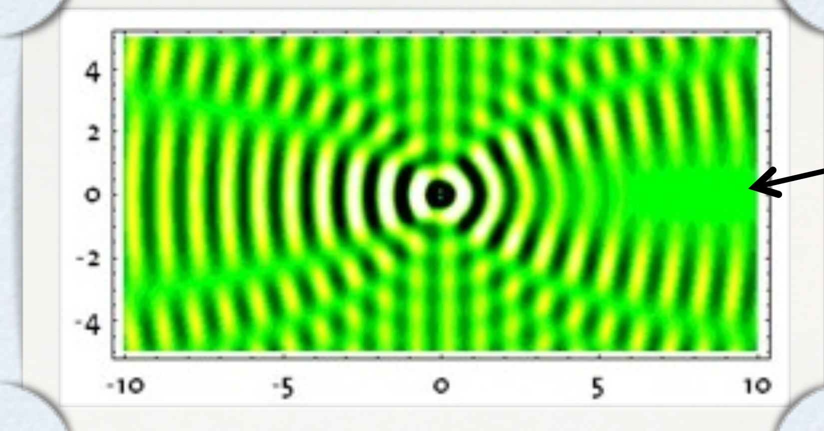
Incoming light



Atom/dipole emits light



Sum

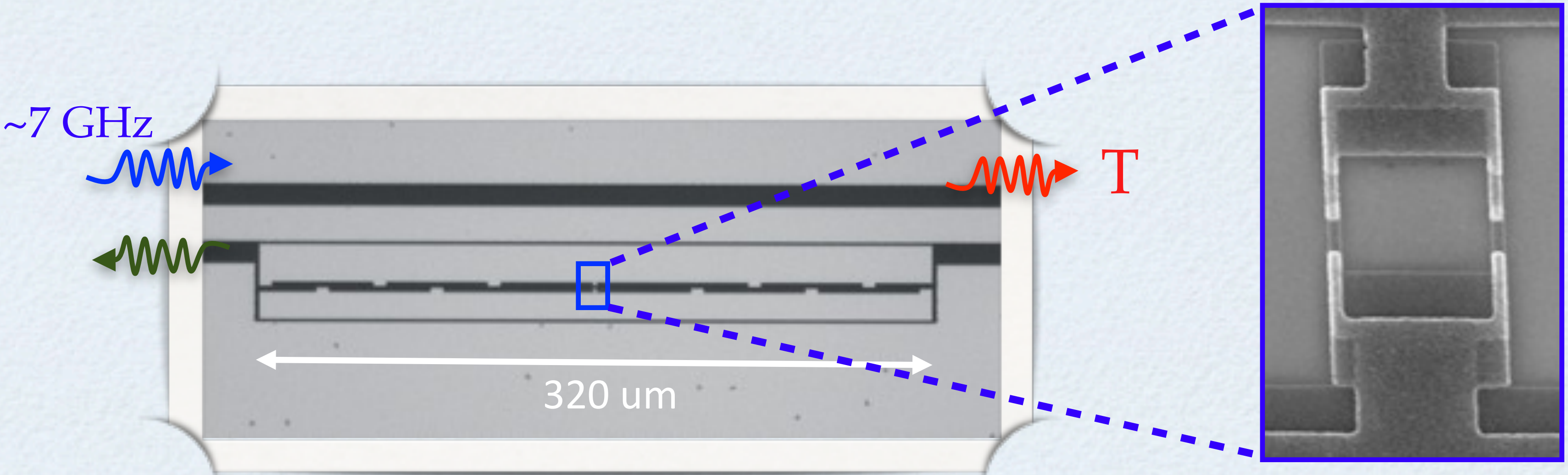


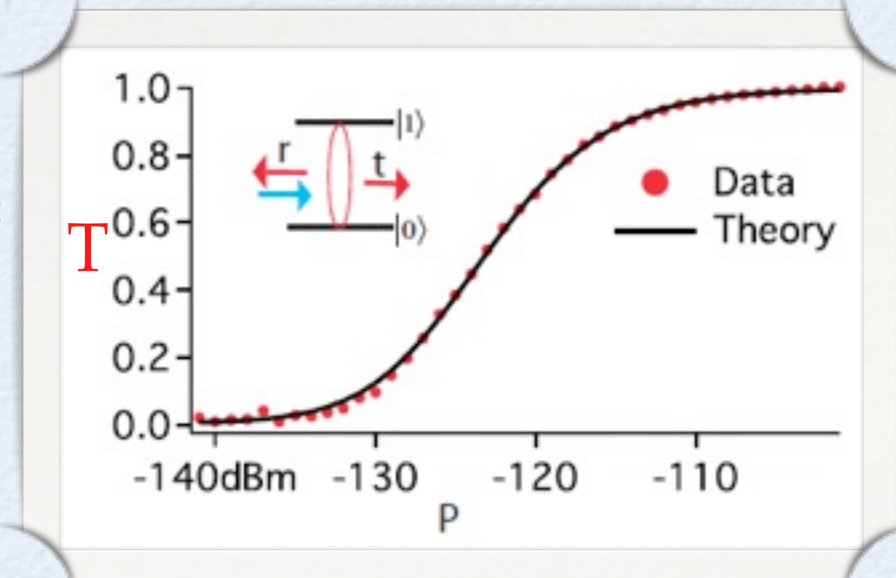
There is perfect extinction in the forward direction due to destructive interference

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).

Single-Atom Scattering





Coupling:
96 MHz

99.6%
reflection

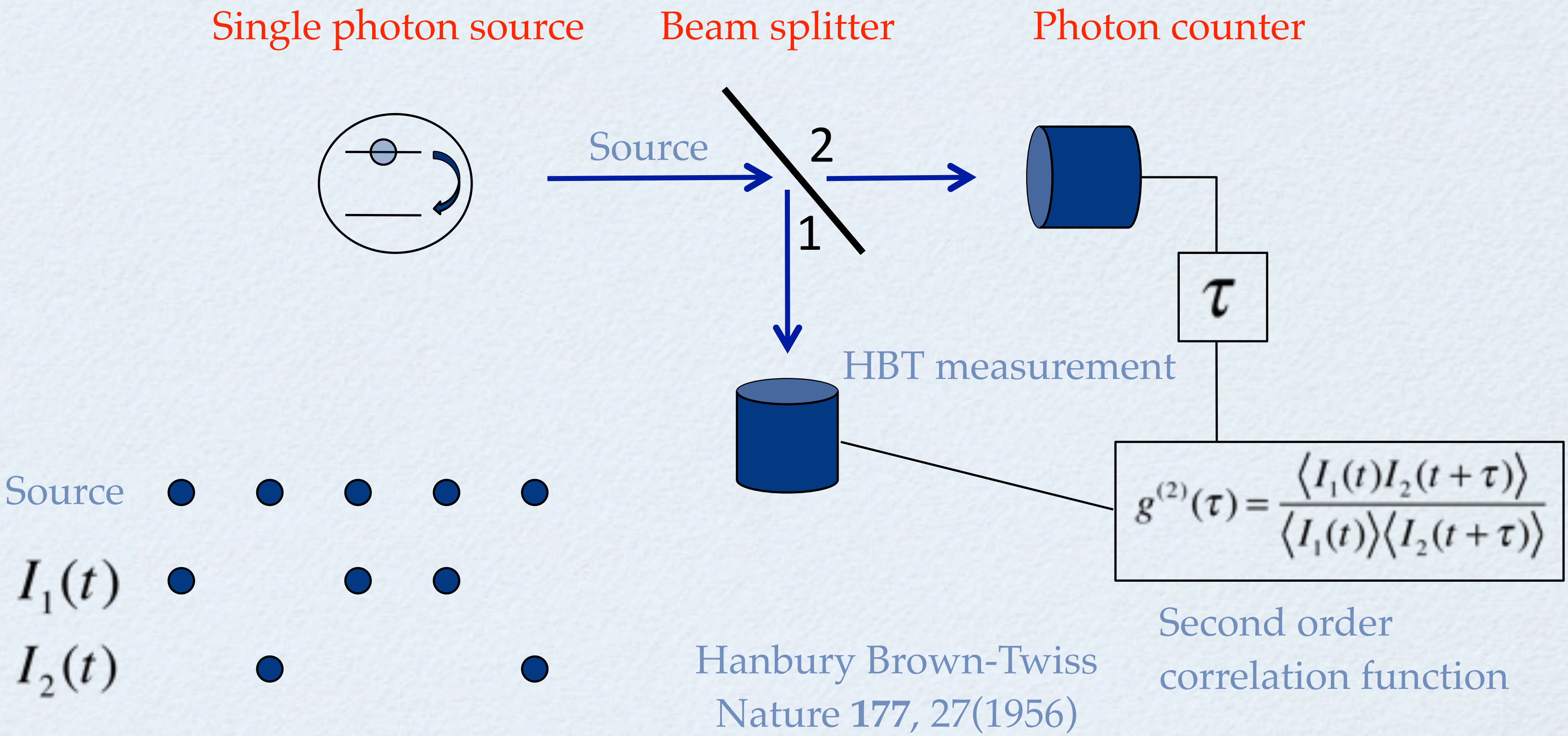
Real molecule: <12%
Nature Physics (2007)
Sandoghdar ETH

Flux qubit: >94%
Astafiev *et al.*, Science (2010).
Abdumalikov *et al.*, PRL (2010)
NEC/RIKEN

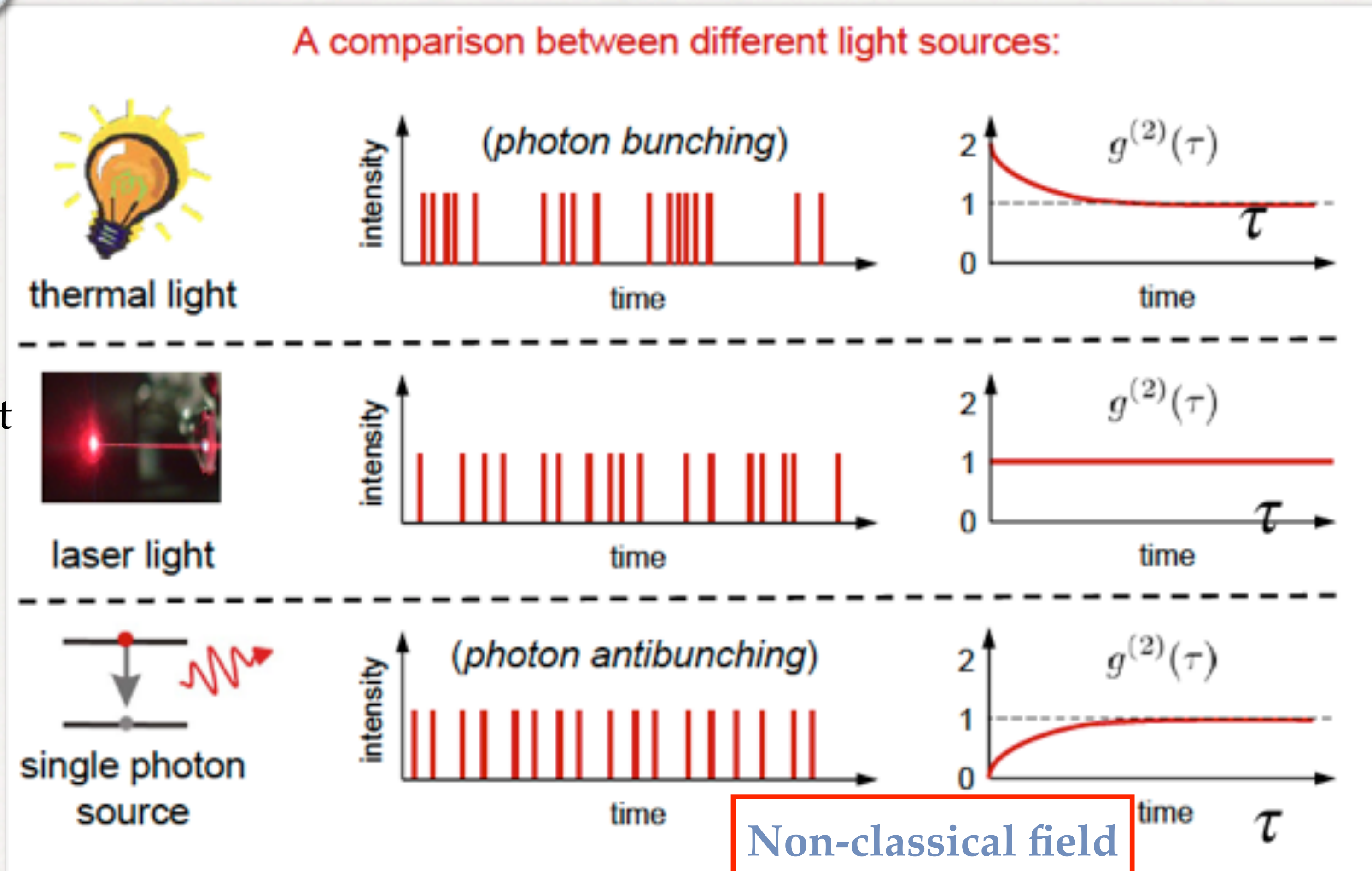
Theory: Chang *et al.*,
Nature Physics (2007)

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

SECOND ORDER COHERENCE



Photon statistics from second order correlation function

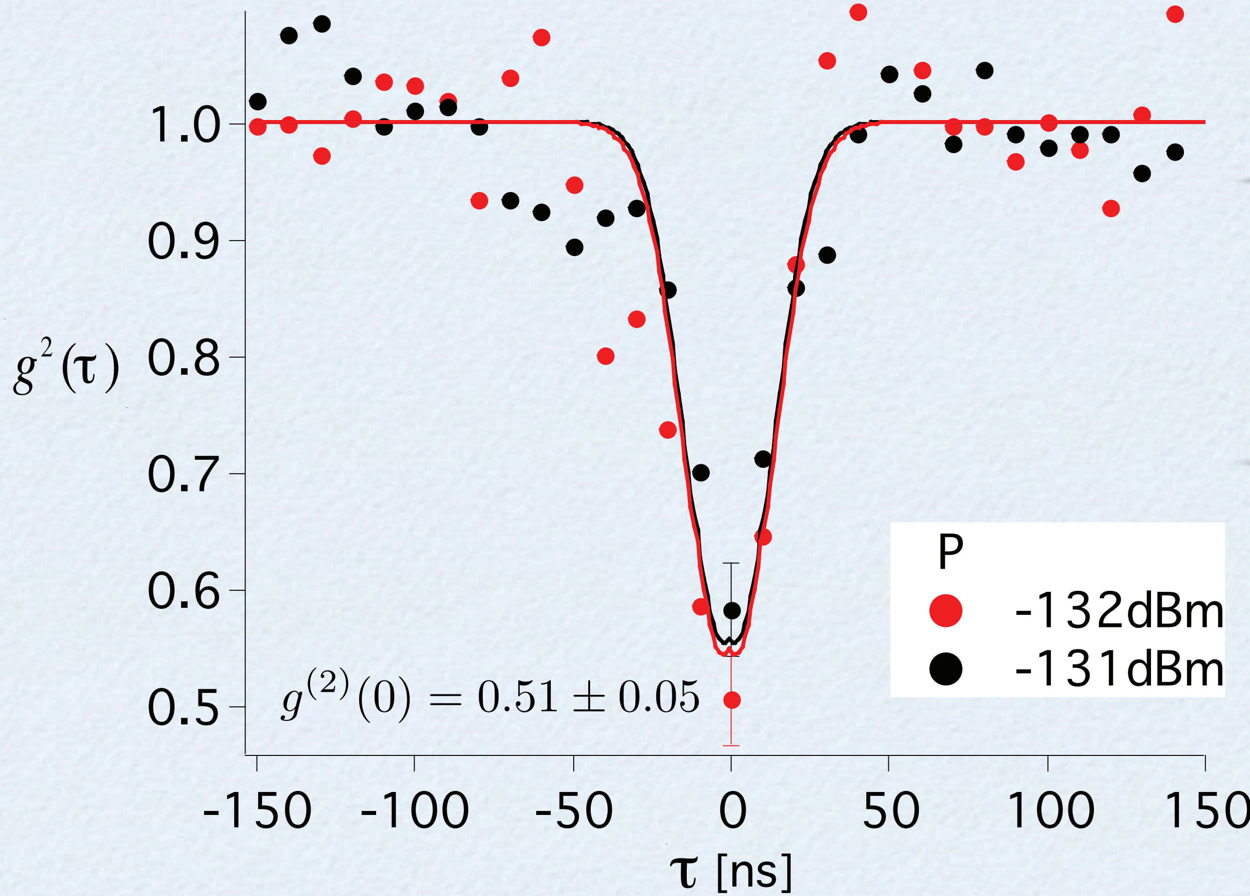


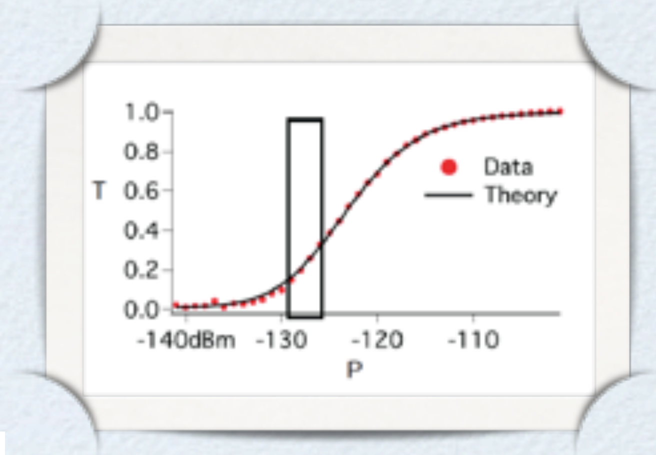
Coherent state

Non-classical field

ESONN 2010 lecture

Observation of antibunching

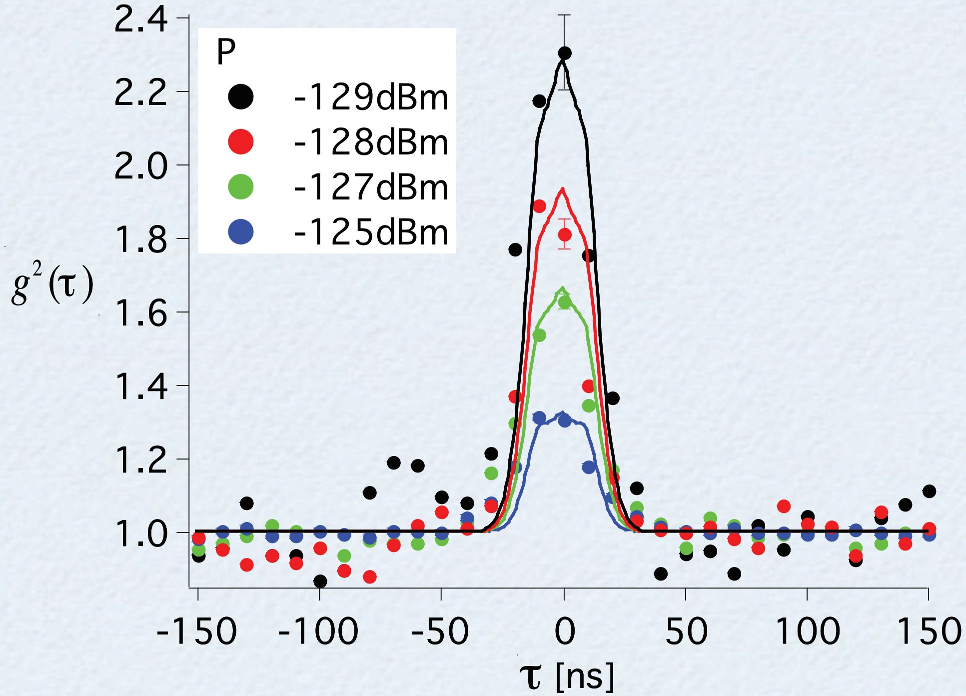


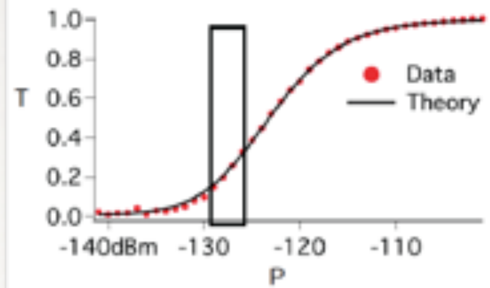


- Observe antibunching of reflected mode
  (~ 2 TB of data, processed at ~30 MB/s for 17 hours)
  - n > 1 states “filtered out”

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

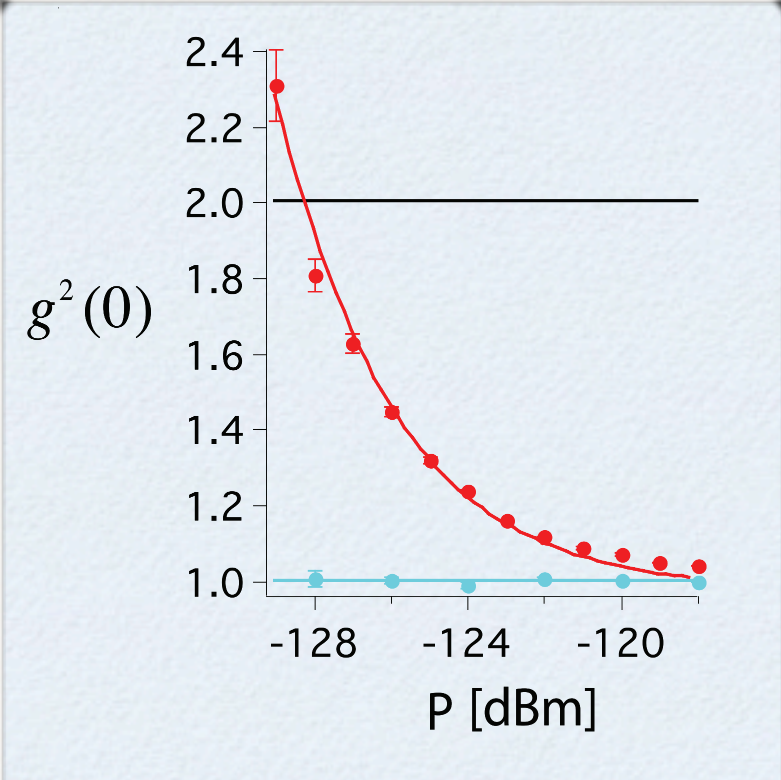
Superbunching (>2) in transmission

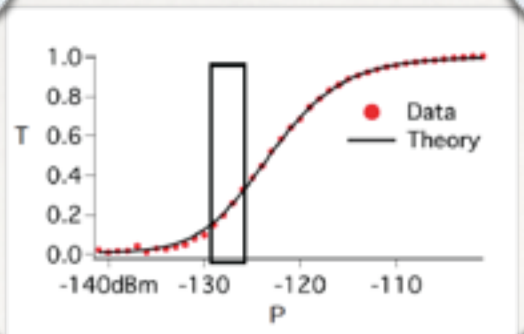




$$g^{(2)}(\tau = 0) = 2.31 \pm 0.09 > 2$$

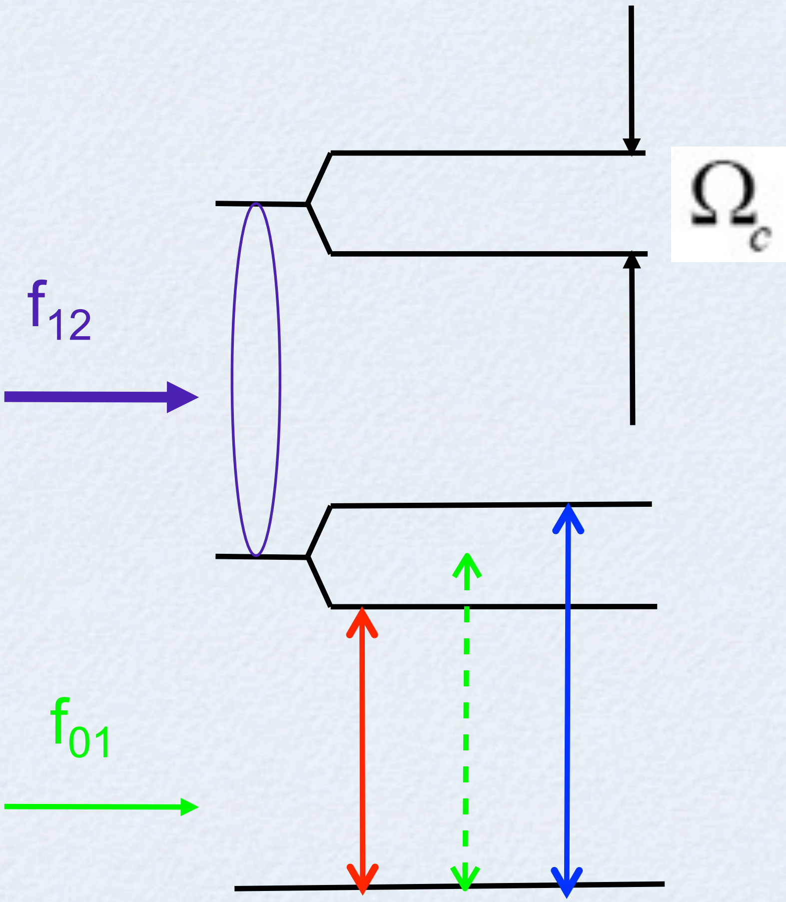
SUPERBUNCHING (>2) IN TRANSMISSION

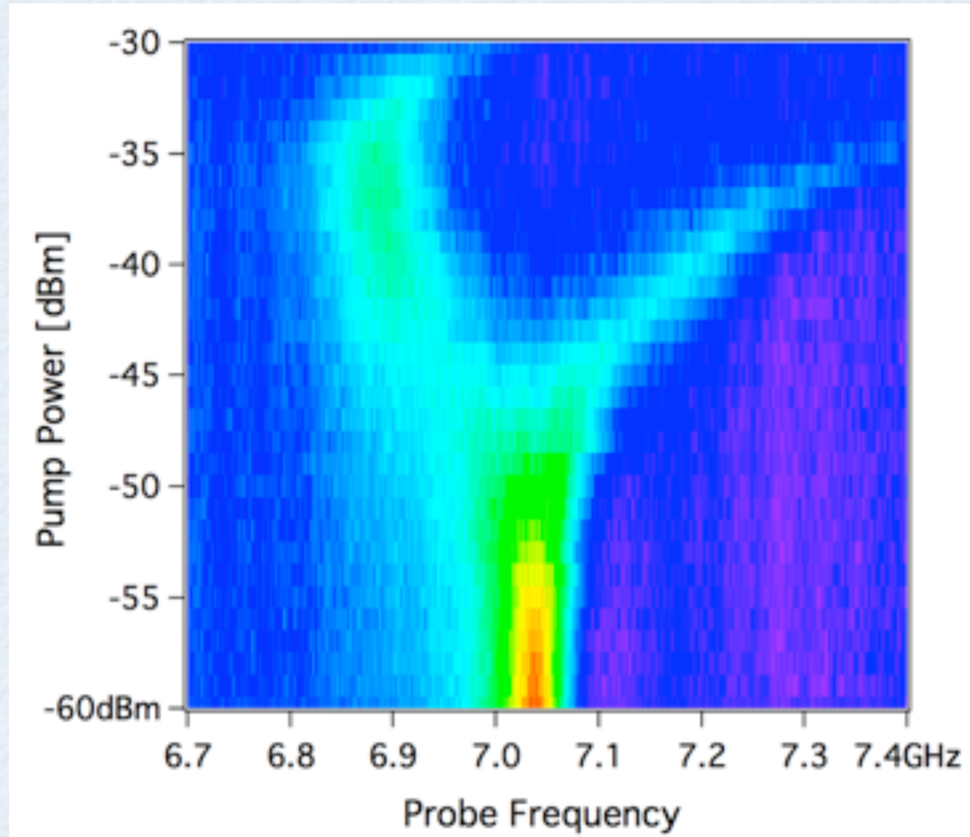




$$g^{(2)}(\tau = 0) = 2.31 \pm 0.09 > 2$$

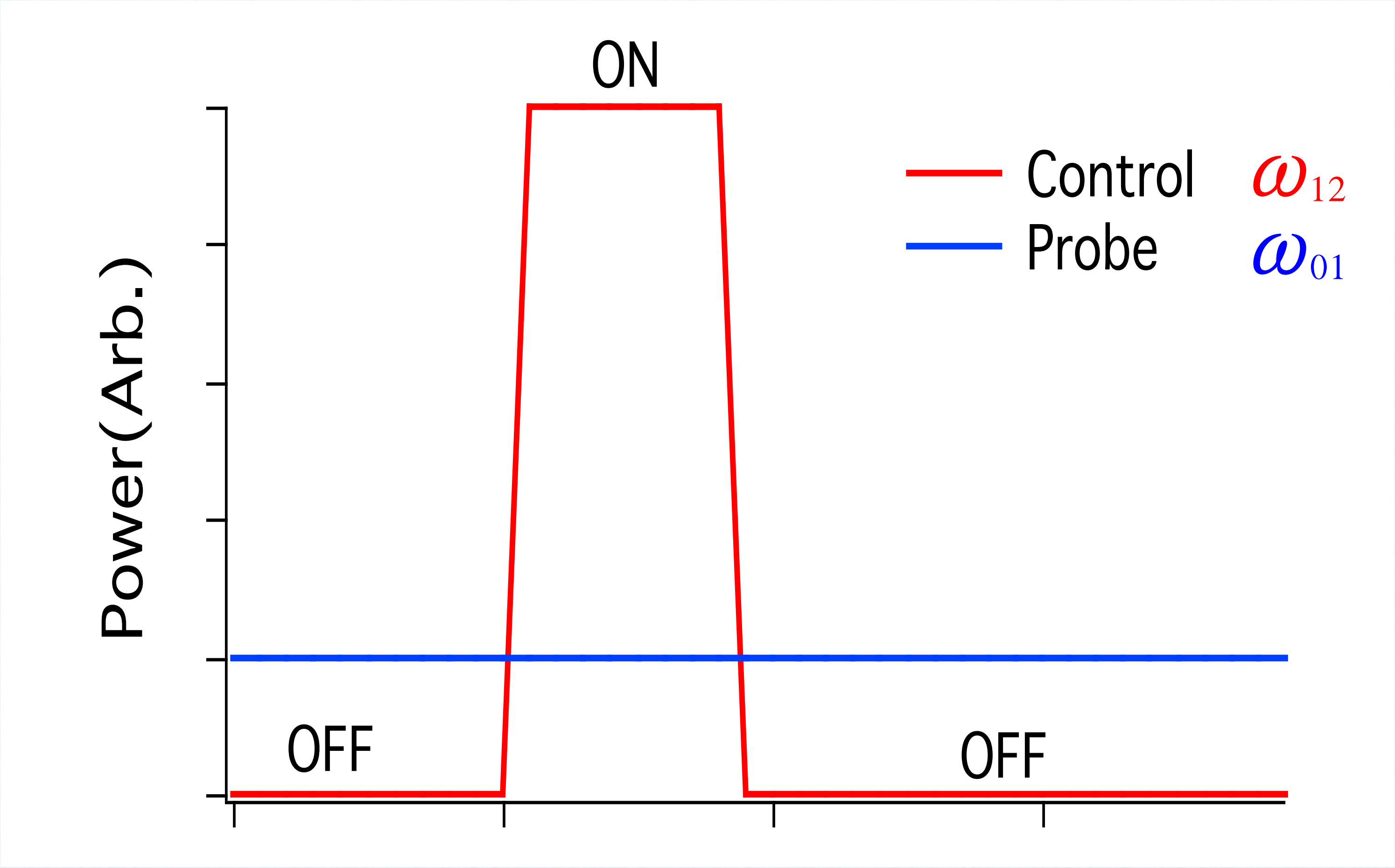
Two-tone experiment
driving |1⟩ -> |2⟩



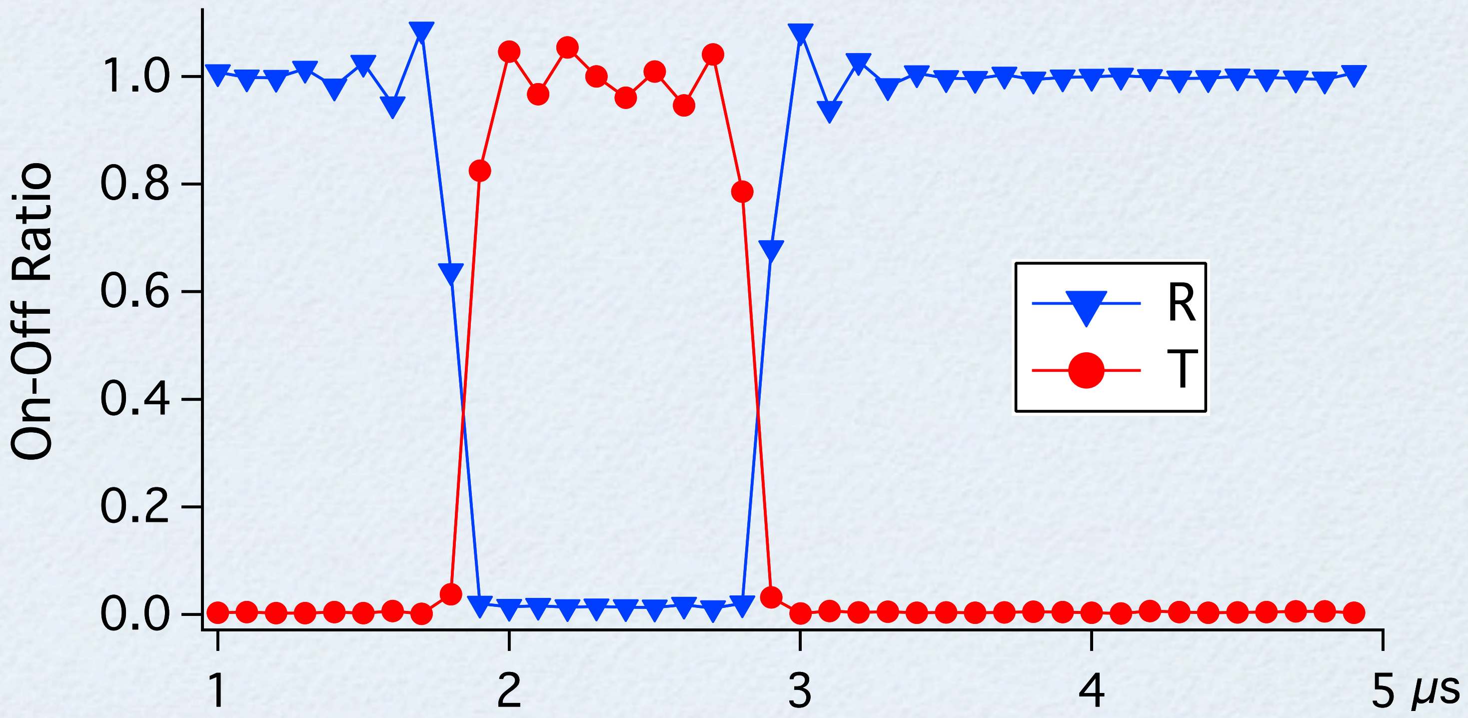


Autler-Townes splitting

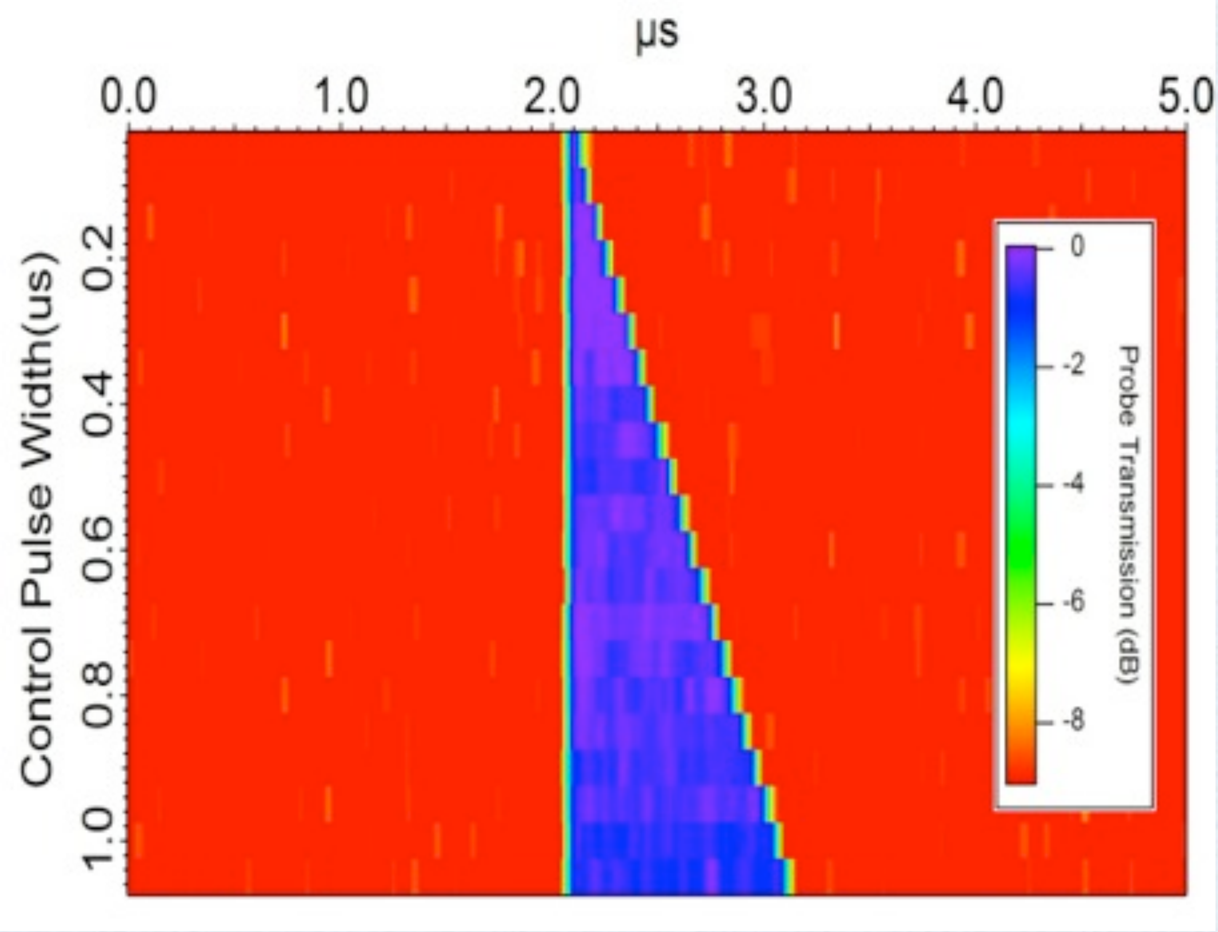
SINGLE-PHOTON ROUTER



Single-Photon Router

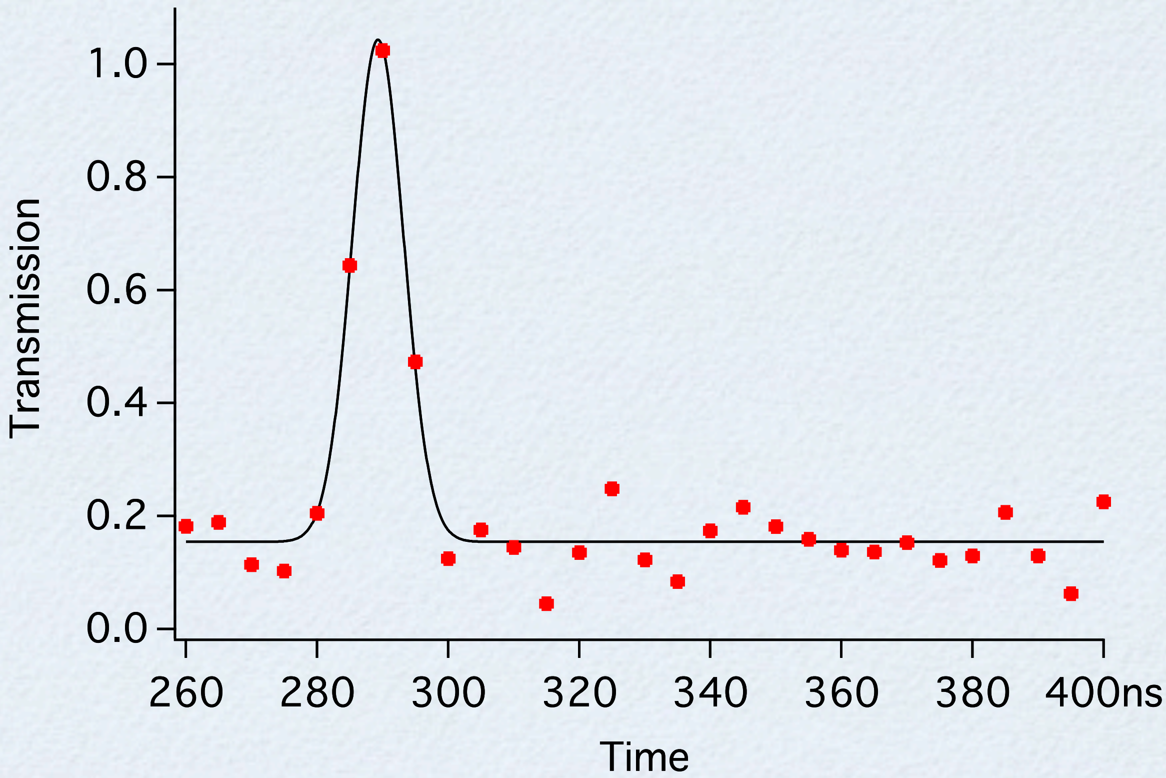


Single-photon router



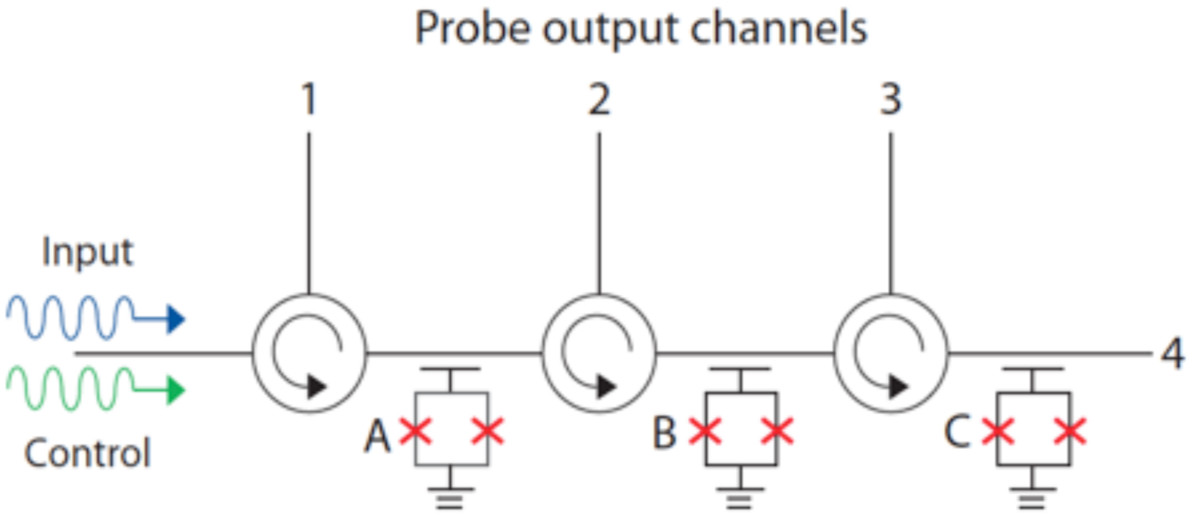
Operation time down to ~ 10 ns

Single-Photon Router



Operation time down to ~ 10 ns

Multiple output single-photon router



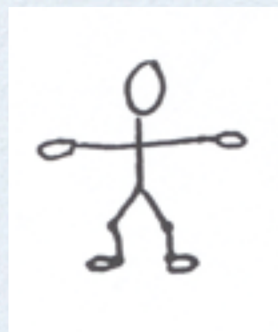
ω_A	Off	On	On	On
ω_B	Off	Off	On	On
ω_C	Off	Off	Off	On
Output	1	2	3	4

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

Single photon router and second order coherence

Io-Chun Hoi

Chris Wilson



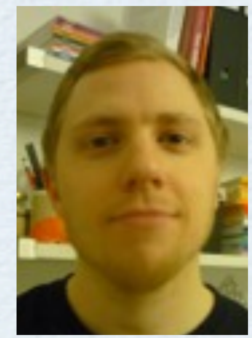
Tauno Palomaki,
now NIST, Boulder

(Router)

Borja Peropadre,
CSIC, Madrid

CSIC
Consejo Superior de Investigaciones Científicas

(Coherence)



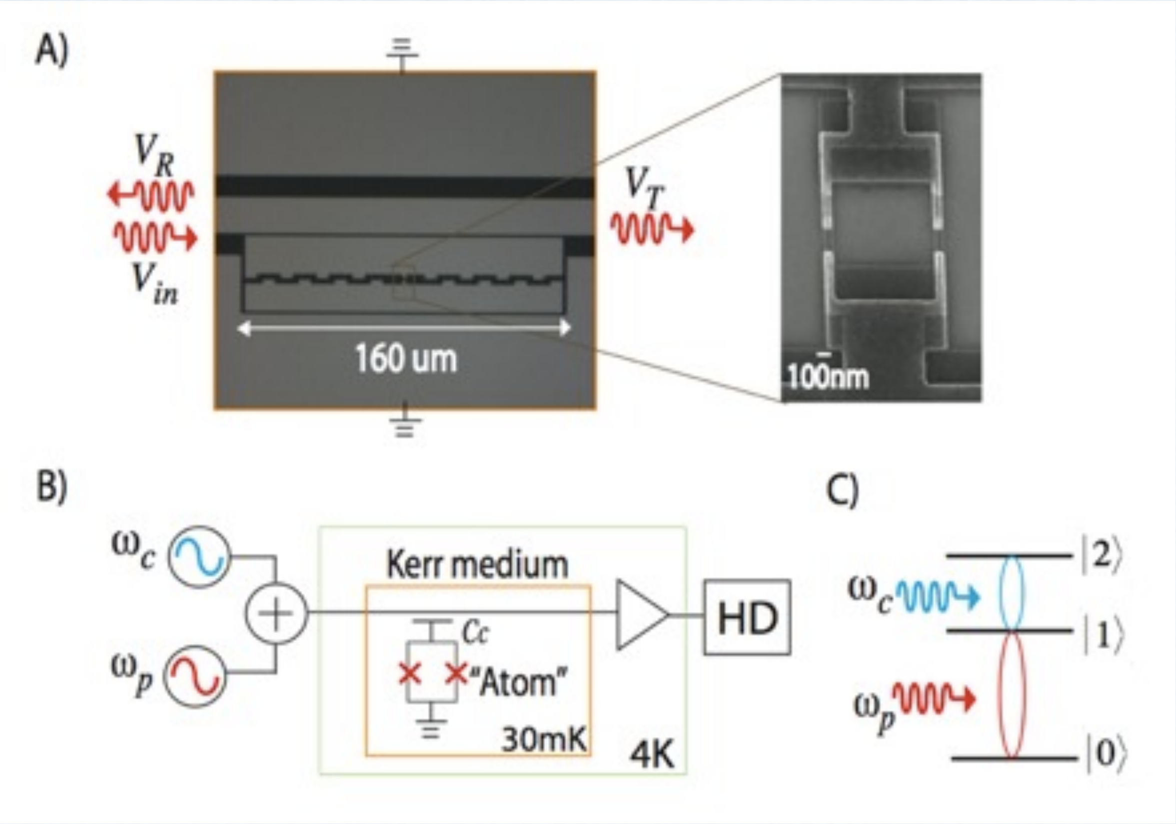
Joel Lindkvist

Per Delsing

Two longer papers submitted to NJP:
arXiv:1210.4303, arXiv:1210.2264

Göran Johansson

Single atom cross-Kerr effect

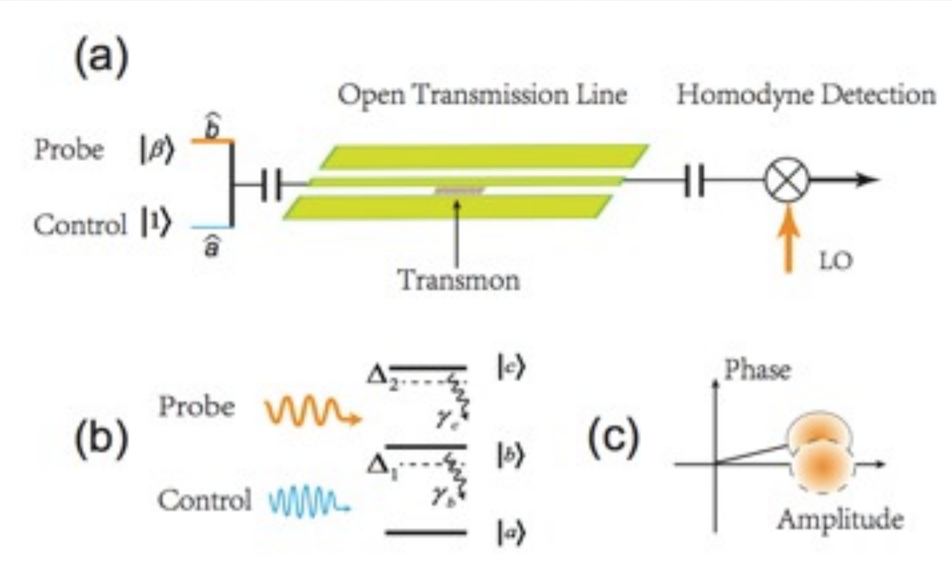


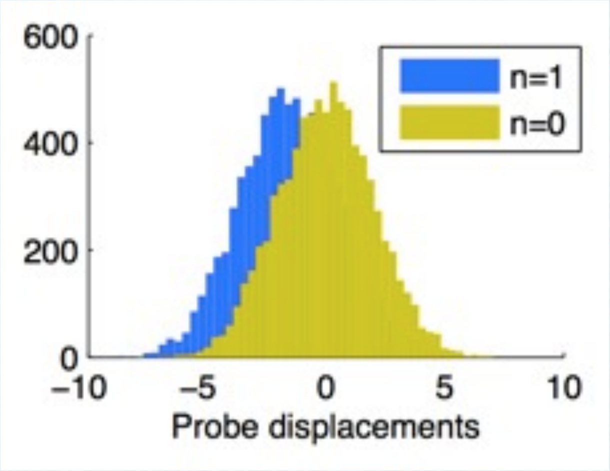
11 degrees phase shift when both control and probe fields are at single photon levels.

Compare: Venkataraman *et al.* Nature Photonics (2012) 0.017 degrees using hollow core optical fibre filled with rubidium atoms

Io-Chun Hoi, C. M. Wilson, G. Johansson, T. Palomaki, T. M. Stace, B. Fan, P. Delsing, *arXiv:1207.1203*

Single Atom Cross-Kerr Effect



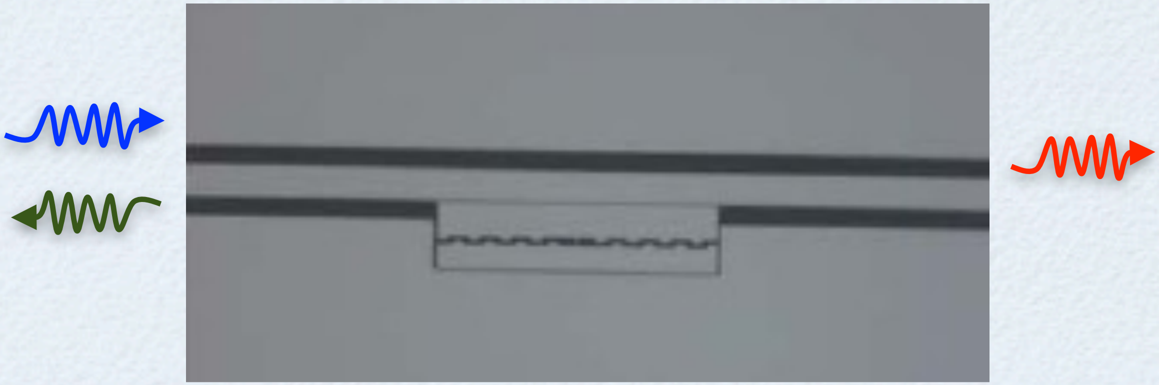


Unfortunately NOT suitable for detecting single microwave photons.
Even if you use many transmons.

Bixuan Fan, Anton F. Kockum, Joshua Combes, Göran Johansson, Io-chun Hoi, Christopher Wilson, Per Delsing, G. J. Milburn, Thomas M. Stace, arXiv:1210.0991 *accepted for publication in PRL.*

Quantum-State Filter

$$|\Phi_{in}\rangle = a_0\,|0\rangle + a_1\,|1\rangle + a_2\,|2\rangle + \ldots$$



$$|\Phi_R\rangle = r_0\,|0\rangle + r_1\,|1\rangle$$

$$|\Phi_T\rangle = t_0\,|0\rangle + t_2\,|2\rangle + t_3\,|3\rangle \ldots$$

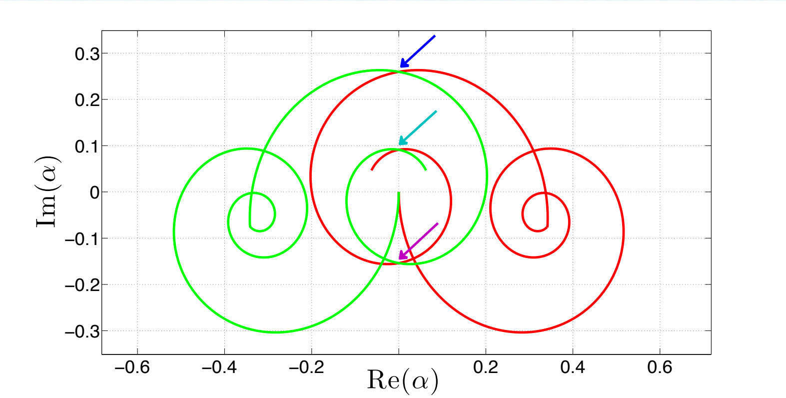
- Atom preferably reflects 1-photon state
- Input coherent state converted to nonclassical state
- Possibly a versatile single photon source

Chang *et al.*, Nature Physics (2007)
H. Zheng *et al*, Physical Review A (2010)

Scattering conclusions

* Observed 99.6% extinction of forward scattering
* Verified switching on 10 ns timescale
* Observed antibunching (limited by detection)
* Observed Giant Cross-Kerr effect
* No-Go for single photon detection by cross-Kerr

Feedback-assisted parity measurement in circuit QED



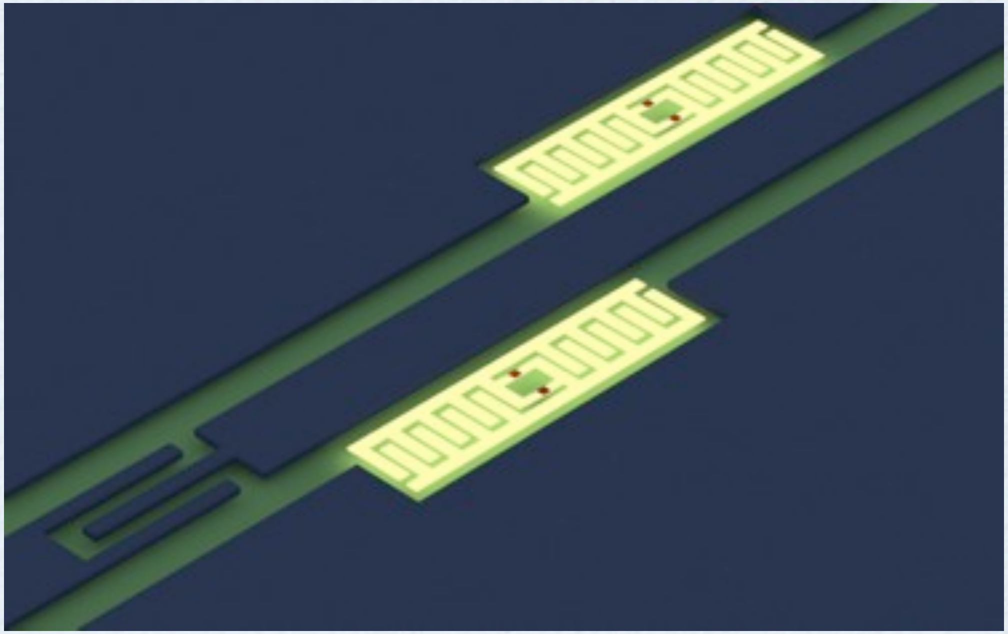
Lars Tornberg, Göran Johansson, PRA (2010)
Anton Frisk Kockum, Lars Tornberg, Göran Johansson, PRA (2012)

Parity measurement in circuit QED

Coherent probe on resonator with qubits

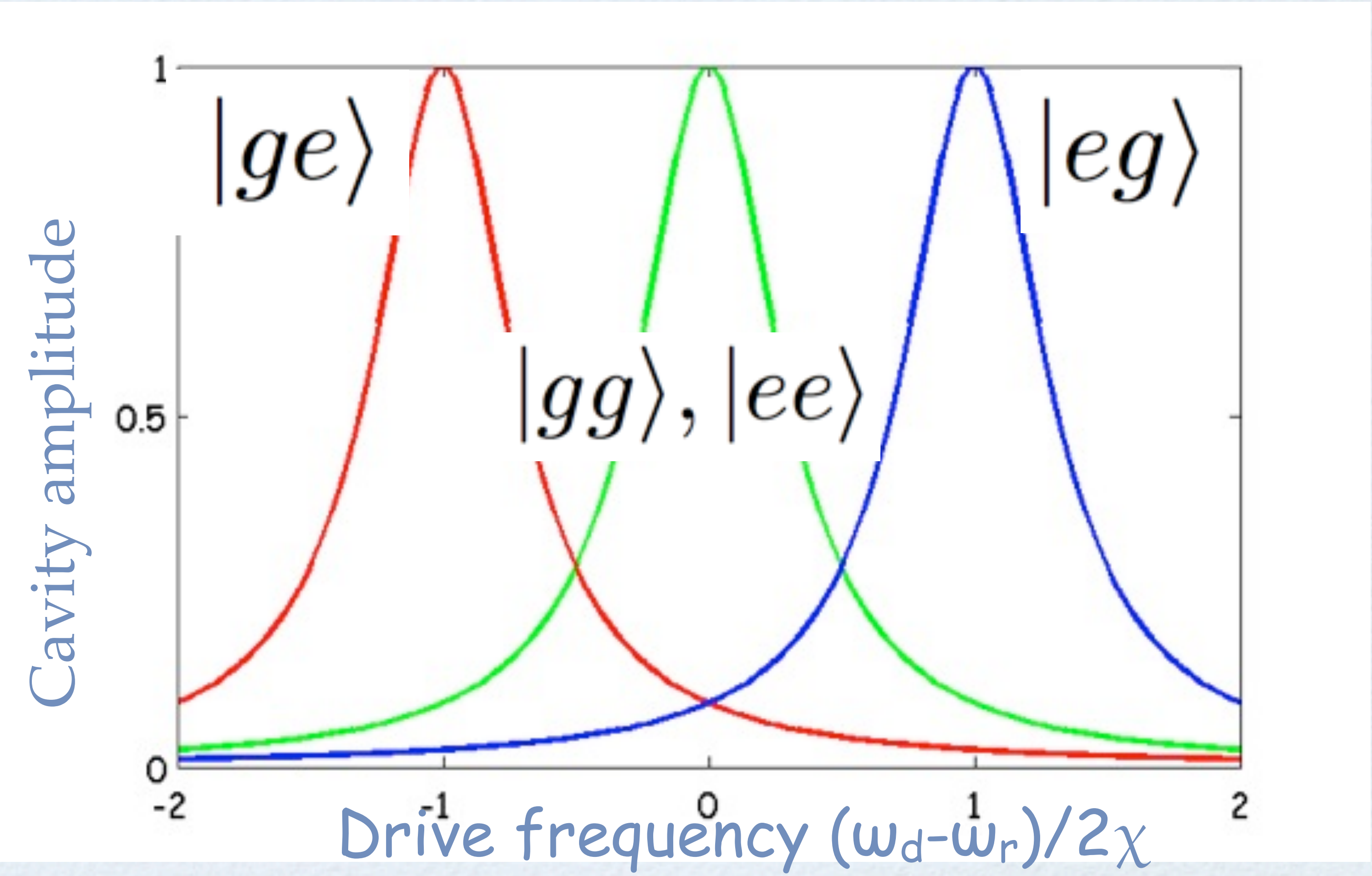
Dispersive regime: qubit state shifts resonator frequency

Phase shift of the probe

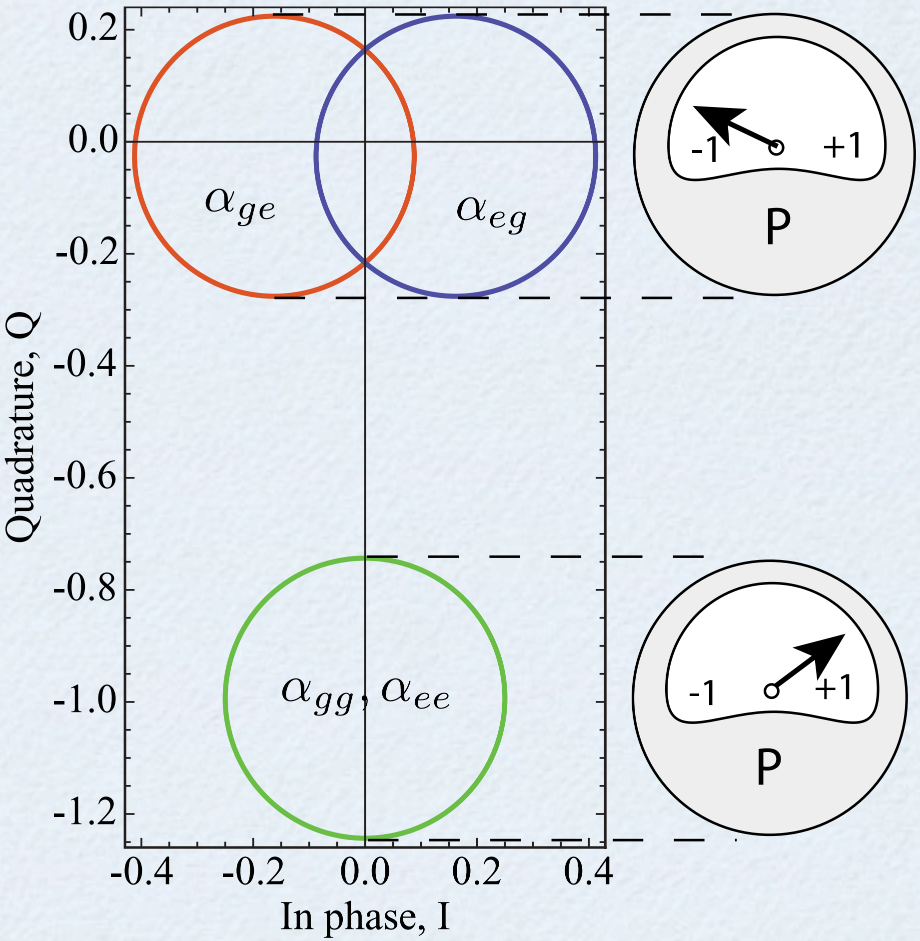


$$H_{\text{eff}} = \left[\Delta_r + \chi\left(\sigma_z^{(1)} - \sigma_z^{(2)}\right)\right] a^\dagger a + (a\epsilon_m^* + a^\dagger \epsilon_m)$$

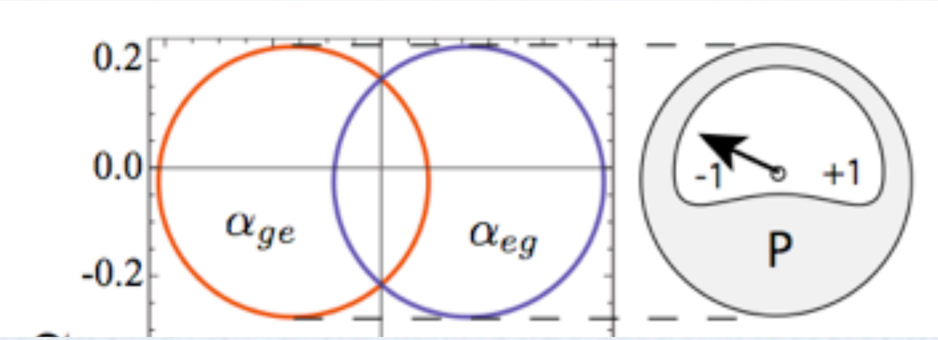
Cavity Amplitude



HOMODYNE DETECTION



Strong Measurement

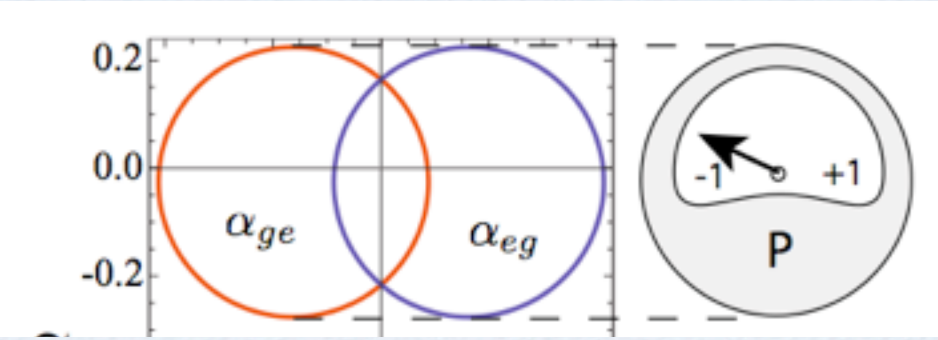


Strong homodyne measurement - project on Quadrature

$$|ge\rangle|\alpha_{ge}\rangle + |eg\rangle|\alpha_{eg}\rangle \Rightarrow e^{i\phi(x)}|ge\rangle + e^{-i\phi(x)}|eg\rangle$$

"A symmetry analyzer for non-destructive Bell state detection using EIT", S. D. Barrett, P. Kok, K. Nemoto, R. G. Beausoleil, W. J. Munro, and T. P. Spiller, Phys. Rev. A **71**, 060302(R) (2005).

Strong Measurement



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The stochastic phase $\phi(x)$

is given by the measurement result.

Continuous Measurement

We model continuous measurement with a stochastic master equation

$$d\rho_c = \mathcal{L}_{\mathrm{tot}}\rho_c\, dt + \sqrt{\kappa\eta}\mathcal{M}[ae^{-\phi}]\rho_c dW(t)$$

Solution:
The initial state always works!

$$\frac{|ge\rangle + |eg\rangle}{\sqrt{2}}$$

(Can be shown analytically.)

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The stochastic phase can be determined from state-estimation, i.e. knowing the initial state and determine dW(t) from the measurement record.
But the initial state is unknown???

Solution:
The initial state always works!

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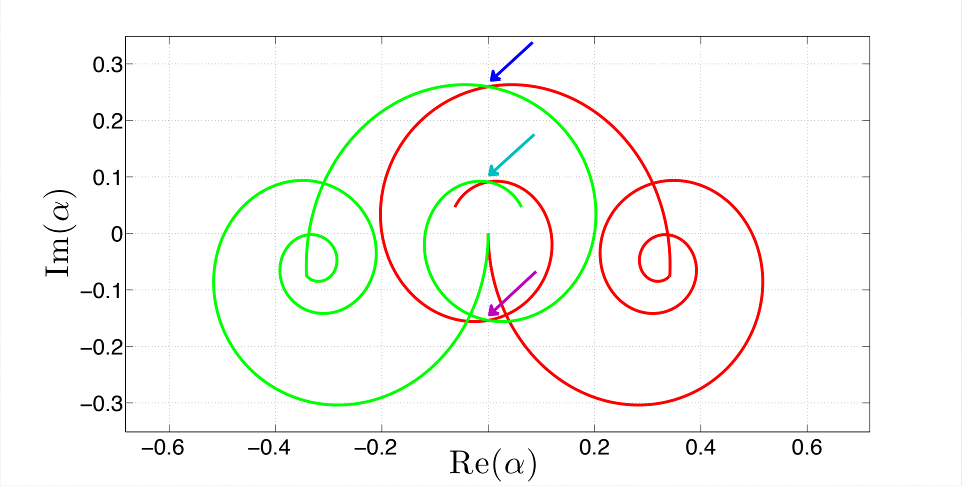
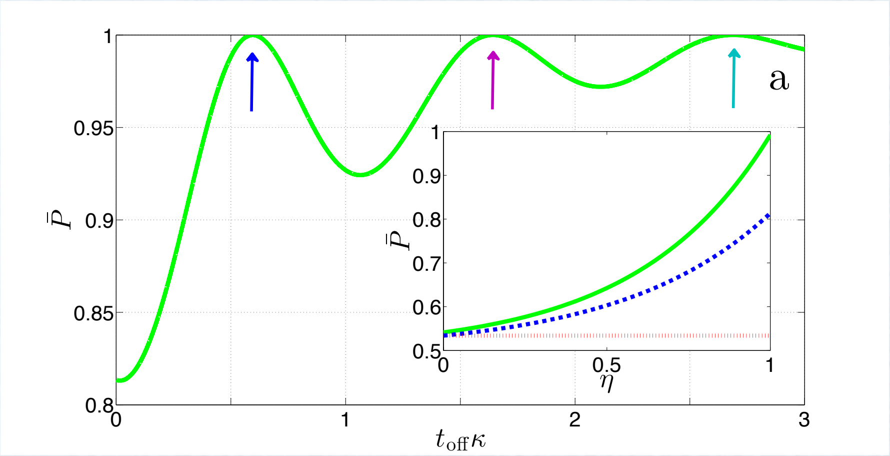
(Can be shown analytically.)

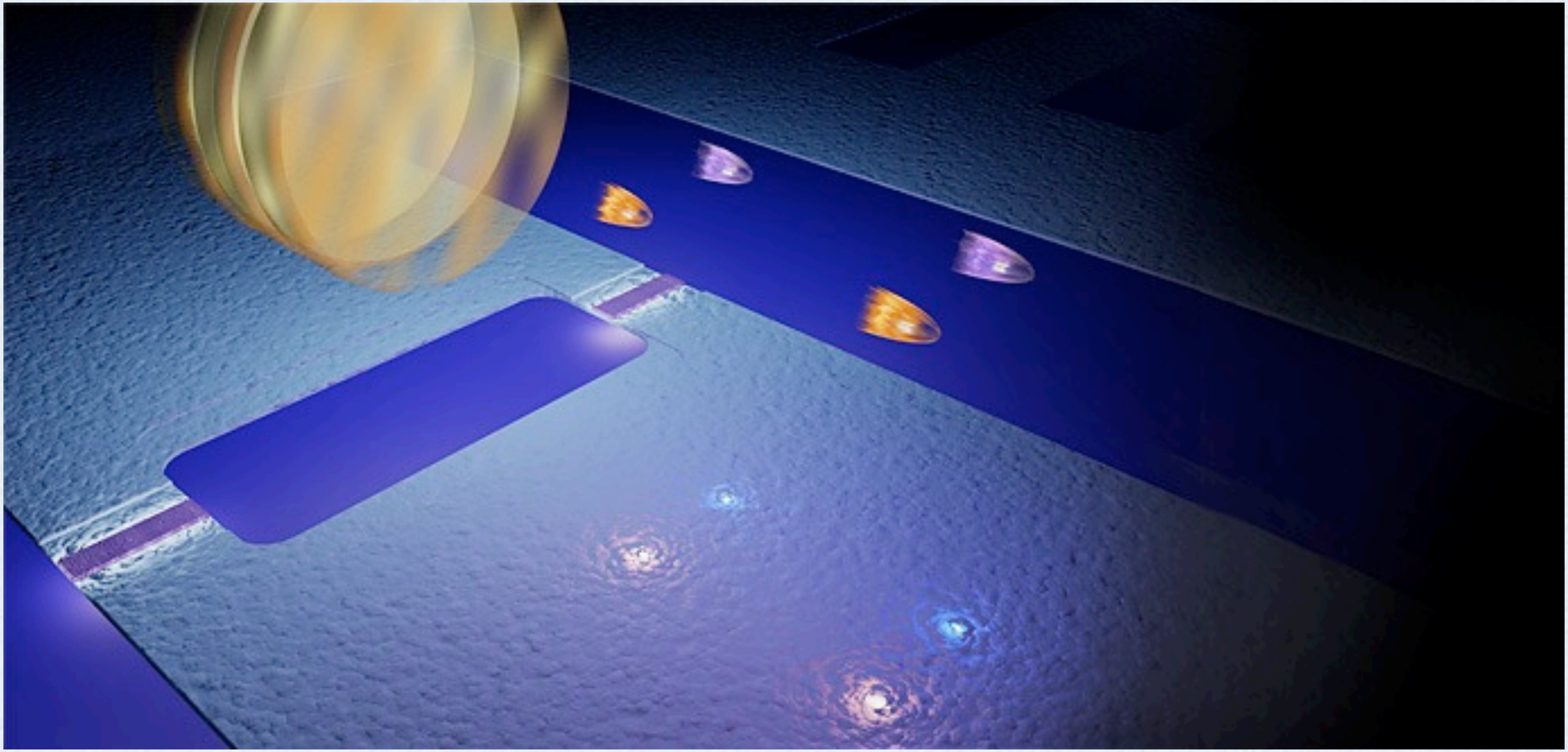
Perfect Measurment -> No Dephasing





- Extracting information about the phase kicks
- All photons must be let out from the resonator
- The measurement-induced dephasing can be completely undone
- Not completely unrealistic experimentally

The first report on experimental observation of the dynamical Casimir effect



C.M. Wilson, G. Johansson, A. Pourkabirian, M. Simoen, J.R. Johansson, T. Duty, F. Nori & P. Delsing, Nature **479**, 376-379 (2011)

SUMMARY

- Superconducting circuits is a playground for quantum physics.
- Artificial atoms in 1D transmission line
  - Anti-bunching, photon-routing, cross-Kerr, (no) photon detection
- Feedback-assisted parity measurement in circuit QED

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Thank you for your attention!