Amplification, entanglement and storage of microwave radiation using superconducting circuits

laboratoire pierre aigrain
électronique et photonique quantiques

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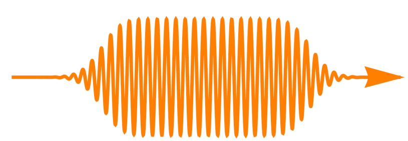
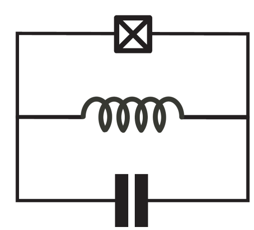
Philip Kim's group at Columbia University, New York, USA

Work done in Quantum Electronics group, LPA
Ecole Normale Supérieure de Paris, France





Microwave: powerful and versatile platform

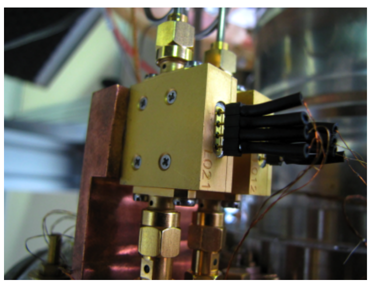
Standard commercial apparatuses due to decades of use in telecommunication

Vector Network Analyzer

Cable

Directional coupler

Amplifier



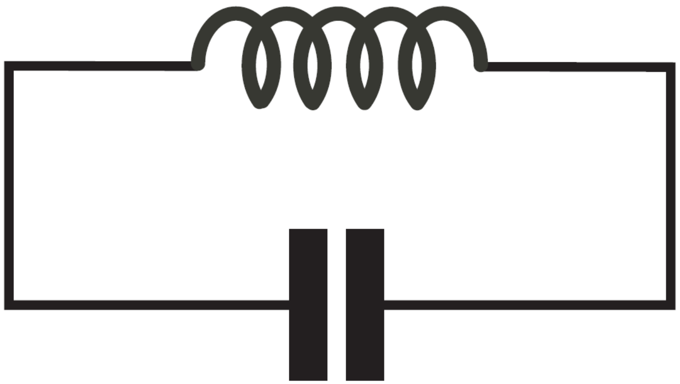
Microwave generator

Circulator

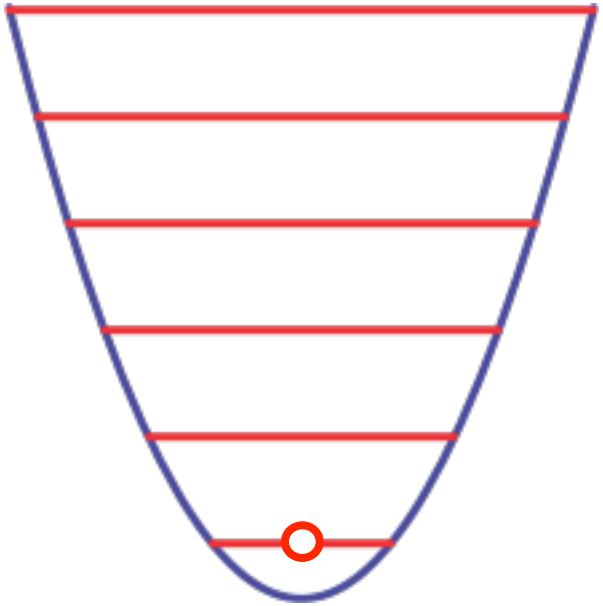
Phase shifter

Processing at single photon level

LC circuit



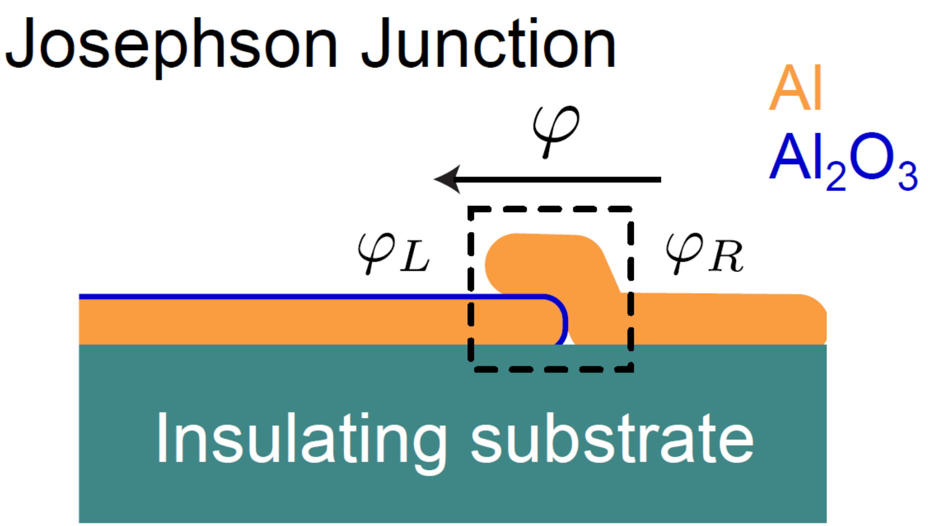
Harmonic oscillator

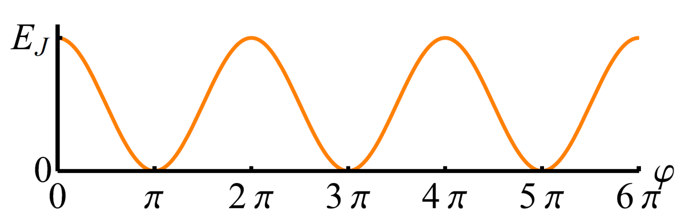


$$\omega_0 = \frac{1}{\sqrt{LC}} \sim \mathrm{GHz}$$

$$T = 50\ \mathrm{mK} < \hbar\omega_0/k_B \approx 250\ \mathrm{mK}$$

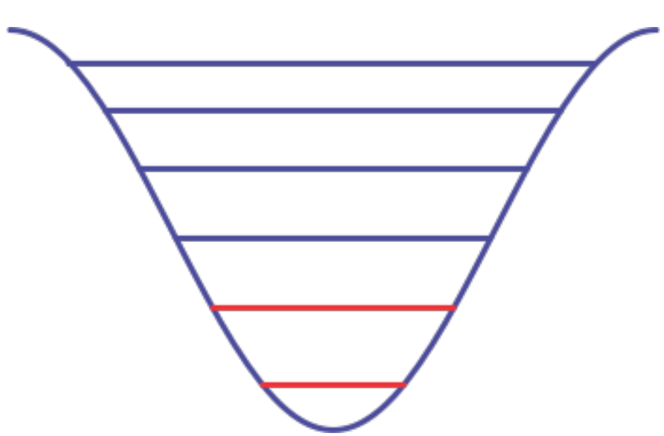
A unique component: the Josephson junction



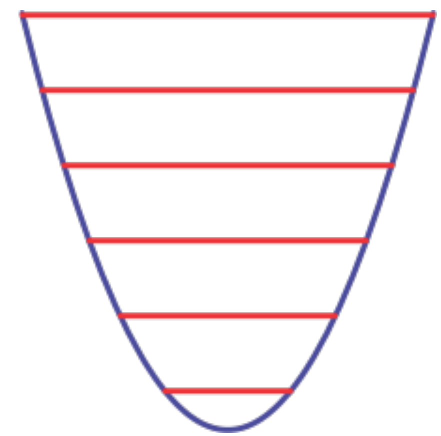


Dimensions ~ 100 nm < wavelength ~ 1 cm
=> metamaterials

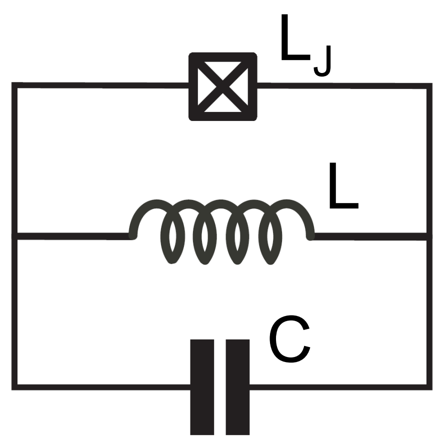
Josephson circuits



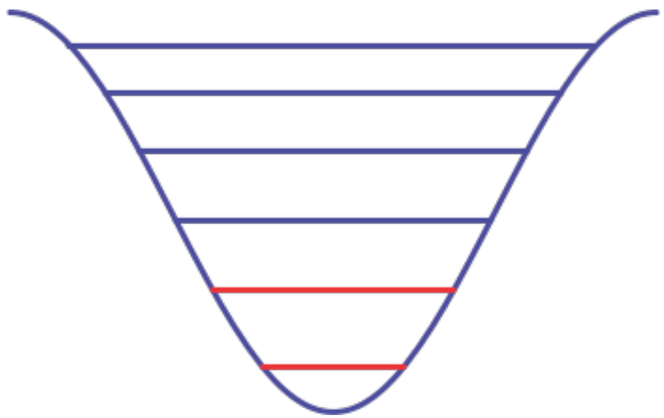
Strongly anharmonic oscillator



Weakly anharmonic oscillator



State preparation in microwave quantum optics

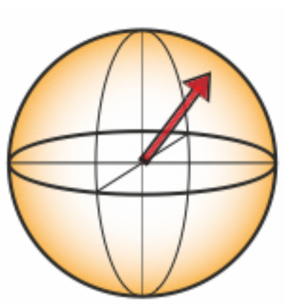


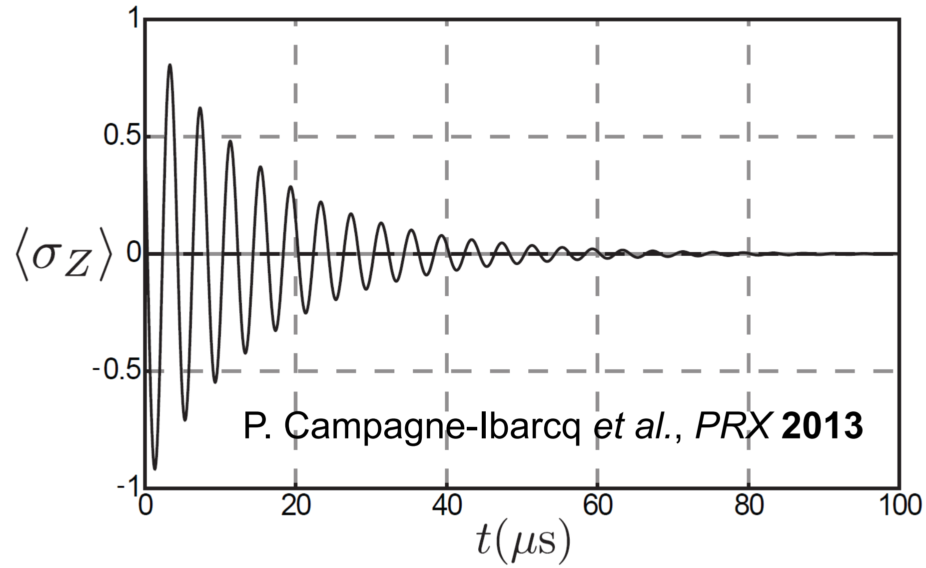
Strongly anharmonic oscillator

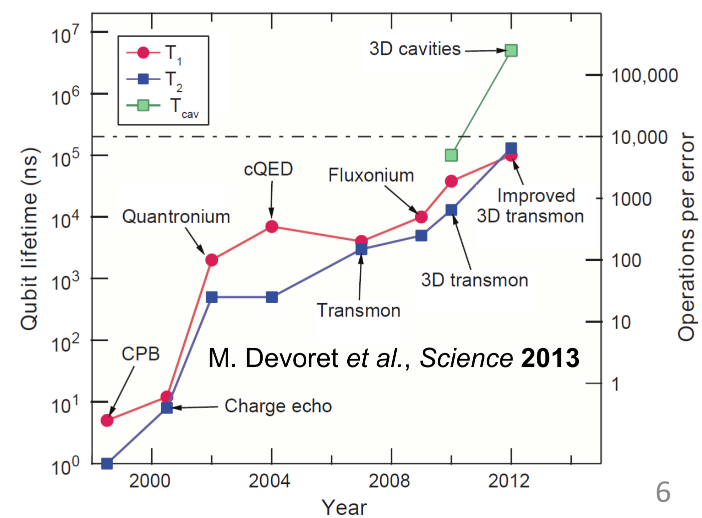
$\Downarrow$

Two-level system $d = 2$

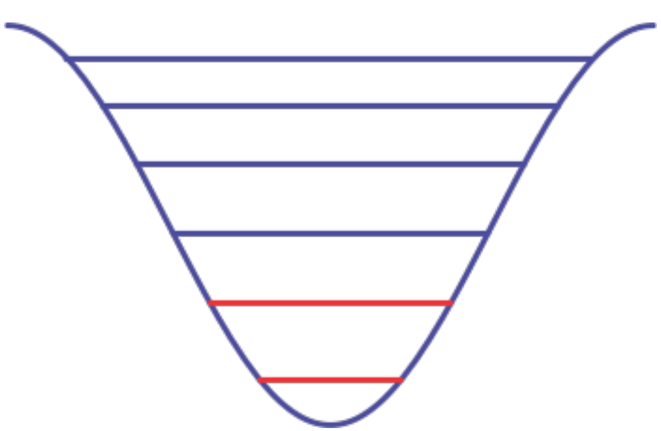
$\Updownarrow$







State preparation in microwave quantum optics



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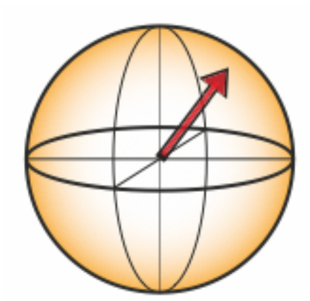
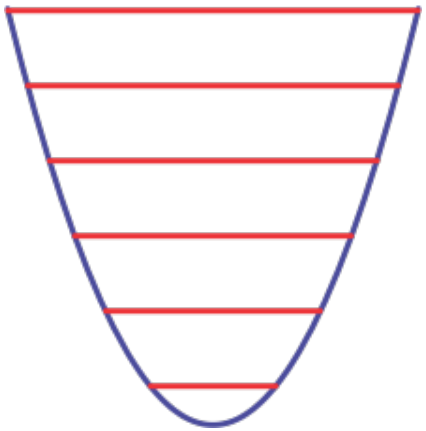




Weakly anharmonic oscillator

$\Downarrow$

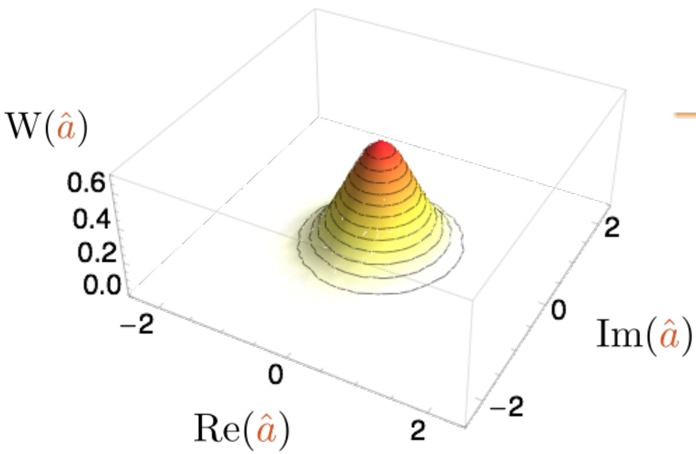
Harmonic oscillator $d = \infty$

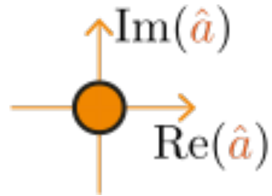
$\Updownarrow$

continuous variable

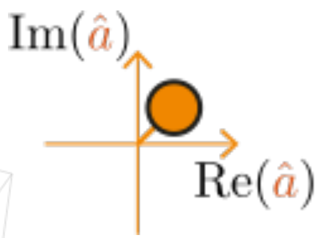
State preparation in microwave quantum optics

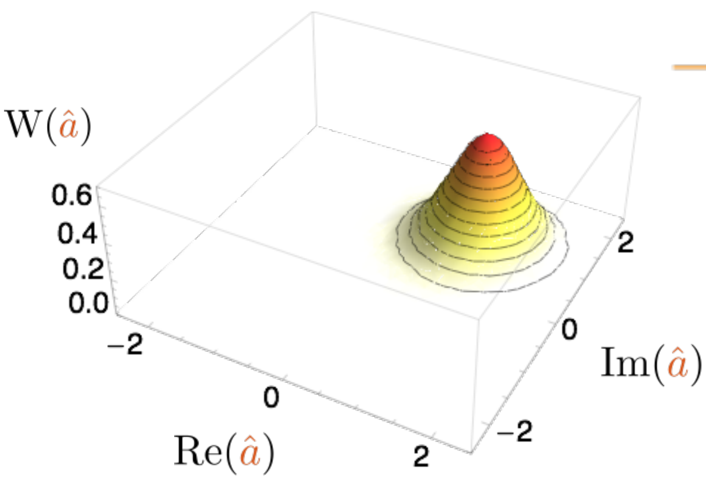
Vacuum state $|0\rangle$

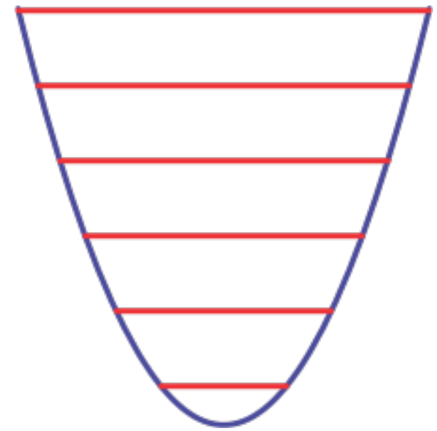




Coherent state $|\alpha\rangle$







Weakly anharmonic oscillator

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Harmonic oscillator $d = \infty$

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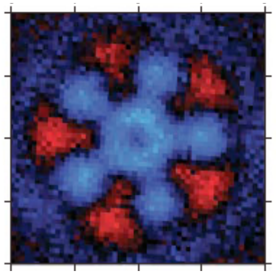
continuous variable

State preparation in microwave quantum optics

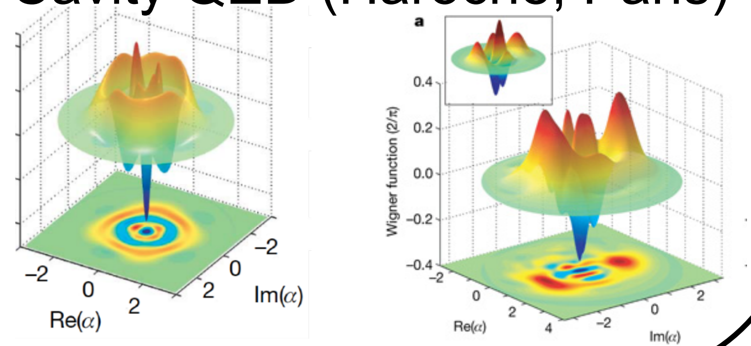
Fock states and superpositions



$$|0\rangle + |5\rangle$$

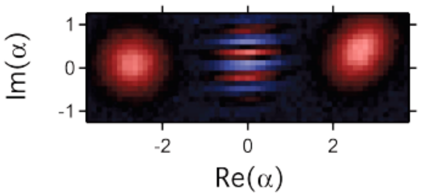
M. Hofheinz *et al.*,
Nature **2010**

Cavity QED (Haroche, Paris)

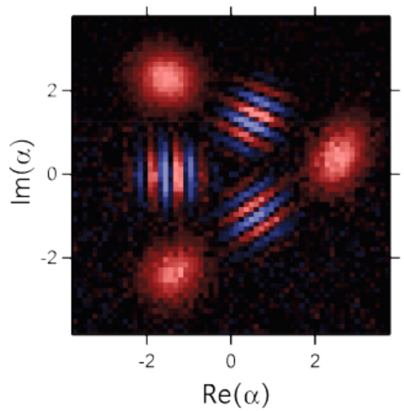


Schrödinger cats

$$|\alpha\rangle + |-\alpha\rangle$$



$$|\alpha\rangle + |e^{i\frac{2\pi}{3}}\alpha\rangle + |e^{i\frac{4\pi}{3}}\alpha\rangle$$

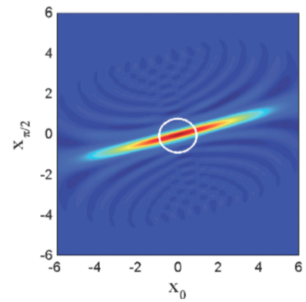


G. Kirchmair *et al.*,
Nature **2013**

Squeezed vacuum state

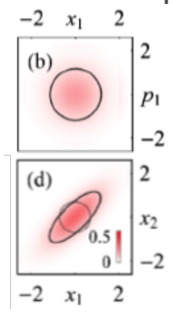
$$e^{ra^{\dagger 2} - r^* a^2}|0\rangle \qquad e^{ra^\dagger b^\dagger - r^* ab}|0,0\rangle$$

1-mode



F. Mallet *et al.*,
PRL **2011**

2-mode



C. Eichler *et al.*,
PRL **2011**

State preparation in microwave quantum optics

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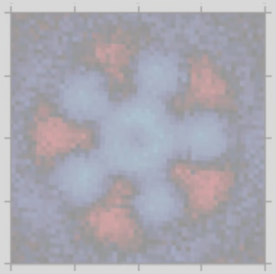
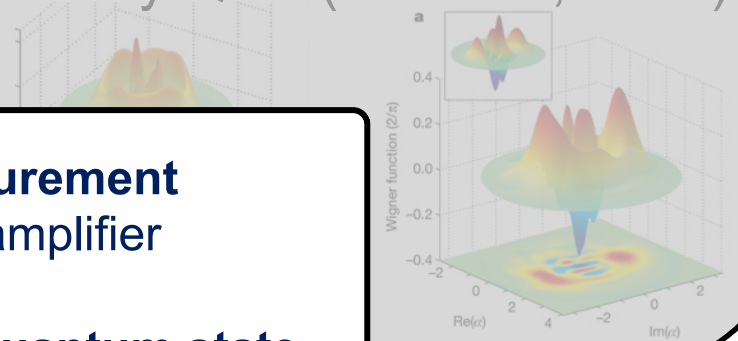


$|0\rangle + |5\rangle$

Cavity QED (Haroche, Paris)



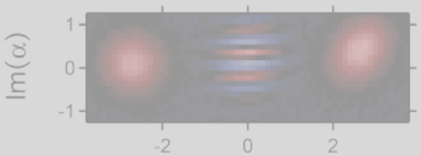
High fidelity measurement
phase-preserving amplifier

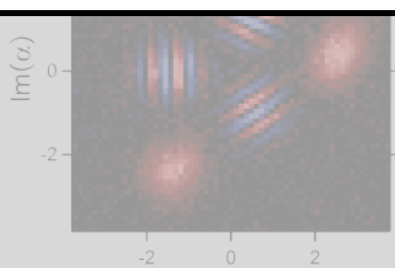
Storage of microwave quantum state
quantum memory

Generation of entanglement
over 2 spatially separated modes

Schrödi…

$|\alpha\rangle + |-\alpha\rangle$



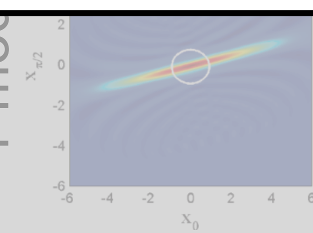


G. Kirchmair *et al.*, *Nature* **2013**

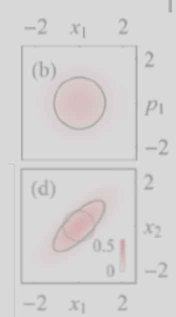
…acuum state

$e^{ra^\dagger b^\dagger - r^* ab}|0,0\rangle$

1-mod…



2-mode



F. Mallet *et al.*, *PRL* **2011**

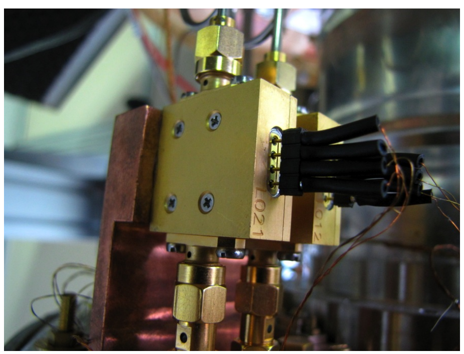
C. Eichler *et al.*, *PRL* **2011**

Microwave phase preserving amplifiers

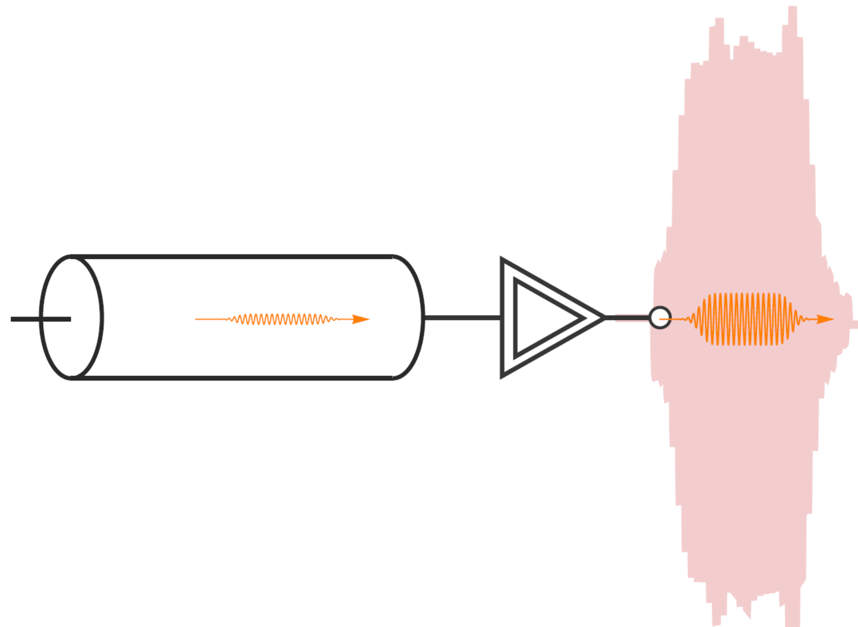
best commercial amplifiers (4K)

Caltech

LNF LOW NOISE FACTORY



4K at 2.5 GHz = 40 photons of noise



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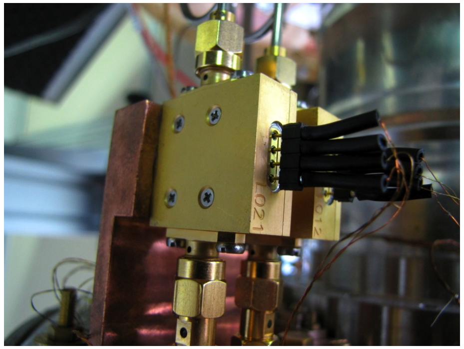

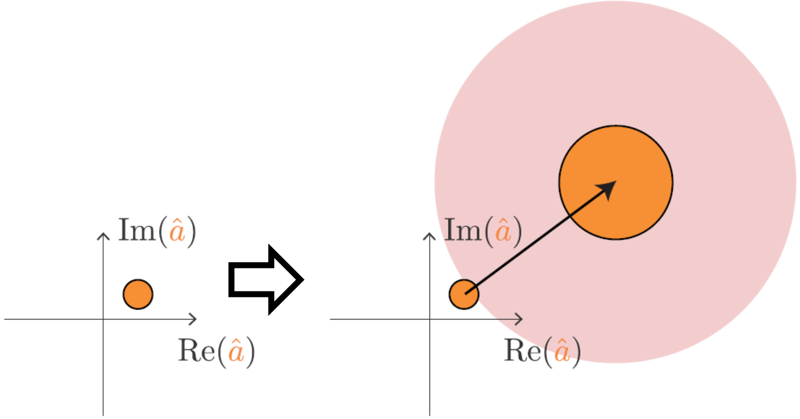

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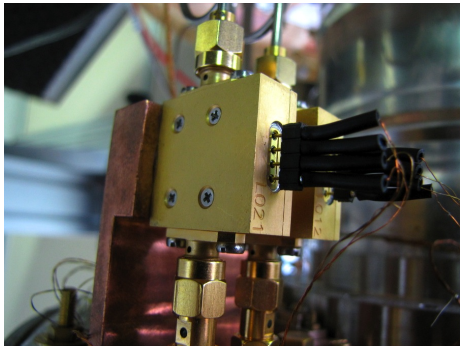
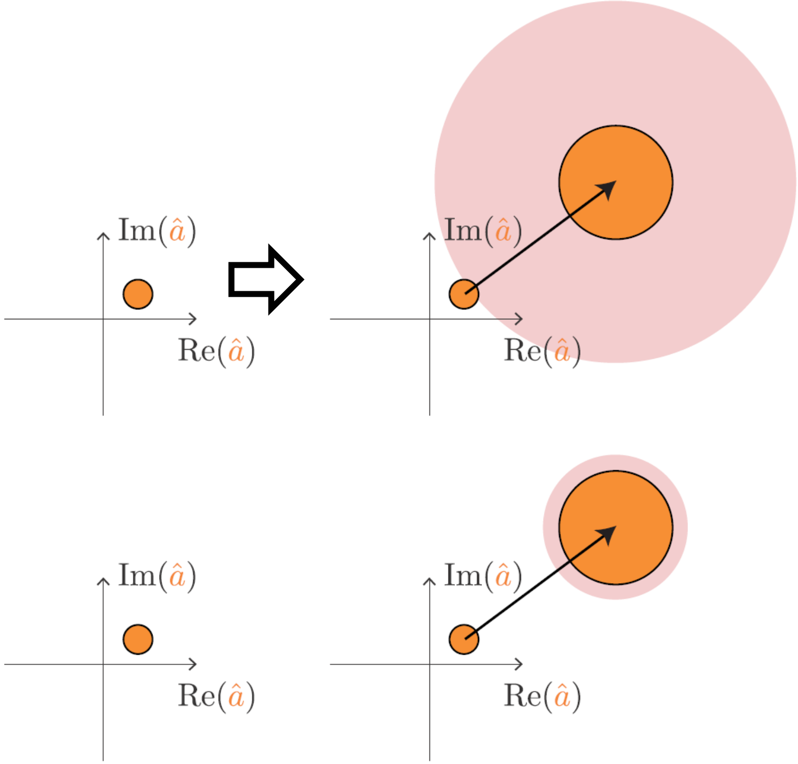
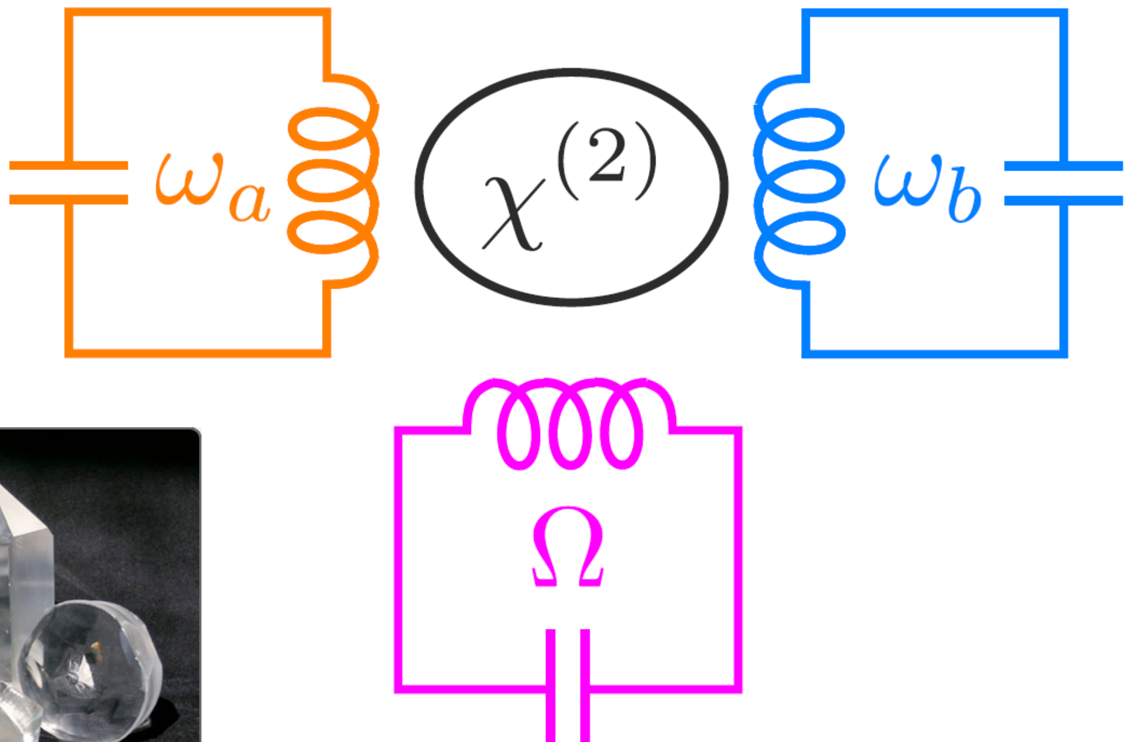




Quantum limited amplifier
½ quantum of noise (Caves, *PRD* **1982**)

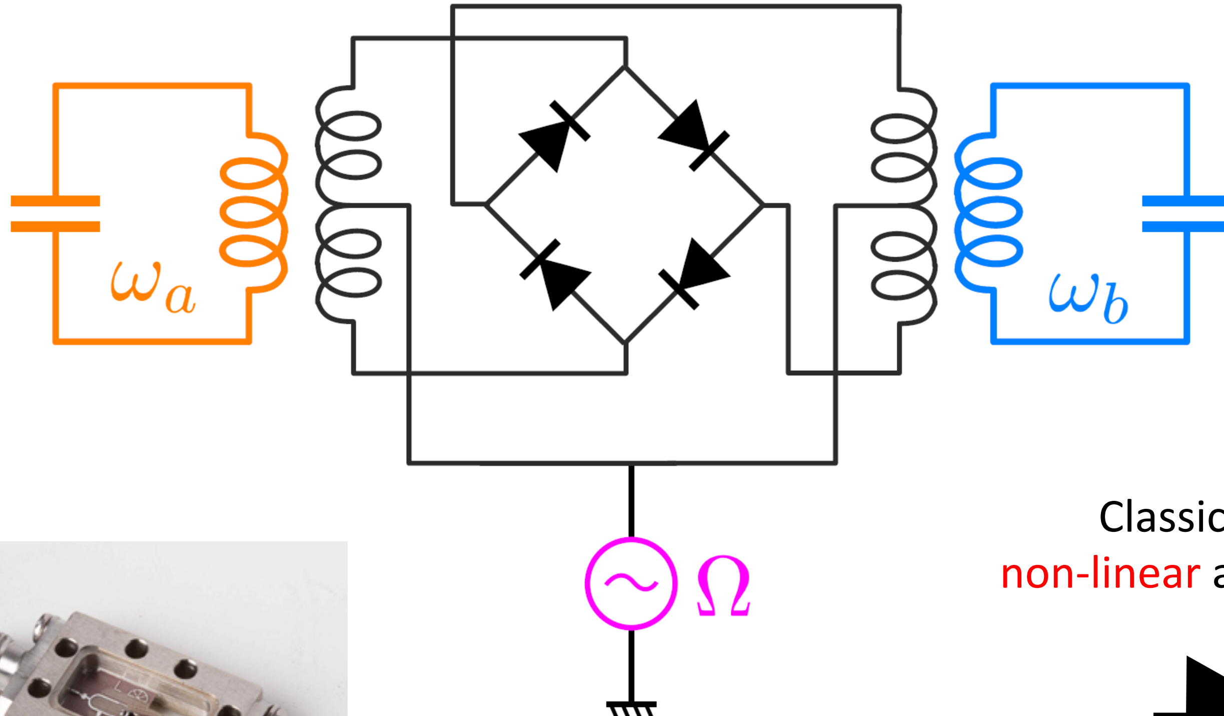
Three wave mixing at microwave frequencies

$$H_{mix} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

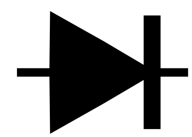


Lithium Triborate – LBO Crystals

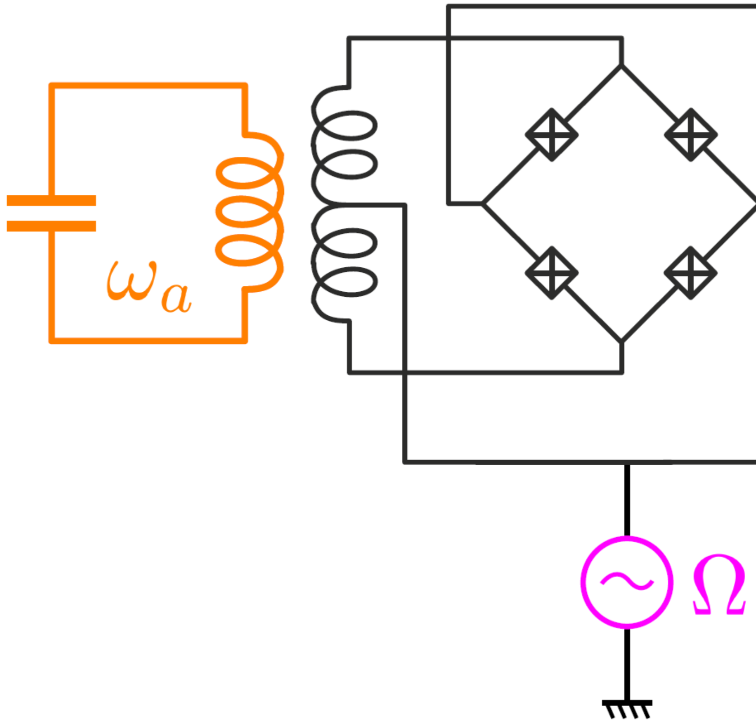
Three wave mixing at microwave frequencies



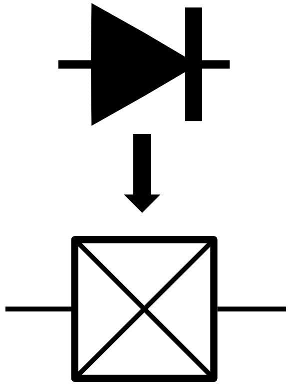
Classical diode :
non-linear and dissipative



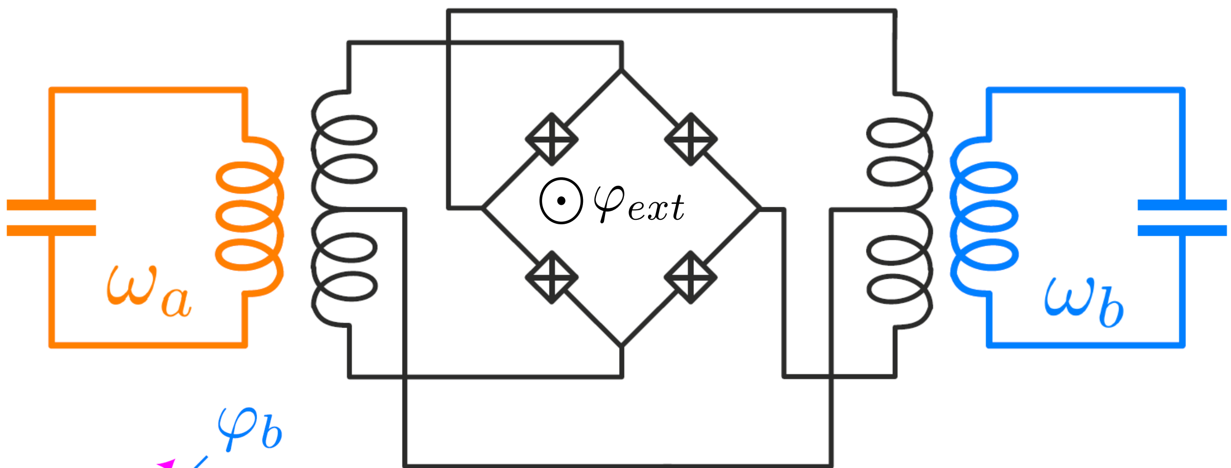
Three wave mixing at microwave frequencies

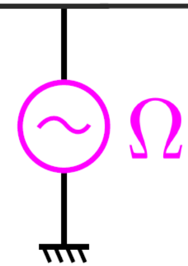


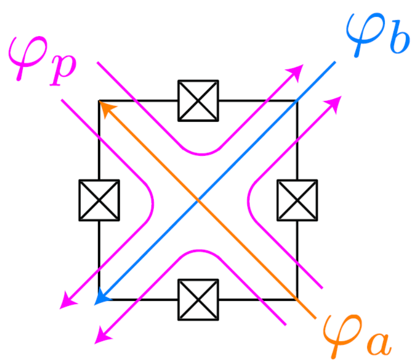
Jospehson junction :
non-linear and non-dissipative



Josephson mixer







$$\varphi_k = \varphi_k^{ZPF}(\hat{k} + \hat{k}^\dagger)$$

$$\varphi_k^{ZPF} = 1/\varphi_0\sqrt{hZ_k/2}$$

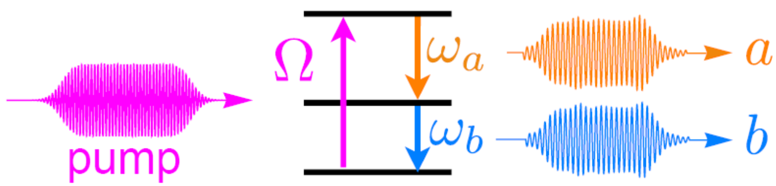
$$H_{mix} = g_3 \varphi_p \varphi_a \varphi_b$$

$$H_{mix} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

Amplification or Conversion

$$\Omega = \omega_a + \omega_b$$

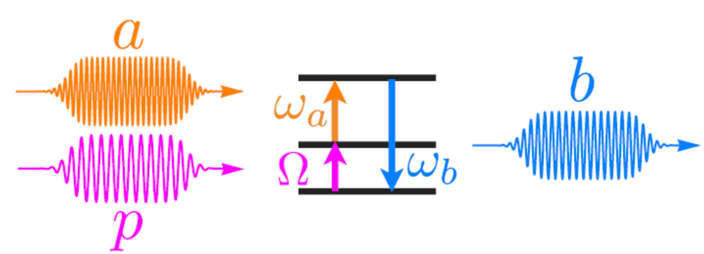
$$H_{mix} = \hbar\chi(p\hat{a}^\dagger\hat{b}^\dagger + p^*\hat{a}\hat{b})$$



Quantum limited amplifier
Entanglement source

$$\Omega = \omega_b - \omega_a$$

$$H_{mix} = \hbar\chi(p\hat{a}\hat{b}^\dagger + p^*\hat{a}^\dagger\hat{b})$$



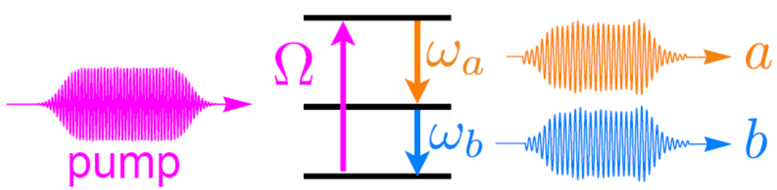
Noiseless frequency converter
Tunable coupler

$$H_{mix} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

Amplification or Conversion

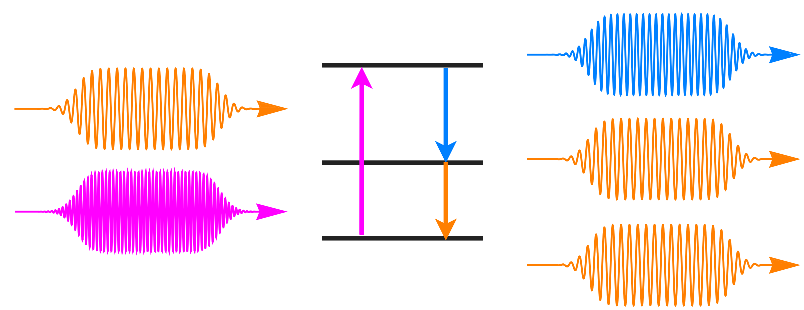
$$\Omega = \omega_a + \omega_b$$

$$H_{mix} = \hbar\chi(p\hat{a}^\dagger\hat{b}^\dagger + p^*\hat{a}\hat{b})$$



Quantum limited amplifier
Entanglement source

Basis of quantum limited amplification:
Stimulated emission

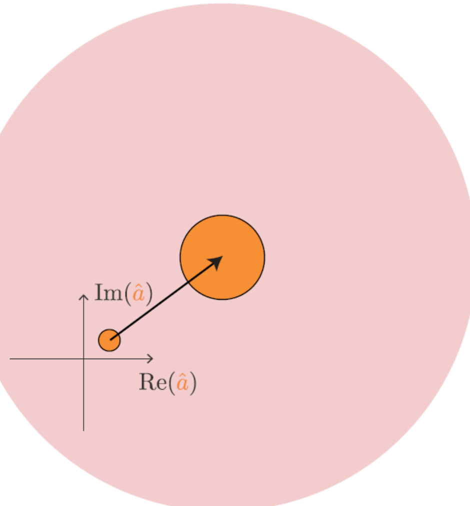


$$G = \frac{P + P_c}{P - P_c}$$

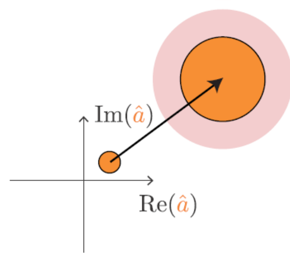
$$H_{mix} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

Amplification or Conversion

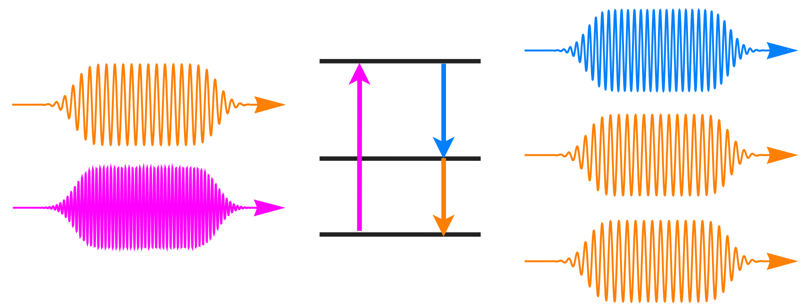
Commercial



Quantum limited



Basis of quantum limited amplification:
Stimulated emission

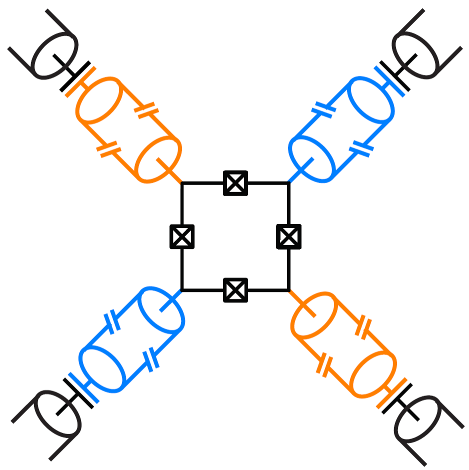


$$G = \frac{P + P_c}{P - P_c}$$

Phase-preserving quantum limited amplifier
½ quantum of noise (Caves, *PRD* **1982**)

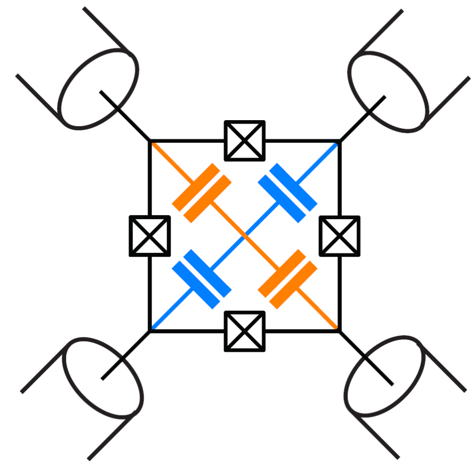
$$H_{mix} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

Distributed or lumped resonators



λ/2 resonators
High Q

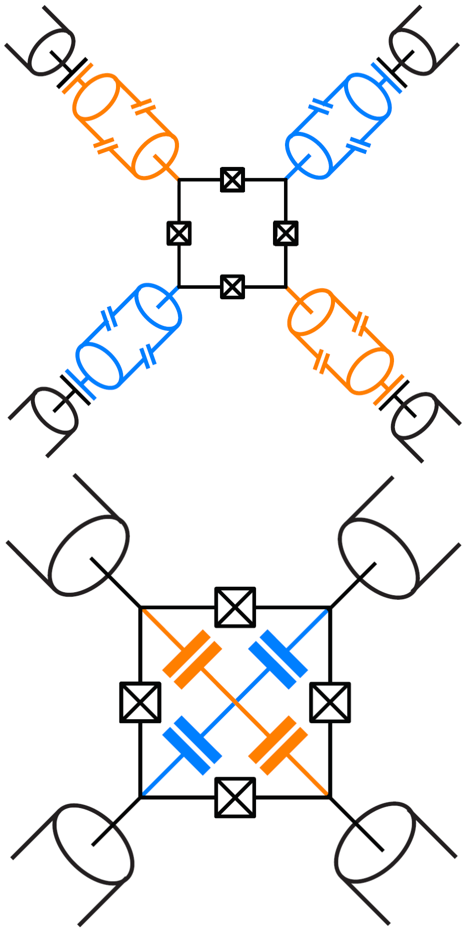
Bergeal *et al.*, *Nature* **2010**
N. Roch *et al.*, *PRL* **2012**

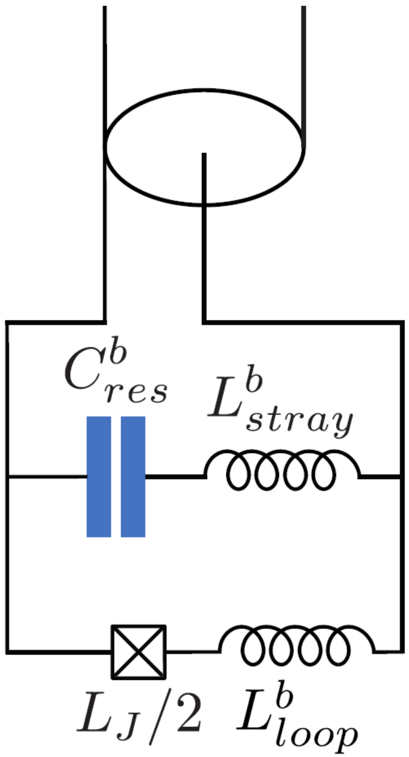


Lumped elements
Low Q
Optimal design for amplifier

$$H_{mix} = \hbar\chi(\hat{p} + \hat{p}^{\dagger})(\hat{a} + \hat{a}^{\dagger})(\hat{b} + \hat{b}^{\dagger})$$

Why lumped is the optimum amplifier ?





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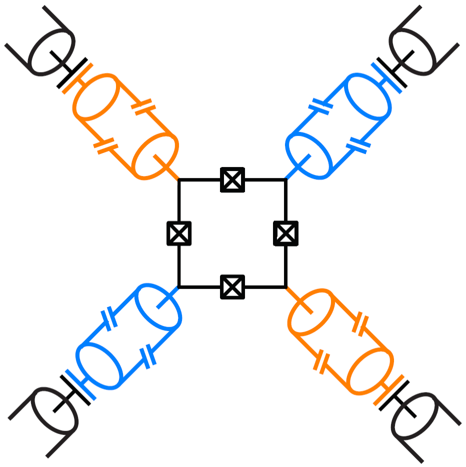
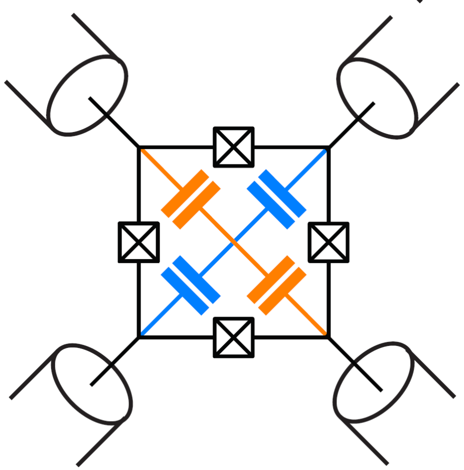
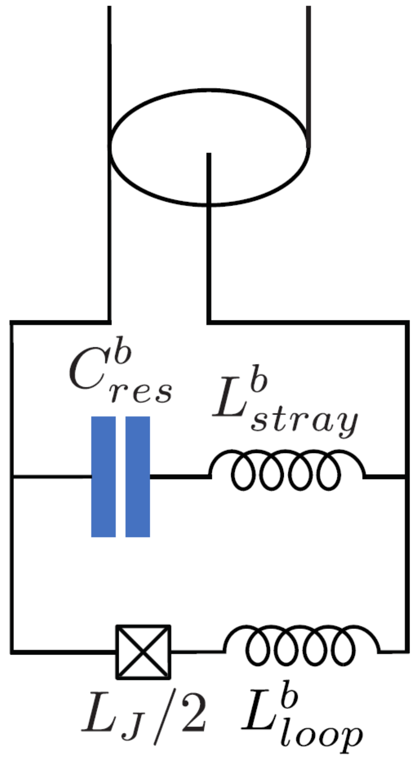




Amplification is a trade off

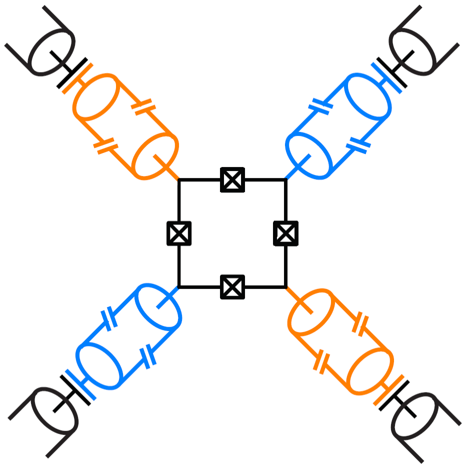


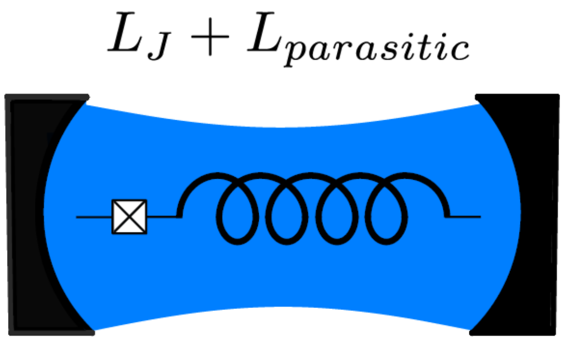
$$L_J = \frac{\varphi_0}{2\pi I_c}$$

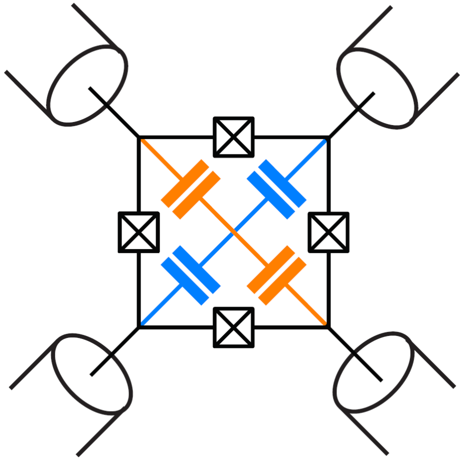
L_J small => non-linearity too weak

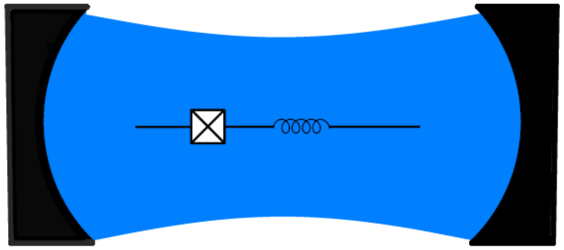
L_J large => junctions can't sustain few photons

Why lumped is the optimum amplifier ?

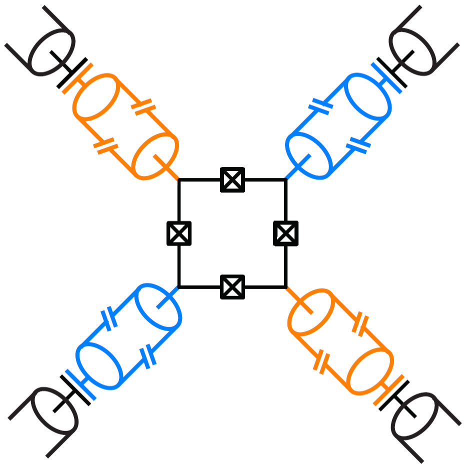




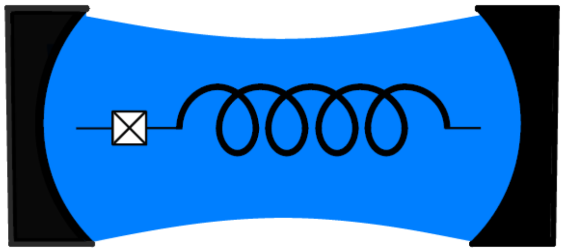




Why lumped is the optimum amplifier ?

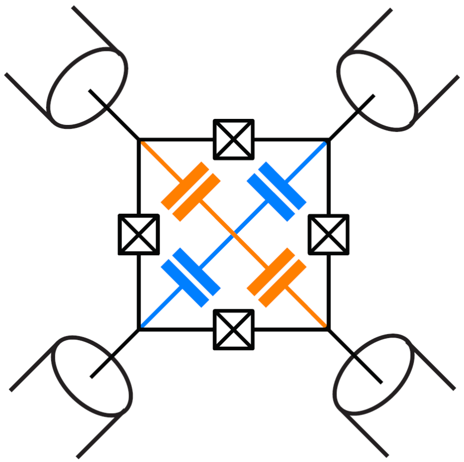


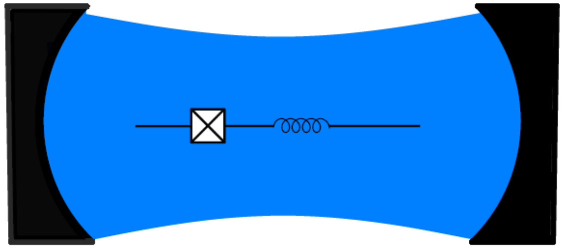
$$L_J + L_{parasitic}$$



$$p = \frac{L_J}{L_J + L_{parasitic}}$$

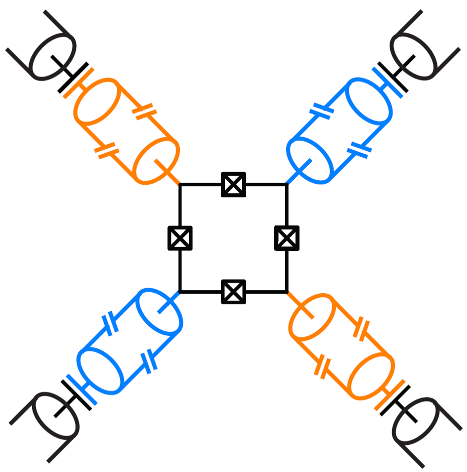
$p \approx 0.01$



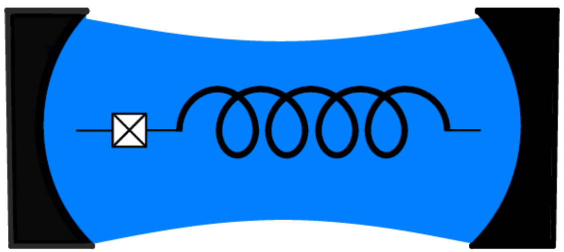


$p \approx 0.3$

Why lumped is the optimum amplifier ?



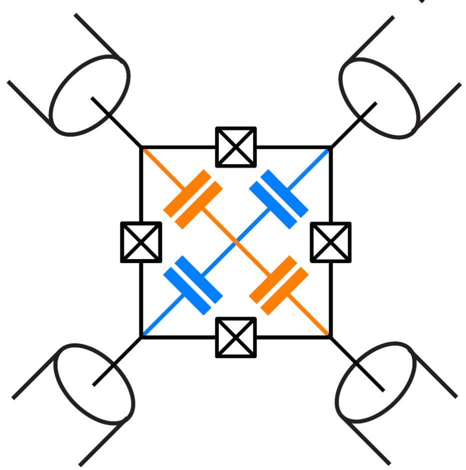
$L_J + L_{parasitic}$

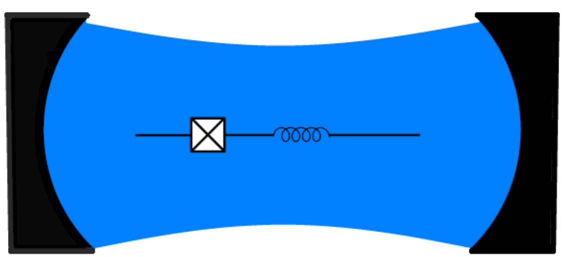


$p = \frac{L_J}{L_J + L_{parasitic}}$

$p \approx 0.01 \rightarrow Q \approx 100$

High Q => slower, smaller bandwidth



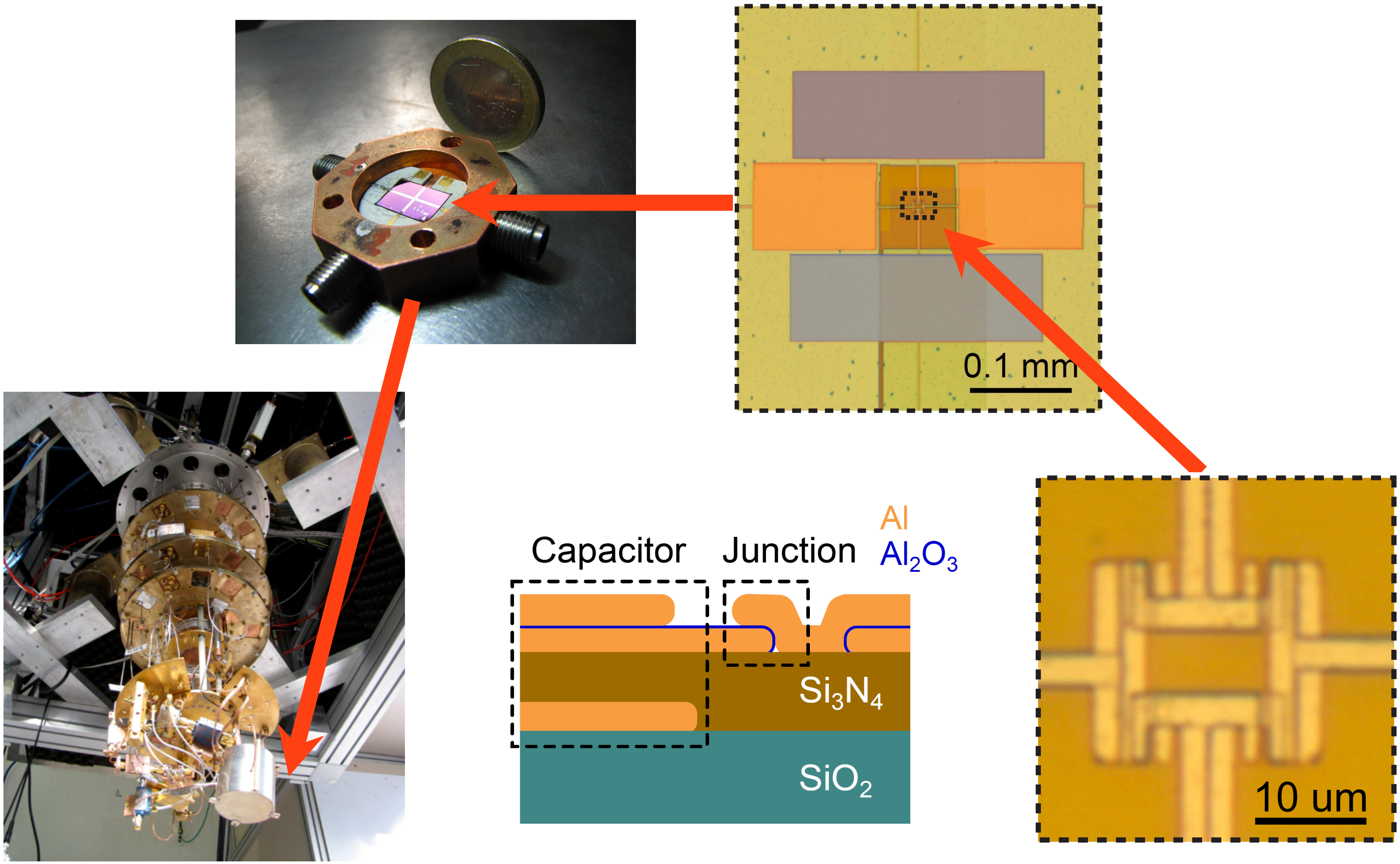


$p \times Q >\approx 1$

$p \approx 0.3 \rightarrow Q \approx 10$

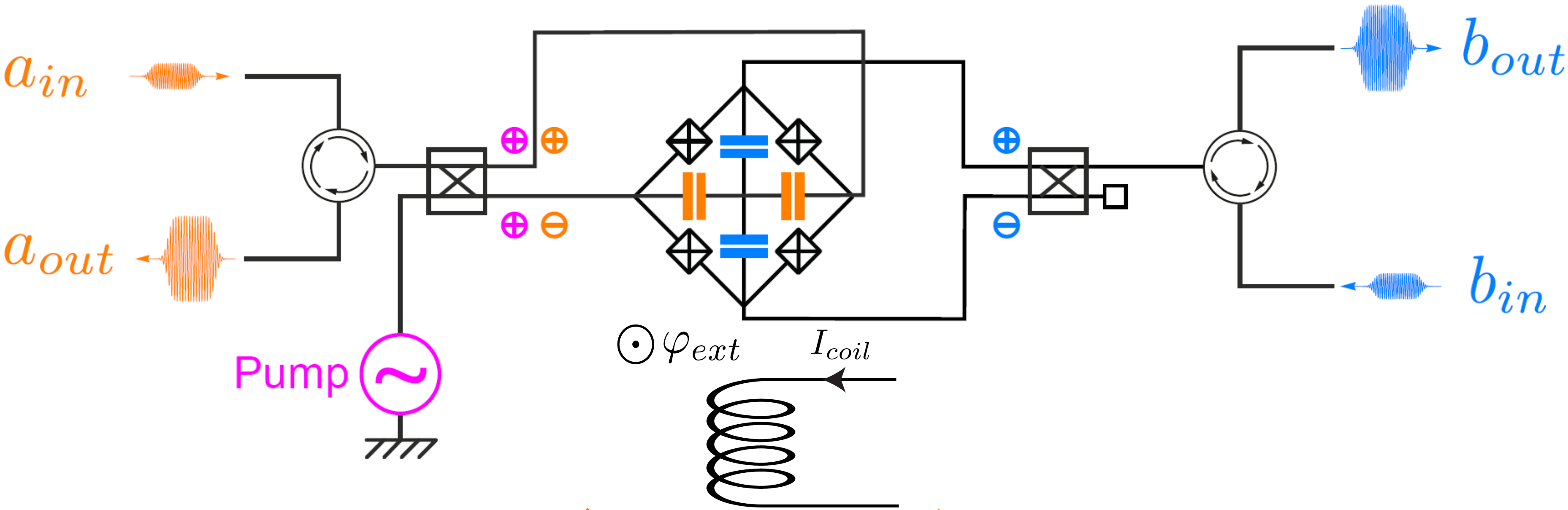
Larger bandwidth for similar performance

Realization

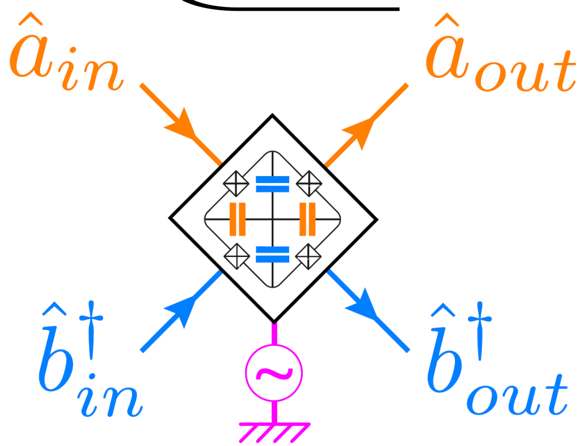


T=40 mK

Setup



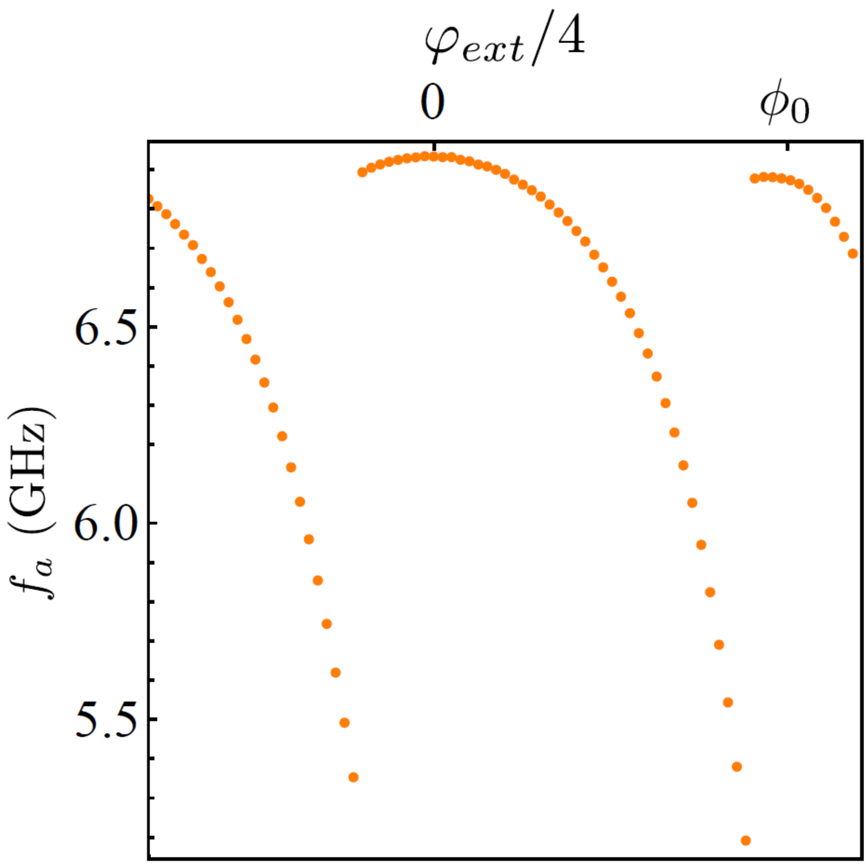
a_{in}
a_{out}
b_{out}
b_{in}
Pump
$\odot\, \varphi_{ext}$
I_{coil}

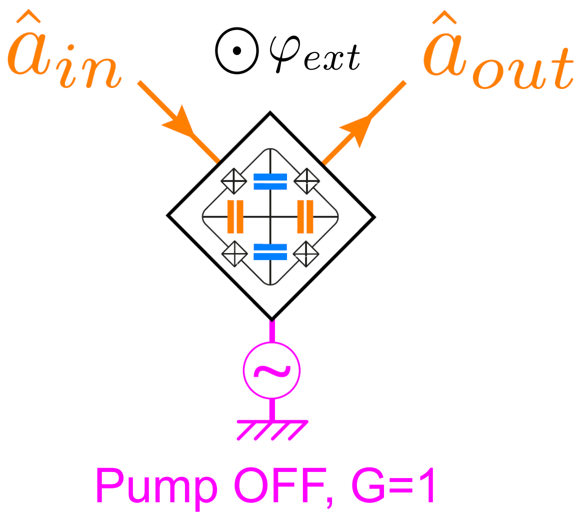


$\hat{a}_{in}$
$\hat{a}_{out}$
$\hat{b}^{\dagger}_{in}$
$\hat{b}^{\dagger}_{out}$

Characterization of the resonators

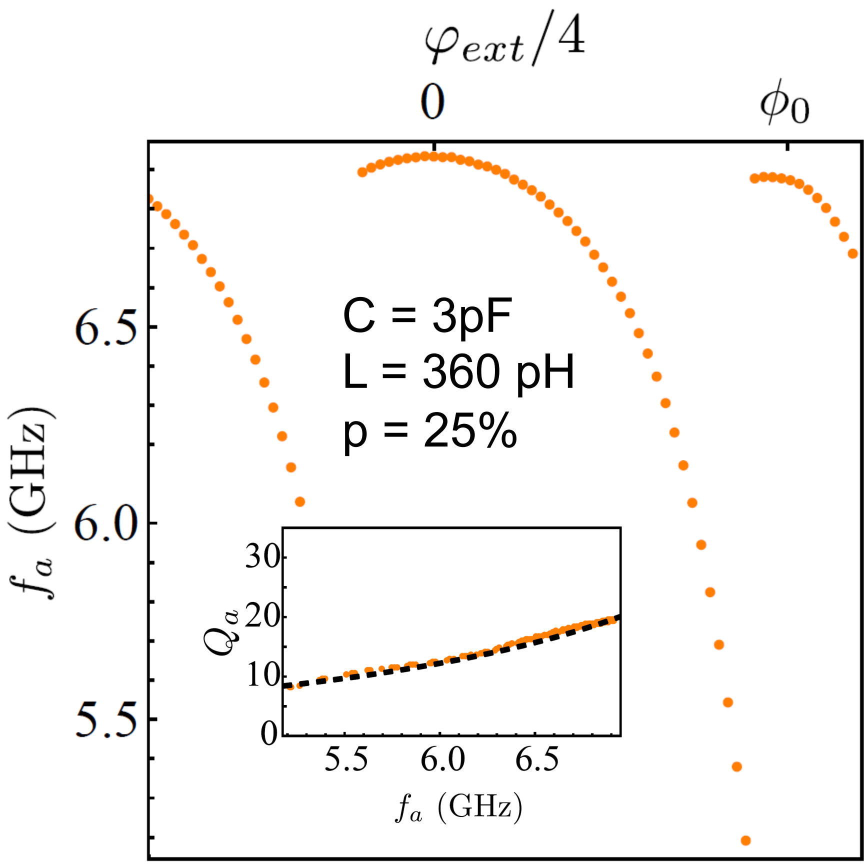
Measurement of the resonant frequency

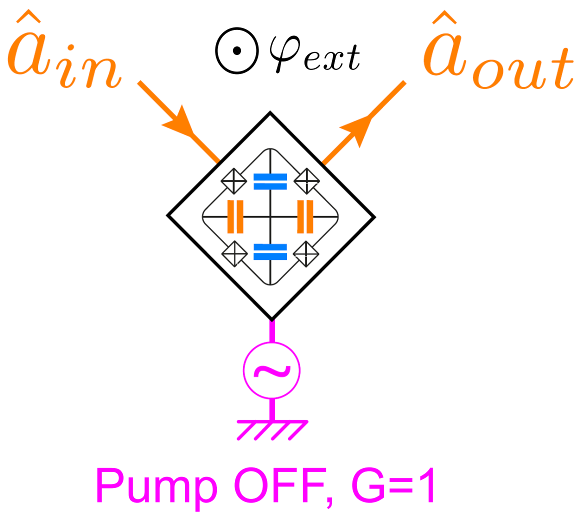




Characterization of the resonators

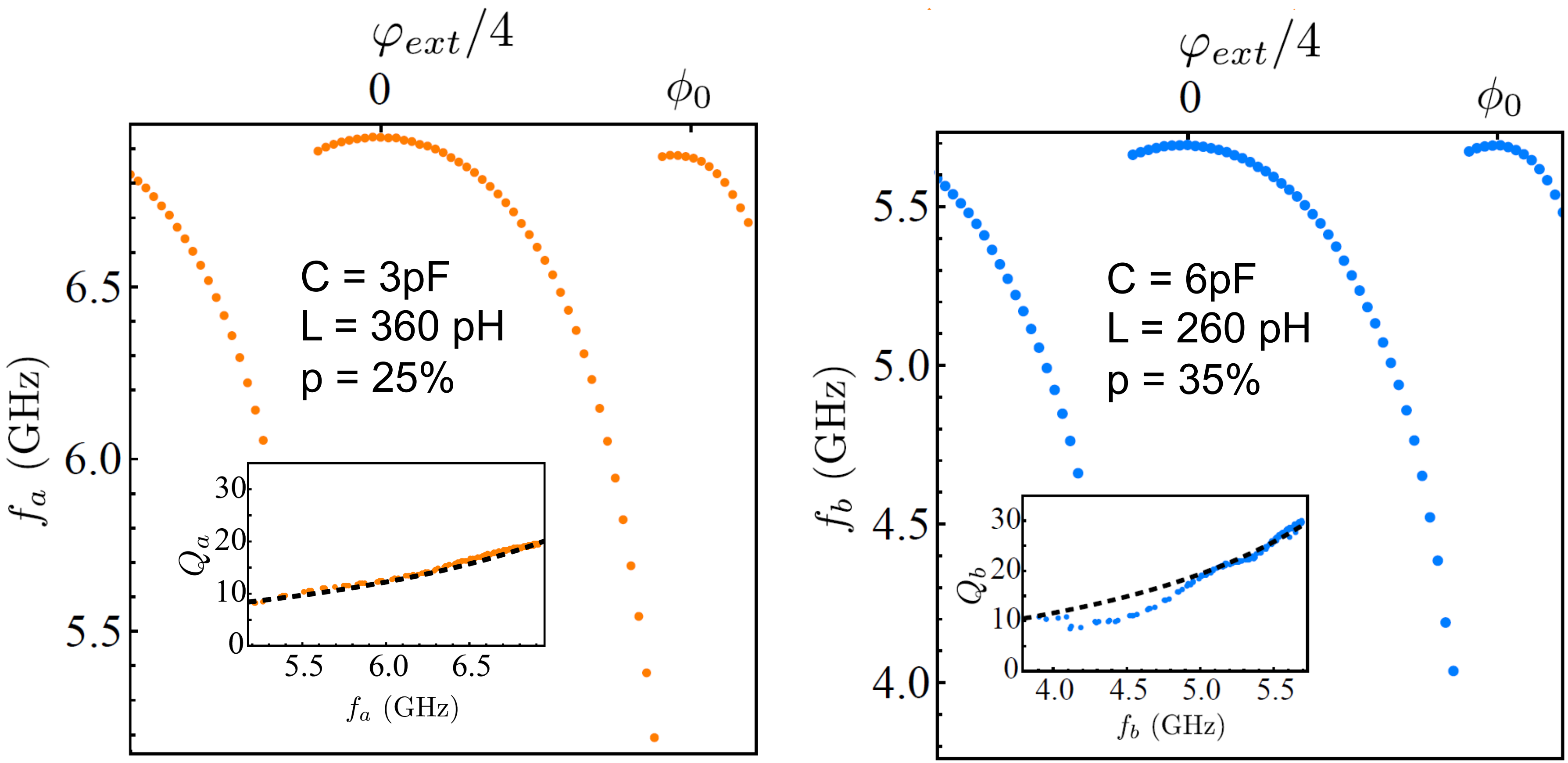
Measurement of the resonant frequency





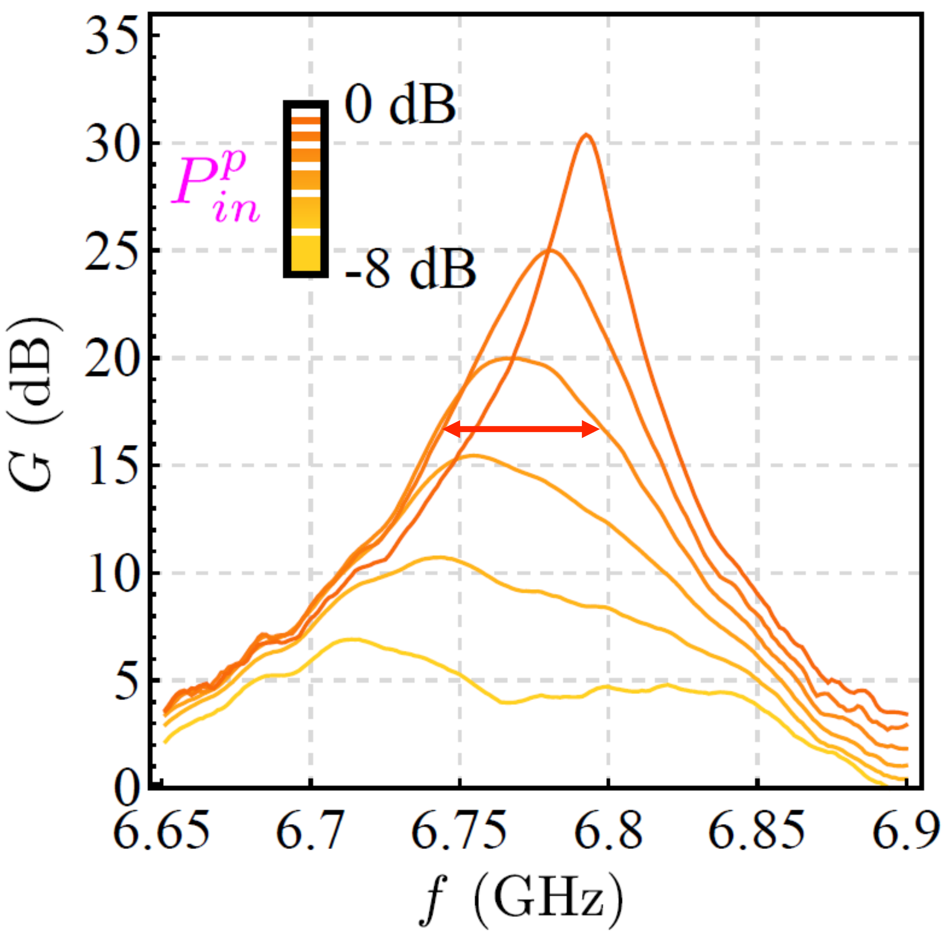
Characterization of the resonators

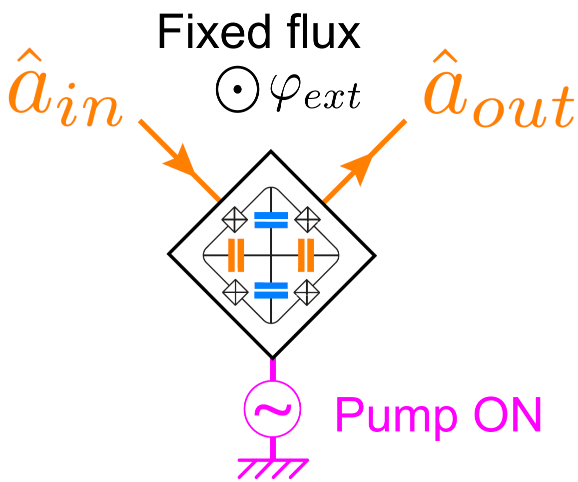
Measurement of the resonant frequency



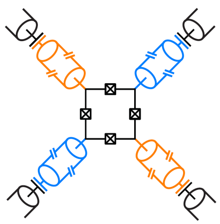
Very Large tunability (thanks to large p)

Amplification

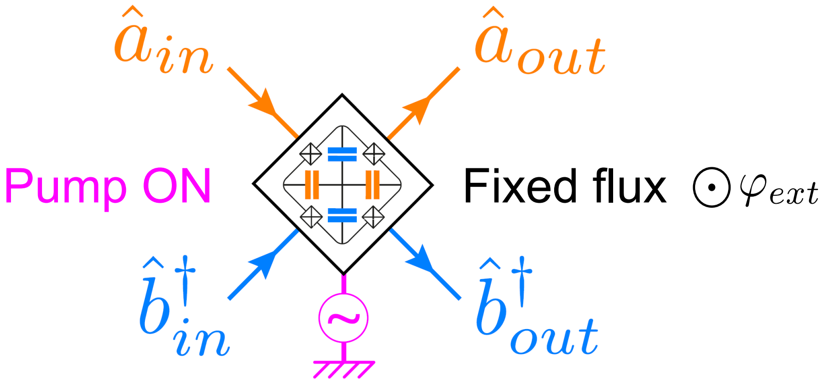




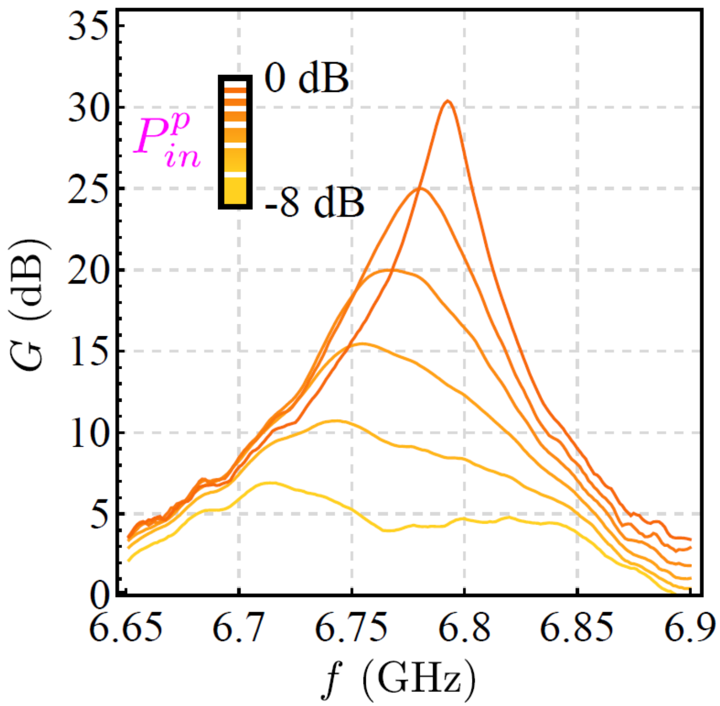
- More than 50 MHz at 20dB
- One order of magnitude higher than Josephson amplifier with distributed resonator

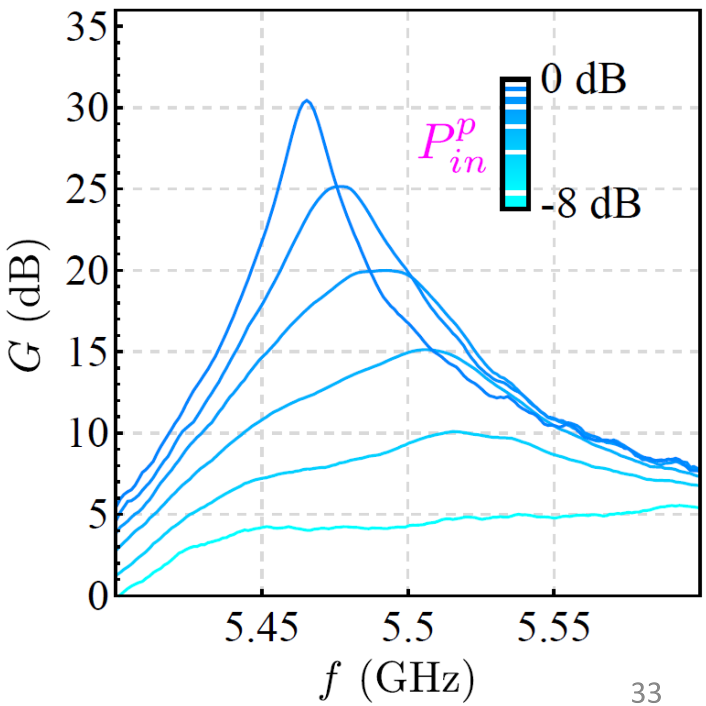


Amplification



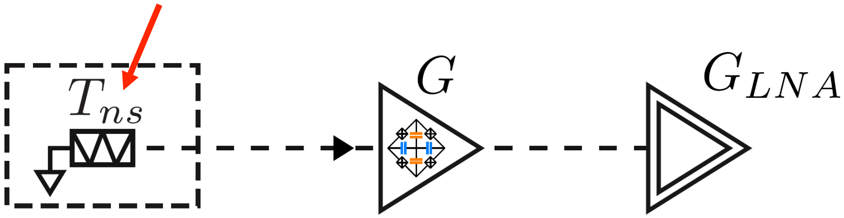
Large bandwith => multiplexing of qubits
Low Q => fast enough for Quantum feedback





Quantum limited

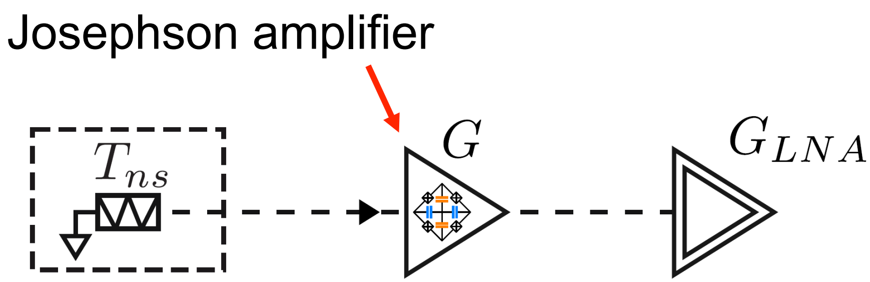
50 Ohm noise source (controllable temperature)



Black body radiation

$$S(T_{ns}) = \frac{1}{2}\coth\left[\frac{hf_b}{2k_B T_{ns}}\right]$$

Quantum limited

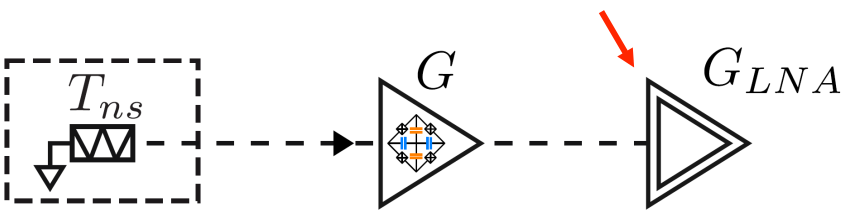


Black body radiation

$$S(T_{ns}) = \frac{1}{2}\coth\left[\frac{hf_b}{2k_B T_{ns}}\right]$$

Quantum limited

Commercial amplifier

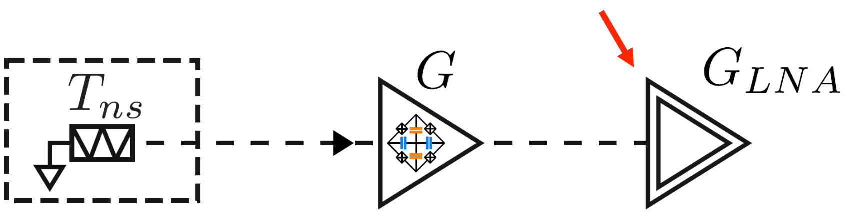


Black body radiation

$$S(T_{ns}) = \frac{1}{2}\coth\left[\frac{hf_b}{2k_B T_{ns}}\right]$$

Quantum limited

Commercial amplifier



Black body radiation

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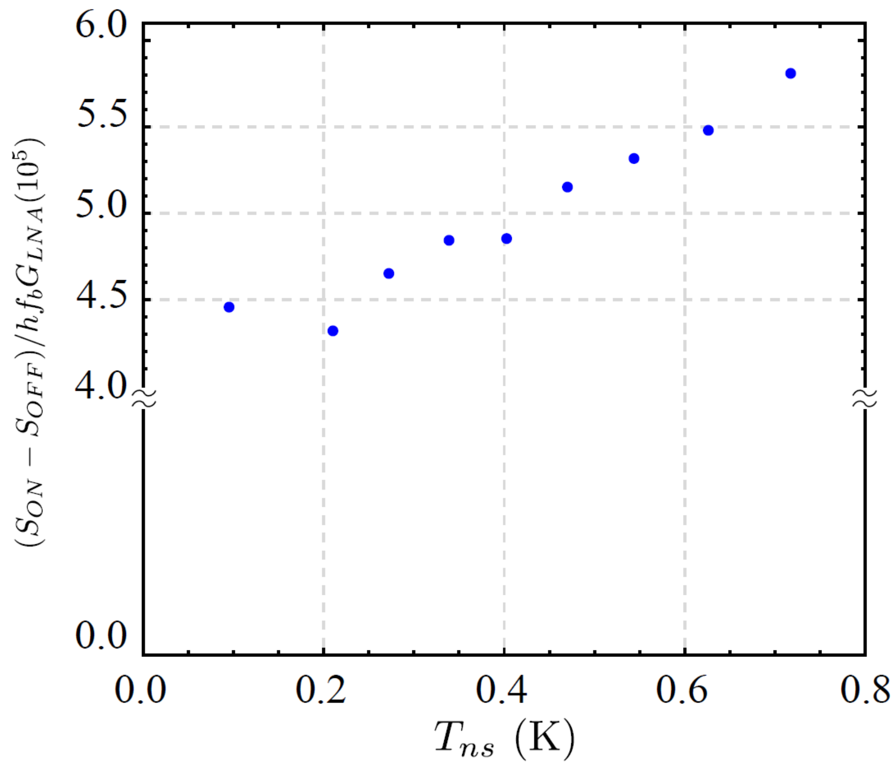
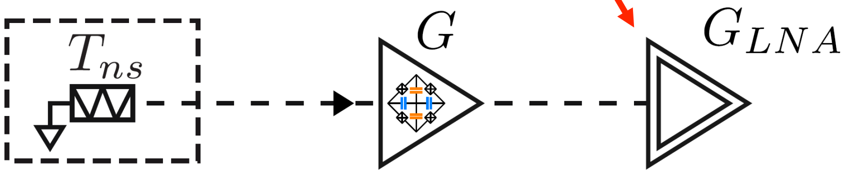


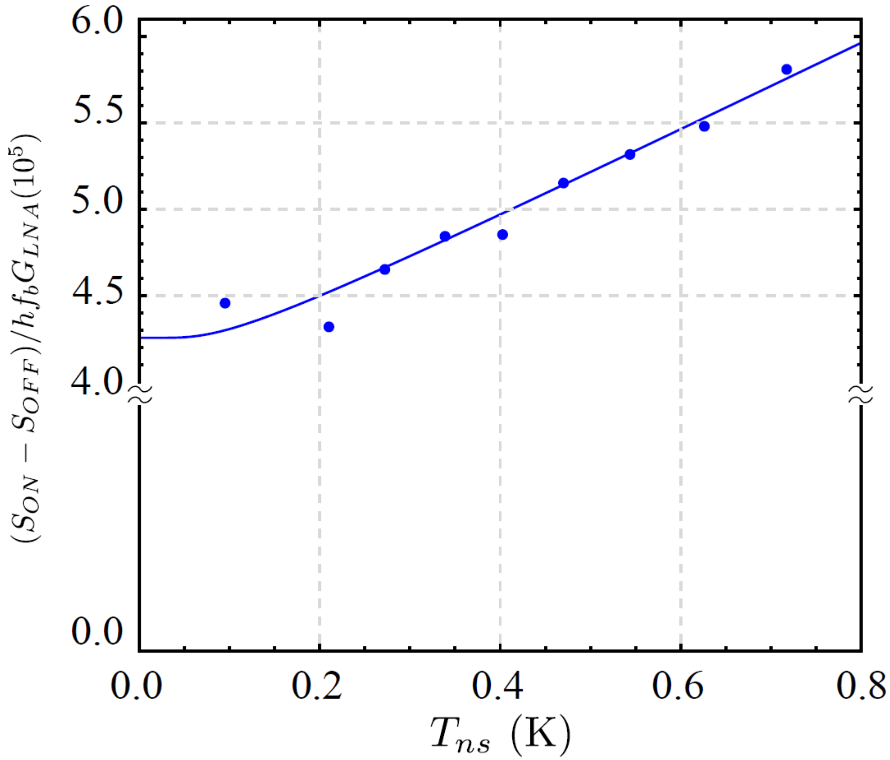
Quantum limited

Commercial amplifier



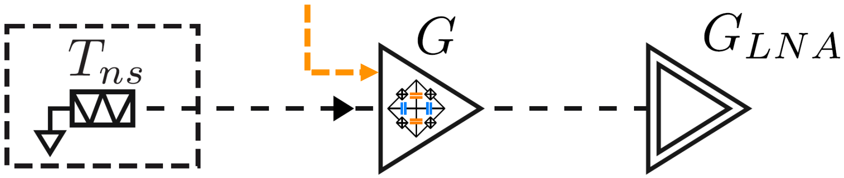
Black body radiation

$$S(T_{ns}) = \frac{1}{2}\coth\left[\frac{hf_b}{2k_B T_{ns}}\right]$$



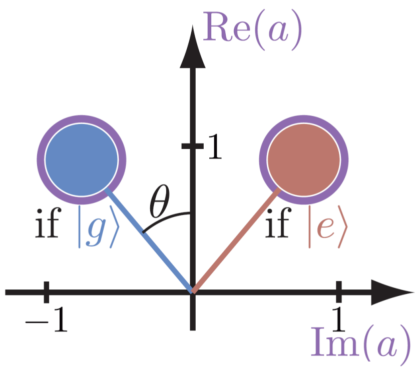
Quantum limited

T = 50 mK

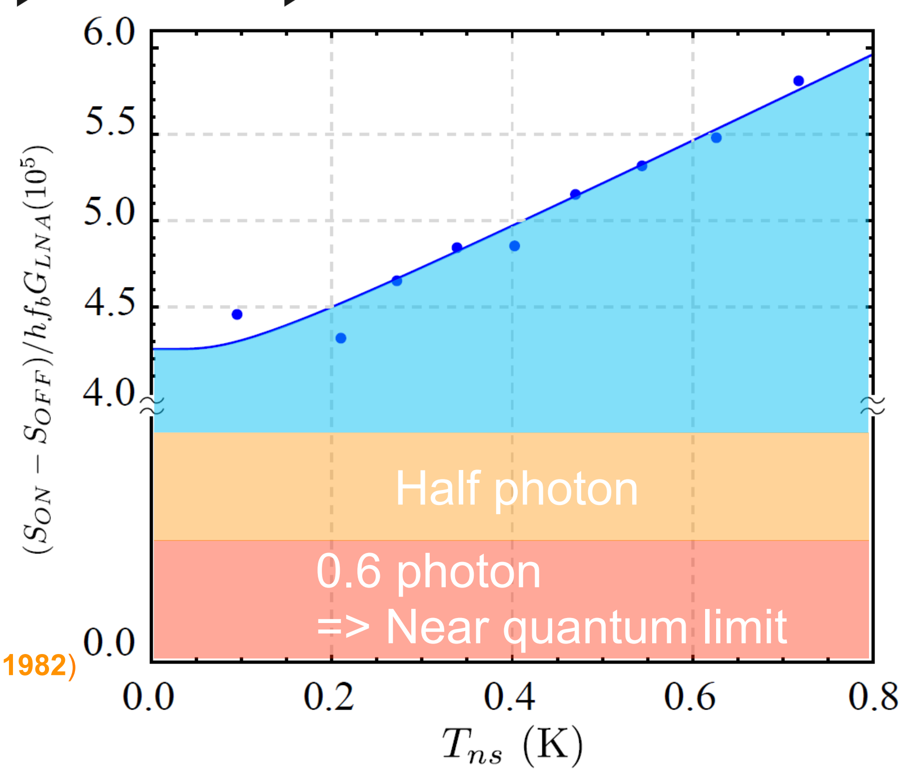


Black body radiation

$$S(T_{ns}) = \frac{1}{2}\coth\left[\frac{hf_b}{2k_BT_{ns}}\right]$$



Less than 0.2 photons of noise



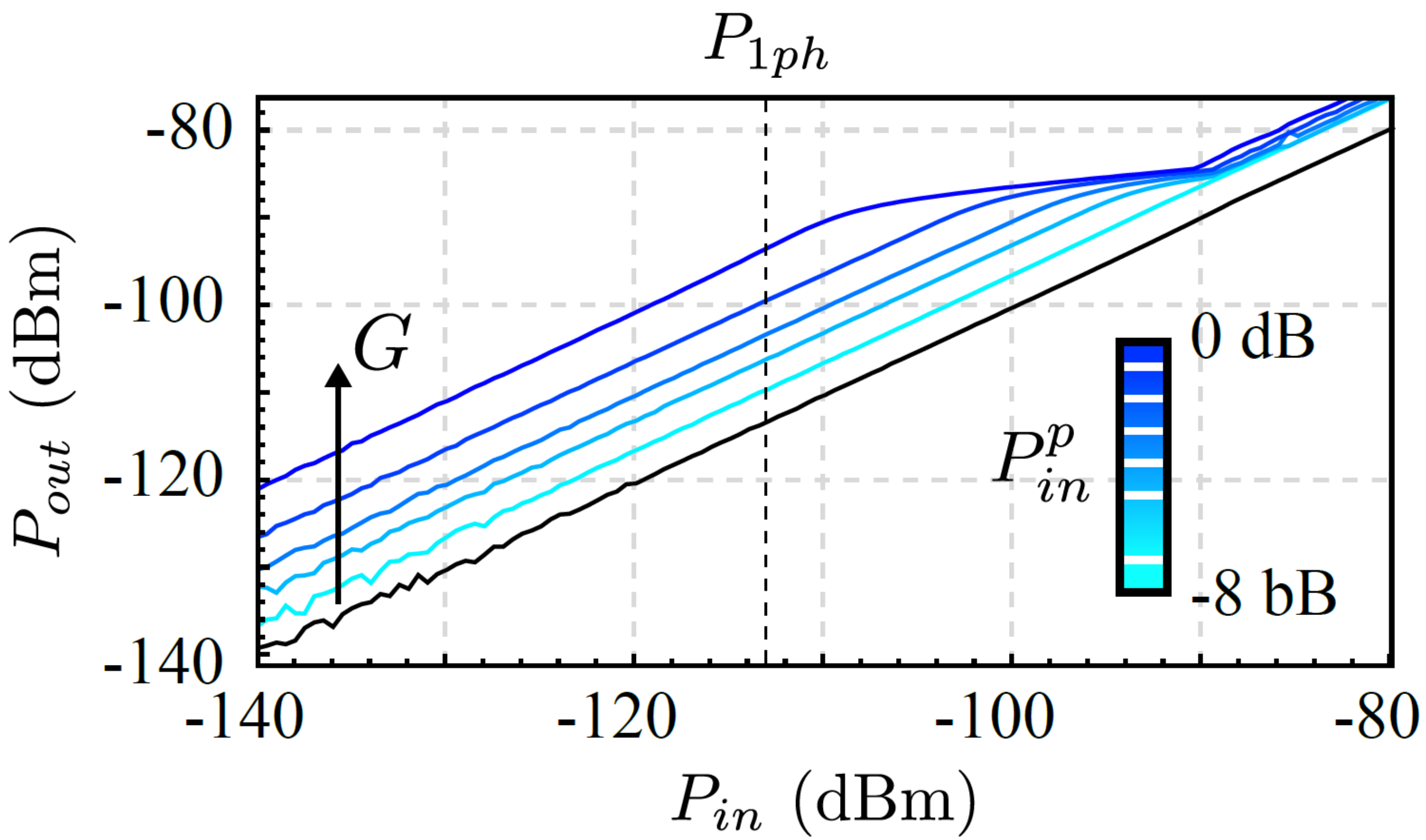
Amplified noise source radiation

Minimum Quantum noise

Amplifier extra noise

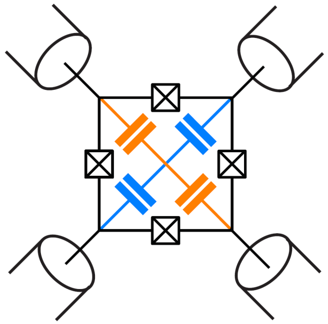
Quantum limited amplifier
½ quantum of noise (Caves, *PRD* **1982**)

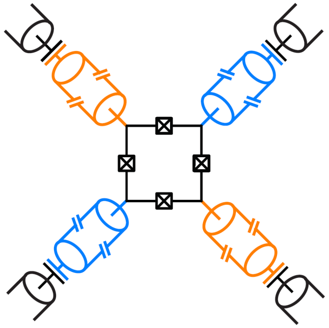
Dynamical range



Amplifier suitable for few photons measurements

Low Q versus high Q



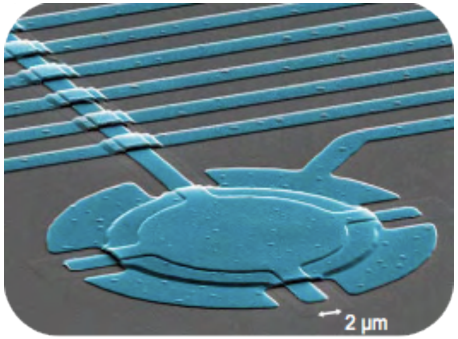


Low Q
Higher bandwidth
Faster
Optimal amplifier

High Q
Longer lifetime resonator
Quantum memory

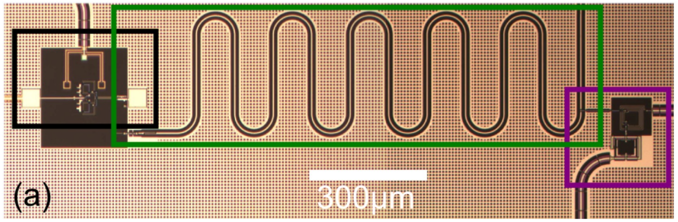
Quantum memory for microwave

Mechanical resonator



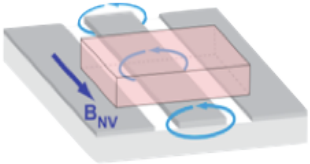
Palomaki *et al.*, *Nature* **2013**

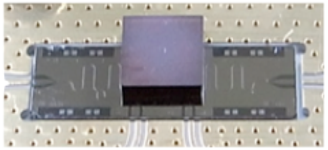
High Q 2D cavity



Yin *et al.*, *PRL* **2013**

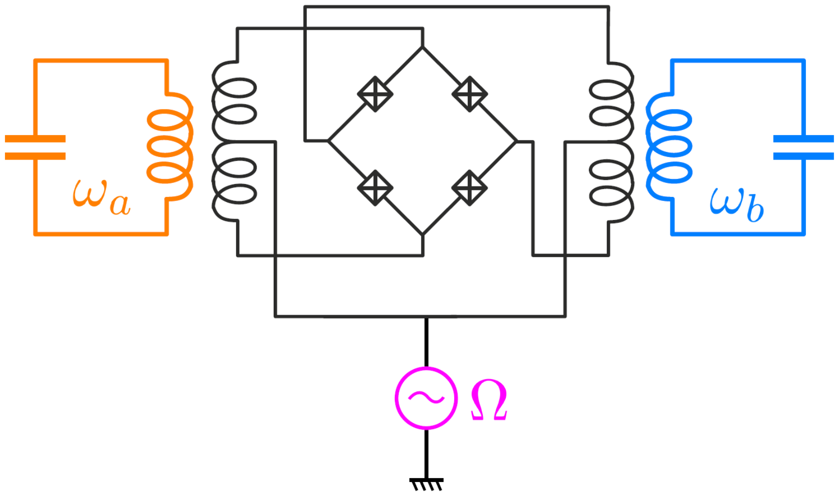
Spin ensembles



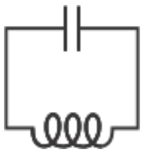


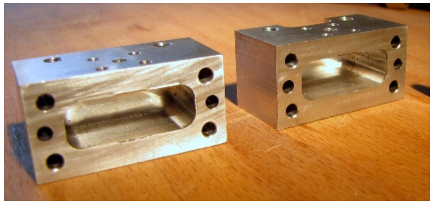
Zhu *et al.*, *Nature* **2011**
Kubo *et al.*, *PRL* **2011**

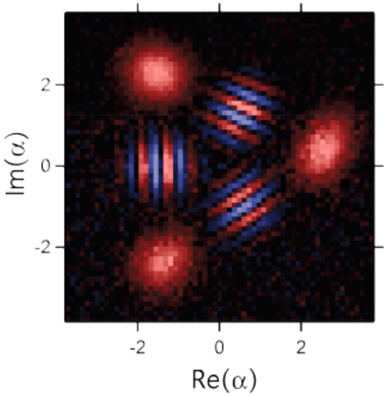
3D cavity for storage



High-Q superconducting cavities



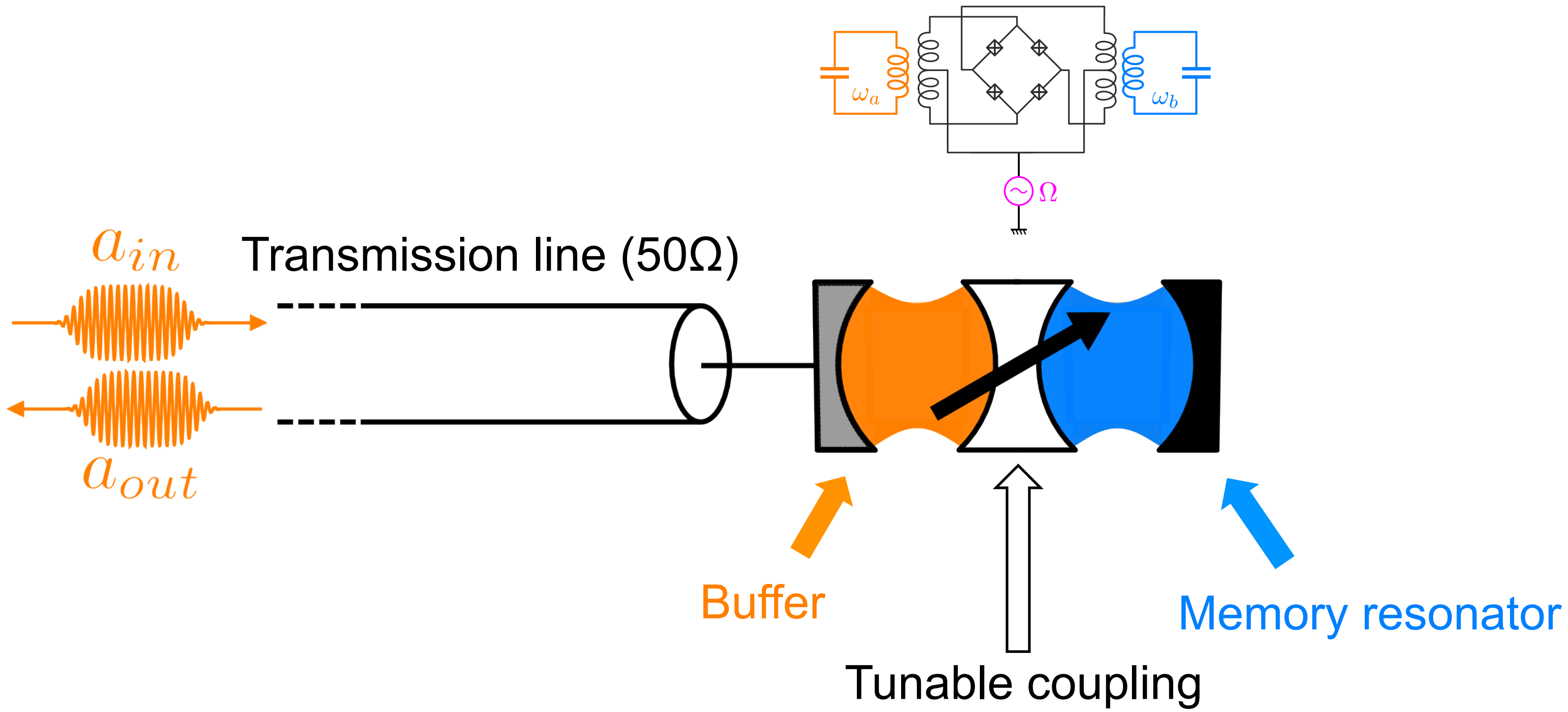




G. Kirchmair *et al.*, *Nature* **2013**

Q up to 1 million

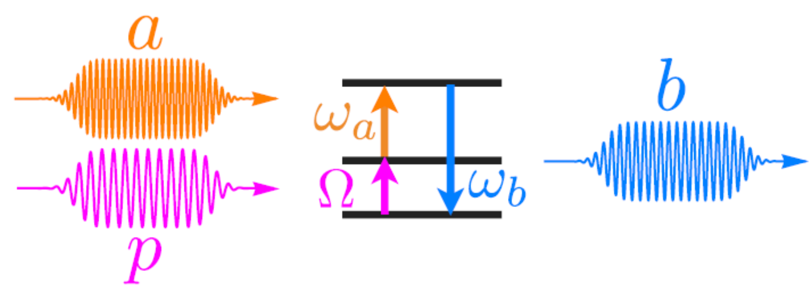
Quantum memory for microwaves

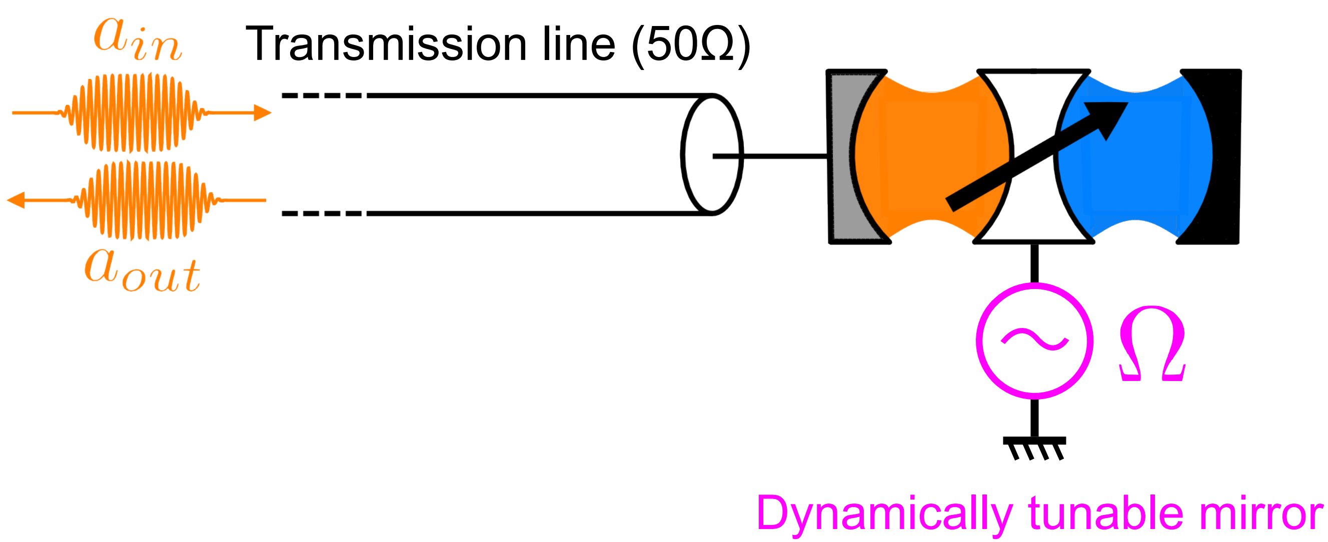


Quantum memory for microwaves

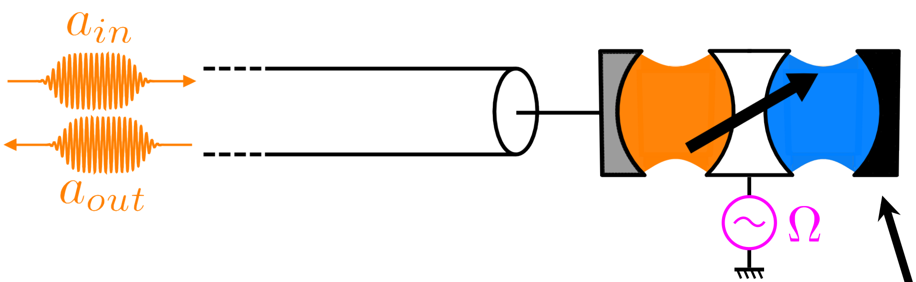
$$\Omega = \omega_b - \omega_a$$

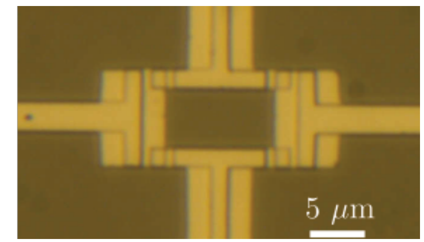
$$H_{mix} = \hbar\chi(p\hat{a}\hat{b}^\dagger + p^*\hat{a}^\dagger\hat{b})$$



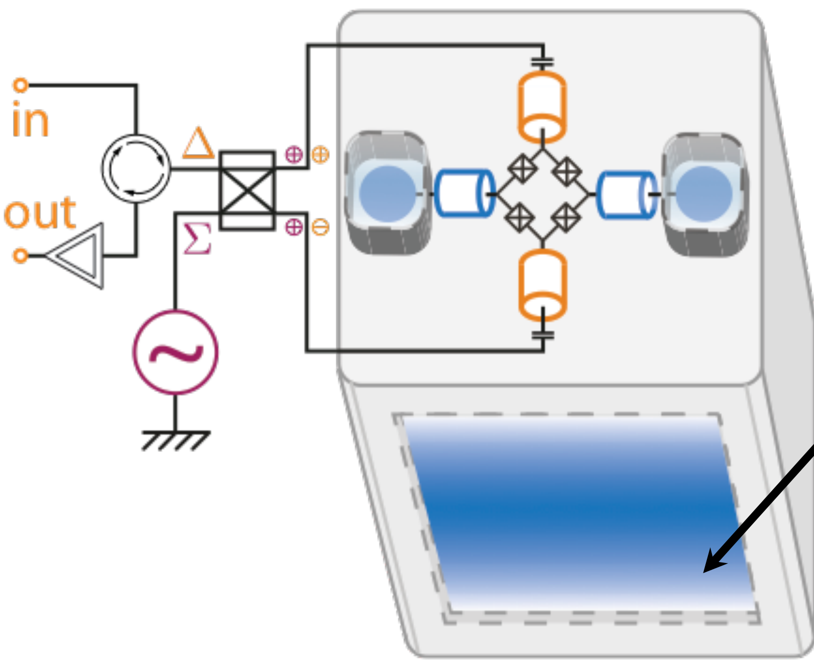


Quantum memory for microwaves



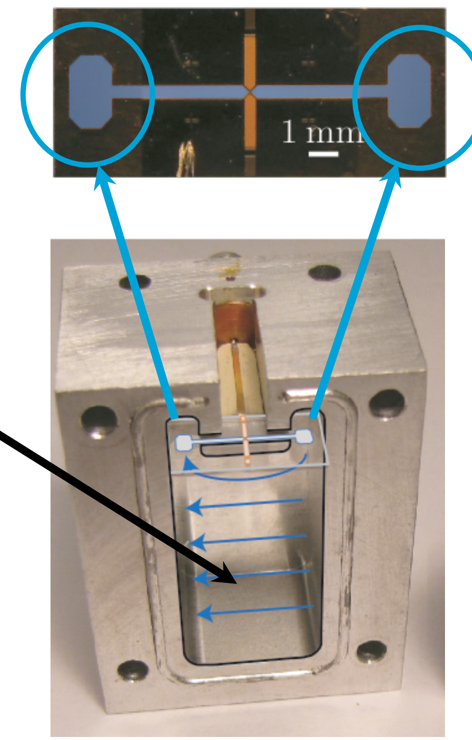


memory cavity

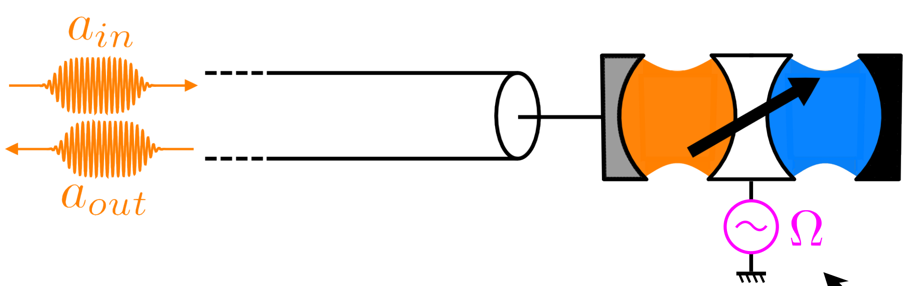


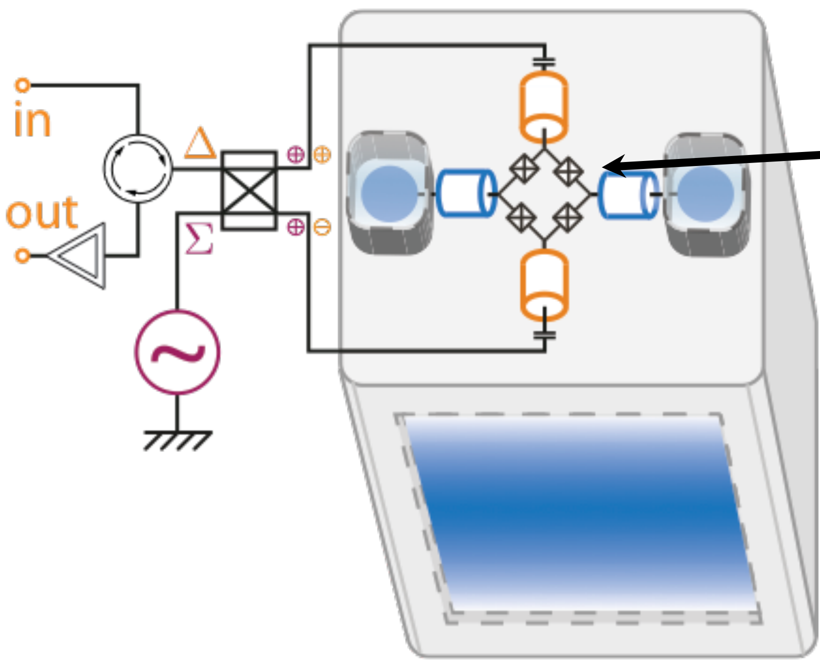
3D superconducting cavity for enhanced storage time

$$f_b = 7.5 \text{ GHz}$$



Quantum memory for microwaves

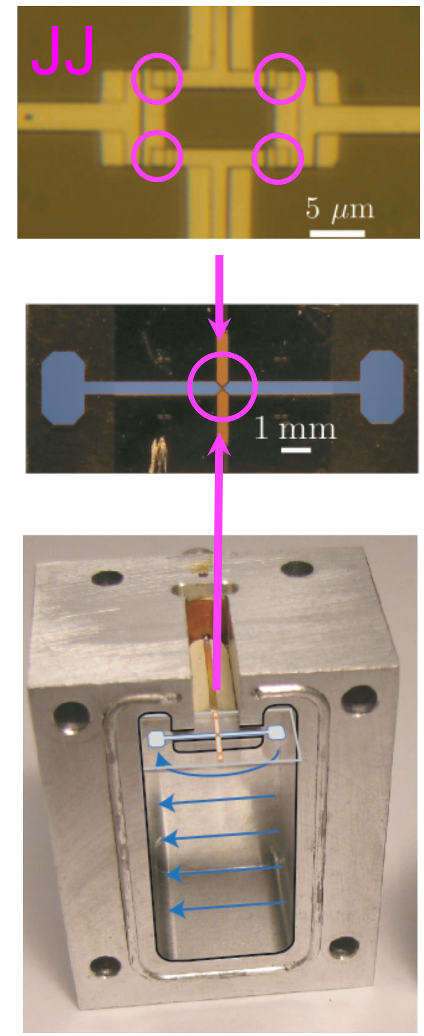




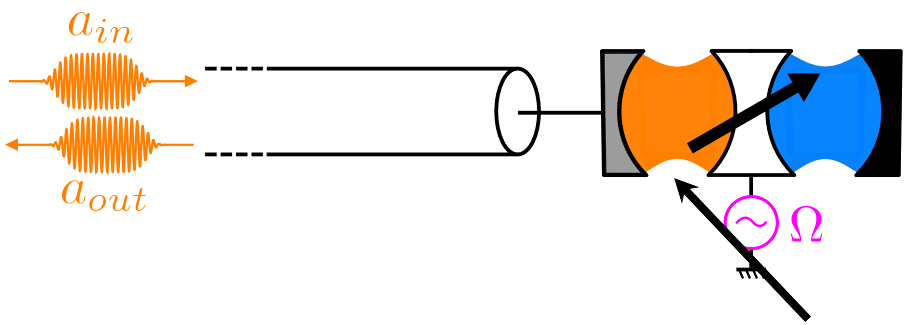
Fast tunable coupling

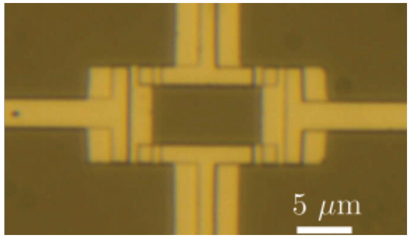
Josephson Ring

$$f_b = 7.5 \text{ GHz}$$

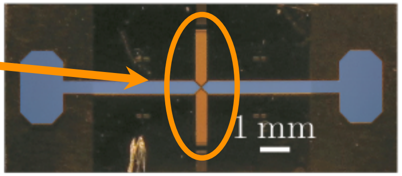


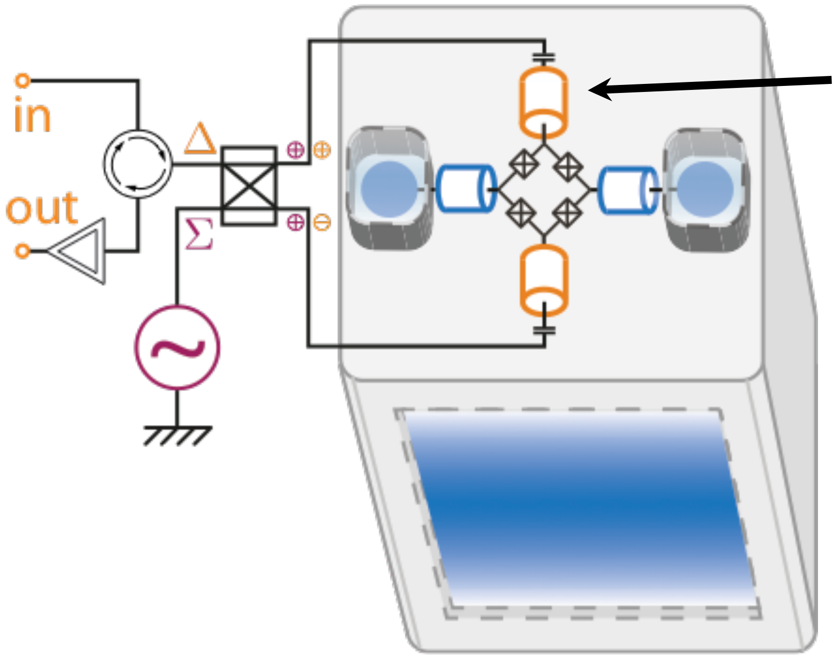
Quantum memory for microwaves





buffer cavity

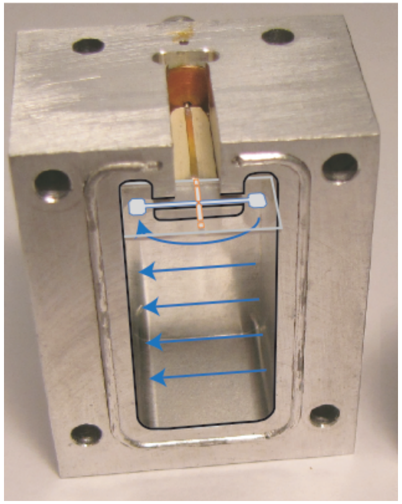




bandwidth ↘

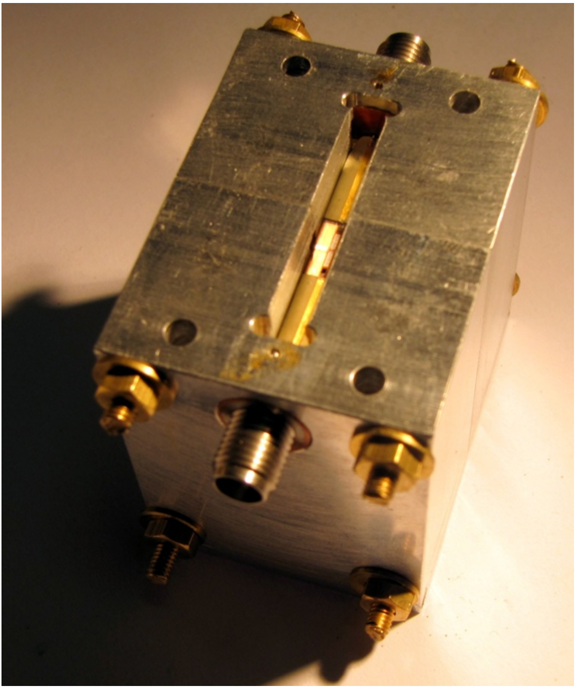
vs

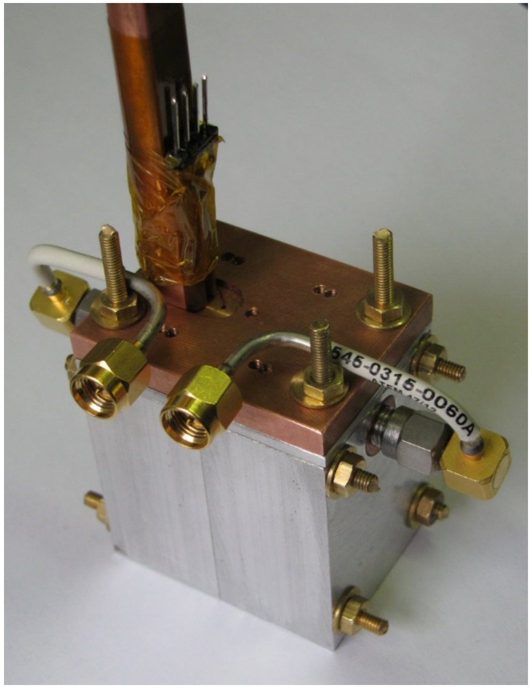
efficiency ↗



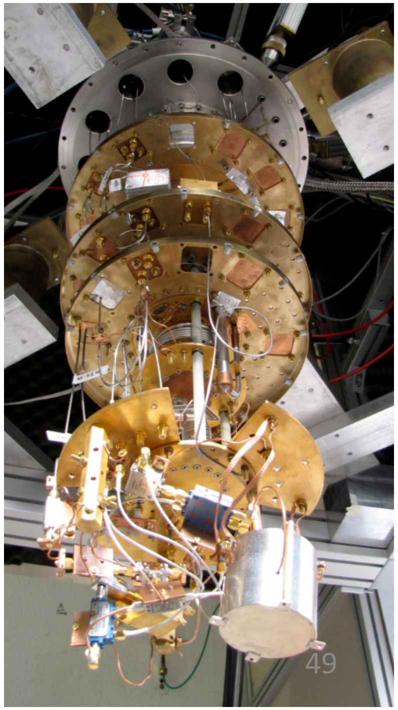
$$f_a = 9.5 \text{ GHz}$$
$$f_b = 7.5 \text{ GHz}$$

Quantum memory for microwaves

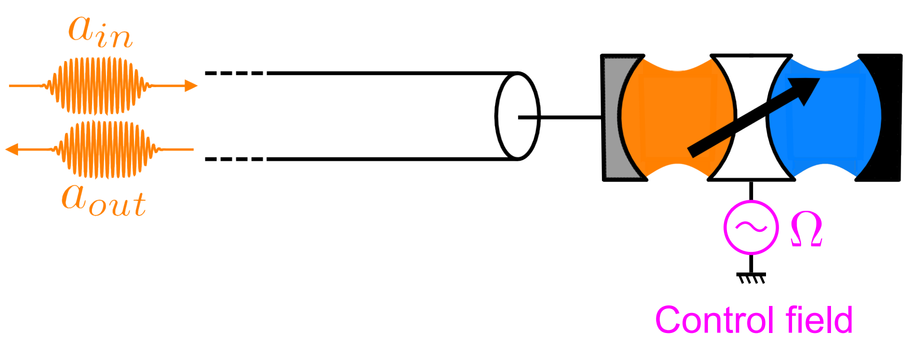


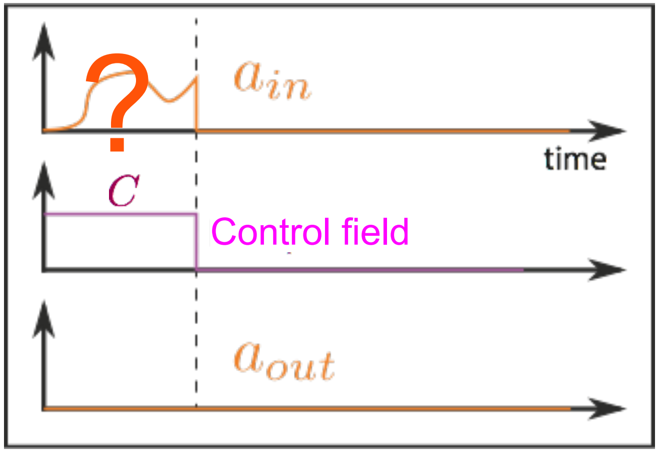


down to 40 mK



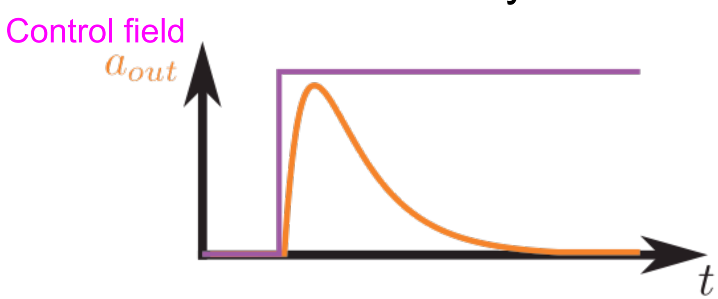
Pulsed experiment





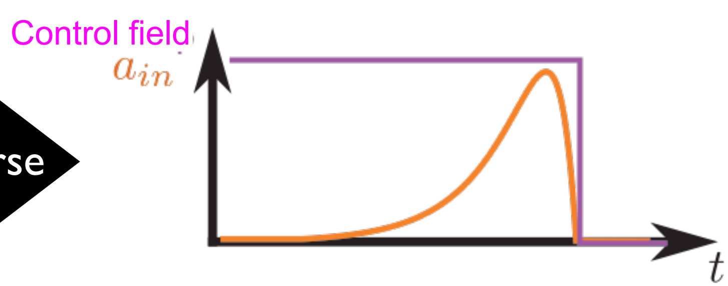
What waveform can the memory capture optimally ?

waveform released by the memory



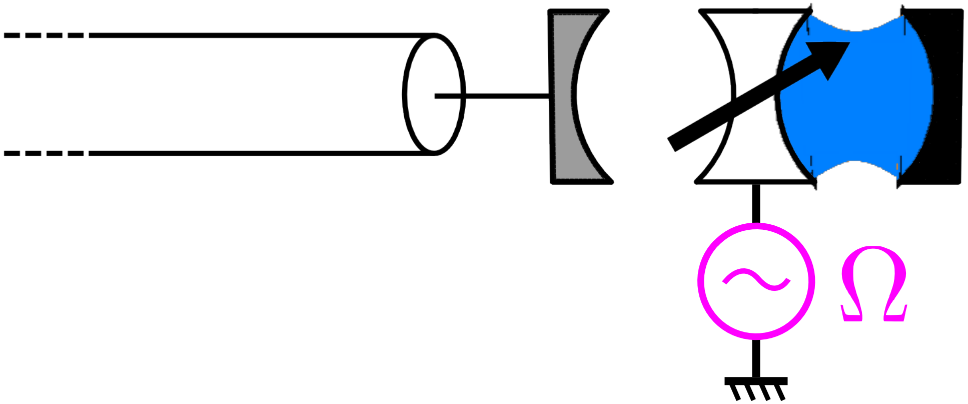
time reverse

waveform optimally capture



Quantum memory for microwaves

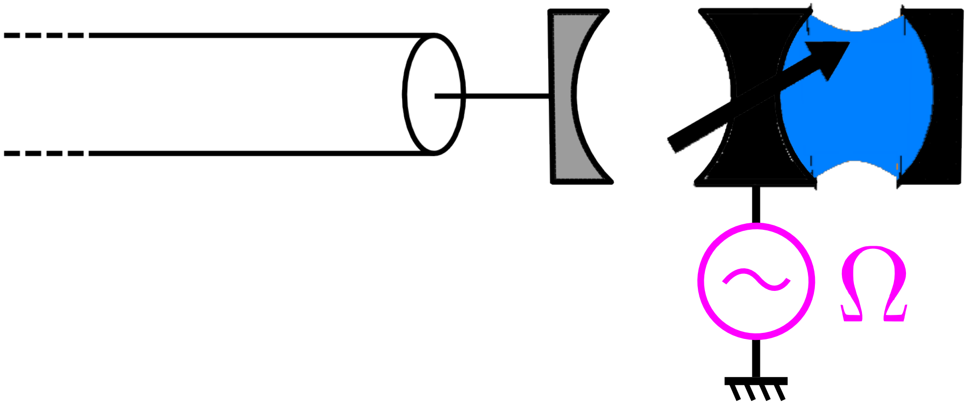
Write the memory



Pompe ON => Coupling ON

Quantum memory for microwaves

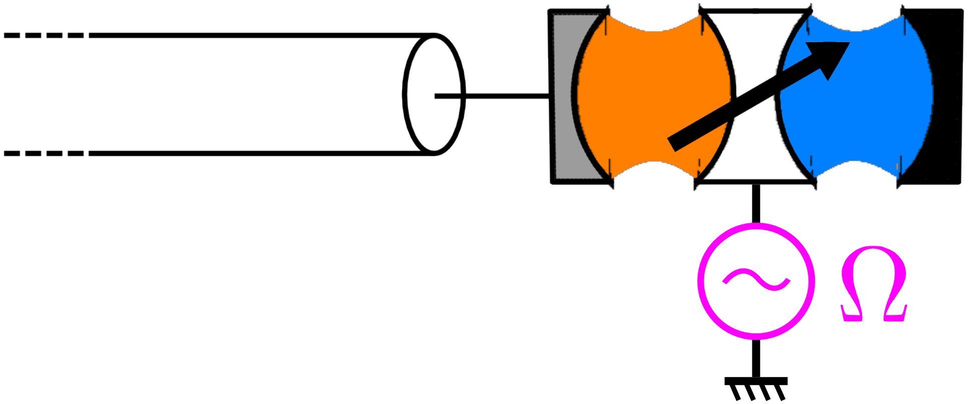
Write the memory



Pompe OFF => Coupling OFF

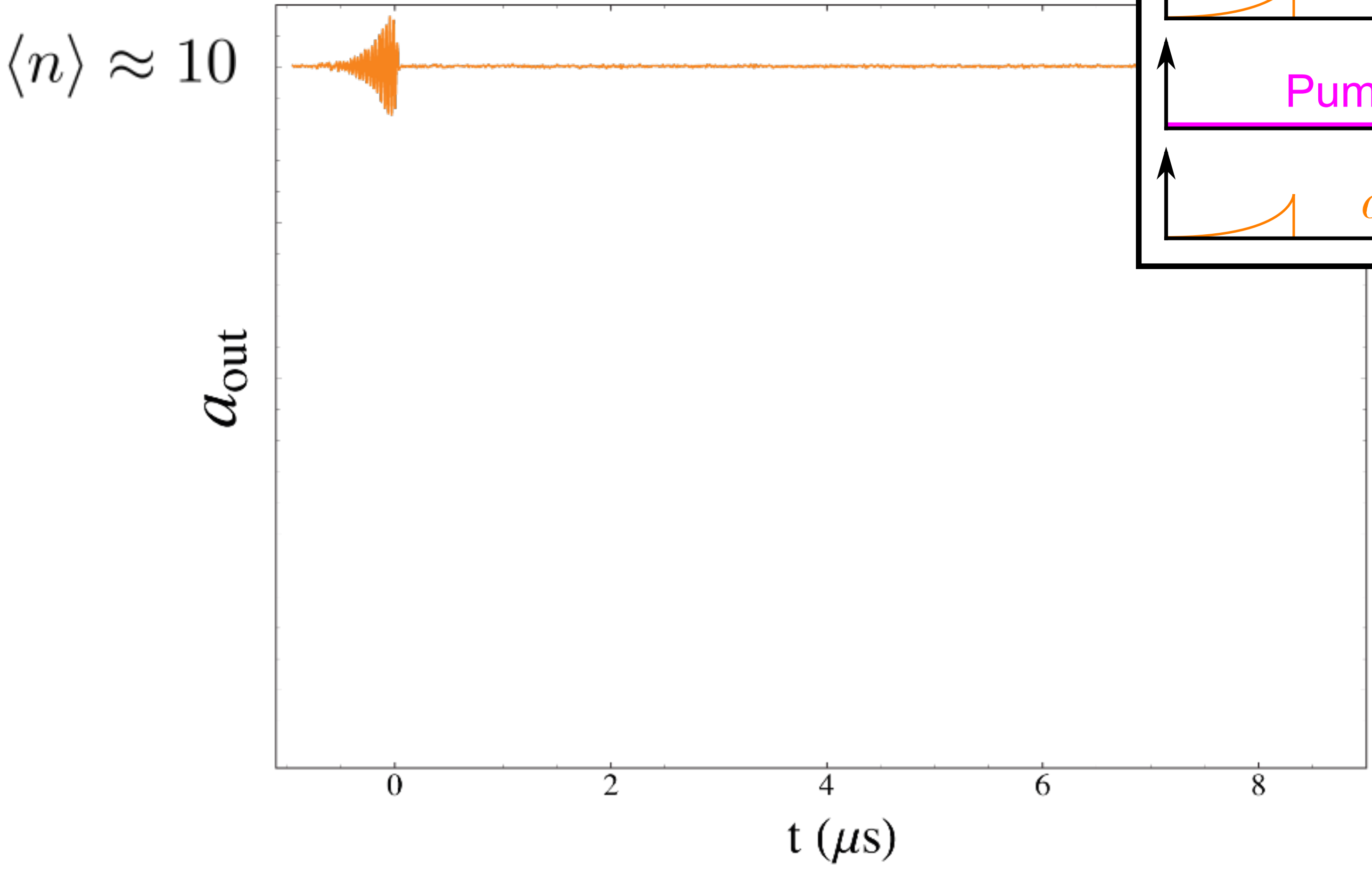
Quantum memory for microwaves

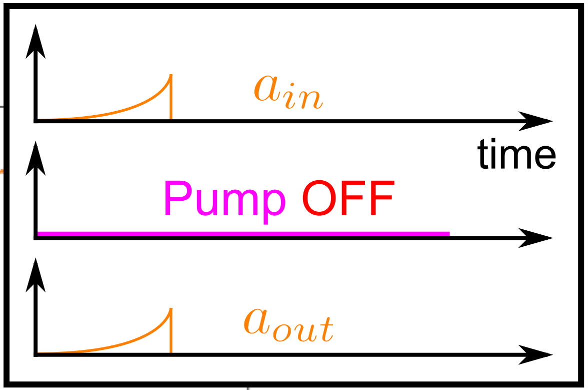
Read the memory



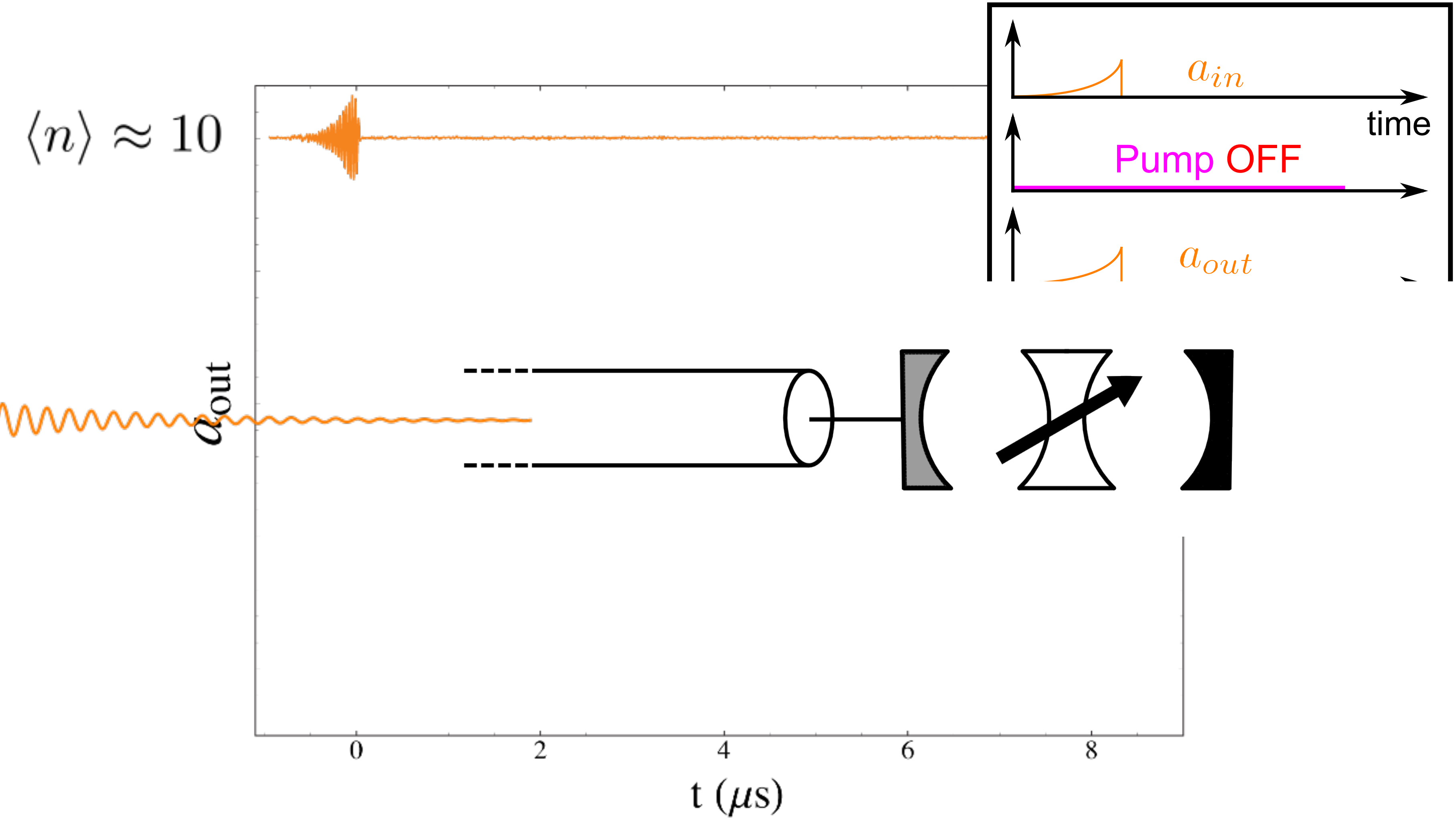
Pompe ON => Coupling ON

Coupling OFF

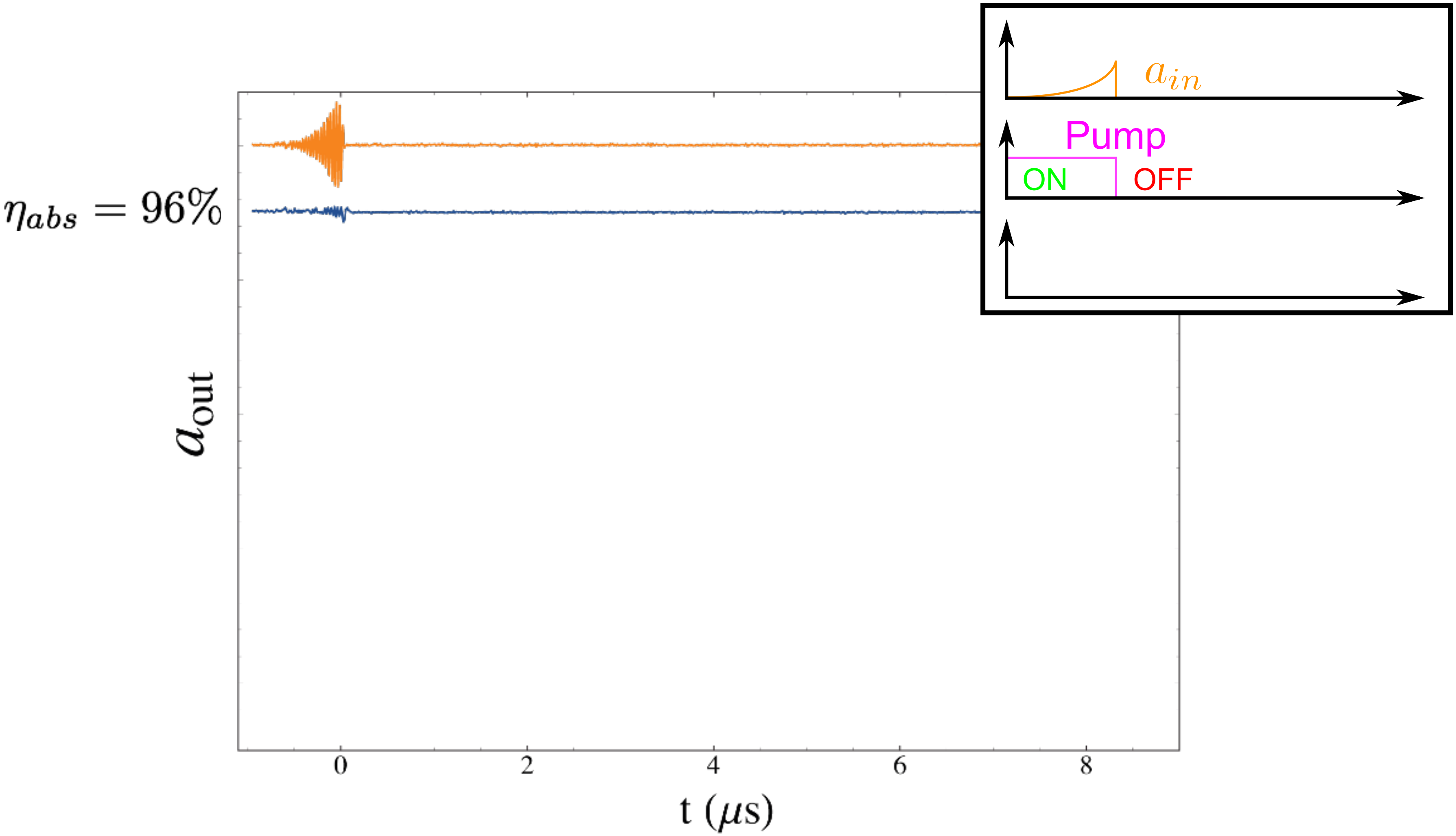




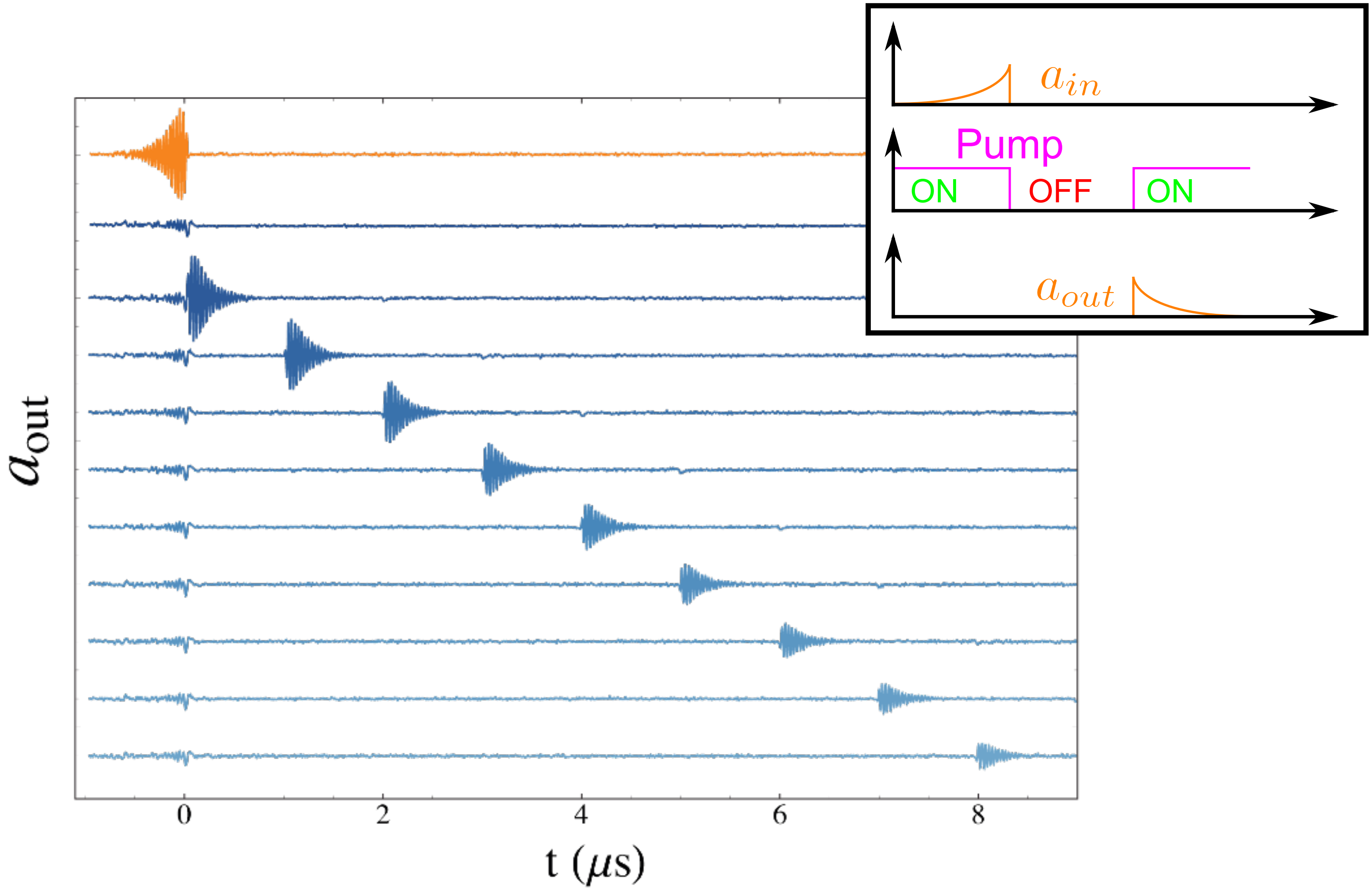
Coupling OFF



Optimal capture

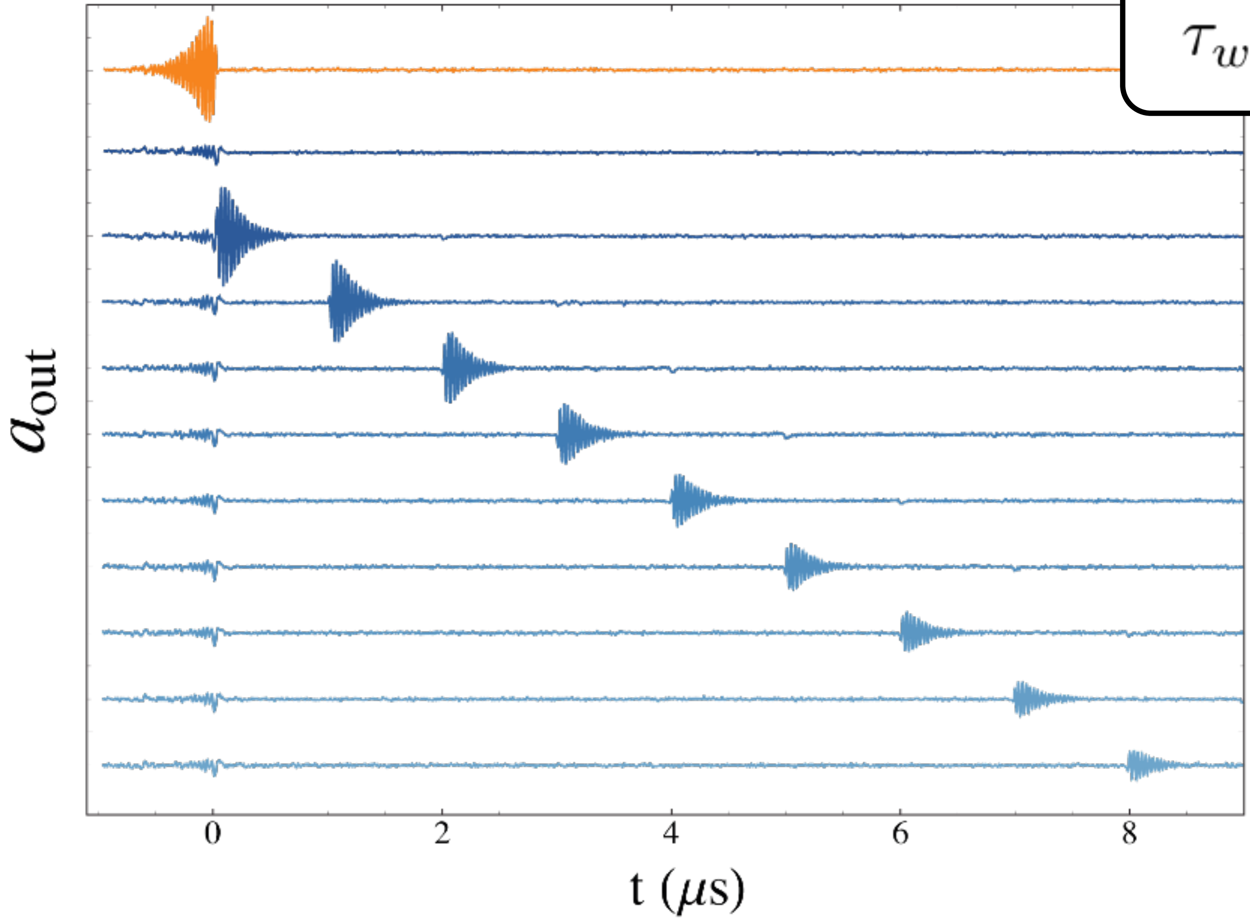


Optimal capture

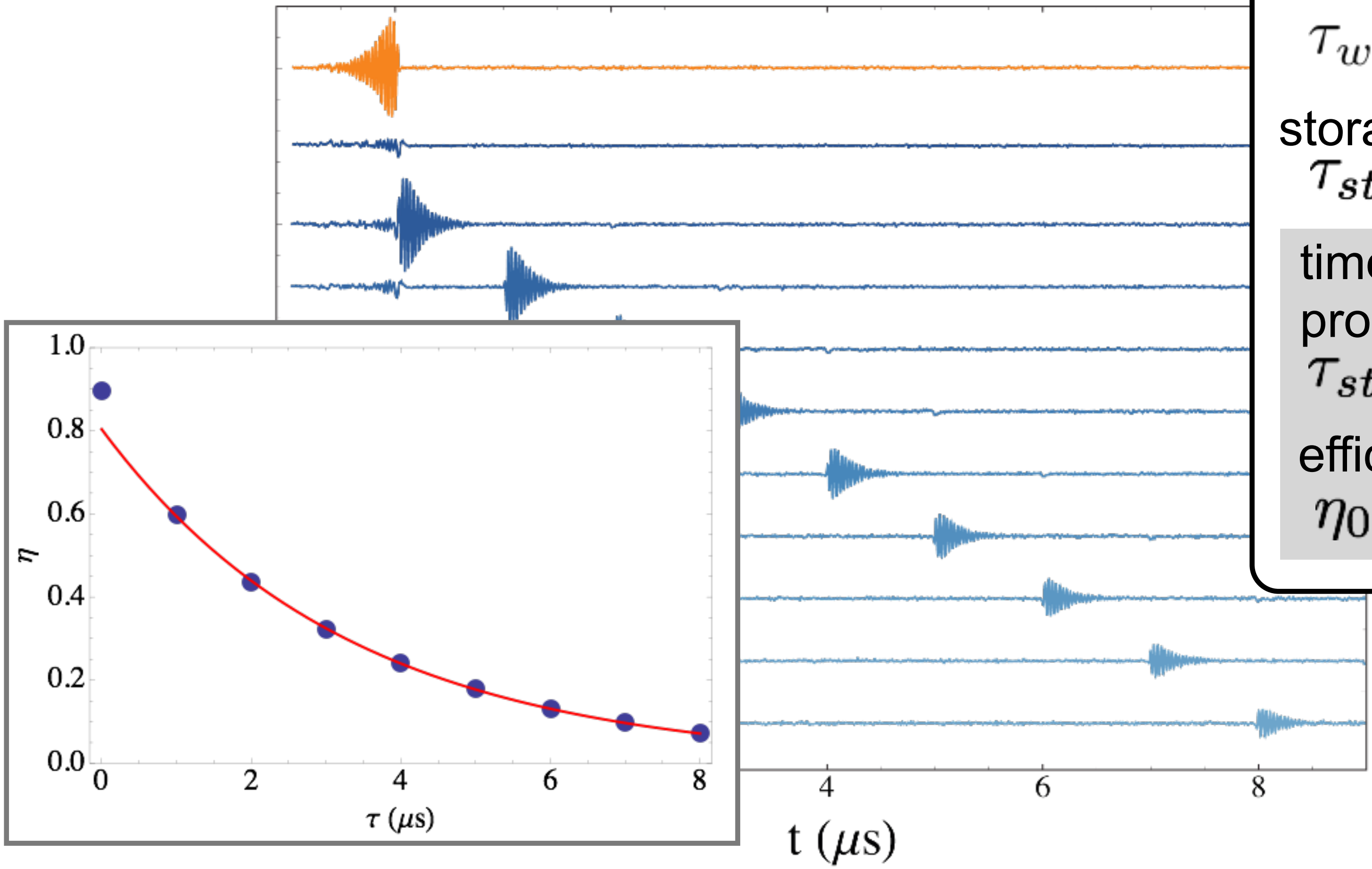


Optimal capture and delayed retrieval

writing/reading time
$\tau_{w/r} = 110 \text{ ns}$



Quantum memory performance



writing/reading time

$\tau_{w/r} = 110 \text{ ns}$

storage time

$\tau_{store} = 3.3\ \mu\text{s}$

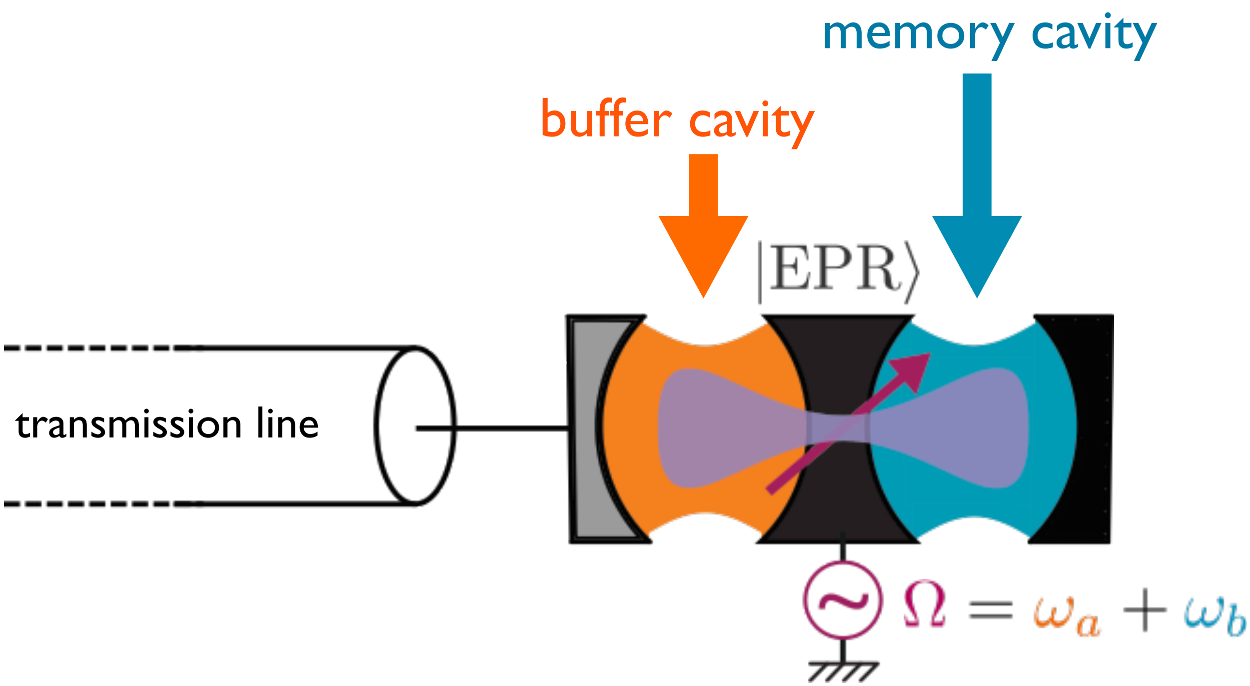
time bandwidth product

$\tau_{store}/\tau_w = 30$

efficiency

$\eta_0 = 80\%$

Entanglement generation



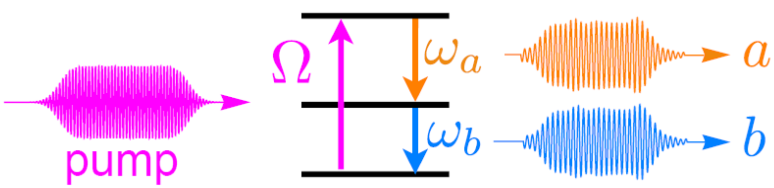
Entanglement generation

Generating Entangled Microwave Radiation Over Two Transmission Lines, E. Flurin *et al.*, *PRL* **2012**

Entanglement generation

$$\Omega = \omega_a + \omega_b$$

$$H_{mix} = \hbar\chi(p\hat{a}^\dagger\hat{b}^\dagger + p^*\hat{a}\hat{b})$$



Quantum limited amplifier
Entanglement source

Hamiltonian evolution

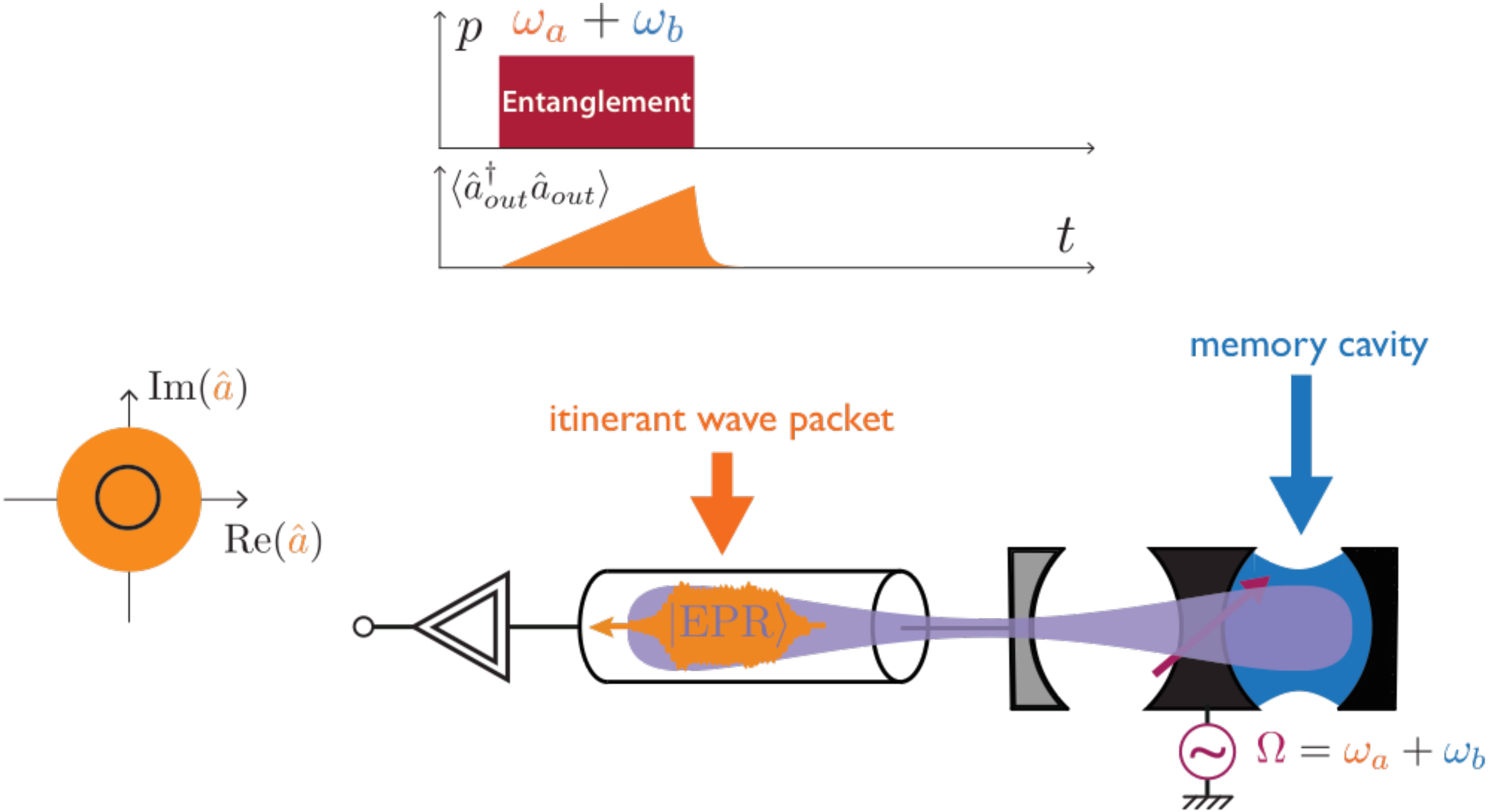
2-mode squeezing operator

$$\hat{S} = e^{r\hat{a}^\dagger\hat{b}^\dagger - r^*\hat{a}\hat{b}}$$

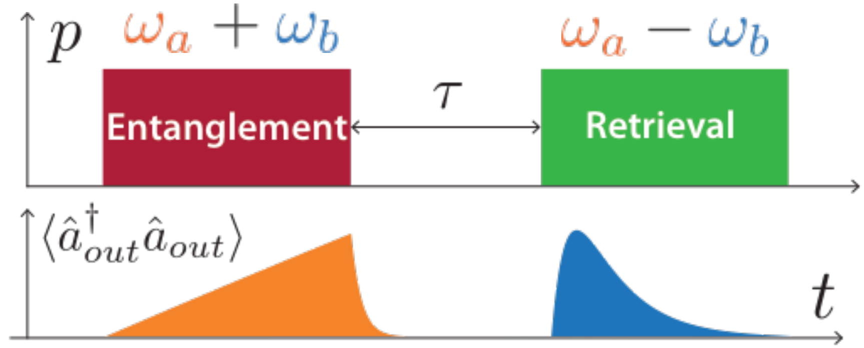
$$|\mathrm{EPR}\rangle = e^{r\hat{a}^\dagger\hat{b}^\dagger - r^*\hat{a}\hat{b}}|0\rangle_a|0\rangle_b$$

$$= \frac{1}{\cosh r}\sum_n(\tanh r)^n|n\rangle_a|n\rangle_b$$

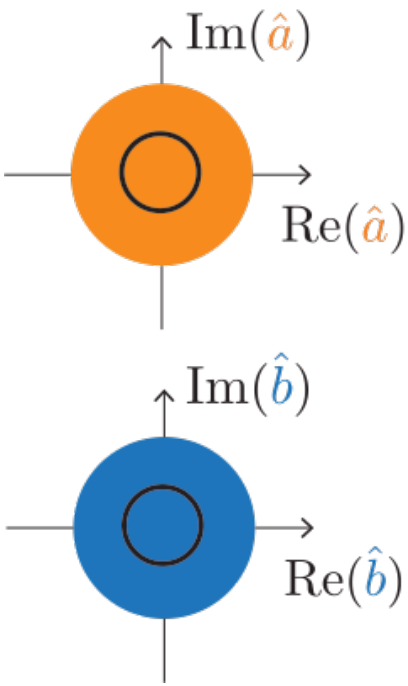
Entanglement generation



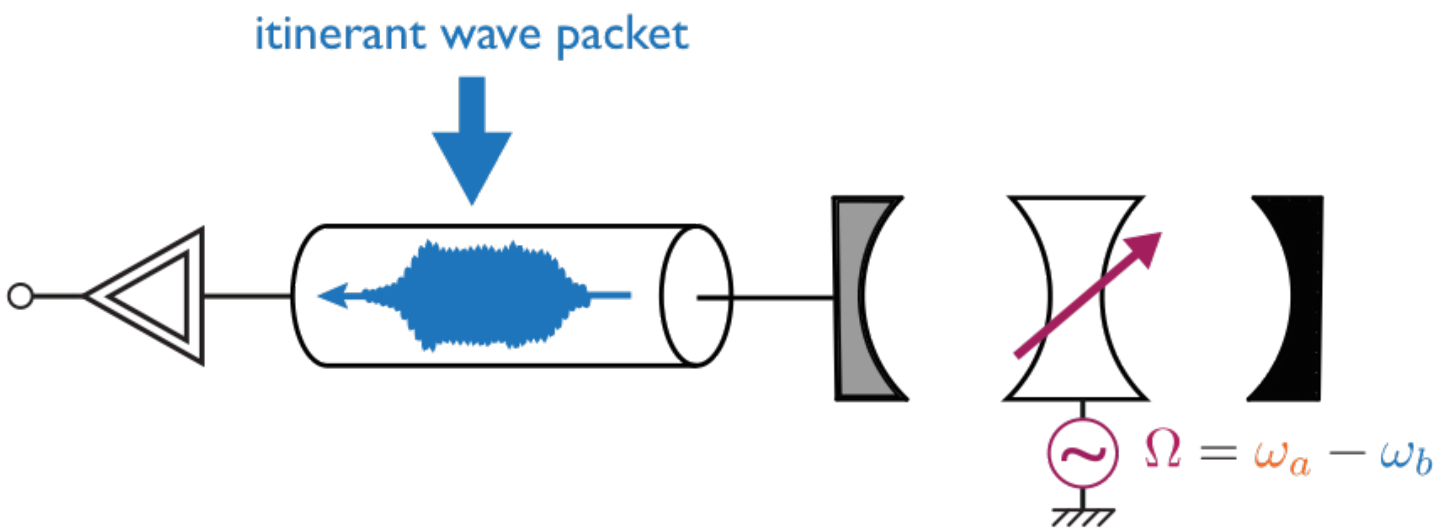
Retrieval



p
$\omega_a + \omega_b$
$\omega_a - \omega_b$
Entanglement
τ
Retrieval
$\langle \hat{a}^\dagger_{out} \hat{a}_{out} \rangle$
t

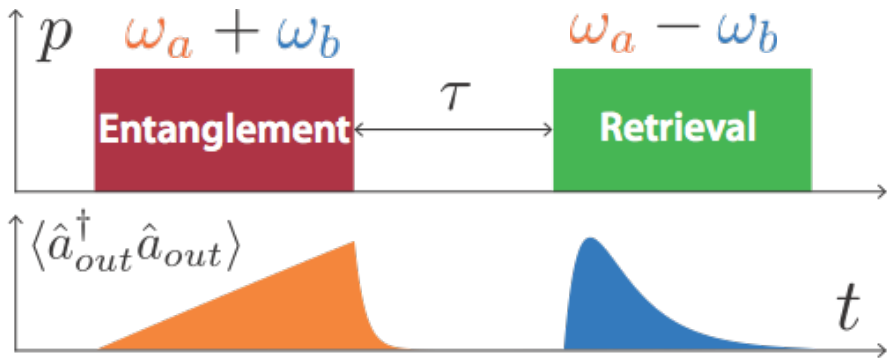


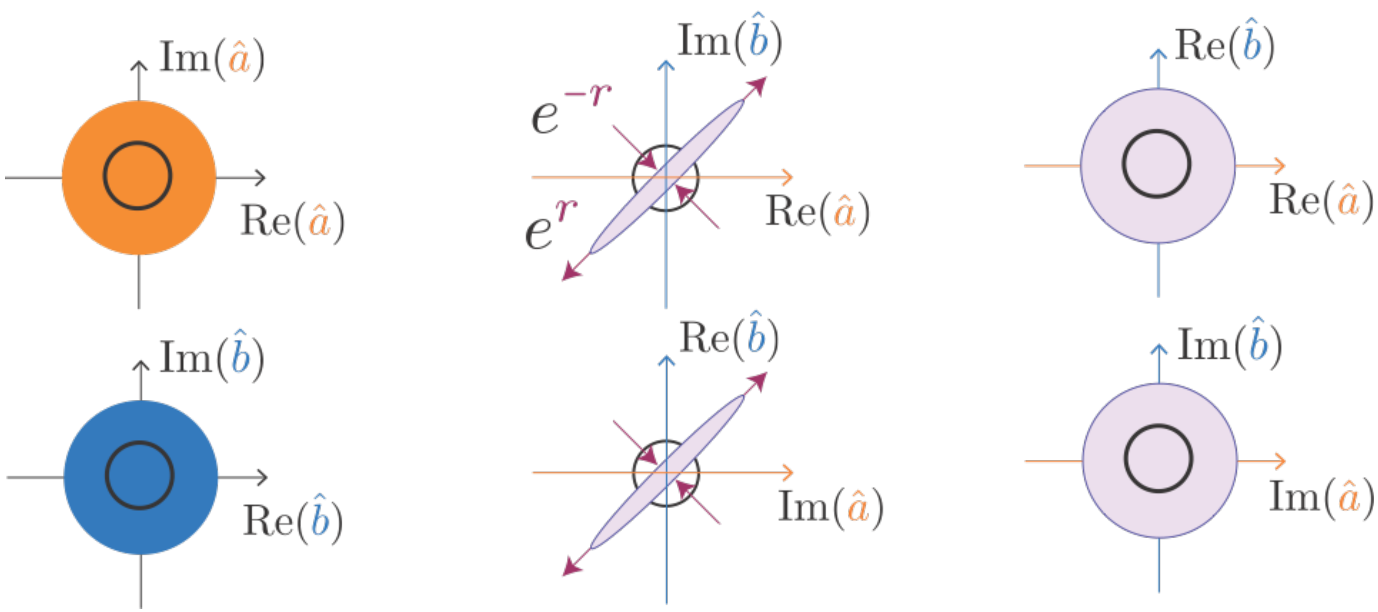
$\mathrm{Im}(\hat{a})$
$\mathrm{Re}(\hat{a})$
$\mathrm{Im}(\hat{b})$
$\mathrm{Re}(\hat{b})$



itinerant wave packet
$\Omega = \omega_a - \omega_b$

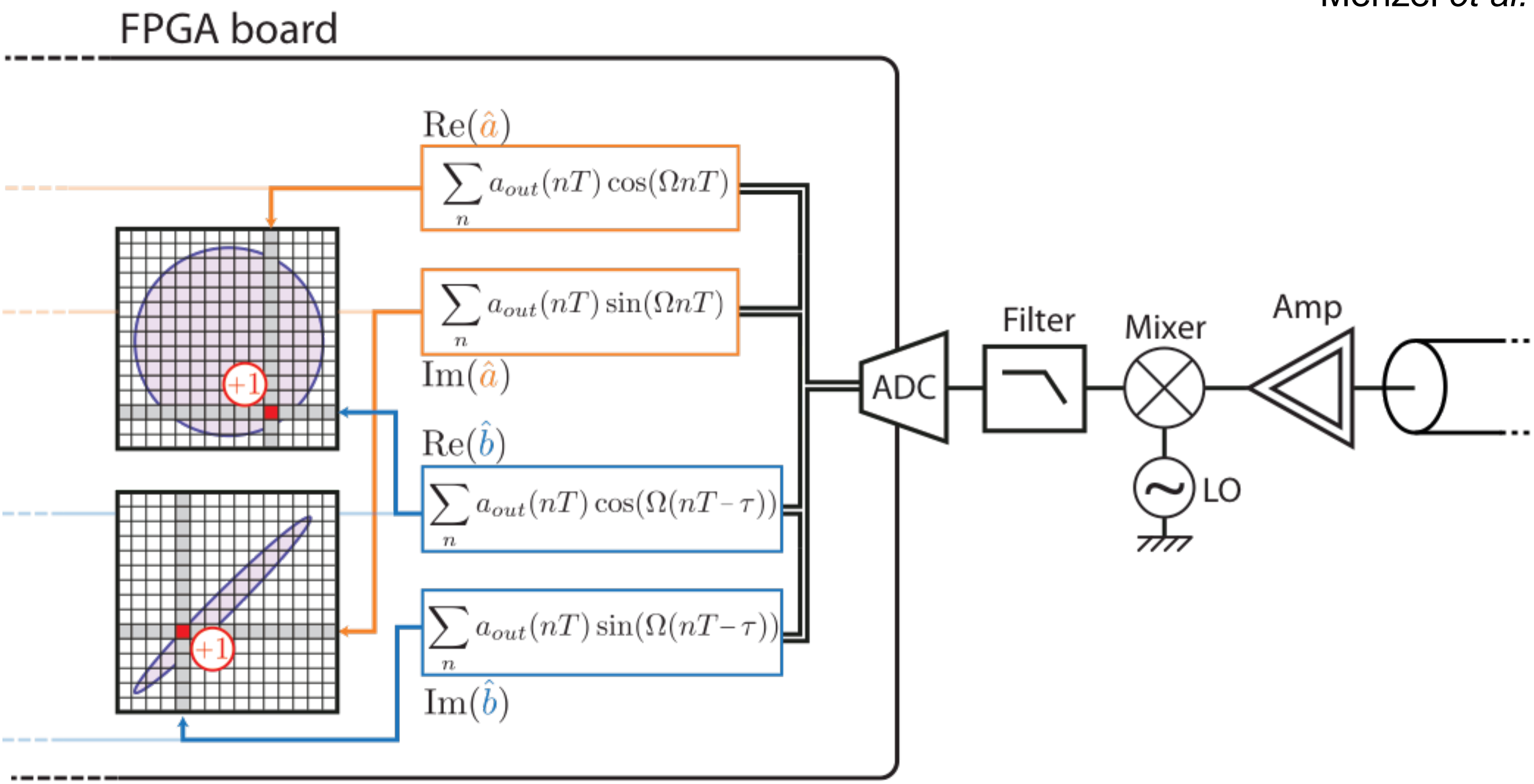
Squeezed cross-correlation





Squeezed cross-correlation

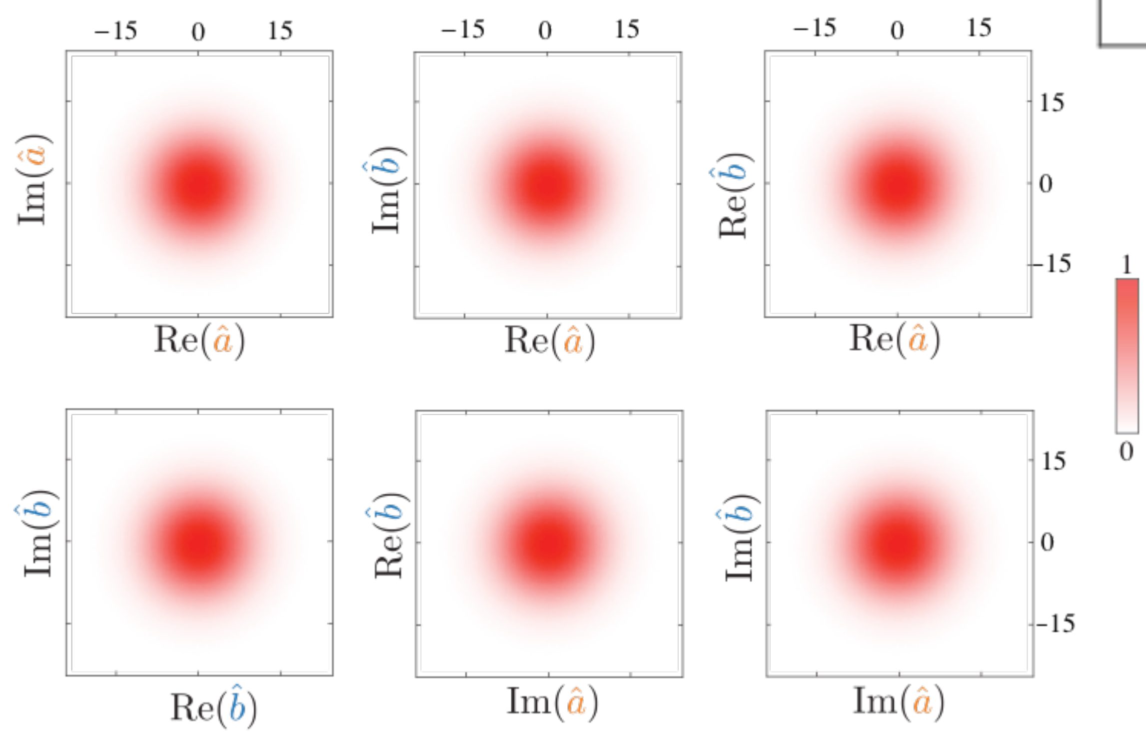
Eichler *et al.*, *PRL* **2011**
Menzel *et al.* *PRL* **2012**

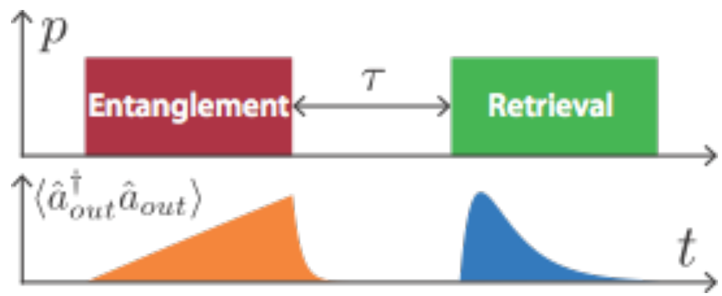


$\times 3.10^7$ points ⟶ measurement time 5 min

Experimental results

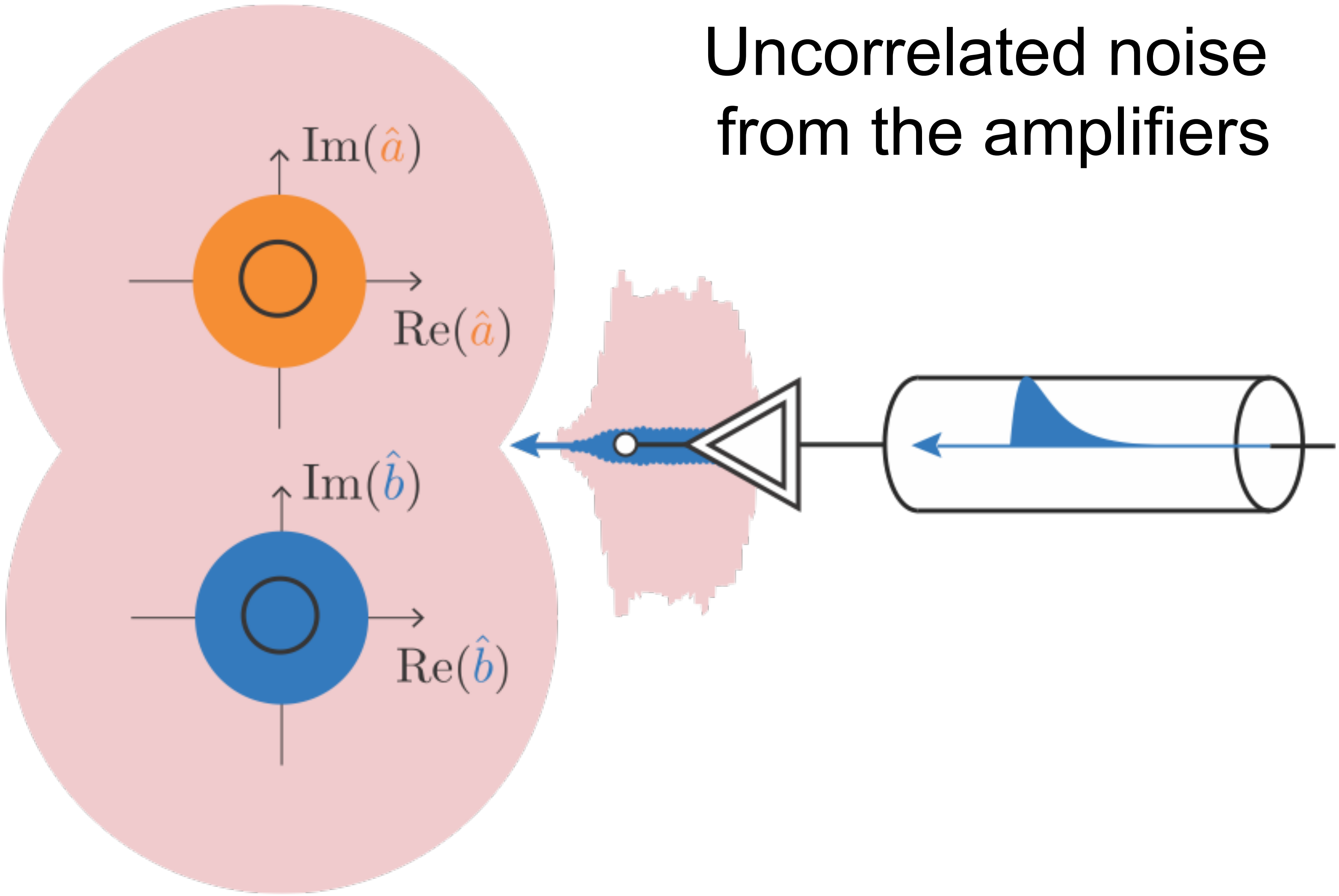
Control field ON





Amplification chain noise

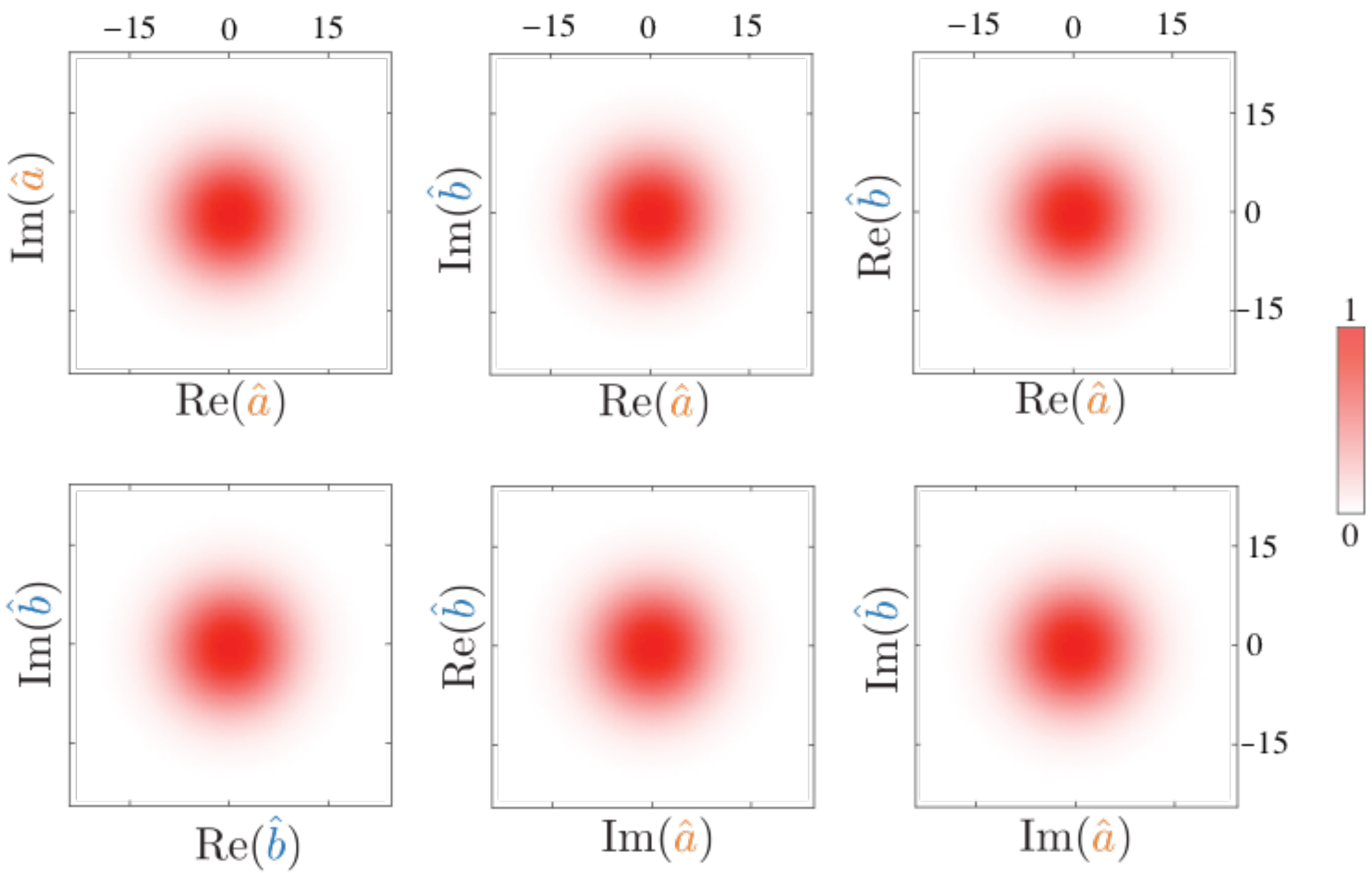
Uncorrelated noise from the amplifiers



Experimental results

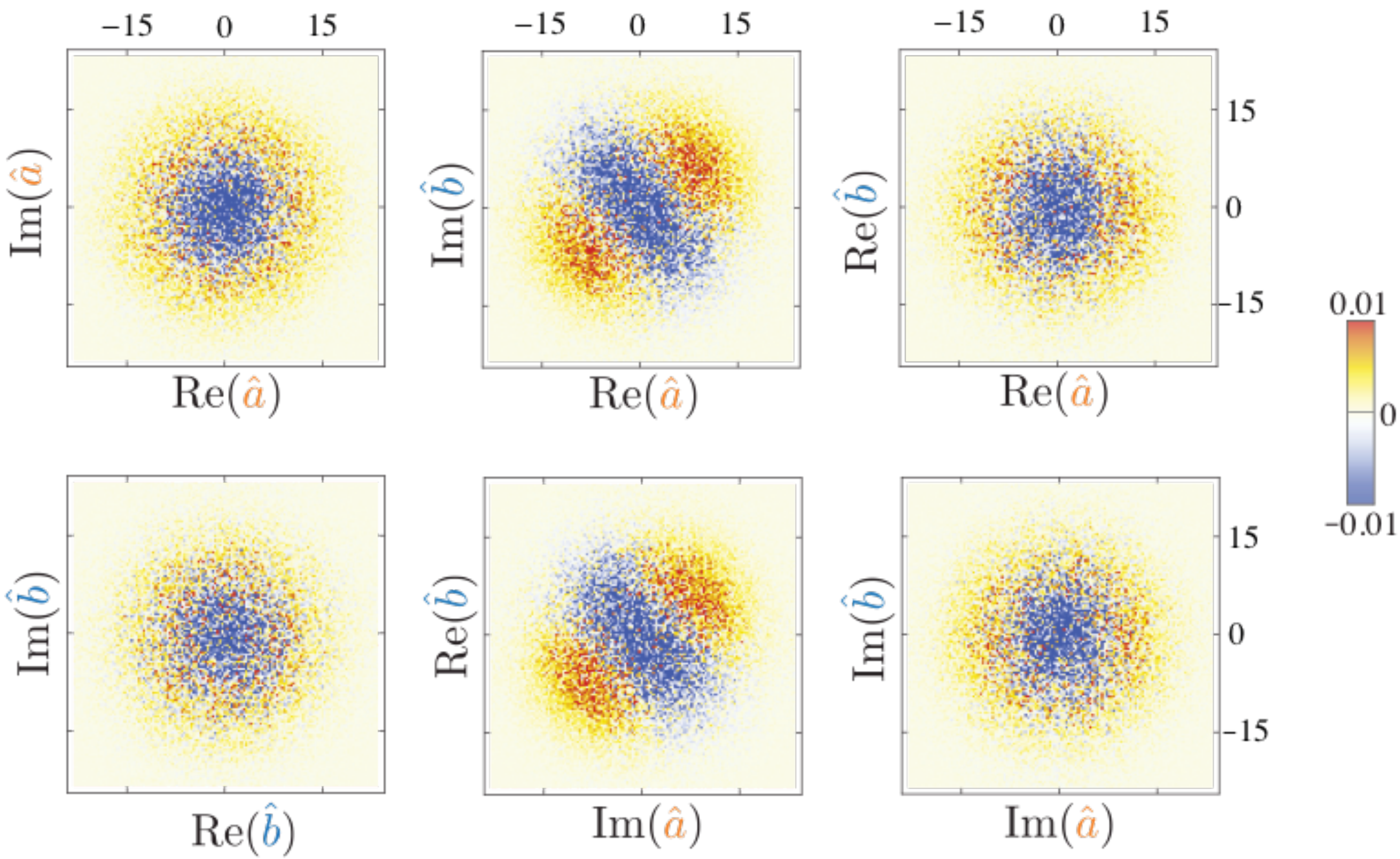
Control field OFF

$|0\rangle_a |0\rangle_b$

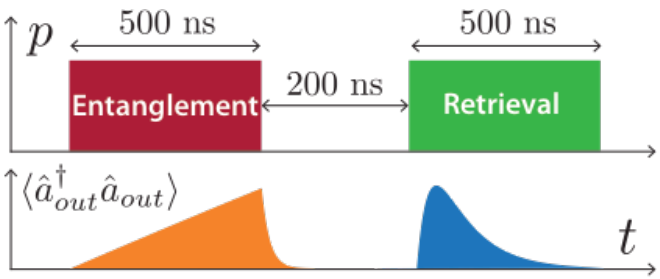


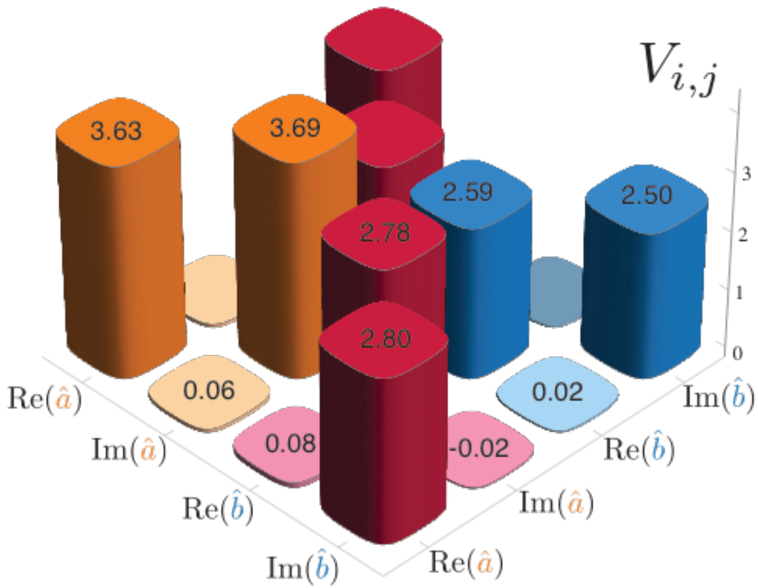
Experimental results

Subtracted ON-OFF histograms

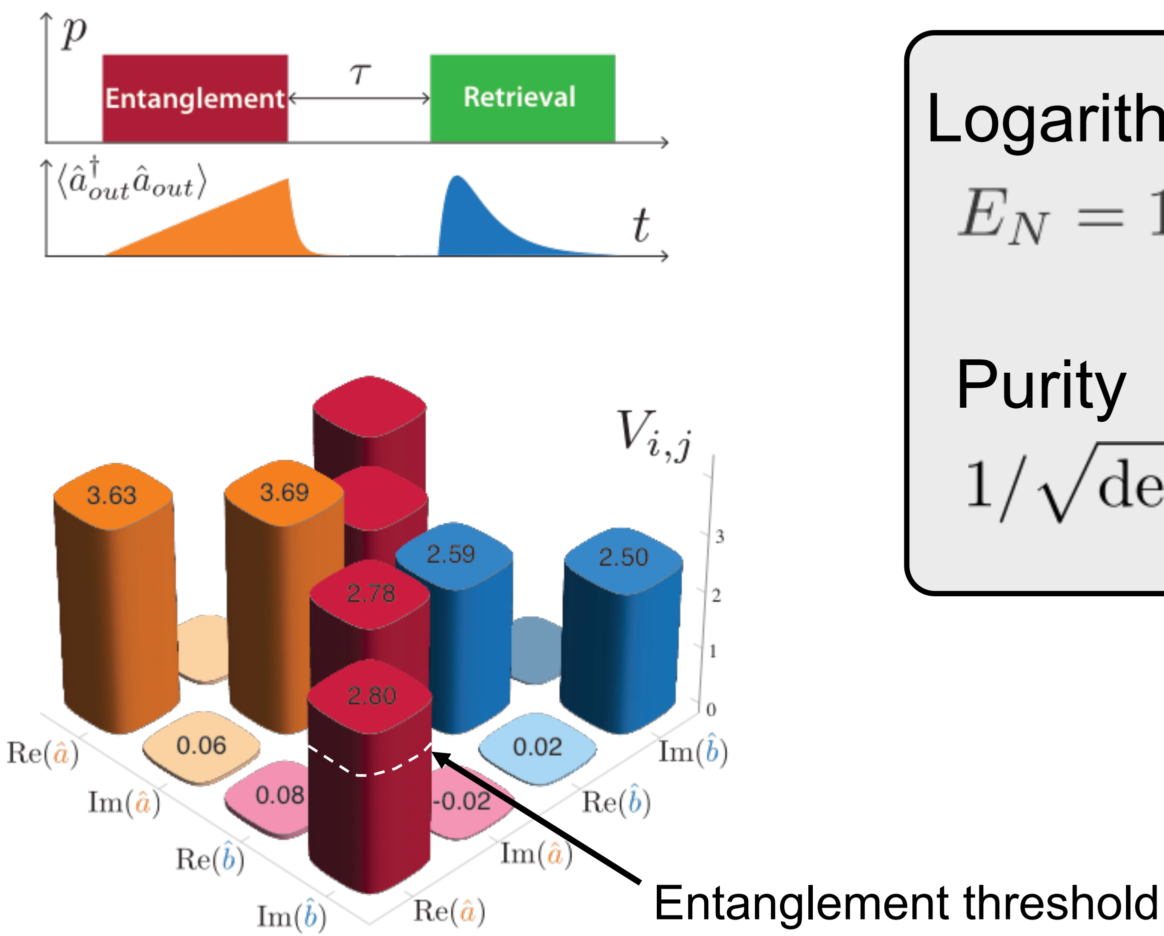


Measured covariance matrix





Covariance matrix and entanglement witness



Logarithmic negativity

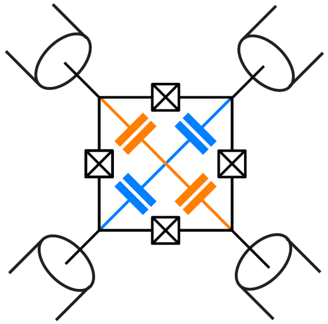
$E_N = 1.36 \text{ e-bits}$

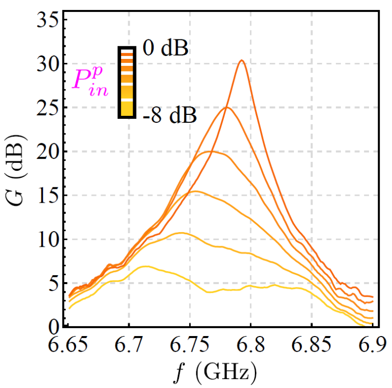
Purity

$1/\sqrt{\det(\mathbf{V})} = 0.66$

Conclusions

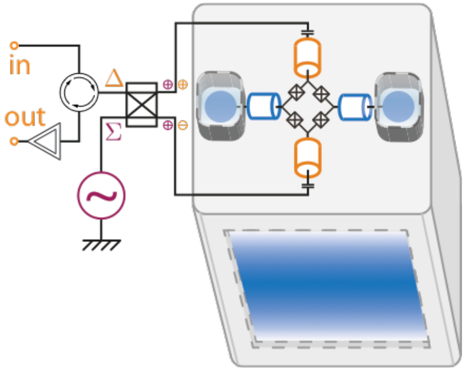
Optimal phase preserving amplifier

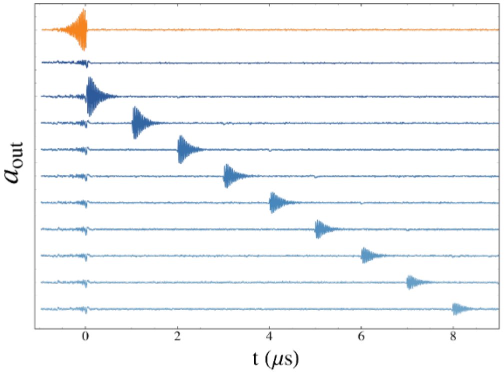




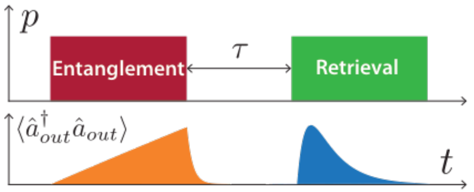
Pillet *et al.*, in preparation

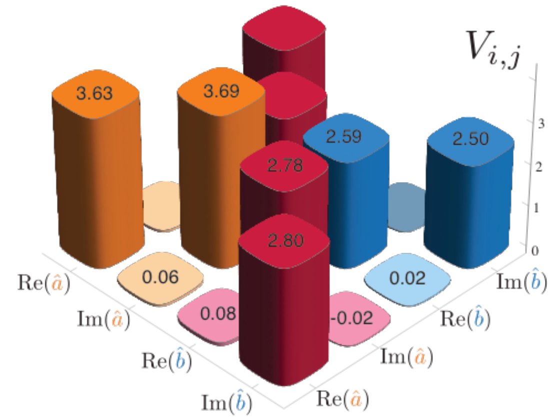
Quantum memory





Generation of entanglement on demand





Flurin, Roch, Pillet *et al.*,
arxiv:1401.5622

Thanks

Vladimir MANUCHARYAN

Landry BRETHEAU

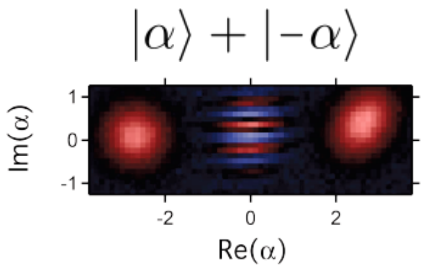
Michel DEVORET

Nicolas ROCH

Benjamin HUARD

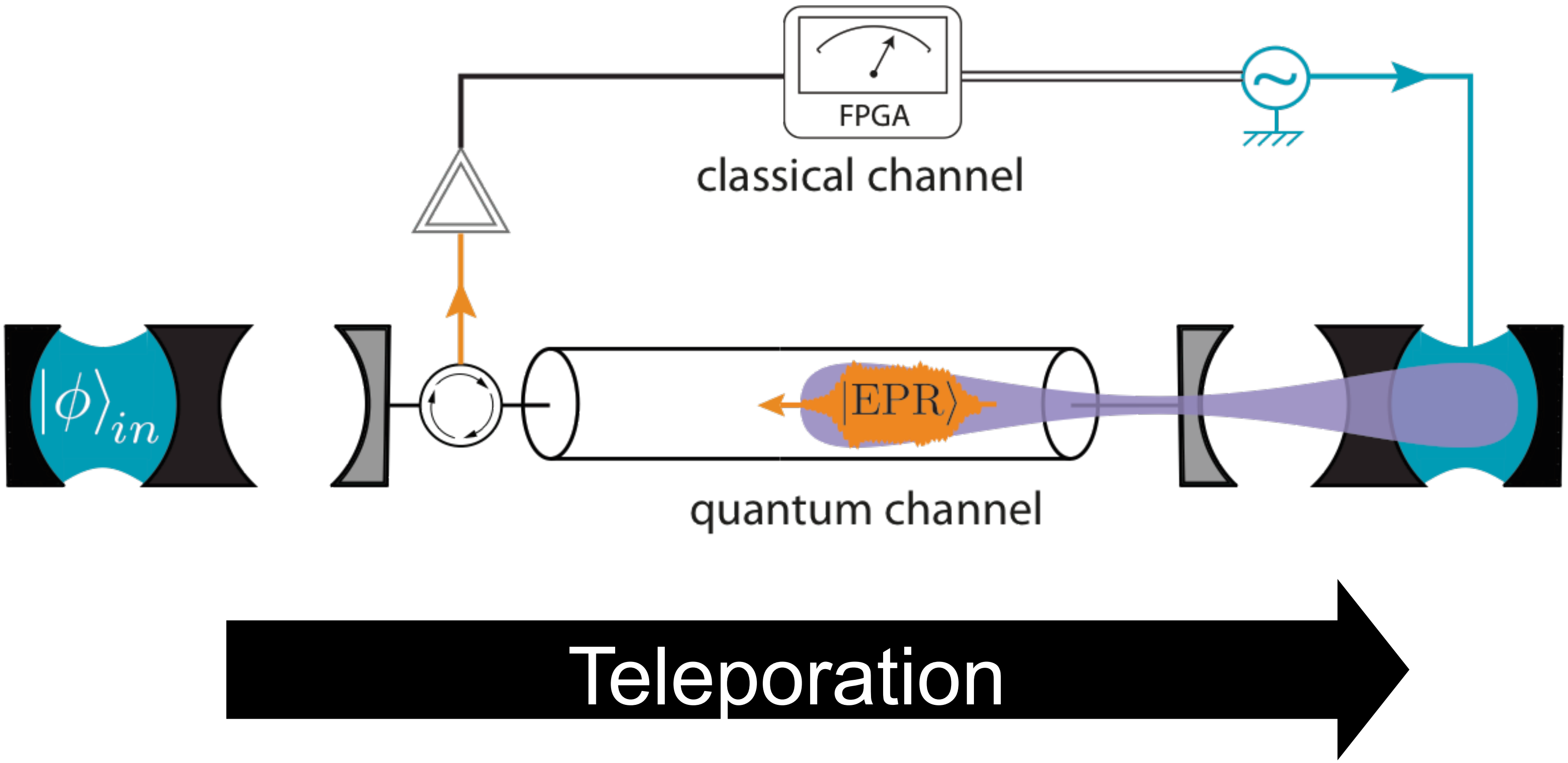
Philippe CAMPAGNE-IBARCQ

Perspectives



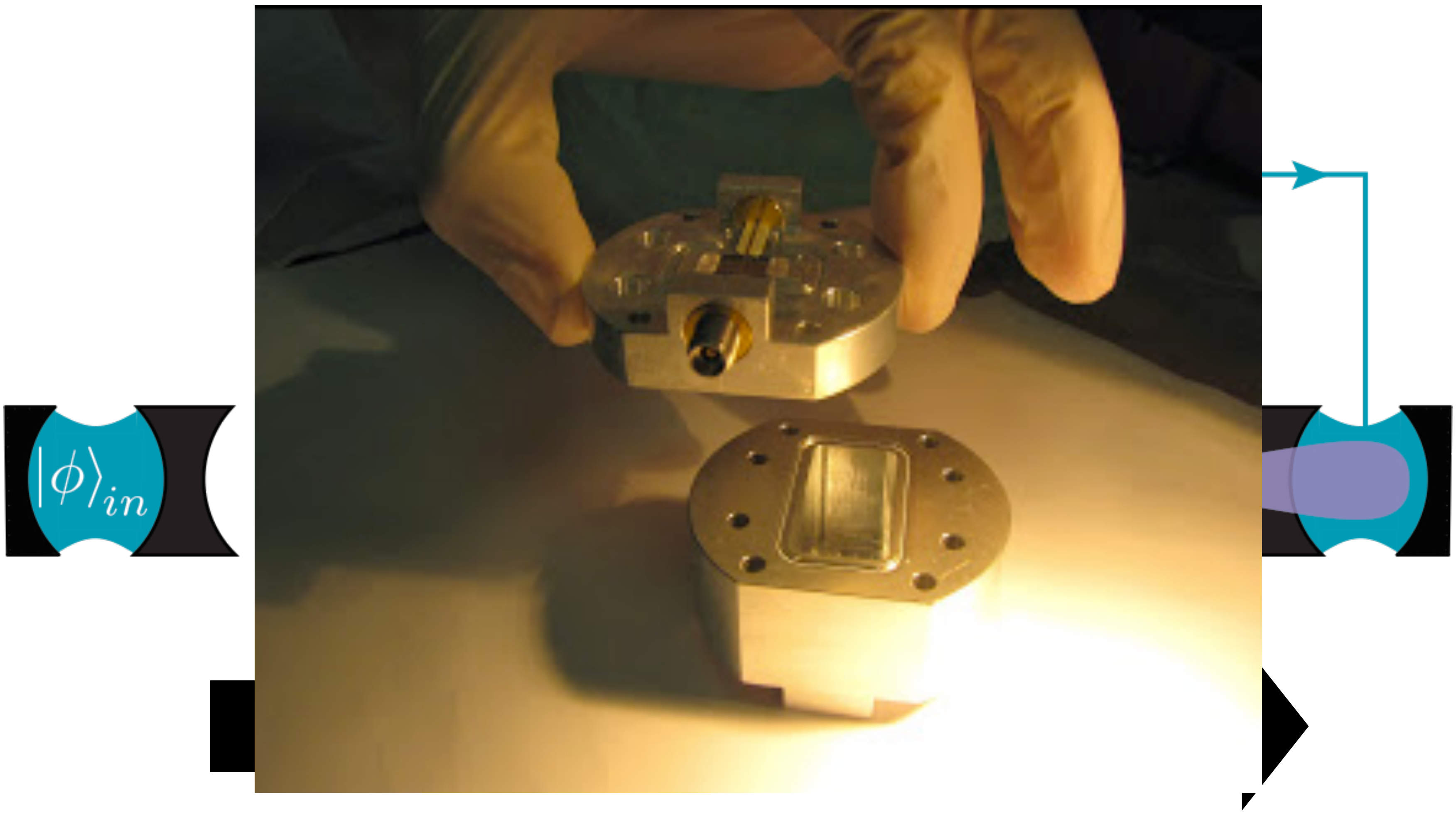
Pas de pause
Pas de repit
Marquer le temps entre slides de transition

Teleportation of a quantum state from one memory to another



Perspectives

Teleportation of a quantum state from one memory to another



Trash

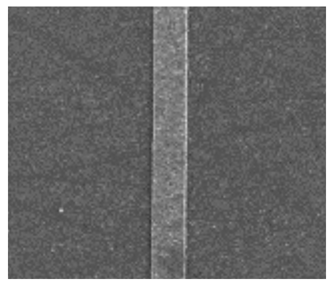
Microwave: powerful and versatile platform

processed at the single photon level with non-dissipative superconducting

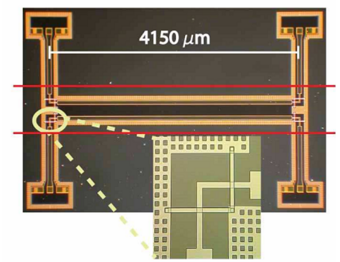
In dilution fridge T=30mK

Add superconducting qubit

Transmission line

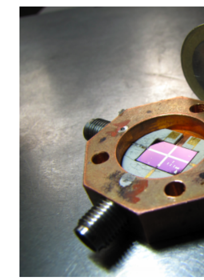


Directional coupler



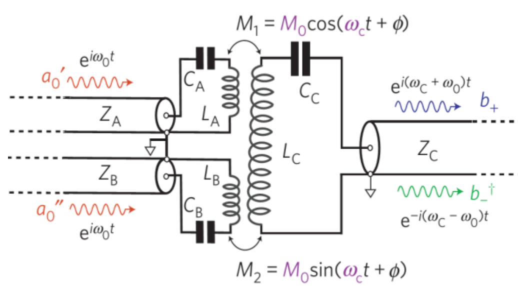
Ku et al., *Applied Superconductivity* (2011)

Quantum ampli

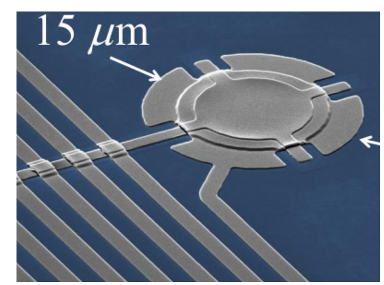


Circulator

Kamal *et al., Nat. Phys.* 2011



Quantum Memory



Sev

Palo
arxi