(PHOTON DETECTION IN) SUPERCONDUCTING QUANTUM TECHNOLOGIES

POL FORN-DÍAZ,

BARCELONA SUPERCOMPUTING CENTER

Meeting point for radiation and photon detectors community

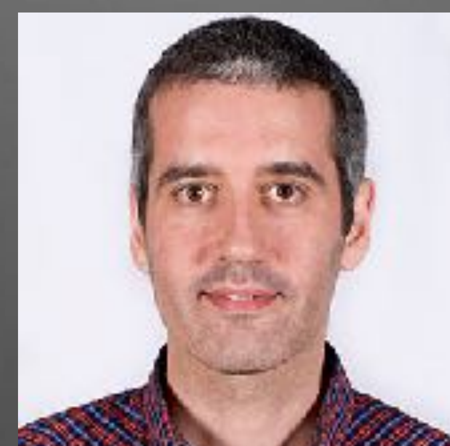
UB, Jul 9 2018

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

QUANTIC group at BSC

http://quantic.bsc.es/

J. I. Latorre



A. García-Sáez

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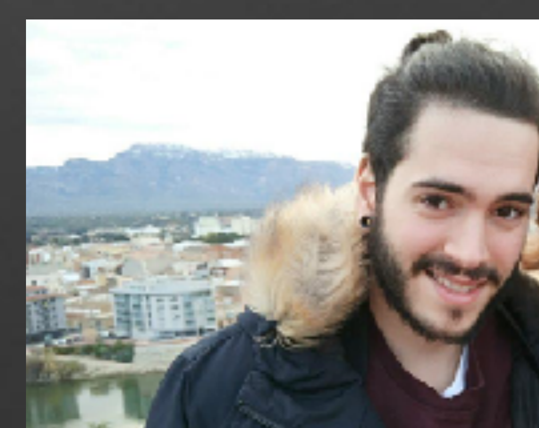


C. Bravo

QUANTIC group at BSC

http://quantic.bsc.es/

Quantum computation for real:

Quantum processors (in collaboration with ICN2)

Quantum annealer with superconducting qubits

Explore new processor architectures with quantum gates

Quantum algorithms

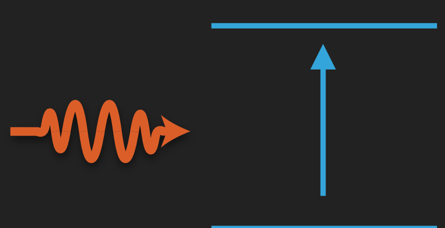
Develop novel algorithms for practical problems:
-For small processors
-Quantum Machine learning
-Quantum simulation
-Optimization

GENERAL CONSIDERATIONS ON PHOTON DETECTION

Di Vincenzo criteria: ▸ A qubit-specific measurement capability.

- Not easy to find natural microwave absorber

$$k_B T \ll h\nu$$



Optical photons $T \sim 10^4\ \mathrm{K}$

Microwave photons $T \sim 50\ \mathrm{mK}$

Photocounter: Y. F. Chen *et al.*, PRL 107, 217401 (2011) (no sensitivity at single photon level)

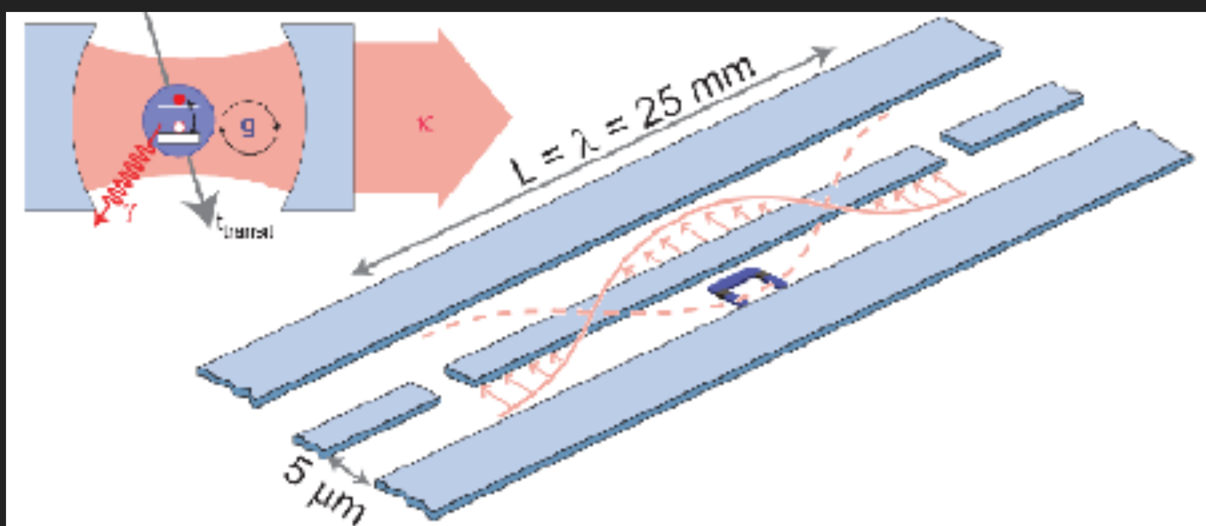
Photon sensor: J. C. Besse *et al.*, PRX 8, 021003 (2018)

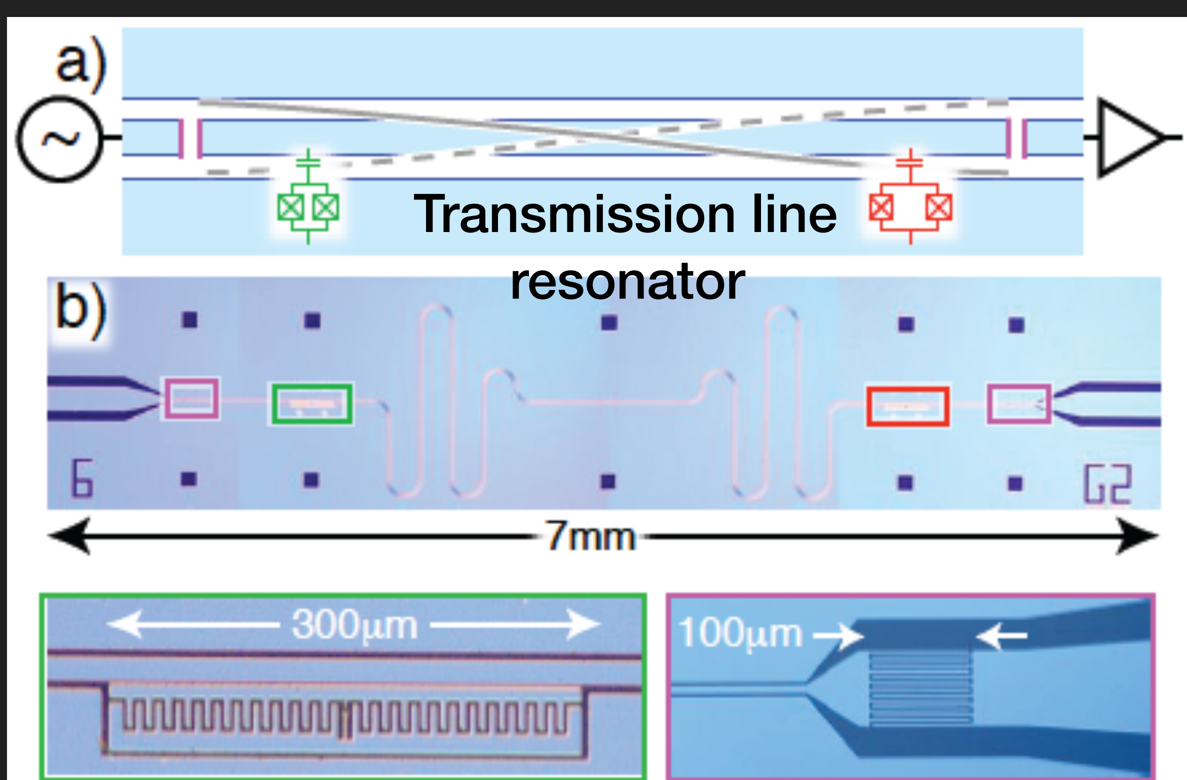
K. Inomata *et* al., Nature Communications 7, 12303 (2016) (narrow bandwidth, gated)

› Linear amplification

SUPERCONDUCTING QUANTUM TECHNOLOGIES

- Circuit QED readout (in a nutshell)

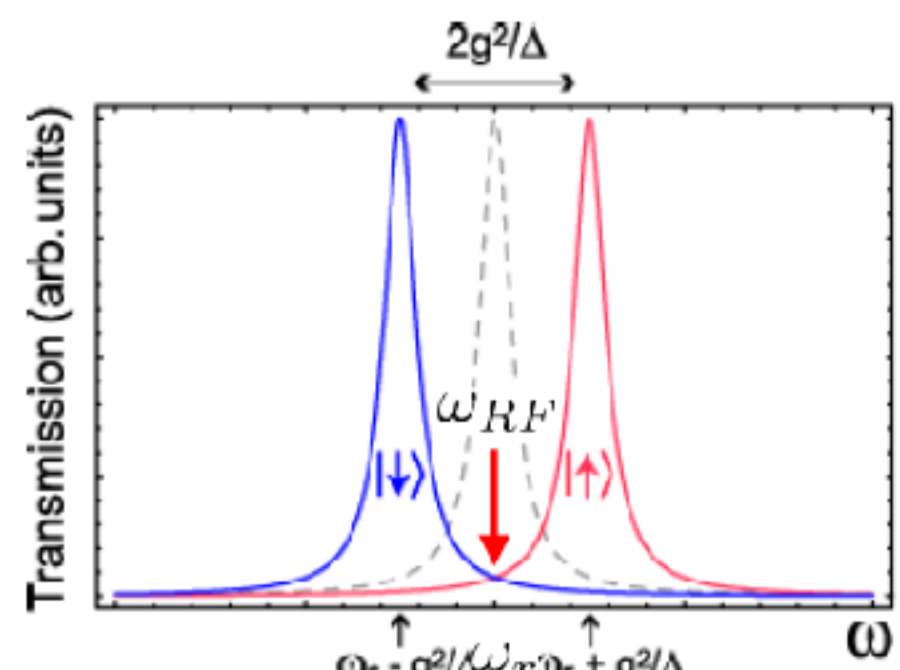




$$H \approx \hbar\left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right)a^\dagger a + \frac{1}{2}\hbar\left(\omega_a + \frac{g^2}{\Delta}\right)\sigma_z$$

cavity frequency shift *and* qubit ac-Stark shift

Lamb shift

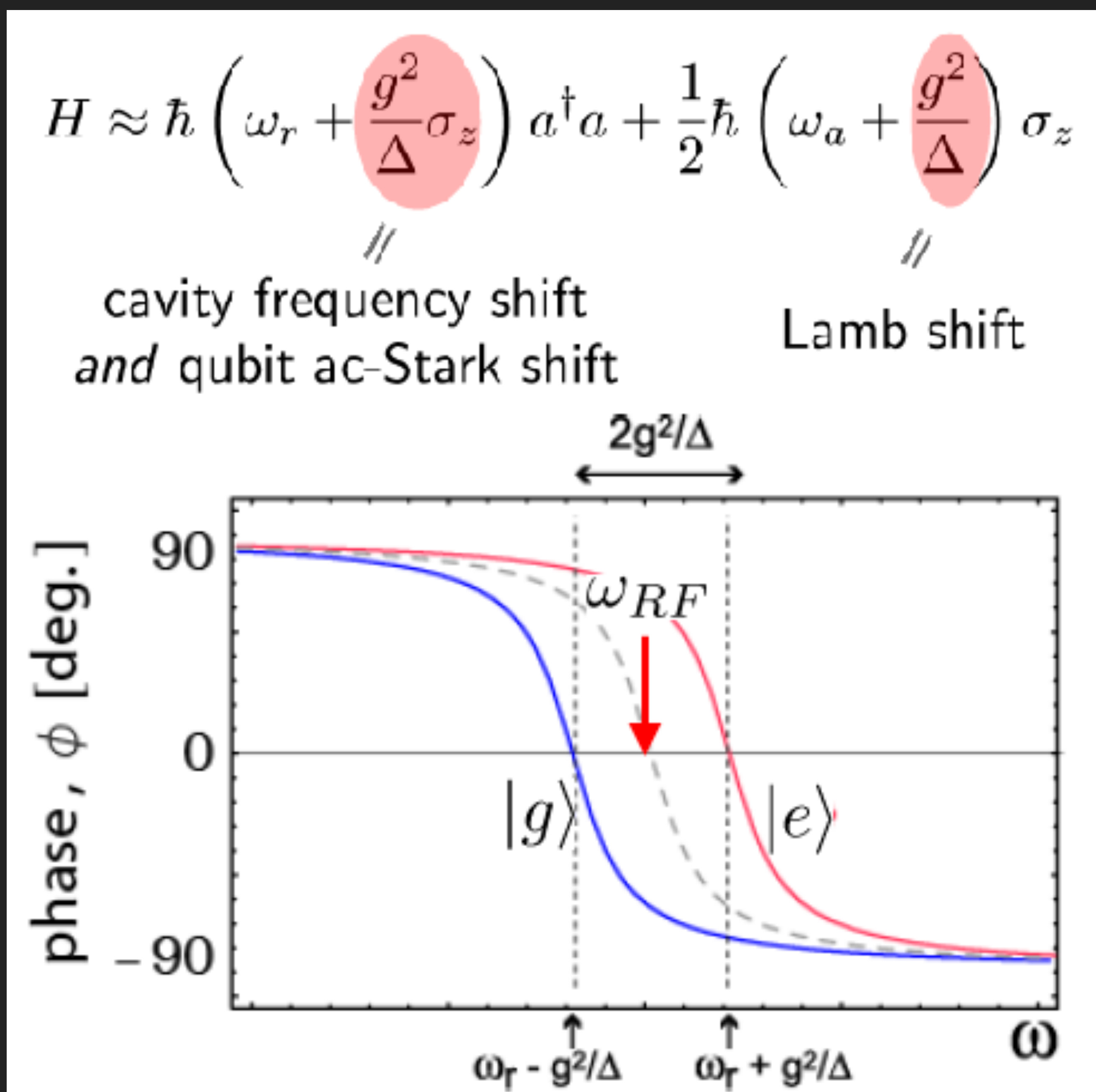


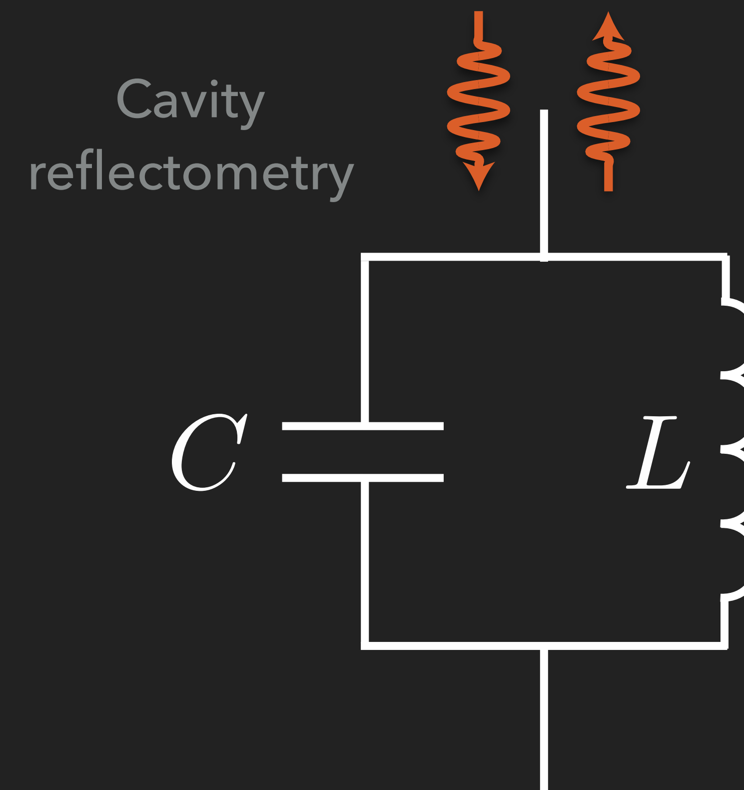
A. Wallraff et al., Nature 431, 162 (2004)

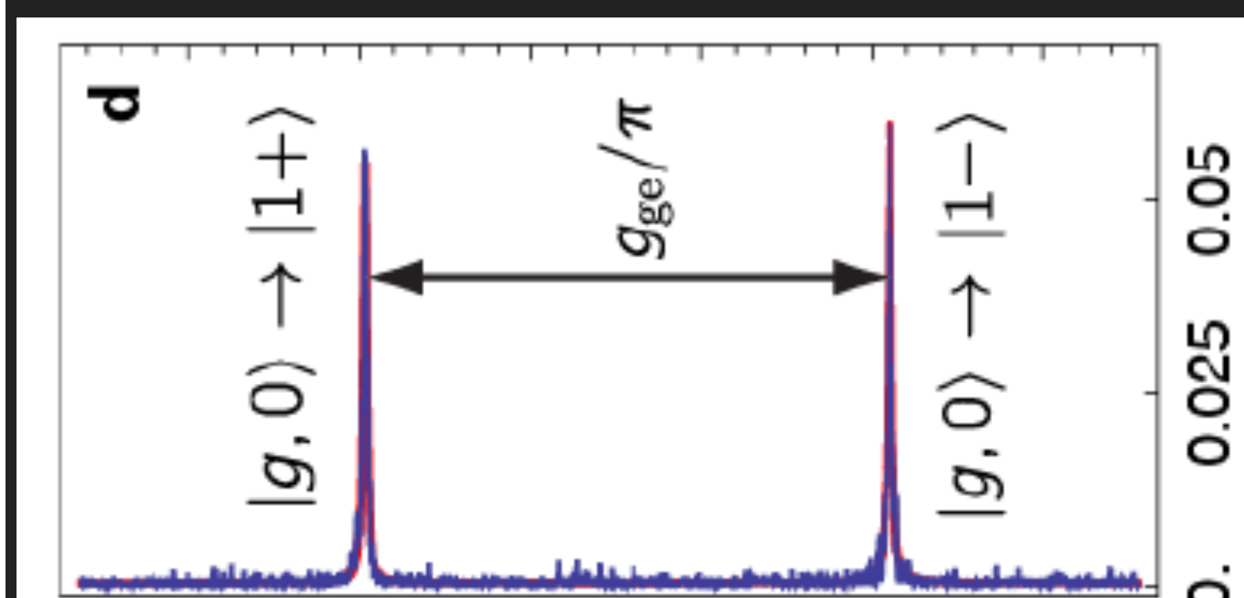
J. Fink et al., Nature 454, 315 (2008)

SUPERCONDUCTING QUANTUM TECHNOLOGIES

- Cavity-based readout







J. Fink et al., Nature 454, 315 (2008)

QUANTUM-LIMITED AMPLIFICATION

- Ideally, we want a perfect phase-preserving amplifier

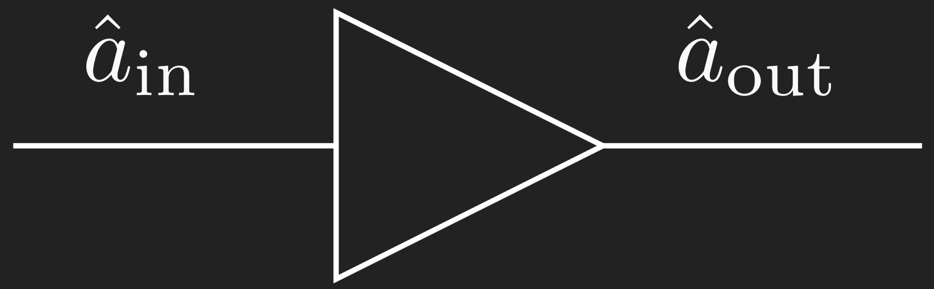
Signal: single-mode e.m. field:

$$\hat{E}(t) = \frac{1}{2}(\hat{a}e^{-i\omega t} + h.c.)$$

$$\langle E(t) \rangle = \mathrm{Re}(\langle a \rangle e^{-i\omega t})$$

$$\hat{a}_{\mathrm{out}} = g\hat{a}_{\mathrm{in}} + \hat{L}^{\dagger}$$

Added noise, internal d.o.f.



$$\hat{a}_{\mathrm{out}} = g\hat{a}_{\mathrm{in}}?$$

No! violates unitarity (commutator)

C. Caves, Phys. Rev. D 26, 1817

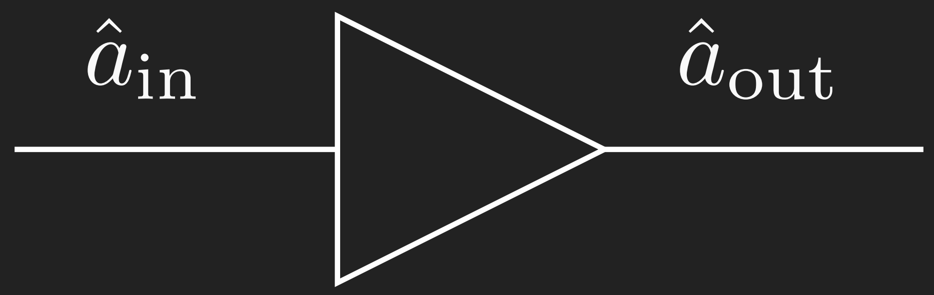
QUANTUM-LIMITED AMPLIFICATION

- Noise from amplifier appears in second moments

Variance of modes:

$$\langle|\Delta\hat{a}_{\mathrm{out}}|^2\rangle = g^2\langle|\Delta\hat{a}_{\mathrm{in}}|^2\rangle + \langle|\Delta\hat{L}|^2\rangle$$

$$\langle|\Delta\hat{a}_{\mathrm{out}}|^2\rangle/g^2 = \langle|\Delta\hat{a}_{\mathrm{in}}|^2\rangle + N_G$$



Noise added by amplifier:

$$N_G \geq \frac{1}{2}\left|1 - \frac{1}{g^2}\right|$$

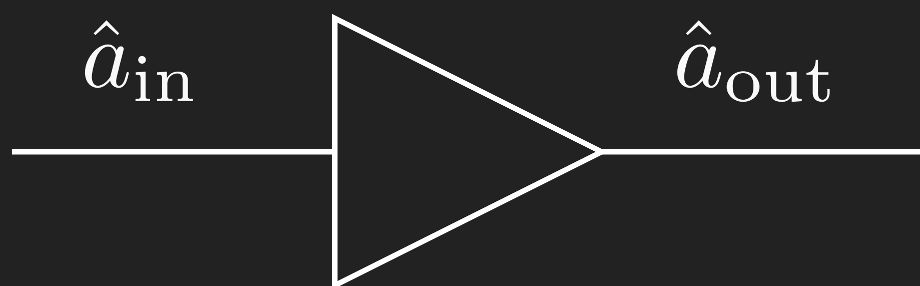
Quantum-limited amplifier:

$$N_{\mathrm{QL}} = \frac{1}{2}\left|1 - \frac{1}{g^2}\right|$$

C. Caves, Phys. Rev. D 26, 1817

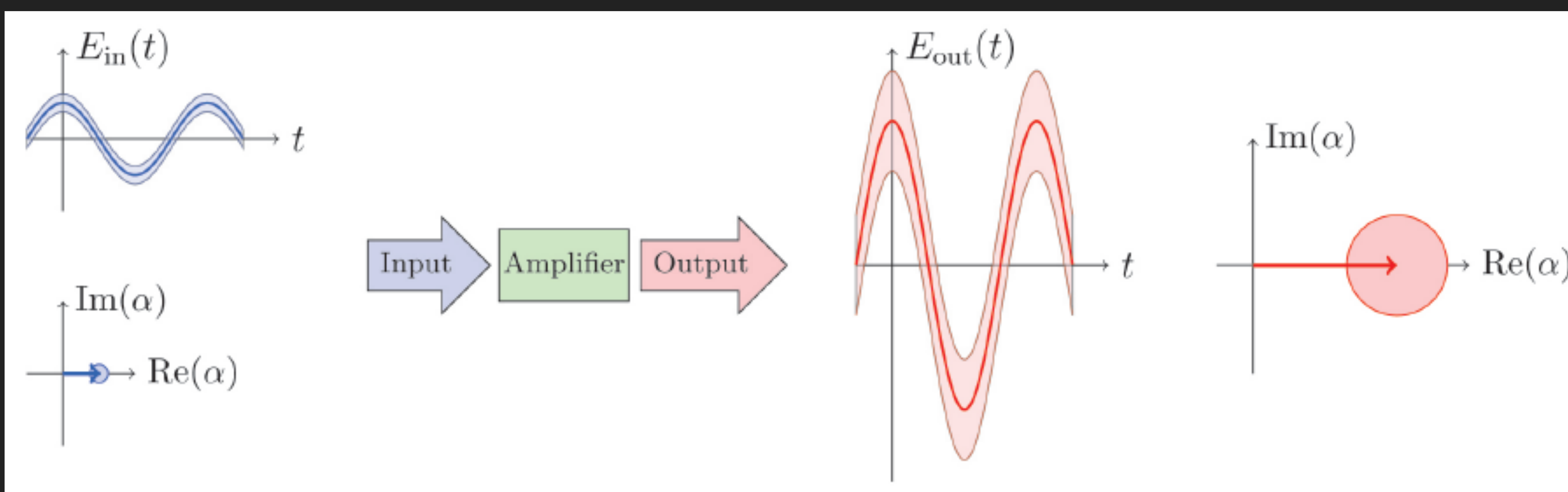
QUANTUM-LIMITED AMPLIFICATION

- Graphical representation with coherent states



$$N_{\text{QL}} = \frac{1}{2}\left|1 - \frac{1}{g^2}\right|$$

$$E_{\text{in}}(t) = E_0 \cos\omega t \qquad E_{\text{out}}(t) = gE_0 \cos\omega t$$



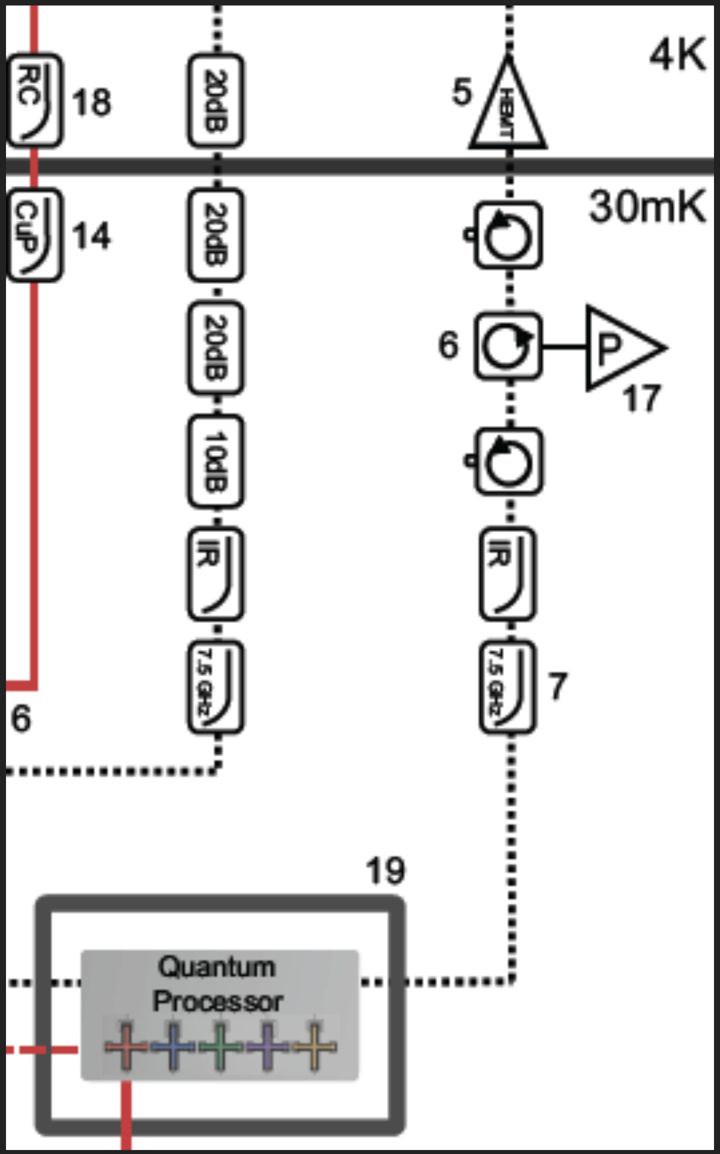
C. Caves *et al.*, Phys. Rev. A 86, 063802 (2012)

REAL-LIFE AMPLIFIERS

- Best commercial amplifier (and most used): HEMT LNA

T_N = 2.3 K
NF = 0.034 dB
G = 39 dB

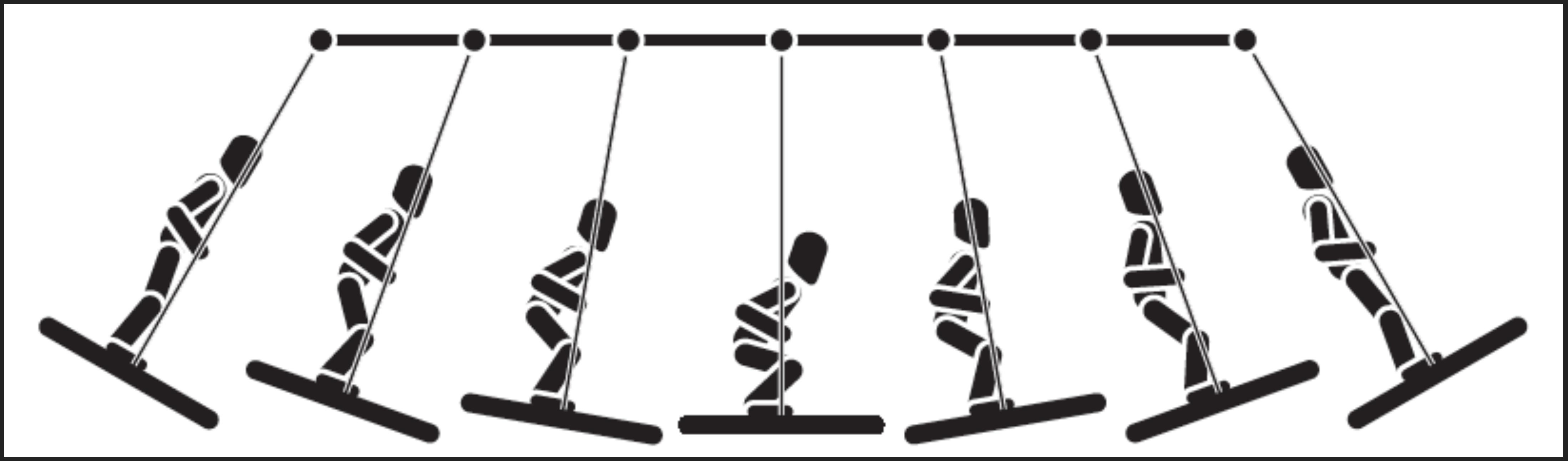
N_G = 30-40 photons



R. Barends *et al.*, Nature 508, 500 (2014)

JOSEPHSON PARAMETRIC AMPLIFIERS

- Externally-controllable parameter



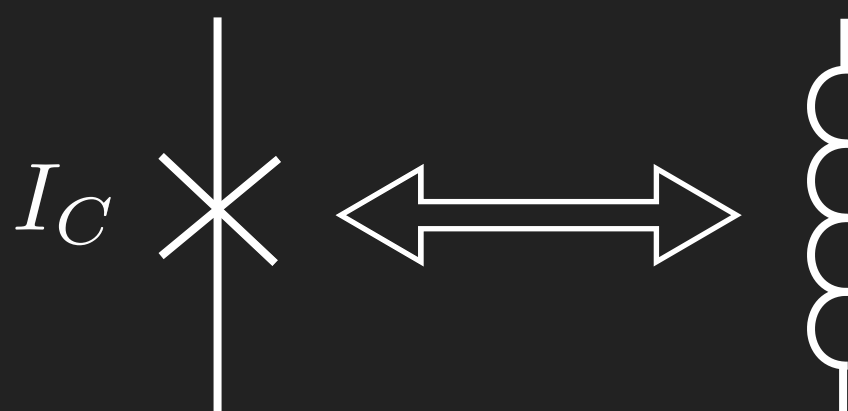
Duffing oscillator…

SQUID-BASED PARAMETRIC RESONATORS

- SQUID principle

Josephson junction

Tuneable, nonlinear, nondissipative inductance



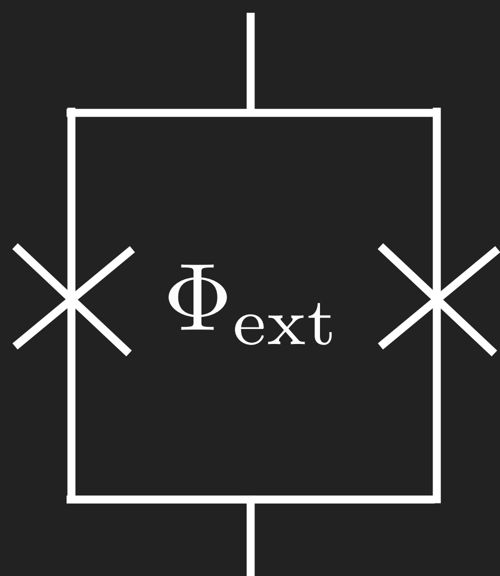
Josephson inductance

$$L_J = \left(\frac{\Phi_0}{2\pi}\right)\frac{1}{\sqrt{I_C^2 - I^2}}$$

Quantum of flux

$$\Phi_0 = \frac{h}{2e} \approx 2.07 \times 10^{-15}\ \mathrm{Wb}$$

SQUID: 2 junctions in parallel



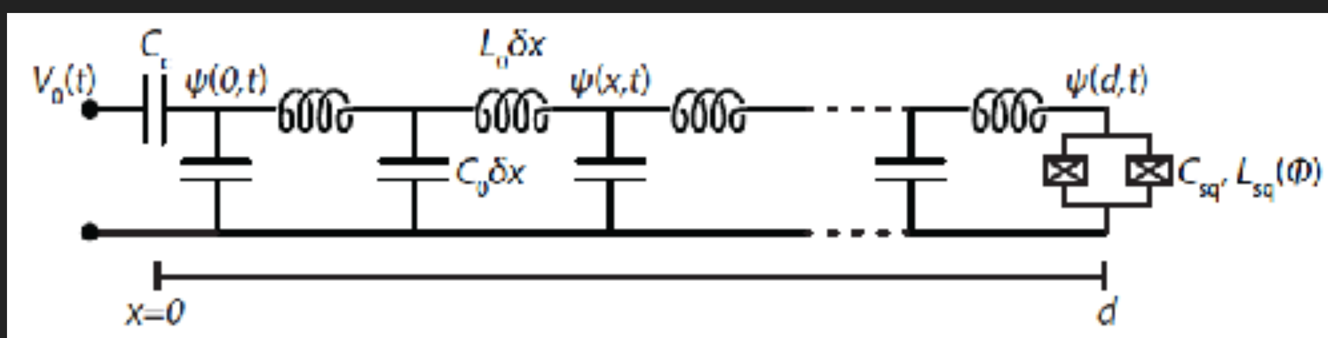
$$I_C(\Phi_{\mathrm{ext}}) = 2I_C \cos\left(\pi\frac{\Phi_{\mathrm{ext}}}{\Phi_0}\right)$$

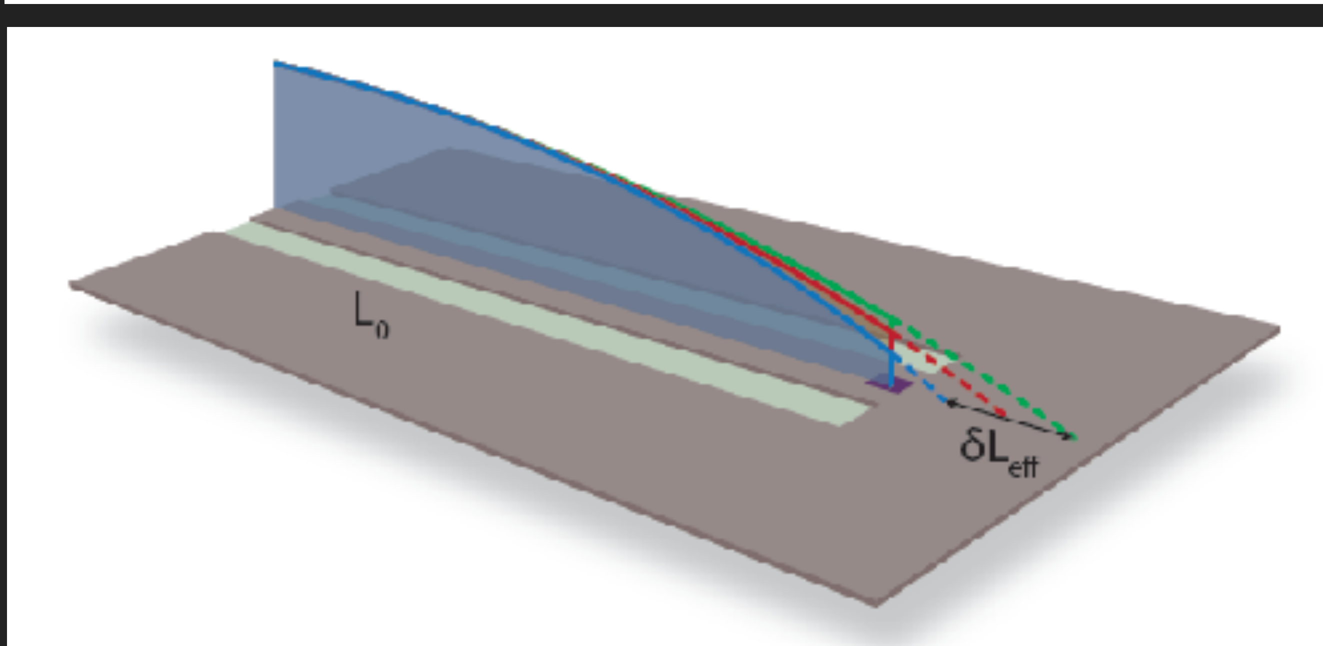
$$L_J(\Phi_{\mathrm{ext}}) = \left(\frac{\Phi_0}{2\pi}\right)\frac{1}{\sqrt{I_C(\Phi_{\mathrm{ext}})^2 - I^2}}$$

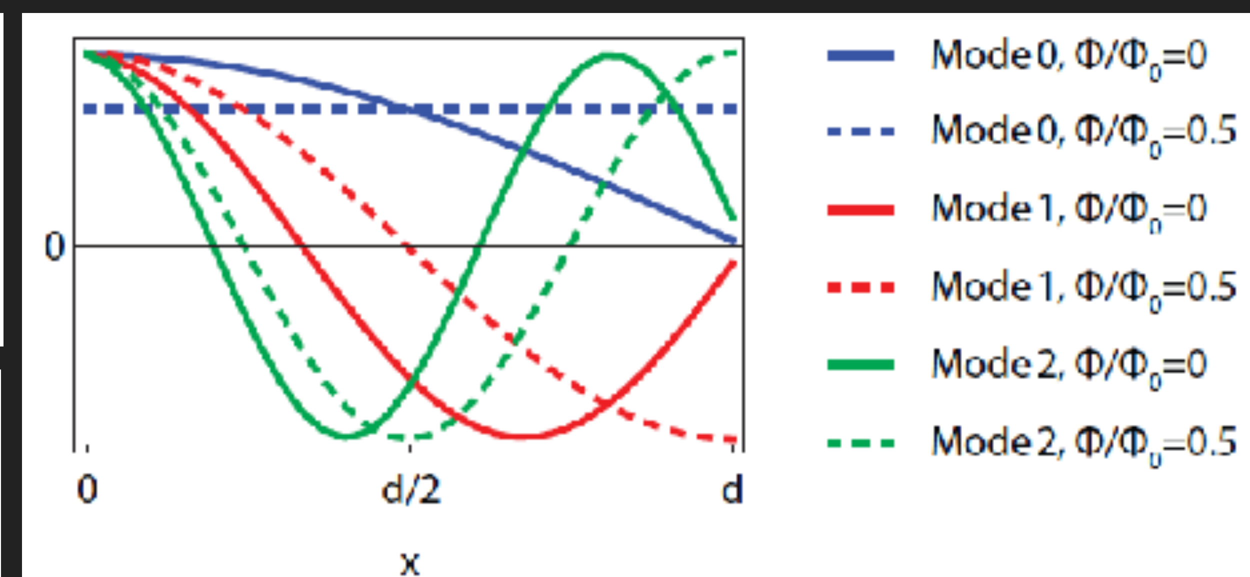
Flux-tunable, nonlinear inductance

SQUID-BASED PARAMETRIC RESONATORS

- Josephson parametric amplifier



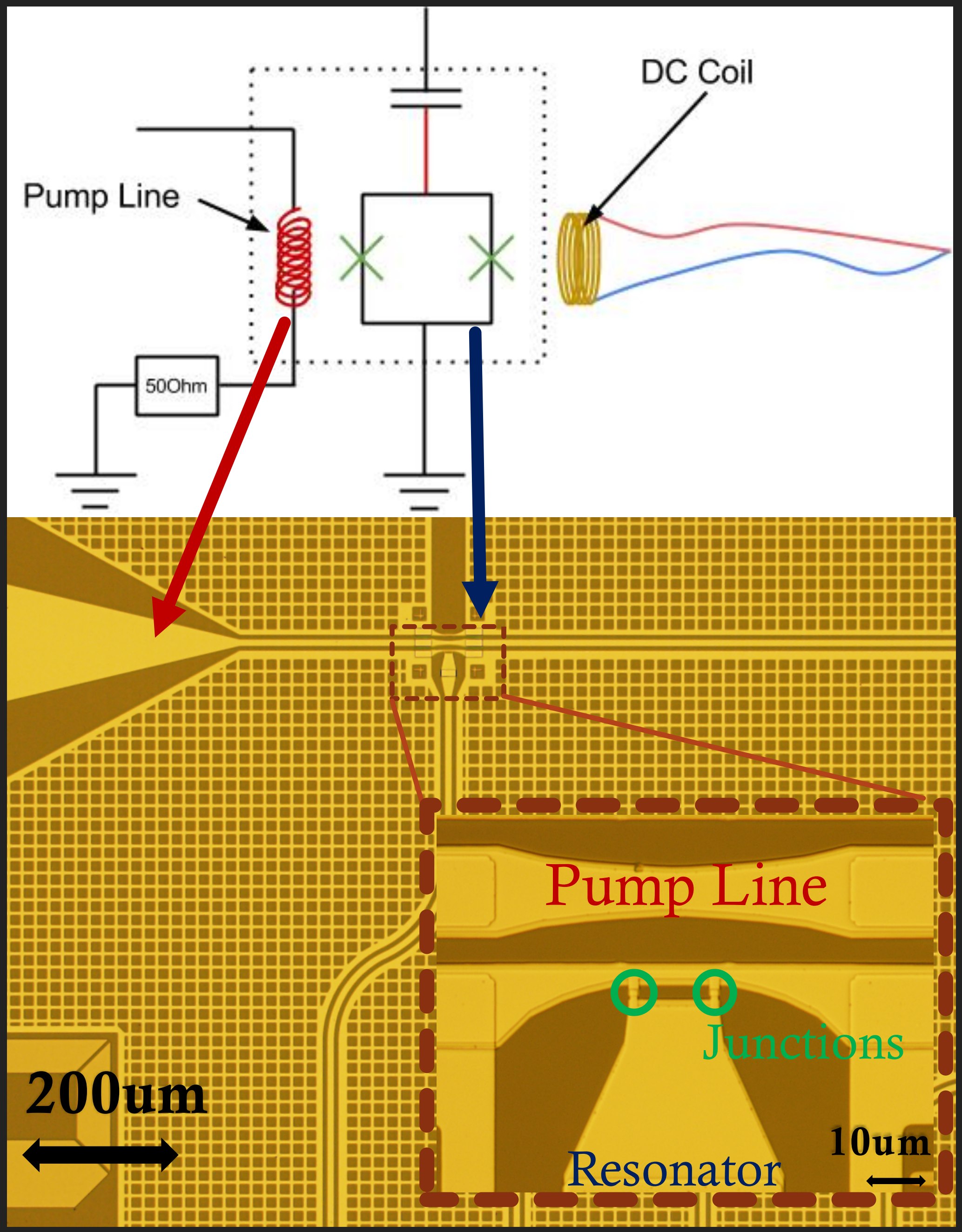


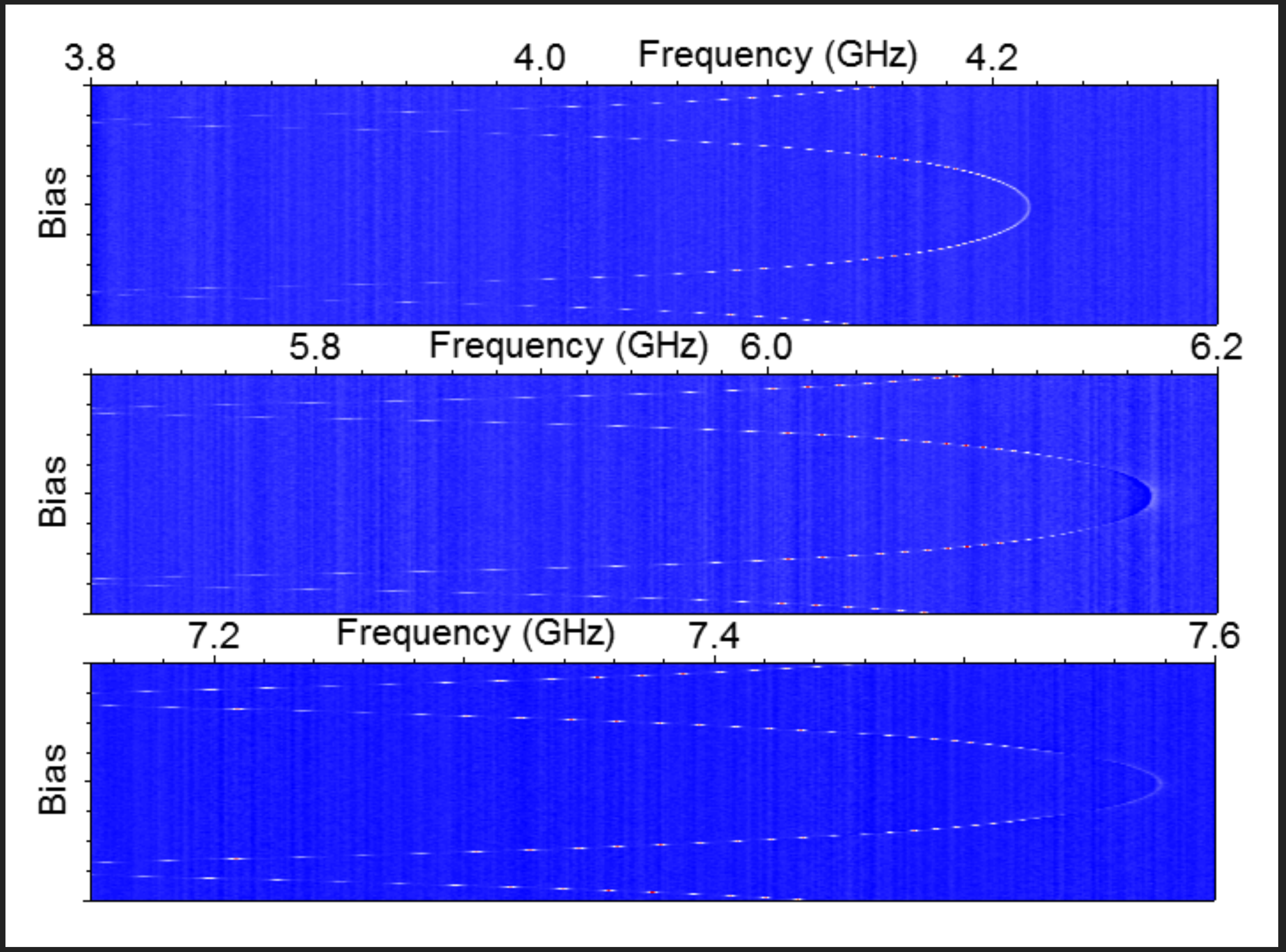


M. Simoen, PhD thesis

SQUID-BASED PARAMETRIC RESONATORS

- Josephson parametric amplifier: real devices

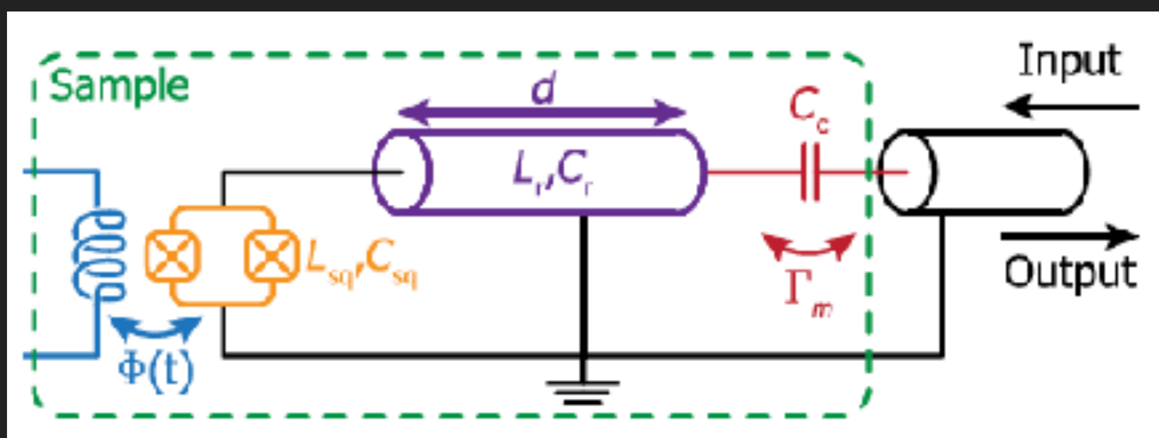


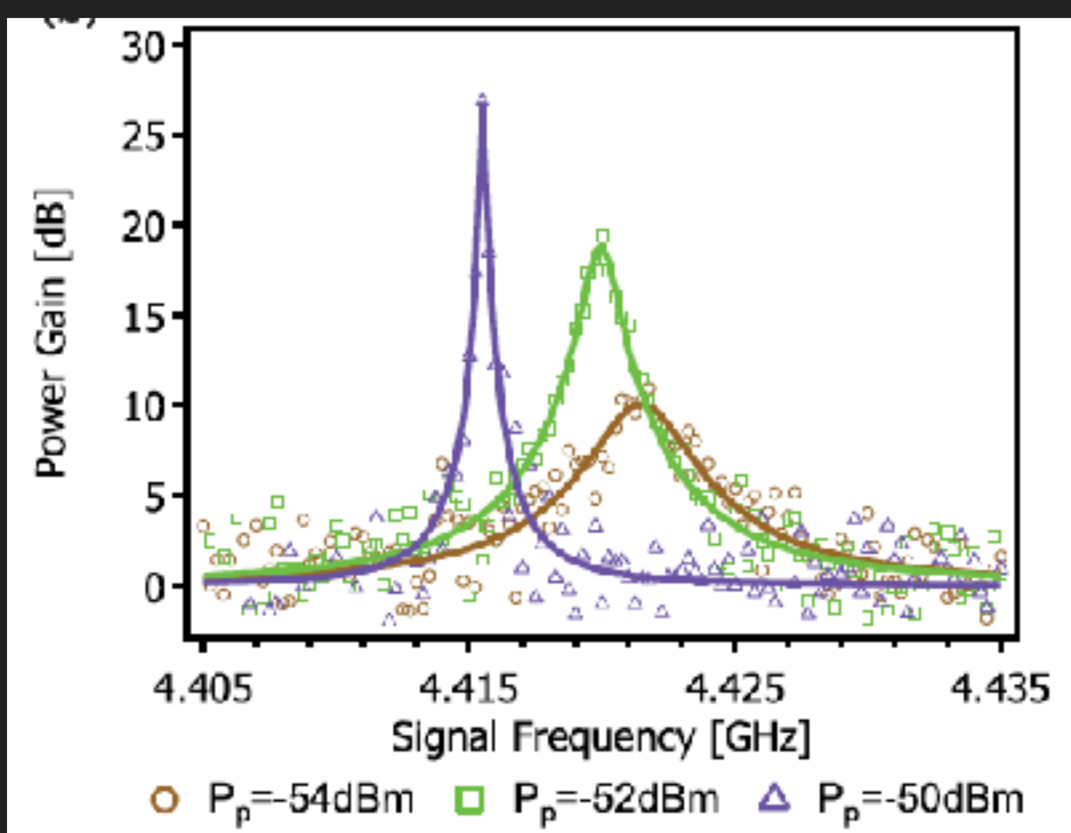


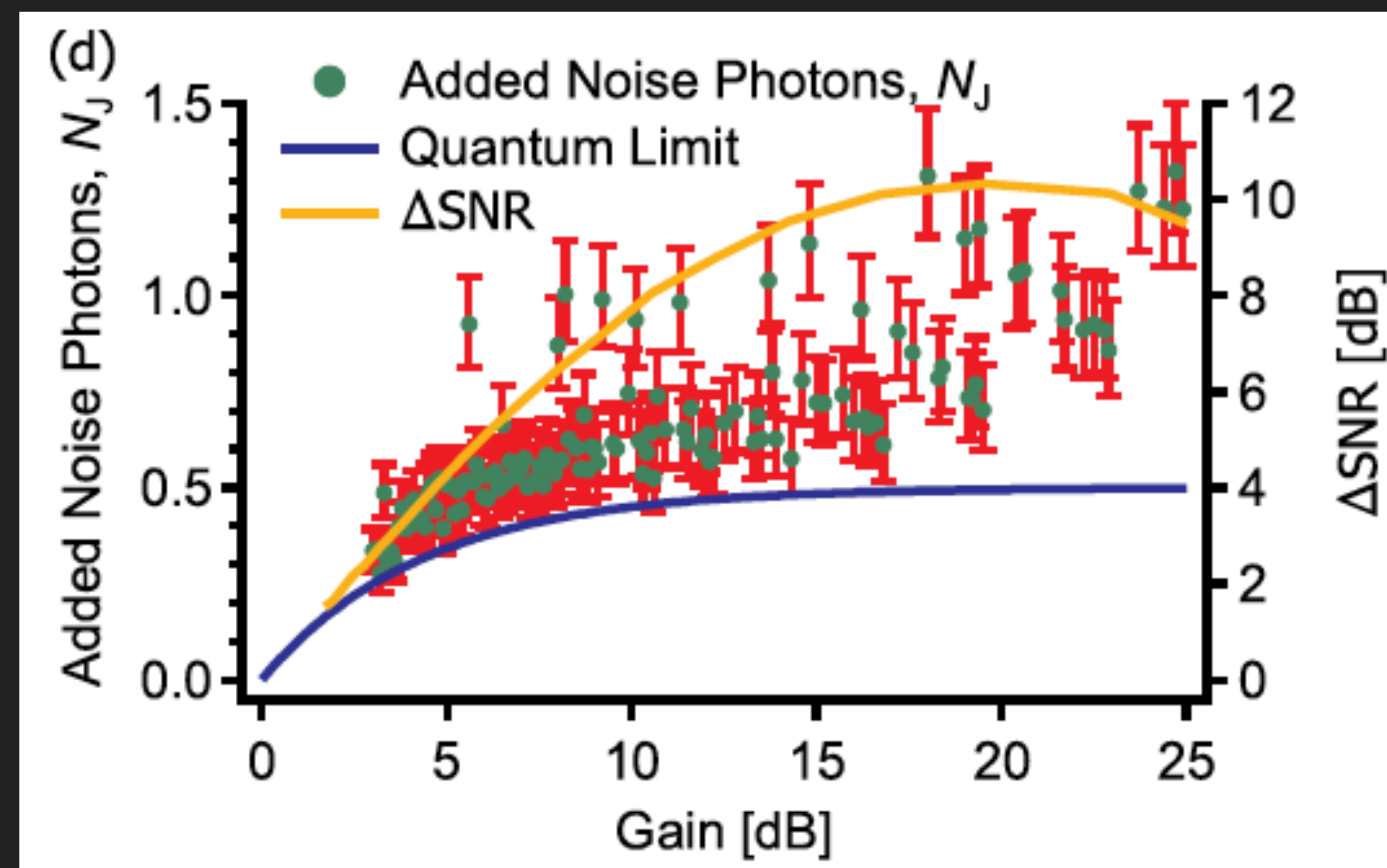
S. Chang, MSc thesis

SQUID-BASED PARAMETRIC RESONATORS

- Josephson parametric amplifier: performance



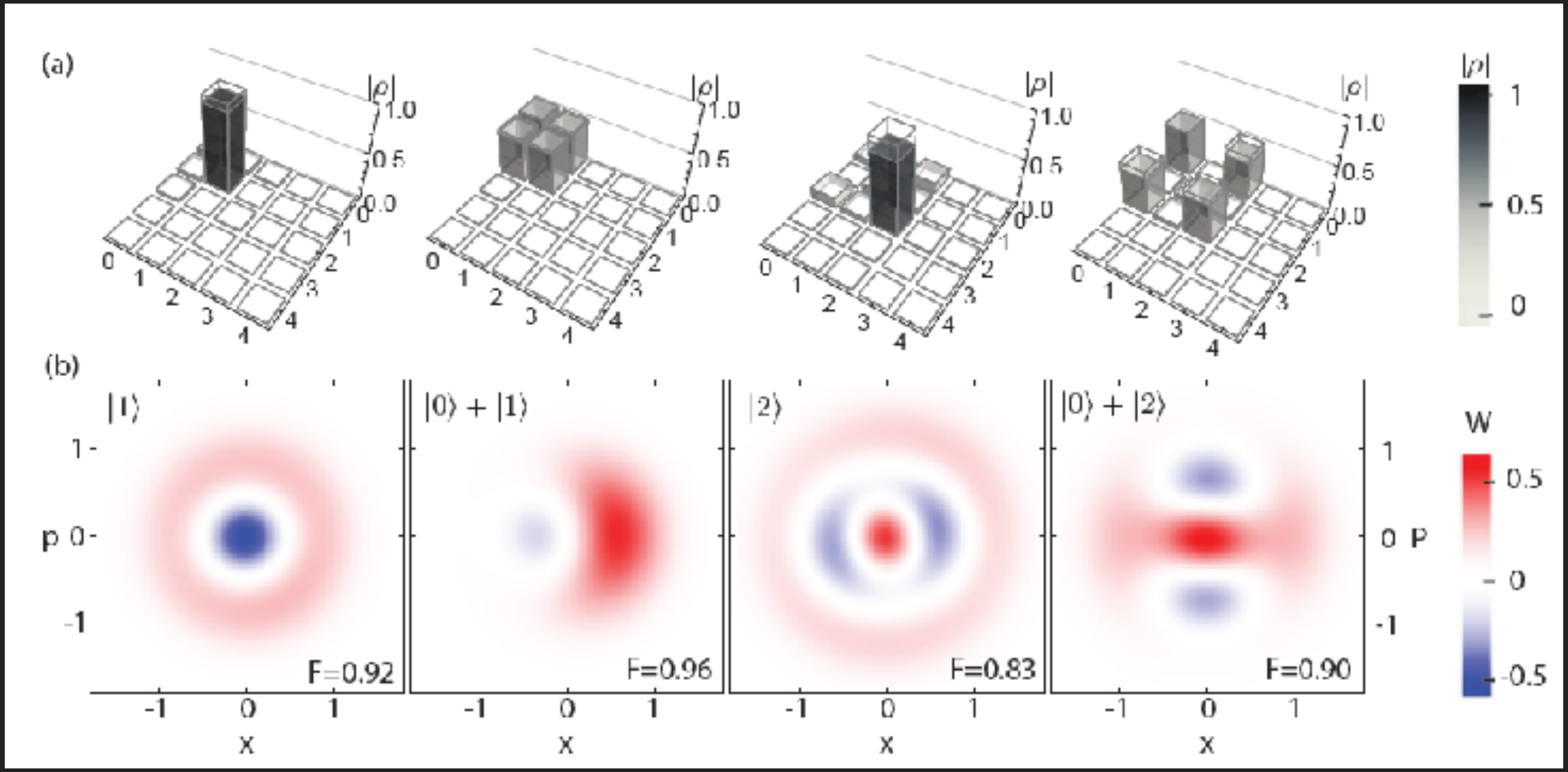




M. Simoen *et al.*, J. Appl. Phys. 118, 154501 (2015)

SQUID-BASED PARAMETRIC RESONATORS

- Some results using JPAs



C. Eichler *et al.*, Phys. Rev. A 86, 032106 (2012)

CONCLUSIONS

- Photon amplifiers/detectors are crucial to quantum information
- Josephson parametric amplifiers are quantum-limited amplifiers
- JPAs integrate with qubit technology, even beyond superconducting circuits
- Almost any superconducting qubit-based experiment since ~2012 has a JPA
- JPAs enable quantum feedback, quantum teleportation, quantum state tomography, etc.

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- Thank you!

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READING OUT QUANTUM BITS

Di Vincenzo criteria:

- A scalable physical system with well characterized qubits.
- The ability to initialize the state of the qubits to a simple fiducial state.
- Long relevant decoherence times.
- A ``universal” set of quantum gates.
- A qubit-specific measurement capability.
- The ability to interconvert stationary and flying qubits.
- The ability to faithfully transmit flying qubits between specified locations.