Towards Quantum Error Correction with Superconducting Circuits

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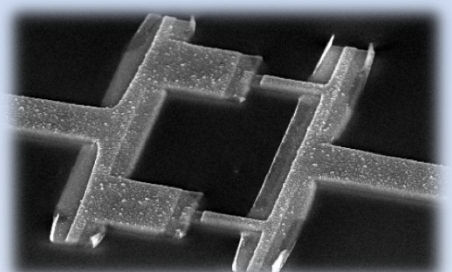

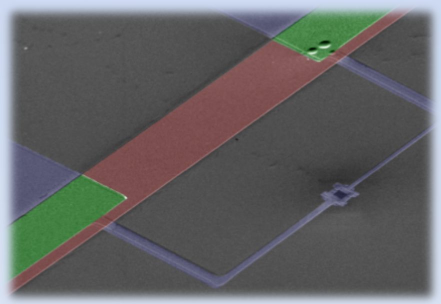

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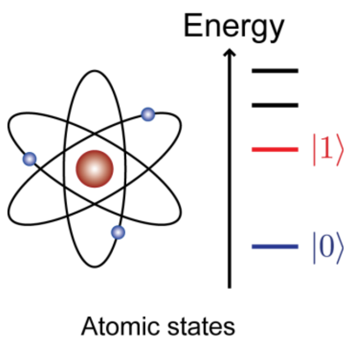
Outline

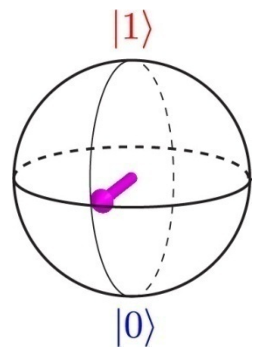
- Introduction
  - Quantum Error Correction
- Superconducting quantum circuits
  - Quantum bits
  - Measurement Architecture
- Current and Future Directions

Requirements for Quantum Information

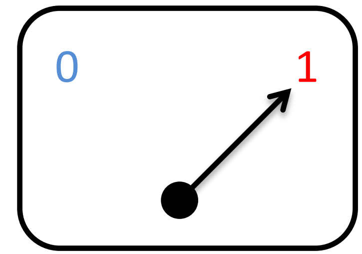
Quantum Two Level Systems



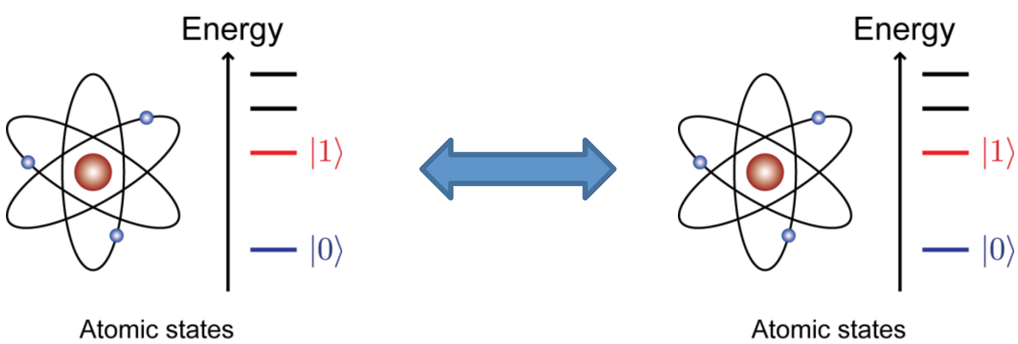
Create arbitrary states



Measure quantum state



Coupling between qubits

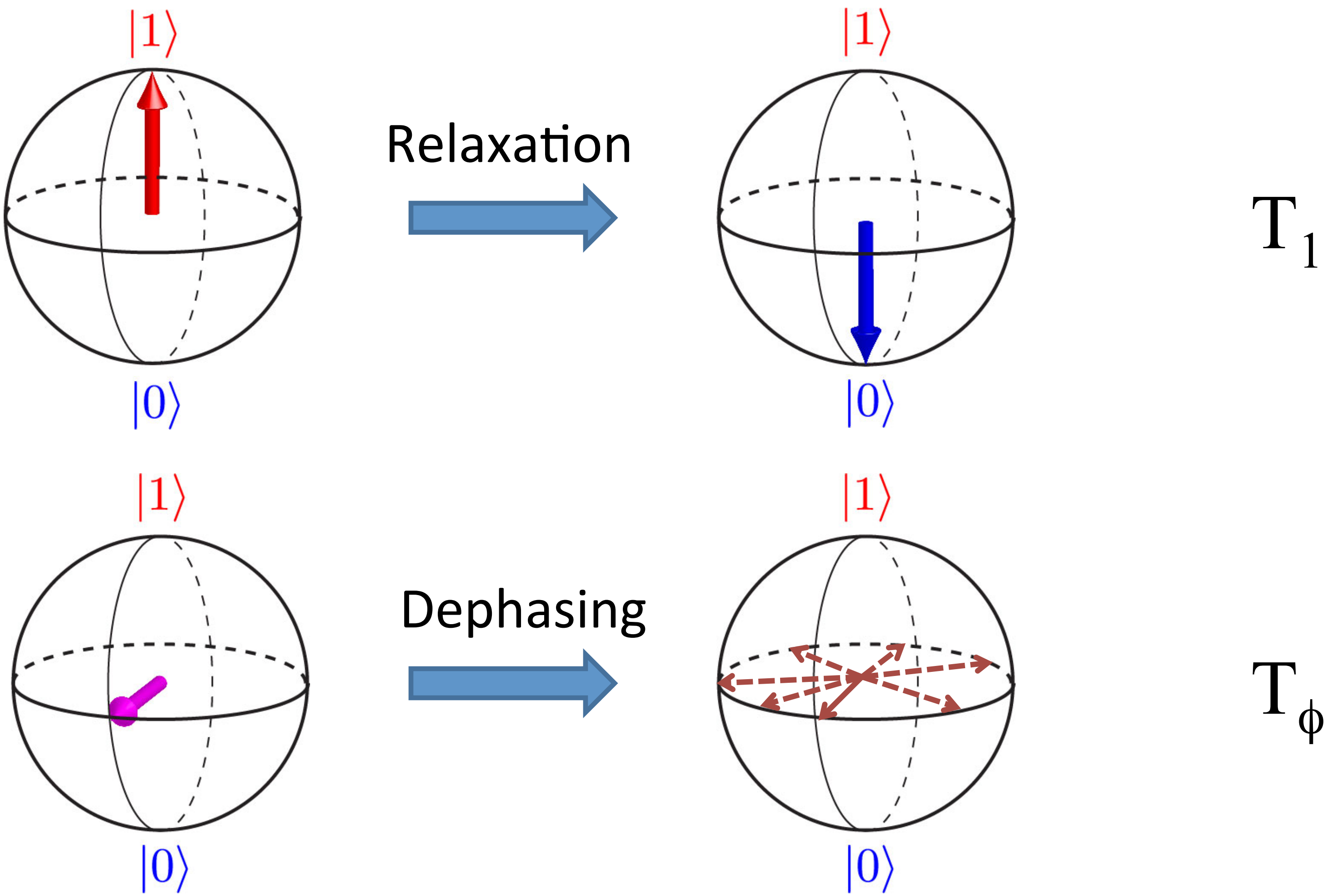


Challenge:

Finite quantum coherence

Fast, high-fidelity measurement

Quantum Decoherence



CAN WE PROTECT A QUANTUM STATE AGAINST SUCH PROCESSES?

Quantum Error Correction

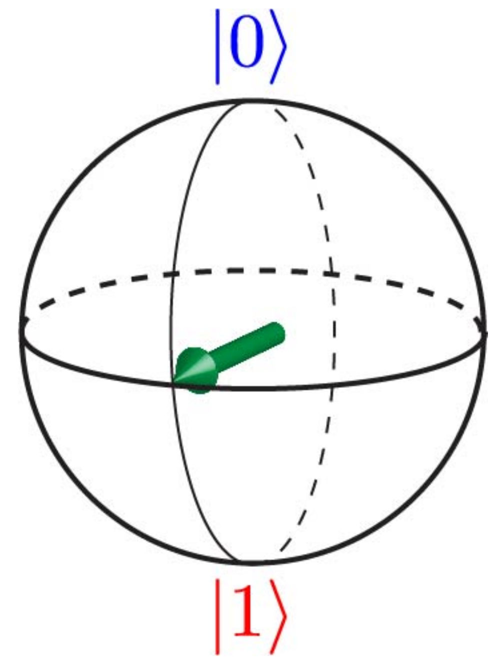
CLASSICAL ERROR CORRECTION:

0 → 000 1 → 111

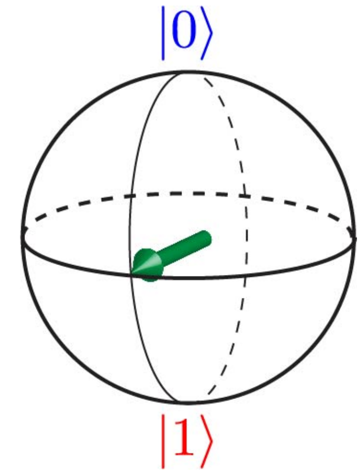
REDUDANCY , MAJORITY VOTE

CAN WE DO THIS WITH QUANTUM BITS?

- NO CLONING THEOREM
- CONTINUOUS ERRORS
- MEASUREMENT DESTROYS STATE



Quantum Error Correction



Protecting an unknown qubit state

Multiple physical qubits for one logical qubit

Example: Shor's three qubit bit-flip code

$\Psi = \alpha\,|0\rangle + \beta\,|1\rangle$ → $\Psi = \alpha\,|000\rangle + \beta\,|111\rangle$

<u>Protects against single bit flip errors</u>

$\Psi = \alpha\,|000\rangle + \beta\,|111\rangle$

$\Psi = \alpha\,|\underline{1}00\rangle + \beta\,|\underline{0}11\rangle$

$\Psi = \alpha\,|0\underline{1}0\rangle + \beta\,|1\underline{0}1\rangle$

$\Psi = \alpha\,|00\underline{1}\rangle + \beta\,|11\underline{0}\rangle$

Distinguish these four possibilities

MEASURE THE ERROR, NOT THE STATE : PARITY MEASUREMENTS

PARITY MEASUREMENTS

$\Psi = \alpha\, |000\rangle + \beta\, |111\rangle$

$\Psi = \alpha\, |100\rangle + \beta\, |011\rangle$

Check if pairs of qubits are "pointing the same way"

USE TWO ANCILLA QUBITS:

- ENTANGLE WITH QUBITS PAIRS
- ANCILLA MEASUREMENT YIELDS FOUR OUTCOMES
  - NO ERROR , BIT FLIP ON QUBIT 1 , 2 OR 3

Shor's 9 qubit code (Phys. Rev. A 52, R2493(R)):

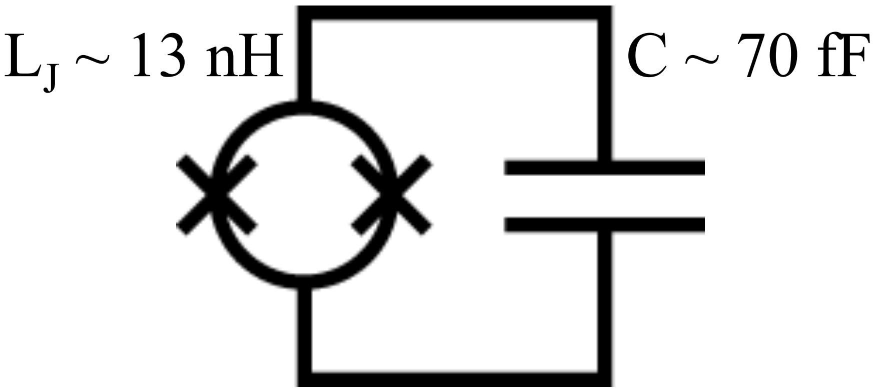
$|0\rangle : \quad (|000\rangle + |111\rangle)(|000\rangle + |111\rangle)(|000\rangle + |111\rangle)$

$|1\rangle : \quad (|000\rangle - |111\rangle)(|000\rangle - |111\rangle)(|000\rangle - |111\rangle)$

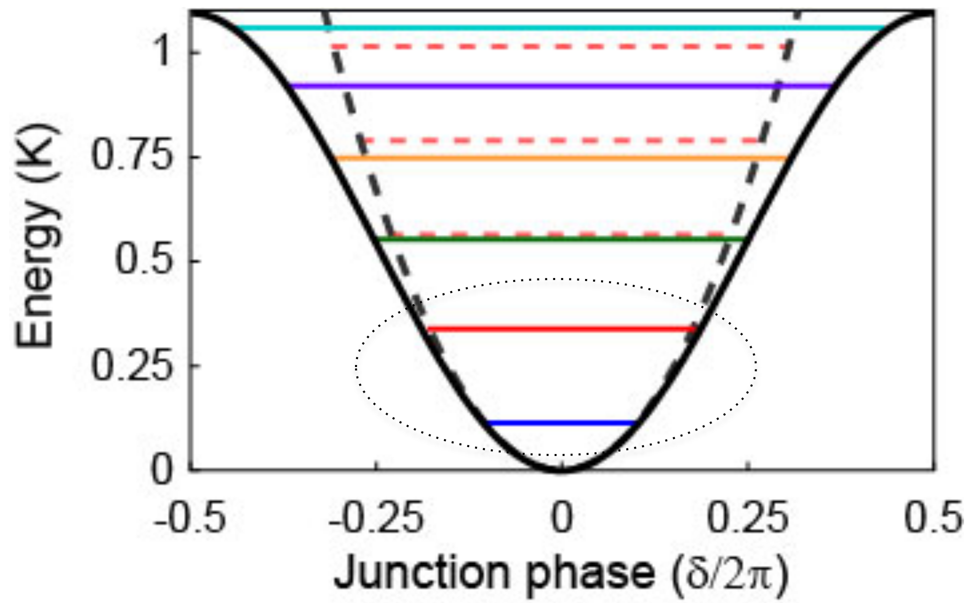
ALL ERRORS GET PROJECTED TO FINITE SET OF CORRECTABLE ERRORS

Superconducting Quantum Circuits

Superconducting quantum bit



Transmon qubit



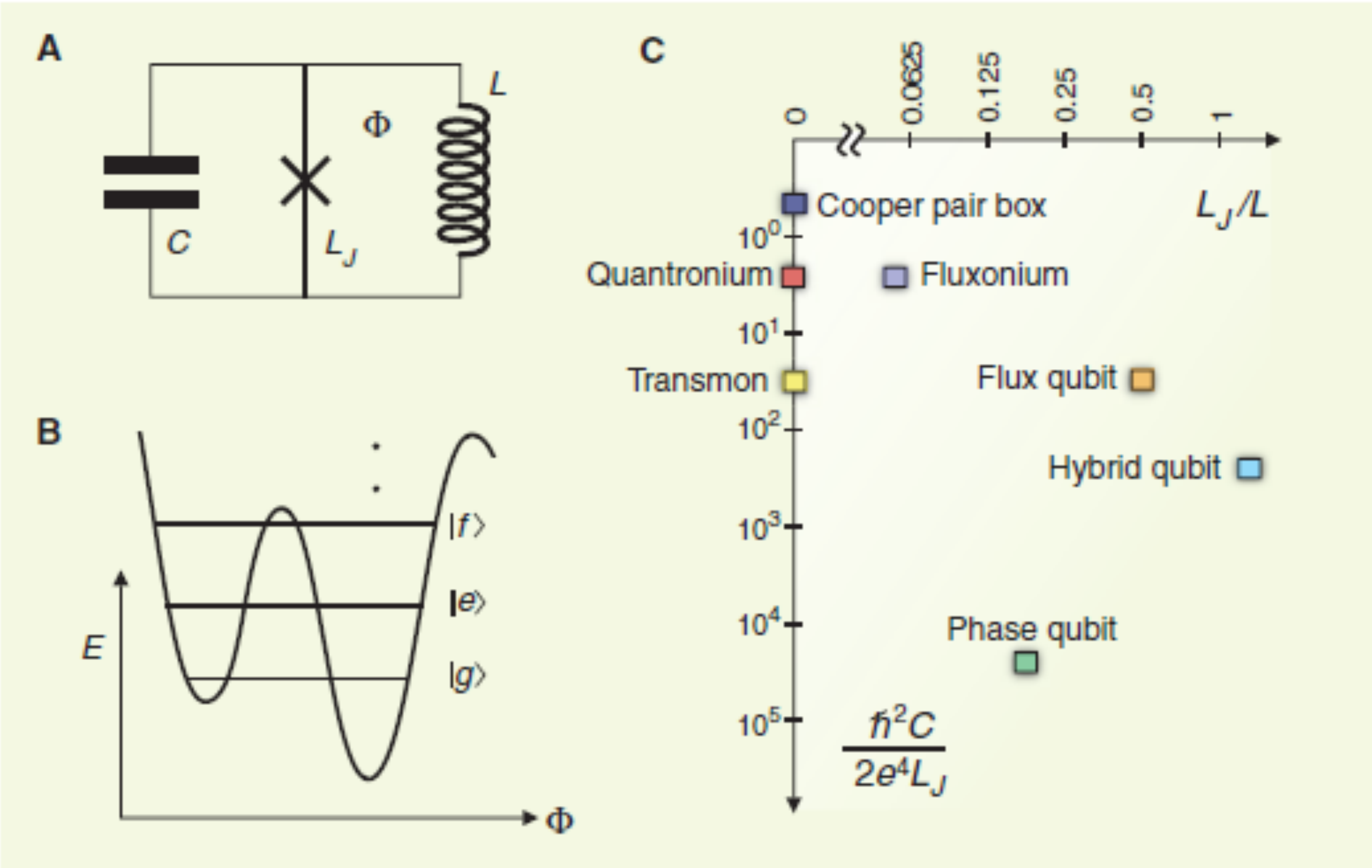
- Tunable qubit frequency
- Sufficient anharmonicity
- Other qubit designs: flux qubit, phase qubit, fluxonium….

$$\omega_{01} \simeq \frac{1}{\sqrt{L_J C}}$$

$$\omega_{01} \neq \omega_{12}$$

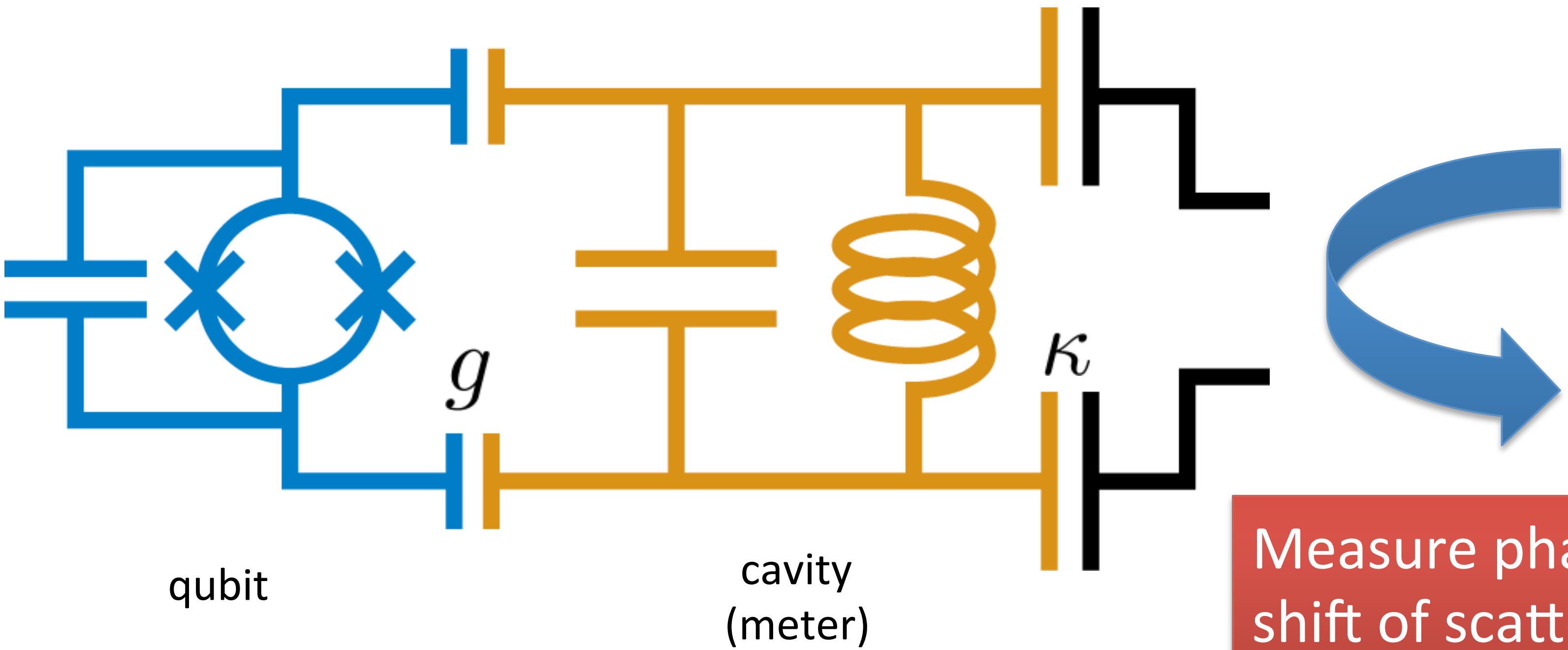
Koch et al. , Phys. Rev. A 76, 042319 (2007)

Qubit designs



Devoret and Schoelkolpf, Science **339**, 1169 (2013)

Measurement architecture



Measure phase shift of scattered microwaves

$$H_{disp} = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\left(\omega_r + \chi\sigma_z\right)\left(a^\dagger a + \frac{1}{2}\right)$$

$$\omega_r(|0\rangle) + 2\chi = \omega_r(|1\rangle)$$

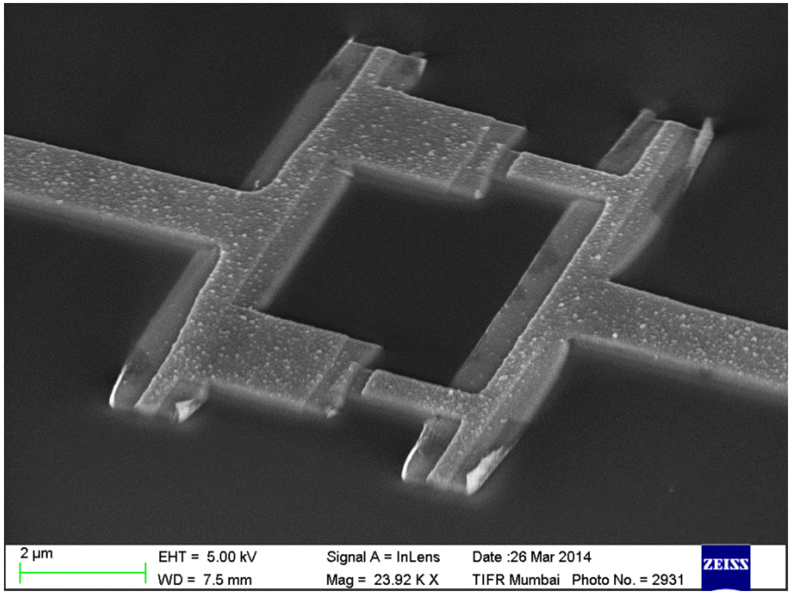
$\Delta=\omega_r - \omega_q >> g$

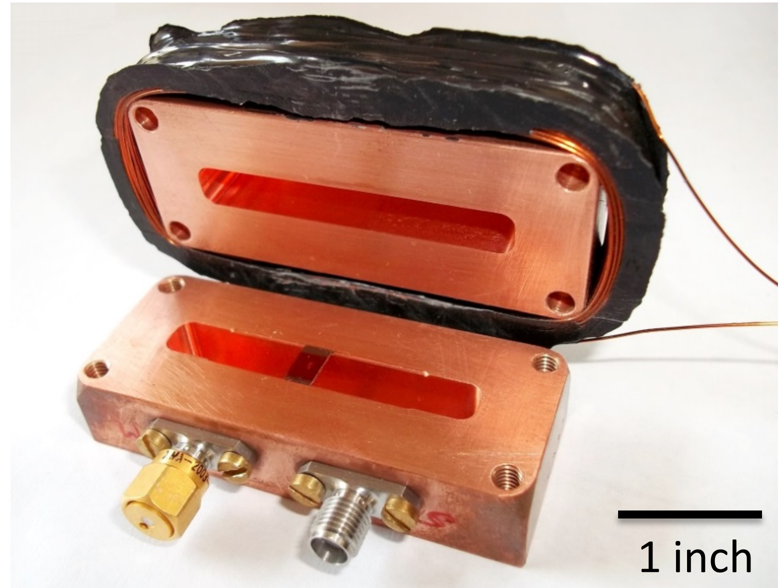
$\chi \sim g^2/\Delta$

Cavity frequency changes with qubit state

Blais et al. , Phys. Rev. A 69, 062320 (2004)

Transmon qubit + 3D cavity

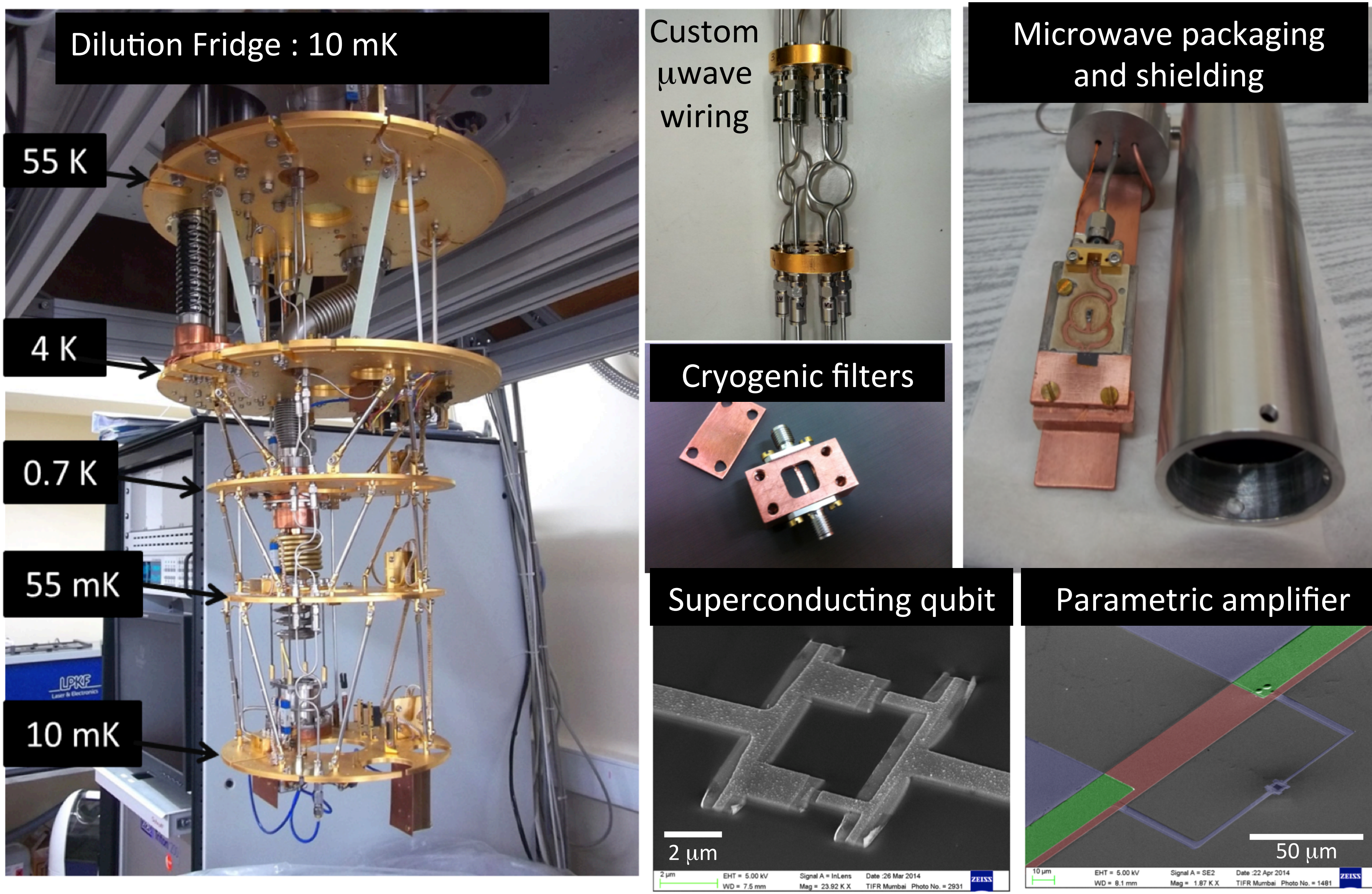




- Full 3D control of microwave environment
- Minimization of lossy materials
- Long coherence times, $T_1 \sim 10 - 100\ \mu s$, $T_2 \sim 5 - 150\ \mu s$
- Robust and modular design

H. Paik et al. , Phys. Rev. Lett. **107**, 240501 (2011)

Cryogenic measurement setup



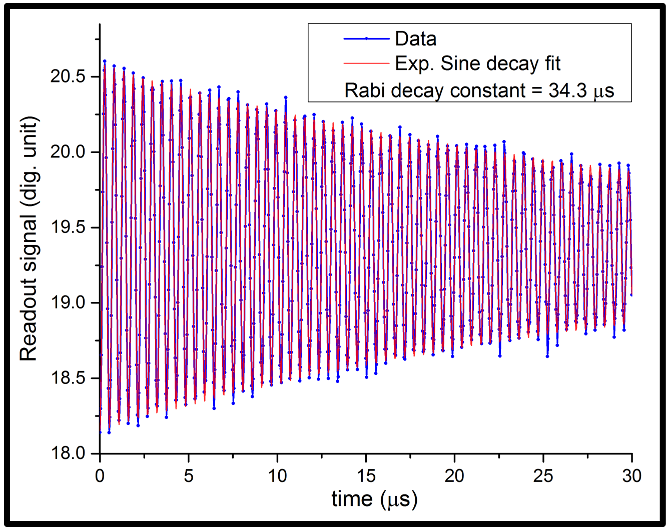
What do we need for QEC?

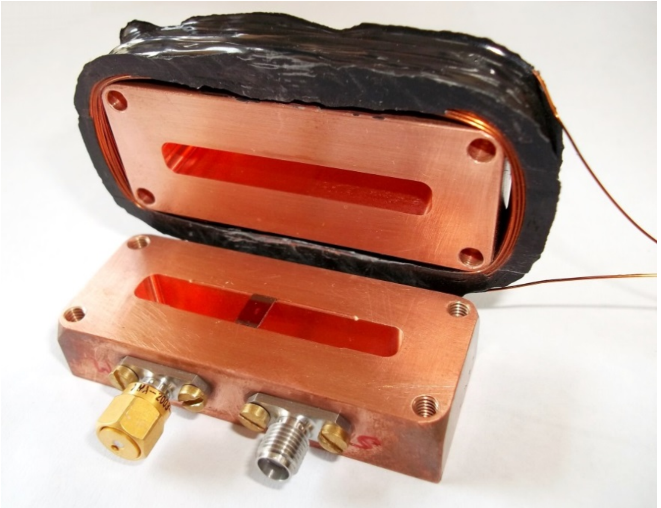
Good coherence qubits

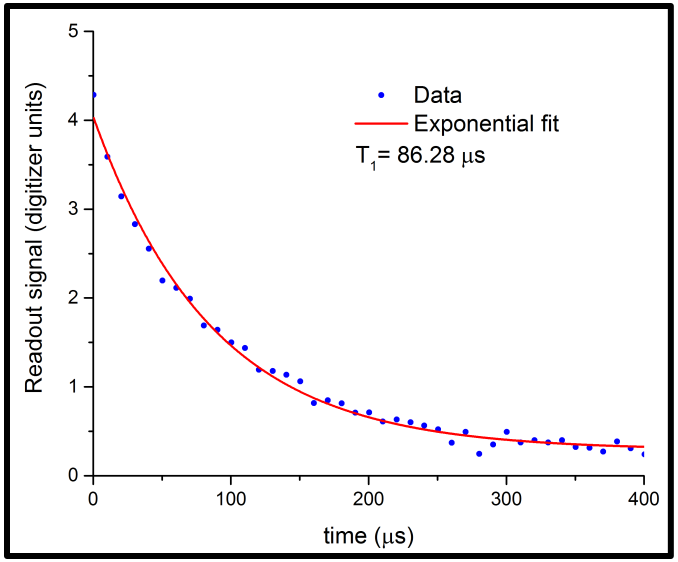
High fidelity measurement
- Broadband amplifiers

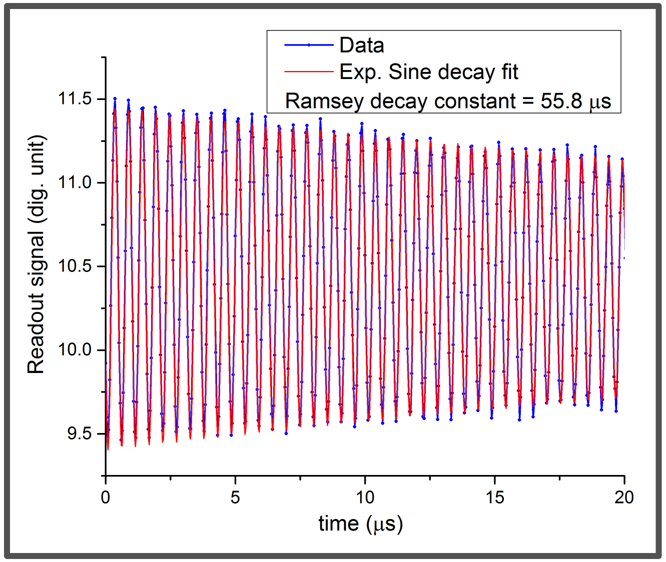
Ability to do parity measurements

Qubit Coherence



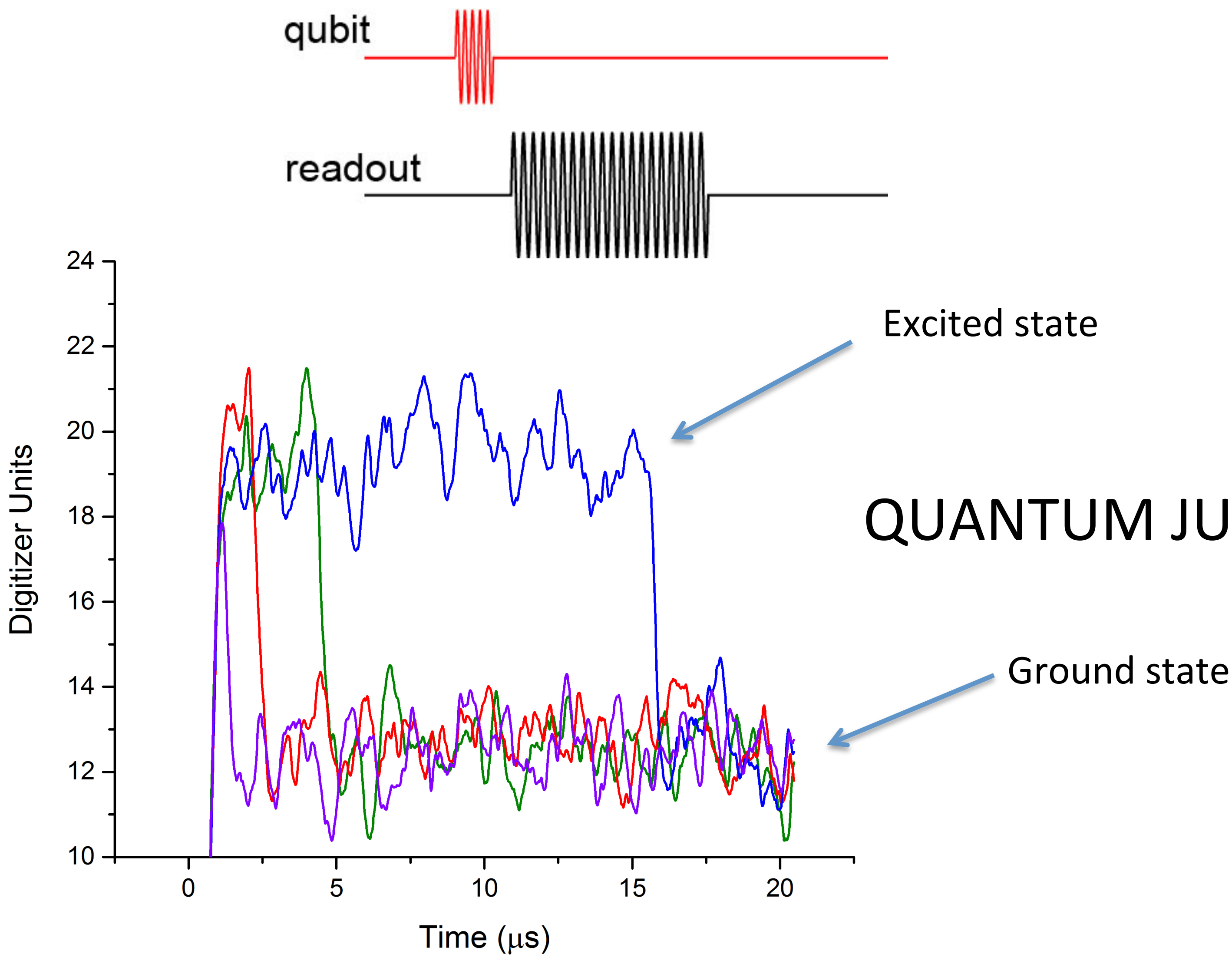






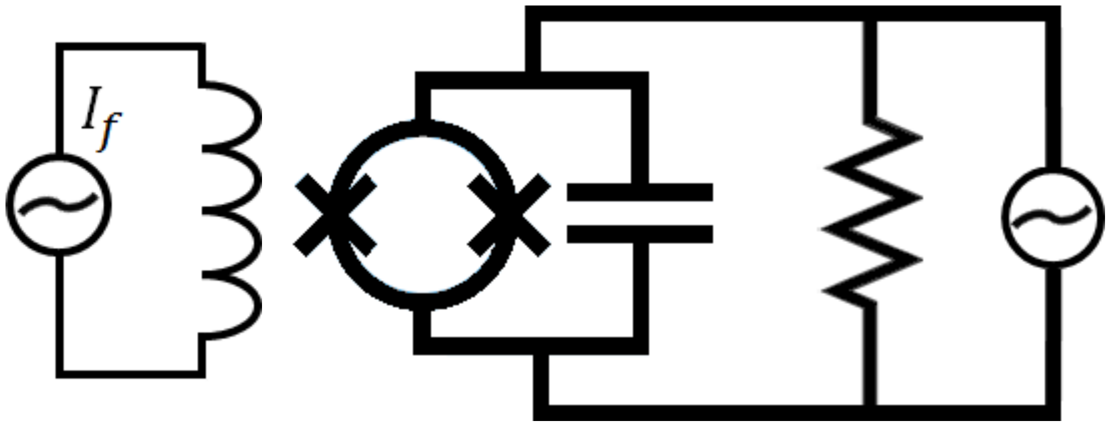
<u>See poster by Madhavi Chand</u>

High fidelity measurement



QUANTUM JUMPS

Parametric Amplifiers



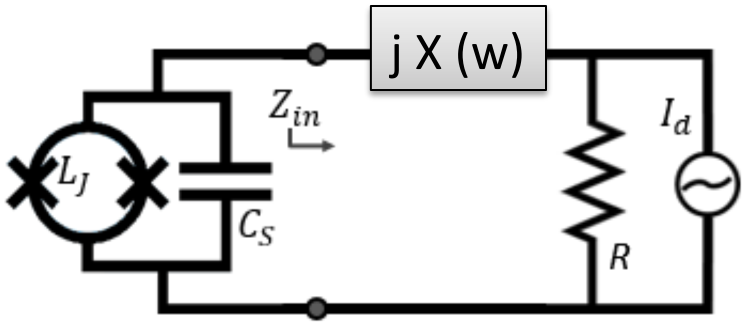
- Crucial for quantum measurements
- Typical bandwidth : 50 MHz
- Need larger bandwidth for multi-qubit experiments

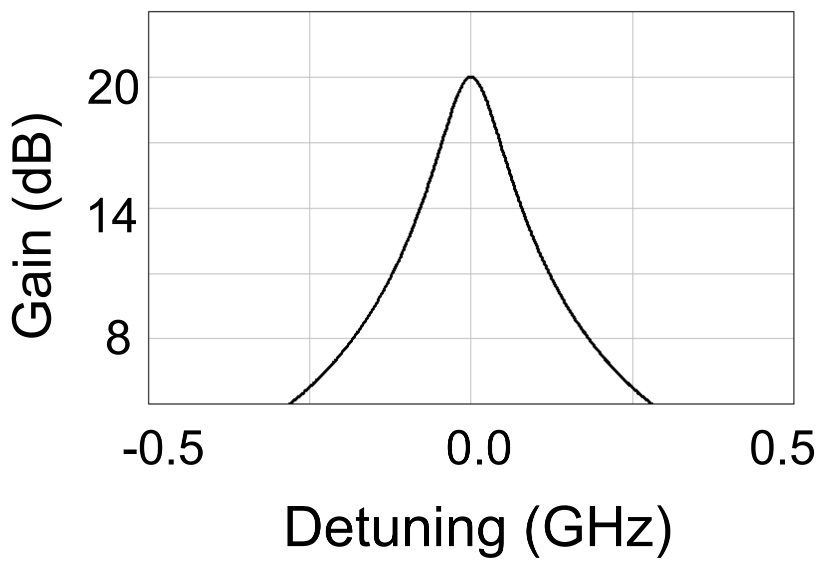
Bandwidth set by oscillator damping

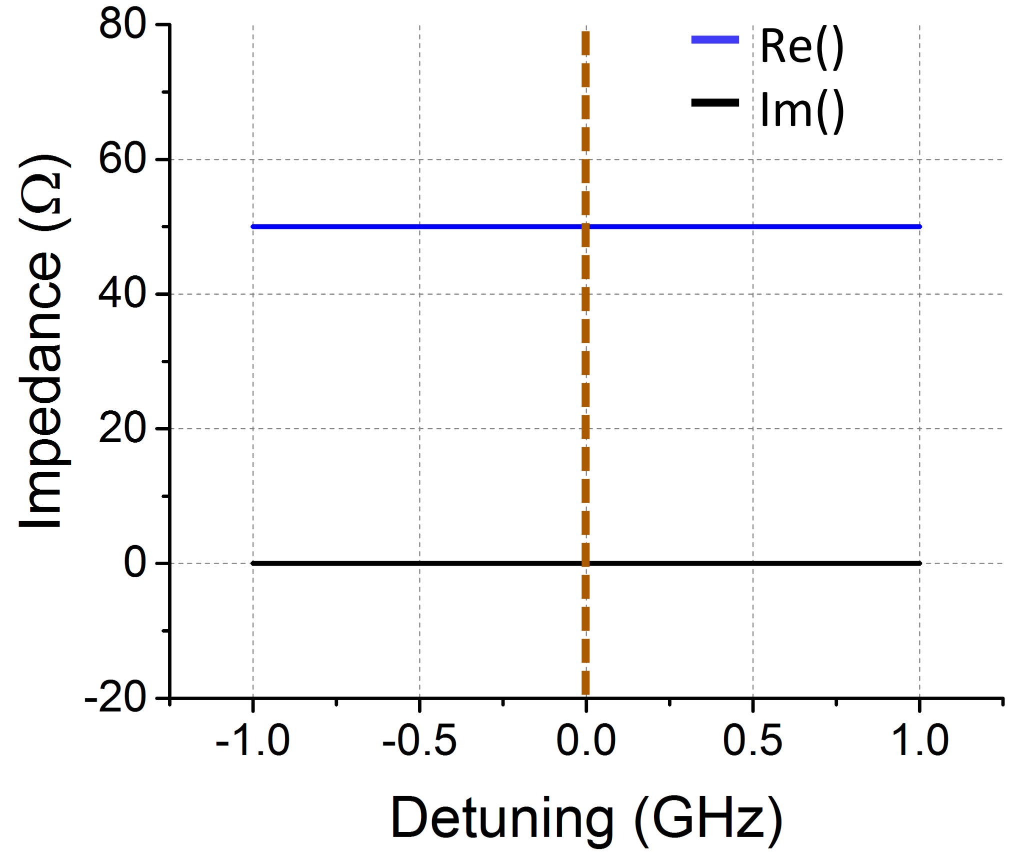
Increase damping: drive harder ; instabilities

More bandwidth without increasing damping?

Impedance Engineering

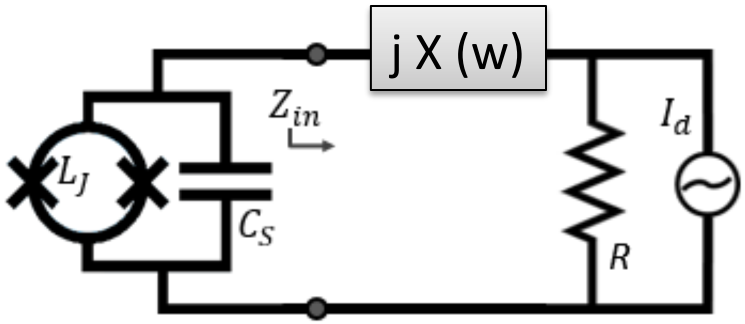


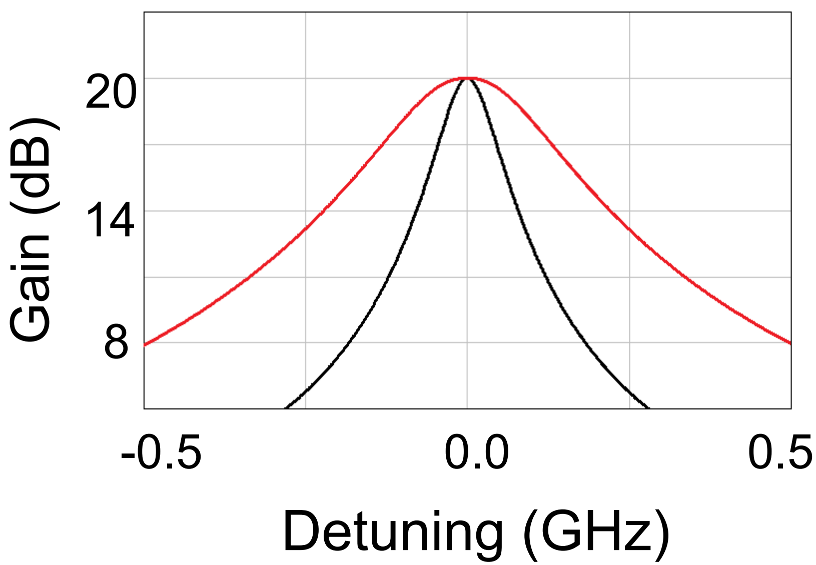


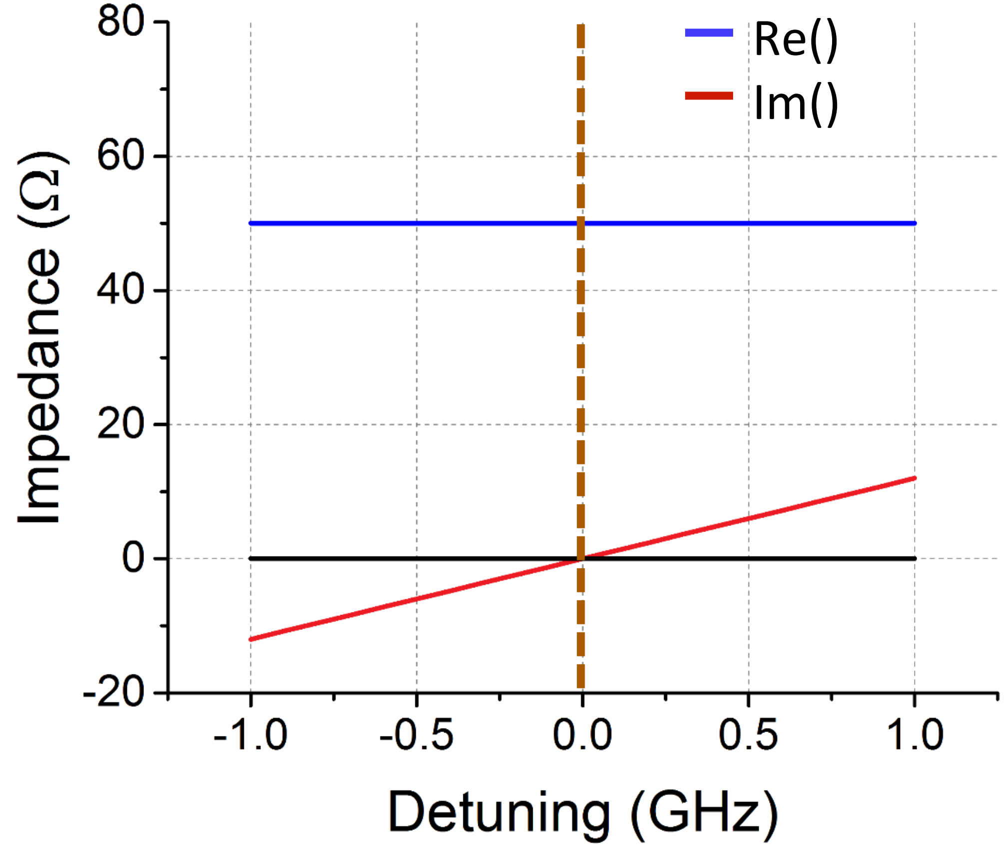


Tanay Roy et al. , (under review at APL)
arXiv:1510.03065

Impedance Engineering







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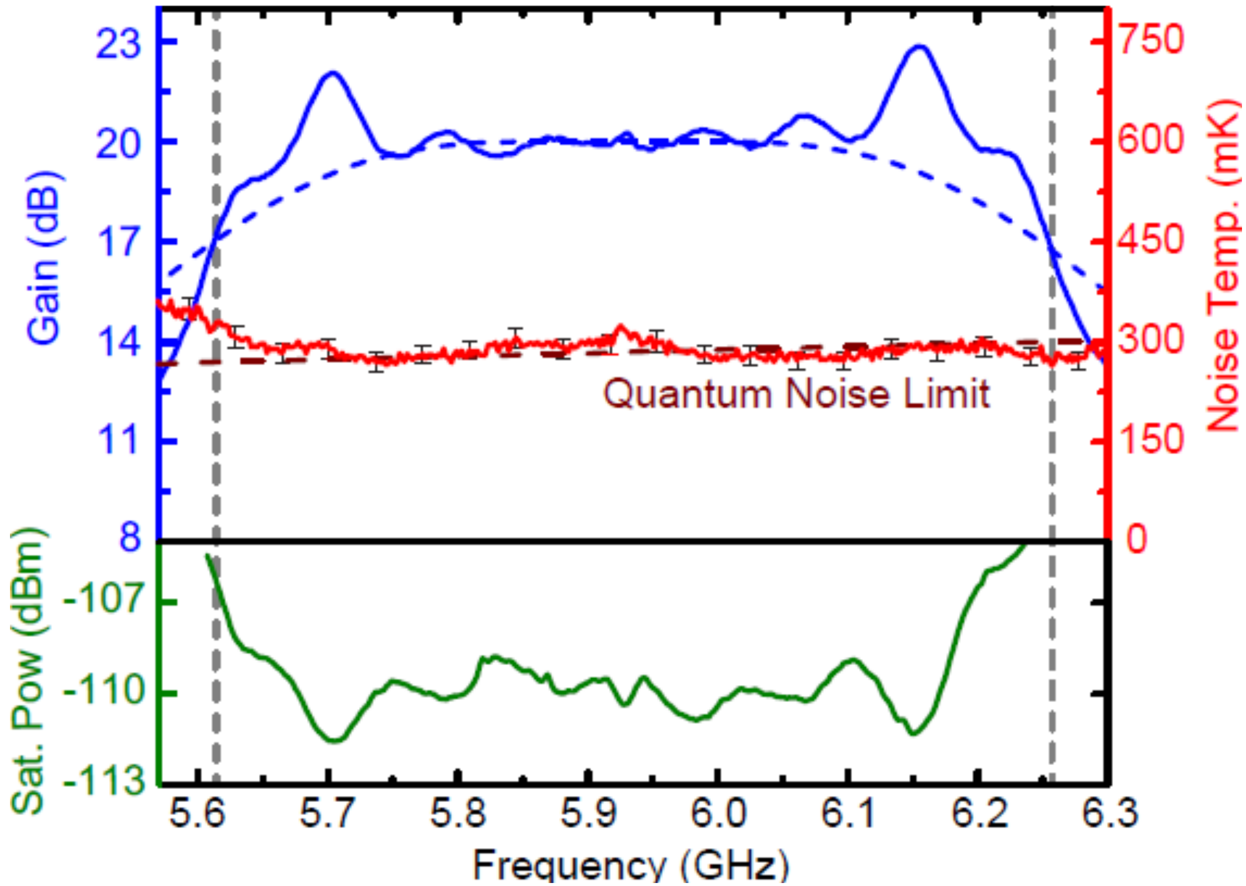
Bandwidth Enhancement



- ~ 600 MHz bandwidth
- 10 x improvement
- Quantum limited noise

See poster by Tanay Roy

Tanay Roy et al. , (under review at APL)
arXiv:1510.03065

QEC with superconducting qubits

Proof of principle demonstrations:

Fedorov et al. , *Nature* **481**, 170–172 (2012)
Reed et al. , Nature 482, 382–385 (16 February 2012)

Gate Based

Riste et al. , Nature Communications 6, 6983 (2015)
Kelly et al. , Nature **519,** 66-69 (2014)
Corcoles et al., Nature Communications 6, 6979, (2015)

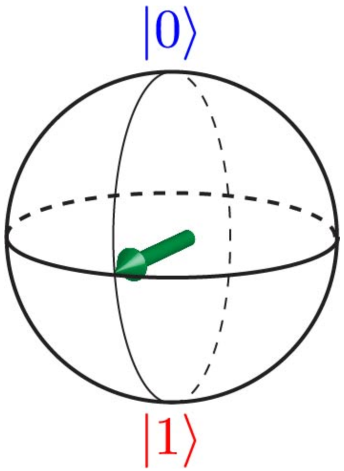
Measurement Based

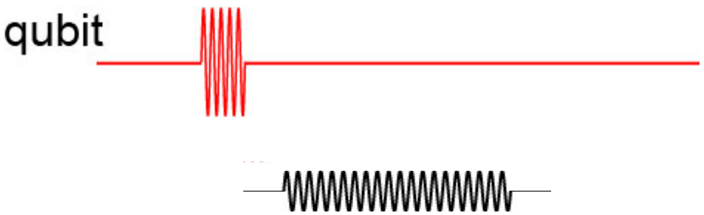
Our approach:

- Novel qubit design
- Multiple qubits in single physical device
- Direct access to syndrome measurements?
- Weak measurement and feedback?

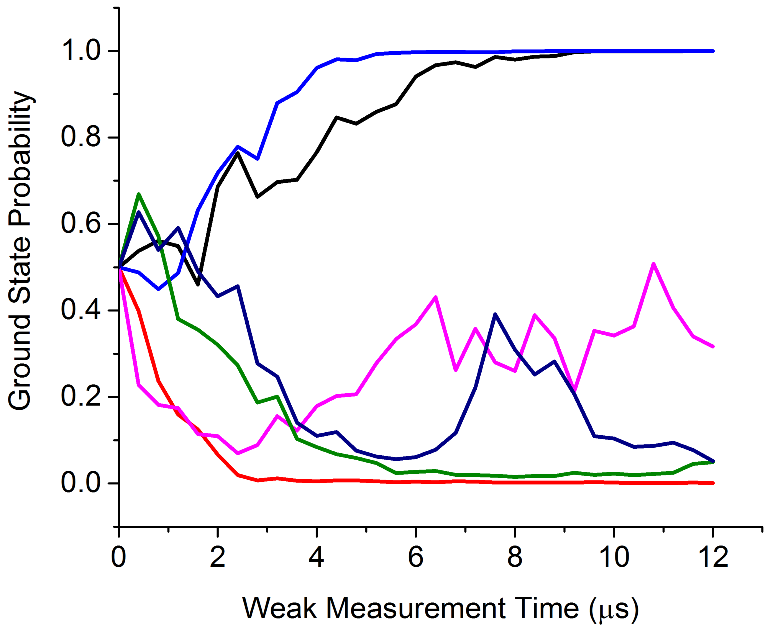
Other projects

Weak quantum measurements





Weak measurement

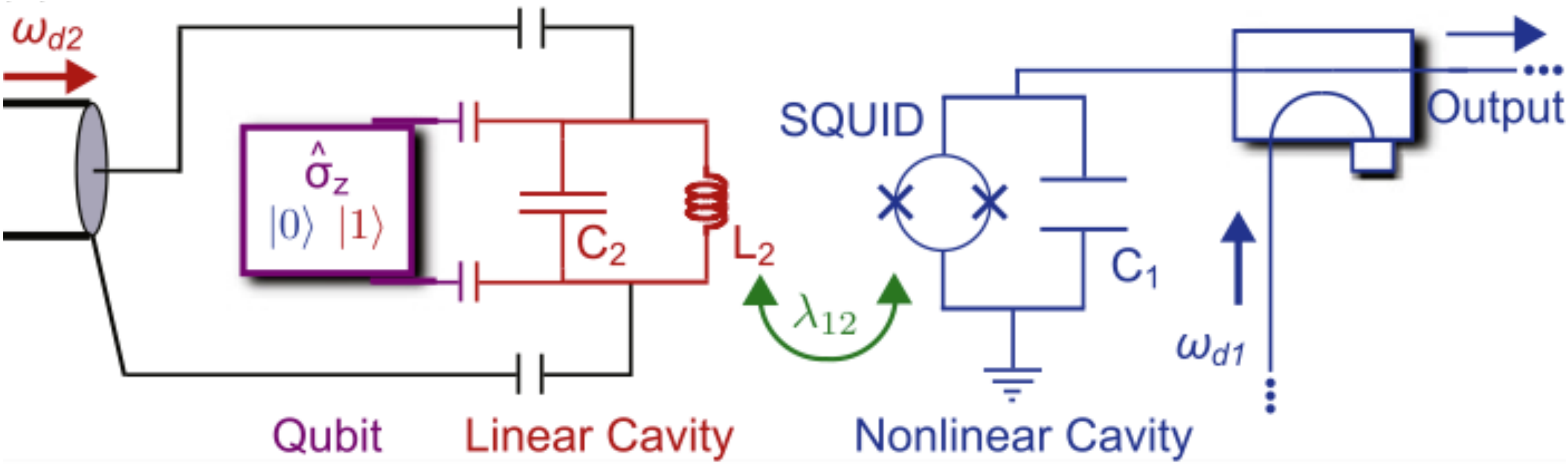


Stochastic evolution of qubit state under weak measurement

- QEC with weak measurements
- Continuous feedback
- Weak values

See poster by Parveen

Integrated Qubit measurement



- Combine linear cavity for qubit with non-linear cavity
- Parametric coupling between two oscillators
- Flexibility to tune the relative amplitude and phase of two drives
- Measurement efficiency and backaction

S Khan, **R Vijay**, I Siddiqi and A A Clerk , New J. Phys. 16 113032 (2014)

Summary

- Good quality superconducting qubits and amplifiers fabricated and tested successfully
- Demonstrated ~10x enhancement in parametric amplifier bandwidth
- Preliminary experiments on multi-mode qubit look promising
- Stage is set for quantum feedback and error-correction experiments

Quantum Measurement & Control Lab

Thank You

www.tifr.res.in/~quantro/