Introducing 3D transmon

Hanhee Paik

Department of Applied Physics
Yale University

Experiment

Dave Schuster
Gerhard Kirchmair
Adam Sears
Blake Johnson
Matt Reagor
Luyan Sun
Matt Reed
Leo DiCarlo
Eric Holland
Brian Vlastakis

PI's

Luigi Frunzio
Steve Girvin
Leonid Glazman
Michel Devoret
Rob Schoelkopf

Theory

Lev Bishop
Gianluigi Catelani
Dong Zhou
Simon Nigg
Eran Ginossar

Outline

- Review :
  Superconducting qubits, transmon and circuit QED

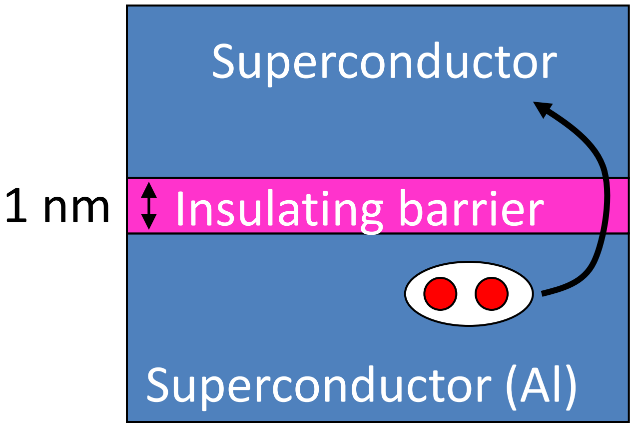
- 3D transmon - a transmon in a waveguide cavity :
  Coherence improved by an order of magnitude

- New physics observed in superconducting qubits :
  What can T_1 and T_2 tell us?

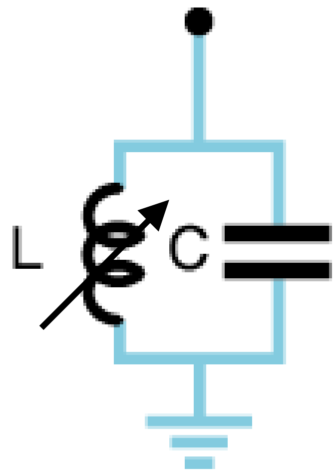
- How to manipulate 3D transmons? :
  Single and two qubit gates using microwave driving

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

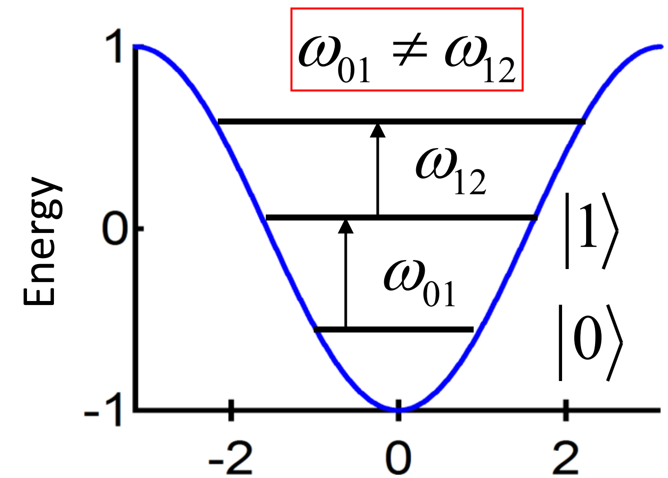
Superconducting Qubits



nonlinearity from
Josephson junction
(dissipationless)



electromagnetic oscillator



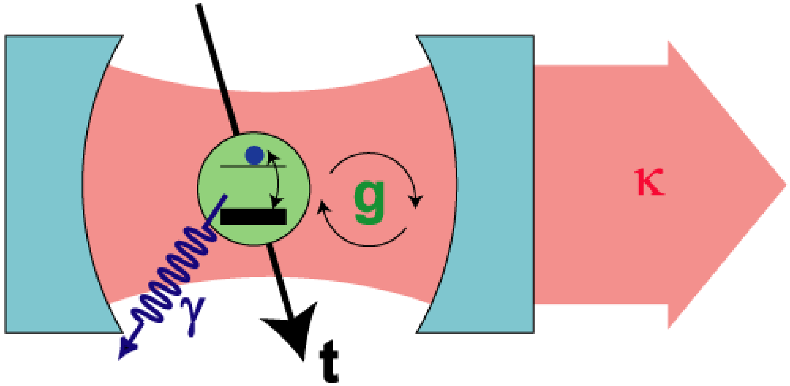
$\omega_{01} \sim 5-10$ GHz

$$\hat{H} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\varphi}$$

Charging energy $E_C = \dfrac{e^2}{2C_\Sigma}$ Josephson energy $E_J = \dfrac{\hbar^2}{4e^2 L_J}$

Interacting with SC qubits: Circuit QED

A Circuit Implementation of Cavity QED



2g = vacuum Rabi freq.

κ = cavity decay rate

γ = "transverse" decay rate

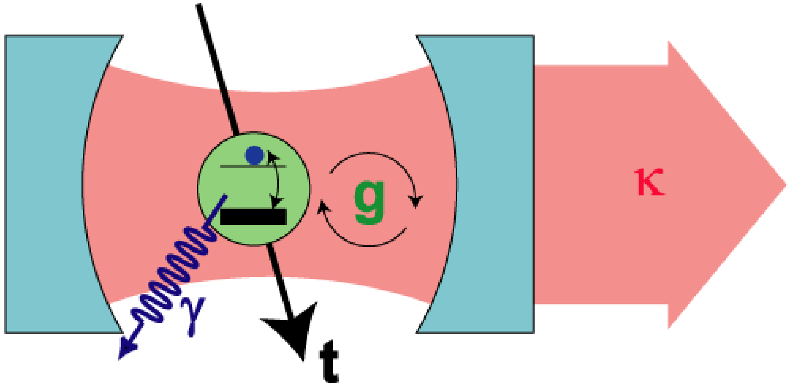
Jaynes-Cummings Hamiltonian

$$\hat{H} = \hbar\omega_r(a^\dagger a + \tfrac{1}{2}) - \frac{\hbar\omega_a}{2}\hat{\sigma}_z - \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma$$

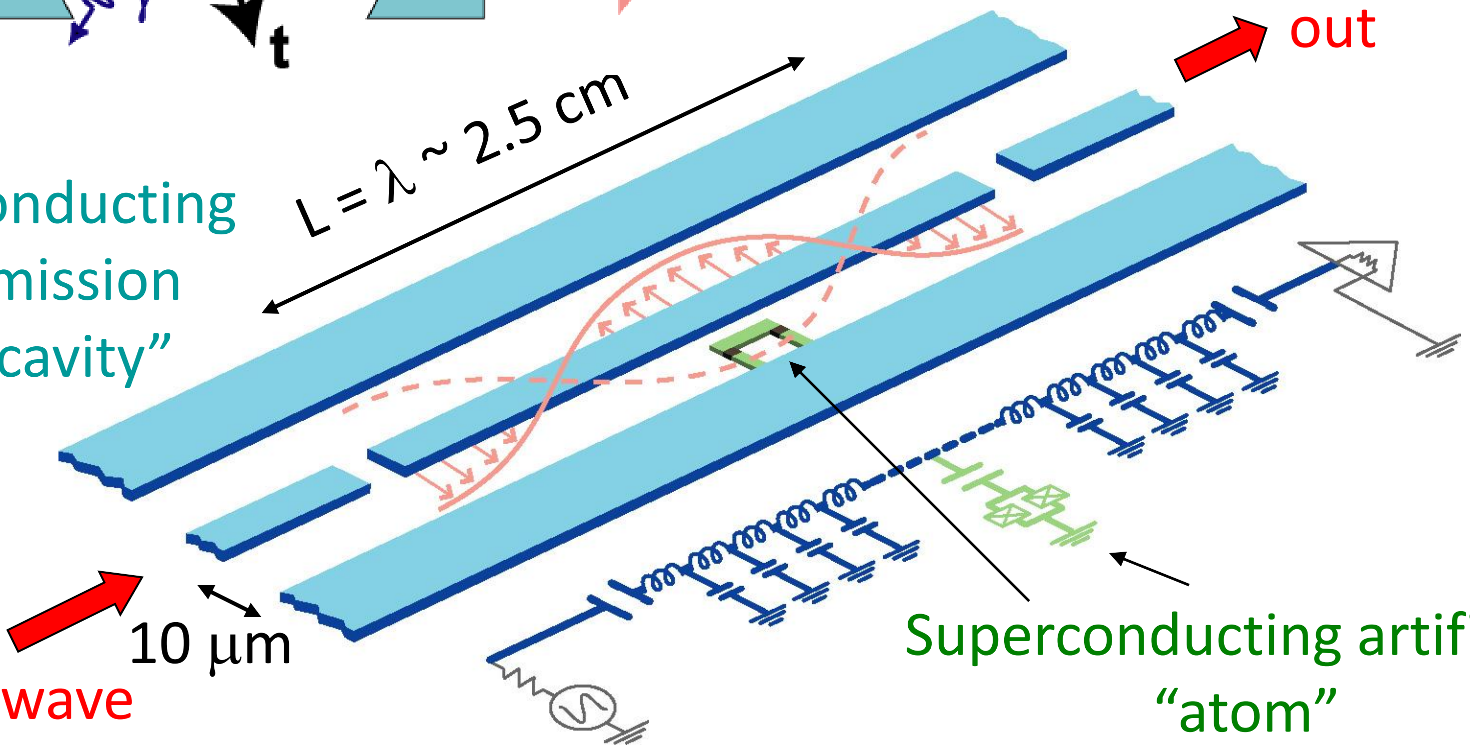
Quantized Field | 2-level system | Electric dipole Interaction | Dissipation

Interacting with SC qubits: Circuit QED

A Circuit Implementation of Cavity QED



Strong Coupling = $g > \kappa , \gamma$



Superconducting transmission line "cavity"

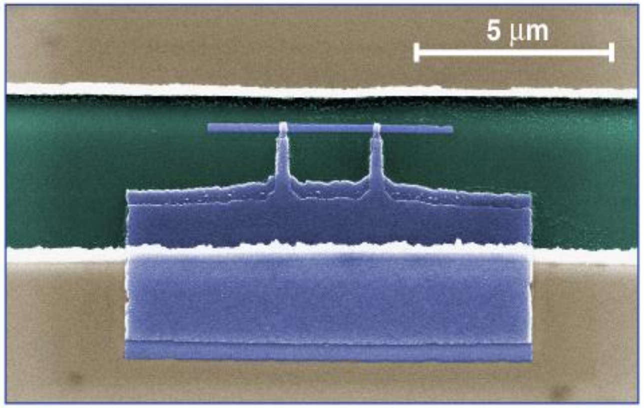
Microwave in

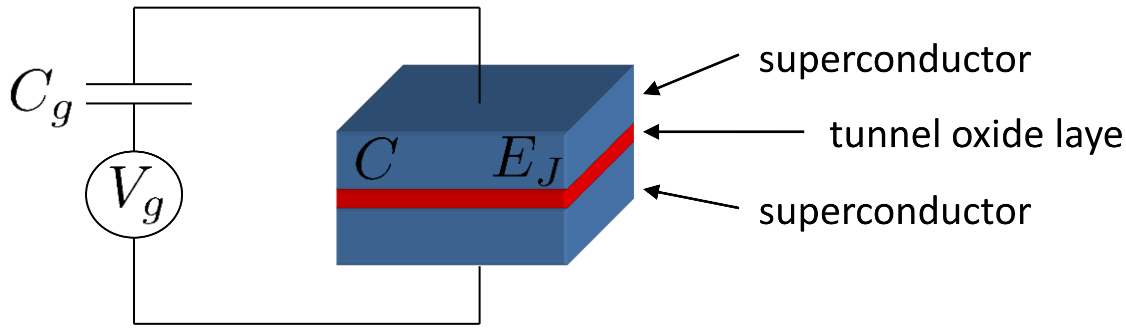
Superconducting artificial "atom"

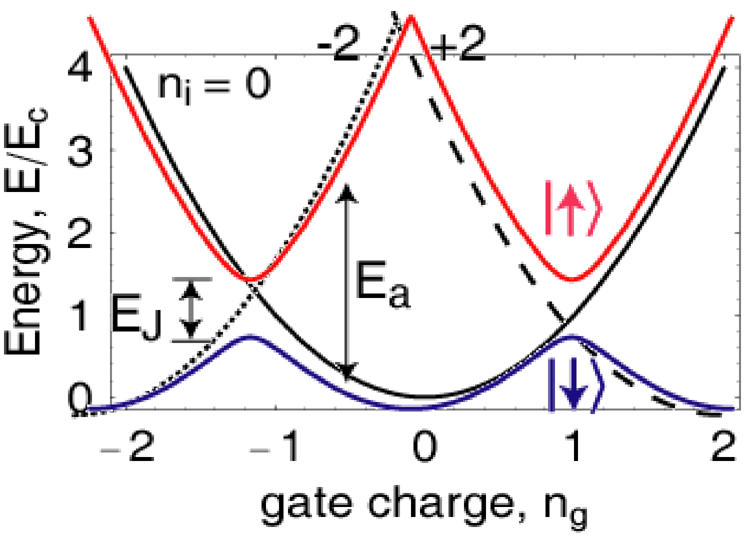
Theory: Blais et al., Phys. Rev. A **69**, 062320 (2004)

Charge Qubits

$$\hat{H} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\varphi}$$







electrostatic energy

$$E_{\mathrm{el}} = \overset{E_C}{\frac{e^2}{2C_\Sigma}}\left(n_i - \overset{n_g}{\frac{C_g V_g}{e}}\right)^2$$

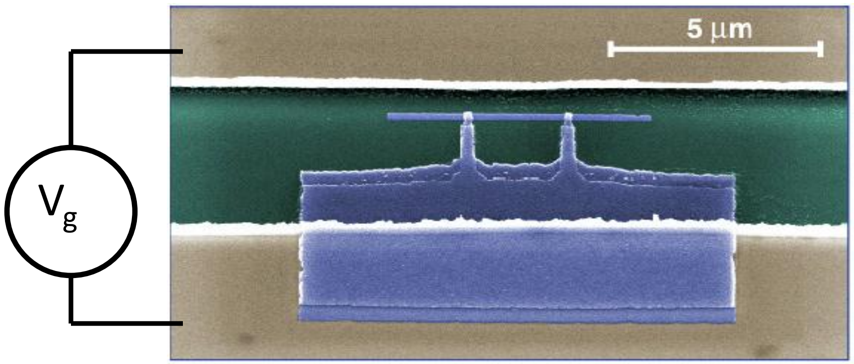
Josephson energy

$$E_J = \overset{E_{J,\max}}{\frac{h\Delta}{8e^2 R_J}} \cos\left(\pi \overset{\Phi_b}{\frac{\Phi}{\Phi_0}}\right)$$

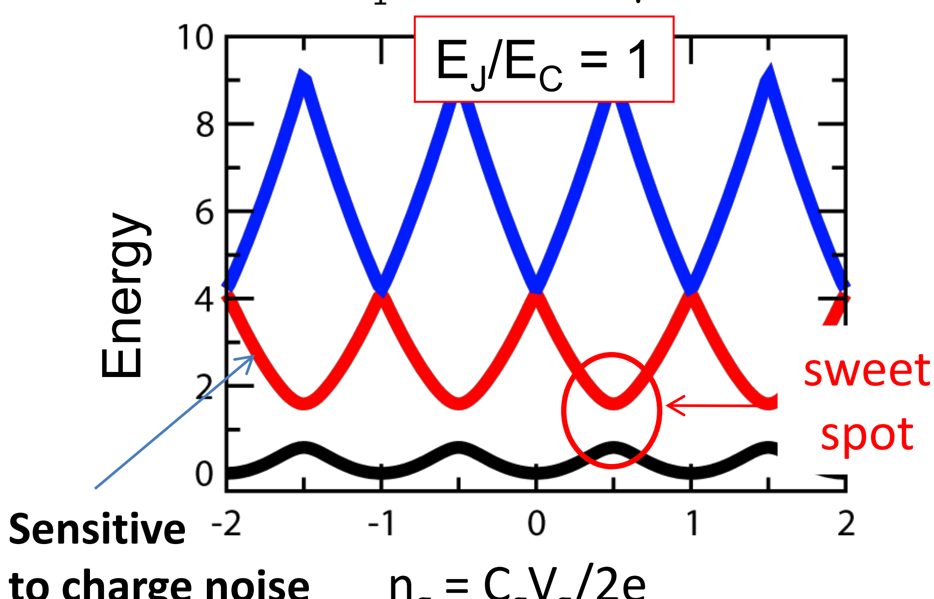
V. Bouchiat, D. Vion, P. Joyez, D. Esteve, & M.H. Devoret, *Physica Scripta* **T76**, 165 (1998).

Transmon : Outsmarting 1/f Charge Noise

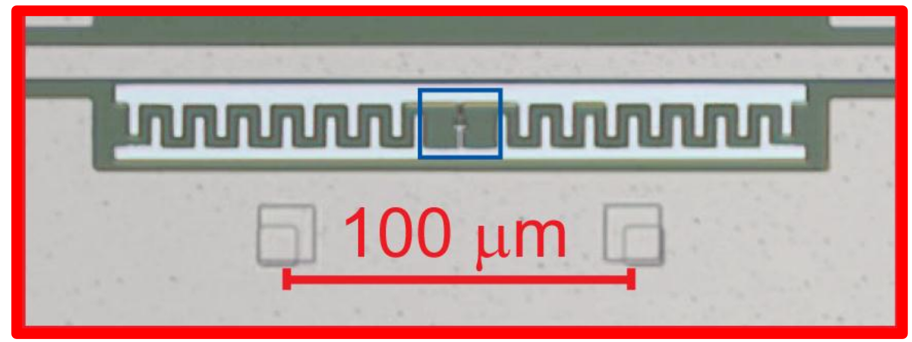
Cooper-pair Box



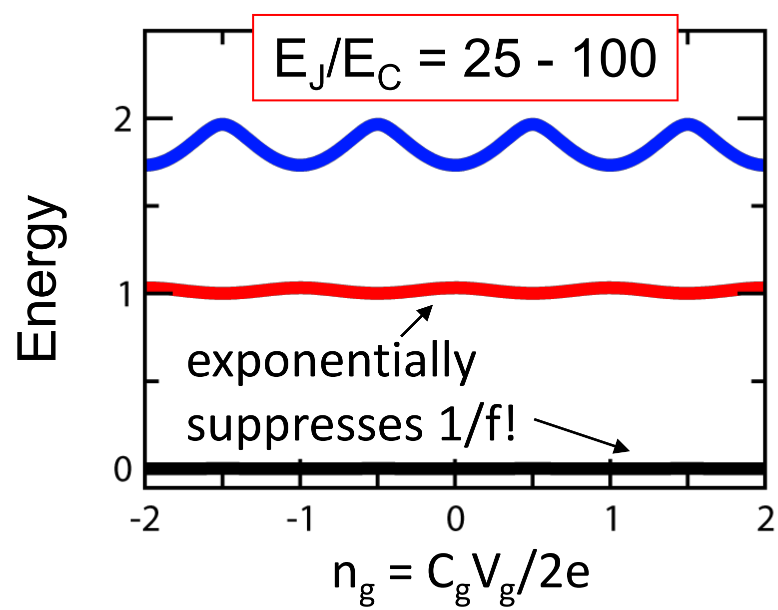
T_1 can be ~ 10 μs



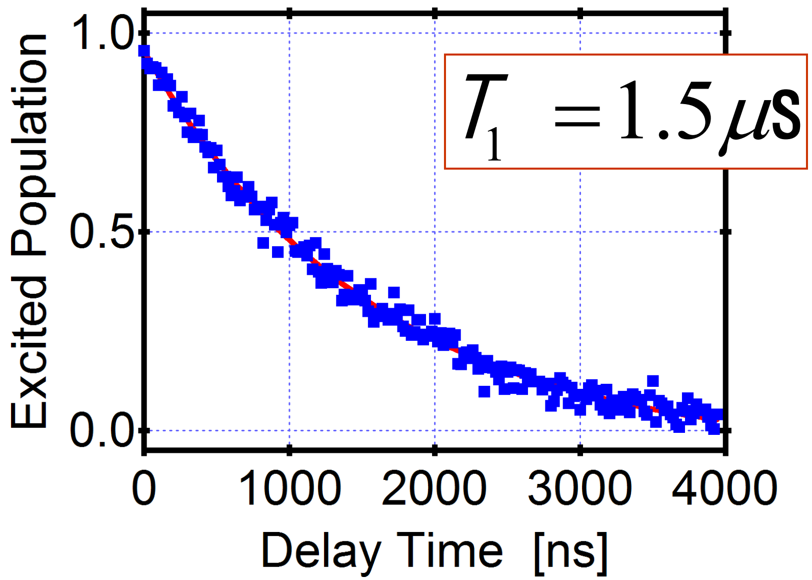
"Transmon"

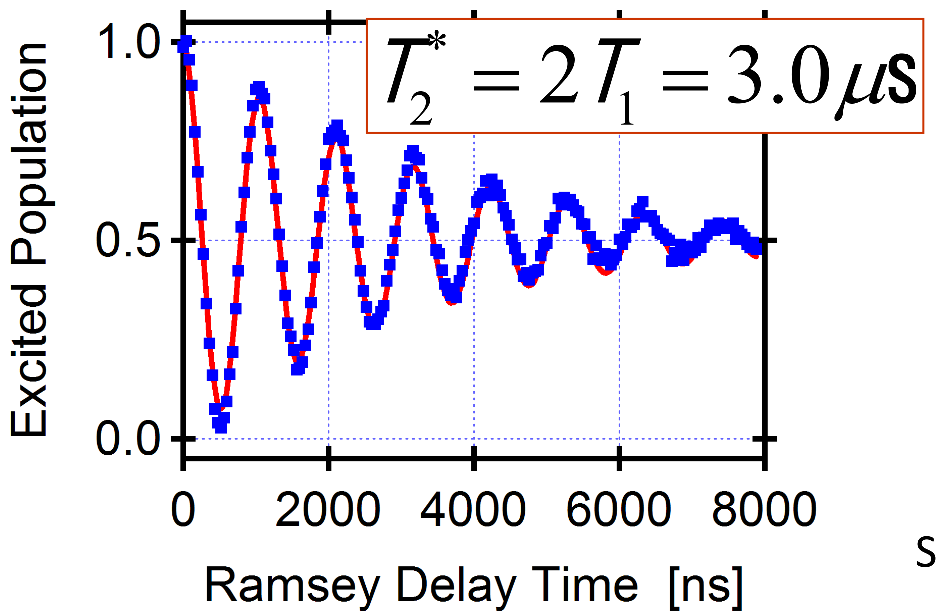


Koch et al., 2007; Houck et al., 2008



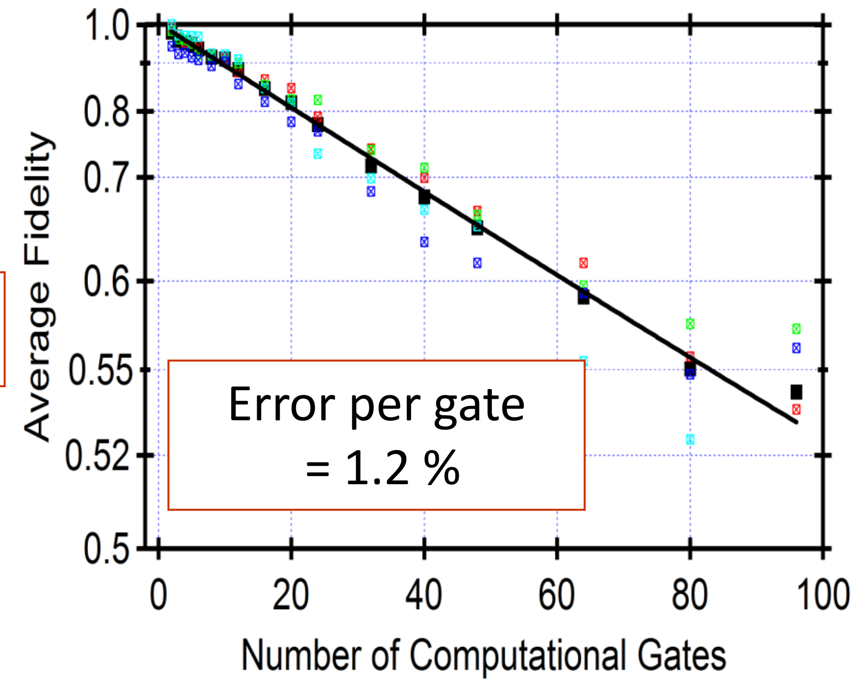
Coherence in **Conventional** Transmon Qubit





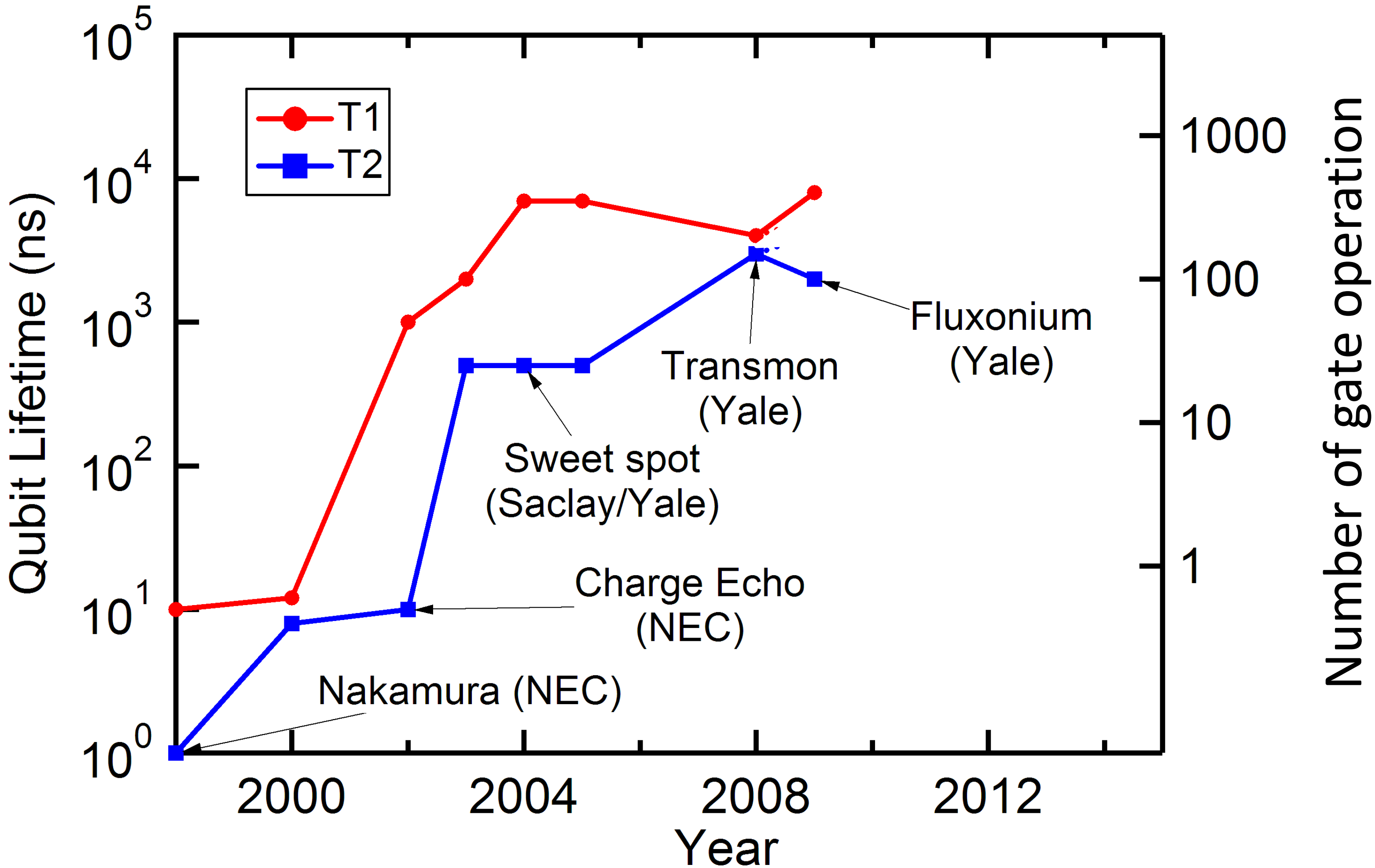
Random benchmarking of 1-qubit ops

Chow et al. PRL 2009:
Technique from Knill et al. for ions



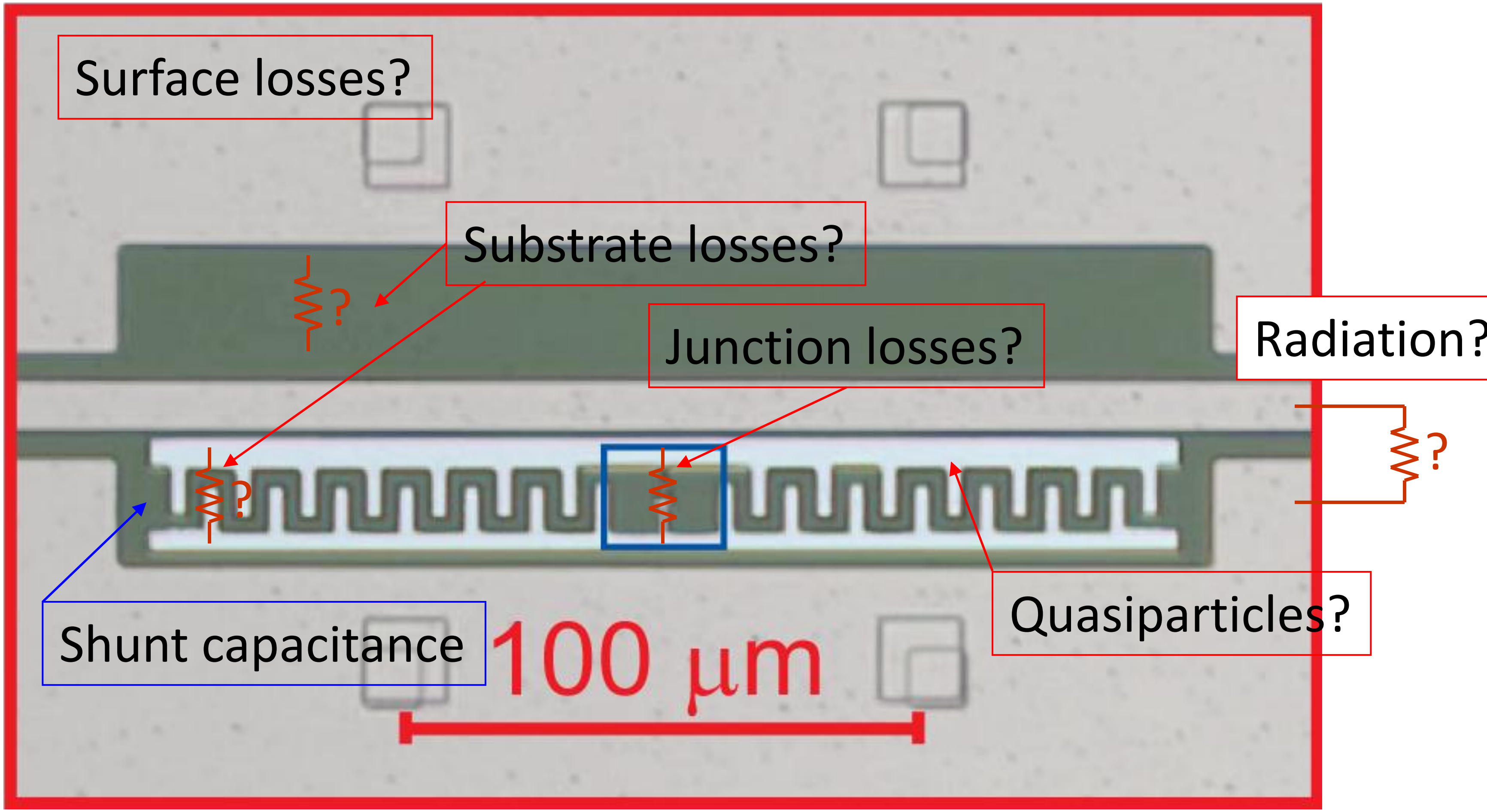
Similar error rates in phase qubits (UCSB):
Lucero et al. *PRL* 100, 247001 (2007)

History of Charge Qubit Coherence



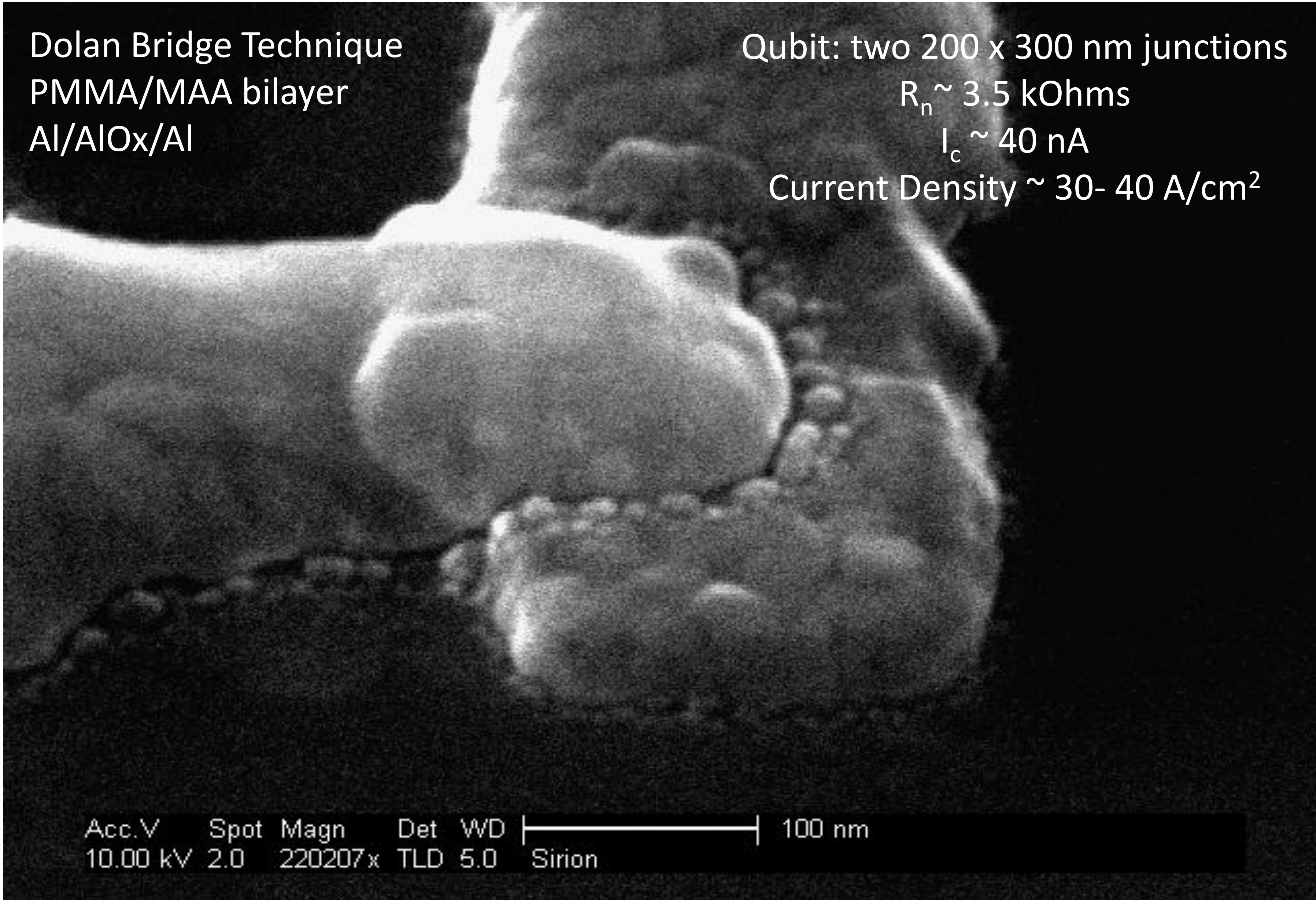
What is limiting coherence?

THE Question : Where's the Dissipation?

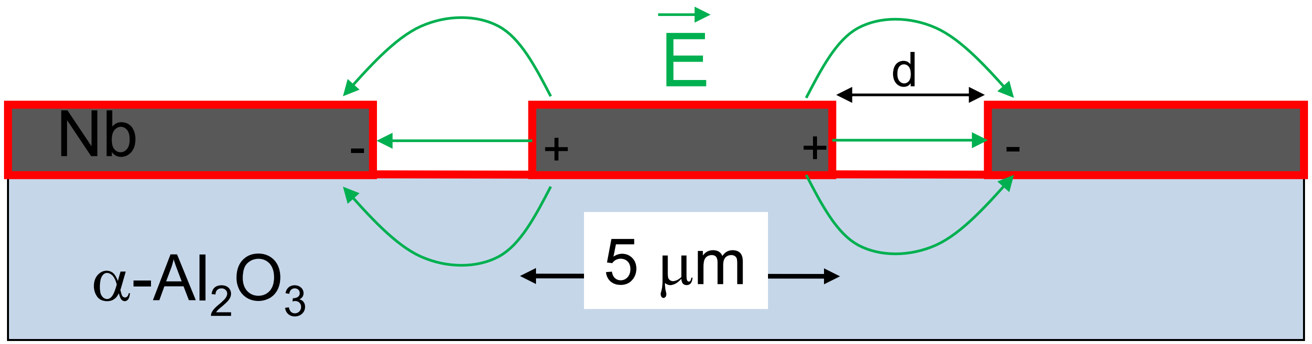


Which element matters the most?

Typical Junction: Dirt Happens



Surfaces Can Matter



"participation ratio" = fraction of energy stored in material

even a thin (few nanometer) surface layer
will store ~ 1/1000 of the energy

If surface loss tangent is poor ($\tan\delta \sim 10^{-2}$) would limit $Q \sim 10^5$

Increase spacings
➡ decreases energy on surfaces
➡ increases Q

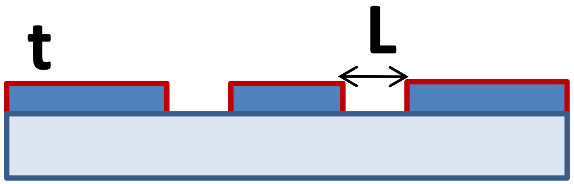
as shown in:

Gao et al. 2008 (Caltech)
O'Connell et al. 2008 (UCSB)
Wang et al. 2009 (UCSB)
Recent IBM work
by Chow and Colores el at. 2012

How to Reduce the Importance of the Surface

CPW/Compact Resonator*

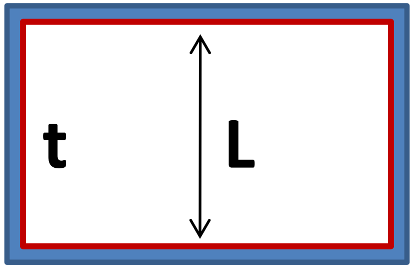
Surface participation ratio



L ~ 10 μm

$$p_{surf}^{diel} \sim 10^{-2} - 10^{-3}$$

3D



L ~ 5,000 μm

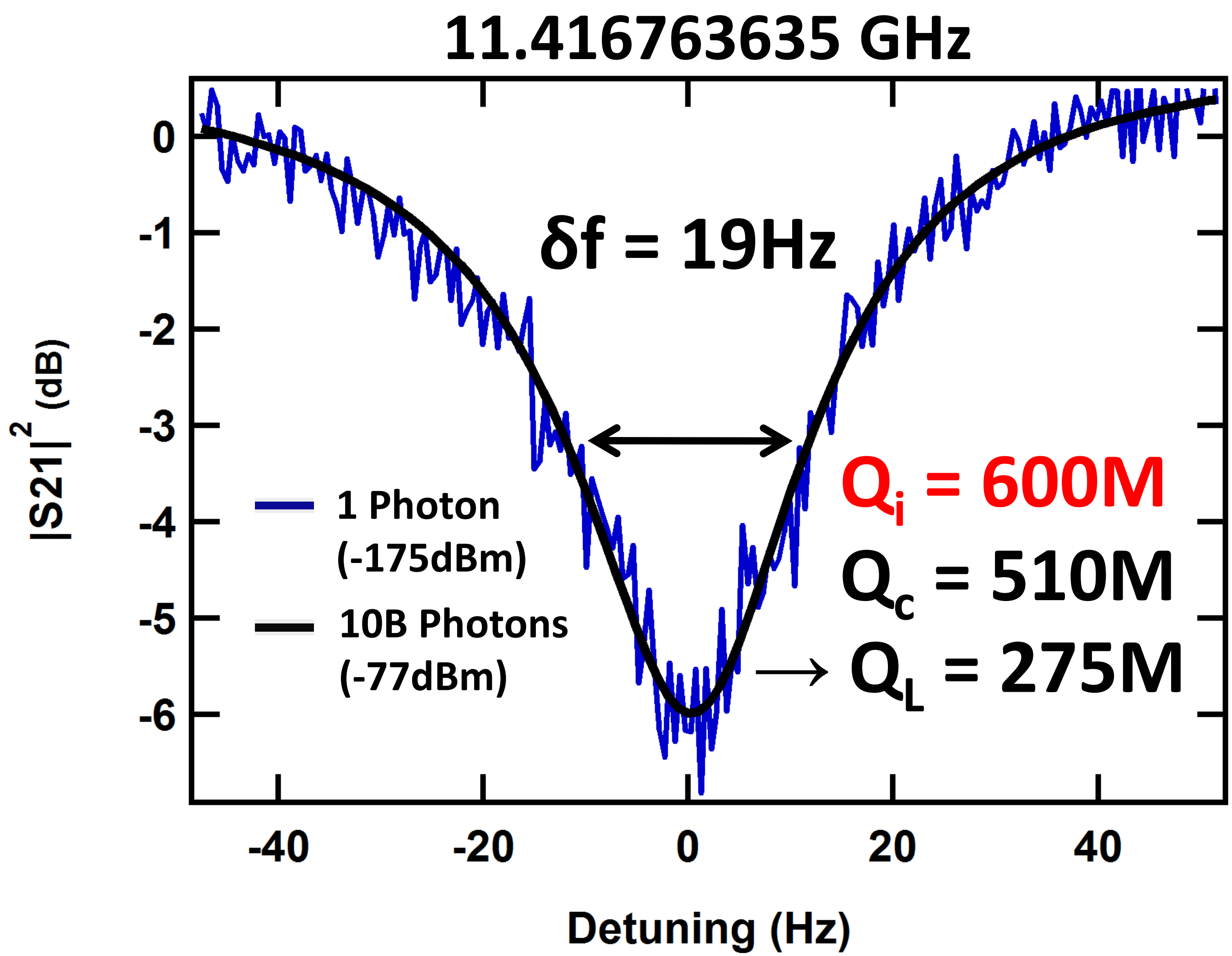
Assume:

t ~ 3 nm

$$p_{surf}^{diel} \sim 0 - 10^{-6}$$

Use 3D cavity for circuit QED experiment!

A High-Q Aluminum Superconducting (3D) Cavity

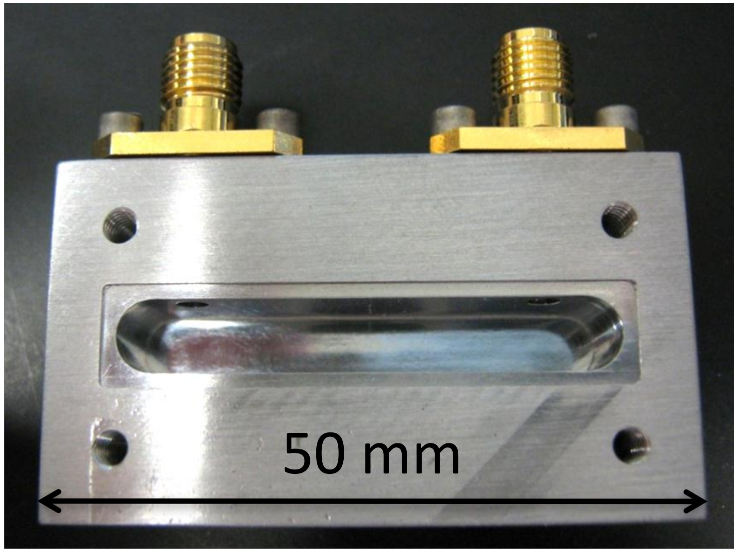


Aluminum cylindrical waveguide cavity : TE011 mode (ideally Zero E field On surface)

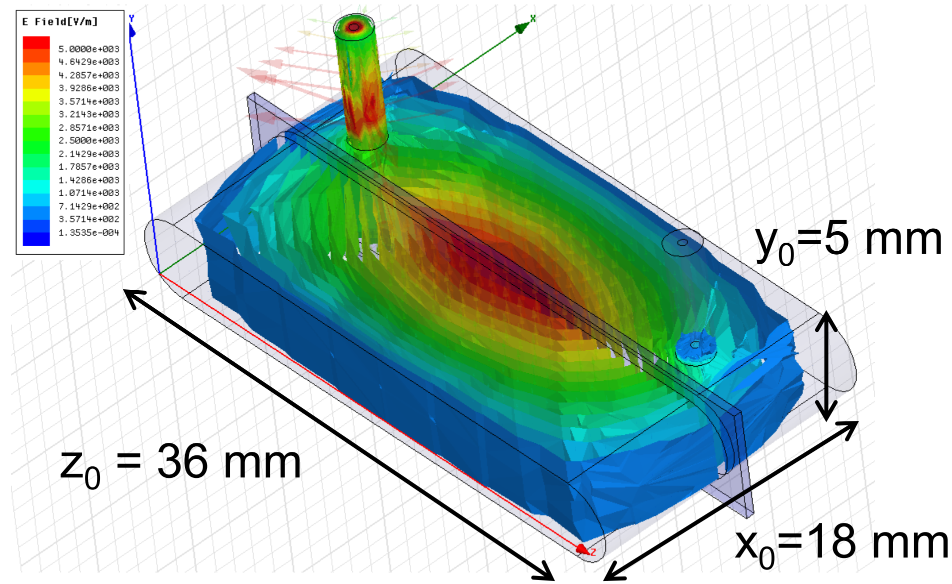
no power dependence of Q : absence of surface dielectric loss

M. Reagor, H. Paik et al. in preparation (2012)

Rectangular Waveguide Cavity



aluminum alloy
(6061-T6, Tc ~ 1.5 K)



TE101 fundamental mode

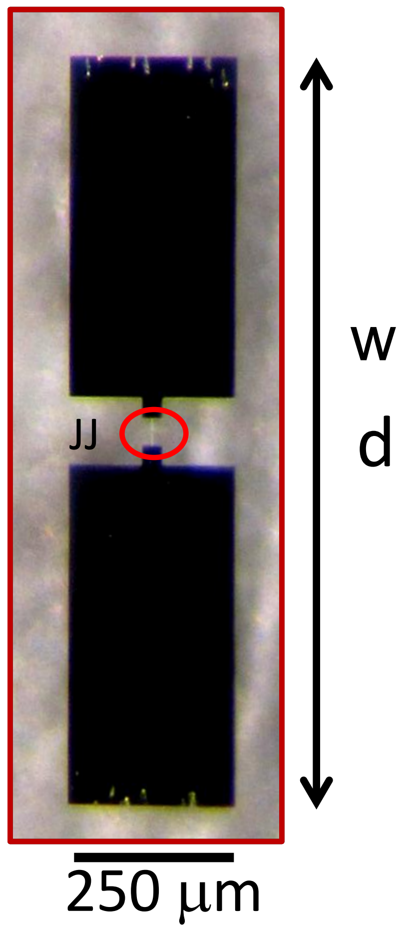
- Internal Q ~ 5,000,000 with 6061 aluminum alloy :
  - Q > 30M can be obtained with pure aluminum.
- Rectangular cavity - lower symmetry than a cylindrical cavity
  - lower density of modes in the measurement bandwidth

Q) How do we couple the qubit to this cavity?

250 μm

Q) How do we couple the qubit to this cavity?

A) Add an antenna!



Single small
Al Josephson junction
with a short dipole antenna

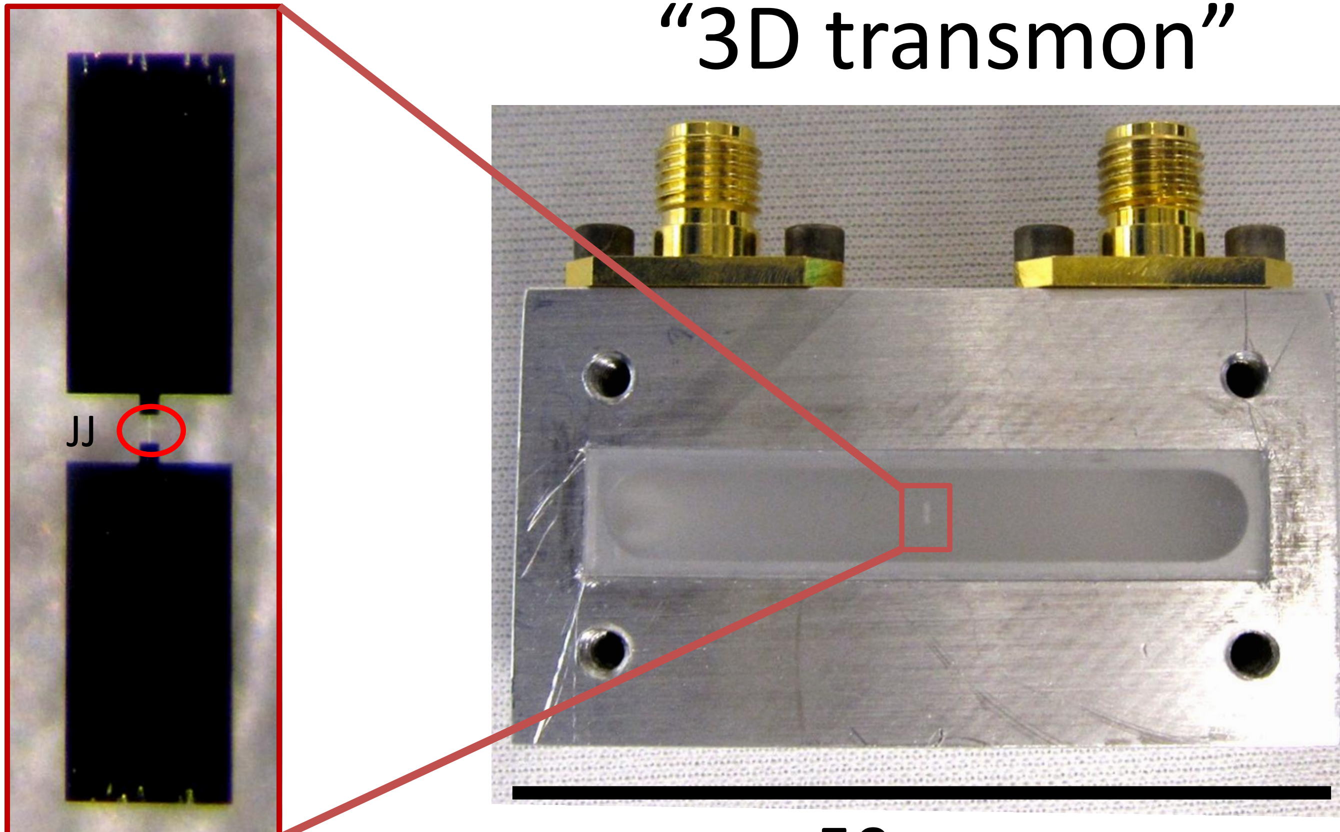
$d \sim 0.01\lambda$

Rectangular Waveguide Cavity for circuit QED

single small Al JJ with a short dipole antenna

$d \sim 0.01\lambda$

“3D transmon”



250 μm

50 mm

$$g = \frac{\vec{d} \bullet \vec{E}_{rms}}{h}$$

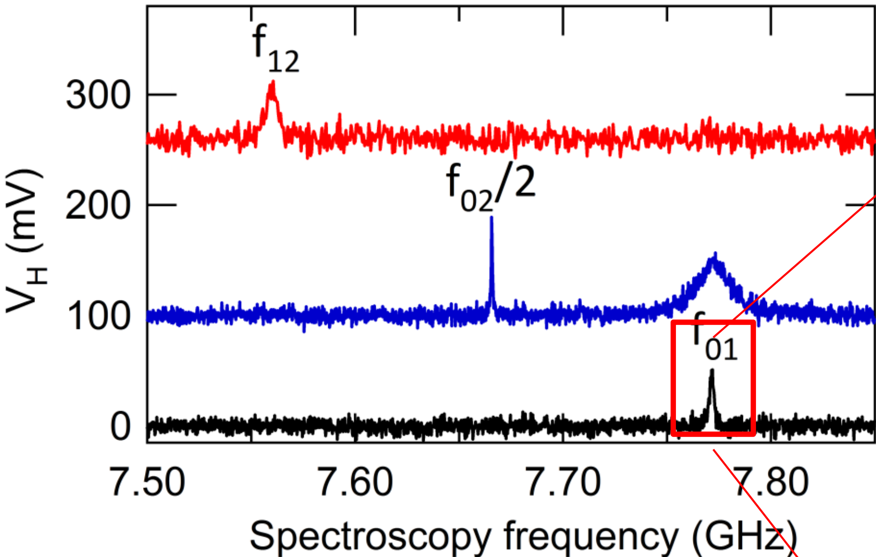
Smaller fields compensated by larger dipole

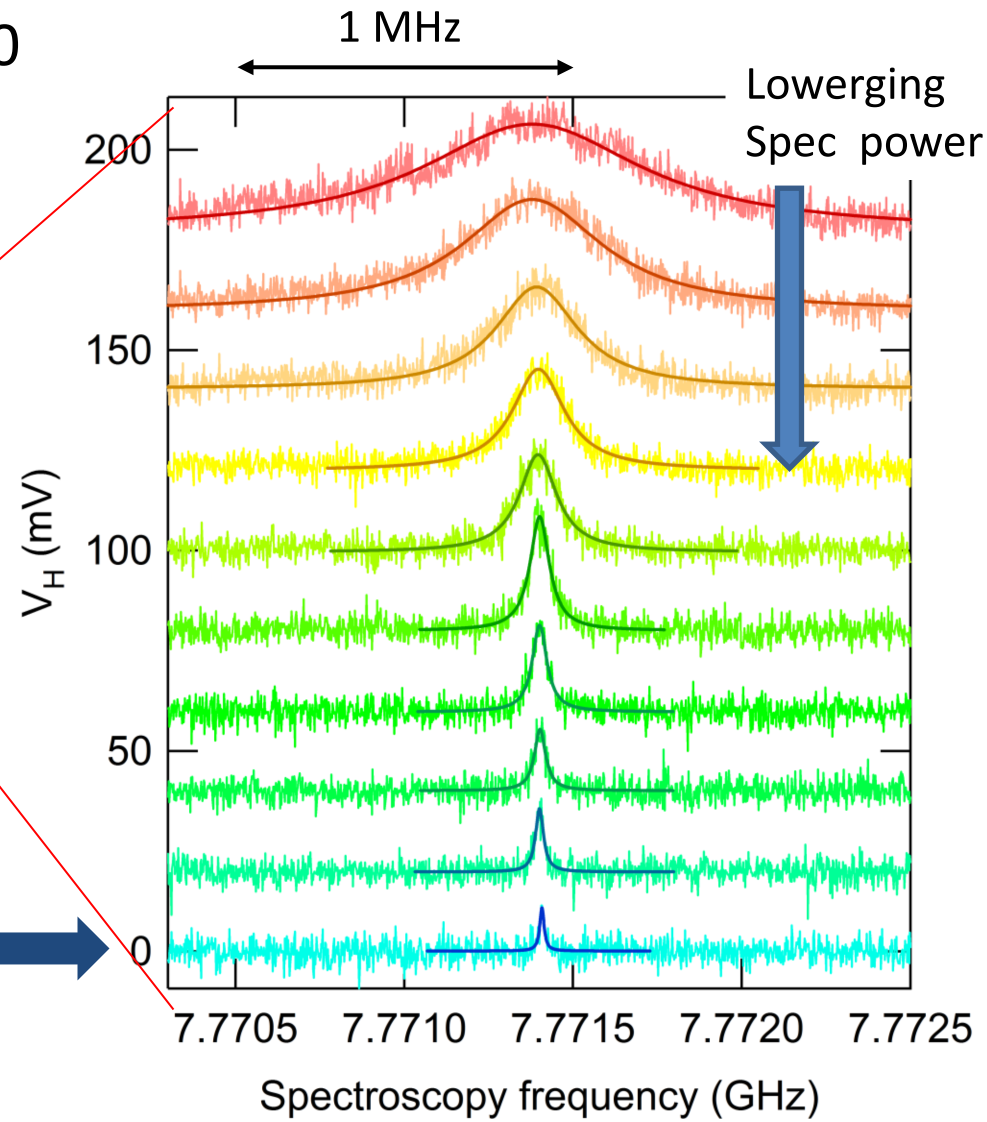
→ Still has same net coupling!

$\boxed{g \sim 100\ \mathrm{MHz}}$

It is a transmon! (only coherence time is longer)

Antenna makes E_j/E_c ~ 50 to 100



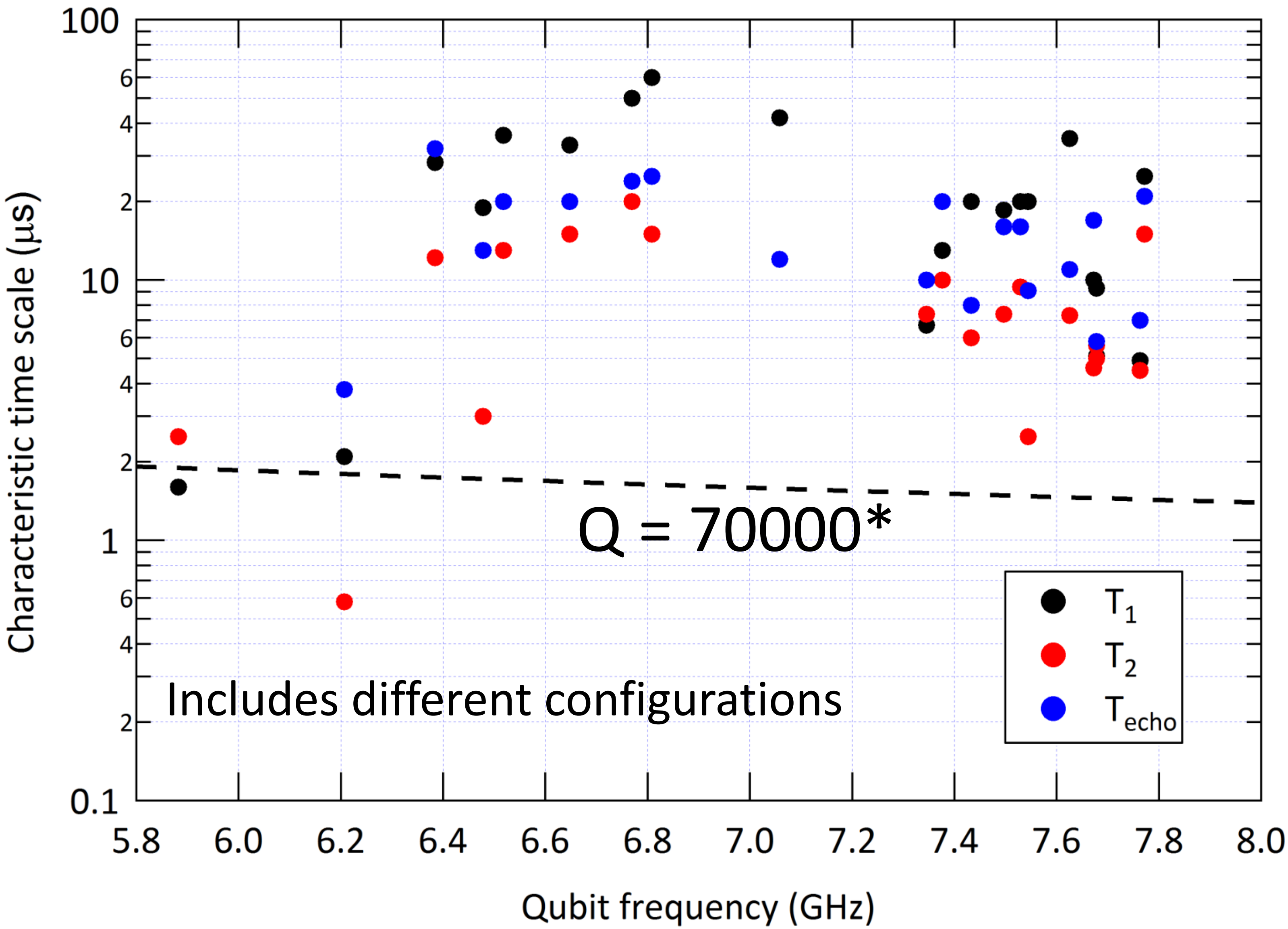


Anharmonicity ~ 300 MHz

Linewidth < **10 kHz**

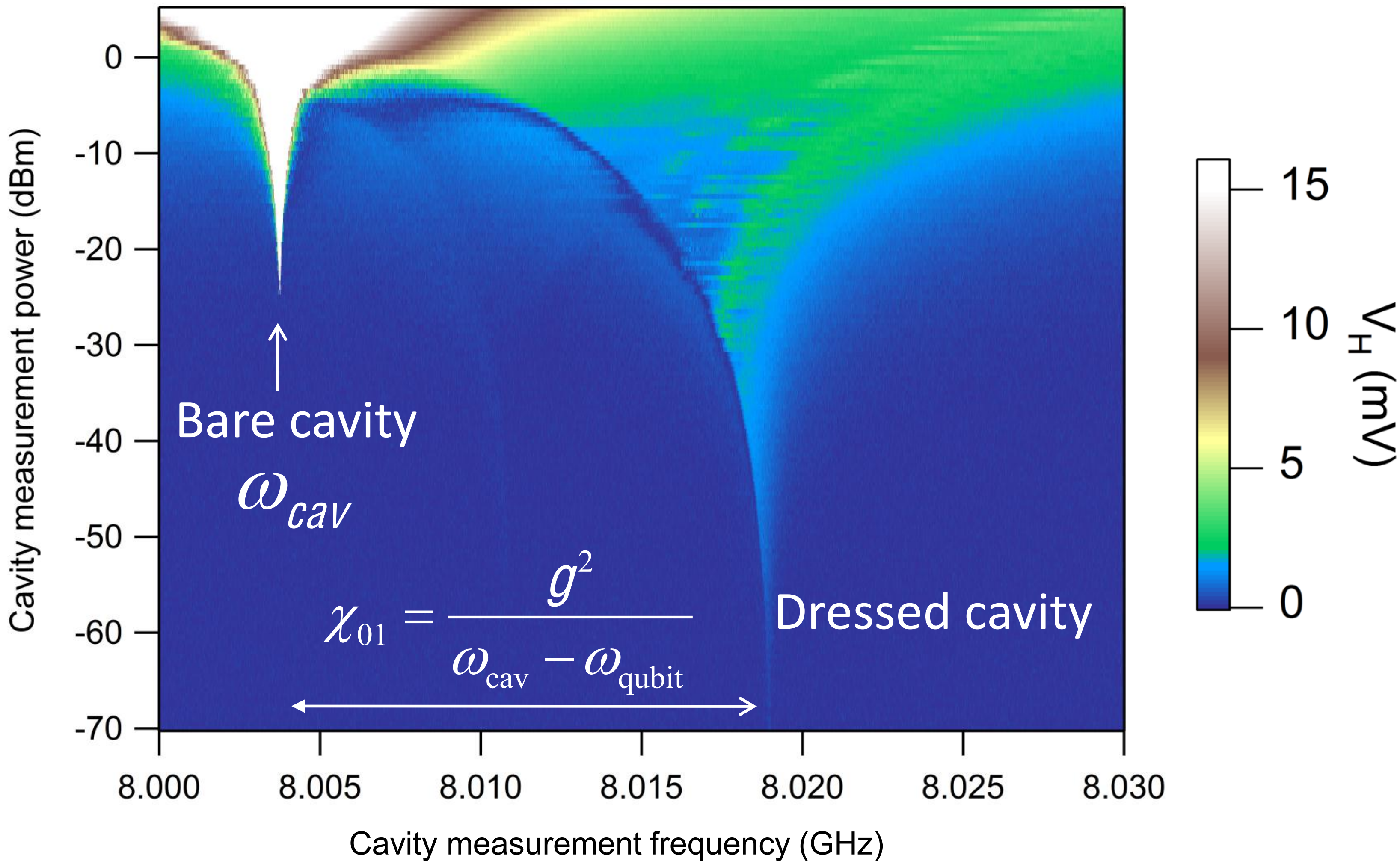
$$T_2^* = \frac{1}{2\pi\Delta f} \geq 15\ \mu s$$

All 3D Qubits Measured at Yale



*Bound on conventional transmon T_1 : Houck et al. Phys. Rev. Lett. **101**, 080502 (2008)

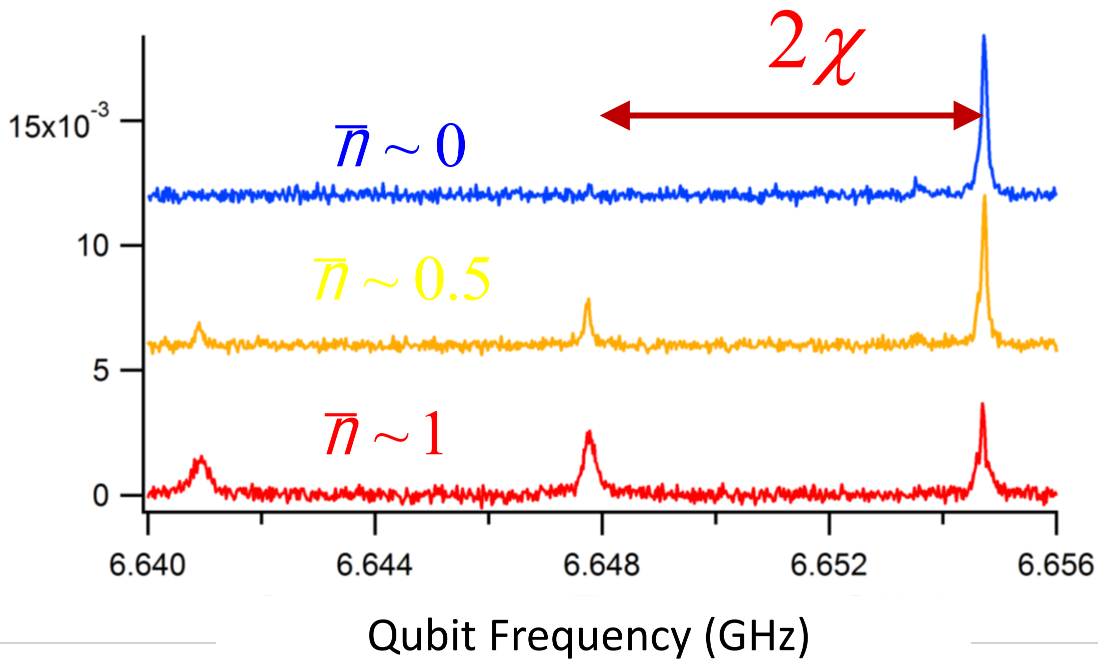
Strong Coupling Achieved

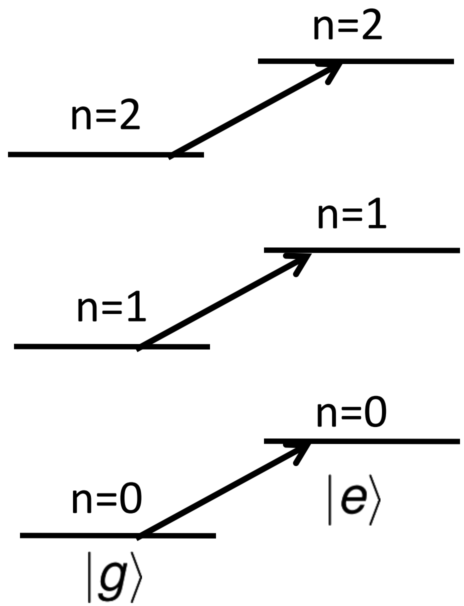


g ~ 140 MHz ⇒ Strong coupling g > κ , γ

Strong Dispersive Regime

$|g \to e; n=2\rangle \quad |g \to e; n=1\rangle \quad |g \to e; n=0\rangle$





$$\boxed{\chi \gg \gamma, \kappa}$$

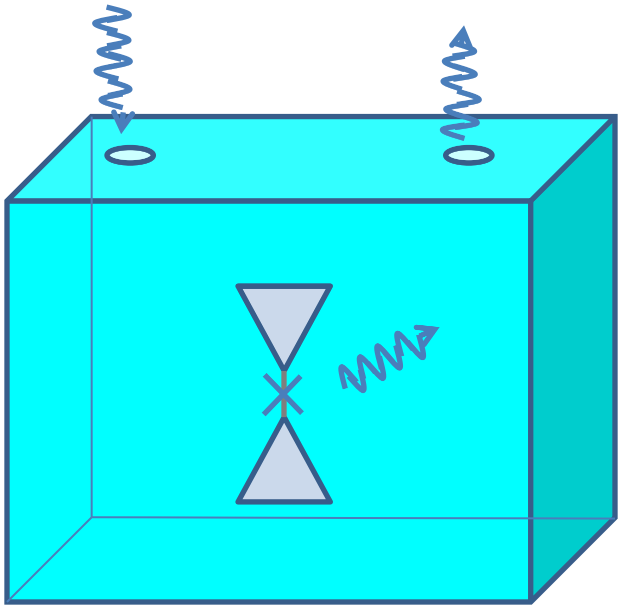
Strong Dispersive Hamiltonian:

$$H_{\text{eff}} = \hbar\omega_{\text{cav}} a^{\dagger} a + \left(\frac{\hbar}{2}\omega_q' + \hbar\chi a^{\dagger} a \right) \sigma_z$$

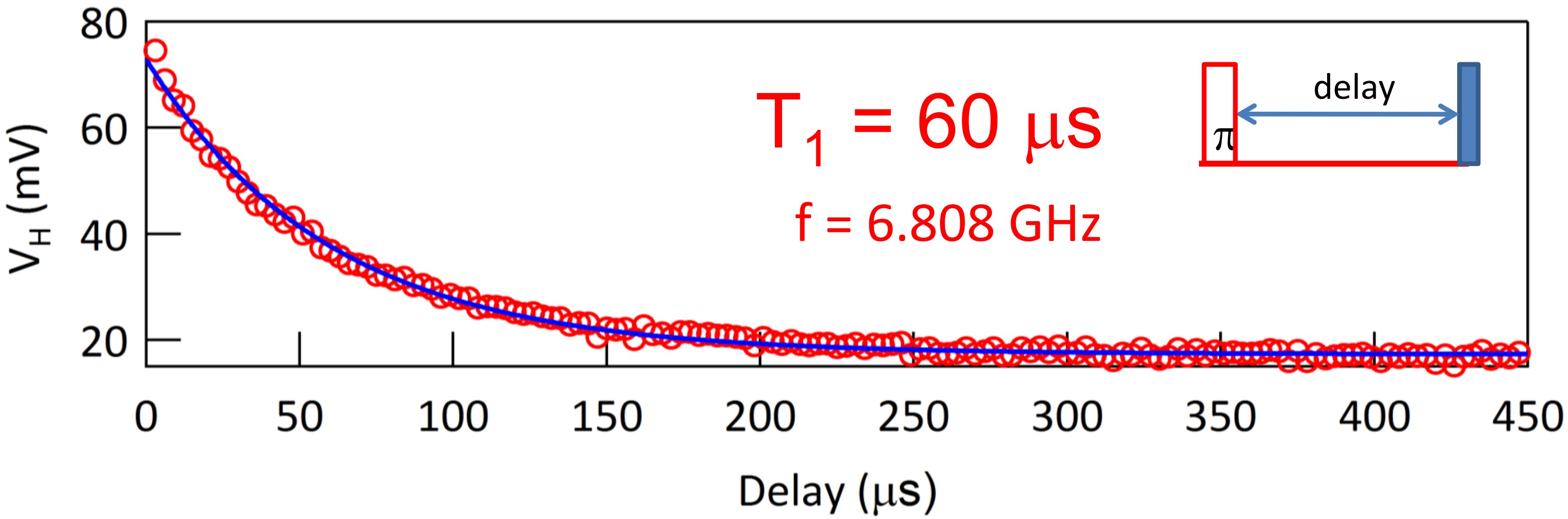
State dependent frequency shift

Stark shift per photon now > 1,000 linewidths

What do we learn about Josephson junctions from 3D transmon?



Quality Factor of Josephson Inductance



$$Q = \omega T_1 \approx 2,000,000$$

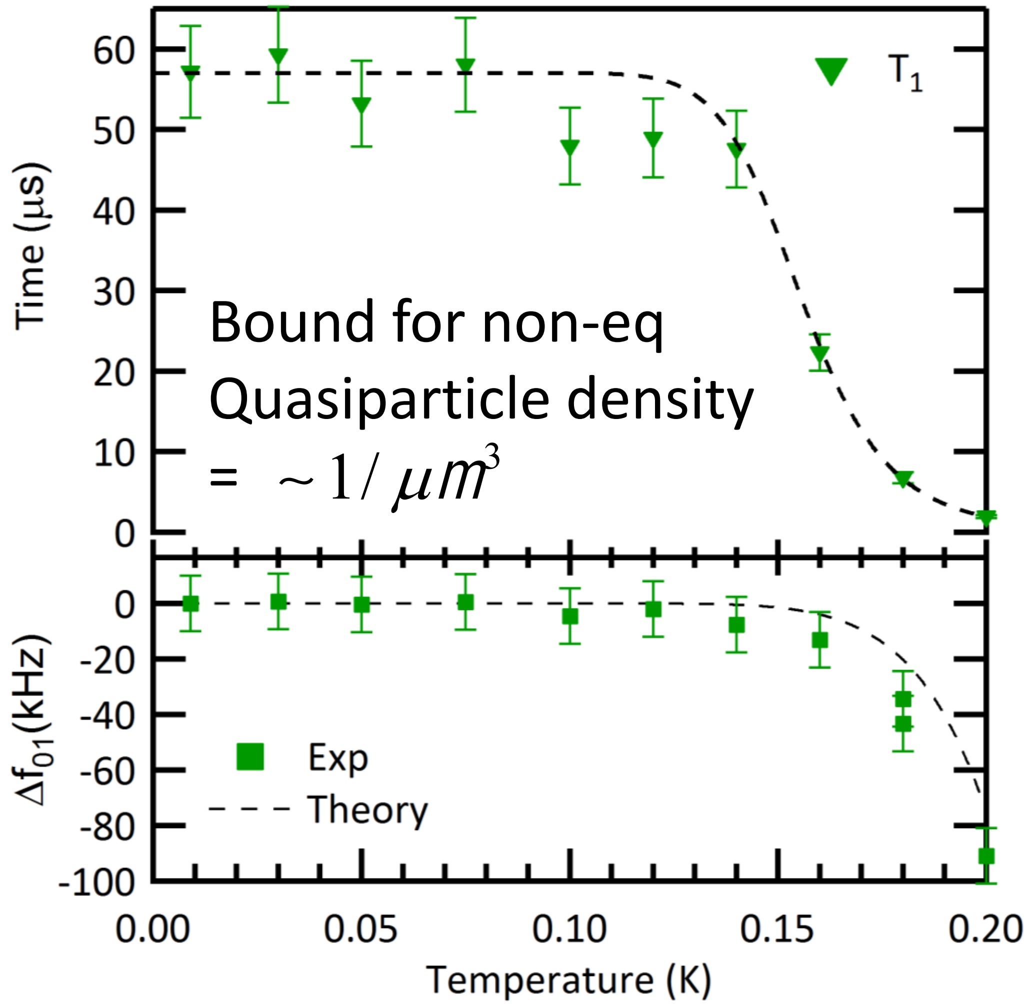
Most stringent bound on the quality of Josephson inductance

$$Q_{Lj} \geq 2,000,000$$

$$Q_C \geq 2,000,000$$

The Josephson junction has not been limiting the SC qubit coherence

Quasiparticles in Josephson Junction



Fractional quasiparticle density

$$x_{qp} = x_{ne} + \sqrt{\frac{2\pi kT}{\Delta}} e^{-\Delta/kT}$$

$$\frac{1}{T_1} = x_{qp} \frac{\omega}{\pi} \sqrt{\frac{2\Delta}{\hbar\omega}}$$

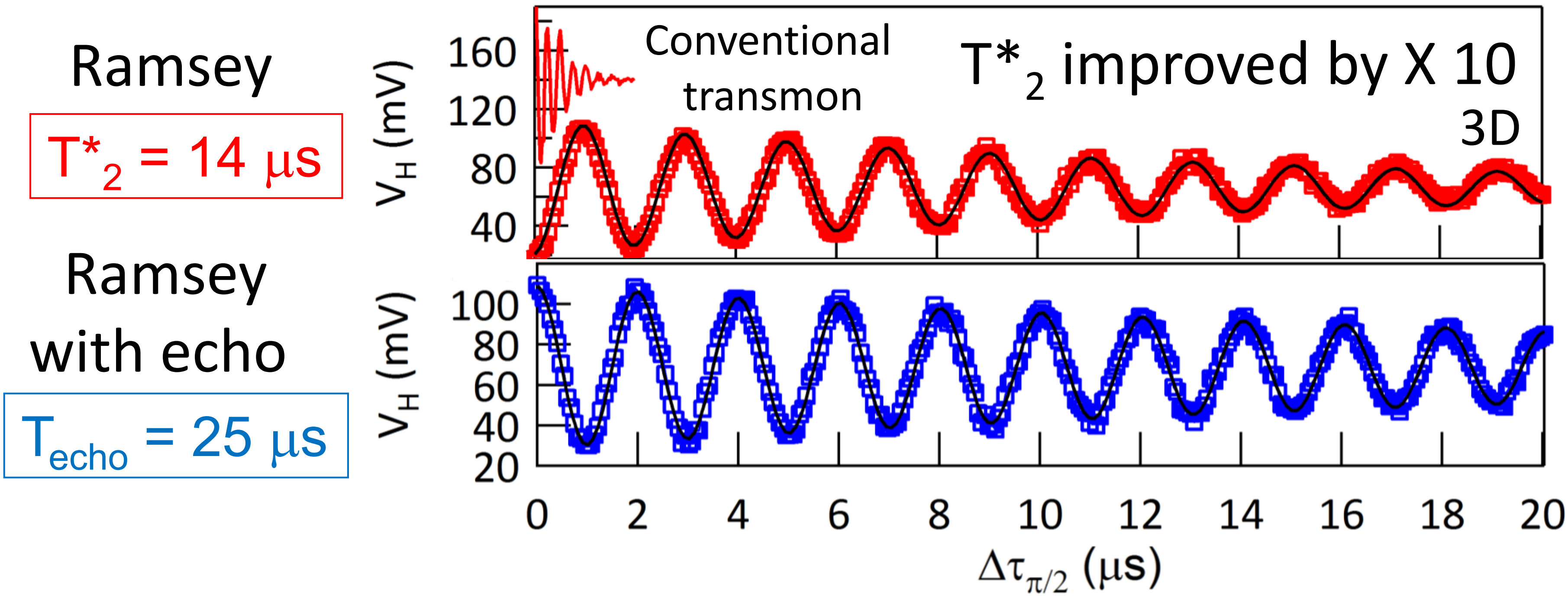
$$\frac{\Delta f}{f} = -\frac{x_{qp}}{2} \left(\frac{1}{\pi} \sqrt{\frac{2\Delta}{\hbar\omega}} + 1 \right)$$

T_1 and frequency shift agree with theory by Catelani et al.*

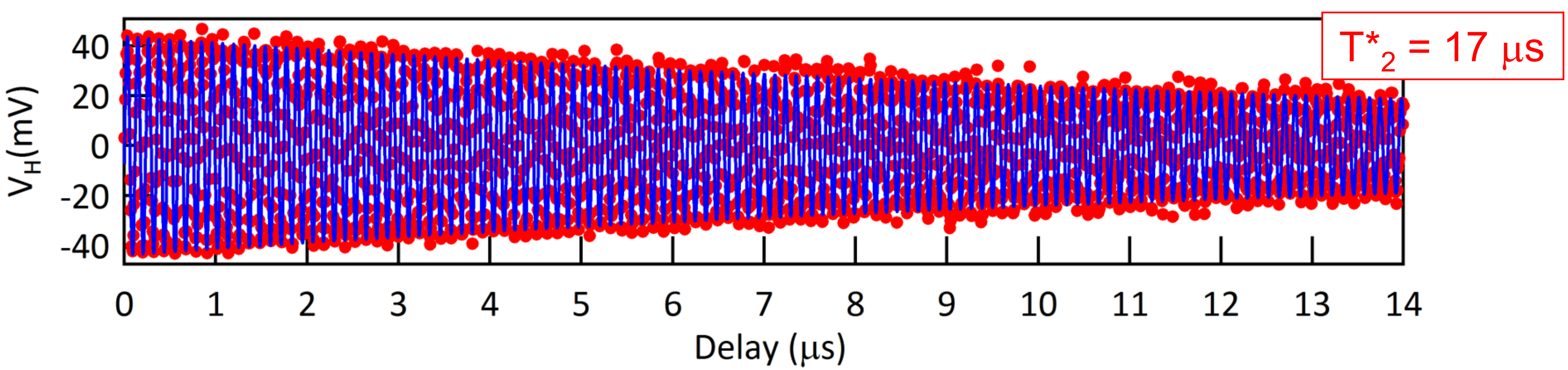
One free parameter
- gap $\Delta = 194\ \mu V$

*Catelani et al. PRL **106**, 077002 (2011)

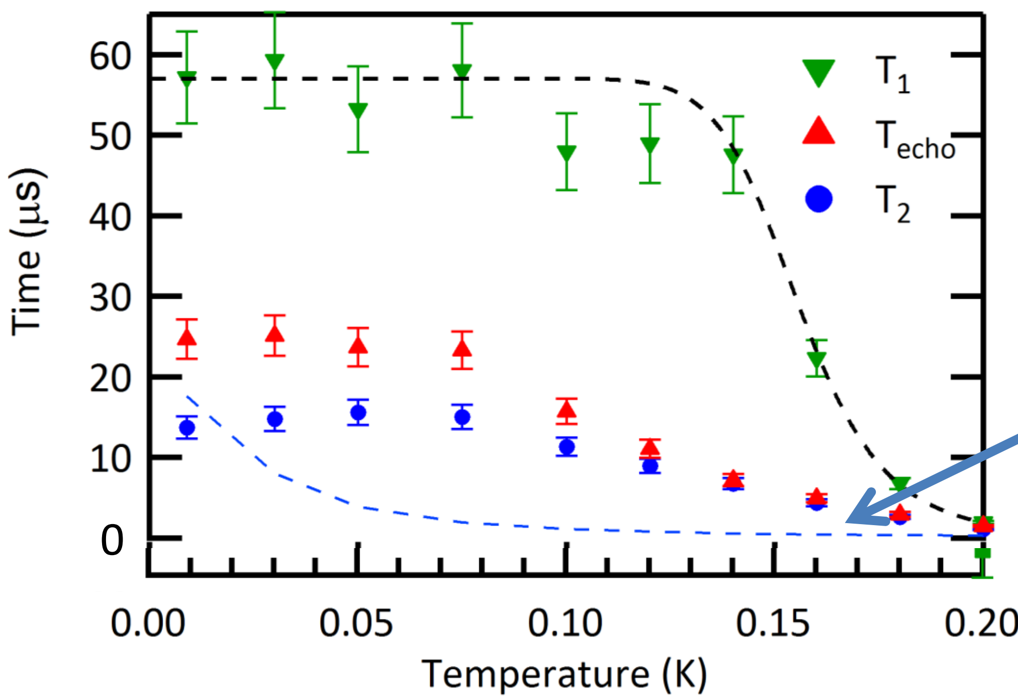
Coherence Dominated by Non-1/f noise



Exponential Ramsey envelope : Absence of 1/f noise



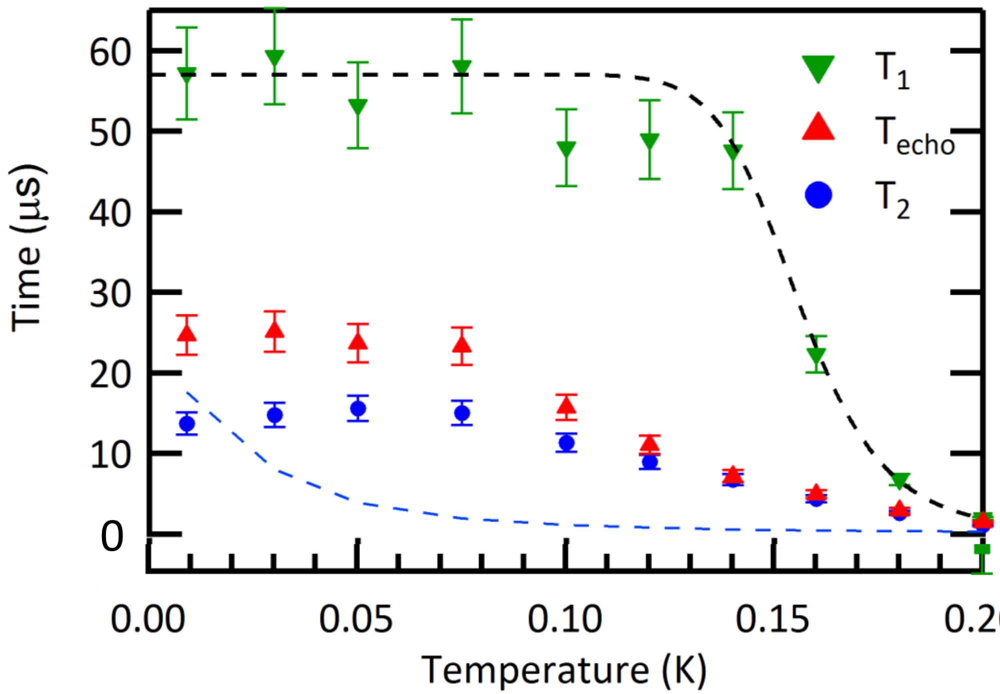
Dephasing not yet limited by 1/f critical current noise



Reported 1/f critical current noise model** does not explain this behavior.

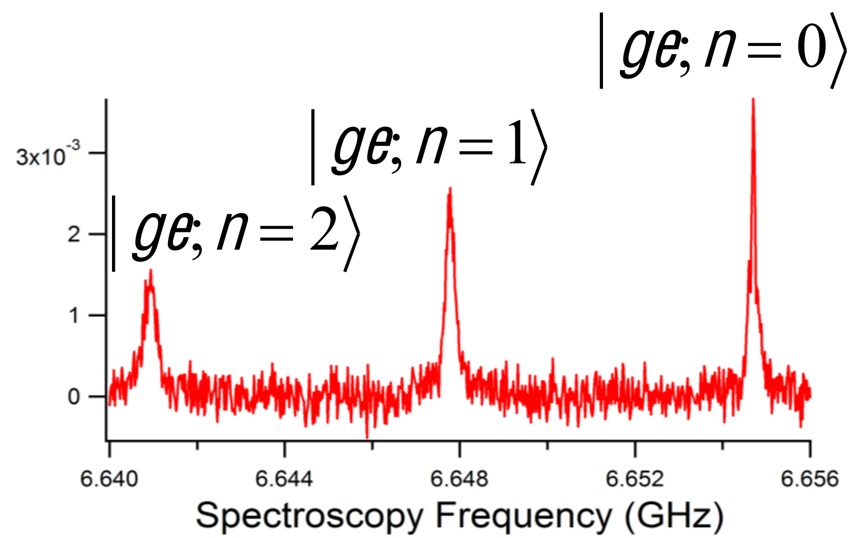
D. J. Van Harlingen *et al.*, Phys. Rev. B **70, 064517 (2004)

What's limiting T^*_2?



T^*_2 is not T_1 limited
- source of dephasing?

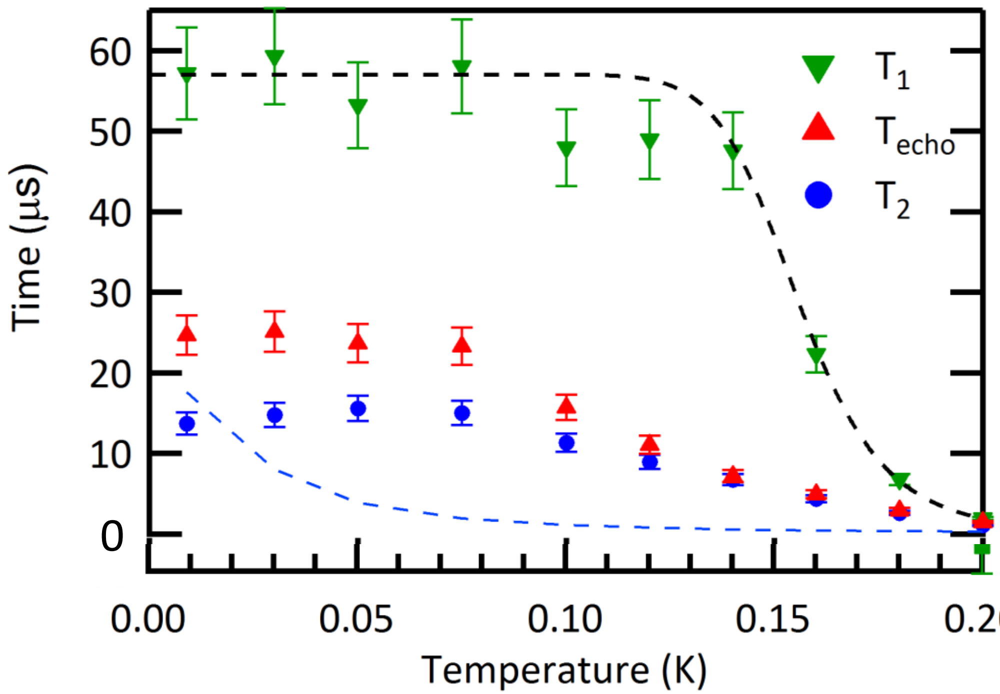
Fluctuations of photons in the cavity



The qubit dephases
when the photon state *changes*

*A. Sears et al. in preparation (2012)

What's limiting T^*_2?

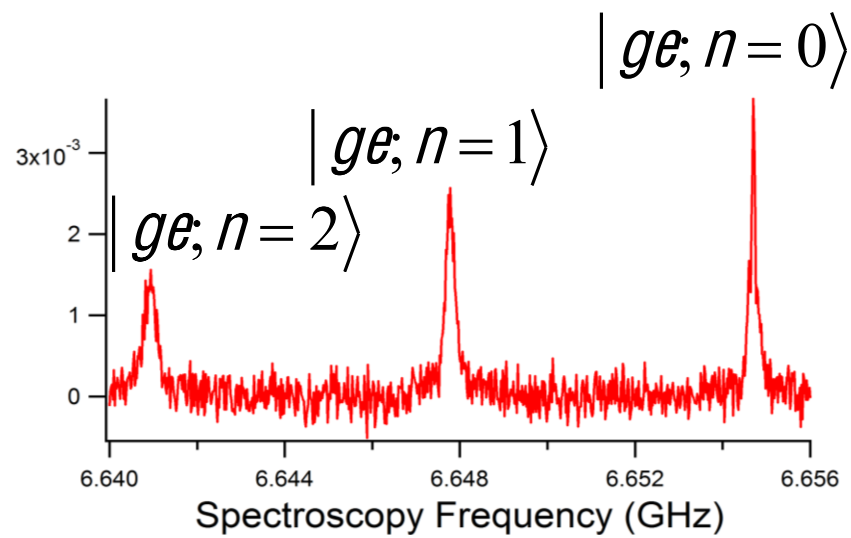


T^*_2 is not T_1 limited

- source of dephasing?

Fluctuations of photons in the cavity

$$T_\varphi^{-1} \sim \bar{n}\kappa$$



*A. Sears et al. in preparation (2012)

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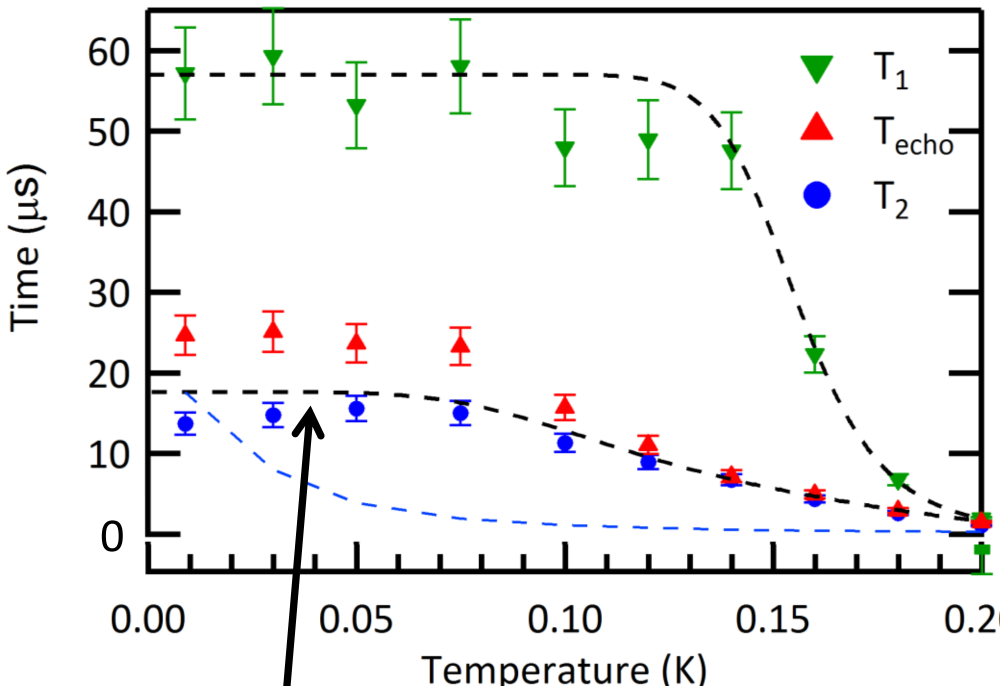

T^*_2 is not T_1 limited
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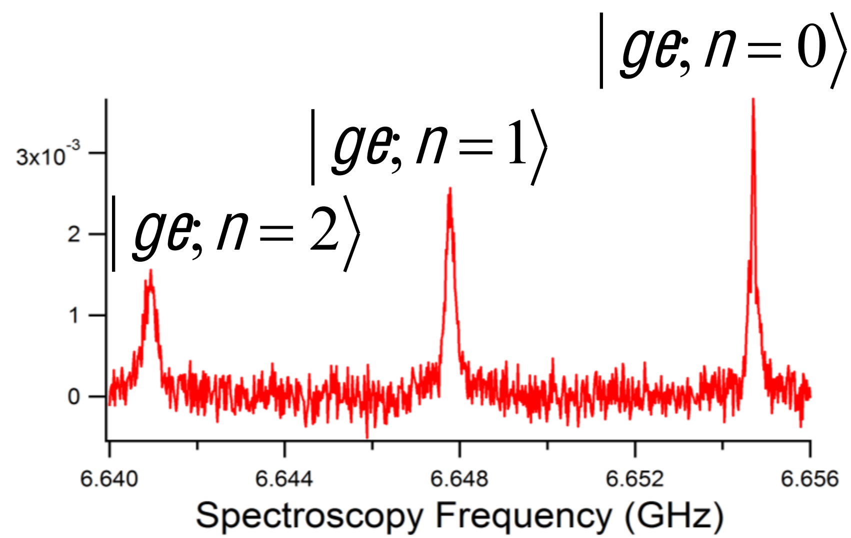
Fluctuations of photons in the cavity

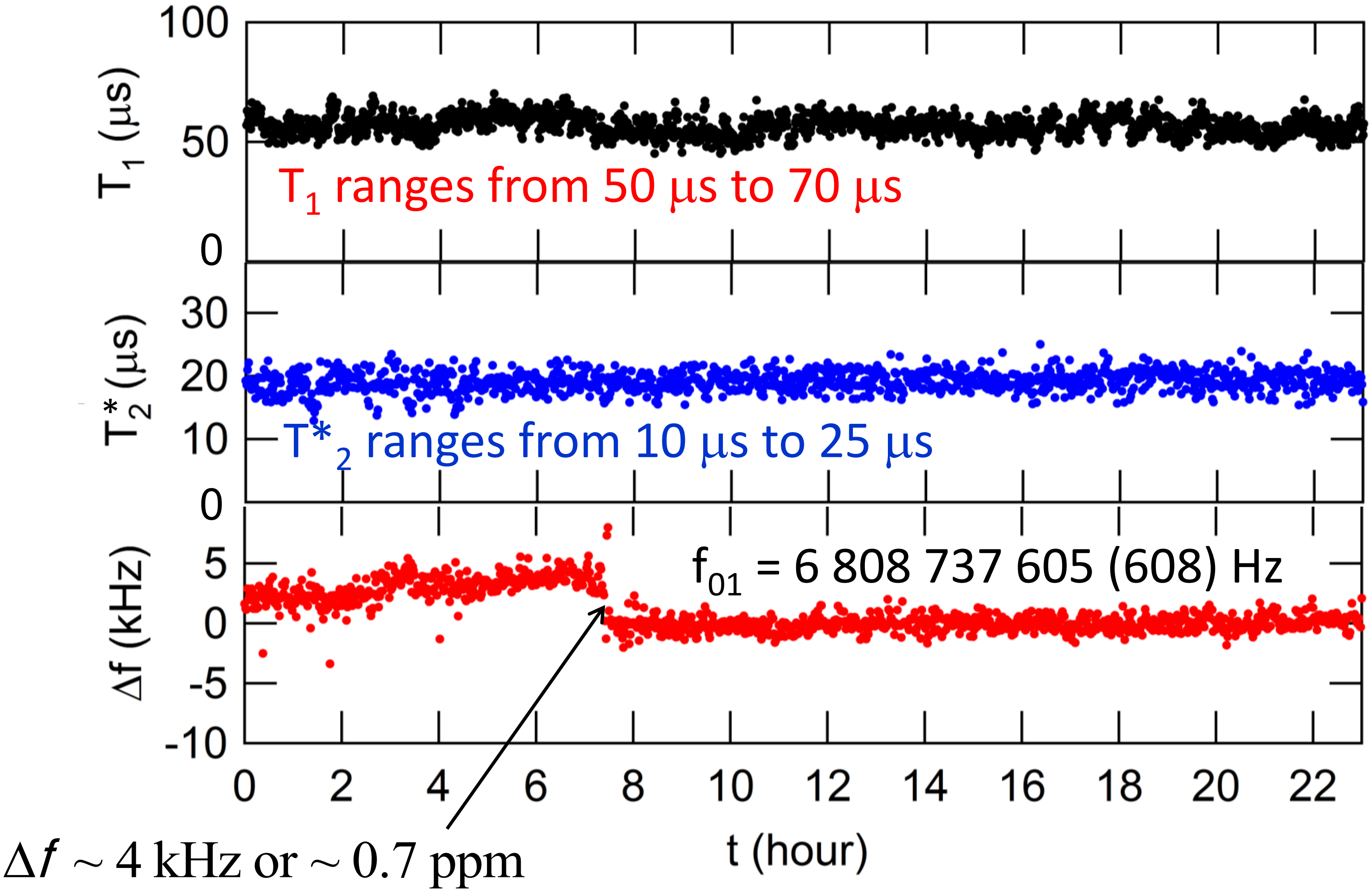


$$\frac{1}{T^*_2} = \frac{1}{2T_1} + \frac{1}{T_{\varphi,\mathrm{int}}} + \sum_i \bar{n}_i \kappa_i$$

with thermal population of photons at each $\bar{n}_i$ cavity modes i.

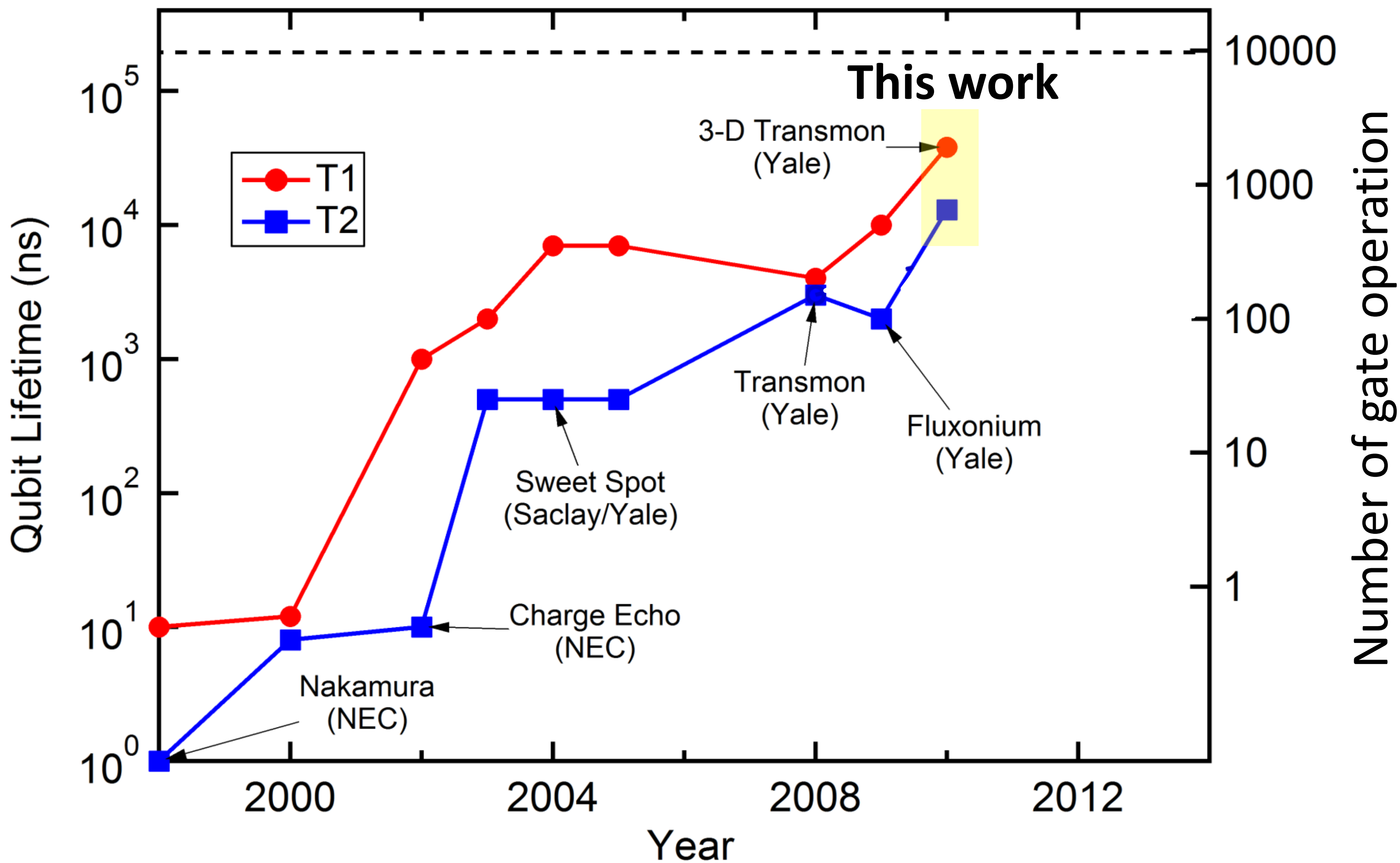
*A. Sears et al. in preparation (2012)

Stability of Josephson Junction



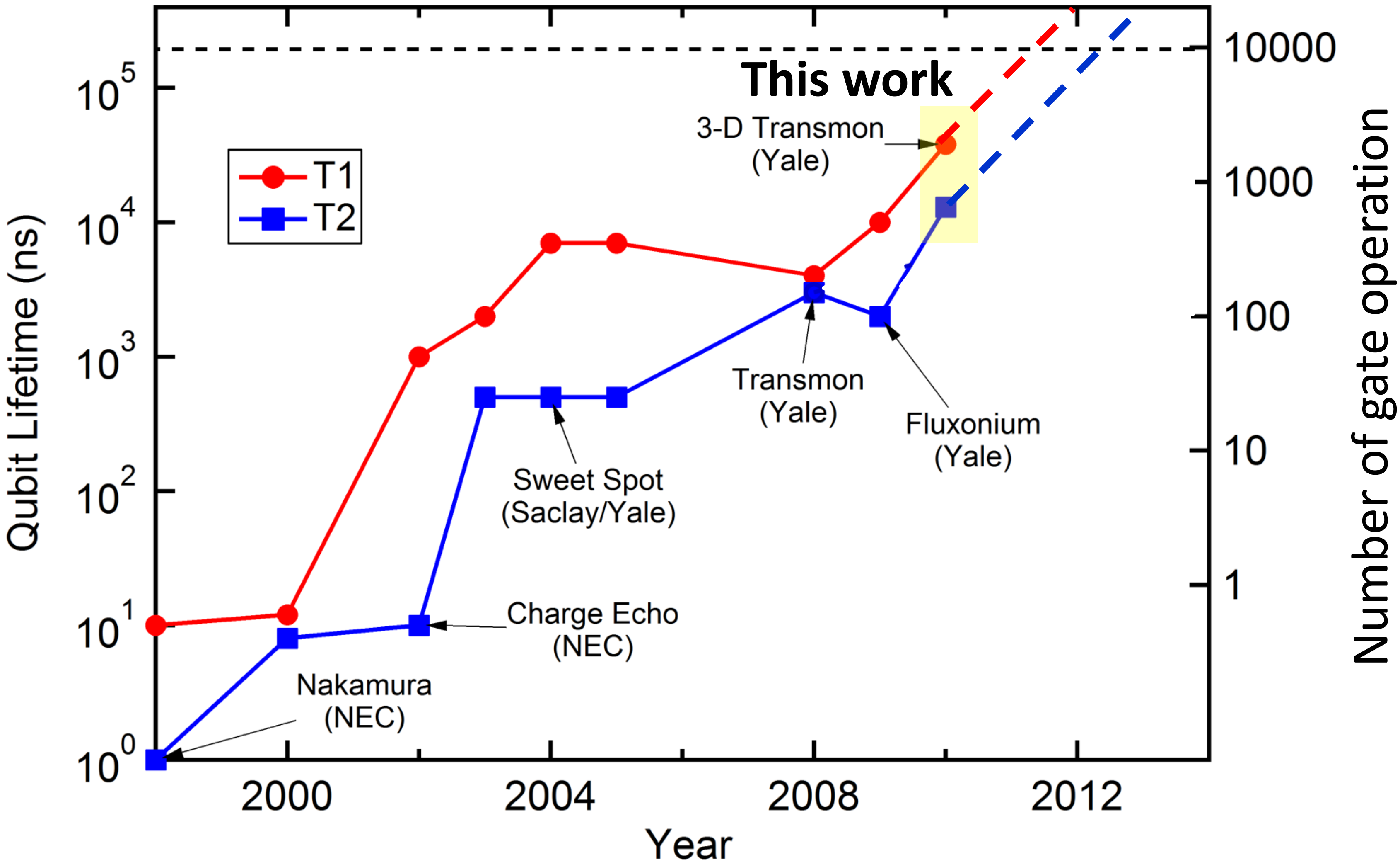
Frequency stable < 600 Hz : Stability in E_J or E_c - 80 ppb

Breakthrough in SC Qubit Coherence



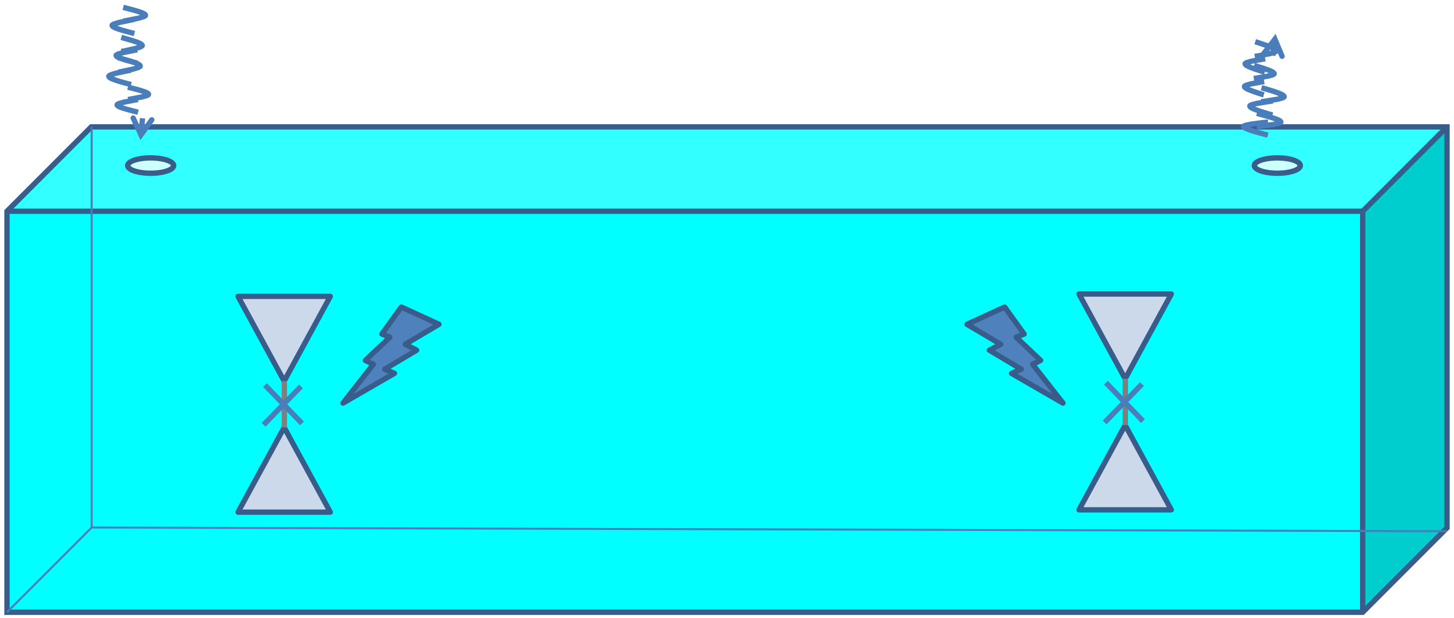
by introducing 3D circuit QED architecture

Charge Qubit Coherence : Saga continues



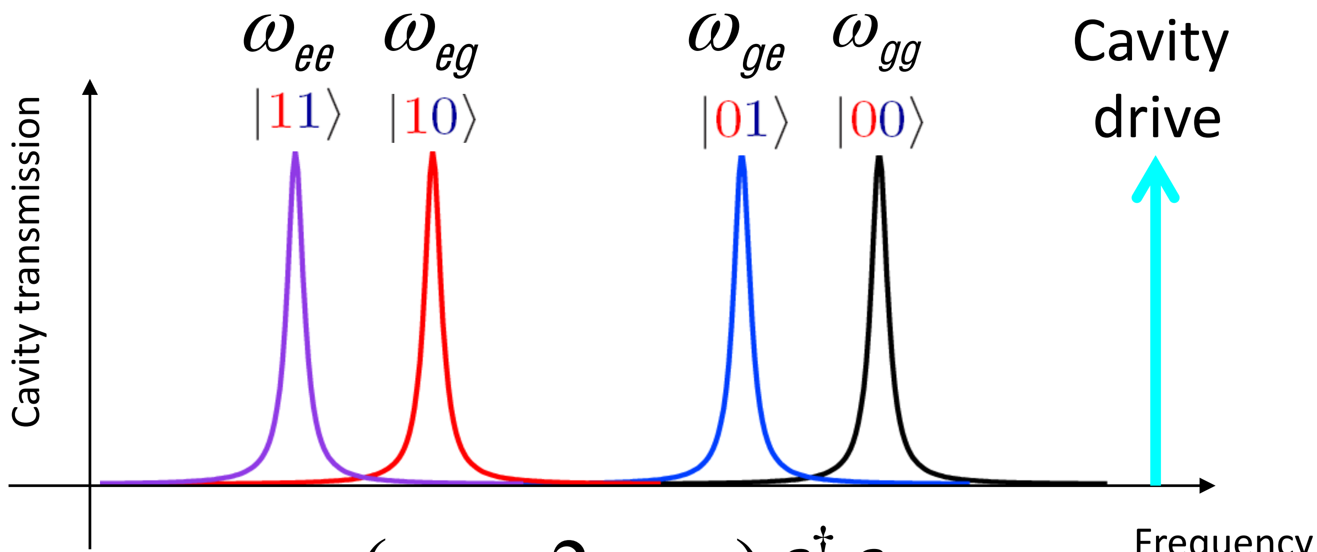
No evidence found that
the Josephson junction is limiting the qubit coherence

Coherent control of 3D transmons



- Use microwave to perform single/two qubit gates

Phase Gate
using Off-Resonant Cavity Driving



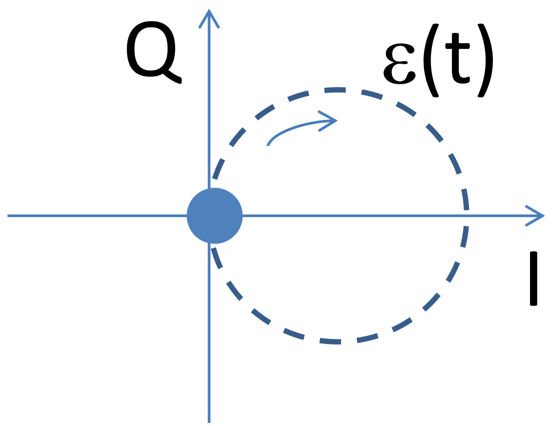
$$(\omega_c + 2\chi\sigma_z)a^\dagger a$$

- Use a qubit state-dependent cavity coherent states

- When the cavity is driven, cavity coherent state evolves giving phase to each qubit state.

Phase of Driven Harmonic Oscillator

$$H = \omega_c a^\dagger a + \epsilon(t) e^{-i\omega_d t} a^\dagger + \epsilon^*(t) e^{i\omega_d t} a$$



Apply off-resonant drive to displace the cavity

$$\left|\alpha(T)\right\rangle = e^{i\phi(T)}\left|\alpha(0)\right\rangle$$

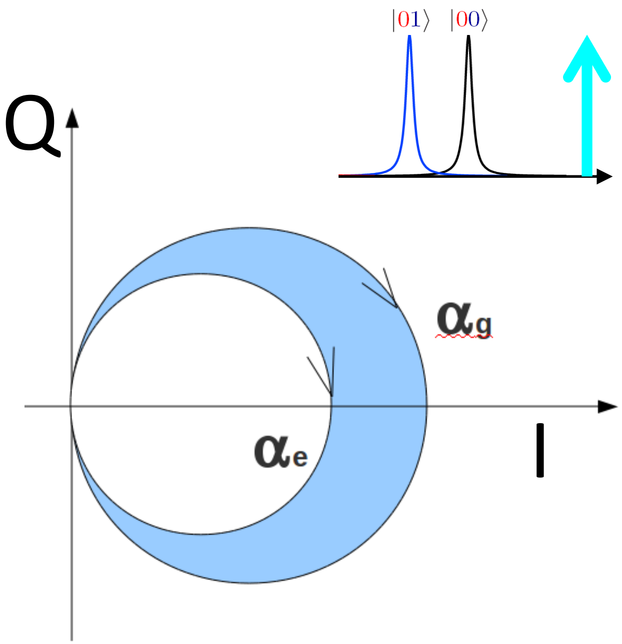
$$i\dot{\alpha} = \Delta\alpha + \varepsilon(t) \qquad \Delta = \omega_c - \omega_d$$

$$\phi(T) = \int_0^T Im[\dot{\alpha}\alpha^*]dt + \int_0^T \Delta|\alpha|^2\, dt$$

Geometric origin (Area)

Dynamical origin (energy)

Single-Qubit Phase Gate (z-gate)



Two coherent states α_g and α_e corresponding to |g> and |e>

$$\phi_g(T) = \int_0^T Im\dot{\alpha}_g \alpha_g^* dt + \int_0^T \Delta_g |\alpha_g|^2 \, dt$$

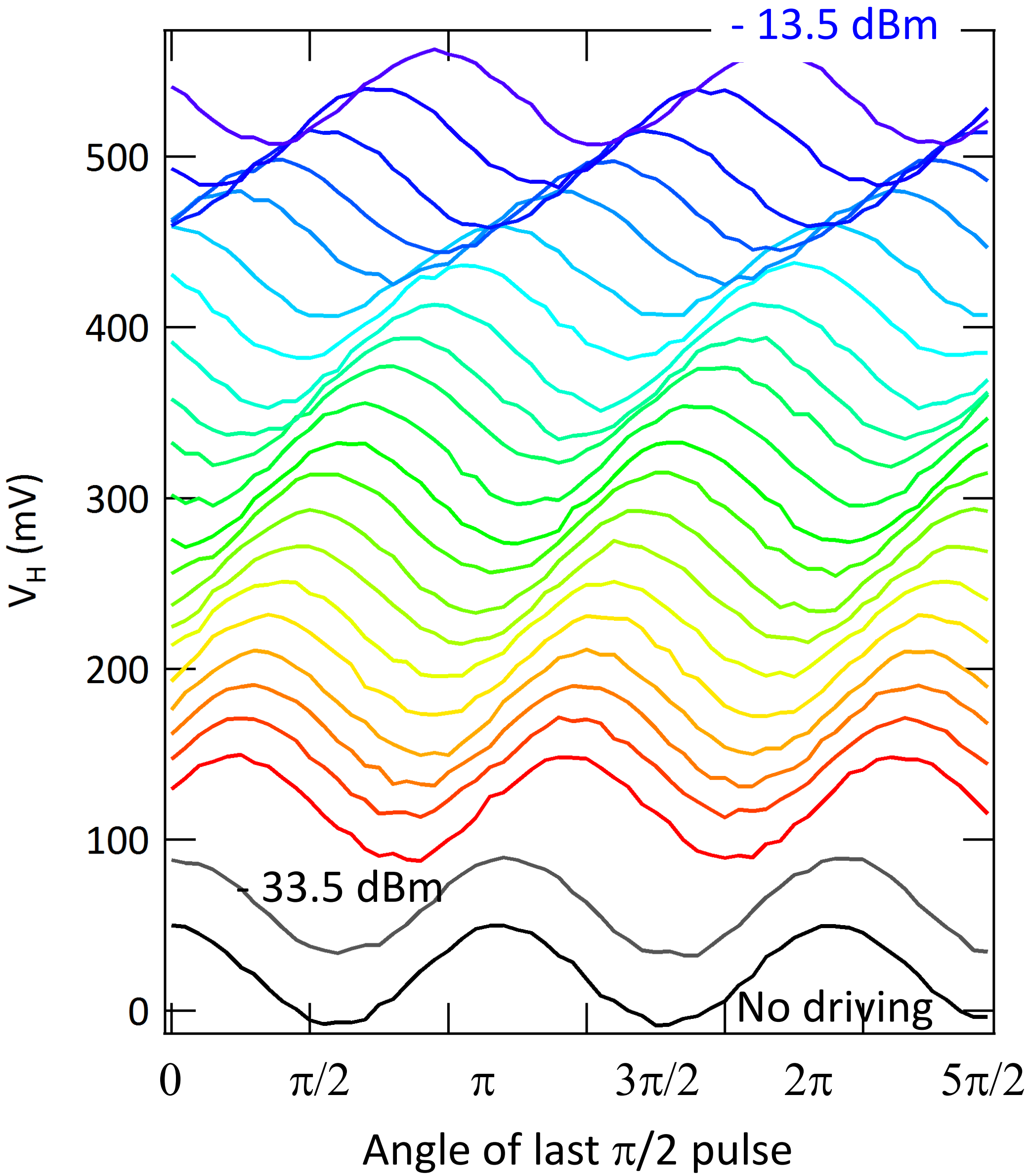
$$\phi_e(T) = \int_0^T Im\dot{\alpha}_e \alpha_e^* dt + \int_0^T \Delta_e |\alpha_e|^2 \, dt$$

$$(|e\rangle + |g\rangle)\,|0\rangle \longrightarrow \left(e^{i\varphi_e(T)}\,|e\rangle + e^{i\varphi_g(T)}\,|g\rangle\right)|0\rangle$$

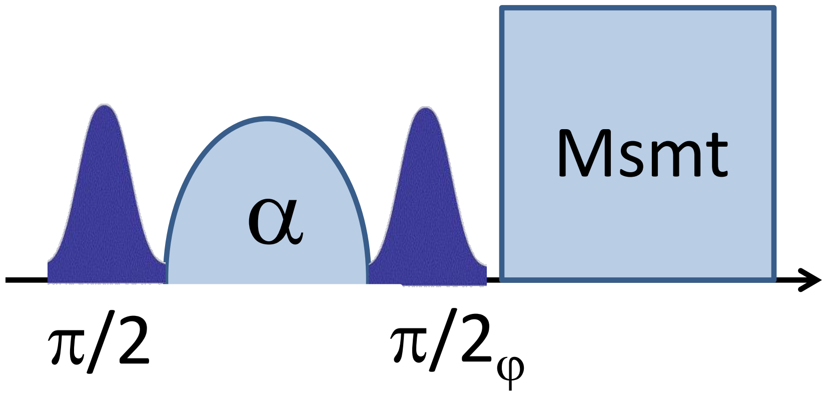
If $\quad \phi_e - \phi_g = \pm\pi \quad$: Z-gate

Also single qubit geometric phase demonstrated by M. Pechal, et al. *arXiv:1109.1157 (2011)*

Single-Qubit Phase Gate



Ramsey experiment

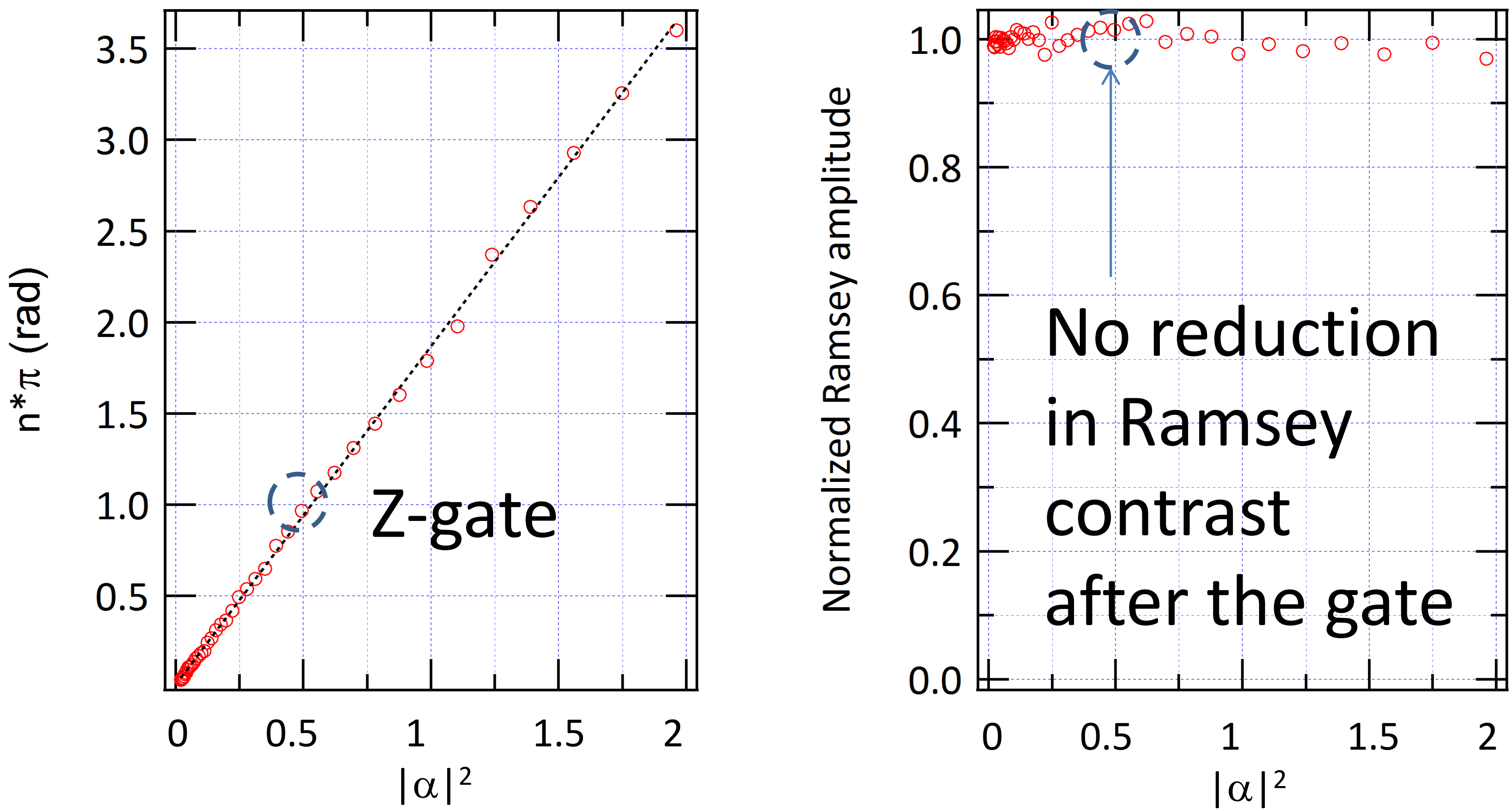


$$\phi \propto |\alpha|^2 \propto |\varepsilon|^2$$

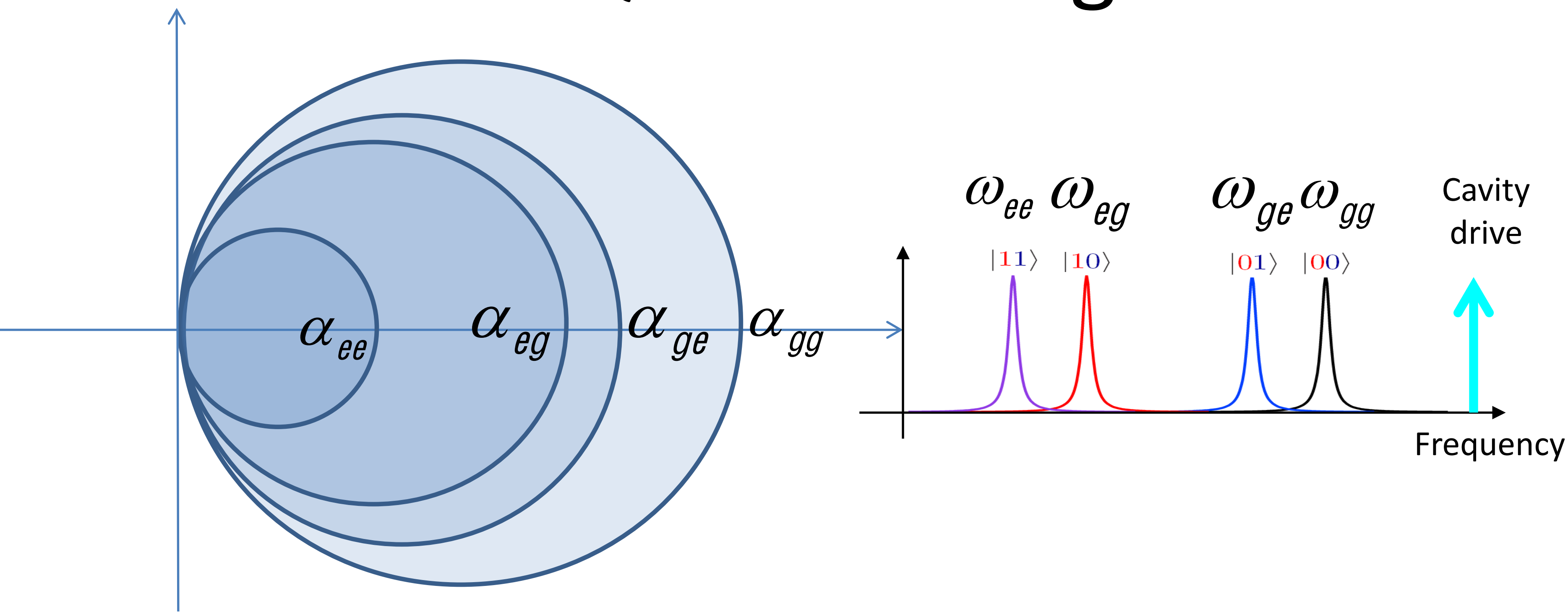
Phase is proportional to the driving power.

Detuning f =60 MHz

Single Qubit z-gate



Two-Qubit Phase gate

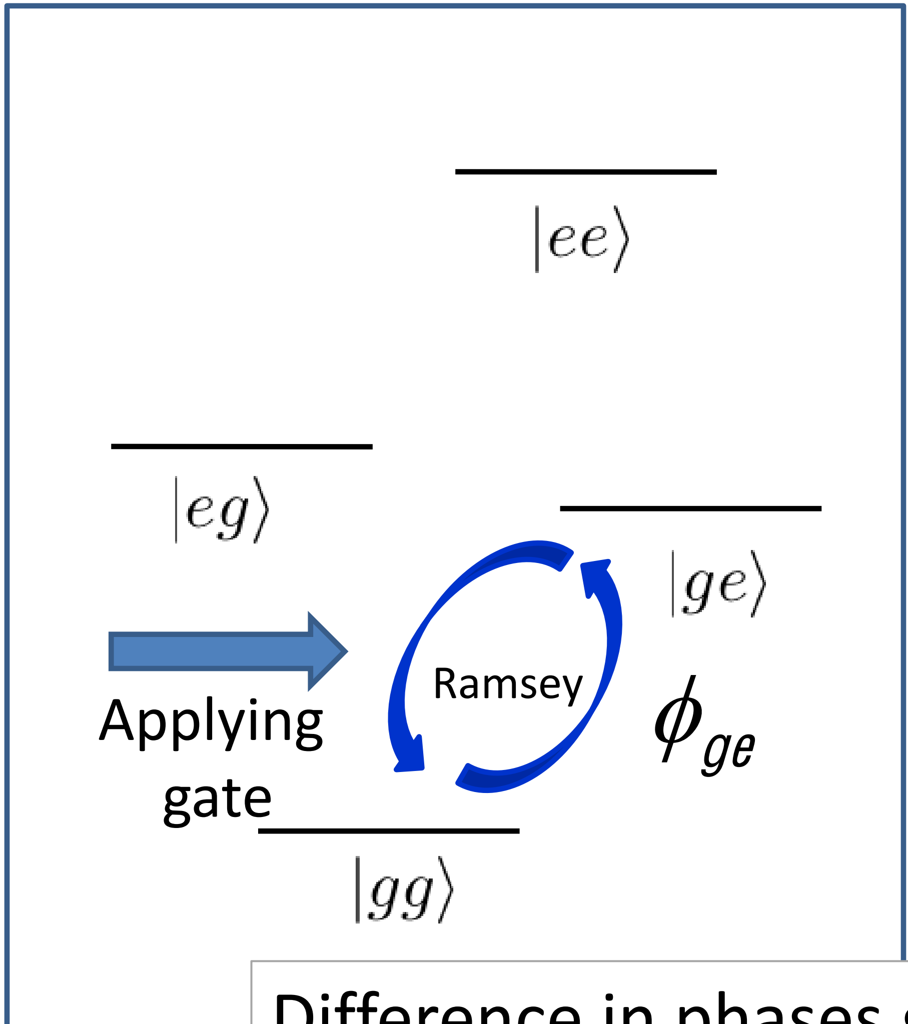


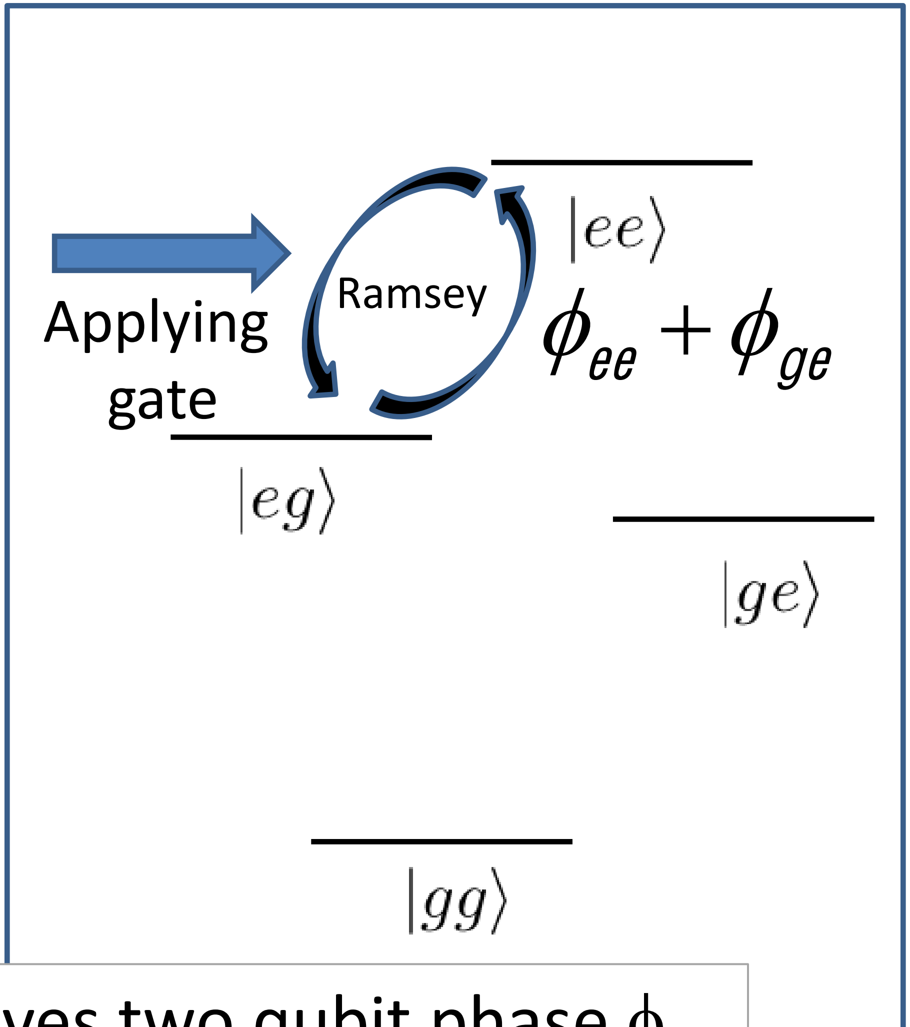
$$\left(|gg\rangle + |ge\rangle + |eg\rangle + |ee\rangle\right)|0\rangle$$

$$\rightarrow \left(|gg\rangle + e^{i\phi_{ge}}|ge\rangle + e^{i\phi_{eg}}|eg\rangle + e^{i\phi_{ge}+\phi_{eg}+\phi_{ee}}|ee\rangle\right)|0\rangle$$

If $\phi_{ee} = \pi$: cPhase

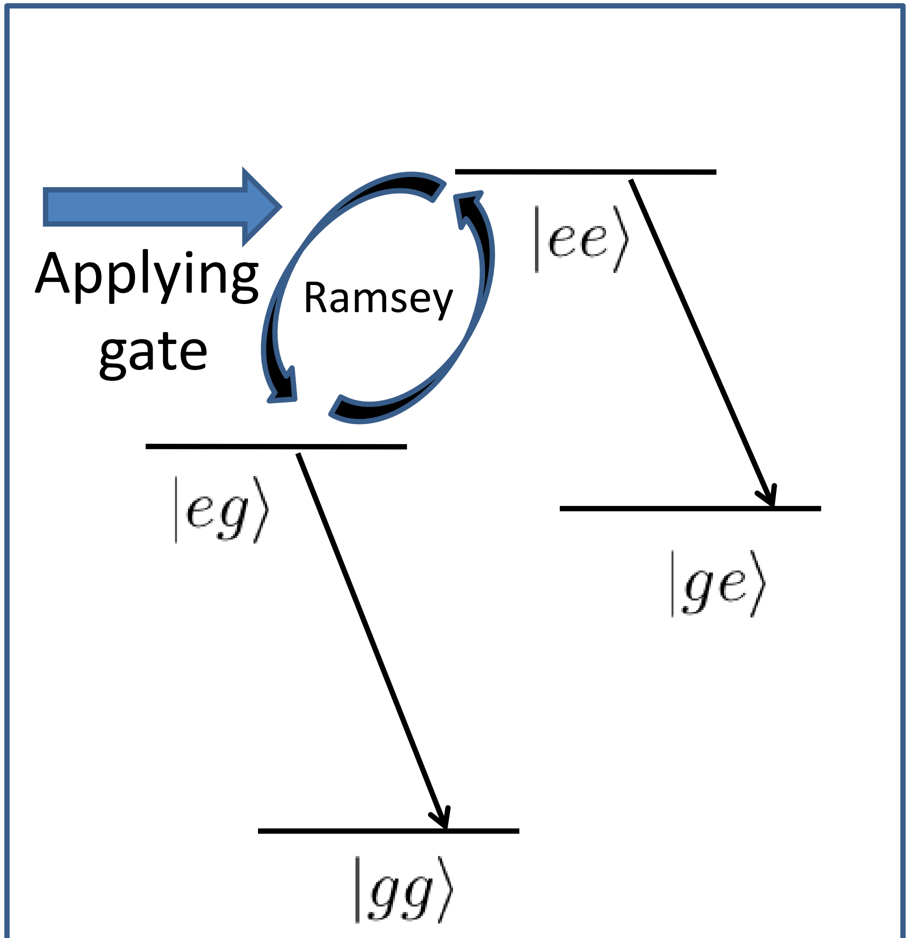
Ramsey experiments to measure two qubit phase

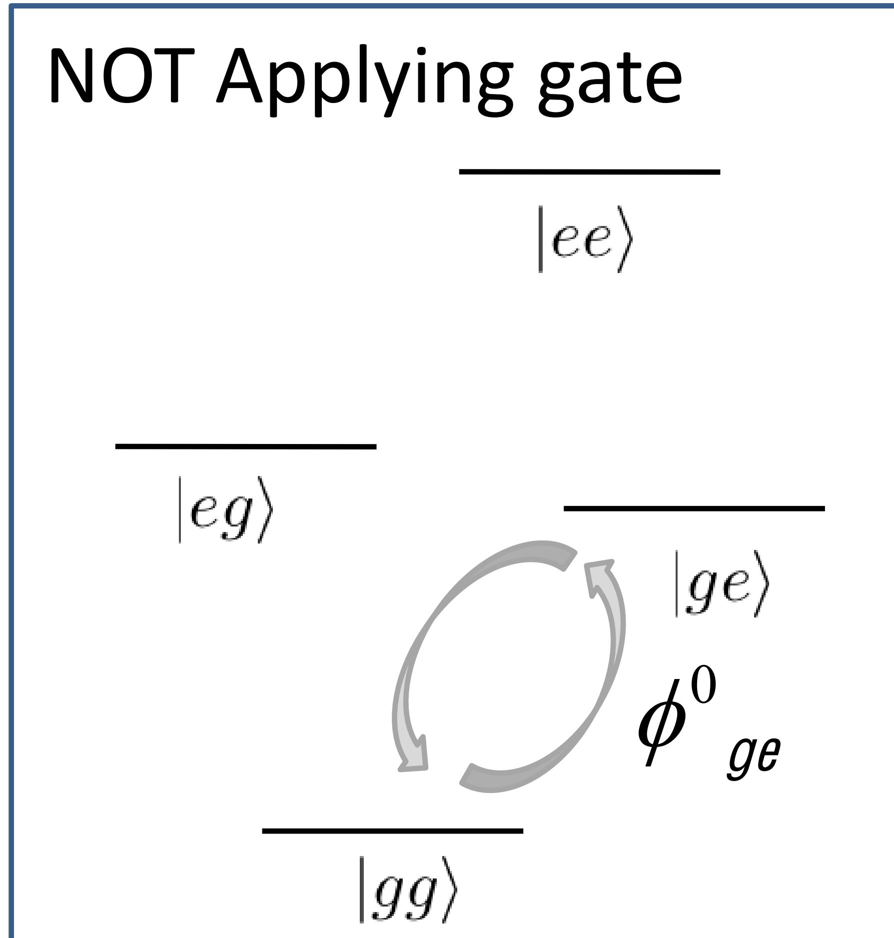




Difference in phases gives two qubit phase ϕ_{ee}

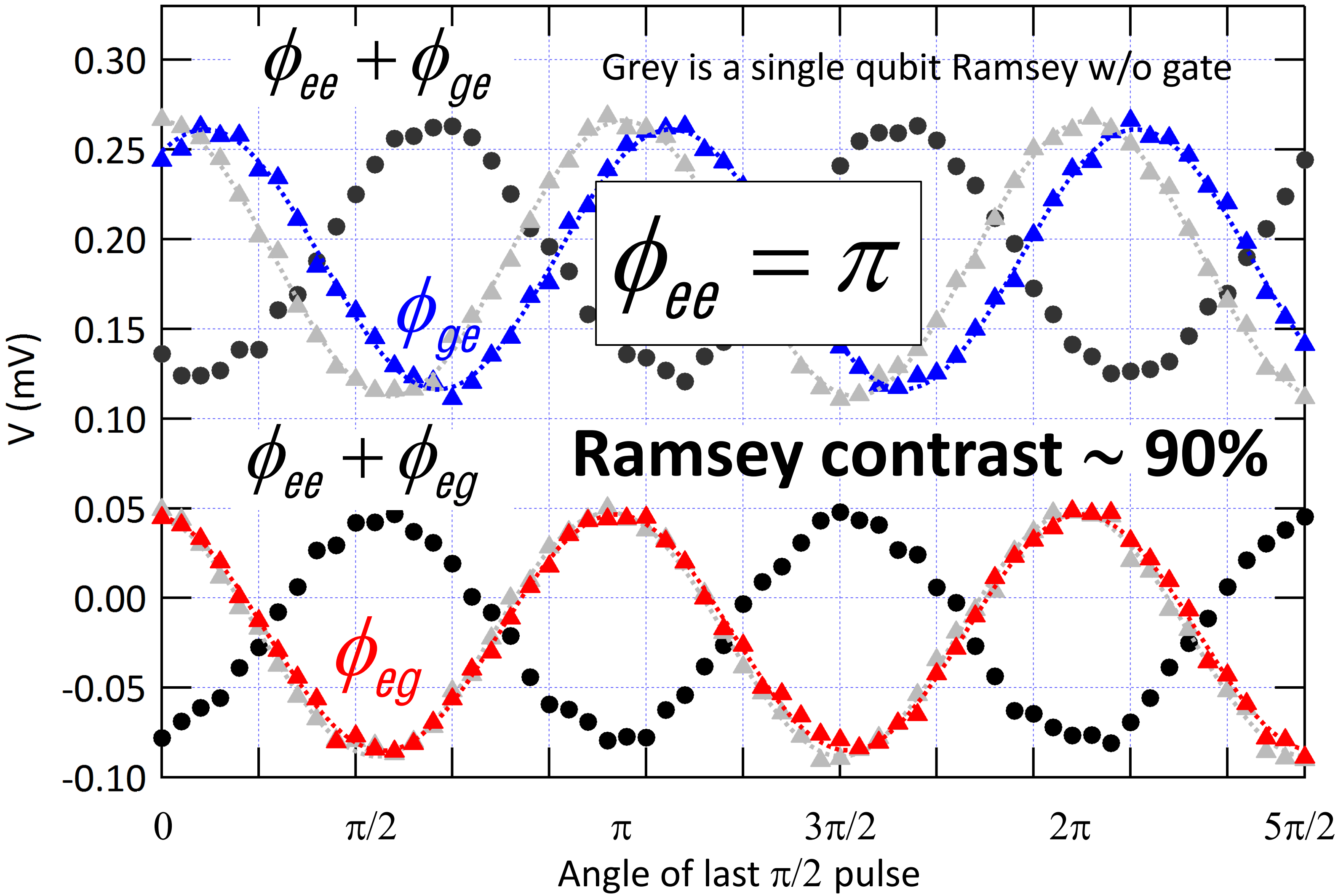
Ramsey experiments to estimate gate fidelity





Comparing Ramsey contrast gives estimate on gate fidelity

Demonstrating cPhase gate



T_{gate} = 200ns, Δ = 80 MHz, P = 1.2 dBm

Paik et al. work in progress (2012)

Conclusion

- Demonstrated new coherence time for superconducting qubit using a new 3D cQED architecture

  $T_1 \sim 60\ \mu s$ (up to $75\ \mu s$)

  T_2 (Ramsey) $\sim$ up to $30\ \mu s$, T_2 (Echo) $\sim$ up to $45\ \mu s$

- New observation of physics in Josephson junction qubits
  - Josephson junction Q > 2 M
    (current coherence limitation in SC qubit is not the junction)
  - Sensitive detection of non-equilibrium quasiparticles
  - No evidence of 1/f noise in critical current/capacitance
  - Dephasing from cavity photon fluctuations.

- Demonstrated single and two qubit phase gate using cavity geometric/dynamical phase in coupled 3D transmon qubits.

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