Departments of Physics
and Applied Physics,
Yale University

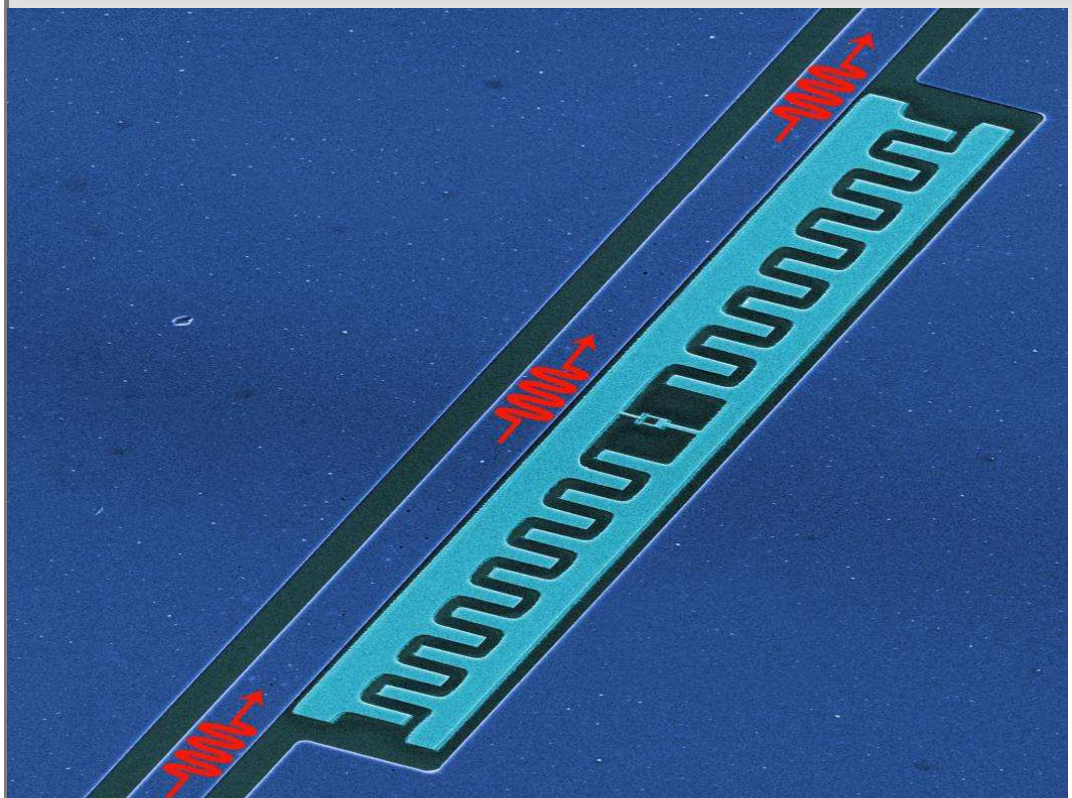
Quantum computation and quantum optics with circuit QED

Jens Koch

filling in for
Steven M. Girvin

KECK FOUNDATION
PACKARD FOUNDATION
CRSNG NSERC

Quick outline



Superconducting qubits

► overview and challenges

► from the CPB to the transmon

Circuit QED

► basic concept

► quantum bus:

coupling of qubits over long distance

(► quantum optics with circuits)

Outlook

Departments of Physics
and Applied Physics,
Yale University

Circuit QED at Yale

EXPERIMENT

PIs: Rob Schoelkopf, Michel Devoret

Andrew Houck
Johannes Majer
David Schuster
Luigi Frunzio

Jerry Chow
Blake Johnson
Jared Schwede
Joseph Schreier
Emily Chan

Andreas Wallraff (ETH Zurich)

THEORY

PI: Steve Girvin

Jay Gambetta
Terri Yu
David Price
Jens Koch
Lev Bishop
Daniel Ruben

Alexandre Blais (Sherbrooke)
Joe Chen (Cornell)
Cliff Cheung (Harvard)
Aashish Clerk (McGill)
R. Huang (Taipei)
K. Moon (Yonsei)

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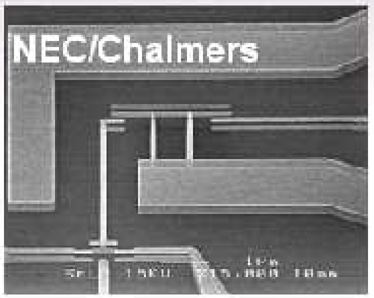
Superconducting Qubits

Nonlinearity from Josephson junctions ($Al/AlO_x/Al$)

Charge

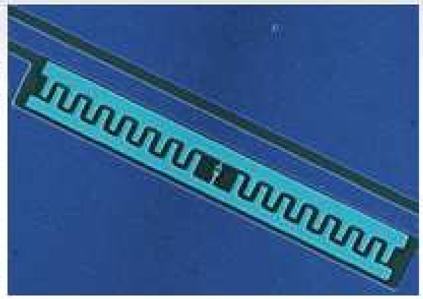


$E_J = E_C$

Charge/Phase

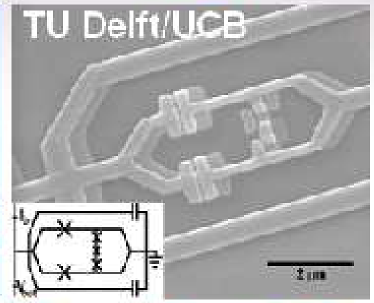
$E_J = E_C$

Charge/ac Susc.



$E_J = 30\text{-}100 E_C$

Flux



$E_J = 40\text{-}100 E_C$

Phase

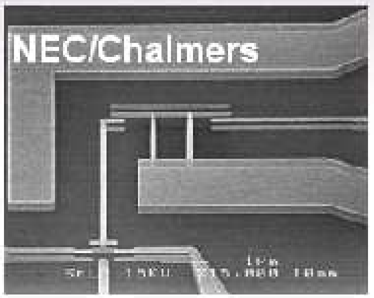
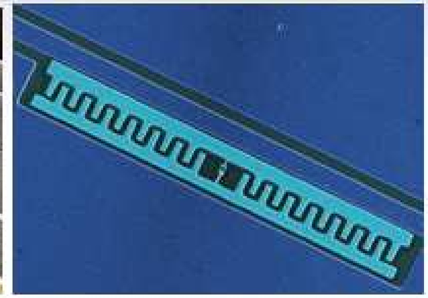
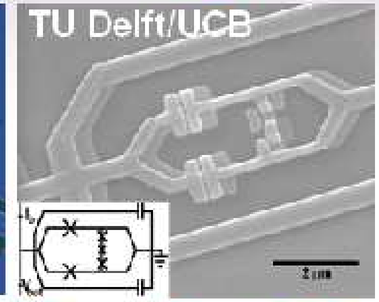
$E_J = 10{,}000 E_C$

Reviews:
Yu. Makhlin, G. Schön, and A. Shnirman, Rev. Mod. Phys. **73**, 357 (2001)
M. H. Devoret, A. Wallraff and J. M. Martinis, cond-mat/0411172 (2004)
J. Q. You and F. Nori, Phys. Today, Nov. 2005, 42

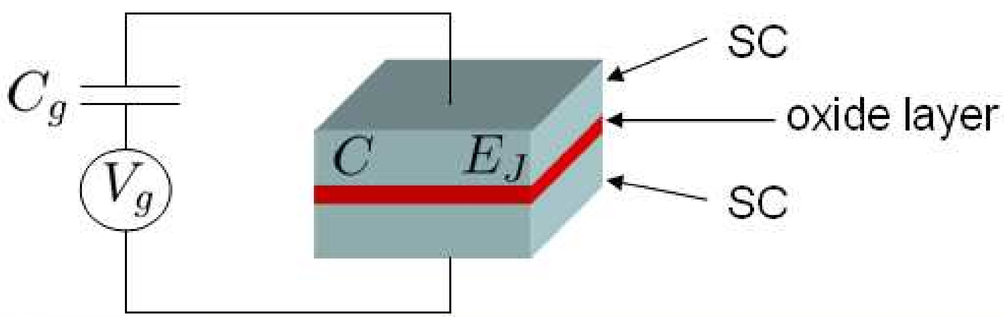
Transmon:
J. Koch, ..., M. H. Devoret, S. M. Girvin, R. J. Schoelkopf, Phys. Rev. A **76**, 042319 (2007)

Superconducting Qubits

Nonlinearity from Josephson junctions (Al/AlO$_x$/Al)

Charge	Charge/Phase	Charge/ac Susc.	Flux	Phase
				
$E_J = E_C$	$E_J = E_C$	$E_J = 30\text{-}100E_C$	$E_J = 40\text{-}100E_C$	$E_J = 10{,}000E_C$

circuit QED:
interaction w/ ***quantized*** fields → **quantum optics with circuits!**



Cooper pair box

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

Sometimes… noise is NOT the signal!

[… sorry, Mr. Landauer]

- Noise can lead to energy relaxation (T_1)
  dephasing (T_2) → **bad** for qubit!

- Persistent problem with superconducting qubits: short T_2

Reduce noise itself

► materials science approach
► eliminate two-level fluctuators

J. Martinis et al.,
PRL **95,** 210503 (2005)

Reduce sensitivity to noise

► design improved quantum circuits
► find smart ways to beat the noise!

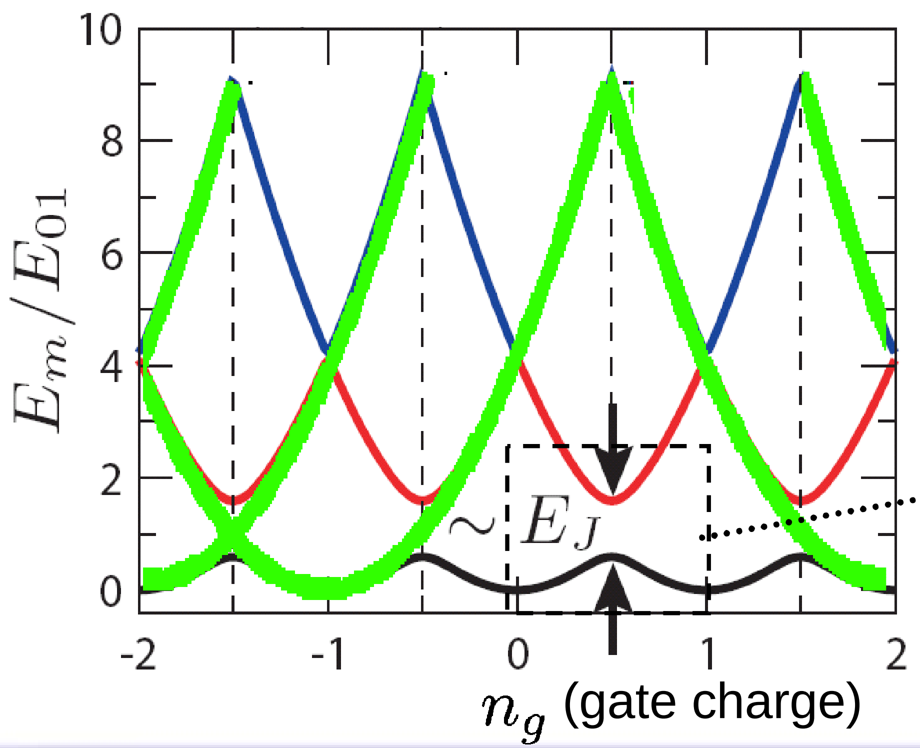
Paradigmatic example:
sweet spot for the Cooper Pair Box

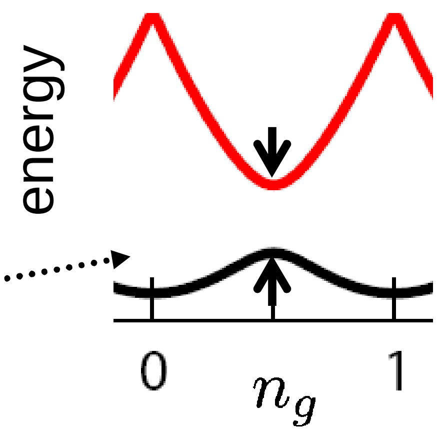
Quantronics Group (Saclay)
D. Vion et al., Science **296**, 886 (2002).

CPB as a charge qubit, sweet spot

Charge limit: $E_J/E_C \ll 1$

$$\hat{H} = \underbrace{4E_C(\hat{n}-n_g)^2}_{\text{big}} - \underbrace{\frac{E_J}{2}\sum_{n=-\infty}^{\infty}\Big[|n+1\rangle\langle n| + |n\rangle\langle n+1|\Big]}_{\text{small perturbation}}$$



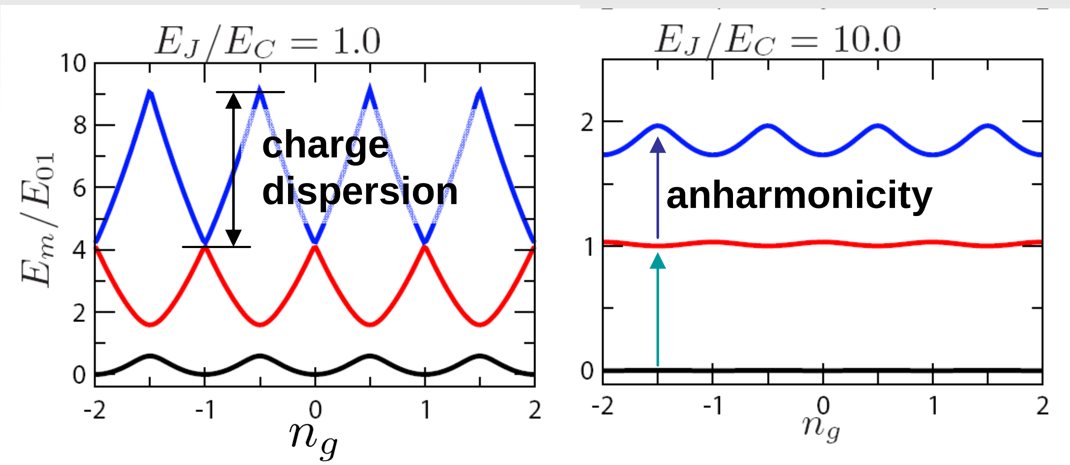


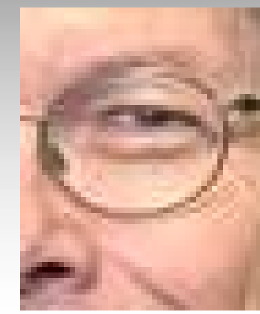
sweet spot

only sensitive to 2nd order fluctuations in gate charge!

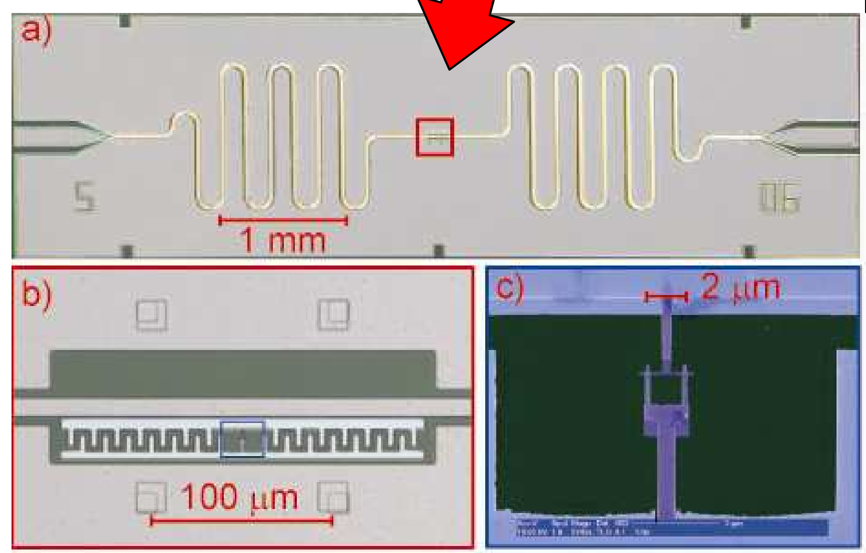
Vion et al., Science **296**, 886 (2002)

Make the sweet spot sweeter: increase E_J/E_C





Steve can see it with his naked eye!



Anharmonicity decreases…

…only algebraically

Flatter charge dispersion, become **insensitive to charge noise**!

…exponentially!

Island volume ~1000 times bigger than conventional CPB island

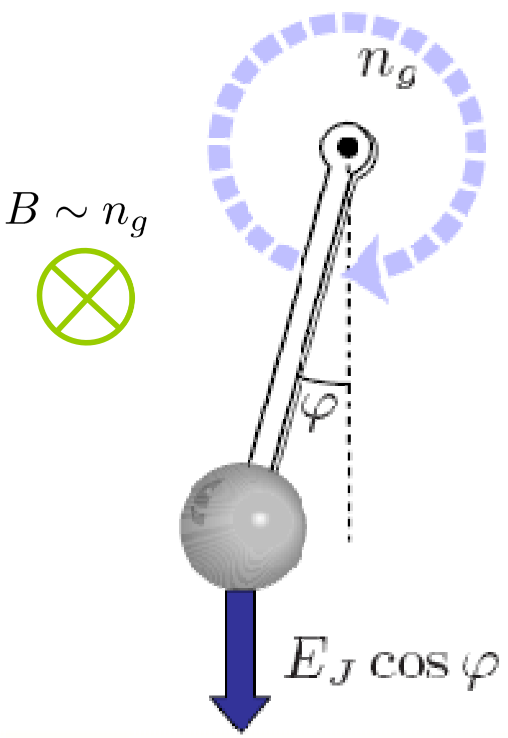
Quantum rotor picture for the CPB

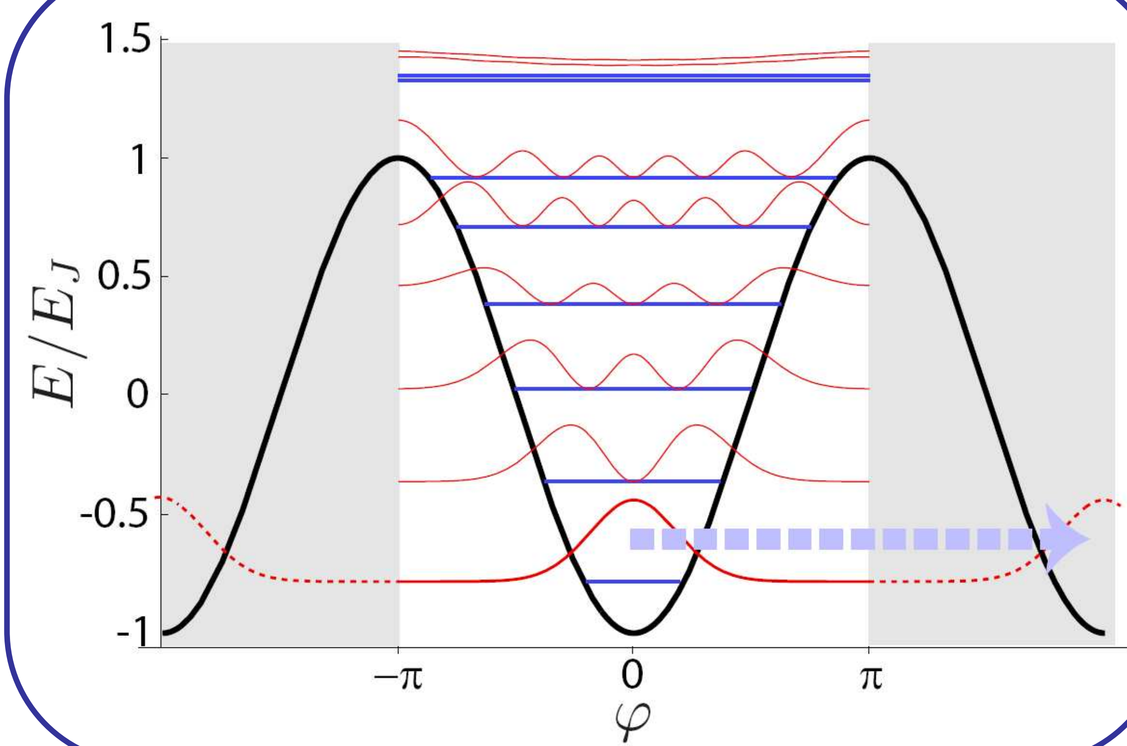
Schrödinger eq. for the CPB circuit (phase basis)

$$\left[4E_C\left(-i\frac{d}{d\varphi}-n_g\right)^2-E_J\cos\varphi\right]\Psi(\varphi)=E\Psi(\varphi)$$

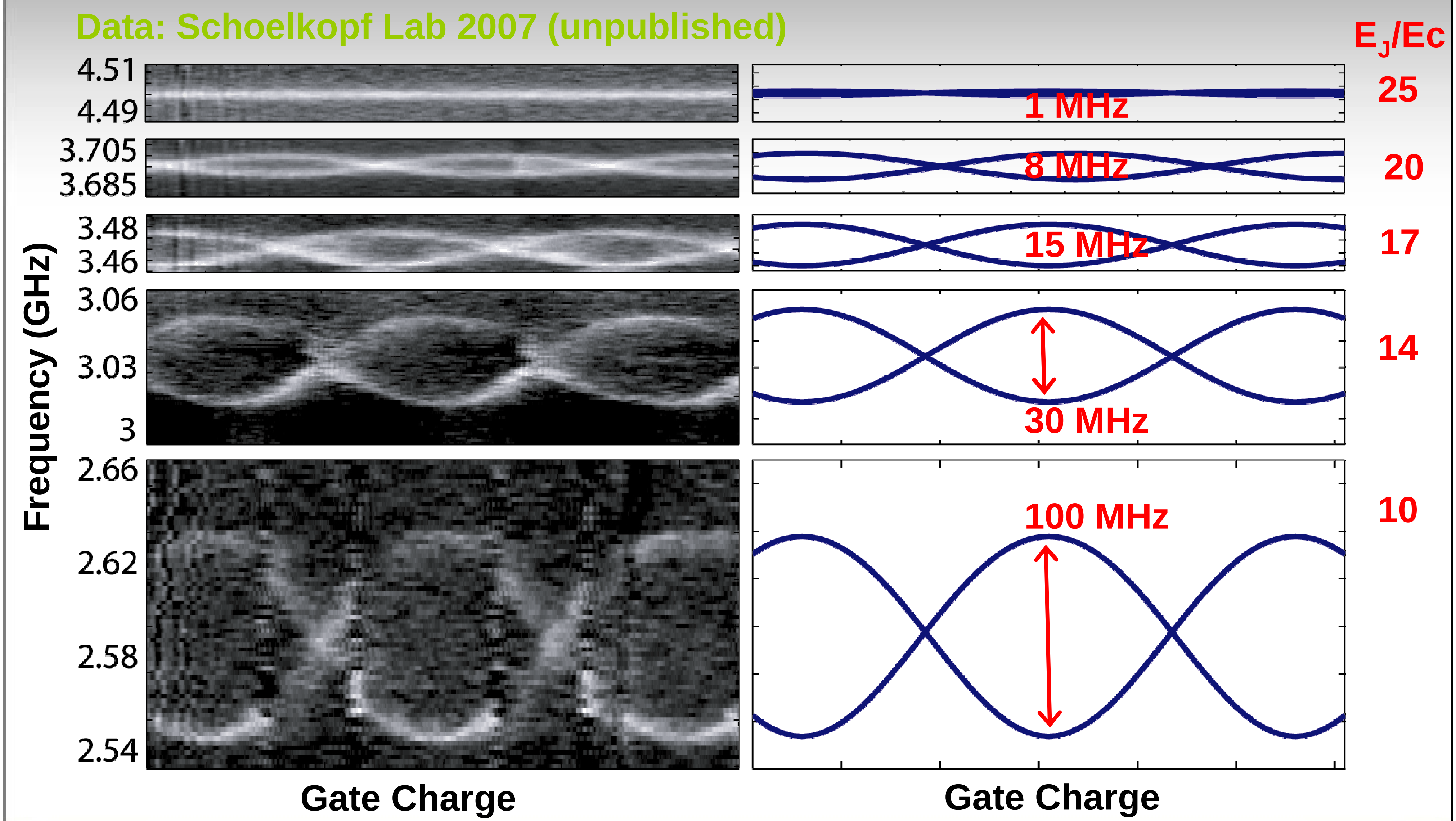
quantum rotor
(charged, in constant magnetic field $\sim n_g$)

▶ has exact solution
(Mathieu functions, Mathieu characteristic values)





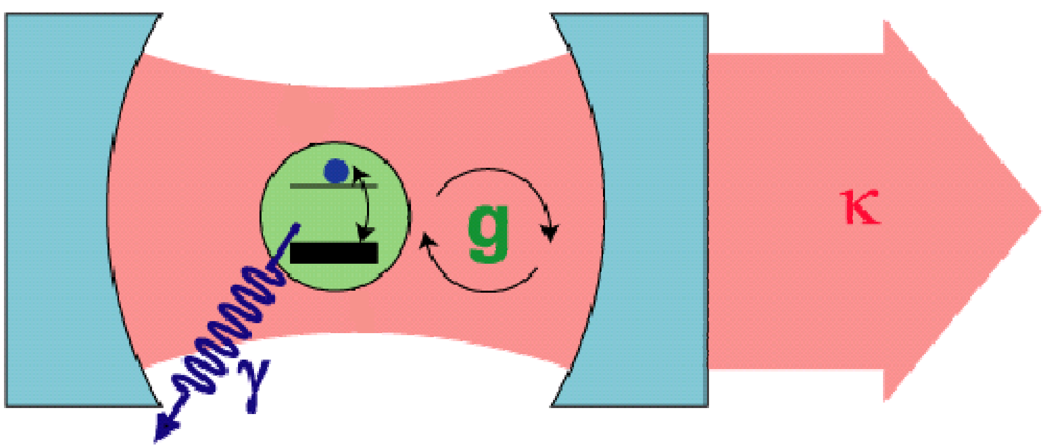
Exponential suppression of charge noise: it works!



Cavity & circuit quantum electrodynamics

- coupling atom / discrete mode of EM field
- central paradigm for study of open quantum systems

▶ coherent control, ▶ quantum information processing
▶ conditional quantum evolution, ▶ quantum feedback
▶ decoherence



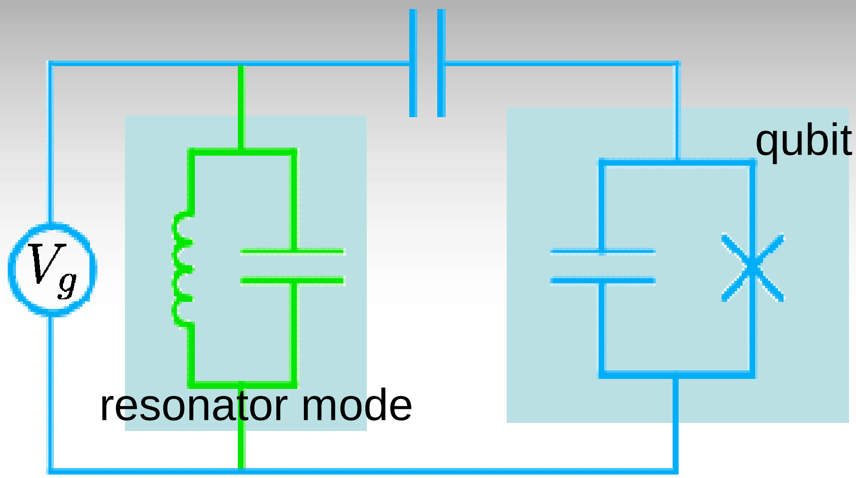
2g = vacuum Rabi freq.

κ = cavity decay rate

γ = “transverse” decay rate

strong coupling: $g > \kappa, \gamma$

Coupling transmon - resonator



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

coupling to resonator:

$$V_g \rightarrow V_g + V_{\text{rms}}(\hat{a} + \hat{a}^\dagger)$$

$$\Rightarrow \quad \hat{H}_{\text{coupling}} = \frac{4E_c C_g V_{\text{rms}}}{e} \hat{n}(\hat{a} + \hat{a}^\dagger)$$

$\longrightarrow$ **coupling becomes even bigger!**

Generalized Jaynes-Cummings Hamiltonian

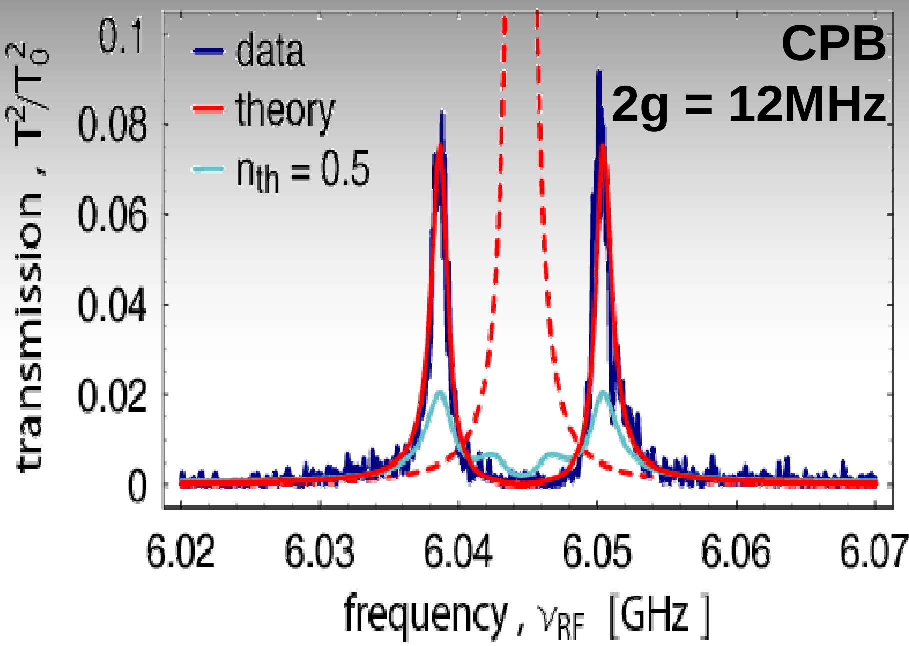
$$\hat{H} = \hbar \sum_j \omega_j \,|\, j \,\rangle \langle\, j \,| + \hbar\omega_r \hat{a}^\dagger \hat{a} - \left[\hbar \sum_i g_{i,i+1} \,|\, i \,\rangle \langle\, i+1 \,|\, \hat{a}^\dagger + \text{h.c.}\right]$$

Dispersive limit: dynamical Stark shift Hamiltonian

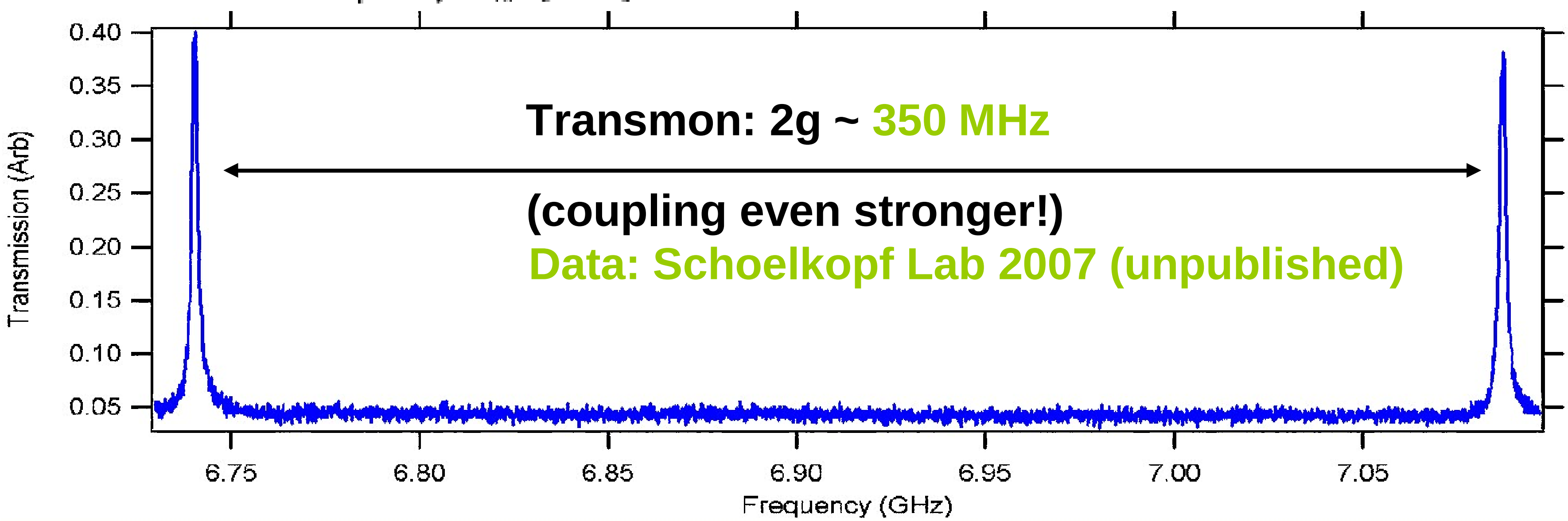
$$\hat{H}_{\text{eff}} = \frac{\hbar\omega'_{01}}{2} \hat{\sigma}_z + (\hbar\omega'_r + \hbar\chi\sigma_z)\, \hat{a}^\dagger \hat{a}$$

► QND readout, coherent control

Strong coupling to cavity



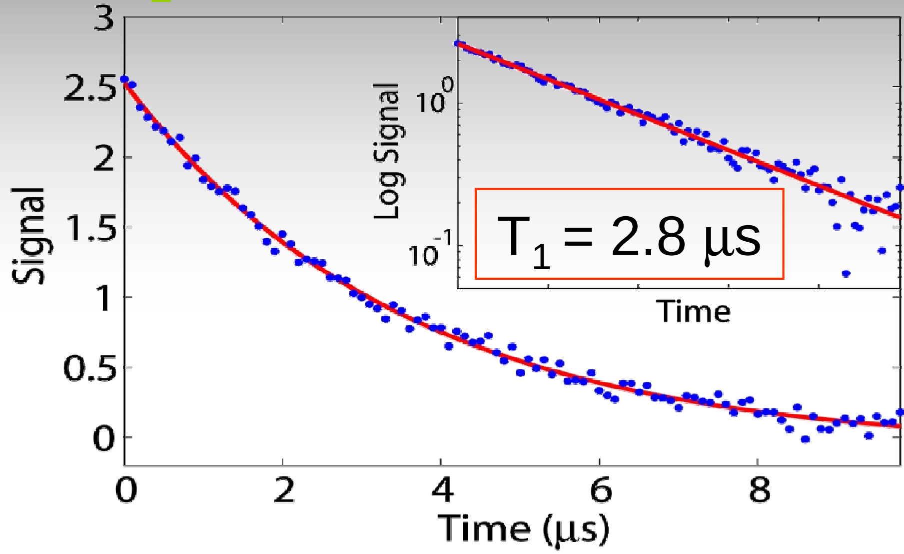
- Transition dipole matrix element gets larger
- Measure vacuum Rabi avoided crossings to see large coupling



Coherence in 2nd generation transmon

Schoelkopf Lab 2007

T_1 Measurement

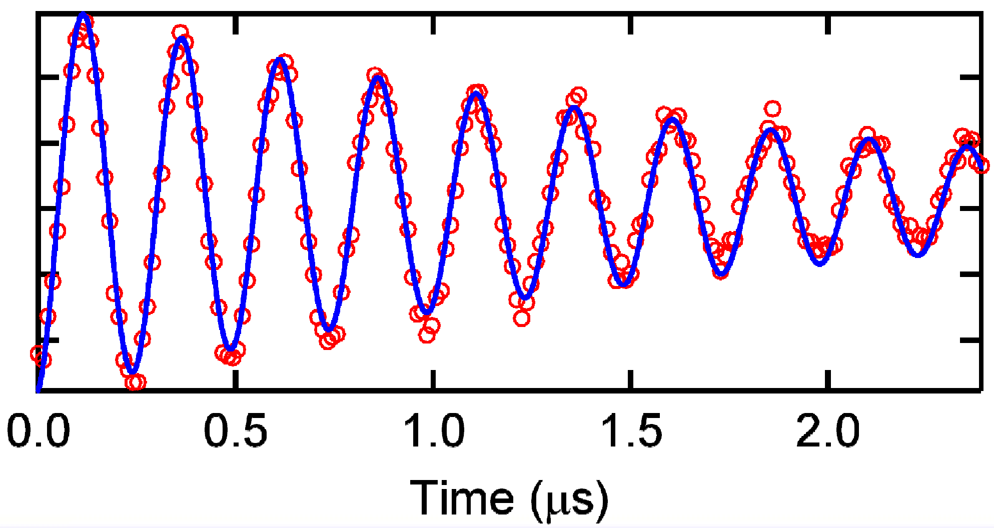


At flux sweet spot:

$$T_2 = 2.05 \pm 0.1\,\mu\text{s}, \quad T_1 = 1.5\,\mu\text{s}$$

$$\Rightarrow \quad T_\varphi = 6\,\mu\text{s} \qquad (\omega_a = 7.5\,\text{GHz})$$

still not limited by 1/f noise!



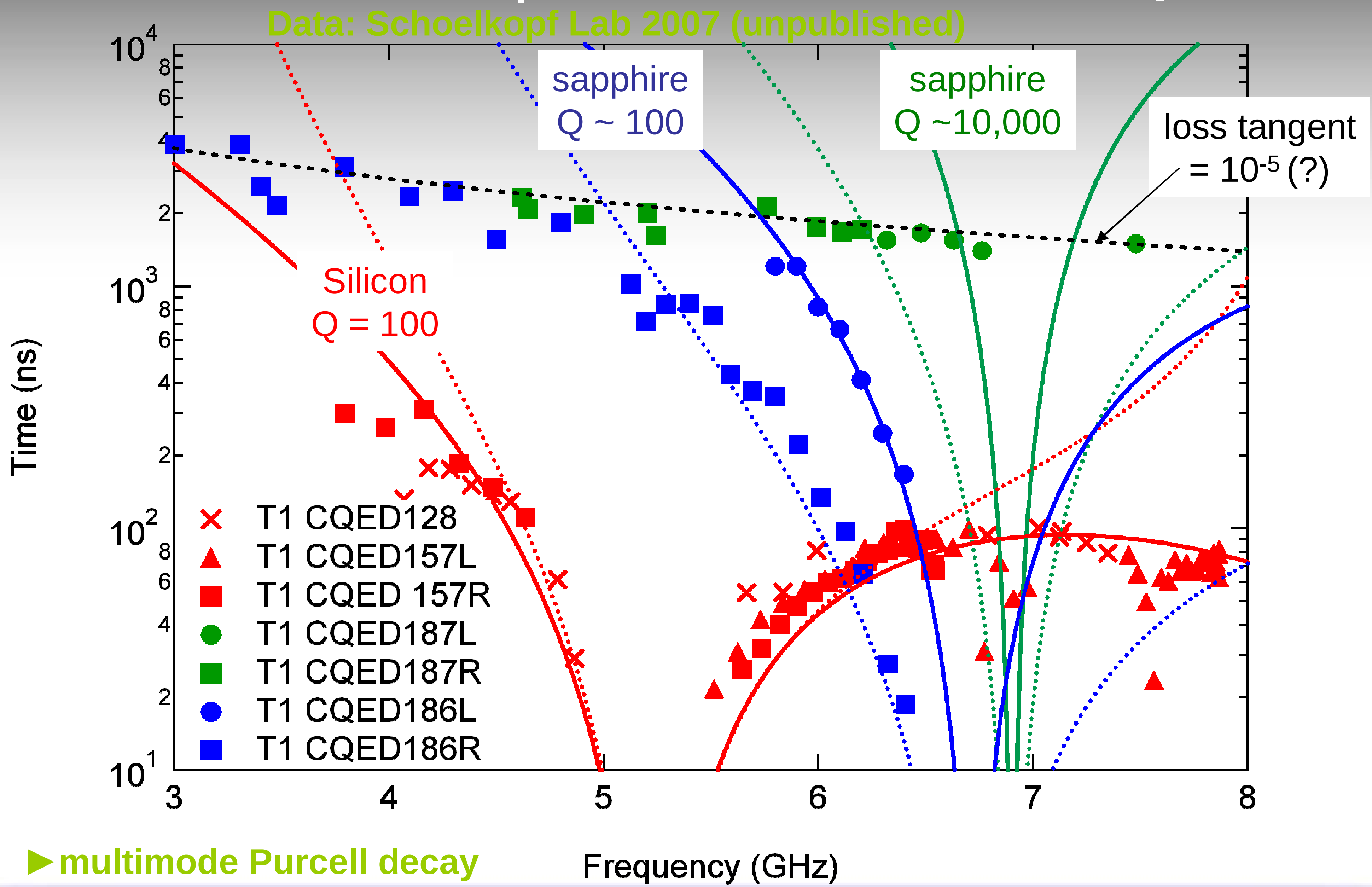
Ramsey experiment

dephasing time

T_2 = 1.75 μs

no echo,
not at flux sweet spot

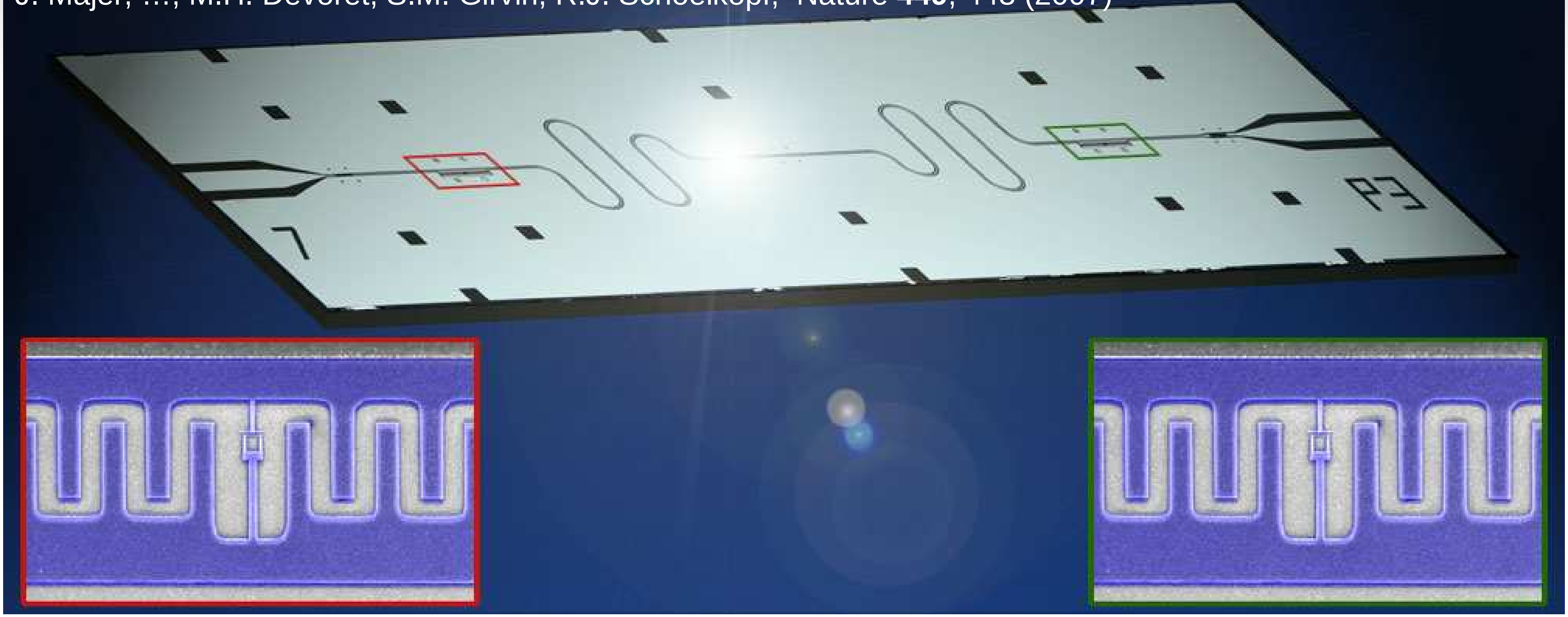
Consistent T_1 times for seven qubits



► multimode Purcell decay

Cavity as a Quantum Bus:
circuit QED with two qubits

Schoelkopf Lab –
J. Majer, …, M.H. Devoret, S.M. Girvin, R.J. Schoelkopf, Nature **449**, 443 (2007)

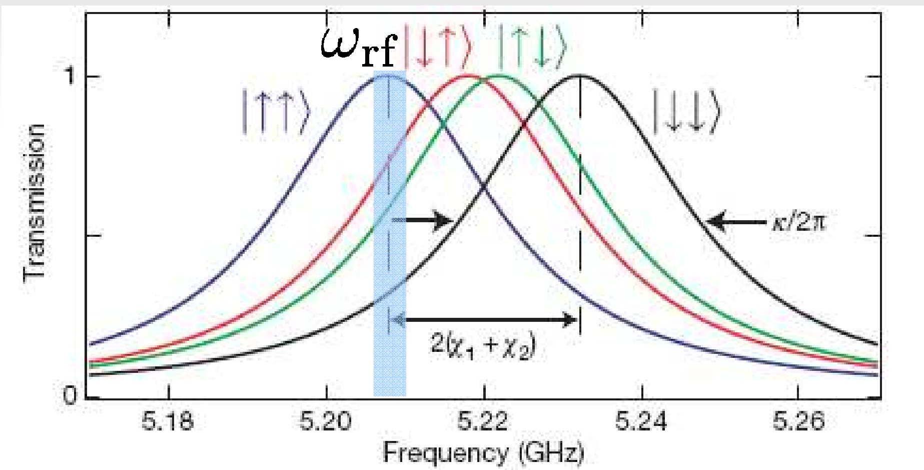


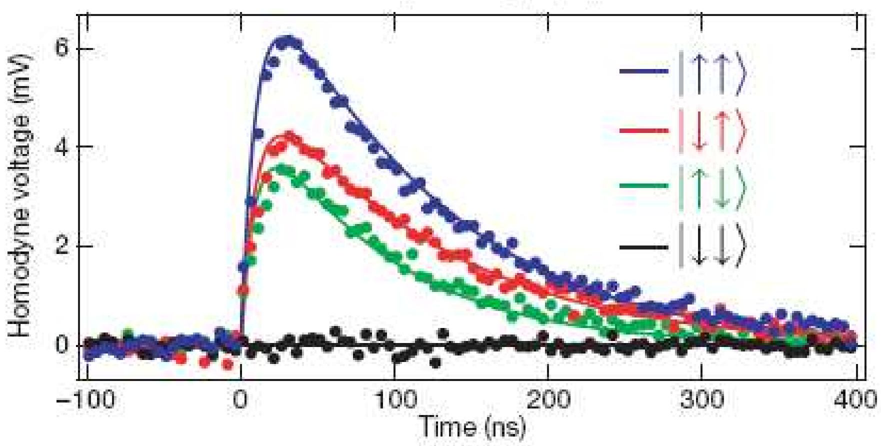
- ► two (several) qubits in resonator
- ► coupling via virtual photons
- ► multiplexed control and readout
- ► resonator as "quantum bus"

similar work: M.A. Sillanpää, J.I. Park, R.W. Simmonds, Nature **449**, 438 (2007)

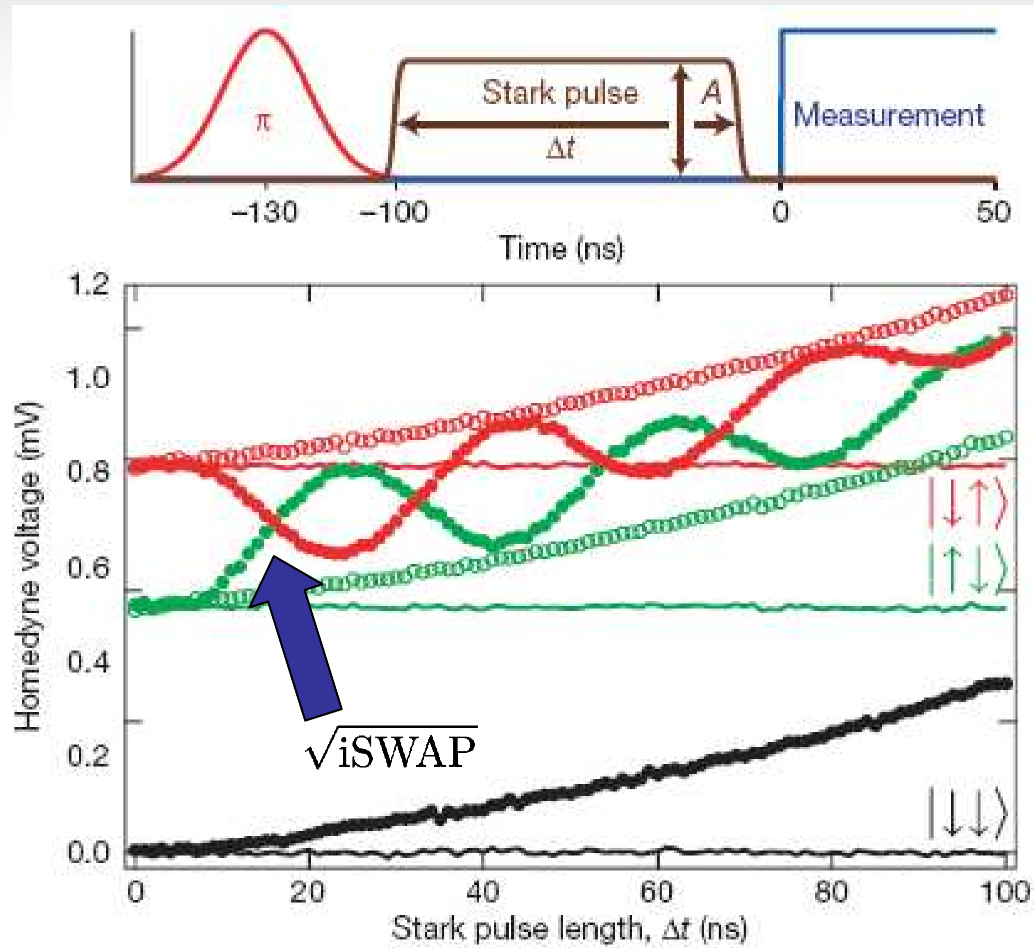
I and 2-qubit gates with the quantum bus

Control and measurement of individual qubits



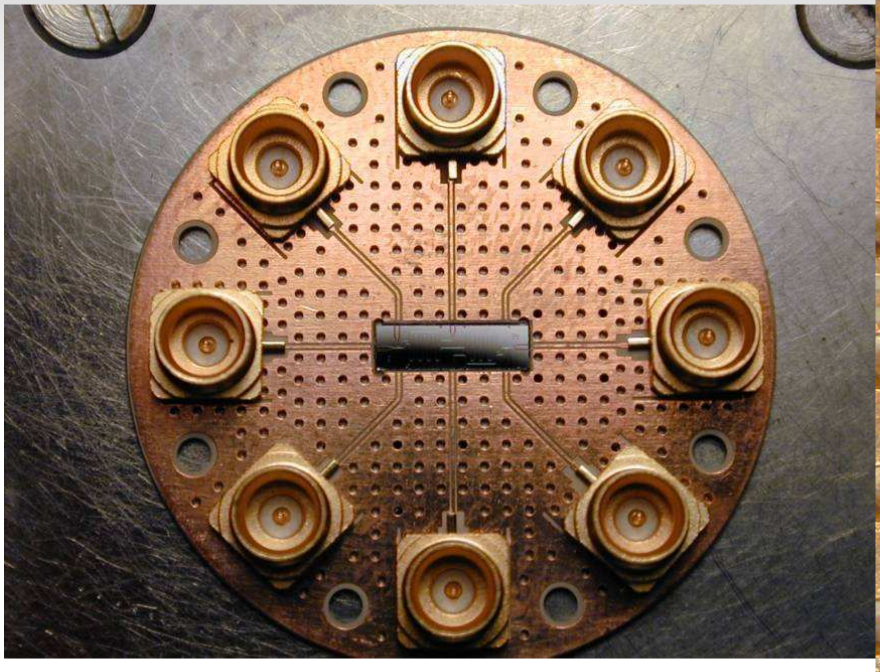


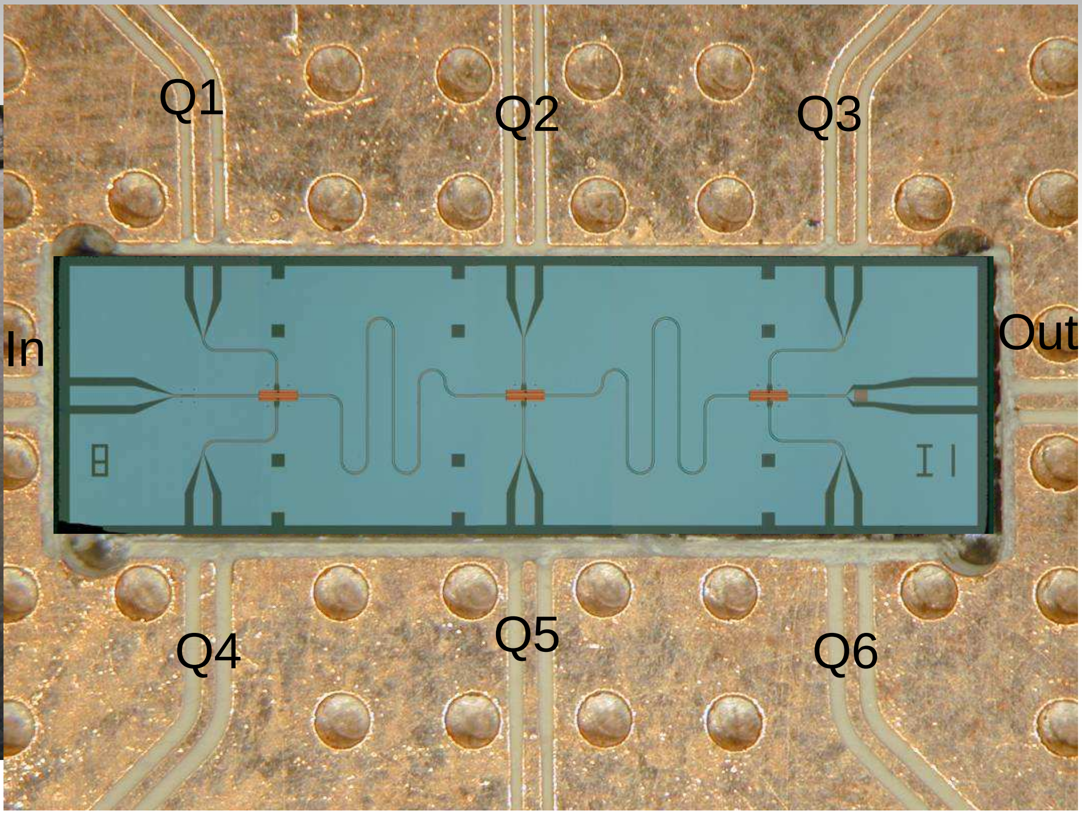
Coherent 2-qubit oscillations



Design for six qubits

coupled on a single bus, with individual flux control





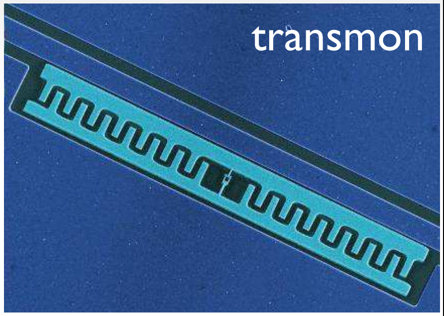
Sample box with
8 x 20 GHz connections

6 flux lines: qubit addressing,
2 flux lines: input/output
for measurement and control

Schoelkopf lab

Summary

- Need to improve coherence in superconducting qubits
  - ► reduce overall noise (materials science)
  - ► reduce sensitivity to noise (sweet spots, new quantum circuits)



- Transmon: optimized CPB by increasing E_J/E_C
  - ► become exponentially insensitive to charge noise!
  - ► retain sufficient anharmonicity (loss only algebraic)
  - ► confirmed in recent experiments (T_1~3μs, T_2~2μs)

- circuit QED with transmons
  - ► one and two-qubit gates
  - ► multiplexed control and readout via the cavity
  - ► quantum optics with circuits