Superconducting circuits: A new platform for quantum optics

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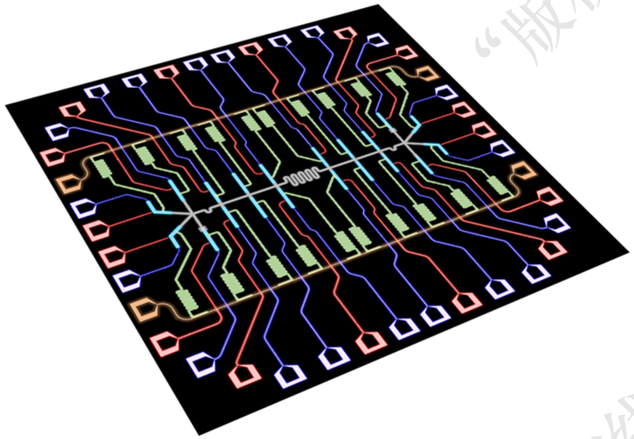
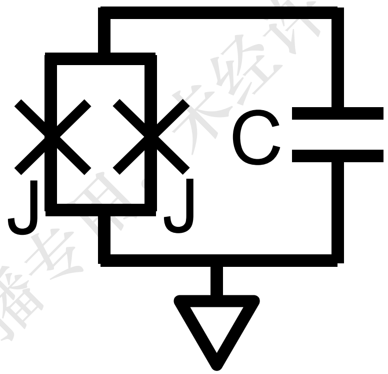
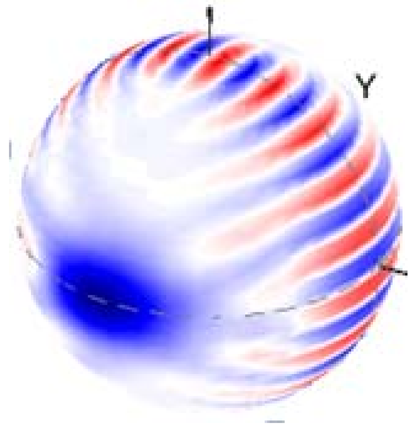






5th West-Lake Photonics Symposium, Nov. 28, 2020, Zhejiang

Outline

(I) Introduction

Fundamentals of superconducting qubits

(II) Experimental platform at Zhejiang University

(III) Quantum Optics Experiments with Superconducting-Qubits

1. Quantum chiral rotation
2. 5-components Schrodinger cat states
3. Control of superradiant and subradiant states
4. Excitation of two atoms with entangled photons

Important Development Related to Quantum information

1984: BB84 Scheme, Bennett and Brassard,
1993: Teleportation, Bennett, PRL 70, 1895
1997: teleportation experiment， A. Zeilinger， Nature 390， 575

1998: Kimble， Science 282,706
1998: D. Boschi et al, PRL 80, 1121

1985: Josephson joints, Clarke et al, PRL 55, 1543
1994: Shor Algorism, P.W. Shor,

2001 IBM did the experiment factored 15 into 3*5， Nature

1996: Grove Search, L.K. Grover,
1999: Made Josephson joints, Tsai et al, Nature 398, 786
2004: Josephson joints +Cavity, Schoelkopf et al, PRA 69, 062320

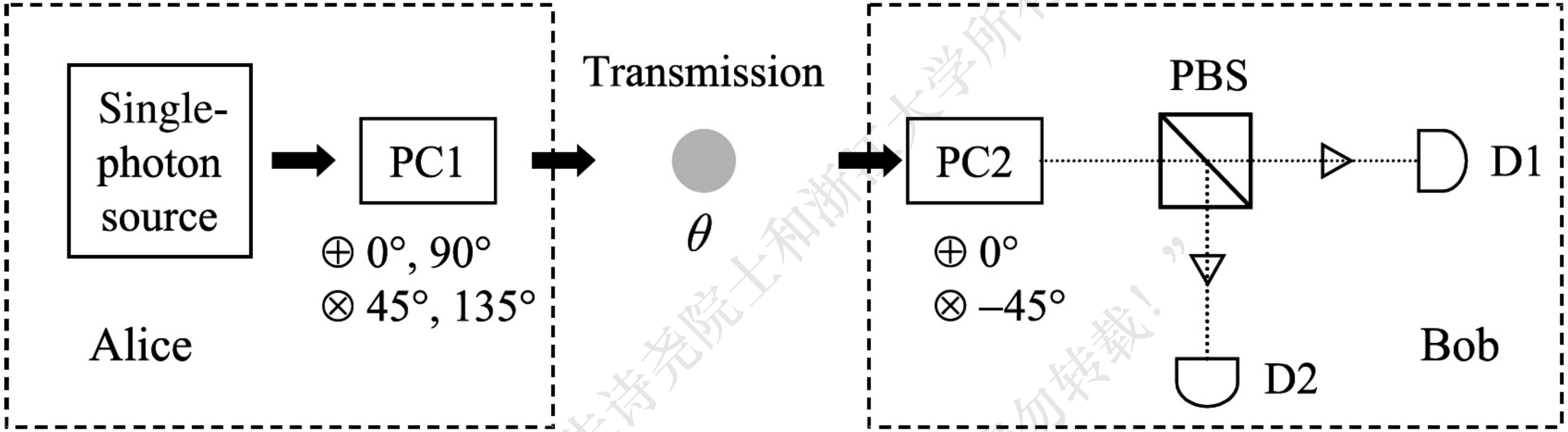
2007: Josephson joints with very long coherent time
J. Q. You (游建強), PRB 2007/4; and J. Koch, PRA 2007/10)

1945 (1930): Atomic clock (2000年1秒) , I. Rabi (1944 Nobel Prize)
1955: First atomic clock, Louis Essen and Jack Parry

1989年Nobel Prize，Ramsey

Optic Clock

BB84 Schem: quantum key distribution



Alice's bit	0	1	1	0	1	0	0	1
Alice's basis	+	+	X	+	X	X	X	+
Alice's polarization	↑	→	↖	↑	↖	↗	↗	→
Bob's basis	+	X	X	X	+	X	+	+
Bob's measurement	↑	↗	↖	↗	→	↗	→	→
Public discussion								
Shared Secret key	0		1			0		1

Bennett and Brassard suggested in 1984年

Proc. Int. Conf. Comput. Syst. Signal Process

Shor算法：实验演示

NATURE | VOL 414 | 20/27 DECEMBER 2001

Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

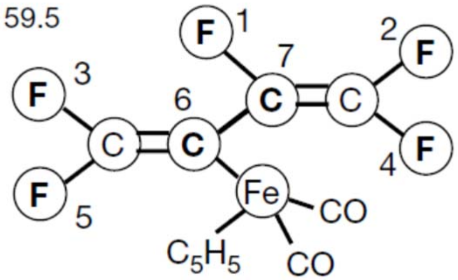
Lieven M. K. Vandersypen*†, Matthias Steffen*†, Gregory Breyta*, Costantino S. Yannoni*, Mark H. Sherwood* & Isaac L. Chuang*†

* *IBM Almaden Research Center, San Jose, California 95120, USA*
† *Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA*

7量子比特系统：

$15 = 3 \times 5$

i	$\omega_i/2$	$T_{1,i}$	$T_{2,i}$	J_{7i}	J_{6i}	J_{5i}	J_{4i}	J_{3i}	J_{2i}
1	−22052.0	5.0	1.3	−221.0	37.7	6.6	−114.3	14.5	25.16
2	489.5	13.7	1.8	18.6	−3.9	2.5	79.9	3.9	
3	25088.3	3.0	2.5	1.0	−13.5	41.6	12.9		
4	−4918.7	10.0	1.7	54.1	−5.7	2.1			
5	15186.6	2.8	1.8	19.4	59.5				
6	−4519.1	45.4	2.0	68.9					
7	4244.3	31.6	2.0						



Grover's algorithm: quantum search

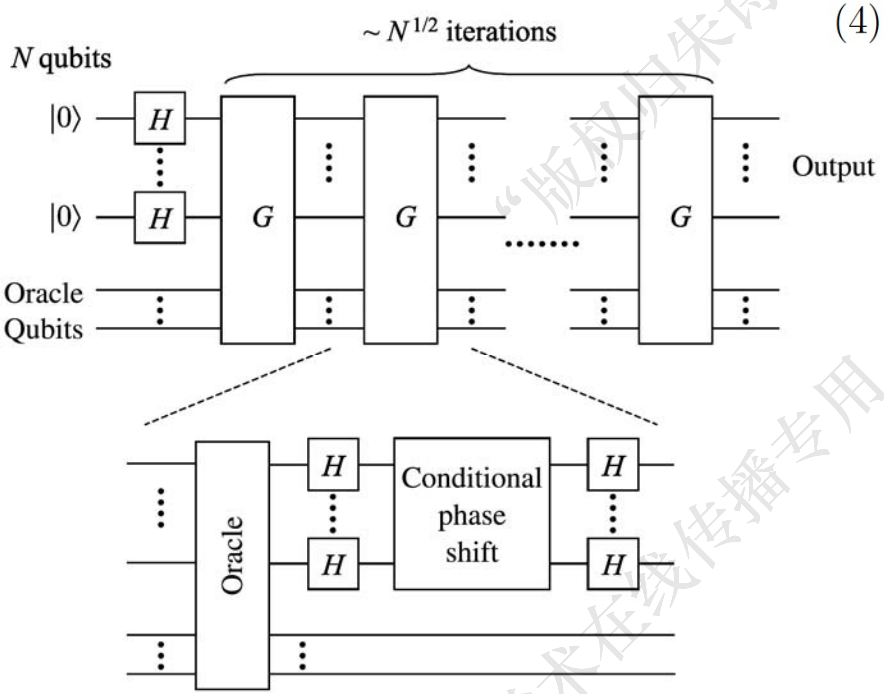
L.K. Grover: *A fast quantum mechanical algorithm for database search*,
Proceedings, 28th Annual ACM Symposium on the Theory of Computing, p. 212, May **1996**.

$$|\psi_1\rangle = \left(\frac{1}{\sqrt{2}}\right)^N (|0\rangle_1 + |1\rangle_1)(|0\rangle_2 + |1\rangle_2)\cdots(|0\rangle_N + |1\rangle_N)$$

$$= \frac{1}{N_{\text{data}}{}^{1/2}} \sum_{x=0}^{N_{\text{data}}-1} |x\rangle,$$

The Grover operator employs four steps:

(1) apply the **oracle** operator;
(2) apply a Hadamard gate to each qubit in the register;
(3) apply a conditional phase shift;
(4) apply a Hadamard gate to each qubit in the register.



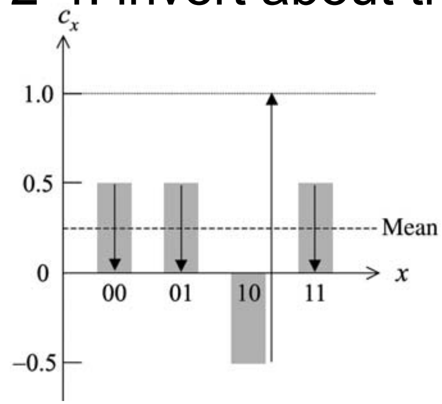
oracle: $|x\rangle \rightarrow (-1)^{f(x)}|x\rangle,$

where $f(x)$ is a function defined by:

$f(x) = 1$ if x is the solution,

$f(x) = 0$ otherwise.

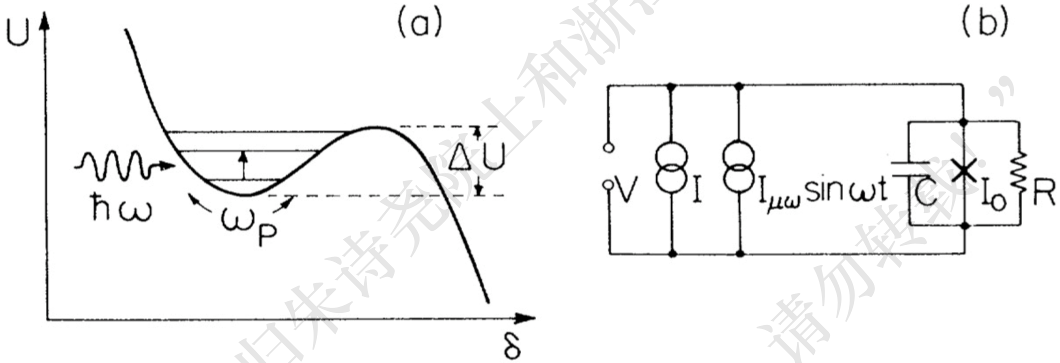
steps 2-4: invert about the mean



Superconducting quantum qubits

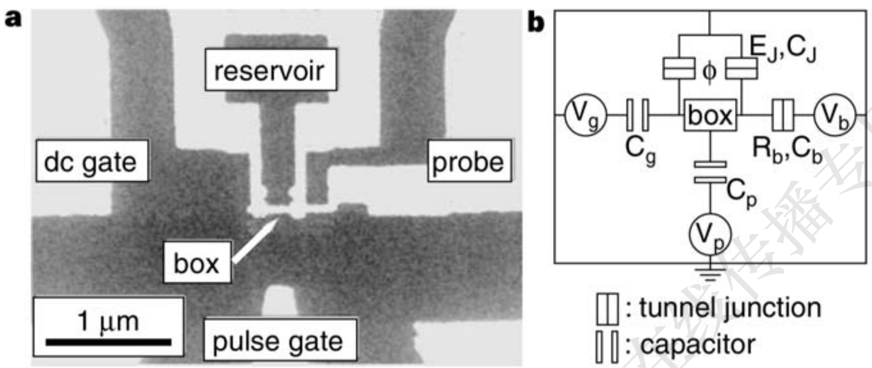
Josephson joints + Cavity

Quantized levels of Josephson junction



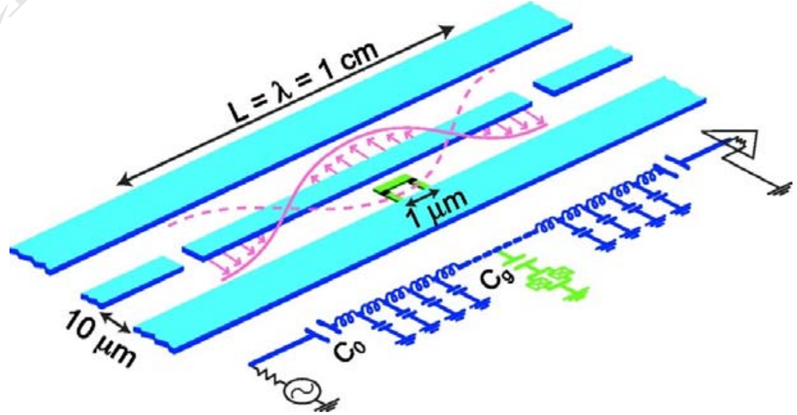
Clarke et al, PRL 55, 1543 **(1985)**

Qubit in a Cooper pair box



Tsai et al, Nature 398, 786 **(1999)**

Cavity QED with coplanar resonator

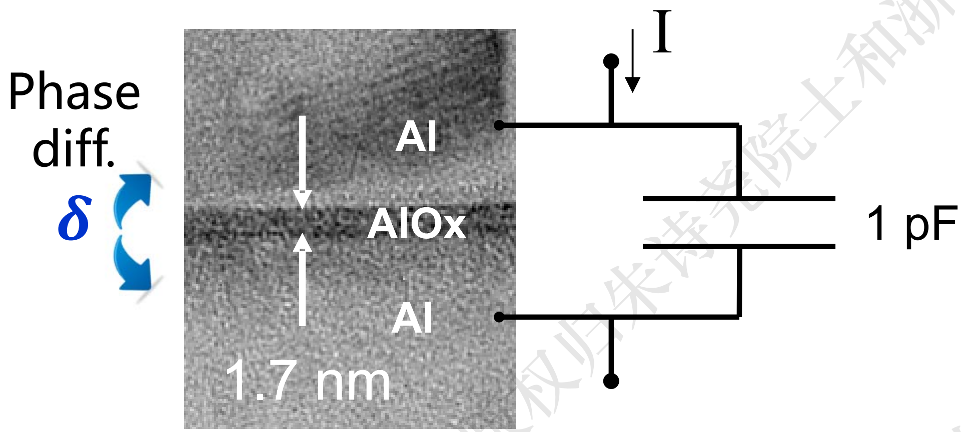


Schoelkopf et al, PRA 69, 062320 (2004)

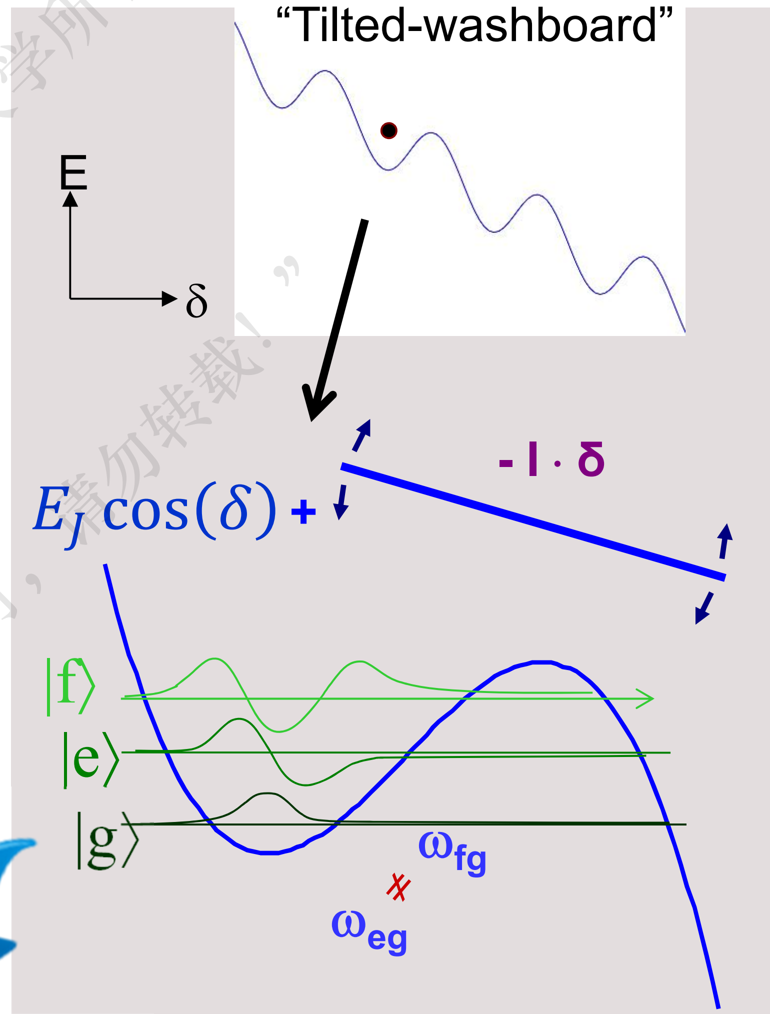
Josephson junction—the heart of a qubit

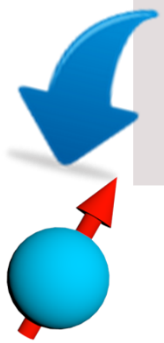
- Josephson junction:

<u>nonlinear inductor</u>



$$I_J = I_c \sin(\delta)\,, \qquad V = \frac{\Phi_0}{2\pi}\frac{d\delta}{dt}$$





Nonlinear $\widehat{L}$C resonator:

Stores quantized EM fields

|g⟩ (low energy), |e⟩ → |0⟩, |1⟩ of a qubit

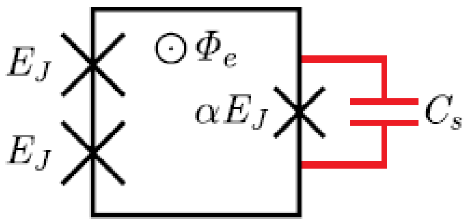
Artificial atom:
level separation ~6 GHz,
~2GHz tunability

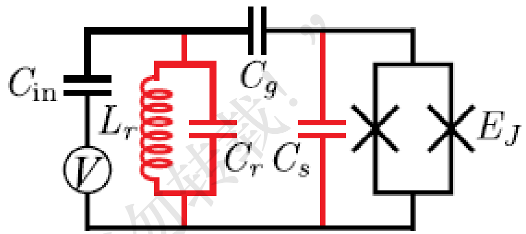
Qubit with reduced noise

Coherent time：0.01ms - 0.1ms；3-4 order longer.

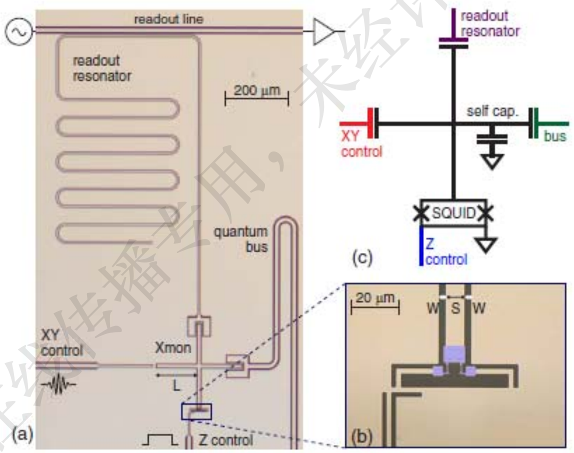
C-shunt flux qubit
J. Q. You et al., PRB **2007**.

Transmon qubits (*C*-shunt Cooper-pair box)
J. Koch et al., PRA **2007** (Yale组).





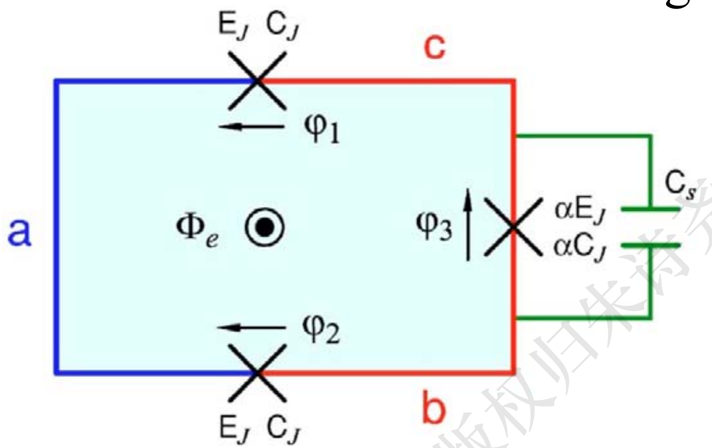
Xmon qubits：similar to deformed Transmon
R. Barends et al., PRL 2013 (UCSB/Google组).



Make quantum supremocy and quantum simulation possible.

Qubit with reduced noise

Make the coherent time 3 order longer

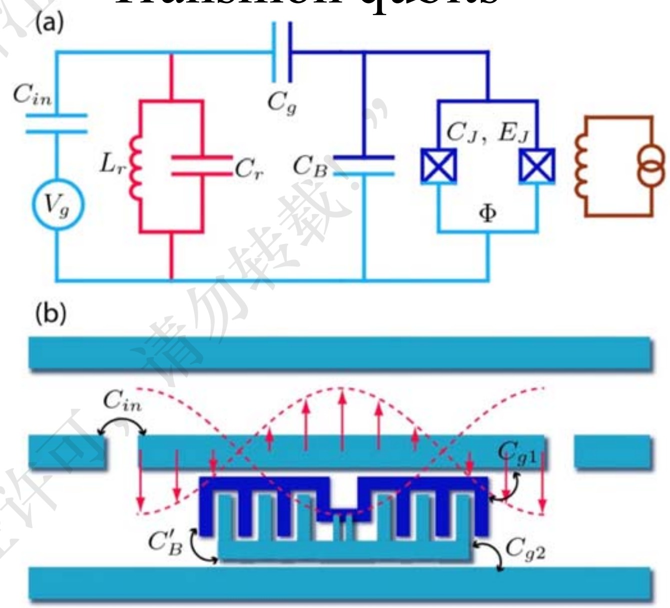


C-shunt flux qubit

You et al, PRB 75, 140515 (2007)

(Received 3 April 2007; published 27 April 2007)

Transmon qubits



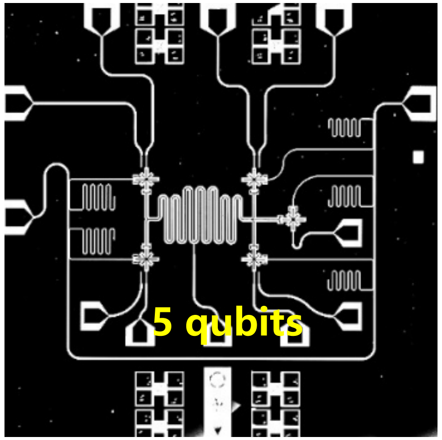
Koch et al, PRA 76, 042319 (2007)

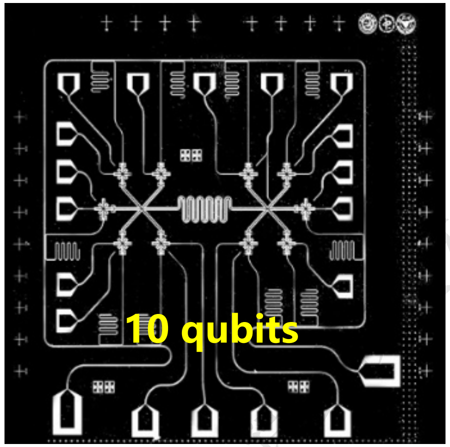
(Received 22 May 2007; published 12 October 2007)

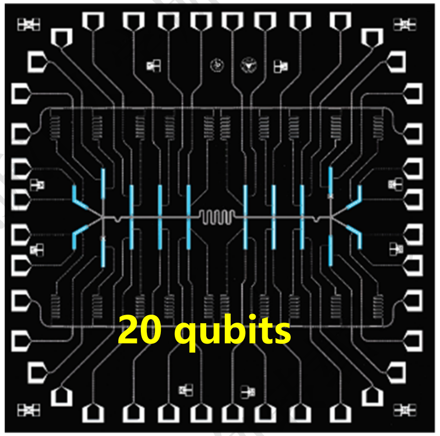
(II) Superconducting quantum qubits as an experiment platform in Zhejiang University

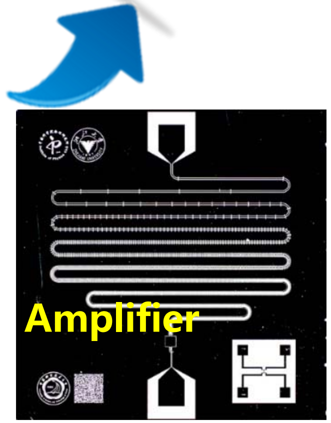
Characterizations

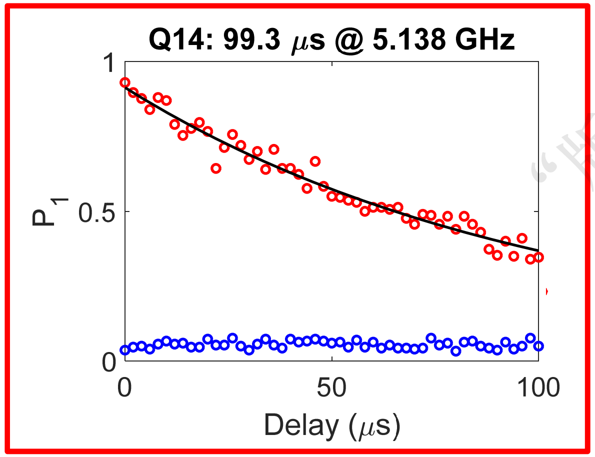
more qubits ...











✓ Freq. tunable qubits: Best T_1 close to 100 μs @ 5GHz,
about 20 – 50 μs on average,
T_2 above 10 μs (5 – 10 μs on average).*

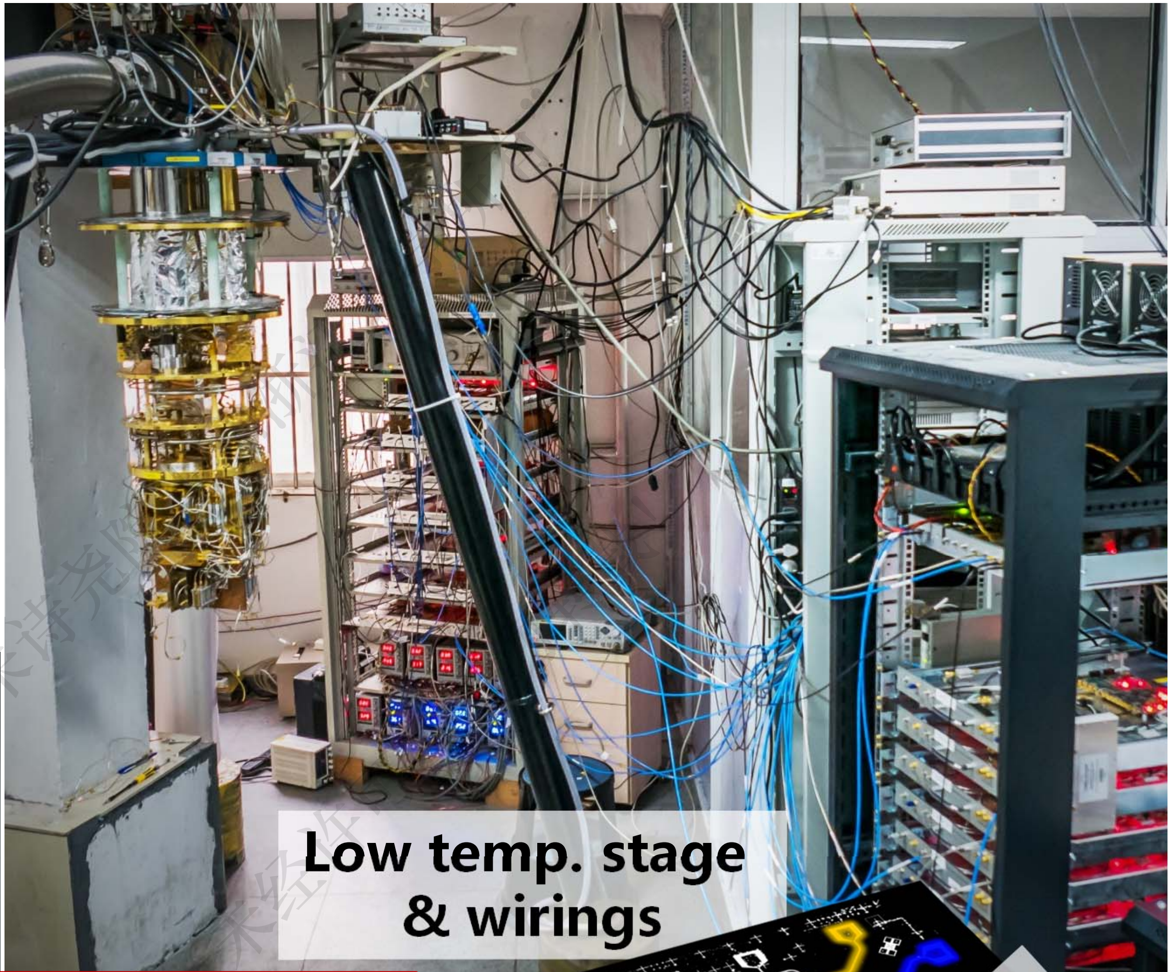
⇔ **Gate times 10-100 ns**

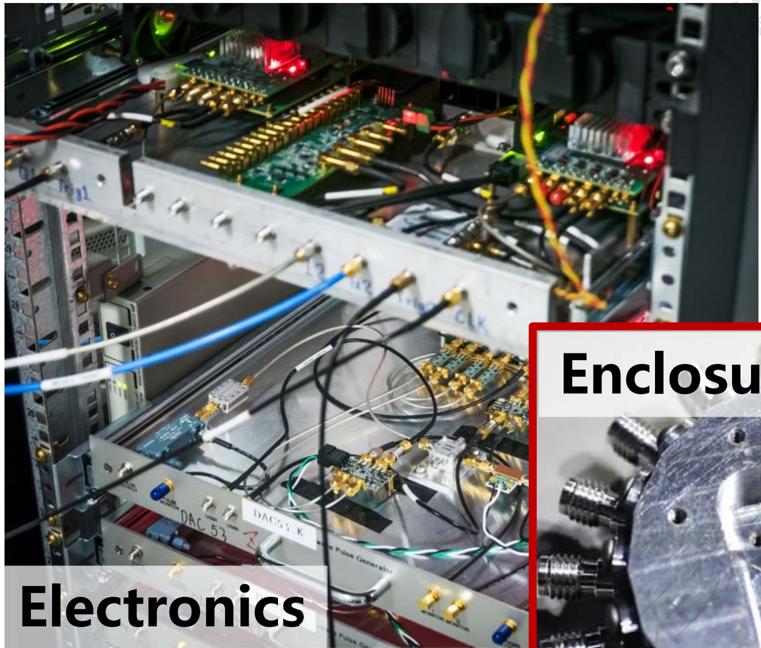
✓ Single-qubit gate fidelity above 99.9% [H. Wang group, PRL 119, 180511 (2017)].

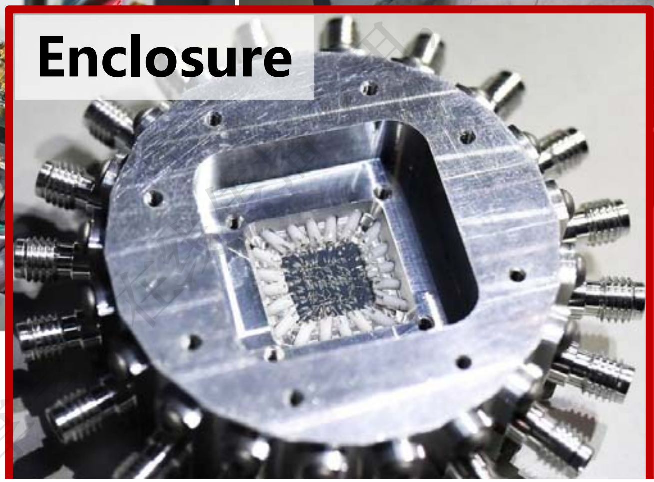
|ZJU-QLab⟩

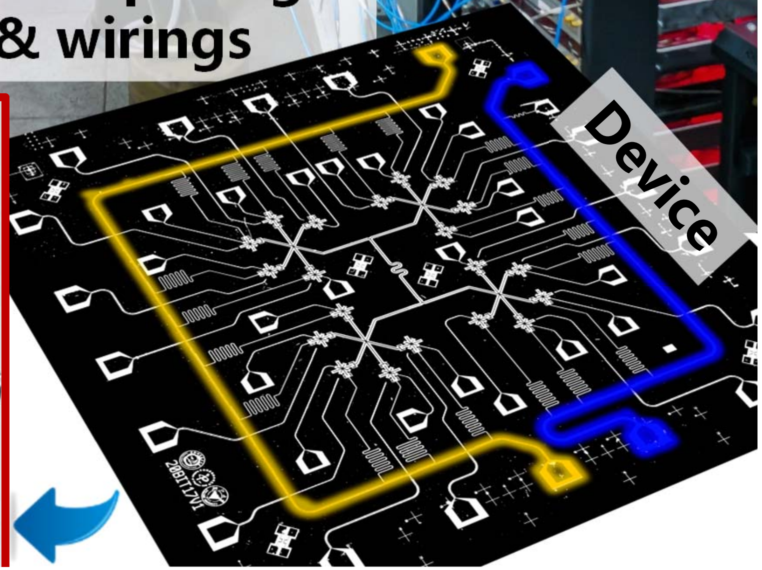
- ✓ >20-Q device
- ✓ Multi-port enclosure
- ✓ Home-made electronics
- ✓ Large 10mK space

⇒**Powered by Q.E.**

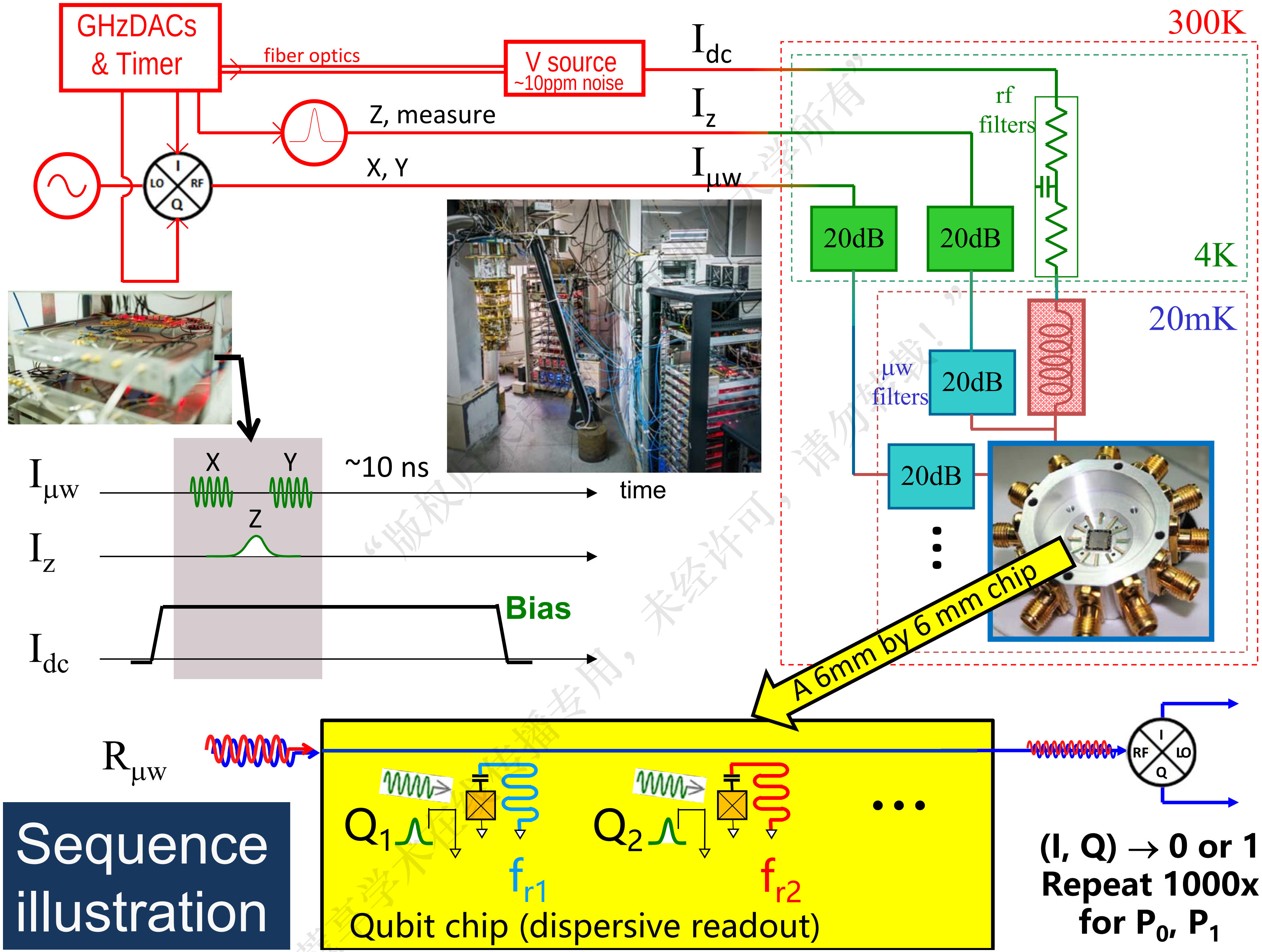








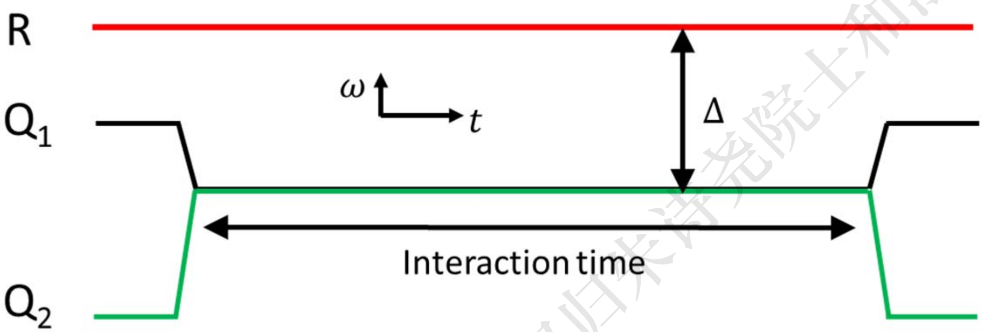
Sequence illustration



Two-qubit interaction

- **Interaction between two qubits enabled by bus resonator**

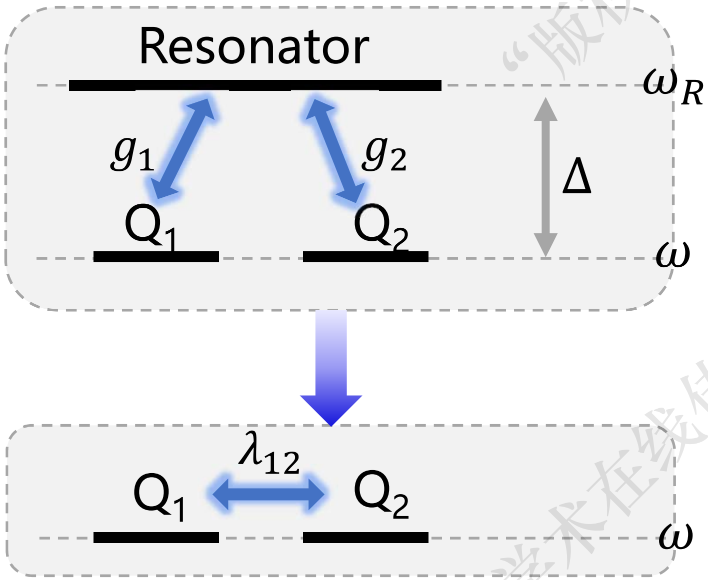
$$H = \sum_{j=1}^{2} \omega_j \sigma_j^+ \sigma_j^- + \omega_R a^\dagger a + \sum_{j=1}^{2} g_j (a\sigma_j^+ + a^\dagger \sigma_j^-),$$

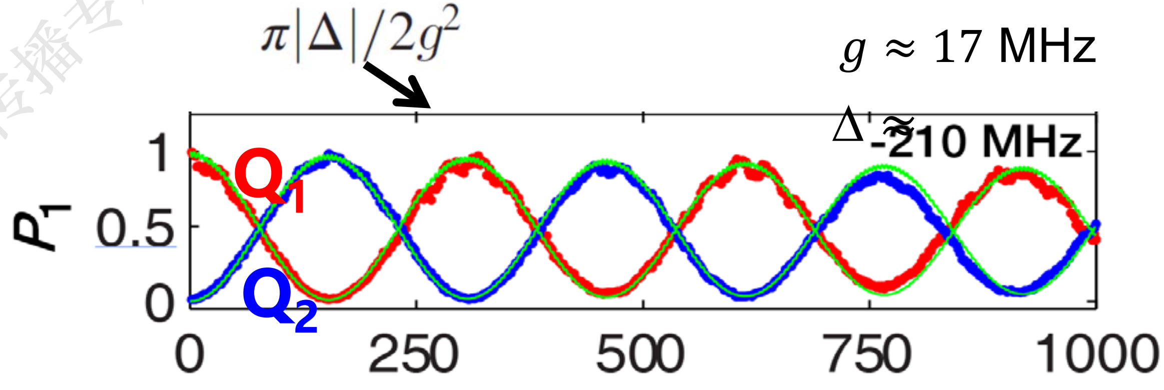


- Resonator in vacuum state
- $\omega_1 = \omega_2 = \omega$, rotating frame
- $\Delta \gg g_1, g_2$

$$H_{eff} = \sum_{j=1}^{2} \lambda_j \sigma_j^+ \sigma_j^- + \lambda_{12}(\sigma_1^+ \sigma_2^- + \sigma_1^- \sigma_2^+),$$

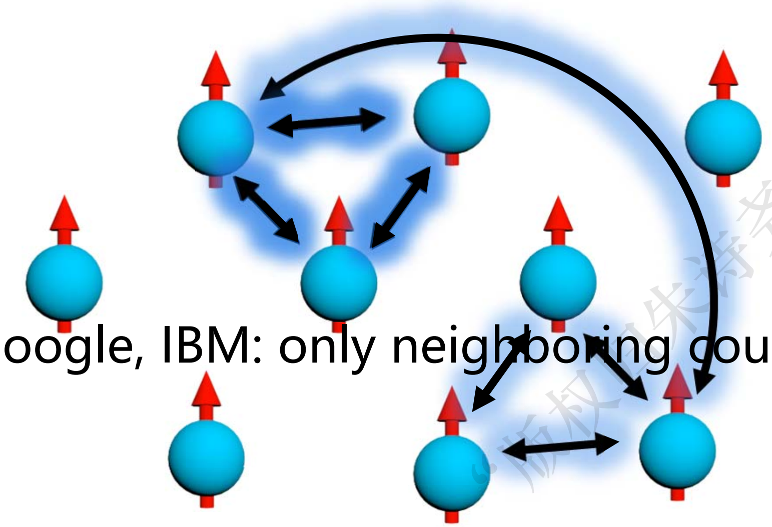
where $\lambda_j = \frac{g_j^2}{\Delta}, \lambda_{12} = \frac{g_1 g_2}{\Delta}$.



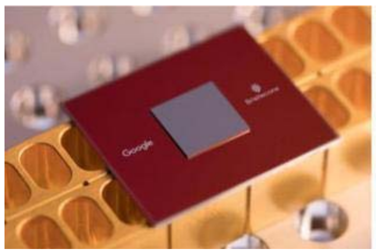


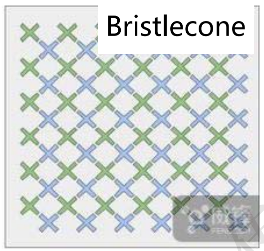
Circuit QED with many qubits (atoms)

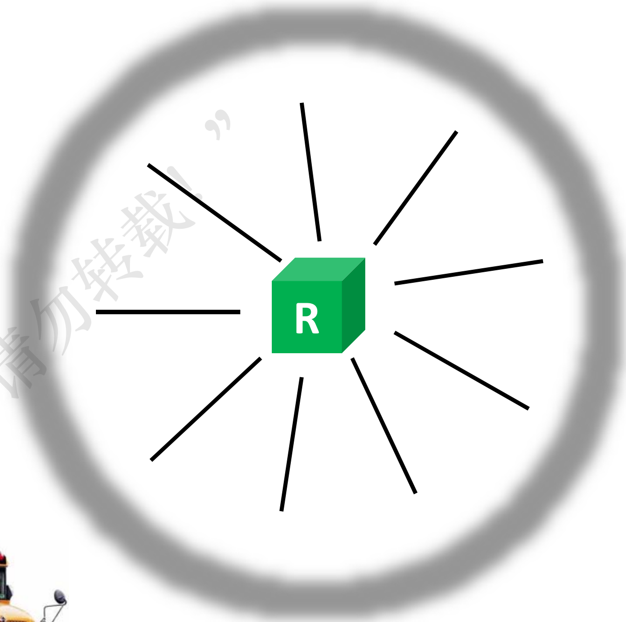
✓ Wirings that can target various combinations of of qubits



Google, IBM: only neighboring couplings







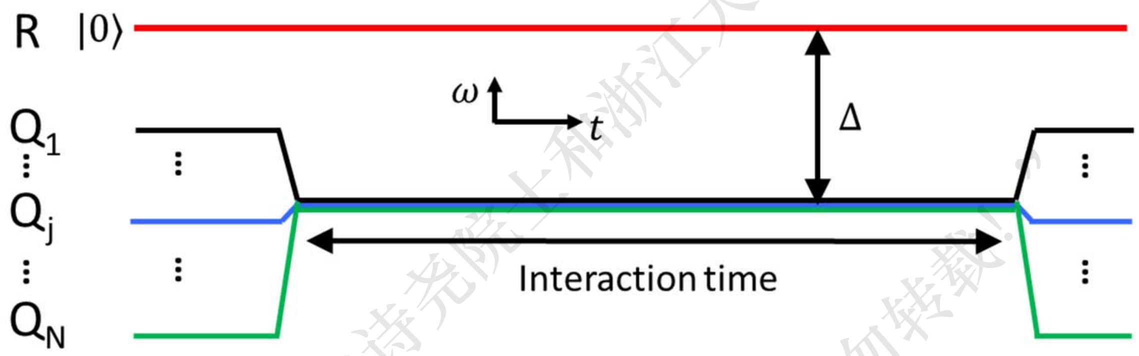
Interaction mediated

by bus resonator R

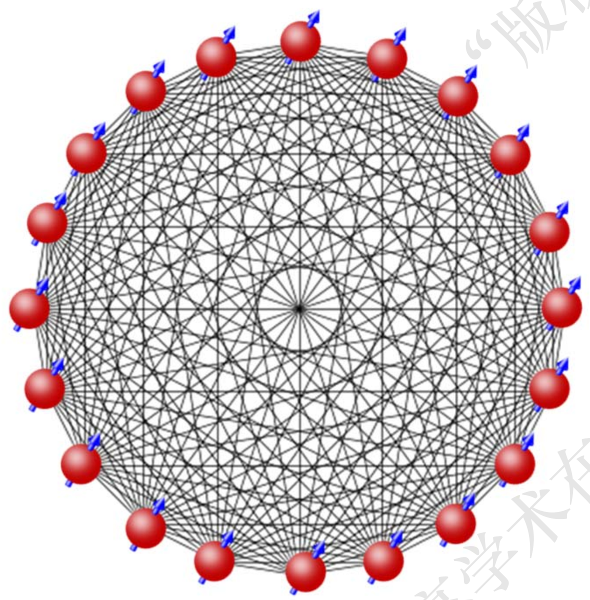
✓ Two-qubit and collective multiqubit interactions *(see next)*

Multiqubit interactions

- **Collective multiqubit interactions enabled by bus resonator**



- **Full-connectivity**

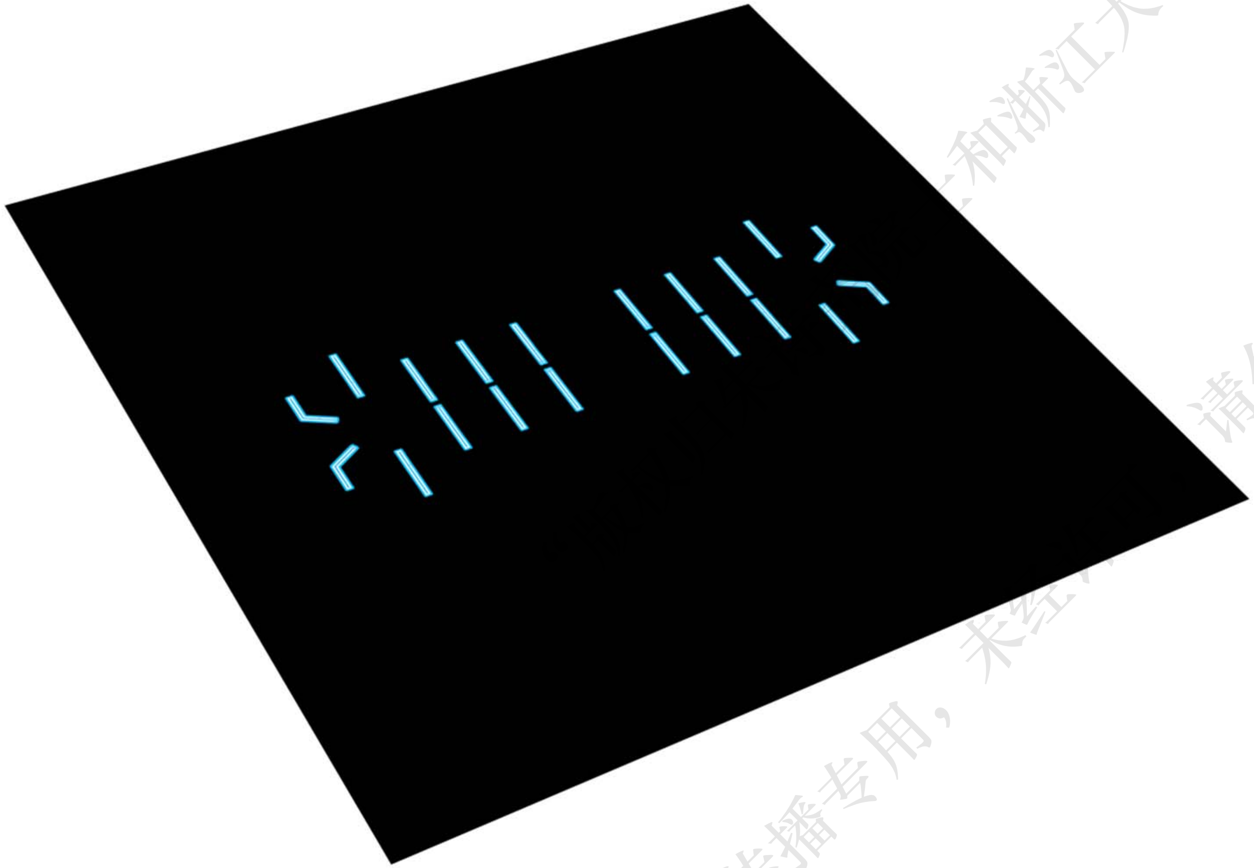


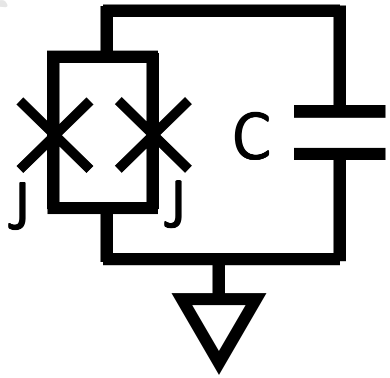
$$H_{eff} = \lambda \sum_{j=1}^{N} \sigma_j^+ \sigma_j^- + \sum_{i<j} \lambda(\sigma_i^+ \sigma_j^- + \sigma_j^+ \sigma_i^-)$$

- Uniform coupling strength g, $\lambda = g^2/\Delta$

Layout of the device

- Transmon Qubit × 20





T1: ~30 μs

T2: ~10 μs @ sweet point

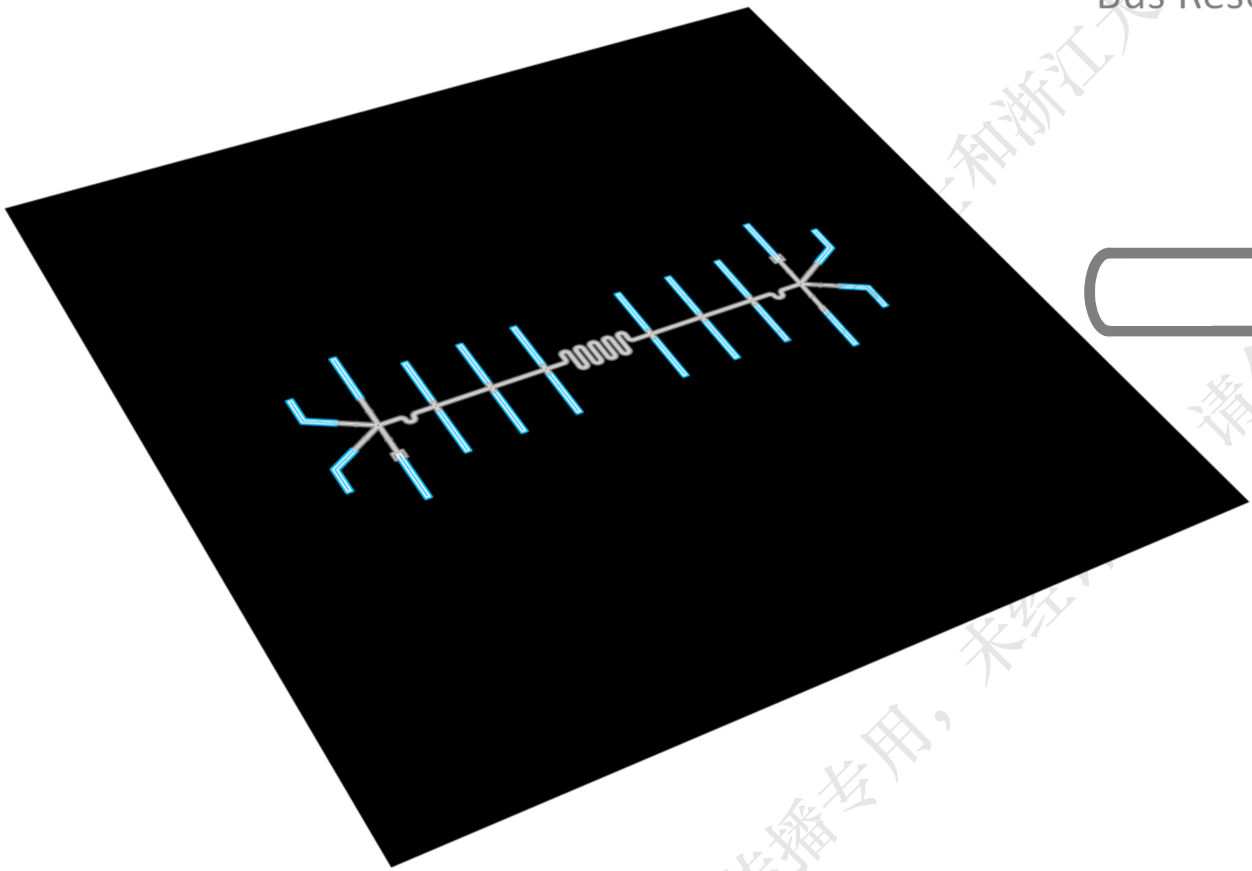
f_{sweet}: ~5.7 GHz (max. freq.)

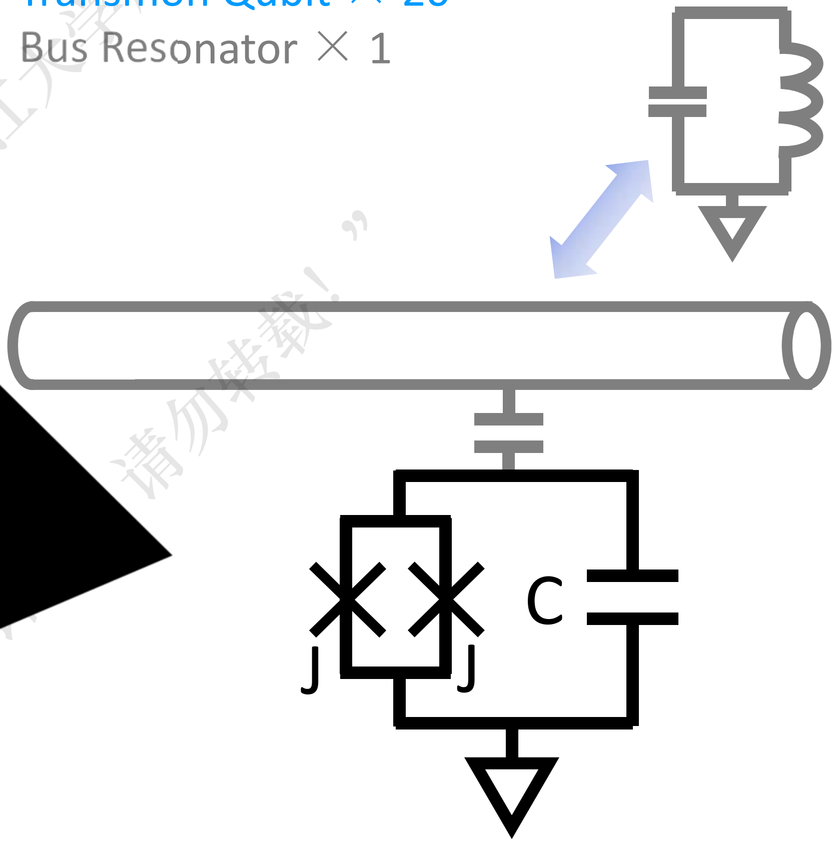
$\eta/2\pi$: ~-240 MHz (nonlin.)

E_J/E_C: ~90

Layout of the device

- Transmon Qubit × 20
- Bus Resonator × 1

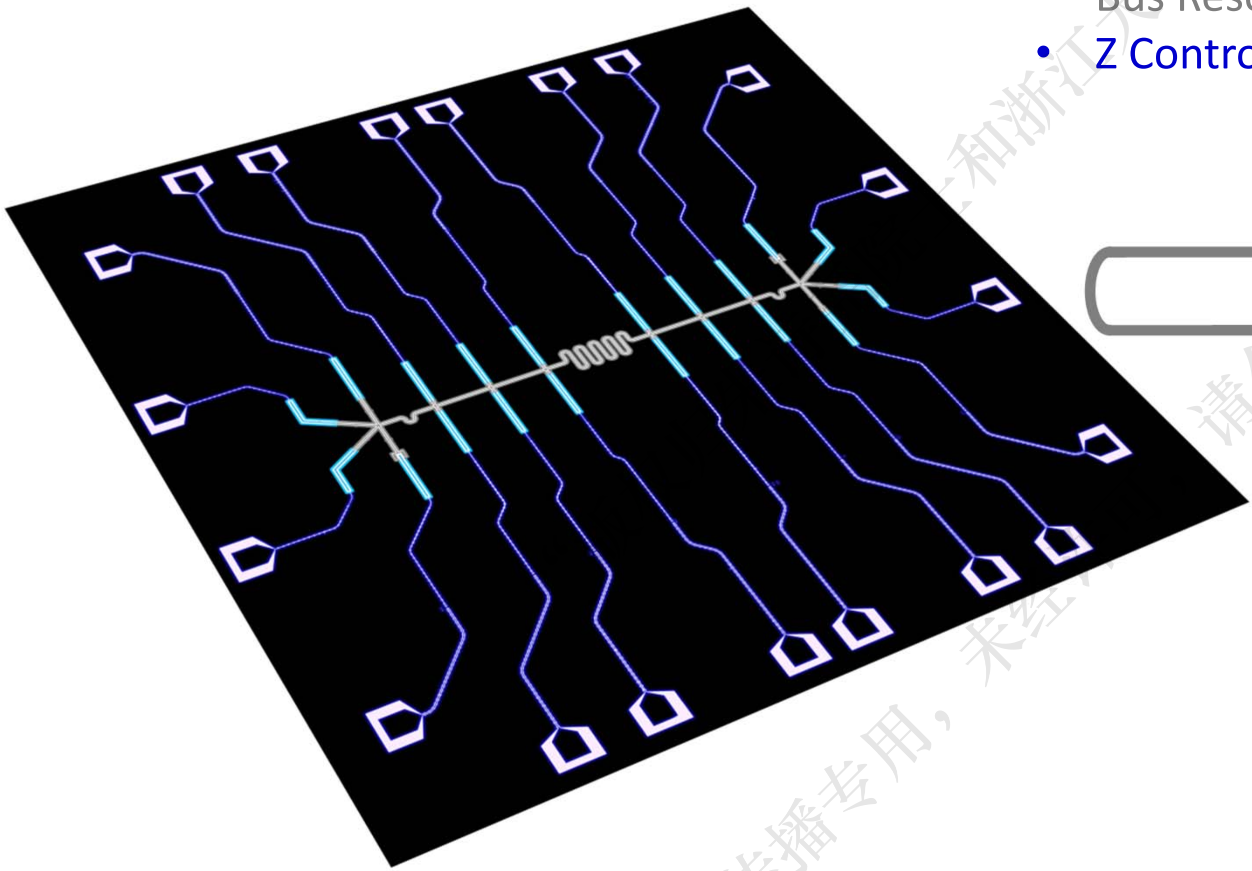


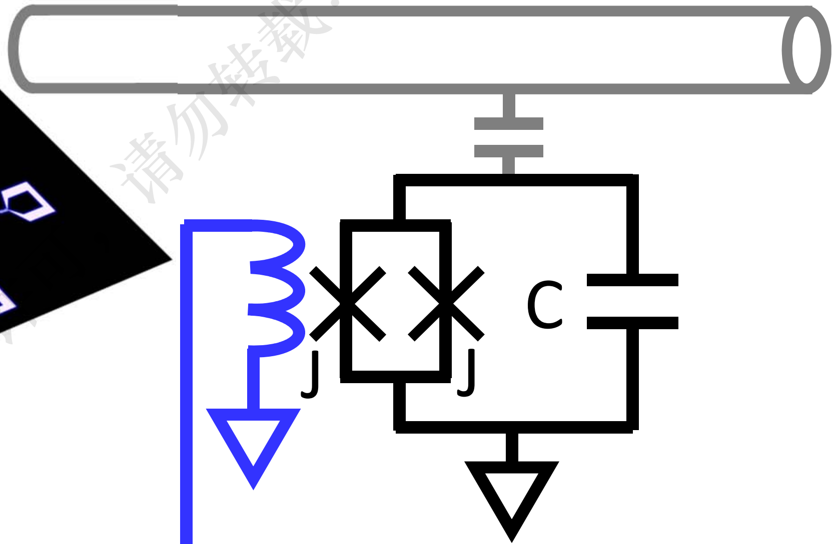


f_R: ~5.5 GHz
$g/2\pi$: ~27 MHz

Layout of the device

- Transmon Qubit × 20
- Bus Resonator × 1
- Z Control Line × 20

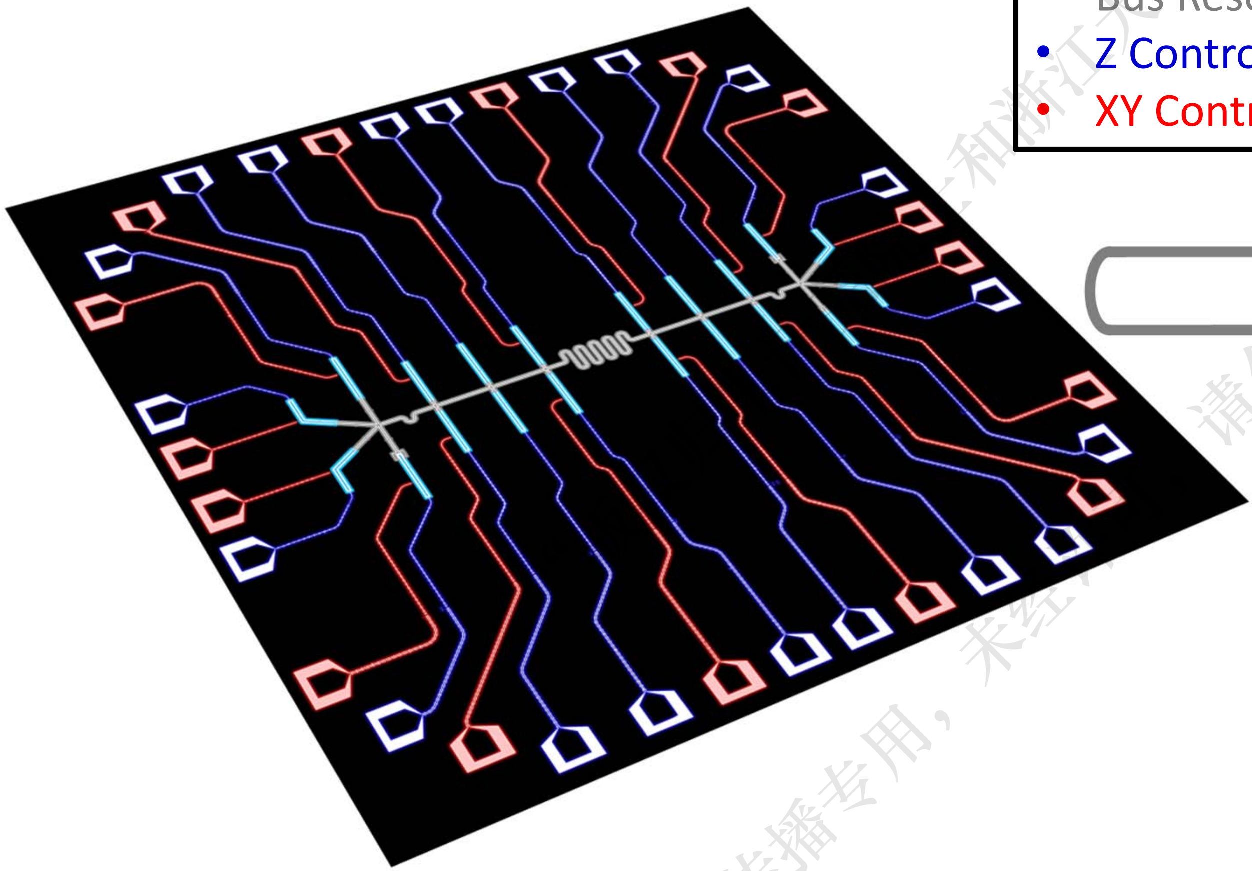


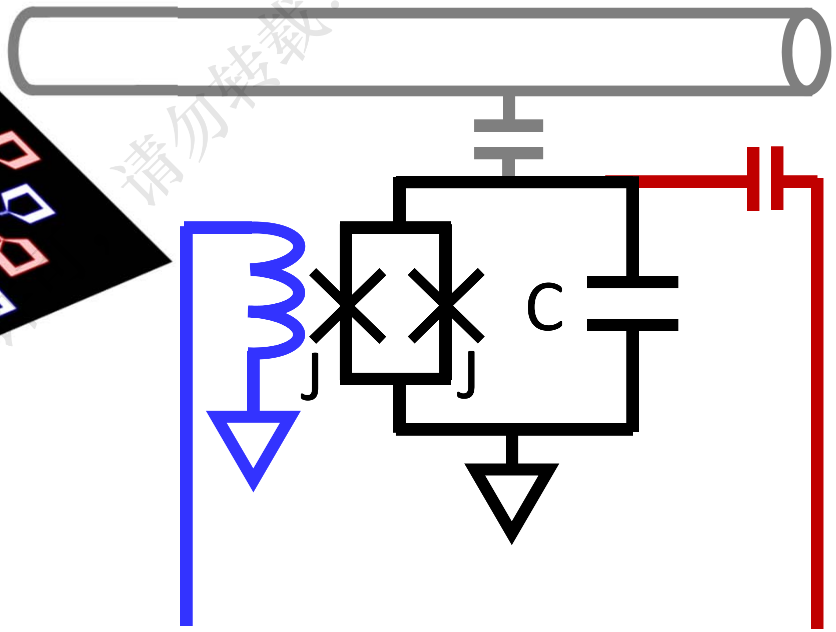


Tunable range: ~2 GHz

Layout of the device

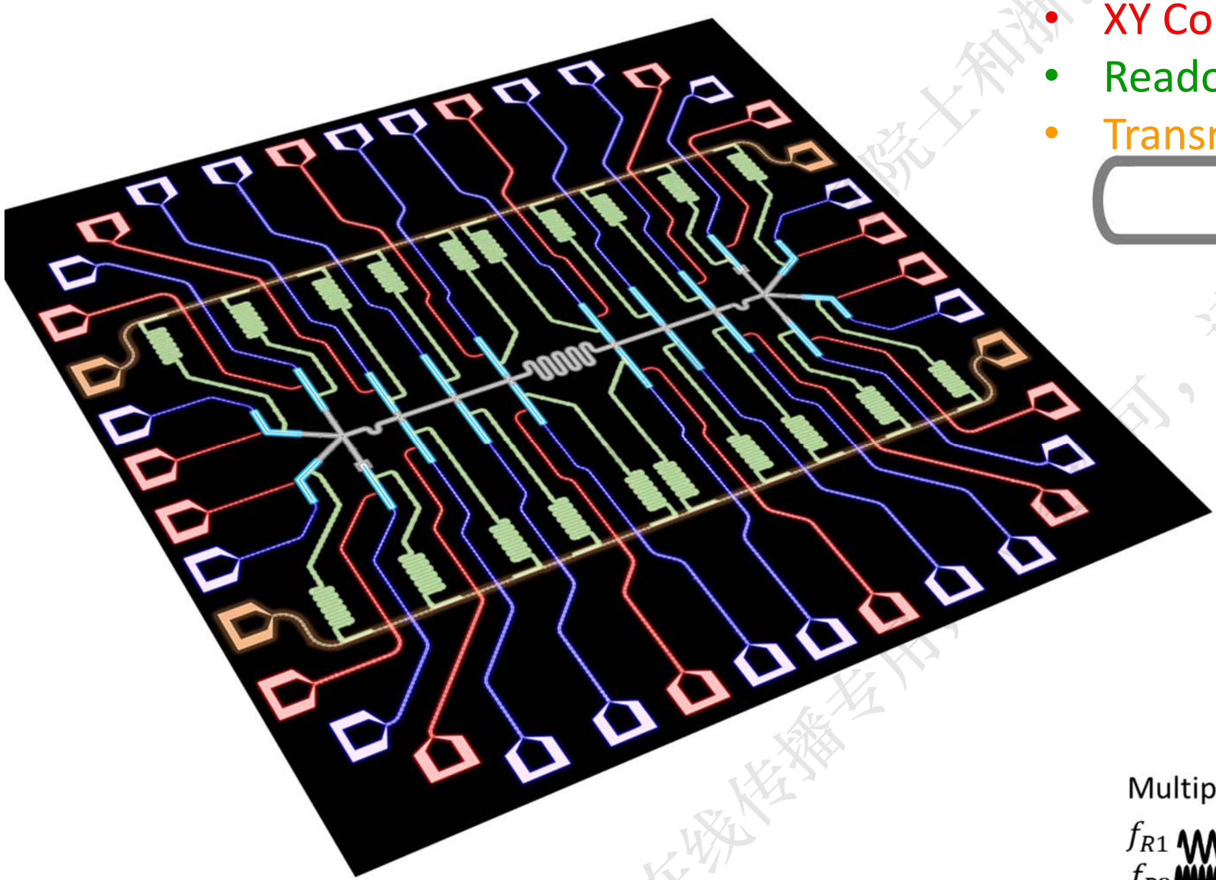
- Transmon Qubit × 20
- Bus Resonator × 1
- Z Control Line × 20
- XY Control Line × 16

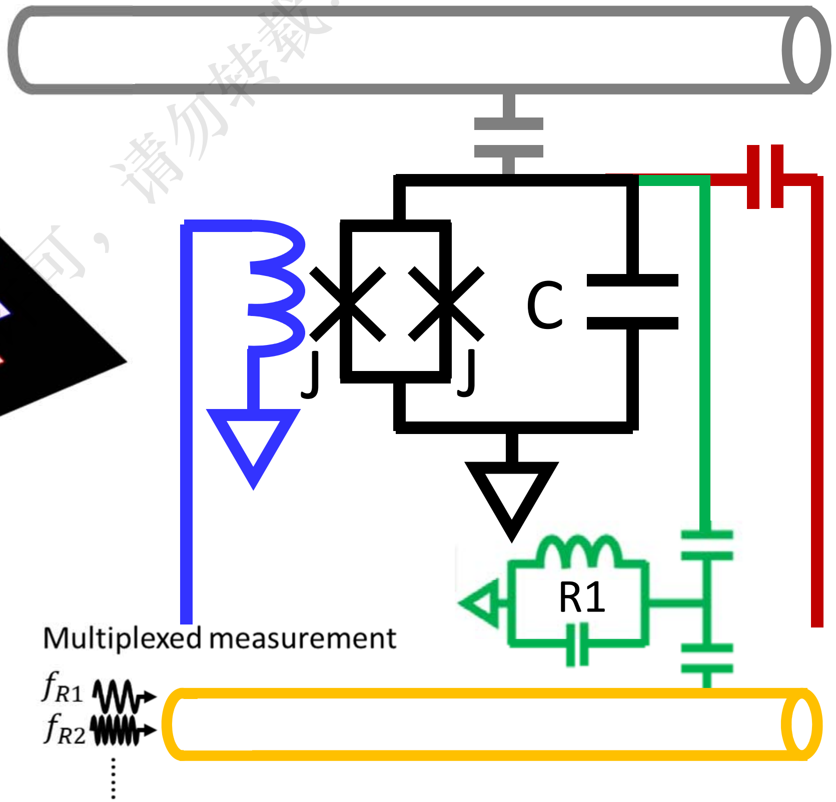




Layout of the device

- Transmon Qubit × 20
- Bus Resonator × 1
- Z Control Line × 20
- XY Control Line × 16
- Readout Resonator (RR) × 20
- Transmission Line × 2





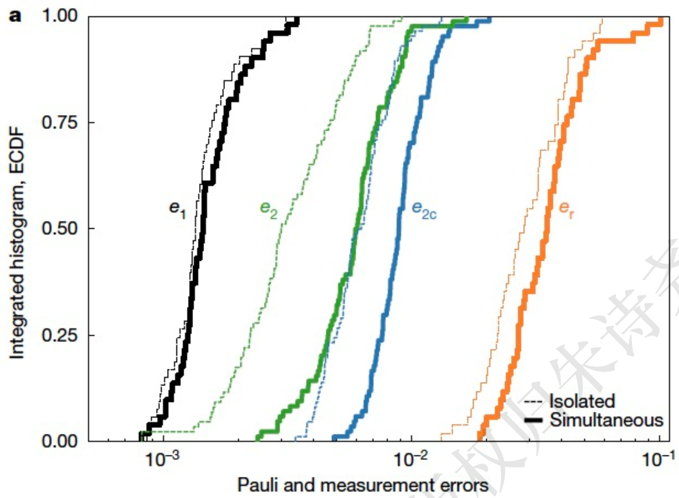
f_{RR}: ~[6.5,6.8] GHz

$g_{RR}/2\pi$: ~40 MHz

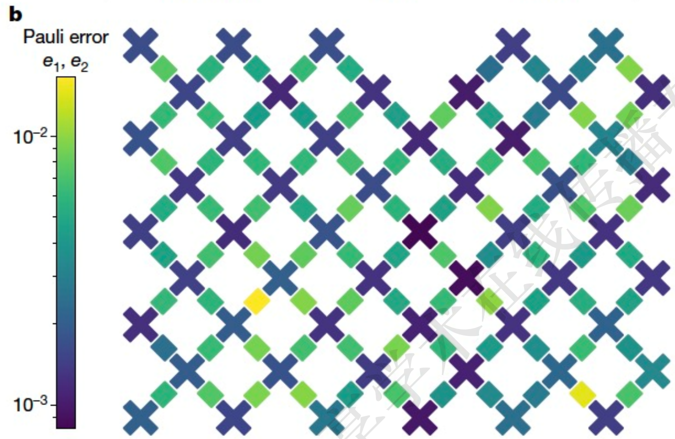
10 qubits per line

Current Quantum Computing Situation

Google 53-qubit sycamore quantum processor



Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



Quantum Supremacy

Matinis's group

Nature 574, 505 (2019)

Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years.

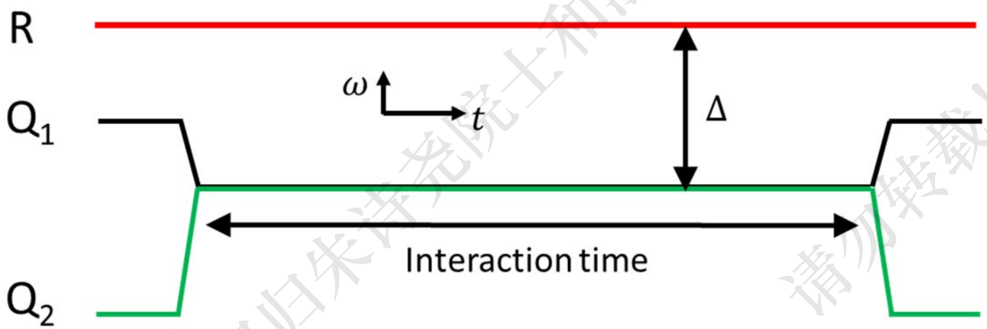
Fidelity ~ 0.1%

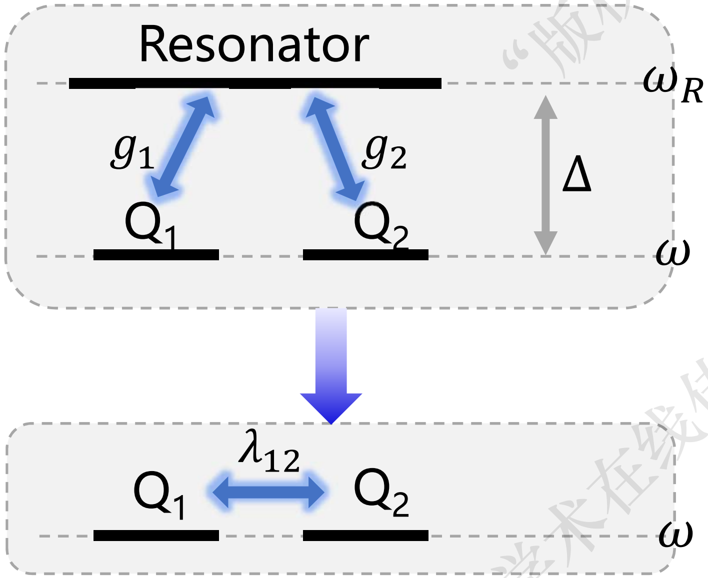
(III) Quantum Optics Experiments with Superconducting-Qubits

Two-qubit interaction

- **Interaction between two qubits enabled by bus resonator**

$$H = \sum_{j=1}^{2} \omega_j \sigma_j^{+} \sigma_j^{-} + \omega_R a^{\dagger} a + \sum_{j=1}^{2} g_j (a\sigma_j^{+} + a^{\dagger}\sigma_j^{-}),$$





- Resonator in vacuum state
- $\omega_1 = \omega_2 = \omega$, rotating frame
- $\Delta \gg g_1, g_2$

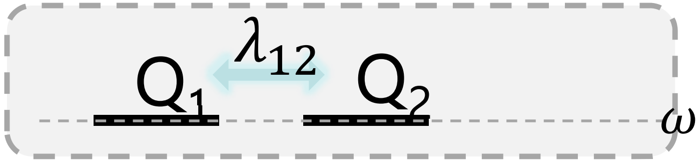
$$H_{eff} = \sum_{j=1}^{2} \lambda_j \sigma_j^{+} \sigma_j^{-} + \lambda_{12}(\sigma_1^{+}\sigma_2^{-} + \sigma_1^{-}\sigma_2^{+}),$$

where $\lambda_j = \frac{g_j^2}{\Delta}, \lambda_{12} = \frac{g_1 g_2}{\Delta}.$

1. Quantum chiral rotation

- **Anti-symmetric spin exchange interaction**

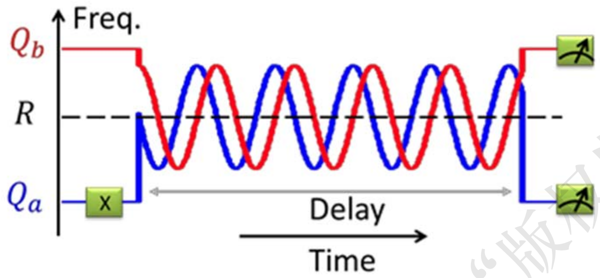
(Dzyaloshinskii-Moriya interaction)



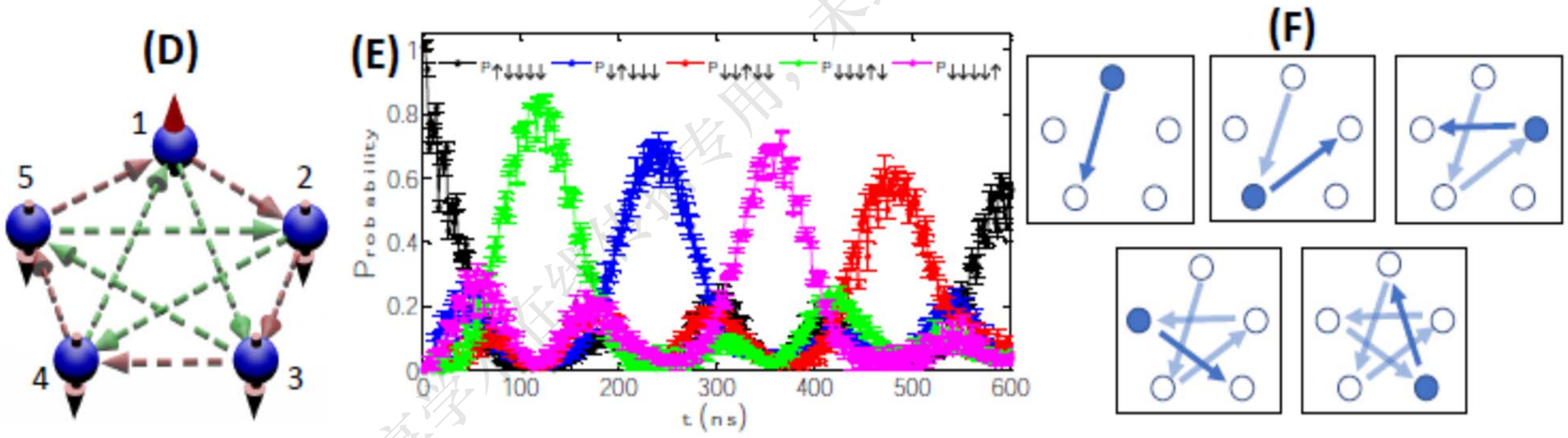
$$H_{eff} = \sum_{j=1}^{2} \lambda_j \sigma_j^+ \sigma_j^- + i\lambda_{12}(\sigma_1^+ \sigma_2^- - \sigma_1^- \sigma_2^+),$$

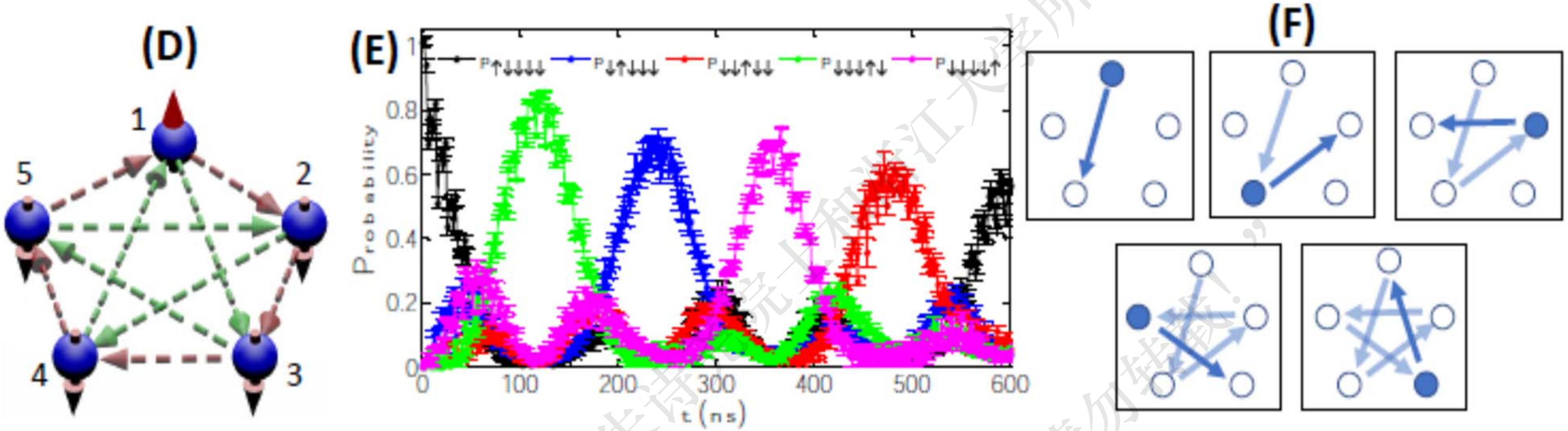
$$\lambda_{12} = \sum 2 g_1 g_2 J_n^2(f) \sin n(\phi_2 - \phi_1)/n\nu.$$

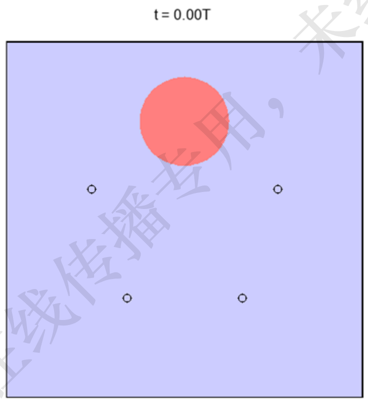
$$\omega_j(t) = \omega_R + \Delta \cos(\nu t - \phi_j)$$



Wang et al, Nat. Phys. 15, 382 (2019)




(D)
1
2
3
4
5
(E)
Probability
t (ns)
0
0.2
0.4
0.6
0.8
1
100
200
300
400
500
600
(F)


t = 0.00T

2. 5-component Schrodinger cat states

Multiqubit interactions

$$H_{eff} = \lambda \sum_{j=1}^{N} \sigma_j^+ \sigma_j^- + \sum_{i<j} \lambda (\sigma_i^+ \sigma_j^- + \sigma_j^+ \sigma_i^-)$$

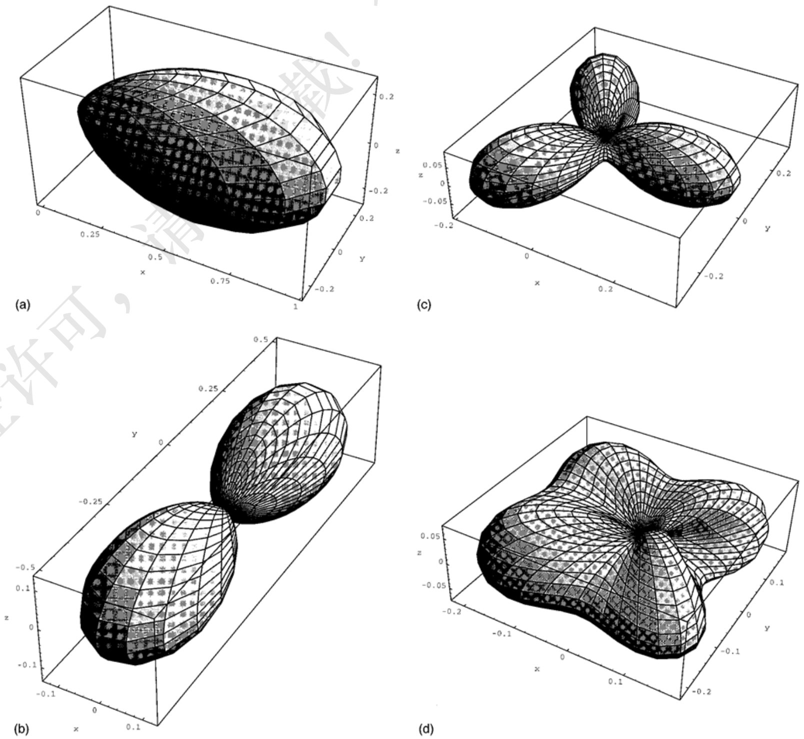
$$H_{eff} = \lambda S^+ S^-$$

$|s, m\rangle$ is the eigenstate of the system:
$S^+ S^- |s, m\rangle = a |s, m\rangle$

$$S^+ S^- = (S_x - iS_y)(S_x + iS_y) = S_x^2 + S_y^2 - S_z = S^2 - S_z^2 - S_z$$

$$H_{eff}^s = \lambda[s(s+1) - S_z^2 - S_z]$$

One-axis twisting Hamiltonian in the subspace labeled by s



multi-component Schrodinger cat

Multi-qubit case [**G. S. Agarwal**, R. R. Puri, R. P. Singh, Phys. Rev. A 56, 2249 (1997)].

Schrödinger cat states

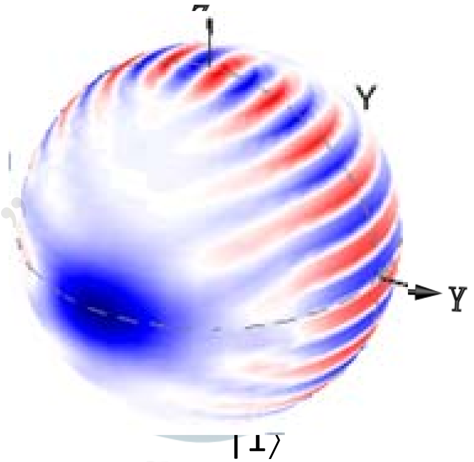
- **Visualization and characterization** R. P. Rundle et al., Phys. Rev. A 96, 022117 (2017).

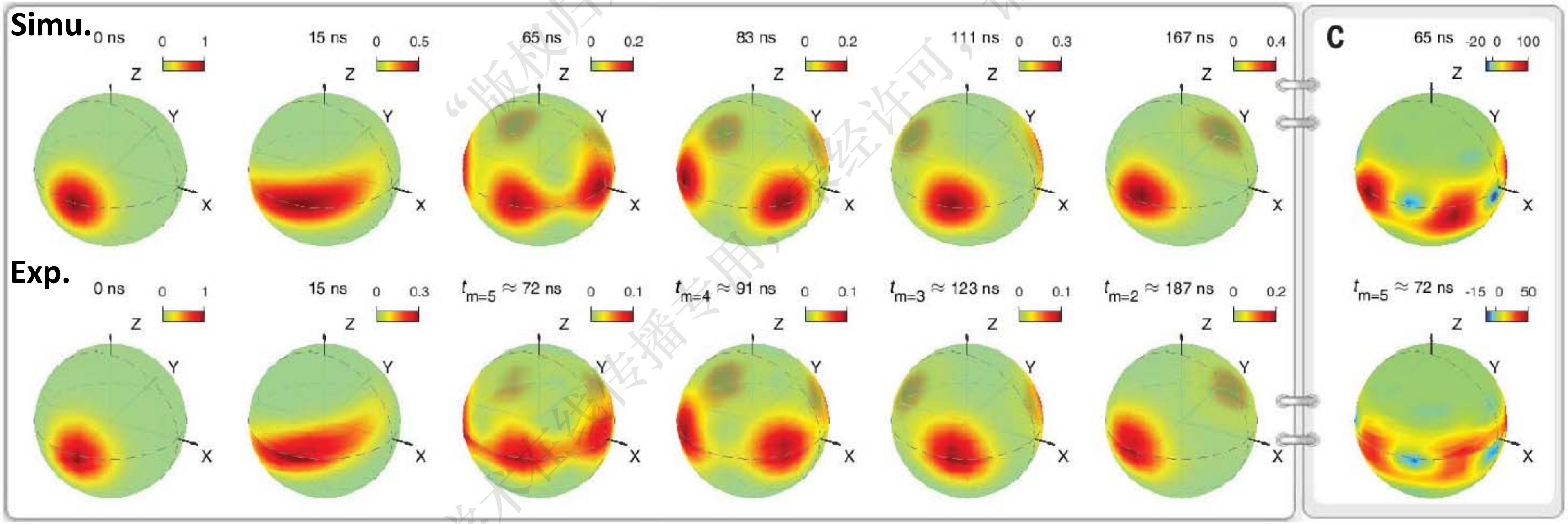
Sliced spin Wigner function:

$$W(\theta,\phi) = Tr\left(\hat{U}^{\dagger}(\theta,\phi)\rho\hat{U}(\theta,\phi)\hat{\Pi}\right)$$

$$\hat{U}(\theta,\phi) = \otimes_{j=1}^{N} \hat{u}_j(\theta,\phi)$$

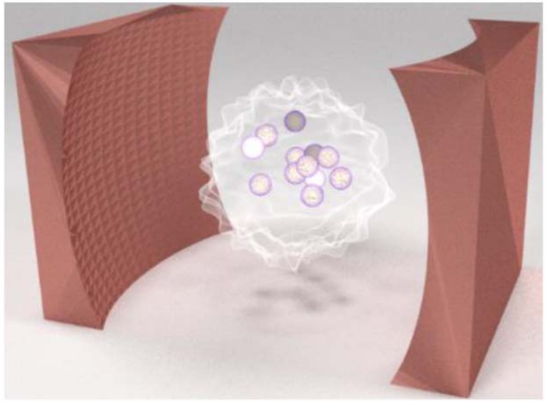
$$\hat{\Pi} = \otimes_{j=1}^{N} (1-\sqrt{3}\sigma_{z,j})$$ ⟶ extended parity operator

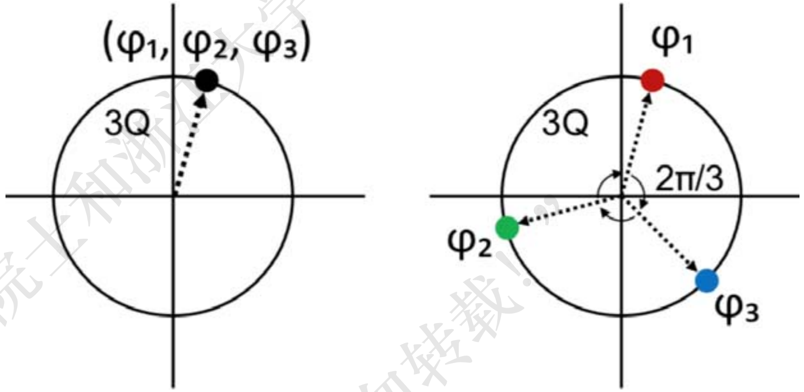


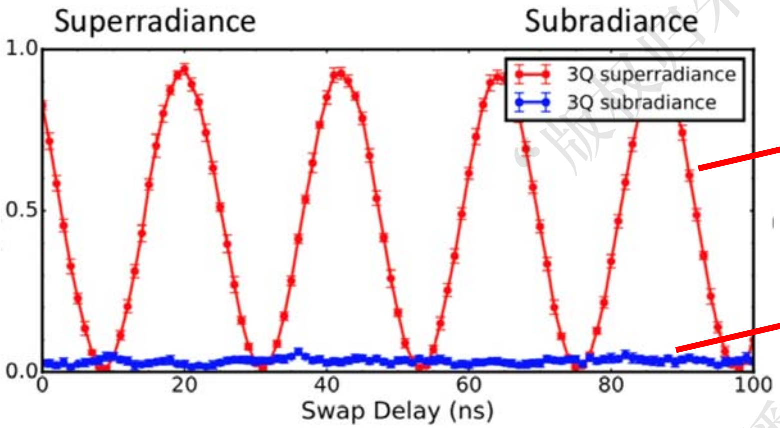


Song et al, Science 365, 574-577 (2019).

3. Control of Superradiant and subradiant states







No. of cavity photons

superradiant and subradiant states

$$|\psi_{super}\rangle = \frac{1}{\sqrt{3}}(|100\rangle + |010\rangle + |001\rangle)$$

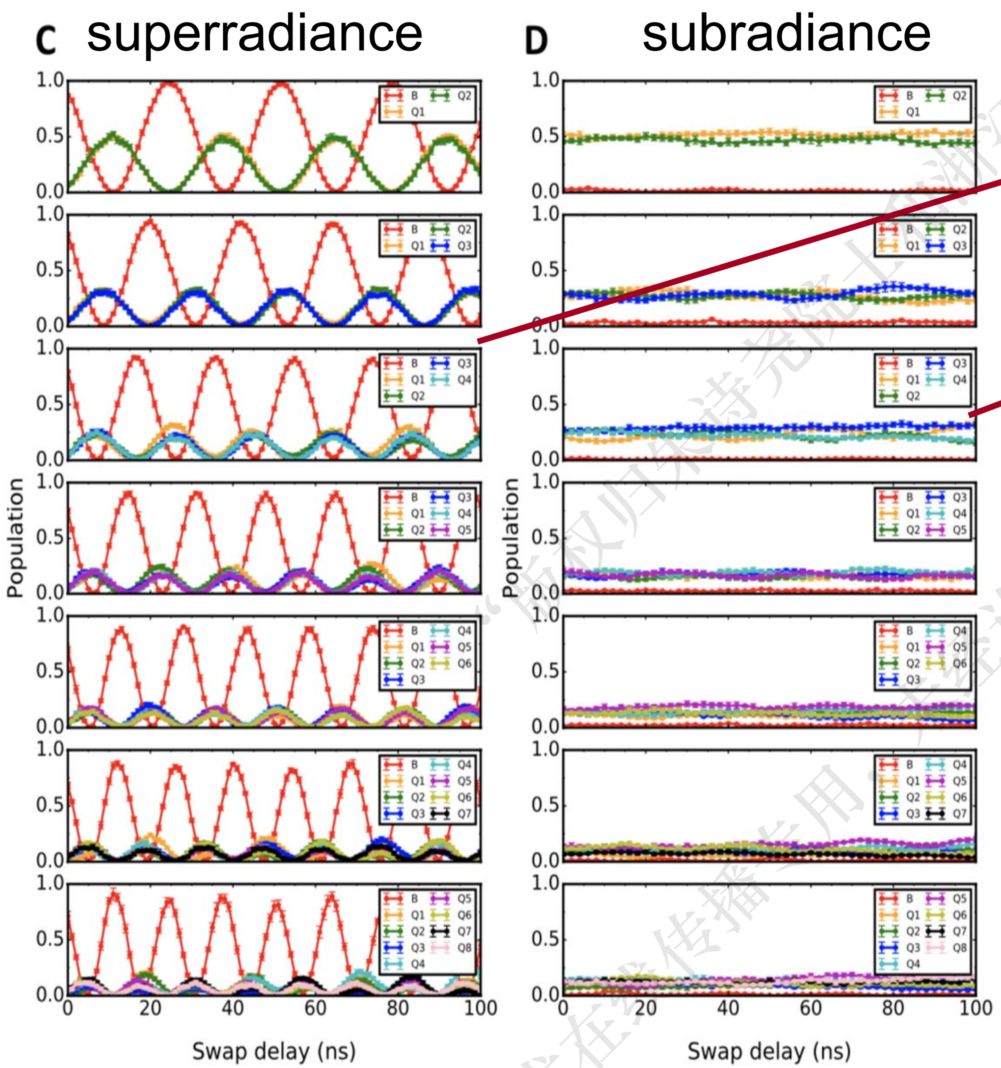
$$|\psi_{sub}\rangle = \frac{1}{\sqrt{3}}(|001\rangle + e^{i2\pi/3}|010\rangle + e^{i4\pi/3}|001\rangle)$$

$$\langle 000|\Sigma\sigma_j^-|\psi_{super}\rangle = \sqrt{3}$$

$$\langle 000|\Sigma\sigma_j^-|\psi_{sub}\rangle = 0$$

Scully, PRL 115, 243602 (2015)
Vetter et al, Phys. Scr. 91, 023007 (2016)
Wang et al, PRL 124, 013601 (2020)

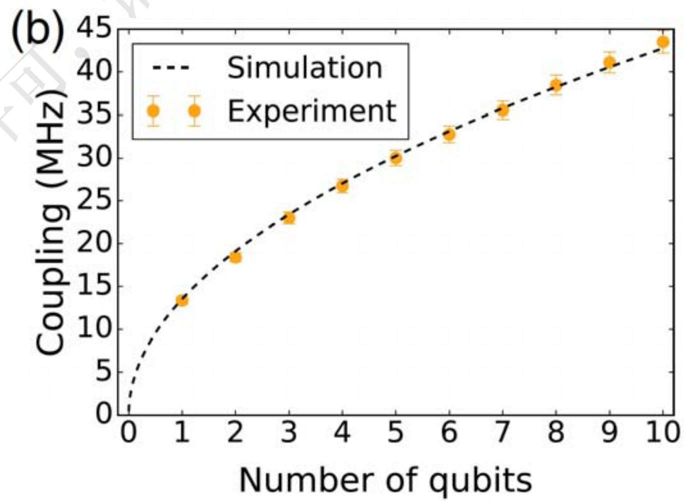
Superradiant and subradiant state



Wang et al, PRL 124, 013601 (2020)

$$|\psi_{super}\rangle = \frac{1}{\sqrt{N}} \sum_j \sigma_j^+ |g_1, \ldots, g_N\rangle$$

$$|\psi_{sub}\rangle = \frac{1}{\sqrt{N}} \sum_j e^{i2\pi j/N} \sigma_j^+ |g_1, \ldots, g_N\rangle$$



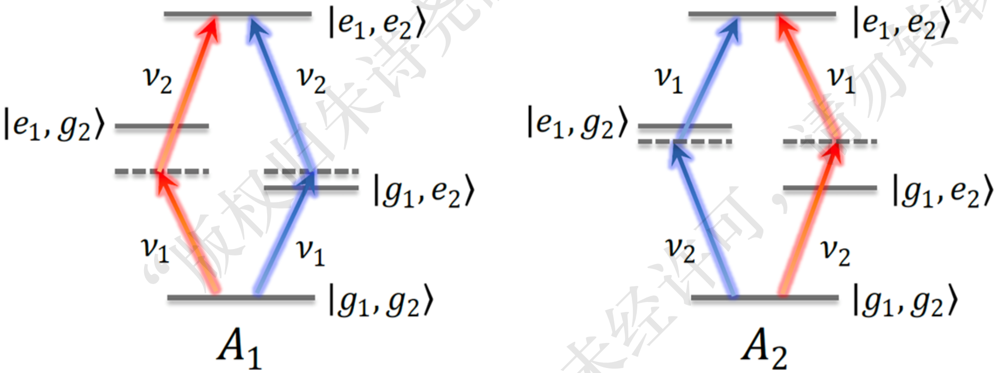
$\sqrt{N}$-scaling

3. Two-atom excited by entangled photons

VOLUME 93, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 27 AUGUST 2004

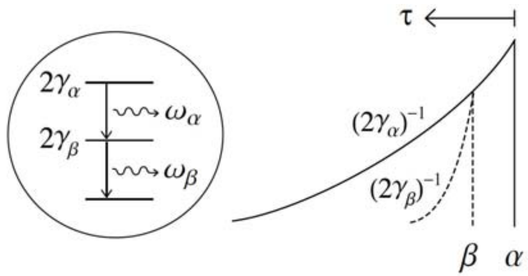
Inducing Disallowed Two-Atom Transitions with Temporally Entangled Photons

Ashok Muthukrishnan,[1] Girish S. Agarwal,[2] and Marlan O. Scully[1,3]



$$A_1 = \frac{\kappa_{22}\kappa_{11}}{\nu_1 - \omega_1} + \frac{\kappa_{12}\kappa_{21}}{\nu_1 - \omega_2},$$

$$A_2 = \frac{\kappa_{21}\kappa_{12}}{\nu_2 - \omega_1} + \frac{\kappa_{11}\kappa_{22}}{\nu_2 - \omega_2},$$



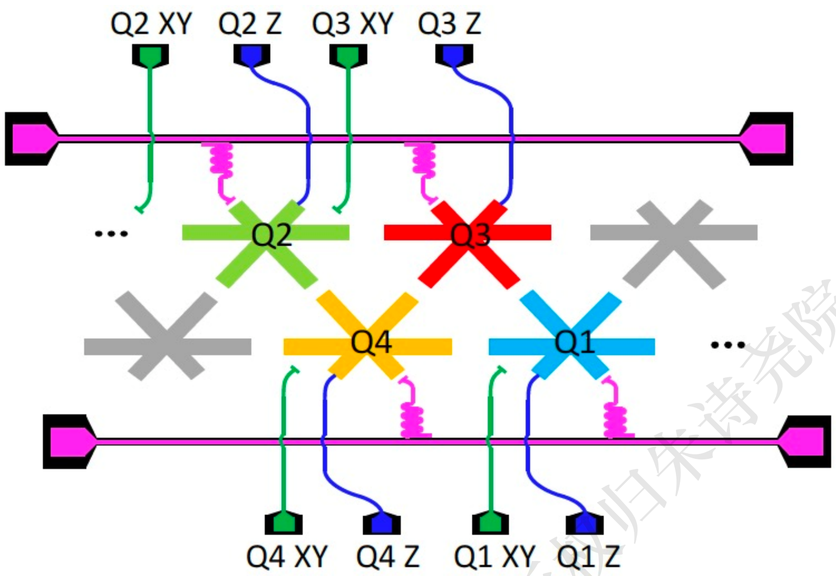
$$|A_1 + A_2|^2 = 0$$

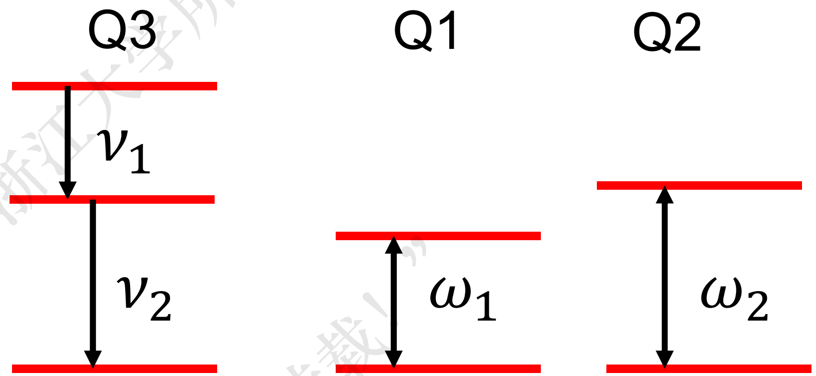
Independent photons

$$|A_1|^2 \neq 0$$

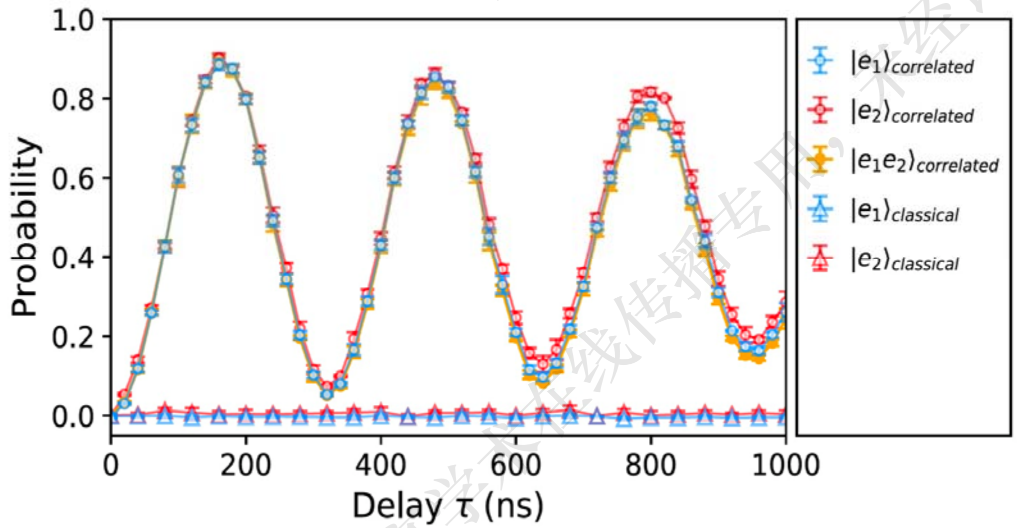
entangled photons

Two-atom excited by entangled photons





$$\nu_1 + \nu_2 = \omega_1 + \omega_2,$$
$$\nu_i \neq \omega_j \text{ for all } i, j = 1, 2$$



Effective 3-body int. H.

$$H_{\text{eff}} = A_1 \sigma_1^+ \sigma_2^+ \Xi_3^- + h.c.$$

Ren et al, RPL 125, 133601 (2020)

Outlook

1. Devices and new physics

   Experiments with more than 20 qubits is going on

- New quantum device: quantum circulator etc.
- Topological physics of quantized light

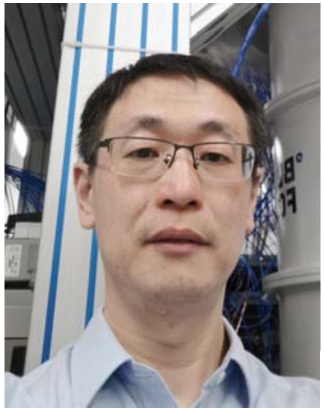
2. Quantum simulation

- Many-body interaction: $\sigma_1^- \sigma_2^+ \ \sigma_3^+ \ \sigma_4^+ \ \sigma_5^+$ etc
- Quantum origin of chiral molecules
- Simulation of energy transfer in photo-synthetic processes

3. Applications in quantum chemistry

- Ground state energy estimation of molecules

Collaborators



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Thanks