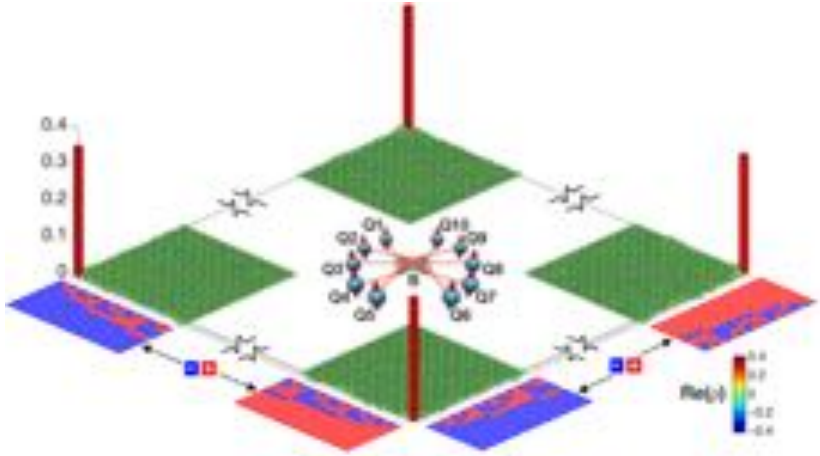
QC WARE

Q2B, NASA AMES RESEARCH CENTER, 2017-12-05



Chinese QC Funding

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CAS Center for Excellence in Quantum Information and Quantum Physics

University of Science and Technology of China

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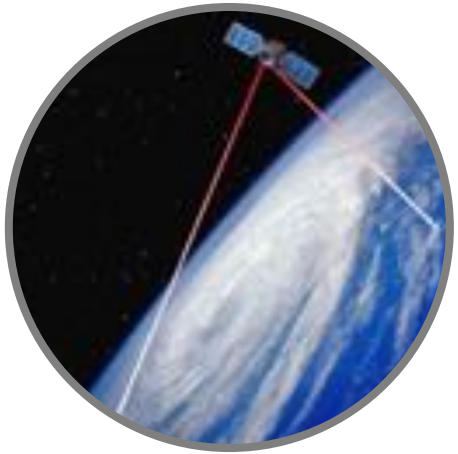
Overview of Chinese government Quantum information programs

Overview of the major Chinese government QC programs

- 2006-2010 (Eleven Five-Year Plan) ~1 billion CNY
- 2011-2016 (Twelve Five-Year Plan) ~5 billion CNY
- 2016-present (Thirteen Five-Year Plan) ~2 billion CNY

~4 billion CNY from Anhui , Shanghai, Shandong, etc. Province

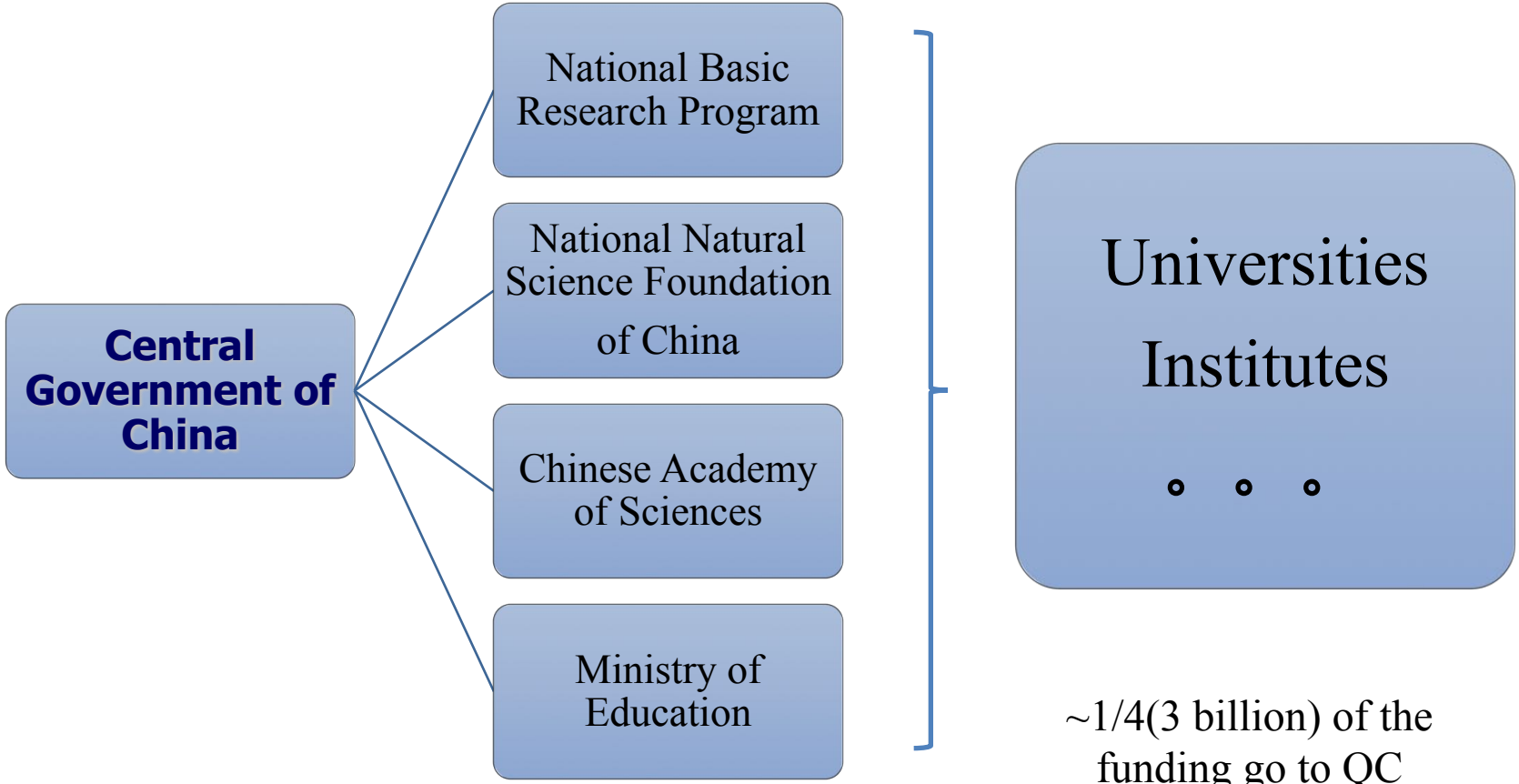


Quantum communication

Quantum computation and simulation

Quantum Metrology

Overview of the major Chinese government QC programs

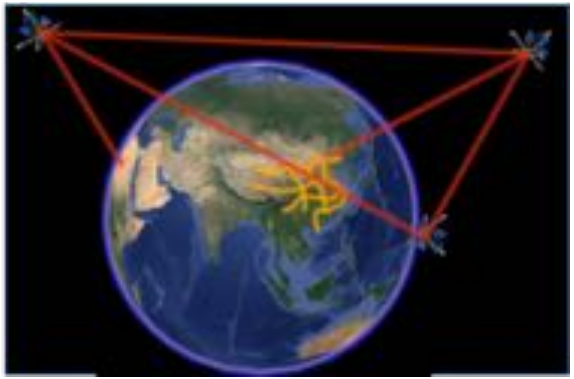


China’s Future National Projects

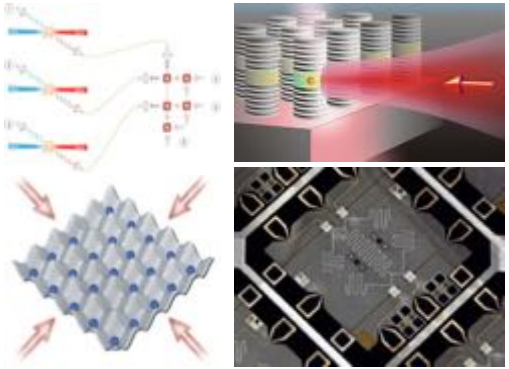
China's Future National Projects

CAS Center is now playing a leading role in organizing

- National Science and Technology Project on Quantum Information in the next 15 years, similar to European Quantum Technologies Flagship
- National Laboratory for Quantum Information Sciences (NLQIS)



Global Quantum Communication Networks



Scalable Quantum Computation and Quantum Simulation

Super-resolution Quantum Metrology

Introduction to the CAS Center

- Jointly supported by CAS and the Ministry of Education
- Annual budget ~100 million RMB

Hosted by **USTC**

includes top institutes and universities on quantum physics

Shanghai Institute of Technical Physics

Institute of Semiconductors

Institute of Optics and Electronics

Nanjing University

and excellence groups among China's universities:

Tsinghua University, Peking University, Fudan University, etc.

National Quantum Communication Backbone Project

- Inter-city quantum communication backbone with 32 trusted relays (~2000km)
- For financial applications, public affairs, etc.
- Test-bed for quantum foundations (e.g. frequency dissemination)
- Established in the end of 2016

CAS Strategic Priority Research Program: Quantum Satellite

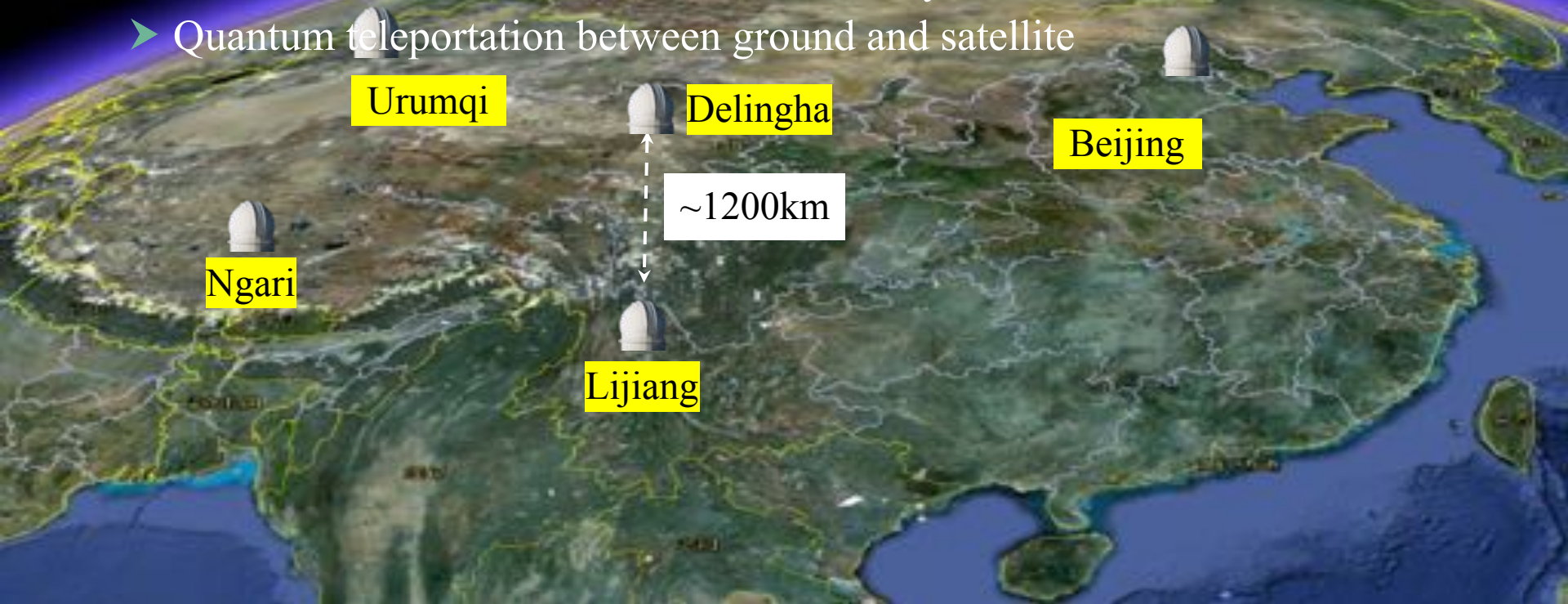
- Quantum Science Satellite “Micius” was launched on Aug 16, 2016

- Tracking the satellite

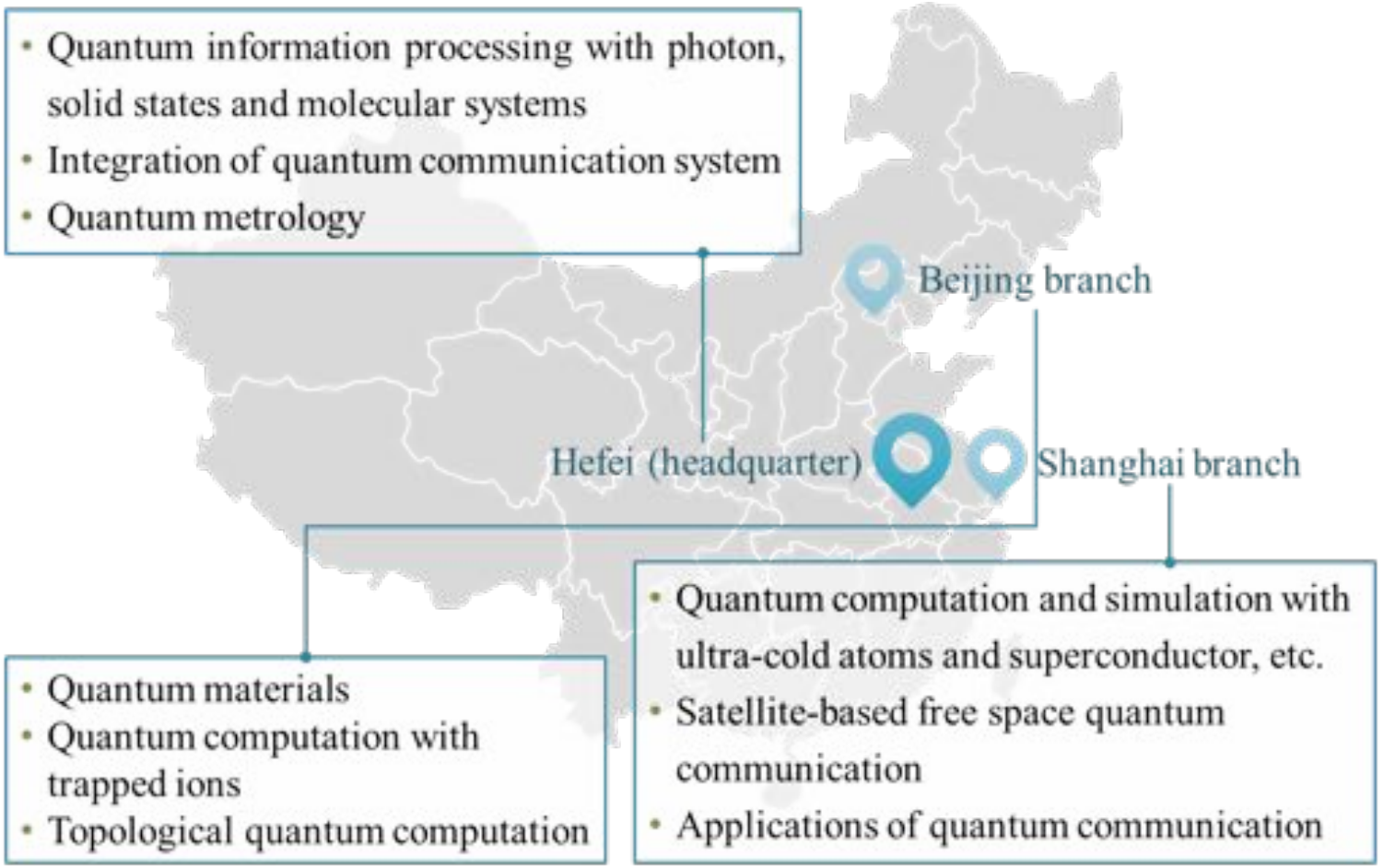
  (in Xinglong observatory, Beijing)

Micius' Three Missions

- High-rate quantum key distribution (QKD) between satellite and ground
- Quantum entanglement distribution from satellite, test of "spooky action at a distance" under strict Einstein's locality condition
- Quantum teleportation between ground and satellite



National Laboratory for Quantum Information Sciences (NLQIS): Organization



Towards Global Quantum Communication Network

- Widespread fiber quantum communication infrastructure
- Compatibility with classical optical communication networks
- Quantum repeater enabling quantum communications at a range of ~1000km
- Technology standards for quantum communication

……

Towards Global Quantum Communication Network

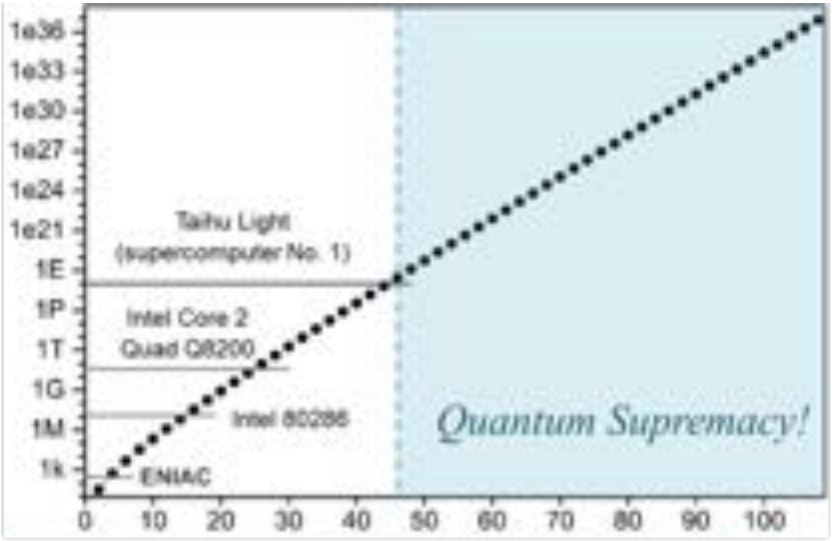
- Quantum Constellation covering the whole earth directly, with MEO and GEO satellites which will be launched in next 5-10 years
- Global quantum communication infrastructure ➡ “Quantum Internet”

Candidates for Quantum Computation and simulation

Superconductor	Photons	Cold atoms
Topological	**Trapped ions**	NV center
NMR	Quantum dot	. . .

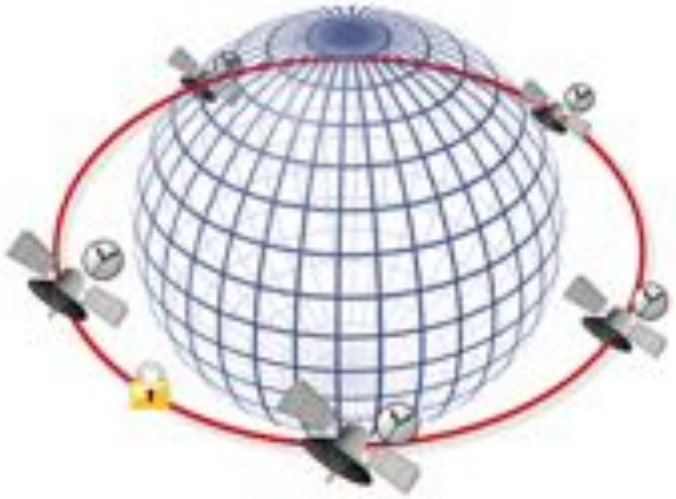
~1/3 of budget will go to QC

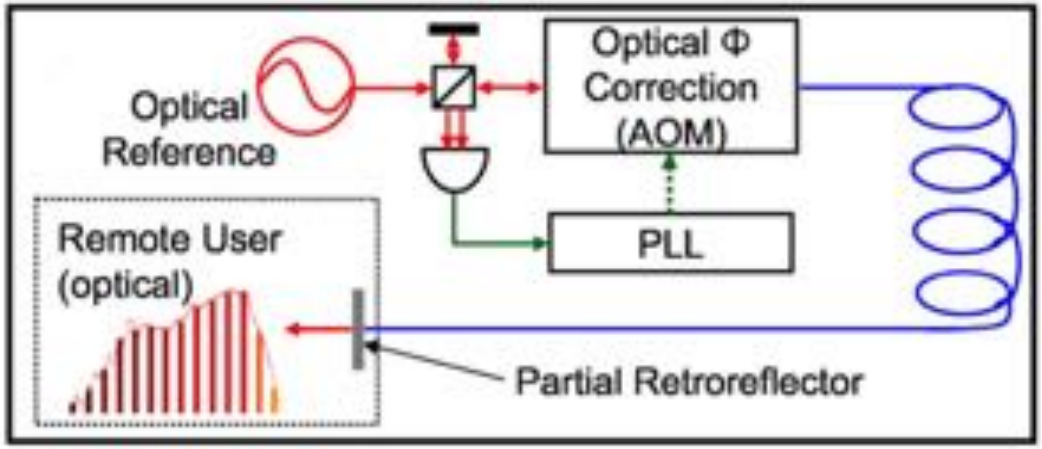
Scalable Quantum Computation and Simulation



- In next 5 years: quantum computer with 50-60 qubits ➡ beating classical super computer in specific tasks (e. g. Boson sampling and portfolio optimization)
- In next 10-15 years: quantum computer with hundreds of qubits ➡ mimicking condensed matter physics (e. g., high temperature superconductor, quantum Hall effect, etc.)

Precise Timing Information Sharing





Global microwave time and frequency network

Long time instability below 10^{-15}

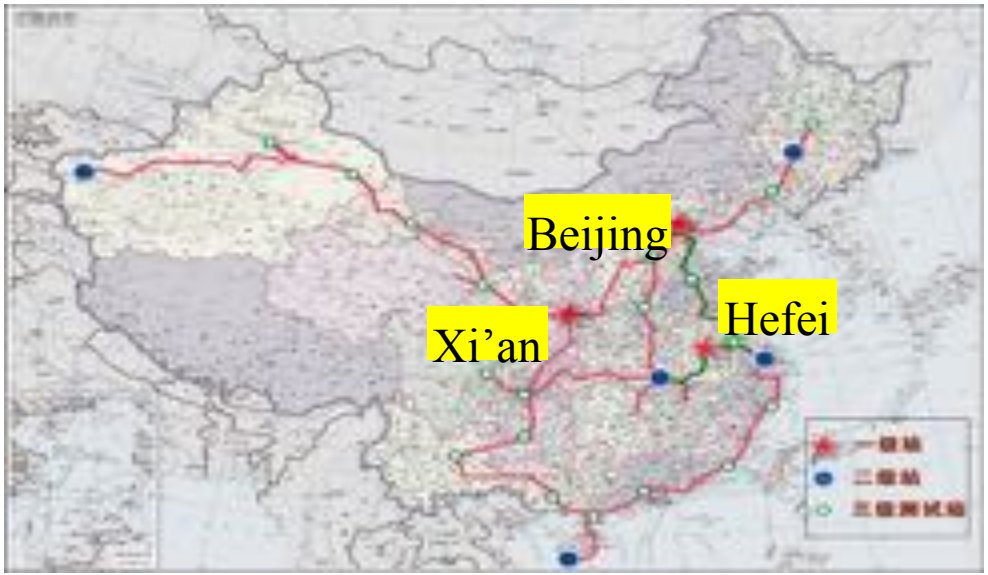
V. S.

Fiber frequency transfer

long time instability to 10^{-19}, 4 magnitudes better than microwave scheme

Precise Timing Information Sharing

The Project “High-precision ground-based time service system”



- To build the world's largest optical fiber time-frequency transfer network, with the most advanced indicators of the performance
- 3 primary stations, 5 secondary stations and 19 tertiary test stations

High-resolution and Highly Sensitive Measurements

Optical clock (stability at the 10^{-19} level)

+

large scale optical time-frequency transfer network

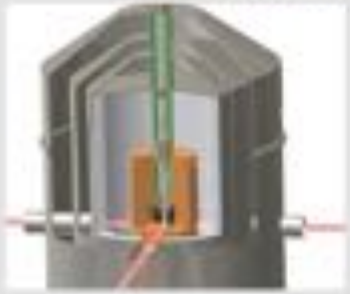
High precision navigation and timing

High precision inertial navigation

Atomic gyroscope

Atomic gravimeter

Applications for medical test and environmental monitoring, etc.



Atomic magnetometer

Single photon LIDAR

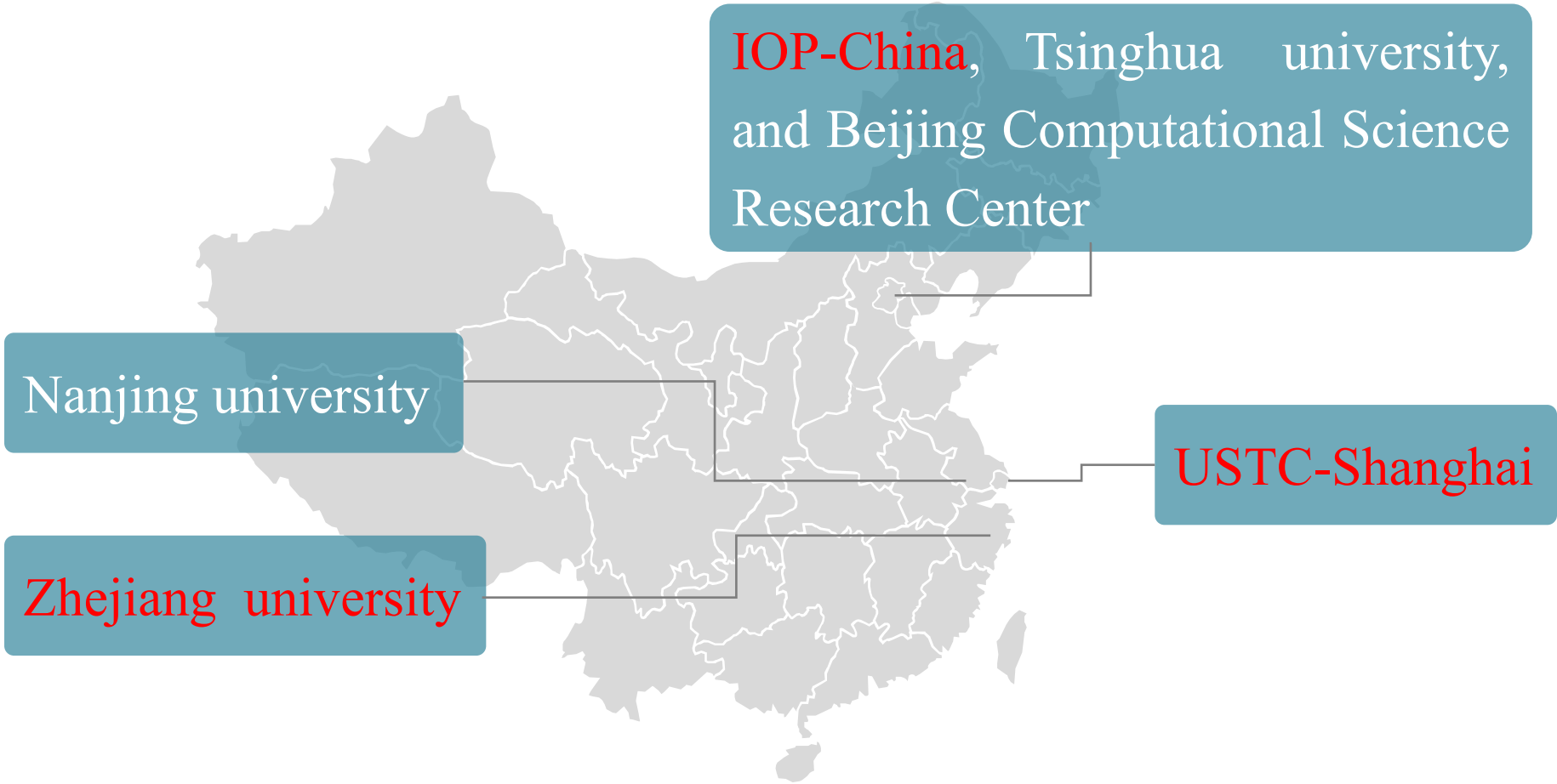
Commercial partnerships

Commercial partner of CAS Center

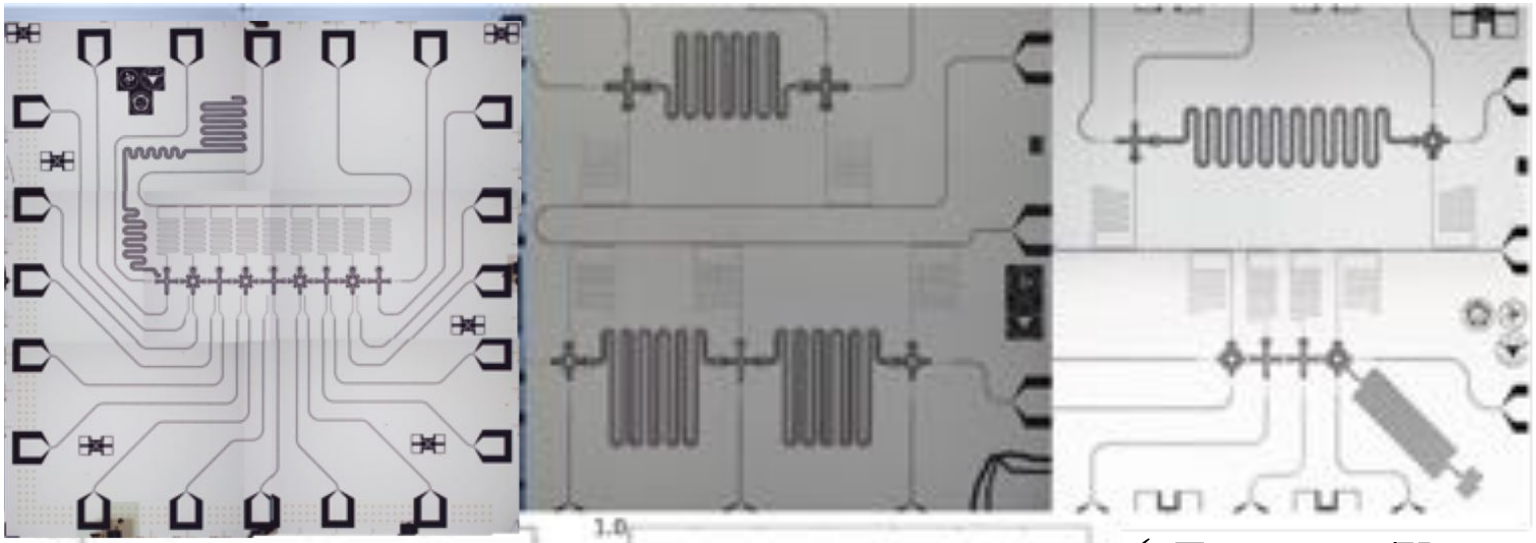
Most of the commercial applications are focused on the quantum communications. Alibaba sponsored CAS center since 2016, and established CAS-Alibaba quantum computing laboratory

Progress on superconducting and Photonics QC

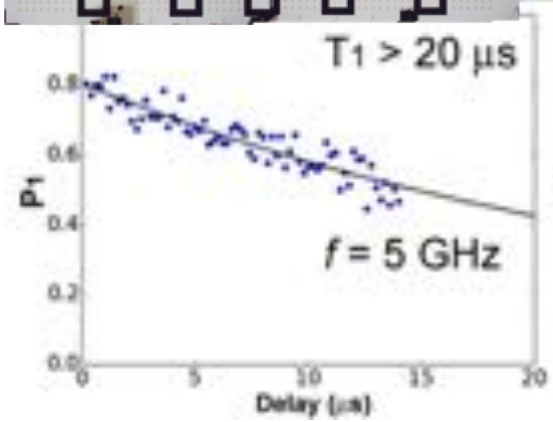
Superconducting QC groups in China

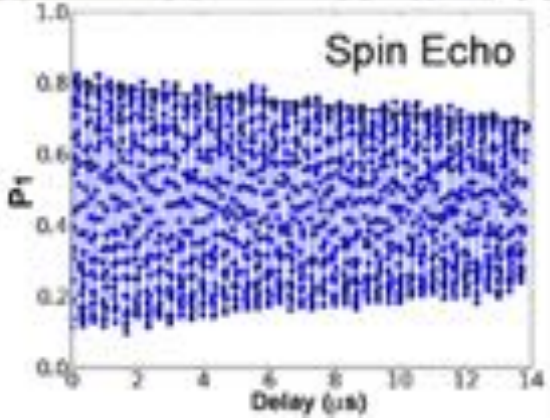


Qubit characterizations



5 qubits
6 qubits
9 qubits
10 qubits
20 qubits
. . .



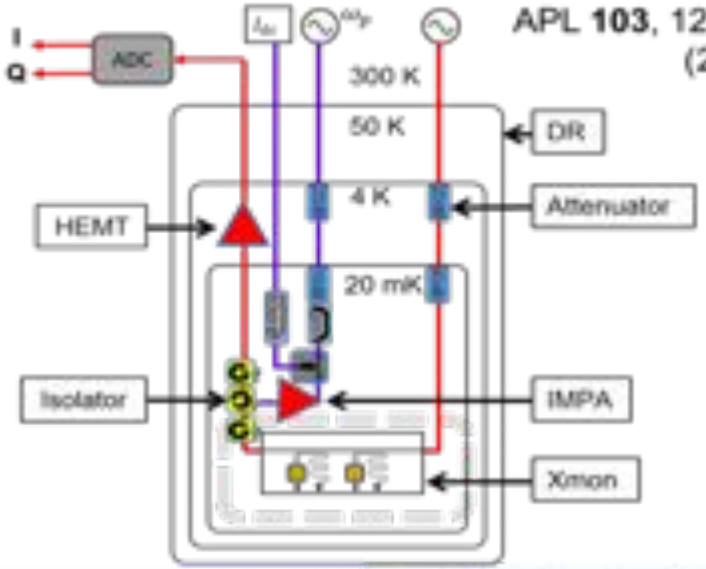


✓ **Transmon/Xmon qubits:**

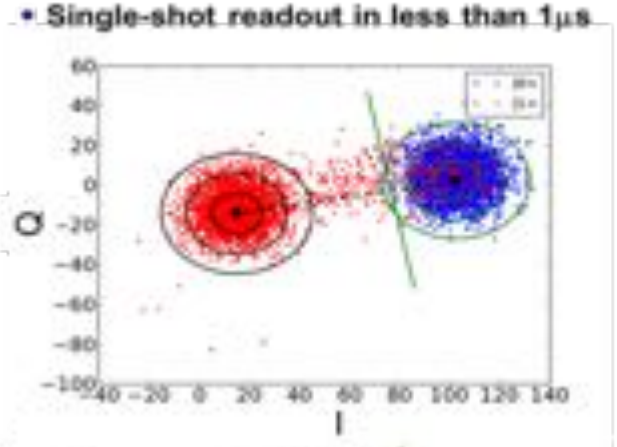
Best T_1 ~ 30 μs (10 – 20 μs on average), T_2* above 20 μs (- 10 μs on average).

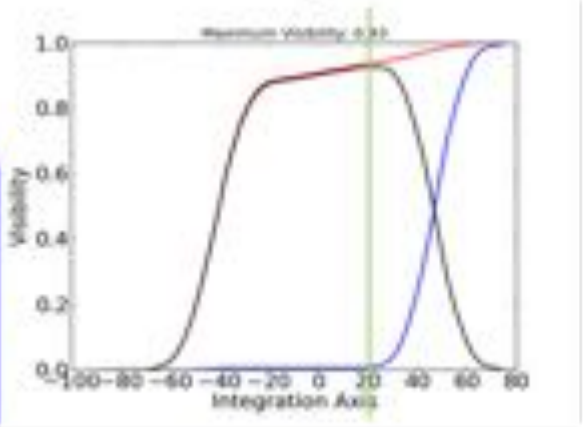
✓ **Single-qubit gate fidelity above 99.9% (RB), two-bits gate ~99.1%**

Readout with home-made paramps

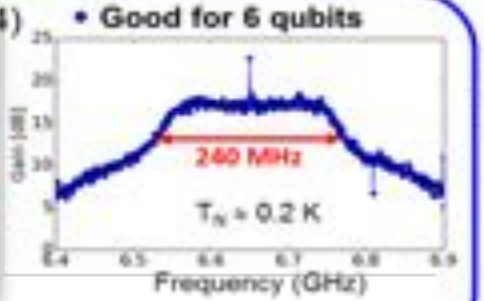


APL **103**, 122602 (2013)

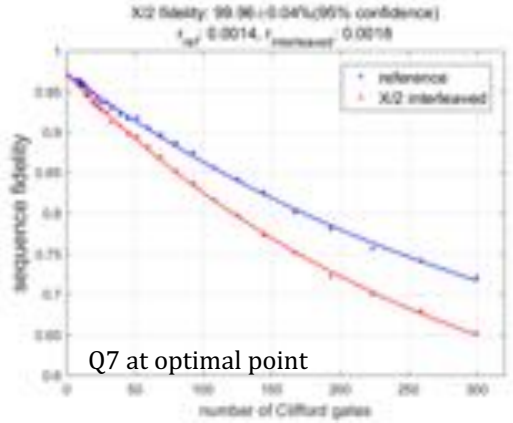


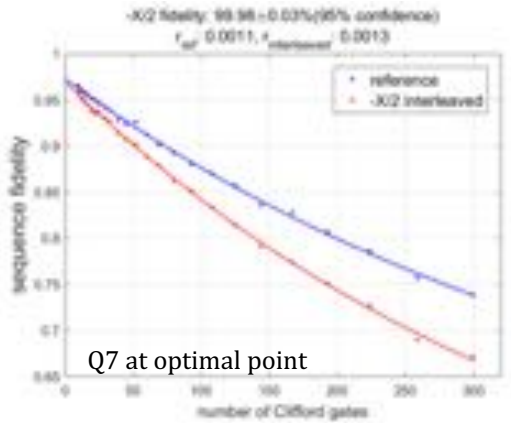


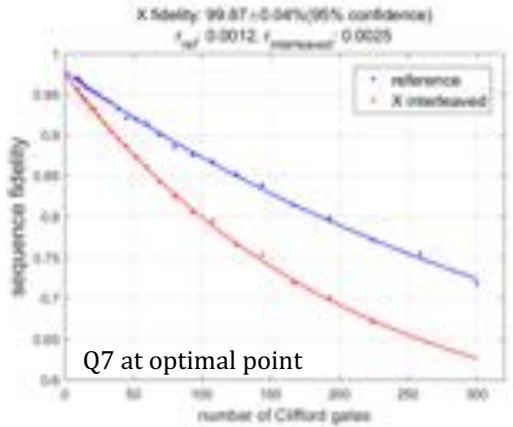
APL **104**, 263513 (2014)

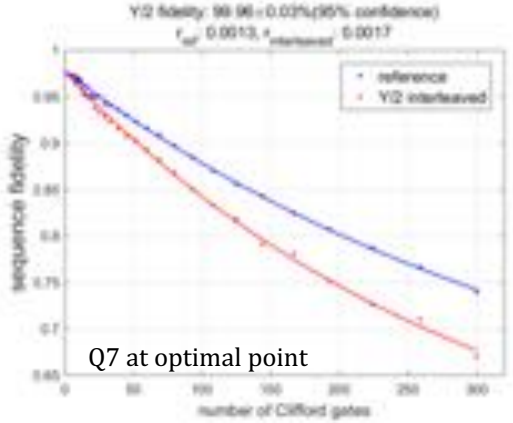


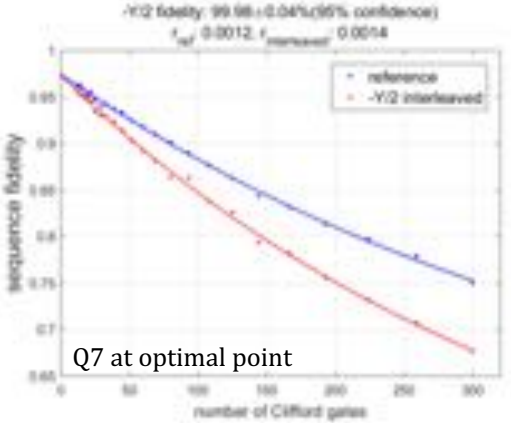
Single Qubit Gates

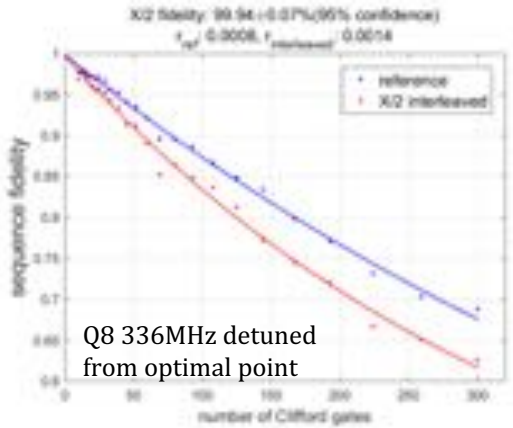






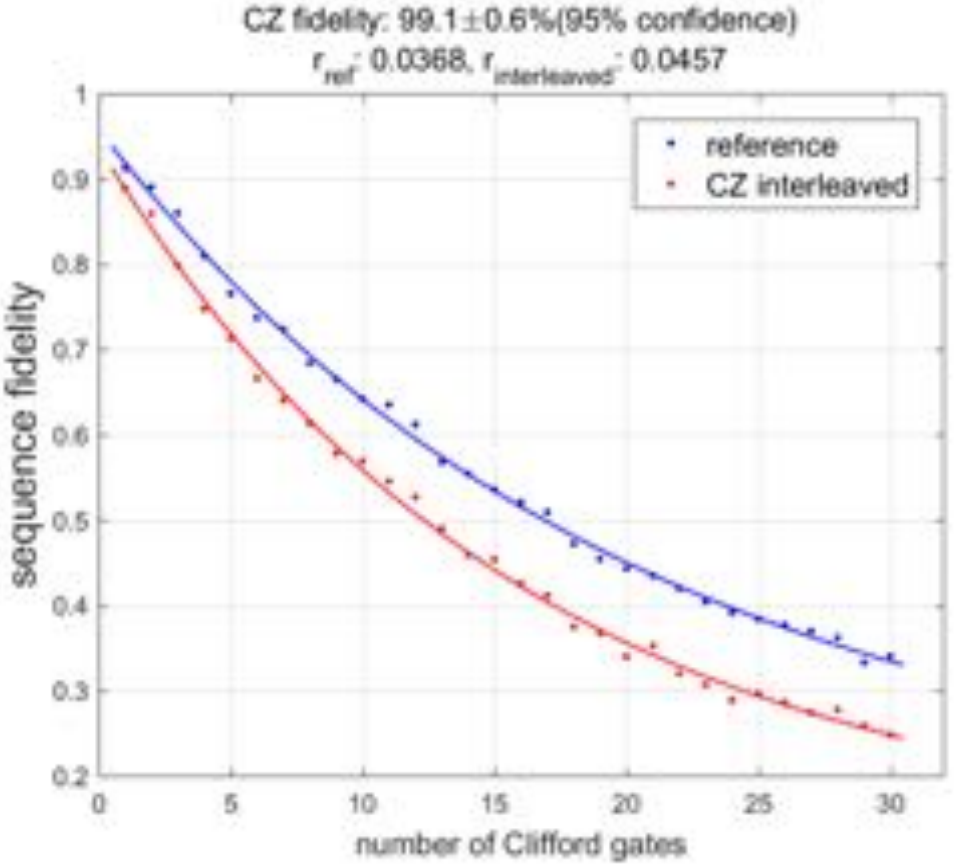






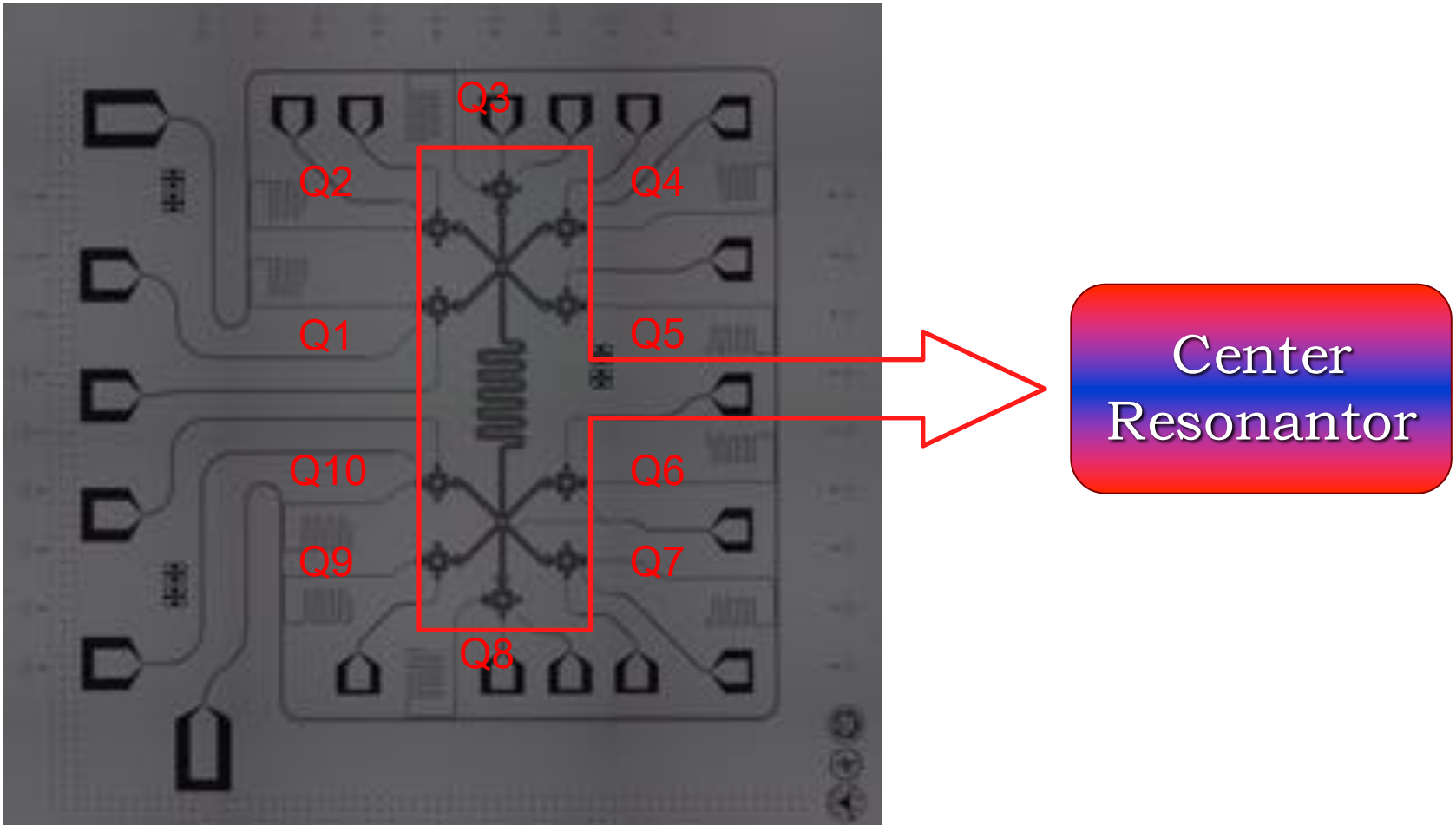
Single qubit gate randomized benchmarking>99.9%

CZ Gate



CZ randomized Benchmarking
70 random sequences
1500 averages

10-Qubits processor with complete connection



List of parameters

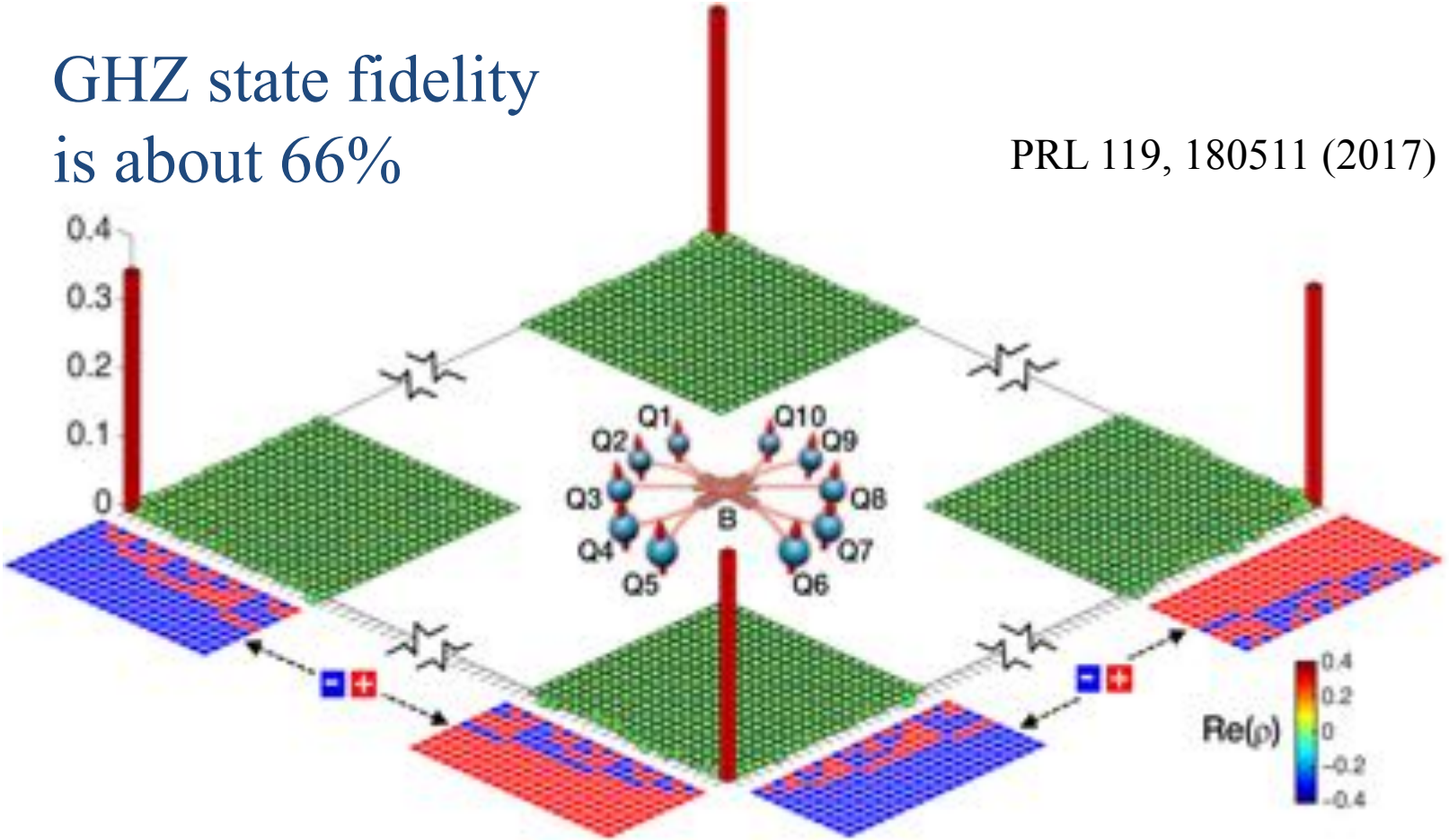
	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}
$\omega_j^0/2\pi$ (GHz)	5.782	5.831	5.828	5.780	5.760	5.863	5.780	6.004	5.893	5.930
$\omega_I/2\pi$ (GHz)					≈ 5.655					
$T_{1,j}$ (μs)	27.2	24.4	10.9	15.0	19.2	23.7	13.8	11.8	17.1	22.0
$T_{2,j}^*$ (μs)	2.9	2.8	2.8	2.2	2.6	1.8	1.1	2.1	1.7	4.4
$T_{2,j}^{\text{SE}}$ (μs)	11.8	10.6	10.0	10.8	11.7	8.9	8.0	8.0	7.9	11.8
$\omega_j/2\pi$ (GHz)	5.080	5.467	5.657	5.042	5.179	5.605	4.960	5.260	5.146	5.560
$g_j/2\pi$ (MHz)	14.2	20.5	19.9	20.2	15.2	19.9	19.6	18.9	19.8	16.3
$X/2$ fidelity	0.9985(2)	0.9992(1)	0.9984(1)	0.9987(2)	0.9991(1)	0.9964(5)	0.9987(1)	0.9980(3)	0.9988(3)	0.9989(1)
Simultaneous $X/2$ fidelity	0.9978(7)	0.9980(2)	0.9953(5)	0.9955(5)	0.9985(2)	0.9962(3)	–	–	0.9979(2)	0.9931(12)
$\omega_j^r/2\pi$ (GHz)	6.509	6.541	6.615	6.614	6.635	6.694	6.691	6.794	6.809	6.891
$g_j^r/2\pi$ (MHz)	41.3	39.9	40.6	38.2	38.5	40.4	41.8	40.9	40.2	38.7
$\delta\omega_j^m/2\pi$ (MHz)	31.1	32.7	21.1	46.5	9.0	45.1	22.5	19.5	26.0	70.2
n_j^r	92	59	31	180	30	81	93	74	103	203
$1/\kappa_j^r$ (ns)	291	275	272	348	223	284	248	266	239	242
$F_{0,j}$	0.921	0.955	0.982	0.974	0.962	0.988	0.950	0.970	0.961	0.971
$F_{1,j}$	0.867	0.915	0.904	0.928	0.927	0.917	0.922	0.880	0.894	0.934

$\omega_B/2\pi \approx 5.795$

Full state tomography

GHZ state fidelity
is about 66%

PRL 119, 180511 (2017)



4 qubits HHL algorithm

In the frequency range for this work:

T_1 ~ 10-15 μs
T_2^* ~ 3-5 μs

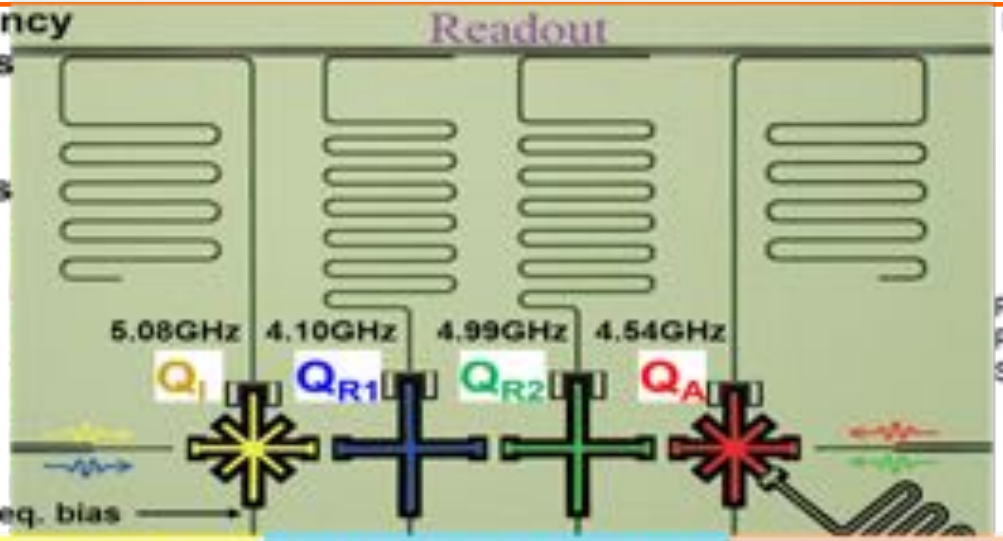


Photo Courtesy: Yarui Zheng

$$A = \begin{pmatrix} 1.5 & 0.5 \\ 0.5 & 1.5 \end{pmatrix}$$

Phys. Rev. Lett. **110**, 230601 (2013)
Phys. Rev. A **89**, 022313 (2014)
Scientific Reports **4**, 115 (2014)

No solid-state demonstration so far.

Input qubit

1 input qubit to encode a 2-component vector.

Register qubits

2 register qubits for $|01\rangle$, $|10\rangle$, or $|11\rangle$,

λ_j = 1, 2, or 3.

Ancilla qubit

No constraint

Immediate goal with these 4 qubits: to solve 2 × 2 linear eqns.

4 qubits HHL algorithm

Input for $\vec{b}$

$$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

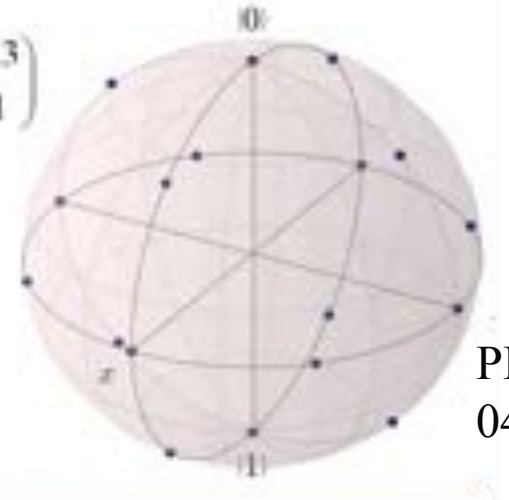
Exp. state tomography of $\vec{x}$

$$\begin{pmatrix} 0.82 & -0.17-0.03i \\ -0.17+0.03i & 0.18 \end{pmatrix}$$

ideal $\vec{x}$

$$\begin{pmatrix} 0.9 & -0.3 \\ -0.3 & 0.1 \end{pmatrix}$$

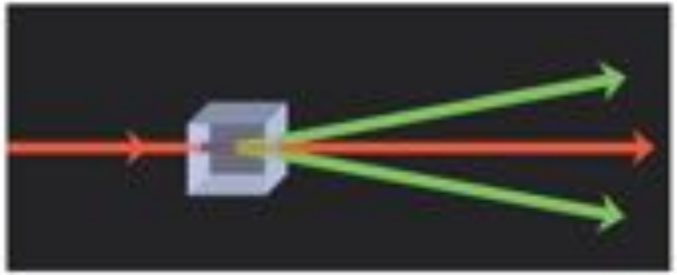
Input state	Fidelity
$\|0\rangle$	0.859
$\|1\rangle$	0.874
$\cos(\pi/8)\|0\rangle - i\sin(\pi/8)\|1\rangle$	0.861
$\cos(\pi/4)\|0\rangle - i\sin(\pi/4)\|1\rangle$	0.886
$\cos(3\pi/8)\|0\rangle - i\sin(3\pi/8)\|1\rangle$	0.881
$\cos(\pi/8)\|0\rangle + i\sin(\pi/8)\|1\rangle$	0.881
$\cos(\pi/4)\|0\rangle + i\sin(\pi/4)\|1\rangle$	0.856
$\cos(3\pi/8)\|0\rangle + i\sin(3\pi/8)\|1\rangle$	0.840
$\cos(\pi/4)\|0\rangle + e^{-i\frac{\pi}{4}}\sin(\pi/4)\|1\rangle$	0.890
$\cos(\pi/4)\|0\rangle + e^{i\frac{\pi}{4}}\sin(\pi/4)\|1\rangle$	0.872
$\cos(\pi/4)\|0\rangle + e^{-i\frac{3\pi}{4}}\sin(\pi/4)\|1\rangle$	0.884
$\cos(\pi/4)\|0\rangle + e^{-i\frac{3\pi}{4}}\sin(\pi/4)\|1\rangle$	0.882

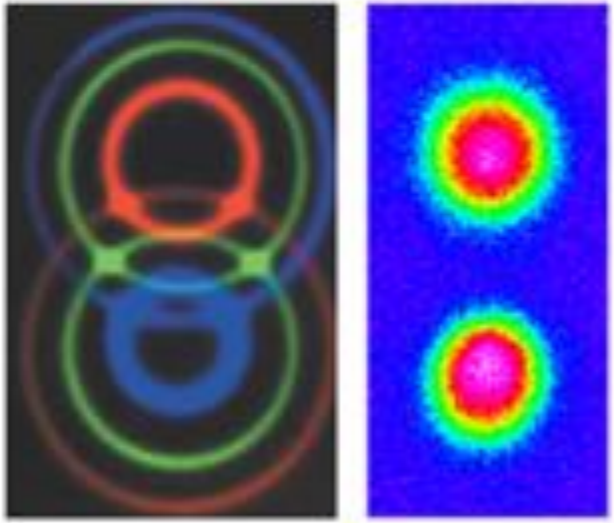


Input state	Fidelity
$\cos(\pi/8)\|0\rangle + \sin(\pi/8)\|1\rangle$	0.878
$\cos(\pi/4)\|0\rangle + \sin(\pi/4)\|1\rangle$	0.923
$\cos(3\pi/8)\|0\rangle + \sin(3\pi/8)\|1\rangle$	0.882
$\cos(\pi/8)\|0\rangle - \sin(\pi/8)\|1\rangle$	0.891
$\cos(\pi/4)\|0\rangle - \sin(\pi/4)\|1\rangle$	0.888
$\cos(3\pi/8)\|0\rangle - \sin(3\pi/8)\|1\rangle$	0.876

PRL 118.210504 (2017)

Controlling a large number of photon entanglement





3-photon entanglement & GHZ test:
Pan *et al. Nature* (2000)

4-photon entanglement:
Pan *et al. Phys. Rev. Lett.* (2001)

5-photon entanglement:
Zhao *et al. Nature* (2004)

6-photon entanglement:
Lu *et al. Nature Physics* (2007)

8-photon entanglement:
Yao, *et al. Nature Photonics* (2012)

10-photon entanglement:
Wang, *et al. Phys. Rev. Lett.* (2016)

Review: Pan, *et al.* Multiphoton entanglement and interferometry, *Rev. Mod. Phys.* **84**, 777 (2012)

Quantum logic, QEC, and algorithms

- Quantum controlled-NOT logic

  Zhao *et al.*, PRL 94, 030501 (2005)

- Shor's algorithm

  Lu *et al.*, PRL 99, 250504 (2007)

- Deustch & Grover's algorithm

  Gao *et al.*, Nat. Photonics 5, 117 (2011)

- Revealing fractional statistics of anyons

  Lu *et al.*, PRL 102, 030502 (2009)

- Topological error correction

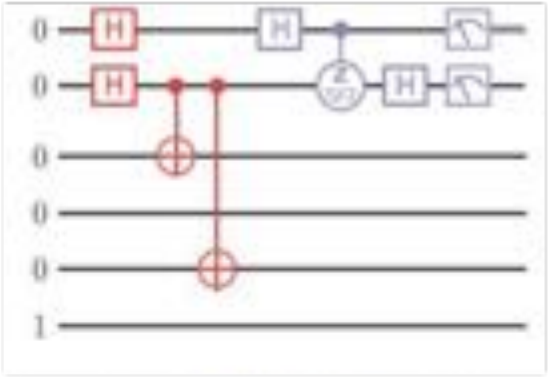
  Yao *et al.* Nature (2012)

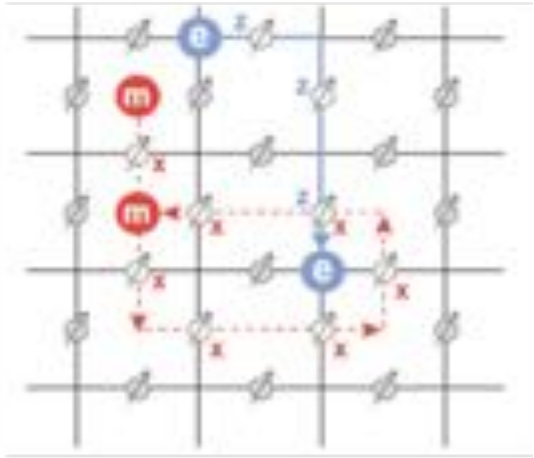
Solving systems of linear equations

Cai *et al.*, PRL 110, 230501 (2013)

Quantum artificial intelligence

Cai *et al.*, PRL 114, 110504 (2015)





QC WARE