Photonic Quantum Advantage

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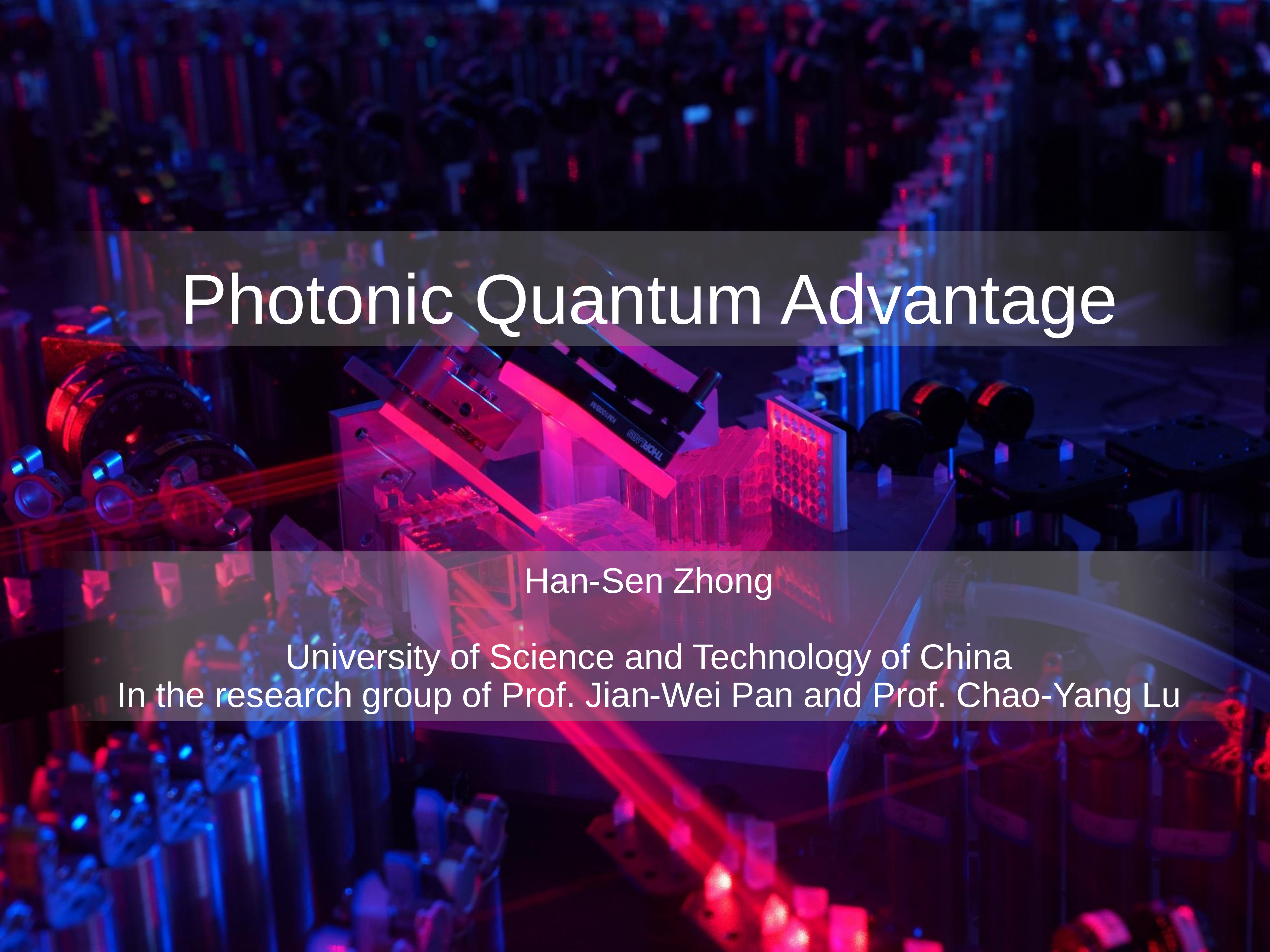
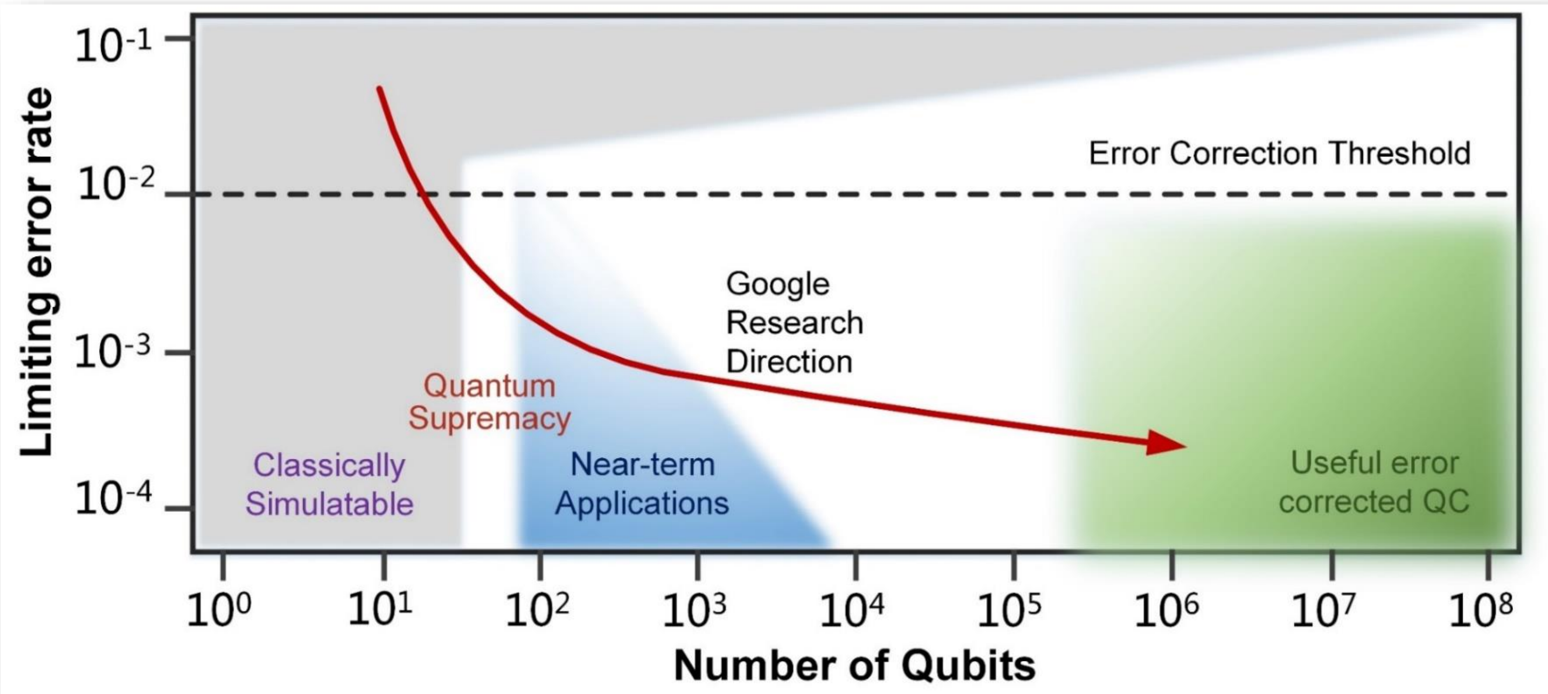


Near-, intermediate-, and long-term goals of QC

The need for →

<u>Qubits quality + quantity + control, simultaneously</u>



"laying eggs along the way"

Motivation:

A computational analogue of Bell experiments

Bell experiments:

Refute EPR's local hidden variable model

Stronger-than-classical correlation

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Supremacy experiments:

Refute the old Extended Church–Turing thesis

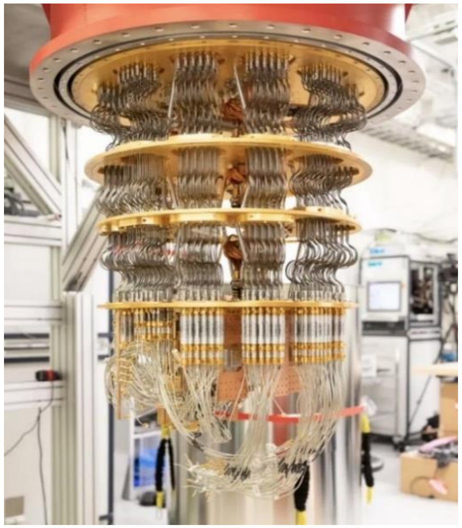
Faster-than-classical computation

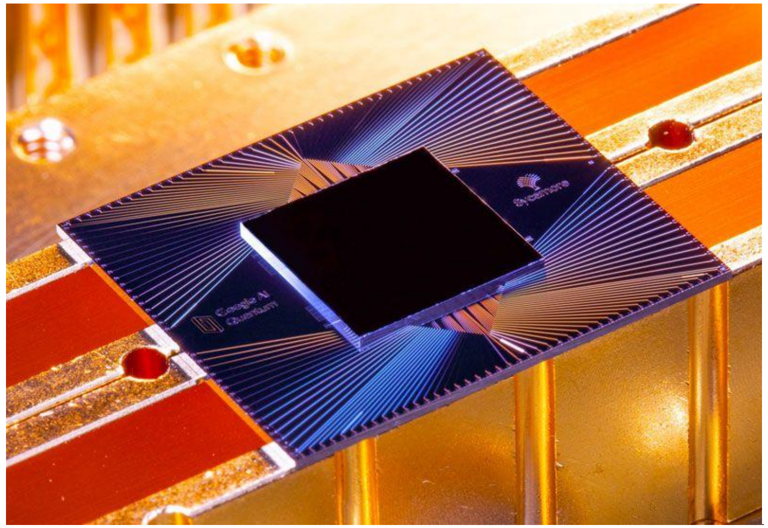
The Extended Church-Turing Thesis (ECT)

Any physically realisable system can be efficiently simulated on a Turing machine

Bernstein, Vazirani, (1993)
Harrow & Montanaro, Nature 549, 203 (2017)

Google's Sycamore quantum processor





Google's quantum processor "Sycamore" with 53 superconducting qubits

Arute *et al.*, Nature 574, 505 (2019)

- IBM & Alibaba: the 10,000 years can be shortened to few days
- USTC: With sufficient storage, the advantage is sample-size dependent
  For 10 billion samples, no quantum advantage
- Institute of Theoretical Physics, CAS: simulating using few tens of GPU

“Quantum computational advantage, rather than being a one-shot experimental proof, will be the result of a long-term competition between quantum devices and classical simulation.”

-- Ian S. Osborne

Science 370(6523), 1428 (2020)

Umesh Vazirani,
SFB workshop
16 February 2021

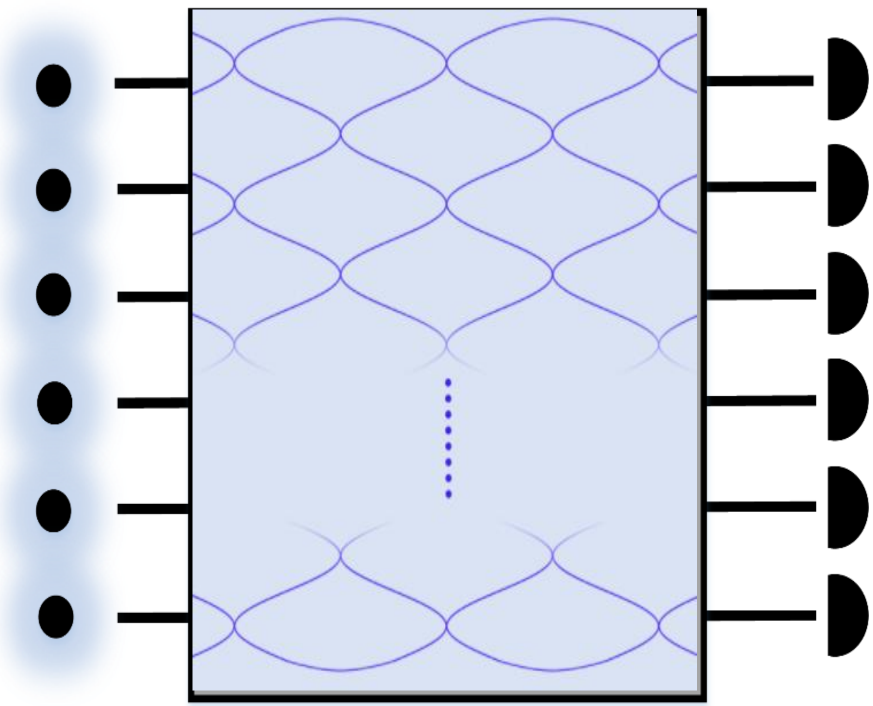
Quantum supremacy is not a one-and-done. It is an important scientific experiment:

1. Exponential growth arguably the most counter-intuitive aspect of quantum mechanics.
2. Testing the limits of physics: high energy, Planck scale, speed of light...
   New limit in which to test physics: high complexity.

Quantum supremacy experiments have to be refined over time to eliminate loopholes.

This means better guarantees that the underlying computational problem is classically intractable, and verification that the quantum device actually solved the problem

Boson Sampling



THEORY OF COMPUTING, Volume 9 (4), 2013, pp. 143–252
www.theoryofcomputing.org

The Computational Complexity of Linear Optics*

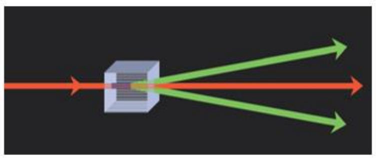
Scott Aaronson† Alex Arkhipov‡

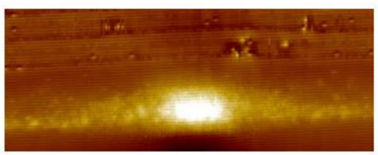
$$P(\mathbf{S}|\mathbf{T}) = |\langle \mathbf{S}|\Psi_{\mathrm{out}}\rangle|^2 = \frac{|\mathrm{Per}(\mathbf{\Lambda}^{(\mathbf{S},\mathbf{T})})|^2}{\prod_{j=1}^{M} S_j! \prod_{i=1}^{M} T_i!}$$

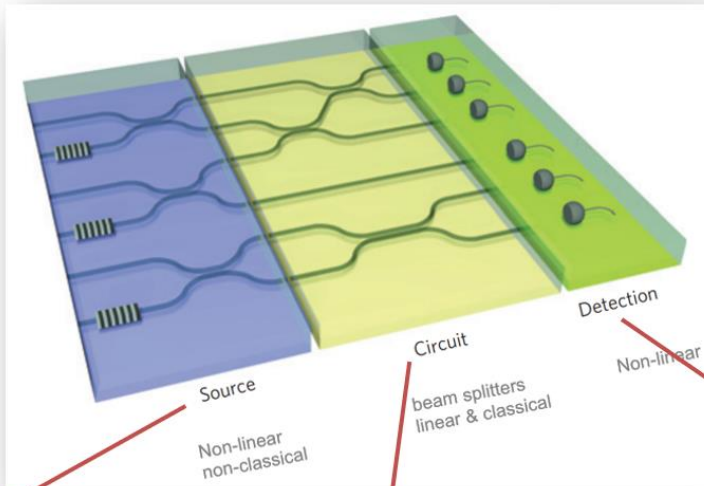
Even an approximate or noisy classical simulation of boson sampling would imply a collapse of the polynomial hierarchy.

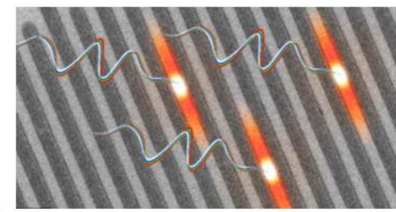
Where we started on 2013…

(winning millions $$$ lottery)^20





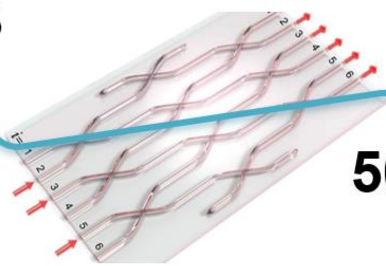




Counts ~600,000/s
Indistinguishability ~90%
Source efficiency ~0.8%

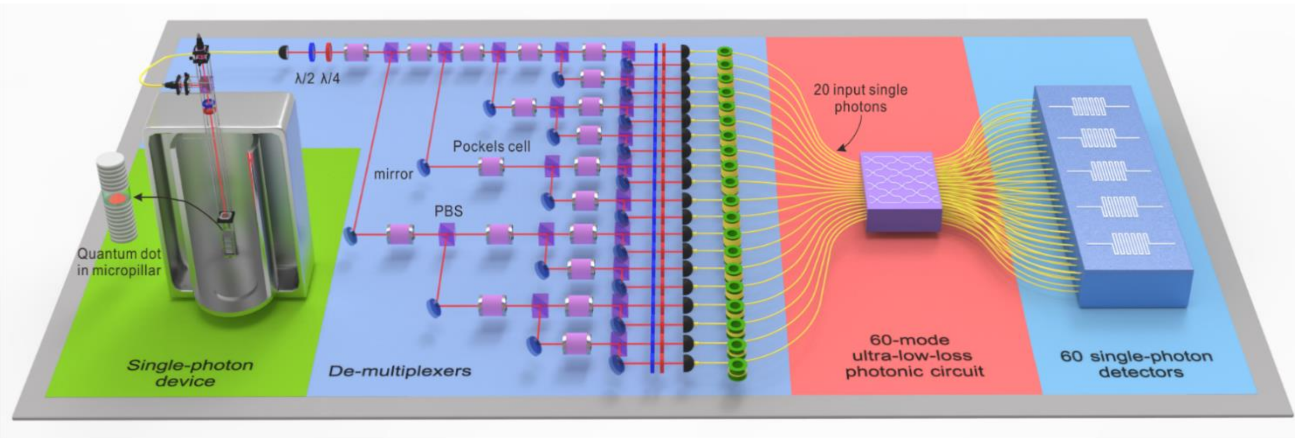
Circuit efficiency: 10%-30%

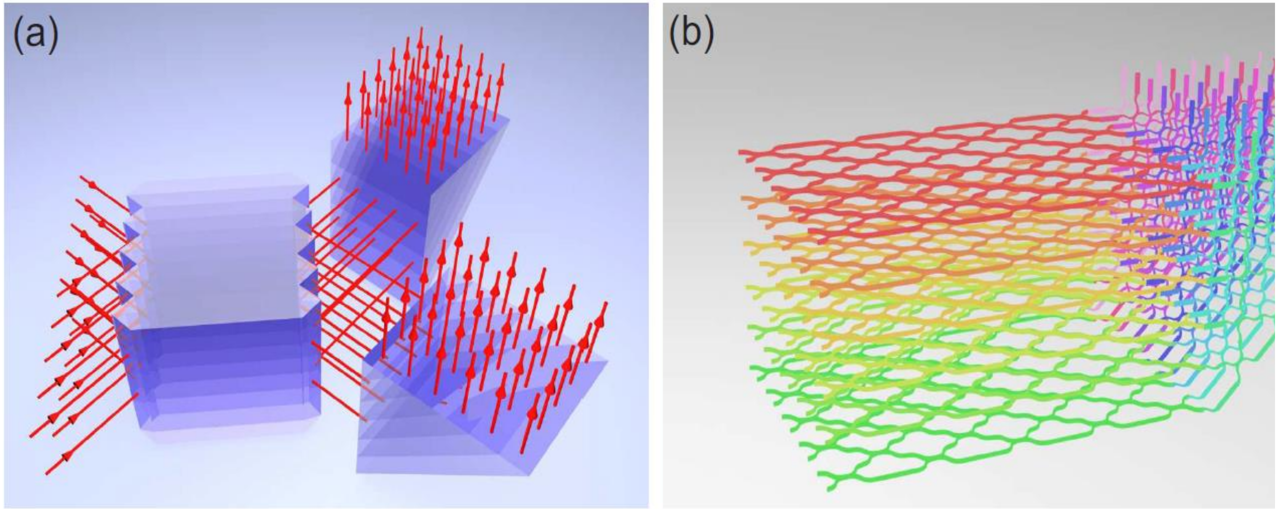
Detection efficiency: 85-90%



50-photon rate about 10^{-150} Hz

State-of-the-Art Standard Boson Sampling





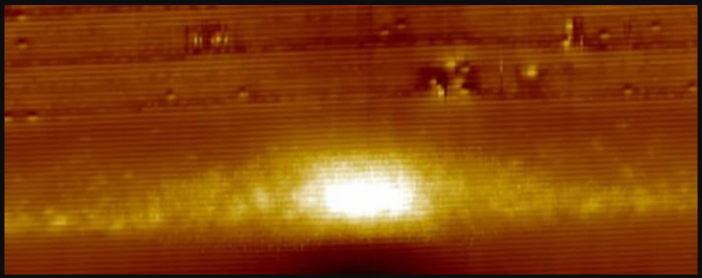
With further optimized sources, boson sampling with 30 photons are in progress

Old estimations from 2013 to 2016 on the regime of quantum supremacy were 20-30 photons

Neville, A. *et al.* (2017) proposed Metropolised independence sampling and raised the bar to ~50 photons!

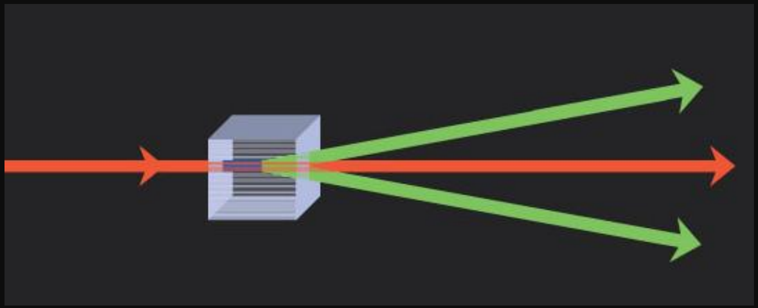
How to go beyond 50?

Phys. Rev. Lett. 123, 250503 (2019)



Pro: Single quantum emitter

Con: Dipole emission inside high-reflective index material hard for collection



Pro: Direction & Gaussian profile inherit from the laser: easy for single-mode collection

Con: Probabilistic & double pair

Conclusion:

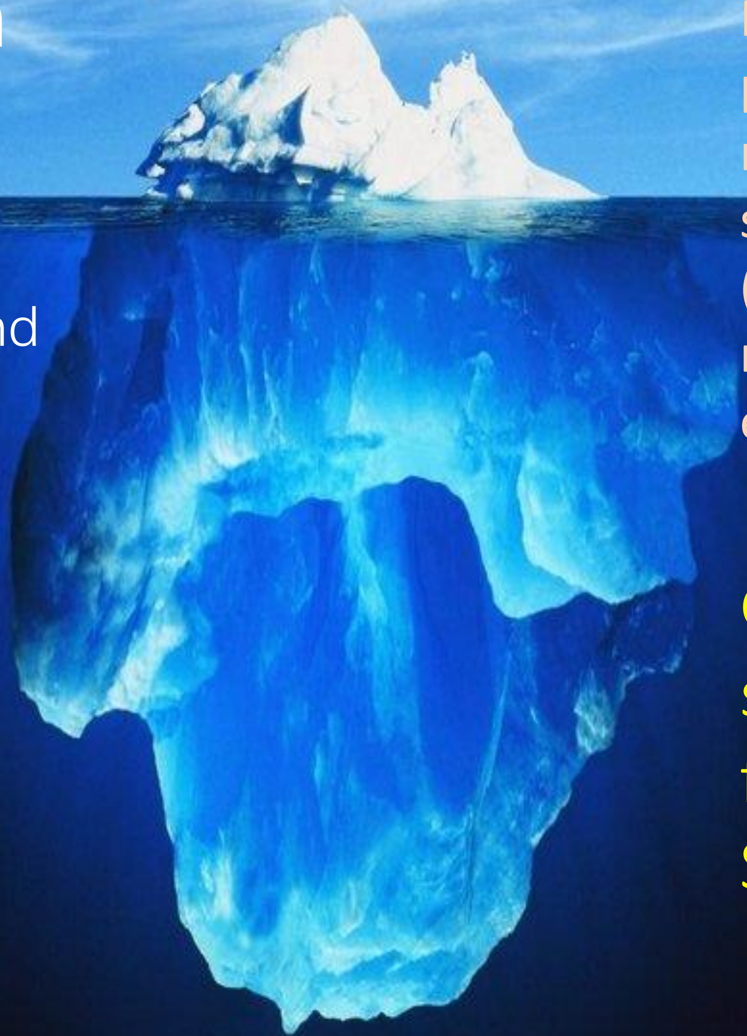
It is still difficult to engineer an indistinguishable (>99% visibility) single-photon source with >90% system efficiency,

however,

It is much easier to have an SPDC with >99% indistinguishability and >90% collection efficiency simultaneously - if the Gaussian nature of the PDC is not a problem.

Gaussian boson sampling:

How I stop worrying the multiphoton emission and fall in love with the full states of SPDC



Most previous multi-photon experiments restrict themselves to a small SPDC probability (<0.05) regime to reduce multi-pair emission

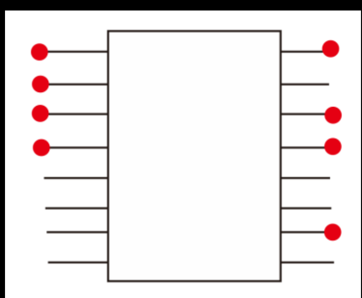
Gaussian boson sampling makes full use of the SPDC

Hamilton, Kruse, Sansoni, Barkhofen, Silberhorn & Jex, Gaussian Boson Sampling. Phys. Rev. Lett. 119, 170501 (2017).
Quesada, Arrazola, & Killoran, Gaussian boson sampling using threshold detectors. Phys. Rev. A 98, 062322 (2018).

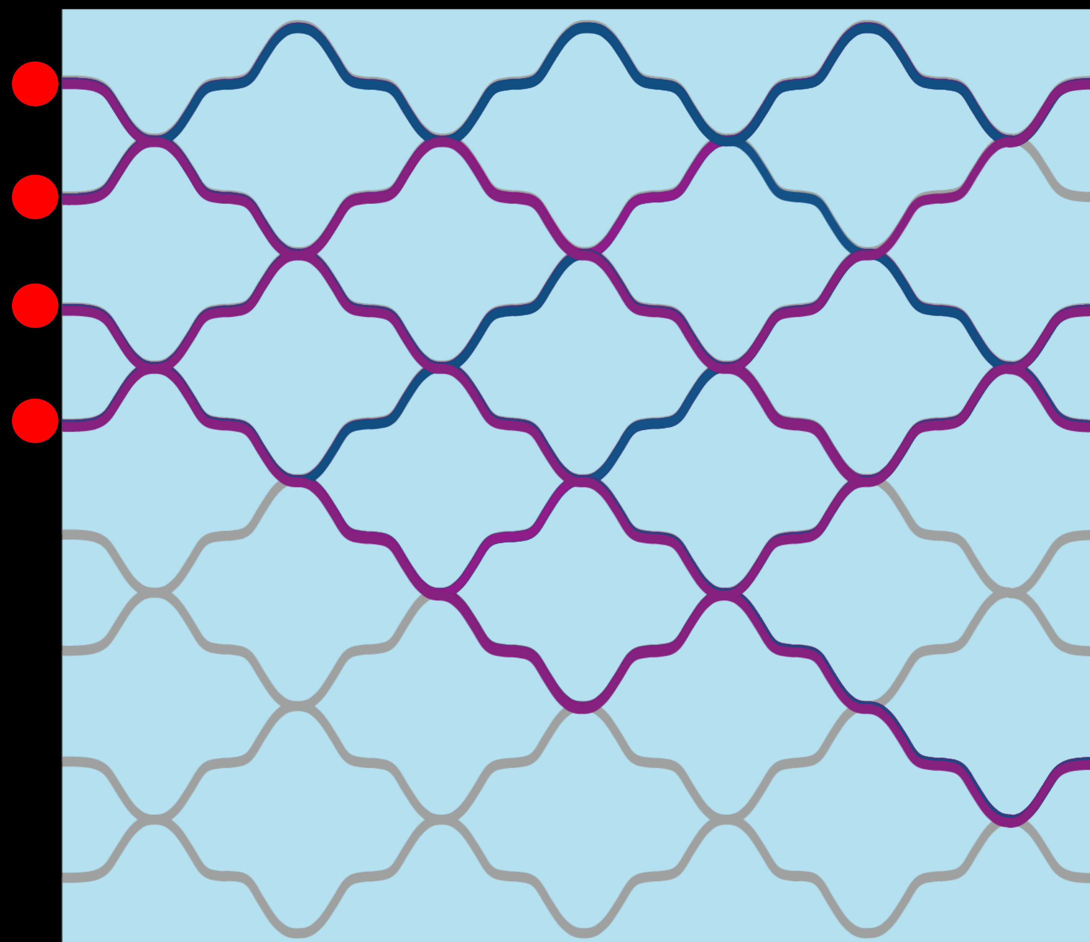
It's all about the sum of the probability amplitudes of all indistinguishable paths that can lead to the event

Output N-photon coincidence count

1234→1347; already 23520 combinations

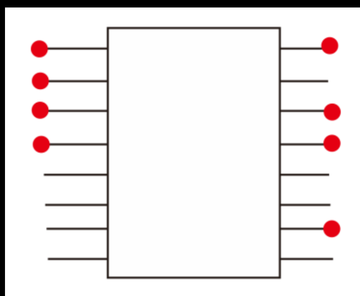


Aaronson-Arkhipov boson sampling



It's all about the sum of the probability amplitudes of all indistinguishable paths that can lead to the event

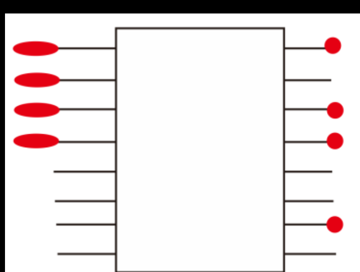
Output *N*-photon coincidence count



Aaronson-Arkhipov boson sampling

$$\left|\text{single photon}\right\rangle_{\text{input}} = \left|1\right\rangle$$

$$\begin{aligned} P_N &= \left|\sum \text{all possible paths lead to N-photon count}\right|^2 \\ &= \left|\text{Permanent(submatrix)}\right|^2 \end{aligned}$$

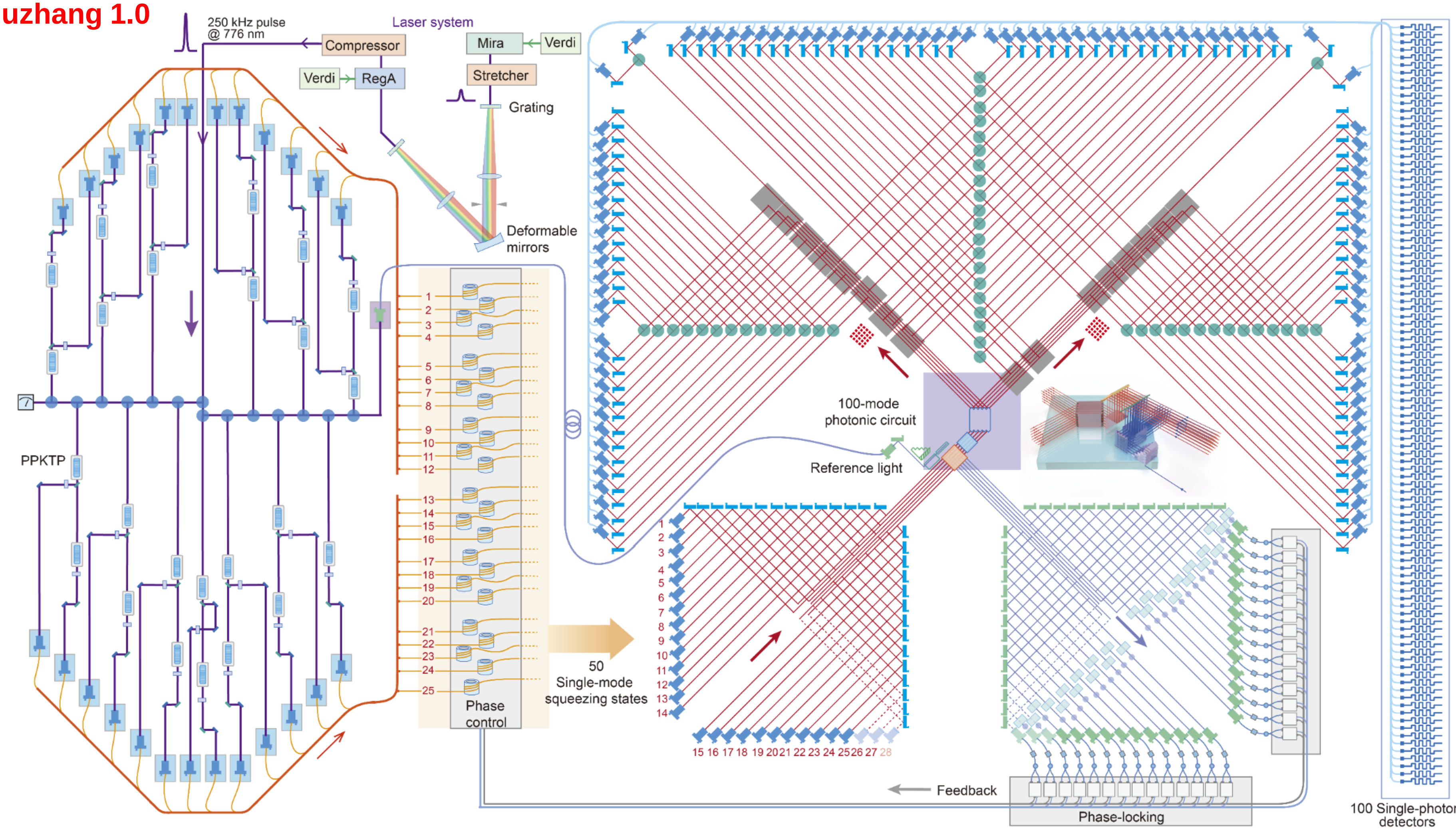


Gaussian boson sampling

$$\left|\text{squeezed vacuum}\right\rangle_{\text{input}} = \sum_{k=0}^{\infty} g(\mathrm{k})\, e^{ik\phi} \left|2k\right\rangle$$

$$\begin{aligned} P_N &= \left|\sum \text{all possible input photon-number combination} \sum \text{all possible paths}\right|^2 \\ &= \left|\text{Hafnian[submatrix}(\gamma, \phi, \mathrm{U})]\right|^2 \end{aligned}$$

Jiuzhang 1.0



250 kHz pulse
@ 776 nm
Laser system
Compressor
Mira
Verdi
Verdi
RegA
Stretcher
Grating
Deformable
mirrors
PPKTP
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19
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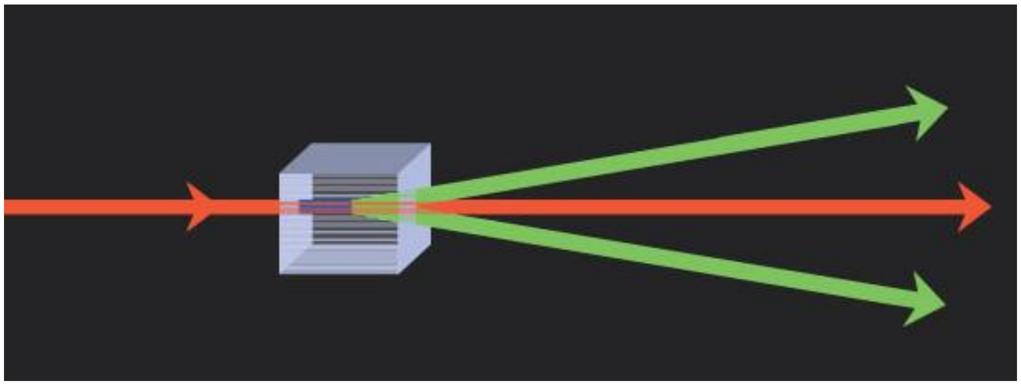
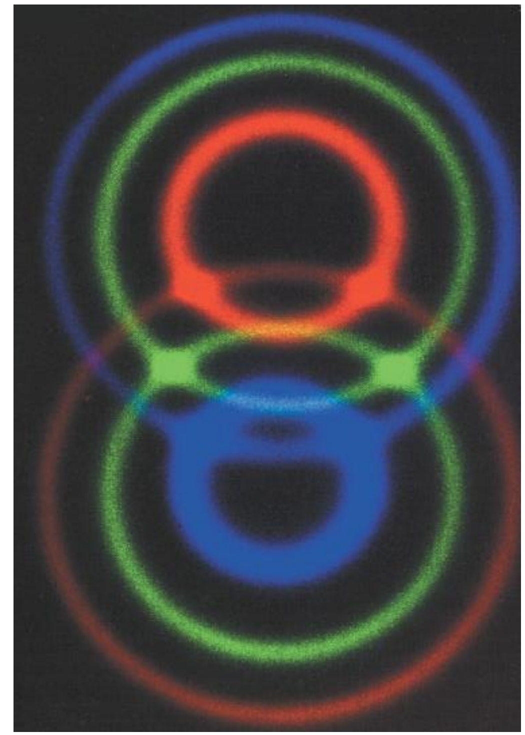
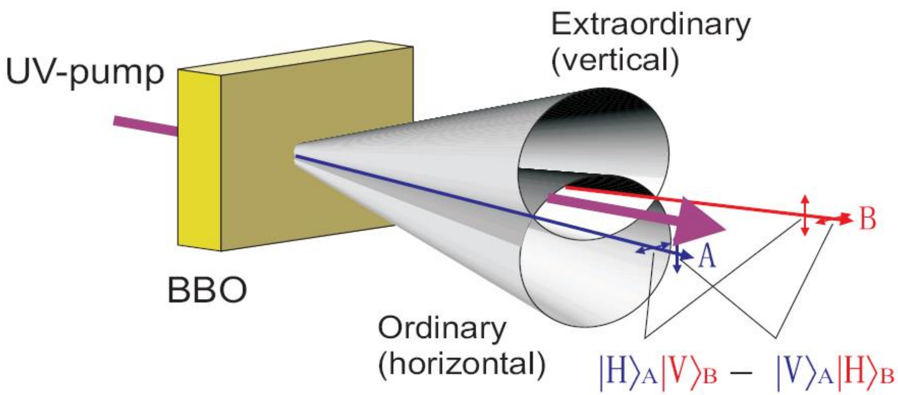
21
22
23
24
25
Phase
control
50
Single-mode
squeezing states
100-mode
photonic circuit
Reference light
15 16 17 18 19 20 21 22 23 24 25 26 27 28
Feedback
Phase-locking
100 Single-photon
detectors

Optimal squeezed light source





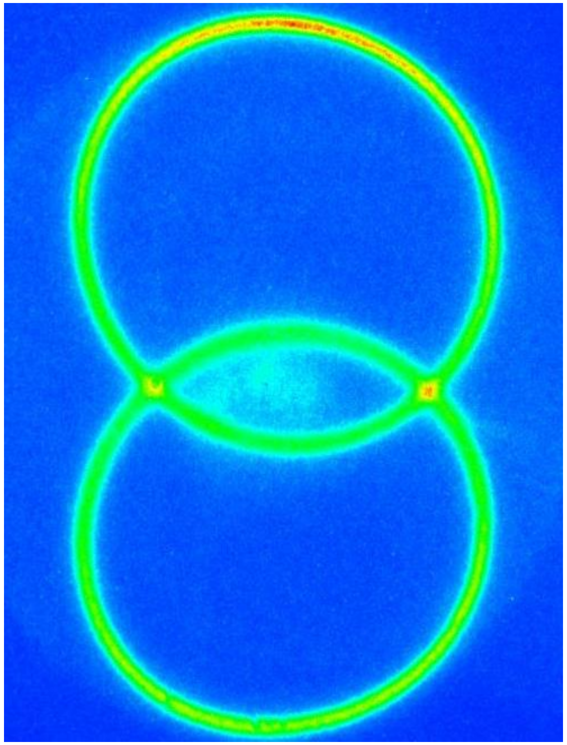


Kwiat *et al.* PRL (1995)

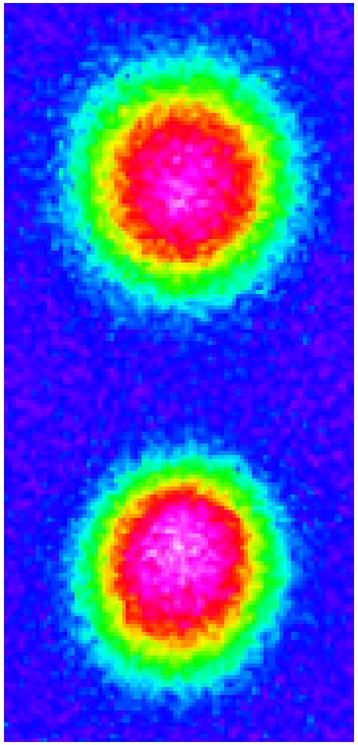
$|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B$

Optimal squeezed light source

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



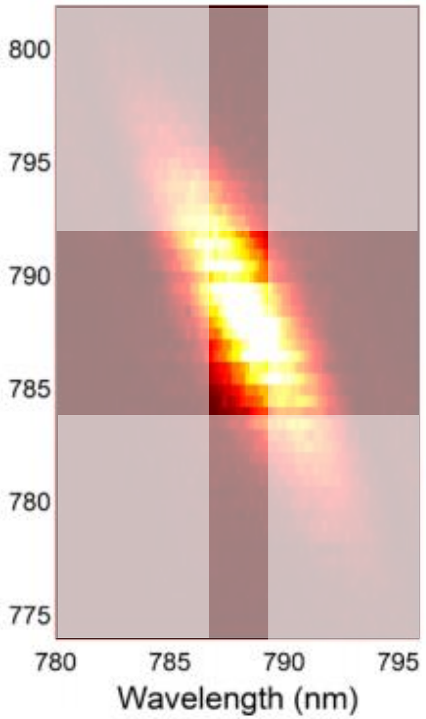
10-photon entanglement,
Wang et al. *Phys. Rev. Lett.* (2016)



Efficiency: 40% >>> 70%

Optimal squeezed light source

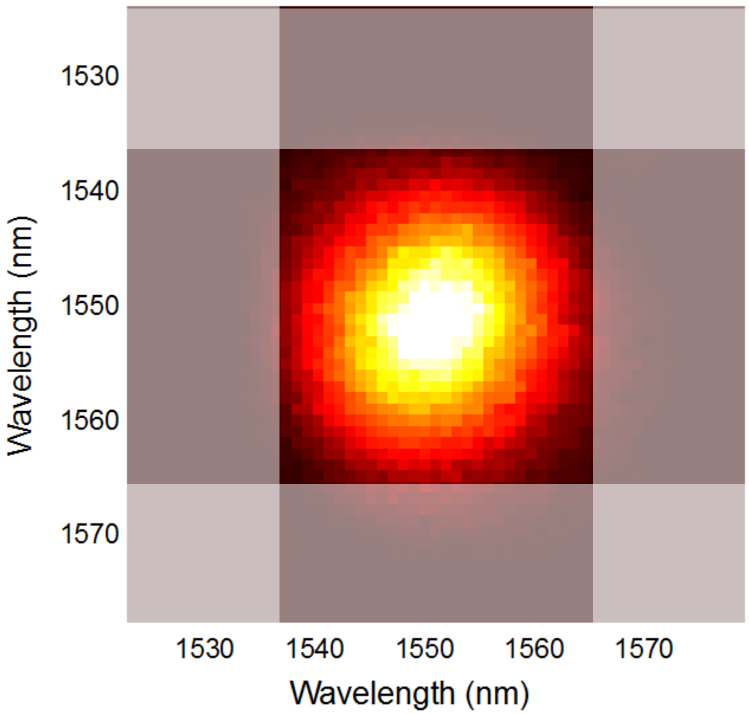
10-photon entanglement,
Wang *et al.* *Phys. Rev. Lett.* (2016)



3 nm – 8 nm filter

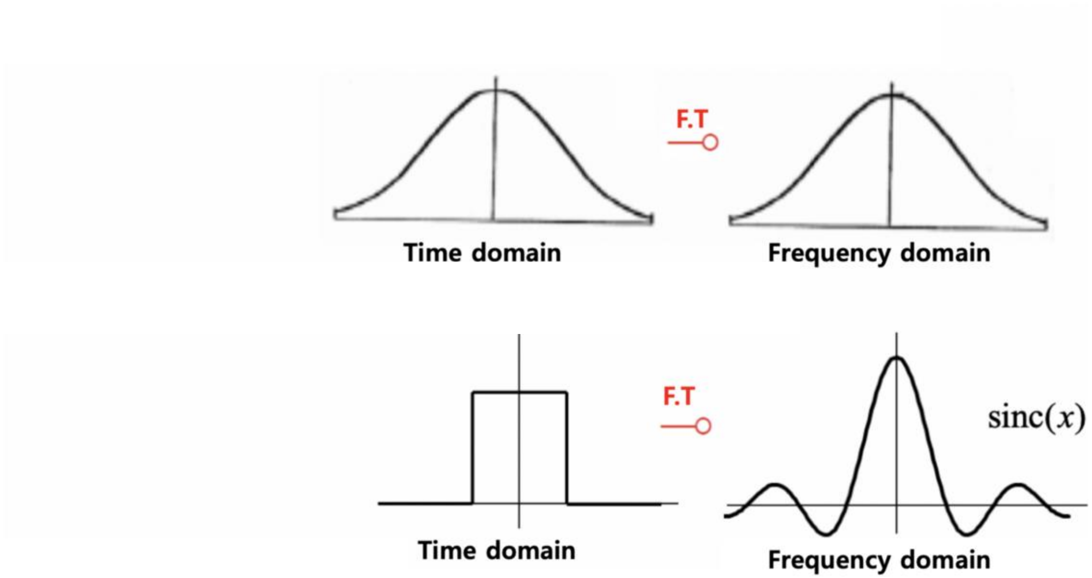
Efficiency: 70% >>> 87%

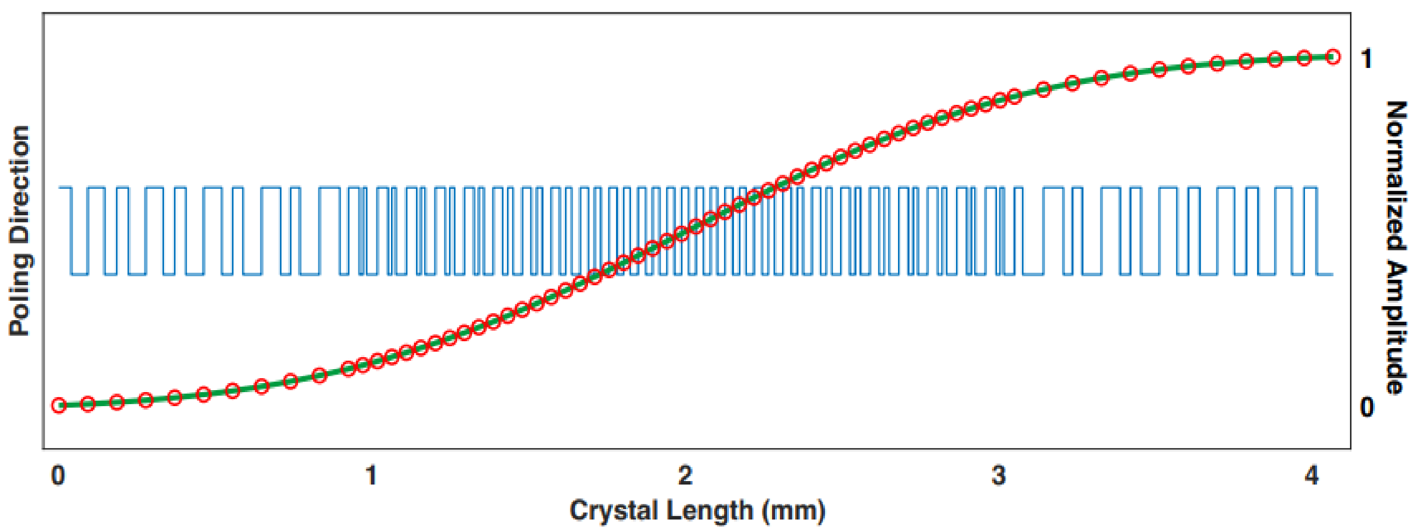
12-photon entanglement,
Zhong *et al.* *Phys. Rev. Lett.* (2018)



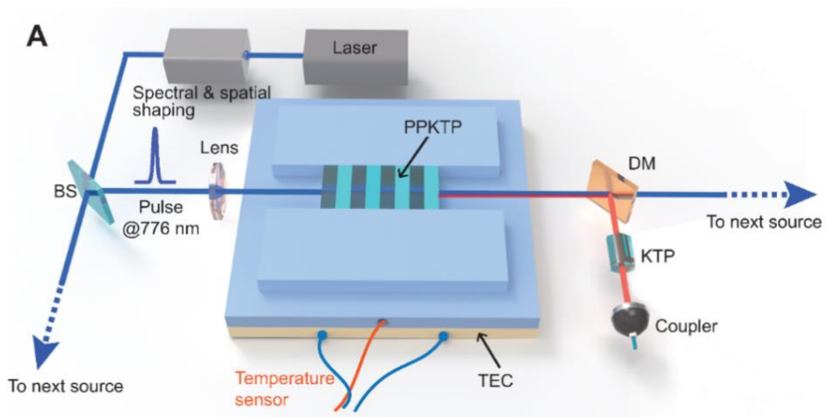
30 nm filter

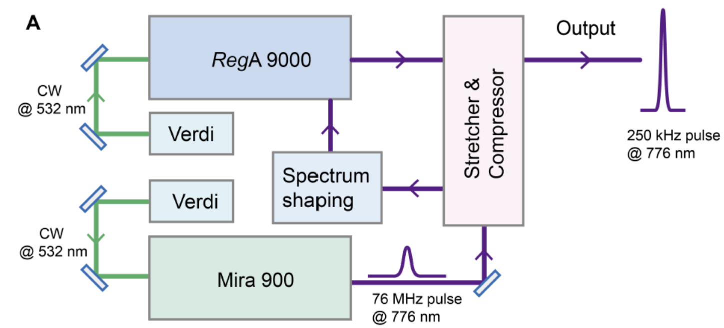
Optimal squeezed light source

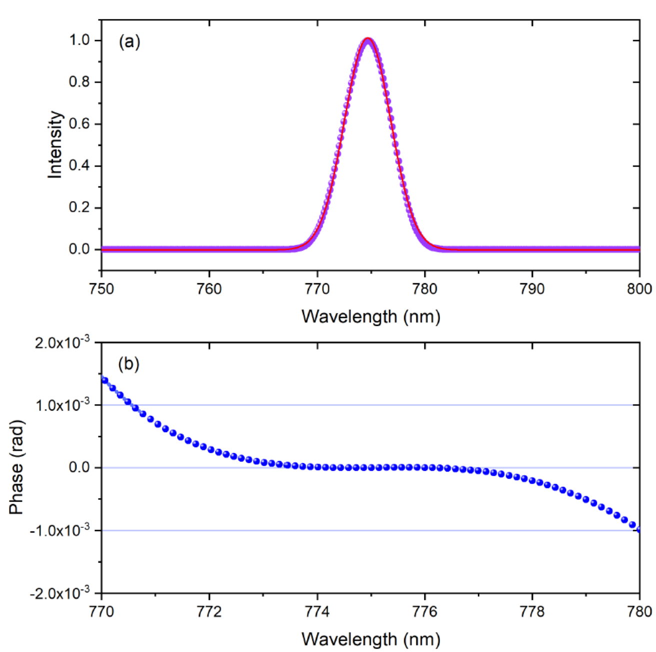


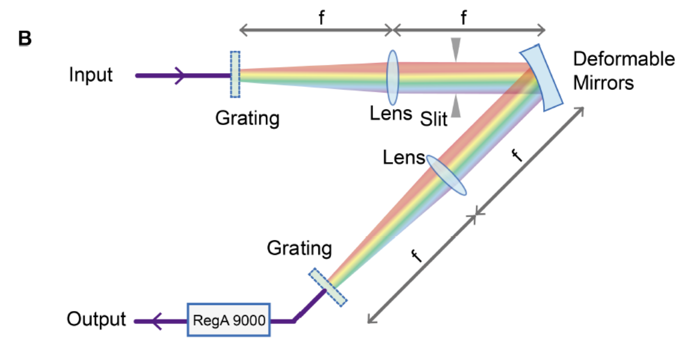


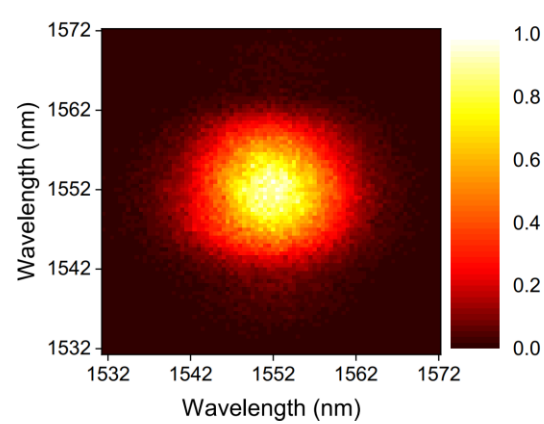
High Quality Quantum Photon Source







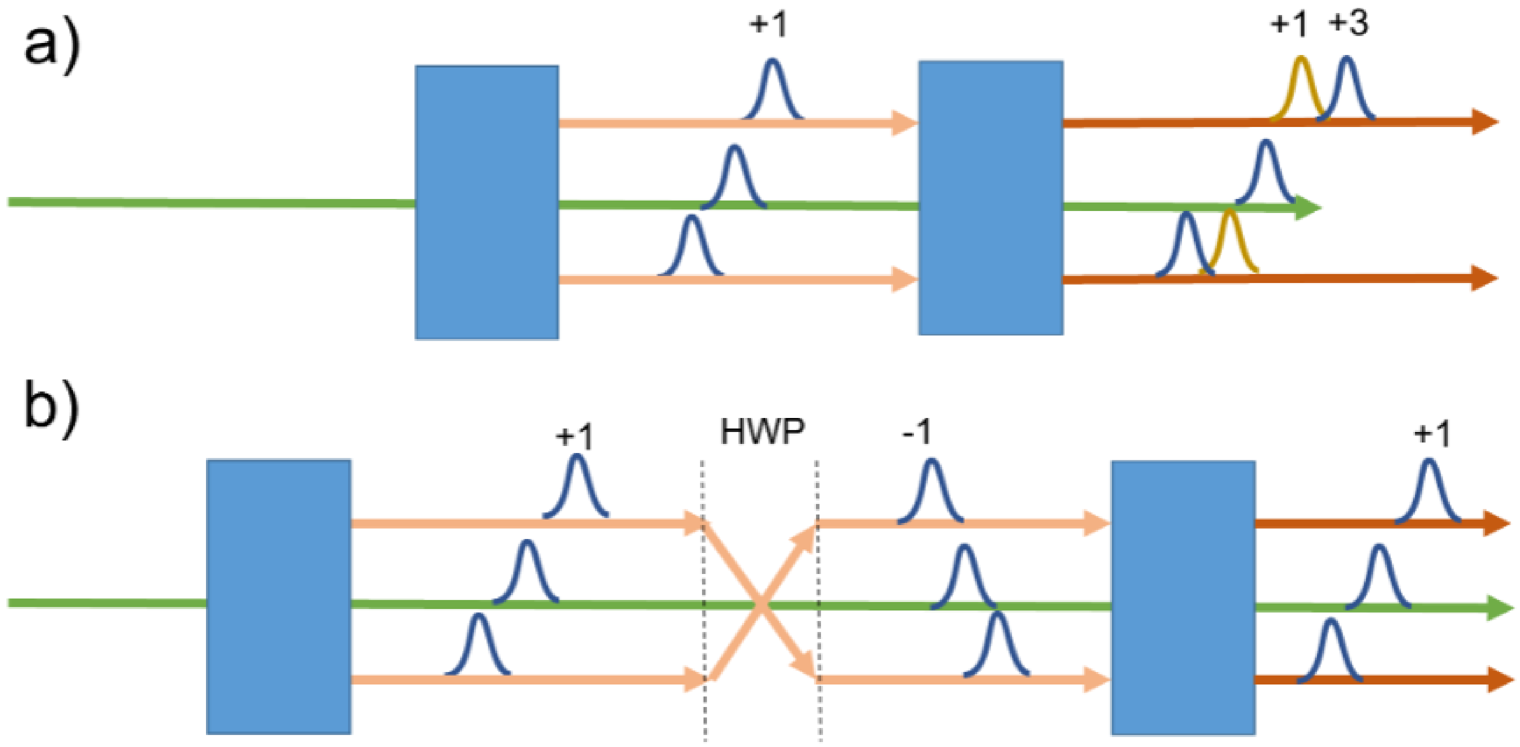




High Quality Quantum Photon Source

Stimulated PDC:

same laser power, 4 times brighter
squeezed light



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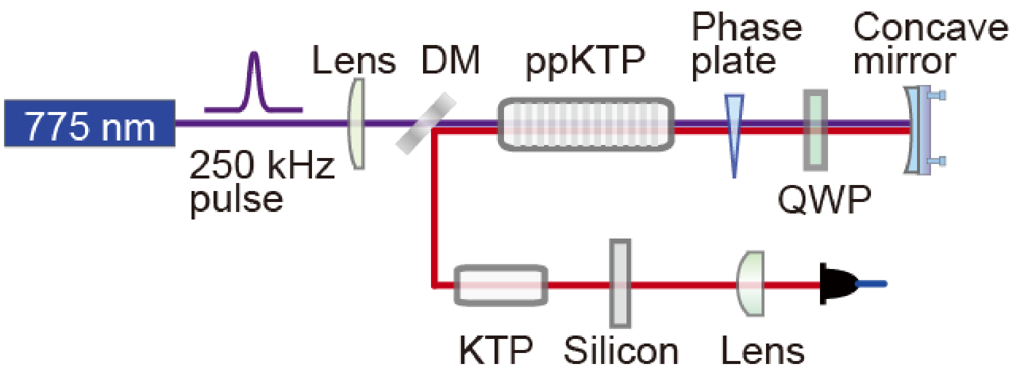

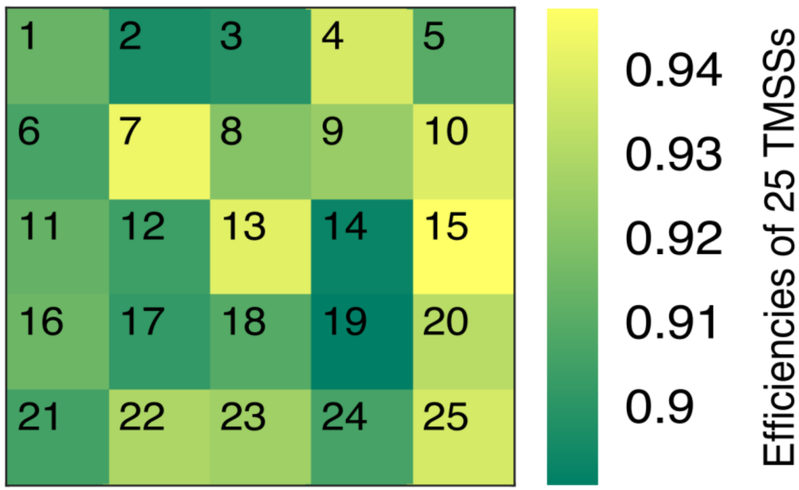

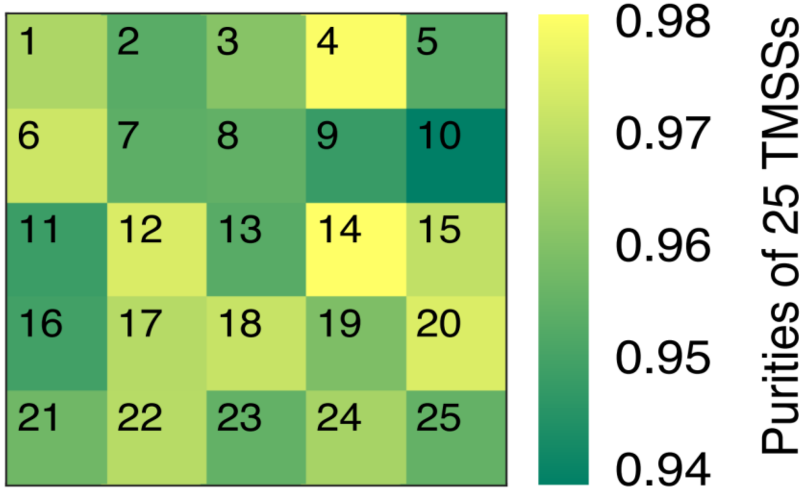

Science 370, 1460 (2020); arXiv:2106.15534

High Quality Quantum Photon Source

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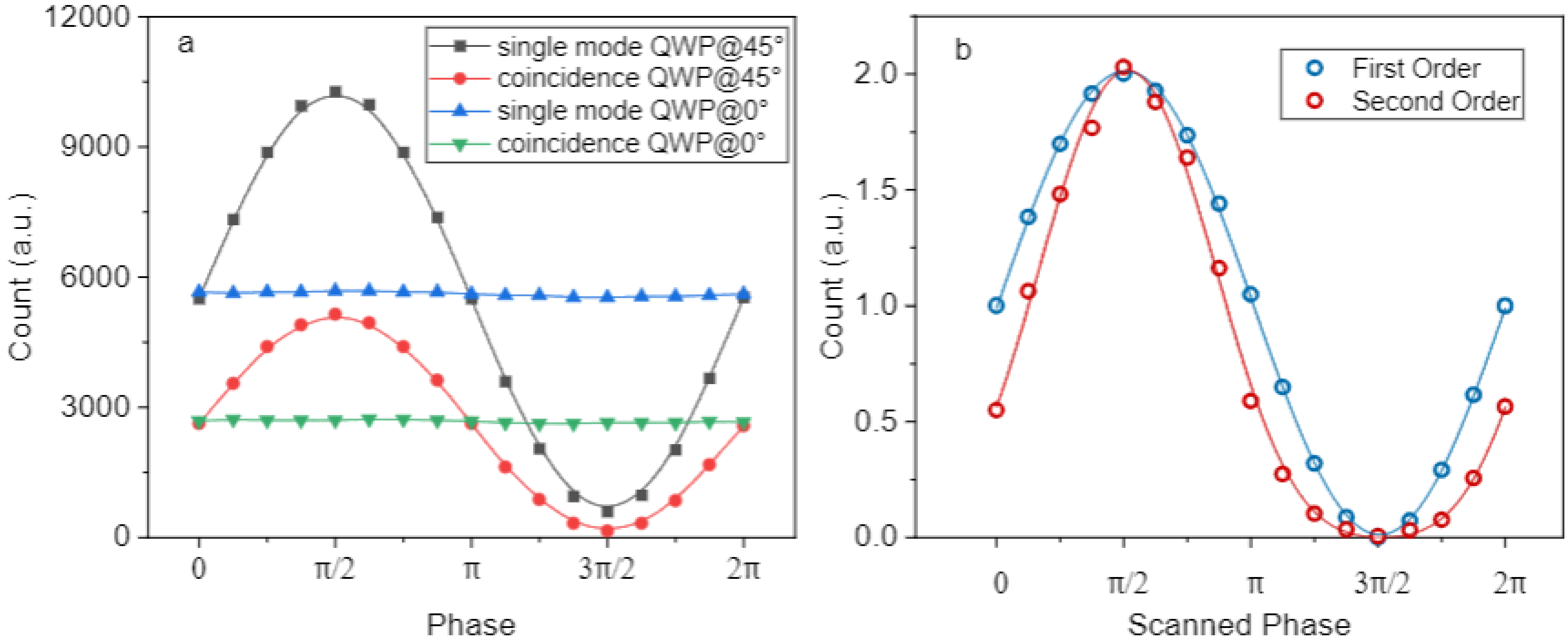
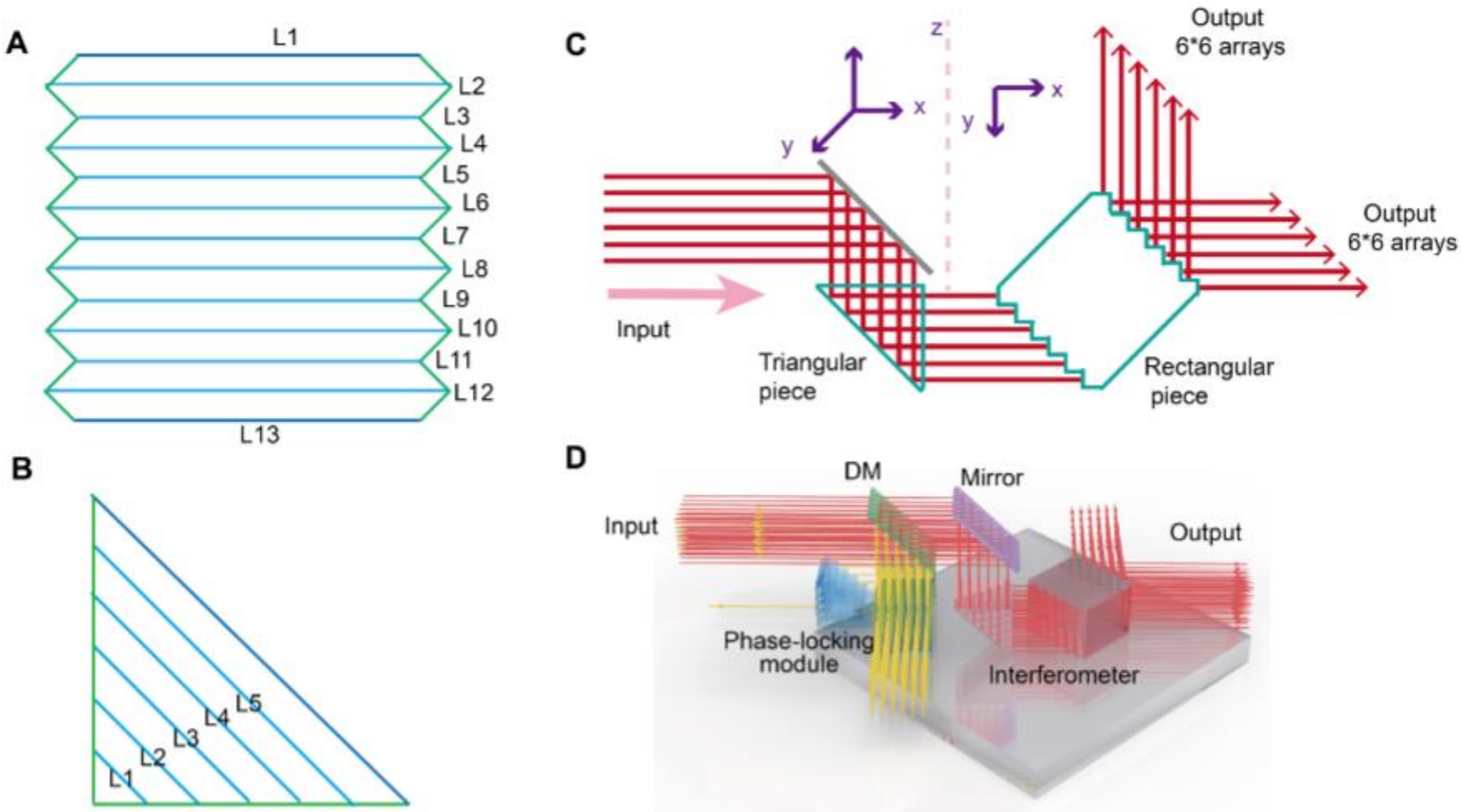
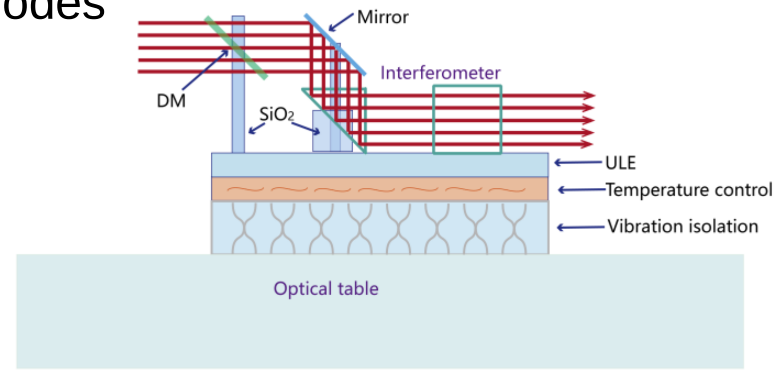


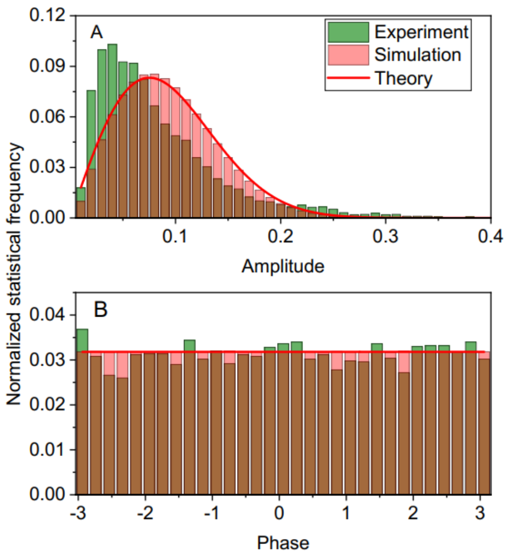
Scalable Ultra-High Efficiency Interferometer

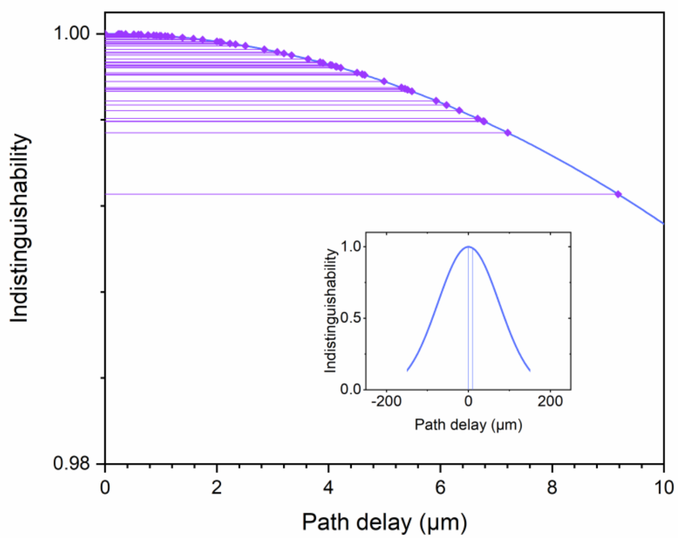


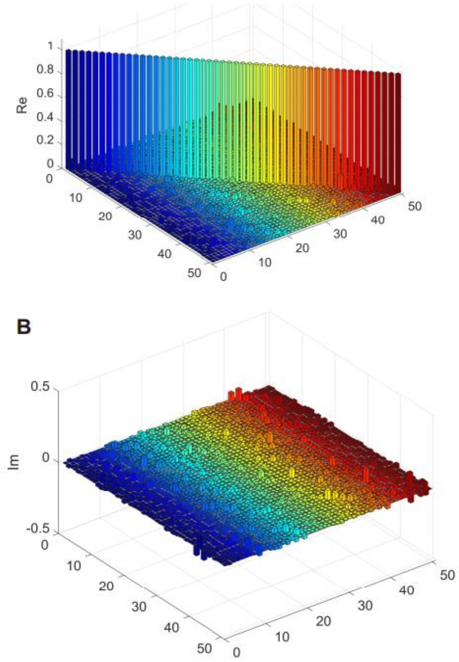
Scalable Ultra-High Efficiency Interferometer

- State-of-the-art scale: 144×144 input-output modes
- Full-connection
- Random matrix
- Stable phase
- Wave-packet overlap >99.8%
- Transmission efficiency >98%

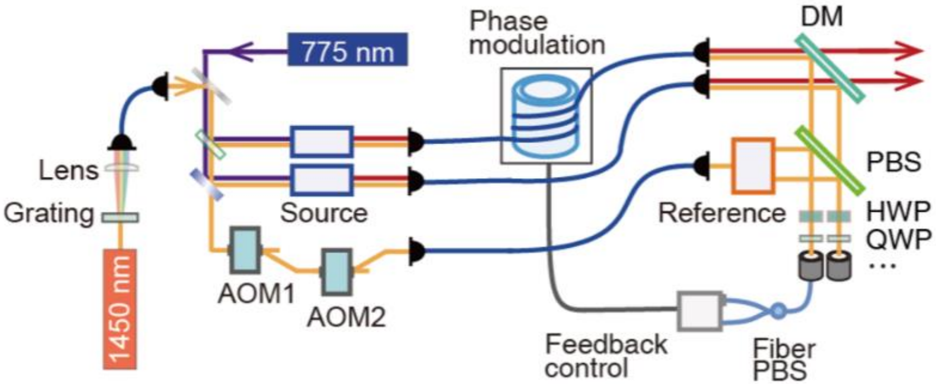


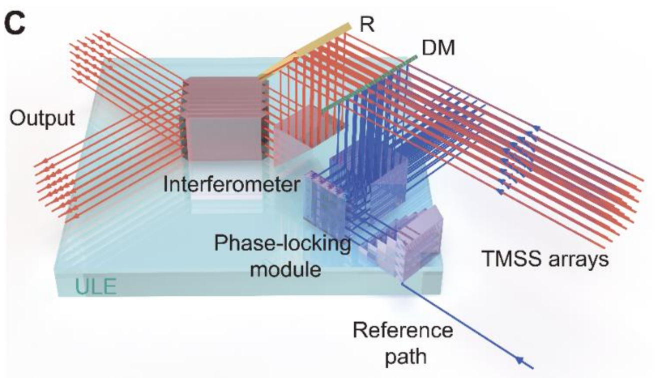


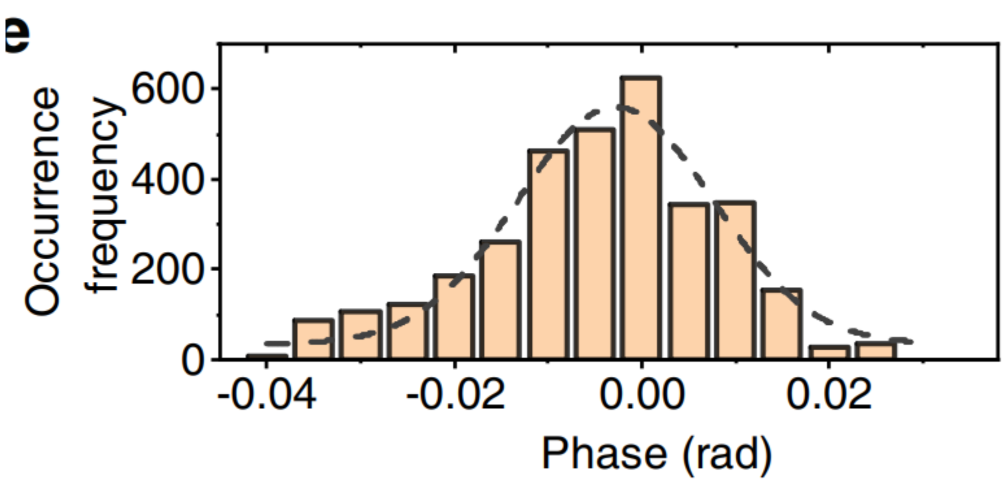




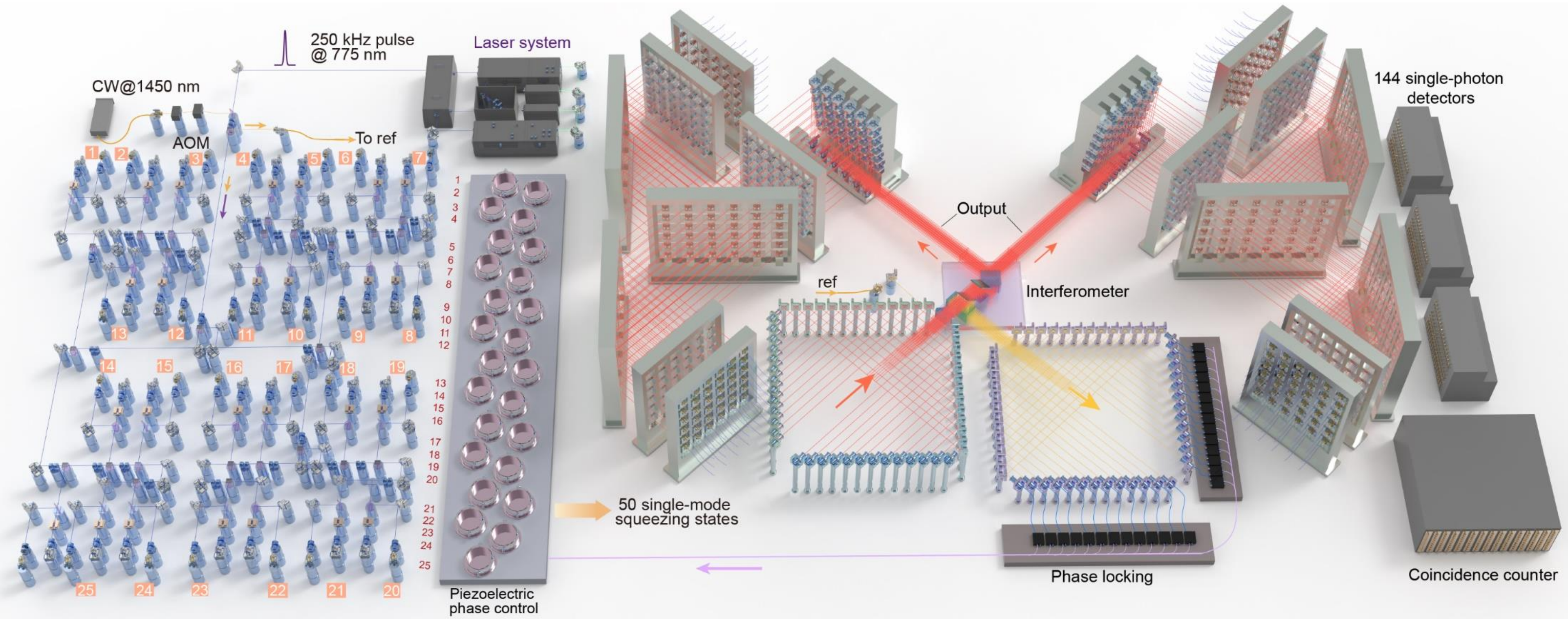
Active phase locking







Jiuzhang 2.0

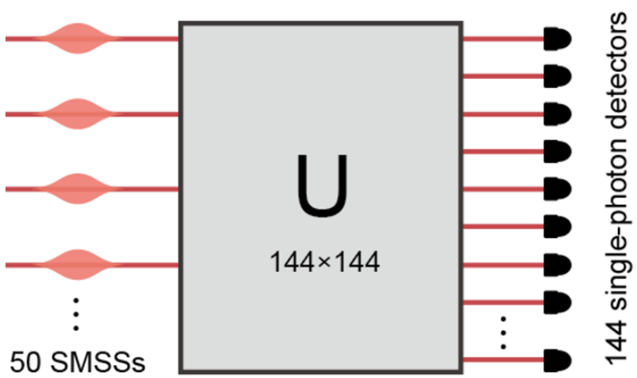


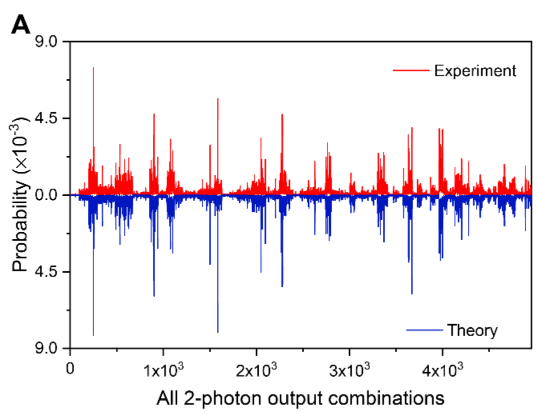
Science 370, 1460 (2020); PRL 127, 180502 (2021)

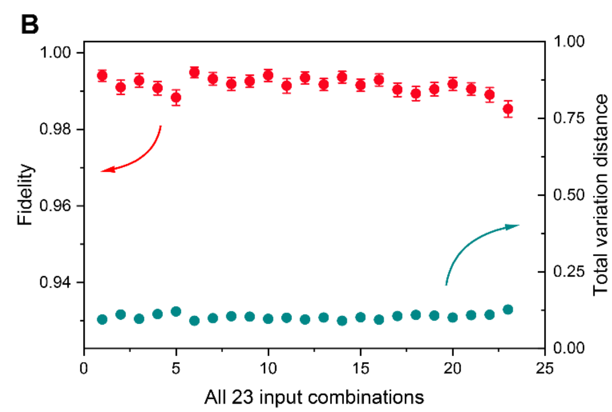
Three different regimes:

- **Easy regime**: can obtain the full output distribution. (2-4 photons)
- **Sparse regime**: only a small fraction of output combinations can obtain one event, while most output will have zero events. (5-40 photons)
- **Intractable regime**: when the output click number exceeds ~40, the calculation of one matrix function becomes classically too hard. (>40 photons)

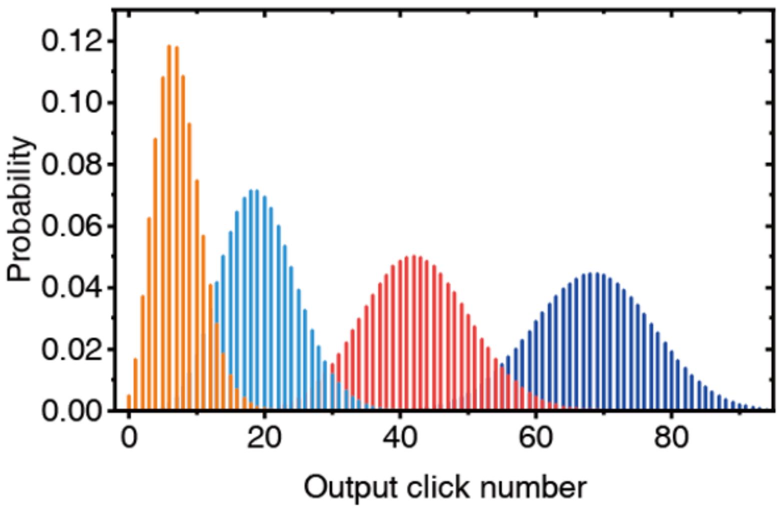
System calibration at easy regime

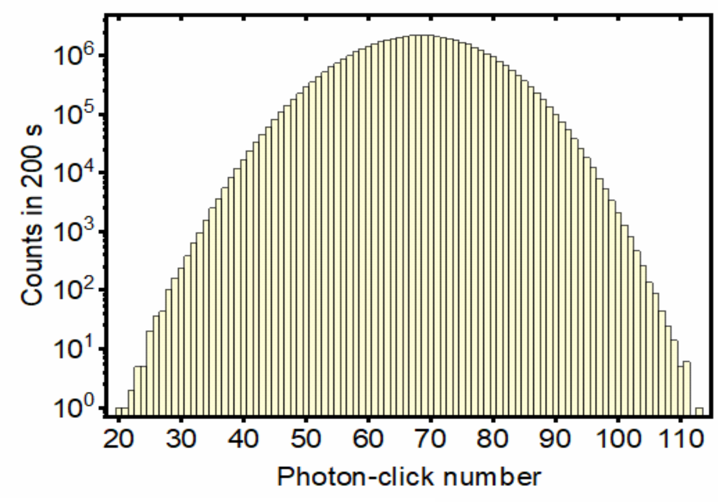




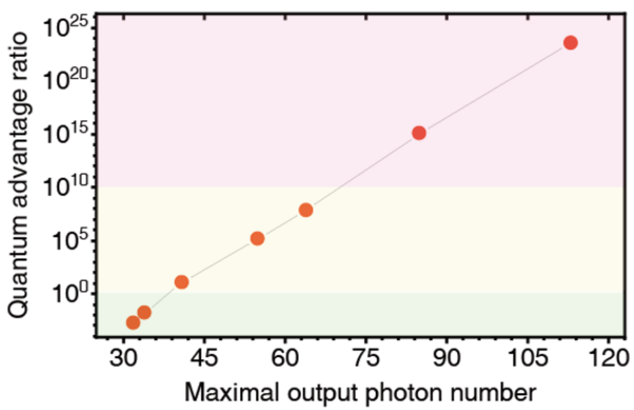


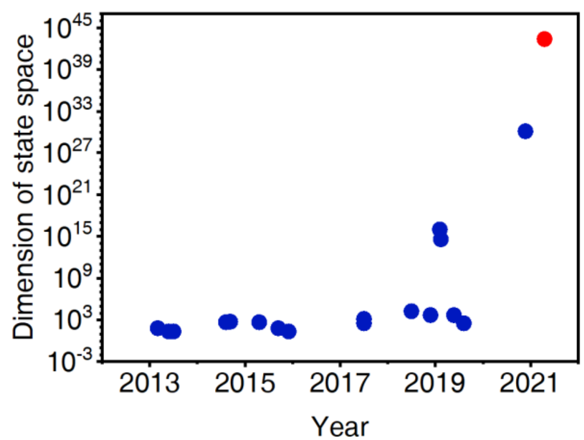
All the raw data are available at
http://quantum.ustc.edu.cn/web/node/951





Max photon click: 113





Hilbert-space dimension

Sycamore: 10^{16}

Jiuzhang 1.0: 10^{30}

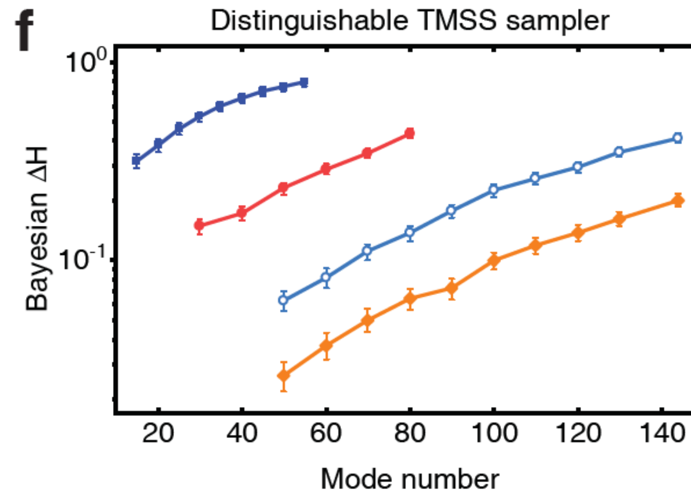
Jiuzhang 2.0: 10^{43}

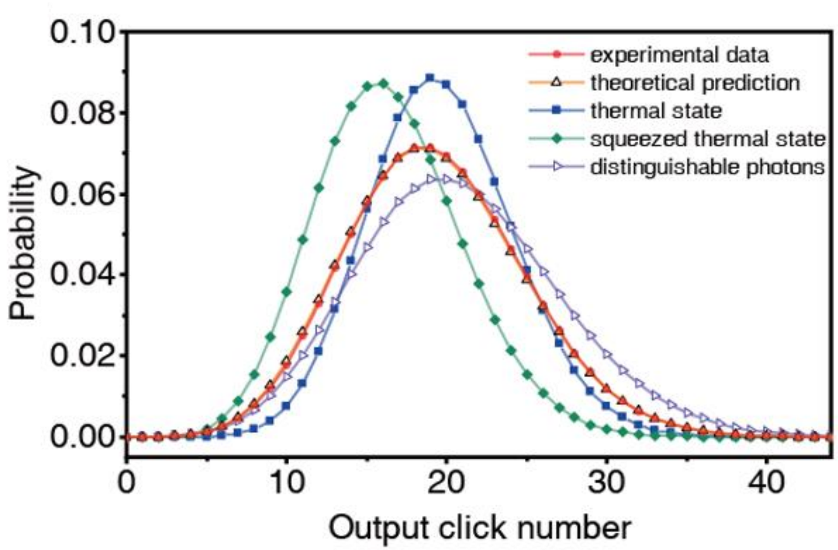
Unlike **Shor's algorithm** where its solution can be efficiently
of the outcome is strongly conjectured to be intractable for cla

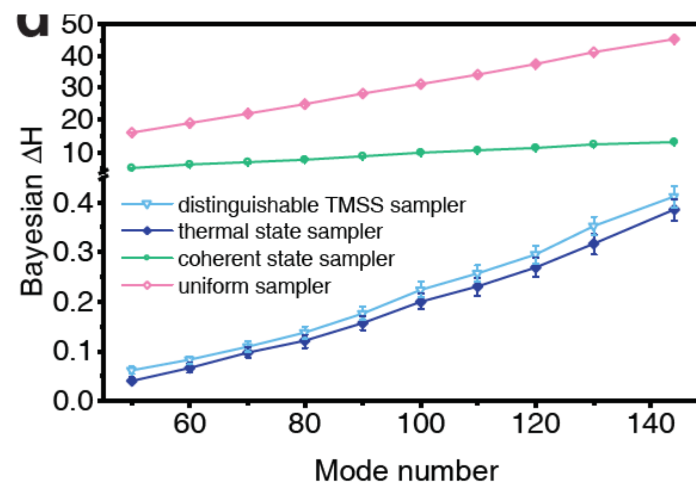
How to validate?

Gathering circumstantial evidence while ruling out possible hy

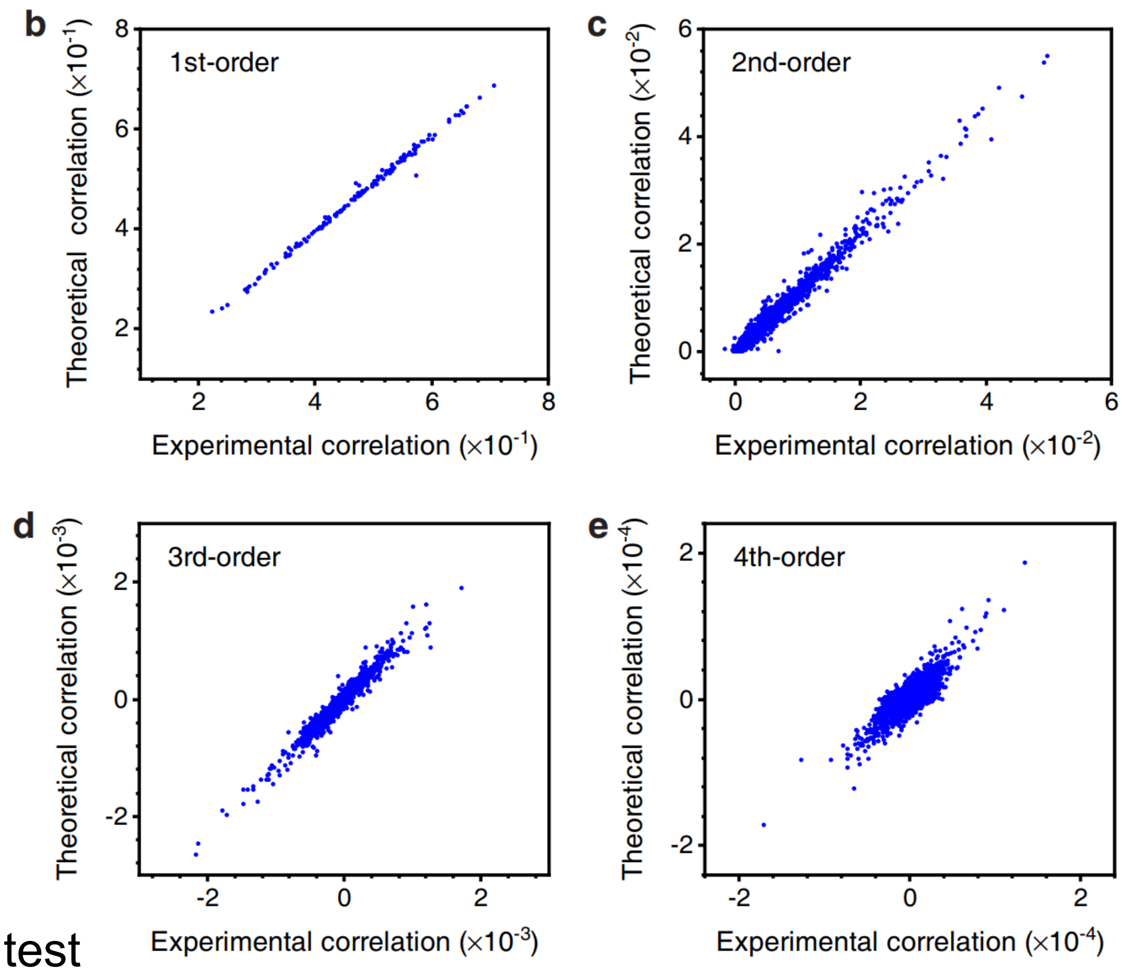
- Thermal states—would result from excessive photon loss
- Distinguishable—would be caused by mode mismatch
- Uniform, coherent, … more are welcome!







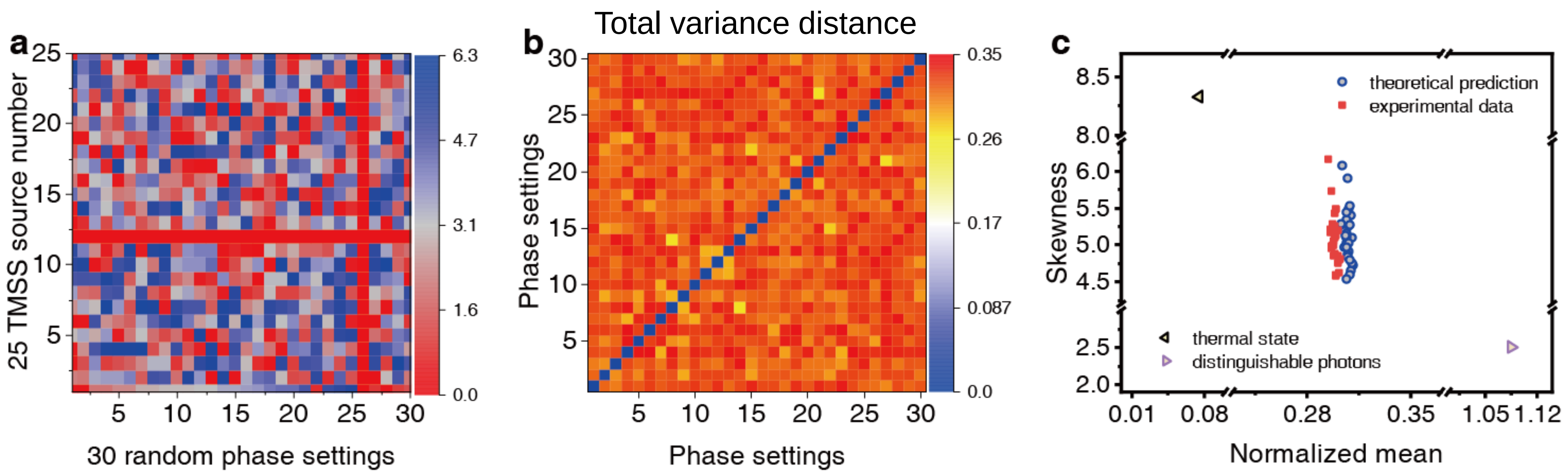
High order correlation



Spearman's rank order test

$p<0.05$ for k=19+/-1

Phase-programmable GBS



We change 30 random input squeezed state phases and obtain 30 statistically different samples, each are validated against mockups.

Science 370, 1460 (2020); arXiv:2106.15534

<u>Next:</u>

- Make the interferometer fully tunable. Looking for applications.
- Any genuine quantum advantage in the existing protocols?

Applications

Fig. 5: Vibronic spectra experiment.

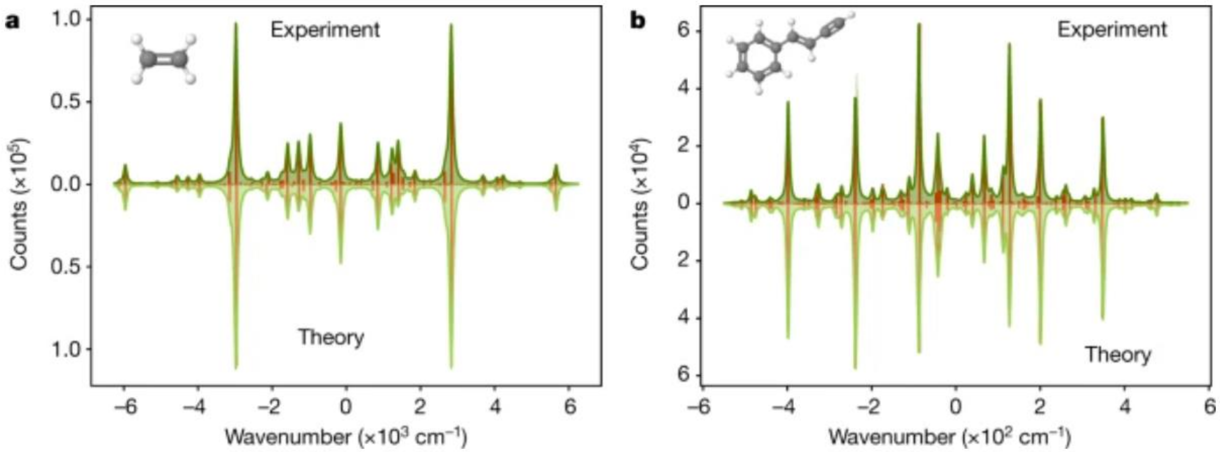
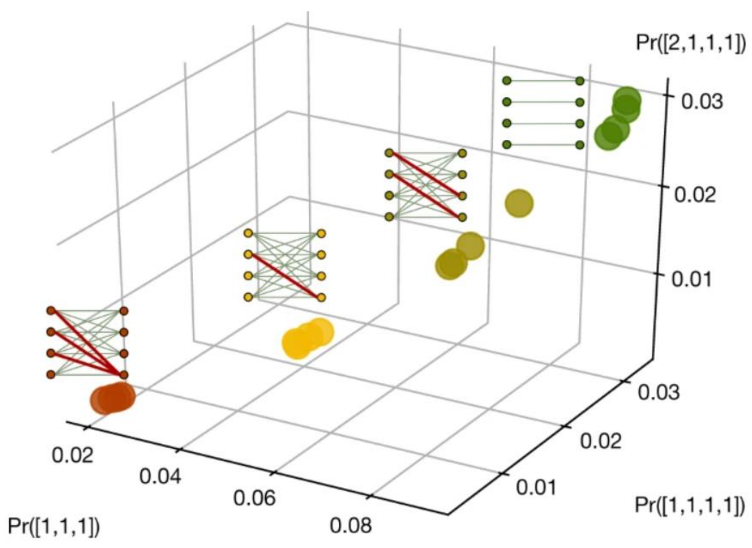


Fig. 6: Graph similarity experiment.



Nature **volume 591**, pages54–60 (2021)

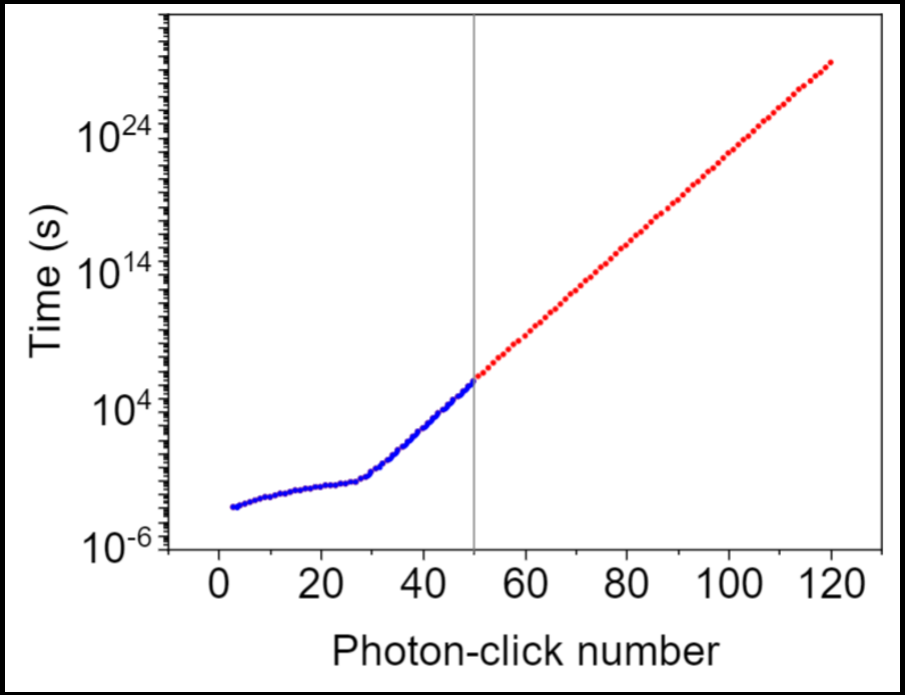
Xanadu

A computational analogue of Bell experiments

Quantum computation advantage experiments:

Refute the extended Church–Turing thesis

10^{24} times faster than a supercomputer



"We hope this work will inspire new theoretical efforts to verify large-scale GBS, improve the classical simulation strategies, and challenge the observed quantum computational advantage."

I Thank Chao-Yang Lu and Yu-Hao Deng for sharing some slides.

Acknowledgement