Quantum computational advantages using photons and beyond

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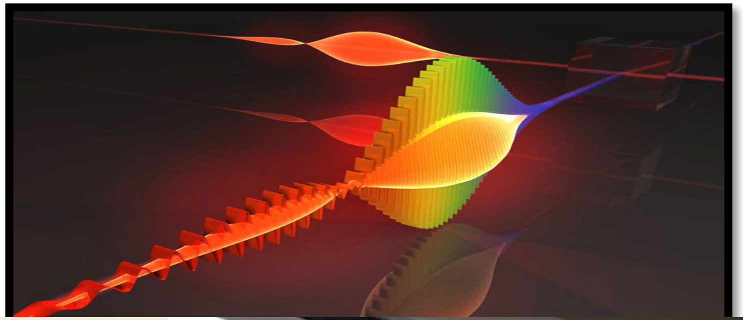
Quantum information technologies with photons

Quantum bits can be encoded in the polarization of single photons



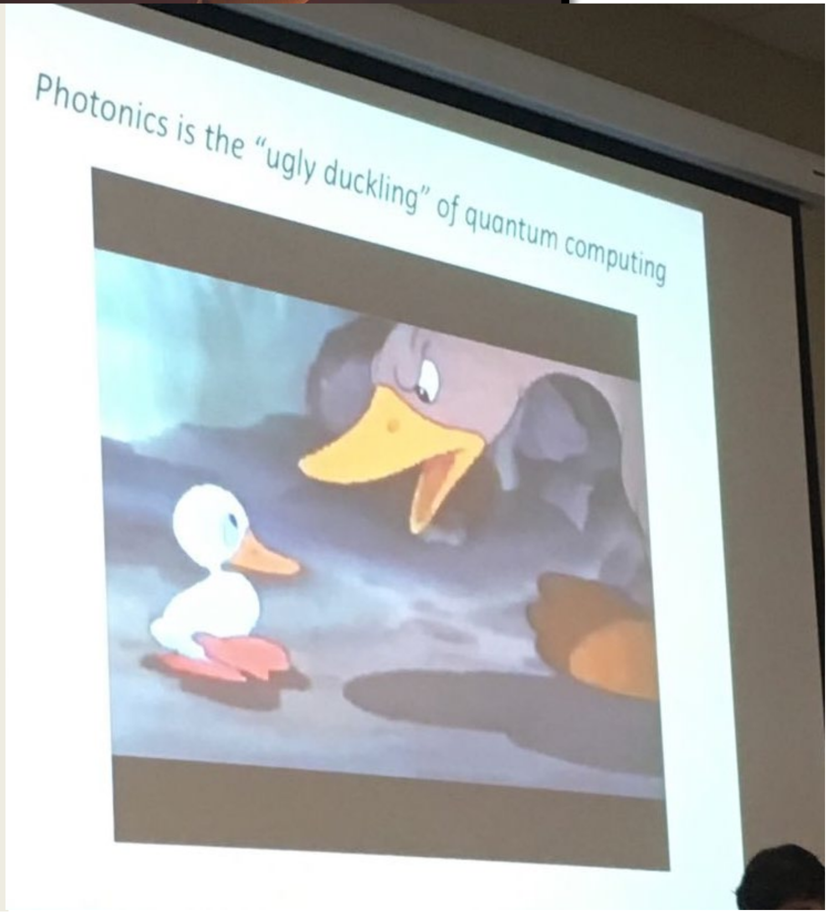
$$|H\rangle = |0\rangle \quad |V\rangle = |1\rangle$$

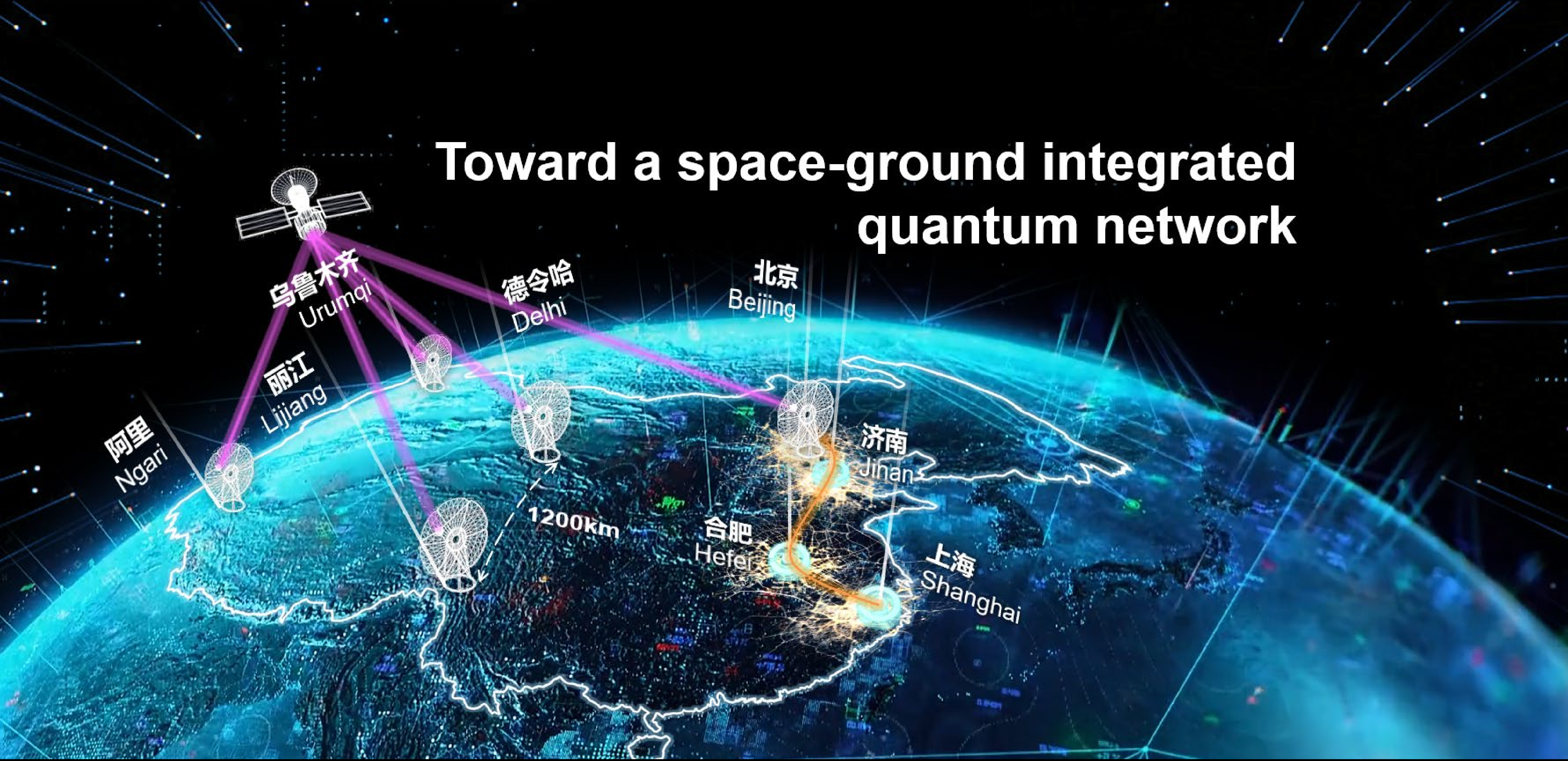
Why do people like photons?

- ☑ Flying qubit (fastest quantum information transmitter)
- ☑ Robust qubit (with weak interaction with environment)
- ☑ High-precision manipulation with off-the-shell devices
- ☑ Interconnections between distant physical systems

Why do people dislike photons?

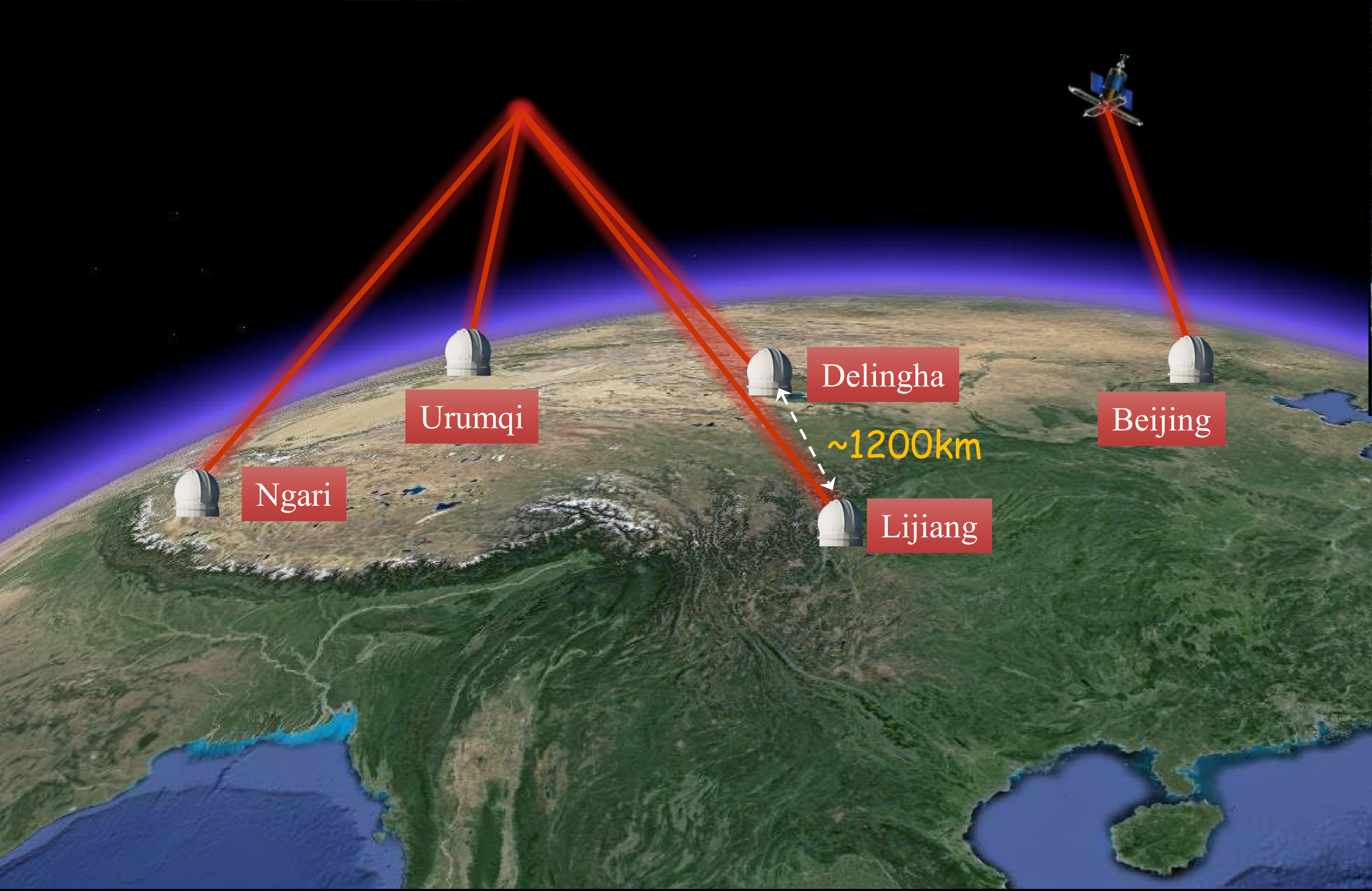
- ☑ Photon loss is everywhere…
- ☑ Weak interaction – deterministic CNOT is hard



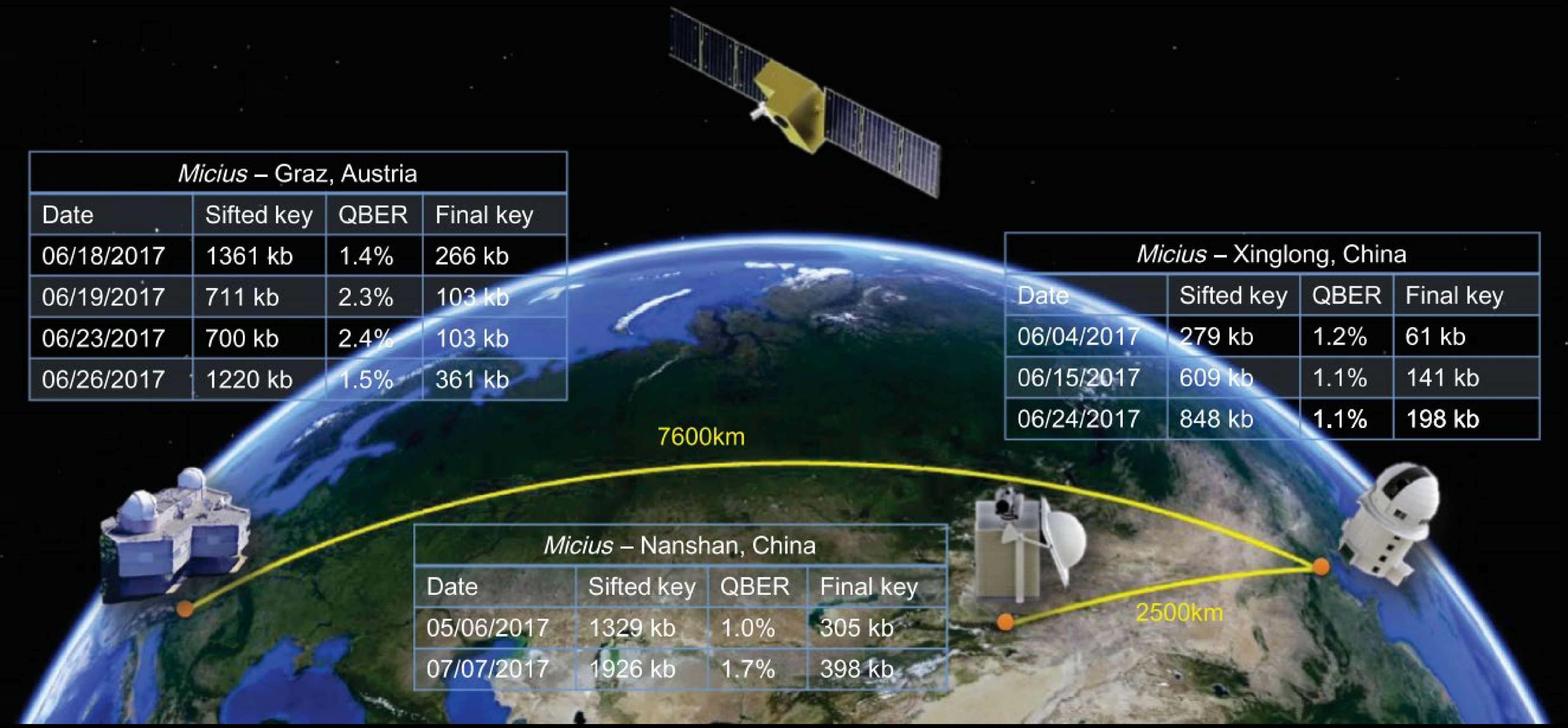


Micius quantum experiments in space, Lu, Cao, Peng, Pan, *Rev. Mod. Phys.* **94**, 035001 (2022)

Quantum communications and network



Quantum communications and network



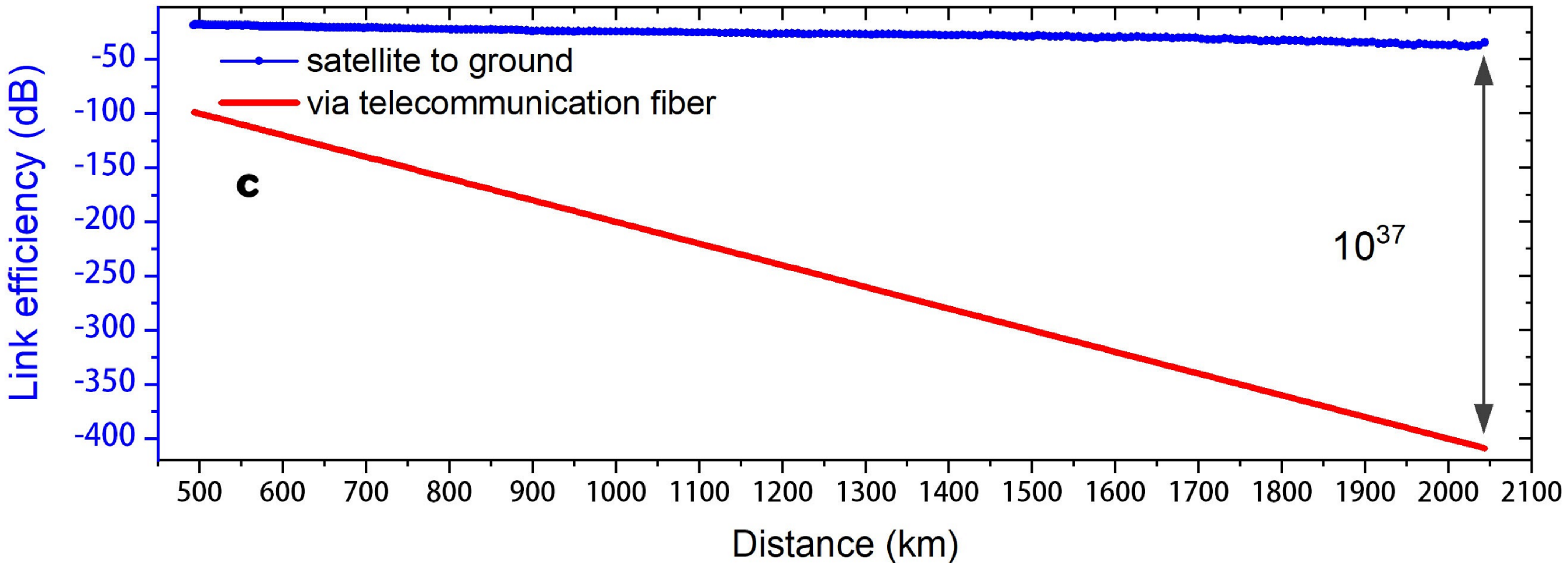
Micius – Graz, Austria			
Date	Sifted key	QBER	Final key
06/18/2017	1361 kb	1.4%	266 kb
06/19/2017	711 kb	2.3%	103 kb
06/23/2017	700 kb	2.4%	103 kb
06/26/2017	1220 kb	1.5%	361 kb

Micius – Xinglong, China			
Date	Sifted key	QBER	Final key
06/04/2017	279 kb	1.2%	61 kb
06/15/2017	609 kb	1.1%	141 kb
06/24/2017	848 kb	1.1%	198 kb

Micius – Nanshan, China			
Date	Sifted key	QBER	Final key
05/06/2017	1329 kb	1.0%	305 kb
07/07/2017	1926 kb	1.7%	398 kb

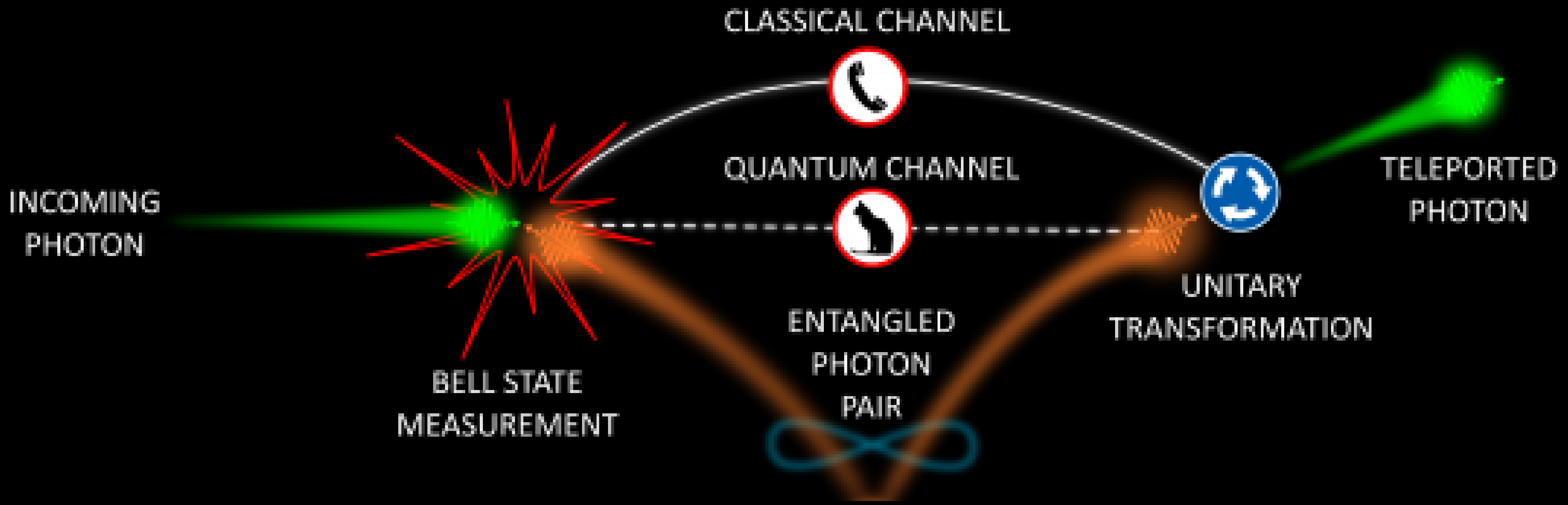

The second quantum communication satellite, named “Jinan”, a city in China, is launched in 27 July 2022.

Why satellite? Is optical fiber not good enough?



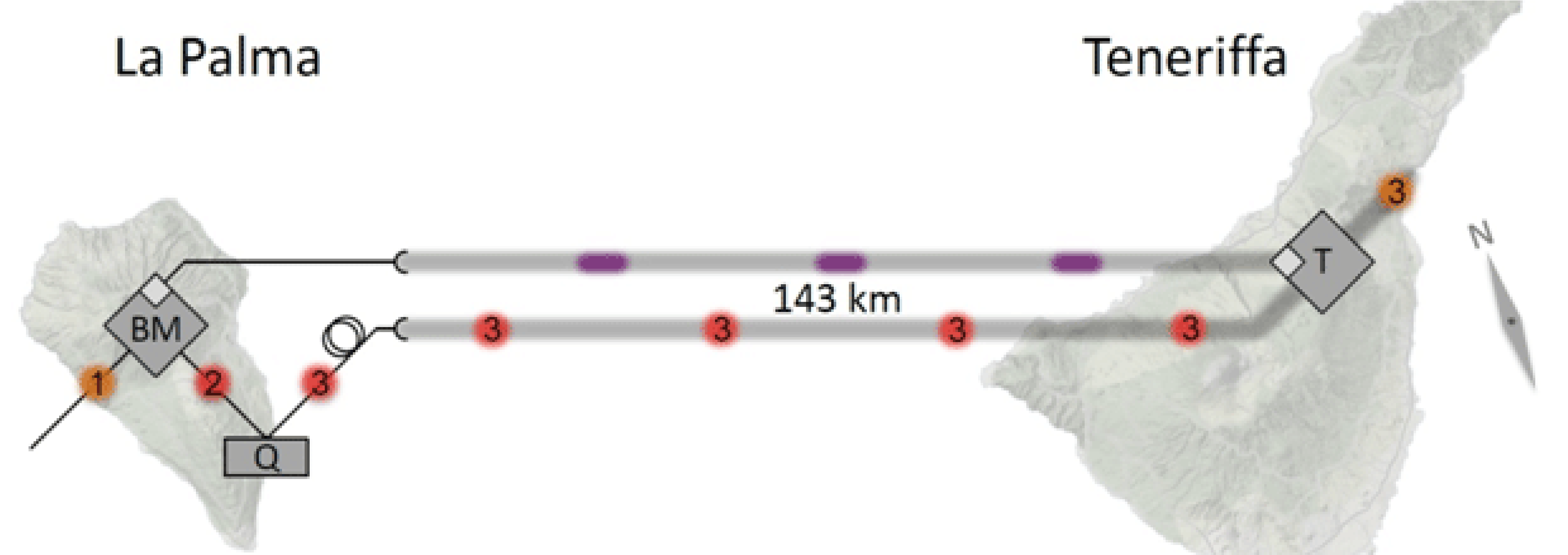
<u>Photon loss</u> is the biggest enemy in quantum communications and optical quantum computation…

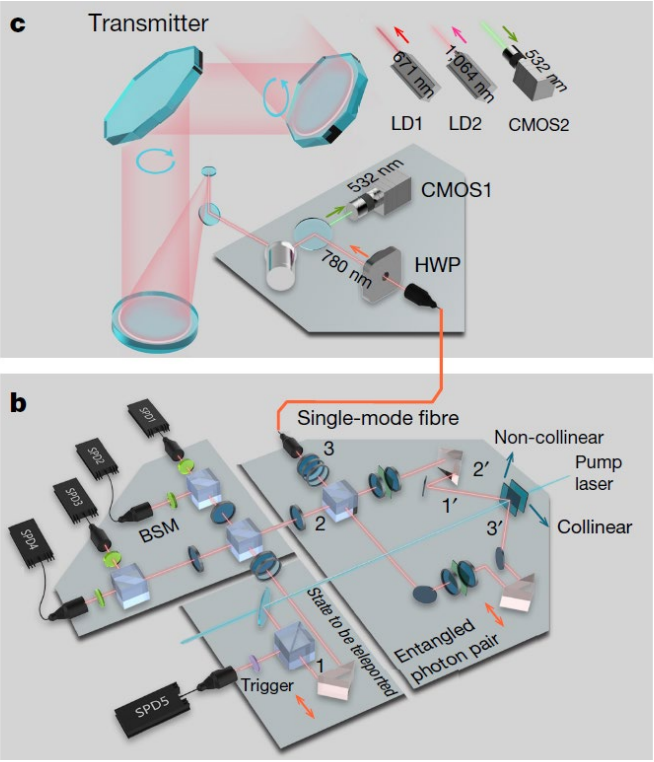
Speaking of long-distance lossless travel…

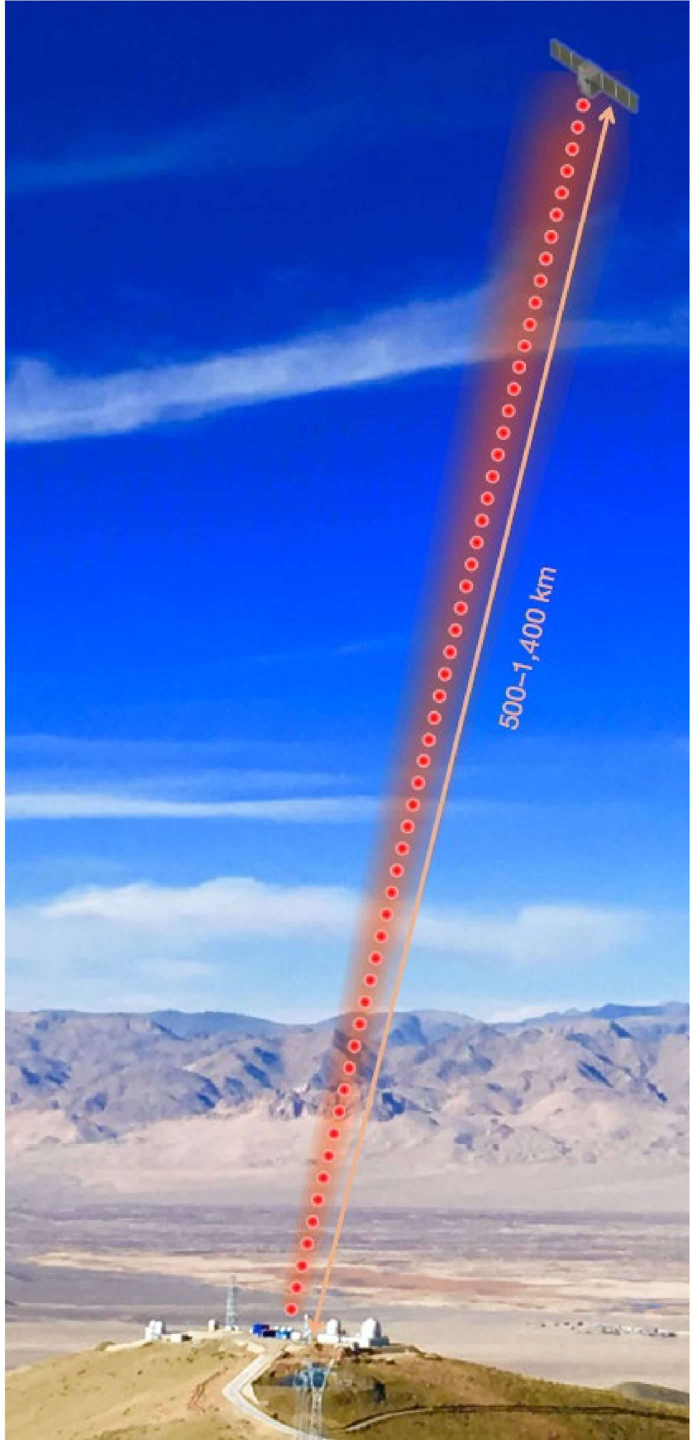


By sharing an entanglement channel and LOCC, quantum teleportation can transfer the quantum state of a photon to a distant location without actually moving the particle.

So, lossless already? Not at all....





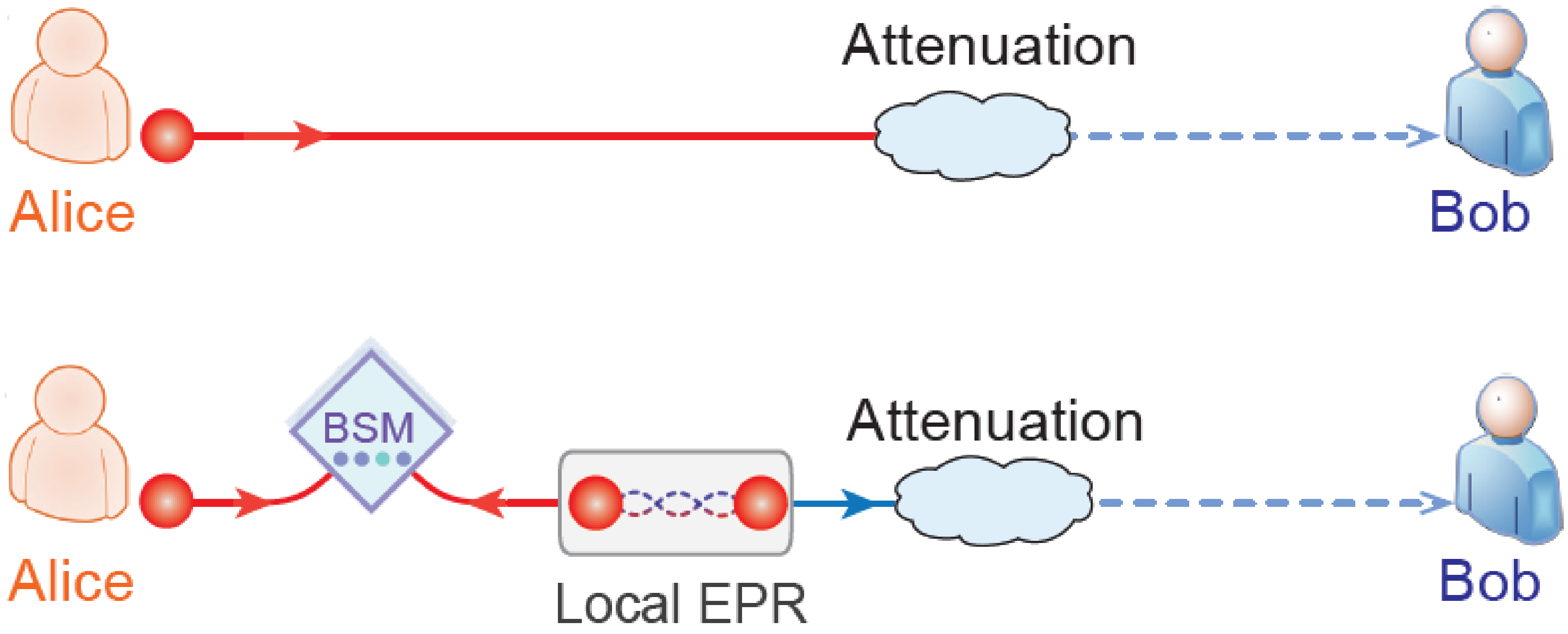


The previous long-distance single photon teleportation experiments are actually:

local teleportation + long-distance transmission of the teleported photon!

Quantum teleportation advantage?

By using teleportation, the single photon has a better survival probability than using direct transmission.

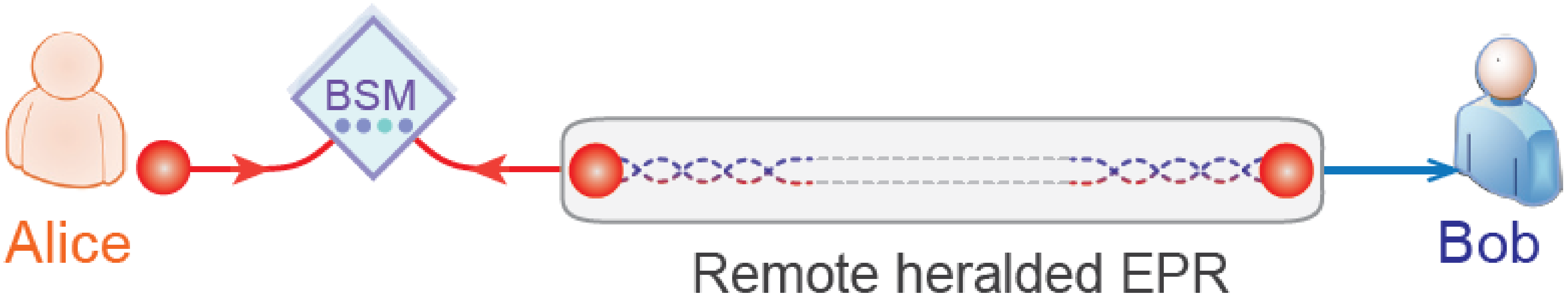


direct transmission

Local teleportation + transmission

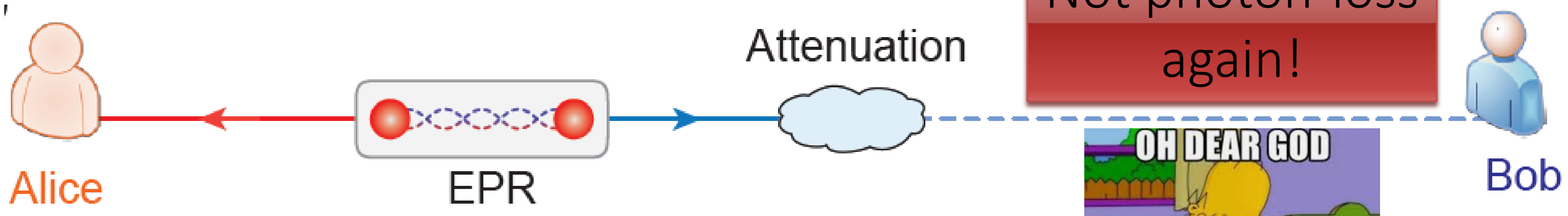
Do it the right way:

Prior distributed entangled photons with high heralding efficiency, then teleportation



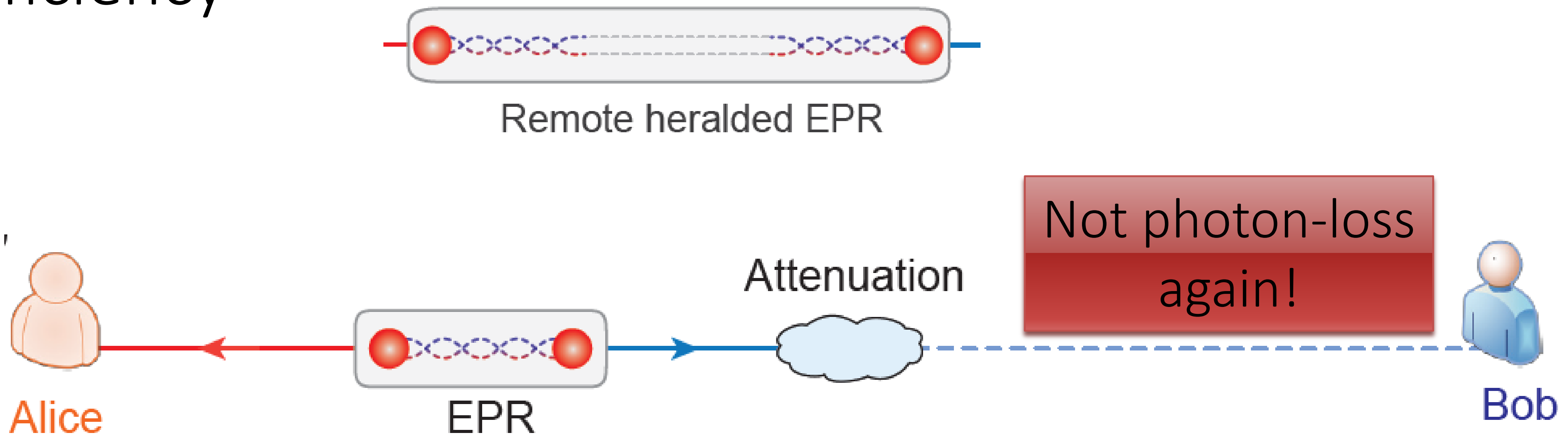
How to do this?

Remote heralded EPR



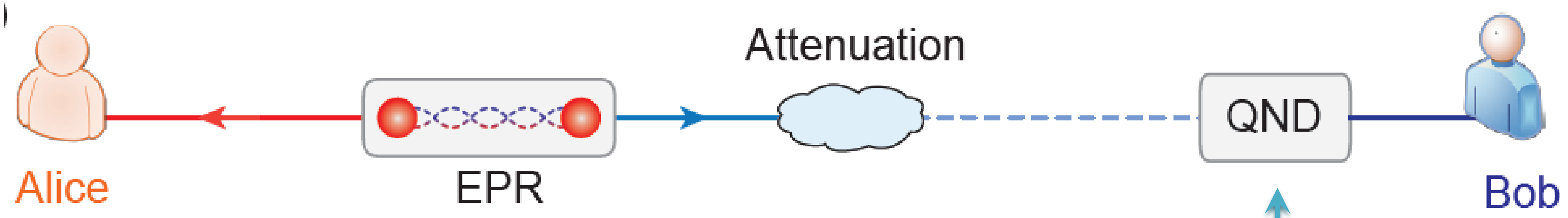
Not photon-loss again!

Prior distributed entangled photons with high heralding efficiency



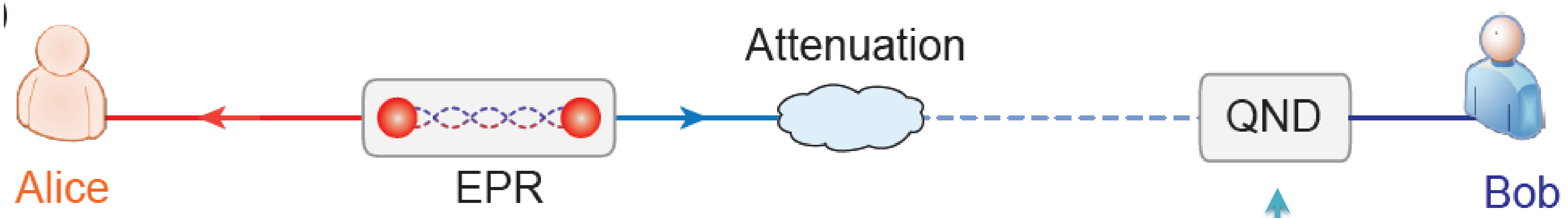
Not photon-loss again!

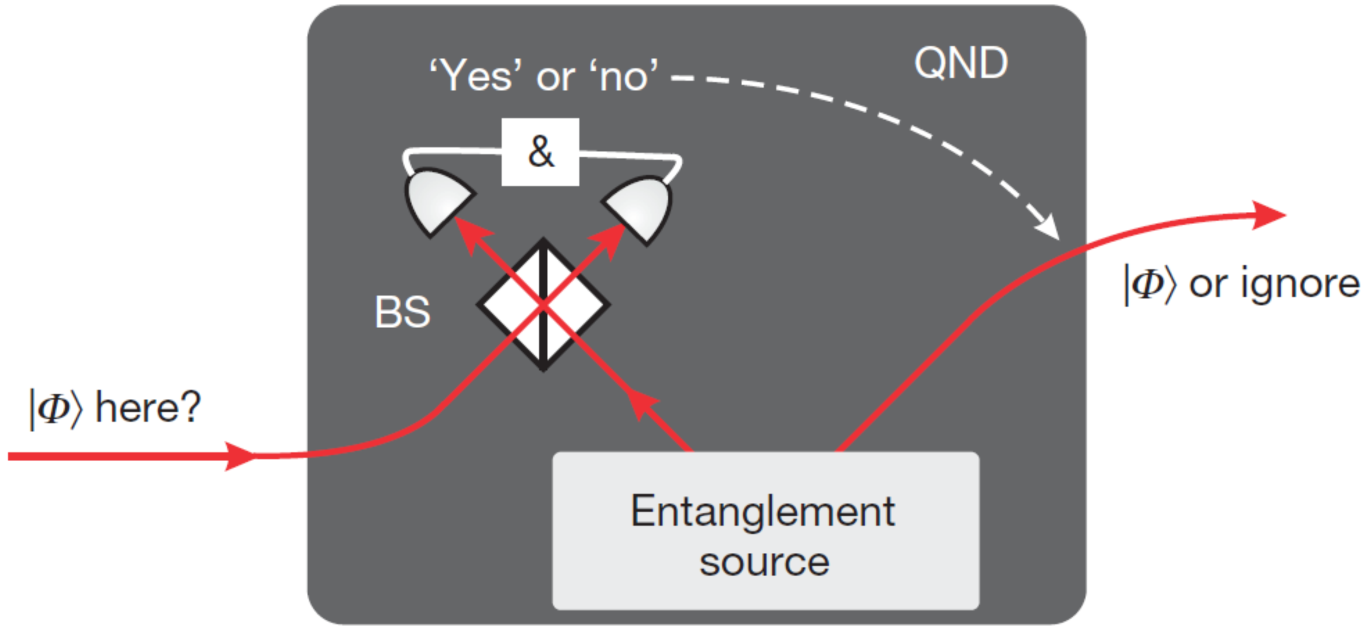
What if, you have this magic, to see a photon but without destroying it?



Now, tell me where is this magic from?

Teleportation itself!?





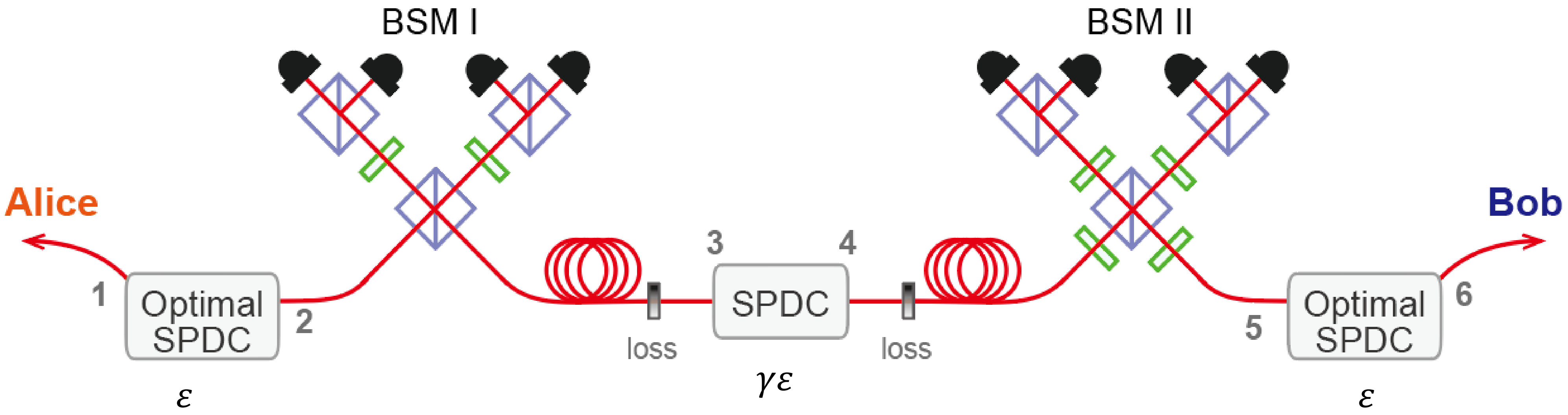
Now, tell me where is this magic from?

Teleportation itself!?

In principle, OK

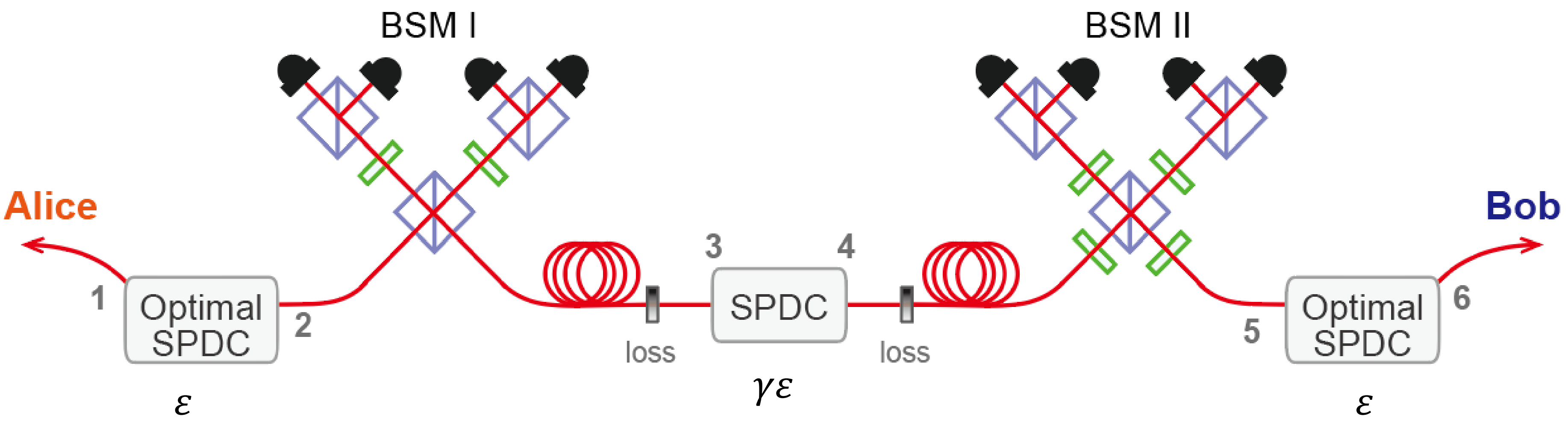
But in practice, two technological problems:

1. Probabilistic and multi-pair emission of SPDC



Noise: (1-2) 2 pairs, (3-4) 1 pairs, (5-6) 0 pairs;
(1-2) 0 pairs, (3-4) 1 pairs, (5-6) 2 pairs;
(1-2) 2 pairs, (3-4) 0 pairs, (5-6) 2 pairs;

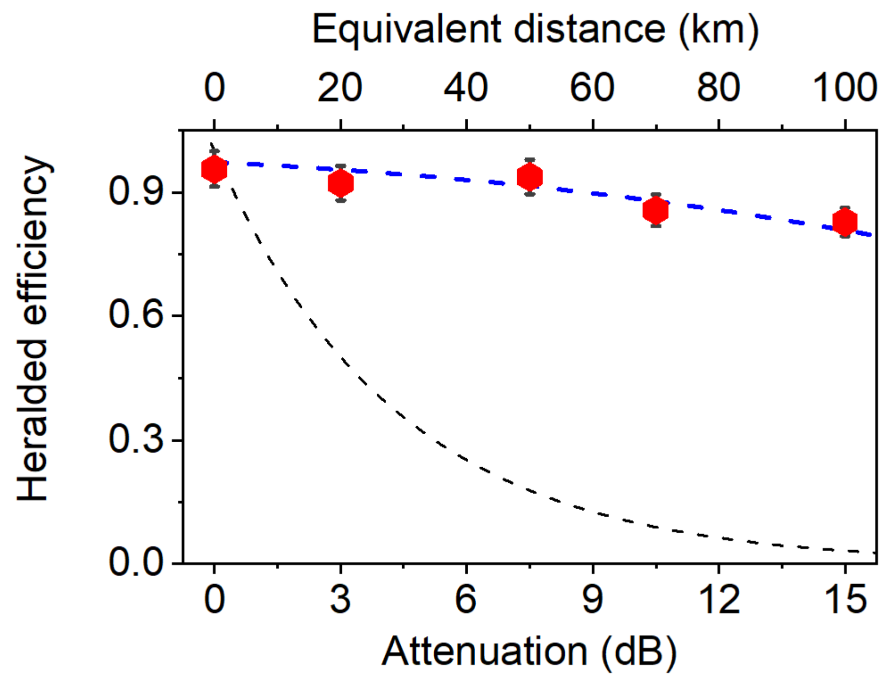
1. Probabilistic and multi-pair emission of SPDC



Trigger event sets: (from left to right)

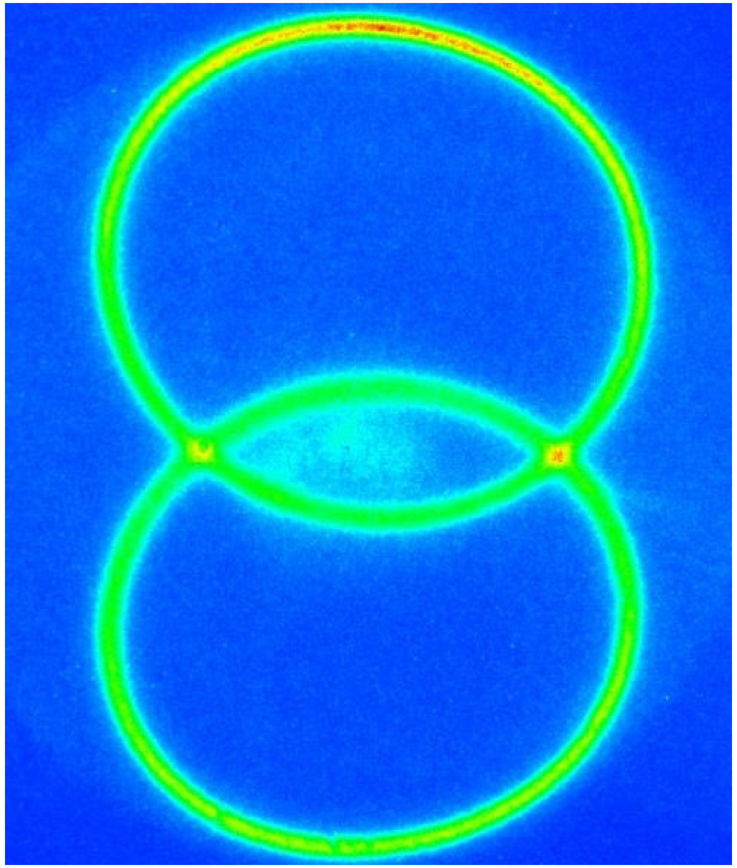
	Generation	Probability
Signal	{1, 1, 1}	$p_0 \approx \gamma\varepsilon^3\eta/4.$
Noise 1	{2, 0, 2}	$p_1 \approx \varepsilon^4/16.$
Noise 2	{1, 2, 0} & {0, 2, 1}	$p_2 \approx \frac{18}{224}\eta^2\gamma^2\varepsilon^3+\frac{6}{28}\eta^{\frac{3}{2}}(1-\sqrt{\eta})\gamma^2\varepsilon^3.$

Success rate = $p_0/(p_0 + p_1 + p_2)$.

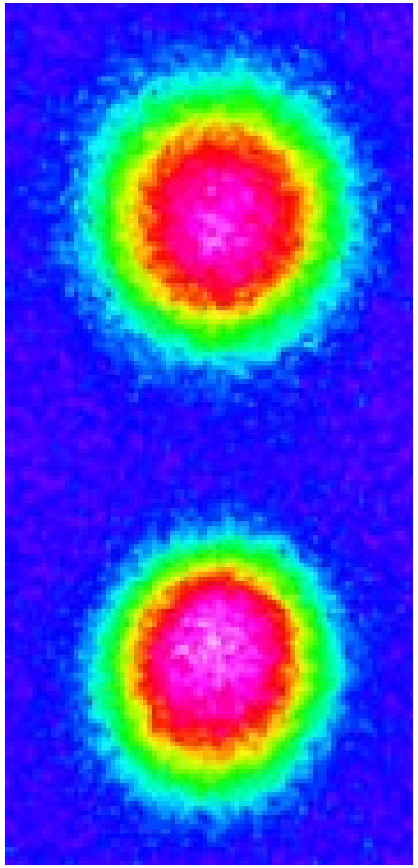


2. Telecom SPDC entangled photon pairs with high indistinguishability and high heralding efficiency

8-photon entanglement, *Nature Photonics* (2012)



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



- Key technique: beamlike type-II SPDC emitting as two separate circular beams in a Gaussian-like intensity distribution
- Increasing the collection efficiency to 70%, with an indistinguishability of ~91% simultaneously
- 4 times brighter entangled photon source than the 8-photon source, by using only 65% pump power

2. Telecom SPDC entangled photon pairs with high indistinguishability and high heralding efficiency

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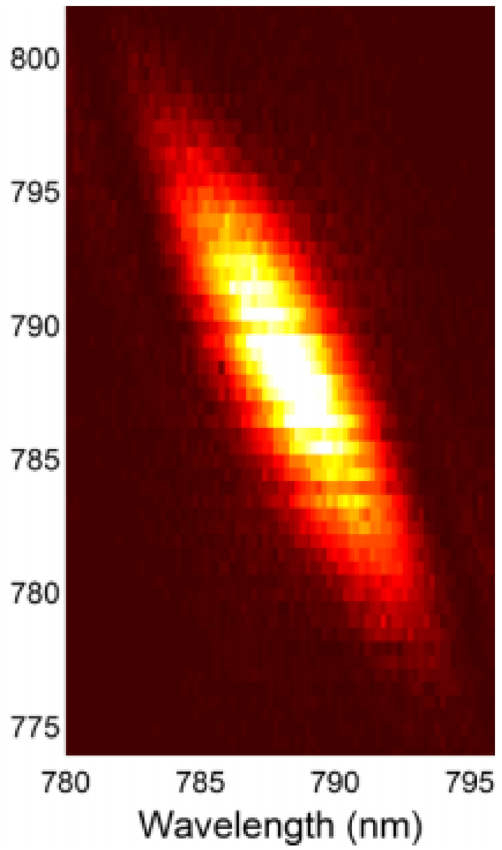
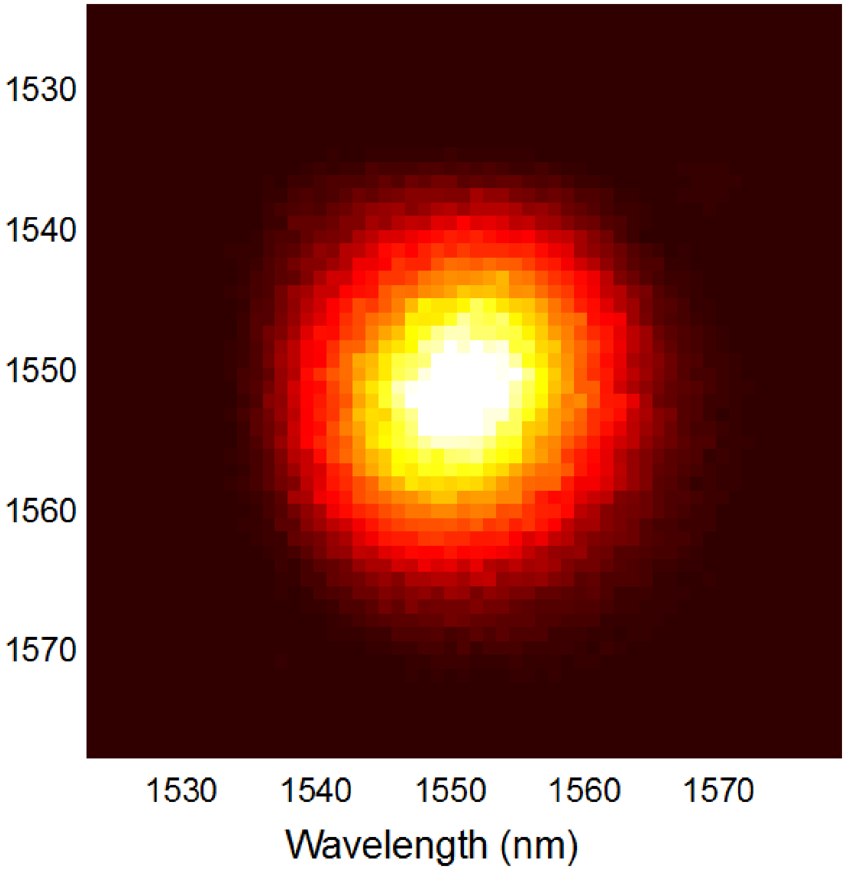


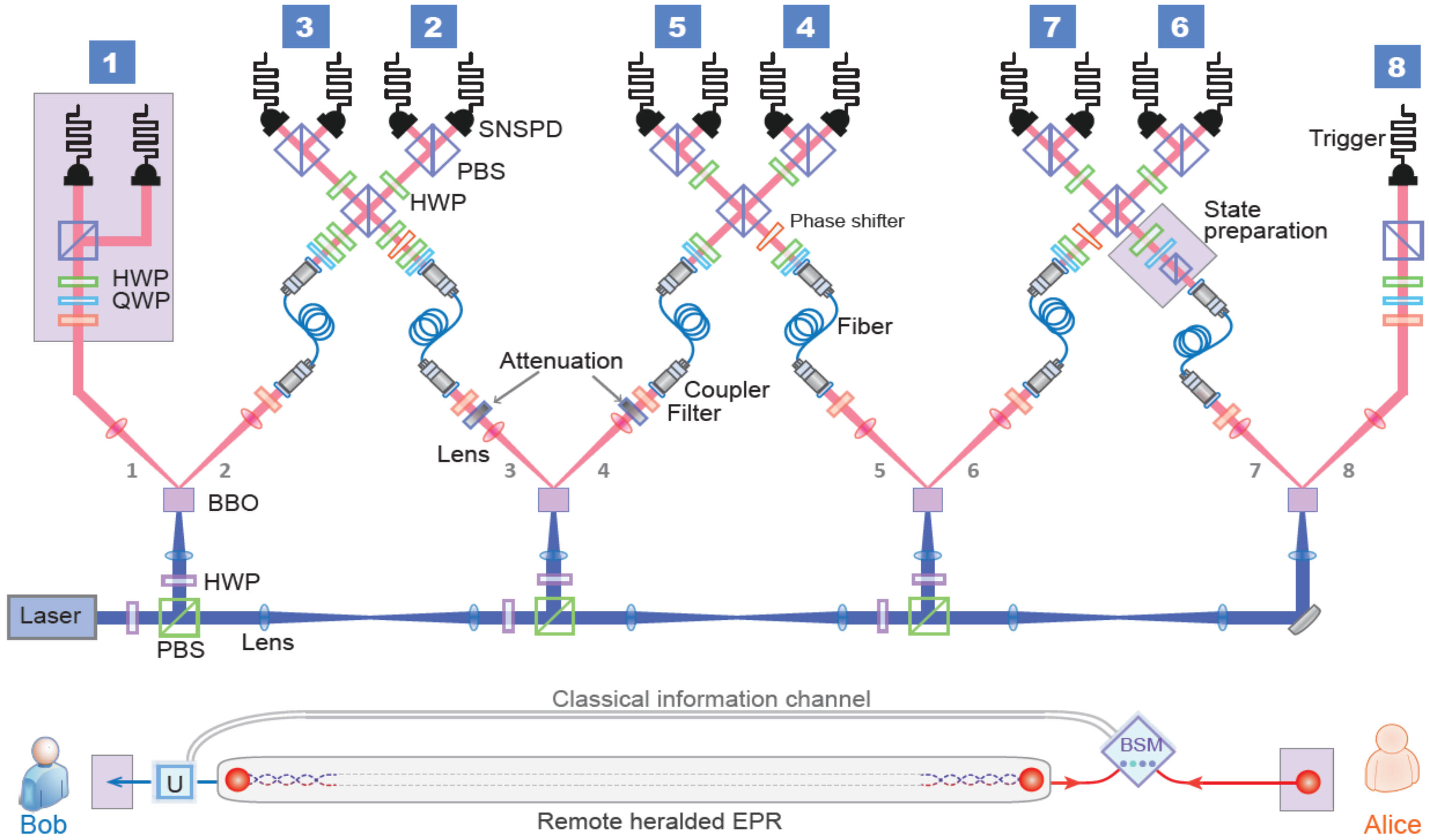
12-photon entanglement, Zhong et al. *Phys. Rev. Lett.* (2018)

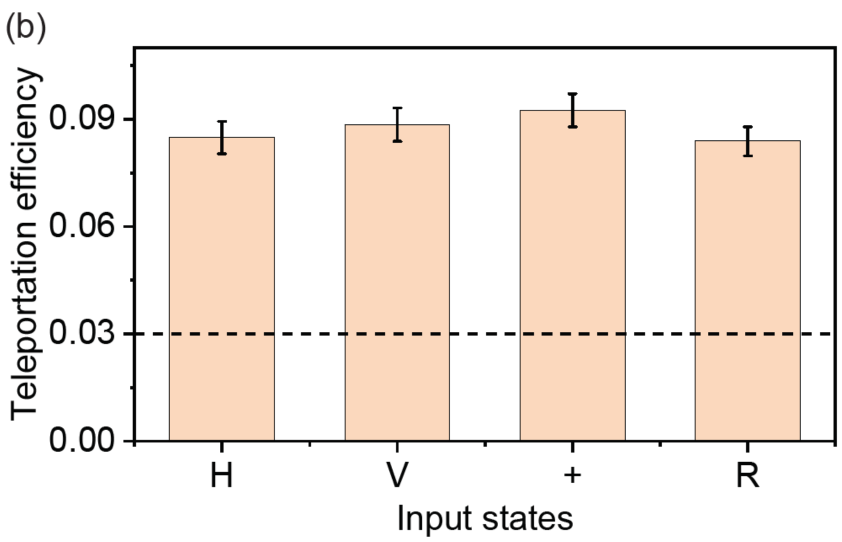


- Key technique: frequency uncorrelated & beamlike SPDC
- Simultaneously 97% heralding efficiency and 96% indistinguishability between independent single photons
- "Make SPDC great again" CYL 15/03/2018 QCMC

Quantum teleportation advantage

By using teleportation, the single photon has a better survival probability than using direct transmission.





Manuscript submitted (2022)

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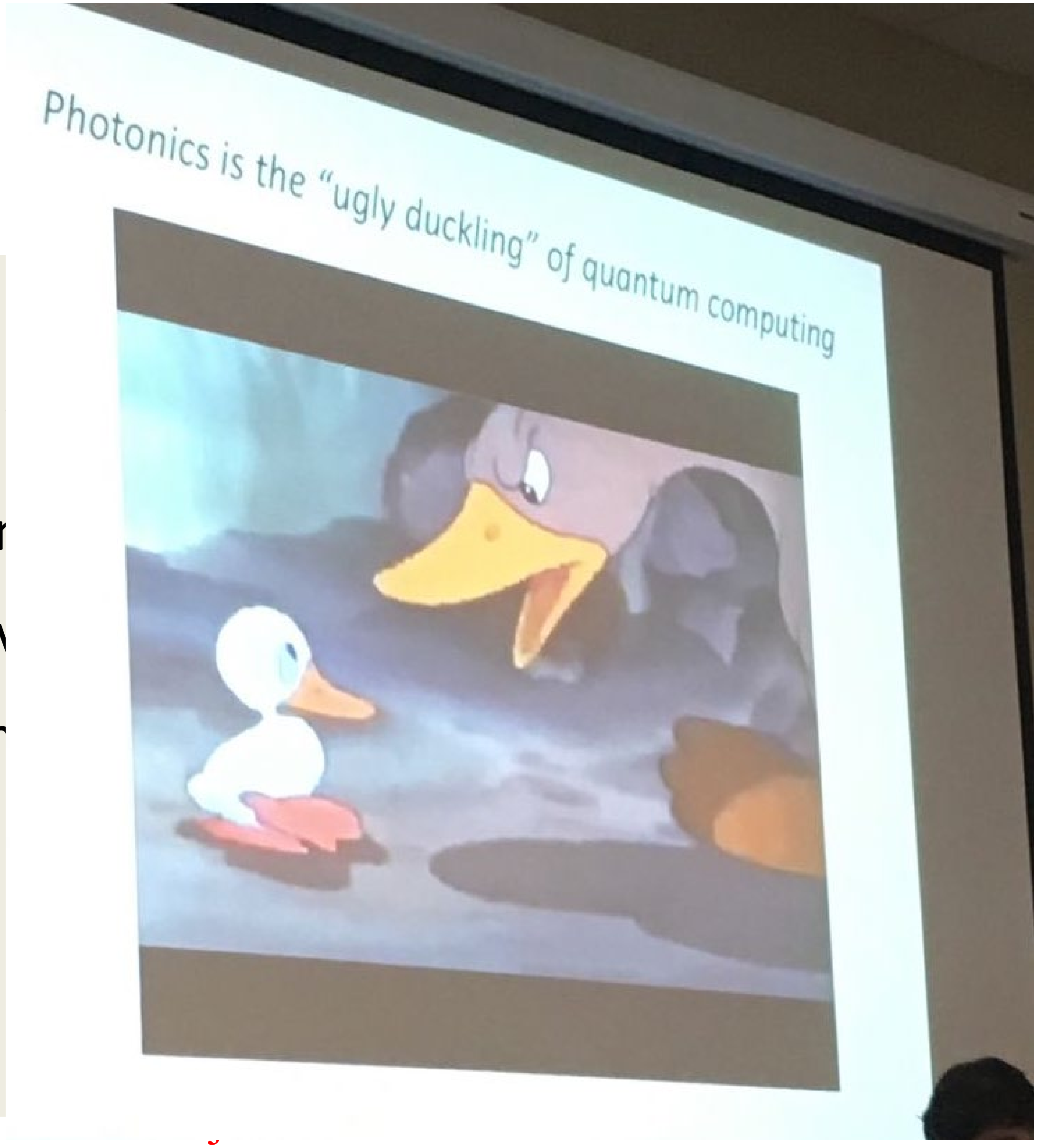


Two remarkable insights reshaped our view on photonic quantum computing

Knill Laflamme Milburn (2001)

You can get the required nonlinearity from single-photon detection, boost the CNOT success rate using ancillary single photons, teleportation, and QEC…

But, although with huge overhead reduction (10^5 to 10^2 per gate), this scheme is still very, very, very out of the reach of the current technologies.

Aaronson Arkhipov (2011):

Remarkable (and surprising to us) computational power from seeming simple linear optics networks!

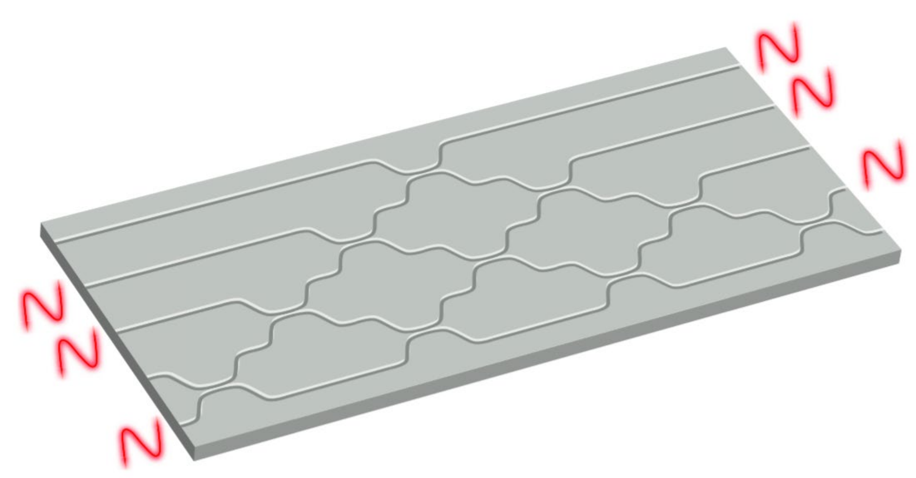
Greatly relaxed experimental demands (get rid of the most challenging parts).

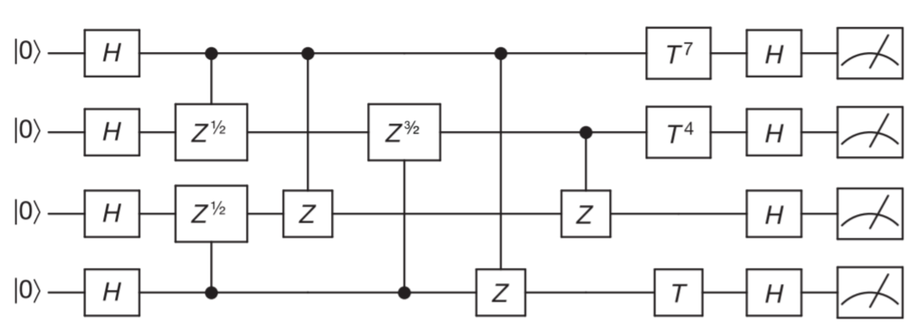
J.K. Rowling Harvard Commencement Speech 2008

Achieveable goals, the first step to self improvement

Quantum computational advantage/supremacy

- Boson sampling
- IQP
- Random circuit sampling





50-100 physical qubits with ~1% error rate

Compared to Shor's algorithm:

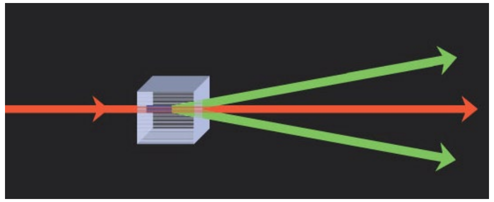
- Much easier to experimentally implement,
- With more compelling complexity-theoretic evidence

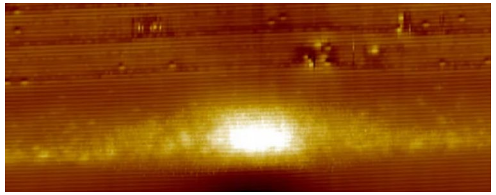
Qubit budget for Shor's algorithm

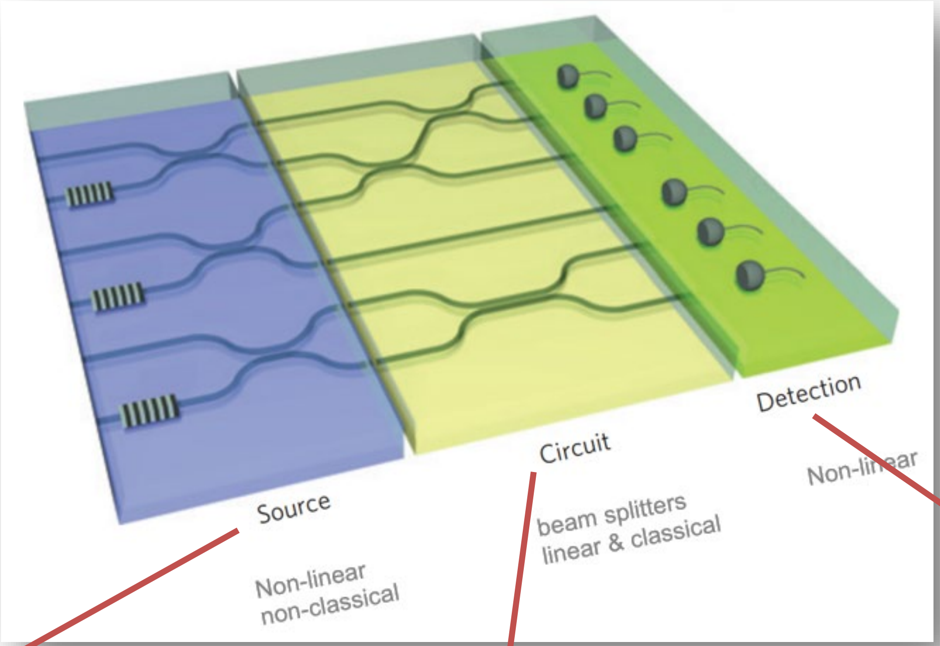
Historical cost estimate at $n = 2048$	Physical gate error rate	Physical qubits (millions)
Fowler et al. 2012 [9]	0.1%	1000
O'Gorman et al. 2017 [18]	0.1%	230
Gheorghiu et al. 2019 [19]	0.1%	170
(ours) 2019 (1 factory)	0.1%	16
(ours) 2019 (1 thread)	0.1%	19
(ours) 2019 (parallel)	**0.1%**	**20**

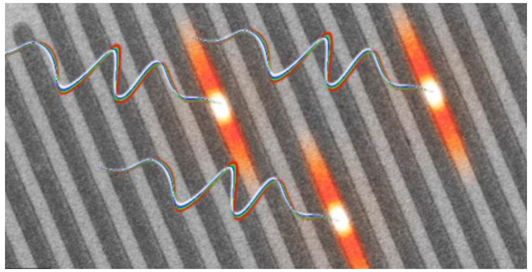
Gidney et al. https://arxiv.org/abs/1905.09749

In 2013…









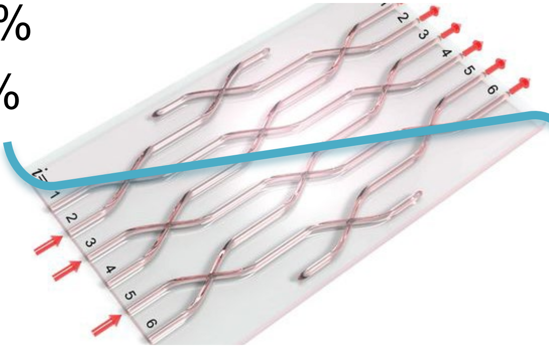
Counts ~600,000/s

Indistinguishability ~90%

Source efficiency ~0.8%

Circuit efficiency: 10%-30%

Detection efficiency: 85-90%



30-photon boson sampling

~10^{-100} Hz

BosonSampling Experiments

Last year, groups in Brisbane, Oxford, Rome, and Vienna reported the first 3- and 4-photon BosonSampling experiments, confirming that the amplitudes were given by 3x3 and 4x4 permanents

# of experiments ≥ # of photons!

BosonSampling Experiments

Last year, groups in Brisbane, Oxford, Rome, and Vienna reported the first 3- and 4-photon BosonSampling experiments, confirming that the amplitudes were given by 3x3 and 4x4 permanents

# of experiments ≥ # of photons!

Obvious challenge for scaling up: Need n-photon coincidences (requires either postselection or deterministic single-photon sources)

Check list for a *perfect* single-photon source

1. High efficiency

I. Quantum efficiency—the decay of excited states should predominantly result in an emitted photon.

II. Deterministic generation—upon a **pulsed** excitation, the source should deterministically emit one photon in a push-button fashion.

III. High collection efficiency—the radiated photons should be extracted with a high efficiency to a **single spatial mode**.

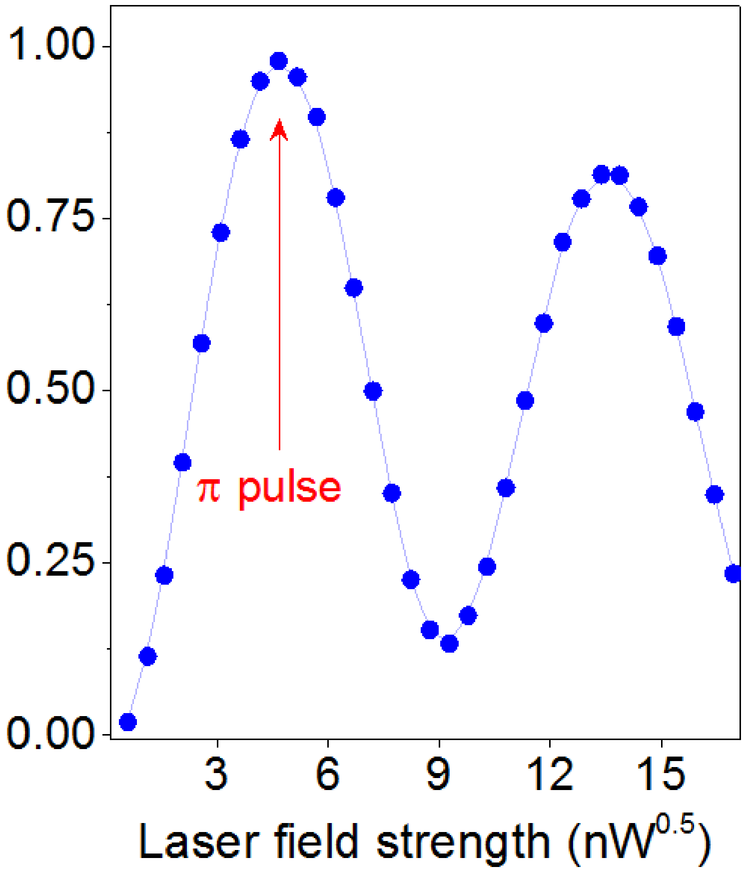
2. High purity—the emission should have a **vanishing** multi-photon probability. $G^2(0)=0$

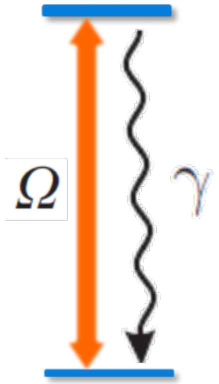
3. High indistinguishability—individual photons emitted at different trials should be quantum mechanically **identical** to each other in **all degree of freedom (time, frequency etc.)**

Check list for a *perfect* single-photon source

Getting them all working together is difficult…

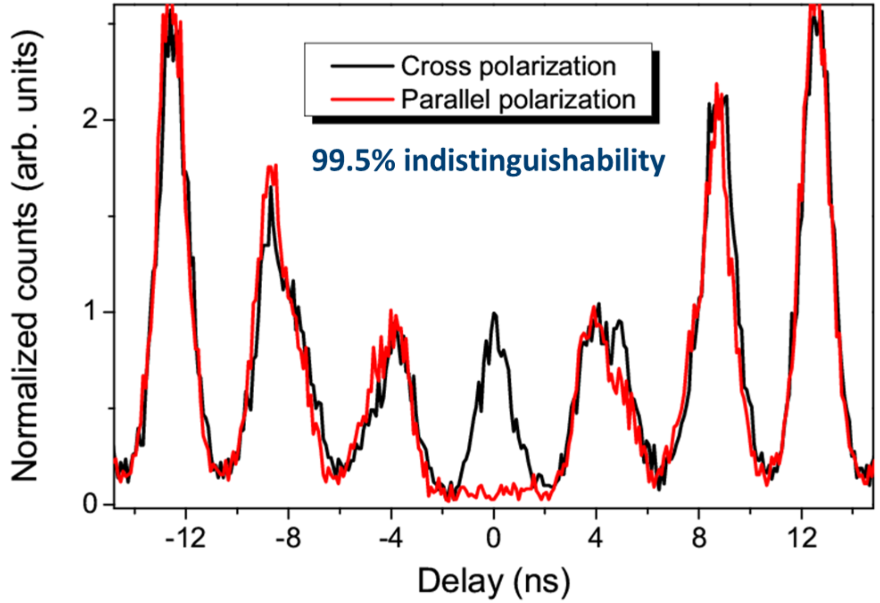
Pulsed resonance fluorescence



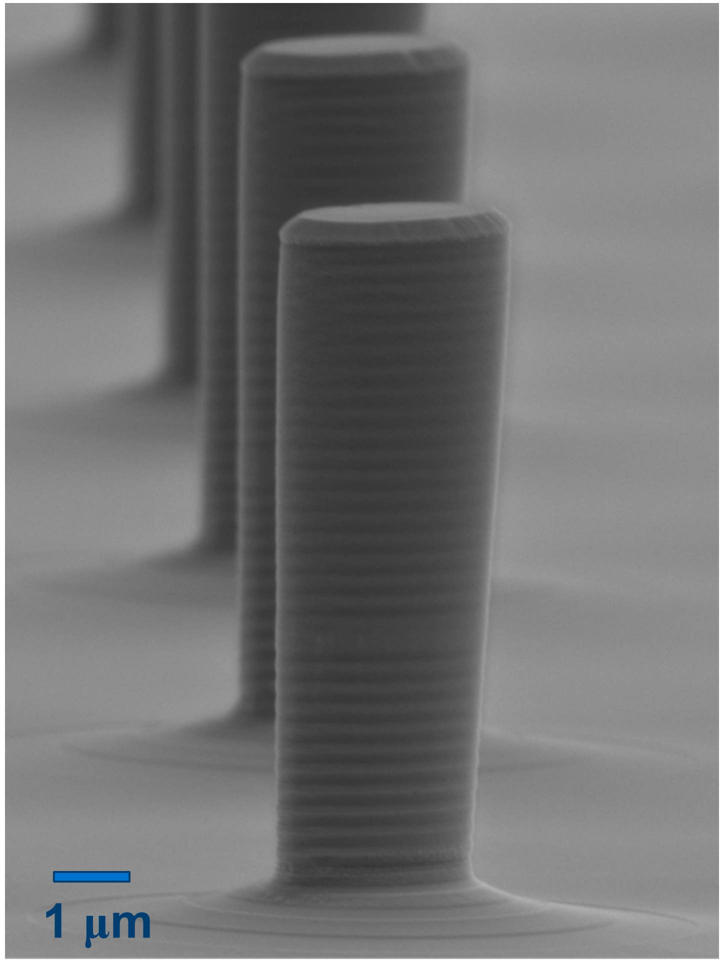


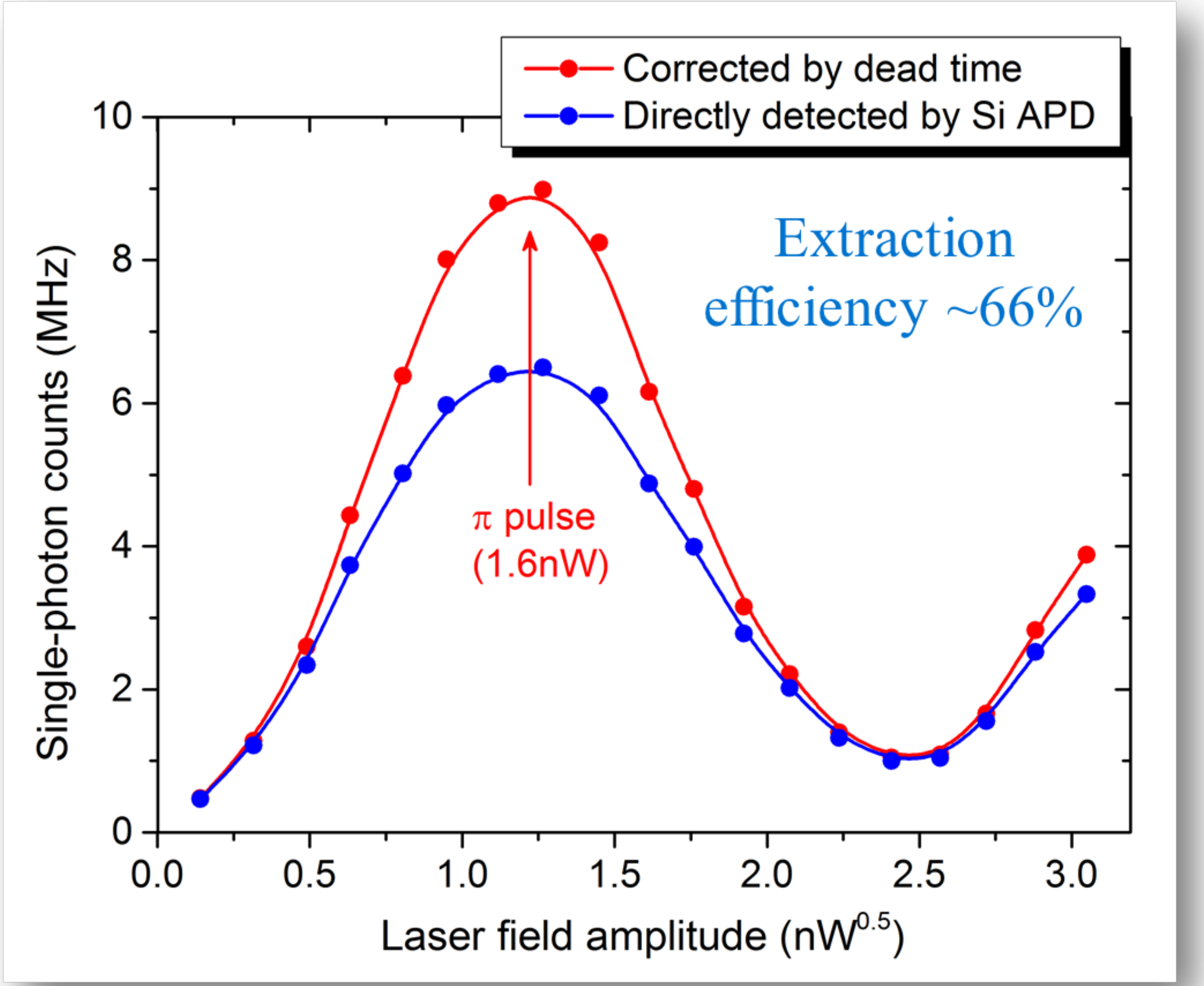
Coherent drive, no time jitter

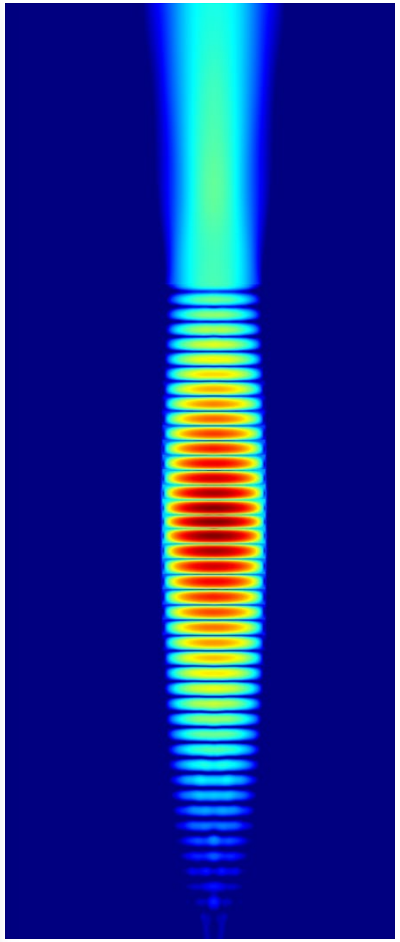
Pump power ~4 orders of magnitude lower, deterministic



Quantum dot in a micropillar

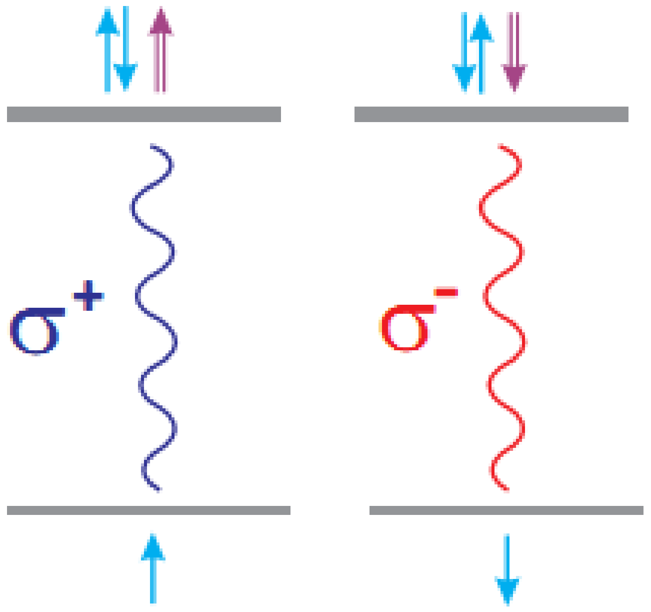






Ding *et al.* PRL **116**, 020401 (2016)

The last-mile, "50%" efficiency, problem

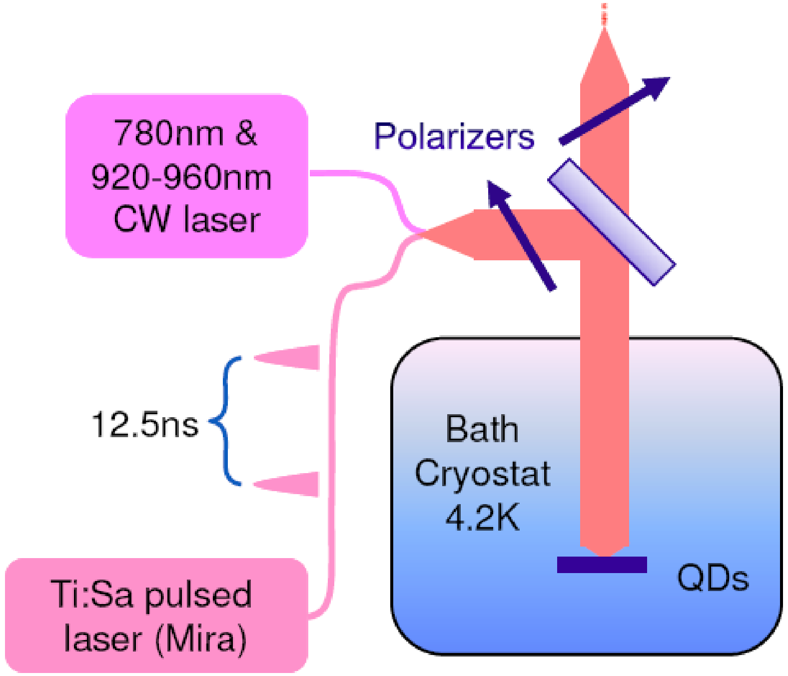


Degenerate two-level system, emit single photons randomly at left or right circular polarization.

→ Polarization filtering with 50% loss

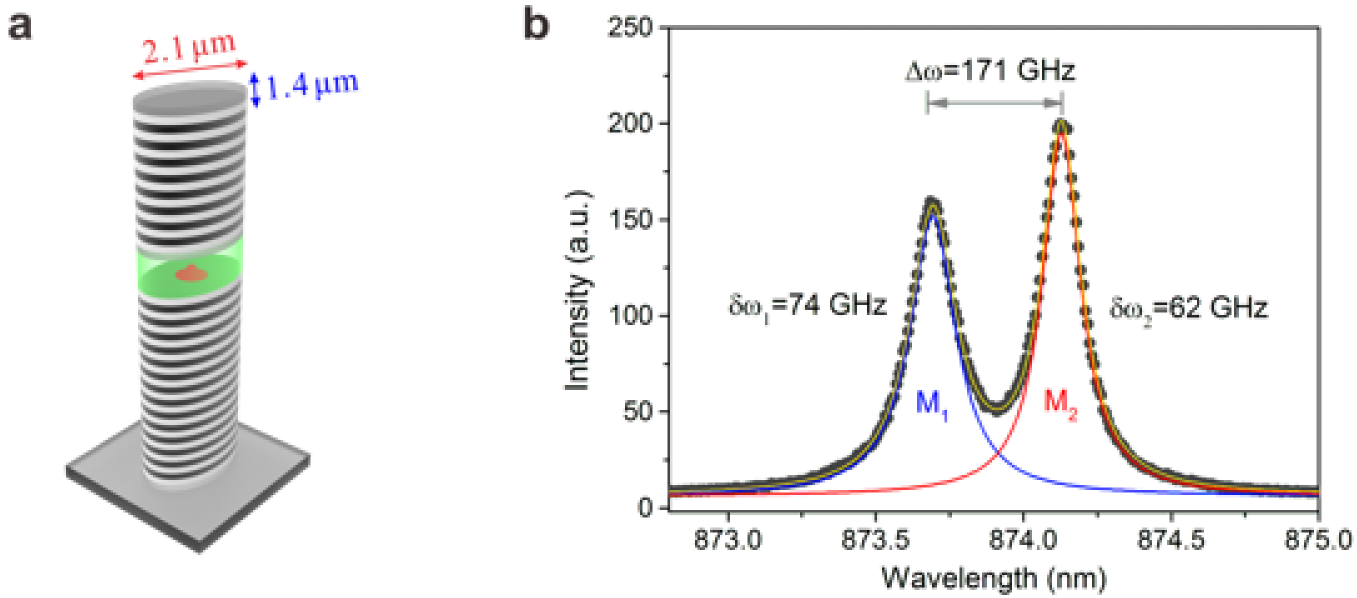
Cross-polarization to extinguish the huge excitation laser background

→ Polarization filtering with 50% loss

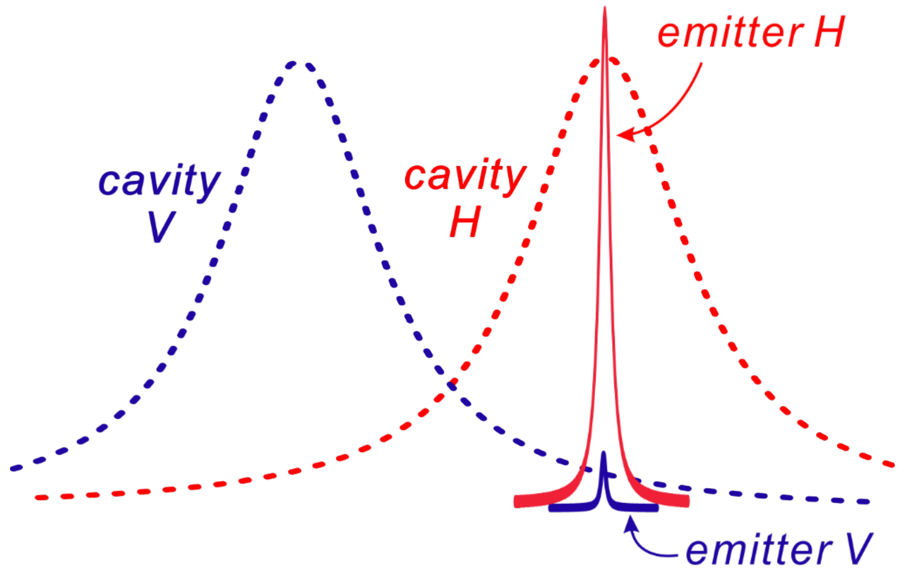


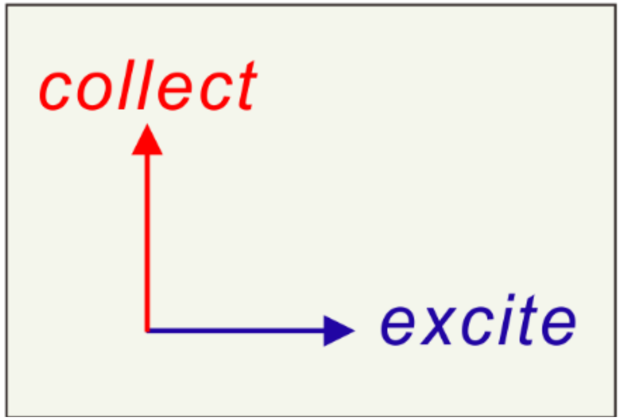
Polarized microcavity: Kill two birds with one stone

→Breaking the symmetry of the microcavity
→Polarization-selective Purcell enhancement
→Orthogonal excitation-collection geometry

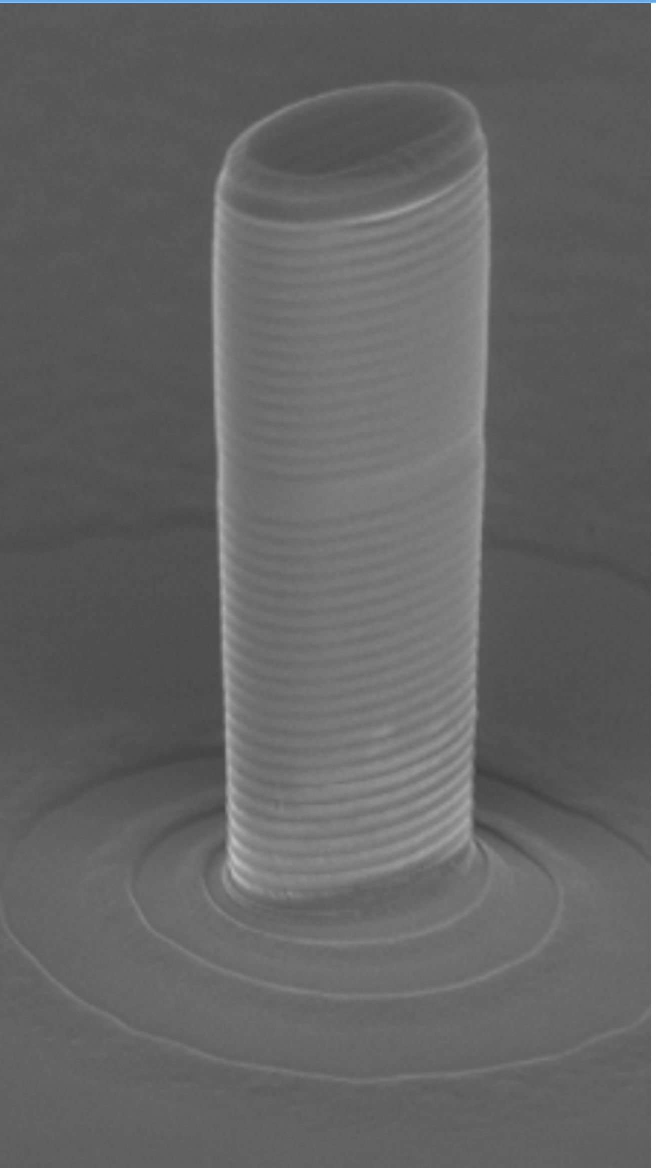


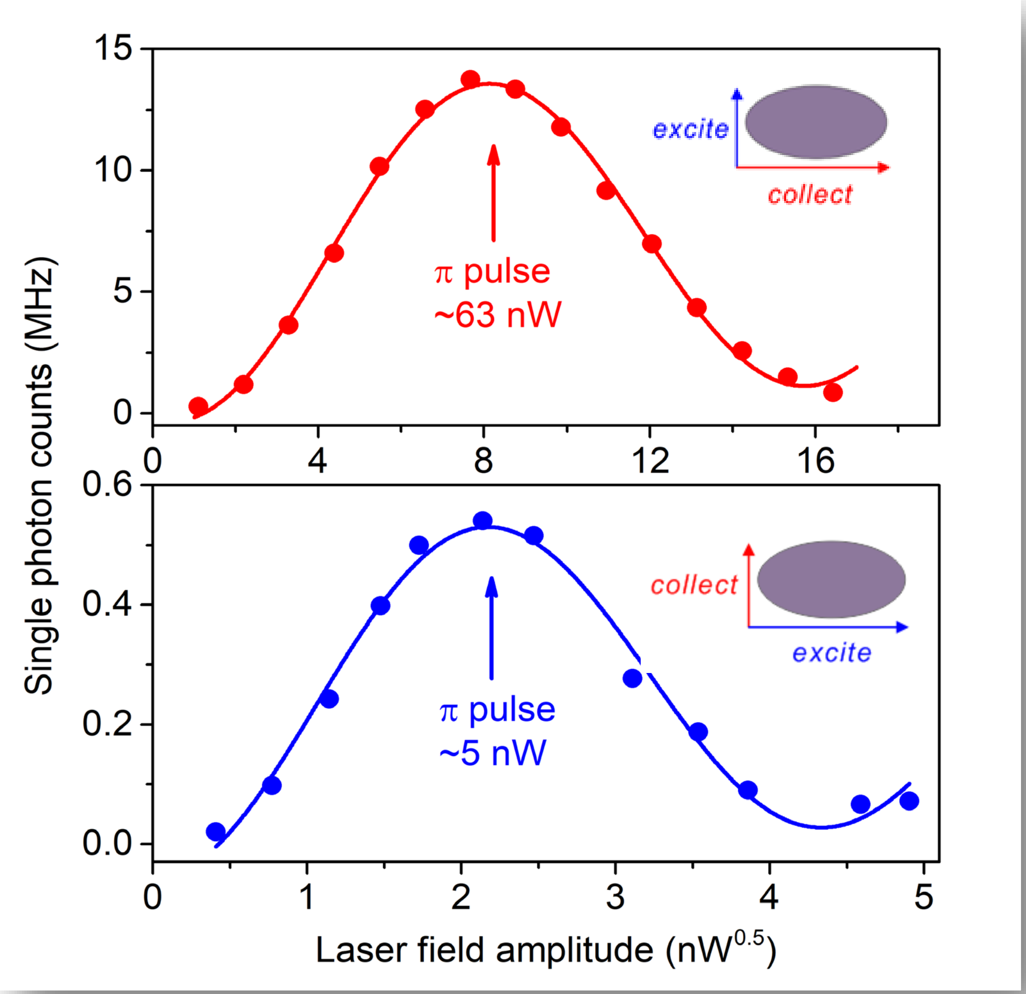
Wang et al., Nature Photonics 13, 770 (2019)





Polarized indistinguishable single photons





Purity 99%, Indistinguishability 97%

Wang et al., Nature Photonics 13, 770 (2019)

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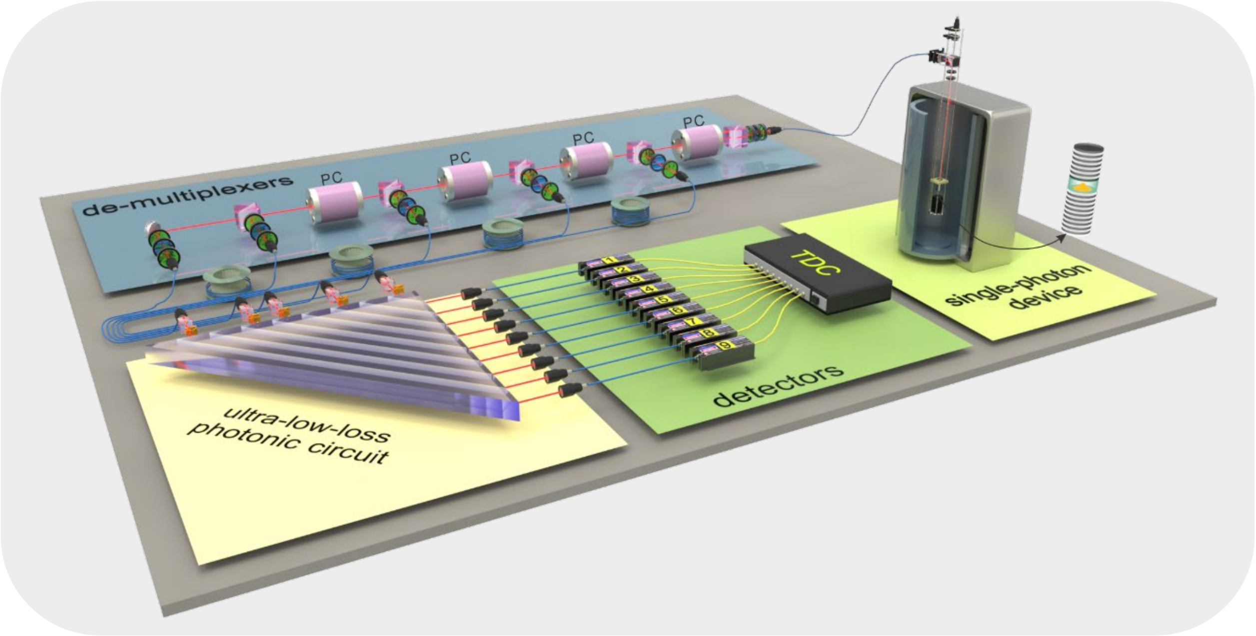
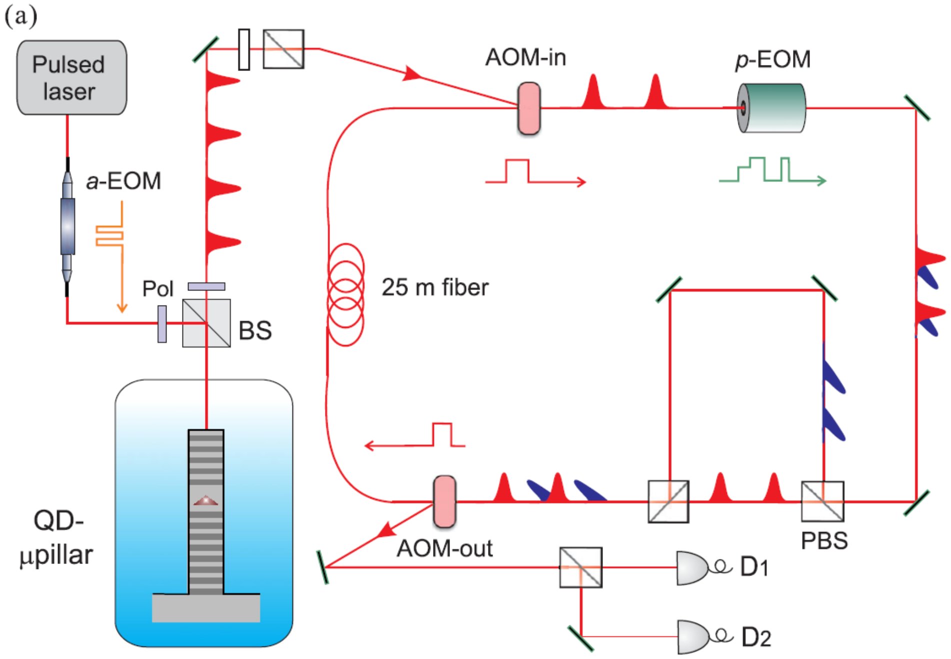
Interferometer:

high transmission rate, random, full connectivity, phase stability, spatial overlap, simultaneously.

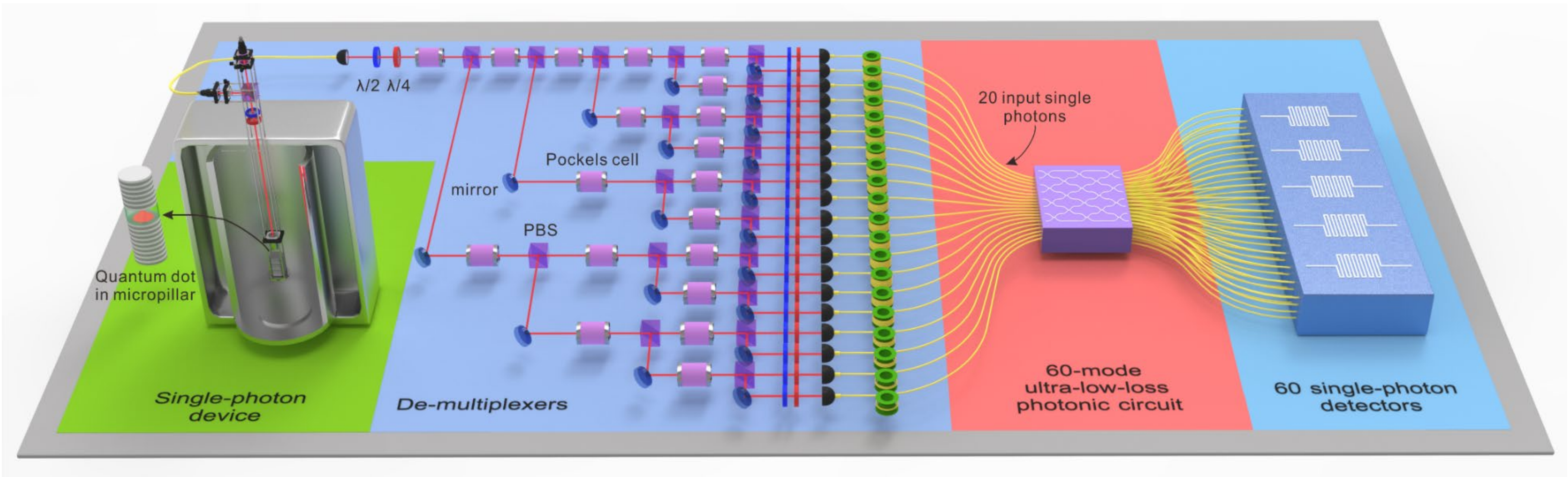


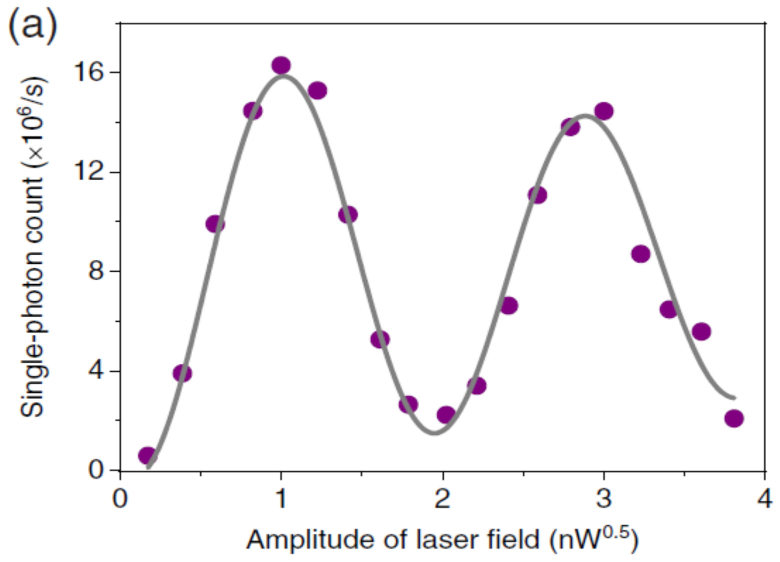
Micro-optics, high efficiency, Nat Photon 11, 361 (2017)

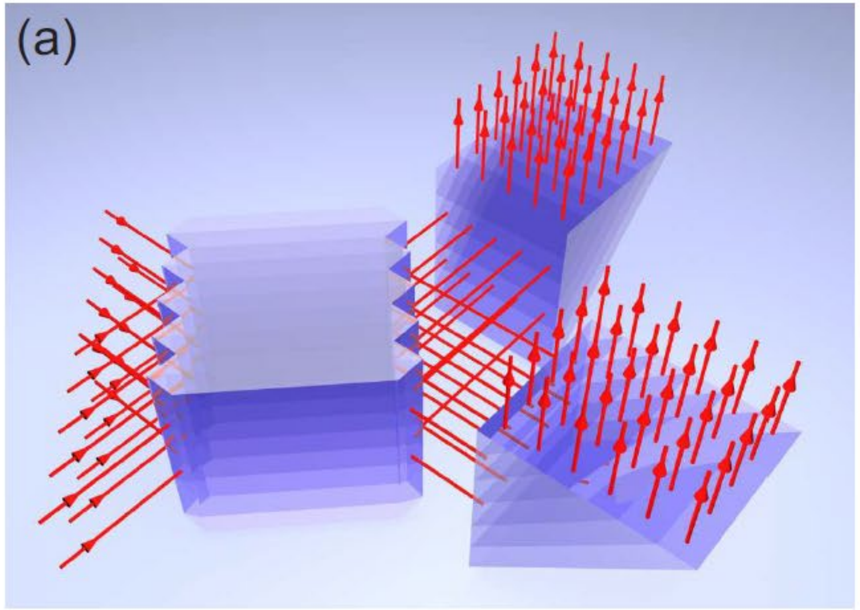


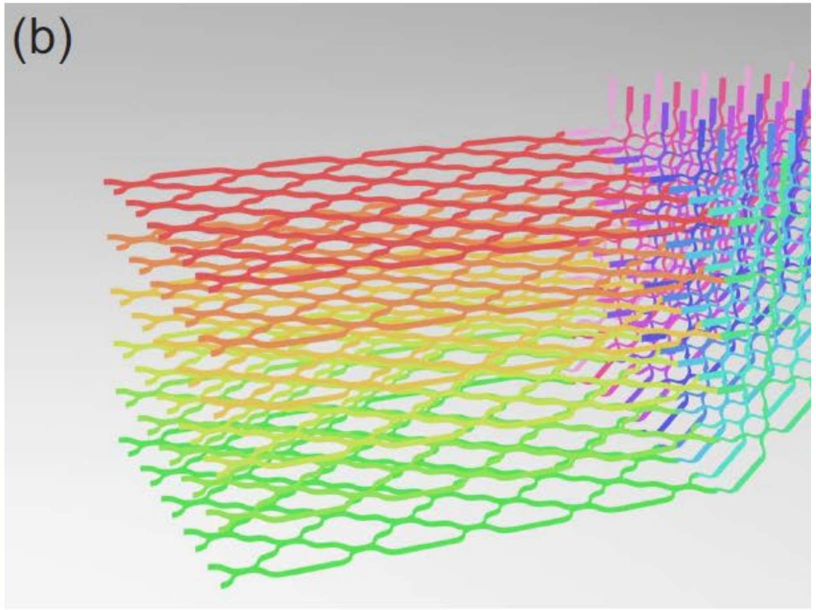
Electrically programmable, PRL 118, 190501 (2017)

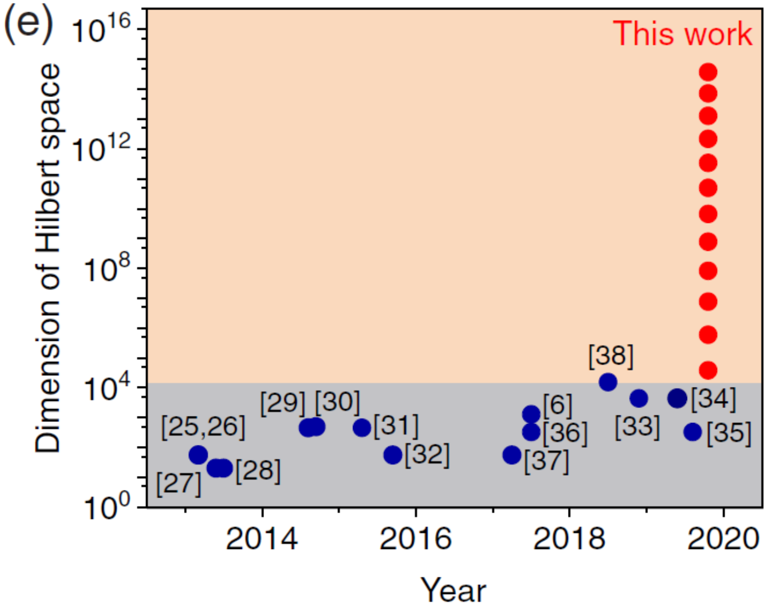
2019: 20 single photon input 60-mode circuit



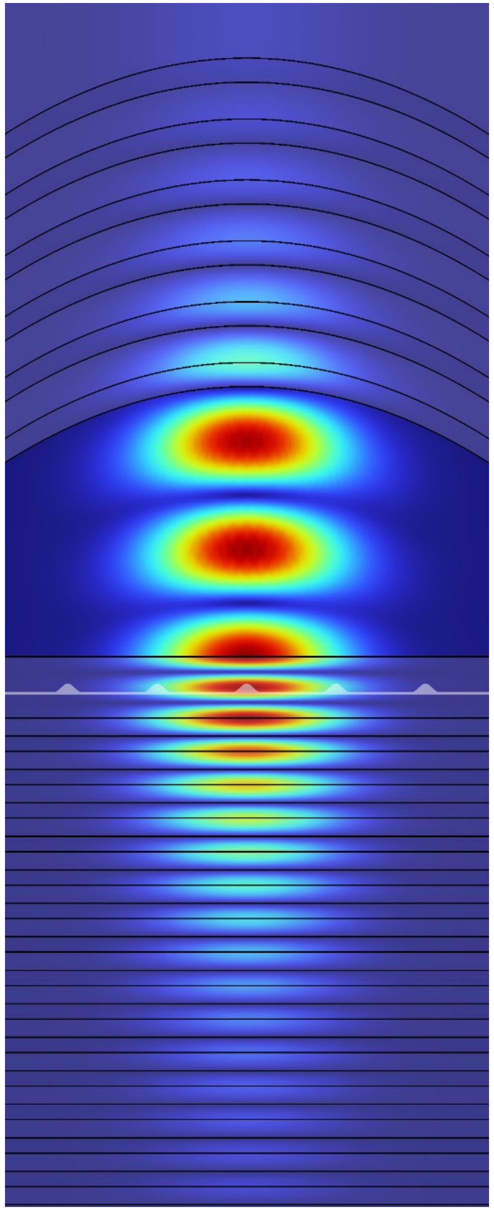


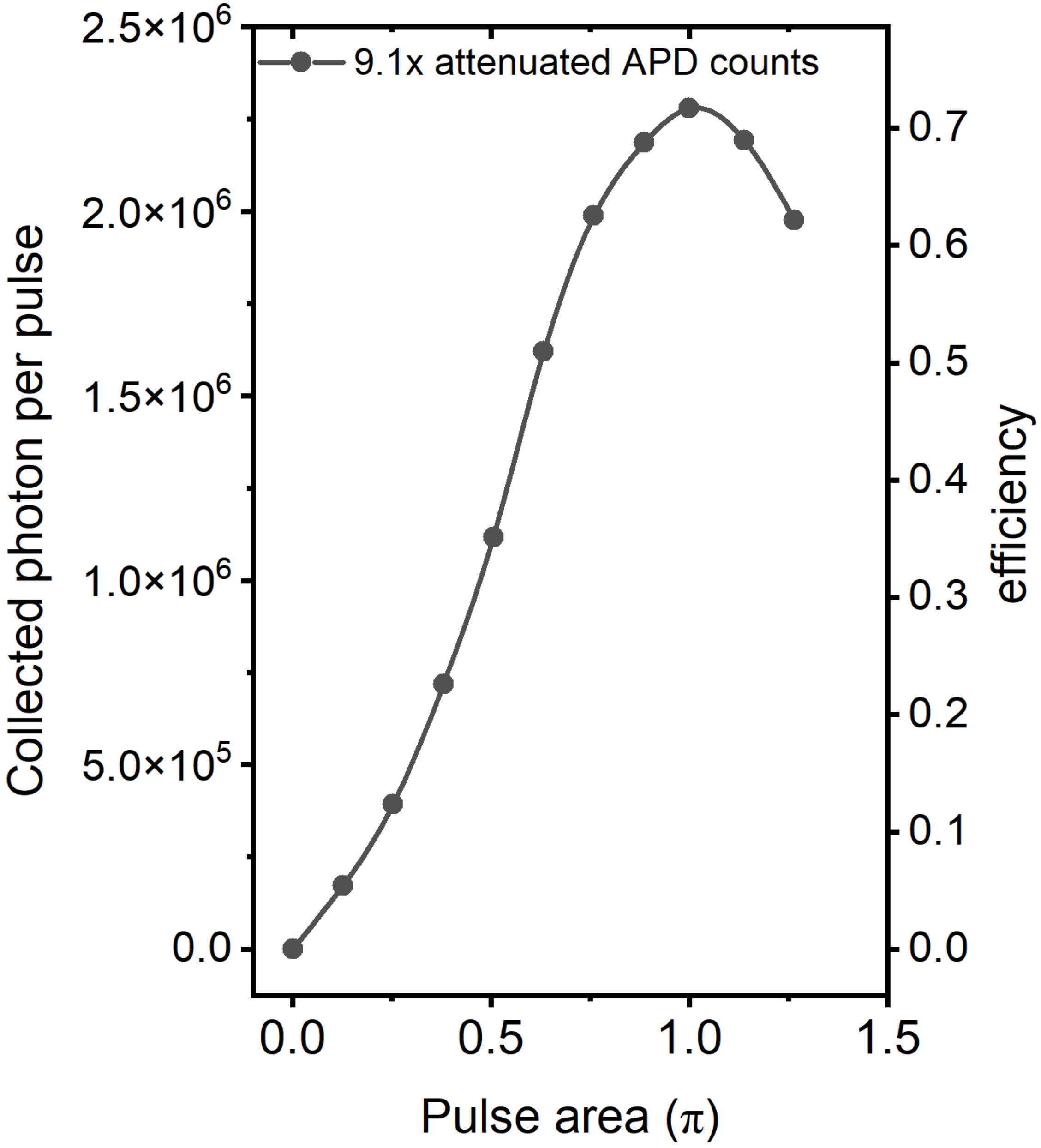






Phys. Rev. Lett. 123, 250503 (2019)





With further optimized sources, boson sampling with ~30 photons is possible

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?

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

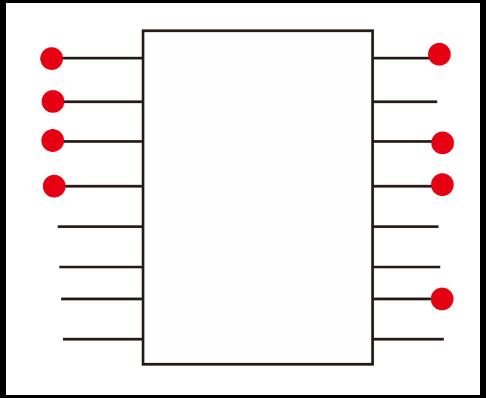
Hamilton, Kruse, Sansoni, Barkhofen, Silberhorn, & Jex, Gaussian Boson Sampling. Phys. Rev. Lett. 119, 170501 (2017).
Quesada, Arrazola, & Killoran, Gaussian boson sampling using threshold detectors. Phys. Rev. A 98, 062322 (2018).

Gaussian boson sampling:

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

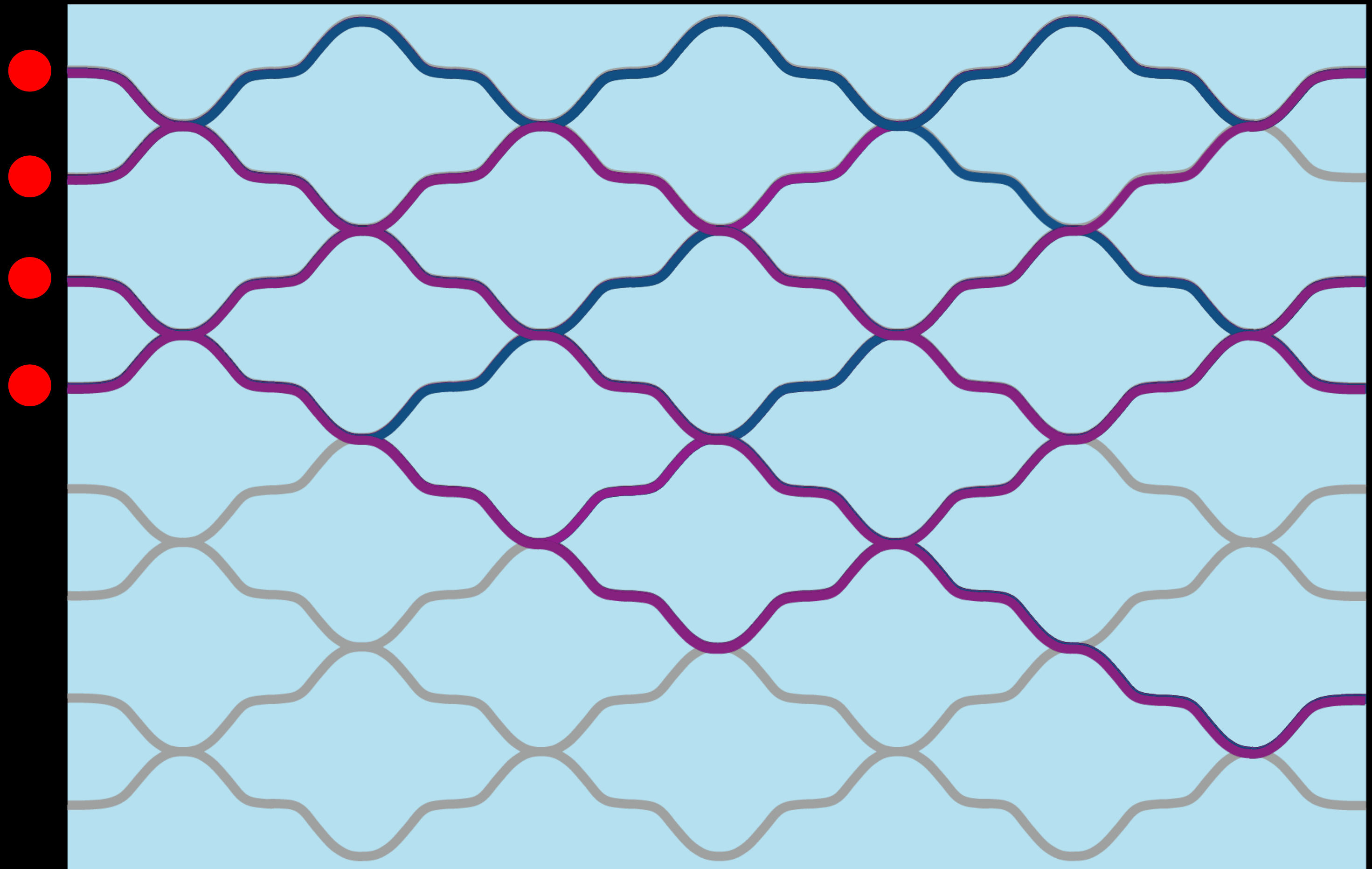
It's all about the sum of the probability amplitudes of all indistinguishable paths that can lead to the event

Output N-photon coincidence count



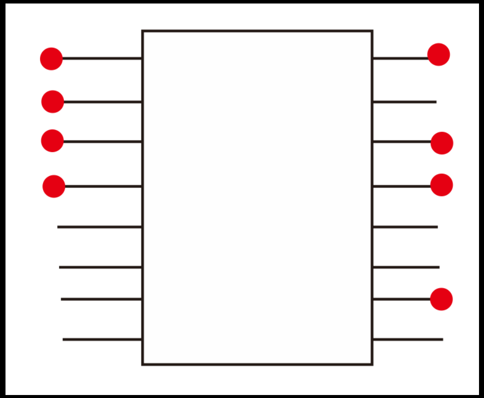
Aaronson-Arkhipov boson sampling

1234→1347; already 23520 combinations



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

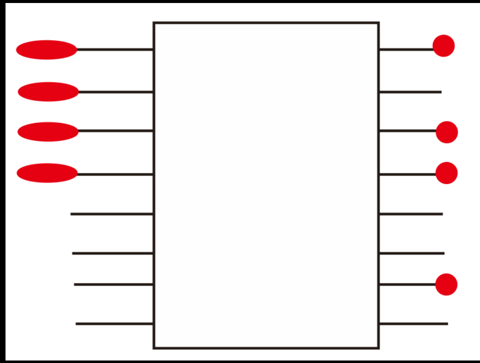
Output N-photon coincidence count



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

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

Aaronson-Arkhipov boson sampling

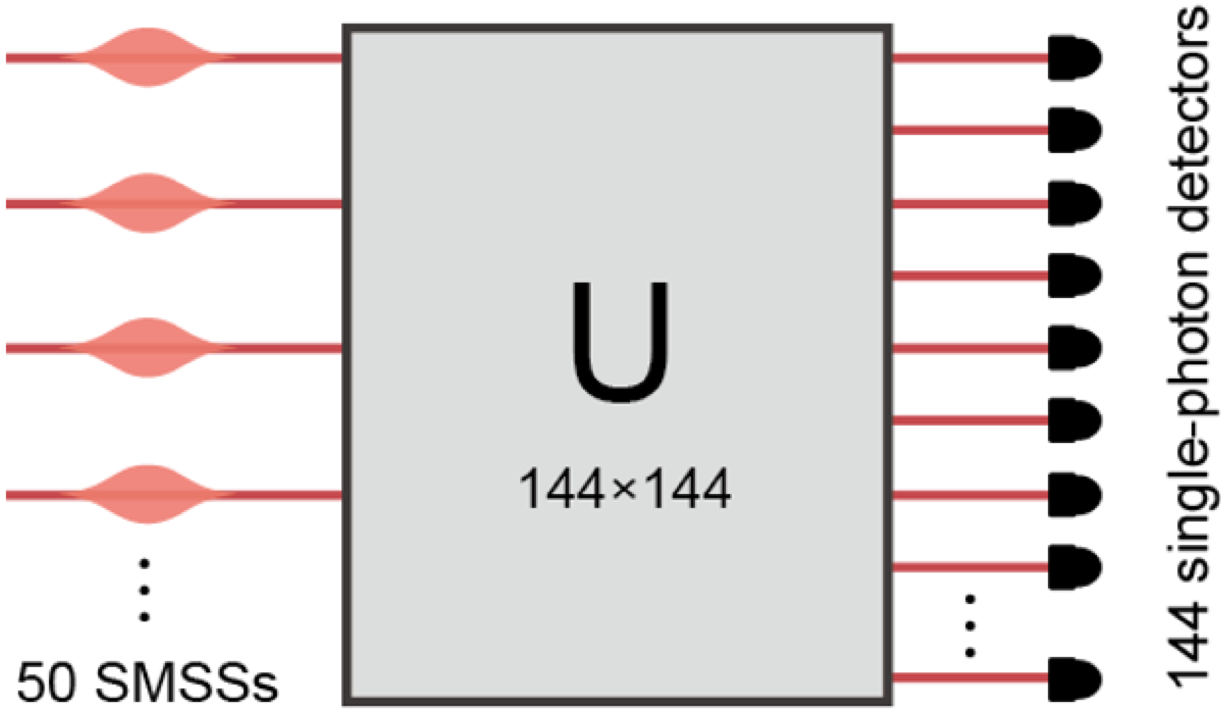


$$|\text{squeezed vacuum}\rangle_{\text{input}} = \sum_{k=0}^{\infty} g(\text{k})\, \text{e}^{ik\phi} |2k\rangle$$

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

Gaussian boson sampling

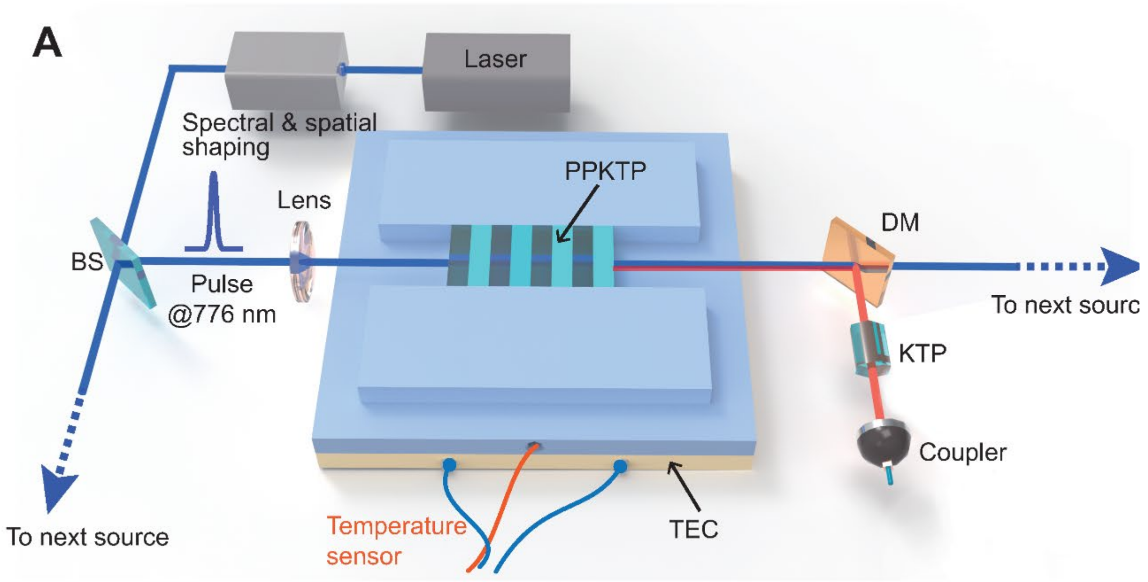
Shopping list of a large-scale GBS

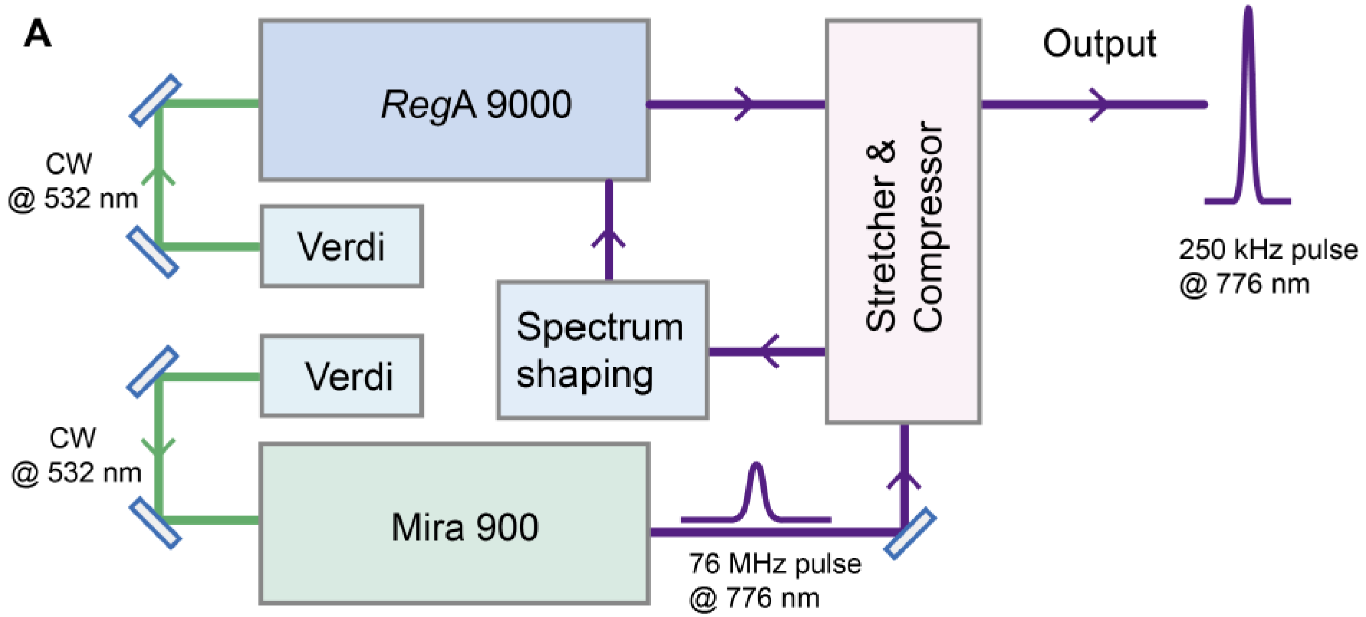


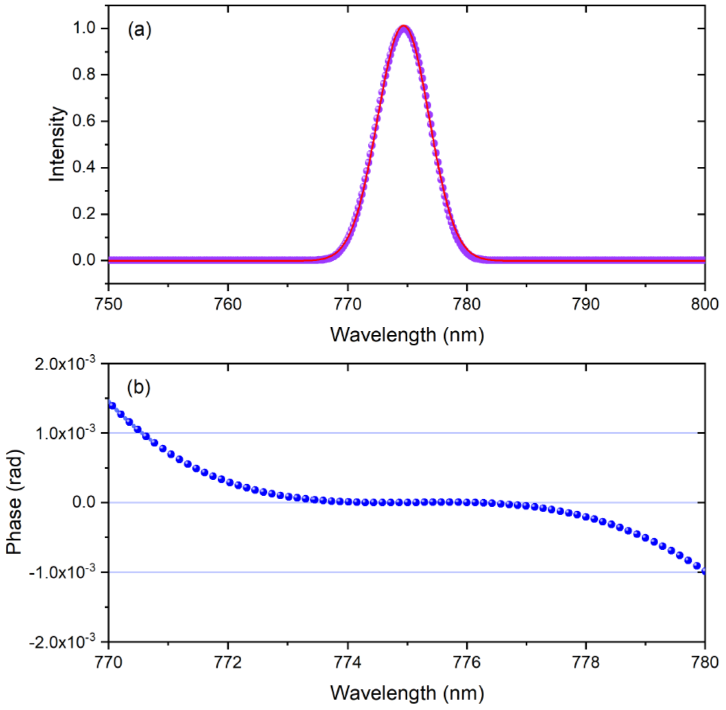
Jiuzhang 2.0

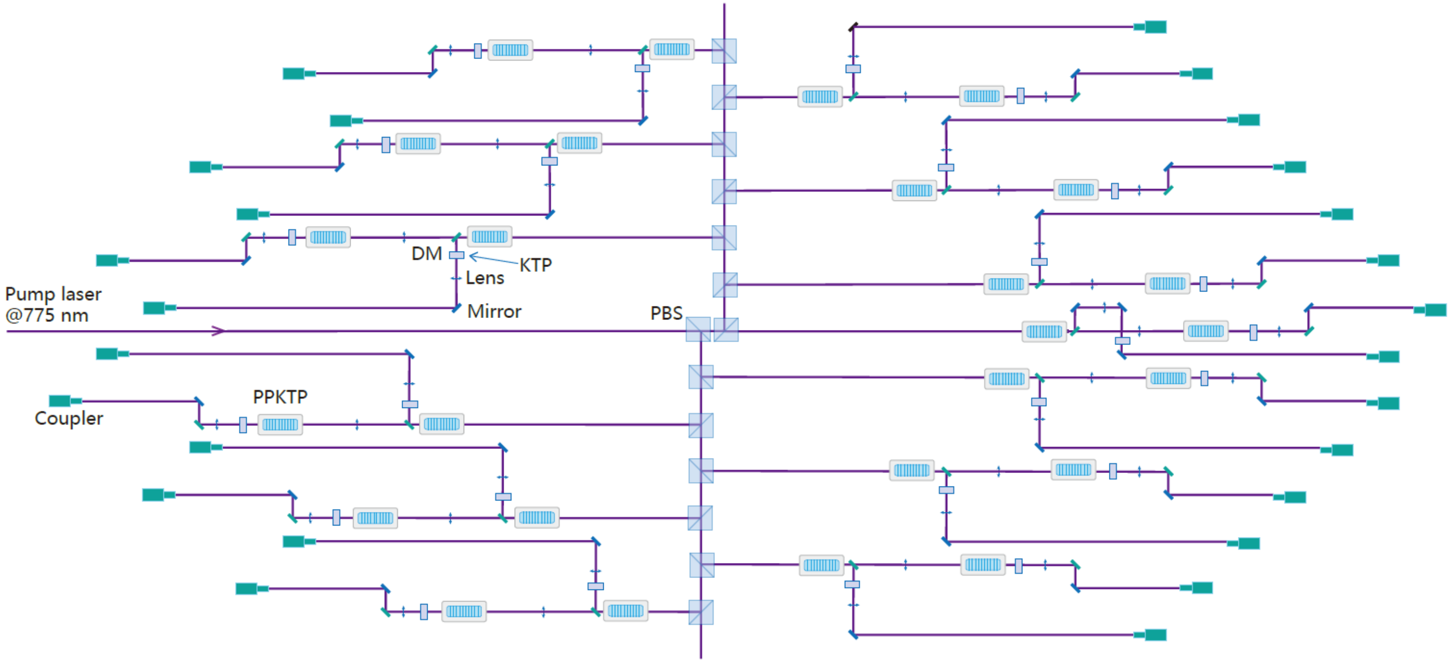
Science 370, 1460 (2020); Phys. Rev. Lett. 127, 180502 (2021)

- Source: SMSS with high squeezing parameters, indistinguishability, and collection efficiency, *simultaneously*.
- Interferometer: large and deep, full connectivity, randomness, wave-packet overlap and phase stability, and near-unity transmission rate, *simultaneously*.
- Phase control from SMSS generation to propagation inside the interferometer.
- Detectors: many, high efficiency, fast.
- Validation of the obtained samples, and benchmarking using a supercomputer.


A
Laser
Spectral & spatial
shaping
PPKTP
Lens
DM
BS
Pulse
@776 nm
To next sourc
KTP
Coupler
To next source
Temperature
sensor
TEC


A
RegA 9000
Stretcher &
Compressor
Output
CW
@ 532 nm
Verdi
Spectrum
shaping
250 kHz pulse
@ 776 nm
Verdi
CW
@ 532 nm
Mira 900
76 MHz pulse
@ 776 nm

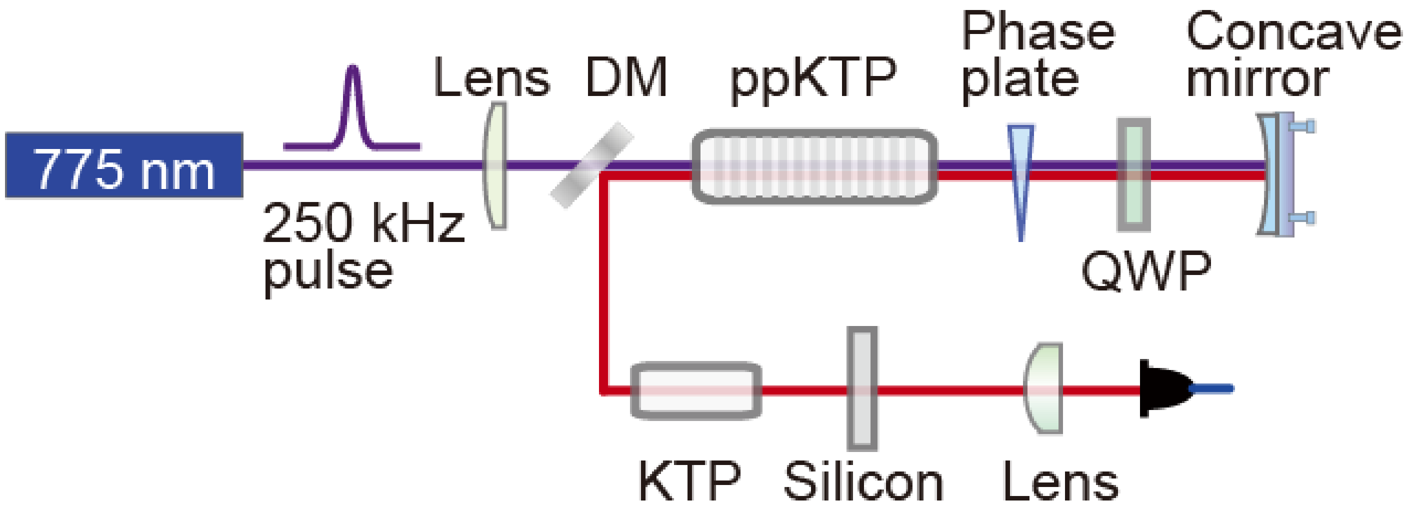

(a)
Intensity
Wavelength (nm)
(b)
Phase (rad)
Wavelength (nm)

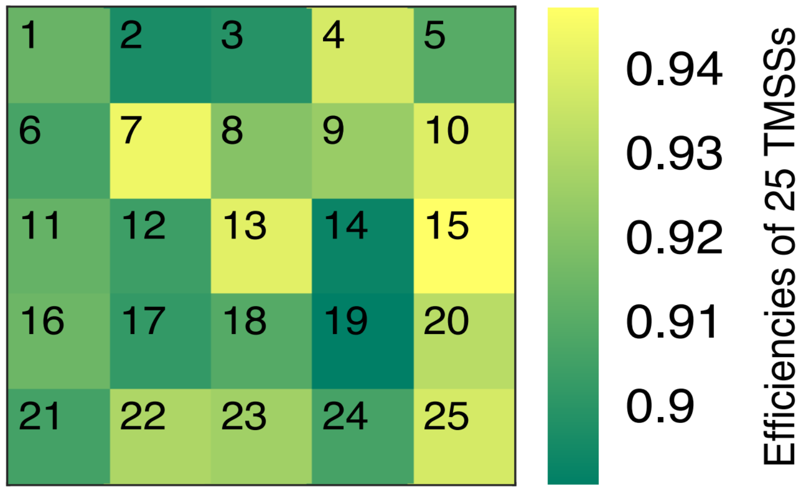

DM
KTP
Lens
Pump laser
@775 nm
Mirror
PBS
PPKTP
Coupler

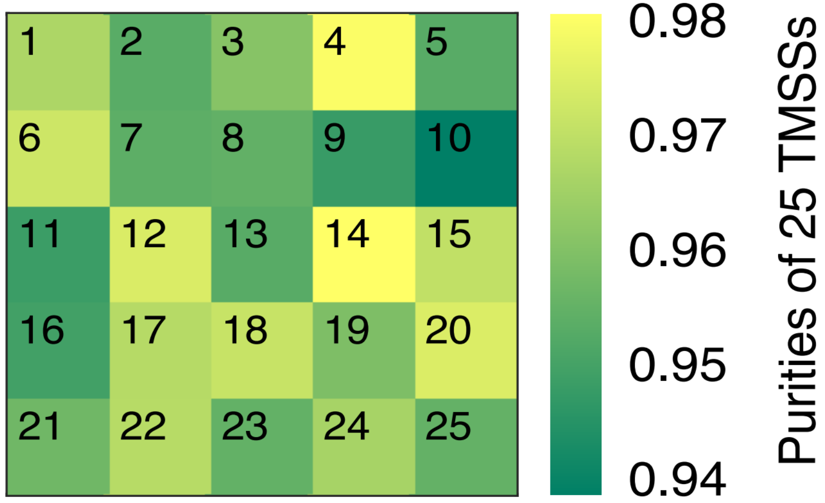
LASER inspired new source

Stimulated PDC:

same laser power, 4 times brighter squeezed light

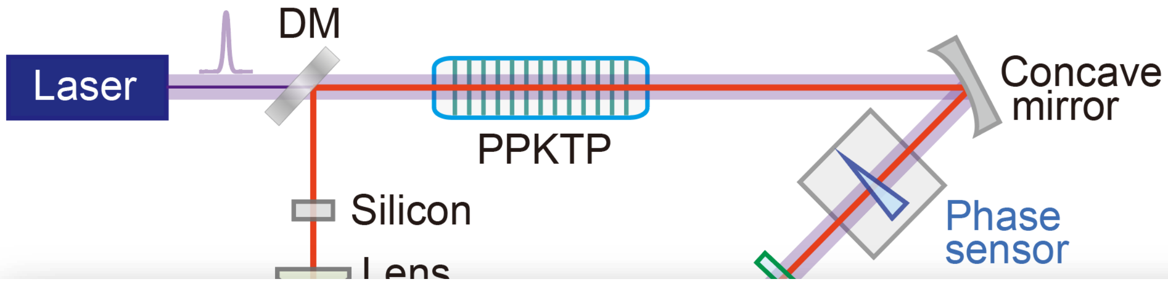


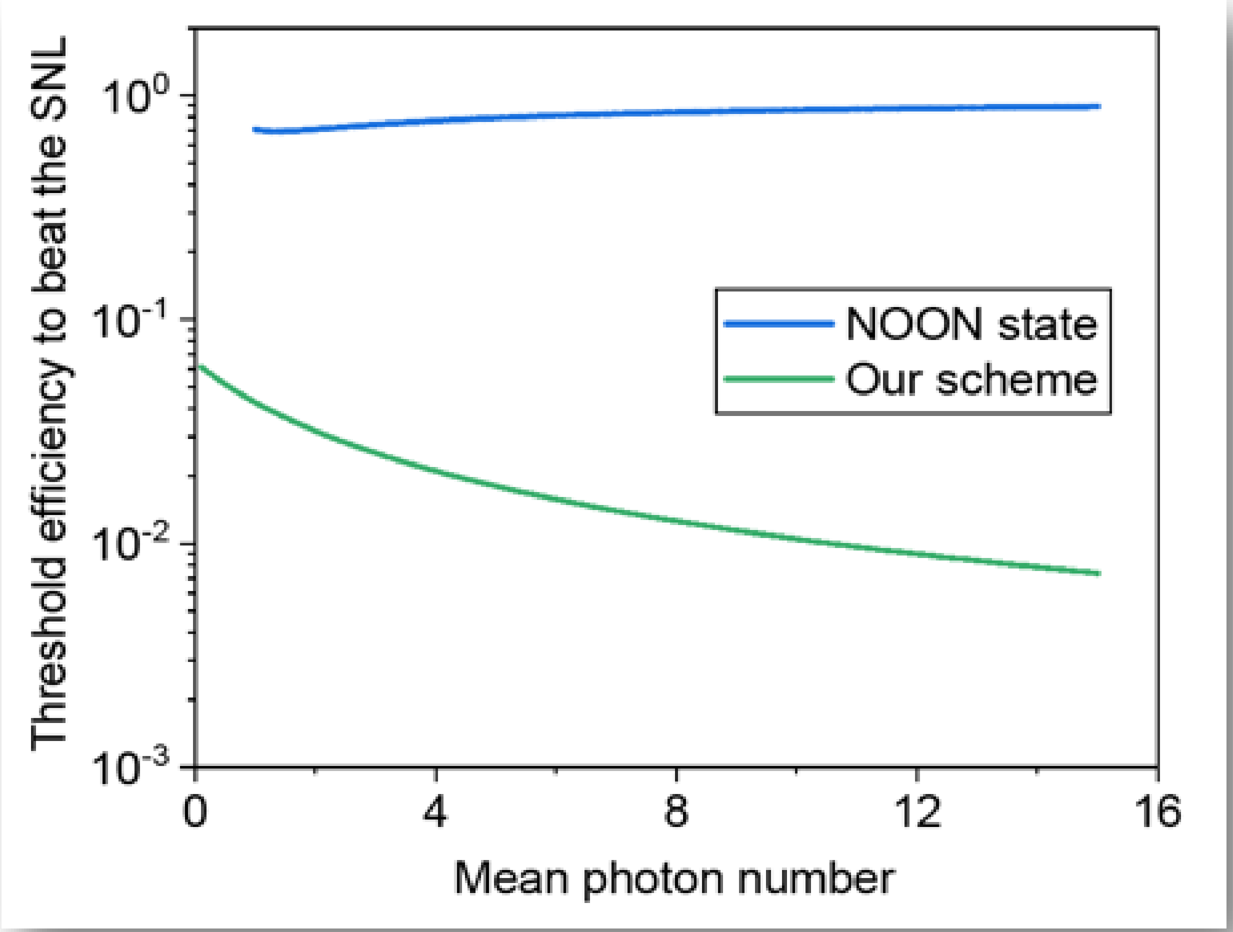


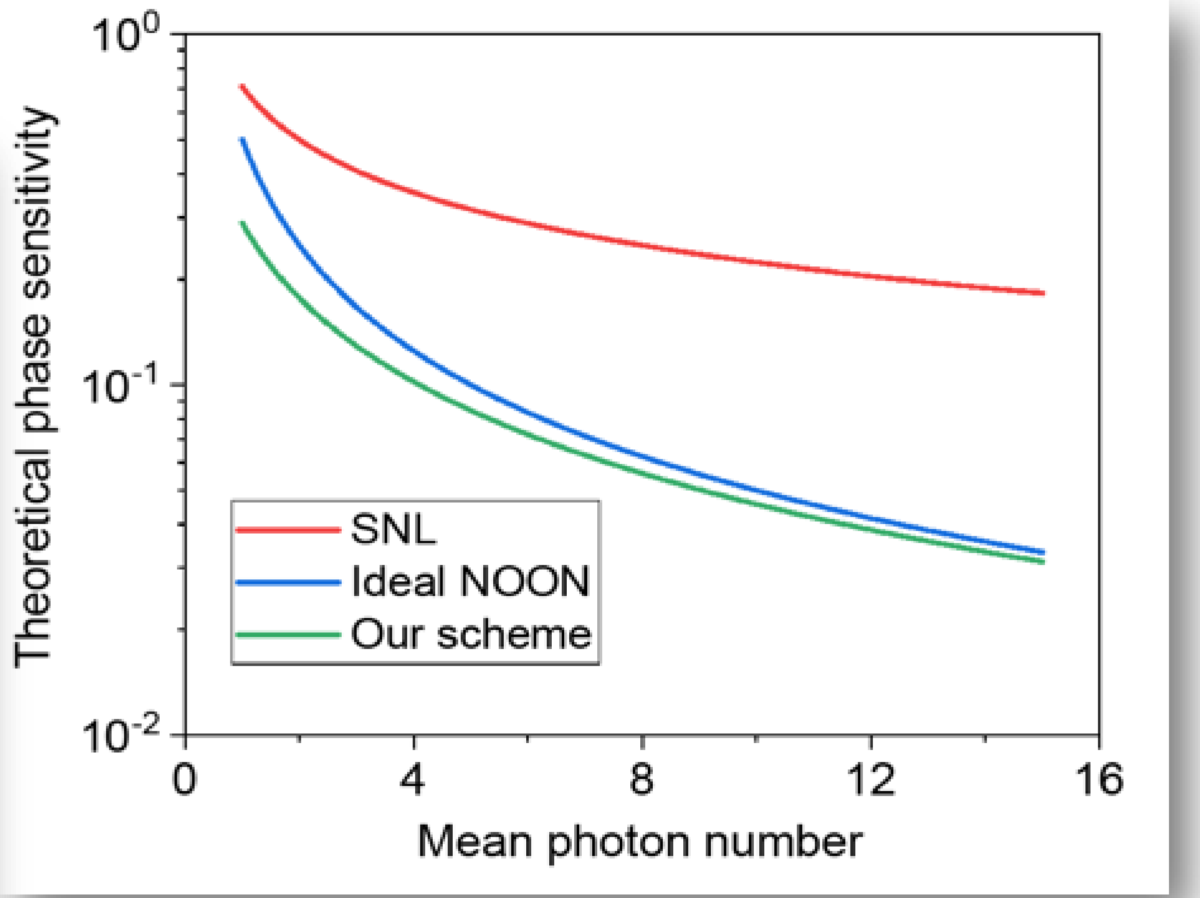


Science 370, 1460 (2020); Phys. Rev. Lett. 127, 180502 (2021)

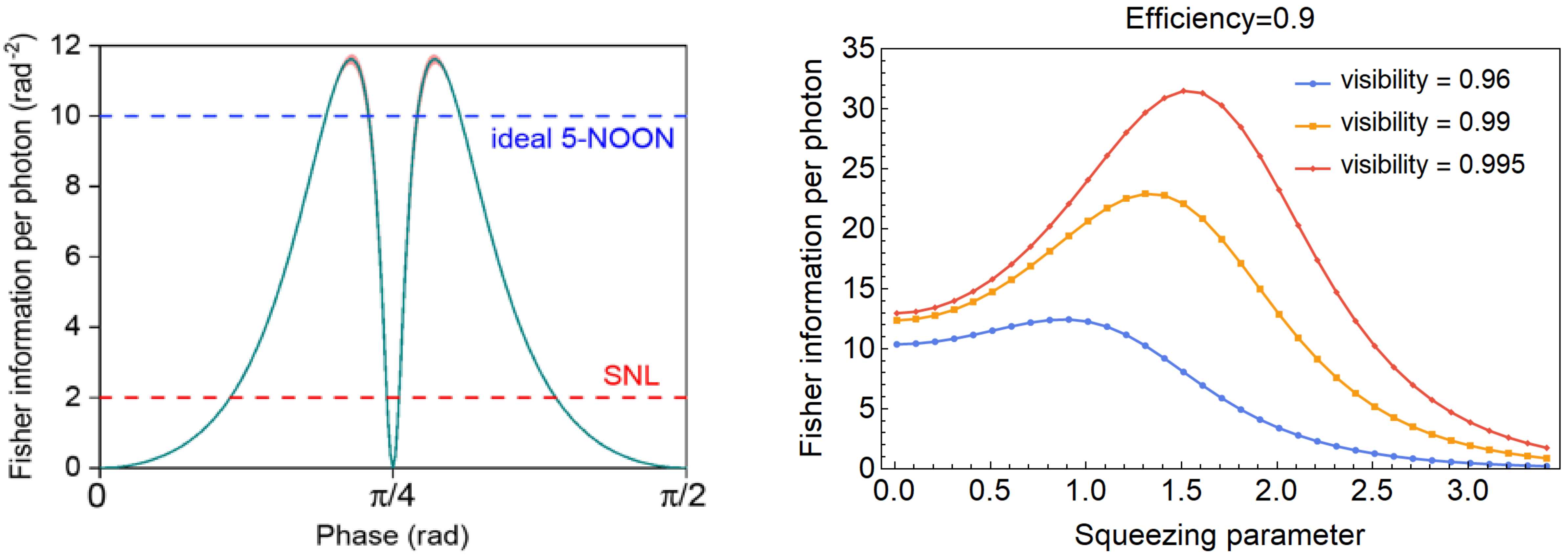
Spin-off: Beyond-NOON metrology, unconditional, robust

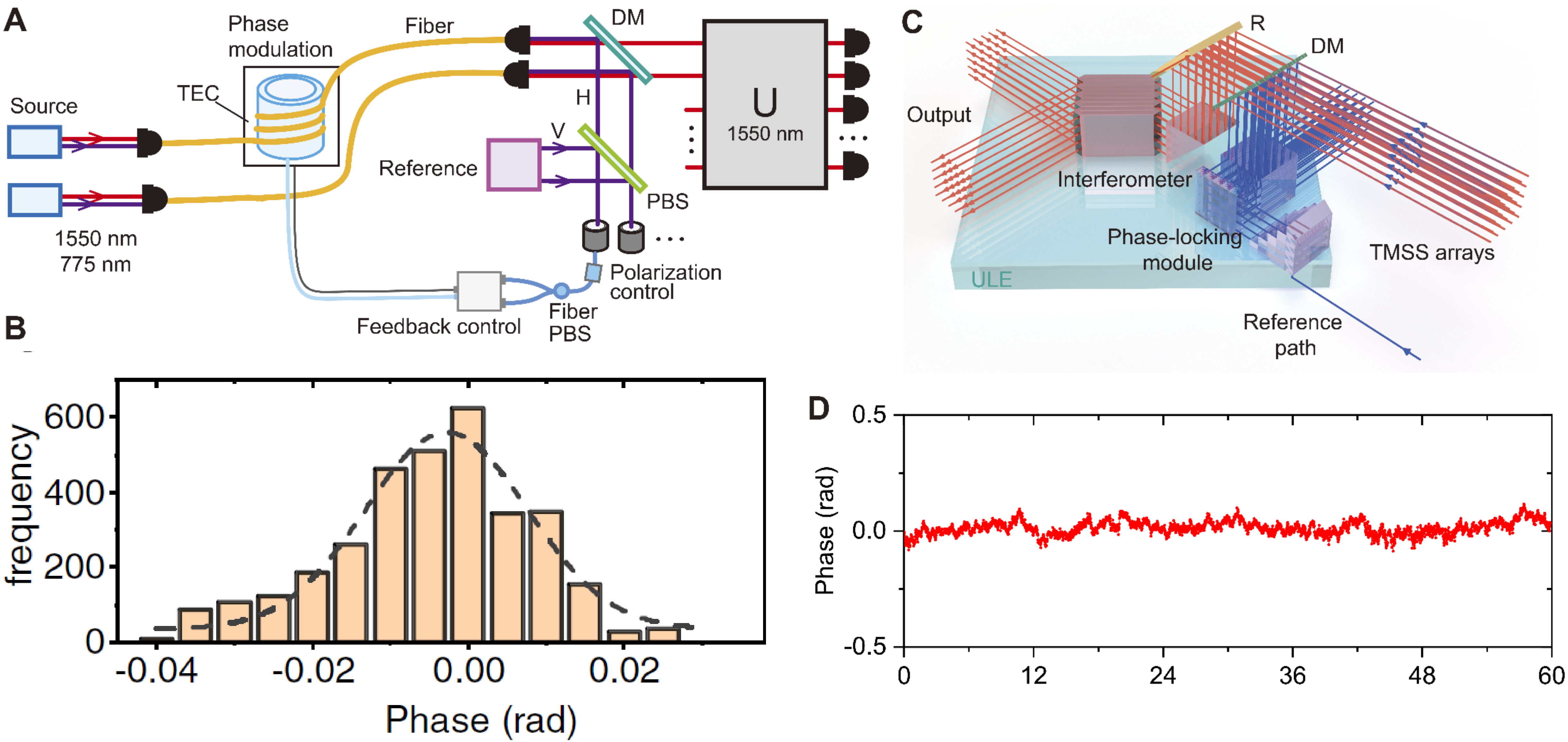






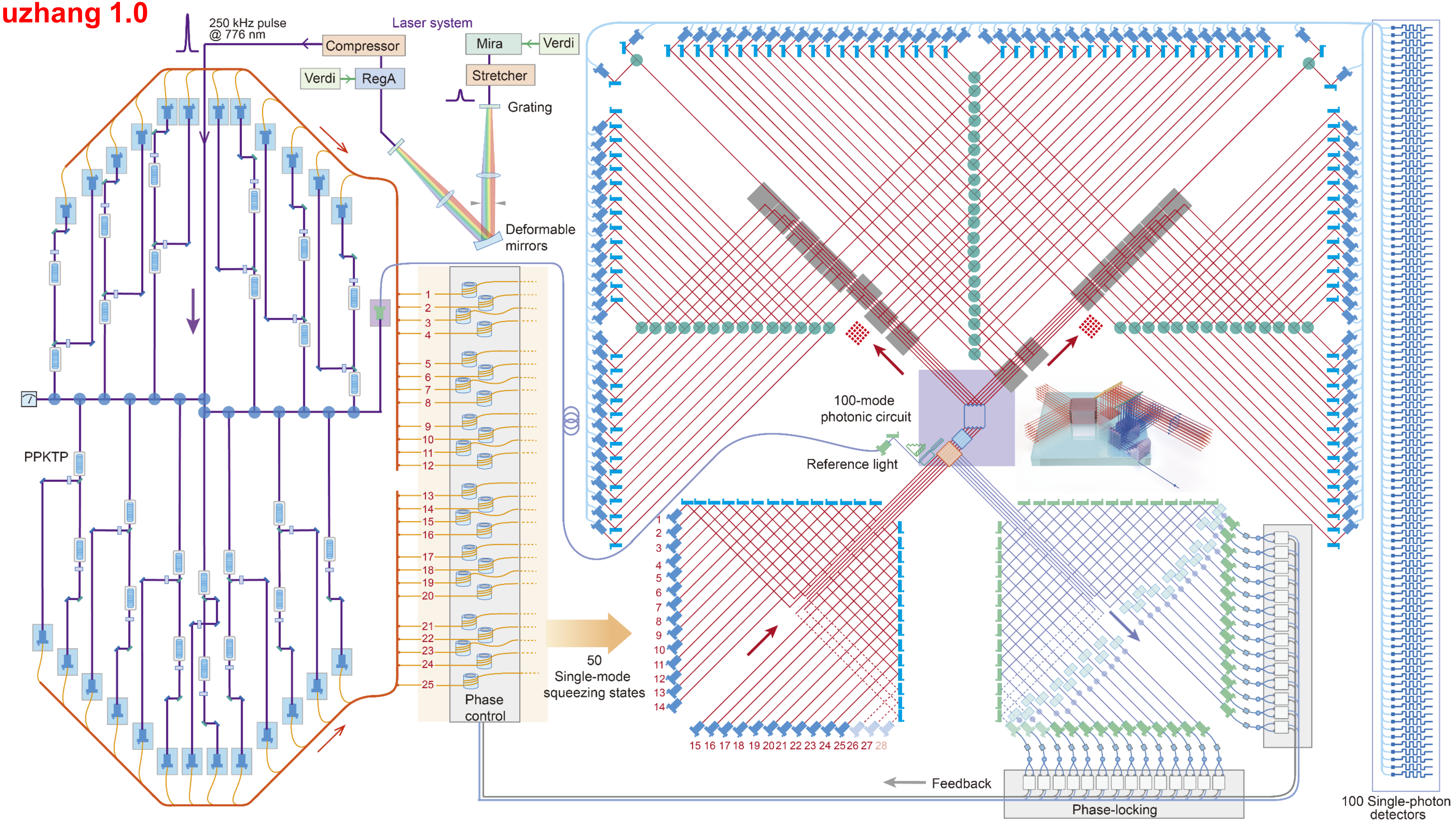
Spin-off: Beyond-NOON metrology, unconditional, robust




A
Phase modulation
Fiber
DM
Source
TEC
H
V
U
1550 nm
Reference
PBS
1550 nm
775 nm
Polarization control
Feedback control
Fiber PBS
B
frequency
600
400
200
0
-0.04
-0.02
0.00
0.02
Phase (rad)
C
R
DM
Output
Interferometer
Phase-locking module
TMSS arrays
ULE
Reference path
D
Phase (rad)
0.5
0.0
-0.5
0
12
24
36
48
60

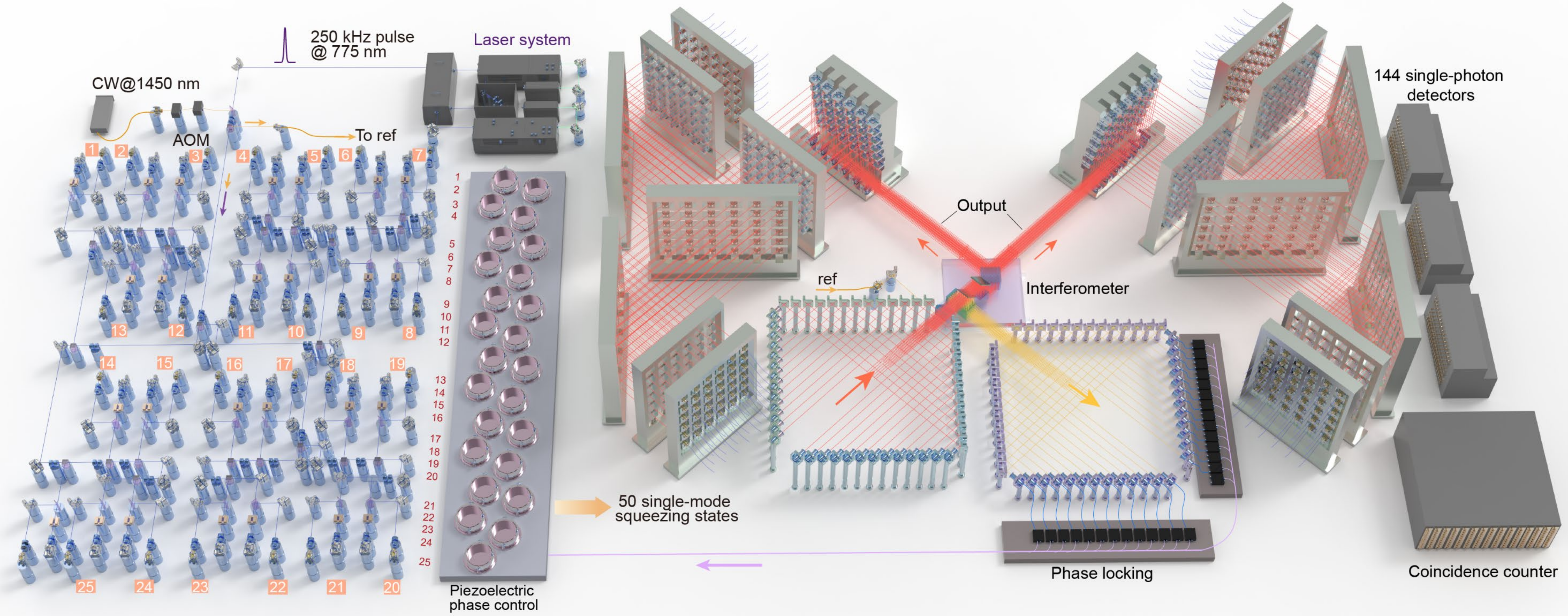
Quantum computing is like collecting seven dragon balls; only by putting all of them together, can it show the quantum computational power.

Jiuzhang 1.0



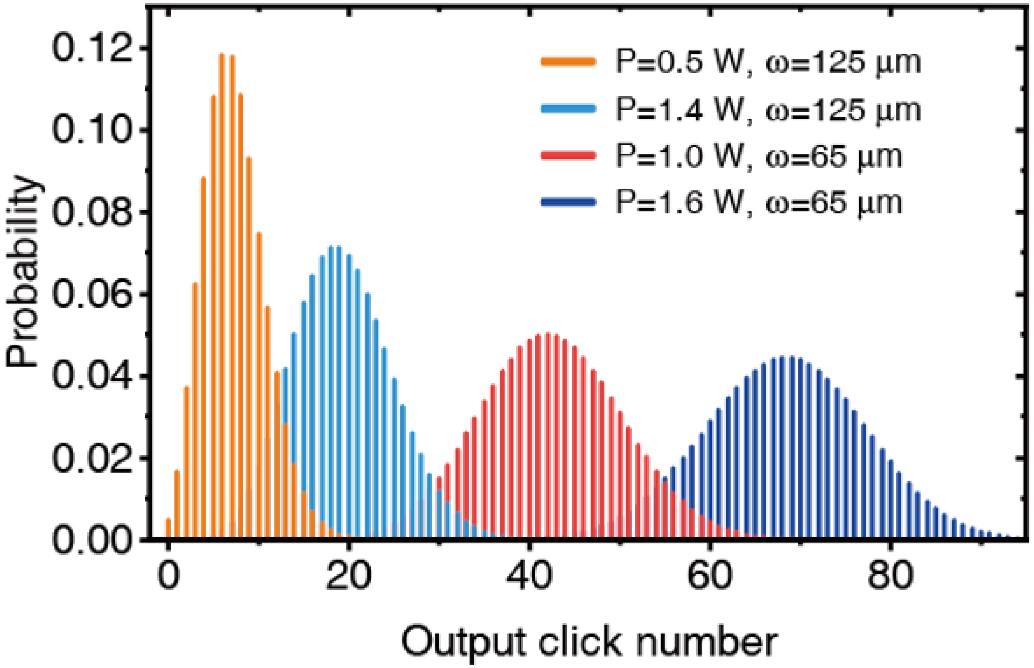
250 kHz pulse
@ 776 nm
Laser system
Compressor
Mira
Verdi
Verdi
RegA
Stretcher
Grating
Deformable
mirrors
PPKTP
Phase
control
50
Single-mode
squeezing states
100-mode
photonic circuit
Reference light
Feedback
Phase-locking
100 Single-photon
detectors

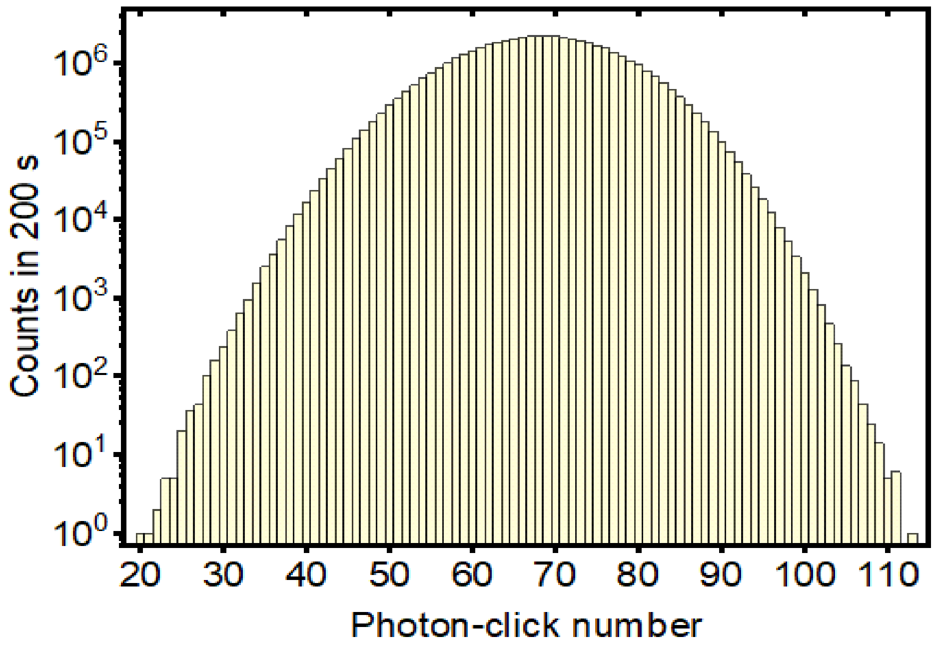
Jiuzhang 2.0



Science 370, 1460 (2020); Phys. Rev. Lett. 127, 180502 (2021)

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

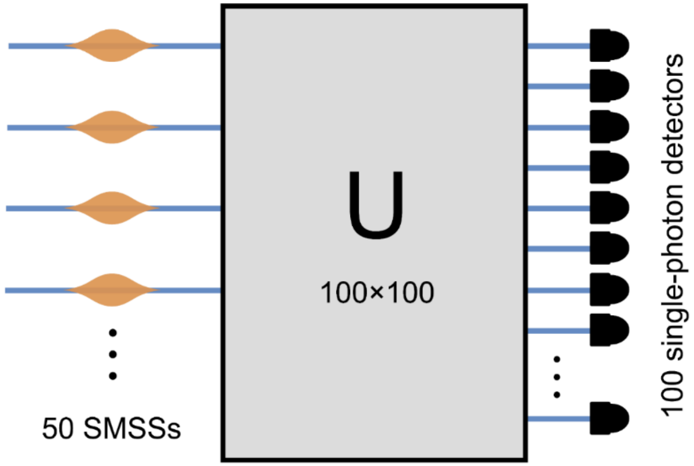


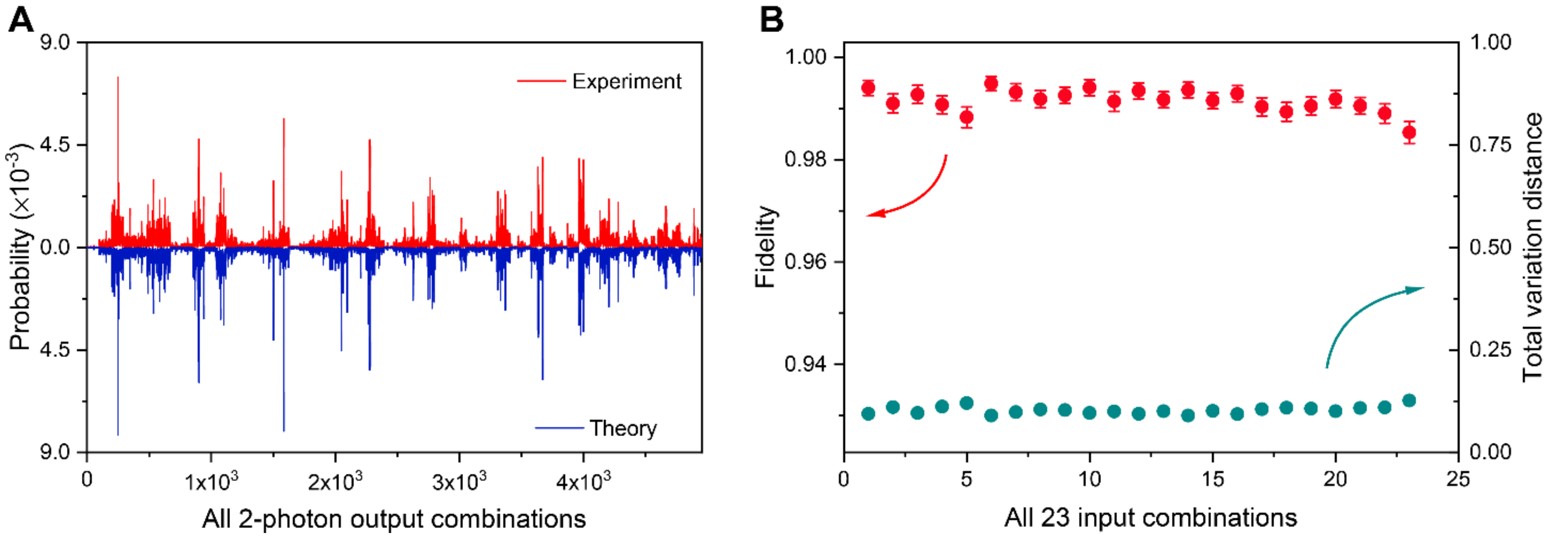


Max photon click: 113

Unlike **Shor's algorithm** where its solution can be efficiently verified;
For the GBS, a full certification of the outcome is strongly conjectured to be intractable for classical computation.

System calibration





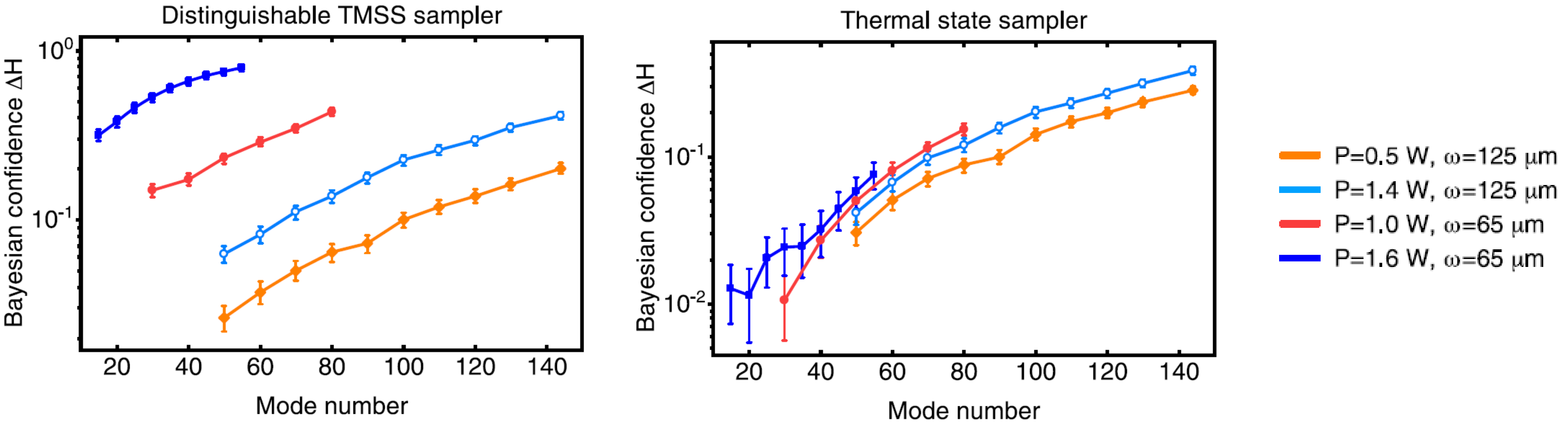
Validating the GBS

Gathering circumstantial evidence & ruling out possible hypotheses (spoofs):

- Thermal states—would result from excessive photon loss
- Distinguishable—would be caused by mode mismatch
- Squeezed thermal states—would be caused by thermal noise
- Coherent state, uniform sampler, …

Bayesian test

A larger value of ΔH indicates a larger deviation between the GBS and the mockups.



- The data are successfully validated (ΔH>0).
- The validation confidence becomes even stronger for a larger mode number, with effectively smaller photon loss.
- This allows us to infer that the same setup with all modes in the quantum advantage regime would be validated with an even stronger confidence.

"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."

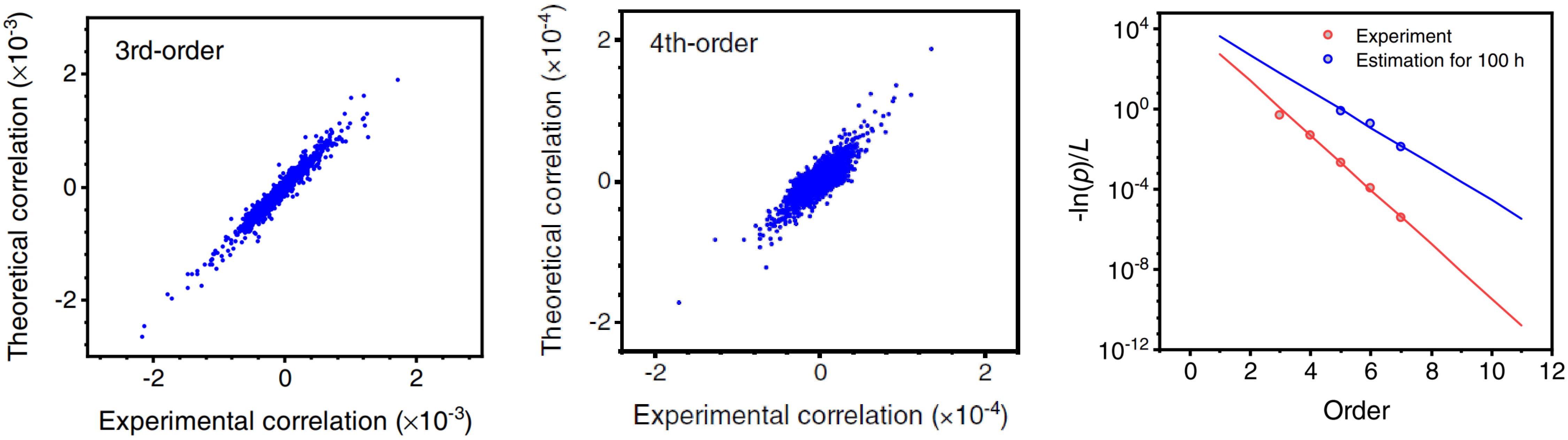
– Zhong *et al.* (2020)

Spoof attacks

- Movie of Stephen Chow, *The Mermaid*

Google's classical attack: greedy algorithm [Villalonga *et al.* arXiv:2109.11525]

- Using only 1-order and 2-order correlation to generate mock up samples, which has better total variance distance on small-scale subsystem. But no high-order correlation.

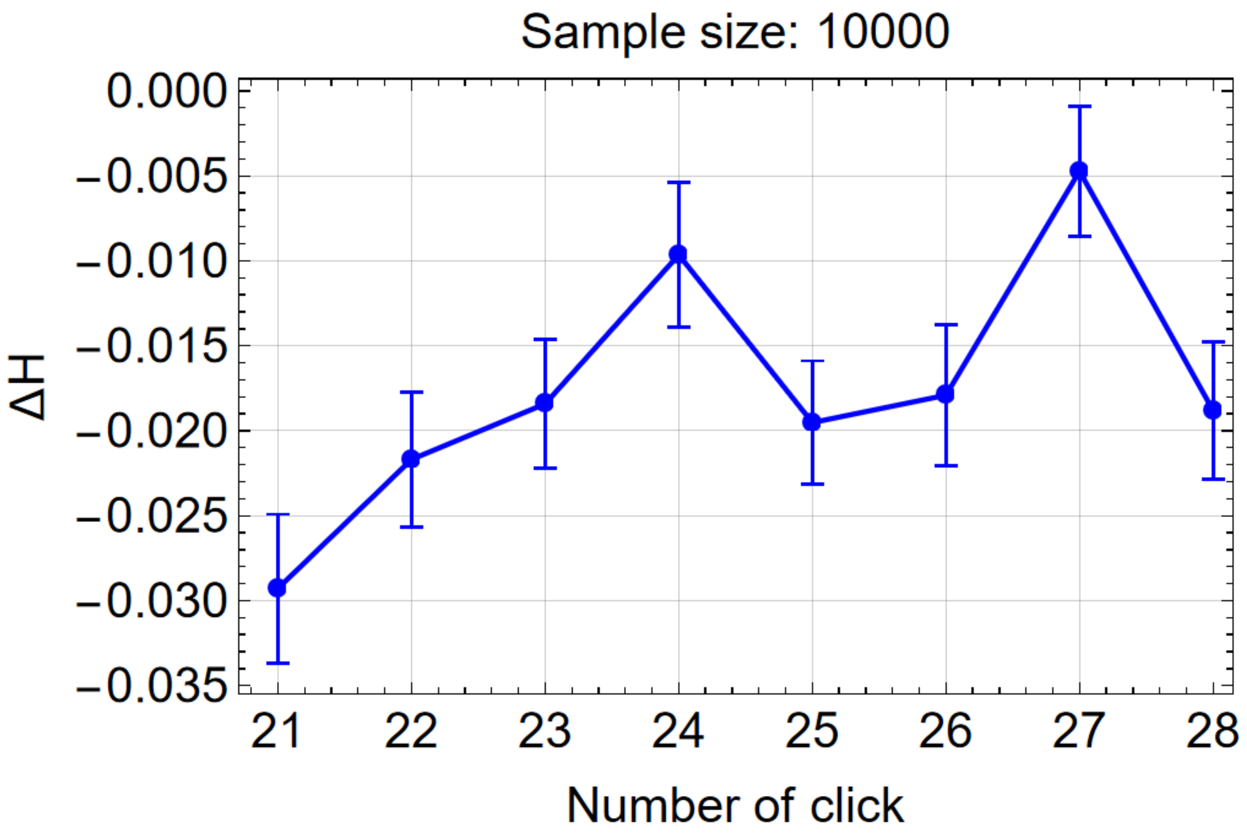


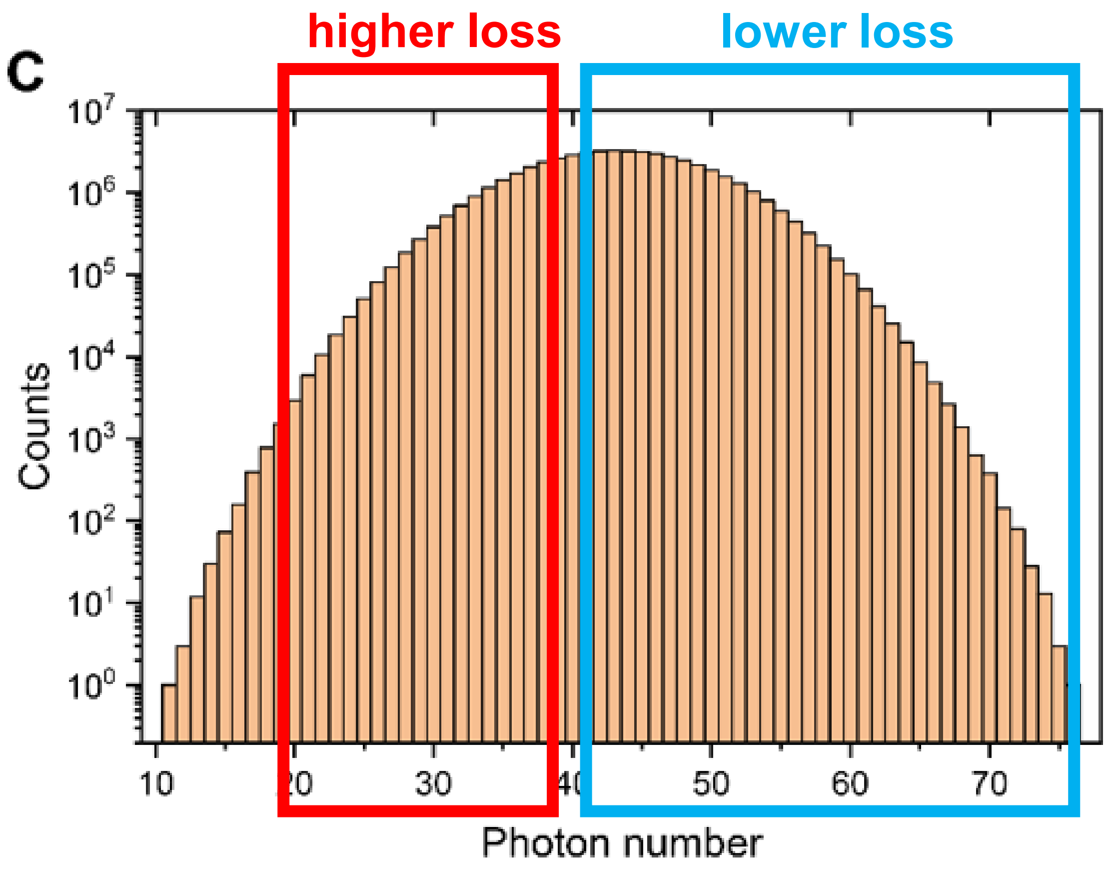
[Shchesnovich, arXiv:2204.07792] *Boson sampling cannot be faithfully simulated by only the lower-order multi-boson interferences*

Classical simulations accounting for only the lower-order multi-boson interferences can be efficiently distinguished from the quantum device with finite noise by checking the higher-order correlations.

Quesada's classical attack: modified squash states [Martínez-Cifuentes, *et al.* arXiv:2207.10058]

- Similar high-order correlations
- Have better Bayesian test (???), but HOG can validate





The history toward loophole-free Bell test…

Freedman and Clauser, PRL 1972; Fry and Thompson, PRL 1976

Aspect *et al.* PRL 1982
Zeilinger *et al.* PRL 1998

Space-like separation

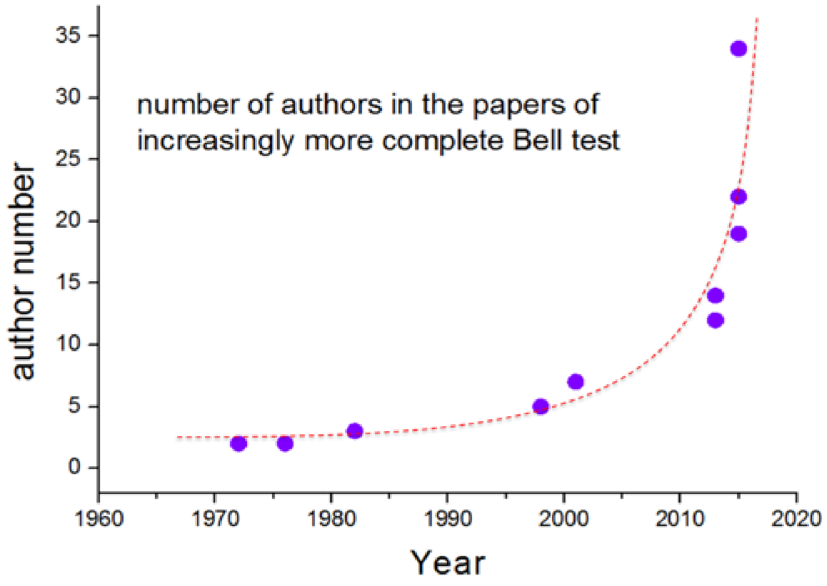
Rowe *et al.* Nature 2001
Giustina *et al.* Nature 2013

Efficient detection

Hanson *et al.* Nature (2015)
Zeilinger *et al.* PRL (2015)
Shalm *et al.* PRL (2015)

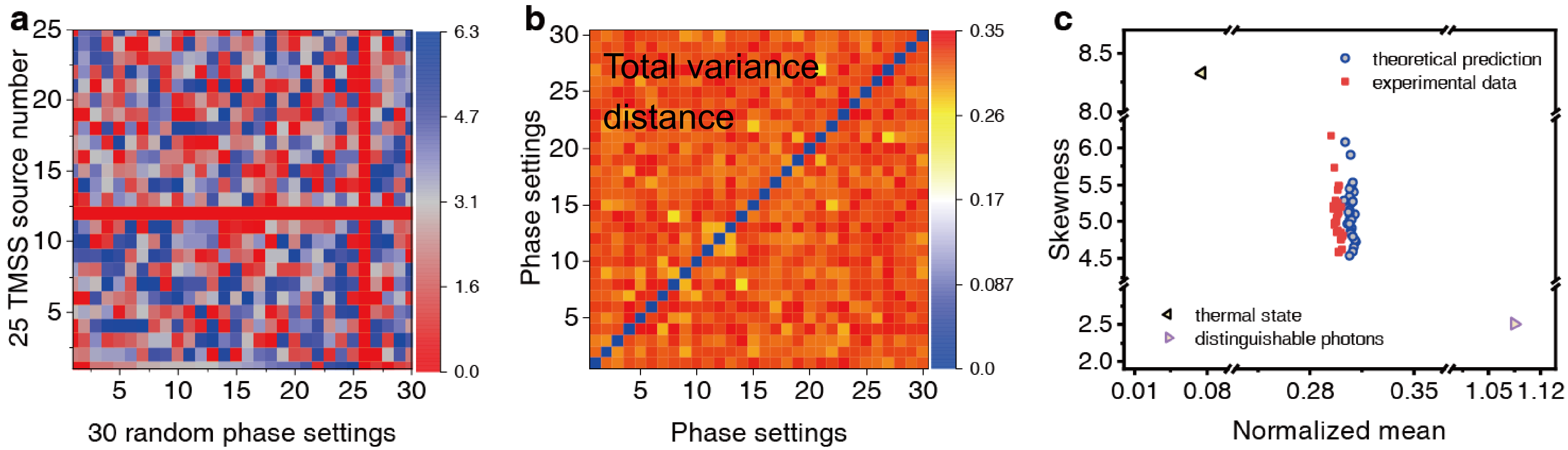
Locality and detection

… …



Locality, detection, freedom of choice, free will? …

Phase-programmable GBS



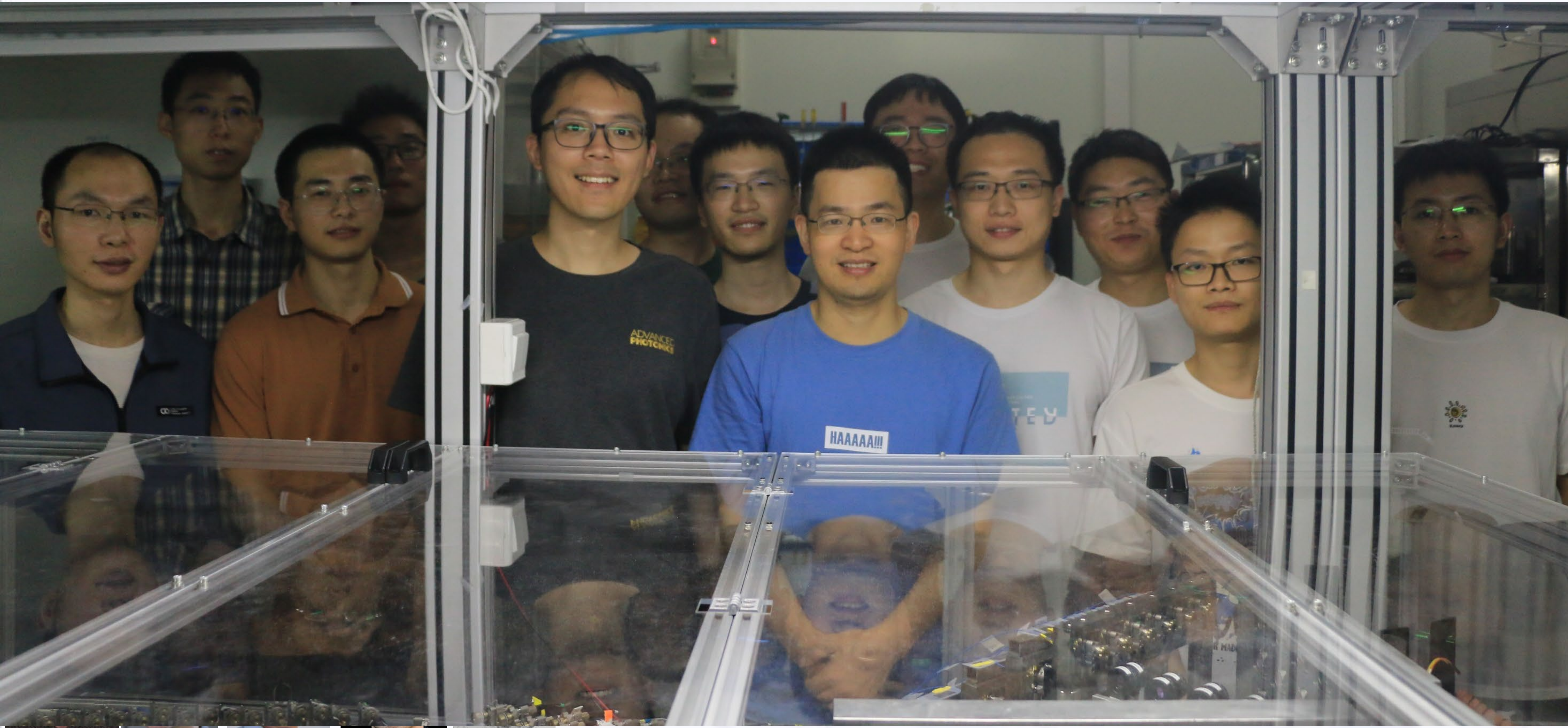
We change 30 random input squeezed state phases and obtain 30 statistically different samples, each are validated against mockups. Phys. Rev. Lett. 127, 180502 (2021)

Future:

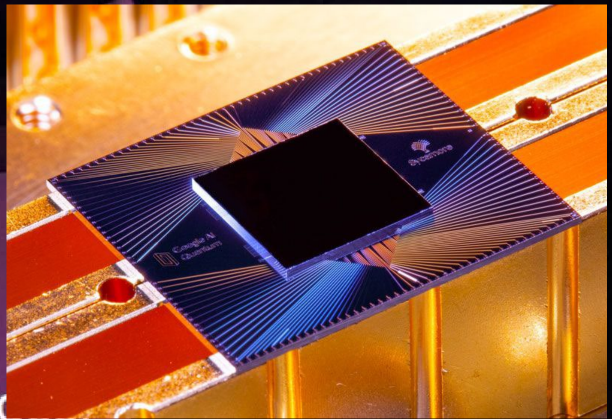
Higher efficiencies (source, transmission, detectors); possible applications; GKP code; photon-photon CNOT gate, superconducting qubits & optical tweezers…

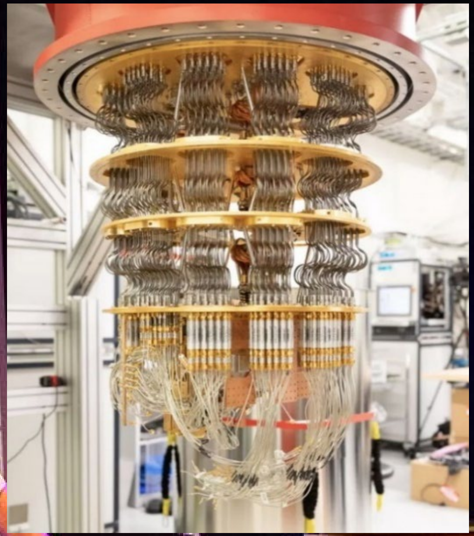
Ruling out real-valued standard formalism of quantum theory, PRL 128, 040403 (2022);
Strong quantum computational advantage with 56 and 60-qubit RCS, PRL 127, 180501 (2021)

Acknowledgement



Thank you





arXiv:2111.03011 [pdf, other] quant-ph physics.comp-ph

Solving the sampling problem of the Sycamore quantum supremacy circuits

Authors: Feng Pan, Keyang Chen, Pan Zhang

Abstract: We study the problem of generating independent samples from the output distribution of Google's Sycamore quantum circuits with a targ

uantum supremacy. We propose

ly more efficient than existing m

uit with 53 qubits and 20 cycles,

Limitations of Linear Cross-Entropy as a Measure for Quantum Advantage

Xun Gao, Marcin Kalinowski, Chi-Ning Chou, Mikhail D. Lukin, Boaz Barak, Soonwon Choi