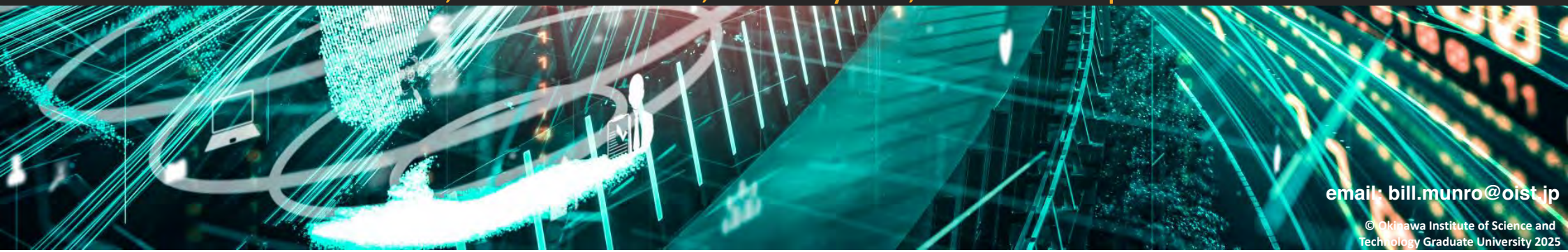
Photons: Powering quantum processors today, building the quantum internet of tomorrow

William John Munro, Akitada Sakurai, Aoi Hayashi, Nicolo Lo Piparo and Kae Nemoto



email: bill.munro@oist.jp

A brief history of Bill

Freedom in Science

- BSc (Chemistry) - University of Waikato (NZ)
- PhD (Quantum Optics) - University of Waikato (NZ)
- Postdoc at the University of Queensland (Australia)

- Principal staff scientist - Hewlett Packard (UK)
  - Quantum Technology and Security
- Director & Senior Distinguished Scientist - NTT (Japan)
  - Quantum Technology

More than 20+ years in industry

- **Recently a Professor at OIST**

unesco

INTERNATIONAL YEAR OF
Quantum Science
and Technology

100 YEARS OF QUANTUM IS JUST THE BEGINNING

The 2025 International Year of Quantum Science and Technology (IYQ) recognizes 100 years since the initial development of quantum mechanics. Join us in engaging with quantum science and technology and celebrating throughout the year!

OIST | Quantum

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Quantum technology: the second quantum revolution

Jonathan P. Dowling and Gerard J. Milburn

Phil. Trans. R. Soc. Lond. A 2003 **361**, 1655-1674
doi: 10.1098/rsta.2003.1227

OIST | Quantum

We are currently in the midst of a second quantum revolution. The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies. In this review we discuss the principles upon which quantum technology is based and the tools required to develop it.

OIST Center for Quantum Technologies

Hiroki Takahashi
Ion trap
Quantum computing & communications

Kae Nemoto
Design & Implementation of quantum technologies
Quantum computer Science

Najwa Aaraj
Quantum-safe Cybersecurity
Quantum Internet Security

William Munro
Quantum Engineering
Security & Communications

Sile Nic Chormaic
Atomic and optical physics

Thomas Busch
Cold atom physics and its applications
many-body physics

Carlos Cid
Post-quantum cryptography
Secure computation

David Elkouss
Quantum networks and devices

Denis Konstantinov
Low temperature physics

Jason Twamley
Hybrid quantum systems
Quantum sensors

SIP members

Engineering

Physics Experiments | Physics Theory | Computer science | Applied Crypto & Cybersecurity

Cover the wide spectrum of quantum related fields

Philipp Höhn
Qubits and quantum information

Keshav Dani
Femtosecond spectroscopy

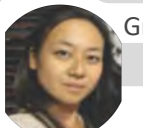
Shu Zhang
Collective Quantum Dynamics and Transport

Nic Shannon
Quantum Materials

Artur Ekert
Quantum physics
Quantum Cryptography

Yoshinori Okada
Quantum materials, nano-electronics

Yasha Neiman
Gravitation with quantum theory

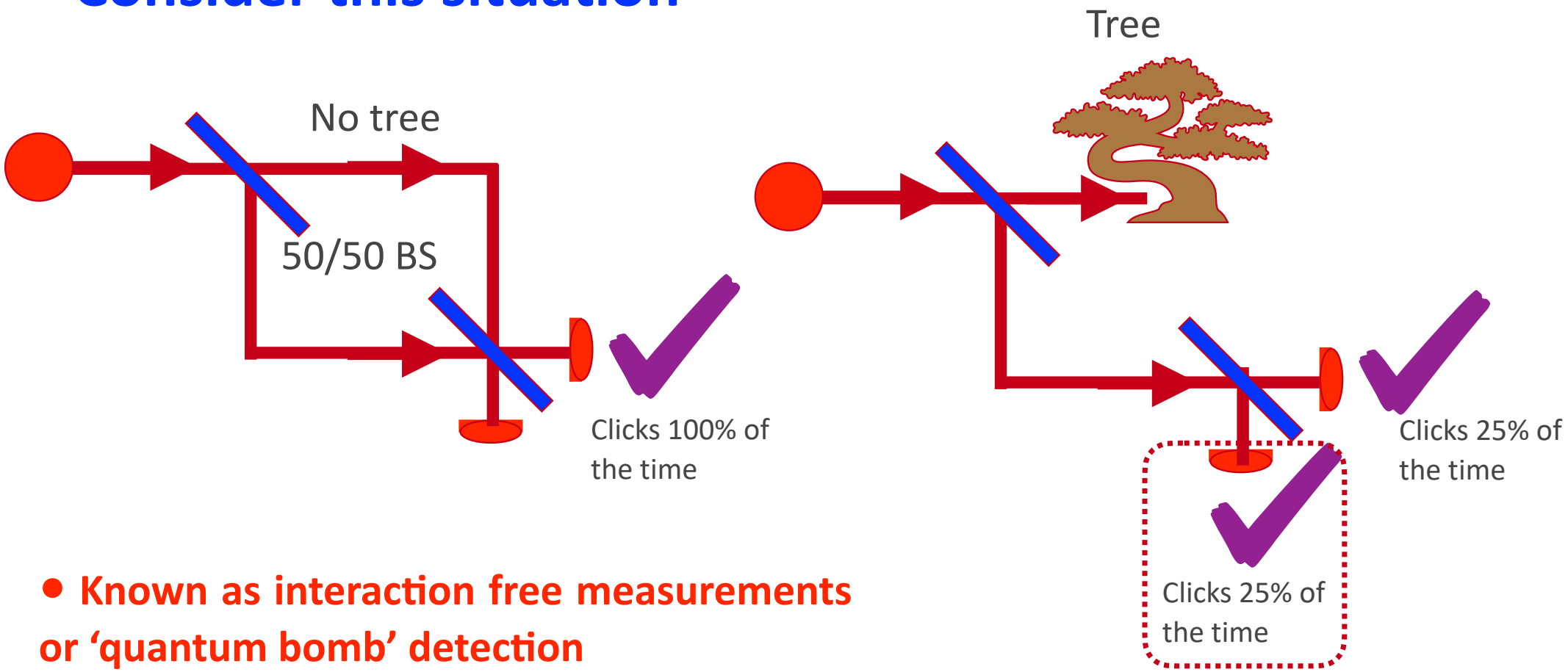


Reiko Toriumi
Quantum Gravity

18 units and 1 STG

Observing without looking

- **Consider this situation**

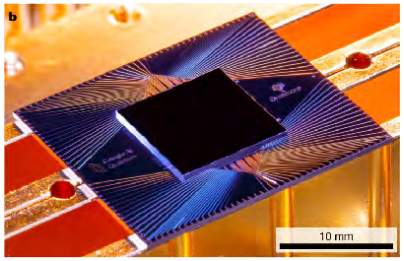


- **Known as interaction free measurements or 'quantum bomb' detection**

Can be improved to 100%

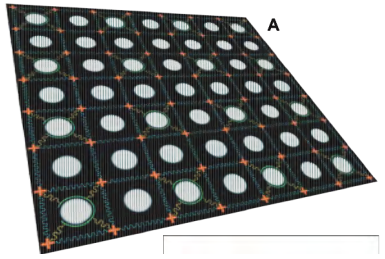
The move to the quantum regime

- **The quantum regime is interesting !!!**
  - We already have a range of small scale quantum technologies including NISQ processors, quantum sensors & quantum clocks.
  - The NISQ processors involve 100's of qubits



Elizabeth Gibney, Nature 574, 461 (2019)


Credit: Chao-Yang Lu/USTC



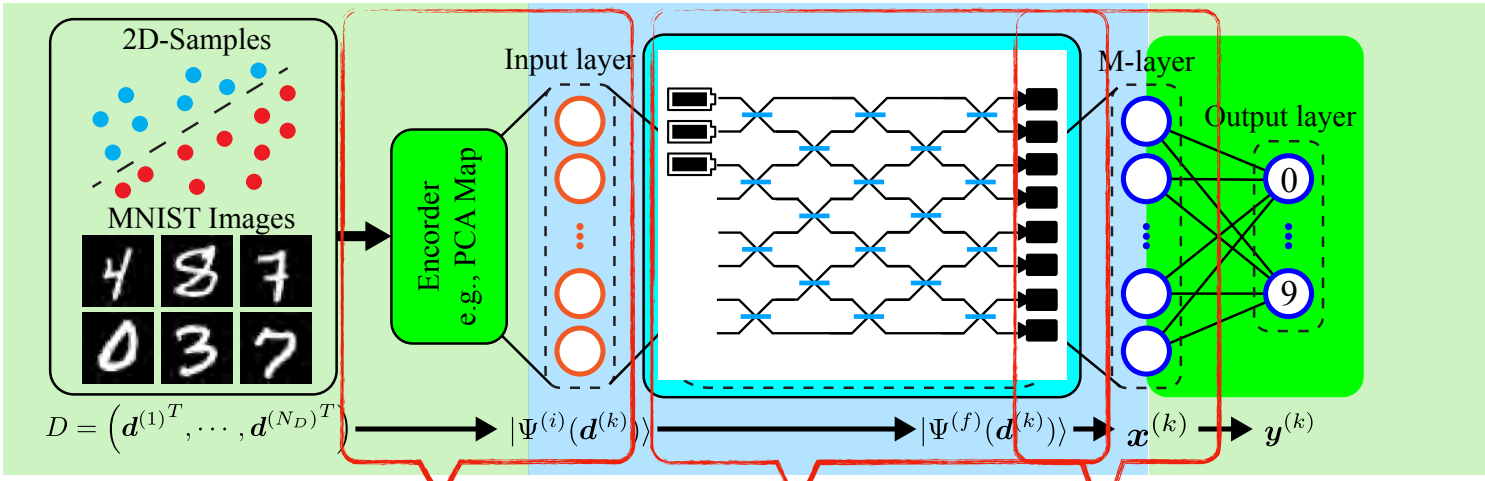
Science 372 (6545), 948 - 952 (2021)

- **Quantum communication systems are limited**
  - No large scale general purpose quantum network exists
  - Small-scale QNs have been distributed entangled resources.
    - The rate and quality of such resource is low
    - Will soon face **network issues like bandwidth, latency and congestion**

Quantum Extreme Reservoir Computing (QERC)
The linear optical version

Classical input

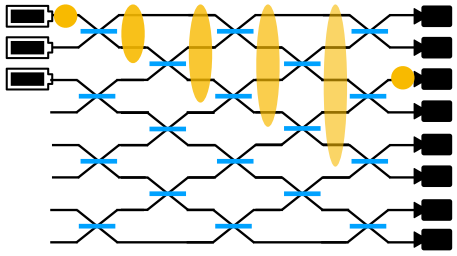
Classical linear classifier



Q. How to encode an image into Fock space (photon)?

Q. Why linear optics?

Q. How to get information in photons?



Probability distribution: $P(t_1, t_2, \cdots, t_N) = \frac{|\mathrm{Perm}U_T|}{t_1! \cdots t_N!}$

Permanent (computational complex is #P-hard)

They show that if boson sampling can be solved in classical computers, the polynomial hierarchy collapses to its third level.

S. Aaronson et. al. Theory of Computing. 9, 143–252 (2013).

OIST | Quantum

Does it work in principle?

Numerical simulation

QORC

Classifier only

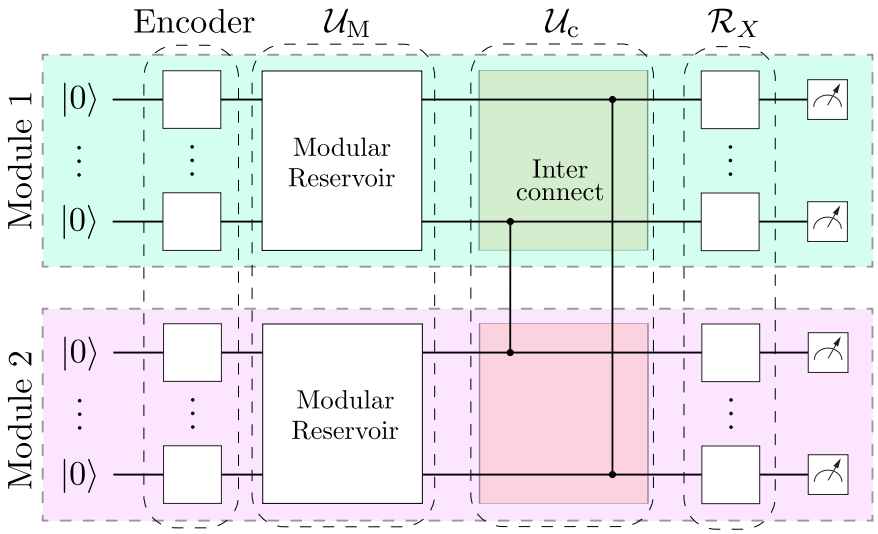
(N,M)	Dataset		
	MNIST	**K-MNIST**	**Fashion-MNIST**
(3,12)	0.9700 ± 0.0002 0.9569 ± 0.0005	0.9310 ± 0.0003 0.8176 ± 0.0011	0.8938 ± 0.0005 0.8662 ± 0.0006
(3,16)	0.9853 ± 0.0003 0.9688 ± 0.0004	0.9541 ± 0.0003 0.8479 ± 0.0014	0.9050 ± 0.0004 0.8750 ± 0.0010
(3,20)	0.9896 ± 0.0002 0.9705 ± 0.0003	0.9663 ± 0.0004 0.8643 ± 0.0010	0.9097 ± 0.0006 0.8766 ± 0.0019
(3,24)	0.9953 ± 0.0002 0.9753 ± 0.0007	0.9795 ± 0.0007 0.8857 ± 0.0016	0.9173 ± 0.0003 0.8801 ± 0.0020
(3,32)	0.9996 ± 0.0001 0.9784 ± 0.0004	0.9932 ± 0.0003 0.8991 ± 0.0011	0.9297 ± 0.0009 0.8826 ± 0.0025
(3,40)	1.0000 ± 0.000 0.9783 ± 0.0005	0.9978 ± 0.0002 0.9013 ± 0.0016	0.9383 ± 0.0008 0.8769 ± 0.0055
L-SVC	0.9262 0.918	0.835 0.676	0.873 0.839
RFF	1.0000 0.9713 ± 0.0002	0.9954 ± 0.0002 0.8438 ± 0.0011	0.9337 ± 0.0006 0.8752 ± 0.0020

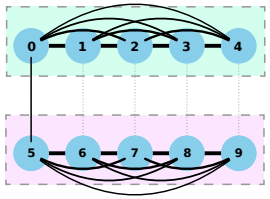
Important comparison

OIST | Quantum

Modular QORC

- Do we really need large interferometer or can we use modules?





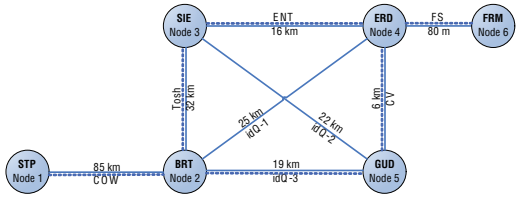
(a)	n_ℓ	$R_\times = 0$	$R_\times = 1$	$R_\times = 2$	$R_\times = 3$
$\alpha = 1.0$	0	0.9112	0.9269	0.9360	0.9565
	1	0.9313	0.9463	0.9506	-
	2	0.9464	0.9520	-	-
	3	0.9531	-	-	-
$\alpha = 1.5$	0	0.9520	0.9514	0.9588	0.9629
	1	0.9561	0.9586	0.9636	-
	2	0.9599	0.9619	-	-
	3	0.9636	-	-	-
$\alpha = 2.0$	0	0.9376	0.9404	0.9437	0.9624
	1	0.9495	0.9544	0.9549	-
	2	0.9576	0.9597	-	-
	3	0.9614	-	-	-

OIST | Quantum

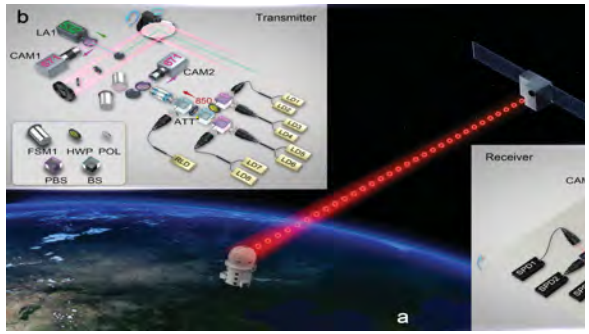
The necessity of quantum communication

Range/rate limited?

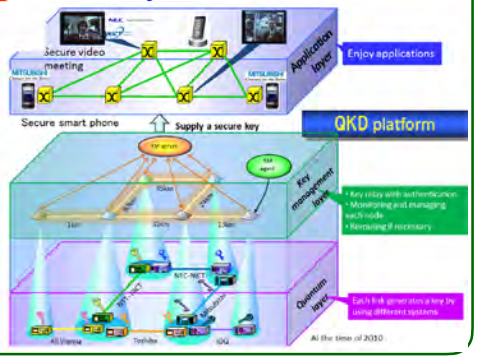
SECOQC - EU network inVienna



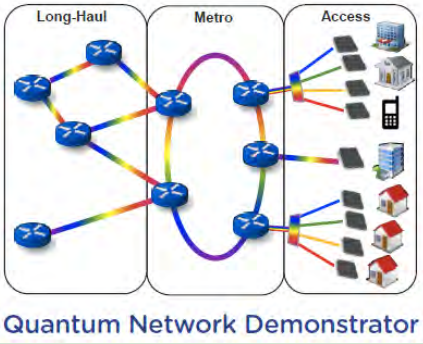
China - Q Networking satellite



Japan - Tokyo QKD network



UK - Quantum Communications Hub



Quantum Key Distribution is being tested!!!

Global Quantum Internet

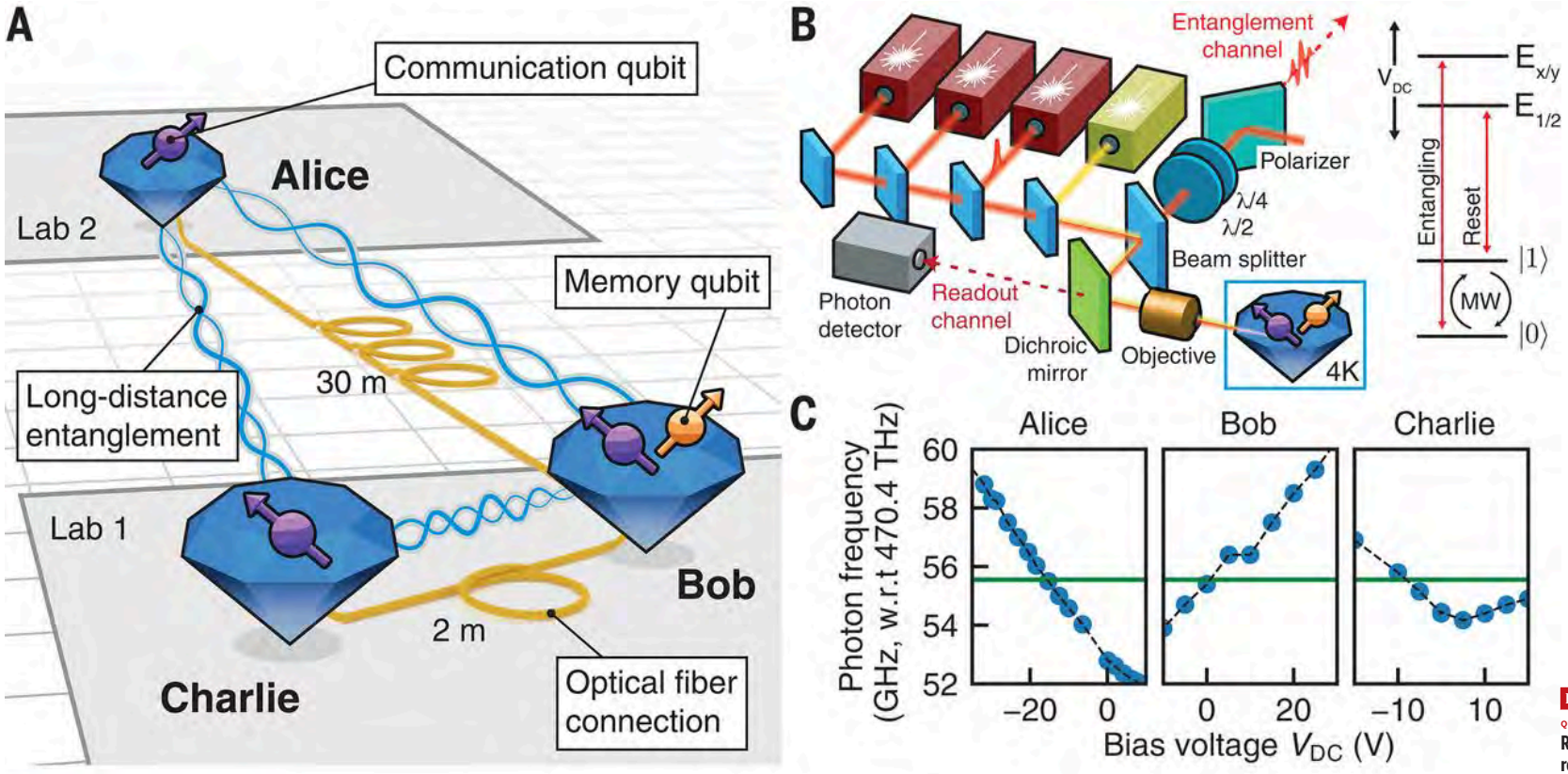
How?

Quantum Communications is much more than QKD

N. Gisin et. al. *Nature Photon. 1,* 165 (2007)
H. J. Kimble, 453,1023 (2008)
W. J. Munro et. al, Nature Photonics 6, 777 (2012).
K. Azuma et. al, Nature Commun. 6, 10171 (2015).

Small scale quantum networks

The beginning our tomorrow internet: a 3 node network



RESEARCH ARTICLE

QUANTUM NETWORKS

Realization of a multinode quantum network of remote solid-state qubits

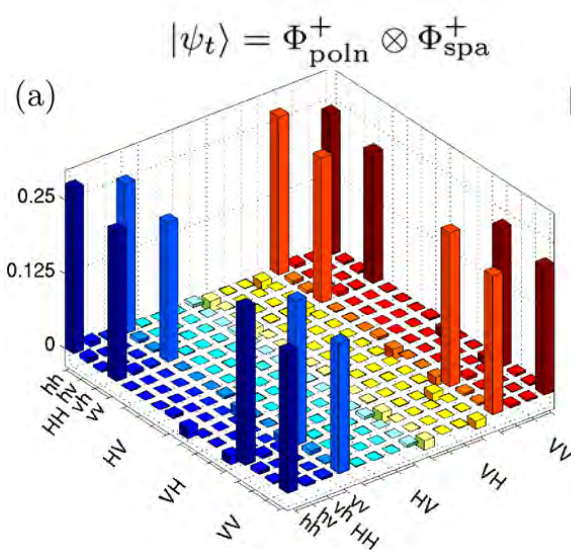
M. Pompili[1,2]†, S. L. N. Hermans[1,2]†, S. Baier[1,2]†‡, H. K. C. Beukers[1,2], P. C. Humphreys[1,2]§, R. N. Schouten[1,2], R. F. L. Vermeulen[1,2], M. J. Tiggelman[1,2]¶, L. dos Santos Martins[1,2], B. Dirkse[1,2], S. Wehner[1,2], R. Hanson[1,2]*

OIST | Quantum

Pompili *et al.*, *Science* **372**, 259–264 (2021)

Quantum Multiplexing

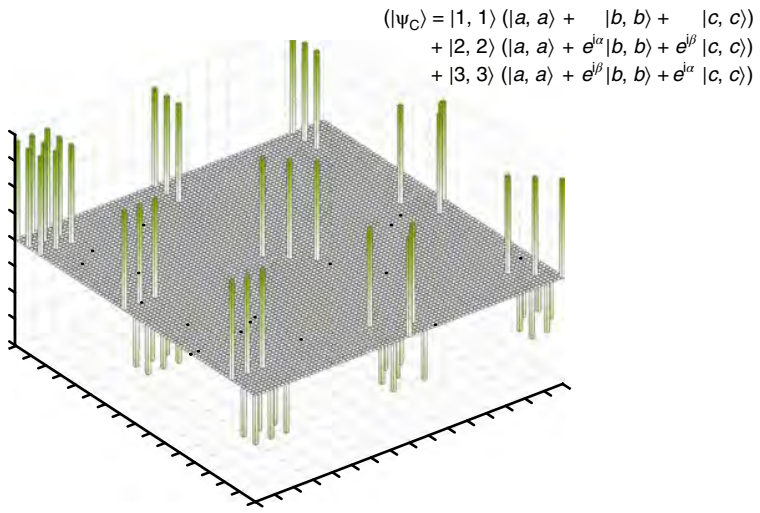
- **As photon get lost in optical fiber channels should we not try to conserve them?**
- **Why not use higher dimensional encoding or multiple degrees of freedom**



Polarization and spatial

Julio T. Barreiro et.al, Rev. Lett. 95, 260501 (2005)

Cluster state

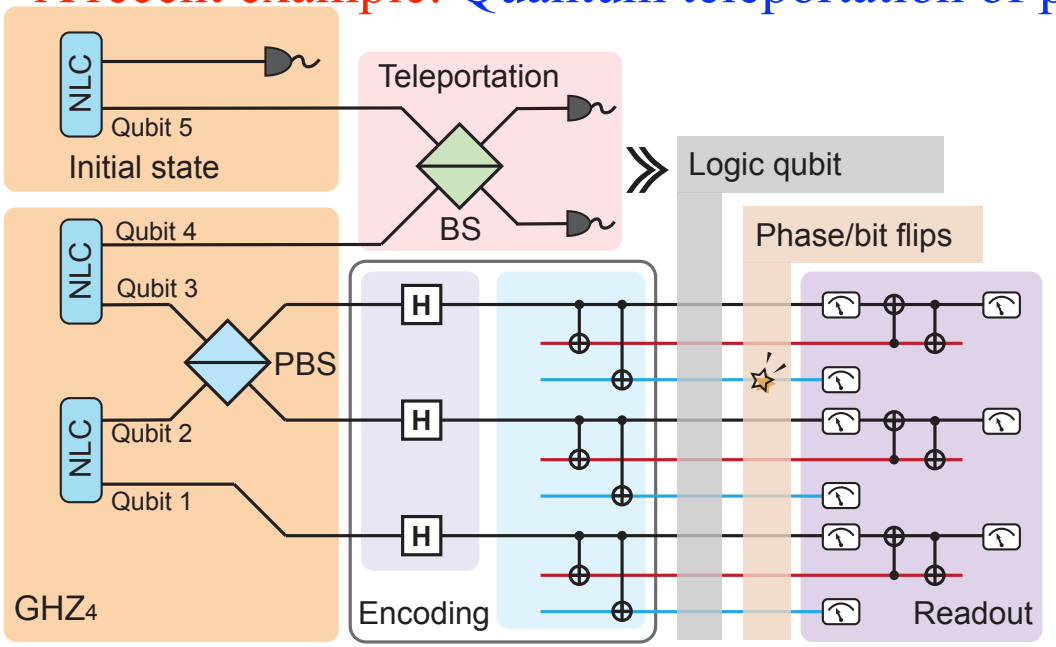


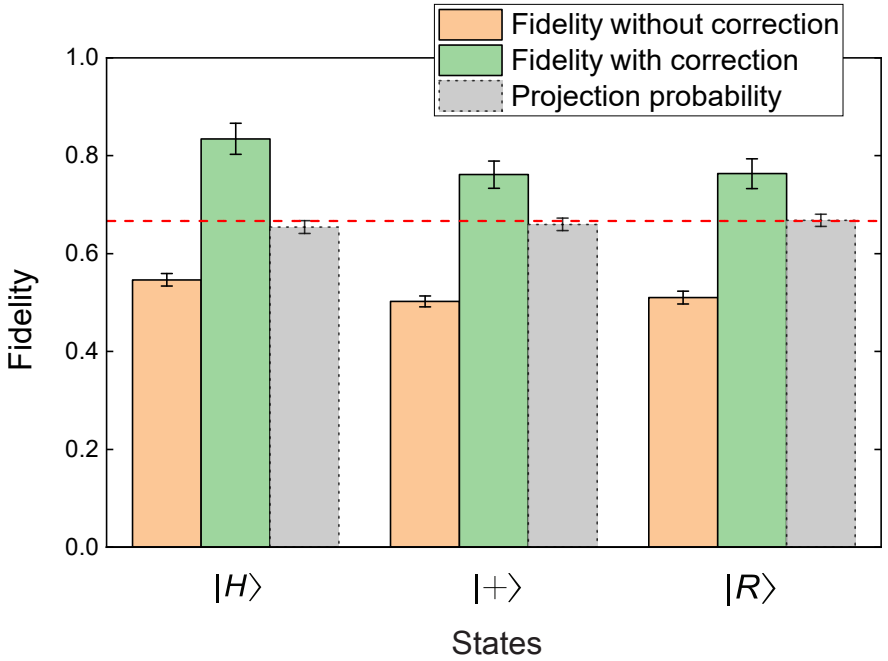
Time and frequency bin

Christian Reimer et.al, Nature Physics 15, 148-153 (2019)

Quantum multiplexing in action

- Photonic many degrees of freedom are very useful when we have limited resources
- In photonic quantum computation we do.
- A recent example: Quantum teleportation of physical qubits into logical code-spaces





6 photon - but 12 qubits

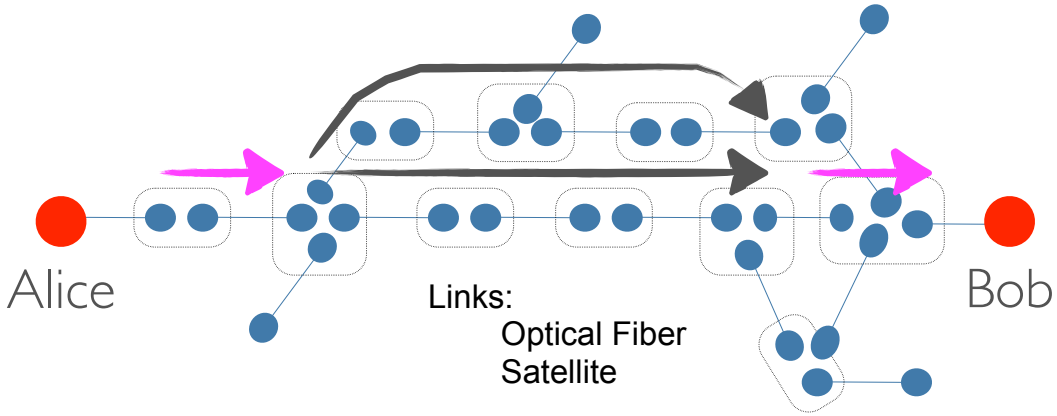
Yi-Han Luo et.al, Proc Natl Acad Sci USA 118 (36), e2026250118 (2021).

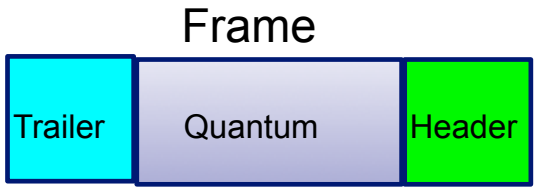
Why not for quantum communication

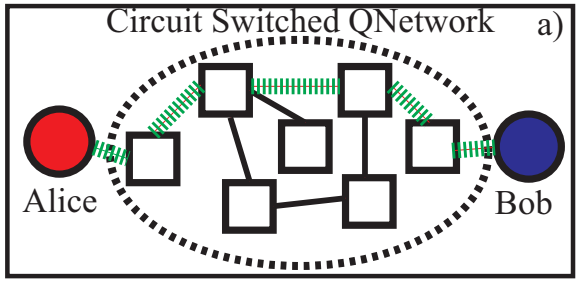
OIST | Quantum

Entanglement Switched Networks

- From naive considerations: it seems we are looking at a circuit switched network approach. May have to establish the path before we start

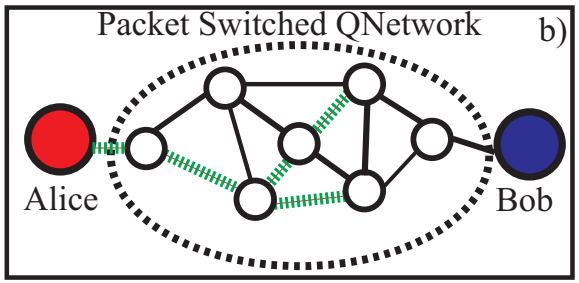






- Route is reserved.
- Frame arrive in order

- Do we really want the old fashion telephone exchange models?
  - First generation repeater probably leave us no choice
  - Second and third can use packet switched approaches - so much more multi user friendly

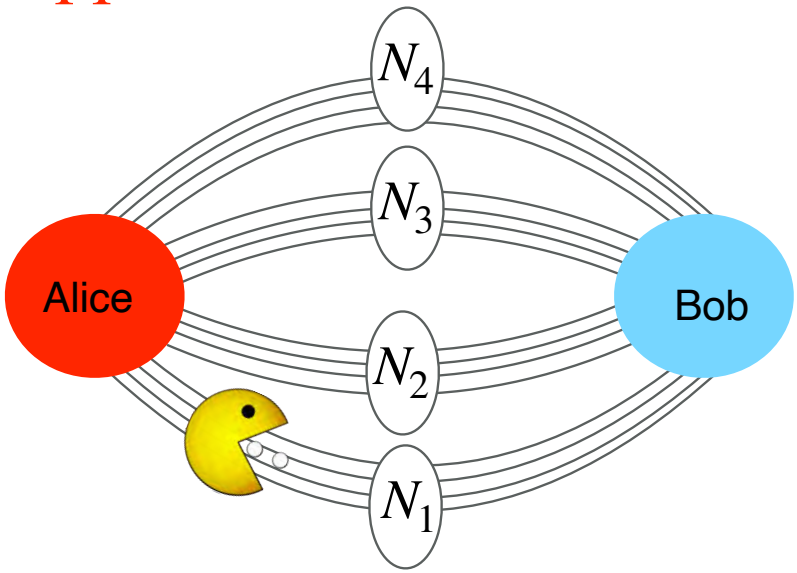


- Route is dynamic.
- Frame arrive out of order

OIST | Quantum

Quantum Aggregation

- Generally one thinks of our quantum packet taking one route (similar to what happens in the classical world)



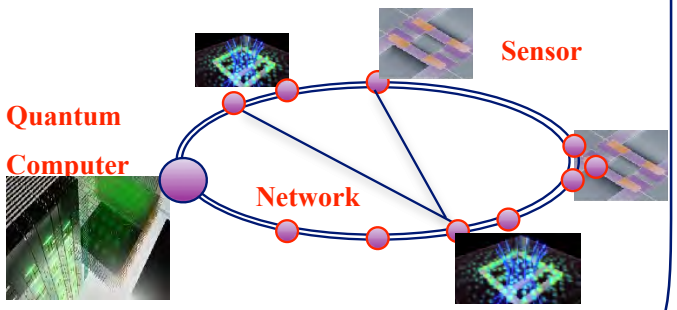
- What happens when we have constrained resources?
- **In the quantum world we could route this single packet over 2 or more independent paths.**

N. Lo Piparo, et.al. Phys. Rev. A **102**, 052613 (2020)

A potential route forward

Quantum Edge Computing

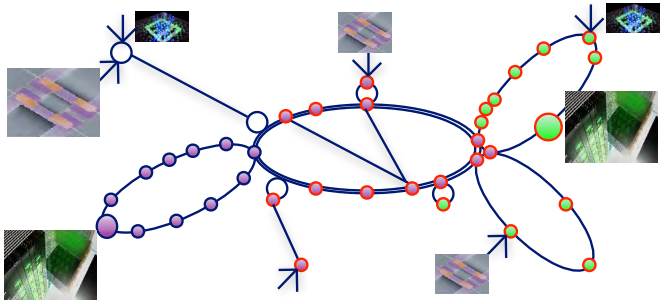
- Initial quantum networks will only be able to distribute physically encoded quantum resources over short distances
- Quantum communication will be a bottleneck
- Need to keep our quantum processing and storage as close to possible to the edge nodes in the network where it is generated



a few km's

Quantum Fog Computing

- Quantum data transmission will require quantum repeaters (probably first generation and potentially second).
- Will need to begin logically encoding quantum data.
- Quantum routing protocols will need used.



a few hundred km's

Quantum Internet and Cloud

- A quantum network of quantum networks supported by an efficient classical internet.
- Fully fault tolerant
- Most likely based on third generation QR's

Global

OIST | Quantum

Time and Degree of Networking

The take home message

Quantum communication is the key enabler to fully realize the potential the second quantum revolution gives

Thank You!!

Just to mention OCQT has a number of collaborations with the University of Tokyo

email: bill.munro@oist.jp