Systems for Distributed Quantum Computing

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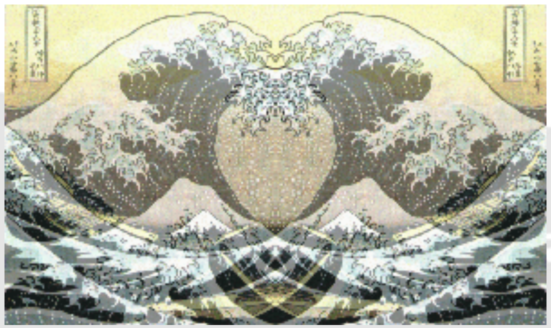
Keio Yagami Campus, 2009/12/14



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Why Quantum?

Two Reasons:

Because Moore says we *must.*

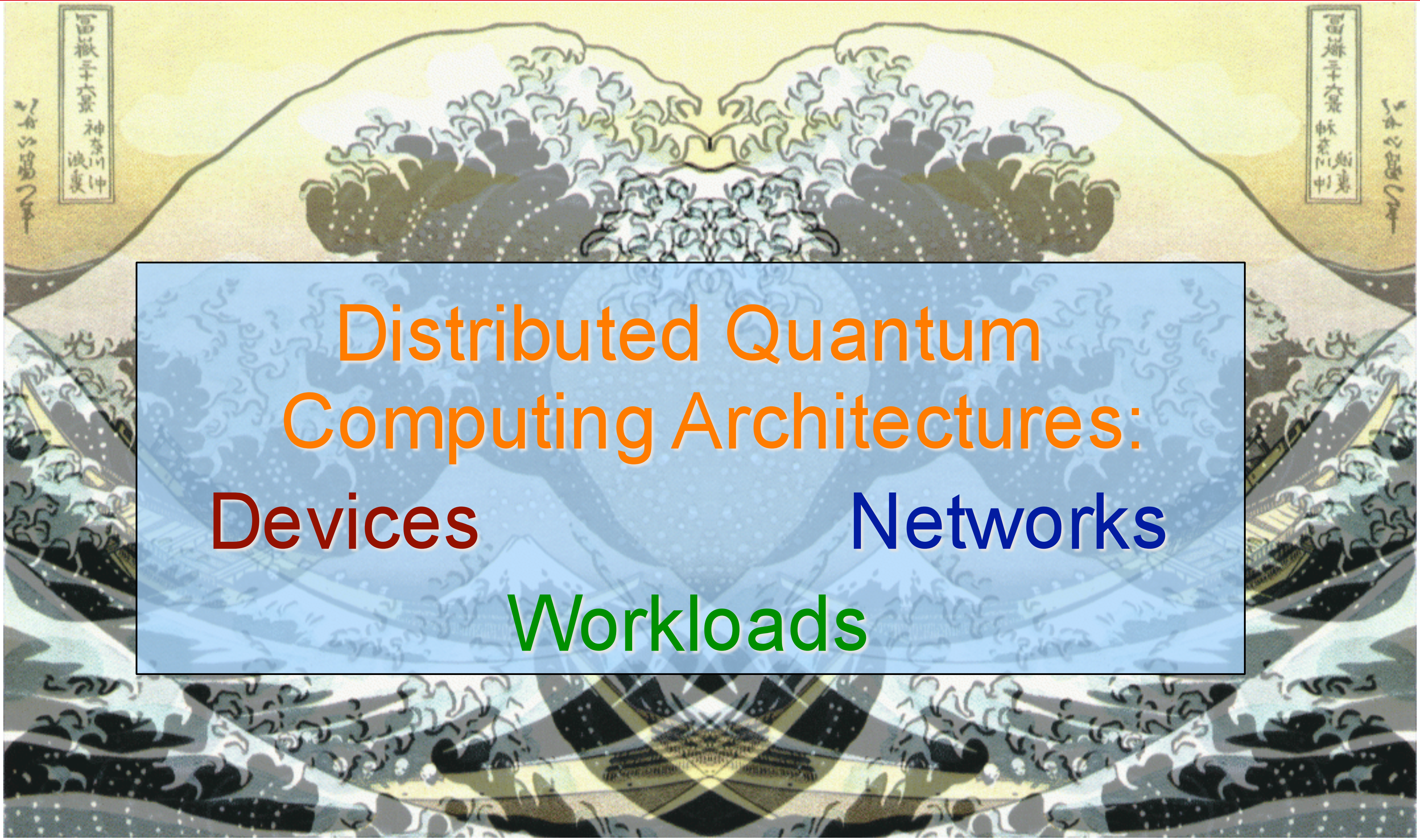
Will also influence classical atomic-level architecture.

Quantum brings new capabilities:

a) Better computational class for some problems (but not universal)

b) Quantum Key Distribution (QKD)

AQUA: Advancing Quantum Architecture



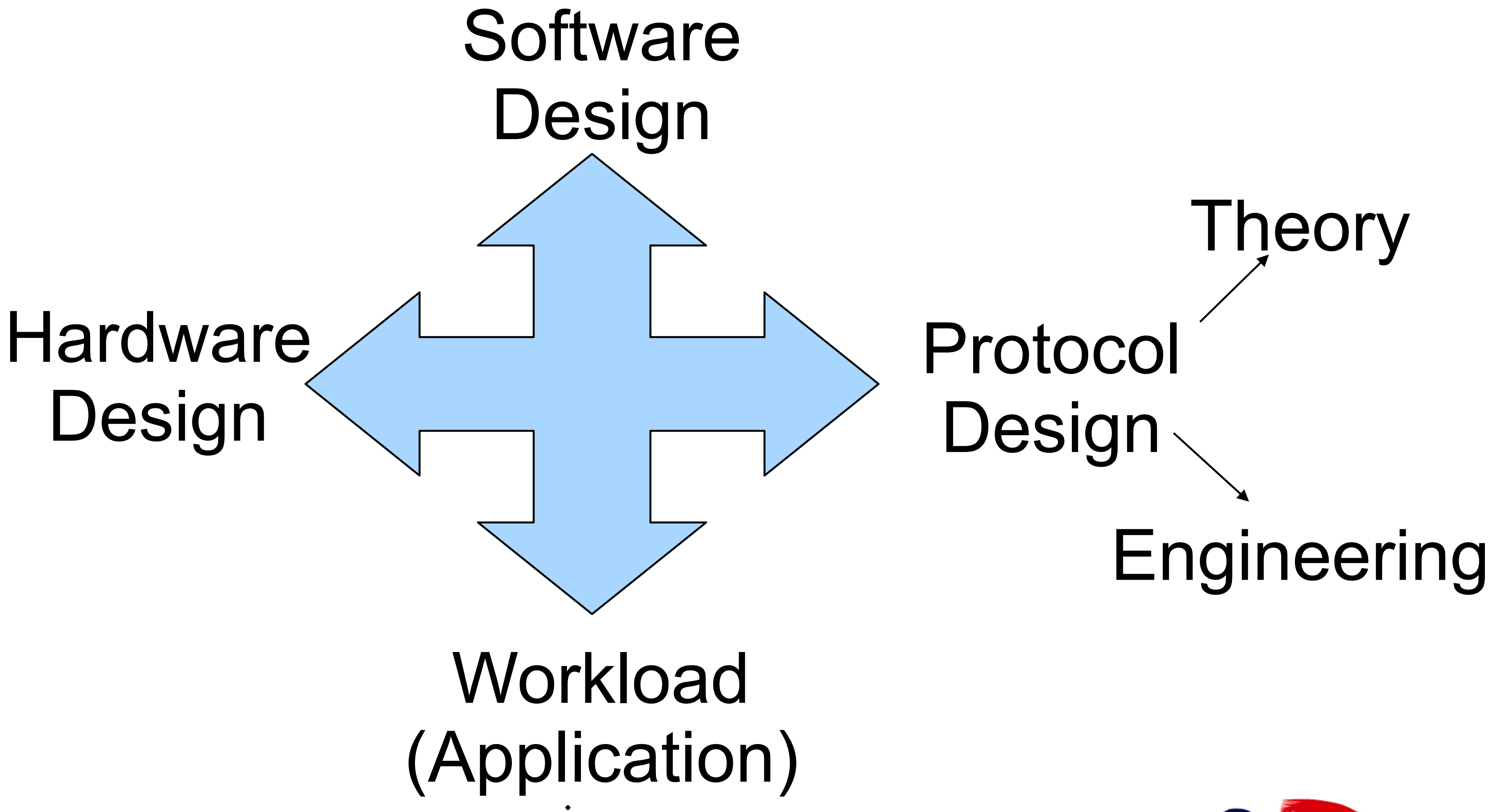
Distributed Quantum Computing Architectures:

Devices

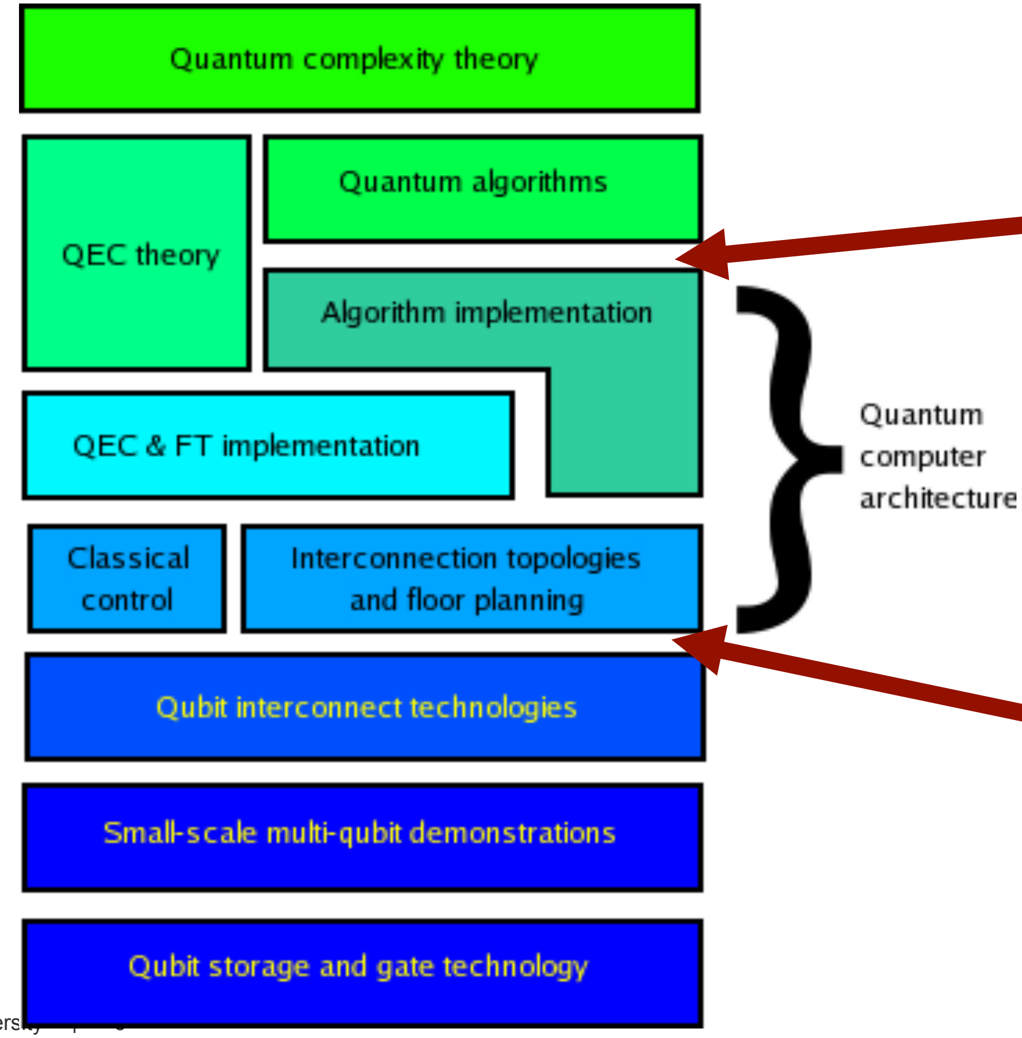
Networks

Workloads

System Co-Design



What is Quantum Computer Architecture?



Balance generality and performance

Extract commonality (e.g., qubit motion)

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How Do Architects Contribute?

- Identify critical problems
- Improve efficiency of design
- Establish targets for fidelity, memory time
- Match applications to systems
- Classical control design
- Architects understand *resource management*

“If you can get to 1Hz, the engineers can get another one to two orders of magnitude.”

N. Gisin, via C. Monroe

...I’m an engineer.

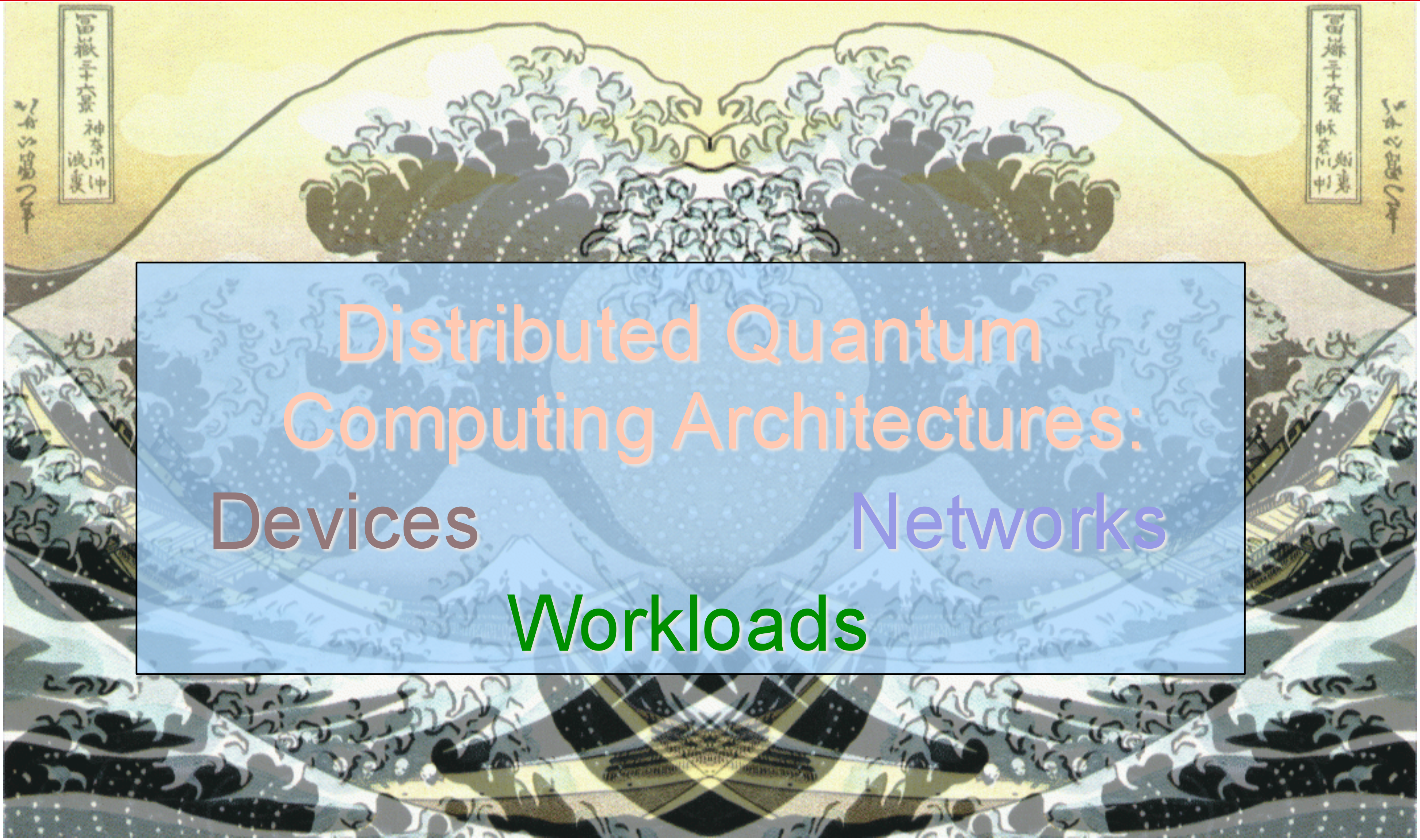
Results: Workloads, Devices, Systems

- Solidified workload definitions, matched to architecture, significantly improved performance
- Proposed *quantum multicomputer architecture* using quantum system-area network (QSAN)
- Developed semiconductor quantum dot nanophotonic node architecture using (topological) surface code error correction

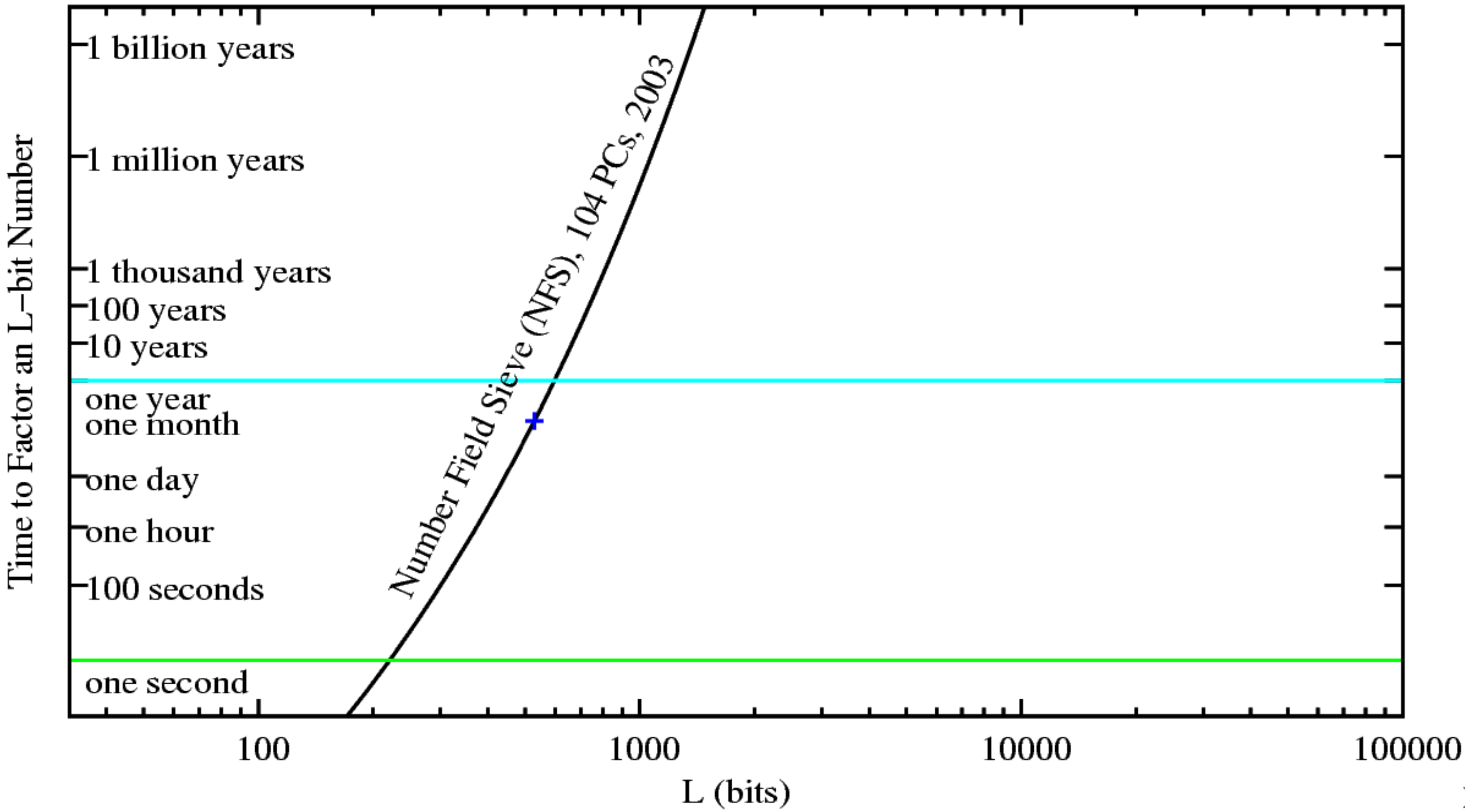
Results & Current Work: Networking

- Showed that linear network works well for QSAN
- Improved qubus repeater performance 50x
  by scheduling purification
- Designing quantum repeater protocol stack
- Defining Quantum Dijkstra: path selection in heterogeneous repeater networks
- Currently examining resource allocation
- Integrating quantum networks with the Internet: attempting to standardize
  quantum key distribution with IPsec

AQUA: Advancing Quantum Architecture

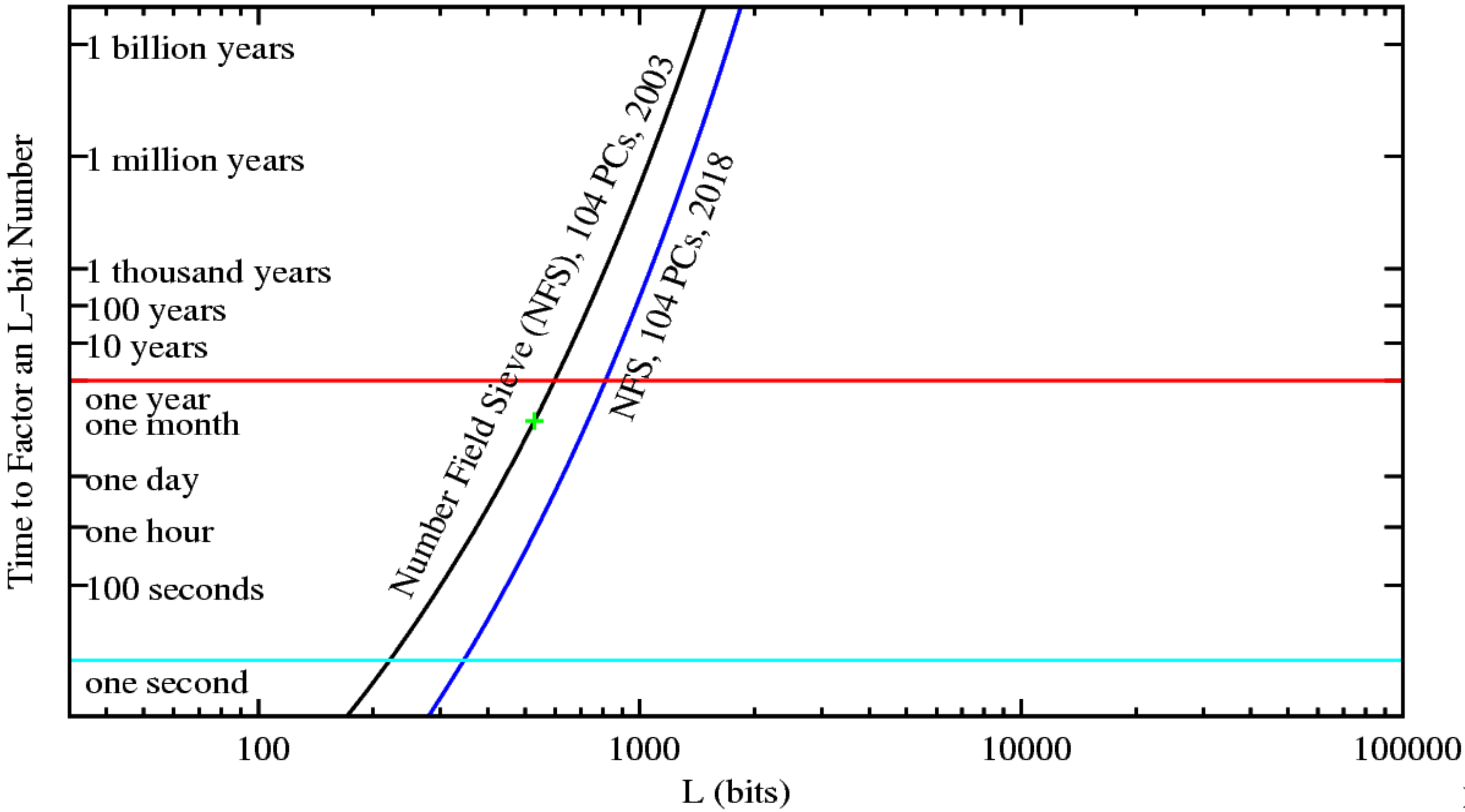


Factoring Large Numbers



rdv, TDL, KMI, quant-ph/0507023

Factoring Large Numbers



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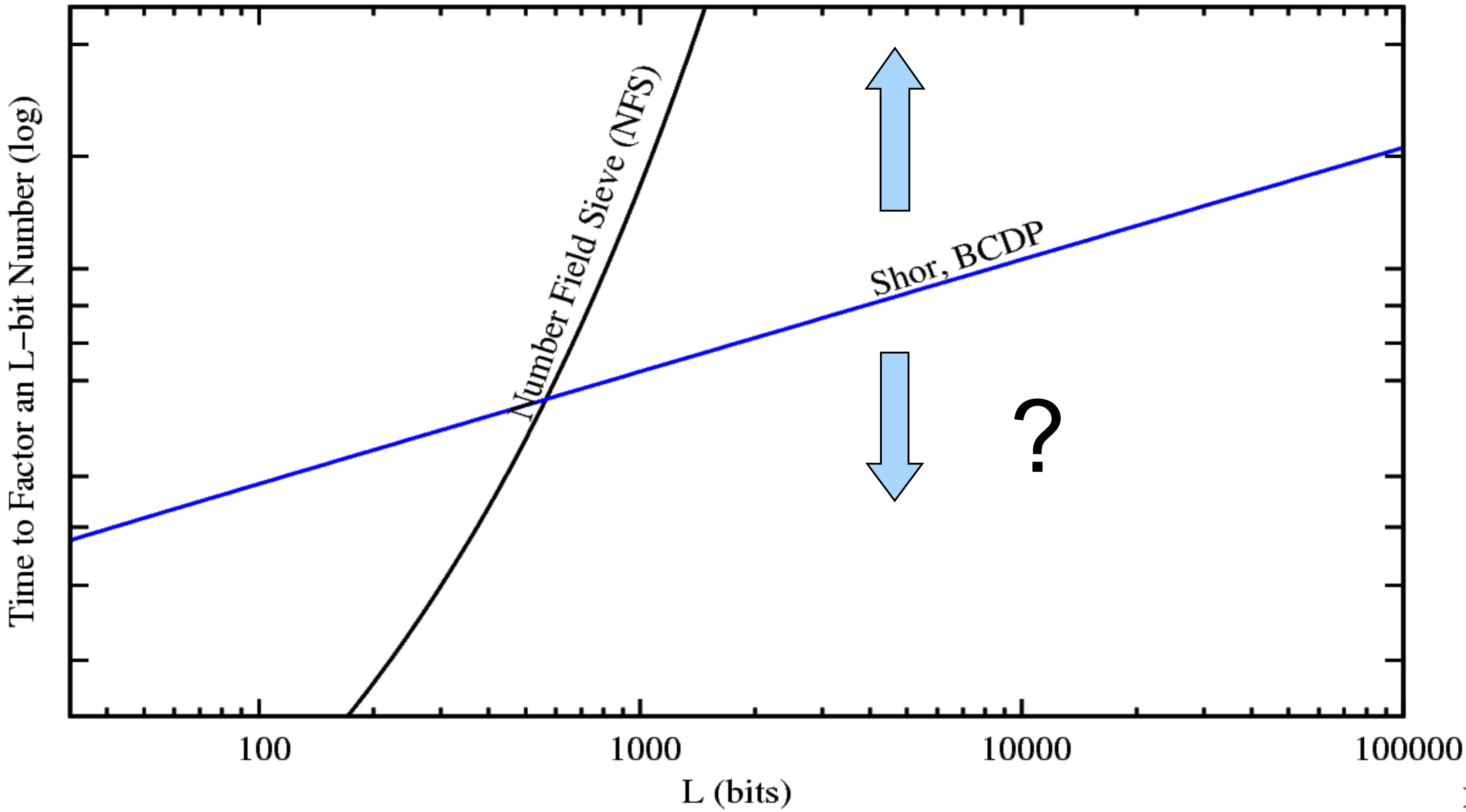

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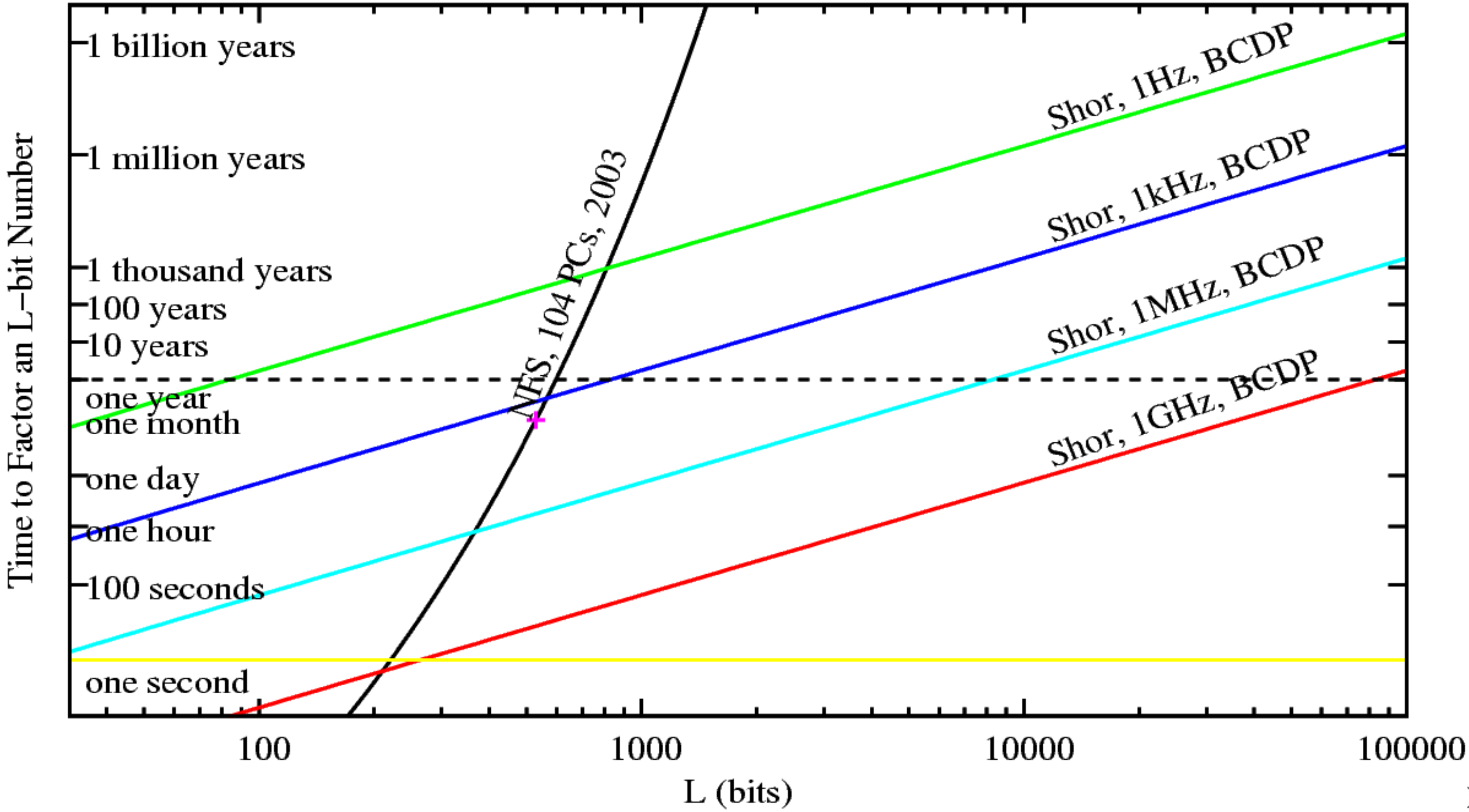

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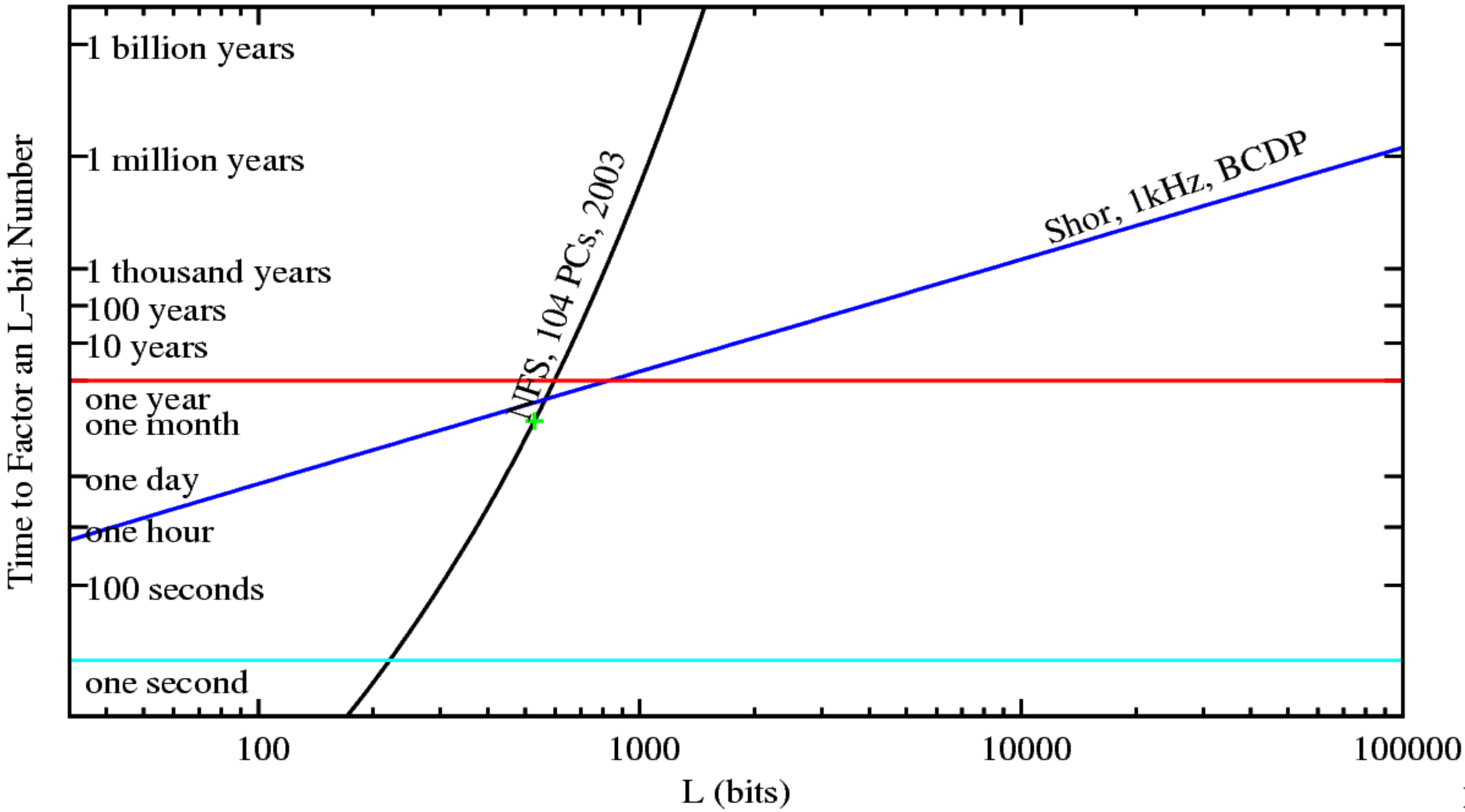
Factoring Larger Numbers



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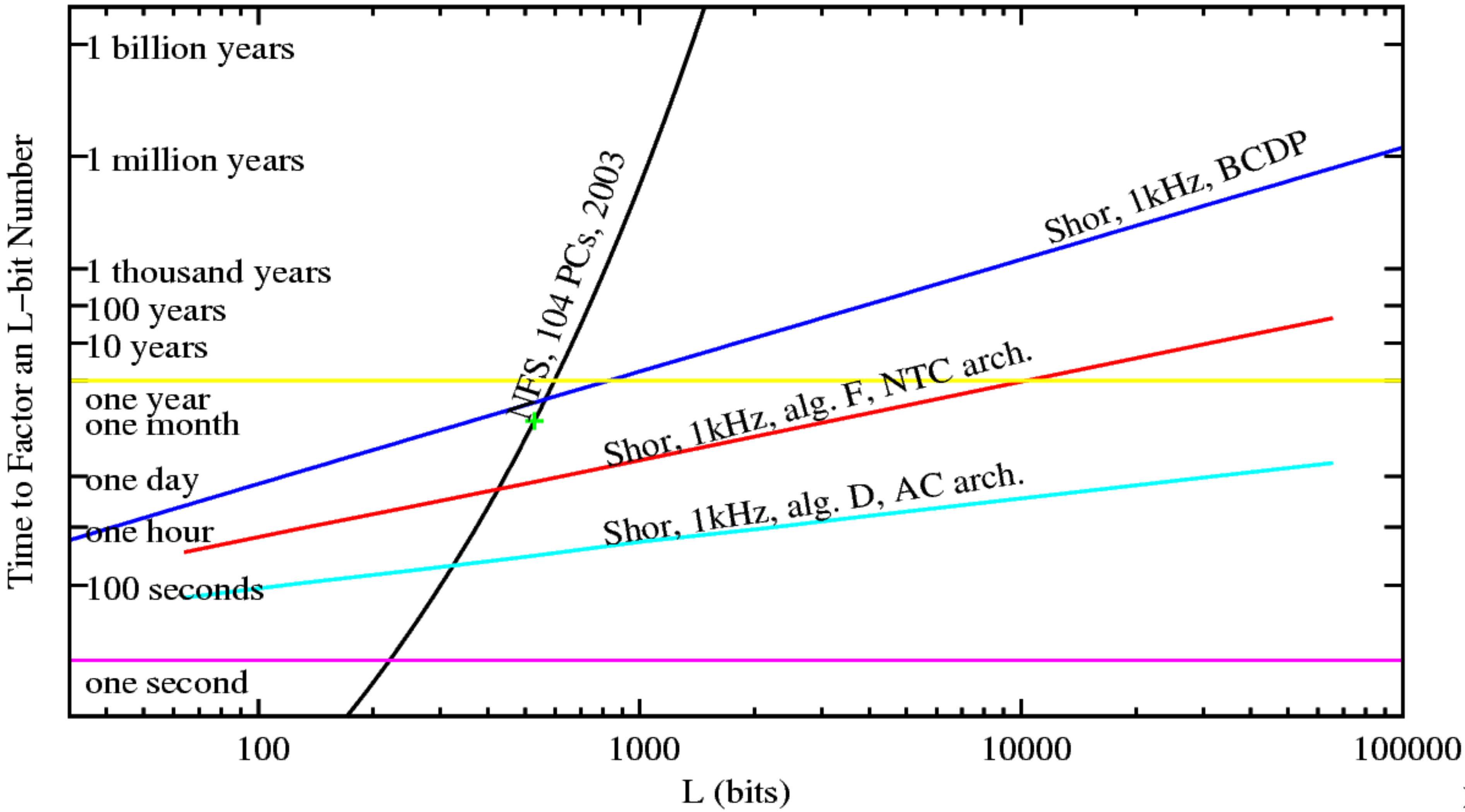
Factoring Larger Numbers



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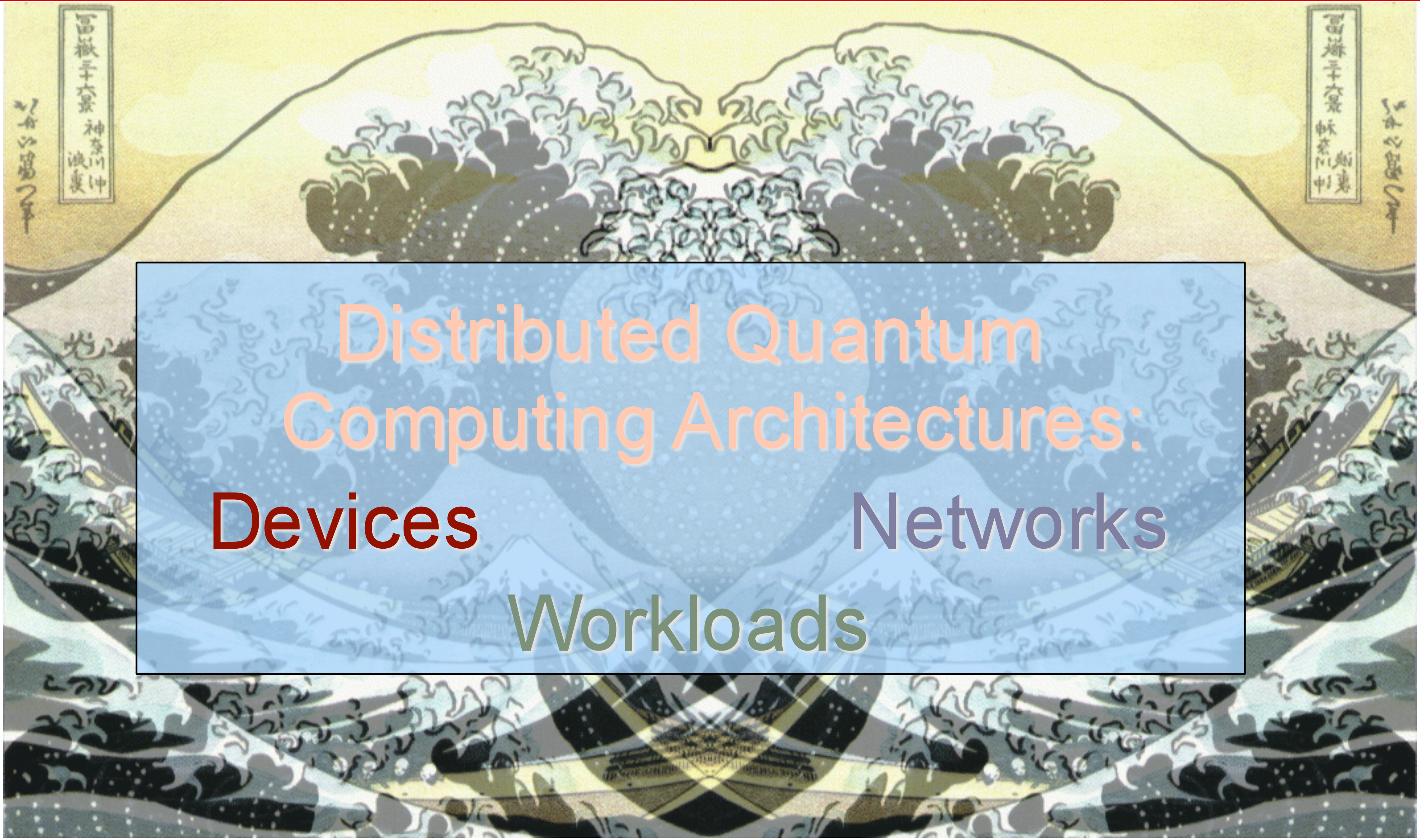
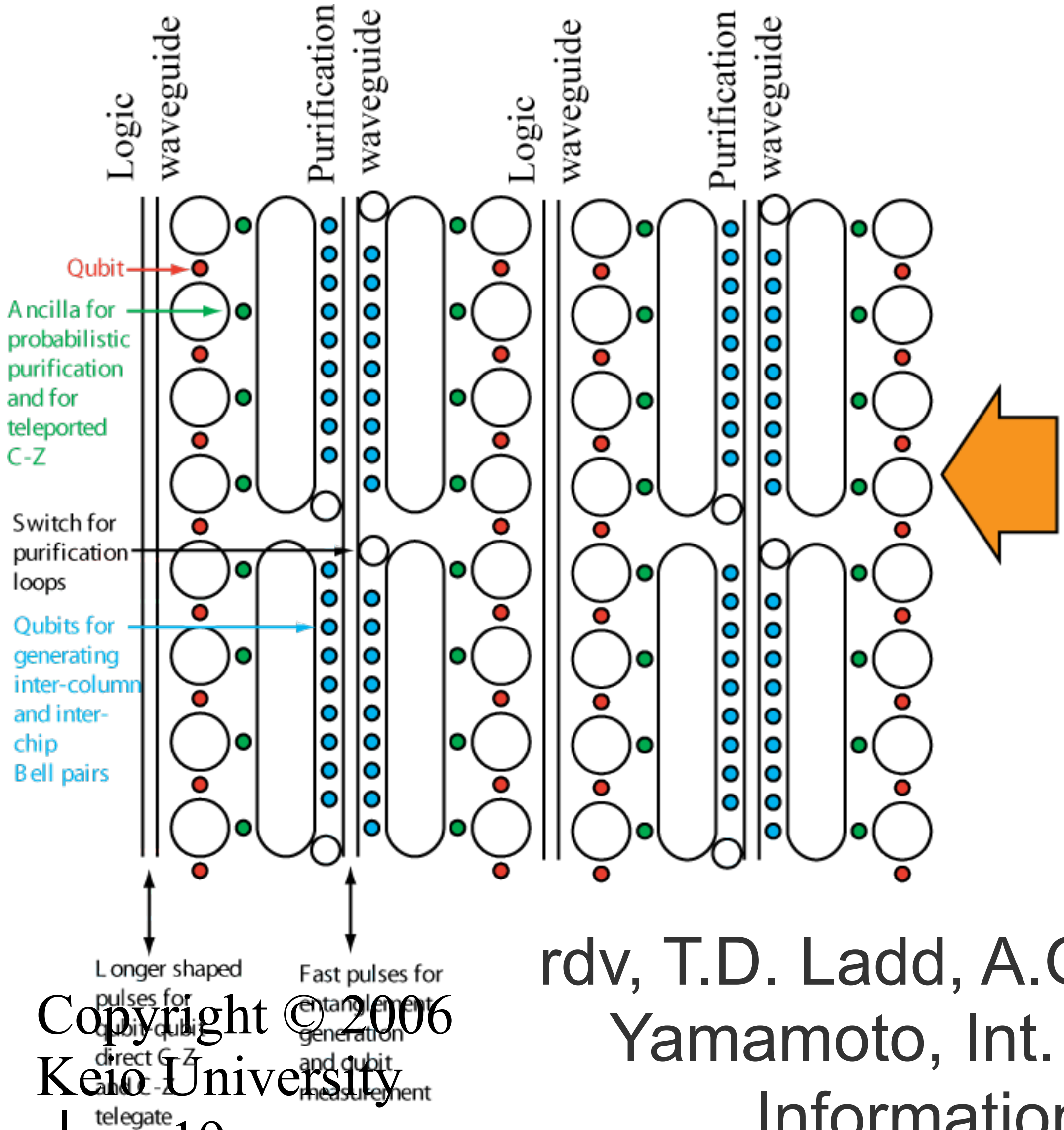
Workload Summary

- O(.) is not good enough; constant factors matter!
- Interconnect & qubit movement high impact
- Some algorithms parallelize well;
  can trade space for time
- Arithmetic is key

AQUA: Advancing Quantum Architecture



Nanophotonic Device



4 repeating "cells" of architecture. Columns extended vertically to about 100 qubits, with multiplexed lasers and detectors above and below. Purification waveguide snakes between columns to allow inter-column entanglement. Waveguides must be dynamically connected as needed with multiplexing network at top and bottom edges.

rdv, T.D. Ladd, A.G. Fowler, Y. Yamamoto, Int. J. Quantum Information, 2010

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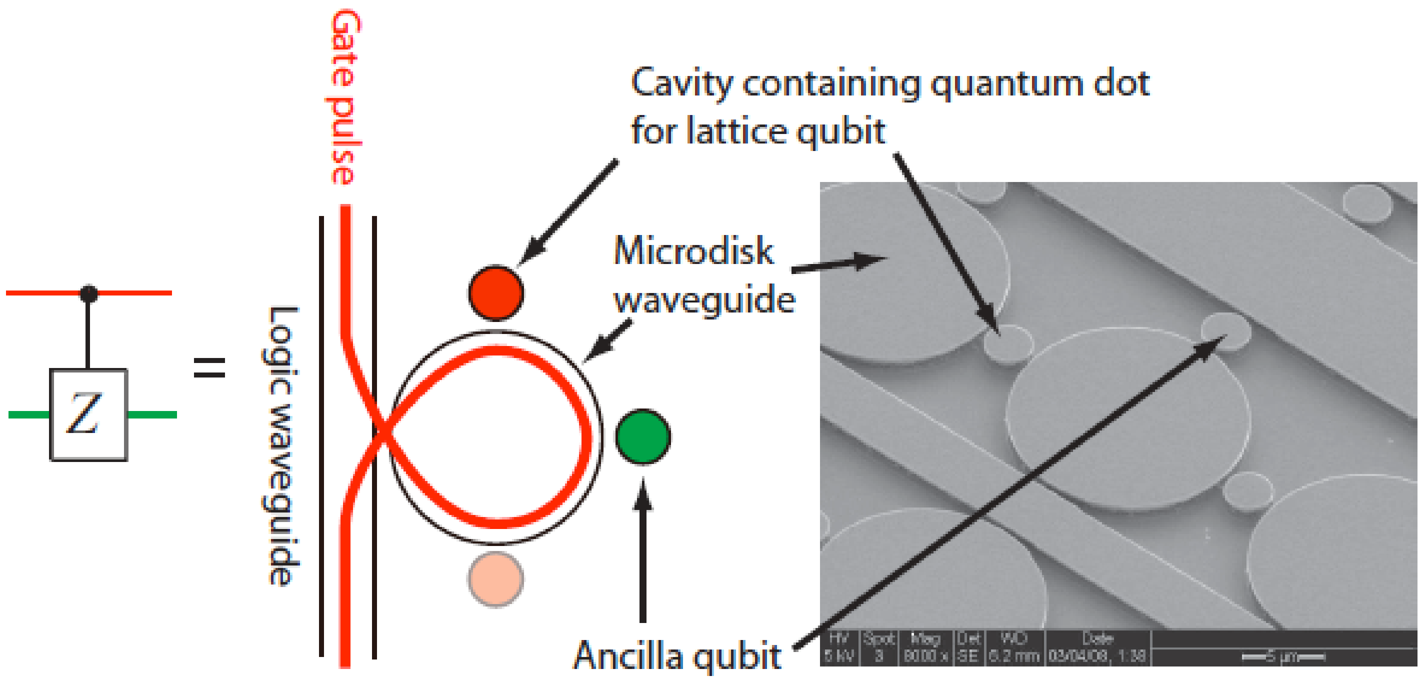
Basic Gate



rdv, T.D. Ladd, A.G. Fowler, Y. Yamamoto, Int. J. Quantum Information, 2010

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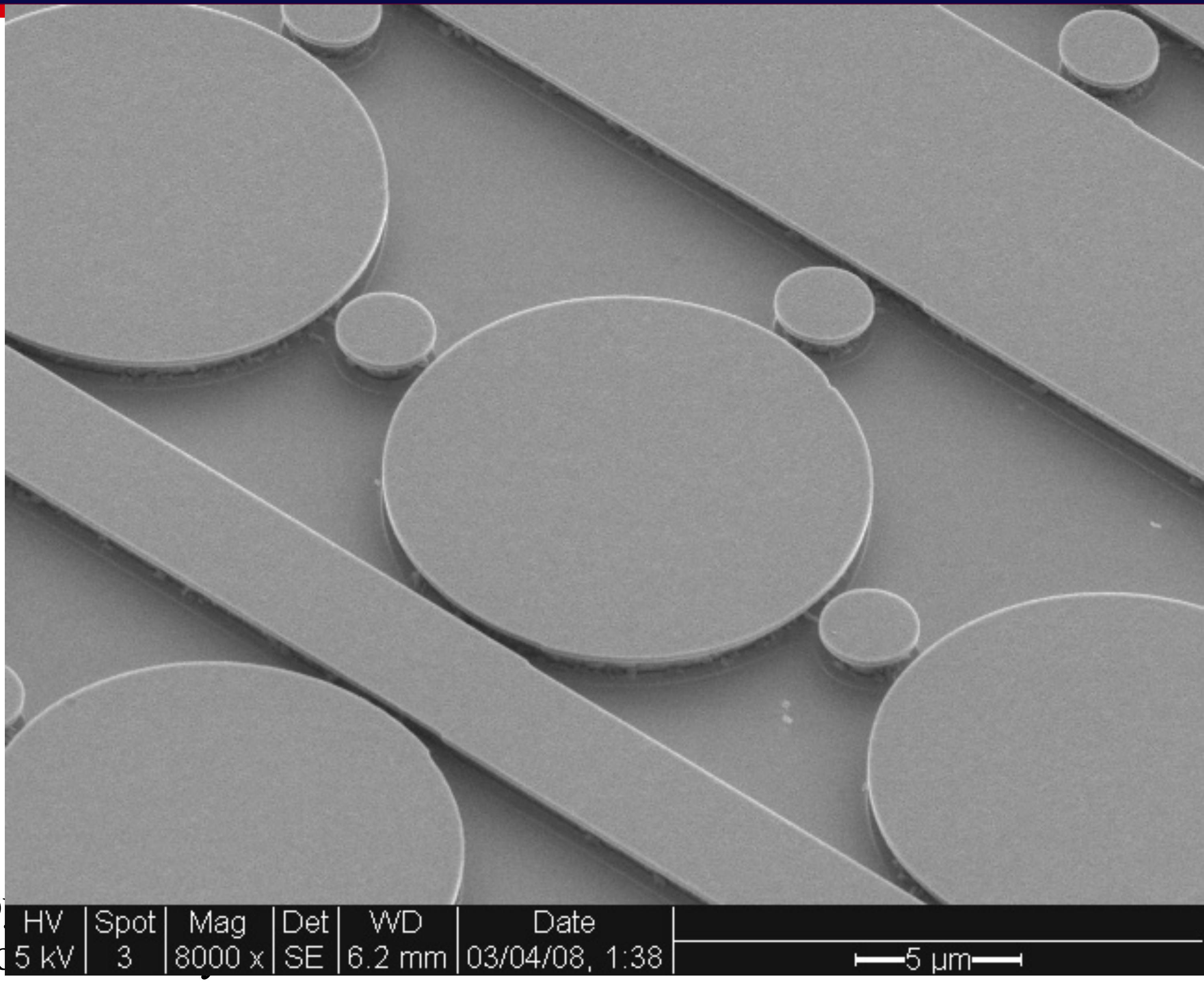
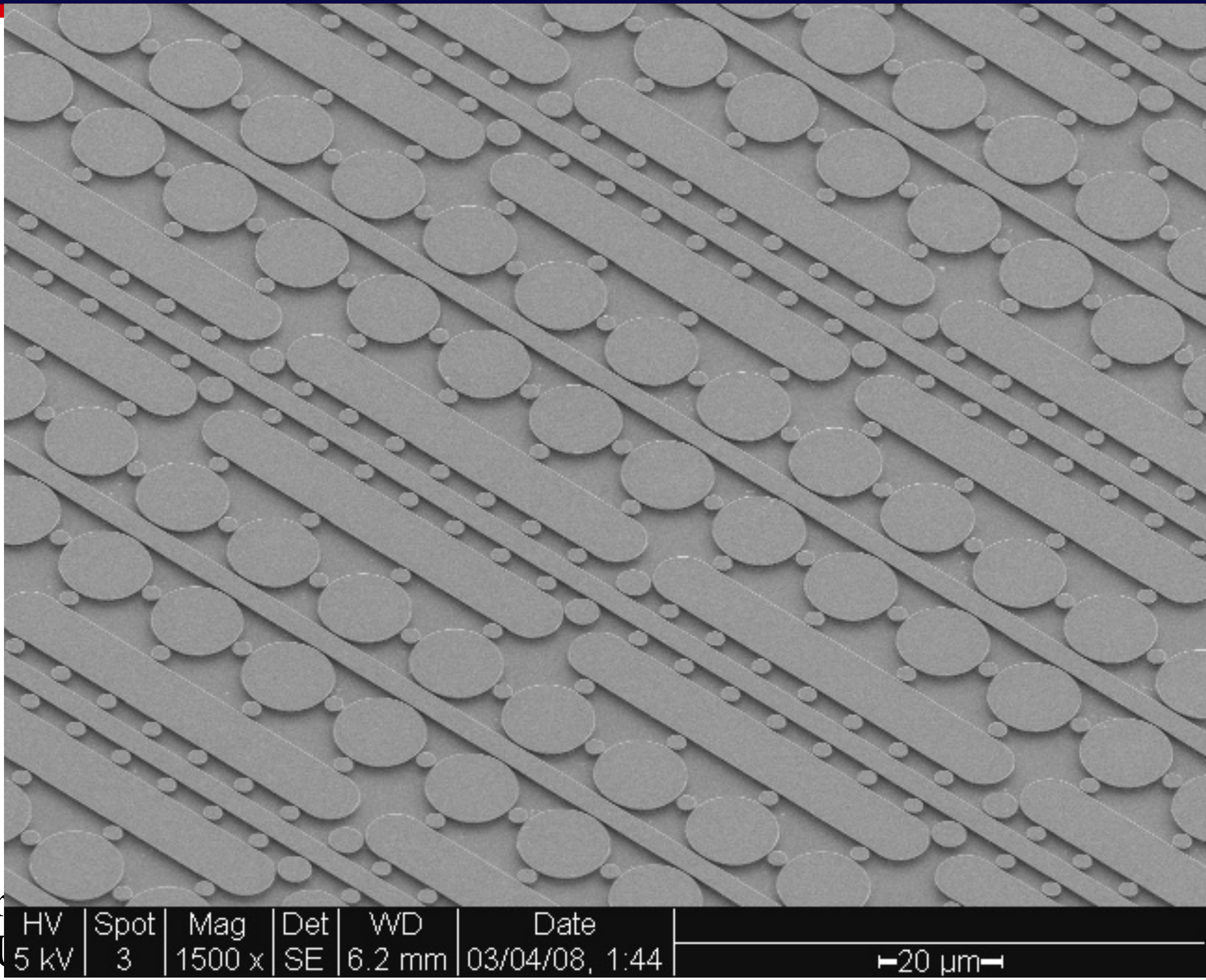
First Fab Tests @Stanford



First Fab Tests @Stanford



A Solid-State Quantum Computer

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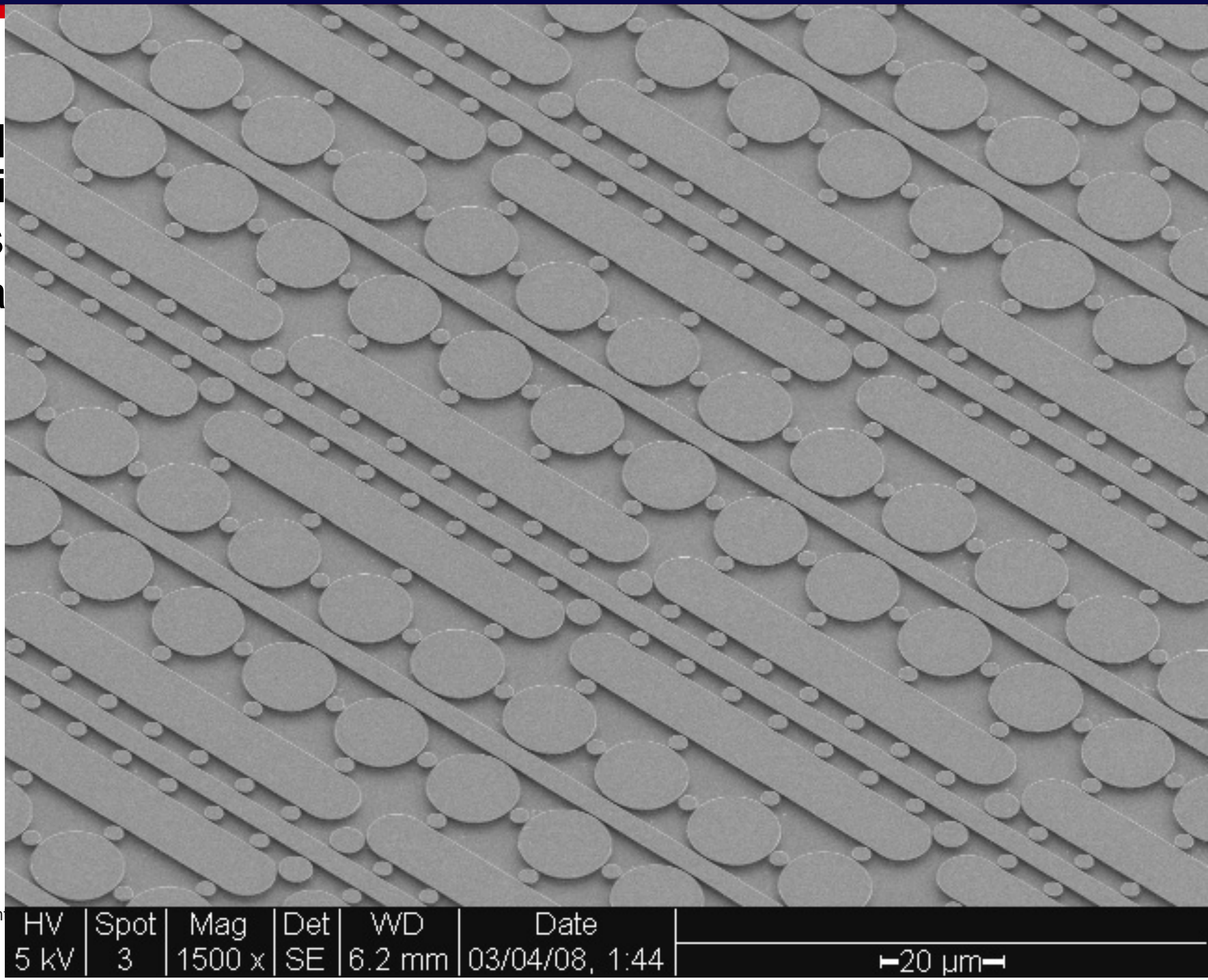

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System Summary

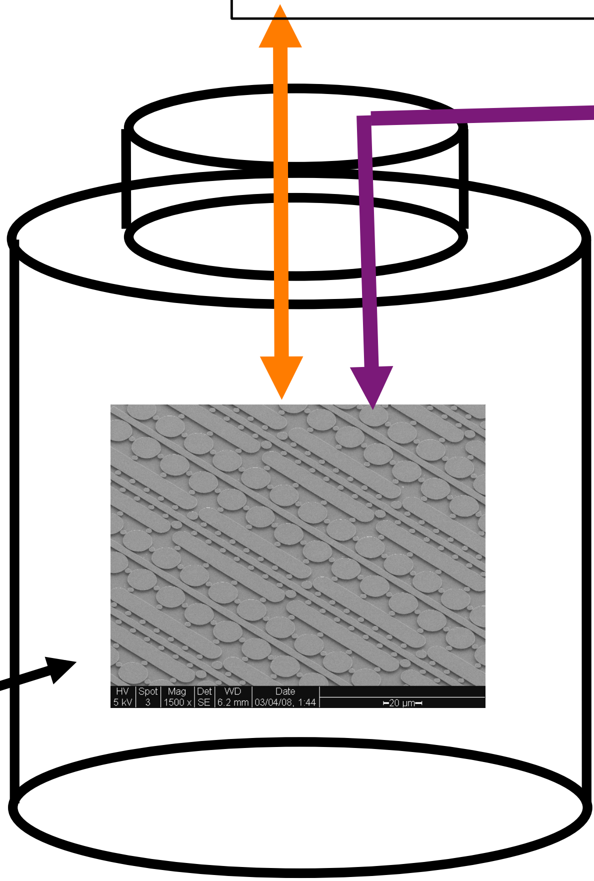
- One chip: 128x770 physical quantum dots
- 64K chips in total system
- 6 billion physical qubits in total system!
- Uses (topological) surface code
- 120K logical qubits
- In-plane waveguides give fault tolerance
- Yield of a few percent will enable lattice-building experiments
- 40% yield will give us a functional, large-scale system
- Will factor 2048-bit number in a year

A Solid-State Quantum Computer

classical program
classical data
classical control & measurement

quantum gates
(instructions)
selected classically,
act on 1-3 qubits

quantum data
(create Bell pairs)



quantum
device
(register)

Dilution
refrigerator

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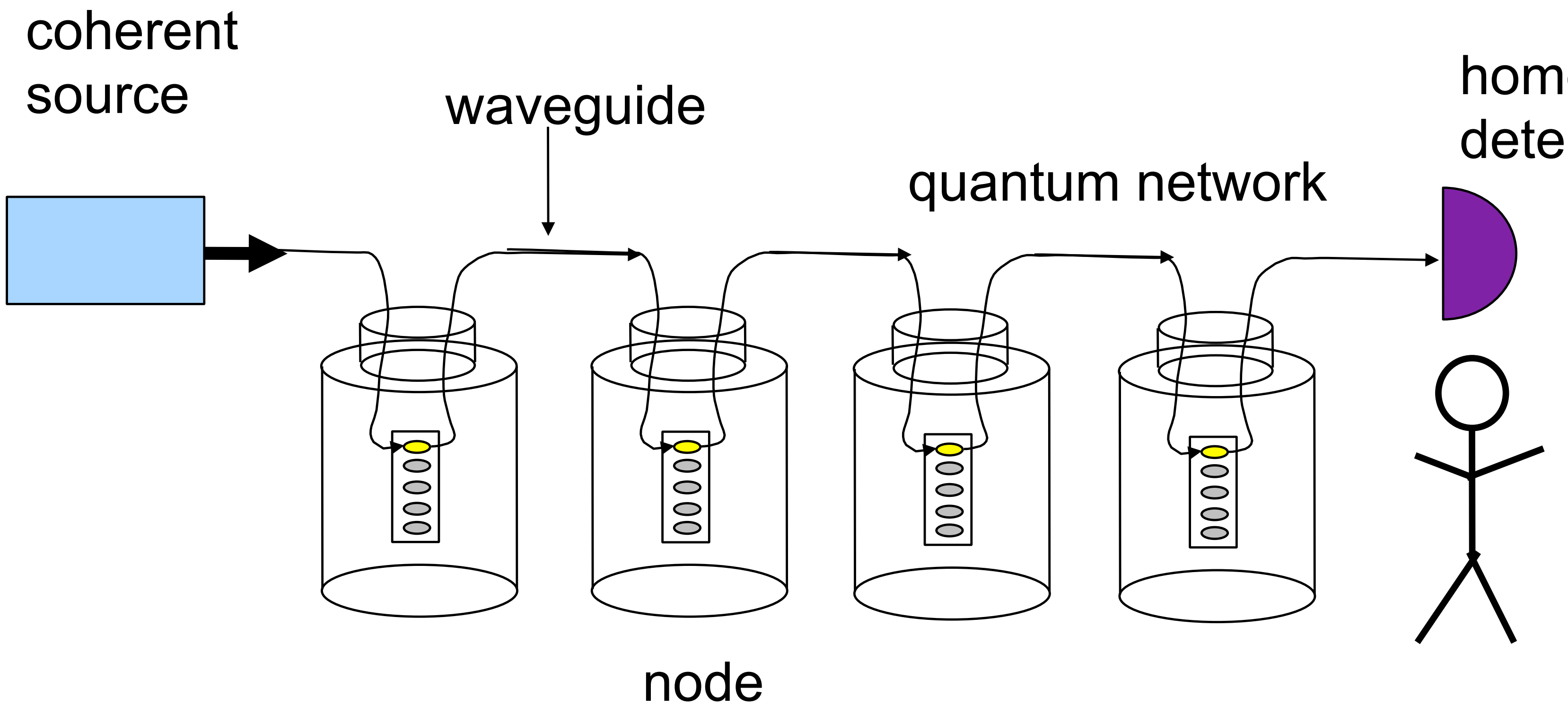
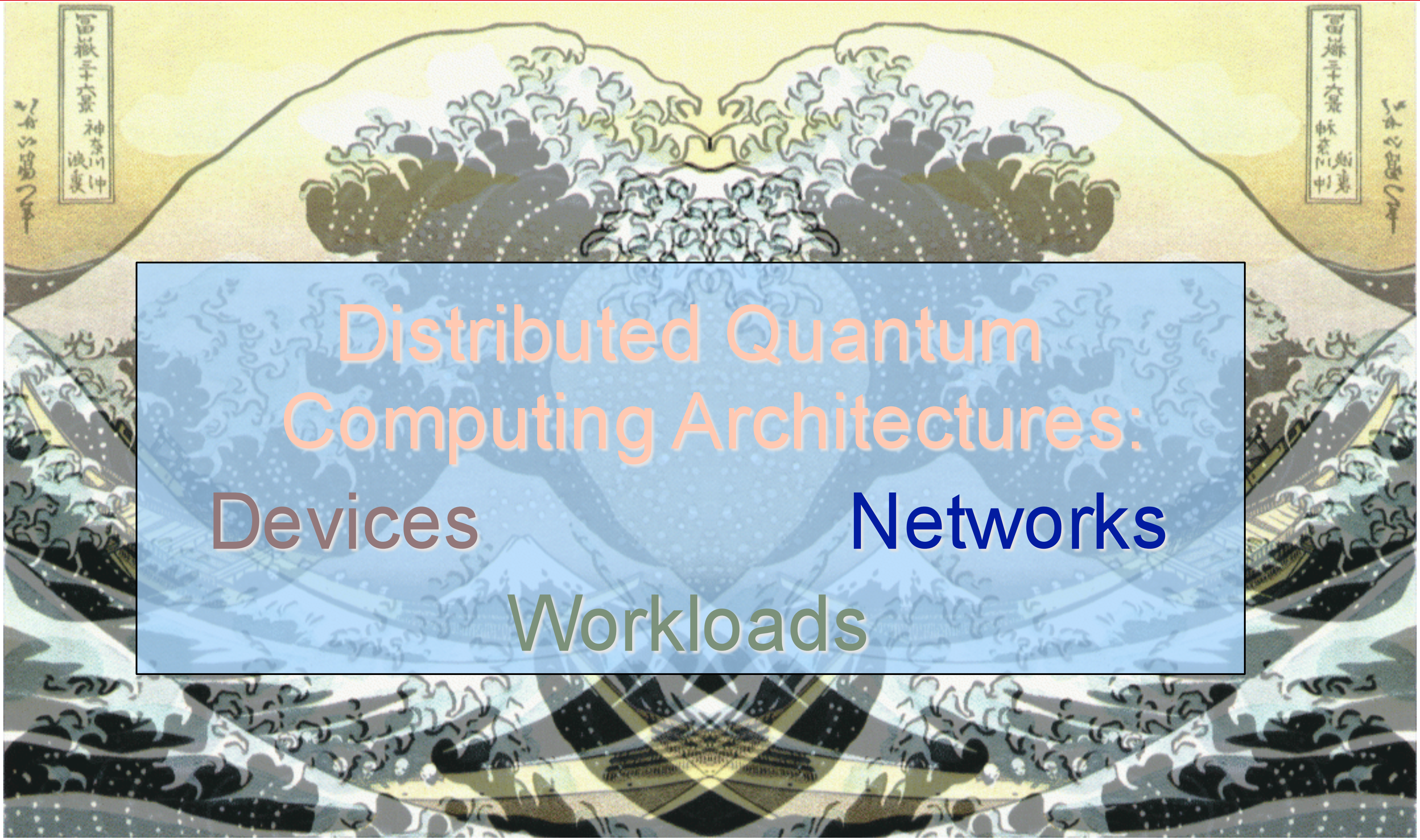
The Quantum Multicomputer



Laboratory-sized quantum multicomputer or transcontinental network, either one!

AQUA: Advancing Quantum Architecture



Distributed Quantum Computing Architectures:

Devices

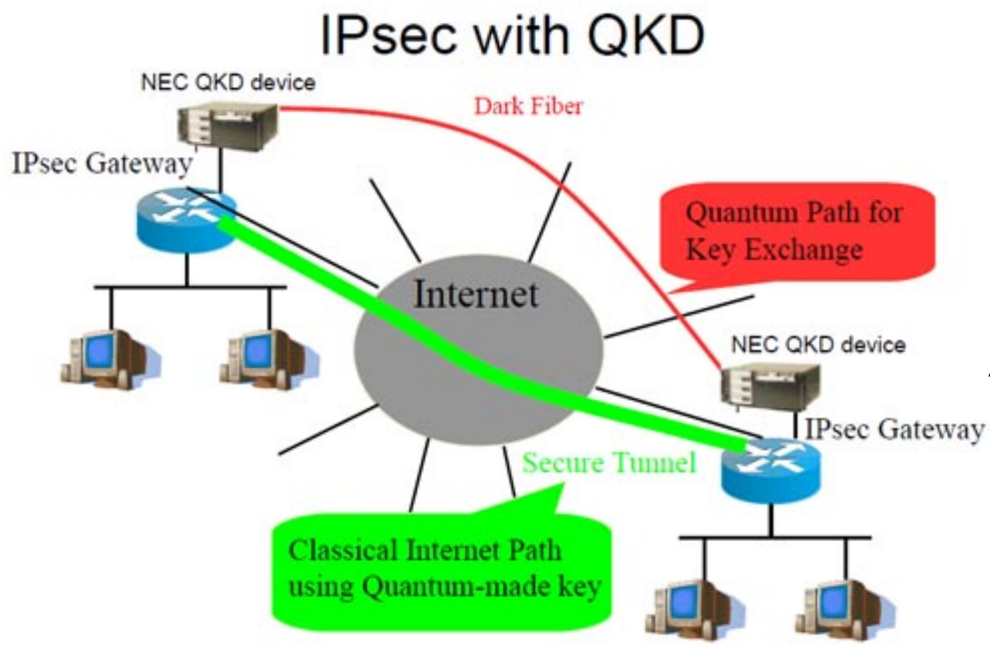
Networks

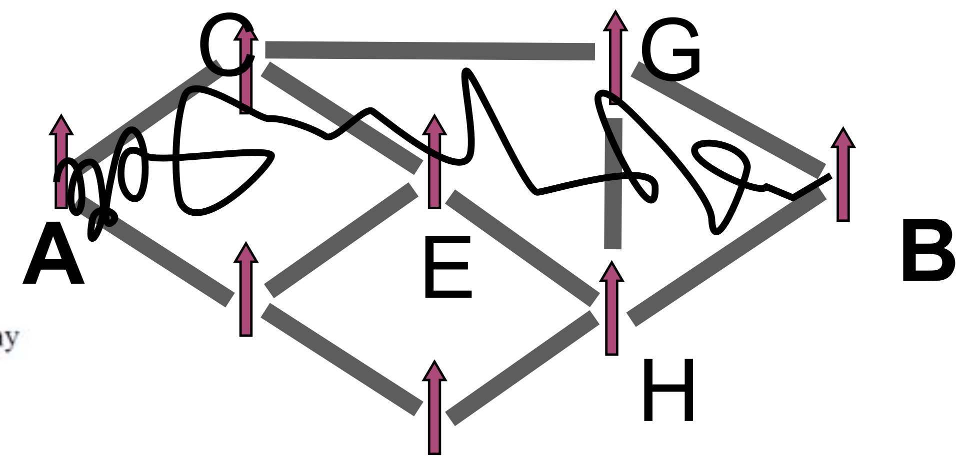
Workloads

Two Types of Quantum Networks

Unentangled Networks

Entangled Networks





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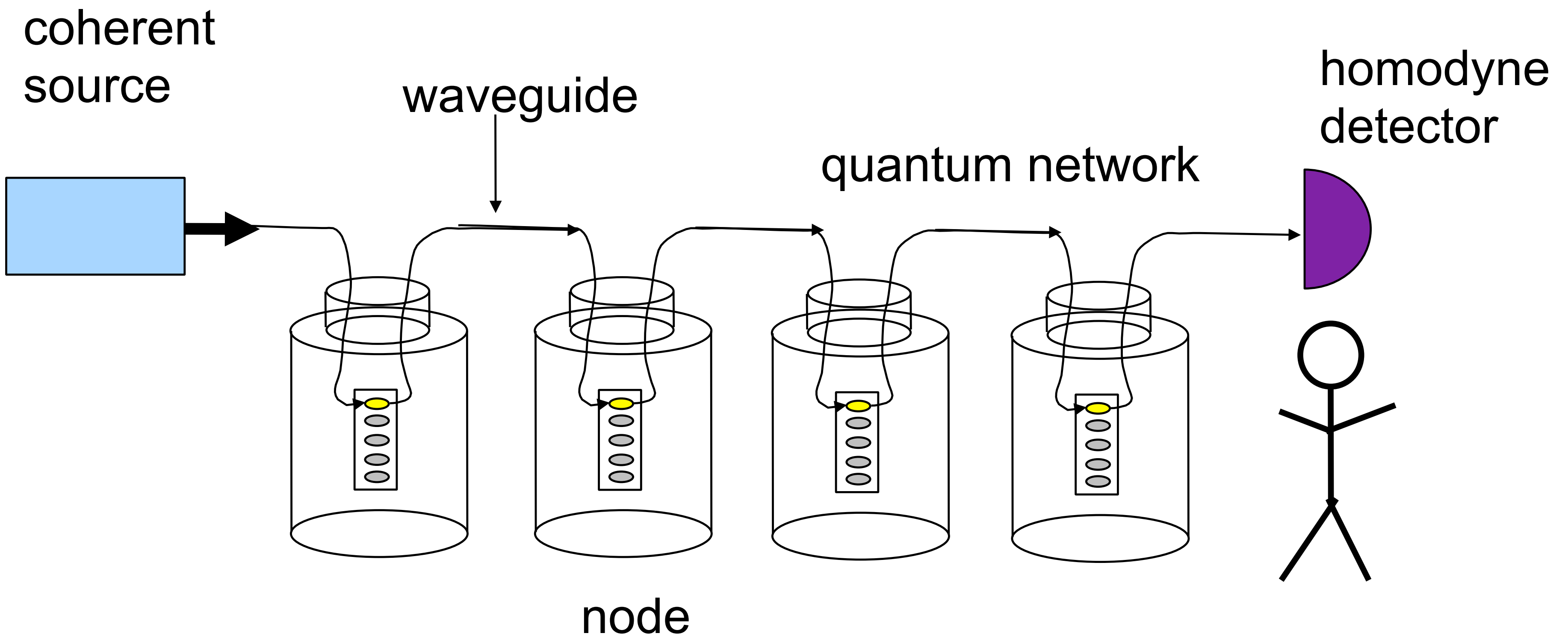
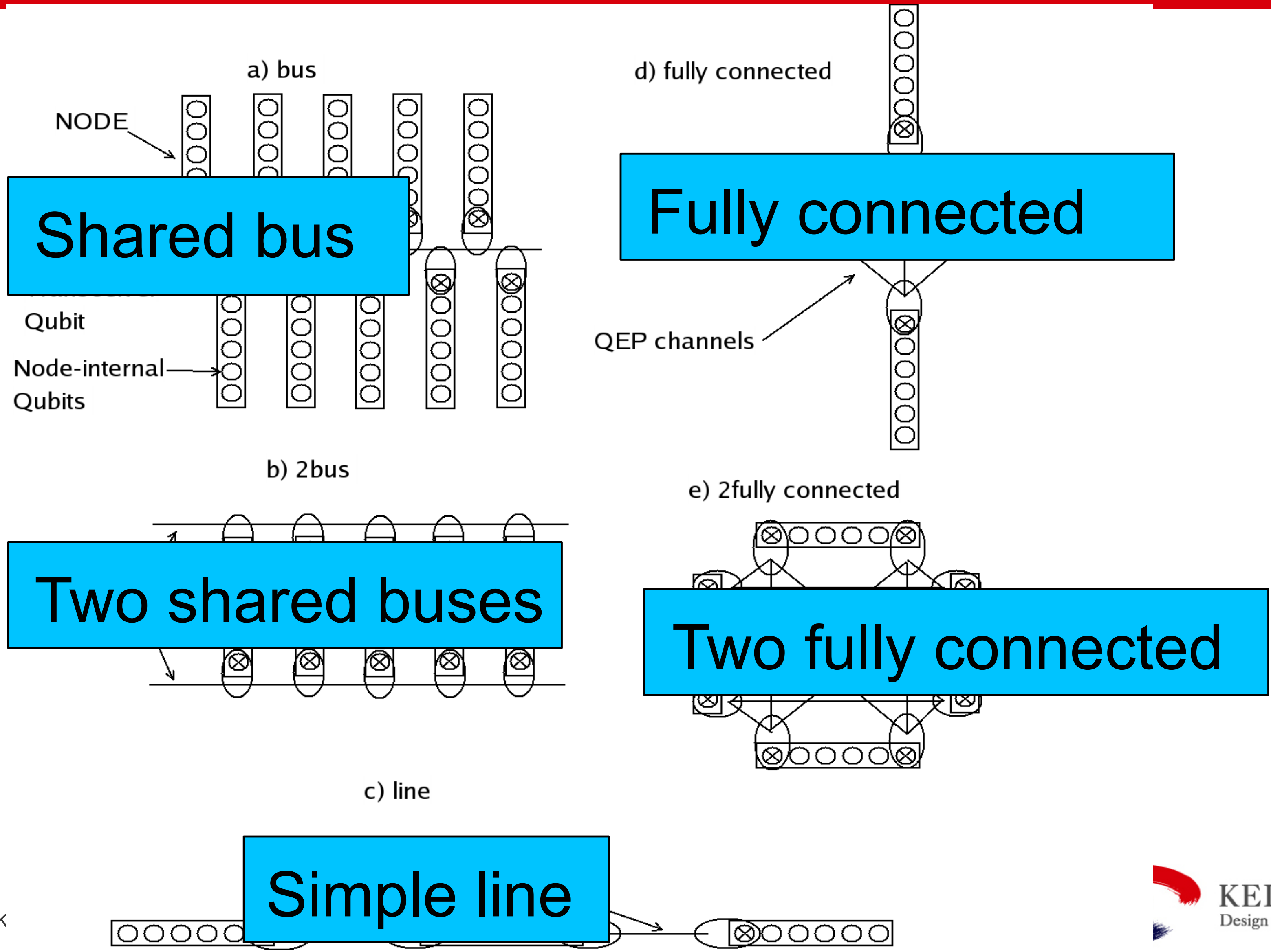
Variables

- Two types of quantum networks
- Four network architectures
  - CSAN
  - QLAN, QMAN, QWAN
- Applications:
  - QKD: QMAN, QWAN (entangled or not)
  - Shor: QSAN, QLAN (entangled)
  - Generally, connect people, machines, and data in separate locations, same as classical
  - Other uses for long-distance entanglement?

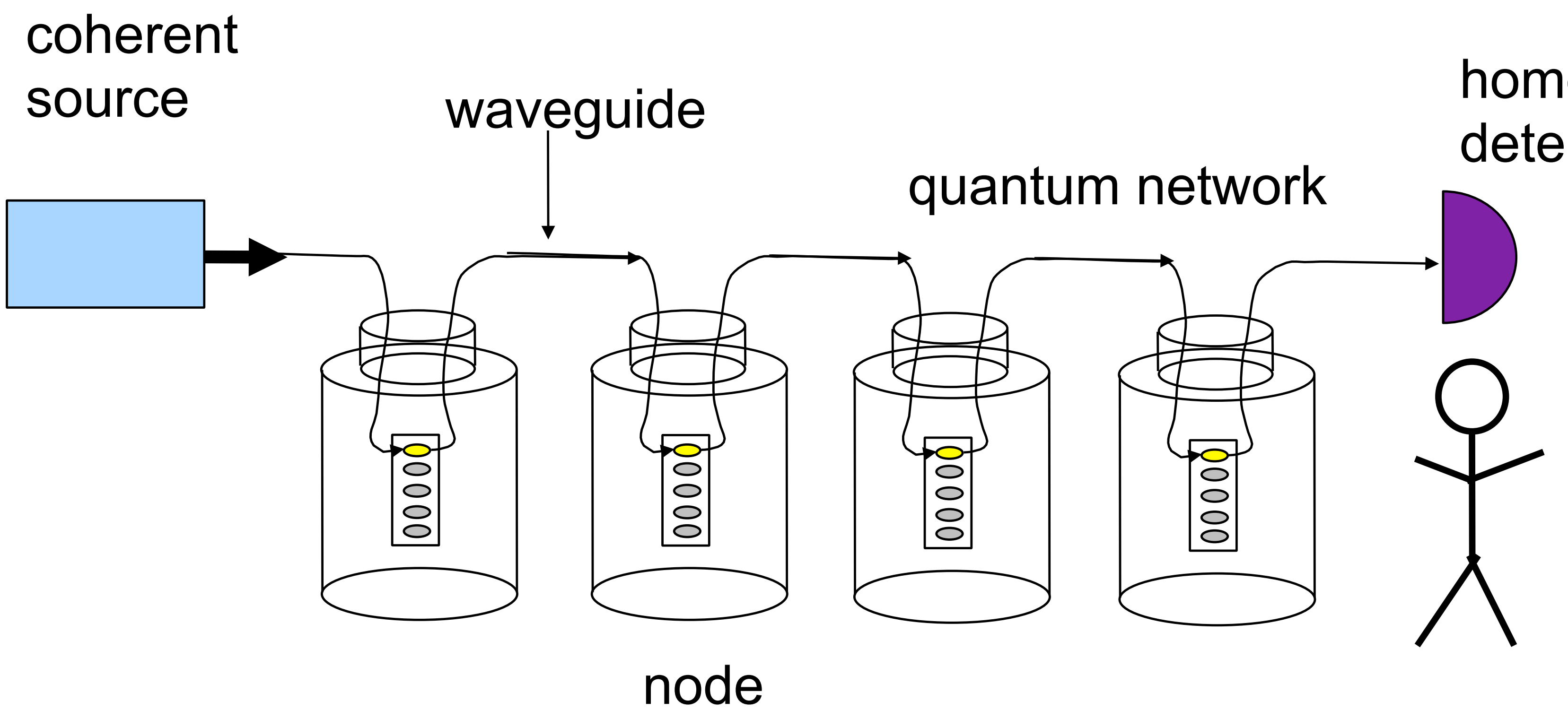
The QMC QSAN


coherent
source
waveguide
homodyne
detector
quantum network
node

QMC Network Topologies



The Quantum Multicomputer



Linear connection works well for arithmetic

Serial links work surprisingly well with QEC

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The Repeater's Jobs

Entanglement swapping & purification, which require:

- A little bit of quantum communication
- Quantum memory
- Local quantum operations (gates & measurements)
- Lots of decision making (both local and distributed)
- Lots of classical communication

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Repeater Protocol Stack

Application	End-to-End
Purification Control (PC)	End-to-End
Entang. Swapping Ctl (ESC)	Repeated at Different Distances
Purification Control (PC)	Repeated at Different Distances
Entanglement Control (EC)	Distance=1
Physical Entanglement (PE)	Distance=1

Only quantum!

Van Meter *et al.*, IEEE/ACM Trans. on Networking, Jun. 2009, quant-ph:0705.4128

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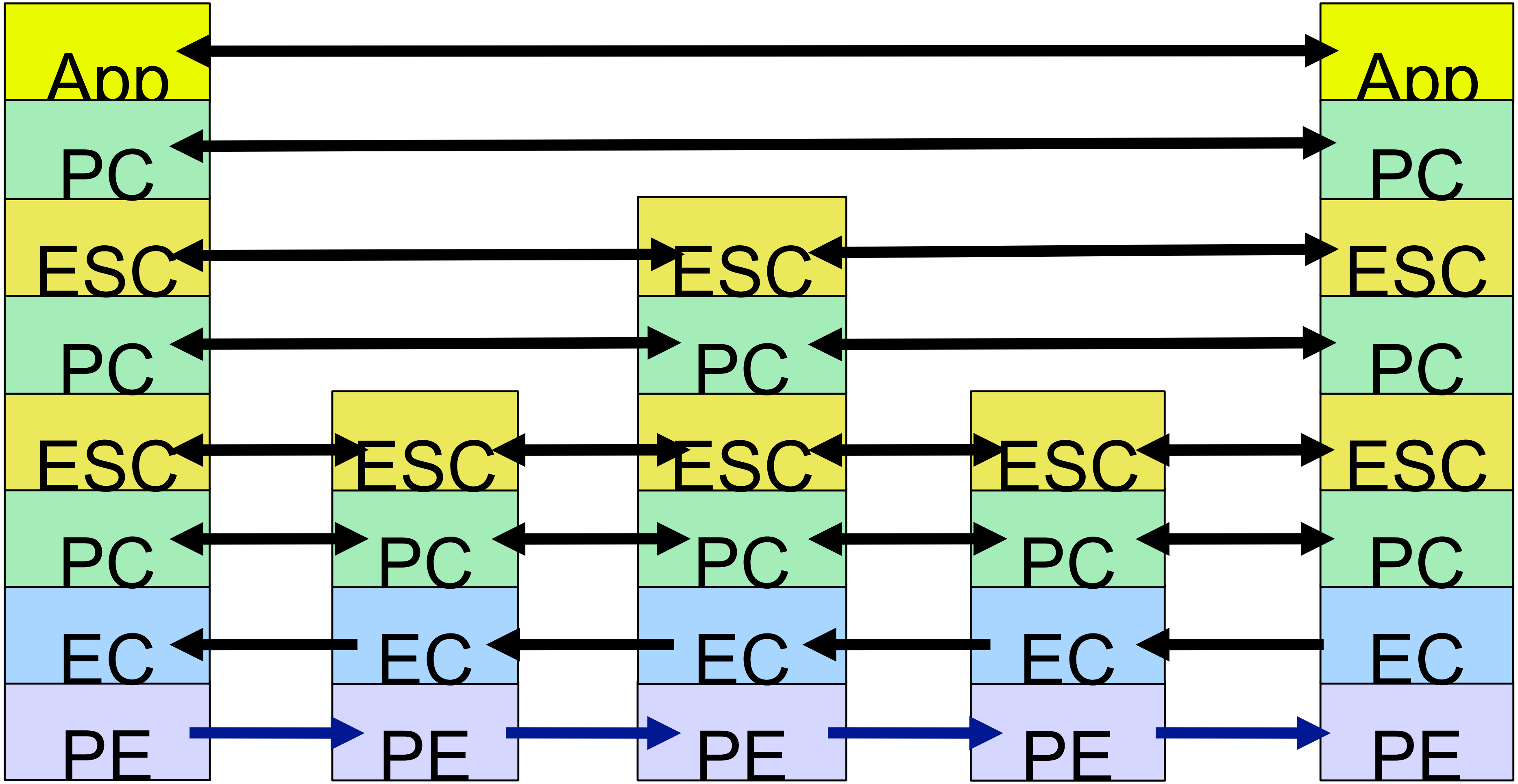
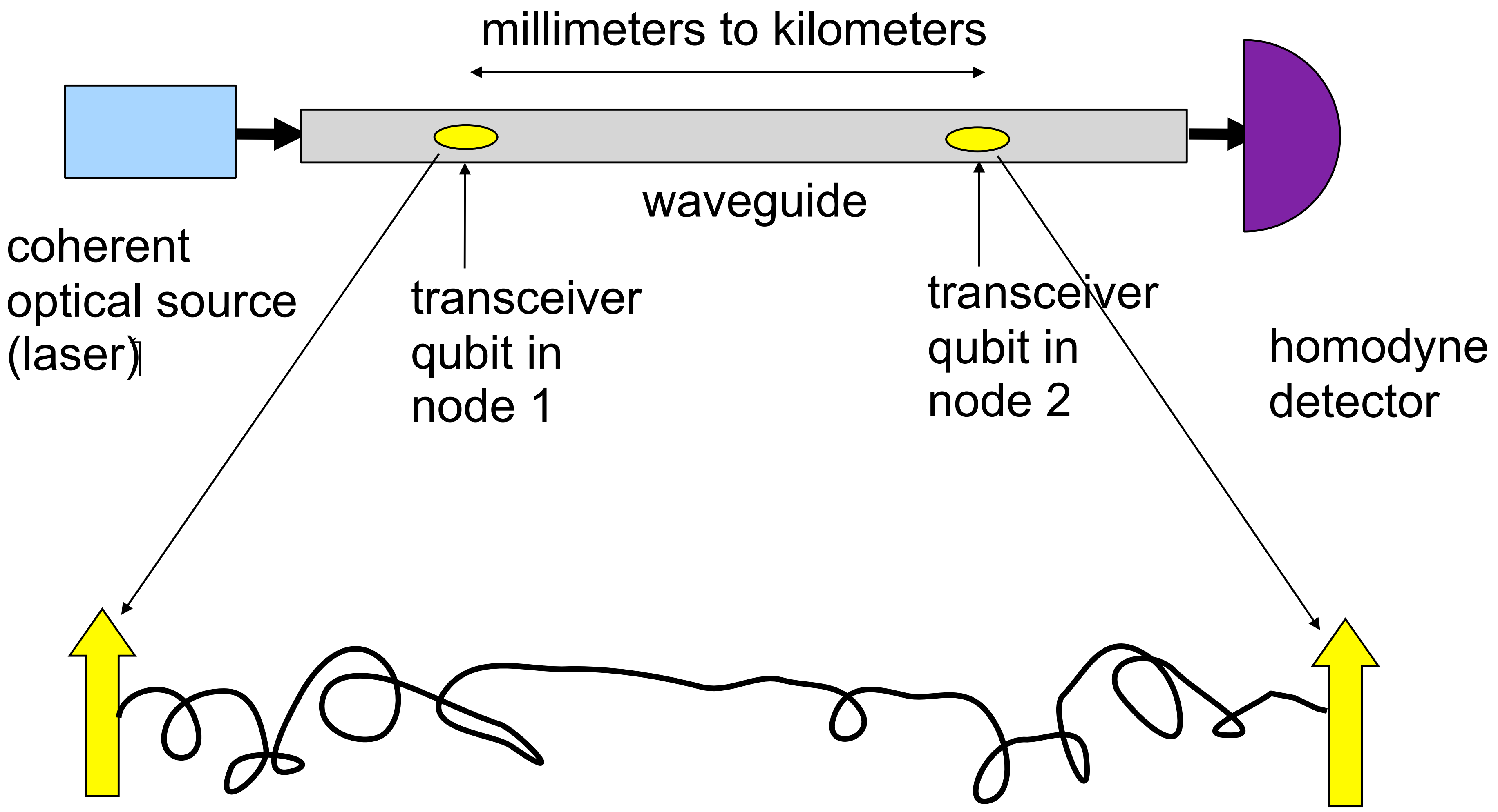
Four-Hop Protocol Interactions



Van Meter *et al.*, IEEE/ACM Trans. on Networking, Aug. 2009 (to appear)

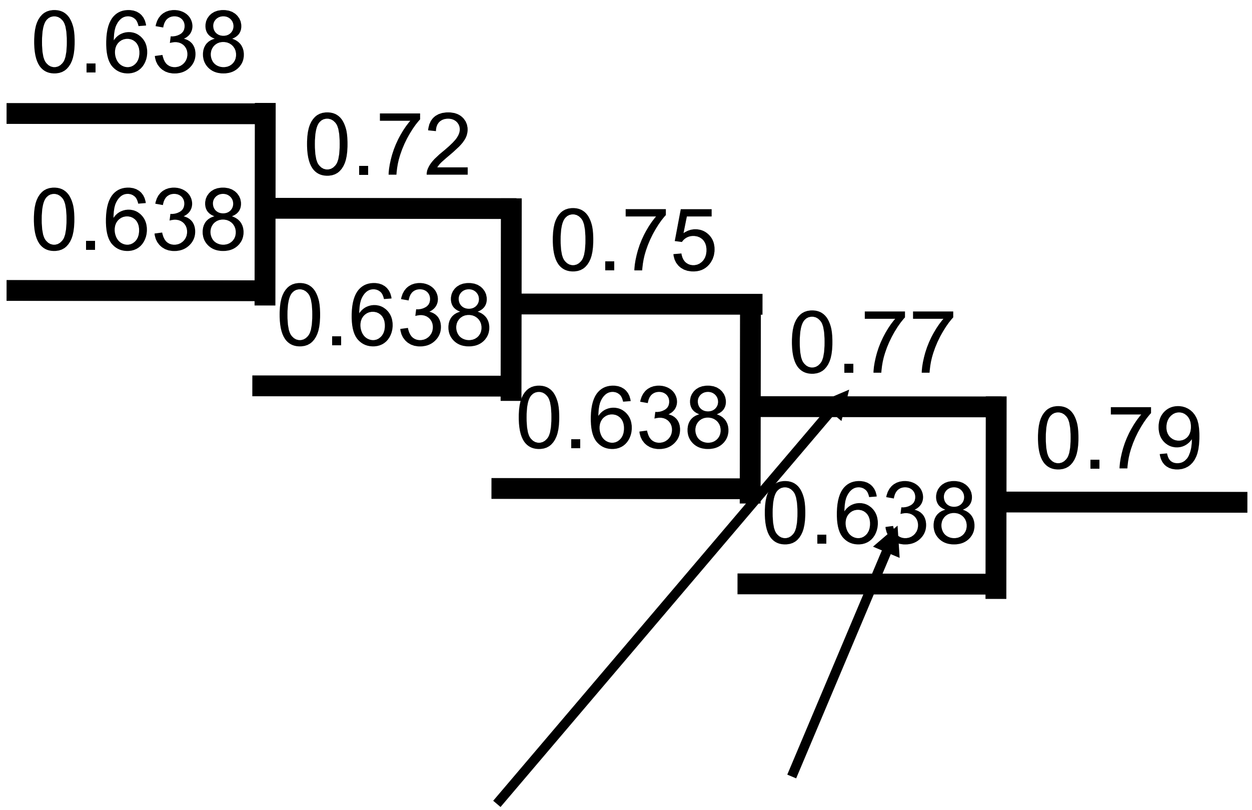
Network Link Technology (Qubus)



Munro, Nemoto, Spiller, New J. Phys. 7, 137 (2005)

Ladd et al., NJP 8, 184 (2006)

Entanglement Pumping



Ineffective w/ large fidelity difference

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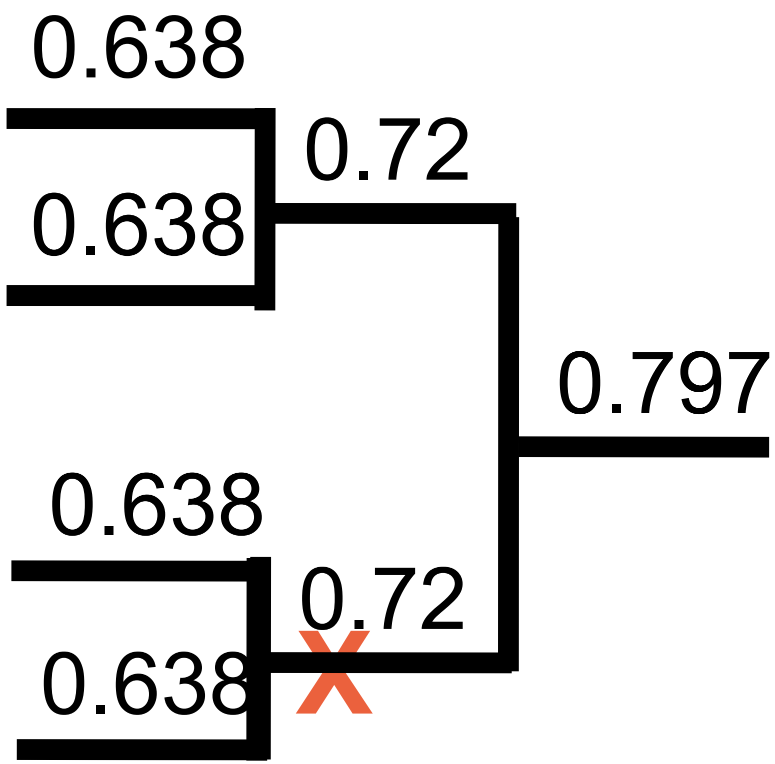
Symmetric Purification



Problems:
Exact matching can require long waits.
Not realistic when memory effects (decoherence) considered.
Can deadlock if resources are limited.

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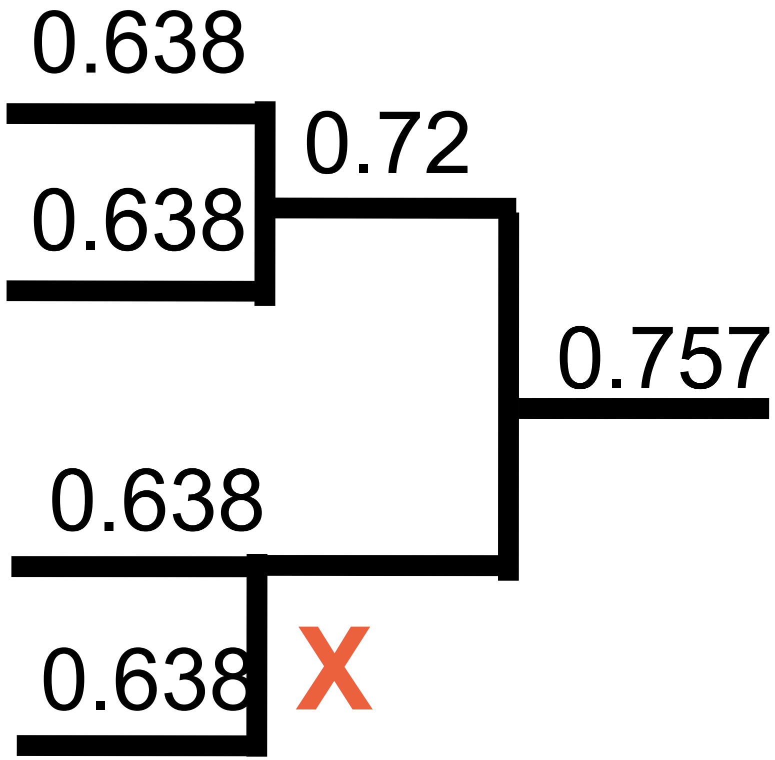
Greedy Purification



Doesn't wait for anything, uses whatever's available.

Works well w/ large number of qubits per repeater.

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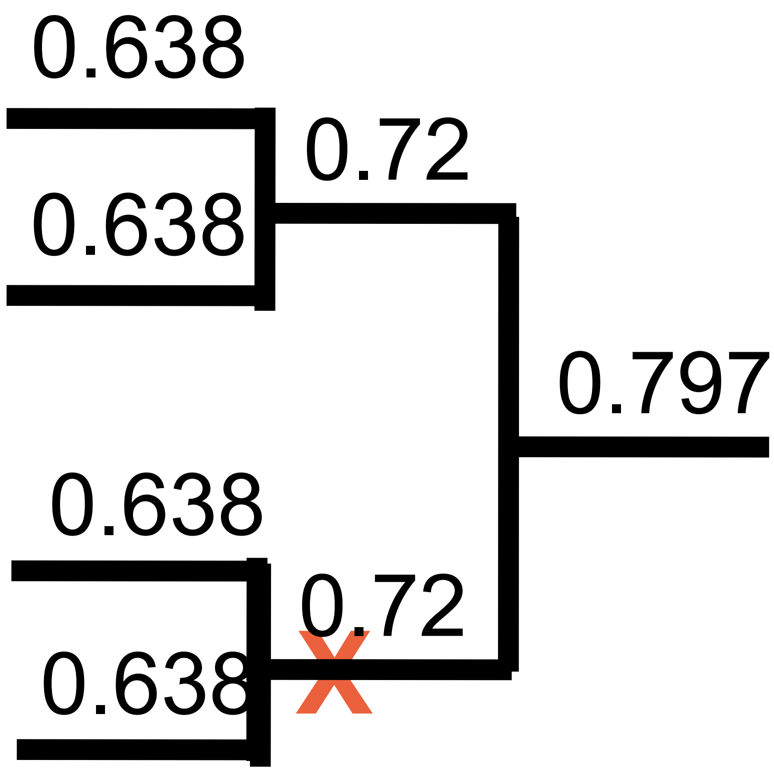
Banded Purification



Large gains in throughput.
Moderate # qubits (5-50).
Avoids deadlock.
Realistic memory model.
Simple to implement in real time (even in HW).
Probably not optimal, but probably close.

Divide fidelity space into multiple *bands*
e.g., above & below 0.70

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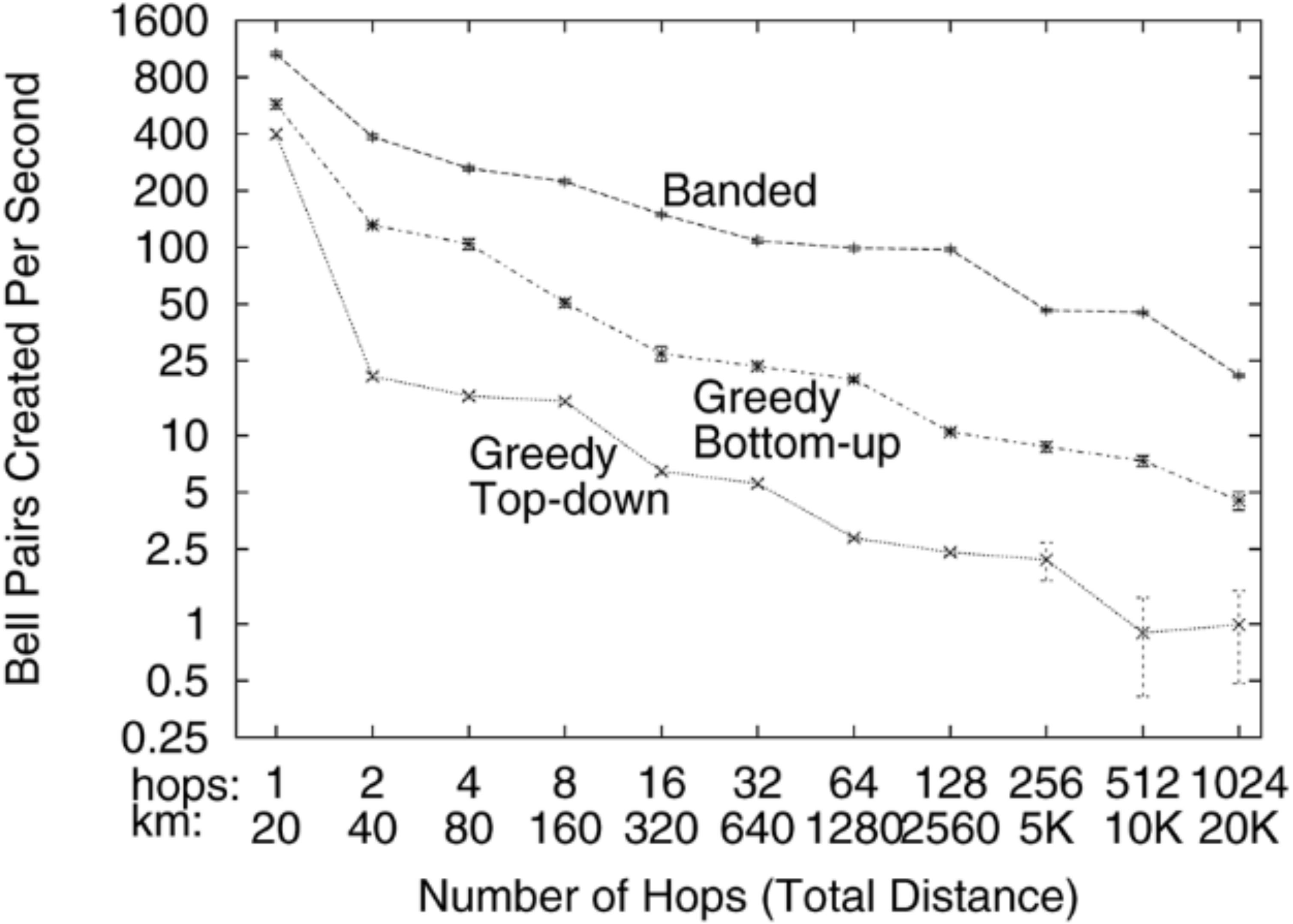
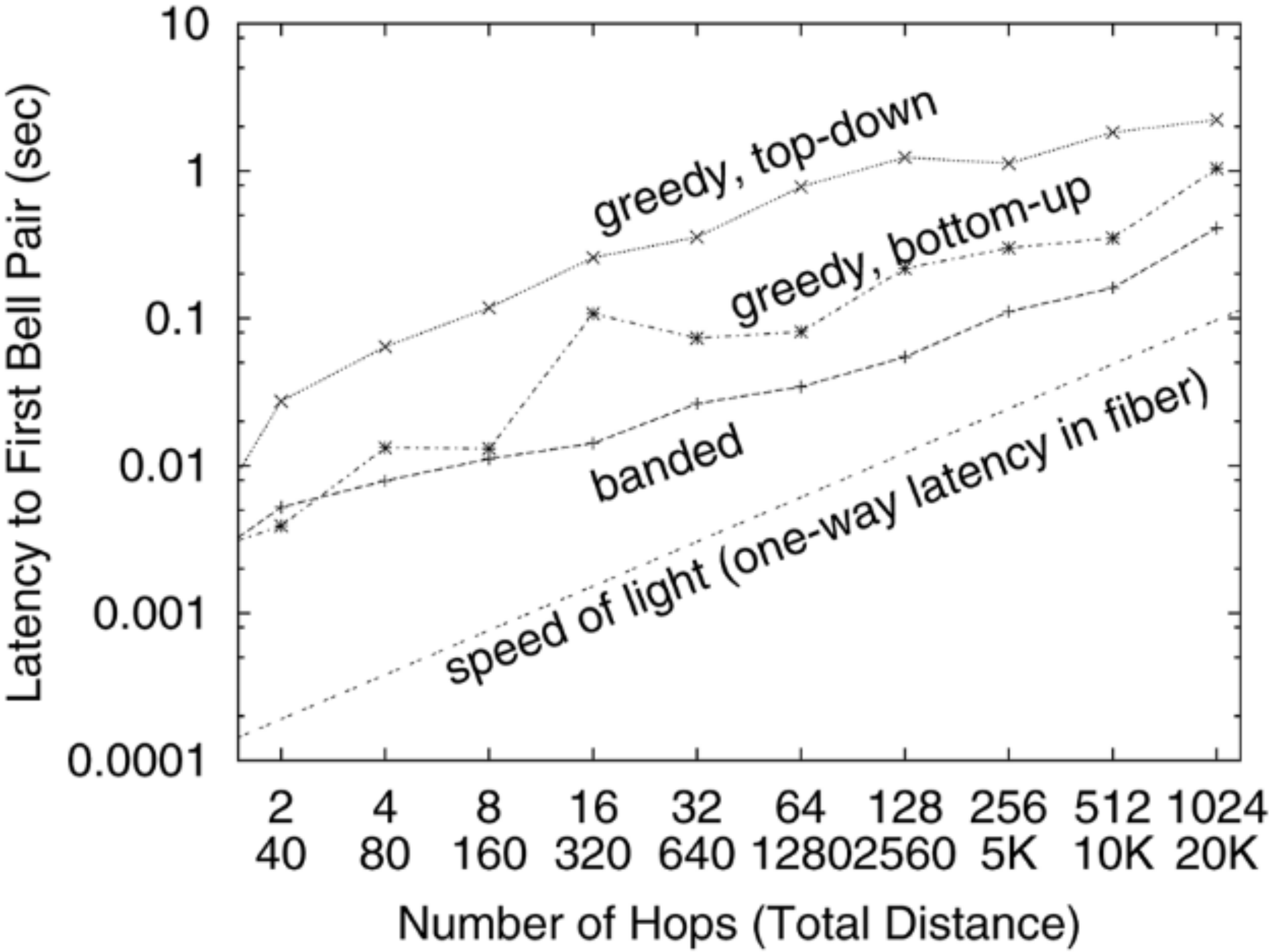
Banded Purification Performance



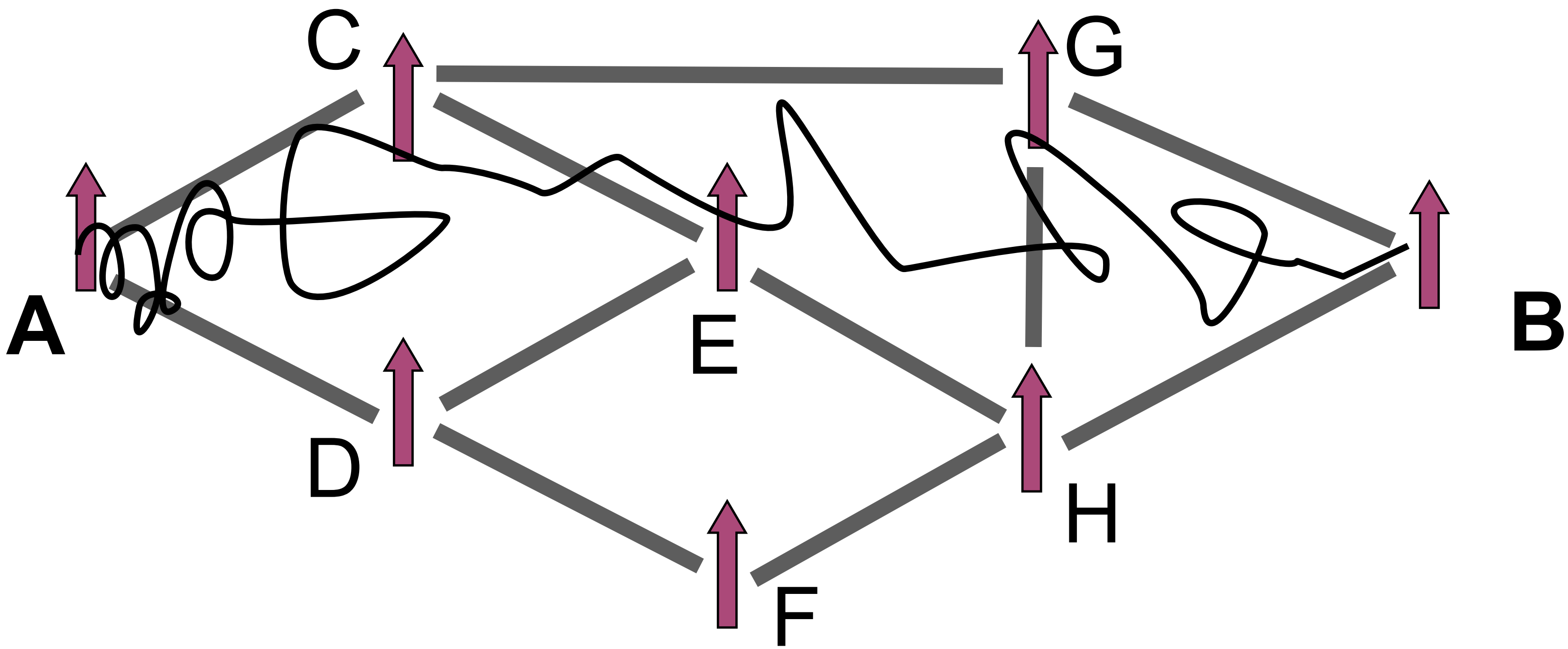
Van Meter *et al.*, IEEE/ACM Trans. on Networking, Aug. 2009 (to appear), quant-ph:0705.4128

Banded Purification Latency



Van Meter *et al.*, IEEE/ACM Trans. on Networking, Aug. 2009 (to appear), quant-ph:0705.4128

Routing



Simple: use Dijkstra's Shortest Path First.

...but we don't yet know the cost metric.

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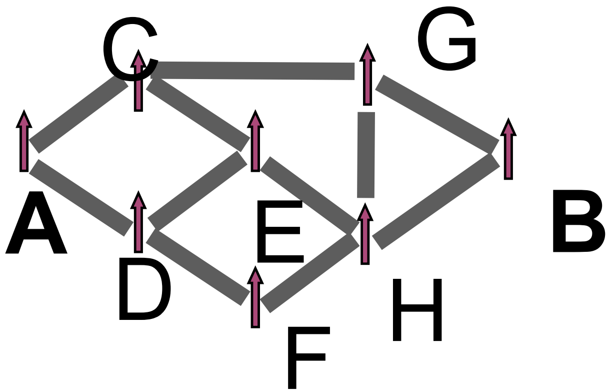
Different "Which Path"?



3 hops: ACGB

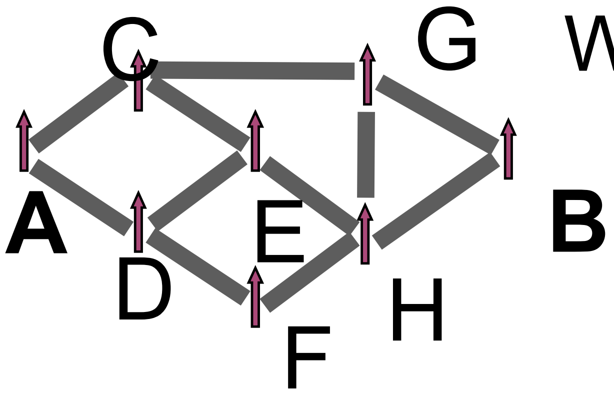
4 hops: ACGHB
ACEHB
ADEHB
ADFHB

5 hops: ACEHGB
ADEHGB
ADECGB
ADFHGB

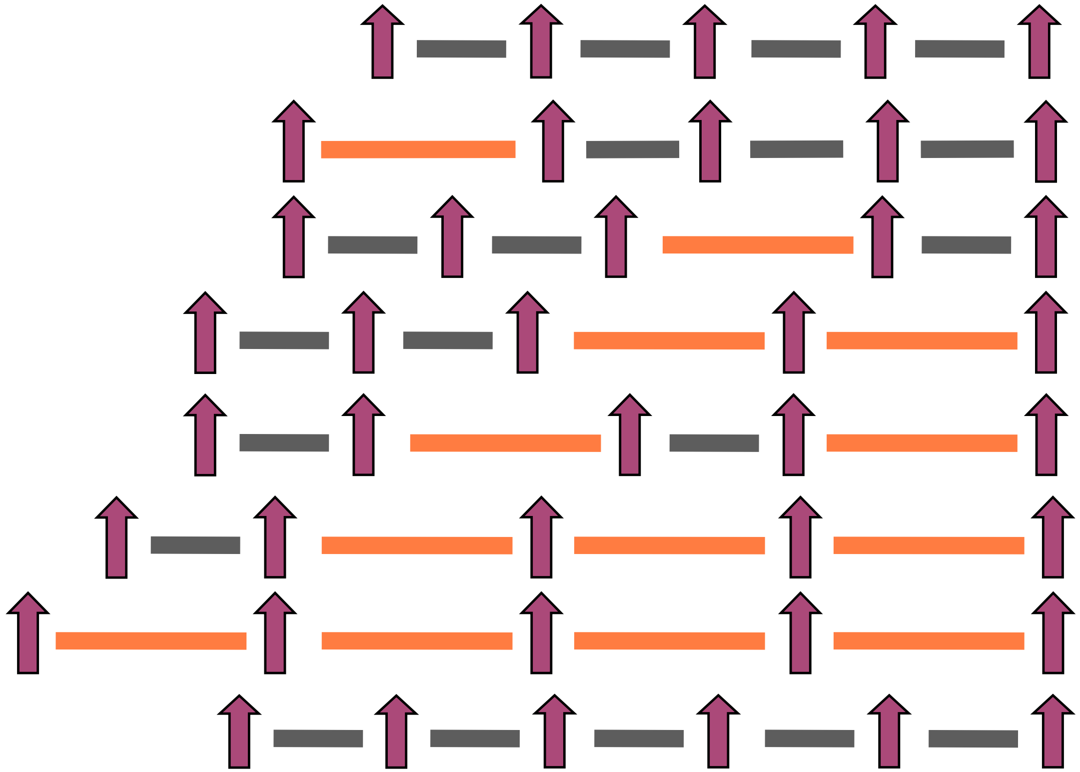
6 hops: ACECGHB

7 hops: ADFHECGB
ACEDCHGB

But What is Distance?



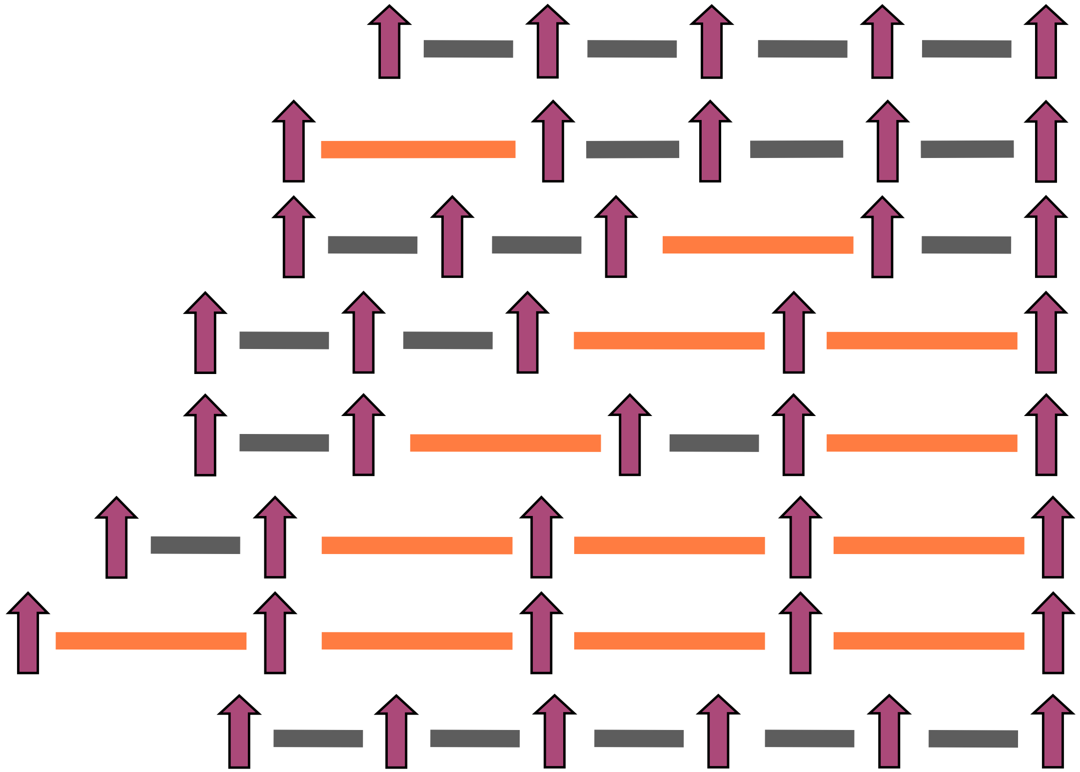
What if hops are not homogeneous?



Are 2^n-1 hops,
2^n hops,
and 2^n+1 hops
significantly different?

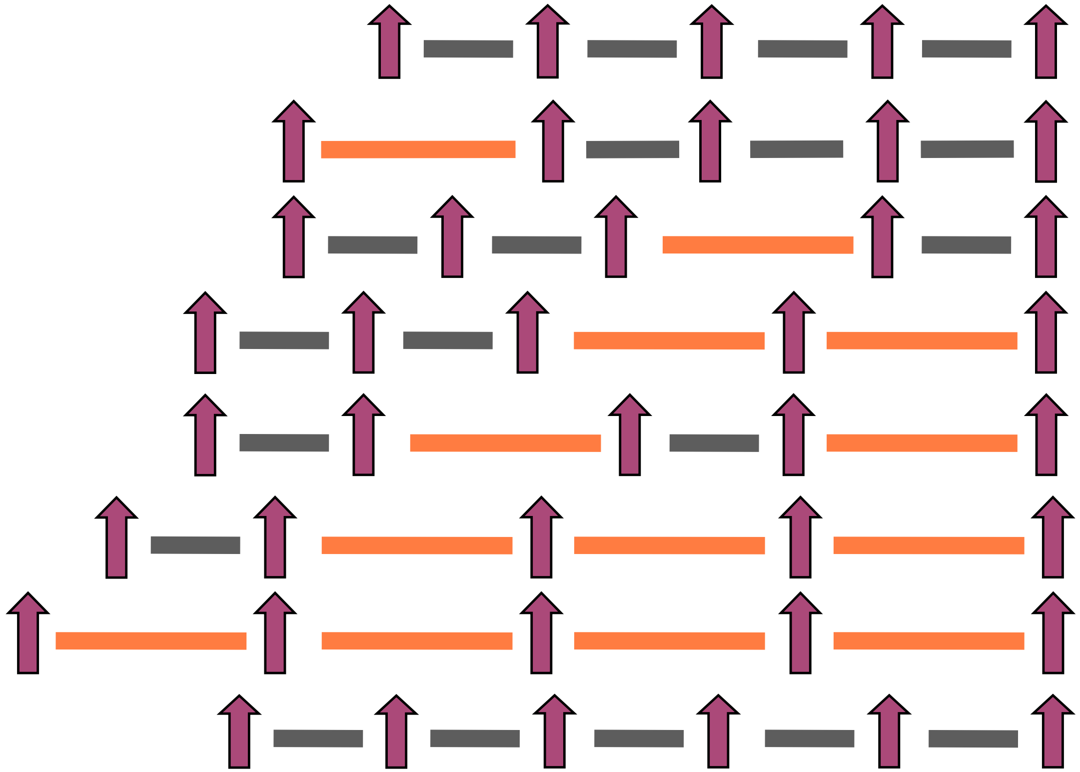
How Do We Order These?

- How does *number* of links matter?
- Does *number* of **weak** links matter?
- Does *position* of weak link matter?
- Is cost **additive?**
- At this logical level, is this technology-independent?

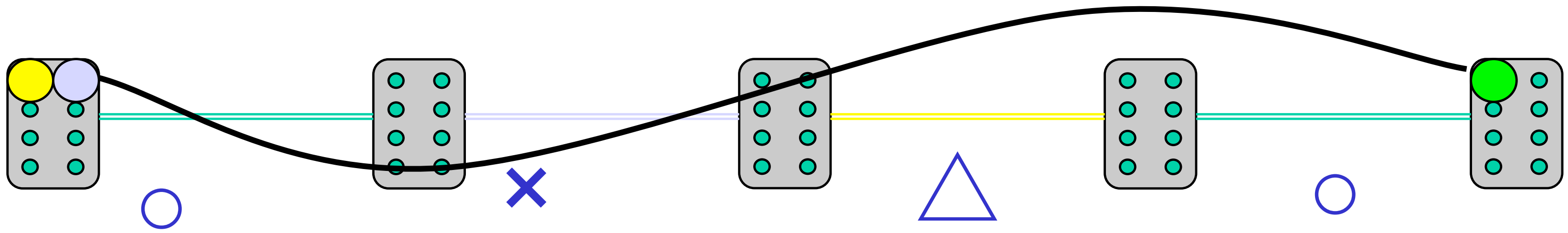


Other Problems

- Defining swap points
- Static or dynamic?
- Avoiding leapfrog
- Avoiding deadlock
- Minimizing waits for classical messages



Defining Cost in a Quantum Network

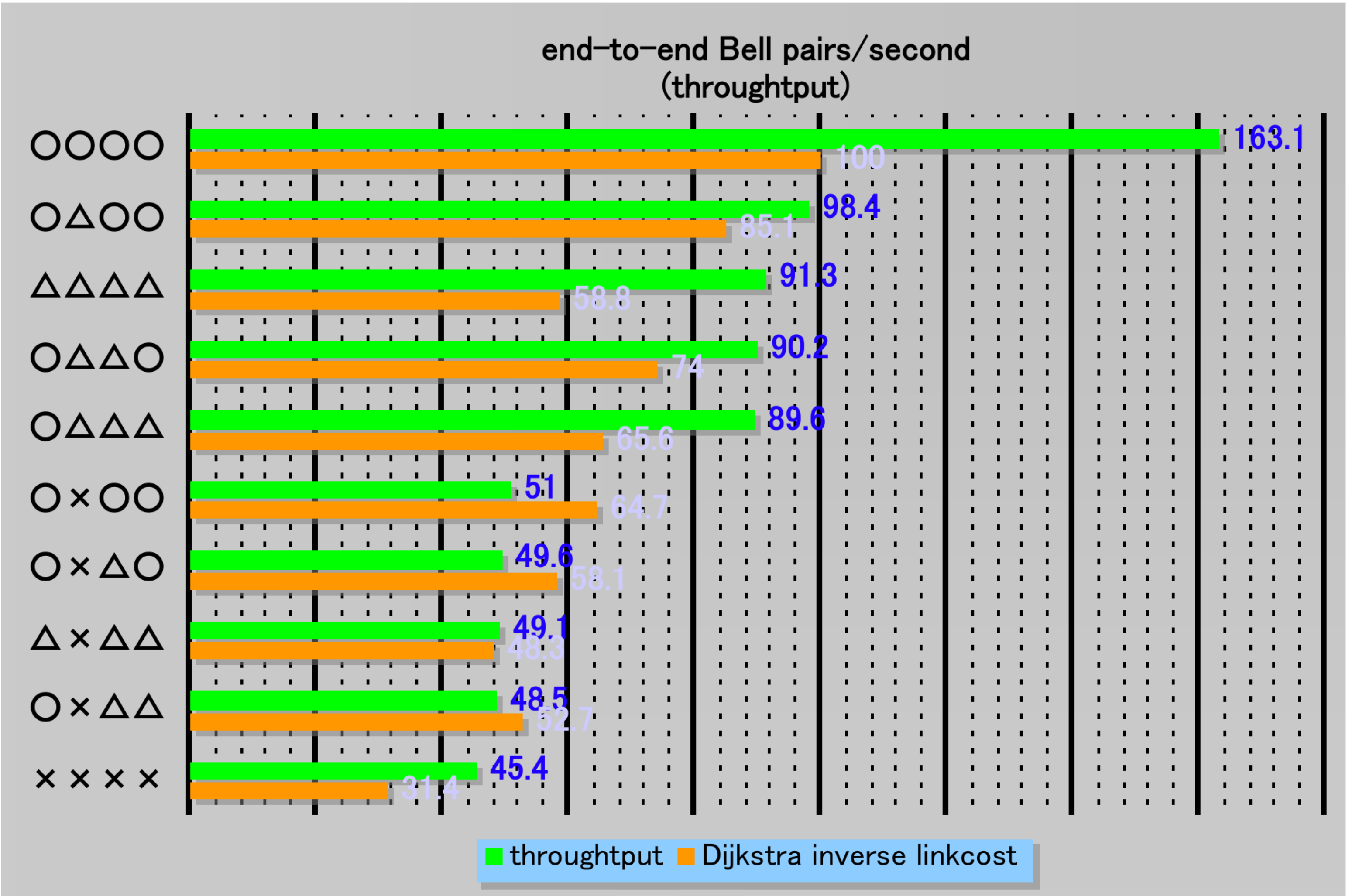


Cost =f(○,×,△,○)

- Classical Dijkstra:
  Cost＝○＋×＋△＋○

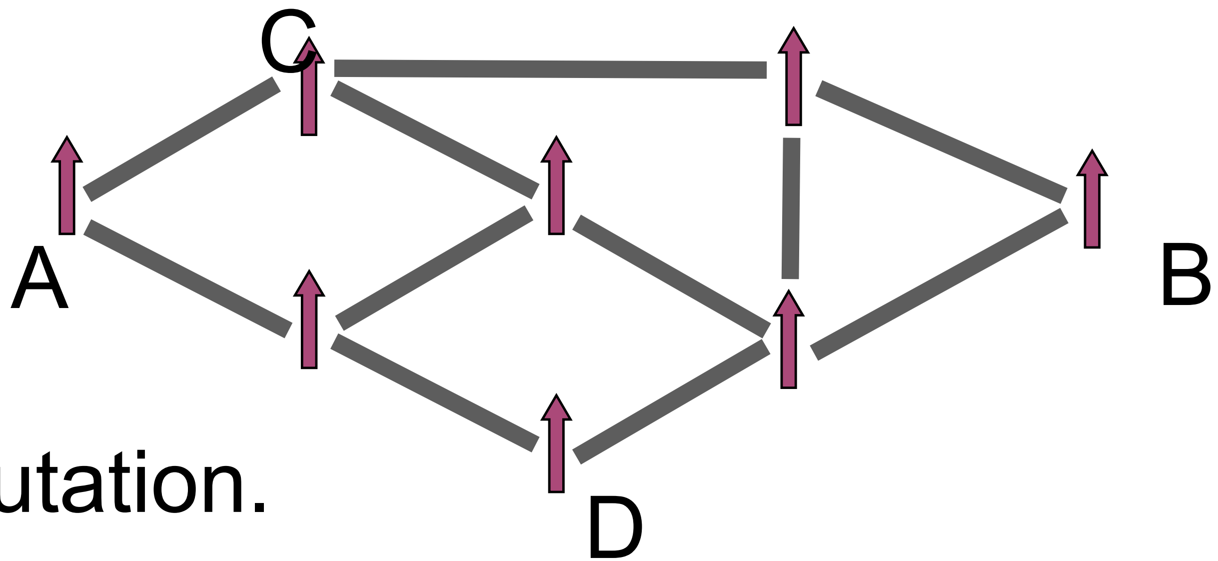
- Quantum: Dijkstra?
  Cost＝○?×?△?○
  What functions are possible?

Quantum Dijkstra's Algorithm



Resource Management (QoS?)

A<->B & C<->D
want to talk.



Remember, it's a
distributed computation.

Worse, fragile quantum memory means there is a *hard real time* component.

==>requires *circuit switching*???
(bottleneck likely is memory per node)

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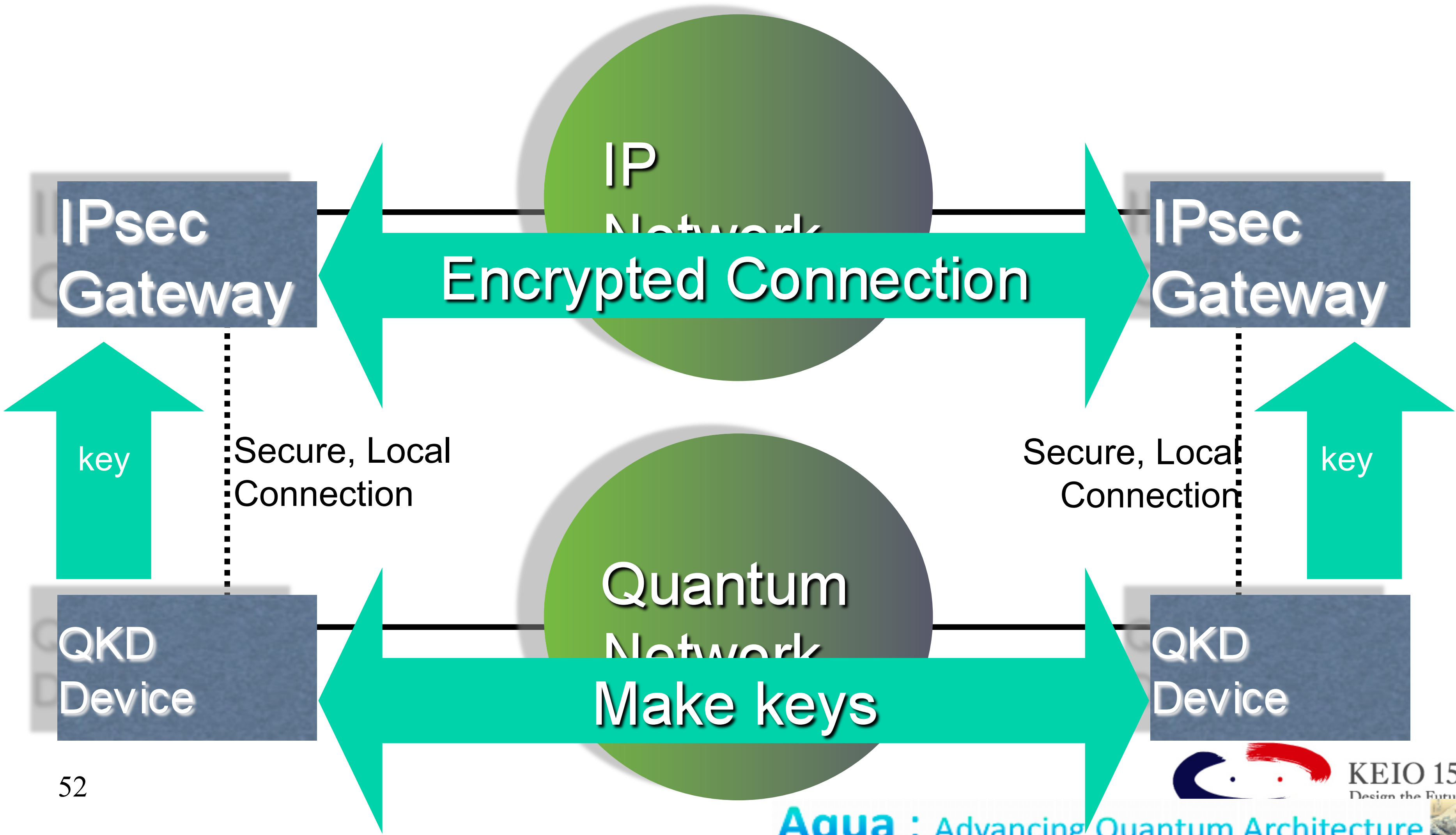
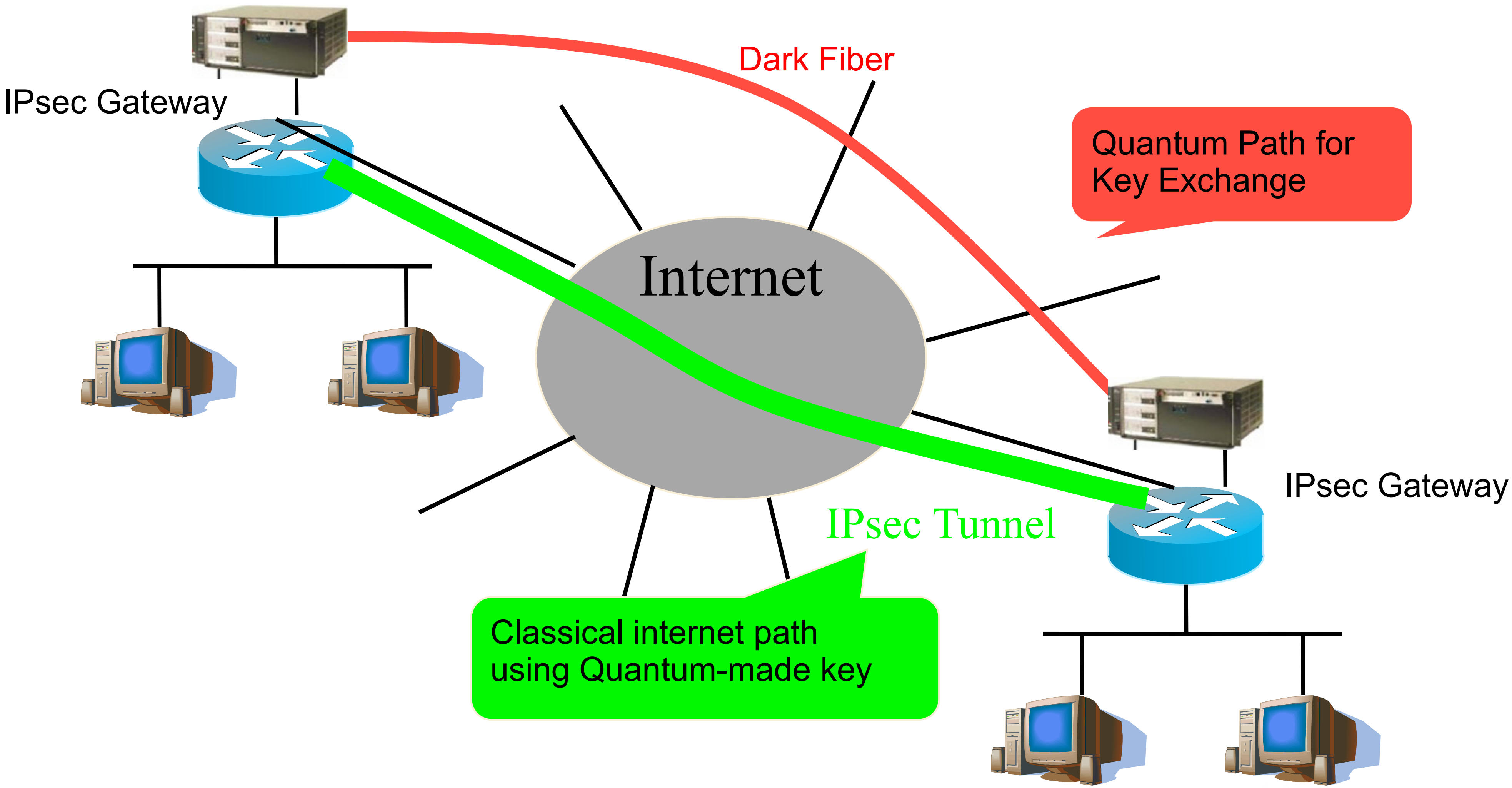
Open Repeater Problems

- Well, repeater HW doesn't work yet...
  - Establishing swapping points
  - Non-power-of-two hops
  - Finish & publish protocol state machine
  - Resource management models
  - Optimizing classical communication
  - Other error correction mechanisms besides purification

IPsec with QKD



IPsec with QKD



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The Message

- Architecture and architects matter
- Interconnects and networks matter
- Distributed systems are the only way to achieve scalability
- Classical architecture techniques are viable in the quantum domain
- ...and our group is having fun and solving important problems, so come hang out with us!

Collaborators on Four Continents

- Kohei Itoh & Agung Trisetyarso, Keio Yagami
- Takahiko Satoh & Shota Nagayama, Keio SFC
- Thaddeus Ladd & Yoshi Yamamoto, Stanford
- Bill Munro, HP Labs, Bristol, UK
- Kae Nemoto, NII, Tokyo
- Austin Fowler, Melbourne, Australia
- Byung-Soo Choi, Ewha Woman's U., Korea
- Thanks to NSF and JSPS for current funding, and MICT, MEXT, QAP, and Keio's Mori Fund for past funding
- ...and thanks to NEC for the loan of the QKD devices

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Papers

- “Distributed Quantum Computation Architecture Using Semiconductor Nanophotonics,” IJQI, 2010
- “System Design for a Long-Line Quantum Repeater,” IEEE/ACM Trans. On Networking, Jun. 2009
- I-D: “IKE for IPsec with QKD,” Oct. 2009 draft-nagayama-ipsecme-ike-with-qkd-00.txt
- These & others available on my web page

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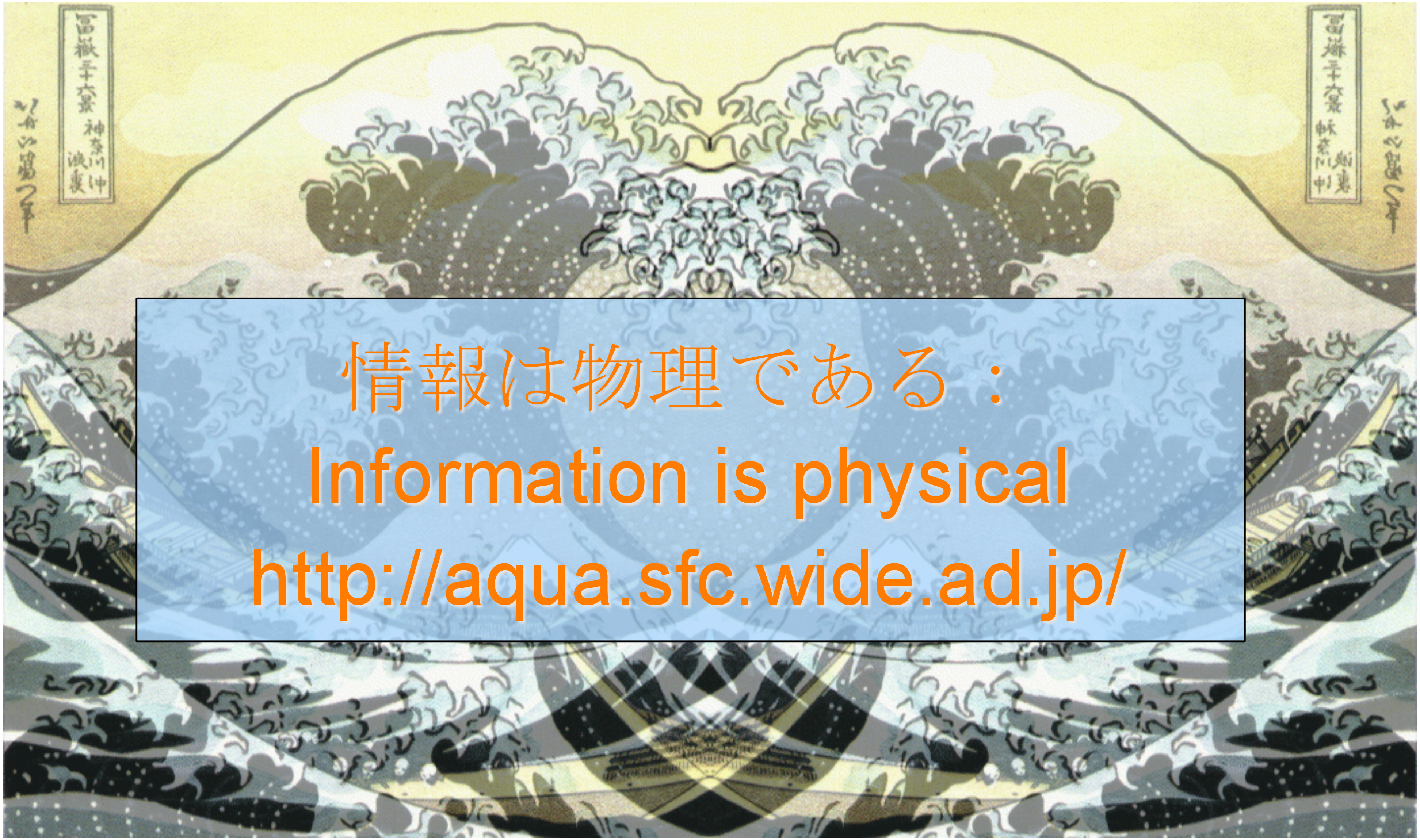
Food for Thought

- When will first *Science* or *Nature* paper appear *using* a quantum computer, but not *about* the quantum computer?
- That is, when will a quantum computer ***do*** science, rather than ***be*** science?
- Answers from quantum researchers range from “less than five years” to “more than forty years”

AQUA: Advancing Quantum Architecture



情報は物理である：

Information is physical

http://aqua.sfc.wide.ad.jp/