# Distributed Quantum Error Correction

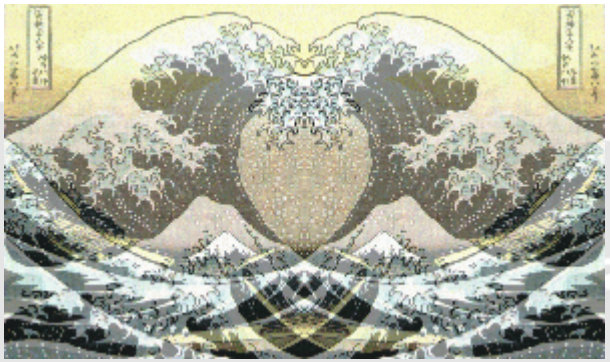
First International Conference on Quantum Error Correction

December 19, 2007

Rodney Van Meter (Keio) rdv@sfc.wide.ad.jp

Jacob M. Taylor (MIT),

Liang Jiang (Harvard)



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I don’t care about quantum error correction.

I  care about *quantum computer system architectures*.



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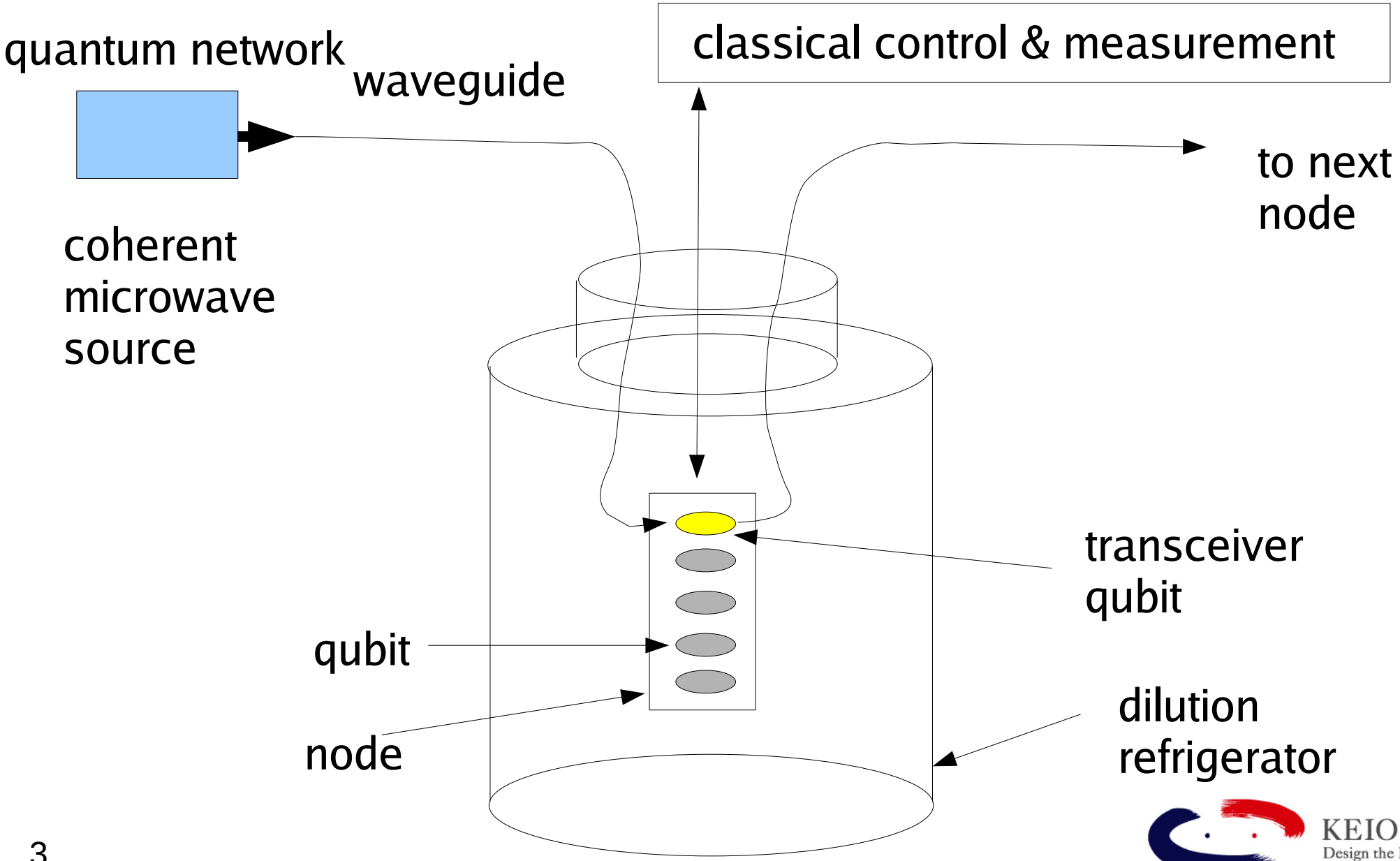
# A Quantum Multicomputer Node



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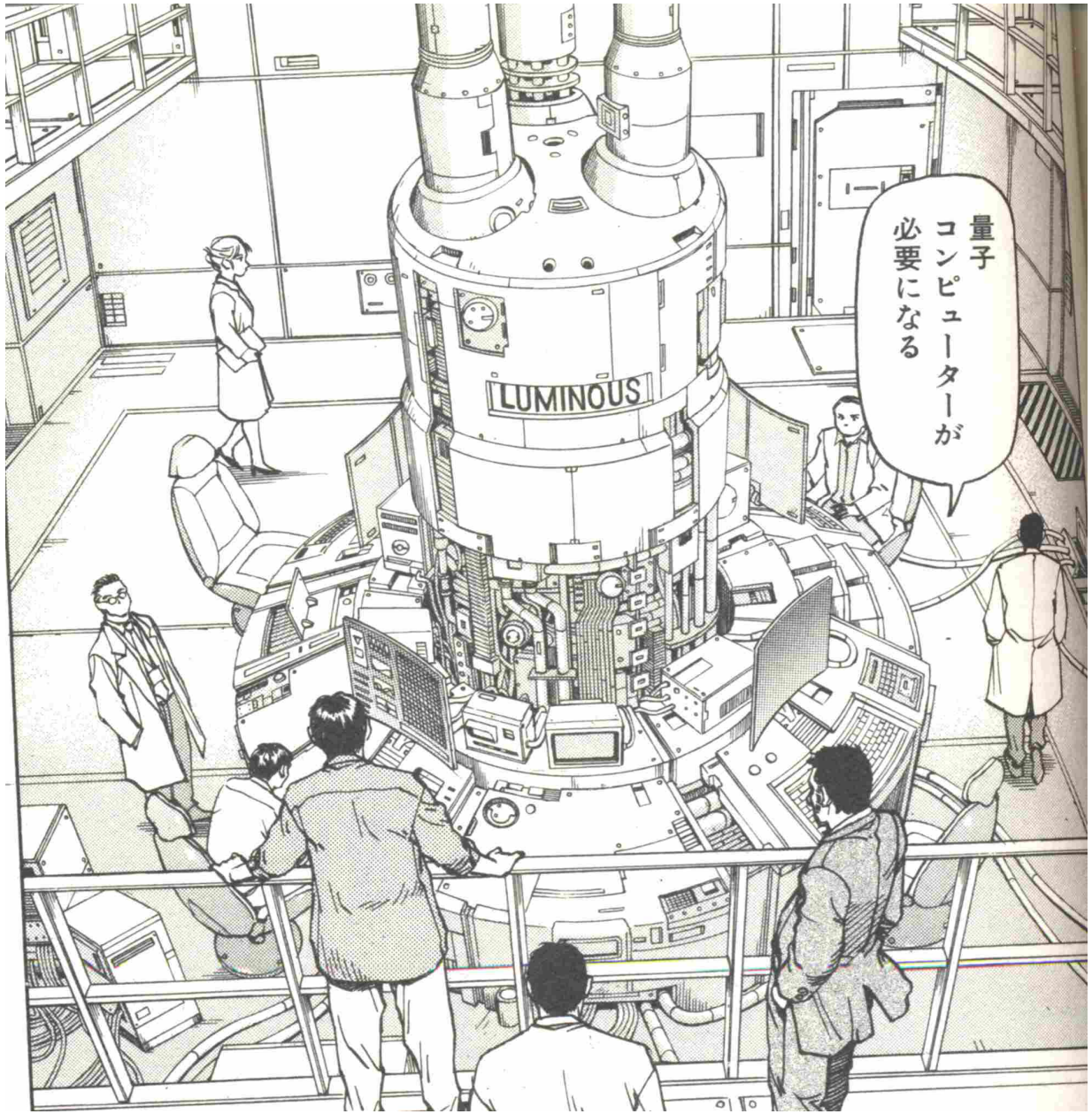
# One Like This?



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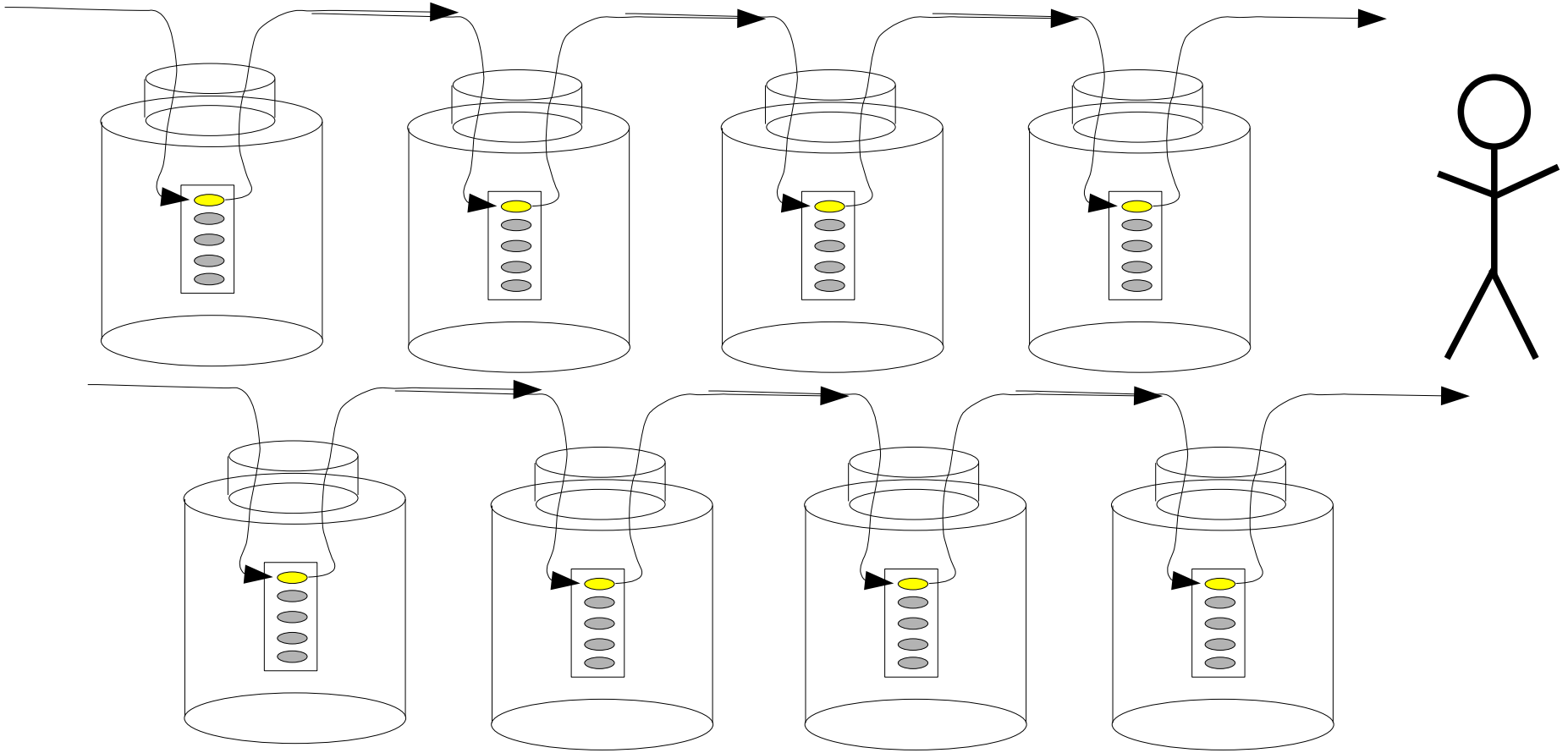
# A Quantum Multicomputer





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# Multicomputer Research

- Architecture:
  # of nodes? Qubits/node?
  Network topology? Link design?
- Software: applications, language design
- Error management:
  Quantum Error Correction (QEC),
  purification for teleportation
- Performance analysis

rdv, KMI, PRA 71(5), 2005; rdv, KMI, TDL, MS+S2006;
rdv, WJM, KN, KMI, Proc. Int. Symp. Computer Architecture (ISCA) (2006)
J. Emerging Tech. in Computing Systems (2007)



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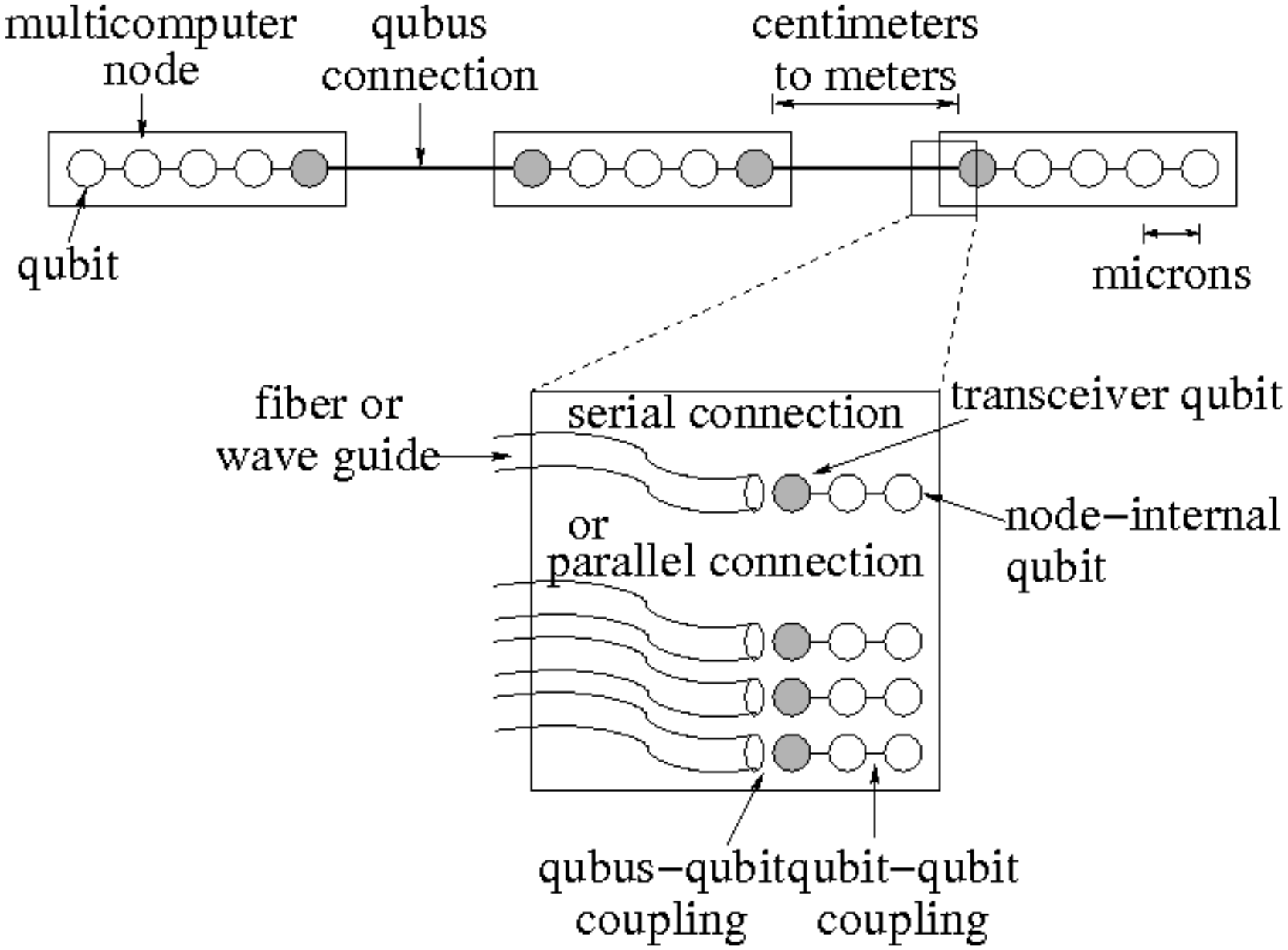
# Link Design


multicomputer node
qubus connection
centimeters to meters
qubit
microns
fiber or wave guide
serial connection
transceiver qubit
node–internal qubit
or parallel connection
qubus–qubit coupling
qubit–qubit coupling

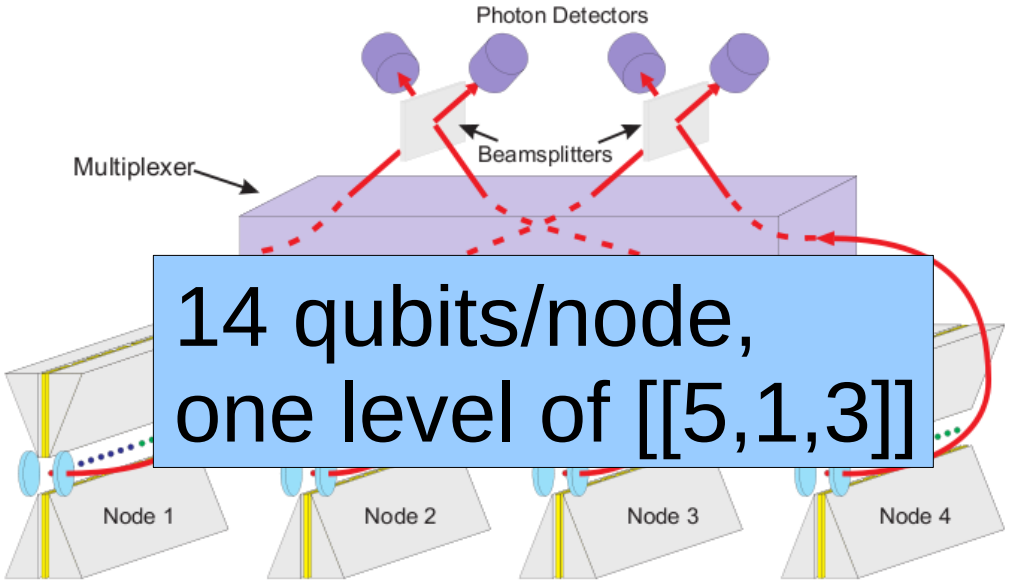
# Link Design

- Two levels of [[23,1,7]] code allow 1% physical teleportation failure when factoring a 1024-bit number
- Serial links work well when memory error rate 100x better than teleportation
  - Preferable for engineering reasons
- *Creating and using distributed logical zeros is painful and unlikely to work well.*

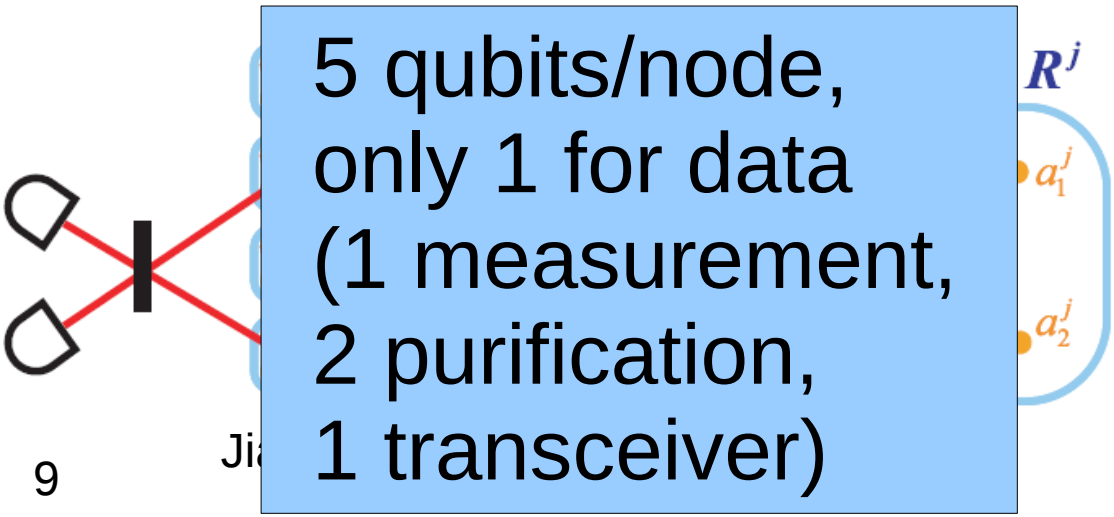
rdv, KN, WJM, IEEE Trans. on Computers, 56(12), 2007

# Small Nodes

Oi, Devitt, Hollenberg, PRA 74

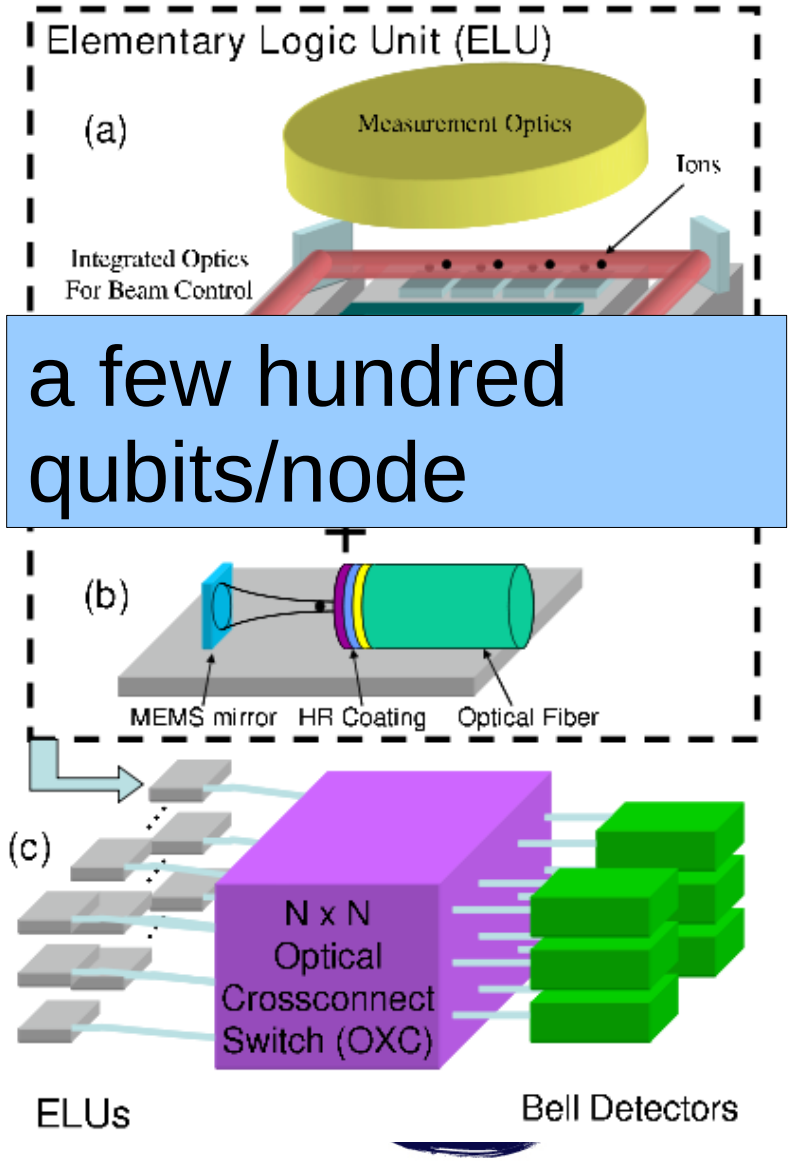



14 qubits/node,
one level of [[5,1,3]]




5 qubits/node,
only 1 for data
(1 measurement,
2 purification,
1 transceiver)

Kim & Kim, arxiv:0711.3866

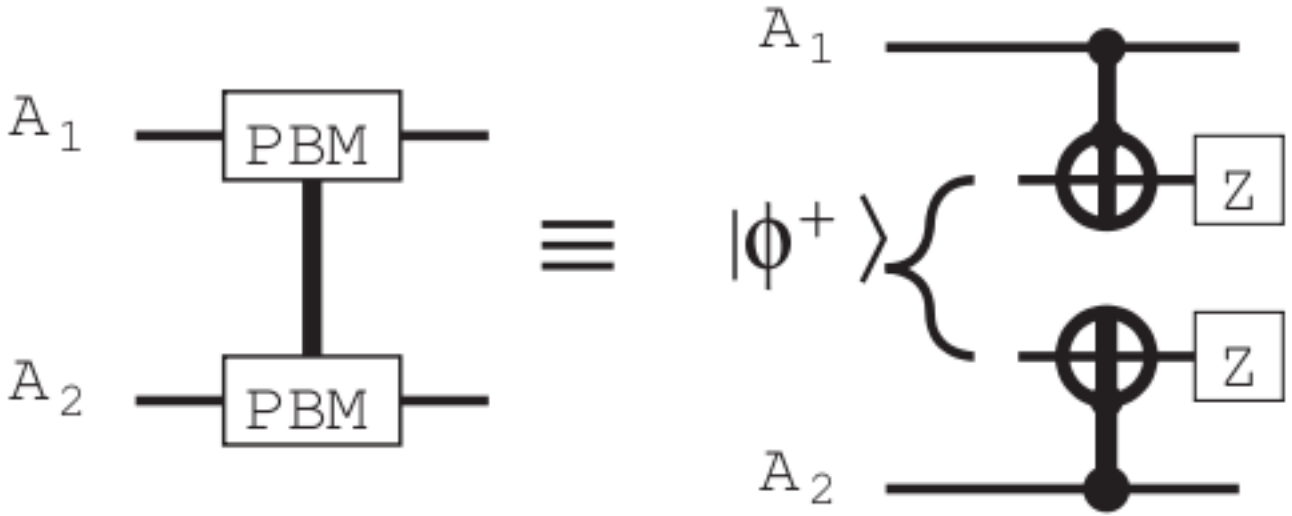


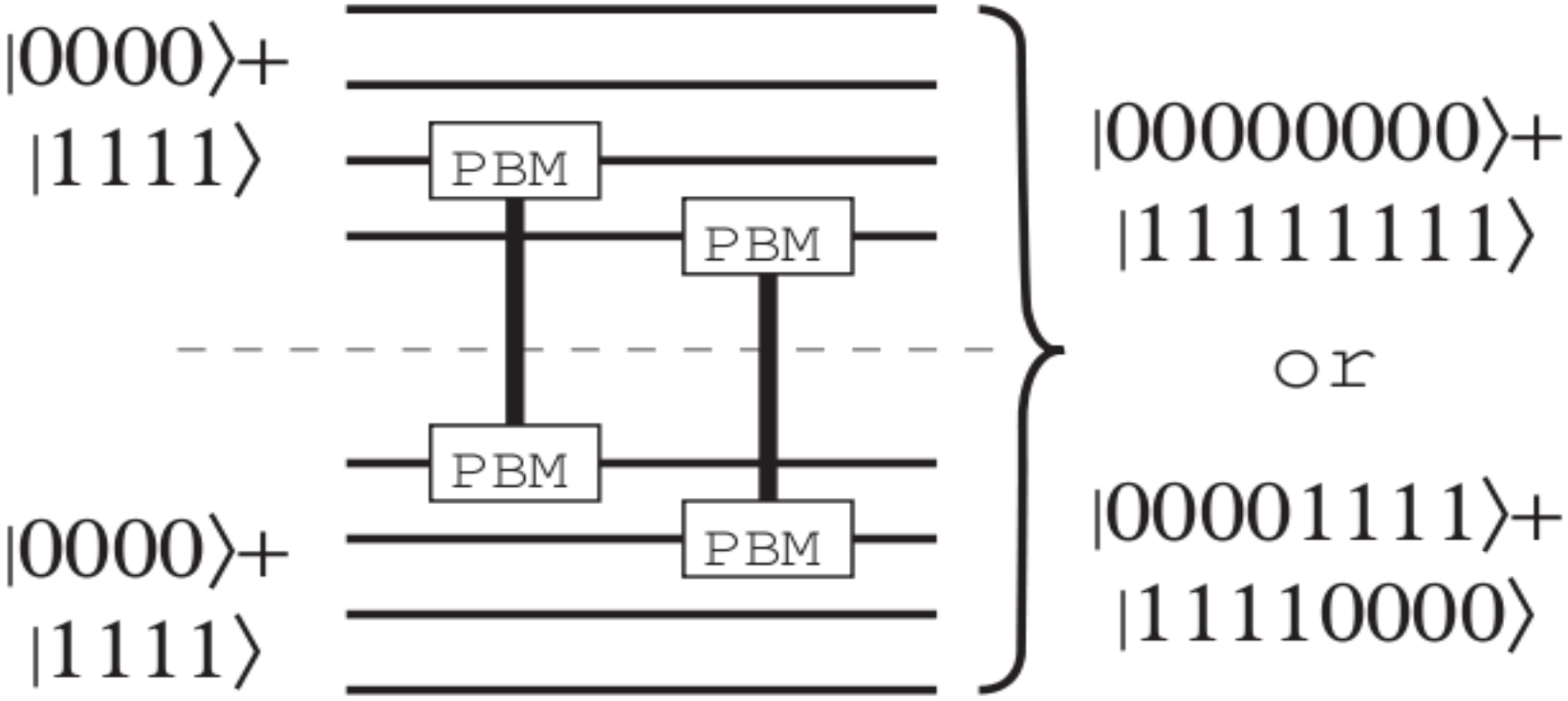

a few hundred
qubits/node

# Small Nodes

- Many technologies support small nodes, not the 3-5 thousand physical qubits we want
- At first glance, teleportation failure rates must meet standard threshold arguments

# Partial Bell Measurement



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# [[9,1,3]] Shor Code Stabilizer

```
X X X X X X I I I I I I
X X X                 X X X
I I I                 X X X
```

```
Z Z I  II IZ IZ I II II I  I I I I I I I I I
I I I   I  I  I  Z Z I  I Z Z I I I I I I I
I I I   I  I  I  I I I  I I I Z Z I I Z Z
```



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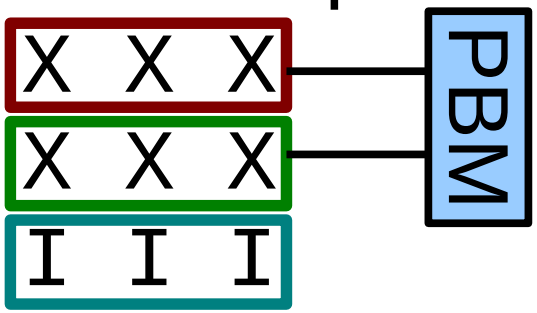
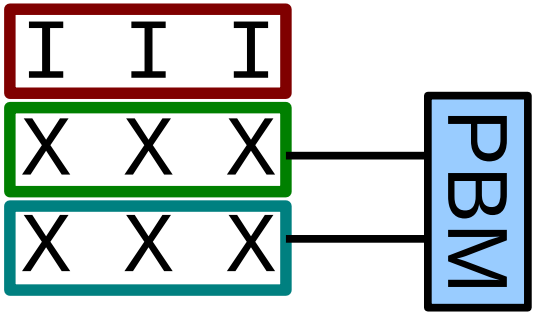
# Shor Stabilizer in 3 Nodes

2 Bell pairs

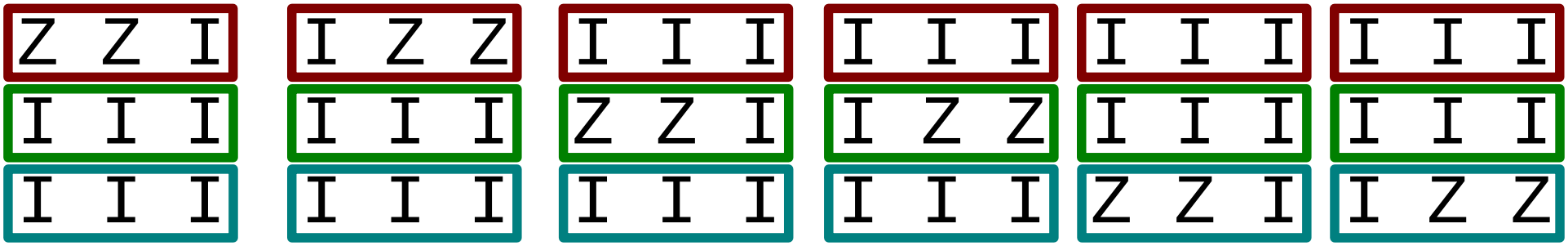



+ 2 Bell pairs = 4 Bell pairs for one round of level one QEC




PBM uses one |000000>+|111111>, built & verified using two Bell pairs

Zero Bell pairs consumed!




PBM = Partial Bell Measurement



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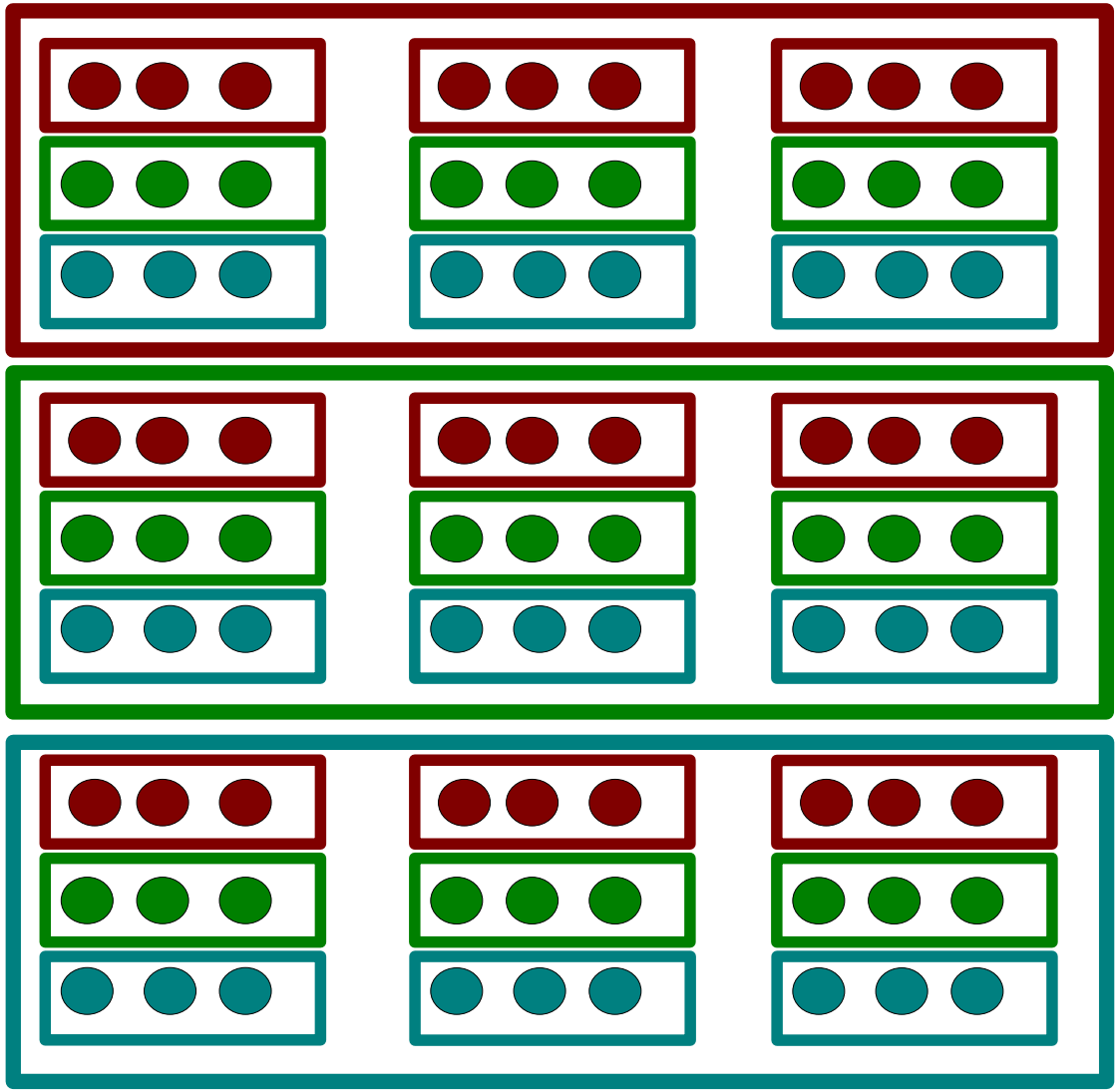
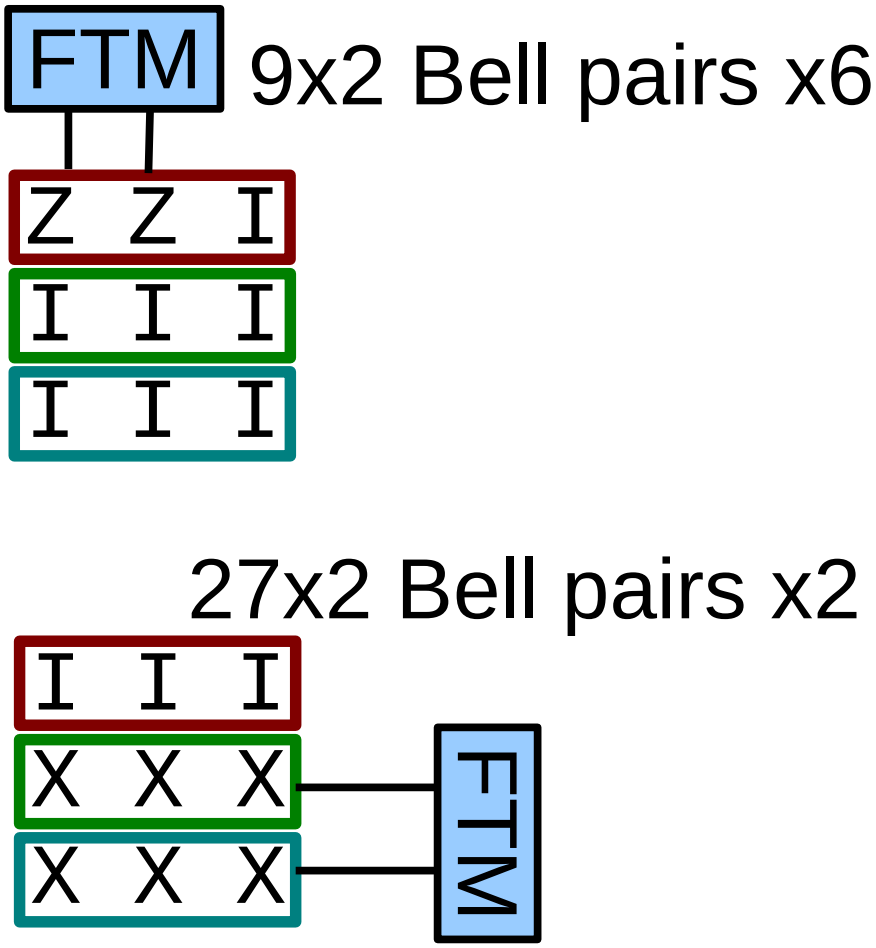
# Concatenation






 FTM = Full Transversal Measurement

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# [[9,1,3]]x[[9,1,3]]

- Single-data-qubit (5 phy qubit) nodes require
  (5+6)x2x9 + 9x2x6 + 27x2x2 = 414
  physical Bell pairs
- 3-data-qubit nodes (9 phy) require
  4x9 + 9x2x6 + 27x2x2 = 252
  physical Bell pairs
  - ~1.6x for scaleup 5-->9 physical qubits/node
- 9-data-qubit nodes (20 phy) require
  9x2x6 + 27x2x2 = 216
  physical Bell pairs
  - but first level QEC will cycle faster
- Plus 81 Bell pairs per logical gate or teleportation



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# Observations

- All codes require entanglement btw nodes
  - Some syndromes purely local, some “hard”
- Mitigation approaches:
  - match to error type (biased error model)
  - reduce frequency in “hard” direction
  - relax constraints: Bacon-Shor?
- For detailed performance calculation, need to separate Bell pair creation from actual teleportation



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# Conclusions

- Small nodes not ideal, but usable
  - full logical qubits/node much better (how much depends on ratio of logical gates to QEC)
- At second level and above, the *interconnect* remains teleportation



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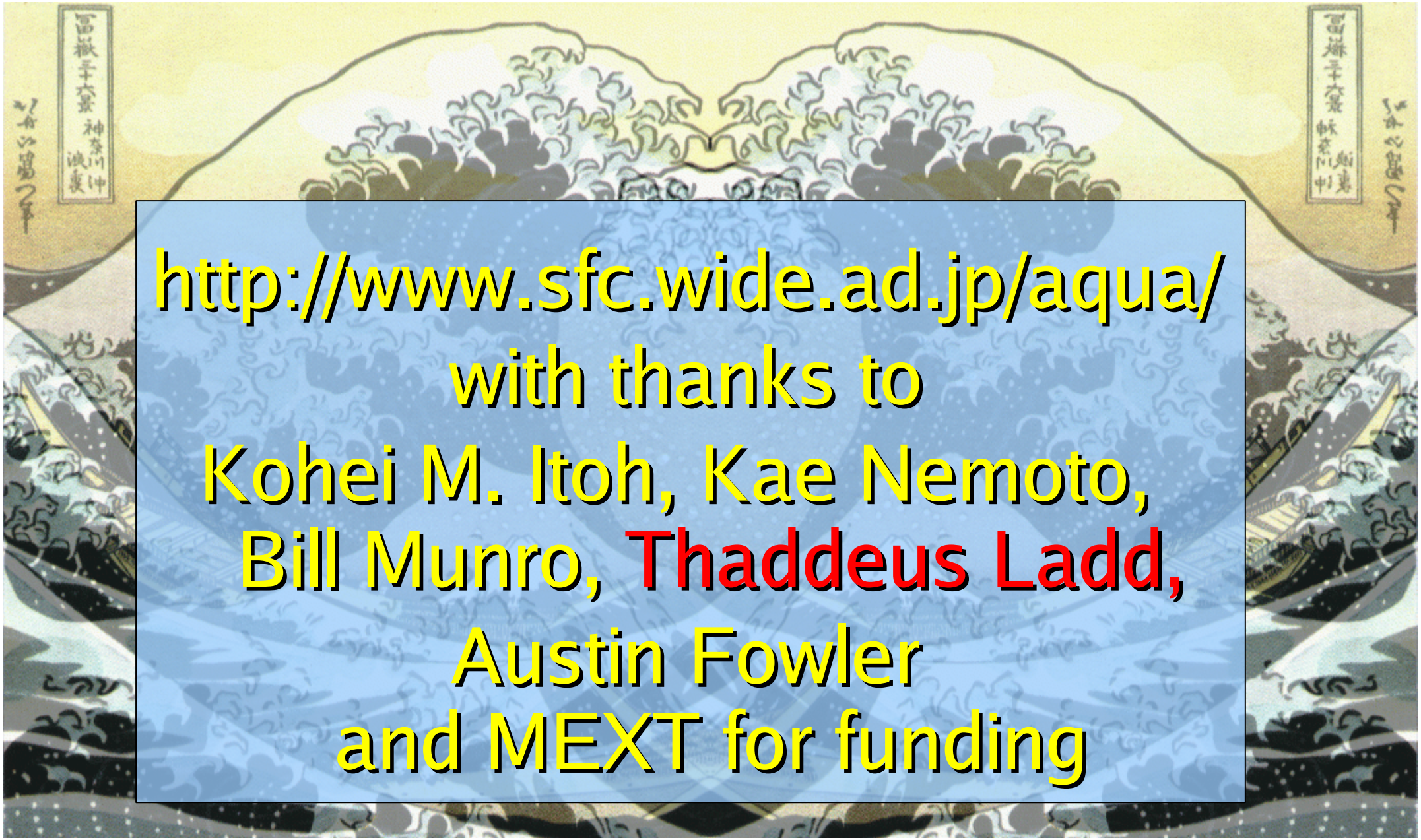
# AQUA: Advancing Quantum Architecture



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

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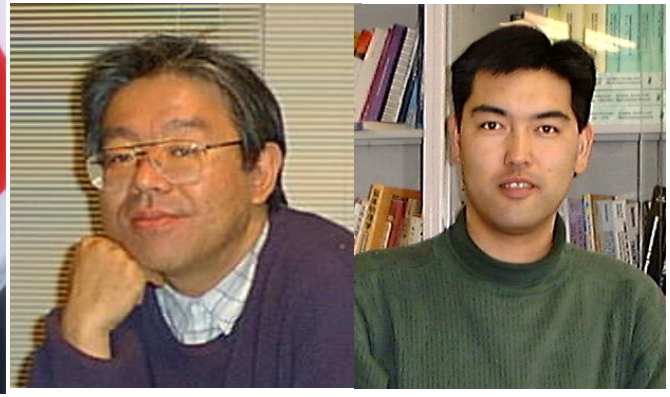
and MEXT for funding

# Keio?