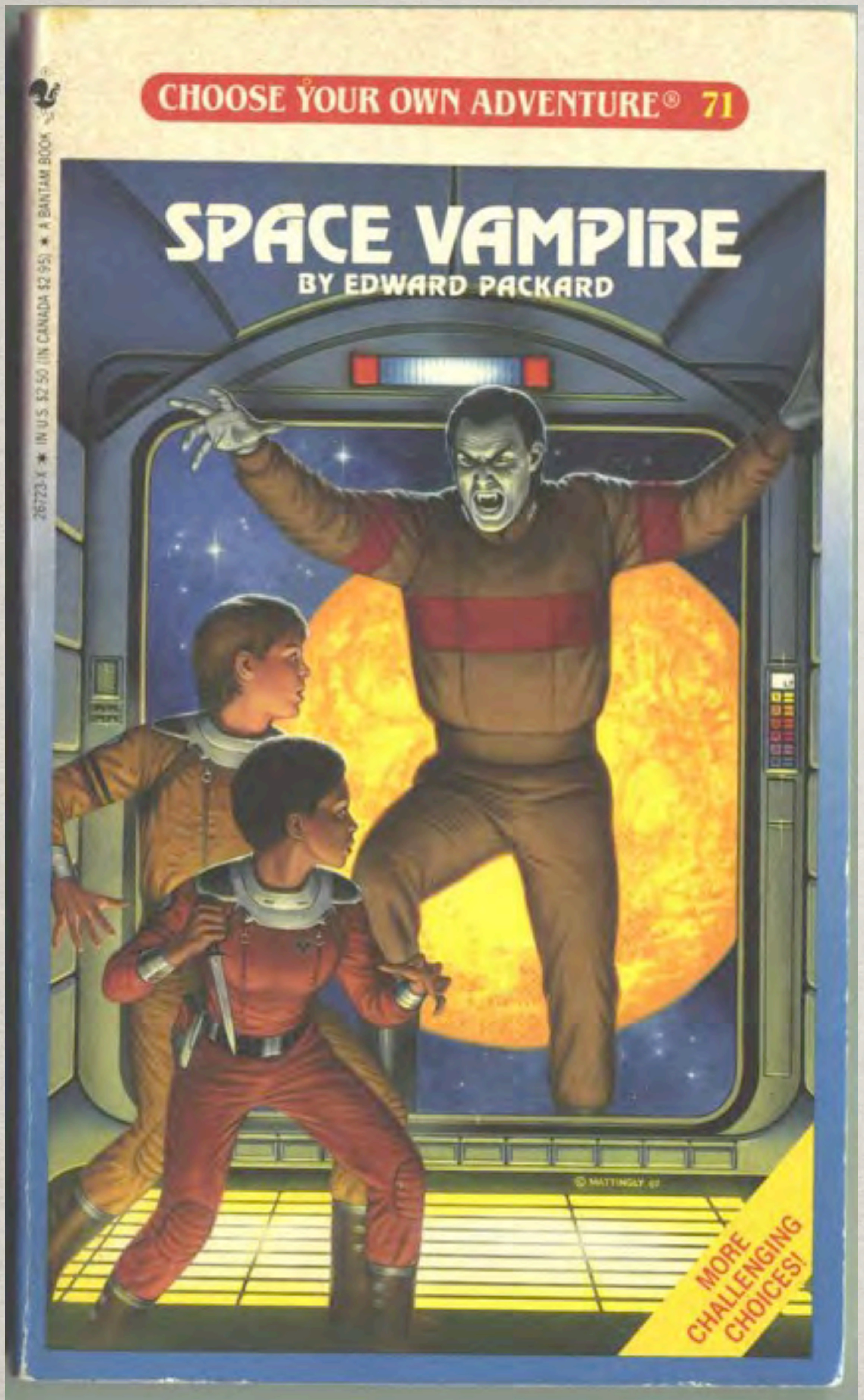
Simon's Mystery Talk



To hear about a new test of Leggett Garg inequalities,
Turn to page 2.

To hear about a method for fault tolerant quantum computing using networked small systems,
Turn to Page 10.

nature COMMUNICATIONS

ARTICLE

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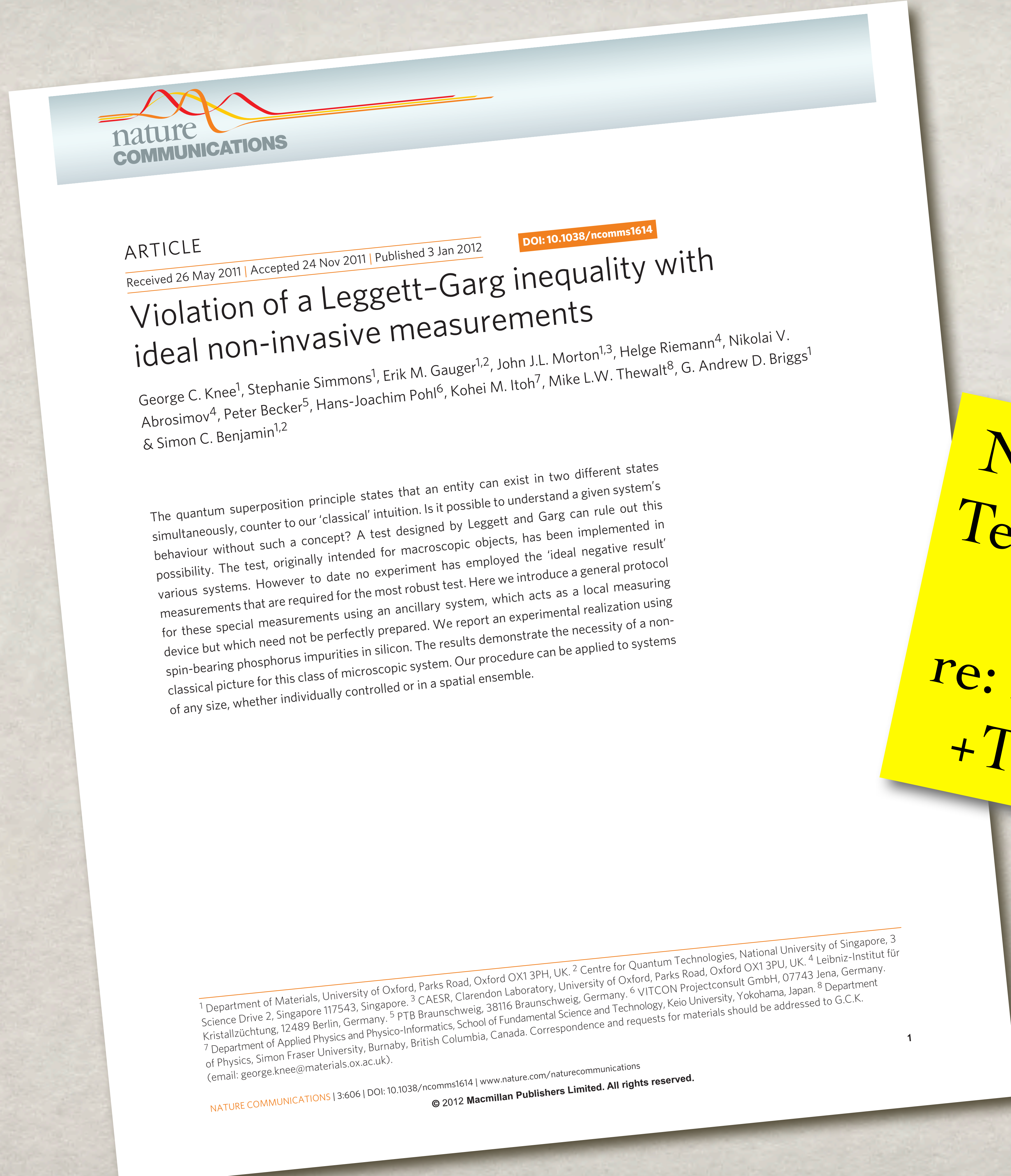
Violation of a Leggett–Garg inequality with ideal non-invasive measurements

George C. Knee[1], Stephanie Simmons[1], Erik M. Gauger[1,2], John J.L. Morton[1,3], Helge Riemann[4], Nikolai V. Abrosimov[4], Peter Becker[5], Hans-Joachim Pohl[6], Kohei M. Itoh[7], Mike L.W. Thewalt[8], G. Andrew D. Briggs[1] & Simon C. Benjamin[1,2]

The quantum superposition principle states that an entity can exist in two different states simultaneously, counter to our 'classical' intuition. Is it possible to understand a given system's behaviour without such a concept? A test designed by Leggett and Garg can rule out this possibility. The test, originally intended for macroscopic objects, has been implemented in various systems. However to date no experiment has employed the 'ideal negative result' measurements that are required for the most robust test. Here we introduce a general protocol for these special measurements using an ancillary system, which acts as a local measuring device but which need not be perfectly prepared. We report an experimental realization using spin-bearing phosphorus impurities in silicon. The results demonstrate the necessity of a non-classical picture for this class of microscopic system. Our procedure can be applied to systems of any size, whether individually controlled or in a spatial ensemble.

[1] Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK. [2] Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore. [3] CAESR, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK. [4] Leibniz-Institut für Kristallzüchtung, 12489 Berlin, Germany. [5] PTB Braunschweig, 38116 Braunschweig, Germany. [6] VITCON Projectconsult GmbH, 07743 Jena, Germany. [7] Department of Applied Physics and Physico-Informatics, School of Fundamental Science and Technology, Keio University, Yokohama, Japan. [8] Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada. Correspondence and requests for materials should be addressed to G.C.K. (email: george.knee@materials.ox.ac.uk).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Note to self:
Tell them the caveat
re: Maroney +Timpson

- A scheme to determine whether we should believe that a given (2 state entity) is ever in a superposition.

- Intended for testing macro-realism.

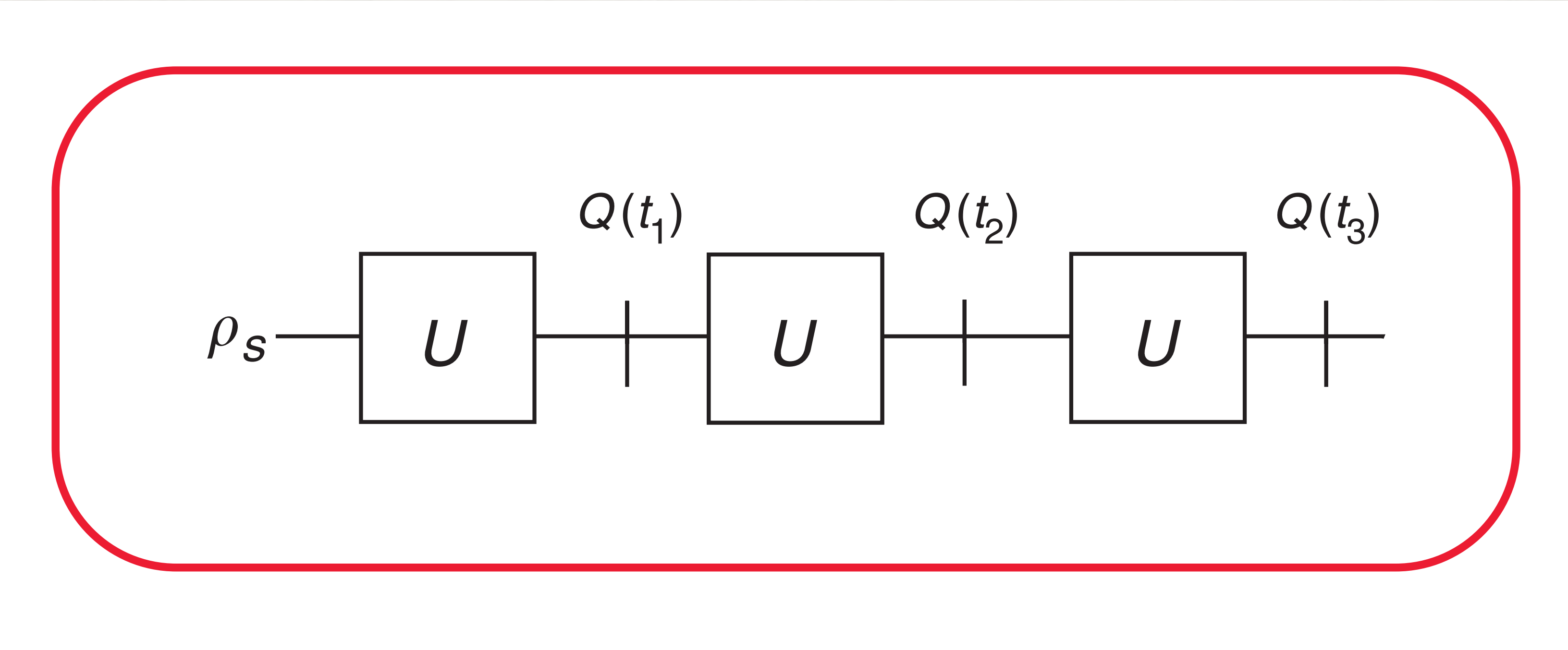
- Measure system at three times, work out the correlations, check

$$f = K_{12} + K_{23} + K_{13} + 1$$

...to see if it goes negative.

Leggett, A. J. & Garg, A.
Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks?
Phys. Rev. Lett. 54, 857–860 (1985).

What the realist wants us to do:



$$f = K_{12} + K_{23} + K_{13} + 1$$

for now pretend those measurements are non-invasive

(a) The Realist Table

t_1	t_2	t_3	$\mathbb{P}$	f_{LG}
$\downarrow$	$\downarrow$	$\downarrow$	$\mathbb{P}(\uparrow_1\uparrow_2\uparrow_3)$	4
$\downarrow$	$\downarrow$	$\uparrow$	$\mathbb{P}(\uparrow_1\uparrow_2\downarrow_3)$	0
$\downarrow$	$\uparrow$	$\downarrow$	$\mathbb{P}(\uparrow_1\downarrow_2\uparrow_3)$	0
$\downarrow$	$\uparrow$	$\uparrow$	$\mathbb{P}(\uparrow_1\downarrow_2\downarrow_3)$	0
$\uparrow$	$\downarrow$	$\downarrow$	$\mathbb{P}(\downarrow_1\uparrow_2\uparrow_3)$	0
$\uparrow$	$\downarrow$	$\uparrow$	$\mathbb{P}(\downarrow_1\downarrow_2\downarrow_3)$	0
$\uparrow$	$\uparrow$	$\downarrow$	$\mathbb{P}(\downarrow_1\downarrow_2\uparrow_3)$	0
$\uparrow$	$\uparrow$	$\uparrow$	$\mathbb{P}(\downarrow_1\downarrow_2\downarrow_3)$	4

We, the QM guys, will choose

$$U = \cos(\theta/2)\mathbb{I} + i\sin(\theta/2)\sigma_x$$

then we find

$$K_{ij} = \cos(\theta)$$

which means

$$f = 2\cos\theta + \cos 2\theta + 1$$

and so

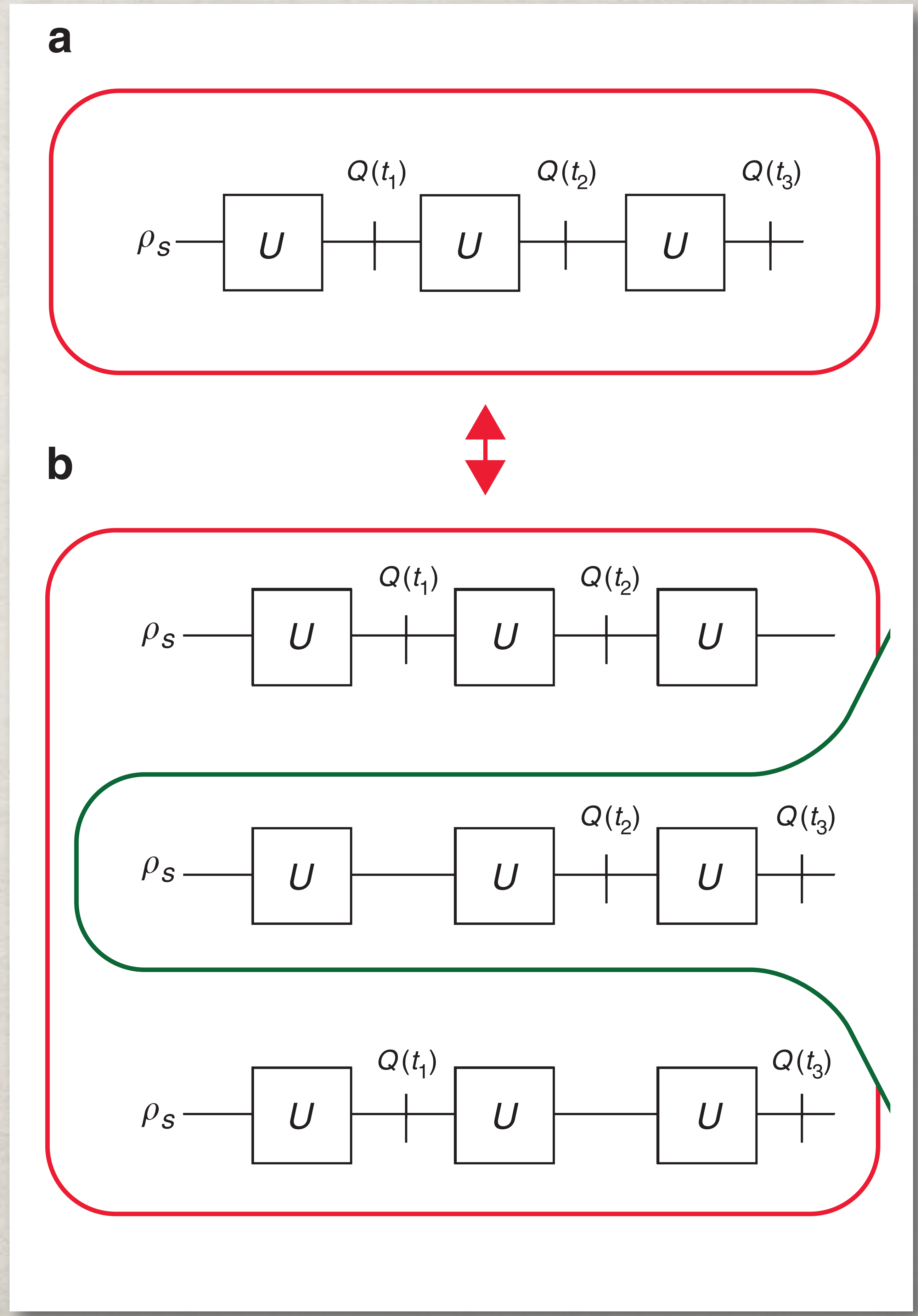
$$f = -0.5 \text{ for } \theta = 2\pi/3$$

- Problem: macro-realist says: “maybe when you measure it, you disturb it, and invalidate the experiment”.
  Wants to see that it’s “non-invasive”.

- But the quantum physicist knows we can’t do that, we can’t help disturbing it.

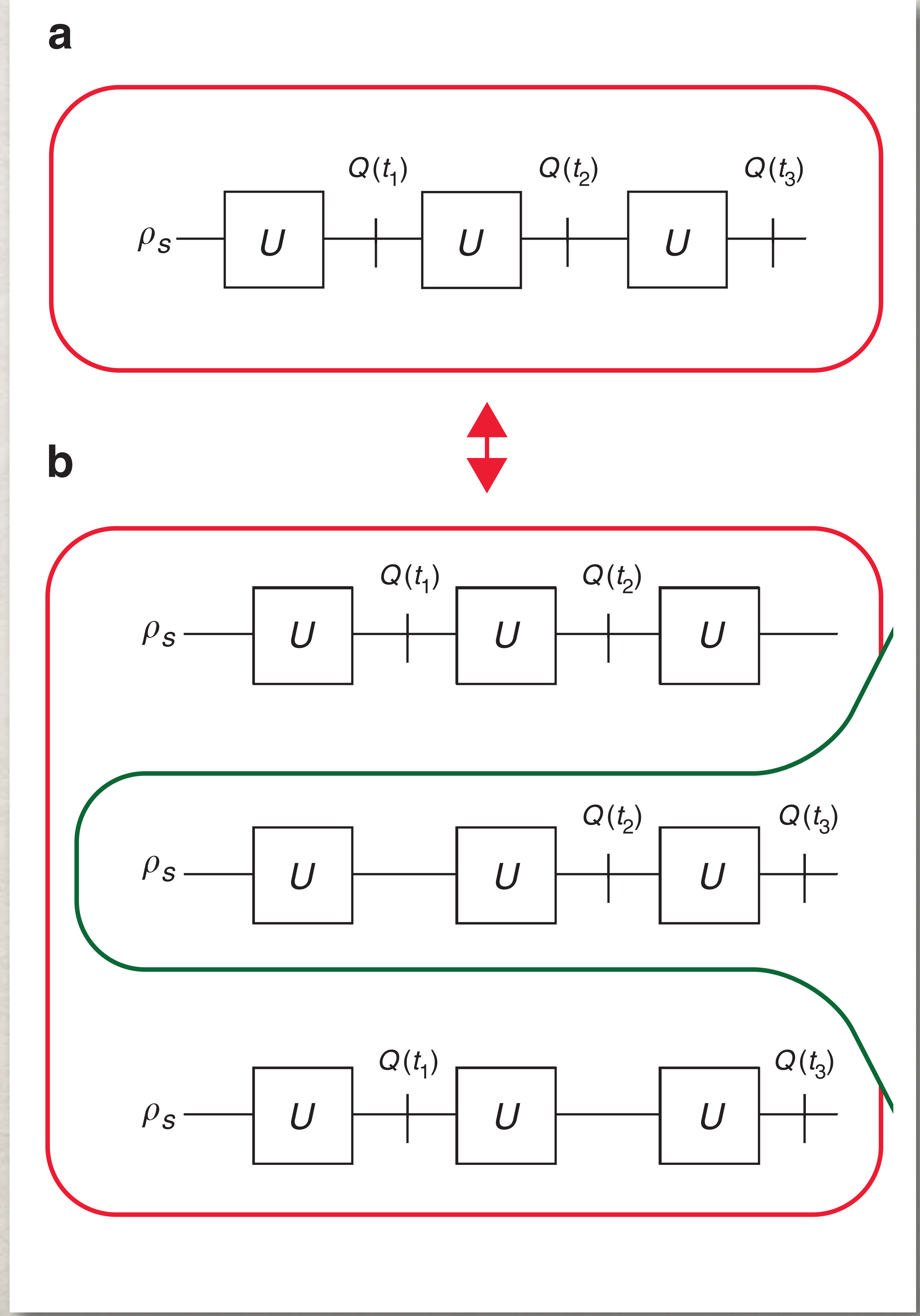
- One answer: weak measurement. But Leggett went a different way... remember only the realist needs to believe it’s non-invasive.

What we actually do, part 1.

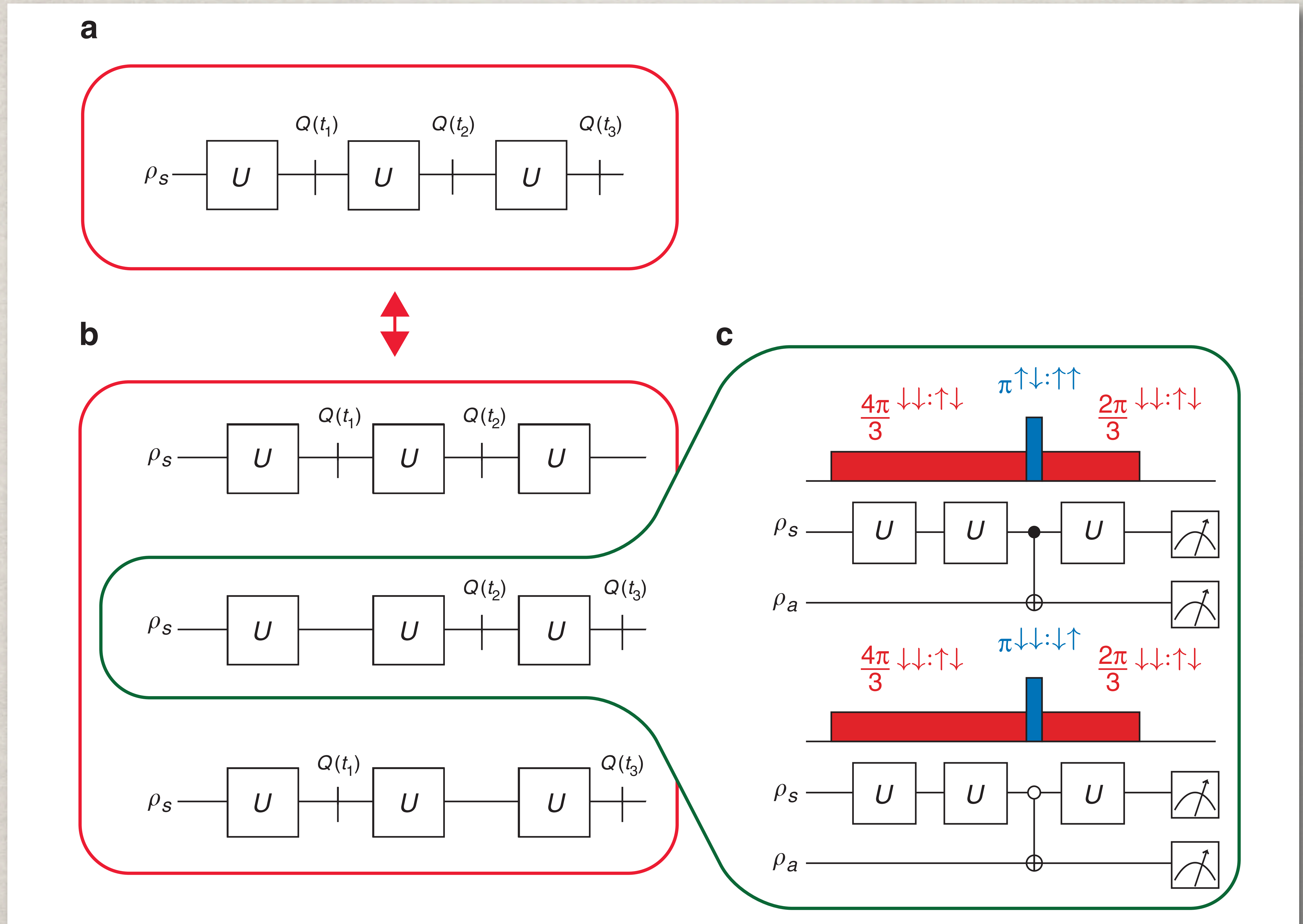


What we actually do, part 1.

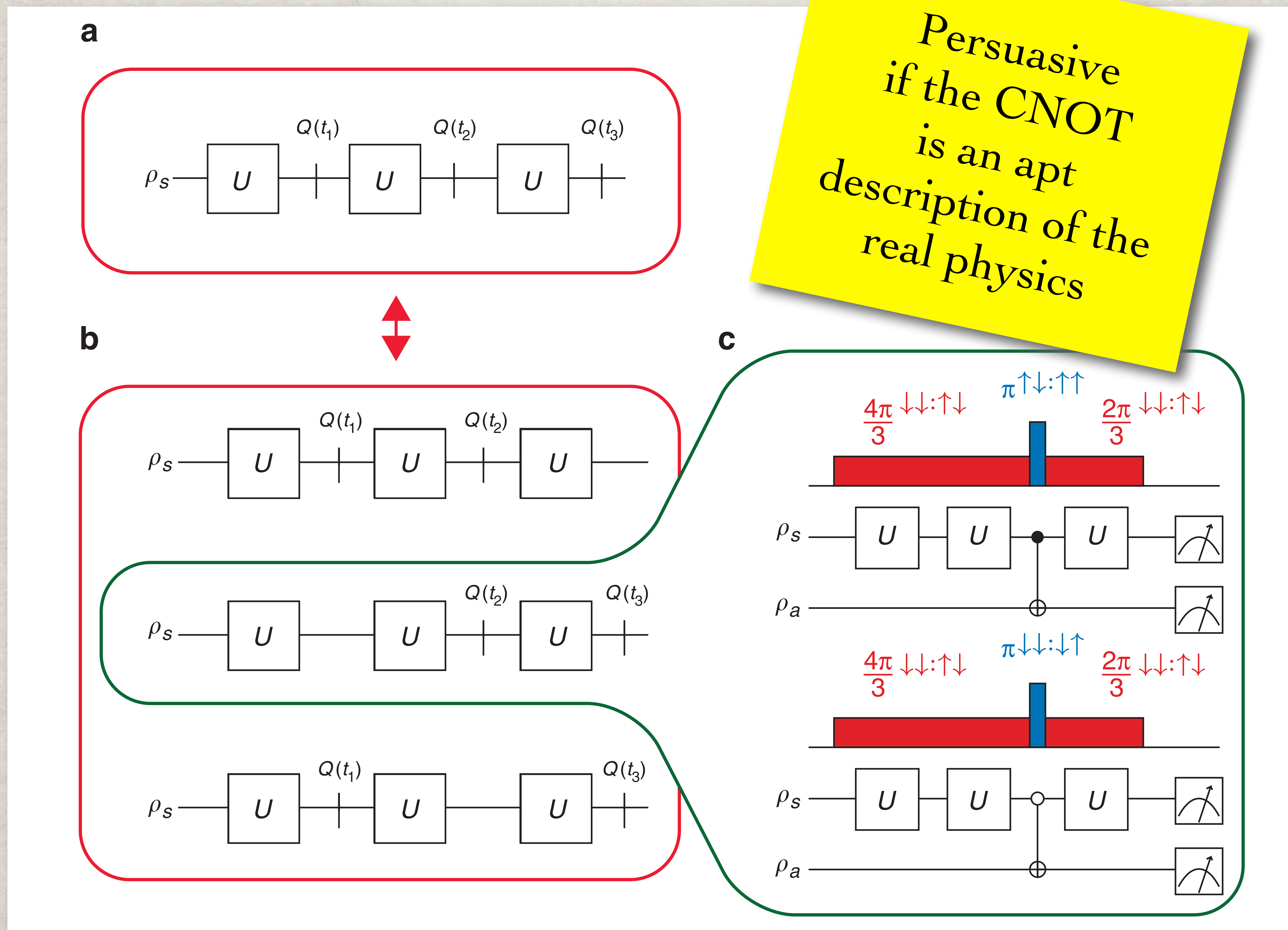
This is a valid equivalence to the realist if he buys the idea that the measurements are non-invasive



What we actually do, part 2: we make it into SIX experiments



What we actually do, part 2: we make it into SIX experiments



Persuasive if the CNOT is an apt description of the real physics

How about the problem that the system will be imperfectly initialised?

Depends what the realist thinks happens when the measuring qubit is wrongly initialised

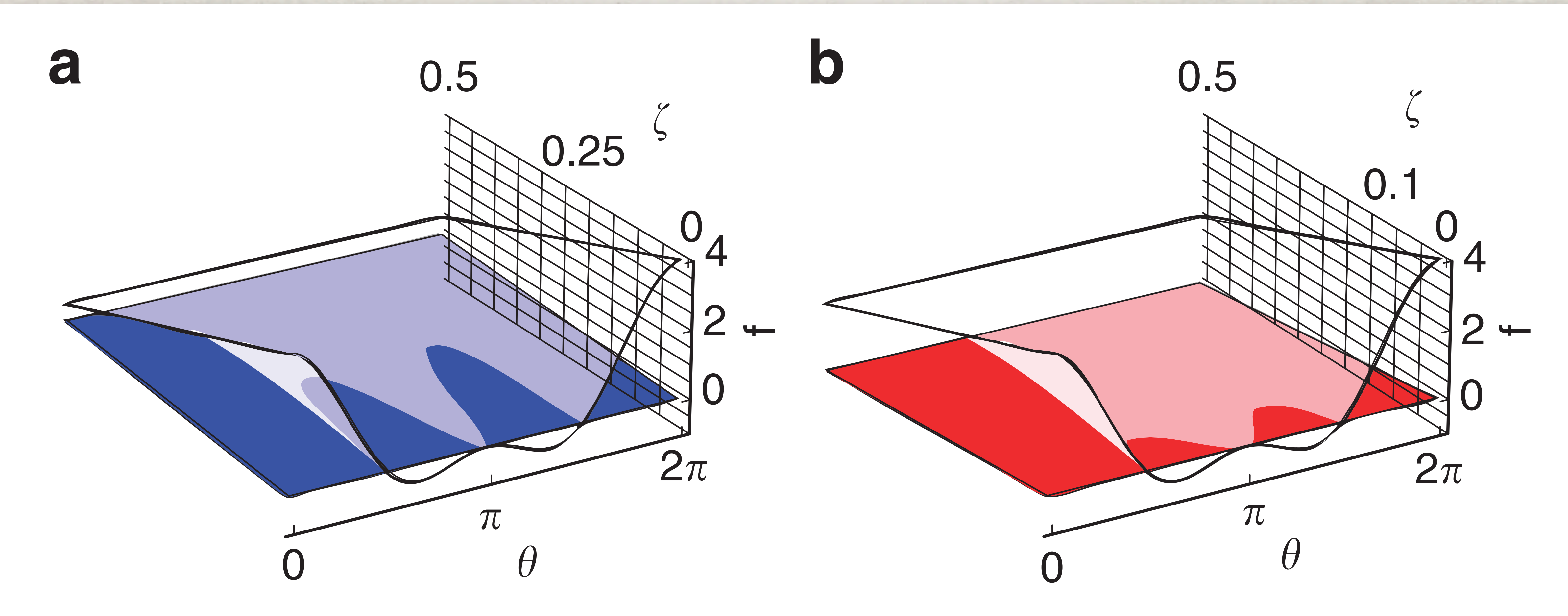
Define the venality ζ as the portion (or prob) of corruption

What do the K_{ij} become?

Quantum guy: $(1-\zeta)\,K_{ij} - \zeta K_{ij}$

Moderate realist: $(1-\zeta)\;K_{ij}$

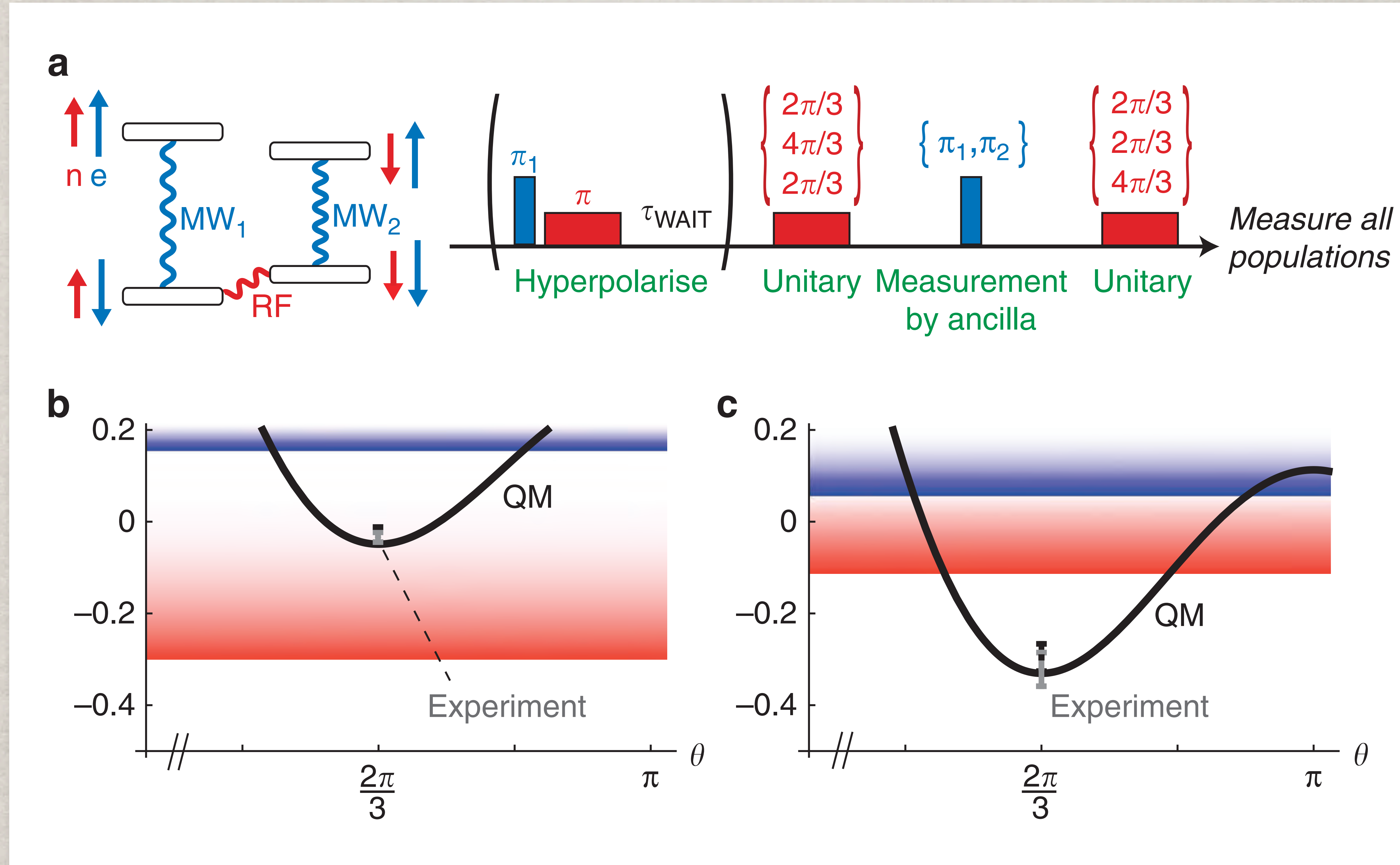
Adversarial realist: $(1-\zeta)\,K_{ij} - \zeta$


a
0.5
ζ
0.25
0
4
2
f
0
2π
π
0
θ
b
0.5
ζ
0.1
0
4
2
f
0
2π
π
0
θ

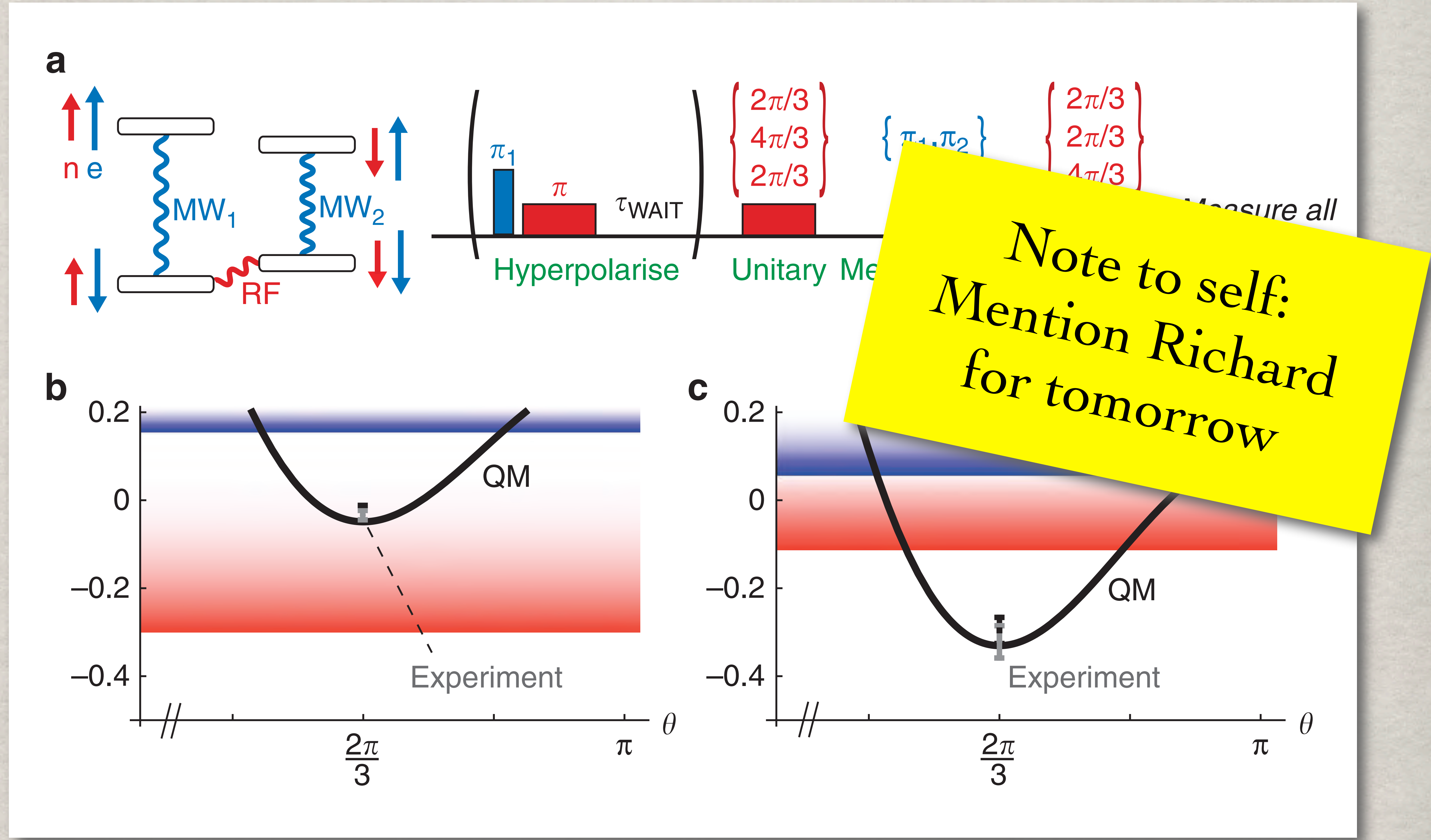
Let's try it! (ok ok let's *get* someone to try it)

- Use phosphor impurities in silicon, each an electron-nuclear spin pair.
- IGNORE the fact that the nuclear is hardly macro.
- Great a beautiful sample (pure) and cool it a lot (2.6K), put it in a high field (3.6T), and let's see if we can get that venality down low enough.

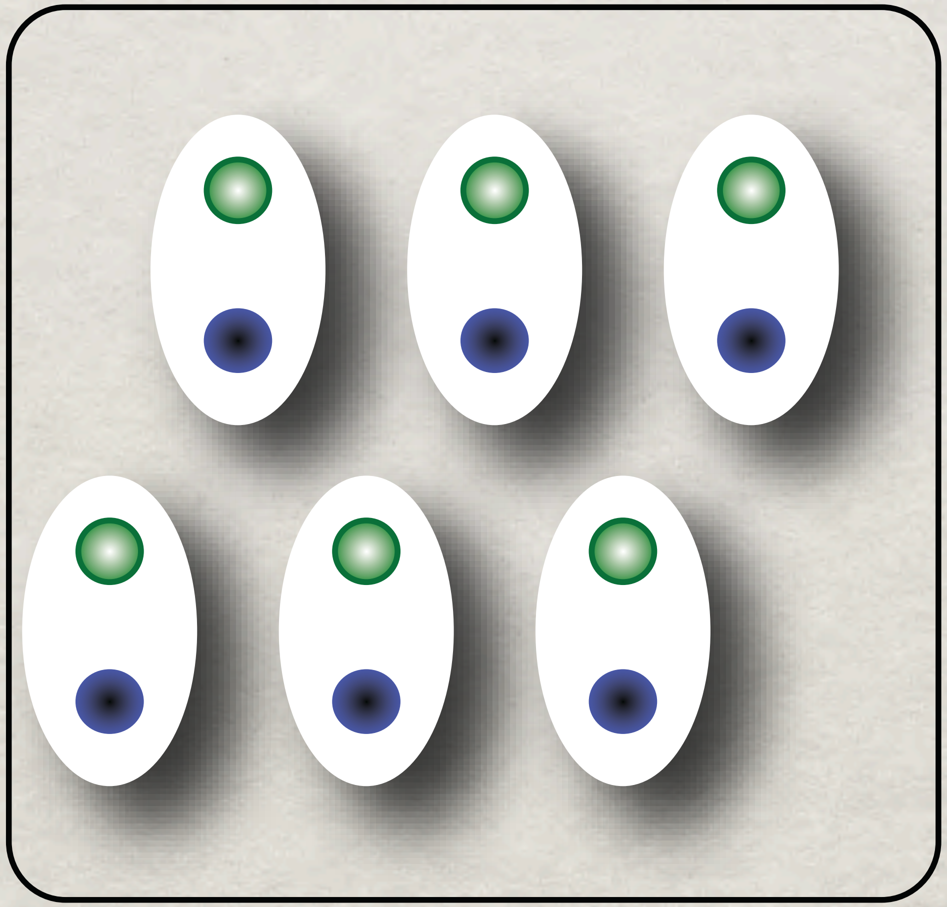
Scary overloaded Nature style figure:



Scary overloaded Nature style figure:



Disjoint topic: Distributed QIP!



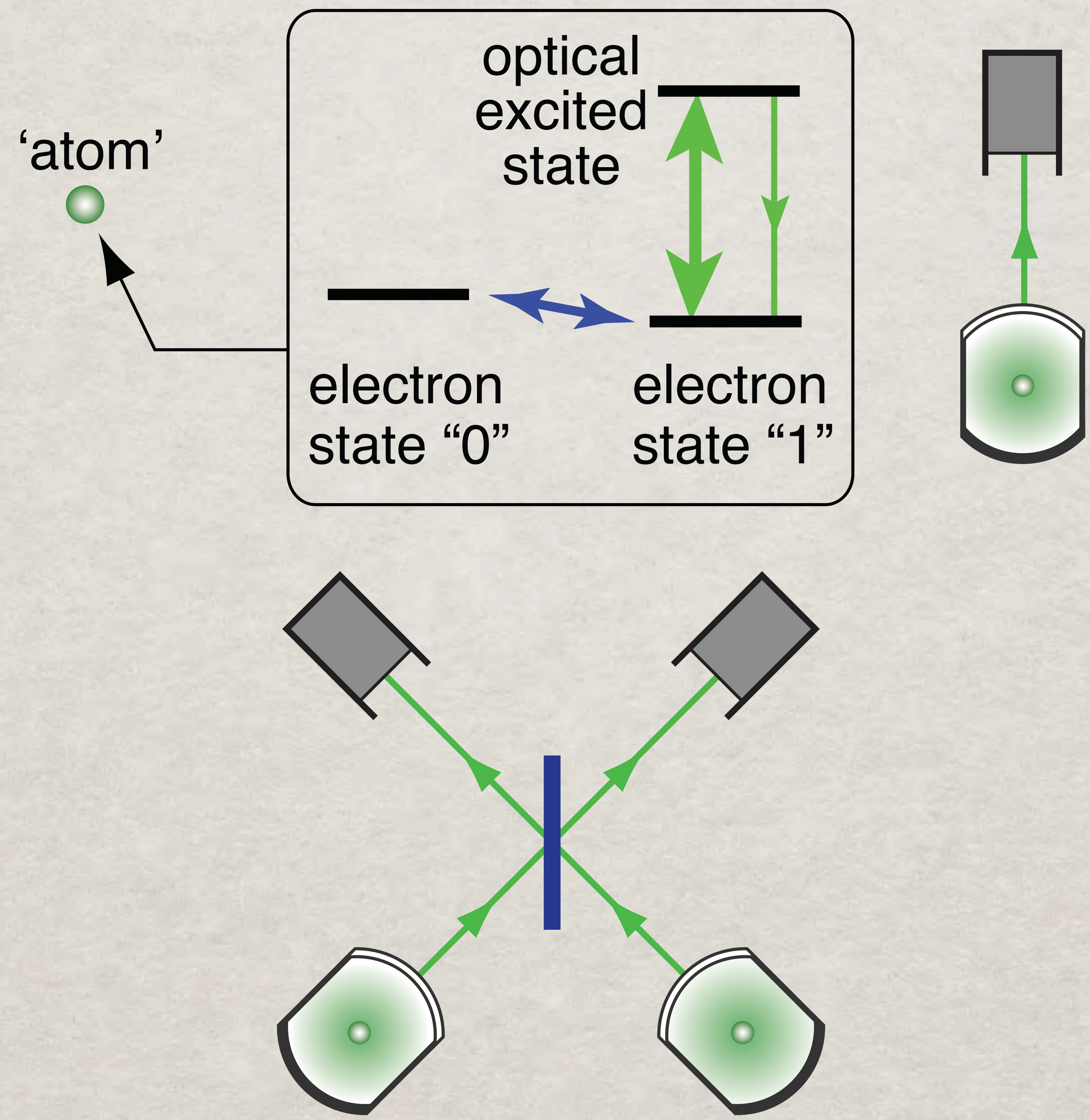
I mainly want to talk about DQC-1 and DQC-3

The basic question:

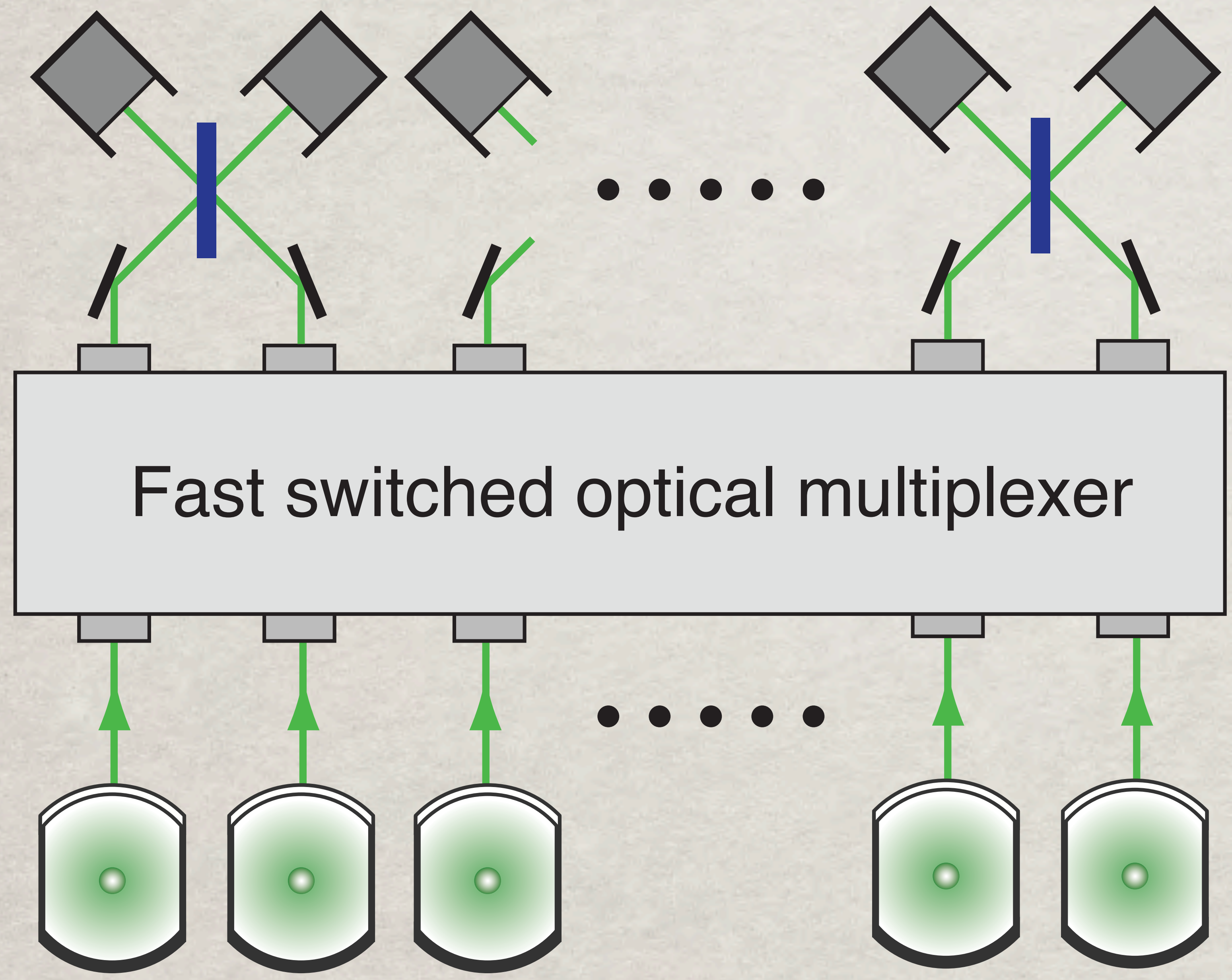
How should we perform quantum computation (and communication) when the entanglement operations are very prone to *heralded* failure, and maybe have bad noise too?

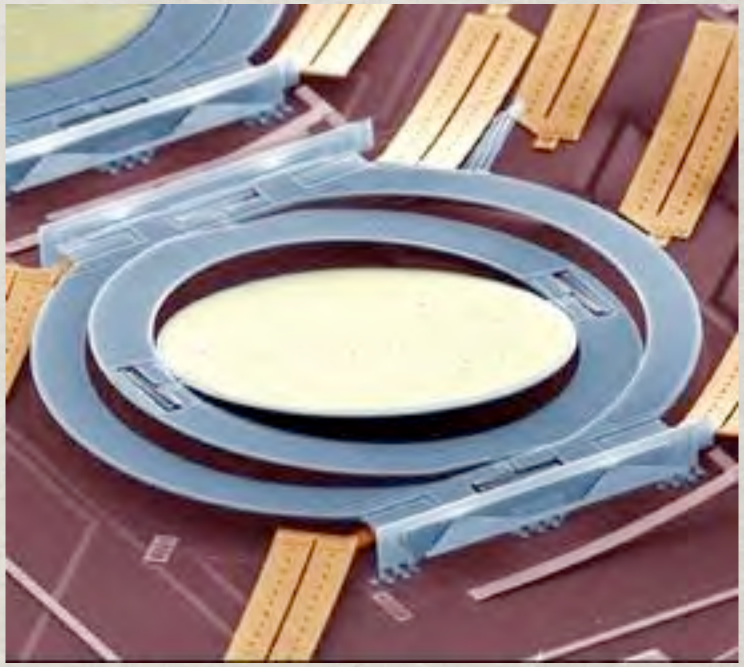
- How will the failure rate affect error accumulation and resource overhead?
- Can we find thresholds for fault tolerant QIP as a function of both failure rate and error rate?

One example to have in mind:



Matter qubits entangled via optical emission

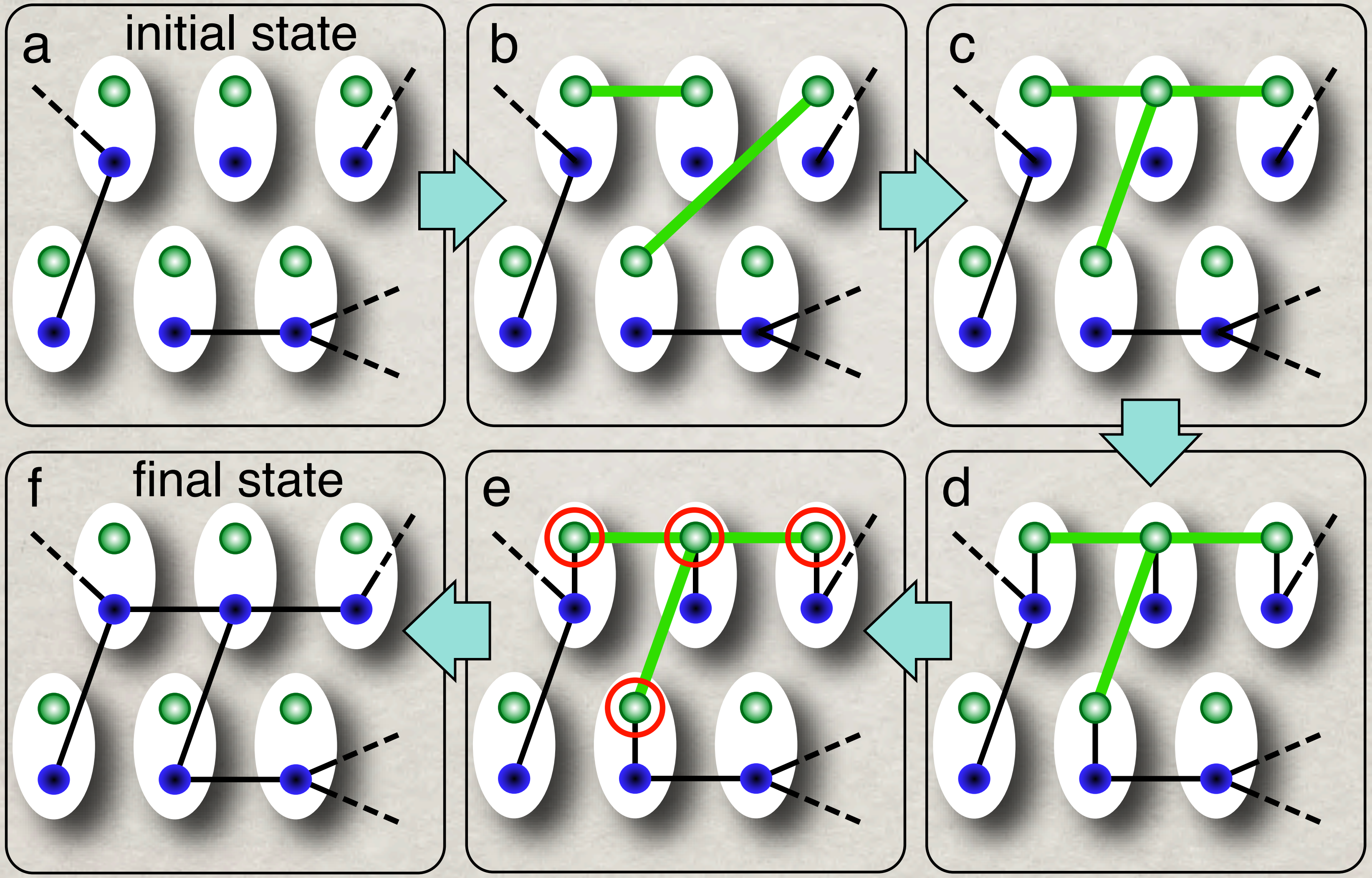




Potentially nice scalability

Let's first think about handling heralded failures.

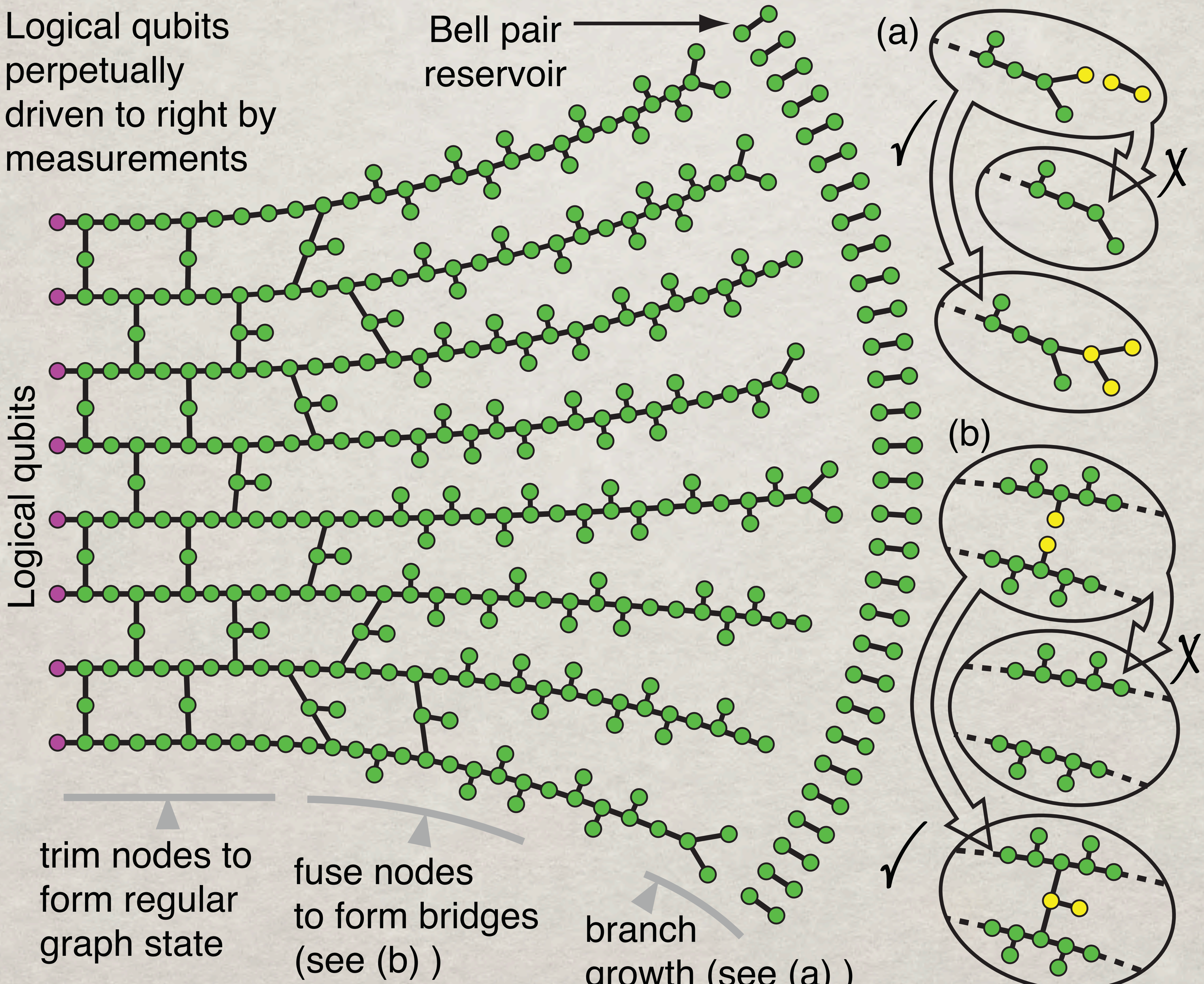
With 2+ qubits per module, it's easy to see options



Brokered graph-state quantum computation, NJP **8,** 141 (2006).

- How about with only one qubit per module?

Easy to tolerate modest heralded failure rates, e.g. 60%

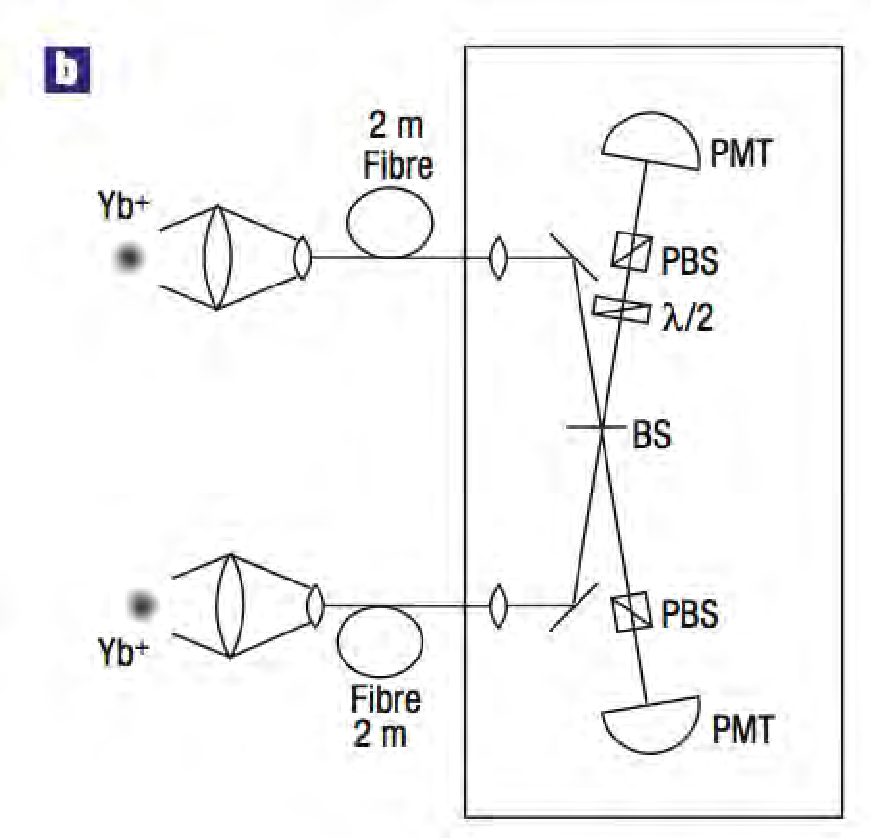


Laser and Photon. Rev., 3, 556 (2009)

So, efficient universal QIP with one 3-level system per node!

But what if photon loss is *really bad!?*

Moehring et al, Nature 449, 68 (2007).



output ports, there is an additional factor of 1/4 in our success probability: $P = (1/4)[(1/2)\eta\zeta T\rho P_{\mathrm{exc}}(\Delta\Omega/4\pi)]^2 \approx (0.25)[(0.5)(0.15)(0.2)(0.8)(0.995)(0.5)(0.02)]^2 \approx 3.6 \times 10^{-9}$. With an experiment repetition rate of $R \approx 5.5 \times 10^5\ \mathrm{s}^{-1}$, this results in a heralded entanglement event approximately every 8.5 min.

Improvement x13: PRL **100**, 150404 (2008).

NV centres - still a lot of losses

QUANTUM COMPUTING

Snapshots of diamond spins

Defects in diamond crystals possess rare physical properties that can enable new forms of technology. Unlocking this potential requires rapid quantum-state measurement, a 'quantum snapshot', which has now been achieved.

John J. L. Morton and Simon C. Benjamin

When Nicéphore Niépce created the first photographic images in the 1820s, each frame required eight hours of exposure. Fifty years later, technology had advanced enough for Eadweard Muybridge's famous demonstration that horses become 'airborne' in mid-stride (see Fig. 1). Photography had become a tool to investigate timescales beyond human perception. Numerous devices now depend on swift measurement, but none more so than the emerging family of quantum technologies. These use measurement not only to read out, but also to prepare and entangle quantum states to create exotic new sensors, simulators and computers. A certain kind of defect that occurs in

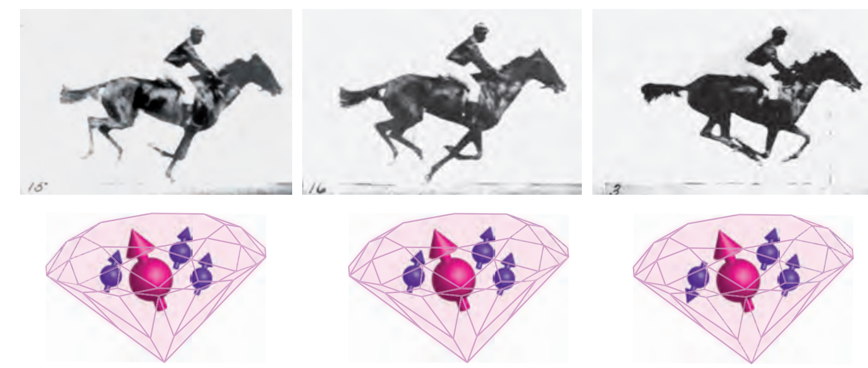


Figure 1 | Today, as in 1877 when Eadweard Muybridge photographed a horse in motion, it is crucial to be able to perform measurements that are fast on the timescale of the natural dynamics of an object. This is especially important in emerging quantum technologies given the unique power of quantum ... e nitrogen–vacancy defect in diamond consists of a collection of electron and nuclear ... e can now be probed by fast, high-fidelity optical measurement in a single experimental ... e © Eadweard Muybridge Collection/Kingston Museum/Science Photo Library.)

... diamond are particularly exciting because it is possible to measure the electron spin of

... ough optical methods[3]. This ... s crudely exciting the NV ... minate optical pulse, and ... at the emitted fluorescence ... me dependence on the ... ate. Although this highly ... nique has underpinned an ... earch into NV centres, it ... ntial averaging of many ... ns (or 'shots') to determine ... n state. Achieving fast, ... asurements requires new ... ingle-spin measurement ... es.

... years have seen significant ... lerstanding the nature of ... of the NV centre[4], laying ... for more sophisticated ... By picking particular NV ... w strain and working at ... mperatures, it is possible ... ant optical techniques to ... e the centre only when the ... in a particular state[5]. This ... ement can be made much faster and more efficient than the previous technique. This has now allowed Lucio

Robledo *et al.*[1] to measure the NV electron spin in a single shot for the first time. With their approach they could, also in a single shot, read out the state of up to three nuclear spins in the immediate vicinity of the NV centre. Emre Togan *et al.*[2] borrowed a further technique from the toolbox of trapped atoms, exploiting a phenomenon known as coherent population trapping[6]. In this method, if the magnetic field at the NV centre is precisely zero, the energy levels of the electron spin possess a symmetry that causes them to fall into a 'dark state', which scatters no photons. This measurement is also fast, providing a glimpse of the environment of the NV centre in real time, by monitoring the fluctuating magnetic field created by a bath of more distant carbon-13 nuclear spins.

High-fidelity quantum measurements can do more than just probe the state of a system; they can also be used to initialize it into a given state. Although the result of the measurement may be intrinsically random, the system could then, in principle, be manipulated conditionally on the result of this measurement. This would ensure

Two-photon quantum interference from separate nitrogen vacancy centers in diamond

Hannes Bernien,[1,*] Lilian Childress,[2] Lucio Robledo,[1] Matthew Markham,[3] Daniel Twitchen,[3] and Ronald Hanson[1]

[1]*Kavli Institute of Nanoscience Delft, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*
[2]*Department of Physics and Astronomy, Bates College, 44 Campus Avenue, Lewiston, Maine 04240, USA*
[3]*Element Six, Ltd., Kings Ride Park, Ascot, Berkshire SL5 8BP, United Kingdom*

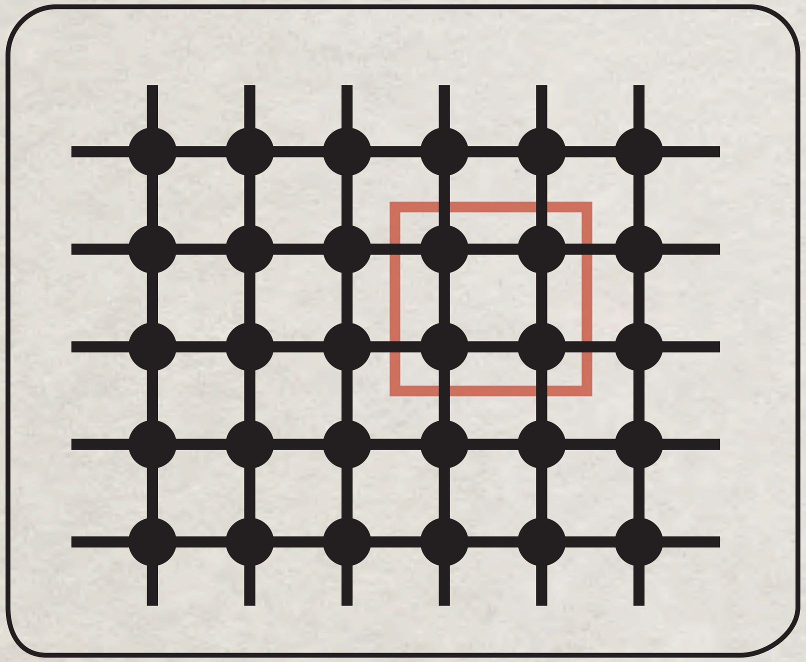
(Dated: October 18, 2011)

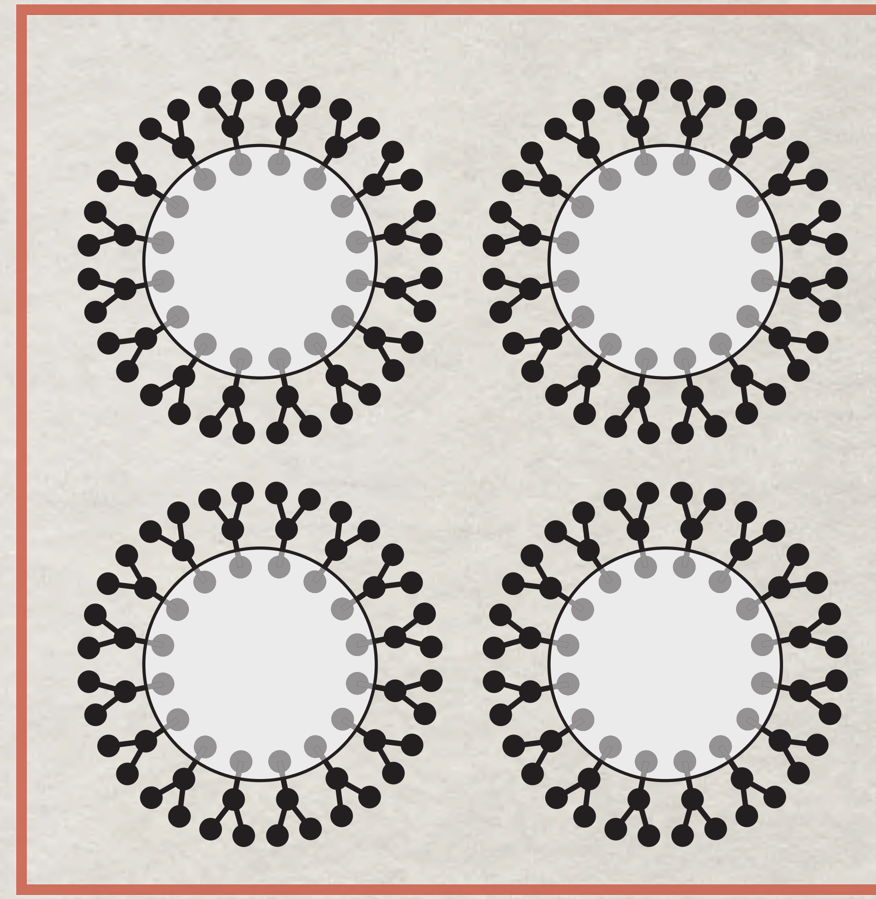
We report on the observation of quantum interference of the emission from two separate nitrogen vacancy (NV) centers in diamond. Taking advantage of optically induced spin polarization in combination with polarization filtering, we isolate a single transition within the zero-phonon line of the non-resonantly excited NV centers. The time-resolved two-photon interference contrast of this filtered emission reaches 66%. Furthermore, we observe quantum interference from dissimilar NV centers tuned into resonance through the dc Stark effect. These results pave the way towards measurement-based entanglement between remote NV centers and the realization of quantum networks with solid-state spins.

arXiv:1110.3329

So let's think about how to do QIP when there are *bad* (e.g. >90%) heralded failures

Target: A large cluster state type thing

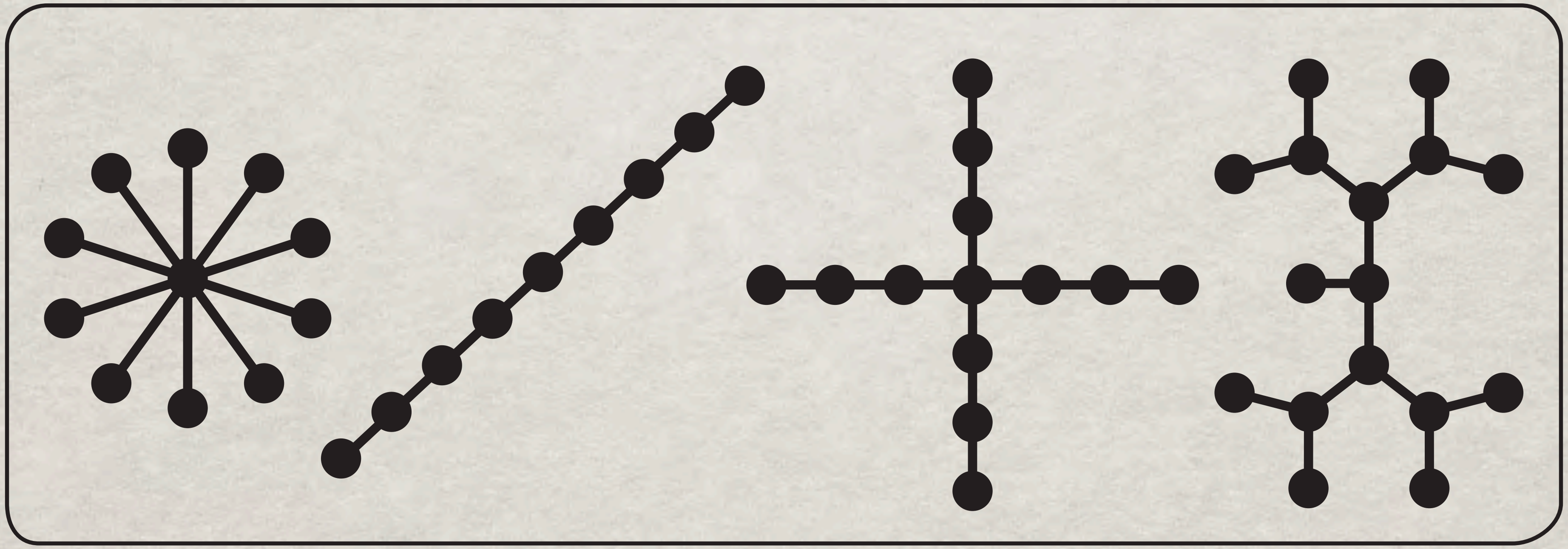




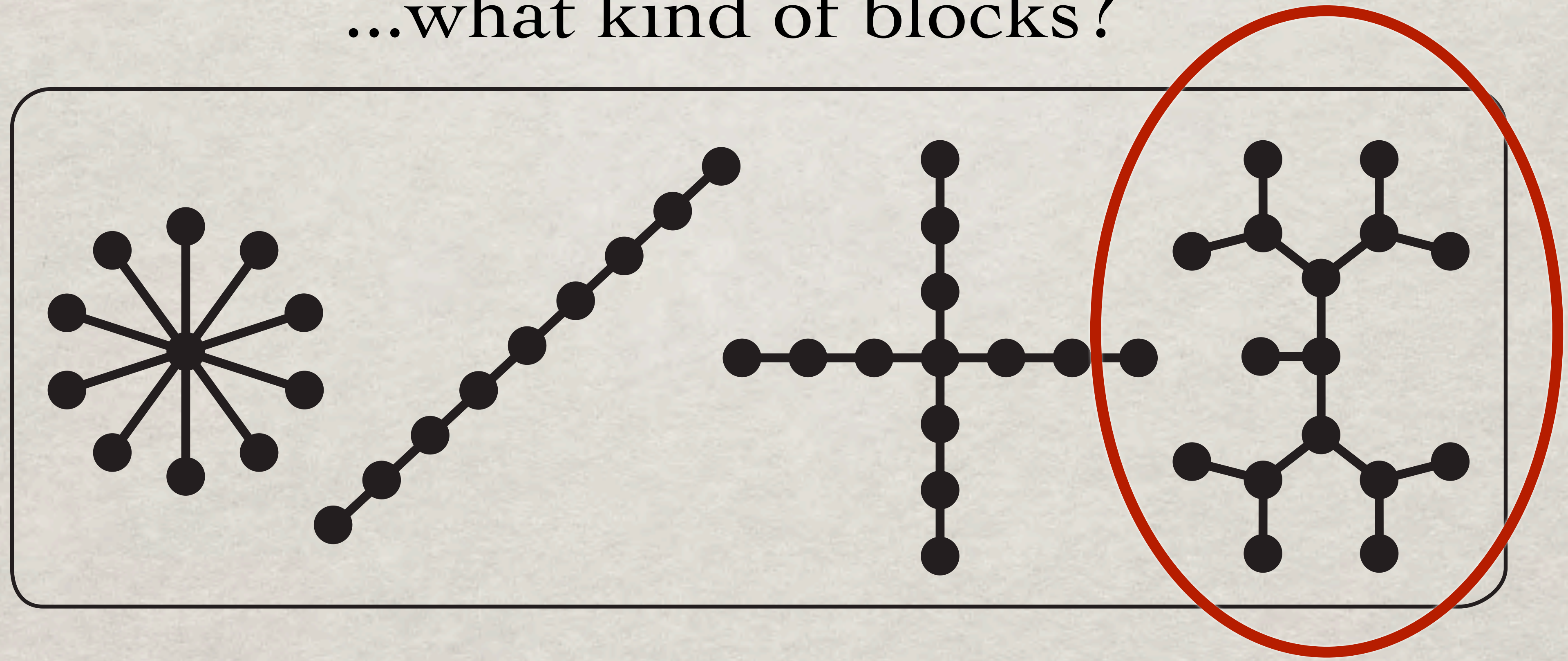
The plan (& do this with only logarithmic errors):

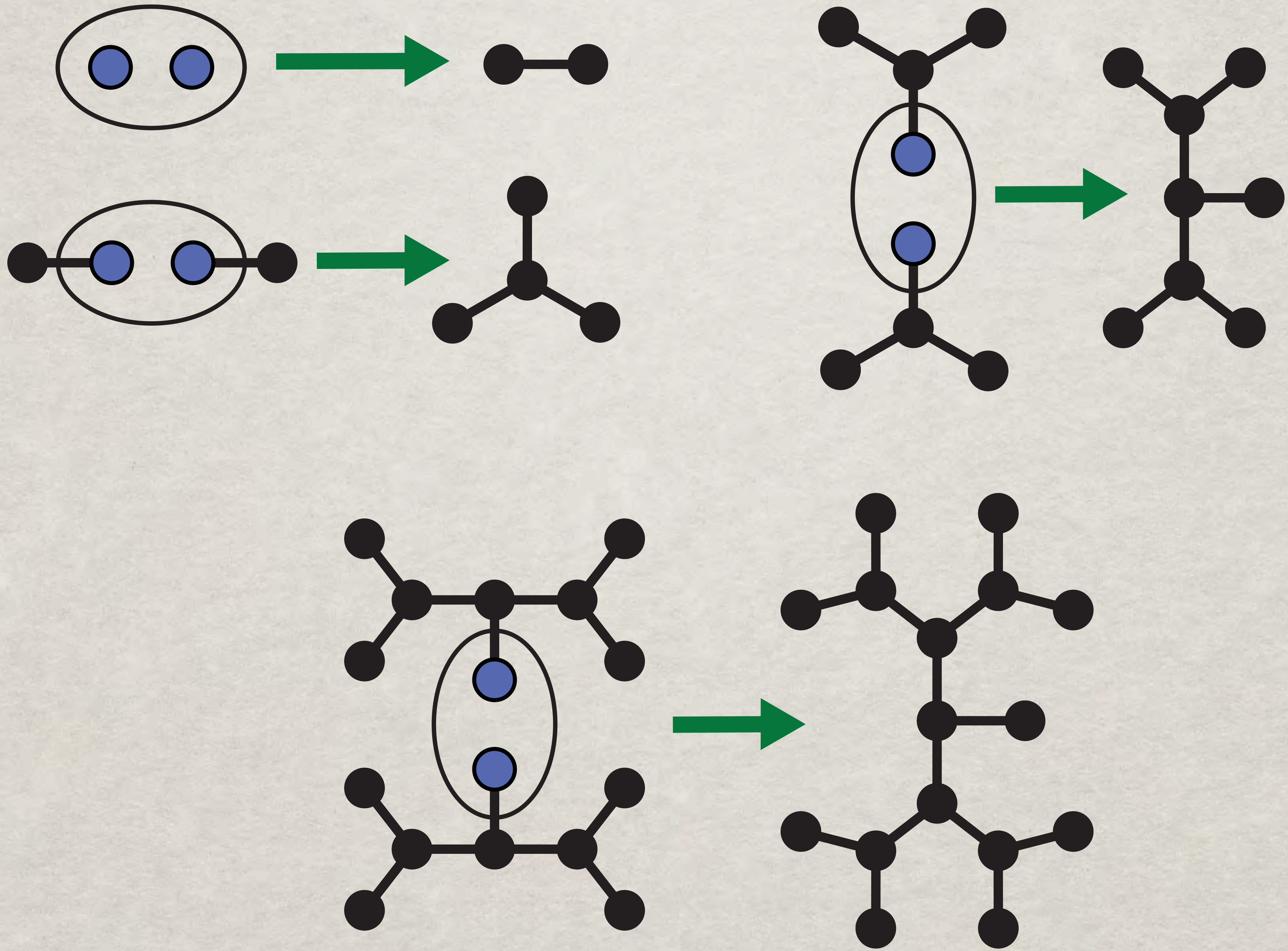
- Make a bunch of "building block" resources: blobs each with enough qubits that they can *probably* connect to four other blobs
- Join them all up (~ one step)
- Prune the resulting structure down.

OK so building blocks...
...what kind of blocks?

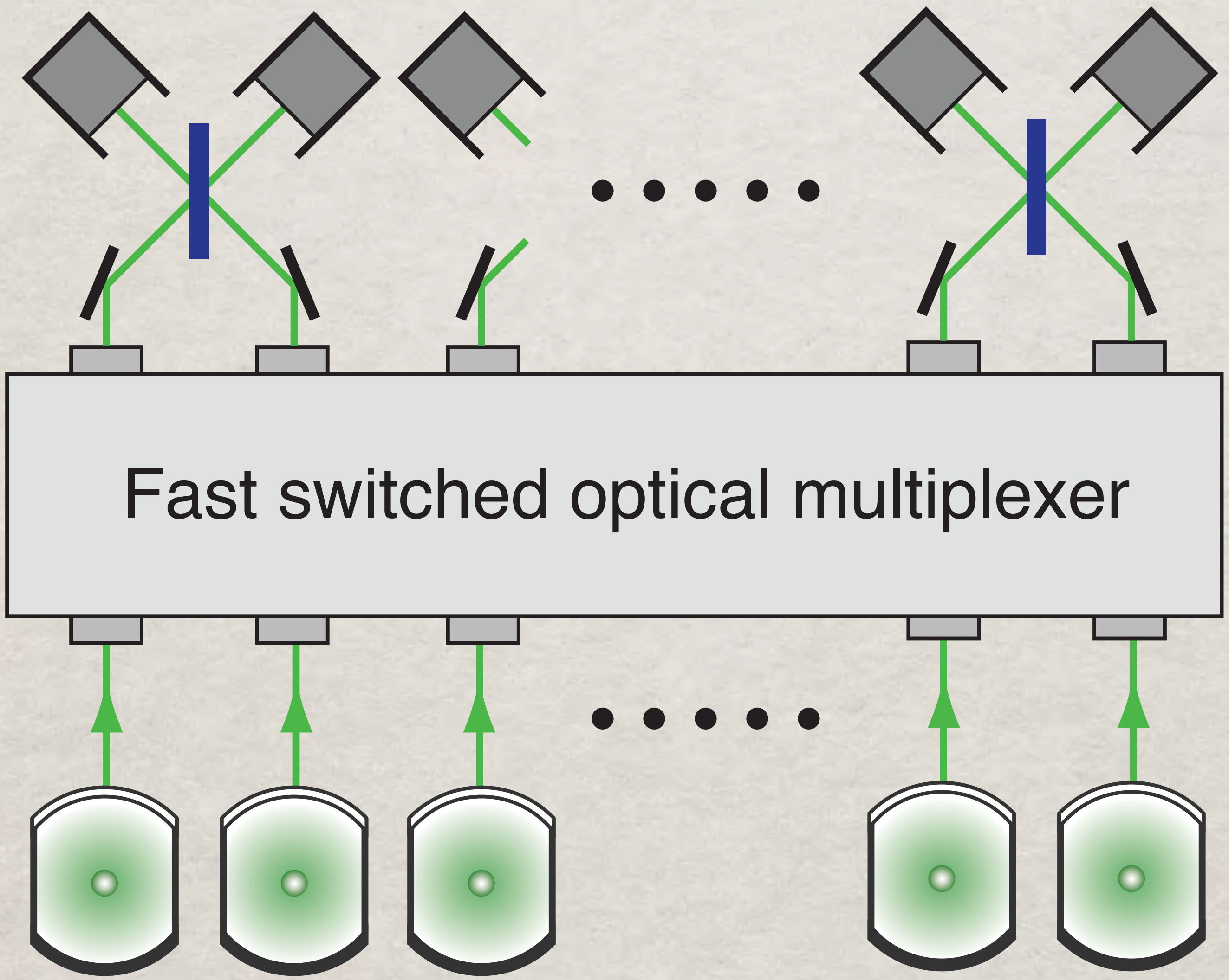


OK so building blocks...
...what kind of blocks?



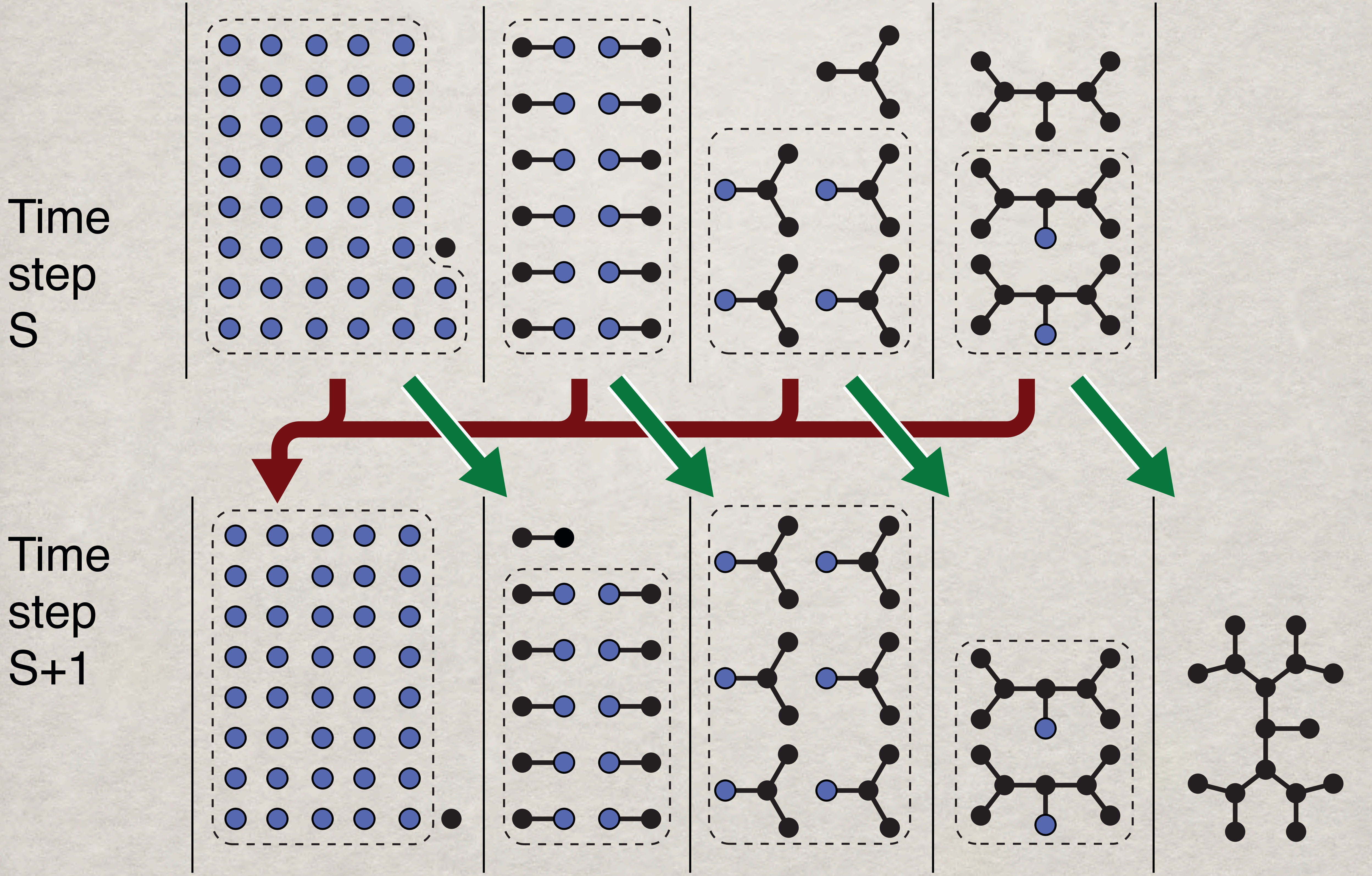


Remember our machine is something like this:



- Parallel operations
- Total connectivity (well...)

Inside, this is going on:



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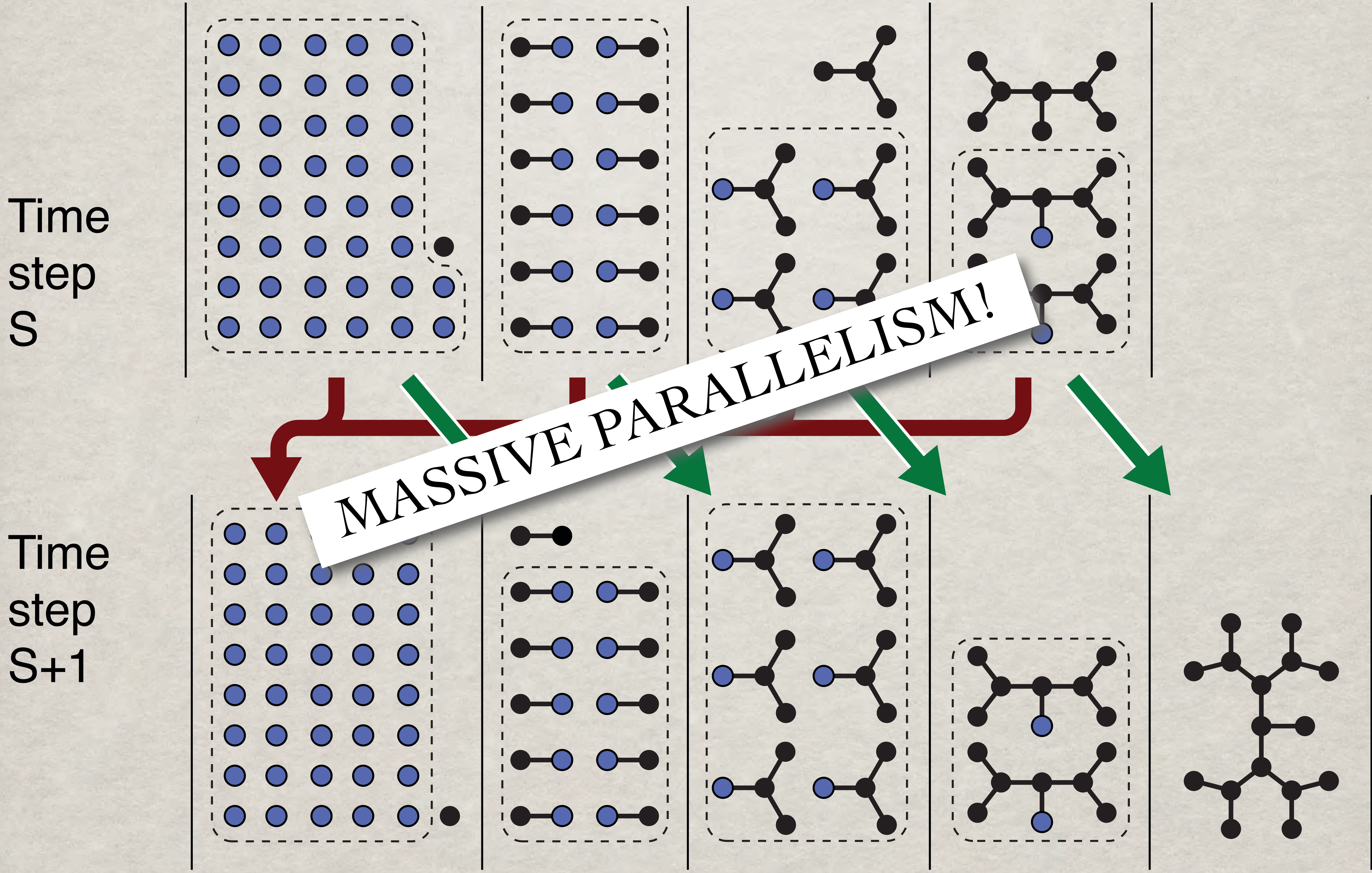
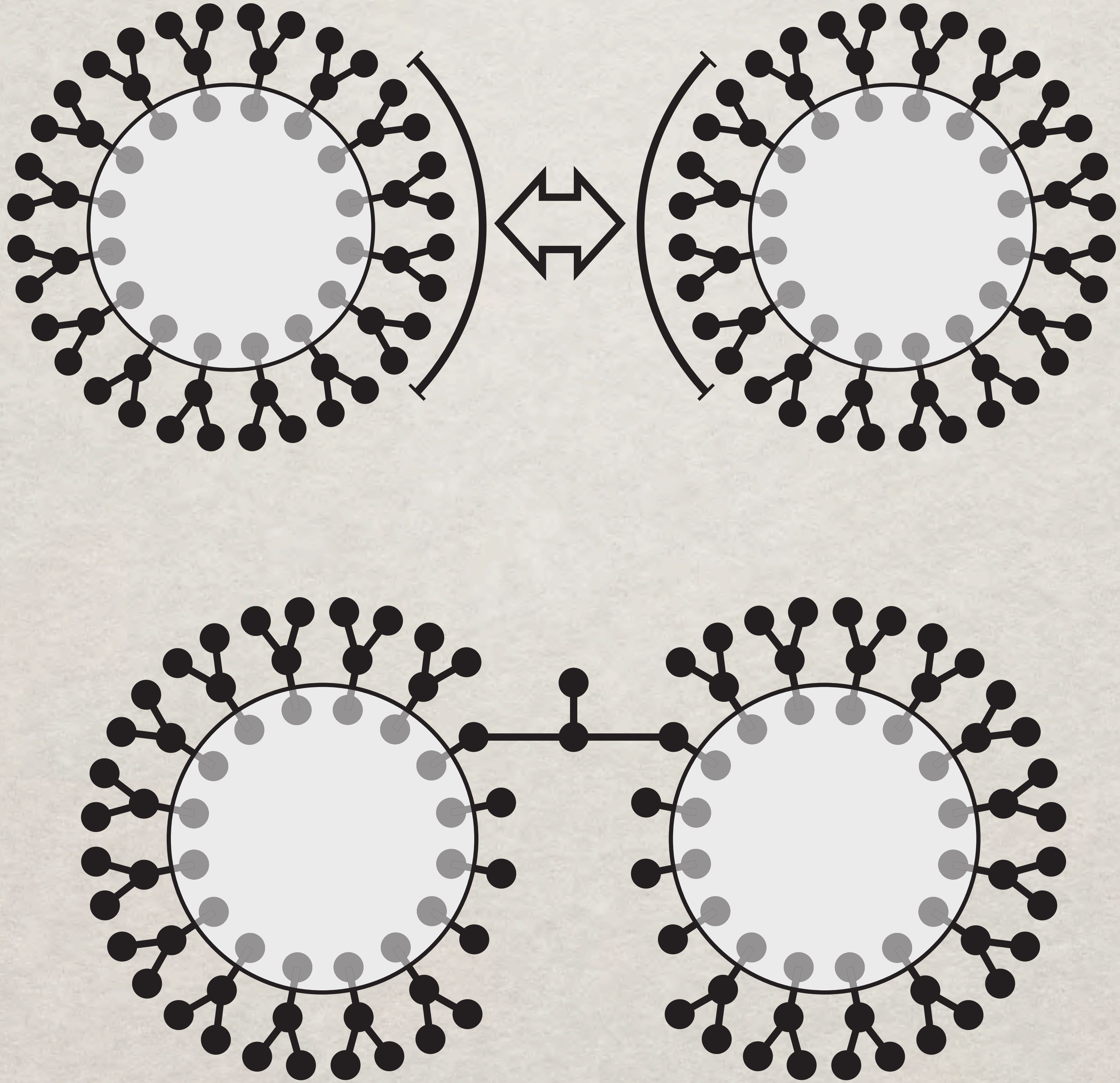
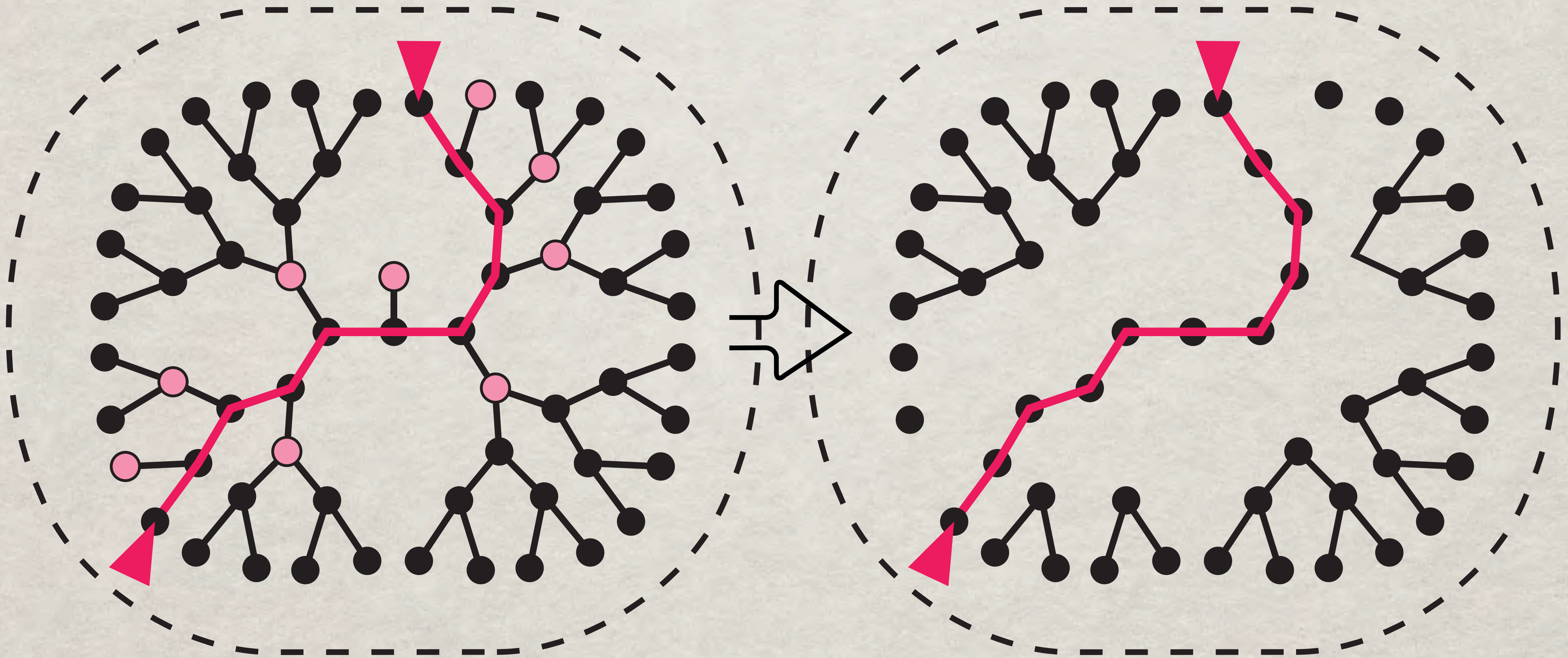






That was:

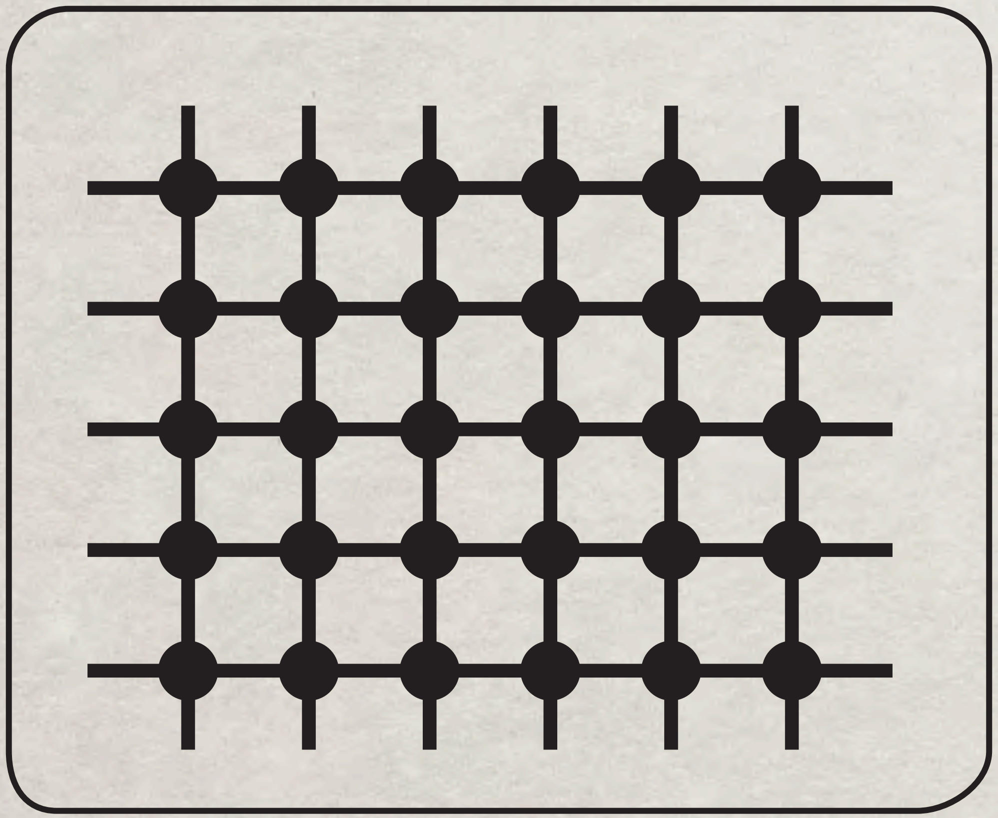
Yuichiro Matsuzaki,
Simon C. Benjamin,
and Joseph Fitzsimons,
PRL **104**, 050501 (2010)

But it merely showed that errors can be kept to (poly) log rates.

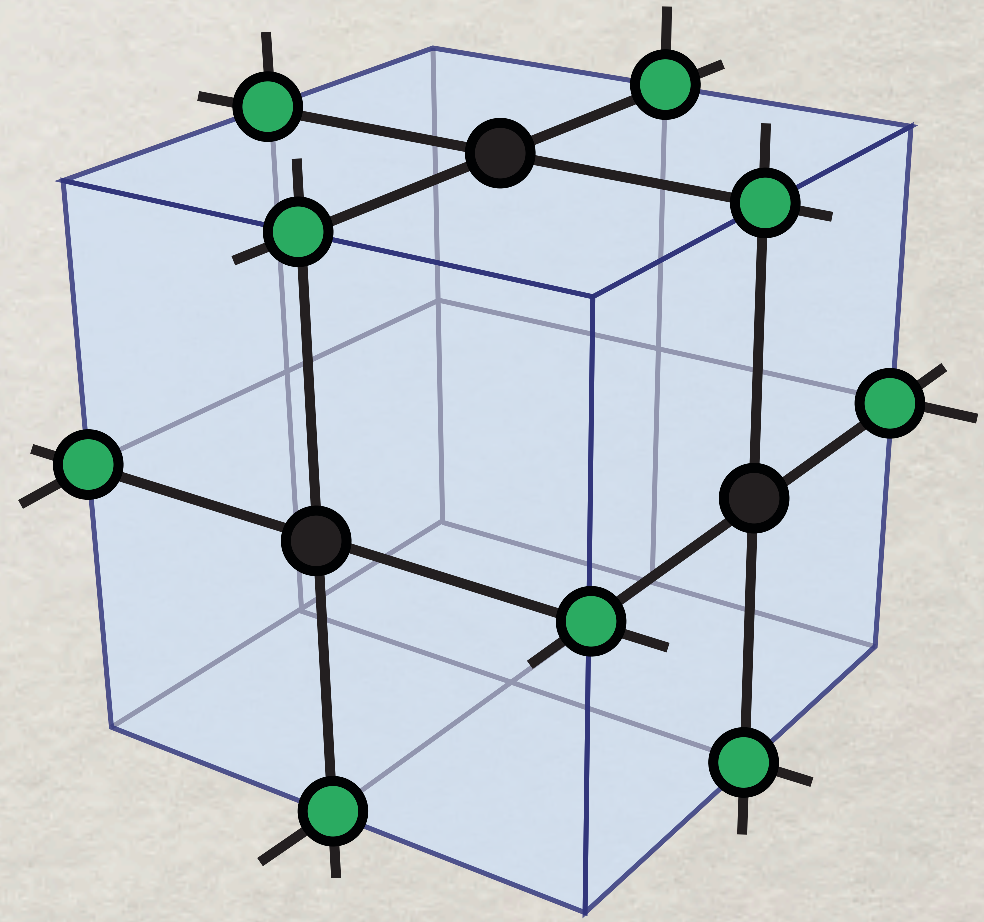
$$(p_A + p_P)\log_2^2(1/p_S)$$

How about actually getting a threshold!

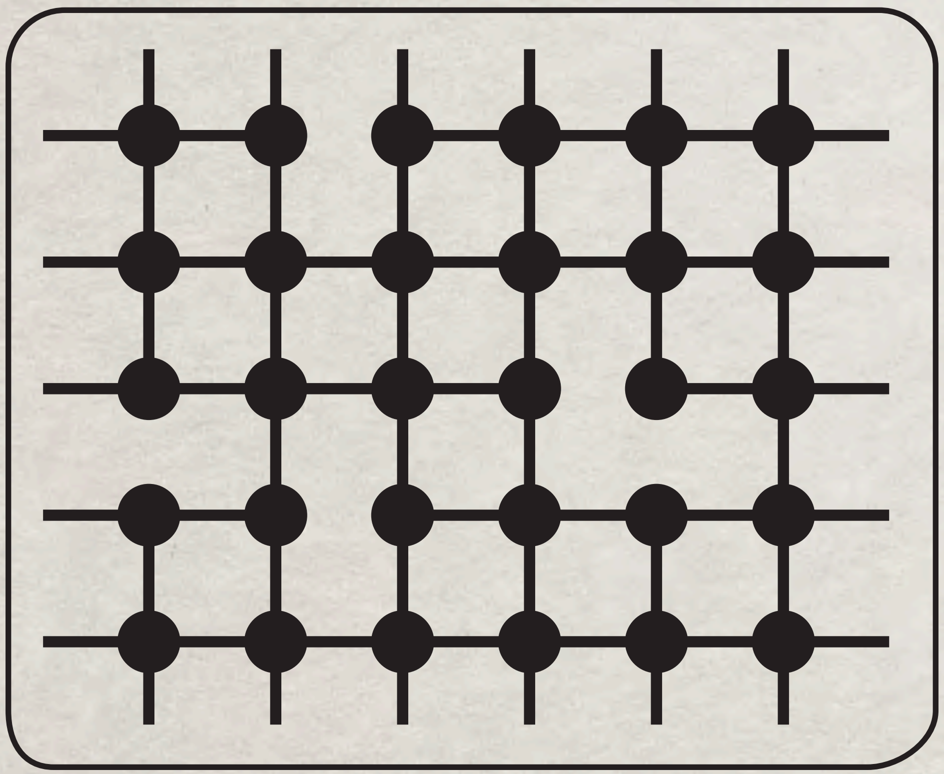
Then instead of
this target...



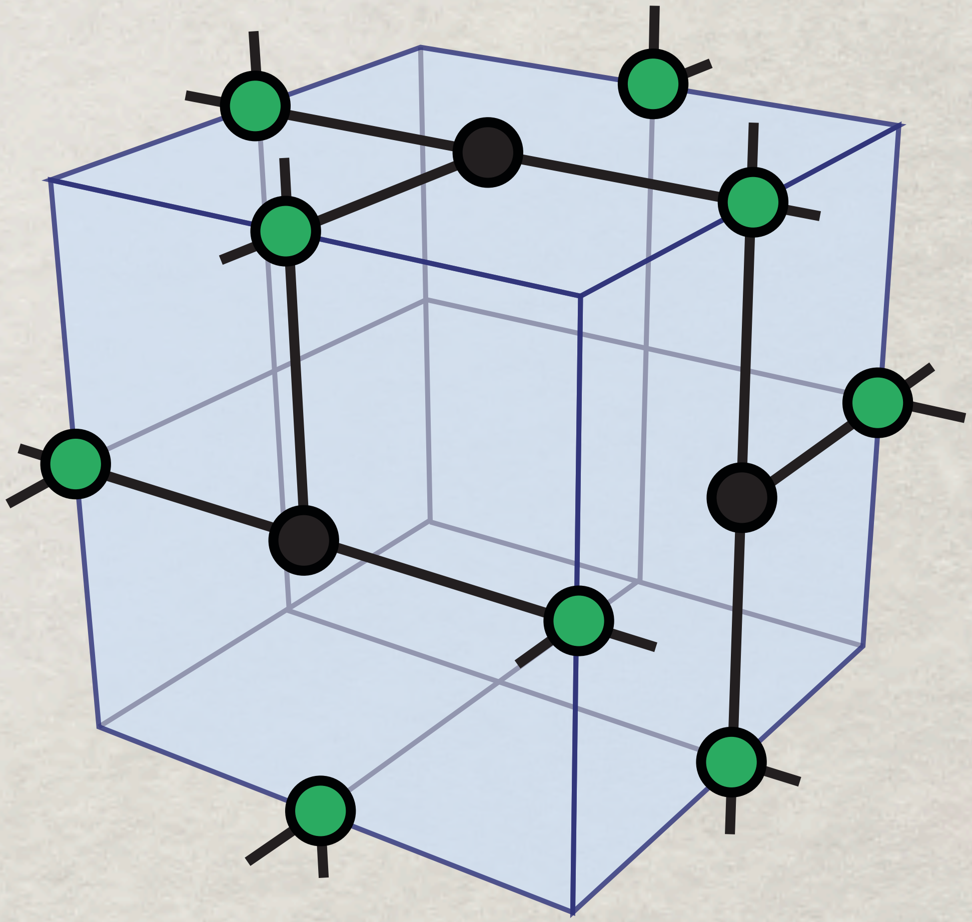
...make this thing.



Will that work?
We need some kind of threshold for tolerance of missing edges

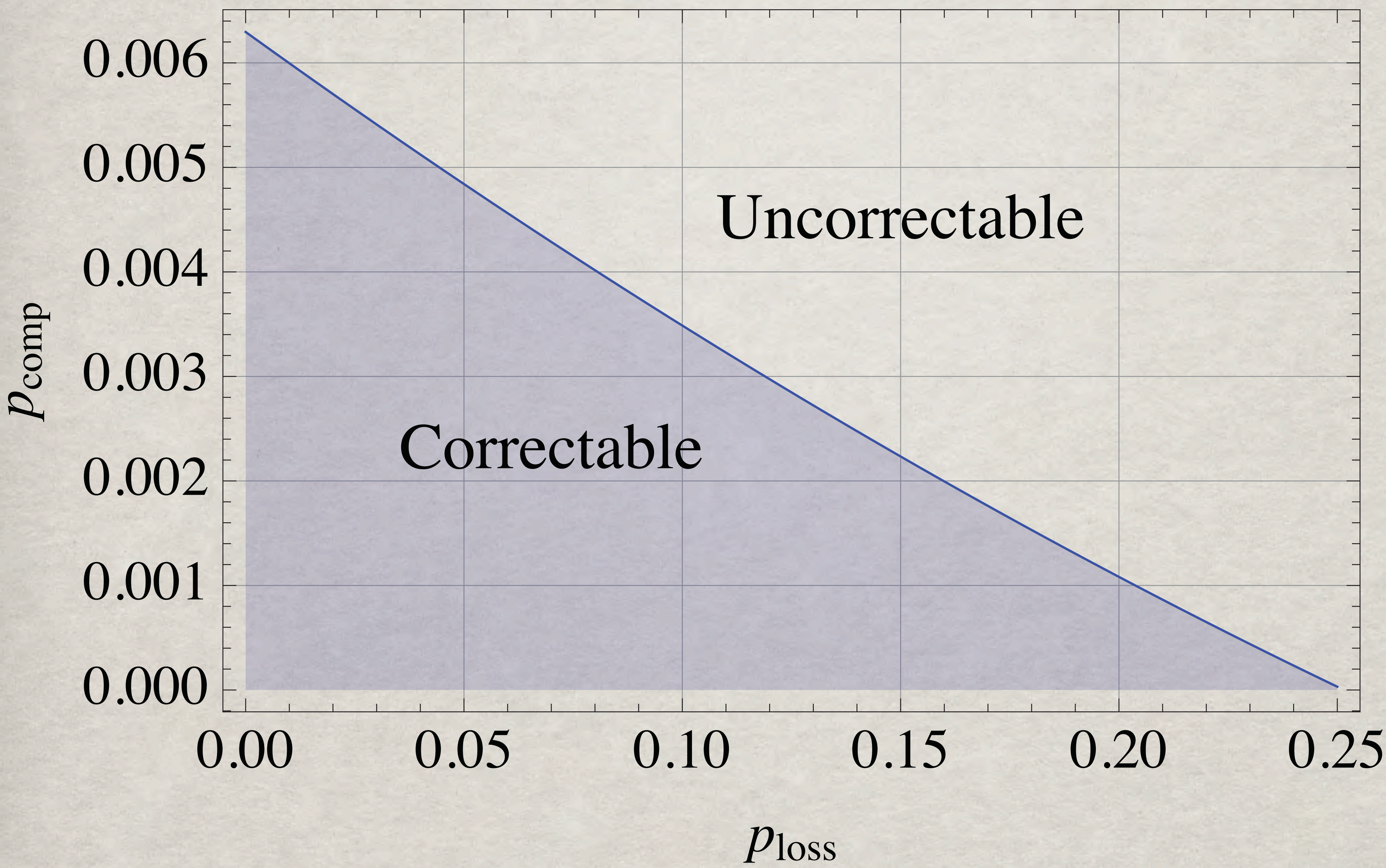


...for the simple cluster state
we had percolation.

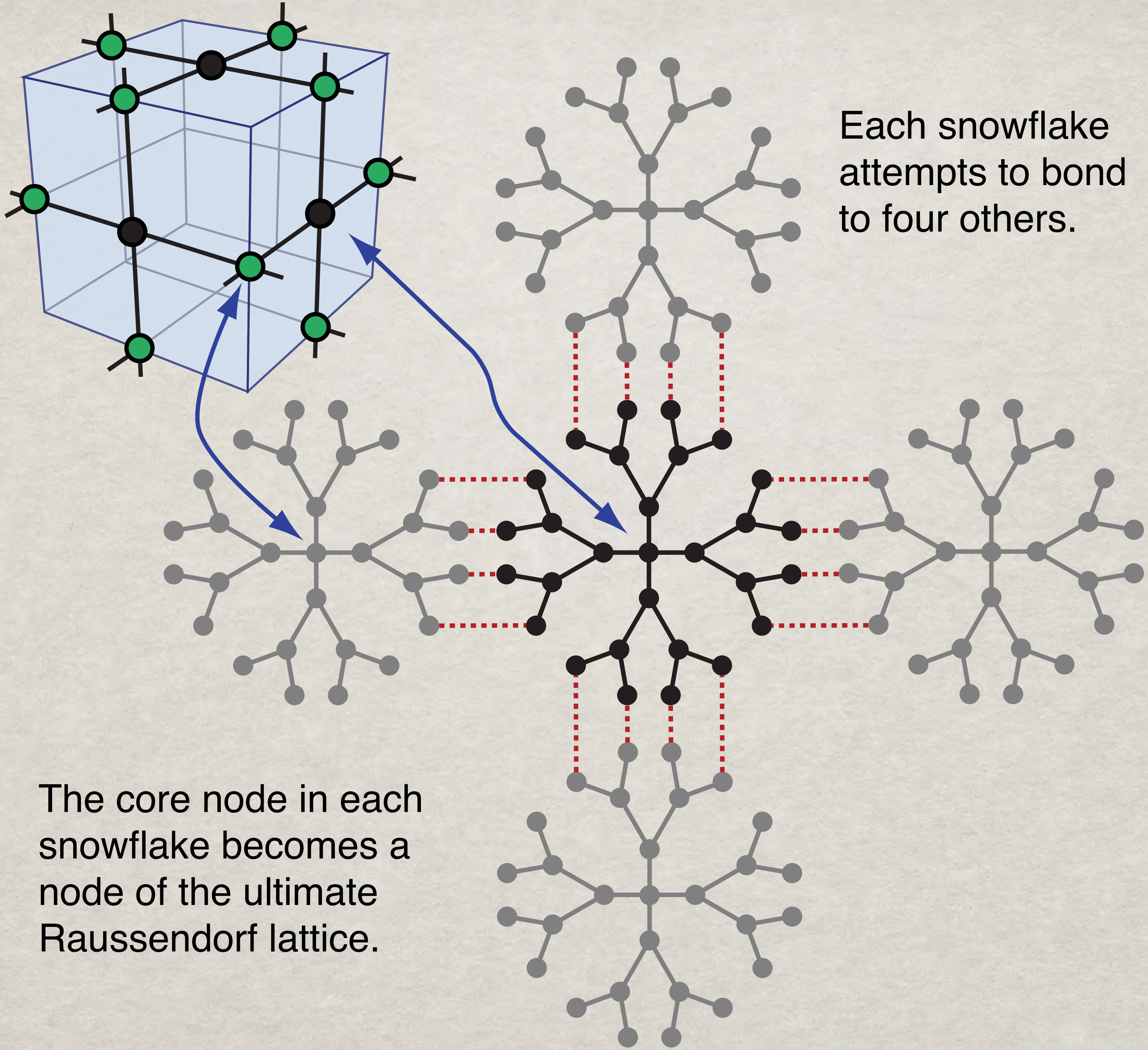


What in this case?

...Now we have Barrett/Stace result for missing qubits

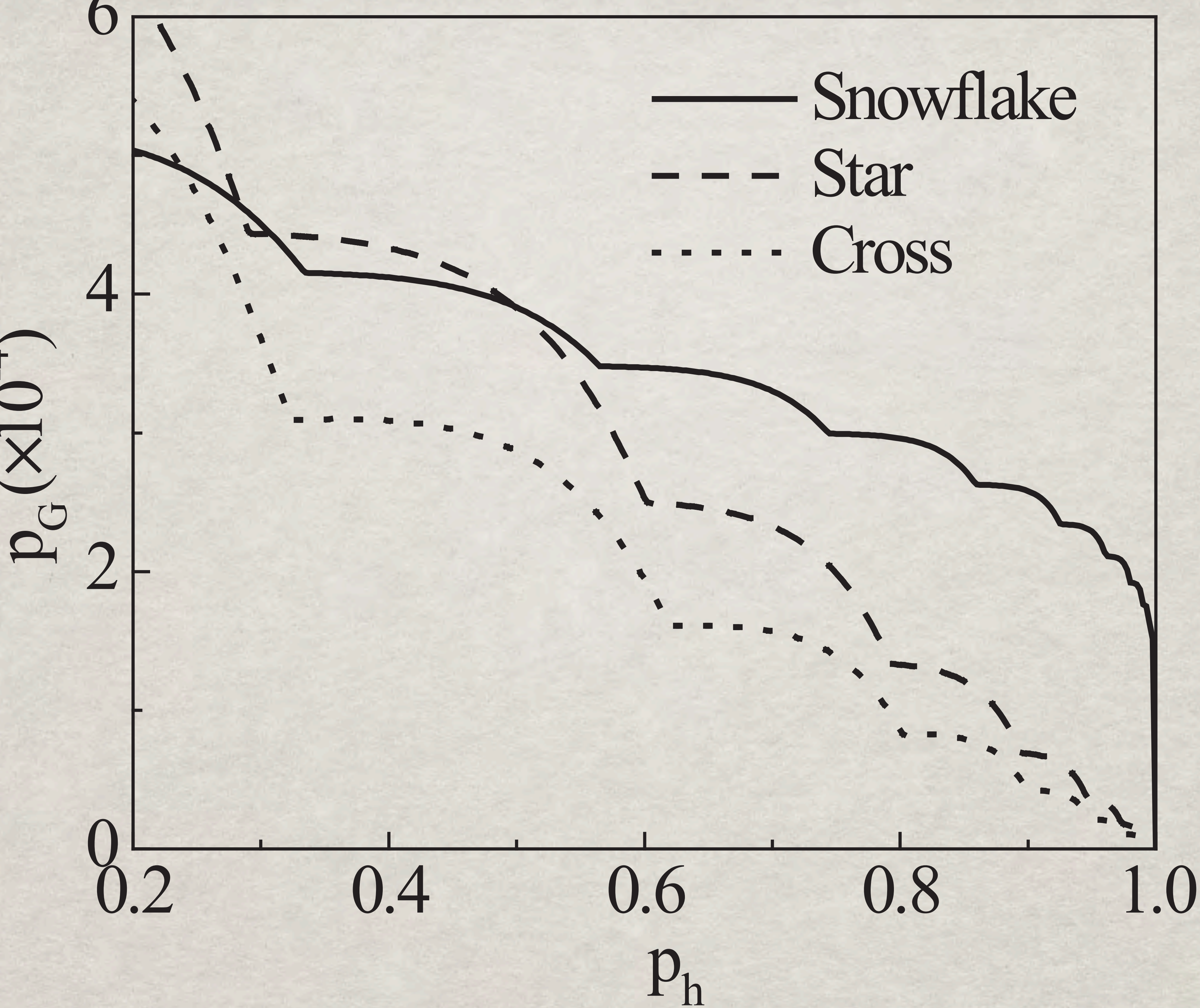


Sean and Tom, Phys. Rev. Lett. **105**, 200502 (2010).

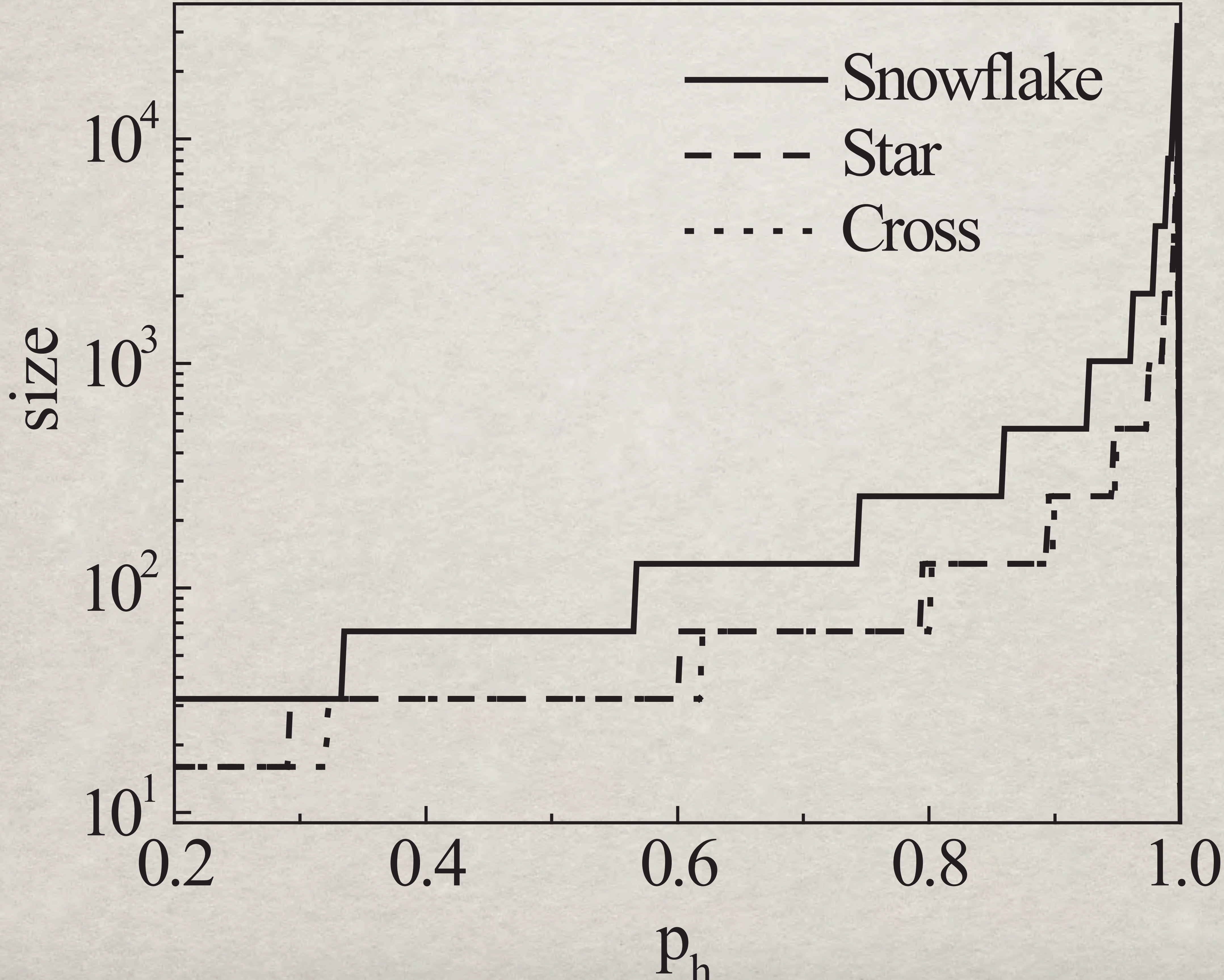


Each snowflake attempts to bond to four others.

The core node in each snowflake becomes a node of the ultimate Raussendorf lattice.



Ying Li, Sean Barrett, Tom Stace and Simon Benjamin,
PRL **105**, 250502 (2010).



Snowflake
Star
Cross
size
10^4
10^3
10^2
10^1
0.2
0.4
0.6
0.8
1.0
p_h

Y. Li, S. D. Barrett,
T. M. Stace and S. C. Benjamin,
PRL **105**, 250502 (2010)

also
K. Fujii and Y. Tokunaga,
PRL **105**, 250503 (2010).

The message of all that seems to be:

With DQC-1 we can tolerate high heralded failures, but only at heavy cost in resource overhead.
We can't do anything about bad network noise on 'successful' entanglement.

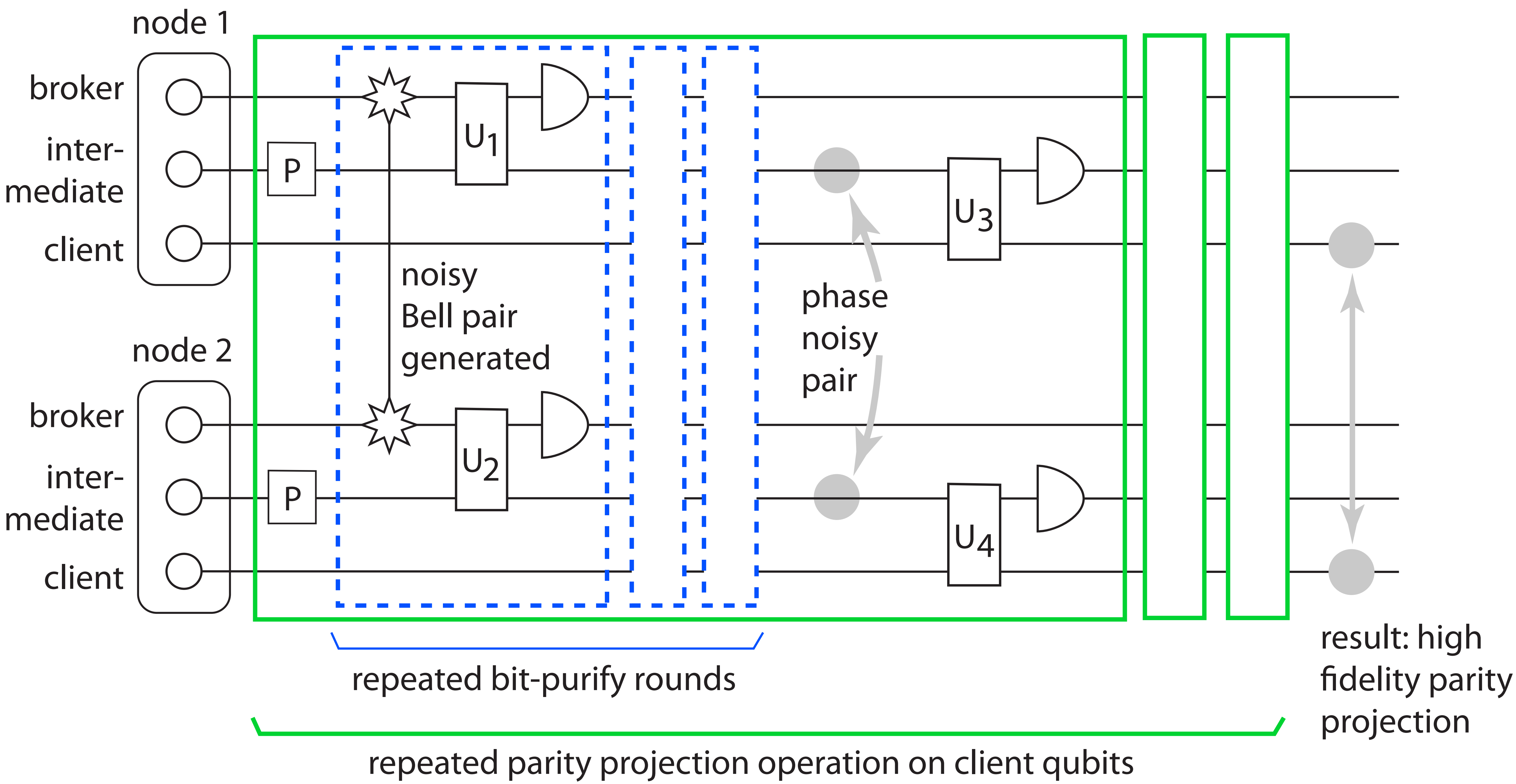
How complicated to the nodes have to be in order to give us something feeling really PRACTICAL?

Answer: DQC-3.

We'll need to do some kind of purification

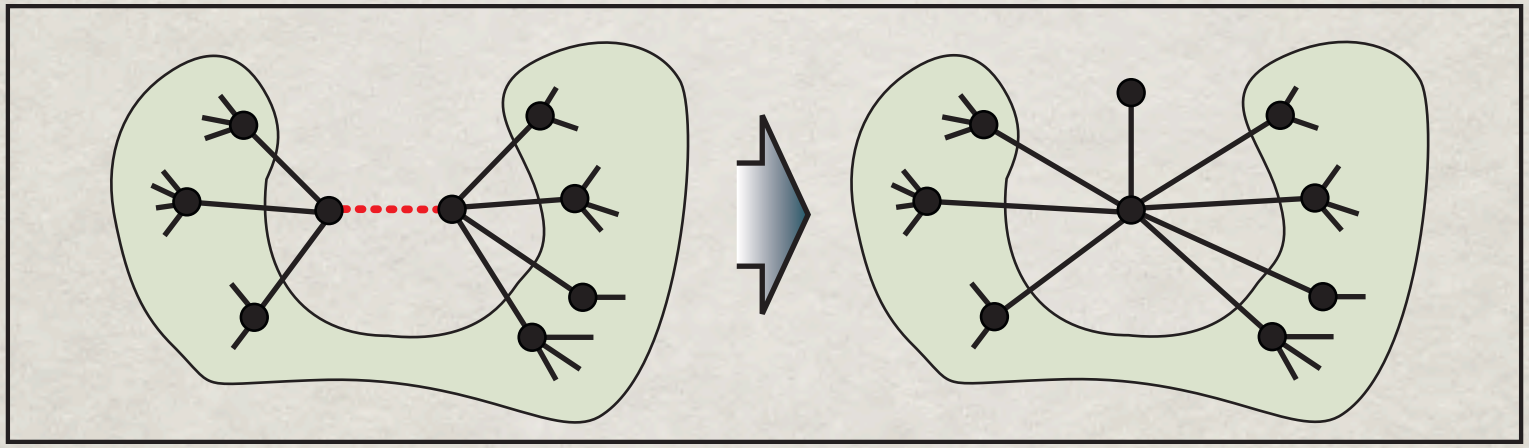
That seems like it might need DQC-4.

But it doesn't if we remember Earl Campbell's 2007 paper (Phys. Rev. A 76 040302)

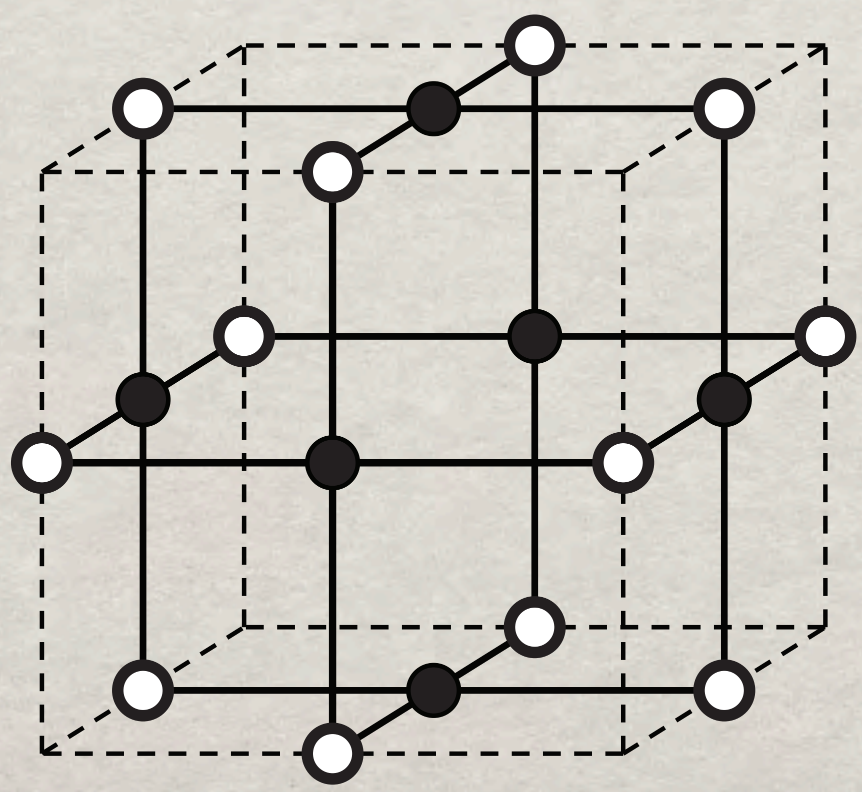

node 1
broker
inter-
mediate
client
node 2
broker
inter-
mediate
client
P
P
U_1
U_2
U_3
U_4
noisy
Bell pair
generated
phase
noisy
pair
repeated bit-purify rounds
repeated parity projection operation on client qubits
result: high
fidelity parity
projection

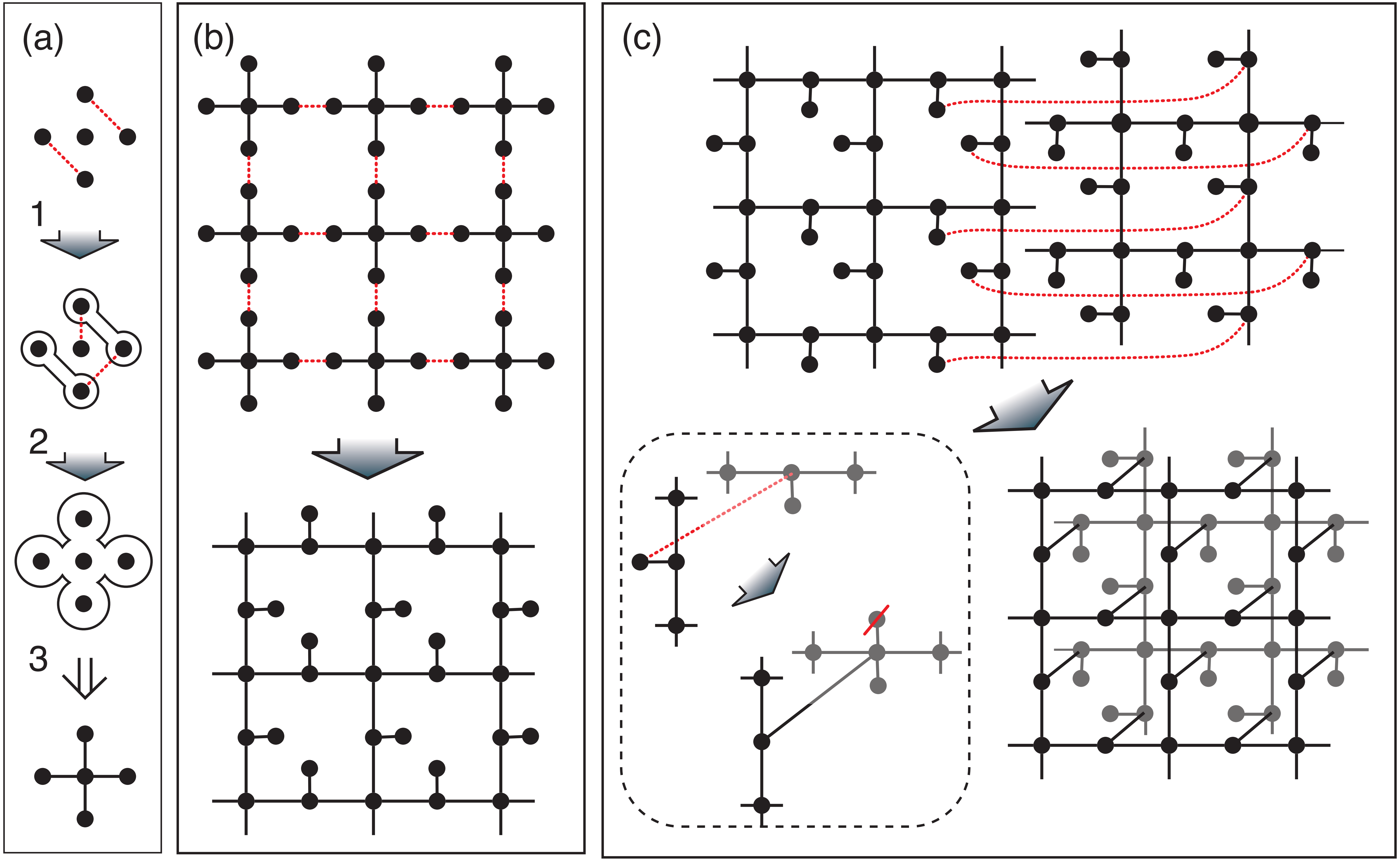
Now a puzzle.....

How to use this primitive:

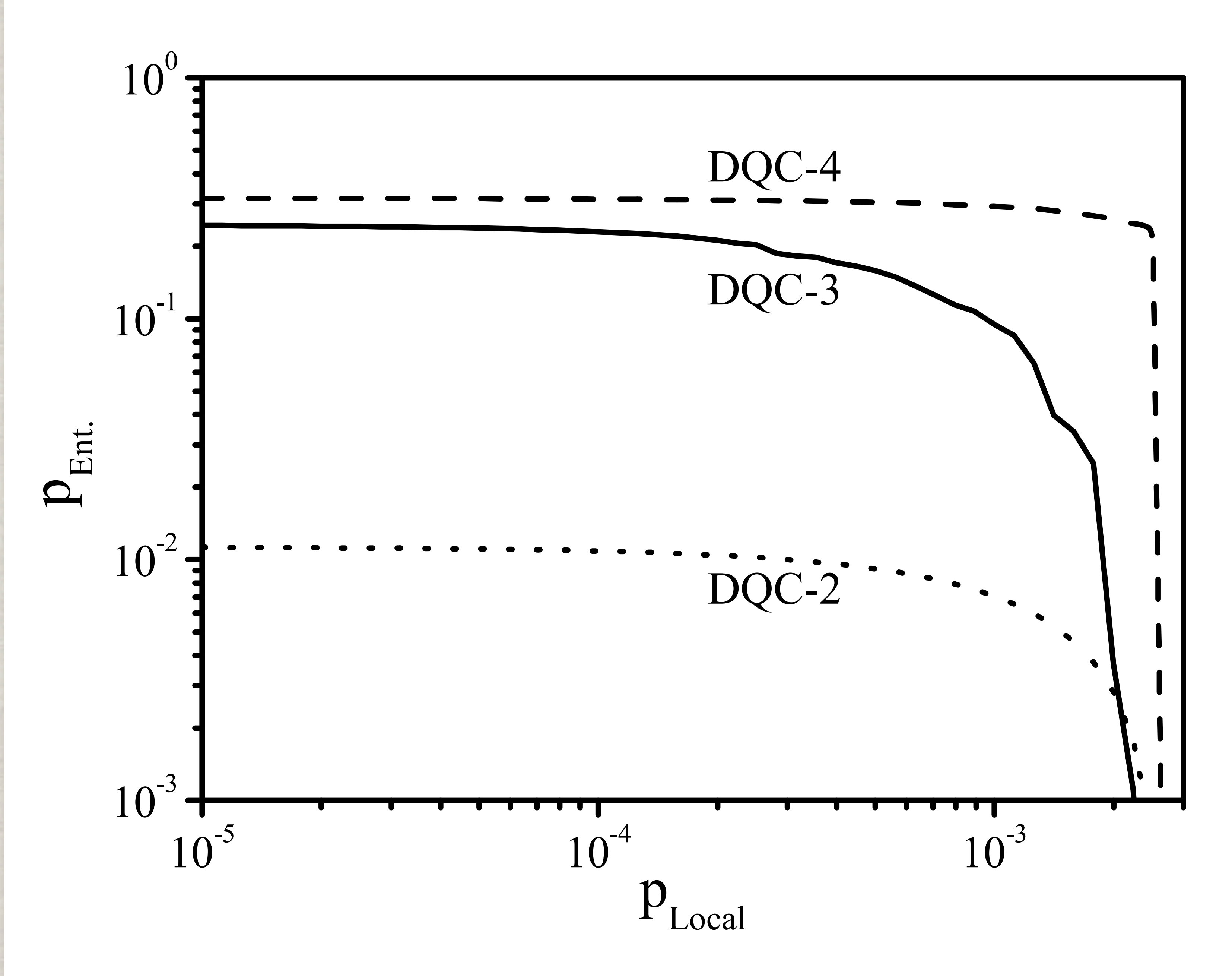


to make this:





(a)
1
2
3
(b)
(c)



Regions to lower left of each line are where FT QIP works

Figure from **arXiv:1204.0443v1** Ying Li and SCB
(DQC-4 line imported from arXiv:1202.6588v1 Fujii *et al*)