Photonic quantum information: applications & challenges

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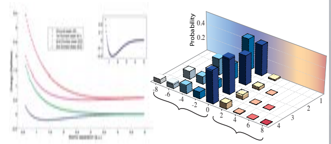
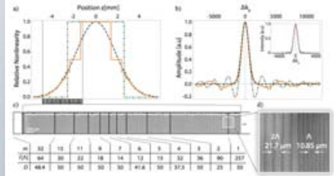
Quantum simulation & emulation



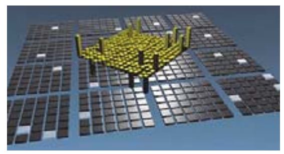
Nature Chemistry **2**, 106 (2010)
Physical Review Letters **104**, 153602 (2010)
New Journal of Physics **13**, 075003 (2011)
arXiv,1105.5334 (2011)

Quantum photonics



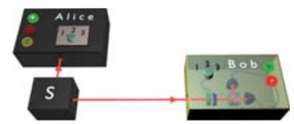
Optics Express **19**, 55 (2011)
Journal of Modern Optics **58**, 276 (2011)
Optics Express **19**, 22698 (2011)

Quantum computation



Nature Physics **5**, 134 (2009)
Journal of Modern Optics **56**, 209 (2009)
New Journal of Physics **12** 083027 (2010)
Physical Review Letters **106**, 100401 (2011)

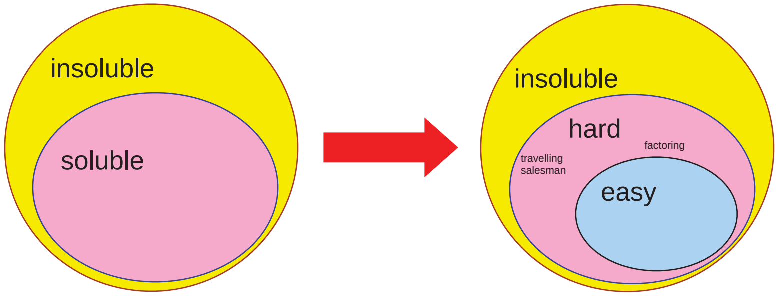
Quantum foundations



Physical Review Letters **104**, 080503 (2010)
Proceedings of the National Academy of Sciences **108**, 1256 (2011)
New Journal of Physics **13**, 053038 (2011)
Physical Review Letters **106**, 200402 (2011)
Nature Communications **3**, 625 (2012)

Quantum Computing:
What is it?
Why do it?

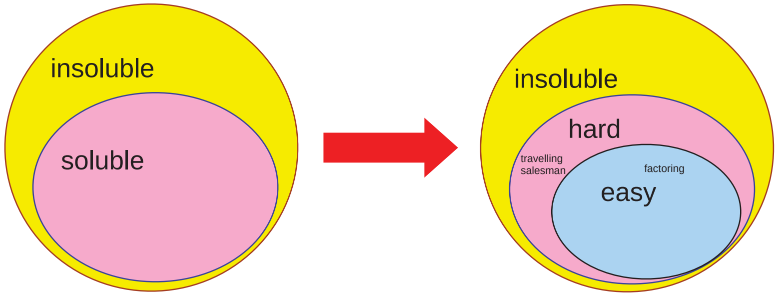
What is classical computing?



Nomenclature

easy = “tractable” = “efficiently computable”
hard = “intractable” = “not efficiently computable”

What is quantum computing?



Nomenclature

easy = “tractable” = “efficiently computable”
hard = “intractable” = “not efficiently computable”

In a world of quantum computers then we would need to abandon most of the algorithms that are in use today. —Robin Balean, VeriSign Australia, 2008

Software updates, email, online banking, and the entire realm of public-key cryptography and digital signatures rely on just two cryptography schemes to keep them secure—RSA and elliptic-curve cryptography (ECC). They are exceedingly impractical for today’s computers to crack, but if a quantum computer is ever built it would be powerful enough to break both codes. Cryptographers are starting to take the threat seriously, and last fall many of them gathered at the PQCrypto conference, in Cincinnati, to examine the alternatives. —IEEE Spectrum, January 2009

Why do quantum computing?

Shor's factoring algorithm →

- Extended Church-Turing Thesis—foundation of theoretical computer science for decades—is wrong

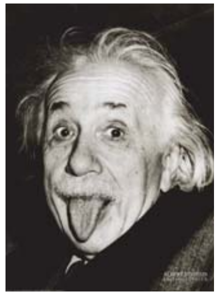
The assertion of the Church-Turing thesis might be compared, for example, to Galileo and Newton's achievement in putting physics on a mathematical basis. By mathematically defining the computable functions they enabled people to reason precisely about those functions in a mathematical manner, opening up a whole new world of investigation.

—Michael Nielsen, UQ, 2004

Why do quantum computing?

Shor's factoring algorithm →

- Extended Church-Turing Thesis—foundation of theoretical computer science for decades—is wrong
- Quantum mechanics is wrong



It's entirely conceivable that quantum computing will turn out to be impossible for a fundamental reason. This would be much more interesting than if it's possible, since it would overturn our most basic ideas about the physical world. The only real way to find out is to try to build a quantum computer. Such an effort seems to me at least as scientifically important as (say) the search for supersymmetry or the Higgs boson. I have no idea—none—how far it will get in my lifetime.

—Scott Aaronson, MIT, 2006

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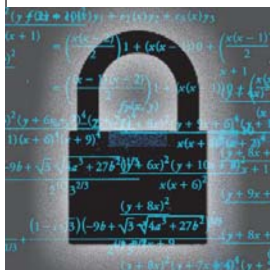
Why do quantum computing?

Shor's factoring algorithm →

- Extended Church-Turing Thesis—foundation of theoretical computer science for decades—is wrong
- Quantum mechanics is wrong
- A fast classical factoring algorithm exists

All three seem crazy. At least one is true!



Lots of mathematicians have looked and think it can't be done, and lots of maths is now based on the impossibility of doing it. – Andrew White, 2009

Computer scientists
and / or
Theoretical physicists
and /or
Mathematicians
will be
badly upset

Why do quantum computing?

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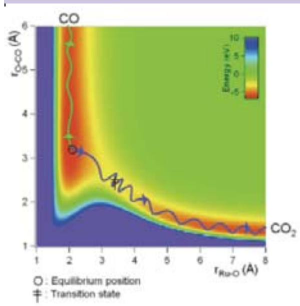
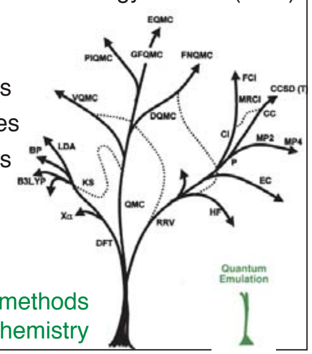
Church-Turing-Deutsch principle: **Any** physical process can be efficiently simulated on a quantum computer



Nuclei move on the electronic potential energy surface (PES)

Knowledge of PES enables:

- Minima: equilibrium structures
- Saddle points: transition states
- Reaction rates & mechanisms
- PES characterise **most** of physical chemistry



Tree of approximation methods for quantum chemistry

Why do quantum computing?

Shor's factoring algorithm →

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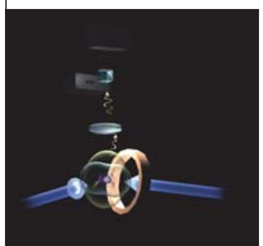
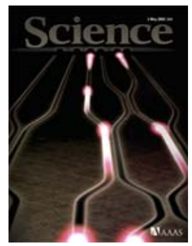
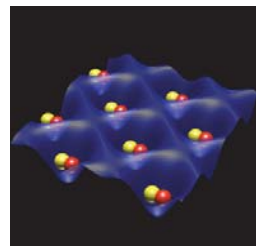
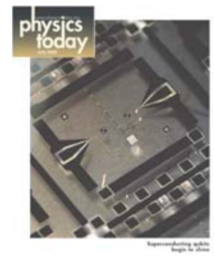
Church-Turing-Deutsch principle: **Any** physical process can be efficiently simulated on a quantum computer

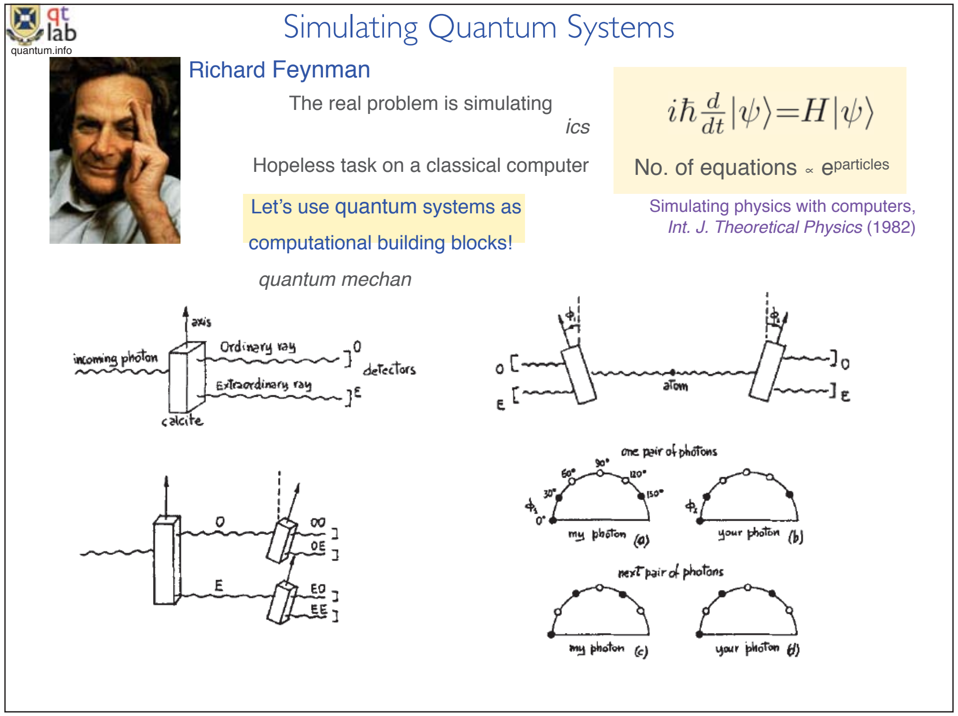
Quantum computers are interesting physical systems in their own right











• Richard Feynman recognised that simulating QM was hopeless with classical computers. Suggested using quantum systems to do an end run around the problem.

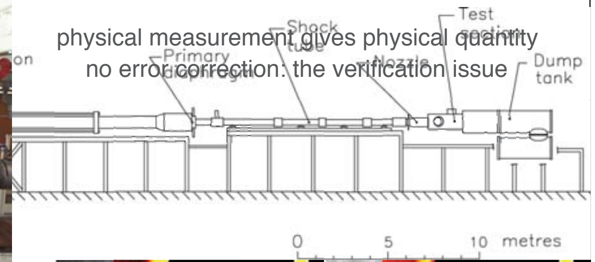
• In 1996 Seth Lloyd showed that Feymna was correct, at least for a very large class of physical systems. (In more detail: correct for Hamiltonians that are a 'sum of local interactions'.) He showed that an arbitrarily good approximation of Hamiltonian evolution could be achieved with an initial wavefunction encoded into a polynomial number of qubits, acted on by a polynomial number of logic gates. The final wavefunction would be a very good approximation to that achieved with the physical Hamiltonian.

• Well that's great, but how can we calculate some physical properties with this apporach?

• As you heard on Monday, in 2005, Alán Aspuru-Guzik showed that you could use this apporach to calculate nergy in a chemical problem, using the iterative phase estimation algorithm. Now this is good news for photonics, as we realised the phase estimation algorithm a couple of years ago for Shor's algorithm, as reported in the 2007 Review.

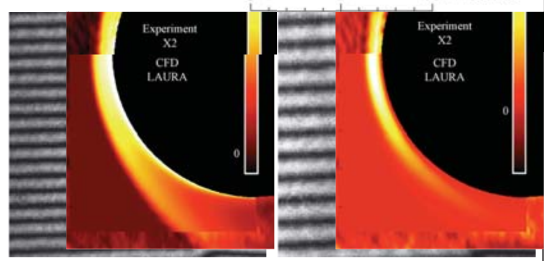
Emulators vs Simulators

Emulator



physical measurement gives physical quantity
no error correction: the verification issue

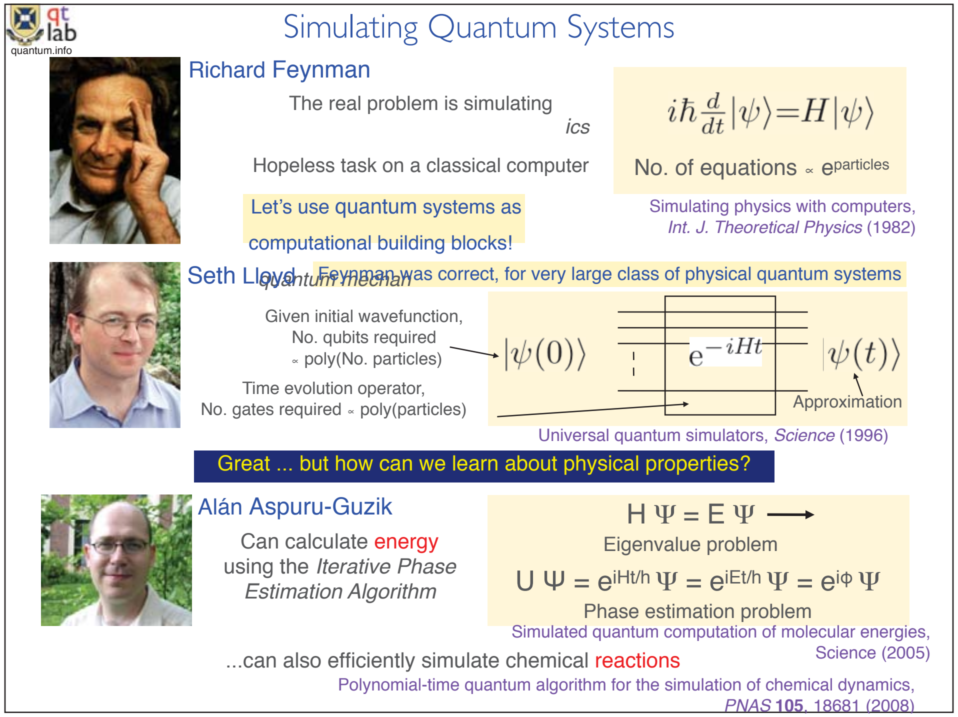
Simulator



digital model gives physical quantity
error correction: behaviour is due to physics

Data images courtesy of Dr T. McIntyre, UQ

Simulating quantum chemistry



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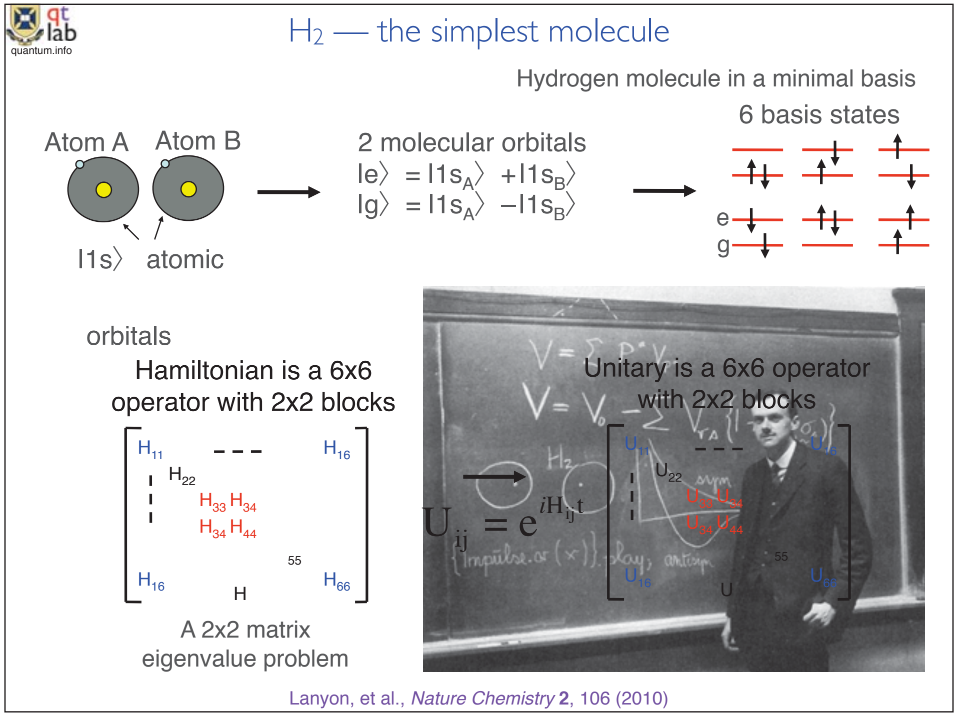
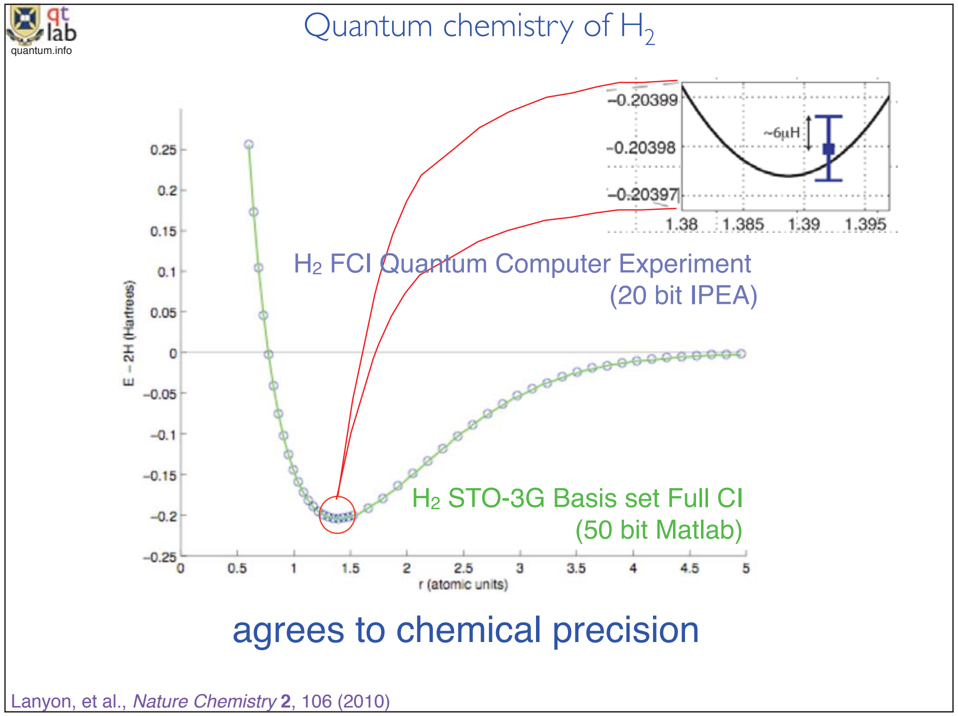


So solving this molecule directly will require a 6x6 unitary operator to be implemented with logic gates.

WAY BEYOND WHAT WE CAN DO AT THE MOMENT.

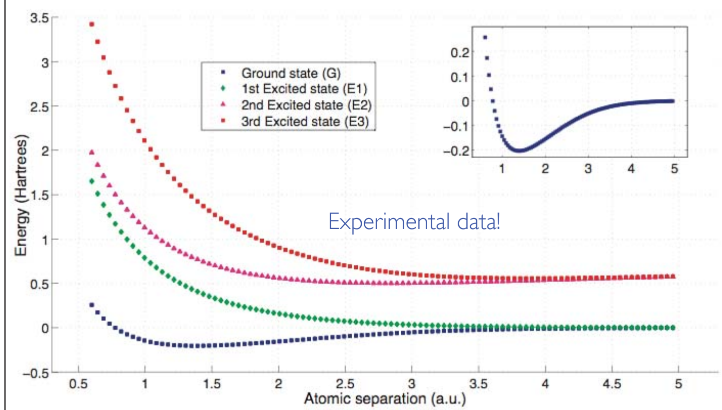
Exploit the block-diagonal structure, and just solve each 2x2 block separately.



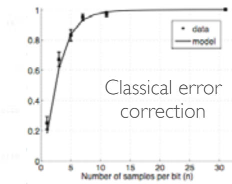
We parameterized the Hamiltonian by the atomic separation - and calculated all the eigenvalues, using the quantum algorithm, at a range of different separations.

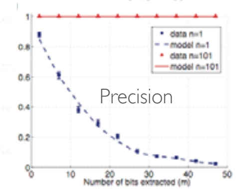
There are 4 eigen values, as opposed to 6 for the 6x6 hamiltonian due to some degeneracy

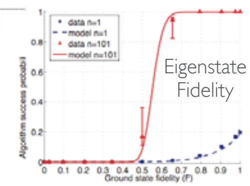
Quantum chemistry of H_2



Explored a range of algorithmic features:







Lanyon, et al., *Nature Chemistry* **2**, 106 (2010)

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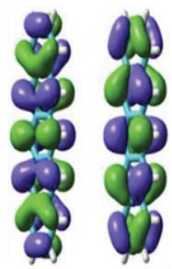
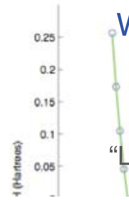
What next?

Today



The Future



Wavefunction representation on a grid of 2^n points

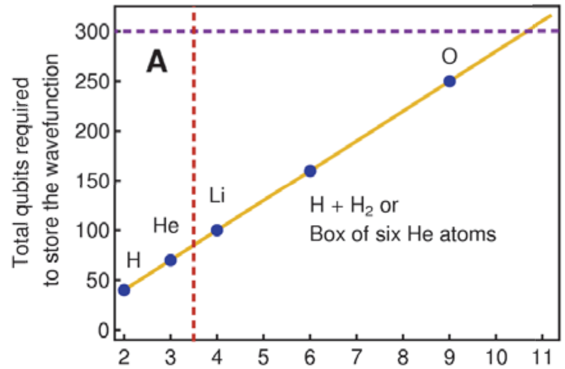
Experiments with < 10 qubits are cute but useless

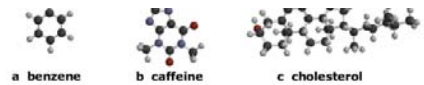
— Steve Flammia, Perimeter, 2009

Can do H, He

"Li impossible in foreseeable future"

Ruiz et al., PRL **94**, 063002 (2005)

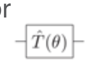




Lloyd's approximation: Building-Blocks

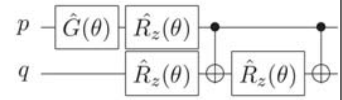
Number operator

$h_{pp}a_p^{+}a_p$



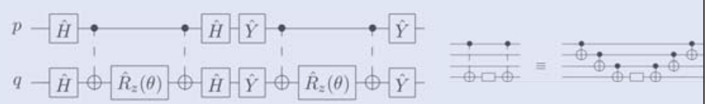
Coloumb & exchange operators

$h_{pqqp}a_p^{+}a_q^{+}a_q a_p$



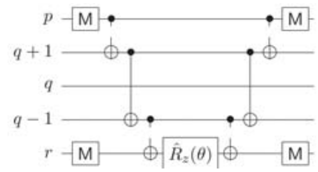
Excitation operator

$h_{pq}(a_p^{+}a_q + a_q^{+}a_p)$



Number-excitation operator

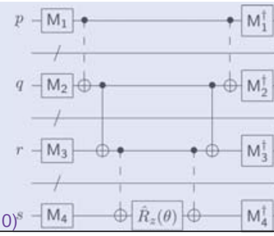
$$h_{pqqr}\ (a_p^{+}a_q^{+}a_q a_r + a_r^{+}a_q^{+}a_q a_p)$$



where $\mathsf{M} = \{\hat{H}, \hat{Y}\}$

Double-excitation operator

$$h_{pqrs}\ (a_p^{+}a_q^{+}a_r a_s + a_s^{+}a_r^{+}a_q a_p)$$



where $(\mathsf{M}_1, \mathsf{M}_2, \mathsf{M}_3, \mathsf{M}_4)=$
$\{(\hat{H},\hat{H},\hat{H},\hat{H}), (\hat{Y},\hat{Y},\hat{Y},\hat{Y}), (\hat{H},\hat{Y},\hat{H},\hat{Y}), (\hat{Y},\hat{H},\hat{Y},\hat{H}), (\hat{Y},\hat{Y},\hat{H},\hat{H}), (\hat{H},\hat{H},\hat{Y},\hat{Y}), (\hat{Y},\hat{H},\hat{H},\hat{Y}), (\hat{H},\hat{Y},\hat{Y},\hat{H})\}$

Lanyon, et al., *Nature Chemistry* **2**, 106 (2010)

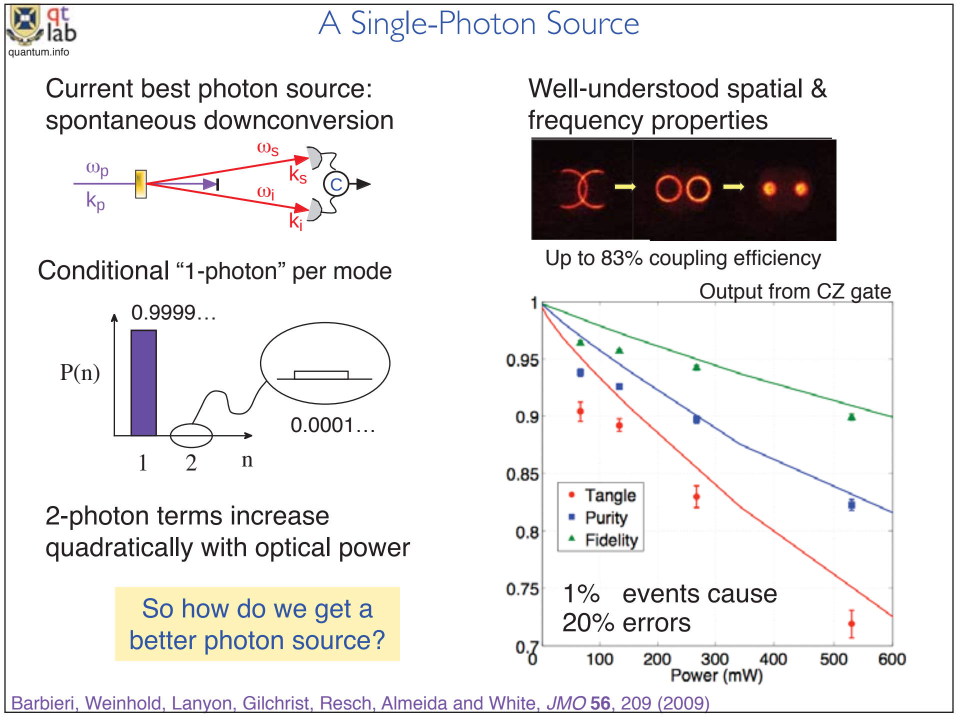
Challenges & Solutions

The Challenges

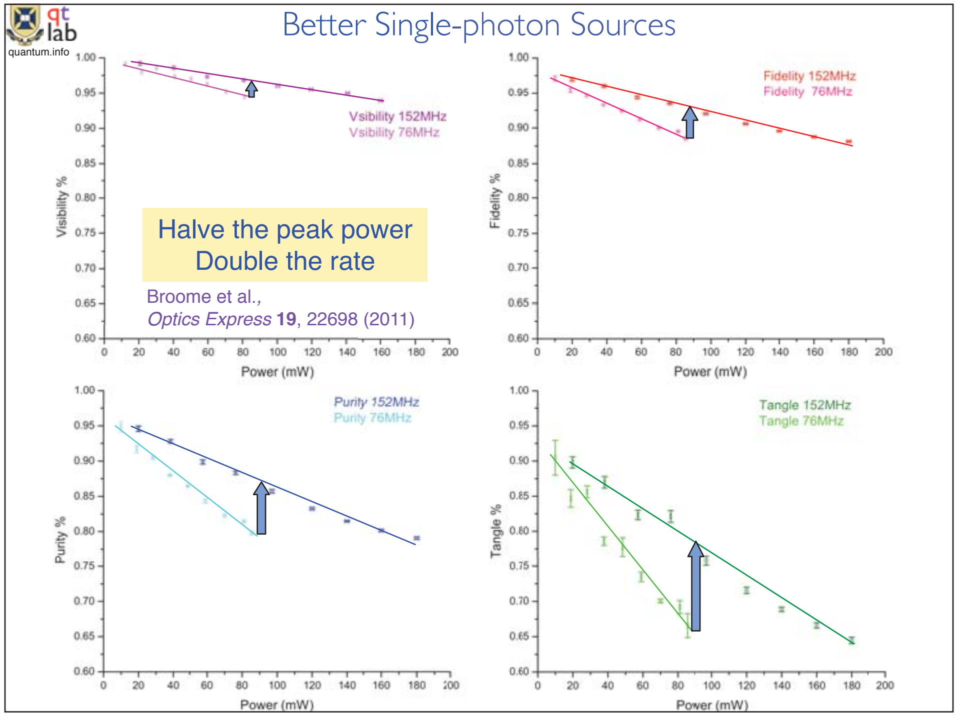
It is difficult to efficiently produce and detect single photons.

Current photonic entangling gates are inherently random

It is difficult to store photons



- Photonic QC needs single photons
- The best current apporixmation to a true single photon source is spontaneous downconversion.
- Downconversion modes with well-understood spaital and frequency properties, and excellent coupling efficiency: up to 89% has been demonstrated (ADD reference to Franson?)
- By conditioning on detection of single photon in one mode, with high probability there is a single photon in the other … except sometimes, there are two! Downconversion produces photon-pairs with some probability of two or three pairs occurring.
- Two-photon terms increase quadratically with power. So the brighter the downconversion source, the worse it gets as a single-photon source.
- At first glance this isn't such a bad effect: for example, Hong-Ou-Mandel visibility drops only slightly as the power is increased nealry 10-fold.
- However, now let's look at the output from a UQ-style optical CNOT gate. We see that higher-order terms seriously degrade the entangled-state fidelity, purity, and tangle.
- So how can we get a better downconversion source? Reducing pump power does the trick, but also reduces the count rate.



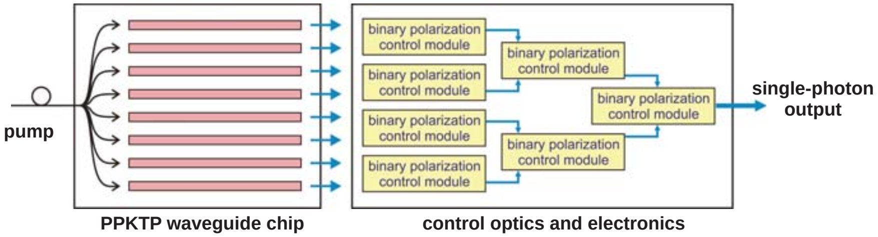
• So the first part of our solution is to reduce the power, but increase the repetition rate.

• Doubling the rate improves everything as you can see! (For 3 of these plots, each data point is from a full state tomography measurement).

• The next two steps are to multiplex these sources, and to use them to improve the performance of integrated-photonic gates, e.g. in this photo from UQ. Note that we've used the wrong wavelength laser to highlight things. You can just see the fibre on the right here, but the chips are very low-loss and you can't see the waveguides at all. (Note: you *can* nicely see the reflection of Andrew's finger and iPhone in the metal support under the chip).

Better Single-photon Sources: Multiplexed downconversion

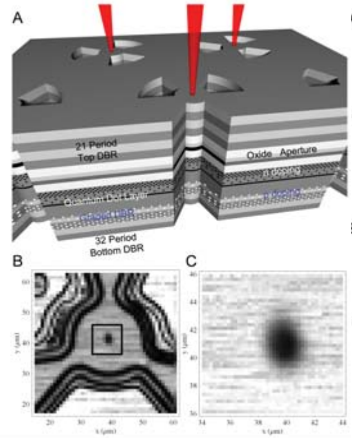
8-downconverter modular single-photon source



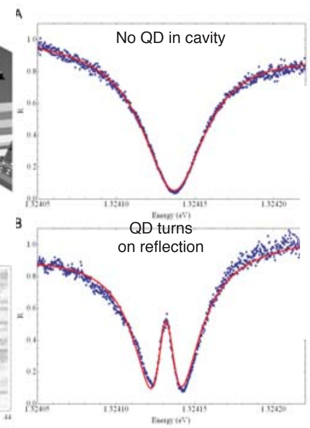
From Franco Wong

Modular on-demand source proposal: OL 32, 2698 (2007)
Single-mode biphoton experiment: PRL 101, 153602 (2008)
PPKTP waveguide downconversion: OE 17, 12019 (2009)

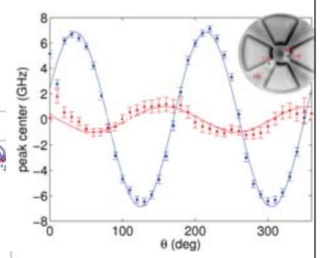
Better Single-photon Sources: Quantum Dots in Micropillars



- Controlled single-electron loading
- Excellent single-photon source due to elimination dark states by charging
- 96% matching to external mode
- Optical cavity Q > 40,000
- Fibre-coupled



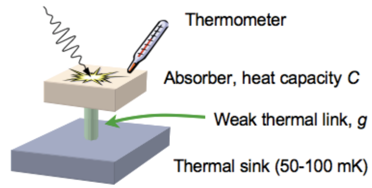
Reflection spectroscopy of micropillar

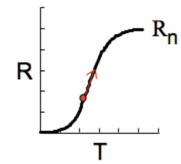


Polarization degenerate micro- pillar by strain induced by optically burning of small holes

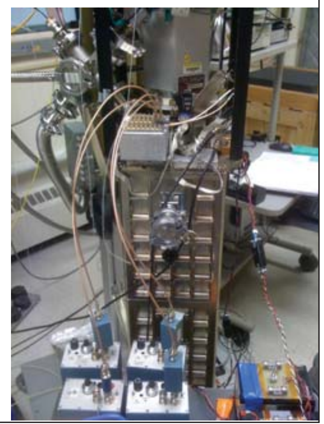
From Dik Bouwmeester

Better Single-photon Detectors





UQ: ~98.5%



Quantum efficiency, η~20 %
w. AR coating η ~ 95 %

From Sae Woo Nam

It is difficult to efficiently produce and detect single photons.

Current photonic entangling gates are inherently random

It is difficult to store photons

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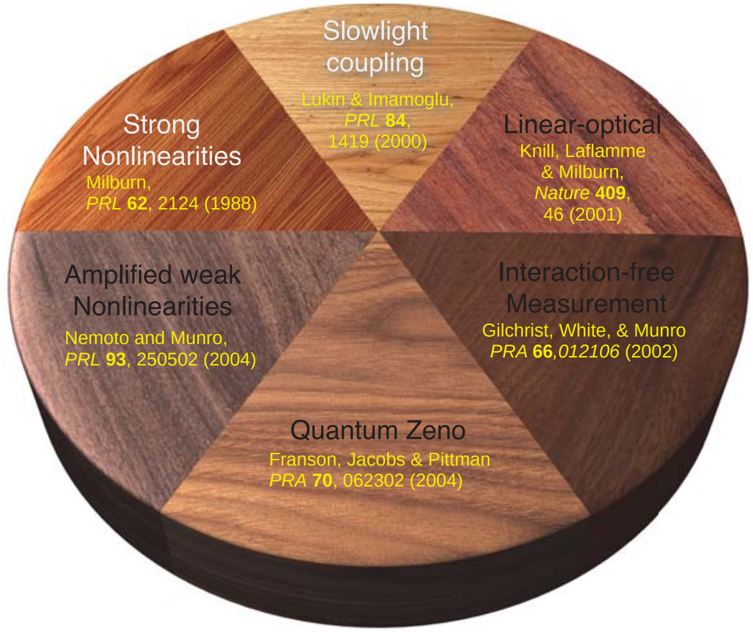
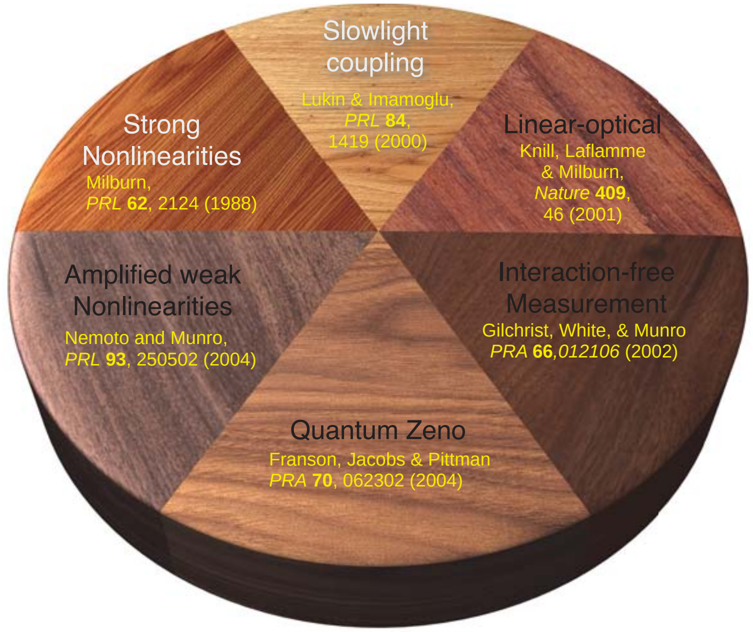
Proposed photonic entangling gates



Proposed photonic entangling gates

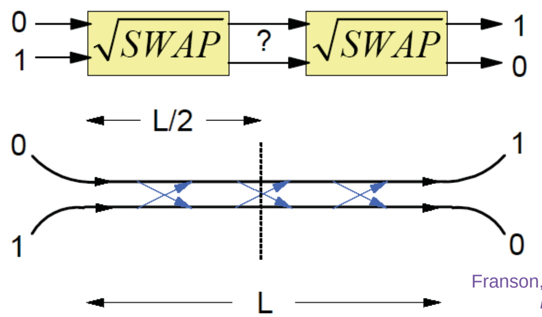


Quantum Zeno

- 2004 - Franson's solution: deterministic entangling gate by combining linear optics gates, quantum Zeno effect and nonlinear optics

    1. Linear-optical gates fail by emitting 2 photons into one mode
    2. Quantum-Zeno effect can suppress 2 photon events
    3. Requires nonlinear interaction

e.g. universal gate: √SWAP



Franson, Jacobs, and Pittman, *Physical Review A* **70**, 062302 (2004).

Quantum Zeno

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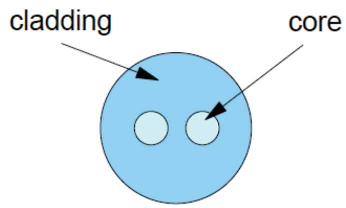
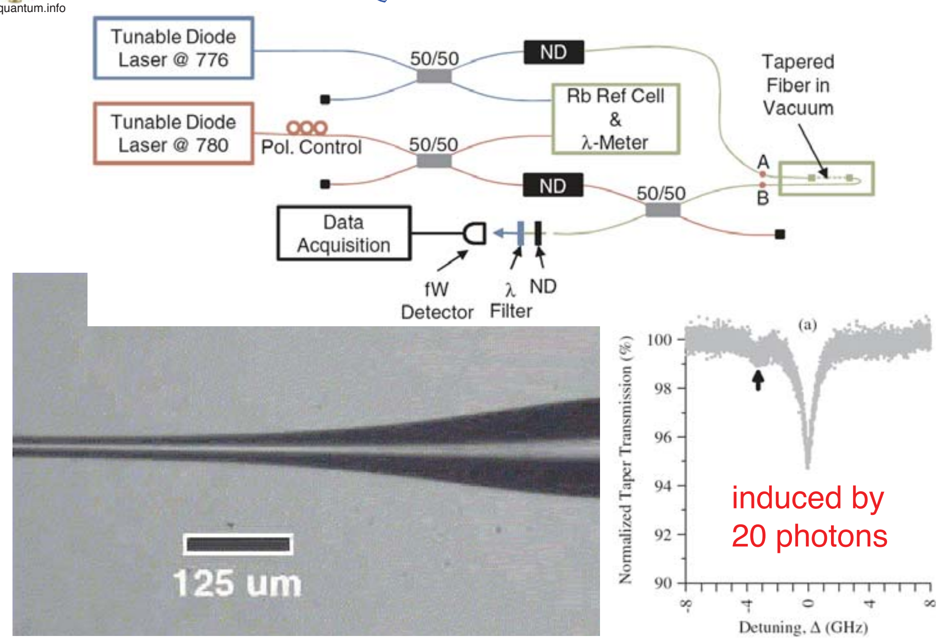


effects of loss? c.f. "interaction-free" measurements

Franson, Jacobs, and Pittman, *Physical Review A* **70**, 062302 (2004).

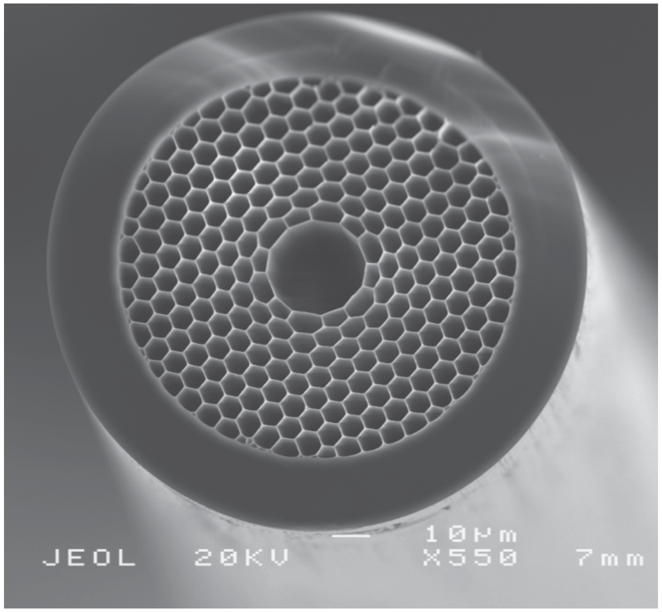
Kwiat, et al., PRL **83**, 4725 (1999)   Gilchrist, et al., PRA **66**, 012106 (2002)

Quantum Zeno



Hendrickson, Lai, Pittman and Franson, PRL **105**, 173602 (2010)

Quantum Zeno



Luiten et al., preprint (2011)

It is difficult to efficiently produce and detect single photons.

Current photonic entangling gates are inherently random

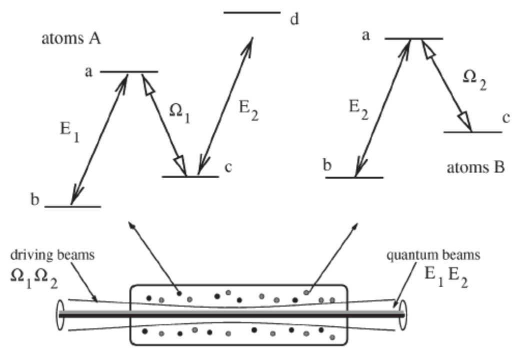
It is difficult to store photons

Using quantum memories

VOLUME 84, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 2000

Nonlinear Optics and Quantum Entanglement of Ultraslow Single Photons

M. D. Lukin[1] and A. Imamoğlu[2]
[1]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
[2]Department of Electrical and Computer Engineering, and Department of Physics, University of California, Santa Barbara, California 93106
(Received 19 October 1999)



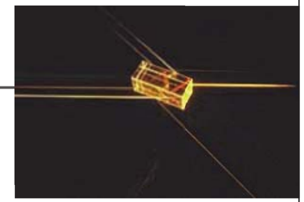
Using quantum memories

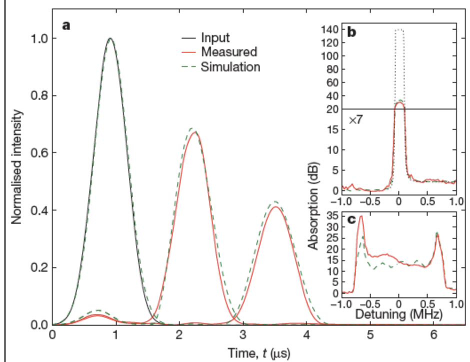
nature Vol 465|24 June 2010|doi:10.1038/nature09081

LETTERS

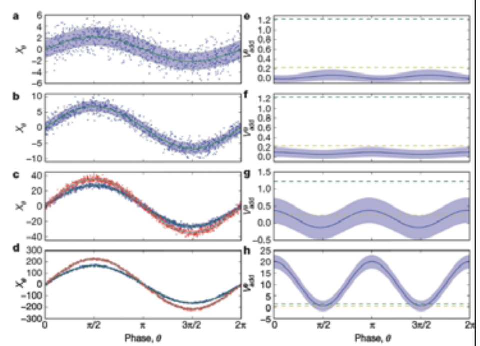
Efficient quantum memory for light

Morgan P. Hedges[1], Jevon J. Longdell[2], Yongmin Li[3] & Matthew J. Sellars[1]



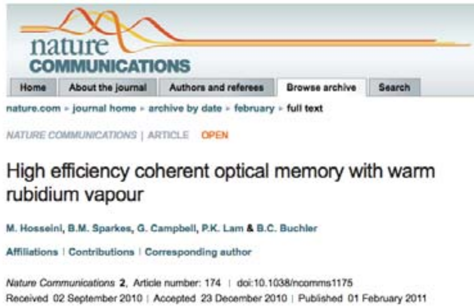


recall efficiency of 69%



quantum-noise limited

Using quantum memories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NATURE COMMUNICATIONS | ARTICLE OPEN

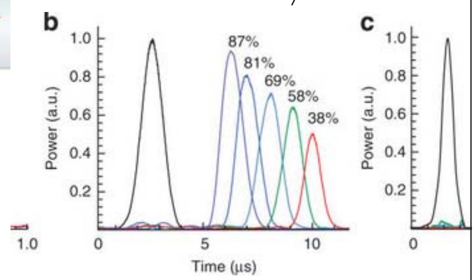
High efficiency coherent optical memory with warm rubidium vapour

M. Hosseini, B.M. Sparkes, G. Campbell, P.K. Lam & B.C. Buchler

Affiliations | Contributions | Corresponding author

Nature Communications 2, Article number: 174 | doi:10.1038/ncomms1175
Received 02 September 2010 | Accepted 23 December 2010 | Published 01 February 2011

recall efficiency of 87%




nature physics

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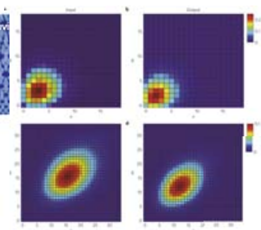
NATURE PHYSICS | ARTICLE

Unconditional room-temperature quantum memory

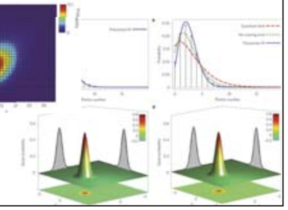
M. Hosseini, G. Campbell, B. M. Sparkes, P. K. Lam & B. C. Buchler

Affiliations | Contributions | Corresponding author

Nature Physics 7, 794–798 (2011) | doi:10.1038/nphys2021
Received 03 March 2011 | Accepted 09 May 2011 | Published online 12 June 2011



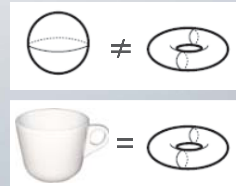
fidelity of 98%



Emulating quantum physics

TOPOLOGY

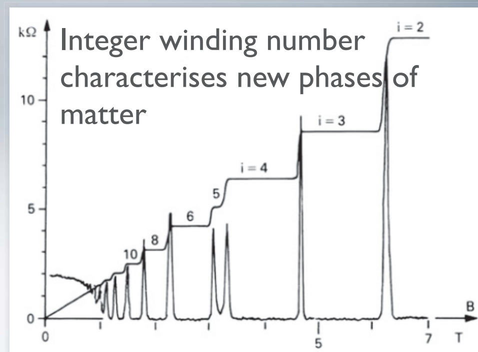
Geometry:
concerned with spatial properties which persist under continuous deformations of objects



Topological invariant, Z = Number of holes

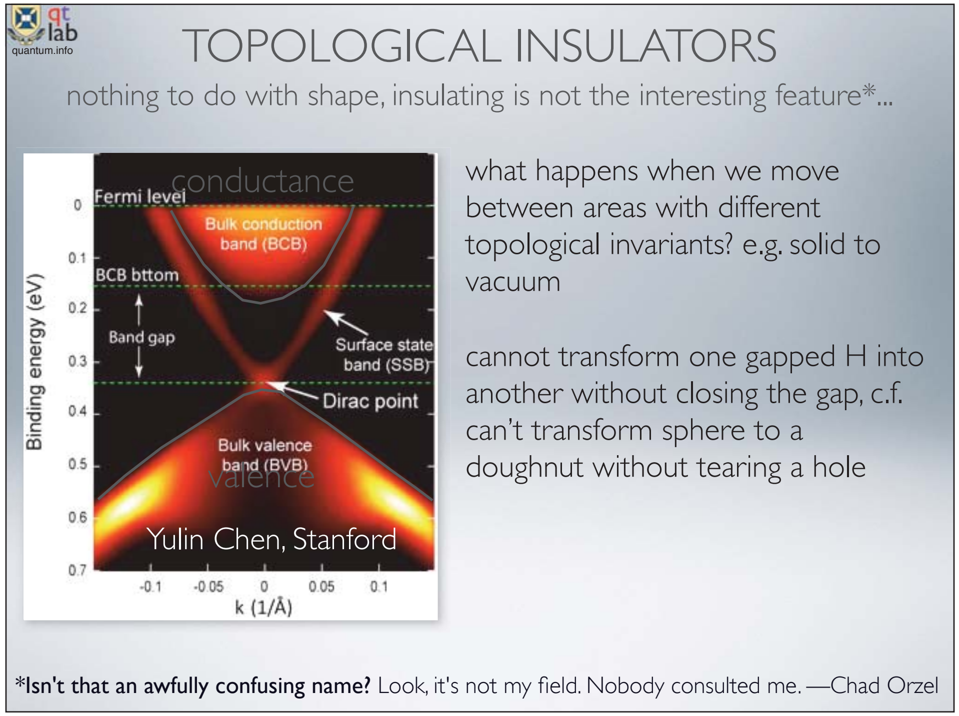
Quantum physics:
properties which persist under continuous deformations of system Hamiltonian

eigenstates have closed trajectories
winding in ground-state
wavefn, not undone by microscopic details



Quantum Hall effect

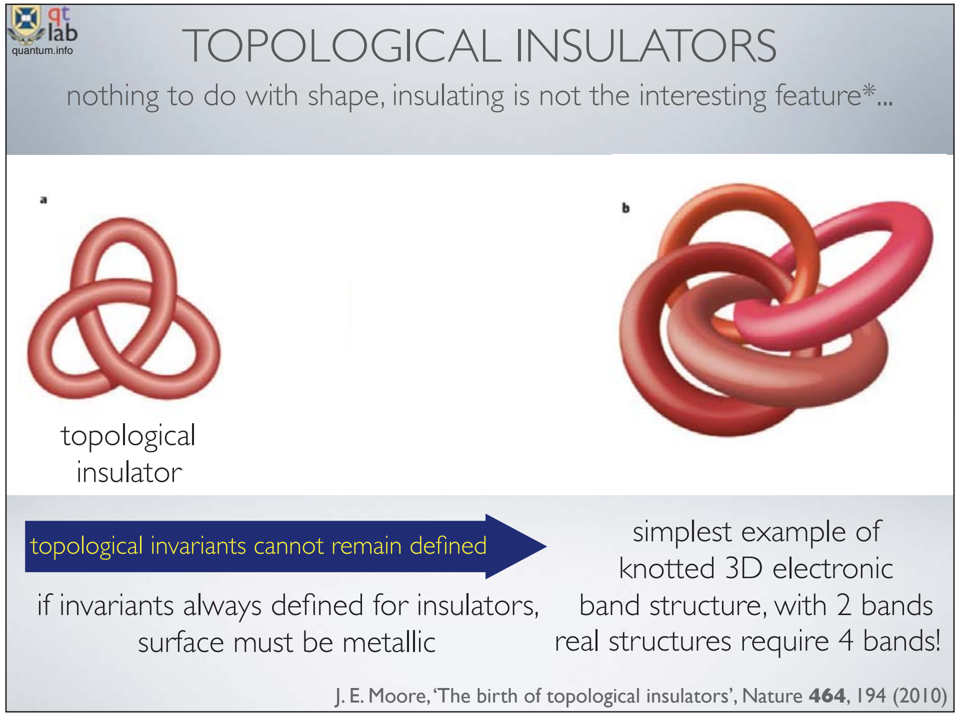
We study 1D topological phases using quantum walks



move from one bulk to another area, e.g. vacuum, with a different topological invariant

cannot transfrom one gapped H into another without closing the gap, c.f. can't transfrom sphere to doughnut with tearing a hole.

so insulator now has significant surface condductance, protected by topology



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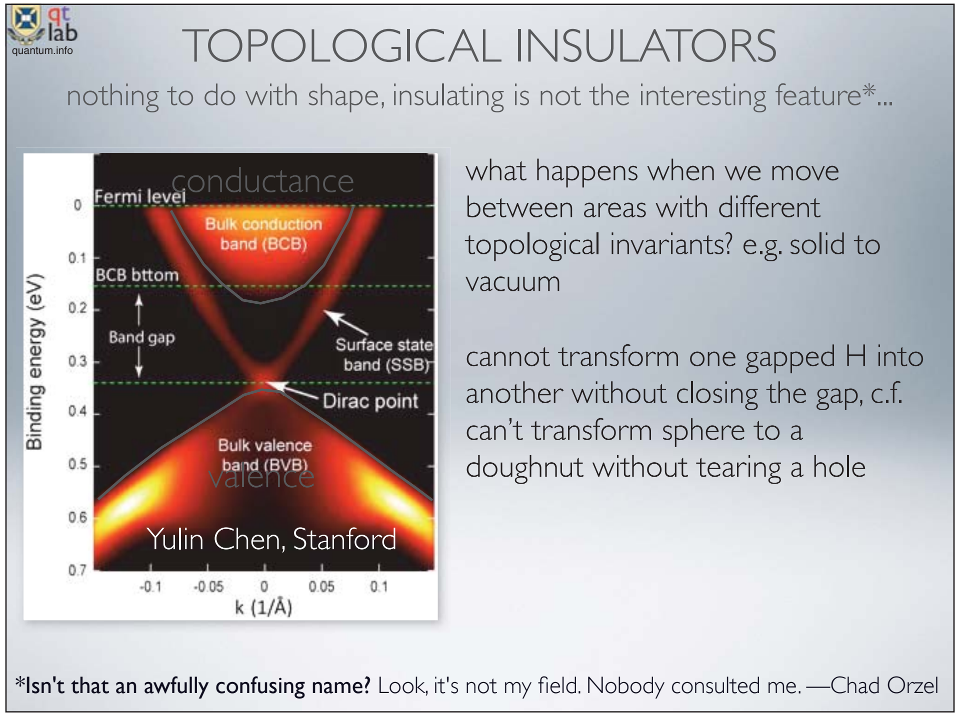

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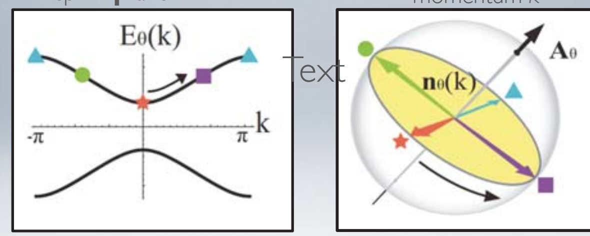
TOPOLOGICAL INSULATORS & QUANTUM WALKS

$$H(\theta) = \int_{-\pi}^{\pi} dk[E_\theta(k)n_\theta(k)\sigma] \otimes |k\rangle\langle k|$$

Quasi-energy spectrum for spin **up** and **down**

Spinor eigenstates at each momentum *k*



winding number, Z

$$U(\theta) = e^{iH(\theta)\delta t} \qquad U(\theta) = \hat{T}\hat{R}(\theta) \qquad U^N(\theta) = e^{iH(\theta)N\delta t}$$

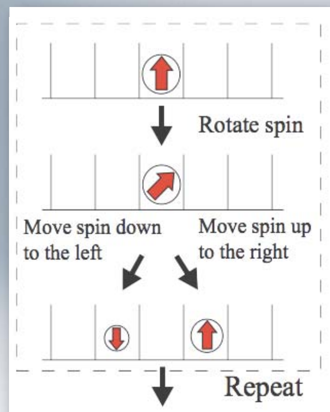
Kitagawa, Berg, Rudner and Demler, *Exploring Topological Phases With Quantum Walks*, PRA, **82**, (2010)

unitvector $n_\theta(k)$= (n_x, n_y, n_z) defines the quantization axis for the spinor eigenstates at each momentum k, $\sigma = (\sigma_x, \sigma_y, \sigma_z)$ is the vector of Pauli matrices

Because the evolution is prescribed stroboscopically at unit intervals, the eigenvalues $\pm E_\theta(k)$ of $H(\theta)$ are only determined up to integer multiples of 2π. The corresponding band structure is thus a "quasi-energy" spectrum, with 2π periodicity in energy.

Etheta energy eigenstates,
A theta are the spinor eigenstates

QUANTUM WALKS



$$\hat{R}(\theta) = e^{-i\theta\sigma_y} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix}$$

$$\hat{T} = \sum_x |x-1\rangle\langle x| \otimes |0\rangle\langle 0| + |x+1\rangle\langle x| \otimes |1\rangle\langle 1|$$

$$= \sum_k e^{ik\sigma_z} \otimes |k\rangle\langle k|$$

$$U(\theta) = \hat{T}\hat{R}(\theta)$$

Kitagawa, Berg, Rudner and Demler, *Exploring Topological Phases With Quantum Walks*, PRA, **82**, (2010)

coin and step now rewritten in momentum space

TOPOLOGICAL PHASES & DISCRETE QUANTUM WALKS

$$H(\theta) = \int_{-\pi}^{\pi} dk[E_\theta(k)n_\theta(k)\sigma] \otimes |k\rangle\langle k|$$

Particle-hole symmetry ✓

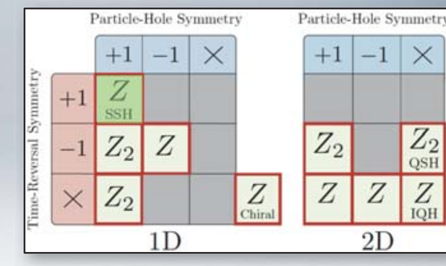
$$PHP^{-1} = -H$$
$$P^2 = 1$$

Chiral symmetry ✓

$$\Gamma_\theta^{-1} H(\theta)\Gamma_\theta = -H(\theta)$$
$$\Gamma_\theta = e^{-i\pi A_\theta \sigma/2}$$

Time-reversal symmetry ✓

$$THT^{-1} = H$$
$$T = \Gamma_\theta P$$
$$T^2 = 1$$

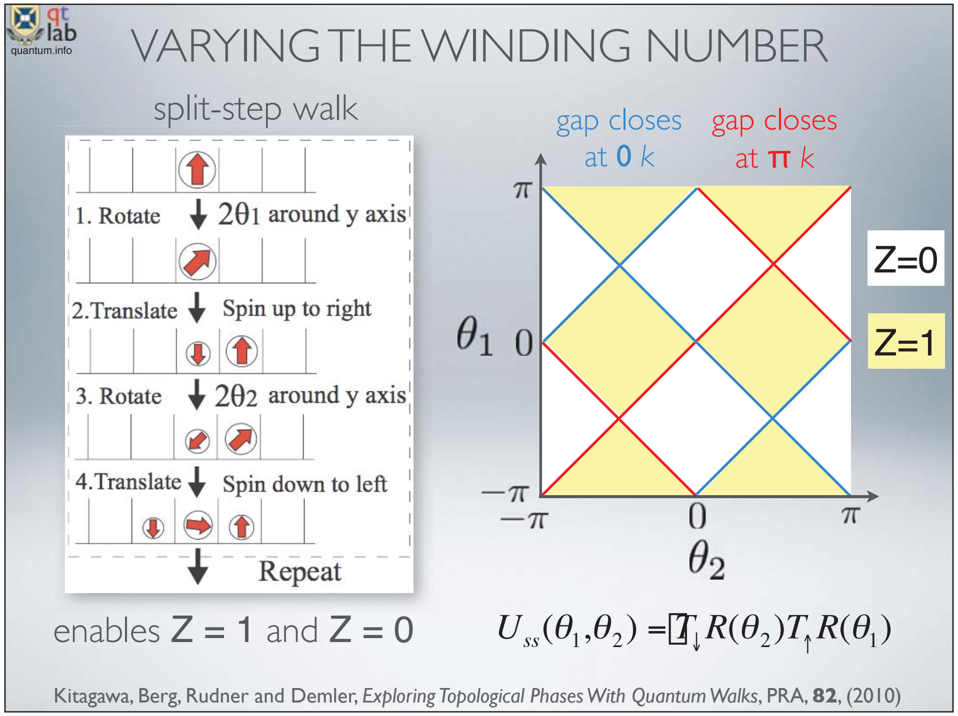


All QW to date, **Z = 1**

Kitagawa, Berg, Rudner and Demler, *Exploring Topological Phases With Quantum Walks*, PRA, **82**, (2010)

TR follows from chiral and PH. The other CPT. So must be in top-left box, PH and TR classify, and chiral gives the flavour.

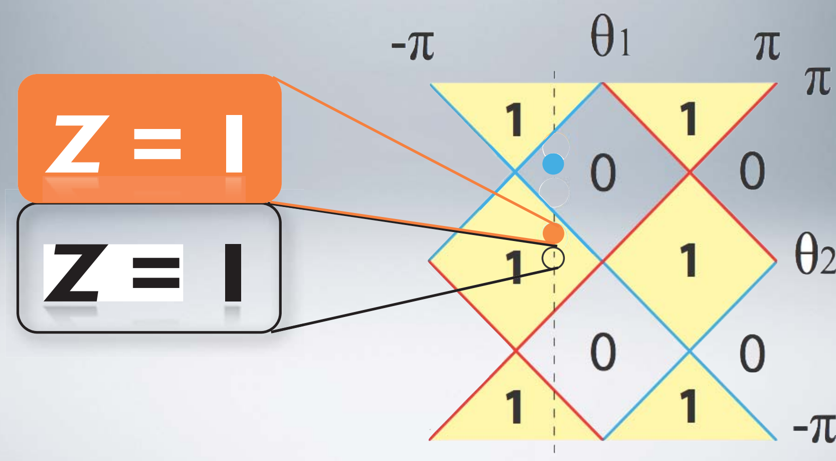
For canonical QW (using Hadamard), Z=1. Everyone who has done QW has done this. We want to study transition, to another Z. Modify H to allow different chiral sym.



different translations for spin-up and spin-down. Go back to syms, get this phase diagram. Blue is gap closes at pi, red is gap closes at 0.

VARYING THE WINDING NUMBER

$$U_{ss}(\theta_1, \theta 2) = T_\downarrow R(\theta_2) T_\uparrow R(\theta_1) = T_\downarrow R[\theta_2(x)] T_\uparrow R(\theta_1)$$



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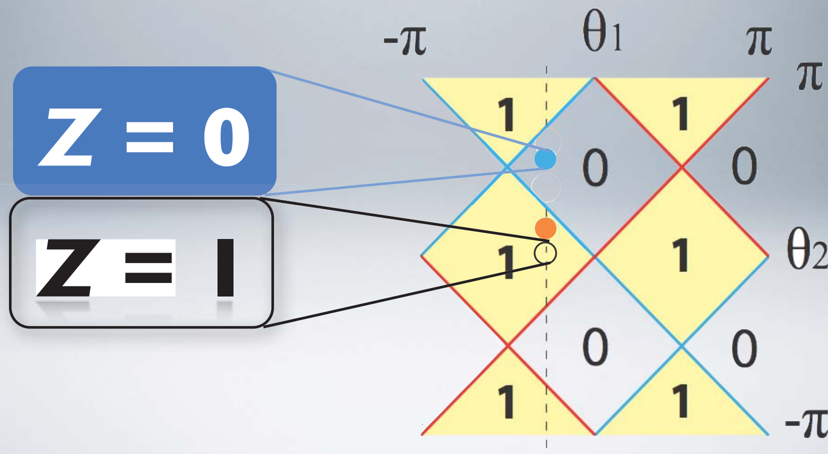
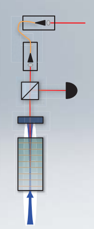
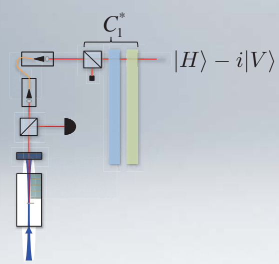


PHOTONIC DISCRETE-QW



Broome, Fedrizzi, Lanyon, Kassal, Aspuru-Guzik & White, PRL **104**, 153602 (2010)

PHOTONIC DISCRETE-QW



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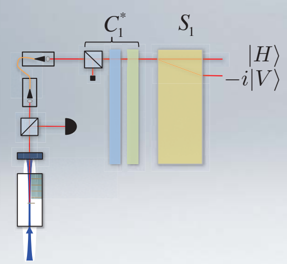

Broome, Fedrizzi, Lanyon, Kassal, Aspuru-Guzik & White, PRL **104**, 153602 (2010)

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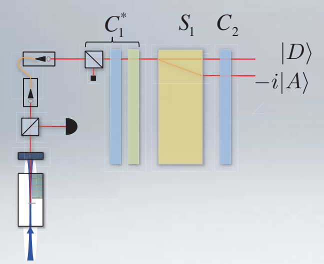

Broome, Fedrizzi, Lanyon, Kassal, Aspuru-Guzik & White, PRL **104**, 153602 (2010)

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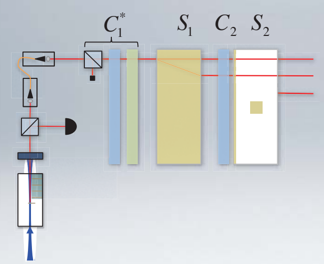


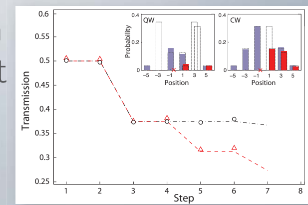
Broome, Fedrizzi, Lanyon, Kassal, Aspuru-Guzik & White, PRL **104**, 153602 (2010)

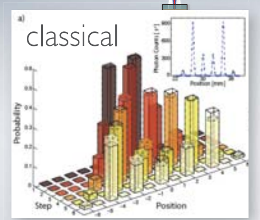
PHOTONIC DISCRETE-QW

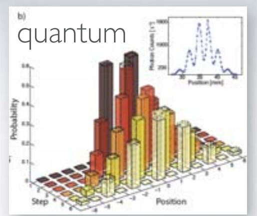
directly image
system wavefunction

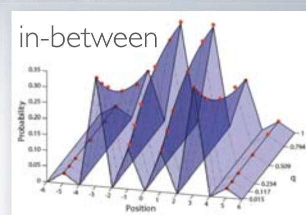
quantum
transport

See Alán's
slide on
ENACT

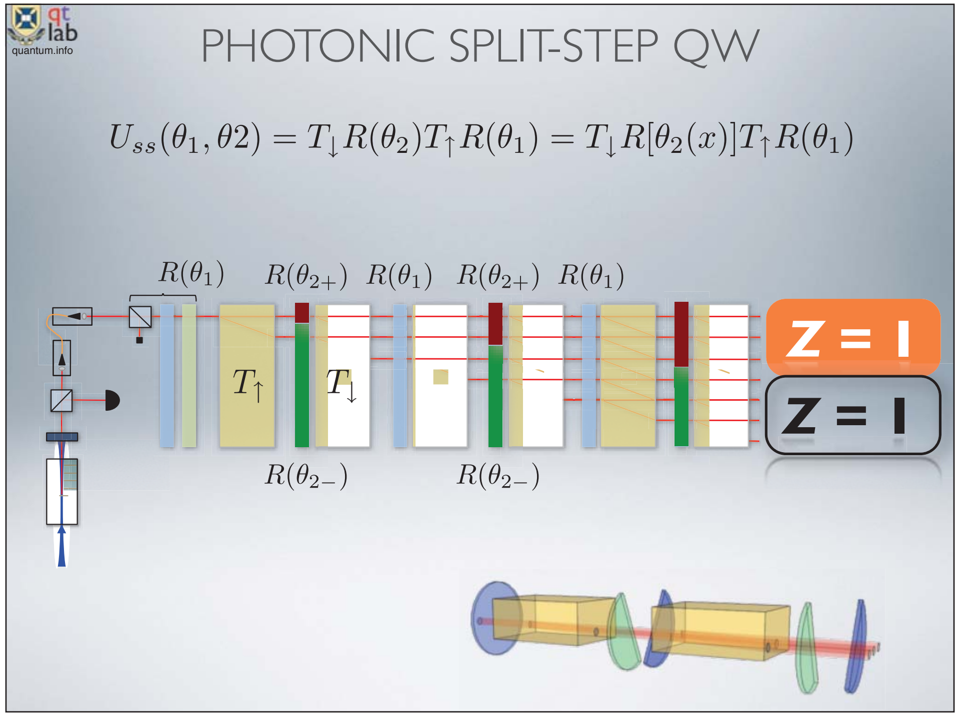




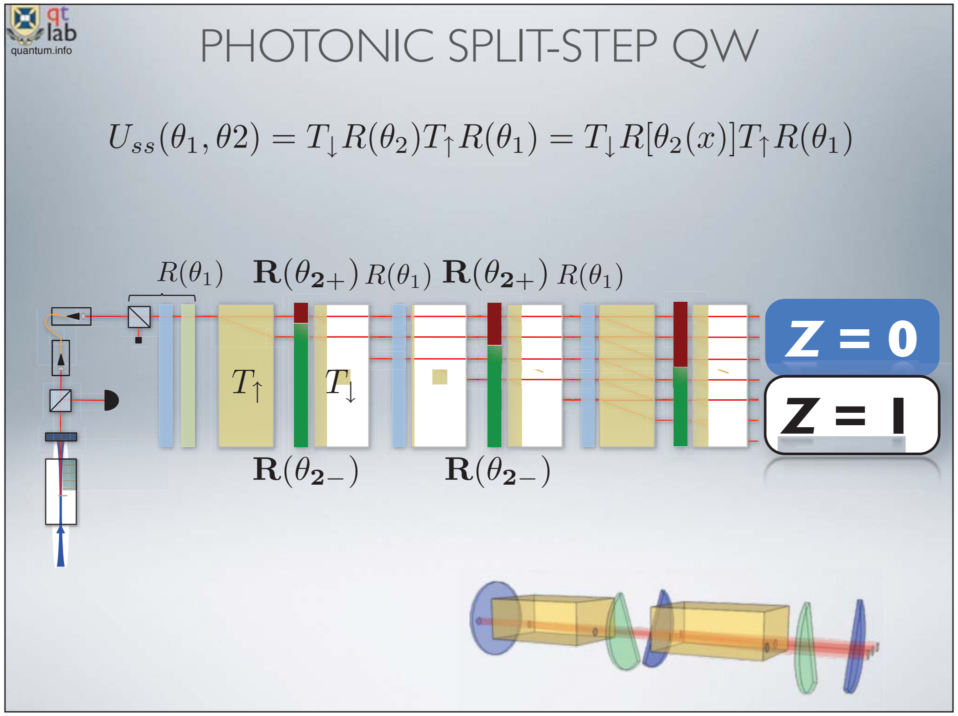




Broome, Fedrizzi, Lanyon, Kassal, Aspuru-Guzik & White, PRL **104**, 153602 (2010)



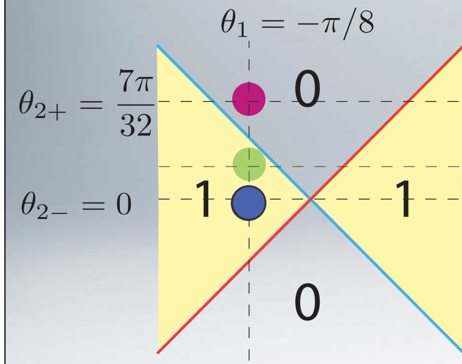
We can setup two distinct topological phases across the lattice



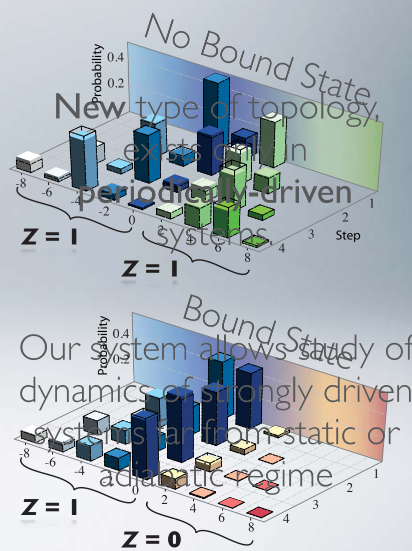
We can setup two distinct topological phases across the lattice

TOPOLOGICAL PHASE SIGNATURES

First confirmation of **robust bound states** as predicted for SSH – polyacetelyene and Jackiw-Rebbi – Fermi/Bose



behaviour function of **topology**, not start & end points



New type of topology, exists only in **periodically-driven** systems

Our system allows study of dynamics of strongly driven systems far from static or adiabatic regime

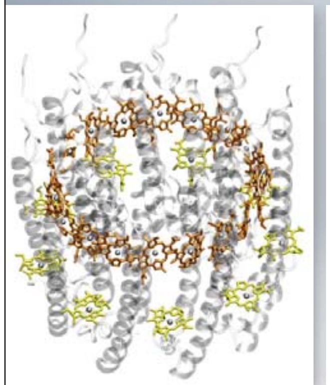
'Observation of topologically protected bound states in photonic quantum walks', *preprint* (2011)

Emulating quantum biology

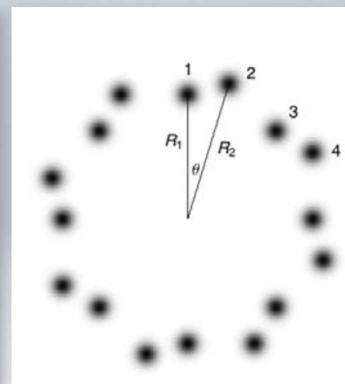
PHOTOSYNTHETIC TRANSPORT

Purple bacteria Rhodobacter Sphaeroides: light-harvesting complex (LH II)

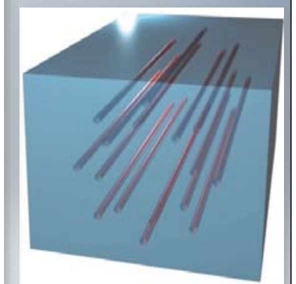
Exciton in light-harvesting complex: too fast for tunnelling



Bacteriochlorophyl rings
B800 and B850



Quantum walk
continuous,
circular, decohered



$$i\frac{\partial}{\partial z}a_k^\dagger(z) = \beta_k a_k^\dagger(z) + \sum_{j\neq k}^{N} C_{jk} a_j^\dagger(z)$$

$$C_{ij} = C_0 e^{-r_{ij}/r_0}$$

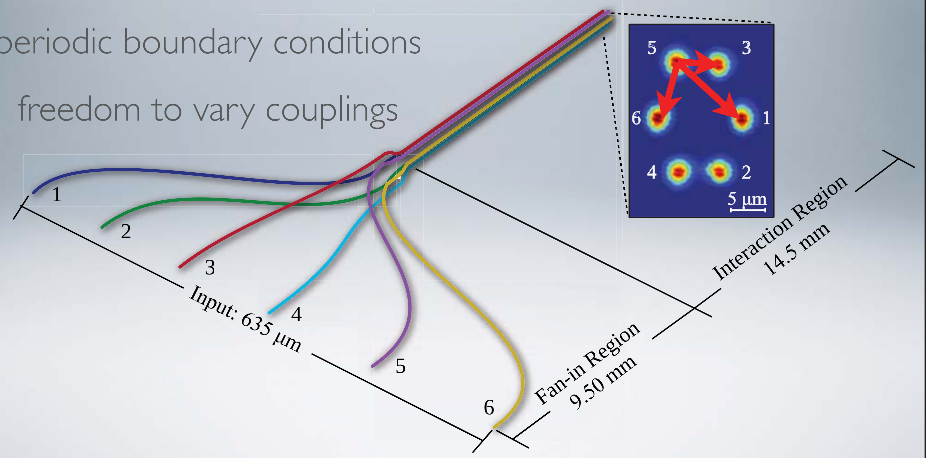
PRELIMINARY MODEL

Advantages

access to all inputs and outputs

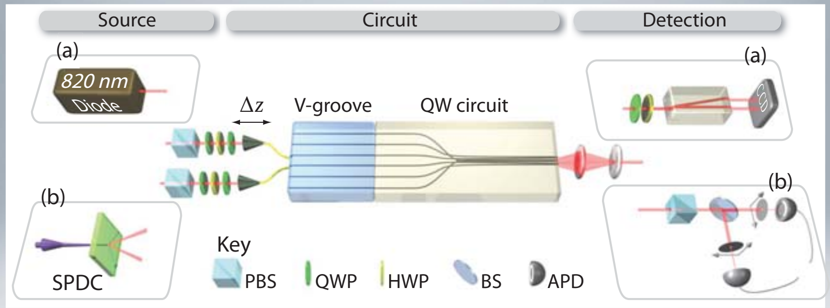
periodic boundary conditions

freedom to vary couplings



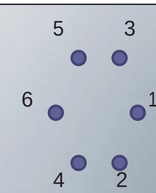
Owens, Broome, et al., New Journal of Physics **13**, 075003 (2011)

PRELIMINARY MODEL



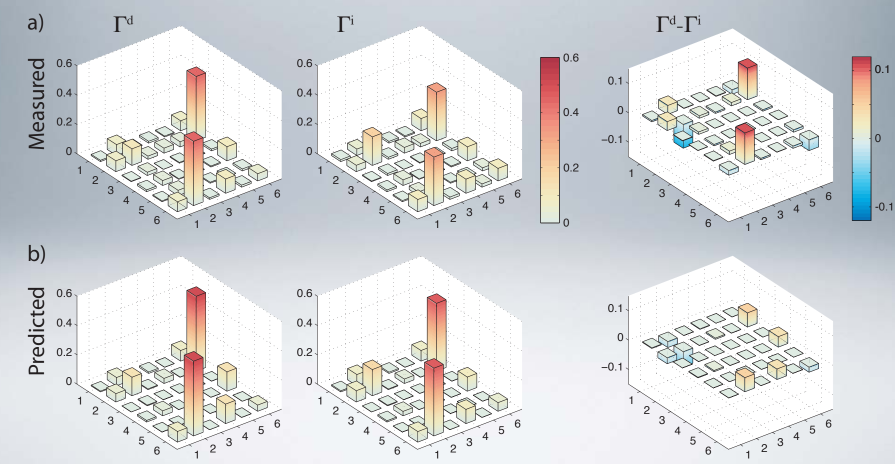
Owens, Broome, et al., New Journal of Physics **13**, 075003 (2011)

PRELIMINARY MODEL



Distinguishable
= non-interacting walkers

Indistinguishable
= interacting walkers



Owens, Broome, et al., New Journal of Physics **13**, 075003 (2011)

QUANTUM TOMOGRAPHY

State tomography: measure combinations of basis states

0	1	0 + 1	0 + i1
H	V	D	R

For 2-photon states, bi-photon Stokes parameters

HH	VH	DH	RH
HV	VV	DV	RV
HD	VD	DD	RD
HR	VR	DR	RR

n-qubit state requires: 4^n measurements (minimal)
6^n measurements (overcomplete)

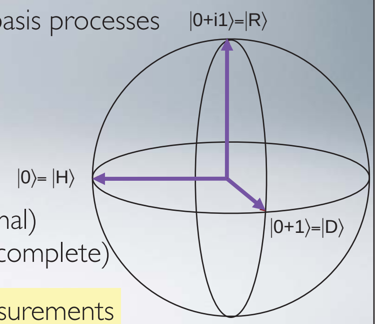
Process tomography: measure combinations of basis processes

For 1-photon gates: I X Y Z

For 2-photon gates:

I I	X I	Y I	Z I
I X	XX	YX	ZX
I Y	XY	YY	ZY
I Z	XZ	YZ	ZR

n-qubit gate requires: 16^n measurements (minimal)
24^n measurements (overcomplete)

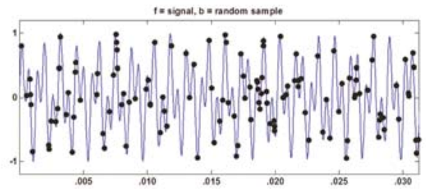


rotations on Poincaré sphere

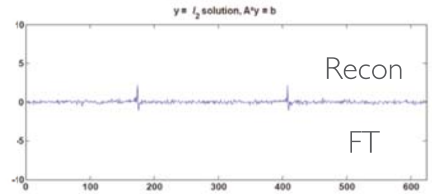
6-node ellipse circuit requires 191,102,976 measurements
Rhodobacter circuit requires 1.21×10^{22} measurements

White et al., JOSA B **24**, 172-183 (2007)

COMPRESSED SENSING



500 random samples ●
from 5000-pt signal



Compressed sensing
Least-squares reconstruction
(Sparse matrix)

Candès, Romberg, and Tao, IEEE Transactions on Information Theory, **52** 489 - 509 (2006)

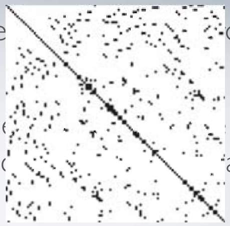
COMPRESSED TOMOGRAPHY

d-dimensional quantum system needs how many measurement configurations?

for qubits $d=2^n$

	Full QT	Compressed QT	
state	$O(d^2)$	$O(d\ r \log^2 d)$	quadratically faster blind, r is matrix rank
process	$O(d^4)$	$O(s \log d)$	exponentially faster needs prior, s is matrix sparsity

engineered quantum systems aim to imple ocess which is maximally-sparse in its eigenbasis



in practice—as observed in QPT experim NMR, photonics, ion traps, and superconducting arse, still compressible!

Gross, Liu, Flammia, Becker, & Eisert, PRL **105**, 150401 (2010).

Shabani, Kosut, Mohseni, Rabitz, Broome, Almeida, Fedrizzi, & White, PRL **106**, 100401 (2011)

COMPRESSED TOMOGRAPHY

two-photon CZ gate   low-noise, 91% purity

Compressed tomo   **Full tomo**

32 combinations

16 inputs
of H,V,D,R

2 measurements
of RI and IR

local measurements!

Re(χ_{32})

Re(χ_{576})

F=95%

Im(χ_{32})

Im(χ_{576})

Shabani, Kosut, Mohseni, Rabitz,
Broome, Almeida, Fedrizzi, and White,
PRL **106**, 100401 (2011)

COMPRESSED TOMOGRAPHY

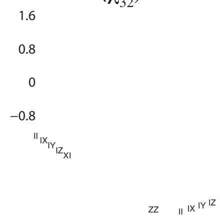
four-photon CZ gate

high-noise, 62% purity

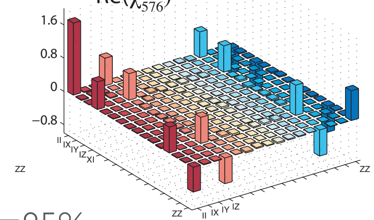
Compressed tomo	Full tomo

32 combinations

$\mathrm{Re}(\chi_{32})$



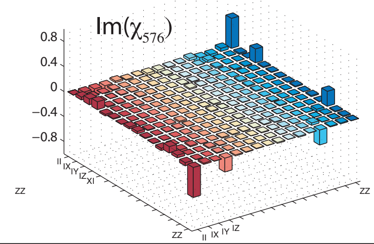
$\mathrm{Re}(\chi_{576})$



F=85%

$\mathrm{Im}(\chi_{32})$

$\mathrm{Im}(\chi_{576})$



Shabani, Kosut, Mohseni, Rabitz, Broome, Almeida, Fedrizzi, and White, PRL **106**, 100401 (2011)

Conclusions

quantum.info

Take home messages

Simulation and emulation are different, and both valuable
Photonic quantum information is rapidly becoming scalable
Tomography is now a lot faster than it was

PhD, Postdocs available! See quantum.info

PRL **90** 193601 (2003)
Nature **426**, 264 (2003)
PRL **92**, 190402 (2004)
PRL **93**, 053601 (2004)
PRL **93**, 080502 (2004)
PRL **94**, 220405 (2005)
PRL **94**, 220406 (2005)
PRL **95**, 048902 (2005)
PRL **95**, 210504 (2005)
Nature **445**, E4 (2007)
PRL **98**, 203602 (2007)
PRL **98**, 223601 (2007)
Nature Phys. **5**, 134 (2009)
Nature Chem. **2**, 106 (2010)
PRL **104**, 153602 (2010)
Optics Express **19**, 55 (2011)
PNAS **108**, 1256 (2011)
PRL **106**, 100401 (2011)
PRL **106**, 200402 (2011)
Nature Comm. **3**, 625 (2012)
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