Physics Illinois

Optical Quantum Information Processing

P. Kwiat

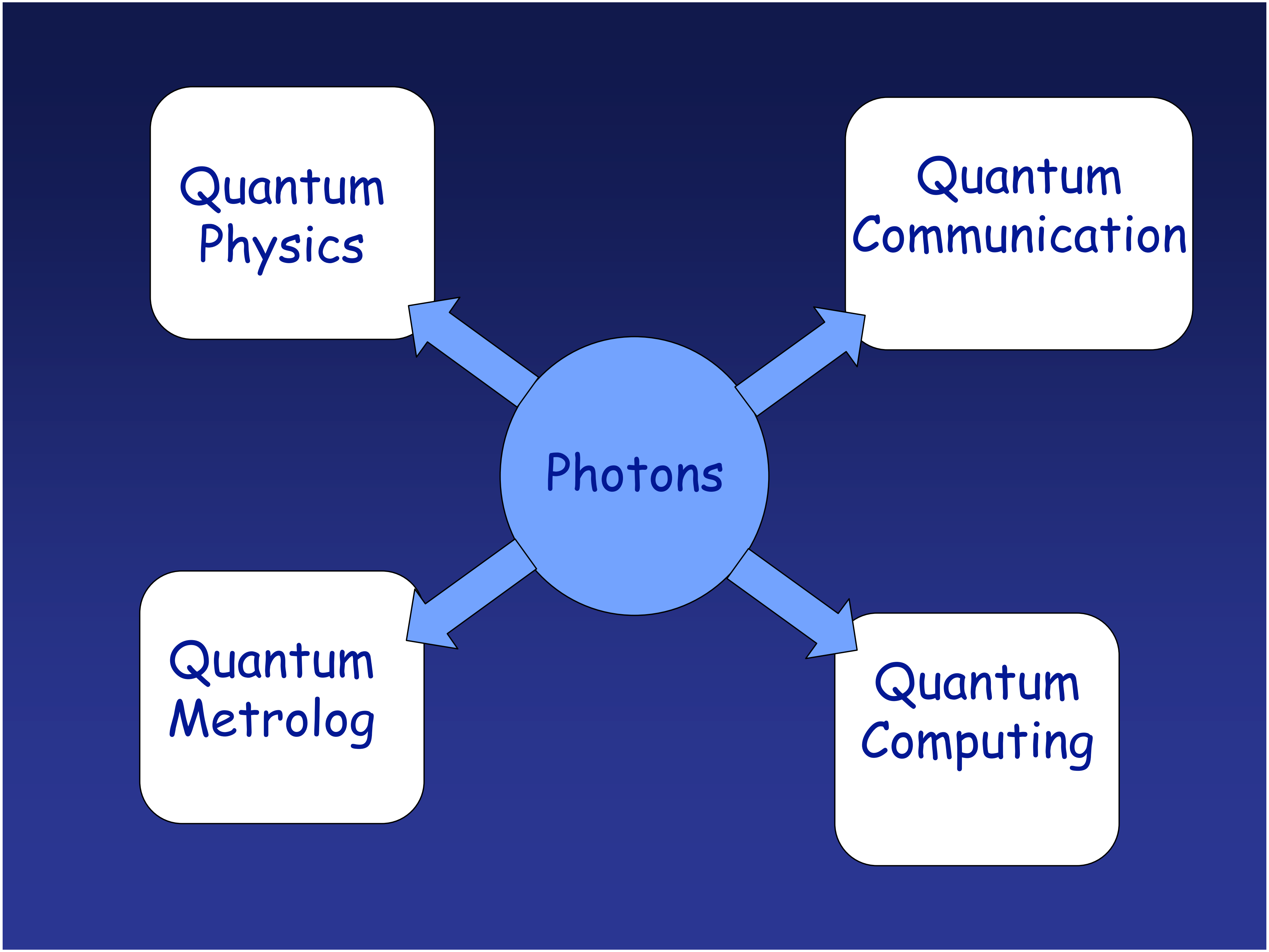
An inaccurate history

An incomplete progress report

An unbiased vision…not

Anti-Outline

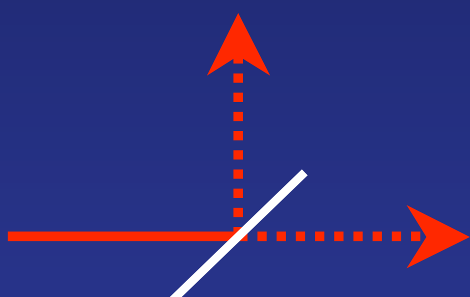
- Continuous-variable systems
- Atom-photon systems (cf. Kimble)
- Hybrid systems (cf. Lukin)
- Quantum imaging, or not
- …


Quantum Physics
Quantum Communication
Photons
Quantum Metrolog
Quantum Computing

1905: Einstein proposed that light was really particles (for which he got the Nobel prize!)

How do you prove it?

The Beamsplitter...



Photon only detected in one output.

-use $g^{(2)} = 0$ to test sources...

Equally likely to be transmitted or reflected -- cannot tell which:

-quantum random number generator (patented)

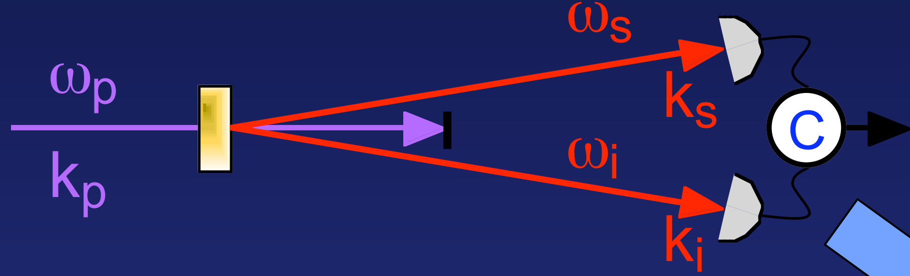
Resources for *Photonic* Quantum Information Processing

Photonon, but just 1:

- -Single emitter
  - -atom/ion (Kimble) [hard to collect]
  - -quantum dot ("designer atom")
    - [BUT no two exactly alike…]

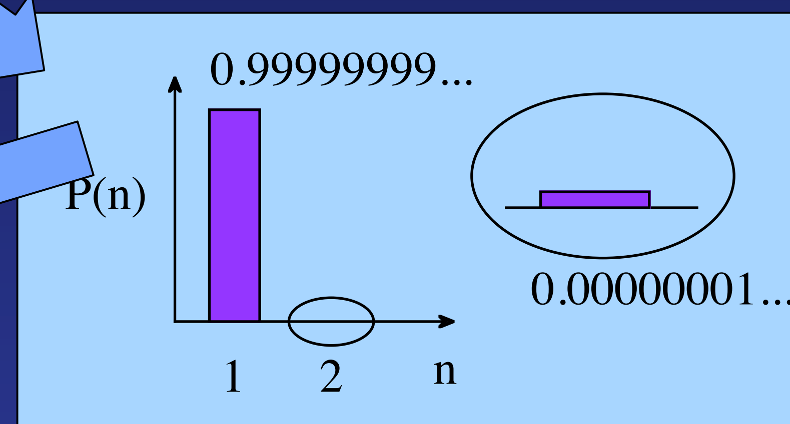
- -Pair sources (SPDC, 4-wave mixing)
  - -detection of signal photon -->
    "heralds" presence of idler photon
    in well-defined mode

Resources for *Photonic* Quantum Information Processing



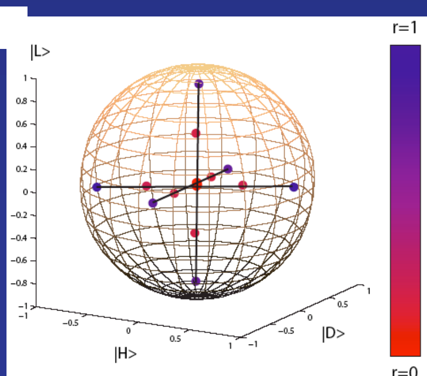
Spontaneous Parametric Downconversion

Well-behaved spatial modes



Conditional 1-photon per mode

High-quality OTS components ⇒ >99.9% fidelity 'gates'



NOT "on-demand" (multiplexed sources help)

Resources for Photonic Quantum Information Processing

Detectors:

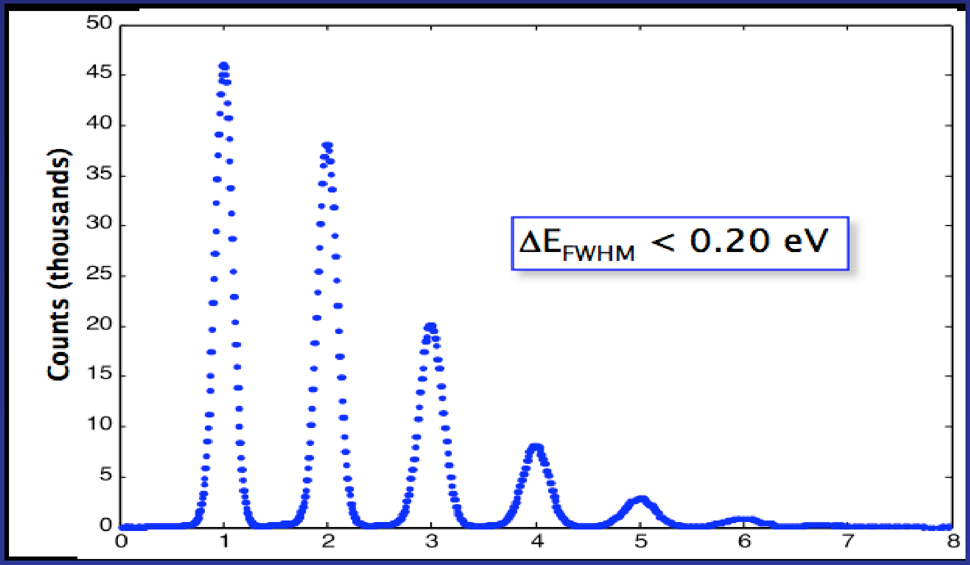
- What we want
  - high efficiency (at λ), low noise
  - fast (ideally at 100-fs scale)
  - photon-number resolving
- What we have now*
  - APDs, VLPCs, TES, SSPDs
  - η ~ 85-95% (visible to 1550 nm)
  - 1 MHz - 1 GHz
  - can resolve up to ~10 photons

But NOT all at once!

Resources for Photonic Quantum Information Processing

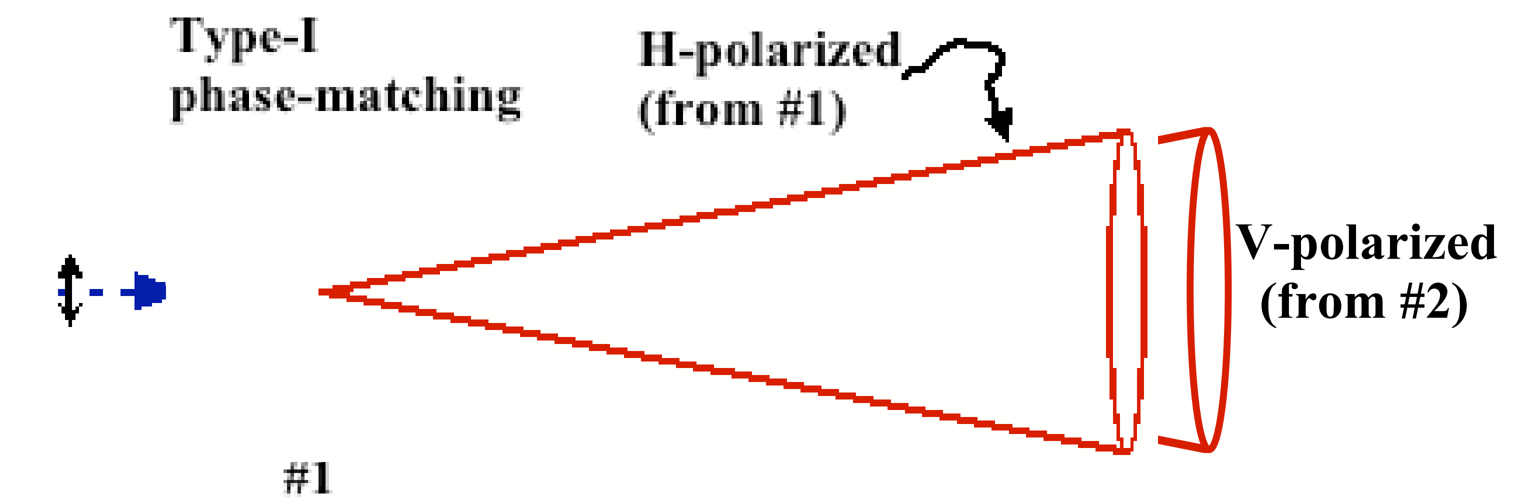
Superconducting bolometric detectors NIST

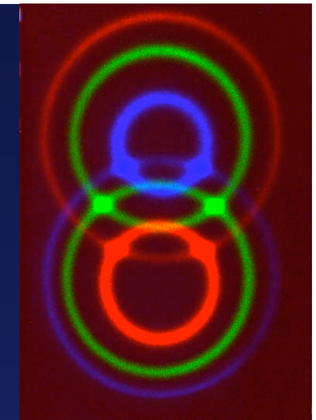
-system efficiency (at 1550 nm) ~95%
(pushing toward 99%)
-near-perfect photon-number resolution
-slow-ish (0.1 - 1 μs)



A.E. Lita, A. J. Miller, and S. W. Nam, Opt. Exp. 16, 3032 (2008)

(Polarization-) Entangled Source:

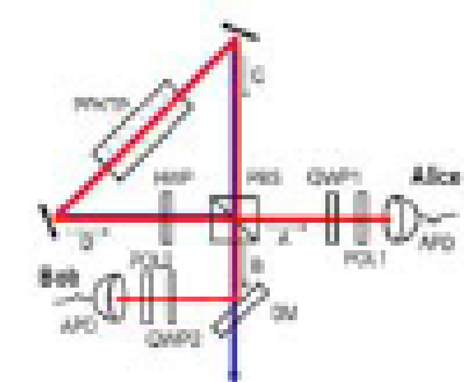




PRL **75**, 4337 (1995)

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2 + e^{i\varphi}|V\rangle_1|V\rangle_2\right)$$

Maximally entangled state



Tune pump polarization: → Nonmax. entangled, mixed states
Stable, simple → Used to test QM in various undergrad labs
New ultra-bright versions, narrow bandwidth, …

Not on-demand, unwanted entanglement in other DOFs

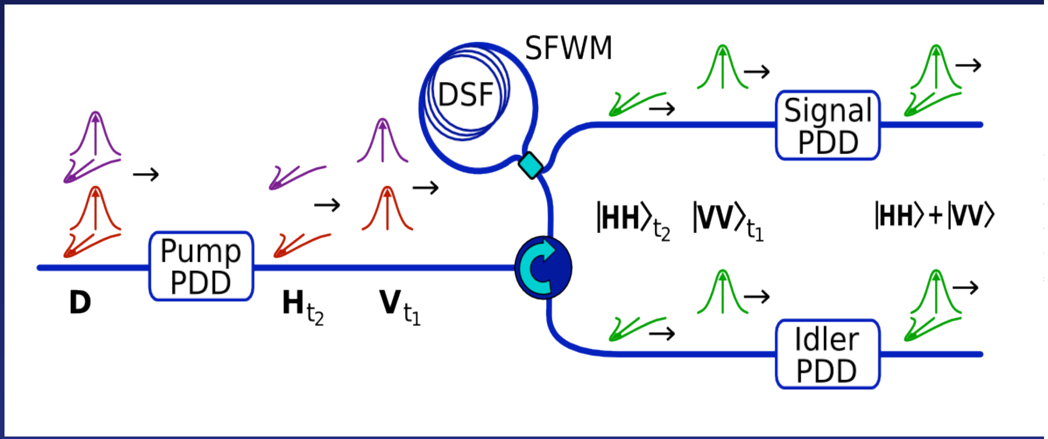
Fiber-Based Sources (4-wave mixing)

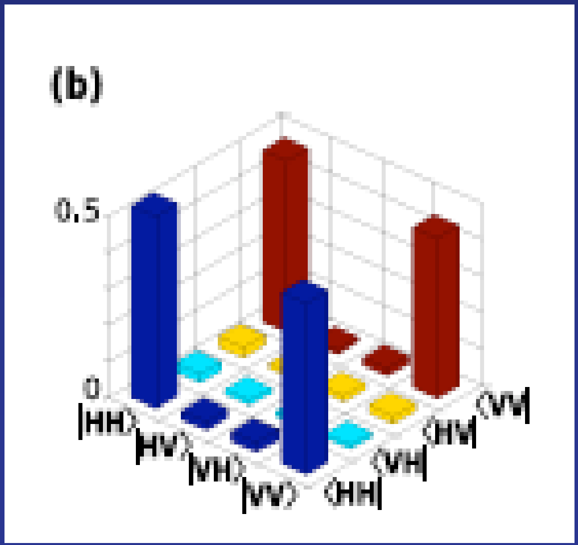
@ NIST, Northwestern,…

- Pairs created in fiber i.e., naturally single-mode
- Low-loss
- Exploits existing telecom infrastructure
- 1550 nm or 1310 nm
- Require cryogenic cooling

Degenerate Entanglement

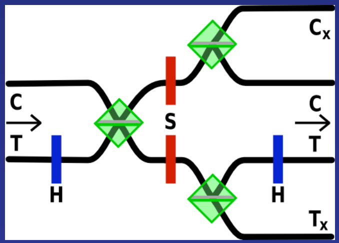
Medic, et al. *CLEO Conference 2009*, paper ITuE7.

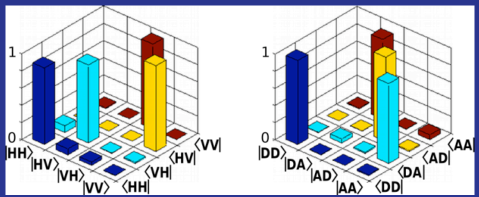




F = 96%

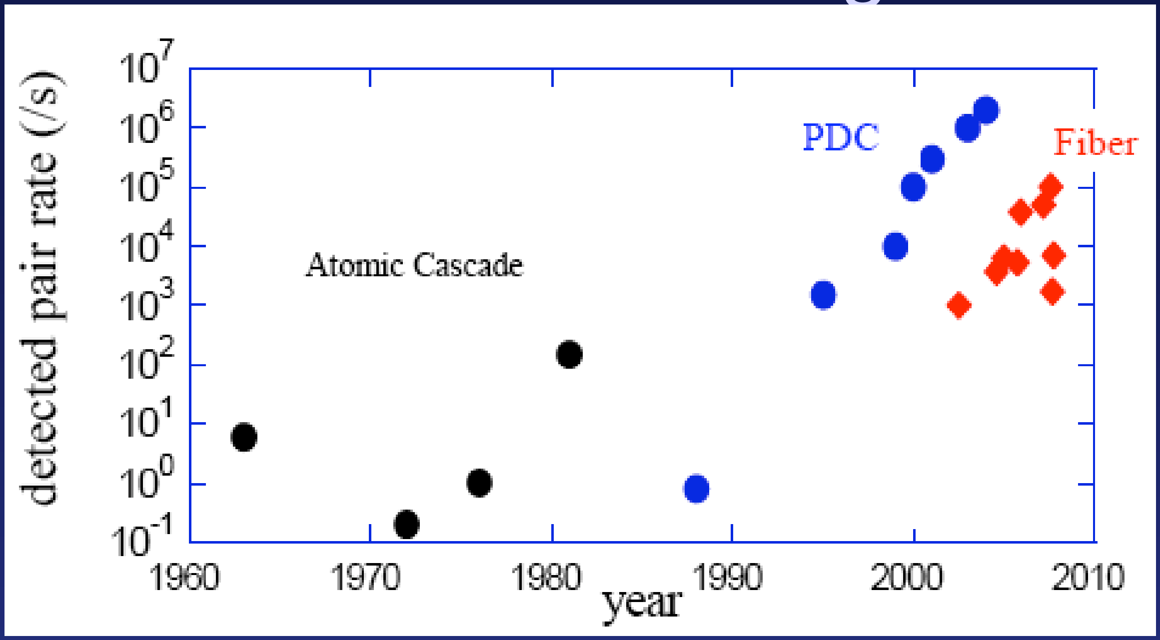
LOQC Gates



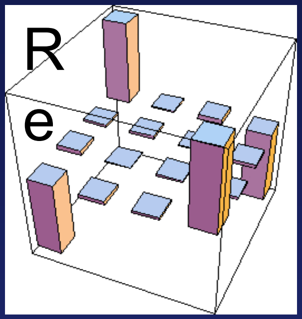


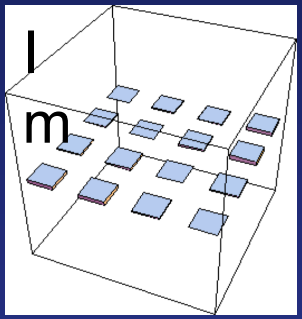
Chen, et al. *Phys. Rev. Lett.* **100**, 133603 (2008).

Moore's law for entanglement



$\Phi^{(-)} \sim |HH\rangle - |VV\rangle$





F >99.5%

Polarization-entangled pairs @ 2,000,000 s^{-1}, with F ~98%, T > 96% Opt. Exp. **13**, 8951 (2005)

Next main limitation: detector saturation

Now: Various tests with 2-5 photons (GHZ), with different DOFs, "qudits", etc.
More to come…

Bell-Ineq. Tests

$S_{LHV} \leq 2$ $|S_{expt}| = 2.7260 \pm 0.0008$ (216σ in 0.8 s)

Optimized Bell test: **$|S_{QM, max}| = 2\sqrt{2} = 2.828$**

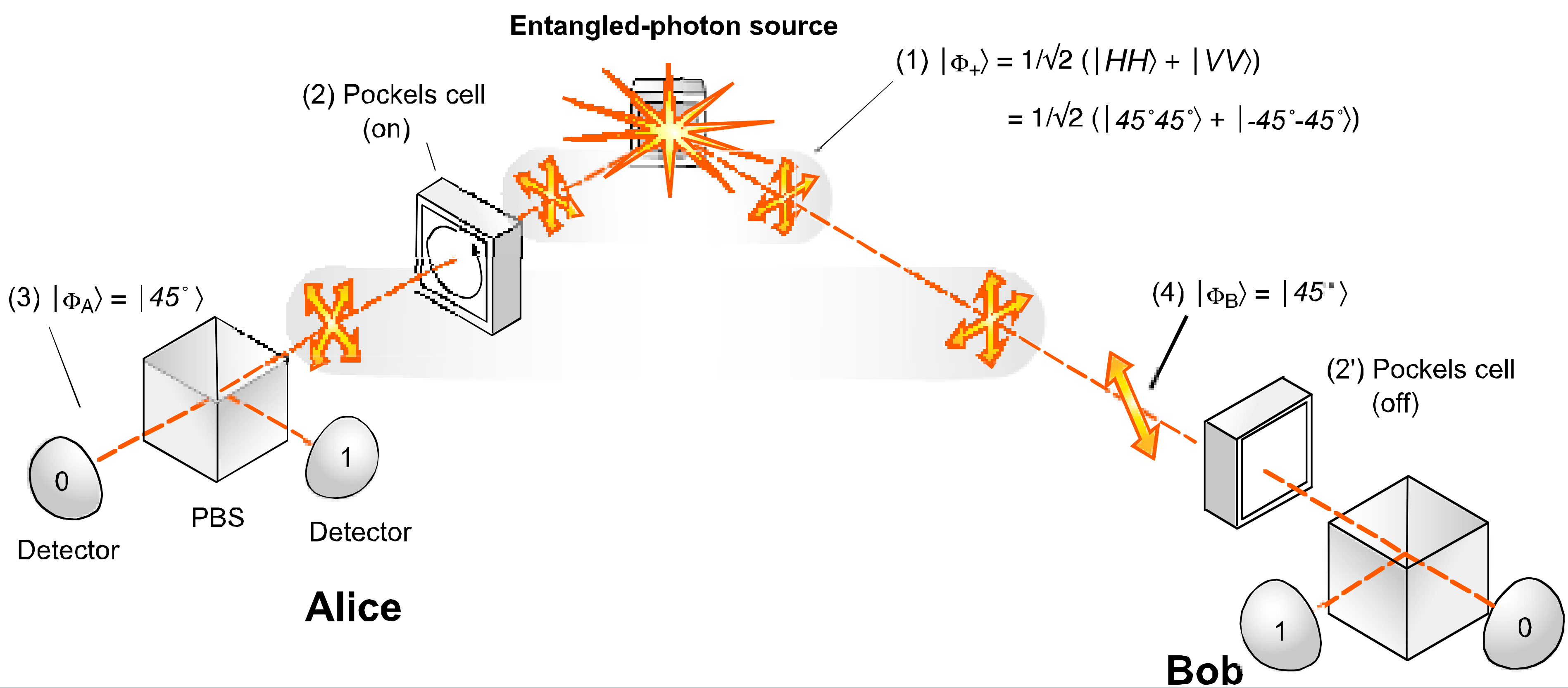
$|S_{expt}| = 2.826 \pm 0.005$ 165σ

on (and QKD) over 144-km
nd Tenerife (QIPS)

Now heading into space…

R. Ursin, et al. Nat. Phys. 3, 481 (2007)

Entangled-Photon Quantum Cryptography



- Alice & Bob randomly measure polarization in the (HV) or the (45 -45) basis.
- Discuss via a "public channel" which bases they used, *but not the results*.
- Discard cases (50%) where they used different bases → uncorrelated results.
- Keep cases where they used the same basis → *perfectly correlated results!*
- Define H ≡ "0" ≡ 45, V ≡ "1" ≡ –45. **They now share a secret key.**

Entanglement Advantages for QKD

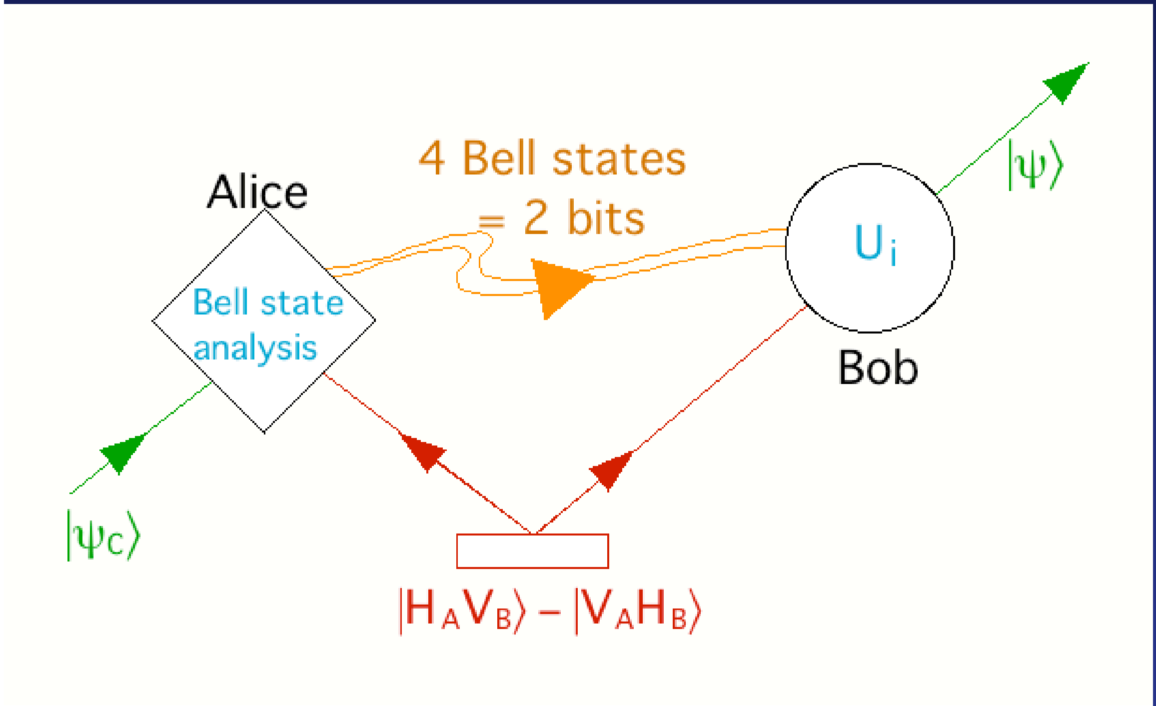
- **Automatic randomness of key**
- **Longer distances accessible (since Bob knows *when* to look for a photon) [But decoy states…]**
- **Established methods to verify security of key**
- **Source can be automatically verified (even if "sold" by Evesdropper!)**
- **"Monogamy of entanglement":**
  Any leakage of info to other DOF
  ⇒ increased bit error rate (BER)

Challenges: Source brightness/robustness to compete, e.g., with Decoy-state QKD. *Fast* quantum repeaters for long distance key distribution.

Quantum Teleportation [Bennett *et al. Phys. Rev. Lett.* **70**, 1895 (1993)]

The basic idea –> transfer the (infinite) amount of information in a qubit from Alice to Bob without sending the qubit itself.

Requires Alice and Bob to share entanglement:



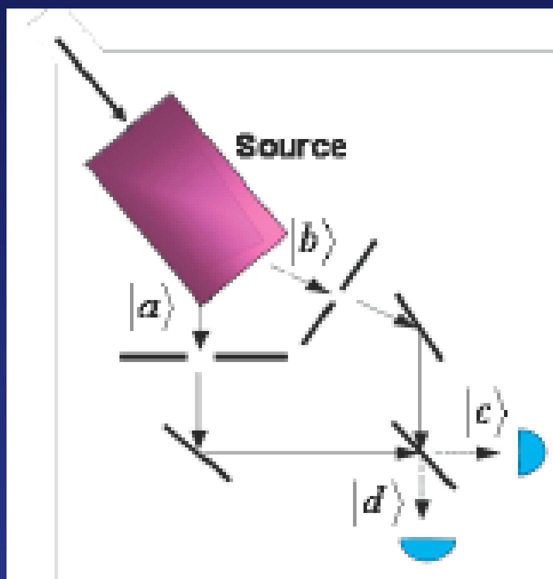
E.g. Alice measures photons C and A to be in a singlet state. Since C and A are orthogonal, and A and B are orthogonal, C and A must be *identical*!

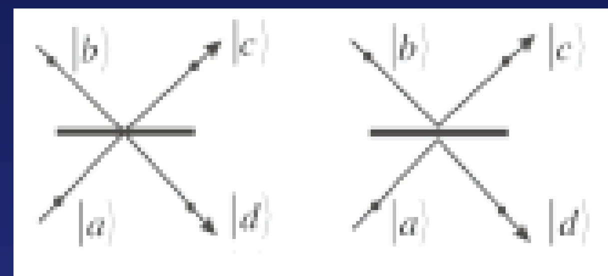
Remarks:

- **The original state is gone.**
- **Neither Alice nor Bob know what it was.**
- **Requires classical communication – no superluminal signaling.**
- **Bell state analysis is *hard*…**

Two-Photon Interference

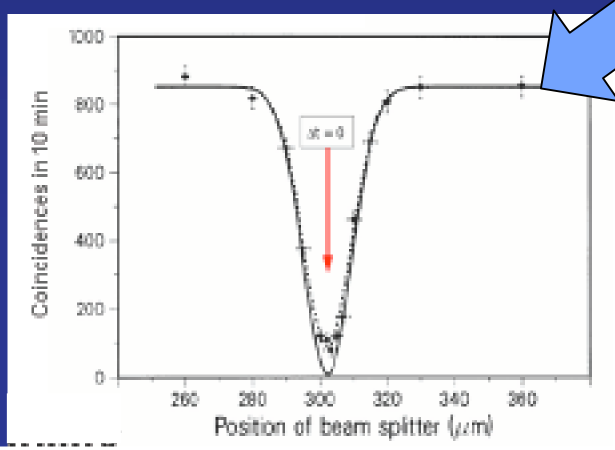
Traditional Hong-Ou-Mandel: interfere two photons (from same source):





$$\left|\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}+\frac{i}{\sqrt{2}}\frac{i}{\sqrt{2}}\right|^2=0$$

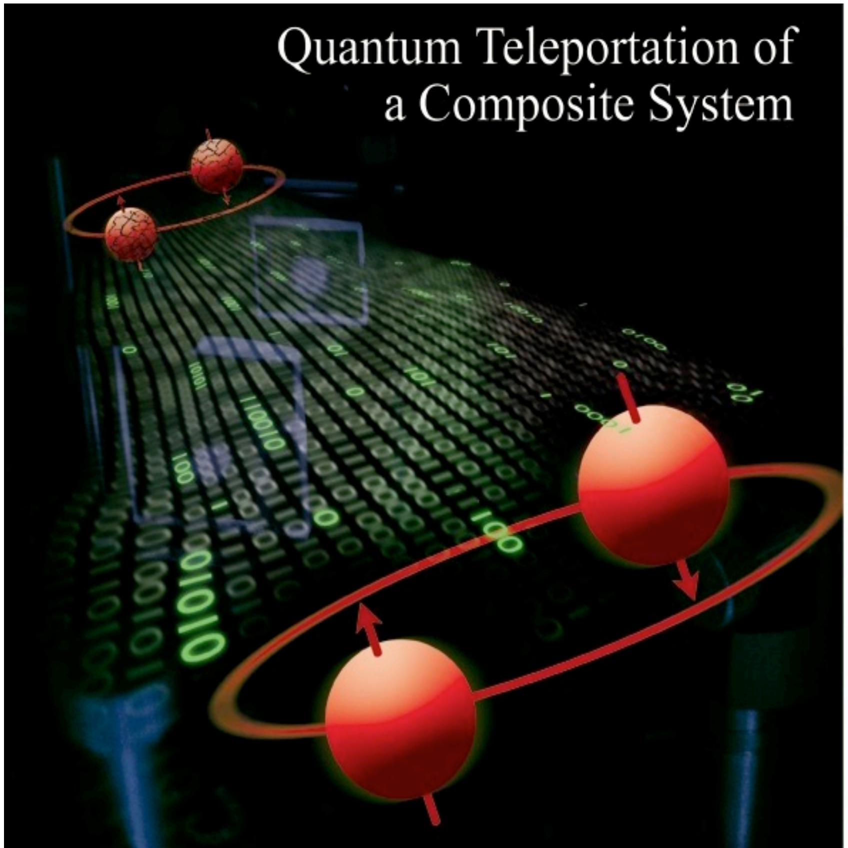
Coincidence Probability



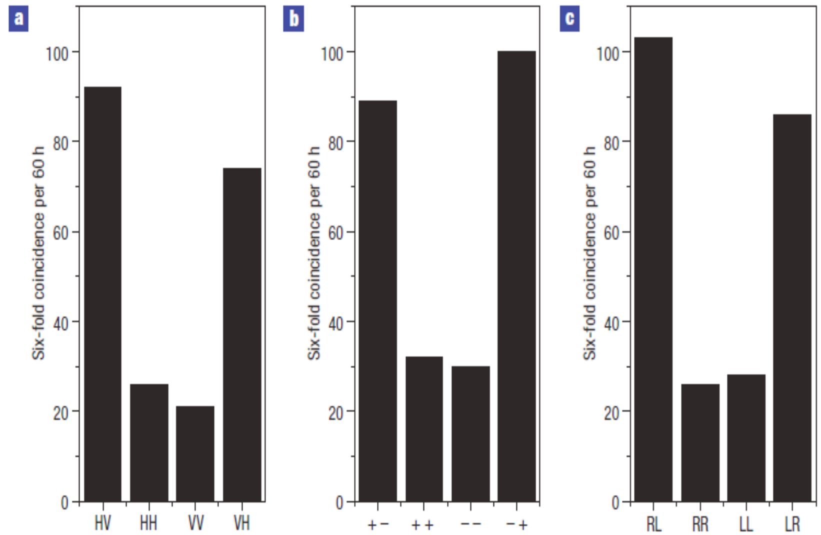
Photons must be indistinguishable (& not entangled to *other* photons)!

Experimental Teleportation

Bouwmeester et al., Nature **390**, 575 (1997)



Experimental results of teleporting an entanglement



But very low rate -- 6-photon experiment: 100/60 hours

Q. Zhang et al. Nature Physics 2, 678 (2006)

N

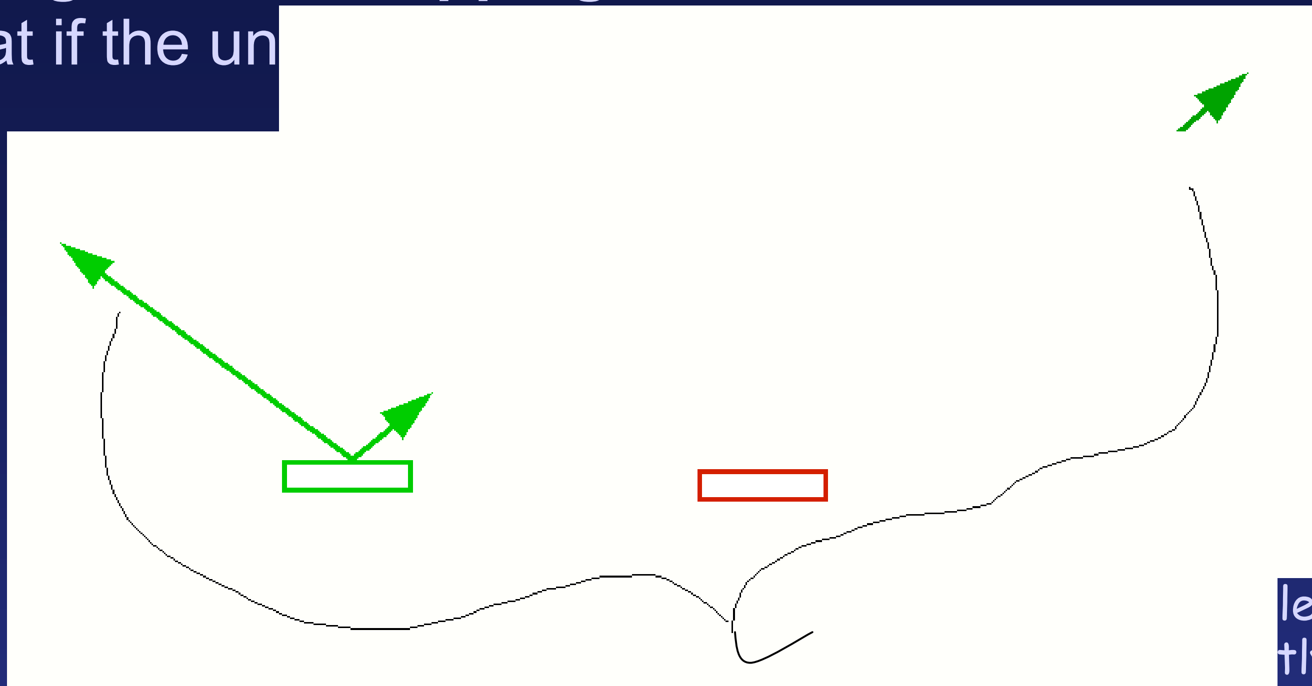
states of ions, other degrees of freedom, 2-qubits, entanglement,…

What are the limits? How large (complex) of a system?

How far? How fast? Teleport complex “process”?

Entanglement Swapping

What if the un … a 4th particle?

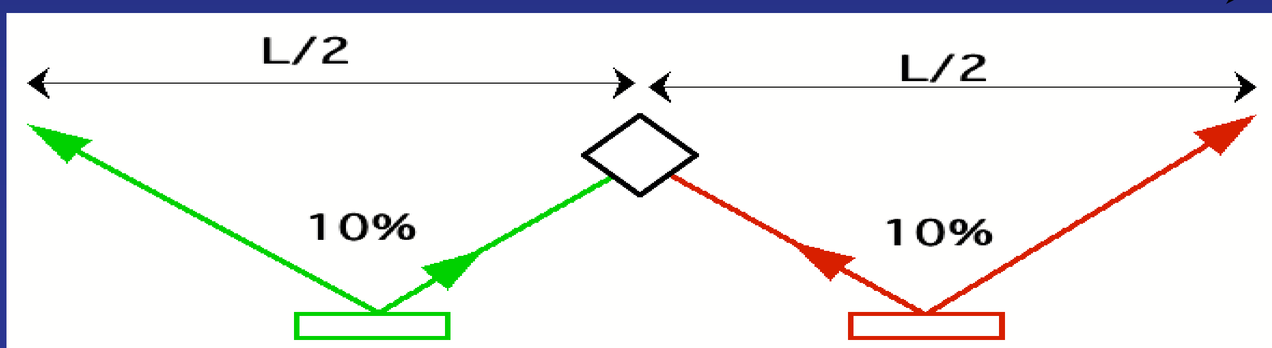


led, despite that
tly interacted!

Need to distribute entanglement over longer distances (repeaters):

L (1%)

Need ~100 pairs



Need ~20 pairs

If we have a quantum storage device we can wait until we have a pair from both sides.

Photon Entanglements

- **Polarization (spin)**

  (Ou & Mandel, Shih & Alley, etc., etc.)

- **Linear momentum**

  (Rarity & Tapster)

- **Orbital angular momentum**

  (Zeilinger et al.)

- **Time-Bin**

  (Gisin et al., Inoue et al.)

- **Energy-Time**

  (Franson et al., Howell et al.)

- **3,4,5, high photon number** (many)

Hyper-Entanglement

PGK, JMO **44**, 2173 (1997)

- Photons simultaneously entangled in multiple DOFs:

$$\underbrace{(|H,H\rangle + |V,V\rangle)}_{polarization} \otimes \underbrace{(|rl\rangle + \alpha|gg\rangle + |lr\rangle)}_{spatial\ modes} \otimes \underbrace{\int_0^{E_p} dE A(E)|E\rangle_s|E_p - E\rangle_i}_{energy}$$

- Enlarged Hilbert space: $2 \otimes 2 \otimes m \otimes m \otimes n \otimes n$

- Easy to perform quantum logic *between* DOFs
- More efficient n-qubit transfer: T vs T^n

- New capabilities in quantum info. processing
  - full Bell-state analysis
  - "super-duper" dense coding
  - quantum communication with higher alphabets
  - remote preparation of entangled states
  - ???

Quantum “superdents coating”

PHYSICAL REVIEW LETTERS

VOLUME 69 | 16 NOVEMBER 1992 | NUMBER 20

Communication via One- and Two-Particle Operators on Einstein-Podolsky-Rosen States

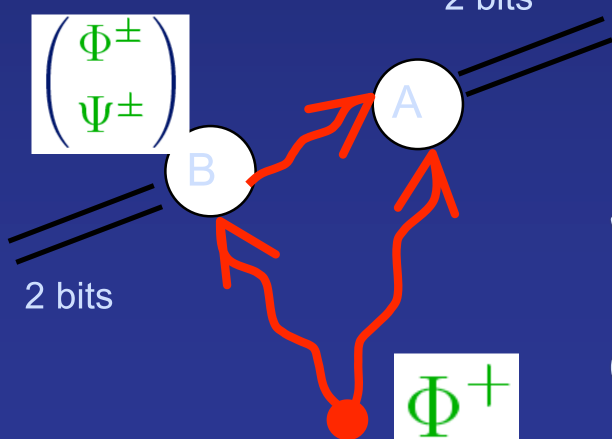
Charles H. Bennett

IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598

Stephen J. Wiesner

74 Parkman Street, Brookline, Massachusetts 02146

(Received 16 June 1992)



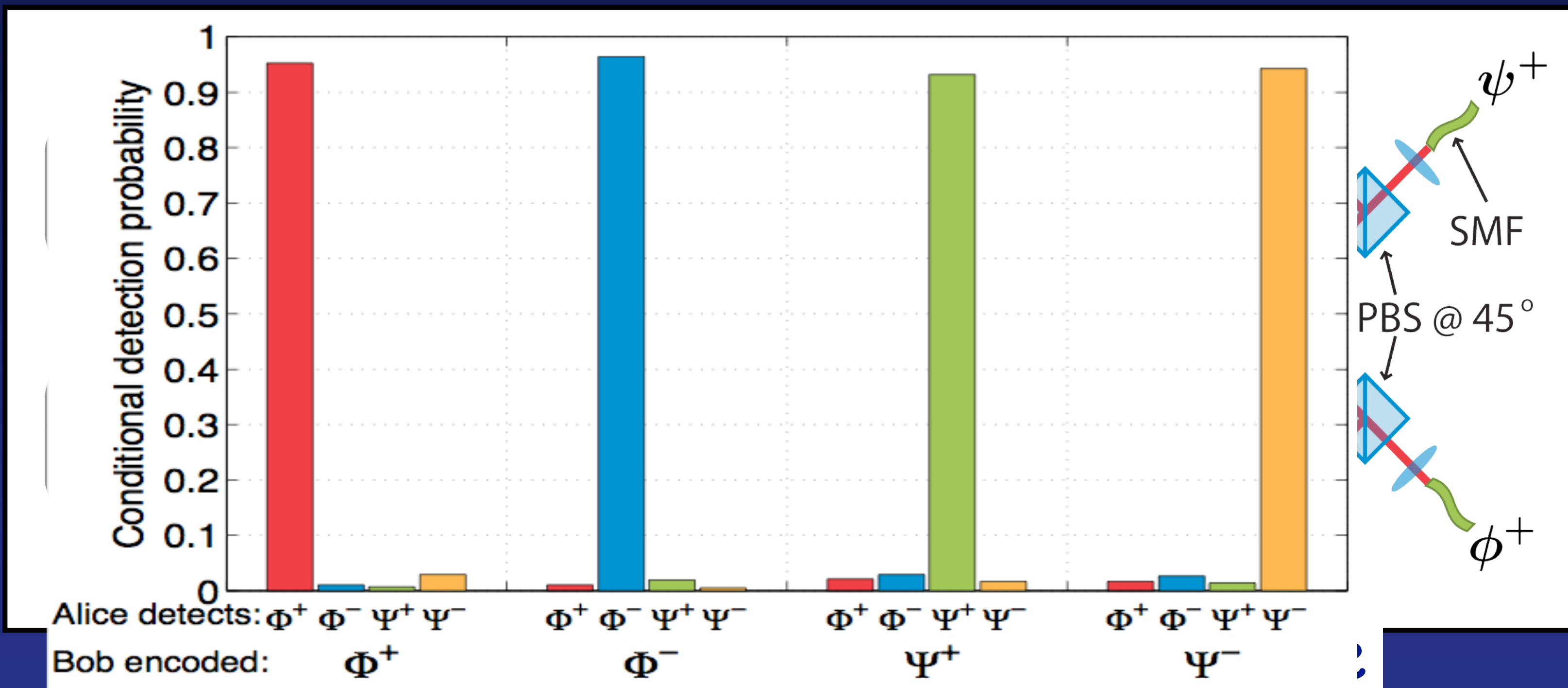
- ✓1 entangled photon each to Bob and Alice
- ✓Bob applies one of 4 U’s ➠1 of 4 Bell states; sends photon to Alice
- ✓Alice: BSA ➠ infer one of 4 messages

Channel cap. = $\log_2 4$

= 2bits/photon_from_Bob

Full BSA analysis “impossible” with linear optics…

Hyperentanglement-enhanced Superdense Coding



Average success probability: 95%
⇒ channel capacity: 1.630(6) > 1.58
("limit" for linear optics superdense coding, i.e., without hyperentanglement)

Barreiro et al., Nature Physics **4**, 282 (2008)

What are the limits?
How many bits/photon?
Can the "hitchhiker" qubits be used, e.g., for error correction?

Why Optical Quantum Computing?

“Photons been very very good to me”

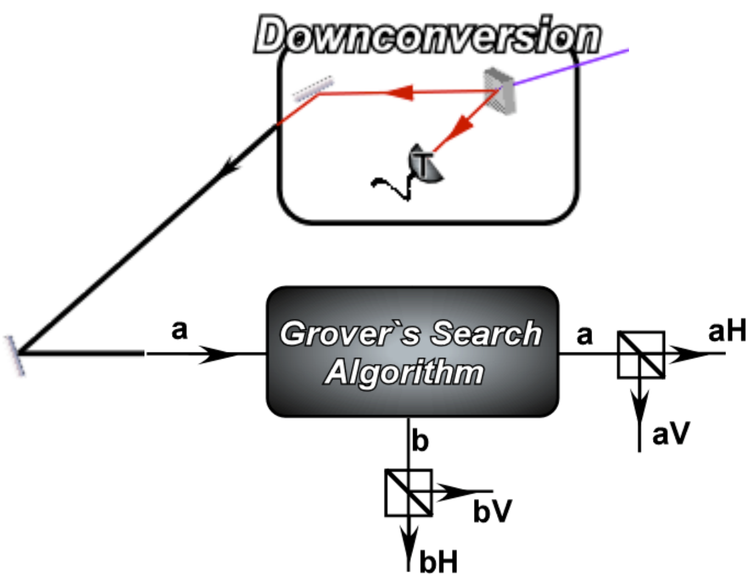
- Very little/no decoherence -- photon’s don’t interact
- Excellent performance with off-the-shelf optics
- Very fast gates: single-qubit ~10 ps - 5 ns
  two-qubit <150 ns

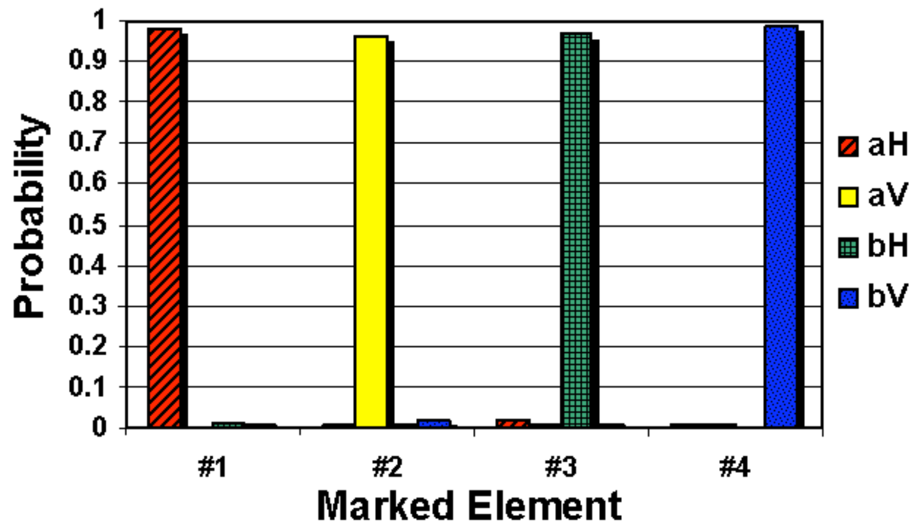
Why *not* Optical Quantum Computing?

- Photon’s don’t interact -- 2-qubit gates hard
- Linear approach: measurement-induced nonlinearity
- Nonlinear approach: Zeno and QND gates

Grover's search algorithm with linear optics

Optical realization with single photons: A database of four elements





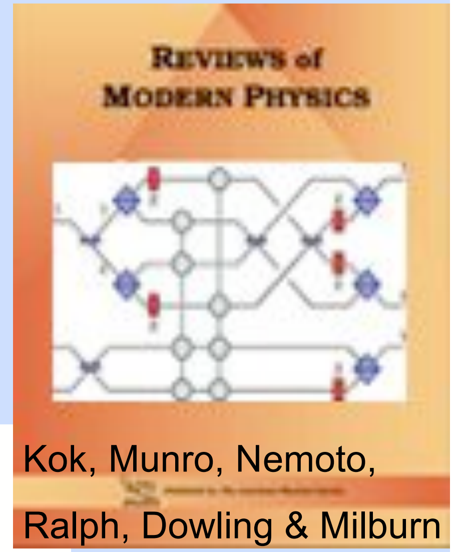
Accuracy: ~97.5% (as of 2004)

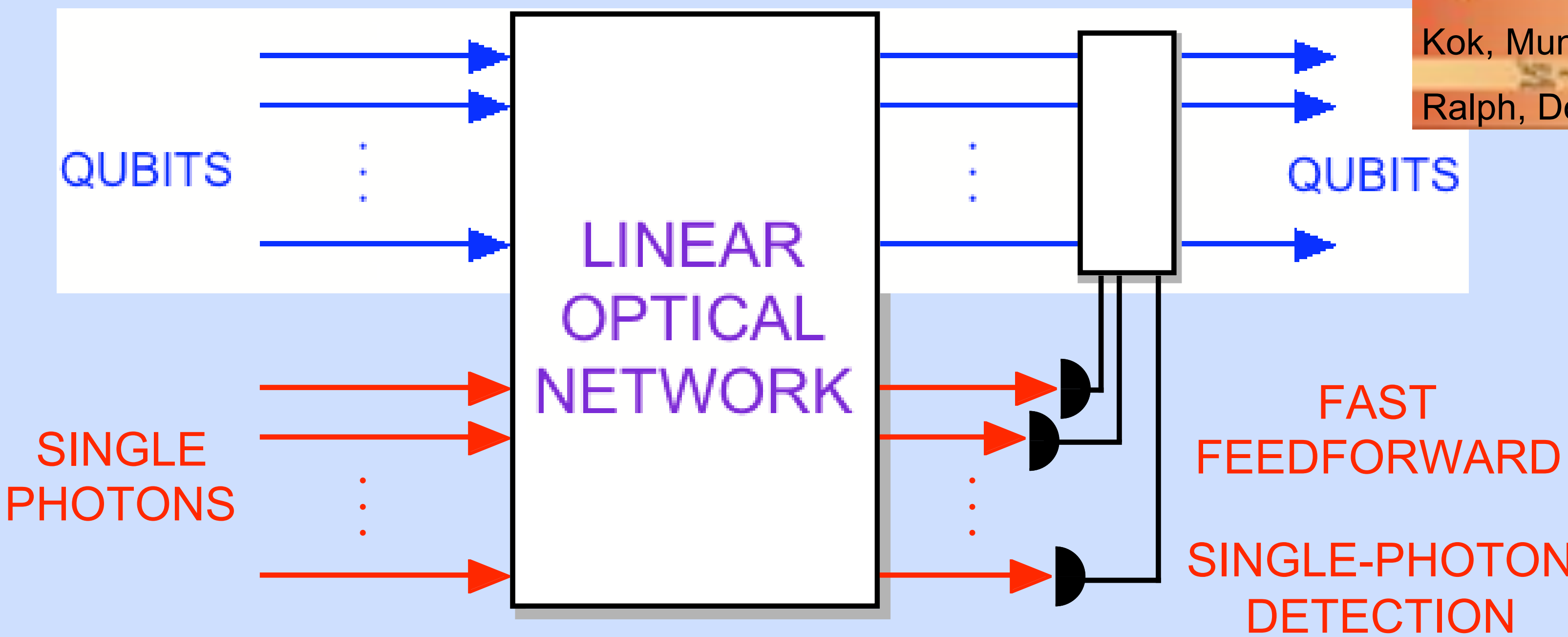
- Gates: Linear optical elements
- Nonscalable -- each new qubit doubles the required number of optical elements

PGK et al., J. Mod. Opt. 47, 257 (2000)

Linear optical quantum computing

Knill, Laflamme and Milburn,
Nature **409**, 46 (2001)



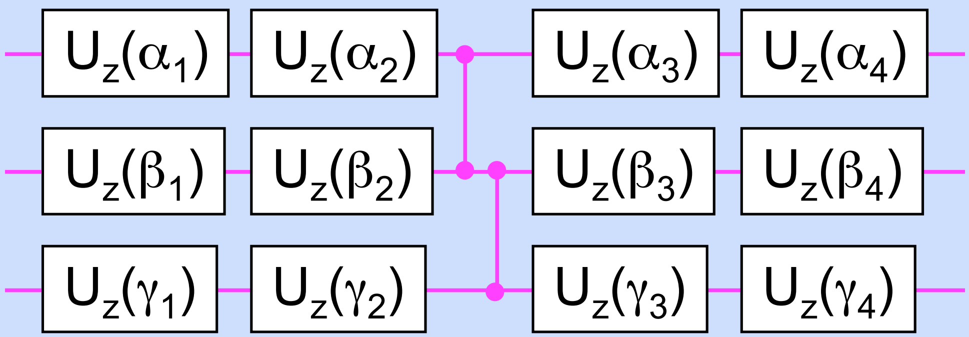


LARGE overhead requirements…($>10^5$/gate)

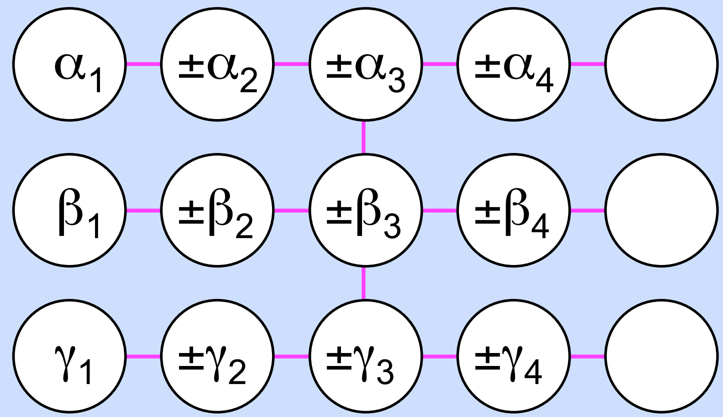
A New Paradigm: Measurement-based computation

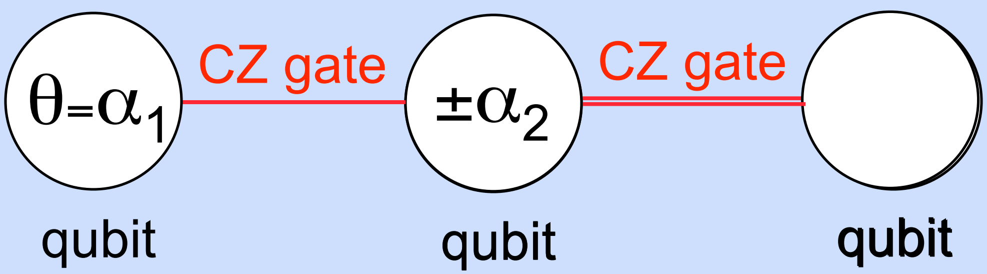
• 2004 - Nielsen's solution: combine KLM non-deterministic gate with cluster-state model of quantum computation

conventional circuit



cluster circuit





Measurement on qubits

$$\cos(\theta)\sigma_x + \sin(\theta)\sigma_y$$

Raussendorf and Briegel, PRL 86, 5188 (2001)

Nielsen, PRL 93, 040503 (2004)

Photons are hard to hold, but with cluster states you can build as you go…

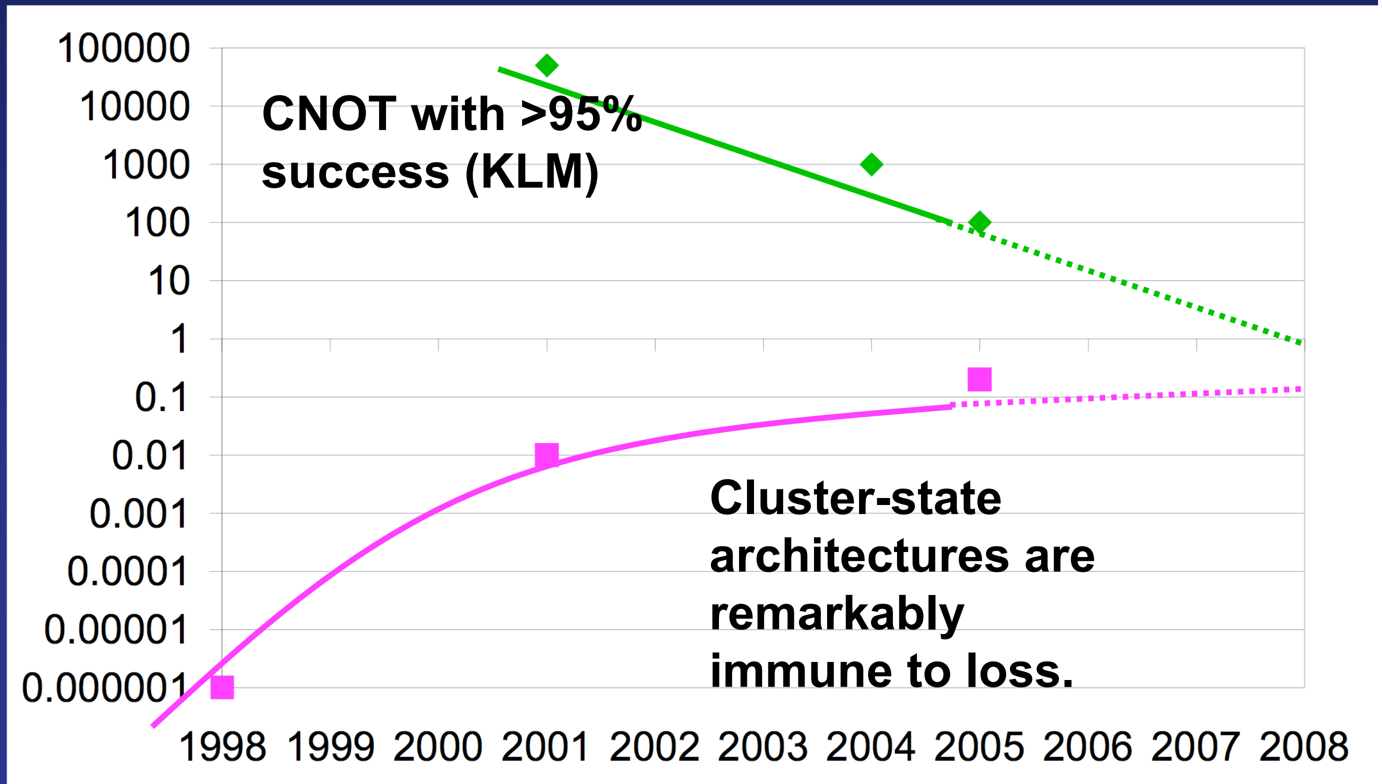
Optical quantum computing

OQC Anti-Moore's Law

Graph states (clusters and parity-encoding techniques) have greatly reduced the required resources and the loss-tolerance threshold for LOQC:

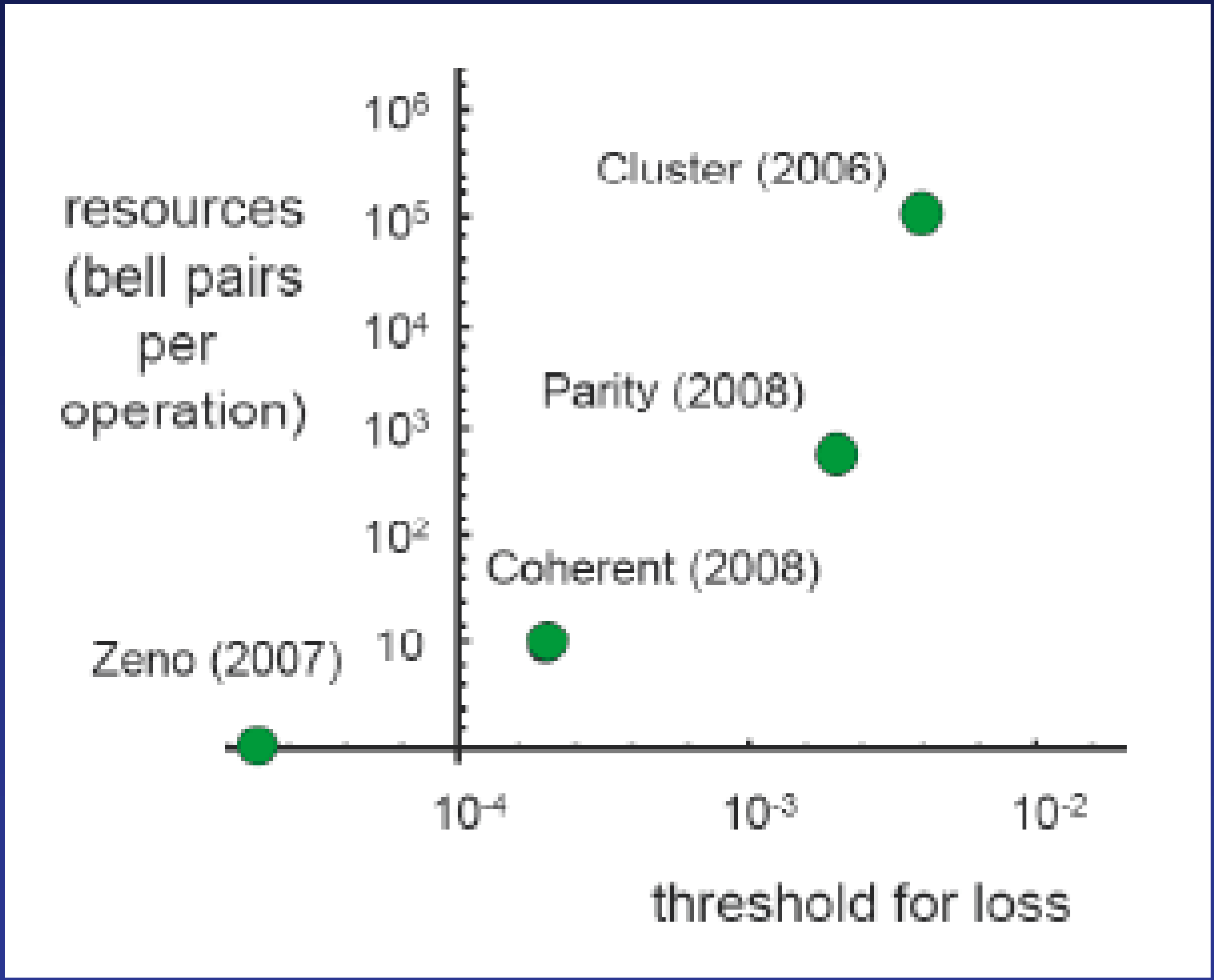
Resources (Bell states, operations, etc.) for a reliable entangling gate

Acceptable loss for a scalable architecture



Efficient LOQC possible if (source purity)×(detection effic.) > 2/3.

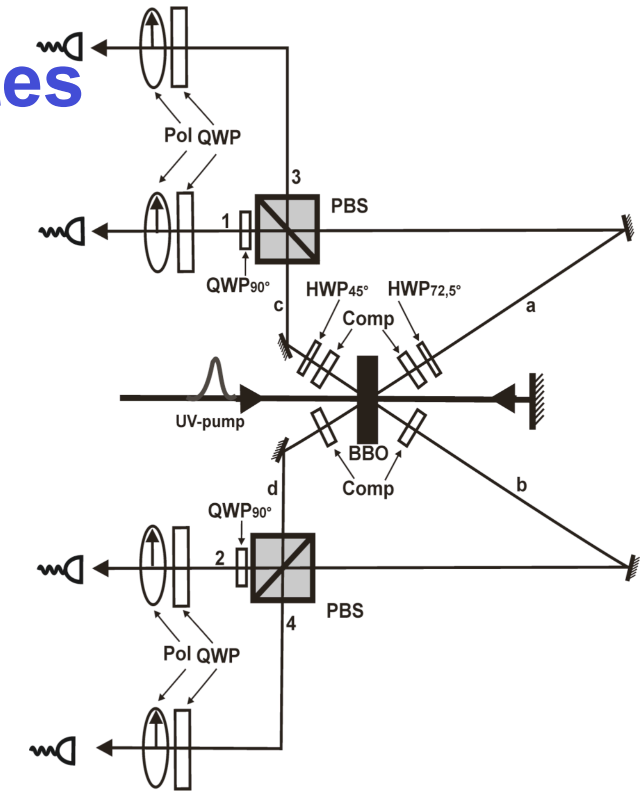
The tradeoffs between Resources and Loss-threshold

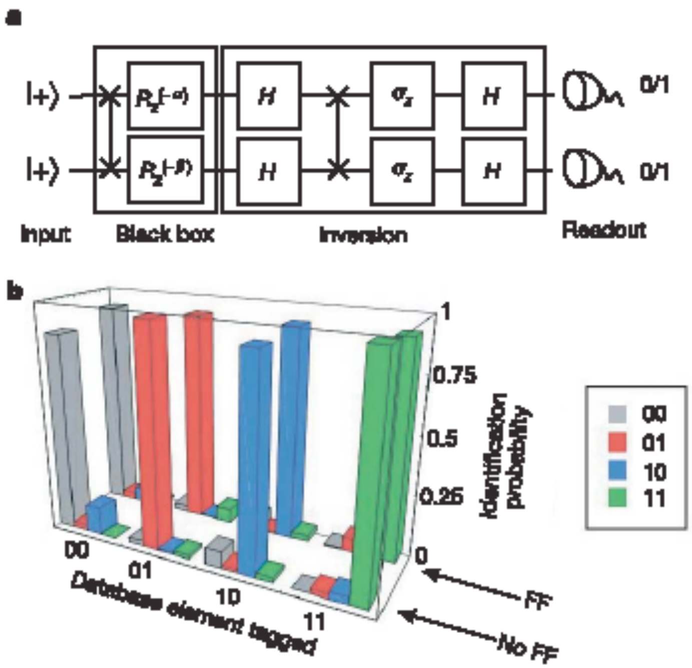


➢ Realization of photon cluster states

- **Direct creation** via down-conversion
- **Interferometeric** setup
- Simple polarizers

$$\frac{1}{2}\Big(|H\rangle_1|H\rangle_2|H\rangle_3|H\rangle_4 + |H\rangle_1|H\rangle_2|V\rangle_3|V\rangle_4 + |V\rangle_1|V\rangle_2|H\rangle_3|H\rangle_4 - |V\rangle_1|V\rangle_2|V\rangle_3|V\rangle_4 \Big)$$





Grover search algorithm
Walther et al., Nature **434**, 169 (2005)

➢ Present status:

- 1-qubit gate fidelity: F >90%
- Few count rates: 10^{-1} 3-pair/s
- Thus far up to n = 6 (at very low rates)

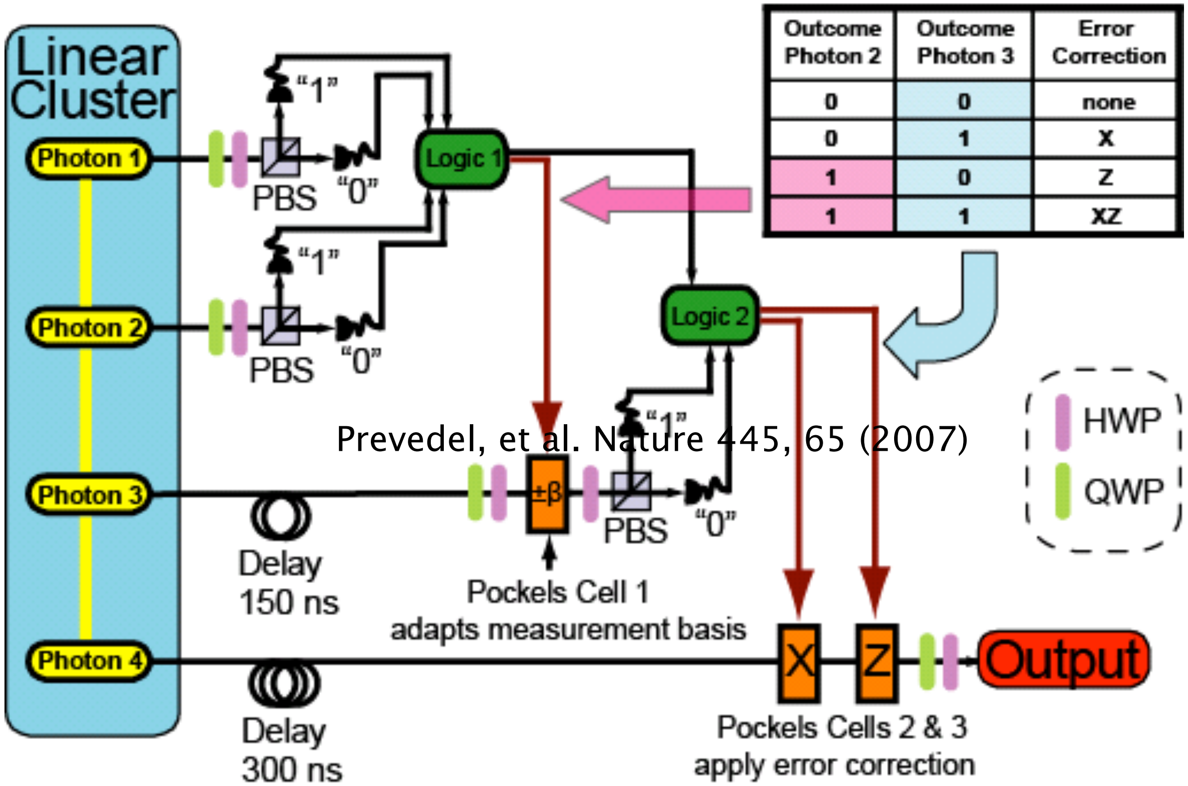
Need ‘on-demand’ sources, better detectors, and better wires…

Feed-Forward Implementation

Prevedel, et al. Nature 445, 65 (2007)

EOM Switching Scheme

Outcome Photon 2	Outcome Photon 3	Error Correction
0	0	none
0	1	X
1	0	Z
1	1	XZ



Prevedel, et al. Nature 445, 65 (2007)

Pockels Cells:

KD*P crystals ~ 6.3 kV

Over 99 % fidelity (500:1)

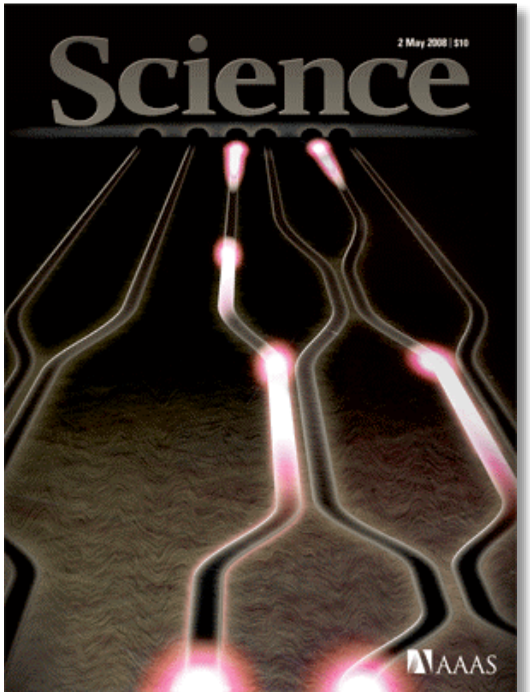
Fibers to detector 15ns
Detector-Delay 35ns
EOM-Delay 65ns
Logics-Delay 7.5ns
Misc. cables 20ns

Feed-Forward Time < 150 ns !!

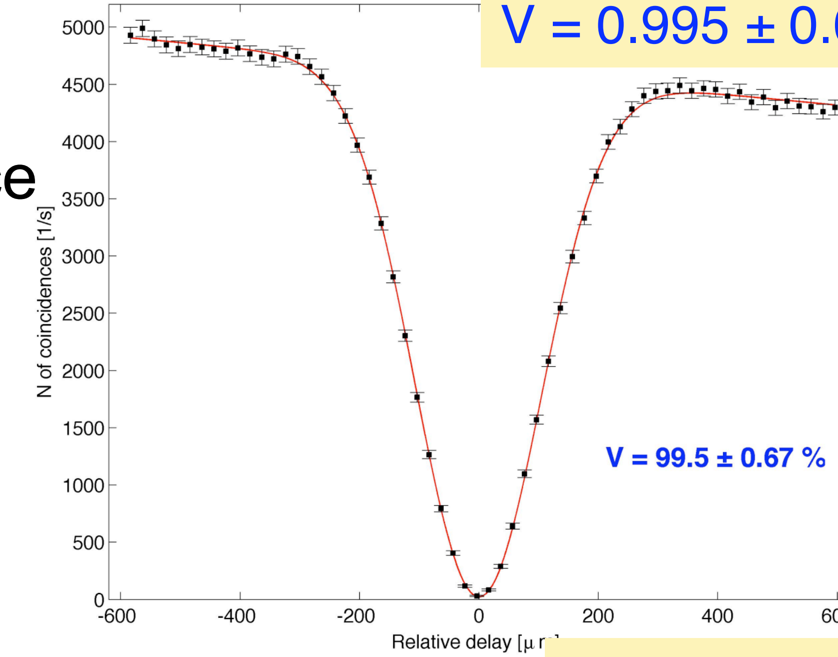
~1 ns possible (w better detectors, integrated optics)

Silica-on-silicon Quantum Photonics

University of Bristol

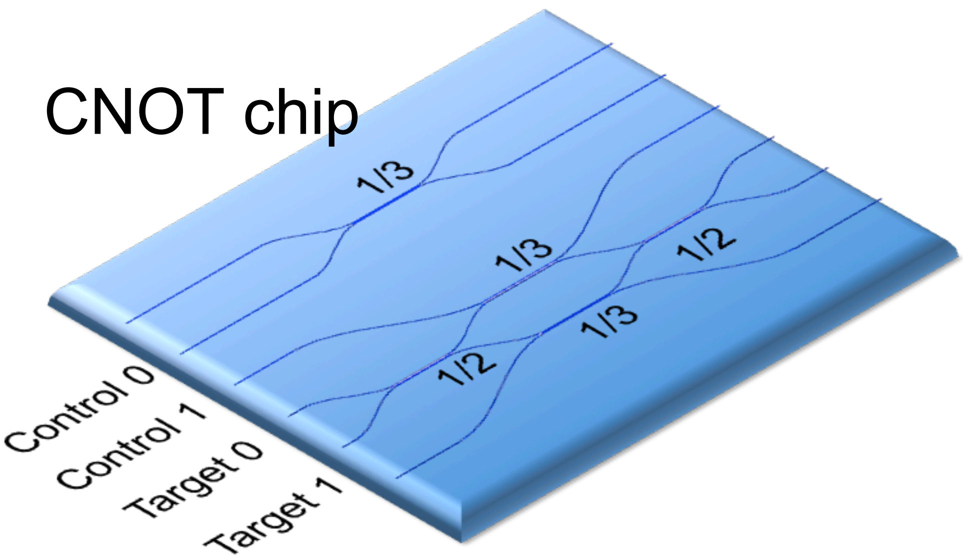


Quantum interference

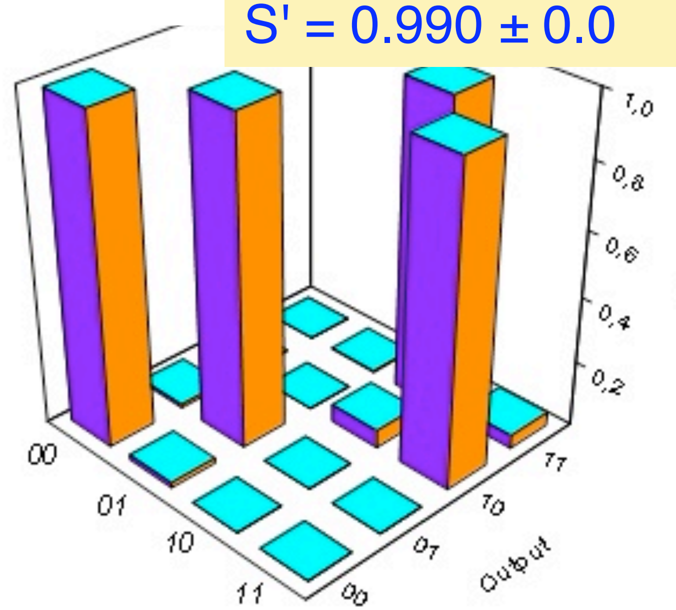


V = 0.995 ± 0.007

CNOT chip



S' = 0.990 ± 0.0



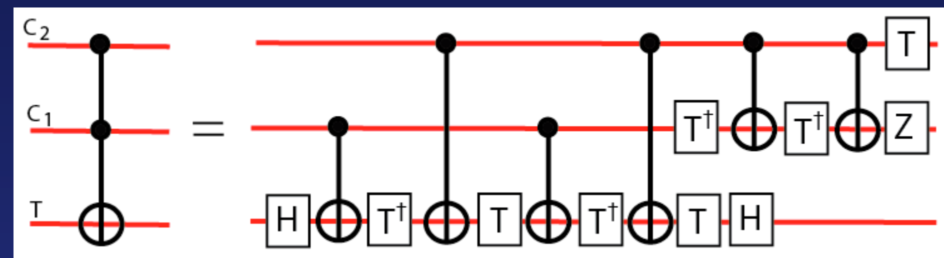
Harnessing higher dimensions to reduce LOQC resources

- Even small quantum algorithms require large numbers of CU and Toffoli gates

controlled-U gates: phase estimation, quantum chemistry..
Toffoli gates: Shor's, error correction, fault tolerance…

- What if your architecture only has 2-qubit gates?

e.g., build Toffoli with 6 CNOT's



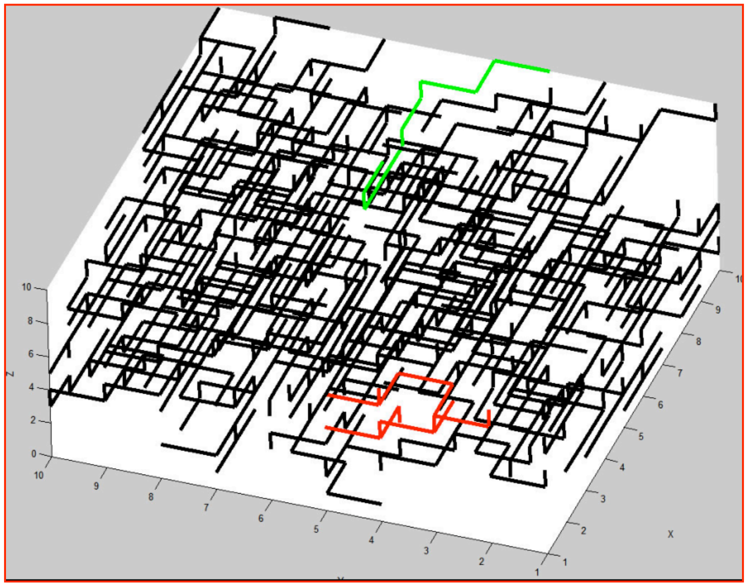
- Works by coherently isolating some quantum information from gate actions

	chained gates		new scheme		
no. photons	11	15	3	7	practical circuit for demonstrating Toffoli Gate
probability of success	1/20736	1/4096	1/72	1/32	
	min. photons	max. prob.	min. photons	max. prob.	

What are the limits, e.g., when going for fault-tolerance…?

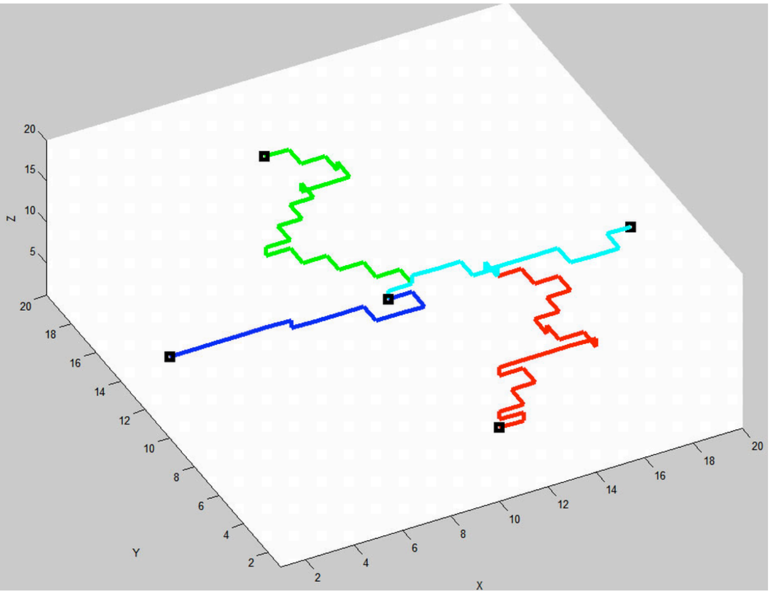
How to brew Really BIG Cluster-states: Percolation

Fusion success probability =1/2, above percolation threshold.
⇒ get large piece of connected cluster state with high probability



Red & Green – not connected
Black - connected

From the percolated cluster it is easy to compute measurement patterns to produce any desired cluster circuit:



- Every photon undergoes only one Type-I gate and one single-qubit measurement
- Removes requirement for photon rerouting (only requires feedforward to classical measurement settings)
- Initial resources can be as small as 4-photon cluster states

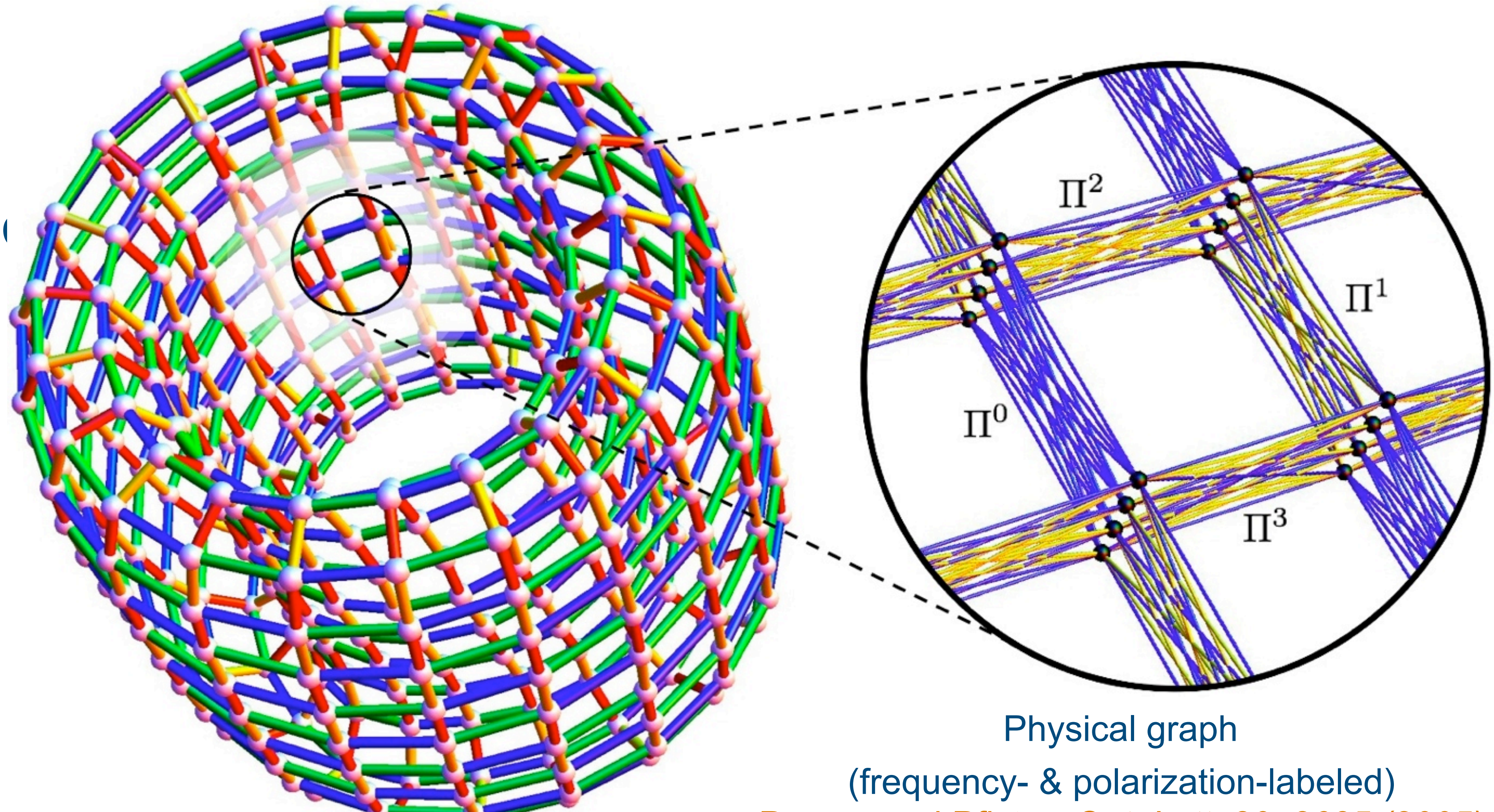
Imperial College London

Scalable quantum computing in the optical frequency comb

Menicucci, Flammia, and Pfister, *Phys. Rev. Lett.* ***101****, 130501 (2008)*

Classical frequency comb

The eigenmodes of a cavity form a naturally scaled ensemble of classically coherent modes



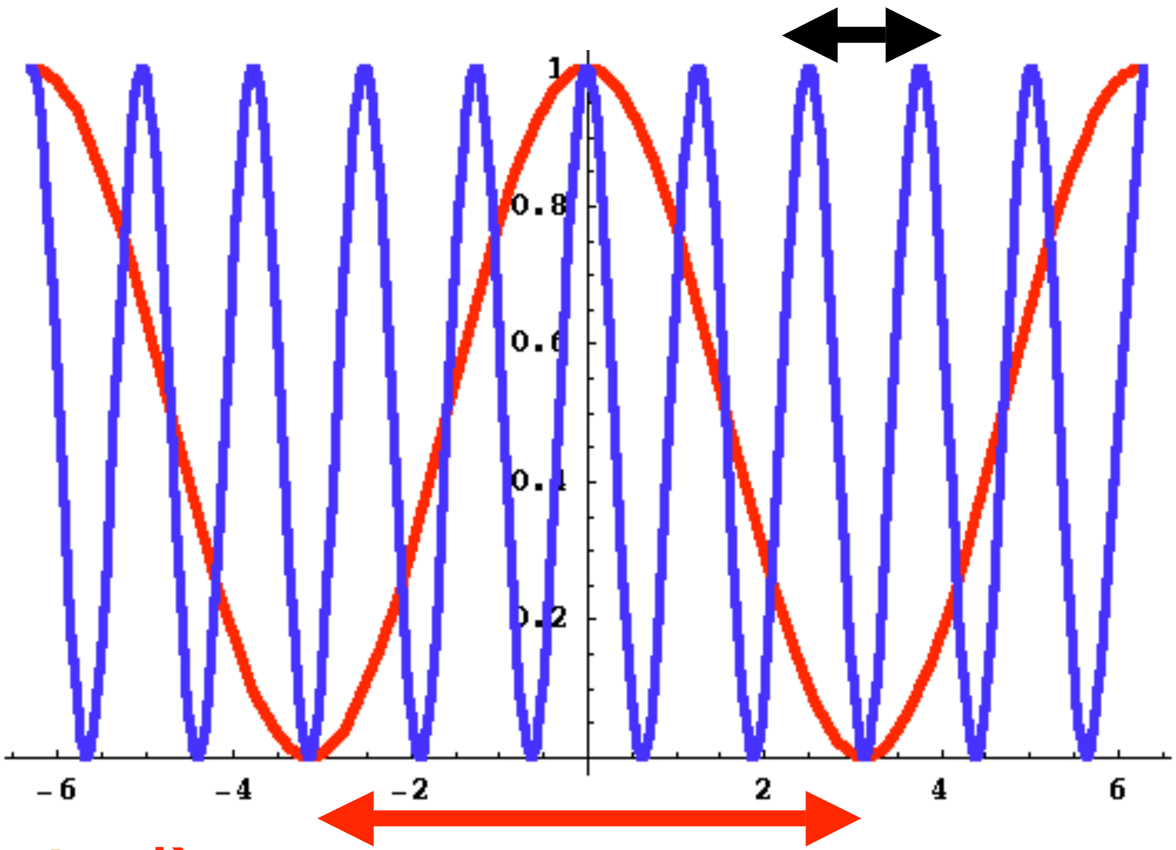
Physical graph
(frequency- & polarization-labeled)

Pooser and Pfister, *Opt. Lett.* **30***, 2635 (2005)*

Super-Resolution á la N00N

$$|N :: 0\rangle_{a,b} \equiv \frac{1}{\sqrt{2}}\left(|N,0\rangle_{a,b} + |0,N\rangle_{a,b}\right)$$

λ / N



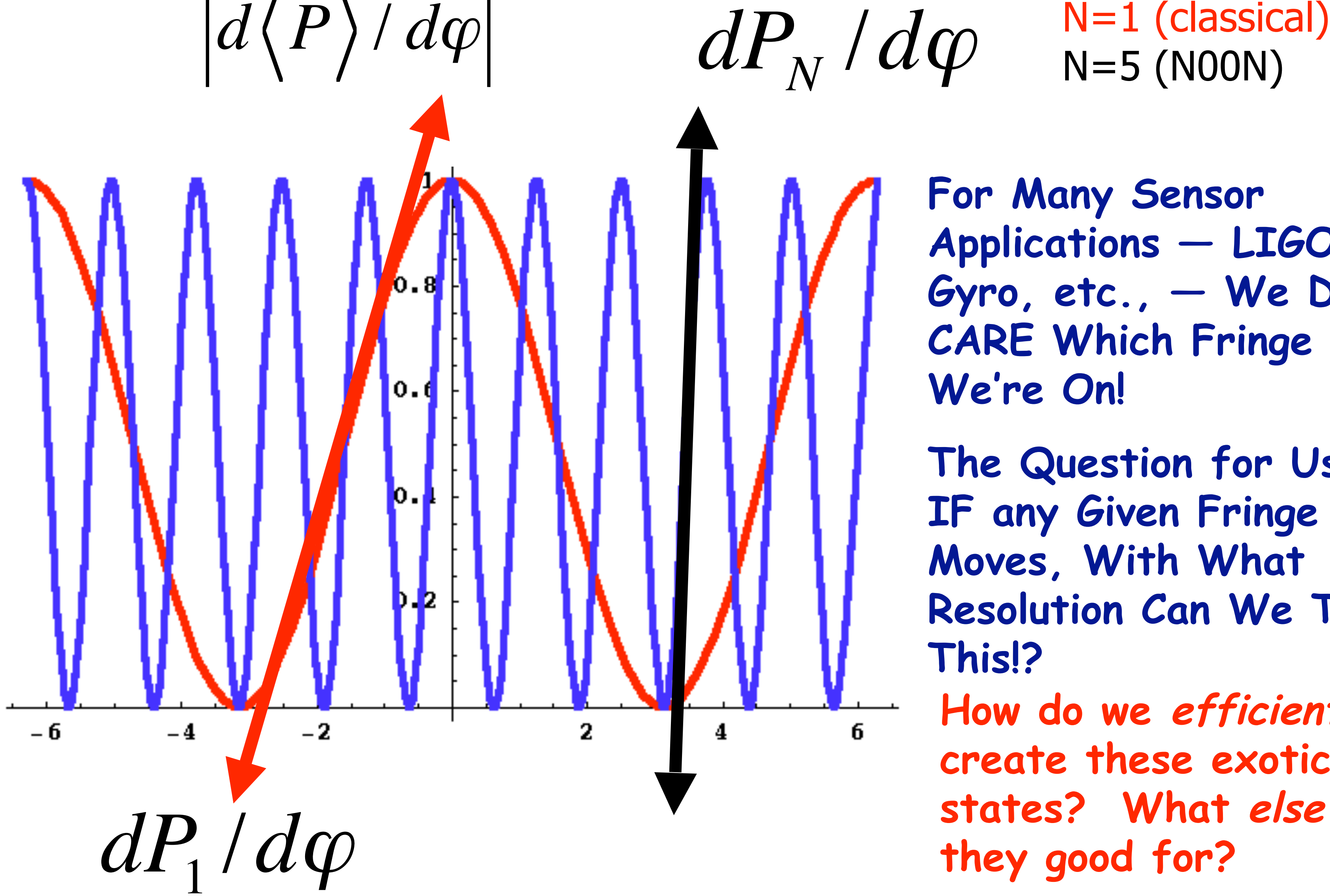
λ

N=1 (classical)

N=5 (N00N)

Super-Sensitivity

$$\Delta\varphi = \frac{\Delta\hat{P}}{\left| d\langle\hat{P}\rangle / d\varphi \right|}$$



For Many Sensor Applications — LIGO, Gyro, etc., — We Don't CARE Which Fringe We're On!

The Question for Us is IF any Given Fringe Moves, With What Resolution Can We Tell This!?

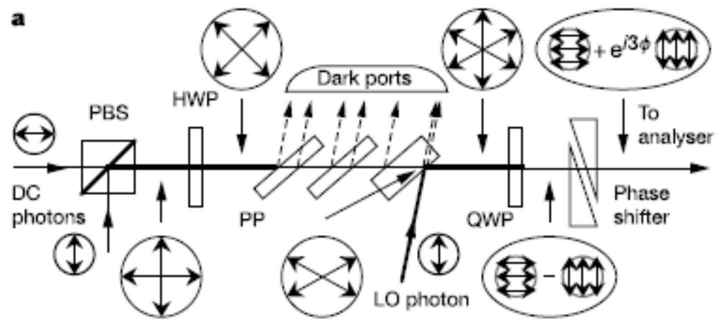
How do we *efficiently* create these exotic states? What *else* are they good for?

Quantum (or not) Phase Metrology

1990
2-photon

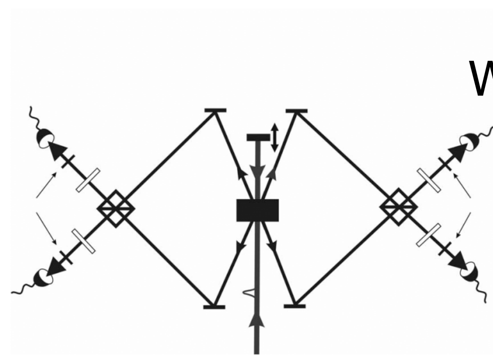
Rarity, (1990)
Ou, et al. (1990)
Shih, Alley (1990)
….

6-photon Super-Resolution
Resch,…,White
PRL (2007)
Queensland



Mitchell,…,Steinberg
Nature (13 MAY)
Toronto

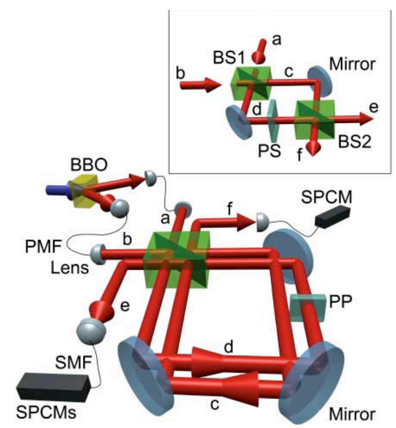
2004
3, 4-photon
Super-resolution



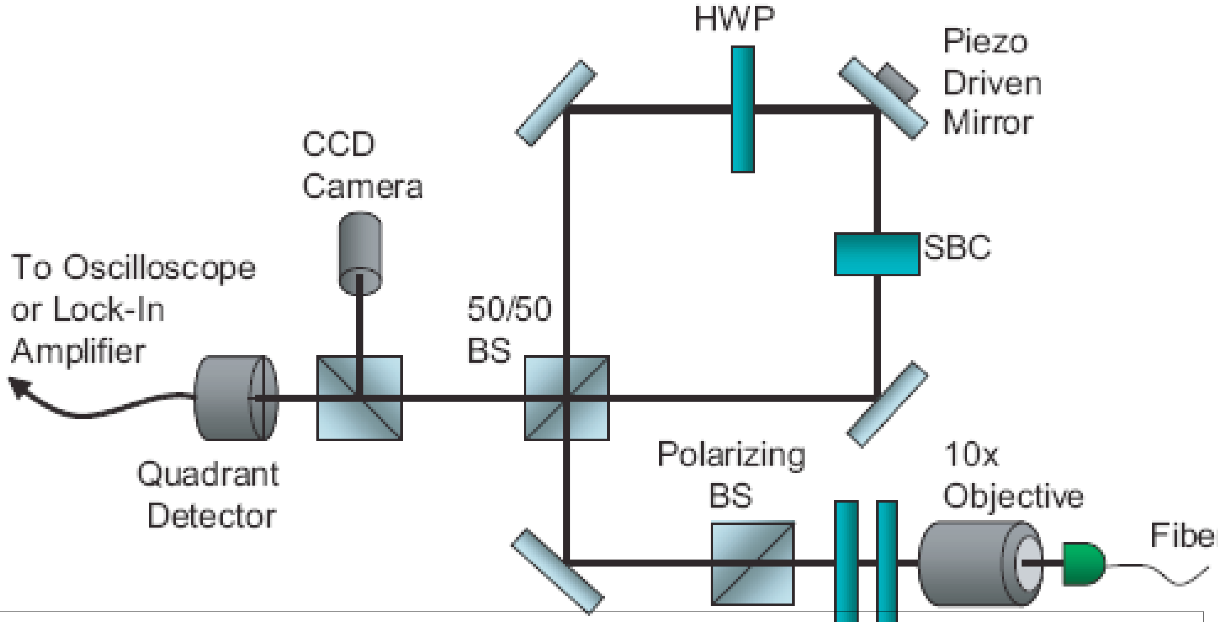
Walther,…,Zeilinger
Nature (13 MAY)
Vienna

2007
4-photon
Super-sensitivity
&
Super-resolution

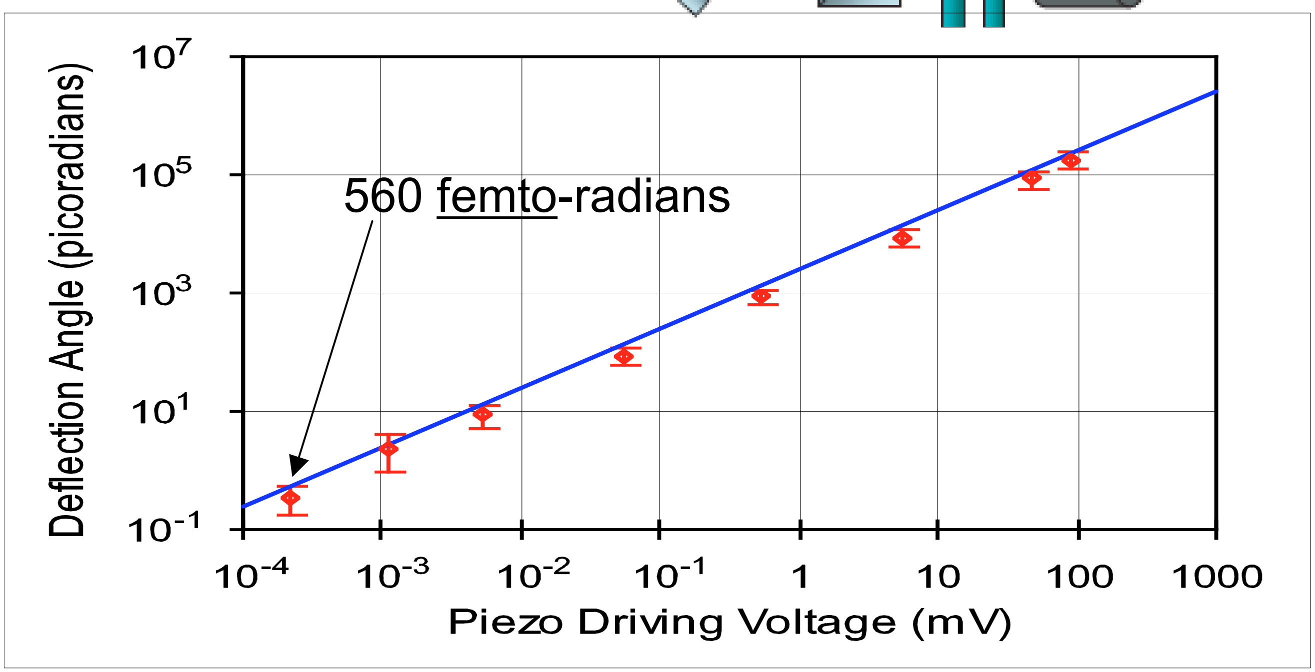
Nagata,…,Takeuchi,
Science (04 MAY)
Hokkaido & Bristol



Weak-Value-Enhanced Deflection-Detection

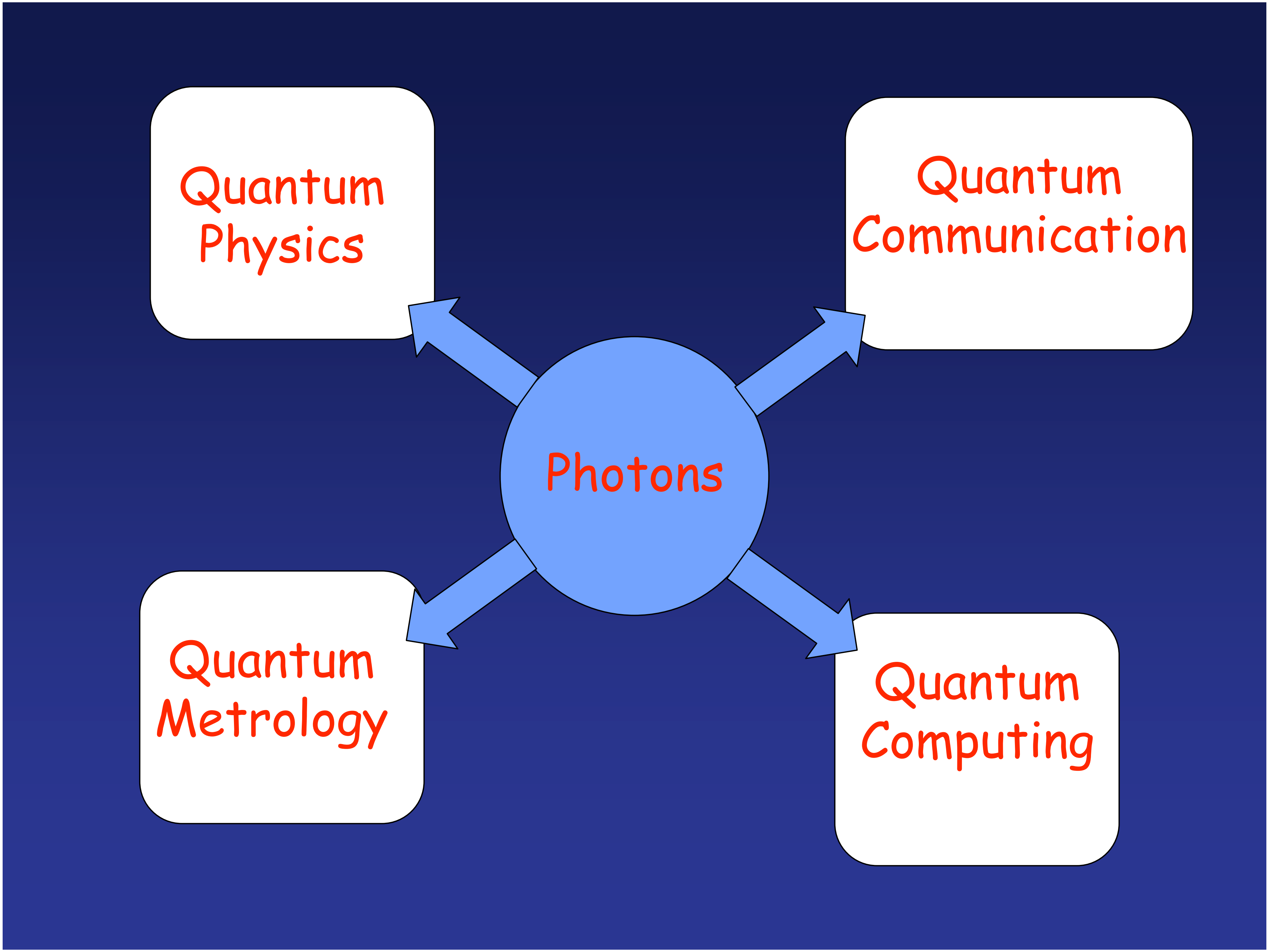


J. Howell et al., Phys. Rev.Lett. (In Press for April)



This is a *classical* enhancement, discovered by studying QM weak measurements.
So what!

What are the limits when combined, e.g., with squeezed input light, or N00N states, or…?


Quantum Physics
Quantum Communication
Photons
Quantum Metrology
Quantum Computing


Quantum Battle
Space of Tomorrow
What good is
Quantum
Information for
Video Games??