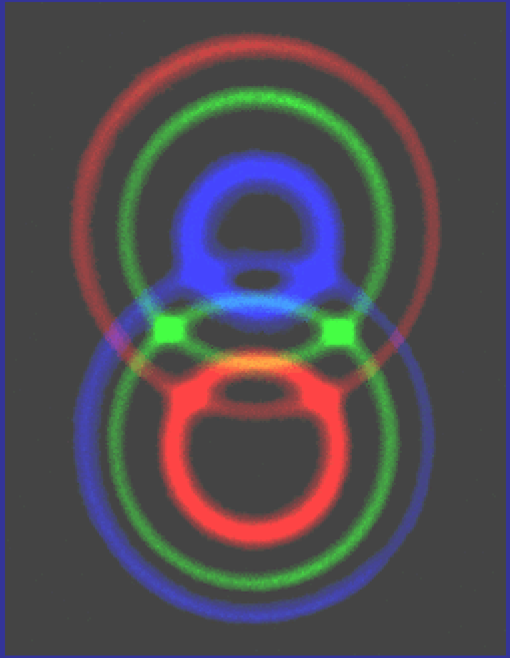
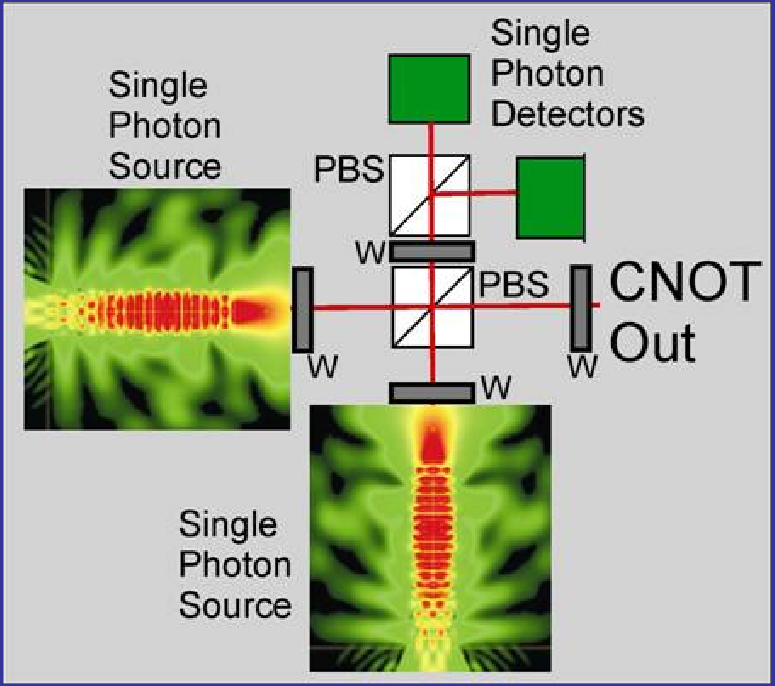
Optical qubits

http://focus.aps.org/



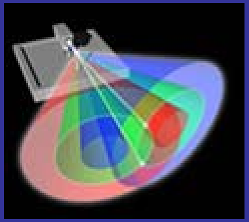


http://www.qipirc.org/images/projects/image018.jpg

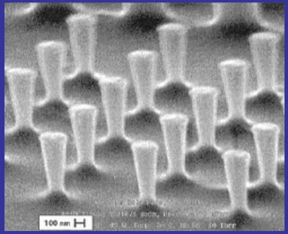
http://www.quantum.at/

Outline

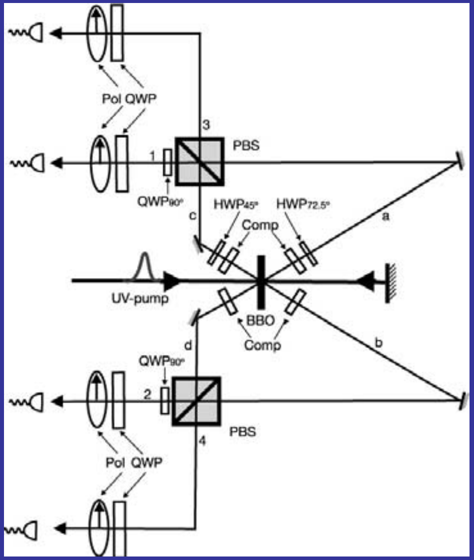
- Parametric down-conversion



- Single photon sources



- Linear-optical QC architectures



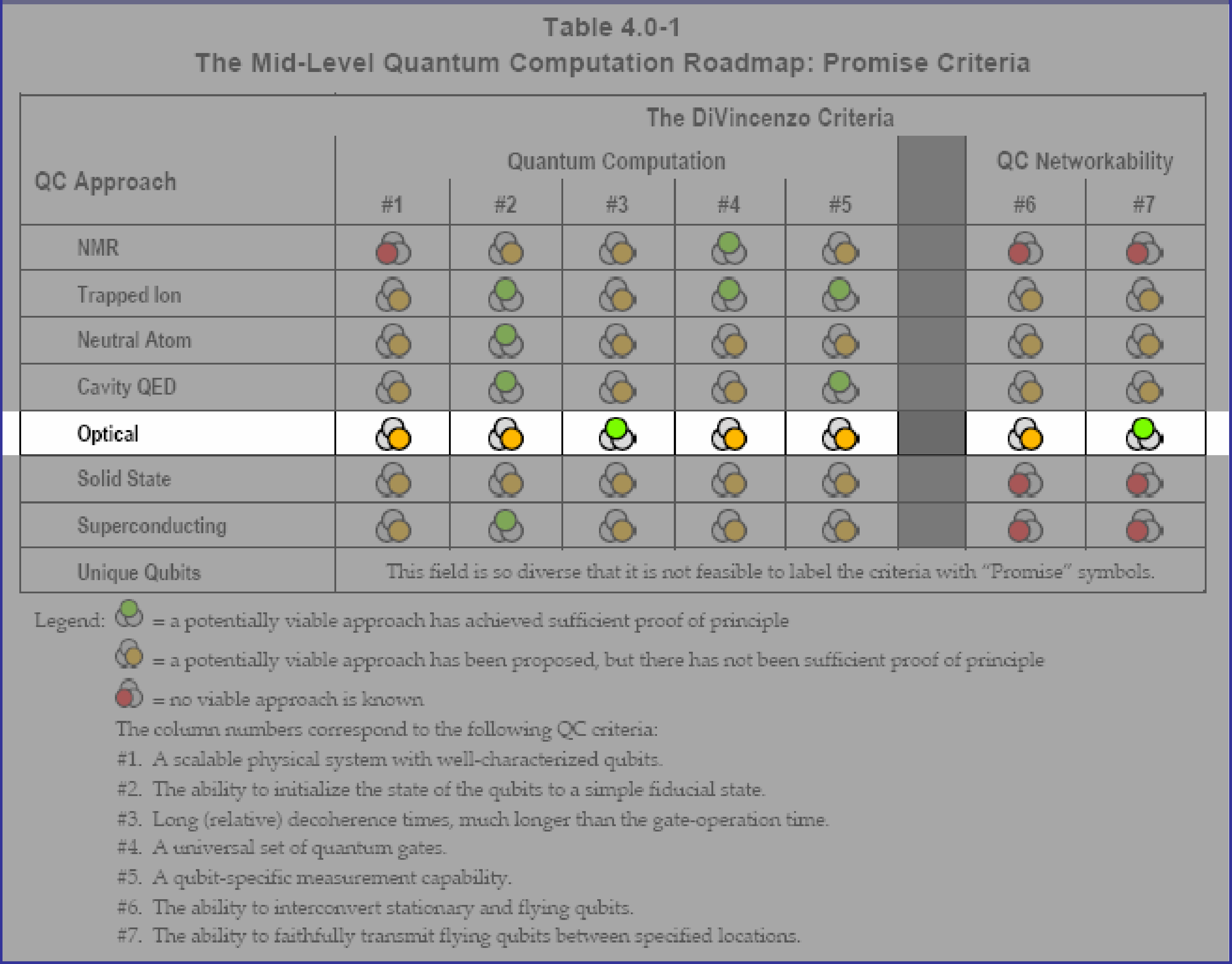


Table 4.0-1

The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria						
	Quantum Computation					QC Networkability	
	#1	#2	#3	#4	#5	#6	#7
NMR	🔴	🟡	🟡	🟢	🟡	🔴	🔴
Trapped Ion	🟡	🟢	🟡	🟢	🟢	🟡	🟡
Neutral Atom	🟡	🟢	🟡	🟡	🟡	🟡	🟡
Cavity QED	🟡	🟢	🟡	🟡	🟢	🟡	🟡
Optical	🟡	🟡	🟢	🟡	🟡	🟡	🟢
Solid State	🟡	🟡	🟡	🟡	🟡	🔴	🔴
Superconducting	🟡	🟢	🟡	🟡	🟡	🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.						

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟡 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.

#2. The ability to initialize the state of the qubits to a simple fiducial state.

#3. Long (relative) decoherence times, much longer than the gate-operation time.

#4. A universal set of quantum gates.

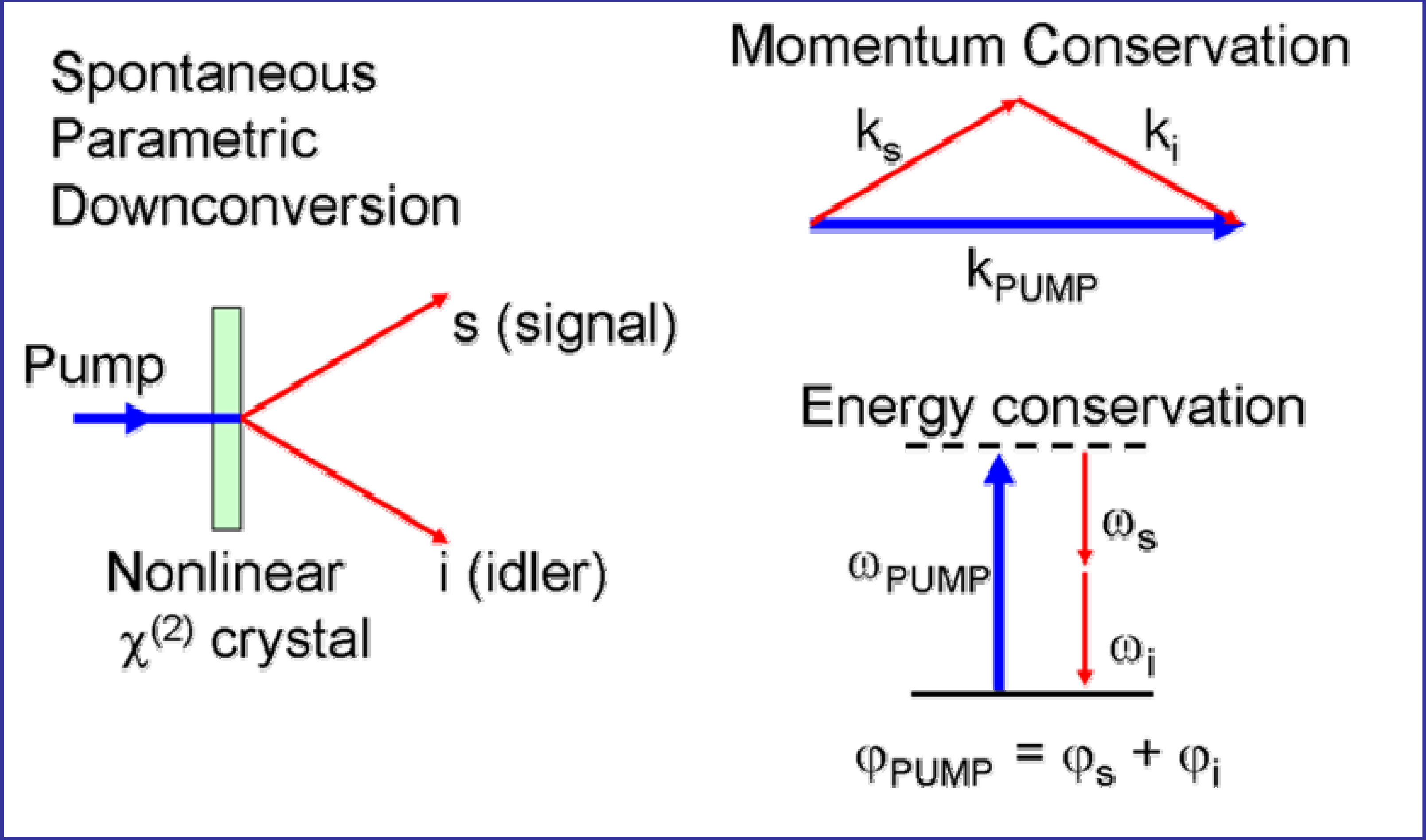
#5. A qubit-specific measurement capability.

#6. The ability to interconvert stationary and flying qubits.

#7. The ability to faithfully transmit flying qubits between specified locations.

http://qist.lanl.gov/qcomp_map.shtml

Parametric down-conversion: source of entangled pairs of photons



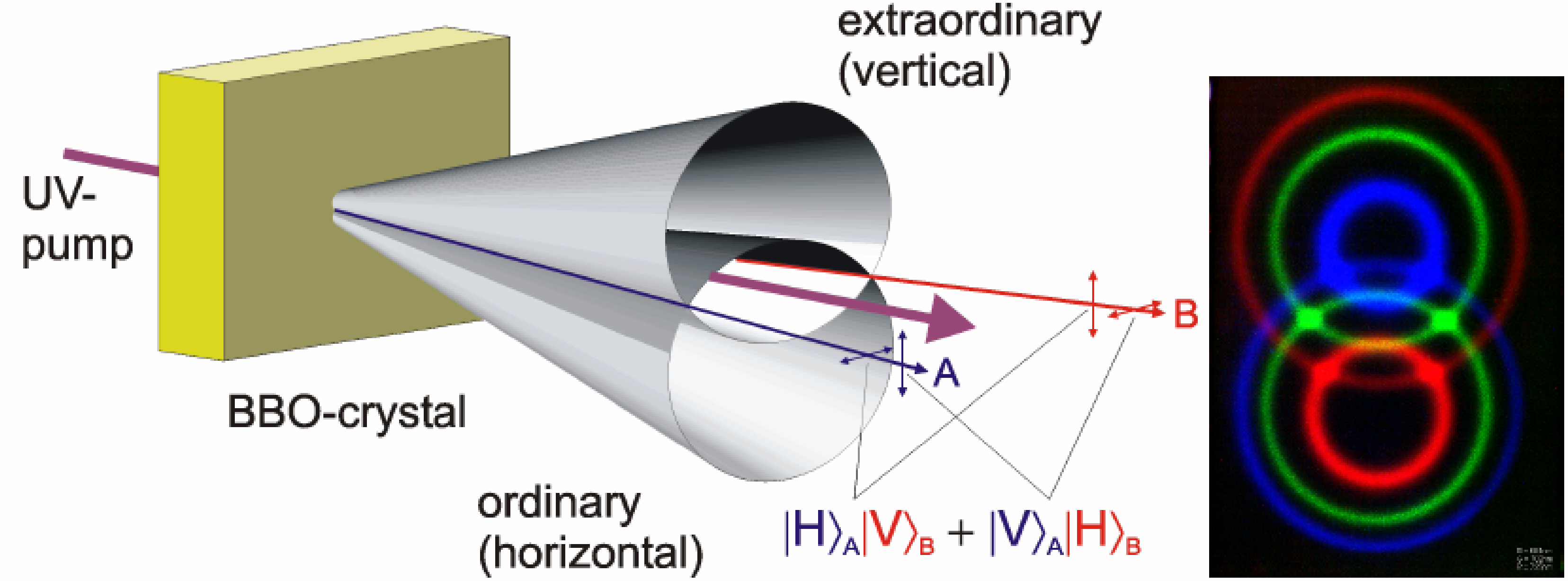
Spontaneous Parametric Downconversion

Momentum Conservation

Energy conservation

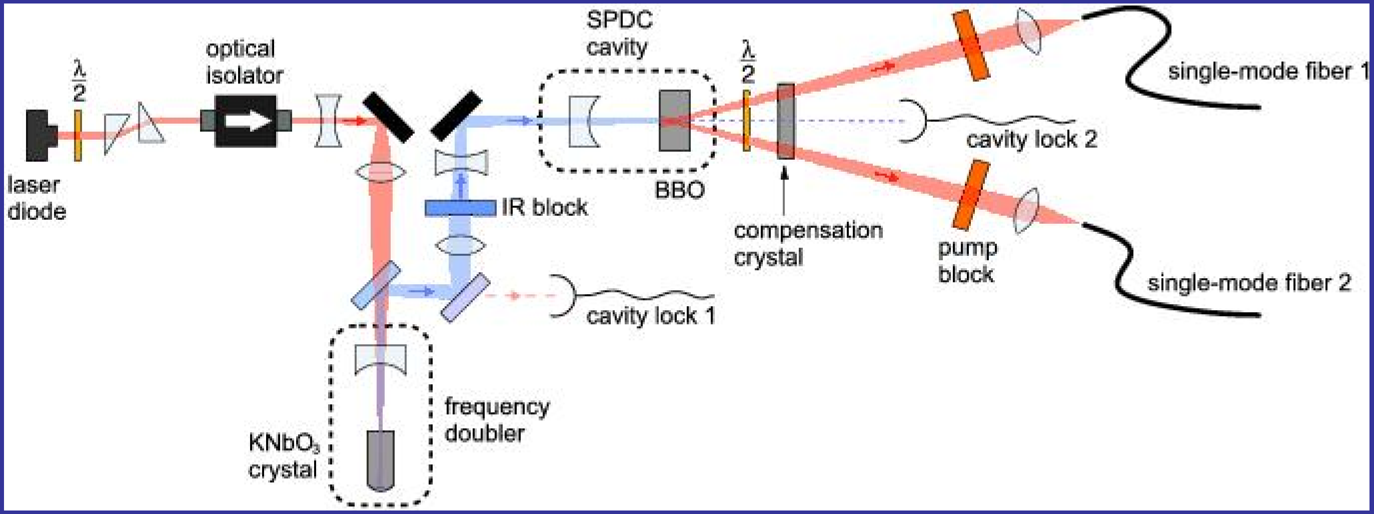
$$\varphi_{PUMP} = \varphi_s + \varphi_i$$

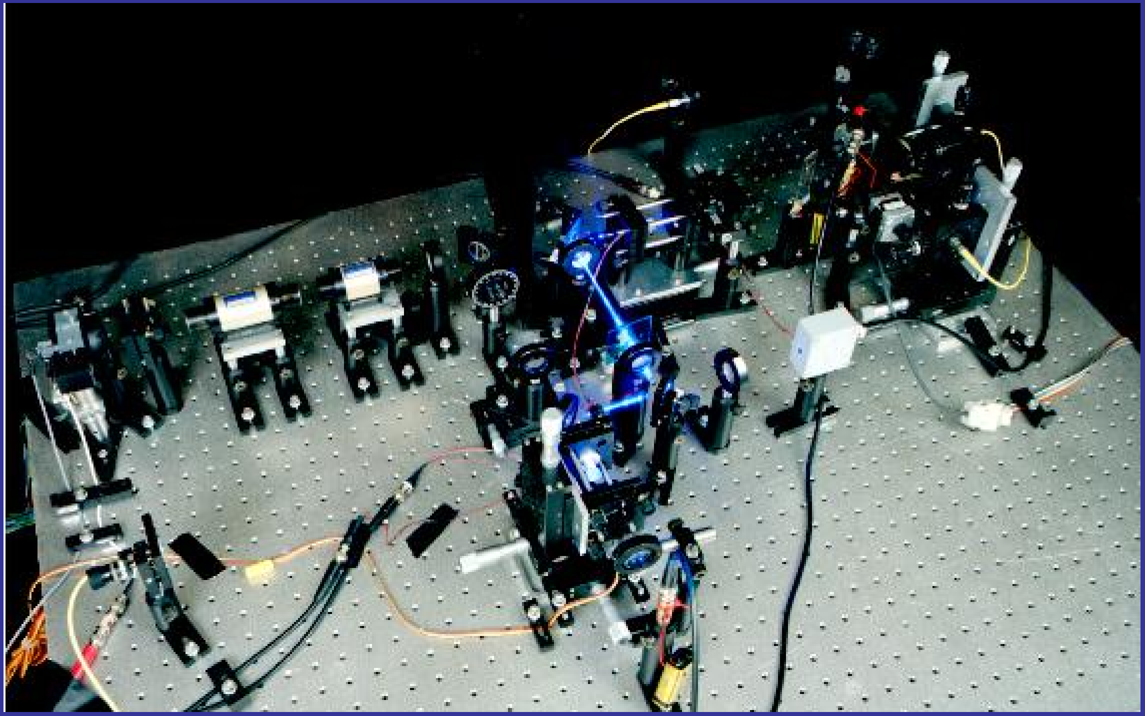
Parametric down-conversion: typical setup



Kwiat et al. PRL 75 4337 (1995)

Parametric down-conversion: unusual setup





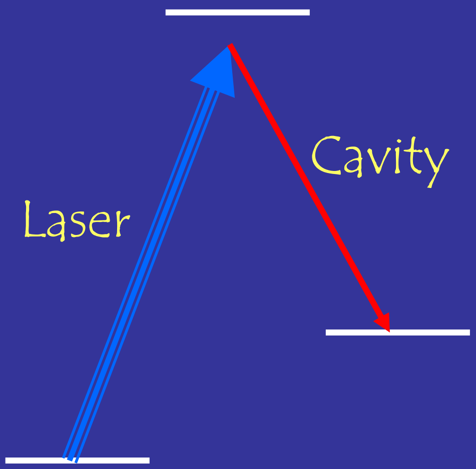
Setup from Experimental Quantum Physics group at MPQ-Munchen

Single photons from atoms, atomic ensembles, artificial atoms and other photons

- Single photons are essential for optical quantum computing, quantum communication and cryptography
- Photons emitted by single atoms during spontaneous emission exhibit anti-bunching – only one photon can be emitted at a time, and it takes about the lifetime of the excited state to emit the next photon.
- Electromagnetically Induced Transparency can be used to make single photons from large, optically-thick atomic ensembles
- Artificial atoms, such as quantum dots, can also emit single photons
- PDC can be used as a "triggered" source of single photons: detecting a photon in the idler arm indicates that there is a single photon in the signal arm.

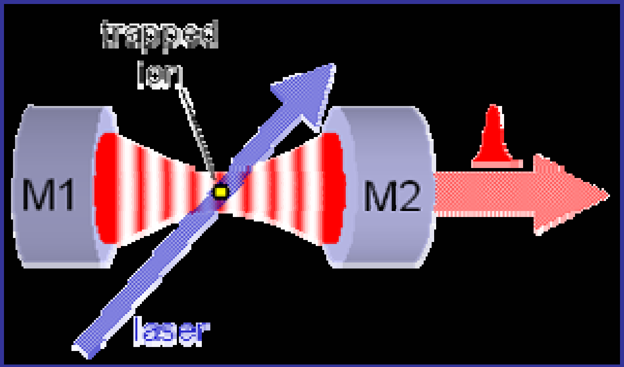
Atomic sources of single photons

- Cavity QED

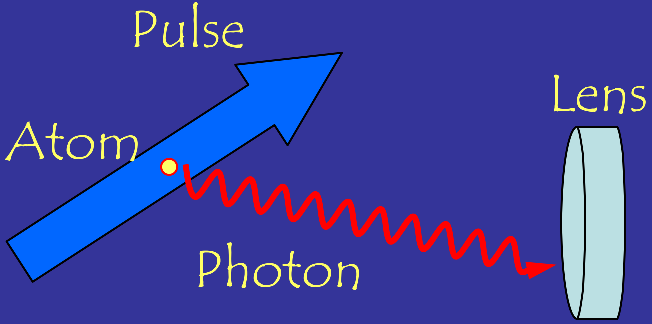


Laser

Cavity



- Ultrafast laser excitation of atoms

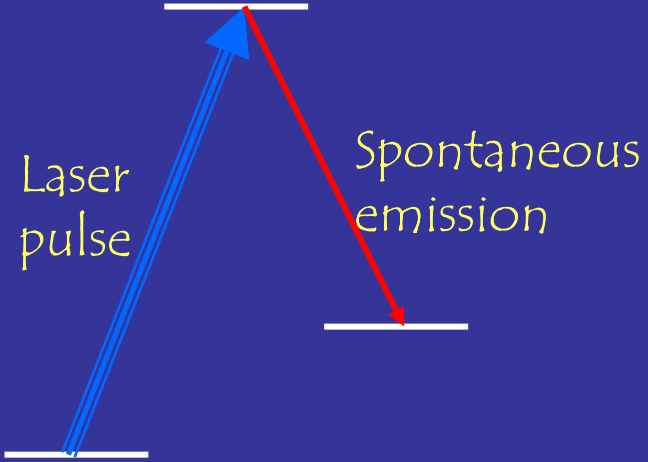


Pulse

Lens

Atom

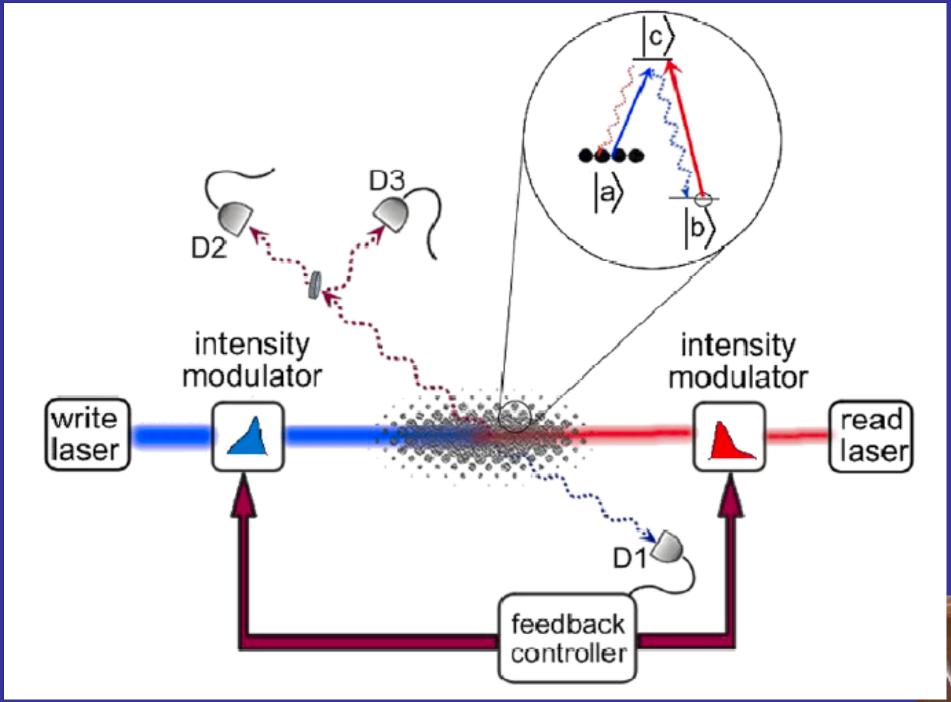
Photon



Laser
pulse

Spontaneous
emission

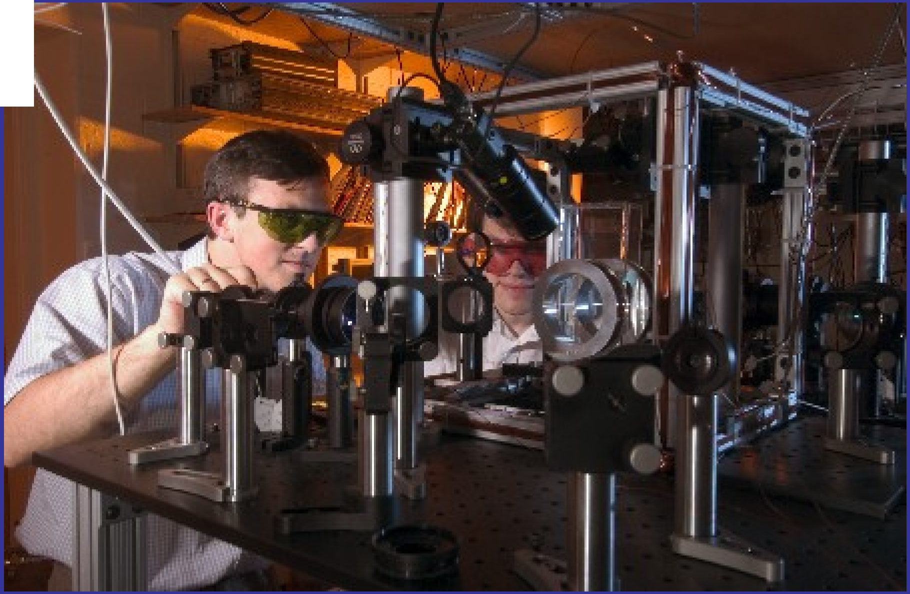
Atomic ensembles produce single photons



"write" pulse creates a single photon detected by D1 and a collective excitation of atoms

"read" pulse retrieves a single photon, measured by D2 and D3

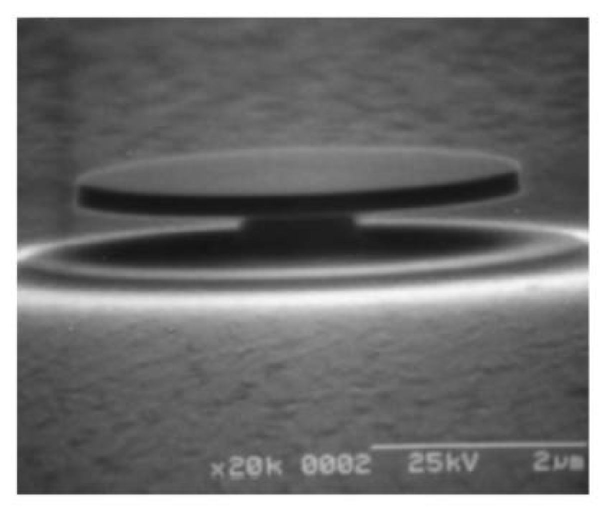
demonstrated overall efficiency ~1.2%

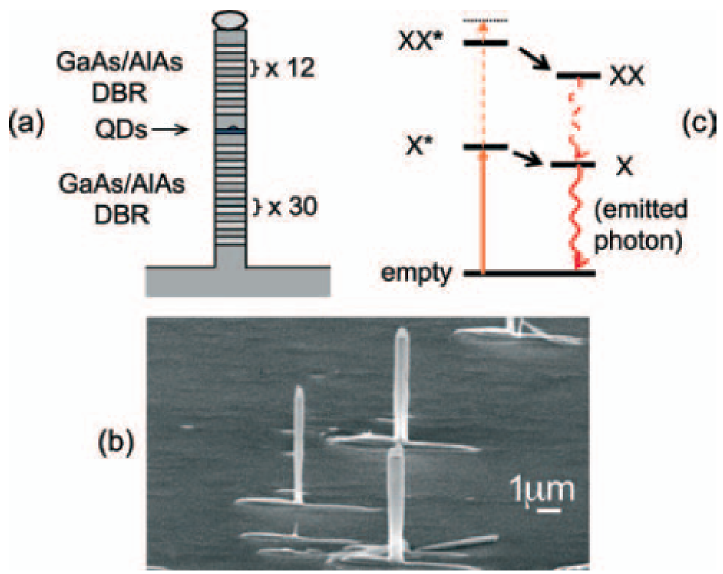


Alex Kuzmich and Dzmitry Matsukevich, GATech

Quantum dots and such…

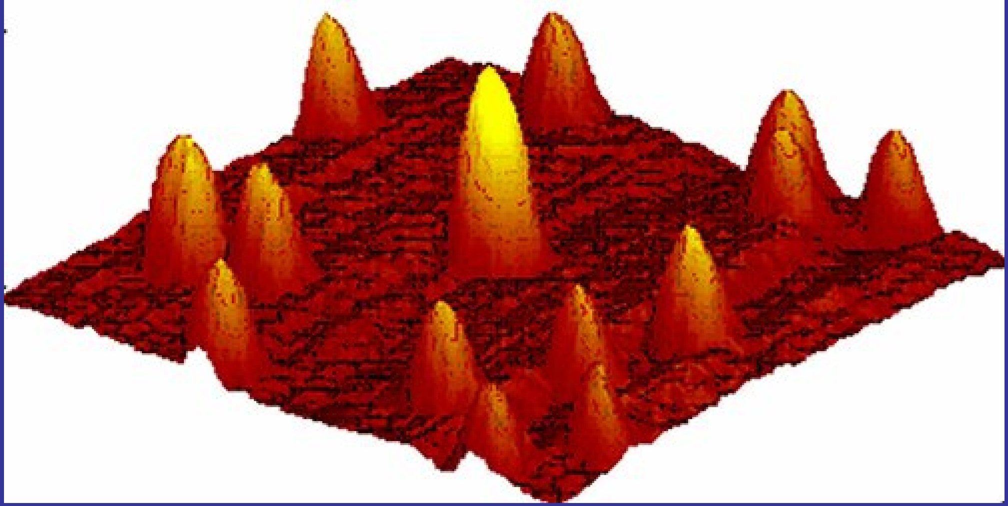
Can put them in a cavity…





▲ **Fig. 1:** (a) Schematic diagram of single-photon device, (b) scanning-electron microscope image of actual pillar structures; and (c) optical excitation scheme. Santori et al. *New Journal of Physics* 6, 89 (2004)

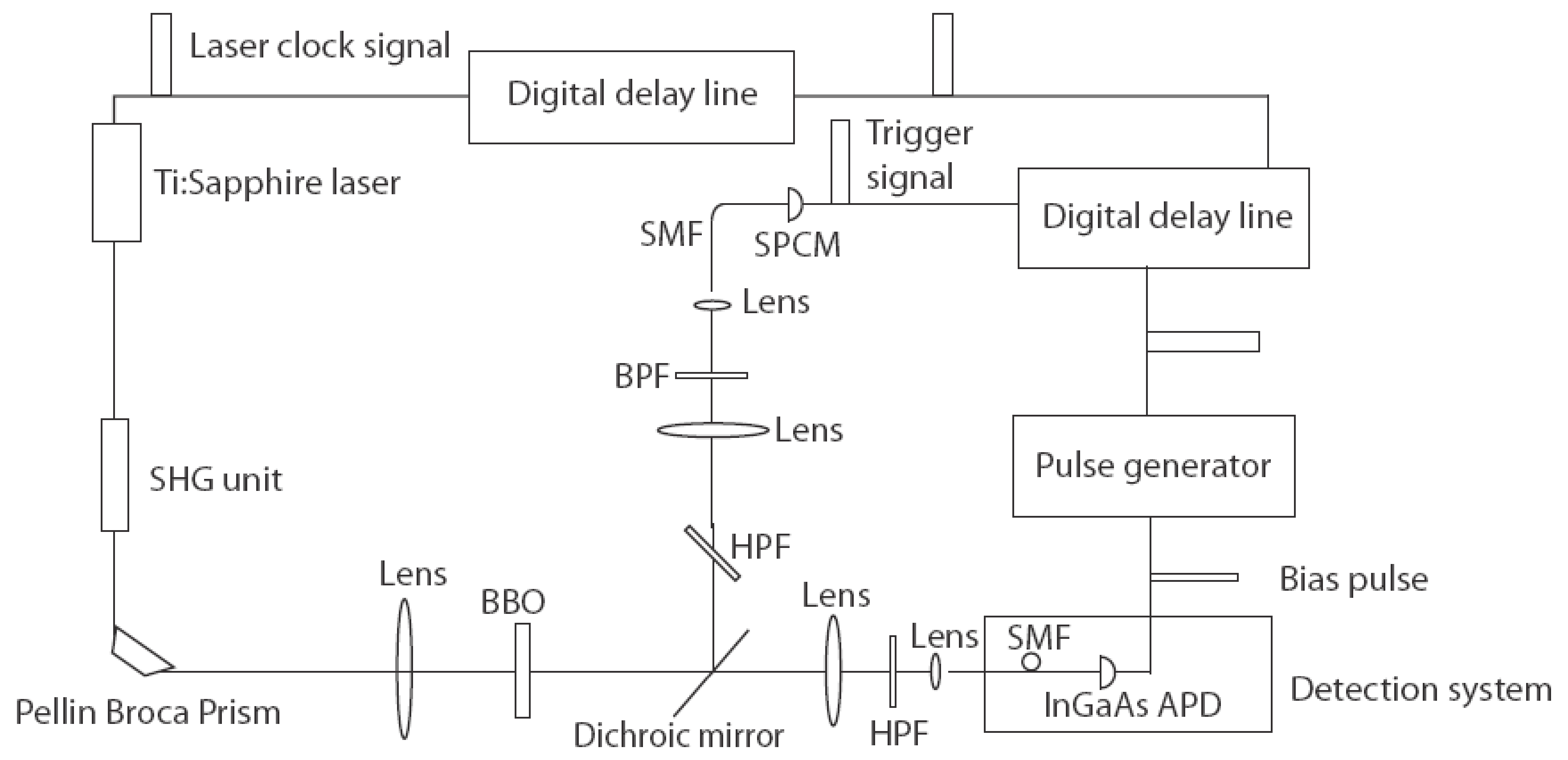
… or excite them with ultrafast pulses and collect spontaneous emission.



1.3 micron photons from QDs (Toshiba/Cambridge)

PDC as a single photon source

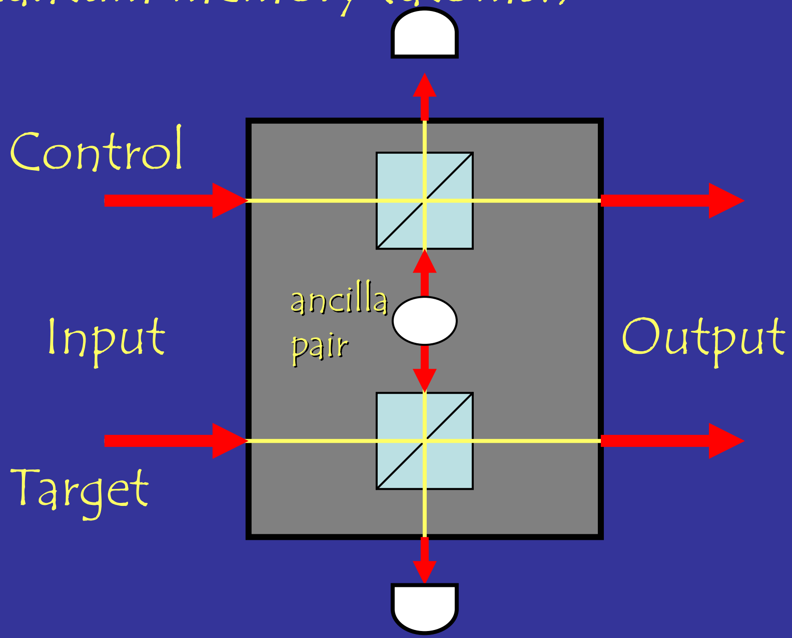
Detect a photon from the PDC process; that indicates presence of a single photon, the other half of the EPR pair.



Linear-optical QC architectures

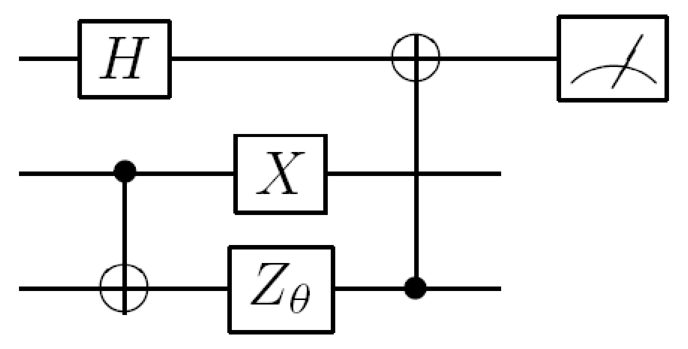
- Knill – Laflamme – Milburn (KLM) proposal:
  - Conditional non-linear two-photon gates
  - Teleportation
  - Error correction
- Nonlinearity is the measurement; the gates are probabilistic, but **heralded**
- Need:
  - Single-photon source
  - Number-discriminating photon detectors
  - Feed-forward control and quantum memory (atoms!)
- Example: CNOT gate

CNOT is performed if only one photon is detected; probability of success is 25%; scalability by teleporting the gates



Cluster state LOQC architecture

- Circuit model quantum computing: initialize, perform (conditional) gates, measure



- Cluster state quantum computing (Raussendorf and Briegel): prepare an entangled state, perform measurements. Cluster state can be efficiently (i.e. scalably) prepared using probabilistic entanglement; quantum memory is essential.

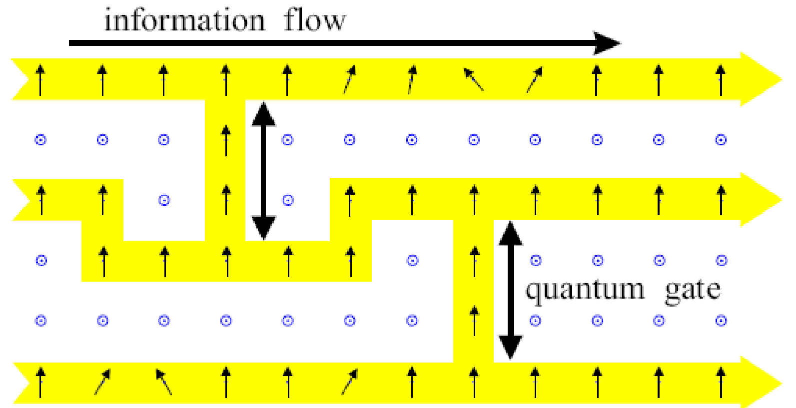
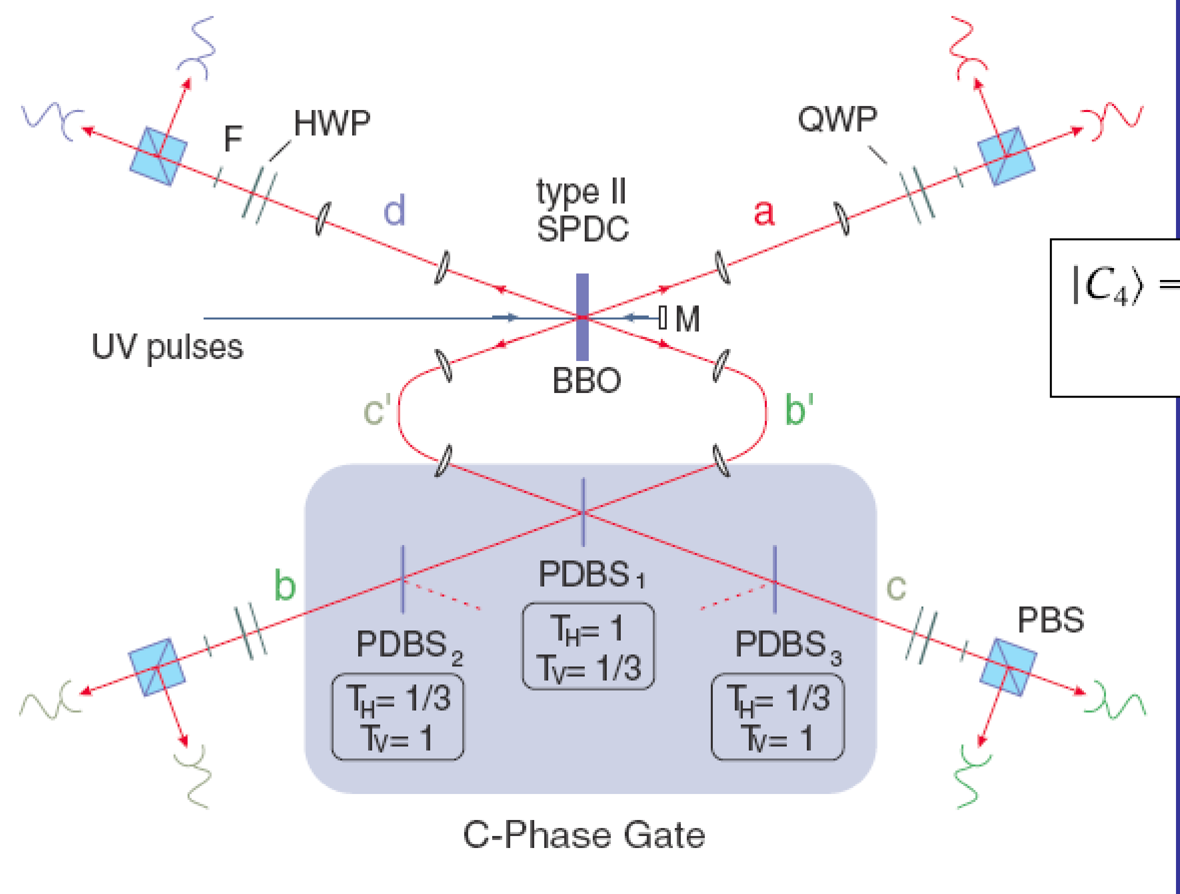


FIG. 1. Simulation of a quantum logic network by measuring two-state particles on a lattice. Before the measurements the qubits are in the cluster state $|\phi\rangle_C$. Circles $\odot$ symbolize measurements of σ_z, vertical arrows are measurements of σ_x, while tilted arrows refer to measurements in the x-y-plane.

Four-qubit cluster state



$$|C_4\rangle = \tfrac{1}{2}(|HHHH\rangle_{abcd} + |HHVV\rangle_{abcd} + |VVHH\rangle_{abcd} - |VVVV\rangle_{abcd}),$$

Weinfurter group, MPQ (2005)

Optical qubits: already practical!

- Single photons are already being used as quantum information carriers in quantum cryptosystems.

MagiQ Technologies (USA)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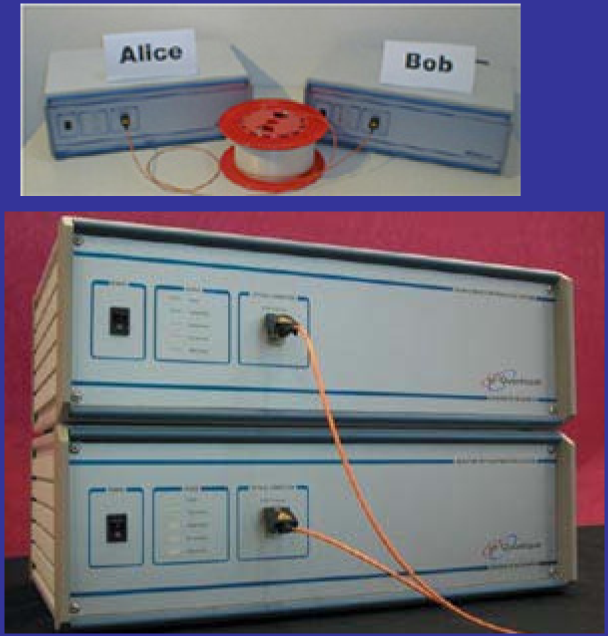

id Quantique (Switzerland)